Peut-on violer le principe d'équivalence

Philippe Brax

IPhT Saclay

Gravity is described by General Relativity (GR):

$$S_{\rm EH} = \frac{1}{16\pi G_N} \int d^4x \sqrt{-g} R$$

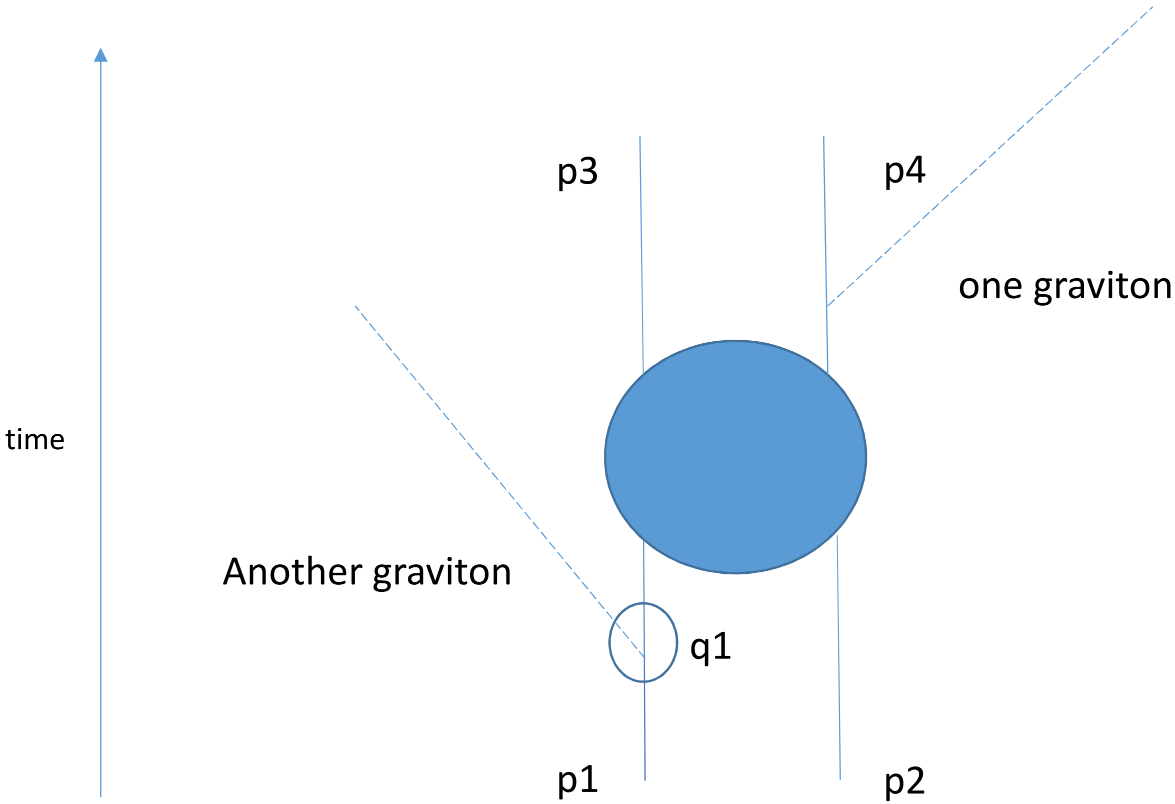
Uniqueness theorem (Weinberg 1965):

GR is the unique Lorentz invariant theory of massless helicity 2 fields

Lorentz invariance implies the weak equivalence principle (Weinberg 1965) for elementary particles.

$$S_m(\psi_i, g_{\mu\nu})$$

Particles couple to a unique metric.



A two body collision between particles

$$\sum_i \epsilon_i q_i p_i^\mu = 0$$

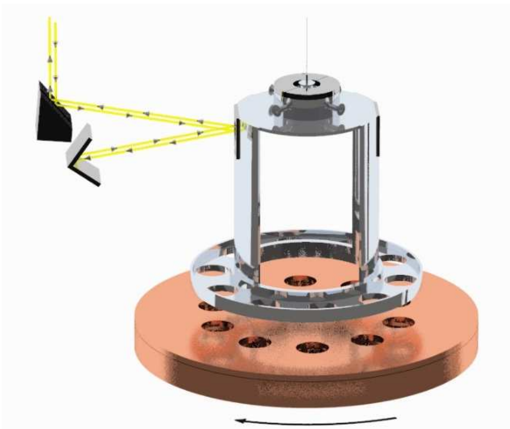
Lorentz invariance of the quantum amplitude

$$\sum_i \epsilon_i p_i^\mu = 0, \qquad q_i = q \equiv 1$$

Conservation of momentum

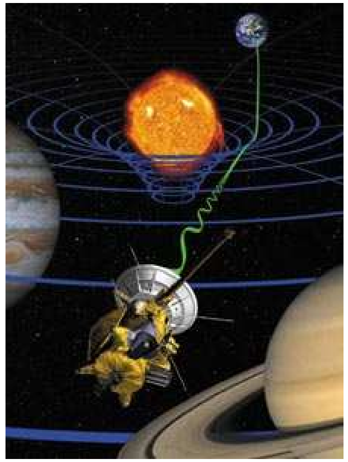
Uniqueness of gravitational charge

GR has been wonderfully tested on many length scales:

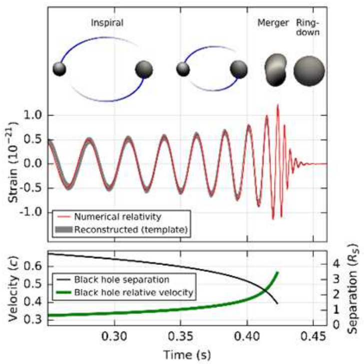


Laboratory experiments (Eotwash) tests of fifth forces and equivalence principle
0.1 mm

Cassini probe test of fifth forces
1 a.u., 150 million km.

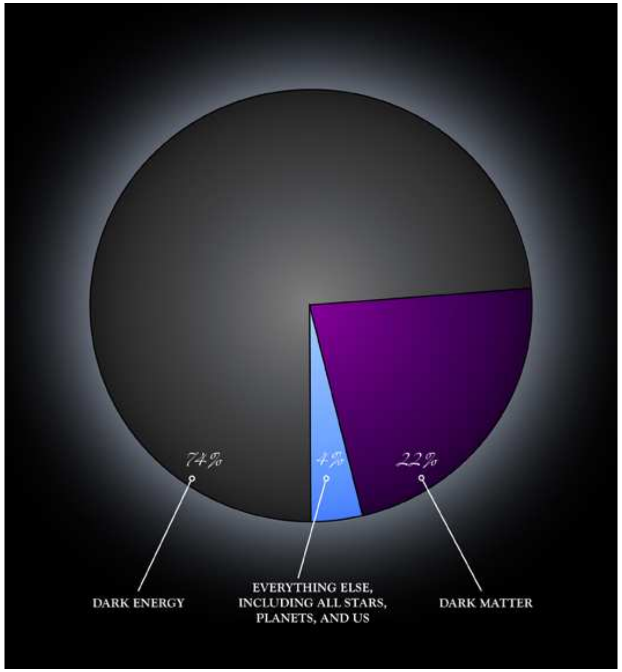


Lunar ranging tests of strong equivalence principle and time variation of Newton's constant,
400 000 km



Gravitational wave emissions from black hole and neutron star mergers
50 Mpc

But GR fails miserably on cosmological scales where both dark matter and dark energy are necessary to explain Baryon Acoustic Oscillations (BAO) or the Cosmic Microwave Background (CMB).



$$S_{\Lambda\mathrm{CDM}} = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}(R-2\Lambda)$$

Cosmological constant

The cosmological constant behaves like a constant and uniform vacuum energy.

The physics of the acceleration of the Universe can be encapsulated using a new ingredient:

a scalar field

Very much like the temperature field in classical field theory. One scalar field is known: the Higgs field.

Why a scalar field? Because cosmology breaks Lorentz to the rotation group only (isotropy of the Universe).

Lorentz invariance can be restored by introducing a scalar field: the Stuckelberg trick

$$t \to t + \pi(\vec{x}, t)$$

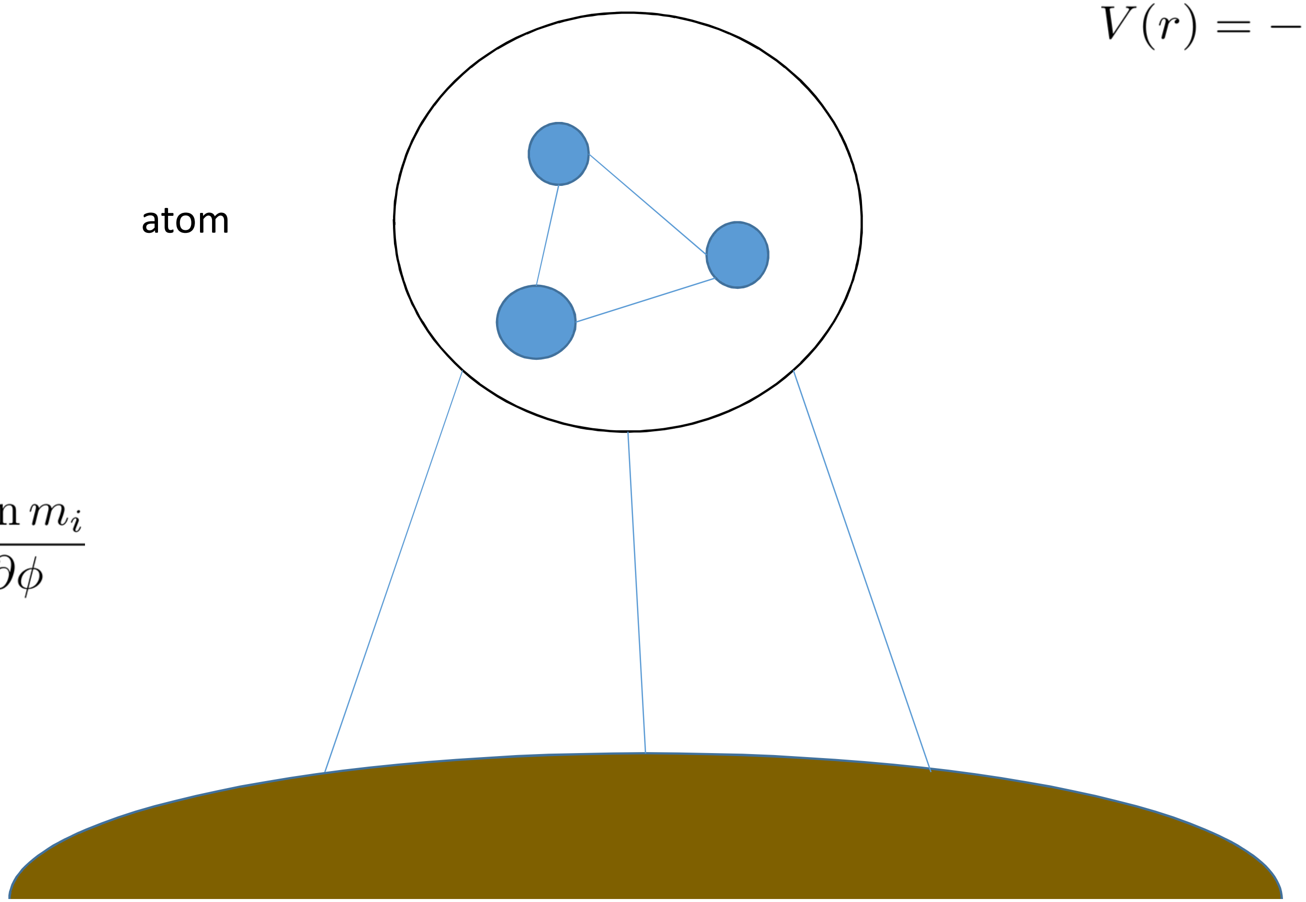
$$\begin{cases} t \to t + \xi(\vec{x}, t) \\ \pi(\vec{x}, t) \to \pi(\vec{x}, t) - \xi(\vec{x}, t) \end{cases}$$

A scalar field can couple to matter, and different types of matter like baryons (quarks) or leptons (electrons) with a different scale. As the mass of protons and neutrons, and subsequently atoms is essentially a function of the QCD energy, quark masses and electromagnetic energy, such a dependence implies that different atoms fall differently in a gravitational field:

$$V(r) = -\frac{G_N m_1 m_2}{r}(1+\alpha_1\alpha_2)$$

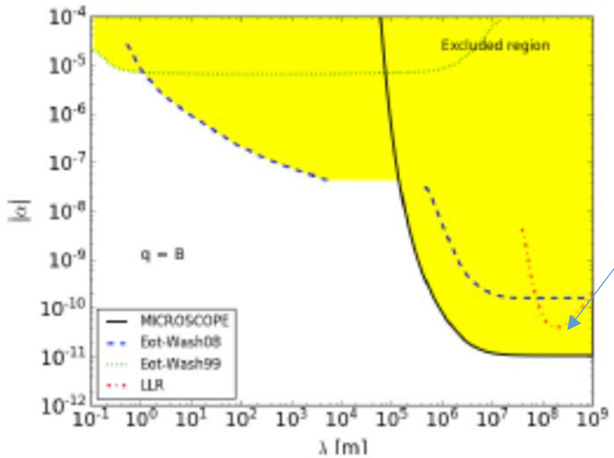
Scalar charges of the interaction bodies.

$$\alpha_i = \frac{m_{\rm Pl}}{\sqrt{2}}\frac{\partial \ln m_i}{\partial \phi}$$



One typical class of models posits that the interaction of the scalar is via the baryonic number:

Strength of the interaction



One order of magnitude improvement

$$\alpha_i = \alpha(\frac{B}{\mu})_i$$

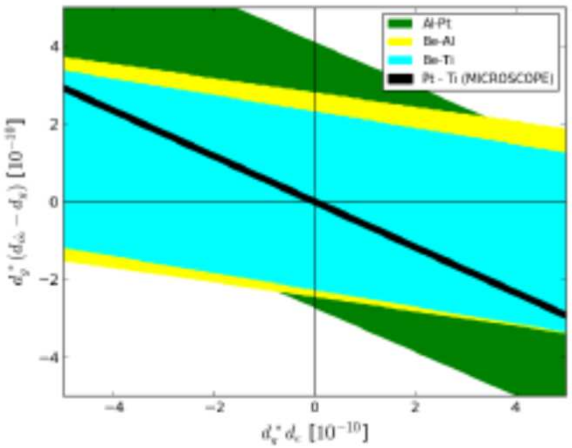
Range of the scalar interaction

$$\eta_{AB} = 2\frac{|a_A - a_B|}{a_A + a_B}$$

$$\eta_{AB} \sim \alpha_E |\alpha_A - \alpha_B|$$

Another type of model, called dilatonic, assumes that the scalar couples differently to the gluons, photons, electrons and quarks u and d.

Very small charges



$$\frac{\delta m_{u,d}}{m_{u,d}} \sim d_{u,d} \frac{\phi}{m_{\rm Pl}}$$

$$\frac{\delta \alpha_{QED,QCD}}{\alpha_{QED,QCD}} \sim d_{e,g} \frac{\phi}{m_{\rm Pl}}$$

$$\alpha_i = d_g^\star + ((\bar{d}_m - d_g)Q_m + d_e Q_e)_i$$

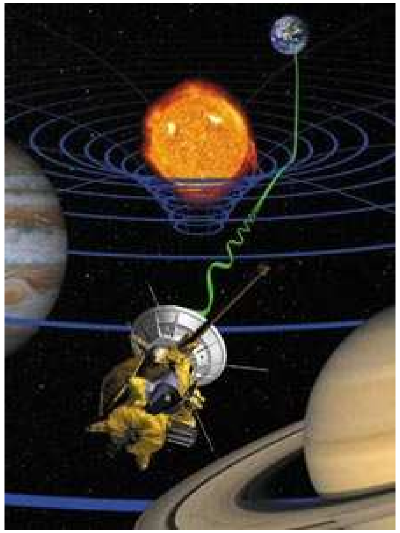
$$Q_m = 0.093 - \frac{0.036}{A^{1/3}} - 1.4 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}}$$

$$Q_e = -1.4 \times 10^{-4} + 7.7 \times 10^{-4} \frac{Z(Z-1)}{A^{4/3}}$$

Plenty of scalar field models which could play a role in the dynamics of the Universe.

LOOPHOLE: one wants long range interactions on cosmological scales

Strong deviations from GR in the solar system?



SCREENING

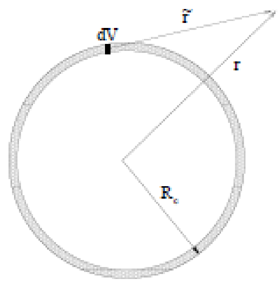
This mechanism is present for certain scalar-tensor theories:

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

Interaction potential leading to the cosmic acceleration

Coupling between scalar and matter preserving the weak equivalence principle

Three mechanisms of screening have been uncovered. The simplest one: the chameleon effect.



Inside a dense body, the range of the new force is so small that no force emanates from the body: the new force is screened.

The range of the new force is extremely small in matter and very large in vacuum. This is the environment dependence of chameleons.

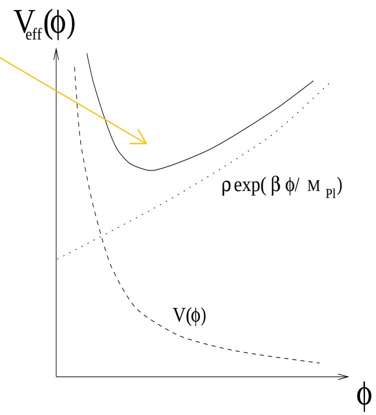
The effect of the environment

When conformally coupled to matter, scalar fields have a matter dependent effective potential:

$$V_{eff}(\phi) = V(\phi) + \rho_m(A(\phi) - 1)$$

Environment dependent minimum

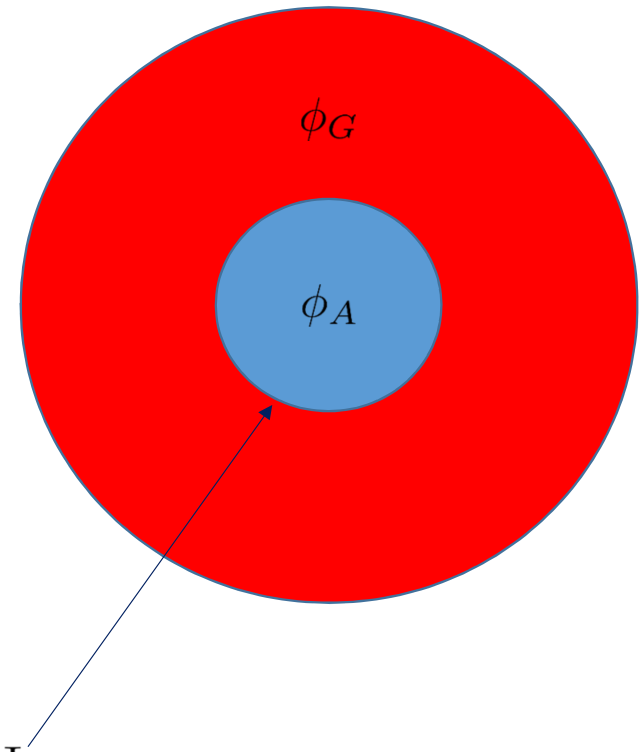
$$\beta(\phi) = m_{\rm Pl}\frac{d\ln A(\phi)}{d\phi}$$



Chameleon

Chameleons:

The screening criterion for an object BLUE embedded in a larger region RED expresses the fact that the Newtonian potential of an object must be larger than the variation of the field:



Φ_A Newton's potential at the surface

Scalar charge: $$Q_A = \frac{|\phi_G - \phi_A|}{2m_{\rm Pl}\Phi_A}$$

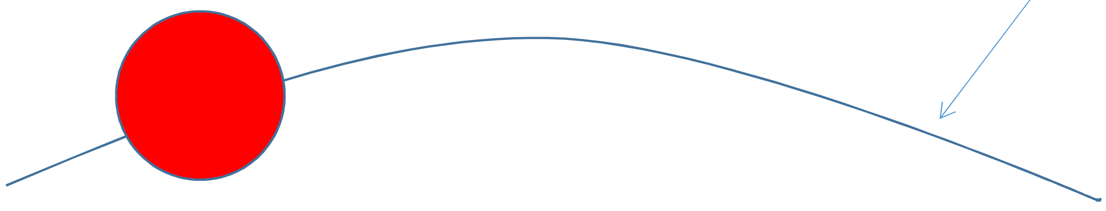
"small" objects are not screened

$$Q_A \leq \beta_G$$

Screening criterion

Only three types of screening:

Trajectories due to gravity + scalar

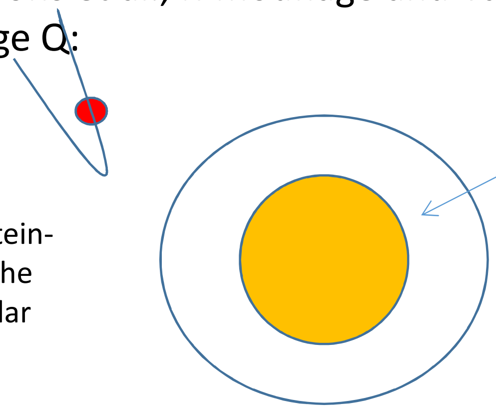


Chameleons: $Q \ll \beta$

$$\ddot{X} = -\nabla\Phi_N - Q\nabla\phi_{\rm ext}$$

Unlike chameleons et al., K-mouflage and Vainshtein do not affect the charge Q:

$Q = \beta$

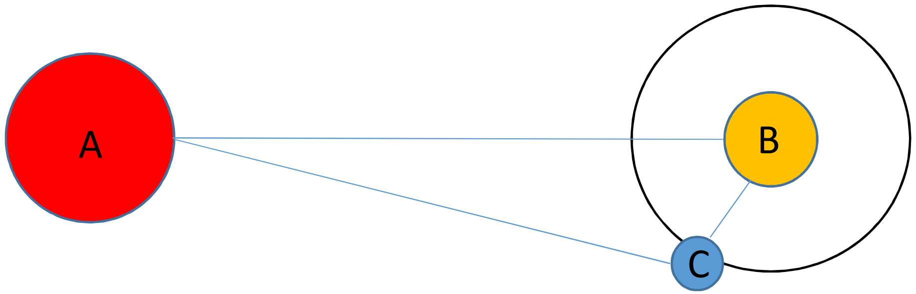


$\nabla\phi_{\rm ext} \ll 2\beta\nabla\Phi_N$

Outside the Vainshtein-Kmouflage radius, the object feels the scalar force

$\nabla\phi_{\rm ext} = 2\beta\nabla\Phi_N$ outside the Vainshtein-Kmouflage radius

VIOLATION OF THE STRONG EQUIVALENCE PRINCIPLE



$\eta_{\mathrm{moon-earth}} \leq 10^{-13}$

$$\eta_{BC} \equiv \left|\frac{a_C - a_B}{a_C + a_B}\right|$$

Lunar ranging experiment

This tests the strong equivalence principle: the universality of free fall for self-gravitating objects.

$$\eta_{AB} = Q_E |Q_A - Q_B|$$

$$Q_{A,B} = \frac{\phi_\infty}{2m_{\rm Pl}\Phi_{A,B}}$$

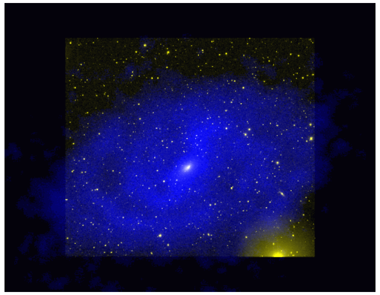
Screened scalar theories violate the strong equivalence principle as their coupling depends on their Newtonian potential.

$$Q_\oplus \lesssim 10^{-6}$$

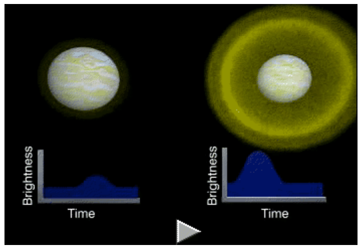
The stringest bound on the violation of the strong equivalence by the LLR experiment

Astrophysical tests:

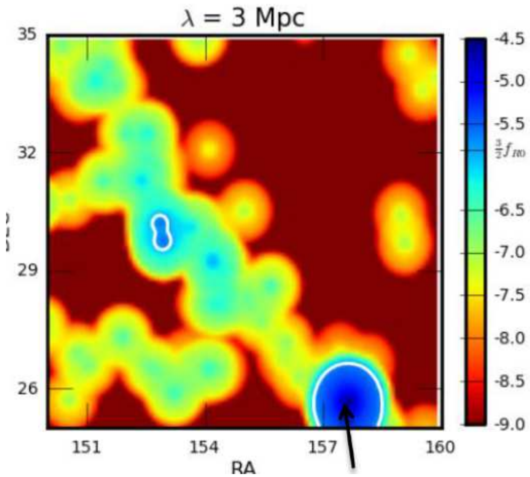
Motion of screened stars different from unscreened HI gas in unscreened dwarf galaxies.



Distance indicators for cepheids and TRGB stars in screened and unscreened dwarf galaxies are different as their luminosities vary



$\Phi_N \sim 10^{-7}$



$\xi = 10^{-6}$

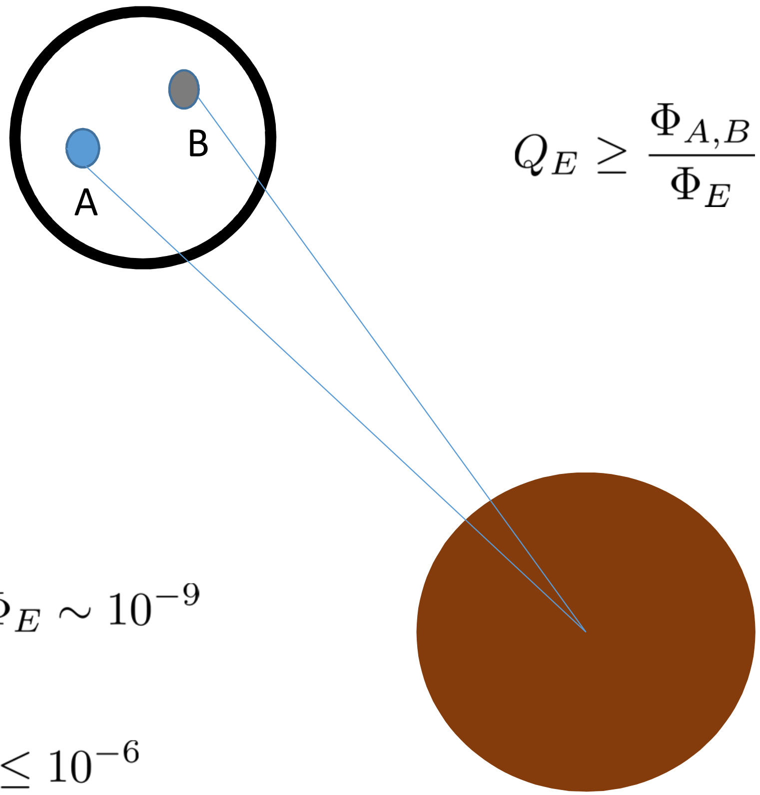
screened

SDSS catalogue, within 200 Mpc, scalar range 1 Mpc

No effects measured so far: bound on the range of the scalar interaction.

A Gedanken Satellite Experiment

A and B falling towards E



$$Q_E \geq \frac{\Phi_{A,B}}{\Phi_E}$$

If A and B are not screened and couple differently to the scalar:

$$\eta_{AB} = Q_E |\beta_A - \beta_B|$$

$$\Phi_A \sim 10^{-26}, \quad \Phi_E \sim 10^{-9}$$

$$10^{-17} \leq Q_E \leq 10^{-6}$$

$$10^{-17} \leq \eta_{AB} \leq 10^{-14}$$

Microscope bound

Conclusion

- It is possible to violate the weak equivalence principle a the microscopic and macroscopic levels if a new interaction mediated by a scalar field is present and couples in a composition dependent manner to matter. The strength of the coupling must be extremely small.

- The cosmic acceleration suggests that the gravitational physics ought to be modified on large cosmological scales with an order one effect. This is incompatible with solar system tests of gravity unless the cosmological effects are screened locally. This allows for order one effects for tiny objects like the microscope test masses. This may lead a violation of the equivalence principle aboard Microscope.