The coming of age of cosmophysics

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ABSTRACT

''Cosmophysics'' as reviewed is a multidisciplinary domain which brings together astroparticle physics, fundamental physics in space and topics related to the structure and evolution of the Universe. It represents a growing interface between high-energy particle physics and astro-physics. This paper presents a general overview of the subject, focusing on cosmology, cosmic rays, dark matter searches and the soon-expected observation of gravitational waves.

Key words: astrophysics, cosmology, gravitational wave, space research, Universe (structure and evolution).

1 INTRODUCTION

A couple of years ago, it was deemed appropriate to coin a word, namely ''cosmophysics'', to circumscribe a new domain of science developing at the interfaces of particle physics, astrophysics and gravitational physics. In the spring of 2000, a workshop on ''Fundamental Physics in Space and Related Topics'' took place at CERN. It was initiated and organized by the Joint Astrophysics Division of the European Physical Society and the European Astronomical Society (JAD), while benefiting from the sponsorship of ESA and CERN. The meeting was an opportunity for laboratory and space physicists to realize the extension of their common goals [1]. There was much more to discuss than what one usually refers to as ''astroparticle physics'', since several tests of gravitation theory now appear on the list together with many challenging questions related to astrophysics and cosmology. Many particle physicists are bringing new blood and technical expertise to the study of the cosmos at large, beside

that of its ultimate constituents. They do that with new types of detectors originating from accelerator-based research, while also benefiting from recent advances in space technology. The early Universe and violent events in the cosmos such as gamma ray bursts are the natural habitat of high energy phenomena. At the same time many astrophysicists are actively studying the global properties of the Universe and its origin. The word, which would cover all that, short of a long explanatory circumlocution – ''cosmophysics'' – was coined at that workshop, and soon picked up by the highly respectable CERN Courier [2]. This paper attempts to portray some of the pertinent domains of research which it covers. In March, 2002, a symposium jointly organized by CERN, ESO and ESA, in Garching (the first of its kind!) came back in depth on all these topics [3]. This review was written at that time and we extensively use these 2000 and 2002 references.

2 COSMOPHYSICS, AN OVERVIEW

Cosmophysics is a new multi-disciplinary field and it therefore resists at first sight any clear and sim-

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ple definition. Nevertheless, one can attempt doing so by listing some of the topical research themes that can definitely be associated with it. This cannot be exhaustive unless one generates a long shopping list. The practical definition which we shall use in our selection of topics, consists in focusing on astrophysics or space science domains which experience a big influx of particle physicists. This is practical but too restrictive. Nevertheless we shall follow it for the limited scope of this review. For those willing to go further, a special issue of Europhysics News (initiated by JAD) now provides short but authoritative coverages of most topical issues [4]. References [1] to [4] can act as stepping stones to the current technical literature.

The relatively new field of astroparticle physics has almost come of age and it is part of cosmophysics. Whereas most of the cosmic-ray physicists switched to accelerator based research, when the first synchrotrons were commissioned in the mid fifties of the 20th century, some particle physicists have more recently come back to cosmic-ray research with new types of detectors sensitive to very rare events, whether associated with weakly interacting or highly energetic primaries. Dedicated laboratories have been built deep underground, to study highly penetrating particles and screen away all the others. Among such penetrating particles one has in particular the neutrinos, whether of atmospheric, solar or cosmic origins, and the still elusive supersymmetric partners of the known particles [5]. In the latter case, one searches for those particles, which would happen to be neutral and stable, and which are referred to as neutralinos. Extensive arrays are also built to study rare very high energy events. Along both lines, key questions relate to particle physics and astrophysics alike and this leads us already to two important components of cosmophysics, namely the question of dark matter in the Universe and the study of events of extreme energy which have both long been associated with astroparticle physics. But there is much more to cosmophysics!

2.1 The Global Properties of the Universe, Cosmology in a Nutshell

As part of cosmophysics, we have first to mention the global study of the Universe with the more and more precise measurement of the constants which define its general properties and evolution. We have all reasons to consider the Universe as isotropic and spatially homogenous on a large scale (hundreds of millions of light-years) and these constants refer to the whole Universe (hence their name) even if they are time dependent! Among them, one has the Hubble constant H, the deceleration (or acceleration) parameter q, the global density, the shining matter density, the baryonic density, the ''exotic'' dark matter density (hot and cold) and the vacuum energy density. These densities are all scaled, as usually done, according to the critical density which would imply a flat Universe [6]. In the absence of vacuum energy, the expansion would then be asymptotically slowed down by the matter density (deceleration) but with vacuum energy providing a negative pressure, it would accelerate. Before moving further, we have however to set the stage and first discuss the expansion of the Universe starting with a Big Bang.

This is part of the standard model of cosmology, based on general relativity.

Most of the research under way attempts to put it on firmer grounds or to find evidence for departures. The overall consistency of the picture offered by all present data is impressive. This is referred to as ''Cosmic convergence''. We shall here touch mainly two points, namely the expansion of the Universe and the structure of the microwave radiation background (MRB). But, before doing so, we recall that in the well known Einstein-Friedmann-Robertson framework, the square of the Hubble constant is the sum of three terms:

$$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \qquad (1)$$

The first term is proportional to the matter-energy density of the Universe (ρ) and to the Newton gravitational constant, G. If $R(t)$ stands for the time

dependent dimension scale of the Universe (with $H = (dR/dt/R)$, this term goes as R^{-4} for a radiation dominated Universe and as R^{-3} for a matter dominated one. The second term is associated with the overall curvature of the Universe, where $k = 1$, 0, or -1 for, respectively, a closed (positive curvature), flat or open (negative curvature) Universe. The third one brings the cosmological constant (Λ), first introduced by Einstein in an attempt to stabilize an otherwise expanding or contracting Universe imposed by the other terms alone. It can be associated with a vacuum energy density which is independent of R [6]. It could however vary according to a special dynamics as the case in the quintessence approach [3].

The presence of vacuum energy (a vacuum or ''dark'' energy density) may seem peculiar since the vacuum is defined as the state of lowest energy, an energy which, for most practical purposes, can be taken to be zero, all energies being then measured with respect to that vacuum. This however does not hold for gravitation since gravitation is coupled to all forms of energies including that which may be associated with the vacuum, even in the absence of matter or radiation. The presence of a non zero vacuum energy is a challenging problem to which we shall come back later in this section.

It is well known that, in the absence of k and Λ, the matter-energy density is simply related to the Hubble parameter and takes its critical value. The Hubble constant is the present value of the Hubble parameter which changes with time according to relation (1). With the first term only, the Universe is flat and expands only once, the expansion being asymptotically slowed down by gravitational forces. Our present Universe may however not be critical but one may say that its observed/inferred density is actually of the order of magnitude of the critical value. In any case, unless anything special occurred, the density should have been very close to the critical value when the Universe was young and R was small, since the constant term and the R^{-2} term become negligible in front of the first one, which increases as R^{-4} as one approaches the Big

Bang origin of the Universe. If Λ is zero, as it was long thought to be the case, the Universe will recontract or expand forever according to the actual values of the matter-energy density, the critical behavior, with its asymptotically slowed down expansion and zero global curvature being the limiting case in between. In any case, the young Universe behaved as if it had been critical. This is the reason why one can describe its behavior even with only an approximate knowledge of its present density.

Something special may however occur if, for a certain lapse of time, the third term happens to become big as compared to the other two. Solving then for R under this new condition, one gets an exponentially expanding Universe. This is an inflation period [6].

An inflation period in the very early Universe, as first proposed by Guth and developed in particular by Linde [6], could have occurred circa 10^{-38} s. after the Big Bang (breaking of GUT symmetry) or even earlier and it should have blown up the dimensions of the Universe by tens of orders of magnitude. This idea has now gained much currency, up to the point of becoming the present working hypothesis of many cosmologists. This important vacuum energy density feeding inflation may have resulted from supercooling during a phase transition of the vacuum which occurred as the temperature was decreasing. The energy of the vacuum contained in the inflated Universe was released as latent heat when the normal vacuum phase was eventually reached. This caused inflation to stop in a state of very high radiation energy density. If the present vacuum energy density is not zero (and, as we will see later, there are some reasons to believe that it could be comparable to the matter density!), the Universe will finally expand exponentially as its matter density drops dramatically, even if the present acceleration is still very small.

As is well known, the value of R at present is equal to its value at a remote time multiplied by $(1 + z)$ where z is the redshift corresponding to that particular time of emission, or that particular location now with respect to ours. Since light follows a zero geodesic with a time dependent metric, its ob-

served wavelength (different from that at emission) scales according to R, hence its red shift [7].

After bringing the standard model of cosmology into a nutshell, we can come to the actual expansion of the Universe [6].

The present expansion rate is given by the Hubble constant. The current accuracy of the measured value is limited by the errors affecting measurements of large distances in the Universe. Type Ia supernovae, corresponding to collapsing white dwarfs after accretion from a companion star, now appear to offer reliable reference candles and they have been tested and used up to $z = 1$, the redshift being determined by their host galaxy. The apparent luminosity is reduced by the square of the present distance but also by an extra factor $(1 + z)^2$, corresponding to the change in effective emission rate as a function of the redshift z. Using these new reference-candles has helped pinning down the value of H, which is now known to be between 60 and 70 km/sec/Mpc (1pc = 3.1 light years). At the same time this has however brought a surprising result. While the expansion of the Universe was expected to be decelerating because of the attracting masses which it contains, it is found to be slightly accelerating! In fact, the supernovae with z-values between 0.5 and 1 appear to be fainter by about 20% than they should be according to the parameters which one used to give to the Universe, with, in particular, a zero cosmological constant or no vacuum energy [8]. One can reproduce the observed results with an expansion accelerated by vacuum energy and reach a reasonable fit with a critical Universe where 70% of the energy density would be that of the vacuum and only 30% would correspond to matter (dominating over radiation at large R) (Fig. 1). This is an extraordinary result. One may still challenge it on the ground that it is not very significant statistically, but it is the more so exciting that it fits with the recent analysis of the fluctuations seen in the microwave radiation background [9]! A single supernova observed at high z (between 1 and 2) appears to be brighter than expected, as if the Universe first decelerated (when matter energy density was still dominant), before

it accelerated as the vacuum energy eventually took the largest role. However, success cannot be claimed with this single event and the more so that the nature of this supernova is not known!

This supernova result calls for a far more extensive study whereby one could analyze over a period of time (typically a month) each supernova among thousands of them and reach with reasonable statistics redshift values up to 2. One should remember that the result relies on supernovae being reliable reference-candles and behaving the same way over half of the duration of the Universe! This calls for more tests [10].

It is natural that pursuing such studies calls for an ambitious programme as presented, in particular, in the SNAP proposal [10, 11].

SNAP (SuperNova Acceleration Probe) aims at collecting a much-enlarged sample of supernovae (several thousands). This implies a large sky survey and the individual study of each supernova over a time of at least several weeks, in order to record brightness and evolution. This is difficult, if not impossible to do with the present large telescopes, since their observing time is completely subscribed. In fact, the proposal considers use of a dedicated satellite [10]. The proposed space mission foresees a collaboration including many members from high – energy physics laboratories and thus would be a typical cosmophysics venture.

2.2 THE MICROWAVE RADIATION BACKGROUND

First mentioned by Gamow, as he looked for a proof of the Big Bang, it was first observed by Wilson and Penzias in 1964. More recently, the results of the COBE satellite and those of balloon flights and ground-based observations [9] have verified its almost-perfect black-body nature and checked its remarkable isotropy and uniformity once obvious corrections are performed. The latter include, in particular, the Doppler shift associated with the overall motion of the Sun towards the ''great attractor'' at about 600 km/s, once the motion of the sun in the galaxy and the infall of the galaxy toward the Virgo cluster are taken into account. The temperature is
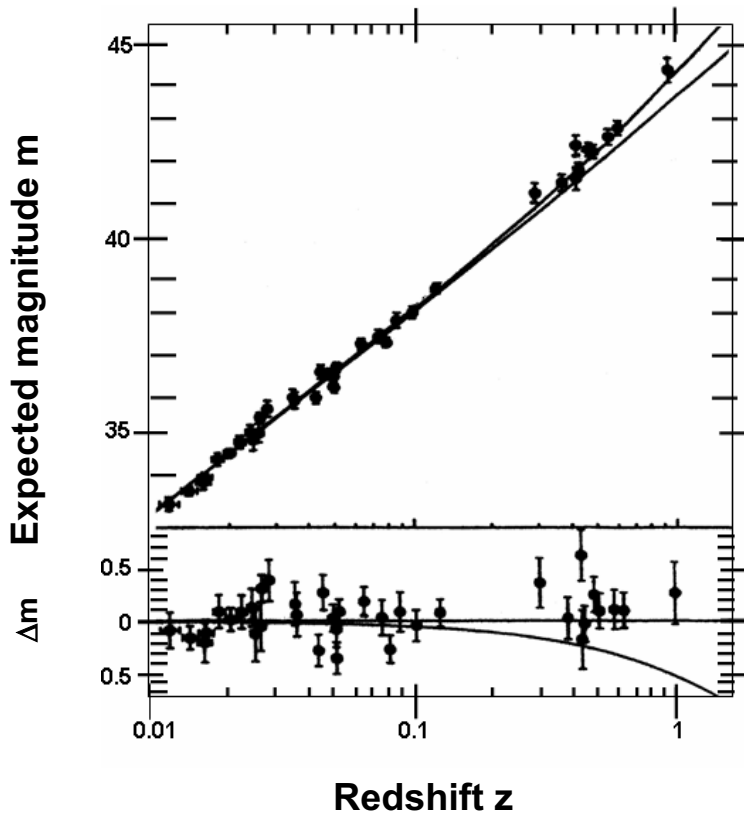
Fig. 1 – The present situation with Ia supernovae: Effective magnitude as a function of redshift [10] The lower curve is without deceleration. The best fit (upper curve) implies vacuum energy.

2.73K with fluctuations of only a few parts per million over the whole sky! These fluctuations keep the memory of the effects of gravitational attraction caused by density inhomogeneities up to the time of last scattering of light as it escaped from matter. The microwave radiation is indeed a signal, which originated when atoms were formed from a plasma, as light dissociated itself from matter and the Universe became transparent. This occurred when it was about 300.000 years old ($z = 1000$).

Whatever their origin may have been, any large fluctuation could have affected only a plasma regions where components were in ''speaking terms'' at that time. With a speed of sound in the plasma equal to $c/3^{1/2}$, such regions were limited to at most 200.000 light years. The expansion of the Universe has since blown them up by a factor of order 1000 but even such a new distance represents today only about one degree across in the sky. The spherical harmonic multipole analysis of the observed fluctuations in relative temperature should, accordingly, show a peak at an angular momentum L of about 200 that corresponds to this maximum size of one-degree. This was the first observed acoustic peak. Dips and peaks are following it as expected at multipole values of L corresponding to compression and dilatation within each particular connected domain (Fig. 2). Their relative heights are therefore sensitive to the baryonic (and electronic) composition of the matter since this plasma is the only part which interacts with light as opposed to other forms of dark matter also contributing to the gravitational inhomo-

geneities. When the second peak was not yet clear, the baryonic density looked inconsistent with other observations, with too much baryonic matter. This is no longer the case and a value of 5% of the critical density fits with the analysis of the nucleosynthesis of the light elements [3,4]. This clear pattern of peaks as now observed could hold only provided that the signal was not modified by a global gravitational lensing as it traversed the Universe. The observation of the first peak and, more recently, of the second and third ones, at the expected values of L, leads therefore to the conclusion that the Universe is flat, with no global curvature. A global curvature would have otherwise strongly modified the signal, smearing it or at least modifying its pattern. For instance, the first peak would shift to a higher value of L for an open Universe of sub-critical density and do the opposite for a closed Universe.

At that remote time, the observed fluctuations were probably the seeds of the big structures which developed later through gravitational attraction and indeed their present size agrees with the largest structures that are observed in the Universe and which are at the level of about 200 million light years. The remarkable constancy with L of the large-angle fluctuations (before the first acoustic peak) stands for their scale-independence property. Such a behavior is expected as the result of primordial (quantum) fluctuations blown up by the inflation of the Universe, a tremendous inflation which should also have imposed a practically flat Universe whatever its primordial curvature might have been and a white noise for the fluctuations before their gravitational amplifications.

The observed fluctuation pattern is therefore taken as evidence for a critical density implied by a flat Universe. Present measurements of the second peak point to a baryonic density which would be of the order of 5% of the critical value. The shining luminous mass of the Universe is, at most, 1% of the critical density. A best fit to the fluctuation pattern appears to favor a vacuum density of 50 to 75% of the critical value, the matter density being limited to about 30% [3,4].

The information contained in the tiny fluctuations of the microwave background radiation is remarkable, the key element being evidence for a flat Universe. The new balloon data represent an order of magnitude increase in angular resolution and in signal-to-noise ratio (S/N) as compared to the first COBE results. But their global angular coverage is small! COBE provided a full-sky coverage but with a 7-degree resolution and a S/N ratio per pixel of order 1 only. The present NASA-MAP mission should reach a resolution of 12-arc-min with a S/N of 10 and later the ESA mission PLANCK [11] should achieve a 5-arc-min resolution with a S/N of 100. Satellites offer full sky coverage whereas balloon flights cannot. In a few years, after the PLANCK launch foreseen for 2007, one should have a precise knowledge of the microwave radiation background that will strongly constrain most cosmological parameters and act as a precision test of the standard model of cosmology [12].

2.3 COSMIC CONVERGENCE

The present status of these two highly topical cosmology questions leaves us with extraordinary results. The Universe is flat. Its density is therefore critical, its baryonic content being of the order of 5% of the critical value. Dark matter is likely to be only a fraction of the remainder, since best fits considering the radiation background or the expansion seem to favor 70% of the critical density as vacuum energy and 30% only as matter energy. With such a vacuum energy, the expansion will keep accelerating. The global matter density thus inferred agrees with the one obtained through the analysis of gravitational lensing of distant objects (cosmic shear) which brings evidence for a large amount of dark matter and also with the simulation analysis of large structures [13]. This convergence of cosmic parameters measured according to very different approaches is remarkable. This is illustrated by figure 3. Nevertheless one should remember that ''theory is the bottom line'' and that all these measurements have a meaning only in the framework of a particular theory as summarized by relation (1),
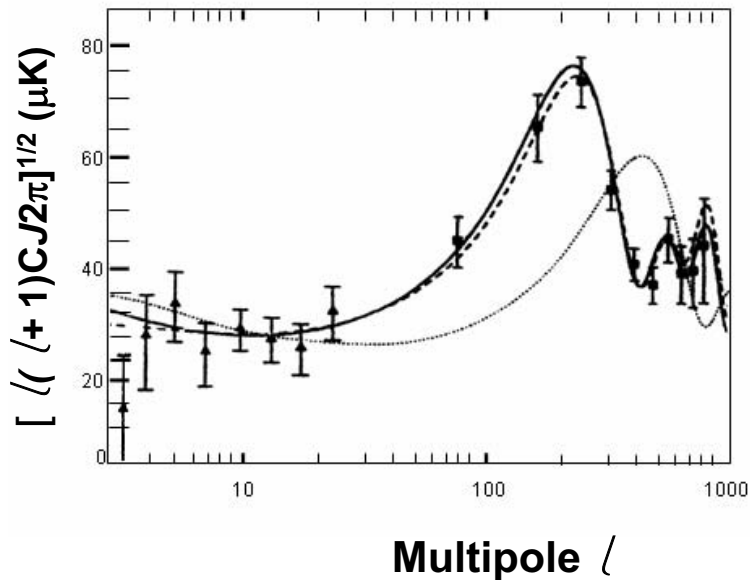
Fig. 2 – The multipole analysis of the microwave radiation background, combining present satellite (COBE-triangles) and balloon flight-squares) data [3,4]. The dashed curve is the best fit with a critical density. It does not depart very much from the best fit overall (solid curve). The dotted curve is expected for an open Universe with no vacuum energy.

which we may challenge. Indeed, isn't it embarrassing to have to conclude within the present theoretical framework that baryonic matter (the only one we know about) should be only 5% of the energy in the Universe? One can only wonder at the absence of contradiction among the different measurements [14]. This is also the case if one brings into the picture the value H and the age of the oldest stars on the one hand and, on the other hand, the agreement between the baryonic density thus found and that determined from nucleosynthesis [3]. Yet one cannot avoid being afraid of contriving too much the already precise data with the present theory without new ideas which might be needed, as in the time of Ticho-Brahe when trajectories had to be circles!

A vacuum-energy density present over a long period of time, as opposed to the violent but short inflation period which could have occurred in the early Universe, is constant (independent of R), whereas the matter density behaves as R^{-3} (cold)

or R^{-4} (hot) and eventually vanishes with the expansion of the Universe. Why are we then at an epoch when they compare in value? Our present time has otherwise nothing peculiar to it. Even if the vacuum appears to have a large energy density as compared to that of shining matter (at most 1% of the critical value), it is very small according to the ''natural'' scale provided by the Planck mass since one may naively expect it to be proportional to the 4th power of the cut-off energy associated with the Planck scale. It would then miss by 120 orders of magnitude! At that level of mismatch, even considering instead the other ''natural'' electroweak scale of 200 GeV, does not help much. Why is it non-zero and so small? As previously said, the vacuum energy can usually be redefined as zero, physics dealing with energy gains or losses. This is however no longer the case when one brings gravitation into the picture since gravitation couples to all forms of energy including that of the
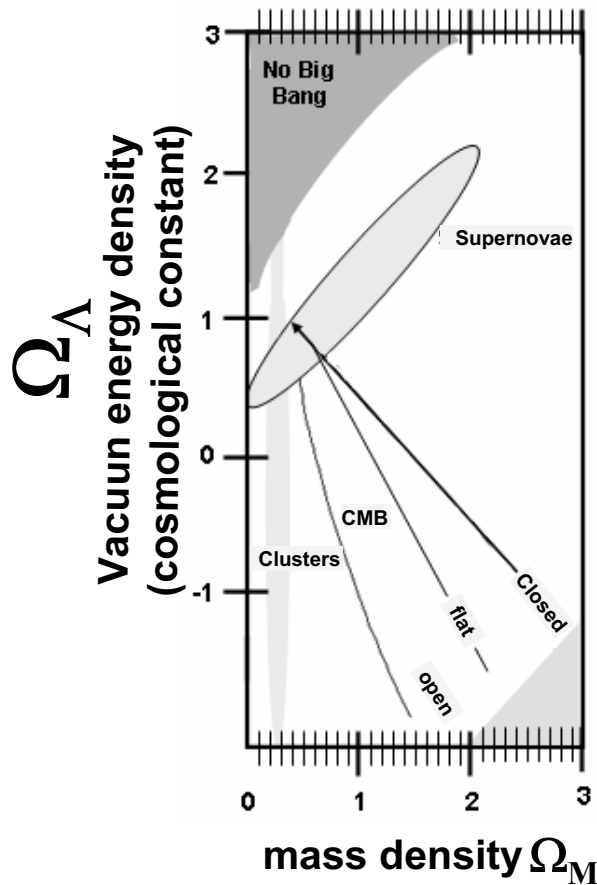
Fig. 3 – The acceptable zones in the $\Omega(M)$ and $\Omega(\Lambda)$ plane which are associated with different measurements. It illustrate the impressive ''cosmic convergence'' met according to the standard model.

vacuum. The vacuum energy can thus no longer be cast aside. The recent findings are therefore bringing up formidable new problems with this vacuum energy [15]. Quintessence proposes a dynamical origin for the vacuum energy but did not solve so far these problems [3].

A violent inflation at an early time (circa 10^{-38} s.) nicely fits with all the recent findings. It implies zero curvature and a critical density, which should otherwise have been tuned to an amazing accuracy (one part in 10^{17} when the Universe was 1 second old) in order to be not critical, but yet close to critical, today, as it is at least. Inflation explains not only the fluctuation pattern of the microwave

radiation background but, first of all, its overall uniformity valid to a high precision. We have seen that domains of the distant sky one-degree apart were in no speaking terms when light escaped and they could not have been a fortiori in contact before. How come that they look so similar up to a few parts per million? With inflation they once overlapped before being blown apart and their similarity is no longer surprising. Understanding inflation (or falsifying it) is also a great meeting ground between particle theoretical physics (and in particular string theory) and cosmology [14]. The very early Universe could have extended in more dimensions and we could live only in one of its 3-dimensional branes.

To summarize, it is customary to divide all terms in relation (1) by the one on the left hand side taken at its present value. This reads:

$$1 = \Omega(M) + \Omega(k) + \Omega(\Lambda) \qquad (2)$$

There is now evidence to give the value 0 to the second term on the right and the question is the relative role of the first and last ones. We have seen that there is evidence for a value ranging from 0.25 to 0.5 for the former one, a value which tallies with direct dark-matter searches (overall motions, gravitational lensing, X-ray background, etc). The latter one would then range accordingly between 0.75 and 0.5. All this is relatively new and very interesting but still tentative. It brings a great challenge and calls for further studies [15].

2.4 Neutrinos, Sparticles and Dark Matter

With neutrinos, we meet the fundamental question of oscillations between neutrino species as they travel from source to detector. This is possible if neutrinos have a tiny but non-zero mass and this is now the first observed departure from the standard model which assumes them to be massless. Evidence for such oscillations is now compelling [16]. Whereas the question came from particle physics the behavior of neutrinos are very relevant to astronomy. They offer the possibility to study the deep interior of stars. They are produced at the core but, given their tiny cross section, they are free to pass through the star and come out with an unaltered spectrum defined by stellar nuclear dynamics. Huge neutrino fluxes are associated with the collapse of a supernova and some neutrinos were indeed caught when the nearby SN 1987 A, located in the Large Magellanic Cloud, was observed. The number of those captured (about ten events) tallies with the huge expected flux. Neutrinos could also possibly contribute to dark matter and a neutrino mass of a few eV would indeed be enough to close the Universe. The Big Bang has left several billions of neutrinos for each proton, and neutrinos with even a very small mass could contribute in a significant manner to the hot dark matter density. They will connect to the study of extreme energy events, when one can detect in significant numbers very high-energy neutrinos of cosmic origin [17] as soon possible with km-cube-detectors deep under the sea or under polar ice. As most likely π-meson daughters, their direction would point toward sources of extreme-energy protons.

Even though the question is not fully settled yet, present results on neutrino oscillations seem to point at mass difference squared which are of the order of 10^{-3} eV^2 (or 10^{-5} eV^2) and to maximum mixing [16]. One may argue that their actual masses should be also of the order of 10^{-2} eV. This deprives them of any big role in dark matter, the elusive axion being left as a possibility for hot dark matter [5].

The question of supersymmetric particles has long been a hot topic in particle physics [5] but they have so far resisted discovery. In the framework of a Grand Unified Theory (GUT), they are expected to provide needed cancellations among radiative corrections without which the masses of the weak vector bosons and that of the still elusive Higgs boson could be driven up to too high values. In order to meet that task their masses should be between 100 GeV (the present lower experimental limit) and 1 TeV (a value where radiative corrections extending to the GUT scale should start becoming embarrassing without the compensations offered by supersymmetry). They are hard to avoid in attempts to bring gravitation together with the other forces, as it is the case with superstring theory [5]. Observing supersymmetric particles (sparticles) would indeed be a strong experimental encouragement to superstring theorists who still cannot advance any prediction at the present experimental energy scale of a few hundreds GeV. The possible role of sparticles in astronomy brings us back to dark matter. Whereas the cosmic density of the stable sparticles could be relatively low as compared to that of protons, their heavy masses could still make them an important contender for the cold dark matter part of the Universe. Survivors of the Big Bang, they hardly interact with ordinary matter since this implies the exchange of a very heavy sparticle. They would be seen as WIMPs (Weakly Interacting Massive Particles). Despite ex-

tensive searches with underground detectors, there is no convincing evidence of their presence [18].

One may also mention two elusive candidates provided by particle physics and which could also contribute to dark matter. There are the very massive monopoles (at the GUT scale (10^{16} GeV)), which could come from a domain separation in the breaking of grand unified symmetry. They may however be irrelevant, if the early Universe went through an inflation period, a scenario that is gaining much currency. The other ones are the previously mentioned axions. The axion was invented to provide a dynamical explanation for the lack of violation of CP invariance in strong interaction, when it could most generally occur otherwise in the framework of non-perturbative quantum chromodynamics. Axions, if they exist at all, could however remain invisible because of their vanishingly small interactions [5]. Monopoles and axions have been extensively searched for, but, so far, to no avail.

According to the cosmic convergence found with the standard Big Bang scenario, we think that most of the matter in the Universe is dark and that only a fraction of that dark matter is likely to be of a known type (baryonic), the dominant remainder being of an hitherto unknown nature since neutrinos cannot play a big role.

Dark matter should have normal gravitational interactions, since gravitation is universal, and gravitational lensing is indeed a promising approach when searching for this missing component of the Universe. It was once thought that the halo of galaxies could contain a significant amount of dark baryonic matter and, in particular, in the form of non-radiating stars. They were called MACHOs (Massive Compact Halo Objects). Their presence can be seen through their providing gravitational lensing to bright background objects in the Magellanic cloud [10]. Even though many dark objects of that type have been found, they are definitely neither numerous nor massive enough to amount for what is needed. Velocities measured in the outer parts of the galaxy imply a large amount of matter in an extended non radiant region referred to as the halo,

and this is where they were searched for. At the same time, gravitational lensing on the cosmic scale has provided evidence for very large dark structure and in particular one with 10^{15} solar masses, corresponding typically to 10^4 galaxies [13]. It has also been realized through the study of X-ray emission that there is nothing like a well-defined halo for each galaxy with empty space in between them, but that dark matter seems to fill clusters of galaxies. As previously said, the analysis of cosmic shear and the dynamical analysis of these clusters have provided an independent estimate of 0.3 for the global matter contribution to Ω in relation (2), as shown on figure 3. The prevailing view is that dark matter first organized itself in filament-like structures with galaxies appearing at the nodes [1].

With MACHOs out of fashion and now in search for a non-baryonic component, one is focusing on WIMPs (Weakly Interacting Massive Particles) with stable sparticles offering possible contenders. As previously said, nothing has been seen so far and the search for such massive neutralinos continues.

2.5 Gamma Rays and Extreme Energy Events

High energy events appear in a variety of ways. Cosmic photons of very high energies have been seen. They originate, some of the times, in bursts of gamma rays and they often come from well-localized sources [19]. As a minority component of cosmic rays they are particularly interesting, since their voyage to the detector has been unaltered by galactic and intergalactic magnetic fields. Understanding their origin is a fascinating astronomical problem. They bear witness to the fact that parts of the cosmos are natural realms for high-energy phenomena. It is not surprising that some particle physicists are now tuning their detectors to high-energy cosmic photons, on the ground, but also in space. In the latter case, the GLAST (Gamma ray Large Area Space Telescope) project is very promising [10,11]. A NASA mission, GLAST was proposed and is constructed by particle physicists from America and from Europe. It stands as a great in-

strument for cosmophysics.

Gamma ray bursts could be the most violent events ever seen in the Universe. A beautiful example of serendipity since discovered while looking for something else (nuclear tests in the atmosphere) they are gigantic cosmic explosion. Those now observed with present means occur at the level of one per day and the energy output could reach that of a million supernovae. It is usually beamed but with isotropic emission the energy release could reach up to the equivalent of a solar mass. They last from seconds to minutes, with millisecond spikes. They appear at random in the sky, something natural since they are known to be at cosmological distances ($z = 1$ to 2 and up to 4.5) now that X-ray and visible-light afterglows could be seen and associated with a host galaxy of high red shift. The emitting fireball has an ultrarelativistic bulk motion with gamma factors of 100 to 1000 [19]. The host galaxy (typically a blue compact one) is usually excited with important star formation. With present effort soon to pay off (SWIFT satellite for detection and the VLT and KEK telescopes for the quick study of the afterglow, they should be better analyzed and observable up to $z = 12$.

Very energetic Gamma ray burst could result from the merging of very massive black holes as those present at the center of galaxies, with galaxy collisions being frequent at high z in a much denser Universe. They could also be associated with giant supernovae called collapstars. In both cases, they should emit strong pulses of gravitational waves.

However, as advocated by A. Dar and A. de Rujula, some Gamma Ray bursts could be of much lower energy but very strongly beamed, and correspond to the early stage of a 1 A supernova.

In the range 100 GeV to 10^9 GeV, the atmosphere is a natural part of a good detector, which comes for free. It produces extensive air showers, which can be analyzed with large arrays on the ground. A decade ago, the brain storming exercise carried about cosmic-ray studies on the moon by ESA (Lunar Science Study Group), did not lead very far since big proposals on the ground, under-

ground or underwater, which were still in search for funding, looked economically far more promising. However, satellite studies were still limited by rate to about 1 GeV and it was recognized that a relatively modest gamma-ray detector on the moon could cover the interesting range extending from 1 GeV to 1 TeV, for which the detectors existing at the time were blind. Progress in space technology has however since allowed one to cover it on satellites. The EGRET satellite [11] covers the 50 MeV to 30 GeV range and the GLAST (Gamma project, which will be launched in 2005, will cover the 10 MeV to 1 TeV range (300 GeV for sure). The sensitivity of GLAST will exceed by a factor of 50 times that of EGRET and its angular resolution by a factor of 5 to 100 times better, reaching 20 arc second under best conditions. GLAST is a wide field imaging telescope [10].

There are plenty of challenging sources to analyze. For instance, GLAST will study up to 200 gamma-ray bursts per year and analyze the time evolution of flares from active galactic nuclei. It will study pulsars and X-ray binaries and extra galactic-sources, referred to as blazars [1]. Its accurate positioning will be a cardinal asset. It will analyze the emission of supernova remnants and therefore check the present model for cosmic ray acceleration up to 10^6 GeV.

AUGER [11], with its extensive ground-based arrays, is also a great example of cosmophysics research. It also originated with some particle physicists and eventually attracted many more of them. It will allow the observation of cosmic rays of extreme energies. Indeed, a very challenging question under the heading of extreme energies is that of the few cosmic-ray events, which have been observed with energies above 10^{11} GeV [20]. Ultra-high-energy cosmic rays should, in principle not be seen beyond the Greisen-Zatsepin-Kuzmin limit of 10^{11} GeV, since the microwave radiation background should act as a wall at higher energies. Nevertheless a few well established events have already been seen [21]. This was achieved in experiments with 100 km^2 coverage. The nature and origin of

these particles is a great puzzle. They could be heavy ions (iron) produced relatively nearby (closer than the Virgo cluster) [21] but more exotic origins have been proposed, such as there being daughters of Z produced in neutrino-neutrino collisions [1]. In that latter case, the production rate would take benefit from the non-zero mass of the neutrinos in the cosmic neutrino background, this raising the centre of mass energy. This is a challenge.The primary energies are such that the observation rate is down to 1 particle per km^2 per century and observing thousands of them requires a very large detector [10].

Indeed, the primary rate falls from 1 particle/ m^2/s at (1000 GeV) to 1 particle/km^2/day at (109 GeV), roughly like the inverse cube of the energy. Reaching for very-high-energy cosmic rays thus calls for very extensive detectors. The present AUGER project, with its detector arrays covering altogether 3.000 km^2 soon to be completed in Argentina, is very promising for the study of the top energies in that range, about which little is known [21].

The EUSO (Extreme Universe Space Observatory) project [10, 22] would meet that challenge. Installed on the ISS (International Space Station), the detector would survey an area of about 100.000 km^2 of the Earth's atmosphere and detect cosmic-ray interactions beyond 10^{11} GeV through the UV luminescence, which they produce. The signal can be disentangled from those expected from other sources such as gamma-ray bursts. The part of the atmosphere under watch is equivalent to a detector of 10^{13} tons. The observed development of the shower would distinguish hadrons from neutrinos. The systems used in the detector benefit much from recent developments triggered by the LHC, the Large Hadron Collider, a 14 TeV proton-proton collider under construction at CERN.

One looks forward to the detection of very high energy neutrinos using Km^3 detectors under water (ANTARES) or under the polar ice (Ice Cube) as possible in a few years [17].

2.6 SEARCH FOR ANTIMATTER

Cosmophysics also includes searches for antimatter in space.

The very high temperature during the Big Bang, which first fell as the square root of the time elapsed since the beginning, implies a young Universe where matter and antimatter were present in equal amounts. However, all antiquarks disappeared at 10 microseconds and all positrons at 1 second and all that remained was a small excess of matter over antimatter (one part per billion), which is expected to have resulted from conditions met at the end of the GUT (Grand Unified Theory) era (circa 10^{-38} s.) The present Universe, indeed contains over a billion photons per proton which were left by the early annihilation of matter with antimatter and red shifted by the expansion.

The story could, however, have been more complicated and antimatter could remain dominant in some parts of the Universe. This would have resulted in the formation of antihelium during the first 200 seconds and of heavier antinuclei produced through the evolution of antistars. Searchers for antimatter at the cosmic scale have been conducted by looking for the gamma-ray annihilation line of positrons against electrons, but with no result so far. Current accuracy levels brings any antimatter density in the Universe down to a value of less than 10^{-4} of that of matter; ant this over the whole visible Universe [23]. The collision of a galaxy with an antigalaxy is expected to be a slow process since a hot radiation buffer quickly prevents their interpenetration and rapid annihilation. There is plenty of time to check for electron-positron annihilation and nothing is seen. Nevertheless, it is always worthwhile to push down a limit by several orders of magnitude and, may be, detect a signal. The AMS (Alpha Magnetic Spectrometer) project will push down the antihelium over helium ratio from 10^{-6}, which it already reached on a Shuttle flight in 1999, to 10^{-9}, which it will achieve when installed on the space station after 2002 [24] (Fig. 4). Antiprotons and positrons are present among cosmic-rays primaries,
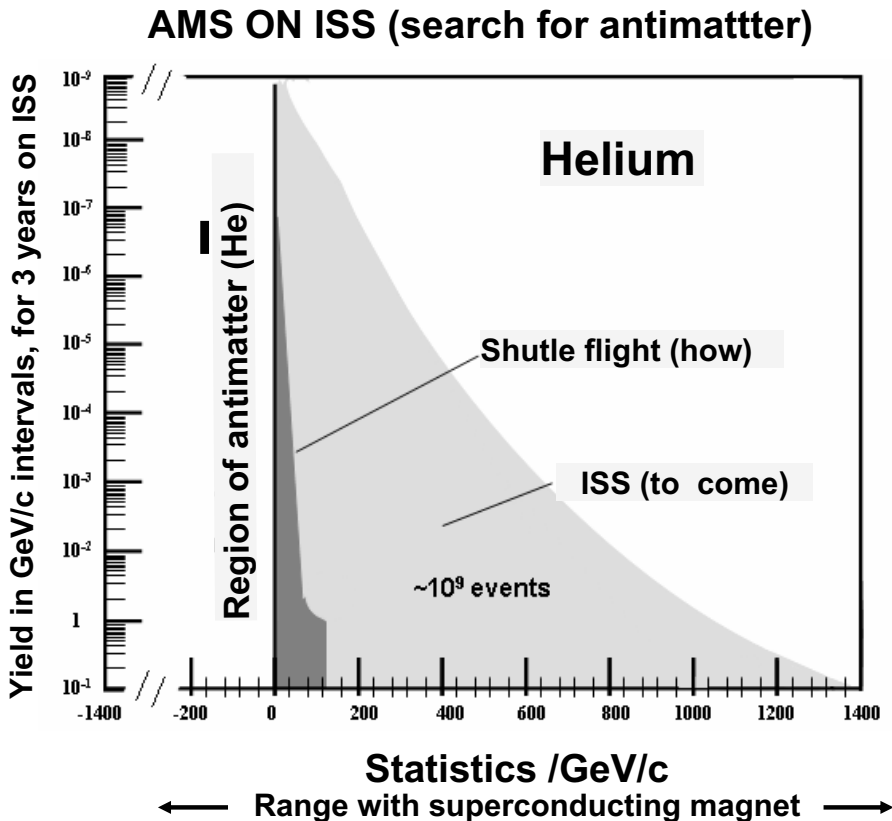
AMS ON ISS (search for antimattter)

Fig. 4 – The AMS detecting power for antihelium during the Shuttle flight (dark area) and as it will be on the ISS [10].

but they are expected to result mainly – if not entirely – from proton collisions with interstellar dust. The jackpot would be finding antihelium and, even better, anticarbon as evidence for antistars.

Searching for antimatter in space with such accuracy and over a wide energy range (up to 100 GeV), calls for a sophisticated particle detector. AMS is a NASA mission but prepared, constructed and operated by particle physicists from America and Europe and all over the world [10,11]. This research is again a clear part of cosmophysics.

The Shuttle flight of AMS in 1999 has already provided a host of interesting data about cosmic rays up to 10 GeV, observed at an altitude of 400 km altitude. The Earth acts as a shield for high-energy protons (over 6 GeV) and they come only downward but, at low latitudes (higher magnetic field),

one finds as many upward as downward protons among those of lower energies (up to 6 GeV) that have all been trapped in the Earth magnetic field. The positron over electron ratio is found to be of the order of 3 but this follows most likely from the relatively abundant production of $\pi+$ in proton-proton collisions. The first experiment used a permanent magnet. Flying a very sophisticated detector with a superconducting magnet, as in the space station version to come, will be a great première [24].

2.7 IN SEARCH OF GRAVITATIONAL WAVES

In much the same way as the acceleration of a charge gives an electromagnetic radiation which propagates in a transverse way at the speed of light and with a field value decreasing as the inverse of distance (and energy flux decreasing like its square), the rapid de-

formation of a massive object produces gravitational waves with similar global properties. This is a consequence of Einstein's theory of General Relativity. Gravitational waves propagate as ripples on the fabric of space-time, which is locally curved by the presence of masses. Since gravitation couples the same way to all forms of energy, and since waves are associated with the rapid changes of shapes, the simplest form of gravitational radiation is of a quadrupole type and not of a dipole one as in the case of electromagnetism. The latter distinguishes between charged and neutral particles whereas gravitation affects all particles and they all behave the same way in a gravitational field according to the equivalence principle. One therefore needs a tensorial relation to connect a displacement due to the passage of a gravitational wave at a particular space-time point to a different displacement at an other one (a tidal effect). This tensorial relation is all that is allowed by the universality of free fall [25]. Such a difference in displacements can be measured as the wave encounters a detector sensitive to tiny relative displacements as a laser interferometer, and the detected signal will follow the periodicity of the wave.

Let us consider a dipole made of two opposite charges which separate at constant velocity, one being kept at the origin. There should be no net physical effect according to relativity and no radiation can be associated with the first (and only) time derivative of that dipole. The same applies to the second derivative of a quadrupole made of objects which separate at constant velocity. Whereas the electromagnetic flux is therefore proportional to the square of the second time derivative of an emitting dipole, the gravitational energy flux is proportional to the square of the third time derivative of an emitting quadrupole [25]. The collapse of a supernova may result in an important quadrupole change within a few milliseconds. The rotation of a massive binary system provides a periodic change of its quadrupole with a typical frequency of 10^{-3} Hz and that over millions of years. They are both likely sources of gravitational waves. In the latter case the evolution of the Hulse-Taylor binary fits perfectly with what

is expected from gravitational radiation.

The difference in displacement l between two points separated by a distance x is related in a tensorial way to the wave amplitude which produces it. One may however refer for the sake of simplicity to a linear relation, with a wave amplitude h defined as dl/dx. Tiny differences in displacement can be measured by laser interferometry and h can be detected down to values of 10^{-22} to 10^{-23} [23,26]. With such sensitivity, a host of expected sources could be detected whereas they were, so far, out of the reach of existing detectors. Detectable waves carry much energy (as much as that received with the light of the full moon) but the fabric of space-time is very rigid and the detectable effect is exceedingly small.

In order to estimate the value of h which is expected from some sources, one can consider a self-gravitating mass M with size R. It has a typical frequency:

$$f = \left(\frac{GM}{R^3} \right)^{\frac{1}{2}} \qquad (3)$$

The energy flux, which is received, is proportional to the square of the frequency times h^2 and h thus relates to the second time derivative of the quadrupole moment. In relations (3) and (4), the ''proportionality'' wiggly sign means ''same order of magnitude''. The amplitude h is proportional to the gravitational constant G. It is inversely proportional to the distance from the source r and, as just said, proportional to the second time derivative of the quadrupole moment. The presence of these three terms is fairly obvious. The velocity of light is taken as unity; and this is actually all there is to it. One can then estimate the time variation of the quadrupole moment from the size R and the typical frequency of the source, and one easily reaches the most interesting relation [27] at the order of magnitude level.

$$h = \left(\frac{GM}{rc^2} \right) \left(\frac{GM}{Rc^2} \right) \qquad (4)$$

It gives h as the product of two terms. The first one is the gravitational potential of the source and

the second one is its compactness. If one explicitly introduces the velocity of light c, as done in relation 4, both terms carry a c^2 factor and they are then dimensionless, as h is by definition.

Unless the compactness is high (0.5 for a black hole),the amplitude is therefore small as compared to the gravitational potential created by the source. One thus gets the image of ripples on the fabric of curved space-time, already referred to twice. Indeed, the compactness factor may often be only of the order of 10^{-6}, even for a compact binary.

The flux can then be easily calculated from (3) and (4), bringing the different terms together. One finds that it is proportional to the fifth power of the compactness [27]. This shows that black-hole or neutron neutron-star formation or their merging are very favourable sources, whereas stable compact binaries could seem to be out of reach. This is however not the case since one can rely on their periodicity to reach much lower values of h, actually gaining a factor $n^{1/2}$, where n is the number of rotations which can be studied [27]. This provides an effective (much increased) value for h which is the one to be matched by the sensitivity of the detector. If there would be no problem with observation time, the number n would be the larger the weaker the radiation (or the compactness) is, since high compactness increases the flux and reduces the lifetime. In practice, the observation time will be very much shorter than the lifetime of a binary (hundreds of millions of years) but there is anyway a compensating effect thanks to which the relation between the overall recorded signal and the compactness of the source is much reduced. Compact binaries in the galaxy are thus also observable with effective values of h ranging from 10^{-22} to 10^{-20}, and this even if these binaries have a relatively small compactness.

There are different sources of gravitational waves. They can come in bursts. This is the case for a supernova collapse and for a binary coalescence, ring down and merging. A typical frequency in both cases is 10^{-3} (Hz), which the binary ''chirps'' through when it radiates most strongly as it rings down and coalesces. For black-hole formation or

merging, the typical frequency is inversely proportional to the mass and is of the order of 10^4 Hz at the Chandrasekhar limit, ie the mass above which black hole formation can no longer be stopped by Fermi pressure. This means a typical frequency of 10^{-3} Hz for a black hole of 10 millions of solar masses. These massive black-hole effects extend over months or years.

Waves can be periodic as those emitted by compact binaries. The typical frequency then ranges from 10^{-5} to 10^{-2} Hz.

They can also be stochastic such as the gravitational noise due to the superposition of many binary emissions, that which was left by the Big Bang or that due to cosmic strings passing through.

There are other potential sources but these few illustrate the possibilities offered by present and designed detectors.

A key point is that one should distinguish a high frequency range (circa 10^3 Hz) where one finds sources stemming from a supernova collapse and the end stage of compact binaries. This is accessible to ground-based detectors which can be screened from noise at frequencies greater than 10 Hz, but not below. These events are very rare in our own Galaxy (at most a few per century) and one has to reach for the Virgo cluster with its thousand of galaxies and loose accordingly two orders of magnitude in amplitude as measured on the Earth.

At low frequencies (i.e. around 10^{-3} Hz), one finds the regular emission of compact binaries and phenomena associated with very massive black holes (having tens of millions of solar masses) such as those, which exist at the centre of most galaxies. This should therefore be a frequency range accessible only with a detector in space (10^{-1} to 10^{-4} Hz) and this is the range of the LISA project, which should be launched circa 2010 as an ESA-NASA mission [26]. Wave lengths at such frequencies may range up to many millions of km and the LISA space interferometer has, accordingly, arm lengths of 5 Gm. The proportionality between the measured relative displacement and h times the arm length holds only if the latter is small as compared to the wave-
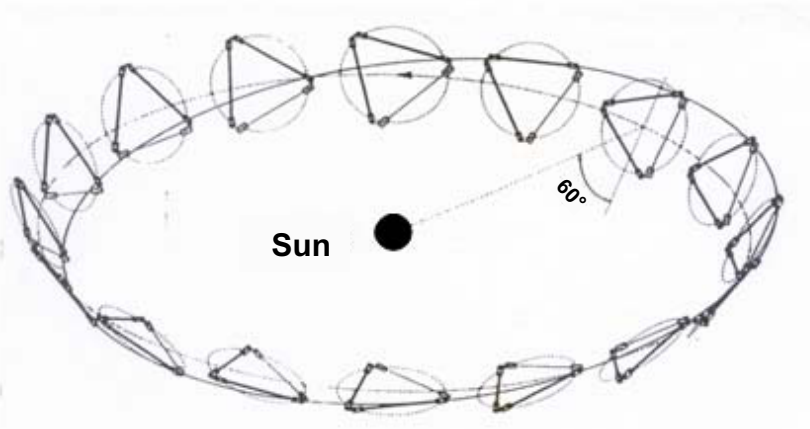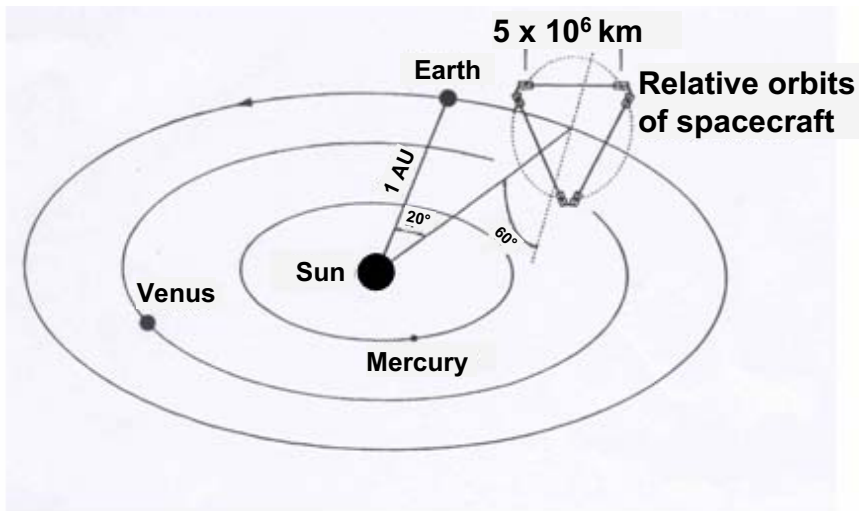
Fig. 5 – The LISA interferometer, which ''tumbles'' as it orbits the Sun, trailing the Earth by 20 degrees on the same orbit. The 60-degree inclination of the plane of the interferometer with respect to the ecliptic is chosen to minimize the relative displacement of the 3 spacecrafts, which follow similar, but different orbits that are slightly inclined against the ecliptic. The tumbling varying orientation of the plane of the interferometer will help in determining direction and polarization. The size of the detector is not in scale with the orbit!

length (Fig. 5).

Sources exhibiting a higher frequency are transient ones and assured detection requires coincidence measurement from different detectors to avoid spurious noises. The estimated amplitudes depend much on astrophysics models and the detected signals will have to be checked against templates calculated accordingly. For sources in the lower frequency range, signals extend over long periods of time and one detector is enough. The values of h can be more safely estimated and the observation of gravitational waves stands as a test of Einstein theory that is independent of astrophysical modelling. As shown by figure 6, observations from space and from the ground are clearly complementary. Space offers access to very massive black holes anywhere in the Universe with the detection of phenomena which could not be seen otherwise. It should meet

assured success with the many compact binaries in the Galaxy. Nevertheless, working on the ground is obviously easier and cheaper and this is coming first. There is actually a sizeable overlap between the ground and space research communities and one may look forward to most exciting discoveries within the coming 10 to 15 years.

Detecting gravitational stochastic waves and in particular noise which would be the echo of the Big Bang, would be a great event. However, one cannot predict at which level of h it should be expected. It would extend over both the space and ground windows of figure 6. Observing gravitational waves from objects with high compactness will open experimentally the domain of gravitation in high fields, with its non-linear effects. It can also be shown that the flux received from compact binaries together with its time variation could be enough to provide an independent measurement of their distance [27]. They could turn into interesting standard candles.

Long searched for with no success with bar detectors set to resonate at frequencies of the order of 10^3 Hz, (typical of a supernova collapse), they have triggered long and steady improvement of those detectors, carried out in particle or nuclear physics laboratories. The sensitivity currently reached, which corresponds typically to a value of 10^{-19} for the amplitude of a detectable gravitational wave, is however still not enough for the estimated amplitude expected from frequent or stable signals, which are at the level of 10^{-22} only (figure 6). This is what is expected from promising sources such as a supernova in Virgo (around 10^3 Hz) or a rotating compact binary in the galaxy (around 10^{-3} Hz). Laser interferometry should allow one to reach the required sensitivity level and even exceed it by an order of magnitude [1,10]. Particle physicists have taken a very important role in the conception and construction of such detectors with arms of several km, such as LIGO in America and VIRGO in Europe. One may hope that a signal will at long last be seen within a few years. Among the new interferometer-type detectors at the completion stage, there are also GEO, in Germany, and TAMA, in Japan [1]. However,

such ground detectors cannot be screened from low frequency noises (below 10 Hz) and a space detector is required to detect and study gravitational waves at low frequencies. A generous band width around 10^{-3} Hz is particularly interesting, since, beside compact binaries in the galaxy (which should number in the thousands), it also covers signals from very massive black holes (with millions of solar masses), which are known to exist at the centre of most galaxies [28]. The achievable sensitivity is such that merging of such black holes could be detected anywhere in the Universe (up to high redshif values). The observation of gravitational waves is expected to open a new window in astronomy, much as radioastronomy did in the past. However, their existence and study also clearly connect to fundamental physics. Observing them is a test of Einstein's gravitation theory. Studying them will, at times, give access to gravitational phenomena in high fields about which no observational information is yet available and where advancing predictions is still a great theoretical and computational challenge. Indeed, the dimensionless parameter (compactness), which characterizes that regime, is of order 1 for a black hole (0.5 to be precise) whereas compactness is of the order of 10^{-6} only for compact binaries or for the Sun. This factor tells us how the dimension of an object differs from its Schwarzschild radius. The study of gravitational waves should soon become an important component of astroparticle physics and cosmophysics.

Back in the seventies of the 20th century, a panel on fundamental physics in space chaired by Hermann Bondi had recognized the great value of the observation of gravitational waves in space but had to admit that the needed technology would rather be that of the 21st century. This enabling technology is now within reach and should be soon tested in free flying conditions. This includes in particular the so-called drag-free conditions which provide for the test masses to always be in free fall [23].

Drag-free systems also make it possible to test gravitation theory to unprecedented accuracy. In particular the equivalence principle should soon be
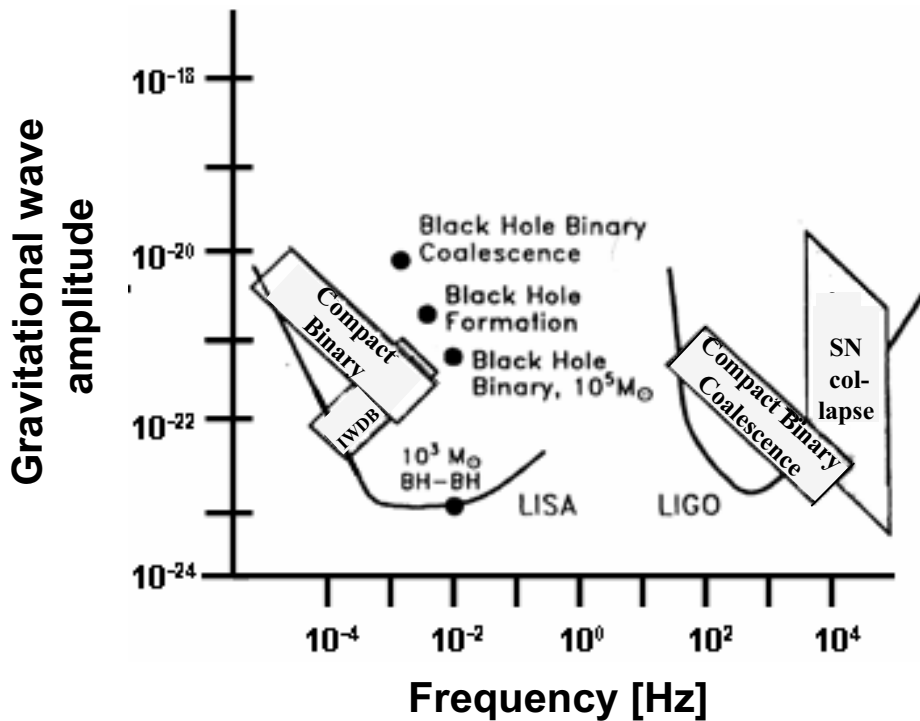
Fig. 6 – Detection efficiency (effective h versus frequency) of the space detector (LISA) and ground based ones under construction (VIRGO, LIGO). It also collects values of h expected from some promising sources, like massive black-holes (taken at $z = 1$) compact binaries in the galaxy and supernovae taken to be in Virgo.

tested at a level a million times better than the one presently available, which is of the order of 10^{-12} [10]. This is the goal of the STEP proposal (ESA/NASA). Somewhat earlier, the MICROSCOPE mission (CNES) should reach 10^{-15} [29]. The post-Newtonian parameters of Einstein's theory could also be measured with a precision better than one part in a million, when the present limit is 10^{-4}. This is in particular the case for the parameter gamma which relates the presence of masses to the curvature of space-time [30]. Tests have been proposed but no mission has been yet seriously considered along that line.

The NASA mission Gravity Probe-B [1,11] should soon test the frame dragging due to rotating bodies (the Lense-Thirring effect), which is predicted by Einstein theory. All these tests of gravitation theory belong to fundamental phsics in space

and more generally to cosmophysics. Gravity Probe A was already flown on a rocket 25 years ago. It tested (to 70 parts per million) the change in the flow of time associated with the earth gravitational potential.

We have thus attached to cosmophysics an important part of what is usually referred to as fundamental physics in space [11,23]. The latter, however, comprises more since we left aside its condensed matter physics part (in particular, the study of helium superfluid transitions) and its atomic physics part (in particular the study of Bose condensates and atombeam-interferometry). They all can be studied with high precision under microgravity or, even better, free-fall conditions [11].

In the case of microgavity conditions, as provided by the ISS, the conception and construction of better clocks is also an important asset for cosmo-

physics. Caesium (and rubidium) clocks and hydrogen masers flown in space will increase present clock precision by at least an order of magnitude. This is in particular the goal of the ACES (Atomic Clocks Ensemble in Space) project for the Space Station. Precision clocks in space represent a key enabling technology access to many precision tests of gravitation and to checking the assumed constancy of fundamental entities such as the fine structure constant [1].

3 CONCLUSIONS

The topics which have been thus selected to illustrate cosmophysics bring together many exciting results and carry great hopes for the near future. What is most impressive is the consistency of all the data with the standard model of Big Bang cosmology, but with a new and surprising result about the vacuum energy density, which looks like a revenge of the steady state picture! Angular coverage and accuracy are still often limited and the conclusions drawn certainly call for further tests and perhaps new ideas. At the same time, new detectors are soon to open new windows or improve greatly on present accuracy.

Cosmophysics was born from some great challenges offered by the study of the cosmos, which cut across standard disciplines, and from the recent developments in instrumentation, which make such studies possible with unprecedented accuracy and efficiency. Many high-energy physicists have turned to this research making use of recent progress in instrumentation brought by particle physics research on accelerators. Among them, one may mention: the time projection chambers, the silicon detectors, the hardened electronics, the bolometers, new photomultipliers, cryogenic detectors, but one should also mention simulation programmes like GEANT and new data-acquisition and data-handling techniques. There are also the construction skills for very large or very compact detectors. This is not the place to describe this in any detail [1,10]. Many particle physicists are introducing these new detection techniques, strengthening the present revival of cosmic-ray research. This research is still largely conducted on the ground or underground/underwater but it is increasingly turning to space, benefiting in that case from recent progress in satellite construction and operation.

It is clear that the core of particle-physics research will remain anchored on accelerators and the LHC stands as the promising machine for many years to come, with thousands of users. The present challenges of particle physics are best met that way and cosmophysics can represent but a complementary approach to some of them, such as the properties of neutrinos and the possible presence of sparticles. But cosmophysics offers great challenges of its own and, whereas the migration towards space-oriented projects implies many researchers, it is to be seen in terms of particle physicists turning to space (experimentalists and theorists) far more than in terms of particle-physics questions, which could be better studied in space or with cosmic rays.

Some particle physicists did turn to space-oriented research when tired of the very large collaborations, which have become the rule with accelerator-based research. They have however quickly discovered that cosmophysics also calls for important international collaboration on a large scale, and they now often miss the flexible administrative umbrella, which they had long taken for granted as users of CERN. It is important for them not to loose contact with the laboratory as it is important for CERN to remain a focal point for this research. Cosmic-ray research was actually listed long ago among the missions of the Organization. The concept of ''recognized experiment'', which has been recently implemented, follows such lines. It allows approved astroparticle physics – or now cosmophysics – experiments to feel at home at the laboratory even if they do not benefit from any funding from the Organization. This is already the case for AMS, AUGER and LISA. Others will certainly follow. In the United States, the large particle physics laboratories and in particular Fermilab and SLAC also conduct cosmophysics research.

RESUMO

''Cosmofísica'' é um campo multidisciplinar de pesquisa
que abrange física de astropartículas, física fundamen-
tal no espaço e tópicos relacionados com a estrutura e a
evolução do Universo. Representa uma interface cada vez
mais importante entre física das partículas elementares a
altas energias e astrofísica. Neste artigo é apresentada
uma revisão geral do assunto, com foco em cosmologia,
raios cósmicos, matéria preta e ondas gravitacionais, que
se espera que sejam detectadas em futuro próximo.

Palavras-chave: astrofísica, cosmologia, ondas gravi-
tacionais, pesquisa espacial, Universo (estrutura e evo-
lução).

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about their goals. They are described in details in
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we can be here to observe it. This tenacious myth is
neither quantitative nor falsifiable and does not teach
anything new. Nevertheless, it has gathered new mo-
mentum within a framework where many different
universes could have been born, or even within a sin-
gle Universe where widely differing domains could
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