ERG2026

13th International Conference on the Exact Renormalization Group

https://indico.global/event/16125/

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MANCHESTER 1824
The University of Manchester

Peter Millington
UKRI FLF, University of Manchester

The phenomenology of modified gravity theories

Annual Theory Meeting 2025

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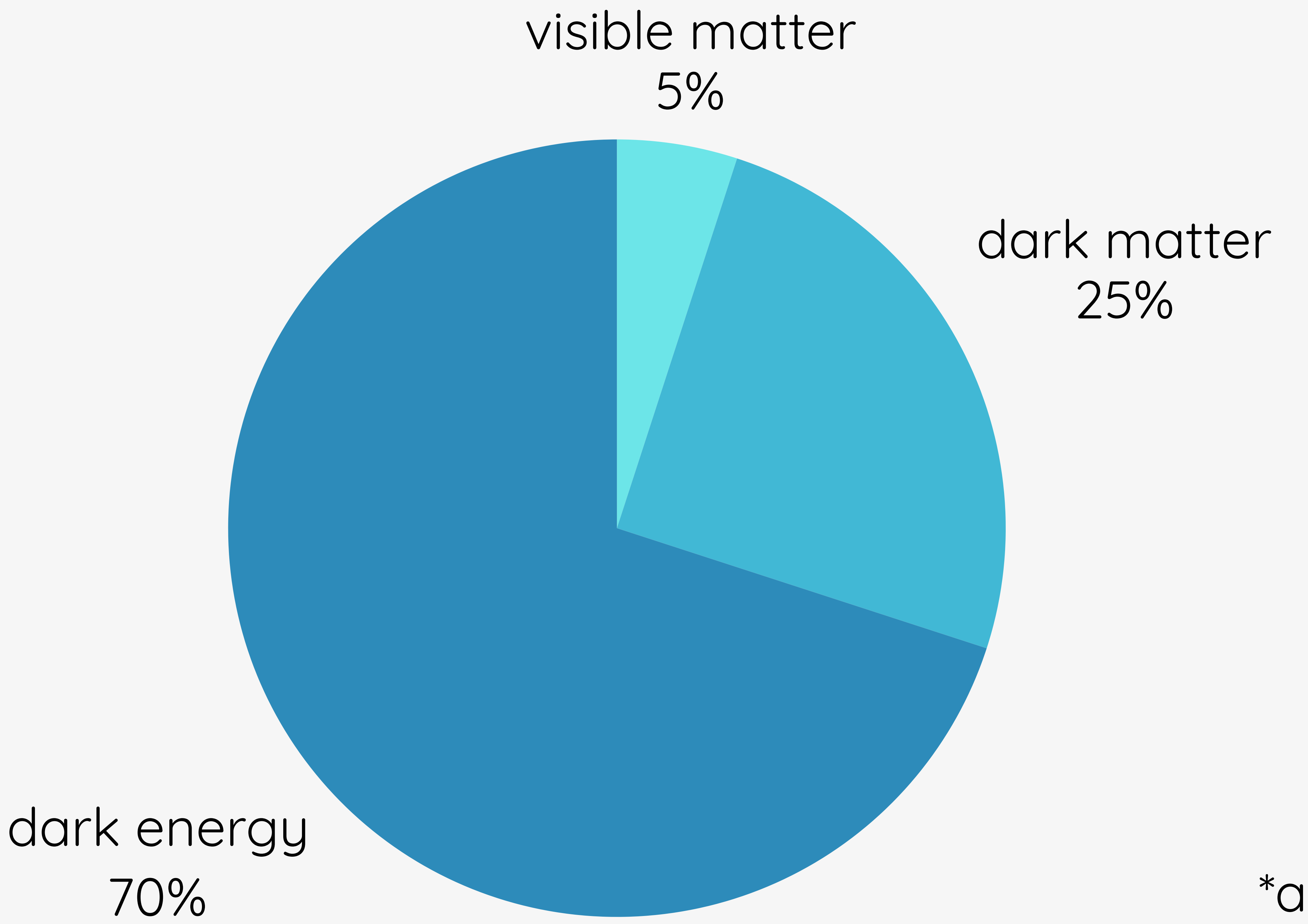
Why would you modify gravity?

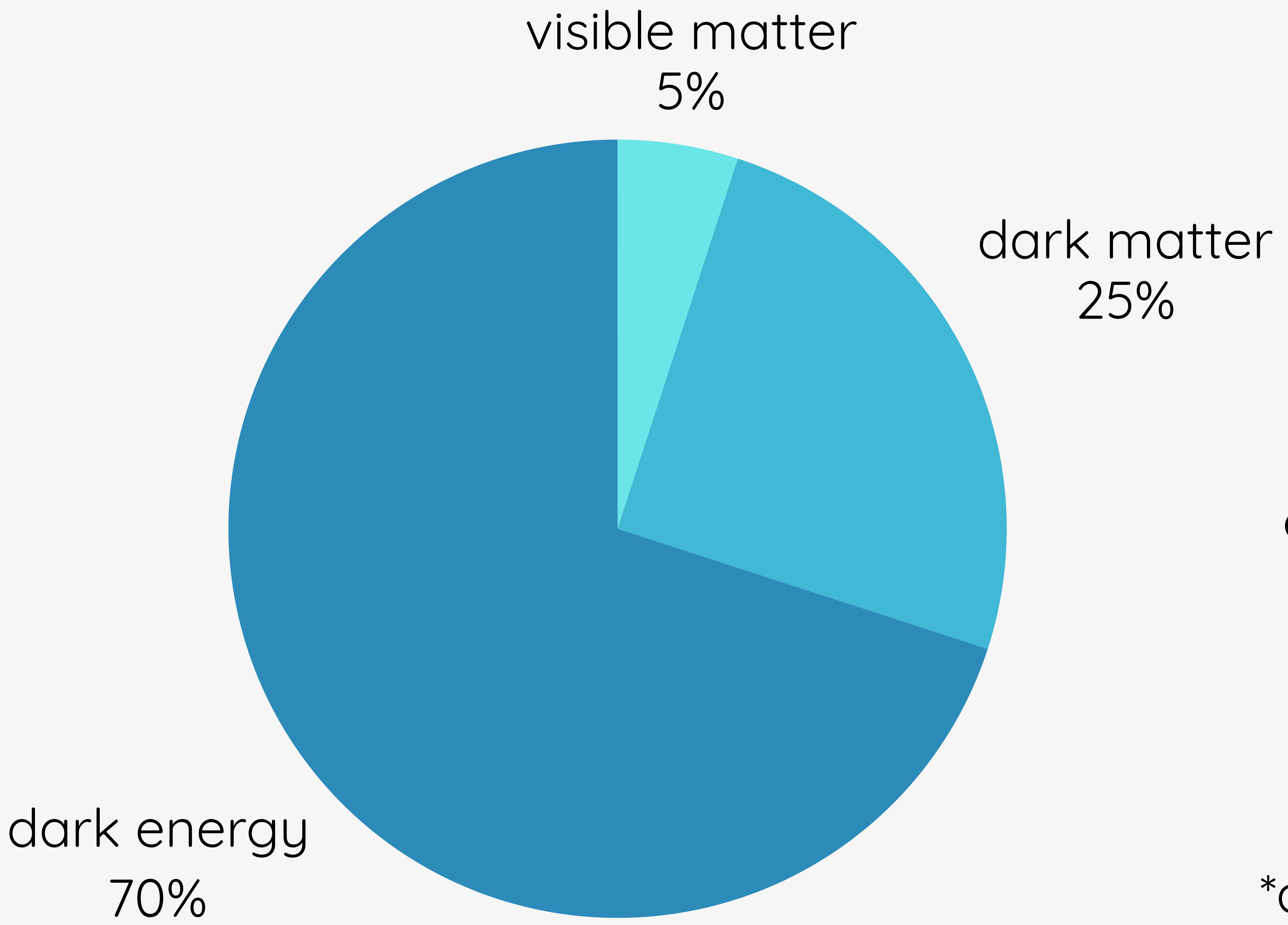
Annual Theory Meeting 2025

The Dark Universe



*approximately

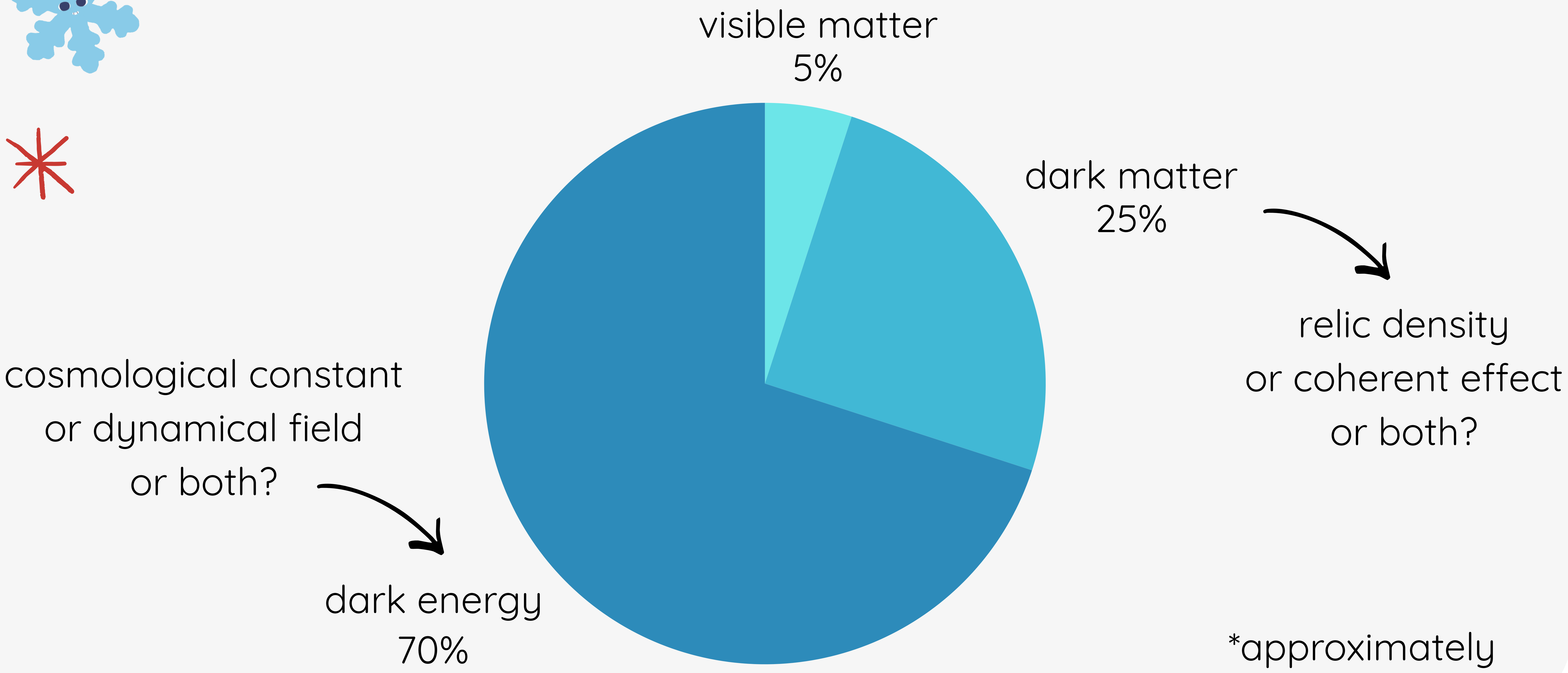
The Dark Universe



relic density
or coherent effect
or both?

*approximately

The Dark Universe



*approximately

The Einstein-Hilbert Action

$$S = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\mathrm{Pl}}^2}{2} (R - 2\Lambda)$$

Things to like about GR:

- It seems to work.
- It doesn't use up much ink.
- Non-perturbatively renormalisable?

Things to dislike about GR:

- The cosmological constant problem.
- It contains dimensionful parameters.
- It is not perturbatively normalisable.

To fix problems on large scales, we may want to introduce **new physics** in the **infrared**.

Add new light degrees of freedom.

Lovelock: a local gravity action in (3+1)D containing only 2nd-order derivatives of the metric necessarily leads to the **Einstein field equations**

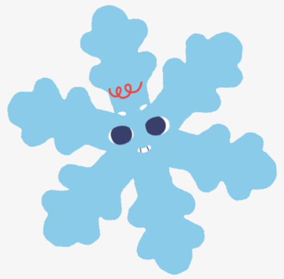
Lovelock, 1971

And then hide the evidence.

screened fifth-force models

screened fifth-force models

(scalar-tensor theories of gravity)



non-minimal gravitational couplings

potential

$$S=\int \mathrm{d}^4x\,\sqrt{-g}\,\left[\frac{1}{2}F(\phi,\partial\phi,\dots)R+\cdots-\frac{1}{2}Z^{\alpha\beta}(\phi,\partial\phi,\dots)\partial_\alpha\phi\partial_\beta\phi-V(\phi)\right]$$

higher curvature terms +
derivative couplings to
curvature tensors

non-canonical kinetic terms and
derivative interactions

Horndeski → Beyond Horndeski
→ DHOST → ...

Horndeski, 1974; Gleyzes, Langlois, Piazza, Vernizzi, 1404.6495; Langlois, Noui, 1510.06930;
Babichev, Bansal, Mylova, Padilla, 2512.13453

non-linear field redefinitions
→ redundancy of operators

non-minimal gravitational couplings

potential

$$S = \int \mathrm{d}^4x\, \sqrt{-g}\, \left[\frac{1}{2}F(\phi, \partial\phi, \dots)R + \dots - \frac{1}{2}Z^{\alpha\beta}(\phi, \partial\phi, \dots)\partial_\alpha\phi\partial_\beta\phi - V(\phi)\right]$$

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Weyl rescaling

$$\sqrt{-g}\,F(\phi)R \longrightarrow \sqrt{-\tilde{g}}\,M_{\rm Pl}^2\tilde{R}$$

Jordan frame **Einstein frame**

Standard Model fields still move on geodesics of the **Jordan-frame metric**

$$g_{\alpha\beta} = \frac{M_{\rm Pl}^2}{F(\phi)}\tilde{g}_{\alpha\beta} = M_{\rm Pl}^2 A^2(\tilde{\phi})\tilde{g}_{\alpha\beta}$$

giving a **fifth force** $\propto -\nabla \ln A(\tilde{\phi})$

Field-space geometry

$$\mathcal{L} \supset g^{\alpha\beta} G^{AB} \partial_\alpha \Phi_A \partial_\beta \Phi_B$$

field-space metric

Allows to construct field reparametrisation-invariant formulations
→ **frame covariance**

Also at the level of the quantum effective action via **Vilkovisky–DeWitt** and generalisations

Vilkovisky, 1984; Gattus, Pilaftsis, 2406.13594; Karamitsos, Muntz, 2512.07929;
cf. functional geometric approaches: Cohen, Lu, Sutherland, 2312.06748; Kluth, PM, Saffin, 2311.17199

Screening

new long-range forces are heavily constrained
(see Clare Burrage's talk this afternoon)

$$\phi \to \phi + \delta\phi : \; Z(\phi)\left(\ddot{\delta\phi} - c_s^2(\phi)\nabla^2\delta\phi\right) + m^2(\phi)\delta\phi = A_{,\phi}(\phi)\mathcal{M}\delta^3(\mathbf{x})$$

symmetron/
Damour–Polyakov

chameleon

$$U(r) = -\frac{1}{Z(\phi)c_s^2(\phi)}A^2_{,\phi}(\phi)\frac{1}{4\pi r}\exp\left[-\frac{m(\phi)r}{Z^{1/2}(\phi)c_s(\phi)}\right]\mathcal{M}$$

Vainshtein

Joyce, Jain, Khoury, Trodden, 1407.0059

Scale symmetry

$$g_{\alpha\beta} \to \Omega^2(x) g_{\alpha\beta} \qquad \frac{\mathrm{d}}{\mathrm{d}\tau} \to \Omega^{-2}(x)\frac{\mathrm{d}}{\mathrm{d}\tau}$$

“fifth force”

$$\ddot{x}^\mu + \Gamma^\mu_{\alpha\beta}\dot{x}^\alpha\dot{x}^\beta - \underbrace{g_{\alpha\beta}\dot{x}^\alpha\dot{x}^\beta}_{\text{zero for null geodesics}}\partial^\mu \ln\Omega = 0$$

Higgs-dilaton

Fifth force couplings depend on the origin of
scale symmetry breaking.

explicit scale breaking in the matter sector → fifth forces couple

no explicit scale breaking in the matter sector → fifth forces decouple

$$V = \frac{\lambda}{4!}\left(H^\dagger H - \frac{\beta}{\lambda} S^2\right)^2$$

But **dimensional transmutation** breaks scale symmetry.

Shaposhnikov, Zenhäusern, Wetterich, Buchmüller, Dragon, Blas, Garciá-Bellido, Rubio, Bezrukov, Karananas, Ghilencea ...

An important corollary

Fifth forces couple via explicit scale breaking terms.

fifth force couplings $\longleftrightarrow$ Higgs portals

$$\phi^2 R \qquad\qquad \phi^2 H^\dagger H$$

Many BSM models share the phenomenology of the scalar sectors of scalar-tensor theories of gravity and vice versa.

Moreover, non-minimal couplings to curvature terms are generated by radiative effects.

Burrage, Copeland, PM, Spannowsky, 1804.07180; Copeland, PM, Sevillano Muñoz, 2111.06357;
for RG: Markannen, Nurmi, Rajantie, Stopyra, 1804.02020

Prototype: symmetron

Screening driven by spontaneous symmetry breaking.

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

low ambient density

$$\rho < \mu^2 M^2$$
$$\langle\phi\rangle \to v$$
$$F \propto \langle\phi\nabla\phi\rangle \neq 0$$

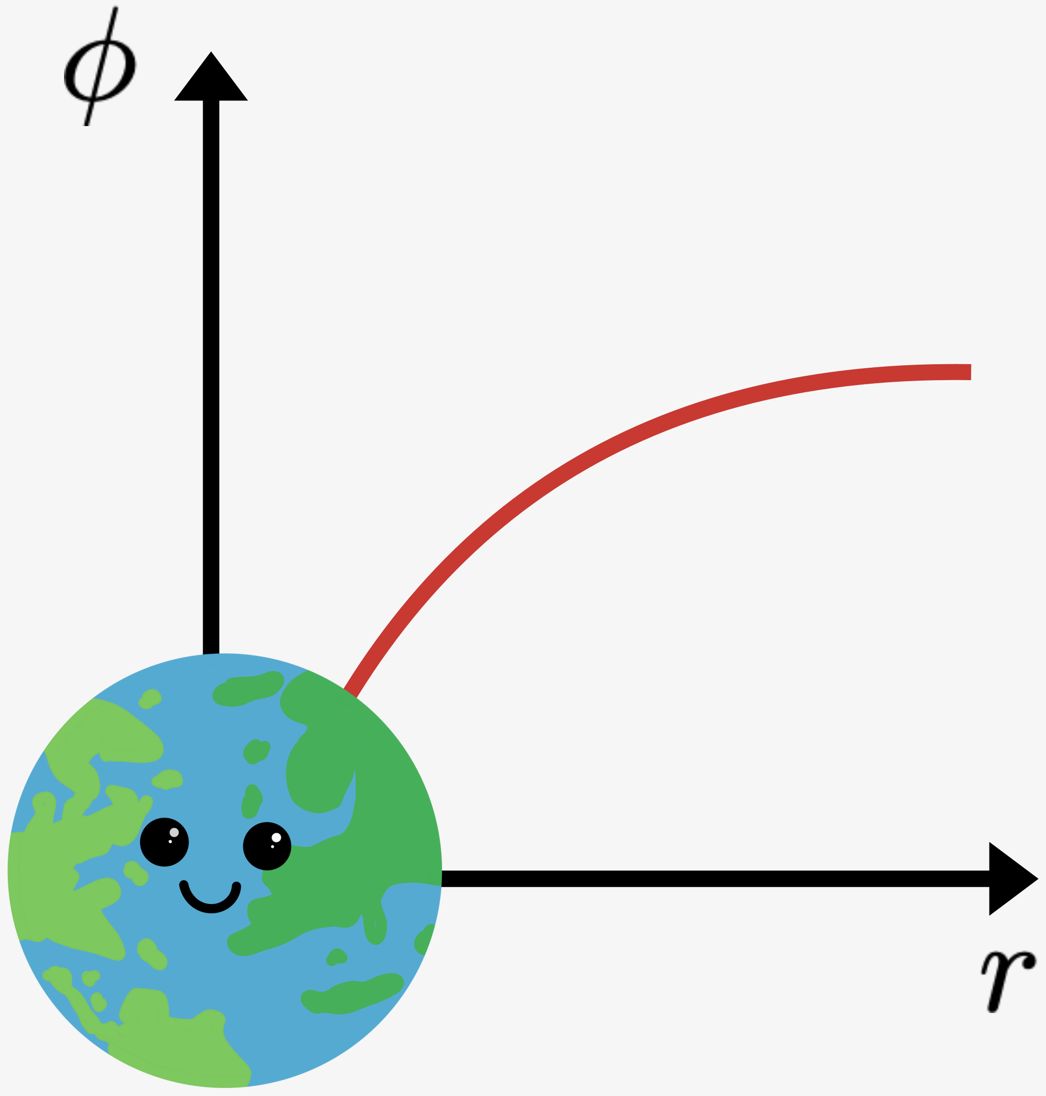
high ambient density

$$\rho > \mu^2 M^2$$
$$\langle\phi\rangle \to 0$$
$$F \propto \langle\phi\nabla\phi\rangle \to 0$$

Hinterbichler, Khoury, 1107.2112

Fifth-force profiles

Matter sources generate non-trivial classical field profiles.



- fifth forces from spatial gradients
- gradient energy also gravitates
- time-dependent coherent phenomena beyond the static ground state

→ **multiple phenomenologies**

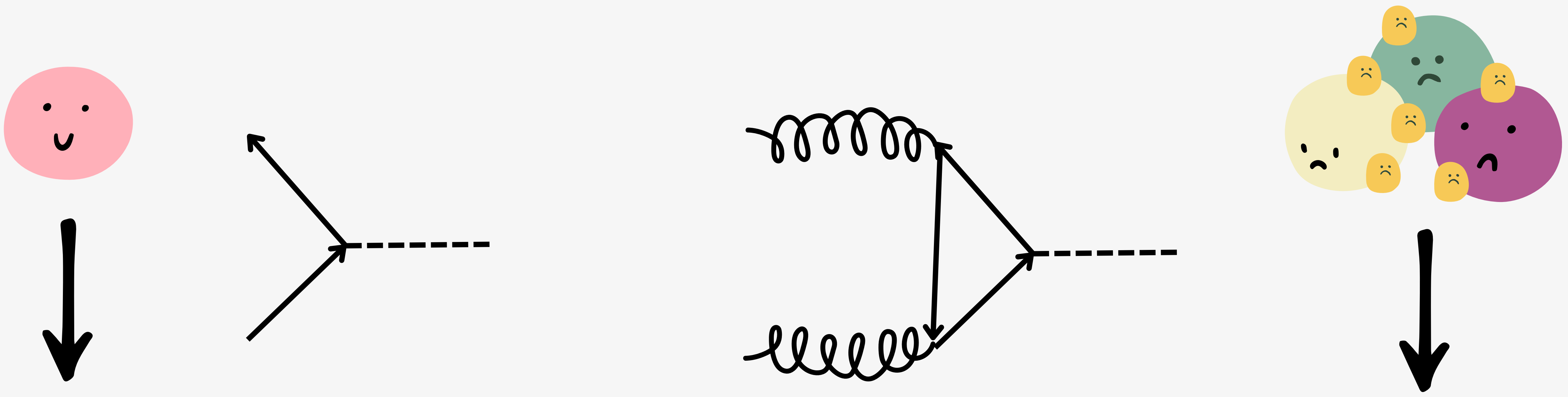
Equiv. principle violations

Macroscopic level:

When an extended mass distribution is (partially) screened, not all of the mass sources a fifth force.

Microscopic level:

Elementary and composite states couple differently to fifth forces.



$F \propto m$ $\quad\quad$ $F \propto \eta m, \;\; \eta < 1$

Bottom: Burrage, Copeland, PM, Spannowsky, 1804.07180; cf. the case of axion fifth forces: Bauer, Rostagni, 2307.09516

Fine tuning

If we want to see these models as more than prototypes, we need to acknowledge fine tuning.

SM Higgs field →

non-linearities are important

environmental dependence

coupling QFTs to classical sources

Quantum corrections

Quantum fields coupled to spatially varying classical sources:

Quantum corrections cannot be renormalized away
where there are gradients in the classical field profile.

The classical field will be meaningful if

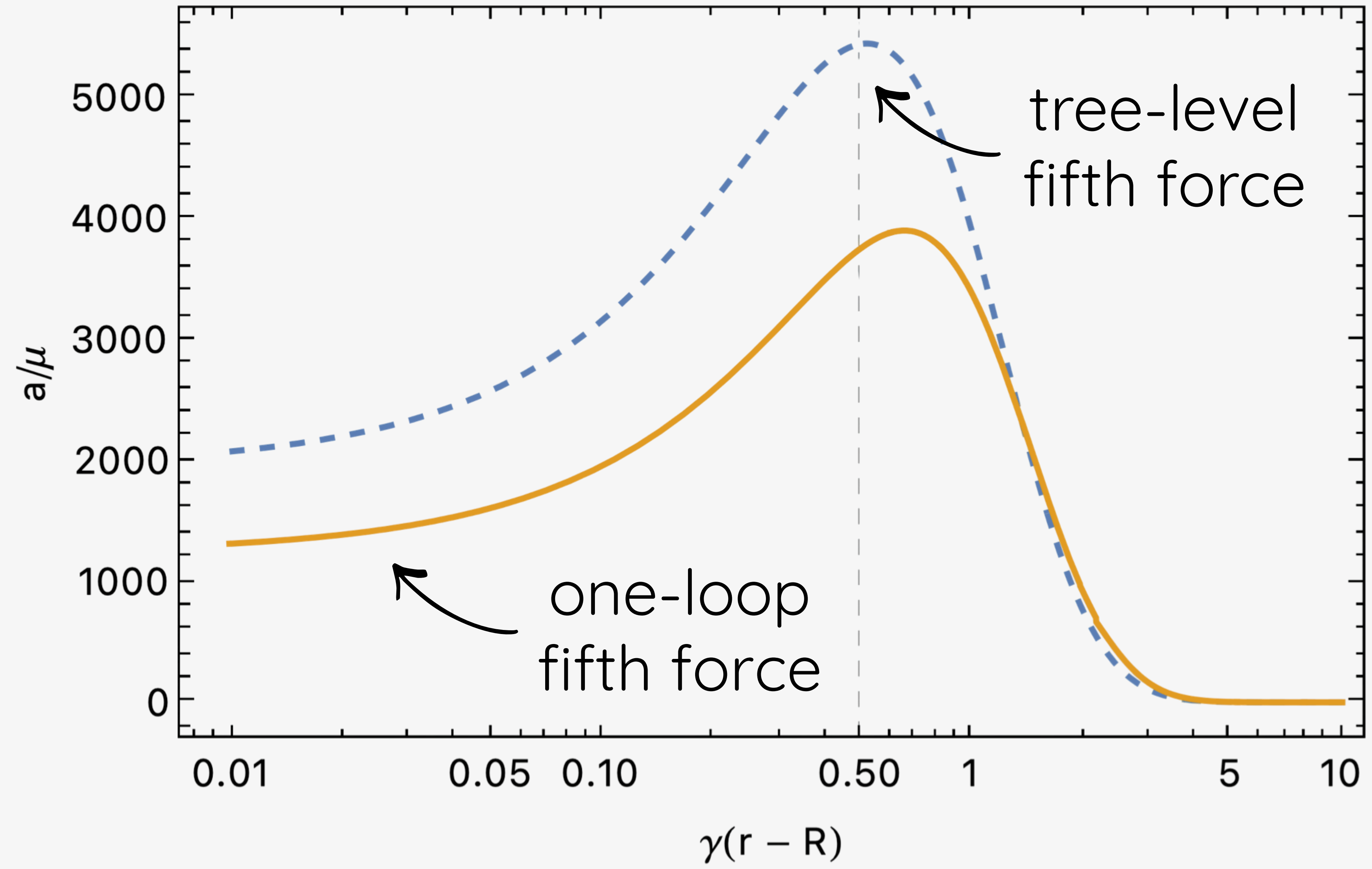
$$L \ll \mu^{-1}: \ (\Delta\phi_L)_{\mathrm{QM}} \ll (\Delta\phi_L)_{\mathrm{cl}}$$

quantum corrections
smeared over L

change in the
classical field

E. Weinberg, 2012; Burrage, Elder, PM, Saadeh, Thrussel, 2104.14564

Quantum corrections



(a) Parameters appropriate for hydrogen spectroscopy [53] ($\mu = 1\,\text{GeV}$, $M = 10\,\text{MeV}$, $\lambda = 0.5$ and $\rho_0 = 2.54 \times 10^{-3}\,\text{GeV}^4$).

M Udemba + PM, arXiv:2508.16726; [53] is Brax, Davis, Elder, 2207.11633; see also Brax, Fichet, 2203.01342

Key takeaways

- **Field theories whose phenomenology depends on interplay of**
  - non-linear (self-)interactions
  - couplings to classical sources
  - the structure of the Standard Model and its extensions
- **Much of the analysis of these models has been (semi-)classical**
- **Multiple phenomenologies shared by many other models**
  - ultra-light dark matter
  - Higgs portals (albeit in very different parameter regions)