Modifying Gravity: the view from below

EFTs, Naturalness & the CC problem:

and other Alternative Facts

Testing Gravity Workshop SFU
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Outline

- EFTs and gravity
  - mods in the IR vs mods in the UV
- Naturalness and the CC problem
  - does modifying gravity help?
- Lessons for tests of gravity
  - some possible surprises

EFTs & Gravity

EFTs & Gravity

- Precision comparison with experiment requires quantification of theoretical error
  - $a(\text{muon}) = 1159652188.4(4.3) \times 10^{-12}$ (exp)
  - $a(\text{muon}) = 1159652140(27.1) \times 10^{-12}$ (th)
- QED's renormalizability is important for its calculability, and so underpins theory error

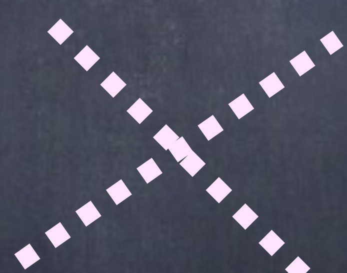
EFTs & Gravity

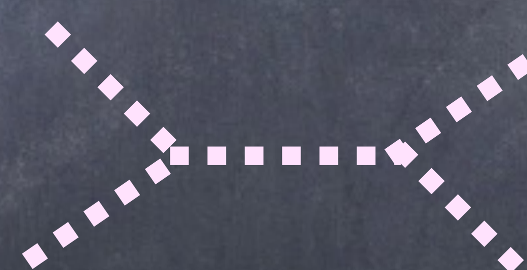
- GR is also tested with precision
  - $dP/dt = -2.408(10) \times 10^{-12}$ (exp)
  - $dP/dt = -2.40243(5) \times 10^{-12}$ (th)
- Why doesnt nonrenormalizability of GR undermine ability to fix theory error?
  - It would, if we believe we cannot say anything at all about quantum corrections in gravity

EFTs & Gravity

- e.g. for graviton scattering on a fixed weakly-curved background:

$$\mathcal{L} = (\partial h)^2 + \frac{1}{M_p} h(\partial h)^2 + \frac{1}{M_p^2} h^2(\partial h)^2 + \cdots$$

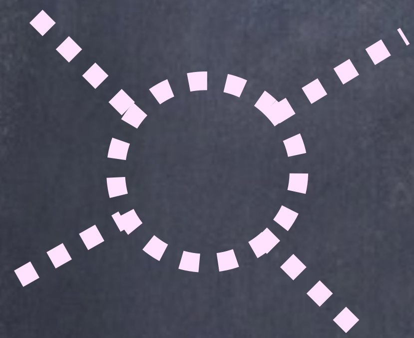




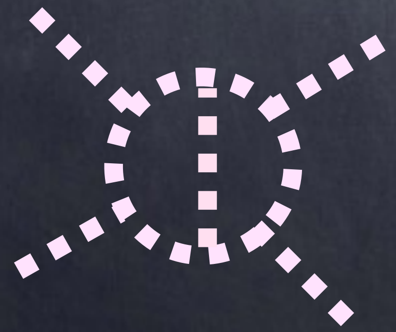
$$\mathcal{A}_{\text{classical}} = \frac{Q^2}{M_p^2} + \cdots$$

EFTs & Gravity

- Higher order contributions diverge more and more due to dimension of the coupling



$$\mathcal{A}_{1-\mathrm{loop}} = \frac{Q^2}{M_p^4} \int \frac{\mathrm{d}^4 p}{(2\pi)^4} \frac{p^6}{(p^2+Q^2)^4}$$



$$\mathcal{A}_{1-\mathrm{loop}} = \frac{Q^2}{M_p^6} \int \left[\frac{\mathrm{d}^4 p}{(2\pi)^4}\right]^2 \frac{p^{10}}{(p^2+Q^2)^7}$$

EFTs & Gravity

- New divergences cannot be absorbed into G

$$\frac{\mathcal{L}}{\sqrt{-g}} = \Lambda + \frac{M_p^2}{2}R + c_1 R^2 + c_2 R_{\mu\nu}R^{\mu\nu} + \frac{c_3}{m^2}R^3 + \cdots$$

- But new divergences can be absorbed if GR is first term in derivative expansion involving higher curvatures

EFTs & Gravity

- How to interpret the non-GR terms?

$$\frac{\mathcal{L}}{\sqrt{-g}} = \Lambda + \frac{M_p^2}{2} R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + \frac{c_3}{m^2} R^3 + \cdots$$

- As would have arisen after integrating out a collection of particles with masses m >> Q.

- largest mass (M_p) wins in numerator, but smallest mass (m) wins in denominator

EFTs & Gravity

- Predictive despite many terms, provided one recognises one is doing an expansion in Q/m

$$\mathcal{A}_E(Q) \sim \left(\frac{Q^2}{M_p^{E-2}}\right)\left(\frac{Q}{4\pi M_p}\right)^{2L} \prod_{i,d>2}\left(\frac{Q}{M_p}\right)^{2V_{id}}\left(\frac{Q}{m}\right)^{(d-4)V_{id}}$$

- e.g. L-loop amplitude involving E external particles of energy Q, in which V_{id} interactions appear that have i fields and d derivatives

EFTs & Gravity

$$\mathcal{A}_E(Q) \sim \left(\frac{Q^2}{M_p^{E-2}}\right)\left[1 + k\left(\frac{Q}{4\pi M_p}\right)^2 + \cdots\right]$$

- Leading contribution:
  - L=0 and V_{id} = 0 for all d > 2 (i.e. Classical GR)
- Next-to-leading contribution:
  - L=1 using only d=2 or L=0 with V_{id}=1 for d=4 (i.e. 1-loop GR plus 0-loop with one R^2 interaction)

EFTs & Gravity

$$A_E(Q) \sim \left(\frac{Q^2}{\cdots}\right)\left[1 + k\left(\frac{Q}{\cdots}\right)^2 + \cdots\right]$$

Predictive because only a finite number of unknown coefficients enter at any given order of Q/m

- Leading cont
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EFTs & Gravity

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Notice that Q/M_p is loop-counting parameter as well as controlling the derivative expansion

EFTs & Gravity

- Lessons for proposed mods to GR
  - Known to be consistent: GR+light low-spin fields (scalars, vectors); in derivative expansion subject to naturalness constraints.
  - If deviations from derivative expansion, e.g. P(X) theories, should also check validity of classical approximation (what is m in Q/m?)
  - Normally need not worry about runaways due to higher derivatives (e.g. without recourse to Horndeski models)
  - In particular should avoid effects with non-negative powers of m (dangerous e.g. for preferred-frame theories)

Naturalness

Patron Saint of Naturalness

Naturalness

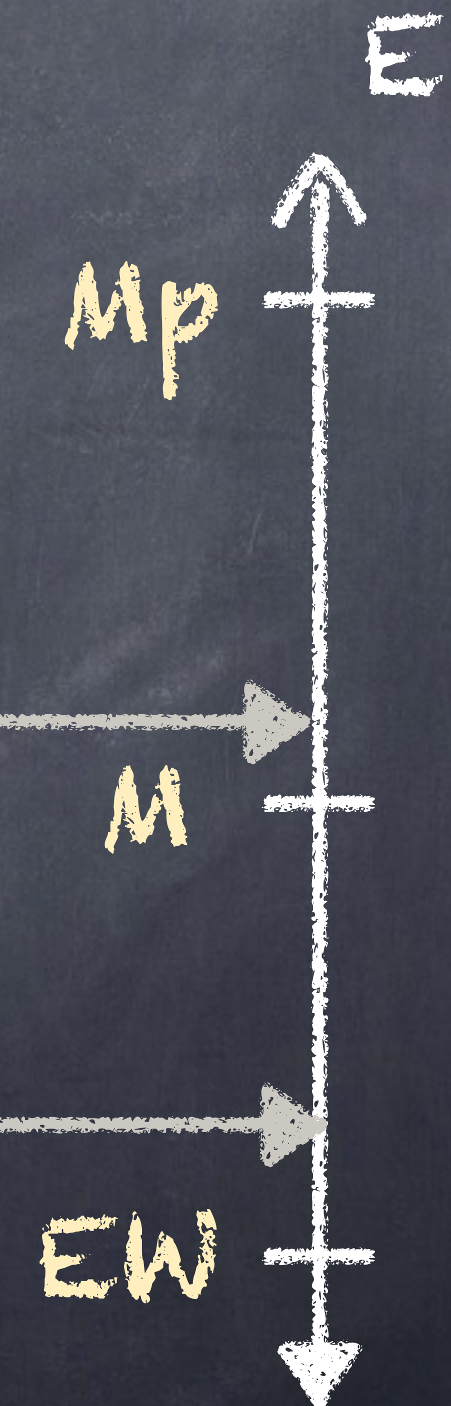
- Nature comes to us with many scales, and each seems understandable on its own terms
    - Contribution to dimension-D effective interaction $L = c\ O_D$ once integrated out is $c \sim m_i^{4-D}$
- Should worry if we find small c when $D < 4$:   important clue!

Naturalness

- Parameters are specific to a particular effective theory. e.g. for Higgs mass:

$$m_H^2 = \underbrace{2\mu_1^2 + cM^2} + (\text{loops})$$

$$m_H^2 = 2\mu_0^2 + (\text{loops})$$

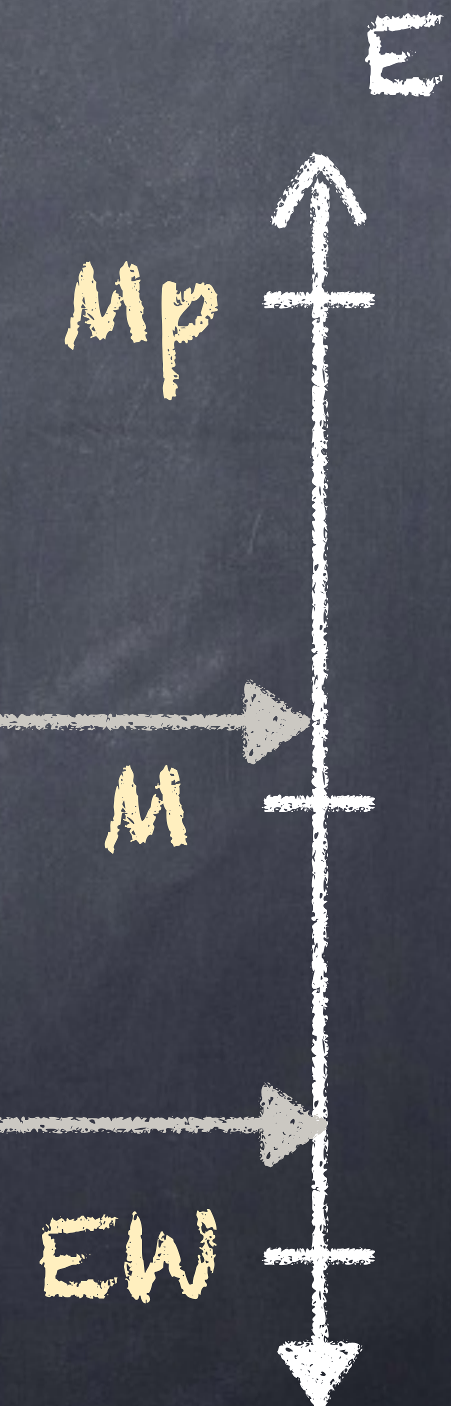


Naturalness

- Must cancel to many many decimal places the larger M is

$$m_H^2 = 2\mu_1^2 + cM^2 + (\text{loops})$$

$$m_H^2 = 2\mu_0^2 + (\text{loops})$$



Naturalness

- Technical naturalness:
  - Why is a parameter small in the 'fundamental' theory at very high energies?
  - Why does it remain small when coarse-graining scales down to where it is measured?
- If both answered then 'technically natural'
  - Enhanced symmetry when parameter vanishes provides a simple way to ensure tech. natural
  - Understood hierarchies seem natural in this way

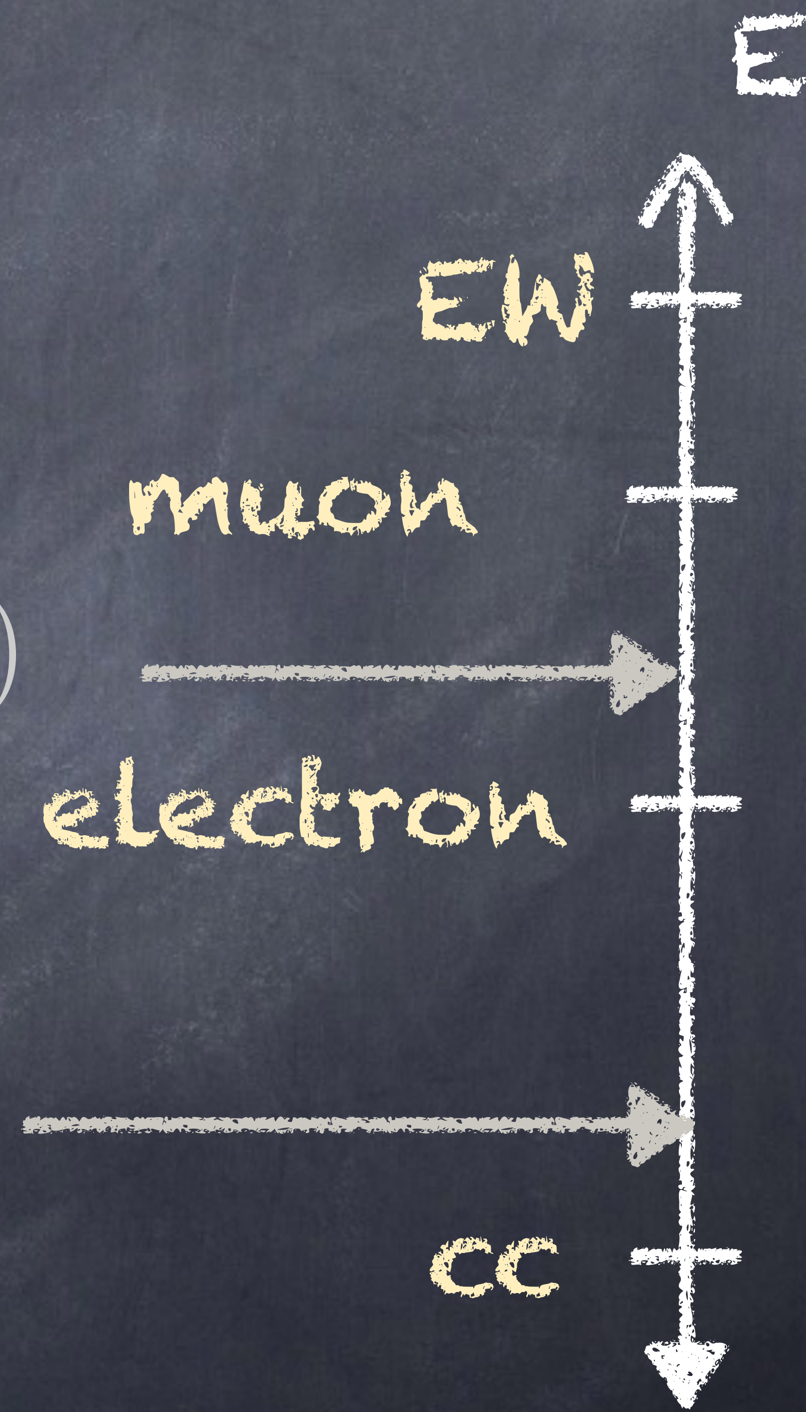
CC Problem

CC Problem

- (Old) CC problem: Vacuum energy is also unnatural

$$\rho = \Lambda_1 + cM^4 + (\text{loops})$$

$$\rho = \Lambda_0 + (\text{loops})$$

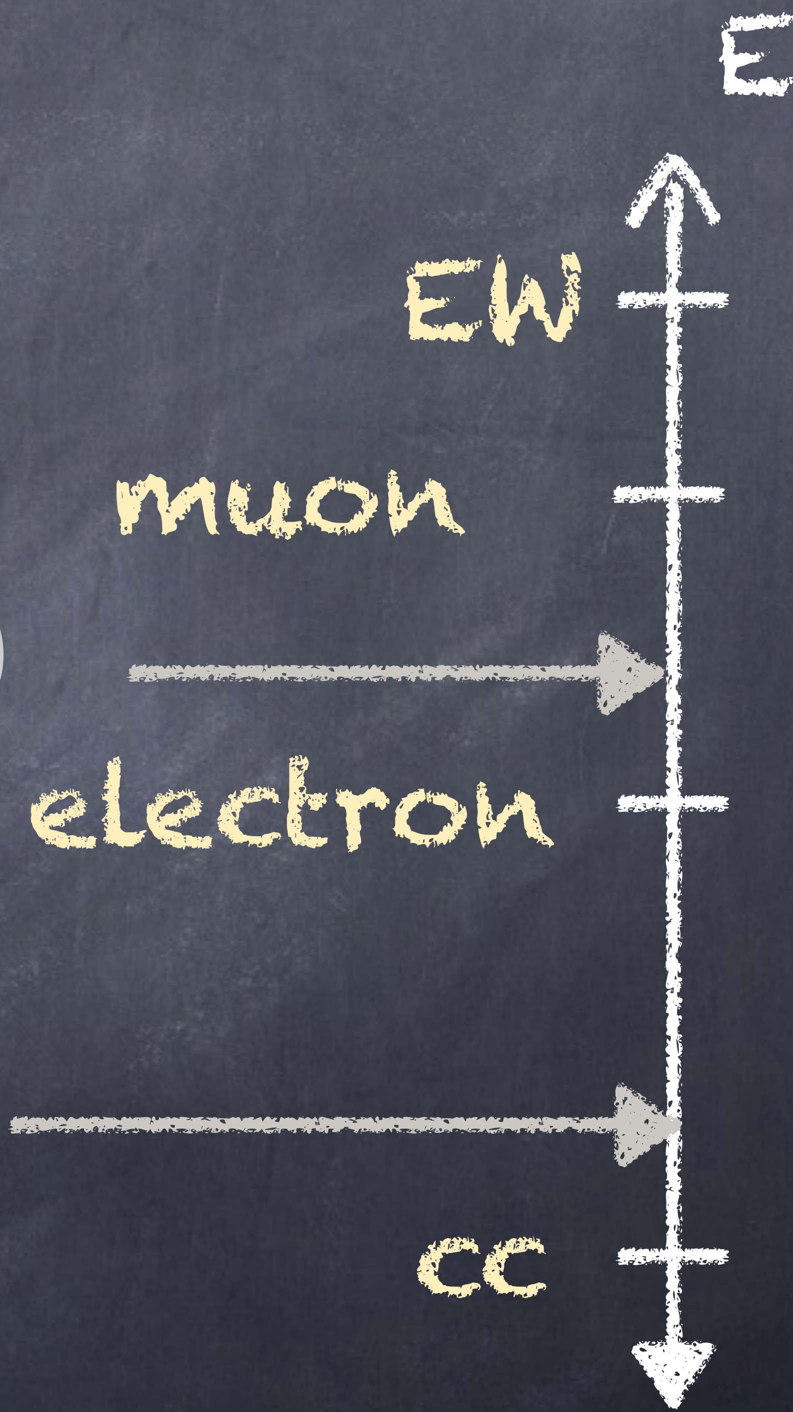


CC Problem

- Now the cancellation occurs at scales we think we understand

$$\rho = \Lambda_1 + cM^4 + (\text{loops})$$

$$\rho = \Lambda_0 + (\text{loops})$$



CC Problem

- Not a problem if we can modify how quantum fluctuations gravtate in vacuum (but NOT also in atoms)
- Any reasonable solution must:
  - go beyond classical approx
  - extend to energies higher than the cc itself
  - do no harm

CC Problem

- No proposals do all three
- Odd situation: no agreed viable proposals yet no no-go result.
- Most common point of view: naturalness arguments may sometimes be wrong or misleading; but when?
  - eg: anthropic proposals that argue that unnatural cancellations might occur given enough vacua, and although such vacua may be rare we may only be able to live there

CC Problem

- Some serious contenders exist: e.g. galileons and graviton mass
  - Hope to find screening mechanism for cc

$$(\Box - m^2)h_{\mu\nu} = \kappa^2 T_{\mu\nu}$$

- Inclusion of interactions so far appears to require UV cutoff below cc scale

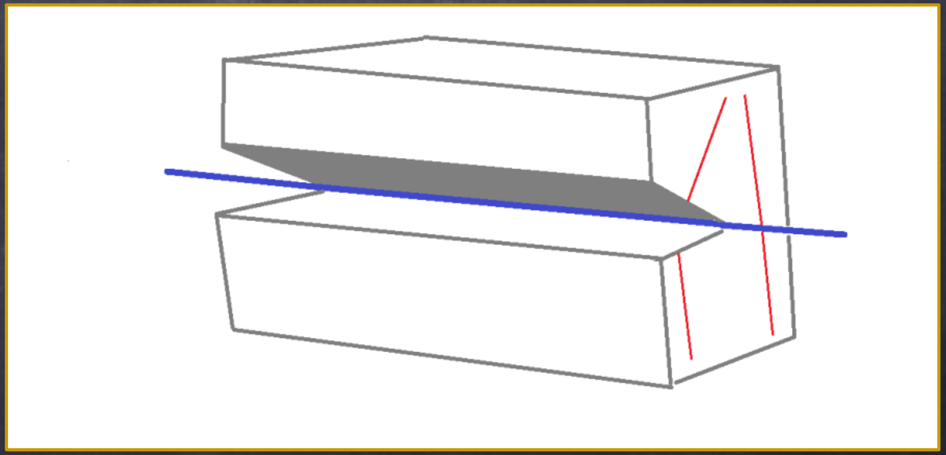
CC Problem

- My own opinion: must break link between vacuum energy (which we think is large) and universe's curvature (measured to be small)

- Problem: because vacuum is lorentz invariant its stress energy $T_{mn} = c\ g_{mn}$ with Einstein eqs is an obstruction to small curvature

CC Problem

- My own opinion: can break this link with extra dimensions of order micron in size (i.e. size of the cc)
  - Large 4D lorentz-invariant tension can curve extra dimensions instead of ours
  - no explicit examples work (yet)
- Deviation of inverse square law: smoking gun



Might there be Surprises?

The Economist

EFT Surprises?

- No evidence for gravitational exceptionalism
- But gravitational situations explore aspects of EFTs in different regimes than in particle physics, and so can contain surprises
  - t-dependent EFTs break down for non-adiabatic evolution
  - Instabilities can be features not bugs

EFT Surprises?

- Gravitational environments can be closer effective description of particle in a medium than to traditional low-energy EFT
  - Are open systems when horizons are present, since degrees of freedom are excluded not based on conservation laws (so can entangle)
  - Generic difficulties computing late-time behaviour
  - EFT exterior to black hole possibly nonlocal over horizon scales? (usual arguments against neednt apply)

Summary

- EFTs: Love them or Hate them, but use them!
  - Embedding gravity into broader context contains useful clues
  - Tools developed elsewhere in physics can be useful in gravitational applications
  - Gravitational problems provide mind-broadening examples for EFT applications