Non-linear structure formation in modified gravity

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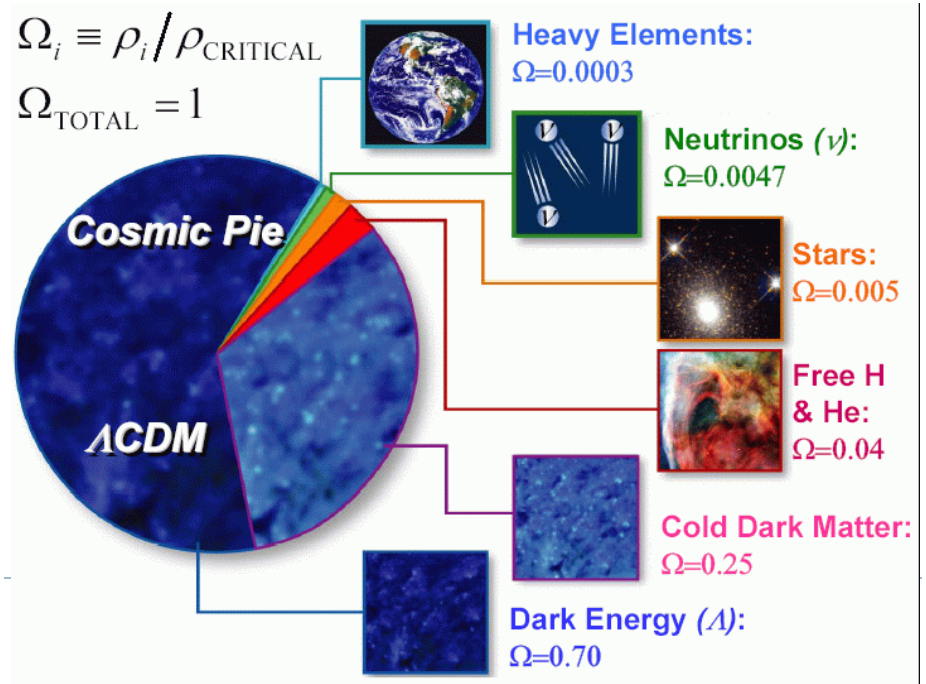
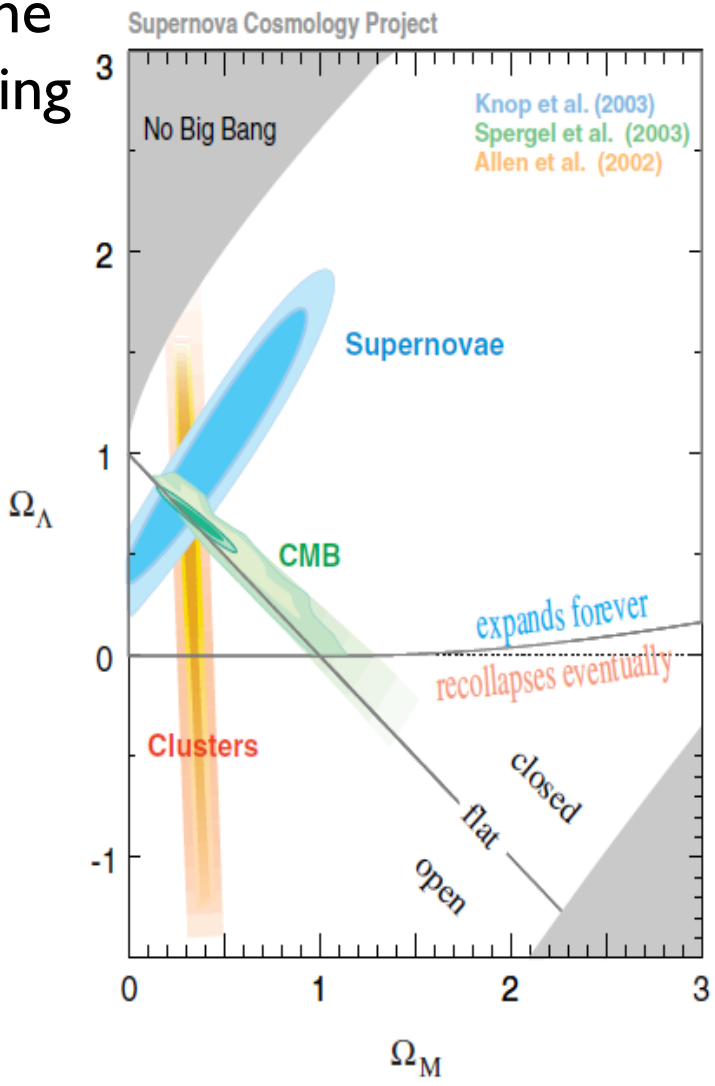
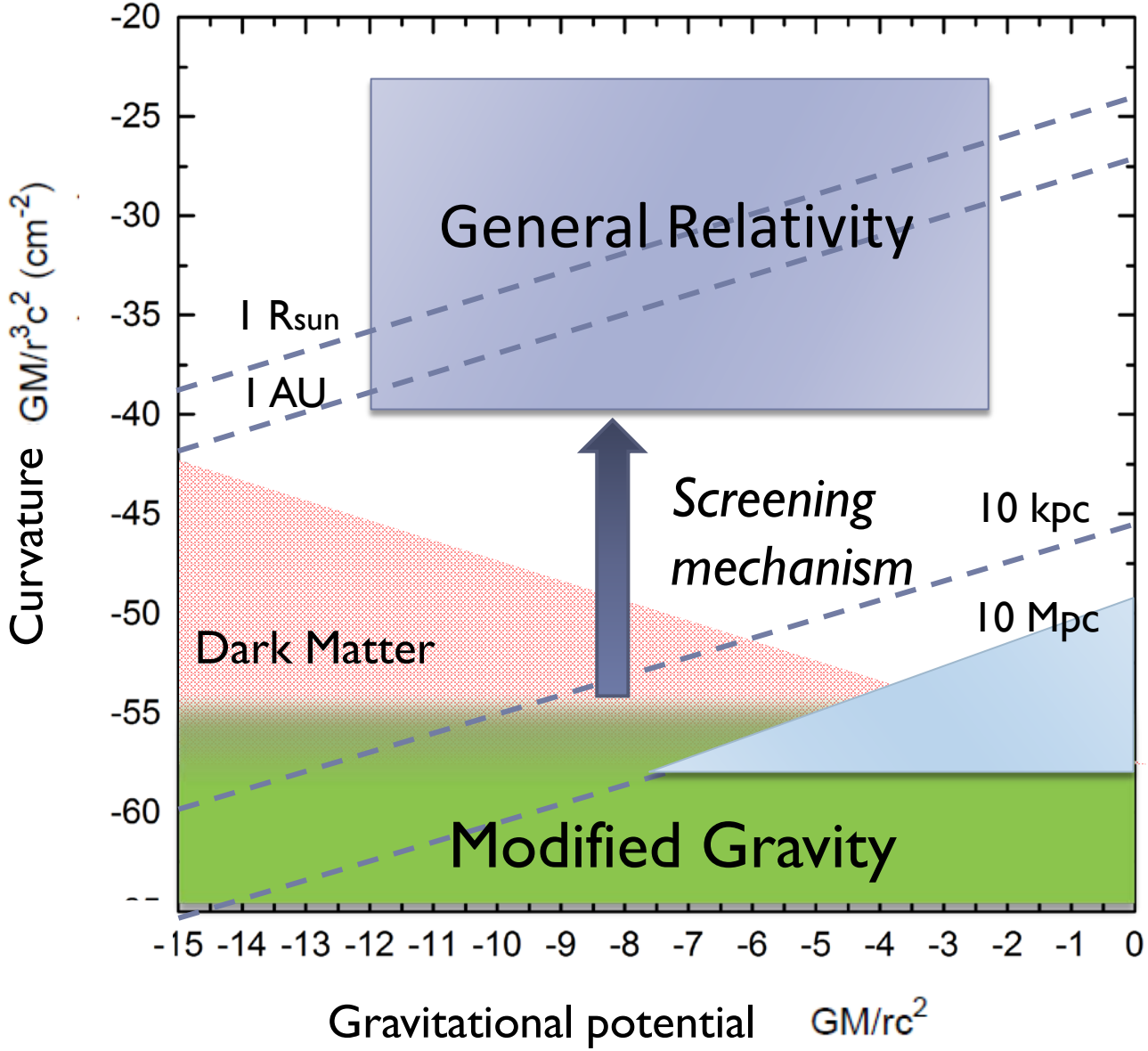
Cosmic acceleration

- Many independent data sets indicate the expansion of the Universe is accelerating

- Standard cosmology requires
  70% of unknown 'dark' energy







Cosmological tests of gravity

Psaltis Living Rev. Relativity 11 (2008), 9, Baker, Psaltis, Skordis arXiv:1412.3455

General picture

- Largest scales

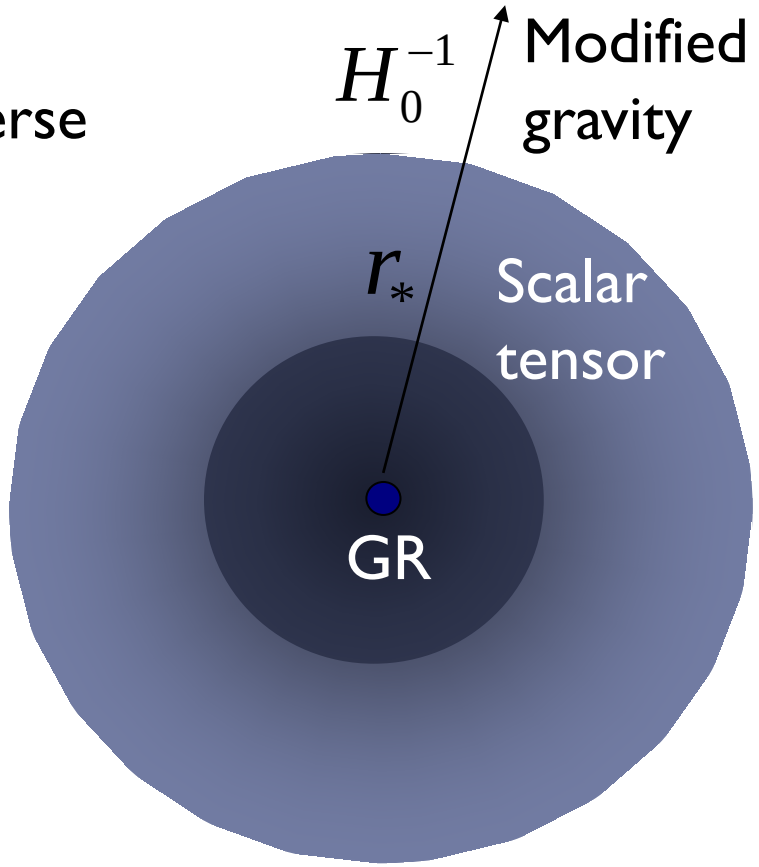
  gravity is modified so that the universe accelerates without dark energy

- Large scale structure scales

  gravity is still modified by a fifth force from scalar graviton

- Small scales (solar system)

  GR is recovered



How do we test gravity in cosmology?

- Newton potential Ψ

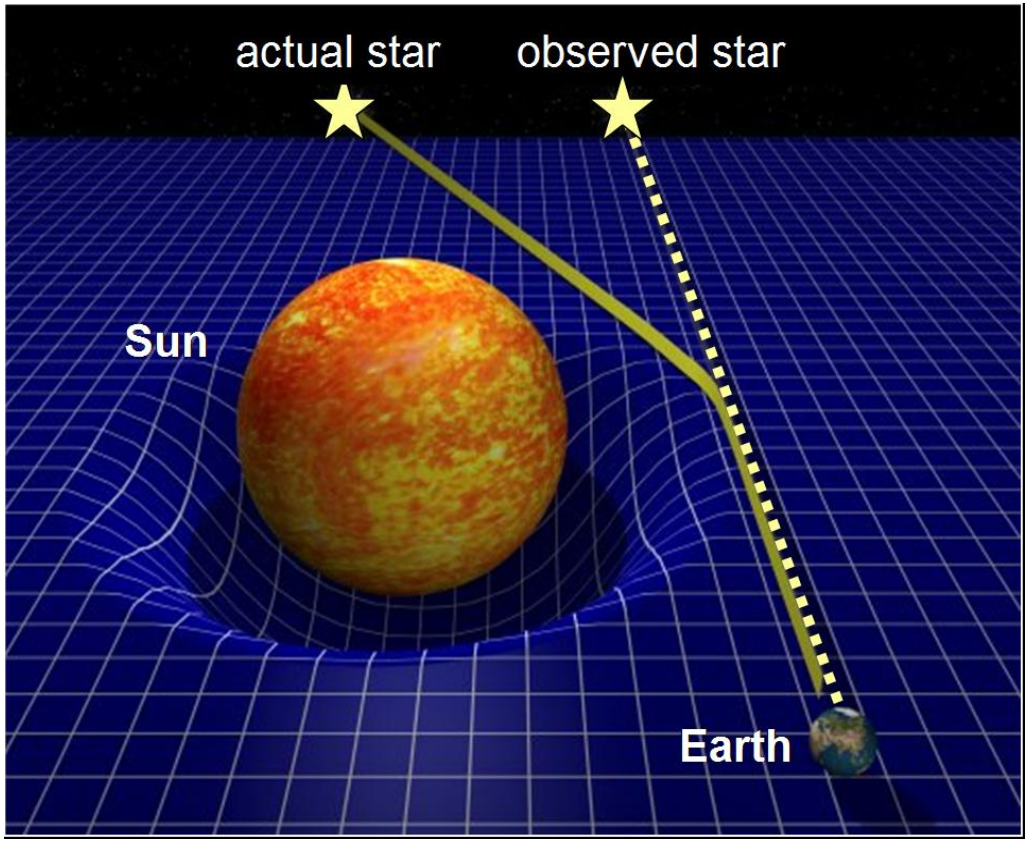
  controls dynamics of non relativistic particles

- Space curvature Φ

  also deflects lights

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

dynamical mass = lensing mass in GR



Linear scales

- Geometry (FRW metric + perturbations)

$$ds^2 = a(\eta)^2\left[-(1+2\Psi)d\eta^2 + (1-2\Phi)d\vec{x}^2\right]$$

- Matter

$$T_0^0 = -\rho_m(1+\delta_m), \qquad \text{:over-density}$$

$$T_i^0 = \rho_m v_{mi}, \quad \partial^i v_{mi} = \theta_m \qquad \text{:peculiar velocity}$$

energy-momentum conservation

$$\dot{\delta}_m - \frac{1}{a}\theta_m - 3\dot{\Phi} = 0$$

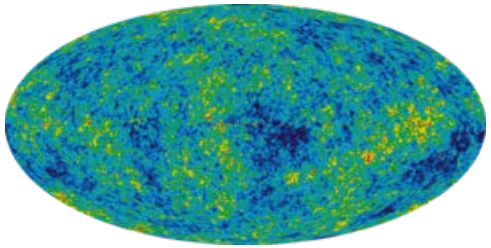
$$\dot{\theta}_m + H\theta_m - \frac{k^2}{a^2}\Psi = 0$$

$$\Rightarrow \quad \ddot{\delta}_m + 2H\dot{\delta}_m = \frac{k^2}{a^2}\Psi$$

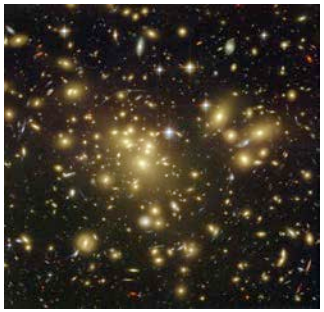
modified gravity changes the growth of structure formation

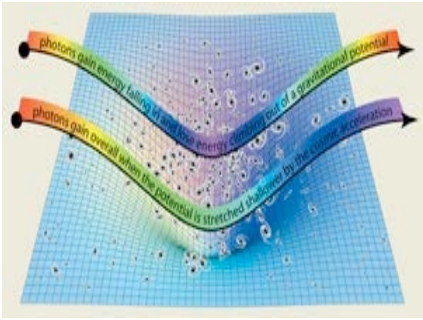
Observations

- Background
  CMB, BAO,SNe



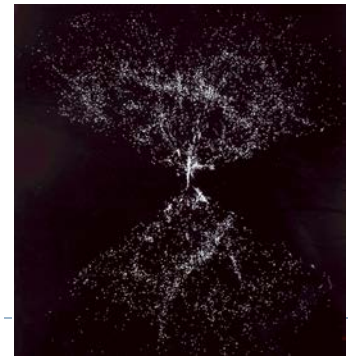
- Lensing potential $\Phi + \Psi$
  weak lensing

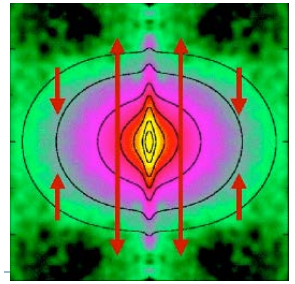




- Time variation of lensing potential
  Integrated Sachs-Wolfe effect

- Matter perturbations
  galaxy clustering δ_m
  peculiar velocities θ_m





Consistency relation

Zhang & Jain Phys. Rev. D78 (2008) 063503
Song & KK JCAP 0901(2009) 048

- In GR, gravitation equations are given by

$$H^2 = \frac{8\pi G}{3}\rho_T, \quad \rho_T = \sum_i \rho_i$$

$$\frac{k^2}{a^2}\Phi = 4\pi G a^2 \rho_T \delta_T, \quad \rho_T\delta_T = \sum_i \rho_i \delta_i$$

- Consistency relation

$$\alpha(k,t) = \frac{2k^2}{3a^2H^2}\frac{(\Phi+\Psi)-\Psi}{\delta_T} = 1$$

Peculiar velocity

$$k^2\Psi = \frac{d(a\theta_m)}{dt}$$

background

Weak lensing

Galaxy distribution

$$\delta_g = b_T\delta_T$$

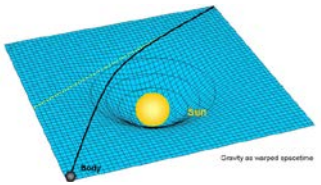
We have just enough number of observations to check the relation

Parametrisation

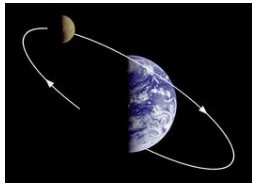
Amendola et.al JCAP 0804 (2008) 013
Zhao et.al. Phys. Rev. Lett. 103 (2009) 241301
…..

- Parameterised modified Einstein eq.

$$k^2(\Psi+\Phi) = -8\pi G a^2 \Sigma(a,k)\rho_m\delta_m \quad : \text{Lensing}$$



$$k^2\Psi = -4\pi G a^2 \mu(a,k)\rho_m\delta_m \quad : \text{Newton potential}$$



- Brans-Dicke gravity

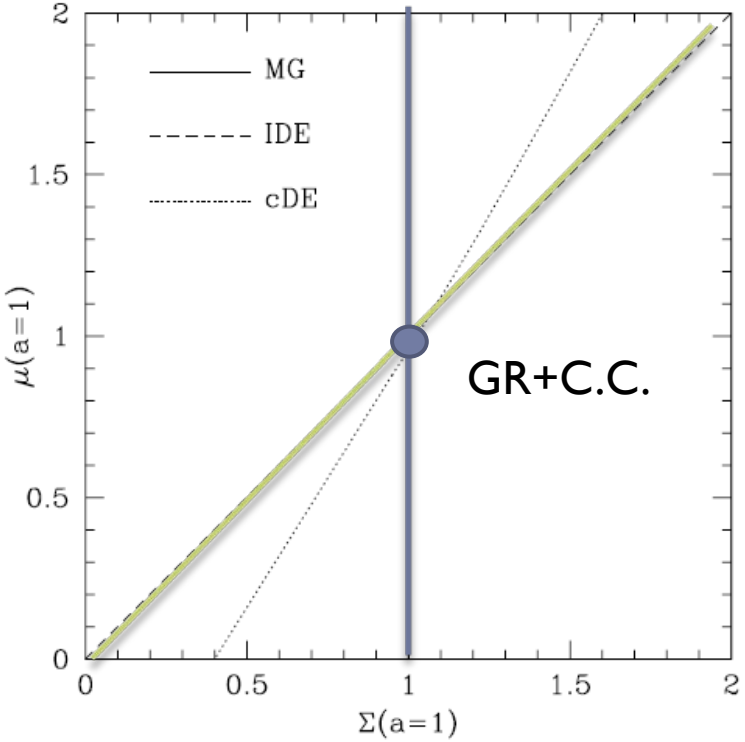
$$\Sigma(a,k) \simeq 1$$

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

- dark energy model

no anisotropic stress

$$\Sigma = \mu = \left(1+\frac{\rho_{DE}\delta\rho_{DE}}{\rho_m}\right)$$

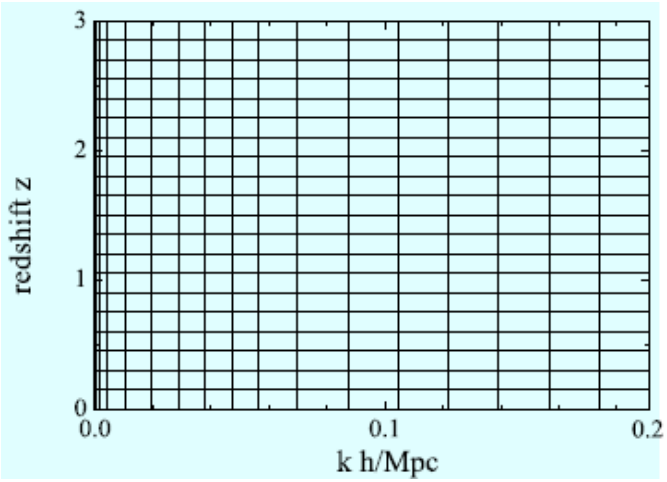


Model independent constraints

- Make bins

  treat $\mu(k_i, z_i), \Sigma(k_i, z_i)$ in each bin as parameters

  Errors on these parameters are highly correlated



- Principal component analysis

  Diagonalise the covariant matrix

  $$C_p = W\ \Lambda^{-1}\ W^T, \quad W = (\vec{e}_1, \vec{e}_2, ...,)$$

  $$p = \{\mu_1, ..., \Sigma_1, ...\}$$

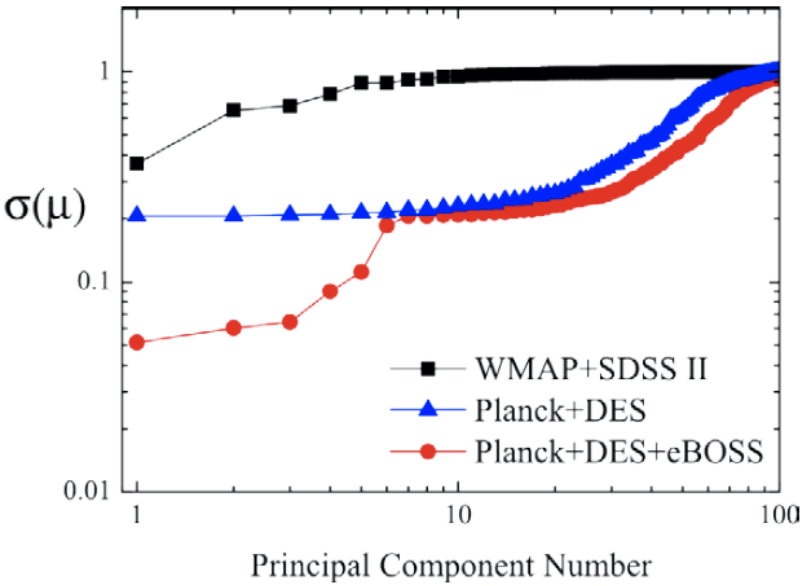
  Zhao, Pogosian, Silvestri, Zylberberg
  PRL 103 (2009) 241301
  PRD79 (2009) 083513

  Uncorrelated parameter $q_i = -1 + \sum_j W_{ij} p_j / \sum_j W_{ij}$ $\quad \mathrm{GR} : q_i = 0$

Future forecasts

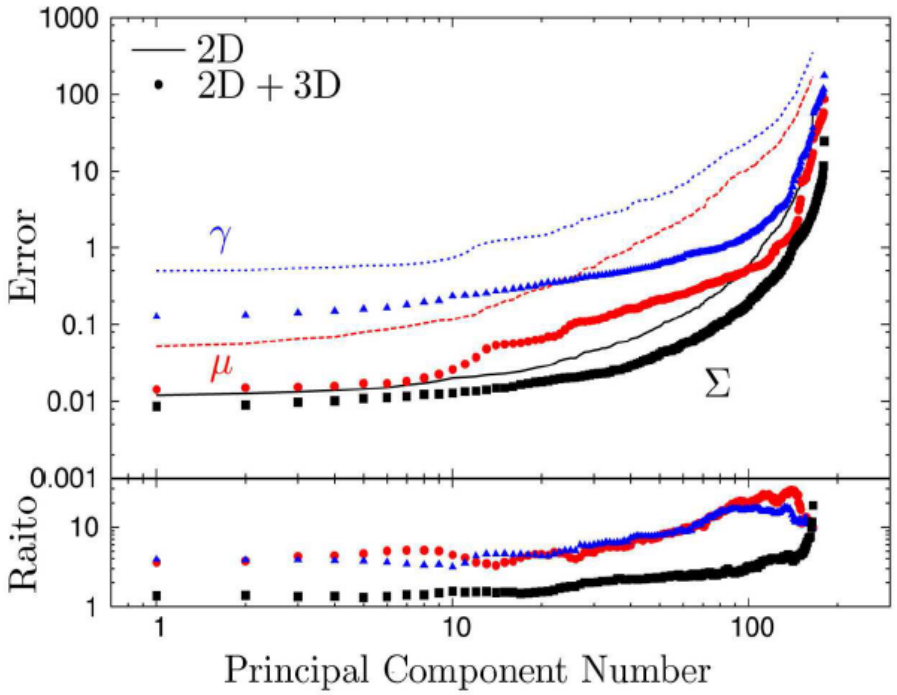
Hojatti et.al. PRD85 (2012) 043508
Asaba, Hikage, KK et.al. JCAP 1308 029

- Next 5 years



DES (2012-2017) imaging
eBOSS (2014-2018) spectroscopic
Seveal parameters at the 5-10% level

- Next 10 years



Euclid (2020-)
10 parameters at the 1% level

General picture

- Largest scales

  gravity is modified so that the universe accelerates without dark energy

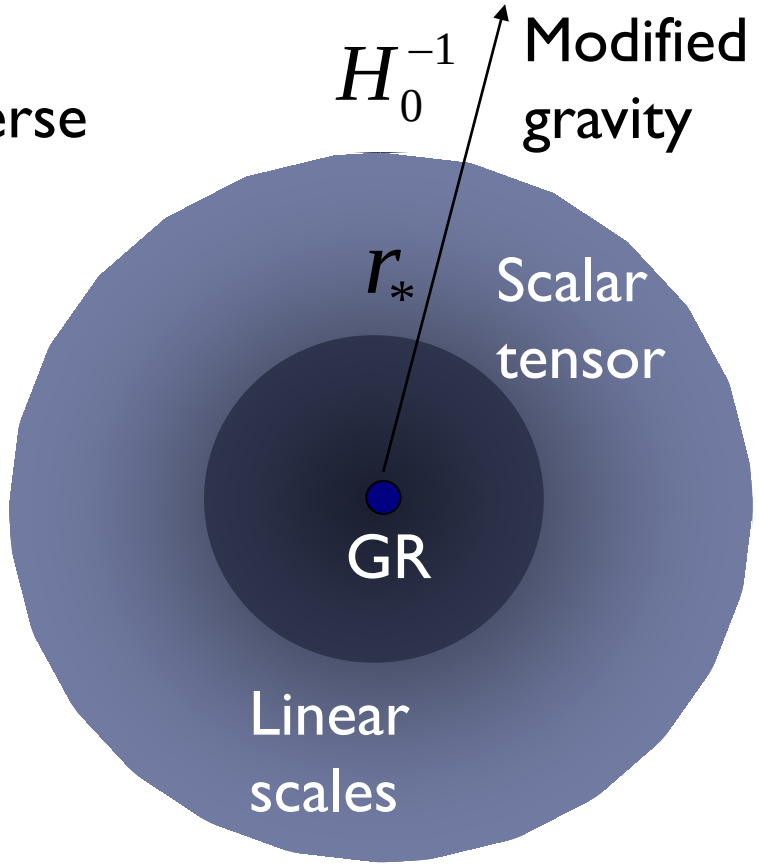
- Large scale structure scales

  gravity is still modified by a fifth force from scalar graviton

  model independent tests of GR

- Small scales (solar system)

  GR is recovered



Talks by Bean, Langlois, Silverstiri, Ishak/Dossett

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

  The mass of a scalar mode becomes large in dense regions

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

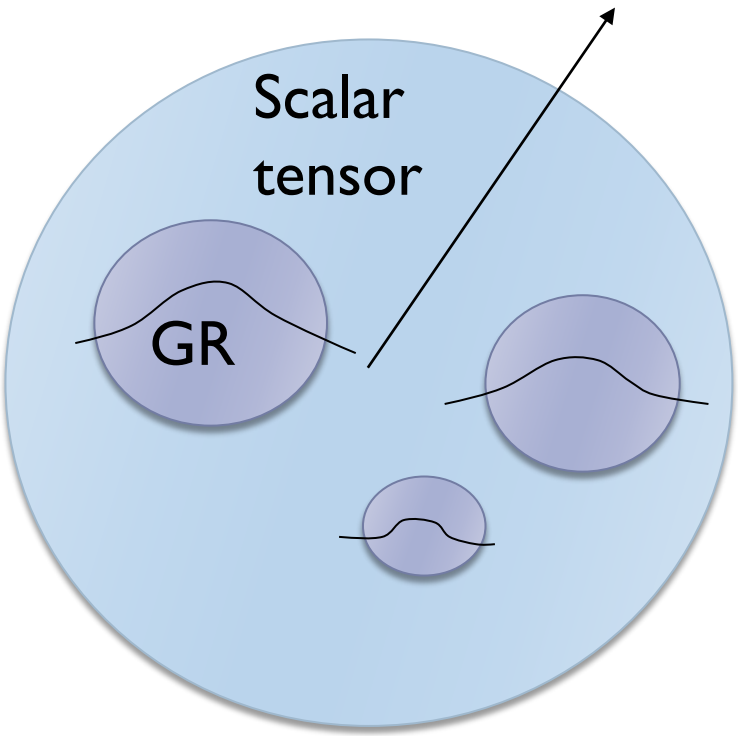
- Vainshtein mechanism

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

  - first discovered in the context of massive gravity models, which has attracted renewed interest recently
  - also appears naturally in braneworld models

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

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

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

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

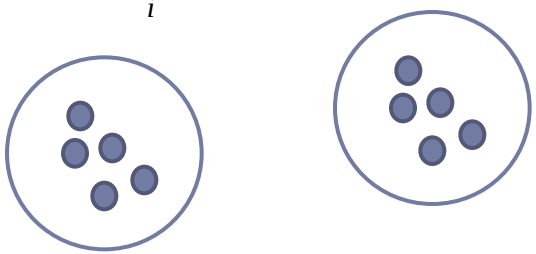
Understandings of non-linear clustering require N-body simulations where the non-linear scalar equation needs to be solved

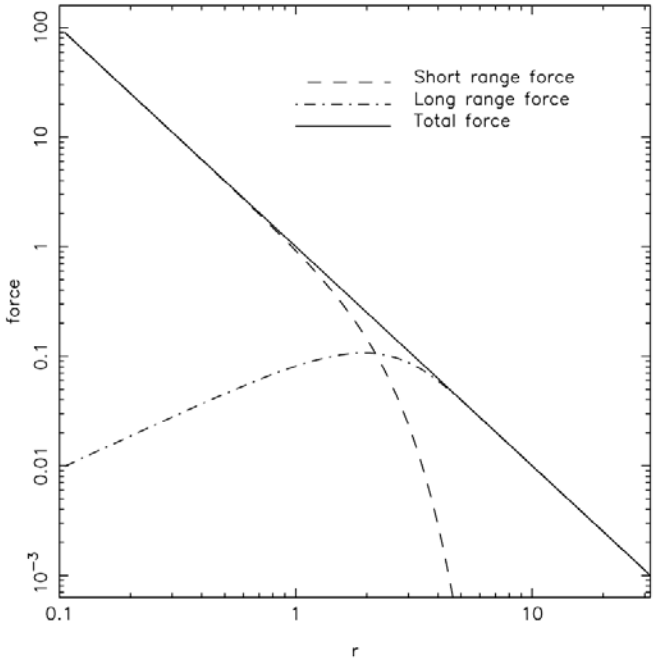
N-body simulations

- GR (Newton)

  superposition of forces

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





- Modified gravity models

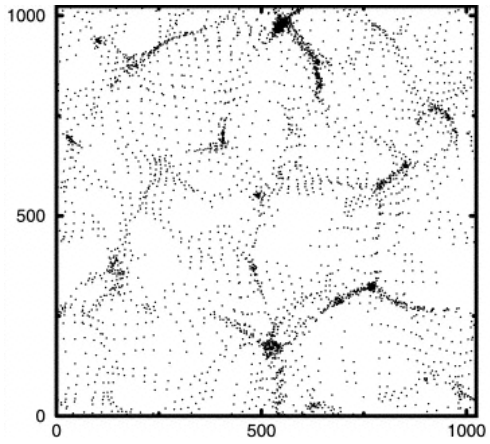
  the non-linear nature of the scalar field equation implies that the superposition rule does not hold

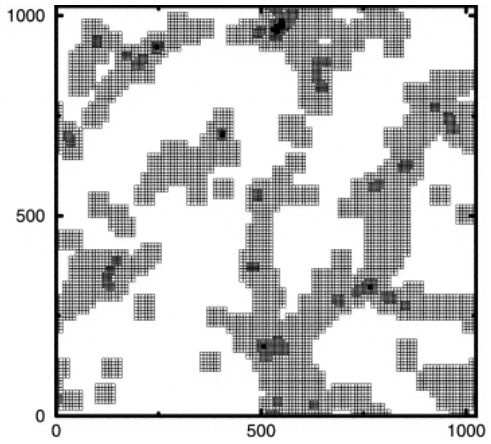
  - It is required to solve the non-linear scalar equation directly on a mesh a computational challenge!
  - The breakdown of the superposition rule has interesting consequences

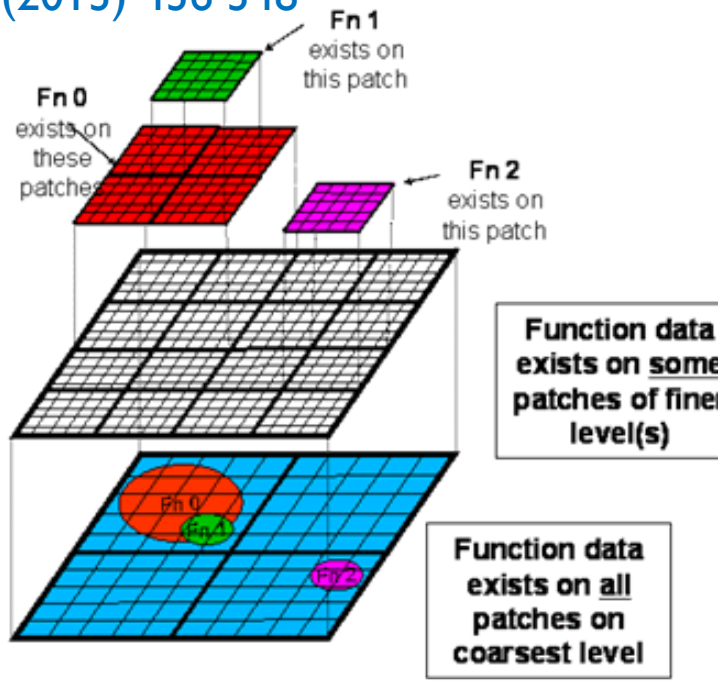
N-body Simulations Talk by Zhao

- 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 arXiv:13076748

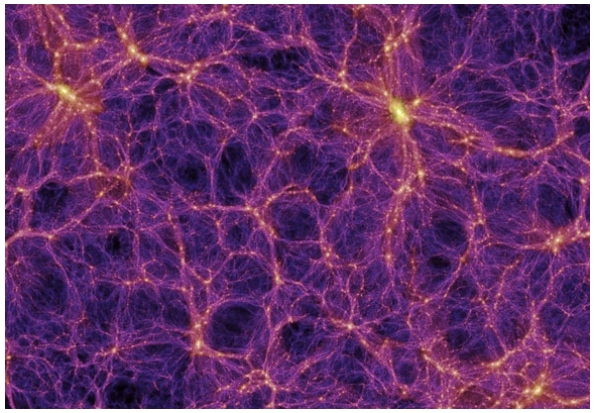


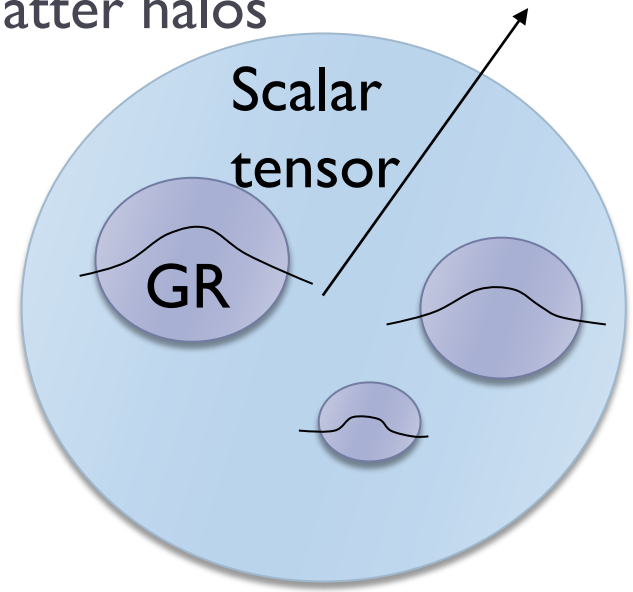




Where to test GR (we consider the chameleon mechanism here)

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





  - Environmental effects

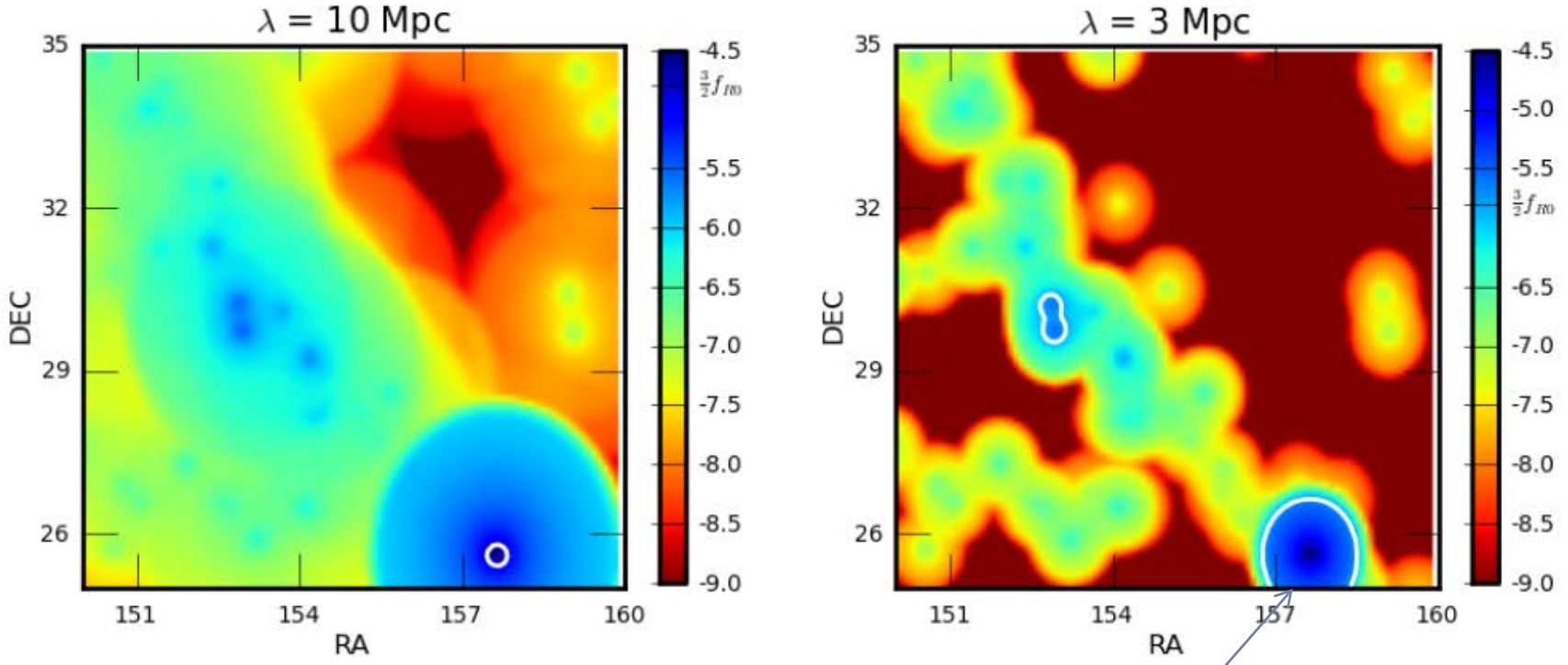
    Even if dark matter halo itself is small, if it happens to live near massive halos, GR is recovered

Using simulations, we can develop criteria to identify the places where GR is not recovered Zhao, Li, KK Phy. Rev. Lett. 107 (2011) 071303

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

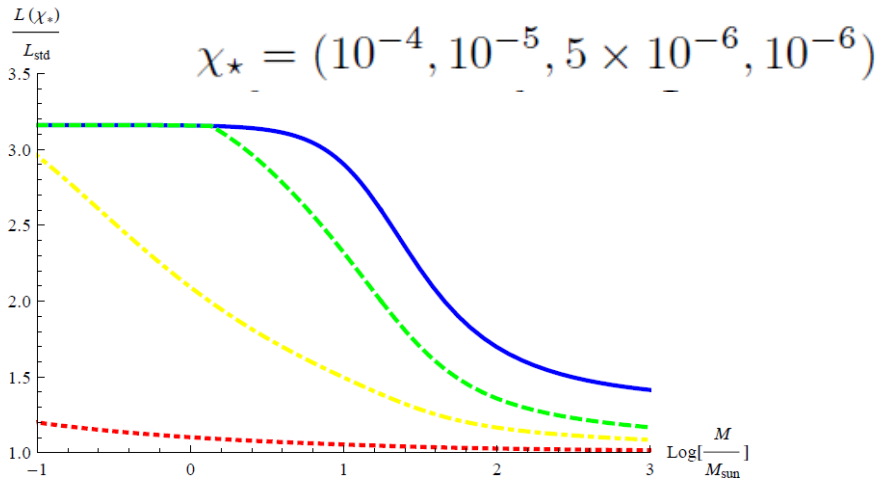
- (we consider the chameleon mechanism here)

Tests of gravity on small scales

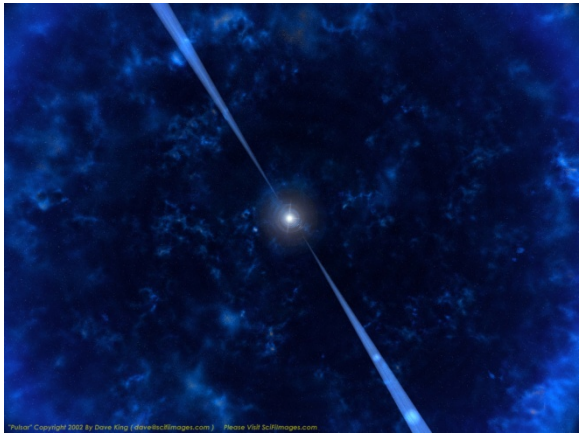
- dwarf galaxies in voids

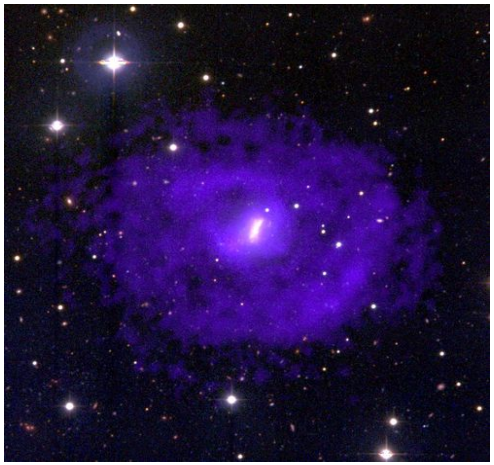
  strong modified gravity effects
  - Galaxies are brighter
  - Pulsers pulsate faster
  - Various other tests

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



Jain & VanderPlas JCAP 1110 (2011) 032

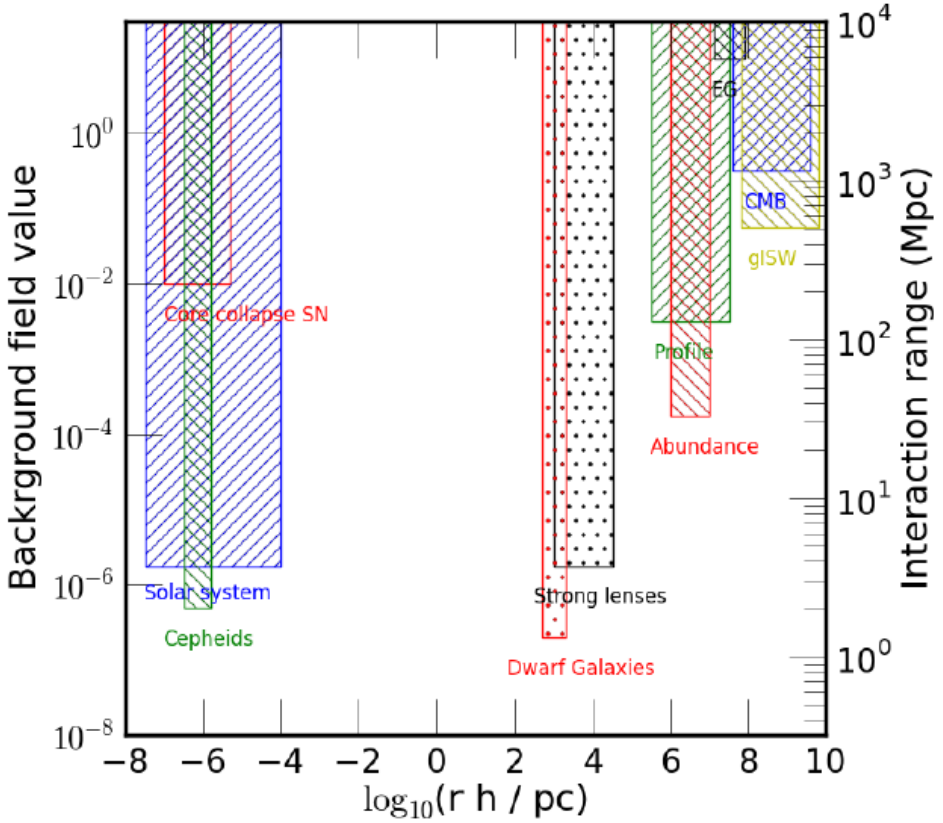




Davis et.al. Phys. Rev. D85 (2012) 123006
Jain et.al. ApJ 779 (2013) 39
Vikram et.al. JCAP1308 (2013) 020

- (we consider the chameleon mechanism here)

Constraints on chameleon gravity



Jain et.al. 1309.5389

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

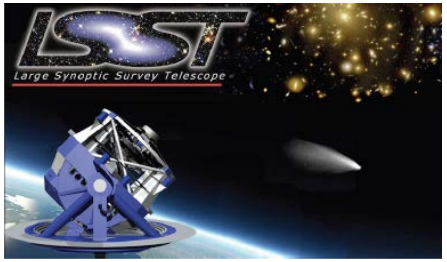
GR

- 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

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

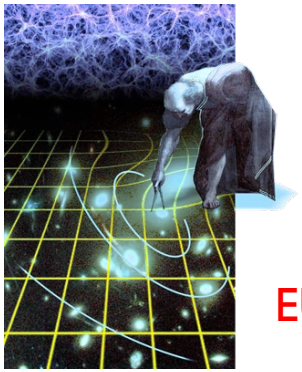


SUMIRE

  - Non-linear scales

    novel astrophysical tests of gravity

    (in a model dependent way)



EUCLID

It is required to develop theoretical models from fundamental theory