# Screening mechanism and dark coupling

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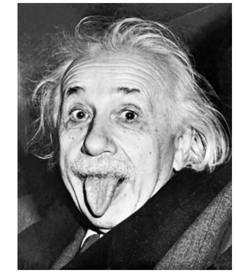
# General relativity

- Why do we believe general relativity?



  - Observational point of view

    GR is tested to very high accuracy by solar system experiments and pulsar timing measurements

    C.Will gr-qc/0510072

  - Theoretical point of view

    GR is the unique metric theory in 4D that gives second order differential equations

# FIFTH FORCE

FIFTH FORCE ENERGY IS THE BUILDING BLOCK ON WHICH ALL LIFE IS CREATED AND IS THE ESSENCE OF LIFE ITSELF. FIFTH FORCE IS IN FACT MATTER BUT IT CANNOT BE SEEN AND THIS MATTER IS THE NATURE OF THE PRIME. OUT OF ALL THE ENERGIES IN THE UNIVERSE FIFTH FORCE IS THE MOST POWERFUL ENERGY OF ALL BECAUSE IT IS IN EVERY LIFE THING AND IT IS IN EVERY LIFE BEING WHETHER THEY ARE OF THE HUMAN RACE OR AN ALIEN RACE LIVING ON A PLANET IN A FAR AND DISTANT GALAXY IN OUR UNIVERSE OR IN A PARALLEL UNIVERSE LIGHT YEARS WAY.

NEW WEBSITE COMING SOON...

# Brans-Dicke theory

- Action

$$S = \int d^4x \left( \psi R - \frac{\omega_{BD}}{\psi} (\nabla \psi)^2 + V(\psi) \right) \qquad V \sim H_0^2 M_{pl}^2$$

f(R) gravity: $\omega_{BD} = 0$

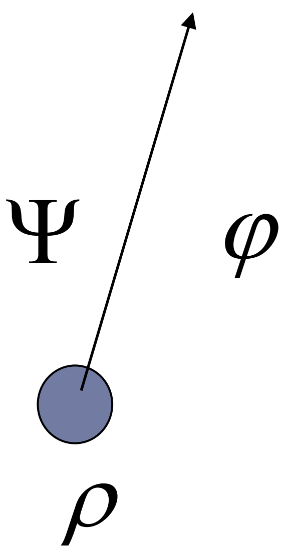
quasi-static approximations (neglecting time derivatives)

$$ds^2 = -(1+2\Psi)dt^2 + a(t)^2(1-2\Phi)d\vec{x}^2 \quad \psi = \psi_0 + \varphi$$

$$(3+2\omega_{BD})\nabla^2\varphi = -8\pi G\rho$$

$$\nabla^2\Psi = 4\pi G\rho - \frac{1}{2}\nabla^2\varphi$$

$$\Phi - \Psi = -\varphi$$



# Constraints on BD parameter

- Solutions

$$(3+2\omega_{BD})\nabla^2\varphi = -8\pi G\rho$$

$$\nabla^2\Psi = -4\pi G\left(\frac{4+2\omega_{BD}}{3+2\omega_{BD}}\right)\rho, \quad G_{eff} = \left(\frac{4+2\omega_{BD}}{3+2\omega_{BD}}\right)G$$

$$\Psi = \frac{2+\omega_{BD}}{1+\omega_{BD}}\Phi \equiv \gamma^{-1}\Phi$$

- PPN parameter

$$\gamma = \frac{1+\omega_{BD}}{2+\omega_{BD}}$$

$$\gamma - 1 = (2.1 \pm 2.3)\times 10^{-5} \qquad \omega_{BD} \geq 40,000$$

*This constraint excludes any detectable modifications in cosmology*

# How we suppress fifth force (1)

- Break equivalent principle

$$\alpha = \sqrt{\frac{1}{3+2\omega_{BD}}}$$

Einstein frame

$$S_E = \int d^4x \left[ \sqrt{-\bar{g}} \left( \bar{R} - \frac{1}{2}(\bar{\nabla}\phi)^2 + \bar{V}(\phi) \right) + L_m[e^{-\alpha\phi/M_{pl}} \bar{g}_{\mu\nu}] \right]$$

Remove coupling to baryons (Interacting dark energy)

Wetterich , Amendora Baldi's talk

$$S_E = \int d^4x \left[ \sqrt{-\bar{g}} \left( \bar{R} - \frac{1}{2}(\bar{\nabla}\phi)^2 + \bar{V}(\phi) \right) + L_{DM}[e^{-\alpha\phi/M_{pl}} \bar{g}_{\mu\nu}] + L_{baryon}[\bar{g}_{\mu\nu}] \right]$$

Jordan frame

$$S = \int d^4x \left( \psi R - \frac{\omega_{BD}}{\psi} (\nabla\psi)^2 + V(\psi) + L_{DM}[g_{\mu\nu}] + L_{baryon}[f(\psi) g_{\mu\nu}] \right)$$

the coupling compensates the fifth force acting on baryons (however, interpretation of observations is non-trivial)

Deruelle, Sasaki 1012.5386

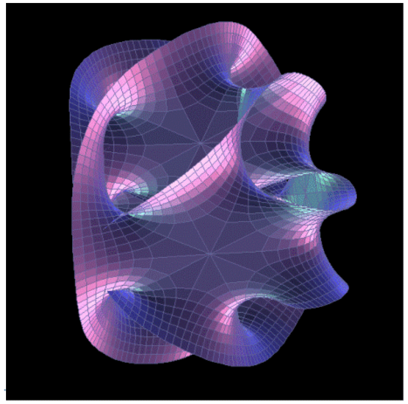
# How to suppress the fifth force (2)

$$S = \int d^4x \left( \psi R - \frac{\omega_{BD}(\psi)}{\psi} (\nabla \psi)^2 + V(\psi) + L_m[g] \right)$$

GR is recovered if (i) the mass is large $V'' \rightarrow \infty$ or

(ii) the kinetic term is large $\omega_{BD} \rightarrow \infty$

These limits should be realised in environmentally (density) dependent way to avoid the recovery of GR on all scales

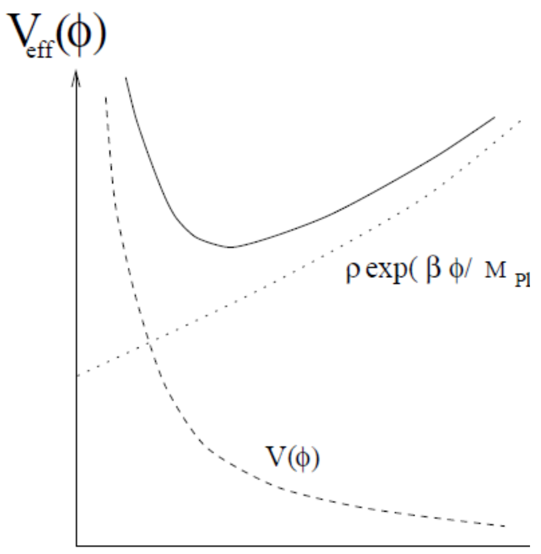
# Chameleon/symmetron/dilaton

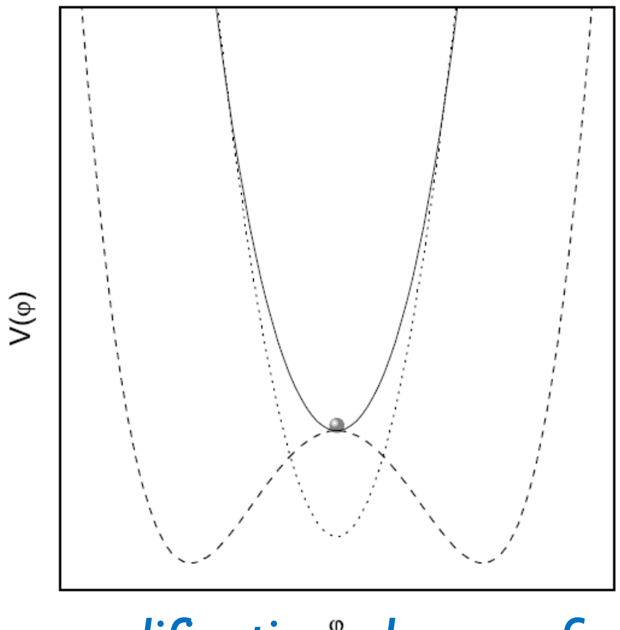
- Einstein frame

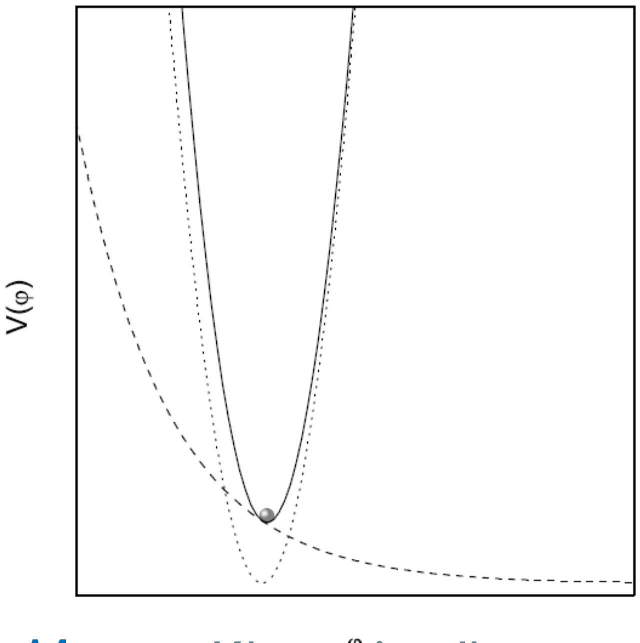
Talks by Brax, Davis, Khoury, Li, Hu,..

$$S_E = \int d^4x \left[ \sqrt{-\bar{g}} \left( \bar{R} - \frac{1}{2} (\bar{\nabla}\phi)^2 + \bar{V}(\phi) \right) + L_m [A(\phi)^2 \bar{g}_{\mu\nu}] \right]$$

$$\Box\varphi = V_{eff}(\varphi), \quad V_{eff}(\varphi) = \bar{V}(\varphi) - (A(\varphi) - 1)\rho$$




*Local tests forbid the modification above a few Mpc*

Khoury's talk

# How to suppress the fifth force (3)

- Vainshtein mechanism

  originally discussed in massive gravity

  rediscovered in DGP brane world model

  linear theory $\omega_{BD} = 0$

$$3\nabla^2 \varphi = -8\pi G \rho$$

$$\nabla^2 \Psi = 4\pi G \rho - \frac{1}{2}\nabla^2 \varphi$$

  even if gravity is weak, the scalar can be non-linear

Talks by Hu, Hui

$$3\nabla^2 \varphi + r_c^2 \left\{ \left( \nabla^2 \varphi \right)^2 - \partial_i \partial_j \varphi \, \partial^i \partial^j \varphi \right\} = 8\pi G a^2 \rho \qquad r_c \sim m^{-1} \sim H_0^{-1}$$

# Vainshtein mechanism

- Spherically symmetric solution for the scalar

$$\frac{d\varphi}{dr} = \frac{r_g}{r^2}\Delta(r), \quad \Delta(r) = \frac{2}{3}\left(\frac{r}{r_V}\right)^3\left(\sqrt{1+\left(\frac{r_V}{r}\right)^3} - 1\right) \quad r_V = \left(\frac{8r_c^2 r_g}{9}\right)^{\frac{1}{3}}, \quad r_g = 2GM$$

$r_g$ $\qquad$ $r_V$ $\qquad$ $r_c$


4D Einstein:

$$\Phi = \frac{r_g}{2r} + \sqrt{\frac{r_g r}{2r_c^2}},$$

$$\Psi = -\frac{r_g}{2r} + \sqrt{\frac{r_g r}{2r_c^2}}$$

4D BD:

$$\Phi = \frac{r_g}{2r}\left(\frac{2}{3}\right),$$

$$\Psi = -\frac{r_g}{2r}\left(\frac{4}{3}\right)$$

2.95km $\qquad$ 0.1 kpc $\qquad$ 3000Mpc $\quad$ for the Sun

# Solar system constraints

- The fractional change in the gravitational potential $\varepsilon = \frac{\delta\Psi}{\Psi}$

  The anomalous perihelion precession

$$\delta\phi = \pi r \frac{\partial}{\partial r}\left[ r^2 \frac{\partial}{\partial r}\left(\frac{\varepsilon}{r}\right)\right]$$

The vainshtein radius is shorter for a smaller object

Lunar laser ranging: the Erath-moon distance $r_{E-M} = 4.1\times 10^5 \mathrm{km}$

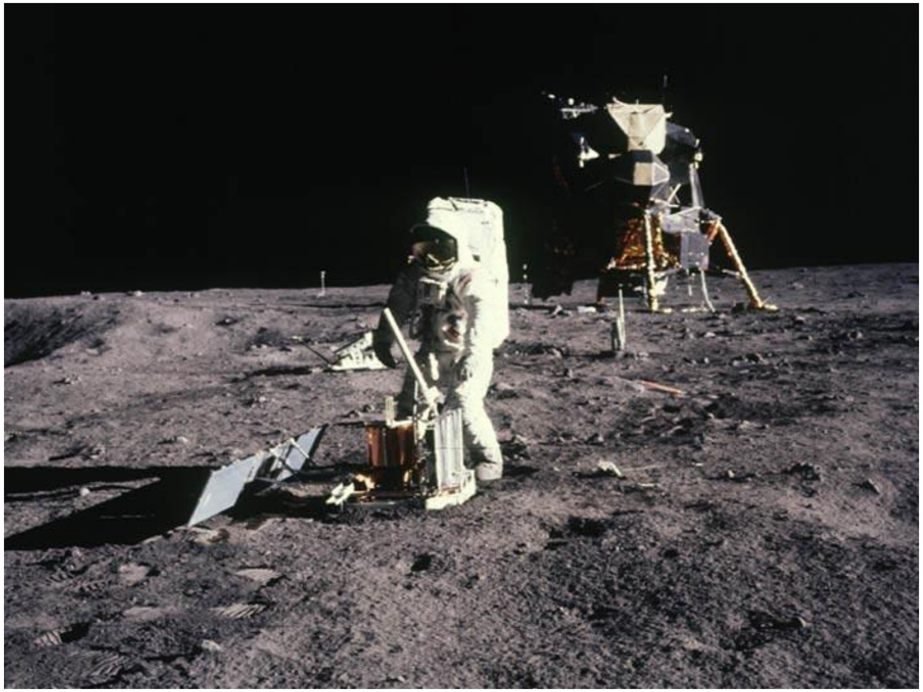
$$\delta\phi = \frac{3\pi M_{pl}}{4}\left(\frac{r_{E-M}{}^3}{8\pi r_c^2 M_\oplus}\right)^{1/2} < 2.4\times 10^{-11}, \quad r_{E-M} << r_V$$

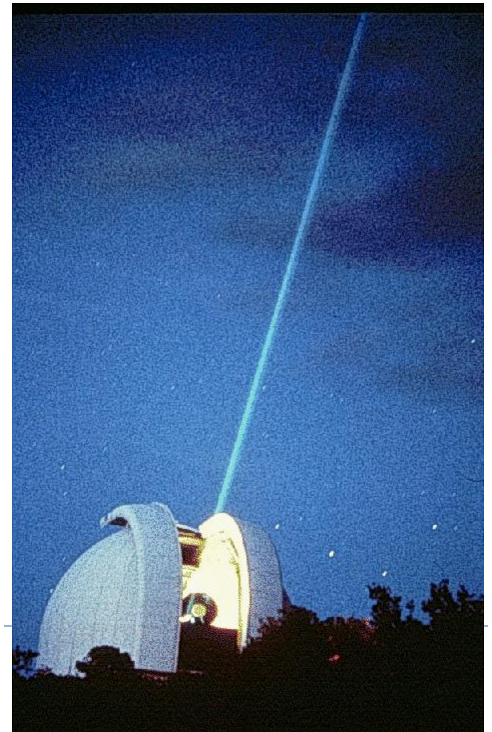
$$\Rightarrow \quad r_c > 10^{60} M_{pl}^{-1} \sim H_0^{-1}$$

Dvali et.al 0212069
Burrgae & Seery 1005.1927

*Local tests are beginning to exclude the acceleration from new physics*


Lunakhod 1
Lunakhod 2
Apollo XV
Apollo XIV
Apollo XI
SCIENCEphotoLIBRARY





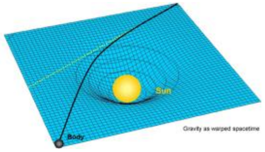
# Observational implications (1) equivalence violation

- (1) Equivalence violation

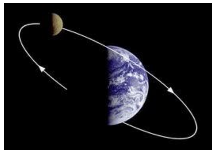
  interacting dark energy model (Einstein frame)

  modified gravity models (Jordon frame)

$$k^2(\Psi+\Phi) = -4\pi G a^2 \Sigma(a,k)\rho_m\delta_m$$




$$k^2\Psi = -4\pi G a^2 \mu(a,k)\rho_m\delta_m$$



BD

$$\Sigma(a,k) \simeq 1$$

$$\mu(a,k) \simeq \frac{2(2+\omega_{BD})}{3+2\omega_{BD}}$$

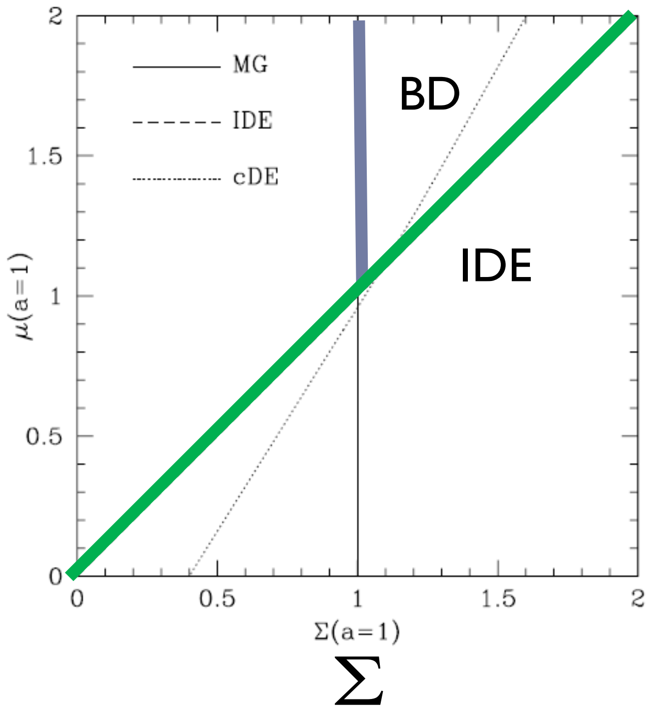
IDE

$$\Sigma = \mu$$

$$(\Phi = \Psi)$$

*A combination of weak lensing and RSD can break the degeneracy (i.e. Eg parameter)* Reyes's talk

$\mu$

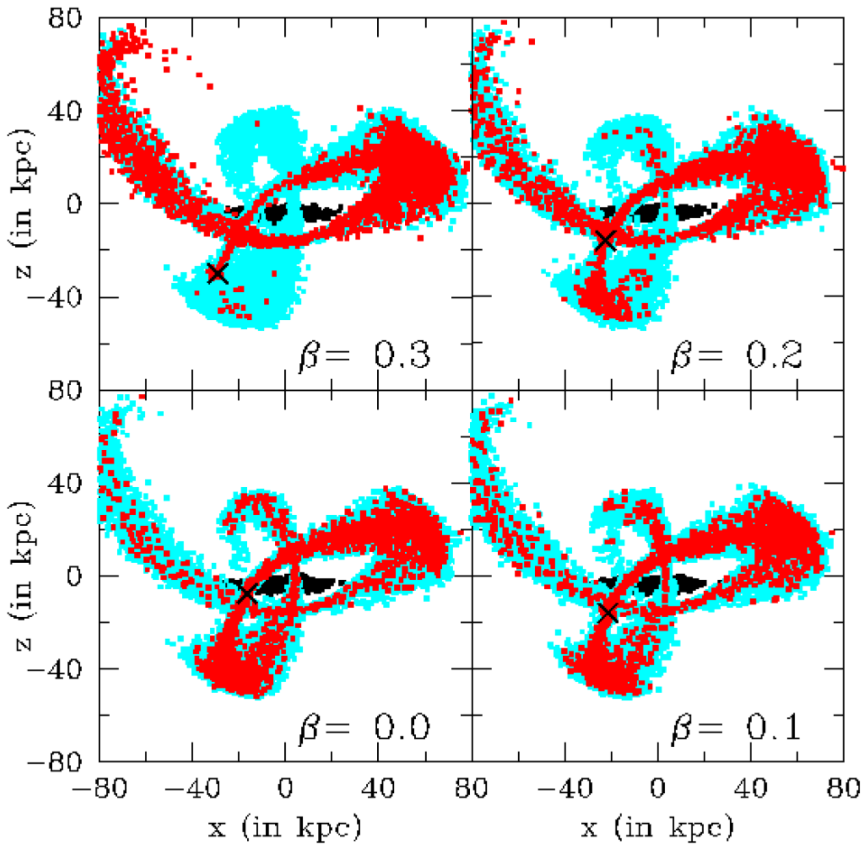



$\Sigma$

# Observational implications (1) equivalence violation

- Tidal disruption of satellite galaxies

Kesden, Kamionkowski
astro-ph/0608095




An enhanced force acting on DM redistribute stars from the leading stream to the trailing stream

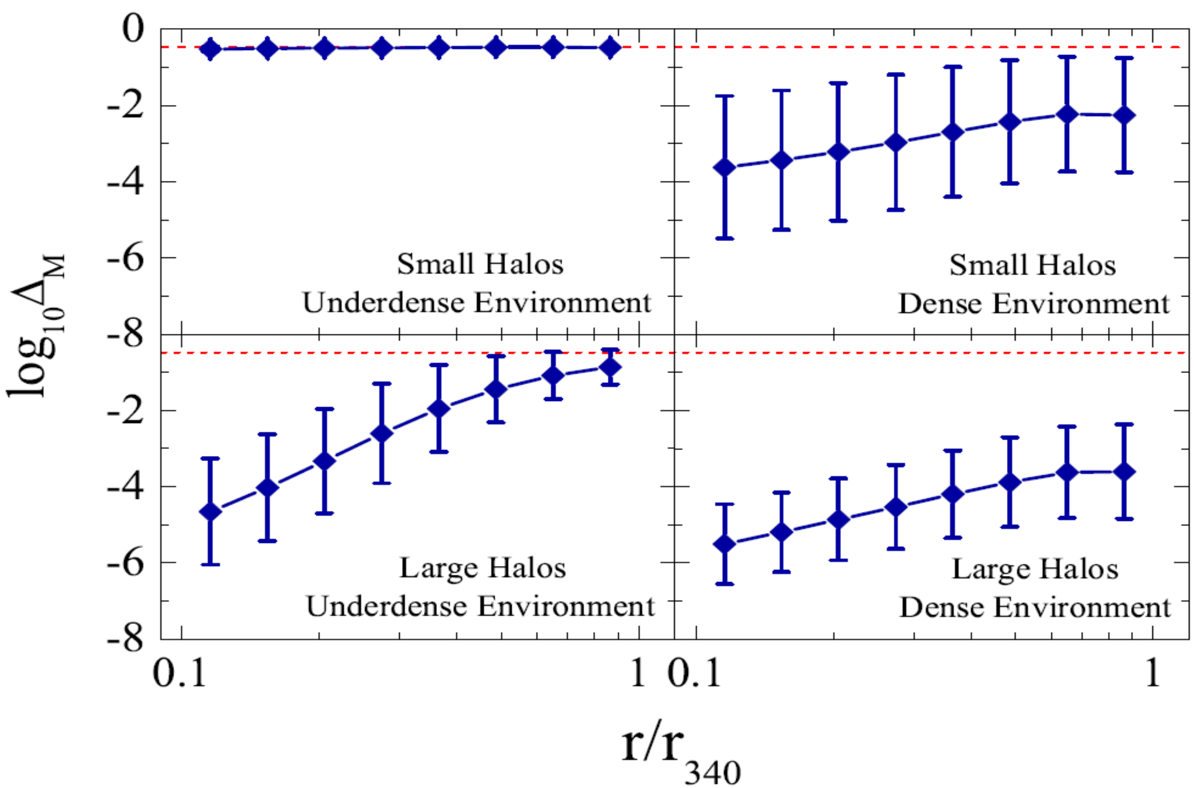
10% enhancement of DM force would be excluded

# Observational implication (2) Environmental screening

- (2) Environmental dependent screening   Zhao's talk

  dark matter halos   Schmidt 1003.0409, Zhao, Li Koyama 1011.1257
  Li, Zhao, Koyama 1111.2602

  screening depends on environment and halo mass




$$\Delta_M(r) = \frac{d\Phi(r)/dr}{d\Phi_+(r)/dr} - 1$$

$$\Phi_+ \equiv (\Phi + \Psi)/2$$

difference between lensing and dynamical mass cf. f(R) gravity

$$\Delta_M = [0 : 1/3]$$

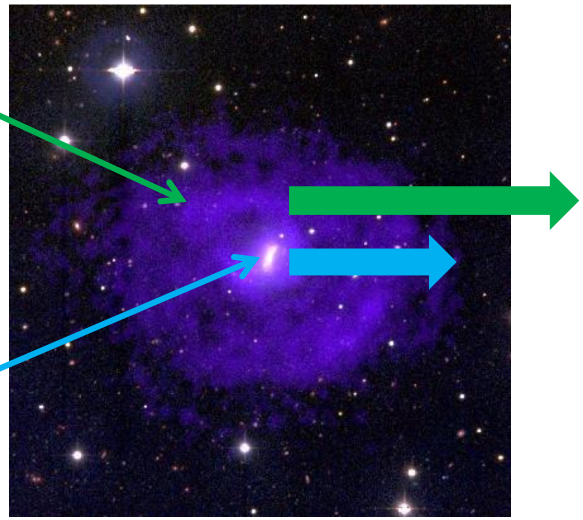
# Observational implication (2) Environmental screening

- Apparent violation of equivalent principle

Hui, Nicolis, Stubbs 0905.2966
Jain & VanderPlas 1106.0065

HI gas: unscreened

Stellar disk: screened



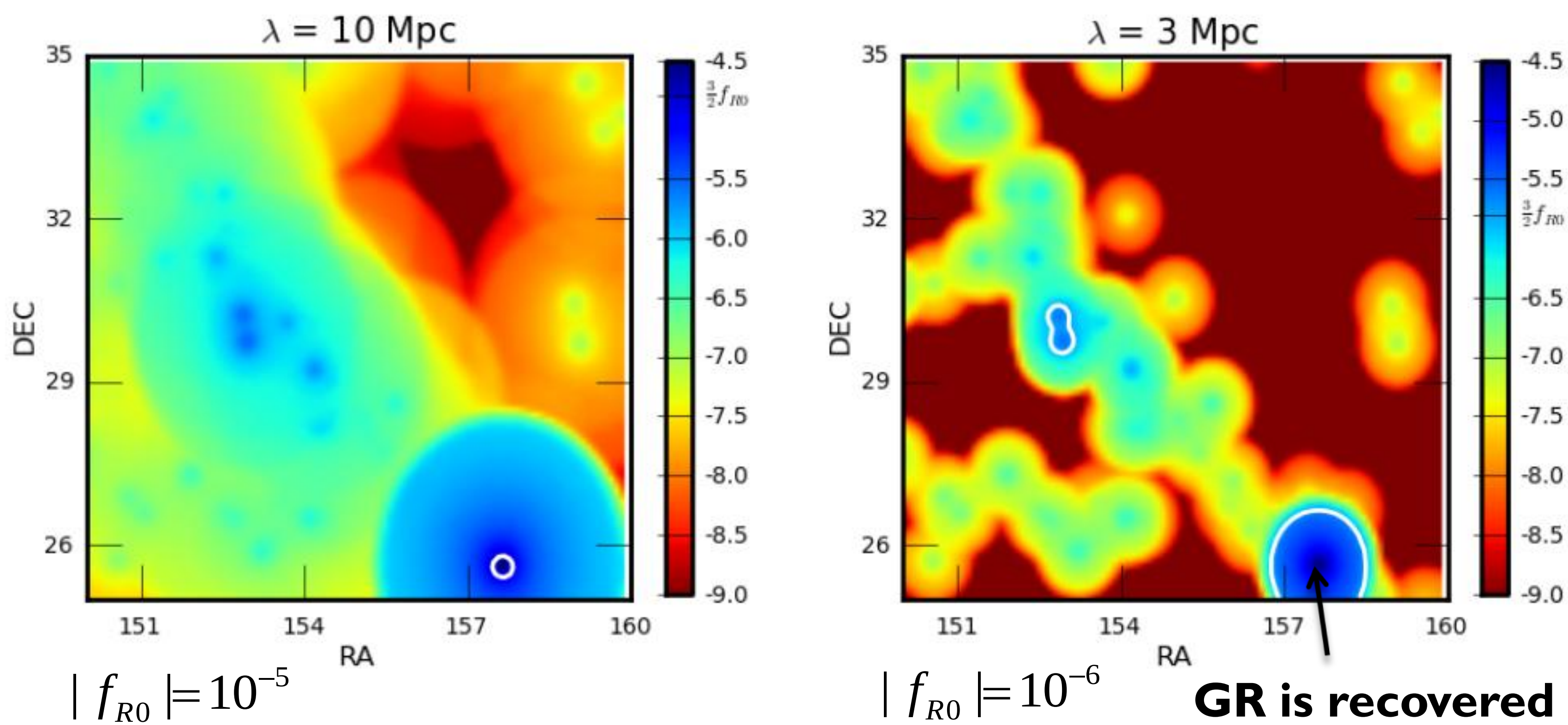
  - The rotation curve of HI gas is enhanced compare with stars
  - The stellar disk is displaced from the HI gas disk

*If we can use dwarf galaxies in voids that have shallower potentials than the Milky way, we can go beyond local tests*

# Creating a screening map

- It is essential to find places where GR is not recovered
  - Small galaxies in underdense regions
  - SDSS galaxies within 200 Mpc

Cabre, Vikram, Zhao, Jain, KK 1204.6046



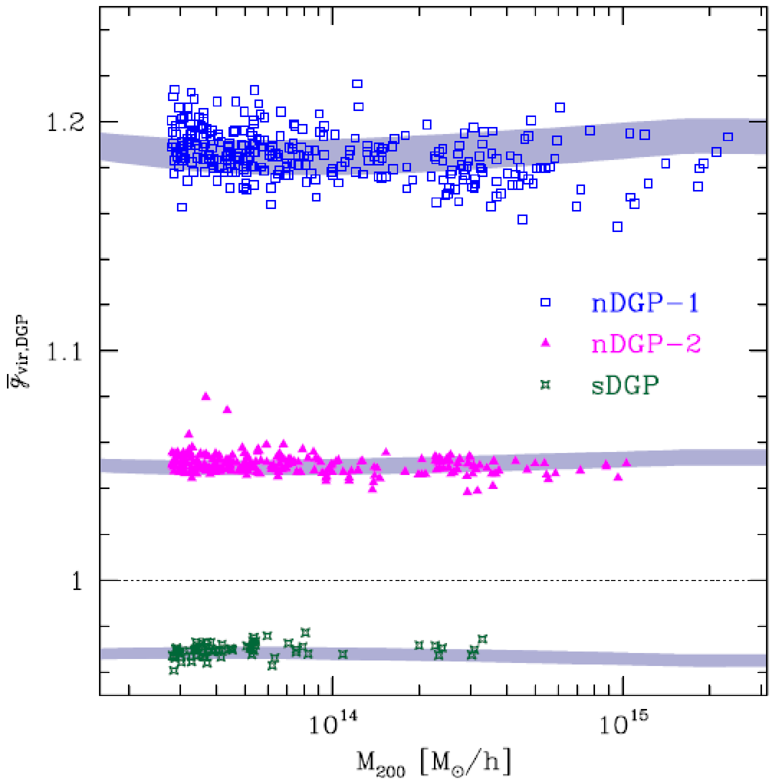

$|f_{R0}| = 10^{-5}$ $|f_{R0}| = 10^{-6}$

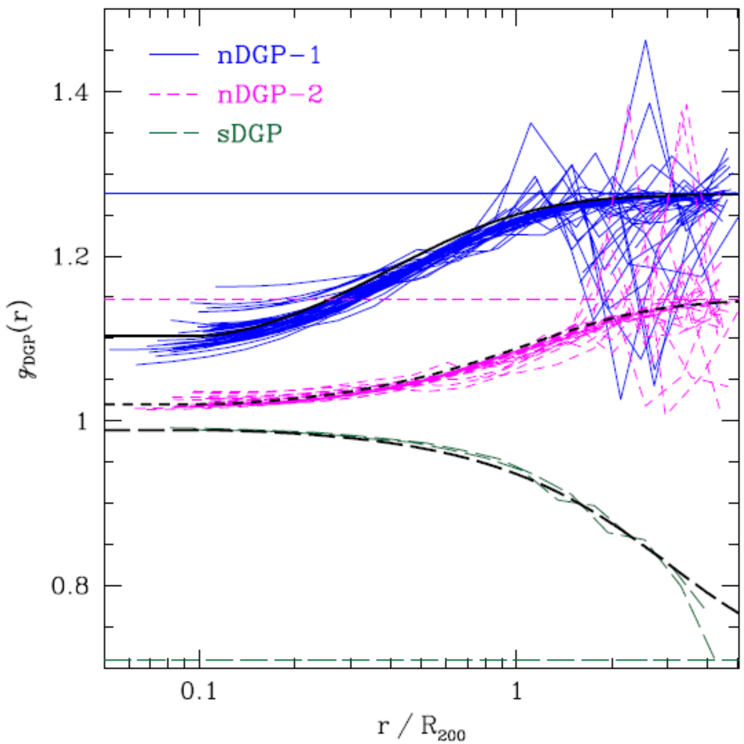
# Observational implication (3) Vainshtein mechanism

- (3) Vainshtein mechanism

  dark matter halos Schmidt 1003.0409

  Screening depends on environment and mass very weakly



# Observational implication (3) Vainshtein mechanism

- Morphology dependence

The non-linear term vanishes for 1D plane wave

$$\left(\nabla^2\varphi\right)^2 - \partial_i\partial_j\varphi\,\partial^i\partial^j\varphi$$

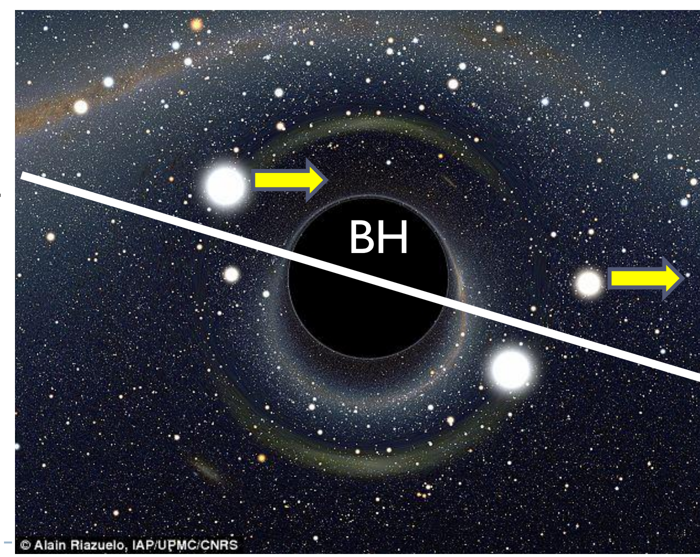
*screening is weak in filaments*

- Apparent equivalent principle violation

Hui, Nicolis 1201.1508

stars can feel an external field generated by large scale structure but a black hole does not due to no hair theorem    Hui's talk

*central BH lag behind stars*



# Observational implication (3) Vainshtein mechanism

- Non-superposition Hiramatsu, Hu, KK, Schmidt

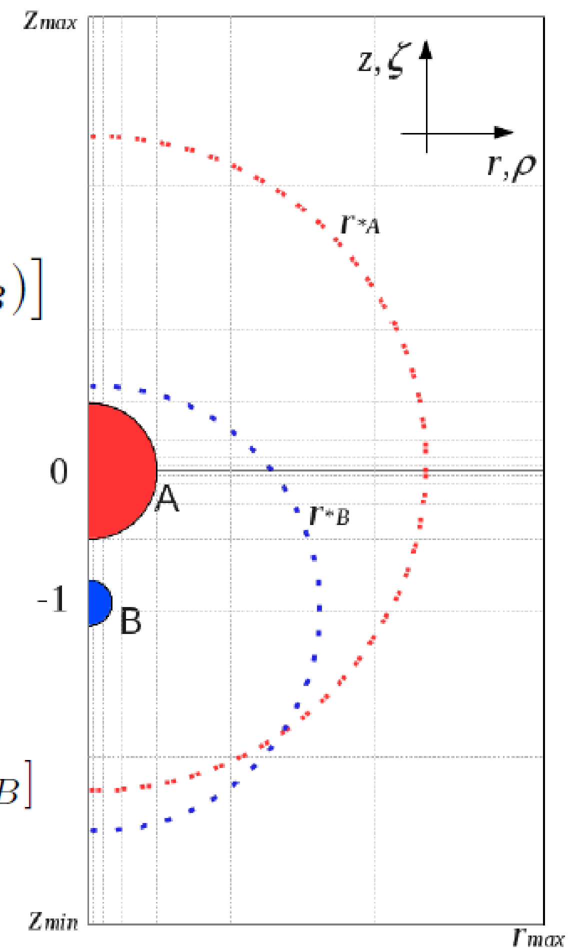
$$\nabla^2\phi = g(a)a^2\left(8\pi G\delta\rho - N[\phi,\phi]\right)$$

$$N[\phi_A,\phi_B] = \frac{r_c^2}{a^4}\left[(\nabla^2\phi_A\nabla^2\phi_B - (\nabla_i\nabla_j\phi_A)(\nabla^i\nabla^j\phi_B)\right]$$

Two body problem (cf. Earth-moon)

$$\phi = \phi_A + \phi_B + \phi_\Delta$$

$$\nabla^2\phi_\Delta + N[\phi_\Delta,\phi_\Delta] + 2N[\phi_A+\phi_B,\phi_\Delta] = -2N[\phi_A,\phi_B]$$



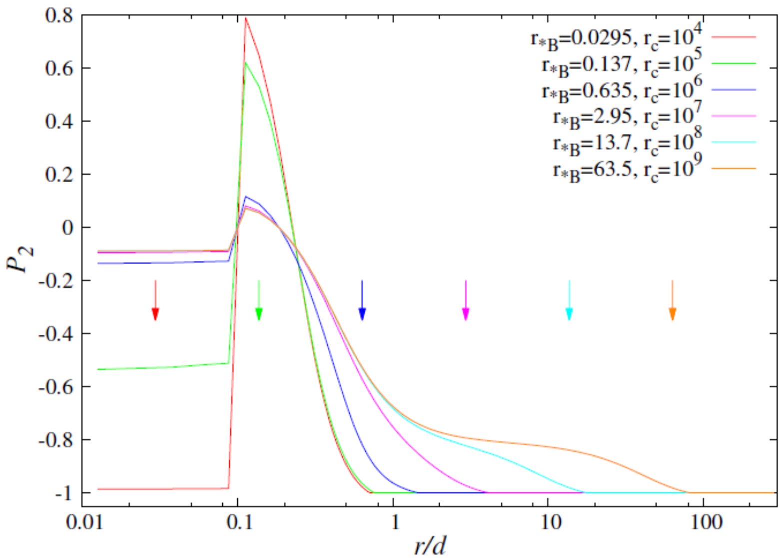
# Observational implication (3) Vainshtein mechanism

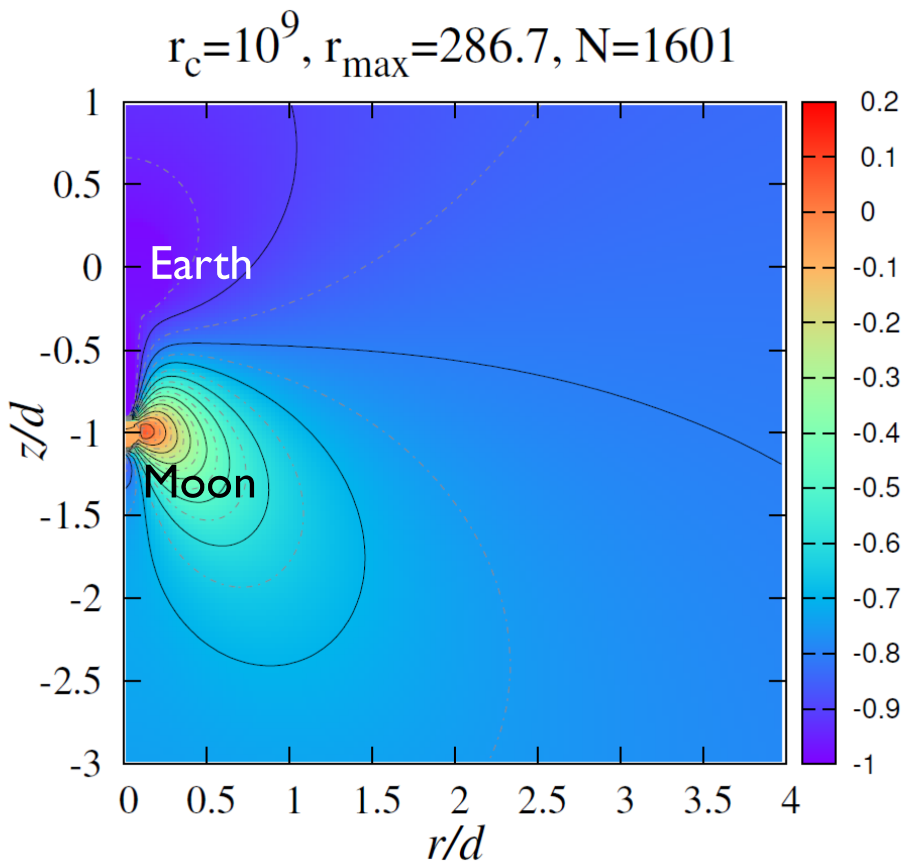
- Near a small body B (moon)

$$\nabla^2\phi_\Delta = -\nabla^2\phi_A + O(\sqrt{M_A/M_B})$$

the interference term cancels the second derivative of the field from the large body (Earth)

$$P_2 = \frac{\nabla^2\phi_\Delta + \nabla^2\phi_A}{|\nabla^2\phi_\Delta| + |\nabla^2\phi_A|}$$

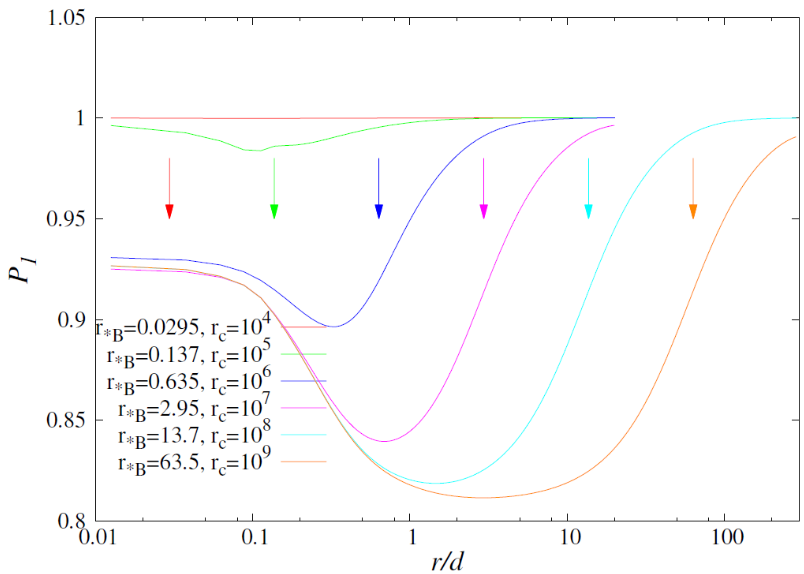


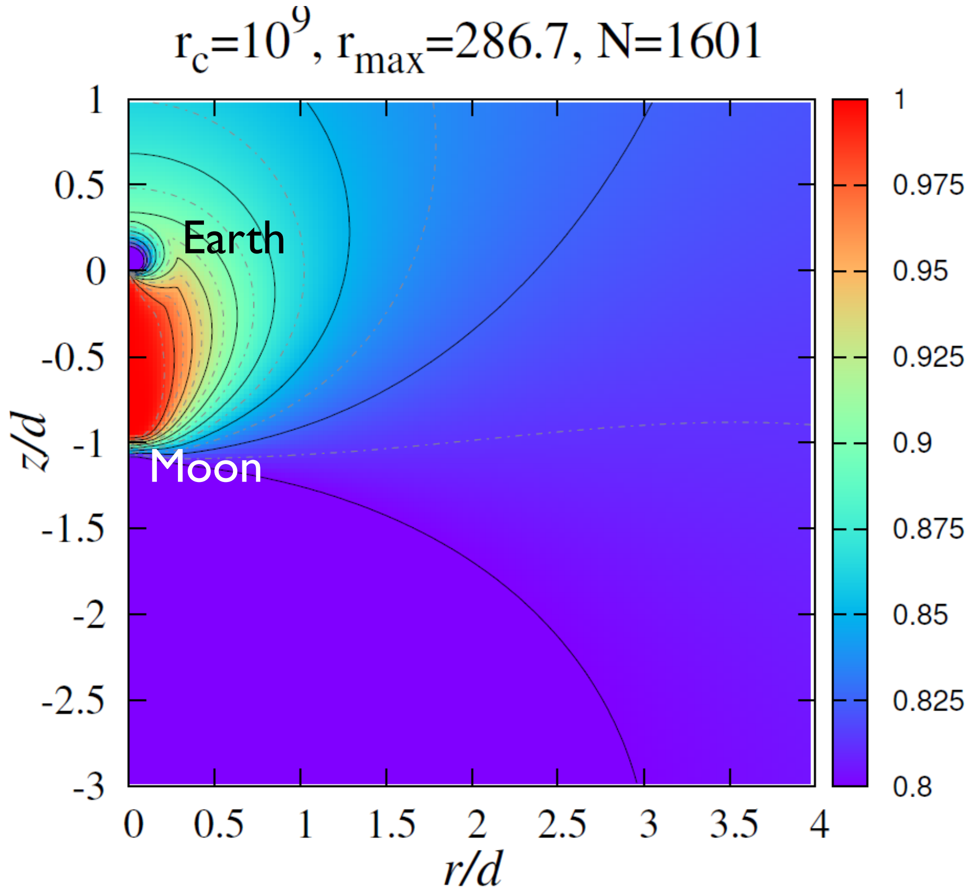



# Observational implication (3) Vainshtein mechanism

- Effects on the first derivative (force) is small

$$P_1 = \frac{|\nabla\phi_\Delta + \nabla\phi_A|}{|\nabla\phi_\Delta| + |\nabla\phi_A|}$$




*There is a 5-10% effect on the fifth force from the interference term*

# Challenge for simulations

- Screening mechanism

governed by a non-linear Poisson equation

$$\nabla^2\phi = 4\pi G A(\phi)\rho + V'(\phi) + N[\partial\phi, \partial^2\phi]$$

*no superposition rule*

Oyaizu et.al, Schmidt et.al.

it is not possible to separate long and short range forces

need to solve the non-linear Poisson equation on a mesh

MLAPM

Li, Zhao 0906.3880, Li, Barrow 1005.4231
Zhao, Li, Koyama 1011.1257

ECOSMOG (based on RAMSES)

Li, Zhao, Teyssier, Koyama 1110.1379
Jennings et.al. 1205.2698, Li et.al. 12064317
Brax et.al. 1206.3568

***ECOSMOG-Vainshtein simulations are underway Li, Zhao, Koyama***

Schimidt 0905.0858, 0910.0235 Chan & Scoccimarro 0906.4548

# Conclusion

- Modification of GR

  generally introduce the fifth force, which should be screened

  1) break equivalence principle and remove coupling to baryons

     Einstein frame - interacting dark energy models

  2) Environmentally (density) dependent screening

     Chameleon/Symmetron/dilaton models

  3) Vainshtein mechanism

     massive gravity, Galileon models, braneworld models

  Non-linearity of the Poisson equation for the fifth force leads to rich phenomenology