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Testing the weak equivalence principle

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Abstract. The discovery of Dark Energy and the fact that only about 5% of the mass of the universe can be explained on the basis of the current laws of physics have led to a serious impasse. Based on past history, physics might indeed be on the verge of major discoveries; but the challenge is enormous. The way to tackle it is twofold. On one side, scientists try to perform large scale direct observations and measurements – mostly from space. On the other, they multiply their efforts to put to the most stringent tests ever the physical theories underlying the current view of the physical world, from the very small to the very large. On the extremely small scale very exciting results are expected from one of the most impressive experiments in the history of mankind: the Large Hadron Collider. On the very large scale, the universe is dominated by gravity and the present impasse undoubtedly calls for more powerful tests of General Relativity – the best theory of gravity to date. Experiments testing the *Weak Equivalence Principle*, on which General Relativity ultimately lies, have the strongest probing power of them all; a breakthrough in sensitivity is possible with the "Galileo Galilei" (GG) satellite experiment to fly in low Earth orbit.

Keywords. Gravitation, Large-scale structure of universe

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1. Dark energy and its challenge

Ever since Newton's *Philosophiae Naturalis Principia Mathematica* was published in London in 1687 gravity is known to govern the physics of the cosmos. In the following two centuries, based on Newton's law of gravity, the best scientists of the time developed sophisticated mathematical tools which allowed them to predict the position of planets in the sky. By comparison with extremely accurate and systematic observations carried out at major astronomical observatories – particularly in Europe – theoretical predictions and observations were found to agree with each other amazingly, superceding Ptolomy's model which had lasted 14 hundred years. Celestial Mechanics became the paradigm of exact science, so much that the existence of Neptune could be inferred, and the planet actually observed in 1846 at the predicted position (though with a bit of luck), on the basis of its gravitational influence on the motion of Uranus which had been found by observations to deviate more and more with time from the theoretical prediction. In point of fact, the contribution from theory was crucial, while the capability to observe Neptune was already there 234 years earlier, when Galileo did indeed see Neptune (Kowal & Drake, 1980; Standish & Nobili, 1997).

Newton's theory of gravity dominated for more than 200 years, even beyond the publication of Einstein's theory of General Relativity (Einstein, 1916). Despite the consistency and beauty of this new theory of gravity, and its profound revolutionary nature with respect to Newton's theory, its observable consequences were minute and hard to measure. Even Einstein's beautiful explanation of the small additional perihelion advance of Mercury predicted by his theory – and until then *missing* in the predictions of Celestial Mechanics as based on Newton's gravity (see, e.g. Nobili & Will, 1986) – was anyway adding only a small contribution to a much larger and astonishingly good prediction of the effects of planetary perturbations to the motion of the perihelion of Mercury.

On a larger scale, since 1929 it became apparent that the universe is expanding. By comparing measurements of velocities (by means of redshifts) and measurements of distances (using Cepheids as standard candles) Edwin Hubble proved that the universe is actually expanding. Gravity would slow down that expansion, and so the question was to establish whether the density of matter is sufficient to "close" the universe or else it will keep expanding forever. About 10 years ago, two teams of astronomers found that there is too little matter in the universe to stop its expansion and, moreover, that the outward motion is indeed speeding up. The conclusion was based on more than 20 years measurements of the distance of extremely far away galaxies using very bright supernovae as standard candles (the Cepheids being too dim at such distances). The discovery was named by Science journal "Breakthrough of the Year for 1998" in Astronomy (see Glanz, 1998 and references therein)

A new, unknown, form of energy – the so called "dark energy" – is required.

Though some skepticism about dark energy remains among scientists, it is quite remarkable that completely different astronomical measurements – namely those of the cosmic microwave background anisotropy performed by BOOMERanG (de Bernardis *et al.*, 2000) and WMAP (Bennet *et al.*, 2003) – lead to the same conclusion. In the future, a dedicated space survey as proposed with the ESA mission EUCLID should provide the scientific community with considerable new insights.

In February 2005 a Dark Energy Task Force (DETF) was established in the US by the Astronomy and Astrophysics Advisory Committee and the High Energy Physics Advisory Panel to advise the Department of Energy, NASA and the National Science Foundation on future dark energy research.

In 2006 DETF published its final report (Report of the Dark Energy Task Force, 2006). The cover page reads:

"Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation for its existence or magnitude. The acceleration of the Universe is, along with dark matter, the observed phenomenon that most directly demonstrates that our theories of fundamental particles and gravity are either incorrect or incomplete. Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration. For these reasons, the nature of dark energy ranks among the very most compelling of all outstanding problems in physical science. These circumstances demand an ambitious observational program to determine the dark energy properties as well as possible."

And the Executive Summary of the Report begins as follows:

"Over the last several years scientists have accumulated conclusive evidence that the Universe is expanding ever more rapidly. Within the framework of the standard cosmological model, this implies that 70% of the universe is composed of a new, mysterious dark energy, which unlike any known form of matter or energy, counters the attractive force of gravity. Dark energy ranks as one of the most important discoveries in cosmology, with

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profound implications for astronomy, high-energy theory, general relativity, and string theory.

One possible explanation for dark energy may be Einstein's famous cosmological constant. Alternatively, dark energy may be an exotic form of matter called quintessence, or the acceleration of the Universe may even signify the breakdown of Einstein's Theory of General Relativity. With any of these options, there are significant implications for fundamental physics."

In addition, the existence of "dark matter" – whose nature is not yet understood – has been postulated long before the discovery of dark energy. Invoked by most astronomers, dark matter probably consists of undiscovered elementary particles whose aggregation produces the gravitational pull capable of holding together galaxies and clusters of galaxies in agreement with observations. The amount required is more than 20% of the total. Hence, only about 5% of the mass of the universe is understood at present.

In this framework it is apparent that the challenge for theoretical physics – especially for General Relativity as the best theory of gravity to date – is enormous.

2. The physical theories: success and problems

The theory of General Relativity (GR) and the Standard Model (SM) of particle physics, taken together, form our current view of the physical world. While the former governs physics in the macroscopic and cosmic scales, the latter governs the physics of the microcosm. According to GR gravity is not a force but a manifestation of space-time curvature. The relation between space-time curvature and space-time content (mass-energy and momentum) being given by Einstein's field equations. The theory has been extensively tested and no astronomical observation or experimental test has been found to deviate from its predictions. Thus it is the best description we have of gravitational phenomena that we observe in nature. The Standard Model of particle physics, since the 1970s gives a unified formalism for the other three fundamental interactions (strong, weak and electromagnetic) between the fundamental particles that make up all matter. It is a quantum field theory which is consistent with both Quantum Mechanics and Special Relativity. It has been spectacularly successful at describing physics down to a distance scale of about 10^{-18} m and no experiment to date contradicts it. Considerable new insights, down to even smaller scales, are expected from the Large Hadron Collider.

However, merging these two very successful theories to form a single unified theory poses significant difficulties. While in SM particle fields are defined on a flat Minkowski space-time, GR postulates a curved space-time which evolves with the motion of mass-energy. The definition of a gravitational field of a particle, whose position and momentum are governed by the Heisenberg Uncertainty Principle, is unclear. In addition quantum mechanics becomes inconsistent with GR near singularities. Current theories break down when gravity plus quantum mechanics both become important.

It is apparent that in spite of their own success, GR and the SM need to be reconciled with each other. Most attempts in this direction indicate that the pure tensor gravity of GR needs modification or augmentation. New physics is needed, involving new interactions which are typically composition dependent. As such, they would violate the Universality of Free Fall (UFF), hence the Weak Equivalence Principle which is the founding pillar of General Relativity (see next Section).

The need to put General Relativity to more and more stringent tests – despite its great success so far – comes therefore not only from facing the challenge of a universe whose mass-energy is mostly unknown, but also from the absence of a quantum theory of gravity.

This need has been clearly identified by the "Committee on the Physics of the Universe" which was appointed by the National Research Council of the US National Academies to investigate the subject and advise the major national research funding agencies. The results of the panel's work have been published in the book "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" (2003).

The 3rd of the eleven questions identified in the book is:

"Did Einstein Have the Last Word on Gravity?" and reads:

"Black holes are ubiquitous in the universe, and their intense gravity can be explored. The effects of strong gravity in the early universe have observable consequences. Einstein's theory should work as well in these situations as it does in the solar system. A complete theory of gravity should incorporate quantum effects-Einstein's theory of gravity does not-or explain why they are not relevant."

The last chapter of the book, under the title "Realizing the Opportunities", is devoted to giving recommendations as to how to proceed in order to answer the 11 questions identified. The recommendations focus on very large scientific projects; however, a specific Section is devoted to the importance of setting up an effective program by balancing few big long term projects with more numerous, more affordable, small ones addressing specific crucial issues. The Section is entitled:

"Striking the Right Balance'' ("Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century", 2003 p. 162) and reads:

"In discussing the physics of the universe, one is naturally led to the extremes of scale – to the largest scales of the universe as a whole and to the smallest scales of elementary particles. Associated with this is a natural tendency to focus on the most extreme scale of scientific projects: the largest space observatories, the most energetic particle accelerators. However, our study of the physics of the universe repeatedly found instances where the key advances of the past or the most promising opportunities for the future come from work on a very different scale. Examples include laboratory experiments to test gravitational interactions, theoretical work and computer simulations to understand complex astrophysical phenomena, and small-scale detector development for future experiments. These examples are not intended to be exhaustive but to illustrate the need for a balanced program of research on the physics of the universe that provides opportunities for efforts that address the scientific questions but that do not necessarily fit within major program themes and their related large projects.

Two of our scientific questions – "Did Einstein have the last word on gravity?" and "Are there additional space-time dimensions?" – are being addressed by a number of laboratory and solar-system experiments to test the gravitational interaction. Tests of the principle of equivalence using laboratory torsion balances and lunar laser ranging could constrain hypothetical weakly coupled particles with long or intermediate range. These experiments have reached the level of parts in 10^{13} and could be improved by another order of magnitude. Improvement by a factor of around 10^5 could come from an equivalence principle test in space. .. null experimental results provide important constraints on existing theories, and a positive signal would make for a scientific revolution."

In the US the National Research Council of the National Academy of Sciences has recently appointed the "Astronomy and Astrophysics Decadal Survey" (Astro2010) Committee. The Committee on Astro2010 will survey the field of space and ground-based astronomy and astrophysics, recommending priorities for the most important scientific and technical activities of the decade 2010–2020. It would be surprising if further and more stringent tests of General Relativity were not recommended.

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3. Tests of the weak equivalence principle as the most powerful probes of General Relativity

According to the so-called Universality of Free Fall (UFF), in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition. First tested by Galileo around 1600 (see e.g. Bramanti *et al.*, 1993) UFF is the most direct experimental consequence of the Weak Equivalence Principle (WEP), in Einstein's own words not a *principle* but rather a *hypothesis* (Einstein, 1907). In this paper Einstein formulates the "*hypothesis of complete physical equivalence*" between a gravitational field and an accelerated reference frame: in a freely falling system all masses fall equally fast, hence gravitational acceleration has no local dynamical effects. Any test mass located inside "Einstein's elevator" – falling with the local acceleration of gravity g near the surface of the Earth – and zero initial velocity with respect to it, remains motionless for the time of fall. An observer inside the elevator will not be able to tell, before hitting the ground, whether he is moving with an acceleration g in empty space, far away from all masses, or else he is falling in the vicinity of a body (the Earth) whose local gravitational acceleration is also g (with the same direction and opposite sign).

This is the WEP, whereby the effect of gravity disappears in a freely falling reference frame: since all bodies fall the same whatever their mass and composition there is no motion relative to each other.

The WEP holds only locally. The elevator is free falling in the vicinity of the Earth, which amounts to saying that the height of fall is much smaller than the radius of the Earth. The cancellation of gravity in a freely falling frame holds locally for each frame, but the direction of free fall is not the same in all of them. Which is a direct consequence of the fact that the gravitational field of a body (like Earth) is non uniform, giving rise to the so called tidal forces between test particles whose centers of mass are not coincident. With the WEP Einstein has moved from Newton's concept of one global reference frame with gravitational forces and the UFF, to many free falling local frames without gravitational forces.

In his further development of the theory of General Relativity (Einstein, 1916), Einstein formulated what is known as the Einstein Equivalence Principle (EEP), which is an even more powerful and far reaching concept. EEP states the following (see e.g. Will, 2006):

- WEP is valid.
- The outcome of any local non-gravitational experiment is independent of the velocity of the freely-falling reference frame in which it is performed (Local Lorentz Invariance).
- The outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed (Local Position Invariance).

EEP is regarded as the "heart and soul" of GR because it is the validity of this "principle" to ensure the fact that in GR the effects of gravity are replaced by a curved 4-dimensional space-time. Since EEP assumes the WEP to be valid, it is apparent that the WEP is the founding pillar of General Relativity. Though all experimental tests of GR are valuable as they contribute to assess its validity and provide further constrains, it is expected that testing the very foundation of GR has a stronger probing power than testing its numerous predictions.

Within string-inspired models, Damour & Polyakov (1994), Damour (1996) and Damour *et al.* (2002) have estimated the level at which a breakdown of the equivalence principle might occur and made quantitative comparisons between the probing power of weak equivalence principle – i.e. composition dependent – tests, and most of the other – composition independent – tests of deviations from GR ("post – Einsteinian" effects in gravitationally interacting systems: solar system, binary pulsars etc. ...). The most remarkable composition independent tests have been performed both in weak-field conditions, by means of radio links with Cassini spacecraft (Bertotti *et al.*, 2003), and in strong-field regime by timing the double pulsar (Kramer *et al.*, 2006). This is a unique system in which both neutron stars are detectable as radio pulsars and is becoming the best available testbed for general relativity and alternative theories of gravity in the strong-field regime (Kramer & Wex, 2009).

The comparison by Damour and colleagues shows the superior probing power (by several orders magnitude) of composition dependent WEP tests.

Most to our amazement, we are led to look back at Galileo's pioneering tests of the UFF in the early 1600, taking advantage of 400 years advance in science and technology, particularly in space science and space technology.

4. WEP tests: state of the art and prospects for improvements

The Weak Equivalence Principle is tested by testing the Universality of Free Fall. In an experiment to test UFF the observable physical quantity is the differential acceleration Δa of two test masses of different composition, relative to each other, while falling in the gravitational field of a source body with an average acceleration a (also referred to as the "driving acceleration"). A deviation from UFF is therefore quantified by the dimensionless parameter:

$$\eta = \frac{\Delta a}{a} \ . \tag{1}$$

The finding of a value $\eta \neq 0$ would disprove the UFF and indicate a violation of WEP on which General Relativity ultimately relies. Instead, $\eta = 0$ (in real experiments η is limited to a minimum value depending, for a given driving signal, on the sensitivity of the experiment to differential accelerations towards the source mass) – as reported by all experiments so far – confirms the basic assumption of General Relativity. By writing the equations of motion of each individual test mass without assuming *a priori* the equivalence of their inertial and gravitational (passive) mass, the parameter η becomes

$$\eta = \frac{2[((m_g/m_i)_A - ((m_g/m_i)_B]}{[((m_g/m_i)_A + ((m_g/m_i)_B]} \tag{2}$$

where subscripts A and B refer to the individual test masses and allow them to be distinguished by their different composition. This parameter is also known as the Eötvös parameter.

It is apparent from (1) that – for any given experimental apparatus – the larger the driving acceleration, the more sensitive the UFF test (hence the WEP test) that it provides. In a Galileo-type mass dropping experiment the driving acceleration is the gravitational acceleration of the Earth along the local vertical ($9.8\,\mathrm{ms}^{-2}$). If the test masses are suspended on a torsion balance the driving acceleration is $0.017\,\mathrm{ms}^{-2}$ (at most) in the field of the Earth – directed along the North-South direction of the local horizontal plane – and $0.006\,\mathrm{ms}^{-2}$ in the field of the Sun (with components along the North-South and East-West directions of the horizontal plane and 24-hr period due to the diurnal rotation of the Earth on which the balance sits). Yet, the first experimental apparatus to provide very accurate UFF tests in the field of the Earth (to 10^{-8}–10^{-9}) was the torsion balance used by Eötvös at the turn of the 20th century, and later on by his students (Eötvös *et al.*, 1922). This is because torsion balances are both extremely sensitive and inherently differential instruments.

The next leap in sensitivity (to 10^{-11}–10^{-12}) came in the 60s and early 70s using again a torsion balance but also recognizing that by taking the Sun as the source mass rather than the Earth, any differential effect on the test masses of the balance would be modulated by the 24-hr rotation of the Earth (Roll *et al.*, 1964; Braginsky & Panov, 1972). Indeed, the modulation frequency should be as high as possible, in order to reduce low-frequency $1/f$ electronic noise.

A turning point came in 1986 with the famous re-analysis of the Eötvös experiment (Fischbach *et al.*, 1986), a paper which made it to the first page of the *New York Times* and attracted the interest of scientists and space agencies alike. Since then, the best tests of UFF (to about 1 part in 10^{13}) have been performed by the "Eöt-Wash" group at the University of Seattle in a systematic series of remarkable experiments using torsion balances placed on a turntable which modulates the signal with a period down to about $20'$ (Su *et al.*, 1994; Baeßler *et al.*, 1994; Schlamminger *et al.*, 2008). Despite the much larger driving acceleration, Galileo-type mass dropping tests of UFF have been unable to compete with rotating torsion balances. The success of torsion balances relies on 3 main properties: i) high sensitivity to differential accelerations; ii) long time duration of the experiment; iii) up-conversion of the signal (DC from the Earth and 24-hr period from the Sun) to higher frequency (the rotation frequency of the balance).

Completely different tests of UFF are performed by laser ranging to the retroreflectors placed on the surface of the Moon by the *Apollo* astronauts and checking if the Moon and the Earth fall any differently in the field of the Sun. With almost 40 years of Lunar Laser Ranging data (currently to cm accuracy), LLR tests have found no deviation from UFF to about 10^{-13} (Williams *et al.*, 2004).

As for the future, rotating torsion balances might still improve by one order of magnitude, though past experience (also at low temperature) indicates how difficult that is. The LLR community has undertaken a considerable effort (Murphy *et al.*, 2007) with the so called "APOLLO" project to employ a bigger telescope and more powerful laser so as to improve laser ranging accuracy from cm to mm level.

For the UFF test to be improved by 1 order of magnitude the physical model used for propagating the orbit of the Moon must be improved to match the improved technology of laser ranging. Which is not an easy task, because of several gravitational (e.g. lunar librations, asteroid perturbations etc...) and non gravitational perturbations (e.g. atmospheric and tidal effects) whose relevant physical parameters are poorly known.

It is worth stressing that ultimately, LLR tests are limited by the non uniformity of the gravity field of the Sun. As shown by Nobili *et al.* (2008) this limitation results in a "classical" dimensionless parameter $\eta_{\rm class}$ indistinguishable from the η parameter of UFF tests as defined above. The authors show that $\eta_{\rm class} = 3\Delta \mathrm{a}_{\rm sma}/\mathrm{d}$ ($\Delta \mathrm{a}_{\rm sma}$ being the measurement error in the semimajor axis of the orbit of the Moon around the Earth and d the orbital distance of the Earth-Moon system from the Sun). For a given value of $\eta_{\rm class}$, typical of the experiment, no deviation from UFF smaller than that can be claimed, no matter how good is the physical model employed. The physical model should be sufficiently good for the UFF test to reach the value of $\eta_{\rm class}$, thus being limited only by the unavoidable non uniformity of the gravitational field. For LLR tests, $1\,cm$ measurement error in the semimajor axis of the moon is consistent with the current level of LLR tests to 10^{-13}; laser ranging to the Moon at $1\,mm$ level with the new APOLLO facility sets the limiting value of $\eta_{\rm class}$ close to 10^{-14}. We note in passing that this kind of limitation is even more severe for laser ranging to LAGEOS (in the field of the Earth) due to its smaller orbital distance from the source body.

High precision gravity measurements can now be performed using atom interferometry (Peters *et al.*, 2001). Experiments of this type are in preparation at Stanford University aiming at measuring the relative gravitational acceleration of falling cold atoms ^{85}Rb and ^{87}Rb – hence testing the UFF for these atoms – to 10^{-15} or even 10^{-17} (Dimopoulos *et al.*, 2007). Such a test of the UFF has already been performed a few years ago – dropping cold atoms ^{85}Rb and ^{87}Rb – at Max-Planck Institute, in Germany, by Fray *et al.* (2004) (with Nobel laureate Ted Hänsch among the authors), yielding a minimum relative difference in the acceleration of the falling atoms $\Delta g/g \simeq 10^{-7}$. The experiment concept is totally new, but the result is not yet competitive with torsion balance tests of the equivalence principle based on macroscopic test bodies, which have achieved 10^{-13} as reported above.

Directly relevant to cold atoms tests of the UFF are experiments devoted to measuring the local gravitational acceleration g by atom interferometry dropping cold atoms. Ten years ago (Peters *et al.*, 1999) (including Nobel laureate Steven Chu) have been able to measure g with an absolute uncertainty of $\Delta g/g \simeq 3 \cdot 10^{-9}$, and this is the best result so far.

Atom interferometry is likely to contribute more and more to precision gravimetry, and a Local Lorentz Invariance test has been performed by Mueller *et al.* (2008). However, from the viewpoint of UFF tests, dropping atoms which differ by 2 neutrons only makes the case for a possible violation depending on composition extremely weak. The choice of different materials is restricted to atoms that can be laser cooled. When comparing with classical tests based on macroscopic test masses, this issue is probably more a matter of concern than the limited statistics and sensitivity.

All other proposals aiming at a considerable improvement over the 10^{-13} level achieved by rotating torsion balances and by LLR refer to experiments to be performed: *i)* inside a capsule dropped during a balloon flight (Iafolla *et al.*, 1998) with target 10^{-14}–10^{-15}; *ii)* in a suborbital flight with a sounding rocket (Reasenberg, 2008) with target 10^{-16}; *iii)* in low Earth orbit inside a spacecraft: μSCOPE (see μSCOPE Website) with target 10^{-15}; MWXG (Ertmer *et al.*, 2009)) with target 10^{-16}; "Galileo Galilei" (GG) (Nobili *et al.*, 2009; GG Website) with target 10^{-17}; STEP (see STEP Website) with target 10^{-18}.

5. A breakthrough possible in space

A spacecraft in low Earth orbit offers major advantages for testing the UFF (hence the WEP) several orders of magnitude more accurately than now, thus probing a completely unknown physics domain and possibly leading to the discovery of a new fundamental force of Nature. The advantages are unquestionable: a driving signal acceleration 3 orders of magnitude stronger; absence of weight (which allows the tests masses to be coupled very weakly, hence with very high sensitivity to differential effects); isolation in space of the "whole lab" (i.e. the spacecraft), thus eliminating a large number of nearby disturbances unavoidable in ground laboratories; possibility to design the spacecraft as co-rotating with the apparatus, to provide the signal modulation (which has made the success of rotating torsion balances) while also passively stabilizing the spacecraft – with no need for a motor.

However, in order to succeed, one should be aware of the difficulties and risks. The lesson of GP-B, which has performed incredibly well, and yet not enough to produce the expected scientific results, should be learned by the entire community.

We can convincingly argue that the "Galileo Galilei" (GG) proposed satellite experiment has been designed to exploit all the advantages of space listed above. GG aims at testing the UFF to 10^{-17} and is now at Phase A-2 Study level by Thales Alenia Space Italy (TAS-I) with ASI (Agenzia Spaziale Italiana) funding. A full scale prototype of the flight instrument ("GG on the Ground" – GGG) is operational in the INFN lab of Pisa – San Piero a Grado and an advanced version of it is under construction (Comandi *et al.*, 2006I; Comandi *et al.*, 2006II).

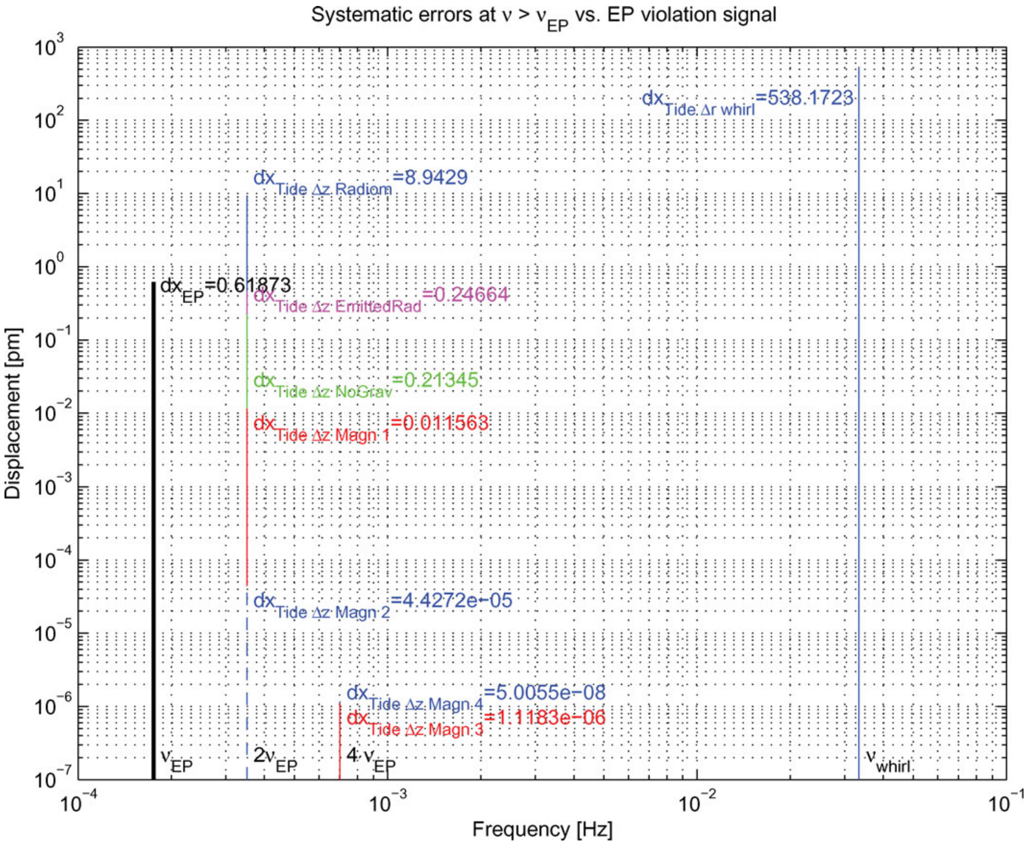

Figure 1. Graphical representation of the GG error budget as obtained from the Space Experiment Simulator. The mission requirements are embedded in the Simulator during a science run; the time series of the relative displacements of the test cylinders (which should be zero if Universality of Free Fall and the Weak Equivalence Principle hold!) allows us to establish systematic and random errors. The plot reports major systematic errors only, caused by various (classical) perturbations, as function of their frequency (in the inertial frame) to be compared with the signal expected for an EP violation to 10^{-17} (indicated by the thick line, first from left). The relative displacement caused on the test masses by the signal and the various perturbations is expressed in picometers. The frequency of the signal is the satellite orbit frequency, indicated as $\nu_{\rm EP}$. It is apparent that even though in some cases the perturbing effects are larger than the signal, they are always sufficiently separated in frequency to be distinguished from it.

GG has been designed to rely on physics laws and physical symmetries more than on brute force, and to be as passive as possible as this is a must for small force gravitational experiments. Very schematically:

• GG has large mass test bodies (10 kg each), to reduce thermal noise and aim at high sensitivity without cryogenics.

• GG has mechanical suspensions (weightlessness makes their stiffness competitive with that of contactless suspensions) in order to guarantee passive electric grounding.

• GG is a cylindrically symmetric co-rotating system, to avoid active attitude control and achieve high frequency signal modulation *for free*.

• The test cylinders are sensitive in the plane perpendicular to the axis – not along the axis (as in STEP and μSCOPE). This is a crucial theoretical condition (which has been known since 1934) in order to guarantee the existence of a physical position of

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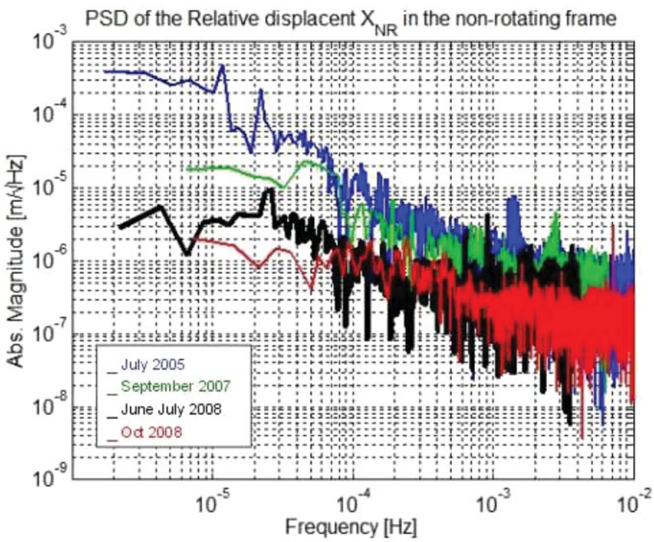

Figure 2. Power Spectral Density of the relative displacements of the GGG test cylinders showing improvements in sensitivity since 2005 (from top to bottom curve). The bottom curve corresponds to the same 2-day run whose Fast Fourier Transform is reported in Figure 3

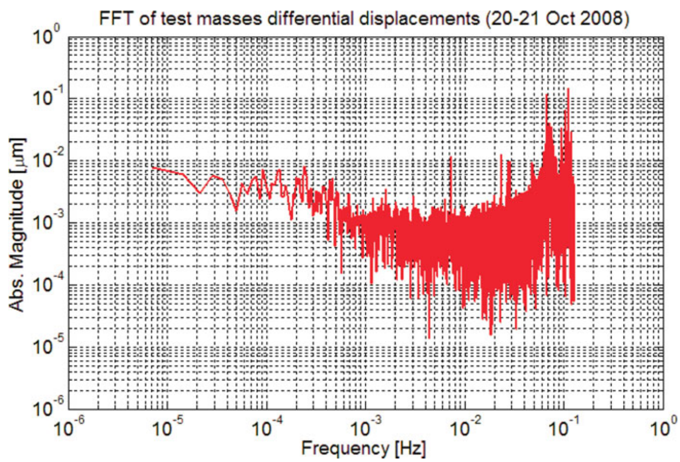

Figure 3. Fast Fourier Transform of the relative displacements of the GGG rotating test cylinders, 10 kg each (in the horizontal plane of the lab). Units are in μm. Even at low frequencies their separation is below 10^{-8} m, reaching a nanometer at higher frequencies. In the GG space experiment, a weak equivalence principle violation to 10^{-17} would produce a displacement of about 10^{-12} m at orbital frequency

relative equilibrium of the test masses at a rapid rotation frequency (1 Hz in the present baseline) well above their natural coupling frequency. In the plane of sensitivity the GG test masses move around that position and a capacitance read-out gives their relative displacements: the masses are not "actively" re-centered, like in the original STEP design and in μSCOPE (the signal being – in those cases – the active force required to re-center them).

• The only active control required on the test masses is that of whirl motions, which require forces much smaller than the coupling ones at frequencies far apart from the

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signal frequency. Moreover, they will not be applied during science runs (Nobili *et al.*, 1999).

• The spacecraft is capable to provide partial drag compensation with FEEP thrusters.

• Residual electric patch effects are DC or slowly varying (and they are measured in GGG).

• A wide choice of materials for the test masses is possible (rotation makes mass anomalies effects DC) and can be optimized for maximum possible physical effect depending on composition (one test mass might contain H).

• Major radiometer disturbance is negligible by design (otherwise it would be impossible to aim at 10^{-17} at room temperature; see Nobili *et al.*, 2001).

The industrial study team of GG comes from the ESA mission GOCE, for which TAS-I has acted as prime contractor. GOCE has been launched recently and is already in drag-free mode, with a performance a factor 10 better than planned, to the level of 1 to $2 \cdot 10^{-9}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ in a range from 2 mHz to 0.1 Hz; see GOCE Website.

The Drag Free Control of GG and a complete Space Experiment Simulator have been built based on expertise from GOCE, on previous GG studies and on inputs from the GGG experimental results. Fig. 1 reports in a graphical manner the error budget (systematic effects) of the GG experiment obtained in April 2009 for a target violation signal of 10^{-17}. Fig. 2 reports the results of the GGG prototype. Platform noise (notably terrain tilt noise and motor noise) needs to be reduced. However, GGG has the same number of degrees of freedom as in GG, the test masses are dominated by their coupling (though stiffer than in space) and not by local gravity and therefore provides a reliable testbed for the instrument to fly in GG.

The technologies required are available, the most recent being the technology of field emission electric propulsion (FEEP) which has been developed for LISA Pathfinder and μSCOPE.

To conclude, a major scientific advance in fundamental physics is possible with current space technology. A null result in testing the Weak Equivalence Principle at the 10^{-17} level that GG is designed to reach would be a milestone for physics theories; a positive result would point at the existence of a new fundamental force of Nature and make for a scientific revolution.

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