Astrophysique Instrumentation Modélisation

Unité Mixte de Recherche N° 7158

Report 2007 – mid 2012
Project 2014 - 2018

Cover legend:
Herschel image of the Aquila region
where the filamentary structure
has been extracted thanks to the *xfilaments*
algorithm, used by the *getsources* extraction
software package (Menshchikov et al. 2012).

PROJECT TEAM BY TEAM

APPENDIX 139

REMERCIEMENTS...179

LCEG - Laboratoire Cosmologie et Evolution des Galaxies

1. Présentation de l'unité

The LCEG team involved in the 2014-2018 period will consist of 10 staff members: M. Arnaud, F. Bournaud, E. Daddi, D. Elbaz (*head*), E. Le Floc'h, R.Lehoucq, M. Pierre (CEA), H.Aussel, P.-A. Duc (CNRS), and S. Juneau (since Nov. 2012).

2. Analyse SWOT et objectifs scientifiques de l'unité

SWOT analysis for the LCEG team

Strengths: A key asset of the LCEG team is the existence *within* the group of a synergy between observations, theoretical data modelling and numerical simulations, naturally benefitting from the complementary expertise of team members. This synergy covers a wide range of spatial scales and physical processes (from interstellar gas physics to large-scale cosmological structures) and wavelength areas (from far infrared to X-rays). Complementary scientific skills converge to target well-defined scientific objectives as described in the scientific report.
On a practical level, the team has benefitted from: (i) a strong implication in proprietary time for space observatories (*Herschel*, *Planck*), (ii) a unique set of large programs of observations (centered on but not limited to *Herschel*, XMM, CFHT) and simulation programs (PRACE & GENCI, 37 Mhours since mid-2010 on Curie and Supermuc Petaflopic computers and the new CNRS Blue Gene), (iii) a strong success rate in prestigious grants (2 ERC, 7 ANR, 1 FP7 SPACE), (iv) tight perennial connections with researchers providing complementary expertise from external (e.g. IRFU-SPP/IAS/IRAP for Planck) and internal institutes within the SAp (for e.g. the cosmological context/LSPNA, modelling of dust emission/LFEMI).

Weaknesses: On the observational side, interferometry plays an increasing role for extragalactic studies but the team will need to adapt its local expertise accordingly. On the modeling side, the present numerical simulations of our group lack a proper treatment of the role of black hole growth and feedback, and only include a marginal connection with the global cosmological framework and associated large-scale physical ingredients such as the merger rate. We also note a pending challenge to sustain the broad range of expertise through which our group has reached a leading position in the field of galaxy formation: this is a potential weakness because an increasing part of this expertise has been developed through the contribution of non-permanent researchers. The ratio of non-permanent over permanent staff researchers is now greater than three, and our current scientific success can be maintained only through the new hiring of outstanding researchers.

Opportunities: A new generation of powerful instrumentation will provide us with tools to extend our investigation on dust-obscured star formation and black hole growth in distant star-forming galaxies with the advent of ALMA, JVLA and later on NOEMA at IRAM and APEX/ARTEMIS, followed by the mid-infrared spectro-imaging capabilities of JWST scheduled for 2018. Our leadership in the field places our group in a unique position to fully exploit these facilities, from the successful access to observing time to the theoretical interpretation and modelling. These facilities will provide much larger samples and extend to higher redshifts the measurements obtained for moderately distant galaxies. More importantly for our group, they will enable us to resolve the actual physics of star-formation and black hole growth in distant galaxies. The new generation of wide-field and multi-object IFU spectrographs (such as KMOS and MUSE on the VLT) will offer an unprecedented possibility to distinguish star formation and nuclei activity when they occur jointly in high-redshift galaxies (using new diagnostics such as the mass-excitation diagram: Juneau et al.2011, ApJ 736, 104), which puts us in excellent position to obtain a much more complete census of black hole growth and its interplay with star formation in all types of galaxies. We have already been very successful in obtaining open observing time on this topic over the past 12 months (several regular programs and two DDTs on JVLA, IRAM/PdBI, VLT/XSHOOTER, VLT/SINFONI). This opportunity on the observational side is perfectly matched on the simulation side with the rapid growth of computation facilities at the European scales. Our group is perfectly positioned to maximize their use with high-resolution simulations ideally suited to compare to deep spectroscopic data from such IFUs.
At larger, cosmological scales, we are entering a true panchromatic era in the study of galaxy cluster populations up to high redshifts thanks to the combination of the Planck survey legacy, the extension of XMM potentially up to 2018, the e-Rosita X-ray survey, recent or upcoming radio and high energy facilities (LOFAR, ASKAP/EMU, nuSTAR, CTA) and ultimately, the Euclid mission. We will also investigate a possible participation in the CCAT project of a 25m sub-mm telescope at Chajnantor led by JPL and Cornell University. Altogether, this offers a truly unique opportunity to reveal the full properties of an unbiased cluster population, which is essential for a precise understanding of cluster astrophysics as well as for cosmological applications.
Several team members are strongly involved in the preparation of the Euclid scientific exploitation, especially regarding the Legacy Science on galaxy evolution and AGN (D.Elbaz is co-coordinator of the Euclid Galaxy Science Working Group and other team members are assigned to scientific work packages). This will lead to new and strategic

collaborations extending our expertise in the field, and furthermore placing our team in good position for the scientific exploitation of Euclid and related simulations, when it is launched soon after the coming five-year period.

Threats: In the coming years, we will become increasingly dependent on accessing time on new facilities such as 2nd generation instruments at VLT (KMOS, MUSE) or ALMA because we do not hold guaranteed time and we are not currently part of major surveys like Pan-Stars, DES, LSST and e-Rosita. With the increasing complexity of astronomical instrumentation and project sizes, the coming era will likely involve teams of greater sizes making it more challenging to develop new projects that are managed *in-house*. The foreseen competition will be stronger with facilities expected to be central in the field of galaxy formation/evolution, such as ALMA. However, the expertise and leadership of our team associated with the comprehensive study of the most observed fields of the sky such as the GOODS fields, and our recognized forefront position in topics such as molecular gas reservoirs (Daddi et al) among others, should represent an asset for our group. Therefore, we need to capitalize on this strength in order to mitigate against the threat of reduced guaranteed access to world-class facilities. The expertise of the team has grown thanks to our strong success rate in obtaining a rich financial support but with no definitive guarantee that future proposals will bring a similar success rate. Also, part of our success is a result of our involvement in the building of new instrumentation for e.g. *Herschel* and XMM. The next major instrument with similar local involvement is Euclid. To secure our leadership, we therefore need to maintain a critical threshold in size and expertise.

Scientific objectives of the LCEG team

(1) Unveiling the main physical mechanisms responsible for the growth of galaxies in stellar and black hole mass: can theory and observations be reconciled?

Context: a series of observational and theoretical results in which our team have played a leading role have concomitantly converged towards a scenario of galaxy growth dominated by continuous mass accretion and star formation rather than stochastic bursts of star-formation resulting from merging events. This is supported by:
(i) the phenomenological correlations between a galaxy star formation rate and stellar mass found for redshifts z~0 to 1 (Elbaz et al. 2007), 2 (Daddi et al. 2007, Elbaz et al. 2011), 4 (Daddi et al. 2009) which has been confirmed and extended to higher redshifts by others,
(ii) the finding that diffuse gas accretion dominates the fueling of galaxies (perhaps in collimated cold flows) responsible for the bulk of the star formation history of galaxies and for a large part of the growth of their supermassive black holes as we have started to argue,
(iii) the existence of large clumps of star formation in distant galaxies seen in high-resolution HST images and expected from numerical simulations developed by our team; these clumps arise when high gas fractions together with a rapid gas supply lead to violent dynamical instabilities.
This emerging scenario offers a new starting point in our understanding of galaxy evolution but in details it fails when comparing quantitatively model expectations with observations. In particular, models are far too efficient in forming stars at early epochs compared to the observed Universe. As a result, model galaxies use their gas reservoirs sooner and produce fewer stars at fixed stellar mass at intermediate redshifts (z~1). Although affecting all redshifts, this issue is particularly relevant at the still weakly explored z>2 epoch, a peak era in galaxy and black hole growth. Thus, a major goal of our team for the coming years is to better quantify the still incomplete observational picture at z>2 and to investigate numerical/theoretical solutions to remaining disagreements with these improved observations.

Challenge: The central question here is to understand the balance between the cosmological supply of gas and its conversion into stellar mass and supermassive black holes.

Prospective for 2014-2018:
• ***Linking small-scale gas and star formation physics to scaling relations on galactic scales and cosmic inflows and outflows***. The violent dynamical instabilities specific to distant galaxies with large gas supplies are likely accompanied with feedback mechanisms different in strength and possibly nature, compared to local star-forming regions. Strong supernova rates likely involve outflows that can expel as much as half of the gas infall, while AGN radiative and/or jet feedback may compress or expel the ISM and lead to either a diminution or possibly an enhancement of star formation. These mechanisms can now be investigated owing to new generations of numerical simulations, capable of resolving molecular clouds with sub-parsec resolution. In the next few years, our team will couple these detailed models to the full cosmological context in order to study samples of galaxies with initial conditions reproducing realistic cosmological galaxy populations.
The “broadly Universal” Schmidt-Kennicutt law is now thought to describe complex star formation processes encompassing different modes: (i) galaxies presenting an excess SFR given their gas surface density as compared to most "normally" star-forming galaxies, (ii) distant gas-dense galaxies showing a reduced star-formation efficiency (SFR/Mgas) as compared to a pure Schmidt law possibly due to negative feedback, and (iii) low-efficiency systems which, surprisingly, can be either dwarf galaxies or massive early-type galaxies. Fundamental questions have emerged from these findings that we will address in the coming years by perfecting a better control on systematic uncertainties in existing data and by taking advantage of new facilities offered to the community such as ALMA. In particular, these various observed modes contrast with the puzzling homogeneity of Main Sequence galaxies. Does this homogeneity still hold at the scale of their star-forming regions (the well-known « giant SF clumps » of high redshift galaxies), or can the clump be “local starbursts” with efficiencies higher than their host galaxies? What is the response to feedback from newly formed stars? What causes starbursts in galaxies, i.e. enhanced SFR per unit stellar mass or gas mass and oppositely reduce strongly their star-formation efficiency? A major step forward in understanding star formation scaling laws from redshift 0 to z~2 can now be done by resolving and mapping the ISM properties in moderately distant

galaxies, to link small-scale star formation physics to galaxy-scale properties.

• ***Build a new picture of gas properties and star formation at z>2***. The cosmic evolution of the specific SFR (sSFR=SFR/M*) of galaxies above redshift 2-3 is still misunderstood, and even poorly constrained in current observations. Current, sparse data seem to indicate that the sSFR cosmic density stops increasing with redshift above z=2, which may be in conflict with theoretical models (e.g. Davé et al. 2011). Using various and complementary tracers of star formation activity within galaxies, we will refine the existing constraints on the sSFR evolution above redshift two and seek for dependence on galaxy mass. We will also constrain the evolution of the relative contribution of Main Sequence and Starbursts galaxies to the cosmic-averaged sSFR toward the highest redshifts.

• ***Understanding the concurrent growth of stellar and black hole mass***. Central Black Holes have grown in proportions tightly connected to the stellar mass growth of galaxies, but the physics driving this concurrent growth is unknown. The census of active BHs in the distance Universe is far from being complete, as standard selections are sensitive mostly to the brightest and less obscured AGN and QSOs (which may dominate the BH mass budget, but may not include important phases of feedback). Yet there is growing evidence that many high-redshift AGN reside in normally star-forming galaxies (not only in spheroids or starbursting mergers). Once we are able to thoroughly identify these AGN+SF systems, we will study the link between the nuclear activity and star formation: is star formation triggered/quenched in AGN regions or even in entire galaxies, are outflows triggered by the AGN or does the gas continue to flow toward the central BH over long duty cycles?

Tools:

• Exploitation of **multi-wavelength** surveys: we benefit from the deepest *Herschel* extragalactic surveys GOODS-*Herschel* (PI D.Elbaz) and CANDELS-*Herschel* (co-PI D.Elbaz, observations mid-2012) in the 4 best-studied extragalactic survey fields (GOODS-N, GOODS-S, COSMOS, UDS). Simulations using *a priori* knowledge of the typical IR SED and redshift distribution of galaxies will be used to quantify the local impact of source confusion due to the large beam size and dig deeper into these far-IR images. Refined prior source extraction techniques will be used to combine in a consistent manner survey data at all wavelengths from the radio, sub-mm, far-IR to the optical, UV, X-ray in these fields. Extension to deeper levels will be obtained from **stacking** images from various selection techniques including **NIR-selected high-z population** using **HST-WFC3**. This effort is strongly supported by a European network (ASTRODEEP, EC FP7 SPACE, 0.5 M€ for our group to hire postdocs), in collaboration with U.Bologna, U.Edinburgh and the CDS Strasbourg. Forthcoming *Herschel* data will be used in particular to search for z>2 rare analogues to local ULIRGs, i.e. extreme starbursts, so as to probe high-redshift star formation in extreme conditions.

• Intensive follow-up campaigns with **ALMA, APEX/ARTEMIS** as well as **IRAM PdBI+NOEMA and JVLA** will be performed. Access to ALMA time will not only beneficiate from the strength of our team to obtain open observing time but will also be facilitated thanks to our connection with Universidad de Concepcion, Chile (one co-advised thesis in 2009-12, starting program for long-term visiting students in the next years, and on-going preparation of a formal cooperation agreement between AIM and U. Concepcion). The bimodal distribution of galaxies depending on their star-formation efficiency between Main Sequence and Starburst galaxies remains to be firmly established by using more thorough studies of the molecular gas content of galaxies from the CO line as well as by probing the amount of high-density gas (e.g., using HCN). These will be compared to predictions of numerical and theoretical models of starburst galaxies (models that we now start to use for quantitative predictions of molecular line observations – based on a new coupling that we have developed between the **AMR hydro-simulations and LVG models**).

• Exploring these multi-parameter scaling laws linking the gas, stellar, metal and black hole content of galaxies will require very large samples, hence will be first explored on limited samples paving the way for later on statistically significant studies with **Euclid**.

• The interpretation of these observational results will intensively use our **in-house numerical models**, which as of mid-2012 are able to resolve the turbulence cascade in interstellar gas clouds over five decades of volume density, and include predictive prescription for stellar feedback processes (photoionization, stellar winds and radiative pressure, supernovae). A major development in these numerical models will be the inclusion of high-resolution recipes to model the accretion of mass by supermassive black holes and the re-injection of energy in the interstellar medium. We will develop a detailed physical understanding of the gathering of gas in proto-galaxies (observations of ionized and atomic gas), its conversion into cold and dense clouds (observations of various molecular transitions), the structure of these cold gas clouds (through high-resolution modeling down to the sub-parsec scale), and the effect of feedback from young stars and accreting black holes (in simulations and observations). As for black hole growth and AGN feedback, we will exploit a new “Grand Challenge” simulation program (recently awarded on the new CNRS Blue Gene, P.I. Gabor) to model self-consistently the dynamics of entire galaxies at ~2pc resolution and the formation of accretion disks around their central supermassive black hole up to ~0.02pc resolution using AMR zoom techniques. We will use these news models to study the link between large-scale gas flows and real black hole accretion/feedback.

• Our **simulations** can resolve the main scales of ISM turbulence, hence they can predict the chemical enrichment of gas reservoirs through turbulent mixing, when these have low star formation efficiencies. This will be used to propose **observational diagnostics** on the gas reservoirs in early galaxies at z>2, with ALMA and other instruments. We will also use other tracers of gaseous reservoirs than the usual CO molecule in order to better probe low-metallicity gas in galaxies that have merely started to assemble their stellar mass (e.g., [CII], CH+, etc.).

• **Optical+near-infrared IFU spectroscopy and radio interferometry** will be extensively used to resolve galaxies, separate AGN signatures from star-forming regions, and study their mutual properties. We will use more complete selections in observational dataset, including moderate/obscured AGN from studies of their infrared SEDs, or novel in-house expertise on emission line diagnostics (e.g. MEx, Juneau+11). **High-resolution simulations** (to describe the ISM structure, SF efficiency, and gas flows in detail) and prescriptions of the BH accretion rate (standard Bondi-Hoyle prescription, viscous/turbulent disk models, etc) will be compared to determine the most realistic solutions, interpret the observed gas motions and search for the main source of AGN feeding (merger-driven, secular modes and disk instabilities, stochastic processes) as well as mechanisms of black hole seed formation. IFU and interferometric observations will be used to determine when and where such BH activity occurs, in galaxies that have a mass-deficient SMBH, or conversely in active galaxies that have not formed a central stellar bulge yet.

(2) Morphological evolution of galaxies and the cause of their star-formation quenching

Context: the "death" of star formation in galaxies remains a major mystery both from the observational and theoretical perspectives. At cosmic scales, star formation has declined steeply since z~1-2 and a dominant fraction in mass among present-day galaxies exhibit red colors typical of systems that stopped forming stars long ago. Massive galaxies appear to have died first, possibly through internal negative feedback processes emptying their gas reservoirs and/or preventing further gas infall, as well as environment effects. Forming Red-and-Dead spheroids may require energy injection by active nuclei but a better understanding of this mechanism requires (i) a more complete census and detailed studies of the interplay between active nuclei and the interstellar medium and (ii) more realistic modeling of feedback in high-resolution simulations in a cosmological context, to resolve accurately the dynamical and stochastic interactions between AGN and surrounding gas, and study the resulting effects on gas ouflows/inflows.

Challenge: to establish the relative roles of galaxy mergers, large-scale environment, internal galaxy dynamics and feedback in shaping the morphology of galaxies, triggering and/or quenching star-formation and black hole growth.

Prospective for 2014-2018
• **MATLAS**: probe of galaxy evolution with extremely deep optical images (**CFHT-MEGACAM** g=29 AB)
New observational techniques and data processing can now achieve unprecedented levels of surface brightness in the optical imaging of nearby galaxies allow us to study the stellar populations in the outermost regions. Their properties (color, morphology) provide information about their growth in mass over the last billion years. A CFHT Large Program has just been accepted (2013-2016) to image the closest 260 early-type galaxies in five bands, completing a set of data that has started to be achieved through the international collaborations Atlas3D and NGVS. Expertise in the detection and identification of structures of lower surface brightness (e.g. tidal tails) is in the process of being acquired. Results will be compared to predictions of cosmological models and simulations in cosmological context already available as part of the Atlas3D collaboration (and largely developed in the LCEG laboratory).

• Exploitation of **numerical simulations of galaxies at cosmological scales**: our objective will be to strengthen the use of our numerical simulations with the adaptive mesh refinement code RAMSES to cosmological scales. So far, the focus was on the analysis of "dedicated" simulations or simulations in cosmological context; we want to bring these simulations to a more global scale in the cosmological context. Developing accurate models of baryonic processes (AGN and stellar feedback, outflows…), as proposed in part (1) above, is of fundamental importance for cosmological simulations, in particular in the context of EUCLID: these processes can significantly affect both the baryonic distribution and the dark structure of the Universe at relatively large scales and may affect cosmological parameters estimates. However the effect of baryonic processes on dark matter structures remains poorly understood because of the lack of accurate, predictive models, in particular for accretion and feedback processes. Our high-resolution simulations (idealized galaxy-sized models with accurate ISM modeling + cosmological zoom-in techniques) are ideal tools to study these multi-scale effects.

• We are extending our expertise on **quantitative morphological analysis of distant galaxies**, in order to better quantify the contribution at cosmological scale of the various mechanisms that govern the evolution of galaxies and in the prospect of preparing the **Euclid** mission (start of a new postdoc, A. Cibinel with E. Le Floc'h). Technically: we will produce maps of stellar mass density and star-formation density from WFC3 and ACS images. Scientific goal: study of the morphology of galaxies in the "starburst" mode of star-formation, identification of interacting systems among galaxies following the SFR–Mstar fundamental relation, identification of stellar bars, evolution of the bulge-to-disk ratio and comparison with simulations obtained in our laboratory.

• We plan to dedicate substantial effort to link the properties of galaxies (stellar mass, SFR, nuclear activity) to those of their **dark matter haloes using clustering** and abundance matching techniques in order to characterize the effects of **environment** and the role of the phases of "**quenching**" in the formation of elliptical galaxies. This project will also enable us to position ourselves in the scientific exploitation of **Euclid** data, particularly on the link of "Legacy" and "cosmology" type analysis (e.g., tomography of the distribution of dark matter halos). In parallel, we will lead zoomed cosmological re-simulations (with our in-house multi-scale techniques e.g. Martig & Bournaud 2010 or other techniques) with high-resolution capturing the details of interstellar gas physics, star formation and AGN feeding. We will study the interaction between AGN outflows (and star-formation outflows) and infalling baryons to better understand the conditions that can lead to quenching of fresh gas infall and star formation.

(3) Unveiling the physics of large-scale structure formation in the dark-dominated universe

Context: The statistical properties of galaxy clusters (structure and scaling laws, mass function, and their evolution) are uniquely sensitive to cosmology and the physics of structure formation. The properties of local clusters ($z<0.2$) are now well established. Excellent quantitative agreement between X-ray derived dark matter profiles on relaxed clusters and theoretical prediction is observed. However there is not yet perfect convergence between X-ray and lensing studies and the critical test on the full population, and its evolution is a severe bottleneck. Similarly while the present-day gas entropy is well measured, pointing out the importance of AGN heating, the entropy evolution is critical to disentangle the effect of the various non-gravitational energy inputs. Finally the understanding of non-thermal component is in its infancy.
Current best cosmological constraints from clusters on the equation of state of the Dark Energy are from the X-ray observations with typical precision of $\delta w=\pm 0.2$ (Vikhlinin et al. 2009; Mantz et al. 2010). Constraints are still limited by systematics due to selection and uncertainties on the mass-observable relations.

Challenge: Limited redshift leverage and selection bias have reduced the pertinence of our understanding until now.

Prospective for 2014-2018: Our work will build on the Planck survey and the XMM Very Large Program XXL, which will provide largely complementary cluster data sets. The Planck catalogue, based on the full mission, is expected to contain essentially all the rare, massive ($M > 7 \times 10^{14}\ M_\odot$) clusters in the Universe up to z=1, while the dominant population at the XXL sensitivity will be group scale objects at z~0.5. The former population is ideally suited for the study of dark matter collapse, as well as the dynamical evolution of baryons in the dark matter potential well, as it is the least affected by complex non-gravitational physics. The latter population is sensitive to such non-gravitational processes like galaxy feedback and are privileged targets for the understanding of these effects. Both samples have the necessary redshift leverage and size for competitive assessment of evolution, a key diagnostic to distinguish between various theoretical models. Both samples are relevant for cosmological studies and again are complementary in that respect as they probe different regime of the mass function and selection techniques.

Exploitation of the *Planck* survey
This will be conducted in synergy with other major surveys (**RASS, WISE, LOFAR/ASKAP**), together with intensive follow-up (**XMM** including the two recently granted Large Programs, **VLT, HST**) and numerical simulations to test the standard ΛCDM scenario and understand gravity driven structure formation (M. Arnaud, G. Pratt, H. Aussel, R. Teyssier and J.B. Melin (SPP) in coordination with Planck Working Group 5):
Continue active involvement in **Planck** collaboration to build unbiased mass-selected samples of massive galaxy clusters up to z~1. The Planck catalogue for the extended mission is expected to contain about ~1500 clusters detected at S/N>4. It will be published early 2014, but full validation and scientific follow-up (e.g. redshift estimate) will continue much beyond that date. We also envisage to develop novel detection techniques based on a simultaneous SZ and X-ray search, to extend the catalogue, with potential application to upcoming surveys like **e-Rosita** and as a pathfinder for other multi-wavelength cluster searches.
Provide a decisive **test of the ΛCDM model** of the dark matter gravitational collapse from full statistical analysis of the dark matter profiles of massive clusters, and of their evolution. Extension of the X-ray mass profile estimate to the full cluster population made possible from systematic confrontation of observations with tailor-made numerical simulations.
Assess the **dynamics of baryons** within the evolving dark matter potential: 1) provide the first census of the dark matter and hot and cold baryonic phases up to z~1, 2) measure the dynamical state, entropy and pressure profiles as probe of hierarchical formation and gravitational heating, 3) probe the redistribution of energy between the thermal gas and non-thermal components (relativistic particles and magnetic fields)
This work will provide inputs for the **cosmological exploitation of the Planck cluster sample** (e.g. evolution of $M-Y_{SZ}$ relation, of pressure profiles), to which we will continue to participate.

XXL: The Ultimate XMM extragalactic survey
End of 2010, a Very Large XMM program – the XXL survey - has been allocated to the SAP to perform a medium-deep survey of 50 deg2 (M. Pierre, PI). This will yield some 500 clusters of galaxies out to z~1.5 and provide constraints on the Dark Energy equation of state at the Stage III level (last step before missions to cover very large fractions of the sky), as advocated by the Dark Energy Task Force. The XXL survey, with numerous associated surveys in radio, IR, optical and UV, will enable truly innovative extragalactic studies:
-The cosmological analysis along with a careful modelling of the survey selection function will unveil the evolution of the **scaling relations** for the cluster mass-range pertaining to the survey. The associated STP-pol, ACT-pol (S-Z) and Subaru-HSC(lensing) guaranteed time surveys will allow us to pinpoint cluster masses and the properties of the ICM.
- A census of the **cluster population** in the 1<z<1.5 range.
- A detailed study of the **z~0.5 groups**, which constitute the dominant population at the XXL sensitivity
- Some **10 000 AGNs** will be detected in the survey; for the first time, we will be in a position to compute the X-ray AGN correlation function on very large scales.
- The **legacy aspect** is very important: by the completion of the survey, the consortium will deliver the full X-ray source lists and images, an online catalogue of clusters (http://xmm-lss.in2p3.fr:8080/xxldb/index.html) as well as a multi-wavelength source catalogue (http://cosmosdb.iasf-milano.inaf.it/XXL/)
- In parallel to the science analysis, four independent teams are performing **real-size XXL numerical simulations**. The comparison with the observed cluster and AGN populations will help interpreting the physical processes at work in structure formation. The four virtual XXL surveys will be made public under the same format as the real data.

LFEMI - Laboratoire Formation des Etoiles et Milieu Interstellaire

1. Présentation de l'unité

a. Historique

The LFEMI results from the fusion of the Galactic star formation group with the nearby galaxies and interstellar medium group. This occurred around the exploitation of the Herschel programs, as both groups were poised to exploit similar observations, large maps of similarly extended and sub-structured objects, i.e. dust clouds of various sizes and temperatures, and with complementary scientific objectives, namely understanding star formation processes on different physical scales.

b. Caractérisation de la recherche

The LFEMI is essentially a fundamental research laboratory, as its principle aim is to work at the frontier of knowledge in its areas of expertise (i.e. star formation processes and the physics of the interstellar medium). However, as a part of AIM and CEA, the LFEMI also has an implicit mission to provide momentum to the instrumental research and development at AIM. It does so by continuously identifying the key questions in its fields and participating in the different prospective exercises aimed at defining which future facilities the community will need. This is clearly demonstrated by the constant involvement of our members in instrument consortia at various maturity stages, as well as by the fact that a significant number of the grants we have received contain an instrument development part.

Even-though LFEMI is primarily connected with the academic research community, we devote a fraction of our activities to the public at large, given the strong appeal that our research fields have. We regularly volunteer to participate in science-related events, on a large range of audiences, from the local to the national ones.

2. Analyse SWOT et objectifs scientifiques de l'unité

Strengths

- Our research themes (initial conditions for star formation and the origin of the IMF, massive stars and the interstellar medium in galaxies) have led us to significant discoveries that gave us a high visibility. This is demonstrated through our success with national and international funding agencies: as PI, the LFEMI secured 1 Advanced ERC grant, 3 ANR projects, and 2 ASTRONET proposals. Not counting Herschel programs, we also obtained, as PI, about 34 observing proposals (including large programs on facilities such as IRAM PdBI).
- We gather in the laboratory comprehensive competences regarding Herschel, from the instrumental expertise, to the development of innovative data processing techniques (map-making, source extraction, large-scale structure identification).
- Our in-house general-use tools have reached maturity level: the dust emission model by F. Galliano, the multi-scale and multi-wavelength source extraction and structure detection algorithm of A. Men'shchikov, and the massively parallel inverse problem solver of P. Chanial are now used beyond their creators' circle. These tools will not only strengthen our own projects, but open new possibilities of collaborations.
- We attracted a significant number of PhD students and post-docs, 18 in total. Particular emphasis was placed on training for ALMA-related science and techniques, as well as physical modeling tools, in order to prepare for the future.
- We have significant stakes in future projects for large submillimeter focal plane arrays (ArTéMiS, NIKA) that offer interesting perspectives for our research themes.

Weaknesses

- No young scientist was recruited since F. Galliano in 2008. With the increased pressure from management responsibilities (M. Sauvage is Euclid Ground Segment Scientist, ERC and ANR PI-ships for P. André and S. Madden), our permanent staff has a reduced capacity to steer the science activities. With respect to our future initiatives on gas+dust modeling or interferometric observations, our inability to recruit some of our efficiently trained temporary staff is worrying.
- As the laboratory was formed from two entities, one concentrating on star formation in the Galaxy and one concentrating on the interstellar medium of galaxies, a risk exists of evolving toward a structure made of two unconnected groups within the same laboratory. A number of internal initiatives have been taken to steer us away from this risk, and the new generation of instruments offers clear opportunities as well (cf. Opportunities section).

Opportunities

- With the recruiting of P. Hennebelle in the numerical simulation laboratory (now Laboratoire de Simulation des Plasmas Astrophysiques, with which we have a long term collaboration), AIM is in a position to realize simulations of the star formation process from the smallest scales of the pre-stellar core to the large scale of galaxies themselves. Strong collaborations with this part of AIM can help us understand better key questions raised by the Herschel observations.
- Large submillimeter interferometric arrays (ALMA, NOEMA) are coming on-line. Thanks to their high spatial resolution, star-forming regions of nearby galaxies can be studied with as much details as what was offered by Herschel on Galactic high-mass star-forming regions. This is an opportunity to truly join the main science themes of the laboratory, as nearby galaxies enlarge the spectrum of interstellar physical conditions.
- The airborne SOFIA observatory is now operating. This telescope is well adapted to prolong our studies on the physical conditions around massive star clusters in nearby galaxies, a theme on which we have gained significant expertise with Herschel.
- P2IO LabEx: this structure gathers many local laboratories among which the Institut d'Astrophysique Spatiale. We have numerous individual collaborations with the IAS (in the framework of the Herschel programs for instance), but the LabEx offers the opportunity to reach a higher level.
- FOCUS LabEx: this program is geared toward the development of new detectors for the IR and sub-mm domains and has star formation as one its main scientific themes.

Threats

- The next period will see the transition to a post-Herschel era. We have now a demonstrated scientific track record that should allow us to fare well in the competition for time on international facilities, but the mode of access to new data will effectively radically change. This combines to the fact that the submillimeter projects in which we are actively participating (ArTéMis on Apex, NIKA for IRAM through the ORISTARS ERC) imply a change in our methods (e.g. no science exploitation support from CNES for instance) or are in the very distant future (SPICA).
- For a laboratory, and science themes, that relied heavily on space-borne submillimeter observations, the long-term European future is worrisome: there is no selected mission, or projects about to be submitted to future calls in the coming decade, and development of ground-based instrumentation is focused toward the optical and mid-IR domains for the ELT.

The main features of the LFEMI project

Looking at the principal milestones that lay in our future, it is quite clear that on a five-year term the Herschel data will feature prominently in our activities. However the period will offer many opportunities to expand on our research themes (using e.g. ALMA, SOFIA, and the new generations of large submillimeter cameras). This expansion beyond the Herschel-supported science will be necessary to prepare ourselves for the longer term, when facilities such as SPICA/Safari, and the JWST will become available.

To detail our project for the next reviewed period, we must realize that we have now reached a state where we understand the properties of the Herschel instruments, we have the tools needed to interpret the data and the fundamental questions raised by these new observations have been clearly laid out. We thus plan to devote most of our energy to the optimal exploitation of this very rich database, obviously along the lines of the two ANR projects (SYMPATICO and STARFICH) and the ERC AdG ORISTARS as their time spans will cover an important fraction of the period envisioned in this report. In their broad lines we describe here the main topics that our project will address and we will provide more details in section 3:

- Dynamical processes in star-forming regions. With the large and sensitive submillimeter interferometers ALMA and NOEMA, we shall investigate issues related to the mass accretion on filaments, pre-stellar cores and protostars. Indeed Herschel has revolutionized our view of the structure of star-forming regions, and the relations of this structure with the star formation process itself, but the dynamical information is severely lacking. Numerical simulations will be called upon to disentangle the complex dynamical signatures we will unveil.
- Massive stars near and far. Both through the identification of a critical column density threshold for massive dense core formation, and through the source-per-source estimation of the star formation rate in Galactic clouds, we can now directly compare Galactic and extragalactic star-forming processes. We will pursue this activity by identifying more regions that can bridge the divide between our Galaxy and its more distant neighbors, and by validating the consistency of the different tracers used on these vastly different scales.
- Accounting for all the ISM phases. As we developed our understanding of the ISM tracers, it has also become clear that very significant biases still exist in the dust and gas mass tracers, and that significant phases of the ISM have escaped detections, e.g. the so-called "dark gas" phase. We have demonstrated how important a precise accounting of the structure of the ISM is in interpreting the information from the physical tracers. We have developed a number of investigative tools for this purpose (e.g. FIR lines, Density-Temperature diagrams), and through modeling work and new observations (ArTéMis, SOFIA, ALMA), we plan on tackling this issue on a wide range of galactic environments.

3. Mise en œuvre du projet

Dynamical processes in star-forming regions

Altogether, the early results from Herschel imaging surveys have led us to build a scenario in which interstellar filaments and pre-stellar cores represent two fundamental steps in the star formation process: first, large-scale MHD turbulence generates filamentary clouds in the ISM; second, the densest filaments fragment into pre-stellar cores (and ultimately protostars) through gravitational instability. A number of critical issues are however still open that we intend to tackle during the next period, all related to the issue of the universality of this scenario for all mass scales.

The first of these deals with the formation of the filament network itself. For instance, in the turbulent formation picture, we would need to evidence low-velocity interstellar shocks associated to the filaments. In the same line of thought, the static picture revealed by the Herschel observations raises many questions regarding its evolution and we can wonder whether the thermally-subcritical filaments observed with Herschel are long-lived structures with thermally-dominated velocity dispersions or transient, highly-turbulent structures. This is connected to the fate of this subcritical filaments, namely whether they evolve into supercritical filaments by gaining mass or disperse in the diffuse ISM? Given that we have identified that the filamentary structure is the first stage in the star formation process, understanding its formation and evolution is key to understanding the formation of stars themselves and particularly the efficiency of the process.

On the theoretical front, we will perform magneto-hydrodynamic (MHD) numerical simulations with the RAMSES code including cooling, self-gravity, and magnetic fields. These simulations will be used to investigate the properties of MHD turbulence in a thermally bi-stable flow (such as atomic hydrogen), as well as the properties of the filaments and clumps formed in such a flow. We will compare the statistical distributions of properties such as filament thickness in the simulations with the observed distributions. We expect these quantitative comparisons to yield much insight into the mechanism responsible for the formation of filamentary molecular clouds.

On the observational front, we have an approved Herschel project (OT1_pandre_4, 58.3 hr of priority 1 time) to test the hypothesis that filaments are formed behind low-velocity interstellar shock waves, by searching for shock signatures in the form of CII, CI, CO emission lines from the post-shock gas. We also plan to use the NRAO Green Bank telescope (GBT) and the Nançay radio telescope to carry out wide-field mapping of atomic gas in several cloud complexes of the Gould Belt. These telescopes can map fields of linear sizes ~ 10-30 pc, at a spatial resolution ~ 0.4 pc at the distance of the nearest molecular clouds (d = 140 pc). This is well matched to the size of the above-mentioned numerical simulations and will therefore allow us to test the theoretical view of molecular cloud formation from atomic gas.

On the instrumental front, in collaboration with the NIKA consortium as part of the ORISTARS project, we will take advantage the polarization channel that we are developing for the next generation large-format bolometer array planned by IRAM for the 30m telescope. This will allow polarized 1.2 mm dust continuum emission to be mapped on scales ranging from individual cores to cluster-forming clouds, revealing the morphology of the magnetic field lines in molecular clouds, thereby helping to clarify the role of magnetic fields in generating filaments and forming pre-stellar cores.

The second aspect of this theme deals with the onset of gravitational instabilities in filaments, as this is the key step leading to the formation of pre-stellar cores. To confirm/refine the picture of core formation by gravitational instability within filaments, it is crucial to characterize the velocity field of the filaments seen in the Herschel dust continuum images. In particular, the simple gravitational stability criterion used in André et al. (2010) assumes that the filaments have thermally-dominated velocity dispersions when they approach the verge of instability. However, the non-thermal (turbulent) velocity dispersion may not always be small compared to the thermal velocity dispersion, in which case the critical mass per unit length at which filaments become unstable can significantly change. For a proper gravitational stability assessment, the 1-dimensional velocity dispersion within the filaments should thus be measured. This can be done by mapping lines such as $^{12}CO(1\text{-}0)$, $^{13}CO(1\text{-}0)$, and $C^{18}O(1\text{-}0)$ to probe the low-density outer envelopes of molecular filaments, and dense gas tracers such as $N_2H^+(1\text{-}0)$ to probe the inner crest of the densest filaments.

If the picture of the star formation process outlined here is even approximately correct, we also expect a significant fraction of the thermally supercritical filaments seen with Herschel to be globally gravitationally unstable and to undergo large-scale collapse/contraction motions, eventually leading to the formation of proto-clusters. We thus plan to use ground-based (sub-) millimeter radio telescopes, such as the IRAM 30m or the APEX 12m telescopes, to carry out follow-up molecular line studies of a representative sub-sample of the filaments identified with Herschel in a wide range of star-forming clouds, in order to set constraints on the dynamics of filament fragmentation and core formation. The methodology we propose to follow is directly inspired from our successful study of the NGC 2264-C cluster-forming clump (Peretto et al. 2006, 2007). We will use the Herschel submillimeter dust continuum maps to trace the spatial distribution of mass, molecular line mapping in both optically thick and optically thin tracers to set constraints on the velocity fields, radiative transfer calculations to derive quantitative properties of the velocity fields, and numerical MHD simulations to derive self-consistent physical models. We note that, while quite successful, the simulations of Peretto et al. (2007) did not include magnetic fields. Using the MHD version of the AMR code RAMSES, we intend to perform new, dedicated simulations of several cluster-forming clumps, such as the densest filaments revealed by the Herschel Gould Belt survey, which will include magnetic support self-consistently.

Massive stars near and far

With the HOBYS survey, we have been able for the first time to statistically study the formation of 10-20 $M_\odot$ stars in 100 pc molecular complexes in nearest portion of the first Galactic arm towards us (Motte et al. 2010). Exploitation of the survey is far from over; furthermore, other surveys by Herschel such as the Hi-GAL have mapped more star-forming regions of the Galaxy containing massive protostars. Thus a substantial amount of work in the next period will be dedicated to a proper and as complete as possible accounting of massive proto-stars in large Galactic complexes. This emphasis on massive stars in our galaxy is quite natural in the LFEMI given that it is that fraction of the IMF that has the most detectable impact on the ISM properties of galaxies, and thus on their FIR and submillimeter SEDs. Therefore it is through the study of massive star formation that the laboratory truly finds its unity.

A first aspect of this work will be a natural extension of the investigations detailed above. Indeed the question still remains whether ridges, the high column density counterparts of the ubiquitous filaments, in which massive proto-stars are found, require a different mass accretion mechanism or not. The scenario that is developing for low column density filaments has turbulence and gravity slowly concentrating matter on and along the filaments. Yet ridges are most probably forming and growing through a more dynamical process such as free-fall or converging flows on the most massive structures. Given the physical size of the structure, we wish to obtain dynamical information on scales from 10 to 0.1 pc, i.e. comparable to the characteristic widths of filaments. This is possible, using instruments such as HERA and EMIR on the IRAM 30m, and as of today we have indeed shown that the DR21 and W43 are globally free-falling (Schneider et al. 2011, Motte et al. in prep.) and display shocked gas (Nguyen Luong et al. in prep.). We intend to use the Herschel surveys to focus on the many-more interesting ridges for these dynamical studies, in order to identify whether the formation of massive dense cores involves another physical threshold in gas density.

A second important aspect of this work is that these massive star-forming regions allow an in-situ study of the star-formation process in its "high-state", i.e. close to the so-called starburst regime encountered in galaxies. Given that the regions have been surveyed at high spatial resolution with Spitzer and Herschel, it is now possible to directly count the number of sources at different stages of the formation process, and thus measure past, present and future star formation rates. We will perform these counts in a systematic way over a large number of Galactic regions that we have surveyed (e.g. Cygnus X, W43). This opens very interesting perspectives both toward extragalactic studies and simulation studies, with an ultimate prospect of closing the loop between these two fields, i.e. providing a physically-based recipe for computing the star formation rate in simulated galaxies.

On the simulation side, the interest of these Galactic regions is that we can estimate the star formation rate as well as measure the properties of the molecular cloud in which this is taking place (e.g. total mass and mass distribution as a function of physical scale). This allows the computation of quantities that can directly be related to the simulation such as the star-formation rate per free-fall time. Another such "observable" is the mass transfer of gas from pre-stellar cores to massive stars: comparing the evolution of the star formation rate as a function of time or total mass involved can reveal how cores fragment or merge as they evolve. Thus we plan to interact tightly with the numerical simulation laboratory to define which features can be extracted from our observations that provide the strongest constraints on the simulation free parameters.

On the extragalactic side, we have already shown that we observe in Galactic star-forming regions a relation between the star formation rate surface density and the gas column density that is very similar to the Schmidt-Kennicutt law observed in galaxies. Given the practical importance of the Schmidt-Kennicutt law (i.e. it is the foundation on which almost all numerical recipes for star formation rest) this observation needs to be studied in many more details to certify that it is not coincidental. Indeed there are large differences between the way the star formation rate can be measured in Galactic molecular clouds and on the scale of galaxies, and the beam dilution that occurs when molecular clouds are observed in external galaxies significantly affect what we measure as a column density. However once again, we now have in our possession a broad sample of Galactic star forming regions where these investigations can be done. In the coming period we shall also benefit from large ground-based submillimeter cameras (e.g. ArTéMiS) that we shall use to obtain higher resolution maps of our regions. This will be quite important to identify possible substructure in the massive cores, which can bias our estimation of the star formation rate.

Accounting for all the ISM phases

In order to preserve our originality among our competitors and partners, our project will favor very detailed studies of nearby objects, with high sensitivity and spatial resolution. Our goal is to refine our physical diagnostics, and remove the various degeneracies (e.g. between the ISM structure and the physical conditions or between the dark gas and exotic grains), which are currently limiting our interpretations. The body of experimental data that we plan to exploit will consist in the rich archive of Herschel spectroscopic and photometric data that we have accumulated thanks to our participation to a wide range of programs (augmented when needed by the publicly available Herschel archive), while follow-up with new ground-based and air-born telescopes will expand on sensitivity, wavelength range and spatial resolution (e.g. SOFIA, CCAT, ALMA, LMT and APEX, etc.). The overall plan is to use the period to enhance our expertise and participate in the emergence of research themes that will be hot topics for SPICA/SAFARI, an instrument dedicated to FIR and submillimeter spectroscopy that should fly at the end of the decade.

The SPIRE FTS and the PACS spectrometer gave us access to the full rotational ladder of CO along with the highest quality FIR and submillimeter fine structure and molecular transitions. These can be turned into valuable diagnostics of density, temperature and column density, and trace the energy sources in the molecular, atomic and ionized ISM. In particular, we have shown (Lebouteiller et al. 2012, accepted by A&A, Cormier at al. 2012, submitted to A&A) how the combination of [NII] (122 and 205 µm), [OI] 63 µm and [CII] 158 µm can be used to trace a wide range of ISM phases, from the Warm Ionized Medium to the Cold Neutral Medium and the PDRs, revealing the ambiguities associated with the broadly used [CII] line. We are also investigating how the Temperature-Column Density diagrams of star-forming clouds can reveal the different phases in the clouds (Didelon et al., in preparation), providing further constraints to the line-only diagnostics. This broad observational basis will make for a more realistic approach to the structure of the ISM of galaxies, in the sense that it will capture more of its intrinsic complexity. Our group has already made significant steps toward complex multi-phase models of galaxies: we produced the general dust model of Galliano et al. (2011) and we are now implementing this model in a multipurpose tool to provide Bayesian SED fitting, continuum radiation transfer, and computation of non-thermal grain emission (Galliano et al., in preparation). To complete our capacities to decipher the FIR-submillimeter spectral energy distribution we need to also treat the line emission and to this aim we will link the excellent photoionization physics of CLOUDY to a better-suited PDR model that has more predictability for the molecular gas physics and can deal with the PDR geometry issues: i.e. include 3D geometry in PDR codes. This will allow the generation of clumpy ISM models, which we know are essential to represent the multiphase ISM of real galaxies. This is the aim of the efforts we will develop in the SYMPATICO ANR project, in collaboration with the LUTH (Observatoire de Paris). By linking IR to mm dust and gas observations, we will be able to study the heating and cooling of all ISM phases and explore how this is related to the star formation, ISM structure, and the propagation of the ISRF in galaxies.

In particular, we plan to use this comprehensive approach to move beyond the famous X_{CO} obstacle (i.e. the extremely uncertain relation between the CO luminosity and the H_2 mass). This will be beneficial for the interpretations deployed on global scales of galaxies where different assumptions on the X_{CO} value can possibly lead to, or blur, the identification of different regimes of star formation. This work will be part of the interface we intend to keep active with the LCEG at AIM.

We will, however, keep the emphasis on nearby objects, as it is especially well suited to the expertise present in the LFEMI. It will open areas of fruitful collaborations on Galactic and extragalactic star-forming regions: for instance, we can study on a wide range of physical scales the impact of the past, present and future star formation activity in the traces it leaves on turbulence, cosmic rays, or magnetic fields (that we can access through velocity information, high-energy gamma-rays, and polarization studies).

Application of this suite of tools to our rich observational database that will provide several well-constrained empirical diagnostics of the physical conditions in galaxies, as well as qualitative understanding of the nature (composition and physical conditions) of the ISM in galaxies of different masses and evolutionary stages.

In future development, these studies will also connect to the issues of the evolution of galaxies. In particular, we will study dust production and destruction mechanisms, as these processes are crucial to explain the evolution of the gas-to-dust ratio as a function of metallicity, another highly uncertain ISM parameter. We plan on studying these mechanisms both through the modeling of the Herschel observations of low-metallicity object as well as through a dedicated network (called SUNDANCE for "SUperNovae, Dust, And its Cosmic Evolution: observations and theory) that P. Bouchet will submit to the Marie Curie Actions. In this way, we will understand the first stages of dust production at low metallicity, and explore the deviation from the trend of metal-to-dust mass ratio vary as a function of metallicity.

The further developments of our ISM modeling tools will also let us test the nature of the mysterious submillimeter excess in dwarf galaxies that we were the first to unveil. Theoretical modeling of spinning grains, as well as grain cross-sections varying with the physical conditions (temperature, metallicity, UV field, etc.) are currently advocated to explain the excess. Combining our rich observations, with an increase capacity to disentangle the phases giving rise to the emission, and the possibility to perform high-resolution continuum follow-up observations will definitely enable us to progress in our understanding of this regime.

LDEE - Laboratoire Dynamique des Etoile et de leur Environnement

1. Présentation de l'unité

LDEE is a fundamental astrophysics research laboratory seeking to better understand stars and their environment. As in most academic research entity, the permanent members of LDEE supervise masters & PhD students, postdocs and CDD's who are actively participating to the research activity. It also regularly participates and organizes public outreach events. LDEE will contribute to societal challenges via its project of developing solar activity forecasting tools. Through various projects (SO/STIX, Herschel/ISM, COAST/Simulations, Tidal effects, etc…) LDEE is exchanging regularly with other AIM laboratories contributing to its overall scientific goals. Through its numerous international collaborations LDEE is developing state-of-the-art research in stellar dynamics and interactions with their surroundings.

2. Analyse SWOT et objectifs scientifiques de l'unité

Strength: -3 Complementary & Synergistic approaches: Theory, Observations/Analysis (ground and space) and Simulations/Models
-High citation publications count (240+ ref papers, 4600+ citations) for a team of 4 tenure researchers
-Several funded projects via grants/networks: ERC-STARS2, ANR-Toupies & IDEE, FP7 networks IRSES, SPACE-INN
-Various national funding sources: PNST, PNPS, PNP, CNES, Campus Spatial
-High Attractivity: Many high quality PhD students + experienced postdocs from US, Japan, EU
-Strong links between inner and outer stellar dynamics, between astero/sismo/magnetism/planet search, between evolved and massive stars, between star-planet/disk/MIS interactions
-World-leading simulation programs & tools (ASH, PLUTO, STELEM, STAREVOL); new ASH-FD scaling beyond 10,000+ cores, simulations > 2 billions cells – Prize La Recherche 2011 in Astrophysics
Potentially leads to discovery or observation confirmation via direct simulations
- Leader for two international code benchmarks (dynamo & convection)
-World-leading data analysis pipelines (light curves treatment for Kepler-KASC & calibration – analysis of SOHO/Golf)
- World-leading theoretical results and prescriptions for stellar and multi-layers giant planets, implemented in most stellar evolution and planetary codes
- Our involvement in various teaching programs (M2S, Master Fusion, ENSTA, PostMaster IdF,…) help us find bright/motivated students
- Many keynote lectures and invited reviews, high visibility in international conferences; Several « faits marquants »
- We have an established strong national network via various key large observation programs: MAGIC, Mimes/Binamics/Matysse, satellites CoRoT, SoHO-GOLF and institutes LESIA, IAS, IRAP, IPAG, IPGP, IRFM- Fusion,
- Likewise, we have many international scientific links via SoHO, *Kepler* KASC, Herschel, our MOUs with CU Boulder and STAREVOL consortium, HAO, JAXA/NAOJ, LMSAL, St Andrews, IAC, Obs Genève, U. Birmingham, U. Sydney, ….
-Links within CEA/AIM: Cosmostat: wavelet/MRE; ADP: tides dissipation/Moon formation; COAST: Simulations; LFEMI: formation/MIS
-Active participation in STIX and Solar Orbiter – Lien LSIS – Lesia (N. Vilmer)

Weakness: Overbooked tenure scientists: Need to reinforce Laboratory following recent Cosmic Vision selection (SO) in order to prepare science return
-Fundings post STARS2/Toupies era
-Fundings post GOLF, Herschel, CoRoT
-Possibility (time-wise) of maintaining – developing 3-D codes and analysis pipelines
-Difficulty of most committee to fund real innovative/risky projects

Opportunity:
- Our direct involvement in Solar Orbiter via STIX will give us direct access to top of the line solar data and constraints, likewise with our participation to Jaxa/Solar C selection panel and our link to NAOJ and Kyoto University.
- The fast development and (competitive) access to supercomputing infrastructure at the national and European level CEA TGCC-GENCI-PRACE allow us to answer key scientific questions and to push the realism of our simulations to the forefront thanks to our state-of-the-art parallel codes.
- Development of new collaborations within LabEx P2IO/UnivEarthS, Idex Paris-Sorbonne-Cité, Campus Spatial, DIM ACAV, FP7 Network, ERC. Our main research themes centered on Stars-environment dynamic and interaction and habitability conditions are among the main objectives of many of these funding bodies.
- The European Space Situation Awareness (SSA) program puts forward the need for an integrated solar vision and model and to the development of tools that can serve the civil society via solar activity predictions program using modern data assimilation techniques such as the ones developed in LDEE
- The selection of JUICE/Echoes, or PLATO, or PLAVI will reinforce our leading position in analysis/calibration of seismic data, 3-D simulations of large scale flows and dynamos in star and planets and theoretical prescriptions for stars and planets.
- Main research topics of LDEE (coupling in a common view observations, simulations and theoretical development of stars, planets and their interactions) is in line with ESA's Cosmic Vision and open new opportunities in space research

Threat :
- Access to supercomputing time due to higher Pressure factor

- Radical change in parallel supercomputing Infrastructures – survival of simulations codes
- Multiplicity of funding bodies – time spent on proposal vs science/research
- Lost of key postdocs to higher bidder
- Continuity of research team (knowledge) due to the multiplication of soft money/non tenured position
- Non selection of PLATO as M3 or PLAVI as S1 or Di-Echoes as part of JUICE payload

3. Mise en œuvre du projet

Over 2014-2018, LDEE's main scientific objective is to answer the central question :

How do stars and their environment work and interact ?

To answer this fundamental astrophysical question we have divided our research efforts into two main themes : *A) Dynamics of stars* and *B) Physics of stellar environment*. This project rest on the strong scientific results to understand and characterize the dynamics of stars of various types that we have published over the 2007-2012 period, with the clear objective of consolidating our current leading position in that field as well as to expand our blossoming research activity on the interactions between stars and their environment bringing this more recent activity to a similar level of maturity than task A.

A) Dynamics of stars

We seek to answer the following two major questions:

- How can we explain the history of stellar rotation and their abundances?
- What triggers magnetic activity and cycles in stars?

A.1) Simulations and models of the Sun and stars

In order to model stellar structure, evolution and dynamics on short (minutes to centuries) and secular (millenia to billion years) time scales one must take into account macroscopic physical processes that redistribute heat, chemical species, magnetic field and angular momentum. Processes such as convection, turbulence, rotation, waves, magnetic field and their associated instabilites are key to study and model and LDEE has largely contributed to the latest progress made in that domain. Over 2014-2018 we will consolidate our efforts by modeling and simulating stars of various masses and ages in 1-D, 2-D and 3-D thanks to our theoretical work and set of modern state-of-the-art numerical tools (STAREVOL, STELEM, ASH).

We will:
- Extend our analytical prescriptions of MHD processes to include a full description of angular-momentum history and waves transport in radiative interior; providing scaling laws and formulations for stellar evolution codes
- Develop 2-D solar and stellar dynamo models with nonlinear feedback (of the Malkus-Proctor type) and applied external torques (wind, tides) to model over long time scales stellar magnetism and activity
- Compute 3-D nonlinear high-resolution models of stellar convection, rotation and dynamo, seeking to determine what set their rotation profiles, stellar cycles and periods, the role of tachoclines and gravito-internial-Alfven waves
- Obtain self-consistent magnetic flux emergence in dynamo simulations and study the link between cycles, polar field reversals and flux transport and cancellation in full 3-D global nonlinear settings
- Model high-energy particles acceleration in solar flares in support of SO/STIX from 3-D MHD configurations of turbulent magnetic current sheets using the PLUTO code
- Develop and seek collaborations to post process our simulations to model UV, X fluxes, g waves detectability levels

We anticipate delivering the following milestones:
- 2yr: STELEM dynamo models with Lorentz force feedback and wind torque; G-K stars rotation and activity study; 3-D models of selected Kepler target stars; analytical theory and prescriptions for G-waves excitation and propagation in the presence of magnetic field
- 5 yr: 1-D MHD secular STAREVOL solar and stellar models; 1-D data grid portal of Omega(r) profile deduced from 3-D ASH models of various mass and rotation rates; Full gravito-inertial-Alfven waves theoretical treatment; Solar-like stars dynamo simulations with self-consistent flux emergence; High resolution simulation of the Sun (6,000^3) down to supergranulation; 11 yr solar cycle prediction/forecasting ; Post treatment pipeline of stellar numerical simulations (X, UV, etc…) ; Preparation of SO/STIX simulations and data analysis post processing ; 2 International meetings
- 10 yr: Grand challenge 3-D whole Sun models (12,000^3 resolution) in order to model convective scales down to granulation and small magnetic features (pores) and its nonlinear coupling to a deep radiative interior in a global spherical code; Interpretation SO/STIX data by state-of-the-art particle acceleration simulations in realistic 3-D magnetic field topology; Derive a complete MHD+waves framework for stellar evolution.

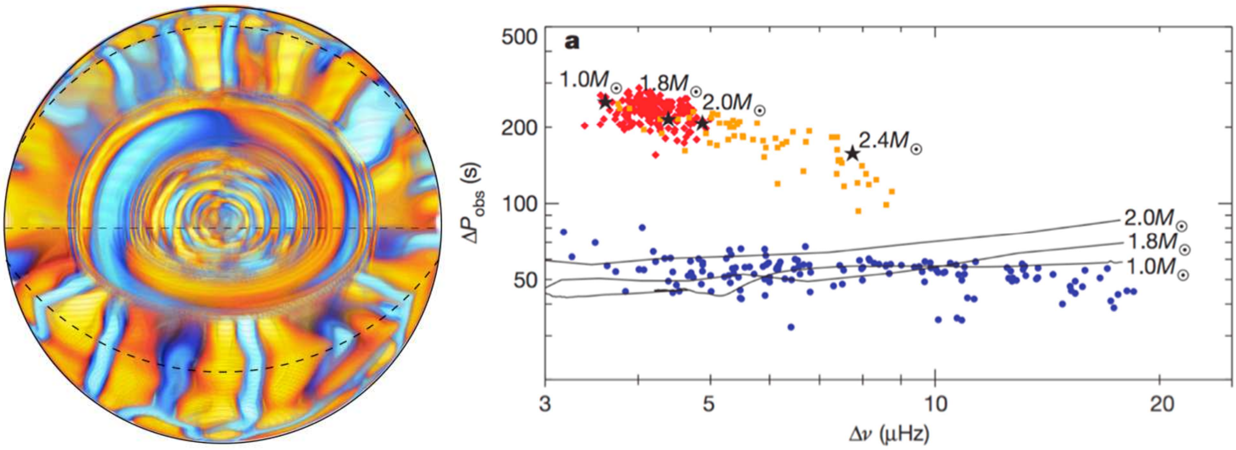


Fig 1: Left: Color rendering of the normalized radial velocity in a 3-D whole Sun model from which we have omitted one quadrant in order to see the internal waves propagating in the deep radiative interior (Brun et al. 2011). Right: Seismic H-R diagram showing how seismology can help distinguishing between RGB stars burning H or He in their core (Bedding,…, Garcia et al. 2011).

A.2) Observations and new constraints

Over 2014-2018, the extension of both the NASA's *Kepler* mission till 2016 and the French-led CoRoT satellite for 3.5 more years will provide an unprecedented set of data never obtained before in asteroseismology. On the one hand, more than seven years of continuous high-precision photometry on the *Kepler* targets will be available reaching a frequency resolution never obtained in a star other than the Sun, for hundreds of solar-like stars and even thousands of red giants. On the other hand, CoRoT --with its ability to observe bright stars in different regions in the galaxy-- will allow the study of particular stars for which we will have a much better ground-based follow up because they will be brighter than the *Kepler* ones, as well as several thousands of red giants in several directions of the galaxy outside the solar neighbourhood.

We expect to:

-Progress on the understanding of the physical mechanisms driving stellar magnetic activity cycles and dynamos by measuring activity cycles of *Kepler* stars thanks to the long datasets available. Indeed, with asteroseismology we will be able to measure, at the same time, the surface and the internal (differential) rotation, the properties of the convection zones (sizes and characteristic time scales) and the periods of the magnetic cycles (both surface and internal activity).

-Put new constraints on the temporal distribution of magnetic activity cycles as well as be able to establish the frequency in which two magnetic activity cycles (a short and a long one) are present in solar-like stars.

-Progress on the study of the chemical evolution of Galactic stellar populations by coupling the asteroseismic measurements providing masses, radius and ages with spectroscopic measurements done by the APOGEE survey (APOKAS survey).

-Study if there any statistical differences in the intrinsic properties of stars depending if they are isolated or if they are harboring planets

- with BinaMICS, we will obtain constraints on magnetism of all classes of stars in binary and multiple systems. Obtained results will give important information on the impact of gravitational interactions on stellar magnetism and also on MHD interactions in such systems.

- Participate to the development of a data analysis pipeline for SO/STIX in link with our colleagues in Lesia while developing turbulent MHD numerical simulations with the MHD PLUTO code.

- Continue the development of a physically based solar dynamo 11-yr cycle forecast model, working on various proxies

The expected deliverables would be:

-2yr: to create catalogues of seismic observables -including surface and internal (differential) rotation-, and inferred global stellar properties for *Kepler* and CoRoT solar-like and red giant stars

-2yr: provide the length of the stellar cycles, surface rotation, depth of the convection zone, and characteristic time of the granulation for the stars in which stellar cycles could be measured.

-5yr: to produce all the necessary hardware and scientific pipelines in support of the PLANET-VISION mission If it is selected by ESA.

-5yr: to produce a merged spectroscopic and seismic catalogue inside the APOKAS (APOGEE + KEPLER) consortium

- 5yr: Operational solar data assimilation (variational method) based on a Babcock-Leigthon dynamo model to forecast solar activity

-10yr: For those asteroseismic targets observed by GAIA, we will be able to infer a mass estimation down to a few per cent by combining the seismic variables with the radius obtained from GAIA's distances and a good estimation of Teff, and everything being approximately model independent.

-10yr: to provide, if PLATO is selected as a M3 mission, the software and the required management necessary to accomplish with our commitments within the consortium.

B) Physics of stellar environment

We seek to answer the following two major questions:

- How do stars interact with their environment and which processes are dominant?
- What is the impact of these interactions on habitability?

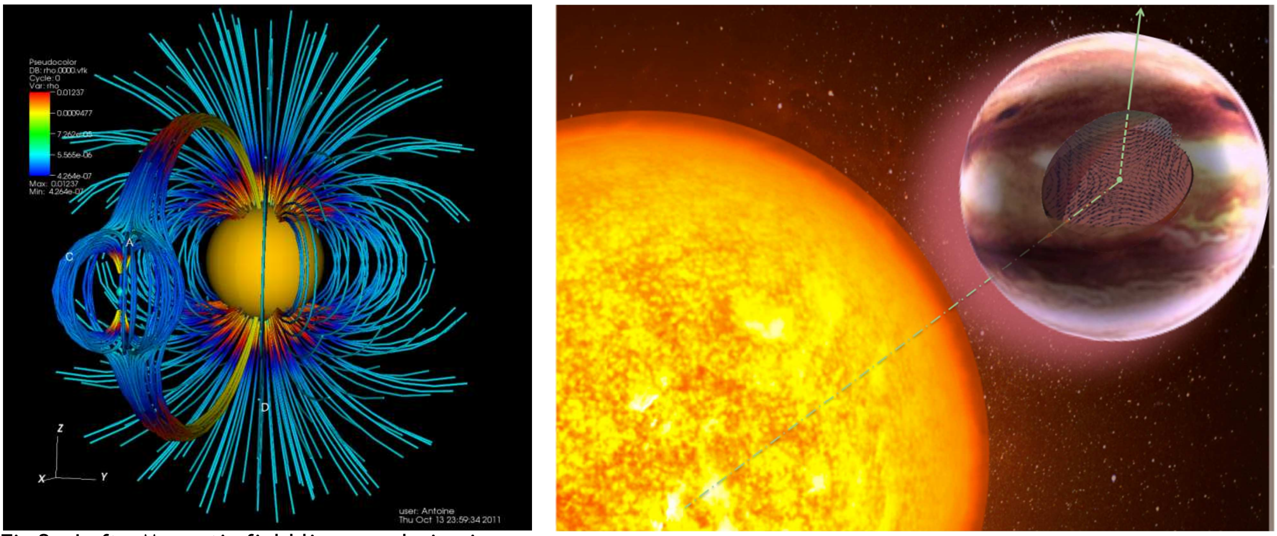


Fig 2 : Left : Magnetic field lines rendering in a star-planet interaction (SPI) configurations, in which both the star and the planet are magnetized (Strugarek et al. 2012). Right : Rendering of the elastic deformation of a Hot Jupiter's core due to the host star tidal interaction (Remus et al. 2012).

B.1) Star-Environment Interactions (tides, MHD, radiations)

As a continuity of what has been achieved during the period 2007-2012, the general study of the interactions of stars with their environment will be strengthen. The key questions on which we want to answer are: what are the physical processes that drive the Star Interstellar Medium Interactions (SISMI), the Star Planet Interactions (SPI), the Star Star Interactions (SSI) and the Planet Satellite Interactions (PSI). To answer this question, LDEE members will continue to develop coherent dynamical models of gravitational and MHD interactions in such systems. Then, strong efforts will be devoted to improve the modeling of stellar winds and of their interactions with their surrounding media (other stellar or planetary magnetospheres, region of stellar and planetary formation) and of tidal interactions.

To reach these scientific objectives, we will:

- Develop MHD models and simulations of stellar winds for all classes of stars using the PLUTO code taking into account realistic stellar magnetic configurations obtained in A.1. with 2D and 3D simulations or observed through spectropolarimetric observations (end of MAPP/MiMeS, BinaMICS and Matysse).
- Develop complete simulations of the interactions of stellar winds with planetary magnetospheres (SPI, preparation and exploitation of SPIROU) or stellar magnetospheres in the case of binary (multiple) stars (SSI, BinaMICs) and with the regions of formation of stellar and planetary systems (SISMI).
- Develop integrated models of tidal dissipation in stellar and in planetary interiors and of their consequences on stellar and planetary evolution (tidal heating, spins and internal redistribution of angular momentum) and on systems architecture (orbital evolution).
- Develop models of dynamical evolution of systems, taking into account simultaneously the obtained models of gravitational and MHD interactions.

We anticipate delivering the following milestones:

- 2yr: stellar wind models for various classes of stars; model of the interaction between massive star winds and stellar formation regions; advanced models of magnetospheric interactions in star-planet systems and in binary stars; first integrated models of tidal dissipation in stellar and planetary interiors.
- 5 yr: Deliver to the community complete grids of the value of the efficiency of tidal dissipation as a function of the stellar and planetary types and related applications to the Solar system bodies and to exoplanets; models of dynamical evolution of systems taking simultaneously into account realistic tidal torques and those related to MHD interactions (stellar winds and magnetospheric interactions);
- 10 yr: Global treatment of angular momentum exchanges in planetary systems taking into account both gravitational and MHD interactions and the internal exchanges of angular momentum both in stellar and in planetary interiors; obtain a comprehension of the impact of such interactions on the systems architecture (and their stability) and of their global impact on habitability conditions. Obtained results will be applied to systems studied by CoRoT, KEPLER and JWST and by PLAVI, PLATO, ECHO, etc. if they are selected. Moreover, systems of giant planets hosting moons like the Jovian one will be studied for their possible habitability (JUICE).

B.2) Habitability

Planet habitability obeys to various definitions. It is linked to the presence of liquid water on the planetary (or moon) surface in a thermodynamic state between the water triple point (273 K) and the critical temperature point (647 K). This led to define a *circumstellar habitable zone* in function of the star luminosity (or mass) and its distance to the planets. Habitability is actually a complex and dynamic concept and can be defined as the relation between a planet (or a moon) and its environments, and their co-evolution. Habitability is first a property of a planet-star system, and then becomes the property of its internal and external environments. This includes the relation between the star and its galactic environment, the relation between the planets and the central star, between the planets and their moon.

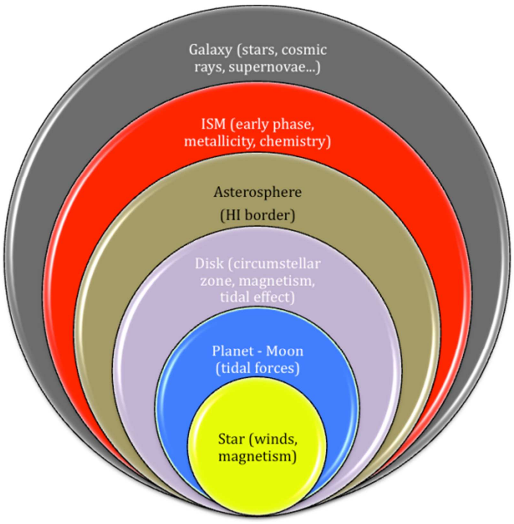


Fig 3 : Star environment and interactions between the internal zone (planet, moon, disk, astrosphere) and the external zone (interstellar medium, galactic).

Based on LDEE growing expertises in Star Interstellar Medium Interactions, Star Planet Interactions, the Star Star Interactions and the Planet Satellite Interactions, we aim to tackle the complex concept of habitability. In particular, we will characterize the importance of a given interacting mode in shaping the conditions for habitability. Habitability will be studied under two angles:

- Internal impact on habitability: planet – moon interaction (tidal effects, energy balance, water phase state, magnetic field), star – planet interaction (energy balance, UV, magnetism, green-house effect)
- External impact on habitability: star – galaxy interaction (metallicity, chemistry, cosmic rays, impact of early phase of star formation in the metallicity and chemistry).

Methodology: simulation, theory, observation (SKA for radio search in HI, ELT for visible/IR imaging, JWST for search for early phases, Herschel archives for interstellar medium).

We anticipate delivering the following milestones:

- 2 yr: prospective on habitability, research of astronomical factors in which LDEE can bring values to the debate.
- 5 yr: application of LDEE expertise to habitability and proposition of criteria to exoplanets.
- 10 yr: search for habitable zones under new criteria.

Facilities useful in habitability and interaction studies:

SKA (radio detection, ionization, HI) will image the thermal emission from dust in the habitable zone in unprecedented detail and will show where dust evolves from micron sized interstellar particles to centimeter sized “pebbles”, the first step in assembling Earth-like planets. Other facilities will contribute such as ELT: Direct imaging of habitable planets; ALMA, APEX, and NOEMA/IRAM: Astrochemistry; Herschel: Early phase of star and planet formation in the interstellar environment; JWST: Early phase of star and planet formation; Cassini, JUICE: Habitability in icy moons of giant planets.

Factual Summary:

Methodology: We intend to manage the existing programs and grants we are PI or CO-I of such as: SO/STIX; ANR Toupies/IDEE; FP7 networks IRSES, Space-Inn ; LP Binamics/Matysse), contribute to driving science via the various committees we are members of (PNST, IAU WG on solar-stellar connections, Kepler-KASK, MoU on stellar dynamo and on 1-D stellar evolution (STAREVOL)) and search for new fundings reinforcing our main scientific objectives.

Hiring policy: 1) Solar dynamics in support of Solar-Orbiter/STIX; 2) Asteroseismology in support of Plato/Plavi

Publication policies: We will maintain our high publication rates by publishing articles in major astrophysical journal, aiming for Nature/Science when appropriate or by coordinating books and reviews (ISSI, CUP, etc…)

Public outreach: Continue our efforts to organize general public conference, interviews/articles in popular science magazines, Herschel-App and Astrophysical-TV on daily motions

Teaching/Supervising: We will continue being involve in PhDs and postdocs supervision, having between 1 and 2 PhD students per year and as many postdocs that our present and future grants will afford us. We will continue teaching in various Master (graduate) courses, as this is key to find the best students and to pass on to the young generation our passion for research and astrophysics.

Grants/time allocations: We will seek financial support through for instance FP8, ANR, IDEX to bridge the gap between the end of the quinquennal (Dec 2018) and our existing fundings (most would be over by the end of 2016). Since many tasks require HPC supercomputing time allocation we will continue requesting of order 20 Million node hours, amount we have been securing through Genci and now Prace over the last few years. Likewise we will compete for telescope time, having already secured our participation in two large programs at CFHT.

LADP - Laboratoire Anneaux, Disques et Planètes

1. Présentation de l'unité

a. Team history

The LADP has been created in 2010 with the aim of offering a new visibility to planetology and exo-planetology research within the AIM Laboratory. This has effectively boosted its attractiveness to students and post-docs, who have definitely contributed to science results and to the development of transversal collaborations within the team. The group, originally composed of 2 permanent members (A. Brahic, C. Ferrari) took roots in the SAp in 1996 to insure the scientific return of the CIRS-CASSINI instrument. The collaboration was further extended to the exploration of the Saturn system by the ISS cameras. The main research theme has long been the dynamics and properties of planetary rings, as driven by Pr. A. Brahic (ISS-CASSINI Team member) and supported by the unrivalled Voyager and Cassini missions data. To this regard, the team is unique at the international level for its competences, knowledge and excellence in planetary rings research. The group has grown up in the early 2000s with 2 more permanent members (S. Charnoz & E. Pantin) to address the question of planetary formation by coupling its competence in disk dynamics with the search and characterization of new circumstellar disks and the development of infrared instruments (VLT/VISIR, JWST/MIRI). In 2006, S. Rodriguez joined the Team and brought his experience in studying planetary surfaces and atmospheres in the near-IR with the VIMS-CASSINI spectrometer.

2. Analyse SWOT et objectifs scientifiques de l'unité

- **Strengths.** The LADP has the ability to address the questions on the evolution of planetary rings, satellites and of grains in circumstellar disks (proto-planetary or debris) through theory, simulation, modelling and multi-wavelength observations. Most members share a common culture in disks or in radiative transfer and are able to work together on very diverse objects. A major asset of the Team is its large implication in the CASSINI mission on 3 different remote sensing instruments, allowing a multi-wavelength approach that provides independent diagnostics and observables of a same object. The Team has a definite expertise in dynamics of disks and related numerical simulation, in radiative transfer, in multi-wavelength data analysis and processing, or in the development and exploitation of infrared spectro-imagers. The Team has the expertise to handle a large multi-instrumental and multi-object database, both from ground-based telescopes or space missions. The Team is also fitted to address multi-scale problems, from the size of a grain to that of a large terrestrial body with an atmosphere. Team members have demonstrated their ability to get substantial financial support for their project from LABEXs or ANRs.
- **Weaknesses.** The group of planetology, formerly embedded in a larger Team of the AIM lab, had lost visibility to PhD and post-doc students. The recent creation of the Team has had highly positive effects to this regard. No member has full dedication to science in its activity and the science return from instruments may not be completely satisfying. This is particularly critical for VISIR key program analysis, not completely published yet, when VISIR-upgrade and ALMA are ready to operate. This might raise a difficulty to obtain observing time on these new installations. Finally, the group chronically suffers from a lack of engineering support to maintain its databases and analysis software.
- **Opportunities.** The instrumental context at short and mid-term is highly favorable to support the research of the Team. As far as circumstellar disks are concerned, the conjunction is very favorable to constrain their structure and properties thanks to Herschel data on debris disks, ALMA and VISIR-II coming on-line to collect new and more precise data on disks and with the perspective offered by our implication within the ELT/METIS and JWST/MIRI projects. As far as ring questions are concerned, the CASSINI mission will come to an end in 2017 and science analysis will still be supported by the CNES. The Solstice mission (2013-2017) is dedicated to seasonal effects, which are central in our research plan for the next 5 years plan (see below). The structural context of research is also most favorable for the Team. The creation of the LABEX UnivEarths for the ten coming years (2011-2021) at University Paris Diderot offers new vectors for science development and synergies around planetology with the IPGP (Institut de Physique du Globe de Paris). Team members are already deeply involved in this structure, both at research and educational levels, with financed workpackages.
- **Threats.** The context of the AIM lab within the University Paris Diderot has changed significantly recently with the creation of the LABEX UnivEarths and of the IDEX. Those big opportunities also generate threats for the LADP as mainly composed of "enseignants-chercheurs", in front of very time-consuming administrative or pedagogical tasks that will add up inevitably and may entail subsequent loss in science productivity. The project of moving the AIM Lab from the Physics Department to a new department for Earth and Universe Sciences may generate collateral effects like preventing new hiring of university staff. If all teams of the AIM lab are impacted, the LADP Team is all the more sensible to it in that its recruitment mostly comes from University. The Team is exposed to enduring lack of recruitment since 2006 despite high level science results and productivity. Positive signals have to be sent to PhD and post-docs of the Team by pushing hard for new permanent position to be opened in this field both at University and at CEA.

2.2 Scientific objectives

The big picture. Grains collide, stick, accrete and grow to form large ensembles driven by forces at play. The processes that give birth to kilometer-sized planetary embryos from sub-micron grains in proto-planetary disks and their characteristic timescales stay weakly constrained by observations. Accretion and fragmentation of grains also happen in planetary ring disks, which offer close laboratories in our Solar System to observe accretion at smaller spatial and temporal scales. Temporary accretion indeed happens in ring disks, showing gravitational accretion and tides struggling to form self-gravity wakes (Jeans-Toomre instabilities). These wakes give clues to the ring surface mass density and thickness. Determining the ring mass from its thickness gives insights on its origin, considered as the result from the break-up of a large satellite. The question of the origin of rings, their genetic link with regular small satellites is still in debate. As rings spread out of the Roche limit, they may form new low-density satellites younger than the Solar System. The rheological properties of Enceladus support this idea of young satellites, suffering impact cratering as they are already partially differentiated, i.e. later than the LHB. The origin and evolution of the complex world of Saturn largest moon Titan are still puzzling. Its surface, as an interface between its internal structure and its dense atmosphere, is a clue to its history but remains difficult to read and analyze. On Titan and terrestrial surfaces, grains stick up in dunes and are transported by winds, if any. Their morphogenesis and dynamics reveal both the properties of grains and the history of the climate as resulting from the interactions of soil with atmospheres. Properties of regolith grains are clues to their chemical composition and evolution over ages.

2.2.1 How did the satellites of giant & terrestrial planets form and evolve?

Context: We have explored the complex links between a circumplanetary ring and nearby satellites for the case of Saturn both with numerical simulations and observations with the CASSINI spacecraft. Spontaneous processes of gravitational accretion conflicting with tides yield to the formation of self-gravity wakes (Porco et al. 2005; Ferrari et al. 2009), of a spiral structure in the F ring (Charnoz et al. 2005) attesting collisional processes between rings and satellites. Satellites were also shown to accrete ring material in an equatorial bulge (Charnoz et al. 2007). A new process has been proposed to form new generations of low-density satellites from rings (Charnoz et al. 2010). We have also shown that Saturn mid-size satellite like Enceladus would already been partially differentiated at the epoch of their bombardment, supporting this new scenario (Degiorgio et al. 2012).
Challenges: Explain the close isotopic ratios of the Earth and Moon when it should have been formed from the material of the impactor, accreted far away or the equatorial orbits of Mars satellites Phobos and Deimos / Lead a consistent analysis of rheological parameters for all satellites of giant planets and confirm (or not) the singular behavior of Mimas against the empirical law for craterisation / Determine the surface composition of Titan and reveal the nature of the sediment/ Disclose information on the past or present climate contained in the morphology, size and orientation of Titan dunes.
Prospective for 2014-2018:

- The accretion process proposed for Saturn satellites, may have also forged the Moon from a debris disc after a large impact. This explaination may hold if the proto-lunar disc has survived 1000 years, which requires the disc to stay hot to prevent rapid accretion. We propose to include the thermodynamical evolution of the disk in our current code HYDRORINGS to tentatively solve this paradox. The origin of Mars satellites Phobos and Deimos is still controversial as an asteroid capture can hardly explain their equatorial orbits. Accretion in a tidal disc may naturally explain the Phobos circulation below synchronous orbit. This research on the origin of terrestrial planets satellites is supported by the LabEx UnivEarths (Workpackage “Origin and evolution of the first solids and of the moon”, PI S. Charnoz). It involves collaboration with S. Mathis (AIM/CEA, LDEEP team), A. Crida (Nice Observatory), and V. Lainey (IMCCE).
- The photometric model, built to analyze wide data sets of poorly resolved impact craters of satellites surfaces and derive their rheological parameters, will be improved to take into account more realistic craters shapes and the method will be extended to all mid-sized satellites of the giant planets. This will yield a consistent analysis among satellite systems. Also the currently singular behavior of Mimas against the empirical law for craterisation, which may reveal a new craterisation regime at very low surface gravity and/or special ground properties, will be re-examined. This research involves K. Degiorgio, S. Rodriguez, C. Ferrari in collaboration with the ISS-CASSINI Science Team (C. Porco, A. Brahic).
- Saturn largest moon Titan is already a target of major interest of several new projects proposed to pursue its exploration at the 2025 horizon (TSSM, TAE, JET, TIME, AVIATR). Understanding how its atmosphere is continuously replenished requires elucidating the links between internal structure, surface and atmosphere. However the CASSINI mission will be providing until 2017 always more constraints on the seasonal evolution of its climate and these interactions (formation of lakes, clouds, winds). Characterizing the present dynamics of the system is required. The determination of the surface composition is highly challenging due to the few narrow spectral windows opened in the atmosphere. We’ll lead the task of retrieving the surface albedo and composition in the context of the ANR “Apostic” project (2012-1015) with the development of a new fast forward radiative transfer model and a new inversion scheme to massively retrieve both atmosphere and surface composition from a large volume of spectroscopy data. S. Rodriguez will also lead the ANR “Exodunes” project (2013-2016) which objective is to develop new quantitative methods to disclose the fundamental information about the nature of the sediment and the links between the past or present climate and the morphology, size and orientation of dunes. Three questions will be addressed: what’s the role of inter-grain cohesion? What is the role of topography and of the variability of winds intensity and orientation? Images and topography of dunes in different environments will yield quantitative characterization of their morphodynamics, which will be completed by experiments in granular physics and numerical simulations. This research is supported by ANR and by an exploratory workpackage of the LabEx “UniverEarthS” (2011-2021). It involves collaboration with the VIMS Science Team.

2.2.2 What is the mass of Saturn's rings?

Context: Currently estimated ring-satellite interactions and erosive flux from meteroids push for a young age of Saturn's rings. Ring mass is estimated to be that of Mimas. Providing such a mass every 0.8 Gyr within the Roche limit remains difficult. Were rings more massive and the meteoroid flux less intense, rings may resist over the age of the Solar System and nurture new generations of mid-sized satellites (Charnoz et al. 2011).

Challenge: Determine the mass of the most opaque of Saturn's rings, the B ring.

Prospective for 2014-2018. The surface mass density is usually derived from the damping of density waves driven in the rings by satellites. Such waves are scarce in the most opaque and largest ring of Saturn, the B ring. We have proposed a new method to derive the surface mass density of a thick ring from the seasonal change of its unlit side temperature (Ferrari and Reffet 2012). The heat diffusion time from one side to the other and the transient thermal regime within the planetary shadow are both key factors to estimate its thickness, controlled by self-gravity instabilities and then directly related to surface mass density. We plan to analyze the seasonal temperature variations of the B ring in this densest part over two seasons (2004-2017) to constrain its thickness and surface mass density as a function of distance. We also plan to independently constrain the ring porosity and thickness from the opposition effect. The different contributions to this effect can be separated by a multi-wavelength study. We will benefit from our various competences in data analysis of the ISS and VIMS-CASSINI instruments. This research involves C. Ferrari, E. Reffet, K. Degiorgio, S. Rodriguez, collaboration with the ISS-CASSINI Science Team (C. Porco, A. Brahic, et al.), the CIRS-CASSINI Ring Team at JPL (L. Spilker et al.) and the VIMS-CASSINI collaboration.

2.2.3 Detect and characterize exorings.

Context: The origin and age of rings around giant planets are still uncertain. The multiplicity of detection methods of exoplanets has yielded a marvelous diversity of planetary systems. Numerous exoplanets are expected to have a Roche limit that might shelter rings. The detection of exorings will help understanding planet and ring formation. Numerous projects focus on the characterization of exoplanets at the 2020 horizon, like JWST/NIRCAM, JWST/MIRI, the ELT/METIS, ECHO…

Challenge: Establish the detectability of exorings with future instruments as a function of wavelength.

Prospective for 2014-2018. A PhD student currently dedicates her activity to establish this detectability in the near- and mid-infrared domains, both in stellar diffuse light and thermal infrared emission. Radiometric ring models as developed by C. Ferrari and colleagues are exported to exoplanet observing configurations. This work is in direct link with E. Pantin co-I ship for the ELT-METIS instrument and related to the upstream ANR NG-MIDE project.

2.2.4 Transport, erosion and coagulation of grains in protoplanetary discs.

Context: The early stages of planetary formation within the first few million years are complex to clarify. This requires a multi-physics approach (celestial mechanics, hydrodynamics, radiative transfer and geophysics), numerical simulations, observational constraints from known circumstellar discs and from the chemical composition of meteorites.

Challenge: Study the spatial distribution and transport of dust grains at large scale in 3D, coupling dynamics, coagulation, fragmentation.

Prospective for 2014-2018: The LIT3D code (Charnoz et al. 2011, Charnoz and Taillifet 2012) is currently the only one able to individually follow dust grains trajectories in turbulent discs and include coagulation and fragmentation processes. We aim to study their spatial distribution and transport at large scale in 3D, coupling dynamics, coagulation and fragmentation. Grains, as a function of their size, suffer different thermal and chemical alterations and settle in diverse regions of the disc. Coupling modelled spatial distribution of sizes, chemical or isotopic compositions with the radiative transfer code MCFOST developed by C. Pinte (IPAG; former collaboration within the ANR DUSTYDISK) will allow direct comparison with proto-planetary discs as observed by VISIR/VLT or JWST/MIRI, the first candidate being HD97048. We will benefit for this study of the new "High Angular Resolution" modes of the VISIR/VLT instrument. The coronagraphic and SAM modes will provide disc probing in the 30-100 AU region with much higher contrast compared to the previous VISIR version. We also plan to compare models with millimetre ALMA observations that will focus on the larger grains settling in the disc median plane, looking at the very early stages of planetary accretion. This will be done in collaboration with Bordeaux and Grenoble observatories.

2.2.5. Methodology: Multiscale Radiative & Heat transfer in grains ensembles.

Context: Planetary surfaces and rings are all but flat and regular surfaces. Rugosity happens at all scales, both above and beyond the resolution of instruments. These multi-scale and irregular structures, like self-gravity wake in Saturn's rings or complex craters of satellite surfaces, condition the way stellar light is reflected and thermal radiation emitted towards the observer. A complexity in front of which current analytical models can appear trivial or not valid.

Challenge: Include the complex multi-scale structure of rings in radiative transfer models (scattering and emission) to analyze CASSINI multi-wavelength and multi-viewing data set.

Prospective for 2014-2018: We aim at developing a multi-physics and multi-scale model of Saturn's rings coupling realistic outputs of numerical simulations of the dynamics of dense rings, ray-tracing and heat transfer in complex objects. The plan is to parallelize the available code (built by S. Charnoz) to handle wide size distributions of ring particles with numerous collisions in a dense ring, together with optimized ray-tracing, wise treatment of spatial and temporal scales and coupling of scattering, absorption, radiation and conduction. A similar approach will be adopted to handle more realistic photometric modelling complex craters in the determination of rheological properties of satellites (see § formation of satellites). This tool is also intended to question the effect of multi-scale rugosities of a real surface on the scattering function about opposition (which is expected to be null in analytical theories), for example on the amplitude of the LIDAR echo of a terrestrial terrain or on a self-gravity wake in a ring. A combined approach is chosen, comparing backscattered light from a ray-traced high-spatial resolution DEM of a real terrain with the LIDAR echo actually observed (Collaboration S. Jacquemoud IPGP).

2.2.6 Data processing

Context: Most of our scientific objectives rely on the processing of a multi-instrumental and multi-mission data set. ***Challenge:*** Maintain the CASSINI multi-instrumental databases; develop new software to handle VISIR-upgrade. ***Prospective for 2014-2018***: Restore a satisfactory archiving and accessibility of the CASSINI ISS and CIRS data thanks to a perennial engineering support. The threat is that the Team members still loose substantial time in this instead of analyzing data. The VISIR pipeline and VISIR data analysis software will have to be upgraded to be adapted to the new VISIR configuration. This is very important to insure continuity in the formation of master and graduate students.

2.2.7 Instrumental perspective

Apart from the already mentioned context of the VLT/ELT/JWST and ALMA instrumentation to fully support our activities, long-term perspectives are worked out by the Team. The ESA **JUICE** L-mission is intended to study Jupiter's satellites and their relation with the planet as well as the rings. Our team is involved in the proposal of the JIMI NAC and WAC cameras to respond to the ESA'AO (consortium led by the Applied Physics Laboratory, John Hopkins Observatory, Maryland, USA). Similarities and differences with Saturn will help us to better understand the diversity of satellite formation processes in the Solar System. The **Marco-Polo-R** mission has been elected for the assessment study phase of ESA M3 missions in 2011, with a launch opportunity in 2022-2024. Aimed at returning a sample of a primitive NEA asteroid, it will also provide crucial elements to answer the fundamental questions of interest for the Team like, 1) what were the processes occurring in the early solar system and accompanying planet formation? 2) What are the physical properties and evolution of the building blocks of terrestrial planets? C. Ferrari and S. Rodriguez are already participating Working Groups on the global characterization of the target (spectral and visible), mechanical or thermal properties and morphology, properties or craters.

3. Mise en œuvre du projet

3.1 **Recruitment plan.** The team has its specificity as being mostly composed of university personal, as the result of an understandable and coordinated strategy of the AIM Lab with the Paris Diderot. The hiring rate of this Team is about one every 5 years. The next one will not happen before 2014, at the soonest, and this is a concern. Any additional permanent position will obviously bring an efficient support to the Team. Permanent positions are desired to support projects as follows:

- One researcher (CEA, UPD, CNRS) having competences in infrared/high angular instrumentation, circumstellar disks and data processing for: 1) the exploitation of existing and future data, 2) modelling of METIS data; preparation of future METIS observation programs. At minimum, 1 post-doc position over 3 years is required to conduct the VLT/VISIR project only.
- One researcher (CEA, UPD, CNRS), having skills in radiative transfer, parallel processing, multi-physics problems and inversion of large data sets to support characterization of ring and planetary surfaces.
- One engineer with expertise in database handling and processing of huge amount of data for: 1) keeping updated on a regular basis and improving the storage efficiency of the huge volume of data gathered and to be gathered by the group, 2) helping the group to process and analyze the datasets.

3.2 **Funding Plan.** CNES will guarantee the funding on CASSINI-related research of CIRS Co-I, ISS and VIMS associated scientist and ISS Team member (most probably until 2019). Researches on Titan are funded with two ANR programs until 2016 with two 2-years postdoc (T. Appéré & A. Lucas, 2012-2014) and by an exploratory workpackage of the LabEx “UniverEarthS” (2011-2021). Funding from ANR/PNP and LABEX UnivEarthS funding will be solicited in a near future for the radiative transfer project. S. Charnoz is funded for 5 years through its nomination to IUF. In addition, through the LabEx Workpackage on the “evolution of first solids in the Solar System” a post-doc will be hired within the 4 next years. Asking for an ERC funding is also considered in the “consolidator” funding scheme. To be achieved, ground-based observational projects (VLT/VISIR; ELT/METIS) will need to find financial support from national (PNP), regional (DIM) or LABEX programs.

LEPCHE - Laboratoire d'Etude des Phénomènes Cosmiques à Haute Energie

1. Analyse SWOT et objectifs scientifiques de l'unité

Scientific objectives of the LEPCHE team

The main topics studied by our team concern the accretion/ejection processes around compact objects, supernova remnants, the acceleration and propagation of cosmic rays and their interplay with the interstellar medium

Accretion is a very efficient process in the Universe and it is often associated with the expulsion of highly energetic jets of material. Accretion/ejection processes are ubiquitous and seen at all (temporal and spatial) scales (young stellar objects to -ray bursts, microquasars, active galactic nuclei). Understanding the physics governing microquasars and X-ray binaries (XRB) — bright objects that evolve on human time scales and are seen with little absorption— will shed light on a wide range of cosmic phenomena.

The origin of the Galactic cosmic rays still defies our understanding 100 years after their discovery. Our team aims at answering questions regarding their acceleration, feedback on the acceleration site, and their propagation and impact on the interstellar medium (ISM). This goes from supernova remnants to star formation regions and the Galaxy as a whole. Cosmic rays are also used to trace and gauge the different gas phases in the ISM.

SWOT Analysis

Strengths:

• ***Strong experience in mission development:*** participation to a wide variety of calls for new missions, to the definition of scientific requirements, to science working groups, to the definition and development of data centers; close collaboration with AIM/LSIS and AIM/LISIS teams involved in the design/building of satellites/detectors.

• ***Direct involvement in most of the high-energy observatories in operation (XMM-Newton, INTEGRAL, Fermi, HESS):*** software development, participation in data centers, calibration, sky surveys and source catalogues. Thanks to this we beneficiate of CNES-funding which, in particular, allows us to have a rather large number of post-docs.

• ***Vast amounts of high-quality data from radio to TeV:*** at high energy, this includes guaranteed time and an extensive use of the large existing archives. We have a high success rate for obtaining observations in the X-rays, optical, infrared, sub-mm, and radio.

• ***Involvement in SVOM at multiple levels:*** involvement in the data center (together with LISIS) and responsible for the definition and management of the general program (non-gamma-ray burst science).

• ***High rate of high-impact-factor publications:*** with a large number of breakthroughs (see the summary) and numerous publications in prestigious journals.

• ***Recognition as world leaders:*** in the topics of supernova remnants, cosmic-ray sources, interstellar γ-ray emission, microquasars, and related physical processes, resulting in a large number of international collaborations, invitations to symposia, prizes, and the strong participation to the local or scientific organizations of international symposia.

• ***Strong involvement in outreach activities:*** 2 of our permanent staff dedicate most of their time to this activity. This consists of website news, press releases, organization of expositions. We also actively participate to the organization of conferences, write books, give support for teachers and students

• ***International attractiveness***: our team comprises 9 different nationalities (7 for PhD+post-doc)

Weaknesses:

• ***Weak participation to HESS and CTA at present:*** the arrival of a particle physicist in 2012 has increased our participation to 2.5 FTE (2 permanent, 0.5 post-doc) with several leadership roles in both projects. However we need to further strengthen our participation in the CTA collaboration where we could have a strong scientific impact.

• ***Weak theoretical/modelling manpower:*** theoretical modelling is under-represented in our team and we often rely on external collaborations for modelling. We need to recruit a permanent theorist to strengthen the team's work.

• ***Lack of students:*** although most LEPCHE scientists are habilitated, and 3 are full professors, we still have too few students. We need to enhance our implication in education through research, starting at master level.

• ***Mean age of the permanent staff:*** 48.5 y-old.

Opportunities:

• ***Next X-ray missions (at different stages of maturation):*** contribution to several scientific white papers for **Astro-H** (Japan), access to data through call of opportunity; possible participation to **SRG** (Russia); at longer term, participation to the **LOFT** (ESA) observatory science working group and all sky survey, and to the topics of g-ray bursts and transients.

• ***ESA-L2/L3 call for mission (*foreseen in 2013**)**: We will participate to the resubmission of an updated version of the Athena proposal.

• ***Development of new generations of radio telescopes:*** members of science groups for LOFAR (Europe), ASKAP (Australia) and MeerKAT (South Africa), the precursor instruments of the major international SKA facility to be developed for 2020+. We need to increase our participation at various levels (preparation to observations and data reduction)

• ***New generations of high-energy telescopes:*** CTA will image the TeV sky with unprecedented sensitivity and resolution. We are also discussing with the Russian teams preparing the Gamma-400 satellite at GeV energies (>2019).

• ***Numerical simulations in rapid progress:*** the topics studied at LEPCHE will greatly benefit from the development of dedicated programs with LNSPA on supernova remnants and cosmic-ray interactions with the interstellar medium.

• ***Creation of a new department of Earth and Universe Sciences (University P. Diderot):*** Our direct participation will allow us to increase notably the number of students.

<u>*Threats:*</u>

• ***The future of X-ray astronomy:*** No (or weak involvement in) new missions foreseen at the <2022 horizon**.** Athena was not selected as ESA L1; selection of LOFT as an M3 mission is uncertain

• ***SVOM currently frozen***: Decision pending —and dependent upon— agreement between the Chinese space agency, and its related institutes, and the French CNES. Launch is in any case postponed to > 2017.

• ***No breakthrough mission planned at MeV-GeV energies after Fermi:*** the possible Gamma-400 project provides a modest increase in performance over Fermi. No R&T program across the world has reached the level of readiness allowing the preparation of a new generation of gamma-ray telescopes.

• ***Current space missions ageing:*** XMM, INTEGRAL, and Fermi are fully functional, but already 13, 10, and 4 years old, respectively. The instruments, in a hostile environment, are subject to sudden and unpredictable degradations.

2. Mise en œuvre du projet

Scientific projects and strategy:

1. Accretion and ejection

How ejection episodes and flares relate to instabilities in the accretion flow and how persistent outflows are sustained are still largely unknown. **We need to go beyond the standard model of an □-disc to understand accretion in its integrity.** In particular we want to study **what controls the evolution of XRB during outbursts. How do we measure the initial conditions to jet launching?** Key answers lie in the study of the **differences between the different modes of accretion (efficient vs inefficient) that give two different branches in the fundamental plane of black holes**. Can a system evolve between these two modes, or are we witnessing two populations of sources with different jet properties? We want to **constrain the formation and destruction of jets and their relation to the accretion states** (spectral and rapid temporal behavior)**. How are jets collimated and what fraction of the accretion power is fuelled into them? The derivation of scaling relations between objects at different time scales provides powerful constraints to numerical models. Furthermore, we want to understand the impact of jets on the interstellar medium** (ISM)? The latter can serve as a calorimeter to measure the jet energy and momentum, and its feedback on the ambient medium. A very debated question today is whether or not **intermediate mass black holes exist.** Answering this question has a direct impact on the hierarchical evolution of galaxies and their nucleus. Accreting systems are also known to emit up to the TeV range: are these rare exceptions or **just the tip of the iceberg? Which observational signature can differentiate the three potential scenarios depicted in Figure 1?**

The current high-energy missions, the soon-to-be-launched Astro-H, and the current and future radio telescopes will be our primary tools to progress. Observations will be compared to theoretical models and simulations, notably within the ANR CHAOS (with IPAG, and IRAP) in order to test different accretion instabilities thought to trigger spectral transitions during outbursts. We will for example test the evolution of jet power and the relation with the properties of the accretion disc (temperature, size). Of particular relevance will be the comparison of the system properties (temperature, typical timescales of variability, jet luminosity,…) between the different branches of the outbursts (rise vs decay). The AIM group is in charge of the analyses of the multi-wavelength light curves and spectra spanning the different phases of outbursts of most microquasars. We have obtained several programs on major facilities (ATCA in radio, INTEGRAL, Swift, at X-ray energies), and we will make use of the archival data of RXTE. At longer term we will also access data from Astro-H for which we have submitted several scientific white papers for the study of microquasars (outburst evolution and timing).

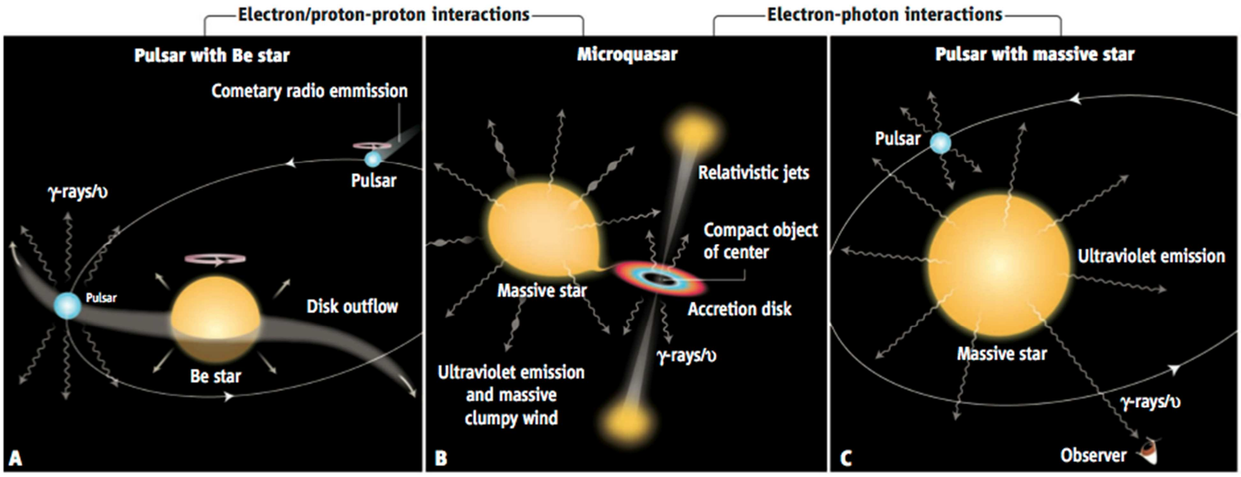


Fig. 1: Schematic representation of the three main types of accreting objects studied by our team, and possibilities for the emission of g-rays. A) Be-HMXB, B) Microquasar, C) sg-HMXB. From Mirabel (2012).

The multi-wavelength spectra of jets are also extremely important to quantify their energetic budget (for example the energy of electrons in cases of leptonic jets). This necessitates, in particular, a precise parameterization of the level of jet emission at hard X-ray and g-rays. This will be tested with the use of specific models (Comptonising 'coronae' vs. synchrotron jets) through spectral modelling, and also with the study of polarization at hard X-rays, first with INTEGRAL, and at longer term with Astro-H. We will also study these aspects within our international collaborations (in particular Berkeley, the University of Amsterdam, the Observatory of Bamberg, and the University of Southampton), which allow us access to different specialities (numerical simulations) and observational time (NuSTAR, e-Rosita).

The future generation of high-resolution spectrometers (Astro-H, then Athena) and radio arrays (ALMA, ASKAP, MeerKAT, and later SKA) will permit us to study the formation, destruction, and composition of discs winds (absorption and emission lines) and jets, and to test their feedback on the ISM. In the next decade, time domain studies in the radio will be the new terra incognita. Rapid variability of jets will be accessible, and we can expect new discoveries (as when rapid timing in X rays became available). By scaling the properties of stellar mass (galactic) objects, we can obtain constraints on the parameters of ULXs which, in conjunction with X-ray data will allow to construct a census of black hole masses in ULXs. Here again our collaborations will allow us to put together a large multiwavelength database.

The large improvement in sensitivity of HESS II, and even more for CTA, will permit a much larger number of γ-ray binaries to be detected and studied with higher precision and across a broad energy band that overlaps with Fermi.

2. Source Populations

We will continue to **characterize the high-energy sky** (keV, GeV, TeV). This involves the detection and spectral and time characterization of sources in a controlled manner (catalogues) that **allows statistical studies of their global properties, the search for specific signatures of different populations, and the confrontation of their properties with population syntheses that include the observational biases to** follow **evolutionary patterns** within **our Galaxy**. This will be applied to Fermi and HESS/HESS II datasets to study the evolution of young pulsars and their wind nebulae and to try and solve their puzzling overabundance with respect to models.

With the extension of the INTEGRAL, Fermi, and HESS/HESS II observatories and X-ray/optical/IR/radio follow-up campaigns we aim at extending the small samples of the three types of binaries depicted in Figure 1 toward very faint or dormant objects which will possibly impact the understanding of their geometries (orbital periods), evolutionary patterns (absorption/absorbers, winds, orbital evolution), their physics, and their relation to stellar evolution.

3. Cosmic rays, supernova remnants , and the high-energy side of the interstellar medium

The **origin (composition, acceleration) and propagation of cosmic rays (CRs), and their interaction with the interstellar medium (ISM)** are still highly enigmatic. Supernova remnants (SNRs) are natural places for CR acceleration. How do SNR shocks evolve when including particle acceleration, magnetic field amplification and feedback on the thermal gas? **To which energy can they accelerate particles and what fraction of the shock energy is transferred to CRs?** Our recent results have shown that star-forming regions may also act as accelerators, re-accelerators, or confinement regions. **Are the majority of star-forming regions filled with enhanced CR densities? How do shocks propagate in turbulent media, and how does this impact their acceleration capacity?** In the near future, data from Fermi, XMM-Newton, Astro-H, and HESS, together with numerical simulations, will be used to study these questions. CTA and hopefully Athena will then open studies at higher angular and spectral resolutions, respectively, both to study in-situ acceleration in SNR, their impact on shock-heating of the gas, and to follow the release and early propagation of fresh CRs into the ambient medium.

An XMM-Newton **large Program of deep observations of SN 1006** to determine consistently the energy partition between thermal gas, relativistic particles and magnetic field has been obtained by our team. A key determination is to extract the spatial width and the spectral break frequency along the synchrotron filaments of this shell-type SNR. This gives access to the **magnetic field amplitude and the maximum energy reached by electrons** for different initial orientations of the magnetic field with respect to the shock front, allowing for precision tests in an object where the distance, shock speed and ambient density are rather well known.

The comparison of the spectral breaks recently found at GeV energies for middle-aged remnants and at TeV energies for younger ones provides new clues on how CR acceleration responds to environmental effects and on the energy-dependent escape of CRs from the shock as it expands. Fermi, HESS and the future CTA data are well suited to **statistically study** SNRs over a large range of age and ambient ISM density. The starting point will be a **catalogue of γ-ray SNRs**, currently in progress. To interpret the correlations, we are improving our **global models of SNR evolution and emissions** (including both CRs and thermal gas), and of CR leakage and diffusion in collaboration with APC within the UnivEarths LabEx.

We will continue to search for CR cocoons in star-forming regions with Fermi, HESS II and CTA. The GeV-TeV data are crucial to evaluate the impact of the turbulent environment of massive stars and SNRs on the CR spectrum emerging from these regions, thus to connect the CR spectrum at the sources and in the Milky Way at large. For the present we ignore whether the spectrum hardens while diffusing through random shocks or if short diffusion lengths and severe radiation losses soften the emerging spectrum.

The Galactic center itself is a good place to look at the collective effect of shock acceleration and shock heating. We have deep X-ray observations of that region (e.g. the Arches cluster), and we participate to a Large XMM Program (lead by APC) to complement them, allowing a full characterization of individual sources and of the various components (thermal, non-thermal) of the diffuse emission. Dedicated work on the gas structure is planned to disentangle the γ-ray emission (as seen by Fermi) produced along the line of sight from CR interactions in the central molecular zone and its massive stellar clusters. On a larger scale, the CR spectrum will be extracted as a function of Galactocentric distance and in regions of different star-formation rates to infer constraints on the CR source distributions and diffusion properties in and out of spiral arms.

Enhanced CR irradiation affects chemical abundances, hence gas-density tracers and mass diagnostics in molecular clouds, because CRs are the main ionization source in the dense, UV optically thick, cloud cores. The COSMIS ANR (P. Hennebelle, AIM-LSNPA) aims at joining numerical models of CR shock acceleration and of a multi-phase turbulent ISM. We have **3D SNR simulations** in a realistic ISM to investigate how this changes their evolution and impact on the ISM. We will also study CR propagation in a realistic MHD representation of the ISM. CRs are indeed key to improving the **census of Galactic interstellar gas** by revealing, in conjunction with dust, **the large masses of dark neutral gas present at the transition between the atomic and molecular phases**. Joint Fermi, Planck, and Gaia (for interstellar extinction) studies, combined with radio-line surveys, will aim at providing a realistic **3D census of the different ISM phases within 500 pc of the Sun and in the spiral arms** with increasing difficulty. Tracing the dark-gas phase and understanding its response to environmental effects (total HI and CO mass and dynamics) is essential for the interpretation of external galaxies, and of interest to other AIM teams.

SNRs can also be used to provide constraints to SN explosion models and we are working on **3D simulations of the thermal emission from young SNRs**. X-ray calorimeters promise to give access to the velocity dimension (with a resolution of a few 100 km/s) via atomic lines of highly ionized ejecta. This will allow much more precise estimates of the amount of metals in young SNRs, and will give access to asymmetries in the explosion process. Astro-H should open the way with limited spatial resolution. A large telescope with good optics as in the Athena project will revolutionize this field.

Instrumental involvement and relevance to our activities

Table 1 and the opportunities listed in the SWOT section summaries the instrumental perspectives relevant to our team and its science objectives. Here we present a more detailed description of the few projects and the associated activities expected in the next five years. Future scientific activities and projects for the period to come are as well strongly connected to potential, innovative and unexpected developments on detectors and devices. Extensive and close collaborations with the laboratories at the front-end of detectors developments, especially AIM-LSIS will be pursued.

1. Involvement in HESS II and CTA (GeV-TeV domain)

HESS II is the upgrade of the HESS Cherenkov telescope array (with first data taken on July 26, 2012). HESS-II will be the largest atmospheric Cherenkov telescope in the world and will extend the HESS energy range down to a few tens of GeV. This will overlap well with the band covered by the Fermi satellite, but with a much larger effective detection area. Combined with multi-wavelength observations from radio, X-ray, and GeV gamma-ray telescopes, this will provide for the first time, a complete picture of the energy spectrum of many objects, in particular the spectral breaks that occur at GeV or tens of GeVs in energy: distant AGN, micro-quasars, other gamma-ray binaries, gamma-ray pulsars, globular clusters, and starburst galaxies fit into this category. Note that a Fermi synergy with HESS II and CTA will be important to constrain the maximum energies particles can achieve in these different types of accelerators and how they evolve after they leave the accelerating site.

LEPCHE and the IRFU are also strongly involved in the development of the next-generation VHE gamma-ray instrument, CTA (the Cherenkov Telescope Array), which will increase the sensitivity and angular resolution of existing instruments by an order of magnitude. The CTA project is currently in the preparation phase and is likely to begin science operation in 2016, when part of the array construction will be completed. The current involvement of the team in the project is with simulation work, data and analysis development, science definition, and site selection. An internal re-shuffling is ongoing to strengthen our participation, but will not be enough; a HESSII/CTA scientist is one of our priorities for a new permanent position.

2. The SVOM (0.1-400 keV) gamma-ray burst Franco-Chinese mission

The SVOM mission is a major project of AIM and IRFU. After a period of uncertainty concerning its continuation, it is very likely that the project will restart before the end of 2012. The instrumental baseline should be affected, but little changes with respect to our short and long-term involvement are expected.

Our team is directly involved in the definition and development of the French data center (under the supervision of LISIS). We are, in particular in charge of the definition and management of data products for non-gamma-ray-bursts observations (from the raw data to the scientific products), their production, distribution to the community, archiving and compliance with the virtual observatory. We will thus have access to all non-burst data, in particular the all-sky X-ray survey with a particular interest in accreting sources of all types (microquasars and AGNs), this in synergy with the ground based follow-up telescopes.

3. The transient radio sky with ASKAP, MeerKAT, and SKA

The capability to study transient phenomena with a continuous coverage on time scales from seconds to years is starting timidly with g-ray (Fermi) and optical monitoring surveys. It will leap forward with the radio monitors under construction. The advent of this new window opens an entirely new potential for discoveries (new types of transient objects or phenomena, key time constraints on models,…). We currently participate in the LOFAR project that has already started observations. We also have a strong involvement in a network of large and innovative radio telescopes currently under construction (MeerKAT, ASKAP) to prepare the square kilometer array (SKA) project (> 2020).

One key objective of these new facilities is the systematic search for and monitoring of sources across the sky. Of particular relevance for our science goals is the study of the radio bursts associated with explosive events that can be seen at high energies (X-ray and gamma-ray all-sky monitors). The multi-wavelength non-thermal spectra will shed light on the acceleration processes at work in these events and their characteristic timescales. The excellent sensitivity in the radio allows for the sampling of very short timescales, inaccessible at high energy.

Our strong expertise in transients of various types, their physics behavior and their multi-wavelength observations, has permitted some of us to join these international efforts to deal with on-the-fly detections and analyses and multi-wavelength follow-up campaigns. The huge data rates involved require the development of new analysis methods. The synergy with the AIM-CosmoStat team and their algorithmic developments is a strong asset for building and testing innovative analysis methods and softwares, and for building a visible role in this international endeavor.

		XMM-Newton	Integral	Fermi	HESS HESS2	Astro-H	SVOM	CTA	Athena	LOFT	LOFAR	ASKAP MeerKAT SKA
Accretion	Pulsars magnetars	green	green	green	yellow	green	yellow	yellow	green	green	green	green
	Binaries X-Gamma	green	green	green	green	green	yellow	green	green	green	green	green
	μ-quasars	yellow	green	green	green	green	yellow		green	green	green	green
	γ-ray burst	yellow	green	green	yellow	yellow	green	yellow	yellow	green	green	green
Acceleration	SNR	green	yellow	green	green	green		green	green		green	yellow
	Diffuse	green		green	green	yellow		green	green			
	Cosmic-rays			green	green			green				

Table 1: List of missions (current and future) with specific involvement from LEPCHE. Green (resp. yellow) indicates a mission with direct (resp. secondary) impact on each science topic

Involvement in education: teaching, phDs and postdocs

Our involvement in the education of young researchers should increase in the near future, notably through the funding obtained with grants from ANR and LabEx UnivEarthS. The future PhD subjects, (some currently discussed in the team), will be original and notably largely based on our involvement in the new projects. These could for example concern the study of gamma-ray binaries with Fermi and HESS II, or focus on the transient radio sky with dedicated X-ray programs.

A Marie Curie/ITN proposal (HTRA: High Time Resolution Astrophysics) was submitted by some of us (selection is pending), and a Marie Curie ITN "Black Hole Universe 2" proposal is to be submitted for the 2014 call. A particular effort will be made to increase the number of PhDs.

The current AIM-PhD correspondent was recently nominated to be PhD correspondent at the institute level, which means a larger involvement in education at the level of CEA, but also a tight contact with the different doctoral schools. In addition, this will permit us (and the AIM lab) to have a more precise follow-up of the young researchers after the PhD, which in turns will permit a better advising of the PhDs.

LCS - Laboratoire CosmoStat

1. Analyse SWOT et objectifs scientifiques de l'unité

The scientific field of the CosmoStat interdisciplinary entity, created in February 2010, is **Computational Cosmology**. CosmoStat goals are:

- **Statistics & Signal Processing:** Develop new methods for analyzing astronomical data, and especially in cosmology (PLANCK, EUCLID, etc) where the needs of powerful statistical methods are very important.
- **Cosmology**: Analyze and interpret data.
- **Projects:** Participation to important astronomical projects: PLANCK, Fermi, HERSCHEL, EUCLID, CFHTLenS, XXL, etc
- **Education:** teach students and young researchers how to analyze astronomical data.
- **Dissemination:** take opportunity to disseminate our idea and tools in and outside the astronomical field (CEA, CNRS, University, Industry...).

Analyse SWOT

- Strengths
  - CosmoStat is an interdisciplinary laboratory, at the interface between cosmology, applied mathematics and signal processing. There are many collaborations between members, and most papers are written by researchers coming from different scientific fields.
  - It is clearly a very attractive laboratory, attracting young researchers from many countries (8 different nationalities in 2012).
  - The activity has a high visibility, with one Advanced ERC grand, one prize from the French Academy of Sciences, many invited talks, etc…
  - Our group has many collaborators in Europe and in US. Furthermore these collaborations are in different scientific fields.
  - We have developed many packages, that are available on the web.
  - Strong involvement in large international spatial missions, especially PLANCK and EUCLID.

- Weaknesses
  - Departure of EUCLID P.I.: Alexandre Refregier, former P.I. of Euclid, left CEA and his P.I. position in 2011, which has weakened our weak lensing group. We have hired a young promising researcher to maintain this activity, but it will obviously take time to recover from this loss of visibility.
  - Weak Lensing Manpower did not reach the critical number to have a world leading group.
  - Highly original idea based on new concepts such as sparsity or compressed sensing take time to be accepted in a given field.

- Opportunities
  - Strong involvement in large international missions (PLANCK & EUCLID): being involved in such important missions gives us the possibility to apply our ideas to the most exciting cosmological data set.
  - New mathematical concepts may change our way to understand cosmological data sets.

- Threats
  - Project policy: in large international mission, decisions relative to the choice of the methods to be used are taken by the science team. These decisions are generally based on the quality of the proposed methods, but also on more political aspects, such as the repartition between countries of the different selected methods, lobbying of some groups, etc. Therefore, we can never be sure, independently of the quality of the proposed method, that what we propose will be accepted. This is however true for any group involved in large scientific missions.

- Statistical Methods

Hyperspectral imaging: Hyperspectral imaging has emerged as an essential tool for multiwavelength observations in a very wide range of scientific and industrial areas including astronomy and astrophysics. The development and study of methods leading to better estimated components or targets in hyperspectral data is therefore extremely important. Standard analysis methods are generally based on blind source separation techniques; unfortunately, these methods are not well suited to account for some prior knowledge on the spectral content of the data. Our goals are i) understand how prior knowledge on the spectra, even only approximate, can be accounted for in a source separation process. We will focus on different settings ranging from the single target case to high dimensionality cases (i.e. high number of potentially active targets) and ii) understand how this spectral prior information can be incorporated into a blind source separation method. A typical example of application is the research of water ice on Mars, where we know the spectrum of one component (i.e. water ice), but not the others. We expect the main outputs of these methodological developments to be a novel source separation framework combining the robustness and adaptivity of blind source separation methods and informative priors on the spectra of parts of the sought after components. This new approach will be tested on Mars Express data.

Polarization: Instruments such as PLANCK provide multichannel polarization data. To analyze such multi-valued data set, we have recently proposed new multiscale decompositions such as polarized wavelets or polarized curvelets (Starck et al, *A&A*, 2009). Using these new transforms, we will develop the following applications:

• Blind Source Separation: The GMCA method that we recently developed (Bobin et al., *A&A*, 2012), entirely based on the concept of sparsity, is an efficient way to solve source separation problem. Therefore, we want to build a new blind source separation method for polarized data (GMCA-POL), by putting together our new polarized multiscale decomposition and the GMCA methodology.

• E and B mode extraction: when some data are missing (which is generally the case for Cosmic Microwave Background (CMB) observations, due to the masking of dirty area), a linkage between E and B modes may appear. Some papers have proposed a way to handle this problem (Schneider and Kilbinger, 2007; Smith and Zaldarriaga, 2007). We believe that extending the inpainting (i.e. missing data interpolation) framework proposed in (Abrial, Starck et al., 2008) using the polarized decompositions could be a very efficient way to correct the map from the missing part.

• Gaussianity test: Testing the inflationary paradigm can also be achieved through detailed study of the statistical nature of the CMB anisotropy distribution. In the simplest inflation models, the distribution of CMB map fluctuations should be Gaussian, and this Gaussian stationary field is completely determined by its power spectrum. A large number of studies have recently been devoted to the subject of the detection of non-Gaussian signatures. During the last years, wavelets have become a standard tool for searching non-Gaussian signatures in the CMB temperature map (Vielva et al., 2004; Vielva et al., 2006). It will be of importance to test Gaussianity by properly adapting to the polarized CMB data the statistical tests we previously proposed in the scalar case (Starck et al., 2004a; Jin et al., 2005). Statistical Gaussianity tests will be derived based upon our new polarized decompositions..

Dictionary Learning: The best data decomposition is the one which leads to the sparsest representation, i.e. few coefficients have a large magnitude, while most of them are close to zero. Hence, for some astronomical data sets containing edges (planetary images, cosmic strings, etc.), curvelets should be preferred to wavelets. For a signal composed of a sine, the Fourier dictionary is optimal from a sparse point of view since all information is contained in a single coefficient. Hence, the representation space, also called Dictionary, that we use in our analysis can be seen as a prior we have on our observations. Larger is the dictionary, better will be analysis of our data, but also larger will the computation time to derive the coefficients in the dictionary. For some specific dictionary limited to a given set of functions (Fourier, wavelet, etc) we however have very fast operators allowing us to compute the coefficients, which makes these dictionary very attractive. But what can we do if our data are not well represented by these fixed existing dictionary ? or if we don't know the morphology of features contained in our data ? Is there a way to optimize our data analysis by constructing a dedicated dictionary ? To answer these questions, a new field has recently emerged, called *Dictionary Learning* (DL). Dictionary learning techniques propose to learn an adaptive dictionary directly from the data (or from a set of simulations that we believe to well represent the data). DL is also related to the Learning scientific field, and establishes a bridge between harmonic analysis and the learning theory. We will study whether the concept could improve our data analysis. DL could extremely interesting for many different applications such as astronomical image restoration, detection of feature such as Cosmic Strings in PLANCK data, or Point Spread Function representation for EUCLID.

B) Cosmology

Cosmic Microwave Background (CMB):

- **CMB B-Mode Recovery:** Within the competitive field of CMB studies, the sparse component separation method GMCA has provided the best results on PLANCK FFP4 simulation. As described, previously, our goal is to extend GMCA to polarized data as well. Thanks to PLANCK data, foreground modeling will significantly improve in the next coming years, especially on the polarization emission of galactic components. Obviously, this knowledge should be very useful to separate the CMB from the galactic components. But including this knowledge in blind source separation algorithm such as GMCA is not obvious. Symmetrically, better will the component separation better, better will be our understanding of the physical mechanisms will lead to the observed polarized emission. To attack this highly difficult problem, members from the CEA-CosmoStat group (Starck, Bobin, Sureau, Basak) and Francois Boulanger group from IAS have built a common team (MISTIC Team) in order to reach necessary the expertise on both CMB component separation and galactic foregrounds. Tuhin Gosh is a join postdoc, sharing his time between IAS and CEA. Hence, **the MISTIC team has the unmatched ambition and capability to tie polarization data analysis and component separation to state-of-the-art understanding and modelling of the magnetized interstellar medium.** We will develop a new concept in sky modeling: we will discover how to express it linearly. This breakthrough will allow us to use the model to have a physically motivated estimate of the mixing matrix, which can vary spatially to account for spatial changes in the spectral dependence of the Galactic components, and thereby to introduce the relevant physics of Galactic foregrounds into the mathematical writing of the separation problem. Two recent breakthroughs, one in harmonic analysis (sparse signal recovery in case of matrix uncertainty) and one in optimization theory (proximal operator theory), open the possibility to design a new component separation method that can be coupled to a physical model of the Galactic foregrounds. i) **First Breakthrough: sparse signal recovery**

in case of matrix uncertainty. Several studies (Rosenbaum and Tsybakov 2008, Hoffmann and Reiss 2008) have considered the following equations:

$$y = Ax + \xi$$
$$B = A + \Delta$$

where the matrix A is the true mixing matrix and B is an estimate of A. In particular, it was demonstrated that it is possible to recover a sparse solution $\tilde{x}$ provided some assumptions on the original matrix A (for instance on the coherence of the matrix) and the errors ξ and Δ are made (Δ should be small). This means that we may retrieve the original components even when using an approximate (but close) mixing matrix. ii) **Second Breakthrough: proximal operator theory:** Proximal operator theory (Combettes and Pesquet 2008) allows us to solve the problem set by previous equation, with proven convergence to a unique minimum under various assumptions. Indeed, recovering the various components given an approximate mixing matrix *B* may then be written as a convex problem that belongs to the flexible framework proposed in Combettes et al. (2008):

$$\min_{x \in H} \sum_{i=1}^{m} f_i(x)$$

where *H* is a real Hilbert space, $\{f_i\}_{i=1..m}$ are proper lower-continuous convex functions (representing for example a discrepancy function and a regularization term). In this framework, the solution $\tilde{x}$ may be constrained to belong to the intersection of closed convex subsets, representing for instance some physical knowledge of the spatial support or bounds on the values of the various components. Several optimization algorithms have already been proposed to solve such problems (Combettes and Pesquet 2008). We will use these two breakthroughs to introduce an original two-stage approach in component separation. The sky model will be introduced in this new method in two ways: i) A good estimate of the mixing matrix will be obtained at each sky pixel by linearizing a parameterized description of the Galactic components, which will take into account the spatial variability of their spectral energy distribution, and ii) the sky model will also be used to define physically meaningful constraints to be included into the proximal decomposition algorithm, which will be used in solving the minimization in the last equation.

- Cosmological Parameter Estimation: In (Paniez, Starck, Fadili, A&A, 2012), it was shown on simulations that we can recover an extraordinary estimation of the underlying theoretical CMB power spectrum using sparsity. But if we can recover so well this theoretical power spectrum, maybe this estimation could be useful also for the estimation of the cosmological parameters. The main difficulty to solve will be due to the fact that we need to work with a covariance matrix which is completely full, and not diagonal at all.

- **Tomographic Integrated Sachs-Wolfe effect detection (ISW):** We have developed a new method to detect the ISW effect (Dupe, Rassat, Starck, *A&A*, 2012). We plan to extend it in order to take in account galaxies coming from different redshift bands coming from different surveys (2MASS, SDSS) or from surveys such as Euclid.

Galaxies Surveys:

- **BAO:** Apply our BAO analysis methods to the next SDSS data release (BOSS).
- **Tomographic-ISW** (see also CMB above). We want to work on better estimation of the 2D spherical galaxy density field, by taking properly the Poisson noise effect. Methods that have been developed for Fermi could also be useful for this talk.
- **Spectroscopic redshift estimation:** Accurate determination of the redshifts of galaxies comes from the identification of key lines in their spectra. Large sky surveys, and the sheer volume of data they produce, have made it necessary to tackle this identification problem in an automated and reliable fashion. Current methods attempt to do this with careful modeling of the spectral lines and the continua, or by employing a flux/magnitude or a signal-to-noise cut to the dataset in order to obtain reliable redshift estimates for the majority of galaxies in the sample. We plan to develop new methods to analyze spectroscopic data. Several problems will be studied:
    - Automatic detection of outliers in spectroscopic redshift estimation: if we are able to detect automatically outliers, we could reject them and build extremely low signal-to- noise catalogue.
    - Galaxy templates construction: similar techniques to those proposed for PLANCK component separation could help us to build more efficient Galaxy templates, and to derive more accurate redshift.
- **3D Density estimation taking into account redshift distortions:** For many applications (tomographic ISW, comparison between Weak Lensing Mass map and visible matter, etc), we want to estimate the 3D density map. This requires to properly take into account the redshift distortions. We will develop a sparsity based method, using 3D wavelets and 3D curvelets, to make this task.

Weak Lensing: We have identified three major bottlenecks in the weak lensing data processing to optimally exploit future weak lensing survey like Euclid.

1- The first point is the shear estimation that is based on the measure of the slight deformations caused by weak gravitational lensing effect on the background galaxy images. This effect is so small that it requires the control of any systematic error that can mimic the lensing signal; in particular the smearing due to atmospheric and instrumental

effects. Several methods have already been developed and have achieved an accuracy of a few percent. However, the accuracy required for future surveys will be of the order of 0.1%. Consequently, the injection of new ideas is of crucial importance to achieve this precision and extract significant results for cosmology. To develop a new method to estimate the shear with the accuracy required for future wide-field surveys, we propose to introduce stochastic geometry to the estimation of the shape of the galaxies and optimal transportation theory to the problem of estimation of the PSF across the field. Moreover, we will explore Bayesian methods for weak-lensing measurements, quantifying and accounting for the model uncertainty. This can be applied to shape measurement and PSF modeling.
2- The second point is the 2D mass inversion that consists in deriving a 2D projected mass distribution from the shear measurements of background galaxies located at a given redshift. This is a difficult inverse problem and classical methods are not optimal in presence of observational effects such as non-Gaussian noise or complex geometry of the field. To solve optimally this problem, we propose to explore the use of the Helmholtz decomposition in the wavelet domain. Our preliminary results on noise free data have already shown significant improvements in bounded domains (E. Deriaz, Starck, Pires, *A&A*, 2012). A particular emphasis will be put on the use of wavelets adapted to noise and boundary effects.
3- The last point is to develop a new method to reconstruct a 3D mass (or density) distribution, making use of the photometric redshift information. Several linear methods have been developed recently under the assumption of Gaussian noise. However, the proposed methods show a number of problematic artefacts. Notably, structures detected using these methods are strongly smeared and shifted (relative to their true positions) along the line of sight and theirs amplitudes are damped. We propose to use recent results in proximal splitting theory to explore a new way to solve optimally this inverse problem in presence of realistic noise. A first important step has already been made in this direction with the 1D method (A. Leonard et al., *A&A*, 2012). Afterwards, we expect to obtain tighter cosmological constraints from these 3D (deprojected) density distributions.
The originality of the project is that we propose to use new techniques that have emerged recently in the field of applied mathematics, such as optimal transport formalism or border divergence-free wavelets to improve significantly the current weak lensing data processing methods.

C) Project

- **PLANCK:** We are involved in the PLANCK project. We will participate to the PLANCK Consortium activity (meeting, challenges on simulation, data analysis, etc), mainly on the scientific subjects presented in the CMB section.

EUCLID: the Euclid mission is now selected, and we will continue to prepare the mission. We are strongly involved in the Weak Lensing scientific working group, the OU-SHE (shear estimation) and the management of the OU-LE3 (unit in charge of designing the algorithms to be used to derive the Euclid products).

- **CFHTLenS**: The weak-lensing data from the Canada-France Hawaii Lensing Survey (CFHTLenS) will be released in November 2012. One member of CosmoStat (M. Kilbinger) is part of this collaboration, which is finalizing a number of publications (technical and scientific results) until the release date. After that date, we plan to apply to the lensing data several methods developed in our group (mass reconstruction, peak counts to constrain cosmological models, PSF and shape measurement). We will make use of the expertise and first-hand knowledge of the data.
- **COSMOS:** The recent re-analysis of weak-lensing data in COSMOS (Schrabback, Hilbert, Joachimi, Kilbinger, Simon et al. 2010) is of excellent quality, both concerning the measured shapes as well as the 30-band photometric redshifts. This allows us to apply 2D and 3D mass reconstruction algorithms, and, for the first time quantify the statistical properties of those lensing mass maps on real data. The wealth of observations in other wavelengths allows us to compare the reconstructed total mass with other tracers of the large-scale structure, e.g. galaxy overdensity or X-ray signal.
- **XXL:** Our involvement in the XXL surveys is two-fold: First, our wavelet tools will be used for detection and classification of extended objects in very low signal-to-noise X-ray images. Second, we will use the CFHTLenS data to measure the weak-lensing signal of X-ray selected clusters, to obtain independent mass estimates. For that purpose, we will run ray-tracing analyses of several suites of N-body simulations to predict the expected lensing mass constraints including systematic effects (astrophysical and instrumental).

D) Teaching/Training

We will continue to teach at different levels:

- MASTER 2 MVA of ENS-CACHAN
- Post-master class of the Ecole Doctorale d'Astronomie d'Ile de France.
- We plane to have two PhD students.

E) Dissemination:

We will keep collaborating with non astronomical laboratories and external companies to transfer our knowledge.

F) Conferences:

We plan to organize one international conference and two international workshops during the next five years.

LMPA - Laboratoire de Modélisation des Plasmas Astrophysiques

1. Présentation de l'unité

In the 2014-2018 period during which our project is scheduled, the LMPA team will be composed of **11 staff members**. The CEA researchers will be J-P. Chièze, J-E. Ducret, T. Foglizzo, S. Fromang, D. Gilles, P. Hennebelle, F. Masset, R. Teyssier (head), S. Turck-Chièze. Only one CNRS researcher will remain: B. Gaffet. We will also have one Paris 7 lecturer: M. Gonzalez. Our intent is to hire at least 10 new PhD students and a similar number of post docs during this 5 years period. We will also try to attract a senior scientist, expert in numerical modeling of core collapse supernovae simulations.

2. Analyse SWOT et objectifs scientifiques de l'unité

SWOT analysis for the LMPA team

Strengths

The strength of our team is to be able to develop complex numerical tools from scratch. We have complete control of all aspects of the design, optimization and distribution of our 3 codes: FARGO, RAMSES and HERACLES. This requires a very specific set of skills in applied mathematics, computer science and computational astrophysics. Our expertise in developing complex analytical models is also a very strong complementary approach, especially when it comes to code validation and theoretical models design. We also benefit greatly from the support of the computer science teams in IRFU, with D. Pomarède and B. Thooris, in term of data visualization, parallel computing and outreach, within the COAST project. Our team has also a very strong scientific track record, with 5 ANR projects, 2 ERC grants and 1 prestigious prize from the French Academy of Science being awarded. We have also produced key contributions to our understanding of galaxy, star and planet formation, as well as core collapse supernovae and stellar structure. One strong aspect of our team is related to our very presence in a world-leading observational department such as AIM: cutting-edge astronomical observations have proven very valuable in the past to foster new analytical and numerical development. In return, we believe our help in interpreting observations and preparing proposals has a positive impact on the other teams of AIM.

Weaknesses

AIM has a very strong team in high-energy astrophysics and compact objects. Although the work of T. Foglizzo has been quite visible in the context of core collapse supernovae, we believe we need to strengthen our modeling abilities in the physics of compact objects, especially related to special and general relativistic aspects. Another weak point of our team is that we have to spend quite a lot of time developing and debugging our codes. Since these tools are all freely available open sources, other teams in France and abroad quite often exploit them, with sometimes minimal credit to our work. We believe this Open Source philosophy to be very important in validating our scientific methodology, since it allows other teams to check our results. It also increases our worldwide visibility and helps developing new international collaborations. On the other hand, these other teams often make interesting discoveries with our own software.

Opportunities

A great opportunity that our team will most certainly exploit is the strong strategy of France in general and CEA in particular in High Performance Computing. Our position inside CEA is a great opportunity for our developments: we have privileged access to CEA supercomputers, especially during the commissioning phases. Our reputation in code testing and benchmarking on massively parallel system is quite good, so we can benefit directly from new hardware opportunities inside CEA. In this very favorable context, E. Audit has created recently the "Maison de la Simulation", whose goal is to provide services in code optimization and algorithmic development for petascale and exascale computing. This new institute is a great opportunity for our team, since astrophysics has been identified as one "key customer" of this new service.

Threats

Computational astrophysics is a very competitive field. Being the first to reach a certain resolution or to include a certain physical process is quite often what matters in term of scientific discovery. We need to be fast, efficient and we need to have access to the largest facilities in the world. Losing our leadership in term of adaptive mesh techniques and Godunov methodology is a great threat. Another threat, that applies to astrophysics in general, is to lose our currently dominant position in term of access to massively parallel systems. Other important sciences, such as computational biology or climate modeling, might grow significantly in the next decade, limiting our time allocations on large systems. A very important tool in our every-day work is our department cluster. It will still be active in 2016, but we need to plan in advance the acquisition of a new system for 2016-2018, especially since it will depend on external sources of funding.

Scientific objectives of the LMPA team

(1) Computational astrophysics at the era of exascale computing

Context: The large supercomputing facilities that we are currently using offer usually slightly less than 100 000 compute cores. Typical state-of-the-art simulations feature a couple of 1000 cores, while extreme simulations require 10 000 cores. Only a couple of very large simulations have approached the barrier of 100 000 cores. Only a small number of codes are able to deal with such a large number of independent compute elements. Our codes, RAMSES and HERACLES, are among them. In order to maintain our leadership position in the field, we need to be ready for the next generation of supercomputers, the so-called "exaflops" machines, with probably more than 1M cores systems commonly available. These new machines will have a very different architecture than traditional present day clusters: they will feature very large compute nodes, with more than hundred cores per node, with a very heterogeneous node structure. Graphic cards (GPU) will play an essential role as accelerators within these heterogeneous nodes.

Challenge: We need to upgrade constantly our codes, so they remain at the bleeding edge of computational astrophysics. This will require significant modifications, beyond the traditional "message passing" strategy that we use now, based on the MPI library. We will have to use new hardware, probably new programming languages and we will have to exploit extremely large machines, for which the mean time to failure (MTTF) will become prohibitively small (below 1 minute).

Prospective for 2014-2018

• *Hybrid OpenMP-MPI programming strategy*

We have recently developed a new strategy based on using both MPI and the OpenMP directives. This strategy is based on the fact that compute nodes have a larger and larger number of compute-core, each core having access to the same shared memory within the node. The idea is to have one MPI processing elements for each node, with a large shared memory allowing to define larger physical domains, with less associated overheads. Within each MPI domain, parallel computations are performed by distributing the work using OpenMP directives. This allows us to perform optimization and balancing of computations at the system level. We have tried this strategy with mixed successes on both HERACLES and RAMSES. This requires a very good knowledge of both the hardware (especially the memory architecture) and the compilers. We will need help from computer scientists, both from IRFU, within the COAST project, but also from the "Maison de la Simulation", with dedicated projects to optimize our codes.

• *GPU acceleration*

The recent years have seen the advent of scientific computing based on graphic cards, especially since NVidia has made available the CUDA language, and more recently floating-point arithmetic in double precision. GPU offer a very fast memory access together with many-core parallel computing. The problem is to copy the information from the host (CPU) memory to the GPU, a very slow process funneled through by a PCI express port. The key is therefore to design science algorithms with a very large "Float to byte" ratio, in order to take advantage of the capabilities of the GPU. Radiative transfer and MHD are good examples of such floating-point intensive problems, especially if they are performed on a simple Cartesian grid structure, that can be mapped trivially on the GPU many-core architecture. We have already exploited this technology to perform cosmic reionization simulation (in collaboration with D. Aubert and P. Ocvirk at the University of Strasbourg). S. Fromang will also exploit GPU acceleration for long-term integration of magnetized turbulence. We will be working on this with P. Kestener (Maison de la Simulation).

• *Fault tolerant computing*

A supercomputer with 1.5 million cores is already available in the US, with the BlueGene/Q Sequoia machine. The number of machines with more than 1 million cores will grow significantly in the next couple of years. Although the Operating System running on these machines is robust to node and disk failures, we need to make our applications similarly robust to hardware and software failures. The methodology associated to such robust behavior is called "fault tolerant computing". It requires the design of new algorithms (for gravity and hydro for example) that can be restarted without loss of data and without unnecessary computations. The MTTF of existing hardware is quite good, although it was predicted 10 years ago to be dramatically small. Can we expect the same to happen for the next generation of supercomputers? Fault-tolerant computing is a new paradigm with a lot of interesting consequence on algorithmic developments.

• *Developing new algorithms for astrophysics*

The last activity in our project will be to design new algorithms, taking advantage of our local expertise on Godunov schemes, adaptive meshes and elliptic solvers for gravity and implicit time integration. One missing physical ingredient in our code suite is relativistic hydrodynamics. This key addition will allow us to tackle high-energy astrophysics problems, such as relativistic jets, high velocity winds, and supernovae physics. Relativistic hydrodynamics can be expressed as a hyperbolic system of conservation laws: it is therefore ideally suited for the Godunov methodology and for the AMR technique. This project will be led by S. Fromang and T. Foglizzo, in collaboration with LAOG in Grenoble. We will also continue our exploration of numerical algorithms for radiative transfer, building up on both standard diffusion solvers and our M1 moment-based techniques. One difficulty is to be able to solve the radiation diffusion equation with an implicit solver with adaptive time step for AMR. This will be done in collaboration with G. Chabrier and B. Commercon. We will also continue to extend of photo-ionization solver (with D. Aubert, J. Blaizot and J. Rosdahl) to multigroup radiation and photo-dissociation problems.

(2) Interpreting and preparing astronomical surveys in the next decade

Context: our department is involved in many important experiments in the next 10 years, such as the coming EUCLID mission, the exploitation of the Herschel satellite, ALMA and JWST. We need to upgrade our codes and plan our participation for the preparation and the scientific exploitation of these important missions.

Challenge: EUCLID will go wide, while ALMA and JWST will go deep and reach ultra-high resolution. We need to be able to deliver simulations that meet new challenging requirements: very large simulated volume with enough resolution (EUCLID) and very high-resolution simulations with the appropriate physics (JWST).

Prospective for 2014-2018

• *Preparation of the EUCLID mission*
R. Teyssier, co-lead of the Cosmological Simulation Working Group within the EUCLID collaboration, will coordinate the activity related to performing large simulations for EUCLID. This will require running large (a few trillion particles) simulations with enough resolution (1 billion solar masses per particle) to model the mass distribution in the universe. These simulations will be performed with *at least* 3 different codes, one of which will be RAMSES. We will also explore the role of baryons in re-shaping the mass distribution in the universe, and affecting the determination of the cosmological parameters by introducing a bias in the measurement.

• *Exploitation of Herschel, ALMA and JWST*
Both Herschel and ALMA will require detailed simulations of galaxy formation and star-forming regions. In collaboration with the LCEG team, we will perform high-resolution simulation of high-redshift galaxies, for which our team and the LCEG team have a strong leadership position (R. Teyssier and F. Bournaud). This will require new tools to model the sub-mm emission of these high-redshift galaxies. We will have also to develop new models to account for realistic feedback processes, regulating the formation of giant molecular clouds in these extremely star-forming objects. P. Hennebelle will also develop new tools to model the sub-mm emission of star-forming regions in the Galaxy, supporting ALMA proposals and interpreting the observations performed by the LFEMI team and P. André. Sub-mm mock observations are very hard to perform: we will need complex radiative transfer tools to model both continuum and line emission. Given our expertise in radiative transfer, as well as complementary tools developed elsewhere with AIM (both in LCEG and LFEMI), we are in a very good position to deliver competitive results for these forthcoming observations.

(3) A common theoretical approach for star formation and galaxy formation

Context: Our understanding of galaxy formation is currently limited by small-scale processes, such as star formation, stellar and AGN feedback. In order to make a significantly leap-forward and go beyond current phenomenological models, we need to address more directly the problem of star formation and feedback within the galactic context. The theory of star-formation is also limited by our poor understanding of interstellar turbulence: where does it come from? How is the turbulent energy injected so efficiently inside molecular clouds? Why doesn't it dissipate? Our team has pioneered many aspects of this problem during the last 5 years (sensitivity of galaxy morphology to star formation efficiency, formation of molecular clumps from galactic colliding flows). Our various studies all point towards the necessity to address the problem of star and galaxy formation together, in order to overcome the limitations of both fields. Fundamental questions such as the Initial Mass Function in star forming regions or the (non-) formation of bulges in galaxies will be solved only if one tackles both scales (galactic and star-forming clouds) together.

Challenge: the main challenge is obviously related to the multi-scale nature of the problem, with 10 kpc-sized discs, down to a few AU-sized molecular cores. This is also a problem of physical modeling: magnetic and radiation fields are both required to determine the chemistry of the star-forming gas, as well as the morphology of star-forming filaments. Modeling an isolated disk while forming stars one by one is a formidable task that will probably not be reached within the next 5 years: our goal is to pave the road towards this ultimate goal, identifying the main problems to solve.

Prospective for 2014-2018
Our goal is to perform first simulations of isolated Milky Way-like disk with an implementation of stellar feedback that allows us to destroy the molecular clouds. We will obviously rely on a phenomenological model of stellar feedback to reach this goal, since the disruption of molecular clouds is still an unsolved problem. These simulations will be performed in collaboration between R. Teyssier and F. Bournaud. It is worth mentioning that a simulation of an isolated Milky Way disk has been performed in 2012 with a spatial resolution of 0.1 pc, a world premiere in this context. In the same time, we will perform in parallel simulation of turbulent molecular cloud, using both the classical set-up of decaying turbulence in a box and the now traditional set-up of colliding flows. The idea is to use a proper modeling of both radiation and magnetic field to get the correct size of proto-stellar fragments, and explore in the same time the interruption of star formation by stellar winds or other feedback mechanisms (P. Hennebelle, S. Fromang and M. Gonzalez will lead this project). When these 2 types of simulations will be under control, we will try to couple them by performing an isolated disk simulation and by zooming on a collapsing giant molecular cloud, following the collapse self-consistently down to the formation of the star cluster. This will be a massive collaborative effort within our team, with the RAMSES code as the main tool.

(4) Understanding the formation of planets

Context: As uncovered by the Kepler mission, planetary systems like our own are numerous in the universe. They have diverse and sometimes unexpected properties. In order to understand their architecture, we first have to obtain an acute understanding of the environment in which they form, namely protoplanetary (PP) disks. This subclass of accretion disk is a complex beast: believed to be partially turbulent as a result of the MRI, they also feature complex radiative and chemical processes. Such highly nonlinear effects are best studied with the help of cutting edge MHD numerical simulations. Key questions that will be studied in the next five years are: 1- what is the saturation amplitude of MHD turbulence in protoplanetary disks? 2- what are the consequences on radiative processes on the disk dynamics? Do they result in any observable consequences? 3- what is the large-scale structure of PP disks (dead zone, jets, winds)?

Challenge: The main challenge is the enormous computing time required by such simulations. Millions of time steps are needed to extract meaningful statistical diagnostics of the flow from a simulation. Coupled to the high resolutions intimately associated with any turbulence simulation, this makes that project a formidable numerical challenge.

Prospective for 2014-2018: The questions outlined above will be tackled within the framework of the PETADISK project, an ERC starting grant that has just been awarded to S. Fromang (2011-2016). A group of 5 researchers (1 PhD student, 2 Postdocs, 1 engineer and the PI) will develop dedicated MHD numerical simulations. Subgrid models of MHD turbulence will help reach the parameter regime relevant for PP disks. Non-ideal MHD effects as well as the link between MHD turbulence and disks winds will be considered. On the computational side, a GPU version of our code will be developed in collaboration with P. Kestener (Maison de la Simulation). In parallel, more realistic physical modules will be included in global simulations of turbulent PP disks: temperature dependent resistivity will help study the dynamics of the dead zone while coupled MHD/radiative transfer simulations of PP disks will open a link between dynamical simulations and observations. At the dawn of he ALMA era, this should prove an exciting adventure.

(5) Towards a complete modeling of core-collapse supernovae

***Context*:**
The theory of core collapse supernova describes the interplay of gravitation, hydrodynamics, nuclear physics, neutrino interactions and transport during the first second following the formation a proto-neutron star. Most of the recent progress is related to the consequences of hydrodynamical instabilities that break the spherical symmetry, such as neutrino-driven convection and the Standing Accretion Shock Instability (SASI), but their relative roles in 3D are a subject of vivid controversy. Numerical simulations from different groups are still too different and too few to disentangle issues of numerical convergence from the possible stochastic nature of the explosion process. While the sloshing oscillations of SASI have been recognized in most 2D simulations assuming an axisymmetric evolution, the spiral asymmetry expected in 3D for rotating progenitors has not been confirmed yet (Yamasaki & Foglizzo 2008, Wongwathanarat+2012). Additional complexity concerns the structural diversity of stellar cores before collapse (Mueller+2012, Ugliano+2012), and uncertainties in the equation of state of nuclear matter (Marek & Janka 2009).

***Challenge*:**
Our goal is to develop a numerical model of core-collapse characterizing the conditions for a successful supernova explosion in 3D, depending on the properties of the stellar core such as its radial structure and rotation rate. This model will also be able to describe the birth conditions of neutron stars (mass, kick and spin), with particular attention to the threshold of black-hole formation. Direct signatures of the explosion mechanism are the time dependence of the neutrino signal and the emission of gravitational waves. Expertise in the many required topics (including condensed matter Equation-Of-State, neutrinos transport, nuclear burning and general relativity effects) is currently note present in our team. Our goal is to build the missing skills by inviting or hiring an expert in core collapse numerical modeling.

***Prospective for 2014-2018*:**
The numerical cost of simulating core-collapse in 3D precludes a direct and systematic exploration of the parameter space. The theory of core-collapse supernovae in the future 5 years will rely on a few complex simulations complemented by simplified ones. A deep understanding of the hydrodynamical processes will be necessary to evaluate the sensitivity of the explosion mechanism to the physical ingredients and approximations. This project will benefit from the expertise of the LMPA team in hydrodynamics in general (Fromang, Masset), and core-collapse hydrodynamics in particular (Foglizzo) in numerical techniques with the codes RAMSES and HERACLES (Teyssier, Fromang, Audit, Gonzalez, Hennebelle), and in transport methods (Audit, Gonzalez). A collaboration with the experts in numerical relativity and nuclear physics at Meudon Observatory (Novak, Gourgoulhon, Oertel) and IPN Orsay (Margueron, Kahn) has been initiated by the ANR project SN2NS (2011-2015). The collaboration with the team at MPA Garching will be continued (Foglizzo+2006, 2007, Scheck+2008). We also expect to attract in our team an expert in core-collapse modeling, which will increase our knowledge in this difficult science.

(6) Unveiling the structure and the internal dynamics of stars on secular timescales

Context: Previous studies on stellar interiors lead to crucial questions on the existence of magnetic field in the core of stars and on the evolution of the magnetic field of solar-like star near their surface (Turck-Chièze & Couvidat 2011, T-C, Piau, Couvidat 2011, Piau et al. 2011, Simoniello et al. 2012). These dynamical effects compete with microscopic physics that today mainly governs the theoretical evolution of stars and the pulsations of massive stars (Cepheids, Beta Cepheids…) (Turck-Chièze et al. 2009, 2010, Gilles et al. 2011). So, progress and verification of the quality of the physics describing the equation of state and opacities are also clearly useful along the HR diagram. The lack of knowledge of the respective role of these competing processes leads to the absence of prediction of the solar activity of the next decade or to its precise secular evolution during the last centuries, this fact limits our understanding of the relationship between Sun and Earth, at an epoch where more and more planets are detected and where one tries to understand how they interact with their host star. Moreover one has not a proper description of the accretion ejection phase of solar-like stars, nor of their dynamical pre-main sequence description at the period of the planet formation. This phase is a key phase to understand the whole story of the deep internal stellar magnetic field and of the dynamo actions at different periods of a stellar life.

Challenge: No direct signature of deep magnetic field topology and strength in solar-like stars is today accessible as the magnetic pressure is generally negligible in comparison with gas pressure. But indirect manifestations through the splitting of the gravity modes or the evolution of the internal rotation profile of twins of the Sun at different ages become available. The history of the internal magnetic field along the HR diagram represents a real challenge for a good understanding of the early and final stages of evolution of stars.

Prospective for 2014-2018: We shall develop two activities. The first one is to validate or improve the description of the microscopic physics used in stellar evolution in confronting detailed opacity calculations performed with the code HULLAC and other codes of the OPAC consortium to some key experiments realized with high energy lasers of LULI, LMJ and maybe ORION facilities (Turck-Chièze, Ducret, Gilles, Le Pennec). The already performed experiments push us to improve the individual opacity coefficient used in the envelopes of stars for elements of the iron group. The second activity is dedicated to the phase transition between the formation of stars and the main-sequence stage after the first contraction period. We would like to follow how the strong rotation of the stellar core can induce some magnetic field, what could be its strength and if this magnetic field is sufficiently strong to diffuse in main sequence and modify the rotation profile as the radiative region extends (Turck-Chièze, Le Pennec). Of course seismic observations of the rotation profile of different stars will be useful to constrain such models together with the understanding of the role of magnetic field in the helioseismic data (Turck-Chièze, Simoniello in collaboration with Piau, Kosovichev and Rozelot) in order to prepare the next generation of instrument like GOLD.

LSIS - Laboratoire Spectraux Imageurs Spatiaux

1. Présentation de l'unité

LSIS was created in 2010 from the Space Detector Group of a former larger Space Detection Lab., keeping the same people, management and missions. The size of the team grew from 13.5 FTE up to 18.5 people between 2007 and 2012. The creation of LSIS gave more internal visibility and permits a more flexible management. As consequence, lab activity is more active: enhancing discussion, ideas, and hardware exchange.
The number of permanent staff grew from 9 up to 13 during the contract. In 2007, the staff was: 13.5 FTE, 10 permanent people, 3.5 researchers, 4 technicians, 4 engineers or other, 2 PhD students or postdocs. In 2012, the team is: 18,5 FTE, 13 permanent people, 6.5 Researchers, 3 technicians, 4.5 engineers or other, 4.5 PhD students or postdocs.
One of our permanent technicians leaved after 36 months in the lab, three apprentices ended their contracts after spending 54 months in total and graduated either at engineer degree or technician degree. In addition, 2 PhD students defended a thesis after 60 months in total, and one postdoc spent 24 months with us.
In the same period of time, a new apprentice, 3 PhD students, 2 postdocs joined us. Two researchers were hired (one from another lab of AIM and one from a previous non-permanent position in our lab. In addition, a non-permanent position engineer was hired.
In the future, our objective is to maintain our skills and creativity by hiring a new technician, and giving training opportunities for new PhD students and postdoc (one every other year).

2. Analyse SWOT et objectifs scientifiques de l'unité

<u>**SWOT analysis for the LSIS team**</u>

Strengths
The most important strength of our R&T lab is creativity. LSIS draws its creativity of its multidisciplinary expertise, from basic material research to advanced space systems for imaging spectrometry.

LSIS strategy is consistent and durable. It relies on developments in parallel at different levels of maturity. When a R&T program concludes to a successful space proven detection system, team leaders are active to promote attractive and flexible product lines in relation with AIM astrophysicists. This benefits from space instrumentation experts to emphasize their capability to join ambitious international instrumentation programs from design to flight.

LSIS space imaging spectrometer expertise is recognized internationally and allows setting prestigious collaborations and reliable research networks in all our fields of applications from the far infrared to gamma rays.

R&T efforts enable high maturity level imaging spectrometers attractive to international instrument payload consortia in new missions. LSIS has the ability to quickly respond to new opportunities. Active participation to space mission proposals, phase 0 and A gives our lab a chance to enter into new space science projects and new collaborations (UC Berkeley CINEMA/TRIO, ASTRO-H, STIX, EChO, SPICA/safari…).

Managing new opportunities and R&T programs is achievable because LSIS permanently pays attention to get coherent programmatic and synergistic activities.

LSIS facilities are numerous, modern and often extend to clean room facilities when clean operations and tests are critical. No less than six experimental areas are currently available to receive our instrument developments. Our technical environment is a force.

Weaknesses
Whatever the skill of our lab, politics and lobbying is extremely important to raise our chances to play a major role in a space program. Even with excellent technologies, we often contributed to phase 0 and A being a back-up option while our skill are often at a very high level (SPICA, LOFT, IXO/XMS, IXO/HXI,…). The lack of leader involvement at science level in new program communities is a major weakness.

It is difficult for LSIS to be attractive to PhD students. The duration of a space project development is very different from the thesis duration. Our location into an Astrophysics division hides our technological face from universities and requires extra efforts to draw the attention. Although there are well suited sources of funding for PhD grants like CTCI (shared contract between industry and CEA), the process is complex and pretty slow, preventing us from being attractive with respect to some industries where excellent candidates showing similar profiles are also welcome.

Finally, probably the most critical weakness is that LSIS has an unbalanced configuration of the number of our technicians with respect to the number of our engineers and researchers.

Opportunities
LSIS environment is conductive to innovation and to high performance apparatus for astrophysics. As a matter of fact, LSIS works systematically with every instrumentation labs of AIM (LEDE, LSAS, LQIS and LISIS) and is well established within Irfu institute. This enables strong and sustainable cooperations, mostly with technical services and labs, SEDI/LEDEF, the detector and front-end electronics lab but also other divisions like SIS and its mechanical engineering office for instance. Moreover, implantation within CEA and more specifically direct connections with DRT/Léti DRT/LIST, DSM/INAC/PTA, … gives access to most advanced technological facilities and platforms. When innovation and skills are positioned in the industry, LSIS contracts and cooperates, sometimes on the long run.

Our R&T space programs are supported by Cnes, the French national space agency, but also more recently by ESA, the European space agency. In these frameworks either preliminary studies or payload participations studies and realizations are conducted.

Success into international collaborations is fruitful and triggers new opportunities and new perspectives (SORRENTO, SRG, ASTRO-H, …). Sometimes LSIS may contribute significantly to science missions out of the main historical science topics (SENIC, Solo/EPT…) but increasing very much our visibility and opening new horizons.

Recently, LSIS was successful in diversifying funding resources: applying to ESA calls for instance. Moreover, as the landscape of research has changed significantly in France in the last few years, especially with the creation of LabEx structure, LSIS had new opportunities. This framework is beneficial to LSIS when cooperating with other labs in related and synergistic field. LSIS is contributing actively to P2IO, UnivEarthS and Focus and answers to calls for projects from these structures. Recent proposals and funding opportunities came with FP7 or ANR. In the future, these sources may extend to Regional support for industry-institutions cooperation's for innovation and technologies (FEDER, FUI,…)

Threats
R&T and innovation relies on anticipation and risk taking which is somehow contradictory with contractual commitments, demanding schedules, set with funding agencies. How to guarantee on-time success into innovation without paying the price of performance? Similarly, it is sometimes difficult to take in our wake industrial partners who have to share the risks with us. This immediately causes the developments to be expensive.

Our resources, in particular funding, are difficult to obtain in a very competitive field. This task is therefore time consuming and solicits our experts, possibly pushing them away from their main technical skills.

LSIS cannot escape attempting to reply to many calls for new space projects. As a result, great efforts are made in vain, possibly discouraging the involved staff.

New opportunities for imaging spectrometer development could have the effect of easily overloading LSIS with projects that could be decoupled from the main scientific goals of AIM.

Participation to space programs at the moment requires a very high level of maturity, which requires anticipation: the main threat is certainly failing to anticipate a key development for future missions.

Intellectual Property is partially covered by patents. Patenting requires secret, time and anticipation, which is somehow contradictory with participation to proposals in phase 0 and A. As a matter of fact, disclosure of fresh results in innovating fields before patentability has been performed is required to reinforce space mission proposals. A R&T lab cannot anticipate every emerging technology.

3. Mise en œuvre du projet

Global trends in the field of imaging spectrometers in space
The permanent mission of LSIS is to raise the imaging spectrometers sensitivity as much as possible. In the case of sub-mm range bolometers, it essentially means reducing the Noise Equivalent Power by several orders of magnitudes. In the IR domain it drives to large arrays and fine pitch detectors, having ultra-low dark current and readout by bump bonded CMOS readout ASICs, while in the X or gamma ray domain, the goal is mainly to improve as much as possible the energy resolution, to Fano limit for CdTe based detectors, in small pixel arrays.
This is reflected by a systematic search for **noise reduction** in LSIS activities. The trend is to raise the pixel density, integrate electronics functions or optical functions near or inside the pixels, making more and more complex detection systems (low power, multiplexing, cryogenics, on chip real time analysis, …), without sacrificing reliability (radiation hardness, mechanical stress, …) and build large surface detectors.
On the other hand, there is a general keen interest in **polarization** measurements for astronomical purpose in addition to spectrometry and photometry resolved in time. This is an emerging parameter that most of our technologies can integrate at detector level.
In the next sections, we detail the perspective to follow the general trends in each individual LSIS activity.

LSIS Strategy 2014-2018

LSIS strategy remains valid for the next period to 2018 that is to conduct in parallel low maturity level basic research with advanced systems applications. The technological merry-go-round will probably push X-ray micro calorimeter into the prototyping stage while CdTe activities will start a new cycle of basic R&T studies as well as IR detectors.

In terms of organization, we'll reinforce and improve internal communication in LSIS for better cooperation between staff in apparently different skills. This happens when organizing periodic Science and Technical Forums where LSIS staff is invited to share and comment on new innovating ideas without any external public. This kind of forum comes in addition to periodical general-purpose lab meetings where information's are shared; opportunities are discussed and prioritized according to AIM technical director advices. Conversely, LSIS must communicate efficiently inside AIM to influence its main scientific items.

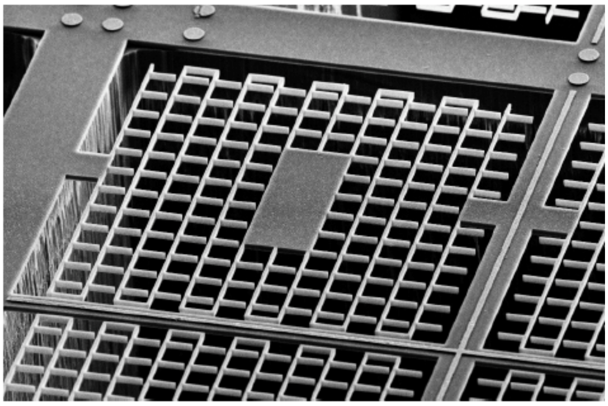
LSIS will pay attention to sustain valorization efforts to other fields than astronomy, enabling new sources of funding.

LSIS life

LSIS pays attention to staff skills and encourage participation to professional training and conference participation. It is also our role to go ahead in teaching our cutting edge knowledge, especially giving lectures. This was done previously including students training (Postdocs, PhD students and apprentices or students at any degree of technical training). The goal for each team is to incorporate at least one PhD, Postdoc and student (i.e. more than a dozen of new non-permanent positions).

LSIS shall hire at least one technician in its permanent staff during the 2014-2018 contract, while replacing retired members.

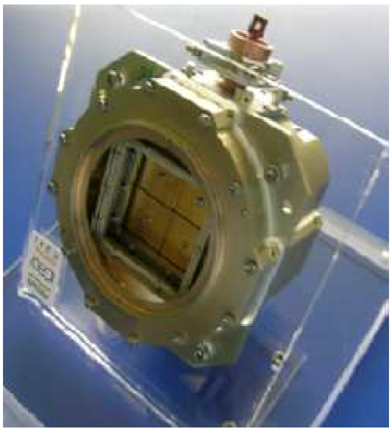
R&T prospective for sub millimeter range bolometers



Our aim is to reach a Noise Equivalent Power below 10^{-18} W/sqrt(Hz) on PACS type sub millimeter bolometers (Metal-Insulator Semiconductors – MIS). The future observatory like SPICA (Jaxa) requires an improvement by a factor of 1000, (i.e. 10^{-19} W/sqrt(Hz)) with respect to current arrays. It is a major acceleration of the typical detector improvement step (one order of magnitude par step). This goal is a real challenge and succeeding here would be a breakthrough in this field.

LSIS believes that MIS resistive bolometers are still capable to evolve this way and remains competitive with respect to Transition edge sensors or more recent KIDs arrays. Nowadays, even if TES are faster than MIS, serious limitation come from the complicated manufacturing process and high power readout electronics needed, which eventually limit the number of achievable channels in a space program. On the other hand, KIDS are very promising and easy to build, but possibly sensitive to cosmic rays. They require complex warm electronics and have a low maturity level. Improvement of MIS sensitivity relies on:

- First, detail knowledge and modeling shows that current bolometer architecture, when cooled down to 50 mK, instead of 300mK, enables to access the 10^{-18} or 5 10^{-19} W/sqrt(Hz) range. Cryogenics is obviously not sufficient to succeed as careful doping of the resistive thermometers is absolutely mandatory and a technological development is in progress. As the temperature goes down, thermal conductivity drops together with heat capacity, which improves drastically the Noise Equivalent Power as well as the bolometer response.
- Second, entirely new pixel design is foreseen to reduce the Noise Equivalent Power even more. This design called ULG from Léti (see top right figure), combines a complex shape and ultra-low thermal conductivity link to a radiation absorber in a single micro machined ~250 µm silicon pixel bringing another improvement factor of 5 or 10.
- Finally, adjusting carefully the shape of the absorber, the pixel is eventually sensitive or not to radiation polarization, on demand.



This has never been achieved up to now and is fully part of our program for 2014-2018 period.

In parallel to this ambitious noise hunting, it is planned to quadruple at least the number of channels in a bolometer module increasing the detector surface and reducing the pixel pitch (bottom right figure chose a mockup of what should be a mosaic of four 1024 pixel bolometer arrays with 650 micron pitch).

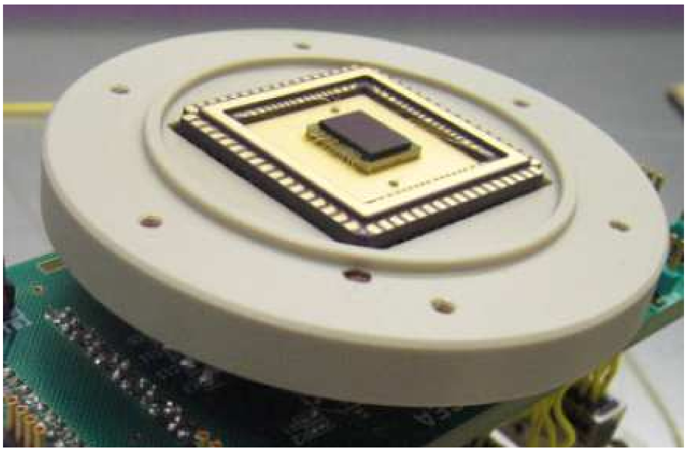
Of course, such a development is associated to a parallel effort on cryogenic electronics, as the amplification, readout, multiplexing etc. must fit these extreme noise requirements. This is the goal of CESAR program led by LSIS. The Sub-millimeter R&T coupled to CESAR cryo-electronics programs also aims also at contributing to applications in the medical imaging techniques, more precisely in magneto metric brain imaging.

Within the framework of the Focus LabEx, LSIS will investigate possible hybrid bolometers using manufacturing process of MIS together with KIDS.

In addition to this coherent program on ultra-high sensitivity bolometers, more exotic studies will be reinforced, for instance to design and model some entirely new bolometers integrating some spectrometry capabilities. This idea relies on the resonant cavity adaptation on demand, either dynamically with a cavity motion or using magnetic modulation of a dielectric absorption.

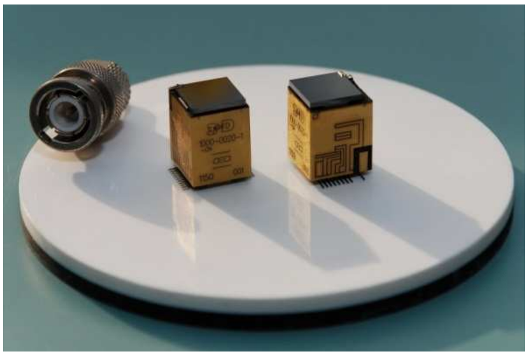
R&T prospective for IR sensors

European Space Agency has established a roadmap for the development of infrared detectors in Europe that shall be used in space both for astrophysical and Earth Observation purpose. The roadmap responds to a strategic plan to overcome the US supremacy in this field for space applications. The main goal of ESA is to support a European source of ultra-low dark current IR detectors built in a large format configuration up to 2K x 2K and operated at cryogenic temperatures and covering the whole spectrum from NIR (1-2 µm) to VLWIR (16 µm).



CEA/Léti – AIM duo and Sofradir, a French company born from CEA, are in a very good position to play a major role in this European MIR development because this consortium disposes of cutting edge technology: large scale, fine pitch MCT (HgCdTe) bump bonded to CMOS readout chips (see left picture), operated at cryogenics temperatures in the range from 30 K to 110 K and capable to meet the science requirements of most demanding missions like Euclid or EChO in several bands: SWIR, MWIR or LWIR. A single technology process is available to fine-tune MCT detectors in any of these wavelength channels. The requirements for such applications are ambitious because the source flux is extremely low, which obviously requires ultra-low dark current in the pixels: the typical range is a few tens of ato-amps. Consequently, R&T efforts are mandatory for design, fab and fine characterization of ultra-low dark current detectors. LSIS is expert in IR sensor fine characterization while CEA/Léti is expert in IR detector physics and manufacturing. This association of these competences enables challenging this R&T effort to the space qualification au CEA/Léti IR products.
The current main frame for such developments is EChO/ITT published by ESA that AIM and Léti won. On the other hand, Cnes has established its own road map and LSIS is funded for R&T program devoted to EChO activities in France. This activity is accelerating, as the IR demand is strong. LSIS is preparing answer to new ITT coming up soon, especially for earth observation in the LWIR-VLWIR range.

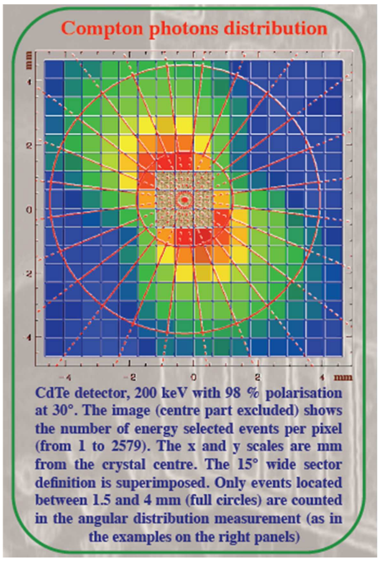
R&T prospective for semiconductor imaging spectrometers



CdTe based imaging spectrometer Caliste R&T is over and the device is ready for flight in its Caliste-SO version (see picture on the right). It will be used in the ESA Solar Orbiter mission inside the STIX X-ray spectrometer in charge of observing the solar flares in a ultra-wide domain of luminosity, with a good timing accuracy, good spectral resolution, large dynamic range down to 4 keV through a thermal shield and with an unprecedented angular resolution near perihelion, 0.22 astronomical unit from the sun. Solar orbiter will be LSIS first opportunity to fly a set Caliste but hopefully will trigger new opportunities such as Spectrum Roentgen Gamma ART-XC focal planes or Inter-Helio Probe SORRENTO focal planes Russian payloads under discussions for the period of 2014-2018. In addition, this mature technology is also ready for ground application in the industry and is proposed for valorization in programs such as ORIGAMIX, a ANR devoted to post-Fukushima activities where Caliste could act as a building block of a ultra low wright and high performance portable gamma camera (collaboration between CEA and industry).

Time has come to start a new cycle of R&T for such imagers towards higher pixel density devices and lower noise. This is the goal of MC2 (Mini CdTe on Chip). This program supported by Cnes, starts with microelectronics developments and aims at designing entirely new CdTe imaging spectrometer with 300 µm pitch (instead of 580) and Fano limited spectral response, i.e. ~500 eV fwhm at 60 keV. A particular attention will be drawn on the attractive low threshold capabilities of our designs, which allows extended dynamic range down to 1 keV, in the X-ray domain. MC2 program has been triggered recently and hosts one PhD's in the field in LSIS. Another student is about to finish a microelectronics PhD at Irfu/LDEF, our main partner. Preliminary results show very promising performance that encourage us to start building prototypes and develop basic technologies for integration of a 3D hybrid, based on advanced technologies such as heterogeneous Wire-less Die on Die technology (3D plus) and/or Through silicon via's (TSV "last") techniques. Innovative funding for integration phase is under study in the prospective of getting closer relationships with industry, in a collaborative approach.

As our imager hybrid technology (but the ASICs) is in principle not limited to CdTe sensors, we now pay attention that our recent design is compatible with silicon diodes having reverse current with respect to CdTe diodes, or silicon double-sided strip detectors having connection both at the cathodes and anodes. This approach reinforces emerging collaboration with UC Berkeley - NASA/GSFC and JAXA/ISAS for space weather and solar physics or hard X-ray astronomy respectively. The latter pushes us to study double sided detector (DSD), whether they are CdTe based or Si based. In this case, LSIS will run a ESA funded program, in the frame of the European contribution to ASTRO-H, to study the stability of high spatial resolution Double sided CdTe as used in HXI instrument, and the stability of such detectors on the long run, taking into account radiation damage. On the other hand, development of DSD feeds new developments committed in the framework of the LabEx UnivearthS/WP I5, that consists of building prototypes of large area silicon based DSSD's for Compton imaging in the frame of LabEx UnivearthS.

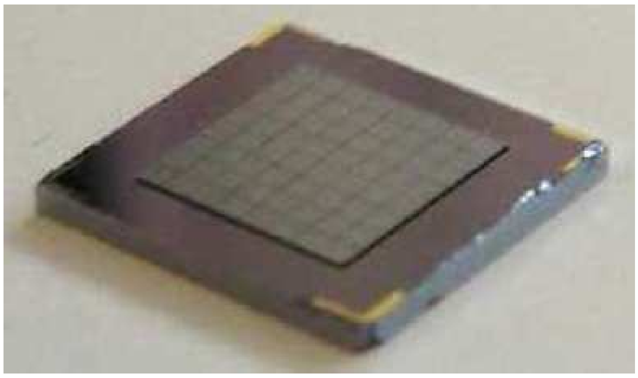


CdTe detector, 200 keV with 98 % polarisation at 30°. The image (centre part excluded) shows the number of energy selected events per pixel (from 1 to 2579). The x and y scales are mm from the crystal centre. The 15° wide sector definition is superimposed. Only events located between 1.5 and 4 mm (full circles) are counted in the angular distribution measurement (as in the examples on the right panels)

Compton imaging is the key to access the polarization measurements of each single photon hitting the sensors in the gamma ray range. A polarimeter would count at list a pixelated or DSD CdTe camera or a stack of it, or a stack of Si DSSDs. A pixelated CdTe Caliste-256 module has been successfully experienced at the European Synchrotron Research Facility in 2011 giving promising results (see figure above). This triggered a new international collaboration, joining IAAT/Tubingen, INAF/Bologna, University of Coimbra and APC, that LSIS intend to animate for further research, new ESRF campaigns towards instrument concept development in the period 2014-2018. This Project is called ASTROPOL.

R&T prospective for X-ray microcalorimeter

The micro-calorimeter in the X-ray domain is a very challenging R&T program of LSIS. Basic research on materials, manufacturing process and collective building-up of an entire array is achieved. This includes Tantalum absorber preparation, purification and bonding, cryogenics systems and benches, radiation-hard and ultra low-power cryo-electronics, massive interconnection systems at 50 mK (see figure bottom right), multiplexing strategy, warm electronics and data acquisition. Building blocks are ready and no more technological barrier is ahead. The team will build a first full functional prototype. The goal is clearly to realize an ultra-high energy resolution spectrum in the short term and to go ahead with a demonstrator of quarter of focal plane with 32x32 pixel array, 500-micron pitch, operated at 50 mK.



The expected performances are in the range of only 2 to 5 eV fwhm at 6 keV. The system approach of the development will allow building the full assembly in the next period of 2014-2018 showing a Technological Readiness Level at 4/5. The demonstrator will be the largest X-ray micro-calorimeter array ever built and will certainly enter in a competing position with respect to Transition Edge Superconductor based micro-calorimeters of our main competitors, i.e. NASA/GSFC and SRON.

LSIS is leader of a large collaboration involved in the X-ray micro-calorimeter focal plane development, ready to face future call for large mission.