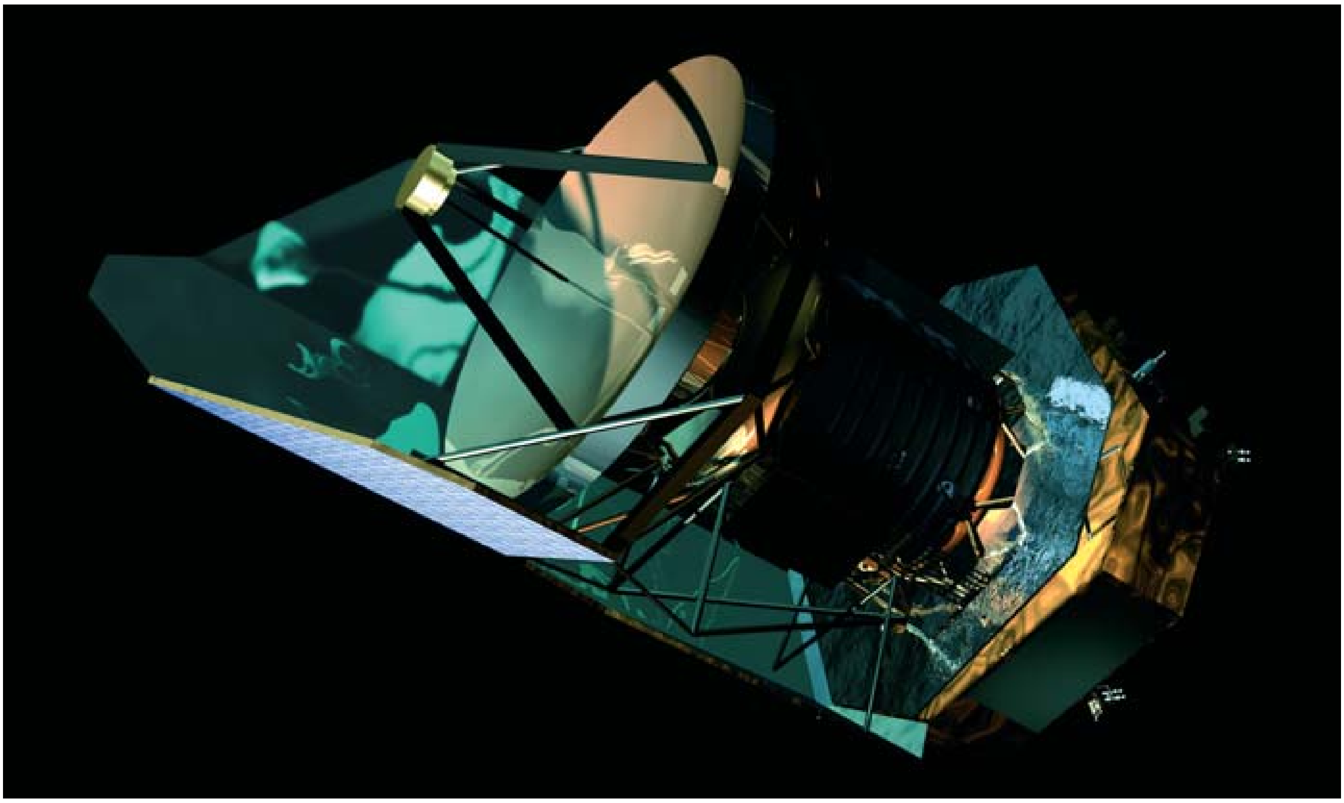
Infrared, **X-** and **gamma** radiation: nonvisible wavelengths to probe the **Universe**

On the scale of the Universe, seeing further and further afield is to go back in time, getting ever closer to the Big Bang – or at any rate down to the time when the primordial plasma became transparent to radiation. In two major regions of the electromagnetic spectrum, the infrared, on the one hand, gamma and X rays on the other, advances in spaceborne detection are allowing, through ever more precise measurements, major information to be accessed, on the first stars and galaxies.



ESA

Artist's impression of the European Herschel satellite, taking its name from Sir William Herschel, who discovered infrared light in 1801. It is due to be launched in 2007, by an Ariane 5 launcher.

It is generally agreed, nowadays, that our Universe originated in the "**Big Bang**", an event that may be viewed as a tremendous explosion, occurring slightly over 13 billion years ago (see Box A, ***The standard cosmological model***). Initially, the Universe was just a very dense, very hot plasma, in which light was constantly **absorbed** and reemitted by **free electrons**, resulting in a medium opaque to its own radiation. Gradually, due to expansion, the Universe became more diffuse, cooling down to such an extent that, some 300,000 years after the initial explosion, electrons and **protons** came together, forming the first **atoms**. At that point, it became electrically neutral, and transparent.

Looking for the Universe's first light sources

That transition – *recombination* – was accompanied by an intense burst of radiation, emitted in the **ultraviolet** originally, which is nowadays detected, however, in the ultra short radio range, and is known as the **cosmological background** microwave radiation. After recombination, there remained no light source to illuminate the Universe; the dark ages began. During this period, the Universe went from a stage of extreme uniformity, as shown by investigation of the cosmological microwave background – with discrepancies in homogeneity no greater than one in one hundred thousand – to one close to its present state, with the Universe fragmenting into clusters of stars, the **galaxies**. The dark ages ended as the first cosmic beacons lit up, their radiation contributing to **ionize** the universe anew. According to the most recent investigations of the cosmic microwave background, this reionization occurred barely 200 million years after the onset of expansion (see Figure 1).

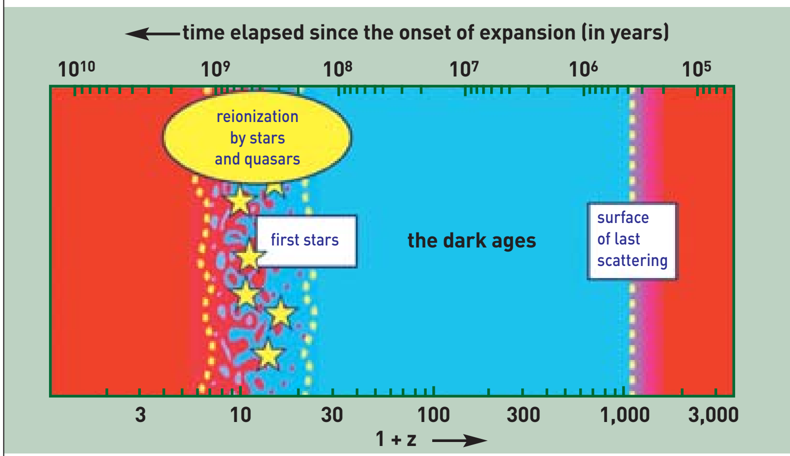


Figure 1.
Schematic representation of the evolution of the Universe. Along the x-axis, Z stands for the galaxies' recessional velocity, and is thus an expression of their distance from us, i.e. of the time when the light now reaching the earthbound observer was emitted.

Such an extremely swift change is somewhat puzzling to astrophysicists, who have sought to understand the mechanisms involved, by endeavoring to observe these first light sources. A mighty challenge indeed, since these objects are located at the outskirts of the Universe, over ten billion light-years or so away. Only a minute "smidgeon" of their brightness reaches our telescopes, even though it be the cumulated light from billions of stars within a galaxy. Moreover, owing to the redshift entailed by the expansion of the Universe, the light from these primeval beacons must be sought in the **infrared**.

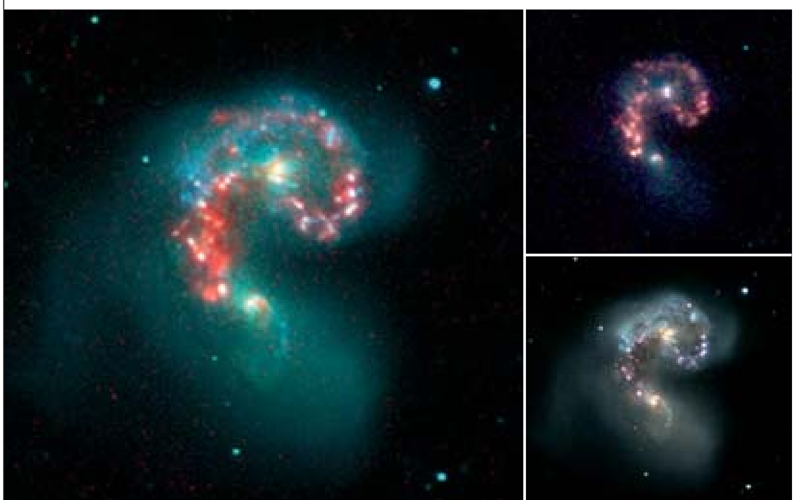
Over the past few years, indeed, particularly with the discovery of a cosmological infrared background radiation, it has become apparent that the primordial galaxies (those that had not yet generated the major part of their stars) radiated the greater part of their light output in the infrared. The ultraviolet radiation from massive stars is absorbed by the interstellar dust clouds in which they are born, and it is the dust, thus heated, that radiates this energy in the infrared.

And so it is in the infrared that astronomers are looking for a signature from these first galaxies – to wit, the radiation emitted by the dust particles prevalent in interstellar clouds, heated as they are by the massive stars enveloped in these clouds. The ultimate challenge, of course, would be to capture the light from one of these initial stars, however this could only be achieved if its brightness were vastly increased. Such an eventuality may well be entertained, provided the star under consideration is a massive star, and its evolution leads it to a point where it generates a tremendous burst of high-energy radiation, a gamma ray burst. For such instances, it is in the range of **gamma rays** that the quest for the first stars in the Universe has to be taken up. Probing the confines of the observable Universe to detect primitive galaxies in the infrared, and the first stars in the gamma spectrum is indeed one of the major goals pursued by CEA's Astrophysics Department (SAp: Service d'astrophysique).(1) This paper provides an overview of the way these investigations are being conducted.

Seeking out the first galaxies in the infrared

The galaxies close to us are also the oldest. Like the Milky Way – our own galaxy – they mainly comprise stars of low mass, slightly less massive on average than the Sun (some 80% of the Sun's mass), and of a greater age. These are known as cool stars, since they radiate mainly in the **near infrared**, a light hue associated to wavelengths close to one micrometer. When seeking out the primordial galaxies, on the other hand, i.e. galaxies that are still very young and only just beginning to form their first stars, it is to be expected they will be found to have an altogether different appearance: when gas is turned into stars, less than 20% of that gas is converted into stars, ten times more massive than the Sun, however these stars generate over 80% of the galaxy's light. Massive stars are so effective at converting, inside their core, hydrogen into helium that they only live a few tens of million years. The outcome is their explosion, in the form of **supernovae**, within the condensed clouds that gave birth to them, and their light – mainly in the ultraviolet – is predominantly absorbed by this dusty medium, opaque as it is to ultraviolet.

How may one hope to detect the formation of such stars, if they are so well hidden from view? The interstellar dust masking these stars is itself heated by their ultraviolet light, to temperatures of some tens of **kelvins** (i.e., to around – 230 °C!). At such temperatures, any body will radiate light in the **mid**- and **far-infrared** regions of the spectrum, i.e. at wavelengths of some tens of micrometers. Since the dust particles themselves are smaller than one micrometer in size, this light is not affected by that dust, and may travel effortlessly through the dense clouds where such stars are born. By measuring the galaxies' light in the far (or mid)

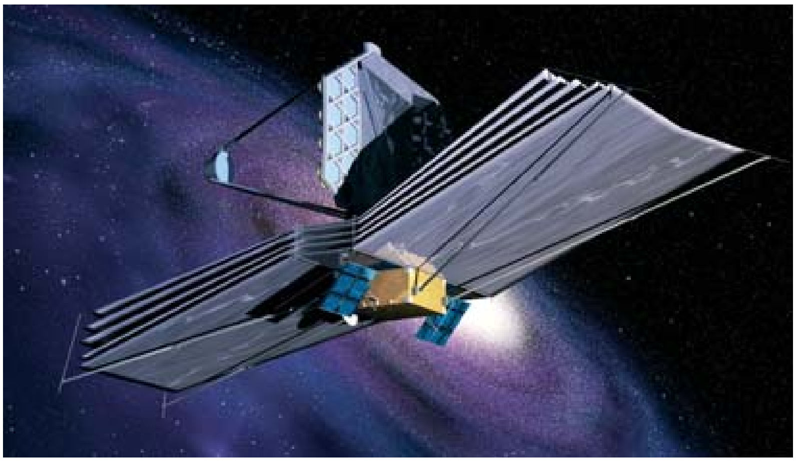


NASA/JPL-Caltech/Z. Wang (Harvard-Smithsonian CfA)

Composite view, in visible light (blue) and mid-infrared (red) of the Antennae Galaxy, as viewed by the Spitzer satellite, this being the successor to the European ISO satellite. This shows a system of two colliding galaxies, on the point of merging. The violence of the impact is causing starbursts, involving the formation of stars visible in the mid- and far infrared only (in red in the image), outside the centers of either galaxy (white). Inset, infrared view by the satellite's IRAC camera (top right), and view in the visible range (bottom; credit: M. Rushing/NOAO).

(1) SAp is part of DAPNIA, CEA's research laboratory on the fundamental laws of the Universe.

infrared, the concealed face of star formation in distant, young galaxies may thus be laid bare. Paradoxically, the extremes meet, since one must observe the cool radiation from interstellar dust to uncover the hottest regions in the Universe, where stars are born in blazing conflagrations, or starbursts…
Reality, however, is always slightly more complicated: the Earth's atmosphere is itself an infrared light source, and, in order to carry out this quest for hidden stars, spacecraft must be used, carrying instruments that are cooled to preclude their becoming blinded from their own heat glare.
It has been over ten years since the ISOCAM camera, developed under design leadership from CEA, was put in space on the ISO (Infrared Space Observatory) satellite. In three and a half years' existence, it brought about an upheaval in our understanding of the history of star formation in the Universe. Whereas its forerunner, the US–UK–Netherlands IRAS mission, had detected but a few, infrequent instances of nearly wholly (far-) "infrared" galaxies, ISOCAM revealed a profusion of so-called LIRGs (luminous infrared galaxies), in which star formation was occurring at rates 50 times greater than is the case in the Milky Way. Astrophysicists believe, nowadays, that the greater part of the stars that may be presently observed in the nearby universe were born in starbursts, blazes of star formation, during which galaxies radiated the greater part of their light in the far infrared.
ISOCAM, however, only made it possible to fathom the final 60% of the history of the Universe, and a new stage will soon be entered, with the **European Space Agency**'s (**ESA**) Herschel mission, in which CEA is to play a central role, contributing in particular the bolometer arrays that will be fitted to the satellite's PACS instrument (see *Detectors: novel technologies and new markets*). This will enable 80% of the Universe's lifespan to be accessed, finally allowing the investigation to be launched, of the initial stages of starburst. The **standard model** predicts that these galaxies were rather small, and that the massive galaxies found today were born as the outcome of successive mergers of smaller ones. If, counter to that model, Herschel provides evidence hinting at the existence of massive galaxies forming large numbers of stars in the early ages of the

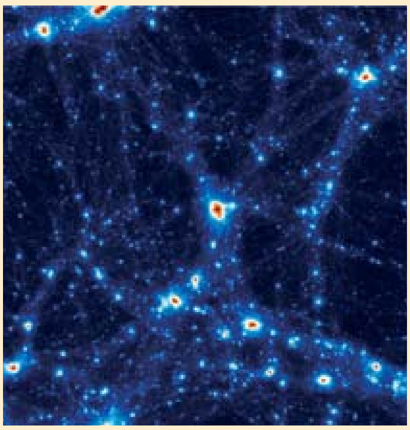


ESA/NASA

The James Webb Space Telescope (JWST), scheduled as the successor to the Hubble Space Telescope (HST), comprises a 6.5-m telescope operating in the infrared. CEA is participating in construction of MIRI, one of the three main instruments carried on this satellite, due to be put in space by an Ariane 5 launcher in 2013. Comprising a camera and spectrometer operating in the mid-infrared (5–27 micrometers), MIRI will combine the advantages of the ISOCAM satellite's sensitivity and the VISIR ground facility's angular resolution.

A The standard cosmological model

The **standard cosmological model**, i.e. the currently agreed representation of the Universe, is based on a theory of **gravitation**, Einstein's **general relativity**. This model takes into account a degree of expansion of the Universe, as evidenced by the observations made by US astronomer E. P. Hubble, showing that **galaxies** are receding from one another at a rate that increases with distance.
The model's basic assumptions are that the Universe is *homogeneous*, i.e. that it exhibits throughout identical properties (at a cosmological scale, at any rate), and *isotropic*, i.e. its appearance remains unchanged, in whichever direction it is viewed.
Three parameters characterize the evolution of the Universe, in this model: **Hubble's constant**, first, which characterizes its rate of expansion; **mass density** (the ratio of its own density over a *critical density*); and the **cosmological constant**. Introduced by Einstein in the guise of a force acting against gravitation, in order to account for a stable Universe, this constant rather corresponds to the manifestation of the action of *dark energy*, in an expanding Universe. [(1)]
If mass density is less than, or equal to, 1, that expansion will carry on indefinitely. The latest observations would appear to support a density of matter equal to 1, this implying a "flat" Universe (i.e. one where the sum of the angles in a triangle is precisely equal to 180°).
The current standard cosmological model involved a radius of the observable Universe of some 45 billion light-years, with an age of around 13.7 billion years, as counted from an initial "singularity" (primordial explosion) known as the **Big Bang**, followed, some 300,000 years later, by an uncoupling of matter and radiation, leading to a stage of **inflation**.
The model further makes it possible to account for the **cosmological background** (diffuse radiation), at a temperature of 2.7 K, and for the fluctuations in radiation/density leading, very early on, to the formation of the initial "seed" structures for the galaxies.



D. Aubert/CEA-C. Pichon (IAP)

Numerical simulation of a universe during formation, carried out in the context of the Horizon Project, bringing together, around a program targeted at the investigation of galaxy formation, the numerical simulation activities of a number of French teams, including the DAPNIA team (CEA). Its aim is to gain an understanding of the physical mechanisms leading to the structure and distribution of the galaxies around us – and particularly our own, the Milky Way.

(1) Interpretation of measurements from the WMAP (Wilkinson Microwave Anisotropy Probe) space probe, and from SDSS (Sloan Digital Sky Survey) leads to a value close to 71 (km/s)/Mpc ± 0.03 for Hubble's constant, however surprises as to the value of this parameter remain a possibility, should the disconcerting composition of the Universe, whereby 95% of the Universe is made up of dark matter and dark energy, in fact turn out not to be correct.

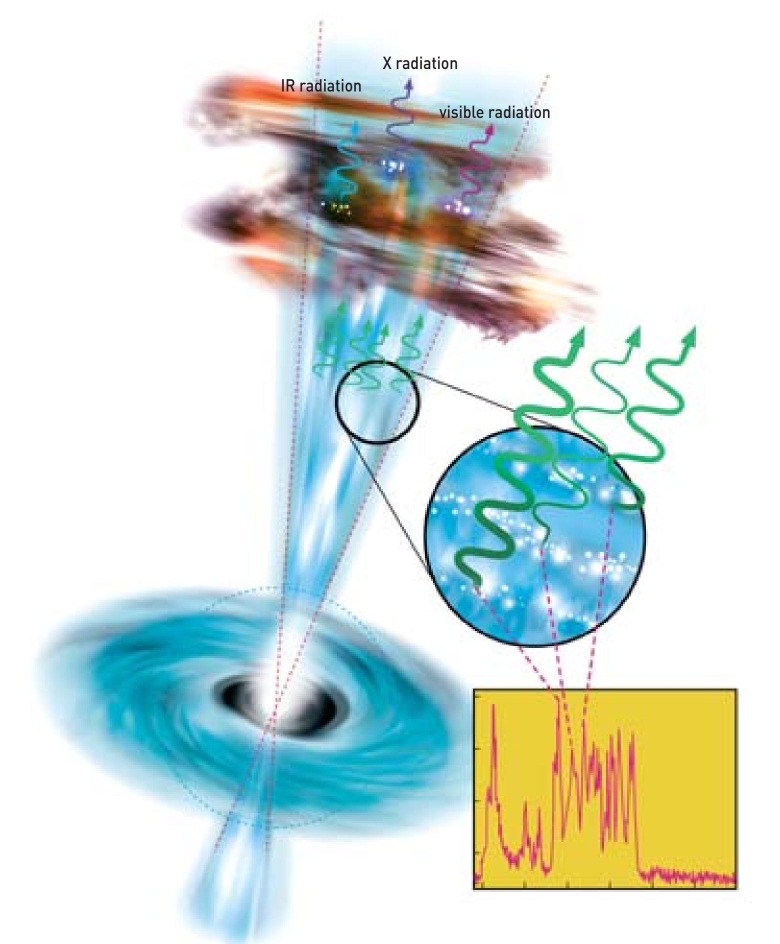


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Figure 2.
Schematic representation of the standard model of gamma ray bursts.

Universe, then that model would have to be revised… One further space mission in which CEA is a participant will make it possible to test the role played by galaxy mergers, namely the James Webb Space Telescope (JWST) mission, which is to replace the Hubble Space Telescope (HST) in 2013. With JWST, it will be feasible to "weigh" the more distant galaxies, by measuring the luminosity of their low-mass stars, i.e. those radiating around the 1-micrometer mark, in the near infrared. It will then be possible to compare the history of star formation, as measured in the far infrared, to that of galaxy mass growth, measured in the near infrared, and thus home in, from both extremes (small stars, predominant in mass terms, and large stars predominant in terms of light) on the history of galaxies from their earliest ages.

There will remain, however, one further stumbling block to overcome: that of ensuring the light being measured does indeed come from massive stars, and not from some other physical process… Now there is indeed one other process with the ability to generate a comparable luminosity: supermassive black holes.(2) Once again, extremes meet: a black hole takes its name from its ability to prevent light from escaping out of it, however as matter falls towards it, attracted by its gravitational force, it heats up, emitting radiation sufficiently far from the hole to evade it. As the black hole is surrounded by a torus of gas and interstellar dust, this brings about the same effect as with massive stars: it absorbs the radiation, heats up and radiates in turn in the infrared. It is thus crucial to combine observations at both extremes of the electromagnetic spectrum: on the one hand far infrared, for the cold dust, on the other X radiation, for the emission due to the "active nucleus," the radiant region surrounding the black hole. To that end, observations will have to be carried out in the region of **hard X** radiation, this being the purpose of the SIMBOL-X space mission, for which SAp is design leader.

Seeking out the first stars with gamma ray bursts

Aside from the Big Bang, gamma ray bursts are the most energetic explosive phenomena in the Universe: 10^{44} **joules** are radiated in this radiation range. They are also unique in terms of the physical processes involved. It is now agreed that by far the greater number of gamma ray bursts, those exhibiting a duration of 1–2 s, are the signature of the final stage in the evolution of certain stars having a mass of over several tens of solar masses. Barely a few million years after such massive stars are formed, the core collapses into a black hole. Still shrouded by debris from the star, this black hole, undergoing rapid rotation, then generates a bipolar system, comprising two jets of matter accelerated to ultra-relativistic velocities.(3) This causes two kinds of emission, both ranking among the brightest light sources in the Universe. The *prompt emission* – the gamma ray burst proper – is radiated, essentially, in the low-energy gamma radiation region, providing the signature for the dissipation of relativistic shocks within the jets themselves. The *afterglow*, exhibiting a brightness dropping off exponentially after the burst, is generated by the interaction between the ultra-relativistic outflows and the circum- and interstellar medium surrounding them (see Figure 2).

Owing to their extreme brightness, gamma ray bursts may be observed from very great distances. The most distant burst ever detected, to date, GRB 050904,(4) is over 12 billion light-years away. The star in which this event arose was thus formed when the Universe was only 900 million years old, just at the end of the reionization phase. Despite being so far away, the brightness of GRB 050904 was still so intense, 8 minutes after detection, that it was spotted in the near infrared by a modest 20 cm-diameter telescope! There can thus be no question that, using gamma ray bursts, investigation of the first stars in the Universe is a feasible proposition. Provided, that is, that astronomers avail themselves of an instrument working in the gamma range, to detect the prompt emission from gamma bursts, and measure its direction of origin – a necessary condition, if large telescopes are to be able to investigate the afterglow in the visible spectrum, and the near infrared. Observing the sky in the gamma region, however, is an altogether thankless task. On the one hand, the

(2) Black hole: a singularity in the Universe, where spacetime "parallels" meet within a body so dense and so compact that it retains everything, light included. There is no better characterization of a black hole than its horizon, the boundary setting apart our Universe and a region from which it is causally disconnected. What occurs within a black hole's horizon exerts no influence on the outside, where only an intense gravitational field remains.

(3) This refers to processes involving velocities close to the velocity of light.

(4) GRB for "gamma ray burst," followed by the date of the event (year, month, day).

Earth's atmosphere presents an opaque shield to this kind of radiation; gamma ray astronomy thus needs must be carried out aboard manmade satellites. And, on the other hand, due to the fact their wavelength is shorter than intervals between atoms, gamma rays are not amenable to the combinations of mirrors that form the basis for the telescopes operated in other regions of the spectrum.

Obtaining images using neither mirror nor lens is feasible, however, by means of coded-aperture devices. The principle of the coded-aperture camera harks back to the camera oscura, used by early photographers. By making a pinhole in the front of a box made in an opaque material, and placing a light-sensitive plate on the opposite side, a very primitive photocamera may be constructed, which is nonetheless capable of forming images that are all the sharper, the smaller the hole is. Nothing is to prevent such a device being transposed to the gamma range. The only requirement, to achieve this, is the use of a high-**atomic-number** material, and substituting for the photographic emulsion a detector layer, sensitive to gamma radiation. Image brightness may be improved, with no loss of detail, by perforating the front of the device with a large number of pinholes, arrayed according to a definite code. The latter is chosen in order to allow decoding of the image thus formed from this multiplicity of pinholes, by means of a simple mathematical **algorithm**.

For over twenty years, SAp has been contributing to the deployment of coded-aperture devices, to explore the gamma-ray sky. First came the SIGMA telescope, put into orbit from 1989 to 1998, on board the Russian GRANAT satellite; then the IBIS telescope, which has been in orbit since 2002, on board ESA's INTEGRAL satellite. IBIS, combining as it does a coded aperture with a detector plane, comprising an array of cadmium telluride (CdTe) semiconductor crystals, has proved highly effective in locating the gamma ray bursts it has been detecting, at a rate of one a month (see Figure 3). Renewed use of this type of device may thus well be contemplated, for a space mission dedicated to the investigation of gamma ray bursts, particularly if the distance between coded aperture and detector plane is reduced, to open up wide the field of view with no degradation of source localization accuracy. It is on this very principle that the design has been based for the ECLAIRs telescope, an apparatus for which SAp is considering taking on design leadership, in the context of a collaboration involving the **Centre d'études spatiales des rayonnements** (**CESR**: Radiation Space Research Center) in Toulouse (France) and the **Astroparticule et cosmologie** laboratory, in Paris. Submitted to the French **Centre national d'études spatiales** (**CNES**: National Space Research Center) in response to their 2004 call for tenders, ECLAIRs now stands as the key instrument in the Chinese–French SVOM mission, this being the outcome of a collaboration involving CNES, the China National Space Administration, and the China Academy of Sciences.

Launch of SVOM is scheduled for the end of 2010–early 2011. ECLAIRs will then be able to detect close to one hundred gamma ray bursts a year, and evaluate their position in the sky with an accuracy of a few minutes of arc. Using new-generation IDeF-X readout electronics, developed under the aegis of a CEA–CNES R&D program, the ECLAIRs telescope's CdTe detector plane will be sensitive into the X-ray range, a performance that should prove decisive for the detection of the more distant bursts, i.e. those for which gamma brightness is seen to be strongly shifted towards the X-ray region, owing the expansion of the Universe. As the only mission wholly dedicated to investigation of gamma ray bursts around 2010, SVOM will stand as the main provider of new data, on the basis of which astrophysicists will finally be in a position to survey the Universe, down to the onset of the age of reionization. It will then be possible to set constraints on the cosmological parameters, to the extent of elucidating the nature of that mysterious **dark energy**, which is now agreed to form the main constituent of the Universe.

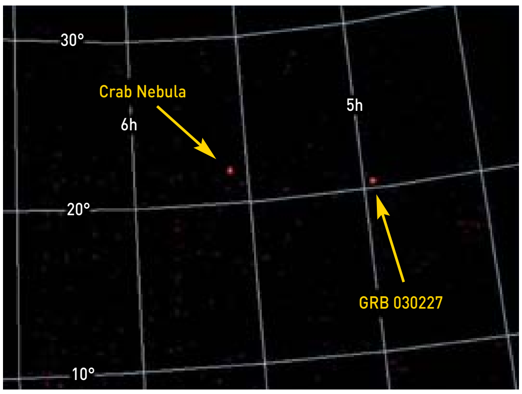
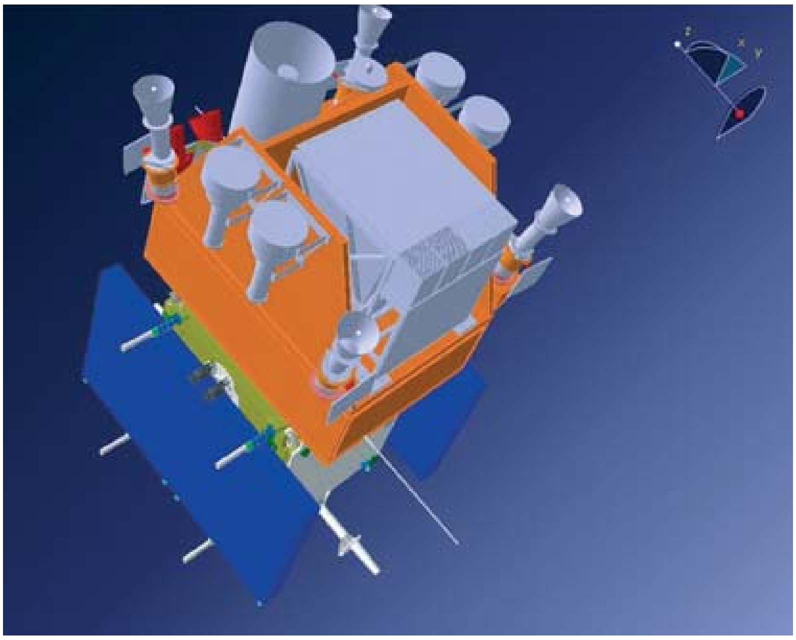


Figure 3.
Area in the sky observed on 27 February 2003, in the low-energy gamma radiation range, by the IBIS telescope on board the INTEGRAL satellite, to calibrate the telescope by means of the Crab Nebula, the standard candle for gamma astronomy. It was during this very calibration run that there appeared by chance, in the apparatus's field of view, GRB 030227, a gamma ray burst located at a distance of some 8 billion light-years.



Schematic of the Chinese–French SVOM satellite. On view, in green: the space platform, of the Proteus type, carrying (blue) its solar panels, here retracted, (brown) the payload module, onto which are mounted the items of scientific equipment (grey), including – center – the ECLAIRs telescope.

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B Fundamental interactions and elementary particles

The standard model of particle physics is the reference theoretical framework describing all known elementary particles (see Table 1) and the fundamental interactions these particles are involved in (see Table 2). The basic constituents of matter, known as fermions, are partitioned into two main categories, as determined by their partcipation in the fundamental interactions, or forces (the gravitational, electromagnetic, weak, and strong forces), which are mediated by vector bosons, the fundamental particles which carry out the transmission of the forces of nature[1] (see Table 2). Whether a particle belongs to the category of fermions, or to that of bosons depends on its spin (i.e. its intrinsic angular moment, or internal rotation moment), depending on whether it exhibits half-integer spin (fermions) or integer spin (bosons).
At the same time, to every constituent of matter is associated its antiparticle, a particle having the same *mass*, but the opposite *charge*. The positron is thus the positively charged antiparticle of the electron, which exhibits a negative charge.

Leptons and quarks

Fermions include, on the one hand, leptons, which may travel freely and do not participate in the *strong interaction*, which ensures the cohesion of atomic nuclei (it is consequently termed a *nuclear* interaction), and, on the other hand, quarks, which participate in all interactions but are not individually observed, enmeshed and confined as they are within hadrons, the particles susceptible to strong interaction, of which they are the constituents.[2]
In the lepton category, charged leptons participate in the *electromagnetic interaction* (which ensures the cohesion of atoms and molecules, and in the *weak interaction* (which underlies decay processes, in particular β radioactivity). Neutral leptons, or neutrinos, for their part, participate in the weak interaction only. Exhibiting very low mass, there is one type of neutrino for each type of charged lepton.
Independently from their involvement in interactions, the basic constituents of matter are classified into three *generations*, or *families*, of particles. From one family to the next, quarks and leptons having the same charges only differ by their mass, each family being heavier than the preceding one.
The electron, up quark (symbolized *u*) and down quark (symbol *d*), which belong to the first generation, are the lightest massive particles, and are stable. These are the sole constituents of normal matter, so-called baryonic matter (a baryon is an assembly of quarks), which is made up of protons and neutrons, this however only accounting for 4% of the Universe's energy content!
Particles in the other two families are heavier, and are unstable, except for neutrinos, which on the other hand exhibit non-zero mass, but are stable. These latter particles may only be observed or detected in the final states resulting from collisions effected in accelerators, or in cosmic radiation, and rapidly decay into stable first-generation particles. This is why all the stable matter in the Universe is made up from constituents from the first family.
According to quantum mechanics, for an interaction to take place between particles of normal matter, at least one elementary particle, a boson, must be emitted, absorbed, or exchanged. The photon is the intermediate (or vector) boson for the electromagnetic interaction, the W^+, W^- and Z are the intermediate bosons for the weak interaction, and gluons are those of the strong interaction, acting at quark level.
As to the graviton, the putative vector for the gravitational interaction, it has not so far been empirically discovered. The gravitational force, which acts on all fermions in proportion to their mass, is not included in the standard model, due in particular to the fact that quantum field theory, when applied to gravitation, does not yield a viable scheme, as it stands. While gravitational effects are negligible in particle physics measurements, they become predominant on astronomical scales.

Interaction ranges

Quarks and charged leptons exchange photons. The photon having no electric charge, these particles conserve their electric charge after the exchange. Since the photon's mass is zero, the electromagnetic interaction has an infinite range. Having no electric charge, neutrinos are the only elementary fermions that are not subject to electromagnetic interaction.
In the electroweak theory (a unification of the weak and electromagnetic interactions), the weak interaction has two aspects: charged-current weak interaction, for which the interaction vectors are the W^+ and W^-; and neutral-current weak interaction, for which the mediator is Z^0. These two forms of weak interaction are active between all elementary fermions (quarks, charged leptons and neutrinos). The mass of these bosons being very large (about 80 GeV/c^2 for $W^\pm$, 91 GeV/c^2 for Z^0), the range of the weak interaction is tiny – of the order of 10^{-18} m. Since $W^\pm$ bosons have a non-zero electric charge, fermions exchanging such bosons undergo a change in electric charge, as of nature (*flavor*). Conversely, since the Z^0 boson has no electric charge, fermions exchanging one undergo no change in nature. In effect, neutral-current weak interaction is somewhat akin to exchanging a photon. As a general rule, if two fermions are able to exchange a photon, they can also exchange a Z^0. On the other hand, a neutrino has the ability to exchange a Z^0 with another particle, though not a photon.
Only those quarks that have a color charge[1] exchange gluons, these in turn being bearers of a color charge. Thus,

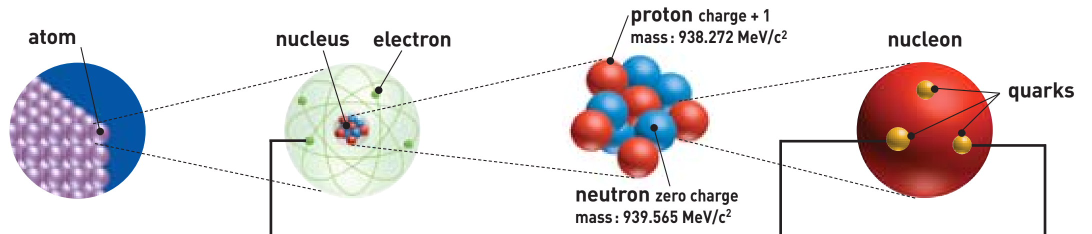
(1) The participation of basic constituents in fundamental interactions is governed by their *interaction charges* (electric charge, color charge), or "conserved quantum numbers." *Color charge*, a quantum number that determines participation in strong interactions, may take one of three values: "red," "green," or "blue" (these colors bearing no relation to visible colors). Every quark bears one of these color charges, every antiquark one of the three anticolor charges. Gluons are endowed with double color–anticolor charges (eight combinations being possible).

(2) To take e.g. nucleons: the proton holds two up quarks and one down quark, the neutron two down quarks and one up quark. A meson is made up of just two quarks (one quark and one antiquark).

when a gluon exchange takes place between quarks, the latter exchange their respective colors. Gluons have zero mass, however, since they do bear a color charge, they are able to interact together, which greatly complicates theoretical treatment of this interaction. The range of the strong interaction is consequently very restricted – of the order of 10^{-15} m.

The quest for unification

The theoretical framework for the standard model is quantum field theory, which allows a quantitative description to be made of the fundamental interac-



		leptons able to move freely		quarks assembled into triplets, or quark–antiquark pairs, to form the many subatomic particles	
Fermions Normal matter is made up of particles from this group.	First family	**electron (e)** responsible for electricity and chemical reactions charge:- 1 mass : 0.511 MeV/c²	**electron neutrino** (ν_e) has no electric charge, and interacts very seldom with the ambient medium.	**down (*d*)** electric charge: - 1/3 the proton holds one, the neutron two mass : 4 – 8 MeV/c²	**up (*u*)** electric charge: + 2/3 the proton holds two, the neutron one mass : 1.5 – 4 MeV/c²
Most of these particles were around just after the Big Bang. Presently only to be found in cosmic rays, and around accelerators.	Second family	**muon (μ)** a more massive companion to the electron. mass : 105.658 MeV/c²	**muon neutrino** (ν_μ) properties similar to those of the electron neutrino.	**strange (*s*)** a heavier companion to "up" mass : 80 – 130 MeV/c²	**charmé (*c*)** a heavier companion to "down" mass : 1.15 – 1.35 GeV/c²
	Third family	**tau particle (τ)** heavier still. masse : 1,776.99 ± 0.29 MeV/c²	**tau neutrino (ν_τ)** properties similar to those of the electron neutrino.	**beauty (*b*)** tau particle. mass : 4.1 – 4.4 GeV/c²	**top (*t*)** heaviest in the family (observed in 1995) mass : 171.4 ± 2.1 GeV/c²
Vector bosons Fundamental particles carrying out transmission of natural forces.		**photon** elementary grain of light, vector for the electromagnetic force	**gluon** bearer of the strong force between quarks	**W±, Z⁰** (W⁺, W⁻, Z⁰) bearers of the weak force, responsible for some forms of radioactive decay	
Higgs boson?		responsible for "electroweak symmetry breaking"			

Tableau 1.
Table showing the twelve elementary constituents for which the standard model describes the interactions involved. The three charged leptons (electron e-, muon, μ^-, tau particle τ^-) are subject to electromagnetic and weak interactions, neutrinos (ν_e, ν_μ, ν_τ) are only affected by weak interaction, and the six quarks (up, charm, top – or *u*, *c*, *t* – bearing a charge of 2/3; and down, strange, bottom – *d*, *s*, *b* – bearing a charge of – 1/3) are subject to all three interactions. Every elementary constituent has its antiparticle, having the same mass, and algebraic quantum numbers (such as electric charge) of the opposite sign.

B (cont'd)

tions between elementary particles, while respecting the principles of *special relativity*, as those of quantum mechanics. According to the latter theory, if one seeks to observe a microscopic structure at high temporal and spatial resolution, this entails transferring to it an amount of energy–momentum, the greater, the higher the resolution being sought. However, according to the theory of relativity, such an energy–momentum transfer is liable to undergo transformation, yielding particles not present in the initial state: fermions may be generated, or annihilated, in particle–antiparticle pairs, while bosons may be so in any arbitrary number.
All processes involving one and the same fundamental interaction are interrelated. The quantum field theory approach, in which properties of **symmetry** play a fundamental part, seeks to describe all of the processes relating to each fundamental interaction, within overarching theoretical constructions.
The strong and electromagnetic interactions are formalized, respectively, in the theories of **quantum chromodynamics**, and **quantum electrodynamics**. The weak interaction, for its part, is not subject to a separate description, being described jointly with the electromagnetic interaction, in the unified formalism of **electroweak theory**. Theories of the *grand unification* of all fundamental interactions do exist, however they remain as yet lacking any experimental validation.
All the predictions of the standard model have been corroborated by experiment, except for just one, to wit, the existence of the **Higgs boson(s)**, which particle (particles?), it is hoped, will be discovered with LHC. The **Higgs mechanism** is thought to be responsible for the mass exhibited by elementary particles, the eponymous boson making it possible for zero-mass fermions interacting with it to be endowed with mass. This would allow the unification, at high energies, of the weak and electromagnetic interactions within the electroweak theory, while effectively accounting for the **breaking** of this **electroweak symmetry** at low energies, taking the form of two interactions, which may be seen as distinct at that energy level (see *The electroweak interaction from one accelerator to the next: the LHC roadmap and the yardstick of LEP measurements*, p. 23).

Going beyond, or completing the standard model?

The standard model features a set of parameters (such as the masses of elementary particles, or the intensities of fundamental forces) which are "anchored" in experimental findings. It is, in any event, a theory that is liable to be improved, or further elaborated, or even surpassed and left behind. It does not account in any way for the classification of the constituents of matter into three generations of particles, whereas it is precisely the existence of these three generations which makes it possible to account for **CP** (charge–parity) **invariance violation** (meaning that a physical process involving the weak interaction is not equivalent to its own mirror image), a violation that is in all likelihood the source of the matter–**antimatter** imbalance, running in favor of the former, in the primordial Universe. The model neither allows quantum treatment of gravitation, nor does it fully account for the fundamental property of *confinement*, which prevents quarks from propagating freely outside hadrons.
To go beyond, or to complete the standard model, research workers are mainly exploring two avenues:
– **supersymmetry** (widely known as SUSY) would associate, to every particle (whether a boson or a fermion) in the standard model, a partner from the other series, respectively a fermion or a boson. Supersymmetric partners would, at first blush, be highly massive, the lightest of them being a particle interacting very weakly only. This would be an ideal candidate to account for the **hidden matter** (or **dark matter**) in the Universe, accounting as it does for some 21% of the Universe's energy content, the remainder (close to 75%) consisting in a **dark energy**, the nature of which likewise remains to be determined. These WIMPs (acronym for "weakly interacting massive particles") are actively being sought (see *EDELWEISS II, the quest for dark matter particles*);
– the **substructure** path assumes there could be a new level of elementarity, underlying the particles in the standard model (or some of them). This would lead to a veritable blossoming of new, composite particles, analogous to hadrons, but exhibiting masses two to three thousand times heavier.
It should be noted that, whereas supersymmetry theories yield predictions that agree with the precision measurements carried out at LEP, the theories propounding substructures (or their simpler variants, at any rate) fail to do so. As for the more complex variants, these are encountering difficulties at the theoretical level.

fundamental interaction	associated particles (messengers)	actions
gravitation	graviton?	having an infinite range responsible for the mutual attraction of any two masses and for the law of falling bodies
electromagnetic interaction	photon	having an infinite range responsible for the attraction between electrons and atomic nuclei, hence for the cohesion of atoms and molecules
weak interaction	W^+, W^-, Z^0	responsible for β^- and β^+ radioactivity, reactions involving particles as neutrinos
strong interaction	gluons (there are 8 gluons)	ensures the cohesion of the atomic nucleus

Tableau 2.
Fundamental interactions, their vectors, and effects.

A The standard cosmological model

The **standard cosmological model**, i.e. the currently agreed representation of the Universe, is based on a theory of **gravitation**, Einstein's **general relativity**. This model takes into account a degree of expansion of the Universe, as evidenced by the observations made by US astronomer E. P. Hubble, showing that **galaxies** are receding from one another at a rate that increases with distance.

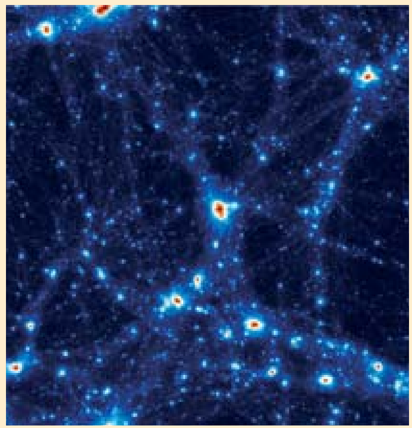
The model's basic assumptions are that the Universe is *homogeneous*, i.e. that it exhibits throughout identical properties (at a cosmological scale, at any rate), and *isotropic*, i.e. its appearance remains unchanged, in whichever direction it is viewed.

Three parameters characterize the evolution of the Universe, in this model: **Hubble's constant**, first, which characterizes its rate of expansion; **mass density** (the ratio of its own density over a *critical density*); and the **cosmological constant**. Introduced by Einstein in the guise of a force acting against gravitation, in order to account for a stable Universe, this constant rather corresponds to the manifestation of the action of *dark energy*, in an expanding Universe. [1]

If mass density is less than, or equal to, 1, that expansion will carry on indefinitely. The latest observations would appear to support a density of matter equal to 1, this implying a "flat" Universe (i.e. one where the sum of the angles in a triangle is precisely equal to 180°).

The current standard cosmological model involved a radius of the observable Universe of some 45 billion light-years, with an age of around 13.7 billion years, as counted from an initial "singularity" (primordial explosion) known as the **Big Bang**, followed, some 300,000 years later, by an uncoupling of matter and radiation, leading to a stage of **inflation**.

The model further makes it possible to account for the **cosmological background** (diffuse radiation), at a temperature of 2.7 K, and for the fluctuations in radiation/density leading, very early on, to the formation of the initial "seed" structures for the galaxies.



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Numerical simulation of a universe during formation, carried out in the context of the Horizon Project, bringing together, around a program targeted at the investigation of galaxy formation, the numerical simulation activities of a number of French teams, including the DAPNIA team (CEA). Its aim is to gain an understanding of the physical mechanisms leading to the structure and distribution of the galaxies around us – and particularly our own, the Milky Way.

(1) Interpretation of measurements from the WMAP (Wilkinson Microwave Anisotropy Probe) space probe, and from SDSS (Sloan Digital Sky Survey) leads to a value close to 71 (km/s)/Mpc ± 0.03 for Hubble's constant, however surprises as to the value of this parameter remain a possibility, should the disconcerting composition of the Universe, whereby 95% of the Universe is made up of dark matter and dark energy, in fact turn out not to be correct.