Non-linear structure formation in modified gravity models

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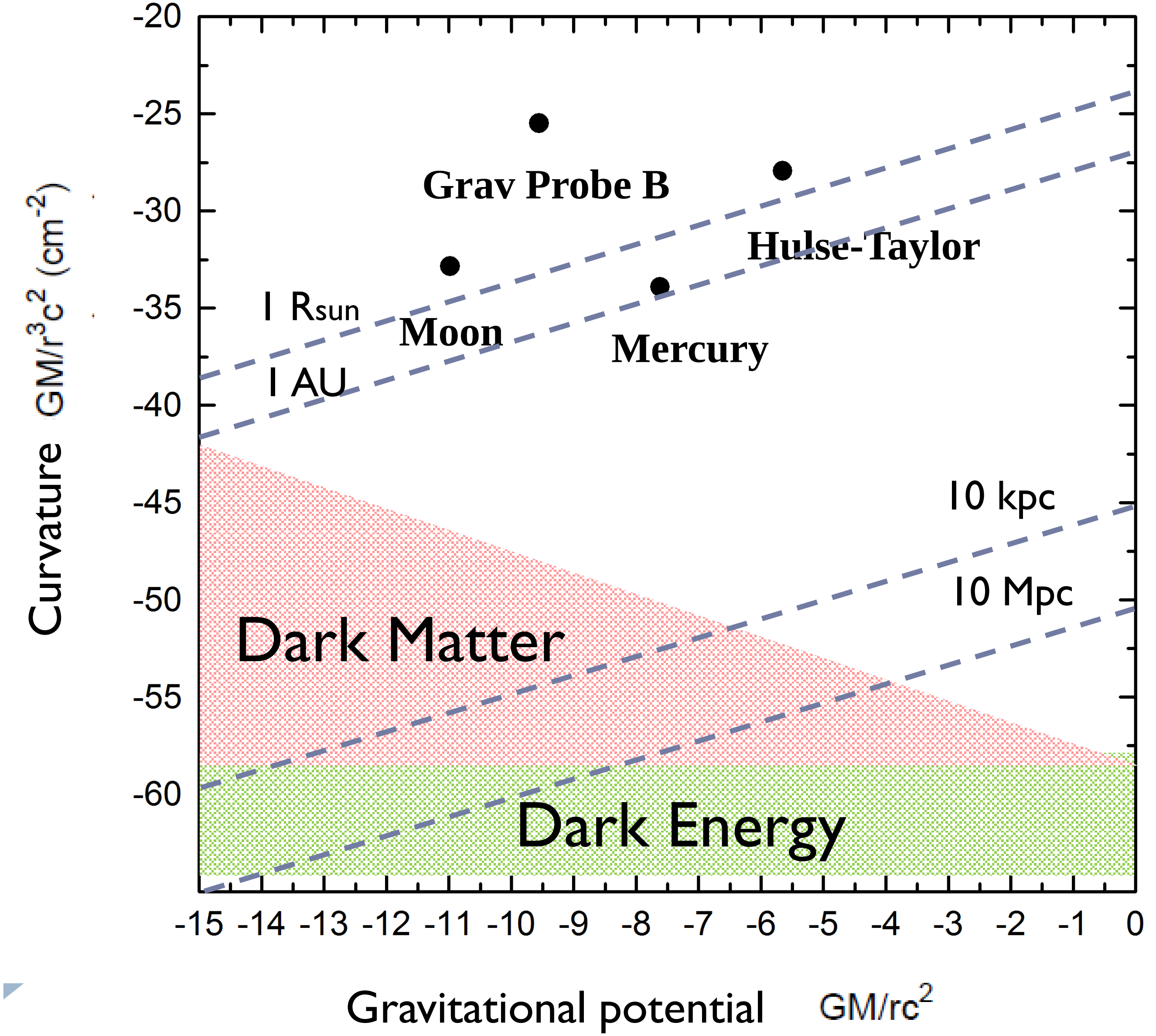
Assuming GR

Psaltis Living Rev. Relativity 11 (2008), 9
Baker et.al. 1412.3455

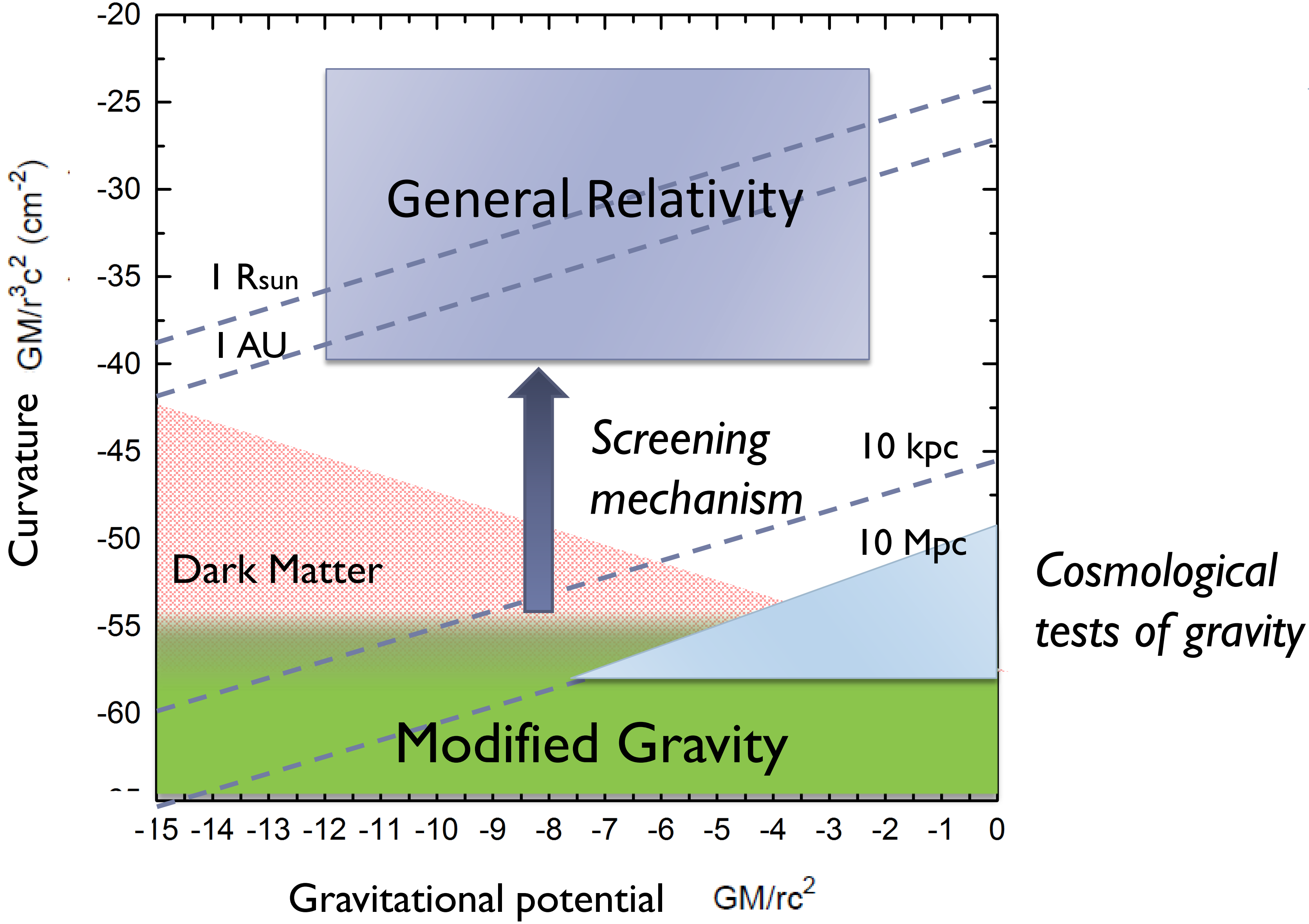


curvature

$$R = \frac{GM}{r^3 c^2}$$

potential

$$\Phi = \frac{GM}{rc^2}$$



General Relativity
1 Rsun
1 AU
Screening mechanism
10 kpc
10 Mpc
Dark Matter
Modified Gravity
Cosmological tests of gravity
Curvature GM/r^3c^2 (cm^-2)
-20
-25
-30
-35
-40
-45
-50
-55
-60
-15 -14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0
Gravitational potential GM/rc^2

General picture

- Largest scales

  gravity is modified so that the universe accelerates without dark energy

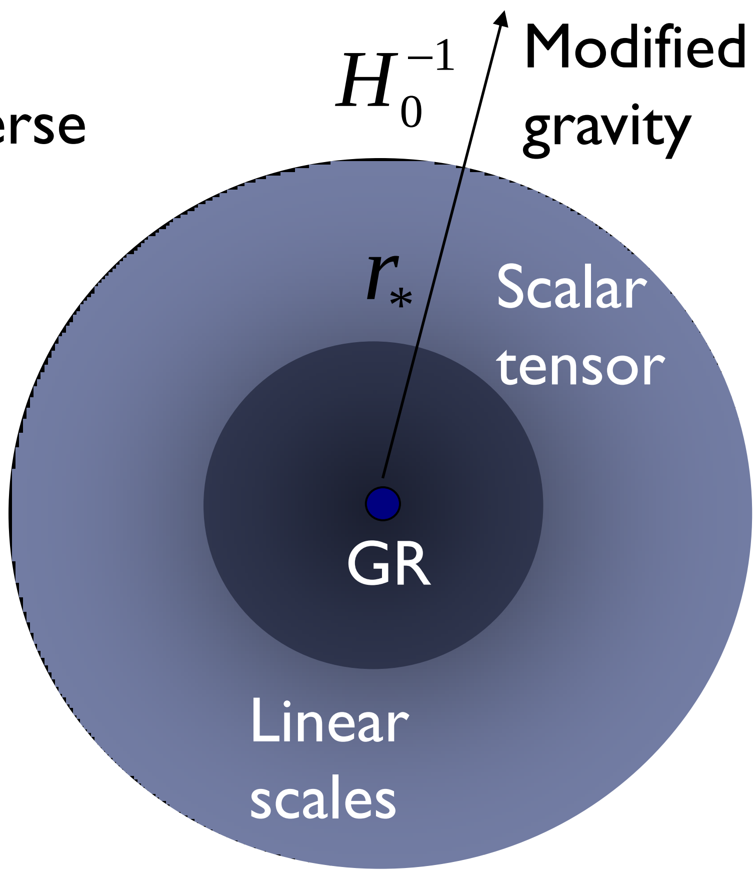
- Large scale structure scales

  gravity is still modified by a fifth force from scalar graviton

  model independent tests of GR

- Small scales (solar system)

  GR is recovered



KK: arXiv:1504.04623

How to recover GR on small scales?

On non-liner scales, the fifth force must be screened by some mechanisms Joyce, Jain, Khoury & Trodden arXiv:1407.0059

- Chameleon mechanism Khoury & Weltman Phys. Rev. Lett. 93 (2004) 171104

  The mass of a scalar mode becomes large in dense regions

$$\nabla^2\phi = \partial_\phi V + \frac{\alpha}{M_{pl}}\rho e^{\alpha\phi/M_{pl}}$$

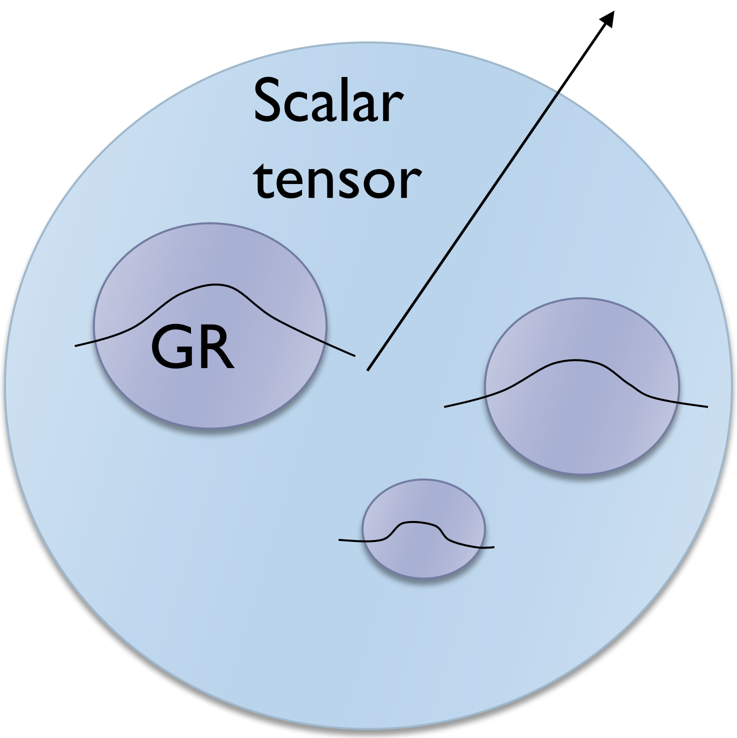
- Vainshtein mechanism

  Non-liner derivative self-interactions become large in a dense region

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

Behaviour of gravity

There regimes of gravity



In most models, the scalar mode obeys non-linear equations describing the transition from the scalar tensor theory on large scales to GR on small scales

$$\rho_{crit} \approx 10^{-29} g / cm^3,$$

$$\rho_{galaxy} \approx 10^{-24} g / cm^3,$$

$$\rho_{solar} \approx 10 g / cm^3$$

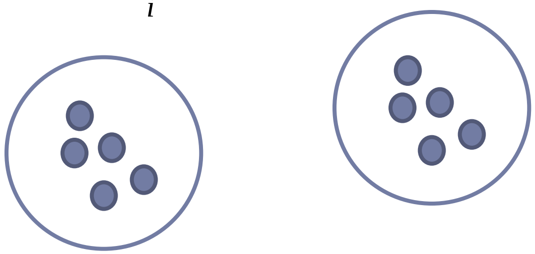
Understandings of non-linear clustering require N-body simulations where the non-linear scalar equation needs to be solved

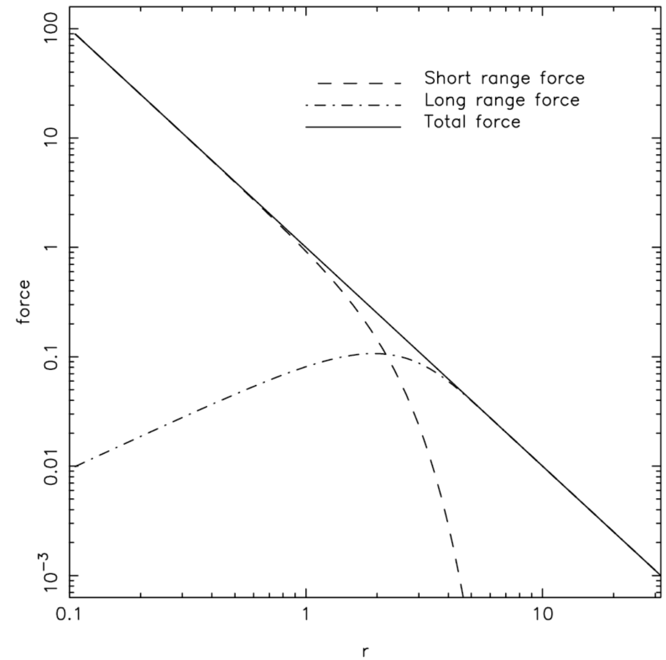
N-body simulations

- GR

  superposition of forces

$$\vec{F}(r) = \sum_i m_i \ \vec{f}_i(r - r_i)$$





- Modified gravity models

  the non-linear nature of the scalar field equation implies that the superposition rule does not hold

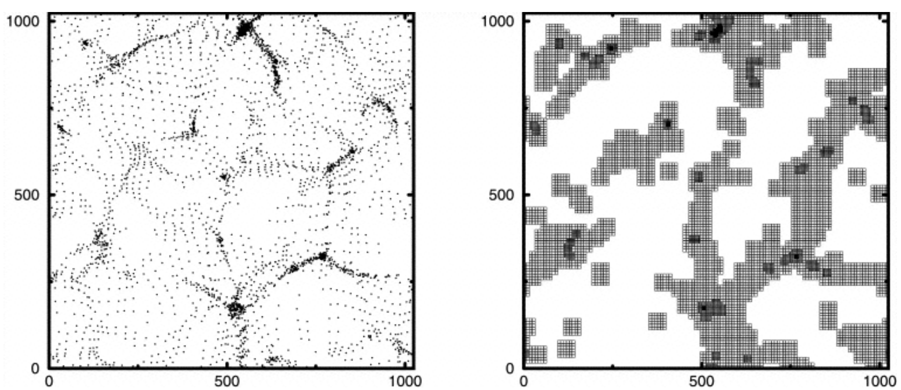
  - It is required to solve the non-linear scalar equation directly on a mesh a computational challenge!
  - The breakdown of the superposition rule has interesting consequences

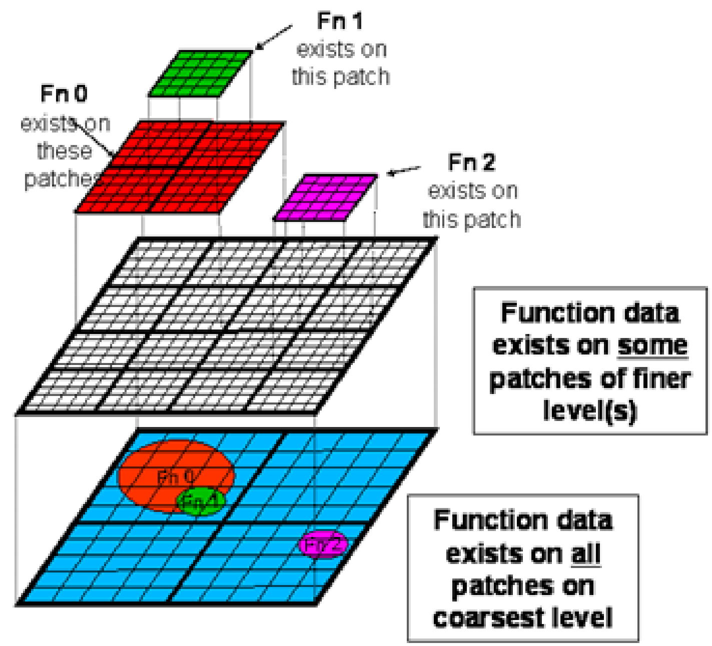
N-body Simulations (Puchwein's talk)

- Multi-level adaptive mesh refinement
- solve Poisson equation using a linear Gauss-Seidel relaxation
- add a scalar field solver using a non-linear Gauss Seidel relaxation

ECOSMOG Li, Zhao, Teyssier, KK JCAP1201 (2012) 051
MG-GADGET Puchwein, Baldi, Springel MNRAS (2013) 436 348
ISIS Llinares, Mota, Winther A&A (2014) 562 A78
DGPM, Schmidt PRD80, 043001

Modified Gravity Simulations comparison project
Winther, Shcmidt, Barreira et.al. arXiv: 1506.06384





Redshift space distortions

- Power spectrum in redshift space is anisotropic

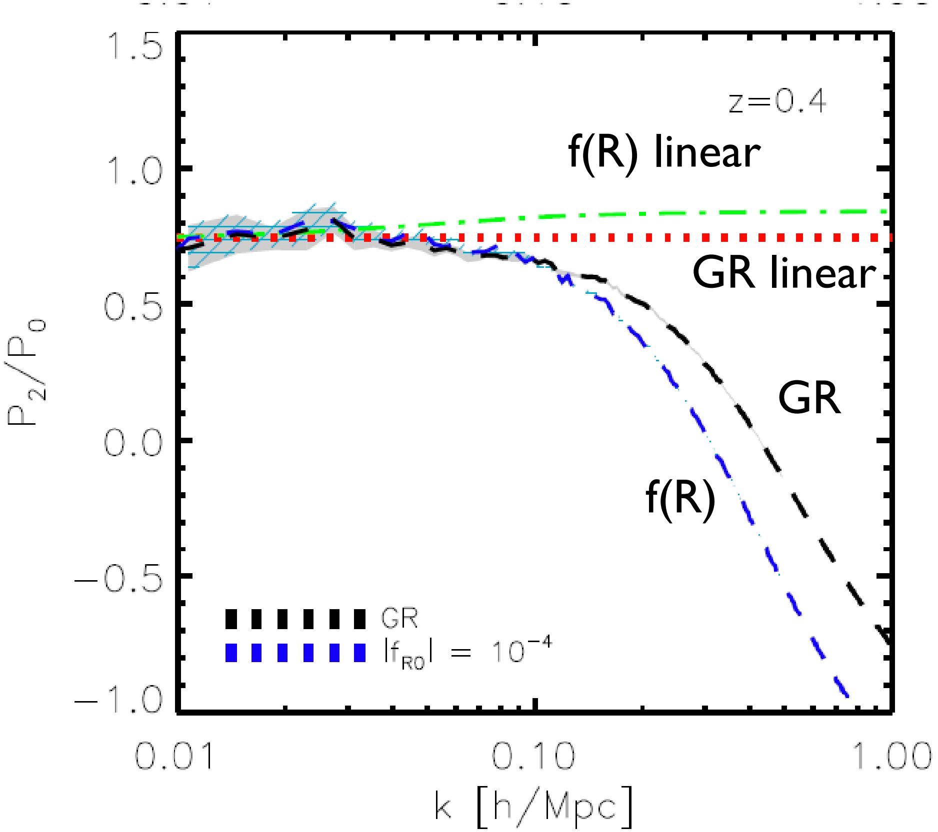
$$P(k,\mu),\quad \mu = k_{\parallel}/k$$

- Multipole decomposition

$$P(k,\mu) = \sum_{\ell} P_{\ell}(k) L_{\ell}(\mu)$$

$$\left.\frac{P_2}{P_0}\right|_{linear} = \frac{\frac{4}{3}f + \frac{4}{7}f^2}{1 + \frac{2}{3}f + \frac{1}{5}f^2}$$

$$f = \sqrt{\frac{P_{\theta\theta}}{P_{\delta\delta}}},\quad \theta = \nabla \cdot v$$



Modelling of non-linear effects is crucial to extract the differences in the linear growth rate between GR and modified gravity models

- Jennings, Baugh, Li, Zhao, Koyama, 1205.2698

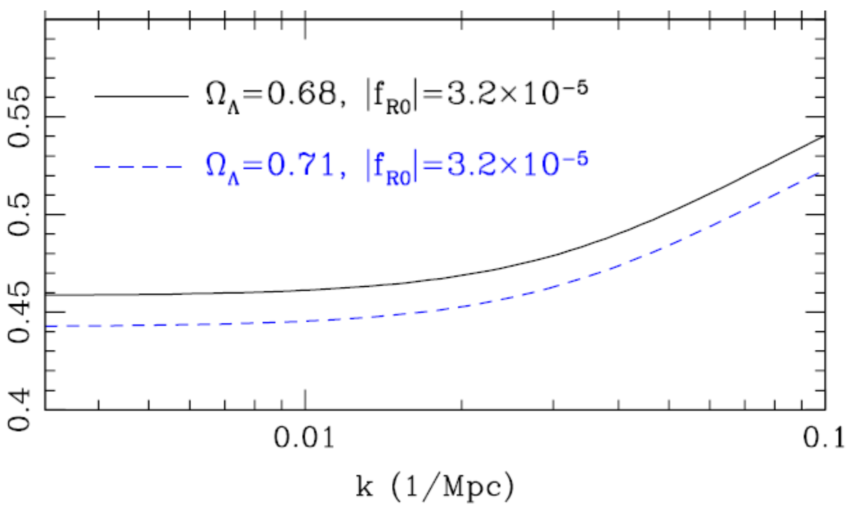
Perturbation theory

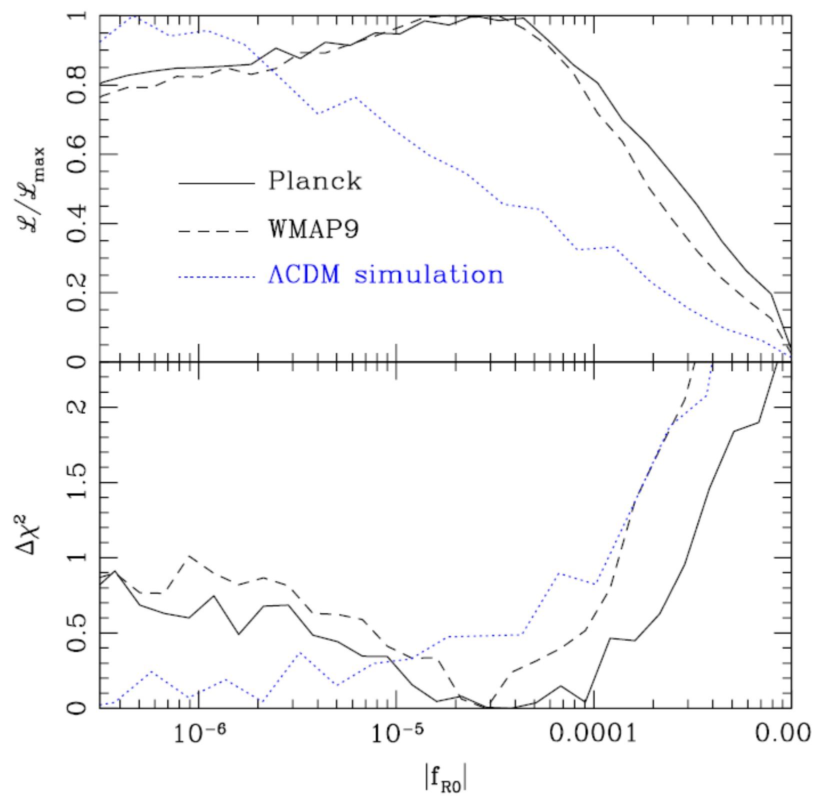
KK, Taruya, Hiramatsu PRD79 123512
Taruya, KK, Hiramatsu, Oka, PRD89 043509
Taruya et.al. PRD90 123515

- Peturbation theory based template (Taruya's talk)

$$\begin{aligned}\tilde{P}(k,\mu) &= \{b^2 P_{\delta\delta}(k) + 2\mu^2 b G_\Theta P_{\delta\Theta}(k) + \mu^4 G_\Theta^2 P_{\Theta\Theta}(k) \\ &\quad + A(k,\mu;b,G_\Theta) + B(k,\mu;b,G_\Theta)\} \times D_{\mathrm{FoG}}(k\mu\sigma_p)\end{aligned}$$

- Scale dependent growth





BOSS DR11 constraints $|f_{R0}| < 8 \times 10^{-4}$

Song, Taruya, Linder, KK et.al. 1507.01592

How do we test gravity in cosmology?

- Newton potential Ψ

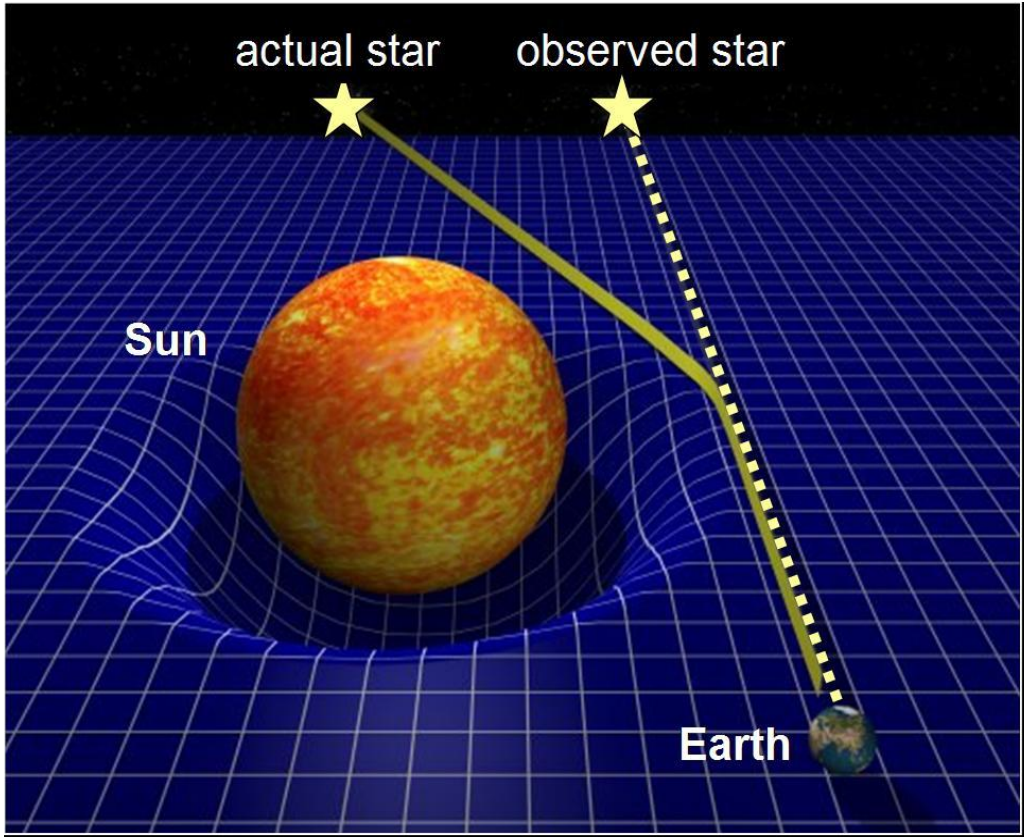
  controls dynamics of non relativistic particles

- Space curvature Φ

  also deflects lights

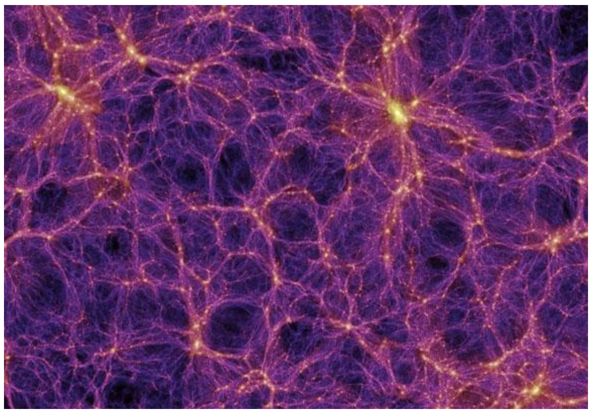
In GR there is a special relation between the two $\Psi = \Phi$

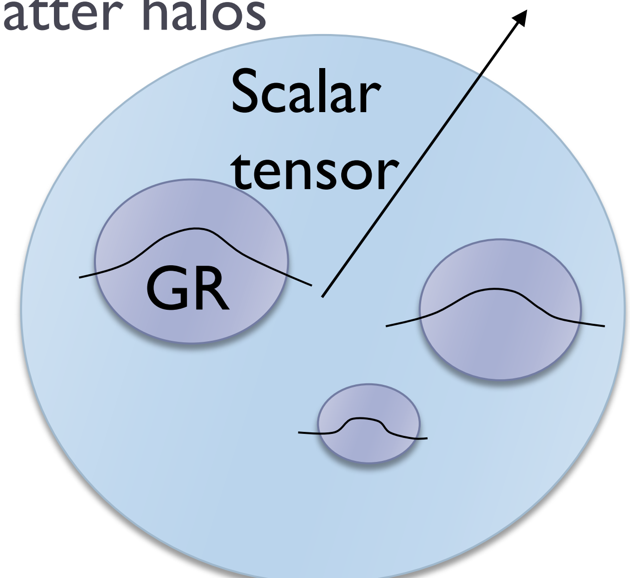
dynamical mass = lensing mass in GR



Where to test GR (we consider the chameleon mechanism here)

- GR is recovered in high dense regions
  - GR is restored in massive dark matter halos





  - Environmental effects

    Even if dark matter halo itself is small, if it happens to live near massive halos, GR is recovered

Using simulations, we can develop criteria to identify the places where GR is not recovered

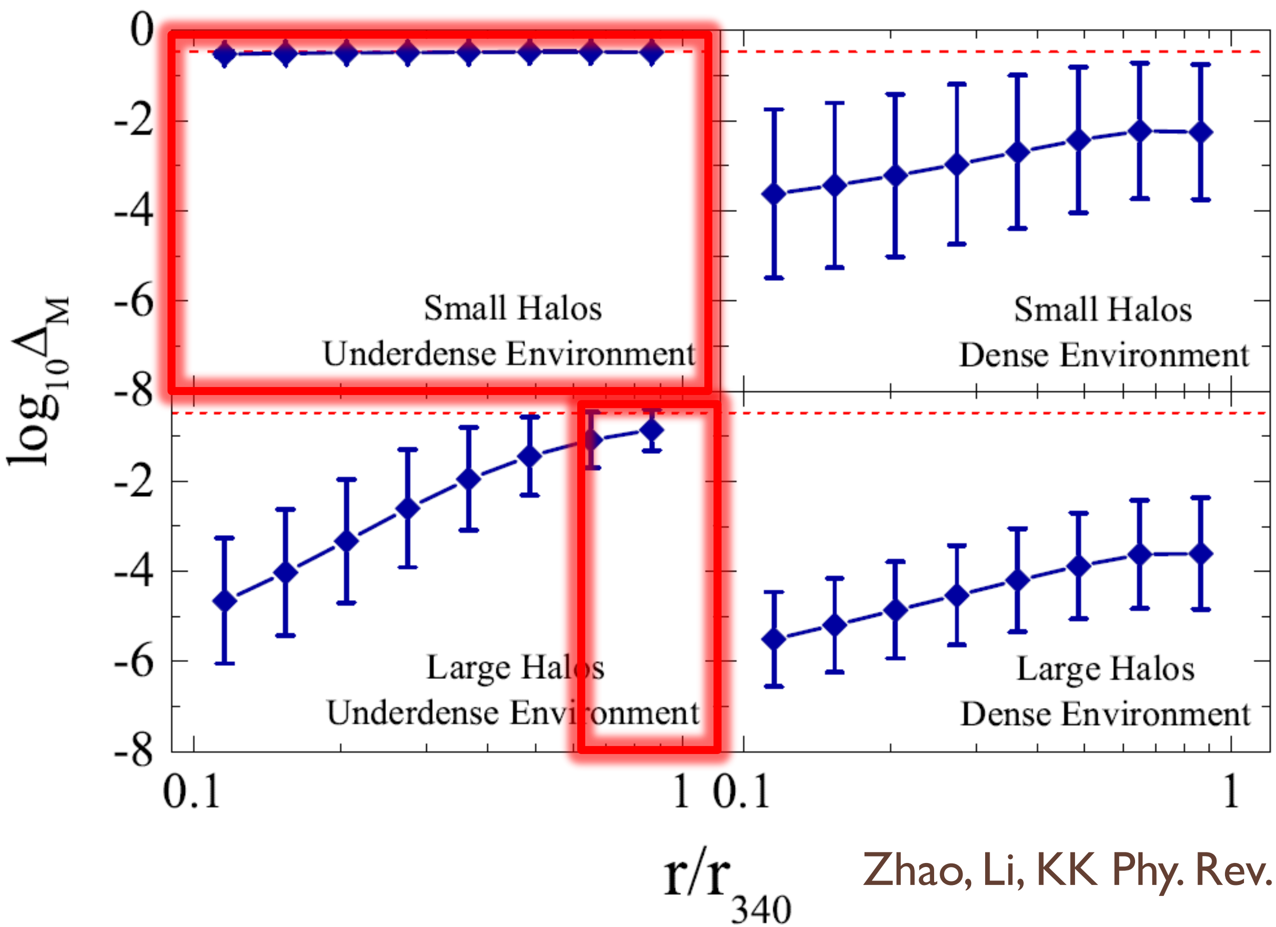
Zhao, Li, KK Phy. Rev. Lett. 107 (2011) 071303

Environmental dependence

- Difference between lensing and dynamical mass

$$\Delta_M(r) = \frac{d\Psi(r)/dr}{d\Psi_+(r)/dr} - 1, \quad \Psi_+ = \frac{\Phi + \Psi}{2}$$

environment: $D = d / r_{NB}$



O(1) difference

no difference

O(1) difference

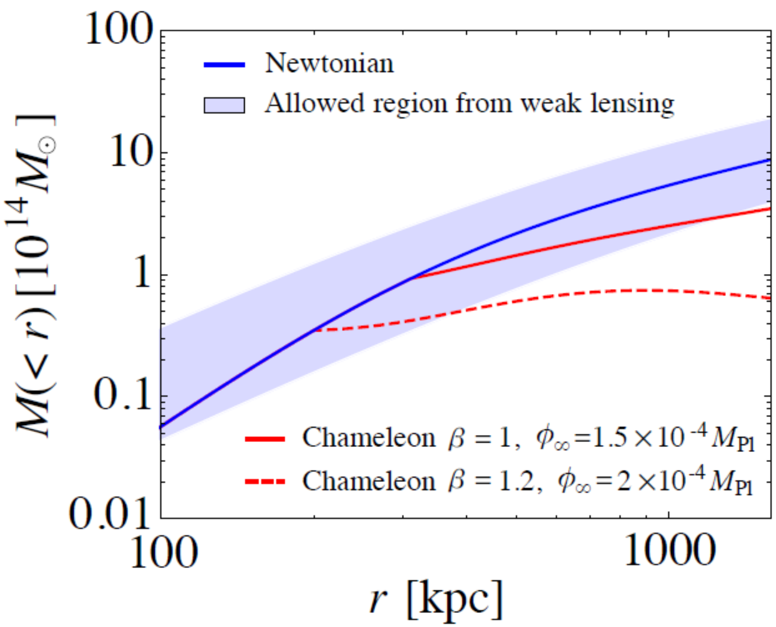
no difference

Zhao, Li, KK Phy. Rev. Lett. 107 (2011) 071303

Testing chameleon gravity

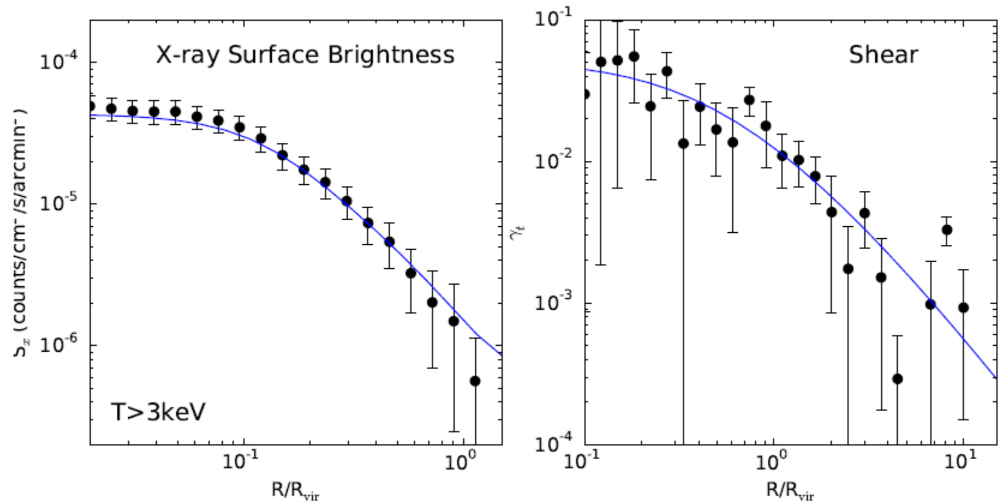
- Outskirt of clusters

Terukina. et.al. PRD86 103503, JCAP 1404 013



$$M_{lens} = M_{dyn} - M_\phi$$

Dynamical mass can be inferred from X-ray and SZ



48 X-ray clusters from XCS compared with lensing (shear) from CFHTLS

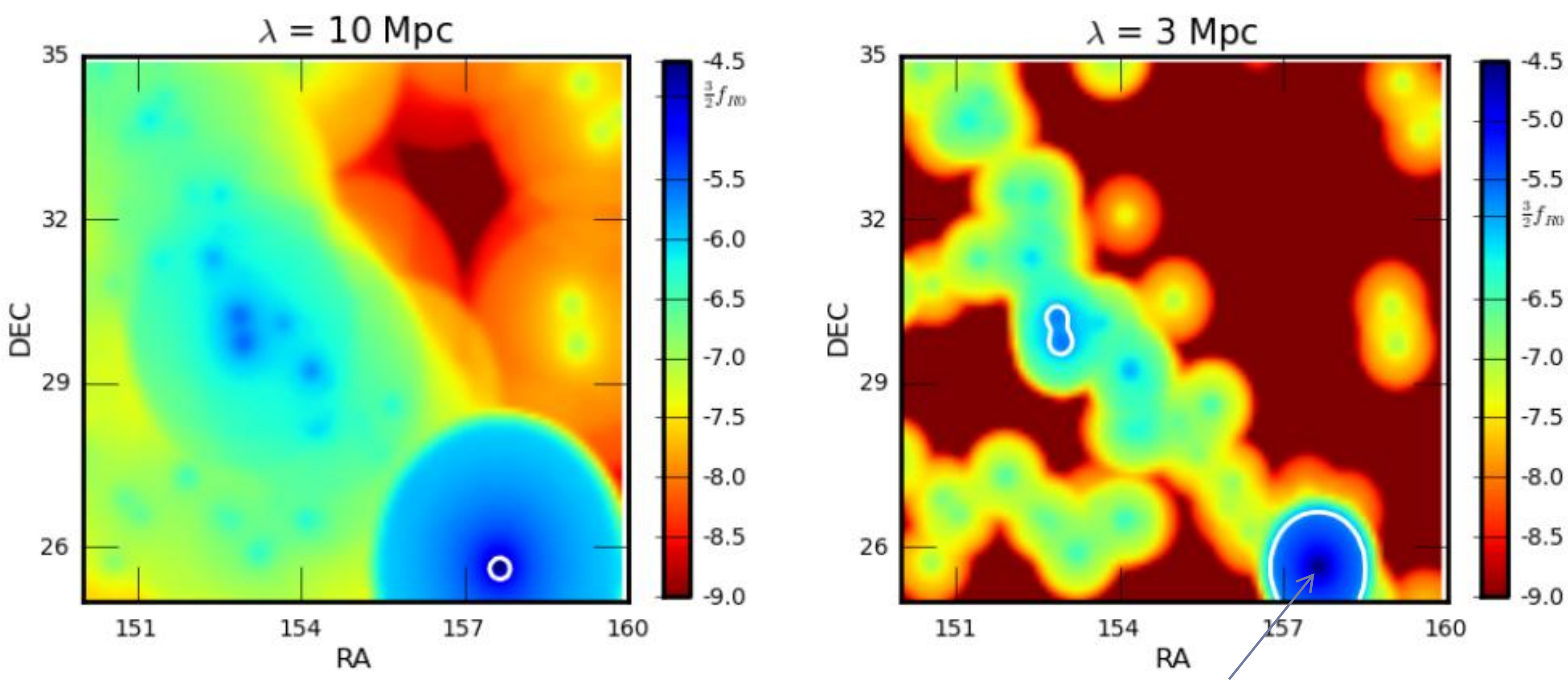
$$| f_{R0} | < 7.9\times10^{-5}$$

Wilcok et.al. MNRAS (1504.03937)

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
JCAP 1207 (2012) 034



GR is recovered

- (we consider the chameleon mechanism here)

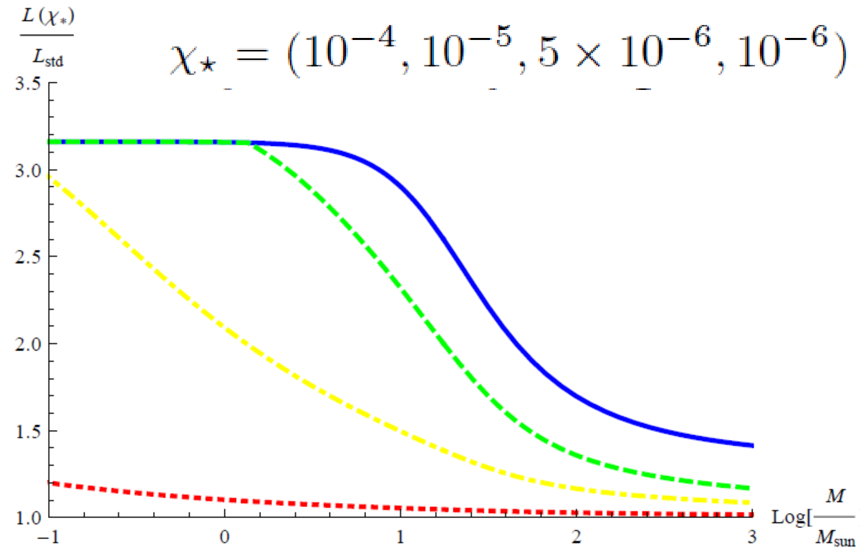
Tests of gravity on small scales

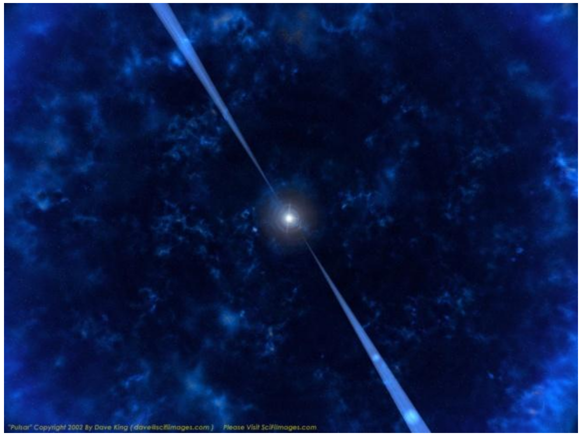
Hui, Nicolis & Stubbs Phys. Rev. D80 (2009) 104002

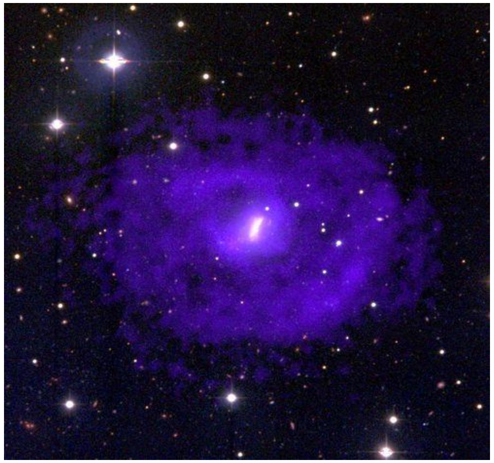
- dwarf galaxies in voids

  strong modified gravity effects
  - Galaxies are brighter
  - Pulsers pulsate faster
  - Various other tests

  Jain & VanderPlas JCAP 1110 (2011) 032





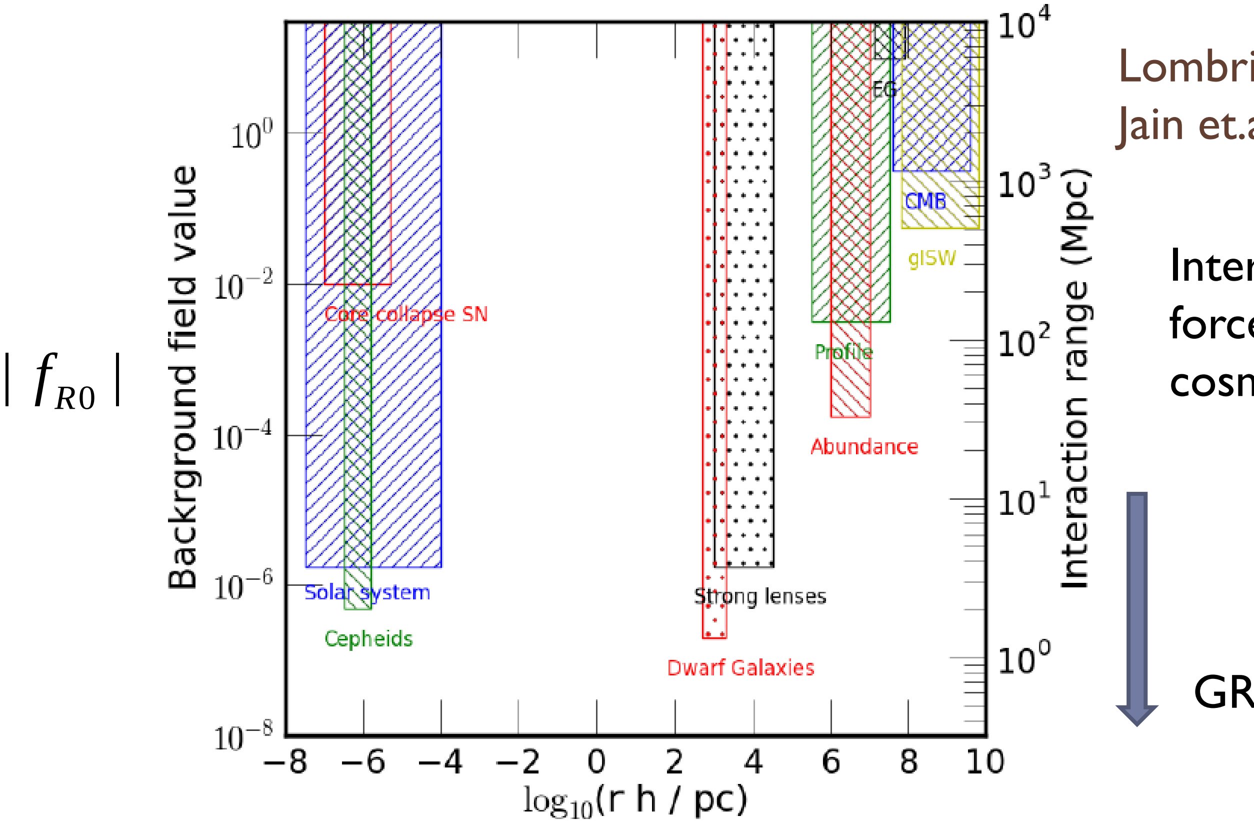


Davis et.al. Phys. Rev. D85 (2012) 123006
Jain et.al. ApJ 779 (2013) 39
Vikram et.al. JCAP1308 (2013) 020

$$|f_{R0}| < 5\times10^{-7}$$

- (we consider the chameleon mechanism here)

Constraints on chameleon gravity



Lombriser et.al. PRD85 102001
Jain et.al. 1309.5389

Interaction range of the extra force that modifies GR in the cosmological background

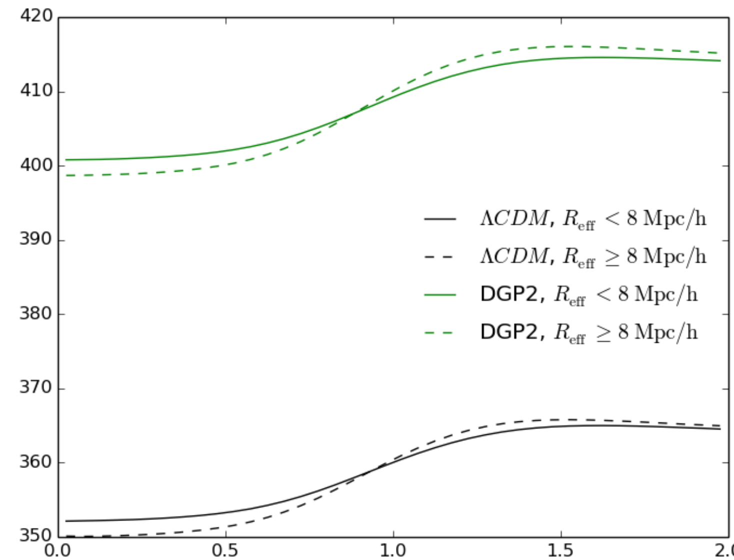
- Non-linear regime is powerful for constraining chameleon gravity
- Astrophysical tests could give better constraints than the solar system tests and can be done by "piggybacking" ongoing surveys

Vainshtein mechanism (Falck's talk)

- Vainshtein mechanism is very efficient
  - dark matter halos are all screened regardless of mass and environment Schmidt PRD81103002
  - linear/quasi non-linear scales are the best place to test the models
- Screening depends on dimensionality of the system
  - lower dimensional objects are less screened Falck et.al. JCAP1407 058 1503.06673
- Voids (Barreira, Cai's talk)
  - Voids are unscreened by definition

Falck, Cautun, Zhao, KK in preparation

Tangential velocity

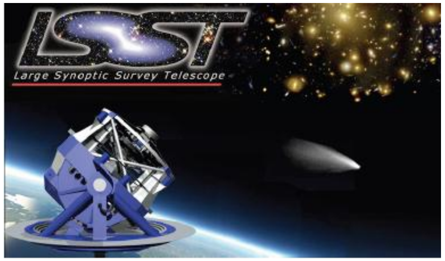


Radius

Summary

- In the next decade, we may be able to detect the failure of GR on cosmological scales
  - Linear scales

    model independent tests of gravity

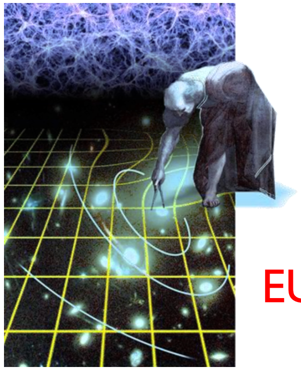


SUMIRE

  - Non-linear scales

    novel astrophysical tests of gravity

    (in a model dependent way)



EUCLID

It is required to develop theoretical models from fundamental theory