VACUUM ENERGY SEQUESTERING

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Nordic String Theory Meeting

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THE COSMOLOGICAL CONSTANT PROBLEM: SOME USEFUL REVIEWS

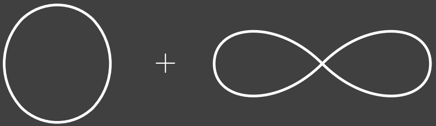
- S. Weinberg, Rev. Mod. Phys. 61 (1989)
- J. Polchinski, hep-th/0603249 (2006)
- J. Martin, arXiv:1205.3365 (2012)
- C. P. Burgess, arXiv:1309.4133 [hep-th] (2013)
- A. Padilla, arXiv:1502.05296 [hep-th](2015)

SEQUESTERING REFERENCES

- arXiv:1309.6562
- arXiv:1406.0711
- arXiv:1505.01492
- arXiv:1604.04000
- arXiv:1606.04958

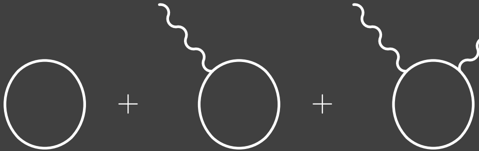
THE COSMOLOGICAL CONSTANT PROBLEM

- Vacuum fluctuations



$$+ \quad \dots \quad = V_{\text{vac}}$$

- Equivalence principle



$$+ \quad \dots \quad = -\sqrt{-g}\, V_{\text{vac}}^{\text{1-loop}}$$

- In General Relativity, vacuum fluctuations affect space-time according to

$$M_{\rm pl}^2 G_{\mu\nu} = T_{\mu\nu} = -g_{\mu\nu}(V_{\rm vac} + \Lambda_c)$$

- Taking $(V_{\rm vac} + \Lambda_c) \geq 0$ we have de Sitter space-time with curvature

$$H^2 = \frac{V_{\rm vac} + \Lambda_c}{3M_{\rm pl}^2}$$

- Observations are consistent with an asymptotically de-Sitter cosmology with

$$H^2 \leq \frac{(\rm meV)^4}{3M_{\rm pl}^2}$$

- Corresponding to a cosmological horizon $\sim 10^{26}$m

- Spilt degrees of freedom into high energy modes ϕ_h and low energy modes ϕ_l. The Wilsonian effective action for ϕ_l is then

$$\exp(iS_{\text{eff}}[\phi_l]) = \int D\phi_h \exp(iS[\phi_l, \phi_h])$$

- V_{vac} receives large POWER LAW threshold corrections – which require large fine tunings to match the observed cosmological constant

- Now decrease the Wilsonian cut-off by integrating out more particles – requires further fine tuning

- We would like the understand why a parameter is small at all scales – Naturalness

"The observed value of the cosmological constant is unnaturally small – requires repeated fine tuning as we change effective description of field theory sector"

- V_{vac} is very sensitivity to unknown high energy physics – violation of decoupling
- Contrast to e.g. electron mass which is protected by symmetry, comparable to Higgs mass which receives no protect from loops
- For example, in the absence of tuning the Higgs at 1-loop would yield $r_H \leq 1$mm but we observe $r_H \sim 10^{26}$m (N.B. Pauli, 1920)
- Observed cosmological constant $<<$ standard model scales

"Why is the universe big?"

CAN WE MAKE THE COSMOLOGICAL CONSTANT RADIATIVELY STABLE?

- Field theory symmetry e.g. SUSY
- Anthropic selection of vacua – no Naturalness, string landscape (Hints from LHC?)
- Violate the equivalence principle with infra-red modifications of gravity – Warning: Lamb shift!
- Define a space-time average

$$\langle Q \rangle = \frac{\int d^4x \sqrt{-g}\, Q}{\int d^4x \sqrt{-g}}$$

THE COSMOLOGICAL CONSTANT IS...CONSTANT

$$\Lambda = \langle \Lambda \rangle$$

- *Is it possible to stop the vacuum energy loops from gravitating while all other sources gravitate in the usual way? i.e. can we consistenly violate the equivalence principle only for infinite wavelength sources?*

THE COSMOLOGICAL CONSTANT AND CAUSALITY

- Let $T^{\mu}{}_{\nu} = \tau^{\mu}{}_{\nu} - \delta^{\mu}{}_{\nu}(\Lambda_c + V_{\text{vac}})$

$$
\begin{aligned}
M_{pl}^2 \left(R^{\mu}{}_{\nu} - \frac{1}{4}\delta^{\mu}{}_{\nu} R \right) &= \tau^{\mu}{}_{\nu} - \frac{1}{4}\delta^{\mu}{}_{\nu}\tau^{\alpha}{}_{\alpha} \\
M_{pl}^2 R &= 4(\Lambda_c + V_{\text{vac}}) - \tau^{\alpha}{}_{\alpha}
\end{aligned}
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$$M_{pl}^2 \langle R \rangle = 4(\Lambda_c + V_{\text{vac}}) - \langle \tau^{\alpha}{}_{\alpha} \rangle$$

THE COSMOLOGICAL CONSTANT AND CAUSALITY

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$$\boxed{M_{pl}^2 \langle R \rangle = 4(\Lambda_c + V_{\mathrm{vac}}) - \langle \tau^\alpha{}_\alpha \rangle}$$

A FURTHER COMPLICATION: WEINBERG'S NO-GO THEOREM

- For details see Weinber's review of the cosmological constant

"It is not possible, in a theory with a mass gap, to add extra fields which self-adjust to eat up the cosmological constant thereby keeping the space-time curvature small, without simply transfering the fine tuning to the new sector"

- Look for consistent ways of by passing Weinberg

VACUUM ENERGY SEQUESTERING: ACTION

- Phys.Rev.Lett. 116 (2016) no.5, 051302 (arXiv: 1505.01492)

- Not all fields couple to $g_{\mu\nu}$!

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

- where $F_{\mu\nu\lambda\rho} = 4\partial_{[\mu}A_{\nu\lambda\rho]}, \quad \hat{F}_{\mu\nu\lambda\rho} = 4\partial_{[\mu}\hat{A}_{\nu\lambda\rho]}$

EQUATIONS OF MOTION I

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

$$\frac{\sigma'}{\mu^4} F_{\mu\nu\lambda\rho} = \frac{1}{4!}\sqrt{-g}\,\epsilon_{\mu\nu\lambda\rho}, \qquad \frac{\hat{\sigma}'}{M_{pl}^2}\hat{F}_{\mu\nu\lambda\rho} = -\frac{1}{2\cdot 4!}\sqrt{-g}\,R\,\epsilon_{\mu\nu\lambda\rho}$$

$$\frac{\sigma'}{\mu^4}\partial_\mu \Lambda(x) = 0, \qquad \frac{\hat{\sigma}'}{M_{pl}^2}\partial_\mu \kappa^2(x) = 0$$

where we have used $\displaystyle\int d^4x\sqrt{-g} = \int \frac{1}{4!}\sqrt{-g}\,\epsilon_{\mu\nu\lambda\rho}\,dx^\mu dx^\nu dx^\lambda dx^\rho$

EQUATIONS OF MOTION II

$$\kappa^2 G^{\mu}{}_{\nu} = T^{\mu}{}_{\nu} - \delta^{\mu}{}_{\nu}\Lambda_c$$

$$\frac{\sigma'}{\mu^4} F_{\mu\nu\lambda\rho} = \frac{1}{4}\sqrt{-g}\epsilon_{\mu\nu\lambda\rho}, \qquad \frac{\hat{\sigma}'}{M_{pl}^2}\hat{F}_{\mu\nu\lambda\rho} = -\frac{1}{2\cdot 4}\sqrt{-g}R\epsilon_{\mu\nu\lambda\rho}$$

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$$\begin{aligned} \kappa^2 G^\mu{}_\nu &= T^\mu{}_\nu - \delta^\mu{}_\nu \Lambda_c \\ \frac{1}{4}\kappa^2 \langle R \rangle &= -\frac{\mu^4}{2} \frac{\kappa^2 \hat{\sigma}'}{M_{pl}^2 \sigma'} \frac{\int \hat{F}}{\int F} = \Delta\Lambda \end{aligned}$$

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$$\Lambda_c = \frac{1}{4}\langle T^{\alpha}{}_{\alpha}\rangle + \frac{1}{4}\kappa^2\langle R\rangle = \frac{1}{4}\langle T^{\alpha}{}_{\alpha}\rangle + \Delta\Lambda$$

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

EQUATION OF MOTION DECOMPOSITION

$$\begin{aligned}
\kappa^2\left(R^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu R\right) &= \tau^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu \tau^\alpha{}_\alpha \\
\kappa^2(R - \langle R\rangle) &= \langle \tau^\alpha{}_\alpha\rangle - \tau^\alpha{}_\alpha \\
\kappa^2\langle R\rangle &= 4(\Lambda + V_{\mathrm{vac}}) - \langle \tau^\alpha{}_\alpha\rangle
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$$\kappa^2 \left(R^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu R \right) = \tau^\mu{}_\nu - \frac{1}{4}\delta^\mu{}_\nu \tau^\alpha{}_\alpha$$

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

$$\star F_4 - \langle \star F_4 \rangle = 0, \qquad \langle \star F_4 \rangle = \frac{\mu^4}{\sigma'}$$

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\kappa^2(R-\langle R\rangle) &= \langle\tau^{\alpha}{}_{\alpha}\rangle-\tau^{\alpha}{}_{\alpha} \\
\kappa^2\langle R\rangle &= 4(\Lambda_c+V_{\mathrm{vac}})-\langle\tau^{\alpha}{}_{\alpha}\rangle
\end{aligned}$$

$$\star F_4-\langle\star F_4\rangle=0, \qquad \langle\star F_4\rangle=\frac{\mu^4}{\sigma'}$$

$$\begin{aligned}
\star\hat{F}_4-\langle\star\hat{F}_4\rangle &= \frac{M_{pl}^2}{2\kappa^2\hat{\sigma}'}(\tau^{\alpha}{}_{\alpha}-\langle\tau^{\alpha}{}_{\alpha}\rangle) \\
\frac{1}{4}\kappa^2\langle R\rangle &= -\frac{\kappa^2\hat{\sigma}'}{2M_{pl}^2}\langle\star\hat{F}_4\rangle
\end{aligned}$$

OPEN QUESTIONS

- Origin of the four forms and their couplings to the scalars?
- A more complete/fundamental framework? Generalisations?
- Observational predictions?
- Quantum corrections N.B. scalar gravity