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
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
  
- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

**Dark matter could also be a light scalar**
Modified Gravity

1. Strings & Branes
   - Einstein-Dilaton-Gauss-Bonnet
   - Cascading gravity
   - DGP
   - 2T gravity
   - Horava-Lifschitz
   - Lorentz violation
   - Conformal gravity

2. Generalisations of $S_{EH}$
   - Kaluza-Klein
   - Gauss-Bonnet
   - Lovelock gravity

3. Higher dimensions
   - Higher-order
   - Add new field content
   - Vector
   - Tensor

4. Emergent Approaches
   - CDT
   - Padmanabhan thermo.
   - Scalar-tensor & Brans-Dicke
   - Ghost condensates
   - Galileons
   - the Fab Four
   - KGB
   - Coupled Quintessence
   - Horndeski theories
   - KGB
   - Torsion theories

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

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \overline{\psi} D\psi + h.c. \\
+ X_i Y_{i\bar{j}} X_{\bar{j}} \phi + h.c. \\
+ \overline{D_{\mu} \phi} - V(\phi) \]
Scalar Fields – The Higgs

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} D\psi + h.c. + \chi_i \bar{Y}_{ij} Y_{jk} \phi + h.c. + |D_\mu \phi|^2 - V(\phi) + \xi \phi^2 R \]
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

\[ \Xi \equiv \left( \xi - \frac{1}{6} \right) / \left( \xi_{\text{EW}} - \frac{1}{6} \right) \]

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

$$\tilde{\mathcal{L}} = -\frac{1}{2} g^{\mu\nu} \partial_{\mu} \tilde{\phi} \partial_{\nu} \tilde{\phi} + g^{\mu\nu} \tilde{\phi} \partial_{\mu} \tilde{\phi} \partial_{\nu} \ln A(\chi) - \frac{1}{2} g^{\mu\nu} \tilde{\phi}^2 \partial_{\mu} \ln A(\chi) \partial_{\nu} \ln A(\chi)$$

$$+ \frac{1}{2} \mu^2 A^2(\chi) \tilde{\phi}^2 - \frac{\lambda}{4!} \tilde{\phi}^4 - \bar{\psi} i \gamma^\mu \gamma^5 \psi - y \bar{\psi} \tilde{\phi} \psi,$$

Mass mixing of Higgs with conformally coupled scalar

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

PPN Constraints & the Higgs Mass

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

\[ V(r) \supset - \frac{y^2 \alpha^2_M}{4\pi m^4_\phi} \frac{1}{r} \quad y^2 \frac{\alpha^2_M}{m^4_\phi} = \frac{m^2_e}{M^2} \frac{4\mu^4}{m^4_\phi} \]

Tracking of the Cassini satellite constrains, through PPN parameters,

\[ |\gamma - 1| < 2.3 \times 10^{-5} \quad \frac{\mu}{m_h} \lesssim 0.03 \left( \frac{M}{M_{Pl}} \right)^{1/2} \]
SCREENING: WHAT IF THE NEW PHYSICS IS NON-LINEAR?
Screening Mechanisms

Start with a non-linear scalar field theory

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

Scalar potential around a spherical point source

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

where

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

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

• **Locally large kinetic coefficient**
  Vainshtein mechanism, Galileon and k-mouflage models
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

\[ S = \int \, d^4x \, \sqrt{-g} \left( \frac{M_p^2}{2} R - \frac{1}{2} \sum_{2 \leq i \leq 5} c_i \Lambda^{3(2-i)} \mathcal{L}_i \right) \]

\[ \mathcal{L}_2 = (\nabla \phi)^2 \]
\[ \mathcal{L}_3 = (\nabla \phi)^2 \nabla \phi \]
\[ \mathcal{L}_4 = (\nabla \phi)^2 \left[ 2(\Box \phi)^2 - 2 \phi_{;\mu\nu} \phi^{;\mu\nu} - \frac{R}{2} (\nabla \phi)^2 \right] \]
\[ \mathcal{L}_5 = (\nabla \phi)^2 \left[ (\Box \phi)^3 - 3(\Box \phi) \phi_{;\mu\nu} \phi^{;\mu\nu} + 2 \phi_{;\mu} \phi_{;\nu} \phi_{;\rho}^{;\mu} - 6 G_{\nu\rho} \phi_{;\mu} \phi^{;\mu\nu} \phi^{;\rho} \right] \]

Galileon symmetry around flat space

\[ \phi(x) \to \phi(x) + b_\mu x^\mu + c \]

Equations of motion are second order in derivatives

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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Chameleon

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

\[ S_\phi = \int d^4 x \sqrt{-g} \left( -\frac{1}{2} (\partial \phi)^2 - V(\phi) - A(\phi) \rho_m \right) \]

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

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

Astrophysical Hints

Correlated with expected direction of 5\textsuperscript{th} 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, \(M \sim 10 M_{Pl}\), and background Compton wavelength \(\sim 1.8\) Mpc

\(~7\sigma\) significance, but potentially challenging systematics

Radiative Stability

Screening mechanisms rely on non-linearities

• Requires the introduction of non-renormalisable 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