1. SCIENTIFIC BACKGROUND

General Theory of Relativity (GTR) 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 GTR, 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 (the most accurate of which have been performed in space) 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 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 Theory of Relativity. To date, almost all experimental tests of the Standard Model have also agreed with its predictions.

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, GTR 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 GTR near singularities. Attempts at reconciling these theories often lead to a violation of the Equivalence Principle on which GTR is based. Therefore tests of the Equivalence Principle address a crucial problem which is at the heart of fundamental physics today.

In addition, the need to understand the nature of dark matter, the recent remarkable discoveries of observational cosmology and the puzzle of dark energy, all indicate that physics beyond the Standard Model and the General Theory of Relativity is needed. 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. It should account for more than 20% of the total mass in the universe but is not understood as yet. Dark energy is an even deeper mystery. Recent measurements show that the expansion of the universe is speeding up rather than slowing down, thus contradicting the fundamental idea that gravity is always attractive and calling for the presence of an unknown form of energy (the "dark energy") –whose gravity is repulsive and whose nature determines the evolution of the universe– which should contribute by about 70% to its total mass.

The major questions now being asked about the universe at its two extremes –the very large and the very small– appear to be inextricably intertwined.

The National Research Council of the US National Academies has appointed a specific “Committee on the Physics of the Universe” 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” [1].

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 called “Striking the Right Balance” reads (p. 162):

“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 addition to the "Committee on the Physics of the Universe", a Dark Energy Task Force (DETF) has been 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 the DETF published its final report [2], where the Executive Summary 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 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. "

A few pages below, the Section of the Report on "Goals and Methodology for Studying Dark Energy" ends with the following sentence:

"Just as dark-energy science has far-reaching implications for other fields of physics, advances and discoveries in other fields of physics may point the way toward understanding the nature of dark energy; for instance, any observational evidence for modifications of General Relativity."

The principle of equivalence has historically played a major role in the development of gravitation theory. It is possible to ascribe two conceptually different kinds of mass to a body: an <u>inertial</u> *mass* and a <u>gravitational</u> *mass*. The inertial mass is the proportionality factor between a force (any kind of force) applied to the body and the acceleration it acquires in response to it in an inertial laboratory. The gravitational mass is a measurement of the property of the body to attract gravitationally any other body (gravitational *active* mass), or to be gravitationally attracted by any other body (gravitational *passive* mass). Assuming the validity of the action–reaction principle (which leads to conclude that the center of mass of an isolated system must move with constant velocity in an inertial frame of reference) also implies that the gravitational passive and active mass of a body must be the same. The gravitational mass is the analog in a gravitational field, of the electric charge in an electric field –it can be viewed as a gravitational charge– and it has no apparent relation (in spite of the name) with the concept of inertial mass. Using Newton's law of gravitation to write the equation of motion of a body of inertial mass m_i and gravitational mass m_g in the field of a source body of gravitational mass M_g (for instance, the Earth), if $m_i \propto m_g$ the resulting acceleration is the same for all bodies. With the measured value of the gravitational constant G and a proportionality factor +1 ($m_i = m_g$) , the local acceleration of gravity on the surface of the Earth –the same for all bodies regardless of their mass and composition– amounts to about 9.8 m/s^2. This is the so called Universality of Free Fall (UFF). No such thing holds for all other fundamental forces of Nature. For instance, a proton and an electron do not have –in the same electric field– the same (in modulus) acceleration, because the inertial mass of the proton is much larger than the inertial mass of the electron and no proportionality holds between the inertial mass of a body and its electric charge.

Galileo was most probably the first one to provide experimental evidence for the UFF [3]. However, he was not aware of the law which rules the gravitational interaction. Therefore, he had no awareness either of the equivalence between inertial and gravitational mass, and of the link between this concept and his own experimental results on the UFF. The fact that the two concepts of inertial and gravitational mass refer in fact to the same physical quantity was first stated by Newton in the opening paragraph of the *Principia* [4]: "*This quantity that I mean hereafter under the name of ... mass ... is known by the weight ... for it is proportional to the weight as I have found by experiments on pendulums, very accurately made... "*

At the beginning of the 20th century, almost 300 years since Galileo's work, Einstein realized that because of the proportionality between the gravitational mass and the inertial mass, the effect of gravitation is locally equivalent to the effect of an accelerated frame and can be locally canceled. This is known as the Weak Equivalence Principle (WEP) which Einstein introduced in 1907 [5] as 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 <u>local</u> dynamical effects. Any test mass located inside the famous Einstein 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 Einstein 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.

Einstein's formulation of the Weak Equivalence Principle whereby the effect of gravity disappears in a freely falling reference frame, holds only <u>locally</u>. The elevator is free falling <u>in the vicinity</u> 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 General theory of Relativity 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.[6]): i) WEP is valid; ii) 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); iii) The outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed (Local Position Invariance). The Einstein Equivalence Principle –which assumes the weak one– is regarded as the "heart and soul" of the General Theory of Relativity because it is the validity of this "principle" to ensure the fact that in General Relativity the effects of gravity are replaced by a curved 4-dimensional space-time.

Quantitative comparisons between the "probing power" of equivalence principle tests and tests of the PPN-Parametrized Post Newtonian parameters (such as the Eddington parameter, best measured with the space mission Cassini [7]) have been performed [8,9]. They show the superior probing power (by several orders magnitude) of equivalence principle tests, thus indicating that a breakdown of General Relativity (if any) is more likely to be detected by putting to more and more stringent tests the foundations of the theory (hence the equivalence principle), rather then its numerous predictions.