EFTs & Modified Gravity: the view from below

A liberally conservative point of view

QVG: Testing Gravity in Cosmology
MITP March 2017

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Outline

- EFTs and gravity
- Naturalness issues
  - decoupling and its uses
- Time dependent issues
  - against exceptionalism
- Lessons for tests of gravity
  - some possible surprises

EFTs & Gravity

EFTs & Gravity

- Precision comparison with experiment requires quantification of theoretical error
  - a(muon) = 1159652188.4(4.3) x 10^{-12} (exp)
  - a(muon) = 1159652140(27.1) x 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 believed nothing could be said 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

- e.g. for gr
weakly-cu

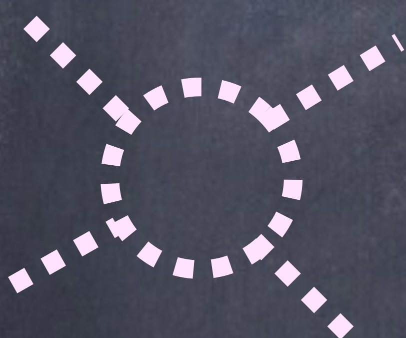
$$\mathcal{L} = (\partial h)^2$$

Need not be expansion about strictly flat space: Q generically denotes size of derivatives, including background curvature

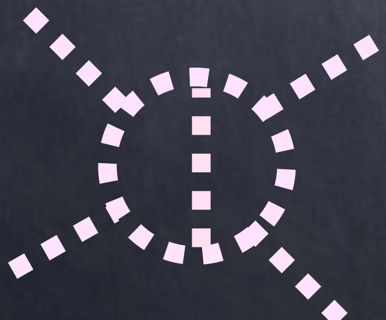
$$\mathcal{A}_{\text{classical}} = \frac{Q^2}{M_p^2} + \cdots$$

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 part of a general 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.

EFTs & Gravity

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

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

EFTs & Gravity

- As in Wilsonian EFT where effective action (or hamiltonian) is obtained by coarse-graining modes

$$\langle \mathcal{O}_1(\ell) \cdots \mathcal{O}_n(\ell) \rangle = \int \mathcal{D}\ell \, \mathcal{D}h \, e^{iS(\ell,h)} \, \mathcal{O}_1(\ell) \cdots \mathcal{O}_n(\ell)$$

$$= \int \mathcal{D}\ell \, e^{iS_{\rm eff}(\ell)} \, \mathcal{O}_1(\ell) \cdots \mathcal{O}_n(\ell)$$

$$e^{iS_{\rm eff}(\ell)} = \int \mathcal{D}h \, e^{iS(\ell,h)}$$

EFTs & Gravity

- As in Wilsonian EFT where effective action (or hamilton...

Seff local *if* expanded in powers of 1/M (due to uncertainty principle)

$$\langle \mathcal{O}_1(\ell) \cdots$$

$$= \int \mathcal{D}\ell \, e^{iS_{\text{eff}}(\ell)} \, \mathcal{O}_1(\ell) \cdots \mathcal{O}_n(\ell)$$

$$e^{iS_{\text{eff}}(\ell)} = \int \mathcal{D}h \, e^{iS(\ell,h)}$$

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)

EFTs & Gravity

$A_E(Q) \sim$

Classical GR provides leading low-energy description for almost *any* UV completion!

- Leading contribution:
  - L=0 and $V_{id} = 0$ for all d > 2 (i.e. Classical GR)

EFTs & Gravity

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

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- 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

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

- Leading contribution:

These guys renormalise these guys

  - (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
  - L=0 and V_{id}
    (i.e. Classical GR)
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EFTs & Gravity

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- Leading contribution:
  - L=0 an
    (i.e. Cl

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

- Next-to-l
  - 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

- Lessons for testing GR
  - Known to be consistent: GR+light low-spin fields (scalars, vectors); in derivative expansion; possibly higher D; subject to naturalness constraints.
  - Long-distance implications of many UV theories are captured by limited number of low-dimension interactions

EFTs & Gravity

- Lessons for proposed mods to GR
  - Exotic UV effects?: what is the local effective description at low-energies?
  - Deviations from derivative expansion, e.g. P(X) theories, should check validity of classical approximation (what is m in Q/m?)
  - Should avoid effects with non-generic & non-negative powers of m (dangerous e.g. for preferred-frame theories)

EFTs & Gravity

- Lessons for proposed mods to GR
  - Exotic UV ... descripti...
  - Deviation... theories, should check validity of classical approximation (what is m in Q/m?)
  - Should avoid effects with non-generic & non-negative powers of m (dangerous e.g. for preferred-frame theories)

e.g.

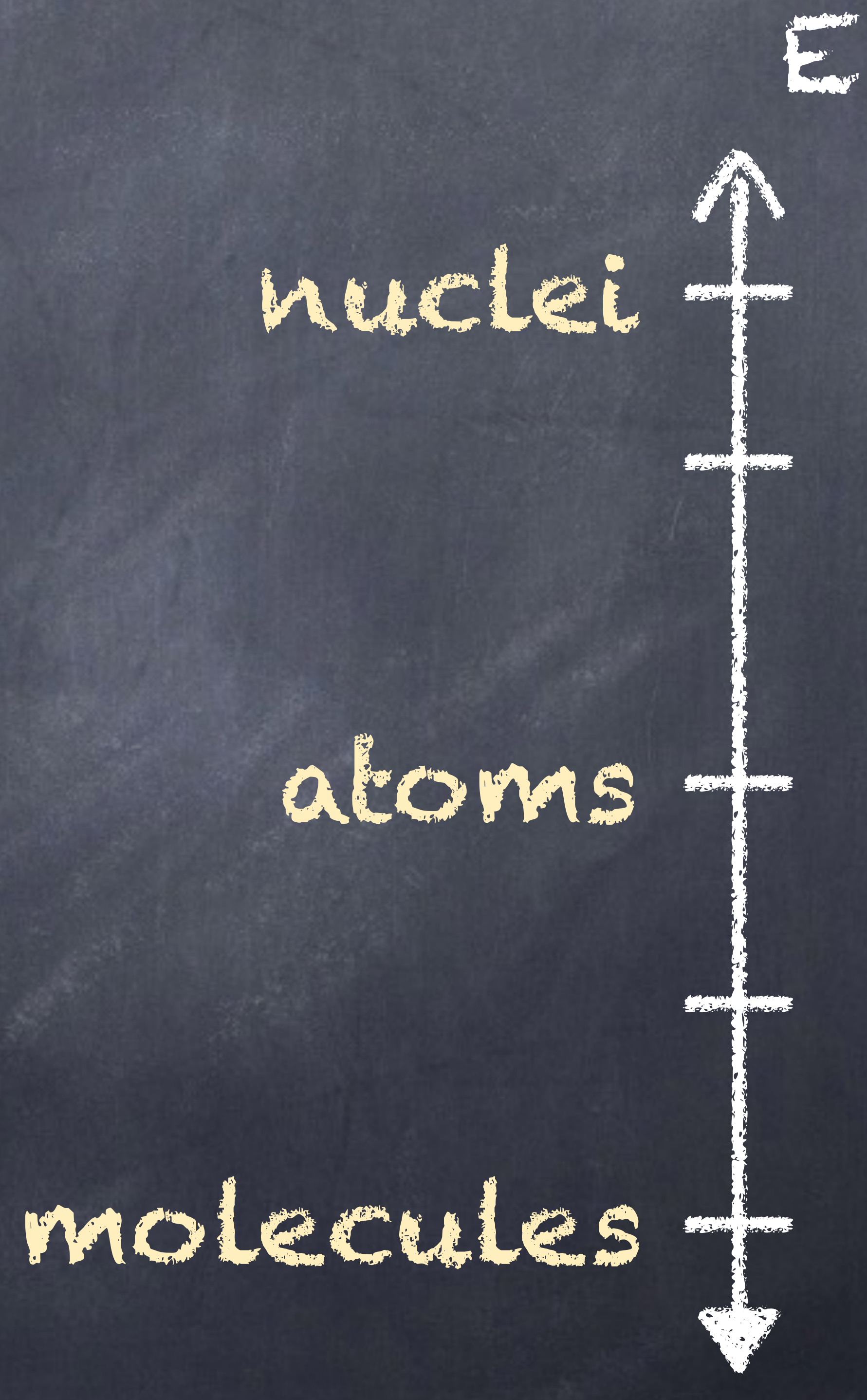
$$L = c_1(\dot{\phi})^2 + c_2(\nabla\phi)^2$$

Naturalness

Patron Saint of Naturalness

Naturalness

- Nature comes to us with many scales, and each seems to be understandable on its own terms
  - Each is described by an effective theory, obtained by coarse-graining shorter-distance physics



Naturalness

- Nature comes to us with many scales, and each seems to be understandable on its own terms
    - Contribution to dimension-D effective interaction $L = c\ O_D$ after integrating out scale m_i is $c \sim m_i^{4-D}$
- Naturalness: should worry if we find small c when $D < 4$

Naturalness

- Two such interactions in standard theory: one natural one seems not

$$\mathcal{L} = \sqrt{-g}\left[M_p^2 R + \mu^2 H^* H - \lambda (H^* H)^2 - \frac{1}{4} F^2 + \cdots\right]$$

$$8\pi G_N = M_p^{-2} \simeq \left(10^{18}\,\mathrm{GeV}\right)^{-2}$$

$$m_H^2 = 2\mu^2 + (\text{loops}) \simeq (125\ \mathrm{GeV})^2$$

Naturalness

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

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

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

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

Naturalness

- Useful criterion because suggests kinds of new physics that should not be too distant in energy
  - Composite Higgs

    (no H field, so no μ, at high E)

Naturalness

- Useful criterion because suggests kinds of new physics that should not be too distant in energy
  - Composite Higgs
  - Supersymmetric partners

  (bose-fermi partners partly cancel)

Naturalness

- Useful criterion because suggests kinds of new physics that should not be too distant in energy
  - Composite Higgs
  - Supersymmetric partners
  - Extra dimensions

(deny quantum gravity enters at Mp)

Naturalness

- Lessons for proposed mods to GR
    - If phenomenology requires small low-dim interactions (eg light scalars in cosmology) should ask why they can be light)

Naturalness

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  - If phenomenology requires small low-dim interactions (eg light scalars in cosmology) should ask why they can be light)
  - If symmetry is broken at high energies (eg Lorentz invariance) should ask why it should appear unbroken at low energies

Naturalness

- Lessons for proposed mods to GR
  - If pheno
    interacti
    should a

Why dont $(d\phi/dt)^2$ and $(d\phi/dx)^2$ have coeffs that differ with size $\ln(M/m)$?

  - If symmetry is broken at high energies (eg Lorentz invariance) should ask why it should appear unbroken at low energies

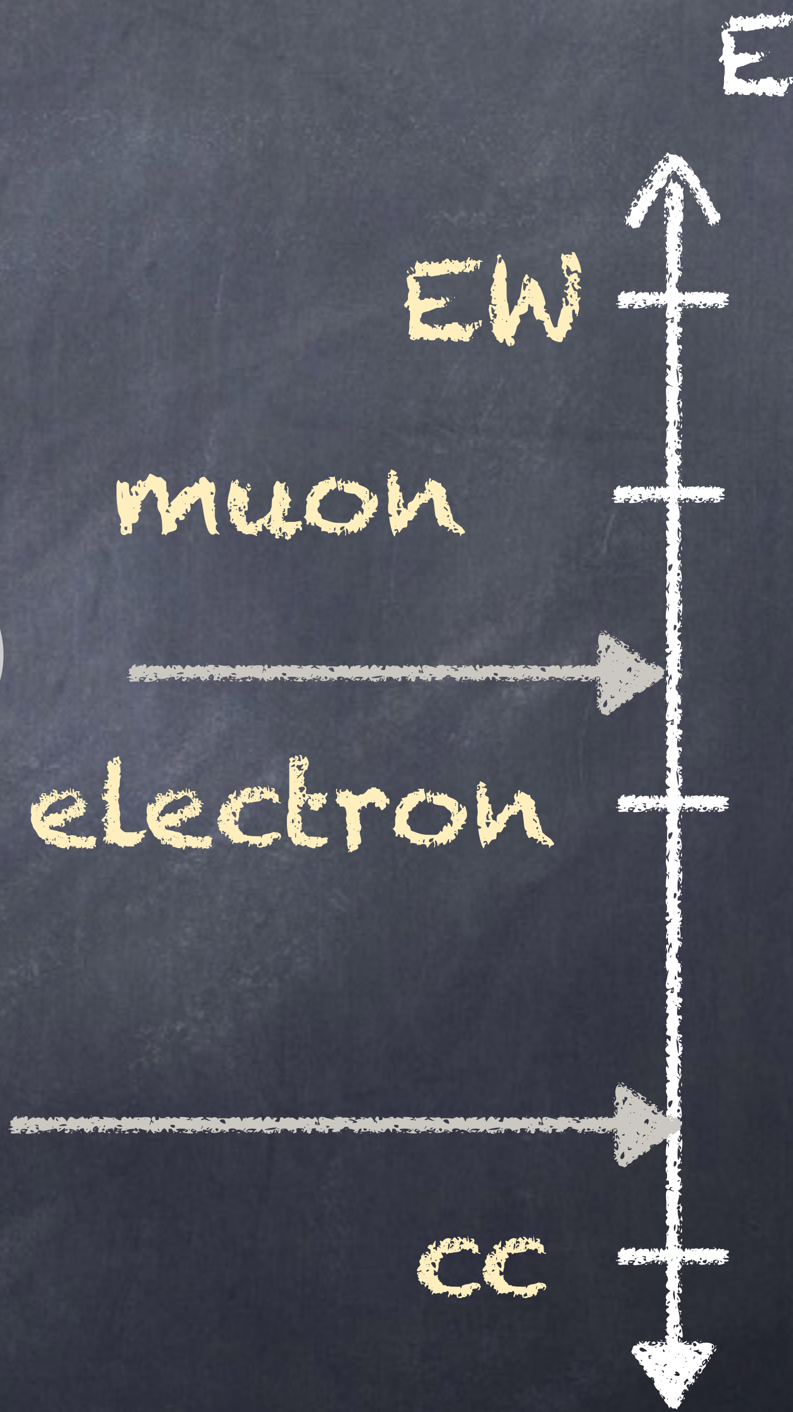
CC Problem

CC Problem

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

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

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

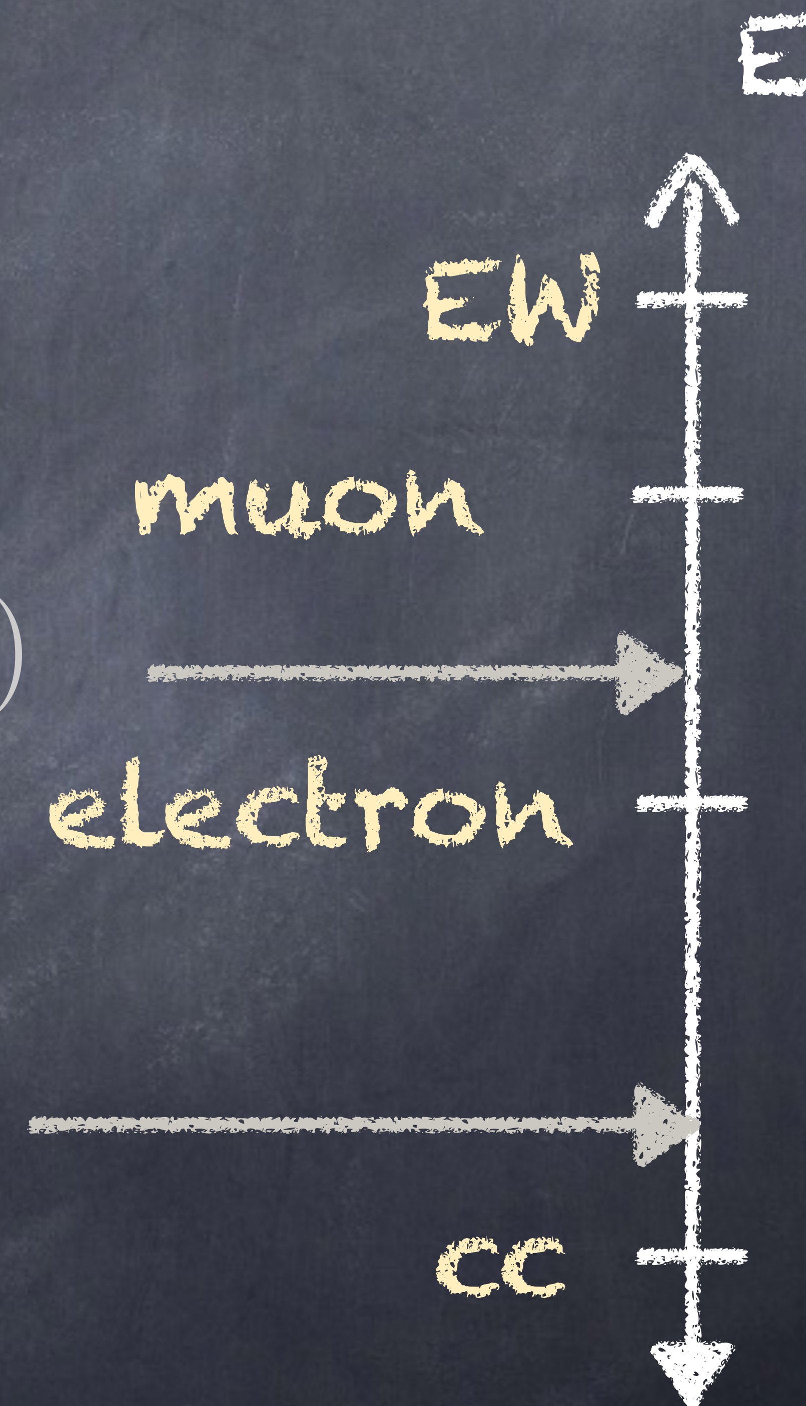


CC Problem

- 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 gravitate 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
- This is not evidence for failure of EFT itself!

CC Problem

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

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

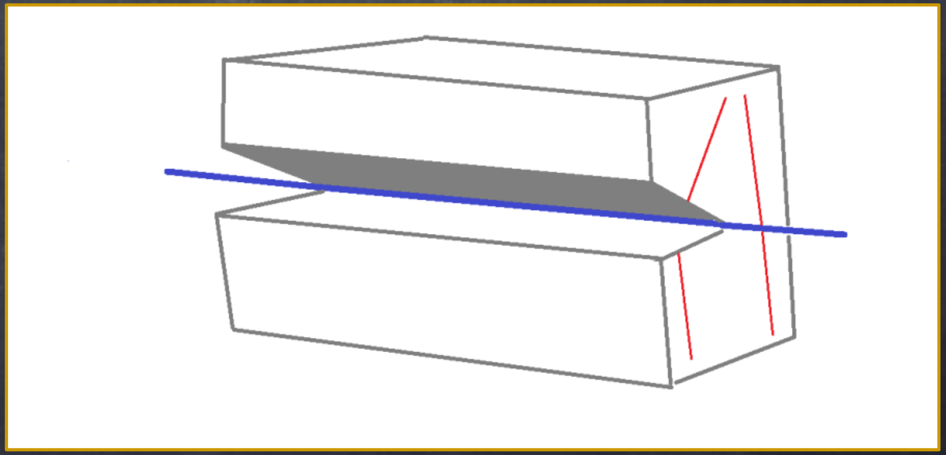
- Inclusion of interactions so far appears to require UV cutoff below cc scale

CC Problem

- My own opinion: Not yet clear conservative scalar-tensor-gauge models cannot work
- 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

- More opinion: might 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



Time dependence

Time dependence

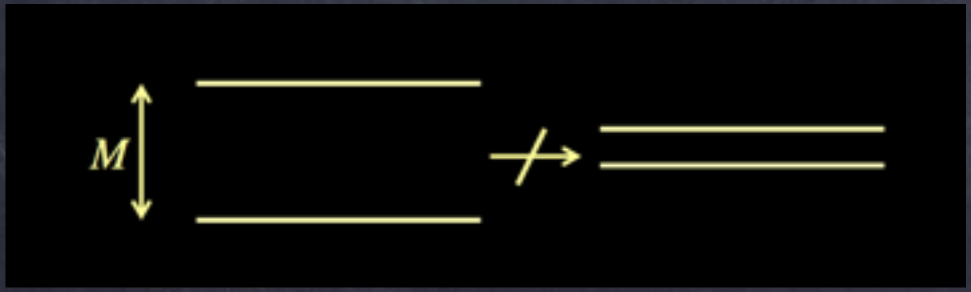
- Can EFTs apply to time-dependent situations where E is not conserved?
- Higher time-derivatives usually imply ghosts; does their absence constrain EFTs?
- What is the most efficient description of fluctuations about t-dependent background?

Time dependence

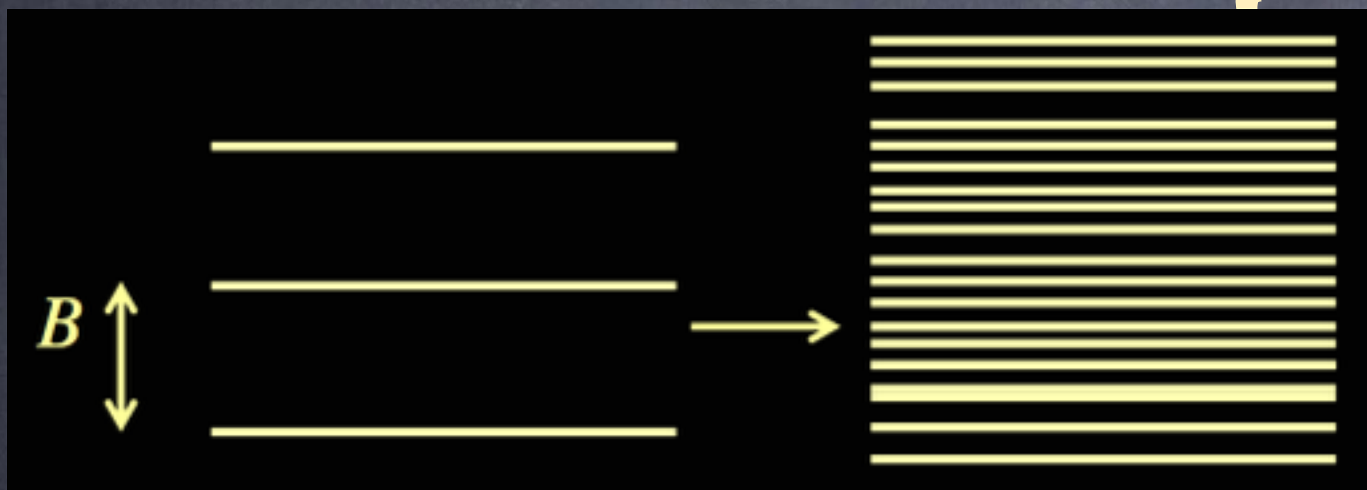
- Can EFTs apply to time-dependent situations?
  - E not strictly conserved, but can still apply EFT reasoning if evolution is adiabatic:

$$\frac{\dot{\phi}}{\phi} \ll M$$

  - Must also check other conditions (eg low energy) still apply as time evolves



Time dependence

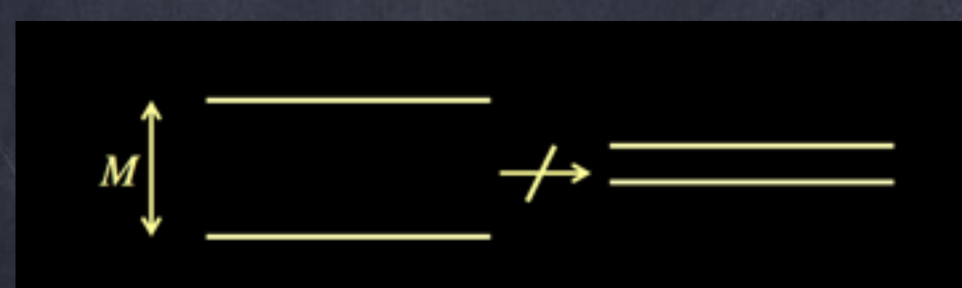


-dependent situations?

ed, but can still apply EFT reasoning if evolution is adiabatic:

Related example: 'Transplanckian' issues; are not unique to gravity

- Must also check other conditions (eg low energy) still apply as time evolves



Time dependence

- Must EFTs be constrained not to have higher time derivatives? (Implicit to Horndesky-type models)
  - Dangerous ghosts generically absent at fixed order in 1/M

$$L = \dot{q}^2 + \ddot{q}^2/M^2$$

$$\ddot{q} + \ddddot{q}/M^2 = 0$$

$$q(t) = A + Bt + Ce^{Mt} + De^{-Mt}$$

Time dependence

- Related (but not identical) issue: what EFT best describes fluctuations about time-dependent backgrounds: e.g. EFT for inflationary fluctuations
  - Exploit breaking of time-translation invariance by background to identify leading low-energy contributions to CMB
  - Reasoning similar to EFT for goldstone bosons in QCD and in condensed matter

Tim

$$t \to t + \xi^0(t, \vec{x}) \qquad \delta\phi \to \delta\phi + \dot{\phi}\,\xi^0$$

$$L = M_p^2\,\dot{H}(\partial_\mu \pi)(\partial^\mu \pi)$$

$$+2M_s^4\left[\dot{\pi}^2 + \dot{\pi}^3 - \frac{\dot{\pi}(\partial_i \pi \partial^i \pi)}{a^2}\right] + \cdots$$

- Related (bu
describes fl
backgroun
fluctuations

- invariance
w-energy

Most constraining for single-field models, where few terms possible (Cheung et al)

- Reasoning similar to EFT for Goldstone bosons in QCD and in condensed matter

Might there be Surprises?

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, some to do with t-dependence:
  - Adiabatic requirements for t-dependent EFTs
  - Instabilities can be features not bugs
  - Fluid-like systems, such as arise in LSS

EFT Surprises?

- Gravitational environments closer to effective description of particle in a medium than to traditional low-energy Wilsonian 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 due to 'secular' effects and breakdown of perturbative tools
  - 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 allows assessment of theoretical error and contains useful clues
  - Tools developed elsewhere in physics can be useful in gravitational applications
  - Gravitational problems provide mind-broadening examples for EFT applications