Draft of the Fundamental Physics Roadmap

The Fundamental Physics Roadmap Advisory Team (FPR-AT) has been convened by ESA in order to draw up recommendations on the scientific and technological roadmap necessary to lead Europe toward the realization of future space missions in the framework of the Cosmic Vision 2015-2025 plan in the field of fundamental physics. The scientific fields covered are:

– tests of fundamental laws and principles;
– detection and study of gravitational waves;
– quantum mechanics in a clean environment;
– cold atom physics, new frequency standards and quantum technologies;
– the fundamental physics of dark energy and dark matter;
– space-based efforts in astroparticle physics.

What follows is a draft of the roadmap document submitted to the community in order to be discussed at the workshop convened at ESTEC on 21-22 January 2010 (see http://sci.esa.int/fprat). It should be stressed that this is by no means a final document. The final version of the Fundamental Physics Roadmap will be made public a few months after the workshop.[1]

[1] Given the nature of this document, no explicit references are given. The reader is referred to the excellent reviews existing on the subject for references.

Table of contents

A. Introduction

A field at the crossroads of many scientific interests

The topics listed in the mandate of FPR-AT form a very visible science program which lies at the interface between the two fundamental theories of physics in the XX^{th} century: general relativity and the quantum theory.

One may group the searches associated with this program under two intimately connected areas of research:

Tests of fundamental laws: tests of fundamental principles, in particular the equivalence principle (weak equivalence principle, local Lorentz invariance and local position invariance including constancy of constants), tests of the law of gravity at all length scales, as well as in its weak or strong regime, structure and dimensionality of spacetime, tests of the foundation of quantum mechanics,

Search for fundamental constituents: scalar fields for dark energy, wimps for dark matter, fundamental strings, etc.

The field has an agenda and priorities of its own but it cannot be completely separated from astrophysics or solar system physics. Several examples: astrophysical observations put complementary constraints on fundamental laws; recent excesses observed in high energy cosmic particles may be due to wimp annihilation but also astrophysical sources (e.g. PAMELA positron excess and pulsars), planetary missions provide strong constraints on important tests of fundamental physics (e.g. Cassini) but the exploitation requires a good knowledge of these missions and of the dynamics of the solar system.

Finally, one should note the rich interface with a large variety of other fields, such as Earth observation (GRACE, GOCE), geodesy, and navigation. This is a very special feature of this field, which provides a complementary reason for the fundamental physics community to have access to the space program and to develop its own technology.

New communities

It is important to stress that fundamental physics as a whole represents communities with recent access to space. Even though this may lead to difficulties at a time of budget constraints, it is a sign of vitality and progress that space agencies have the potential to attract new communities and make the necessary room for them. One would be worried about the future of these agencies otherwise.

These new communities bring new and diverse technologies to space. This requires the evolution of development plans adapted to the specifics of these technologies, in particular sufficient financial and personnel investments, and a specific attention to the novelty of the requirements. It has been stressed that the technologies of fundamental physics have, despite their specificity, a large potential for application to very diverse fields.

Finally, even though these communities are relatively new to space, they already have some space experience: the LISA program is almost 2 decades old; T2L2 is under operation and ACES and MICROSCOPE are well advanced; and in astroparticle physics, besides PAMELA and Fermi, AMS is ready to be launched.

The Cosmic Vision plan

Europe has set up in 2005 an ambitious plan for the years 2015-2025: this is the Cosmic Vision plan [*www.**esa**.int/**esa**pub/br/br247/br247.pdf*]. A call has already been issued for two medium (i.e. 450M€) missions, called M1 (launch in 2017) and M2 (launch in 2018) , and one large (i.e. 650M€) mission, called L1 (launch in 2020). The missions Solar Orbiter (M) and LISA (L) were transferred from the earlier program of ESA and LISA will be a candidate for L1.

The selection process is ongoing with crucial dates in early 2010 for the M missions (down selection from 6 to 3 or 4 missions); and in 2011 for the L missions (down selection from 3 to 2 missions). A call is expected to be issued in 2011 for a M3 mission (launch in 2021) and later for a L2 mission (launch in 2025?). These are obviously tentative dates, subject to change as the Cosmic Vision program develops.

In the first Cosmic Vision call in 2006, fundamental physics had a disappointing performance. Apart from the dark energy mission (now called Euclid), which has some scientific relevance to the field, and the proposal of an instrument (GAP for Gravity Advanced Package) on a planetary mission, no mission was selected in the first round (LISA which was included later was already in the ESA program). Reasons for this will tentatively be analyzed below but it is clear that the importance of the next M3 call for fundamental physics cannot be overemphasized. This is one important aspect of the present roadmap effort.

Given this, and the general Cosmic Vision schedule, we will define short, mid and long term as follows:

short term: 2010-2011 (getting ready for M3 call)

mid term: 2015 (getting ready for L2 call)

long term: 2020 (preparing the post-CV era)

B. The scientific field covered by this roadmap : present status

B.1 Overview

The field of fundamental physics is described by two extremely successful theories developed through the XXth century: quantum mechanics and general relativity. The basic principles of quantum mechanics have been tested with great success. Together with special relativity, the quantum theory provides the framework for the Standard Model which describes successfully the electroweak and strong interactions of fundamental particles. General relativity provides a very detailed description of the gravitational interactions.

Until now, there has not been any clear indication that the quantum theory or general relativity is not consistent with observational or experimental facts. But the theory encompassing both the Standard Model and general relativity is yet to be written. The clearest sign of a difficult confrontation between the two theories lies in the concept of vacuum energy, computed within the quantum theory to be many orders of magnitude larger than allowed by the constraints coming from the rate of expansion of the Universe.

Theories, which are candidates for achieving such a unification (string theory, quantum gravity, extra spatial dimensions) tend to lead to tiny violations of basic principles:

- The space-time frame is modified (quantum nature, possibly extra spatial dimensions as in string and brane models): this may lead to violations of Lorentz invariance.
- Some constants of physics are found to have a dynamical origin : they tend to evolve with time which leads to violations of the equivalence principle.
- The law of gravity may be modified at some scale (from microscopic to cosmological).

In parallel, there might be good reasons to modify the theory of gravity to account for the observational facts that lead to the concepts of dark matter and dark energy. But most endeavours in this direction are plagued with difficulties showing that, if there is an alternative to general relativity, it is probably a very special theory.

An alternative is to introduce new long range forces. There are many proposals in this direction, most of them using scalar fields. The best known examples are found among the dark energy models. When put in the context of realistic theories, these new long range forces very generally tend to lead to violations of some laws, especially of the equivalence principle.

Fundamental laws

The equivalence principle i.e. the equality between the inertial and the gravitational mass has played an important role in development of gravity. It is central in general relativity and, as such, tends to be violated in many extensions of general relativity, whether they are modifications of gravity or they include extra long range forces. Testing the equivalence principle and searching for its violations is therefore central to the field of fundamental physics.

The form of the equivalence principle used by Einstein has three manifestations:

i) universality of free fall (UFF), usually referred to as the weak equivalence principle, tested by comparing the accelerations of two bodies of different composition in an external gravitational field;

ii) local Lorentz invariance (LLI), tested by comparing the speed of light and the limiting speed of massive test particles, by determining the Lorentz transformations, and by testing the independence from laboratory orientation and velocity;

iii) local position invariance (LPI), which states that the result of any non-gravitational experiment is independent of where and when it is performed; it implies the constancy of the fundamental constants of non-gravitational physics.

Many theories considered in the context of unification or of dark energy lead to time-dependent constants and thus to violations of the local position invariance. This in turn leads to violations of the weak equivalence principle. The Einstein equivalence principle is the basis of metric theories of gravity, which predict a universal gravitational redshift and the universality of free fall. A stronger version of the equivalence principle (Strong Equivalence Principle) is satisfied by general relativity: it goes one step further than the Einstein equivalence principle by replacing test bodies by self-gravitating bodies and generalizing to all experiments (instead of non-gravitational experiments only).

Precision tests of the Einstein Equivalence Principle have made remarkable progress in recent years. High stability and accuracy atomic clocks in combination with time and frequency transfer links can be used to measure the effect of gravitation on time, to perform tests of the local Lorentz invariance and local position invariance. Clocks in GPS satellites have provided precision tests of LLI. The comparison of terrestrial atomic clocks based on different atoms and atomic transitions is today providing stringent tests of LPI in the Sun's gravitational field, at the same time searching for time variations of fundamental constants to unprecedented uncertainty levels and in well controlled and reproducible environments. On the other hand, the most accurate measurement of the gravitational red-shift, a consequence of metric theories of gravitation, is still based on the space to ground comparison of two hydrogen masers performed by the GP-A rocket experiment in 1976.

The ACES mission, designed to distribute a microwave cold atom clock signal with frequency instability and inaccuracy of $1x10^{-16}$ to ground and to compare clocks on ground to a frequency uncertainty below $1x10^{-17}$, will allow the improvement of the gravitational redshift measurement by a factor 35. In doing so, it will also perform the most precise test of LPI in the terrestrial gravitational field.

Best tests of the weak equivalence principle (WEP) are today coming from laboratory experiments based on torsion balances and laser lunar ranging. Compared with Earth-based experiments, precision measurements in space can benefit from the advantages of a freely falling laboratory and significantly reduced contributions from seismic noise and many other sources of non-gravitational disturbances. MICROSCOPE will test the WEP to $1x10^{-15}$ using differential electrostatic accelerometers. Atom interferometers represent an interesting alternative that in the future could test the universality of free fall on quantum objects.

Gravity may be tested in the slow motion weak field limit, known as the post-Newtonian limit: typically for a binary system, $\varepsilon \sim v^2/c^2 \sim GM/(Rc^2) \ll 1$ where v is the typical velocity of the bodies, M their mass and R their separation ($\varepsilon \sim 10^{-9}$ for the Earth and 10^{-6} for the Sun). It is traditional to perform these tests in the context of the parameterized post-Newtonian (PPN) formalism. Many alternative frameworks with qualitatively different phenomenology have been developed and tested. In the PPN formalism, departures from general relativity are parameterized by 10 parameters. The most commonly used are β associated with nonlinearity in the superposition law of gravity and γ which measures the amount of curvature produced by mass (both of them have a value equal to 1 in general relativity).

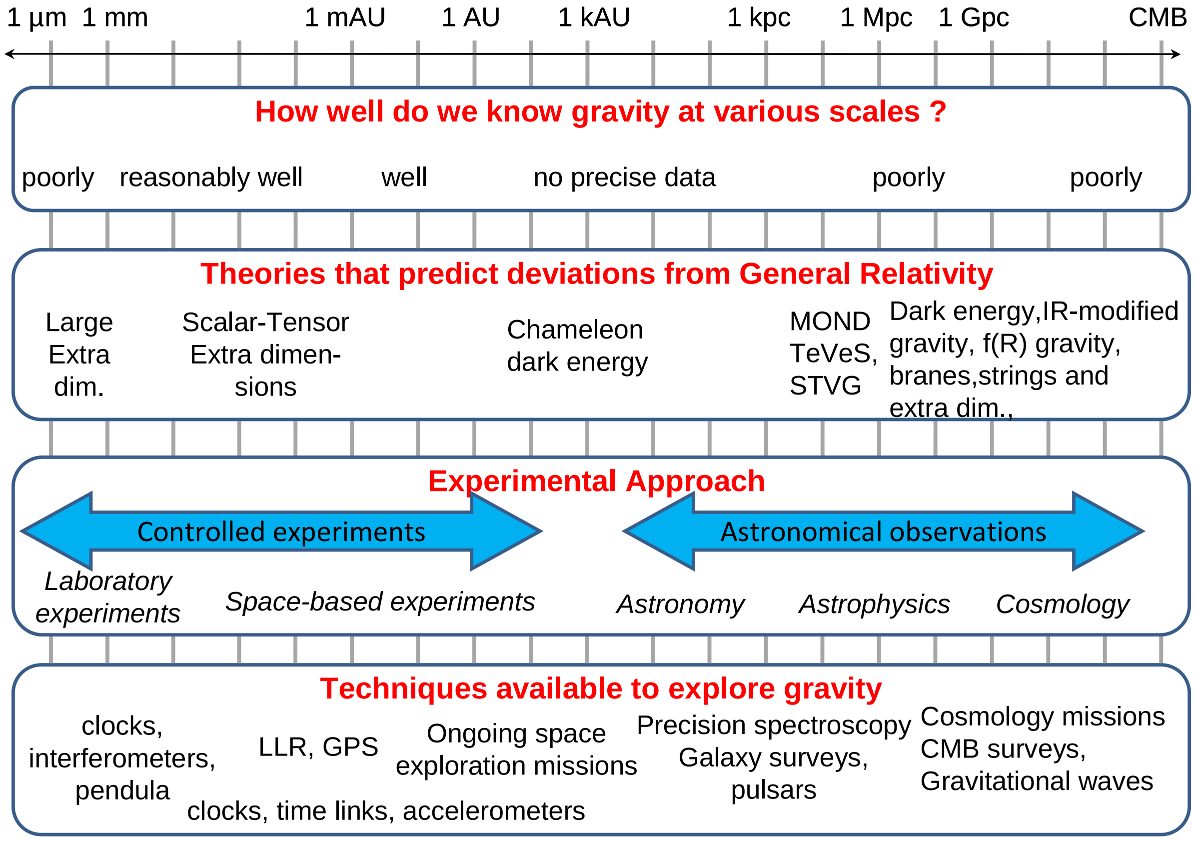
Standard tests of γ are carried out either by precise astrometry measuring light deflection (VLBI, GAIA), or by measuring the gravitational time delay (Shapiro effect) of light signals passing close to a gravitating mass (Cassini, BepiColombo). It should be noted that the two types of measurement are complementary as the latter is dominated by the effect when the light signals pass close to the sun (grazing incidence), whilst the former is the result of averaging over all light sources and trajectories, which in the context of scale dependent gravity probes a different region. Doppler tracking of the Cassini spacecraft while on its way to Saturn gives the most stringent constraint on γ : $\gamma -1 = (2.1 \pm 2.3)\times10^{-5}$. The GAIA mission will measure light deflection and γ to the 10^{-6} level. Similar accuracies will be attained by the mission BepiColombo to Mercury, which will also measure other PPN parameters. The availability of independent tests at the same level of accuracy is especially important if a violation is jointly detected by both experiments.

Beyond the slow motion weak field limit, one enters the regime of strong field gravity: $\varepsilon \sim v^2/c^2 \sim GM/(Rc^2) \sim 1$. The detailed study of millisecond pulsars (especially the double pulsar system J0737-3039A,B) already allows tests in this regime because the large self-gravitation of neutron stars does not influence their orbital motion: in other words, no violation of the strong equivalence principle is observed.

The detection of gravitational waves will provide key tests of gravity in the strong regime: LISA will observe physics taking place just outside the event horizon of black holes, where typical velocities are of order c. The coalescence of massive black holes at cosmological distances produces a powerful burst of gravitational radiation, which LISA will be able to measure with amplitude signal-to-noise as high as several thousand. In the months prior to merger, LISA will detect the gravitational waveform due to the binary inspiral, which will allow the determination of the masses and spins of the two black holes to high accuracy. Given these physical parameters, numerical relativity will be able to predict the exact shape of the burst waveform, and this can be compared directly to the observed burst – providing an ideal test of the theory. Stellar-mass compact objects spiralling into massive black holes will provide a qualitatively different test. The compact object travels on a near-geodesic of the spacetime of the massive black hole, and as it spirals in, it effectively maps out the spacetime surrounding the black hole. For these extreme-mass-ratio inspirals (EMRIs), LISA will typically observe of order 10^5 cycles of inspiral waveform, all of which are emitted as the compact object spirals from 10 horizon radii down to a few horizon radii. This will allow the acquisition in a direct way of unprecedented knowledge on the structure of spacetime close to black hole horizons.

Experimental tests of gravity show a good agreement with general relativity at scales ranging from the laboratory scale to the size of planetary orbits but it is challenged by larger-scale (galaxies, cosmology) observations. Meanwhile, most theoretical models aimed at inserting General Relativity within the quantum framework predict observable modifications at smaller and/or larger scales. Given the immense challenge posed by the observed large scale behaviours (dark matter, dark energy), it is important to explore any possible option, in particular by testing the gravitational laws at all possible distances. The largest scales reachable with controlled, man-made experiments are of the size of the solar system, and thus space probes to the outer solar system play a special role in this context.

Over the past years, a large number of theoretical frameworks that allow for a scale dependent modification of general relativity have been investigated *e.g.* generalized metric extensions of general relativity, Modified Newtonian Dynamics, Tensor-Vector-Scalar-theory, Metric-Skew-Tensor Gravity, $f(R)$ modified gravity theories, string and brane motivated scenarios, dark energy models and many others. It is beyond the scope of this document to list all the corresponding predictions. It remains clear that it is important to test gravity at all possible length scales.



Gravity at all length scales (adapted from S. Turyshev, arXiv:0809.3730 [gr-qc]).

We have insisted above on tests of the laws of gravity and the search for deviations from general relativity, but the field covered by fundamental physics in space provides unique ways to test the laws of the Standard Model as well.

As an example, we may recall that the study of the propagation of ultra-high energy cosmic rays allows the probing of energy scales a few orders of magnitude beyond the most powerful accelerators (energy being measured in the centre of mass for comparison).

Another illustration is provided by the observation of cosmological backgrounds of gravitational waves. LISA may indeed turn out to be the space counterpart of the Large Hadron Collider (LHC) which has just started running at CERN. The first goal of this collider is to discover the Higgs particle, i.e. the central building block in the spontaneous symmetry breaking mechanism which lies at the heart of the Standard Model of electroweak interactions. If the corresponding phase transition is sufficiently first order (not favoured in the Standard Model but often the case in its extensions), then it is sufficiently violent to generate a characteristic background of gravitational waves. The frequencies of these waves fall precisely into the LISA window. In other words, LISA is the tool to study Terascale physics (i.e. physics in the few TeV energy range). Even if the electroweak phase transition is not sufficiently first order to generate a detectable gravitational wave background, there might be other first order phase transitions in the Terascale regions. A well-known example is the phase transition associated with baryogenesis (the generation of the asymmetry between matter and antimatter in the Universe): as shown by A. Sakharov, a necessary condition for generating the asymmetry is a first order phase transition. If the corresponding energy is the Terascale, a background of gravitational waves would be observed by LISA.

Finally, astroparticle physics uses high energy cosmic particles to understand violent phenomena in the Universe. These rapidly varying phenomena are usually associated with compact objects: black holes or neutron stars. A careful analysis of phenomena associated with neutron stars allows a better understanding of the behaviour of matter at high densities. This is complementary to what can be learned at colliders using heavy ions.

Another fundamental aspect of the field that we consider here is that it provides novel and important tests of the principles of quantum mechanics. It is known that the validity of quantum laws, developed for the microscopic world, extends to the macroscopic world. Quantum interference or quantum entanglement is one example. Space provides a unique way to test these laws at even larger distances, and possibly test the effect of the gravitational field on the associated phenomena.

Fundamental constituents

For several decades, astronomical measurements have found discrepancies between the velocities of stars and gas in galaxies and the mass inferred from luminous matter, leading to the concept of dark matter. Rotation curves of spiral galaxies, the inferred mass-to-light ratios in dwarf galaxies and gravitational lensing are all consistent with dark matter being a new type of matter, most probably consisting of weakly interacting massive particles or wimps. From Big Bang nucleosynthesis it is inferred that they cannot have a baryonic nature.

Direct detection of these particles relies on the production of wimps at colliders (LHC) or through their interaction with matter in underground labs. Indirect detection relies on the observation of annihilation products of wimps accumulated at the centre of the Sun or at the galactic centre: depending on the mass of the wimp, the annihilation products are more or less energetic cosmic particles. Indirect detection may be undertaken on ground (high energy photons – HESS, MAGIC, CTA – or neutrinos – ANTARES, Km3Net -) or from space (INTEGRAL, PAMELA, SWIFT, AMS). Recent observations by the PAMELA and SWIFT space missions, the ATIC balloon and the HESS telescopes on positron excess have initiated considerable activity to check whether this was due to some form of dark matter. This has been a very active field recently and will remain so probably for the years to come : experimental sensitivities have now reached the predictions of the majority of wimp dark matter models.

We have alluded before to the important problem of understanding why matter overwhelmingly dominates over antimatter in the observable universe. Presumably, the mechanism has to be searched for in the cosmological evolution of the Universe. It remains important however to perform as complete as possible a search for antimatter, such as AMS was designed to do.

Conversely, experimental or observational data may put constraints on the existence of hypothetical particles. For example top-down models of cosmic rays, i.e. models where ultra-high energy cosmic rays are produced by the decay of superheavy particles have basically been ruled out by the photon data of the Pierre Auger Observatory.

Among the fundamental particles of the microscopic quantum world some play a very central role: they are the mediators of fundamental interactions. The larger the range of the interaction, the smaller the mass of the mediator. Since many of the tests discussed above deal with long range forces of the gravitational type, it is not surprising that they may provide key information on these mediators and on their fundamental properties.

First and foremost, there is the graviton, mediator of the gravitational interaction (if gravity is indeed quantized). The discovery of classical gravitational waves does not imply the existence of the graviton but LISA observations will improve significantly on the current solar system bound on the mass of this hypothetical particle: $m_g < 4\times10^{-22}$ eV. One method is to observe the phase delay between optical and gravitational signals for white dwarf binaries, at the moment they are eclipsing i.e. aligned along the line of sight (potentially $m_g < 10^{-23}$ eV). Another test uses the phase evolution of massive black hole inspiral signals (potentially $m_g < 10^{-25}$ eV).

Most models of dark energy involve a fundamental scalar field which is extremely light (typically 10^{-33} eV). Embedding such a field into a realistic model usually implies some level of gravitational-type coupling between this scalar field and ordinary matter, dark matter or neutrinos. The exchange of this scalar field induces a long range force (10^{-33} eV corresponding to a range of the order of the size of the visible universe) which is severely constrained by the tests that we discussed earlier. Pushing further the corresponding limits may lead to a discovery of this new long range force and of its corresponding mediator.

Finally, there is the possibility of discovering fundamental objects which are not point particles but extended objects. The best known example are strings, whether cosmic strings often associated with the spontaneous breaking of some continuous symmetry or the fundamental strings of string and brane theories (even though these are microscopic strings, some are believed to reach a macroscopic, even cosmological, size). Such strings form a network, producing loops which decay by emitting gravitational waves. They can also be pinched, and produce bursts of gravitational waves localized in space and/or time (cusps, kinks). Thus the study of gravitational wave backgrounds (or bursts) may prove to be key in identifying these objects which have been searched for through lensing observations or through their effect on the cosmic microwave background.

B.2 Multiple connections

Connection to astrophysics

Since their discovery in the 1960s pulsars, in particular pulsars in binary systems, have been used as clocks for testing general relativity. Relativistic effects on their orbits and the Shapiro delay of their signals when travelling through the potential of the companion are in excellent agreement with the predictions of general relativity to better than 1%.
Precise timing of the arrival times of pulses of an ensemble of pulsars distributed over the sky can be used to measure the displacement of the Earth due to very low frequency (< 10^{-5} Hz) gravitational waves compared to the distant pulsars in a so-called Pulsar Timing Array.

X-ray measurements of gas orbiting close to black holes can provide information about the local geometry and thus probe strong field gravity. Reflection spectra of the inner accretion disk show distorted Iron emission lines that are thought to extend to the innermost stable orbit. Their maximum redshift then depends on the size of this orbit and thus on the spin of the black hole. Reflection of X-ray flares across the accretion disk will produce additional variability in the emission lines and can be used to map the spacetime geometry, as photon paths passing close to the horizon will suffer strongly from curvature and frame dragging. The next generation X-ray mission, the International X-ray Observatory (IXO) will increase the collecting area compared to Chandra and XMM-Newton by more than a factor 10 and will be able to study several hundred local AGN in detail and study the spacetime geometry of several tens. This is somewhat complementary to what LISA can achieve, although in the case of LISA, EMRIs allow the direct mapping of the gravitational field outside the horizon of the black hole. LISA will clearly test the strong gravity regime in a more focused and definitive manner.

In the case of dark energy, there is also a rich interplay between astrophysical observations and tests of fundamental physics: astrophysical observations will probe the equation of state of dark energy and its evolution, but in the case where dark energy is dynamical (i.e. not just vacuum energy, for example a scalar field), fundamental tests will probe more deeply its dynamics and couplings. One may also note that the coalescence of massive black holes observed by LISA will provide a new type of standard candle (or siren) to study the geometry of the Universe, and in particular dark energy. If an electromagnetic signal is recorded simultaneously from the merger, precision should be similar to that from a dedicated dark energy mission, but with completely different systematics.

The search for a primordial background of gravitational waves, sometimes called the Holy Grail of cosmology, is also a convergence point between complementary observations: big bang nucleosynthesis puts a mild but frequency-independent constraint; the search for B polarization modes in the Cosmic Microwave Background addresses very low frequencies (below 10^{-16} Hz); millisecond pulsars put the most stringent constraints at 10^{-8} Hz whereas detectors of gravitational waves operate in their respective frequency windows. If the source of this primordial background is due to standard inflation, it is probable that the sensitivity of ground interferometers or even LISA will be insufficient to detect it.

Conversely, gravitational wave instruments and dark energy missions will provide a wealth of astrophysical information ranging from Galactic binaries to properties of large samples of galaxies.

As concerns dark matter, we have seen above that the indirect detection of dark matter particles is attempted by looking for the signal of annihilation (i.e. energetic particles and photons). In order to reliably perform such experiments, it is crucial to carefully take into account all the possible astrophysical sources of energetic particles and photons. Recent examples have shown that this is crucial before attributing any excess to the presence of dark matter. It is probable that, in the hypothesis that dark matter is formed from wimps, its nature will be fully identified by relying both on direct and indirect detection.

Any anisotropies observed in the arrival directions of cosmic rays above ~ 4 x 10^{19} eV (UHECRs) lead to the prospect of using these particles for astronomical purposes. They must have been produced dominantly within a volume of radius ~ 100 Mpc defined by the distance that UHECRs can travel through the 2.7 K microwave background (the Greisen-Zatsepin-

Kuzmin effect). Observations of UHECRs will provide information about nearby sources and intervening magnetic fields.

The anisotropy observed above ~ 5 x 10^{19} eV by the Pierre Auger Collaboration appears to be associated with the nearby local matter distribution. In particular, Cen A, and other nearby active galactic nuclei may be sources of UHECRs. However the rate of events is only ~ 2 per month and it is therefore impossible to construct a spectrum for individual sources, information that would provide an important clue to understanding the mechanisms of particle acceleration in the most energetic objects in the Universe. These range from compact objects to active galactic nuclei with their super-massive black holes, relativistic jets and giant radio lobes and to gamma-ray bursts. Identification of features of individual UHECR sources would enable the study of physics in extreme conditions (high magnetic field, matter density and/or gravitational field). By gaining access to the three main accessible parameters (the power imparted to UHE particles, their maximum energy, and the shape of their spectrum at the source) with sufficient statistics, the physics of the sources will be strongly constrained.

Individual sources also provide a tool to test different models of the galactic magnetic fields. Back-tracking particles through different magnetic field structures will allow the identification of those that are most effective in reducing the region on the sky from which the particles come.

Work with the Pierre Auger Observatory has shown that an instrument with a much greater aperture is required. This can come from a Mission of Opportunity (JEM-EUSO) which will take forward the astrophysical connections and also meet some fundamental physics objectives.

Connection to solar system science

Fundamental physics in the solar system is necessarily and intimately related to solar system science. In particular, a non exhaustive list comprises lunar, planetary and solar observation, planetary missions, interplanetary spacecraft navigation, etc.. Historically, and at present, some of the best bounds on deviations from the known laws of gravity are obtained from the analysis of data from lunar and planetary observations and from planetary missions. Either those data are obtained as a routine product related to the primary goal of the observations and missions, or as the result of a dedicated experiment carried out using state-of-the-art radio or laser technology. Some of the most striking examples are:

- The current best bounds on a violation of the weak and strong equivalence principle and of any time variation of the gravitational constant obtained from 34 years of lunar laser ranging (LLR), together with the most stringent bound on the PPN parameter combination $4\beta-\gamma-3$.
- The best limit on the PPN parameter γ from radio ranging to the Cassini spacecraft during solar occultation.
- The best upper limit on stochastic gravitational wave backgrounds in the 10^{-6} to 10^{-3} Hz range obtained from radio ranging to Cassini during the cruise to Saturn.

Although in many cases missions and technologies with primary goals in solar system science have been “opportunistically” used for fundamental physics (with the possible exception of LLR), the inverse may also become true in the future, where missions and technologies whose primary goals are in fundamental physics may additionally provide useful information for solar system and planetary science.

Another intimate link is provided by the necessity of using the solar system science results to correct for the “classical” effects in fundamental physics experiments, before being able to analyse the data for deviations from the known laws of physics. This requires, in particular, an accurate determination of planetary and solar ephemerides and gravity and the cancellation, or at least the strong reduction of propagation noise due to the solar corona and the Earth’s atmosphere. In addition, the use of a spacecraft as a proof mass for gravity tests requires an adequate knowledge (or estimation) of the non-gravitational accelerations, and/or the adoption of drag-free systems. These aspects were crucial in all past solar system experiments in fundamental physics and will be even more important with the improved accuracy expected in future experiments.

Indeed, precise orbit determination of interplanetary spacecraft or landers is an excellent tool to test general relativity and alternate theories of gravity. Any inconsistencies in the analysis and modelling of the navigation data may be hints towards new physics and must be studied with the greatest care. Errors in the analysis and modelling of the navigation data have to be ruled out, if necessary additional data and instruments must be used to allow further and complementary information to be obtained. This is of particular interest for missions that cover large parts of the solar system (e.g. missions to the outer planets and Kuiper belt) in the light of scale dependent gravity as discussed above. Landers may also provide excellent opportunities to improve solar system ephemerides and test deviations from the adopted dynamical laws. Being essentially immune to non-gravitational accelerations, the determination of their long-term dynamics is much easier than for an orbiting spacecraft. Range and range rate measurements of landers provide crucial information for the study of planetary interiors, and are therefore of the greatest interest to the planetary community.

In a more global picture, planetary spacecraft and planetary landers provide the most precise data for the construction of solar system ephemerides, which in turn provide additional tests of gravitation at precision levels comparable to those obtained from LLR and individual missions. For example, solar system ephemerides provide the best limits to Yukawa type modifications of the Newtonian gravitational potential with ranges between 3×10^9 m and 10^{15} m. Furthermore, the ephemerides are a crucial component of any dynamical model used in precise orbit determination. Currently available models of solar system dynamics are now limited by the poor knowledge of the masses and distribution of asteroids. Although these effects are relatively small (to the level of 10 m on the orbit of Mercury), they will likely be among the main limitations in precise tests involving spacecraft in planetary orbits and landers. Long term observations of planetary probes and high accuracy astrometric measurements from GAIA may lead to a significant improvement in solar system ephemerides.

In the future this intimate connection between solar system science and fundamental physics is expected to further strengthen with the expected improvement of the instrumentation and the development of new high precision technologies specific to fundamental physics (accelerometers and drag free technologies, optical atomic clocks, optical links and optical interferometers). That will lead to a stronger interdependence for the interpretation and comprehension of the data, be it in planetary or fundamental physics, certainly aided by the availability of more diverse high precision measurements (local acceleration, local time, astrometry) additional to the already available ranging and Doppler data.

A potential to a wide array of applications

Most of fundamental physics in the Earth's vicinity and in the solar system is concerned with a deviation from the known laws of gravitation, and thus with precise measurements of the gravitational field of different types (motion of bodies, light propagation, clocks). The precision required in fundamental physics is in general significantly better than in other applications (e.g. clocks in ACES, drag free and accelerometers in LISA PathFinder and Microscope), but once the technology is developed it also leads to significant improvements and new applications in many other fields (geodesy, planetary gravity, global positioning, altimetry, telecommunications, etc…). Often, the technology development is carried out with several applications as drivers, a good example being accelerometers and gradiometers which have found widespread use in space geodesy (CHAMP, GRACE, GOCE) and fundamental physics (Microscope, LISA PathFinder, LISA). Similarly the precise clocks and radio/optical links available on ACES will yield benefits not only for fundamental physics but also for positioning, geophysics and atmospheric studies, either with the ACES mission or in future deployment. A good current example of the synergy between Earth observation and fundamental physics is the optical link (T2L2) onboard Jason2 (launched in 2008), which allows the calibration of the onboard oscillator with respect to ground clocks, which in turn improves altimetry observations and positioning.

Quite generally, any instrument allowing significant reduction in the measurement uncertainty of the crucial observables is important for fundamental physics and other applications. Research in fundamental physics is a driver for the development of high precision instrumentation that will naturally find its way into other applications. As an example oriented towards the future, the availability of high precision space clocks points towards a long term perspective where international time scales will be constructed in space and precisely disseminated to ground. That would overcome barriers related to the terrestrial environment that are already perceptible today, and exploit novel global positioning techniques with significantly improved uncertainty over present systems (GPS, GLONASS, Galileo), which are already outstanding examples of applications of the resources of quantum mechanics and general relativity.

B.3 A rich space program and associated experiments

We briefly describe the existing program in space, outlining only the projects with significant European participation.

T2L2: Time Transfer by Laser Link (T2L2) is an optical link for clock comparisons and time transfer experiments. The package, launched on the Jason-2 satellite on June 20th 2008, uses the ultra stable oscillator in the DORIS orbit determination system as on-board frequency reference. Over 30 ground stations are contributing to the experiment. The T2L2 package aims at demonstrating a time stability of a few ps in the comparison of distant clocks and a time accuracy of 100 ps in the distribution of time scales.

ACES: Atomic Clock Ensemble in Space (ACES) is a mission based on a new generation of atomic clocks to be installed on the International Space Station, at the external payload facility of the Columbus module. The on-board clock signal is generated by an active hydrogen maser (SHM) and a primary standard based on samples of laser cooled Cs atoms (PHARAO). Fractional frequency instability and inaccuracy of $1{\cdot}10^{-16}$ will be reached by the ACES frequency reference under microgravity conditions. A high-performance link in the microwave domain will distribute on ground the ACES signal allowing clock comparisons to a frequency resolution of $1{\cdot}10^{-17}$.
ACES will connect ground clocks based on different atoms and atomic transitions in a worldwide network that will probe fundamental laws of physics to high accuracy. Space to ground and ground to ground comparisons of atomic frequency standards will be used to perform tests of Einstein's theory of general relativity including a precision measurement of the gravitational red-shift, a search for time variations of fundamental constants, and tests of the Standard Model Extension.
ACES will also support applications in different areas of research. The measurement of the differential redshift between clocks on ground will provide direct access to the local geopotential with a resolution down to the 10 cm level. The on-board GNSS receiver used for precise orbit determination of the ACES clocks will also support applications in GNSS remote sensing (radio-occultation and coherent reflectometry). A link in the optical domain is presently under development for clock comparisons, time transfer, and ranging experiments (optical vs. microwave).
Tests recently performed on the engineering models of key instruments and subsystems of the ACES payload have characterized the system performance releasing the manufacturing of the flight models. ACES will be ready for launch in 2013.

MICROSCOPE: The CNES-ESA mission Microscope will test the weak equivalence principle, with a sensitivity to a possible EP-violating relative acceleration difference of 10^{-15}. The experiment, which is scheduled for launch into a polar orbit at the end of 2012, uses electrostatic position sensing to measure the differential acceleration in the Earth's gravitational field between concentric cylindrical test masses of Pt and Ti, with a second Pt-Pt pair used to discriminate systematic errors. The MICROSCOPE differential accelerometry, designed for $pm/s^2/Hz^{1/2}$ level at 1 mHz, is based on electrostatic position sensing and force actuation, with flight heritage from the GRACE and GOCE geodesy missions, and a drag-free satellite, employing FEEP microNewton thrusters that guide the satellite to follow a free-falling test mass. In addition to being the first test of the universality of free fall to be conducted in space, Microscope represents an improvement of more than two orders of magnitude over existing torsion pendulum and lunar laser ranging equivalence principle tests.

LISA PathFinder: LISA PathFinder will probe the limits with which a macroscopic object can be placed into nearly perfect free-fall, with a measurement of the differential acceleration of two geodesic reference test masses to better than 30 $fm/s^2/Hz^{1/2}$ at 1 mHz. LISA PathFinder, scheduled for launch to L1 in 2012, represents a single arm of the LISA gravitational wave observatory that has been squeezed from 5 million km into a single spacecraft, with 30 cm baseline, with the relative test mass acceleration measured with an optical interferometer.

LISA PathFinder tests the current state-of-the-art in high purity free-fall, with hardware designed for the LISA "local measurement" of a free-falling test mass inside a co-orbiting satellite. This includes a 10 $pm/Hz^{1/2}$ interferometric displacement readout, an upgraded 6 degree-of-freedom electrostatic sensor designed to reduce stray forces to the $fN/Hz^{1/2}$ level, and a drag-free satellite with microNewton thrusters. The acceleration resolution is within a factor 10 of the final LISA goal, which would be sufficient to guarantee LISA observation of galactic compact objects and distant massive black hole sources.

In addition to a test of the LISA measurement technique, LISA PathFinder aims at an experimentally-based physical model of the limits of the free-fall, with dedicated measurements of different known force noise sources, including magnetic fields, thermal gradients, cosmic ray charging, and coupling to spacecraft motion, in addition to a global measurement of relative acceleration noise. The LISA PathFinder results will thus be applicable to a wide variety of gravitational missions requiring high precision measurement of the differential acceleration between free-falling test masses, including gravitational wave observation, geodesy, Shapiro time delay measurements, and $1/r^2$ tests on various length scales.

LISA: Laser Interferometer Space Antenna (LISA) is the first planned space based gravitational wave detector and a joint project between ESA and NASA. Three spacecraft in a heliocentric orbit will use laser signals to measure changes in the 5 million km interferometer arms which separate the spacecraft. Each spacecraft will have a drag free control system onboard to enable the effects of Solar Wind pressure to be eliminated in the observing band of 0.1 to 100 mHz. LISA should be ready for launch in 2020.

LISA will record the inspirals and mergers of massive binary black holes throughout the Universe and it will map isolated black holes with high precision. With its enormous reach in space and time, LISA will observe how massive black holes form, grow, and interact over the entire history of galaxy formation. Thus gravitational waves detected from these would provide an independent test of the scenario that galaxies have formed hierarchically. In addition they will provide very accurate mass and distance measurements, and these would contribute in a unique way to measurements of the Hubble constant and of dark energy. LISA observations of inspirals of massive black hole binaries could also constrain a variety of theories of gravity designed as extensions to general relativity.

LISA will measure the 3D positions and orbital properties of thousands of compact binary systems in the Galaxy, providing a new window on matter at the extreme endpoints of stellar evolution. In fact the LISA census of massive black holes and galactic compact binaries will basically be complete. Any merging massive black hole in the observable Universe will be detected. Above a few mHz, where the galactic binaries become individually detectable, LISA will observe all sources in the Galaxy. In addition, several LISA events will likely have electromagnetic counterparts at a wide variety of timescales and wavebands that will stimulate major new observing opportunities across the electromagnetic spectrum. It is also conceivable that LISA will discover new phenomena of nature, like phase transitions of new fields, extra dimensions or string networks produced in the early Universe.

There are a number of instruments in operation or ready to be launched that have astrophysical goals together with the potential for producing important results in the fundamental physics area. These are described briefly below.

Pamela: This is a free-flier on the Resurs-DK1 satellite, with Italian, Swedish and Russian involvement. It was launched in June 2006 and it main goal is to obtain state-of-the-art data on cosmic rays up to energies of ~ 1 TeV. High precision measurements of the electron, positron, proton, anti-proton and light nuclei (to Z = 6) and of the isotopes D and ^{3}He have been made. Of particular interest to fundamental physics have been the interpretations of data on the $\overline{p}/p$ and $e^+/(e^+ + e^-)$ ratios which put strong constraints on certain models of dark matter.

Fermi: The Fermi Gamma Ray Observatory, a NASA instrument involving European Institutions from several countries, was launched in June 2008 and is primarily designed to study gamma rays of energies above ~ 100 MeV from astrophysical sources. In addition there is the possibility of finding clear evidence of dark mater particles, such as neutralinos, by detecting the gamma rays expected when two neutralinos annihilate each other. Such annihilations will occur in clumps of dark matter such as might be found at the galactic centre.

One test of fundamental physics that will be explored with Fermi is the possible dependence of the velocity of light with wavelength. Differences are expected in some models of quantum gravity which attempt to merge Einstein's general theory of relativity with quantum mechanics. Turbulence of spacetime might result in velocity differences. Another test will be made by searching for the phenomenon of photon splitting in which a high-energy photon splits into two lower energy photons in, for example, the magnetosphere of a neutron star.

AMS-02: The AMS-02 instrument, which has involvement from 37 institutions world-wide including some 8 in European countries, is designed to operate on the Space Station; launch is expected within a few years. The instrument will measure the properties of cosmic rays with an improvement of several orders of magnitude over previous work. The key element of the AMS-02 experiment is a superconducting magnet which generates in a cylindrical volume of 0.6 m^3 a magnetic field of 0.9 Tesla. Inside this volume a high-precision double-sided silicon strip detector measures the trajectories of charged particles at 8 planes.

A key question to be answered is the amount of anti-helium in the cosmic ray flux. In addition the instrument will be used to search for objects weighing 10-100 times as much as a carbon nucleus, carrying less than 1/2 or 1/3 of the expected charge, 'strange quark matter or strangelets'.

AMS-02 also has the potential to study the positron to electron ratio, as in Pamela but with higher statistics, to search for cold dark matter.

GAIA: The mission GAIA (Global Astrometric Interferometer for Astrophysics), to be launched in 2011 and placed in the L2 Lagrange point of the Earth-Moon system, will carry out astrometric, photometric and spectroscopic measurements of celestial objects down to magnitude V=20. The core instrument is an optical interferometer built around two 1.45 x 0.50 m telescopes, capable of an end-of-life positional accuracy of 24 microarcseconds for stars of magnitude 15. In its five year nominal mission, the instrument will measure many times the positions of more than 10^9 objects. The extremely precise determination of the angular positions requires precise modelling of the light deflection from the sun and the planets. Rather than assuming $\gamma=1$ as in GR, GAIA will be able to determine that parameter to an accuracy of about 2×10^{-6} or better, thus providing an improvement by a factor of 10 over the Cassini determination. In addition, GAIA will be able to determine other PPN parameters (such as β) by optical tracking of asteroids with pericenters in the inner solar system. A specific experiment is also designed to determine the light deflection by Jupiter to evidence non radial deflection caused by its quadrupolar moment.

BepiColombo: Significant improvements in classical tests of GR will be possible with the mission BepiColombo to Mercury. The spacecraft, to be inserted in a low altitude polar orbit, is endowed with an advanced radio system providing range and range rate measurements, respectively to 0.1 m (after a few seconds integration) and 2 10^{-6} m/s at 1000 s integration time. In addition, an accelerometer will measure the spacecraft non-gravitational accelerations. This combination of instruments will provide Mercury's orbit in the solar system to 10 m or better, making possible a new determination of the PPN parameters β, η, α_1 , α_2, a dynamical determination of the solar J2 and a test of the constancy of G. Data acquired across solar conjunctions (both in cruise and the planetary phase) will provide also an improved determination of γ, to a level of 2 10^{-6}.

B.4 Ground vs space: future prospects on ground versus prospective missions.

There are clear advantages to go into space: a low Newtonian noise, free fall, long distances, large potential differences, large velocities. But there are also major drawbacks, the main ones being the cost of space missions and the time it takes to fully develop a mission up to the launch (some ten years in the case of the M-missions considered in CV1).

It is thus very important to assess what can be achieved on ground in the next ten years and compare it with what will be achieved in space with technologies which will be frozen at least 5 years earlier. In the following, we review a certain number of cases where this question plays an important role.

Clocks on ground vs clocks in space: expected developments in the next ten years

- Atomic clocks on ground

As already stressed in Section B.1, the test of the time invariance of fundamental constants is a test of local position invariance. It makes use of the transition frequencies between energy levels of atoms or molecules, which depend in different ways on the fundamental constants such as the fine structure constant α, the electron-to-proton mass ratio, the g-factors of the electron and nucleons, etc. The time-invariance of fundamental constants is best tested by comparing two closely located atomic/molecular clocks, i.e. measuring their frequency ratio. The close location permits keeping the height difference between the two clocks small and thereby performing an accurate correction for the time variation of the differential gravitational redshift due to the Earth. There is no immediate motivation for performing this type of test in space, except that in the more distant future, when clock performance beyond 10^{-18} will be the goal, today's methods for trapping particles may turn out to be inadequate because of too strong perturbations. However, weakening the trapping strength will eventually conflict with the need to prevent the particles from falling. Then, operating in space may be a solution.

Test of Local Position Invariance

In the gravitational field of the Sun, terrestrial clocks experience the gravitational potential U_S, which is time-varying due to the orbital motion r(t) of the Earth. If local position invariance is violated, a relative frequency change of two dissimilar clocks occurs, proportional to $c^{-2} U_S \Delta r(t)/r$. This quantity varies by $3x10^{-10}$ over the course of a year. A time dependence correlated with r(t) would lead to an additional signal in a clock comparison which can be distinguished from a hypothetical signal by a time dependence of the fundamental constants due to the latter assumed linear time dependence.

In more general terms, tests with clocks at varying distance from a massive body can be interpreted as searches for a variation of fundamental constants with ambient gravitational field, related to a coupling of matter to additional scalar fields whose source is the massive body. A colocated clock test in the gravitational field of the Earth differs in principle from an analogous one in the gravitational field of the Sun because the matter composition of Earth (mostly heavy elements with an important mass fraction stemming from neutrons) and Sun (mostly protons) differ significantly. Assuming that a dissimilar clock pair can be compared at two locations with a maximum height difference on the order 4 km (bottom and top of a tall mountain), the maximum relative effect is proportional to $4x10^{-13}$. Dedicated measurement campaigns of this type have not yet been performed with clocks, but in the course of terrestrial clock development colocated clock comparison tests will naturally take place, as the developing labs happen to be at different height,

Measurement of the gravitational redshift in the Earth field

Assuming that on the 10 year timescale one terrestrial clock type reaches inaccuracies of $1x10^{-18}$, and assuming the comparison of two such clocks located at the bottom and top of a mountain with 4 km height difference is possible (which is feasible using current optical fiber link technology), this would give a relative redshift resolution of $2x10^{-6}$. This is similar to the goal of the ACES mission (based on a clock with (1-2) $x10^{-16}$ inaccuracy). The gravitational potential difference would have to be measured with the same resolution by a chain of gravimetric measurements where distance measurements with millimetric accuracy and state of the art gravimetry must be employed.

- Atomic clocks in space

On the timescale of 10 years, it seems feasible to develop flight models of optical clocks with 1x 10^{-17} inaccuracy, ten times better than ACES. At the time of flight, terrestrial clocks may have reached a performance ten times better.

Spacecraft offer first of all large travel distances, which implies probing the gravitational field over larger distances, where the radius vector to a second clock can be oriented in different directions, as well as grazing paths around massive bodies. Three qualitative options, with increasing complexity and cost, are available: a low-altitude Earth orbit provided by the ISS or a dedicated satellite, a high Earth orbit, or an interplanetary mission. In the first two, the variation of Earth gravitational potential with respect to the Earth's surface is about two or three orders larger compared to a terrestrial experiment. For a test in the Sun's gravitational field using a planetary or solar mission the gain is between $2x10^4$ and $1x10^6$.

Gravitational redshift

The Earth's gravitational redshift measurement could be performed with a 10 to 100-fold improvement compared to ACES for a near-Earth and high altitude orbit, respectively.

A variation on this theme consists in making use of the high stability of optical clocks and a "modulated" orbit, in particular a highly elliptical one. The relevant potential difference is then not between space and ground but between points on the orbit, which simplifies the gravitational potential metrology. A large number of orbits enables statistical averaging and a further gain in precision by a factor of 10 seems possible.
The Sun's gravitational field redshift can be determined very accurately with an interplanetary mission, thanks to the large potential difference between the clock on the spacecraft and the terrestrial (or second space clock). The improvement associated with the measurement will be huge: for a clock with 10^{-17} uncertainty at Mercury, an improvement of 10^3 to 10^4 compared to the expected ACES results. The metrology of the gravitational potential with corresponding accuracy will require determining spacecraft-Sun and Earth-Sun distances at the meter and ten-meter level, respectively.

Test of Local Position Invariance (LPI)

As for an Earth gravitational redshift measurement also an Earth field-LPI test could be performed with a 10 to 1000-fold improvement compared to ACES for a low-Earth and high altitude elliptical orbit, respectively. It would necessitate two dissimilar clocks on the spacecraft.
A Sun-field LPI test with a spacecraft going close to the sun could take advantage of a very large gravitational potential (US mission proposal SpaceTime). Equipped with dissimilar optical clocks, the resolution of an LPI test would be outstanding, with an improvement of 100 compared to terrestrial measurements and in addition searching for effects to second-order in the gravitational potential.

Scale dependent gravity

Depending on the theoretical model used, a scale dependence of gravity will have different effects on the motion of massive test bodies, the propagation of light and the behavior of clocks (gravitational redshift). Therefore the observation of the motion of satellites and the evolution of onboard clocks via a microwave or optical link (light propagation) is sensitive to all three effects and thus allows the most complete characterisation of gravity and its variation with distance from the gravitating body. Ideally such observations should span the maximum possible range of distances, ie. a mission to the outer solar system would provide a significantly larger range than going towards the sun. However, even at smaller distances the additional observable provided by an onboard clock could be useful, as it will provide additional information towards separating fundamental physics effects from modelling errors and other systematic effects.

Test of light propagation (Shapiro time delay, light deflection)

A precision measurement of the gravitational delay requires a transponder or a clock on the opposite side of the sun from the observing station (Earth or second spacecraft) with a radio or optical link between the two at close (grazing) incidence to the sun during a conjunction. Using an optical link and an optical transponder (or clock) onboard a solar system orbit spacecraft during a solar conjunction, a measurement at the 10^{-7} level when using ground clocks or 10^{-8} level when using a clock on a second spacecraft seems feasible.

The following Table summarizes the improvement factors expected with 10^{-17} clocks in space, in comparison to those in principle feasible over the next 10 years on the ground and with the ACES mission, assuming that (transportable) ground clocks gradually improve to $1\text{x}10^{-18}$ inaccuracy level.

Mission type **Relevant gravitational potential difference**	Ground	ISS or low altitude orbit	Highly elliptic high-altitude Earth orbit	Inner solar system (Mercury)	Close fly-by of Sun (6 Solar radii)	Outer solar system
in Earth field	4×10^{-13} (c)	4×10^{-11}	5×10^{-10}	-	-	-
in Sun field	3×10^{-10} (f)	4×10^{-13} (d,e)	4×10^{-13} (d,e)	2×10^{-8}	4×10^{-7}	9×10^{-9}
Type of test	**Ground improvement in 10 years., incl. ACES**	**Improvement with next-generation space optical clocks**				
Time invariance of fundamental constants	40 (a,b)	-	-	-	-	-
Local Position Invariance I: Coupling of Earth gravity to fundamental constants	35 (c)	300	40 000 (k)	-	-	-
Local Position Invariance II: Coupling of Sun gravity to fundamental constants	10 (a,b)			70 (m)	1000 (m)	-
Redshift measurement in Earth field	35 (i)	350	40 000 (k)	-		-
Redshift measurement in Sun field	10 000 (e,g)	100 000 (e,k)	100 000 (e,k)	4×10^{7}	7×10^{6} (h)	2×10^{7}
Other science opportunities	Local mapping of Earth gravitational field at 10 cm level	Local and real-time mapping of Earth gravitationa l field at 1 cm level Lorentz Invariance	Local and real-time mapping of Earth gravitational field at 1 cm level Lorentz Inv.	2^{nd} order redshift test, Shapiro time delay x 100 Lorentz invariance	2^{nd} order redshift test Combine with Shapiro Time delay?	Probe gravity on large scale; Combine with Shapiro Time delay?

Table 1: Potential improvement of tests performed with 10^{-17} clocks in space, in comparison to those in principle feasible over the next 10 years on the ground and with the ACES mission, where the (transportable) ground clocks gradually improve to 1×10^{-18} level. Values are approximate improvement factors. See notes for explanations.

Notes:
a: dissimilar terrestrial clocks with inaccuracy gradually increasing to 1×10^{-18} level
b: combined improvement from clock improvement and long measurement time
c: ACES, in comparison with Gravity Probe A result
d: clock on spacecraft as part of link to compare clocks on ground
e: comparison via space link of terrestrial clocks separated by one Earth radius
f: due to Earth orbital motion, used for LPI test
g: using ACES for comparison of 10^{-17} ground clocks and a large number of repeats
h: limited by ability to measure spacecraft position; assumed to be 10 m at 6 solar radii
i: comparing ACES to ground clocks
k: assuming repeated measurements over many orbital periods reduce uncertainty 10 fold
m: dissimilar clocks on spacecraft

Auger vs EUSO: fundamental physics opportunities with ultra high energy cosmic rays

Currently the Pierre Auger Collaboration is operating a detector of 3000 km^2 containing 1600 water-Cherenkov detectors overlooked by 24 telescopes that detect fluorescence light produced by giant air showers as they propagate through the atmosphere. The integrated exposure now exceeds 10^4 km^2 sr yr and should reach 10^5 km^2 sr yr by 2020. A second observatory is planned for the northern hemisphere covering an area 7 times as large. Construction of this device might start in 2013 and take three to five years to complete.

The study of the very highest-energy cosmic rays can be extended by observations from space. A mission, JEM-EUSO, to be located on the Japanese Experiment Module (JEM) on the International Space Station, has been proposed as a new type of cosmic ray observatory that will use very large volumes of the earth's atmosphere as a detector of the most energetic particles in the Universe. JEM-EUSO (EUSO for "Extreme Universe Space Observatory") observes the brief flashes of light in the earth's atmosphere caused by cosmic rays of energy above ~ 5 x 10^{19} eV. The key element of the sensor is a very wide-field, very fast, large-lens telescope that can detect these flashes. JEM-EUSO is planned be mounted on the Space Station in 2015 and, in a projected life of 5 years, is expected to yield an exposure of (1.2 – 2) x 10^6 km^2 sr yr, after allowing for a duty cycle of 10 – 20%.

In addition to the astrophysical as aspects of ultra high energy cosmic rays, the JEM-EUSO mission has significant potential for fundamental physics exploration through the detection of photons and neutrinos. Measurement of the UHE photon flux will provide a direct constraint on the contribution of *top-down* models to the flux of UHECRs. Moreover, UHE photons are produced as secondary particles during the propagation of UHE protons. While high-energy photons have a limited horizon due to pair production over CMB photons, a known loophole of quantum gravity and the Coleman-Glashow effect may prohibit e^+e^- production above 30 TeV, allowing the UHE photon path-lengths extend beyond ~10 Gpc, which would result in an “anti-GZK effect” with an increasing number of sources contributing at higher energy – and thus a much larger flux of UHE photons. JEM-EUSO has the capacity to detect such photons and to identify them.

The ν-cross-section at high energies is very uncertain and highly model-dependent: a measurement is needed. Extra-dimension models in which the Universe is supposed to consist of ten or eleven dimensions are among the favoured models to unify quantum mechanics and gravitation theory. In these models, the neutrino cross-section is predicted to be 100 times that predicted by the Standard model. Under these conditions, JEM-EUSO should observe 100s of ν events, which would allow experimental validation of extra-dimension models. In addition, the ratio between the fluxes of horizontal and upward ν-originated EAS gives a quantitative estimate of the ν cross-section around a centre-of-mass energy of 10^{14} eV. JEM-EUSO has a strong potential for UHE neutrino detection, which also implies the possibility to constrain the source models directly.

The quantum space-time effects generically known as Lorentz-Invariance Violation (LIV) also predict a modification of the proton attenuation length, and thus of the GZK horizon, with direct consequences on the super-GZK proton spectrum. Indeed, a difference between the maximum velocities of protons and pions ($\delta_{p\pi}$) modifies the inelasticity of the pion production interactions at UHE, and thus the attenuation length.

The two instruments, the Auger Observatory and JEM-EUSO, should be seen as complementary. The Auger Collaboration is using well-established techniques in a wellunderstood environment and is capable of measuring the energy spectrum with high precision to 10^{20} eV and of making a detailed study of the nuclear mass composition. However the flux of particles that display anisotropy, as noted above, is too small to define spectra from individual sources while it is possible that only upper limits will be set on the fluxes of photons and neutrinos above 10^{19} eV and even if there are detections the numbers found are expected to be small.

The Auger Observatory is able to measure the energy of cosmic rays above 10^{19} eV to ~20%, the direction of the particle to 1º and can make statements about the mass of the nuclear component of cosmic rays through accurate measurements of the depth of shower maximum (to ~ 25 g cm^{-2}).

By contrast, JEM-EUSO will have an energy resolution of about 50% at its threshold of 5 x 10^{19} eV increasing to better than 30% at higher energies. The directions will be measured to about 2.5º and the depth of shower maximum to <120 g cm^{-2}. Although this latter figure will prevent separation of different nuclear masses, it is easily adequate for the detection of neutrinos and photons and, when combined with the enormous aperture, will provide the very important fundamental physics measurements discussed above.

Ground vs space interferometers for gravitational waves

In the last few years the first generation of large-scale interferometric gravitational wave detectors (LIGO, GEO600 and Virgo) have reached the original design sensitivity in a broad frequency window, achieving a sensitivity to detect a (dimensionless) strain amplitude of $h < 10^{-21}$ at a frequency around 100 Hz. The next decade will see the operation of an international network of ground-based gravitational-wave interferometers (Advanced LIGO in the US, Advanced Virgo and GEO HF in Europe, and LCGT in Japan) which will reach the level of sensitivity where the first detection can be expected (about one order of magnitude more sensitive than the first generation). Meanwhile, the discussion of third generation detectors has begun in earnest with the EU funded Einstein Telescope (ET) design study. The aim of third generation detectors is to improve the broadband sensitivity by another order of magnitude. On the other hand, LISA will provide detection in a frequency window which is inaccessible to ground interferometers and which is very interesting from the point of view of astrophysics and cosmology.

Ground-based gravitational wave detectors are sensitive to signals in the audio-band, ranging from a few Hz up to several kHz. They can detect a variety of astrophysical sources, including rapidly spinning non-axisymmetric neutron stars, supernovae, and coalescing binaries consisting of compact objects such as neutron stars and/or black holes, that give us an opportunity to investigate general relativity in strong field conditions.

Third generation detectors, such as ET, will be able to observe binary black holes with stellar- and intermediate (i.e. a few hundred times solar) mass, out to a redshift of z=2 and z=0.5, respectively, that would have an enormous impact in several key areas of astrophysics, cosmology and fundamental physics. Observation of intermediate-mass binary black holes would provide an inventory of the recent history of black hole formation in the universe.

When combined with the redshift of their electro-magnetic counterpart, binary black holes would lead to an accurate measurement of several cosmological parameters, and facilitate a deeper understanding of dark energy and its equation of state.

The origin of gamma-ray bursts (GRBs) has remained an enigma for over four decades after their serendipitous discovery in the 60's, although some are thought to be the result of the merger of neutron star-neutron star or neutron star-black hole binaries. ET could pin down the origin of GRBs and confirm or rule out their association with binary systems. Transient astronomical sources that are powerful emitters of radio waves and x-rays could also be visible in the ET gravitational window. For example, oscillations of neutron stars could be used to infer the equation-of-state and the internal structure of matter at extremes of density, temperature and magnetic fields.

ET would facilitate high precision tests of general relativity that are not possible with solar-system or binary pulsar observations. By probing the highly curved structure of space-time near dense objects we would be able to answer fundamental questions about the final fate of gravitational collapsing (is it a rotating black hole or a naked singularity or some other exotic object?) and confirm if the emitted signals from such events are consistent with general relativity to very high order in post-Newtonian perturbation theory.

The frequency domain much below one Hz can be only explored from space. LISA, with 5 million kilometers long arms, will cover a frequency range of 3.10^{-5} to 1 Hz, complementary to the frequency window covered by ground-based instruments. It should be stressed also that, contrary to present ground interferometers, the signal to noise ratio of most astrophysical events is large (from a few 10 to a few hundred) in the case of LISA. This makes LISA ideally suited for the study of massive black holes binaries that form after galactic mergers, compact stellar remnants as they slowly spiral to their final fate in the black holes at the centers of galaxies, galactic compact binaries and potentially the signatures of new physics beyond the standard model.

Ground vs. space for atom interferometers

Promising tools for fundamental physics tests in the quantum domain are matter-wave sensors based on cold atoms or atom lasers, which use atoms as unperturbed microscopic test bodies for measuring inertial forces or as frequency references. The rapid advance of atom-interferometer technology in recent years has motivated several studies and proposals : measuring forces at small distances, testing the universality of free fall, searching for gravitational waves ... Already in the very early papers on matter-wave interferometers based on the atom-light interaction as a coherent beam splitter mechanism it was pointed out that these devices are a symbiosis of an atom and a light interferometer. The atoms serve as read-out for the phase evolution of the beam-splitting laser. For testing the equivalence principle, two atomic species can be used simultaneously in a single atom interferometer and for gravitational wave detection, the effect of gravitational waves is monitored by performing a differential measurement between two space separated atom interferometers run simultaneously using the same laser pulses. In both cases, the laser provides a common "ruler" for comparison of the two interferometers. In the latter case, the distance between the interferometers can be large because only the light travels over this distance, not the atoms. The gravitational wave detection signal, which scales with this distance, can be competitive with light interferometers. In a sense, the atom interferometers are the analogue of the test masses in a light interferometer like VIRGO and it is the distance between them that determines the size of the signal.

For ground-based interferometer, previous calculations performed by the group of M.A. Kasevich at Stanford University have shown that there is an oscillatory gravitational wave signal in a configuration of two atom interferometers separated by a distance L that is as large as experimentally achievable. Intuitively the atom interferometer can be thought of as precisely comparing the time kept by the laser's clock (the laser's phase), and the time kept by the atom's clock (the atom's phase). A passing gravitational wave changes the normal flat space relation between these two clocks by a factor proportional to the distance between them. This change oscillates in time with the frequency of the gravitational wave. This is the signal that can be looked for with an atom interferometer. Equivalently, the atom interferometer can be thought of as a way of laser ranging the atom's motion to precisely measure its acceleration. Calculating the acceleration that would be seen by laser ranging a test mass some distance away in the metric of the gravitational wave shows a similar oscillatory acceleration in time, and this is the signal of a gravitational wave in an atom interferometer. This radar ranging picture is very similar to the foundation of the space-based LISA interferometer, where a macroscopic test mass is used instead of the atoms here.

A natural extension of all these proposals is to perform an experiment in space. The sensitivity of matter-wave interferometers for rotations and accelerations increases with the square of the measurement time. Current experiments on ground operate at about 100 ms, which could be extended in space to up to 10 or more seconds. For example increasing the measurement time ten times improves the sensitivity of acceleration measurement by a hundred times. As for long baseline light interferometers, the collimation of the source is important and operating in space implies reducing the speed of the expansion of the atomic cloud. The spectacular success of techniques to cool atoms with laser light and by evaporation resulted in temperatures of nanokelvins to microkelvins. Long interrogation time can be obtained on ground in fountain clocks, where atoms are launched upwards to take benefit of the slow expansion. Taking full benefit out of the accessible temperature range would mean to realise fountains with 10 to 100 meters height. The long flight distance represents an intrinsic problem, as all perturbations have to be shielded over this distance in a uniform way. Measures to compensate for gravity with additional forces unavoidably perturb the sensor and are therefore not a solution. Consequently, on ground the 1-g environment sets clear limitations for ultimate sensitivities. Microgravity is thus of high relevance for matter-wave interferometers and experiments with quantum matter (Bose-Einstein Condensates or degenerate Fermi gases) as it permits the extension the unperturbed free fall of these test particles in a low-noise environment.

Future of astrophysics instruments with relevance for fundamental physics

Currently studies of dark energy missions and ground-based instruments that can be used to constrain the properties of dark energy are under way. As the results are not yet fully known, we leave these out of this first version of the roadmap. Here we briefly describe the next generation general astronomy instruments and the expected improvement in tests of fundamental physics that they will offer.

The Square Kilometer Array (SKA) is a large radio telescope planned to be operational around 2020. It will discover thousands of new pulsars, including possibly more extreme systems than currently known such as pulsar – black hole binaries, and provide a new basis for pulsar timing array measurements of very low frequency gravitational waves. More pulsars and in particular lower residual noise will improve the sensitivity compared to current pulsar timing arrays by several orders of magnitude..
There are plans to study UHECRs and neutrinos with energies above 10^{20} eV using radio telescopes (in particular SKA) to observe emissions from the regolith of the moon. No such detections have been made in preliminary work by the GLUE project, using the Goldstone radio telescope. Pilot projects using the Westerbork Synthesis Radio Telescope Array are under way. These efforts are particularly interesting for the highest energies, substantially above 10^{20} eV where the technique is most sensitive and thus are complementary to JEM-EUSO which is designed to work at lower energies where UHECR are known to exist.

Continued pulsar timing studies will give increasing accuracy in their tests of GR as some effects (apsidal angle and time of periastron) are secular effects that build up in time.

The next generation optical telescopes (Extremely Large Telescopes or ELTs) will have diameters in the 20-40m range and are expected to become operational in 2015-2020 time frame. They will be able to observe supernovae to much larger distances and may provide strong constraints on varying fundamental constants or time varying redshifts by very high accuracy spectroscopy.

C. A roadmap for fundamental physics in space

C.1 Key science objectives

Before embarking in the next Section on setting up priorities in fundamental physics for the space programme, let us pause to summarize the key scientific objectives, as well as the experimental or observational means necessary to address the corresponding questions (in bold are those means specific to the field of fundamental physics).

- Can we make new tests of the fundamental principles of GR?

(**properties of gravitational waves in the 10^{-4}, 10^{-1} Hz range, test of equivalence principle, measurement of PPN coefficients, clock redshift**)

- What is the law of gravity at all scales?

(**motion of massive bodies, propagation of light, clock redshifts**, galactic and cosmological observations)

- How does gravity behave in the strong field regime (close to black holes, neutron stars)?

(**gravitational waves in the subHz range**, X-ray missions,…)

- Is Lorentz invariance a symmetry of our Universe?

(**test of local Lorentz invariance, test of the equivalence principle, study of distant sources of energetic particles and photons**)

- Can we make new tests of the laws of quantum mechanics?

(**entangled photons, matter interferometry**)

- Can we get insight into the possible unification of gravity and the quantum theory (Standard Model)?

(**test of equivalence principle, nonconstancy of constants, test of Lorentz invariance, neutrino cross section at high energies, detection of superheavy particles**)

- If dark energy exists, what is its nature?

(**test of equivalence principle, tests of nonconstancy of constants, test of long range forces,** gravitational lensing, standardizable candles/rulers…)

- If dark matter exists, what is its nature?

(**detection of high energy cosmic particles**, **test of long range forces,** lensing)

- What are the mechanisms of the acceleration of cosmic particles?

(**detection of high energy cosmic particles of various kinds**)

C.2 Priorities for the space program

- Approved missions

It has already been stressed that a certain number of missions have already been approved, namely LISAPathfinder, ACES and Microscope. These missions have allowed the development of some key technological programs for the future of fundamental physics in space. It is of vital importance for the field that they are launched. This will increase the TRL of some important subsystems, a key to the success of future missions.

- Candidate missions of CV1

It is not in the mandate of the Advisory Team to discuss missions already present in CV1. We only stress here their importance for the field of fundamental physics.

The dark energy mission EUCLID is presently undergoing a further selection process. We thus refrain to interfere with this process. As is clear from the discussions above, the issue of dark energy has far reaching consequences in fundamental physics.

The LISA mission was included two years ago into the competition for the L1 mission of the Cosmic Vision program. It will undergo the next selection in some two years. Obviously, the LISA mission is central to fundamental physics, both through its scientific program and the technologies developed for its completion.

- Regarding the forthcoming M3 call, it is felt by the Advisory Team that it is important to provide guidelines for a mission that would improve by some two orders of magnitude the precision of key parameters testing the laws of gravity, especially general relativity.

Given the expectations of space clock development (see the subsection “Clocks on ground vs clocks in space” and especially Table 1 in Section B.4 as an important input to the present discussion), one may seriously envisage an M-mission with an optical clock, addressing a large number of the scientific questions listed in subsection C1. Assuming an uncertainty of the onboard clock of $1x10^{-17}$, and an optical link allowing the comparison of such a clock to ground optical clocks at the same level of uncertainty, one can envisage two scenarios that would allow significant improvements (> 100) on several key parameters (see Table 1). In a high Earth orbit, such a mission could provide an improvement by about two to three orders of magnitude on the redshift measurement expected from ACES, perform improved LPI (Local Position Invariance) and LLI (Local Lorentz Invariance) tests, and contribute to other fields (international time/frequency metrology, geodesy). In an inner solar system orbit (approaching the sun to about Mercury distance) the improvement of the redshift measurement with respect to ACES would be 10^3 to 10^4, with 10^3 improvement on the LLI test (with respect to ACES) and moderate improvement on the LPI test. Additionally a solar conjunction would allow a measurement of PPN γ at the 10^{-7} level or slightly below (limited mainly by the terrestrial atmosphere) representing an improvement by more than an order of magnitude on the result expected from GAIA and BepiColombo. An onboard accelerometer (and possibly drag free technology) will be essential for precise orbit determination in the presence of non-gravitational perturbations. Finally, an extension of the orbit towards the outer solar system (possibly to Jupiter or further), if feasible, would allow some insight into scale dependent modifications of the S/C trajectory, light propagation and clock frequency.

- Equivalence principle and accelerometers

As we have discussed above, tests of the principle of equivalence are at the heart of fundamental physics and are an important tool to get deeper insights into the fundamental interactions. The current findings such as dark energy and dark matter motivate tests even more than in previous times.

On ground, tests have been performed with an accuracy of 1 part in 10^{13} by pendulum experiments and lunar laser ranging. Currently the MICROSCOPE mission is prepared to test the free fall of classical macroscopic test bodies in a near-earth orbit with an accuracy of parts in 10^{15}. Future tests aiming at 1 part in 10^{17} and better are considered a very important test of the fundamental laws of nature and have to be developed further.

There are different approaches and technologies outlined showing the potential to achieve this goal. Current approaches, including that adopted by for MICROSCOPE, use carefully machined bodies of different materials combined with different read out techniques such as electrostatic sensors, superconducting magnetometers or optical interferometry. A new, alternate approach is based on quantum sensors which rely on the wave nature of matter. Depending on the findings of the MICROSCOPE mission, developing complementary experimental techniques, with different systematic uncertainties and possibly probing different physical models, may become even more important.

Testing the weak equivalence principle at the 10^{-17} level is the object of several mission concepts involving macroscopic test masses. STEP, and related proposed experiments, extends the MICROSCOPE concept with contact-free test masses, liquid He-temperatures, and a SQUID-based readout, with cryogenic and SQUID heritage from the NASA GPB relativistic gyroscope mission. The GG concept aims at similar sensitivities and employs mechanically suspended coaxial test masses in a “spinning top” configuration, which moves the EP-violating signal to the 1 Hz bandwidth. Other possibilities include an upgraded

MICROSCOPE configuration exploiting laser interferometry and contact free test masses from LISA Pathfinder to reach higher sensitivities.

The success of converting such equivalence principle test concepts into funded missions will hinge on their ability to demonstrate – either on ground or with drop towers, parabolic flights, or ISS/ATV flight – that their sensitivity goals are compatible with possible performance. This includes pushing measurements of systematic error sources and stray force noise, in addition to readout noise, near to the levels needed in space. A compromise will have to be achieved between the most ambitious science return and realistic probability of a successful mission within budget and time scale constraints.

Testing the equality of inertial mass and gravitational mass with matter waves would extend tests of the principle of weak equivalence to the quantum domain. Some theorists support the idea that tests of the principle of equivalence have to be performed with quantum particles or matter waves. Laser cooling and quantum degenerate gases allow engineering of giant delocalised wave packets of matter, which are subjected to gravity and can be seen as new kind of test masses, which can be pure isotopes of bosonic and fermionic nature. These matter wave interferometers work as calibration-free gravitational sensors. Experiments are being prepared on ground and for space in the ambition to be even more sensitive than current test with classical bodies. The experimental concept is based on matter wave interferometers, where mater waves are coherently split to propagate through gravity over several classical trajectories. Ground based studies aim to narrow down the gap between the sensitivities one may expect in space to achieve more precise extrapolation for the accuracies beyond the MICROSCOPE level towards the range of 1 part in 10^{17} and beyond.

The accuracy and sensitivity of local-acceleration measurements using atom interferometry nowadays rival state-of-the-art conventional accelerometers using macroscopic test masses. With such sensors, the quantity measured directly relates to the acceleration of weakly interacting particles via experimentally well-controlled quantities, such as laser wavelengths. In addition, the evolution of these particles in the gravitational field can be modeled within a covariant quantum field theory. Recent results using atom-interferometric gravimetry to compare the acceleration between two isotopes have demonstrated the possibility of atom-interferometric tests of the UFF. Ongoing efforts to extend the size of inertial-sensing atom interferometers by increasing the interrogation time open the door to high-accuracy atom accelerometers which will be very sensitive to smaller accelerations, thus pushing the limits of these tests. These long interrogation times, i.e. large free-fall heights, can be achieved when using a large experimental chamber to launch the atoms such as a 10 m-high fountain.

Compact apparatuses can also be used in reduced-gravity environments, such as drop towers, orbital platforms or atmospheric parabolic flights. Atoms, isolated in a vacuum chamber, are truly in free fall in the Earth’s local gravity field, as long as they do not hit the chamber walls, or experience field gradients (optical or static magnetic). Measuring differential phase between similar interferometers using the same light has been shown to reject common-mode inertial noise up to large scaling factors and this method can be efficient in performing a differential measurement between two inertial sensors using atoms of different mass and interrogation wavelength. Even for large vibrational noise, and large interrogation times, the measurement of the differential phase shift, i.e. the acceleration difference, can be measured to a high precision. This opens new perspectives for the development of high precision test of fundamental physics such as tests of the equivalence principle. For example, a precision of $\eta \sim 5 \times 10^{-11}$ could be achieved with a free-fall time of 4 s in the Zero-G Airbus, such as for the ICE experiment. Next-generation tests of the UFF should then be developed on dedicated orbital platforms where a target accuracy of $\eta \sim 8 \times 10^{-15}$, close to that of the project μSCOPE , is reachable with no specific drag-free platform. On a dedicated satellite mission a maximum differential accelerational sensitivity of $5 \cdot 10^{-16}$ m/s^2 corresponding to an accuracy of the test of the equivalence principle of 1 part in 10^{16} could be achieved.

- Missions to the outer solar system

We have stressed above the importance of testing gravity at all distance scales.
Dedicated missions and instruments will contribute to closing the observational gap between precision Earth-based observation (*e.g.* LLR, *i.e.* Earth-moon distance) and astronomical observations. Generally speaking, one expects observable effects on the gravitational motion of test-bodies, the trajectory of light, and the behavior of clocks, as a function of distance to the gravitating body. In most space experiments one observes a combination of those three effects, so diverse experiments are required to disentangle them and restrict the corresponding parameter space of alternative theories.

In this context, planetary missions to the outer planets and can play an important role, as their gravitational trajectories, when sufficiently well determined and controlled, offer the current best large scale probe of some of the observable effects discussed above. In particular, any inconsistencies in the analysis and modeling of the navigation data may be hints towards new physics. However, such missions are optimized for their primary (planetary) objectives, and as a result the information available on fundamental physics is not always unambiguous and/or sufficiently precise. In future planetary missions, it would therefore be desirable to include fundamental physics objectives, and if necessary related instruments (when possible), at the earliest possible stages of the mission design.

In future missions to the outer solar system, the key technologies for the efficient study of scale dependent gravity are those required for precise spacecraft navigation and high precision timing: accelerometers and drag free technology, atomic clocks, high performance radio and/or optical links. Ideally, a combination of all of those technologies on a trajectory reaching the outer solar system would provide the most complete mapping of gravity at all attainable scales by man-made artifacts. More modestly, partial inclusion of such technology (with sufficient performance) on planetary missions and/or planetary landers would continue to provide useful information for fundamental physics.

It is felt by the Advisory Team that the science gain from going to the outer solar system does not warrant a dedicated fundamental physics L class mission, as most fundamental physics science objectives of such a mission (with the exception of scale dependent gravity measurements) can be achieved in a more modest mission to the inner solar system. However, an L class mission could be of interest when combined with planetary objectives, and such opportunities should be further explored (Neptune and its moons, Pluto and other Kuiper belt objects,…).

A more modest M-class mission, although less sensitive and less complete, would be of strong interest for the study of large scale gravity, in particular when combined with planetary objectives, like for example the exploration of Neptune and its moon Triton (cf. the Argo proposal) and Kuiper belt objects. However such a mission might be difficult for ESA alone because of the lack of RTG power supplies in Europe, a point that needs to be clarified in the short to medium term ESA technology development plan.

In conclusion, planetary missions to the outer solar system have been (Viking, Cassini-Huygens) a major source of information for fundamental physics in the solar system, and have triggered large interest in the field. This is likely to continue with future planetary missions, provided the fundamental physics objectives and specifics (precise navigation, additional instruments, …) are sufficiently taken into account at an early stage in the mission development. Dedicated fundamental physics missions to the outer solar system (L or M class) are of particular interest in the context of scale dependent gravity, but their chances of selection and success will likely depend on a good combination and compromise of fundamental physics and planetary science objectives.

- High energy missions

In the field of high energy astrophysics, there is a flurry of activity around the signals provided by particle detectors in space (PAMELA, Fermi), and their possible connection with dark matter annihilation. The AMS02 mission will now be launched very soon. Once its first results are obtained, the situation will hopefully clarify. This might lead to the concept of a new mission proposed for the M3 call. It is however felt by the committee that it is presently too early to identify this concept.

- Mission of opportunity: JEM-EUSO

The JEM-EUSO instrument offers a mission of opportunity of interest to scientists in France, Germany, Italy and Spain as well as in Japan, Mexico and the USA. The proposal is to fly a telescope of 2.5 m diameter with ± 30º field of view on the International Space Station to observe cosmic rays above 4×10^{19} eV through the fluorescence radiation that they create in the Earth's atmosphere. It is a high-energy astroparticle physics mission post-PAMELA, AMS and Fermi that offer significant opportunities in fundamental physics and, given 5 years of operation, will provide an exposure more than a factor of 10 larger than likely to be achieved with the Auger South Observatory.

C.3 Technology

Fundamental Physics in Space employs a very wide range of technologies to achieve the instrumental performance required for each mission. In most cases the signals being searched for are at the limits of detection and there are many systematic effects and spurious signals which can generate false outcomes. The scientific progress is therefore very closely linked with the development of precision technologies. This makes such missions challenging for scientists and engineers but also very fruitful as test beds for emerging technologies which have immense potential in other fields of application.

Different stages can be identified in the development of fundamental physics technologies for space:

1) Theoretical and laboratory demonstration of new concepts
2) Improvement of the technological readiness level in cooperation with industry
3) Manufacture, testing and delivery of flight hardware.

While stage 1 might be expected to take place in Universities and research laboratories it is important that there is close cooperation between such institutes and industrial partners with space experience from the earliest moments of stage 2. Indeed, involving appropriate industry even in stage 1 can be beneficial in ensuring that appropriate choices are made of critical components. The QA and schedule requirements of stage 3 make it mandatory that this be carried out by experienced industrial companies, but with the originating institutes available as consultants to support the achievement of the desired performance.

Fundamental Physics can sometimes be carried out as a passenger activity on other space science missions. To facilitate this method of working, ESA should consider offering the early study outputs of all missions to the Fundamental Physics community for analysis to see if a cost effective addition to the payload would generate important new science in the field of Fundamental Physics.

Free-falling test masses, electrostatic accelerometers and drag-free satellites

A large class of fundamental gravitational experiments involve the measurement of the relative acceleration between free-falling test bodies. This ranges from weak equivalence principle tests – where the differential acceleration between nominally coincident test bodies is measured – to gravitational wave observation – acceleration between distant test masses – to time delay and deep space gravity tests with the relevant acceleration that between a distant spacecraft and the earth.

A detector of the relative acceleration between a spacecraft and a free-falling "geodesic reference" test mass inside the spacecraft is at the heart of many of these measurements. Non-gravitational forces acting on the satellite can be effectively removed, by measurement and subtraction or by active orbit compensation. These two principle operations modes are

- Accelerometer mode, in which the reference test mass is forced to follow the satellite, with the satellite non-gravitational acceleration calculated from the applied force;
- Drag-free mode, in which the satellite thruster system uses the sensor of relative test mass-spacecraft displacement to actively servo the satellite to remain centered with respect to the geodesic reference test mass.

Electrostatic displacement sensors and force actuators, commonly referred to as electrostatic accelerometers, are used extensively in both of these roles, including:

- Measurement of non-gravitational spacecraft accelerations for precision trajectory and time delay measurements (BepiColombo), geodesy (GRACE), and future possible deep-space gravity tests.
- Measurement of the relative acceleration of different free-falling test-masses inside the same spacecraft, for a weak equivalence principle measurement (Microscope), and geodesy (GOCE), both employing drag-free control using at least one free-falling test mass.
- Displacement measurement for a drag-free control, and, in general defining the free-fall environment, for a geodesic reference test mass, such as for LISA and LISA PathFinder. Here an interferometric readout substitutes the electrostatic sensor in the most sensitive measurement axis, with the electrostatic sensing and actuation used for sensing and control of the additional degrees of freedom.

Europe has the lead in high precision electrostatic space accelerometers, with the ONERA-based accelerometers flying on-board of GOCE (and planned for Microscope) defining the current state-of-the-art. This allows accelerometry at the $pm/s^2/Hz^{1/2}$ level at several mHz, with displacement sensitivity of order tens of $pm/Hz^{1/2}$.

Several factors limit the sensitivity of electrostatic accelerometers. The inertial or geodesic reference test mass is connected to the surrounding sensor by a thin wire, which fixes the test mass potential in the presence of charging from cosmic and solar particles. The wire introduces sensitivity limiting force noise and an unknown force offset. Small test mass-sensor gaps, of order hundreds of microns, allow pm-sensing, but also introduce significant force noise from stray electrostatic fields and Brownian residual gas impacts. Finally, in applications without drag-free control, the application of electrostatic forces invariably introduces a noisy test mass acceleration, in addition to a force calibration issue for cases where the relevant acceleration must be known to high relative accuracy.

The LISA gravitational wave mission builds on ONERA electrostatic hardware to push the use of geodesic reference test masses to the needed $fm/s^2/Hz^{1/2}$-level. The ground wire is removed, leaving no mechanical connection between spacecraft and test mass. Large, several mm gaps limit stray electrostatics and gas impacts. No electrostatic forces are applied along the sensitive measurement axis, with the spacecraft drag-free controlled. Ground testing with torsion pendulums has demonstrated the absence of unknown acceleration noise sources at the level of tens of $fm/s^2/Hz^{1/2}$ inside the electrostatic sensor, and the LISA Pathfinder mission will provide an all-encompassing acceleration noise test at levels approaching the LISA goal.

The improved performance with the LISA hardware increases complexity and price. The larger gaps limit the electrostatic position sensitivity to the $nm/Hz^{1/2}$ level, which requires the use of an interferometric position readout to reach sub-femto-g acceleration measurement noise at most frequencies. The lack of a grounding wire requires a UV photoelectric discharge system to control cosmic ray charging. Finally, the drag-free system demands high precision, low noise, and long life microNewton thrusters.

In the absence of a drag-free satellite system, an “absolute” accelerometer with high relative accuracy and very low “DC bias” is needed for accurate measurement of the DC or very low frequency acceleration of a satellite. An electrostatic sensor, based on the GOCE heritage, and designed to remove a DC acceleration bias from forces originating in the sensor itself, is currently under development for application in deep space trajectory measurements. The sensor would allow 180° rotation of the accelerometer, thus reversing the sign of any sensor-related test mass acceleration, aiming to allow a "low-bias" accelerometry measurement valid to the 10^{-7} Hz frequencies relevant to a deep space gravity test with spacecraft tracking, to the 40 pm/s^2 level. Such an instrument (GAP) is proposed for inclusion on a planetary mission, as suggested by the FPAG recommendation FPAG(2007)8. More generically, accelerometers with good performance at low frequency are developed in different groups as less costly and less complex alternative to full drag free operation where feasible.

A key technical hurdle for low bias accelerometry and drag free systems for use at DC or extremely low frequency, whatever the type of sensor, is the test mass acceleration due to the self-gravity of the spacecraft itself. The LISA PathFinder mission, for instance, must achieve, and will test, spacecraft self-gravity control to the nm/s^2 level, and significant improvement upon this is demanding for spacecraft design and integration.

A drag-free control system uses an array of high precision thrusters to keep the spacecraft centered upon a geodesic reference TM, based on the readout of an electrostatic or interferometric displacement sensor. In the limit of high drag-free gain, with thruster control quick enough to provide high attenuation of force disturbances acting on the spacecraft, the spacecraft follows the TM to within the displacement sensor noise, giving several key advantages:

- In the absence of applied electrostatic forces, a limiting source of force noise and dynamic range is removed, resulting in a better geodesic reference.
- The quiet spacecraft motion reduces the coupling into the motion of the test mass, again reducing the overall acceleration noise of the reference test mass.
- The quiet spacecraft becomes an inertial platform for further small force experimentation.
- For applications where the test mass (or spacecraft) acceleration must be known to high accuracy, the electrostatic force calibration is eliminated, as is, to first order, the displacement sensor calibration.

Drag-free systems have been implemented on GOCE and GPB, and are envisioned for the upcoming Microscope and LISA PathFinder missions. These last two, and LISA, will employ ionic and/or colloidal propulsion. Development of reliably and durably performing microNewton thrusters has been a challenging technical issue for these missions. Demonstrating their performance is a key aspect of LISA Pathfinder, and testing their useful lifetime for the longer LISA mission remains an important ground testing issue.

Recommendations:

- Launching LISA Pathfinder without further delay is of vital importance to the development and validation of low noise electrostatic accelerometers, drag free technology, and future missions in fundamental physics.
- Ground testing of longer lifetime microNewton propulsion is key for Microscope, LISA and any future multi-year drag-free mission.
- The development of low bias accelerometers, compatible with 10 pm/s^2 spacecraft tracking at frequencies down to 10^{-7} Hz and below is essential for gravity tests using dedicated or planetary missions, and should be pursued. In parallel the

accommodation of such accelerometers onboard the spacecraft and corresponding constraints (including self-gravity) should be investigated from the early stages of the mission design.

- Future missions demanding significant improvement on the fm/s^2-level of free-fall, such as advanced gravitational wave missions, will demand, in addition to all-optical sensing, redesign of the gravitational reference hardware that houses the test mass, likely including significant pressure reduction (below the 10^{-6} Pa level targeted for LISA), larger test mass-sensor separation and/or larger test mass.

Development of optical clocks for space applications

In ground-breaking work performed in Europe, a high-performance cold-atom space clock (PHARAO), an active hydrogen maser (SHM, space hydrogen maser) and associated systems for frequency comparison with ground (MWL, microwave link) have been developed to engineering model level in 2009, a flight model is under construction and to be delivered in 2011. The flight model will be part of the ACES mission ready for launch to the ISS in 2013. The specifications of the PHARAO cold atom clock are $1\times10^{-13}/\tau^{1/2}$ instability (up to 1 000 000 s) and 3×10^{-16} inaccuracy, with a goal of 1×10^{-16} for the latter.

A second flight model of PHARAO for another mission after ACES could be built, capitalizing on the initial investment. The cost would be modest compared to the total cost incurred until delivery of the first flight model. This second clock could be used for a number of missions exploring fundamental physics., capable of producing science results beyond ACES, both with Earth orbiting and interplanetary missions.

Optical clocks represent the next generation of clocks. Considering the performance of PHARAO and considering the efforts and the high costs that the development up to flight hardware of an optical clock would require, such an investment is only justified and will only find support if its metrological performance or other properties (dependence of fundamental constants) will enable science results significantly richer than those achievable with the available space clocks, in particular PHARAO. Parameters such as volume, mass, power may play a role in the mission as well.

For fundamental physics, the availability of a clock with performance significantly superior to that of PHARAO is seen as very important. The higher precision of the experiments that one could reach with an optical clock of such performance could be a decisive factor in justifying a mission. An optical clock also allows more simply the use of a laser link from the space clock to ground clocks, should this be necessary for particular mission scenarios. It is therefore suggested to develop a space clock that will have a performance a factor 10 better in accuracy than PHARAO, as well as a hundred-fold better stability.

Concerning state-of-the-art in Europe, the national metrology and university institutes have developed laboratory optical clocks of different type (single ion, neutral atom ensembles) and are in the process of developing new types. Inaccuracies and instabilities achieved at present are still considerably distant from the above goal, with lowest values at the 4×10^{-16} level. Laboratory optical clock developments are planned to reach 1×10^{-16} inaccuracy for neutral atom optical clocks within the year 2010 (PTB, SYRTE), and a similar level for ion clocks (PTB).

The existing experience on space clocks and current development activity in this direction is in particular:

1. Significant know-how exists in the groups and companies that have developed ACES and more specifically PHARAO. A large number of sub-systems or components as well as modeling, specifications, and testing know-how has been acquired in developing this space atomic clock, on items such as narrow-linewidth lasers, shutters, optics, optical bench, acousto-optic modulators, injection-locking, fibers, UHV vacuum vessels, magnetic field control, thermal control to minimize systematic shifts, calibration and operational procedures, and many more. This is an extremely important experience base that can be applied well to optical clocks and it is considered absolutely necessary to use it in order to save costs and time.
2. Additional space-qualified subsystems (frequency-stabilization units based on ULE cavities, fiber lasers) already developed by space industry in ESA member states for other applications could be adapted to the optical clock needs.
3. A European consortium has made a significant effort in developing compact and transportable optical clock demonstrators, based on lattice-trapped neutral atoms. The development includes a Sr breadboard, a Yb transportable apparatus and the corresponding compact clock laser subsystems. The two clocks are planned to become operational by mid 2010. This work has been funded in the ELIPS program of ESA within a mission plan that foresees a flight on the ISS around 2020. The goal of this development is an optical clock with a performance at the few 10^{-17} level in inaccuracy and an instability, such that it will allow comparing future ground clocks at the few 10^{-18} level as well as performing a ten-fold improved measurement of the gravitational redshift. This consortium has recently been enlarged to 16 European groups, including all major national metrology laboratories, as well as non-space and space industry, in order to effectively continue the development of the above clock demonstrators. In line with a given, moderate funding envelope the goal has been set to demonstrate $1\times10^{-15}/\tau^{1/2}$ instability and $< 5\times10^{-17}$ inaccuracy within a 4 year time span on a breadboard-type clock. The consortium's main rationale behind a development of this type of clocks for space are:

- In the laboratory (NIST, JILA, both in the USA), these clocks have reached performance beyond the best microwave clocks. As of 2009, an uncertainty of 1.5×10^{-16} (Sr at JILA, 2008), limited in part by the black-body radiation shift, and an instability as low as 3×10^{-17} (Yb at NIST, 2009) have been demonstrated.
- It takes advantage of the fact that laboratory lattice clocks and transportable lattice clock demonstrators are under development in 8 European groups, including all major national metrology labs, ensuring a deep and widespread interest, rapid progress, a numerous base of researchers . In paticular, the know-how is not concentrated in a single group. This widespread activity also provides a pool of scientists for space industry to involve in and hire for industrial development of space clocks.
- The development will in particular profit from ongoing studies on laboratory lattice clocks being funded by non-space agencies. As an example, the black-body shift, one of the major systematics, is under study in several national metrology labs. The results of this study, combined with the space industry's experience in thermal control of the atomic environment of the PHARAO clock are expected to allow control of this systematic at the 1×10^{-17} level.
- The required technology for lattice clocks is well under contol, widely available, with most items being commercial off-the shelf components, and offering at least two

different laser technology approaches. The overall system is of a complexity that is reasonable if related to the performance.

Trapped ion clocks offer an alternative to neutral atom ones with equal potential in terms of accuracy and interesting prospects in terms of mass and power budgets. In ground laboratories (NIST, USA) different types of trapped ion clocks (Al^+ and Hg^+) show inaccuracies at 2×10^{-17} and more recently at 9×10^{-18} for one of them, however the complex technology (quantum logic for Al^+ and cryogenics for Hg^+) is not easily adaptable for space clocks. In Europe single trapped ion clocks based on $Yb^+$and Sr^+ have reached inaccuracies of 4.5×10^{-16} and 3.8×10^{-15}, respectively with good prospects of further improvements compatible with the few 10^{-17} goal mentioned above. The technology of those clocks is much more readily adaptable for space than that of the US clocks (Al^+ and Hg^+)

A good part of the new technology developments needed for space optical atomic clocks is independent of the type of atom or ion used (e.g. high-power diodes, ultra stable optical cavities, frequency stabilization, frequency comb, frequency conversion, etc…) and thus generic to the field.

<u>Recommendations:</u>
As PHARAO/ACES have shown, space optical clock development will be very expensive, and the cost is unlikely to be borne by a single country, nor can the work be performed by a single or a few groups. It is imperative to have a Europe-wide activity, and that the development builds on the already existing know-how and capabilities of European industry, European scientific laboratories, and use all suitable existing hardware. Duplications are to be avoided. Only in this way can an efficient use of previous investments and future funding, as well as an efficient and quick progress be made. As funds for development will be limited, concentration on the most promising and realistic system for achieving 1×10^{-17} inaccuracy and $1\times10^{-15}/\tau^{1/2}$ instability is required. In view of this, we recommend :

1. An efficient use of available know-how and resources, previous investments
2. An efficient coordination between the activities of research groups in various countries, and the national agencies and ESA, so as to allow rapid progress
3. First performing the technology development on items that are already well-established in laboratories as well as COTS, towards space versions
   (3.1) the space-qualification of the diodes, fibers, and crystals and coatings for clock, cooling, and manipulation lasers .
   (3.2) the clock laser subsystem (incl. reference cavity) with $<5\times10^{-16}$ instability
   (3.3) the lasers' frequency stabilization, frequency control and power control units.

These activities are suitable for being performed at an industrial level, building on existing experience with diode laser chips, external cavity diode laser subsystems, frequency stabilization, and optical bench. They can be funded in a GSTP or a similar technology development program.

4. The development of the atomics package should follow as a second, later step, taking advantage of significant conceptual improvements, tests and characterizations that are planned or ongoing in research labs in the mean time.
5. As a third step, space technology development for a frequency comb with performance compatible with the above clock specifications is required.

Recent developments on new laser technologies (miniature high-power lasers, micro-optics, integrated optics, micro-combs) are alternatives worth studying in research and development laboratories up to tests on laboratory clocks, for possible subsequent space technology development.

Development of optical links

All space missions use electromagnetic links for navigation, time/frequency transfer, and communication. Generally speaking, the carrier frequency, the modulation frequency and the modulation method (amplitude or phase modulation) all play an essential role in the design and success of the link and therefore the mission. In the radio domain the evolution of the last decades has been marked by a continuous increase in frequency from a few GHz to 30 GHz and more (Ka band) and by the increased use of multifrequency links to mitigate dispersive effects (solar corona, ionosphere). That evolution was accompanied by a corresponding increase of modulation frequency and increased use of phase/frequency modulation (rather than amplitude modulation). The reason for that development is the rapid gain in signal to noise ratio with increasing frequency and the corresponding improvements in measurement precision and data rates. A high-performance link for clock comparisons and time transfer experiments is presently under development in the ACES mission. ACES MWL (MicroWave Link) is a two-way two-frequency (Ku-band and S-band) system that will allow comparison of remote clocks to a frequency uncertainty below 1×10^{-17} after one day of integration time. MWL technology, presently developed and tested to engineering model level, is widely applicable on Earth orbiting satellites, offering the major advantage of being insensitive to weather conditions. Over large distances, the limits of radio links are imposed by the required power which requires large antennas with corresponding difficulties on the control of the antenna motion (vibrations etc.) and thermal noise.

The future development of high performance links will most likely follow the evolution of the last decades, ie. the increase of carrier and modulation frequencies. In this perspective a major technological step is in progress, with the passage from radio to optical frequencies corresponding to a frequency leap of about 5 orders of magnitude. The first step of this change has been achieved by the use of pulsed lasers for satellite and lunar laser ranging, and satellite altimetry. That method has been recently adapted for time/frequency transfer (Time Transfer by Laser Light, T2L2) which is presently being validated onboard the JASON-2 satellite. The basic principle of pulsed optical links is an amplitude modulated optical carrier frequency with typical pulse durations of order 10^{-11} s. This corresponds to a gain of about one to two orders of magnitude with respect to the carrier period of radio links, with a corresponding increase in precision (mm ranging). It is expected that optical links will evolve towards the direct use of the optical carrier (10^{14} Hz) with a potential gain of another 4 orders of magnitude in Doppler tracking and frequency transfer. The phase modulation of that carrier will allow absolute distance measurements and time transfer, additionally to high rate data transfer.

That development is naturally paralleled by the present and expected improvements of clocks, in particular in the optical domain, on ground and in space. Best ground optical clocks already reach uncertainties of $\leq 10^{-17}$, and are expected to further improve. Efforts for the development of space optical clocks are under way (see section B.4). To compare such clocks in distant laboratories on the ground, or ground to space, present radio links via satellites show insufficient performance. In Earth orbit (ISS), the ACES MWL (0.3 ps precision) will require about 1 day integration time to reach the sub 10^{-17} level of the best present optical clocks. An improved version of the ACES MWL for an Earth orbiting satellite is projected to be capable of 1×10^{-18} inaccuracy after one day of integration. However, over interplanetary distances no such method exists or is foreseen.

On the ground, for short to medium distances (up to ≈ 200 km) recently developed methods use optical fibre links with a direct measurement of the optical carrier frequency. Such links have demonstrated sufficient performance for present and future optical clocks. However they are limited to relatively short distances and unusable for clocks onboard terrestrial and interplanetary spacecraft. Extending those methods to free space propagation would open the way to applications not only in fundamental physics, but also in navigation, Earth observation, solar system science, and telecommunications.

Several methods for the realisation of high performance optical links are being investigated in Europe at present. T2L2 is a pulsed system derived from satellite laser ranging, and presently in the process of validation onboard Jason2 (launched in June 2008). A project for an interplanetary version of T2L2, called TIPO (*Télémétrie Inter Planétaire Optique*), is based on the same principle but in a one-way configuration (although generalizable to the two-way case). The T2M project (*Télémétrie laser à 2 Modes*) is developed at the Observatoire de la Côte d'Azur with the aim of absolute distance determination between two satellites separated by up to 1000 km. It is a two-way link that uses the beat note between two laser-modes separated by a radio-frequency. In the medium term we expect the realisation of phase coherent optical links using directly the optical carrier in a two-way configuration, similarly to existing fibre links (and in analogy to the optical interferometry of LISA). This requires an onboard laser and an onboard optical phase coherent transponder and/or an onboard optical clock. The main limiting effect is expected to arise from turbulence when crossing the Earth's atmosphere. First experiments to study those limitations have been carried out in a collaboration between Paris and Côte d'Azur observatories with CNES support, showing the feasibility of such links through the atmosphere, and demonstrating the high potential for navigation and long distance clock comparisons at the level required by the best optical clocks today and in the foreseeable future. Phase coherent links are also being explored for their potential applications in telecommunications, a prototype is presently being tested by DLR onboard the TerraSAR-X satellite.

It should be stressed that at present Europe has a considerable advantage in optical link technologies for navigation and long distance clock comparisons, allowing for a rapid development of that technology for space applications, in particular in fundamental physics. . It is recommended to actively continue the development of high performance links in Europe, working towards the implementation of such links on existing and future space platforms and missions.

Development plan for matter-wave interferometer.

Atomic quantum sensors based on matter wave interferometry, are capable of detecting very small accelerations and rotations. For example, state-of-the art atom accelerometers have a sensitivity of 10^{-9} m/s^2/√Hz and their accuracy limit, yet to be demonstrated on long term gravimetric data acquisition, has proven to be limited by gravitational background noise. These instruments reach their ultimate performance in space, where the long interaction times achievable in a freely falling laboratory improve their sensitivity by at least two orders of magnitude and the possibility to use dedicated drag-free platforms enables the isolation of the sensor to exceed the ground-based background accuracy limit.

Cold atom sensors in space may enable new classes of experiments such as testing gravitational inverse-square law at distances of a few microns, the universality of free fall and others. Matter-wave interferometer techniques may lead to radically new tests of the equivalence principle using atoms as nearly perfect test masses, measurements of the relativistic frame-dragging precession, the value of G and other tests of general relativity. Furthermore, cold atom quantum sensors have excellent sensitivity for absolute measurement of gravity, gravity gradients and magnetic fields as well as Earth rotation, and therefore find application in Earth sciences and in Earth-observing facilities.

Today, a new generation of high performance quantum sensors (ultra-stable atomic clocks, accelerometers, gyroscopes, gravimeters, gravity gradiometers, etc.) is surpassing previous state of the art instruments. They represent a key technology for accurate frequency measurements and ultra-precise monitoring of accelerations and rotations. In addition, studies on ultra-cold atoms, molecules and degenerate quantum gases (BEC, Fermi gases, and Bose-Fermi mixtures) are also steadily progressing. BEC provides gases in the sub-nano-Kelvin range with extremely low velocities (i.e., at the micron per second level), that are ideally suited for experiments in a microgravity environment.

Because of the anticipated strong impact of these new devices on the entire area of precision measurements, the development of quantum technologies for space applications needs an increased activity.

On ground, many programs formed by large teams are already going on in Europe : starting from transportable sensors built as demonstrators to be tested at low inertial noise sites, more ambitious experiments are designed to be operated on parabolic flights and sounding rockets.

Today, Europe, with the support of ESA as well as national space agencies, is leading the studies towards these applications. The first step was the HYPER (hyper-precision atom interferometry in space) proposal led by a European consortium and submitted to ESA in 2000. The proposal consisted in 2 atomic gyroscopes to measure the time dependence of the gravitomagnetic effect as well as verify the equivalence principle. The HYPER assessment study, followed by an Industrial System Level Study, demonstrated the feasibility of the mission but the technique of cold atoms was not considered mature enough for a space mission.

In the last decade several initiatives in European and the US aim to demonstrate the technological feasibility of cold atom sensors. On ground, many programs formed by large teams are already going on: starting from transportable sensors built as demonstrators to be tested at low inertial noise sites. For space, we may identify:

– a German pilot project to develop a mobile BEC platform for microgravity experiments in the drop tower and during parabolic flights, has been running since January 2004. The QUANTUS team, currently comprising 13 Institutions, realised a compact facility which achieved for the first time a Rubidium Bose-Einstein Condensate in the extended free fall at the drop tower in Bremen. The facility permits the study of the generation and outcoupling of BEC in microgravity, decoherence and atom interferometry as well as opening an avenue to perform atom-optical experiments with ultra-cold gases, e.g. quantum reflection, in a new parameter range. The facility could represent a prototype for a sounding rocket mission.

– a French RT project to develop a transportable two-species atom interferometer for parabolic flights, has been running since 2004. The ICE team, comprising 3 institutions with a well established expertise in space components, operates a cold atom light pulse interferometer in aircraft parabolic flights, which was recently successfully tested and demonstrates the operation of an airborne and 0-g atom interferometer. It will be used to develop the future generation of air/spaceborne atom inertial sensors, as well as the relevant additional subsystems to operate the sensor in the space environment.

All these programs, along with the demonstration of European leadership in compact and airborne cold atoms technology, helped to identify and develop relevant technologies for future space atom interferometers: development of compact laser sources, fully integrated optics optical benches, radiofrequency reference, and vacuum components …

A first effort to combine these advances is sponsored by ESA through the SAI program (Space Atom Interferometers). The SAI consortium joined eleven leading European groups for realizing a transportable atomic accelerometer. SAI will realize a prototype for a space-compatible inertial quantum sensor for testing the device at system and subsystem level, and for exploring new schemes based for example on quantum degenerate gases as source for the interferometer. Additionally, it will investigate the realistically expected performance limits and potential scientific applications in a micro-gravity environment considering all aspects of quantum, relativistic and metrological sciences. The resulting set-up could be tested in both the QUANTUS and the ICE facility, thus providing the community with a wide range of validation and tests.

Future developments on ground: Ground based experiments can still provide, in addition to the microgravity facilities, useful environments to verify the bias stability and the long term performance of the atom sensors. It will be of particular interest to operate the devices at very low-noise facilities e.g. environment similar or better to that where the Einstein telescope will be operated. It will be of particular interest to access underground facilities for instance.

In addition to the first demonstration in parabolic flight, further efforts should be made to operate ultra-cold atom sensors in a microgravity environment such as the drop tower, parabolic flights and very soon, sounding rockets. Because development cycles on ground-based facilities (either in a plane or in a drop tower) can be short enough to offer rapid technological evolution for these future sensors, this will allow for a rapid cost-effective development of the future space sensors. It will also offer the possibility to explore most of the atom-sensors related science objectives at an intermediate level of precision. Precision drag-free space-born applications will strive for extending the time of free fall towards regimes where NanoKlevin cold atoms are a prerequisite.

Future developments for and in space: The recent advances in the three programs mentioned above show that many subsystems are already in a far advanced stage, where no further scientific investigation is necessary. For instance, two optical bench technologies have been demonstrated for their ability to sustain the high vibrations, pressure and temperature variations encountered in the dropped tower or the 0-g flights. In addition, the PHARAO technology could be easily adapted to such instruments. Therefore, a technology program should rapidly focus on the development of space proof optical benches for future atom sensors. Indeed, the laser cooling and atom manipulation bench will be at the core of any future instruments, and its miniaturization will be a key to extend the scope of its utilizations in space. Such a compact cooling bench could actually rapidly be tested on a first sounding rocket mission for testing components of matter wave sensors. Similar technological development could already be funded for high precision frequency references …

Rapidly in the future, it will be efficient to perform a differential measurement between two inertial sensors using atoms of different mass and interrogation wavelength. Even for large vibrational noise, and large interrogation times, the measurement of the differential phase shift, i.e. the acceleration difference can be measured to a high precision. Although deploying atom interferometric inertial sensors on dedicated orbital platforms for next-generation tests of the UFF will increase the measurement sensitivity at the price of an increased sensitivity to vibrational noise, the use of fast-convergence estimators in the differential acceleration estimate will help reject this acceleration noise and thus relax the requirement on drag-free vibration isolation performance. Hence, a one year mission on the ISS could reach a target accuracy of $\eta \sim 8 \times 10^{-15}$, close to that of the project MICROSCOPE, but with quantum objects and no specific drag-free platform.

Recommendations :

The technology development on cold atom sensor should focus on:

- 1st : Ground based experiments to test the accuracy of atom interferometers.
- 2nd : Advanced technology development of relevant subsystems such as laser bench, frequency reference. These technological developments could be done in coordination with the development of compact and/or advanced atomic clocks.
- 2nd : Operation of atom interferometer under environments such as drop towers or parabolic flights and future sounding rocket mission.
- 3rd : Bridging the accuracy gap between space missions and ground-based missions.
- 4th : Exploring the quantum tests of the EP on the ISS.

Technology developments for Ultra High Energy Cosmic Rays

Work in Germany and Russia is underway with the goal of developing advanced Si-Photomultipliers (SiPM) for space missions dedicated to study UHECR. The SiPM devices offer low weight, very low power consumption (< 50 W m^{-2}) and compactness and would allow the threshold for the detection of UHECR to be pushed at least as low as 10^{19} eV. Currently the photon detection efficiency of SiPMs is 45% and it seems possible to raise this to 70%. Technological effort from ESA is highly desirable to qualify these devices for space applications and to set up a framework with European Industry for mass production. It is likely that there would be spin-off for applications in other fields including quantum optics, communications and medicine.

C.4 A set of recommendations

Our recommendations for future free flyer missions are summarized as follows:

- It is of vital importance to the field of fundamental physics that the missions presently approved (LISA Pathfinder, ACES and MICROSCOPE) are launched with no further delay.
- In the context of the M3 call, the Advisory Team supports the concept of an M-mission with an optical clock with an uncertainty of $1x10^{-17}$, and a link allowing the comparison of such a clock to ground optical clocks at the same level of uncertainty and allowing comparisons of clocks on ground at the $1x10^{-18}$ level. This will allow a highly accurate test of the structure of space-time by testing the gravitational redshift at the inaccuracy level of approximately 1 part in 10^9, in addition setting a corresponding limit to a possible spatial variation of the fundamental constants. This represents an approximately 10^3 fold improvement compared to ACES or potential future ground results. The mission may be considered with two options, a (highly elliptical) high Earth orbit or an inner solar system orbit (approaching the sun to about Mercury distance). The latter option would provide sensitivity to effects of second-order in the gravitational potential. Moreover, it could in addition enable a Shapiro time delay test, measuring the γ parameter of post-Newtonian gravity theories at the inaccuracy level of 1 part in 10^7, a hundredfold improvement. The mission also provides the opportunity for improved tests of Lorentz invariance, and provides strong science results in other fields (geodesy, time metrology).
- A test of the weak equivalence principle, at the level of 10^{-17} or better, would provide an important test for many theories proposed beyond the Standard Model and General Relativity. For candidate mission concepts, using macroscopic test masses, to be successful in the M3 call, it is important that they be able to demonstrate on ground that their sensitivity goals are compatible with possible performance. This includes pushing measurements of systematic error sources and stray force noise, in addition to readout noise, near to the levels needed in space. Matter wave interferometry could represent a very interesting alternative, especially if a violation is observed by MICROSCOPE or other experiments.
- Despite the strong interest in testing gravity at all length scales, the Advisory Team thinks that fundamental physics alone does not provide a broad enough scientific motivation to justify a dedicated fundamental physics L-mission in the outer solar system, but that such a mission needs to be combined with substantial planetary science objectives.
- When combined with a planetary mission the fundamental physics instruments are likely to impose stringent constraints and need to be included in the mission design at an early stage. The Advisory Team recommends that a genuinely mixed fundamental physics and planetary mission be considered.
- The rich activity in the field of space detection of high energy particles, especially in connection with the identification of dark matter, justifies a need for a new generation of space experiments. The exact mission concept will be more clear in a few years when all missions presently designed will have been launched.

Because experimental developments on the International Space Station are important to the field of fundamental physics, we make the following recommendations:

- The Advisory Team supports the continuation of the development of the ISS mission "SOC" with lattice optical clocks, that aims at improving the Earth gravitational redshift measurement, Local Position Invariance test, and ground clock comparison accuracy by one order compared to ACES. The technology developments required for this mission and for a M3 clock mission will have significant overlap.
- The strong technology development program on atom interferometry sensors, presently undertaken in drop towers, parabolic flights, sounding rockets and in the ISS should be vigorously pursued. These sensors have to be tested during the extended free fall, where they approach the targeted sensitivity. The outcome of tests on the Space Station or an other adequate platform are considered as milestones for missions beyond 2020 targeting tests of the principle of equivalence better than 1 part in 10^{17}. From this point of view, the Advisory Team supports the continuation of the "Space Atom Interferometer" (SAI) project.
- The Advisory Team supports the active participation of the European community in ultra-high energy cosmic rays in the Japanese mission JEM-EUSO on the Japanese module of the ISS. This is an excellent opportunity to test the possibility of detecting such cosmic rays from space. If successful, this would open the road to an even higher statistics of cosmic rays of the highest energy.

As far as short-term technology developments are concerned:

- A strong technology program should be continued in order to bring the LISA mission closer to its completion.
- The required technology development (clock and link) necessary for the M3 mission proposed above should be implemented in an efficient manner, building on existing know-how in European research labs and industry, in particular on the ACES heritage. We recommend concentrating on the most promising and realistic clock and first developing space versions of the already well established optics and laser components and subsystems, followed by the atomics package and the frequency comb. In parallel, the appropriate space-to-ground link technology should be developed.
- We recommend advancing the technology of inertial sensors with a high bias stability at the lowest Fourier frequencies and a sensitivity better than 10^{-11} $m/s^2/\sqrt{Hz}$ (atom interferometry sensors or other) because of the high interest for many space applications such as planetary gravitational observations , gravity in our solar system as well as for deep space navigation. Therefore, the required developments to advance this technology should be supported.

Regarding the organization of the community, we make the following recommendations:

- Fundamental physics often requires a very specific technical expertise which cannot be acquired in a few years. Space requires on the other hand the development of competence in quality assurance, integration and testing. From this point of view, close cooperation and interchange between research institutes, space agencies, and space industries becomes of key importance for accelerating the necessary transfer of know-how, vital for any successful space project. In particular,
    - Space agencies and industries need to acquire know-how in cutting edge research, technology, and measurement methodology, based on the expertise of scientific institutes across Europe. This includes the understanding of the

physical processes at the basis of precision measurements and precision instruments.
- Research institutes need to develop expertise in space missions and space technologies. This includes a profound understanding of all the challenges and the limitations that a space project brings along.

Given the technological challenges of the field of fundamental physics, it is important that, very early in the projects, industry and academic labs be closely associated.

- The Advisory Team recognises the close links with other science fields, in particular astrophysics and solar system science and recommends active exchange of ideas and collaboration in the proposal stage of new (space) projects.

Appendix: **The community and its organization**

This section will rely on the questionnaire sent to the community to identify its size and the type of participation. It will be included in the final version of the roadmap document, once all answers have been received and analyzed.

List of acronyms

ACES: Atomic Clock Ensemble in Space
AMS: Alpha Magnetic Spectrometer
ATV: Automated Transfer Vehicle
CHAMP: CHAllenging Minisatellite Payload
CTA: Cherenkov Telescope Array
ELIPS: European program for Life and Physical sciences and applications utilising the International Space Station
ELT: Extremely Large Telescope
ET: Einstein Telescope
FPR-AT: Fundamental Physics Roadmap Advisory Team
GAIA: Global Astrometric Interferometer for Astrophysics
GAP: Gravity Advanced Package
GLONASS: GLObal'naya NAvigatsionnaya Sputnikovaya Sistema
GOCE: Gravity and Ocean Circulation Explorer
GPS: Global Positioning System
GRACE: Gravity Recovery And Climate Experiment
GRB: Gamma Ray Burst
GSTP: General Support Technology Program
HESS: High Energy Stereoscopic System
HYPER: Hyper-Precision Cold Atom Interferometry in Space
IXO: International X-ray Observatory
LHC: Large Hadron Collider
LISA: Laser Interferometer Space Antenna
LLI: Local Lorentz Invariance
LLR: Lunar Laser Ranging

LPI: Local Position Invariance
MWL: MicroWave Link
PPN: Parametrized Post-Newtonian (formalism)
SiPM: Silicon PhotoMultiplier
SAI: Space Atom Interferometers
SKA: Square Kilometer Array
SOC: Space Optical Clocks
SYRTE: SYstèmes de Référence Temps-Espace
TIPO: Télémétrie Inter Planétaire Optique
TRL: Technology Readiness Level
T2L2: Time Transfer by Laser Link
T2M: Télémétrie laser à 2 Modes
UFF: Universality of Free Fall
UHECR: Ultra-High Energy Cosmic Rays
VLBI: Very Long Baseline Interferometry
WEP: Weak Equivalence Principle
wimp: weakly interacting massive particle