The Cosmological Constant Problem
(and its sequester)

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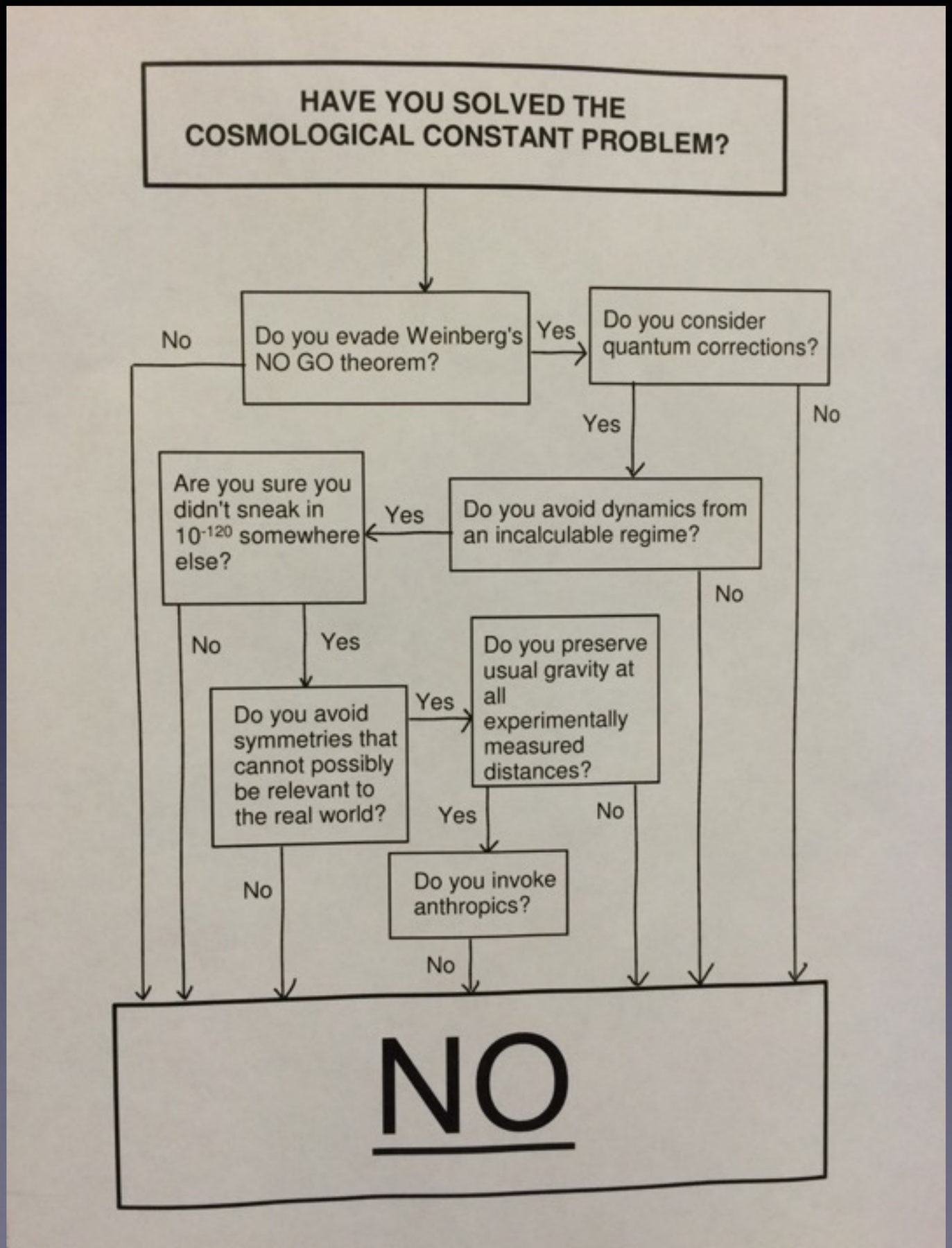
THE ROYAL SOCIETY

McCullen's no go theorem



McCullen Sandora, 2016

“Sequestering the Standard Model Vacuum Energy” Phys.Rev.Lett. 112 (2014) no.9, 091304

“Vacuum Energy Sequestering: The Framework and Its Cosmological Consequences” Phys.Rev. D90 (2014) no.8, 084023,

“Sequestration of Vacuum Energy and the End of the Universe” Phys.Rev.Lett. 114 (2015) no.10, 101302

“Manifestly Local Theory of Vacuum Energy Sequestering” Phys.Rev.Lett. 116 (2016) no.5, 051302

“Sequestering effects on and of vacuum decay” Phys.Rev. D94 (2016) no.2, 025022

“Vacuum Energy Sequestering and Graviton Loops” Phys.Rev.Lett. 118 (2017) no.6, 061303

“An Etude on Global Vacuum Energy Sequester “ arXiv:1705.08950

“Obstructions to self-tuning and possible ways around“ arXiv:1706.04778

Collaborators: Nemanja Kaloper, Guido D’Amico, Florian Niedermann, David Stefanyszyn, Alexander Westphal, George Zahariade

The Cosmological Constant Problem

General Covariance & Equivalence Principle ⇒ Vacuum Energy Gravitates

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

The Cosmological Constant Problem

General Covariance & Equivalence Principle ⇒ Vacuum Energy Gravitates

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

…add a bare cosmological constant…

$$-(V_{vac}+\Lambda_{bare})\int\sqrt{-g}d^4x \implies T_{\mu\nu} = -\Lambda_{tot}g_{\mu\nu}$$

where $\Lambda_{tot} = V_{vac} + \Lambda_{bare} \lesssim (meV)^4$

Estimating the vacuum energy

$$V_{vac} \supset \sum_m \int d^3k \frac{1}{2}\hbar\sqrt{k^2+m^2}$$

$$\sim c_\nu m_\nu^4 + c_e m_e^4 + c_\mu m_\mu^4 + \ldots + M^4_{\mathrm{cut-off}}$$

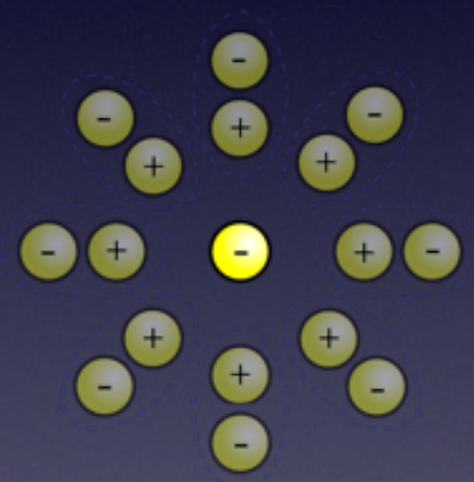
+ vacuum loops involving virtual gravitons

+ counterterms

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	$(100MeV)^4$	*fine tuning to 44 decimal places*
electron	$(MeV)^4$	*fine tuning to 36 decimal places*
	$(meV)^4$	*observed value*

Contrast to electron mass

electron mass, $\Delta m \sim m\log(M_{cutoff}/m)$



protected by chiral symmetry in massless limit

Electron mass & vacuum are both UV sensitive — cannot be predicted in EFT, must be measured!

Electron mass is only mildly sensitive to unknown UV ← NATURAL

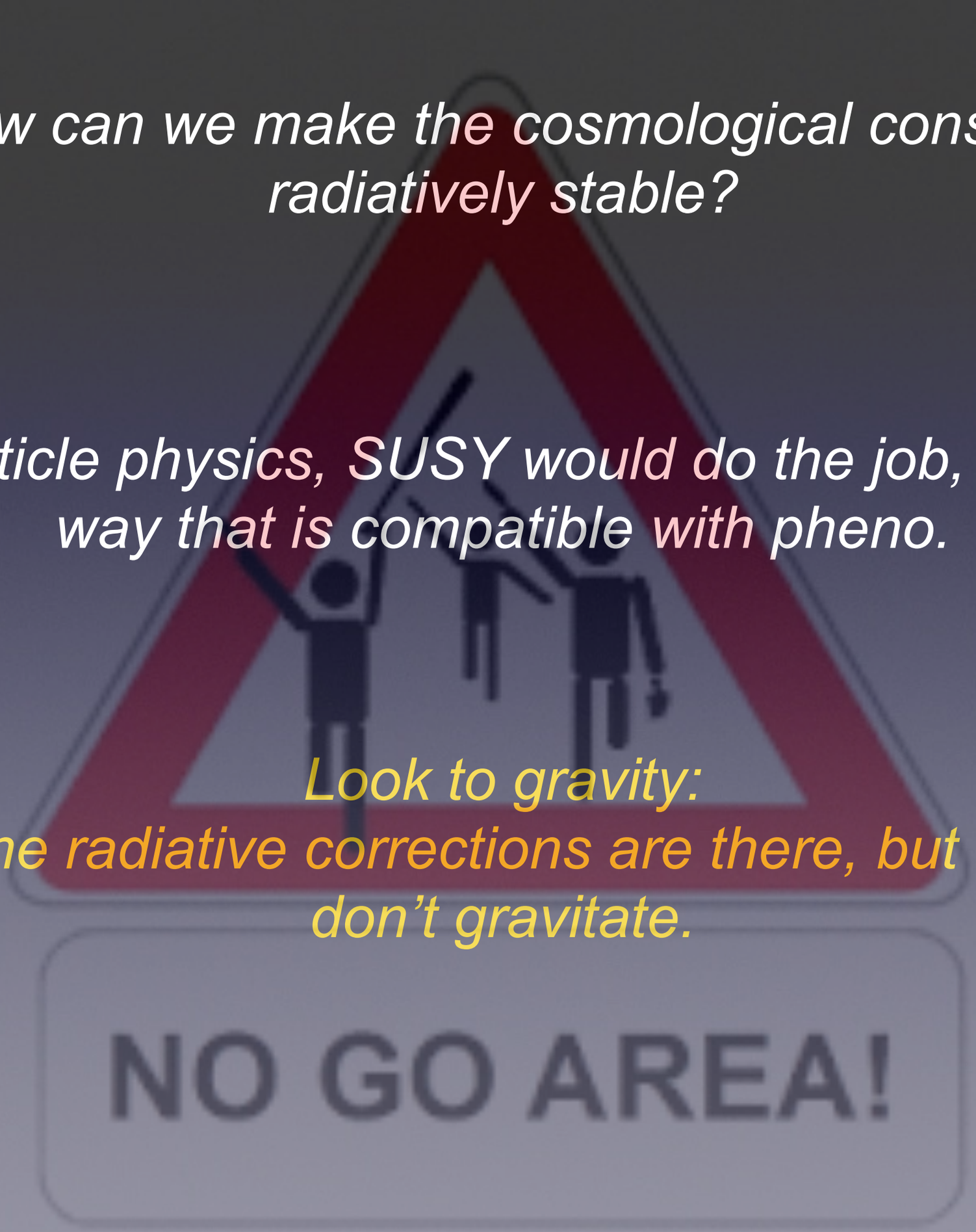
Vacuum energy is extremely sensitive to unknown UV ← UNNATURAL

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

How can we make the cosmological constant radiatively stable?

Within particle physics, SUSY would do the job, but not in a way that is compatible with pheno.

Look to gravity:
perhaps the radiative corrections are there, but they simply don't gravitate.



Sequestering the Standard Model Vacuum Energy
Nemanja Kaloper, Antonio Padilla.
Phys.Rev.Lett. 112 (2014) no.9, 091304

Global Vacuum Energy Sequester

Introduce global dynamical variables: Λ, λ

$$S = \int d^4x\sqrt{g}\left[\frac{M_{Pl}^2}{2}R - \Lambda - \lambda^4 \mathcal{L}_{matter}(\lambda^{\mu\nu-2}g^{\mu\nu}, \Phi)\right] + \sigma\left(\frac{\Lambda}{\lambda^4\mu^4}\right)$$

Λ is the CC counterterm

λ sets hierarchy between matter scales & Planck mass

$$\frac{m_{phys}}{M_{pl}} \propto \lambda$$

Equations of motion

$$\Lambda \text{ equation} \quad : \quad \frac{\sigma'}{\lambda^4 \mu^4} = \int d^4x \sqrt{g}$$

$$\lambda \text{ equation} \quad : \quad 4\Lambda \frac{\sigma'}{\lambda^4 \mu^4} = \int d^4x \sqrt{g}\, \lambda^4\, \tilde{T}^{\mu}{}_{\mu}$$

$$g_{\mu\nu} \text{ equation} \quad : \quad M_{pl}^2 G^{\mu}_{\nu} = -\Lambda \delta^{\mu}_{\nu} + \lambda^4 \tilde{T}^{\mu}_{\nu}$$

$$T_{\mu\nu} = \lambda^4 \tilde{T}_{\mu\nu}$$

$$\tilde{T}_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta}{\delta \tilde{g}^{\mu\nu}} \int d^4x \sqrt{-\tilde{g}} \mathcal{L}(\tilde{g}^{\mu\nu}, \Psi)$$

Equations of motion

space-time average

$$\Lambda \text{ equation} \quad :$$

$$\lambda \text{ equation} \quad :$$

$$\Lambda = \frac{1}{4}\langle T^{\alpha}{}_{\alpha}\rangle, \qquad \langle Q\rangle = \frac{\int d^4x Q\sqrt{g}}{\int d^4x\sqrt{g}}$$

$$g_{\mu\nu} \text{ equation} \quad : \quad M_{pl}^2 G^{\mu}_{\nu} = -\Lambda\delta^{\mu}_{\nu} + T^{\mu}_{\nu}$$

$$M_{pl}^2 G^\mu{}_\nu = T^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu \langle T^\alpha{}_\alpha \rangle$$

$$T^\mu_\nu = -V_{vac}\delta^\mu_\nu + \tau^\mu_\nu$$

$$M_{pl}^2 G^\mu{}_\nu = \tau^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu \langle \tau^\alpha{}_\alpha \rangle$$

$$T^\mu_\nu = -V_{vac}\delta^\mu_\nu + \tau^\mu_\nu$$

$$M_{pl}^2 G^\mu{}_\nu = \tau^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu \langle \tau^\alpha{}_\alpha \rangle$$

Vacuum energy drops out at each and every loop order

No hidden equations — this is everything!

Residual CC is radiatively stable, value should be measured

Symmetries?

Approximate scaling

$$\delta_\epsilon \lambda = \epsilon\lambda,\ \delta_\epsilon \Lambda = 4\epsilon\Lambda,\ \delta_\epsilon \left(\eta_{\mu\nu} + \frac{h_{\mu\nu}}{M_{pl}}\right) = -2\epsilon\eta_{\mu\nu} - \epsilon\frac{h_{\mu\nu}}{M_{pl}}$$

$$\delta_\epsilon S = \mathcal{O}\left(\frac{1}{M_{pl}}\right)$$

Approximate shift

$$\delta_\alpha \Lambda = \alpha m^4 \lambda^4,\ \delta_\alpha \mathcal{L}_m = \alpha m^4$$

$$\delta_\alpha S = \alpha \frac{m^4}{\mu^4}\sigma'$$

$$\frac{\Lambda_{eff}}{M_{pl}^2} \sim \frac{1}{4}\frac{\langle\tau\rangle}{M_{pl}^2}$$

$\rightarrow$ 0 as $M_{pl} \to \infty$

$\rightarrow$ 0 as $\mu \to \infty$ (for fixed volume)

conformal limit, vanishing λ

An Etude on Global Vacuum Energy Sequester

Guido D'Amico, Nemanja Kaloper, Antonio Padilla, David Stefanyszyn , Alexander Westphal George Zahariade

e-Print: **arXiv:1705.08950**

An Etude ...

Duality symmetric string theory and the cosmological constant problem
Arkady A. Tseytlin
Phys.Rev.Lett. 66 (1991) 545-548

Tseytlin's original idea ....

$$S_T = \frac{\int d^4x\sqrt{g}\left[\frac{M_{Pl}^2}{2}R - \mathcal{L}(g^{\mu\nu},\Phi)\right]}{\left[\mu^4\int d^4x\sqrt{g}\right]}.$$

$$\mathcal{L}(g^{\mu\nu},\Phi) = V_{vac} + \ldots$$

higher dim operators

In QFT, powers of hbar (generically) count loops

$$S_{eff} = \frac{S_0}{\hbar} + S_1 + \hbar S_2 + \hbar^2 S_3 + \ldots$$

Tseytlin introduces an ***effective*** *hbar proportional to spacetime volume,* $\Omega = \mu^4 \int d^4x\sqrt{g}$ *, so….*

$$S^T_{eff} = \frac{S^T_0}{\Omega} + S^T_1 + \Omega S^T_2 + \Omega^2 S^T_3 + \ldots$$

vacuum energy ***loops not cancelled***

VES fixes this by exploiting universality of matter coupling, eg

$$\Omega^{-1}\int d^4x\sqrt{g}\left[\frac{M_{Pl}^2}{2}R-\mathcal{L}(g^{\mu\nu},\Phi)\right]$$

$$\downarrow$$

$$\int d^4x\sqrt{g}\left[\frac{M_{Pl}^2}{2}R-\Omega^{-1}\mathcal{L}(\Omega^{\frac{1}{2}}g^{\mu\nu},\Phi)\right]$$

now all matter loop corrections scale as Ω^{-1}

A Nonlocal Approach to the Cosmological Constant Problem
Sean M. Carroll, Grant N. Remmen
Phys.Rev. D95 (2017) no.12, 123504

Carroll & Remmen's recent idea ....

$$S_{CR} = \eta \int d^4x \sqrt{\tilde{g}} \left[\frac{M_{Pl}^2}{2} \tilde{R} - \mathcal{L}(\tilde{g}^{\mu\nu}, \Phi) - \frac{1}{48} \tilde{F}^2_{\mu\nu\lambda\sigma} + \frac{1}{6} \tilde{\nabla}_\mu (\tilde{F}^{\mu\nu\lambda\sigma} \tilde{A}_{\nu\lambda\sigma}) \right]$$

Global *variable η is originates as magnetic dual of a 4 form field, H*

Dual of the 4 form F acts like the CC counterterm

Claim: *Global constraint from η … forces action to vanish … forcing CC counterterm to cancel radiative corrections*

$$S_{CR} = \eta \int d^4x \sqrt{\tilde{g}} \left[\frac{M_{Pl}^2}{2} \tilde{R} - \mathcal{L}(\tilde{g}^{\mu\nu}, \Phi) - \frac{1}{48} \tilde{F}^2_{\mu\nu\lambda\sigma} + \frac{1}{6} \tilde{\nabla}_\mu (\tilde{F}^{\mu\nu\lambda\sigma} \tilde{A}_{\nu\lambda\sigma}) \right]$$

*CC counterterm **cannot adjust** if*

- *it is an integration constant, i.e. fixed by boundary condition*
- *it stems from a quantised 4 form (in presence of membrane sources)*

OK, so assume CC counterterm can adjust i.e. not fixed by BCs, there are no membrane sources

Are we good then?

No!!

*- Effective hbar is proportional to η, so **loops will spoil the constraint***

Can fix this theory by moving η

$$\eta \int d^4x \sqrt{\tilde{g}} \left[\frac{M_{Pl}^2}{2} \tilde{R} - \mathcal{L}(\tilde{g}^{\mu\nu}, \Phi) - \frac{1}{48} \tilde{F}^2_{\mu\nu\lambda\sigma} + \frac{1}{6} \tilde{\nabla}_\mu (\tilde{F}^{\mu\nu\lambda\sigma} \tilde{A}_{\nu\lambda\sigma}) \right]$$

$$\int d^4x \sqrt{\tilde{g}} \left[\frac{M_{Pl}^2}{2} \eta \tilde{R} - \mathcal{L}(\tilde{g}^{\mu\nu}, \Phi) - \frac{1}{48} \tilde{F}^2_{\mu\nu\lambda\sigma} + \frac{1}{6} \tilde{\nabla}_\mu (\tilde{F}^{\mu\nu\lambda\sigma} \tilde{A}_{\nu\lambda\sigma}) \right]$$

Improved version….

- places global constraint on geometry (as opposed to geometry + radiatively unstable matter)
*- is just a **hybrid** of global VES and local VES (see later)*

Global VES in "Jordan frame"

$$S = \int d^4x\sqrt{g}\left[\frac{M_{Pl}^2}{2}R - \Lambda - \lambda^4\mathcal{L}_m(\lambda^{-2}g^{\mu\nu},\Phi)\right] + \sigma\left(\frac{\Lambda}{\lambda^4\mu^4}\right)$$

$$g_{\mu\nu} \to \frac{\kappa^2}{M_{pl}^2}g_{\mu\nu},\ \Lambda \to \Lambda\left(\frac{M_{pl}}{\kappa}\right)^4,\ \kappa^2 = M_{pl}^2/\lambda^2$$

$$S = \int d^4x\sqrt{g}\left[\frac{\kappa^2}{2}R - \Lambda - \mathcal{L}_m(g^{\mu\nu},\Phi)\right] + \sigma\left(\frac{\Lambda}{\mu^4}\right)$$

Vary over metric and constants κ and Λ

κ variation yields a global constraint on R, Λ adjusts accordingly

Manifestly Local Theory of Vacuum Energy Sequestering
Nemanja Kaloper,Antonio Padilla, David Stefanyszyn , George Zahariade
Phys.Rev.Lett. 116 (2016) no.5, 051302

Local Vacuum Energy Sequester

Why bother?

Consistency with QM requires action to be additive

$$S_{AC}=S_{AB}+S_{BC}$$

$$\mathcal{A}_{A\to B} = \langle B, t_B | A, t_A \rangle = \int dx_1 \dots dx_{N-1} \langle B, t_B | x_{N-1}, t_{N-1} \rangle \langle x_{N-1}, t_{N-1} | x_{N-2}, t_{N-2} \rangle \dots \langle x_1, t_1 | A, t_A \rangle$$
$$= \int dx_1 \dots dx_{N-1} e^{\frac{i}{\hbar} \sum_i L(t_i)\delta t} = \int Dx e^{\frac{i}{\hbar} S_{AB}[x]}$$

Hint: UMG a la Henneaux & Teitelboim

$$S_{UMG} = \int d^4x\sqrt{g}\left[\frac{M_{pl}^2}{2}R - \mathcal{L}_m(g^{\mu\nu},\Phi)\right] - \int d^4x\Lambda(x)(\sqrt{g}-1)$$

non-gravitating but breaks diffs

$$S_{HT} = \int d^4x\sqrt{g}\left[\frac{M_{pl}^2}{2}R - \mathcal{L}_m(g^{\mu\nu},\Phi)\right] - \int \Lambda(x)(\sqrt{g}d^4x - F_4)$$

alternative measure: the 4 form

retains diffs
does not gravitate
exact 4 form $F_4=dA_3$ forces constant Λ

Local VES

$$S \quad \cancel{S} = \int d^4x\sqrt{g}\left[\frac{\kappa^2(x)}{2}R - \Lambda(x) - \mathcal{L}_m(g^{\mu\nu},\Phi)\right]$$

$$+\int \sigma\left(\frac{\Lambda(x)}{\mu^4}\right)F_4 + \hat{\sigma}\left(\frac{\kappa^2(x)}{M_{Pl}^2}\right)\hat{F}_4\,.$$

$$\kappa^2 G^\mu{}_\nu = (\nabla^\mu \nabla_\nu - \delta^\mu{}_\nu \nabla^2)\kappa^2 + T^\mu{}_\nu - \Lambda(x)\delta^\mu{}_\nu$$

$$\frac{\sigma'}{\mu^4} F_4 = \sqrt{g} d^4x \,, \qquad \frac{\hat{\sigma}'}{M_{Pl}^2} \hat{F}_4 = -\frac{1}{2} R \sqrt{g} d^4x \,,$$

$$\frac{\sigma'}{\mu^4} \partial_\mu \Lambda = 0 \,, \qquad \frac{\hat{\sigma}'}{M_{Pl}^2} \partial_\mu \kappa^2 = 0 \,.$$

$$\Longrightarrow \kappa^2 G^\mu{}_\nu = T^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu \langle T^\alpha{}_\alpha \rangle - \Delta\Lambda \delta^\mu{}_\nu$$

constant

radiatively stable

$$\Delta\Lambda = -\frac{\mu^4}{2} \frac{\kappa^2 \hat{\sigma}'}{M_{Pl}^2 \sigma'} \frac{\int \hat{F}_4}{\int F_4}$$

Is $\Delta\Lambda = -\frac{\mu^4}{2}\frac{\kappa^2\hat{\sigma}'}{M_{Pl}^2\sigma'}\frac{\int \hat{F}_4}{\int F_4}$ *radiatively stable?*

Effect of vacuum loops:

$$\Lambda \to \Lambda + M_{UV}^4 \implies \sigma' \to \mathcal{O}(1)\sigma'$$

$$\kappa^2 \to \kappa^2 + M_{UV}^2 \implies \hat{\sigma}' \to \mathcal{O}(1)\hat{\sigma}'$$

smooth functions

$\mu > M_{UV}$

$M_{pl} > M_{UV}$

$\int F_4, \int \hat{F}_4$ *geometric, IR quantities, not UV sensitive*

$$\implies \Delta\Lambda \to \mathcal{O}(1)\Delta\Lambda$$

Global trace equations

$$\frac{\sigma'}{\mu^4}\langle {}^\star F_4\rangle = 1 \qquad \frac{\kappa^2\hat{\sigma}'}{2M_{Pl}^2}\langle {}^\star \hat{F}_4\rangle = -\frac{1}{4}\kappa^2\langle R\rangle$$

GR

fixed by assumption

$$4\Lambda + 4V_{vac} = \langle \tau^\alpha{}_\alpha\rangle + \kappa^2\langle R\rangle$$

Sequester

fixed by ratio of fluxes

Key points

Λ is sink for vacuum energy, channelled there by non-gravitating 4 forms

Works to any order in matter loops — gravity loops on the other hand….

Equivalence Principle violated GLOBALLY — local theory is GR, Weinberg no go evaded

Residual CC is radiatively stable— like any relevant coupling, should be measured.

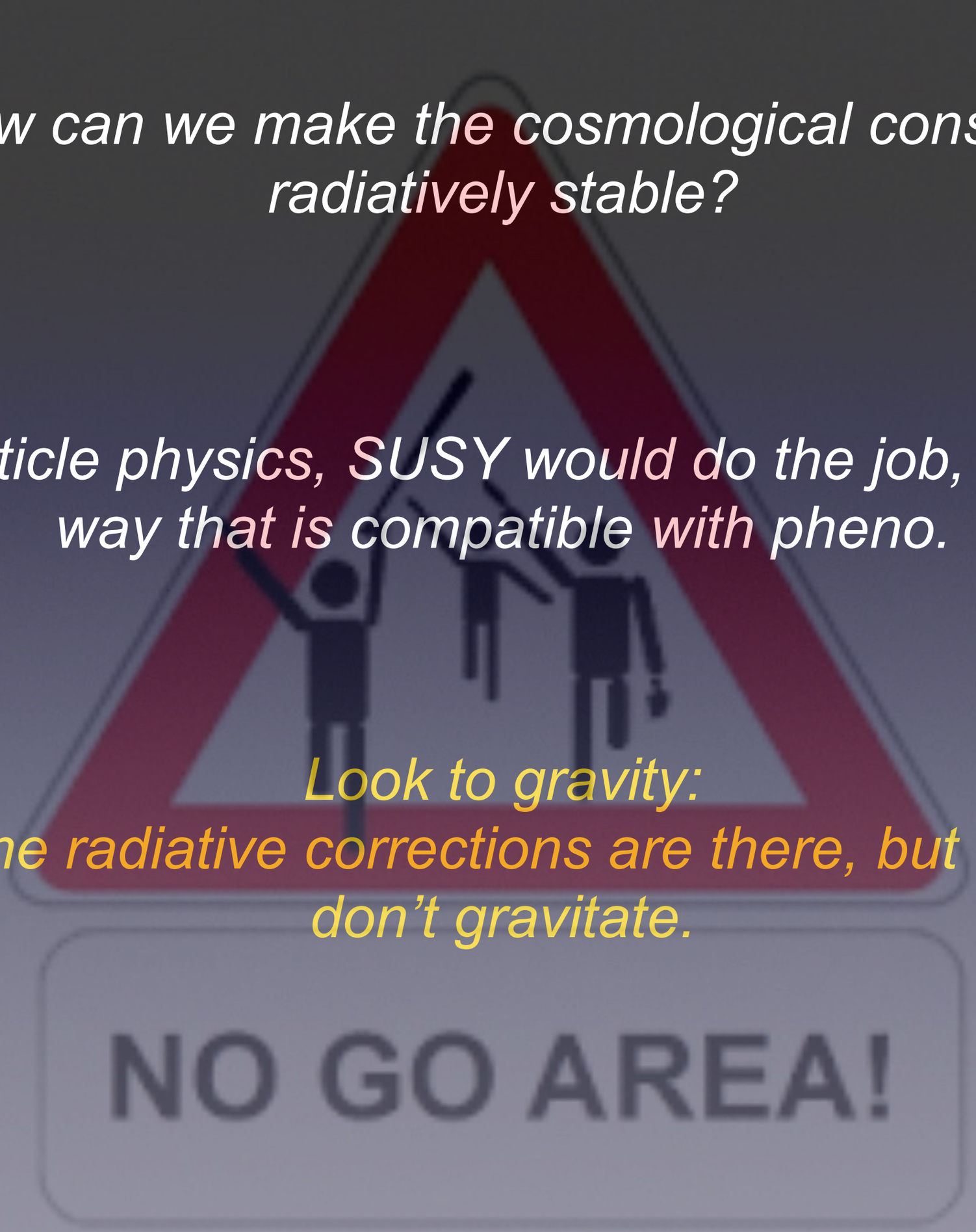
Obstructions to self-tuning and possible ways around
Florian Niedermann, Antonio Padilla
arXiv:1706.04778

And finally, an aside on self-tuning …

How can we make the cosmological constant radiatively stable?

Within particle physics, SUSY would do the job, but not in a way that is compatible with pheno.

Look to gravity:
perhaps the radiative corrections are there, but they simply don't gravitate.



Self-tuning :

"admits Minkowski solution for any value of vacuum energy"

Weinberg makes assumptions e.g.

- *local 4D effective theory*
- *All fields are Poincare invariant*

Relax these assumptions and self-tuning ***can*** *be possible e.g.*

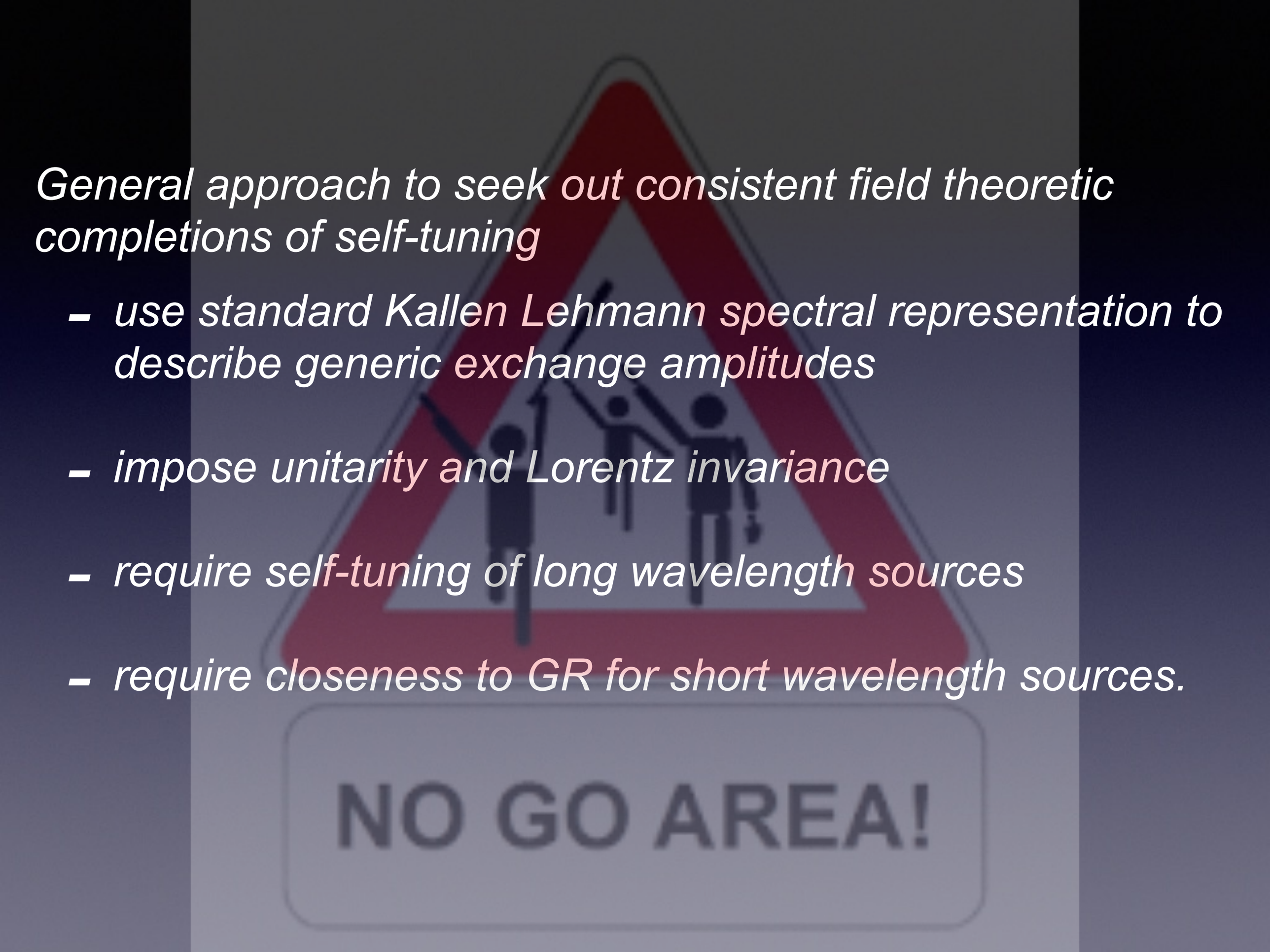
- *branes in 6D*
- *Fab Four*
- *VES*

But

- *6D models cannot recover 4D phenomenology without spoiling the self-tuning*
- *Fab Four has a light scalar, bad for pheno.*
- *many other models run into problems with ghosts, singularities etc*

General approach to seek out consistent field theoretic completions of self-tuning

- *use standard Kallen Lehmann spectral representation to describe generic exchange amplitudes*
- *impose unitarity and Lorentz invariance*
- *require self-tuning of long wavelength sources*
- *require closeness to GR for short wavelength sources.*



The AdS loop hole

Result generalises to dS but not AdS … can find explicit examples of AdS self-tuning that tick every box.

The VES loop hole

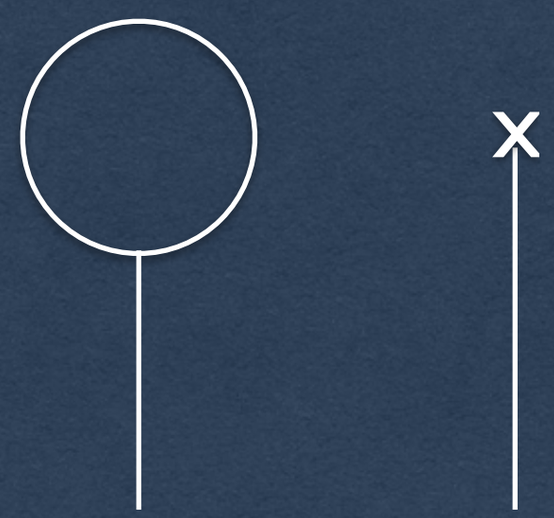
VES does not admit a standard KL spectral representation in terms of canonical free-field propagators…it decapitates!

Decapitation

Decapitating tadpoles
Allan Adams, John McGreevy, Eva Silverstein
hep-th/0209226

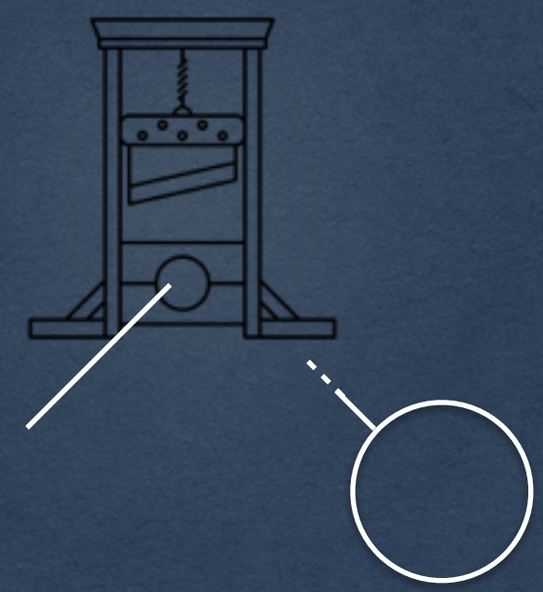
$$\frac{-i}{k^2 + i\epsilon} \to \frac{-i(1 + F(k))}{k^2 + i\epsilon}$$

$$F(k) = \begin{cases} 0 & k^\mu \neq 0 \\ -1 & k^\mu = 0 \end{cases}$$



divergence + counterterm=0

vs



divergence + guillotine=0

GR

single massless graviton

massless graviton

massless scalar

Fab Four

massless graviton

massless scalar

Vacuum energy sequestering

is a new mechanism through which loop corrections to vacuum energy can be rendered gravitationally harmless

is an effective field theory and, in keeping with standard ideas behind renormalisation, makes no prediction for precise value of the CC, rather

— it should be measured

— it's value is only mildly sensitive to the details of the unknown UV

….. just like the mass of electron.

a new way to tackle problems of naturalness

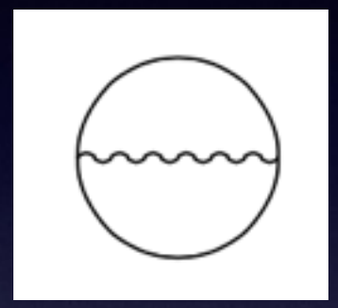
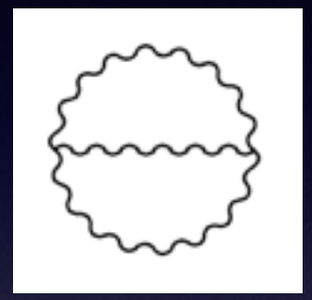
LOTS MORE EXCITING DEVELOPMENTS ON THE WAY. STAY TUNED!

Back up slides

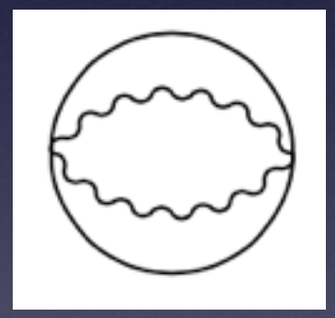
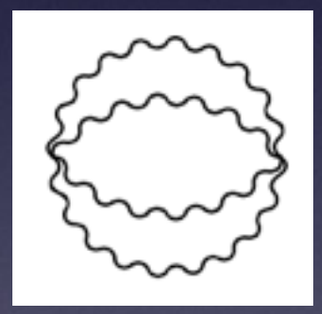
Vacuum Energy Sequestering and Graviton Loops
Nemanja Kaloper , Antonio Padilla
Phys.Rev.Lett. 118 (2017) no.6, 061303

What about graviton loops?

these introduce new κ dependence in renormalised 1PI effective potential

$$\sim \frac{M_{\rm cutoff}^6}{\kappa^2}$$

$$\sim \frac{M_{\rm cutoff}^8}{\kappa^4}$$

Screws up the κ EoM - no longer able to constrain R at large wavelength with four form fluxes

$$S = \int d^4x \sqrt{g} \left[\frac{\kappa^2(x)}{2} R - \Lambda(x) - \mathcal{L}_m(g^{\mu\nu}, \Phi) \right]$$

$$+ \int \sigma\left(\frac{\Lambda(x)}{\mu^4}\right) c + F_4\left(\frac{\kappa^2}{M_{Pl}^2}\right) \hat{F}_4 \, .$$

$$- \left[a_0 M^4 + a_1 \frac{M^6}{\kappa^2} + a_2 \frac{M^8}{\kappa^4} + \ldots \right] \int \sqrt{g} d^4x$$

Variation wrt to rigid κ protects ***NOTHING*** *at long wavelength*

Two key insights

to avoid undesirable corrections to the effective potential, need an unbroken shift symmetry

any curvature invariant that is NOT scale invariant can be used to constrain R at large wavelength

$$\int d^4x\sqrt{-g}\theta(x)(R^2_{\mu\nu\alpha\beta} - 4R^2_{\mu\nu} + R^2)$$

$$S = \int d^4x \left\{ \sqrt{g} \left[\frac{M_{Pl}^2}{2} R + \theta(x) R_{GB} - \Lambda(x) - \mathcal{L}_m \right] + \frac{\epsilon^{\mu\nu\lambda\sigma}}{4!} \left[\sigma \left(\frac{\Lambda}{\mu^4} \right) F_{\mu\nu\lambda\sigma} + \hat{\sigma}\left(\theta\right) \hat{F}_{\mu\nu\lambda\sigma} \right] \right\} .$$

$$M_{Pl}^2 G^\mu{}_\nu = T^\mu{}_\nu - \frac{1}{4} \delta^\mu{}_\nu \langle T^\alpha{}_\alpha \rangle - \Delta\Lambda \delta^\mu{}_\nu \, ,$$

$$\Delta\Lambda^2 = \frac{3M_{Pl}^4}{8} \left[\langle R_{GB} \rangle - \langle W^2_{\mu\nu\alpha\beta} \rangle + \frac{2}{M_{Pl}^4} \langle (T_{\mu\nu} - \frac{1}{4} T g_{\mu\nu})^2 \rangle - \frac{1}{6M_{Pl}^4} \left(\langle T^2 \rangle - \langle T \rangle^2 \right) \right] .$$

Gauss-Bonnet integral anchored in place by four forms

$$\langle R_{GB} \rangle = -\mu^4 \frac{\hat{\sigma}'}{\sigma'} \frac{\int \hat{F}_4}{\int F_4} \, .$$

Weyl tensor

Vacuum energy drops out

$$T^\mu_\nu = -V_{vac} \delta^\mu_\nu + \tau^\mu_\nu$$

How big is Λ_{eff}?

For standard matter, space-time integrals dominated by time when universe is largest

$$\int d^4x\sqrt{-g} \sim \frac{1}{H_{age}^4}$$

where lifetime $t_{age} \sim \frac{1}{H_{age}} \gtrsim 13.7$ Gyrs

$$\langle \tau^\alpha_\alpha \rangle \sim \rho_{age} \sim \text{energy density at largest size} < \rho_c$$

$\Rightarrow$ *Λ_{eff} is not dark energy … too small!*

Observational consequences?

Universe has finite spacetime volume

$$\frac{\sigma'}{\lambda^4 \mu^4} = \int d^4 \sqrt{g}$$

space-time volume must be finite or else $\lambda \to 0$

$$\frac{m_{phys}}{M_{pl}} = \frac{\lambda m}{M_{pl}}$$

if $\lambda \to 0$ particle masses go to zero

Ends in a crunch
w=-1 is transient
Ω_k>0

circles in the sky?
possible correlation
between 1+w and Ω_k

Weinberg No Go

$$S[\pi, g_{\mu\nu}] = \int d^4x \sqrt{-g} R + \Delta L(\pi, g_{\mu\nu}, \text{derivatives})$$

Assume translation invariant solution for ANY vacuum energy:

$$\text{On shell field eqns: } \left.\frac{\partial \Delta L}{\partial g_{\mu\nu}}\right|_{g,\pi=\text{const}} = 0, \quad \left.\frac{\partial \Delta L}{\partial \pi}\right|_{g,\pi=\text{const}} = 0$$

Scalar eqn $\implies$ trace of gravity eqn

$$2g_{\mu\nu}\frac{\partial \Delta L}{\partial g_{\mu\nu}} - f(\pi)\frac{\partial \Delta L}{\partial \pi} \equiv 0$$

If $g_{\mu\nu}$ and π are constant then ΔL is invariant under

$$\delta g_{\mu\nu} = 2\epsilon g_{\mu\nu}, \;\; \delta\phi = -\epsilon$$

where we define $\phi = \int \frac{d\pi}{f(\pi)}$

Then $\Delta L = \sqrt{-\hat{g}}\mathcal{L}(\hat{g}_{\mu\nu}, \text{derivatives})$ where $\hat{g}_{\mu\nu} = e^{2\phi} g_{\mu\nu}$

$$\Longrightarrow \left.\frac{\partial \Delta L}{\partial g_{\mu\nu}}\right|_{g,\pi=\mathrm{const}} = \frac{1}{2} g^{\mu\nu} \Delta L \Big|_{g,\pi=\mathrm{const}}$$

Recall $\Delta L_{g,\pi=\mathrm{const}} = -V_0 \sqrt{-\hat{g}}$

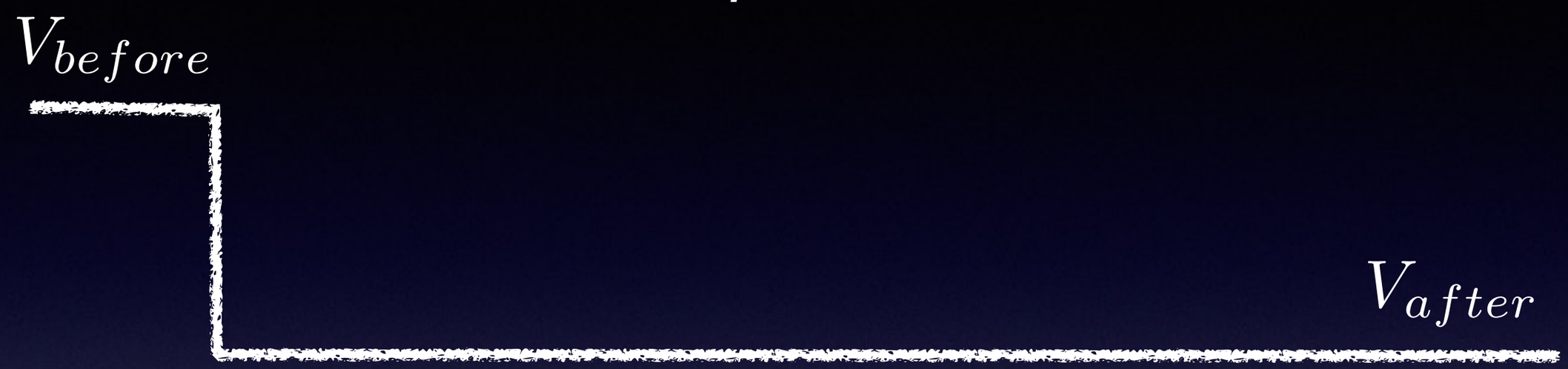
So translation invariant EOMs give $\Delta L = 0 \implies V_0 e^{4\phi} = 0$

$$\Longrightarrow V_0 = 0 \text{ or } e^{2\phi} \to 0$$

Fine tuning *Scale invariance*

Phase transitions?

Sequestering works best in domains that dominate spacetime volume



$$\tau^{\mu}{}_{\nu} - \frac{1}{4}\delta^{\mu}{}_{\nu}\langle\tau^{\alpha}{}_{\alpha}\rangle = \begin{cases} -\langle V_{before} - V\rangle\delta^{\mu}{}_{\nu} & t < t_* \,, \\ -\langle V_{after} - V\rangle\delta^{\mu}{}_{\nu} & t > t_* \,. \end{cases}$$

For an early transition….

$$\langle V_{after} - V\rangle = -\Delta V \frac{\int_{t_{in}}^{t_*} dt a^3}{\int_{t_{in}}^{t_{fin}} dt a^3} \ll \Delta V$$

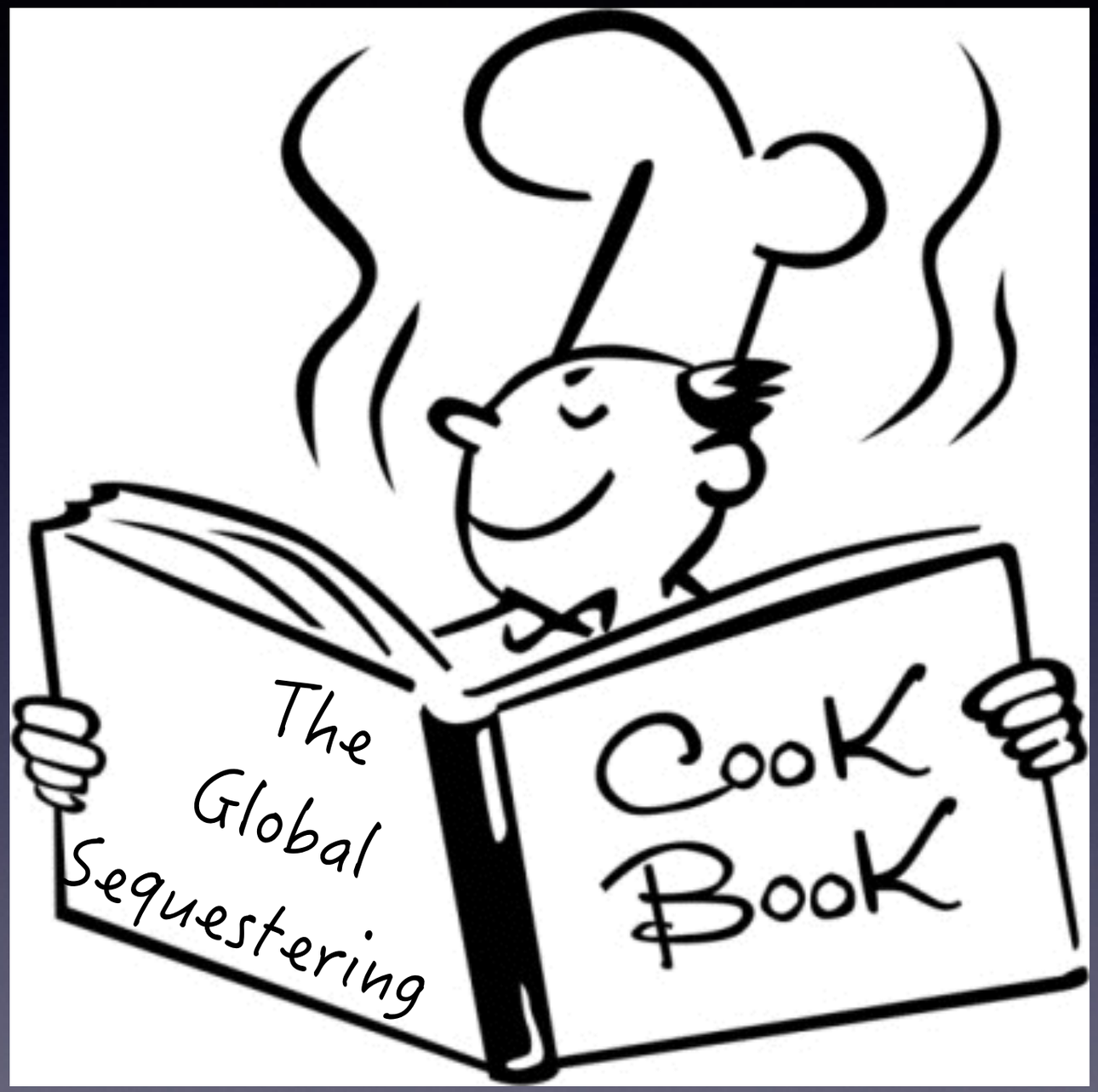
$\langle V_{before} - V\rangle \sim \mathcal{O}(1)\Delta V$ *short burst of inflation in build up to a transition*

CDL bubbles

Sequestering works best in near Minkowski vacua

tunnelling rates

from ds to Minkowski - generically enhanced compared wrt GR
from Minkowski to AdS — generically suppressed wrt GR


The
Global
Sequestering
Cook
Book

$$S = \int d^4x\sqrt{g}\left[\frac{\kappa_0^2}{2}R - \Lambda_0 - \mathcal{L}(g^{\mu\nu},\Phi)\right] - \Lambda\int d^4x\sqrt{g} + \sigma_1\left(\frac{\Lambda}{\mu^4}\right)S_1 + \theta S_g[g_{\mu\nu}] + \sigma_2(\theta)\,S_2$$

1. a globally adjustable CC counterterm

2. a second global variable for constraining the global geometry

3. S1 and S2 should have no variation wrt SM fields or metric, g

4. S1 should not vanish on shell (to avoid unphysical constraint on spacetime volume)

5. Sg chosen

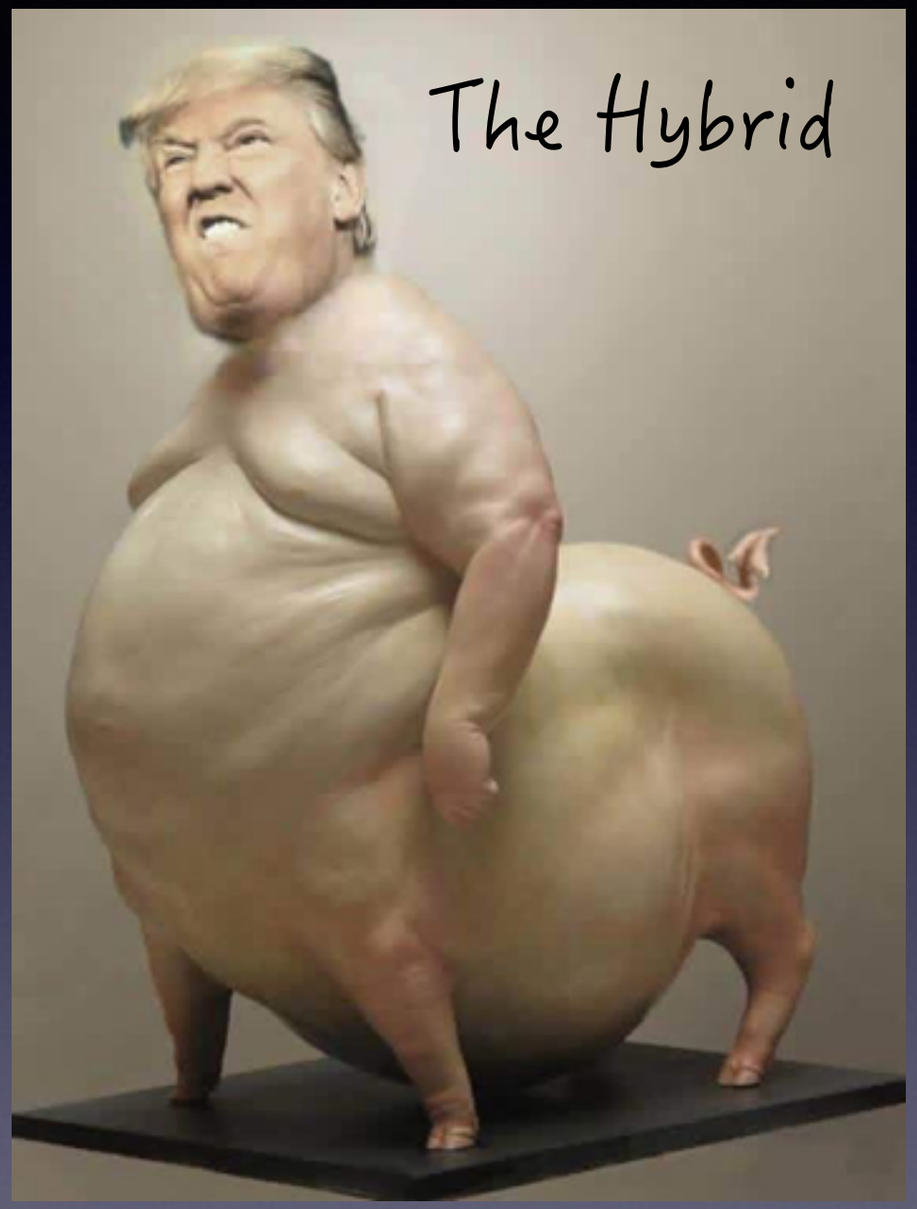
- *so as not to screw up gravitational phenomenology*
- *so as to yield a constraint on the scale dependent part of the geometry*

e.g:

- *a constant*
- *a 4 form field strength, F=dA*
- *∫G ^G, where G=dB is a 2 form field strength*
- $\int d^4y\sqrt{f}\,[\alpha R(f) + \beta]$.

e.g: Einstein-Hilbert, Gauss-Bonnet

Graviton loops?



Start with local VES

$$S = \int d^4x\sqrt{g}\left[\frac{\kappa^2(x)}{2}R - \Lambda(x) - \mathcal{L}_m(g^{\mu\nu},\Phi)\right] + \int \sigma\left(\frac{\Lambda(x)}{\mu^4}\right)F_4 + \hat{\sigma}\left(\frac{\kappa^2(x)}{M_{Pl}^2}\right)\hat{F}_4\,.$$

Integrate out Λ and $\hat{A}$

$$S = \int d^4x\sqrt{g}\left[-\mu^4\epsilon\left(\frac{\star F_4}{\mu^4}\right) + \frac{1}{2}\kappa^2 R - \mathcal{L}_m(g^{\mu\nu},\Phi)\right]$$

where κ is now global and function ε is related to Legendre transform of σ

compare with $\int d^4x\sqrt{\tilde{g}}\left[\frac{M_{Pl}^2}{2}\eta\tilde{R} - \mathcal{L}(\tilde{g}^{\mu\nu},\Phi) - \frac{1}{48}\tilde{F}^2_{\mu\nu\lambda\sigma} + \frac{1}{6}\tilde{\nabla}_\mu(\tilde{F}^{\mu\nu\lambda\sigma}\tilde{A}_{\nu\lambda\sigma})\right]$

The End

COLLAPSE TRIGGER = DARK ENERGY

Linear potential $V=m^3\varphi$

form protected by shift symmetry, size of m^3 technically natural

If $\varphi_{in} > M_{pl}$, then when scalar dominates, does so in SLOW ROLL until collapse time

$$t_{collapse} \sim \sqrt{\frac{M_{pl}}{m^3}}$$

Radiatively stable choice of collapse time?

Yes, thanks to m^3

Radiatively stable choice of φ_{in}?

Yes, thanks to shift symmetry

But its not even a "choice".... $\langle R \rangle = 0$ picks out precisely those solutions with $\varphi_{in} > M_{pl}$!!!!!!!

WHY NOW?

Because the end is nigh!!!

Why is it nigh?

Because the radiatively stable parameter
$m^3 \sim M_{pl} H_0^2$

Prediction: $1+w \sim \Omega_K^2$