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Part I

Introduction

Avant-propos

Ce document présente les lignes directrices du Programme National de Cosmologie et Galaxies (PNCG), qui est issu de la fusion des anciens Programmes Nationaux de Cosmologie (PNC) et Galaxies (PNG).

La brève introduction ci-dessous décrit l'évolution des priorités scientifiques du PNC et du PNG au cours des dernières années et les grandes questions du futur en cosmologie et physique et évolution des galaxies. Dans le chapitre II sont illustrés les faits saillants des recherches récentes conduites par des équipes françaises dans ce vaste domaine. Le chapitre III présente une réflexion élaborée de la communauté sur les grands objectifs de la discipline, et le chapitre IV les projets et instruments qui permettront d'en relever les défis. Les rôles transversaux joués par les recherches théoriques, les simulations et l'observatoire virtuel sont abordés au chapitre V. Les chapitres II, III, IV et V sont rédigés en anglais, car ils sont susceptibles d'intéresser des lecteurs non francophones.

Evolution du PNC et du PNG en PNCG

Le PNCG est né de la fusion des anciens PNC (1997–2008) et PNG (2001–2008). Le PNC fut créé après le regroupement de la communauté des chercheurs travaillant sur la physique de l'Univers et l'évolution de son contenu dans un Groupe de Recherche (GdR) en 1993. Il était financé par la CSA de l'INSU, le CNES, le CEA, l'IN2P3 et le SPM (MPPU). De son côté, le PNG fut créé après le regroupement de la communauté des chercheurs travaillant sur la physique des galaxies dans un GdR en 1997. Il était financé par la CSA de l'INSU et le CNES. La constitution de 'Programmes Nationaux' a permis d'aller au-delà de l'établissement des collaborations entre équipes et l'animation de la communauté. Elle a permis d'initier et favoriser des grands projets aussi bien instrumentaux (ballon Archeops; expériences de recherche de matière noire EDELWEISS, MANOLIA/ROSEBUD; instrument VLT de deuxième génération MUSE; Fabry-Perot 3D-NTT) que de traitement et d'archivage de données (Terapix, Hyperleda, Migale) et de simulations numériques (Horizon). Le PNC et le PNG ont aussi permis à la communauté de prendre une part très active dans l'exploitation des TGE (CFHT; VLT: VIMOS, GIRAFFE, UVES, NAOS; IRAM; HST; GALEX) et la préparation scientifique des grands équipements futurs (VLT-2, E-ELT, ALMA, Herschel/Planck, GAIA, mission spatiale énergie noire, LOFAR/SKA). Ainsi, le PNC et le PNG ont procédé par leurs financements à l'initiation de projets (dont le financement lourd a ensuite été pris en charge par l'INSU), à leur évaluation, à l'établissement des priorités, au soutien de la communauté pour l'exploitation des grands équipements, et à la réflexion sur la prospective scientifique pour les projets à moyen et plus long termes.

La nécessité d'une fusion entre le PNC et le PNG peut se comprendre en examinant plus en détail les thèmes scientifiques qui ont été soutenus par ces programmes au cours des dernières années. Le PNC s'est intéressé, très schématiquement, à deux grandes catégories de thèmes:

1. **Physique et contenu de l'Univers** (conditions initiales; modèles standard/alternatifs; paramètres cosmologiques; composantes de matière noire et d'énergie noire)

    - Modèles théoriques de l'Univers primordial
    - Paramètres cosmologiques
    - Matière noire et formation des structures
    - Energie noire

2. **Evolution des structures de l'Univers** (structuration de la matière; formation et évolution des galaxies; évolution du milieu intergalactique)

    - Fonds diffus
    - Réionisation
    - Populations de galaxies
    - Milieu intergalactique

Le PNG s'est intéressé plus aux détails de la formation et l'évolution des galaxies en tant qu'objets individuels, que l'on peut regrouper sous deux grand thèmes:

1. **Processus physiques de formation et d'évolution des galaxies** (influence de l'environnement; galaxies à différentes époques; nature des premiers objets)

    - Histoire de la formation d'étoiles
    - Dynamique des galaxies à différentes époques
    - Environnement (groupes et amas) et fusion des galaxies
    - Alimentation des AGN

2. **Galaxies résolues en étoiles** (formation d'étoiles à petite échelle en relation avec le milieu interstellaire; populations stellaires; dynamique et histoire des composants)

    - La Voie Lactée: dynamique
    - Histoire fossile de l'évolution chimique
    - Formation d'étoiles à petite échelle, IMF
    - Groupe Local: diagrammes couleur-magnitude, amas globulaires

Le PNC et le PNG se sont donc tous deux fortement intéressés à la formation et l'évolution des galaxies. Cette interface PNC/PNG est devenue prépondérante au cours des dernières années, car des moyens observationnels de plus en plus performants permettent d'étudier les propriétés de grands échantillons de galaxies distantes avec presqu'autant de détail que celles des galaxies de l'Univers local. De ce fait, les études sur la formation et l'évolution des galaxies en tant qu'objets individuels et celles sur l'évolution de populations de galaxies dans un Univers hierarchique dominé par la matière noire se sont entremêlées. Cette synergie a conduit à une fusion des communautés PNC et PNG dans divers domaines: l'étude des premiers objets (galaxies ou noyaux actifs) qui ont illuminé l'Univers à la sortie de l'âge sombre; la structuration de l'Univers (sous l'influence de la matière noire et l'énergie noire) qui détermine l'environnement et les propriétés physiques des galaxies individuelles; les histoires de formation d'étoiles et d'enrichissement chimique des galaxies; l'évolution du milieu intergalactique (réservoir de gaz accrété par une galaxie); la résolution des fonds diffus multi-longueurs d'onde en objets individuels à différentes époques; etc. Le soutien par le PNC et le PNG des nombreux projets portés par cette communauté composite demandait une coordination étroite entre les conseils scientifiques des deux programmes.

C'est donc en toute logique que, à l'occasion du renouvellement du PNG et avec un an d'avance sur le renouvellement du PNC, les communautés PNC et PNG ont décidé de se regrouper au sein d'un seul Programme National de Cosmologie et Galaxies, dont les axes scientifiques prioritaires sont:

- La physique de l'Univers primordial et de l'inflation
- L'Univers invisible et la formation des structures: énergie noire et matière noire
- L'histoire cosmique des baryons (gaz, etoiles, galaxies, poussière)
- Les processus physiques des galaxies (dynamique, formation d'étoiles)

Ces questions, au coeur des problèmes actuels de l'astrophysique, regroupent l'ensemble des thèmes phares des anciens PNC et PNG. Toutefois, leur articulation nouvelle au sein d'un même Programme National permettra un soutien plus efficace et une meilleure harmonisation des travaux de la communauté. Dans ce sens, le PNCG représente plus qu'une simple union des actions du PNC et du PNG. C'est une véritable *fusion* qui devrait augmenter sensiblement l'impact scientifique du soutien des organismes de tutelle aux recherches nationales dans le domaine 'cosmologie et galaxies'.

A l'instar du PNC et du PNG, le PNCG est un programme pluri-organisme financé par la CSA de l'INSU, le CNES, le CEA, l'IN2P3 et le MPPU. L'objectif premier du programme est un rôle fédérateur de prospective pour la communauté 'cosmologie et galaxies', en particulier dans la définition des priorités scientifiques et donc des grands équipements présents et futurs. Le PNCG continuera ainsi de mettre en place des ateliers et des groupes d'experts pour identifier et promouvoir les programmes clés à accomplir pour maximiser le retour scientifique de ces grands équipements, dans la lignée des actions menées de concert par le PNC et le PNG depuis quelques années (journée 'LOFAR/SKA'; journée 'énergie noire'; journée 'E-ELT'). Ce rôle fédérateur dans l'accompagnement sur le long terme des grands projets nationaux et internationaux se distingue de celui de l'ANR, qui peut fournir un soutien plus substantiel mais ponctuel à certaines phases de projets très ciblées.

La cosmologie et les galaxies

Les axes scientifiques prioritaires du PNCG décrits ci-dessus recouvrent l'évolution de l'Univers depuis son origine jusqu'aux propriétés des galaxies locales telles que la Voie Lactée. Pour réponde à ces questions, de nombreux grands projets d'observations, de modélisation et de simulations sont en cours, dans lesquels la communauté française est active, compétitive et a une expertise reconnue.

Parmi les principaux résultats de ces dernières années dans lesquels les équipes françaises se sont distinguées, on peut citer par exemple les avancées majeures en cosmologie de précision avec la mesure des paramètres fondamentaux de l'Univers par la statistique des supernovae à grand décalage spectral (avec le SNLS) et celle du cisaillement gravitationnel (CFHT-LS). Des progrès importants ont été accomplis aussi dans la caractérisation de la physique du gaz chaud emprisonné dans les halos sombres de groupes et amas de galaxies, grâce à la spectroscopie X (avec XMM et Chandra), et dans celle de l'histoire de la formation d'étoiles et de l'empoussièrement des galaxies depuis des décalages spectraux $z \gtrsim 1$, grâce aux observations ulraviolettes et infrarouges (avec GALEX et Spitzer). Les relevés modernes comme le SDSS, le 2dFGRS, le VVDS, COSMOS et GOODS ont permis l'extraction de contraintes révolutionnaires sur les propriétés physiques (masses, taux de formation d'étoiles, activité nucléaire, enrichissement chimique, structure, cinématique etc.) de centaines de milliers de galaxies locales et de dizaines de milliers de galaxies à des décalages spectraux $z \gtrsim 1$ et de leur distribution à grande échelle. A très grands décalages spectraux ($z \gtrsim 7$), les études d'objets amplifiés par les télescopes gravitationnels que sont les amas de galaxies ont ouvert une nouvelle fenêtre sur le jeune Univers. En parallèle, des efforts majeurs ont été déployés dans les simulations numériques de formation de galaxies dans un contexte cosmologique (comme le projet Horizon). Pour accompagner l'exploitation et la valorisation de ces projets ambitieux dans lesquels les données prennent une importance capitale, le PNC et le PNG ont également soutenu le traitement, l'archivage et la diffusion de données observationnelles (Terapix, Hyperleda, Migale, VVDS, Denis, Goldmine, etc.), de modélisation (Galaxev, Pegase) et de simulations (Galics, Horizon).

Ces travaux ont contribué à la définition des quatre axes scientifiques prioritaires du PNCG mentionnés plus haut. Plusieurs grandes questions seront au centre des préoccupations des prochaines années dans le domaine de la cosmologie et de l'évolution des galaxies. Pour commencer, les recherches théoriques sur les conditions initiales du modèle cosmologique et les modèles d'inflation vont bénéficier de nouvelles contraintes sévères apportées par le satellite Planck et le LHC (et les expériences sur la polarisation du rayonnement de fond cosmologique, comme BRAIN). Par ailleurs, une préoccupation majeure sera de soutenir une participation française forte et prédominante, dans la lignée des efforts déployés jusque là, aux expériences multi-sondes de recherches sur l'énergie noire (supernovae distantes, oscillations acoustiques baryoniques et cisaillement gravitationnel), au moyen de grands relevés astronomiques à partir du sol (projets VIPERS, BOSS, HSHS, LSST) et de l'espace (mission ESA/NASA). Côté matière noire, les progrès techniques des détecteurs laissent espérer la découverte prochaine de particules supersymétriques stables (WIMPs; avec les projets EURECA, CYGNUS et XENON), et la détection de premières particules supersymétriques par le LHC consituerait un pas important dans ce sens.

De grands projets d'observations et de simulations numériques dans lesquels plusieurs équipes françaises sont fortement impliquées devraient aussi permettre des avancées majeures dans notre compréhension de l'évolution des stuctures et de la formation des galaxies. Par exemple, la perspective d'observations radio du gaz neutre à des décalages spectraux de l'ordre de $z \sim 10$ avec LOFAR (et plus tard SKA), combinées avec la détection des premiers objets – galaxies ou noyaux actifs – ayant illuminé l'Univers avec le JWST (et plus tard SPICA et l'E-ELT), laisse entrevoir des études détaillées de l'époque de la réionisation. A des époques cosmiques plus récentes, la structuration de la matière noire et les propriétés physiques des baryons qu'elle abrite vont pouvoir être explorées en détail grâce à plusieurs nouveaux développements: la statistique du gaz intergalactique (composition, degré d'ionisation, distribution spatiale) observé en absorption le long des lignes de visée d'objets lointains (VLT, E-ELT, SDSS-III) et en émission X et ultraviolette (expérience FIREBALL); la statistique des amas de galaxies (détectés par LOFAR, Chandra, XMM, Planck, XEUS/IXO); les anisotropies des fonds de rayonnement à diverses longueurs d'onde (Planck, Herschel, Fermi, IXO); et la mesure directe de la distribution de masse dans l'Univers par tomographie du cisaillement gravitationnel (KIDS/VIKING, LSST, mission spatiale énergie noire).

Par ailleurs, la possibilité d'observer aux très petites échelles les galaxies aussi bien proches que distantes avec les futurs équipements multi-longueurs d'onde à haute résolution spatiale (KMOS/VLT, MUSE, JWST, ALMA) ouvre la voie aux études dynamiques de galaxies à toutes les époques cosmiques. Ces études devraient révolutionner notre compréhension du lien entre formation d'étoiles et activité nucléaire et permettre d'éclaircir l'influence de l'environnement sur l'évolution des galaxies. Aux échelles galactiques encore, les futures observations infrarouges et radio (Herschel, IRAM/NOEMA, ALMA) révèleront des détails sans précédent sur le lien entre milieu interstellaire et formation d'étoiles. Enfin, dans la Voie Lactée et certaines galaxies du Groupe Local, la spectroscopie multi-objets (SEGUE, RAVE, et surtout GAIA, puis E-ELT) permettra de caractériser la cinématique et les abondances de grands échantillons d'étoiles, apportant des contraintes d'un type nouveau à la fois sur l'histoire de fusion hiérarchique de ces galaxies et sur la nucléosynthèse primordiale.

Une part importante de ces avancées viendra des progrès attendus des simulations numériques. Les équipes françaises ont mené à bien au cours des dernières années certaines des plus ambitieuses simulations jamais accomplies aux échelles cosmologiques (Horizon; époque de la réionisation) et galactiques (interactions de galaxies; formation de sous-structures). Deux défis majeurs des prochaines années consisteront d'une part à introduire une description multiphasique du milieu interstellaire, et d'autre part à améliorer le traitement de la formation d'étoiles et de l'évolution chimique pour mieux décrire les phénomènes tels que la rétroaction des supernovae (et noyaux actifs) sur le gaz.

L'aboutissement de ces grands chantiers dans un domaine en pleine effervescence, qui va bénéficier de la mise en opération de plusieurs nouveaux grands équipements internationaux, devrait bouleverser notre compréhension des phénomènes physiques qui ont façonné l'évolution de l'Univers depuis son origine jusqu'à l'épanouissement de la population de galaxies que nous observons aujourd'hui. La communauté française a oeuvré au cours des dernières années pour se forger une place au premier rang dans cette thématique. Elle y est parvnu. Le PNCG a la volonté de maintenir et conforter cette place en soutenant les équipes et les projets phares et en fédérant les chercheurs.

Part II

Recent Scientific highlights

II.1 Recent advances in precision cosmology

II.1.1 Cosmic Microwave Background

Xavier Désert, LAOG

The Cosmic Microwave Background (CMB) is the relic radiation that signs, along with the primordial nucleosynthesis, the presence of a hot phase in the early Universe. Due to the expansion, its blackbody temperature is now a mere $2.725 \pm 0.001\,\mathrm{K}$ as measured by COBE, the first-generation CMB satellite. COBE, WMAP (the second-generation satellite) and sub-orbital experiments have measured with increasing precision and angular resolution the minute temperature fluctuations (Fig. II.1). The power spectrum of these anisotropies is remarkably well fitted by very simple models using a set of about ten cosmological parameters (e.g. the Hubble constant, the baryonic matter, the dark matter, and the dark energy densities). The parameters of such a model are listed in Table II.1. Even though the assumptions behind these inflationary-based cosmological models are heavy, the scientific community has massively embarked into the so-called precision cosmology which will soon culminate with Planck (2009) the third-generation CMB satellite. The price to pay is an awkward universe which is dominated by dark energy and dark matter of which we know practically nothing. On the positive side, the CMB observations allow one to set the scene for the evolving universe. It provides the initial conditions (a near Harrison-Zel'dovich power law spectrum of fluctuations) that will lead to the formation, by gravitational collapse, of the large-scale structures, the galaxies, the stars and ultimately us. Finally, polarization and high angular resolution observations are the most promising tools for further advance in the CMB field. Large-scale polarization measurements are one of the few experimental tests of the inflationary paradigm and CMBPol (NASA), Sampan (CNES) and BPol (ESA) were space (4th-generation) projects towards this goal. Along with high-resolution cameras to observed secondary anisotropies, these projects and their successors require the development of thousand-pixel millimeter and radio arrays.

Table II.1: 5-year WMAP constraints on the main parameters of a simple ΛCDM cosmological model [189]. The derived Hubble constant is $H_0 = 71.9 \pm 2.7\,\mathrm{km\,s^{-1}Mpc^{-1}}$.

Ω_Λ	Ω_c	Ω_b	n_s	σ_8	τ
0.742	0.214	0.044	0.963	0.796	0.087
±0.030	±0.027	±0.003	±0.015	±0.036	±0.017

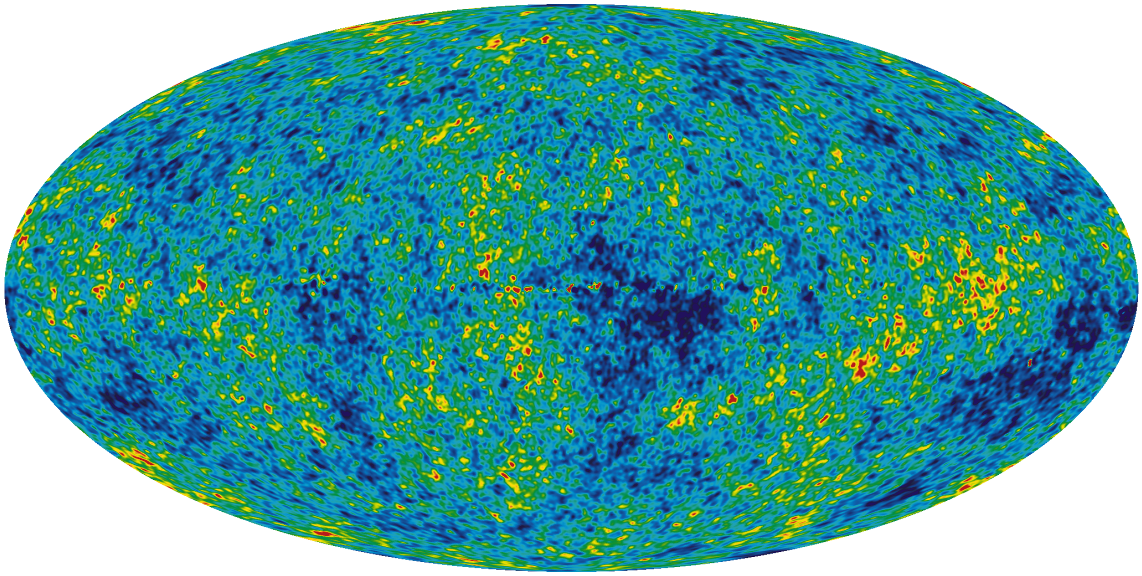

Figure II.1: The latest WMAP (5-year) all-sky Mollweide Galactic projection of the CMB. It is obtained by optimally combining the centimetric radio observations at different wavelengths. The color scale spans a range from −200 to +200 microK only as compared with the total 2.725 K background [276].

II.1.2 Type Ia Supernovae

Pierre Astier, LPNHE

Over the last decade, type Ia supernovae (SNe Ia) have been used as distance indicators. The comparison of distances to distant SNe Ia's (at $z \sim 0.5$) and nearby ones ($z \lesssim 0.1$) led in late 1998 to the discovery of the acceleration of the expansion of the Universe. The last decade has confirmed the leading role of distances to SNe Ia to constrain the expansion history of the universe, through the distance-redshift relation, where distances are derived from the apparent luminosity of the events.

The photometry of SNe Ia events is now obtained using the 'rolling-search' approach, i.e. the repeated multi-band imaging of the same telescope pointings using wide-field imagers. Four large-scale surveys have been conducted using this technique : the PANS survey using HST, the SDSS-SN search, ESSENCE at CTIO, and the SNLS (within the CFHT Legacy Survey)[470, 230, 388, 27]. The French SN community (supported by PNC) has been involved in the SNLS, which produced the tightest constraints so far on the dark energy equation of state using its first year dataset. This demonstrated that the rolling-search approach improves both the statistics and the quality of the measurements. For example, in the SDSS and the SNLS, most of the events are measured in at least 3 photometric bands, enabling stringent tests on the reproducibility of SNe Ia colors. The analyses of these surveys are expected to appear within the next two years.

Although the evolution of supernovae properties with redshift was the dominant concern regarding this cosmological probe, the new high-quality data have revealed no sign of evolution of supernova properties with redshift. The metrologic limitation of the supernova approach is that distances (and even ratio of distances) rely on a photometric calibration. Quantitatively, measuring the dark energy equation-of-state parameter w (Section III.1.2) at a 1% precision requires a better than 2‰ precision of the photometric calibration. For reference, the currently achieved accuracies lie around 1% and constitute a serious bottleneck for modern surveys. All large-scale supernova projects, be they ground- or space-based, propose a scheme to beat this limitation. A serious challenge for a substantial increase of SNe Ia statistics over the current surveys is to setup a photometric selection of events. This is because the spectroscopic confirmation of events from current surveys is already a heavy load on 8-m class telescopes. Another challenge is to collect a large enough nearby sample matching in quality the distant samples, in particular relying on the rolling-search approach.

The techniques for measuring distances to supernovae have matured over the last decade through the successful achievement of second-generation surveys. The route to third- and fourth-generation of projects seems clear enough for this approach to continue to deliver a significant (if not leading) contribution to the measurements of the late expansion history of our Universe.

II.1.3 Cosmic shear

Yannick Mellier, IAP

The Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) is now entering its last year of observations. Over the period 2007-2008, a large fraction of night was dedicated to the CFHTLS-'Wide'. When completed by the end of January 2009, the four patches W1, W2, W3 and W4 of this survey will comprise 170 deg^2 observed with Megacam in u, g, r, i and z bands, and exposure time of about one hour per filter. The mean redshift of the Wide galaxy sample is about 0.9. A subsample of galaxies also belong of the CFHT-'Deep' survey and the VVDS spectroscopic survey (Section II.2.5), which anchors the measurements of photometric redshifts for the entire galaxy population in each field.

During the past year, an international team of French and Canadian astronomers lead by scientists based at the Institut d'Astrophysique de Paris (IAP) and the Université Paris 6 (UPMC) in France, the University of British Columbia (UBC) and the University of Victoria (UVic) in Canada has made a major advance in weak lensing studies of the Universe using the CFHTLS Wide data [231]. The team used the third-year Terapix release (T0003) of CFHTLS-Wide data to explore the weak gravitational distortion of galaxies by large-scale structure, in the linear regime. Their results place the best constraints ever obtained using weak lensing surveys on the scaling of the amplitude of the matter power spectrum σ_8 with the matter density Ω_m.

The unprecedented contiguous area of this survey, which spans 57 square degrees to $i'_{AB} = 24.5$ over 3 independent fields, permits high signal-to-noise measurements of the 2-point shear statistics on scales from 1 arcmin to 4 degrees. The control of systematic errors was achieved by first validating the ellipticity measurement software using STEP (Shear TEsting Program) simulations (an international database of simulated sheared images). Then, an E/B-mode decomposition of the data was performed, followed by a check of the star-galaxy cross correlation function. This allowed the team to demonstrate the percent-level accuracy of the weak lensing analysis, the most accurate obtained so far. The amplitude of the cosmological weak lensing signal was then scaled accurately by calibrating the galaxy redshift distribution of lenses and sources using redshift data from overlapping T0003 CFHTLS-Deep/VVDS fields. This unique matching between Wide and Deep samples provides a bias-free galaxy distribution.

Using this fully calibrated dataset, the team explored the variation of the weak lensing signal as a function of angular scale, which probes the projected dark matter power spectrum. The lensing signal was analyzed on all scales ranging from 1 arcmin to 4 degrees. The resulting largest physical scale probed by this study is thus 85 h_{70}^{-1} Mpc, assuming a mean redshift of the lenses of 0.5 and a ΛCDM cosmology. Using the 'aperture-mass' statistic over the full range of angular scales yields the constraint $\sigma_8(\Omega_m/0.25)^{0.64} = 0.785 \pm 0.043$, in excellent agreement with WMAP 3-year constraints. Moreover, the large angular scales probed by cosmic-shear data allows one to constrain cosmological models from the weak-lensing signal detected on linear scales only. Using only angular scales $\theta > 85$ arcmin yields $\sigma_8(\Omega_m/0.25)^{0.53}_{\rm lin} = 0.837 \pm 0.084$, in agreement with the results from the full analysis. The combined constraints from this study and WMAP 3-year results yield $\Omega_m = 0.248 \pm 0.019$ and $\sigma_8 = 0.771 \pm 0.029$. The WMAP team has since found excellent agreement between these results and their 5-year data.

The synergy between the VVDS redshift survey and the CFHTLS weak lensing survey sets the cosmological lensing signal on solid grounds. The early decision to select the same fields for both surveys proved to be of primary importance for cosmological constraints derived from the CFHTLS Wide data. Perhaps the most promising results from this work is the exploration of lensing signal on scales where the linear theory of structure formation applies.

II.2 Recent advances in galaxy formation and evolution

II.2.1 XMM & Chandra

Etienne Pointecouteau, CESR

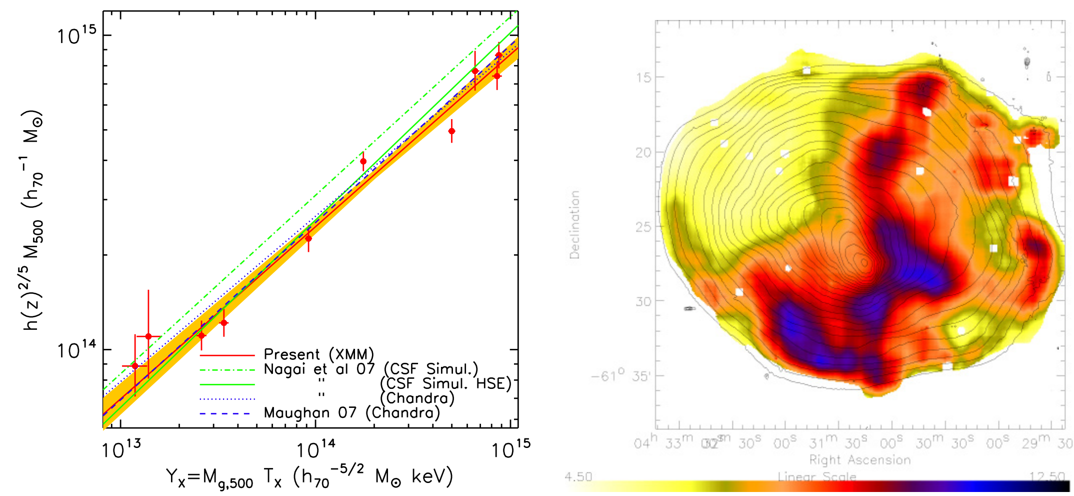

Figure II.2: Left: Relation between cluster mass and Comptonization parameter, $M_{500} - Y_X$, derived from the XMM observations of 10 nearby relaxed galaxy clusters [23]. **Right:** Temperature map of the post-merging cluster A3242 [491].

Over the past five years, the possibility to perform spatially resolved X-ray spectroscopy with the XMM and Chandra observatories has greatly improved our understanding of the formation and evolution of dark-matter halos and the physics of the hot gas hosted by halos on galactic and cluster scales.

Studies of local samples of relaxed objects have allowed precise measurements of gas density and temperature profiles, which in turn can be translated into dynamical-mass profiles. The observed universal shape of these profiles on scales from early type galaxies to clusters [443, 567, 280, 110, 453, 154] is in good agreement with the prediction of a simple model in which structure formation is driven purely by gravity. Moreover, scaling relations, such as the mass-temperature relation, $M - T_{\rm X}$ [20, 567], and the mass-Comptonization parameter relation, $M - Y_{\rm X}$ [405, 23], are now well calibrated for nearby relaxed clusters. These results demonstrate our basic qualitative and quantitative understanding of the dark-mater physics in the framework of the standard model (see Fig II.2, left panel). They justify the use of X-ray clusters as cosmological tools via studies of, for example, the baryonic mass fraction [361] and the cluster mass distribution [568]. X-ray data have also helped test theories of MOdified Newtonian Dynamics (MOND) [390] on the scale of galaxy clusters [444, 15].

In detail, however, X-ray observations show important departures from the predicted statistical properties of hot gas in dark-matter halos [453]. This presumably reflects the influence of non-gravitational physical processes in the intergalactic/intracluster medium (IGM/ICM) on the baryonic component of halos [569, 20]. The ghost cavities, ripples and other density and temperature features unveiled by XMM and Chandra have allowed detailed investigations of feedback heating by AGNs and starbursts in clusters and groups. The precise way in which this heating occurs and is linked to the cooling material accreted onto the supermassive black holes hosted by active galaxies and to the starburst activity of the brightest cluster galaxies is still unclear [208, 457, 380]. Recent deep XMM and Chandra surveys have also shown that the ratio of low-luminosity to high-luminosity AGNs is more important at low than high redshift [268]. This 'downsizing' effect is also observed in the star formation activity of galaxies and may be a consequence of a co-evolution of galaxies and supermassive black holes [272, 513].

The observed density and temperature rims revealed by X-ray observations, the discontinuities, cold fronts and other shocks in hot-gas halos are additional valuable signatures of the dynamical state of clusters and groups (see Fig II.2, right panel) [191, 491, 366]. XMM and Chandra have played a crucial role in linking the merger and accretion histories of halos, galaxy mergers and interactions and the ram-pressure stripping of gas to the evolution of galaxies in dense environments [458, 294] and the process of chemical enrichment (traced via observations of X-ray lines) [336, 576].

Finally, XMM and Chandra have allowed the detection of the most distant galaxy clusters known to date, which set strong constraint on models of structure formation [96, 275].

II.2.2 GALEX & Spitzer

Véronique Buat, LAM

By opening windows on the Universe at ultraviolet ($\lambda = 1500$ and 2300 AA) and infrared ($\lambda > 8\,\mu$m) wavelengths, respectively, the GALEX and Spitzer missions have allowed measurements of the star formation activity of galaxies out to redshift $z \sim 1$.

A major result from these studies is that the galaxy luminosity function in the rest-frame infrared appears to have strongly evolved since the epoch $z = 1$, in the sense of galaxies were significantly brighter in the past [334]. The galaxy luminosity function has also been found to evolve in the rest-frame ultraviolet [584, 24], but to a lesser extent than in the infrared. This implies that the mean dust obscuration in the Universe, measured as the ratio of the infrared-to-ultraviolet flux densities [104], increases from $z = 0$ to $z = 1$ [535]. At the same time, the dust attenuation in individual galaxies of fixed bolometric luminosity appears to decrease slightly from $z = 0$ to $z = 1$, the effect being strongest for Lyman-Break Galaxies at $z = 1$ [105, 287, 112, 113].

These studies have also allowed the first quantitative exploration of the role of environment on the evolution of galaxies at redshifts out to $z = 1$. Unlike in the local Universe, star formation at $z \sim 1$ appears to be enhanced in dense environments [198], a phenomenon which must now be reproduced by models aimed at predicting the evolution of galaxies.

GALEX and Spitzer have also been used to carry out detailed studies of the local Universe. For example, GALEX has collected spatially resolved images of several hundred nearby galaxies [246], including most of the 75 galaxies of the Spitzer Infrared Nearby Galaxies Survey (SINGS) [308]. A very broad multi-wavelength coverage of this representative set of galaxies is now available for the community. The dust attenuation remains a major issue when using the ultraviolet emission alone, and it has been shown that methods based on the shape of the ultraviolet continuum are not universal and must be used with much caution [316, 104, 149, 65]. Among the many other original studies enabled by GALEX and Spitzer observations are a detailed investigation of the star formation history of nearby cluster galaxies, including the dwarf galaxy component [68, 69]; a reassessment of the relation between gas content and star formation [65]; and the discovery of a new class of extended ultraviolet galaxies[247].

II.2.3 SDSS

Vivienne Wild, IAP

After eight years of operation, the Sloan Digital Sky Survey (SDSS) has recently been completed; the final data release took place in November 2008. The survey consists of deep, multi-colour images covering more than a quarter of the sky and spectroscopic follow-up of more than one million galaxies and 10^5 quasars. The legacy aspect of this project is considerable. Not only are the majority of recent papers based on SDSS led by researchers from outside the consortium, countless follow-up proposals to telescopes worldwide are now based upon SDSS data.

An accurate cosmological model is required for interpreting galaxy formation and evolution data. By using galaxies to trace cosmological structures in the present-day Universe, the SDSS and smaller 2dF galaxy redshift survey (2dFGRS) have been combined with the CMB measurements which probe the early universe to tighten constraints on cosmological models [537]. The imprint of acoustic oscillations from the early universe on the clustering of present-day galaxies, first observed in the 2dFGRS and SDSS, allowed a precise measure of the geometry of the Univserse, confirming standard model predictions [197].

The SDSS has revolutionized our understanding of low-redshift galaxy populations. Already the SDSS provides the benchmark for comparisons with high-redshift surveys such as the VVDS. The strong bimodality in galaxy characteristics, such as colour, mass and star formation rate, has been accurately quantified [527, 302]. The relation between galaxy stellar mass and metallicity has been measured, crucial for understanding the chemical build-up of the Universe [549, 233]. The SDSS has allowed the precise measurement of the evolution of the oldest and most massive galaxies in the universe: their stellar populations have evolved almost passively after a formation epoch around 9 Gyr ago [53]. One surprise lay in studies of galaxy environments. The local environment was found not to be a leading cause of the structural and stellar population differences of galaxies, as had previously been suggested [33]. Neither does a dense environment lead to an enhancement in the fraction of low luminosity Active Galactic Nuclei (AGN) hosted by galaxies [392]. Instead, stellar mass appears to be the main driver of the bimodal nature of the galaxy population and the physical processes which lead to the triggering of an AGN remain to be found.

The link between supermassive black holes and their host galaxies has been another topic on which the SDSS has made a large impact. Present day black hole growth occurs in relatively massive galaxies with young stellar populations, helping to explain why the growth of the supermassive black hole can be tightly coupled with the growth of the galaxy bulge even today [272]. The SDSS has been the survey of choice for detecting the highest redshift quasars known [213], providing crucial constraints on the epoch of reionization in the early Universe [38].

And finally, closer to home, the millions of stars detected in the photometric survey have allowed a detailed structural analysis of the Milky Way and its local surroundings. Evidence for recent cannibalism of satellite galaxies has been found [413, 43] and a plethora of newly detected dwarf satellites elicit some clues on the nature of dark matter [44].

II.2.4 Galaxy clustering with the CFHTLS

Henry J. McCracken & Yannick Mellier, IAP

Understanding the distribution of luminous matter on the sky and its relationship to the underlying dark matter distribution is a key question in observational cosmology. Such measurements can a direct probe of the galaxy formation process and can measure the efficiency with which galaxies 'light up' inside their halos of dark matter. Combined with realistic models of the distribution of dark matter (which can be tested against cosmic shear measurements) it can provide independent estimates of the masses of the dark matter halos which host all galaxies and useful information on the biasing factor and its evolution with redshift, scales, galaxy type or local environment.

The CFHTLS survey, combined with accurate photometric redshifts calibrated using very large spectroscopic surveys, represents an unprecedented opportunity to investigate the clustering of galaxies at intermediate and high redshifts. The size of the CFHTLS survey offers three important advantages over previous studies: firstly, it is possible to provide a reliable estimate of the field-to-field variance, uncertainties in which plagued previous galaxy clustering studies; secondly, one can follow similarly-selected galaxy samples (either in mass or absolute magnitude) over large ranges of redshifts (typically from $z \sim 0.5$ to $z \sim 1$); lastly one can investigate clustering dependencies on very large ranges of mass and luminosity typically from sub-L^* dwarf galaxies to massive ellipticals.

First-generation CFHTLS clustering results [378], computed from precise photometric redshifts derived in the CFHTLS deep fields [289], provided for the first time a robust measurements of the galaxy correlation length *simultaneously* as a function of type, redshift and luminosity. The four CFHTLS deep fields, separated widely on the sky, enabled a reliable estimate of the dependence of galaxy clustering on absolute luminosity and type. Blue dwarf galaxies have an extremely low clustering amplitudes (of around a few h^{-1} Mpc) which is largely invariant of redshift and absolute magnitude; redder galaxies show the expected trend of increasing clustering strength with increasing rest-frame luminosity. At intermediate redshifts ($z \sim 0.5$) we find that faint red galaxies ($0.1L^*$) have clustering amplitudes much larger than galaxies nearer L^*; this is to be expected if such galaxies exist preferentially as satellites of more massive galaxies.

The addition of near-infrared data from WIRCAM the WIRDS Large program on the CFHTLS Wide D2 field to the CFHTLS survey fields has permitted for the first time a detailed investigation of the clustering of massive ellipticals at redshifts around two, a domain largely unexplored due to the low sky density of these objects and the need for wide-field near-infrared and deep optical imaging. In a work in preparation, the dependence of clustering amplitude on angular scale for massive galaxies is shown (for the first time) to be dominated by power on very small scales (much less than a Mpc), coming from pairs within a given halo of dark matter, very different from measurements made for less massive galaxies at the same redshift. Comparing these measurements with a realistic 'halo model', which describes how galaxies populate dark matter halos, allows one to derive an independent estimate of the mass of the hosting dark matter halo. The derived halo masses of around $10^{13}M_{\odot}$ confirm that this population represents one of the most massive classes of objects known today. Any candidate theory of galaxy formation will have to explain the clustering and abundances of these objects.

With the release of the TERAPIX-T0005 dataset, the stage is now set to make a massive improvement over these preliminary studies and greatly expand our knowledge of the cosmic history of star formation and the interplay between mass and light. The latest TERAPIX release provides 125 deg^2 of five-band photometric measurements; accurate photometric redshifts for millions of galaxies have already been computed [151]. A subset of 100,000 of these galaxies from W1 and W4 fields will serve as input for a 400-hour very large spectroscopic program on ESO, led by L. Guzzo and which LAM, Marseille and IAP/TERAPIX play a leading role. The zCOSMOS spectroscopic survey carried at ESO by Lilly et al and the COSMOS collaboration is also using the CFHTLS + WIRCAM data to select its galaxy samples. The CFHTLS will finally fulfill its promise of being a 'Sloan at redshift one' and provide a unique and world-leading picture of how galaxies are distributed on the largest scales when the Universe was only half its current age.

II.2.5 VVDS

Olivier Le Fèvre, LAM

The VIMOS VLT Deep Survey (VVDS) has currently assembled a total of 45,000 spectroscopically measured galaxies and AGNs in the redshift range $0 < z \leq 5$. The galaxies have been selected on the basis of only their I-band magnitude, making this survey free of color pre-selection biases. Three sub-samples have been observed with VIMOS on the VLT, an instrument built by a consortium led by LAM [329]: a 'Deep' sample of 12,000 galaxies with $22.5 \leq I_{AB} \leq 24$, a 'wide' sample of 32,000 galaxies with $18.5 \leq I_{AB} \leq 22.5$ and an "ultra-deep" sample of 1000 galaxies with $23.0 \leq I_{AB} \leq 24.75$. Details of the Deep and Wide samples can be found in [331] and [236].

The VVDS team, composed of French and italian institutes, has been analyzing these samples to study the evolution of galaxies and their distribution in large scale structures since $z \sim 5$. The strong evolution of the luminosity function since $z \sim 2$ as been demonstrated to result mainly from an evolution late- and irregular-type galaxies [288, 590]. We find that the UV-rest luminosity density is strongly evolving since $z \sim 1.2$ [550] (combined with Galex imaging in [496]). It is mostly the low-mass galaxies which have strongly evolved since $z \sim 1.2$, as evidenced by the behavior of the stellar mass function [451]. When computing the stellar mass density evolution since $z = 2$ for all galaxies and for a 'blue' and a 'red' samples defined from the observed color bi-modality, it became evident that red galaxies went through an episode of rapid stellar mass build up during the epoch $1 < z < 2$, followed by a more quiescent phase since $z \sim 1$ [25].

The evolution of the distribution of galaxies in large scale structures has been scrutinized in details. The observed global correlation function evolution [332] is coming from the evolution of late-type galaxies, while early-type galaxies were already in place in the most massive dark matter halos at $z \sim 1$ [384], combined with a stronger clustering of brighter/more massive galaxies [446, 385]. We find that the galaxy to dark matter bias has evolved by about 40% from $z = 1.4$ to $z = 0.7$, and that the bias is more pronounced for red than for blue galaxies [364]. With a modelisation based on the Halo Occupation Distribution formalism, we find that the mass of dark matter halos has grown by a factor of 3 from $z \sim 1$ to $z \sim 0.5$, in accordance with hierarchical models of the assembly of dark matter halos [2]. The VVDS has been the first to demonstrate the strong impact of local environment on galaxy evolution since $z = 1$ as the spectral type-density relation (analogous to the morphology-density relation observed at low redshift) evolves from a steep correlation of early type galaxies with high density at low redshift, to a flat relation at $z \sim 1$ with equal probability to find red galaxies in dense and under-dense regions [158]. Finally, VVDS-Wide data at $z \sim 0.8$ have allowed the measurement of a clustering 'anisotropy parameter' $\beta = 0.70 \pm 0.26$, which demonstrated the usefulness of deep redshift surveys to measure the growth rate of large-scale structure and to separate a 'dark energy' component of the Universe from a more complex form of gravity law [264].

With a complete census of the galaxy population based on the pure magnitude selection of the VVDS, we have found that the population of bright galaxies at $z \sim 2-3$ is $2-3$ times larger than found when making a priori color selections, such as 'ugr' or 'BzK' selections [330]. This has a strong impact on the amount of star formation activity at early times in the life of the Universe [430]. We are currently analizing why a magnitude-limited sample finds more high-redshift galaxies, using the VVDS Ultra-Deep sample limited at $I_{AB} = 24.75$.

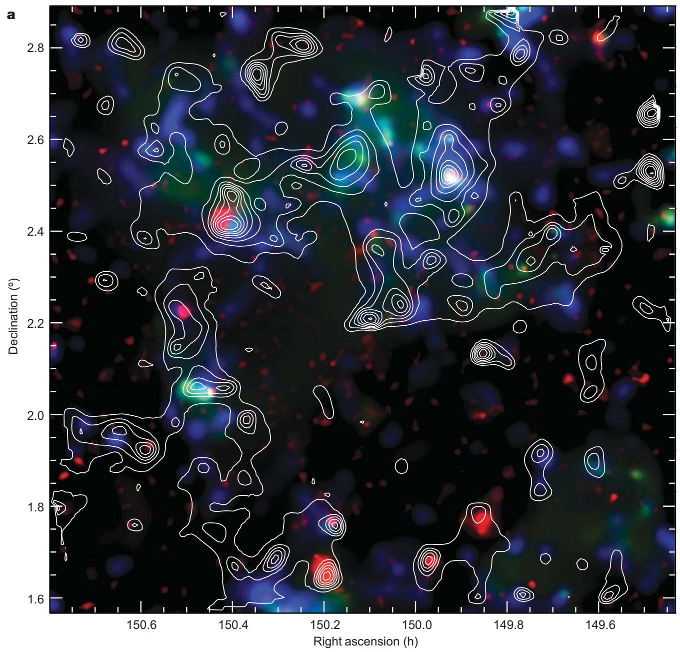

Figure II.3: Comparison of masses observed with different tracers: the total projected mass from weak lensing, dominated by dark matter, is shown as contours superimposed on an underlying color-coded image of the baryonic mass (blue: stellar mass; yellow: galaxy number density; and red : X-ray emission from clusters) [372].

The VVDS has already produced tens of refereed papers. The data from VVDS-Deep and VVDS-Wide, including spectra and redshift measurements, are publicly available on the CENCOS database at LAM (http://cencos.oamp.fr).

II.2.6 COSMOS

Hervé Aussel, CEA/IRFU/SAp

The Cosmological Evolution Survey (COSMOS) [503] is an extragalactic survey designed to study the impact of large-scale structure on the evolution of galaxies and AGNs. Started as an ACS/HST treasury-program imaging of a 2 deg^2 equatorial field, it is now one of the richest multiwavelength imaging dataset, from the X-ray to the radio domain, and is complemented by a spectrometric survey with VIMOS at ESO: zCOSMOS [342]. Thanks to the deep ACS i-band imaging and ground-based photometric redshifts, COSMOS has produced the first three dimentional map of the dark matter distribution and has compared it with that of the luminous matter, as traced by stars in the optical/near infrared and by the intra-cluster medium in the X-ray (see figure II.2.6) [372]. This study shows the possibilities that an all-sky dedicated space mission like Euclid will offer.

As of Summer 2008, the COSMOS team has published more than 50 refereed papers. COSMOS is an ongoing project where the French community is especially active in lensing studies, the spectroscopic followup and its exploitation, the near-infrared imaging with CFHT/WIRCAM and soon VISTA, and the far-infrared imaging with Spitzer and Herschel, COSMOS being a guaranteed-time target of both imagers.

II.2.7 GOODS

David Elbaz, CEA/IRFU/SAp

The Great Observatories Origins Deep Survey (GOODS) project combines a Spitzer Legacy Program (PI M. Dickinson), an HST Treasury Program (PI M. Giavalisco) and a Herschel Key Program (PI D. Elbaz). The two fields covered by this project, GOODS-North (centered on the Hubble Deep Field) and GOODS-South (centered on the Chandra Deep Field South, CDFS), were subject to intensive spectroscopic follow up from Keck, VLT and other facilities, and deep imaging follow-up at all wavelengths. This makes the GOODS fields ideal targets for future facilities such as ALMA.

The French community played a key role in exploiting GOODS data to constrain the history of star formation in the Universe, down to the level of normal galaxies at $z \sim 1$ and to that of very active galaxies (LIRGs/ULIRGs, with star formation rates $> 20\, M_{\odot}\, \mathrm{yr}^{-1}$) at $z \sim 2-3$. Support by the PNC+PNG helped the team participate actively to both the data reduction (through the funding to visits to the Spitzer Science Center) and science analysis (mainly of Spitzer data, in continuity with the expertise gained from ISO). This produced a series of important papers, showing for example for the first time that the relation between star formation actvity and local density is reversed at $z \sim 1$ compared to the present time [198]. This also led the French community to become the leading component of the natural continuation of this project in the Herschel era (see Section IV.1.2).

II.2.8 Very-high-redshift galaxies

Roser Pelló, LATT

The study of $z \gtrsim 7$ sources is an important challenge of modern cosmology in a context of international competition. Considerable advances have been made during the last years in the exploration of the early Universe, in particular on the identification of distant star-forming systems which could have been responsible for a significant part of the cosmic reionization. Recent results by WMAP seem to place the first building blocks of galaxies at redshifts up to $z \sim 10 - 15$ [518, 315]. An additional motivation comes from the detection of $z \sim 6$ galaxies with relatively large stellar masses and evolved stellar populations, which require a significant level of star-formation within $\sim 1\,\mathrm{Gyr}$ of the Big Bang [206].

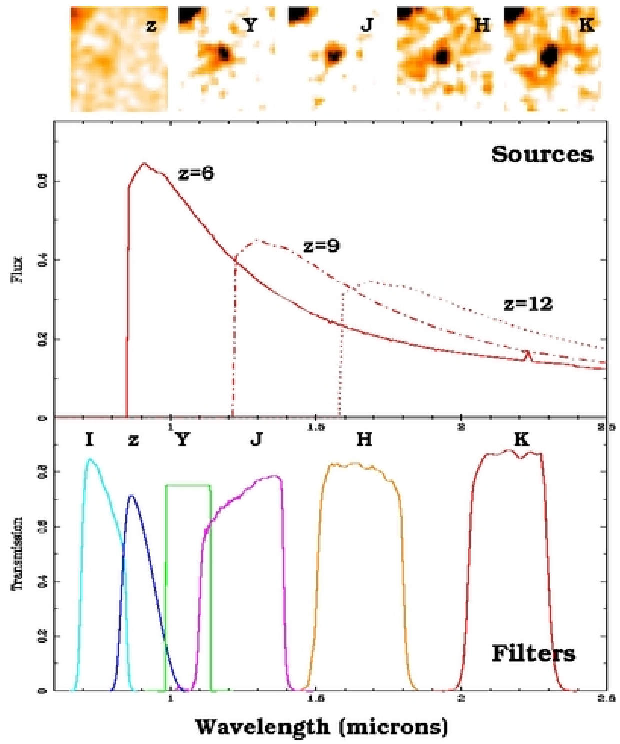

Figure II.4: Example of photometric selection of high-z galaxy candidates based on the Lyman-break dropout technique. Spectra of star-forming galaxies at $z = 6$, 9 and 12 are compared to the filter transmissions used in the photometric selection.

Current high-z surveys are based mainly on two different and complementary techniques: photometric dropout identification (Fig. II.4) and detection of Lyman-α emission by means of narrow-band imaging. Both approaches require subsequent spectroscopic confirmation of the selected candidates. At present, about 10 galaxies beyond $z \sim 6.5$ have secure spectroscopic redshifts [313, 278, 157, 536, 292], but all samples beyond this redshift are mainly supported by photometric considerations [312, 83, 84, 85, 467, 86].

The abundance of $z \sim 7-10$ galaxies selected through their stellar continuum in blank and lensing fields was first discussed by [83] and [467] and recently updated by [85, 468] (see Fig. II.5). The conclusion from these studies is that strong evolution occurs between $z \sim 7-8$ and $z \sim 3-4$, the cosmic density of star forming being smaller at the highest redshifts out to the limits of the different surveys. The galaxy luminosity functions derived from these photometric surveys exhibit a turnover at bright magnitudes with respect to that measured at $z \sim 3-5$, suggesting a decline in the abundance of luminous star-forming galaxies at high redshift (although the strength of this effect is still a matter of debate). Spectroscopic 'blind' searches around the 'critical lines' in lensing clusters suggest

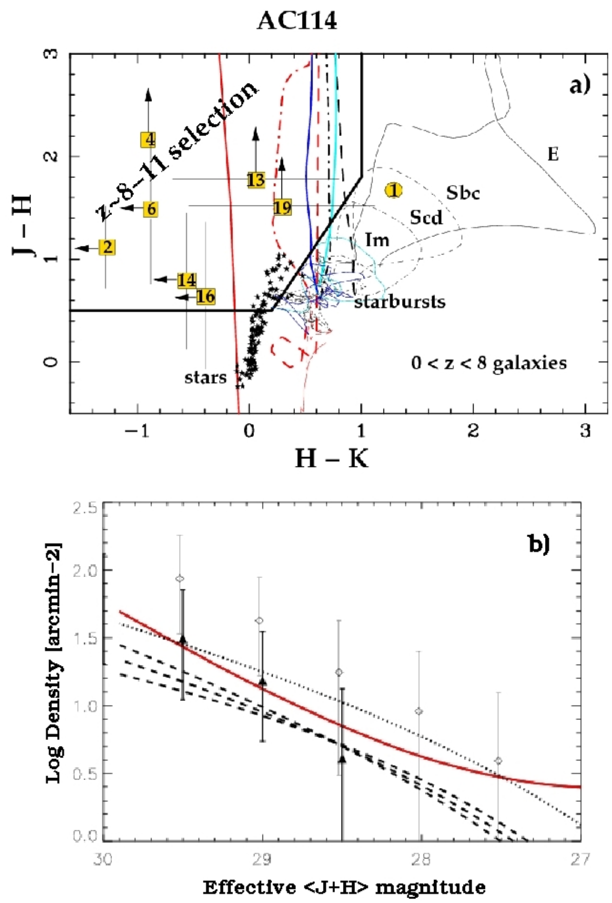

Figure II.5: Top: Color-color diagram (Vega system) showing the expected colors of galaxies at $z \sim 0-11$, together with the location of optical dropouts detected in the lensing cluster AC114 and the selection region used in the $z \sim 8-11$ redshift domain. Thin and thick lines display models below and above $z = 8$, respectively [467]. **Bottom:** Cumulative number density of star-forming galaxies at $z \sim 7-8$ as a function of the effective (lens-corrected) magnitude [468]. Points and error bars correspond to different selection criteria (based on the $z - J$ color) for candidate galaxies in six lensing clusters observed with NICMOS/HST. The best fit to these data is shown by the light dotted line. Also shown for comparison are estimates of the galaxy luminosity function in the HUDF and GOODS fields (light dotted line: [84]; bold dashed lines: [85]). The red line is the upper limit if none of the photometric candidates in this sample is a genuine high-z galaxy.

an important contribution of intrinsically faint star-forming systems to cosmic reionization [524]. Also, the number density of sources detectable with narrow-band imaging techniques seems to be much smaller at $z \geq 7$ [292, 156]. A main issue, which is expected to improve in the near future, is the fact that present ultra-deep surveys, wether space- or ground-based, wether in lensing or in blank fields, are still dramatically too small in terms of effective covolume at high-z to derive statistically significant results.

Making further progress in the study of primeval galaxies requires the use of new ground- and space-based facilities and a multi-wavelength approach (e.g., VLT/Hawk-I, Herschel, GTC/ EMIR, HST/ WFC3), in preparation for future observations with ALMA and JWST. The availability of near-infrared multi-object spectrographs in the near future will significantly improve the follow-up efficiency on the photometric candidates identified by present surveys.

II.2.9 The Horizon project

Romain Teyssier, CEA/IRFU/SAp

The Horizon project (http://www.projet-horizon.fr) was initiated in 2003 after a recommendation of the PNC to support Computational Cosmology in France. Five partner institutes have decided to join forces and gather most, if not all, French experts in the field. These were, in random order: CEA Saclay (CEA), Institute of Astrophysics Paris (IAP), Paris Observatory (LERMA), Meudon Observatory (LUTH) and Lyon Observatory (CRAL). Later on, the project was augmented by a team from Marseille Observatory (LAM). In total, more than 20 permanent researcher are involved in the Horizon project, not counting a similar number of post-docs and students. Thanks to the support of the PNC and the community as a whole, Horizon was funded by the Astroparticle program, the PNG, and last but not least, the ANR. The Horizon project will be terminated on December 2008. Thanks to this unprecedented initiative in computational astrophysics, the French community has now become one of the leader in this highly competitive field. The Horizon project has achieve 4 major scientific highlights: the largest N body simulation ever peformed, with 70 billion particle in a cubic volume of $2h^{-1}$Gpc aside, using the new CEA Supercomputer [539]; a cutting-edge large scale Galaxy Formation simulation using the Barcelona Supercomputer 'MareNostrum', leading to a revolutionary view on star formation at high redshift [421, 175]; the new GALICS database, providing new and insightful virtual galaxy catalogs; and the GALMER database, providing a unique interactive database of galaxy collision simulations [178]. Beyond these striking examples, the Horizon project has enabled very fruitful collaboration between the various member teams. New codes have been developed, which are now availabe and used by a rather wide community. A few examples are the RAMSES code [538, 540], a new moment-based radiative transfer code called ATON [28], a new Monte-Carlo radiative transfer code called LICORICE [508] and a new parallel initial conditions generator called MPgrafic [455].

Part III

Prospective: main science themes and major open questions

III.1 Physics of the Universe

III.1.1 Theory of the early Universe

Cédric Deffayet, APC & IAP

The current cosmological observations are very well described by a *standard model*. In this model the dynamics of the Universe is given by Friedmann's equations, themselves derived from General Relativity, while the matter content of the universe encompasses not only standard matter (i.e. baryonic matter, photons, etc...) but also non baryonic dark matter and a dark energy component which currently represents about 70% of the mass of the universe. Applying the well established laws of physics, one reaches, with those ingredients, a good description of the history of the universe from a time slightly earlier than cosmological nucleosynthesis to the present epoch. Besides the knowledge of the 'laws' governing the evolution of the universe during this period, one needs initial conditions to be provided at the time when we start to compute the evolution from. Providing a good explanation to those initial conditions is one of the greatest largely open question to early-universe cosmology. Indeed, those appear very unnatural and the standard cosmological model offers no good understanding of what appears to be a very high fine tuning of the initial inhomogeneities (also called horizon problem) and velocities (also called flatness problem). A better understanding of the initial conditions of standard cosmology is also linked to the attempt to give a description of the universe at epochs earlier than the one described in the standard cosmological model. Last, one also wishes to understand the real nature of the speculative initial singularity, which is predicted by theorems based on general relativity. Schematically, one can separate theoretical studies on the so-called early universe into two classes. One class of studies aim at providing an understanding of the initial conditions required by the standard cosmological model (including investigations of the initial singularity) and try to extend in the past the period of the history of the universe which is understood. A second class of studies deal with a precise investigation of the part of the early history of the universe which is usually described by the standard cosmological model and aim either at giving a more refined description of it using standard physics, or at introducing non-standard variants of the usual scenario and at trying to identify observables associated with those deviations.

Both directions of theoretical studies are crucial in the time when cosmology is entering the 'precision era'. Indeed, starting from the second direction, it is clear that, as the precision of more and more cosmological observations will increase, the understanding of the standard cosmological scenario will improve and variants of it will be more and more constrained. At the same time, the increased precision of cosmological observations also opens the possibility to describe more accurately the initial conditions of the standard cosmological evolution, and hence, it opens a window on possible theoretical explanations of those conditions. Examples of both developments are easily offered by CMB observations:

the WMAP observations provided a clear new signal for the need of a non-vanishing dark energy component, which was not available before; on the other hand, the power spectrum obtained by WMAP and the improvement expected in particular by the PLANCK mission will severely constrained several model of inflation, one of the leading approaches to provide suitable initial conditions.

In recent years, many interesting theoretical developments have been made in early cosmology, opening in turn interesting prospects for the close future. It is worth noting that work in this field is often led by physicists having a strong connection with high-energy theoretical physics, which opens a unique window for collaborations between scientists with different backgrounds: high-energy physics and astrophysics.

First, following the discovery of the superstring dualities and the major role played there by branes, a whole new body of string phenomenological constructions has been developed. This led in turn to various new ways to build up models of inflation inside string theory. This field is currently very active and led to new types of scenarios of inflation, which can be tested against observations and discriminated from more standard inflationary paradigms. A related issue, which attracted a lot of attention, is that of the computation of non-gaussianities in various models of the very early Universe, which is crucial for future observations. Following the same 'superstring revolution', the interest for cosmic strings has been renewed with the discovery that cosmic strings with specific features and signatures (in term of their equation of state in particular, or in the way those cosmic string interact) could form, if the superstring theory were a correct description of our world. This effort is also in full development. More generally, the 'superstring revolution' led to the understanding that there could be a new fundamental energy scale in the universe much lower that the Planck scale, and subsequently to the idea that effects which where once thought to be much too remote to be observed could in fact be much easier to be made manifest. For example, theories with large (in a high-energy physics sense) extra-dimensions flourished. Those theories usually imply observable effects at low energy and can modify the history of the early universe. This direction of research has been very well explored in the last ten years. It also led indirectly to new theoretical proposals to modify gravity, such as the so-called DGP model, the 'ghost condensate', etc... This is still a very active field of investigation. Moreover, efforts have recently been made to better understand the nature of the initial singularity not only within string theory, but also with alternative approaches such as loop quantum gravity. Last but not least, the discovery of the so-called string landscape has triggered a renewal of interest for models based on the anthropic principle.

In addition to what we have stressed above, a major part of future theoretical work on the cosmology of the early Universe should benefit from the soon-expected results of the LHC, which has just started operation. Indeed, should the LHC discover supersymmetry, or large extra-dimensions, this would affect tremendously our understanding of the beyond-standard model of high-energy physics. This in turn would imply new developments in early (and also late – concerning e.g. the problem of dark matter) theoretical cosmology. Such developments in fact would follow from virtually any new understanding, brought by

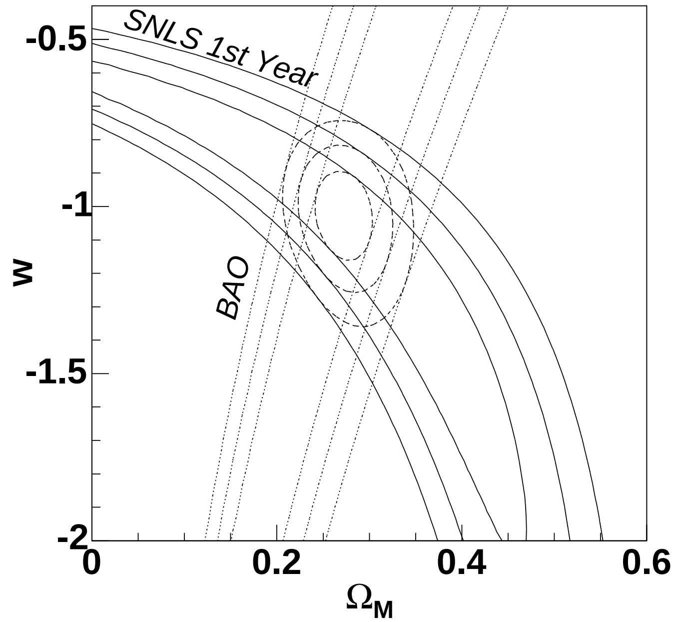

Figure III.6: Current constraints on the equation-of-state parameter from the SNLS survey. Here the spatial section of the Universe is assumed to be flat and the equation-of-state parameter is assumed to be constant [27].

the LHC, of what lies beyond the standard model of high-energy physics.

Hence, these are highly interesting times for theoretical studies of the early Universe, for which various new directions are currently under development. This field should also benefit from stronger and stronger interaction between observers and theorists, in order to fully exploit the always improving precision of cosmological observations.

III.1.2 Dark energy

Francis Bernardeau, CEA/IPhT

As stressed in the report of the Dark Energy Task Force to the AAAC [177], *the acceleration of the Universe is, along with dark matter, the observed phenomenon which most directly demonstrates that our theories of fundamental particles and gravity are either incorrect or incomplete.* That gives the magnitude of the task that awaits observational and theoretical researches in this field.

The accelerated expansion of the Universe

Over the last few years, a growing body of observational evidence has accumulated, which indicates that the Universe is now undergoing a phase of accelerated expansion. The whole set of observations available today is fully compatible with the existence of a uniform and constant energy density representing about 70% of the current energy density of the universe (see Fig. III.6 and table III.2). This suggests that the universe is filled with a new fluid component which is able to counteract the universal attraction of standard matter by inducing a repulsive force. Unlike Newtonian gravity, General Relativity offers a theoretical framework which could incorporate such a phenomenon. Classically it can be attributed to the existence of a new fundamental constant, the cosmological constant. However, the nature of this phenomenon remains fundamentally not understood. This discomfort is particularly strong from a point of view of high-energy physics. The current theoretical constructions are indeed hardly compatible with the existence of a cosmological constant. In fact, the acceleration of the universe questions the nature of the quantum vacuum in a theory that would incorporate gravity and quantum field theories.

How then can one make sense of the observations? What are the theoretical constructions that have been forward to explain the recent acceleration of the Universe?

- **A mere cosmological constant.** The current observations are fully compatible with the existence of a cosmological constant. Besides those already mentioned, such a hypothesis poses a number of problems: why does it start to dominate the energy content of the Universe just now – this is the 'coincidence' problem – and why is its energy scale so much smaller that the Planck energy scale (the energy scale associated with the other fundamental constant that describes gravity, the Newton constant)?

- **A new type of cosmological fluid.** Such a fluid would have a genuine dynamical evolution. One can think of the emergence of a late inflationary phase caused by the existence of new scalar degrees of freedom. This is an a priori slightly more comfortable situation from the point of view of high-energy physics, though such constructions are, for the time being, quite artificial. The models invoke include quintessence, Chaplygin gas [49], Chameleon [95], etc.

- **Modification of gravity.** An alternative to the existence of a new cosmological fluid is a large-scale modification of gravity. This would shatter our usual conceptual framework. Such constructions are legitimate [193], although no fully coherent one has been proposed to date.

- **Or something else...** Among possibilities which cannot be discarded at this stage, one can mention for instance photon-axion interactions, the breaking of Corpernican principles [558], etc.

How to measure the dark-energy equation of state?

The new generation of observational surveys will have to answer a number a pressing questions. Their formulations are guided by the spectrum of theoretical possibilities:

1. Is the equation of state of a cosmological constant $P/\rho = -1$ fully compatible with observations?

2. Can the observations be accounted for with a novel component in the cosmological fluid within General Relativity?

3. What would then be the equation of state of this novel component?

To answer those questions, various means have been proposed, all of which probe the properties of the low redshift Universe. It is worth stressing that, **in contrast with dark-matter experiments, there is no hope of exploring dark energy from ground experiments. Astronomical observations and cosmological surveys are the only key to address this fundamental question of physics.** This places astronomy in a unique position. This also sets strong demands on the accuracy and robustness of the proposed methods by the rest of the physics community.

The proposed methods are fundamentally of two kinds: some are based on geometrical properties (they involve measurements of the distance and volume cosmological evolution) and some make use of the influence of dark energy on the dynamical properties of the Universe (through the determination of the formation rate of the large-scale structure). It is worth stressing that those two classes of constraints are based on different physical hypotheses, and hence, one might want to combine both types simultaneously. This is the case, in particular, when addressing the second of the above questions.

The geometrical properties of the Universe are usually determined through measurements of angular, or equivalently, luminosity distances. Such measurements provide information about the time dependence of the Friedmann-Robertson-Walker metric, irrespective of the energy content of the universe. They amount to measuring

$$d_A = \int_0^z \frac{\mathrm{d}z'}{H(z')} \tag{III.1}$$

and therefore constrain $H(t)$. The use of distant supernovae has proven so far to be the most effective of the methods aiming at such measurements. Baryon acoustic oscillations (BAOs) are also part of this family, along with, to some extent, galaxy-cluster counts. An alternative approach consists in the direct measurement of the time drift of cosmological redshift over a period of a few years, $\mathrm{d}z/\mathrm{d}t$, which probes the time variation of H in a slightly different (and complementary) manner [558].

The dynamical properties of the Universe are based on the determination – directly or indirectly – of the linear growth rate $D_+(t)$ of density fluctuations. This rate is determined

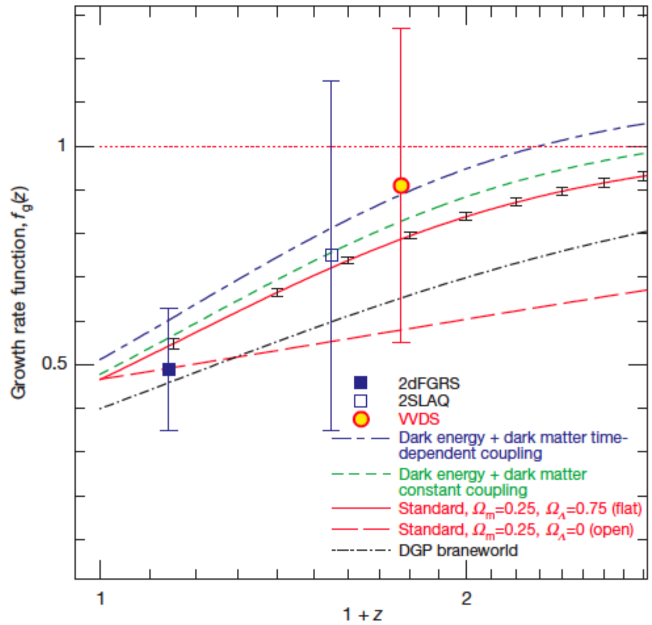

Figure III.7: Observational estimates of the growth rate of cosmic structure compared to the predictions of various theoretical models. Values of $f = \beta\, b_L$ are plotted as a function of the inverse of the cosmic expansion factor $1 + z = a(t)^{-1}$, assuming $b_L = 1.0 \pm 0.1$ (as estimated from higher-order clustering properties). Also shown along with determinations from existing surveys is an example of the accuracy potentially achievable in future surveys: the small black error bars on the standard curve (in red) show expected measurements in bins $\Delta z = 0.2$ from an all-sky survey of 500,000 infrared-selected ($H < 23$) galaxies [264].

by solving the equation

$$\frac{\mathrm{d}^2}{\mathrm{d}t^2} D_+(t) + 2H(t)\frac{\mathrm{d}}{\mathrm{d}t} D_+(t) = \frac{3}{2}\Omega_\mathrm{m}(t) H^2(t) D_+(t), \tag{III.2}$$

where $\Omega_\mathrm{m}(t)$ gives the energy fraction in the matter fluid. Note that the link to the dark-energy properties relies on the validity of the Friedmann equation, etc. Cosmic shear effects have been put forward for over a decade as a robust and effective way to make such a measurement with the required accuracy. In fact, in principle, cosmic shear measurements can probe directly, on various scales, the distribution of dark matter whose dynamical evolution is given by equation (III.2). Other approaches exist, which are based on the determination of the magnitude of the velocity field (more precisely of $f \equiv \mathrm{d}\log D_+/\mathrm{d}\log a$). This quantity intervenes, for example, in the redshift distortion effects whose amplitude can be determined in large galaxy redshift surveys [264] (see Fig. III.7).

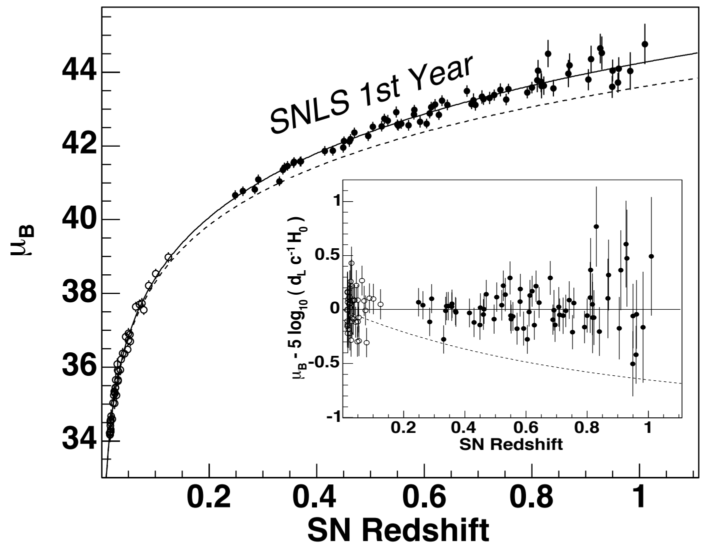

Figure III.8: The Hubble diagram of a set of supernovae detected during the first year of SNLS observations. Dotted lines correspond to an Einstein-de Sitter Universe without cosmological constant and the solid line to the concordant model [27].

Observational methods

While the effect of dark energy is ubiquitous in the phenomenology of the low-redshift Universe, constraining its nature (e.g. answering the fundamental questions formulated above) is challenging. As we have seen, a number of approaches have been advertised in the literature. However, these have been studied to very different levels of detail, in particular regarding systematic errors of instrumental and astrophysical origin. For example, redshift distortion effects and cosmological drift measurements have not been investigated in much details regarding possible sources of astrophysical effects (bias, environment effects, etc.), which may hamper the forecasted precisions of the determination of dark energy properties. This is also the case, to a lesser extent, for galaxy-cluster counts, which are presumably highly sensitive to both evolution and dynamical effects. The mass calibration here may prove very hard to achieve to the required accuracy. Future surveys (e.g. Planck, SKA) will allow us to better assess the constraints on dark energy properties using this approach.

We can review the methods that have been investigated in detail in the perspective of a mission dedicated to probing the properties of dark energy:

- **Distant SN Ia.** The rate at which the apparent luminosity of distant type-Ia supernovae (which can be defined as standard candles) decreases with redshift allows a direct determination of the behavior of luminosity distance. This method, which has been used for about a decade, allowed the demonstration that the expansion of

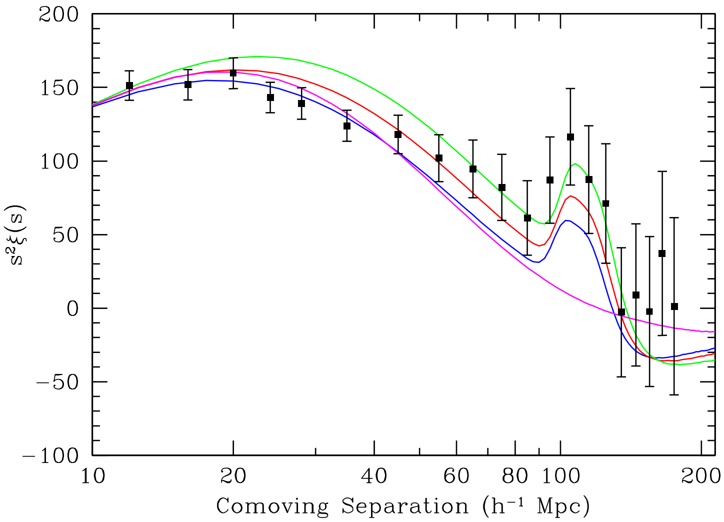

Figure III.9: Observations of baryon acoustic oscillations in the density power spectrum measured in a red-galaxy catalogue extracted from the SDSS [197].

the Universe accelerates (see Fig. III.8). A systematic use of this method for high-precision measurements depends on the degree to which type-Ia supernovae can be used as standard candles (which requires accurate photometric measurements). This is one of the methods on which the SNAP project is based.

- **Baryon acoustic oscillations.** The observation of BAOs in galaxy catalogues can be achieved only in very large surveys. It consists in detecting the distance scale of baryonic oscillations, similar to those seen in CMB anisotropy spectra, at scales around 100 Mpc (see Fig. III.9). The main advantage of this method is that it is based on a robust feature of the linear matter spectrum. The number of modes which can be exploited is however limited (compared to the cosmic-shear approach). Such oscillatory constraints have now been detected in a sub-catalogue of the SDSS (see Fig. III.9). Future projects (BOSS, HSHS, SKA) aim at generalizing this type of measurement. This is also one of the objective of the SPACE project.

- **Cosmic Shear.** This method has attracted a lot of interest because the underlying physics on which it is based (the gravitational dynamics of the cosmic fluids) is well understood and directly probed. This method could in principle provide the best constraints of the equation-of-state parameter (because of the number of independent degree of freedom which can be measured, see Fig. III.10.) However, its implementation poses a number of problems (PSF corrections, need for accurate photometric redshifts), which have so far proven to be difficult to solve to the required accuracy,

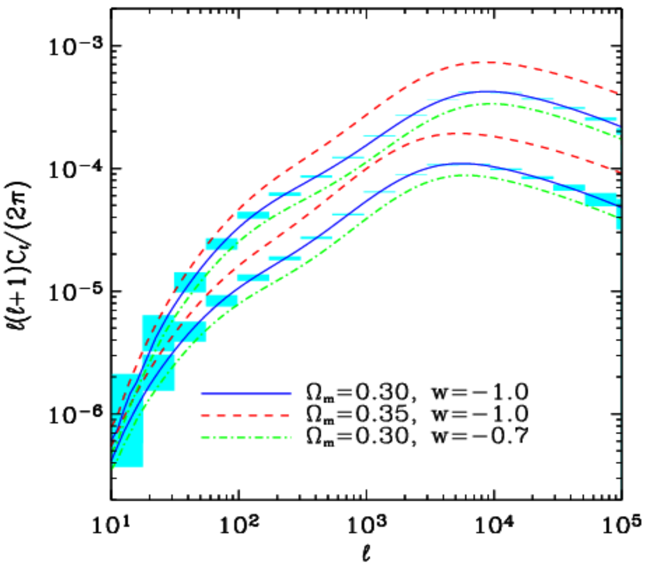

Figure III.10: Cosmic-Shear power spectrum C_l expected from a DUNE-like mission for low-redshift sources ($z < 1$, blue lower curve) and high-redshift sources ($z > 1$, blue upper curve), including statistical errors. Also shown are different cosmological models.

at least for ground-based observations. The space projects DUNE and, to a lesser extent, SNAP are exploiting this method to constrain dark energy. An identified potential Achilles' heel of these surveys is their need for not only precise wide-field imagery but also spectroscopic complementary surveys.

A convincing case will require a very significant improvement over our current ability to measure w (the present state-of-the-art studies are summarized in Table III.2), in a way which can be as indisputable as possible from the point of vue of systematic errors. That can only be achieved with the help of at least two different primary probes based on different tracers (SN Ia, BAO, Cosmic Shear). This is important not only to ensure that the theoretical framework is correct (e.g. the second question formulated above) but also because these different methods are expected to be sensitive to different astrophysical systematic errors. This makes dark-energy projects multi-purpose and with complex data-analysis requirements. These considerations have guided the development of most of the projects mentioned in the next paragraph.

Table III.2: Current constraints on the equation-of-state parameter w (95% confidence level). The number in parentheses is the best-fit value. Also indicated are the probes used in each study. Notes: (1) from SNLS survey; (2) from CFHLS survey; (3) from WMAP1 data, other constraints were derived from WMAP5 data; (4) from SDSS data.

Reference	CMB	SN Ia	BAO	WL	Lyα	Cl.	Gal.	w (95%)
[311]	X	X$^{(1)}$	-	X$^{(2)}$	-	-	-	$-1.19 < w(-1.02) < -0.90$
[361]	X	X	X	-	-	X	-	$-1.08 < w(-1.02) < -0.96$
[315]	X	X	X	-	-	-	-	$-1.11 < w < -0.86$
[505]	X$^{(3)}$	X	-	-	X	-	X$^{(4)}$	$-1.08 < w(-0.99) < -0.90$

Projects, Participation of the French community

The French community has been very active over the last few years in this topic. This is the case for theoretical investigations (see for instance [557] and references therein) as well as for observational surveys. The current best constraints on dark energy come from the SNLS (see Figs. III.6 and III.8 and Section II.1.2), and the CFHTLS is the leading cosmic-shear survey currently under progress. Its completion should take place by the end of January 2009 (Section II.1.3. This survey has already produced significant results regarding the dark energy constraints [507]. In contrast, the French community has so far been largely absent from BAO studies. The situation is now changing with the participations to BOSS (Section IV.4.3) and HSHS (Section IV.4.2. The leadership of the French community in many segments of the research on dark energy is real and deserves to be secured and reinforced. What is at stake in the next few years is a participation of the French community in a satellite mission on this topic. The physics of dark energy has been identified as a major goal for the US agencies NASA and DOE, which led to the DEFT report [177] and the *Joint Dark Energy Mission* (JDEM) concept. The French community is an important part of the SNAP collaboration – a major candidate for JDEM – and has been leading the DUNE proposal to the recent ESA call for proposals.

Given the importance of the projects under discussion, the community has organized itself in a working group (*Groupe de Travail Energie Noire*, hereafter GTEN), which has met regularly over the last few years. At the end of a 2-day meeting in February 2007, this group has formulated a set of recommendations, which can be summarized as follows for medium- and long-term projects (see http://www2.iap.fr/pnc/Enoire2007 for the full text):

- The GTEN insisted on the participation of the community in a medium-term project (2010-2015), which would follow the CFTHLS an KIDS surveys, to maintain a strong leadership of the French community in cosmic-shear measurements. Human resources, especially for cosmic-shear analyses, have to be reinforced in the short and medium terms.

- The group also recalled that the coming cluster survey provided by Planck, together with X-ray and optical surveys, should allow precise investigations of the cosmic evolution of the mass function of galaxy clusters. These complementary observations are perceived as very important to build a convincing case.
- In the long term (2015+), the group has recognized the great scientific potential of the LSST project. A participation of (a part of) the French community is encouraged through various institutional supports.
- The GTEN stressed the need for ground-based complementary observations for many dark-energy surveys which are proposed in the long term. In particular, complementary photometric and spectroscopic surveys have also been identified of crucial importance. The GTEN has encouraged the exploration of the possibility of having such facilities at ESO.
- The group encouraged the participation of the French community to SKA and supports the development of HSHS which, for dark-energy projects, can be seen as a precursor of the former.
- The GTEN strongly supported a participation in one of the space missions, SNAP or DUNE.

Since these recommendations were written, the scientific situation has been rapidly evolving, with the emergence of new ideas (cosmic drift, redshift distortions) and new projects. A ground-based project for BAO, BOSS, has been proposed as part of SDSS-III (see Section IV.4.3 and [498]). The participation of the French community to this project is funded by the ANR.

The participation of the French community in a medium-term cosmic-shear survey is however still unclear (and quite worrisome for the development of this community). France has no participation in two major ground-based projects, pan-STARRS [299] (http://pan-starrs.ifa.hawaii.edu/public/) and DES [554].

The French community has been very active in the preparation of long-term space projects, although here again the institutional context is evolving rapidly. A new conpect, called SPACE, has emegered in the ESA Cosmic Vision program [142] (see Fig. III.7). This consisted in a wide space-born spectroscopic survey. SPACE, as an independent concept, was actually to be short lived. Following ESA recommendations, SPACE and DUNE have now merged into a single mission concept EUCLID (Section IV.3.3). The possibilities and performances of EUCLID have still to be assessed by the various partners, including the PNCG.

The community is aware that the participation in a space-mission program is demanding and will require the mobilization of large resources over a long period of time. While dark energy appears as a major driver for these projects, we are fully aware that their respective merits should also be weighted with their other scientific capabilities. There is no doubt that wide-field spectroscopic and imaging surveys would be of tremendous interest for the entire PNCG community (see for example Section III.2).

The PNCG is eager to see the participation of the French community in one of these missions secured, although it is not possible to predict now when and which project/mission will eventually be completed/fly. The program will continue to follow the development of these projects, assess their respective scientific benefits for the whole extragalactic community, and express its support for the projects of interest.

III.1.3 Dark matter

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Introduction: the global dark matter content of the Universe

The global mass content of the present-day Universe has recently reached a concordance between various methods. On one hand, internal motions of clusters, as well as their gas fractions, and also the large-scale velocity field all point to a mean total (dark+baryonic) mass density, expressed in units of the critical density of the universe, $\rho_{\rm crit} = 3\,H^2(z)/(8\pi G)$ of $\Omega_{\rm m} \approx 0.3$. Moreover, this value is directly obtained by the most recent analysis (WMAP5) [189] of the angular fluctuation spectrum of the Cosmic Microwave Background (CMB), yielding $\Omega_{\rm m} \simeq 0.25$. These values of $\Omega_{\rm m}$ are consistent with two observational constraints: (i) the (nearly) flat universe of cold dark matter with a cosmological constant (ΛCDM: $\Omega_{\rm m} + \Omega_\Lambda = 1$, where Ω_Λ is the dimensionless dark energy content) observed by WMAP5; and (ii) the joint constraint on $(\Omega_{\rm m}, \Omega_\Lambda)$ obtained using type-Ia supernovae as standard candles (yielding the luminosity distance to the redshift). Given that the dimensionless baryonic matter density, measured both by Big-Bang nucleosynthesis and by WMAP5, is roughly 4.5%, one concludes that the dark matter component of the universe contributes to over 80% of the mass of the universe.

The following discusses recent advances on understanding how this dark matter component is distributed, what is the principal alternative to dar matter, and what are the prospects for detecting dark matter.

The distribution of dark matter in the Universe

Cosmologists are now advancing in their understanding how the dark matter component is distributed in the Universe in comparison with the luminous tracers of the baryonic component.

☆ Dark matter mass profiles from observations

The total mass profiles (hence the DM mass profiles after subtraction of the baryonic component) of structures can be probed using 3 methods: internal kinematics, X-rays and lensing (both strong and weak). Internal kinematics of spherical structures suffers from lack of data and from the mass-velocity anisotropy degeneracy of the underlying Jeans equation of local equilibrium. X-ray analyses depend on uncertain temperature profiles. Both methods assume local (dynamic or hydrostatic) equilibrium. Lensing analyses cannot be performed on nearby objects and the surface mass density suffers from a mass-sheet degeneracy [210].

- **Spiral galaxies.** The flat rotation curves of spiral galaxies are a strong indication of dark matter, with a density profile falling roughly as r^{-2} [195, 426].

  Numerical simulations of the gravitational collapse of dark matter halos predict a steep density profile with a cusp in the center (power law of slope -1, as in the NFW model [410]), in contradiction with the slowly increasing inner rotation curves of dark-matter-dominated low surface brightness (LSB) spiral galaxies [323]. Solutions to this problem have been thought in terms of feedback due to star formation and heating due to dynamical friction of a rotating bar. However, all appear to be insufficient, especially since in presence of baryons, there is an even stronger concentration of dark matter, entrained by the baryonic collapse. An argument has been to say that ΛCDM halo potentials are increasingly prolate (axial ratios of 0.7) towards their centers, with the angular momentum perpendicular to the major axis [269], hence the baryons cannot follow perfect circular orbits. However, non-circular motions cannot statistically make the cusp disappear in the kinematic signature of the cold gas component. Two-dimensional spectroscopy of LSBs by [137] indeed indicates non-circular motions in the central regions. However, analogous 2D spectroscopy by [323] lead these authors to rotation curves requiring non-circular motions of typically $20\,\mathrm{km\,s^{-1}}$, i.e. roughly twice the observed inner velocity dispersions.

  All attempts to detect dark matter in the Milky Way halo through micro-lensing (MACHOS, EROS) have failed, suggesting that the dark matter is made of objects much smaller than stellar, but not of low-mass stars and planets, since dark matter must be mainly non-baryonic in the Universe.

- **Dwarf spheroidal galaxies.** There is a variety of dark-matter normalizations in dwarf Spheroidal (dSph) galaxies: from low M/L (Fornax) to high M/L (Draco). Several authors [528, 37] suggest that the dark matter component has a core, but this issue is not yet settled. Nevertheless, with 200 velocities per dSph, [529] was able to lift the mass-velocity anisotropy degeneracy and derive the mass within 600 pc for 9 dSph galaxies. The values found are near $10^7 M_\odot$, independent of luminosity, thus demonstrating the increasing role of dark matter in lower luminosity objects.

- **Elliptical galaxies.** Giant elliptical galaxies are difficult to study, because the dark matter component dominates only beyond one or several effective (half-projected-light) radii, and there is a lack of internal-kinematics tracers beyond that radius. Still, the internal kinematics of the several hundred planetary nebulae detected around several giant elliptical galaxies show low velocity dispersions, which were first interpreted as a serious lack of dark matter [479]. Yet, binary-merger N-body + gas simulations of two spirals embedded in dark matter produce giant ellipticals with properties in perfect agreement with the observed properties of planetary nebulae in projected phase space [174], simply because the stars in the outer envelopes evolve along elongated orbits perpendicular to the line of sight. X-ray emission confirms the presence of dark-matter halos, but it is clearly detected only in the brightest group/cluster galaxies [280]. Lensing analyses, performed on stacked samples, indicate singular isothermal total mass profiles [317], as expected from adding the observed and ΛCDM components [357]. Recently, [237] were able to measure in a non-parametric way the density profile out to the virial radius, but the large inferred normalization suggests that their sample (extracted from the Sloan Lens ACS Survey) is contaminated by the group component. Similarly, [360] measure a dark-matter concentration within the virial radius, which actually corresponds to that of a galaxy group. In contrast, [335] finds mass profiles consistent with the sum of observed Sérsic (for stars) and NFW (for the dark matter) profiles.

- **Clusters and groups.** Clusters of galaxies have been probed by all three methods. The results are generally consistent with NFW models for the dark-matter profile with concentrations generally in agreement with the predictions from ΛCDM halos [301, 443, 348]. Preliminary results on an internal-kinematics analysis of X-ray-emitting groups indicates that low-mass groups are less concentrated than high-mass ones, contrary to expectations for ΛCDM halos [357]. Moreover, weak lensing has been producing beautiful 2D maps (Fig. III.11) and more recently 3D maps (Fig. III.12 [372]), although the depth component is very uncertain.

✰ Dark matter profile predictions from cosmological simulations

The halos in cosmological N-body simulations, run with ΛCDM initial conditions using a single dark-matter component, display a fairly universal profile. At first, this appeared to extrapolate to power laws of index -1 and -3 in the inner and outer regions (the NFW model [410]), with two unpleasant features: a divergent density at the center and a divergent mass outwards. Recent more thorough analyses [409] point to a slightly different distribution (the 3D equivalent of a Sérsic profile, first proposed in another context by Einasto in 1963), with very different extrapolations: a homogeneous core and a converging mass profile.

When a gaseous component is added in the simulations, it dissipates to a condensed disk at small radii, thus becoming the dominant component and dragging with it the dark matter, in a process called adiabatic contraction [63]. Cosmological simulations with gas run by [255] showed that the dark-matter density profile follows a singular isothermal ($\rho \propto r^{-2}$)

Figure III.11: Bullet Cluster with X-ray-emitting hot gas (pink) and total matter (blue, from weak lensing) [143]. This merging cluster shows the total matter (mapped with weak lensing) following more the galaxies and less the massive hot gas, which is an argument in favor of non-baryonic dark matter. This configuration has been also reproduced with modified gravity models (MOND [16]), but including neutrinos.

instead of an NFW (or Einasto) model. However, this effect is counterbalanced at low redshift by the dynamical-friction heating of the dark-matter halos by subhalo motions [277], but the issue is not settled.

Cosmological simulations now resolve subhalos within halos. The distribution of subhalos within halos is much less cuspy than NFW, in apparent disagreement with the distribution of galaxies within clusters [181] and with that of satellites around the Milky Way [351]. The global boost to the γ-ray annihilation signal from subhalos is predicted to be ≈ 300, as estimated from halos with as many as 4×10^9 particles [408]. On the other hand, the thin and long caustics caused by material at apocenter are sufficiently broad that the boost to the γ-ray signal from caustics should not be large [180].

✰ Summary

There has been rapid progress in our modeling of the dark matter distribution, and some theoretical predictions are now constrained with these observations. There are some strong disagreements between predictions from simulations and observations that still need to be explained, and the general feeling is that a more accurate treatment by the modelers

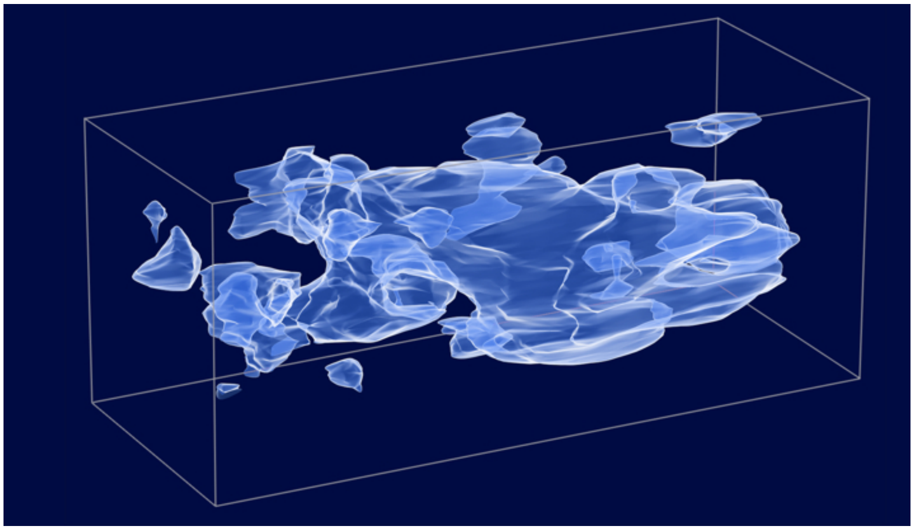

Figure III.12: 3D dark-matter map from weak-lensing measurements [372].

of the baryonic physics and especially the reionization of the Universe and the feedback from galaxy formation will be necessary.

Alternatives to dark matter

Despite its many successes, the ΛCDM model of structure formation suffers from several problems: the issue of the cusp is still unsettled (see above); the model also predicts too many low-mass subhalos (i.e. galaxy satellites – but galaxy feedback may destroy the lower-mass satellites, whose observed mass function is well matched by that of the earliest-formed and accreted subhalos [529]), and the distribution of satellites appears too flat in the inner regions of the halos; finally, the ΛCDM model requests that over 80% of the mass of the Universe is made of particles that have never yet been detected.

The MOdified Newtonian Dynamics (MOND) hypothesis [390] has been so far the most successful alternative to the ΛCDM model. MOND is able to reproduce the rotation curves of spiral galaxies and predict at the same time stellar mass-to-light ratios in full agreement with the observed galaxy colors [489]. In fact, MOND has been able to reproduce the internal kinematics of elliptical galaxies and groups of galaxies. Nevertheless, there are at least two regimes where MOND appears to have difficulties in reproducing velocities as high as observed: the Draco dwarf spheroidal galaxy [347] (but the influence of the Milky Way has to be incorporated into the analysis) and clusters of galaxies [244, 444].

The discovery of the Bullet Cluster, which appears to be a system of two clusters merging on the plane of the sky (Fig. III.11), has generated much discussion concerning MOND: a weak-lensing analysis indicates that the mass is around the galaxies [143], as expected in the classical scenario, whereas MOND would predict the mass to concentrate where the hot gas lies, since this component is more massive than galaxies. On the other hand, the morphology of the hot gas indicates that the shock velocity is as large as $4700\,\mathrm{km\,s^{-1}}$ [365], and a cluster-cluster collision at that speed is very unlikely [270], while it is easy to produce in MOND [17]. However, a realistic simulation of the bullet cluster reveals that the cluster-cluster velocity can be as low as $2700\,\mathrm{km\,s^{-1}}$ [520], which would not be a problem for ΛCDM.

The capacity of merging clusters, like the Bullet, to discriminate between the different theories of dark matter, has been hampered by the discovery [355] of another merging cluster (Abell 520), where the dark matter is not associated with the galaxies, contrary to the Bullet. In this case, the major component of total matter is associated with the central hot gas, a configuration exactly opposite to the Bullet, and in contradiction to non-dissipative cold dark matter. It is necessary to wait for the discovery of many other configurations, observing many other clusters, and understanding better their non-equilibrium states.

More work has to be done on the alternative theories of modified gravity, to check whether current problems could find a solution, among which: (i) it is difficult for MOND to predict the observed 3rd peak in the CMB angular fluctuation power spectrum; (ii) there is no good relativistic theory of MOND: the TeVeS theory proposed by [39] was shown by [101] to be unstable. There is a growing consensus that a dark matter component is still necessary, even in the MOND formalism ([18] propose that this component could be 2 eV neutrinos).

In summary, while the ΛCDM paradigm rests upon particles which have not (yet) been detected, the MOND formalism lacks a secure theoretical basis. Both alternatives suffer from inconsistencies with observations, which depend on the astrophysical modeling of these observations. In an interesting development, a dipole formulation for dark-matter particles has recently been proposed, which leads to MOND-like behavior [56, 57]. In this model, the CMB spectrum can be reproduced and the dark energy of the Universe comes out naturally [58].

Dark matter detection

With the general consensus that over 80% of the matter of the Universe is made of non-baryonic, yet undetected, dark matter, the detection of dark-matter particles has become one of the most pressing questions in cosmology today. Weakly Interacting Massive Particles (WIMPs) at the electroweak scale represent well motivated candidates to solve this enigma, with the lightest supersymmetric (SUSY) particle expected to be stable. Other particle dark-matter candidates exist, such as the axion, light bosonic particles, s-neutrinos and Kaluza-Klein particles, but in the following, we will focus on WIMP detection and identification.

☆ Direct detection of dark matter: experimental strategy

A distinct signature of WIMP interactions with ordinary matter is that they interact mainly by nuclear recoils of a few keV to a few tens of keV [256]. On the other hand, radioactivity induces mostly electron recoils in the same energy interval. Therefore, WIMP detectors detect ionization, scintillation and phonon emission from the recoils and usually combine two such signals to obtain the best background suppression in the protected environment of underground laboratories. The small recoil energy and interaction cross section require detectors with threshold energies in the keV range, excellent background suppression, large target mass, long-term and stable operation. No WIMP candidate has been found so far. This is not unexpected, since the predictions of Minimal Supersymmetric Standard Model (MSSM) for neutralino cross sections range from 10^{-5} to 10^{-12} pb (1 pb $\equiv$ 1 picobarn $\equiv 10^{-36}$ cm^2). Assuming that all dark matter is made of WIMPs, present experiments with a few kilogram active target mass can therefore exclude WIMPS with a spin-independent interaction cross section larger than a few 10^{-7} pb. Therefore, experiments at the ton-scale will be necessary to sample a large fraction of the MSSM parameter space and to characterize the parameters of a WIMP candidate, once it is discovered. Following the identification of a nuclear recoil signal, clearly distinguished against background, a 'smoking-gun' signature ensuring that the signal is really due to WIMPs will be desirable.

Three such signatures, using the annual modulation, directionality and target dependence of the signal, have been proposed. First, the DAMA experiment, recording the scintillation light in a 100-kg sodium iodide (NaI) detector, has reported an observation of the annual modulation signature [51]. Recently, DAMA has confirmed the observation with data from 3 years using the 250-kg NaI DAMA/LIBRA detector [52]. However, this effect is hardly compatible with a WIMP signal, since it remains unobserved by experiments more sensitive to the detection of nuclear recoils. The target-dependence signature follows from the different interaction rate and energy spectrum of WIMPs with different nuclei. In a final stage, the directionality signature would clearly distinguish the WIMP signal from a terrestrial background and search for a large forward/backward asymmetry. This however requires detectors capable of measuring the nuclear recoil direction, a condition potentially met only by gaseous detectors. At present, these detectors are in an R&D phase. Experimental sensitivities are expected to reach the level of 10^{-8} pb by the end of 2010 and may reach, with ton-scale detectors, 10^{-10} pb within the next 10 years. Therefore, there is a fair chance to detect dark-matter particles during the next decade, provided that progress can be realized in background rejection and that dark matter is made of super-symmetric particles.

✰ Detection techniques

Most of the progress in detection sensitivity over the last few years is mainly related to the development of two discrimination techniques: cryogenic detectors with simultaneous detection of phonons and light or charge, and noble liquid detectors with simultaneous detection of charge and light.

- **Cryogenic detectors.** Cryogenic detectors are operated at a temperature of $10-50$ mK and detect the feeble heat, ionization and scintillation signals from WIMP interactions in crystals made, e.g., from germanium, silicon and $CaWO_4$. CDMS, operating since 2002 in the Soudan Mine (Minnesota, USA) has reached in 2008 a record sensitivity limit of about 4.5×10^{-7} pb [7], while the second-generation CRESST-II (Gran Sasso Laboratory, Italy) and EDELWEISS-II (Frejus Laboratory, France) are starting taking data. These three experiments, with ≈ 10 kg of active target mass, intend to reach a sensitivity of $\approx 10^{-8}$ pb in 2010.

- **Noble liquid detectors.** Noble liquid detectors record ionization and scintillation from nuclear recoils in liquid xenon, argon or neon. XENON-10 (Gran Sasso, Italy) is the present leader of the technique with a $\approx 5.5 \times 10^{-7}$ pb sensitivity reached in 2007 [14]. ZEPLIN-III (Boulby mine, UK) has also started taking data with a liquid xenon target of about 10-kg mass, while WARP (Gran Sasso) and ArDM (Canfranc, Spain) operate liquid argon detectors. All these detectors are 2-phase detectors. Single-phase detectors like DAMA-LXe (Italy) and XMASS (Japan) use liquid xenon, while DEAP and CLEAN (Canada/US, R&D phase) use argon and neon. Combining pulse-shape discrimination and fiducialization to reject the background, double-phase xenon detectors have achieved impressive progress over the last few years.

- **The impact of LHC.** One of the main scientific goals of the LHC is the discovery of supersymmetry. However, LHC will not be able to demonstrate that the SUSY particles produced are stable, and are therefore WIMPs. On the other hand, observations of SUSY particles at the electroweak scale would provide a very strong incentive towards large-scale direct detection experiments, placing these observations in a well-confined particle physics context. Defining precisely the properties of the WIMP candidate would require the ILC (International Linear Collider) or CLIC (Compact Linear Collider) program in a later stage, along with high-statistics direct-detection experiments, which would probe the local distribution of the dark-matter particles [34].

☆ Conclusion

Progress in the performances of experiments aiming at the discovery of WIMPs has been impressive over the last ten years. The present generation of experiments has now a significant potential for discovery. The detection of supersymmetric particles by the LHC would constitute a tremendous motivation to observe in controlled laboratory conditions the interactions of remnant WIMPs. The contribution of French groups to LHC, indirect and direct detection of WIMPs is important and should be strongly supported.

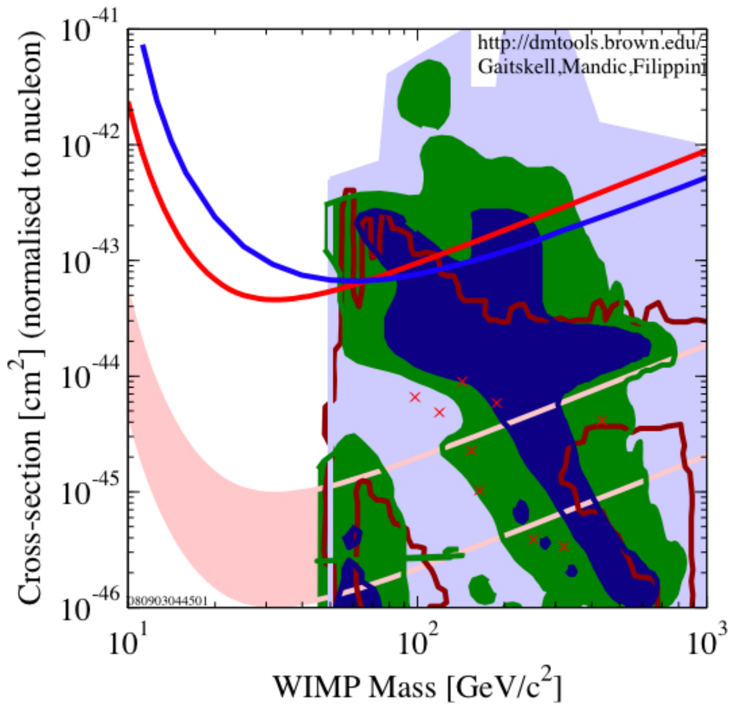

Figure III.13: Spin-independent WIMP cross section as a function of WIMP mass for various models (shaded blue, green and light-blue regions and crosses), and limit sensitivities obtained by the present leading experiments. The two upper curves represent the limits obtained by CDMS (blue curve), a bolometric detector operated in the US, and by XENON (red curve), a liquid xenon detector operated in the Italian Gran Sasso Underground Laboratory. The two lowest curves indicate the sensitivities expected in 2010 by the present round of experiments, and in ≈ 2015 by the next generation of experiments in the 100-kg kilogram range.

Role of the French community

French groups have made strong contributions to Direct and Indirect Detection experiments, and their perspectives are briefly summarized in the following.

✰ Direct detection

At present, approximately twenty dark-matter direct detection experiments are competing internationally. After the first pioneering experiments of CDMS in 2000 [4] and EDELWEISS in 2002 [194] demonstrating efficient γ-ray and electron background rejection, the dark-matter community is converging towards a phase of definition of experiments requiring ton-scale detectors with zero or limited background, and a sensitivity goal of $\approx 10^{-10}$ pb. The expected individual cost of each of these projects is in the 50-M€ range. The French groups benefit from their expertise in cryogenics, cryoelectronics and cryogenic detectors, and from the quality of the Modane underground laboratory, with a dedicated extension for dark-matter experiments built and equipped around 2012.

- **EURECA.** French groups are strongly involved in the EURECA project [320], a European collaboration gathering the CRESST and EDELWEISS teams, together with groups from the CERN Cryolab, Russia, Spain and UK. EDELWEISS and CRESST can be considered as a test stage of the ton-scale EURECA. With a current number of about 30 detectors (≈10 kg total target mass), EDELWEISS is entering a crucial phase with the validation of second-generation discriminating germanium detectors with active rejection of surface events (Fig. III.14). Such events represent today the main limitation of an otherwise extremely powerful identification of nuclear recoil events. The participation in EURECA of the French groups is strongly linked to the success of the new generation of Interdigit detectors, presently tested in EDELWEISS. EURECA is competing with the CDMS collaboration in the US, now focusing on a germanium target. Common working groups on neutron background, ultra-low radioactivity and data analysis are gradually organized between the CDMS and EURECA collaborations.

  Teams in IAS-Orsay and IPN-Lyon are also developing phonon-scintillation detectors in EURECA, in collaboration with German groups. The main challenge here is that the light signal suppression (quenching) factor for nuclear signals is very high, resulting in events with phonons but no light, which can have several other origins (such as spurious heating and relaxation).

  A decision on the technique chosen for EURECA will be taken around 2011. Since a confirmation detection of a WIMP candidate will require the observation of a clear nuclear recoil signal from at least two target nuclei, EURECA would like to develop, if possible, at least two different nuclear targets.

- **Other projects: CYGNUS and XENON.** Another contribution comes from the groups (LPSC Grenoble, CEA Saclay, IRSN Cadarache, ILL Grenoble) involved in the CYGNUS project, studying the possibility of identifying WIMPs through a directional signature. This project is in the development stage and supported by ANR funding. Due to its very high cost for a ton-scale project, CYGNUS is intended as demonstration stage of the directional technique, which will be implemented at large scale if a nuclear recoil signal is confirmed. A group in Subatech (Nantes) is discussing the possibility to join the XENON collaboration, presently leading with CDMS the sensitivity to WIMP interactions.

✰ Indirect detection

The French groups contribute very significantly to two major spatial projects with a potential impact on dark-matter indirect detection, Fermi (formerly GLAST), launched in

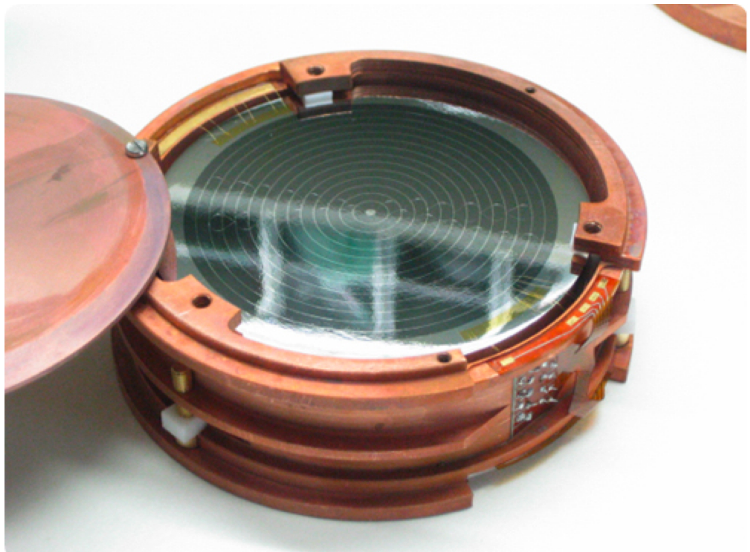

Figure III.14: Photograph of an Interdigit 400g Germanium detector built at CSNSM in Orsay. The interdigit detector measures simultaneously the charge and phonon signals of particle interactions. It has a field structure allowing efficient identification and rejection of surface interactions, which represent the main limitation of current Germanium detectors.

June 2008, and AMS-2. On the ground, HESS-2, which is currently the leading experiment in TeV γ-ray astronomy, studies the constraints on dark matter. On the other hand, astrophysical uncertainties, and the tentative signals reported by several groups (HEAT, CANGAROO, CACTUS, EGRET, INTEGRAL, PAMELA) indicate that it will be probably very difficult to establish firmly and with reasonable confidence the existence of a WIMP signal using only indirect detection. While indirect detection can probably exclude large samples of specific models leading to the production of γ-rays from the annihilation of WIMPs, a convincing existence proof of WIMPs will almost certainly require a direct detection in the controlled environment of the laboratory.

✰ Modeling the dark matter distribution

The French community is active in measuring the dark-matter content of the Universe and its distribution in various astrophysical structures. Applications have ranged, for example, from measures of the rotations curves of spiral galaxies using 2D spectroscopy [517], to constraints on the dark matter in the inner regions of giant elliptical galaxies using SAURON, to the development of the first non-parametric internal-kinematics mass inversion of spherical systems with anisotropy velocities [359] and a new method to lift the mass-velocity anisotropy degeneracy [358], to state-of-the-art cluster mass-profile determinations from X-ray observation [443] and associatied new limits on MOND [444], to studies of the detectability of dark-matter caustics by various means [396, 238, 239, 395], to sophisticated strong- and weak-lensing analyses of the dark matter distribution, to a wide variety of small- and large-scale simulations, which are being analyzed by several teams in various countries.

☆ Alternatives to dark matter

The French community has been active in understanding how MOND can produce a good alternative to the problems faced by ΛCDM. This includes the demonstration that TeVeS relativistic theory of MOND is unstable [101], a new formulation for dark-matter particles, which has both MONDian and dark-energy behaviors and is being tested with realistic cosmological simulations [56, 57], and the first realistic simulations of galaxy encounters with MOND [545].

Perspectives

Within the next five years or so, fundamental advances in the understanding of dark matter are foreseen through several approaches, in particular: (i) the possible detection of dark matter, either by bolometers, scintillation or γ-rays from dark-matter annihilation (although, as mentioned above, it will be easier to rule out dark-matter particle candidates in this way than to have an unequivocal detection); (ii) increased data samples for internal-kinematics, X-ray and lensing analyses; (iii) systematic joint analyses of lensing, X-ray emission and internal kinematics of galaxy clusters, which will soon be also coupled to SZ analyses; (iv) new internal-kinematics modeling techniques; (v) 2D spectroscopy of giant elliptical galaxies out to a few effective radii with MUSE; (vi) realistic hydrodynamical cosmological simulations, which resolve well the scales of the thickness of galaxy disks; (vii) realistic hydrodynamical cosmological simulations in the MOND formalism.

III.2 Large-scale structures

III.2.1 Reionization of the Universe

Benoît Semelin, Observatoire de Paris, LERMA

The early Universe (at redshifts $z > 1000$) is warm, and the baryonic matter (75% hydrogen and 25% helium resulting from primordial nucleosynthesis) is fully ionized. Matter and radiation are strongly coupled, and the photons mean free path is very short. As the universe expands, baryonic matter cools until, at $T \sim 3000$ K, protons and electrons start to recombine. This happens at $z_{\rm rec} \sim 1000$, when the mean free path of the photons becomes larger than the cosmological horizon. While the CMB today traces the free photons from this epoch, recombination is the onset of the 'dark age' of the Universe. During this era, the coupling between matter and radiation is minimal: we still have no observational data

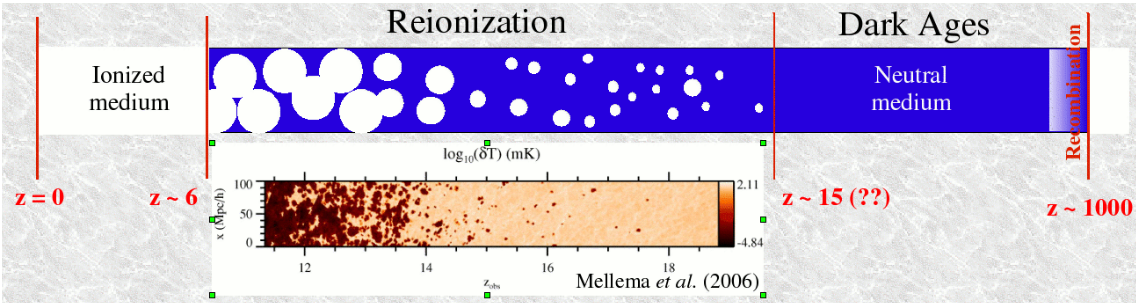

Figure III.15: Schematic representation of the reionization history.

between $z \sim 1000$ and $z \sim 10$. The end of the dark age begins around $z \sim 30$, when the first sources of radiation form as a result of the non-linear gravitational growth of primordial density fluctuations. The first sources, population III stars and/or quasars, have strong X-ray and ultraviolet continuum emission capable of ionizing hydrogen and helium. Thus, they start to ionize the gas in their vicinity. This marks the beginning of the Epoch of Reionization (EoR). Ionized bubbles centered on clusters of sources grow until different bubbles overlap: the universe becomes transparent to ultraviolet and X photons. By $z \sim 6$ the universe is fully reionized.

To this day, there are two main observational constraints on the EoR. The first comes from the Gunn-Peterson effect seen in the spectra of high-redshift quasars. If neutral hydrogen is found along the line of sight, continuum photons redshifted to the local Lyα frequency of neutral hydrogen will be absorbed: an absorption feature will appear in the spectrum. As even a small neutral fraction in the Intergalactic Medium (IGM) is enough to create a strong signature in the spectra, the Gunn-Peterson effect is able to pinpoint the end of the EoR. Data from a number of quasars give a value $z \sim 6$ [212]. The second constraint comes from the results of WMAP5 [315]. It provides a value $\tau = 0.087 \pm 0.017$ for the optical depth due to the Thomson scattering of CMB photons by free electrons. The ionized IGM from $z = 0$ up to the EoR contributes to the optical depth. The current value of τ yields $z = 10 \pm 2$ for the redshift of an instantaneous-reionization model. There is, as yet, no constraint on the beginning of the EoR.

Upcomming observations

In the years to come, we expect to learn much about the end of the dark age and about the EoR by the direct observation of the 21-cm emission line of neutral hydrogen with SKA and its pathfinders. Indeed, instruments like LOFAR and MWA will measure the sky-averaged brightness temperature of the 21-cm signal as a function of redshift and will evaluate the power spectrum of the brightness temperature fluctuations, albeit in a limited scale range. From these first data, we will learn about the reionization history. For example, the existence of a strong absorption phase in the average signal would favor stars against quasars as first sources [254]. Another possible diagnostic is the maximal value of the power spectrum at comoving scales $\sim 20h^{-1}$ Mpc as a function of redshift; this pinpoints the phase of overlap in the reionization history [341]. SKA will produce much more extensive data and will enable the 'tomography' of the 21-cm emission, i.e. the mapping at many different redshifts with an angular resolution of ~ 1 arcmin.

State of the art of the simulations

- **Reionization.** In recent years, radiative transfer simulations of the EoR have improved enough to take the complex interplay between matter and radiation into account. Indeed, there are several possible scenarios for the reionization history. A crucial unknown parameter is the quantitative effect of feedback. The first ionizing sources may quench further source formation in their neighborhood by preventing the formation or photo-evaporating clumps of gas below a mass threshold [290]. The strength of this effect depends both on the fragmentation efficiency in the gas (since self-shielding opposes photo-evaporation) and on the nature of the sources: a stellar Initial Mass Function (IMF) biased toward very massive stars or a large contribution from quasars provide a hard spectrum which can prevent the formation of clumps by heating the IGM but favors fragmentation by catalyzing H_2 formation inside the clumps [232]. Depending on the nature of the sources, clumping of the IGM, and feedback efficiency, the EoR can extend over a variable redshift range, occur in a single or multiple bursts, produce a patchy configuration with more or less sharp transitions between neutral and ionized regions. Simulations can accommodate all these possibilities; the final answer will come from the observations in the next decade. At this time the main issue is to model correctly the small scale physics with sub-grid recipes. This requires to run first simulations on small scales with high-mass resolution and very detailed physical and chemical processes, then compile the result of these simulations into subgrid recipes for large-scale simulations.

- **21 cm.** Numerical simulations of the 21-cm signal are useful to explore the different possible source models and derive constraints for the design of future instruments in terms of frequency range, bandwidth, angular resolution and sensitivity. Comparison with observations will then enable us to discriminate between source models and formation histories. Predicting the 21-cm signal requires the knowledge of three local quantities: the baryonic density field, the ionization fraction of hydrogen and the Lyα flux (to compute the spin temperature). Moreover, high resolution is critical to obtain realistic, non-spherical ionized regions arising from the high photon consumption in dense small-scale structures, and large simulation boxes ($> 100h^{-1}$ Mpc) are necessary to correctly sample the clustering in the source distribution. With the development of 3D radiative transfer codes [253, 407, 370, 460, 382, 472, 531, 577, 548] and the increase in computational power, it has become possible in the last few years to predict the 21-cm signal. However some compromises are still necessary. The most common approximation is to assume that the hydrogen spin temperature T_S is much smaller than the CMB temperature T_{CMB}, i.e. $T_S \gg T_{CMB}$. In this regime, the 21-cm brightness temperature is independent of the spin temperature: no information about the gas temperature and local Lyα flux is needed. This approximation fails, for example, if the coupling of T_S to the gas kinetic temperature T_K by Lyα is weak (early on and/or far from the sources), which implies $T_S \sim T_{CMB}$. Also, if the gas is not heated in the voids by X-ray photons from quasars, then $T_S \sim T_K < T_{CMB}$. In other words, this approximation removes any possible absorption regime, even if the signal seen in absorption could potentially be stronger than in emission [232]. In fact, recent work not making this approximation [31] produces a strong absorption regime (see Fig III.16).

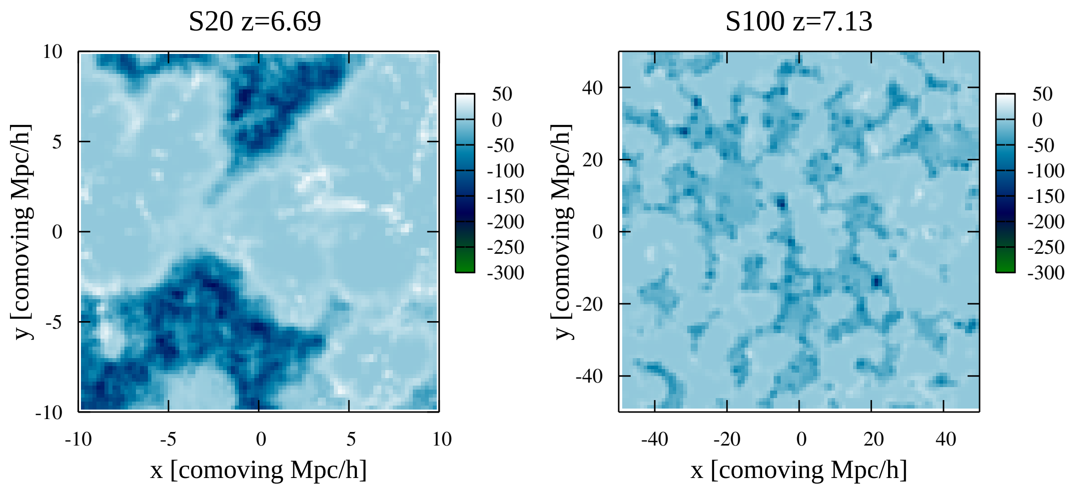

Figure III.16: Simulated 21-cm maps for a 20 (left panel) and a 100 (right panel) h^{-1} Mpc boxsizes. The color scale is linear in units of mK. The full effect of Lyα pumping is taken into acount.

Prospects

The great challenge of the next decade will be to confront the observations with the results from simulations. From the point of view of the observations, the main difficulty will be to remove foregrounds $\sim$ 1000 times stronger than the EoR 21-cm signal, but with a different frequency dependence. From the point a view of the simulations, there are two natural directions for further work. The first is to improve the quality of the simulations. In particular, we need better mass resolution and larger box sizes: this means more computational power and continuously improved algorithms. We note that reionization simulations are among the most demanding in astrophysics, and they also present very specific parallelization difficulties. The vast improvement in the competitiveness of the national computing center (IDRIS and CINES) is boostsing the international visibility of the French community. In addition to raw power, much remains to be done to simulate the physics of the signal emission more accurately (role of Lyman-α pumping, careful description of the thermal state of the IGM, etc.). The second main direction for future work in simulations of the reionization is a in-depth exploration of the space of parameters. These are connected mainly to the formation history and spectral energy distributions of the sources. The confrontation of models with future observations will greatly enhance our understanding the of thr reionization history of the Universe.

III.2.2 Absorption-line studies and the intergalactic medium

Patrick Petitjean, IAP

Introduction

Absorption-line spectra of distant sources contain a wealth of information on the ionic content and physical conditions of the interstellar and intergalactic clouds toward the source of radiation. The restframe ultra-violet bandpass (912−3000 Å) is a particularly rich region, containing many ionic lines, whose study forms the primary way in which astronomers piece together the chemical composition of the baryons from the close vicinity of the sun to the most remote places in the Universe.

It is often forgotten that any lump of gas in the Universe can produce an absorption in the spectrum of a remote source. This is why the absorption technique is an unavoidable tool of modern cosmology. In addition, most of the (visible) baryons in the universe are in the form of gas rather than stars. The Intergalactic Medium (IGM) at high redshift, which is detected through the 'Lyman-α forest' (arising from the absorption by spatially continuous density fluctuations around the mean density), is a reservoir for galaxy formation containing 90% of all baryons. Thus, even the largest and deepest high-redshift galaxy survey will not probe the overall baryon content of the Universe, its state and physical properties. The interaction between this intergalactic gas and galaxies is of crucial importance for the process of galaxy formation. The IGM is also the best tracer of large-scale structure in the high-redshift universe.

Damped Lyα (DLA) systems are the IGM absorbers with highest column densities, $N_{\rm HI} > 2 \times 10^{20}\,{\rm cm}^{-2}$. The Lorentzian damping wings of the Lyα absorption line in these systems are prominent and allow precise measurements of hydrogen content (and hence of metallicities). DLAs are generally thought to be the precursors of present-day large galactic disks, held together by dark matter-dominated potential wells. Molecules are being detected in these systems, which represent out best hope to explore in details the physical state of the interstellar Medium of remote galaxies.

We now address in more detail a few questions of particular interest in studies of the intergalactic medium.

Evolution of the field and prospects

✰ The Warm-Hot Intergalactic Medium (WHIM)

Feedback processes have been known for a long time to be an important ingredient of galaxy formation. For example, the ionizing photons produced during star formation ionize and heat the surrounding gas. Also, the explosion of supernovas produces powerful galactic winds, which expell metals from galactic disks out to the intergalactic medium. This feedback from star formation slows down the cooling and infall of intergalactic gas onto forming galaxies. The importance of this process has been fully realized only recently. Several groups in France are working on the interplay between galactic winds, the metal enrichment of the IGM and galaxy formation.

The resonant lines of highly ionized species such as O VI, N V, C IV, and Si IV at ultraviolet wavelengths offer paticularly good probes of the hot, collisionally ionized (or low-density, photoionized) gas clouds. The most abundant of these ions, O VI, has now been detected in many astronomical environments, from the Milky Way disk, to the Mily Way halo, to the Magellanic Clouds, to starburst galaxies, to the intergalactic medium, to the interstellar medium (ISM) of remote galaxies. Thus, diffuse, hot gas clouds appear to be an ubiquitous component of the Universe.

In the Galactic environment, O VI is found in gas at temperatures near 300,000 K, where cooling occurs very quickly. Clouds containing O VI are therefore likely to be out of thermal equilibrium and may trace dynamical events, such as shocks, the boundaries of supernova remnants, and cooling gas flows [493]. In high-velocity clouds – a network of nearby structures which are not co-rotating with the Galaxy – highly-ionized species appear to be produced in conductive boundary layers between a cool/warm core and a surrounding, hotter medium [506, 227]. This hotter medium could well represent the extended Galactic corona, first predicted by Spitzer in 1956 and possibly detected in recent measurements of X-ray absorption in the lines of O VII and O VIII [214].

Moving out to the low-redshift IGM, the *Hubble Space Telescope* (*HST*) and the *Far-Ultraviolet Spectroscopic Explorer* (*FUSE*) satellites have been used to investigate the origin of highly-ionized gas in the redshift range $z = 0 - 0.3$ [551, 469]. Studies of the redshift number density of these systems, $\mathrm{d}N(\mathrm{O\,VI})/\mathrm{d}z$, show that O VI absorbers in the low-z IGM contain ∼10% of baryons at the current epoch, forming a baryonic reservoir of similar size to the total content of stars in galaxies.

At higher redshift, the same spectroscopic diagnostic techniques can be applied to systems observable with ground-based optical telescopes. The atmospheric cutoff at 3000 Å for ground-based observations implies that O VI absorbers in the IGM become accessible at $z > 2.20$ and C IV systems at $z > 1.13$. The high-resolution capabilities of ground-based instruments allow detailed kinematic studies of absorption-line profiles, and the large collecting areas of 10 m-class telescopes yield spectra of much higher signal-to-noise ratio (> 100) than space-based observations. Various studies [463, 121, 514, 50, 19] have addressed the nature of the ionization source, the metallicity and the baryonic content in high-redshift intergalactic O VI absorption-line systems. The observed narrow O VI line widths revealed by these studies do not favor collisional ionization in a hot IGM as the dominant production mechanism of O VI at high redshift. Instead, photoionization by the ultraviolet metagalactic flux appears a more likely mechanism.

✰ The ISM of remote galaxies: Damped Lyman-α sytems

Damped Lyman-α systems trace regions of highest neutral-gas density (i.e. corresponding to $N_{\rm HI} > 2\times10^{20}\,{\rm cm}^{-2}$) along the lines of sight to distant sources. Although the nature of these systems is not entirely clear, they presumably probe the ISM of high-redshift galaxies.

From the physical conditions within DLAs, it is possible to study the star formation history in the vicinity of the absorbing clouds, to determine the chemical composition of the associated ISM, and hence document the first steps in the formation of present-day galaxies. Even though observational studies of DLAs have been pursued for over two decades now, important questions remain unanswered, such as: (i) the presence of in-situ star-formation activity in DLAs; (ii) the connection between observed metal-abundance ratios and dust content; and (iii) how severe is the bias caused by dust obscuration of background sources in current DLA samples. Several groups in France have studied Damped Lyman-α systems in detail. An interesting result, for example, is the demonstration that sub-DLAs ($1019 < 2\times10^{20}\,{\rm cm}^{-2}$) could contain an important fraction of the neutral gas and therefore an important fraction of the missing metals at $z \sim 2$.

Assessing the molecular content of DLAs can provide a direct means of studying the physical state of the neutral ISM phase in remote galaxies. In fact, H_2 molecules are expected to form at the surface of dust grains if the gas is cool, dense and mostly neutral. Alternatively, they will result from the formation of negative hydrogen if the gas is warm and dust-free [296, 128]. Since the former process is most likely dominant in the neutral gas associated with DLAs, the observation of H_2 molecules can provide an indirect probe of the amount of dust in DLAs, without having to worry about extinction and heavy-element depletion effects. Moreover, the populations of different rotational levels of H_2 can constrain the kinetic and rotational excitation temperatures and particle densities [437]. The effective photo-dissociation of H_2 takes place in the energy range $11.1-13.6$ eV through Lyman- and Werner-band absorption lines. Thus, the observed molecular fraction $f = 2N({\rm H_2})/[2N({\rm H_2})+N({\rm H\,I})]$ constrains the intensity of the local ultraviolet radiation field. A direct determination of this quantity will have important implications for our understanding of the link between DLAs and the star-formation activity in high-redshift galaxies.

At H I column densities as large as those measured in DLAs, H_2 molecules are conspicuous in our Galaxy: gas clouds with $N_{\rm HI} > 10^{21}\,{\rm cm}^{-2}$ usually have $N_{\rm H_2} > 10^{19}\,{\rm cm}^{-2}$

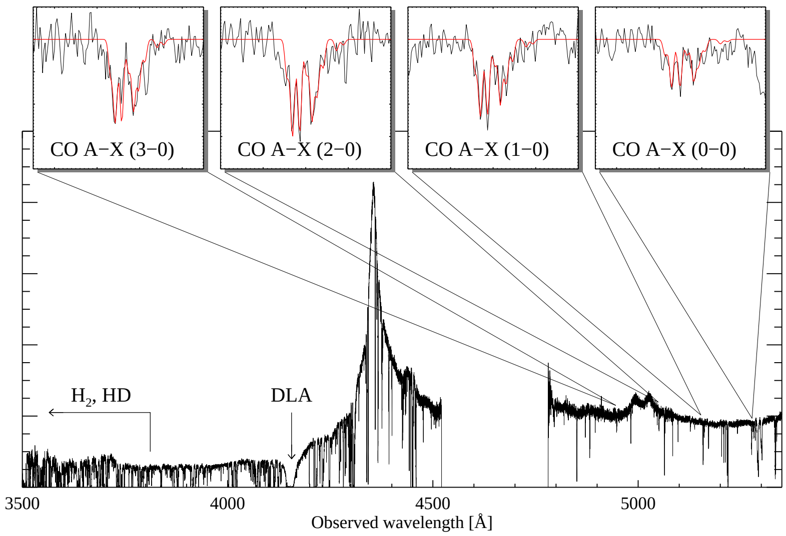

Figure III.17: First detection of CO absorption in a Damped Lyman-α system toward a quasar. The molecules HD and H_2 are also detected. This opens the new field of astrochemistry in the ISM of remote galaxies [417].

[492, 297]. Given this fact, it is somewhat surprising that early searches for molecular hydrogen in DLAs, though not systematic, have found either upper limits on or small values of the molecular gas fraction [55, 339]. A major step forward in understanding the nature of DLAs through their molecular-gas content has recently been enabled by the unique high-resolution capabilities of UVES at the VLT. A French team has led the first unbiased survey for H_2 in the ISM of high-z galaxies. The detection of H_2, HD and CO molecules in this campaign (see Fig. III.2.2) has opened a new field of astro-chemistry at high redshift.

✰ Spatial distribution of the Intergalactic Medium

The gas in the IGM is revealed by the numerous absorption lines seen blueward of the Lyman-α emission line in the spectra of background quasars. The IGM has been shown to contain most of the baryons in the Universe at high redshift. The IGM therefore constitutes the reservoir of baryons for galaxy formation. In return, star-forming galaxies produce ionizing photons and eject metals and energy through powerful winds, which affect the physical state of the gas in the IGM. The interplay between galactic winds and the gas in the IGM is therefore central to the field of galaxy formation. This happens on scales of the order of 1 Mpc or less, or about 2 arcmin at $z \sim 2.5$ (for the concordance cosmology). On larger scales, the gas is in the linear regime and probes large-scale structure of the universe.

The idea to reconstruct the 3D density field of the IGM at $z \sim 2.5$ to study the topology of the IGM in the linear regime has been proposed 10 years ago in France. The first thing to do is to measure the correlation between lines of sight which are close to each others (e.g., toward pairs or groups of quasars). Numerical hydro-simulations have demonstrated that the fluctuations of the neutral gas density responsible for Lyman-α absorption trace very well the fluctuations in the underlying dark-matter density field on scales larger than the well Jeans length of the gas [153, 566, 539]. In this picture, most of the baryons are located in filaments and sheets, which are only overdense by factors of a few. Within the new picture revealed by these simulations, the cross-correlation of absorbers in the spectra of a pair of quasars can be quantified rigorously, e.g. with a cross-correlation coefficient

$$\chi(r_\perp) = \int_{Ly\alpha} \frac{(\mathcal{F}_0 - \overline{\mathcal{F}_0})(\mathcal{F}_1 - \overline{\mathcal{F}_1})}{\sigma_{\mathcal{F}_0}\sigma_{\mathcal{F}_1}}\,, \tag{III.3}$$

where $\mathcal{F}_0$ and $\mathcal{F}_1$ are the two normalized spectra of the pair of quasars separated by a transverse distance $r_\perp$ [477]. The value of χ gives a quantitative estimate of the correlation, ranging from 0 if the spectra are uncorrelated to 1 for identical spectra.

The mapping of the IGM on wide sky areas is hindered by the lack of quasar pairs bright enough to be observed with current instrumentation. Recently, a French team has assembled the up-to-date largest sample of 30 quasar pairs selected from the 2dFGRS, which they observed using FORS at the VLT [148]. This revealed that the correlation is very strong for separations below ~ 2 arcmin and is still present out to roughly 4 arcmin. This result is important because it demonstrates the coherence of the IGM on scales of a few arcmin. Therefore, if we can build a grid of background sources with a mean separation of about $2-3$ arcmin, we will be able to reconstruct the 3D density field of the neutral hydrogen in the IGM. This will allow the study of the IGM topology using different techniques, including the Euler characteristics and the powerful skeleton [125]. Such studies will provide important clues about the formation of structures in the Universe at high redshift. In addition, by observing galaxies in the same fields, it will be possible to investigate the spatial correlation between galaxies and the IGM.

As mentioned above, the Lyman-α forest most likely arises from the absorption by spatially continuous density fluctuations around the mean density in a warm photo-ionized IGM. The spatial distribution of the IGM is therefore related to the distribution of dark matter in a simple manner [420, 476]. Several authors have demonstrated that this simple relation allows one to infer the continuous dark-matter distribution along the line of sight. This method has been extended in France to a full 3D reconstruction of the matter distribution using a grid of spatially close lines of sight [439, 125]. The bayesian inversion method interpolates the structures revealed by the absorptions in the spectra. Fig. III.18 shows to which level the matter distribution could be recovered from the artificial spectra

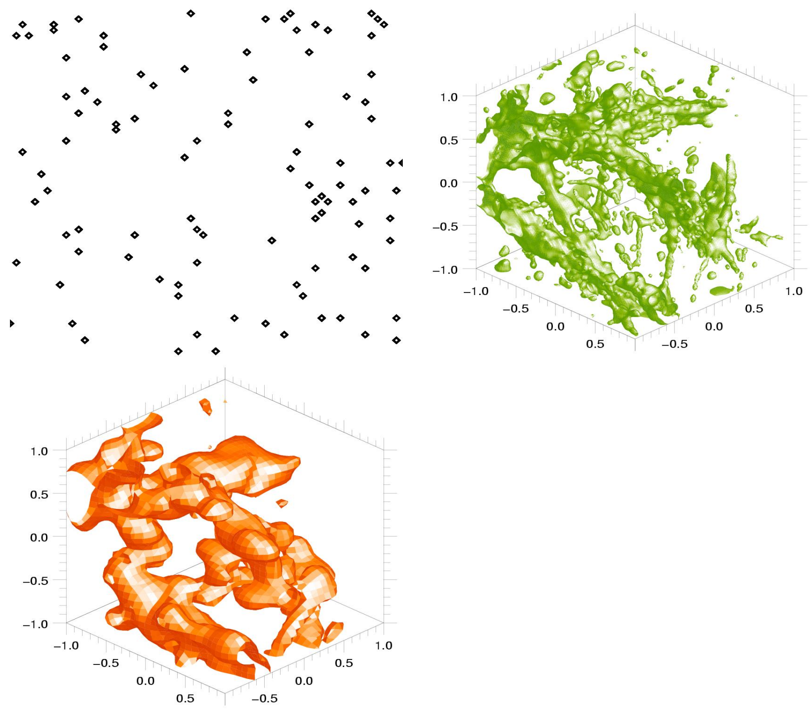

Figure III.18: Reconstruction of the matter density field. The 3D density field in the simulation is shown in the right-hand panel. The top left panel shows the positions of 100 background sources from randomly drawn lines of sight. The corresponding absorption spectra are taken as input data for the reconstruction. The reconstructed density field is shown in the bottom left panel [125].

generated from 100 lines of sight randomnly drawn through a $50 \times 50 \times 50\,$Mpc N-body simulation box (parallel to one dimension of the box). The structures on scales of the order of or larger than the mean separation of the lines of sight are well recovered.

Recovering the tomography of the IGM using these techniques is a highlight project of several instruments foreseen for the next generation of telescopes (e.g., EVE on the E-ELT). Structures in the spatial distribution of the IGM at moderate overdensities are expected to be seen on scales larger than the Jeans scale, which corresponds to a transverse separation of about $0.5-2\,$arcmin at $z \sim 2$. Therefore, in principle, scales from $\sim 2\,$arcmin to 1 degree should be investigated. About 900 randomly distributed targets per square degree would be required to recover the matter distribution with this resolution.

Several authors [279] also pointed out that by comparing the correlation and cross-correlation lengths in the Lyman-α forest, it is possible to derive constraints on the geometry of the Universe in a fashion similar to the standard Alcock & Paczinski test [8]. The

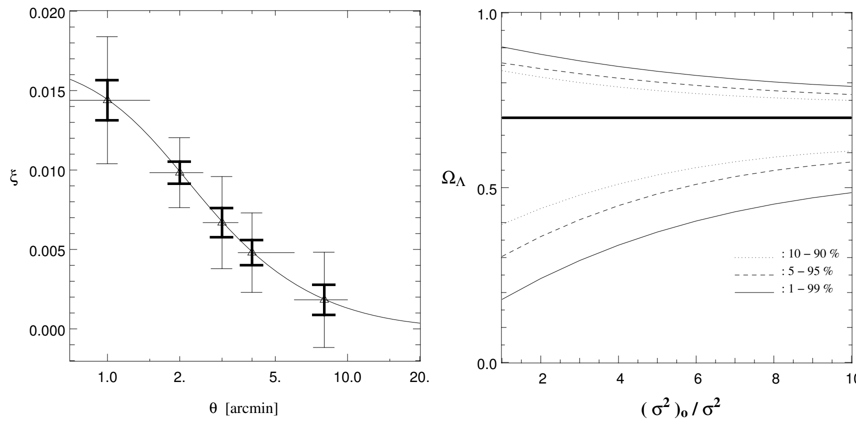

Figure III.19: The transverse correlation in the IGM has been measured for the first time very recently from 30 quasar pairs [148]. **Left:** The results (points with thin error bars) are consistent with the expectation of the standard model for structure formation (solid line). The thick error bars show the gain expected from the observation of 100 quasar pairs. **Right:** Corresponding constraints on Ω_Λ at the 99 (solid), 95 (dashed) and 90% (dotted line) confidence levels as a function of the increase in the number of useful pixels by a factor of σ_0^2/σ^2 compared to the current survey [148, 477].

correlation lengths should be the same in the line-of-sight and transverse directions for a homogeneous universe. The former is measured in expansion velocity and the latter in arcmin. Thus, measuring the two lengths gives the transformation from one direction to the other and hence the geometry of the Universe. The main parameter in this transformation is Ω_Λ. The transverse correlation in the IGM has been measured for the first time very recently from a sample of 30 quasar pairs [148]. The results are consistent with the expectation of the standard model for structure formation, although the observational errors are large (left-hand panel of Fig. III.19). The observation of 100 quasar pairs would reduce the errors significantly (as shown by the comparison between the thick and thin error bars in Fig. III.19). The corresponding constraints on Ω_Λ at the 99 (solid), 95 (dashed) and 90% (dotted line) confidence levels are shown in the right-hand panel of Fig. III.19 as a function of the increase in the number of useful pixels relative to the present study.

✰ Variations of fundamental constants

The development of fundamental physics relies on the constancy of various fundamental quantities, such as the fine-structure constant α. Contemporary theories of fundamental interactions treating gravity and quantum mechanics in a consistent way, such as the supersymmetric grand unified theory (SUSY GUT) and the supersymmetric string (superstring) theory, not only predict a dependence of fundamental physical constants on energy (as has been observed in high-energy experiments) but also allow their variations with cosmological time and space. Constraining the possible time variations of fundamental physical quantities is therefore an important step toward a complete understanding of basic physics. In the framework of standard Big-Bang models, the time evolution of various physical quantities can be explored by means of measurements at different redshifts. As the energy of atomic transitions depends on the electromagnetic coupling (fine-structure) constant α, possible variations of this quantity over time will be registered in the form of small shifts in the absorption-line spectra seen toward high-redshift quasars. The variations of several constants can be probed in this way, the main two being the fine-structure constant α and the electron-to-proton mass ratio μ. The constraints obtained at high redshift are complementary to those derived from measurements of clock stability on Earth.

A controversy arose recently between the different groups working in this field on the question of whether or not a variation of α has been detected [401, 131, 402, 522], while an agreement appears to exist on the fact that no variation of μ is found down to a limit $\Delta\mu/\mu \sim 10^{-5}$. Important efforts are made by the international community (except in France, see below) not only to solve this controversy, but also to increase these fundamental constraints. The high spectral resolution spectrograph CODEX foreseen for the European ELT will undoubtedly yield an order-of-magnitude increase in the sensitivity of the method.

✫ Spectroscopy of Gamma-Ray-Burst afterglows

The exceptional brightness of Gamma-Ray-Burst (GRB) afterglows makes them powerful extragalactic background sources. Since GRBs can be detected out to very high redshifts, the afterglow spectra can be used to study the properties and evolution of galaxies and the IGM, similarly to what is traditionally achieved using quasar spectra. Two advantages of these sources make them very interesting: (i) although the highest known GRB redshift at the moment is 6.24, they are expected to be detected at even higher redshifts, where quasars may be very difficult to find; (ii) GRB afterglows can be very bright and yield spectra of unprecedently high signal-to-noise ratio if observed at the peak of the light curve.

In principle, GRB lines of sight should not be different from quasar lines of sight, as the Universe in front of GRBs has no reason to be different from that in front of quasars. However, the number of strong (i.e. with rest equivalent width $W_{\rm r} > 1\,$Å) intervening Mg II absorbers appears to be 4 times larger along GRB lines of sight than expected for quasars over the same path lengths. This is puzzling and should be investigated with a much larger sample. GRB lines of sight could be gravitationally amplified by this excess of absorbers. The bias would come from the fact that spectroscopy is performed for the moment on the brightest GRBs. However, much larger samples of GRBs are required to clarify this issue. X-shooter, a second-generation instrument for the VLT, will be the perfect instrument to investigate this problem further. An important step will be to identify the galaxies associated with the intervening Mg II systems, which is easier to perform than along quasar lines of sight, thanks to the fading of GRBs.

Another highly interesting feature of GRBs is that their lines of sight probe the gas inside the GRB host galaxies. GRB-DLAs have on average higher column densities and probably also larger dust content than DLAs associated with intervening galaxies further down the lines of sight. In any case, once a GRB has faded away, the host galaxy can eventually be observed directly, while it is usually very difficult to detect the emitting counterpart of a quasar DLA because of the constant blinding by the quasar.

Spectroscopy of GRB afterglows is only in infancy. The main problem with these observations si that the telescopes have to react fast after the GRB detection. The advent of SVOM together with X-shooter at the VLT will boost this field tremendously.

Contribution of the French community to the field

The French community in this field, though small, has always been very active and recognized internationally. The advent of new observing capabilities will make the importance of this field grow further, as it is one of the few ways to study the gas content of the Universe. Several institutes in France have realized this and try to help the emergence of new teams. It would be very important that this be recognized at the national level so that these teams are given the support they deserve.

- **The Warm-Hot Intergalactic Medium.** Several groups are involved in the characterization of the warm-hot intergalactic medium. At low redshift, it may be possible to detect the WHIM by its X-ray and/or ultraviolet *emission* (e.g., using the ultraviolet FIREBALL experiment to which LAM participates). Further away, the medium can be probed through the *absorption* (by mostly O VI but also Ne VIII intervening absorption-line systems) of background ultraviolet spectra. The new COS spectrograph on HST should be used to systematically search for these lines. At higher redshift, the classical studies of the Lyman-α forest in the spectra of distant quasars will be boosted by the advent of EXPRESSO on VLT and then CODEX on the European ELT.

- **Variation of fundamental constants.** The French astronomical community is being surprisingly slow at reacting to this important new topic. In other countries, the claim for a variation of the fine-structure constant α has triggered much stronger interest. Although the French groups involved in this topics do not confirm the detection, the issue is far from being settled. The controversy has brought strong activity to the field, and the recent lack of manpower and support is a handicap for the French teams, who could loose at term their rank of internationally recognized experts in this field.

- **Correlation in the IGM.** The use of inversion techniques to recover the tomography of the IGM, which we briefly described above, is a highlight project of several instruments foreseen for the next generation of telescopes (e.g., the multi-object spectrograph EVE for the E-ELT, but also WFOS on the TMT). In this context, the implication of the French community in the SDSS-III project BOSS (Section IV.4.3) is very promising, as it will provide the best fields for performing the inversion experiment.

- **Spectroscopy of Gamma-Ray-Burst afterglows.** The French community has recently made an important effort to gather forces on this subject from both theoretical and observational perspectives. The advent of the X-shooter spectrograph ($3000 - 19,000$ Å), an instrument of second generation on the VLT, will yield a tremendous increase of information on GRB lines of sight. The launch of SVOM, the French-Chinese GRB satellite, will further boost the activity in this promising field.

III.2.3 Physics of galaxy clusters

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Located at the crossing of filaments, clusters of galaxies define the nodes of the cosmic web. Because of their large sizes, their mass content reflects that of the Universe: $\sim 85\%$ of the mass of galaxy clusters is made of dark matter. They are the last manifestation of the hierarchical growth of structure, the first small clusters having formed in the recent cosmological epoch, around $z \sim 2$. Clusters then formed and grew by continuous accretion of surrounding matter and through sporadic merger events. The observed properties of this evolving population provide crucial information on the physics of structure formation, for both the dark matter and the baryonic components, as well as constraints on the fundamental cosmological parameters.

Dark matter in clusters and cluster mass

Recent XMM and Chandra observations have allowed significant progress in our understanding of the dark matter component in galaxy clusters. High-precision mass profiles have been derived from the hydrostatic equilibrium equation for local relaxed clusters. The dark matter profiles of these clusters appear universal in shape [443, 567], with a central cusp similar to that predicted by numerical simulations. The steep slope in the center severely limits self-interacting dark-matter models [111]. The observed concentration-mass relation shows excellent quantitative agreement with the prediction of the flat concordance ΛCDM model down to the group regime, providing further evidence in favor of this model [443, 567, 110]. The concentration-mass relation even starts to provide interesting constraints on the fundamental cosmological parameters [110]. All this suggests that the physics of the dark-matter collapse is well understood, at least on group and cluster scales. This is important for any assessment of the baryon physics, since intracluster gas and galaxies evolve in potential wells dominated by the dark matter. The above data also helped calibrate precisely the local mass-temperature $M - T_{\rm X}$ and mass-Comptonization parameter $M - Y_{\rm X}$ relations [22, 567, 405, 23]. This represents an important step forward, as these 'mass-proxy' relations are a key ingredient when using clusters as cosmological probe or when constraining baryon physics from cluster gas scaling properties: they provide the link between observables and the mass, which is the fundamental cluster property in theoretical models.

These precise studies of nearby clusters still leave many questions unanswered, such as: how do the shapes of the dark-matter profiles of clusters covering a representative variety of dynamical states compare with theoretical predictions? What is the mass distribution like in the cluster outer regions, where infall dominates? What is the intrinsic dispersion in dark-matter profile shapes, in the concentration-mass relation and in the mass-proxy relations? What is the bias in cluster-mass estimates as a function of dynamical state? How does the observed evolution compare with theoretical predictions? In particular, we must calibrate the evolution of the mass-proxy relations, still poorly constrained [318] and whose normalisation is affected by poorly understood non-gravitational physics.

These questions are the subject of intense efforts, and answering them requires combining X-ray observations, galaxy dynamics and lensing observations (masses derived from lensing studies being a priori less sensitive to cluster dynamical state than those derived from X-ray emission), observations of the Sunyaev-Zel'dovich (SZ) effect and numerical simulations. Long restricted to small samples [35] and 'spectacular' clusters [344], comparison studies between X-ray and lensing data are now moving to representative cluster samples (e.g. the LoCuSS survey [589]) and will benefit from continuous progress on the optical side. For example, the 'caustic technique' is a powerful new optical technique to probe the outer mass distribution [473]. Probing the evolution of the dark-matter profiles over cosmic time is very demanding in observing time. Yet, it is feasible with XMM, which can constrain the masses profiles of distant massive clusters at a precision currently reached for local clusters. Very significant progress is expected from the XMM follow-up of Planck data, which will increase by two orders of magnitude the (small) number of known massive clusters at high redshift [36]. This follow-up will also help calibrate precisely the $M - Y_{\rm SZ}$ relation. This is important because the SZ comptomisation parameter is expected to be the cluster property most tightly related to mass (i.e the best mass proxy).

Hierarchical cluster formation

Clusters are now detected in X-Ray out to redshifts $z \sim 1.5$, the most distant confirmed cluster discovered by XMM lying at z=1.457 [523]. Significant galaxy overdensities have been found at higher redshift, mostly Lyman-α emitters and Lyman-Break galaxies concentrated around radio galaxies, including serious protocluster candidates at z=4.1 and 5.2 [389, 427]. Clusters shows a variety of morphologies (and thus dynamical states) out to very high redshift, with some evidence that high-redshift clusters have more substructures and are dynamically more active than low-redshift ones, as is qualitatively expected from hierarchical clustering [295, 375]. However, quantitative comparisons with models require reliable estimators of cluster dynamical state, which in turn require an understanding of the relation between dynamical state and morphology.

Merger events are an essential ingredient of cluster formation. Even though we now better understand the physics of merger events from detailed optical/X-ray studies of merging clusters, these studies have also revealed the dynamical complexity of cluster formation.

This includes the discovery of shocks and unexpected gas features like cold fronts [366], the existence of off-axis mergers [46], the evidence for multi-merger events [45, 219], in which the gas relaxation time can be longer than the interval between successive merger events, especially in dense environnements. It appears clearly now that the dynamical state of clusters and their morphology do not always simply depend on the most recent merger event, but also on the cluster formation history, which depends in turn on its large-scale environment. This makes quantitative studies of dynamical state evolution even more challenging.

Another important issue related to cluster formation is that of the non-thermal components of the intra-cluster medium: relativistic particles, revealed by radio observations of diffuse synchrotron emission [221], and residual bulk motion and turbulence of the thermal gas. This non-thermal component of clusters is now the subject of sustained observational and theoretical efforts. Open questions include: what are the origin and acceleration mechanism of the relativistic particles in clusters? How is the energy released by hierarchical cluster formation redistributed between the thermal and non-thermal components? Are the statistical properties of radio halos (e.g. frequency as a function of redshift) consistent with current scenarios of hierarchical cluster formation? Can the non-thermal pressure be neglected when estimating the total cluster mass, a key issue for cosmology? Dramatic progress in this field is expected from the next-generation radio observatories such as LOFAR, especially when combined with Chandra, XMM and PLANCK observations. For example, the relation between the properties of thermal gas and those of the relativistic plasma will provide key information to distinguish between various models [257, 215, 123]. Also, SIMBOL-X will enable the mapping of inverse-Compton emission from the relativistic plasma, which is so far not even clearly detected [21]. The combination of this with LOFAR observations will provide important information on the energy density and magnetic fields, by breaking the degeneracy between magnetic-field strength and relativistic-electron density, which is intrinsic to radio observations. Measuring and mapping the bulk motion and turbulence of the thermal gas is very challenging and requires spatially resolved high-resolution spectrometry. First observations of nearby objects will be enabled by the X-ray-bolometer arrays on the Japanese satellite Next, while XEUS/IXO will allow this type of study out to very high redshift (Section IV.3.5).

Gas thermodynamical history and feedback

One of the most important revelations of recent X-ray and optical/IR studies has been that feedback from supernovae and supermassive black holes must play a significant role, not only in the history of all massive galaxies, but also in the evolution of groups and clusters as a whole. Feedback mechanisms are likely to provide the extra energy required to keep the cluster centers from cooling all the way down to molecular clouds, to account for the entropy excess observed in the gas of groups and clusters, and to solve the overcooling problem and regulate star formation. Feedback mechanisms may also account to some extent for the correlation between black-hole mass and velocity dispersion of the host galaxy, as well as for the loss of gas and hence the onset of the red sequence shown by elliptical galaxies. Star formation feedback (e.g. via supernova-driven galactic winds) also plays a central role in the chemical enrichment of cluster gas.

Understanding these complex non-gravitational processes is a major objective of modern cosmology: what are the relative roles played by cooling, AGN heating and supernova heating? How do these vary in time? What is the interplay between these processes? How precisely is the energy transferred from the galaxies to the intracluster medium (ICM) and the IGM? How do the IGM properties affect galaxy formation? Recent X-ray observations has shed new light on these complex physical processes. The precise mapping of entropy profiles of relaxed clusters over a wide range in mass firmly established that the gas entropy exceeds the value attainable through gravitational heating, not only in the core but throughout the whole ICM [452]. This ruled out pure pre-heating models, while localized entropy modification, by cooling and central-AGN feedback, may be needed to explain the dispersion in the inner regions. Detailed observations of cooling cores revealed that shocks may be the most significant channel for AGN energy input [225], while violent outbursts of the central AGN may also play a fundamental role in shaping the global properties of clusters [252]. Millimetric observations have revealed the existence of large amounts of cold gas in the central regions of cooling-flow clusters [484, 485, 486], whose analysis brings new constraints on feedback processes [464].

The continuous confrontation of observations with numerical simulations of galaxy-cluster formation is essential for further progress in this field. Numerical simulations have reached a stage where the inclusion of all hydrodynamical and galaxy formation feedback processes becomes feasible, although the modeling of AGN feedback is still in infancy. On the observational side, future progress will come from the extension of systematic studies of large unbiased samples of local clusters (e.g. REXCESS [64, 154, 453]) to the group-mass regime (where heating is presumably dominated by galaxy feedback). In addition, very deep studies of cooling cores with the RGS (the high resolution spectrometer of XMM) can make a major contribution to the understanding of cluster-core physics and the ICM enrichment. Key diagnostics of non-gravitational processes are expected to arise from cluster-evolution studies, as local observations provide only a fossil record of the gas history. This is challenging because the departures from standard pure gravitational self-similar evolution are expected to be small. Some recent studies have started to measure these deviations [422] and the evolution in element abundances [32], but deep exposures of large cluster samples covering wide ranges in mass and redshift (including the essentially unexplored $z > 1$ range) are now required to discriminate between models. Large XMM programs are observing representative samples of distant clusters, while the serendipitous XMM Cluster Survey continues to provide new targets. We note however that tracing cluster evolution from the first low-mass systems at z$\sim$ 2 to the present time will be possible only with XEUS/IXO.

Formation and evolution of galaxies in clusters

How did bright elliptical galaxies form in clusters? To what extent do they result from the monolithic collapse of an initial gas cloud or the merging of late-type objects? When did star formation stop in these galaxies and through what physical mechanism? What are the high-redshift progenitors of the population of SO galaxies observed in present-day clusters? How does the evolution of a cluster (in particular, major merger phases) affect the star formation history of its member galaxies? How well does the standard 'concordant' model account for the different observed properties of cluster galaxies? These are open questions today, as the properties of cluster galaxies appear to depend in complex ways on mass, environment and redshift. Relations have been known to exist for years between morphology, local density and star-formation activity, but their dependence on other parameters (e.g. cluster mass and redshift) can be investigated in detail only now. The important recent progress accomplished both in numerical simulations (N-Body + SAM; N-Body + full Hydro, including feedback effects; see below) and in observations (deep multi-wavelength imaging, high resolution spectroscopy) of the cluster galaxy population should help elucidate many of these open questions in the coming years.

Determining the galaxy luminosity function is the standard approach to studying the more fundamental mass function. A consensus has been reached on the determination of the cluster-galaxy luminosity function with the analysis of the X-Ray/optical RASS-SDSS galaxy cluster survey [450]. The luminosity function shows two components: a universal bright end, with a constant slope of ~ -1.25, and a faint end with a steeper slope, which shows variations from cluster to cluster and appears to depend sensitively on the method used for background substraction. The determination of the luminosity function of very faint galaxies is currently an active field, in which some progress has come from detailed studies of targeted clusters [5, 71]. Also, recent investigations of the Virgo cluster [474] suggest that spectroscopic data may be critical for estimating the faint end of the cluster-galaxy luminosity function. The star formation history and the build-up of the overall galaxy luminosity function can also be addressed by means of observations in different wavelength domains (ultraviolet with GALEX [150], infrared with Spitzer [403]; see below). A comparison of multi-wavelength observations with the predictions from standard simulations has been performed recently [490]. This showed that the observed turn-up at low luminosities is well reproduced by the models, but the predicted luminosity function is shallower than observed at bright magnitudes, suggesting that cooling is too efficient for these objects in the models.

The existence of a tight relation between color and magnitude (giving rise to the 'red sequence') is a well-established property of early-type galaxies, both in the field and in clusters. Recent years have brought significant insight into the evolution of this relation with redshift in dense environments, thanks to the increasing number of observations of high-redshift clusters. This provides some clues about the star formation history of early type galaxies, a major question being to disentangle mass assembly from star assembly, i.e.

the relative importance of ‘dry mergers’ (where two galaxies with little gas merge without forming many new stars).

The red sequence of early-type galaxies is detected in clusters out to redshift $z = 0.8-1.2$ [169, 322, 248] and even in proto-clusters at $2 < z < 3$ with near-infrared imaging [314]. A striking result shown by most studies is a clear deficit of faint red-sequence galaxies at high redshift, balanced by an increase in the fraction of faint blue star-forming galaxies. This suggests that star formation stopped early on in the brightest galaxies, while the progenitors of faint, low-mass early-type galaxies continued to form stars down to $z \sim 1$ and later joined the red sequence. While this ‘top-down’ scenario of star formation (also named ‘downsizing’) could appear at first in conflict with the ‘bottom-up’ assembly of mass from hierarchical clustering, the two can be well reconciled in the concordant model. In fact, state-of-the-art models of galaxy formation, including Semi-Analytic Models (SAMs) and hydro/N-body simulations [170, 383], predict the onset of a red sequence in high-redshift clusters, the later transition of faint galaxies to this sequence and a significantly tighter color-magnitude relation in clusters compared to the field, as observed. However, the extremely low observed dispersion of this relation [381] is still a challenge to the models. Also, the relative roles of various physical processes, such as harassment, strangulation, AGN feedback and galaxy formation bias are still matter of debate, in particular to understand in detail the transition of intermediate- and low-mass galaxies to the red sequence.

Spectroscopic studies of large samples of galaxies at various redshifts have also helped constrain several physical properties of cluster galaxies, such as velocity dispersion, stellar mass, star formation history, dust content and metallicity. This has come from analyses of surveys like the SDSS [449, 222], dedicated projects like the NOAO fundamental plane survey [515] and the ESO Distant Clusters Survey (EDISCS [578] and individual clusters [176, 120, 139], using state-of-the-art stellar population synthesis models [102, 327]. Correlations between galaxy star formation rate and various observed quantities can help assess the relative influence of various physical processes at work in dense environments (i.e. galaxy-gas, galaxy-cluster and galaxy-galaxy interactions) and their impact on star formation. An interesting result is that the cluster star formation rate normalized by cluster mass appears to anticorrelate with mass and correlate with the fraction of star-forming galaxies [442]. The investigation of a low-redshift cluster sample further shows that cluster-cluster merging probably enhances the star formation activity of cluster galaxies [220, 376]. Radio-continuum observations of merging clusters can help further investigate this phenomenon [374]. An enhanced star formation activity has also been detected in cluster-feeding filaments using infrared and $H\alpha$ observations [209, 72].

The exquisite spatial resolution provided by observations from space has allowed additional constraints on the morphological evolution of cluster galaxies [398]. Combined analyses of galaxy colors, stellar populations and morphologies have now been achieved for a few clusters. Several HST/ACS key programs have been targetting nearby clusters (Virgo, Fornax, Perseus). The HST/ACS Coma treasury survey [122] is expected to deliver morphologies down to the very faint end of the luminosity function and, combined with spectroscopy, to test scaling laws between structural parameters over an unprecedently wide range of galaxy luminosities.

Studies of the evolution of galaxies in clusters are expected to develop fast, as cluster catalogs extracted from deep multi-band wide-field surveys (CFHT-LS, KIDS, VISTA, and later SNAP and LSST) become available, especially at high redshift. The combination of deep imaging at ultraviolet, visible, infrared but also millimiter and radio wavelengths (with the advent of LOFAR and ALMA) with high-resolution spectroscopy should be particularly helpful to constrain the physical processes that dominate the star formation history of cluster galaxies. The COSMOS project [503], together with the zCOSMOS redshift survey [342] and its multi-wavelength follow-up, will open new windows on galaxy evolution in clusters out to $z \sim 2$. Several Herschel key programs (e.g. LoCuSS, HeVICS) will bring new clues on the issue of obscured star formation in galaxy clusters. SKA will investigate the star formation properties and neutral gas content of galaxies as a function of environment out to redshifts $z \sim 3$. A major step forward is also expected from wide-field spectroscopic IFUs. The second-generation VLT instrument MUSE, with its wide $1{\times}1$ arcmin^2 field of vue (Section IV.2.3), will be particularly useful for deriving the star-formation and kinematic properties of cluster galaxies at redshifts $z \lesssim 1$. Finally, the combination high-spatial-resolution multi-band imaging and spectroscopy from space over wide sky areas, as currently planned for EUCLID, should bring definite answers about the evolution of the morphology, star, gas and dust content of galaxies in clusters out to $z \sim 2$. On the theoretical side, N-body/Hydro cosmological simulations including feedback effects and magnetic fields are mandatory to understand the physics of galaxy clusters. A very strong effort has been performed in the French community around the Horizon collaboration on this topic, providing state-of-the-art simulations of large-scale structures (Section II.2.9). This effort should be extended to detect and characterize the properties of low-mass halos corresponding to low- and intermediate-mass galaxies in galaxy clusters (e.g. through high-resolution resampling of high-density regions). This step will be essential to understand the dynamics and evolution of galaxies within clusters and the interaction of the galaxies with the gas.

Galaxy clusters as cosmological probes

Galaxy clusters have been used for a long time as cosmological tracers, e.g. to constrain the matter density parameter $\Omega_{\rm m}$ and the amplitude of the matter power spectrum σ_8. They have been identified by the Dark Energy Task Force as one of the 4 key experiments to constrain dark energy, together with weak shear, BAOs and type-Ia supernovae (Section III.1.2. Combining results of independent experiments is extremely powerful, as these probe different combinations of cosmological parameters. One can then break degeneracies and test possible systematic biases of the different methods. The main strengths of the cluster experiment are that, first, clusters form in the redshift range $0 < z < 2$, where the influence of dark energy becomes predominant; and second, several independent and complementary methods can be used to constrain cosmological parameters from cluster observations. This include the baryon fraction in clusters (used as standard candles and as fair representation of the baryon content of the Universe), the cluster abundance and its evolution, and the cluster clustering. All 3 methods require a robust estimate of the mass and its relation to observables, including the scatter in these relations. Methods based on cluster growth require large cluster samples with well-controlled selection functions. These are the main source of systematic uncertainties in cluster-based methods.

This field has undergone very significant progress recently. Chandra measurements of the gas fractions of a sample of massive relaxed clusters from Rosat have yielded interesting constraints on the dark-energy equation-of-state parameter (for comparison, the resulting constraints are slightly tighter than those obtained from the last type-Ia supernova results, when used as single independent probe) [10]. This provides new robust determinations of the cluster mass functions at low and high redshifts [568], and the constraint on the dark-energy equation-of-state parameter is $w = -1.14 \pm 0.31$. Including these new data improves the combined constraints on w from SN Ia, CMB, BAO and cluster experiments by factors of ~ 1.5 and ~ 2 in statistical and systematic errors, respectively. In the optical, the new generation of wide-field multi-band surveys has opened new windows to the field. Refined techniques of cluster detection are being developed (e.g. matched-filter, Max-BCG), which provide catalogs of hundreds of clusters (SDSS [391]) with photometric redshifts, on which a selection function can be estimated and a statistical approach performed. On the methodology side, new self-calibration techniques have been shown to be extremely promising for the analysis of future large cluster surveys [356]. These techniques consist in combining multiple observables from a survey (redshift distribution, clustering properties, direct mass estimates of a fraction of clusters), which produces redundancies and allows simultaneous constraints on the cosmological parameters and mass-observable relations.

In the near future, important progress is expected from the analysis of the CFHTLS and PLANCK surveys, in which the French community is deeply involved. The CFHTLS is at the moment one of the most competitive surveys for cosmological purposes (together with the Red Sequence Cluster Survey [587]), due to its depth ($z = 1.3$), angular coverage (200 square degrees) and its 5 photometric bands (Section II.1.3). Several fields have also been observed at complementary wavelengths (X, ultraviolet, infrared, millimeter) and partially covered by deep spectroscopic surveys (VVDS, DEEP2). The XMM-LSS $8 \times 8\,\mathrm{deg}^2$ survey in the CFHTLS fields [441], with its well-controlled selection function [428], is providing new insights into the evolution of X-Ray-emitting clusters [429]. This multi-wavelength coverage will be of first interest to address different mass-observable relations. The CFHTLS will provide a catalog of thousands of clusters in the redshift range $0.5 - 1.3$ [423, 240, 377], allowing comparisons with SDSS studies at low redshift. The methodology for constraining cosmological parameters using such multi-wavelength datasets will be tested in detail to prepare for the analysis of future surveys. In addition, the PLANCK whole-sky survey will detect more than 3000 clusters and increase by two orders of magnitude the number of known very massive ($T > 7\,\mathrm{keV}$) clusters at $z > 0.6$, which are the best for precise cosmological analyses. The combination of these data with X-ray observations (archival data and XMM-Newton follow up) will be essential to fully exploit this sample. Precise mass estimates will allow constraints on the dark-energy equation of state from the gas mass fraction, improved by constraints from cluster clustering and cluster abundance (which relies on a precise calibration of the mass versus Y_{SZ} relation).

On the longer term, one can note the multiplicity of projects which will yield very large, representative cluster catalogs out to redshifts $z > 1$ with well-defined selected functions at different wavelengths. This includes projects using clusters as primary probes, like e-Rosita (50,000 X-ray clusters at $0 < z < 1.5$) and the Dark Energy Survey (30,000 clusters detected in optical and SZ data over 4000 square degrees extending beyond $z = 1.5$), but also projects like SNAP, LSST or EUCLID. The spatial scales involved will allow new constraints from the large-scale clustering of galaxy clusters to the baryonic oscillations of the galaxy-cluster power spectrum.

Concluding remarks

The study of galaxy clusters is directly connected to cosmology and the physics of structure formation. This is a very active field worldwide, which is expected to become even more so in the coming years. The dramatic increase in the performances of new powerful observational techniques (Sunyaev-Zel'dovich effect, weak-lensing, infrared, millimeter and radio observations), so far often restricted to 'test-case' studies, will give access to a multi-wavelength 'panorama' of large samples of galaxy clusters. Also, the cluster galaxy populations can now be resolved both in observational and in theoretical studies, which will allow investigations of galaxy properties as a function of redshift, mass, and local density. Hence, clusters can be fully used as laboratories to investigate the complex interplay between dark matter, gas and galaxies. The next years will also see a renewal of the use of clusters as cosmological probes, in particular to constrain the dark-energy equation of state. The french community is in a good position to continue making important contributions to this field, through its access to present and upcoming key facilities (e.g, CFHT, VLT, IRAM, XMM, Herschel, PLANCK, ALMA, LOFAR), on which it holds the leadership of several Large Programs, and its involvement in future projects (Simbol-X, SKA, SNAP, LSST, XEUS, EUCLID). The sustained development of numerical simulations will be essential to extract the best science from the wealth of future data expected on clusters. Expertise has been developed in the various topics in France, but the 'cluster' community is small and geographically scattered. National initiatives, such as the previous 'Operations' from the PNC and PNG greatly helped improve the communication between the teams, and induced multiple collaborations. Still, the community would need to be strengthened (e.g. with the creation of post-doctoral fellowships and research positions in this field) to be able to face the international competition, which will be tough in a few years.

III.2.4 Large scale matter distribution

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Introduction

In the current 'standard model of cosmology', present-day structures of the Universe are thought to have arisen from tiny quantum fluctuations generated randomly inside a uniform primordial soup of matter-energy. In this picture, fluctuations eventually reached macroscopic scales after an early inflation period, which resulted in the production of the scale-invariant primordial power spectrum of fluctuations. Perturbations then grew under the effect of gravity only; those with sufficient mass and density eventually collapsed, clustered and merged hierarchically with other halos to form the Universe we see today.

The current scenario also assumes that the matter-energy content of the Universe is dominated by the (cold) dark matter and dark energy components, both of unknown nature. Photons, neutrinos and baryonic matter represent only a small fraction of the matter-energy content of our Universe. However, they play a most important role in the thermal evolution, the nucleosynthesis of light elements, the late reionization phase of the Universe and the formation and evolution of structures and galaxies. In this context, the description of large-scale structure at all scales and at all redshifts is a primary key to understanding the physical processes responsible for the cosmic history of structure formation, from the largest linear and scale-invariant structures, down to sub-galactic halo scales.

Much of our current characterization of large scale structure comes from the recent CMB anisotropy experiments, in particular WMAP, and wide-field galaxy redshift surveys, in particular the SDSS and 2dFGRS. The CMB-anisotropy angular power spectrum and the galaxy 2-points correlation function reveal characteristic spectral features, which indicate that our Universe is likely to be almost flat and that the power spectrum of density fluctuations is well described by a single power-law of spectral index close to unity, as expected from simple inflation scenarios. The acoustic peaks detected in both the CMB and galaxy power spectra, which arise from the baryonic cosmic sound waves, are spectacular demonstrations of the big picture drawn by cosmologists over the past decades, i.e., that the large-scale structure has been shaped by gravitational instabilities out of primordial adiabatic metric perturbations. Nearby but also deep redshift surveys (such as VVDS and DEEP2) have strengthened this paradigm. They have shown that the evolution of the galaxy 2-point correlation function as a function of redshift, galaxy intrinsic luminosity (mass) and galaxy type is in good agreement with the expectations from the hierarchical Λ-CDM model.

The standard model of cosmology has indisputable ability to explain most astronomical observations. It therefore represents a solid basis for further progress toward 'precision cosmology'. The next challenge is to describe the properties of large-scale structure with enough detail to uncover its most tiny features and the various physical process that led to these. Significant advances are expected over the next 20 years on the following questions (some of which were addressed in detail in previous sections of this document):

- probes of the history of structure growth and of the gravitational instability theory;
- origin of the accelerating cosmic expansion and the nature of dark energy;
- nature of dark matter;
- neutrino mass;
- cosmological tests and properties of inflation;
- nature of cosmological perturbations;
- probes of cosmological defects;
- probes of early intrinsic anisotropy and the cosmological principle;
- probes of baryogenesis;
- probes of parity violation;
- probes of variations of fundamental constants;
- probes of large-scale primordial magnetic fields;
- topology of the Universe;
- cosmic history of the reionization period;
- properties of the biasing parameter;
- cosmological tests of non-linear halos, small-scale structures, halo profiles and substructures.

Theorists, experimentalists, and observers have been working actively to identify cosmological probes and propose observational tests for each of these questions. Each physcal process produces primary signatures in some specific component (baryons, dark matter and dark energy) at specific cosmic times and on specific scales. It can produce specific cosmic messengers (photons, gravitational waves) at specific wavelengths. Cosmologists already have (or will have soon) a wide arsenal of instruments and cosmic probes to explore these specific signatures. Overall, there are reasonable hopes that most degeneracies will be broken, provided that the exploration of large-scale structure is carried on all fronts simultaneously. It is important to note that the development of complex theoretical models of the early Universe and high-resolution multi-fluid cosmological simulations will be necessary to test theoretical predictions against cosmological observations.

In practice, present-day cosmic probes of large-scale structure include CMB anisotropies, galaxy redshift surveys, quasar absorption-lines surveys, galaxy-cluster surveys and (dark-)matter surveys using gravitational lensing. The immediate products of these surveys are the 2D and 3D power spectra of density fluctuations. To date, cosmological inventories from the characterization of power spectra are the most popular way to probe large-scale structure. The application of this technique to CMB temperature and polarization anisotropies and galaxy surveys has produced strong limits on the primordial spectral index, the curvature of the Universe and its baryon, dark-matter and dark-energy contents. Power-spectrum investigations are likely to still play a primary role in cosmological studies of the next decade. Among the most novel and promising applications to future surveys, one finds weak-lensing 'tomography', which will enable the exploration of dark-energy models from direct observations of the dark-matter power spectrum as a function of redshift, and the CMB-polarization power spectrum on large scales, which will allow tests of inflation scenarios. The increasing accuracy of instruments and measurements continues to trigger the emergence of more complex statistical tools. These will enable always more detailed studies of the growth rate of structure and dark-energy models, non-Gaussian features, tiny deviations from the scale-invariant power spectrum from zero-curvature Universes, deviations from adiabaticity and from primordial fluctuations.

In the following, we briefly review some applications of probes of large-scale structure, which are expected to produce important breakthroughs in cosmology over the next 10 to 20 years. We do not rediscuss here studies the CMB, dark energy, Lyman-α forest and galaxy clusters, which have been described in Sections II.1.1, III.1.2, III.2.2 and III.2.3 of this document.

Direct probes of the dark-matter distribution

Because gravitational lensing is directly sensitive to the gravitational potential, is a most promising and almost unique tool to explore the dark-matter distribution in the Universe. Its signatures are a gravitational magnification and a gravitational shear field, which can be detected from the statistical increase in the size of the background sky and in the size, flux and ellipticity of background galaxies.

One can assume that galaxies have (statistically) no preferred orientation in the absence of lensing, which provides gravitational shear with an absolute-zero calibration (this is not the case for cosmic magnification). Any statistical deviation of galaxy orientation from zero in a galaxy survey can be interpreted as a gravitational-shear effects. The ellipticity correlation function can then be used as a direct probe of dark matter. Gravitational-shear analyses of wide-field galaxy surveys, such as the CFHTLS and the SDSS, have constrained the amplitude and the shape of the dark-matter power spectrum. Galaxy-galaxy lensing (but also Einstein rings around galaxies from the CFHTLS-SL2S and SDSS/HST-SLAC surveys) allowed investigations of the properties of galactic dark halos.

Gravitational lensing works on all scales and only acts on objects located behind structures. Hence, weak gravitational shear is perfectly suited to observe the distorted Universe and the dark-matter distribution in different redshift slices. Using such tomographic explorations, the 3D dark-matter power spectrum and its evolution with redshift can be reconstructed over about 5 decades in size, from filament down to galaxy scales. This can be used to measure the growth rate of the dark-matter distribution and test the predictions of various dark-energy and modified-gravity models. An early attempt to perform weak-lensing tomography using the HST/COSMOS data was very encouraging and produced a spectacular view of the dark-matter distribution at different redshifts (see Fig. III.12). The potential of this technique to probe dark energy in the next-generation weak-lensing surveys motivated its recommendation by the US Dark Energy Task Force and the ESA-ESO working group on fundamental cosmology. It was also a strong case in favor of the pre-selection of the joint imaging+spectroscopy EUCLID space mission for Cosmic Vision and justifies the great value of a dark-energy survey with SKA.

From a technical point of view, the measurement of weak-lensing signal from galaxy ellipticities is a serious issue for future surveys. The difference in the gravitational-shear signal predicted by different dark-energy models is extremely small. Its measurement requires outstanding image quality and the capability to measure the gravitational distortion of galaxy ellipticities at the 0.1% level. Specific image deconvolution techniques and very high stability of the PSF are needed. Present-day techniques are sufficient for the analysis of ground-based surveys like the CFHTLS, but they have not been proven yet to be able to reach the accuracy needed of the next-generation surveys. It will be important over the next decade to support teams and new initiatives, like the STEP project, who focus on this issue.

Possible non-Gaussian signatures in the dark-matter distribution can be investigated using higher-order statistics (e.g. skewness or any 3rd-order cumulant) of the gravitational 'convergence' (the trace of the shear matrix, which can be expressed as an integral of matter density perturbations), the gravitational convergence bispectrum or the 3-point shear correlation function. It is worth noting that, while the CMB is still unique to observe the linear Universe, high-order statistics applied to the shear and the convergence field are unique to directly observe the non-linear dark-matter Universe, without any priors.

It is possible to build statistical probes of non-linear structures, which are independent of the normalization of the dark-matter power spectrum. They can be used to break the intrinsic $(\sigma_8; \Omega_{\rm m})$ degeneracy of the shear power spectrum. A weak-lensing survey using together the power spectrum and the bispectrum of the gravitational convergence as a function of redshift via the gravitational distortion of galaxies can therefore describe in details the emergence of cosmic structures in the context of the gravitational-instability scenario. This will set the bridge between the dark-matter cosmic web, superclusters of galaxies and clusters of galaxies.

The application of high-order statistics to weak-lensing surveys is still in infancy for two main reasons: first, providing high-signal-to-noise-ratio information on relevant scales requires a huge amount of data, and very few theoretical studies have explored how models can be tested against observations. Second, a comprehensive exploration of high-order statistics for a broad range of dark-energy models is still missing. Numerical simulations including ray tracing must be developed in the future to assess (i) the accuracy to which weak-lensing surveys can probe dark-energy models with high-order statistics and (ii) the nature and the amplitude of the most critical systematics involved.

The amplitudes of 2nd- and 3rd-order statistics and the tomographic techniques are scaled by the angular distances of the lensing structures and the lensed sources. Moreover, both statistics are contaminated by several well-known astrophysical systematics, which cannot be removed without a good knowledge of the distances to all relevant objects. This is an important lesson learnt from the past: redshift information is an essential part of a weak-lensing catalog. The analysis of weak-lensing surveys such as the CFHTLS has demonstrated that a rough redshift estimate of the lensed sources is acceptable to derive $(\Omega_{\rm m}; \sigma_8; w)$ to $\sim 10\%$ accuracy, but not sufficient to pin down dark energy to the percent level. It is therefore important to recommend that a massive photometric-redshift survey, combined with a spectroscopic redshift follow-up (for calibration purposes), is a prerequesite to a successful exploration of the dark-matter distribution based on weak-lensing probes.

The large-scale mass distribution also imprints signatures in the CMB temperature and polarization maps. Gravitational magnification and shear increase the CMB-temperature power spectrum at small and intermediate scales. Since the source redshift is known, tomographic techniques applied to CMB maps can in principle probe the background dark-matter power spectrum at all redshifts. In contrast to lensed galaxies, CMB anisotropies are a fixed source plane which keeps the distortion pattern and the number density of lensed CMB features constant. This has great potential to explore high-redshift structures, where the galaxy number density of background sources is too small for standard weak-lensing studies to be performed.

An interesting application of CMB lensing is the exploration of the Integrated Sachs-Wolfe (ISW) effect using the large-scale bispectrum signal. This is derived from the cross-correlation between CMB-temperature and weak-lensing maps. Since gravitational lensing directly probes gravitational potentials, the cross-correlation between weak-lensing and CMB-temperature maps looks more promising than galaxy-CMB ISW studies. This has particularly interesting implications for exploring dark-energy models with a non-constant equation of state, with both weak-lensing and ISW tomography. The combination of next-generation weak-lensing surveys (KIDS/VIKING, DES, Pan-STARRS, LSST, JDEM or EUCLID) with Planck data will be perfectly suited to ISW studies.

Large-scale mass distribution and biasing

The large-scale distributions of baryons and dark matter can be used jointly to probe how baryons, light and dark matter are related. For example, comparisons of the galaxy and Lyman-α-forest power spectra with the weak-lensing power spectrum provide an unambiguous means of probing the properties of the 'bias parameter' as a function of scale, galaxy type, redshift and local environment. In practice, combining Lyman-α-forest statistics together with large-scale weak-lensing analyses is not yet feasible, since the two techniques sample different redshift range. However, galaxy and weak-lensing catalogs are both outcomes of the same surveys and probe the same populations.

The cross-correlation between the dark-matter and galaxy distributions derived from the background (sheared) - foreground (lens) galaxy cross-correlation function provides a unambiguous estimate of the linear bias b at angular scale θ,

$$\frac{1}{b\,(\theta)} = \frac{\langle M_{ap}\,(\theta)\,N\,(\theta)\rangle}{\langle N^2\,(\theta)\rangle}\,, \tag{III.4}$$

and a probe of the bias as a function of angular scale and redshift. Here M_{ap} is the aperture-mass statistics (which measures the tangential shear weighted by a compensated filter function in a circular aperture) and N the galaxy density (in the same aperture). Furthermore, the cross-correlation of galaxy and weak-lensing catalogs probes not only the amplitude and the shape of the bias as a function of scale, but also the light-mass cross-correlation coefficient

$$r\,(\theta) = \frac{\langle M_{ap}\,(\theta)\,N\,(\theta)\rangle}{\langle N^2\,(\theta)\rangle^{1/2}\langle M_{ap}^2\,(\theta)\rangle^{1/2}}\,. \tag{III.5}$$

Thus, both the stochasticity and the deviation from linearity of the bias can be derived from the galaxies-weak lensing cross-correlation signal.

Present-day weak-lensing surveys can probe lensed and lens structures only at redshift $z \lesssim 1$, and hence, the galaxy-mass cross-correlation only applies to structures at redshift $z \lesssim 0.5$. With the exception of the joint VIRMOS-DESCART/RCS analysis, very few studies have been published so far on this subject, mainly because weak-lensing surveys are still relatively small. This approach however represents our best hope to investigate the bias evolution of the low-z Universe, providing remarkable complementary information to the non-linear Universe revealed by weak lensing. Both descriptions will help draw a detailed picture of the late structure-formation processes that formed the densest halos and the galaxies we see today.

A complementary view of biasing is also given by the galaxy bispectrum derived from galaxy surveys. Linear and non-linear bias parameters, b_1 and b_2, can be derived from galaxy surveys, which are related to the reduced galaxy bispectrum Q_{gal} via an expression of the form

$$Q_{gal} = \frac{Q}{b_1} + \frac{b_2}{b_1^2}\,, \tag{III.6}$$

where Q is derived from theoretical models of the bispectrum. Since this approach is independent of weak lensing, a combination of both approaches can provide accurate constraints on the bias and its evolution with look-back time, galaxy type and local environment in the context of hierarchical models of structure formation. A most important outcome will the breaking of the degeneracy of the classical $\beta = \Omega_{\rm m}^{0.6}/b$ parameter that arises from theoretical studies of the linear growth rate of structure in redshift space. This would open a new route for dark-energy exploration from wide-field galaxy redshift surveys. Next-generation deep wide-field spectroscopic surveys, such as DES, WFMOS, SKA, JDEM or EUCLID, could be perfectly suited for this.

Large-scale structure and inflation

The most recent WMAP5 results have strengthened earlier observations that the spectral index of primordial fluctuations is less than unity ($n_s = 0.963 \pm 0.015$) and that the ratio of tensor (gravitational waves) to scalar (density) perturbations satisfies $r < 0.26$. Due to intrinsic degeneracies between n_s, $\Omega_b\ h^2$ and the optical depth of reionization, errors in n_s are still debated. However, the current limits on the spectral index are of considerable importance and have a profound impact on the physics of the early Universe. They already set an upper limit on the energy scale of inflation and show that observational cosmology can now constrain inflation models. There is therefore no doubt that the exploration of inflation models will be the next holly grail of cosmologists, together with dark energy. It places the reconstruction of the primordial power spectrum at the very center of the next-generation cosmological surveys.

Probes of inflation rely on 6 important tests:

- power spectrum of gravitational waves;
- adiabiaticity of primordial fluctuations;
- Gaussianity of primordial fluctuations;
- super-horizon fluctuations;
- flatness of the Universe;
- scale invariance of the primordial power spectrum.

There is no hope to detect on a short time scale tensor-mode perturbations from the spectral analysis of primordial gravitational waves. LISA is likely to be the most promising project to explore these, but not before 2020 at the earliest. B-mode polarization of the CMB on large scales, which are not contaminated by gravitational lensing, would provide an almost direct imprint of the primordial tensor-mode perturbations. The observation of B-mode polarization may therefore be a unique window to explore inflation scenarios. It is however not possible to precisely anticipate the amplitude of primordial B-modes from present-day observations. Theoretical inflation models predict a very broad range of values, which can all be accommodated by current datasets. The Planck mission will represent a major step in the quest for inflation. It will provide the amplitude of the background contamination of polarization modes by Galactic dust and more precise bounds on the tensor-to-scalar perturbation ratio. The hope is to then be able to predict whether primordial B modes will be within the reach of the next-generation CMB surveys. In the meantime, it is important to support projects aiming at measuring polarization from the ground (even though large-scale B-modes are still beyond the capabilities of ground experiments) and to prepare post-Planck polarization space missions.

The observation of primordial non-Gaussianity is a promising and rather easy way to probe inflation. Since simple inflation models predict pure Gaussian primordial spectra, the detection of primordial non-Gaussian features would rule out a wide range of inflation scenarios. The angular bispectrum of CMB temperature anisotropies, despite contaminations on small scales, can reveal useful details on large-scale primordial non-Gaussianity. The first tentative detections of an extreme cold spot and alignments of large-scale modes of the CMB power spectrum in WMAP data show that non-Gaussianity may already be detected and explorable by wide-field cosmological surveys. Non-Gaussianity may therefore be the primary outcome of Planck data.

A promising way to explore primordial non-Gaussianity is the f_{NL} parameterization, where a quadratic correction is added to a Gaussian random field potential

$$\Phi = \phi_0 + f_{NL}\ \phi_0^2 \,. \tag{III.7}$$

Several new theoretical studies of this approach have demonstrated that, depending on the range of permitted values of the f_{NL} correction, one can derive relatively clean and strong constraints on inflation. The bispectrum of the 3-point CMB temperature anisotropy can be related to f_{NL}, so WMAP already provides an upper limit to primordial non-Gaussianity. A recent analysis of WMAP5 data concludes that primordial perturbations were Gaussian within $\leq 0.1\%$.

The f_{NL} description turns out to be complex, and the expression given in eq. (III.7) may be too cursory and simplistic to describe a broad variety of models and sources of non-Gaussianity. In any case, the f_{NL} parameterization is a reasonable *ansatz* to start confronting theoretical predictions with observations. It is therefore important that more theoretical and statistical studies focus on this novel tool and make more precise assessments of its strengths and weaknesses.

The f_{NL} non-Gaussianity parameterization also applies to other large-scale cosmological probes, such as galaxy and weak-lensing surveys. Its application will likely be extended to all cosmological wide-field surveys. In particular, it will be a valuable tool to interpret joint Planck + next-generation imaging and spectroscopic galaxy surveys, which will cover the whole deep sky.

Large-scale baryon distribution and the dark age

Understanding the transition from the linear to the non-linear regimes of structure formation and from the formation of the first dark clumps to the first luminous objects is among the most complex and debated issues of hierarchical cosmological models. A simple way to attack the problem is to start from the observation of the large-scale distribution of baryons as a function of redshift and compare this with the underlying dark-matter distribution. Cosmological probes can be galaxies and quasars, as well as the cold, warm and hot IGMs. It is usually believed that joint studies of galaxy clustering and Lyman-α (neutral hydrogen) cloud statistics are the most promising way to sample the cosmic history of baryons over all epochs since recombination ($z \lesssim 1000$) and to probe the evolution of the Universe before and during the reionization periods.

The clustering history of galaxies and of the Lyman-α forest has already been discussed to some extent above (and in Section III.2.2 of this document). It is important to stress the primary role of galaxy redshift surveys to probe the clustering and merging history of the galaxy population. The discovery of baryon acoustic oscillations in the SDSS and 2dFGRS galaxy power spectra has opened a new window for spectroscopic and photometric redshift surveys of galaxies and quasars. Surveys like DES, BOSS, PRIMUS, PAU, EUCLID, JDEM and SKA will be designed to measure the acoustic signatures of baryons at different redshifts to derive information on dark energy. Similarly, the merging history of galaxies and dark halos and the properties and evolution of the bias as a function of galaxy luminosity, type and local environment have been successfully described from the 2D and 3D galaxy 2-point correlation functions and the pair-wise velocity dispersion of deep VVDS/CFHTLS, DEEP2 and zCOSMOS spectroscopic surveys. These studies demonstrated that, for example, the reddest and most luminous (massive) galaxies formed and clustered differently and at a different epoch than the rest of the galaxy population. Hence, galaxy redshift surveys have considerable value for testing hierarchical models of galaxy formation.

Deep galaxy redshift surveys will continue to be of prime importance in the next decades. The exploration of galaxy clustering at very high redshift ($5 < z < 10$) and over broad ranges of angular scales and galaxy types (e.g., blue, red, spiral, ellipical, Lyman-α emitter, Lyman-break, ultra-luminous, most massive) requires strong support for the experienced French teams involved in new deep redshift surveys, such as the ongoing ultra-deep VVDS and VIPERS surveys and the future WFMOS and EUCLID redshift surveys. It is also important to strenghten the involvement of French teams in infrared-selected galaxy redshift surveys, which can efficiently detect massive luminous halos and very high-redshift red galaxies. The clustering and merger history of these galaxies appear to be a key for understanding the formation process of dense galaxy- and cluster-size halos at high redshift. Galaxy samples extracted from Ultra-VISTA, WYSE, Spitzer and Herschel will be perfectly suited to this challenging project.

In contrast to studies of galaxies and the Lyman-α forest at moderate to high redshifts, the exploration of the large-scale distribution of neutral hydrogen in the early Universe is still in infancy. The observation of neutral hydrogen at extremely high redshift may revolutionize our view of the transition between the linear and the non-linear regimes of structure formation prior to reionization. This makes neutral hydrogen the most attractive way to probe the Universe between the last-scattering surface ($z \sim 1000$) and the epoch of reionization ($z \lesssim 10$). Over the 400 Myr covered by this dark age, the 21 cm emission feature may well be our only window on early structure formation. This unique view, offered by the spin transition of hydrogen, is a new territory of observational cosmology, which fills the gap between the recombination epoch and the appearance of the first luminous stars and quasars.

In practice, neutral hydrogen at high redshift can be detected through the difference between the HI surface brightness temperature and the CMB temperature. The mass density contrast can be derived directly from the temperature contrast

$$\delta T_B \simeq 23\,(1+\delta) \quad x_{HI} \left(1 - \frac{T_{CMB}}{T_S}\right) \left(\frac{\Omega_b h^2}{0.02}\right) \times \left[\left(\frac{0.15}{\Omega_m h^2}\right) \left(\frac{1+z}{10}\right)\right]^{1/2} \text{ mK} . \quad \text{(III.8)}$$

Because of the early coupling between the CMB and the intergalactic medium, the 21 cm HI emission cannot be detected at redshift $z > 200$. At lower redshift, the residual ionization fraction and the density are small enough for the CMB and the IGM temperatures to be considered as decoupled. This makes the 21 cm emission line an efficient tracer of structures in the redshift range $50 \lesssim z \lesssim 200$, i.e. so long as structure growth remains fully linear and simply linked to the distibution of neutral hydrogen. Sky maps at 21 cm in this redshift range should directly reflect the distribution dark-matter fluctuation.

At redshift below $z \sim 30$, non-linear processes start to play an important role, and the first luminous objects arise. The combined observation of 21 cm emission and *absorption* (by the neutral IGM toward very-high redshift radio sources, and by gas associated with the first collapsed structures) can be used to constrain structure formation during the preionization period, and eventually during the early reionization history (before Lyman continuum photons fully reionize the Universe). A remarkable gain relative to the CMB-anisotropy probe is the possibility to explore angular scales below the CMB cutoff associated to Silk Damping. The formation of early dark halos can then be followed down to much lower scales than with the CMB-anisotropy probe.

The 21 cm emission and absorption signals of neutral hydrogen at high redshift also provides valuable redshift information. This can be used in the same way as galaxy redshift surveys to probe the acoustic baryon wiggles in the hydrogen power spectrum and to derive the growth rate of structure using redshift-space distortion at much higher redshift than galaxies. At these high redshifts, the Universe is close to Einstein de Sitter, and cosmic structures are in the linear regime. This makes cosmological interpretations of the 21 cm line much easier and less degenerate than studies of galaxy catalogs. Moreover, the redshift information provides a unique way of describing the 3D Universe using tomographic techniques, as with the weak-lensing and ISW probes. Thus, 21 cm cosmology is essentially a 3D mapping of neutral hydrogen, baryons and dark matter inside linear structures during the dark age.

From a practical point of view, however, the feasibility of primordial-HI observations using the 21 cm emission and absorption lines is still controversial. The expected signal-to-noise ratio of such observations is very small and may be seriously spoiled by foreground contamination (e.g. by galaxies). Furthermore, because of the diversity and complexity of the physical processes occurring during the pre-ionization and reionization epochs, it is impossible to make detailed predictions of the expected signal without appealing to high-resolution hydrodynamical simulations.

Overall, observations of the 21 cm signature of primordial HI may be the most novel field of cosmology for the next decades. Surveys with LOFAR, MWA and SKA seem best suited to probe the dark Universe in this way, especially if combined with ultra-deep galaxy surveys. It is important to keep the French community active in this new and attractive field, as several groups already have strong experience with both the observational and numerical aspects.

III.3 Galaxy formation

III.3.1 Formation of the first stars, galaxies and quasars

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Introduction and background

A lot of progress has been achieved recently in the theory, modeling and observations of the first stars, galaxies, and qusars. For example, powerful numerical simulations have been developed to simulate *ab initio* the formation of the first stars and galaxies with exquisite resolution and including numerous physical and chemical processes [3]. Also, a group led by French astronomers used UVES on the VLT to obtain high-quality spectra of the most metal-poor stars known in the halo of our Galaxy [127, 126]. This has allowed accurate abundance determinations and interesting constraints on, for example, the typical stellar mass of the first stars and the duration of the Population III phase [478]. At high redshift, ultra-deep imaging surveys with 10 m-class telescopes and HST in the optical and near-infrared have unveiled hundreds of galaxies at redshift $z \lesssim 6$ – barely 1 Gyr after the Big Bang – and faint galaxy candidates out to $z \sim 9 - 10$ (see Fig. III.20) [157, 108, 434, 312, 85, 468]. Finally, wide-field surveys, such as the SDSS and the CFHTLS, have provided the first samples of extremely distant quasars ($z > 6$), which have been used to trace the end of cosmic reionization (see Fig. III.21) [212, 580].

These are only examples of a wide variety of results obtained using different search techniques at different observational facilities targeting different wavelength domains, in fields such as stellar physics, star formation, galaxy nuclear activity, the intergalactic medium and cosmic reionization. These studies have started to build a coherent picture (both theoretically and observationally) of the transition from the dark age to reionization, by providing a first glance on galaxy and black-hole formation and evolution during the first $1 - 2$ Gyr of the history of the Universe. The exploration the first stars, galaxies and quasars is now a recognised priority of observational cosmology, and forthcoming facilities such as JWST and the E-ELT will truly be 'first-light' machines.

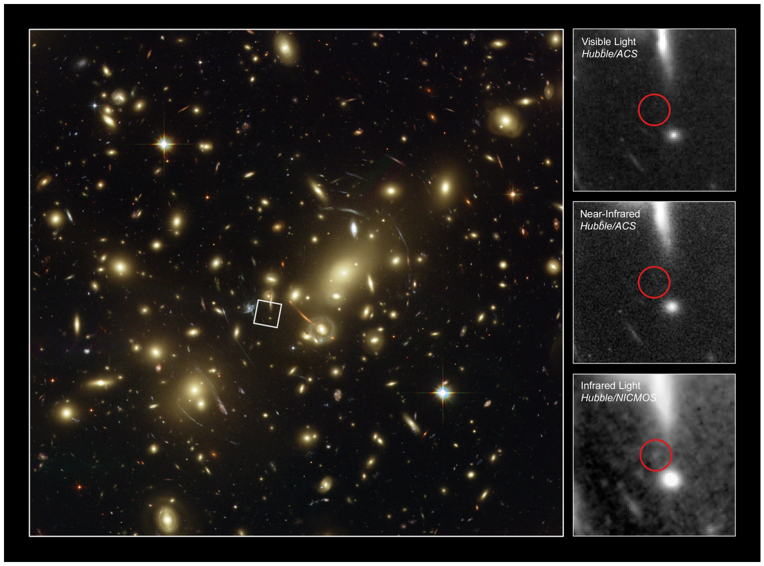

Figure III.20: Deep HST image of the lensing cluster Abell 2218 indicating the position of a $z \sim 7.5$ galaxy shown in detail on the right [468].

Perspectives

Studies of the formation of the first stars, galaxies and quasars represent a very dynamic research field, in which some pressing open questions are the following.

✰ Where are Population-III stars, what are their properties, and what is their influence?

The quest for Population-III stars, the first population of stars to form after the Big Bang, has been revived in recent years both theoretically and observationally. First, powerful *ab initio* simulations have been very successful in exploring numerically star formation in the early/metal-poor Universe. Second, CMB-polarization measurements by the WMAP satellite have revealed the presence of powerful sources of ionizing radiation – possibly Population-III stars – out to very high redshift ($z \sim 11 \pm 1.4$ [189]). Third, searches for extremely metal-poor halo stars, fossils from the first epochs in our Galaxy, have yielded interesting examples. Finally, attempts to find direct signatures of Population-III stars in distant galaxies have started in earnest [165, 406].

A generic prediction from theory and modeling is that star formation below a certain metallicity $Z_{\rm crit} \approx 10^{-5\pm1} Z_\odot$ produces typical stellar masses much in excess of those observed today. Even though this result is quite generally accepted, its robustness is still unclear. Furthermore, among other evidence, the observed abundance pattern of very metal-poor halo stars in the Milky Way seems incompatible with an early top-heavy initial mass function (IMF) [555]. Also, no signature of pair-instability supernovae expected from

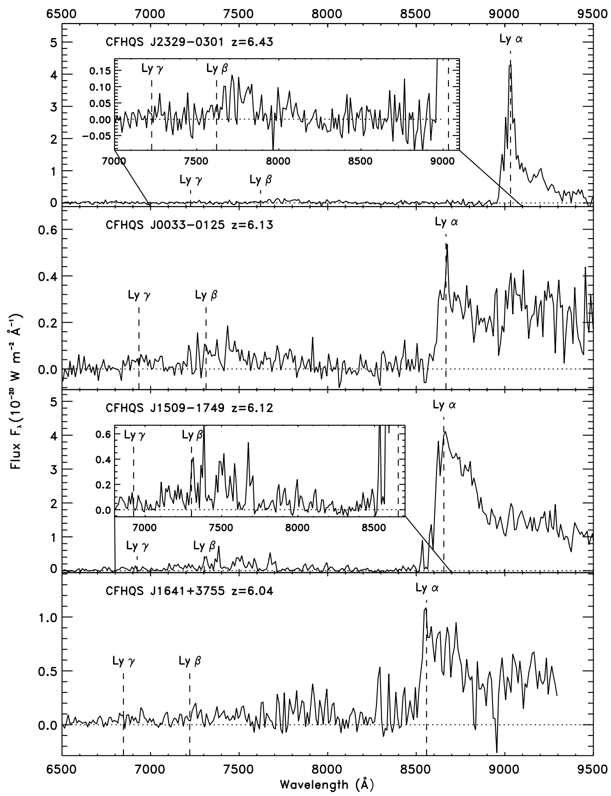

Figure III.21: Spectra of the most distant quasars found with the CFHTLS. The strong Gunn-Peterson absorption trough indicates the end of cosmic reionization near $z \sim 6$ [580].

such very massive stars has been found so far. The question of the typical mass of very metal-poor Population-III stars remains therefore open. We note that, although current simulations of primordial-star formation already include many complex physical and chemical processes, some crucial ingredients may still be lacking. Future, even more sophisticated simulations are being developed to examine these questions and study more accurately the properties of the first stars, the first supernovae and their remnants, their influence on the host proto-galaxy ('feedback' effects) and related questions [97].

On the observational front, the stellar community pursues surveys for the most metal-poor stars in our Galaxy, and searches for very metal-poor galaxies and Population-III stars in galaxies continue using different approaches and techniques, at both low and high redshift. Efficient multi-object spectroscopy, especially in the near-infrared domain (e.g., with EMIR on GTC, KMOS on the VLT, and later NIRSPEC on JWST), should drastically improve our capability to follow up spectroscopically galaxy candidates at $z > 6$. The hope is that specific searches for distant/primeval galaxies (see below) will enable the discovery of direct signatures of Population III stars.

☆ What is the star formation history in the distant Universe, and where are the sources of cosmic reionization?

Since the discovery of the first galaxies at $z \sim 3$ in the late 90's, the advent of near-infrared imaging both from the ground and with HST has allowed astronomers to push the limits further back in distance and time. At present, about 500 galaxies are known at redshift $z \sim 6$, and about $20 - 30$ at $z \gtrsim 7$. The most distant galaxy known is possibly at $z \sim 9.5$ [434, 524, 85, 468]. So far, only some basic properties of these galaxies have been derived. They appear to have typical star formation rates of the order of few to $30\,M_{\odot}\mathrm{yr}^{-1}$, relatively low masses ($\sim 10^{8} M_{\odot}$), a wide dispersion in age and little or no dust. However, the number of observed galaxies is still very small, and we are most likely seeing only the tip of the iceberg.

Shortly after the discovery of the first $z \sim 6$ galaxies, it was realized that the observed galaxy population at $z \geq 6$ falls short of producing enough ionizing photons to reionize the Universe [109, 84, 66, 468]. Is the corresponding apparent decrease of the cosmic star-formation-rate density real at $z > 6$? Are current surveys missing galaxies? Can there be other explanations? Some authors have suggested that the cosmic star-formation density at $z \sim 6 - 10$ may be similar to that observed at lower redshift [467]. The discovery of evolved stellar populations (with ages up to $\sim 500 - 700\,\mathrm{Myr}$) at $z \sim 6$ [207] supports this idea. Other authors have suggested that the bulk of the sources of cosmic reionization may be faint galaxies below the detection limits of current surveys [109, 140]. Settling this issue requires an accurate determination of both the bright and faint ends of the galaxy luminosity function at $z > 6$. Observationally, this implies near-infrared imaging over wide sky areas even deeper than currently achieved (i.e. down to AB magnitudes $\sim 30 - 32$).

New wide-field near-infrared cameras such as HAWK-I on the VLT, WFC3 on HST and later NIRCAM on JWST will provide a tremendous boost for such studies. Investigations of samples of strong gravitational lenses should complement studies of blank fields, and different techniques (Lyman-break dropouts, narrow-band Lyman-α searches) will be used to select high-redshift star-forming galaxy candidates. The spectroscopic follow-up of these candidates with near-infrared multi-object spectrographs (e.g., KMOS on the VLT and later on the E-ELT) will allow redshift measurements and the determination of other properties (excitation, ISM/IGM conditions, galaxy outflows, maybe even metallicity constraints). With such observations, we should be able to find and characterize the faintest and most distant galaxies out to redshift $z \sim 10 - 13$ and trace the complete star formation and reionization history of the Universe.

☆ How do the first quasars form?

One of the striking results of searches for distant galaxies and quasars is that massive galaxies with black holes as massive as the most massive black holes observed today had already formed by $z \sim 6.4$. The basic problem posed by these observations is that of forming black holes of several $10^9 M_\odot$ within a limited amount of time (the Universe is less than 1 Gyr old at this redshift). Such a rapid formation of massive black holes, if started from stellar-mass seeds, would require accretion at super-Eddington rates. Alternatively, the formation could start from massive black-hole seeds, but the origin of these is then a mystery.

Many different authors have tried to solve this puzzle, inconclusively so far [304, 573]. The hope is that simulations following the collapse of protogalaxies, the dynamics of seed black holes (possibly binary black holes) and related processes will ultimately be able to account for such extreme events. Next-generation X-ray satellites and future gravitational-wave detectors may be able to detect high-redshift black holes with masses down to $\sim 10^5 M_\odot$ and the merger events of binary black holes [465], providing a direct view of the build-up of supermassive black holes in the early Universe.

✰ How, when, and how much dust is created in the early Universe?

Dust plays a crucial role in the exploration of the Universe, especially because it may absorb significantly the short-wavelength (ultraviolet and visible) radiation from star-forming galaxies and make them drop out of deep surveys. In the local Universe, and even more so at redshift $z \sim 1 - 2$, a significant fraction of all star formation turns out to be hidden/obscured, in such a way that infrared to submillimeter observations are required to obtain a complete census of star formation including all types of (ultraviolet-bright, normal and very dusty) galaxies [334].

At redshifts in the range $3 \lesssim z \sim 6$, ultraviolet-selected galaxies appear to contain less dust, the highest-redshift known galaxies appearing almost dust-free. No dusty galaxy has so far been discovered at $z \gtrsim 4.5$ [115]. In constrast, quasars – i.e. massive galaxies with central black holes – found out to $z = 6.4$ show vast amounts of molecular gas and dust. This difference raises several important questions, such as: is the difference in dust content driven by galaxy mass? How does the dust content of galaxies evolve in time? Are there undetected populations of dusty $z \gtrsim 4$ galaxies? With a maximum cosmic age of less than 1 Gyr at $z > 5.5$, the origin of dust must also be reconsidered, since the lifetimes of the main dust producers (AGB stars) are typically longer. Type-II and pair-instability supernovae have been suggested along with other possible sources [500].

Answering these questions requires both theoretical and observational approaches, and in particular more sensitive infrared and submillimeter/radio facilities. With improvements at IRAM and APEX and upcoming facilities such as Herschel and ALMA, this field should soon undergo major progress. The new observational facilities will help us build a complete picture of the formation, distribution and destruction processes of dust in the Universe. In addition, we should be able to uncover yet unknown/hidden galaxy populations and hence elucidate the build-up of the different galaxy types and quasars from the earliest epochs on.

Strengths and weaknesses of the French community in the field

French groups issued from the stellar, interstellar, intergalactic, galaxy and cosmology communities with background/expertise in theory, modeling, observations and instrument development have made important contributions to a variety of topics concerning first stars, galaxies and quasars.

The expertise in near-infrared, infrared, submillimeter and radio observations is particularly crucial for future contributions to this field, as is the deep involvement of the community in instrument and satellite projects such as VLT second-generation instruments, Herschel, ALMA, JWST, and the E-ELT. The strong expertise of several teams in wide-field imaging and spectroscopic surveys is another important advantage to make forefront contributions to studies of primeval galaxies.

On the side of simulations, the French community has recognized worldwide expertise in models of stellar population synthesis, galaxy formation and evolution, gravitational lensing and recently also reionization. Tools and expertise exist also in important domains such as hydrocodes (AMR and other techniques), radiative transfer, chemistry etc. However, so far, the French involvement in simulations applied to the first stars, galaxies and quasars has been relatively modest.

III.3.2 Cosmic backgrounds

Guilaine Lagache, IAS

Fig. III.22 gives an overview of background radiation in the Universe. The Cosmic Microwave Background (CMB) is by far the dominant background. The CMB has an energy density of 0.26 eV cm^{-3}, corresponding roughly to 2 billion photons per baryon in the Universe today [502]. The next biggest background – almost two orders of magnitude down in energy contribution – is in the far-infrared/submillimeter part of the spectrum and comes from distant, dusty star-forming galaxies. A little below this is the near-infrared/optical contribution by the sum of all the stars in all the galaxies we can observe. Then, much lower are the X-ray and γ-ray backgrounds, which come predominantly from active galactic nuclei. In between the optical and X-ray backgrounds, the ultraviolet background is generated by the overall population of quasars and star-forming galaxies. Not visible in Fig. III.22 is the cosmic neutrino background, a relic of the Big Bang which decoupled from matter when the Universe was 2 seconds old. The neutrino background is estimated to have a temperature of 1.9 K. Because of this very cold temperature and the difficulty of detecting neutrinos, this background might never be observed directly.

Apart from the CMB (and the cosmic neutrino background), there is no evidence for background emission arising from anything other than known sources of radiation, stars, gas and dust within galaxies. Since the backgrounds in different wavelength domains have different origins, we discuss them separately below, with the exception of the optical/near-infrared background, which is produced by direct starlight and is mentioned in various parts

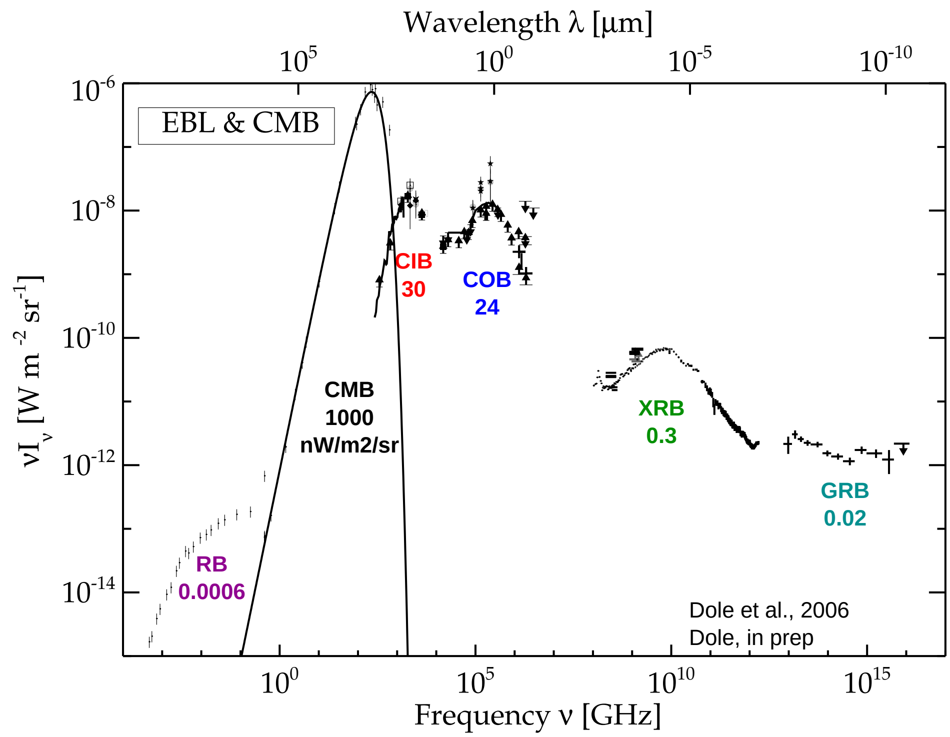

Figure III.22: Compilation of the recent constraints on extragalactic diffuse background radiation. In terms of total energy, the CMB dominates and the far-infrared and optical backgrounds are about a factor of 100 lower (courtesy of H. Dole).

of this section. On the ultraviolet side, although substantial progress has been made recently in understanding galactic emission mechanisms, the remaining uncertainties substantially limit the accuracy with which a cosmologically significant signal may be disentangled from the diffuse galactic background 'noise' [530]. We therefore do not be discussed here the ultraviolet background, except for the prospective to observe it at high redshift.

Anisotropies of the Cosmic Microwave Background

✰ Temperature anisotropies and the Cosmic Neutrino Background

WMAP has brought spectacular results on the measurement of CMB anisotropies, which further support the concordance model and its parameters (Section II.1.1). WMAP measures the CMB at the best frequencies, i.e. where foregrounds are minimal. In fact, its sensitivity is not requiring more than a rough subtraction of the dominant foreground. Very high-accuracy measurements of the CMB temperature and polarization will require the observation and removal of all the foregrounds. In that respect, Planck has been designed to be the ultimate experiment to map the CMB temperature fluctuations. The HFI instrument, in particular, uses innovative cooling and detector assemblies. It will have a sensitivity such that it is close to achieving fundamental detection limits set by the cosmic variance and photon noise due to the CMB itself. Planck will give a definitive zoom-in on the cosmological parameters. However, it will probe the temperature anisotropies only in the linear regime (multipoles $\ell < 2000$). At smaller scales, the primary signal is suppressed because photons diffuse out of the gravitational potential wells, and the fluctuations average out over the line of sight. Here, the dominant contributions to the anisotropy are produced by nonlinear effects at much more recent epochs. Understanding the transition from linear to non-linear structure formation is crucial to our understanding of the cosmological parameters and of how structures formed. Measuring the C_ℓ at small scales will give constraints on the diffuse Sunyaev-Zel'dovich effect, the Ostriker-Vishniac effect, the Rees-Sciama effect and gravitational lensing. After the first experiments ACBAR, CBI and the VSA, two telescopes under construction, ACT and SPT, are designed to measure the small-scale structure in the CMB. French researchers are not involved in these small-scale measurements.

Cosmological neutrinos have a profound impact on cosmology, because they change the expansion history of the Universe and affect the growth of perturbations. Recent cosmological experiments provide strong (albeit indirect) evidence for the presence of a cosmic neutrino background [440]. These experiments have been used to set upper limits on absolute neutrino masses, which compete with those from laboratory experiments. The first interesting indication of primordial anisotropies in the neutrino background has been obtained by combining the WMAP CMB-temperature power spectrum with clustering data from the SDSS [553]. Today, the neutrino background is detected with high significance with an equivalent number of standard massless neutrinos species $N_{\rm eff} > 1.8$ at a better than 99% confidence level [172]. For comparison, the standard model has $N_{\rm eff} = 3.04$. Departures from the standard model can arise from the decay of dark-matter particles, quintessence, exotic models, and additional hypothetical relativistic particles such as a sterile neutrinos. Combined with Planck constraints, the next-generation of large-scale structure data sets (e.g. future spectroscopic surveys of baryon acoustic oscillations) will yield very accurate measurements of $N_{\rm eff}$.

✰ Polarization

Thomson scattering of the CMB by free electrons at recombination and reionization gives rise to linear polarization. A lot of CMB experiments are now dedicated to the measurement of CMB polarization. In fact, measuring the large-scale CMB-polarization signal expected from inflation is one of the highest priorities in CMB research. The primary emphasis is to test whether GUT-scale inflation occurred, by measuring the signal imprinted on the CMB by primordial gravitational waves to a sensitivity limited only by our ability to remove astrophysical foregrounds.

This polarization is commonly decomposed into two components: a curl-free part (E-mode polarization) and a divergence-free part (B-mode polarization). The primordial scalar (density) perturbations that are responsible for the observed temperature anisotropies can produce only E-mode polarization in linear theory, but a cosmological background of gravitational waves (tensor modes), such as that generated in most models of inŕation, and gravitational lensing of the CMB can produce B-mode polarization. The ratio of B-mode to E-mode polarization (tensor-to-scalar perturbation ratio) is currently unknown, and the minimum detectable value of this can be used as a measure of the sensitivity of a CMB experiment. For most current experiments, this value is r$\sim$ 0.01, which corresponds to an energy scale of cosmic inflation around 10^{16} GeV. As of 2008, only E-mode polarization has been detected. Because it resuts from the same scalar perturbations as temperature anisotropies, the E-mode polarization signal should be highly correlated with the previously measured temperature data and have a well-predicted magnitude and power spectrum shape, which is exactly what is observed [456]. Although the E-mode-polarization power spectrum does not test inflation, it can be used the to break degeneracies in cosmological parameters currently constrained by the CMB intensity spectrum and various astronomical observations. The E-mode polarization signal also tell us more about the epoch of reionization. It will be very accuratly measured by Planck (Section IV.1.1). In contrast, Planck has not been optimized for the detection of B-mode polarization, which it could detect only if the energy scale of cosmic inflation is around 10^{16} GeV. Measuring B-mode polarization is a real challenge in terms of technology, control of systematics and foreground subtraction. After WMAP and Planck, future space-based CMB-polarization experiments could be planned, but probably not before 2020 (except the Sport experiment on the ISS). In the meantime, prospects for detecting B-mode polarization via sub-orbital experiments are very good. The number of near-term experiments is impressive: QUIET, Bicep2, Keck Arrays, EBEX, SPIDER, Polar Bear, Clover, BRAIN. However, except for BRAIN (Section IV.4.5), the French implication in these planned near-term post-Planck experiments is quite modest.

The Cosmic far-infrared Background: infrared galaxies and anisotropies

The discovery of the cosmic far-infrared background (CFIB) in 1996, together with recent cosmological surveys at mid-infrared to millimeter wavelengths, has revolutionized our view of star formation at high redshift. It has become clear that infrared galaxies account for a large part of build-up of the entire galaxy population in the Universe. The sources responsible for the CFIB and their redshift distribution have since been investigated by means of several multi-wavelength studies [325]. Several questions are faced by these investigations, such as for example the issue of the relative contributions to the CFIB by starburst galaxies and obscured AGNs. The connection between the starburst phenomenon and AGN activity is still largely unresolved. Recent observations of infrared/submillimeter galaxies have reinforced the evidence for an AGN-starburst connection, but the exact physical link between the two phenomena remains unclear. Also, the spectral energy distributions of infrared-

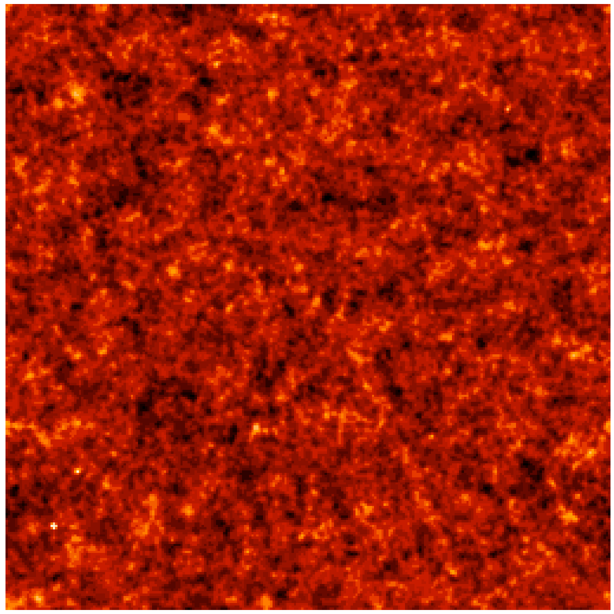

Figure III.23: Simulation of the cosmic far-infrared background anisotropies for the 217 GHz Planck channel [217].

luminous galaxies are not well constrained. Characterizing the spectral energy distributions of the different classes of infrared galaxies is one of the challenges of the coming decade, as it is necessary to accurately constrain the star formation rates of distant dusty galaxies and reconstruct the cosmic star-formation history. Herschel (Section IV.1.2), and later on SPICA (Section IV.3.7), will play a decisive role in this area, as they will help understand (i) the role of infrared-luminous galaxies and their connection to other high-redshift galaxies in the build-up of the general galaxy population, and (ii) the physical properties of infrared-luminous galaxies and their contribution to the CFIB.

ISO, Spitzer and SCUBA observations have resolved the cosmic far-infrared background at 80, 70, 60 and 50% at 15, 24, 70 and 850 μm, respectively. However, at wavelengths near the peak of the CFIB ($\lambda \sim 150\,\mu$m) and out to the submillimeter, point-source confusion severely limits the fraction of resolved CFIB. This fraction is only $\sim 10\%$ at $160\,\mu$m, and it will be about the same in the deepest Herschel/SPIRE observations [217]. At these wavelengths, characterizing the underlying source population requires the study of CFIB anisotropies. In addition to the average properties of infrared galaxies that can be obtained through stacking techniques [183], these anistropies probe the physics of galaxy clustering [12]. On small angular scales, the CFIB anisotropies measure the non-linear clustering within a dark matter halo and the physics governing how infrared galaxies form within a halo. On large angular scales, background anisotropies measure the linear clustering bias of infrared galaxies, thus probing the dark-matter halo mass scale. Thus, although their detection and interpretation are challenging, CFIB correlated anisotropies are a new exciting tool to understand the underlying scenario and physics of galaxy formation and evolution. They have been detected for the first time with Spitzer at $160\,\mu$m [261, 324], corresponding to sources at redshift $z \sim 1$, and Planck and Herschel should allow us to probe them out to $z \sim 4$. Fig. III.23 shows an example of simulated Planck map of CFIB anisotropies at 217 GHz.

Further information will be obtained by cross-correlating the CFIB maps with external tracers of the density field, such as galaxies and quasars. This will further constrain the populations dominating the CFIB and the relative bias between external tracers and the distribution of far-infrared emission. A particularly interesting cross-correlation will be that between the lensing convergence (determined from Planck CMB maps) and the CFIB maps. The lensing and far-infrared-emission windows are expected to have a high degree of overlap and lead to a signal detectable by Planck. This signal will be sensitive to the history of far-infrared emission, as well as to the amplitude and stochasticity of the bias. Also, CFIB maps will be cross-correlated with the CMB map to study the Integrated Sachs-Wolfe effect. The French community is well prepared (although not fully ready) to deal with the CFIB anisotropies that will be measured with Planck/HFI. The community is also well established in the Herschel/SPIRE-related observations (GTO and Open Time Key Project 'Atlas'), but measuring the CFIB anisotropies with Herschel will require a large effort on the map-making side (to map the diffuse emission).

X-ray and γ-ray backgrounds

The fraction of the X-ray background resolved into discrete sources by deep Chandra and XMM-Newton observations smoothly decreases from $\sim 80-100\%$ below $2-3\,$keV to about $50-60\%$ in the $6-10\,$keV energy range [583], becoming negligible at energies above 10 keV, where the bulk of the energy density arises. Recenly, BAT/Swift and IBIS/INTEGRAL have surveyed the hard X-ray sky. Although these surveys found a relatively large number of hard X-ray sources, their limitations to bright fluxes made them sample primarily the very local Universe. As a consequence, the resolved fraction of the hard ($> 10\,$keV) X-ray background is of the order of a few percent only.

The spectral shape of the missing X-ray background component is consistent with a population of highly obscured AGNs at redshifts $z \sim 0.5 - 2$ and with absorption column densities corresponding to heavily obscured ($N_H > 10^{23}$) and compton-thick ($N_H > 10^{24}$) AGNs [583]. The search for and characterization of this population has become increasingly important in the last years, as it represents the last obstacle towards a complete census of accreting supermassive black hole. The most recent X-ray-background synthesis models suggest that heavily obscured compton-thick AGNs may be numerically as relevant as less obscured compton-thin AGN [249]. Therefore, the impact of heavily obscured AGNs on the astrophysics and evolution of the AGN population as a whole cannot be neglected. Imaging observations above $10\,keV$ will offer a unique opportunity to probe the 'missing population' (in combination with mid-infrared observations [223, 162]). Simbol-X (Section IV.4.4) is a new-technology hard X-ray ($0.5 - 80\,\mathrm{keV}$) focusing telescope, which will provide order-of-magnitude improvement in angular resolution and sensitivity compared to the non-focusing instruments that have operated so far in this crucial energy band. By resolving at least 50% of the X-ray background near the peak, Simbol-X will resolve the X-ray background puzzle and allow us to search for counterparts of the sources at other wavelengths. It will reveal fraction of compton-thick AGNs contributing to the X-ray background and yield an unbiased sample to test the cosmological evolution of AGNs and estimate their contribution to the infrared emission of the Universe. The Simbol-X mission, to be launched in 2014, is jointly supported by the French and Italian space agencies. At longer term, IXO (the International X-ray Observatory that supersedes the XEUS mission concept) will probe deeper the physics of the sources of the X-ray background.

At higher energy, the overall diffuse γ-ray radiation can be qualitatively divided into a galactic and an extragalactic contributions. Since the latter is not simply the isotropic part of the ŕux, the separation of these two components can be done at present only by assuming a specific model for the production of secondary emission by cosmic rays in the Galactic disk and halo. A measurement of the cosmological Compton-Getting effect that should be achievable for Fermi (previously named GLAST) would provide a model-independent way to separate the two contributions. Fermi was successfully launched in June, 2008, and it will allow us to pin down the unkown sources of the extragalactic γ-ray background. The leading candidates are unresolved AGNs, especially blazars (but see [433]). However, ordinary galaxies similar to the Milky Way are also likely to be an important component of the background. In addition, some of this background may arise from ultra-high-energy cosmic rays, very distant and very powerful (TeV range) γ-ray sources and primordial black holes. The Fermi Large Area Telescope ($20\,\mathrm{Mev} - 300\,\mathrm{GeV}$) has high enough sensitivity and spatial resolution that it should be able to confirm whether or not AGNs and ordinary galaxies contribute significantly to the γ-ray background. The potential discovery that the background is not made of unresolved point sources would also have major consequences. Five French teams participate to the Fermi mission (LLR, CENBG, LPTA, SaP/APC, CESR). One of the tasks of the french team is related to point-source detection and identification.

III.3.3 Hierarchical galaxy formation

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Given the great successes of the Cold Dark Matter model, it is now widely accepted that galaxy formation proceeds in a hierarchical Universe. This scenario relies on the existence of primordial fluctuations, which are actually seen in the Cosmic Microwave Background, seeding the gravitational instability that leads to the formation of collapsed halos. These dark-matter-dominated halo population will evolve through continuous merging and accretion, starting from very small-mass objects (i.e. with masses between a few $M_\odot$ and $10^6 M_\odot$) at high redshift (around $z \sim 20$), and ending today with very large galaxy clusters (with masses over $10^{15} M_\odot$). Even though baryons represent only a small fraction of the total mass (less than 15%), they play an important role because they are the only observable component, and because inelastic collisions in the baryonic plasma make the gaseous component highly dissipative. Baryons can therefore cool and dissipate their gravitational energy, forming very dense objects like galaxies and stars. On small scales (below a few kpc), the baryonic mass dominates. This gravitational cascade, coupled to the cosmological hierarchy of increasing mass mergers, leads to the modern theory of galaxy formation.

The field of galaxy formation has undergone significant progress recently, thanks to new observations and also more accurate numerical models. A key challenge for numerical simulations is that galaxy formation proceeds in a wide-scale cosmological context. This requires a proper description of the large-scale environment (e.g. tidal fields, gas accretion through diffuse filaments and satellites) and at the same time, enough resolution to follow the dynamics of the ISM. The first successful attempts to model galaxy formation in a cosmological context were made by Matthias Steinmetz and collaborators, Julio Navarro and collaborators, and Jesper Sommer-Larsen and collaborators. These simulations all relied on a well-known particle-based numerical technics called Smooth Particle Hydrodynamics (SPH). Very recently, Adaptive Mesh Refinement (AMR) codes have also been able to follow galaxy formation in a cosmological context, both at high redshift [321, 130] and at low redshift [245, 538]. These state-of-the-art simulations can follow several millions particles within the Virial radius of the simulated galaxy, with a spatial resolution of a few 100 pc (see Fig. III.24). This is barely enough to resolve the vertical scale height of both the stellar and the gasous disks and definitely not small enough to resolve the formation of molecular clouds (even Giant Molecular Cloud complexes, with masses $\gtrsim 10^6\, M_\odot$). In order to capture the proper ISM properties, present-day models have to rely on what is called 'sub-grid physics'. The multiphase, turbulent and clumpy ISM is described using an 'effective' equation of state [588, 521], which allows the code to avoid the formation of numerical singularities, given the limited spatial resolution. This smooth description of galactic disks is the main limitation of current models.

The main predictions of these numerical simulations agree well with observational constraints. The Tully-Fisher relation is roughly recovered, although simulated galaxies appear to suffer from the so-called 'angular-momentum' problem: simulated disks are too small, their rotation curves are too peaky, and they are slightly but significantly offset from the observed Tully-Fisher relation. Another problem encountered by simulations is related to the number of bright satellites orbiting around the central galaxy in a dark-matter halo: when compared to real galaxies, current models form too many bright satellites. A possible solution to this problem is to invoke 'feedback', namely the impact of supernovae explosions on the galactic disk and its surroundings. The combination of supernova-driven winds with radiative heating by a cosmic ultraviolet background (originating from the cumulated radiation of OB stars and quasars) could quench star formation in small-mass galaxies. Another

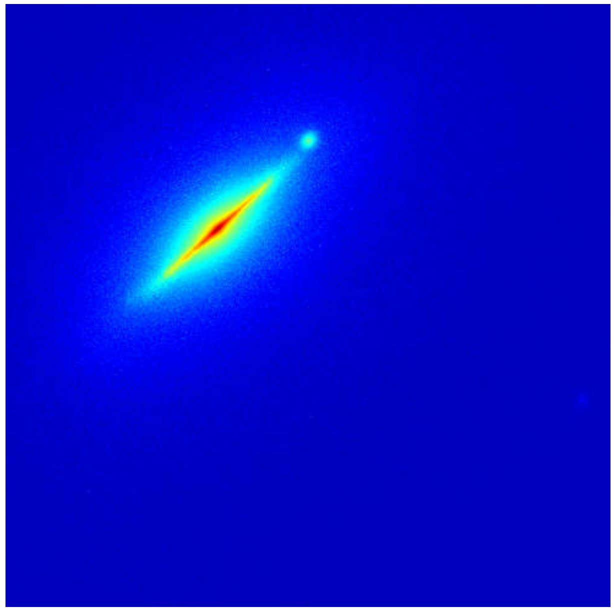

Figure III.24: V-band image of the stellar distribution of a spiral galaxy formed in a ΛCDM Universe in a 'zoom' high-resolution simulation with the RAMSES code. Copyright Horizon Project 2008.

possible solution to the excess of bright satellites in current simulations might be a proper modeling of the clumpy ISM structure, possibly resolving the molecular cloud spectrum down to a few $\times 0.1\,M_\odot$. Recent attemps along these lines seem to be quite encouraging [130, 6].

An important aspect of galaxy formation lies in the statistical properties of the galaxy population. It is therefore necessary to use other tools than the previously described, 'zoom'-like simulations of individual galaxies. One must appeal to large-scale simulations, where thousands of such galaxies are formed in the same virtual Universe. In this respect, the MareNostrum galaxy formation project, joining the effort of a French team (the Horizon project) and a Spanish team (Gustavo Yepes), can be considered as a cutting-edge initiative. The mass (10^5 particle per halo) and the spatial resolution (1 kpc) are both an order of magnitude below the 'zoom' simulations, but they offer the possibility to compute statistical quantities of great interest, which-can be compared to various galaxy catalogs from recent surveys. We have learned from these simulations that gas accretion around high-redshift galaxies proceeds along cold streams and filaments [309, 421, 175], feeding directly the central spiral galaxy with fresh gas at a huge rate ($\gtrsim 100\,M_\odot\,\mathrm{yr}^{-1}$; see Fig. III.25). These extreme accretion flows could be the origin of the extreme star-forming galaxies observed at high redshift (the so-called 'BzK galaxies').

Cold flows might also be related to a mysterious property of present-day galaxies: the

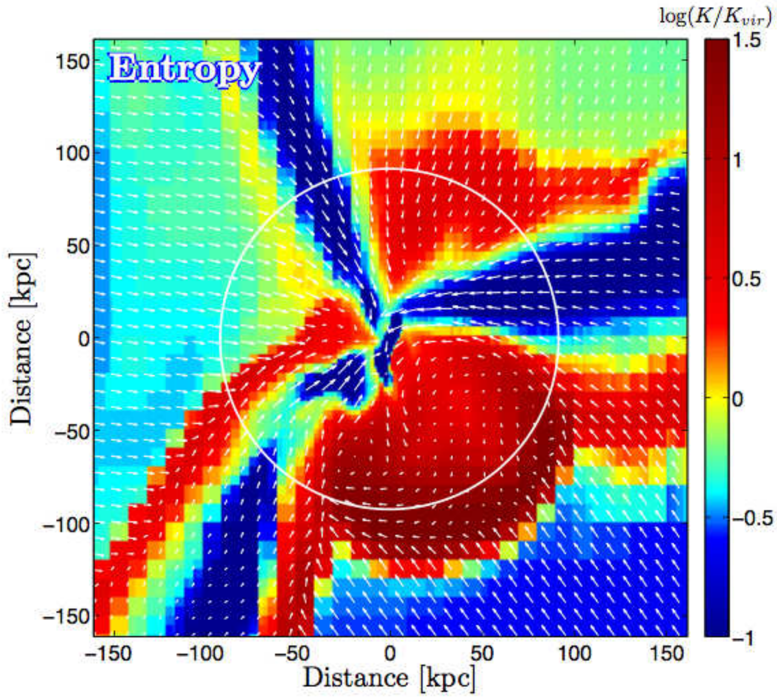

Figure III.25: Entropy map around a high-redshift star-forming galaxy from the MareNostrum simulation. Cold streams are clearly visible, feeding directly the central disk. Copyright Horizon Project 2008.

red- and blue-sequence bimodality observed, for example, in the SDSS. Blue galaxies have young stellar populations, low surface-mass-densities and the low concentrations typical of disks, while red galaxies have old stellar populations, high surface-mass-densities and the high concentrations typical of bulges [302]. These global photometric and geometrical properties of galaxies are still poorly understood within the hierarchical scenario of structure formation. At least three factors are likely to play an important role: (i) the dramatic drop in star-formation efficiency in high-mass objects, which produces massive red, dead spheroids; (ii) violent, equal-mass mergers, which provide a fast evolutionary path from spirals to elliptical galaxies; and (iii) diffuse gas accretion, which can rebuild a gaseous disk around spheroids and, especially at high redhift, control the efficiency of star formation. These complex phenomena remain largely unclear today and will be the subject of important activity in the coming years.

III.4 Physics of galaxies and History of star formation

III.4.1 Galaxy dynamics

Eric Emsellem, CRAL

Recent results and evolution

✰ Observations

Our understanding of galactic dynamics has recently benefited from the advent of a few capabilities, including 3D spectroscopy (or 'integral-field spectrography', with e.g., SAURON/WHT, SINFONI/VLT, GMOS/Gemini) and medium-high spectral resolution spectroscopy (e.g., ISAAC, FLAMES, CRIRES, UVES at the VLT). Constraints on stellar kinematics can be obtained from optical or near-infrared facilities, while constraints on the distribution and kinematics of the gas can be extracted from optical and near-infrared (ionized gas, molecular emission lines), sub-millimeter (molecular species) and radio (neutral gas) instruments. These instruments are used today both in survey modes and for detailed studies of individual targets. Recent progress has originated, for example, from:

- The unique 2D spatial coverage permitted by 3D (optical and near-infrared) spectrographs. This is mainly relevant to studies of line-of-sight-integrated stellar properties in nearby galaxies (e.g., Fig. III.26) [26, 202, 241, 418, 560], although galaxies at medium ($z \sim 0.5$) and high redshift ($z \sim 3$) are also being investigated [70, 243].
- The availability of instruments with high spectral resolution on large apertures, which allow one to probe the lower-mass range of the galaxy population [541, 562, 139];
- The high spatial resolution achieved by new facilities assisted with adaptive optics, such as SINFONI and NIFS [471, 412], and upgrades of exsting interferometric capabilities (e.g., with the A configuration at the Plateau de Bure; see Fig. III.27) [281, 497, 133].

✰ Modeling

A number of new modeling tools and extensions of previous techniques have been developed for studies of galaxy dynamics in the last few years. The most remarkable ones are:

- The implementation of a generalized triaxial Schwarzschild code of orbit superposition [501], which now permits the modeling of galaxies with features such as kinematically decoupled cores, isophote twists and/or complex sets of stellar components [561]. Such

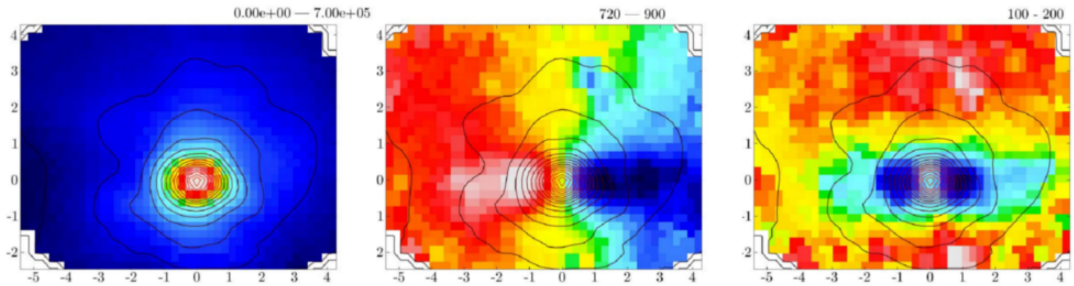

Figure III.26: Surface brightness, velocity and velocity-dispersion maps of NGC 3623, obtained with the ARGUS mode of FLAMES/VLT.

a code has been shown to properly recover the phase-space distribution of standard 'Abel models' [173], although a degeneracy arises in cases where the internal velocity structure is not strongly constrained [559].

- The advent of 'made-to-measure' N-body codes [298, 167, 168], which adapt the weights of discrete particles in a galaxy realization to fit observables, including photometric and kinematic quantities. This technique is a generalization of the so-called Syer-Tremaine method [533].
- A new analytic formalism, which is an extension of the standard 2-integral Jeans models [116], to robustly fit galaxy stellar kinematics (of early-type galaxies) with a minimum set of assumptions.

These techniques have applications to a very broad range of problems, including complex geometries and tumbling potentials. They have been used for mass estimates of supermassive black holes and studies of dark matter and of the internal anisotropy of spheroidal galaxies. New ways have also been suggested to optimize the fitting procedure [353].

Numerical simulations have also been used extensively to further examine the evolution of disks, bars, interacting galaxies and mergers and stellar clusters within galaxies [575, 80, 228, 42, 119]. A number of studies have focused on the orbital structure associated with boxy and peanut-shaped bulges, double bars and the influence of a central dark mass [480, 386, 349, 350], using N-body codes as well as Fokker-Planck approximations. An N-body (+SPH) code implementing a MOND formalism has also been developed and used to study, among others, the formation and evolution of bars [543, 545].

✰ Some recent results

A recent analysis of the COSMOS survey (Section II.2.6) suggests that the fraction of disk galaxies with bars has grown significantly since the epoch $z \sim 1$ [511]. While about 65% of luminous spiral galaxies in the local Universe are barred, this fraction is found to be only

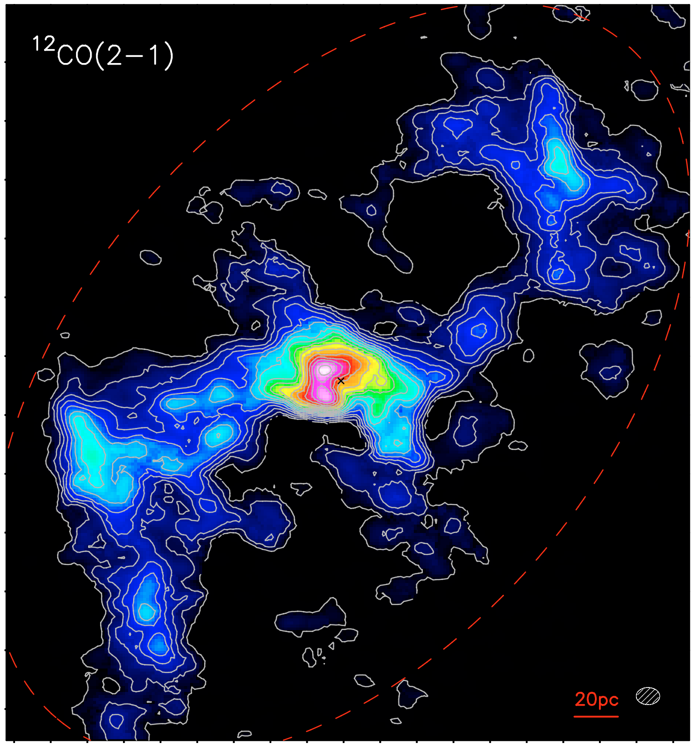

Figure III.27: Distribution of the ^{12}CO(2-1) molecular line for NGC 6946, obtained with the A configuration of the Plateau-de-Bure interferometer (the red ellipse sketches the presence of an inner bar) [497].

about 20% at $z \sim 0.84$. This evolution appears to be related to galaxy mass: the fraction of massive luminous spiral galaxies with bars seems to have remained roughly constant since $z \sim 0.84$, while that of blue, less massive spiral galaxies with bars has grown substantially. This finding however does not necessarily imply that all barred galaxies at $z \sim 0.84$ are still barred galaxies today. In fact, numerical simulations including gas dynamics suggest that bars in gas-rich galaxies may be short-lived ($1-2$ Gyr) phenomena. This is because the central mass concentration arising from gas inflow driven by the bar gravity torque, together with the transfer of angular momentum from the infalling gas to the bar, can efficiently weaken and destroy the bar [75]. Thus, the population of barred spiral galaxies could have been evolving continuously since the epoch $z \sim 1$, with bars being destroyed and reforming (through substantial accretion of new gas) all the time. This is supported by the observed lopsidedness of many disk galaxies today, which can be naturally explained by cosmological gas accretion [61, 74, 192].

There has also been recent progress about the demography of massive objects in galaxy centers. HST observations have revealed that supermassive black holes probably reside at the centers of most massive galactic bulges and early-type galaxies today, and that there is a tight relation between bulge mass (velocity dispersion) and central black-hole mass (the 'Magorrian' relation [354]). This has been confirmed by many refined estimates of central black-hole masses in nearby galaxies [412, 419]. Several recent studies have focused on the extension of this relation to lower-mass galaxies: many intermediate- and low-luminosity galaxies appear to contain compact central nuclei, which structurally resemble massive globular clusters. The masses of these compact stellar nuclei follow a tight correlation with host-galaxy mass, similar to the Magorrian relation for more massive galaxies. Hence, there could be a universal mass fraction (a few tenths of a percent) of any galaxy locked into a central *object*, which may be either a supermassive black hole or a compact nuclear star cluster, depending on the galaxy mass [482, 218, 574]. A few hypotheses have been proposed to explain the possible origin of such a universal scaling relation [379, 204].

Finally, an analysis of the orbital distributions of elliptical (E) and lenticular (S0) galaxies using SAURON integral-field stellar kinematics has revealed a relation between the flattening of early-type fast rotators and their internal velocity ellipsoid [117]. Even though this relation may be only the natural consequence of simple dynamical mechanisms (linked to entropy), it results in a shift of the paradigm regarding the structure of early-type galaxies: slow rotators are more common among the most massive systems. They tend to be fairly round and are generally classified as E from photometry alone. Fast rotators are generally fainter and can appear quite flattened. They tend to be classified as either E or S0. Associated studies have also shown that 2D spectral coverage is a prerequisite for assessing the internal-dynamics structure of hot stellar systems [319].

Perspectives and new problems: a few suggestions

✰ Observing Facilities

New observing facilities (e.g. KMOS/VLT, MUSE, JWST and ALMA) will offer unique capabilities to probe the dynamics of galaxies at all redshifts and will likely revolutionize our view of galaxy evolution. So far, adaptive optics has not been used extensively for detailed kinematics studies of galaxies, often because of the lack of bright and close guiding stars. New observational techniques, including laser guide stars (sometimes without a natural guide star for the tip-tilt), may allow more systematic studies of larger galaxy samples. We note that a detailed look at the internal dynamics of low-mass galaxies at the distance of, for example, the Virgo cluster may have to wait for the availability of larger-aperture telescopes (ELTs).

✰ Modeling

Much progress is expected from future improvement in the resolution of numerical simulations (number of particles, spatial softening) for applications to studies of the highest spatial frequencies in galaxies (via AMR and multi-scales adaptive schemes). This is critical, for example, to model the evolution of clusters embedded in smooth potentials, as well as to properly follow processes such as dynamical relaxation and secular evolution. Refined recipes for star formation and energy feedback (from supernoave and accreting black holes) should allow us to better understand the impact of these important physical processes on the dynamical evolution of galaxies. Also, we need to invest significantly in the implementation of a robust multi-phase interstellar medium in numerical simulations (see also Section III.3.3). This is required for more realistic predictions of the evolution of galactic systems and to compare the spatial distribution and kinematics of the stellar and gas components. Finally, the future of stellar-dynamics models also lies in the coupling of the associated formalism with a proper treatment of stellar populations. By coupling the detailed spectral information and the extracted kinematics (in Schwarzschild and Syer-Tremaine codes, or more generally in chemo-dynamical numerical simulations), we should be able to assess the origin and evolution of stellar-dynamics systems, from disks to early-type spheroids and from bars to stellar nuclei.

✰ Galactic nuclei

The link between nuclear clusters and black holes is certainly one of the main challenges for future observations and theoretical studies. Detailed kinematics of nuclear clusters is today only available for a handful of targets [509]. Future instrumentation (space-based and ground-based with laser-guide-star adaptive optics) should enable studies of both the dynamics and the stellar populations of these compact nuclei. We should also progress significantly in our understanding of the fueling of nuclei (and the triggering of nuclear activity), particularly via very-high-resolution mapping of molecular gas (ALMA) within the central 10 or 100 pc.

✰ Black holes

The search for additional supermassive black holes should probably stall, as the global uncertainty on individual measurements is too large to allow any progress on, e.g., the tightness of the Magorrian relation. It might be more valuable to dedicate new efforts to the sampling of this relation at the high- and low-mass ends. We would also need to reassess current black-hole-mass estimates with a *homogeneous* approach relying on state-of-the-art models and observations.

✰ Modes and internal dynamics

A deep understanding of the orbital making of bars, rings, and spiral waves is within reach. The difficulty will be to associate this knowledge with the available observables. One of the main challenges for the next decade will be to characterize in detail the velocity ellipsoids of disks of large samples of galaxies. This is critical to understand of the dynamical evolution of systems with high angular momentum. We should also pursue the spectroscopic mapping of nearby galaxies (e.g., ATLAS^{3D} project), as this will represent a key marker for studies at higher redshift, where we do not have access to detailed kinematics.

French contribution

✰ Strengths

Our community has ackownledged expertise in integral-field spectroscopy, and we should carefully prepare the scientific exploitation of future facilities, such as MUSE and JWST, which will open new windows on our Universe. This will require more than the present effort on software tools (e.g., ANR DALHIA), and we should gather our forces for this upcoming challenge.

The French community is also significantly involved in ALMA, which will be a cornerstone for studies of gas dynamics in the central regions of galaxies. We may need a more federative approach to gain weight in the international competition (the Action Spécifique ALMA will play a role in this respect).

Our relative leadership in the gathering of large samples of stellar spectra, the development of associated data bases and the interpretation of stellar colour-magnitude diagrams (resolved stellar populations in nearby galaxies) are all clear assets for the coming years.

The national effort on numerical simulations, via the Horizon project (Section II.2.9), should be redirected to address the problems of the next decade. Our position is stronger today than 10 years ago, but still relatively fragile.

✰ Weaknesses

The French 'Galaxy Dynamics' community is very small and often relies on a few individuals. It is not clear whether it will have the means to prepare for the exploitation of major upcoming facilities, such as MUSE or ALMA, both in terms of data volume and complexity and in terms of the new physics that need to be developed.

The French community tends to be generally 'specialized', i.e., with expertise in some specific modeling or observing technique. As we will need to couple gas physics with dynamical evolution, stellar populations and kinematics, it is important to develop our ability to deal with a panchromatic view of galaxies. The post-doctoral population is also much too small to optimize our reactivity to new topics and new techniques.

Finally, a number of major topics of galaxy dynamics are barely represented in France (e.g., nuclear clusters versus black holes).

Conclusion

During the next decade, we should witness the growth of several exciting new scientific issues, together with the advent of amazing observing facilities and new modeling schemes. The French community has a central role to play in a number of topics associated with galaxy dynamics, e.g., in the exploitation of MUSE, ALMA and JWST and in the development of high-resolution numerical simulations with a multi-phase ISM. This ambitious task will require a federative effort and some clearly focused investment in preparing for these challenging instruments. A program such as the PNCG is one of the key components for setting up priorities and accompanying the projects we wish to conduct.

III.4.2 Galaxy interactions

Pierre-Alain Duc, CEA/IRFU/SAP

Introduction

Galaxy collisions are a key element of galaxy formation: in hierarchical scenarios of structure formation, the formation of large dark-matter halos through the merging of smaller halos causes the host galaxies of these halos to interact gravitationally. In the local Universe, only a small fraction ($\sim 1-2\%$) of all galaxies show strong morphological disturbances caused by major (i.e. nearly equal-mass) mergers. Collisions have long been thought to be much more frequent when the Universe was younger (and hence smaller), but this has been challenged recently by detailed observations of distant galaxies and state-of-the-art numerical simulations.

Interacting galaxies exhibit a great variety of phenomena: tidal forces giving rise to long tails, starbursts, star/globular-cluster formation, AGN fueling, etc. This makes them valuable laboratories to study many astrophysical processes.

Galaxy interactions and the evolution of galaxies

✰ Morphological evolution

In the standard CDM paradigm, early-type galaxies are thought to form primarily from the merging of two nearly equal-mass spiral galaxies. Thus, major mergers play a key role in the evolution of galaxies, in particular their morphological transformation.

- **Fraction of galaxy mergers versus redshift.** Numerical simulations of hierarchical galaxy formation predict that the merger rate of dark-matter halos should increase with redshift as $(1+z)^m$, with m around 3. This dependence is difficult to check observationally, because at high redshift, the morphological signs of an ongoing merger cannot be easily distinsguished. The merger rate can be estimated iendirectly from number counts of apparent (i.e., projected) galaxy pairs on the sky. However, the associated uncertainties are large, and constraints derived in this way have led to values of m in the range $0-6$. For example, studies on the (projected) environment of galaxies in the CDFS/GOODS field suggest $m \sim 3.4$ [459], while more precise investigations based on velocity measurements of galaxies in the Canada-France Redshift Survey (CFRS) and the more recent VVDS (Section II.2.5) yield $m \sim 2.5$ out to $z \sim 1$ [328, 171].

If early-type galaxies form hierarchically through merger events, they should be more numerous today than in the past. Several studies have probed the fraction of early-type galaxies as a function of redshift. Surprisingly, these studies revealed that massive elliptical galaxies were already assembled by $z = 1$ and that, more generally, the buildśup of the most massive galaxies preceded that of the less massive ones [160, 141]. This apparent 'downsizing' is not incompatible with hierarchical scenarios of galaxy formation (see below and Section III.2.3).

- **Dry versus wet mergers.** A classical argument against the formation of massive elliptical galaxies by merger has been that their spectral energy distributions are dominated by very old stars. Instead, tidal collisions between galaxies would induce detectable amounts of new star formation. This is however the case only for 'wet' mergers, i.e. mergers between galaxies containing enough gas to trigger a new starburst, and only if the mergers were recent enough for the signatures of the associated starbursts to still be detectable today. Alternatively, 'dry' mergers could occur between two gas-poor galaxies, which would not affect significantly the global age of the stellar population [41]. Yet, SDSS observations suggest that the probability of dry merging is much too low for this scenario to apply, at least at low redshift [371].

  The relative roles played by wet and dry mergers in the formation of early-type galaxies are still matter of debate. Dynamical simulations might help clarify this debate. For example, a challenge is to reproduce the orbital distributions of the massive elliptical galaxies that are slow rotators, as observed in the SAURON and ATLAS^{3D} projects (see Section III.4.1) [203].

- **Major versus minor mergers.** Most scenarios involving mergers in the assembly of early-type galaxies focus on 'major' events, in which the parent galaxies have nearly equal mass (i.e. within a factor of ~ 3). However, repeated minor mergers may also lead to the formation of elliptical galaxies [82]. This is important because cosmological simulations of galaxy formation indicate that minor mergers are much more numerous than major ones. Such simulations are supported by observations of the Local Group, which reveal no strong evidence for any major merger over the past 10 Gyr [267], while signs of minor mergers are numerous: new faint satellites tidally disrupted by the Milky Way (giving rise to stellar streams) are discovered each year [369]. In the outskirts of the Andromeda galaxy as well, extremely deep optical imaging reveals the presence of multiple tails and shells, which are undoubtedly of tidal origin (see Fig. III.28) [282, 283]. The star-forming rings toward the inner regions of that galaxy are also likely to be the result of a head-on collision [62].

- **Disk versus spheroids.** Mergers may not only govern the morphological evolution of early-type galaxies, but also that of spirals. According to the so-called 'rebuilding' scenario [266], disks could be re-formed after a major merger. About 75% of all spiral galaxies today might have experienced a major merger event less than 8 Gyr

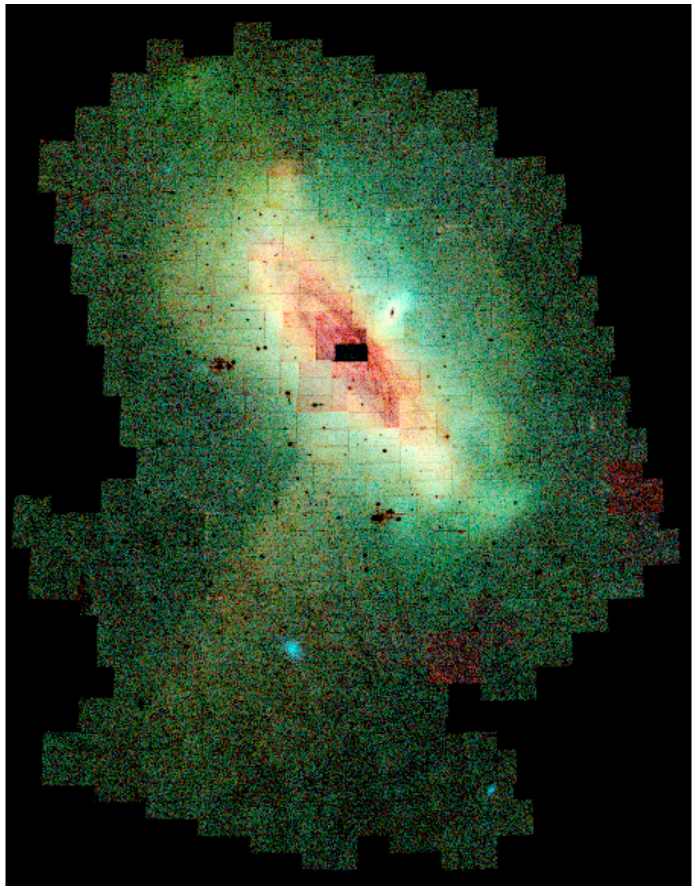

Figure III.28: The Andromeda galaxy, as seen at the extremely low surface brightnesses allowed by stellar counts on large-field-of-view optical images (adapted from [282]).

ago. However, this hypothesis has been challenged and still lacks strong theoretical support. The evolution of disks undergoing multiple collisions and accretions of companions in a cosmological context has recently been simulated by several groups [404].

- **Mergers versus accretion and secular evolution.** In recent years, alternatives to the 'standard merger' scenario have become more popular to account for the evolution of the galaxy population. This is the case for gas accretion from cosmological filaments, which is indirectly supported by some properties of nearby galaxies, such as the frequency of bars [73] and the presence of extra-planar HI in spiral galaxies [487]. Gas accretion has also been modeled in cosmological simulations of galaxy formation [175].

Another scenario, supported by observations of distant ($z > 2$) galaxies and numerical models, has received recent attention: the mutual interaction and coalescence of massive stellar and gaseous clumps formed in unstable gaseous disks (as observed in the so-called 'chain galaxies', previously believed to be mergers). This scenario could potentially lead to the formation of galactic bulges [200, 243].

✰ Galaxy interactions and the star formation history

Galaxy interactions induce shocks and instabilities, which enhance the star-formation activity. In the local Universe, the galaxies forming stars at the highest rates, the Ultra Luminous Infrared Galaxies (ULIRGs, with infrared luminosity exceeding $10^{12}\,L_{\odot}$ and star formation rates of a few $\times 100\,M_{\odot}\,\mathrm{yr}^{-1}$), have all been found to be advanced mergers [488]. Since ULIRGs are far more common at high redshift – as revealed by various surveys carried out with the Spitzer satellite [334], one might expect a large proportion of all stars in the Universe to have formed during galaxy collisions. This turns out not to be the case, because many ULIRGs at high redshift are not mergers [161]. The presumably high gas content of these young galaxies appears to be enough to reach star formation rates typical of ULIRGs, even in the absence of interactions.

We note that the most actively star-forming galaxies in the distant Universe, the submillimeter galaxies (SMGs, with star formation rates derived from the millimetric emission in excess of $1000\,M_{\odot}\,\mathrm{yr}^{-1}$), do show signs of interactions [534]. Hence mergers may enhance the star formation activity of these galaxies relative to average population properties, as is the case for ULIRGs in the local Universe, only at a different level. The precise mechanism enhancing the star formation activity during a galaxy-galaxy encounter is still largely unknown. Simulations suggest that the available gas is driven (via bars) to the central regions, where it is compressed and transformed into stars. However, the simulations do not account naturally for the factor of $10 - 100$ enhancement in the star formation efficiency required to explain the infrared excess of local ULIRGs and distant SMGs [179]. Additional factors might help, such as the external potential well of galaxy groups and clusters [367] and the ram pressure exerted by the intra-cluster medium on the interstellar medium [572]. Future progress in this area requires the introduction of more realistic recipes for the onset of star formation in numerical codes, which in turn requires a better modeling of the interstellar medium (see Section III.3.3).

Colliding galaxies as laboratories

✰ Probing star formation with interacting systems

Observations with the ISO and Spitzer satellites have generated detailed studies of individual dust-enshrouded star-forming regions in nearby interacting systems [393]. These studies have focused on investigations not only of the mid-infrared signatures of nuclear activity and circumnuclear starbursts in the central regions of galaxies [333], but also of

Figure III.29: Stephan's Quintet compact group of colliding galaxies. Intergalactic star-forming regions, traced by their mid-infrared emission (Spitzer), are shown in red. The gas reservoir (VLA HI map) is shown in blue, overlaid on an optical true-color image.

the star formation activity along tidal tails (see Fig III.29). Collisional debris, for example, were found to be particularly rich in atomic and molecular gas [346, 92, 186], which is likely to originate from the disks of the parent galaxies. Multi-wavelength studies have shown that these 'intergalactic' star-forming regions have properties remarkably similar to those within spiral disks, despite the radically different large-scale environment [67].

✰ Probing star cluster / dwarf galaxy formation with interacting systems

The collisional debris produced by galaxy interactions can contain enough gaseous material to form stellar systems with masses ranging from those typical of super star clusters (a few $\times 10^5\, M_\odot$) to those typical of dwarf galaxies ($\sim 10^9\, M_\odot$). How gas clouds are tidally expelled, collapse and start forming stars has been investigated in details with numerical simulations [185]. Models have also shown that a fraction of dwarf galaxies born in tidal tails could be long lived and orbit around the parent galaxy like classical satellites. Such models can predict the probability for tidal dwarf galaxies to form in different environments [76].

✰ Probing dark matter with interacting systems

The long tidal tails emanating from interacting galaxies can be used as dynamical probes of the dark-matter halo that presumably englobes the galaxies. The length of these tails depends primarily on the geometrical parameters of the collision, rather than on the size and mass of the dark-matter halo. In constrast, the internal structure of the tails strongly depends on the shape of the dark-matter halo. Numerical simulations have shown that, for example, massive tidal dwarf galaxies can form only if the dark-matter halo is extended enough [79]. This is all the more important in that the large sizes of dark-matter halos are a prediction of the standard cosmological model, which has been difficult to check observationally.

On the other hand, collisional debris should themselves be dark-matter poor, as they are made of material expelled from the disks of the colliding galaxies. Thus, the dynamical mass of gravitationally bound objects born in tidal tails, such as tidal dwarf galaxies, should be similar to their luminous (stellar + gaseous) mass. Several kinematical studies of interacting systems have been undertaken to check this hypothesis [77, 13]. Surprisingly, the presence of a missing-mass component has been detected in several tidal dwarf galaxies [80, 186], suggesting that this missing component may also be present in the parent-galaxy disks. A possible candidate is dark baryonic matter in the form of extremely cold molecular hydrogen [438], not traceable by carbon monoxide [394, 259]. An alternative (perhaps more controversial) candidate is MOND, which has been implemented in numerical simulations of galaxy collisions [544] and shown to reproduce the observed rotation curves of tidal dwarf galaxies [242], without requiring additional invisible mass.

Perspective and the role of the French community

The role of galaxy collisions in the evolution of galaxies has been investigated actively over the last several years. Determining the relative importance of merging/accretion and internal mechanisms in shaping the properties of the galaxy population will be a key issue in the coming years. The French community, which has contributed to recent progress in this field, is in a comfortable position to tackle the challenging questions of the future.

✰ Observational challenges

Characterizing the evolution of the galaxy merger rate with redshift remains today a key challenging issue. In the nearby Universe, wide-field imagers such as Megacam on the CFHT allow the mapping the stellar populations in the outermost regions of Local-Group galaxies, where faint, low-surface-brightness features provide clues about the past merging history. In the Local Group, in fact, the region encompassing M31 and M33 will soon be fully covered by the Pan-Andromeda Legacy Survey, managed in France by researchers of the Observatoire de Strasbourg. The New Generation Virgo Survey (NGVS, involving in France researchers from several institutes, in particular Observatoire de Lyon, Marseille, Paris, IAP and CEA-Saclay) will obtain deep images of the whole Virgo Cluster. The CFHTLS, which will be completed in January 2009, provides an impressive source of high-quality reference images of galaxies out to at least $z \sim 1$. This imaging survey is being complemented by the large spectroscopic database collected by the VVDS and zCOSMOS teams at the LAM (Marseille) and the LATT (Toulouse).

At higher redshift, wide-field surveys are more difficult to perform. However, observations of individual studies from well-selected samples can provide key information. For example, the kinematics of $z = 0.5-2$ galaxies is now accessible to VLT instruments such as

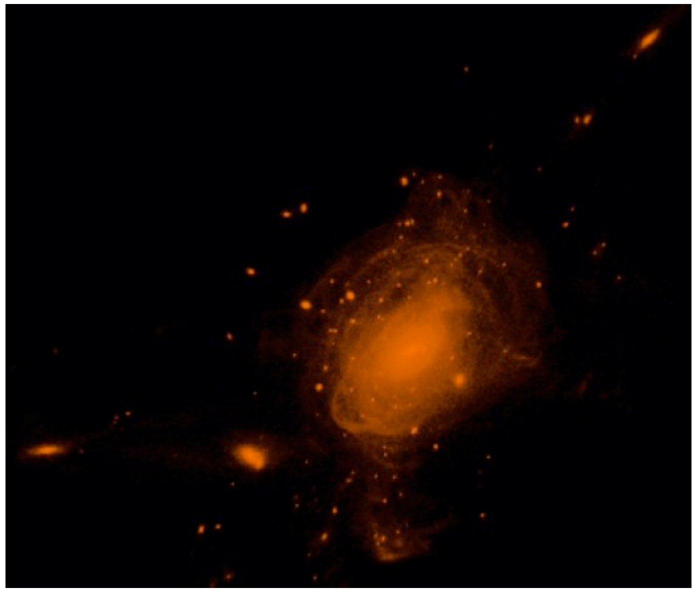

Figure III.30: Late stage (700 Myr after periapse) of a simulated wet merger, with mass resolution $2 \times 10^4\, M_\odot$ and spatial resolution 32 pc (the highest ever achieved for a simulation of galaxy collision). The image shows the young stellar component. The formation of structures with masses ranging from a few $\times 10^5\, M_\odot$ (super star clusters) to $\sim 10^9\, M_\odot$ (tidal dwarf galaxies) is directly resolved in this model [78].

GIRAFFE in the optical and SINFONI in the near-infrared, coupled with laser guide stars. This allows one to investigate whether a distant star-forming galaxy is a rotating disk or involved in a merger, when morphological information alone from optical/infrared images may be more ambiguous. Teams at GEPI (Paris; IMAGES project) [585], LATT (Toulouse; ANR-supported CCDS-SINFONI project) and AIM (CEA-Saclay) [510, 81] are already involved in such studies. Another advantage of the French community is the priviledged access to the millimeter Plateau-de-Bure interferometer, before ALMA starts operation.

✰ Numerical challenges

French teams have performed some of the most ambitious numerical simulations ever achieved, both on cosmological scales (the MareNostrum simulation [421] and the 70-billion-particle Horizon simulation of the CCRT super-calculator; see Section II.2.9 [539]) and on galactic scales (a simulation of the collision between two equal mass spirals, which used 40 millions of particle; see Fig. III.30 [78]). The interpretation of these simulations is in progress. Some of the main next challenges are to include a multi-phase ISM and improved recipes of star formation and chemical evolution, to better describe complex physical processes such as feedback. The ANR-supported OREAGAN project will tackle some of these issues.

As part of the Horizon project (supported by INSU, the CEA and the ANR), a large database of numerical mergers has been compiled at Observatoire de Paris: GalMer (`http://galmer.obspm.fr/`). The first public release of about 900 simulations via a web interface makes this database a valuable reference for future studies of galaxy interactions.

III.4.3 The environment and starburst history

Emmanuele Daddi, CEA/IRFU/SAp

Introduction

The influence of environmental effects on the physical properties and starburst history of galaxies, and their implications for the cosmic star formation history of the Universe as a whole, have been the subject of intense research in recent years. Observational and theoretical advances on both aspects are critical for our understanding of galaxy formation and evolution.

The role of environment

In the local Universe, galaxy properties are known to depend strongly on environment: clusters are dominated in mass and numbers by evolved, early-type galaxies, while the field is preferentially populated by star-forming disk galaxies. The progress achieved in environmental studies in recent years has been mainly of two kinds: first, the completion of major large-area spectrosopic survey, such as the SDSS and the 2dFGRS, has allowed detailed investigations of environmental effects on galaxy evolution in the nearby Universe with much increased statistics. And second, deep spectroscopic surveys (such as VVDS, DEEP/DEEP2, GOODS and zCOSMOS) have allowed first progress in addressing the role of environment at earlier cosmic epochs.

The discussion below focuses on studies directly connecting galaxy physical properties with environmental density, without much mention of the galaxy large-scale distribution (which is discussed in Section III.2.4).

✰ The local Universe

The SDSS has allowed the first detailed analysis of the connection between galaxy physical properties and environmental density [303]. This has shown that the galaxy physical property that most sensitively depends on density is the specific star formation rate (i.e. the star formation rate per unit stellar mass of the galaxy), which decreases sharply with environmental density, rather than morphology (as measured from the light compactness). This finding questions the role of mergers as the main mechanism for driving star formation in galaxies. In parallel, determinations of the galaxy luminosity function in different environments using 2dFGRS data show that this function can be approximated by a Schechter function with parameters which vary smoothly with local density, but in a fashion which differs strikingly for early- and late-type galaxies [155]. Finally, SDSS spectral analyses suggest that the stellar populations of the most massive early-type galaxies are about 1 Gyr older in clusters than in the field, while the chemical enrichment properties are roughly similar in both environments [54, 542]. All this suggest that mass and local density (which drives the mass) have important implications for the star formation history of galaxies.

✰ Surveys in the distant Universe

Deep spectroscopic surveys of faint galaxies have started recently to reach sufficient sizes for addressing the role of environment in galaxy formation and evolution at higher redshifts. For example, the VVDS, COSMOS, DEEP/DEEP2 and GOODS surveys have contributed to recent important advances in this field. The COSMOS survey [503], which has been designed to study galaxy environment at high redshift, is gathering some of the deepest datasets ever obtained across a comprehensive wavelength range over a 2 square degree area. This will allow the investigation of a volume of the Universe comparable to SDSS but over $0.5 < z < 3$. This survey is still relatively young, but interesting results have already appeared, e.g., on the impact of environment on the morphology and colors of galaxies $z < 1.2$ [114, 124]. Also, a study of the dependence of galaxy bimodality (blue, star-forming versus red, passively evolving) and environment in the VVDS shows that the star formation activity has shifted progressively over time from high- to low-luminosity galaxies (downsizing) and from high- to low-density environments [158].

A major new result in this area was recently obtained from analyses of the GOODS and DEEP2 surveys (Fig. III.31), which revealed that the relation between star-formation activity and environment was substantially different at earlier epochs from that in the local Universe [198, 147]. At $z \sim 1$, the typical star formation rate of galaxies appears to moderately increase rather than decline with increase local density. Excess counts of infrared-luminous galaxies have now been detected in cluster environments out to $z \lesssim 1$ [363, 187]. Current theoretical simulations of the distant Universe do not appear to reproduce these findings [198, 250].

The exploration of the distant Universe has also brought the discovery of numerous *proto-cluster* structures out to $z \sim 4 - 5$, and possibly even beyond [563]. We are still far from being able to probe in detail the impact of environment on galaxy formation at these early epochs. However, promising advances are underway, such as for example the discovery of a strong spike in the galaxy redshift distribution aroung $z = 2.4$ propulated by galaxies with average mass and age greater than those of field galaxies at the same epoch [525].

✰ Open challenges: Environment

A main difficulty in assessing the role of environment on galaxy evolution is the current lack of empirical probes, especially at high redshifts. As seen above, deep spectroscopic galaxy surveys have started to improve this situation.

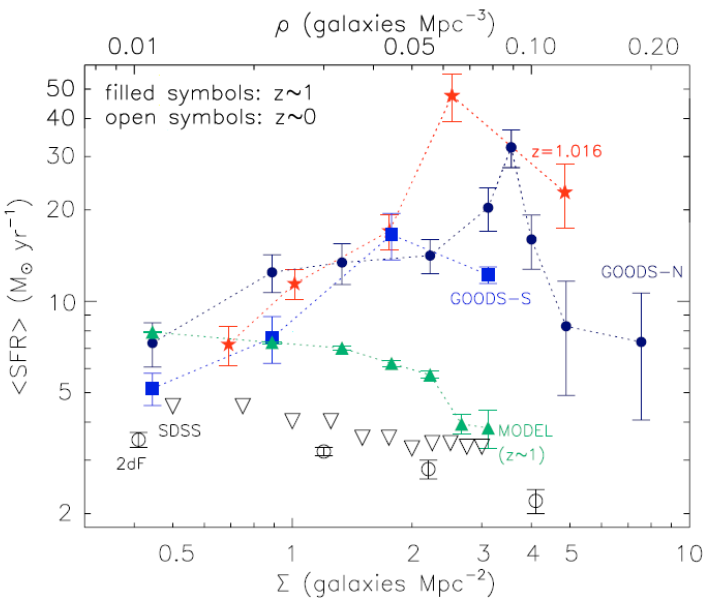

Figure III.31: Environmental dependence of the star formation rate for galaxies in the local ($z\sin 0.1$) and the distant ($z\sim 1$) Universe [198].

One of the main open questions in this field, which must be addressed also for galaxies in the local Universe, is to determine the relative roles of mass (halo mass, but also stellar mass) and environment (e.g., ram pressure, tidal tails, interactions) in driving galaxy properties. This is the well-known problem of *nature* versus *nurture*. Denser environments tend to host more massive and more early-type galaxies than the field on average, and we must clarify whether mass or environment is the primary driver of the morphological, chemical and stellar-population properties of galaxies.

Answering this question requires probing the properties of galaxies in different environments at various redshifts. While *proto-cluster* concentrations of star-forming galaxies are being found at high redshift, the epoch to which we can detect evolved clusters (i.e. containing large amounts of X-ray emitting gas and old-looking elliptical galaxies) is uncertain. Clusters of evoloved galaxies are currently being selected from deep optical and X-ray imaging surveys out to $z\sim 1.5$ [523, 196]. The X-ray emission from less massive structures, such as galaxy groups, can be selected out to $z\sim 1$ (e.g. in the XMM-LSS survey [429]). However, pushing these searches to earlier epochs appears difficult with current facilities. Clearly, it would be of the major importance to search for and characterize the properties of galaxies in these earliest (i.e., highest redshifts) collapsed structures, to test the effects of dense environment when differences with the field are expected to be the largest.

Starburst history

Since the pioneer work of Lilly et al. and Madau et al. more than a decade ago, mapping the cosmic history of star formation (i.e. the evolution with cosmic time of the star formation rate averaged over large volumes of the Universe) has been a major goal of observational cosmology, which has benefited from generous allocation of observing time at nearly all ground-based and space-based facilities [343, 352, 271, 579]. Much effort has also been invested in the development of models to interpret these observables. We briefly review below some of the most recent interesting results in this area.

✰ Starburst history from individual galaxies

The ultraviolet, optical and infrared spectral energy distributions of nearby galaxies contain valuable clues about the past histories of star formation and chemical enrichment in these galaxies. Estimates of the cosmic star formation history in this way from sophisticated spectral analyses of large samples of SDSS and other nearby galaxies are in rough agreement with direct measurements of the star formation rates of galaxies at various redshifts [271, 542, 373, 431]. These studies also support the 'downsizing' picture, according to which massive galaxies formed earlier and over shorter timescales than less massive ones.

The spectral analysis of nearby galaxies to recover the cosmic star-formation history requires appropriate models and techniques to interpret a multitude of photometric and spectroscopic diagnostics over a wide wavelength range. For example, the relative contribution by luminous asymptotic giant branch stars to the near-infrared light of intermediate-age $(0.5-2\,\mathrm{Gyr})$ stellar populations has recently been a subject of debate, which has particularly important implication for stellar-mass estimates in distant galaxies [362, 103]. New stellar evolution calculations and sophisticated stellar spectral libraries are constantly being produced to improve the models.

✰ Mapping the star formation history of the Universe

Recently, observations with the Spitzer satellite have allowed the detection of infrared emission from distant galaxies, and hence, new constraints on the star formation activity at cosmological distances. Measurements of the evolution of the galaxy mid-infrared luminosity function suggest that, at $z \gtrsim 1$, luminous infrared galaxies (LIRGs) are the dominant contributors to the cosmic star-formation density [334]. There are suggestions that, by $z \gtrsim 2$, ULIRGs may become dominant [118]. Local spectral templates and a tight correlation between the radio and far-infrared emission of dusty galaxies have been used to interpret Spitzer observations of distant galaxies, with some success but also some problems, at least at $z > 1.5$ [161, 432].

Far-infrared surveys with other instruments (e.g, SCUBA, AzTEC, MAMBO and APEX) have produced many interesting developments and new results, but the lower sensitivity of these facilities tends to limit investigations to the rare brightest galaxies.

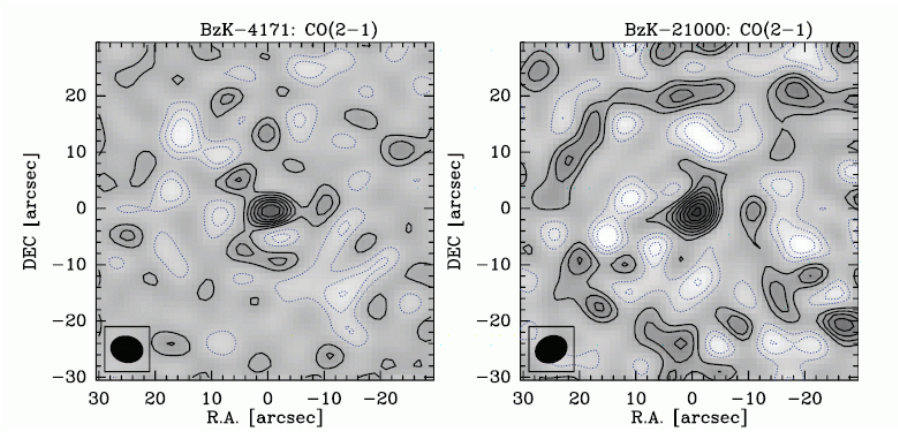

Figure III.32: First detection of molecular gas in ordinary distant ($z \sim 1.5$) galaxies [163], with the IRAM Plateau-de-Bure interferometer. The giant molecular gas reservoirs that have been found can sustain star formation over several $\times 100$ Myr at ULIRG level.

✰ The duty cycle of star formation

The discovery of tight correlations between stellar mass and star formation rate in actively star-forming galaxies at redshifts between in the range $0 < z < 1$ [198, 415], and even out to $z \sim 2$ [161], has brought new clues about the conditions of star formation in the young Universe. To first order, star formation appears roughly proportional to mass at fixed redshift (in reality, the specific star formation rate declines slightly with mass). Moreover, at fixed stellar mass, galaxies at $z \sim 1$ and $z \sim 2$ were forming stars on average ~ 6 and and ~ 30 times faster, respectively, than in the local Universe. The existence of such correlations suggests again that stellar mass plays a primary role in determining galaxy properties, and in particular star formation.

The tightness of these relations at fixed redshift further implies that, at given galaxy mass, the star formation rate does not fluctuate strongly on short timescales. Taken together with the relative observed proportions of galaxies with and without signs of current star formation, this suggest that the typical duration of a star-formation event in distant LIRGs and ULIRGs is much longer than in the local Universe.

This vision is confirmed by studies of the molecular-gas content of distant galaxies (performed mainly with the IRAM Plateau-de-Bure Interferometer). The relatively rare and extremely bright submillimeter galaxies have gas exhaustion timescale of only a few $\times 10$ Myr [260, 516] and appear to be scaled-up version of local ULIRGs. However, the detection of carbon monoxyde (Fig. III.32) in more ordinary, near-infrared-selected galaxies at $z \sim 1.5$ with ULIRG-like luminosities implies gas-exhaustion timescales of several $\times 100$ Myr [163]. These galaxies are more likely to be scaled-up versions of local spiral galaxies. Hence, star formation at high levels appears to be a long-lasting property in distant galaxies.

This is overall consistent with the results from morphological and kinematic investigations of distant star-forming galaxies, which show that the LIRGs dominating the cosmic star formation density at $z \sim 0.7$ are mostly regular, undisturbed galaxies, with no signs of major mergers nor interactions [40]. Integral-field spectroscopic surveys with the VLT have allowed the kinematic mapping of distant star-forming galaxies, unveiling the existence of well-developed spirals at redshifts in the range $0.5 < z < 2.5$ [226]. The overall properties of these galaxies are consistent with secular evolution over long timescales [243, 81, 144].

✰ Open challenges: Starburst history

A major limitation of the above studies, which we have not mentioned so far, is that the bolometric luminosities of ordinary galaxies at high redshift are still extremely uncertain. Thus, strong assumptions have to be made (in particular, about the spectral energy distribution at the longest wavelengths) to estimate the star formation rates of distant galaxies. New data from Herschel and ALMA should help dramatically reduce these uncertainties.

The molecular-gas properties of distant galaxies are only now starting to be explored. This is a fundamental topic, given that the molecular gas is the main ingredient for feeding star formation and probably also nuclear activity in galaxies. Upcoming facilities such as ALMA and SKA will likely make this topic one of the major themes in observational cosmology for the next decade.

Another major open issue is the need for understanding how star formation is terminated in galaxies (both local and distant). This presumably leads to the formation of spheroidal galaxies, which do not form stars through accretion of new gas. Feedback by an AGN is generally thought to be the most likely mechanism, but empirical progress has been slow in this direction, and more work will be needed to settle this issue. Similarly, while galaxy-galaxy mergers are generally thought to be the main process for regulating morphological transformation, much work is needed to empirically assess whether this process prevails in distant galaxies.

The role of French astronomy

Astronomers in France have been contributing substantially to progress in our understanding of the cosmic star formation history and of the influence of environment on the evolution of galaxies at all epochs. This is revealed, for example, by:

- The primary role played by French teams in the VVDS and zCOSMOS surveys at the VLT, which have brought major advances in environmental studies of galaxies at high redshifts;
- The key role played by French teams in surveys of distant clusters with the XMM satellite;

- The priviledged access of the French community to the IRAM facility, which has allowed significant advances in our understanding of the star formation activity at high redshift and represents a major advantage to prepare for studies with ALMA;
- French expertise in the modeling of the ultraviolet, optical and infrared spectral energy distributions of galaxies (e.g. Bruzual-Charlot models, Pegase models) [136, 159];
- The robust activity of several French groups performing state-of-the-art numerical simulation of galaxies formation and large-scale structure. This is required to interpret present and future observations of galaxy populations at all cosmic epochs;
- The strong implication of the French community in Herschel surveys, with a French-led open key program to map the GOODS field with both the PACS and SPIRE instruments.

All these activities should allow French astronomy to remain at the forefront of studies of star formation in galaxies in different environments across cosmic time.

III.5 Resolved stellar populations in galaxies

III.5.1 Star formation and the interstellar medium

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The star formation cycle is generally believed to start from clouds of atomic gas (but see [9]), which condense to form molecular hydrogen, out of which stars form. The most massive stars produce HII regions and photo-dissociation regions and finally disperse much of the star-forming cloud. Then, under the influence of large-scale dynamics (e.g. spiral arms), the scattered material assembles again to form new clouds. Characterizing this cycle in detail requires spatially resolved studies of galaxies. For galaxies in the Local Group, less than 1 Mpc away, molecular clouds can be resolved with large antennae and interferometers. After the pioneer work by [411] and [581], recent studies have provided interesting results, enabling a comparison of the interstellar media of galaxies of a variety of sizes, morphologies and metallicities [205, 481, 235, 258, 337, 414].

Atomic gas

Atomic hydrogen is an extended gas component of galaxies, which can reach out to several times the optical extent in isolated objects. Neutral atomic hydrogen has two stable phases: a warm ($\sim$ 5000K) and diffuse phase, and a cool ($\sim$ 100K) and much denser phase, which is presumably linked to the formation of molecular clouds and subsequent stars. Deep high-resolution HI measurements [94] indicate that the cool phase dominates within the optically bright parts of spiral galaxies, while the outer parts (beyond R_{25}) contain essentially gas in the warm phase. However, recent GALEX ultraviolet observations of nearby, late-type galaxies have shown that star formation can proceed further out in the disks than previously believed and is spatially correlated with the HI. This suggests that there might be a mechanism compressing the warm HI to make it pass into the cool dense phase and then into molecular gas and stars, even in places where the stellar density is very low. The fact that the ultraviolet emission extends further out than the Hα emission could result either from a truncation of the stellar initial mass function (IMF) at the high end or simply from the low probability of detecting the highest-mass, shortest-lived stars [65]. In low-mass, more irregular galaxies, the warm neutral phase appears to dominate throughout, as narrow HI line profiles are not observed. In general, molecular gas is not detected in these objects (see below), even though stars are forming.

The vast majority of star formation in spiral galaxies takes place within the optical radius R_{25}. In isolated objects, the flow rate of gas from the outer disk to the inner disk does not appear sufficient to replenish the gas consumed by star formation. Recent very deep observations [487, 425] have revealed the presence of extra-planar gas in spiral galaxies. Does this gas come from gradual inflow from past tidal encounters, or has it cooled out from the warm ionized halo and fallen toward the disk? The upcoming long-wavelength instruments, SKA and its pathfinders (particularly the Southern instruments which have access to the Magellanic Clouds), will allow a clarification of this issue by enabling high-resolution observations of the atomic component and the mapping of its properties in the vicinity of molecular clouds in nearby galaxies.

Molecular gas

Molecular gas is the direct fuel for star formation. The primary tracer of H_2 is carbon monoxyde CO, the most abundant molecule with an electric-dipole moment, observed in its rotational transitions at 115 GHz and multiples thereof. A secondary tracer is the continuum emission of cool dust in the Rayleigh-Jeans (submillimeter) part of the spectrum. The dependence of both tracers on metallicity makes them uncertain estimators of the H_2 mass, and hence, the star formation efficiency (the rate of star formation per unit mass of molecular gas). Along with IRAM, the Herschel (HIFI) and ALMA observatories will soon enable more sensitive and better-resolved observations of molecular and atomic lines, notably the line of ionized carbon CII at 158 μm. Probing all carbon sinks is essential in measuring the molecular gas mass because, while low-metallicity gas has been detected down to $\sim Z_{\odot}/50$, no pristine material has been found yet. Together with the deep submillimeter maps of dust continuum expected from Herschel PACS/SPIRE, JCMT and APEX in the coming years, these observations should enable a complete census of the carbon reservoirs of galaxies, including low-metallicity objects. This should finally help determine whether there are substantial amounts of unseen (presumably molecular) gas in galaxies.

Atomic and molecular gas correlate strongly both in space and velocity on large scales, but this correlation breaks down close to the cloud scale ($\sim 100\,\mathrm{pc}$). A major outstanding question is what triggers the transformation of HI into H_2. Many lines of reasoning point to a threshold HI column density for H_2 and star formation [495, 368], but this has not been unequivocally observed so far. Also, while H_2 (CO in most cases) forms only where HI is present and is more likely to form where HI column densities are higher, for any given (high) HI column density, there can be quite a bit of H_2 or often none at all. Another intriguing result is the drop in the likelihood of H_2 formation per unit gas surface density beyond a radius of about 4 kpc in the small local-group spiral galaxy M33 [235]. While the formalisms proposed for driving H_2 and star formation (Toomre instability criterion [547]; pressure [201, 60]) provide reasonable results in the bright regions of spirals, they do not predict discrete features such as cut-offs or rings of star formation. This suggests that other factors may be at work. We note that much recent work in this area has made use of high-resolution ($\sim 50\,\mathrm{pc}$) large-scale imaging of the CO emission in local-group galaxies with the IRAM 30-meter single dish and the BIMA interferometer. An interesting result [60, 337, 235] is that small galaxies such as M33 and IC10 appear to have a higher star formation efficiency than the large spiral galaxies that dominate the Universe today [400, 306]. High-resolution mapping of other small galaxies over the next few years should help confirm this result and investigate its physical causes, which will be of primary importance for studying the properties of galaxies at high redshift.

Further insight into the mechanisms that drive star formation may be gained from the analysis of galaxies other than isolated spiral galaxies dominated by rotating disks. For example, although most criteria proposed for star formation apply strictly to rotating disks, star formation takes place in irregular galaxies as well. A main obstacle to studies of star formation in these objects is that measuring H_2 has proven very difficult even in very local, low-metallicity irregular galaxies such as the Small Magellanic Cloud. Tidal dwarf galaxies [188] provide an alternative means of studying star formation in galaxies which are morphologically dwarfs but have metallicities close to solar, for which the same tools (i.e. CO, far-infrared emission) can be used to make a comparison with spiral galaxies. Such a comparison reveals that the star formation efficiency of tidal dwarf galaxies is similar to that of spiral galaxies, despite the huge differences in morphology and surface mass density (and the fact that, in young tidal dwarf galaxies, a self-regulation may not have been reached between molecular-gas production and consumption by star formation) [93, 89, 67, 98]. Whether this suggest that the presence of a rotating disk has no effect on the rate at which stars form is still unclear.

Studies of molecular gas in other environments have also shown that the star formation efficiency is very low in the gaseous bridges created by major galaxy collisions [88, 92] and in the gas swept out of galactic disks by ram pressure in galaxy clusters [570, 571]. In the outer parts of galaxies, where molecular gas is also detected via the CO lines [182, 91, 90] there is no indication of a drop in star formation efficiency and only signs that molecular clouds may be typically smaller. Another environment of interest is that of elliptical galaxies. Molecular gas (and dust), when present in elliptical galaxies, settles typically in a rotating

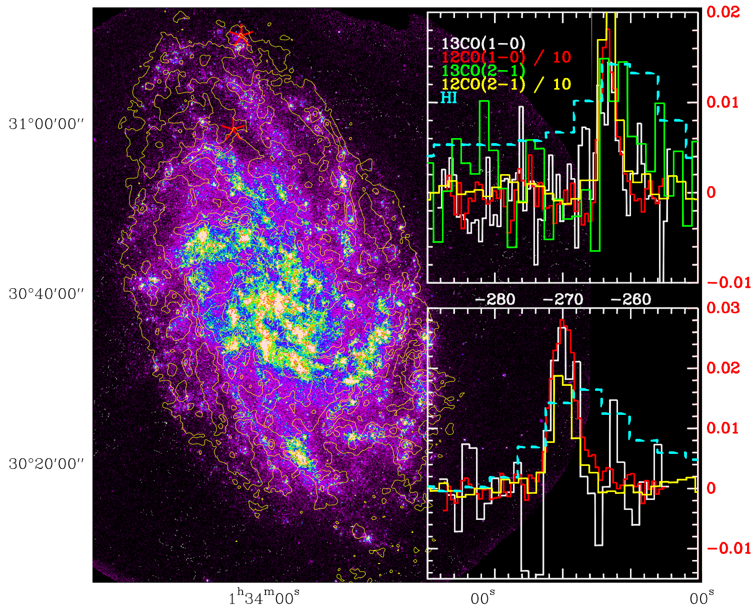

Figure III.33: The small local-group spiral galaxy M33, as seen by GALEX (color image) and in HI (contours). The ^{12}CO, ^{13}CO and HI spectra at the two positions indicated by red asterisks are shown on the right. In each case, the spectra show the IRAM 30-meter antenna temperature as a function of velocity (in $\mathrm{km\,s^{-1}}$), the y-axis scale for the HI being arbitrary. The molecular gas lines are very narrow (typical of small galactic molecular clouds complexes) compared to the HI line.

ring or disk with no clear difference relative to spiral galaxies. Such gas is generally thought to have been accreted recently [152, 146]. In the central parts of galaxies, large starbursts can occur when the average gas density and hence the star formation efficiency become very high. In general, the global star formation rate appears to be roughly proportional to the mass of dense ($\gtrsim 3 \times 10^4\,\mathrm{cm^{-3}}$) molecular gas, as measured from HCN molecules with high electric-dipole moment [234].

Over the past 15 years, carbon monoxyde has been detected in many galaxies and quasars at high redshifts [184, 424] and more recently at intermediate redshifts [145]. Many and perhaps most of these objects are affected by gravitational lensing. Major advances are expected from the increase in resolving power and sensitivity that will be offered in the early years of full ALMA operations, which will allow the detection of ordinary star-forming galaxies and the mapping of the most luminous objects out to high redshift.

Star formation

Standard global star-formation tracers in galaxies include the ultraviolet emission from young stars, the Hα emission produced by the gas ionized by young stars, the mid and far-infrared emission from dust heated by young stars, the thermal and non-thermal radio continuum emission from star-forming regions and supernova explosions, as well as other gas recombination lines and broad-band colors [306]. Some indicators suffer from attenuation by dust, and some require the presence of metals and magnetic fields. A direct comparison of the (HI+H_2) gas surface density with the Hα surface brightness in a sample of 61 normal spiral galaxies suggests that the star formation rate can be parameterized by a global 'Schmidt law' [499] of the form $\sigma_{\rm SFR} \propto \sigma_{\rm gas}^{1.4}$ [305, 307]. A more recent study of a sample of 65 infrared galaxies suggests that the global star formation rate is roughly proportional to the mass of dense molecular gas traced by HCN in normal spiral galaxies and in luminous and ultraluminous infrared galaxies [234]. Perhaps a more direct way to probe star formation, at least in the Milky Way and in nearby galaxies, would be to sample directly the distribution of star-forming clouds. Future instruments, such as the space-borne Far-Infrared Interferometer (FIRI), should be able to measure the mass spectrum of proto-stellar cores not only in the Galaxy, but also in the Magellanic Clouds and the other galaxies of the Local Group.

We are standing today at an important turning point when Galactic and extragalactic star-formation studies can meet: Galactic astronomers observe star formation on large scales throughout the Galaxy, while extragalactic astronomers resolve star-forming regions in nearby galaxies. Extragalactic studies have lower spatial resolution but do not suffer from the uncertainties in distance and extinction determinations inherent in studies of the Galactic plane. Soon, ALMA will enable studies of nearby galaxies at the same resolution as achieved in current studies of Galactic star-forming regions. Herschel will bring new information about the infrared emission from dust both in Galactic and extragalactic star-forming regions. In the meantime, the modeling of star-forming regions, HII regions and photodissociation regions in different environments is progressing fast. All this suggests that comparisons between models and data far more detailed than achievable today will soon be possible to understand why some environments are more favorable than others to molecular-gas and star formation, how rare molecules can be used to reliably trace the evolution of these regions, and whether the initial mass function of proto-stellar cores and stars varies in time and space.

Role of the French community

The French community has benefited from a priviledged position in studies of star formation and the interstellar medium, due to its access to IRAM, which has enabled most current detections of molecular gas in high- and intermediate-redshift galaxies and quasars and the most sensitive interstellar-gas maps of nearby galaxies. The participation of the French community in the upcoming Herschel and ALMA projects is a major advantage for the future. An essential point will be to maintain the manpower necessary for France to keep its scientific leadership in this research area. Maintaining the IRAM 30-meter single dish (still the best single-dish millimeter-wave telescope in the world) and the Plateau-de-Bure interferometer, with up-to-date instrumentation, could play a role in attracting astronomy students and retaining the technical expertise in the front and back ends of high-frequency radiotelescopes. This would also enable French astronomers to have access to the most powerful instruments of the Northen hemisphere in the millimeter-wave range. The situation with respect to longer-wavelength developments, in particular the French participation in SKA, is not yet settled.

III.5.2 Stellar populations and chemical evolution

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Studies of stellar populations have been boosted recently by the advent of high-resolution multi-object spectrographs on 10-meter class telescopes, which have enabled detailed chemical and kinematic analyses of individual stars in a wide variety of environments. The many atmospheric absorption lines in a stellar spectrum contain valuable information about the physical conditions in the interstellar medium when the star was born (modulo the changes in chemical composition induced by the CNO cycle in evolved stars, orbital diffusion, etc.). Studies of the spectral characteristics of the most metal-poor (and hence oldest) nearby stars are of particular interest: this field of 'stellar archeology' provides an important complement to direct analyses of the chemical composition of gas in young galaxies at high-redshift (e.g. damped Lyman-α systems; see Section III.2.2). Another extremely valuable type of study is the combination of measurements of the chemical compositions and kinematics of entire stellar populations, which provides a powerful means of reconstructing the formation scenario of the corresponding star cluster or galaxy.

Current status

☆ Kinematics and chemo-dynamics

Kinematic studies of individual stars allow the identification of streams of stars and dynamical links between stellar populations. Recent studies using the RAVE (Radial Velocity Experiment [526, 592]) and CORAVEL (Correlation Radial Velocities [416, 211]) databases have demonstrated the power of such dynamical surveys. For example, no vertical coherent stream containing hundreds of stars was found in local volumes of the solar neighhourhood, which rules out the passing of the tidal stream of the disrupting Sagittarius (Sgr) dwarf galaxy through the solar neighborhood [504]. RAVE data have also been used to characterize the shape and orientation of the stellar velocity ellipsoid, which is tightly related to the shape and symmetry of the Galactic potential well [512]. In addition, kinematic studies can be used to reveal stellar populations which are not otherwise easily distinguishable on the basis of their chemical properties. This approach has been used to kinematically distinguish stars belonging to the halo, the think disk and the thin disk of the Milky Way and then study the chemical signatures of these different components [565]. Similarly, kinematic studies have allowed the identification of 2 distinct stellar components in the Sculptor dwarf spheroidal galaxy [546]. For faint targets (typically $V > 18 - 19$), chemical diagnostics are limited to estimates of the metallicity using strong features such as the calcium triplet and magnesium lines.

✰ Chemical tagging and chemical evolution

The elements are formed by nucleosynthetic processes associated to different synthesis sites and different timescales. For example, α elements are produced mainly during the hydrostatic-burning phases of massive stars (type-II supernovae). Iron-peak elements are built during the explosive-nucleosynthesis phases of intermediate-mass stars (type-Ia supernovae). Heavy elements (with atomic number ≤ 30) are built by neutron capture of (mainly) iron seeds. These neutron-capture processes are schematically of 2 types, operating during stellar-wind events in low-mass stars (s-process) and in the latest stages of the evolution of massive stars (r-process). Using these different tracers, therefore, the element abundance ratios of observed stars can be used to reconstruct the chemical enrichment history of a stellar population. 'Chemical tagging' can also be valuable to discriminate between different populations. This has been illustrated in a recent analysis of the $[\alpha/\mathrm{Fe}]$ ratios, ages and kinematic properties of 102 dwarf stars in the solar neighborhood, which has set new constraints on the relative formation timescales of the thin and thick disks of the Milky Way [47, 48]. The same study also showed that the Hercules stream, identified by its peculiar kinematic properties, does not arise from a unique Galactic stellar population but probably a mixture of thin- and thick-disc stars.

Multi-object spectrographs (e.g. VLT/FLAMES, Keck/DEIMOS, Magellan/MIKE) have enabled detailed chemical-abundance studies of large samples of giant stars in nearby galaxies, such as the Large Magellanic Cloud [447] and the Sculptor [564] and Fornax [338] dwarf spheroidal galaxies. The different observed dependences of metal abundance ratios on iron content [Fe/H] in these galaxies reveal that they share different histories of chemical enrichment. This type of study is limited to the closest galaxies of the Local Group.

✰ First stars

The metal-poor end of the distribution function of stellar metallicities is a fundamental constraints on models of Galactic chemical evolution. Only 2 stars with $[\mathrm{Fe/H}] \lesssim -4$ have been identified so far in the Milky-Way halo. Analyses of extended surveys containing a substantial fraction of the Galactic halo (SEGUE, GAIA) are essential to make progress in this field. It is interesting to note that a recent study of the stellar metallicity distributions in 4 nearby dwarf spheroidal galaxies (the Milky-Way satellites Sculptor, Sextans, Fornax, and Carina [273]) revealed a significant lack of stars with metallicities below $[\mathrm{Fe/H}] \sim -3$ in all systems. The metal-poor tail of the metallicity distribution in these galaxies is therefore different from that of the Milky-Way halo, suggesting that the progenitors of nearby dwarf spheroidal galaxies may have been fundamentally different from the building blocks of the Milky Way.

Another interesting result is the discovery of an extremely metal-poor, r-enriched star (CS 31082-001), for which U-abundance determinations could be used to constrain directly an age of 15.5 ± 3.2 Gyr using the nucleocosmochronometer [Th/U] [274, 494]. This study demonstrated that U (together with Th) abundance observations in metal-poor stars are a promising tool for dating r-process events in the early Galaxy, independently of assumptions on Galactic chemical evolution. The search for new candidate stars is underway.

Observational limitations

✰ The Galaxy and globular clusters

Determinations of stellar chemical compositions require observations with very high signal-to-noise ratio and are currently limited to bright stars (typically $V \lesssim 18$ at a resolution $R = 20,000$ for moderately metal-poor stars, and $V \lesssim 16$ at a resolution $R = 40,000$ for the most metal-poor stars). In the Galaxy, detailed chemical and kinematic analyses of the different stellar populations (thin disk, thick disk, halo) are essential to constrain the star formation and chemical enrichment histories. This type of study can be achieved, for example, by performing wide-field imaging (VISTA) and VLT/FLAMES spectroscopy in selected regions of the Milky Way.

Chemical studies have also been targetting stars in nearby globular clusters. In the closest 2 globular clusters, NGC 6752 and 47 Tuc, detailed chemical compositions have been obtained for stars down to the main-sequence turnoff. This work has shown that abundance anomalies are found in these clusters all the way down to main-sequence stars. In a few other globular clusters, detailed metal-abundance ratios have been obtained for large samples of red-giant stars (typically 100 stars per cluster, down to the horizontal branch). These observations are currently being analyzed and could be extended to a sample of about 50 Galactic globular clusters.

✰ The closest galaxies of the Local Group

Spectrographs such as FLAMES (VLT), DEIMOS (Keck) and MIKE (Magellan) have enabled determinations of detailed chemical compositions of evolved stars in nearby dwarf spheroidal galaxies. However, the samples studied are still relatively small, of the order of only ~ 100 stars per galaxy. These samples must be enlarged to set reliable constraints on the metallicity distribution functions in these galaxies, which are particularly important to constrain the star formation and chemical enrichment histories. Studies of this kind are currently restricted to metallicity determinations using medium-resolution spectroscopy (e.g., Ca-triplet survey).

✰ The Local Group

Measurements of individual stellar metallicities (using the Ca triplet) in the Andromeda galaxy M31 are the current limit for 10-meter class telescopes. Determinations of stellar metallicities in galaxies outside the Local Group, especially old elliptical galaxies, would be extremely important to contrain early galaxy formation, but such observations are beyond the limits of current instrumentation.

Perspectives

✰ Kinematics

Radial velocities have already been measured for large samples of Galactic stars (e.g. SDSS/SEGUE, AAO/RAVE). These studies will soon be complemented by projects carried out using new instruments mounted on large-aperture telescopes, such as WFMOS on the 8-m Subaru telescope and the 4-m LAMOST (for comparison, SEGUE and RAVE were performed on 1.2 m telescopes). These new projects will be able to acquire spectra of up to ~ 4000 stars simultaneously (compared to 600 for SEGUE and 150 for RAVE), extending dramatically the spectroscopic exploration not only of the Milky Way, but also of nearby dwarf spheroidal galaxies of the Local Group. By 2020, GAIA will also have mapped the 3D kinematics (V_r, μ_l and μ_b) of a complete sample of 1 billion stars down to $V = 20$.

✰ Chemical composition

In the Milky Way and the closest dwarf-spheroidal and dwarf-irregular galaxies, stellar metallicities can be constrained by means of multi-object spectroscopy at a resolution of $5000 - 20,000$ in the visible using the FLAMES, UVES and CRIRES spectrographs on the VLT. Follow-up observations at a higher resolution (20,000 to 40,000) can be performed to obtain more detailed chemical compositions and perform chemical tagging. Current and future low-resolution spectroscopic surveys (SEGUE, RAVE, LAMOST, GAIA) and wide-field photometry (VISTA) will provide valuable samples for such studies.

✰ First stars and globular clusters

Globular clusters and the most metal-poor (i.e., oldest) stars in the Galactic halo contain fossil records of early nucleosynthesis and the chemical enrichment history of the Milky Way. Two ESO Large Programs, in which the French community was largely present ('First Stars' and 'Globular Clusters'), have enabled spectacular progress in this research area since 2001, as described above. The ongoing search for extremely metal-poor stars and peculiar metal-poor stars with enhanced r-process nuclei is proceeding slowly because of the large requirement of telescope time to obtain high-resolution stellar spectra. At this time, the sample of known Galactic stars with [Fe/H] $\lesssim -3$ is also still relatively limited. In studies of globular clusters, a large set of spectra obtained with the high-resolution multi-object spectrograph FLAMES is currently under analysis. This sample can be extended to the ~ 50 nearest globular clusters.

Stellar populations and chemical evolution in the ELT era

'Resolved stellar populations' is one of the prominent science cases (G4) for the ESO ELT. With the ELT, imaging of individual stars at the tip of the red giant branch in galaxies beyond the Local Group, intermediate-resolution spectroscopy to determine abundances and velocities at distances out to $5-10$ Mpc and high-resolution spectroscopy in M31 and Cen A are within reach. Spectroscopically, the planned EAGLE and HARMONI instruments (currently in Phase A) can potentially play an important role. Some limitations will arise from the fact that EAGLE is a near-infrared instrument restricted to wavelengths $0.8 \leq \lambda \leq 2.5\,\mu$m (with resolution $R = 4000$ and 10,000), and that HARMONI has a small field of view and only an optional visible + high-resolution mode (the standard wavelength range is $0.8 \leq \lambda \leq 2.4\,\mu$m and the resolution $R \gtrsim 4000$). This type of instrumentation will limit abundance determinations to the simple measure of the Ca triplet, preventing detailed abundance-ratio analyses. For comparison, the planned WFOS at the TMT will be able to acquire spectra of $\sim$ 1500 objects in a single exposure at wavelengths in the range $0.31-1.1\,\mu$m.

The planned CODEX spectrograph on the ESO ELT, with a wavelength coverage of $0.4-0.8\,\mu$m and a resolution $R \sim 150,000$, will allow detailed studies of a large number of 'first stars' in the Milky Way, the Large and the Small Magellanic Clouds and the Andromeda galaxy. However, the lack of crucial information in the blue part of the spectrum ($0.31-0.4\,\mu$m) will limit the possibilities of detection of the enigmatic r-enriched, extremely metal-poor stars (and also prevent determinations of Be abundances). We note that, since the best-measurable absorption lines of extremely metal-poor stars are in the blue part of the spectrum, abundance analyses of red spectra typically receive low priority in chemical evolution studies of Local-Group galaxies.

III.5.3 Stellar halos and accretion

Rodrigo Ibata, Observatoire Astronomique de Strasbourg

Our understanding of galaxy formation and evolution has improved remarkably over the last decade, most notably with the characterization of the global star formation history of the Universe and the evolution of galaxy morphologies [40, 483]. High-redshift observations however do not allow one to trace back the evolution of individual galaxies. Also, the characterization of low-mass and small-scale structures remain out of reach in all but the nearest galaxies. Observations of nearby galaxies are therefore required to complement studies at cosmological distances to answer fundamental questions such as: which building blocks of high-redshift galaxies end up in the different types of local galaxies? What fractions of stars in different galactic components are formed in situ and are accreted?

In recent years, it has been realized that many of the clues to answer these fundamental questions may be preserved in stars in the outskirts of galaxies [229]. Hierarchical models

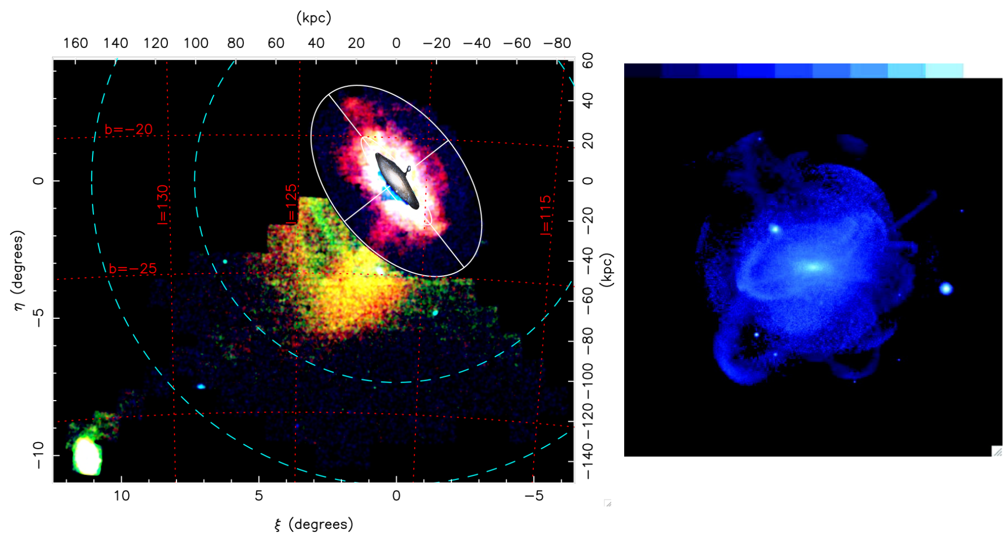

Figure III.34: Left: Stellar halo of the Andromeda galaxy, which is riddled with streams and other signatures of accretion [283]. **Right:** Distribution of halo stars predicted by a simulation of hierarchical galaxy formation [106].

of galaxy formation suggest that galaxy outskirts form by accretion of minor satellites, predominantly at early epochs, when large disk galaxies assemble for the first time. The size, metallicity and amount of substructure in the faint outskirts of present-day galaxies are therefore directly related to quantities such as the small-scale properties of the primordial power spectrum of density fluctuations and the suppression of star formation in small halos [519].

Almost all we know today about the properties of the faint outskirts of galaxies is based on observations of the Milky Way and the Andromeda galaxy M31 [229]. Most recently, the large-scale mapping of the Milky Way has progressed dramatically with the advent of major surveys collecting photometric, kinematic and chemical-abundance data for huge samples of individual stars in wide volumes (e.g., SDSS [263, 291]; RAVE [526]; SDSS-II/SEGUE [475]; GAIA; Pan-STARRS). The study of these data sets will be among the chief astrophysical goals for years to come to unravel the processes by which our Galaxy came into being.

Studies of the sole Milky Way presumably cannot provide definite answers about the nature and origin of stellar populations in all spiral galaxies. To fully assess the implication of Galactic surveys for the formation of spiral galaxies in general, we must first establish how typical the Milky Way is by studying other giant spiral galaxies. This is why the Andromeda galaxy has also been surveyed in great detail in the past few years, both with wide-field photometry (see Fig. III.34) [284, 216, 283] and with multi-object spectroscopy [282, 132, 300, 262]. These analyses show that the Milky Way and M31 are very different, with M31 displaying many signs of both ancient and recent merger activity [62, 283], while the Milky Way appears to have led an unusually quiet existence [267]. Significant effort is currently being devoted to interpret the cosmological implications of these observations [224].

In the currently favored models of galaxy formation, halos are populated by stars which are tidally stripped from satellites as they fall in the potential well of the host galaxy [1]. The structure and chemistry of stellar halos are thus expected to reflect the details of the galaxy assembly process [106]. The realization that hierarchical models of galaxy formation predict almost inevitably 1 to 2 orders of magnitude more dwarf galaxies than are actually seen around the Milky Way [397] has led to suggestions that most of the dwarf satellites formed in the early Universe may have dissolved into the Galactic halo [107].

Observationally, however, the nature and origin of galactic stellar halos remain elusive. Excitement about the formation of stellar halos has been sparked in recent years after the discoveries of disrupted dwarf galaxies and substructures in star samples of the Milky Way [285, 369, 586] and M31 [284, 591, 283], which reinforced the concept that satellite accretion could be an important mechanism for building up galaxies. Studies of the inner parts of the M31 'halo' initially revealed dramatic differences relative to the Milky-Way halo population [190]. While the Milky-Way halo is populated primarily by old metal-poor stars, a few fields in the halo of M31 appeared to show a large population of intermediate-age stars with much higher overall metallicity [99, 100]. Red horizontal branch stars were also found as far as 40 kpc from the nucleus of M31 [466], suggesting that the stellar halo of that galaxy underwent considerably more enrichment than did the Milky-Way halo. In reality, the conclusion that the M31 halo is globally younger and more metal-rich than that of the Milky Way cannot be drawn from current data, since the M31 fields in which the above results were obtained have since been found to be significantly contaminated by various accretion events [283]. Furthermore, spectroscopy of stars either kinematically confirmed members of the M31 halo or sufficiently in the outskirts of the galaxy reveals the presence of a pressure-supported metal-poor population similar to that dominating the Milky-Way halo [132, 300]. Current observations therefore indicate that stellar halos are complex structures. Much larger samples of observed stars will be required to fully understand how halos form and evolve.

Prospects

Over the next 3 years, the French and Canadian communities will invest a significant fraction of CFHT time in a 'Large Program' to survey the Andromeda galaxy out to 150 kpc and M33 out to 50 kpc. This study will image a vast volume of approximately 15 million kpc^3, providing the most complete panorama of galaxy halos ever obtained, which will be used to constrain cosmological models of galaxy formation over an order of magnitude in halo mass. Questions of particular interest include, for example, the chemical composition and mass distribution (especially at the low-mass end) of galactic substructures, and the testing of the ΛCDM prediction that the halo of M33 should be simply a scaled-down version of that of M31. Spectroscopic follow-up of this survey will be difficult to undertake for the French community alone (which will be forced to collaborate with other countries), because of the lack of access to spectrographs on large telescopes in the Northern hemisphere.

In the longer term, the GAIA mission will enable extremely detailed studies of structure and substructure in the Milky Way. The 3D kinematic mapping by GAIA of a complete sample of 1 billion stars represents our best hope of reconstructing the merging history of any galaxy halo in the foreseeable future [251]. It is worth mentioning in this context the WFMOS project of the Gemini community, which will obtain high-resolution spectra to perform the chemical tagging (Section III.5.2) of a substantial subset of GAIA stars [229]. The hope is that this will allow the identification of groups of stars of common chemical origin, hence strengthening the analysis of the Galactic formation history derived from GAIA data.

Unfortunately, the French community is so far not directly participating in two of the most important next-generation surveys for studying resolved stellar populations, Pan-STARRS and LSST. By observing the entire sky down to unprecedented depths at optical wavelengths, these two surveys will provide unique information about the structure and composition of the Milky-Way halo components. Moreover, since both surveys use photometric monitoring, they will uncover variable stars including RR Lyrae variables, which will allow accurate distance determinations to halo structures (in the case of LSST, the entire Local Group lies in range). Hence, the future combination of the astrometric accuracy of GAIA, the chemical constraints from WFMOS and the photometric depth of LSST represents the most powerful means of uncovering ancient accretions, streams and the lowest-mass substructures of the Milky Way. It is worth mentioning here that stellar streams of low-mass progenitors provide an exciting possibility to test theories of gravity. For example, asymmetries between the leading and trailing arms allow one to test the equivalence principle in the dynamics of dark matter [310], while MOND theories produce significant deviations between the unbound stream and any remaining bound core.

All the projects mentioned above are confined to the Local Group. Thus, these projects cannot help determine the relevance of Local-Group galaxies to the general assembly of spiral galaxies, which requires probing galactic halos beyond $\sim 1\,\mathrm{Mpc}$. Several teams are attempting to undertake such challenging observations. Wide-field cameras on large ground-based telescopes are now able to resolve stellar populations out to about $4\,\mathrm{Mpc}$, bringing in particular the M81 and Sculptor groups into range [138, 59]. These panoramic studies allow a census of the global properties of stellar halos, which is a key advantage, as can be perceive from a cursory inspection of Fig. III.34. In contrast, results from small 'pencil-beam' surveys are likely to highly depend on the initial choice of field positions.

Spectroscopic follow-up of the stellar structures detected at such large distances will in general be too costly with current instrumentation, though future facilities may dramatically improve the situation. For example, an optical multi-object spectrograph mounted on the ESO ELT could allow studies of the kinematics and chemistry of accretion events and halo stellar populations in galaxies out to $\sim 5\,\mathrm{Mpc}$ to a similar degree of detail as is currently

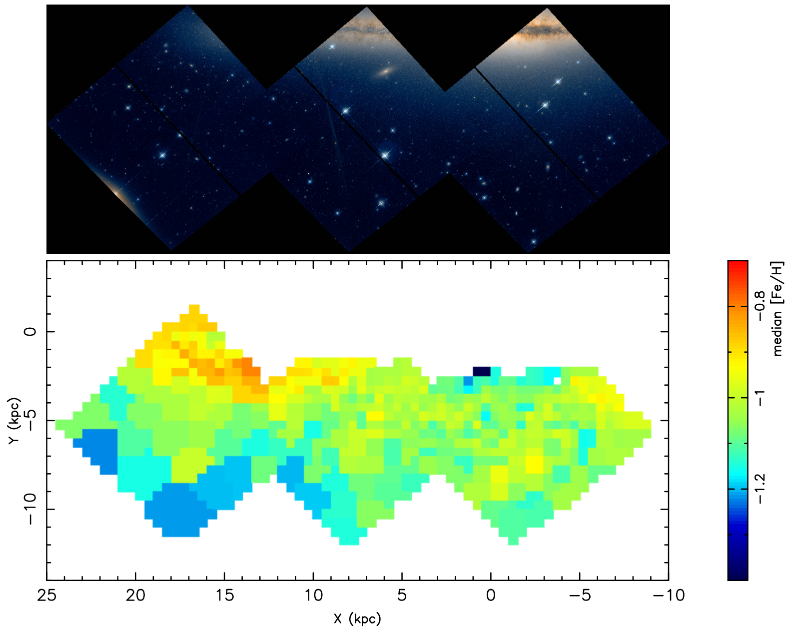

Figure III.35: HST/ACS observations of NGC 891 (top panel), a Milky Way analogue at 10 Mpc, resolve individual red giant branch stars in this galaxy. This reveals a complex and relatively metal-rich stellar halo (bottom panel), markedly different from that of the Milky Way [286].

possible in the Andromeda galaxy.

Nevertheless, space-based 'pencil-beam' imaging is the only means currently available of pushing the study of resolved stellar populations out to 10 Mpc (see Fig. III.35). This is why a very large amount of HST/ACS resources have been spent on this subject, including a Treasury Program and several normal programs devoted to the study of extra-planar stellar populations in galaxies [164, 399, 166]. The ACS 'anomaly' in January 2007 has put progress on these programs on hold, and the hope is that the 2009 repair mission will allow these programs to be continued.

With numerous on-going and future large instruments and surveys, the study of galaxy halos and their formation history looks set to remain a vibrant field of study for at least another 15 years. However, many challenges remain, particularly in modelling low-mass structures in galaxy simulations, incorporating all the relevant physics and comparing model predictions with the complex structures observed.

Part IV

Projects and instrumentation to answer these questions

IV.1 Immediate facilities

IV.1.1 The Planck project

Francois Bouchet, IAP

In 1994 the European Space Agency has selected the Planck project as the major European space mission for CMB cosmology. It will be the third generation CMB satellite following the two NASA missions COBE and WMAP. The mission was delayed following the Ariane failure leading to the need to rebuilt the CLUSTER satellites. It will be launched in early 2009.

The very ambitious goals allowed by the combination of two different technologies (radio receivers used by LFI and very low temperature bolometers used by HFI) have been iterated upon following the WMAP results with an increased emphasis on measurements of the polarization of the cosmic microwave background light. The high frequency instrument (HFI) is the most sensitive one on board Planck but the combination with the LFI instrument will be particularly powerful to remove galactic foregrounds using the very broad frequency coverage (30 GHz to 850 GHz).

The gains in angular resolution and in sensitivity with respect to WMAP leads to a CMB mapping in intensity which will be only limited by fundamental (cosmic variance) and astrophysical limits (ability to remove foregrounds). Planck will then measure, with a signal ratio greater than one, more than fifteen times more modes than WMAP. For polarization, where the improvement is the largest, it is likely that Planck will nevertheless be still limited by the instruments sensitivity. The CMB channels of our high frequency instrument are limited mostly by the background photon noise and thus a substantial gain can only be obtained by increasing significantly the number of pixels from (from 50 to several thousands) keeping the instantaneous sensitivity. It will not be known before Planck flies what is the level at which the uncertainties in the removal of the foregrounds will limit the ultimate sensitivity for CMB polarization.

The high angular resolution (5 arc minutes) and sensitivity of Planck will allow the observations of seven acoustic peaks which, in combination with the E mode polarization, will provide a very powerful tool to test the concordance cosmological model. Planck can also remove degeneracies ignored so far, like those induced by the possible presence of some small isocurvature modes in the primordial fluctuations. Planck will also determine the reionization history of the Universe

The most ambitious goals of Planck concern the tests of inflation and its physics. The very accurate measurement of the primordial density fluctuations through their signatures in the CMB anisotropies (spectral index both average value and curvature, polarized B mode tracing the primordial gravitational waves) are at present the best observational tools to test this physics.

Tests of primordial non-Gaussianity (e.g. f_{NL} tests; see Section III.2.4) will also be powerful probes to constrain interesting classes of inflationary models. And of course Planck will also help assessing whether numerous claims for non-Gaussianity in WMAP data are real features or caused by systematic errors in the WMAP data interpretation. Planck might discover non-Gaussian features like those left by primordial defects.

The Planck mission will provide all sky temperature maps in 9 bands covering a broad spectral range (30 to 850 GHz) in which there is no survey with a comparable sensitivity and angular resolution. It will also deliver polarization maps at 7 frequencies between 30 and 350 GHz. This dataset will provide a basis for the astrophysics and cosmology community allowing to explore many open questions.

In the field of the physics of starburst galaxies which are radiating most of their energy in the far infrared and in the millimeter submillimeter range for redshifted sources, Planck will provide SEDs and maps of nearby galaxies.

The cosmic far-infrared background and deep mid-infrared surveys (from ISO and Spitzer) indicate that the most distant galaxies radiate more energy in the infrared than in the ultraviolet and optical (contrary to what happens in the local Universe). The study of the high-redshift population of infrared galaxies (and particularly their spatial distribution with respect to dark matter) is difficult through large deep surveys because of limitations introduced by the combination of confusion, diffraction and sensitivity. Planck will measure the power spectrum of the cosmic infrared background, which will provide valuable constraints on the high-redshift galaxy population until ALMA can undertake large high-sensitivity surveys not limited by confusion (see Section III.3.2).

The guaranteed scientific return from Planck is spectacular. With such a great increase in capability over previous CMB missions, we can anticipate completely new science as well.

IV.1.2 The Herschel satellite

David Elbaz, CEA/IRFU/SAP

Herschel is a cornerstone mission of ESA which will orbit at the Lagrange point L2 and will have three instruments mounted on a single dish 3.5 m passively cooled (80K) telescope, making it the largest space telescope ever launched. It is expected to be launched in February 2009 for a 3.5 years nominal lifetime.

It has been designed to explore the 'cool Universe', by studying both cool gas and dust, although gas emission lines from very distant galaxies will rapidly be out of scope for Herschel leaving their study to ALMA. Herschel will cover the wavelength range from 60 to 670 μm where the broadband dust emission peaks over the redshift range $z = 0$ to 6 with its two instruments able to detect galaxies at cosmological distance, the Photodetector Array Camera and Spectrometer (PACS) and the Spectral and Photometric Imaging Receiver (SPIRE) observing at 70, 100 and 160 μm (PACS) and 250, 350 and 500 μm (SPIRE) with a spectral resolution of R=$\lambda/\Delta\lambda \sim 3$ for broadband photometry and an intermediate resolution of $R = 20 - 2000$ for spectroscopy. The angular resolution ranges from 5.4

to 35 arcsec from the lowest to largest wavelengths and the expected main limitation for studying the distant universe will be the so-called confusion limit, i.e. the difficulty to isolate individual galaxies from their surrounding neighbors. The third instrument, the Heterodyne Instrument for the Far Infrared (HIFI), will bring limited capacities for extragalactic science.

The French community played an important role in the construction and calibration of Herschel's instruments, in particular by building the PACS bolometers.

PNCG science with Herschel

The main goals of Herschel are related to the study of the earliest stages of star and galaxy formation, i.e. the dust re-radiation of stellar light due to the most massive stars which life-span is at most of the same order than that of their parent giant molecular clouds ($\sim$10 Myr).

57% (11258 hours) of Herschel time will be dedicated to Key Programs (KPs) divided equally between Guaranteed Time (52%) and Open Time (48%), the remaining time will be open for 'normal' proposals after launch. Of main relevance to the PNCG are the following two broad scientific fields: cosmological extragalactic surveys and the study of nearby galaxies and active galactic nuclei.

The main goals of the cosmological surveys will be to identify the constituents of the cosmic infrared background, which measures more than half of all light ever radiated by newly formed stars; to measure the evolution of the star formation rate density of the Universe with cosmic time; to study the connexion between star formation and environment; to characterize the role of active galactic nuclei in galaxy formation and evolution, and the co-evolution of star formation and the growth of supermassive black holes; to identify the most distant galaxies and quantify their activity.

The main goals of the study of nearby galaxies will be to understand the physics of star formation and the growth of super-massive black holes in various environments; to characterize the formation and destruction of metals and dust and the cycle between stars and the multi-phase interstellar medium; to understand the origin of the relations between galaxy mass, morphology, metallicity, age, local environment (field, groups, clusters); to quantify the effects of dust attenuation and identify ways to correct for them to obtain a complete census of all light produced inside galaxies, and hence, of the true star formation rate.

Common to both topics and related to the major open questions that motivate the PNCG are the issues of understanding:

- the role of galaxy interactions and the origin of the apparently anti-hierarchical behavior of galaxy 'downsizing' (i.e., the decrease in the typical mass and intrinsic luminosity of galaxies dominating the star formation rate density of the Universe with decreasing lookback time);

- the physical origin of positive and negative feedback, respectively accelerating and quenching star formation;
- the origin of the tight correlation between mass of stellar bulge and mass of supermassive black hole in local galaxies (the 'Magorrian' relation [354]);
- the role of active galactic nuclei in potentially triggering and/or quenching star formation in galaxies;
- the physical origin of the connexion between galaxy properties on pc (central supermassive blackhole) and kpc scales and the large-scale environment on Mpc scales (e.g. bimodality between red-dead and blue-active galaxies).

IV.1.3 KIDS/VIKING and Ultra-VISTA

Yannick Mellier, IAP

The KIDS and VIKING surveys

The *KIlo Degree Survey* (KIDS) is an ESO public imaging survey accepted by the ESO/OPC in 2005. The PI of KIDS is K. Kuijken, from Leiden Observatory.

The KIDS core survey will be accomplished by using the ESO VST/OmegaCAM to observe 1500 $\deg^2$ in u, g, r and i in 380 nights, with a typical exposure time of $\sim 1000\,\text{sec}$ per filter. KIDS should therefore reach AB magnitudes of $24.1, 24.6, 24.4$ and 23.4 in these wavebands, respectively (10σ, 2" aperture).

KIDS observations will be followed up in the near infrared using the VIRCAM near-infrared camera on the ESO/VISTA telescope. The *VISTA Kilo degree INfrared Galaxy survey* (VIKING) is also an ESO public imaging survey, which was accepted by the ESO/OPC in 2006. The PI is W. Sutherland, from IoA, Cambridge. VIKING will cover the 1500 $\deg^2$ of the KIDS survey in Z, Y, J, H and K_s, with a typical exposure time of $\sim 600\,\text{sec}$ per filter. VIKING should therefore reach AB magnitudes of $22.4, 21.9, 21.7, 21.0$ and 20.6, respectively (10σ, 2" aperture). The total amount of time of the VIKING survey is 2160 hrs.

The optical and near-infrared parts of the KIDS/VIKING survey are expected to be completed after 4 and 5 years of operation, respectively. If VST and VISTA are not delayed any longer, the two surveys should start by the beginning of 2009 (VIKING) and mid-2009 (KIDS). The target fields comprise two strips, KIDS-N ($9:00\,\text{hrs} < \text{RA} < 16:00\,\text{hrs}$, $-5° < \text{DEC} < +4°$) and KIDS-S ($03:30\,\text{hrs} < \text{RA} < 22:00\,\text{hrs}$, $-36° < \text{DEC} < -26°$), of $750\,\deg^2$ each. In these regions, 200,000 galaxy redshift are already available. KIDS-N will contain the CFHTLS Deep D2 and the COSMOS fields, and a small fraction of CFHTLS-W2.

The KIDS/VIKING survey has been delayed several times and face now serious competitors, such as Pan-STARRS and DES. However,no other planned survey will gather data in 9 bands, including 5 near-infrared filters, at a depth between those of SDSS and CFHTLS. Moreover, KIDS/VIKING will cover part of the Southern sky not surveyed by DES. KIDS/KIKING is therefore still unique, provided that it start immediately. Furthermore, its moderate depth will make spectroscopic follow up easier than in the case of CFHTLS.

The main science drivers of KIDS/VIKING are:

- the structure of galaxy halos, via weak lensing (galaxy-galaxy) lensing, as a function of galaxy morphology, colors and environment;
- the search for very high-redshift quasars, with special attention to the redshift range $6.4 < z < 7.2$, which should be optimal for KIDS/VIKING. About 6 KIDS quasars with $J > 19.5$ are expected to be spectroscopically confirmed at $6 < z < 7$;
- the study of baryon acoustic oscillations, using accurate photometric redshifts derived from 9-band photometric data;
- the evolution of the galaxy luminosity function per galaxy type;
- the evolution of clusters of galaxies. KIDS should provide between 1-2 $\times$ 10^4 cluster, of which about 5% will be at redshift beyond 1;
- the galactic white-dwarf population. About 80 ultra-cool white dwarfs (with $19 < g < 22.5$) and 50 ultra-cool brown dwarfs are expected to be spectroscopically confirmed;
- the morphology of host galaxies of active galactic nuclei.

Several byproducts are also expected, in particular a joint CFHTLS-Deep, CFHTLS-Wide and KIDS weak-lensing study. Each survey has different depth and sky coverage but will provide three different cones of the Universe where tomography can be performed.

IAP/Terapix is the only French institute involved in this survey. VIKING is mostly UK and NL, whild KIDS includes Bonn, Munich, Naples, Leiden, Groningen, Cambridge, London (Imperial) and Edinburgh.

The Ultra-VISTA survey

The *Ultra Deep survey with VISTA* (Ultra-VISTA) is another ESO public imaging survey accepted by the ESO/OPC in 2006. It will achieve ultra-deep imaging of the COSMOS field in the near infrared with VISTA/VIRCAM. The PIs are J. Dunlop (Edinburgh), O. Le Fèvre (LAM), M. Franx (Leiden) and J. Fynbo (DCC, Denmark).

Ultra VISTA will be composed of an ultra-deep survey, covering 0.73 deg^2 in the Y, J, H, K_s broadband filters and a narrow band (NB 1185) filter, and a deep survey, covering

1.5 deg^2 in Y, J, H and K_s. The ultra-deep fields consist of 15'-wide vertical strips encompassed inside the 1.5 deg^2 of the deep survey. The expected AB magnitude limits in the above filters are $26.7, 26.6, 26.1, 25.6$ and 24.1 for the ultra-deep survey and $25.7, 25.5, 25.1$ and 24.5 for the deep survey (5σ, 2" aperture). Typical exposure times will be ~ 310 hrs for the ultra-deep broad band-filters, ~ 170 hrs for the narrow band filter and ~ 47 hrs for the deep broad-band filters. The total amount of observing time is 1800 hrs, spread over 5 years. The survey should start by the beginning of 2009, immediately after the VISTA/VIRCAM commissioning, and the last data should be obtained by the beginning of 2013. All data are expected to be reduced by the end of 2013 or the beginning of 2014, just in time for JSWT.

The main science drivers of Ultra-VISTA are:

- a preparation of targets for JWST;
- the study of the high-redshift Universe ($z > 6.5$) and the origin of reionization. A sample of ~ 1000 galaxies is expected to be observed at $z > 6.5$;
- the detection of Lyman-α emitters at $z \approx 8.8$ with the narrow-band filter;
- the formation of halos during the epoch of maximum star-formation activity in the Universe. The deep survey should produce a large sample of $2 < z < 5$ galaxies down to stellar masses of roughly $10^{10}\,M_{\odot}$.

The French institutes involved in Ultra-VISTA are the LAM in Marseille and IAP/Terapix. The other institutes are Copenhagen, Leiden, Edinburgh, the CASU data center in the UK, MPIA in Heidelberg, Groningen and ESO.

IV.1.4 The Atacama Large Millimeter Array (ALMA)

Françoise Combes, Observatoire de Paris, LERMA

ALMA is an outstanding project built jointly by Europe, the US and Japan, with unprecedented sensitivity and spatial resolution in the millimeter and submillimeter range. The main interferometer is composed of 50 antennae of 12 m diameter each, and there will be an additional compact array composed of 7 m and 12 m antennae. ALMA is foreseen to be operational in 2012.

If the angular resolution is exquisite (up to 10 milliarcsec, with the largest baseline at high frequency), the field of view is small, from 1 arcmin (at 3 mm) to 6 arcsec (at 0.3 mm), and ALMA is not an instrument for big surveys. In our domain, the main drivers are the physics of galaxies at high redshifts, the first star-forming objects at the limit of the dark age, and the understanding of the star formation history of the Universe.

The submillimeter and millimeter domains are privileged for the exploration of galaxies at high redshifts, due to the negative K-correction: the peak of the dust emission at 60-100 microns is red-shifted in these domains. With the current instrumentation, blind surveys in blank fields have already discovered of the order of one object per square arcmin in the continuum, with large limitations caused by confusion. In the molecular lines, where the K-correction is not so favorable, it has been difficult to detect the objects so far, except when they are starbursting monsters or gravitationally lensed (about two dozen galaxies have been detected).

ALMA will bring more than one order of magnitude improvement in this area and will not be affected by confusion. More normal star-forming objects will be detected, in particular those enshrouded in dust, so the instrument will be complementary to future planned optical and near-infrared facilities, such as JWST and the ELTs. The high sensitivity of ALMA will allow the detection of non-ULIRG objects, such as the 'Lyman-Break Galaxies', not yet detected in the millimeter. The frequency of these objects is of the order of 150 per square arcmin at $z = 2.5 - 3.5$, which will allow the detection of about 100 times more submillimeter sources than seen today. In addition, a new population of (highly-attenuated) objects not observed today at optical wavelengths are expected to be discovered in (sub)millimeter surveys.

Optical studies are known to miss a substantial fraction of the star formation activity in the high-redshift Universe because the most active starburst galaxies (which were about 10 times more numerous at $z = 1$ than today) tend to be highly obscured by dust. In the infrared domain, a main problem encountered by current surveys at high redshift is that of source identification. This is related to the low spatial resolution (of the order of 15"), which is also source of confusion. The next spatial instruments (such Herschel) will also suffer from confusion, but the high spatial resolution of ALMA (better than 0.1") will solve this problem. Another way to identify distant sources is to obtain redshifts from molecular millimetric lines. This will be possible with wide-band receivers, such as those considered today for the 'redshift machines' on the Large Millimeter Telescope (LMT), the Green Bank Telescope (GBT) and, with more sensitivity, ALMA.

Present submillimeter surveys are starting to allow the first studies of the evolution of the cosmic star formation rate with redshift, and of how much this rate is underestimated by optical surveys. After many controversies and debates, the dust-attenuation correction to apply to ultraviolet and visible data appears to be converging toward a factor about 3, the star formation rate decreasing slightly at high redshift after a maximum around $z = 2$. This finding is also compatible with current constraints of the cosmic infrared background (Section III.3.2). We note that, since most of the energy produced in high-redshift starbursts is reprocessed by dust, submillimeter sources can already account for a large fraction (between 10 and 60%) of the cosmic infrared background. An open question is to determine the relative contributions by starbursts and active galactic nuclei (AGNs) to dust heating in these galaxies. The fact that the sources responsible for the X-ray background are not the same as those dominating the cosmic infrared background does not exclude the possibility that the latter may be mainly heated by obscured AGNs. These questions will be addressed with ALMA, which will be able to resolve the sources of the cosmic infrared background and determine their physics.

Other important issues where ALMA is expected to make breakthroughs are:

- molecular line absorptions: many more continuum sources will be detected in the millimeter and submillimeter domains with the enhanced sensitivity of ALMA; probing high column densities of gas along the lines of sight to remote quasars will allow the exploration of the fate of baryons as a function of z, high-redshift chemistry, etc.;
- the detection of individual molecular clouds in many nearby galaxies: this will allow, through application of the virial theorem, a more accurate determination of the ill-known CO/H_2 conversion factor;
- the detection of CO at large distances from the center in nearby galaxies, and the exploration of the outer parts of galaxies;
- the dynamics of galaxy centers at high resolution, and the role of AGNs. CO will be used as only tracer where HI is deficient (nuclear bars and spirals);
- the detection of the molecular torus expected in AGN unification theories;
- the exploration of the rotation curves and dark-matter content of galaxies as a function of redshift;
- the detection of galaxy clusters through the Sunyaev-Zel'dovich effect, and the detection of secondary anisotropies of the CMB;
- dwarf galaxies, and molecular gas outside galaxies (tidal dwarf galaxies, star formation complexes)

In summary, ALMA will bring considerable progress in our understanding of the molecular component and star formation efficiency in nearby galaxies. One of the main drivers is also to open a window on the formation of galaxies: the cosmic star formation history, the efficiency to make stars and energy from baryons in mergers as a function of redshift, the history of chemical enrichment, the processes driving the formation of bulges and disks, etc. The submillimeter and millimeter domains are a necessary complement to studies at other wavelengths (in particular, the visible domain, since starbursting galaxies suffer significant obscuration).

The French community is very active in the preparation of ALMA, especially through precursor observations with the IRAM instruments, the Plateau-de-Bure interferometer being the most sensitive one in the millimeter domain before ALMA. In addition, the IRAM headquarters in Grenoble is one of the European ALMA regional centers (ARC). The groups in Grenoble, Bordeaux and Paris (LERMA) are the most active in participating in the instrumental (e.g. correlators) and software (reduction pipeline, data models, configuration) developments for ALMA.

IV.1.5 Cosmology and galaxies with LOFAR

Michel Tagger, LPCE Orléans

LOFAR (http://www.lofar.org) is the first of a new generation of low-frequency radio instruments, which will culminate with SKA (the Square Kilometer Array) by 2015-2020. LOFAR explores the lowest radio frequency band (30-240 MHz) permitted by ionospheric absorption. It will provide an improvement by one or two orders of magnitude, in frequency and resolution, over existing instruments. Initially a Dutch instrument, LOFAR is now extending across Europe with stations planned in Germany, the UK, Poland, Ukraine, Sweden, and one in France in Nançay. With baselines of around $\sim 1000\,\mathrm{km}$, this extended network will permit the achievement of arcsecond resolution. LOFAR will be commissioned in 2009. The French scientific community has formed the FLOW consortium (http://www.lesia.obspm.fr/plasma/LOFAR2006/FLOW_Science_Case_r.pdf) to purchase a station and coordinate its contribution to the scientific exploitation of LOFAR.

LOFAR consists in thousands (up to 10,000) of relatively simple antennae, grouped in tens of stations with each 96 low-frequency (30-80 MHz) antennae and 96 tiles of 16 high-frequency (120-240 MHz) antennae, and a local electronic back-end. Each station is linked by a very-high-speed (3Gb/s) network to a central supercomputer, acting as correlator, which concentrates the complexity and originality of the instrument. Each antenna sees the whole sky and the pointing is purely numerical, permitting up to 8 simultaneous observing programs. The resulting flexibility will permit various observing modes, combining interferometry and phased arrays, optimized for the different scientific programs of LOFAR.

The scientific exploitation of LOFAR is organized primarily into 'key science projects' to develop the initial observing programs and corresponding observing modes and software tools. LOFAR will then rapidly turn to open observing programs. The key science projects focus on the epoch of reionization, surveys, transients, high-energy cosmic rays, cosmic magnetism and solar physics. The purchase and operation of the LOFAR station in Nançay (with support from INSU, Observatoire de Paris, Programme National Astroparticules and P2I) gives French researchers access to these key science projects, several of which are central to PNCG science:

- Epoch of reionization: with a survey of the hydrogen 21 cm line at redhift $z > 6$, LOFAR will observe the period of reionization of the Universe by the first stars and quasars, which recent observations place at $6.5 \lesssim z \lesssim 11$. The French participation to this key science project will consist in the combination of Planck and LOFAR data (a MoU is in preparation between the LOFAR and Planck collaborations).

- Surveys: Extragalactic surveys with LOFAR will map the diffuse radio emission from galaxy clusters with unprecedented resolution and sensitivity. This diffuse radio emission is due to the presence of relativistic particles and weak magnetic fields in the intra-cluster volume. The influence of this (non-thermal) component on the thermodynamical evolution and X-ray mass estimates of galaxy clusters is still unknown. Answering these questions requires an understanding of the origin and energetics of relativistic particles and intra-cluster magnetic fields. For this, joint X-ray and radio observations will be essential. We note that the study of starburst galaxies in clusters and their evolution as a function of environment is another main goal of the LOFAR 'surveys' key project.

The observation of pulsars is also part of the 'surveys' key project. France (in collaboration with Ukraine and Austria) has developed a concept of LOFAR Super Station, which would strongly increase the number of new pulsars expected to be discovered with LOFAR. The ultra-precise timing of these pulsars with the Nançay decimetric radiotelescope and other large instruments might help detect gravitational waves of primordial origin.

- Cosmic magnetism: observation at high sensitivity and angular resolution of the polarized synchrotron radiation and of Faraday rotation in the interstellar medium and nearby galaxies will trace the structure of the magnetic field and of interstellar turbulence. French scientists also participate in this key science project.

IV.2 Next-generation facilities

IV.2.1 GAIA

Catherine Turon & Frédéric Arenou, Observatoire de Paris, GEPI

How was our Galaxy assembled? How, when and by which processes was each of its components shaped? What were and what are today the interactions between these components? How will the Galaxy evolve in the future? We still have only fragmentary answers to all these questions. Very large, statistically significant samples are needed to firmly establish the relations between the ages, element abundances, kinematics and dynamics of stars of the various Galactic populations. GAIA, the next cornerstone mission of the European Space Agency (ESA), scheduled for launch by the end of 2011, will measure the positions, distances, space motions, and many physical characteristics of a billion objects in our Galaxy and in its nearest neighbors in the Local Group. The volume and quality of data that GAIA will provide will revolutionize the study of the Galaxy even more than Hipparcos revolutionized the study of the solar neighborhood.

The GAIA mission

A unique expertise in space astrometry has been acquired within Europe with Hipparcos, and the GAIA mission, much more ambitious, is now being developed. GAIA will have a

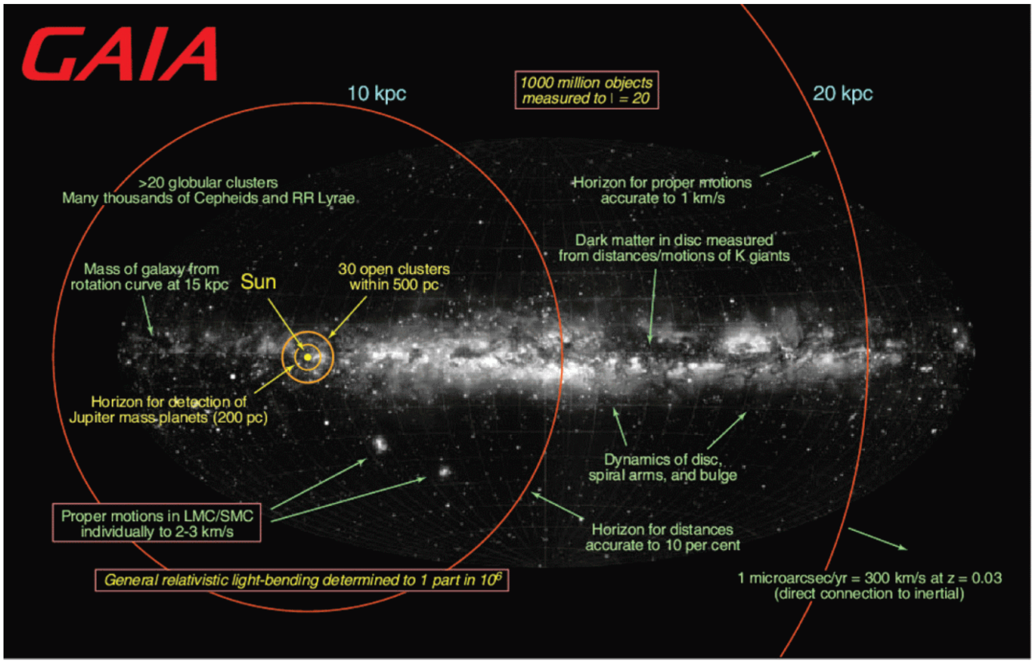

Figure IV.36: Schematic diagram showing the various distances out to which GAIA will contribute to our knowledge of the Galaxy. Credit: (background) Lund Observatory.

fantastic discovery potential [345, 556, 436]: it will perform a complete census of all objects down to magnitude $V = 20$ and observe them with parallel astrometric, spectroscopic and photometric measurements of extreme accuracy. As examples, a few numbers can give a flavor of the giant step which will be achieved with GAIA: thanks to an unprecedented astrometric accuracy of $10 - 20\,\mu$arcsec at $V = 15$ ($11\,\mu$arcsec yr^{-1} on proper motions, $21\,\mu$arcsec on trigonometric parallaxes), and even better for the stars brighter than $V = 13$ (5 and 8 respectively), some 10 million stars will have their distances known to 1%, 100 million to 10% (to be compared with 21,000 with Hipparcos); the photometric accuracy of each of the ~ 80 observations of a star brighter than $V = 15$ will be of a few millimagnitudes in several colors; the radial velocity of stars brighter than 15 will be measured to better than $1\,\mathrm{km\,s^{-1}}$; for stars brighter than $V = 16$, the effective temperature will be obtained to better than 5%, their gravity ($\log g$) to $0.2 - 0.3$, their metallicity to $0.2 - 0.4$ (Fig. IV.36).

GAIA data processing and analysis

The GAIA data processing and analysis is a challenge [387], because of the important volume of data (about 1 petabyte coming from the 700 billion astrometric observations, 150 billion spectrophotometric observations, 15 billion spectra and the provisional raw processing data), the diversity of observed objects (stars – single, double, multiple, variable, with planets, with emission, etc; Solar-system objects; galaxies, quasars), the multiplicity of observations per object ($\sim$ 80 along the 5 years of mission), the huge focal plane (102 CCDs, i.e. about a billion pixels), and the connectivity between the different kinds of data (the astrometric accuracy requires the knowledge of the color and radial velocity of the observed object, the radial velocity determination requires the knowledge of the position and color, etc.). The total amount of required CPU is estimated to 10^{21} Flops. Thirty years would be necessary to achieve the processing if only one second of CPU were dedicated to each object!

A Consortium of astronomy institutes (DPAC, for Data Processing and Analysis Consortium) has been charged by ESA to process the GAIA data. The French community is deeply involved in this Consortium: the chair is François Mignard (OCA), 5 other French astronomers are leaders or co-leaders of one of the 'Coordination Units' (CU) of the Consortium (among 8 CUs), and CNES is one of the two major processing centers (after ESAC). Moreover, France is the first contributor to DPAC with more than 70 scientists involved, equivalent to 45 FTE, which represents about 25% of the total manpower.

GAIA data exploitation

The exploitation of GAIA data is another challenge: new methods will have to be developed, theoretical models adapted and new observations planned to take the greatest benefit of this mass of data. Within the framework of this 'Programme National de Cosmologie et Galaxies', GAIA data will notably contribute by: the characterization of all stellar populations, both in the Galaxy itself and in the brightest parts of the nearest galaxies of the Local Group; the systematic selection of specific objects (very metal poor stars, stellar groups and streams, variable stars, double stars or stars with planets, etc.); the distinction between foreground Galactic stars and bright stars in nearby dwarf spheroidal galaxies; the systematic detection of relativistic effects; etc. Major improvements are expected in several domains: complete census of a large proportion of the Galaxy; dynamical and chemical evolution of the Galaxy; dynamics of the Galaxy and the Local Group, with a much better knowledge of the distribution of the dark matter at small and large scales; distance-scale determination, using various distance candles, and impact on H_0; determination of the parameterized post-Newtonian (PPN) parameter γ (which characterizes the amount of space curvature produced by unit rest mass); etc. Finally, the Galaxy will be described in such exquisite detail that it will be possible to use it as a template for the interpretation of observations of external galaxies.

An important aspect of the preparation of the exploitation of GAIA data is to plan ground-based complementary observations and possibly the design of specific dedicated instruments to complement GAIA data: follow-up high spectral resolution observations of selected star samples or medium spectral resolution observations of stars fainter than 16.5 and not observed by the GAIA spectrometer.

The French community is very actively involved in the preparation of GAIA. It is essential to now take steps to be at the forefront of the exploitation of these unique data. This is one of the goals of the INSU 'Action Spécifique GAIA', created mid-2007. In this framework, preparatory actions are being taken, such as the organization of dedicated workshops to enhance theoretical and modeling activities and complementary ground-based observations. The other essential aspect is to have the required manpower, at the right moment, to be in a position to have a major impact in the exploitation of GAIA data.

IV.2.2 The James Webb Space Telescope (JWST)

Stéphane Charlot, IAP

The James Webb Space Telescope (JWST) is a major collaborative project between ESA, NASA and the Canadian Space Agency (CSA). The 6.5 meter diameter mirror of JWST will make the collecting area of the telescope 7 times larger than that of its predecessor, the highly successful HST. JWST will operate at wavelengths in the range from 0.6 to 28 microns. It will be placed at the Sun-Earth L2 Lagrange point to ensure efficient shielding of infrared emission from the Sun, Earth and Moon, enabling the telescope to radiatively cool to a cryogenic operating temperature of roughly 40 K. JWST, which is currently scheduled for launch by an Ariane 5 rocket in 2013, will operate for a minimum of 5 years and up to possibly 10 years. This will be the largest telescope ever in space.

The infrared capabilities and large collecting area of JWST will allow much deeper observations of the early Universe than ever possible with HST. The capabilities of JWST in this area are exemplified by the formal *Mission Success Criteria*. One of these is to measure the space density of galaxies to a $2\,\mu$m flux density limit of 1.0×10^{-34}Wm^{-2}Hz^{-1} via imaging within the 0.6 to $28\,\mu$m spectral band and to determine how this density varies as a function of age and evolutionary state. Another criterion is to measure the spectra of at least 2500 galaxies with spectral resolutions of approximately 100 (over 0.6 to $5\,\mu$m) and 1000 (over 1 to $5\,\mu$m) and to a $2\,\mu$m emission line flux limit of 5.2×10^{-22}Wm^{-2} to enable determinations of redshift, metallicity, star formation rate, and ionization state of the intergalactic medium. Studies to such depths will help us improve considerably our understanding of the formation and early evolution of galaxies.

Overall, the JWST primary scientific mission has 4 main components:

- *The end of the dark age, first light and re-ionization*: seeks to identify the first bright objects that formed in the early Universe, and follow the ionization history.
- *Assembly of galaxies*: explores how galaxies and dark matter, including gas, stars, metals, physical structures (like spiral arms) and active nuclei evolved to the present day.
- *The birth of stars and protoplanetary systems*: focuses on the birth and early development of stars and the formation of planets.

- *Planetary systems and the origins of life*: studies the physical and chemical properties of solar systems (including our own) and where the building blocks of life may be present.

To achieve these goals, the telescope will carry a suite of 4 science instruments:

- *NIRCam (Near InfraRed Camera)* is a wide-field ($2.2' \times 4.4'$) infrared imager with a spectral coverage from 0.6 to 5 microns. NIRCam is being built by a team led by the University of Arizona (PI Marcia Rieke). The industrial partner is Lockheed-Martin's Advanced Technology Center.

- *NIRSpec (Near InfraRed Spectrograph)* is an infrared spectrograph covering the same wavelength range as NIRCam (0.6 to 5 μm). NIRSpec is being built by ESA/ESTEC (PI Peter Jakobsen), with EADS Astrium (Germany) as the prime contractor. NIRSpec will be capable of observing simultaneously more than 100 sources over a field-of-view of $3.4' \times 3.4'$. The primary goal for this instrument is to enable large surveys of faint galaxies ($1 < z < 5$). NIRSpec provides 3 observing modes: a low-resolution mode ($R \sim 100$) using a prism in the range $0.6 - 5\,\mu$m, an $R \sim 1000$ multi-object mode and an $R \sim 2700$ integral-field-unit and long-slit spectroscopy mode over $1.0 - 5.0\,\mu$m.

- *MIRI (Mid InfraRed Instrument)* contains both a mid-IR camera ($1.4' \times 1.9'$) and spectrograph ($R \sim 2000$) with a spectral range from 5 to 28 μm. MIRI is being developed as a 50/50 collaboration between NASA and a consortium of European countries, including France (co-PIs George Rieke, University of Arizona, and Gillian Wright, Edinburgh).

- *FGS (Fine Guidance Sensor)*, led by CSA (PI John Hutchings, Victoria), is used to stabilize the line-of-sight of the observatory during science observations. It also includes a tunable filter module for astronomical narrow-band imaging in the 1.5 to 5 μm wavelength range.

France involvement in JWST

CRAL (Lyon) is now the only European institute directly involved in NIRSpec, through a contract with EADS-Astrium (the prime contractor for NIRSpec under ESA funding). CRAL is responsible for the performance and calibration aspects in the core engineering team of EADS-Astrium. To this goal, CRAL scientists are developing the NIRSpec instrument performance simulator software. CRAL is also deeply involved in the preparation and execution of the cryogenic calibration and characterization campaigns of the instrument.

France is also involved in MIRI, for which it has focused its efforts on the imager MIRIM. Under contract with ESA, CNES assumes the overall responsibility of the French participation in MIRIM. CNES committed CEA, through the Service d'Astrophysique (SAp) of Dapnia, to lead the technical aspects related to construction of MIRIM. SAp also assumes

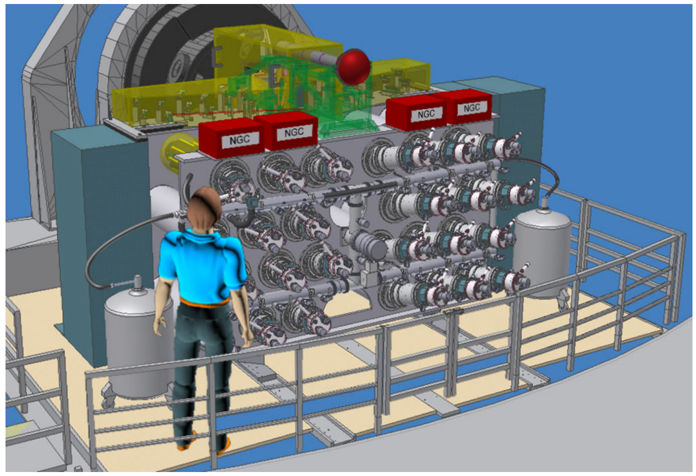

Figure IV.37: General view of MUSE at the VLT Nasmyth Platform.

the scientific leadership of the French contribution to MIRIM, which includes 4 laboratories: Dapnia (CEA-Saclay), LESIA (Paris Observatory), IAS (Orsay) and LAM (Marseille).

IV.2.3 The Multi-Unit Spectroscopic Explorer (MUSE)

Roland Bacon, CRAL - Observatoire de Lyon

The Multi-Unit Spectroscopic Explorer MUSE is one of the second generation VLT instruments. MUSE is a wide-field optical integral field spectrograph operating in the visible wavelength range with improved spatial resolution. The MUSE Consortium consists of groups at Lyon (PI institute, CRAL), Gottingen (IAG), Potsdam (AIP), Leiden (NOVA), Toulouse (LATT), Zurich (ETH) and ESO. The project is currently in its final design phase. Manufacturing, assembly and integration will start after the Final Design Review which is foreseen for the Spring of 2009. The Preliminary acceptance in Europe is scheduled for mid-2011, and the instrument shall be in operation at Paranal in 2012.

Imagers and spectrographs are the most common tools of optical astronomers. In most cases, astronomical observations start with imaging surveys in order to find the interesting targets and then switch to spectrographic observations in order to study the physical and/or dynamical properties of the selected object. An alternative to this classical approach is to perform simultaneously imaging and spectroscopy. The idea is to merge into one instrument the best of the two capabilities: from the imaging world its field of view and high spatial resolution; and from the spectrograph's world its high resolving power and large spectral range. Such an instrument will overcome the difficulty inherent to the classical method. Because there is no longer the need to pre-select the sources, one can even detect objects that would not have been found or pre-selected in the pre-imaging observations. In the most extreme case, such as object with very faint continuum but relatively bright emission lines, the objects can only be detected with this instrument, however not with direct imaging techniques.

In this context, the MUSE concept has been designed to achieve 3D deep field capability using an integral field spectrograph with a field of view and a simultaneous spectral range large enough to allow source detection. MUSE will also benefit from an improved spatial resolution thanks to the second-generation adaptive optics system module for MUSE (GALACSI), which is part of the VLT Adaptive Optics Facility. Moreover, the improved spatial resolution will be achieved for a large sky coverage (including galactic pole) and for a wide range of seeing conditions thanks to the four laser guide stars. Given the expected very long integration time (up to 80 hours), we have designed the instrument to be be very stable and to minimize the systematics. Special attention has also been given to achieve a high throughput and maximize the open science shutter time.

MUSE is composed of 24 identical modules, each of which consists of an advanced slicer, a spectrograph and a detector vessel with a $(4\text{k})^2$ detector. A series of fore-optics and splitting and relay optics is used to derotate and split the square field of view into 24 sub-fields. These are placed on the Nasmyth platform between the VLT Nasmyth focal plane and the 24 IFU modules. Observational parameters are given in Table IV.3.

The most challenging scientific and technical application, and the most important driver for the instrument design, is the study of the progenitors of normal nearby galaxies out to redshifts $z > 6$. These systems are extremely faint and can be detected only through their Lyα emission. MUSE will be able to detect these in large numbers ($\approx 15,000$) through a set of nested surveys of different areas and depths. The deepest survey will require very long integration times (80 hrs each field) to reach a limiting flux of 3.9×10^{-19} erg s^{-1}cm^{-2}, a factor of 100 times better than what is currently achieved with narrow-band imaging. These surveys will simultaneously address the following science goals: (1) study of intrinsically faint galaxies at high redshift, including the determination of luminosity functions and clustering properties; (2) detection of Lyα emission out to the epoch of reionization, study of the cosmic web, and determination of the nature of reionization; (3) study of the physics of Lyman-break galaxies, including their winds and feedback to the intergalactic medium; (4) spatially resolved spectroscopy of luminous distant galaxies, including lensed objects; (5) search for late-forming population III objects; (6) study of active galactic nuclei at intermediate and high redshifts; (7) mapping of the growth of dark-matter halos; (8) identification of very faint sources detected in surveys at other wavelengths; and (9) serendipitous discovery of new classes of objects.

Multi-wavelength coverage of the same fields by MUSE, ALMA, and JWST will provide nearly all the measurements needed to answer the key questions of galaxy formation.

At lower redshifts, MUSE will provide exquisite 2D maps of the kinematics and stellar populations of normal, starburst, interacting and active galaxies in all environments, probing sub-kpc scales out to well beyond the Coma cluster. These will reveal the internal substructure, uncovering the fossil record of their formation, and probe the relationship

Table IV.3: MUSE top-level parameters

Focus	Nasmyth B UT4
Deformable Secondary Mirror	1170 actuators
Laser guide stars	4×5–10 Watts
Instrument	Integral Field Spectrograph
Number of IFU units	24
Detectors	4k $\times$ 4k Deep depletion CCD
Simultaneous spectral range (nominal)	$480 - 930$ nm
Simultaneous spectral range (extended)	$465 - 930$ nm
Resolving Power	1750@465 nm, 3750@930 nm
Datacube Size	1570 MB
Wide Field Mode	
Field of View	1×1 arcmin^2
Spatial Sampling	0.2×0.2 arcsec^2
Spectra/Exposure	90,000
Sky Coverage in AO	70% @ galactic pole
Sky Coverage in AO	99% @ galactic equator
AO Energy gain wrt seeing	$\times 2$
Narrow Field Mode	
Field of View	7.5×7.5 arcsec^2
Spatial Sampling	25×25 milliarcsec^2
Spectra/Exposure	90,000
Spatial resolution	5–10% Strehl Ratio @ 650 nm

between super massive black holes and their host galaxy.

MUSE will also enable massive spectroscopy of the resolved stellar populations in the nearest galaxies, outperforming current capabilities by factors of over 100. This will revolutionize our understanding of stellar populations, provide a key complement to GAIA studies of the Galaxy, and a preview of what will be possible with an ELT.

In addition to Wide-Field Mode science, Narrow-Field Mode science is dedicated to detailed studies of single objects at very high spatial resolution. For example, MUSE offers unique capabilities to study supermassive black holes. During a galaxy merger, supermassive black holes are expected to sink toward the bottom of the potential well, forming binary systems which 'scour out' lower-density cores in the central regions of the remnant. Such processes should leave detectable signatures in the environment of the supermassive black hole. Likewise, accretion of mass onto supermassive black holes should trigger activity and feedback to the local regions and beyond. However, observationally, very little is known about this environment, both in terms of stellar orbital structure and chemical enrichment history. MUSE will help investigate this and other important physical processes of galaxy

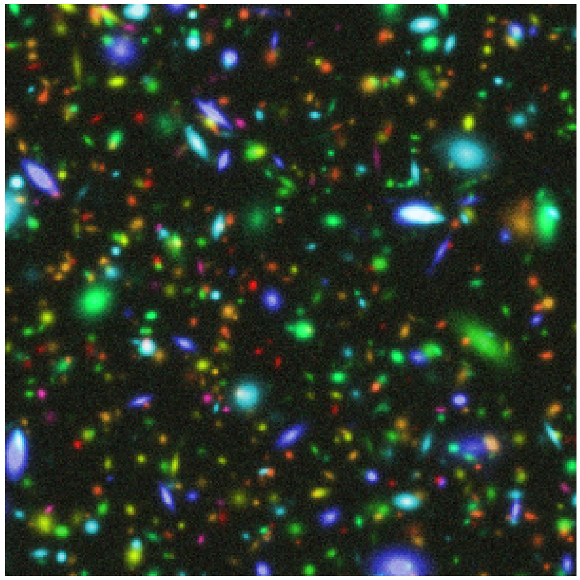

Figure IV.38: A simulated deep-field MUSE exposure. Galaxies are colored according to redshift.

formation.

IV.2.4 Optical-Infrared Interferometry

Guy Perrin, Observatoire de Paris, LESIA

General characteristics of Interferometry in the optical and infrared

Interferometry has long been dubbed 'stellar interferometry' because it was only used to observe stars. The reason for this is that it was possible to find very bright stars, while fainter objects were not accessible. In fact, interferometers measure spatial coherence, which is easily degraded by atmospheric turbulence. Telescope apertures were therefore stopped down to a single atmospheric coherent patch, in practice up to 0.5–1.0 meter in the near infrared. Another reason for poor sensitivity is the complexity of beam transportation and the poor quality of optical trains generally used in past interferometers because of limited budgets. The best sensitivity of interferometers was $K = 6$ in the near-infrared.

Part of the issue was solved with the advent of adaptive optics which restores the spatial coherence of lightwaves over a telescope aperture by flattening the wavefront in real time. This has allowed the efficient use of the VLT Unit Telescopes (UTs) and, in the same vein, the Keck telescopes. A gain of 5 magnitudes has then been achieved thanks to the larger collecting area ($K = 11$ achieved by VLTI). In parallel, work is on-going to improve the throughput of interferometers. The total transmission of VLTI 2nd generation instruments (from the UTs pupil down to the detector, quantum efficiency included) will be ten times better than previous-generation interferometers. Use of single-mode fibers could potentially allow a gain of one order of magnitude, as shown by the OHANA instrument [435].

In the near future, interferometers sensitivity will still improve thanks to off-axis fringe tracking, which allows integration for minutes up to hours, as with any other astronomical instrument. The too-short atmospheric coherence time (a few milliseconds) would not allow to do so otherwise. This is an important feature of VLTI2 opening the way to still fainter magnitudes, $K = 19 - 20$.

Sensitivity is one part of the problem. Spatial resolution is another one. The hearts of galaxies are angularly much smaller than most nearby stars, and baselines of a few 100 m up to a kilometer or more are required. Hectometric interferometers are readily available. OHANA is exploring the possibility to combine large telescopes with single-mode fibers atop Mauna Kea to build a large kilometric array. Future arrays will provide access to this range of baselines to reach resolutions of a few 100 μarcsec.

Breakthrough in the observation of galaxies with Keck and VLTI

Use of interferometry for extragalactic science is very recent. The very first success was achieved with the Keck interferometer in 2003 with the observation of the nucleus of the Seyfert 1 galaxy NGC 4151 in the K band [532]. These first observations left the core of the galaxy unresolved, as one would expect if the unified scheme of AGNs were correct (whereby type-1 and type-2 AGN are drawn from the same parent population of galaxies and differ only in the orientation of the observerÍs line-of-sight). Shortly after, VLTI observed the Seyfert 2 galaxy NGC 1068 both at near and mid-infrared wavelengths. The MIDI observations (N band) fully resolved and identified the putative dusty torus with a direct measurement of temperature (200–300 K) and size (2 pc) for the first time [293, 448]. The torus was also fully resolved by the VINCI K-band observations, but the inner core was not and an upper limit (0.4 pc) for the size of the inner emission was derived [582].

Since then, MIDI has observed a total of 8 AGNs for which the size of dust distributions could be determined. Sizes range between 1 and 10 pc, and the warm dust structures detected have been shown to be heated by the central AGN engines [552].

Interferometers have contributed to establish the validity of the unified scheme of AGNs by showing direct evidence of the existence of the dust torus. The exact structure of the dust distribution is still questionable. Along with the proposal that dust is arranged in clumps to explain the relative compactness of dust distributions, some authors [199] have questioned the doughnut paradigm and proposed a continuous structure extending from the central accreting region outward to the cooler dust regions. Still better interferometric data will most certainly help tackle this issue.

Prospects with VLTI and with future projects

✰ The second generation of VLTI instruments

Only two AGNs have been observed in the K band so far, NGC 1068 and 4151. This is essentially a sensitivity issue. The VLTI VINCI instrument was unfortunately decommissioned despite its high sensitivity and its ability to perform observations complementary to the MIDI ones. In any case, MIDI and VINCI could only provide 2-telescope data. The second generation of instruments will combine up to 4 beams and will be able to take images of these complex sources. The follower of MIDI, MATISSE, will have a broader spectral coverage from the L band up to the N band and possibly the Q band. Given the success of MIDI with AGNs, one can expect still better results, as MATISSE images will probe the structure of dust distributions. In addition, the extended spectral coverage will allow further physical and chemical studies of the dust.

The VSI and GRAVITY near-infrared imagers will be at least as sensitive as VINCI in the short-exposure mode. Off-axis fringe tracking will enable observation of still fainter objects when a nearby reference is available. Although the resolution of VLTI in the near-infrared may still be too small to resolve 'broad-line regions' and accretion disks, a lot is to be expected from AGN images, as the intermediate region between the torus and the broal-line region is not really well understood and quite complex. Other breakthroughs are therefore to be expected with this next generation of powerful imagers.

The design of the GRAVITY instrument was primarily driven by the observation of the Galactic center, our closest AGN. GRAVITY will use 4 UTs and will benefit from the observation of a reference star to stabilize the fringes (one of the IRS 16 complex in the case of the Galactic Center). The reference source will also be used to perform very precise astrometric measurements (10 μarcsecs or 1 Schwarzschild radius) of the region of the supermassive black hole, with the goal to measure the positions of stars orbiting near the black hole and the positions of the flares possibly occurring on the last stable orbit at 3 Schwarzschild radii. In this field, the goals of GRAVITY are to understand the nature of the flares and to study general relativity in the strong-field regime. One can think of the performance of such an instrument when applied to other more distant AGNs. Beyond imaging, astrometry of the cores will provide data to dynamically measure the black-hole masses and draw a still better picture of the AGN phenomenon.

✰ Future large interferometric arrays

Although it is a fantastic instrument, VLTI has a limited angular resolution to study AGNs. The resolution of broad-line regions requires baselines of the order of a kilometer to a few kilometers. This is the goal of future interferometric arrays, of which the design is still in infancy. Brain-storming activities have started in Europe and across the Atlantic. A large American facility may be part of the plan of the next US Decadal Survey, and a collaboration with Europe could be actively sought. Europeans are also striving to get a design study funded by the European Commission.

Future arrays could be based on the ALMA model, with both very long baselines (a few kilometers) and a more compact array for larger and more extended objects. This would make the new facilities useful for extragalactic studies not only of AGNs but also other cosmological objects, including the earliest galaxies. Crowding is a difficult issue, and resolution with interferometers will play a key role, as ELTs will still suffer from limited resolution. A compact array with extended imaging capability and a few hundred meter baseline could be the solution. Once these galaxies are detected, the study of their morphologies and of detailed regions at higher spatial resolution (e.g. star-forming regions) will be of interest for cosmological models of galaxy formation. Other programs will become possible with such facilities and are still to be built, an area where PNCG will help.

IV.3 Major longer-term facilities

IV.3.1 The European Extremely Large Telescope (E-ELT)

Jean-Gabriel Cuby, Observatoire de Marseille

Introduction

The European Extremely Large Telescope (E-ELT) is the next major project for optical and near infrared ground based European astronomy. The E-ELT (figure IV.39) project envisions a 42 meter diameter filled-aperture phased telescope with an internal Adaptive Optics system. The E-ELT will operate at optical and near IR wavelengths, from 0.4 μm to 20 μm approximately and offer a scientific field of view between 5 and 10 arcminutes. Adaptive Optics operating on natural and laser Guide Stars will provide near diffraction limited angular resolution at near IR wavelengths over fields of view varying from a few arcseconds to several arcminutes. The telescope will provide for many focal stations for rapid switchover between instruments.

The E-ELT project started in 2006 following the OWL 100-m concept study and is currently in phase B at ESO. This phase will be concluded end of 2009 with a proposal for construction submitted to the ESO governing bodies. Construction could start in 2010 and the scientific operations in 2017. It is essential that the E-ELT be ready while JWST - scheduled for launch in 2013 - is still operational, and on timescales competitive with other ELT projects – namely the Thirty Meter Telescope (TMT) led by Californian institutes and Canada (possibly joined by Japan) and the Giant Magellan Telescope (GMT), 20 meters in diameter, led by a consortium of US Universities and Australia.

The completion of the E-ELT on competitive timescales has been given the highest scientific and strategic priority by ESO's governing bodies after the completion of ALMA. Approximately half of the project capital cost is available in ESO's long term budget and options for raising the other half are being actively investigated by the ESO's member states

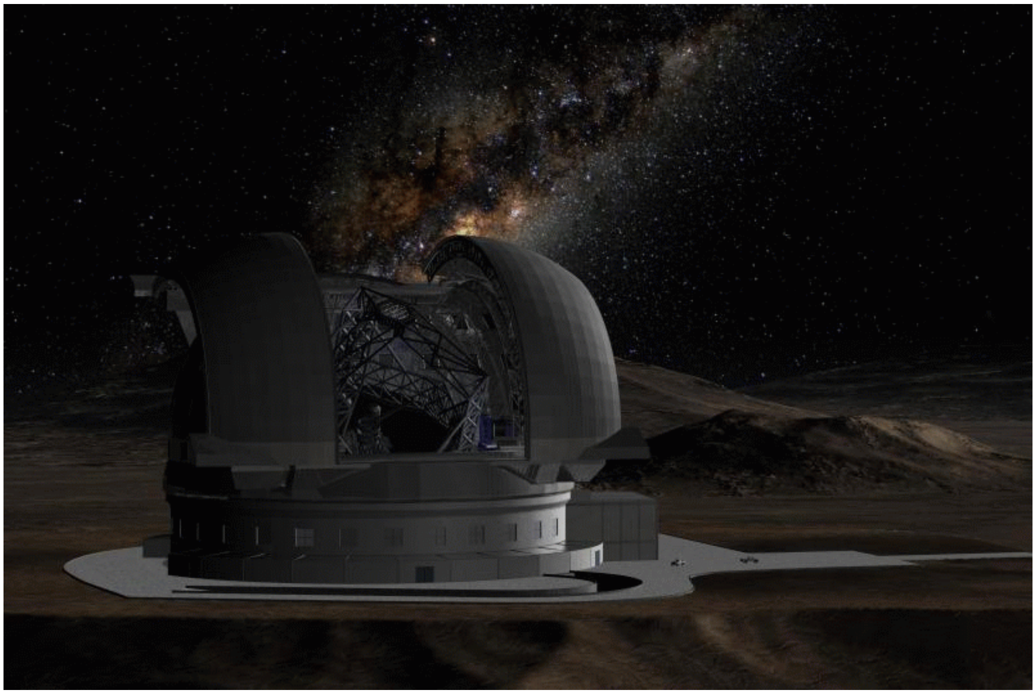

Figure IV.39: Artist's impression of the E-ELT during observations.

– possibly adding new partners. The E-ELT is in the list of Research Infrastructures identified by the European Commission (ESFRI), and is supported by FP6 and FP7 programs. The E-ELT is identified as a top priority flagship mission for future European ground-based astronomy in the 2008 ASTRONET Infrastructure Roadmap.

Science cases relevant to the PNCG

The E-ELT will contribute significantly to many science questions relevant to the PNCG. It will play a major role in tackling some of the most pressing questions in today's physics and fundamental cosmology (dark matter and dark energy, variation of the physical constants), and will allow detailed studies of the evolution of the galaxies and of the Intergalactic Medium from the dawn of the Universe to galaxies in our nearby environment. We list hereafter the science questions that the E-ELT will address, either as an essential facility or in complement to other facilities, as they are identified in the ASTRONET Science Vision:

- Measure the evolution of the dark-energy density with cosmological epoch, to search for deviations from a cosmological constant;

- Test for a consistent picture of dark matter and dark energy using independent and complementary probes, thus either verifying General Relativity or establishing the need for a replacement theory;

- Understand the astrophysics of compact objects and their progenitors, particularly the functioning of the supernova explosion and γ-ray burst mechanisms;
- Map the growth of matter density fluctuations in the early Universe, both during and after the dark age;
- Detect the first stars, black holes, and galaxies, and thus establish the nature of the objects that reionized the Universe and discern the first seeds of galaxies;
- Determine the evolution of the galaxy cluster mass function and constrain the equation of state of the dark energy;
- Make an inventory of the metal content of the Universe over cosmic time, and connect its evolution to detailed models of star formation, and the subsequent metal production and ejection from galaxies by superwinds;
- Measure the build up of gas, dust, stars, metals, magnetic fields, masses of galaxies and thus the evolution of the Hubble sequence with cosmic time and the connection between black hole and galaxy growth;
- Obtain a comprehensive census of the orbits, ages, and compositions of stars in our own Galaxy and the nearest resolved galaxies, aiming to produce a complete history of their early formation and subsequent evolution.

Instruments

ESO has launched Phase A studies for 7 instruments and 2 Adaptive Optics (AO) modules which are reported in Table IV.4. It is very encouraging that the participation of French institutes to these studies is very strong.

IV.3.2 The Square Kilometer Array radio telescope (SKA)

Wim van Driel, GEPI, Observatoire de Paris

The goal of the international SKA (Square Kilometer Array) project is the construction of a giant radio interferometer with a collecting surface of a square kilometer operational in the centimetric to metric wavelength domain (i.e., at frequencies of about 100 MHz to 25 GHz) - see the website http://www.skatelescope.org/.

The SKA will be about fifty times more sensitive than the largest radio telescopes that are presently operational at these frequencies, and its spatial resolution will be 0.1 arcsec at 21 cm. It is designed for extremely large surveys, and expected to have a field of view of at least one hundred square degrees at 21 cm wavelength - this will allow, e.g., the HI imaging

Table IV.4: Table of E-ELT instruments and Adaptive Optics (AO) modules under phase A study and participation of French institutes to these studies.

Instrument	Main Observing Mode	French Participation
EAGLE	Wide Field Multi-Integral Field, Near IR, AO assisted spectrograph	LAM, GEPI, LESIA, ONERA, CRAL
CODEX	High Resolution, High Stability Visual Spectrograph	–
EPICS	Planet Imager and Spectrograph	LAOG, LAM, FIZEAU
MICADO	Near IR Camera sampling to the Diffraction Limit	–
HARMONI	Single IFU, Wide Spectral Band Spectrograph	CRAL
METIS	Mid IR camera / spectrograph	CEA
OPTIMOS	Wide Field Multi-Object Spectrograph	LAM, GEPI
MCAO module	Multi-Conjugate AO, diffraction limited images over a field of view up to 2 arcmin	ONERA
LTAO module	Laser Tomography AO, Diffraction limited images over a field of view < 30 arcsec	ONERA, LESIA, GEPI

and redshift measurements of a billion galaxies out to a redshift of $\sim$2 and the imaging of ten billion radio continuum sources.

It is expected that the system design phase of SKA will be finished by 2012, which means that early SKA science can start in 2014 and the full-size SKA can be operational in the 0.1-10 GHz range by 2020, if the estimated 1.5 GEUR construction budget can be financed. Since it is an interferometer, its science capabilities will increase as the individual antennas of the instrument are being constructed. The choice of the SKA site (in Australia or Southern Africa) is expected in 2011.

The international community has made a first selection of scientific Key Projects for SKA, in which it is expected that the instrument will be able to make a unique and major impact as it becomes operational. To these should be added the Exploration of the Unknown, as the history of (radio) astronomy has taught us. Of specific interest to the PNCG are three Key Projects:

- *The Evolution of galaxies and large structures (the nature of Dark Energy)*: The present-day Universe is seemingly dominated by dark energy and dark matter, but mapping the normal (baryonic) content remains vital for both astrophysics - understanding how galaxies form - and astro-particle physics - inferring properties of the dark components. SKA will provide the only means of studying the cosmic evolution of HI which, alongside information on star formation from the radio continuum, is needed to understand how stars formed from gas within dark matter over-densities and the roles of gas accretion and galaxy merging. 'All-hemisphere' HI redshift surveys of a billion galaxies to z$\sim$2 are feasible with the SKA's wide field-of-view and, by measuring the galaxy power spectrum in unprecedented detail, will allow a precise studies of the equation of state of dark energy. SKA will also enable the measurement of the dark matter power spectrum using weak gravitational lensing.

- *The dark age of the Universe (the Epoch of Reionization)*: The EoR sets a fundamental benchmark in cosmic structure formation, corresponding to the formation of the first luminous objects that act to ionize the neutral intergalactic medium (IGM). Observations imply that we are finally probing into this key epoch of galaxy formation at z$\leq$6. SKA will provide critical insight into the EoR in a number of ways. First, its ability to image the neutral IGM in 21 cm HI *emission* is a truly unique probe of the process of reionization, and recognized as a fundamental step in our study of the evolution of large scale structure and cosmic reionization. Second, study of HI 21 cm absorption toward the first radio loud objects probes small to intermediate scale structure in the neutral 'cosmic web', as well as HI in the first collapsed structures. And third, the incomparable sensitivity of SKA allows for the study of the molecular gas, dust, and star formation activity in the first galaxies, as well as the radio continuum emission from the first accreting massive black holes. Such objects will be obscured at optical wavelengths due to absorption by the neutral IGM.

- *Origin and evolution of magnetism in the Universe*: With SKA, the window to the Magnetic Universe can finally be opened. The origin and evolution of magnetic fields in stars, galaxies and clusters is an open problem in astrophysics and fundamental physics, as is, e.g., their role in galaxy formation. An 'all-hemisphere' SKA survey of Faraday rotation measures towards ten billion background sources will determine the evolution of magnetized structures from redshifts $z > 3$ to the present, distinguish between different origins for seed magnetic fields in galaxies, and allow the development of a detailed model of the magnetic field geometry of the intergalactic medium and of the overall universe.

The French astronomy community is involved in a number of programs which are preparing for the SKA, such as the FP6 SKA Design Studies (SKADS), the FP6 SKADS Marie Curie Conferences and Training Courses, and the FP7 SKA Preparatory Phase PrepSKA, and it will be involved in the proposed FP7 Marie Curie Initial Training Network Path2SKA and the foreseen Aperture Array Verification Program, AAVP. France is also represented in the top-level management of the SKA project, e.g., in the European SKA Consortium and the SKA Science and Engineering Committee.

IV.3.3 The Euclid Mission

Alexandre Réfrégier, CEA/Sap

Euclid is a candidate ESA mission to map the geometry and evolution of the dark Universe with unprecedented precision. Its primary goal is to place high accuracy constraints on Dark Energy, Dark Matter and Gravity using two independent cosmological probes: weak gravitational lensing and baryon acoustic oscillations. For this purpose, Euclid will measure the shape and spectra of galaxies over the entire extragalactic sky in the visible and NIR, out to redshift 2, thus covering the period over which dark energy accelerated the universe expansion ($<$ 10 Billion years). Galaxy clusters and the Integrated Sachs-Wolf effect will be used as secondary cosmological probes. The Euclid datasets will also provide a unique legacy surveys for the study of galaxy evolution, large-scale structure, the search for high redshift objects and for various other fields of astronomy.

The baseline mission is based on a telescope with a primary mirror of 1.2 m diameter. The payload currently being considered comprises three wide field instruments (0.5 deg^2): a visible imaging channel, a NIR imaging photometric channel, and a NIR multi-object spectroscopic channel. The visible channel is used to measure the shapes of galaxies for weak lensing, with a resolution of 0.23 arcsec in a wide visible red band (R+I+Z, 0.55-0.92μm). The NIR photometric channel provides three NIR bands (Y, J, H, spanning 1.0-1.6μm) with a resolution of 0.3 arcsec. The NIR spectroscopic channel operates in the wavelength range 0.8-1.7μm at a spectral resolution $\lambda/\Delta\lambda \sim 400$ with high multiplexing of thousands of spectra taken simultaneously exploiting DMD arrays or using slitless spectroscopy.

The mission will perform a wide survey of the entire extragalactic sky (20,000 deg^2) down to 24.5 AB magnitude in the visible, thus providing 40 resolved galaxies per arcmin^2. For all galaxies, photometric redshifts are obtained from the broad-band visible and near-IR measurements. Ground-based observations in other visible bands will be employed to increase the accuracy in the photometric redshifts. For the $> 10^8$ subsample of galaxies brighter than AB magnitude 22, redshifts are also measured directly from the NIR spectroscopic channel. A deep survey will also be performed to calibrate the photometric redshifts and to search for high-redshift objects.

Project Status

The Euclid mission concept followed from two dark energy related missions which were proposed to ESAs Cosmic Vision program and were jointly selected: the Dark Universe Explorer (DUNE[462, 461]) and the SPectroscopic All-sky Cosmology Explorer (SPACE [142]). The proposal consortia were composed of scientists in 8 European countries (France, Italy, UK, Germany, Spain, Switzerland, Netherlands, Austria and Romania) and in the US, with JPL and STScI the lead US institutions for DUNE and SPACE, respectively. Initial studies in 2008 led to the recommendation of the Euclid merged concept, which is being submitted to the ESA Astronomy Working Group (AWG). Following the AWG recommendation, the formation of the consortia for the Euclid instruments will be initiated by an ESA Call for Interest expected in May 2008.

Euclid is currently undergoing a Assessment Phase study in the context of the ESA Cosmic Vision Plan and is a candidate for the first medium mission launch slot in late 2017. The Assessment Phase study is planned to end in the third quarter of 2009, at which point Euclid will undergo a selection in competition with the other medium mission candidates currently under study. If selected, Euclid will undergo a Definition Phase study lasting until 2011. The second and final decision on its implementation is then expected in late 2011.

French Contribution

France has a founding and leading role in the Euclid Mission. The DUNE project was initially developed during a CNES pre-study phase (Phase 0) in 2005 with a collaboration involving CEA/IRFU/SAP and SPP (and technical Services), IAP, LAM and IAS. The DUNE ESA proposal and consortium was led by a French PI (A. Refregier at CEA/Irfu/SAp). The LAM also played a leading role in the development of the SPACE proposal with crucial contribution in interferometric instrumentation and science. The current instrument consortia for the imaging and spectroscopic instruments of Euclid are based on the initial DUNE and SPACE proposals and thus preserve the leading role of the French laboratories involved.

The Euclid (and DUNE) project benefitted in the past from funding by CNES and PNC. It has also benefited from strategic support from the PNC through the 'Dark Energy Group' led by F. Bernardeau mandated by PNC to coordinate Dark Energy projects in France, and through invited presentations at PNG meetings. Given its dual science returns both in cosmology and galaxy studies, Euclid is ideally suited to be incorporated in the programmatics of the newly created joint PNCG program.

IV.3.4 SNAP project status 2006-2008

Anne Ealet, Observatoire de Marseille

[SNAP was a candidate for NASA's Joint Dark Energy Mission (JDEM). In the new context of international dark-energy missions, SNAP is no longer considered in the form described below. The French particle physicists and astronomers were deeply involved in the development of SNAP over the past decade.]

Scientific objectives and context

One of the most important result of the last decade is the acceleration of the expansion of the Universe. This is a consequence of the observation of supernovae at large distance, and has been verified by the cluster estimation sensitive to matter density and more recently by the WMAP measurements. The understanding of this question, often call 'the dark energy problem', is complex. The gravity itself is poorly known beyond the solar system. We don't know if general relativity holds at large scales (or even within our Galaxy), whether other large-scale unscreened forces concur in the formation of cosmic structures, and whether additional space dimensions play a role in astrophysics. Therefore 'dark energy' can be thought of as a short name for what we still don't know about the large-scale dynamics of the universe. However, we are finally aware of what we were missing. And, even more important, we have a good idea now how to search for the missing pieces of the puzzle.

The investigation of these problems will occupy central stage for many years to come in both astrophysics and fundamental physics, and is one of the priority of space agencies, as it appears clearly from recent independent assessments of NASA (report on the 'Beyond Einstein' space program) and ESA (report on the 'Cosmic Vision'space program). Following these recommendations, it is particularly encouraging that both ESA and NASA are now evaluating dark energy missions for the next decade that will probe into all three realms of cosmology, from background to non-linear effects. The European project, called *Euclid*, is a satellite proposed to study weak lensing and large scale clustering and is now under studies at ESA. The 'JDEM' (Joint Dark Energy Mission) in USA, is an agreement between DOE and NASA and has been recognized by the BEPAC committee (Beyond Einstein Probe Assessment Committee) as the first probe to be selected in 2009 and launched in 2015. The process is going on with an AO expected for the end of 2008.

The SNAP project

The SNAP project is one of the candidates selected for the advanced mission concept study for NASA and DOE's Joint Dark Energy Mission (JDEM), leaded by the Lawrence Berkeley National Laboratory (LBNL). In addition to SNAP, NASA also selected the ADEPT and DESTINY proposals to perform mission concept studies for JDEM.

The SNAP team has completed three years of R&D, reducing mission risk by enhancing readiness of all mission enabling technologies. Detector performance improvements resulting from this R&D program enable the proposed science requirements to be met with a reduced telescope aperture relative to the original SNAP concept.

French groups have been members of the consortium since the beginning and was responsible in the R&D phase of the IFU spectrometer instrument, including simulation and data reduction. The CNRS, the CNES and the PNC have supported this participation with recommendation of their advisory scientific committees. This contribution, well identified in the BEPAC report, gives the possibility to the scientific French community to participate at the project, if selected.

Thanks to the complementarity between weak lensing, supernovae and large scale galaxy distribution, the SNAP program has the potential to reconstruct the metric at first order as a function of space and time, thereby testing directly the foundations of gravity. As a by-product, SNAP will produce a map of *mass and light* in the Universe in a volume *one to two orders of magnitude* larger than we have now.

Status of the French participation

The French community has participated to 'dark energy studies' since many years. The PNC has recognized and supported the activities of French groups since 2003. A 'dark energy' group, leaded by F. Bernardeau has given many recommendations to follow a strategy and to ensure a participation of the French community to one of the future large project in space (Section III.1.2).

In the SNAP proposition, the 'Laboratoire d'Astrophysique de Marseille '(LAM-OAMP, CNRS-INSU and Université Aix-Marseille I), the 'Centre de Physique des Particules de Marseille' (CPPM, CNRS-IN2P3 et Université Aix-Marseille II) and the 'Laboratoire de Physique Nucléaire de Lyon' (IPNL,CNRS-IN2P3, Université Claude Bernard) work together, to propose an on board integral field spectrograph. This contribution is the core of the French participation and has been centered on the construction of a demonstrator and on pushing the slicer technology to a space validation level. A substantial evolution in 2008 has given the opportunity to actively engage and increase the participation of French teams in the project. Since the first proposition, the French participation has involved taking advantage of the French expertise in spectroscopy (VVDS) and photometry (CFHTLS) and in space (COSMOS); This has allowed to bring specific well recognized expertise in the project. On this basis, the French participants are regarding to propose a complete spectroscopic program for the mission including the previous IFU spectrograph for SN follow-up but also an implementation of grisms to ensure the calibration of photometric redshift on board during the deep survey. The implementation of grism in the focal plan in a wide survey will provide a full and wide spectroscopic redshift survey dedicated to BAO, LSS and other spectroscopic techniques. The main realizations during this period were:

- *The spectrograph*: The French SNAP groups have developed a full spectrograph concept, based on a slicer technology which is a LAM expertise [454]. During the R&D phase up to the end of 2007, to prove the performance of this instrument, a complete spectrograph demonstrator has been constructed and tested [29]. This demonstrator has worked in the visible in spring 2007 and in the near infrared end of 2007, thanks of the use of a last generation Rockwell HgCdTe detector, coming from the US project, for which we have developed an original readout system. Fig.IV.40 shows the experimental set up on the left and the integration inside a cryostat which is a facility of the LAM. Results are well within the specifications, showing than even in a sub sampling configuration, the instrument can be well spectrophotometric calibrated, thanks to the slicer properties. These results are under publication [129, 30]. More information can be found on http://marwww.in2p3.fr/renoir/spectro.html and on the readout system developed at Lyon in http://lyoinfo.in2p3.fr/spip.php?article15. Other activities to bring the slicer technology at the TRL6 level are undergoing in Marseille and will allow to be ready to answer the proposal end of 2008.

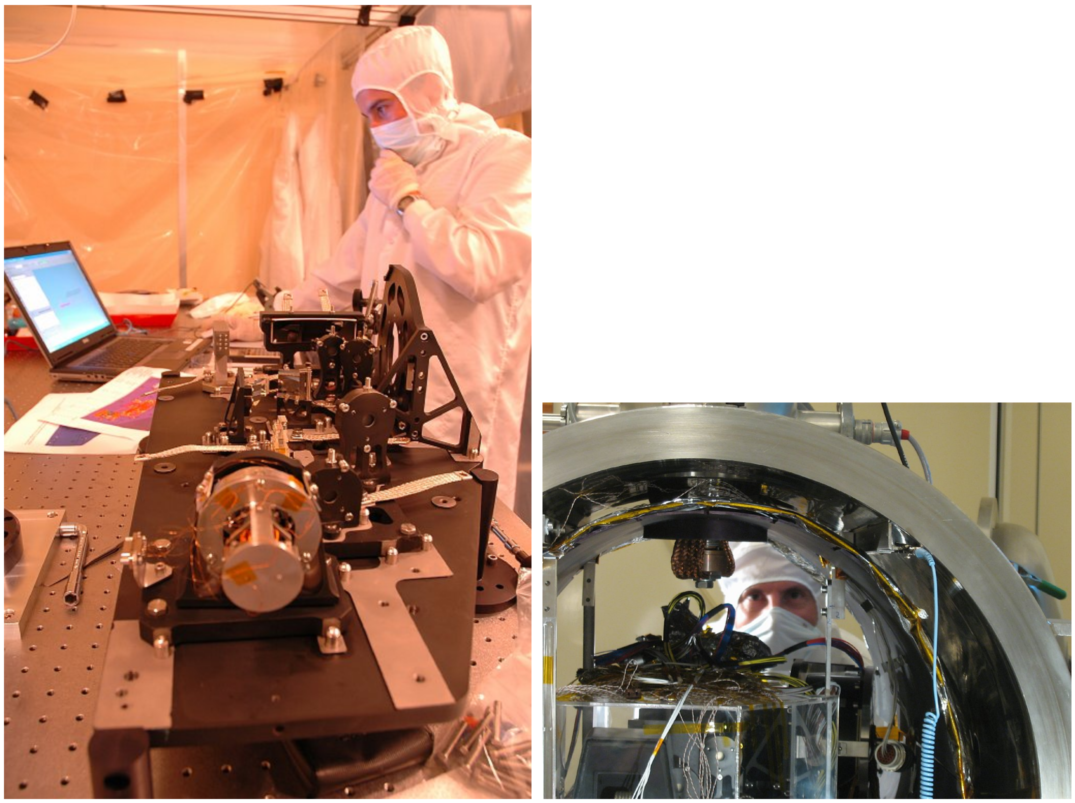

Figure IV.40: The SNAP spectrograph demonstrator setup.

- *The photometric redshift calibration and grisms implementation*: The precision of photometric redshift is fundamental for the weak lensing measurement. It has been shown that this requires a spectroscopic calibration with some thousand of representative galaxies. To do so, we need a large sky coverage, which is easier to do with grisms in the focal plan. A study with large simulation based on the COSMOS catalog has been conducted in France thanks to the expertise of French team (Ilbert et al. 2007). Currently, a strategy with grisms in the focal plan is under investigation which can brings a representative spectroscopic sample for photo z calibration and can provide also a large spectroscopic survey to increase the scientific program with LSS or BAO studies. Some expertise with French vendor to provide cold grism technology is under investigation.

- *Other activities*: During 2006-2008, we have also, thanks to the help of the CNRS,

Table IV.5: Summary of the French 2006-2008 funding for SNAP (in k€).

Expense	IN2P3/ PIAP	CNES	PNC	Total
R&D Detectors	50	10	-	60
Spectro demonstrator	80	70	20	170
Missions	60	45	26	131
Workshops	5	15	8	28
Total	195	140	54	389

CNES and PNC, organized several workshops (as 'probing the Universe with weak lensing surveys' in april 2007) and a collaboration meeting at IAP in September 2007. Meeting around cluster measurement have been organized in France and the cluster estimation for dark energy is now a French responsibility in the project. We continue in parallel to prepare tools for data combination using the GRID facility at CPPM. The PNC support has been useful to support a large number of mission to US for scientists to ensure our visibility in the collaboration.

The spectrograph demonstrator has been supported by CNES, CNRS/INSU and IN2P3 and the PIAP and PNC (see Table IV.5). IN2P3 has supported an activity on the development of a readout electronic for the infrared detectors. The PNC has supported the organization of workshops and meetings in France and has provided mission support for INSU members who are not part of the spectrograph team.

In France, the principal laboratories involved are the Laboratoire d'Astrophysique de Marseille (LAM), the Centre de Physique des particules de Marseille (CPPM), the Institut de Physique Nucléaire de Lyon (IPNL), the Centre de Recherche Astronomique de Lyon (CRAL), and APC.

IV.3.5 The International X-ray Observatory (XEUS/IXO)

Monique Arnaud, CEA

XEUS (for X-ray Evolving Universe Spectroscopy) is the next generation X-ray observatory which has been submitted to the European Space Agency in the framework of the Cosmic Vision 2015–2025 competition. It has been selected in october 2007 for an assessment study as a candidate Large Mission. XEUS aims to provide an X-ray capability comparable in sensitivity to the future generation of ground and space-based observatories such as JWST, ALMA, ELT and SKA. It will open a new window on the history of the warm/hot universe - complimenting the views of the cool universe offered by these facilities.

The prime science goals of the XEUS mission are (1) the formation and evolution of the largest structures and mass concentrations, (2) the coeval growth of galaxies and their supermassive black holes and (3) matter under extreme conditions, as found in the vicinity of black hole and in neutron stars. They correspond to key goals identified in the Cosmic Vision 2015-2025 program. For the third topic, astrophysics is used to probe fundamental physics under conditions that cannot be reach on Earth: the study of gravity in the strong field limit and the search for deviations from General Relativity and the determination of the equation of state of matter at supra-nuclear density. The two other themes directly concern astrophysical cosmology:

- *The formation and evolution of the largest structures and mass concentration*: XEUS aims to study the formation of the first gravitationally bound, dark matter dominated, low-mass cluster of galaxies, at z$\sim$2, and to trace their evolution into todays massive clusters. Furthermore, high-resolution spectroscopy of the hot intra-cluster gas will be used to investigate the evolution of metal synthesis to the present epoch. These observations will provide information on the Dark Matter and Dark Energy content of the Universe and on the complex physics governing the formation and evolution of structures in the universe, including the impact of various galaxy feedback on the intra-cluster gas. In addition, XEUS aims at detecting the missing half of the baryons in the local Universe, believed to reside in warm/hot filamentary structures observable with X-ray absorption spectroscopy. XEUS will allow the mass, temperature and density of this intergalactic medium to be characterized.
- *The coeval growth of galaxies and their supermassive black holes*: Supermassive black holes are an important constituent of the evolving Universe. The fact that practically all galaxy bulges in the local universe contain supermassive black holes, with a tight relation between black hole mass and the stellar velocity dispersion of the host galaxy, indicates a co–existence and co–evolution of stars and central black holes early in the universe. Furthermore, there is increasing (both observational and theoretical) evidence that energy feedback from AGN play a major role in the evolution of the intergalactic medium, the galaxies and ultimately in the star formation history. XEUS aims at detecting X-ray emitting black holes out to $z = 10$, to investigate their nature, to trace the evolution of AGN with cosmic time and to characterize its relation to star and galaxy formation history. In addition, it will be possible, through detailed spectroscopy, to investigate the physics of AGN outflows, which may be transporting most of the mechanical energy emerging from black holes and thus be the key 'ingredient' to link the properties of the nuclear black holes to that of the surrounding host galaxies.

XEUS, Constellation-X and IXO

XEUS was jointly studied by ESA and JAXA (Japan Aerospace Exploration Agency). In parallel NASA and the US community was studying Constellation-X, a X-ray observatory with very similar scientific objectives. In May 2008, ESA and NASA established a coordination group involving ESA, NASA and JAXA, with the intent of exploring a joint mission merging the ongoing XPachonEUS and Constellation-X efforts. In July 2008, an agreement was reached to proceed with the study of an International X-ray Observatory (IXO). This IXO study will be the input to the US Decadal Survey and to the ESA selection for the Cosmic Vision Plan and now supersedes the XEUS and Constellation-X activities.

A single merged set of top level science goals were established. The corresponding detailed science measurement requirements and IXO mission concept are not yet finalized and are objects of the study. The starting configuration for the IXO study is a mission featuring a single large X-ray mirror and an extensible optical bench with a 20-25m focal length, with an interchangeable focal plane. The study will explore how to enhance the response to high-energy X-rays. The instruments to be studied for the IXO concept include an X-ray wide field imaging spectrometer, a high spectral resolution non-dispersive X-ray spectrometer, an X-ray grating spectrometer, plus allocation for further payload elements with modest resource demands, like the High Timing Resolution Spectrometer and the X-ray polarimeter of the XEUS concept.

IV.3.6 The Large Synoptic Survey Telescope (LSST)

Pierre Antilogus, LPNHE, Paris

The Large Synoptic Survey Telescope (LSST) is proposed to be a large-area, wide-field, ground-based telescope designed to provide deep images of roughly half the optical sky every few nights. The survey will be done is 6 bands (*ugrizy*) with a cumulative depth in r of 27.5 AB mag at 5 σ (Fig IV.41).

To maximize the field of view, it is essential to control aberrations off-axis. For LSST, this is achieved with a 3-mirror optical design. Incident light is collected by the primary, which is an annulus with an outer diameter of 8.4 m, then reflected to a 3.4-m convex secondary, onto a 5-m concave tertiary, and finally into three refractive lenses in the camera. This design maintains a 0.2 arc-second point spread function (psf) across the entire optical band over a 3.5-degree diameter field of view. The camera contains a 3.2 Gigapixel focal plane array, comprised of roughly 200 4K $\times$ 4K CCD sensors, with 10 microns pixels. The sensors are deep depletion, back-illuminated devices with a highly segmented architecture that enables the entire array to be read out in 2 s. All of the CCDs, with their associated electronics, are mounted on a silicon carbide grid inside a vacuum cryostat, with an intricate thermal control system that maintains the CCDs at an operating temperature of roughly $-100°$C. The grid also contains sets of guide sensors and wavefront sensors at the edge of the field.

The telescope will be sited atop Cerro Pachon in Northern Chile, on an NSF-developed astronomical site located near the Gemini South and SOAR telescopes, not far from Cerro Tololo Inter-American Observatory. The current R&D phase will continue for 2 more years and should be followed by five years of construction. The first light is expected for 2014 and the start of the scientific program in 2015. The survey itself should run for 10 years.

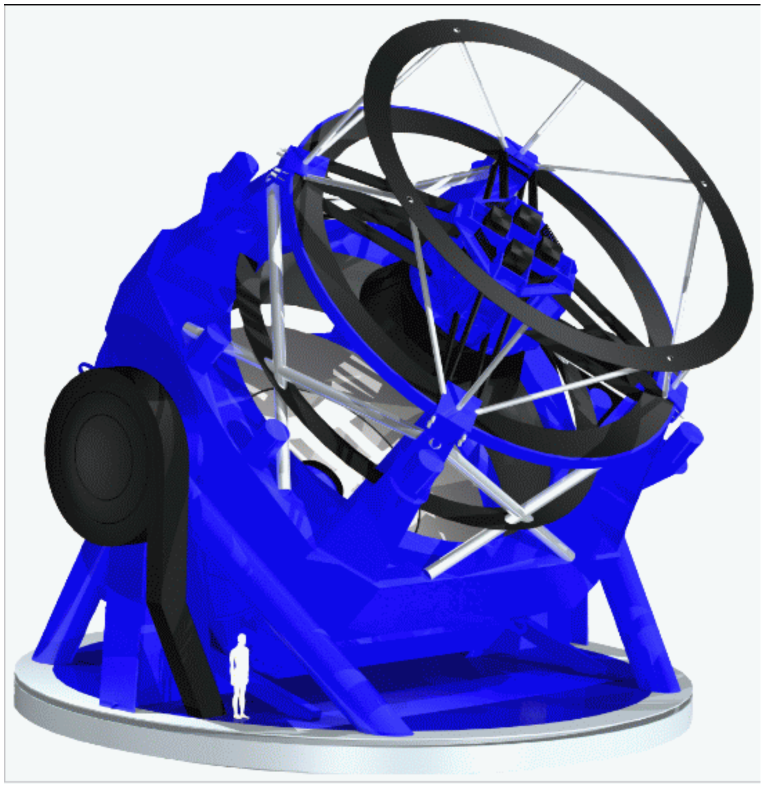

Figure IV.41: LSST instrument summary: Primary mirror 8.4 m – Secondary: 3.4 m – Tertiary: 5 m – Camera: 3.2 Gigapixel – Focal plane: 64cm diameter – **LSST survey summary:** $20,000\,\mathrm{deg}^2$, 0.2 arcsec/pixel – each $9.6\ \mathrm{deg}^2$ is visited > 300 times – observation in 6 bands ($ugriz$) – depth in r band 27.5 AB mag at 5 σ (1 image: 24.7 AB mag) – photometric precision: 0.01 mag – 50 galaxy / arcmin^2 – 2×10^9 galaxies with color redshifts.

This survey would provide a critical resource for a variety of astrophysical investigations -e.g., studies of small bodies in the solar system, programs that map the outer regions of the Milky Way, and searches for faint optical transients on a wide range of time scales. The LSST project is proposed to the US astronomy community. It has also attracted attention in the US particle physics community as a dark energy experiment. LSST would provide detailed constraints on the nature of dark energy, through a variety of distinct and complementary techniques. Four of these techniques: measurement of baryon acoustic oscillations, surveys of clusters of galaxies, photometry of Type 1a supernovae, and measurement of cosmic shear using weak gravitational lensing, were highlighted in the report of the US Dark Energy Task Force, commissioned by both the US AAAC and HEPAP. This report concluded that no single one of these is both sufficiently powerful and well enough established to yield the necessary constraints by itself, but that the combination of all four (as provided by LSST) is especially compelling.

In the US, a large team of scientists and engineers from both the astronomy and particle physics communities has been assembled to pursue the LSST concept. As presently envisioned, LSST would be developed as a multi-agency public/private partnership, with NSF as the lead agency providing the bulk of telescope, site, and data management funding, and DOE supporting the fabrication of the LSST camera and the involvement of members of the particle physics community in the data handling and science analyses. Private funding has been obtained, allowing to start the telescope mirrors production in 2007, which are long-lead, expensive items that must be started before federal funding for proposed construction is officially authorized.

In France too, LSST has attracted attention in the astronomy and particle physics community. Discussions have been ongoing since end 2005 between several research groups and the LSST collaboration, which have resulted at the end of 2006 in the sending of a Letter of interest to LSST, signed by 7 laboratory directors (4 IN2P3 and 3 INSU). Beginning 2007 a joint committee of the PNC and the IN2P3-INSU-DAPNIA French Dark Energy group recommended that R&D actions toward LSST be supported by French funding agencies.

In 2007, six IN2P3 groups (APC, CCIN2P3, LAL, LMA, LPNHE, LPSC) have teamed to contribute to the LSST R&D. They have joined the LSST scientific collaborations for preliminary scientific studies and started a contribution to the LSST R&D focused on key elements of the camera (sensors and filters) and to the calibration of the survey. The IN2P3 scientific council has endorsed their proposal in December 2007. This French contribution to the LSST R&D has already produced results, including: ASIC for CCDs readout, mechanical design of the filters support system, coating studies for filters and atmospheric studies.

IV.3.7 SPICA

Martin Giard, CESR CNRS-OMP/Université de Toulouse

SPICA is a JAXA (Japan) / ESA (Europe) joint mission which intends to send to the L2 Sun-Earth position an infrared observatory with unprecedented capabilities. It will use a 3.5 meter cryogenic telescope cooled to 5 Kelvin and equipped with 3 focal plane instruments: one coronograph-spectrometer, and two infrared imaging-spectrometer to cover the wavelength range from 5 to 210 micrometer. The European contribution will consists in the telescope plus ground station funded by ESA, and SAFARI, a 35-210 micron FTS imaging spectrometer funded by national agencies (PI B. Swinyard, RAL-UK). JAXA will be responsible for the whole mission, including the platform, launch and the two other instruments. On the ESA side it has been pre-selected for assessment studies for a possible launch in 2017. Fig. IV.42 shows an artist view of the SPICA instrument.

SPICA will offer to the scientific community new outstanding capabilities not reached by the existing or fore-coming instruments (including Spitzer, Herschel and JWST). These

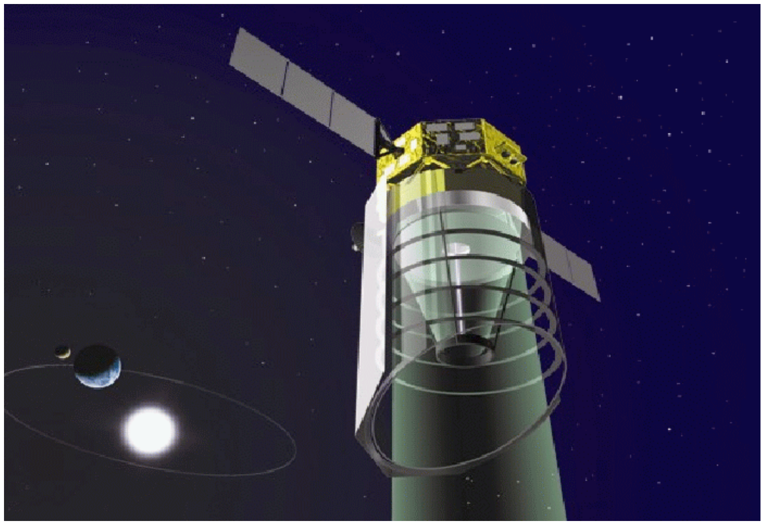

Figure IV.42: Artist view of the SPICA telescope with Sun, Earth and Moon in the background

are mainly of two kinds:

- The SAFARI instrument will allow us to perform spectro-imagery in a wavelength domain not accessible with JWST-MIRI, and with a sensitivity improved by a factor of 10 to 100 compared to Herschel, thanks to the SPICA cryogenic telescope.
- The coronograph will benefit of very high rejection capabilities due to the single dish telescope design, and we will be able for the first time to perform direct spectroscopy of exoplanets and properly characterize their atmosphere.

The first item is of prime interest for the study of the formation and the evolution of galaxies, a subject which is central within the new CNRS Program for galaxies and cosmology. Fig. IV.43 shows that SPICA will be able to measure within one hour the full spectrum of a typical starburst galaxy (here M82) down to a redshift of $z = 2$ with a spectral resolution $R = 1000$, and further down to $z = 5$ with a reduced spectral resolution. The SPICA spectral domain is ideally suited to study the star-formation activity as a function of the cosmic age by tracing the gas lines and solid state features in these objects. The combination of MIR and FIR spectroscopy on SPICA is essential to trace the formation and evolution of the super-massive black holes at galactic centers in relation to galaxy and star formation and trace the life cycles of chemical elements through cosmic history. SPICA will be the first observatory with the ability to detect the MIR and FIR cooling lines out to the peak of star formation activity in the history of the Universe ($z \sim 1-2$). It will do this for a wide range of galaxy types allowing a unique and unbiased view of galaxy evolution, the link between metallicity and star formation, and the relationship between starburst galaxies and active galactic nuclei.

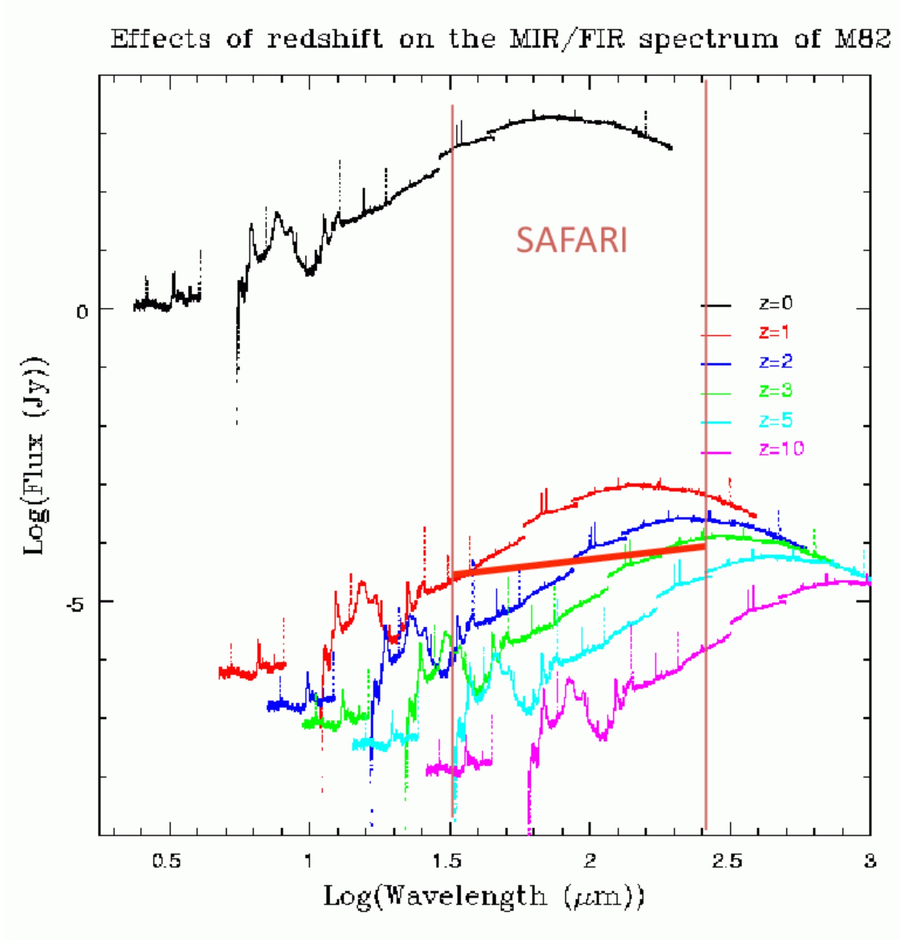

Figure IV.43: Sensitivity of SAFARI, R = 1000 (red bar, 5σ, 1 hour) compared to the redshifted spectrum of the template starburst M82.

IV.3.8 LISA

Pierre Binétruy, APC

Unlike electromagnetic radiation, gravitational waves (GW) interact very weakly with matter, and can penetrate anything without losing intensity. This makes them powerful probes of faraway regions and extreme conditions, but it also makes them very hard to detect. Only recently has technology advanced to the point of building apparatus sensitive enough to measure the minute effects of gravitational waves on matter, with the completion of the first stages of ground interferometers.

In 1993, Taylor and Hulse received the Nobel prize for showing that the orbital period of the binary pulsar PSR 1913+16 (a system of two neutron stars) is decreasing at exactly the rate predicted by Einstein's quadrupole formula for the emission of gravitational waves in binaries.

This indirect proof confirms the existence of gravitational waves but it remains to detect them directly. This is the task assigned to the ground interferometers like VIRGO in Europe or LIGO in the US. Once this is done (the necessary sensitivity will probably be reached by the advanced versions of these interferometers), gravitational waves will open a new window onto the Universe. Even though some astrophysics will be performed by these instruments, gravitational wave astrophysics (especially extragalactic) will be the realm of the space interferometer LISA.

Although GWs have not been detected yet, we know enough about the contents of the Universe to make reasonably accurate guesses about some of the GW sources that LISA will observe. In the same way that accelerated electric charges generate EM radiation, accelerated mass and energy of any kind generate gravitational radiation. The periodic motion of a system of mass M and size R creates GWs at a distance with a strain amplitude of about $h \sim \left[GM/(Rc^2)\right]^2 (R/D)$, with frequency determined by the frequency of the motion. The shapes and strengths of the observed waves give us details about the structure and behavior of the system that produced them.

The strongest waves are generated by the systems with the largest gravitational fields GM/R, which correspond to large masses and small sizes. The strongest of all are generated by the interactions of black holes, which have $GM/(Rc^2) \sim 1$. The lightest black holes (remnants of single stars, with about ten times the mass of the Sun) emit at the highest frequencies, in the 100 Hz band accessible to ground-based detectors. By contrast, the strongest sources in the far lower LISA band (between 0.1 to 100 mHz) are the supermassive black holes at the centers of galaxies; these are the remnants of the process of galaxy formation, with about 10^4 to 10^7 times the mass of the Sun. Optical, radio, and X-ray astronomy have produced abundant evidence that nearly all galaxies have massive black holes in their central nucleus.

From the point of view of cosmology, LISA will also be a unique observatory. Cosmological backgrounds of gravitational waves are produced in the reheating phase that follows inflation, during first order phase transitions or from the evolution of a network of cosmic defects (such as strings). The detection of such GWs would provide key informations on the early Universe, but also on the theory of fundamental interactions. The Holy Grail is of course the observation of gravitational waves produced just after the Big Bang, during the inflationary phase. It is however probable that it is only a successor of LISA that will reach the required sensitivity.

Another aspect of cosmology where LISA should bring precious information is dark energy: the coalescence of two supermassive black holes provides a new type standard candle (or siren) that allows to determine the luminosity distance of the event. This combined with a measure of the redshift allows a precise determination of the dark energy component, in a way similar to supernovae of type Ia, but with completely different systematics.

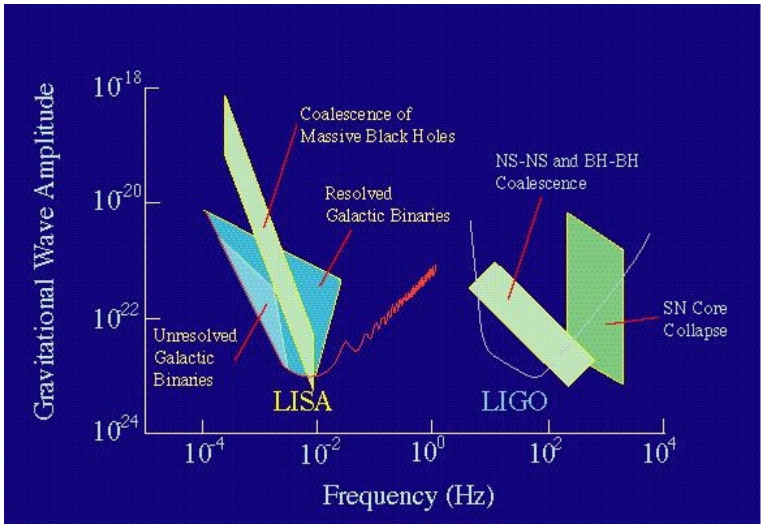

Figure IV.44: The spectrum shows the sensitivity that the space interferometer LISA and an advanced version of the ground interferometers (a 4 km long LIGO) will obtain in their respective operating frequency bands, as well as spectral regions where various sources are predicted to be.

The LISA mission uses three identical spacecraft whose positions mark the vertices of an equilateral triangle five million km on a side, in orbit around the Sun. LISA can be thought of as a giant Michelson interferometer in space, with a third arm that provides independent information on the two gravitational wave (GW) polarizations as well as redundancy. The spacecraft separation – the interferometer arm length – sets the range of gravitational wave frequencies LISA can observe (from about 0.1 mHz to above 0.1 Hz). This range was chosen to reveal some of the most interesting sources mergers of supermassive black holes, ultra-compact binaries, and the inspirals of stellar-mass black holes into supermassive black holes. The center of the LISA triangle traces an orbit in the ecliptic plane, 1 AU from the Sun and behind Earth, and the plane of the triangle is inclined at to the ecliptic. The natural orbits around the Sun of the freely floating proof masses inside each of the three spacecrafts maintain this triangular formation throughout the year, with the triangle appearing to rotate about its center once per year.

The sensitivity of LISA is shown in Figure IV.44 together with a comparable sensitivity curve for the future ground-based Advanced LIGO. Sensitivity over a logarithmic frequency interval is shown here in terms of the GW amplitude h. The LISA sensitivity curve divides into three regions: a low-frequency region where proof-mass acceleration noise dominates, a mid-frequency region where shot noise and optical-path measurement errors dominate, and a high-frequency region where the sensitivity curve rises as the wavelength of the GW becomes shorter than the LISA arm length. Additionally, a diffuse background of unresolved galactic binaries is expected to contribute to the measured strain level in the frequency range from 0.1 - 1 mHz. LISA will see most of its sources in the frequency range below about 10 mHz, corresponding to wavelengths greater than about 30 million km. This is the characteristic size of systems involving massive black holes, as well as compact white-dwarf binaries.

Among LISA advantages, one may note that it has a large intrinsic dynamical range: it could in principle measure accurately signals over an amplitude range of 10^5 or an energy range of 10^{10}. It also has a very large frequency range, spanning four decades, limited by its size and by the difficulty of isolating the proof masses at low frequencies. This means that, unlike optical, ultraviolet, or infrared observatories, LISA is less likely to miss distant sources because they are cosmologically redshifted to lower frequencies: it will be able to study homogeneously populations of objects out to the highest redshifts. Third, LISA has all-sky acceptance of signals; it sweeps three different quadrupolar antenna patterns across the sky as it orbits the Sun, so that its sensitivity for all but the shortest transient sources is fairly isotropic.

The key technology of LISA will be tested in a technological mission, LISAPathfinder, planned for late 2010: it will test that free fall can be achieved for the proof masses at a sufficient precision. The LISA mission is a joint NSA-ESA mission. On the ESA side, it is in its formulation phase. It has been included without further competition in the first stage of the Cosmic Vision call for an L-mission (to be launched around 2018). Down selection will proceed in 2009 and 2011. Obviously, the selection process on the US side, conditioned by the results of the on-going Decadal Survey, will have an impact on the programmatics of the LISA mission.

The French participation to LISA started early but was jeopardized by the CNES financial crisis in the early 2000's. In 2004, the consortium LISA-France was formed which gathers the laboratories interested in various aspects of LISA (science, R&T, data analysis). It presently includes APC, ARTEMIS, IAP, IPhT, LAPP, LPCE, LUTH and ONERA. One to two general meetings are organized every year.

IV.3.9 MANOLIA/ROSEBUD

Noël Coron et Pierre de Marcillac, IAS Orsay

R&D on scintillating bolometers

The ROSEBUD collaboration which gathers teams of thermal spectrometry of IAS and nuclear physics from the University of Zaragoza interrupted in 2001 the ongoing measurements in the underground laboratory of Canfranc: the backgrounds recorded by its sapphire detectors were too high to pretend any detection of dark matter with the experiment as it was.

The teams concentrated then in a Research & Development program called 'BOLERO' supported by INSU: these studies led in 2006 to the achievement of massive scintillating bolometers able to discriminate the expected dark matter signal from the radioactive backgrounds. In addition, an unexpected strong light signal was revealed in the previously used sapphire detectors ([11]). This mixed 'heat and light' technique was retained in the ApPEC roadmap in 2007 (Astroparticle European Coordination) as one of the orientations to follow in the field of dark matter detection for the 10 years to come: it is the only technique to allow for a great flexibility in the choice of targets. If an elastic collision happens in a target with a dark matter particle –but also with a neutron– the recoiling nucleus is far less ionizing than the recoiling electrons induced by interactions with the radioactive beta or gamma background: the amount of light produced is lower, and this is the property used to identify the nature of the particles in the detectors.

Status of ROSEBUD at Canfranc in 2007: a population of non ionizing events in the data

The supports from both PNC and the European Community (ILIAS-TARI funding) allowed a full waking up of ROSEBUD at Canfranc in 2007. The backgrounds registered by a set of three scintillating bolometers in sapphire (Al_2O_3; 50g), bismuth germanate ('BGO' ; $Bi_4Ge_3O_{12}$; 46g) and lithium fluoride (LiF; 33g), each coupled with its own light detector, were studied during the 2007 campaign, divided in four runs of two weeks each (figure IV.45).

Each detector could bring its own contribution to the knowledge of the backgrounds: the low energy events were recorded by the sapphire, which presented a heat threshold close to one keV, the BGO detector was monitoring the gammas with a high efficiency due to the high Z of bismuth (67% in weight in BGO) while the LiF bolometer attempted to measure the neutron background using the exothermic neutron capture reaction of Lithium-6 ($n+{}^6Li \rightarrow {}^3H+{}^4He$; Q=4.78MeV).

The bolometers tested and qualified previously at IAS behaved as expected in the underground laboratory, with effective thresholds for sapphire and BGO of respectively 10keV and 25keV, after rejection of the gamma background with 95% confidence level. The progressive raise of the shielding around the experiment allowed for a significant reduction in the radioactive background encountered by the detectors (figure IV.46). The high identification power of both sapphire and BGO detectors revealed a non ionizing component in the backgrounds that could mimic the signals expected from recoiling nuclei. This population was completely masked by the ambient neutron background at IAS, at ground level.

The rate of this population of non ionizing events –1.5 to 2 counts per hour in both detectors– is far above the one recorded by the most sensitive experiments aiming to detect dark matter underground, so they cannot be due to 'dark matter'. The source of this component which is seen in the heat channel but not in the light one is not yet identified: the rate was not reduced with improvements of the shielding above mentioned, which discarded

Figure IV.45: Configuration of the IAS 20mK refrigerator for ROSEBUD at Canfranc in 2007: from top to bottom, three double scintillating bolometers in BGO (46g), LiF (33g) and sapphire (50g) were mounted.

as a possible origin interactions from external backgrounds in the dead –non scintillating– zones of the detectors (figure IV.47). They could be electric artifacts but their time profiles in the heat channel do not allow to distinguish them from 'good' events happening in the target. Other assumptions are relaxations of mechanical stresses in the detectors, recoiling nuclei following alpha decays occurring in the surfaces regarding the targets, or recoiling nuclei induced by neutrons scatterings from the background... In order to test this last

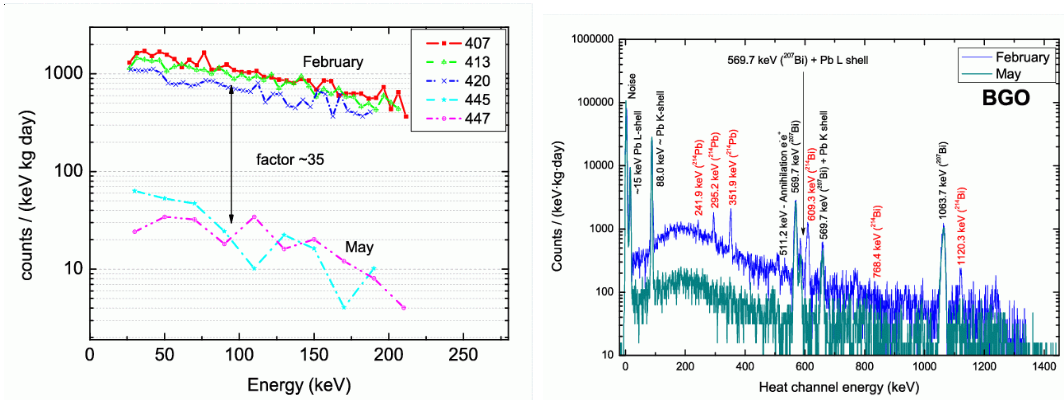

Figure IV.46: Reduction of the gamma background in the sapphire and BGO bolometers along with the improvements in the shielding (with suppression of radon ^{222}Rn in May: the associated gamma lines disappear in the BGO spectrum). The background in BGO is dominated by an internal contamination in ^{207}Bi.

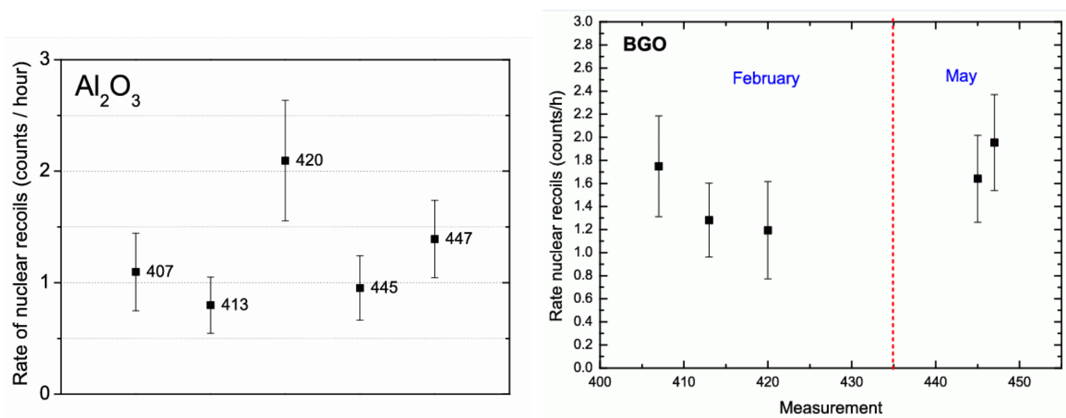

Figure IV.47: Background of non ionizing events in sapphire then in BGO: the rates found are roughly constant with time, while the external backgrounds could be reduced (see figure IV.46).

Prospects: EURECA

The short term goal of ROSEBUD is to understand the origin of the non ionizing component seen in 2007 at Canfranc. The refrigerator is back to Orsay: the high energy backgrounds will be studied and a new set of detectors in BGO and sapphire, less radioactive, will be tested. In parallel, thanks to a PhD grant from CNRS, the studies for the feasibility of high resolution in neutron energy spectroscopy will go on. Fast neutrons are targeted, in the 1keV-10MeV with LiF bolometers and solutions for crystal growth after enrichment in lithium-6 of the raw material will be looked for, to increase their detection efficiency.

Such original studies will be fully integrated in the works for the EURECA (European Underground Rare Events Calorimeter Array) project that the IAS and the Zaragoza group joined in 2006. This federating European project gathers, aside from the small teams of ROSEBUD and of the Institute for Nuclear Research in Kiev, the big CRESST and EDELWEISS collaborations, installed respectively in the underground labs of Gran-Sasso and of Fréjus, each institute adding its own complementary techniques to the project. Scintillating bolometers are one of the options retained for EURECA: we proposed to maintain ROSEBUD alive at Canfranc for the test of prototypes in a low background environment. These tests will be necessary, since EURECA should provide the community with an experiment holding 100kg to one ton of detectors, together with radioactive backgrounds reduced by two orders of magnitude with respect to the best levels obtained so far. The ambitious goal is to explore scattering cross sections of supersymmetric particles with nucleons in the 10^{-10}pbarn range, testing thus a good fraction of the theoretical models that describe the neutralino.

IV.4 Smaller projects

IV.4.1 Super-GIRAFFE

M. D. Lehnert, I. Guinouard, D. Horville, P. Jagourel, F. Chemla, J.-P. Amans, P. Bonifacio, C. Babusiaux, F. Hammer, V. Hill, F. Royer & M. Puech, Observatoire de Paris, GEPI

We are proposing to build super-GIRAFFE, the Next-Generation High-Multiplex Optical Spectrograph with d-IFUs, as an ESO-VLT 2.5-generation instrument. Super-GIRAFFE is a high-multiplex (several hundred fiber), very efficient (total throughput $> 20\%$) spectrograph with deployable IFUs (20-30) that simultaneously covers the full optical band (0.35-1.0microns) at two spectral resolutions ($R = 5000$ and $15,000 - 20,000$). The total field of view of the instrument would be like that of the current FLAMES/GIRAFFE (25'). Our focus with such an instrument is to make it high efficient, with a throughput similar to that of a simple multi-slit spectrometer, and high multiplex. Such a spectrograph could be build cheaply and quickly by upgrading the fiber positioner of FLAMES/GIRAFFE. By building quickly, we believe the VLT will have a unique capability for tackling such important issues as the growth of large scale structure, the tomography of the inter-galactic medium, the spatially-resolved dynamics and emission/absorption line distributions of high redshift galaxies, stellar populations in the halo of the MW and in other nearby galaxies, etc. before anyone else. Also, 'keeping it simple' has the advantage that several copies could be built, allowing for truly significant surveys to start within a few years, rather than within a decade. We also discuss possible enhancements to this baseline design that could enhance its overall multiplex advantage and efficiency in conducting stellar and galaxy surveys.

IV.4.2 The Hubble Sphere Hydrogen Survey (HSHS)

Reza Ansari, LAL, Orsay

The interpretation of various cosmological observations, such as the cosmic microwave background anisotropies, distant supernovae (SNIa) apparent luminosity evolution with redshift, or the large scale clustering properties of galaxy distribution (LSS), implies either a non zero cosmological constant, or the existence of a mysterious energy density component in the Universe. This component, called dark energy (DE), is even more exotic than the dark matter and represents today about 70% of the total mean energy density of the universe. The dark energy component would produce a repulsive gravity force at cosmological scales which might be responsible for the observed acceleration of the space-time expansion.

The observation and precise measurement of the Baryon Acoustic Oscillations (BAO) scale, and its evolution with redshift is considered to be one of the most sensitive and robust probes to study dark energy properties, the so called DE equation of state. Mapping the Universe in radio, through the neutral hydrogen 21 cm transition, is a novel approach to study LSS and DE, complementary to optical photometric and redshift surveys.

Following an original proposal for a radio survey by U.L. Pen (CITA, Canada) and J.B. Peterson (CMU, Pittsburgh, USA) in 2006, the LAL (IN2P3/CNRS & Univ. Paris Sud) and IRFU/SPP (CEA) have initiated a research and development program in electronics intended for 21 cm digital radio interferometers. Our aim is to build a large radio interferometer, in the framework of an international collaboration. This instrument would be able to map in three dimensions (2 angles and redshift), the neutral atomic hydrogen (H_I) distribution, over a large fraction of sky, up to redshift $z \sim 1.5$–2, with a resolution of few arc-minutes. This wide band instrument ($\gtrsim 200\,\mathrm{MHz}$) would have a collecting area around $10,000\,\mathrm{m}^2$, and an instantaneous field of view (FOV) of ~ 100 square degrees. It could be made of about ten cylindrical reflectors ($\sim$ 100 m ×10,m), equipped with a total of few thousands receivers. Each receiver channel will be sampled using fast ($\sim 500\,\mathrm{MHz}$) ADCs, and the data will be fed to a full digital beam-former and correlator.

During the last two years, LAL and IRFU teams have been working on designing and building an affordable system capable of processing the generated data, with a sustained rate of few terabytes per second, as expected for the final instrument. Since last summer, we have a collaboration agreement with the Observatoire de Paris, and the Nançay large radio telescope (RTN). A first version of a specific low noise amplifier chip (LNA) matched to our needs is being designed by the Nançay staff, and we benefit from their expertise for developing and testing the electronic system. In addition, we plan to contribute to the FAN project at the Observatoire de Paris. The aim of FAN is the development of a Focal Plane Array (FPA) prototype for the Nançay radio telescope.

The PNC contributed to support these activities in 2007 and 2008. We have designed and built a signal processing pipeline, featuring analog amplification, filtering and frequency shifter modules, a 500 MHz digitization board, capable of performing FFT on the fly, with fast optical data transfer to the acquisition computer, or to an FPGA based correlator/beam-former.

IV.4.3 BOSS

Eric Aubourg, APC

The SDSS-III project is a sequel to SDSS and SDSS-II, using the APO 2.5 m telescope to pursue four subprojects:

- *BOSS (Baryon Oscillation Spectroscopic Survey)* will take spectra of 1.5 million LRGs up to $z = 0.8$ and $160,000$ quasars around $z = 2.5$ to constrain the properties of dark energy through the measurement of baryon acoustic oscillations (BAO).
- *Segue 2* will measure radial velocities, spectral types and elemental abundances of $350,000$ stars, probing the kinematics and chemical evolution of the outer Milky Way.
- *Apogee* will use high resolution infrared spectroscopy to conduct similar measurements on $100,000$ red giant stars in the inner Milky Way.
- *Marvels* will search for exoplanets through the measurement of radial velocities of $11,000$ bright stars.

A French Participation Group (FPG: APC/IAP/CEA/LAM/CPPM/Besançon) is joining SDSS-III. The group intends to take an active part in BOSS data analysis, focusing particularly on the study of non-linear corrections to the matter power spectrum for the LRG sample, the Lyman-α forest in quasar spectra and the cosmological redshift-space distortion of galaxy clustering. The group has been funded by PNC, P2I and ANR.

On the BAO (BOSS) side, the project will yield cosmic-variance-limited BAO scale measurements at $z < 0.8$, and will make a first measurement at $z \sim 2.5$. For the groups involved in BOSS, it is a first step on a path targeting either LSST, JDEM or Euclid. Some participants are also members of the Horizon project, from which numerical simulations will be used to prepare the analysis.

Part of the FPG is also interested in Segue 2 and Apogee (members at IAP, and the Utinam team), in a larger GAIA context.

IV.4.4 Simbol-X

Monique Arnaud, CEA

[Simbol-X is no longer a top-priority astronomical mission for CNES. It has been cancelled by the CNES-CSP in the Spring of 2009. This mission could reappear in a different context of funding (e.g., ESA space mission).]

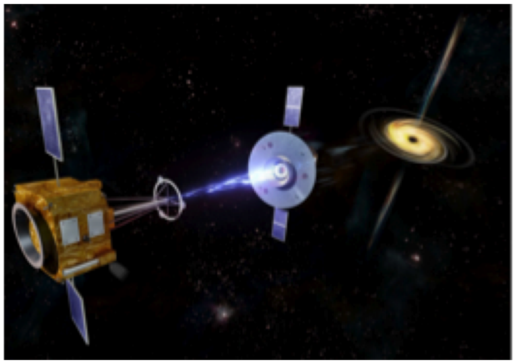

Figure IV.48: Artist view of the Simbol-X configuration, with mirror and detector spacecrafts in a constrained formation.

Simbol-X is a hard X-ray observatory, operating in the 0.5–80 keV range, developed in collaboration between the French and Italian space agencies with participation of German laboratories. The project is now in Phase-B for a launch in 2014. Relying on two spacecrafts in a formation flying configuration (Fig. IV.4.4), Simbol-X uses for the first time a 20 m focal length X-ray mirror to focus X-rays with energy above 10 keV, resulting in more than two orders of magnitude improvement in angular resolution and sensitivity in the hard X-ray range with respect to non-focusing techniques. The prime science objectives of the mission are the black-holes accretion physics and census, and particle acceleration mechanisms. In particular, Simbol-X will address the following outstanding questions, at the interface of cosmology and high energy astrophysics:

- *The cosmic X-ray background, the census of Super Massive Black Holes and AGN feedback*: The Cosmic X-ray Background (CXB) is believed to be the integrated output of the accretion activity onto supermassive black holes in the center of galaxies and determining its origin gives major constrains on the formation and evolution of structures in the Universe. If the major fraction of the CXB has been resolved into discrete sources below ~7 keV, essentially nothing is directly known above 10 keV, and in particular in the 20–40 keV band in which the CXB spectrum is peaking. According to current synthesis models, a significant fraction of the CXB is due to obscured Compton thick (CT) AGNs, essentially missed by XMM and Chandra surveys due to their soft band pass. Simbol-X aims at resolving more than 50% of the CXB in the energy range where it peaks, thus providing an unbiased census of supermassiveblack holes in the Universe. Simbol-X will allow us to uncover the long sought population of CT AGN, evaluate the luminosity function of obscured AGN and its evolution, and to measure the fraction of obscured AGN as a function of luminosity and redshift. This a crucial step to constrain nuclear accretion efficiency and feedbacks on the host galaxies, which are key ingredients toward the understanding of galaxy formation and evolution.

  In addition, Simbol-X will allow a better understanding of the accretion/ejection physics around supermassive black holes, through detailed wide band spectroscopy of massive outflows in nearby AGNs. This is important to quantify the effects of AGN feedback on their host galaxies.

- *Non thermal components in Cluster of galaxies*: Simbol-X will map the hard X-ray emission in cluster of galaxies, determine its controversial origin and disentangle the thermal and non-thermal components. Correlated with radio observations, like obtained with LOFAR, the observation of the non-thermal X-ray emission, when confirmed, will allow to map both the magnetic field and the relativistic electron properties, key information to understand the origin and acceleration of relativistic particles in clusters and its impact on cluster evolution. This has further cosmological implications. The non thermal ICM pressure will be estimated, allowing us to assess potential errors currently made when estimating total cluster mass (a key quantity when using clusters to constrain cosmological parameters) from X-ray observations and the hydrostatic equilibrium equation.

IV.4.5 BRAIN

J.-Ch. Hamilton (APC, Paris), for the BRAIN collaboration

The detection of primordial gravity waves through the B-mode polarization anisotropies in the Cosmic Microwave Background is one of the most exciting challenges of modern cosmology. It would provide a direct information on the energy scale of inflation, possibly associated with GUT [340]. It would also allow one to investigate the standard cosmological model in details through consistency tests involving the spectral indices of scalar and tensor perturbations and their amplitude ratio [326].

Despite the weakness of the expected signal, many teams have decided to join the quest for the B-modes and to construct dedicated instruments that have to combine an exquisite sensitivity and a precise control of systematic effects. Most of the projects proposed up to now are direct imagers, a concept that has proven to be very sensitive. They might however be affected by significant systematic effects such as ground-pickup, beam differences that would less affect an interferometer having no optics before the entry horns. It is therefore sensible to investigate the possibility of developing an high sensitivity interferometer dedicated to the B-mode search. A bolometric interferometer would combine the high sensitivity of bolometers with the clean optics of an interferometer and appears as a good option to complement the ongoing imaging projects. The sensitivity to the B-mode power spectrum was proven comparable to that of imagers and heterodyne interferometers [265].

The BRAIN (Background RAdiation INterferometer) and MBI (Millimeter Bolometric Interferometer) collaborations [445, 135] have now merged into a single one [87] that intends to build such a bolometric interferometer. The final instrument will be formed of 9 independent interferometer modules located in a single cryostat, each consisting in a square array of 144 entry corrugated horns looking directly at the sky. The entering electromagnetic wave will then be split into its 2 orthogonal linear polarizations using a device known as OMT (Ortho-Mode Transducer). Each channel will then be phase-shifted using appropriate shift sequences [134] in order to modulate the signal with optimal signal to noise ratio. The modulated signal will then be re-emitted through back-horns towards a beam combiner located inside the cryostat. The beam combiner, inspired by the MBI-4 design consists of a telescope that superimpose the images coming from all the re-emitting horns. The interference patterns are then formed and detected on the focal plane with a bolometer array. We have shown that this technique allows for the 4 Stokes parameters visibility to be reconstructed in an optimal way. The BRAIN-MBI instrument will be installed in 2010-2011 at the Concordia station in Dôme C, Antarctica that has particularly appealing atmospheric stability and transparence. It will allow us to constrain a tensor to scalar ratio of 0.01 with one full year of data.

Part V

Theory, Simulations and Virtual Observatory

V.1 Theory

Cédric Deffayet, APC & IAP

As shown in the previous sections, many new development are expected in theoretical cosmology in the coming years. This concerns in particular new scenarios of inflation based on superstring theory, issues having to deal with the computation of non-Gaussianities, the understanding of 'cosmic superstrings', the consequences of the expected discoveries of the LHC, in particular for what concerns the nature of dark matter but also for the improvement that should result from the knowledge of the physics beyond the standard model of high energy physics. It also encompasses new ideas in the domain of gravity and recent advances dealing with new ways to modify gravity in the very large distances. In those different directions, an improved relation between *observers* (in the broad sense) and theorists is needed both from the theoretical side and from the observational side in order to fully benefit from the improvement of the precision of the cosmological observations.

This is particularly true in France, where the two communities do not always share the same kind of close relations that one finds in other countries, such as in the United States of America, even though our country has several researchers of high quality in the field of theoretical cosmology whose recent works have been highly recognized by the international community. In particular a large part of the theorists dealing with the physics of the early Universe comes from a high energy physics background and would greatly benefit from more interactions with observers and scientists coming from the astrophysics community. This can be certainly greatly improved by a strong support to the community of theorists, in particular those working on early universe, from programs such that the PNC or the new PNC-PNG.

We wish to strengthen this support taking fully into account the specificity of the way theorists are working. Indeed, in contrast with the observational projects funded by programs such that our, theorist usually do not need important funding, since most of their needs concerns travel money and money for invitations. Moreover, most theoretical works are developed by small teams of a few researchers with collaborators overseas which change from one project to the other. For this kind of work, it is crucial to benefit from short term invitations and missions, and the recurrent funding provided by the labs usually are not enough to cover this type of need. We hence think that our program should be able to fund such needs on the basis of well identified projects, in addition to the more common financial needs such as those necessary to organize school or scientific congresses or workshop that we intend to support as well as was done in the past.

V.2 Simulations

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Numerical simulations play a key role in developing our understanding of complex physical phenomena which drive the evolution of the Universe and its diverse components. They require the analysis of the relevant physical equations, their transcription into robust numerical algorithms, and finally their resolution in a reliable way. During the last couple of decades, they have played a significant role in cosmology (e.g. helping us understand the non-linear dynamics of large-scale structures) and in the study of galaxies (e.g. helping us understand the formation of bars or the complex process of galaxy mergers). These two fields have become the most computationally demanding of astrophysics. In the last decade, thanks to the dramatic increase of computer power and to the implementation of faster algorithms, they have also began to allow us to address the question of galaxy formation in its full cosmological context (e.g. with the 'Mare Nostrum Simulation' form the Horizon Project. Today, simulations have become realistic enough that they also come to play a new role in the study of cosmology and galaxy formation by (i) helping us to interpret observations in a complex theoretical framework, and (ii) by providing observers with accurate mock data which they can use to calibrate their analysis software, or design and optimize further observational campaigns. The importance of these simulations is such that they are now becoming fully integrated in the development plan of any ambitious observational program.

In the last three years, the French numerical landscape has been vastly reshaped by the Horizon Project. In its approach, this project is certainly a precursor of the new Program for Cosmology and Galaxies as it has federated the community of simulators across traditional frontiers separating cosmology and galaxy physics. The expertise within the Horizon Project, in terms of codes and physical models, puts our community in a very competitive position at the international level. For example the two largest cosmological simulations to date, both pure N-body (the 'Horizon 4π' simulation which ran at the CCRT, CEA, France) and hydro-dynamical (the 'Mare-Nostrum' simulation which ran at the BSC, Barcelona, Spain), were run by the Horizon Project. With these, the Horizon Project has shown that the French community of simulators is able to obtain computing time on world-class super-computers in order to run first-rank numerical simulations featuring state-of-the-art physical models. Now that we have acquired this expertise, the real challenge has shifted towards giving our community the means to analyze such simulations and to maximize their scientific return. With this purpose in mind, the Horizon Project did equip some institutes with several 'meso' computers designed to handle large simulations. This computational support, still insufficient, will need to be sustained. Of equal importance, the community has to enhance its manpower dedicated to the analysis of simulations. As an example, the great success of the Millennium simulation can be attributed in part to the fact that about 30-50 researchers (mostly students and post-docs, but also staff) of the Virgo consortium, have analyzed or used this simulation with enough equipment to have copies of the full simulation in Durham and Garching. The Mare Nostrum simulation, which has at least as much scientific content, has until now been analyzed by a handful of people (say three post-docs, three student, and a couple of permanent staff), on remote disk-space rented temporarily by the Horizon project. The issue of manpower and meso-equipment is definitely central if we want to have scientific return from the ambitious simulations which we are able to make. Another aspect of the success of the Millennium simulation if the effort that the Virgo consortium has put (in terms of manpower and equipment) to make part of the data accessible to the public. Here again, despite the efforts of the Horizon Project, manpower and equipment remain a real issue. The PNCG will have to support this activity along these lines if we want the visibility and impact of our simulations to match their unique quality.

The future of simulations for cosmology and galaxies then relies on our ability to implement new physical processes or new original algorithms, and to run and analyze simulations dedicated to a series of astrophysical issues. Some directions for the PNCG may be the following:

- *The development of our simulation codes to incorporate new physics*: Of prime importance today are (i) radiative transfer (which we know how to do as a post-processing but still has to be coupled to hydro algorithms), (ii) sub-grid models for the build-up of black holes and their feedback, (iii) chemistry and related cooling functions in order e.g. to address the issue of the formation of the first galaxies.

- *The exploration of physical processes with existing codes to derive sub-grid or semi-analytical models*: The challenge here often boils down to bridging very small ($< 1\,\mathrm{pc}$) and very large ($> 1\,\mathrm{Gpc}$) scales. For example, we need extremely high resolution simulations, which possibly include MHD, in order to understand the structure of the inter-stellar medium and the impact that star formation has onto it. We need to derive from such simulations sub-grid models which can then be implemented in larger-scale simulations, of cosmological interest, in order to understand e.g. the statistical impact of galactic winds on the intergalactic medium (in terms of metal enrichment, shock heating, etc.). Another example is the use of accurate radiative transfer codes to derive observables for the future instruments (e.g. Lyman-α emission from high-z galaxies, or line emission from the diffuse intergalactic medium). A last example is the exploration of the importance of magnetic fields in structure formation with MHD simulations (RAMSES).

- *The development of new algorithms (e.g. unstructured grids, etc.) to better address cosmological issues (e.g. the small-scale clustering of dark matter or the nature of dark energy*: One interesting direction, here, is the development of codes able to simulate alternative cosmological models, or rather the growth of structures in a fully general relativistic context. For example, the numerical study of *back-reaction* effects in averaged inhomogeneous cosmologies requires one to run large-scale simulations with non-periodic boundary conditions and a coupling to spatial curvature.

V.3 Virtual Observatory

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The Virtual Observatory (VO) aims at providing seamless and transparent access to the wealth of astronomical data, and better analysis and visualization tools. The concept emerged at the turn of the century, and it is one of the very few truly global endeavors of astronomy since the objective is to give access to all data, whatever their location, to all astronomers. The first VO projects were funded from 2001 on. There are national projects in many countries, and the Euro-VO project provides coordination at European level.

VO projects are developing the technical infrastructure, which is the framework for data centers to publish their data in the VO, mainly standards and tools allowing information discovery, retrieval and usage. This development is coordinated by the *International Virtual Observatory Alliance* (IVOA), an alliance of all the national projects (including Euro-VO), to ensure world-wide interoperability. The basic technical development of the VO framework has been successful, and the VO is in transition towards an operational phase. At European level, this transition is supported by the FP7 I3 *Euro-VO Astronomical Infrastructure for Data Access* (EuroVO-AIDA, 2008-2010), coordinated by CNRS (F. Genova).

France has been very active in the VO development from the very beginning. The *Centre de Données astronomiques de Strasbourg* (CDS) had anticipated the VO by many aspects, and has been a major player since the early phases, creating for instance the first international coordination by 2001 as a working group of the OPTICON Fifth Framework Program European Network. This working group was succeeded by the IVOA in 2002. Participation in the VO was recognized as a national priority in the INSU 2003 strategic exercise, and the *Action Spécifique Observatoires Virtuels France* (ASOV) was created by INSU, with support from CNES, in 2004, to coordinate French VO activities. To build the liaison with the national community in the different disciplines of astronomy and with the other technical developments supported at the national level, the ASOV Scientific Council is made of representatives of the *Programmes Nationaux* and of the other *Action Spécifiques*. The PNG and PNC were represented in this Scientific Council and the new Programme will obviously designate a representative, with the mandate to communicate the needs of its scientific community to the VO projects, and to disseminate VO knowledge in the Programme.

The ASOV has a triggering and coordination role, with only has a small financial support from INSU and CNES, which is mainly used to organize meetings and tutorials, and to support participation in the international meetings organized by IVOA. Several Working Groups have been created to gather and develop French expertise on different aspects of the VO. French participation in the VO development mainly relies on the commitment of laboratories, and there are now teams with VO-related activities in all of the French Observatories. French teams contribute significantly to the VO at several levels:

- Development of interoperability standards, with leadership of and active participation in most of the IVOA Working Groups.

- Provision of services and tools.

The importance of the VO as an essential infrastructure for astronomy has been identified by the AstroNet strategic exercise, and it is expected that all new projects and instruments will provide their data in the VO. New instruments sometimes require specific developments, and some are for instance on-going at CDS to deal with Planck and Herschel data. Another example is the development of collaborations between the LSIIT (a Strasbourg IT laboratory specialized in image processing) and astronomy laboratories, initiated in VO-related projects funded by the ACI GRID and *Masses de Données* and through an ASOV Working Group, into the DAHLIA project (*Dedicated Algorithms for HyperspectraL Imaging in Astronomy*), coordinated by E. Slezak. DAHLIA, which has just been selected by ANR in the 2008 IT 'white' announcement of opportunity, will develop algorithms for the processing of 3D data, in particular for MUSE.

VO services can be of many kinds: data archives, value-added services and tools (such as the ones developed by CDS), software suites (such as the ones developed by the Terapix team), or services dedicated to a specific science question.

One emerging aspect of the VO is the inclusion of theory, with the aims of giving online access to modeling services or to model results, and of allowing easy comparison of models and observations. ASOV has an active Working Group in this domain, chaired by H. Wozniak, who will also chair the IVOA Interest Group in charge of Theory for three years, starting in May 2008. Horizon and the Besançon models are among the test cases assessed by the French teams.

The Programme will support French participation to the VO in its domain of action, and disseminate the knowledge of the VO among its community. Importance aspects are scientific evaluation and prioritization of projects on scientific criteria, and the gathering of scientific needs and feedback.

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