Title: Conference Talk

Speakers:

Collection: 50 Years of Horndeski Gravity: Exploring Modified Gravity

Date: July 17, 2024 - 11:45 AM

URL: https://pirsa.org/24070043

ICG Portsmouth

Testing screened modified gravity models

Kazuya Koyama

Institute of Cosmology and Gravitation,
University of Portsmouth

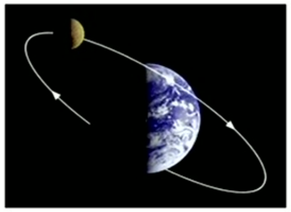
@ 50 years of Horndeski Gravity

Cosmological tests of gravity

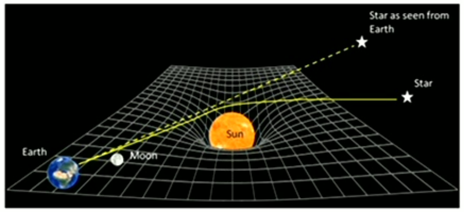
- Parametrisation of ***linearised*** Einstein equations

$$k^2\Psi = -4\pi G a^2 \mu(k,a)\rho_m\Delta_m \quad ds^2 = a^2(\eta)\left[-(1+2\Psi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j\right]$$
$$\Phi = \eta(k,a)\Psi$$

equivalently, we can also parametrise the lensing potential



$$k^2\Psi = -4\pi G a^2 \mu(k,a)\rho_m\Delta_m$$
$$k^2\frac{(\Psi+\Phi)}{2} = -4\pi G a^2 \Sigma(k,a)\rho_m\Delta_m, \quad \Sigma = \frac{\mu(1+\eta)}{2}$$



$\mu = \eta = \Sigma = 1$ for smooth dark energy $\quad \Phi = \Psi = \dfrac{\Phi+\Psi}{2}$

Horndeski gravity

- **Effective Theory of Dark Energy (EFTofDE)**

Bellini & Sawicki 1404.3713
Gleyzes, Langlois, Vernizzi 1411.3712

  - For linear perturbations, Horndeski gravity can be described by EFTofDE

$$S = \int d^4x\sqrt{-g}\left[\sum_{i=2}^{5}\mathcal{L}_i + \mathcal{L}_m\right] \qquad X = -\tfrac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

$$\mathcal{L}_2 = K(\phi, X),$$

$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi,$$

$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4,X}(\phi, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right],$$

$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}^{\nu}\phi_{;\nu}^{\alpha}\phi_{;\alpha}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

$$HM_*^2\alpha_M \equiv \frac{d}{dt}M_*^2, \quad M_*^2 \equiv 2\left(G_4 - 2XG_{4,X} + XG_{5,X} - \dot{\phi}HXG_{5,X}\right)$$

$$HM_*^2\alpha_K \equiv 2X\left(K_{,X} + 2XK_{,XX} - 2G_{3,\phi} - 2XG_{3,\phi X}\right) + \cdots$$

$$\begin{aligned} HM_*^2\alpha_B \equiv\,& 2\dot{\phi}\left(XG_{3,X} - G_{4,\phi} - 2XG_{4,\phi X}\right) \\ & + 8XH\left(G_{4,X} + 2XG_{4,XX} - G_{5,\phi} - XG_{5,\phi X}\right) \\ & + 2\dot{\phi}XH^2\left(3G_{5,X} + 2XG_{5,XX}\right), \end{aligned}$$

$$HM_*^2\alpha_T \equiv 2X\left(2G_{4,X} - 2G_{5,\phi} - \left(\ddot{\phi} - \dot{\phi}H\right)G_{5,X}\right),$$

  - α parameters evaluated in the background determine perturbations

EFT parameters

Bellini & Sawicki 1404.3713

- α_M **Planck mass run-rate**

  This parameter could be constrained by the time variation of Newton constant
- α_K **kineticity**

  This parameter does not affect the sub-horizon evolution and it is very weakly constrained although it plays an important role for stability
- α_B **braiding**

  Mixing between the derivatives of the scalar field and gravity. This could introduce instability of the scalar field in the presence of gravitational waves giving a constraint $|\alpha_M + \alpha_B| < 10^{-2}$

  Creminelli et.al. 191014035
- α_T **tensor speed excess**

  The simultaneous detection of GW and gamma-ray burst put strong constraint locally $|\alpha_T| < 10^{-15}$

  Note that there is a caveat in imposing these GW constraints due to low strong coupling scales

Phenomenological parameters

- Relation to phenomenological parameters on small scales (still linear)

$$\mu_\infty = \frac{m_0^2}{M_*^2}(1+\alpha_T+\beta_\xi^2),$$

$$\Sigma_\infty = \frac{m_0^2}{M_*^2}\left(1+\frac{\alpha_T}{2}+\frac{\beta_\xi^2+\beta_B\beta_\xi}{2}\right)$$

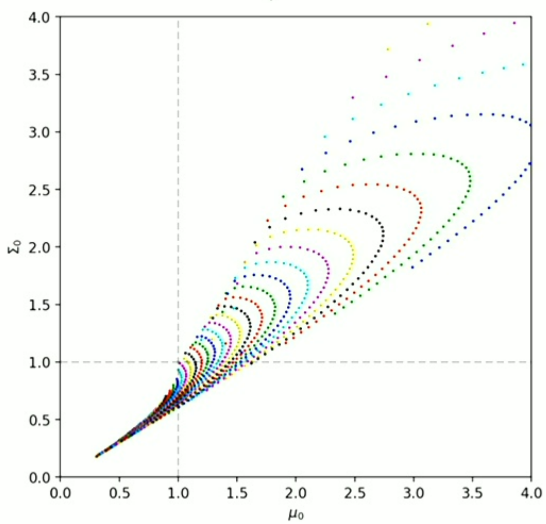
$$\beta_B = -\sqrt{\frac{2}{c_s^2\alpha}}\,\frac{\alpha_B}{2}$$

Gleyzes et.al. 1509.02191

$$\beta_\xi = \sqrt{\frac{2}{c_s^2\alpha}}\left[-\frac{\alpha_B}{2}(1+\alpha_T)+\alpha_T-\alpha_M\right]$$

$$\alpha = \alpha_K + \frac{3}{2}\alpha_B^2\ ,$$

$$c_s^2 = \frac{2}{\alpha}\Big[\left(1-\frac{\alpha_B}{2}\right)\left(\alpha_M-\alpha_T+\frac{\alpha_B}{2}(1+\alpha_T)-\frac{\dot H}{H^2}\right) + \frac{\dot\alpha_B}{2H} - \frac{\rho_m+P_m}{2M_*^2H^2}\Big]\ ,$$

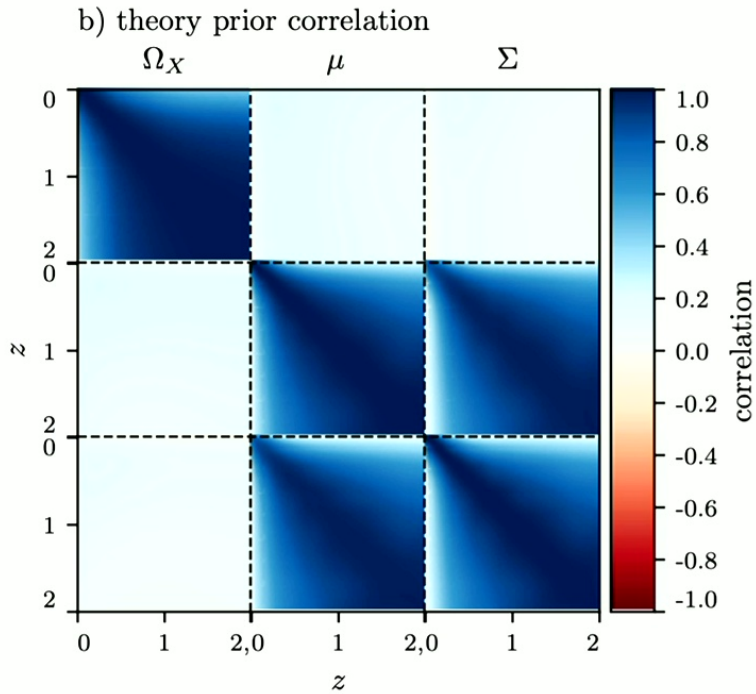


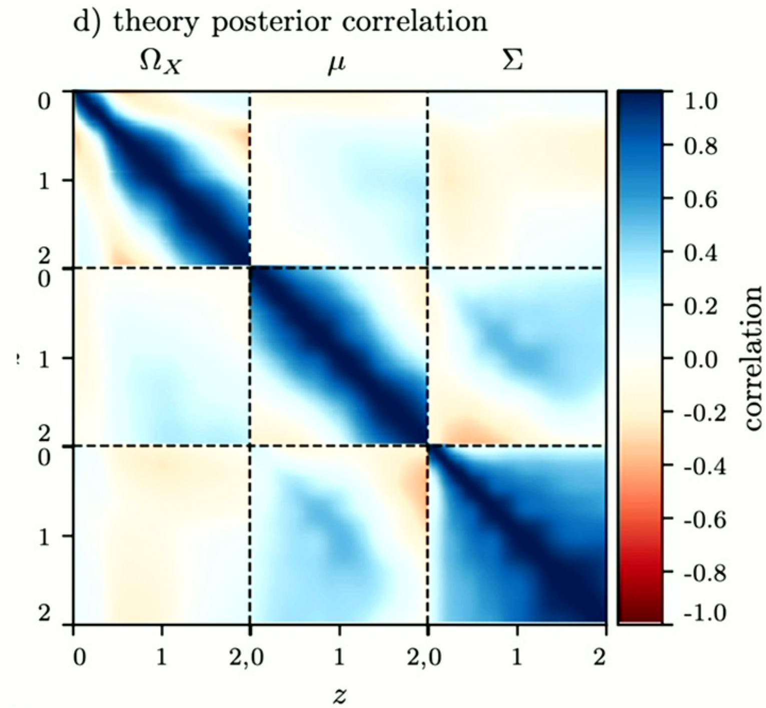
$$\alpha_i = c_i\Omega_{DE}$$

Figure by Neel Shah

Reconstruction of phenomenological parameters

- Theoretical prior from Horndeski on correlation between parameters and redshit bins





- Pogosian, Raveri, KK, Martinelli Silvestri, Zhao 2107.12990, 2107.12992

Going beyond linear scales

- **Ample information on non-linear scales**

  Parametrisation is valid only for linear perturbations

  Conservative cut-offs are required to remove data on non-linear scale, which significantly degrade the constraining power

- **Extraction of linear information**

  Non-linear modelling is required to extract the linear information, which is done normally within LCDM

- **New information on non-linear scales**

  On non-linear scales, ***screening mechanisms*** can be important leaving interesting signatures

Ultra-light scalar field

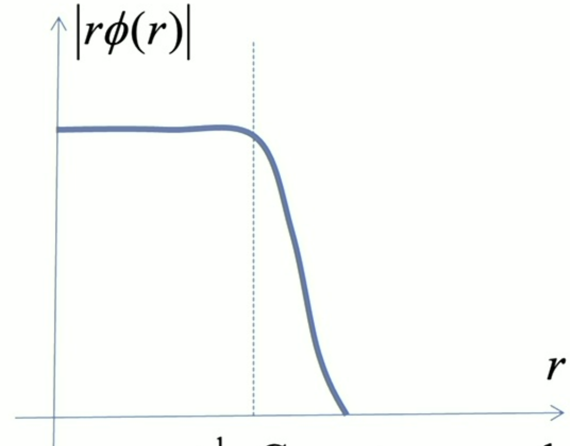
- In most of DE/MG models, there exists a scalar field with tiny mass

$$S = \int d^4x \left[-\frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2} m^2 \phi^2 \right] - \frac{\alpha}{M_{pl}} \int d^4x \, \phi \, \rho$$

static source

$$(\nabla^2 - m^2)\phi = \frac{\alpha}{M_{pl}} \rho, \qquad \frac{\phi}{M_{pl}} = -\left(\frac{\alpha}{4\pi M_{pl}^2} \right) \frac{M}{r} \exp(-m r)$$

$$\Rightarrow \begin{cases} \phi = -\left(\frac{\alpha}{4\pi M_{pl}^2} \right) \frac{M}{r}, & r < m^{-1} \\ \phi \to 0, & r > m^{-1} \end{cases}$$



m^{-1} : Compton wavelength

if $m^{-1} \approx H_0^{-1}$ the scalar field mediates a long-range force

Fifth force

- Due to the coupling between the scalar and matter, the geodesic equation is modified as

$$\vec{a} = -\nabla\Psi - \frac{\alpha}{M_{pl}}\nabla\phi = F_G \boxed{+ F_5}$$ Fifth force

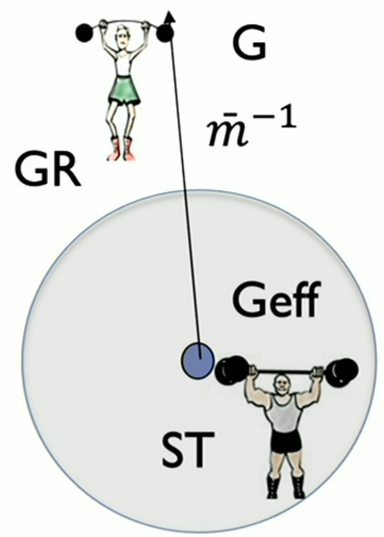
for $r < m^{-1}$

$$F_5 = \frac{2\alpha^2}{8\pi M_{pl}^2}\frac{M}{r^2}$$

$$F_G = \frac{1}{8\pi M_{pl}^2}\frac{M}{r^2}$$

Fifth force is strongly constrained in the solar system

$$\alpha^2 < 10^{-5}$$



Screening mechanism

- The coupling constant or mass need to be scale dependent

$$m\big|_{\cos mo} = O(H_0) \qquad m\big|_{local} >> H_0$$

$$\alpha^2\big|_{\cos mo} = O(1) \qquad \alpha^2\big|_{local} \to 0$$

- Two representative mechanisms

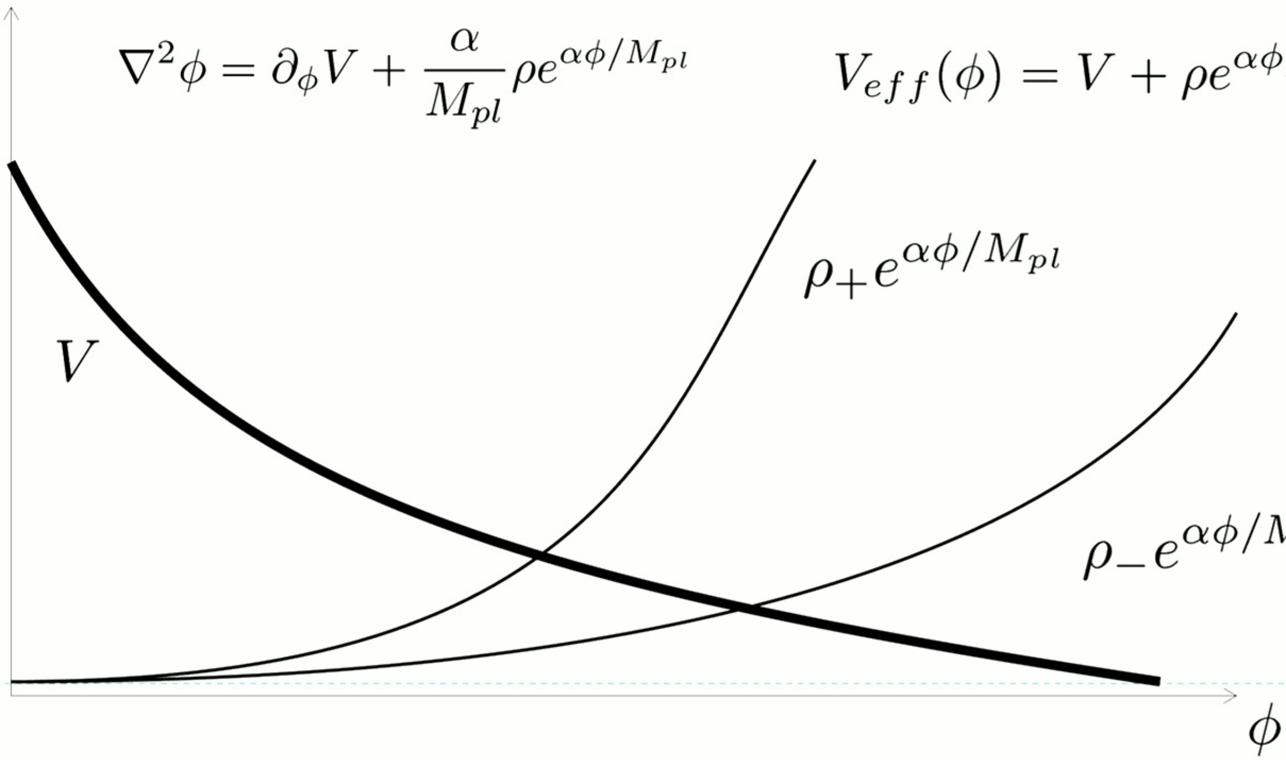
1. Chameleon mechanism
2. Vainshtein mechanism (symmetron/dilaton, Kmoflauge)

Chameleon mechanism

Khoury & Weltman astro-ph/0309300

$$S = \int d^4x \sqrt{-\tilde{g}} \left(\frac{M_{pl}^2}{2} R - \frac{1}{2} (\nabla \phi)^2 - V(\phi) \right) + S_m[A^2(\phi) g_{\mu\nu}] \qquad A(\phi) = \exp\left(\alpha \frac{\phi}{M_{pl}} \right)$$

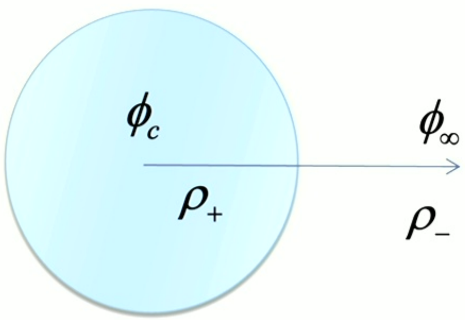
$$\nabla^2 \phi = \partial_\phi V + \frac{\alpha}{M_{pl}} \rho e^{\alpha\phi/M_{pl}} \qquad V_{eff}(\phi) = V + \rho e^{\alpha\phi/M_{pl}}$$



Thin shell condition

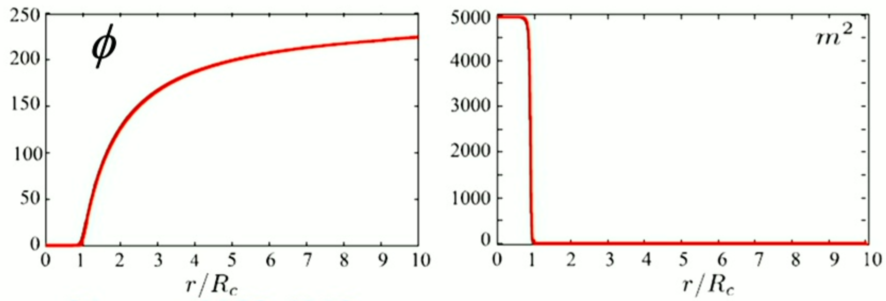
- If the thin shell condition is satisfied, only the shell of the size ΔR_c contributes to the fifth force Khoury & Weltman astro-ph/0309411

$$V_{eff}(\phi) = V + \rho e^{\alpha\phi/M_{pl}}$$



$$\phi(r) = -\left(\frac{\alpha}{4\pi M_{pl}}\right)\left(\frac{3\Delta R_c}{R_c}\right)\frac{M\exp\left(-m_\infty(r-R_c)\right)}{r} + \phi_\infty$$

$$\frac{\Delta R_c}{R_c} = \frac{(\phi_\infty - \phi_c)/M_{pl}}{6\alpha\Psi_c} << 1 \qquad \Psi_c = \frac{GM}{R_c}$$



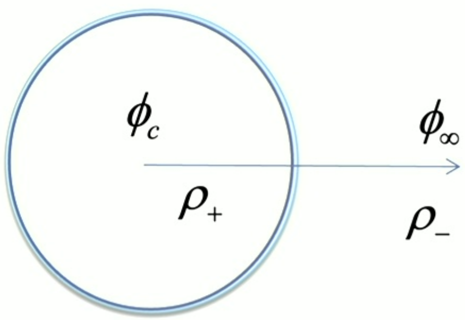
Silvestri 1103.4013

Screening is determined by the gravitational potential of the object

Thin shell condition

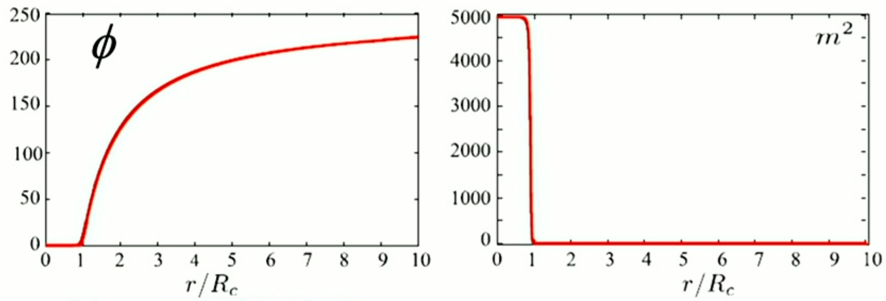
- If the thin shell condition is satisfied, only the shell of the size ΔR_c contributes to the fifth force Khoury & Weltman astro-ph/0309411

$$V_{eff}(\phi) = V + \rho e^{\alpha\phi/M_{pl}}$$



$$\phi(r) = -\left(\frac{\alpha}{4\pi M_{pl}}\right)\left(\frac{3\Delta R_c}{R_c}\right)\frac{M\exp\left(-m_\infty(r-R_c)\right)}{r} + \phi_\infty$$

$$\frac{\Delta R_c}{R_c} = \frac{(\phi_\infty - \phi_c)/M_{pl}}{6\alpha\Psi_c} << 1 \qquad \Psi_c = \frac{GM}{R_c}$$



Silvestri 1103.4013

Screening is determined by the gravitational potential of the object

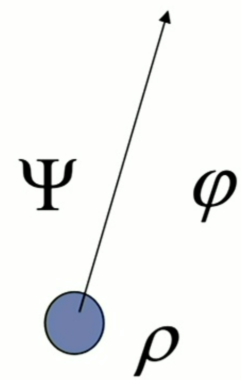
Vainshtein mechanism

- Vainshtein mechanism

  originally discussed in massive gravity

  rediscovered in DGP brane world model

  linear theory



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

$$\nabla^2\Psi = 4\pi G\rho - \frac{1}{2}\nabla^2\varphi \qquad ds^2 = -(1+2\Psi)dt^2 + a(t)^2(1-2\Phi)d\vec{x}^2 \qquad \psi = \psi_0 + \varphi$$

even if gravity is weak, the scalar can be non-linear $\quad r_c \sim m^{-1} \sim H_0^{-1}$

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

Vainshtein radius

- Spherically symmetric solution for the scalar

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

r_g | r_V | r_c

4D Einstein	4D BD	
$\Phi = \frac{r_g}{2r}\left(1+\frac{4}{3}\left(\frac{r}{r_V}\right)^{3/2}\right)$, $\Psi = \frac{r_g}{2r}\left(1-\frac{4}{3}\left(\frac{r}{r_V}\right)^{3/2}\right)$	$\Phi = \frac{r_g}{2r}\left(\frac{2}{3}\right)$, $\Psi = \frac{r_g}{2r}\left(\frac{4}{3}\right)$	

$$\left(\frac{r_V}{r}\right)^{-3/2} \propto \left(\frac{GM}{r^3}r_c^2\right)^{-3/2}$$

Screening is determined by the curvature of the object

- 2.95km 0.1 kpc 3000Mpc for the Sun

Screening mechanisms

- They look contrived but some theories naturally have these mechanisms

f(R) gravity

$$F(R) = R - 2\Lambda - |f_{R0}| \frac{R_0^2}{R}$$

we expect to recover GR in the limit $R/R_0 \gg 1$

In fact, in Einstein frame this is nothing but chameleon with $V = V_0 - M^4 \left(\phi / M_{pl}\right)^{1/2}$

Brax et.al. arXiv:0806.3415

DGP gravity

$$S = \frac{1}{32\pi G r_c} \int d^5x \sqrt{-g_{(5)}}\, R_{(5)} + \frac{1}{16\pi G} \int d^4x \sqrt{-g} R + \int d^4x \sqrt{-g} L_m$$

we expect to recover GR in the limit $r/r_c \ll 1$ and this is realised by Vainshtein

Horndeski gravity/EFTofDE

- Kinetic braiding

$$G_4 = \frac{1}{2}R, \quad G_5 = 0, \qquad \mathcal{L}_2 = K(\phi, X),$$

$$K = K(\phi, X), \quad G_3 = G_3(\phi, X) \qquad \mathcal{L}_3 = -G_3(\phi, X)\Box\phi$$

$$\partial^2\Psi = \frac{\kappa}{2}a^2\delta\rho_{\rm m} - \frac{1}{2}\alpha_{\rm B}H\partial^2 V_X \qquad C_2 \equiv -\frac{\alpha_{\rm B}}{2} - \frac{1}{2H^2}\frac{\mathrm{d}}{\mathrm{d}t}(\alpha_{\rm B}H) - \frac{1}{H^2}(\rho_{\rm DE} + p_{\rm DE})$$

$$\partial^2 V_X + \frac{2\alpha_{\rm B}}{H(4C_2 + \alpha_{\rm B}^2)}\frac{V_X^{(2)}}{a^2} = \frac{2\alpha_{\rm B}}{H(4C_2 + \alpha_{\rm B}^2\kappa)}\frac{\kappa}{2}a^2\delta\rho_{\rm m}. \qquad V_X^{(2)} \equiv \left(\partial^2 V_X\right)^2 - \left(\partial_i\partial_j V_X\right)^2$$

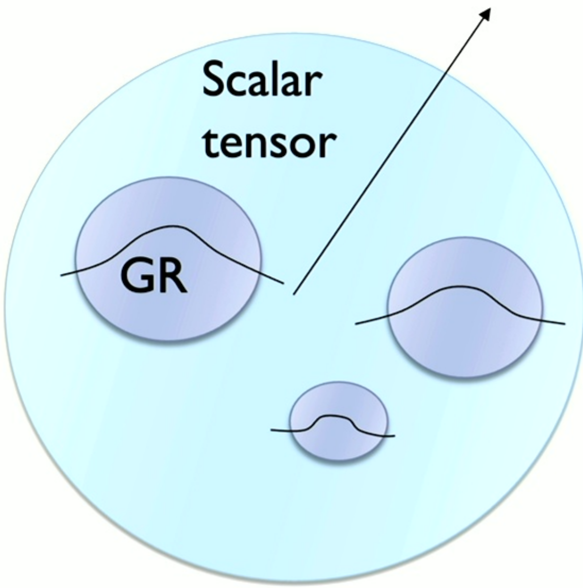
Brando, KK, Winther arXiv:2303.09549

- Linearised gravity

$$G_{\rm eff} = G\left(1 - \frac{\alpha_{\rm B}^2}{C_2 + \alpha_{\rm B}^2}\right)$$ this modification is screened by Vainshtein mechanism

Behaviour of gravity

Three 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

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

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

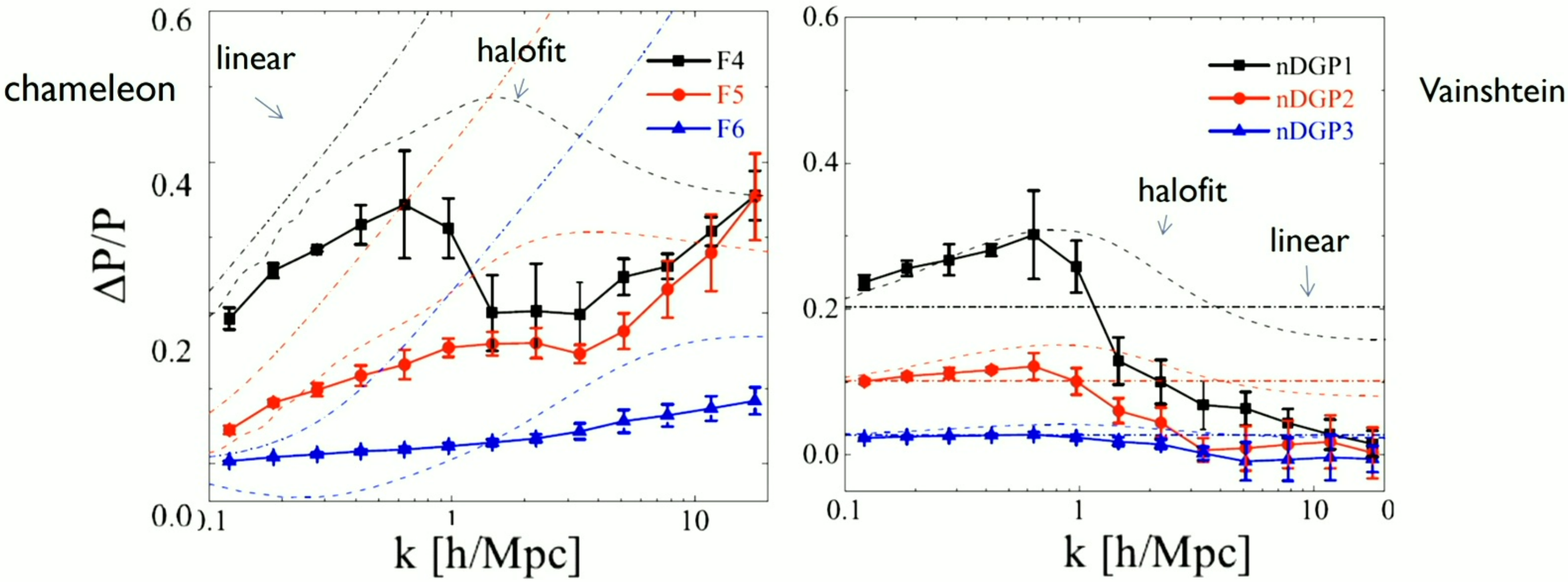
$$\rho_{solar} \approx 10 g / cm^3$$

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

Power spectrum

- Power spectrum deviation from LCDM

Falck, KK, Zhao arXiv:1503.06673



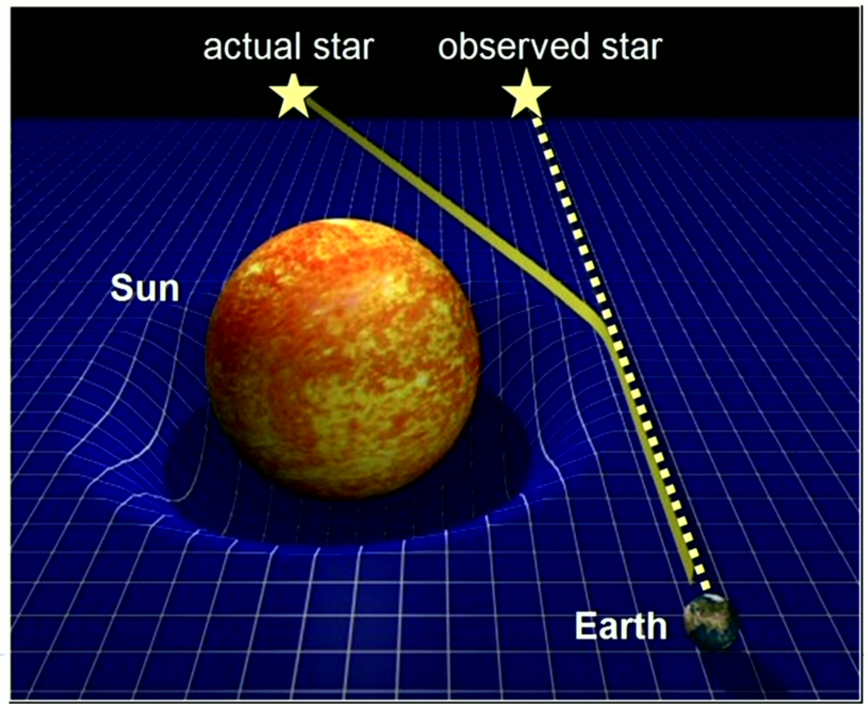
- Scale dependent enhancement of linear growth
- Screening suppresses deviations from LCDM

- Scale independent enhancement of linear growth
- Screening efficiently suppresses deviations from LCDM

How do we test gravity in cosmology?

- Newton potential Ψ
  controls dynamics of non relativistic particles

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



- Space curvature Φ
  also deflects lights

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

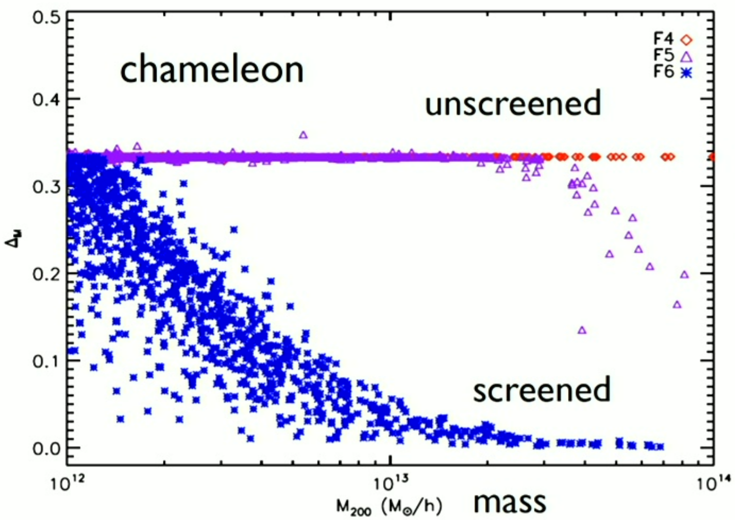
dynamical mass = lensing mass in GR

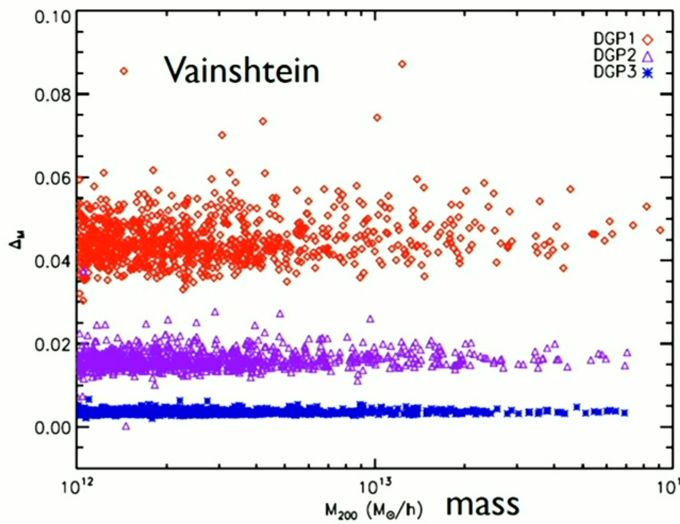
Screening of dark matter halo

Falck, KK, Zhao arXiv:1503.06673

- Dynamical mass/lensing mass

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





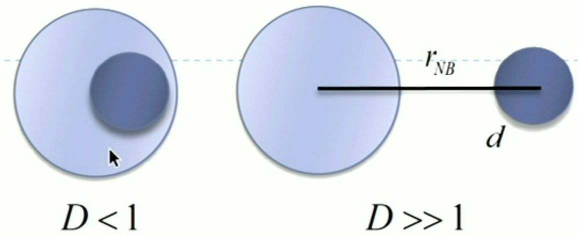
- Screening depends on mass of dark matter halos
- Massive halos with a deeper potential are more screened

- Screening does not depend on mass of dark matter halos
- The Vainshtein radius is always larger than the size of halos

Screening of dark matter halo

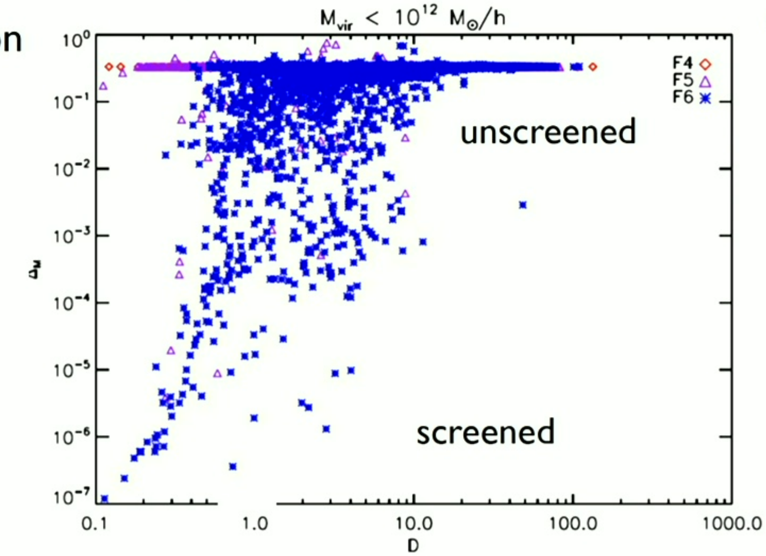
Falck, KK, Zhao arXiv:1503.06673

- Environment

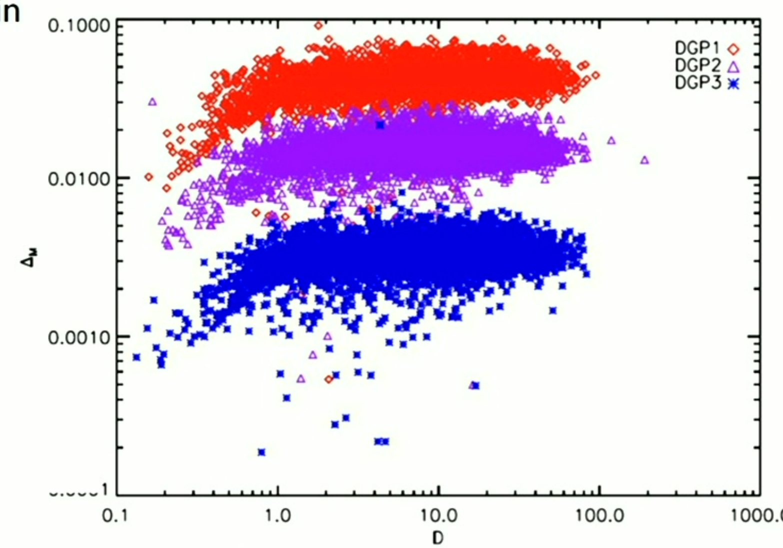


$D = d / r_{NB}$, d : distance to the nearest halo with $M_{NB} > M$

chameleon



Vainshtein



- Screening depends on environment
- Halos in "dense" environment are more screened

- Screening does not depend on environment

Where to test GR

- GR is recovered in "high dense regions"

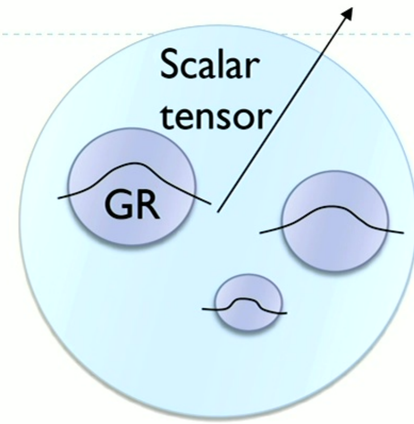
  Details depend on the screening mechanism

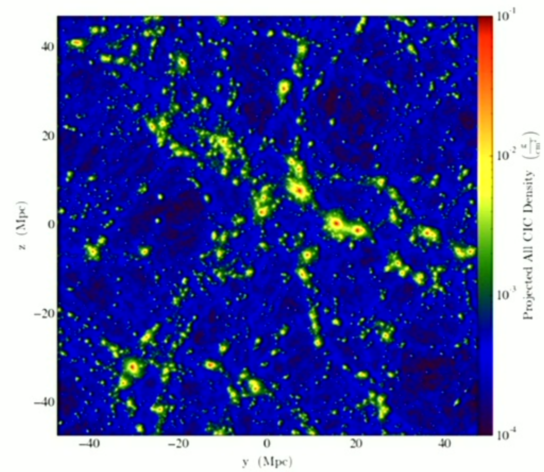
  Chameleon mechanism (environmental dependent mass)

  - Screening of dark matter halos depends on mass and environment
  - Strongest constraints come from objects with a shallow potential in low density environment

  Vainshtein mechanism (derivative interaction)

  - Screening of dark matter halos does not depend on mass and environment
  - Strongest constraints come from linear scales

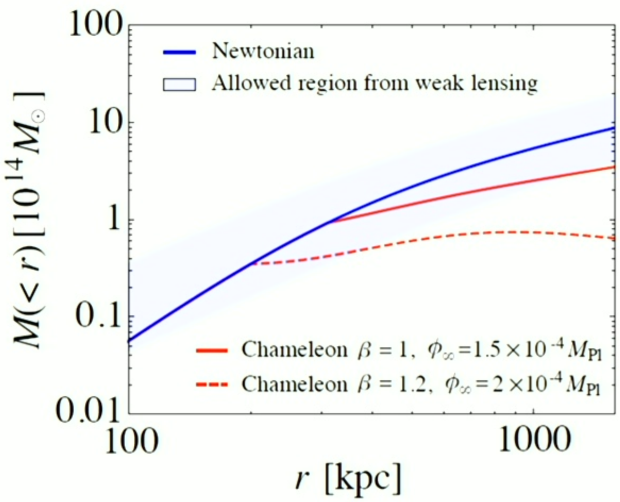




Testing chameleon gravity

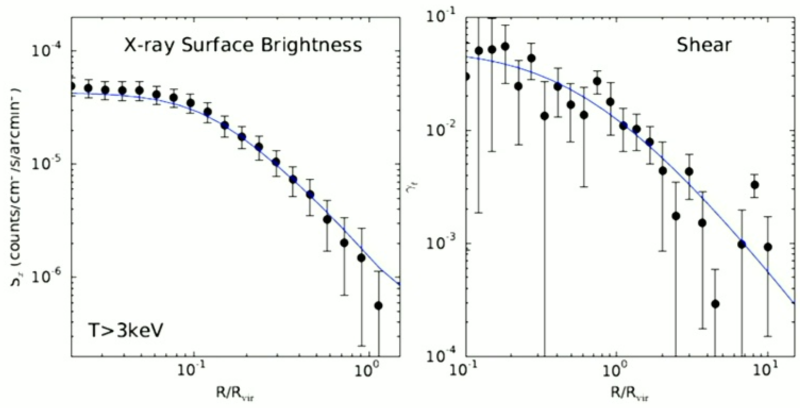
- Outskirt of clusters

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



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

Dynamical mass can be inferred from X-ray and SZ



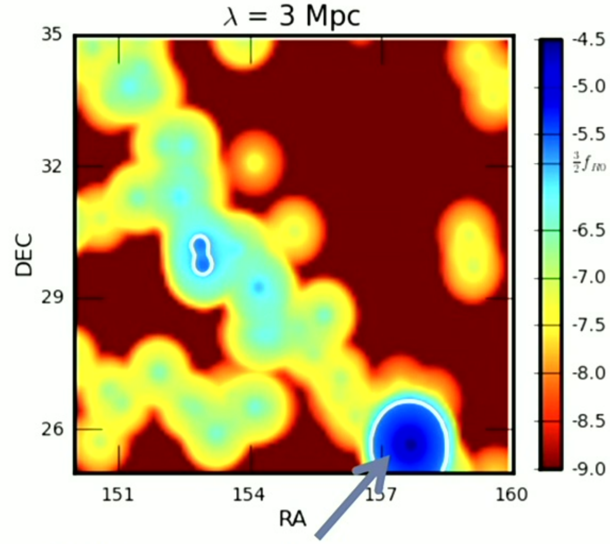
48 X-ray clusters from XCS compared with lensing (shear) from CFHTLS

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

Wilcox et.al. MNRAS 452 (2015) 1171

Creating a screening map (we consider the chameleon mechanism here)

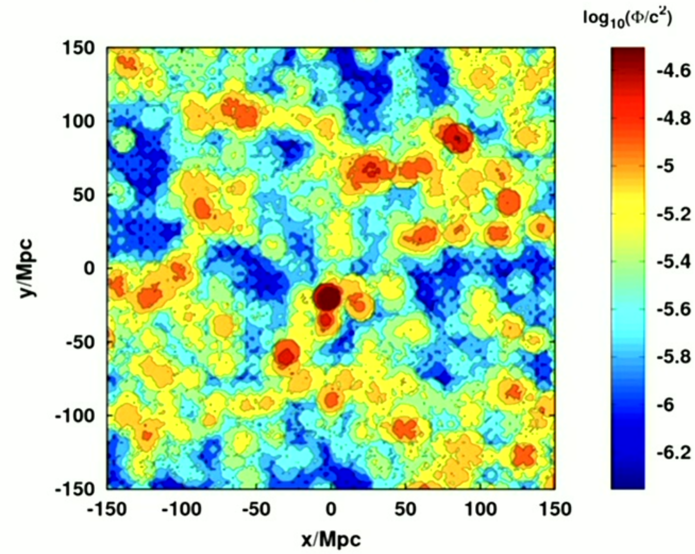
- It is essential to find places where GR is not recovered
  - Small galaxies in underdense regions
  - SDSS galaxies within 200 Mpc



GR is recovered

Cabre, Vikram, Zhao, Jain, KK 1204.6046

2M++ galaxies



(a) Φ

Desmond et.al. 1705.0242

Tests of chameleon gravity

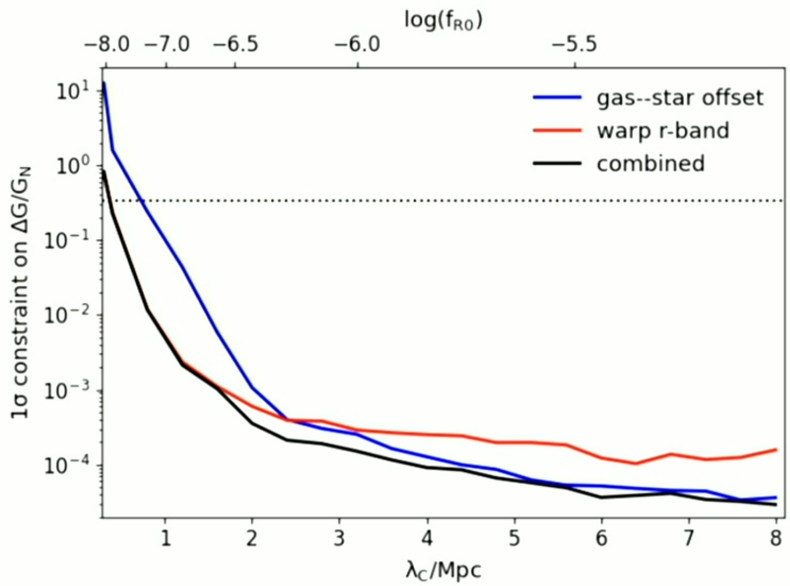
Hui, Nicolis & Stubbs Phys. Rev. D80 (2009) 104002

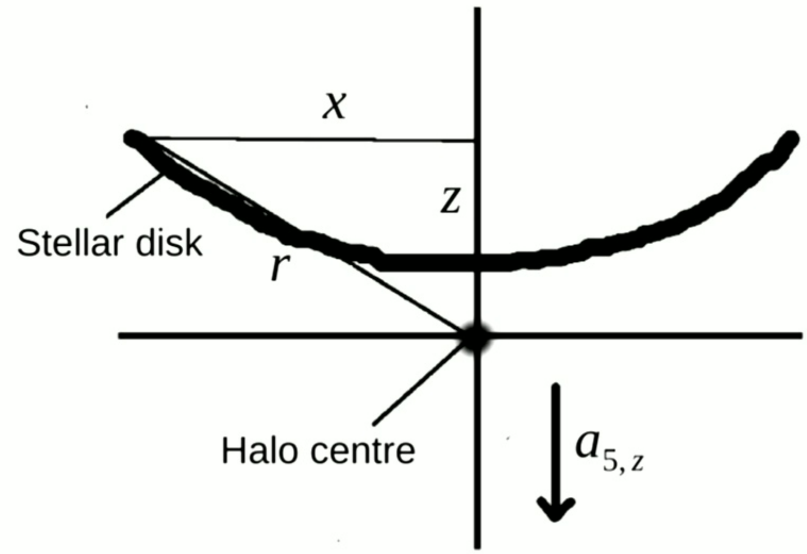
- dwarf galaxies in voids

  strong modified gravity effects on dark matter (but not on stars)

  - Warping of stellar disks
  - Gas-star offset

$$f_{R0} < 1.4 \times 10^{-8}$$





Desmond & Ferreira arXiv:2009.08743

Tests of chameleon gravity

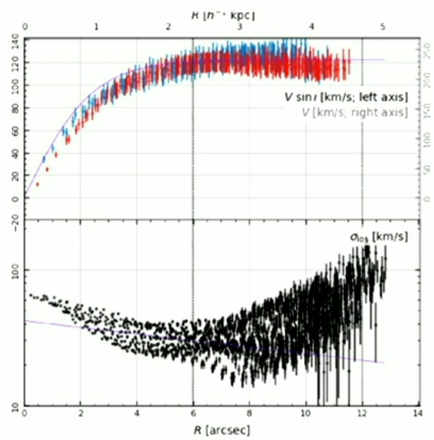
- Rotation velocities of gas and stars Landim, Desmond, KK, Penny 2407.08825

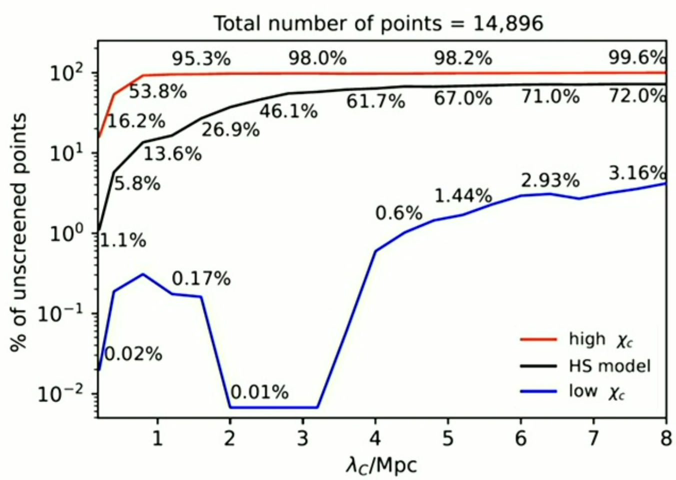
SDSS MaNGA (1110 galaxies)

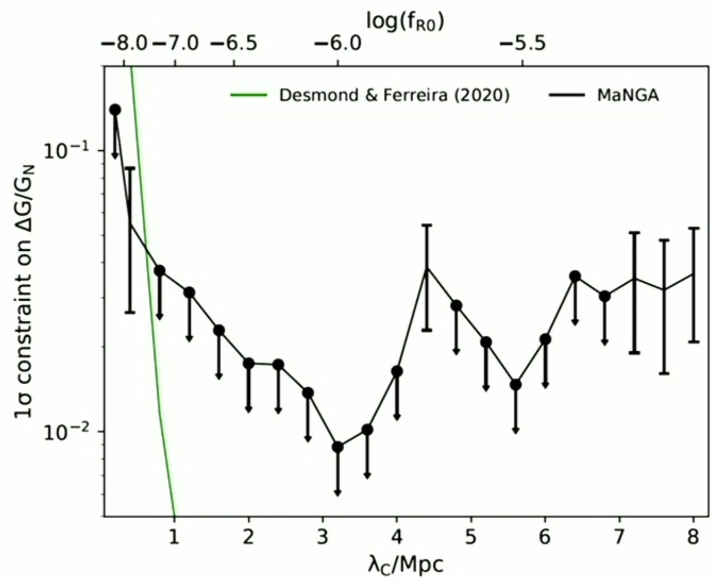
Unscreened points

$$\frac{V_{c,g}^2}{V_{c,*}^2} = 1 + 2\alpha_c^2 = 1 + \frac{\Delta G}{G_N}$$

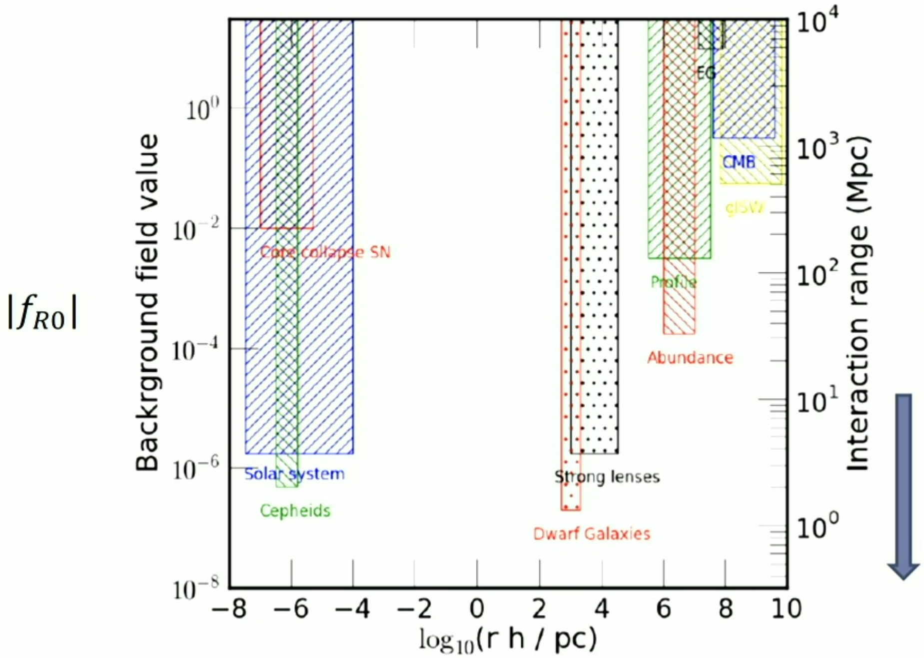
A comparison between screened and unscreened points gives constraints on $\frac{\Delta G}{G_N}$







Constraints on chameleon gravity



Jain et.al. 1309.5389

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

The Novel Proves Project
https://arxiv.org/abs/1908.03430
https://www.novelprobes.org/

- Non-linear regime is powerful for constraining chameleon gravity
- Astrophysical tests could give better constraints than the solar system tests

Chameleon v Vainshtein

- Screening mechanism

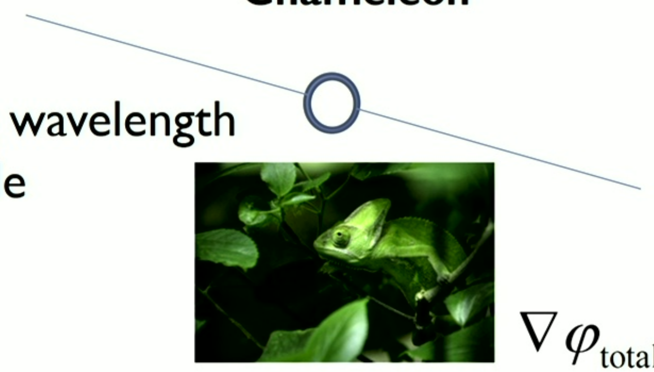
The self-field of the screened body and the external field do not in general superpose but rather interfere in a manner dependent on the non-linear interactions

Hu 0906.2024

$$\nabla\varphi_{\mathrm{total}} = \nabla\varphi_{\mathrm{external}} + \nabla\varphi_{\mathrm{internal}} + \nabla\varphi_{\mathrm{interference}}$$

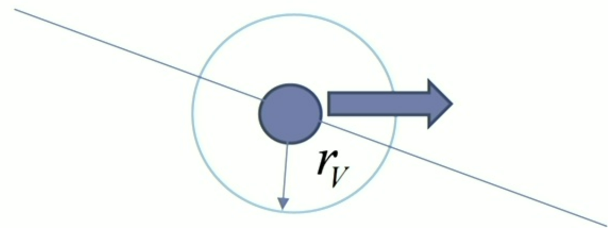
Chameleon

long wavelength mode



$$\nabla\varphi_{\mathrm{total}} \sim 0$$

Vainshtein



$$\nabla\varphi_{\mathrm{total}} \sim \nabla\varphi_{\mathrm{external}}$$

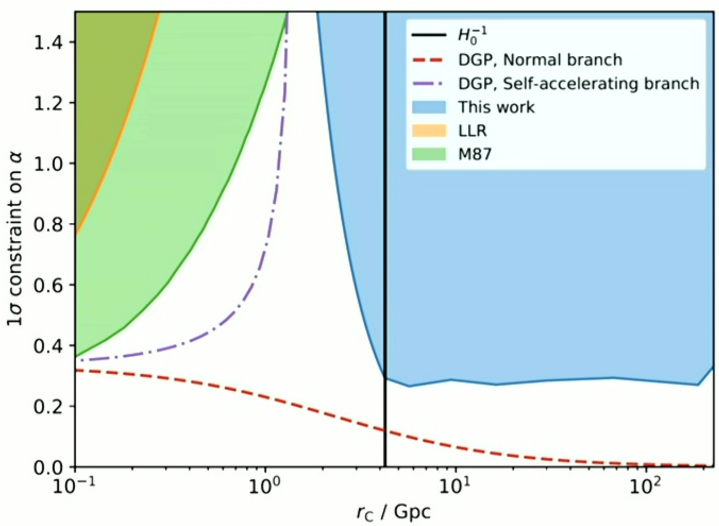
Tests of Vainshtein mechanism

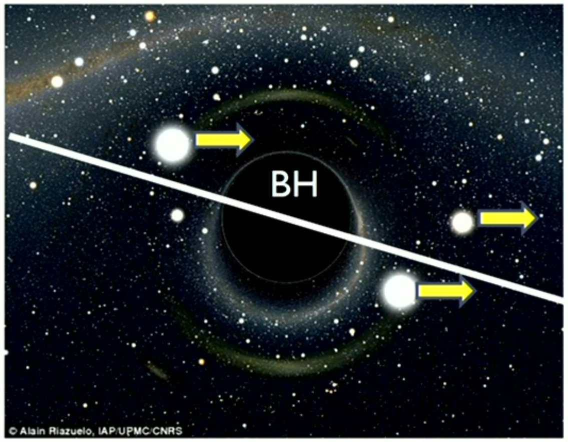
- Apparent equivalent principle violation

  Stars can feel an external field generated by large scale structure but a black hole does not due to no hair theorem

central BH lag behind stars

Hui, Nicolis 1201.1508





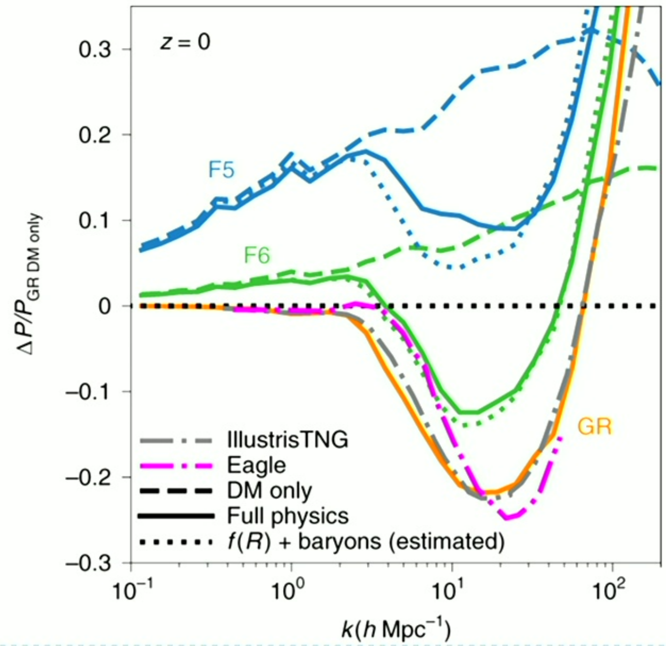
Sakstein et.al. 1704.02425,
Bartlett et.al. 2010.05811

Open questions for future cosmology surveys

- Stage IV surveys (DESI, Euclid, Rubin, …)

Amazing statistical power - can we get competitive constraints compared with solar system/astrophysical/GW constraints?

- This is limited by the accuracy of non-linear power spectrum predictions at high k
- Baryonic effects dominate at high k
- They offer an independent test on different scales with different systematics
- Which model to use. The prediction of the non-linear power spectrum requires a model



Arnold et.al. 1907.02977

Summary

- Horndeski gravity played a central role in developing cosmological and astrophysical tests of gravity
  - Linear scales

    theory informed tests of gravity
  - Non-linear scales

    novel tests of gravity in screened models

Stage IV dark energy surveys

Can we get competitive constraints compared with solar system/astrophysical/GW constraints?

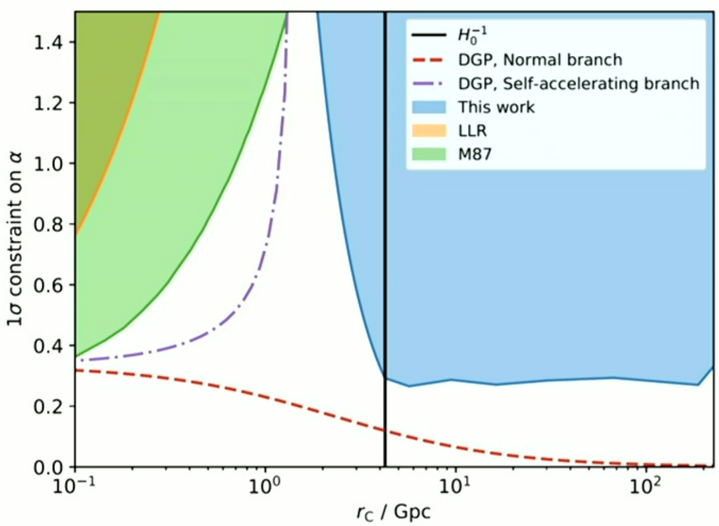
Tests of Vainshtein mechanism

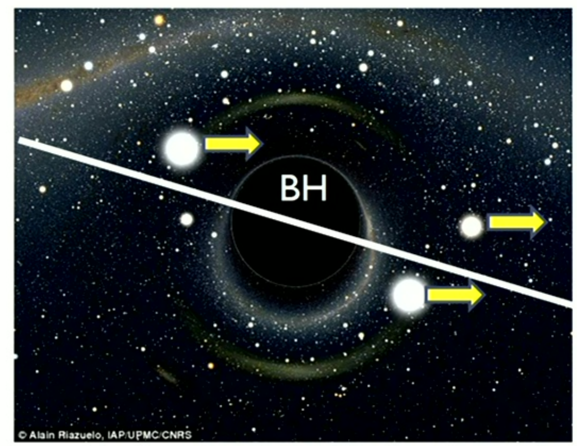
- Apparent equivalent principle violation

Stars can feel an external field generated by large scale structure but a black hole does not due to no hair theorem

central BH lag behind stars

Hui, Nicolis 1201.1508





Sakstein et.al. 1704.02425,
Bartlett et.al. 2010.05811