Fundamental physics in space is a new field. It comes on the map today and should have a brilliant to morrow. Experiments on spacecrafts make use of conditions which are not accessible on the ground. One can thus detect and explore new and exciting phenomena to which we are presently blind because of overwhelming backgrounds or because of the lack of proper detecting devices. At present, the most promising developments have to do with the possible detection of gravitational waves as predicted by Einstein’s theory of General Relativity. Detecting gravitational wave in space (at low frequencies) could probe the physics of very massive black hole and unveil the most violent events in the Universe. Whereas this space science is driven by pure research it is very interdisciplinary in character, borrowing much from cutting edge techniques and motivating enabling technologies with different future uses. The subject is therefore well suited to this conference and the more so that this research has to be international in order to find its needed support. Portugal is well present in the AMS experiment which will search for antimatter in space. This experiment will be installed on the Space Station by 2002 and had a first test run recently on the Space Shuttle, through which NASA and Portugal could jointly celebrate the 500th anniversary of the discovery of the sea route to India by Vasco de Gama.

1-Fundamental physics from space and in space.

At present, one notices an increasing interest in fundamental physics related to space. Indeed, the study of particles from cosmic sources appears to provide most interesting clues for questions originating from particle physics on accelerators as well as from astrophysics. A new field of investigations was born and is referred to as Astroparticle physics. Many particle physicists are turning to it. Some laboratories in particle physics are even concentrating a sizeable fraction of their activities on this new domain. This may look peculiar since cosmic rays, which had long provided the only sources of very high energy particles, had been almost abandoned in the fifties for accelerators which could provide intense sources of high energy particles produced under specific conditions. These accelerators, and now colliders, have allowed one to collect impressive statistics on particle collisions at ever increasing energy and this has resulted in a good understanding of the deep structure of matter. At CERN, the LHC will soon
open the multi-TeV domain (14 TeV in proton-proton collisions) and should provide instrumental clues in our answering many fundamental questions. Particle physics on accelerators is still very much alive and, as a Member of CERN, Portugal is fully involved in this great endeavour. Particle physics on accelerators and astroparticle physics are very much complementary.

Progresses in particle physics, through now already four decades of accelerator based research, have lead to a much better understanding of the structure of matter. This has revealed the quark structure and culminated, with the Standard Model, in a detailed and accurate description of all observed phenomena. This accelerator based research has also provided a much better understanding of the Cosmos at large, and in particular of what happened just after the Big Bang. This has in turn opened to investigation new and fascinating questions. As we understand the universe better, we realize that the shining mass, which is associated with radiant stars, is probably only a few per cent of the total mass in the Universe. The search for "dark matter" has thus become a great challenge. Clues are looked for with accelerator physics but also from space. Whereas the Big Bang was the most violent event ever, the present Universe, observed outside of the visible spectrum, also provides multiple examples of violent phenomena, producing very energetic particles.

We here illustrate present trends with three very different examples, namely cosmic neutrinos, antimatter search and high precision atomic clocks.

Neutrino physics, as now well understood with accelerators, provides a unique way to study cosmic phenomena through particles not affected by their long journey through space and also to look in the interior of the more quiet stars. Several underground (or underwater) detectors have been built, and more ambitious ones are being constructed, for the primary rôle of studying cosmic neutrinos. In Europe, for instance, there is the important Italian lead Gran Sasso laboratory, already busy with many experiments which correspond to large international collaborations. As well known, the Gallex experiment there came up with evidence for an electron-neutrino deficit from the Sun. There is also the Swedish lead project Amanda, deep under the South polar ice-cap, searching for very energetic neutrinos. There are also several other very big projects at the world scale.

Indeed, the results from SuperKamiokande, in Japan, have recently triggered a great interest. It seems that there is a deficit in muon-neutrinos among those which are created in the atmosphere by cosmic ray protons which produce π-meson through their collisions with atmospheric nuclei. These π-mesons, when not absorbed, decay almost exclusively into a muon and a muon-neutrino. The SuperKamiokande detector does not detect as many of them as Monte Carlo predictions predict, as if these neutrinos were turning into other types of neutrinos.

The Standard Model has only massless left-handed neutrinos and this does not allow for oscillations among different neutrino species. Evidence for oscillations would imply that the theory is only part of a larger one where
massive right-handed neutrinos could exist and where the neutrinos would have a very small but non-zero mass. On the other hand, there are so many neutrinos left from the Big Bang that, with a 30 eV mass for the heaviest specie, one would have an high enough energy density to close the Universe.

The KamioKande results show a bigger effect for neutrinos produced on the other side of the Earth and coming upward into the detector than for those coming downward. This implies that the mass difference between the different neutrino species (in that case most likely the muon and tau ones) would be very small, around 1/30 eV and that mixing would be strong.

Whereas much work is still needed, increasing the statistics, analyzing the data and refining the production model, this illustrates very well the extreme interest of astroparticle physics.

This example illustrates particle physics from space. An other example, illustrating this time particle physics in space, is the AMS experiment which, as previously said, had its first test flight on the Shuttle. We do not expect that any anti-matter remains from the Big Bang. Whereas the excess of particles over antiparticles was only one in a billion at the beginning (as a result of grand unification and CP violation in the early exploding Universe), we think that all antiquarks disappeared against quarks when the Universe was 10^-5 second old and that all the positrons disappeared against electrons when it was 1 second old. This should be checked. One should of course find many antiprotons and positrons resulting from collisions of high energy cosmic particles against interstellar dust but is there an excess? Finding anti-Helium would bear witness to some remaining antimatter from the Big Bang and finding anti-Carbon would imply the existence of anti-stars. It is a great challenge to look with high precision, as possible with a spectrometer in space.

Bulks of matter and antimatter, if they exist at all in the Universe and would some of the times be brought into contact, would not annihilate with a violent explosion. The correct metaphor is that of droplets of water on a hot stove which are protected from instant evaporation by a cushion of vapour. A cushion of very hot gas in the zone of contact would similarly impose a slow annihilation process with the long term production of gamma rays of 500 KeV associated with electron-positron annihilation. This has been searched for and not found, up to the super cluster level. A value of the order of 10^-4 is the present upper limit for the antimatter over matter ratio. This is also close the limit of 10^-5 for the antiHelium over Helium ratio already set by short term experiments with balloon flights. The AMS experiment will bring this ratio down to 10^-9 or find something. In any case precise data on antiprotons, positrons and energetic gamma rays in space is of great astrophysical interest.

An other very interesting aspect of fundamental physics in space is the development of atomic clocks in orbit. The present precision of the highly sophisticated laser cooled Cesium clocks (10^-5 over a day) is limited by the fall of the Cesium atoms in the earth gravitational field, an effect minimized in the fountain-clocks. In free fall, the precision of the clock should be
increased by one to two orders of magnitude. Such a clock is part of the approved ACES experiment on the Space Station.

An other important facet of astroparticle physics is the study of gravitation.

The Standard Model still leaves Gravity aside but many physicists are working hard to understand gravity better and to include it in the global study of the basic interactions. We are still far from a quantum theory of gravity, even if superstrings may perhaps already provide insights on what the solutions in such a theory would be. As well known much effort is put along that line, D-Branes and Duality being the hottest topics. But, even at the classical level, collecting evidence for gravitational waves, offers challenging prospects. The study of pulsar binaries leaves little doubt as to their existence as predicted in Einstein's General Relativity. The expected effects are however very tiny. As discussed later, the typical relative displacement effects to be looked for are in the 10-22 range! Detection is therefore extremely difficult. Yet prospects, with new laser interferometers, are high. In Europe there is the Franco-Italian VIRGO detector and a smaller project in Germany, both at the building stage. There is also the LIGO project in America which is already well advanced. Some particle physicists are turning to this research. Sophisticated cryogenic resonating bar detectors have been and are being developed and often in particle physics or nuclear physics laboratories. They now reach a sensitivity of 10-19 and could detect a violent event in the Galaxy.

The cosmos is full of (often erratic) accelerators. The detection techniques and the international collaborations required for experimentation in astroparticle physics bear much similarity with those on particle accelerators. It is therefore natural that many particle physics are turning to astroparticle physics. The funding agencies seem to welcome that. For instance, in France and in Italy, the CNRS-IN2P3 and the INFN respectively, which fund primarily particle and nuclear physics, have already much extend their activities toward astroparticle physics and jointly fund VIRGO, which represents a major investment. In Britain, Particle Physics and Astronomy, have been brought together within a unique funding structure, PPARC, which could be a natural niche for astroparticle physics if the funding envelope were not already very tight. One can easily foresee an important extension of astroparticle physics over the coming decade. It is likely to correspond mainly to earth based research even if it is turned to space. Looking a further decade or two ahead, one can however anticipate that part of this research will be turning from earth based detectors to space based ones. The cost of experiments in space is of course several orders of magnitude higher than on the ground, or even underground (underwater), at equal weight. There are also too many exciting projects on the ground (or underground) which are hard to finance and there is therefore some reluctance to divert some of the available funding to space. However, going to space may eventually become a must in view of the foreseen scientific return.
Indeed, one should say that the results of COBE on the asymmetry of the microwave background have triggered much interest among theorists for which the early universe provides the only experiment at their disposal to test some of their most fundamental theories. There is now a great demand for a much higher resolution than the one provided by COBE. The ESA project, PLANCK, which should fly around 2005-7, should provide that with a two orders of magnitude gain in the angular resolution.

For gravitational waves going to space is a must if one wishes to detect them in their highly promising low frequency band. After its 1994 review, ESA has listed such a detector among its Corner Stones projects for its present long term programme extending into the second decade of the years 2000. The code name is LISA (Laser Interferometer Space Antenna). This will be discussed at some length later. LISA will be the first very big experiment in fundamental physics in space.

Considering fundamental physics in space, one can say that the cost of each experiment will imply a very high specificity. At the same time such ventures will often cut across traditional disciplines in physics and trigger the development of numerous enabling technologies. We already see there a budding but thriving new community of physicists at work.

The relation between astronomy and fundamental physics is interesting. After the success of COBE, the PLANCK mission was classified as an astronomy mission and it eventually met approval that way. It may well be that before COBE, defending such a mission would have been the privilege and task of a fundamental physics advisory group, something which the present one strongly did anyway. It may be that 20 to 30 years from now, the successor of LISA will fall under astronomy, as providing a very precious and unique tool for the observation of galactic compact binaries and of very massive black holes throughout the Universe. But, today, with all the uncertainties attached to such an endeavour, the detection of gravitational waves still falls under fundamental physics. This is actually proper. We are not so much about the detection of gravitational waves which should be certainly detected if they exist, but about understanding their production and in particular in the high field regime.

2-Fundamental physics in space, as part of space research

One may try to anticipate what fundamental physics in space will look like up to two decades ahead using as a guide the ESA’s future long range study. The sophistication and cost of the needed instruments are indeed such that those which may be available by then have already to be discussed today. The ideas and aspirations are those of the scientific community and cover what people are thinking of at present. In 1993, ESA made a call for mission concepts in order to prepare its "Horizon 2000+" programme. This was intended to be a rolling forward continuation of its "Horizon 2000" programme as it had reached mid term. The combination of the two programmes now defines the key elements of space research in Europe, up to many hitherto unknown parameters and in particular the evolution of the budget, with feared possible cuts. Thinking about the distant future (over a decade ahead), one is often not
discussing actual full-fledged proposals, which will probably use a technology still to be developed, but mainly general ideas about what should be attempted and how. One is allowed to dream.

In the context of this conference it is interesting to show how recommendations are made and how projects are eventually selected.

The call for mission concepts referred to resulted in 110 proposals which were presented to a Survey Committee. The proposals were classified and distributed according to 5 general categories and Topical Teams were set up to assess them. These topical teams covered respectively:

1-Moon, Planets and small bodies.
2-Sun, Heliosphere and plasma physics.
3-High energy astrophysics.
4-UV, Optical, Infrared, Radio astronomy.
5-Fundamental physics.

This was the first time that "fundamental physics" appeared so clearly and separately within the ESA planning. There was a need for that. About 30 of the 110 proposals were falling under that heading! Fundamental physics has many facets. Those considered more particularly fell under the general headings of cosmology, gravitation and particle physics. The question of microgravity experiments was reviewed separately, as something which should rather be linked with the space station, considered as a separate entity.

One important element was however later "picked-up" and supported by fundamental physics. It is the now approved ACES project already mentioned, which will combine a laser cooled Cesium clock and an H-Maser clock on the Space Station. This will provide the best clock ever with a precision of the order of at least 10-16 over a day. With the precision achieved gravitational time dilation could become the most precise tool for geodesy!

How does fundamental physics appear within the ESA research programme as a whole?

ESA classifies its missions as "cornerstone", "medium" and "small". A Cornerstone mission is a major one, at the level of up to 600 MEuros, at the present rate. It is also a mission which ESA could carry up all by itself. There is of course the possibility and hope that other agencies could contribute to make it better and quicker but, even if this would fail, ESA would commit itself to do it fully. We see here an interesting parallel with the LHC which the CERN Member States have agreed to build by themselves but hoping that significant contributions by non-Member States will allow to make it better and quicker, as indeed they will.

A medium size mission corresponds to about half the cornerstone value or could be a larger mission in which ESA is only a partner. Small size missions are now prepared to test enabling technologies. They are called "Smart".
There were 4 cornerstones approved in the Horizon 2000 programme. There is the Soho/Cluster complex, with Soho already in orbit for two years and Cluster soon to be replaced after its lost with the maiden flight of Ariane-5. This falls in the area covered by topical team 2. There is Rosetta, a mission to comet Wirtanen, which will fly in 2003. It will follow the comet and send a lander on it. This belongs to the area covered by topical team 1. One also has XMM, an X-ray observatory, which will fly in 1999. It belongs to the area covered by topical team 3. There is also FIRST, a mm-wavelength observatory to study the cold universe. It should fly in 2005-7. It is in the area covered by topical team 4. Each of the first four topical teams had already a cornerstone in their respective domain. Among the cornerstones added for the programme "Horizon 2000+", there is, for the first time, one in fundamental physics. This is LISA, a space interferometer for the study of gravitational waves. It could however fly late. Present budget prospects could indeed delay it much, even beyond 2020. The present attitude is therefore to try to fly it earlier (circa 2010) in the framework of an ESA-NASA collaboration. Future will tell if this is possible. The other two cornerstones are an orbiter mission to Mercury and an interferometric observatory which will provide a 10 microarc-second resolution, respectively. Medium size missions to come include a gamma ray observatory (INTEGRAL) and a Mars orbiter.

Fundamental physics has thus made its entry in the long term space programme of ESA. Over a shorter time scale, one may also now hope for an ESA participation in a relatively small but efficient mission which could test the equivalence principle at the level of 10⁻¹⁸. This is MINISTEP which today appears to be developing well as an ESA-NASA collaboration. It would follow the Gravity-Probe B mission of NASA which will soon test the Lense-Thirring (Magneto-gravific) effect in earth orbit.

The setting up of a specific advisory body for Fundamental Physics within ESA showed foresight. NASA has now followed suite and COSPAR, which runs the world wide conferences on space every other year, has since set up a special commission for fundamental physics. This is Commission-H. The field is born.

3- Fundamental physics in space, as it looks at present.

What is fundamental physics in space now? The best way is still to define it according to the proposal received in 1993. One could define 6 different entries. They are the following:

(i) The detection and study of gravitational waves.
(ii) Precision tests of the equivalence principle.
(iii) Tests of the Newton law and search for new long range forces.
(iv) Qualitative tests of the Einstein Theory.
(v) Particle physics and antimatter in space.
(vi) Search for long range spin dependent interactions.
(vii) Precision clocks in space.
(viii) Testing new technologies needed for the realization of some of the scientific missions falling under the previous entries. Identifying so called "enabling technologies" has indeed much to do with any recommendation.

The outcome of the work of the Topical Team 5 (in 1994) resulted in 5 main points, namely:
(i) Recommending one cornerstone mission associated with the detection of gravitational waves. This is LISA.
(ii) Discussing the relative merits of the space and ground base detection of gravitational waves.
(iii) Highlighting 3 research directions which appeared as particularly promising among those presented in the proposals. They were: the detection of gravitational waves, the test of the equivalence principle at a level 6 orders of magnitude beyond the present limit of 10-12, and the test of the relation between mass and curvature and in particular the spin content of the gravitation interaction, respectively. The test of the equivalence principle now corresponds to MINISTEP.
(iv) Evaluating separately most of the proposals.
(v) Assessing enabling technologies for the missions which were relevant to point (iii). This include high precision clocks in space.

Einstein's Theory introduces 3 post-Newtonian parameters. One of them is alpha, which links the proper flaw of time to the gravitation potential. Another one, gamma, relates curvature to mass and also measures the spin content of the gravitation interaction. Its value is 1 in Einstein Theory which corresponds to a pure spin 2 exchange when considered as a field theory. The possible difference between gamma and 1 could be tested to the precision of 10-7, when the present limit is 10-3. This is important since some theories call for a scalar mixture which could have dropped down with the expansion of the universe.
The test of parameter gamma is still at the level of ideas but Gravity probe-B will allow progress. We thus now concentrate on the detection of gravitational waves.

4- The nature of gravitational waves.

At present one sees the development of a thriving community focusing on the detection of gravitational waves. What are these waves? One can start with the analogy provided by electromagnetic waves. A charged particle with constant velocity does not radiate. The radial pattern formed by the lines of forces travels with it, at the same velocity, and the field strength drops as the inverse square of the distance. If the particle is accelerated during a certain time, the new pattern, as it develops close to the particle, does not match with the old pattern which, at a certain distance, before information which travels at the speed of light has reached there, still points radially where the particle should have been without acceleration. Since lines of force have no end point, the two patterns must connect and they do through flux tubes within a shell which extends outward at the speed of light. Within the flux tube shell the field is proportional to the acceleration of the radiating particle and is
inversely proportional to the distance. The radiation inside the shell is transverse and the energy flux associated with it is conserved. If instead of a single particle, we take an extended object, we reach similar conclusions with a radiated energy flux proportional to the square of the second time derivative of the electric moment. All this is well known.

With this picture for the electromagnetic radiation at our disposal, let us turn to gravitation.

The Sun gravity controls the motion of the earth around it. Conservation of energy and momentum does not allow the Sun neither to disappear nor to change its course suddenly but, according to conservation laws alone, the Sun could change its shape in a very short time, the simplest way being through a modification of its quadrupole moment. The orbit of the earth would eventually change accordingly and would do so in response to a gravity wave emitted as a result of this rapid change. The wave would be transverse and travelling out at the speed of light in much the same way as the electromagnetic wave associated with a rapid change of the dipole moment of a distribution of charges, since the line of force pattern picture which was used as a guide is so general that it should also apply in that case. All that is actually expected in General Relativity.

In the case of a gravitational wave the energy flux should however now be proportional to the square of the third time derivative of the quadrupole moment. It is clear that it should be at least the third derivative that matters. A steady motion, which should be irrelevant to physics in General Relativity, gives a quadratic behaviour of the quadrupole moment with respect to time and not a linear one as for the dipole moment. Only the third derivative can therefore be physically relevant to the radiation process. General Relativity which relates everything to the curvature of space-time, tells us that this is indeed the case. One may heuristically realize that an extra derivative is needed since gravity couples to everything equally. The rapid squash of an object yeilding gravitational waves has to be realized against the squash of another one which will radiate out of phase. The observed net effect results from different reception times of the two signals.

An electromagnetic wave will set charged particles in motion and will ignore neutral ones. One can speak about the acceleration (a vector) felt by charged particles. A gravitational wave will affect all particles. Potential test particles all fall freely and in the same way, following geodesics in curved space-time. The equivalence principle imposes that. As a result gravitation cannot tell us which test particle will be set in motion and which will not; they all will and in the same way. Gravitation theory can however tell us only that, beside free fall for all, there will be relative motions of test particles at different places. They are the result of tidal forces. What is then relevant is only the relative acceleration (a tensor this time) felt by particles at different points.

The wave can be seen as a ripple on the fabric of space time on which the test particles follow their respective world line geodesics. The wave will affect differently particles at different places. If the distance between test particles is small as compared with the wave length the relative displacement (perpendicular to the direction of propagation) will be proportional to the
distance of the test particles. Relative displacement (small) and distance (large) will be related by a dimensionless two indices tensorial relation \( \delta_{ij} \).

Since the source is the variation of the quadrupole moment the wave has a tensorial nature and this tensorial wave will have two different polarization states which are perpendicular to the direction of motion. Test particles initially in a circular configuration are alternatively put in a prolate and oblate pattern in two orthogonal directions as they respond to the passing wave. The two different polarizations according to which polarization is analyzed are 45 degrees apart. In a field theory approach, this is what is expected from the propagation of a massless field of spin two, with two helicity states. We can take test masses as the end points of the two branches of a Michelson interferometer, with a related periodical fringe displacement as the wave passes through with a branch contracting as the other expands and vice versa. Keeping in mind the tensorial nature, we can now forget, for the sake of simplicity, about the indices \( ij \) and speak only about a wave “amplitude” \( h \) which gives the relative displacement at two different points as proportional to the distance between these two points. This is that quantity which, in practice, may be as low as of the order of 10^{-22}, but still within reach of present laser interferometry.

The energy flux will be (for mere dimensional reasons) proportional to the square of the time derivative of \( h \). The wave amplitude \( h \) will then be proportional to the second time derivative of the quadrupole moment the variation of which is providing the source, since we remember that the energy flux is proportional to the square of its third time derivative. For the same reason \( h \) will be inversely proportional to the distance to the source. Granting the fact that the overall constant relating \( h \) to the second time derivative of the quadrupole moment has to be the gravitational constant \( G \), we see already ways to estimate \( h \) from known sources.

We oversimplified matters to the extreme in order to see in an heuristic but consistent way how sources and effects are related. Everything is however in agreement with Einstein theory, which provides all the needed relations to calculate \( h \).

In the past there has been a lot of discussion about the physical significance of gravitational waves, the key point at stake being whether or not they carry energy. With the relations at our disposal we can easily convince ourselves that they do. Let us for instance consider two test particles following parallel world lines (with the same velocity). A passing wave will first bend the two trajectories inward (outward). It will then undo it by bending them outward (inward) but not quite coming back to the initial parallel velocity configuration. Indeed, during the second half of the oscillation the wave finds the test particles slightly closer (apart) and its effect is therefore slightly weaker (stronger) than during the first half of the oscillation. In either case, after the crests and ebbs of the waves have past by, the two test particles will now be slightly converging, a new configuration from which one can in principle extract energy.

There is no doubt about the reality of gravitational radiations and about ways to predict their effects. Detection is within reach since a 10^{-22} effect can
be measured by laser interferometry. We have to detect gravitational waves and we have to analyse the messages which they carry. This is a very rich and complicated physics. We separated the wave (a ripple) from the overall curvature of space time but the wave carries energy and gravitation couples to energy. Gravitation radiation is therefore a complicated non linear phenomena. There are strong complications (tensorial character, non linearity...) not met in electromagnetism. The strong field regime, to be found with black holes, is still widely unknown territory. The analysis of gravitational waves is however the way to learn about it.

Self gravitating objects have typical frequencies and typical velocities which depends on their mass M and their size R. This can be easily calculated in Newtonian dynamics and remains to a very large extent valid in General Relativity. One can thus estimate the value of h associated with their inner motion. As shown by Schutz (see further readings) one finds two key factors in the expression for h. The first one is the gravitational potential at the point of observation GM/r, where M is the mass and r the distance. The other one is the compactness GM/Rc^2 of the system. The latter varies widely according to potential sources. It is of the order of 10^-6 for the sun or for a compact binary system. It is 0.2 for a neutron star and 0.5 for a black hole. The frequency of the emission depends more directly on the density. Since the luminosity of a source is proportional to the square of the time derivative of h, one can derive that it is also proportional to the fifth power of the compactness.

We considered earlier a possible change of the quadrupole moment of the sun as a source of gravitational waves. This is unlikely to occur. However the Sun-Jupiter system represent an ever changing quadrupole moment. The compactness is however very low and the period is very large, the two quantities being obviously related. The power radiated in gravitational waves is therefore very low, of the order of a KW. Compact objects are on the other hand very strong emitters. The energy flux can be enormous (remember the fifth power) but a detector will absorb only a minute fraction of it when it usually absorbs all that it receives in the case of electromagnetic radiations.

Gravitational waves can come in a variety of ways.

We can have bursts.

This is in particular the case for an asymmetric supernova collapse or for the end stage of a compact binary as it chirps, coalesces and rings down. A burst can also be associated with the absorption of a neutron star by a black hole or to the merging of two relatively low mass black holes. The compactness is high. There is a very strong emission. It lasts however but a fraction of a second in the case of a supernova collapse and only about an hour in the case of the coalescence of a binary as the frequency chirps and the radiation rate increases. The typical frequency is 10^+3 Hz but it is inversaly proportional to the mass for a black hole and can go down to 10^-3 Hz for the very massive ones (10 millions solar mass).
We can have a periodic emission.

This is the case for a compact binary (neutron stars, black holes, white dwarfs) in its stable configuration. The compactness is now low but the emission last practically for ever. One can study it over a long time scale and the effective value of $h$ is increased, being proportional to the square root of the number of oscillations which can be registered (see Schutz in further readings). The frequency in that case is typically 10-3 to 10-4 Hz.

Finally there are stochastic sources.

They can correspond to the superposition of many binary emissions which one cannot separate but also and this is far more interesting, to gravitational noises associated with the Big Bang or with cosmic strings. In the latter case the frequency extends over a wide range. The signal is however still unpredictable.

Sources and expected effects are analysed in detail in the contribution of K. Thorne to the book "300 years of gravitation" and also by B. Schutz (see further readings). We here merely quote some of the results. When considering observation limits for $h$, one has to distinguish between burst and stable sources and also the frequency range and the time observation. We shall not go into that technical matter here but merely quote the relevant values which include such effects according to the different cases considered.

We first consider a supernova. Visible ones appear in the galaxy with a frequency of one every forty years. They could be more but, if we wish to have a reasonable chance to see anything during the first year of operation, we have to reach to the Virgo cluster (a thousand of galaxies) and estimate the effect of a supernova collapse there, with $h$ a hundred to a thousand times less than it would be for a galactic supernova. Its value (inversely proportional to distance) is proportional to the square root of the non symmetrical kinetic energy associated with the collapse, which is only capable of creating a quadrupole radiation. It is also inversely proportional to the square root of the frequency. For a frequency of 10+3, at Virgo and with the solar mass as a unit, the overall proportionality ratio is of the order of 10-20. If the non spherical collapse involves only 10-4 solar mass, the amplitude is of the order of 10-22. One therefore sees that the detector should aim at least at that.

Let us now consider forming or coalescing black hole(s). The typical frequency is, as previously said, inversely proportional to the mass. The value of $h$ is proportional to the mass. The Formation of a very massive black hole (10+6 solar mass) will therefore be much more visible than that of a few solar mass one. It is far less frequent at the level of Virgo but one can extend detection much further. The value of $h$ is proportional to the square root of the relative amount of mass involved in the event. If one takes this to be 10-2 and place the event in Virgo and consider a black hole of 10 solar masses, the overall coefficient is 10-20. With the achieved sensitivity such a black hole event should be detected on the ground (10+3 Hz) if 0.01 for the relative amount of mass lost in the radiation happens to be the right order of magnitude. Very massive black holes (10+7 solar masses) should be easily
seen in space, at much lower frequencies and from anywhere in the visible universe.

For binaries the value of $h$ at the coalescing time should be of the order of $10^{-21}$ in Virgo. This should be observable on the ground at high frequencies ($10^{-3}$). Observation should be matched against theoretical templates. The radiation level during their long stable life is much smaller and one has to search in the Galaxy to get as high a value for $h$. The galaxy is probably not big enough to catch a coalescence within one year and one has to watch in Virgo.

Figure 1 shows the expected values for $h$ for some sources together with the sensitivity of LISA. Many sources should be within reach. It also shows the values expected from other sources at high frequencies. They should be within the reach of VIRGO/LIGO.

This illustrates very well the complementarity of ground based and space observations. On the ground one has to focus on high frequency sources ($10^{-3}$ Hz) and one can detect supernova collapse and the violent end stage of compact binaries, or effects associated with lower mass black holes. With a $10^{-22}$ sensitivity, all this should be visible up to the Virgo cluster. In space the frequency range is opened but one should focus on the low frequency domain ($10^{-3}$ Hz) in order to cover complementary grounds. One can then see compact Galactic binaries in their stable mode, and there should be plenty of them in the Galaxy. One can also see effects associated with very massive black holes (over a million solar mass) which are known to exist in the centre of most galaxies, and this anywhere in the Universe.

Stochastic noise associated with the Big Bang should cover both frequency ranges but at a still unpredictable level.

One notices an other complementarity between ground base and space observation. On the ground one is mostly sensitive to cataclysmic events. The detector has to be "on" at the proper time and the calculation of the signal involves much astrophysics. The signal is short and simultaneous observations by different detectors is needed to avoid spurious events. In space, one is sensitive to stable or long time events which can be observed over a long time (a year). A single detector is enough.

5-The detection of gravitational waves

The first signals, which one can now strongly hope for over the coming decade, and which could be detected on the ground, will provide a strong encouragement to develop this research. In the framework of Einstein's General Relativity gravitational waves should exist and the evolution of pulsar binaries, such as the famous Hulse-Taylor one, fits very well with expectations. This can be considered as a proof, however still indirect, of gravitational wave radiation. As previously said, we should however not wait for results on the ground to prepare to go to space.

The rates expected from specific sources, which can now be much better estimated, are very low. Typical values of the (dimensionless) amplitude $h$
are at the level of 10-22, very much lower than the detection limit of the present oscillating bar detectors which have been constructed following the pioneering work of J. Weber. However, following this time the pioneering work of R. Weiss, Km arm length laser interferometers should reach a detectability level corresponding to known sources such as supernova collapse and compact binary ring down all the way to Virgo. This is what is attempted with the VIRGO project in Europe and the LIGO project in America. Prospects are great to detect gravitational waves with these detectors which will be used in coincidence (2 in America and 1 in Europe). Ground based detectors are most efficient in the 10+2 to 10+3 Hz range but they are blind at low frequencies (<1 Hz) because of gravitational noise on the earth. As previously said, this higher frequency domain is were we expect signals from supernova collapse and from the end stage of compact binaries as they eventually chirp, coalesce and ring down. This is very interesting but one has to be lucky because of the not so probable occurrence of such events, even if one reach a detection level corresponding to our near by cluster, Virgo. The signal from a supernova is hard to estimate but, even in Virgo, a 10-22 sensitivity should do. In all cases the signals come only once and they are very brief. As previously said, one has to rely on coincidences between different detectors to be sure. Stable signals which are expected from stable binaries are in the 10-3 to 10-4 Hz range. They are detectable only from space. The continuous signal is much weaker than that of the collapse but, with a sensitivity level of 10-22, thousands of sources should be "visible" in the Galaxy.

The principle of a measurement in space is the same as the one of VIRGO/LIGO. It is based on a Michelson interferometer using laser beams. Going to space, one can focus on the detection of long wave length radiations (frequencies of the order of 10-4 to 10-2 Hz, say). The optimal arm length is then of the order of a few million Km but, in space, space is for free. Transponders, in locked phase with the incident laser beam received with a telescope, will replace the mirrors used on the ground where, despite Perrot-Fabry interferometry, available distances imply focusing on the shorter wave lengths (frequencies of the order of 10+2 to 10+3 Hz, say). As we said, a ground experiment suffers anyway from unescapable gravitational and thermal noise at low frequencies (below 1 Hz) and is "blind" to low frequency signals. In space on the contrary, no such noise is present. There is some drag noise which can be compensated and this becomes worrisome only down to the level of 10-4 Hz. It is therefore natural to optimize a space detector to the lower frequency domain, leaving the higher frequency one to the less expensive ground detectors. The sensitivity levels of the ground and space detectors are shown in Figure 1. The limit at maximum sensitivity comes in both cases from the laser shot noise. On the ground this also cuts off the sensitivity level on the high frequency side, whereas sismic noise cuts it off abruptly at low frequencies. In space, the drag noise provide the sensitivity limit at low frequency (10-4 Hz) whereas the arm length provides the dominant natural sensitivity limit at higher frequency (10-1 Hz).
It is clear that when faced with a new phenomenon it is important to study it over as large a band width as possible. Indeed, the long praised quietness of the heavens is misleading and it reflects observations long limited to the optical visible spectrum. As we saw, there is more to it with gravitational waves and there is a good complementarity between ground based and space detections.

Of particular importance in the latter case is the observation of effects associated with stable compact binaries and with super heavy black holes. The typical emission frequency of such objects is inversely proportional to the mass, with 10^{-3} Hz for 10 times the solar mass. In the former case, there are plenty of sources in the galaxy and a space detectors could most likely see tens of thousands of them. In the latter case, the signals are so strong that they could be detected to a very large distance, well beyond the super cluster level. This should provide a sizeable observation probability even if such event are very rare at the level of a few galaxies and may imply galaxy collisions. Having thus access to the very massive black holes would open a new field of investigation for astronomy. Such objects are expected to exist at the centre of most of the galaxies and galaxy collisions are not very unfrequent. As previously hinted at, the second space gravitational wave detector may thus well fall under the heading of "astronomy" and no longer under "fundamental physics". This however should not belittle the fundamental physics interest which will very much remain. Studying gravitational wave emission in the strong field relativistic regime of very massive black holes should provide many clues for a better understanding of gravitation. Emission in the low frequency domain should extend over a reasonable to extremely long length of time. There is therefore no need for two detectors operating in coincidence. As the detector circles the sun it will provide, through Doppler shift, a localisation of the source.

The observation of gravitational waves would be a dramatic and fundamental discovery. For many reasons, it will probably take place on the ground, during the first decade of the next century. However, if nothing is found, one could put the blame on bad luck on on too crude astrophysical models used at estimating the signals. In both cases, it will make it urgent to go to space, either to explore the rich low frequency range or, in the latter case, to also first really test Einstein Theory. Indeed strong enough stable and predictable sources at low frequency do exist. There are certainly very many binary systems in our galaxy. Failure to observe them would be a serious problem for our present gravity theory.

It is therefore proper to prepare to go to space before ground based results are available. There is actually a good overlap between the ground based and space looking communities and experience with laser interferometry on the ground will be beneficial for the space detector. The space detector should be continuously corrected for drag, correcting erratic motions of the shell as compared to the continuous free fall of the active payload which should be preserved. This calls for important technological developments which should be started early. It is necessary to master accelerometry, drag free control and laser interferometry in space. This is not easy and calls for tests before the experiment is flown.
Gravitational background noise associated with the early universe or with passing cosmic strings should extend over the whole covered spectrum (10^-4 to 1 in space and 1 to 10^+4 on the ground). This could be seen in both types of detector but the size of the signal is however still speculative. One expects the frequency range of "observable" gravitational waves to extend from 10^+4 (formation of a black hole of a little over a solar mass, just at the Chandrashekar limit) down to 10^-18 (when associated with quadrupole deformations at the level of the whole microwave background).

6-Detecting gravitational waves in space.

LISA will consist of 3 spacecrafts. Within each spacecraft the two lasers on board will be phase locked and act as a single laser with beams in phase sent in two different directions making an angle of 60 degrees. This is shown in Figure 2. Each spacecraft is at the apex of an equilateral triangle with a side length of 5 Million Km as shown in figure 3. The laser beams from each spacecraft are directed to two of the distant spacecrafts and interference between the beams received from the transponders is used at detecting minute changes between the two arm lengths defined by the test masses in free fall. The whole system with the 3 connected spacecrafts is providing an active back-up with two independent interferometers and also giving information on polarization. The detector would trail the earth at 20 degrees on a solar orbit as shown in Figure 3. It should be far enough not to be appreciably perturbed by the earth-moon motion. It cannot be too far because of cost containment. The plane of the detector is chosen so as to minimize the changes in arm length as the system tumbles, as shown in Figure 4. The relative pulsative variations in lengths which could be detected are at the level of 10^-23 (10^-3 to 10^-2 Hz). This is also what is eventually aimed at with ground based detectors (VIRGO,LIGO) but now in the 10^-2 to 10^-3 frequency range. As previously said, the ultimate limit comes in both cases from laser photon shot noise.

Detailed information about LISA can be found in the Alpbach summer school proceedings (further readings) and in the LISA pre-phase A study. We gave here only a "bird eye view" of the detector.

We have all reasons to believe that a sensitivity at the level of 10^-22 to 10^-23 should be enough for many interesting sources. One may remark that it is much higher than what is presently achieved with cryogenic resonating bars (at typical frequencies in the 10^+3 range), for which the sensitivity level is now pushed to 10^-19. Whereas some sources in the Galaxy could be detectable with bars, some luck should also be needed. With laser interferometry one benefits from a very significant advance. Detecting a relative change at the level of 10^-22 over 1 Million Km amounts to measuring a displacement of a thousandth of the size of an atom within the space craft. Laser interferometry should however do that. It presently already does even much better on the ground. To put it in a nutshell, one "sits" on a black fringe and collects the few photons which might nevertheless escape as the arm lengths change relatively by minute amounts.
7- Conclusions

Fundamental physics using cosmic sources offers many exciting prospects, whether it is considered on the ground or in space. In particular the observation and study of gravitational waves appears at long last as within reach with a most interesting complementarity between ground based and space based detection. In particle physics we are now used to a long waiting time between dream and reality and physics in space extends that further. Nevertheless its interdisciplinary character is such that fascinating problems also appear on the way developing the needed detectors. They will certainly trigger interesting spin-off because of the complexity and difficulty of some of the needed technological developments. We may then still meet enthusiasm for projects which will allow observation only up to 20 years from now. This is this enthusiasm which I try to pass on in this review. E. Amaldi, who was a great pioneer in the development of gravitational wave detectors used to say decades ago that this is a very great endeavour of a long range nature. It has to be pushed forward even if success is too far ahead for a physicist's lifetime. Thanks to his long past efforts, success now seems within reach within a decade.

Further readings (instead of references)

There are several books on Gravitation Theory and in particular the one of S. Weinberg "Gravitation and Cosmology" (Wiley). For a general introduction the book of J.A. Wheeler "A journey into gravity and space time" (Scientific American Library) provides a wonderful first look with much insight.

Last year (1997) the Alpbach summer school on space science was on fundamental physics in space. The proceedings provide a very good survey of the subject and a gold mine of material. It is available as an ESA publication (SP-420) with the title "Fundamental Physics in Space". Readers who wish to know more about the subject are strongly encouraged to order it from ESA and to read at least part of it. This is there that one finds the articles by B. Schutz referred to in the text. There are also two inspiring texts by H. Bondy and much information about LISA, MINISTEP and AMS.
As further readings, one may also quote

For astroparticle physics:


And for gravitational waves:

K. Thorne. "Gravitational waves" Proceedings of the Snow-Mass '95 Summer Study on Particle and Nuclear Astrophysics and Cosmology, WSPC
G. Fontaine "Ground based detection of gravitational waves, in "Large Facilities in Physics" op.cit.
K. Danzmann "Laser Interferometry Space Antenna (LISA) for gravitational wave measurements" in "Large Facilities in Physics" op.cit.
Horizon 2000+, ESA-SP-1180
See also for up to date information the LISA '98 pre phase A report (contact K. Danzmann, Hannover)

Figure captions.

Figure 1- The sensibility of LISA and VIRGO/LIGO together with signals expected from specific sources. Shown is the expected value for h and the sensitivity limit (for burst or long range observation) as a function of frequency. The very massive black holes are set at z=1

Figure 2- Layout and an artist view of the LISA detector in space. Each spacecraft has a two laser system.

Figure 3- The LISA detector in its heliocentric orbit.

Figure 4- The tumbling of the detector as it circles the sun. This allows one to determine direction and polarization.
LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves