

Experimental Tests of Relativistic Gravity

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The confrontation between Einstein's gravitation theory and experimental results, notably binary pulsar data, is summarized and its significance discussed. Experiment and theory agree at the 10^{-3} level or better. All the basic structures of Einstein's theory (coupling of gravity to matter; propagation and self-interaction of the gravitational field, including in strong-field conditions) have been verified. However, the theoretical possibility that scalar couplings be naturally driven toward zero by the cosmological expansion suggests that the present agreement between Einstein's theory and experiment might be compatible with the existence of a long-range scalar contribution to gravity (such as the dilaton field, or a moduli field, of string theory). This provides a new theoretical paradigm, and new motivations for improving the experimental tests of gravity.

1. Introduction

Einstein's gravitation theory can be thought of as defined by two postulates. One postulate states that the action functional describing the propagation and self-interaction of the gravitational field is

$$S_{\text{gravitation}} = \frac{c^4}{16\pi G} \int \frac{d^4x}{c} \sqrt{g} R(g). \quad (1)$$

A second postulate states that the action functional describing the coupling of all the fields describing matter and its electro-weak and strong interactions (leptons and quarks, gauge and Higgs bosons) is a (minimal) deformation of the special relativistic action functional used by particle physicists (the so called "Standard Model"), obtained by replacing everywhere the flat Minkowski metric $\eta_{\mu\nu} = \text{diag}(-1, +1, +1, +1)$ by $g_{\mu\nu}(x^\lambda)$ and the partial derivatives $\partial_\mu \equiv \partial/\partial x^\mu$ by g -covariant derivatives ∇_μ . Schematically, one has

$$S_{\text{matter}} = \int \frac{d^4x}{c} \sqrt{g} \mathcal{L}_{\text{matter}} [\psi, A_\mu, H; g_{\mu\nu}]. \quad (2)$$

Einstein's theory of gravitation is then defined by extremizing the total action functional, $S_{\text{tot}} [g, \psi, A, H] = S_{\text{gravitation}} [g] + S_{\text{matter}} [\psi, A, H, g]$.

Although, seen from a wider perspective, the two postulates (1) and (2) follow from the unique

requirement that the gravitational interaction be mediated only by massless spin-2 excitations [1], the decomposition in two postulates is convenient for discussing the theoretical significance of various tests of General Relativity. Let us discuss in turn the experimental tests of the coupling of matter to gravity (postulate (2)), and the experimental tests of the dynamics of the gravitational field (postulate (1)). For more details and references we refer the reader to [2] or [3].

2. Experimental tests of the coupling between matter and gravity

The fact that the matter Lagrangian depends only on a symmetric tensor $g_{\mu\nu}(x)$ and its first derivatives (i.e. the postulate of a universal "metric coupling" between matter and gravity) is a strong assumption (often referred to as the "equivalence principle") which has many observable consequences for the behaviour of localized test systems embedded in given, external gravitational fields. In particular, it predicts the constancy of the "constants" (the outcome of local non-gravitational experiments, referred to local standards, depends only on the values of the coupling constants and mass scales entering the Standard Model) and the universality of free fall (two test bodies dropped at the same location and with the same velocity in an external gravi-

tational field fall in the same way, independently of their masses and compositions).

Many sorts of data (from spectral lines in distant galaxies to a natural fission reactor phenomenon which took place at Oklo, Gabon, two billion years ago) have been used to set limits on a possible time variation of the basic coupling constants of the Standard Model. The best results concern the electromagnetic coupling, i.e. the fine-structure constant α_{em} . A recent reanalysis of the Oklo phenomenon gives a conservative upper bound [4]

$$-6.7 \times 10^{-17} \text{ yr}^{-1} < \frac{\dot{\alpha}_{\text{em}}}{\alpha_{\text{em}}} < 5.0 \times 10^{-17} \text{ yr}^{-1}, \quad (3)$$

which is much smaller than the cosmological time scale $\sim 10^{-10} \text{ yr}^{-1}$. It would be interesting to confirm and/or improve the limit (3) by direct laboratory measurements comparing clocks based on atomic transitions having different dependences on α_{em} . [Current atomic clock tests of the constancy of α_{em} give the limit $|\dot{\alpha}_{\text{em}}/\alpha_{\text{em}}| < 3.7 \times 10^{-14} \text{ yr}^{-1}$ [5].]

The universality of free fall has been verified at the 10^{-12} level both for laboratory bodies [6], e.g. (from the last reference in [6])

$$\left(\frac{\Delta a}{a}\right)_{\text{Be Cu}} = (-1.9 \pm 2.5) \times 10^{-12}, \quad (4)$$

and for the gravitational accelerations of the Moon and the Earth toward the Sun [7],

$$\left(\frac{\Delta a}{a}\right)_{\text{Moon Earth}} = (-3.2 \pm 4.6) \times 10^{-13}. \quad (5)$$

In conclusion, the main observable consequences of the Einsteinian postulate (2) concerning the coupling between matter and gravity (“equivalence principle”) have been verified with high precision by all experiments to date (see Refs. [2], [3] for discussions of other tests of the equivalence principle). The traditional paradigm (first put forward by Fierz [8]) is that the extremely high precision of free fall experiments (10^{-12} level) strongly suggests that the coupling between matter and gravity is exactly of the “metric” form (2), but leaves open possibilities more general than eq. (1) for the spin-content and dynamics of the fields mediating the

gravitational interaction. We shall provisionally adopt this paradigm to discuss the tests of the other Einsteinian postulate, eq. (1). However, we shall emphasize at the end that recent theoretical findings suggest a new paradigm.

3. Tests of the dynamics of the gravitational field in the weak field regime

Let us now consider the experimental tests of the dynamics of the gravitational field, defined in General Relativity by the action functional (1). Following first the traditional paradigm, it is convenient to enlarge our framework by embedding General Relativity within the class of the most natural relativistic theories of gravitation which satisfy exactly the matter-coupling tests discussed above while differing in the description of the degrees of freedom of the gravitational field. This class of theories are the metrically-coupled tensor-scalar theories, first introduced by Fierz [8] in a work where he noticed that the class of non-metrically-coupled tensor-scalar theories previously introduced by Jordan [9] would generically entail unacceptably large violations of the equivalence principle. The metrically-coupled (or equivalence-principle respecting) tensor-scalar theories are defined by keeping the postulate (2), but replacing the postulate (1) by demanding that the “physical” metric $g_{\mu\nu}$ (coupled to ordinary matter) be a composite object of the form

$$g_{\mu\nu} = A^2(\varphi) g_{\mu\nu}^*, \quad (6)$$

where the dynamics of the “Einstein” metric $g_{\mu\nu}^*$ is defined by the action functional (1) (written with the replacement $g_{\mu\nu} \rightarrow g_{\mu\nu}^*$) and where φ is a massless scalar field. [More generally, one can consider several massless scalar fields, with an action functional of the form of a general nonlinear σ model [10]]. In other words, the action functional describing the dynamics of the spin 2 and spin 0 degrees of freedom contained in this generalized theory of gravitation reads

$$S_{\text{gravitational}}[g_{\mu\nu}^*, \varphi] = \frac{c^4}{16\pi G_*} \int \frac{d^4x}{c} \sqrt{g_*} \times [R(g_*) - 2g_*^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi]. \quad (7)$$

Here, G_* denotes some bare gravitational coupling constant. This class of theories contains an arbitrary function, the “coupling function” $A(\varphi)$. When $A(\varphi) = \text{const.}$, the scalar field is not coupled to matter and one falls back (with suitable boundary conditions) on Einstein’s theory. The simple, one-parameter subclass $A(\varphi) = \exp(\alpha_0 \varphi)$ with $\alpha_0 \in \mathbb{R}$ is the Jordan-Fierz-Brans-Dicke theory [8], [11], [12]. In the general case, one can define the (field-dependent) coupling strength of φ to matter by

$$\alpha(\varphi) \equiv \frac{\partial \ln A(\varphi)}{\partial \varphi}. \quad (8)$$

It is possible to work out in detail the observable consequences of tensor-scalar theories and to contrast them with the general relativistic case (see, e.g., ref. [10]).

Let us now consider the experimental tests of the dynamics of the gravitational field that can be performed in the solar system. Because the planets move with slow velocities ($v/c \sim 10^{-4}$) in a very weak gravitational potential ($U/c^2 \sim (v/c)^2 \sim 10^{-8}$), solar system tests allow us only to probe the quasi-static, weak-field regime of relativistic gravity (technically described by the so-called “post-Newtonian” expansion). In the limit where one keeps only the first relativistic corrections to Newton’s gravity (first post-Newtonian approximation), all solar-system gravitational experiments, interpreted within tensor-scalar theories, differ from Einstein’s predictions only through the appearance of two “post-Einstein” parameters $\bar{\gamma}$ and $\bar{\beta}$ (related to the usually considered Eddington parameters γ and β through $\bar{\gamma} \equiv \gamma - 1$, $\bar{\beta} \equiv \beta - 1$). The parameters $\bar{\gamma}$ and $\bar{\beta}$ vanish in General Relativity, and are given in tensor-scalar theories by

$$\bar{\gamma} = -2 \frac{\alpha_0^2}{1 + \alpha_0^2}, \quad (9)$$

$$\bar{\beta} = +\frac{1}{2} \frac{\beta_0 \alpha_0^2}{(1 + \alpha_0^2)^2}, \quad (10)$$

where $\alpha_0 \equiv \alpha(\varphi_0)$, $\beta_0 \equiv \partial\alpha(\varphi_0)/\partial\varphi_0$; φ_0 denoting the cosmologically-determined value of the scalar field far away from the solar system. Essentially, the parameter $\bar{\gamma}$ depends only on the

linearized structure of the gravitational theory (and is a direct measure of its field content, i.e. whether it is pure spin 2 or contains an admixture of spin 0), while the parameter $\bar{\beta}$ parametrizes some of the quadratic nonlinearities in the field equations (cubic vertex of the gravitational field).

All currently performed gravitational experiments in the solar system, including perihelion advances of planetary orbits, the bending and delay of electromagnetic signals passing near the Sun, and very accurate range data to the Moon obtained by laser echoes, are compatible with the general relativistic predictions $\bar{\gamma} = 0 = \bar{\beta}$ and give upper bounds on both $|\bar{\gamma}|$ and $|\bar{\beta}|$ (i.e. on possible fractional deviations from General Relativity). The best current limits come from: (i) VLBI measurements of the deflection of radio waves by the Sun, giving [13]: $-3.8 \times 10^{-4} < \bar{\gamma} < 2.6 \times 10^{-4}$, and (ii) Lunar Laser Ranging measurements of a possible polarization of the orbit of the Moon toward the Sun (“Nordtvedt effect” [14]) giving [7]: $4\bar{\beta} - \bar{\gamma} = -0.0007 \pm 0.0010$.

The corresponding bounds on the scalar coupling parameters α_0 and β_0 are: $\alpha_0^2 < 1.9 \times 10^{-4}$, $-8.5 \times 10^{-4} < (1 + \beta_0)\alpha_0^2 < 1.5 \times 10^{-4}$. Note that if one were working in the more general (and more plausible; see below) framework of theories where the scalar couplings violate the equivalence principle one would get much stronger constraints on the basic coupling parameter α_0 of order $\alpha_0^2 \lesssim 10^{-7}$ [15].

The parametrization of the weak-field deviations between generic tensor-scalar theories and Einstein’s theory has been extended to the second post-Newtonian order [16]. Only two post-post-Einstein parameters, ε and ζ , representing a deeper layer of structure of the gravitational interaction, show up. These parameters have been shown to be already significantly constrained by binary-pulsar data: $|\varepsilon| < 7 \times 10^{-2}$, $|\zeta| < 6 \times 10^{-3}$.

4. Tests of the dynamics of the gravitational field in the strong field regime

In spite of the diversity, number and often high precision of solar system tests, they have an important qualitative weakness: they probe neither the radiation properties nor the strong-field as-

pects of relativistic gravity. Fortunately, the discovery [17] and continuous observational study of pulsars in gravitationally bound binary orbits has opened up an entirely new testing ground for relativistic gravity, giving us an experimental handle on the regime of strong and/or radiative gravitational fields.

The fact that binary pulsar data allow one to probe the propagation properties of the gravitational field is well known. This comes directly from the fact that the finite velocity of propagation of the gravitational interaction between the pulsar and its companion generates damping-like terms in the equations of motion, i.e. terms which are directed against the velocities. [This can be understood heuristically by considering that the finite velocity of propagation must cause the gravitational force on the pulsar to make an angle with the instantaneous position of the companion [18], and was verified by a careful derivation of the general relativistic equations of motion of binary systems of compact objects [19]]. These damping forces cause the binary orbit to shrink and its orbital period P_b to decrease. The measurement, in some binary pulsar systems, of the secular orbital period decay $\dot{P}_b \equiv dP_b/dt$ [20] thereby gives us a direct experimental probe of the damping terms present in the equations of motion.

The fact that binary pulsar data allow one to probe strong-field aspects of relativistic gravity is less well known. The a priori reason for saying that they should is that the surface gravitational potential of a neutron star $Gm/c^2R \simeq 0.2$ is a mere factor 2.5 below the black hole limit (and a factor $\sim 10^8$ above the surface potential of the Earth). Due to the peculiar “effacement” properties of strong-field effects taking place in General Relativity [19], the fact that pulsar data probe the strong-gravitational-field regime can only be seen when contrasting Einstein’s theory with more general theories. In particular, it has been found in tensor-scalar theories [21] that a self-gravity as strong as that of a neutron star can naturally (i.e. without fine tuning of parameters) induce order-unity deviations from general relativistic predictions in the orbital dynamics of a binary pulsar thanks to the existence of non-perturbative strong-field effects. [The adjective

“nonperturbative” refers here to the fact that this phenomenon is nonanalytic in the coupling strength of the scalar field, eq. (8), which can be as small as wished in the weak-field limit]. As far as we know, this is the first example where large deviations from General Relativity, induced by strong self-gravity effects, occur in a theory which contains only positive energy excitations and whose post-Newtonian limit can be arbitrarily close to that of General Relativity.

A comprehensive account of the use of binary pulsars as laboratories for testing strong-field gravity will be found in ref. [22]. Two complementary approaches can be pursued : a phenomenological one (“Parametrized Post-Keplerian” formalism), or a theory-dependent one [10], [22], [23].

The phenomenological analysis of binary pulsar timing data consists in fitting the observed sequence of pulse arrival times to the generic DD timing formula [24] whose functional form has been shown to be common to the whole class of tensor-multi-scalar theories. The least-squares fit between the timing data and the parameter-dependent DD timing formula allows one to measure, besides some “Keplerian” parameters (“orbital period” P_b , “eccentricity” e, \dots), a maximum of eight “post-Keplerian” parameters: $k, \gamma, \dot{P}_b, r, s, \delta_\theta, \dot{e}$ and \dot{x} . Here, $k \equiv \dot{\omega}P_b/2\pi$ is the fractional periastron advance per orbit, γ a time dilation parameter (not to be confused with its post-Newtonian namesake), \dot{P}_b the orbital period derivative mentioned above, and r and s the “range” and “shape” parameters of the gravitational (“Shapiro”) time delay caused by the companion. The important point is that the post-Keplerian parameters can be measured without assuming any specific theory of gravity. Now, each specific relativistic theory of gravity predicts that, for instance, k, γ, \dot{P}_b, r and s (to quote parameters that have been successfully measured from some binary pulsar data) are some theory-dependent functions of the (unknown) masses m_1, m_2 of the pulsar and its companion. Therefore, in our example, the five simultaneous phenomenological measurements of k, γ, \dot{P}_b, r and s determine, for each given theory, five corresponding theory-dependent curves

in the $m_1 - m_2$ plane (through the 5 equations $k^{\text{measured}} = k^{\text{theory}}(m_1, m_2)$, etc...). This yields three ($3 = 5 - 2$) tests of the specified theory, according to whether the five curves meet at one point in the mass plane, as they should. [In the most general (and optimistic) case, discussed in [22], one can phenomenologically analyze both timing data and pulse-structure data (pulse shape and polarization) to extract up to nineteen post-Keplerian parameters.] The theoretical significance of these tests depends upon the physics lying behind the post-Keplerian parameters involved in the tests. For instance, as we said above, a test involving \dot{P}_b probes the propagation (and helicity) properties of the gravitational interaction. But a test involving, say, k, γ, r or s probes (as shown by combining the results of [10] and [21]) strong self-gravity effects independently of radiative effects.

Besides the phenomenological analysis of binary pulsar data, one can also adopt a theory-dependent methodology [10], [22], [23]. The idea here is to work from the start within a certain finite-dimensional “space of theories”, i.e. within a specific class of gravitational theories labelled by some theory parameters. Then by fitting the raw pulsar data to the predictions of the considered class of theories, one can determine which regions of theory-space are compatible (at say the 90% confidence level) with the available experimental data. This method can be viewed as a strong-field generalization of the parametrized post-Newtonian formalism [2] used to analyze solar-system experiments. When non-perturbative strong-field effects are absent one can parametrize strong-gravity effects in neutron stars by using an expansion in powers of the “compactness” $c_A \equiv -2 \partial \ln m_A / \partial \ln G \sim G m_A / c^2 R_A$. Ref. [10] has then shown that the observable predictions of generic tensor-multi-scalar theories could be parametrized by a sequence of “theory parameters”, $\bar{\gamma}$, $\bar{\beta}$, β_2 , β' , β'' , β_3 , $(\beta\beta')$... representing deeper and deeper layers of structure of the relativistic gravitational interaction beyond the first-order post-Newtonian level parametrized by $\bar{\gamma}$ and $\bar{\beta}$. When non-perturbative strong-field effects develop, one cannot use the

multi-parameter approach just mentioned. A useful alternative approach is then to work within specific, low-dimensional “mini-spaces of theories”. Of particular interest is the two-dimensional mini-space of tensor-scalar theories defined by the coupling function $A(\varphi) = \exp(\alpha_0 \varphi + \frac{1}{2} \beta_0 \varphi^2)$. The predictions of this family of theories (parametrized by α_0 and β_0) are analytically described, in weak-field contexts, by the post-Einstein parameter (9), and can be studied in strong-field contexts by combining analytical and numerical methods [23].

Let us now briefly summarize the current experimental situation. Concerning the first discovered binary pulsar PSR1913 + 16 [17], it has been possible to measure with accuracy the three post-Keplerian parameters k, γ and \dot{P}_b . From what was said above, these three simultaneous measurements yield *one* test of gravitation theories. After subtracting a small ($\sim 10^{-14}$ level in \dot{P}_b !), but significant, perturbing effect caused by the Galaxy [25], one finds that General Relativity passes this $(k - \gamma - \dot{P}_b)_{1913+16}$ test with complete success at the 10^{-3} level. More precisely, one finds [26], [20]

$$\begin{aligned} \left[\frac{\dot{P}_b^{\text{obs}} - \dot{P}_b^{\text{galactic}}}{\dot{P}_b^{\text{GR}}[k^{\text{obs}}, \gamma^{\text{obs}}]} \right]_{1913+16} &= 1.0032 \pm 0.0023(\text{obs}) \\ &\pm 0.0026(\text{galactic}) \\ &= 1.0032 \pm 0.0035, \quad (11) \end{aligned}$$

where $\dot{P}_b^{\text{GR}}[k^{\text{obs}}, \gamma^{\text{obs}}]$ is the GR prediction for the orbital period decay computed from the observed values of the other two post-Keplerian parameters k and γ .

This beautiful confirmation of General Relativity is an embarrassment of riches in that it probes, at the same time, the propagation *and* strong-field properties of relativistic gravity ! If the timing accuracy of PSR1913 + 16 could improve by a significant factor two more post-Keplerian parameters (r and s) would become measurable and would allow one to probe separately the propagation and strong-field aspects [26]. Fortunately, the discovery of the binary pulsar PSR1534 + 12 [27] (which is significantly stronger than PSR1913+16 and has a more favourably oriented orbit) has opened a new test-

ing ground, in which it has been possible to probe strong-field gravity independently of radiative effects. A phenomenological analysis of the timing data of PSR1534 + 12 has allowed one to measure the four post-Keplerian parameters k, γ, r and s [26]. From what was said above, these four simultaneous measurements yield *two* tests of strong-field gravity, without mixing of radiative effects. General Relativity is found to pass these tests with complete success within the measurement accuracy [26], [20]. The most precise of these new, pure strong-field tests is the one obtained by combining the measurements of k, γ and s . Using the most recent data [28] one finds agreement at the 1% level:

$$\left[\frac{s^{\text{obs}}}{s^{\text{GR}}[k^{\text{obs}}, \gamma^{\text{obs}}]} \right]_{1534+12} = 1.007 \pm 0.008. \quad (12)$$

Recently, it has been possible to extract also the “radiative” parameter \dot{P}_b from the timing data of PSR1534 + 12. Again, General Relativity is found to be fully consistent (at the $\sim 15\%$ level) with the additional test provided by the \dot{P}_b measurement [28]. Note that this gives our second direct experimental confirmation that the gravitational interaction propagates as predicted by Einstein’s theory.

More recently, measurements of the pulse shape of PSR 1913 + 16 [29], [30] have detected a time variation of the pulse shape compatible with the prediction [31], [32] that the general relativistic spin-orbit coupling should cause a secular change in the orientation of the pulsar beam with respect to the line of sight (“geodetic precession”). As envisaged long ago [31] this precession will cause the pulsar to disappear (around 2035) and to remain invisible for hundreds of years [29], [30].

A theory-dependent analysis of the published pulsar data on PSRs 1913 + 16, 1534 + 12 and 0655 + 64 (a dissymmetric system constraining the existence of dipolar radiation [33]) has been recently performed within the (α_0, β_0) -space of tensor-scalar theories introduced above [23]. This analysis proves that binary-pulsar data exclude large regions of theory-space which are compatible with solar-system experiments. This is illustrated in Fig. 9 of Ref. [23] which shows that β_0 must be larger than about -5 , while any value of

β_0 is compatible with weak-field tests as long as α_0 is small enough.

5. Was Einstein 100% right ?

Summarizing the experimental evidence discussed above, we can say that Einstein’s postulate of a pure metric coupling between matter and gravity (“equivalence principle”) appears to be, at least, 99.999 999 999 9% right (because of universality-of-free-fall experiments), while Einstein’s postulate (1) for the field content and dynamics of the gravitational field appears to be, at least, 99.9% correct both in the quasi-static-weak-field limit appropriate to solar-system experiments, and in the radiative-strong-field regime explored by binary pulsar experiments. Should one apply Occam’s razor and decide that Einstein must have been 100% right, and then stop testing General Relativity ? My answer is definitely, no !

First, one should continue testing a basic physical theory such as General Relativity to the utmost precision available simply because it is one of the essential pillars of the framework of physics. This is the fundamental justification of an experiment such as Gravity Probe B (the Stanford gyroscope experiment), which will advance by one order of magnitude our experimental knowledge of post-Newtonian gravity.

Second, some very crucial qualitative features of General Relativity have not yet been verified : in particular the existence of black holes, and the direct detection on Earth of gravitational waves. Hopefully, the LIGO/VIRGO network of interferometric detectors will observe gravitational waves early in the next century.

Last, some theoretical findings suggest that the current level of precision of the experimental tests of gravity might be naturally (i.e. without fine tuning of parameters) compatible with Einstein being actually only 50% right ! By this we mean that the correct theory of gravity could involve, on the same fundamental level as the Einsteinian tensor field $g_{\mu\nu}^*$, a massless scalar field φ .

Let us first question the traditional paradigm [8], [2] according to which special attention should be given to tensor-scalar theories respecting the equivalence principle. This class of theories was,

in fact, introduced in a purely *ad hoc* way so as to prevent too violent a contradiction with experiment. However, it is important to notice that the scalar couplings which arise naturally in theories unifying gravity with the other interactions systematically violate the equivalence principle. This is true both in Kaluza-Klein theories (which were the starting point of Jordan's theory) and in string theories. In particular, it is striking that (as first noted by Scherk and Schwarz [34]) the dilaton field Φ , which plays an essential role in string theory, appears as a necessary partner of the graviton field $g_{\mu\nu}$ in all string models. Let us recall that $g_s = e^\Phi$ is the basic string coupling constant (measuring the weight of successive string loop contributions) which determines, together with other scalar fields (the moduli), the values of all the coupling constants of the low-energy world. This means, for instance, that the fine-structure constant α_{em} is a function of Φ (and possibly of other moduli fields). In intuitive terms, while Einstein proposed a framework where geometry and gravitation were united as a dynamical field $g_{\mu\nu}(x)$, i.e. a soft structure influenced by the presence of matter, string theory extends this idea by proposing a framework where geometry, gravitation, gauge couplings and gravitational couplings all become soft structures described by interrelated dynamical fields. Symbolically, one has $g_{\mu\nu}(x) \sim g^2(x) \sim G(x)$. This spatiotemporal variability of coupling constants entails a clear violation of the equivalence principle. In particular, α_{em} would be expected to vary on the Hubble time scale (in contradiction with the limit (3) above), and materials of different compositions would be expected to fall with different accelerations (in contradiction with the limits (4), (5) above).

The most popular idea for reconciling gravitational experiments with the existence, at a fundamental level, of scalar partners of $g_{\mu\nu}$ is to assume that all these scalar fields (which are massless before supersymmetry breaking) will acquire a mass after supersymmetry breaking. Typically one expects this mass m to be in the TeV range [35]. This would ensure that scalar exchange brings only negligible, exponentially small corrections $\propto \exp(-mr/\hbar c)$ to the general relativistic pre-

dictions concerning low-energy gravitational effects. However, the interesting possibility exists that the mass m be in the milli eV range, corresponding to observable deviations from usual gravity below one millimeter [36], [37], [38].

But, the idea of endowing the scalar partners of $g_{\mu\nu}$ with a non zero mass is fraught with many cosmological difficulties [39], [40], [41]. Though these cosmological difficulties might be solved by a combination of ad hoc solutions (e.g. introducing a secondary stage of inflation to dilute previously produced dilatons [42], [43]), a more radical solution to the problem of reconciling the existence of the dilaton (or any moduli field) with experimental tests and cosmological data has been proposed [44] (see also [45] which considered an equivalence-principle-respecting scalar field). The main idea of Ref. [44] is that string-loop effects (i.e. corrections depending upon $g_s = e^\Phi$ induced by worldsheets of arbitrary genus in intermediate string states) may modify the low-energy, Kaluza-Klein type matter couplings ($\propto e^{-2\Phi} F_{\mu\nu} F^{\mu\nu}$) of the dilaton (or moduli) in such a manner that the VEV of Φ be cosmologically driven toward a finite value Φ_m where it decouples from matter. For such a "least coupling principle" to hold, the loop-modified coupling functions of the dilaton, $B_i(\Phi) = e^{-2\Phi} + c_0 + c_1 e^{2\Phi} + \dots +$ (nonperturbative terms), must exhibit extrema for finite values of Φ , and these extrema must have certain universality properties. A natural way in which the required conditions could be satisfied is through the existence of a discrete symmetry in scalar space. [For instance, a symmetry under $\Phi \rightarrow -\Phi$ would guarantee that all the scalar coupling functions reach an extremum at the self-dual point $\Phi_m = 0$].

A study of the efficiency of this mechanism of cosmological attraction of φ towards φ_m (φ denoting the canonically normalized scalar field in the Einstein frame, see Eq. (7)) estimates that the present vacuum expectation value φ_0 of the scalar field would differ (in a rms sense) from φ_m by

$$\varphi_0 - \varphi_m \sim 2.75 \times 10^{-9} \times \kappa^{-3} \Omega_m^{-3/4} \Delta\varphi. \quad (13)$$

Here κ denotes the curvature of the gauge coupling function $\ln B_F(\varphi)$ around the maximum

φ_m , Ω_m denotes the present cosmological matter density in units of $10^{-29} g cm^{-3}$, and $\Delta\varphi$ the deviation $\varphi - \varphi_m$ at the beginning of the (classical) radiation era. Equation (13) predicts (when $\Delta\varphi$ is of order unity¹) the existence, at the present cosmological epoch, of many small, but not unmeasurably small, deviations from General Relativity proportional to the *square* of $\varphi_0 - \varphi_m$. This provides a new incentive for trying to improve by several orders of magnitude the various experimental tests of Einstein's equivalence principle. The most sensitive way to look for a small residual violation of the equivalence principle is to perform improved tests of the universality of free fall. The mechanism of Ref. [44] suggests a specific composition-dependence of the residual differential acceleration of free fall and estimates that a non-zero signal could exist at the very small level

$$\left(\frac{\Delta a}{a}\right)_{\text{rms}}^{\text{max}} \sim 1.36 \times 10^{-18} \kappa^{-4} \Omega_m^{-3/2} (\Delta\varphi)^2, \quad (14)$$

where κ is expected to be of order unity (or smaller, leading to a larger signal, in the case where φ is a modulus rather than the dilaton).

Let us emphasize that the strength of the cosmological scenario considered here as counterargument to applying Occam's razor lies in the fact that the very small number on the right-hand side of eq. (14) has been derived without any fine tuning or use of small parameters, and turns out to be naturally smaller than the 10^{-12} level presently tested by equivalence-principle experiments (see equations (4), (5)). The estimate (14) gives added significance to the project of a Satellite Test of the Equivalence Principle (nicknamed STEP, and currently studied by NASA, ESA and CNES) which aims at probing the universality of free fall of pairs of test masses orbiting the Earth at the 10^{-18} level [47].

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