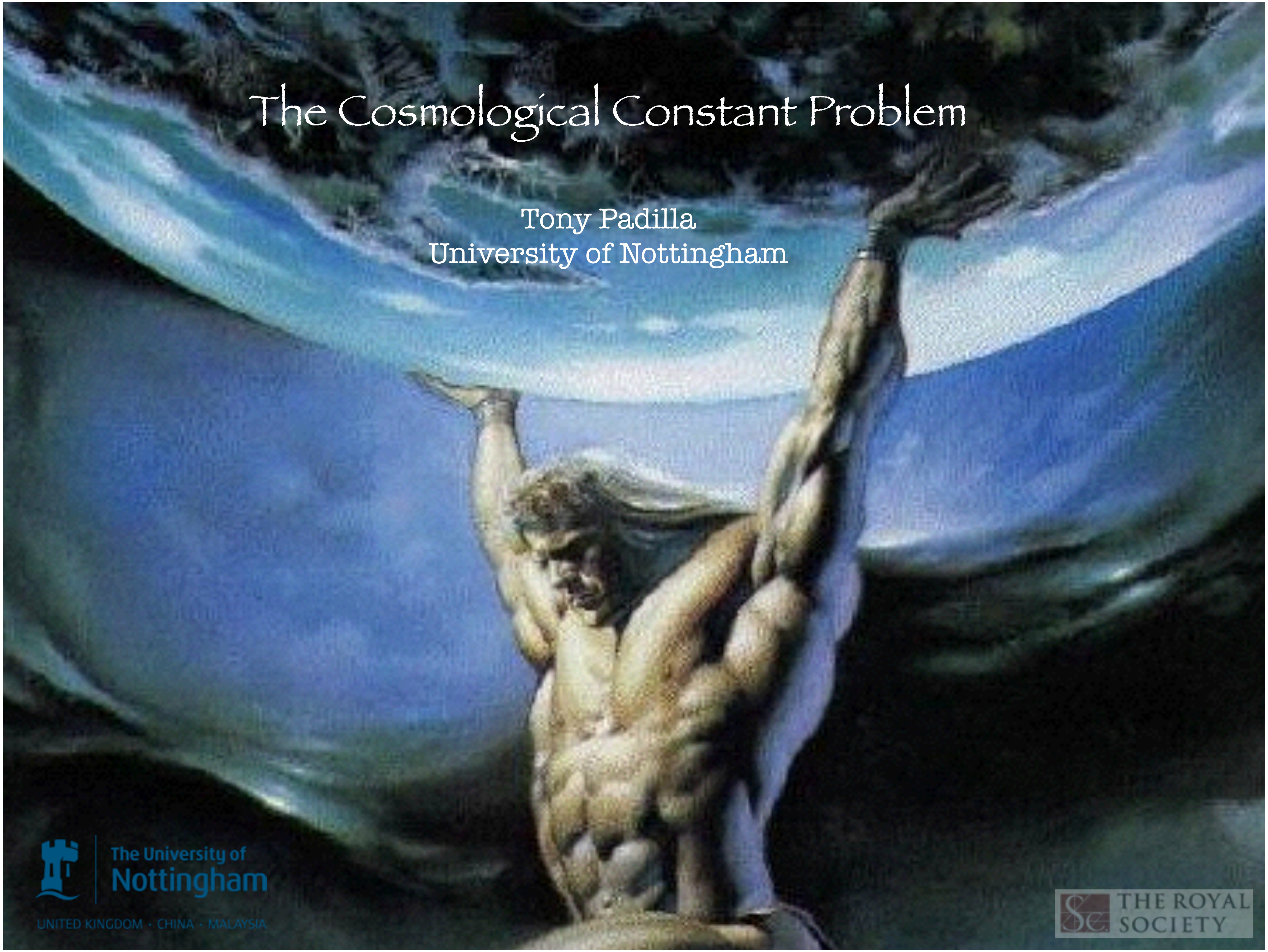
The Cosmological Constant Problem

Tony Padilla
University of Nottingham



Me: I'm going to Switzerland tomorrow jess

Me: I'm going to Switzerland tomorrow jess
Jess: why?

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....
.

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....
.
.

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....

.

.

.

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....
.
.
.
.

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....

.

.

.

.

.

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....
.
.
.
.
.
Jess: ...and that's why the whole universe eats the gravity!

Me: I'm going to Switzerland tomorrow jess
Jess: why?
Me: I'm going to that machine that smashes stuff together
Jess: why?
Me: cos they asked me
Jess: why?
Me: so I could tell em about the cosmological constant
Jess: so they can tell their children afterwards?
Me: er, yeah, maybe
Jess: can you tell me?
Me: er, OK.....
.
.
.
.
.
Jess: ...and that's why the whole universe eats the gravity!
Me: I suppose so.

Overview

1. What is the CCP?
2. How (not) to solve the CCP → unimodular gravity
   → Weinberg's No Go Thm.
3. Symmetries.
4. Short distance modifications of gravity
5. Large distance & global mod. of gravity → 'The Sequester'
6. Colemania.

Useful reviews: Weinberg (1989), Polchinski (2006)
Martin (2012), Burgess (2013)

QFT
(unitarity & locality)

$\Rightarrow \exists$ VACUUM ENERGY.

eg scalar of mass, m

$$\bigcirc \sim \frac{i}{2} \mathrm{tr}\left[\log\left(-i \frac{\delta^2 S}{\delta\phi(x)\delta\phi(y)}\right)\right]$$

$$= -\frac{1}{2}\int d^4x \int \frac{d^4k_E}{(2\pi)^4} \log\left(k_E^2+m^2\right)$$

$$= -\frac{1}{2}\int d^4x \frac{m^4}{(4\pi)^2}\left[-\frac{2}{\varepsilon} + \log\left(\frac{m^2}{4\pi\mu^2}\right) + \gamma - \frac{3}{2}\right]$$

$$= -V_{vac}\int d^4x$$

Add counterterm to remove divergence

(more on this later!)

$$V_{vac} \sim \sum_{\text{particles}} O(1)\, m^4_{\text{particle}} \gtrsim (\text{TeV})^4$$

QFT

(unitarity & locality)

$\Rightarrow \exists$ VACUUM ENERGY.

eg scalar of mass, m

$$\bigcirc \sim \frac{i}{2}\,\mathrm{tr}\left[\log\left(-i\frac{\delta^2 S}{\delta\phi(x)\,\delta\phi(y)}\right)\right]$$

$$= -\frac{1}{2}\int d^4x \int \frac{d^4k_E}{(2\pi)^4}\log\left(k_E^2+m^2\right)$$

$$= -\frac{1}{2}\int d^4x\,\frac{m^4}{(4\pi)^2}\left[-\frac{2}{\varepsilon}+\log\left(\frac{m^2}{4\pi\mu^2}\right)+\gamma-\frac{3}{2}\right]$$

$$= -V_{vac}\int d^4x$$

Add counterterm to remove divergence

(more on this later!)

$$V_{vac} \sim \sum_{\text{particles}} O(1)\, m^4_{\text{particle}} \gtrsim (\text{TeV})^4$$

GR

(EP & GCI)

$\Rightarrow$ VACUUM ENERGY GRAVITATES

$$-V_{vac}\int d^4x$$

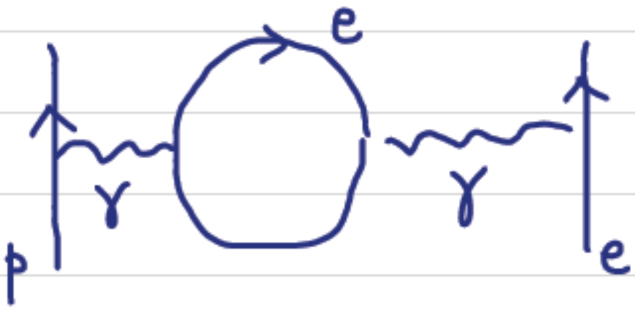
$$\downarrow$$

$$-V_{vac}\int d^4x\sqrt{g}$$

$+ \ldots\ldots$

Q. Do vacuum fluctuations really exist?

It seems so eg Lamb shift



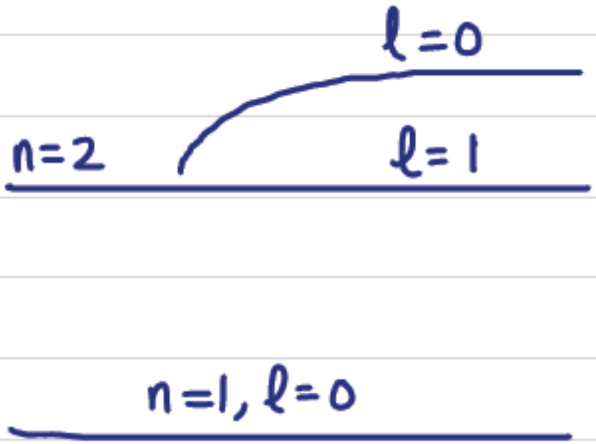
Loops like this alter the energy levels of H atom by

$$\Delta E(n,\ell) \simeq \delta_{\ell 0} \frac{4 m_e}{3\pi n^3} \ln\left(\frac{1}{\alpha}\right) Z$$

n : energy level qu. #   , Z : atomic # (=1 for H)

ℓ : angular mom qu. #

$(\ell = 0, \ldots, n-1)$



Q: <u>But even if they exist, do they gravitate?</u>

It seems so : Lamb shift affects inertial energy of atom, does it affect gravitational energy?

Similar effect more noticeable in heavy nuclei

- Compare $\dfrac{\text{grav'l mass}}{\text{inertial mass}}$ for Aluminium & Platinum.
- Ratio stays fixed (to order 10^{-12}) even though effect of vac. polarisation differs by factor of 3

$$\frac{\Delta E_{Al}}{E_{Al}} \sim 10^{-3} \; ; \; \frac{\Delta E_{Pt}}{E_{Pt}} \sim 3.10^{-3}$$

Of course - all of these diagrams contain external legs of SM fields the ones we are interested in do not (Jaffe, hep-th/0503158)

Q. What is their effect on cosmology?

$$-V_{vac}\int\sqrt{g}\,d^4x \longrightarrow T_{\mu\nu} = -V_{vac}\, g_{\mu\nu}$$

Recall: $V_{vac} \sim \sum_{\text{particles}} m^4_{\text{particle}}$

But if (say) $V_{vac} \sim m_e^4$ the cosmological horizon lies at distance $r \sim \frac{1}{H}$ where $H^2 \sim \frac{m_e^4}{M_{pl}^2} \Rightarrow r \sim 10^6$ km $\sim$ Earth-Moon distance (Pauli)

Observations $\Rightarrow r \sim \frac{1}{H_0}$ where $H_0^2 \sim \frac{(\text{meV})^4}{M_{pl}^2}$

How do we reconcile this?

Remember the "counterterm" (req'd anyway to absorb divergences)

$$\int d^4x \sqrt{g} \left(\frac{R}{16\pi G} - \mathcal{L}_m - \Lambda \right)$$

Contributes V_{vac} (including divs)

"Counterterm"

So what actually gravitates is $\Lambda^{ren} = \Lambda + V_{vac} \lesssim (\text{meV})^4$

IGNORING THE DIVERGENCES, this represents a fine tuning of $\lesssim 10^{-60}$

Since

$$V_{vac}^{finite} \gtrsim (\text{TeV})^4 \sim 10^{60} (\text{meV})^4$$

THIS IS WHAT PEOPLE NORMALLY CALL THE CCP!

NONSENSE !!

Must be more to it – we happily cancel divs!

What is the real problem?

Radiative Instability

Let me work with only thing I know

SM as an EFT, coupled to gravity

Do PERTURBATION THEORY!

$$V_{vac}^{1\text{-loop}} \sim \frac{-m^4}{(8\pi)^2}\left[\frac{2}{\varepsilon} + \log\left(\frac{\mu^2}{m^2}\right) + \text{finite}\right]$$

Add "counterterm" $\Lambda \sim \frac{m^4}{(8\pi)^2}\left[\frac{2}{\varepsilon} + \log\left(\frac{\mu^2}{M^2}\right) + \text{finite}\right]$

arbitrary subtraction scale.

$$\Rightarrow \Lambda^{\text{ren},1\,\text{loop}} \sim \frac{m^4}{(8\pi)^2}\left[\log\left(\frac{m^2}{M^2}\right) + \Delta(\text{finite})\right]$$

So $\Lambda^{\text{ren},1\,\text{loop}} \gtrsim (\text{TeV})^4$ unless we fine tune finite part of counterterm

$\lesssim 10^{-60}$ fine tuning for $\Lambda^{\text{ren},1\,\text{loop}} \sim (\text{meV})^4$

Now go to 2 loops ....

get $\Delta V_{vac}^{2\text{-loops, finite}} \sim \lambda m^4$

For SM $\lambda \sim 0.1$ so $\Delta V_{vac}^{2\text{ loops, finite}} \gtrsim (\mathrm{TeV})^4$

$\Rightarrow$ NEED TO <u>RETUNE</u> COUNTERTERM

Now go to 3 loops ....

RADIATIVE INSTABILITY $\longleftrightarrow$ TUNING IS UNSTABLE TO HIGHER LOOPS.

$\Rightarrow$ V_{vac} is UBER sensitive to details of UV physics of which we are ignorant!

$\hookrightarrow$ encoded in loop instability of the EFT.

JUST SUM ALL THE LOOPS !!

OK, but in what theory? $\rightarrow$ full loop structure depends on full EFT expansion, way beyond leading order, with all the unknown coeffs reflecting the unknown UV theory

corrections to SM EFT $\leftarrow$

$1 \times$ dim 5, $59 \times$ dim 6, ...

Wilson Action

Split dofs into light & heavy $\phi = \phi_l + \phi_h$ $\quad m_{light} < \mu < m_{heavy}$

$$e^{iS_{eff}[\phi_l]} = \int \mathcal{D}\phi_h \, e^{iS[\phi_l,\phi_h]}$$

Vacuum energy in $S_{eff} \sim \mu^4$ $\longrightarrow$ Fine tune counterterm to cancel

Move cut off to $\mu' < \mu$ $\rightarrow$ Vac energy $\sim \mu'^4$ but not allowed retune counterterm

$$\Rightarrow \quad \Lambda(\mu') \sim \Lambda(\mu) + O(1)\mu'^4 \sim O(1)\mu^4 + O(1)\mu'^4$$

Tuning is unstable against changing the cut off

All EFTs should agree on IR – they do not.

Quantum Gravity cut-off — $(10^{18}\ GeV)^4$ — fine tuning to 120 decimal places

SUSY cut-off — $(TeV)^4$ — fine tuning to 60 decimal places

EW phase transition — $(200\ GeV)^4$ — fine tuning to 56 decimal places

QCD phase transition — $(0.3\ GeV)^4$

muon — $(100 MeV)^4$ — fine tuning to 44 decimal places

electron — $(MeV)^4$ — fine tuning to 36 decimal places

$(meV)^4$ — observed value

Why Naturalness?

Why Naturalness?

NATURALNESS requires measured couplings to be RADIATIVELY STABLE

Why Naturalness?

NATURALNESS requires measured couplings to be RADIATIVELY STABLE

naturalness ensures that low energy EFTs agree on low energy couplings.

Example

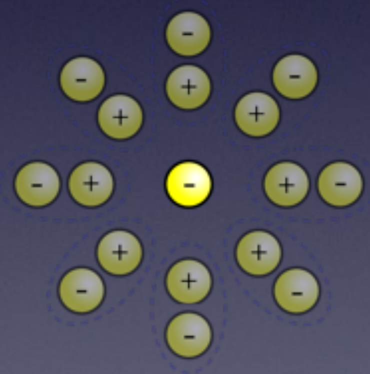
electron mass should be larger than EM energy of electron

but if EM energy ~ α/r, suggests electron is larger than nucleus!

Example

electron mass should be larger than EM energy of electron

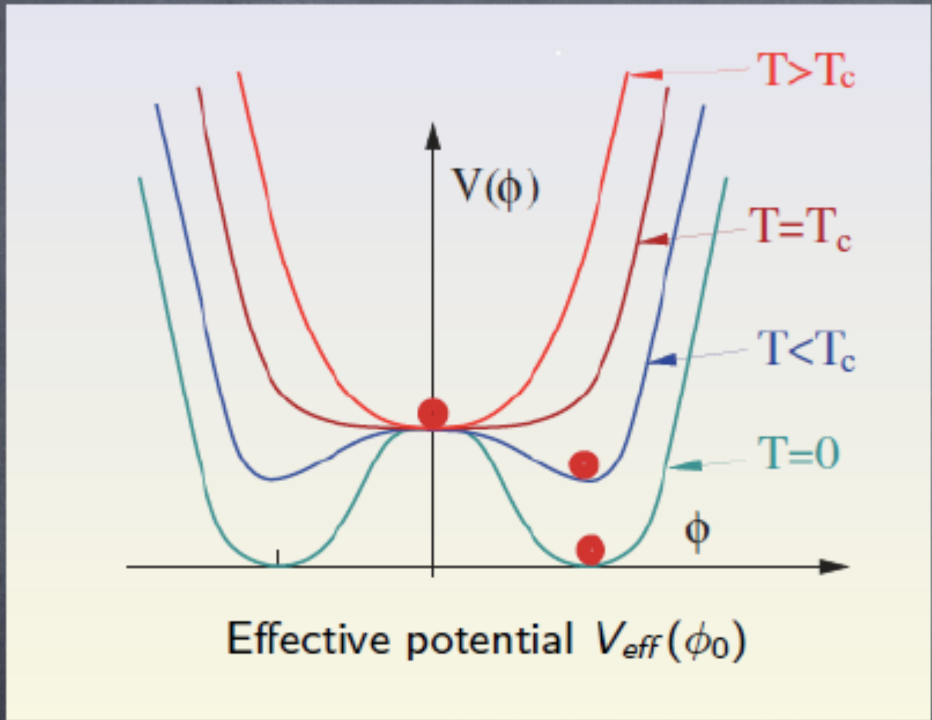
but if EM energy ~ α/r, suggests electron is larger than nucleus!



positrons help preserve naturalness

EM energy ~ $\alpha m \log(mr)$

contributions from phase transitions in early universe



$$\Delta V_{EW} \sim (200\ GeV)^4$$

$$\Delta V_{QCD} \sim (0.3\ GeV)^4$$

Goal: make Λ radiatively stable, then measure

Goal: make Λ radiatively stable, then measure

Within EFT, renormalised couplings of relevant operators CANNOT be predicted, must be measured!

Big, small, who cares? Just measure them.

But NATURALNESS requires measured couplings to be RADIATIVELY STABLE

Two final questions:

How do we measure Λ?

GO GLOBAL! (More later)

How do we make Λ radiatively stable?

Solving the CCP?

Symmetry?

Short distance M.G?

Anthropics?

Long distance M.G?

~~Unimodular gravity?~~

~~Self Adjustment?~~

Unimodular Gravity

Vary the EH action assuming $|\det g| = 1$

$$S_{UMG} = \int d^4x \, \frac{\sqrt{g}R}{16\pi G} + \lambda(\sqrt{g}-1) + S_m$$

$$\Rightarrow \quad R_{\mu\nu} - \frac{1}{4} R g_{\mu\nu} = 8\pi G \left(T_{\mu\nu} - \frac{1}{4} T g_{\mu\nu} \right)$$

$T_{\mu\nu} = -V_{vac} \, g_{\mu\nu}$ drops out!!

BUT: $\det g = 1$ is just a GAUGE CHOICE in GR (at least locally)

Gauge symmetry = Redundancy

No way this can solve CCP.

Write EOM as $G_{\mu\nu} = 8\pi G\left(T_{\mu\nu} - \frac{1}{4} g_{\mu\nu}\left(T + \frac{R}{8\pi G}\right)\right)$

Take div & use Bianchi, Energy conservation

$\Rightarrow \nabla_\mu\left(T + \frac{R}{8\pi G}\right) = 0 \Rightarrow T + \frac{R}{8\pi G} = 4\Lambda$, constant of integ.

$\Rightarrow G_{\mu\nu} = 8\pi G\left(T_{\mu\nu} - \Lambda g_{\mu\nu}\right)$

Integration constant Λ is playing the role of the "counterterm" in GR

It eats the divergences in V_{vac} coming from $T_{\mu\nu}$ but does <u>not</u> cure issue of higher loops

BUT: $\det g = 1$ is just a GAUGE CHOICE in GR (at least locally)

Gauge symmetry = Redundancy

No way this can solve CCP.

Write EOM as $G_{\mu\nu} = 8\pi G\Big(T_{\mu\nu} - \frac{1}{4}g_{\mu\nu}\big(T + R \ldots$

Take div & use Bianchi, Energy conservati...

$\Rightarrow \nabla_\mu\left(T + \frac{R}{8\pi \ldots}\right) = \ldots$ of integ.

$\Rightarrow G_{\mu\nu} = 8\pi \ldots$

FORGET U.M.G !!

Integration constant Λ is playing the role of the "counterterm" in GR

It eats the divergences in V_{vac} coming from $T_{\mu\nu}$ but does <u>not</u> cure issue of higher loops

Self Adjustment

Idea: add extra fields to matter that "eat up" the large vacuum energy protecting curvature

Field content: $g_{\mu\nu}$, ϕ_i

metric

self adjusting matter fields.

<u>Weinberg's No Go</u>

Assume : translationally invariant vacuum

$g_{\mu\nu}, \phi_i \;=\; \text{const}$

Residual $GL(4)$ symmetry $x^\mu \longrightarrow M^\mu{}_\nu x^\nu$ $\qquad M^\mu{}_\nu$ = constant 4x4 matrix

$g_{\mu\nu} \to g_{\alpha\beta} M^\alpha{}_\mu M^\beta{}_\nu \qquad \ldots\ldots \qquad \delta_{\delta M}\, g_{\mu\nu} = \delta M_{\mu\nu} + \delta M_{\nu\mu}$

$\phi_i \to \mathcal{F}_{ij}(M)\,\phi_j$

$\mathcal{L}[g, \phi_i] \to \det M\, \mathcal{L} \qquad \ldots\ldots \qquad \delta_{\delta M}\mathcal{L} = \mathrm{Tr}\,\delta M\, \mathcal{L}$

Field Eqns

$$\frac{\partial \mathcal{L}}{\partial \phi_i} = 0 \quad (1) \qquad\qquad \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = 0 \quad (2)$$

Under GL(4) $\delta_{\delta M}\mathcal{L} = \frac{\partial \mathcal{L}}{\partial \phi_i}\delta_{\delta M}\phi_i + \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}}\delta_{\delta M}g_{\mu\nu} \longrightarrow \mathrm{Tr}\,\delta M\,\mathcal{L}$

(A) Assume (1) & (2) hold independently

Assume (1) holds $\Rightarrow \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}}\left(\delta M_{\mu\nu} + \delta M_{\nu\mu}\right) = (\mathrm{Tr}\,\delta M)\mathcal{L}$

$$\Rightarrow \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = \frac{1}{2}g^{\mu\nu}\mathcal{L} \Rightarrow \mathcal{L} = \sqrt{g}\,\Lambda_0[\phi_i]$$

independent of g

Then $\frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = 0 \Rightarrow \Lambda_0[\phi_i] = 0 \Rightarrow$ fine tuning!

Field Eqns

$$\frac{\partial \mathcal{L}}{\partial \phi_i} = 0 \quad (1) \qquad\qquad \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = 0 \quad (2)$$

Under GL(4) $\delta_{\delta M} \mathcal{L} = \frac{\partial \mathcal{L}}{\partial \phi_i} \delta_{\delta M} \phi_i + \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} \delta_{\delta M} g_{\mu\nu} \longrightarrow \mathrm{Tr}\, \delta M\, \mathcal{L}$

(B) Assume (1) & (2) are not independent - Degeneracy!!

eg let $2 g_{\mu\nu} \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = \sum_i f_i(\phi) \frac{\partial \mathcal{L}}{\partial \phi_i}$ (*)

$\Rightarrow$ New Scaling symmetry $\quad \delta_\varepsilon g_{\mu\nu} = 2\varepsilon g_{\mu\nu}, \; \delta_\varepsilon \phi_i = -\epsilon f_i$

$$\Rightarrow \delta_\varepsilon \mathcal{L} = 0 \text{ by } (*)$$

Transform ϕ_i in field space $\phi_i \to \tilde{\Phi}_i$ st $\quad \delta_\varepsilon \tilde{\Phi}_0 = -\epsilon, \; \delta_\varepsilon \tilde{\Phi}_{i \neq 0} = 0$

Now $\delta_\varepsilon\left[e^{2\tilde{\Phi}_0} g_{\mu\nu}\right] = 0$

$\Rightarrow \quad \mathcal{L} = \mathcal{L}(e^{2\tilde{\Phi}_0} g_{\mu\nu}, \tilde{\phi}_{i\neq 0})$

Independant Eqns are

$\frac{\partial \mathcal{L}}{\partial \tilde{\Phi}_{i\neq 0}} = 0 \quad (3) \qquad\qquad \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = 0 \quad (2)$

Under GL(4) $\quad \delta_{SM}\mathcal{L} = \frac{\partial \mathcal{L}}{\partial \tilde{\Phi}_{i\neq 0}} \delta_{SM}\tilde{\Phi}_{i\neq 0} + \underbrace{\frac{\partial \mathcal{L}}{\partial \tilde{\Phi}_0} \delta_{SM}\tilde{\Phi}_0}_{0} + \frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} \delta_{SM} g_{\mu\nu}$

$= (\mathrm{Tr}\, \delta M)\, \mathcal{L}$

0 since $\tilde{\Phi}_0$ is a scalar

Assume (3) holds $\Rightarrow \mathcal{L} = e^{4\tilde{\Phi}_0} \sqrt{g}\, \Lambda_0(\tilde{\Phi}_{i\neq 0})$

Then $\frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = 0 \Rightarrow e^{4\tilde{\Phi}_0} \Lambda_0(\tilde{\Phi}_{i\neq 0}) = 0$

$\Rightarrow \Lambda_0 = 0$, fine tuning or $e^{\phi_0} \to 0$

$e^{2\phi_0}$ always comes with $g_{\mu\nu}$ via conformal factor

$\Longrightarrow M_{phys} \propto e^{\phi_0} \to 0$ NOT IN OUR UNIVERSE!!

Symmetries

't Hooft Naturalness

"A parameter ε is naturally small if $\exists$ symmetry as $\varepsilon \to 0$"

eg In QCD mass of fermions is protected by chiral symmetry in limit $m_f \to 0$

Consider $\mathcal{L}_0[\phi]$ obeys some (global) symm $\phi \to \phi'$

Add an operator $\mathcal{O}$ that breaks symm

$$\mathcal{L}_\varepsilon[\phi] = \mathcal{L}_0 + \varepsilon \mathcal{O}$$

ε is naturally small.

$\mathcal{L}_0$ cannot generate terms which break symm

Symmetry break terms generated by $\mathcal{L}_\varepsilon$ must be weighted by at least ε

ie $\Delta \mathcal{L}_\varepsilon^{1\text{-loop}} \supset q\mathcal{O}$ then $q \lesssim O(\varepsilon)$

Can we find a global symmetry as $\lambda \to 0$?

Then $\lambda \neq 0$ naturally small.

Susy

Symmetry betw. bosons & fermions

In unbroken susy, $m_F = m_B$, and fermion loops cancel boson loops

 $+$  $= 0$

Scale of $\not{\text{susy}}$, M_{susy}, is technically natural

Above M_{susy} — Vacuum energy cancellation

Below M_{susy} - $m_B^2 \simeq m_F^2 \pm M_{susy}^2$ cancellation fails by $O(M_{susy}^4)$

Annoyingly, $M_{susy} \gtrsim$ TeV (known due to absence of observed superpartners)

Scale Invariance

$$g_{\mu\nu} \to \lambda^2 g_{\mu\nu}$$

$$\Rightarrow G_{\mu\nu} \to G_{\mu\nu} \quad , \quad \Lambda g_{\mu\nu} \to \Lambda \lambda^2 g_{\mu\nu}$$

$\Rightarrow$ $\Lambda \neq 0$ in Einstein eqns incompatible with SI.

Problems

- classical SI usually broken by quantum
- in Nature, SI must be broken spontaneously

Then by Weinberg No Go effective potential must vanish in order to kill Λ
This 'vanishing' of V is not radiatively stable

$$V_{tree}(\phi_{min}) = 0 \not\Rightarrow V_{1\text{-}loop}(\phi_{min}) = 0$$

Energy $\to$ – Energy

Energy parity operator P, $|\psi'\rangle = P|\psi\rangle$

with $\langle\psi|H|\psi'\rangle = -\langle\psi|H|\psi\rangle$

If vacuum is energy parity inv then $|0'\rangle = |0\rangle$ and so

$$\langle 0|H|0\rangle = -\langle 0|H|0\rangle = 0$$

1) Universe Multiplication - Linde (1988)

$$S = \int d^4x \int d^4y \sqrt{g(x)}\sqrt{g(y)} \left\{ \frac{M_{pl}^2}{2} R(x) - \mathcal{L}_m(x) - \frac{M_{pl}^2}{2} R(y) + \mathcal{L}_m(y) \right\}$$

$$M_{pl}^2 G_{\mu\nu}(x) = T_{\mu\nu}(x) - g_{\mu\nu}(x) \left\langle \frac{M_{pl}^2}{2} R(y) - \mathcal{L}_m(y) \right\rangle \qquad \langle Q(x) \rangle = \frac{\int d^4x \, Q(x) \sqrt{g(x)}}{\int d^4x \sqrt{g(x)}}$$

$$M_{pl}^2 G_{\mu\nu}(y) = T_{\mu\nu}(y) - g_{\mu\nu}(y) \left\langle \quad x \quad \right\rangle$$

$\langle 0 | \mathcal{L}_m | 0 \rangle = V_{vac} \qquad T_{\mu\nu}(x) = -V_{vac} \, g_{\mu\nu}(x)$

$\Rightarrow$ V_{vac} cancels

Assumes V_{vac} in $\mathcal{M}(x)$ same as V_{vac} in $\mathcal{M}(y)$

$\Rightarrow$ same effective description for $\mathcal{L}_m(x)$ & $\mathcal{L}_m(y)$

... is this justified?

Ghosts? Field in $\mathcal{M}(x)$ can exchange a graviton $h_{\mu\nu}(x)$ with fields in $\mathcal{M}(y)$ whose couplings are local in $\mathcal{M}(x)$ but global in $\mathcal{M}(y)$

Kaplan & Sundrum hep-th/0505265

$$\mathcal{L} = \sqrt{g}\left\{ \frac{M_{pl}^2}{2} R + \underset{\substack{\uparrow \\ \text{ordinary matter}}}{\mathcal{L}_m(\psi)} - \underset{\substack{\uparrow \\ \text{ghosts}}}{\mathcal{L}_m(\hat{\psi})} \right\}$$

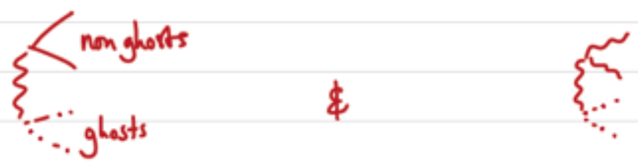
$E \to -E$ broken only by gravity

Effective theory for gravity only valid up to $\mu \sim$ meV

At $E > \mu$, require LV with some way of suppressing mediation between ghost & non ghost

At $E < \mu$, only QG loops contribute to $\Lambda \sim \mu^4$

Instabilities:



Claim is these get suppressed thanks to low cutoff μ & weak grav'l coupling $\frac{1}{M_{pl}}$

— Highly speculative

— Need ghost-nonghost asymm to explain why we don't see antigravity (gh-gh interactions antigravitate, as can gh-nongh)