White Paper #01: Fundamental Physics

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1 General Introduction & overview

The Standard Model (SM) of particle physics and General Relativity (GR) are the two pillars of our current understanding of Nature. Both theories have been probed individually with ever increasing precision and are consistent with nearly all experimental observations. However they fail to explain dark matter, dark energy, or the imbalance between matter and anti-matter in the universe. Yet dark matter and dark energy represent 95% of the energy content of our universe while known matter (atoms, molecules) amounts to only 5%. Today, dark matter and dark energy have an unknown origin and there is a great deal of experimental and theoretical activity to solve this puzzle. The clustering of large-scale structure and the accelerated behaviour of cosmic fluid could be addressed whether finding out new (unknown) forms of matter or assuming that gravity behaves in different ways at infrared scales. Furthermore, the lack of a self-consistent theory of Quantum Gravity prevents the unification of SM and GR at ultraviolet scales. This is one of the biggest challenges that theoretical physics is facing today. String theory or loop quantum gravity are good candidates to solve this puzzle and interestingly both of them foresee violations of the Einstein's Equivalence Principle. In this context, the Einstein's Equivalence Principle assumes a central role in the search for a quantum theory of gravity. The open problems in fundamental physics investigated in this white paper are (see Figure 1):

- Validity of the Einstein's Equivalence Principle;
- Origin and nature of dark matter and dark energy;
- De-coherence and collapse models in quantum mechanics;
- Quantum many-body physics.

They will be addressed from different research corners and with different experimental methods:

- Ultracold atoms;
- High stability and accuracy atomic clocks;
- Matter-wave interferometry;
- Classical and quantum links;
- Cosmology and astrophysics.

The cosmos is a particularly attractive laboratory as it provides particles (cosmic rays) or objects (black holes, neutron stars) which are not produced in manmade laboratories. Space is also an excellent environment for high precision physics as the absence of atmosphere or drag-free satellites provides unique observation opportunities. For instance the MICROSCOPE mission has taken advantage of extremely long free-fall conditions in Earth orbit to set the record in testing the Equivalence Principle beyond what has been possible on Earth. Large velocity, velocity variations and large variation of the gravitational potential are accessible on board a spacecraft, thus providing wide signals for testing GR. Finally, the huge free propagation distances available in space provide very long baselines to test the space-time metric with high performance microwave or optical links both classical and quantum.

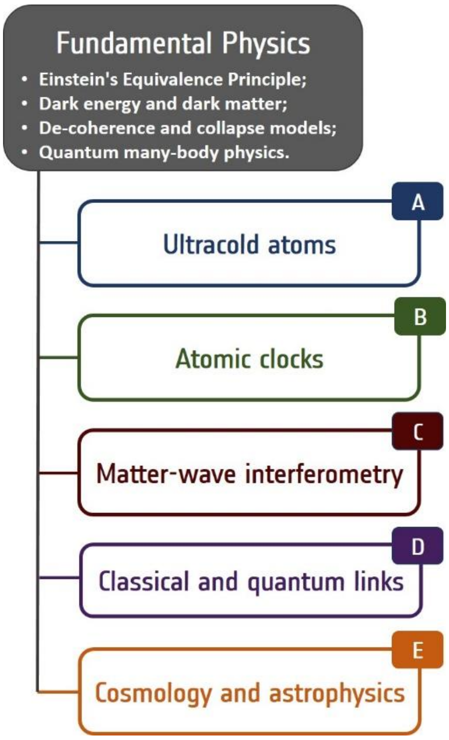

Figure 1: Open problems in fundamental physics and experimental methods identified to address them.

1.1 Open problems in fundamental physics

1.1.1 Einstein's Equivalence Principle

The Equivalence Principle (EP) is at the foundation of Einstein's GR. It states the universal coupling of matter to the gravitational field, which in turn implies that the impact of gravity onto matter can be understood in terms of a common geometric structure of space-time. In case of General Relativity such a geometric structure is a pseudo-Riemannian metric, which is just one of the possible available mathematical frameworks for describing space-time dynamics under the action of gravity [1]. The way in which GR implies the validity of EP is special insofar as in GR the metric structure, that also implies the causal relations, and the geodesic structure, determining the free-fall propagation of test objects and light rays, are intimately linked [2]. This link is given by the requirements that the affine connection being that of Levi-Civita. As a result, all matter components couple to gravity in a universal fashion that is entirely encoded in the geometric (causal) structure of space-time. Moreover, it is required that dynamics of matter, in absence of gravity, is compatible with Special Relativity (i.e. it has to be Poincaré invariant). This leads to some conceptual problems because Quantum Mechanics lacks Poincaré invariance. As a result, there is no obvious way to translate the requirements of the EP to those couplings involving genuine quantum matter. The conceptual status and degree of validity of the EP in the quantum realm therefore remain unclear. Consistent post-Newtonian ab initio calculations of single-particle as well as simple models for atoms in gravitational field only became available recently [3, 4], but important conceptual issues remain on the agenda [5–7] and need to be clarified before all the important question of possible violations of EP at quantum level can be reliably addressed [4]. The relevance of EP is twofold: First, it clearly goes beyond General Relativity and will serve as a decisive tool for discriminating competing theories of gravity [8]. Second, understanding its role and impact for couplings to genuine quantum matter will be a first and decisive step in probing the interface between Quantum Theory and GR in a way guided by experiments, with possible far reaching implications as regards possible reconciliations of the incompatible foundations of these theories.

The first formulation of EP, also known as the Weak Equivalence Principle (WEP), states the universality of free fall (UFF), which is meant to say that the center-of-mass motion of a sufficiently unstructured test body only depends on the initial conditions and not on the details of body's further constitution. In a Newtonian setting, this is sometimes stated as the strict equality of body's inertial mass m_i with its gravitational mass m_g, though these two concepts of masses do not easily generalize to other frameworks outside Newtonian physics. The consequences of UFF include the impossibility to locally distinguish effects due to a gravitational field from those arising in a uniformly accelerated reference frame [1]. For strictly uniform gravitational fields this pertains to ordinary Quantum Mechanics [9]. Generally this entails that it is always possible to locally describe a first-order neighbourhood of any space-time point with the language of Special Relativity. This is a crucial aspect; indeed, in 1920 Einstein himself addressed the EP as "the happiest thought of my life" [10, p.265].

Today the general formulation of the EP, known as the Einstein Equivalence Principle, comes in three parts, of which the universality of free fall is but one. The complete set of demands comprised in EP read as follows:

- Universality of free fall (Weak Equivalence Principle) holds;
- The result of any local non-gravitational test does not depend on the velocity of the free-falling experimental apparatus (no preferred frame effects);
- The result of any local non-gravitational test does not depend on where and when in the Universe it was carried out (no preferred location effect). This last part is also related to the universality of gravitational redshift (UGR) and the universality of clock rates (UCR).

By "local non-gravitational test", we mean an experiment that takes place in a sufficiently small region of a free-falling laboratory so that tidal effects (i.e. gradients of the gravitational field over distances of the extent of the test body) become negligible. Moreover, this statement of EP assumes that one may neglect gravitational self-interactions of the size of the systems used to probe the external gravitational field. In order to account for modifications or extensions of Einstein gravity, there is the need to introduce an even more general concept, which includes both the previous principles in a suitable limit. Such a requirement results in the Strong Equivalence Principle which can be formulated as follows:

- WEP is valid for self-gravitating bodies with appreciable fractions of gravitational binding-energies contributing to their overall energy, as well as for test bodies;
- The result of any local test neither depends on the velocity of the freely-falling experimental apparatus, nor on the position and the time in which it is carried out.

Clearly, the Strong Equivalence Principle reduces to the Einstein Equivalence Principle in the limit in which the gravitational self-field of the probing body is negligible as regards its strength compared to the external field and also as regards its contribution to the total energy budget of the test body.

These considerations, however, work for WEP, not only in the context of GR, but also for its generalizations and modifications, most importantly, scalar-tensor- and higher-order theories of gravity. This is true in the metric formulation of several Extended Theories of Gravity, of which General Relativity is a particular case. For a review we refer to Ref. [11] and Ref. [12,13] for applications. As it is well known, violation of EP may arise in scalar-tensor theories. In particular, at a fundamental level temperature may play a crucial role. Indeed, at zero temperature, EP still holds due to the fact that contributions to m_i and m_g that may allow $m_g/m_i \neq 1$ will vanish as soon as $T \rightarrow 0$. This result can be shown by employing different approaches, though, in any case, the evaluation of radiative corrections will require techniques from Quantum Field Theory [14].

1.1.2 Dark matter and dark energy

Astrophysical and cosmological observations have established [15] that dark matter (DM) and dark energy (DE) are the dominant contributions to the average energy density of the universe. However, the precise nature of dark matter and dark energy remains elusive despite considerable efforts in observational astrophysics and experimental high-energy physics over several decades. Precision measurements based on atom interferometry and atomic clocks in space can make an important contribution to this quest.

Extensive searches [16] for massive dark-matter candidates known as WIMPs (weakly interacting massive particles) have come empty handed, spurring a growing experimental interest in exploring a wider range of dark-matter hypotheses. In this respect, the possibility that dark matter could be attributed to coherent oscillations within subgalactic regions of ultralight scalar (or pseudoscalar) fields has recently been gaining increasing attention [17]. These oscillations can lead to small periodic variations in space and time of the parameters of the Standard Model, which could be detected in highly sensitive gravimetry measurements as a small modulation in the time of the acceleration experienced by freely falling atoms [18]. They can also produce small oscillations of the transition energies between electronic states that could be identified by comparing different atomic clocks at the same location [19] or pairs of identical atom interferometers separated by long distances but interrogated by common laser beams [20].

On the other hand, certain classes of dark-energy theories, known as chameleon-field [21] and symmetron-field [22] models, involve a light scalar field that can mediate a long-range interaction and give rise to a "fifth force". However, through its interaction with matter the chameleon and the symmetron fields acquire a much larger effective mass in any region where the matter density is not too low. This fact leads to a screening of the interaction, which can in this way evade tests of the equivalence principle with macroscopic masses. In contrast, microscopic test masses, such as the atoms in a vacuum chamber, are hardly affected by the screening mechanism, as opposed to the source mass. Hence, atom interferometers can be much more sensitive to forces mediated by such fields [21] and have already been exploited to exclude part of the parameter space for such kind of models [23–25]. However, further constraining these models will require longer interferometer times where the atoms spend a large fraction of the interferometer time close to the source mass and this can be naturally accomplished in microgravity [22,26].

1.1.3 Decoherence and collapse models in quantum mechanics

Quantum Mechanics is grounded in the superposition principle, which is the possibility for quantum systems to occupy two (or more) different states at once. While this principle has been verified over and over in experiments with microscopic systems, its applicability (therefore the validity of quantum theory) to macroscopic objects poses a problem, as first exemplified by Schrödinger with the cat paradox [27]: simply, we do not experience quantum superpositions in our daily life, in spite of the fact that they - mathematically speaking - easily carry over from the microscopic world to the macroscopic one.

Decoherence tells that if quantum systems are not sufficiently well isolated from environmental noises, then their quantum properties are "diluted" in the environment and cannot be seen. This is the case of macroscopic objects, which are impossible to be kept so isolated to detect their quantum behavior. So decoherence gives a partial answer to answer the question why macroscopic systems do not fluctuate like Schrödinger's cat. But this is not the full answer. The reason is that decoherence works because macroscopic systems become rapidly entangled with the environment, which is a highly non classical situation. If quantum mechanics is taken literally, everything becomes entangled with anything else (at the speed of light, in a relativistic world) and one has to find a way to disentangle a classical world.

One way out is to assume that the quantum superposition principle has a limited range of validity: it is not a fundamental principle of nature and progressively breaks down when atoms glue together to form larger and more complex systems [28–33]. Models of spontaneous wave function collapse [34,35] translate this idea into mathematical models: the Schrödinger equation is modified by adding nonlinear and stochastic terms, which induce the collapse of the wave function in space. As such, these models predict that systems progressively lose quantum coherence and behave classically; the larger the system, the faster the transition from a quantum to a classical state.

Such a potential loss of coherence can be tested by suitable interferometric techniques. The basic idea is to create a quantum superposition of a system, which is as massive as possible, make it last as long as possible and then check whether the two branches interfere. If they do, than quantum theory is right, otherwise there is a conflict with the theory. The difficulty is to make the superposition, which requires free evolution, last long enough. Here space helps by ensuring much longer free evolution times than on ground. This will be discussed in Section 4.

Recently, alternative and stronger tests have been developed, which are non-interferometric, because they do not require creating a superposition state. They are based on the fact that, according to collapse models, the collapse of the quantum wave function is triggered by a noise, which also makes particles diffuse. Then, one can test this diffusion process, which takes place also when systems are not in a spatial superposition [36]. Monitoring the diffusion of the center of mass of a system, or the expansion of a gas of particles, has already placed strong bounds on the collapse parameters [37–41]. Space again helps thanks to the longer free evolution times as discussed in Section 2.

1.1.4 Quantum many-body physics

Atoms cooled by laser light followed by evaporative cooling reach ultracold temperatures in the sub-nanokelvin range with average speeds in the 10-100 µm/s. In the last two decades quantum many-body physics with ultracold atoms has experienced a spectacular growth with Bose-Einstein condensates (BEC) and superfluid Fermi gases. Many-body physics has entered a new era where quantitative comparisons can be made between theory and experiments. If mean field theories can be successfully used in some weakly interacting systems, the case of strongly correlated bosons or fermions represents today an outstanding challenge. This covers several fields of physics ranging from QCD, condensed matter, astrophysics (neutron stars), nuclear and atomic physics. For ultracold atoms, the Earth gravity becomes a major perturbation: free atoms fall! If atoms are confined, compensating gravity imposes limitations on the type of traps that must be used and as a consequence imposes limits on the type of physical phenomena that can be explored. Microgravity platforms offer the appealing possibility to overcome this limitation and to access new regimes in ultracold atom many-body physics.

1.2 Need for space

Space provides the ideal conditions for testing fundamental physics. Indeed, a space-based laboratory can ensure long free-fall conditions and long interaction times, important for precision tests where long-duration measurements are needed to average down the noise and characterize the instrument accuracy. Experiments using test masses (macroscopic or atoms) as probes of the space-time metric are a clear example. In 2017, the MICROSCOPE mission could deliver the best test of the Weak Equivalence Principle [42] thanks to the very quiet environment provided by the satellite surrounding the test masses of the differential accelerometer instrument. Atomic clocks and matter wave interferometers reach their ultimate performance under free-fall conditions. Indeed, in space it is possible to reach interaction times between the atomic system and the interrogation fields more than one order of magnitude longer than on the ground. In atomic fountain clocks, the stability is directly proportional to the interrogation time. This allows building instruments like the laser-cooled Cs clock PHARAO that, within a very small volume, mass and power consumption, can reach the same performance of atomic fountain clocks on the ground and even surpass them. PHARAO will soon fly to the ISS as part of the ACES mission to test General Relativity [43]. The benefits of cold atoms for acceleration measurements by matter wave interferometry are even higher, considering that the sensitivity of these instruments scales as the square of the interrogation time [44,45].

The creation of Bose-Einstein condensates in space and first interferometric studies on a DLR sounding rocket flight in 2017 marked the beginning of coherent atom optics and experiments with ultracold atoms in space [46]. Studying ultracold gases continued in orbit thanks to NASA's Cold Atom Lab (CAL) operating since 2018 as a user facility. In 2019, an advanced apparatus of CAL followed to perform interferometric studies with BECs in orbit. CAL will be followed by the DLR-NASA facility BECCAL extending the functionalities. The rapid succession of new instruments shows the maturity of concepts to generate ultracold quantum gases with atom chips. Thanks to their modular designs extensions or adaptations of CAL and BECCAL are comparably fast and also of low costs. Next to studies of quantum gases at lowest energies, they allow method development for quantum technologies and serve as pathfinder for more ambitious missions such as STE-QUEST [47].

Large velocity, velocity variations and large variation of the gravitational potential are accessible on board a spacecraft, thus providing wide signals for testing general relativity and possibly detecting tiny violations of the Einstein's Equivalence Principle. As an example, precision measurements of the gravitational red-shift require large variations of the gravitational potential that can only be achieved in space [43,48,49]. A variety of Standard Model Extension tests based on clock and atom interferometry measurements are possible and have been proposed for space [50].

Finally, the huge free propagation distances available in space call for tests with high performance links, both quantum and classical, in the optical and microwave domains. Lunar laser ranging experiments continue challenging General Relativity, in particular the Universality of Free Fall and the Strong Equivalence Principle [51]. High performance radio link experiments have been designed to measure PPN parameters [52,53]. Quantum links exchanging entangled photons have recently been used to place boundaries on gravity-induced decoherence models [54]. Optical and microwave links are also providing access to networks of clocks both on the ground and in space to test General Relativity and search for dark matter [43,48,49,55].

This document is proposing a white paper for fundamental physics in space, based on the utilization of the platforms currently available or planned in the Human and Robotic Exploration program of the European Space Agency. They include the International Space Station (ISS), Moon and Mars orbiters, landers and rovers, as well as microgravity platforms like sounding rockets, parabolic flights, and drop towers.

1.3 Microgravity and space platforms

There is a variety of platforms to access microgravity conditions and to prepare space missions that provide long and continuous sessions of microgravity conditions in Earth, Moon, or Mars orbits. Europe is in the unique position to have access to a suite of existing or planned experimental platforms:

- Parabolic-flight airplanes;
- Drop towers;
- Elevators;
- Sounding rockets;
- ISS;
- Lunar Gateway;
- Moon and Mars orbiters;
- Moon and Mars landers and rovers.

The first 4 items allow for pre-tests of methods with a too low TRL for an immediate space flight. In view of the success in the past, it is anticipated that in the next ten years, the exploitation of these platforms will continue. While drop tower experiments are well established and benefit from an extended free fall approaching ten seconds in an excellent microgravity environment at a moderate repetition rate, the advent of elevators providing flights of up to several seconds open a new chapter enabling hundreds of experiments a day. These features recommend them for testing functionalities of experimental hardware and methods as well as for atom interferometers and clocks.

Since over 20 years, the ISS is a well established space platform in low Earth orbit currently used for scientific research and application oriented studies. This facility offers access to microgravity conditions for extended periods, up to several years [56].

Further away from the Earth, the Lunar Gateway is a large structure operating in the vicinity of the Moon that will be launched by the partners of the International Space Station. Placed in near-rectilinear halo orbit, the Gateway will offer a post for missions to the Moon and Mars. Similarly to the ISS, it is equipped with a science module dedicated to basic research, a communications module closing the link with Earth, and a robotic arm providing access to external payload facilities [57].

Moon exploration also foresees a series of lander and rover missions that are open to scientific exploitation [58]. An example is provided by the Astrobotics lunar lander [59], which is equipped with interfaces to scientific payload for power, communication, etc. On the longer term, the construction of large structures on the Moon is also to be considered for scientific experiments on the Moon soil.

Along the path that ExoMars is already paving [60], follow on missions are under discussion to address different scientific objectives, including orbiters, landers, and rovers interconnected among themselves and to the Earth. With that respect, this white paper will provide ideas that might guide the design of future scientific missions to the red planet.

A 2 Ultracold atom physics in space

2.1 Background

Nobel-prize awarded landmark achievements such as laser cooling and Bose-Einstein condensation paved the way for cold atom physics in space. Space experiments were pioneered by cold-atom clocks and, very recently, creation and features of Bose-Einstein condensates were studied on a sounding rocket as well as on the ISS. At the same time, the demonstration of their macroscopic coherence established space-borne coherent matter-wave optics. These and other achievements, such as dual species interferometry as well as BEC interferometry, became possible through first experimental tests in microgravity [61] provided in terrestrial platforms as well as in weightlessness established during parabolic flights. Indeed, the PHARAO atomic clock was the first cold-atom experiment tested on parabolic flights [62].

As indicated above, the Earth potential is a major perturbation for dilute gases at nanokelvin temperatures. Take two samples of free rubidium atoms (of mass m) at 1 nK temperature separated vertically by h = 10 µm. The ratio mgh/kT is about 1000! On Earth, one must use trapping potentials to compensate gravity and confine the atoms. In microgravity, this constraint can be vastly reduced.

2.2 Key knowledge gaps

2.2.1 Bose-Einstein condensates (BECs) and quantum-degenerate mixtures

Due to effects such as gravitational sag for harmonically trapped atoms or limited free evolution time, there are plenty of phenomena and unexplored regimes involving quantum-degenerate gases and mixtures whose investigation is impaired by Earth's gravitational field. Magnetic levitation can be employed to compensate the gravitational force [63], but the technique has major limitations. Indeed, it cannot be applied to mixtures involving different internal states or multiple atomic species. Moreover, experiments exploiting Feshbach resonances to tune the inter-atomic interaction cannot be combined with magnetic levitation either. In all these cases the phenomena and regimes alluded to above are inaccessible to ground experiments and require microgravity platforms.

More specifically, the extended microgravity conditions afforded by space platforms such as the ISS offer unique opportunities in the following areas:

- *Scalar BECs*: Long free-evolution times for BECs with very low effective temperatures, gases with record-low entropy per particle, space atom laser, 3D bubble shells of trapped BECs.
- *Coherent atom optics*: Linear optics with nearly monochromatic matter waves, quantum reflection.
- *Spinor BECs and quantum gas mixtures*: Spinor BECs, Bose-Fermi mixtures, study of phase separation, quantum droplets (long-term dynamics in potential-free environment).
- *Strongly interacting gases and molecules*: Feshbach-molecule formation and Efimov physics.
- *Superfluid Fermi gases with tunable interaction.*
- *Critical phenomena near phase transitions.*
- *Entangled atoms.*
- *Quantum memories.*

BECs have already been created in space, both in sounding rockets [46] and on the ISS [64]. Furthermore, there are already plans for a second-generation device with many new capabilities to be operated on the ISS within a few years [65]. These experiments offer a large heritage for future space missions. Their modular character gives flexibility and, depending on the actual experiments, the toolbox can be extended with comparably low efforts. The best example is currently NASA's Cold Atom Lab (CAL) which recently was upgraded by a light beam stimulating Bragg processes for matter-wave interferometry.

This toolbox can be exploited to include additional or other features bringing some of the novel experiments listed above in reach. Examples are cooling of fermions in microgravity, or dual species experiments, or the study of critical phenomena near a phase transition. A pioneering work in this direction was the helium 4 specific heat measurement near the Lambda point realized on the ISS in 2003 [66]. Such space experiment was the most precise test of universal exponents associated to a superfluid phase transition. With ultracold Bose and Fermi gases in microgravity, these critical exponents could also be tested in the strongly correlated regime.

A second class of applications is the possibility to achieve quantum memories with extremely long-lived coherence time based on cold neutral atoms. In many ground experiments, the memory coherence time is limited by the confining potential that must compensate gravity. In a microgravity platform and atom trapping at a magic wavelength, a memory coherence time over 10s of seconds could be attainable.

A third example is the implementation of a set-up to explore high-end methods of atom interferometry as required for testing the Equivalence Principle with unprecedented stringency. Beyond the development and the validation of new methods for space-borne atom interferometry, such a device could be exploited for testing quantum mechanics benefiting of the lowest energy scales nowadays accessible.

Moreover, there exist several concepts to establish entangled atoms at ultralow energy scales, which can benefit from the heritage of current space missions. Entangled atoms open up new avenues to test and explore quantum correlations and, hence, quantum mechanics with massive particles. These sources allow to address the quest of possible fundamental reasons fading these correlations over macroscopic times next to conventional technical reasons. In recent years, space-borne sources of entangled atoms came into reach as non-classical correlations could be demonstrated in ultra-cold atomic systems allowing to benefit from extended free fall. It is anticipated that these experiments will increase their TRL in terrestrial microgravity platforms to be ready for space-borne experiments towards the end of this decade.

2.2.2 Non-interferometric tests of models of spontaneous wave function collapse

Ultracold atoms provide a powerful platform to test deviations from quantum mechanics of the kind envisaged by wave function collapse models. The study of the expansion of a free non-interacting Bose-Einstein Condensate (BEC) already sets a competitive bound [68] on the Continuous Spontaneous Localization (CSL) model of spontaneous wave function collapse [67], one of the reference collapse models in the literature; this result was further improved using double-well systems [69], but is still far from testing the entire parameter space of the model.

The experiment considered in [68] was performed on Earth [70], where a major obstacle was gravity, which limited the total duration of the experiment to about few seconds. Cold atom experiments in microgravity conditions have already been carried out (in a drop tower, in a plane, in a rocket) and some are currently operative in space [64]. This progress points out to the exciting possibility of competitively testing collapse models with cold atoms in space, and in particular of exploring the full parameter space of the CSL model.

Recently, the proposal "CATinSpace: Cold Atoms Tests of the superposition principle in Space" was presented in response to the Call for Ideas to update ESA's SciSpacE Physical Sciences white papers. There, it is suggested to test the CSL model with cold atoms on board of the International Space Station (ISS), by monitoring the collapse-induced expansion of a BEC in a microgravity environment. A BEC with ideally 10^3 or more atoms is prepared and cooled down with state-of-art techniques. Then the trap is released and the cloud is let free to evolve as long as possible; this is where the advantage of a microgravity environment enters. Last, the expansion of the cloud is measured, and compared with the CSL theoretical predictions, bounding in this way the collapse parameters. The great advantage of this approach is that it does not require to set the atoms in a quantum superposition.

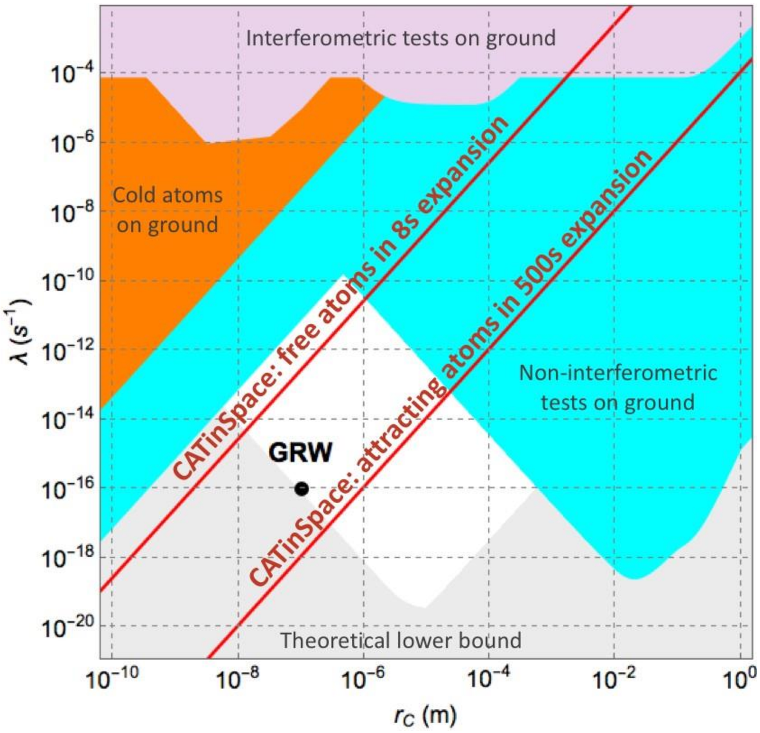

Figure 2: The figure shows the capabilities of CATinSpace to test the CSL model of spontaneous collapse [67], which predicts a progressive breakdown of the quantum superposition principle; this model can be considered as the figure of merit of models of spontaneous wave function collapse. The plot reports the state-of-art exclusion region of the CSL parameter space (λ measures the strength of the collapse and r_C its spatial resolution), compared to the possibilities offered by CATinSpace. Top and bottom red lines: CATinSpace with respectively free and attracting cold atoms. The latter experiment would exclude the values of the collapse parameters originally proposed by Ghirardi, Rimini and Weber [29], which are identified with a black dot. In identifying the boundary of the exclusion region, a precision of 1 μm for the position measurement of the atoms in the cloud has been prudentially considered. The orange region is excluded by cold atom experiments already performed on ground [68]. The pink and blue regions are excluded by several (mainly non-interferometric) experiments [37–40]. The white region has still to be explored experimentally.

Theoretical analysis shows that the size of the cloud grows with the cube of free evolution time under the effect of the collapse noise, hence performing an experiment for longer times in a microgravity environment allows to set stronger bounds - see Figure 2. The analysis has been performed also for a BEC with an attractive interaction: in such a case, the standard evolution predicts basically no expansion, so any increase of the position or momentum will be easier to detect. Preliminary calculation shows that in this way it will be possible to reach a sensitivity high enough to rule out the CSL model with the values for the parameters originally suggested by Ghirardi, Rimini and Weber [29].

2.3 Priorities for the Space Programme

Testing the quantum superposition principle requires isolating a quantum system from potential sources of noise, which hide its quantum behavior. The experiments have to be performed at low temperatures and in vacuum; the quantum system should also be free-falling, since any coupling with a force holding it will introduce additional noise.

According to theoretical models, the larger the system in a quantum delocalized state, and the longer the free evolution, the stronger the quantum mechanical test. This limits the possibility to perform experiments on ground and, to further advance research, micro-gravity conditions are required. Only space allows for quantum experiments with long free evolution times, which are required to test the quantum superposition principle further towards the macroscopic domain.

The capability to perform quantum experiments with cold atoms in micro-gravity has been shown in a drop-tower, parabolic flights and recently on board of the ISS. Therefore, cold atoms represent a mature technology to conduct the space exploration of fundamental physics principles.

Quantum systems with highly controllable degrees of freedom, such as cold atoms, are also extremely precise sensors. In particular, cold atoms are sensitive to very small gravity gradients and therefore hold the potential to improve earth sensing and observation (see Section 4.1.3). Space based quantum sensors will enable better monitoring of the Earth's resources and improve the predictions of earthquakes and the adverse effects of climate changes like the draughts and floods [71].

Reaching a full control of the relevant degrees of freedom for cold atom experiments with long evolution times and high control of the relevant sources of noise requires specific and interdisciplinary expertise from theoretical and experimental physicists, as well as from aerospace engineers.

- *Short-term goals (3-5 years)*: Theoretical analysis of the optimal configurations and of the noises for different platforms; study of a quantum gas facility platform for experiments in elevators; participation of European scientists to CAL and successors and propose relevant experiments among the list on previous page; study of an European laboratory on the ISS or extensions of upcoming facilities.
- *Medium-term goals (5-10 years)*: First tests of collapse models on the ISS; study of quantum gas mixtures or of phase transitions in strongly interacting gases.
- *Long-term goals (> 10 years)*: Realization of an Advanced Atom Interferometer pathfinder; study of entanglement in matter-waves on the ISS.

B 3 Atomic clock tests of General Relativity

3.1 Background

Albert Einstein's theory of General Relativity (GR), which celebrated its 100th anniversary in 2015, is a highly successful theory of one of the four fundamental forces in nature. It is widely applied to understand the structure of our universe on hugely different space and time scales. Applied to special systems such as pulsar double stars, it provides an accurate test of its validity, in particular as far as strong gravity effects and dynamic effects (including gravitational waves) are concerned. Physicists are deeply interested in testing GR in order to probe whether it is really a "perfect" description of gravity. Indeed, it is expected not to be, since unification with quantum physics is an open problem. Tests of GR have been done by observing various astrophysical phenomena. Precision measurements of the deflection of light and the time delay of light signals by massive bodies have been performed by space missions (Cassini, Gaia). It is possible to perform dedicated experimental tests, where custom-built instruments are placed in a controlled setting. Mostly, these experiments are devoted to testing the foundation (assumptions) of GR, in particular the weak equivalence principle (WEP), which states the equivalence of inertial and gravitational mass. After decades of laboratory experiments with torsion balances, in 2017 a space mission, MICROSCOPE, has set the record sensitivity in tests of the WEP in a specially designed, drag-free satellite, with a sensitivity of 1.8 parts in 10^{14} on the Eötvös parameter [42]. WEP tests using cold atoms on the ground have progressed fast in the last years with a sensitivity now at the 10^{-12} level in a 10 meter tower [72] and proposals for space experiments have been made (see below).

Another aspect of the foundations of GR is that gravity affects time. Time flows differently in different gravitational potentials, an effect called gravitational time dilation or gravitational redshift. At the lowest order in the gravitational potential U, this effect represents one aspect of the strong equivalence principle. At higher order, time dilation arises from the specific form of the component g_{00} of the metric tensor of space-time, and is nonlinear in the potential U. In more explicit terms, GR predicts that observers at different gravitational potentials experience different clock rates, even if they use exactly the same clock type. However, the observers realize this only if they communicate with each other, sharing information about how often their clocks have ticked during a common time interval defined by a start and an end signal. This information sharing is accomplished by a frequency transfer link. This gravitational clock shift has been verified in several specifically conceived experiments, at various levels of accuracy. It has also been found to be crucial to include this effect in the synchronization of the constellation of orbiting clocks used for the world-wide global positioning systems. It has also been observed on a quartz oscillator in a spacecraft moving through the solar system. Finally, it has been observed on spectral lines in the Sun's spectrum (with percent-level accuracy) and in astrophysical phenomena. Until 2018, the most precise measurement of the gravitational redshift was at 1.4×10^{-4} fractional inaccuracy level (1976 Gravity Probe A mission), realized by comparing two hydrogen masers at 1×10^{-14} frequency uncertainty level, where one maser was launched into space on a rocket, to a maximum vertical height of 10000 km, while the reference maser clock remained on Earth. This 45-year-old experiment was surpassed in 2018 by a detailed analysis of the clock signals on the two Galileo satellites which were inappropriately launched on an elliptical orbit. The redshift test was improved by 5.6 times, reaching 25 parts per million [48]. The need to improve on the above test result has motivated many researchers towards proposing new space missions. Most importantly, the Atomic Clock Ensemble in Space (ACES) mission will soon be flown on the ISS. Here, a microwave cold atom clock will be used, which was designed to reach an inaccuracy of 1×10^{-16}. Flying at an altitude of ~ 400 km, the experiment will test the time dilation at the level of 2×10^{-6}, providing a further improvement in sensitivity by one order of magnitude.

The developments in the field of atomic clocks in the last 10 years have opened up new exciting possibilities to test the foundation of GR. Indeed a new generation of atomic clocks has been established, the optical atomic clocks. They have been made possible by the development of lasers with superb spectral purity, of subtle atom manipulation techniques, and of the femtosecond frequency comb technique, which were awarded several Nobel prizes in recent decades. The potential of optical clocks relies on the access to narrow atomic transitions in the optical domain ($\nu_0 \sim 10^{15}$ Hz) having a natural linewidth $\delta\nu_0$ of a few mHz, corresponding to a transition quality factor $Q = \nu_0 / \delta\nu_0$ 5 orders of magnitude higher than achievable in microwave standards with $\nu_0 = 10^{10}$ Hz and $Q \sim 10^{10}$. In the last few years this potential has been expressed, with groups demonstrating for the first time fractional stability and accuracy down to the 10^{-18} level or below [73]. This level is a factor of approximately 100 better than obtainable with the best microwave atomic clocks and current progress in this domain is rather fast. It is clear that optical clocks, present implementations and emerging ones, will allow tests of GR of unprecedented accuracy in the near and distant future. In addition, they are also excellent tools for more applied measurements in Earth science (see below).

Several national metrology institutes operate optical clocks in the 10^{-18} stability range, with strontium (Sr) lattice clocks, ytterbium (Yb) lattice clocks, and Yb^+ or Al^+ single ion clocks. Ground clocks may reach the 10^{-20} range in the next 5 years, thanks to the large number of quantum optics and laser specialists contributing to clock developments worldwide, especially in Europe, US, Japan, and China.

An impressive example of the performance of optical lattice clocks was recently given in Japan, where an optical lattice clock at RIKEN (Tokyo) was compared with a similar clock at the University of Tokyo, located at 15 km distance and linked by an optical fiber. The clock frequency difference measured was −709.5(28) mHz (corresponding to a relative uncertainty of 6.5×10^{-18}). This is in agreement with the expected redshift due to the gravitational potential difference, which was independently measured by levelling techniques, −707.48 mHz due to the 15 m height difference. This experiment already achieves an inaccuracy of 4×10^{-3} in testing the redshift. Considering that the height differences was really small, the achieved inaccuracy puts into evidence the tremendous potential of the optical clock technique, if the large height differences that space provides can be made use of. Strong progress is also occurring on implementing ultraprecise optical clocks capable of operating outside of the few advanced metrology laboratories. In Japan one transportable optical clock was operated recently on the Tokyo Skytree radio tower and in Europe three transportable optical lattice clocks have been developed, and one of them has already been transported between countries. The vision of availability, ten years from now, of a large set of optical clocks with 10^{-19} level performance that can be transported and operated anywhere on Earth is becoming realistic.

This progress has implications for space missions with optical clocks:

1. The mission will need to provide links capable of comparing ground clocks at the 10^{-19} level in a moderate integration time, the ground clocks being located anywhere on the Earth.
2. The number of ground clocks available for inter-comparisons will be large (> 20).
3. The improving accuracy of ground clocks implies that more accurate tests of the gravitational redshift become possible when comparing ground clocks with space clocks.

3.2 Key knowledge gaps

The technological and scientific developments occurring for ground clocks facilitate the development of a space clock prototype and promise performance beyond 1×10^{-17} for an actual flight model with a goal for a delivery date in 2025-2027. Given that the most realistic flight option today is the ISS, the first space optical clock to be developed will be of the lattice type, providing low instability already on short timescale, with physical parameters (mass, volume, power consumption) similar to those of ACES. Following the evolution of lasers and quantum technologies, it is expected that eventually a high-accuracy optical clock will be realized with moderate physical parameters (mass < 50 kg, power < 200 W, volume < 500 liters), opening the possibility of flying it on satellites other than the ISS, in particular on highly elliptic orbits or to the inner part of the solar system, with much larger gravitational potential differences.

Furthermore, the technology development also opens the perspective of operating a space clock with two different atomic species, with moderate extra cost in terms of physical parameters, enabling in addition tests of Local Position Invariance. With space clocks of 10^{-17} – 10^{-18} inaccuracy, the sensitivity of the test of the gravitational redshift increases as a function of the orbit size and type (due to an increasing gravitational potential difference). While for Earthbound orbits the term of the redshift effect that is linear in the gravitational potential can be tested, for orbits with segments close to the Sun also the quadratic contribution becomes testable. This represents a qualitatively new regime for redshift tests.

3.2.1 General relativity tests, time and frequency transfer, and relativistic geodesy

General relativity can be tested to high accuracy with a lattice optical clock in space and an optical time transfer link. Different scenarios allowing tests with increasing accuracy can be envisaged.

With an optical clock on the ISS:

- Test of the gravitational redshift in the Earth field with up to 100 times higher accuracy than ACES;
- Test of Local Position Invariance in the Earth gravitational field with up to 100 times higher accuracy than ground experiments;
- Test of gravitational redshift in the Sun field with up to 10 times higher accuracy than with ACES (thanks to the advances in accuracy of ground clocks beyond the ACES time frame).
- Worldwide comparison of ground optical clocks using the Space Optical Clock (SOC) laser links, with applications to e.g. relativistic geodesy down to the 1 mm height resolution level (with improvements in modelling of relativistic frequency transfer and orbital motion);
- Search for dark matter or new physical fields which couple to ordinary matter leading to clock frequency variations of different type;
- Dissemination of time and frequency worldwide, with 10^{-18} inaccuracy, on the time scale of a single pass of the ISS. Dissemination can be to ground, to satellites, or to tropospheric/ stratospheric platforms.

With an optical clock on a highly elliptic orbit around Earth:

- Test of the gravitational redshift with up to 1000 times higher accuracy than ACES;
- Test of Local Position Invariance in the Earth gravitational field with up to 1000 times higher accuracy than ground experiments (with a two-species clock);
- Worldwide comparison of optical clocks, with applications to e.g. relativistic geodesy at the 1 mm level, thus supporting progress in optical clock development; dissemination of time worldwide to a vast range of users.

With an optical clock on an orbit to Mercury:

- Test of the gravitational redshift in the Sun gravitational field with up to 10^8 times higher accuracy than previous space missions/solar spectroscopy;
- Test of Local Position Invariance in the Sun gravitational field with up to 100 times higher accuracy than ground experiments (with a two-species clock).
- Test of light propagation in the gravitational field (Shapiro time delay, light deflection).

The concept of a space mission performed with a high-accuracy optical clock was analysed by P. Bender and colleagues (JILA, USA) [74]. It requires two drag- free spacecrafts, one of which is a laser transponder, the other carrying the optical clock located at the L_1 Lagrange point. The goal is a determination of the PPN parameter γ with inaccuracy in the 10^{-8} range. The ongoing clock developments may render such a mission feasible in the decade. It has recently been suggested to consider whether this test and a test of the solar redshift at Mercury distance could be combined in a single mission, possibly reducing the overall cost. The clock-carrying satellite would be sent on an orbit that brings it into conjunction with the Sun and also includes a fly-by of the Sun.

A clock orbiting around the Earth and a space-to-ground link can be used to establish a network for the comparison of atomic frequency standard, both space-to-ground and ground-to-ground, on a worldwide scale. Ground clocks are today compared via the Global Navigation Satellite System (GNSS) or Two-Way Satellite Time and Frequency Transfer (TWSTFT). IPPP (Integer Precise Point Positioning) processing of GPS data can provide clock comparisons at the 1×10^{-16} level after less than one week of integration time [75]. However, the high stability and accuracy demonstrated by optical clocks is now demanding for a clock comparison infrastructure at least two orders of magnitude beyond current operational systems. The ACES mission will help bridging this gap providing means for comparing clocks on the ground to 1×10^{-17} after a few days of integration time. The next generation of time and frequency transfer systems is expected to reach the 1×10^{-19} uncertainty level in the same measurement duration. Coherent optical links in free space or through optical fibres have already demonstrated such performance [76, 77]. Upgraded versions of the ACES microwave link are currently under development.

A fibre link network for comparing distant clocks is already connecting European metrology institutes (SYRTE to PTB, SYRTE to NPL, PTB to MPQ, SYRTE to INRIM and INRIM to LENS) and additional links will become available in the coming years. However, time and frequency comparisons through fiber links remain confined to a regional basis. In this respect, a space-based system connecting clocks over intercontinental distances for global comparison and distribution of time and frequency standards remains a must.

3.2.2 Lorentz symmetry tests and CPT violations

Lorentz symmetry is at the heart of our most fundamental understanding of matter. Without it our current models of Quantum-Field Theory would be unthinkable. At the same time, local Lorentz symmetry is one of the cornerstones of the Einstein equivalence principle. A violation of local Lorentz symmetry would force us to rethink the most basic principles on which all our current theories of fundamental interactions and gravity rest. State-of-the-art single ion clocks at the 10^{18} level were recently demonstrated to be able to test local Lorentz invariance [78] through sidereal modulations of the frequency offset that hypothetical violations of Lorentz invariance would cause. In fact, already in this case the observed absence of such modulations were used to deduce stringent limits on Lorentz symmetry violation parameters for electrons in the range of 10^{-21}, improving previous limits by two orders of magnitude.

Moreover, being a consequence of Lorentz symmetry, CPT-symmetry is a likewise fundamental property of all our theories, a violation of which would imply Lorentz symmetry violation. Such a violation of CPT-symmetry would show up in unequal moduli for the *g*-factors of the proton and anti-proton, which were, e.g., constrained to below 1.5 parts per billion by means of a two-particle spectroscopy method in a cryogenic multi-Penning trap [79]. Lorentz- and CPT-violating terms of the non-minimal standard model extension can also be constrained by searches for asymmetries in the dark-matter interactions of protons and antiprotons [80].

3.3 Priorities for the Space Programme

- *Short-term goals (3-5 years)*: Complete and fly ACES with utmost priority; prepare for the ACES follow-on mission, I-SOC Pathfinder; develop key optical clock technology for space in preparation for future missions with optical clocks; develop optical and microwave time transfer systems beyond those of ACES.
- *Medium-term goals (5-10 years)*: Fly a space mission in fundamental physics with an optical clock in space (SOC), on the ISS or on dedicated flyer.
- *Long-term goals (> 10 years)*: Explore coherent optical link between the Lunar Gateway and Earth orbiting satellites or ISS for advanced Equivalence Principle tests. Extend this link technology to the red planet.

3.3.1 Exploration relevance

Accurate clocks in the lunar and Mars program can be very profitably exploited in the context of precise spacecraft navigation. The need for innovative, largely autonomous, positioning systems requiring a minimal intervention from ground is highly desirable to effectively support exploration missions, both robotic and human. Today the navigation of lunar probes is carried out with the traditional methods of orbit determination based upon radio-metric measurements (Doppler and range) generated at a ground station. More recently, attempts have been made to exploit the Earth orbiting GNSS satellites to provide real-time radio localization or, more precisely, the dynamical state of lunar orbiters, landers and rovers.

This system has important limitations. In addition to the need of relatively large onboard antennas, it is anyway exploitable only for probes or spaceships not occulted by the Moon (i.e. in the near side of the moon). The geometrical dilution of precision is also quite unfavorable (the GNSS satellites are observed with an angular separation of about 4 degrees from the lunar orbit), leading to a strong degradation of the positional accuracy, especially in the plane orthogonal to the Earth-Moon line.

The use of radio signals provided by a stable and accurate clock on Artemis, or by a handful of pseudolites equipped with atomic clocks (all synchronized with the GNSS time) would drastically reduce this effect. Indeed, the radiolocalization of a probe could rely on a variety of geometries, in addition to the use of the Earth GNSS signals. The combination of signals coming from a variety of directions would end up in substantial improvement in the positional accuracy. One could also conceive pseudolites located in the far side of the Moon to provide navigational assistance that is otherwise impossible or difficult to obtain. Synchronisation with terrestrial time would require a relay satellite with precisely known ephemerides.

One could obviously conceive a full GNSS constellation in lunar orbit. However, for the needs of the current exploration program, probably simpler solutions are sufficient. As mentioned above, if the timekeeping is maintained on an orbiter (e.g. Artemis), the determination of the ephemerides of the host has to be maintained with sufficient continuity with traditional methods.

The concept of a Martian GNSS has been considered since a long time, in view of ambitious plans of Mars exploration. All these systems require accurate clocks onboard a constellation of satellites. The planetary environment and the large distance from the Earth pose significant problems, especially if the constellation is required to operate with an ample degree of autonomy and minimal intervention from ground.

A concept that has been recently investigated is based on a network of small satellites capable of providing the relative and absolute positioning by means of intersatellite radio links (ISL) and the a-priori knowledge of the rotation and the gravity field of the planet. (The Martian gravity field and rotational state is well known from previous missions and is continuously improved.) The ISL configuration need not to be a GRACE or GRAIL-like (which requires frequent synchronization from Earth), but could be based on high accuracy two-way Doppler measurements driven by a standard ultrastable oscillator [81]. The short round-trip light time strongly suppresses the clock noise, allowing range rate measurements with accuracies $< 1 \times 10^{-6}$ m/s from 30 to 1000 s integration time. Once the ephemerides of the constellation have been precisely measured (e.g. by means of a Kalman filter running on a main node), user positioning can be obtained using a GNSS-like time and frequency distribution system, or using Doppler signal (an easier, although less precise architecture).

This concept is likely to deliver positional accuracies that are inferior to those of a full-fledged Martian GNSS, but would certainly require a much less extensive (and expensive) infrastructure. It would be in any case the product of a fruitful joint effort from the fundamental physics community (providing the accurate clocks) and the navigation community.

3.3.2 Benefit for Earth and industrial relevance

Global time scales are relying on the comparison of distant clocks. The International Atomic Time (TAI) is generated by BIPM (Bureau International des Poids et Mesures) based on the comparison of primary frequency standards (Cs clocks) worldwide. TAI plays a major role in the definition of UTC (Universal Time Coordinated), which is today recognized as the official time scale. UTC is at the basis of several everyday's life applications like precise navigation services via the GNSS network, synchronization of worldwide exchanges and markets, communication networks, national defense and security. Optical clocks, which outperform Cs clocks by two orders of magnitude, are already being considered as central elements of new schemes and architectures for generating more precise global time scales [82]. The continuous improvement of optical clocks and the ongoing efforts to compare them worldwide will soon lead to the re-redefinition of the second in the International System of Units (SI).

Global networks of atomic clocks can be used for the in-situ measurement of geopotential differences. Einstein's formula of the gravitational redshift can be used to convert the result of a frequency comparison between two remote clocks into a measurement of the gravitational potential difference at the location of the two clocks. A frequency uncertainty of 1×10^{-18} corresponds to a 1 cm resolution on the geoid height. This technique, usually referred to as relativistic or chronometric geodesy, has already been demonstrated in an experiment comparing two clock separated by a 15 km distance achieving an uncertainty of 5 cm on the height difference [83]. Local measurements of geopotential differences are important to connect national height systems and resolve the discrepancies currently observed over intercontinental distances as well as at regional scales, e.g. in Europe. Phenomena such as sea level changes, ocean circulation, ice melting, glacial isostatic adjustment, and land subsidence as well as their mutual interaction can only be understood through high precision and long-term monitoring of gravity potential changes complemented by information on purely geometric height changes (from the GNSS network) and associated mass changes.

C 4 Matter-wave interferometry tests of General Relativity and Quantum Mechanics

4.1 Atom interferometry

4.1.1 Background

Atom interferometers [84–86] can address central questions in quantum mechanics and general relativity. These two theories, which have been extremely successful, constitute the fundamental pillars of modern physics. However, a fully satisfactory framework bringing both theories together is still lacking. Recent research has shed new light on traditional concepts of general relativity in the context of matter-wave interferometry showing that the latter enables tests which are rather complementary to classical ones regarding the universal free fall of matter as well as the universality of gravitational redshift. Moreover, the progress in quantum engineering of matter waves rises prospects for performing tests of unprecedented rigour for the Eötvös ratio in the 10^{-17} range.

On ground, atom interferometers have already been successfully exploited for high-precision measurements in fundamental physics and for practical applications [87]. However, thanks to the extended microgravity conditions afforded, it is in space that their full potential can be unleashed and where unprecedented sensitivities could be attained.

Only recently, a comparison of matter wave interferometers based on rubidium isotopes reached a sensitivity of 10^{-12} [72] leaving still quite a gap to the performance anticipated for space-borne tests on a dedicated satellite. Perspectives for bridging the remaining gap and for reaching sensitivities beyond current results are opened up by elevator tests allowing for better statistics and a better microgravity environment than other platforms.

Having pioneered dual species interferometry based on potassium and rubidium both on ground [88] and during parabolic flights [89], Europe has a considerable heritage in performing such tests. Moreover, several sounding rocket missions carrying a dual species interferometer to space are already foreseen for the next years. Hence, within this decade, one can expect terrestrial microgravity experiments improving state-of-the-art quantum tests by about two orders of magnitude and rising the TRL for space-borne tests.

4.1.2 Key knowledge gaps

4.1.2.1 Weak equivalence principle tests

Concepts for quantum tests of the equivalence principle have been already established both for the International Space Station as well as for satellites. A satellite-based quantum test of the weak equivalence principle is pursued by a large European consortium [44]. Considered as not mature enough for the ESA’s Cosmic Vision program, it is now proposed for Voyage 2050 acknowledging the recent progress in the field [90].

It has been emphasized that the co-location of the different atomic species in tests of UFF based on atom interferometry, which is an important contribution to systematic effects, poses a major challenge in order to achieve such high sensitivities. Indeed, target sensitivities at the 10^{-17} level imply very stringent requirements on the initial kinematics of the two atomic clouds: their relative initial position and velocity need to be controlled at the level of a few tens of pm and pm/s respectively. This is technically very demanding and, moreover, its verification under the same experimental conditions would require a large fraction of the mission lifetime. Fortunately, an effective mitigation technique has recently been proposed: by suitably adjusting the frequencies of some of the laser pulses, it is possible to compensate the effects of gravity gradients and relax the requirements on the initial kinematics by several orders of magnitude [91].

The experimental implementation of the gravity-gradient compensation technique has been successfully demonstrated in ground experiments [92,93], and it is an important element of a recent atom-interferometric test of UFF at the 10^{-12} level [72] with prospects for further improvement in the near future. Furthermore, in space missions it can be combined with orbital demodulation methods, so that sensitivities up to 10^{-18} can be reached with moderate requirements on the initial co-location [94].

On the other hand, the progress made in performing experiments with Bose-Einstein condensates in space [46,64] offers also new prospects to exploit the heritage for a quantum test in orbit, on the International Space Station. Albeit offering a lower performance than satellite missions, experiments on the ISS are anticipated to reach an intermediate level of stringency between 10^{-13} and 10^{-16} in the Eötvös ratio, depending on the experimental design [95,96]. As initial steps in this direction, there are already preliminary atom-interferometry experiments underway with the Cold Atom Lab (CAL) on the ISS performed in collaboration with NASA, and more advanced ones will be possible thanks to the next-generation device BECCAL [65], which will feature extended atom-interferometry capabilities.

4.1.2.2 Dark energy

Certain classes of dark-energy theories, known as chameleon-field [21] and symmetron-field [22] models, involve a light scalar field that can mediate a long-range interaction and give rise to a “fifth force”. However, through its interaction with matter the chameleon and the symmetron fields acquire a much larger effective mass in any region where the matter density is not too low. This fact leads to a screening of the interaction, which can in this way evade tests of the equivalence principle with macroscopic masses. In contrast, microscopic test masses, such as the atoms in a vacuum chamber, are hardly affected by the screening mechanism, as opposed to the source mass. Hence, atom interferometers can be much more sensitive to forces mediated by such fields [21] and have already been exploited to exclude part of the parameter space for such kind of models [23–25]. However, further constraining these models will require longer interferometer times where the atoms spend a large fraction of the interferometer time close to the source mass and this can be naturally accomplished in microgravity [22,26].

4.1.2.3 Dark matter

Pairs of atom interferometers in space separated by long baselines (from thousands to millions of km or more [97]) and interrogated by common laser beams propagating along that baseline can be exploited to search for dark matter candidates corresponding to ultralight scalar fields [20]. In order to avoid otherwise extremely demanding requirements on laser phase stability, a new kind of atom interferometers based on single-photon diffraction need to be employed [98].

The available platforms and resources do not fulfill the requirements for a fully-fledged mission [45, 99, 100]. However, demonstrators involving single atom interferometers or even pairs of interferometers separated by small distances could help to boost the required TRL for future dedicated missions. Since they employ the same kind of atoms (e.g. Sr or Yb) and lasers (laser cooling and clock transition) as optical atomic clocks, joint efforts with plans for an optical clock in space (I-SOC [101]) should be possible.

Furthermore, by making use of simultaneous pairs of laser pulses driving the clock transition that can simultaneously diffract the two internal states [7], it would be possible to perform WEP tests with atoms in a quantum superposition of internal states (in this case the two clock states, with an energy difference of the order of a few eV). Compared to previous ground experiments with superpositions of hyperfine states [6], this would enable longer interferometer times (and hence higher sensitivity) and would increase the energy difference between the two internal states involved by 5 orders of magnitude.

4.1.2.4 Lorentz symmetry and CPT violations

Up to now, only about half of the coefficients for Lorentz violation, in the context of the fermionic sector of the minimal Standard Model Extension (SME) in Minkowski spacetime, have been investigated experimentally. However, some of these open parameters can be constrained in the future by considering gravitational couplings in the fermionic sector of the SME, with a particular interest for the coefficients for baryons and charged leptons, in principle unobservable in Minkowski spacetime, which could be large due to gravitational countershading.

A major class of experiments that can achieve sensitivity to these coefficients involve tests with ordinary neutral matter. They are analyzed via a Langrangian describing the dynamics of a test body moving near the surface of the Earth in the presence of Lorentz violation, revealing that the gravitational force acquires tiny corrections both along and perpendicular to the usual free-fall trajectory near the surface of the Earth, and the effective inertial mass of a test body becomes a direction-dependent quantity. The tests can be classified as either gravimeter or WEP experiments and as either force-comparison or free-fall experiments.

Atom interferometry provides extremely sensitive and accurate tools for the measurement of inertial forces and are then of particular interest to test Lorentz violations. During the free fall of cold atoms, they experience a sequence of three laser pulses, that split and recombine the atomic wavepackets. Operation of atom interferometers in microgravity is expected to increase the duration of free-fall and then to enhance the performance of such sensor. Consequently we expect to increase their sensibility to possible Lorentz violation in the gravity-matter couplings of SME.

4.1.3 Priorities for the Space Programme

Long free-evolution times are especially important for experimenting with interferometers involving quantum states of ultracold atoms or even quantum degenerate gases. The main drivers for exploring ultracold atoms in space are testing the fundamental laws with better stringency and explaining new phenomena such as dark matter and dark energy as well as Earth observation, space navigation, and planetary science and exploration.

Regarding the quests in fundamental science, the proposals submitted in response to ESA's call for ideas within the Voyage 2050 program and the associated white paper reflect the crucial importance of interferometry based on ultracold atoms and quantum degenerate gases. Obviously, the underlying concepts have also technological relevance.

- *Short-term goals (3-5 years):* Experiments in elevators performing quantum tests of the universality of free-fall for narrowing the gap to sensitivities of 10^{-17} targeted by space missions.
- *Mid-term goals (5-10 years):* Exploring dual atom interferometry on the ISS or free flyers; pathfinder experiment on the ISS or a free flyer involving atom interferometry based on an optical clock transition.

- *Long-term goals (> 10 years):* Space-borne quantum test of the equivalence principle; space-borne detectors of ultralight dark matter.

4.1.3.1 Exploration relevance

After the commercialization of the first atomic gravimeters surpassing classical techniques in various important aspects, such as quasi continuous absolute measurements [102], prospects for further improvements exploiting ultracold atoms [103–105] and mobile operation [106–108], atom interferometers have become an established method for exploration. Indeed, since the first proposals for bias-free accelerometers in the SAGE mission to investigate the Pioneer anomaly, the underlying concepts have experienced substantial development and first atom interferometry experiments in space have already been performed [46,64]. With a demonstrated long-term stability of 0.5 nm/s^2 [109], these sensors are a promising technology for bias-free space navigation [110–115].

4.1.3.2 Benefit for Earth and industrial relevance

Missions such as GOCE, GRACE and the current GRACE-FO have been successfully completed or are still delivering important observations. Without doubt, their results have been boosting and transforming satellite geodesy and gravimetry. New mission concepts are in the focus of current research [116–121]. They are based on new, laser-interferometric distance measurements combined with atom interferometers featuring a sensitivity of 6×10^{-10} $ms^{-2}Hz^{-1/2}$ [119,121], atomic gradiometers with a sensitivity of 5×10^{-12} $s^{-2}Hz^{-1/2}$ [116,118,120], new proof-mass concepts and associated tracking methods.

Atom interferometers merge new approaches of optical read-out and entirely new test masses based on floating ultracold atoms or quantum degenerate gases. Several proposals have been studied by ESA and national agencies like CNES, DLR and ESA [116,118–121].

Commercialization of these sensors has already started [102] and they represent the earliest commercial products of the latest quantum technologies. It is therefore foreseeable that this evolution will grow in view of the new concepts developed for space exploration.

4.2 Large -mass interferometry

4.2.1 Background

Beside the mature science and technology of cold atoms, there is a growing number of large-mass experiments to test various aspects of fundamental physics, ranging from testing the quantum superposition principle, gravitational decoherence, relativity and gravitational waves, the interplay between quantum and gravity as well as typical high-energy particle physics such as predictions for dark matter and dark energy. Experiments with large-mass systems (typically from 10^9 to 10^{15} atoms) include non-interferometric opto/electro/magneto-mechanical systems [122] as well as matter-wave interferometric experiments with molecules and nanoparticles [123]. Large-mass systems pushing the envelope of realisation of quantum states towards the macroscopic domain, while at the same time providing an ultra-sensitive test bed for standard model and exotic forces and acceleration. Similarity with cold atomic manipulation is the goal to quantum control the center of mass motion and most of the ideas for fundamental test with atoms can be translated forward to heavier particles.

At the same time, there is an important development going on in our approach to fundamental physics by challenging our common understanding of nature, while taking a fresh view on the topics of relativity and quantum mechanics. Some ideas have been put forward and have to be evaluated by the scientific community in the context of the best choice for an experimental platform in order to test them. In this respect, these new ideas are less mature, when compared to some of the other ideas discussed in this white paper, but there is for sure a new horizon.

4.2.2 Key knowledge gaps

What is in common for large-mass experiments and new ideas is that they all will *benefit from extended periods of evolution in the micro-gravity environment* available in space stations such as the ISS, the Lunar Gateway or satellites to Mars.

Below is an overview of some of those fresh approaches for testing fundamental physics.

4.2.2.1 Non-interferometric tests with large-mass systems

Proposals are based on the mature experiments of optomechanics and especially levitated optomechanics and include testing of predictions from General Relativity such as gravitational waves in a higher frequency domain complementary to large-footprint experiments such as LIGO, VIRGO and GEO600 on compact designs and geometries [124,125], and the testing of classical gravity and spacetime curvature [126], while pilot experiments on Earth have been realised already [127]. Using large-mass systems to probe the high-energy particle physics sector beyond the standard model includes testing dark matter candidates [128,129] as well as dark energy [130]. Experimental geometries for gravitationally interacting one- and two-mass systems include ideas for testing the gravitational field generated by a massive quantum system [131, 132], but also include probing the GR frame dragging effects [133]. Last but not least, the quantum superposition principle has been tested already non-interferometrically in the lab [40], but would certainly benefit from the envisaged space environment as well.

4.2.2.2 Interferometric tests with large-mass particle systems

Large-mass matter-wave interferometers in space will be able to test DM candidates [128,134–136], as well as quantum superpositions in the large-mass limit of macroscopicity, which has been put forward as the MAQRO proposal [137]. The idea has been successfully evaluated within the Quantum Physics Platform (QPPF) CDF study by ESA already and is awaiting technology development of components, which is underway in the optomechanics community [138]. The design of a matter-wave interferometer for nanoparticles fit for space has been theoretically proposed and discussed [139–141] using different types of coherent beam splitters for nanoparticle matter-waves. A progressive idea is to utilise the rotational degree of freedom of large mass systems, actually in interferometric and non-interferometric settings, to test quantum mechanics in the macroscopic domain [142,143]. Again, key to conduct those experiments is access to extended periods of time in micro-gravity environments. A review summarising the experimental challenges of interferometric experiments with large-mass particles has recently appeared [144].

4.2.2.3 New ideas to test the interplay between gravity and quantum mechanics

Proposals have been worked out in the context of gravitational decoherence and semi-classical gravity [145,146], the role of gravity in the collapse of the wavefunction according to the Diósi-Penrose ideas [31,147–149] as well as in the context of stochastic gravity [150,151]. Ideas which attracted much attention include a new take on testing quantum gravity by using quantum information protocols for the state preparation of large-mass systems [152–155]. Further ideas have been put forward to test gravitational decoherence and general relativistic time dilation effects also with large-mass system in interferometric settings [156] and a scientific debate is underway to explore the correct physics description and solid prediction of the effects [7,157]. Furthermore, experiments to test Quantum Mechanics in accelerated reference frames, aiming to exploit the correspondence between acceleration and gravity utilised by the equivalence principle and the use of stark accelerated systems. First experiments have been performed in research laboratories and with quantum states of light, such as entangled states [158] or those showing other strong and non-classical correlations [159], but can also be extended to large-mass systems and indeed the space settings [160].

4.2.3 Priorities for the Space Programme

Fundamental physics questions with such objects are concerned with tests of large-mass limits of quantum mechanics and the interplay between gravity and quantum mechanics. For example, the presently considered mass limit for quantum superpositions on Earth is 10^8 amu (atomic mass units). Space seems the only reliable option for a test of quantum mechanics beyond that mass limit within the foreseeable future. Direct tests of dark matter and dark energy will be considered.

At the theoretical level, there is a strong need for the development and use of interdisciplinary approaches based on current knowledge in the fields of General Relativity, quantum information, quantum field theory in curved space-time, quantum gravity theories in relation with the propagation of light and matter, decoherence theories (including time dilation effects, gravity induced phase shifts for single photons) aimed at the design and characterization of experimental efforts in the large-mass particle platforms addressed in this section, but also beyond in synergy with photonic and cold atom platforms.

Scientific research and technology development of cavity optomechanics, electro-mechanics, magneto-mechanics and large-mass interferometry are rapidly growing into the fundamental physics platform to investigate massive systems in the quantum domain.

- *Short-term to medium-term goals (< 10 years):* The immediate goal is to develop and grow a community of academics, industry, space agencies and funding bodies, coordinated by the QPPF effort with an efficient management structure to work on large-mass matter-wave interferometry and optomechanics based test of fundamental physics in space based on the successful CDF study, which has clear recommendations for technology development. Such technology development is already underway, supported by ESA, National and European funding agencies as well as the preparation for first tests in micro-gravity environments. The community has to foster proof-of-principle experiments on ground and the development of technology into sufficient TRLs. A large ERC project has been funded recently to test nanoparticle interferometry to the maximum possible mass on Earth. Especially important is the early collaboration of the large-mass interferometry community with the space sector and relevant industry to establish flight opportunities such as in CubeSats and tests in micro-gravity environment (drop-tower, parabola flights, sounding rockets) for proof-of-principle experiments or prototyping, such as large-particle interferometry on platforms such as ISS.
- *Long term goal (> 10 years):* The community has to work towards a fundamental science space mission, using heritage of the LISA and LISA Pathfinder missions and technology, in collaboration with ESA. This will need a considerable push of TRL on component level. Then to fly a dedicated space mission to perform a fundamental physics experiment in space based on quantum states of a large-mass object with a timescale for launch in the mid or late 2030s. Technology needs to be developed to the right TRLs. QPPF needs the development of a reproducible particle source and the selection of an appropriate particle type with tailor-made optical and electric properties, as well as the development of efficient particle detectors.

4.2.3.1 Exploration relevance

Beside the unparalleled ability to explore fundamental physics [144] in a multitude of directions, large-mass systems are also superb sensing platforms for inertial forces, gravity, rotation and electro-magnetic interactions to a record low level as demonstrated in research labs [161–166], even outperforming for instance the best magnetic sensors realized by cold and warm atomic vapours and defect centres in diamond [167–169] to record low level of 10^{-15} Tesla and indeed low-frequency classical mechanical silicon-based sensors are already used as gravimeters on Mars [170] demonstrating the technical applicability of mechanical sensors in space environment and especially on ISS, Moon and Mars missions.

4.2.3.2 Benefit for Earth and industrial relevance

This immense potential will soon find applications of mechanical systems, classical or quantum, in space, such as for the measurement of non-gravitational accelerations on the spacecraft like magnetic fields, e.g. the measurement of the World Magnetic Model (WMM), gravity gradient mapping [171]. It will be straight forward to extend the large-mass technology for planetary studies from space.

The unique physical performance of mechanical oscillators at record low force noise of 10^{-21} N/Hz$^{1/2}$, torque noise of 10^{-29} Nm/Hz$^{1/2}$ and position resolution of 10^{-15} m allows for a broad variety of application, which are just appearing on the horizon and will soon find their well-deserved place amongst high-precision devices for sensing and metrology. Some examples beyond the aforementioned applications are frequency conversion and timing [172–174], also hybrid devices which can do sensing and timing at the same time [175]. And indeed the use of quantum metrological tools for the application of mechanical systems for gravimetry and gradiometry have already been proposed [126].

Indeed mechanical sensors have already found their way for exploration in gravity based geology and resource exploration, mining as well as navigation and the defence sector and various industry projects, spin-out activities are under way in many European countries and we will see the benefit of such developments for the fundamental science space sector very soon.

D 5 Classical and quantum links

5.1 Solar system tests

5.1.1 Background

The solar system continues to be a valuable laboratory for tests of gravitational theories in the weak field limit. Its main advantage is that all measurements are carried out in a well known and controlled environment. Strong field tests made possible by current and future gravitational wave detectors, besides testing different aspects of gravity, cannot claim the same precise knowledge of the dynamical environment. Solar system tests rely almost entirely on the exchange of photons between Earth and a distant spacecraft. At the moment deep space links are established using microwave frequencies, in particular Ka-band (32-34 GHz) for higher measurement accuracy. In the future laser links may offer improved accuracies and a more accurate metrology system.

There are laser retroreflector arrays (LRAs) on the Moon since about 50 years, deployed by Apollo 11, 14 and 15 astronauts [176] and by the Lunokhod 1 and 2 rovers. There were no laser retroreflectors on Mars, until a downsized, lightweight LRA (or “microreflector”) [177,178] was deployed on Mars with NASA’s InSight lander in 2018 [179]. Apollo and Lunokhod LRAs are positioned by time-of-flight measurements of short laser pulses shot by ground stations of the International Laser Ranging Service (ILRS, ilrs.gsfc.nasa.gov). This is the so-called Lunar Laser Ranging (LLR) geodetic technique, which is performed regularly by three ILRS stations: Grasse in France (in service since the longest time), APOLLO (Apache Point Lunar Laser-ranging Operation) in the USA (the most modern and accurate) and MLRO (Matera Laser Ranging Observatory) in Italy. Several other ILRS stations are starting or testing LLR, in China, Europe and Russia. Microreflectors are designed to be positioned by orbiting spacecrafts equipped (for example) with laser altimeters like NASA’s Lunar Reconnaissance Orbiter (LRO, currently active) and NASA’s Mars Global Surveyor (MGS, active until 2007). This is an “inverse” Satellite Laser Ranging (SLR) geodetic measurement if compared to the routine operation of the ILRS (laser stations on the ground and LRAs on orbiting satellites).

Already in 2005 laser links at 1064 nm have been proven [180] between an ILRS stations (including the NASA-GSFC 1.2 m laser telescope) with: 1) MOLA (Mars Orbiter Laser Altimeter) onboard MGS at distances of 80-100 million km: 2) MLA (Mercury Laser Altimeter) onboard MESSENGER (MErcury Surface, Space ENvironment, Geochemistry, and Ranging) at a distance of about 25 million km. The former was a laser uplink (Earth to spacecraft), while the latter was the first uplink and downlink laser communication at interplanetary distances. In the 2010 decade, laser uplink campaigns were performed at 532 nm from multiple ILRS stations to LOLA (Lunar Orbiter Laser Altimeter) onboard LRO [181]. In 2013 successful high-rate lasercom to and from Moon orbits (uplink and downlink at 1550 nm) was demonstrated by the LLCD payload (Lunar Laser Communications Demo) onboard NASA’s LADEE orbiter (Lunar Atmosphere and Dust Environment Exploration) [182]. Also ESA’s Optical Ground Station (OGS) at the Canary islands participated in this international lasercom campaign. Finally, in 2018 and 2019 the Grasse ILRS station was also able to perform SLR at 1064 nm to an LRA onboard the anti-nadir side of LRO [183].

5.1.2 Key knowledge gaps

Solar system tests rely essentially on two methods:

1. The measurement of the time delay, frequency shift and angular deflection of radio beams (in the latter case using extragalactic sources, not spacecraft);
2. The precise monitoring of the motion of solar system bodies, carried out using active spacecraft tracking.

These tests are enabled by precise measurements of spacecraft range and range rate. Several technological developments have been carried out in the last decade in order to improve the measurement quality. The most important are listed below:

1. Use of higher frequency or multi-frequency radio links to reduce or suppress charged particle noise;
2. Use of more precise ranging systems by means of pseudo-noise modulation codes at higher chip rate;
3. Use multistation tracking, with a small listen-only antenna located at high altitude) to reduce tropospheric and mechanical noise in Doppler measurements.
4. Use stable clocks onboard a spacecraft to establish precise one-way radio links for Doppler measurements.

It is important to point out that in order to fully exploit improved measurement systems, a corresponding improvement of the dynamical model of the spacecraft and the solar system itself is necessary. On the spacecraft side, the measurement of non-gravitational accelerations, or even the transition to drag-free systems, is a necessary step. Accelerometers are the simpler solution, but the real difficulty, requiring considerable technological development, is the extension of the operational band to lower frequencies ($10^{-7} - 10^{-6}$ Hz).

After the start of operations of GAIA, the launch of BepiColombo is probably the most relevant event for solar system missions with a substantial set of objectives in fundamental physics. BepiColombo uses a multilink radio system for full plasma calibration both for Doppler and range measurements, and 24 Mcps pseudo-noise range modulation (corresponding to a wavelength of 25 m). Early results from inflight tests show an accuracy of the ranging system at the level of 1-2 cm over 4 s integration time, for the entire duration of a pass (about 8 h). Ground and onboard delay calibrations were crucial to attain such an unique result for a radio system. If this measurement accuracy will be demonstrated to be an absolute one (i.e. an absolute round-trip light-time measurements), it will be possible to resolve the phase ambiguity, at least for the X-band signal.

BepiColombo will exploit six solar conjunctions during cruise to carry out the classical test of time delay and frequency shift, with the prospect of significantly improving the Cassini result for the PPN parameter γ [$(2.3 \pm 2.1) \times 10^{-5}$]. During the orbital phase, BepiColombo data, combined with solar system dynamics knowledge acquired by other missions (past, ongoing and close to launch) is expected to improve significantly the accuracy from almost all PPN parameters. The table below summarizes the expected accuracies, under the assumption of 20 cm ranging accuracy (according to instrument specifications) rather than actual performance (2 cm), and different assumptions for the analysis.

GAIA is also expected to release soon a substantially improved measurement of γ, using astrometric measurements. The diversification of methods in precise tests of GR is of course of the utmost importance.

Being carried out in a fully relativistic frame, the generation of solar system ephemerides offers another method to test gravity laws (see [185], with earlier references therein). The BepiColombo data are expected to improve significantly our knowledge of solar system dynamics.

Parameter	Imperi et al.	De Marchi and Cascioli
γ	6.6×10^{-7}	1×10^{-6}
β	4.5×10^{-7}	1.7×10^{-5}
J_2	1.37×10^{-9}	2.8×10^{-9}
η	1.36×10^{-6}	6.9×10^{-5}
α_1	1.2×10^{-7}	3.4×10^{-7}
α_2	4.6×10^{-8}	6.7×10^{-8}
$GM_{\odot}(\mathrm{km^3 s^{-2}})$	0.015	0.08
$\zeta\,(yr^{-1})$	3.2×10^{-15}	9.2×10^{-15}
$\lambda_g\,(km)$	–	$< 1.1 \times 10^{14}$

Table 1: Expected accuracies in PPN parameters, gravitational parameter of the sun, relative time derivative of the Newtonian gravitational constant (ζ), and Compton wavelength of the graviton (λ_g), using 20 cm range accuracy (instrument requirement) and different assumptions in the analysis, and for a 2 year mission duration (from [184]).

Among future projects being proposed to improve solar system ephemerides, the TRILOGY concept [186] is especially interesting. The main goal of TRILOGY is twofold: on one hand, to improve the range measurements by using interplanetary laser links; on the other hand remove degeneracies in the orbital solutions related to the fact that all measurements are carried out from the Earth. Using planetary orbiters (or even landers) exchanging laser pulses would provide a more robust determination of the planetary ephemerides and the associated relativistic parameters. In addition, TRILOGY could measure the expansion of the solar system ensuing the mass loss from the sun.

The TRILOGY concept would certainly require significant technological development in interplanetary laser links and accelerometers. It will certainly benefit from the technological fallout from LISA and the space gravitational wave detectors proposed for the very low frequency band (roughly 10^{-4} – 1 Hz).

We cannot conclude this overview on ongoing and future solar system tests without noticing that in the framework of the ESA Voyage 2050 not a single white paper has been proposed for fundamental physics tests in the solar system. Previous concepts such as LATOR were not presented. The lack of proposals should however not be interpreted as a lack of interest. Rather, it appears clear to the fundamental physics community that expensive dedicated missions will have little chance of being approved in the absence of a sufficiently strong theoretical framework able to make reasonably solid predictions on the level at which the violations of GR will occur. Since then, fundamental physics tests in the solar system will have to rely of instrumentation mounted on planetary missions.

For about 50 years LLR to Apollo/Lunokhod Cube Corner laser Retroreflector (CCR) arrays supplied accurate tests of General Relativity and new gravitational physics: possible changes of the gravitational constant $\dot{G}/G$, weak and strong equivalence principle, gravitational self-energy (Parametrized Post Newtonian parameter β), geodetic precession, inverse-square force-law [187–189], spacetime torsion [190,191] and nonminimally coupled gravity [192,193]. LLR has also provided significant information on the composition of the deep interior of the Moon, complementary to that of NASA's mission GRAIL (Gravity Recovery And Lunar Interior Laboratory). In fact, already in the later 1990s LLR first provided evidence of the existence of a fluid component of the deep lunar interior [194], confirmed later by a re-analysis of Apollo lunar seismometry data in 2011 [195]. Therefore, Apollo/Lunokhod LRAs have supplied the first realization of a passive Lunar Geophysical Network (LGN) not only for precision tests of GR but also for lunar planetary science [196]. However, nowadays they only allow slow statistical improvements with data accumulation, which does not support the priorities of the modern science program.

For Moon missions the relevant laser ranging instruments are full-size LRAs for direct LLR from Earth. In 1969 multi-CCR arrays contributed a negligible fraction of the LLR error budget. Since laser station range accuracy improved by more than a factor 100, now, because of lunar librations, the Apollo/Lunokhod LRAs dominate the LLR error budget due to their multi-CCR geometry and large geometric size. For direct LLR by ILRS, a next-generation, single, large CCR payload has been developed by a US-European collaboration, which is unaffected by lunar librations, that supports an improvement of a factor 100 of the space segment contribution to the LLR error budget (see [188,189,197]). This instrument has a mass of the order of the kg.

For Mars missions the relevant instruments are microreflectors with masses of the order of few tens of grams that are positioned by laser ranging from Mars orbiters. Direct laser ranging from Earth like for the Moon is not practically feasible. ESA's ExoMars Schiaparelli, which unfortunately failed its landing in 2016, was carrying a microreflector [198] like the one on InSight. Two additional microreflectors will be deployed on the surface by NASA's Perseverance and ESA's ExoMars rover missions in 2021 and 2023, respectively [199]. Similar instruments can be proposed for the Mars Sample Return program of NASA and ESA: one for ESA's Sample Fetch Rover and one for NASA's Sample Retrieval Lander [200,201].

5.1.3 Priorities for the Space Programme

Dedicated missions devoted to tests of relativistic gravity in the solar system, whether with traditional or laser links are not being considered before 2060, at least in the framework of the ESA Science Programme. But improvements in the next decades are possible thanks to the many exploration and planetary missions under development or being planned, especially if equipped with advanced instrumentation. In terms of technological advances and new concepts, the following areas deserve attention:

1. Spacecraft-to-spacecraft radio and laser links over interplanetary distances.
2. Develop low-mass-low power accelerometers for use on planetary spacecraft, extending the bandwidth toward low frequencies (10^{-6} Hz), to realize better pseudo-drag free systems.
3. Deployment of a 5-10 m antenna outside the atmosphere, with rms surface accuracy of 1 mm or better (to support Ka band radio links).
4. Development of stable clocks (MDEV ≈ 10^{-15} or better over time scales of 1000-10000 s), suitable for accommodation on spacecraft or, preferably, landers (low mass, low power).

All those developments are technically feasible or conceivable, but are also, undoubtedly, expensive. However the benefits for the global planetary exploration program are certainly significant.

To improve significantly over Apollo/Lunokhod next-generation single, large laser retroreflectors are mandatory. Furthermore, in order to optimize and maximize the laser return of new laser retroreflectors, their deployment should include:

1. A dual-gimbal Earth-pointing actuator to compensate lack of pointing accuracy of landers;
2. A removable cover to protect the optical face from regolith dust deposition at landing and until final deployment (the one-time-only pointing to Earth).

The accumulation of lunar dust after deployment is a slow process that for Apollo reflectors has been estimated to cause about a factor 10 reduction of the laser return over about 40 years [202]. Finally, in order to maximise the science output for fundamental physics (but also geophysics), single, large retroreflectors should be deployed towards the rim of the near side of the Moon, but not within 10 degrees of the limbs (E-W) to avoid clipping of the direct line-of-sight from Earth.

In the framework of ESA's European Exploration Envelope Programme (E3P) the "ESA Strategy for Science at the Moon" [203] was released in 2019. This strategy recommends the deployment of laser retroreflectors for geophysics and fundamental physics. The first European single, large CCR is expected to be deployed by ESA on a NASA lunar mission landing in 2023 at the Reiner Gamma site of coordinates about (7N, 59W). This large longitude is quite favourable and this instrument will be equipped with both a dual pointing actuator and a removable dust cover [204]. In the same year the first NASA next-gen lunar retroreflector will also be deployed, although without an Earth-pointing actuator and possibly (but to be confirmed) with a removable dust cover.

Any next-gen retroreflector will improve the fundamental physics (and geophysics) reach over Apollo/Lunokhod. The expected improvements of fundamental tests of gravity with three or more next-gen retroreflectors compared to Apollo/Lunokhod LRAs and as a functions of the LLR error budget are reported in Table 2. This analysis [188] is performed with the Planetary Ephemeris Program (PEP) developed by I. Shapiro et al (PEP is described for example in [205]). The test of the inverse-square force-law ($1/r^2$) reported at the last row of Table 2 refers to the test of an additional Yukawa-like potential, with a standard parametrization in terms of a range λ (at the exponent) and a multiplicative strength α. LLR probes the Earth-Moon distance, that is $\lambda \sim$ 384000 km.

Gravitational measurement	Apollo/Lunokhod LLR accuracy (~ few cm)	Next generation LLR accuracy (~ 1 mm)	Time scale	Ultimate goal LLR accuracy (~ 0.1 mm)
WEP	$\left\lvert\frac{\Delta a}{a}\right\rvert < 1.4 \times 10^{-13}$	10^{-14}	Few years	10^{-15}
SEP	$\lvert\eta\rvert < 4.4 \times 10^{-4}$	3×10^{-5}	Few years	3×10^{-6}
β	$\lvert\beta - 1\rvert < 1.1 \times 10^{-4}$	10^{-5}	Few years	10^{-6}
$\frac{\dot{G}}{G}$	$\left\lvert\frac{\dot{G}}{G}\right\rvert < 9 \times 10^{-13}$ yr^{-1}	5×10^{-14}	~ 5 years	5×10^{-15}
Geodetic precession	6.4×10^{-3}	6.4×10^{-4}	Few years	6.4×10^{-5}
$1/r^2$ deviation	$\lvert\alpha\rvert < 3 \times 10^{-11}$	10^{-12}	~ 10 years	10^{-13}

Table 2: This specific compilation reports: tests of gravitational physics (1st column) performed with current LRAs and associated LLR error budget (2nd column [187]); test improvements with current LRAs plus next-gen retroreflectors and associated improved error budget (3rd column) expected in approximate reference periods (specified at the 4th column) [188]; the ultimate LLR goal in terms of test accuracies and LLR error budget supported by next-gen retroreflectors (5th column), to be reached with multiple lunar missions (NASA-Artemis [206], ESA-E3P [203,207], other national/international programs), as well as progressive improvements of lunar orbit software (like PEP [188] reported here and other ephemerides software systematically reviewed by Fienga et al in [185]).

In addition, the next-generation single, large CCRs will extend and enhance significantly the reach of the next-generation LGN being proposed to NASA, composed of a suite of core instruments: seismometer, laser retroreflector, heat flow probe and em/magneto-telluric sounder. In the E3P context, a European Lunar Geophysical Observatory (ELGO) including the same core instruments, has been proposed to ESA in July 2020 in response to the “Call for Ideas for a European Large Logistic Lander (EL3)” for the Moon [207]. In this EL3 framework, an ESA Topical Team dedicated to Geophysics has been formed and formally kicked-off on December 15, 2020.

Concerning Mars, the goals of the microreflectors and their role as the passive, maintenance-free, long-lived instrument component of a future international Mars Geophysical Network (MGN) for fundamental physics are described in [208] and in the following. InSight is the first, core node of such an MGN. Mars planetary science applications of microreflectors include [199] surface geodesy and

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[1] EASEP, Early Apollo Scientific Experiment Package/Payload for Apollo 11 and ALSEP, Apollo Lunar Surface Experiments Package for Apollo 12-17.

interior geophysics when combined with seismometers, heat flow probes, etc., like the instrument of InSight [179] and Apollo[1] (see [194] and [195]).

To address the fundamental physics reach with Mars surface laser retroreflectors, we performed simulations of the contribution of a five-microreflector MGN to test General Relativity by means of the PEP software. Under specific and conservative assumptions (described below) the contribution of this MGN is found to improve the measurements of $\dot{G}/G$ and of β (see Table 3). γ is used as a control observable, by comparing its estimate with measurements by Cassini and the ESA missions BepiColombo and GAIA (Global Astrometric Interferometer for Astrophysics) [209].

Time/σ(CCR)	$\lvert\beta - 1\rvert$ accuracy	$\lvert\gamma - 1\rvert$ accuracy	$\dot{G}/G$ accuracy
10 years / 10 m	1.5×10^{-4}	7.0×10^{-4}	3.5×10^{-14}
10 years / 1 m	3.4×10^{-5}	1.4×10^{-5}	1.1×10^{-14}
10 years / 10 cm	7.1×10^{-7}	3.0×10^{-6}	2.6×10^{-15}
Accuracy With data/mission	$< 1 \times 10^{-4}$ LLR, MESSENGER	2.3×10^{-5} Cassini	9×10^{-13} LLR

Table 3: Test of gravity with a five-retroreflector MGN (PEP simulations).

Table 3 is obtained under the following assumptions:

- Hypothetical MGN with coordinates: Phoenix (68N, 234E), Viking 1 (22N, 50W), Viking 2 (48N, 258W), Curiosity roving region (4S, 137E), Opportunity roving region (2S, 354E). This is a non-ideal MGN, since almost all nodes are in the northern hemisphere.
- One laser orbiter observation every 7 Sols. This takes into account weather conditions, although for example the visibility of Curiosity from MRO (Mars Reconnaissance Orbiter) is about once/Sol (source: NASA).
- $\sigma(CCR)$ is the positioning accuracy of the MGN node (the microreflector) on Mars. $\sigma(CCR) = 10$ m and 1 m can be obtained by adding the Earth-Mars orbiter positioning by radio science and the orbiter-reflector positioning by laser ranging/altimetry. This would give significant improvements, since the current accuracy of Mars ephemeris is 50-100 m (see [198] for a discussion). To reach $\sigma(CCR) \sim 10$ cm, future Earth-Mars orbiter optical links would be required.

These gravity tests with Mars will be complementary to the ones performed with LLR [187,188]. These Mars and Moon gravity tests will also have different and largely independent experimental errors.

To test gravity with the Mars system, an additional option is deploying laser retroreflectors on Phobos (or Deimos): 1) exploit a laser orbiting Mars or Phobos; 2) position the reflectors on Phobos; 3) determine the Mars center of mass (and therefore its ephemeris) by reconstructing the Phobos orbit. This is basically the concept of the GETEMME mission (Gravity, Einstein's Theory, and Exploration of the Martian Moons Environment), which is a past Medium Class mission proposed to ESA [210]. A future opportunity (2024) may be JAXA's MMX mission (Martian Moons eXploration), which includes a lidar onboard the orbiter, a Phobos lander and (TBC) a Phobos mobility element. Although the laser tracking of a Mars and/or Phobos orbiter by ILRS (already proposed by GETEMME about a decade ago) is a frontier technology effort, one should also acknowledge recent progress of laser link/ranging to lunar orbiters [181-183], the consolidation of past interplanetary links to Mars and Mercury [180], as well as modern demands for efficient lasercom in deep space (for example at Jupiter for NASA's Europa Clipper mission). These arguments make optical links at Mars worth to be considered for this white paper.

5.1.3.1 Exploration relevance

The growing effort towards the exploration of Mars and the Moon poses the question whether the programs undertaken by ESA, NASA, and other space agencies could offer opportunities for fundamental physics tests and, vice versa, whether the technologies developed for scientific goals can be beneficial to the exploration programme. Lunar laser ranging has been exploited since a long time to measure PPN parameters and, more recently, to set upper limits to the Compton wavelength of the graviton [211]. It is therefore conceivable that in the framework of the lunar exploration program a new set of high accuracy corner cube reflectors will be deployed on the lunar surface, perhaps tied to the rocky layer below the regolith. Mars missions will also offer the opportunity to repeat classical tests of GR, both in the radio band as well as with laser links. As indicated in [148], the improvement of the orbit of Mars, combined with the BepiColombo measurements, would end up in a significant improvement of all PPN as well as other classical gravitational parameters. The development of space-to-space radio or laser links and better accelerometers will be certainly beneficial to precision deep space navigation.

The benefits of a near earth space antenna (being pursued for VLBI since a long time) or an orbiting laser link station are also clear. Besides increasing the overall link availability and boosting the performances of a laser communication links, it would allow tests of relativistic gravity about 1-2 orders of magnitude better than those available now. In addition, if radio or laser links could be combined with the accommodation of accurate clocks on landers, new sets of observable quantities would be available and the problem of stray accelerations marring all orbiting spacecrafts would be waived. In addition, clocks on landers, combined with suitable electronics, can be used as pseudolites, aiding the navigation of crafts in the critical mission phases, such as EDL and orbit capture. Many of the proposed technologies would be extremely useful for geophysical studies if considered in the framework of network of landers, especially on Mars and the Moon. Methods such as Same Beam Interferometry (SBI), in several flavours, could be used to provide crucial information on the interior structure of those bodies, through a precise measurement of tides and polar motion.

LLR to the 5 Apollo/Lunokhod LRAs has also established an absolute local lunar Cartesian reference frame that is: 1) a key component of the ICRS/F (International Celestial Reference System/Frame); 2) through the ILRS, tightly and accurately tied to the ITRS/F (International Terrestrial Reference System/Frame). The ITRS/F is maintained by the IERS (International Earth rotation and Reference system Service) based on the four main geodetic services: ILRS, IVS (International VLBI Service), IGS (international GNSS Service) and IDS (International DORIS Service).

Next-gen European single, large CCR deployed on landers can determine with high accuracy over time (meter to dm to cm) the landing position of future ESA's EL3 missions on the Moon. EL3 is part of E3P. Surface spacecraft include landers and rovers as wells as several other types of proposed smaller mobility elements. LRAs perform the same positioning service to exploration for all components of NASA's lunar exploration programme: CLPS (Commercial Lunar Payload Services, first flights expected in 2021) [212], PRISM (Payloads and Research Investigations on the Surface of the Moon, first flights expected in 2023) [213], Artemis [214,215] and the Lunar Orbital Platform and Gateway (LOP-G) [214]. The latter is foreseen to follow a very special orbit, the so-called Near-Rectilinear Halo Orbit (NRHO), whose stability over long periods needs to be characterized accurately. This study can be efficiently performed, for example, by deploying laser retroreflectors customized for NRHO on precursor missions and tracking them by ILRS. Ultimately, laser retroreflectors on the LOP-G will allow for continuous, accurate monitoring of its orbit.

Martian landers and rovers equipped with microreflectors can be accurately positioned on the surface from orbiting lasers. Martian microreflectors can be used to redefine the geographic Meridian

Zero of the planet, with an accuracy more than 100 times better than the current definition based on the shallow Airy Zero crater.

5.1.3.2 Benefit for Earth and industrial relevance

Retroreflectors on the Moon and Mars will significantly improve lunar/martian cartography, enable positioning and navigation between orbit and the surface. For example, they can be the passive component of the "Lunar Communications and Navigation Services (LCNS)" that is being considered by ESA (and is currently subject to the industrial tender AO 10438). Active LCNS components can be laser devices with lasercom, lidar and laser ranging capabilities. A lunar orbit infrastructures approved, funded and awarded to industries by ESA is the LOPG International Habitat Module (I-HAB)[2]. The latter might be considered to host such laser positioning and lasercom devices.

Exploration and exploitation of the lunar resources [216] (like ISRU, In Situ Resource Utilization), will benefit from laser retroreflectors. We reported an excerpt from a recent White Paper submitted to NASA for the Artemis program [217], discussing lunar positioning and navigation: "Exploration of the Moon will require locations be accurately known and sortie excursions from the Artemis Base Camp can be carefully planned. Starting with a local GPS that could be expanded to regional and global over time enabling for human and robotic missions. Spatial referencing would be especially critical for robotic assets undertaking exploratory or follow-up studies before and after human stays. An alternative is laser ranging from orbit to surface retroreflectors. It would also enable science by knowing exact sample locations and accurately mapping out geologic structures (e.g., lobate scarps). This capability would also be critical in evaluating the epicenters of moonquakes detected by astronaut-deployed stations and equating them with lobate scarps. Miniaturized retroreflectors also could be deposited at sample locations of interest as geodetic reference marks and/or for future lidar based landing and sample return from those locations. The point is that whatever local system that is set up should be scalable to regional and whole Moon networks". These considerations for lunar Artemis missions are applicable also to the prospecting of Mars resources and their ISRU, as well as similar activities supported by ESA's EL3 missions.

5.2 Fundamental physics with entangled photons

5.2.1 Background

Ground-to-space optical links provide an unparalleled experimental framework for testing phenomena arising from the interplay of General Relativity (GR) with Quantum Mechanics (QM). Such links offer experimental conditions impossible to achieve on the ground, in terms of gravitational potential variations, length scales and relative velocities, that are crucial for verifying these phenomena. A scenario of particular interest regarding gravitational decoherence, currently studied in the framework of the Space QUEST mission [218], concerns the observation of the strength of quantum correlations using photonic states. In this scenario, a quantum mechanical system consists of entangled photon pairs; one photon of each pair is detected on the ground while the other travels uplink to the ISS. Interestingly, there is a number of theoretical models attempting to predict how quantum correlations would evolve in the presence of such a curved space-time, with contradicting results. Standard quantum mechanics predicts no additional decoherence due to the difference in gravitational curvature between the two photon paths in such an experiment. Other theories, however, predict various types of effects. More specifically, the event operator formalism studied in

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[2] https://www.cosmos.esa.int/web/i-hab-industry-day/home.

Space QUEST [219,220] predicts a gravitational decoherence effect due to a speculative nonlinear back-action of the metric on the quantum fields that leads to particle loss into a causally disconnected region of space–time. Furthermore, this type of decoherence effect is expected to be seen only by entangled systems, which means that purely classical correlations would not be affected. The prospect of bringing experimental evidence to this discussion opens up exciting possibilities for testing QM and GR together using technology conceivable within the next few years. Preliminary tests, with negative results, have already been conducted with the Chinese satellite Micius [54].

Exchanging quantum states not only results in entanglement distribution but can be used for picosecond level clock synchronisation which is crucial for navigation. By linking orbital and terrestrial atomic clocks, we can potentially measure changes to physical constants and make more precise measurements of time dilation. In Ref. [221] the authors propose a way to measure time dilation when a single photon follows multiple paths in a Mach-Zehnder interferometer. This proposal is based on the Collela, Overhauser and Werner (COW) experiment, which tested gravitational effects on matter interferometry in the Newtonian regime [222]. Similar experiments with precessing polarisation states to serve as a local clock [223] and others using a "folded" interferometer with a single Earth orbiter and a ground station [224] have also been proposed. Furthermore, tests of quantum field theory on propagating photonic wave packets have been proposed [225,226]. With an array of synchronised atomic clocks all exchanging quantum states, the state of an atom in one clock can be teleported to another for high precision comparative measurements. A large in orbit array of synchronised clocks can be used to test for topological defects which could be a consequence of dark matter [227].

Some modified theories of gravity predict the existence of some sort of screening scalar fields, such as Chameleon fields [228]. Using the phase picked up by the propagation of photons between Earth and a satellite link [229], it may be possible to search for such Chameleon fields [230]. To some extent the desired types of phase shifts were already observed in the COW experiment [222]. Further, while creating large baseline single photon interferometers may seem daunting, experiments like Ref. [231] have already demonstrated interference from time-bin entangled photons after travelling for ≈ 5000 km in free space.

The entanglement of massless fields in curved space time predicts several potential experiments where the nature of entanglement is changed by the presence of gravity. Ref. [230] offers a review of several such effects. Entanglement can be created by curved space-time [232,233], it can also be destroyed through decoherence [225]. For example, curved space time affects the entanglement of Gaussian states [225,226], two mode-squeezed states [234] and multipartite W-states [235]. Other relativistic theories predict the formation of entanglement during non-uniform acceleration for single localised quantum fields (such as electromagnetic [236] or phononic cavity modes [237]).

Entangled states and entanglement distribution in orbit can be used to estimate many physical parameters that appear in relativistic quantum field theory [238], such as proper acceleration [239], gravitational field strengths [240], proper times [241], space-time parameters, etc. Other proposals put forward ways of measuring earth's equatorial angular velocity [226,242].

Using a network of quantum sensors in orbit can be extremely useful to measure phenomena like Exotic Light Fields [243] (which are predicted in several Beyond the Standard Model (BSM) theories [244]).

5.2.2 Key knowledge gaps

The gravitational decoherence phenomenon on the entangled photons, if present, would be weak for quantum signals sent to the low-Earth-orbit ISS. Dispersion of the quantum signals imposed by air could also pose a crucial obstacle to these measurements, as it could potentially cover up the effect.

It is expected however that the effect would be measurable and an attempt to measure it is crucial to verify the standard theories. Since this would be the first experiment of its kind to test QM in a changing gravitational field, it would ideally allow us to place a bound on the maximum possible decorrelation due to gravity. This would help differentiate between different classes of theories pertaining to GR as well as QM, and to narrow down the approaches that have been put forward to describe the precise mechanism of quantum decoherence and its relation to gravity. Of particular interest from a fundamental point of view are radical objective state-reduction models that call for a break-down of quantum mechanics [245,246]. These are based on a thought experiment of Penrose, in which it was argued that a massive object placed in a superposition should quickly decohere in the position basis due to the inherent uncertainty induced in the space-time metric. By contract, the event operator formalism motivating the Space QUEST experiments is based on a thought experiment on the self-consistent dynamics of quantum systems near closed time-like curves due to Deutsch [247]. It considers exotic space-times in which gravity creates closed time-like curves and hence permits time-travel into the past. Deutsch argued that the usual paradoxes associated with such solutions of GR can be resolved by QM. He does not attempt to quantize gravity, but considers quantum systems localized to semi-classical trajectories in a classical background space-time, and argues that a system scattering from a closed time-like curve in space-time exhibits globally nonlinear and non-unitary dynamics. The event formalism extrapolates Deutsch’s model to massless fields propagating in a globally hyperbolic space-time background, in which case it predicts a decorrelation of entanglement due to gravitational curvature [219]. Unlike Penrose and other models that also treat space-time classically and posit a non-linear dynamical equation, the event formalism has a number of novel features: it predicts decoherence only for entangled systems and not for single systems in a superposition; the effect is in principle reversible by further gravitational interactions (hence it is better called “de-correlation” than decoherence); and it may exhibit information processing power greater than that of standard QM [248].

In addition to testing the above theories, ground-to-space optical links and the advanced quantum (and associated classical) technologies developed in the framework of the Space QUEST mission (entangled-photon source, single-photon detectors with low timing jitter and dark counts, clock synchronisation techniques) can be used for fundamental tests relevant for quantum information [249]. In particular, it is unknown to date at which length scale the violation of Bell inequalities as a signature of the non-locality of QM may still be confirmed or whether such fundamental features of QM break down. Beyond their foundational interest, such tests are crucial for validating the concept of device independence in very long-distance quantum communication experiments, which allows to reduce to the minimum the trust assumptions on quantum devices in cryptographic scenarios, hence opening the way to global-scale secure communications. In the longer term, exploring the limits of QM would require to go beyond the low-Earth orbit of ISS, and perform the gravitational decoherence and Bell tests on geostationary orbits. Significant developments for designing the necessary quantum payloads (including the entangled-photon source for the Bell test) would be necessary for such experiments.

Quantum physics and General Relativity are the two best tested and arguably most successful theories in human history. However, it is clear that neither offers a complete picture because they are incompatible. Speculative theories offer various possible solutions but these theories are mostly untested. The next major revolution in fundamental physics hinges on merging these two theories and the only way we can do it is to perform these types of experiments.

The upcoming advent of a nano-spacecraft weighing a few grams and propelled via solar sails and vastly powerful ground based lasers offers new opportunities to test fundamental quantum physics. Calculations show that such spacecraft can be accelerated to velocities > 0.2 c with just a 10 minute burst of laser power from an earth or lunar station. Creating the sails out of a nonlinear optical material or the payload consisting of a photonic chip would allow for the generation of entanglement and the whole host of fundamental tests that entanglement enables at these unprecedented velocities.

5.2.3 Priorities for the Space Programme

All the experiments discussed in Sections 5.2.1 and 5.2.2 hinge on space based quantum technologies and satellite constellations for optical communication. The major driving force behind the development of these technologies is space based quantum communication. The commercial motivation behind this is rapidly driving improvement in space-suitable detectors, photonic chips, entangled photon sources, and quantum information processing nodes. Since many of these experiments require long base line measurements, constellations of CubeSats is potentially the most cost effective way forward.

In terms of mission timeline, we can in general group the proposed experiments as follows:

- *Short-term goals (3-5 years):* In the short term, space qualification and technology readiness will limit us to experiments testing theories that predict the largest effects (such as Space QUEST on the ISS).
- *Medium-term goals (5-10 years):* More sensitive experiments will benefit significantly from lower loss links (i.e., links without the Earth's atmosphere) and are thus medium-term goals because they rely on constellations of a few satellites. Bell inequality experiments from GEO may also become possible in this time frame.
- *Long-term goals (> 10 years):* Tests of dark matter, exotic light fields, etc., are based on large numbers of quantum sensors operating in tandem and are thus longer term goals.

Clock distribution/synchronisation and mapping of gravitational fields are vital for navigation/space exploration. The proposed experiments promise significant technological development along these lines. In the long term, understanding the potential modifications to general relativity due to quantum physics could possibly help design better relativistic and possibly even faster than light propulsion methods.

5.2.3.1 Benefit for Earth and industrial relevance

An important driving factor for the development of quantum links comes from their relevance for achieving global-scale quantum-enabled secure communication that can be beneficial for the protection of both private (e.g. financial, medical) and public (e.g. governmental or critical infrastructure) sensitive data. The distribution of complex entangled states (required by some of the above experiments), would enable quantum networks to link quantum computing nodes ushering in a new information era. Additionally, better measurements of physical constants, relativistic effects, and the relationship between quantum physics and GR are all immediately applicable towards better navigation for space crafts, propulsion methods, etc. These applications are expected to stimulate an important industrial activity covering the entire supply chain of technologies required for establishing quantum links.

E 6 Cosmology and astrophysics projects related to fundamental physics

6.1 Key knowledge gaps

6.1.1 Ultra-high energy cosmic rays

Ultra-high energy (UHE) cosmic rays are charged particles with energies from a few 10^{19} eV to beyond 10^{21} eV, at the very end of the known energy spectrum of cosmic radiation. One of the main science objective is to identify the sources of the UHE cosmic rays (UHECRs). There has been considerable progress over the last decade due to observations by giant ground arrays. Observation of UHECRs from space is based on the measurement of fluorescence and Cherenkov photons produced in Extensive Air Showers (EAS). A UHECR hitting the atmosphere produces secondary particles that, in turn, collide with the air atoms producing a shower largely dominated by electrons and positrons. Crossing the atmosphere, these particles excite metastable energy levels in atmospheric molecules, especially nitrogen. When the electrons in these atoms return to the ground state, they emit characteristic fluorescence light in the ultraviolet (UV) band, with wavelengths between 290 and 430 nm. This light is emitted isotropically, with an intensity proportional to the energy deposited by the shower in the atmosphere. The EAS thus forms a streak of fluorescence light along its path in the atmosphere, depending on the energy and zenith angle of the primary particle. Another detectable component is the Cherenkov light emitted in the forward direction by the charged, relativistic particles of the EAS and reflected into space by the ground or the clouds. Looking downward at the Earth's atmosphere from space, a specifically designed telescope can detect the light emitted in the EAS path. At any atmospheric depth, the recorded amount of light is nearly proportional to the shower size at that point. By imaging the motion of the UV track on timescales of microseconds or less, it is possible to define the arrival direction of the primary cosmic ray. The integral of recorded light allows a determination of the energy of the primary UHECR. The shape of the shower, especially the position of the shower maximum in the traversed slant depth, gives a hint about the nature of the primary particle.

The Extreme Universe Space Observatory (EUSO) is a mission to be hosted on-board the International Space Station. EUSO is being designed by a large international collaboration, which (called also JEM-EUSO collaboration) includes more than 300 scientists from 90 participating institutes, in 16 countries. This program includes several missions, some of which have already been successfully implemented, like satellites, balloons and in particular the MiniEUSO, which was brought to the ISS by the uncrewed Soyuz MS-14, on August 22, 2019 [250]. First observations from the nadir-facing UV transparent window in the Russian Zvezda module took place on October 7, 2019. Since then, it has been taking data periodically, with installations occurring every couple of weeks. The instrument is expected to operate for at least three years. Once this mission will be done successfully, it is foreseen to proceed with the implementation of EUSO.

6.1.2 Radio interferometer on the Moon

There are plans, in particular by NASA but which could be joined by ESA, to put a ultra-long-wavelength radio telescope on the far-side of the Moon. Such a telescope would have advantages compared to Earth-based and Earth-orbiting telescopes, including: (i) Such a telescope can observe the universe at wavelengths greater than 10 m (i.e., frequencies below 30 MHz), which are reflected by the Earth's ionosphere and are hitherto largely unexplored by humans, and (ii) the Moon acts as a physical shield that isolates the lunar-surface telescope from radio interferences/noises from Earth-based sources, ionosphere, Earth-orbiting satellites, and Sun's radio-noise during the lunar night. Such a Lunar Crater Radio Telescope (LCRT), with 1 km diameter, would be the largest filled-aperture radio telescope in the Solar System, which could lead to important scientific discoveries in the field of cosmology by observing the early universe in the 10 – 50 m wavelength band (i.e., 6 – 30 MHz frequency band), which has not been explored by now. More generally the Moon's surface would allow to host telescopes and other facilities with which to explore the Universe in a unique way (see e.g. [251]).

6.1.3 Gravitational-wave lunar observatory for cosmology

One of the most demanding spectral regimes to measure by gravitational waves (GWs) is from deci-Hz to 1 Hz, as it is too low for Earth detectors due to seismic noise and too high for space missions. In that frequency range the seismic noise on the Moon should be three order of magnitude lower than on Earth as measured by the seismometers left from the Apollo missions. In particular sub-solar compact objects coalescing up to intermediate mass black holes could be detected up to cosmological distances. A proposal for such an observatory has been recently submitted in the NASA Artemis program [252].

6.1.4 Dark matter in the solar and Earth-Moon systems

Dark matter (DM), if in form of particles is expected to be present in the solar system, in which case it can cause an extra-perihelion precession on the planets [253]. The effect on the orbit of a planet is essentially given by the total DM mass contained within its orbit around the Sun [254]. It is expected that DM density varies slowly within the solar system and can be considered as nearly constant and distributed roughly spherically symmetric. Within these assumptions the best upper bound on local dark matter density in the solar system comes at present from Mars data, however the accuracy on Mars precession should improve by more than six orders of magnitude to get constraints competitive with local estimates based on Galactic observables. Similarly, it is possible that dark matter is gravitationally bound to the earth. Bounds can be put by tracking accurately the orbit of satellites in earth orbit. The present bounds are several orders of magnitude higher than the average galactic dark matter density [255]. By better data on Moon's orbit it might be possible to get tighter constraints on the dark matter density around the earth as well, in particular this can be done by improving the lunar laser ranging observations. Current data show that the mass of such earth-bound dark matter must be less than 4×10^{-9} of the earth's mass [255].

6.2 Priorities for the Space Programme

The topics discussed in this section are at the intersection between astrophysics and fundamental physics. The astrophysical implications will be also discussed in the white paper part on astrophysics. Here, we concentrate on the fundamental physics aspects. The study of UHECR might open a window to dark matter or acceleration mechanisms of cosmic rays. The latter aspects are of interest for particle physics but might led for instance to more information on the environment around black holes. A radio interferometer or a gravitational wave observatory on the Moon might also open new windows by allowing observation in frequencies (both for electromagnetic waves as also gravitational waves) which are otherwise not accessible. Clearly this will allow to perform new tests on various aspects of fundamental physics.

In the framework of the Human and Robotic Exploration Directorate of ESA,

- *Short-term goals (3-5 years):* It is recommended to proceed with the EUSO experiment on board of the ISS.
- *Long-term goals (> 10 years):* On a longer time scale, ESA should start (in collaboration with other agencies in particular NASA) plans for the development of the need technology to put gravitational wave and radio interferometers on the Moon.

7 Summary

The table below summarizes the different topics discussed in this white paper on fundamental physics. It gives an overview for each scientific question we identified as being relevant for making progress on modern fundamental physics problems. We identify the needed platform, its space relevance and the timeline.

Scientific question	**Future space experiment and suitable environment (LEO, Moon, Mars)**	**Space and/or exploration and/or Earth and/or industrial relevance**	**Timeline (short, medium, long term)**
A - Ultracold atom physics in space			
Validity of the quantum superposition principle and wavefunction collapse models	ISS or free flyer	(Space) Long free evolution time	Short to medium term
Quantum gases in microgravity at ultralow energies	ISS or free flyer	(Space) Long free evolution time and no need for levitation for mixtures in microgravity	Short to medium term
B - Atomic clocks tests of General Relativity			
Test of GR with ACES	ISS	(Space) Gravitational potential difference and global coverage (Exploration/Earth/industrial) Gravitational potential measurements; Global timekeeping and time distribution	Short term
Test of GR with optical clock	ISS or free flyer		Medium to long term
Precise Time and frequency distribution from space at 10^{-18} with microwave and optical links	ISS or free flyer	(Space) Global coverage (Exploration/Earth/industrial) Global timekeeping and time distribution	Medium term
Coherent optical link from Moon	Lunar Gateway and ISS	(Exploration) Positioning and navigation	Medium to long term
C - Matter-wave interferometry tests of General Relativity and Quantum Mechanics			
Validity of Einstein's equivalence principle in the quantum world I: Approaching the sensitivity achievable in space	Einstein elevator	(Microgravity facility) Extension of interferometry time	Short term
Validity of Einstein's equivalence principle in the quantum world II: with so far unrivalled stringency	ISS or free flyer	(Space) Extension of interferometry time (Exploration/Earth/industrial) Gravimetry, navigation, precision sensing	Short to medium term
Testing entanglement over long time scales	ISS or free flyer in an advanced atom interferometry set up (replacement unit for BECCAL)	(Space) Extension of atomic drift time	Short to medium term
Pathfinder experiment for dark-matter detection with atom interferometers based on an optical clock transition	ISS or free flyer	(Space) Longer interferometer time; For a full-fledged mission: long baseline between atom interferometers (> 1000km), gravitationally quiet environment	Medium term (pathfinder) and long term (full-fledged mission)

Validity of quantum superposition principle in the large-mass limit	Einstein elevator or Drop tower or ISS or free flyer	(Space) Long free evolution time (Exploration/Earth/industrial) Gravimetry, navigation, precision sensing	Short to medium term
Dark Matter detection with large-mass interferometers	ISS or free flyer	(Space) Long free evolution/hold time	Medium to long term
D - Classical and quantum links			
PPN Parameters	Mercury, Moon, Mars/Phobos/Deimos: Radio science and laser ranging experiment	(Space) Solar system tests (Exploration/Earth) ESA EL3, NASA Artemis, International LOP-G and I-HAB, reference systems	Short, medium and long term
$\dot{G}_N/G_N$ and Sun $\dot{G}/G$	Mercury, Moon, Mars/Phobos/Deimos: Radio science and laser ranging experiment	(Space) Solar system tests (Exploration) ESA EL3, NASA Artemis, International LOP-G and I-HAB, reference systems	Short, medium and long term
Deviations from the Inverse-Square force Law	Mercury, Moon, Mars/Phobos/Deimos: Radio science and laser ranging experiment	(Space) Solar system tests (Exploration) ESA EL3, NASA Artemis, International LOP-G and I-HAB, reference systems	Short, medium and long term
Weak Equivalence Principle (Moon composition dependent) and Strong Equivalence Principle (Nordtvedt effect)	Moon: Lunar laser ranging experiment	(Space) Solar system tests (Exploration) ESA EL3, NASA Artemis, International LOP-G, I-HAB, LCNS, reference systems	Short, medium and long term
New Gravitational Physics (spacetime torsion, nonminimally coupled gravity, f(R), f(T))	Mercury, Moon, Mars/Phobos/Deimos: Radio science and laser ranging experiment	(Space) Solar system tests Exploration: ESA EL3, NASA Artemis, international LOP-G, I-HAB, LCNS, reference systems	Short, medium and long term
Testing quantum physics and general relativity	LEO, GEO	(Space) Gravitational potential difference, long base-line measurements and free evolution time (Earth/industrial) Quantum communication, cryptography	Short, medium and long term
E - Cosmology and astrophysics projects related to fundamental physics			
Sources of UHECRs	ISS	(Space) Using Earth atmosphere as detector	Short to medium term
New frequency window for radiotelescopes	On Moon's surface	(Space) No interference from terrestrial sources	Long term
New frequency window for gravitational wave detectors	On Moon's surface	(Space) No seismic noise	Long term

8 Recommendations

In the following, we summarize our recommendations to ESA for future fundamental physics experiments in space.

A 8.1 Ultracold atom physics in space

As immediate action, we recommend that ESA launches a call for ideas for European research with ultracold atoms in microgravity or in-orbit facilities. Next ESA should support joint European research directed towards microgravity and in-orbit quantum gas experiments.

In the medium term we recommend the establishment of a European in-orbit quantum gas facility for exploring low temperature many-body physics, entangled atoms, and tests of quantum mechanics.

In a longer term perspective, we propose to search for dark matter with space-borne matter-wave interferometers and quantum memories based on cold atoms.

B 8.2 Atomic clock tests of General Relativity

First we recommend to fly ACES on the ISS as soon as possible. Second, ESA should advance the ACES follow-on mission I-SOC Pathfinder. This implies to develop in the near term optical and microwave time transfer systems beyond those of ACES. In parallel ESA should support the development of compact and robust optical clock technologies for space applications and prepare future missions with optical clocks. With these developments it will be possible to fly a fundamental physics space mission with an optical clock at a reasonable cost (I-SOC, Space Optical Clock on ISS). A more ambitious goal with even higher scientific return would be to fly such an optical clock on a dedicated flyer, for instance on a highly elliptical Earth orbit.

Another medium term goal would be to explore the feasibility of a coherent optical link between the Lunar Gateway and Earth orbiting satellites or ISS. This would drastically advance lunar ranging and associated fundamental physics tests such as WEP.

Finally it would be highly interesting to investigate applications of an ultrastable clock on Artemis/Lunar Gateway.

C 8.3 Matter-wave interferometry tests of General Relativity and Quantum Mechanics

8.3.1 Atom interferometry

Europe has a very active community working on atom interferometry, in particular for spaceborne applications. As an immediate action, ESA is recommended to support joint European research on selected topics (according to CCOOL and other call-based ITTs) advancing quantum engineering methods as well as the readiness level of cold-atom based quantum technologies (including miniaturization). Ideally, it would be implemented in a joint action of European research laboratories and industrial partners developing required hardware components. It is moreover very timely to support European laboratories in establishing tests with joint hardware in microgravity facilities to bridge the sensitivity gap for future missions on quantum tests of the Equivalence Principle or geodesy-grade accelerometers

In the medium term, these activities will set the stage for developing the payload for an in-orbit atom-interferometry laboratory as well as a quantum gravimeter for space exploration. Moreover, future missions involving an optical atomic clock on the ISS or a dedicated free flyer will provide the opportunity to include a pathfinder atom-interferometry experiment based on single-photon transitions, which would in turn strengthen the scientific case for such a mission. In the long term this kind of atom interferometers could be exploited for space-borne searches of ultralight dark matter.

8.3.2 Large-mass interferometry

For the medium term, we recommend to support the science-engineering community to address the technical challenges defined in the recent ESA-CDF QPPF study on particle sources and detection to enable large-mass interferometers in space. First steps have been taken by ESA to support a dedicated technology development, but more support and collaboration of ESA with the scientific community is needed to focus the efforts and to generate the technology in the most efficient way. Again the technical heritage from LISA-PF and LISA technology and other ESA missions and projects needs continuous monitoring as large-mass technology develops further. Immediate steps for the large-mass interferometry community will be to demonstrate large-mass experiments in micro-gravity environments such as drop towers, Einstein elevators or sounding rockets and to collaborate with and learn from achievements in the atom interferometer community in respect to such tests. A trajectory for the work to be done is clear, but ways have to be found to intensify the progression along that trajectory.

We further recommend to support the exploration of new fundamental physics tests based on large-mass systems in the classical and quantum regime which need the space environments. Ideas include the test of the Dark Sector of high-energy particle physics, gravitational waves in complementary parameter ranges to LIGO/LISA, and the experimental exploration of the interplay of gravity/relativity and quantum mechanics. First theoretical physics studies of new ideas have been published, but each needs a technical scrutiny analysis and a clear identification where a space environment is needed to perform the key experiments. For instance, some Dark Matter candidates indicate a test outside Earth’s atmosphere is needed. While this is clearly a talk for the scientific part of the community, collaboration and guidance by ESA on space relevance and capabilities will be needed. For sure the key element provided by space is the extension of the free evolution time of large-mass quantum systems, which is restricted on Earth to reasonable free-fall times of a few seconds and could be extended only in space to much longer.

Large-mass systems have a clear and demonstrated potential for force, acceleration and inertial sensing for gravimetry and gradiometry as well as for magnetometry. This potential needs to be explored for the space context.

D

8.4 Classical and quantum links

All recommendations below apply in the near, medium and long term, because based on missions to the inner rocky planets and Moon/moons (Phobos/Deimos), which are the destinations of ongoing (Apollo/Lunokohd Lunar Laser Ranging, NASA InSight, NASA Perseverance), imminent (BepiColombo, NASA CLPS/PRISM/Artemis III, ExoMars 2022) or sustained mid-long term exploration programs (NASA Artemis, ESA EL3, LOP-G, I-HAB, possibly the LCNS, ESA-NASA ExoMars-Perseverance and Mars Sample Return).

- Missions to Mercury (BepiColombo), multiple missions to the surface of the Moon (the closest destination) and to the Mars system (including Phobos/Deimos) for the precision measurements of PPN parameters with radio science and laser ranging experiments, both separate (Mercury Radio Science and Lunar Laser Ranging) and combined (Lunar Same Beam Radio Interferometry and Laser Ranging; Mars Radio Science and Laser Ranging).

- Precision tests of $\dot{G}/G$ with Mercury, Moon and Mars; disentanglement of $\dot{G}_N/G_N$ (measured with Lunar Laser Ranging) from the Sun $\dot{G}/G$ (measured with Mercury Radio Science and with Mars Radio Science/Laser Ranging).
- Lunar Laser Ranging tests of: the Weak Equivalence Principle with the Moon (that has a specific matter composition, which is very different, for example, from the test mass of the MICROSCOPE experiment in LEO); the Strong Equivalence Principle (Nordtvedt effect) with the Moon; deviations from the inverse-square law in the form of an additional Yukawa gravitational potential (see next recommendations on new gravitational physics).
- Mercury/Mars/Lunar Radio and Laser Ranging test of: new gravitational physics theories, like spacetime Torsion (T), NonMinimally Coupled Gravity, f(R) and f(T).

European microreflectors are already deployed on all four ESA and NASA missions to the Mars surface. Microreflectors are recommended also for NASA-ESA's Mars Sample Return programme [200],201]. To perform PPN and $\dot{G}/G$ test in the Mars system, Radio Science and Lase Ranging payloads are recommended to be onboard next Mars orbiters. Finally, to enhance and extend this work laser retroreflectors are recommended to be deployed on Phobos and Deimos, as already proposed by the GETEMME mission study [210]. Phobos is of interest to JAXA's Mars Moons Exploration currently foreseen to be launched in 2024.

Test of fundamental physics with Lunar Laser Ranging is already among the recommendations by the following programmatic documents: ESA Strategy for Science at the Moon [203] and by the Artemis III Science Definition Team [215]. Two of the three laser ground stations currently performing routine LLR operations are in Europe (OCR in France, which is the most active in terms of data quantity and time span, and MLRO in Italy); a third European one is working to join them (Wettzell in Germany).

Multiple missions to the lunar surface are foreseen (and already funded) by NASA for the Artemis programme [214] (the first one will be Artemis III [215] to the South Pole). Multiple missions are also foreseen by the EL3 programme [207] started in 2019 by ESA.

E

8.5 Cosmology and astrophysics projects related to fundamental physics

The program for the detection of UHECRs as mentioned in the Section 6 under "Ultra-high energy cosmic rays" is also extensively discussed in this white paper in the chapter dedicated to Astrophysics, similarly the plans for a radio interferometer on the Moon as well as a gravitational-wave lunar observatory. This overlap underlines the fact that these projects are considered very relevant for the progress in astrophysics and also for being able to answer open issues in fundamental physics. Clearly, the plans for Moon observatories will be implemented on a much longer time scale, whereas the detection of UHECRs has already started.

In summary for the projects described in Section 6 we recommend in the short term to proceed and bring to completion the EUSO experiment on the ISS; whereas in the medium term we propose to start with the feasibility studies and the development of the technology for a radio interferometer and a gravitational wave observatory on the Moon, whose realization is expected on a long term time scale.

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