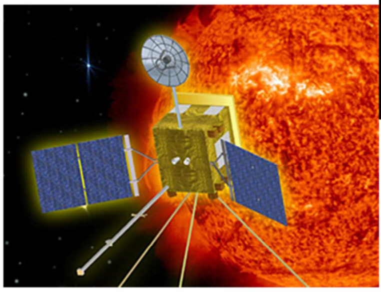
Astrophysique Instrumentation Modélisation

Unité Mixte de Recherche N° 7158

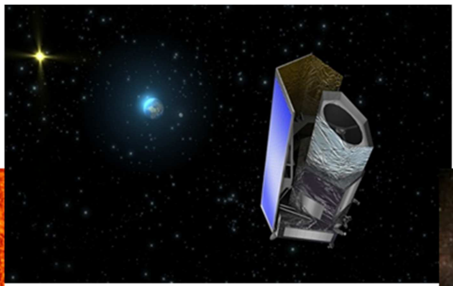
Report 2007 - mid 2012
Project 2014 - 2018

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).

SECOND PART : PROJECT :



Solar Orbiter
Participation in STIX
(Caliste)



EUCLID
VIS focal plane
Ground segment

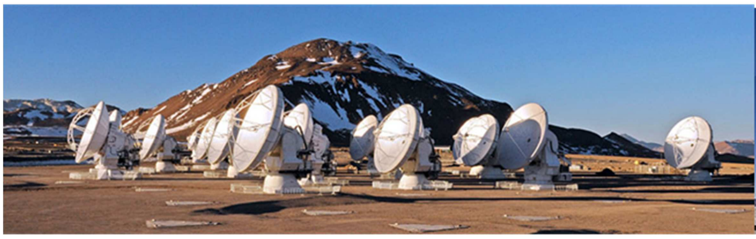
JWST
MIRI

Second PART Project

JUICE
Participation in ECHOES
(if selected)

Massively parallel computers
Scientific exploitation

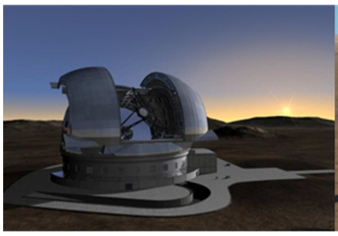
Pilot
Providing focal plane



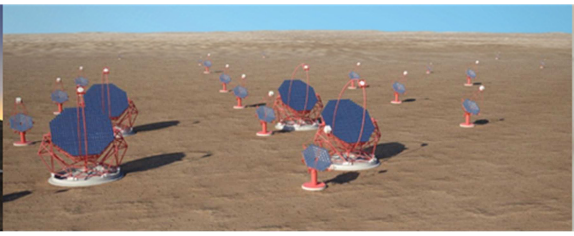
ALMA
Scientific exploitation

APEX
Providing ArTéMiS

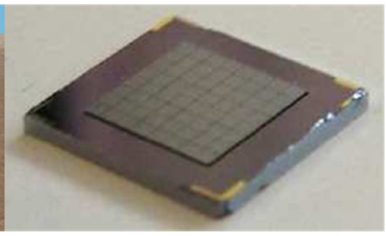
IRAM
Participation in NIKA
(polarimetry)



E-ELT
Participation in METIS



CTA
Participation ground segment

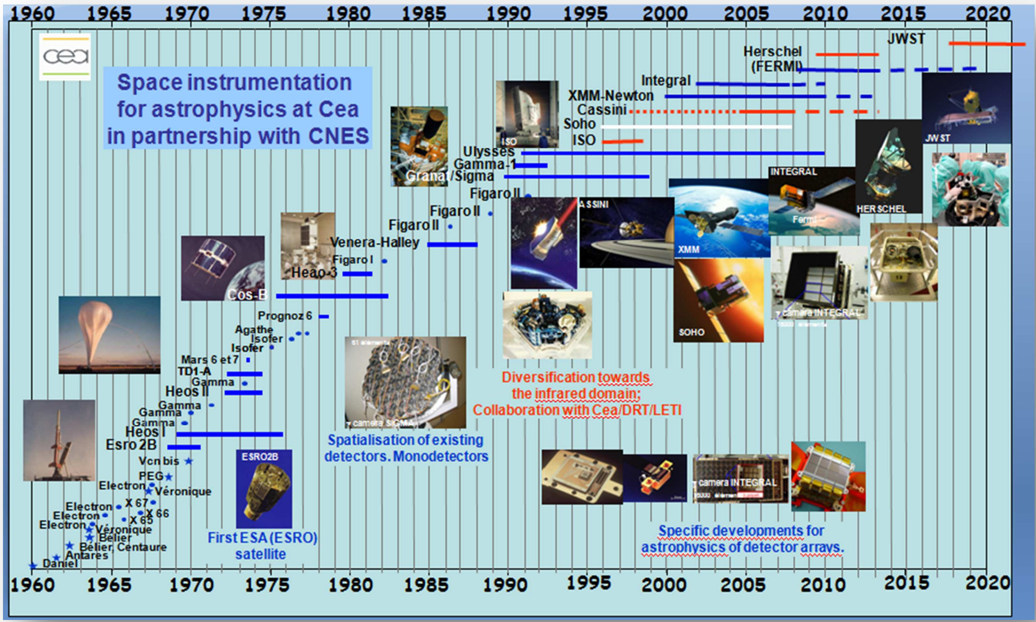


Novel detectors
Detector characterisation platform

A. Introduction

1. Historical background

AIM benefits from the long tradition of space projects at SAp (the CEA's Astrophysics Department) (see Figure below).



Since the early 60's, SAp/AIM has been participating in most of the major astrophysics space missions.

The presence of astrophysics within the CEA has always benefited astrophysics and has been beneficial to CEA. Research in astrophysics at CEA began in the 1960s and built upon the wide experience in X-ray and γ-ray detectors and instrumentation. At the same time, space studies were starting to develop with the foundation of CNES in 1961. Since X and γ radiations from space are absorbed by the atmosphere, it was natural to combine the expertise of the CEA and CNES to develop high-energy astrophysics. Thus SAp became one of the first French space laboratories dedicated to astronomy and, in partnership with CNES, it went on participating in most of the major astronomy projects investigating cosmic radiation (HEAO, Ulysses), γ radiation (Cos-B, Sigma, Integral) and X rays (XMM).

Since the 1980s, the CEA has diversified and developed a high-technology center. Astrophysics is a driver of technological developments ripe for industrial use because its instruments require exceptionally high performances in order to observe the faintest objects in the Universe. Astrophysics also required new observing windows across the electromagnetic spectrum. SAp kept up with these evolutions and diversified into a new sphere of excellence: the detection of infrared radiation, based on technological developments in detectors made at Léti, CEA Grenoble. SAp consequently took charge of the development of the ISOCAM camera on board the ISO satellite (1995 – 1998), and participated in the CIRS instrument for the Cassini mission (launch 1997, insertion into orbit around Saturn in 2004). Development at Léti of new types of detectors for astrophysical applications has continued with the production of bolometer arrays for the PACS instrument for the Herschel mission and, now, with the production of bolometers arrays for the APEX/ArTeMiS large-field camera and the development of near-InfraRed (IR) and mid-IR HgCdTe arrays in the context of the ECHO M3 mission candidate.

Until the end of 2001, SAp was organized into groups of engineers and researchers according to the wavelength being studied (X, γ, IR, etc.), plus a «theoretical» group and a space experiments group (GERES). At the start of 2002, SAp was reorganized into nine teams, five bringing physicists together around a science topic, and four space instrumentation teams – including a detection team combining physicists, engineers and technicians. This structure also took account of the fact that, since SAp became part of Irfu in 1992, it has worked with Irfu's technical services, particularly for ground-based projects. As a result, SAp and now AIM has been able to focus most of its technical activities on aspects specific to space. The potential of numerical simulations was fully recognized and a dedicated transverse program, the COAST program, was set up in 2005.

Since the late 70's, SAp has hosted CNRS researchers and since the 90's, research-lecturers from the Paris Diderot University. On 2005 January 1st, a joint research unit, AIM, supervised by CEA-Irfu[4], Paris-Diderot University and CNRS-INSU[5], has been created; at that time, only researchers were part of the unit. Following the only major recommendation of the AERES visiting committee in 2008, the engineers and technicians from SAp have now been included in AIM.

[4] Institute of Research into the Fundamental Laws of the Universe at the French Alternative Energies and Atomic Energy Commission
[5] National Institute for Earth Science and Astronomy of the French National Centre for Scientific Research

2. Characterization of the research

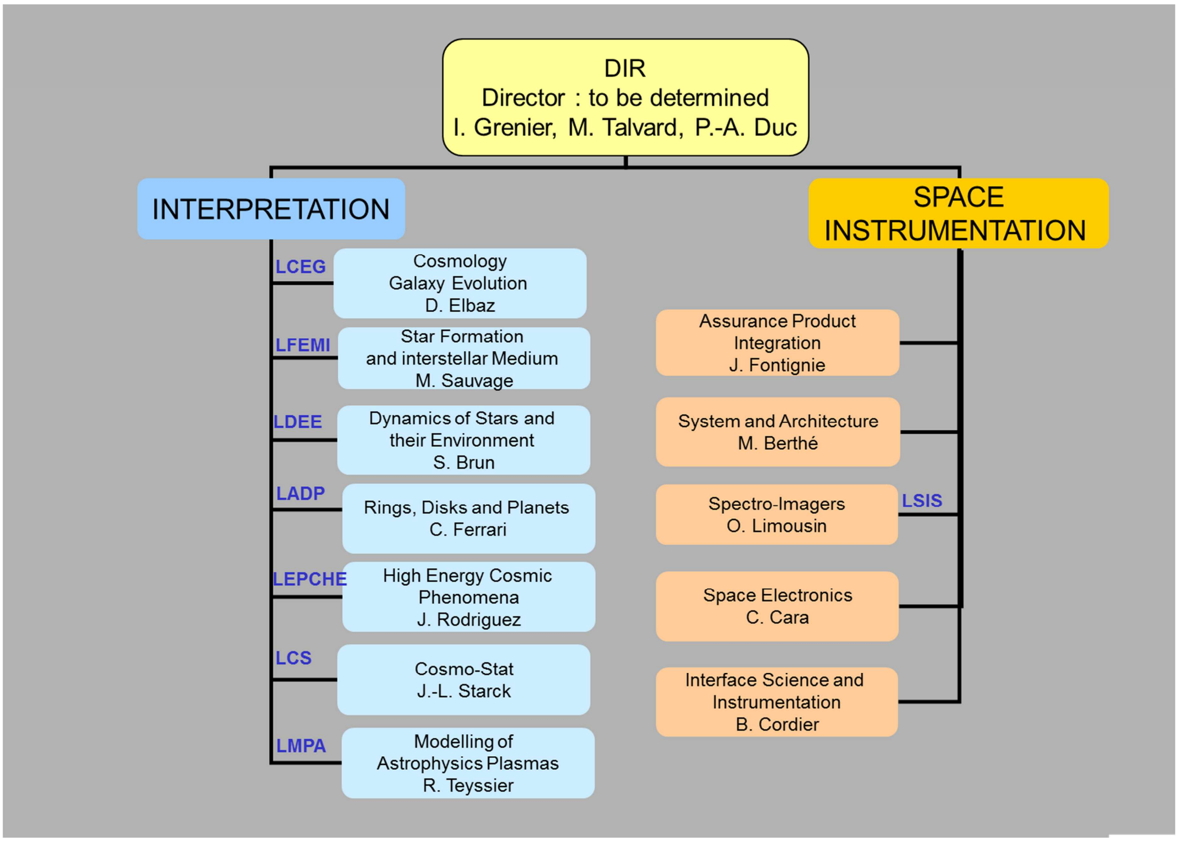
AIM is a fundamental research unit. The missions of the unit are twofold:

- first, to acquire new knowledge about the Universe and its constituents by :
  - developing research programs in Astrophysics at the best international level,
  - developing the state of the art instrumentation required for this research, mainly for space missions, but also for large ground-based telescopes;
- second, to disseminate new knowledge by training PhD students, lecturing, and making the results accessible to the general public.

Thus, the unit interacts, in a first place, with the research world and students, and, in a second place, with a large public to participate in the dissemination of the scientific culture.

3. Organization chart

Below is the organization chart. It is similar to that in the result report; the only change being the director. Indeed, after 12 years of directorship, the current director will step down and a new director will be appointed starting his job on January 1st, 2014. The deputy directors and technical director can provide continuity.



Organization chart

There is no need to change the present organization. Future adjustments will follow the needs, as done in the past, for example with the set-up of the CosmoStat team in 2009.

At the level of the unit, we will continue fostering many interactions between the teams (e.g., regular meetings, journal clubs). Particular attention will be given to transverse studies across teams. For instance:

- studies related to “dark energy” will strongly develop during the next period using galaxy clusters as a cosmological tool (LCEG team), developing signal processing for weak lensing (LCS) and cosmological numerical simulations (LMPA), designing, manufacturing, and testing the Euclid VIS focal plane (instrumental teams);
- comparative studies of the star formation rate in our galaxy and nearby galaxies (LFEMI and LMPA) with its history at low to high redshifts (LCEG);
- improving our understanding of the gas and dust tracers in the interstellar medium from observations, numerical simulations, and taking into account the role of cosmic-rays (LFEMI, LPCHE, and LMPA);
- studies of star and planets interactions (LDEE and LADP) and formation of planetary systems (LADP, LMPA).

B. SWOT analysis

1. Strengths

- The unit is present all along the chain of new knowledge acquisition and has developed synergies between the various activities. The size of the unit (200 staff, including PhD students and post-docs), the high capacity to raise funds and to attract young talented scientists or engineers, the numerous national and international partnerships, allow us to hold such an ambition.
- The unit has built an international leadership in several fields, such as galaxy clusters, galaxy evolution, star formation, Sun studies, microquasars, cosmic rays, statistical methods for cosmology, computational astrophysics, space spectro-imagers… and has a high profile in managing large observing programs or instrumental projects. This is well recognized by prizes, invitations to conferences, …. The publication rate is excellent with about 300 publications a year, including about 10 per year in Nature and Science.
- Covering a broad range of expertise in themes and wavelengths (from γ-rays to mm) is a definite advantage when there are increasingly longer delays between two projects in a given field or at a given wavelength (for example the launch of the SPICA mission is expected 10 years after the end of Herschel). We also have rare expertise, such as space radiation effects on detectors.
- The technical and scientific staff is very professional, experienced, and strongly motivated. It has demonstrated a strong reactivity that is essential to rapidly evaluate and answer to solicitations to participate in instrument or ground-segment proposals; (e.g. see our recent implication in the JUICE Echoes proposal with the NASA Jet Propulsion Laboratory and the Nice Observatory).
- The unit has a remarkable and reliable instrumental road map, with, in particular, two flagship space missions: the JWST, to be launched in 2018, and Euclid to be launched in 2020, and on ground–based telescopes: APEX-ARTEMIS to be fully operational in 2014 and E-ELT-METIS expected to operate in 2024.
- The unit is involved in three Laboratories of Excellence "LabEx" (FOCUS, UnivEarthS, P2IO).
- We have built a very good partnership with technical departments of Irfu that provide additional expertise (for example ASICS), with the Paris-Diderot University and the "Institut de Physique du Globe de Paris" (IPGP), with several national and international astrophysics laboratories.
- For the CEA staff, we can fully recognize the investment of scientists in the development of large codes or instruments because the career management is evaluated first at the level of the unit and because the career path at CEA is the same for scientists and engineers.
- A long tradition in popularizing science in France and abroad.
- A good connection with various Masters in astrophysics, physics, signal processing, numerical modelling; numerous lecturers (40).

2. Weaknesses

- In a few cases, there is a single expert in a field; (for example, following the recent departure of an architect in space instrumentation assembly, integration and tests, we have now a single one left, which will not be sufficient in the near future.
- There is a risk for the technical staff to be overloaded (for example if the SVOM mission eventually goes ahead); but given that space projects are selected after parallel competitive studies with a relatively low rate of success, we must take this risk to mitigate the even higher risk of being underloaded. In that respect, we benefit from the technical support of Irfu which brings flexibility in addition to their expertise.
- Strong dependence on the CNES funding, mitigated by our participation in ground-based projects (ESO E-ELT) and our recent contracts with ESA (detector development/characterization) or in the framework of the European FP7 (e.g. cryogenic electronics).
- Because in the past we have been able to develop novel detectors arrays (for ISO-ISOCAM, CASSINI-CIRS, INTEGRAL-IBIS and recently HERSCHEL-PACS) and because of the lack of funding for such costly developments out of an approved project, we have not been able to build a strong enough R&T and demonstrator program especially in the sub-mm (for example for SPICA/SAFARI). This is one of the reasons why we have co-lead the proposal for the FOCUS LabEx, which has been successful.
- With the strong growth and visibility of the "Observation/Signal-Processing/Interpretation/Modelling" activities in the unit (ERC grants, ANRs…), there is a mid-term risk to lose the good balance (for example in terms of hiring) between science activities linked to "Interpretation" and science activities directly linked to "instrumentation" (Instrument scientist, calibration scientist…) and a long term risk of a decoupling between the scientific exploitation of instruments built at home and other facilities.

3. Opportunities

- Onset of new observing facilities matching well the need for several of our research themes: APEX/ARTEMIS, ALMA, NOEMA in the sub-mm/mm, for the evolution of galaxies and star formation themes; LOFAR, MeerKAT, ASKAP, in the radio wavelength range for the accretion-ejection theme...
- Development of massively parallel computing facilities in the framework of GENCI and PRACE, collaboration with the "maison de la simulation".
- CEA-Irfu hiring on a permanent position in the framework of ERC (3 years funded by ERC), which allows to hire in a tight funding situation and with few expected retirements (retirement age recently extended from 60 to 70 years old at CEA); this is also a way to alleviate the potential problems at the end of an ERC contract.

- Forthcoming ESA calls: second Large mission (L2), fourth medium size mission (M4), small missions (new concept), R&T.
- CNES call for ideas in the framework of the CNES prospective exercise.
- The creation of a department of Earth and Universe Sciences in the framework of the new Sorbonne-Paris-Cité University, with IPGP, AIM, and APC and with new opportunities to develop inter-disciplinary collaborations and teaching courses within a multidisciplinary university.
- Development of the Paris-Saclay Idex with new opportunities to develop collaborations, for example in the framework of space activities, with engineering schools, to benefit from new facilities (a large conference room, researcher and student apartments…) making the Saclay plateau even more attractive.

4. Threats

- Loss of the opportunity to hire new staff after the departure of key staff. High-profile astrophysicists or engineers may be presented with important responsibilities elsewhere (for example E. Audit has recently become director of the "maison de la simulation"; F. Mirabel was director of ESO Chile for several years). So far, we have been able to keep those positions; if it were no longer the case, we would have to substantially revise the strategy of the unit.
- Due to the large increase of post docs and students (+40 since January 2007), we have reached our limit in terms of office space; a short-term solution has been proposed with a set of "algeco" pre-fabricated buildings to be in place beginning of 2013. Alternative solutions for the long term should still be investigated.
- Further decrease in the recurrent funding (mainly CEA for us) will force us to apply to even more external sources and to spend even more time filling forms and proposals, at the significant expense of a potential decrease of our research productivity.
- Continuation of the ESA politics to maintain competition through the labor-intensive assessment and definition phase studies, as it was done for the M1, M2 missions. It seems that a reorientation is underway with the decision to select a single M3 mission at the end of 2013 for the definition phase study, and with discussions about a cornerstone approach for the L missions.
- The Technical Readiness Level now required by ESA at the end of the assessment and definition phase of an instrument is much higher than before. We would not have passed this level to get selected for the focal plane of ISO-ISOCAM, INTEGRAL-IBIS or HERSCHEL-PACS.
- Increase in the size of the consortia around space missions (more than 500 astrophysicists-cosmologists for Euclid), with the risk of making the discipline less attractive to young people and of increasing the organization burden in the consortium.
- Development of a "mercato" for astrophysicists.

C. Strategy and projects

1. Strategy

<u>All along the chain of new knowledge</u>

The strategy developped so far, i.e. to be present all along the chain of acquisition of new knowledge (detector R&T, space instrumentation, observations/interpretation, signal processing, modelisation) in a co-ordinated way and at the best international level, appears to be more relevant than ever.

Interplay between observations, signal processing and numerical simulations

The interplay between observations, signal processing and numerical simulations is becoming essential. As shown in the AIM report, surveys with various observatories now provide large databases which require sophisticated data mining and signal processing tools, especially in cosmology (see the project by the LCS team). We have well anticipated this evolution by creating the Cosmo-Stat team in 2009; a handful of similar teams have been created around the world. Thanks to the analysis of these large databases, the underlying laws describing the properties of the astrophysical objects can be discovered. Detailed numerical simulations are often needed to find the main physical mechanisms at work behind these laws; thanks to the GENCI agency in France and PRACE at the European level, we have access to internationally competitive massively parallel computers, which are regularly updated. Standalone numerical simulations are also very useful as they can pin point specific processes at work in given objects and then trigger new observations (for example the search for cold flows feeding galaxies). Note that numerical simulations generate a large amount of data that require, as for large observational datasets, dedicated analysis and visualisation tools. The forthcoming computational power increase will open new avenues to the astrophysical computing (see the project by the LMPA team).

When applying for observing time, it is a definite advantage to present a so-called "dream team", i.e. composed of specialists in observations/interpretation, signal proceessing, numerical simulations. This advantage will be of particular importance for us during the next period with the reduction of guaranteed time from space missions and our greater dependence on the success of observing proposals; the next guaranteed time observations are expected from the JWST in 2019. National and international collaborations are of course another way to combine expertises, and we have indeed developped numerous collaborations, but having the three types of activities within AIM is a definite advantage in terms of cross fertilization and to set up collaborations in full knowledge of facts.

Instrumentation: mastering the scientific performances

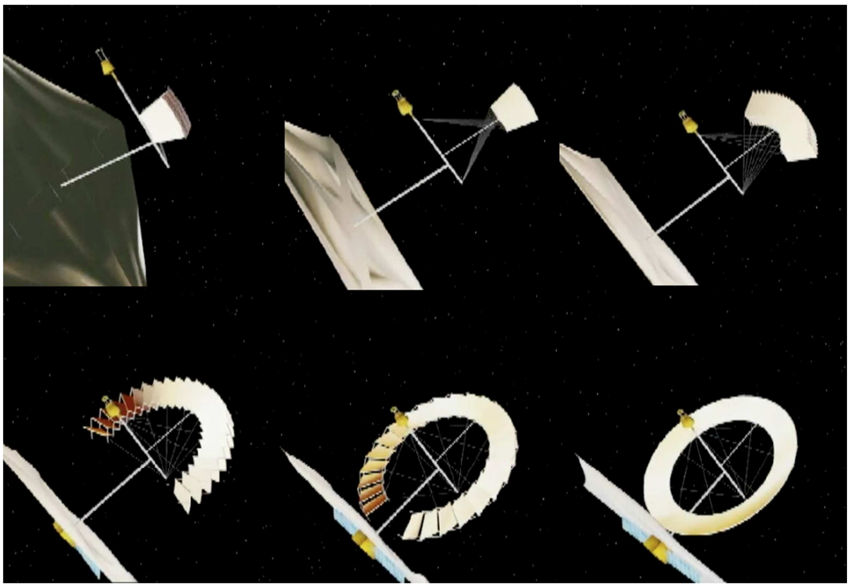
To achieve the scientific performances of future missions, the demand in terms of instrumental characterization and calibration in order to build performant data reduction pipelines will keep increasing, especially at the level of the detector focal plane. An example is given in Euclid, which requires an exquisite knowledge of the optical CCDs transfer function, response to cosmic rays, etc., in order to be able to measure faint changes in the ellipticity of the galaxies due to weak lensing effects. Another example is the 10^{-5} precision requirement to measure a photocenter in a future astrometric mission to detect Earth-like exoplanets around nearby Sun-like stars, such as the NEAT mission (F. Malbet et al. 2012).

The focal plane system is the part we concentrate our construction and characterization efforts on, for which we have the needed competence, and for which we take advantage of our links inside CEA, (ASICS expertise at Irfu/SEDI, collaboration with Léti, INAC, etc.) and of the CEA staff status (same career path for researcher and engineers (see SWOT section). Our system team provides essential knowledge at the system level (cooling if any, electronics…) to really control the focal plane performance. Our “radiation team” has the rare competence needed to secure the performance against the effect of radiation. Note that an intimate knowledge of the focal plane is a definite advantage to participate in the ground segment and to the best scientific exploitation of an instrument.

Enhanced R&T activities

Our participation in the development of the focal plane of future space missions must be anticipated well in advance. As shown in the SWOT section, given the change in the Technical Readiness Level requested at the selection of a space mission, we can no longer develop novel focal planes within an approved project or even a project under study. The recent concept of a new class of small ESA missions, to be launched 4-5 years after the call, also goes in the direction of anticipating the development of instrumentation. Thus during the next period, we plan to increase the amount of upstream activities in R&T and demonstrators. To be successful, a system approach and the constraints of a space mission must be followed from the start. We have the two teams (product assurance team, and system and architecture team) to follow this mandatory approach.

Note that the increase in R&T driven by astrophysical needs fits quite well the general trend to increase technological developpements in France and in Europe (FP8), so that we expect to be able to raise R&T funds. The labex FOCUS, which we are co-coordinating with the IPAG laboratory, will provide seed money for the R&T, will increase our credibility when applying for funds, and will provide a forum to discuss the future needs for novel detectors. For example, in the LabEx proposal, we have clearly identified a need for much higher performances sub-mm arrays, for example for the next cosmology mission that should aim at measuring the polarisation of the Cosmic Microwave Background (CMB), or for future sub-mm missions that aims at improving the angular resolution, which is still in its infancy. Indeed, with a diameter of 3.5 Meters, Herschel is the largest telescope dedicated to astronomy in space. But, used in the sub-mm wavelength range, its angular resolution is not better than the one of the small (5 cm) Galileo telescope. After the first discoveries by Galileo, many discoveries have been made thanks to the increased size of the optical telescope. We can predict a brillant future to the sub-mm. We are developping a novel concept of a 20 meters deployable annual mirrors for sub-mm observations, as the next step to get enhanced angular resoltion, before the interferometric missions, such as FIRI.



Concept of deployable annular 20 meters telescope for sub-mm observations (G. Durand, A. Bonnet et al. 2012); This concept will be proposed to CNES in the framework of the CNES prospective (2013).

Multi-wavelengths strategy?
The 2014-2018 period will see new large observatories, such as ALMA, GAIA, Solar Orbiter, entering in operation, and the extension of the operations of many others (XMM, INTEGRAL, Fermi, CASSINI, KEPLER, HESS, HESS 2 LOFAR and SKA precursors), so that we will be able to keep on our multi-wavelength strategy.

On a longer time scale, the prospectives are good for many wavelengths, except for the X-ray domain. Indeed, when the visible, near- and mid-IR domains are well covered with the JWST in space and the ELTs on the ground, when LOFAR, MeerKat and ASKAP pave the road towards SKA in the radio, when CTA, the Hess successor at TeV energies, is underway, there is no plan for the X-ray domain. And, it is not due to the lack of proposals and studies (XEUS → IXO → ATHENA).

During the next period, we will keep lobbying for the great scientific value of a large X-ray space observatory, participating to new proposals (e.g. answering an L2 call by ESA), and we will keep developing R&T on micro-calorimeters for spectro-imagers.

2. Themes and questions

Dark dominated Universe and Euclid

Constraining theorigin of the re-acceleration of the Universe is a prime objective, recognized as such in all the prospective exercises (Europe, US…). In the previous period, we had prepared the ground for results in the coming period with weak lensing and galaxy clusters (Planck, XMM, CFHT-MEGACAM observations), and later on with Euclid. We have made the right choice proposing and studying Euclid, as it has been selected and is now "THE" dark Universe space mission. We are very well positionned in terms of instrumentation and ground segment; we have to keep increasing our scientific visibility.

Weak lensing and "dark energy"
One of the two main EUCLID probes for dark energy is weak lensing; we have partipated in the weak lensing program with the HST, developing sophisticated signal processing tools (e.g. Berger et al. 2008). The study was done over a two-square-degree field. The larger the field, the more stringent the constraint on "dark energy" is. We are part of the large consortium associated to the CFHTLens program, a 155 square degree multi-color optical survey in *u, g, r, I, and z made* with the MEGACAM camera (built at Irfu). Space measurements have a definite advantage in terms of point spread function (PSF) stability, which is a key requirement for weak lensing. That is why we have proposed the DUNE mission to ESA: a full extragalactic sky survey (15 000 square degrees) with a 1.2 meter telescope in space, which has become the EUCLID mission.

The Euclid mission is our first priority. We have major responsibilities at the level of:

- project management (project coordinator for the consortium, system engineer of the consortium, ground-segment scientist) in direct interface with ESA,
- hardware (responsible of the visible focal plane),
- ground-segment (responsible of the level 3 data reduction algorithms),
- cosmological simulations (co-responsible),
- science legacy (co-leading the distant galaxy legacy science group).

Our strategy has been to occupy key positions related with weak lensing, one of the two key probes of Euclid. The 2014–2018 period will be very active with the development and test of the hardware (VIS focal plane), the development of our contribution to the ground segment (level 3), and preparation of the scientific exploitation. After the departure of A. Refregier, former PI of Euclid, from CEA to ETH Zurich, we have hired M. Kilbinger, a specialist in weak lensing. Y. Mellier, the new Euclid PI from IAP, has accepted to be formally associated to AIM (by CEA contract), and collaboration with IAP has started with regular meetings. On January 2014, Jean-Charles Cuillandre (astronomer from CNAP, resident for 10 years at CFHT, mainly working on MEGACAM data reduction) will work on Euclid and has decided to join AIM and its scientific, instrumental and data reduction activities for Euclid. In the next period, efforts to hire or attract two other scientists for Euclid will continue (see our hiring plan).

Galaxy clusters in a dark dominated Universe.
The statistical properties of galaxy clusters (structure and scaling laws, mass function, and their evolution) are uniquely sensitive *both* to cosmology and to the physics of structure formation. We will pursue both avenues, building on the Planck All Sky survey and the 50 square degrees XMM XXL survey. These will provide largely complementary cluster data sets: Planck is detecting through the SZ effect essentially all the rare, massive 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 detected in X-ray.

A very large effort will be devoted to catalogue construction with the new surveys, and in understanding their selection function and the mass-observable relations. The Planck cluster catalogue is well suited for the study of dark matter profiles as a probe of the LCDM paradigm as well as the dynamical evolution of baryons. 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, Subaru) and numerical simulations. The XXL population will be privileged targets for the understanding of galaxy feedback effects. Constraints on cosmology from each catalogue will be extracted and compared. It is also important to have different methods to probe "dark energy" to control the systematics.

Euclid will provide a full sky catalogue of galaxy clusters in the optical, not only through galaxy overdensity but also directly as dark matter concentration via their lensing signal. We will prepare the science exploitation of its cluster catalogues. For instance, we intend to explore stacking methods to constrain dark matter profile as cosmology probes.

Structuration of the Universe and ArTeMiS, ALMA, IRAM, CFHT, then EUCLID, JWST, then E-ELT

As seen in the report, we have made major discoveries during the last period on galaxy evolution and star formation. We have a leading role in these fields, well recognized at the international level. We have to capitalize on these results and lead the programs that will bring answers the new questions raised by our discoveries.

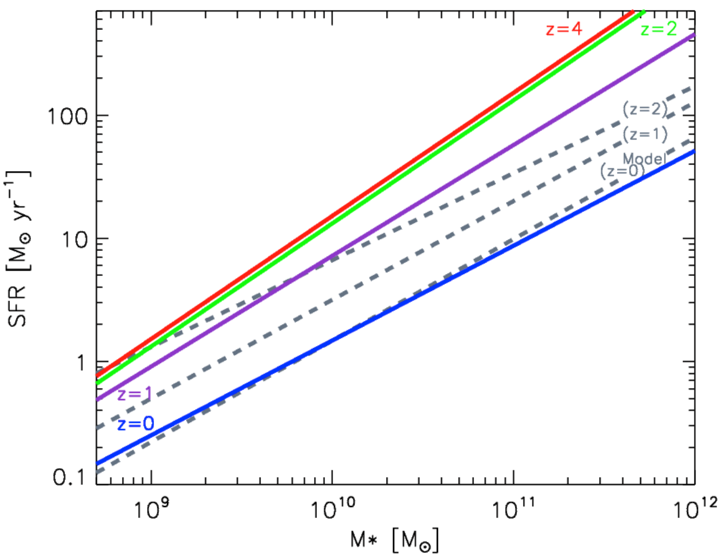
Galaxy evolution: mass growth and star formation history

Collecting large samples of galaxies from surveys with current facilities such as Herschel or IRAM, we have been very successful at finding laws describing the star formation rate in galaxies, such as a so-called "main sequence" dominant mode of long-lasting rather than starbursting star-formation. The phenomenological correlations between the star formation rate and stellar mass in galaxies for redshifts $0 < z < 1$ (Elbaz et al. 2007, 309 cit.), $z = 2$ (Daddi et al. 2007, 366 cit.), and $z = 4$ (Daddi et al. 2009, 118 cit.) have been confirmed and extended to higher redshifts by our team (Elbaz et al. 2011, 93 cit.) and others (see figure below).

At the same time, numerical simulations have been developed and have reached a point where discoveries of the main mechanisms governing the evolution of galaxies can be studied. Bridging the observed and numerical worlds, a new scenario has emerged in which galaxies are continuously, rather than stochastically, fed through infall of extragalactic matter, in large part consisting of collimated cold flows. However, this qualitative agreement fails quantitatively, with simulations predicting too inefficient star formation at $z<2$ (figure below) as compared to observations, as a result of a possibly too rapid gas consumption at higher redshifts leaving not enough gas reservoirs for more recent star formation.

A prime goal for the next period is to quantitatively reconcile simulations and observations by linking small-scale gas and star formation physics to scaling relations on galactic scales and cosmic inflows and outflows. Two ways will be followed in parallel:

- Using the increasing power of massively parallel computers (GENCI, PRACE) to enrich the simulations by increasing their resolution – by, e.g., making them capable of resolving the formation of molecular clouds - and adding physics so far treated at a sub-grid level, such as the effect of feedback (supernovae, radiative pressure, central black hole jets, winds) on the efficiency of star formation.
- Observationally, we will, in particular, dedicate a large effort to access the gas content of galaxies, derive directly their star formation efficiency and study the parallel growth in stars and black holes taking advantage of new facilities such as Alma, ARTEMIS, as well as IRAM PdBI + NOEMA, JVLA, KMOS, MUSE for optical/near-infrared IFU spectroscopy. We will use refined stacking and deblending methods to combine *Herschel* with multi-wavelength surveys of the deepest extragalactic fields. 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, statistically significant, studies with Euclid.



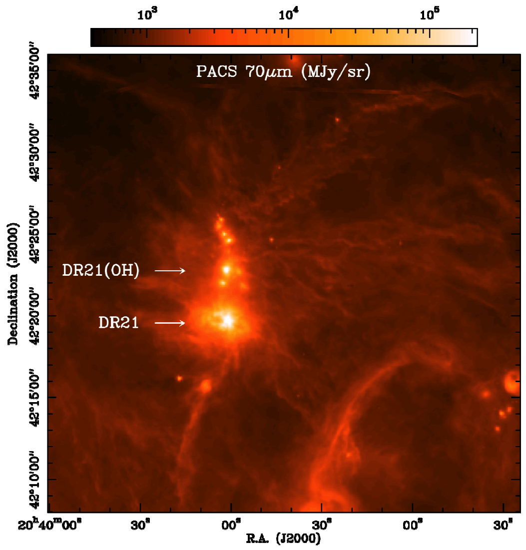
SFR-M relation or scaling law from observations (solid lanes) at z~0, 1 (Elbaz et al. 2007), 2 (Daddi et al. 2007) and 4 (Daddi et al. 2009) as compared to model expectations (dashed line) at cosmological scales from the Millennium simulations, based on the mock light cones of Kitzbichler & White (2007).*

For more details, see the section about the LCEG team project.

Star formation: filamentary structure, IMF

With Herschel, we have revealed the deep connection between the structure of the cold molecular clouds, and the star formation process. We have evidenced the role of turbulence in the generation of a characteristic thickness in interstellar filaments, and that of gravity in the onset of infall inside the filaments. Very recently we have seen that structure of the magnetic field is ordered in cold molecular clouds and could both provide a mechanism for the growth of mass inside filaments and support against collapse (see figure below). Thus the key question for the coming years is to understand the interplay of dynamics, magnetic field and gravity in the formation of the observed structures in the ISM, and how these contribute in building up a dense core mass function that is parallel to the initial mass function. We can address this difficult question thanks to the combination of talents assembled in AIM:

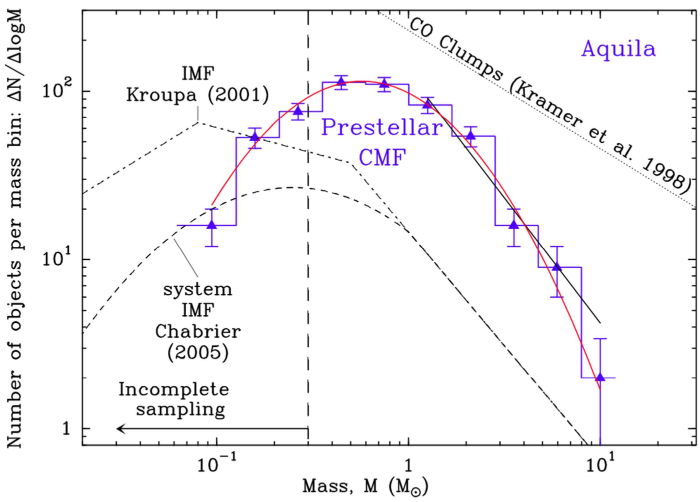
- We will develop new simulations which, for the first time, will be able to treat in a consistent way the issue of structure formation in the cold ISM, incorporating the aspect of turbulence decay and magnetic support.
- Thanks to the development of polarization capacities on new submillimeter cameras (e.g. our involvement on IRAM-NIKA), we will have access to the organization of the magnetic field in star-forming clouds, thus complementing the set of constraints needed by the numerical simulations.



How does the filament mass grow? This Herschel image of Cygnus X shows a central filament connected to a rich network of adjacent fainter filaments, suggesting a possible "feeding" mechanism. Polarization and dynamical measurements with forthcoming facilities (e.g. Alma, IRAM-NIKA…) will make possible to test this scenario (from Hennemann et al., 2012).

Herschel has also robustly confirmed the fact that the initial mass function is imprinted in the ISM when dense cores are formed. The question which has now to be tackled is how this footprint is kept at later stages of star formation and what reduces the efficiency of the process that turns these cores into stars (corresponding to the shift between the mass functions on figure below). The combination of complex numerical simulations and observations at higher resolution that can be performed with Herschel (using e.g. ALMA to focus on individual star-forming cores) will be deployed to address the issue.

The core mass function (blue histogram with error bars) derived from the Herschel mapping of the Aquila region. The IMF of single stars (corrected for binaries) and multiple systems, as well as the typical mass spectrum of CO clumps are shown for comparison (From André et al., 2011).



At larger scales, we have also shown that regions of massive star formation in our own galaxy can reach a star-formation rate surface density that is comparable to that measured in starburst galaxies. Exploitation of the Herschel surveys of these regions, as well as higher resolution studies with newly developed facilities (e.g. Artemis) will bring new light on the physical conditions require for intense high-mass star formation, and will be used to address the question of the universality of the high-mass end of the IMF.

For more details, see the section about the LFEMI team project.

Interstellar tracers : a transverse teaser

From star formation to galaxy evolution and to cosmic-ray physics, several teams across AIM are working on complementary probes of the interstellar medium (ISM). Reliably quantifying the mass, physical state, spatial distribution, and dynamics of the different gas phases is key to understanding the matter cycle from cloud to filaments, and conversely from clouds to galactic scales. The body of ISM tracers has recently expanded to atomic and molecular lines and ladders in the sub-mm, to the full sub-mm to infrared thermal dust emission, and to gamma rays from cosmic-ray interactions with gas (Planck, Herschel, Fermi). It will further expand with follow-up observations (SOFIA, ALMA, APEX, Fermi, …) and with stellar reddening and DIBs from dust (2Mass, Gaia). Our studies have revealed significant non-linearities in the gas and dust tracers and that an entire phase (dark gas), albeit as massive as the CO-bright molecular phase, easily escapes detection. This rich panel of observational data and the joint expertise present within AIM strongly calls for an in-depth study of the ISM tracer diagnostics at different cloud scales and in a variety of irradiation and metallicity environments in the Milky Way and nearby galaxies. Confronting observations with realistic ISM simulations will help sort out how faithfully different sets of tracers can account for the total gas in the turbulent multi-phase structure of clouds. To this aim, simulation work will proceed toward two goals : implementing more precise photoionization physics on one hand, and implementing MHD turbulence and cosmic rays on the other hand. Understanding the limitations of ISM tracers in a comprehensive way will directly serve the interpretation of distant galaxies and reduce the large uncertainties in the current derivation of star formation efficiencies in main-sequence and starburst galaxies.

Cosmic phenomena at high energy and Fermi, HESS2, CTA, LOFAR and SKA precursors

Cosmic-ray acceleration and transport in the Galaxy remain largely unknown. In the last period, our teams have contributed novel results both observationally and numerically. We plan to further build on these strengths to study the acceleration and youth of cosmic rays. Studying their youth represents a novel step in linking the cosmic-ray properties at the sources and at large in the ISM. Several paths will be followed in parallel:

- multi-wavelength images of specific supernova remnants will be used to probe the efficiency of shock acceleration by studying the cosmic-ray feedback on the shock compression and magnetic field amplification. The data will be confronted to new MHD simulations coupled to a kinetic model for particle acceleration and feedback to model the complex stratification in a remnant.
- the known GeV and TeV emitting remnants span a large enough range of ages and interstellar environments to start and study how the acceleration efficiency and particle release into the ISM evolve with age.
- 1-100 GeV observations and numerical modeling will be combined to study the emergence of cosmic rays into surrounding clouds and to search for new examples of fresh cosmic-ray cocoons in bright stellar clusters to constrain their early propagation inside turbulent superbubbles.
- TeV data can probe young cosmic rays at high energies, but the current background subtraction methods in the Cherenkov data prevent an efficient detection of diffuse or broadly extended emission. We will take advantage of our expertise in HESS and HESS-2 data to try and lower this methodological barrier in preparation for the next major CTA observatory.

Accretion of matter onto a compact object is the most efficient way to transform gavitationnal energy into radiative and kinetic energy transported to large scales. We want to probe the possible origin of the different modes of accretion we have just found in the fundamental plane of microquasars. We also want to constrain the associated emission processes and to study how these different paths impact the physics of jets (type, power, ...).

- One way to do so is to follow the evolution of a complete black-hole outburst from the radio to gamma rays, in order to connect the jet non-thermal emission to the evolution of the thermal pool in the accretion disc and its potential oscillations and instabilities. To carefully model this interplay, we have created, in collaboration with IPAG and IRAP colleagues, the ANR program CHAOS that has just started. Its goal is to bring theoreticians and observers together to provide a unified picture of black holes properties along the course of their outburst.
- We will also develop new imaging tools to search for transient sources in the massive data flows of the next generation of radio arrays (in preparation for SKA). This will open a new window on the rapid variability of jets and accretion disc coronae, to be tested with LOFAR, ASKAP and MeerKat.

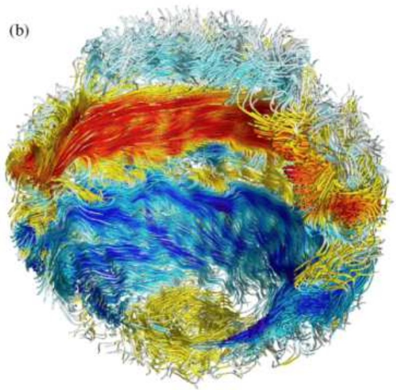
For more details, see the section about the LEPCHE team project.

Stars and their environment; Kepler, Solar Orbiter, JWST and then E-ELT

Over the last decade two majors advances have been realized in stars and planet research: the outcome of asteroseismology in one hand and the detection of exo-planets on the other hand. New exo-planetary systems are discovered almost every day and need to be characterized. One key aspect is to know several global parameters of the host star as well as its intrinsic variability in order to help disentangling the presence of planets from the stellar variability. Among the most frequent stellar variabilities we are leaders in the observational, theoretical, 1-D modeling and multi-D high performance numerical simulations study of stellar oscillations and magnetic activity. We intend to reinforce and develop further this activity over the next 5 years period by developing a global view of how do stars, planets and their environment work and interact. This will take the following form:

- improve our ability at modeling stellar dynamos and the associated cycles, using the Sun as a guide and the Sun-star relationship as a way of adapting current dynamo models to the various conditions existing in stars with different age, mass, chemical composition and rotation rates;
- develop an operational solar activity models based on modern data assimilation techniques and dynamo models;

- analyze thousands of Kepler's stars and strengthen our ensemble asteroseismology pipeline in order to give improved constraints to both the stellar and planetary communities;
- improve our theoretical modeling and high performance multi-D numerical simulations of stars and planets, with a special emphasis on their internal structure and large scale dynamics on short (of order few cycles or rotations) and secular time scales;
- develop the first steps towards an integrated model of star-planet interactions taking into account both magnetic (wind, spectral luminosity variability) and tidal effects in order to determine how host stars and planets influence their surrounding;
- characterize with such models the habitable zones for various configurations of stars and planets, using the solar system as a guide;
- develop models of particle acceleration in realistic magnetic topologies in support of Solar Orbiter and the STIX instruments as well as a seismology pipeline in support of Juice/Echoes.



Recent 3-D numerical simulations with the ASH code of fastly rotating Suns (Brown, Browning, Brun et al 2010, 2011) have revealed the existence of large-scale magnetic wreaths. Such horizontal (toroidal) magnetic structures were not anticipated within turbulent convection zones, as one would have expected flux expulsion to act and to push them outside of the convection zone (likely in a tachocline below). ASH simulations actually demonstrate that by acquiring a fibril, non-axisymmetric nature, they can accommodate such expulsion phenomena, yielding intense localized magnetic concentration that can then rise buoyantly to the surface (Nelson, Brown, Brun et al. 2011) and contribute to the establishment of a cyclic magnetic activity and stellar butterfly diagram (Nelson, Brown, Brun et al. 2012).

We also intend to keep on working on Cassini data to understand the Saturn system and to increase our implication in the characterisation of the atmosphere of exoplanets, coordinating the large program (130 hours) to be conducted in the framework of JWST-MIRI guaranteed observing time. We are also investing in future exoplanets missions, participating in the studies of the ECHO M3 mission candidate (G. Tinetti et al. 2012), in the METIS instrument for the E-ELT project (B. Brandl et al.) and in the R&T for an astrometric space mission dedicated to the dedection of exoplanets systems (including Earth like) around nearby stars, such as the NEAT mission proposal to the M3 (F. Malbet et al. 2012).

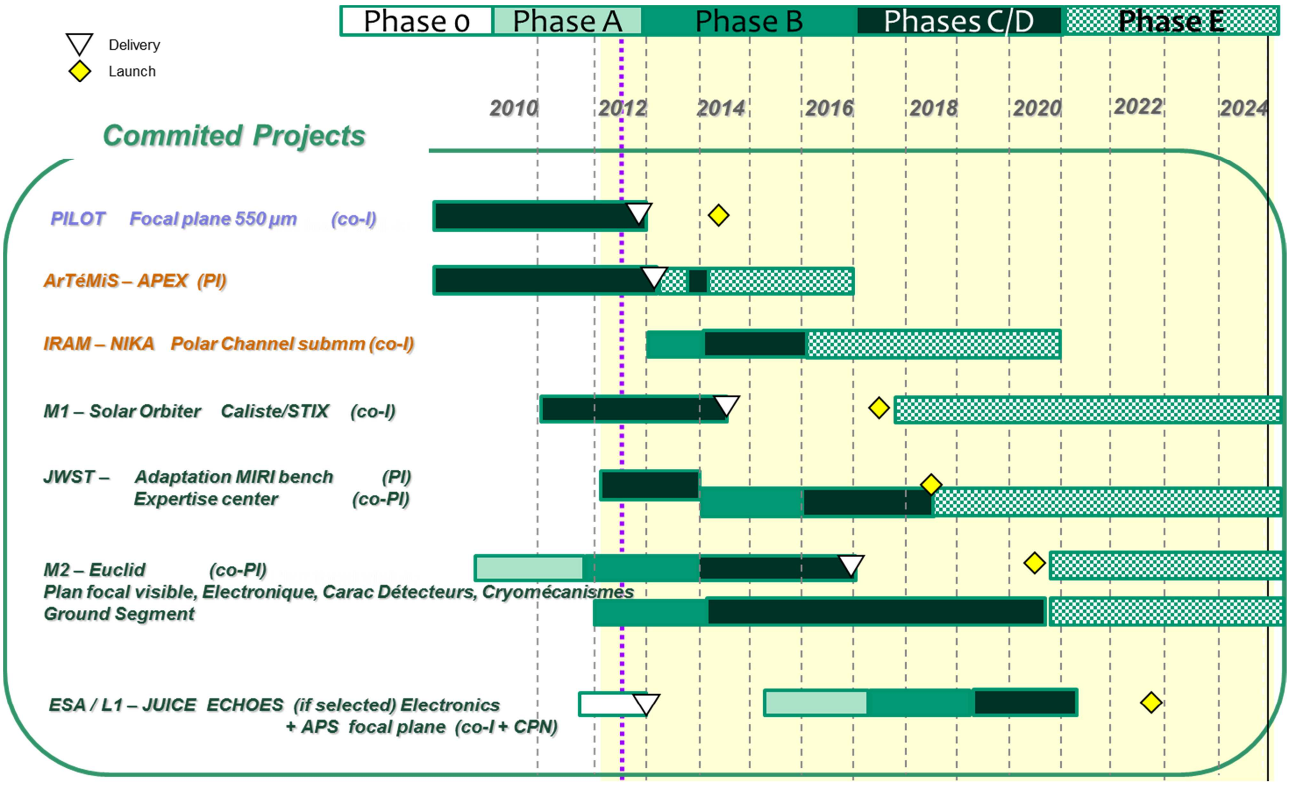
For more details, see the section about the projects of the LDEE and LADP teams.

3. Instrumentation

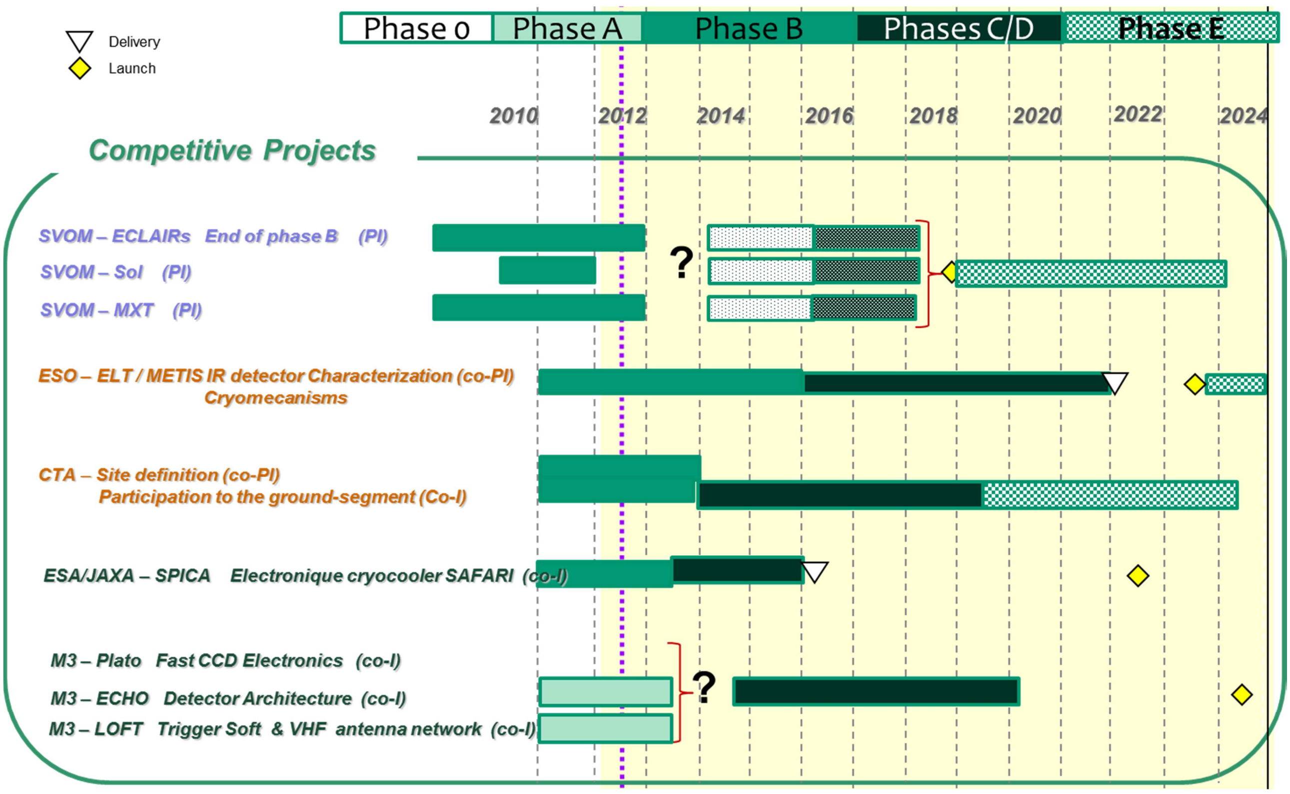
Strategy considerations lead us to work on several projects at different phases of their development:

- scientific exploitation of available facilities and on-going monitoring the behaviour of the instruments we have provided (for example, still monitoring the ISGRI detector INTEGRAl)
- hardware design and construction for mid-term future facilities and preparing their science exploitation (ground segment, science) (JWST, Euclid, Solar orbiter),
- anticipating the emergence of important fields and the associated R&T, answering calls for missions, assessment phase, definition phase (JUICE instrumentation, M3, L2, E-ELT…).

The following figure shows the instrumental roadmap, distinguishing between the committed projects and those which are still in a competitive phase.



Phase 0
Phase A
Phase B
Phases C/D
Phase E
Delivery
Launch
2010
2012
2014
2016
2018
2020
2022
2024
Commited Projects
PILOT Focal plane 550 µm (co-I)
ArTéMiS – APEX (PI)
IRAM – NIKA Polar Channel submm (co-I)
M1 – Solar Orbiter Caliste/STIX (co-I)
JWST – Adaptation MIRI bench (PI)
Expertise center (co-PI)
M2 – Euclid (co-PI)
Plan focal visible, Electronique, Carac Détecteurs, Cryomécanismes
Ground Segment
ESA / L1 – JUICE ECHOES (if selected) Electronics
+ APS focal plane (co-I + CPN)

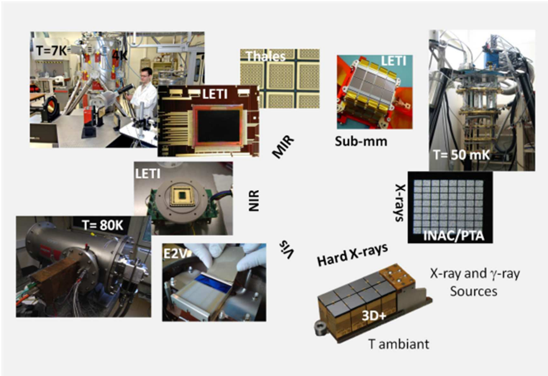


Phase 0
Phase A
Phase B
Phases C/D
Phase E
Delivery
Launch
2010
2012
2014
2016
2018
2020
2022
2024
Competitive Projects
SVOM – ECLAIRs End of phase B (PI)
SVOM – SoI (PI)
SVOM – MXT (PI)
?
ESO – ELT / METIS IR detector Characterization (co-PI)
Cryomecanisms
CTA – Site definition (co-PI)
Participation to the ground-segment (Co-I)
ESA/JAXA – SPICA Electronique cryocooler SAFARI (co-I)
M3 – Plato Fast CCD Electronics (co-I)
M3 – ECHO Detector Architecture (co-I)
M3 – LOFT Trigger Soft & VHF antenna network (co-I)
?

4. Research and Technology

One of our key objectives is to anticipate the development of novel focal planes, but they can be very costly and cannot enter in the usual R&T CNES funding. That is one of the reasons why we have co-led with IPAG the FOCUS laboratory of excellence (LabEx) proposal devoted to sensors for astrophysics. It has been accepted and will get a budget of 1.2 M€ per year during 8 years. This is not enough for all the developments, but the LabEx is a helpful label to get additional funding, for example in the framework of Horizon 2020. Moreover, we have sucessfully started to answer ITT calls from ESA and plan to continue answering future calls.

We also plan to coordinate our various test benches in a “detector characterization platform”, to increase the visibility of the detector characterization and development activities.



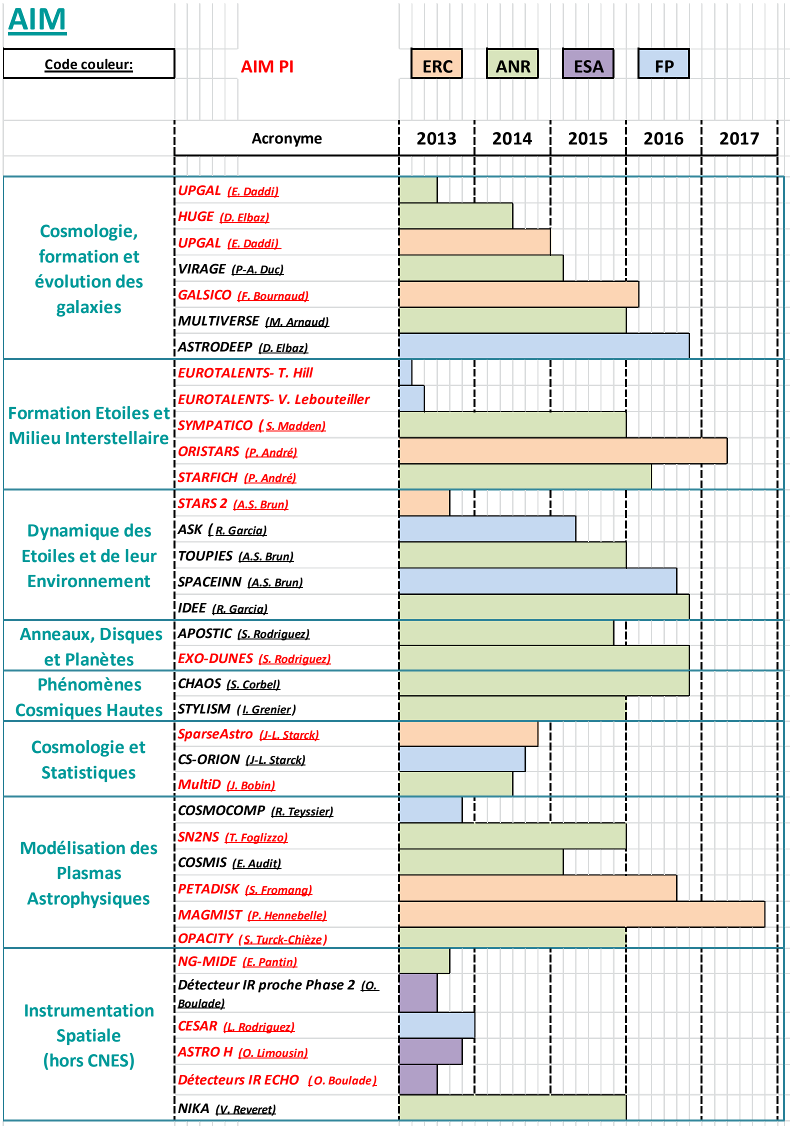
Different detectors characterized at AIM (from visible to hard X-ray) and the associated test benches (from ambient temperature to 50 mK).

5. Resources

A lot of projects funded by the ANR or ERC are ongoing (see Figure beside); we are also part of 3 LabEx funded for 8-10 years, and we are part of the Ile de France ‘’Domaine d’Intérêt Majeur’’ ACAV.

We are an important partner of a large European space project that is accepted (Euclid) and can be considered as funded (with the caveat that we have to wait for the endorsement by the CNES board at the beginning of 2013). We are part of a pre-selected E-ELT instrument (METIS) whose hardware cost will be funded by ESO. We have also started to get funding from ESA via successful answers to call to tender.

We suffer from the absence of margin to initiate projects or to fund any post-doc on internal resources. We will of course continue to answer the various calls to fund our projects.



6. Hiring plan

While our internal funds are very limited, we have a great richness : the permanent staff. Given our dynamism, our capacity to raise funding, and our attractiveness, we hope for a slight increase in permanent positions, as it has been the case during the previous period. Our permanent position hiring plan is an immediate consequence of the SWOT analysis and of our objectives. It is difficult to estimate the number of retirements as we have the new possibility to work until 70 years old at CEA; it can vary from 2 to 8 if everyone leaves at 70 or 62.

Regarding the space instrumentation, we should rapidly hire a space AIV expert for Euclid (replacement of a departure in 2010; need in 2013) and replace any unexpected departure because, most often, there is only one specialist per domain. If possible, we should decrease the risk by having two experts in a given domain (for example an additional space mechanical architect). A strategic line for the future is R&T; we should reinforce this activity by hiring one specialist of detection and by replacing any departure. Given the age histogram (see report), we do not have immediate retirement problems, but we have to anticipate the large number of retirements over the following period (2019 – 2024), especially in terms of technicians.

For astrophysicists, the situation is slightly different in the sense that we need both to reinforce our fields of excellence with new expertise and to evolve in our themes. The first priority is to hire a specialist in ALMA interferometric observations which will be beneficial to both fields of star formation and galaxy evolution. Then we must prepare the cosmological exploitation of Euclid by hiring, at least, a weak-lensing expert and a galaxy cluster expert; we also have to prepare the exploitation of the Euclid Legacy science. The field of the Sun, stars, planets and exoplanets is in full expansion and we have several cards to play (Solar Orbiter, JWST, E-ELT), but at least two hires are needed to reach a critical size. With the development of LOFAR, SKA precursors and, on the long term, SKA, the radio domain will have an important impact in many fields of astrophysics; we aim at hiring a specialist in observations with these upcoming facilities. In terms of numerical simulations, the unit is barely at a critical size (a single specialist per field), so that any departure should be replaced. There is one field of research for which the synergy between observations and simulations should be improved: the cosmic phenomena at high energies. The hiring of a specialist of numerical simulations in that domain would therefore be highly valuable.

D. Conclusions

New facilities such as ALMA and massively parallel computers are just in time to follow-up the discoveries that we have made in the fields of galaxy evolution, star and planet formation, and stellar evolution.

We are deeply involved in future major space missions such as JWST and Euclid, which will be key missions to study most of our fields of research, including exoplanets and dark energy.

We are preparing the long-term future by developing a solid R&T, especially concerning sensors, with extensive discussions between engineers and astrophysicists.