Screening Dark Energy and Modified Gravity

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Outline:

Light scalars and fifth forces

Can we forbid a coupling to matter?

Non-linear effects and screening

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Why Introduce Light Scalar Fields?

A new type of matter eg dark energy

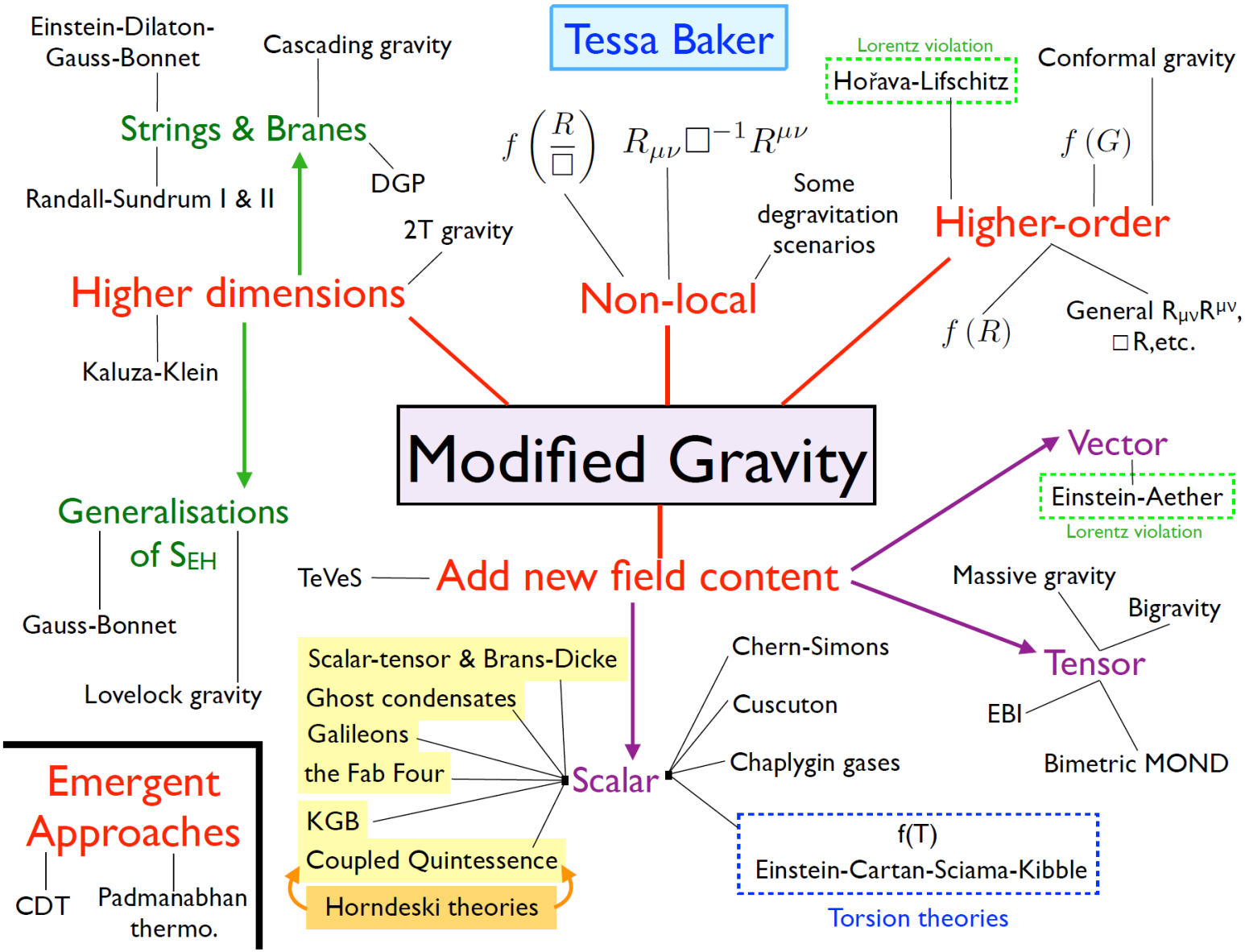
- Quintessence directly introduces new fields
- New, light (fundamental or emergent) scalars

A modification of gravity

- General Relativity is the unique interacting theory of a Lorentz invariant, massless, helicity-2 particle

  Papapetrou (1948). Weinberg (1965).
- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

Dark matter could also be a light scalar

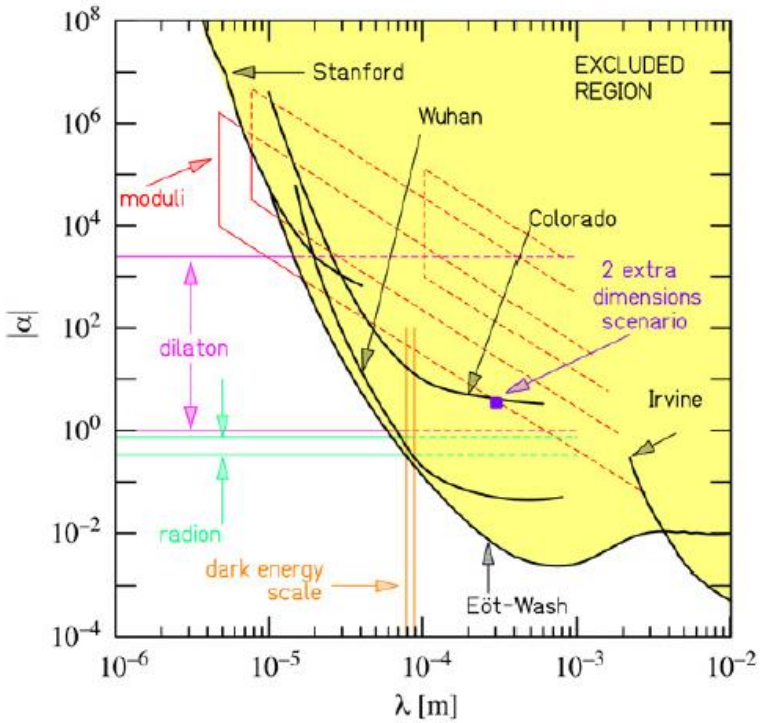


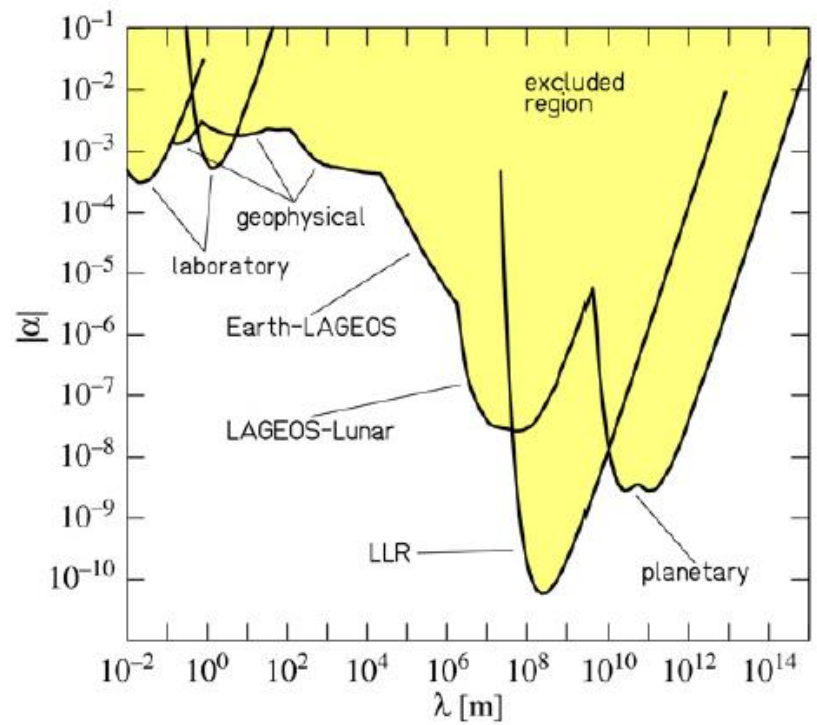
Bull et al. 2016

Yukawa Fifth Forces

A long range Yukawa fifth force is excluded to a high degree of precision in the solar system

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$

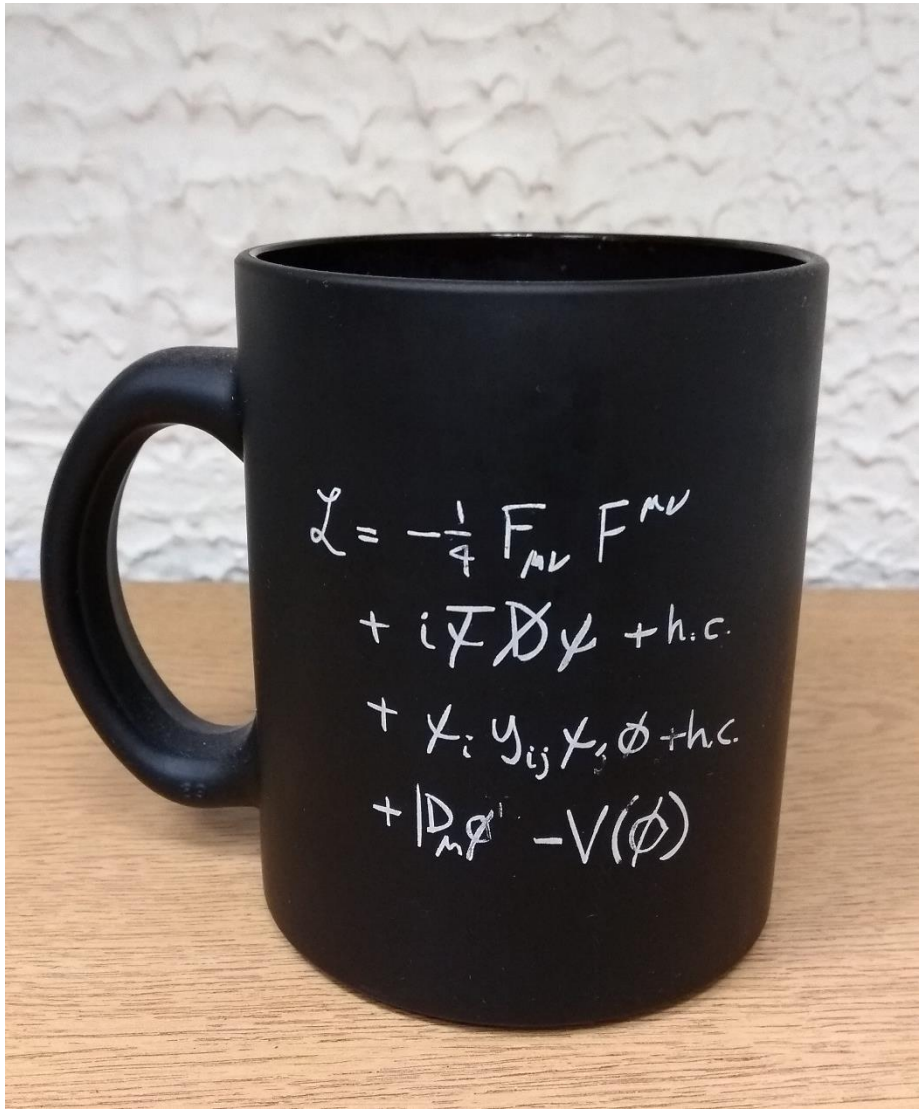




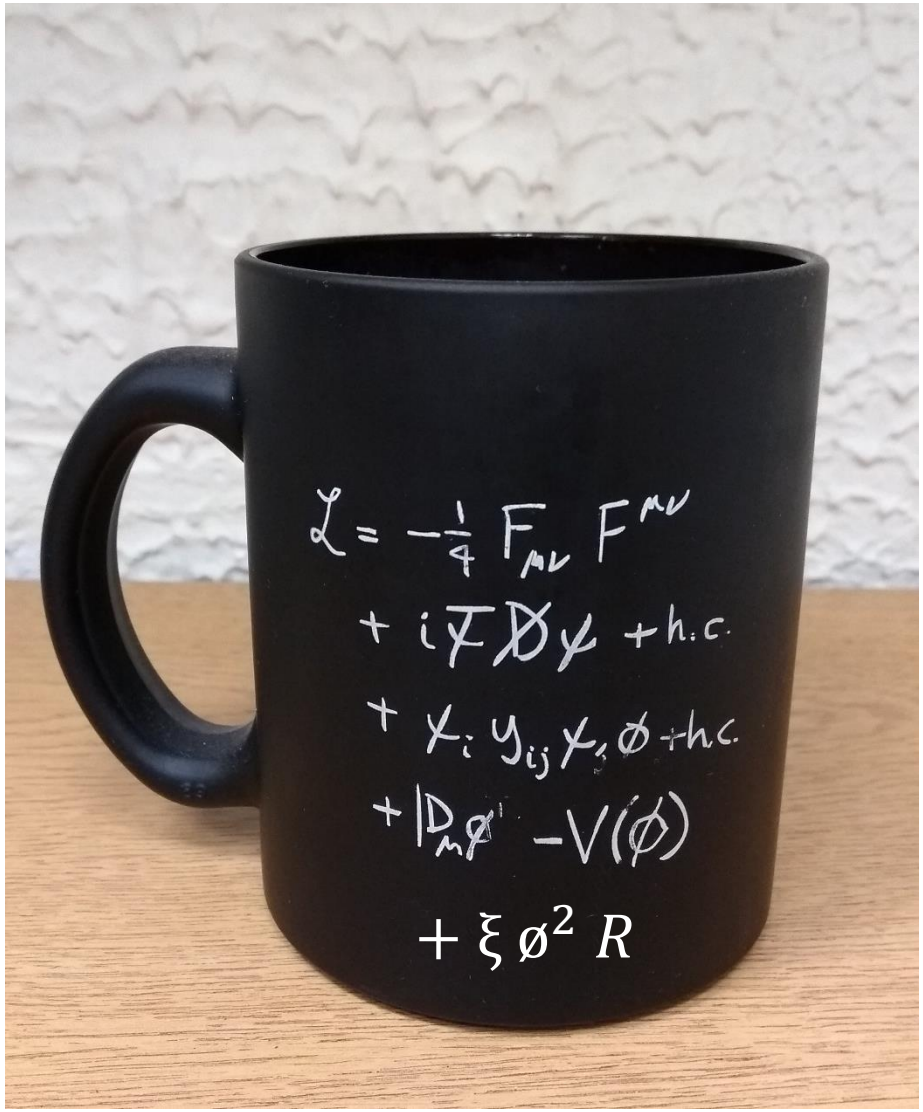
Adelberger et al. 2009

CAN WE FORBID A COUPLING TO MATTER?

Scalar Fields – The Higgs



Scalar Fields – The Higgs



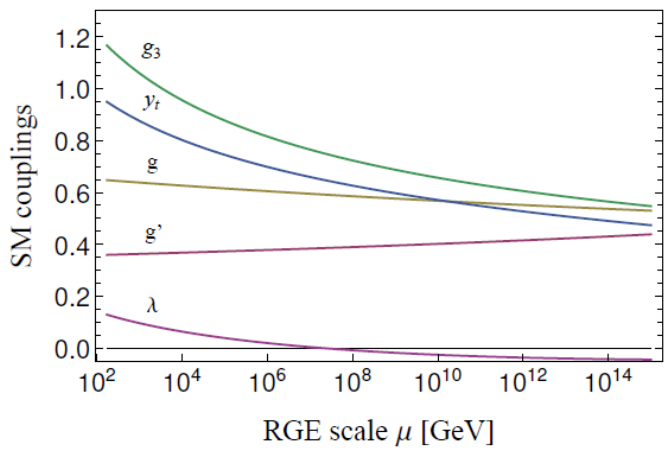
Conformally Coupled Scalar Fields

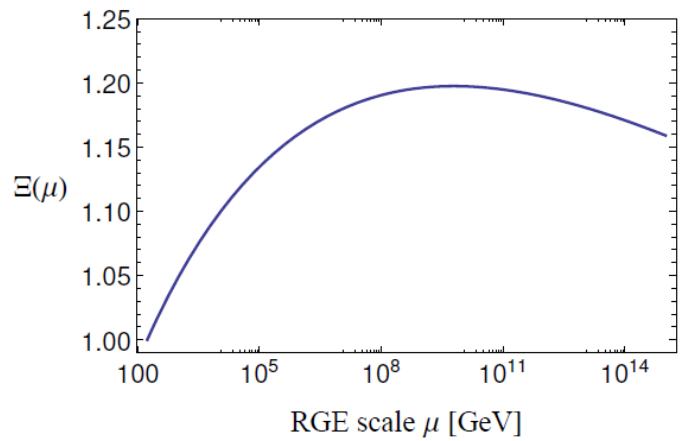
Non-minimal couplings to gravity are generated radiatively for scalar fields with interactions

If the Lagrangian contains

$$\xi(\mu) R \Phi^\dagger \Phi$$

Cannot set this to zero at all scales





$$\Xi \equiv (\xi - 1/6)/(\xi_{\rm EW} - 1/6)$$

Herranen, Markkanen, Nurmi, Rajantie, 2015

CAN WE FORBID A COUPLING TO MATTER? - SCALE INVARIANCE

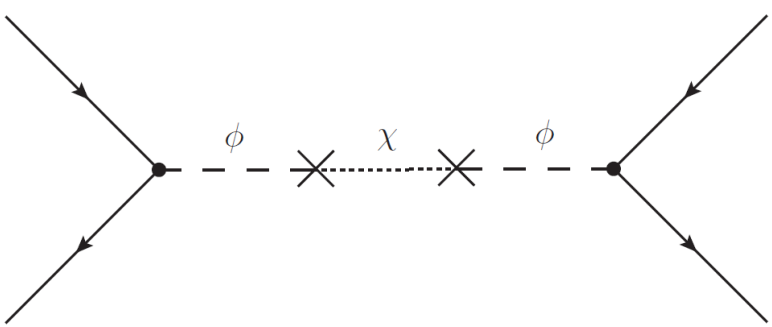
Fifth Forces & the Higgs Portal

In the Einstein frame, canonically normalising the fermions, scalar only couples to the Higgs

$$\tilde{\mathcal{L}} = -\frac{1}{2}\tilde{g}^{\mu\nu}\,\partial_\mu\tilde{\phi}\,\partial_\nu\tilde{\phi} + \tilde{g}^{\mu\nu}\,\tilde{\phi}\,\partial_\mu\tilde{\phi}\,\partial_\nu \ln A(\chi) - \frac{1}{2}\tilde{g}^{\mu\nu}\,\tilde{\phi}^2\,\partial_\mu \ln A(\chi)\,\partial_\nu \ln A(\chi)$$
$$+ \frac{1}{2}\mu^2 A^2(\chi)\,\tilde{\phi}^2 - \frac{\lambda}{4!}\tilde{\phi}^4 - \bar{\tilde{\psi}} i \overleftrightarrow{\tilde{\partial\!\!\!/}} \tilde{\psi} - y\,\bar{\tilde{\psi}}\tilde{\phi}\tilde{\psi}\,,$$

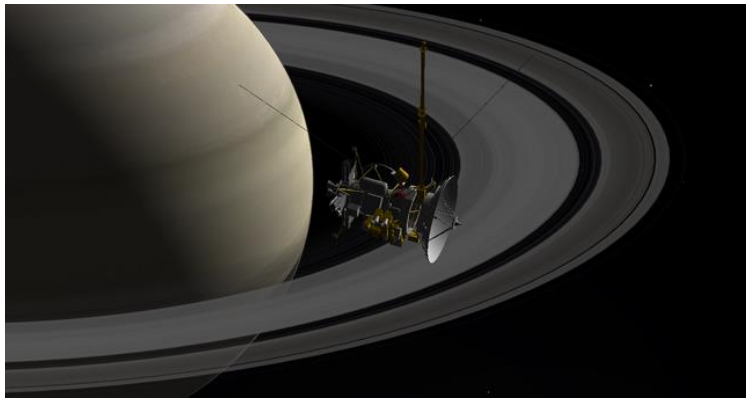
Mass mixing of Higgs with conformally coupled scalar

$$\tilde{\mathcal{L}}_M = \alpha_M\,\tilde{\phi}\,\tilde{\chi}$$



CB, Copeland, Millington, Spannowsky, 2018 See also: Wetterich, 1988. Buchmüller, Dragon, 1989. Shaposhnikov, Zenhausern, 2009. Blas, Shaposhnikov, Zenhausern, 2011. Brax, Davis, 2014. Ferreira, Hill, Ross, 2017.

PPN Constraints & the Higgs Mass



If (part of) the mass of the Higgs comes from spontaneous symmetry breaking

$$V(r) \supset -\frac{y^2}{4\pi}\frac{\alpha_M^2}{m_\phi^4}\frac{1}{r} \qquad y^2\frac{\alpha_M^2}{m_\phi^4} = \frac{m_e^2}{M^2}\frac{4\mu^4}{m_\phi^4}$$

Tracking of the Cassini satellite constrains, through PPN parameters,

$$|\gamma - 1| < 2.3\times 10^{-5} \qquad \frac{\mu}{m_h} \lesssim 0.03\left(\frac{M}{M_{\rm Pl}}\right)^{1/2}$$

SCREENING: WHAT IF THE NEW PHYSICS IS NON-LINEAR?

Screening Mechanisms

Start with a non-linear scalar field theory

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}(\phi, \partial\phi, ...)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

Scalar potential around a spherical point source

$$V(r) = -\frac{g^2(\bar{\phi})}{Z(\bar{\phi})c_s^2(\bar{\phi})} \frac{e^{-\frac{m(\bar{\phi})}{\sqrt{Z(\bar{\phi})}c_s(\bar{\phi})}r}}{4\pi r}\mathcal{M}$$

where

$$Z(\bar{\phi}) = Z^\mu_\mu(\bar{\phi}) \quad c_s^2(\bar{\phi}) = Z_{ii}(\bar{\phi})/Z(\bar{\phi}) \quad m^2(\bar{\phi}) \equiv \frac{d^2V}{d\phi^2}|_{\bar{\phi}}$$

For further details see: Joyce, Jain, Khoury, Trodden, 2014

Scalar Screening Mechanisms

- **Locally large mass**

Chameleon models

Khoury, Weltman, 2004

- **Locally weak coupling**

Symmetron and varying dilaton models

Pietroni, 2005. Olive, Pospelov, 2008. Hinterbichler, Khoury, 2010. Brax et al. 2011.

- **Locally large kinetic coefficient**

Vainshtein mechanism, Galileon and k-mouflage models

Vainshtein, 1972. Nicolis, Rattazzi, Trincherini, 2008.
Babichev, Deffayet, Ziour, 2009.

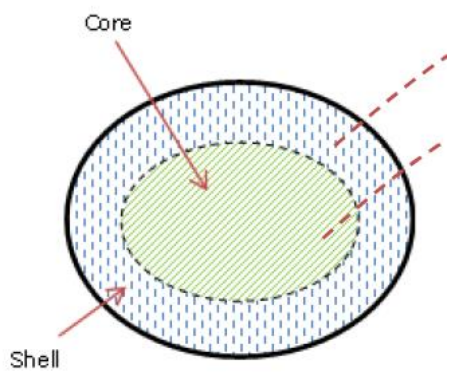
Screening Phenomenology

Compare to Yukawa fifth force

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$

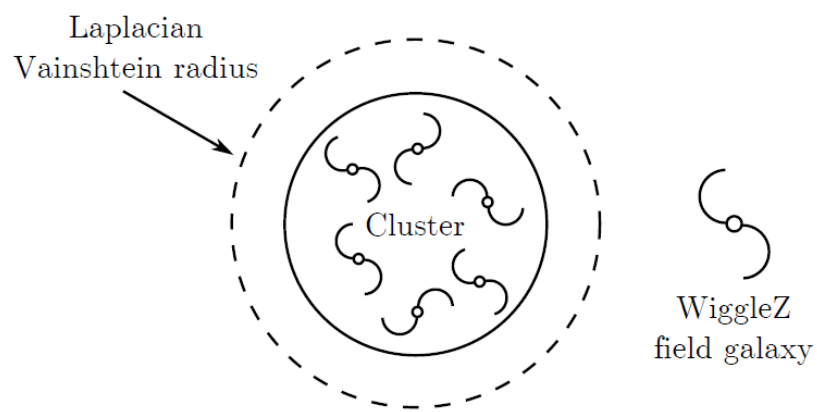
Change the way in which matter sources the scalar field

- thin-shell effect



Change the dependence on distance

- Vainshtein screening



The Galileon

Lagrangian includes higher derivatives

$$S = \int \mathrm{d}^4x \sqrt{-g}\Big(\frac{M_{\mathrm{P}}^2}{2}R - \frac{1}{2}\sum_{2\leqslant i\leqslant 5} c_i \Lambda^{3(2-i)}\mathcal{L}_i,\Big)$$

$$\mathcal{L}_2 = (\nabla\phi)^2$$

$$\mathcal{L}_3 = (\nabla\phi)^2\Box\phi$$

$$\mathcal{L}_4 = (\nabla\phi)^2\Big[2(\Box\phi)^2 - 2\phi_{;\mu\nu}\phi^{;\mu\nu} - \frac{R}{2}(\nabla\phi)^2\Big]$$

$$\mathcal{L}_5 = (\nabla\phi)^2\Big[(\Box\phi)^3 - 3(\Box\phi)\phi_{;\mu\nu}\phi^{;\mu\nu} + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\rho}\phi_{;\rho}{}^{\mu} - 6G_{\nu\rho}\phi_{;\mu}\phi^{;\mu\nu}\phi^{;\rho}$$

Galileon symmetry around flat space

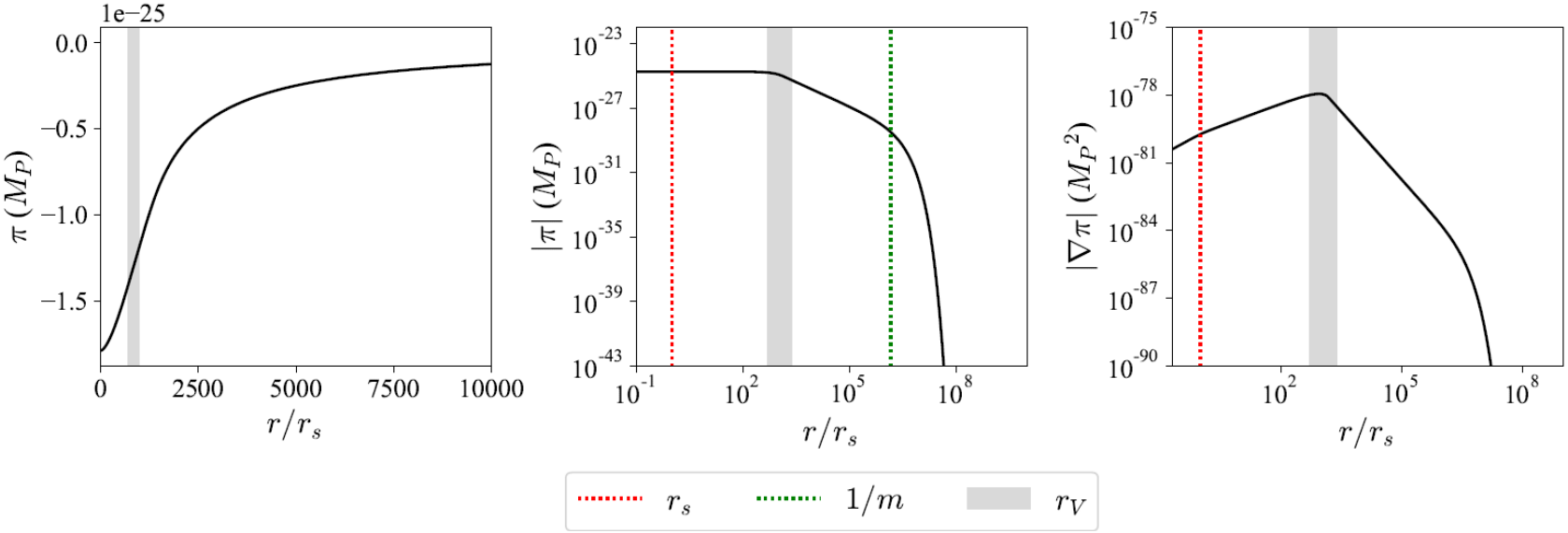
$$\phi(x) \to \phi(x) + b_\mu x^\mu + c$$

Equations of motion are second order in derivatives

Nicolis, Rattazzi, Trincherini, 2009. Generalisations: Horndeski, 1974. Deffayet, Esposito-Farese, Vikman, 2009. Deffayet, Deser, Esposito-Farese, 2009. Gleyzes, Langlois, Piazza, Vernizzi, 2015. Langlois, Noui, 2016. Ben Achour, Langlois, Noui, 2016. Crisostomi, Koyama, Tasinato, 2016.

Vainshtein Screening

The force can be made substantially weaker than gravity if non-linearities become important



Field profiles simulated with ϕ-enics. CB, Braden, Elder, Saadeh. Coming soon!

Vainshtein Screening

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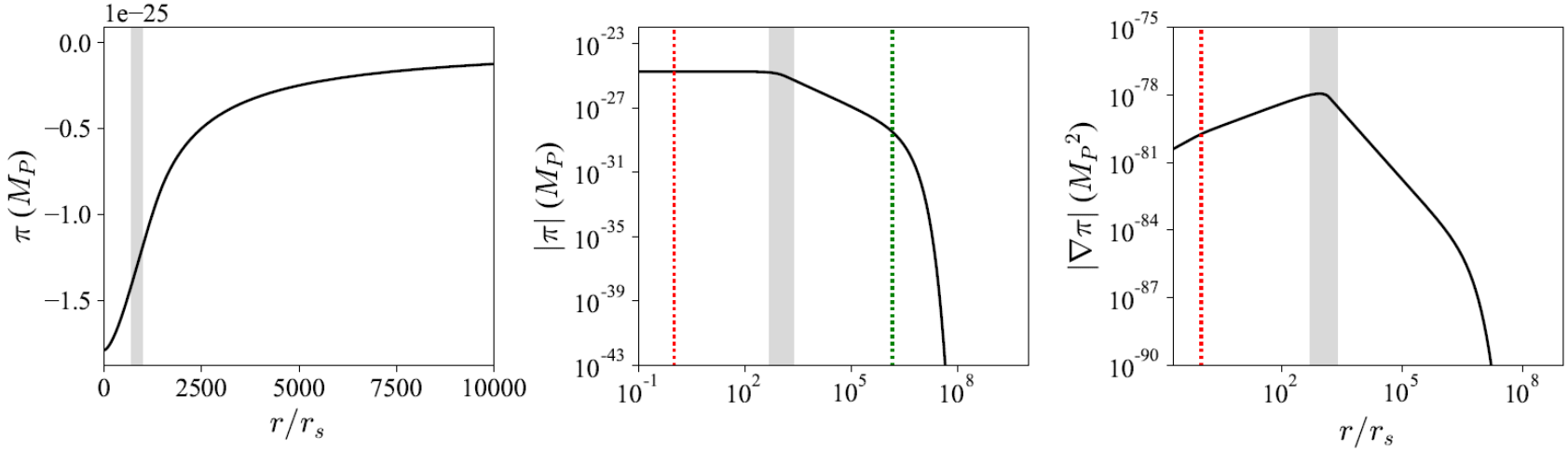
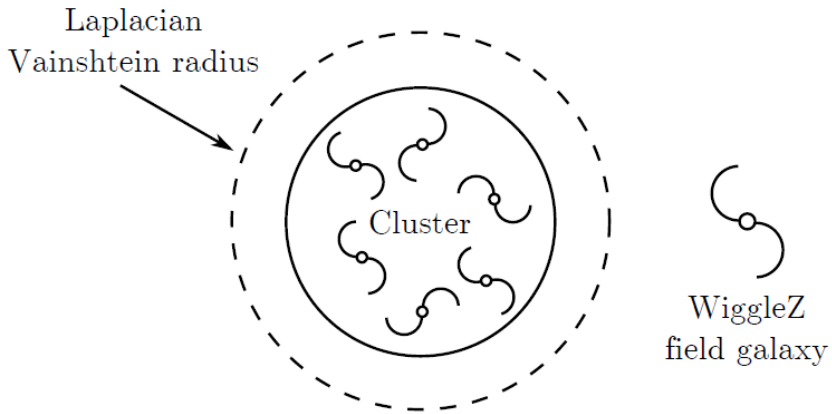




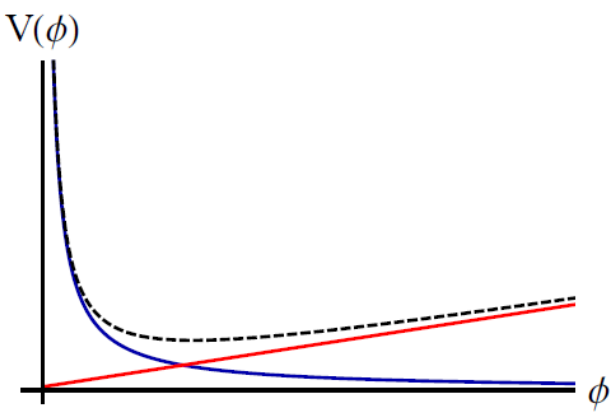
Field profiles simulated with ϕ-enics. CB, Braden, Elder, Saadeh. Coming soon!

Chameleon

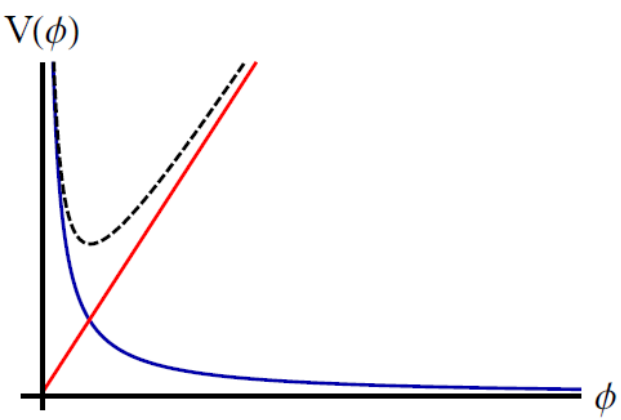
A scalar field with canonical kinetic terms, non-linear potential, and direct coupling to matter

$$S_\phi = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - V(\phi) - A(\phi)\rho_\mathrm{m}\right)$$

$$V(\phi) = \frac{\Lambda^5}{\phi}, \quad A(\phi) = \frac{\phi}{M} \ ,$$



Low density

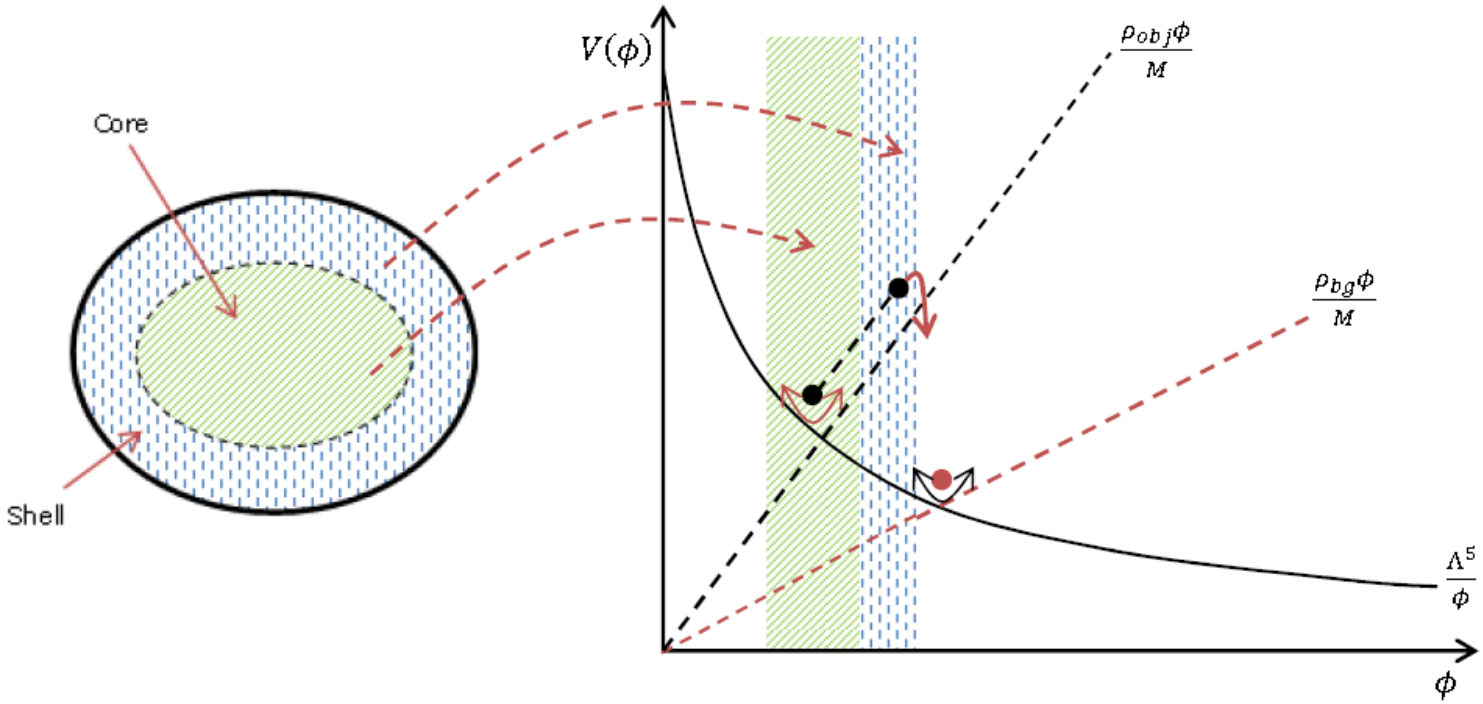


High density

Khoury, Weltman. (2004).

Chameleon Screening

The increased mass makes it hard for the chameleon field to adjust its value

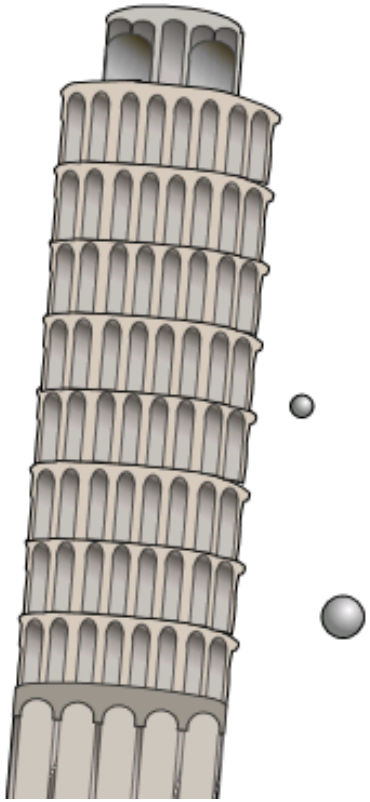


The chameleon potential well around 'large' objects is shallower than for canonical light scalar fields

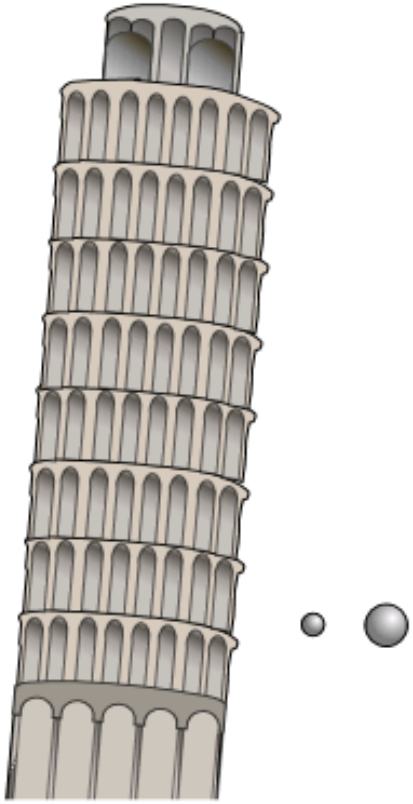
CB, Copeland, Stevenson. (2015)

A Very Old Idea

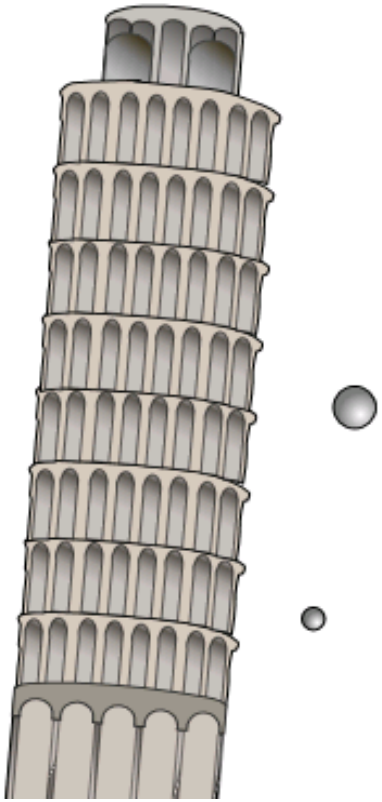
Do large objects and small objects fall at the same rate?



Old idea



Galileo



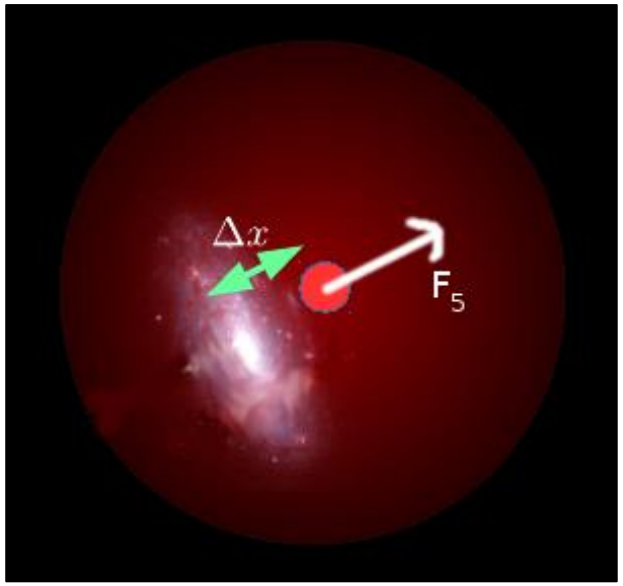
Dark Energy?

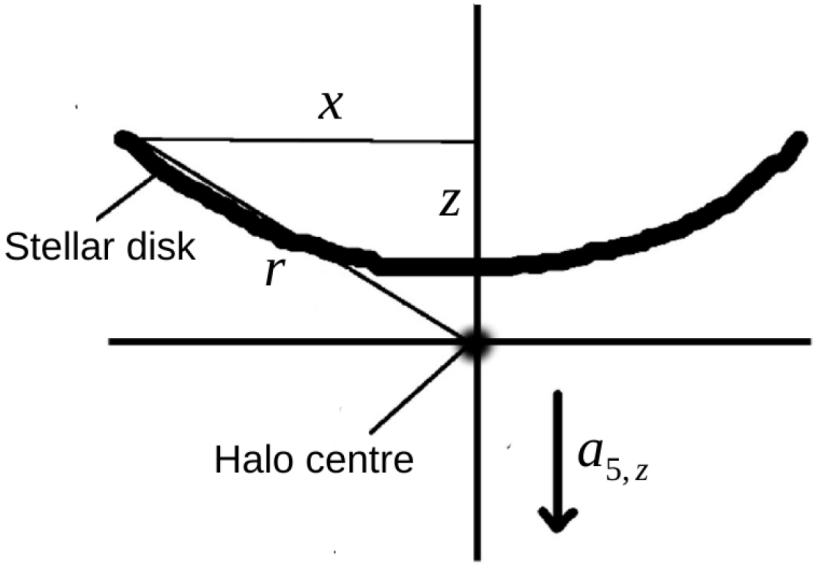
Image credit: Theresa Knott

Astrophysical Hints

Different components of a dwarf galaxy may fall in a gravitational field at different rates

- Stars are screened, gas and dark matter are not
- Look for gas-star offsets & warping of galactic discs





Desmond, Ferreira, Lavaux, Jasche. (2018)
Tests proposed by Hui, Nicolis, Stubbs. (2009). Jain, VanderPlas. (2011)

Astrophysical Hints

Correlated with expected direction of 5th force:

Evidence for offsets using ~10,000 HI detections from the ALFALFA survey

Evidence for galaxy warps using ~4,000 images from the Nasa Sloan Atlas

Both consistent with screened force, M~10 M_{Pl}, and background Compton wavelength ~1.8 Mpc

~7σ significance, but potentially challenging systematics

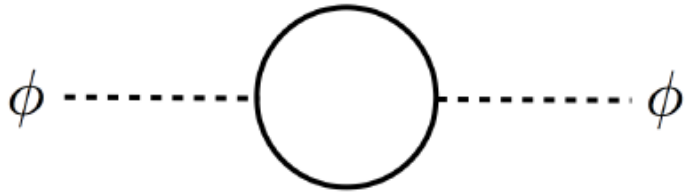
Desmond, Ferreira, Lavaux, Jasche. (2018)
Tests proposed by Hui, Nicolis, Stubbs. (2009). Jain, VanderPlas. (2011)

Radiative Stability

Screening mechanisms rely on non-linearities

- Requires the introduction of non-renormalisible operators
- In the absence of a symmetry (e.g. Galileon, DBI, scale invariance), relevance of these terms would indicate break down of EFT

Coupling to matter can also generate large corrections. E.g. standard model loops generate a large scalar mass



Summary

There are good reasons to consider introducing new light scalars

But we have to explain why we haven’t seen them yet

Challenging to forbid couplings to matter altogether

Non-linearities can hide fifth forces through screening

Can change:

How matter sources the scalar

How gradients of the scalar grow