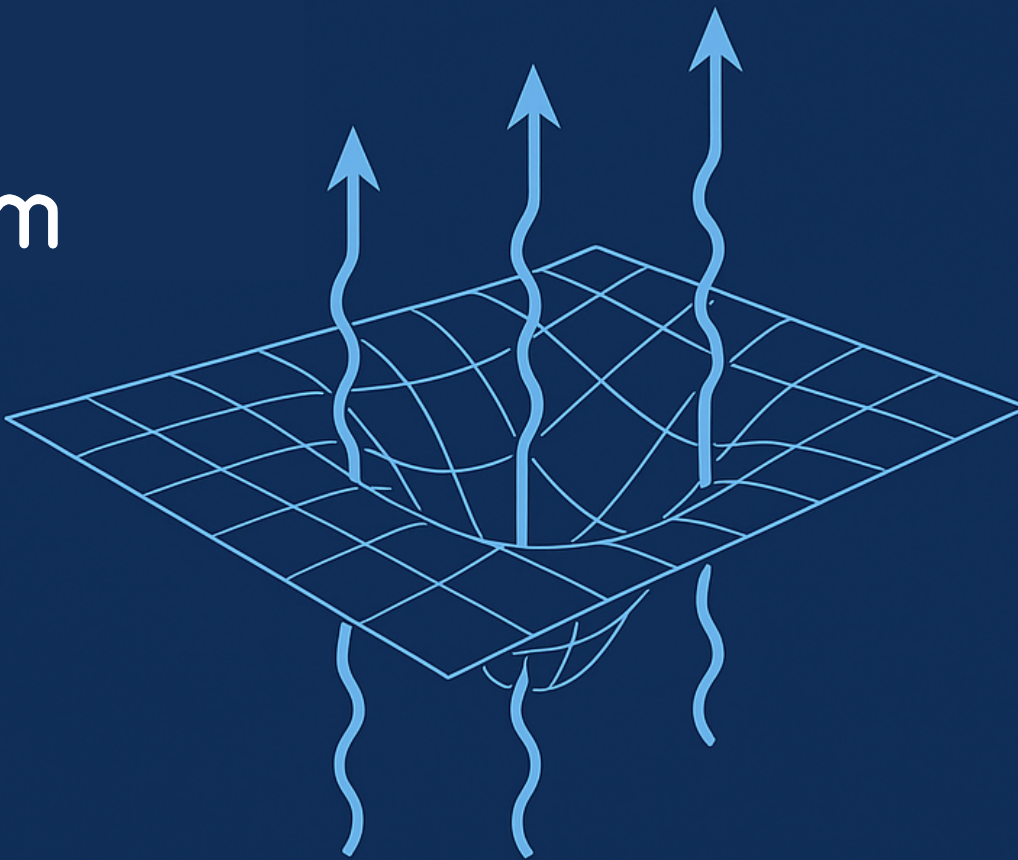
Four Forms and the Cosmological Constant Problem



Tony Padilla
University of Nottingham
PASCOS 2025

Collaborators: D'Amico, El Menoufi, Kaloper, Khoury, Mishra, Muntz, Nagy, Niedermann, Pedro, Saffin, Stefanyszyn, Westphal, Yang, Zahariade

What is the CC problem?

In QFT, corrections to vacuum energy density scales like

$$\delta\rho_{\text{vac}}^{\text{QFT}} \sim \Lambda_{\text{UV}}^4$$

Observed value is

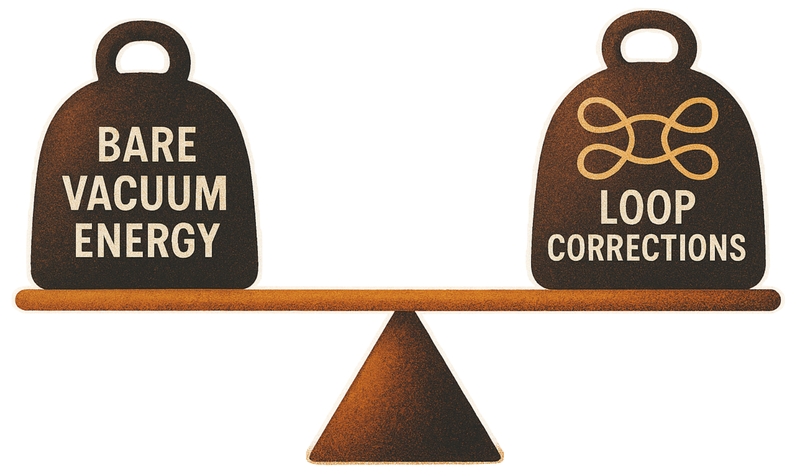
$$\rho_{\text{vac}}^{\text{obs}} = \rho_{\text{vac}}^{\text{bare}} + \delta\rho_{\text{vac}}^{\text{QFT}}$$

In GR, vacuum energy gravitates. Cosmological observations require

$$\rho_{\text{vac}}^{\text{obs}} \sim M_{pl}^2 H_0^2 \sim (\text{meV})^4$$

Comes from UV boundary condition

Comes from quantum corrections up to cut-off



A closer look at the Einstein equation

$$M_{pl}^2 G_{\mu\nu} = -\Lambda g_{\mu\nu} + T_{\mu\nu}$$

Trace: $M_{pl}^2 R = 4\Lambda - T$

Spacetime average: $$M_{pl}^2 \langle R \rangle = 4\Lambda - \langle T \rangle$$

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

is the long wavelength mode of a scalar Q

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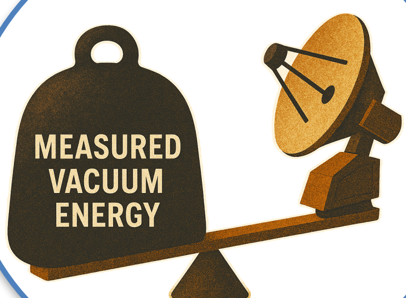

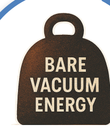

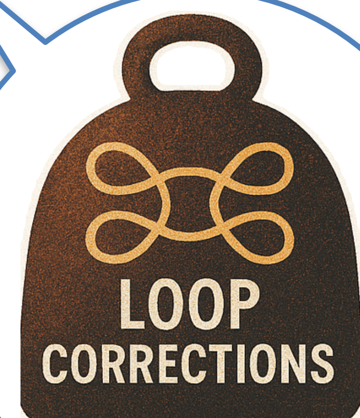

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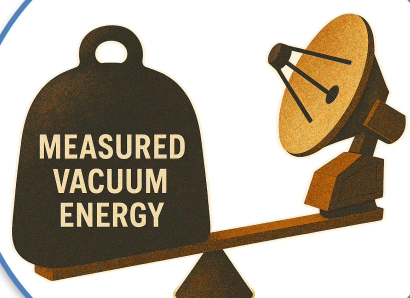

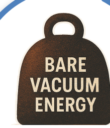

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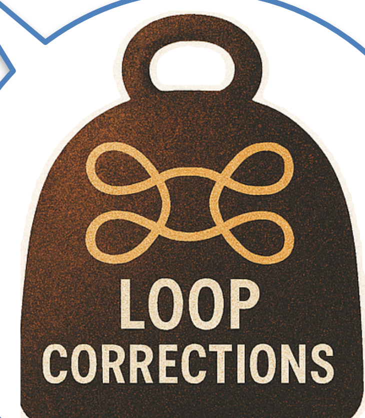

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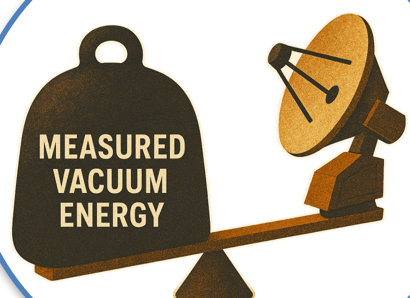

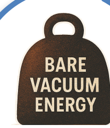

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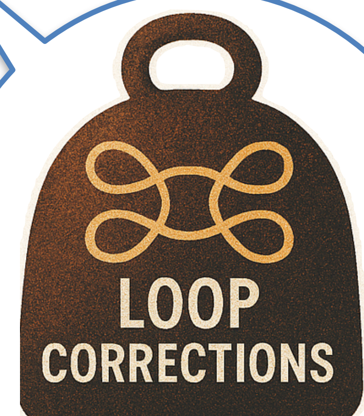

Radiative corrections

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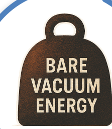

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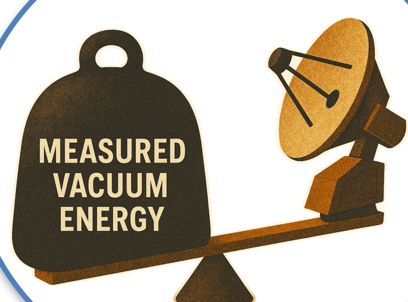
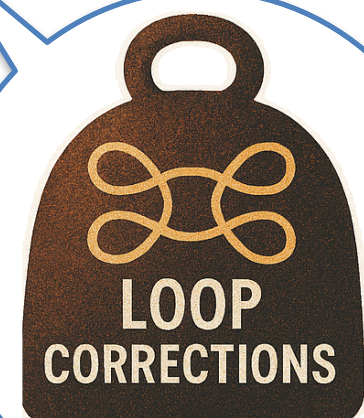


Predictions spoiled



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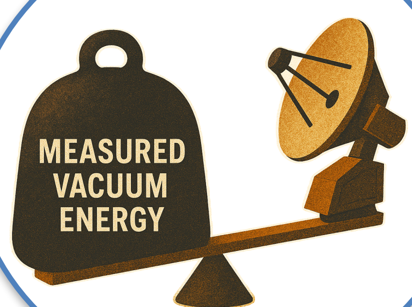

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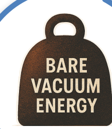

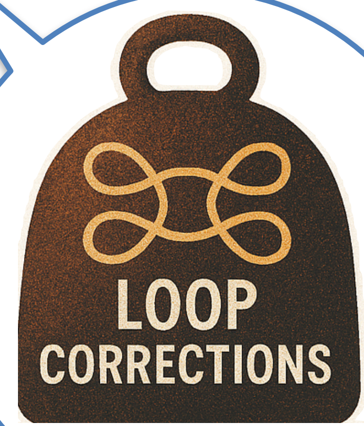

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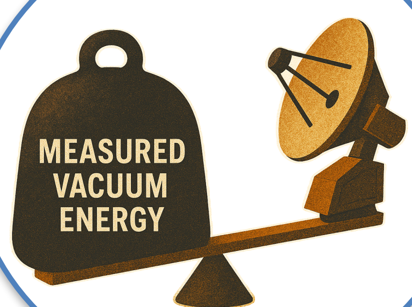

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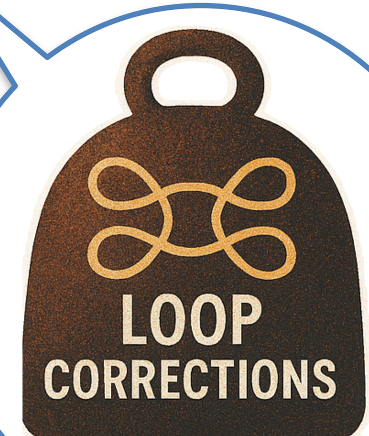

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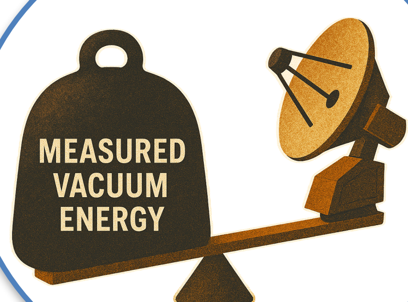

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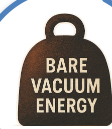

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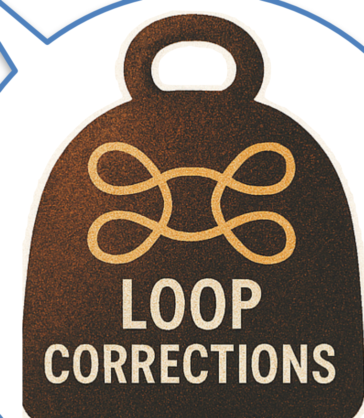

Radiative corrections

Step 1: Unchaining Λ

Λ unchained

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We want Λ to be adjustable, not fixed

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Enter four forms:

$$F = \frac{1}{4!} F_{\mu\nu\alpha\beta} dx^\mu \wedge dx^\nu \wedge dx^\alpha \wedge dx^\beta \quad \text{where } F_{\mu\nu\alpha\beta} = 4\partial_{[\mu} A_{\nu\alpha\beta]}$$

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The canonical action is $S_{\mathsf{F}} = \int d^4x \sqrt{-g} \left[-\frac{1}{2.4!} F_{\mu\nu\alpha\beta} F^{\mu\nu\alpha\beta} \right]$

with energy momentum tensor: $T_{\mathsf{F}}^{\mu\nu} = \frac{1}{3!} \left(F^{\mu\alpha\beta\gamma} F^{\nu}{}_{\alpha\beta\gamma} - \frac{1}{8} g^{\mu\nu} F_{\alpha\beta\gamma\delta} F^{\alpha\beta\gamma\delta} \right)$

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Field equations, $d(\star F) = 0$, where $\star F = F_{\mu\nu\alpha\beta} \epsilon^{\mu\nu\alpha\beta}$; implies no local dynamics and constant flux, $\star F = c$.

... and so this gravitates like a CC, $T_{\mathsf{F}}^{\mu\nu} = -\frac{1}{2} c^2 g^{\mu\nu}$

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Adjust the flux and you adjust Λ

Step 2: Fixing the prediction

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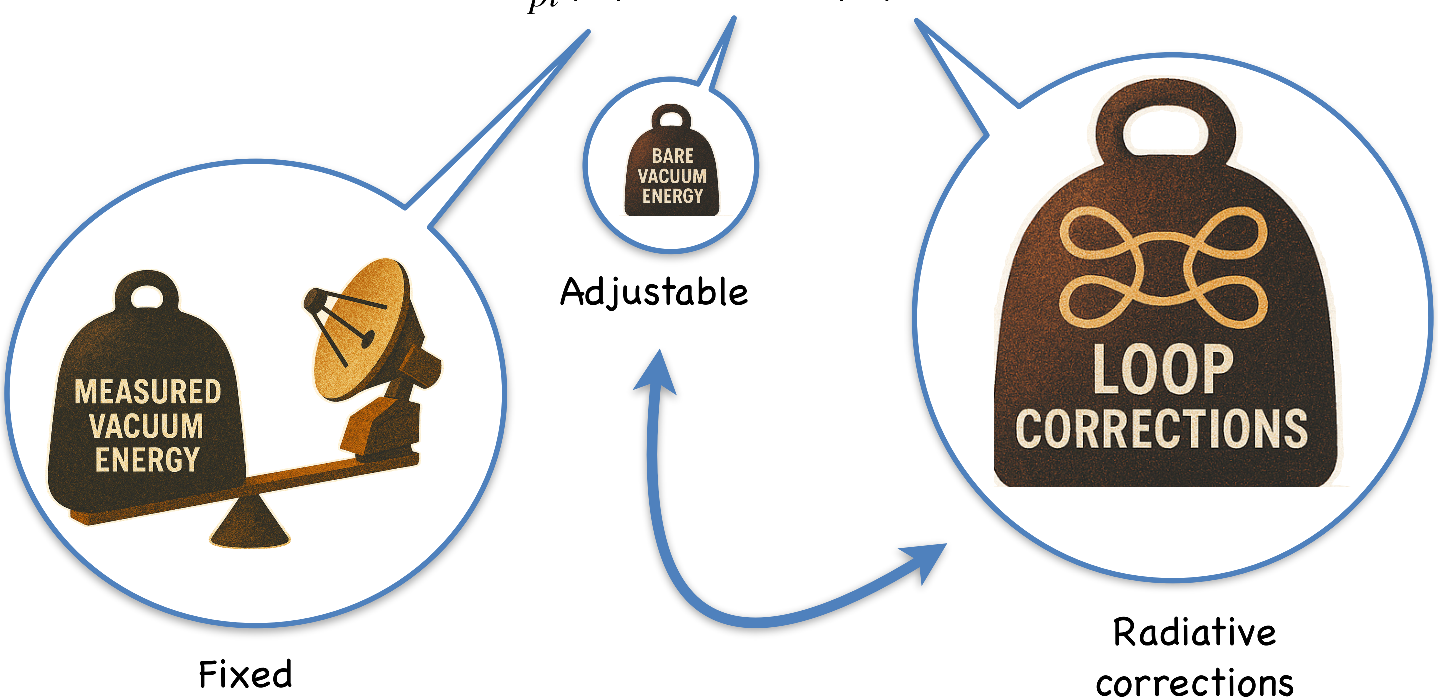

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Hawking 1984: GR + four form

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{pl}^2}{2} R - \frac{1}{2.4!} F_{\mu\nu\alpha\beta} F^{\mu\nu\alpha\beta} \right] + \text{matter}$$

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Vacuum solutions have

$$M_{pl}^2 G_{\mu\nu} = -\Lambda_{\text{total}} g_{\mu\nu}$$

where measured CC is $\Lambda_{\text{total}} = \Lambda + \Lambda_{\text{QFT}}$;

Λ comes from the 4-forms, Λ_{QFT} is the renormalised vacuum energy.

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Problems: No dynamical mechanism for adjustment, Euclidean QG is ill-defined beyond perturbation theory

Charged membranes

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Brown and Teitelboim 1987 & 1988: GR + four form + charged membranes

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Flux is now quantised $\star F = Nq$ and so vacua have

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Landscape of vacua labelled by N

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Scan landscape with nucleation of membranes.

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Scan landscape with nucleation of membranes.

Problems: Near Minkowski, want a dense landscape with $\Delta\Lambda_{\text{total}} \lesssim M_{pl}^2 H_0^2$ which requires a tiny charge

$$q \lesssim H_0^2\sqrt{\frac{M_{pl}^4}{|\Lambda_{\text{QFT}}|}}.$$

Gaps in the landscape are always tiny - takes ages to neutralise the CC; rapid expansion dilutes away all matter.

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Bousso and Polchinski 2000: GR + lots of four forms + charged membranes

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Now we have a landscape living on an n-dimensional lattice:

$$\Lambda_{\text{total}} = \sum_{i=1}^{n}\frac{1}{2}N_i^2 q_i^2 + \Lambda_{\text{QFT}}$$

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No empty universe problem. Our vacuum selected anthropically

The CC is probably still zero?

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Padilla, Pedro, Yang 2023 & 2024; See also Kaloper & Westphal 2022; GR + four forms + charged membranes

New insight: Membrane nucleation rate $\Gamma \propto e^{-B}$ where the bounce B has a potential pole as the parent vacuum approaches Minkowski

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Specifically, as parent vacuum approaches Minkowski

$$B \sim \frac{6M_{pl}^4\Omega_3}{\Lambda_{\text{parent}}}(1-S) + \frac{8M_{pl}^6\Omega_3}{\tau^2 X(X-1)^2}[(X-1)^2(1-S)+2S]$$

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CC of parent vacuum

$$X = \frac{4M_{pl}^2\left(\Lambda_{\text{parent}} - \Lambda_{\text{daughter}}\right)}{3\tau^2} \approx \frac{4M_{pl}^2\left(-\Lambda_{\text{daughter}}\right)}{3\tau^2}$$

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If $X < 1$ we see that $B \sim \dfrac{12M_{pl}^4\Omega_3}{\Lambda_{\text{parent}}}$ as $\Lambda_{\text{parent}} \to 0$

Is the CC probably still zero?

Mishra, Padilla, Pedro, Saffin work in progress

We are carrying out a numerical analysis of relative bubble abundances at late times (based on old work of Garriga, Vilenkin, Schwartz-Perlov and others)

Early days, but...

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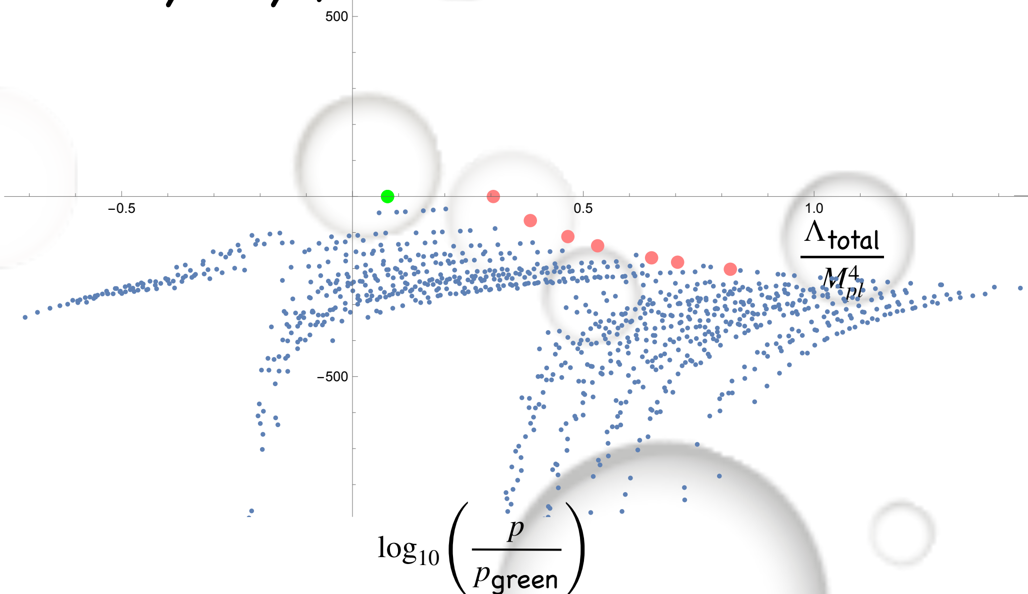
Green vacuum is most stable; red ones are its upwards neighbours



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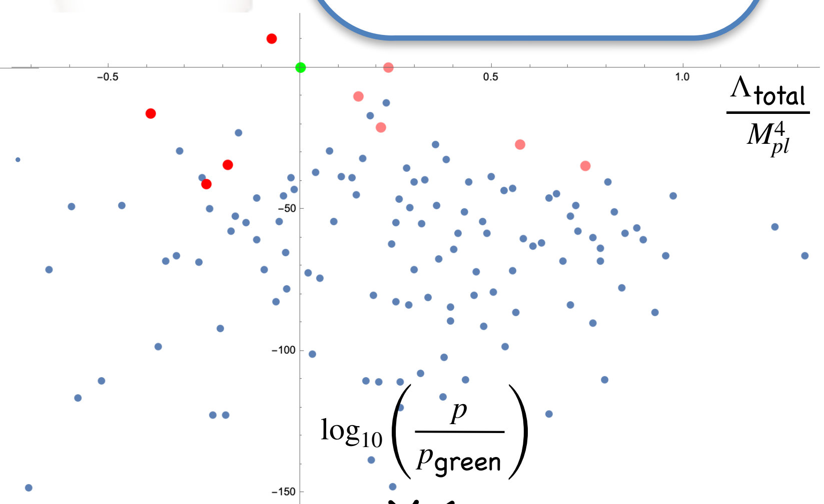

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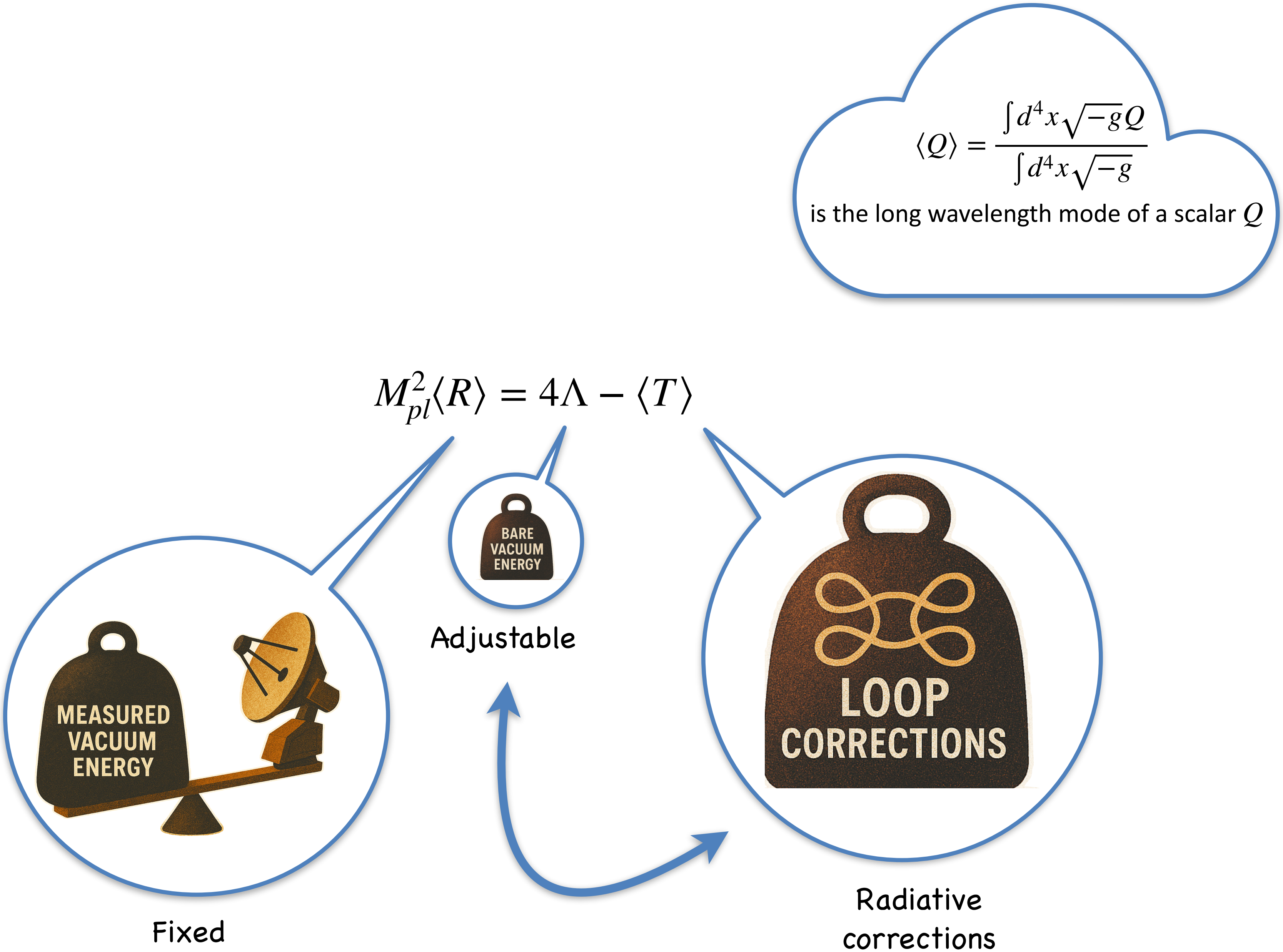

$\langle Q \rangle = \frac{\int d^4x \sqrt{-g}\, Q}{\int d^4x \sqrt{-g}}$
is the long wavelength mode of a scalar Q
$M_{pl}^2 \langle R \rangle = 4\Lambda - \langle T \rangle$
MEASURED VACUUM ENERGY
Fixed
BARE VACUUM ENERGY
Adjustable
LOOP CORRECTIONS
Radiative corrections

Vacuum energy sequestering

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Kaloper & Padilla and many others 2013-

Idea: Global modification of gravity; fix $\langle R \rangle$ using global constraints

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Start with GR, promote Λ and Planck mass to be global variables

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

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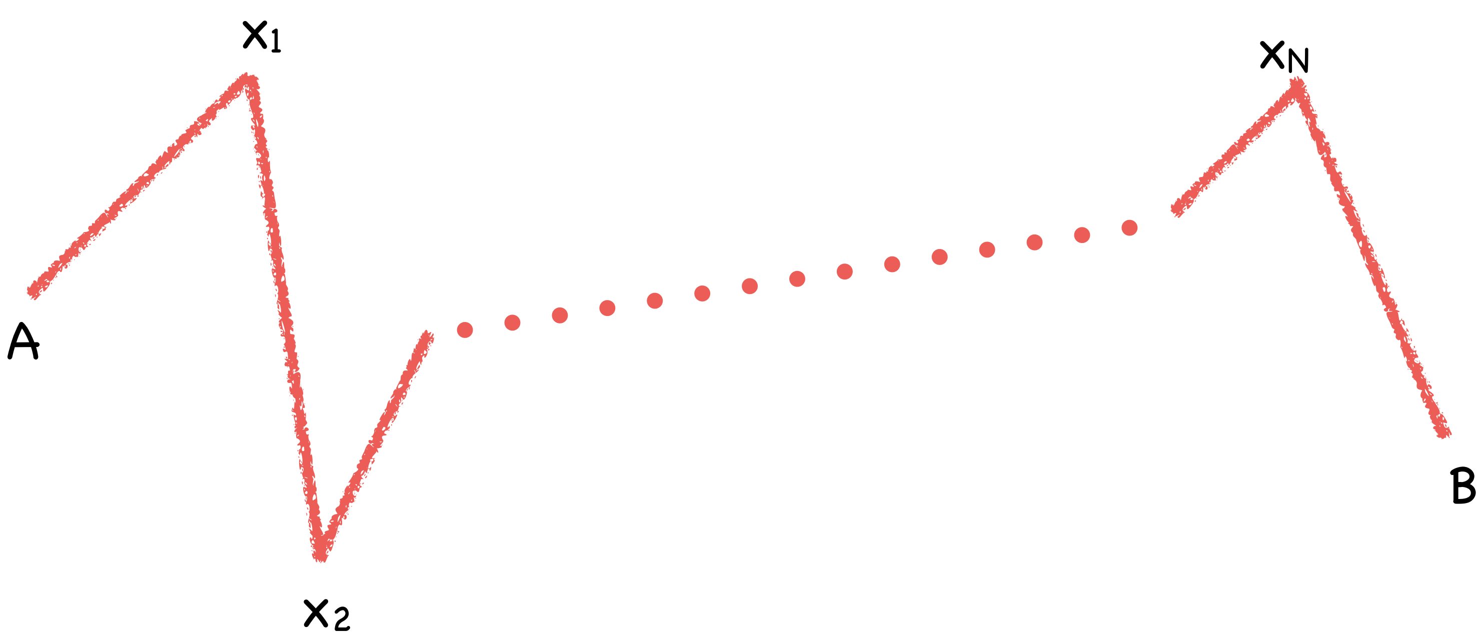
Kaloper, Padilla, Stefanyszyn, Zahariade 2015

Concern over lack of additivity of action $S_{AB} + S_{BC} \neq S_{AC}$



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

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Adding kinetic terms for the 4 forms doesn't spoil the cancellation (see Padilla 2019 and El Menoufi, Padilla, Nagy, Niedermann 2019)

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Khoury, Muntz and Padilla work in progress

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This is subtly different to Vacuum Energy Sequestering. Cf Carroll and Remmen 2017

The take-home message

At the heart of the CC problem is this equation:

$$M_{pl}^2 \langle R \rangle = 4\Lambda - \langle T \rangle$$

4 forms are great for model builders interested in this because they gravitate like a CC and can be a way to loosen Λ

Leads to a landscape of vacua labelled by 4 form flux

But the big question is: how do we fix the effective CC at late times?

- Probabilities?
- New global dynamics?
- Or something else?

Why no EU in BP?

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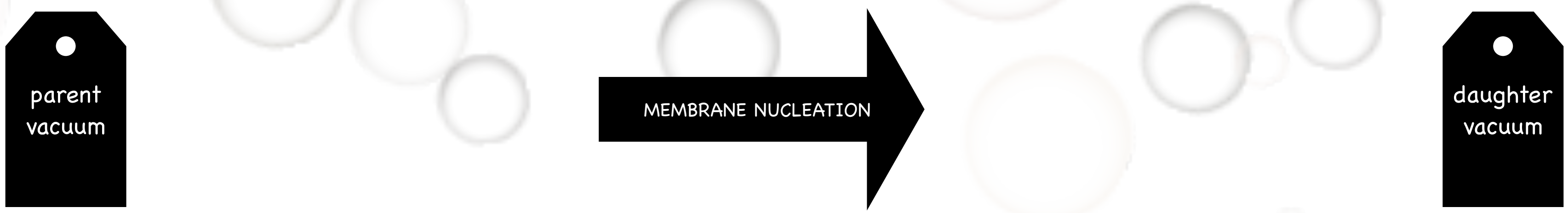

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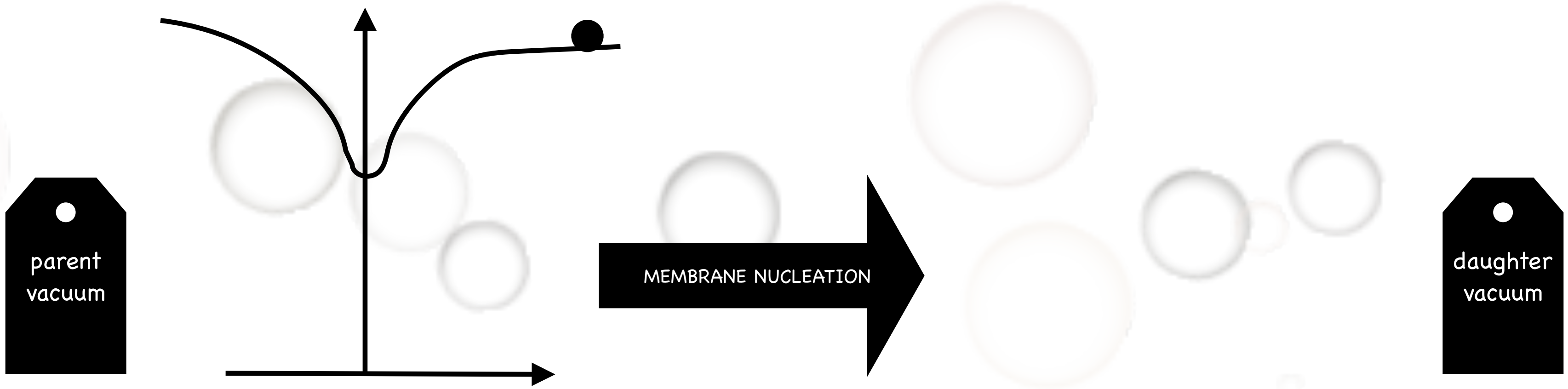

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Inflaton field is displaced by order
$H \sim \sqrt{\Lambda_{\text{parent}}}/M_{pl}$
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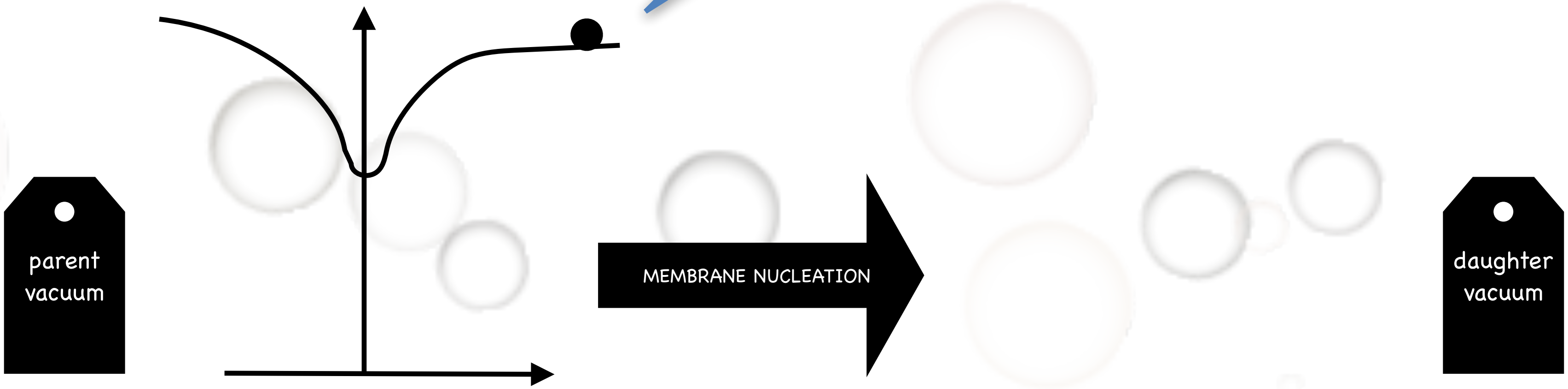

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