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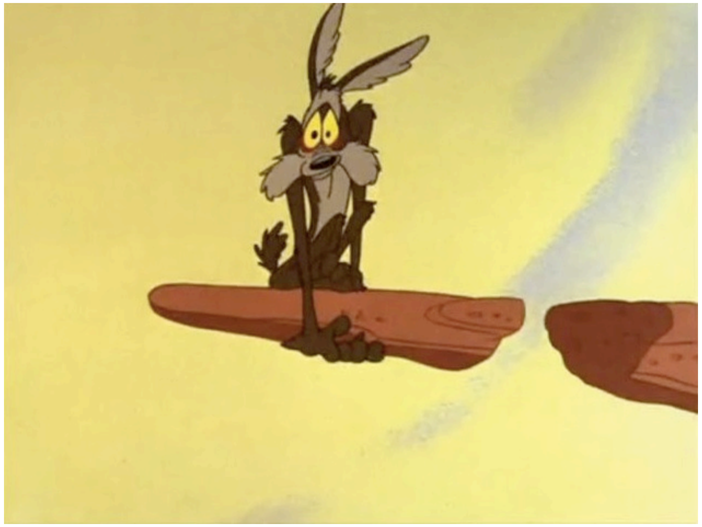

”Gravity quirks: non-linear nuisance or scaling sign?”

or

Galileons in voids

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Overview

- Modified and massive gravity
- Screening of gravity
- Galileons and their effect in voids
- Obervational prospects

Modified Gravity

- Motivations
  - explain dark energy
  - distinct from GR/Lambda
  - very large scales untested
  - upcoming measurements
  - “quantum gravity”

  …

Screening Mechanisms

- Modifications of gravity typically exhibit screening mechanisms: some conditions under which the “fifth force” is suppressed

- Thus we can retain “normal” gravity in tested range, but allow deviations outside

Massive Gravity

- dRGT / bimetric gravity – nolinear completion of GR
  de Rham, Gabadadze & Tolley 2010-11
- Realizes Vainshtein mechanism
- Evades Boulware-Deser ghost,
  Hassan & Rosen 2011
- Hope: self-acceleration, screening of Λ
- Galileons: decoupling limit of massive gravity

Nicolis, Ratazzi, Trincherini 2010

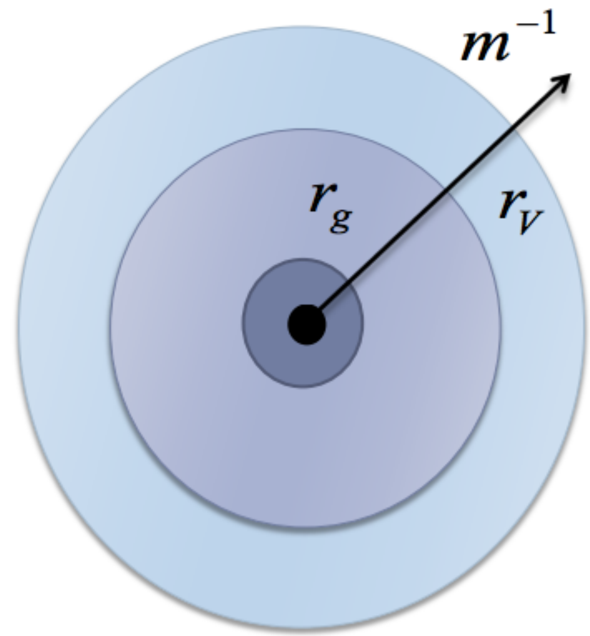
Screening Mechanism: Vainshtein

$$r_V = \left(m^{-4} r_g\right)^{1/5} >> r_g, \quad r_g = 2GM$$

$$\Psi = -\frac{4GM}{3r} \qquad \Psi = -\frac{GM}{r} + O\left(\left(\frac{r}{r_V}\right)^{5/2}\right)$$

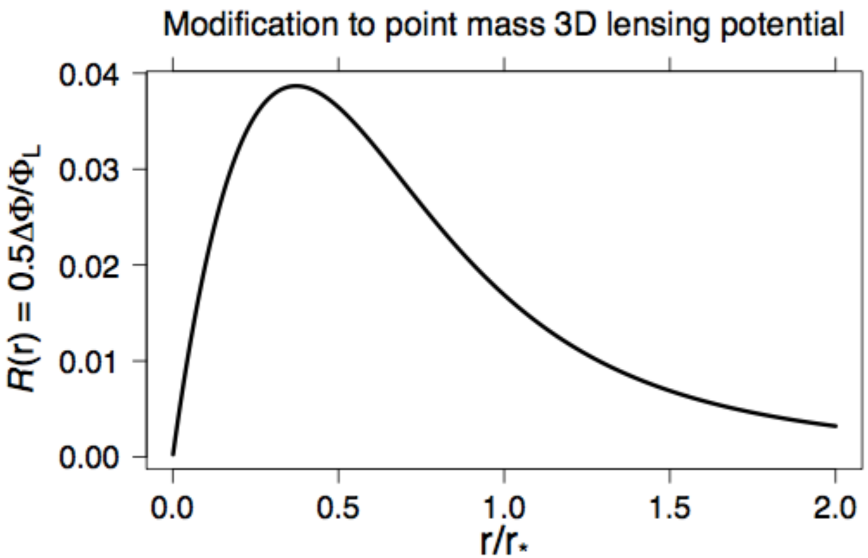
$$\Phi = -\frac{2GM}{3r} \qquad \Phi = -\frac{GM}{r} + O\left(\left(\frac{r}{r_V}\right)^{5/2}\right)$$

$$r_v < r < m^{-1} \qquad r_g < r < r_v$$



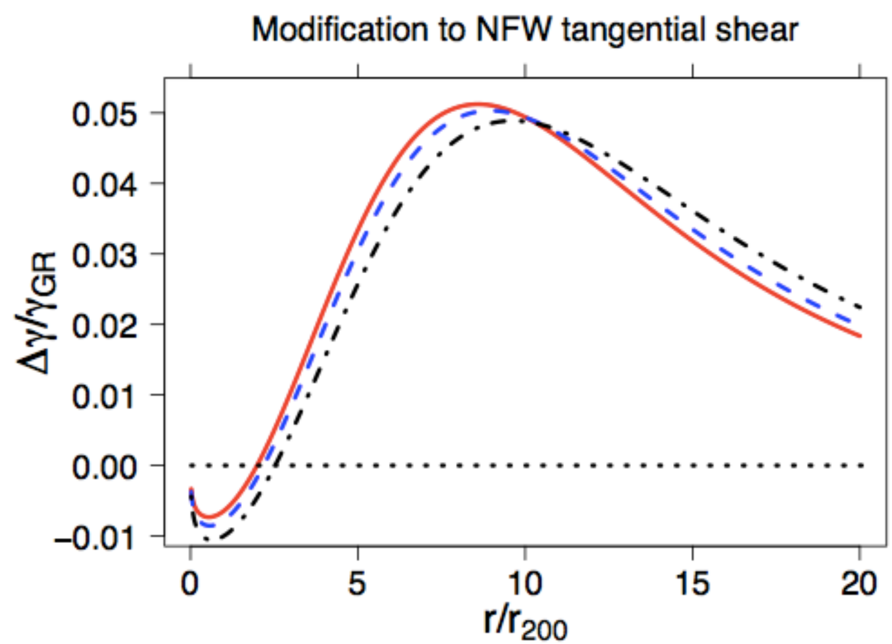
Inside Vainshtein radius: GR
Outside Vainshtein radius: massive gravity
Very large scales: Yukawa fall-off, V ~ exp[-mr]/r

Galileon observational signatures: enhanced lensing – shear for clusters



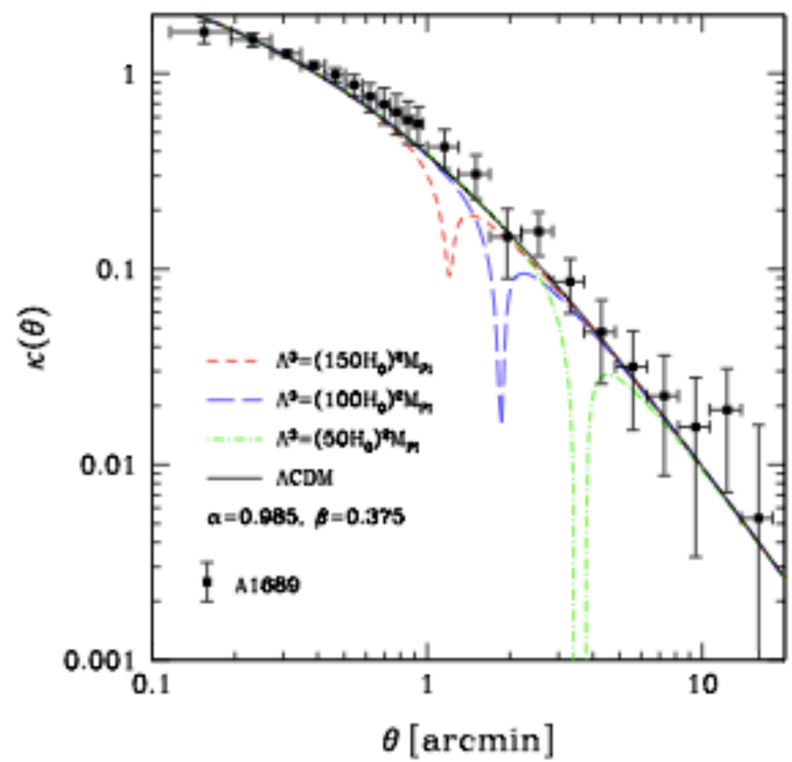
$$\Delta\Phi = \frac{\beta}{\Lambda_3^3}(\partial_r \pi)^2$$

~ 5% effect



Wyman 2011

Galileon observational signatures: enhanced lensing – shear for clusters



Test with galaxy cluster Abell 1689

FIG. 4: The convergence κ as a function of θ for different strong coupling scales. The curves correspond to $\Lambda^3 = (150H_0)^2 M_{\rm Pl}$ (dotted red), $\Lambda^3 = (100H_0)^2 M_{\rm Pl}$ (dashed blue), $\Lambda^3 = (50H_0)^2 M_{\rm Pl}$ (dot-dashed green), and ΛCDM (black solid), respectively. We take $\alpha = 0.985$ and $\beta = 0.375$.

Narikawa et al. 2013

Galileons: dominating in voids?

$$\mathcal{L}(\pi)_{\mu\nu} = \alpha X^{(1)}_{\mu\nu} + (\beta/\Lambda^3) X^{(2)}_{\mu\nu} + (\gamma/\Lambda^6) X^{(3)}_{\mu\nu}$$

$$2\nabla^2\Psi = 8\pi G\langle\rho\rangle + \frac{6\,\alpha}{\mathrm{m_{pl}}}\frac{\pi'}{r} + \frac{6\,\beta}{\mathrm{m_{pl}}\Lambda^3}\frac{(\pi')^2}{r^2} + \frac{6\,\gamma}{\mathrm{m_{pl}}\Lambda^6}\frac{(\pi')^3}{r^3}$$

$$(\nabla^2 - \partial_i^2)(\Phi - \Psi) = 8\pi G\langle p\rangle - \frac{4\,\alpha}{\mathrm{m_{pl}}}\frac{\pi'}{r} - \frac{2\,\beta}{\mathrm{m_{pl}}\Lambda^3}\frac{(\pi')^2}{r^2}$$

$$\alpha\nabla^2(2\Psi - \Phi) + \frac{2\,\beta}{\Lambda^3}\frac{\pi'}{r}\nabla^2(\Psi - \Phi) - \frac{3\,\gamma}{\Lambda^6}\frac{(\pi')^2}{r^2}\nabla^2\Phi = 0$$

arXiv:1304.5239, PRL…
with D. Spolyar and J. Silk

Perturbed equations; quintic eqn. for the galileon field
Solve numerically – static, spherically-symmetric case

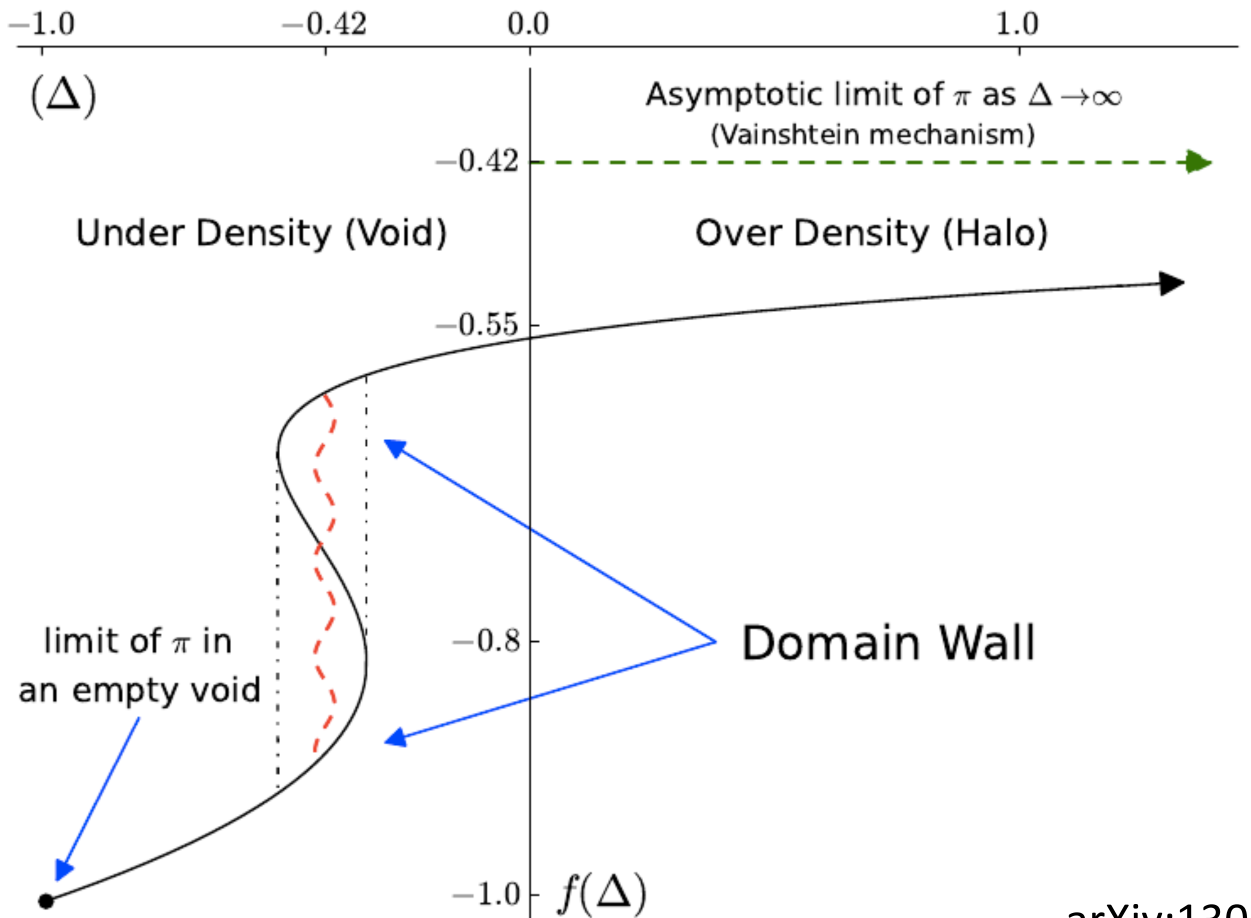
Galileons: Main Findings

- New cosmological solution:
  a) Effective cosmological constant
  b) Phantom-like dark energy
  c) Density-dependent dark energy (with C. C.)
- The effective dark energy equation of state is density- hence time-dependent, and in voids sign. different from background value
- Leads to inhomogeneous/scale-dependent dark-energy properties, with differential expansion rate

arXiv:1304.5239

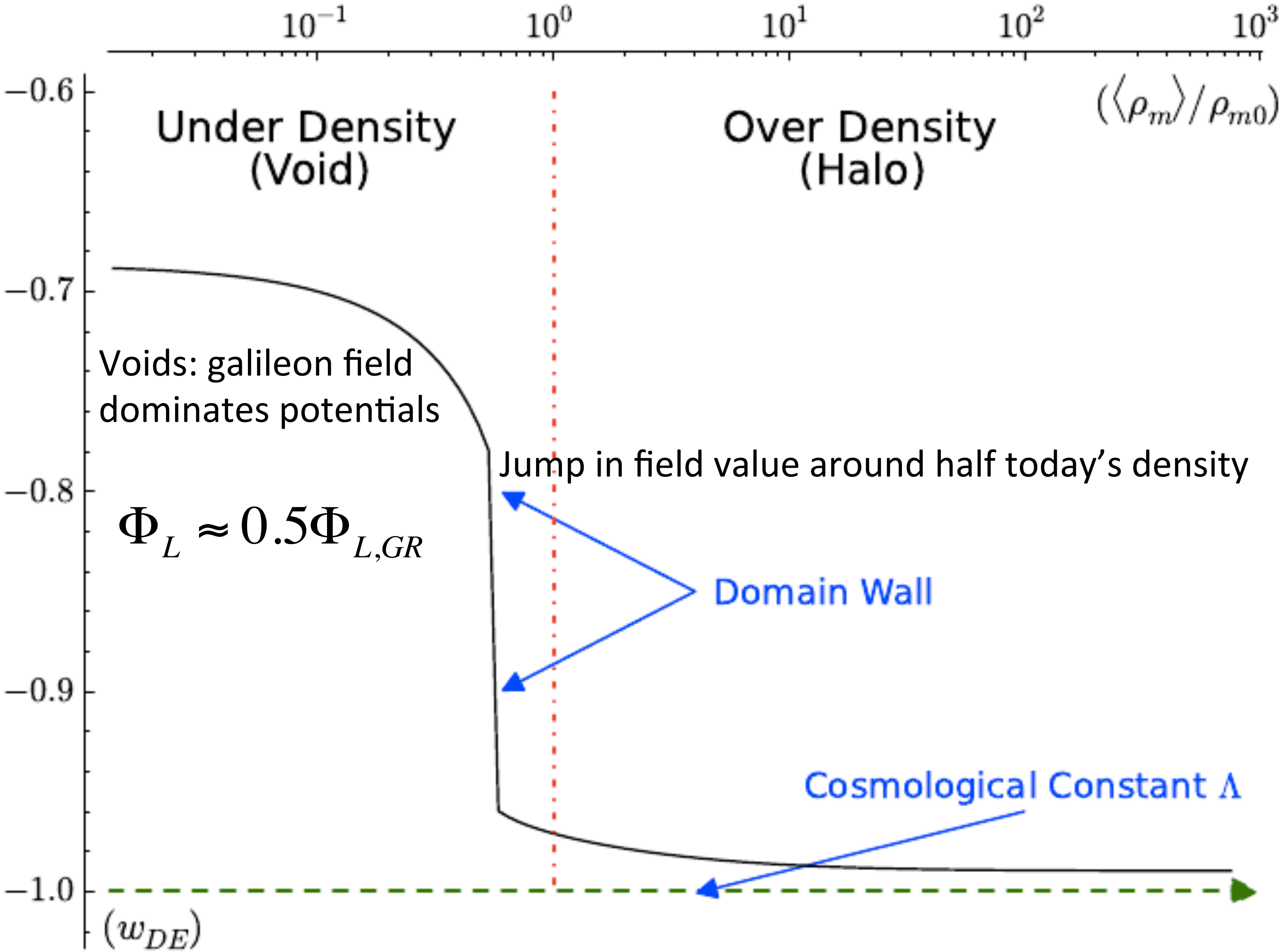
Solution

$$\pi'/r = f(\Delta)\Lambda^3$$
$$\Delta = \delta\rho_{\rm m}/\rho_{m0}$$



arXiv:1304.5239

Dark Energy Equation of State



arXiv:1304.5239

Different effective G for rel./nonrel. species

Observational Prospects

- Could explain a ~10% discrepancy in H_0 (CMB/SNe)
- Weak (de)lensing
  - Euclid, S/N ~ 15 stacked void lensing should allow discerning ~50% difference in potential (Krause et al. 2012)
- Alcock-Paczynski void shapes
  - BOSS, expect 2σ+ detection if Δw>0.25 (Dawson et al. 2013)
  - Euclid, expect 2σ+ detection if Δw>0.1 (Lavaux & Wandelt 2012)
- Galaxy power spectrum, redshift-space distortions [scale]
- Demagnification of supernovae
- Integrate Sachs-Wolfe effect
- CMB lensing

arXiv:1304.5239

Conclusions

- Galileon theory provides a relatively well-motivated modification of gravity
- We have found new, significant and non-standard observational effects for galileons: inhomogeneous, density-, time- and scale-dependent dark energy
- A number of current and future observational programmes could place strong constraints on these models