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A manifestly local Theory of Vacuum Energy Sequestering

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Outline

- Cosmological constant problem
  - Classical aspects
  - Quantum aspects
  - The problems
- Original vacuum energy sequestering proposal (Kaloper, Padilla 2013-2015)
  - **arXiv:1309.6562**
  - **arXiv:1406.0711**
  - **arXiv:1409.7073**
- Localized sequestering model (Kaloper, Padilla, Stefanyszyn, Zahariade 2015)
  - **arXiv:1505.01492**

The cosmological constant problem

Of vacuum energy, phase transitions, bubbles and radiative corrections

The cosmological constant

- Einstein-Hilbert action

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \Lambda\right] - \int d^4x\sqrt{-g}\,L_m(g^{\mu\nu},\phi)$$

- Cosmological observations: accelerated expansion of the universe

$$\Lambda \sim (\mathrm{m}eV)^4$$

- Main energy component of the universe

$$\sim 68\%$$

- What is it?

Vacuum energy

- Equivalence principle: ALL energy gravitates

$$\langle \Omega | T_{\mu\nu} | \Omega \rangle = \mathrm{V}_{vac}\, g_{\mu\nu}$$

- Two contributions
  - Classical minimum of the potential
  - Zero-point energy of quantum fluctuations
- Vacuum energy and the cosmological constant

$$\Lambda = \Lambda_{bare} + V_{vac}$$

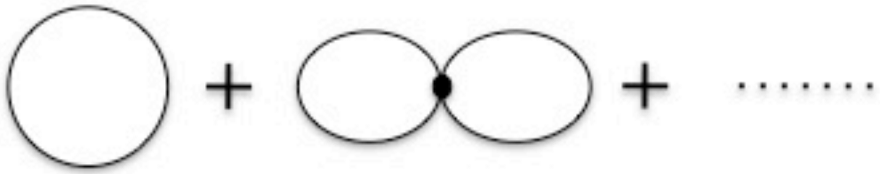
- Problem: high accuracy cancellation!!!

Cosmological constant problem(s)

- Classical cosmological constant problem
  - Phase transitions: classical component of Λ cancellation before XOR after
- Quantum mechanical cosmological constant problem
  - Quantum corrections: zero-point energy component computed in QFT
    - Quantum matter
    - Classical gravity
  - Regularization + renormalization of the bare Λ
  - Instability when changing the effective description: non-naturalness

RADIATIVE INSTABILITY

- Bubble diagrams (scalar $\lambda\,\phi^4$ theory)



- No influence on the correlation functions in the absence of gravity
- BUT in the presence of minimally coupled classical Einstein gravity

Radiative Instability

- One loop bubble diagram (tadpole) + Lorentz invariance preserving regularization

$$V_{vac}^{1\,loop} = -\frac{m^4}{(8\pi)^2}\left(\frac{2}{\epsilon} + finite + \ln\left(\frac{\mu^2}{m^2}\right)\right)$$

- Bare counterterm tuned to cancel the infinities…

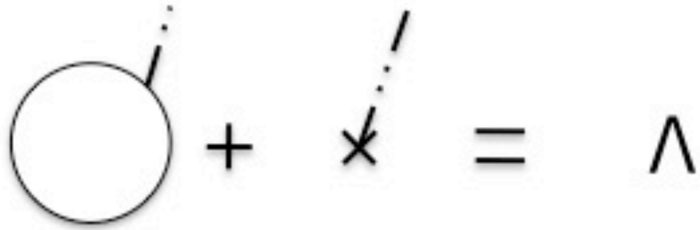
$$\Lambda_{bare} = \frac{m^4}{(8\pi)^2}\left(\frac{2}{\epsilon} + \ln\left(\frac{\mu^2}{M^2}\right)\right)$$

- …and fit the data i.e. Λ HAS to be measured

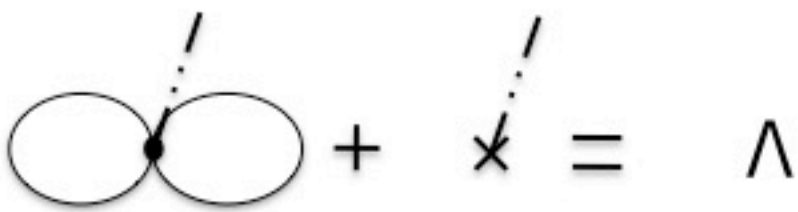
$$\Lambda = \frac{m^4}{(8\pi)^2}\left(\ln\left(\frac{m^2}{M^2}\right) - finite\right)$$

Radiative Instability

- Diagrammatically



- BUT at two loop level…



- Retuning of finite part of Λ_{bare} of order $\lambda\, m^4$
- Same order as tuning at 1 loop (if λ not fine-tuned)

Problems to solving the problem

- Radiative instability = knwoledge of the UV details of the theory

- Supersymmetry: not enough supersymmetry in the world…
  - Technically natural value of $\Lambda \sim (M_{\mathrm{SUSY}})^4$ too big

- No-Go theorem (Weinberg 1989)
  - No local self adjustment mechanisms for Poincaré invariant vacua

- Solution: imposing global constraints?

ORIGINAL SEQUESTERING MECHANISM

GR with global constraints (at the price of a not so local action)

(Global) Sequestering action

- Idea: couple matter sector scales and cosmological constant

- Action

$$S = \int d^4x \sqrt{-g}\left[\frac{M_P^2}{2}R - \Lambda - \lambda^4 L_m(\lambda^{-2}g^{\mu\nu}, \phi)\right] + \sigma\left(\frac{\Lambda}{\lambda^4\mu^4}\right)$$

  - Matter couples to $\tilde{g}_{\mu\nu} = \lambda^2 g_{\mu\nu}$
  - Λ, λ : global variables
  - σ smooth odd function: determined phenomenologically
  - μ mass scale ~ M_{P}

Field Equations and Vacuum energy sequestering

- Einstein equations

$$M_P^2 G^\mu{}_\nu = -\Lambda \delta^\mu{}_\nu + T^\mu{}_\nu$$

- Global equations

$$\left.\begin{aligned} \frac{\sigma'}{\lambda^4\mu^4} &= \int d^4x\sqrt{-g} \\ 4\Lambda\frac{\sigma'}{\lambda^4\mu^4} &= \int d^4x\sqrt{-g}\, T^\mu{}_\mu \end{aligned}\right\} \quad \Lambda = \frac{1}{4}\frac{\int d^4x\sqrt{-g}\,T^\mu{}_\mu}{\int d^4x\sqrt{-g}} \equiv \langle T^\mu{}_\mu\rangle$$

- Key equation: $M_P^2 G^\mu{}_\nu = T^\mu{}_\nu - \frac{1}{4}\langle T^\mu{}_\mu\rangle\,\delta^\mu{}_\nu$

Discussion

- Classical and (matter sector) quantum contributions to Λ cancel to all loop orders!
- Residual cosmological constant (radiatively stable) BUT given by a 4-volume average
- Non-zero mass gap: finite volume universe
- Weinberg No-Go evaded: global constraints decouple cosmological constant from matter mass scales
- BUT non-local action (although GR recovered locally)

Localized sequestering mechanism

Or how to enforce global constraints with local degrees of freedom?

Localizing global constraints

- Henneaux-Teitelboim (1989): unimodular gravity

$$\int d^4x\,\Lambda\left(1-\sqrt{-g}\right) \;\Leftrightarrow\; \int d^4x\,\Lambda\left(\epsilon^{\mu\nu\rho\sigma}\partial_\mu A_{\nu\rho\sigma}-\sqrt{-g}\right)$$

- Diffeomorphism invariance recovered AND Λ global variable

- Key points:
  - New local degrees of freedom with gauge symmetry
  - New volume form

(Local) Sequestering action

- Idea: work in Jordan frame and couple the two "eventually global" variables using HT trick

- Action

$$S=\int d^4x\sqrt{-g}\left[\frac{\kappa^2}{2}R-\Lambda-L_m(g^{\mu\nu},\phi)\right]+\int\sigma\left(\frac{\Lambda}{\mu^4}\right)F+\int\tau\left(\frac{\kappa^2}{M_P^2}\right)H$$

  - Λ, κ : local fields
  - $F=dA$, $H=dB$: 4-forms
  - σ , τ : smooth functions determined phenomenologically
  - μ mass scale ~ M_{P}

Field equations

- Einstein equations

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

- Variation of F and H

$$\partial_{\mu}\Lambda = 0 = \partial_{\mu}\kappa^2$$

- Variation of Λ and κ^2

$$\frac{\sigma'}{\mu^4}F = *1$$

$$-\frac{\tau'}{M_P^2}H = *1\frac{R}{2}$$

Vacuum energy sequestering

- Cosmological constant equation

$$\Lambda = \frac{1}{4}\langle T^{\mu}{}_{\mu}\rangle - \frac{1}{2}\frac{\kappa^2\mu^4\tau'}{M_P^2\sigma'}\frac{\int H}{\int F}$$

- Key equation

$$\kappa^2 G^{\mu}{}_{\nu} = T^{\mu}{}_{\nu} - \frac{1}{4}\langle \mathrm{T}^{\mu}{}_{\mu}\rangle\delta^{\mu}{}_{\nu} + \frac{1}{2}\frac{\kappa^2\mu^4\tau'}{M_P^2\sigma'}\frac{\int H}{\int F}\delta^{\mu}{}_{\nu}$$

- New residual cosmological constant component

Discussion

- Matter sector residual cosmological constant radiatively stable (as in global case)

- New residual cosmological constant component also radiatively stable
  - Volume integrals: IR quantities
  - σ, τ smooth: quantum corrections heavily suppressed by μ^4, M_{P} as long as $\kappa \sim M_P$

- GR recovered locally

- Weinberg No-Go evaded: equivalence principle violated, vacuum energy sector non-gravitating

Conclusion

- Vacuum energy sequestering: mechanism for cancelling matter loop corrections exhaustively via global constraints
- Residual cosmological constant radiatively stable
- Original scenario: non-local action
- Localization via the HT trick
- NB: graviton loops not included

Thank you for your attention