Neutrinos are not in a Rush

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Modified gravity
The speed of fermions in matter

The biggest (non)-surprise of 2011-2012 is certainly the announcement followed by the non-confirmation of a deviation of the speed of neutrinos through earth:

$$\frac{\Delta t}{t} = 2 \cdot 10^{-5}$$

This would have been much larger than the possible time difference for neutrinos emerging from the supernovae SN1987A

$$\frac{\Delta t}{t} \leq 10^{-9}$$

And much bigger than any deviation for charged leptons in the atmosphere and at accelerators:

$$\frac{\Delta t}{t} \leq 10^{-15}$$

The problem with going too fast is Cerenkov radiation. With 20 GeV neutrinos leaving CERN, very few with energy higher than 12 GeV should get to Gran Sasso…(Cohen-Glashow)

Even worse, the neutrinos with energy greater than 5 GeV could not be produced from pion decay…. (Bi et al.)

The only plausible way out (Dvali-Vikman): neutrinos could behave differently in matter and in vacuum (and even in the atmosphere). This seems weird but this type of environment dependent physics has become popular in the last few years in modified gravity models with a screening mechanism.

The acceleration of the expansion of the Universe tells us that something unexpected happens on cosmological scales.

Being a low energy phenomenon, and involving gravity, one should be able to describe it with a low energy effective action. Weinberg's theorem (1965) says that the only Lorentz invariant low energy theory of spin 2 field is General Relativity. As GR + ordinary matter does not lead to acceleration, one can either generate the acceleration :

Adding matter $\longrightarrow$ Dark Energy

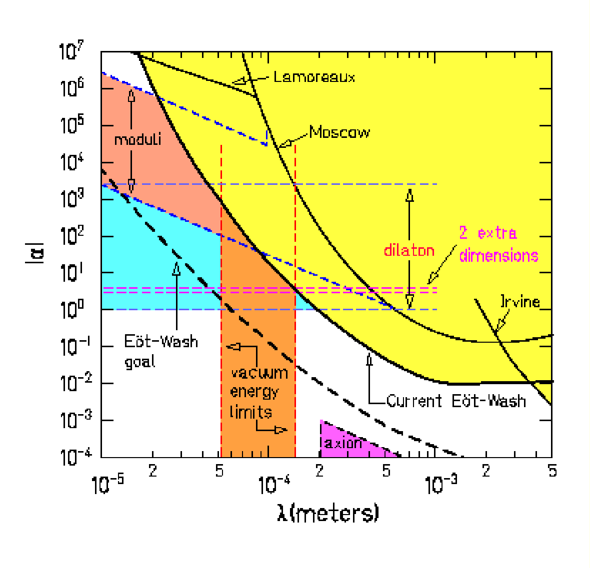
Modifying gravity $\longrightarrow$ new degrees of freedom

In both cases, the simplest degrees of freedom are scalar fields (quintessence, inflation… or scalar part of massive gravitons)

- Locally, deviations from Newton's law are parametrised by:

$$\phi_N = -\frac{G_N}{r}(1 + 2\beta_\phi^2 e^{-r/\lambda})$$

$$\beta_\phi^2 = \frac{1}{2\omega + 3}$$



The tightest constraint on β comes from the Cassini probe measuring the Shapiro effect (time delay):

$$\beta_\phi^2 \leq 1.210^{-5}$$

In the Brans-Dicke case, this translates to

$$\omega \geq 40000$$

Local constraints relaxed if screening

Known models of modified gravity involve scalar fields :

- DGP, Galileon
- Dilaton (runaway)
- Symmetron
- Chameleon, f(R)

Long range fifth force on cosmological scales.

Scalars couple to matter with potential fifth force in the solar system and the laboratory. Need to invoke a screening mechanism locally in order to preserve the possibility of modifying gravity on large scales .

Effective action

Effective field theories with gravity and scalars:

$$S = \int d^4x \sqrt{-g}\left(\frac{1}{16\pi G_N} R - F(\phi, \partial\phi) - V(\phi) + \mathcal{L}_m(\psi_m, A^2(\phi) g_{\mu\nu})\right)$$

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$$\Big\downarrow \text{Galileons}$$

$$\nabla^2\phi + \frac{r_c^2}{3}[(\nabla^2\phi)^2 - \nabla_i\nabla_j\phi\nabla^i\nabla^j\phi] = \frac{8\pi G_N}{3}\delta\rho$$

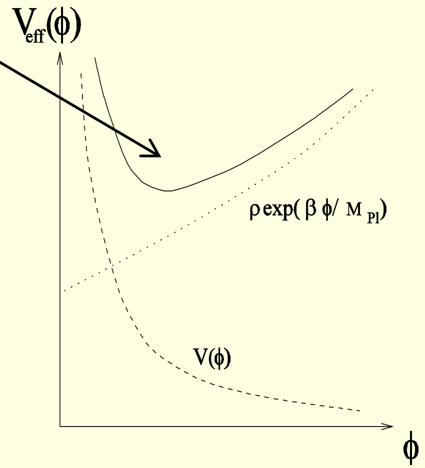
Large non-linearities in the kinetic terms imply a suppression of the coupling to matter (Vainshtein's mechanism)

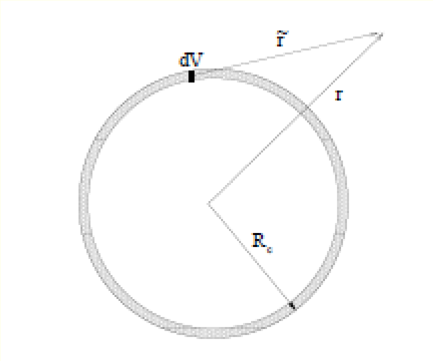
Canonical scalar fields have a matter dependent effective potential

$$V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)$$

Khoury-Weltman

Environment dependent minimum. Chameleon mechanism





The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.

F(R) models

$$\beta = \frac{1}{\sqrt{6}}$$

In a dense environment like the earth:

- For Galileons, the gradient of the field is a smooth function

$$\frac{d\phi}{dr} = \frac{M}{2m_{\rm Pl} r^2}\left(\frac{r}{R_\star}\right)^{3/2} \qquad R_\oplus \ll R_\star$$

-For chameleons, the gradient is non-zero in a thin shell

$$\frac{d\phi}{dr} = \frac{\beta \rho_m}{m_{\rm Pl}}(r - R_s) \qquad \frac{\Delta R}{R} \le 10^{-7}$$

Equivalence principle

If matter couples to:

$$\tilde{g}_{\mu\nu} = A^2(\phi)(g_{\mu\nu} + \frac{2}{M^4}\partial_\mu\phi\partial_\nu\phi)$$

Then a new derivative coupling appears:

$$\int d^4x\sqrt{-g}\frac{\partial_\mu\phi\partial_\nu\phi}{M^4}T^{\mu\nu}$$

For fermions, this coupling leads to a modified dispersion relation and fermions propagating with a speed greater than the speed of light along the gradient of the scalar field:

$$\Delta c = |d|^2, \quad d^i = \frac{\partial^i\phi}{M^2}$$

This immediately leads to a difference of speed in matter for neutrinos interacting with Galileons and chameleons.

As the gradient of the Galileon is essentially constant at the surface of the earth, a large time difference for neutrinos inside the earth would lead to a large deviation from the speed of light for electrons in the atmosphere. This is ruled out unless gauge invariance is broken by the coupling to the Galileon. If this were the case, then neutrinos would go faster than charged leptons inside the earth, leading to too much Cerenkov radiation (pair creation).

Chameleons do not suffer from this problem as they are constant in the atmosphere and in vacuum chambers. This implies that no charged leptons go faster than the speed of light in the atmosphere and in particle accelerators.

The time difference for chameleons is:

$$\frac{\Delta t}{t} = \frac{12\Phi_N^2 m_{\rm Pl}^2}{\beta R_\oplus^2 M^4}(\beta\frac{\Delta R}{R})^3$$

A large time difference is compatible with the tests of the equivalence principle if the coupling scale is very low:

$$M \leq 0.1 \text{ eV}$$

This is a flaw in matter as on can understand M as some cut-off scale for the low energy theory.

For natural values of M, the time difference is negligible and would not be detectable.

If one is really stubborn and insists on having a large time difference for natural values of the coupling M, one can introduce camouflaged chameleons:

$$\frac{1}{2}(\partial\phi)^2 \rightarrow \frac{f(\phi)}{2}(\partial\phi)^2$$

In matter where chameleons are essentially constant, this changes the field normalisation:

$$M \rightarrow M_c = \sqrt{f(\phi_c)}M$$

This allows one to have a large value for the effective M in matter. For these models, the amount of Cerenkov radiation in matter and the time difference from SN1987A are compatible with experimental bounds.

Of course, the most reasonable attitude may be to take a large value of M and therefore to forget any possible Lorentz violation effects due to modified gravity forever!

Conclusion

Scalar fields can modify gravity on large scales and preserve gravity locally.

They may couple to matter non-derivatively and lead to fast fermions.

The only sensible models are the chameleons, and for natural values of the coupling scales, no signal should be detectable (unless chameleons are camouflaged...)