Perspectives in Fundamental Physics in Space

Orfeu Bertolami

Instituto Superior Técnico (IST), Departamento de Física, 1049-001 Lisbon,
e-mail: orfeu@cosmos.ist.utl.pt

Clovis Jacinto de Matos

ESA-HQ, EUI-AC, F-75015 Paris, e-mail: Clovis.de.Matos@esa.int

Jean Christophe Grenouilleau

ESA-ESTEC, HME-EOI, NL-2201 Noordwijk, e-mail: Jean-Christophe.Grenouilleau@esa.int

Olivier Minster

ESA-ESTEC, HME-GAP, NL-2201 Noordwijk, e-mail: Olivier.Minster@esa.int

Sergio Volonte

ESA-HQ, SCI-CA, F-75015 Paris, e-mail: Sergio.Volonte@esa.int

Abstract

We discuss the fundamental principles underlying the current physical theories and
the prospects of further improving their knowledge through experiments in space.

Key words:
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Pioneer Anomaly, Lorentz invariance.
PACS:

1 Introduction

General Relativity (GR) and Quantum Mechanics (QM) are the most funda-
damental and encompassing physical theories of the XXth century. They are
the cornerstones of all developments aiming to unify the four fundamental interactions of Nature, strong nuclear, electromagnetic, weak nuclear and gravitational forces; and to harmonize gravity with the quantum picture of the world. GR explains the behaviour of space-time and matter on cosmologically large scales and of very dense compact astrophysical objects. It is the most accurate theory so far of the gravitational interaction. QM on the other hand, accounts for the behaviour of matter primarily at small scales (Å and below), and ultimately leads, together with Special Relativity, to the so-called Standard Model of strong and electroweak interactions that accounts for all the observable known forms of matter. QM also describes macroscopic quantum phenomena like superconductivity, superfluidity and Bose-Einstein condensation. Despite the great success of these theories, finding ways to unify them into a single framework is the only way to understand the high-energy behaviour of gravity and to avoid that gravity is not consistent with fundamental principles such as, for instance, Heisenberg’s Uncertainty Principle.

Attempts to unify in a single theory the four fundamental interactions of nature, and to harmoniously merge GR and QM, have led to a rich lore of new physical models such as Kaluza-Klein theories, Supergravity, and to the most fecund String/M-theory [1] whose complex implications are still largely untested. Moreover, the conceptual differences between GR and QM seem to require deep changes in the underlying assumptions about the nature of the Universe. String theory suggests for instance, that the basic building blocks of the Universe are not point-like particles, but instead strings and membranes. It also implies that space-time has a non-commutative character. Differences between GR and QM can be better appreciated through still unresolved issues such as:

- The spatial non-separability of physical systems due to the entanglement of states in QM, versus the complete spatial separability of physical systems in GR.
- The Equivalence Principle of GR, versus the Uncertainty Principle in QM which may imply in violations of the Equivalence Principle, as for instance, in some string theory models.
- The possible non-unitary evolution of pure states into mixed states due to the existence of black holes solutions in GR. That is, the presence of black-holes might blur the evolution of observable quantities that in QM is performed by unitary operators.

We should also remember that to a great extent, the enormous technological progress achieved since the beginning of last century in telecommunications, electrical engineering, electronics, photonics, information technology, nuclear technology, etc, stems from the deep understanding of the electromagnetic and nuclear interactions at quantum level. Similarly, it is logical to expect that any gravity-related technology must rely on a comparable level of understanding
of the gravitational interaction from the quantum mechanical point of view.

Clearly, as in any branch of physics, progress is achieved through the interaction between theory and experiments, and for what concerns GR and QM in particular, further experimental testing of the theoretical predictions and foundations of these theories may reveal the important insights necessary to reach a higher level of conceptual knowledge. This paper, argues that space missions may play an important role in the quest for a unification theory and a quantum theory of gravity when ground experiments are not feasible. In this respect, it is interesting to mention the example of cosmology. Driven by important developments in theoretical thinking and a great amount of data gathered by dedicated space observatories, observational cosmology has become a blooming subject. Upgraded versions of the COBE mission [2], such as WMAP [3] of NASA and in the future Planck mission [4] of ESA, have given or will give origin to a burst of activity on the physics of the Cosmic Microwave Background Radiation. Similarly the Compton Gamma Ray Observatory [5] of NASA, together with the INTEGRAL (INTERnational Gamma Ray Astrophysics Laboratory) mission from ESA [6] have prompted new developments of gamma ray astronomy, as have the various X-ray telescopes XMM-Newton [7], Einstein [8], ROSAT [9], Chandra [10], etc.) and above all, the Hubble Space Telescope [11], which has dramatically widened up our view of the Universe. The next generation of space telescopes and observatories will not cease to surprise us and will continue to be our major sources of data and inspiration for new and revolutionary ideas. It is fairly reasonable to assume that fundamental physics in space will follow the same pattern. Of course, developments of fundamental physics in space are intimately connected with the areas of particle physics, and experimental gravity, in particular through the search for deviations from Newton’s law on small scales (below 1 mm).

2 Testing Well Known Theoretical Predictions and Foundations

GR is based on the generalization of the Principle of Relativity, assuming that the laws of Nature are independent of the state of motion (uniform or accelerated) of the reference frame with respect to which they are formulated. This principle provides the foundation of the universality of the laws of physics as it ensures that these are independent of the state of motion, and of the spacetime location of observers. This endows a democratic status for all observers. The set of experiments sustaining the generalized Principle of Relativity are the following:

1. Physical laws are independent of the position and velocity of the frame of reference thanks to the invariance of the world-line distance between events in the spacetime continuum. This is ultimately related with the fact that the
speed of propagation of the electromagnetic and gravitational interactions is constant and independent of the frame of reference. This speed is the speed of light in the vacuum.

2. The acceleration of a test body falling under the single influence of the gravitational interaction is independent of its mass. This can be understood only if inertial and gravitational masses are exactly equal to each other.

The first set of experiments is associated with the invariance of the physical systems under translations and rotations in spacetime usually referred to as:

- Local Lorentz Invariance (LLI) (independence of the frame of reference velocity).
- Local Position Invariance (LPI) (independence of the position of the frame of reference)

The second set of experiments concerns the so-called Weak Equivalence Principle (WEP) or Strong Equivalence Principle (SEP) when gravitational self interaction is important (see e.g. [12]).

The Principle of Special Relativity establishes only the equivalence between inertial reference frames relying on a global version of the first set of experiments above. Therefore, it does not encompass the gravitational interaction. A generalization of the Principle of Special Relativity to include gravity allows for a covariant formulation of this interaction.

The covariant formulation of gravity implies a set of dynamical equations for the spacetime metric, the so-called Einstein field equations. These equations express the geometric nature of the gravitational interaction, and describe how matter/energy and spacetime geometry influence each other.

In the limit of weak gravitational fields and low velocities compared with the speed of light, GR yields small corrections to Newtonian gravity through the addition of terms proportional to $GM/rc^2$, where $G$ is Newton’s gravitational constant, $M$ the mass and $r$ the radius of the source of the gravitational field under consideration. Thus, general relativistic corrections will become important in the case of compact astronomical objects, such as neutron stars ($GM/rc^2 = O(10^{-1})$) and black holes ($GM/rc^2 = O(1)$), and for the Universe as a whole.

2.1 Detection of Gravitational Waves

Einstein’s field equations predict the existence of gravitational waves, which correspond to quadrupole oscillations of the spacetime continuum itself. Those
have already been indirectly detected in binary pulsar systems [13] via tracking of the Post-Keplerian Parameters of the system, and comparison with GR.

LISA (Laser Interferometer Space Antenna) [14] is a particularly eloquent example of a space mission devoted to test fundamental physical principles, through the detection of gravitational waves. LISA consists of a swarm of three satellites forming an equilateral triangle with sides of 5 million km. Each satellite located at a vertex of the triangle emits a laser beam to the other two satellites, so as to form with the phase-locked return beams an interference pattern in the optical modules on-board each spacecraft. When a gravitational wave crosses the triangle, the interference pattern is shifted by an amount proportional to the intensity and the frequency and polarization of the incoming gravitational wave. ESA’s LISA pathfinder mission (formerly called SMART-2) will play a crucial role in developing and testing some of the technological requirements of a mission as sophisticated as LISA.

LISA will lead to a fundamentally new window for observing the Universe through observation of sources of gravitational waves. Astronomy has so far mostly observed the sources of electromagnetic radiation in the Universe. Gravitational astronomy will allow scientists to achieve a deeper understanding of the dynamics of the cosmos since gravitational waves couple very weakly with matter and therefore suffer little scattering and absorption on the way from the source to the observer.

2.2 Detection of Gravitomagnetism

GR also predicts, in the weak field limit and at first order beyond Newtonian gravity, that for certain mass configurations (a current like one), the metric can be decomposed into two vector fields. The first one, usually referred to as gravitoelectric field, corresponds to Newton’s gravitational field. The second corresponds to a “new” field, the so-called gravitomagnetic field. These designations arise from the fact that in this approximation, Einstein’s field equations can be formulated in a way that resembles Maxwell’s equations for the electromagnetic field. Clearly, direct experimental detection of gravitational waves and the gravitomagnetic field produced by Earth’s rotation, are important tests of GR.

ESA Hyper (Hyper precision cold atom interferometry in space) concept [15] and the NASA Gravity Probe-B mission [16], a Stanford University mission which has been launched last 20th April 2004, are dedicated to the detection of Earth’s gravitomagnetic field. The Gravity Probe B satellite circles the Earth in a polar orbit at an altitude of 650 km. Data taking was concluded in August 2005 and results are expected in 2007. The mission concept consists
in using four spinning gyroscopes and a telescope. The telescope has been pointed to a guiding star, IM Pegasi, and the gyroscopes were electrically induced to align parallel to the telescope axis. Over a year of operation about 5000 orbits are expected. The gyroscopes are left undisturbed as the telescope is kept pointing toward the guiding star through attitude control thrusters of the spacecraft. According to GR, the drift angle between the gyroscopes and the telescope is about 6.6′′, due to the Earth’s geodetic effect, while a smaller angle of 0.041′′ should open up in the direction of the Earth’s rotation, due to the Lens-Thirring effect.

Hyper on its hand, aims to perform the measurement of the gravitomagnetic field through the phase shift it causes in an interferometry experiment involving cold atoms rather than through the motion of macroscopic bodies. It is relevant to mention that Hyper is just a mission concept and that most likely it will be made concrete through a mission such as “Fundamental Physics Explorer” described at ESA’s Cosmic Vision 2015-2025 [17], that will provide the drag-free platform on board of which experiments of interference of atomic beams and with Bose-Einstein condensates will be performed.

Another interesting mission concept to detect gravitomagnetism involves the so-called gravitomagnetic clock effect. This effect is based on the time difference caused by the gravitomagnetic field between two high precision clocks orbiting the Earth in clockwise and anti-clockwise directions [18].

2.3 Testing of Basic Assumptions of General Relativity

Testing the basic conceptual assumptions of GR, represents an important challenge for space fundamental physics. This involves experimentally testing the WEP, LLI and LPI.

The WEP establishes a composition-independent limit on the free fall of bodies. This means that in a gravitational field the gravitational mass, cancels out with the inertial mass given their equality. This equality is established with great accuracy and has been tested since Galileo in 1590, Newton in 1686, Bessel in 1832 and so on until the current most stringent limit [19]:

\[ \left| \frac{m_i - m_g}{m_i} \right| < 5 \times 10^{-13} \]  \hspace{1cm} (1)

Ground based experiments designed to verify the WEP are limited by the unavoidable micro seismic activity of Earth. Space experiments offer the possibility of improving the precision of current tests by a factor of $10^2$ to $10^5$.  

MICROSCOPE (MICROSatellite à trainé Compensée pour l’Observation du
Principe d’Equivalence) [20] is a collaborative CNES-ESA mission to be launched in 2009, designed to evaluate the WEP through the monitoring of the free fall of two pairs of masses orbiting the Earth located in a drag-free environment at room temperature. The measured signal is the force required to keep the test masses in a pair centered on each other. Microscope will evaluate the WEP with a precision expected to reach 1 part in $10^{15}$.

Unfortunately, the more ambitious ESA/NASA STEP (Satellite Test of the Equivalence Principle) [21] mission is currently being studied by NASA only. The drag-free STEP spacecraft was to carry four pairs of test masses accommodated in a superfluid He-dewar at $2K$. Differential displacements between the test masses of a pair would be measured by SQUID sensors, and the expected precision with which the WEP would be tested was 1 part in $10^{18}$. Such a level of precision would allow checking constraints introduced by existing string theories [22].

Another promising possibility for testing the WEP uses cold atom interferometry. Ground based High-precision gravimetric measurements have been made using the interferometry of free-falling Cesium atoms, and allowed to reach a precision of 7 parts in $10^9$ [23]. Ultimate precision of this method can only be achieved in space. As an example, the resolution provided by the atom interferometers to be used in ESA’s Hyper concept mission which could be sufficient to perform a test of the WEP with an improved precision by a factor of $10^6$. Hyper would carry two cold-atom Sagnac interferometers (based on the negative Michelson-Morley experiment for detection of the ether drift). By comparing the rate of fall of Cesium and Rubidium atoms in two independent interferometers a precision of the order of 1 part in $10^{15}$ could be achieved, and this would represent an independent confirmation of, or perhaps a disagreement with, the results of MICROSCOPE. As already mentioned, a concrete mission to fulfil Hyper concept will be the “Fundamental Physics Explorer” described at ESA’s Cosmic Vision 2015-2025 [17].

Invariance under Lorentz transformations (LLI), which states that the laws of physics are independent of the frame velocity, is one of the most fundamental symmetries of physics and a basic ingredient of all known physical theories. However, recently some evidence has been found, in the context of String/M-Theory, that this symmetry can be spontaneously broken. Naturally, this poses the challenge of verifying this possibility experimentally. The most accurate laboratory tests of LLI are performed via the so-called Hughes-Drever experiment [24] [25]. In this type of experiment, one searches whether there exists any anisotropy of inertia through the study of resonant absorption of photons by a $Li^7$ nucleus in a strong magnetic field. The ground state has spin $3/2$ and splits into 4 equally spaced energy levels, given that nuclear physics laws are rotationally invariant. Therefore, if inertia is not isotropic, then the four states will not remain exactly equally spaced over the 12 hours period.
of Earth’s rotation in which the magnetic field is carried to two different locations with respect to the galactic center. This technique allows achieving impressive limits, the most stringent being [26].

\[
\delta \equiv \left| \frac{m_I c^2}{\sum A E_A} - 1 \right| < 3 \times 10^{-22},
\]  

(2)

where \( E_A \) are the relevant binding energies. From astrophysical observations, limits on the violation of momentum conservation and the existence of a preferred reference frame can be set from bounds on the post-Newtonian parameter, \( \alpha_3 \) which vanishes identically in GR. It can be determined from the pulse period of millisecond pulsars [27], [28]. The most recent limit, \( \alpha_3 < 2.2 \times 10^{-20} \) [29], indicates that Lorentz symmetry holds up to this level. We should mention that, in broad terms, in the Parametrized Post-Newtonian Formalism the metric is expanded in powers of the Newtonian potential, velocity of matter and velocity with respect to a preferred frame. Clearly, the presence of the latter implies in the breaking of translation and/or rotational invariance and hence, yielding that momentum conservation is violated.

It is known that the propagation of the ultra-high-energy protons is limited by inelastic collisions with photons of the Cosmic Microwave Background radiation making it impossible to protons with energies above \( 5 \times 10^{19} \)eV to reach Earth from distances farther than \( 50 - 100 \) Mpc. This is the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff [30]. However, events where the estimated energy of the cosmic primaries is beyond the GZK cutoff have been observed by different collaborations [31] [32] [33] [34]. The issue is controversial. For instance, for the AGASA collaboration [35] this is only a 2.2\( \sigma \) effect. The confirmation of these observations by the most recent HiRes collaboration is still under debate [36]. Despite that, it has been suggested [37] that slight violations of Lorentz invariance would cause energy-dependent effects which would suppress otherwise dynamically inevitable processes, e.g. the resonant scattering reaction, \( p + \gamma_{2.73K} \rightarrow \Delta_{1232} \), where \( \Delta_{1232} \) is the 1232 MeV hadronic resonance. The study of the kinematics of this process allows to set quite stringent bounds on the degree to which Lorentz invariance holds, \( \delta_{\text{Lorentz}} < 1.7 \times 10^{-25} \) [37] [38] [39].

In what concerns LPI, experiments on the universality of the gravitational red-shift set the measure to which this symmetry holds. Hence, violations of the LPI would imply that the rate of a free falling clock would be different when compared with a standard one, for instance on the Earth’s surface. Thus, one of the most accurate determinations of the LPI has been achieved from the comparison of hydrogen-maser frequencies on Earth and on a rocket at 10000 km altitude [40]. The most recent band is about \( 2 \times 10^{-5} \) of the Newtonian potential divided by the velocity of light square.
On very large scales, the Hot Big-Bang Model describes the Universe through GR and the assumption that matter and radiation are homogeneously and isotropically distributed. Compatibility with data suggests that we are living in an accelerating, low matter-density Universe. The origin of this acceleration can be due to either to a cosmological constant \([42]\), or a slow-varying vacuum energy of some scalar field, usually referred to as Quintessence \([43]\), or due to an exotic new equation of state, the generalized Chaplygin equation of state \([44]\). This dark energy amounts for a substantial part of the energy density of the Universe, \(\Omega_\Lambda \simeq 0.73\), with the contribution from matter, dark\(^1\) and baryonic, \(\Omega_{DM} \simeq 0.23\), \(\Omega_{\text{Baryons}} \simeq 0.04\), so that \(\sum_i \Omega_i = 1\) but with no contribution from the spatial curvature \([46]\) \([47]\) \([45]\) \([48]\) as predicted from Inflation (see for instance, \([49]\)).

Thus, at late times the rate of expansion of the Universe is controlled by the dark energy component, which has negative pressure. It should be mentioned that the understanding of the quantum properties of vacuum and how it relates with the observed value of energy density are amongst the greatest challenges for XXI\(^{st}\) century physics.

### 2.4 Testing quantum Mechanics in Space

Space platforms, such as the "Fundamental Physics Explorer" that is part of ESA’s long-term scientific objectives, a "cosmic vision" \([17]\), also offer a unique drag-free environment to investigate the predictions of quantum physics. A test of quantum entanglement over astronomical distances would indeed be of great scientific value. The evaluation of the influence of gravity on quantum entanglement, and therefore the possible use of quantum entanglement to investigate the quantum features of gravity at low energies \([50]\) are issues that deserve more investigation. Space experiments involving entangled systems over large distances and different gravitational environments, are particularly well suited to convey this type of research.

On the other hand, experiments such as EUSO \([51]\) and LOBSTER onboard the ISS for the space observation of cosmic rays with energies greater than the ones achievable in particle accelerators, will also help to push even further our understanding of high-energy physics. Notice that the EUSO experiment has been postponed until ground-based cosmic-ray observatories like AUGER \([52]\) yield results.

Testing QM in space is also very important for the future use of novel tech-

\(^1\) Most likely candidates for dark matter include a linear combination of neutral supersymmetric particles, the neutralinos (see eg. \([53]\)), axions \([54]\) and a self-interacting scalar particle \([55]\).
nologies that will rely entirely on the unusual features of the quantum world. Emerging fields like spintronics, nanotechnology, quantum computing and quantum communication [56] will certainly represent new technological opportunities to expand the possibilities of spaceflight. Nevertheless, these technologies that are still under development on ground, will need proper qualification for possible use in space. Therefore, quantum physics experiments in space will not only provide deeper insights; through fundamental physics missions we will also acquire experience needed to fulfill these qualification steps in the future.

3 Investigating Phenomena not Clearly Encompassed by Theory

Controversy sparked by theoretical thinking and consensus reached through experimentation is the engine of science. A scientific revolution is most often initiated when a new experimental result does not properly fit within the accepted physical theories. According to the science philosopher Thomas Kuhn, the emergence of a new paradigm occurs due to the resistance of the scientific community in accepting at first a new physical picture to explain unexpected experimental results. What are the experimental anomalies and/or theoretical issues in GR and QM that might lead to new insights towards the goal of unifying in a single theoretical frame, the fundamental interactions of Nature and finding a suitable quantizing scheme for gravity? In what follows we shall discuss two issues that we regard as being of particular relevance.

1. Celestial mechanics has been for centuries the main source of discoveries in gravitational physics, from Kepler’s laws to the subtle anomalies of Mercury’s orbit. Recently discovered anomalous trajectories of the Pioneer 10 and 11, Ulysses and Galileo probes seem to indicate that some anomalous gravitational-type force with range beyond several 20 AU or so might exist [57].

2. Analysis of the free fall of physical systems is, as already discussed, a privileged experimental tool to test GR. It is remarkable in this respect, that the free fall of electrically charged particles and of antimatter has been so far poorly investigated. It is extremely relevant that a novel round of free fall experiments is carried out for charged particles and antimatter.

Given the importance of these two issues we discuss them in more detail next.

Of course, other anomalies related with the experimental determination of an unexplained excess of mass of Cooper pairs in superconductors[58] could be pointed out, however we feel that their implications are not so clearly related with our goal of discussing main fundamental physics questions that can be
studied in space.

3.1 Testing the Weak Equivalence Principle for Antimatter

The testing of the WEP for antiparticles remains still a largely open problem, despite recent developments in producing an appreciable number of antihydrogen atoms by the ATHENA and ATRAP collaborations at CERN [59] [60]. It is somewhat urgent that free fall experiments for antimatter are conducted so as to evaluate to which extent gravity complies with CPT symmetry. This is a fundamental symmetry of quantum field theory and corresponds to invariance of three conjugate operations, where C stands for charge conjugation, P for parity, and T for time reversal. In case gravity respects this symmetry, antimatter will fall exactly like matter in a gravitational field. From the experimental point of view, it should be mentioned that special Penning trap devices, magnetic containers, were developed for the purpose of storing substantial amounts of antimatter over a long time. In this respect, experimental proposals like WEAX (Weak Equivalence Antimatter experiment) [62] to be conducted at a cryogenic vacuum facility onboard the ISS and which aim to measure the free fall of antiprotons while orbiting the Earth are particularly appealing. The main idea behind this type of experiments is that antiprotons can be confined for a few weeks in a Penning trap with a geometrical configuration in which the effect of gravity would manifest itself as a perturbation on their motion. The expected precision of the experiment is 1 part in $10^6$, three orders of magnitude better than for a ground experiment. Naturally, testing the gravitational properties of antihydrogen as well as its spectroscopy, will allow a deeper understanding of this symmetry. It is worth mentioning that in some String-Field-Theory models, CPT symmetry can be spontaneously broken, meaning that although it is a symmetry of the theory, it is not shared by its ground state.

It is important to point out that these experiments have a high scientific value as they can provide relevant insights on extensions of the Standard Model. In this context, it is interesting to remark, that free-fall experiments with charged particles are also particularly relevant given the fact that they are very poorly tested experimentally. In the case of ground-based experiments, they involve, at least for the electron and the positron, the Schiff-Barnhill effect [61] (see in Ref. [72], [64]).

3.2 A Novel Intermediate Range Fundamental Interaction of Nature?

The investigation of the existence of new intermediate range interactions of Nature at scales beyond 20 AU, is another open question that awaits a dedicated
mission. An alternative to a dedicated mission, would involve a somewhat more limited experiment mounted as piggy-bag onboard deep space missions like, for instance the Pluto-express mission or the NASA Interstellar Probe mission [65].

A putative new fundamental interaction was first considered by Anderson and collaborators [57] in order to explain the anomalies in the trajectories of the probes Pioneer 10 and 11, Ulysses and Galileo, that imply the presence of an acceleration of the order of $8 \times 10^{-10} \text{m/s}^2$ directed towards the Sun, and that starts manifesting itself at distances beyond 20 AU from the Sun, after the influence of solar radiation becomes negligible. This is the so-called Pioneer anomaly. This additional interaction would manifest itself as being a different kind of gravity with a coupling constant a fraction of Newton’s gravitational constant and a finite range. Its finite range suggests the vector boson of this new interaction has a non-vanishing mass that leads to a Yukawa-type term to be added to the Newtonian gravitational potential. Thus, this subtle deviation from Newtonian gravity could be attributed to the existence of a new force of Nature. This force would in turn lead to violations of the WEP through deviations of the universality of free fall.

It is debatable whether the Pioneer anomaly is due to some un-modeled engineering problem of the probes, or whether it signals new physics (see Refs. [66] and [67,68,69] for a discussion on the theoretical side of the matter. An engineering solution is discussed in Ref. [70]). The demonstration that the gravitational field of Kuiper Belt is not the cause of the anomaly has been recently reanalysed (see [71] and references therein). In any case, it is only through a dedicated deep space tracking experiment that this phenomenon will be more clearly characterised and the issue definitely settled.

A dedicated mission would in its simplest form consist in launching into deep space a spherical probe whose behaviour (mechanical, thermal, electromagnetic, etc.) is very well known [72] [63]. Accurate tracking of its orbit would allow for precise evaluation of the Pioneer anomaly, as any deviation from the predicted trajectory would be used to evaluate the un-modeled Pioneer acceleration. Alternative mission concepts were discussed in Refs [73], [74]. The use of laser ranging techniques and the flying formation concept to the test the Pioneer anomaly were recently discussed [75].

4 Conclusion

For more than half a century, classical physics has provided the knowledge required to propel and transport manned and unmanned missions throughout the Solar System. Contemporary physics however, has not so far played a
similar role. Advances in quantum and relativistic mechanics were not yet fully implemented so to lead to propulsion breakthroughs and to allow for a more efficient exploration and utilization of space.

It is not inconceivable that the crisis of contemporary physics may be partly responsible for this state of affairs since our pictures of the world on very large and on very small scales do not quite fit together.

Suitable space platforms can provide the proper drag free environment for carrying out research in many critical areas of modern physics. It is an exciting prospect to think that fundamental physics missions in space may provide important insights into the nature of the theory still to emerge that would harmoniously encompass QM and GR. In turn, unification and a synthesis of QM and GR may lead to technological breakthroughs that will further push the boundaries of current space systems.

It is often said that quantum gravity is the most challenging synthesis to be achieved in XXIst century physics. Even though, the technological spin-offs of that theory are not clearly visible yet, it may most probably change our society as former scientific revolutions did in the past. Securing the steps to ensure such a paradigm shift, culturally and technologically, is in our view, an inescapable issue.

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A Nomenclature List

AGASA: Akeno Giant Air Shower Array (Japan)
ATHENA: AnTiHydrogEN Apparatus (CERN)
ATRAP: Antihydrogen Trap Collaboration (CERN)
Auger: Pierre Auger Cosmic Ray Observatory (Argentina)
AU: Astronomical Unit
CERN: Centre Europen de Recherches Nuclaires
CNES: Centre National D’études Spatiales (France)
COBE: COsmic Background Explorer (NASA)
CPT: Charge-Parity-Time Reversal
ESA: European Space Agency
EUSO: Extreme Universe Space Observatory (ESA)
HiRes: High Resolution Fly’s Eye Collaboration
HYPER: HYPER-precision cold atom interferometry in space (ESA)
INTEGRAL: INTErnational Gamma Ray Astrophysics Laboratory (ESA)
ISS: International Space Station
LISA: Laser Interferometer Space Antenna (ESA/NASA)
LLI: Local Lorentz Invariance
LOBSTER: All-Sky X-Ray monitor (ISS)
LPI: Local Position Invariance
MICROSCOPE: MICROSatellite à trainé Compensée pour l’Observation du Principe d’Équivalence (CNES-ESA)
NASA: National Aeronautics and Space Administration (USA)
QM: Quantum Mechanics
ROSAT: Roentgen Satellitte (Germany, UK, USA)
STEP: Satellite Test of the Equivalence Principle (NASA)
SMART: Small Missions for Advanced Research in Technology (ESA)
GP-B: Gravity Probe-B (NASA)
GR: General Relativity
WEAX: Weak Equivalence Antimatter Experiment
WEP: Weak Equivalence Principle
WMAP: Wilkinson Microwave Anisotropy Probe (NASA)
XMM: X-ray Multimirror Mission (ESA/NASA)