Fifth forces and discrete symmetry breaking

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Scalar fields, the cure-all of fundamental physics

- The Standard Model contains one dimension-four operator through which we can couple hidden sectors: **the Higgs-portal term**

$$-\mathcal{L} \supset \frac{\alpha}{2}\phi^2 H^\dagger H$$

- General Relativity contains one dimension-four operator through which we can couple hidden sectors: **the Brans-Dicke term**

$$-\mathcal{L} \supset \frac{\beta}{2}\phi^2 \mathcal{R}$$

- What I want to convince you of is that, for the Standard Model, these two couplings are **equivalent**; and that this makes for rich phenomenology.

Conformal frames

- By redefining the metric, we can map between the **Jordan** and **Einstein frames**.

- Start with a conformally (disclaimer) coupled scalar-tensor theory:

$$S = \int \mathrm{d}^4x \sqrt{-g}\left[\frac{1}{2}F(\phi)\mathcal{R} - \frac{1}{2}Z^{\mu\nu}(\phi, \partial\phi, \ldots)\partial_\mu\phi\partial_\nu\phi - V(\phi) + \mathcal{L}_{\mathrm{SM}}[g_{\mu\nu}]\right]$$

- Perform a Weyl/conformal transformation to the Einstein frame via $g_{\mu\nu} \equiv F^{-1}(\phi)\tilde{g}_{\mu\nu} \equiv A^2(\tilde{\phi})\tilde{g}_{\mu\nu}$:

$$S = \int \mathrm{d}^4x \sqrt{-\tilde{g}}\left[\frac{1}{2}\tilde{\mathcal{R}} - \frac{1}{2}\tilde{Z}^{\mu\nu}(\tilde{\phi}, \partial\tilde{\phi}, \ldots)\partial_\mu\tilde{\phi}\partial_\nu\tilde{\phi} - \tilde{V}(\tilde{\phi}) + \mathcal{L}_{\mathrm{SM}}[A^2(\tilde{\phi})\tilde{g}_{\mu\nu}]\right]$$

- We'll come back to **conformal anomalies** later ...

Usual fifth-force story

- Expanding

$$S_{\mathrm{SM}}[A^2(\tilde{\phi})\tilde{g}_{\mu\nu},\{\psi\}] = S_{\mathrm{SM}}[\tilde{g}_{\mu\nu},\{\psi\}] + [A^2(\tilde{\phi})-1]\frac{\delta S_{\mathrm{SM}}[\tilde{g}_{\mu\nu},\{\psi\}]}{\delta\tilde{g}_{\mu\nu}}\tilde{g}_{\mu\nu} + \dots$$

  we find a universal coupling to the trace of the energy-momentum tensor

$$S_{\mathrm{SM}}[A^2(\tilde{\phi})\tilde{g}_{\mu\nu},\{\psi\}] \supset \frac{1}{2}[A^2(\tilde{\phi})-1][\tilde{T}_{\mathrm{SM}}]_{\mu}{}^{\mu}$$

- Approximate matter as a pressureless perfect fluid: $[\tilde{T}_{\mathrm{SM}}]_{\mu}{}^{\mu} = -\tilde{\rho}$

- And matter feels a fifth force

$$\mathbf{F}/m = -\boldsymbol{\nabla}\ln A(\tilde{\phi})$$

- This picture is not strictly wrong, but it is perhaps misleading ...

(Classical) scale invariance

Scale invariance (really Weyl invariance) means that certain terms in the matter action do not contribute to the trace of the energy-momentum tensor:

- gauge-field kinetic terms $F_{\mu\nu} F^{\mu\nu}$
- fermion kinetic terms $\bar{\psi} \not{\nabla} \psi$, including their gauge interactions
- Yukawa interactions $\bar{\psi}_L H \psi_R$
- quartic scalar self-couplings $(H^\dagger H)^2$

So what does this leave for the SM?

- scalar kinetic terms $(D_\mu H)^\dagger D^\mu H$, but these give at most derivative couplings
- **the Higgs mass term**
$$-\mathcal{L}_{\mathsf{SM}} \supset -\mu^2 H^\dagger H$$

Recovering the fifth force

Suppose

$$A^2(\tilde{\phi}) = 1 + \frac{\tilde{\phi}^2}{M^2} + \cdots$$

the leading coupling is

$$-\mu^2 H^\dagger H \to -\mu^2 A^2(\tilde{\phi}) \tilde{H}^\dagger H^\dagger \supset \frac{\alpha}{2} \tilde{\phi}^2 \tilde{H}^\dagger \tilde{H}$$

a **Higgs-portal term**!

But if the additional scalar only couples to the Higgs, where is the fifth force?

It arises if there is a **mass mixing** with the would-be SM Higgs boson:

$$-\mathcal{L}_{\text{SM}} \supset \alpha_M \tilde{\phi} \tilde{h}$$

which requires:

- explicit or spontaneous $\mathbb{Z}_2$ breaking in $A^2(\tilde{\phi})$
- and is possible only after the EW phase transition: $SU(2)_L \times U(1)_Y \to U(1)_{\text{EM}}$

Recovering the fifth force

If these conditions are met, the standard fifth-force story is recovered.
(Burrage, Copeland, PM & Spannowsky '18.)

- **Brans-Dicke theory** and the **chameleon models** provide examples of where there is **explicit** $\mathbb{Z}_2$ breaking.
  (Brans & Dicke '61; Khoury & Weltman '04; Khoury '13.)
- The **Damour-Polyakov** and **symmetron models** provide examples of where there is **spontaneous** $\mathbb{Z}_2$ breaking.
  (Dehnen, Frommert & Ghaboussi '92; Damour & Polyakov '94; Pietroni '05; Olive & Pospelov '08; Hinterbichler & Khoury '10.)

What if the Higgs mass is not due to an explicit scale-breaking term?
No fifth force.
(Bezrukov, Blas, Garcia-Bellido, Karananas, Rubio, Shaposhnikov & Zenhausern '08 onward; Ferreira, Ross & Hill '16 onward.)

What if only some of the Higgs mass is due to an explicit scale-breaking term?
Fifth-force constraints bound the explicit scale-breaking.
(Burrage, Copeland, PM & Spannowsky '18.)

Couplings

To fermions:
The would-be SM Higgs is a linear superposition of the Higgs boson h (the heavy mode) and the light mode ζ that can mediate the fifth force:

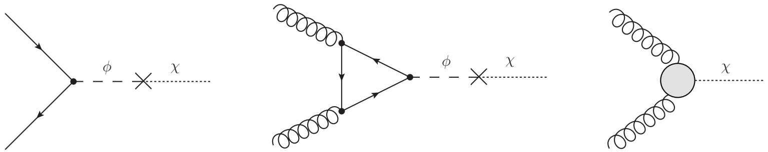
$$\phi \approx h + v \left\{ \begin{matrix} 1 \\ \frac{v_\chi}{M} \end{matrix} \right\} \frac{2\mu^2}{m_\phi^2} \frac{\zeta}{M} \qquad \mathcal{L} \supset -y\bar{\psi}\phi\psi \ \sim -m_\psi \left\{ \begin{matrix} 1 \\ \frac{v_\chi}{M} \end{matrix} \right\} \frac{2\mu^2}{m_\phi^2} \frac{\zeta}{M} \bar{\psi}\psi$$

To nucleons:

$$\mathcal{L} \supset \ -m_N \eta \left\{ \begin{matrix} 1 \\ \frac{v_\chi}{M} \end{matrix} \right\} \frac{2\mu^2}{m_\phi^2} \frac{\zeta}{M} \bar{\psi}_N \psi_N$$

where η parametrizes the uncertainty in the h-N coupling $\eta \sim 0.3$ (eff. WEP?).

PPN constraints (Cassini time delay) can be reinterpreted as a bound on $\mu \lesssim 4$ GeV (Burrage, Copeland, PM & Spannowsky '18).



Some words

Modifed gravity: the new degree(s) of freedom do(es) not contribute significantly to the energy density, but instead mediate(s) long-range Yukawa-like forces.

Dark matter: the new degree(s) of freedom contribute(s) significantly to the energy density, but do(es) not mediate long-range Yukawa-like forces.

The most interesting scenarios may be ones that do both (see Burrage, Copeland, Käding & Millington '18).

Screening mechanisms

Classical EoM for perturbations ($\langle\tilde{\phi}\rangle \equiv \tilde{\varphi} + \delta\tilde{\varphi}$)

$$\tilde{Z}(\tilde{\varphi})\left(\delta\ddot{\tilde{\varphi}} - c_s^2(\tilde{\varphi})\nabla^2\delta\tilde{\varphi}\right) + m^2(\tilde{\varphi})\delta\tilde{\varphi} = -\frac{1}{2}\frac{\mathrm{d}A^2(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\tilde{T}$$

Yukawa potential around a point source $\tilde{T} = -\tilde{\rho} = -A^{-1}(\tilde{\varphi})\mathcal{M}\delta^3(\mathbf{x})$
(Joyce, Jain, Khoury and Trodden '14)

$$\tilde{U}(r) \supset -\frac{1}{\tilde{Z}(\tilde{\varphi})c_s^2(\tilde{\varphi})}\left[\frac{\mathrm{d}A(\tilde{\varphi})}{\mathrm{d}\tilde{\varphi}}\right]^2\frac{1}{4\pi r}\exp\left[-\frac{m(\tilde{\varphi})r}{\tilde{Z}^{1/2}(\tilde{\varphi})c_s(\tilde{\varphi})}\right]\mathcal{M}$$

Suppress the Yukawa potential **environmentally** by:

- Modifying the **kinetic term** — Vainshtein screening
  (Vainshtein '72)
- Modifying the **mass** — chameleon screening
  (Khoury & Weltman '04)
- Modifying the **matter coupling** — symmetron screening
  (Damour & Polyakov '94; Pietroni '05; Olive & Pospelov '08; Brax, van de Bruck, Davis & Shaw '10. Hinterbichler & Khoury '10; Hinterbichler, Khoury, Levy & Matas '11)

Symmetron screening

The symmetron model (Hinterbichler & Khoury '10):

$$\tilde{V}(\tilde{\varphi}) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\tilde{\varphi}^2 + \frac{\lambda}{4!}\tilde{\varphi}^4$$

In regions of **high density** with $\rho > \mu^2 M^2$, the minimum lies at $\tilde{\varphi} = 0$.

In regions of **low density** with $\rho < \mu^2 M^2$, the minima lie at $\tilde{\varphi} = \pm v = \pm\frac{m}{\sqrt{2\lambda}}$, where $m^2 = 2(\mu^2 - \rho/M^2)$.

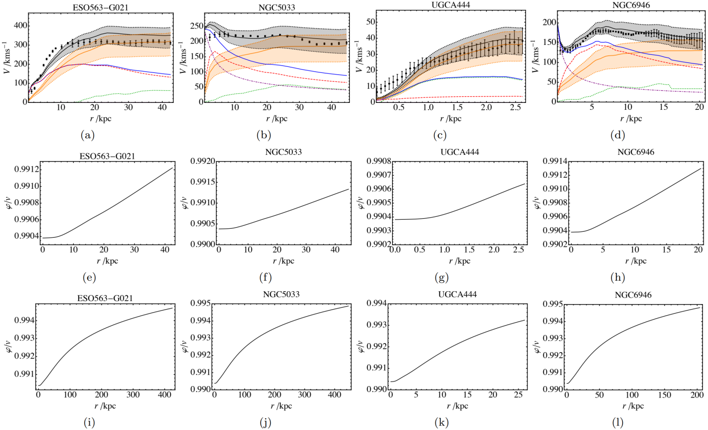
For extended sources with $m_{\rm in} R \gg 1$, the fifth force is **screened** for $r \gg R$.

For extended sources with $m_{\rm in} R \ll 1$, the fifth force is **unscreened** for $r \gg R$.

This can also be realised via the **Coleman-Weinberg mechanism** of spontaneous symmetry breaking (Burrage, Copeland & Millington '16).

Some intriguing cherry-picking

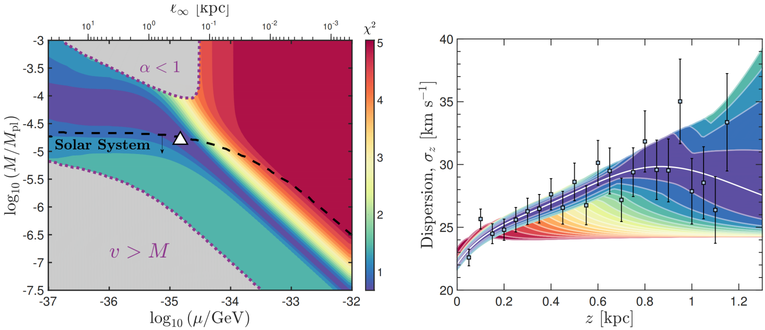
Rotation curves: (for an early and little-known work, see Gessner '92)



Can also stabilise the disc to formation of bars (Ostriker & Peebles '73), but benchmark parameter point **in tension** with Solar System tests of gravity (from Burrage, Copeland & Millington '17, based on SPARC dataset by Lelli, McGaugh & Schombert '16, see also McGaugh, Lelli & Schombert '16).

But also . . .

Vertical motion of stars perpendicular to the plane of the Milky Way disc:



Note the degenerate band $\rho_{\rm gal} \sim \mu^2 M^2$ (from Burrage & O'Hare '18, based on simulated data by Read '14).

Lensing? Minimally, not so easy.

Prospects summarised in Burrage, Copeland, Käding & Millington '18:

- For $\mu^2 M^2 < \bar{\rho}$ and $v < M$, energy density in the symmetron field is **too small** to source a deep enough Newtonian potential.

$$\frac{E_\varphi}{M_{\rm gal}} = \frac{1}{4}\frac{\mu^2 M^2}{\bar{\rho}}\frac{v^2}{M^2} I$$

- Fifth force on photons is induced by the conformal anomaly, but it is **too small**.

$$\mathcal{L}_{\rm eff} \supset \frac{\varphi^2}{M_\gamma^2}\tilde{g}^{\mu\alpha}\tilde{g}^{\nu\beta}F_{\mu\nu}F_{\alpha\beta}$$

- Add a disformal coupling, but terrestrial constraints mean it is **too small** ($M_{\rm dis} \gtrsim 650$ GeV) (see Brax & Burrage '14; Brax, Burrage & Englert '15).

$$g_{\mu\nu} = C^2(\varphi)\tilde{g}_{\mu\nu} + D(\varphi)\partial_\mu\varphi\partial_\nu\varphi$$

- Add a(n environment-dependent) photon mass, but this has to be **too small**.

$$\mathcal{L} \supset -\tilde{\alpha}\tilde{\varphi}^2 A_\mu A^\mu \qquad \mathcal{L}_{\rm eff} \supset -\tilde{\alpha}'\tilde{\varphi}^2(\tilde{\varphi}^2 - v^2)A_\mu A^\mu$$

- **Any hope:** yes, push into the challenging regime $\rho \sim \mu^2 M^2$ and $v \lesssim M$.

Concluding remarks

- For the SM, conformally coupled scalar-tensor theories are equivalent to Higgs-portal theories (at dimension four).
- Some models of ULDM and MG have more in common than previously realised.
- The standard fifth-force story only emerges if there is a mass mixing between the would-be SM Higgs and the conformally coupled scalar.
- Potential effective WEP between leptonic versus hadronic degrees of freedom.
- Screening mechanisms lead to a rich phenomenology that might impact dynamics on astrophysical scales.
- **Joint modified-gravity–dark-matter phenomenology** might be the way forward ...

Thank you for your attention.