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# General Relativity and Experiment

By Thibault DAMOUR

Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France

DARC, CNRS - Observatoire de Paris, 92195 Meudon, France

*Abstract.* The confrontation between General Relativity and experimental results, notably binary pulsar data, is summarized and its significance discussed. The agreement between experiment and theory is numerically very impressive. However, some recent theoretical findings (cosmological attraction toward zero scalar couplings) suggest that the present agreement between Einstein's theory and experiment might be naturally compatible with the existence of a scalar contribution to gravity. This provides a new theoretical paradigm, and new motivations for improving the experimental tests of gravity.

## 1 Introduction

General Relativity 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

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

A second postulate states that the action functional describing the coupling of all the (fermionic and bosonic) fields describing matter and its electro-weak and strong interactions 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  $f_{\mu\nu} = \text{diag}(-1, +1, +1, +1)$  by  $g_{\mu\nu}(x^\lambda)$  and the partial derivatives  $\partial_\mu \equiv \partial/\partial x^\mu$  by  $g$ -covariant derivatives  $\nabla_\mu$ . [With the usual subtlety that one must also introduce a field of

orthonormal frames, a “vierbein”, for writing down the fermionic terms]. Schematically, one has

$$S_{\text{matter}} [\psi, A, H, g] = \int \frac{d^4x}{c} \sqrt{g} \mathcal{L}_{\text{matter}}, \quad (2a)$$

$$\begin{aligned} \mathcal{L}_{\text{matter}} = & -\frac{1}{4} \sum \frac{1}{g_*^2} \text{tr}(F_{\mu\nu} F^{\mu\nu}) - \sum \bar{\psi} \gamma^\mu D_\mu \psi \\ & - \frac{1}{2} |D_\mu H|^2 - V(H) - \sum y \bar{\psi} H \psi, \end{aligned} \quad (2b)$$

where  $F_{\mu\nu}$  denotes the curvature of a  $U(1)$ ,  $SU(2)$  or  $SU(3)$  Yang-Mills connection  $A_\mu$ ,  $F^{\mu\nu} = g^{\mu\alpha} g^{\nu\beta} F_{\alpha\beta}$ ,  $g_*$  being a (bare) gauge coupling constant;  $D_\mu \equiv \nabla_\mu + A_\mu$ ;  $\psi$  denotes a fermion field (lepton or quark, coming in various flavours and three generations);  $\gamma^\mu$  denotes four Dirac matrices such that  $\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu} \mathbb{I}_4$ , and  $H$  denotes the Higgs doublet of scalar fields, with  $y$  some (bare Yukawa) coupling constants.

Einstein’s theory of gravitation is then defined by extremizing the total action functional,

$$S_{\text{tot}} [g, \psi, A, H] = S_{\text{gravitation}} [g] + S_{\text{matter}} [\psi, A, H, g]. \quad (3)$$

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 (2b) depends only on a symmetric tensor  $g_{\mu\nu}(x)$  and its first derivatives (i.e. the postulate of a “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. Indeed, using a theorem of Fermi and Cartan [4] (stating the existence of coordinate systems such that, along any given time-like curve, the metric components can be set to their Minkowski values, and their first derivatives made to vanish), one derives from the postulate (2) the following observable consequences:

$C_1$  : 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. [In particular, the cosmological evolution of the universe at large has no influence on local experiments].

$C_2$  : Local Lorentz invariance : local non-gravitational experiments exhibit no preferred directions in spacetime [i.e. neither spacelike ones (isotropy), nor timelike ones (boost invariance)].

$C_3$  : “Principle of geodesics” and universality of free fall : small, electrically neutral, non self-gravitating bodies follow geodesics of the external spacetime  $(V, g)$ . In particular, two test bodies dropped at the same location and with the same velocity in an external gravitational field fall in the same way, independently of their masses and compositions.

$C_4$  : Universality of gravitational redshift : when intercompared by means of electromagnetic signals, two identically constructed clocks located at two different positions in a static external Newtonian potential  $U(\mathbf{x})$  exhibit, independently of their nature and constitution, the (apparent) difference in clock rate:

$$\frac{\tau_1}{\tau_2} = \frac{\nu_2}{\nu_1} = 1 + \frac{1}{c^2} [U(\mathbf{x}_1) - U(\mathbf{x}_2)] + O\left(\frac{1}{c^4}\right). \quad (4)$$

Many experiments or observations have tested the observable consequences  $C_1 - C_4$  and found them to hold within the experimental errors. 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 fine-structure constant  $\alpha$ . A recent reanalysis of the Oklo phenomenon gives a conservative upper bound [5]

$$-6.7 \times 10^{-17} \text{ yr}^{-1} < \frac{\dot{\alpha}}{\alpha} < 5.0 \times 10^{-17} \text{ yr}^{-1}, \quad (5)$$

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 (5) by direct laboratory measurements comparing clocks based on atomic transitions having different dependences on  $\alpha$ .

Any “isotropy of space” having a direct effect on the energy levels of atomic nuclei has been constrained to the impressive  $10^{-27}$  level [6]. The universality of free fall has been verified at the  $3 \times 10^{-12}$  level for laboratory bodies [7] and at the  $10^{-12}$  level for the gravitational accelerations of the Moon and the Earth toward the Sun [8]. The “gravitational redshift” of clock rates given by eq. (4) has been verified at the  $10^{-4}$  level by comparing a hydrogen-maser clock flying on a rocket up to an altitude  $\sim 10\,000 \text{ km}$  to a similar clock on the ground [9].

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. The traditional paradigm (first put forward by Fierz [10]) 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 [10] in a work where he noticed that the class of non-metrically-coupled tensor-scalar theories previously introduced by Jordan [11] would generically entail unacceptably large violations of the consequence  $C_1$ . [The fact that it would, by the same token, entail even larger violations of the consequence  $C_3$  was, probably, first noticed by Dicke in subsequent work]. 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  $g_{\mu\nu}$  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  $\varphi$  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  $\sigma$  model [12]]. 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

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

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. In the general case, one can define the (field-dependent) coupling strength of  $\varphi$  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. [12]).

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  $\gamma$  and  $\beta$  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

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

$$\bar{\beta} = +\frac{1}{2} \frac{\beta_0 \alpha_0^2}{(1 + \alpha_0^2)^2}, \quad (9b)$$

where  $\alpha_0 \equiv \alpha(\varphi_0)$ ,  $\beta_0 \equiv \partial\alpha(\varphi_0)/\partial\varphi_0$ ;  $\varphi_0$  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) of order  $10^{-3}$  [8], [13]. Recently, the parametrization of the weak-field deviations between generic tensor-multi-scalar theories and Einstein's theory has been extended to the second post-Newtonian order [14]. Only two post-post-Einstein parameters,  $\varepsilon$  and  $\zeta$ , 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:  $|\varepsilon| < 7 \times 10^{-2}$ ,  $|\zeta| < 6 \times 10^{-3}$ . See [14] for a detailed discussion, including the consequences for the interpretation of future, higher-precision solar-system tests.

## 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 aspects of relativistic gravity. Fortunately, the discovery [15] 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 [16], and was verified by a careful derivation of the general relativistic equations of motion of binary systems of compact objects [17]]. These damping forces cause the binary orbit to shrink and its orbital period  $P_b$  to decrease. The remarkable stability of the pulsar clock, together with the cleanliness of the binary pulsar system, has allowed Taylor and collaborators to measure the secular orbital period decay  $\dot{P}_b \equiv dP_b/dt$  [18], thereby giving us a direct experimental probe of the damping terms present in the equations of motion. Note that, contrary to what is commonly stated, the link between the observed quantity  $\dot{P}_b$  and the propagation properties of the gravitational interaction is quite direct. [It appears indirect only when one goes through the common but unnecessary detour of a heuristic reasoning based on the consideration of the energy lost into gravitational waves emitted at infinity].

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). It has been found [19] 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 nonperturbative strong-field effects in tensor-scalar theories. [The adjective “nonperturbative” refers here to the fact that this phenomenon is nonanalytic in the coupling strength of 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. [The strong-field deviations considered in previous studies [2], [12] arose in theories containing negative energy excitations.]

A comprehensive account of the use of binary pulsars as laboratories for testing strong-field gravity will be found in ref. [20]. Two complementary approaches can be pursued : a phenomenological one (“Parametrized Post-Keplerian” formalism), or a theory-dependent one [12], [20].

The phenomenological analysis of binary pulsar timing data consists in fitting the observed sequence of pulse arrival times to the generic DD timing formula [21] 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,  $\gamma$  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 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,  $k, \gamma, \dot{P}_b, r$  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  $k, \gamma, \dot{P}_b, r$  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 [20], one can phenomenologically analyze both timing data and pulse-structure data (pulse shape and polarization) to extract up to nineteen post-Keplerian parameters. Simultaneous measurement of these 19 parameters in one binary pulsar system would yield 15 tests of relativistic gravity (where one must subtract 4 because, besides the two unknown masses  $m_1, m_2$ , generic post-Keplerian parameters can depend upon the two unknown Euler angles determining the direction of the spin of the pulsar). 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,  $k, \gamma, r$  or  $s$  probes (as shown by combining the results of [12] and [19]) strong self-gravity effects independently of radiative effects.

Besides the phenomenological analysis of binary pulsar data, one can also adopt a theory-dependent methodology [12], [20]. 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. In fact, under the assumption that strong-gravity effects in neutron stars can be expanded 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. [12] has shown that the observable predictions of generic tensor-multi-scalar theories could be parametrized by a sequence of “theory parameters”,

$$\bar{\gamma}, \bar{\beta}, \beta_2, \beta', \beta'', \beta_3, (\beta\beta') \dots \quad (10)$$

representing deeper and deeper layers of structure of the relativistic gravitational interaction beyond the first-order post-Newtonian level parametrized by  $\bar{\gamma}$  and  $\bar{\beta}$  (the second layer  $\beta_2, \beta'$  being equivalent to the parameters  $\zeta, \varepsilon$  describing the second-order post-Newtonian level [14], etc.). When non-perturbative strong-field effects develop, one cannot use the multi-parameter approach just mentioned, based on expansions in powers of the “compactnesses”. 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  $\alpha_0$  and  $\beta_0$ ) 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 [22].

After having reviewed the theory of pulsar tests, let us briefly summarize the current

experimental situation. Concerning the first discovered binary pulsar PSR1913 + 16 [15], it has been possible to measure with accuracy the three post-Keplerian parameters  $k$ ,  $\gamma$  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 [23], one finds that General Relativity passes this  $(k - \gamma - \dot{P}_b)_{1913+16}$  test with complete success at the  $3.5 \times 10^{-3}$  level [24], [18]. 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 [24]. Fortunately, the discovery of the binary pulsar PSR1534 + 12 [25] (which is significantly stronger than PSR1913 + 16 and has a more favourably oriented orbit) has opened a new testing 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  $k$ ,  $\gamma$ ,  $r$  and  $s$  [24]. 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 [24], [18]. More 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 current  $\sim 20\%$  level) with the additional test provided by the  $\dot{P}_b$  measurement [26]. Note that this gives our second direct experimental confirmation that the gravitational interaction propagates as predicted by Einstein’s theory. Moreover, an analysis of the pulse shape of PSR1534 + 12 has shown that the misalignment between the spin vector of the pulsar and the orbital angular momentum was greater than  $8^\circ$  [20]. This opens the possibility that this system will soon allow one to test the spin precession induced by gravitational spin-orbit coupling.

To end this brief summary, let us mention that a comprehensive theory-dependent analysis of all published pulsar data has been recently performed within the  $(\alpha_0, \beta_0)$ -space of tensor-scalar theories [22]. This analysis proves that binary-pulsar data exclude large regions of theory-space which are compatible with solar-system experiments: see Fig. 9 of [22] which shows that  $\beta_0$  must be larger than about  $-5$ , while any value of  $\beta_0$  is compatible with weak-field tests as long as  $\alpha_0$  is small enough.

For a general review of the use of pulsars as physics laboratories the reader can consult Ref. [27].

## 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. 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 recent 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%, or even 33% 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  $\varphi$  which could ("50% right") or could not ("33% right") be coupled to matter in keeping with the equivalence principle (2).

Let us first follow the traditional view (initiated by Fierz and enshrined by Dicke, Nordtvedt and Will [2]) that the  $10^{-12}$  level of testing of the universality of free fall is so impressive that one should apply Occam's razor for what concerns the equivalence principle (2), but not yet for the first postulate (1) which is tested only at the  $10^{-3}$  level. If then we impose the usual consistency requirements of field theory (absence of: algebraic inconsistencies, discontinuities in the degree-of-freedom content, causality problems, negative-energy excitations,...) we are uniquely led to considering only the class of metrically-coupled tensor-multi-scalar theories.

It has been shown that the (positive-energy) multi-scalar case did not bring essentially new features with respect to the mono-scalar case [12]. We therefore limit our discussion to the simplest tensor-scalar theories defined in section 3 above.

Because of the authority of Dicke, it has become paradigmatic, when discussing equivalence-principle respecting tensor-scalar theories, to restrict one's attention to the one-parameter subclass characterized by the coupling function  $A(\varphi) = \exp(\alpha_0 \varphi)$ . [This defines the Jordan-Fierz-Brans-Dicke theory, introduced by Fierz [10] as the one-parameter, metrically-coupled subclass of the two-parameter theory of Jordan [11]]. For many years, the low precision of solar-system relativistic tests (and the possibility of the Sun having a sizable quadrupole moment) did not put strong constraints on the coupling constant  $\alpha_0^2 = (2\omega + 3)^{-1}$ , leaving open the possibility that  $\alpha_0$  be of order unity (as expected if  $\varphi$  is to be a fundamental field, on the same footing as  $g_{\mu\nu}^*$ ). The result of the Viking relativistic time delay experiment [13] (namely  $\alpha_0^2 < 10^{-3}$ ) shattered this idea, and cast a serious doubt on the a priori plausibility of tensor-scalar theories. In my view, the situation has been significantly transformed by the work [28] which found that the general class of (metrically-coupled) tensor-scalar theories, with arbitrary coupling function  $A(\varphi)$ , generically contain an "attractor mechanism" toward General Relativity. More precisely, as soon as the function

$a(\varphi) \equiv \ln A(\varphi)$  admits a minimum, the cosmological evolution tends to drive the cosmic value (or Vacuum Expectation Value, VEV)  $\varphi_0$  of the scalar field toward a value where  $a(\varphi)$  reaches a minimum, i.e. a value where the effective coupling strength of the scalar field  $\alpha(\varphi) = \partial a(\varphi)/\partial\varphi$ , eq. (8), vanishes. Seen from this point of view, it is natural to expect (in a wide class of tensor-scalar theories) that the present value of the scalar coupling strength  $\alpha_0 = \alpha(\varphi_0)$  be much smaller than unity. Note that the Jordan-Fierz-Brans-Dicke theory, with  $a(\varphi) = \alpha_0 \varphi$ , does not belong to the wide class of “GR attracting” theories. As a generic minimum is locally parabolic, it is natural to replace the one-parameter Jordan-Fierz-Brans-Dicke class of theories by the two-parameter one introduced above:  $a(\varphi) = \alpha_0 \varphi + \frac{1}{2} \beta_0 \varphi^2$ .

Analytical estimates of the efficiency of the cosmological attractor mechanism suggest that a natural level for the expected present deviations from General Relativity is

$$\alpha_0^2 \gtrsim \Omega^{-3/2} \times 10^{-7}, \quad (11)$$

where  $\Omega = \rho^{\text{matter}}/\rho^{\text{critical}}$  is the usual dimensionless measure of the average mass density in the universe. The estimate (11) shows that the present agreement at the  $10^{-3}$  level between General Relativity and experiment might be a red herring. This gives a new motivation for experiments which push beyond the precision of relativity tests, such as Stanford’s gyroscope experiment (Gravity Probe B) which aims at the level  $\bar{\gamma} \sim \alpha_0^2 \sim 10^{-5}$ .

Let us however draw back and question the traditional paradigm which led us to restrict our attention to equivalence-principle respecting theories. This paradigm stemmed from the work of Fierz who noticed that the most general tensor-scalar theory of Jordan would strongly violate the equivalence principle. Fierz’s proposal to modify the scalar couplings so as to be in keeping with the postulate (2) was an ad hoc way of preventing too violent a contradiction with experiment. However, if we ask in turn why Jordan had been led to considering theories containing equivalence-principle violating couplings  $\propto e^{\alpha\varphi} F_{\mu\nu} F^{\mu\nu}$ , between  $\varphi$  and gauge fields, the answer is that such couplings were necessary consequences of the Kaluza-Klein unification programme that Jordan was developing. And if we ask what kind of couplings are predicted by all the modern versions of the programme of unifying gravity with the other interactions (generalized Kaluza-Klein, extended supergravity, string theory) the answer is that they generically predict the existence of massless scalar fields coupled in an equivalence-principle-violating way. At this juncture, one would be tempted to conclude that this suggests that all the eventual scalar partners of the Einsteinian tensor field must acquire a mass and thereby bring only negligible, exponentially small corrections  $\propto \exp(-mr/\hbar c)$  to the general relativistic predictions concerning low-energy gravitational effects. This (popular) way of reconciling gravitational experiments with the existence, at a fundamental level, of scalar gravitational fields is, however, fraught with many cosmological difficulties [29]. An alternative possibility has been proposed [30] : string-loop effects (i.e. quantum corrections induced by worldsheets of arbitrary genus in intermediate string states) may modify the low-energy, Kaluza-Klein-type, matter couplings of the massless scalars present in string theory (dilaton or moduli fields) in such a manner that, through a generalization of the attractor mechanism discussed above, the vacuum expectation values of the scalar fields be cosmologically driven towards values where they decouple from matter. For such a “least coupling principle” to hold, the coupling functions of the scalar field(s)

must exhibit certain properties of universality. More precisely, the most general low-energy couplings induced by string-loop effects will be such that the various terms on the right-hand side of eq. (2b) will be multiplied by several different functions of the scalar field(s) : say a factor  $B_F(\varphi)$  in factor of the kinetic terms of the gauge fields, a factor  $B_\psi(\varphi)$  in factor of the Dirac kinetic terms, etc... It has been shown in [30] that if the various coupling functions  $B_i(\varphi)$ ,  $i = F, \psi, \dots$ , all admit an extremum (which must be a maximum for the “leading”  $B_i$ ) at some common value  $\varphi_m$  of  $\varphi$ , the cosmological evolution of the coupled tensor-scalar-matter system will drive  $\varphi$  towards the value  $\varphi_m$ , at which  $\varphi$  decouples from matter. As suggested in [30] 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  $\varphi \rightarrow -\varphi$  would guarantee that all the scalar coupling functions reach an extremum at the self-dual point  $\varphi_m = 0$ ]. The existence of such symmetries have been proven for some of the scalar fields appearing in string theory (target-space duality for the moduli fields) and conjectured for others ( $S$ -duality for the dilaton). This gives us some hope that the mechanism of [30] could apply and thereby naturally reconcile the existence of massless scalar fields with experiment. Indeed, a study of the efficiency of attraction of  $\varphi$  towards  $\varphi_m$  [which happens to be generically larger than in the simple case of Ref. [28], which led to eq. (11), because of the steep dependence of all the physical mass scales upon the gauge coupling function  $B_F(\varphi)$ ] estimates that the present vacuum expectation value  $\varphi_0$  of the scalar field would differ (in a rms sense) from  $\varphi_m$  by

$$\varphi_0 - \varphi_m \sim 2.75 \times 10^{-9} \times \kappa^{-3} \Omega^{-3/4} \Delta\varphi \quad (12)$$

where  $\kappa$  denotes the curvature of  $\ln B_F(\varphi)$  around the maximum  $\varphi_m$  and  $\Delta\varphi$  the deviation  $\varphi - \varphi_m$  at the beginning of the (classical) radiation era. Equation (12) predicts (when  $\Delta\varphi$  is of order unity<sup>1</sup>) 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, i.e. of the consequences  $C_1 - C_4$  recalled above. 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. [30] 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

$$\left( \frac{\Delta a}{a} \right)_{\text{rms}}^{\text{max}} \sim 1.36 \times 10^{-18} \kappa^{-4} \Omega^{-3/2} (\Delta\varphi)^2, \quad (13)$$

where  $\kappa$  is expected to be of order unity (or smaller, leading to a larger signal, in the case where  $\varphi$  is a modulus rather than the dilaton). Let us emphasize again 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. (13) has been derived without any fine tuning or use of small parameters. The estimate (13) gives added significance to the project of a Satellite Test of the Equivalence Principle (nicknamed STEP, and currently studied by ESA, NASA and CNES) which aims at probing the universality of

<sup>1</sup>However,  $\Delta\varphi$  could be  $\ll 1$  if the mechanism of ref. [28] already applies during an early stage of potential-driven inflation [31].

free fall of pairs of test masses orbiting the Earth at the  $10^{-17}$  level [32].

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