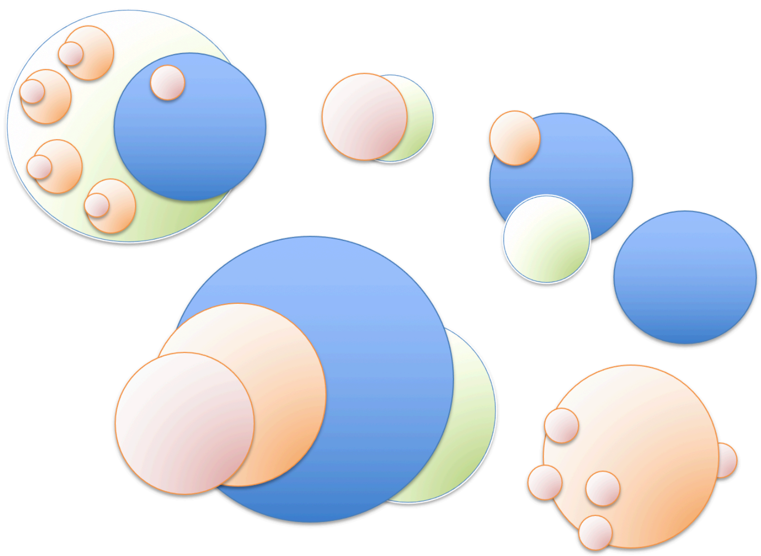
Nemanja Kaloper
UC Davis

Pancosmic Relativity and the Cosmological Constant Problem



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Origin of Scales and Gravity

- If scales and parameters are to be treated as `variables', how do they vary?
- Common - but confusing - idea: promote them to fields, integrate out local dofs, let cosmology select zero modes
- Realization is hard and very tricky
- Instead will show that there exists a simple and straightforward way of introducing only discrete variables: gravity has discrete degrees of freedom which persist in the far IR
- Identifying them introduces new symmetries; interpreting those as gauge symmetries requires introducing charges; discharge of those charges realizes a very simple, GR-only example of Landscape
- Will demonstrate how this simple a Landscape solves the cosmological constant problem without deploying anthropics

Hidden Degrees of Freedom of GR

- Usual textbook statement: the measure in GR is unique.
- NOT TRUE!

$$\int d^4x \sqrt{g}\, \frac{M_{pl}^2}{2}\, R \to \int \mathcal{F}\, R \qquad\qquad \mathcal{F} = d\mathcal{A}$$

- This measure is perfectly valid: but this is BD-like: $\frac{\mathcal{F}}{\sqrt{g} d^4x} = \Phi$
- Project out the local fluctuations; add $-\frac{1}{4!}\int \mathcal{F}\, \frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}} \mathcal{G}_{\mu\nu\lambda\sigma}$ $\qquad \mathcal{G} = d\mathcal{B}$
- Couple QFT minimally, and consider

$$S = \int \mathcal{F}\Big(R - \frac{1}{4!}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}\mathcal{G}_{\mu\nu\lambda\sigma}\Big) - \int d^4x \sqrt{g}\, \mathcal{L}_{\mathtt{QFT}}$$

- Locally, this is JUST GR!!!

Proof

- Vary the action:

$$-\frac{2}{4!}\frac{\epsilon^{\rho\zeta\gamma\delta}}{\sqrt{g}}\mathcal{F}_{\rho\zeta\gamma\delta}\Big(R^\mu{}_\nu - \frac{\epsilon^{\alpha\beta\lambda\sigma}\mathcal{G}_{\alpha\beta\lambda\sigma}}{2\cdot 4!\sqrt{g}}\delta^\mu{}_\nu\Big) = T^\mu{}_\nu\,,$$

$$R - \frac{1}{4!}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}\mathcal{G}_{\mu\nu\lambda\sigma} = 2\lambda\,, \qquad -\frac{1}{4!}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}\mathcal{F}_{\mu\nu\lambda\sigma} = \frac{\kappa^2}{2}\,.$$

- Here λ, κ^2 are integration constants due to the (rigid) gauge symmetries of $\mathcal{F} = d\mathcal{A}, \mathcal{G} = d\mathcal{B}$

- Now manipulate the eqs a bit: substitute bottom 2 into the top

$$\kappa^2\Big(R^\mu{}_\nu - \frac{1}{2}R\,\delta^\mu{}_\nu\Big) = -\kappa^2\lambda\,\delta^\mu{}_\nu + T^\mu{}_\nu$$

$$R - \frac{1}{4!}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}\mathcal{G}_{\mu\nu\lambda\sigma} = 2\lambda\,, \qquad -\frac{1}{4!}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}\mathcal{F}_{\mu\nu\lambda\sigma} = \frac{\kappa^2}{2}\,.$$

- Locally this is just GR!!! BUT: a fascinating new thing happens

- Since λ, κ^2 are integration constants this is infinitely many GRs!

A Proto-Landscape

- Since λ, κ^2 are completely arbitrary - they are fluxes of the 4-forms - the meta-theory has infinitely many versions of GR which behave as superselection sectors as long as the QFT parameters are fixed. These sectors, for now, do not mix.

- However, if there is a QFT phase transition, which changes QFT vacuum energy, then the superselection sectors can mix - transitioning into one another.

- This suggests to generalize the theory by promoting rigid to local gauge symmetries: add charges of 4-forms; those are membranes.

$$\begin{aligned} S &= \int \mathcal{F}\Big(R - \frac{1}{4!}\frac{\epsilon^{\mu\nu\lambda\sigma}}{\sqrt{g}}\mathcal{G}_{\mu\nu\lambda\sigma}\Big) - \int d^4x\sqrt{g}\,\mathcal{L}_{\mathtt{QFT}} + S_{\mathtt{boundary}} \\ &- \mathcal{T}_A\int d^3\xi\sqrt{\gamma}_A - \mathcal{Q}_A\int \mathcal{A} - \mathcal{T}_B\int d^3\xi\sqrt{\gamma}_B - \mathcal{Q}_B\int \mathcal{B}\,. \end{aligned}$$

- A landscape of couplings - which is spanned by fluxes

Dual Description

- Replace 4-forms by their magnetic duals - analogous to E&M, $\vec{E} \to \vec{B}, \vec{B} \to -\vec{E}$
- The trick: use 1st order path integral & integrate out 4-forms

$$Z = \int \dots [\mathcal{DA}][\mathcal{DB}][\mathcal{DF}][\mathcal{DG}][\mathcal{DP}_A][\mathcal{DP}_B]\, e^{iS(\mathcal{A},\mathcal{B},\mathcal{F},\mathcal{G},\dots)+i\int \mathcal{P}_A(\mathcal{F}-d\mathcal{A})+i\int \mathcal{P}_B(\mathcal{G}-d\mathcal{B})}$$

- Answer:

$$S = \int d^4x \Big\{ \sqrt{g}\Big(\frac{\kappa^2}{2}R - \kappa^2\lambda - \mathcal{L}_{\mathtt{QFT}}\Big) - \frac{\lambda}{3}\epsilon^{\mu\nu\lambda\sigma}\partial_\mu \mathcal{A}_{\nu\lambda\sigma} - \frac{\kappa^2}{12}\epsilon^{\mu\nu\lambda\sigma}\partial_\mu \mathcal{B}_{\nu\lambda\sigma}\Big\}$$
$$+ \; S_{\mathtt{boundary}} - \mathcal{T}_A \int d^3\xi \sqrt{\gamma}_A - \mathcal{Q}_A \int \mathcal{A} - \mathcal{T}_B \int d^3\xi \sqrt{\gamma}_B - \mathcal{Q}_B \int \mathcal{B}\,.$$

- We could have started with this action - it is technically simpler; note the topological sector
- We need to specify the matter-magnetic dual couplings

QFT-magnetic dual couplings

- The issue is the form-covariance in the loop expansion which we want to be able to make any statements which are radiatively stable - ie natural
- Minimal coupling $\sqrt{g}\mathcal{L}_{\mathtt{QFT}}(g^{\mu\nu})$ and conformal coupling $\sqrt{\hat{g}}\mathcal{L}_{\mathtt{QFT}}(\hat{g}^{\mu\nu})$ where the hatted metric is conformal to the canonical metric by rescaling dependent on the Planck scale are both form invariant in the loop expansion as long as the regulator depends on it in the same way. We take the rescaling to be a linear function of κ^2
- This is for technical reasons since in this case we can devise the proof that the resulting theory is ghost free
- Final action:

$$S = \int \Big\{ \sqrt{g}\Big(\frac{M_{pl}^2+\kappa^2}{2} R - \kappa^2\lambda - \frac{\kappa^2}{\mathcal{M}^2}\mathcal{L}_{\mathtt{QFT}}\big(\frac{\mathcal{M}}{\kappa} g^{\mu\nu}\big)\Big) - \frac{\lambda}{3}\epsilon^{\mu\nu\lambda\sigma}\partial_\mu \mathcal{A}_{\nu\lambda\sigma} - \frac{\kappa^2}{12}\epsilon^{\mu\nu\lambda\sigma}\partial_\mu \mathcal{B}_{\nu\lambda\sigma}\Big\}$$
$$+ \; S_{\mathtt{boundary}} - \mathcal{T}_A \int d^3\xi \sqrt{\gamma}_A - \mathcal{Q}_A \int \mathcal{A} - \mathcal{T}_B \int d^3\xi\sqrt{\gamma}_B - \mathcal{Q}_B \int \mathcal{B}\,.$$

$$S_{\mathtt{boundary}} = \int d^3\xi \Big([\frac{\lambda}{3}\epsilon^{\alpha\beta\gamma}\mathcal{A}_{\alpha\beta\gamma}] + [\frac{\kappa^2}{12}\epsilon^{\alpha\beta\gamma}\mathcal{B}_{\alpha\beta\gamma}]\Big) - \int d^3\xi \sqrt{\gamma}[\kappa^2_{\mathtt{eff}} K] \qquad \kappa^2_{\mathtt{eff}} = M_{pl}^2 + \kappa^2$$

- Now we can analyze it; in particular we care about QM of the fluxes and membranes

QM of Fluxes and Membranes

- The full analysis is given in all the gory detail in the papers on the title page
- Here I will skip some of the technical steps for simplicity's sake.
- The idea: Euclideanize the action and consider semiclassical discharge processes by solving equations with membrane sources and cosmological constant alone, taking the bulk geometry to be locally maximally symmetric
- Construct instantons which change the geometry as sourced by membranes and compute the bounce actions which control instability rates
- Will find that λ, κ^2 are not constant but change discretely, controlled by membrane charges and tensions
- Will focus on the differences relative to Brown-Teitelboim (BP).
- The bottomline: dS is unstable. It decays to Minkowski. (Almost) Flat space is accumulation point.

Euclidean Field Eqs

- Bulk:

$$ds_E^2 = dr^2 + a^2(r)\, d\Omega_3 \qquad 3\kappa_{\texttt{eff}}^2\Big((\frac{a'}{a})^2 - \frac{1}{a^2} \Big) = -\kappa^2\lambda = -\Lambda$$

- Membrane junction conditions:

$$\lambda_{out} - \lambda_{in} = \frac{1}{2}\mathcal{Q}_A \qquad \kappa_{out}^2 - \kappa_{in}^2 = 2\mathcal{Q}_B$$

$$a_{out} = a_{in} \qquad \kappa_{\texttt{eff}\ out}^2 \frac{a'_{out}}{a} - \kappa_{\texttt{eff}\ in}^2 \frac{a'_{in}}{a} = -\frac{1}{2}\Big(\mathcal{T}_A + \mathcal{T}_B \Big)$$

- 3-form boundary conditions can be neglected since they cancel out

- Bulk solutions are sections of (horo)spheres

$$a(r) = a_0 \sin(\frac{r+\delta}{a_0})\,, \quad \text{for} \quad \Lambda > 0\,; \qquad a(r) = r + \delta\,, \quad \text{for} \quad \Lambda = 0\,; \qquad a(r) = a_0 \sinh(\frac{r+\delta}{a_0})\,, \quad \text{for} \quad \Lambda < 0$$

- Now we glue them together

$\mathcal{T}_A, \mathcal{Q}_A \neq 0$

- Bulk sections:

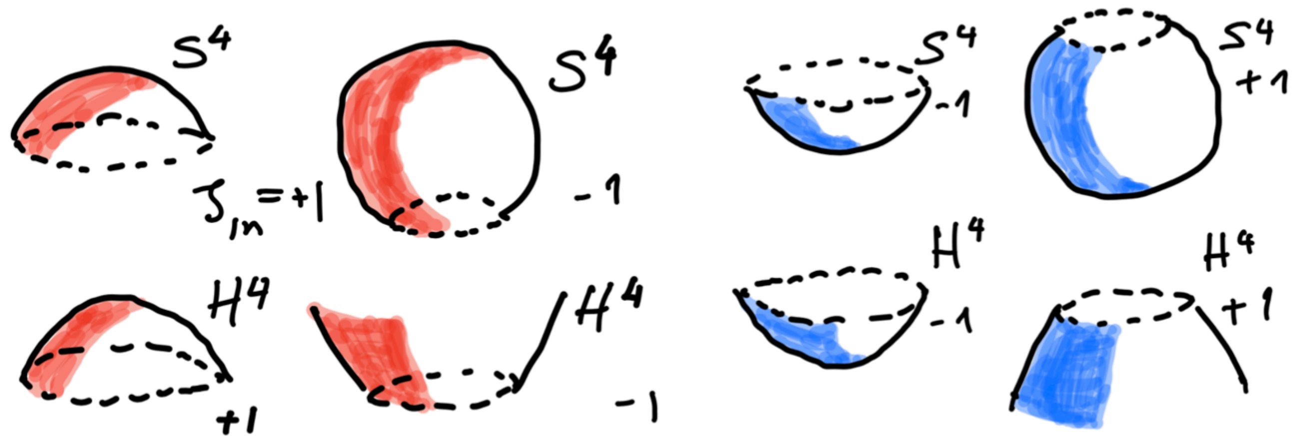


Figure 1: Spherical (S^4, top row) and horospherical (a.k.a. hyperbolic; H^4, bottom row) sections which are glued together to form instantons. Red ones are the interiors and the blue ones the exterior geometries of the instanton. The $\pm$ are the values of $\zeta_{in/out}$.

- Junction conditions: massaging the eqs, can rewrite them as

$$\zeta_{out}\sqrt{1-\frac{\Lambda_{out}a^2}{3\kappa_{\tt eff}^2}} = -\frac{\mathcal{T}_A}{4\kappa_{\tt eff}^2}\left(1-\frac{2\kappa_{\tt eff}^2\kappa^2\mathcal{Q}_A}{3\mathcal{T}_A^2}\right)a\,,$$

$$\zeta_{in}\sqrt{1-\frac{\Lambda_{in}a^2}{3\kappa_{\tt eff}^2}} = \frac{\mathcal{T}_A}{4\kappa_{\tt eff}^2}\left(1+\frac{2\kappa_{\tt eff}^2\kappa^2\mathcal{Q}_A}{3\mathcal{T}_A^2}\right)a\,.$$

A Crucial Feature of Junction Conditions

- Junction conditions controlled by

$$\left(1 \mp \frac{2\kappa_{\tt eff}^2 \kappa^2 \mathcal{Q}_A}{3\mathcal{T}_A^2}\right)$$

- This differs from BT (BP) in a crucial way: in BT the junction conditions depend on charge QUADRATICALLY - one power of charge and one power of background flux
- Thus the specifics of the instanton depend on the background flux
- IN OUR CASE NOT SO - the instantons do not care about the background value of the flux
- They only care about

$$\frac{2\kappa_{\tt eff}^2 \kappa^2 \mathcal{Q}_A}{3\mathcal{T}_A^2} = q > 1 \quad or \quad < 1$$

Instanton 'Baedeker'

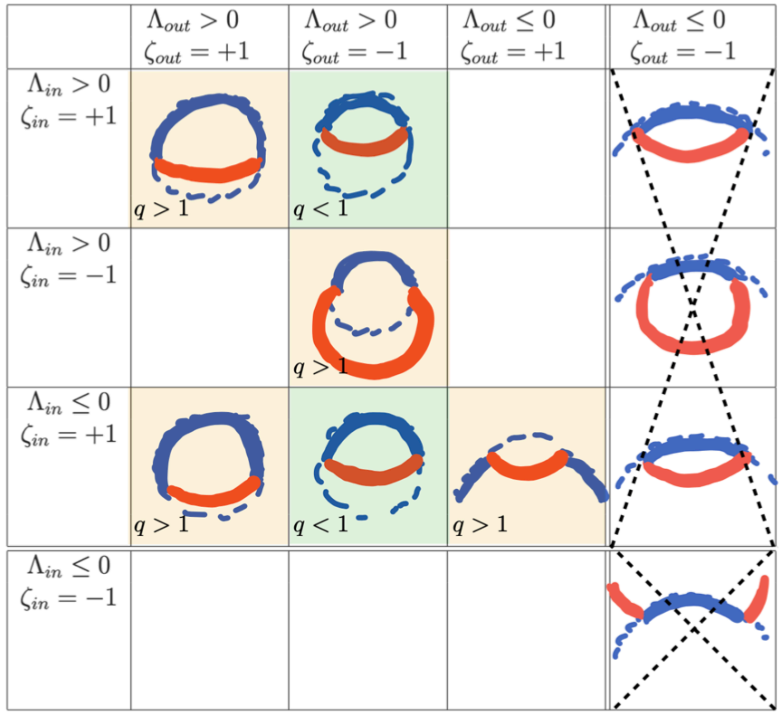


Figure 2: The instanton 'Baedeker'. The instantons fall into four types, divided by double lines in the table, and counted clockwise from the top corner [44]. The transitions corresponding to empty squares are ruled out kinematically by Eqs. (49), (50). The top nine are further split by $q = \frac{2\kappa_{\mathtt{eff}}^2 \kappa^2 |\mathcal{Q}_A|}{3\mathcal{T}_A^2} < 1$ (pale green) or $q > 1$ (pale gold). We keep both since $\kappa_{\mathtt{eff}}^2$ *might* vary independently (we will suppress those variations later on). The "ogre"-like configurations in the right column which are crossed out are allowed kinematically, but are suppressed dynamically since their bounce action is huge and positive, $S_{\mathtt{bounce}} \gg 1$, diverging when Anti-de Sitter sections are non-compact (see the text).

An Example of a `Gold' Instanton

$$\frac{2\kappa_{\text{eff}}^2 \kappa^2 Q_A}{3\mathcal{T}_A^2} = q > 1$$

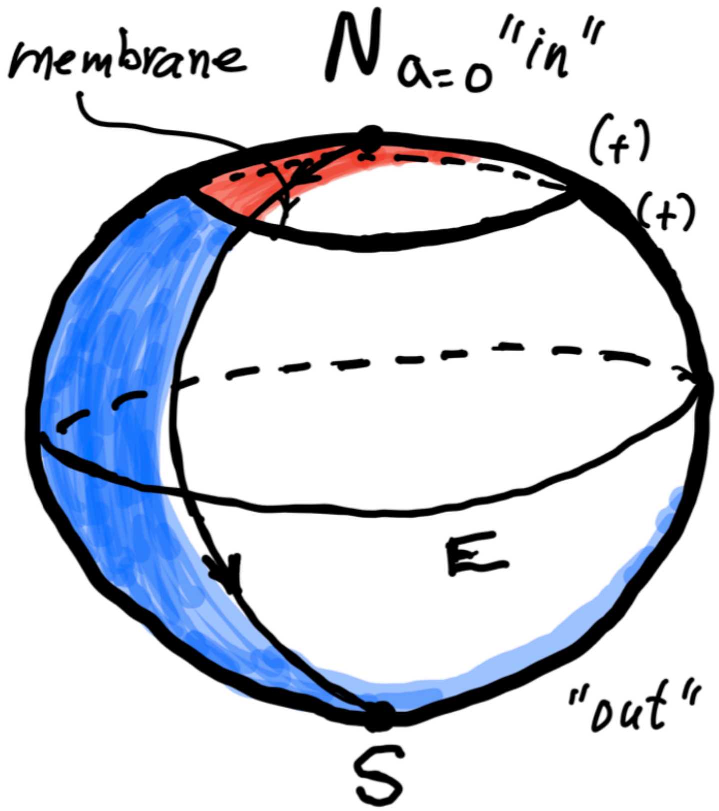
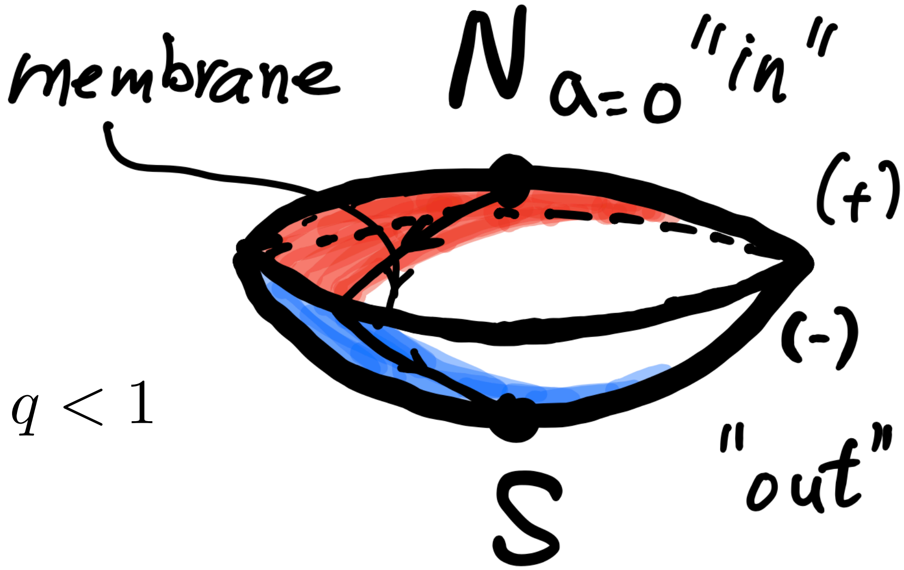


Figure 3: A cartoon of an instanton comprised of two sections of S^4. The region around the North Pole, shaded red, has a larger curvature radius because $\mathcal{T}_A > 0$, by Israel junction conditions [55].

This instanton is `bad': the processes it mediates lead to the discharge rate which does not depend on the background cosmological constant and so it overshoots the Minkowski space. This instanton is unavoidable in the quadratic flux models like Brown-Teitelboim (BP) and so vanishing cosmological constant is not the natural final state

An Example of a `Green' Instanton



$$\frac{2\kappa_{\mathtt{eff}}^2\kappa^2\mathcal{Q}_A}{3\mathcal{T}_A^2} = q < 1$$

This instanton is `GOOD': the processes it mediates lead to the discharge rate which DOES depend on the background cosmological constant. This selects Minkowski as the accumulation point of the evolution and makes (almost) Minkowski (quasi)stable. This instanton is favored in our setup by junction conditions when

$$q < 1$$

Bounce Action and Decay Rate

- The rate and bounce action are defined by

$$\Gamma \sim e^{-S(\texttt{bounce})} \qquad S(\texttt{bounce}) = S(\texttt{instanton}) - S(\texttt{parent})$$

- The bounce action evaluated on the instanton is

$$S(\texttt{bounce}) = 2\pi^2 \left\{ \Lambda_{out} \int_{North\ \ Pole}^{a} da \left(\frac{a^3}{a'}\right)_{out} - \Lambda_{in} \int_{North\ \ Pole}^{a} da \left(\frac{a^3}{a'}\right)_{in} \right\} - \pi^2 a^3 \mathcal{T}_A$$

$$2\pi^2 \Lambda_{in/out} \int_{North\ \ Pole}^{a} da \left(\frac{a^3}{a'}\right) = 18\pi^2 \frac{\kappa_{\texttt{eff}}^4}{\Lambda_{in/out}} \left(\frac{2}{3} - \zeta_{in/out}\left(1 - \frac{\Lambda_{in/out} a^2}{3\kappa_{\texttt{eff}}^2}\right)^{1/2} + \frac{\zeta_{in/out}}{3}\left(1 - \frac{\Lambda_{in/out} a^2}{3\kappa_{\texttt{eff}}^2}\right)^{3/2}\right)$$

- (After quite a bit of algebraic tedium)
- Using these formulas we can calculate the rate for any instanton from the \`Baedeker'; in some cases it diverges (the corresponding entries are crossed out).
- These formulas are identical to Brown-Teitelboim (Coleman etc too), except that the differences in junction conditions produce different final answers.

$\mathcal{T}_B, \mathcal{Q}_B \neq 0$

- Much uglier junction conditions; they start off simple,

$$a_{out} = a_{in} = a\,, \quad \lambda_{out} = \lambda_{in} = \lambda\,,$$

$$\kappa^2_{\mathtt{eff}\ out}\frac{a'_{out}}{a} - \kappa^2_{\mathtt{eff}\ in}\frac{a'_{in}}{a} = -\frac{1}{2}\mathcal{T}_B\,, \qquad \kappa^2_{out} - \kappa^2_{in} = 2\mathcal{Q}_B$$

- But on spherical sections, the resulting eqs are more involved:

$$\begin{aligned}\zeta_{out}\kappa^2_{\mathtt{eff}\ out}\mathcal{R}_{out} &= -\frac{\mathcal{T}_B a}{4} - \frac{4\mathcal{Q}_B}{\mathcal{T}_B a}(\kappa^2_{\mathtt{eff}\ out} - \mathcal{Q}_B)\Big(1 - \frac{\lambda a^2}{3}\Big)\,,\\ \zeta_{in}\kappa^2_{\mathtt{eff}\ in}\mathcal{R}_{in} &= \frac{\mathcal{T}_B a}{4} - \frac{4\mathcal{Q}_B}{\mathcal{T}_B a}(\kappa^2_{\mathtt{eff}\ out} - \mathcal{Q}_B)\Big(1 - \frac{\lambda a^2}{3}\Big)\,.\end{aligned}$$

$$\mathcal{R}_j = \sqrt{1 - \frac{\kappa_j^2}{M_{pl}^2 + \kappa_j^2}\frac{\lambda a^2}{3}}$$

- The a in the denominator a clue: we need to suppress superplanckian bubbles

$$16\,\frac{\kappa^4_{\mathtt{eff}}|\mathcal{Q}_B|}{\mathcal{T}_B^2} \ll 1$$

- Solve for a: unique real branch is

$$\begin{aligned}\frac{1}{a^2} = &\quad \kappa^2_{\mathtt{eff}\ out}\Big(\frac{\mathcal{T}_B}{4\kappa^3_{\mathtt{eff}\ out}}\Big)^2\Bigg(\frac{1 - \frac{2\lambda}{3\kappa^2_{\mathtt{eff}\ out}}\frac{16\kappa^4_{\mathtt{eff}\ out}\mathcal{Q}_B}{\mathcal{T}_B^2}\big(1 - \frac{\mathcal{Q}_B}{\kappa^2_{\mathtt{eff}\ out}}\big)}{1 - \big(\frac{\mathcal{T}_B}{4\kappa^3_{\mathtt{eff}\ out}}\big)^2\frac{16\kappa^4_{\mathtt{eff}\ out}\mathcal{Q}_B}{\mathcal{T}_B^2}\big(1 - \frac{\mathcal{Q}_B}{\kappa^2_{\mathtt{eff}\ out}}\big)} + \mathcal{O}\Big(\big(\frac{\kappa^4_{\mathtt{eff}\ out}\mathcal{Q}_B}{\mathcal{T}_B^2}\big)^2\Big)\Bigg)\,,\\ = &\quad \kappa^2_{\mathtt{eff}\ in}\Big(\frac{\mathcal{T}_B}{4\kappa^3_{\mathtt{eff}\ in}}\Big)^2\Bigg(\frac{1 + \frac{2\lambda}{3\kappa^2_{\mathtt{eff}\ in}}\frac{16\kappa^2_{\mathtt{eff}\ in}\mathcal{Q}_B}{\mathcal{T}_B^2}\big(1 + \frac{\mathcal{Q}_B}{\kappa^2_{\mathtt{eff}\ in}}\big)}{1 + \big(\frac{\mathcal{T}_B}{4\kappa^3_{\mathtt{eff}\ in}}\big)^2\frac{16\kappa^2_{\mathtt{eff}\ in}\mathcal{Q}_B}{\mathcal{T}_B^2}\big(1 + \frac{\mathcal{Q}_B}{\kappa^2_{\mathtt{eff}\ in}}\big)} + \mathcal{O}\Big(\big(\frac{\kappa^4_{\mathtt{eff}\ in}\mathcal{Q}_B}{\mathcal{T}_B^2}\big)^2\Big)\Bigg)\,.\end{aligned}$$

- Looks like a mess but it is much simpler than it looks: suppressing superplanckian physics, using

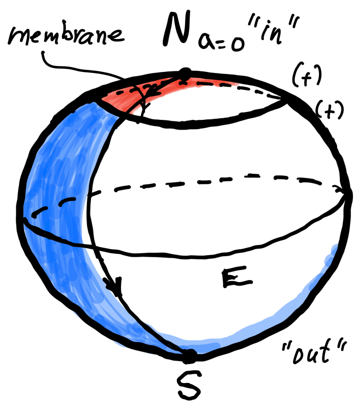
$$16\,\frac{\kappa_{\tt eff}^4|\mathcal{Q}_B|}{\mathcal{T}_B^2} \ll 1$$

- implies that the only bubbles which are kinematically allowed are those for whom

$$\frac{1}{a^2} \simeq \kappa_{{\tt eff}~out}^2 \Big(\frac{\mathcal{T}_B}{4\kappa_{{\tt eff}~out}^3}\Big)^2$$

- This condition simultaneously suppresses both the bubbles which are very small and the bubbles which could potentially flip the sign of the effective Planck scale
- Moreover the top condition also selects only the `Green' instantons from the Baedeker for this class of transitions too. This means the processes which change the Planck scale in this regime will also stop near the Minkowski limit!!!
- In other words, we have a chance of fitting the real world in this picture
- Henceforth I will largely ignore the processes which change the Planck scale

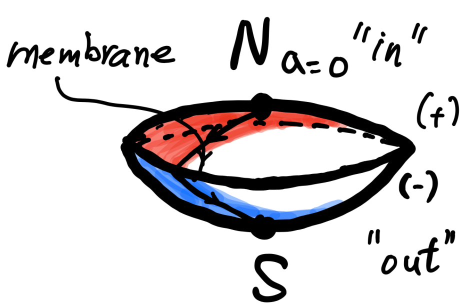
Comparison of Decay Rates



$$S_{\texttt{bounce}} \simeq \frac{27\pi^2}{2}\frac{\mathcal{T}_A^4}{(\Delta\Lambda)^3} \simeq 108\pi^2\frac{\mathcal{T}_A^4}{\kappa^6\mathcal{Q}_A^3} \qquad for \quad q>1$$

- Can easily overshoot $\Lambda = 0$ by approaching it and then being supplanted by another instanton that changes dS into AdS

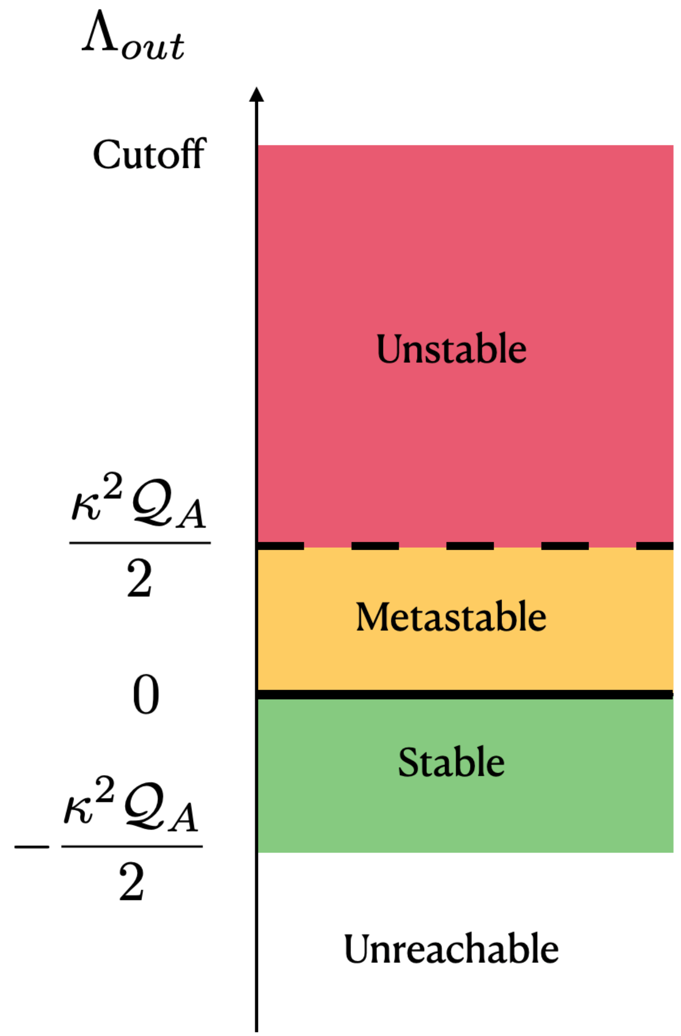
- Such a process does not exist for $q<1$



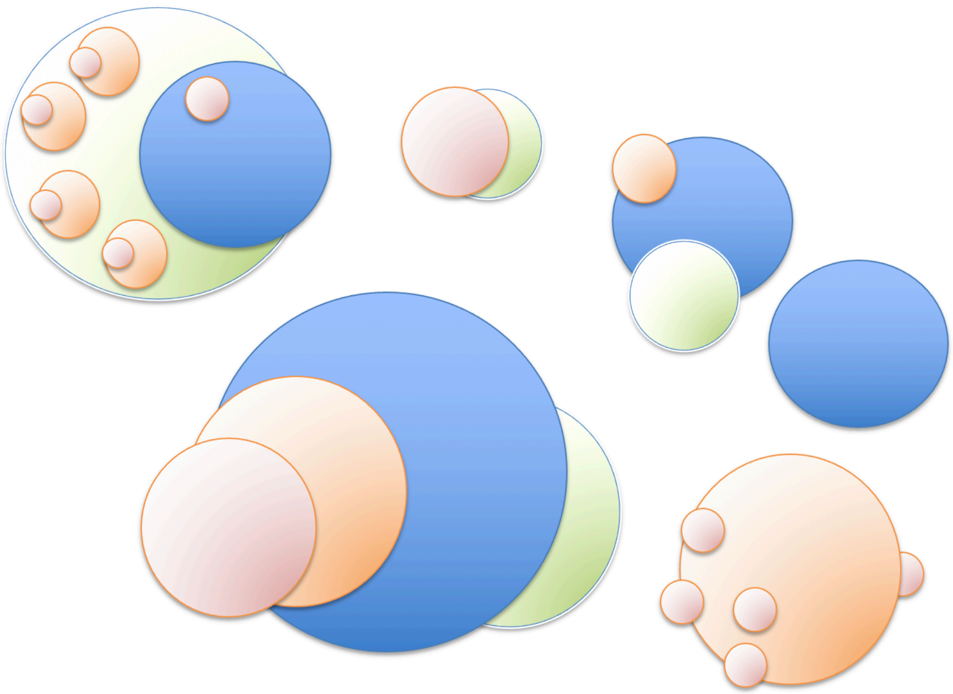
$$S_{\texttt{bounce}} \simeq \frac{24\pi^2\kappa_{\texttt{eff}}^4}{\Lambda_{out}}\left(1-\frac{8}{3}\frac{\kappa_{\texttt{eff}}^2\Lambda_{out}}{\mathcal{T}_A^2}\right) \qquad for \quad q<1$$

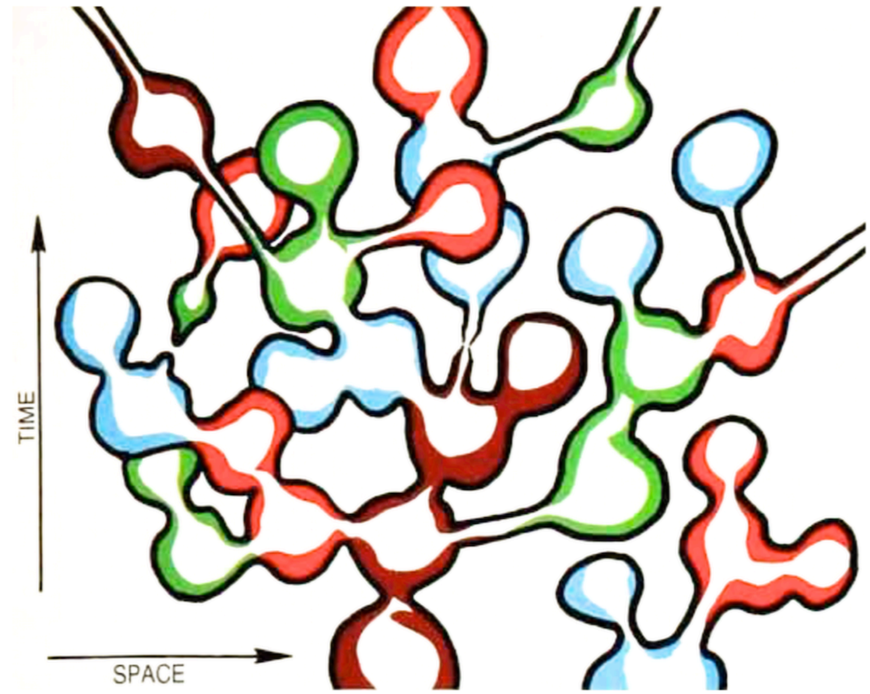
- Crucially in this case the parent dependence on Λ persists in the dS->AdS instanton too - this "brakes" the evolution

The Green Spectrum



Sic Transit Gloria Mundi





Cosmological Constant: No Problem!

- Define the problem first

$$\Lambda_{\texttt{total}} = \kappa^2\Big(\frac{\mathcal{M}_{\texttt{UV}}^4}{\mathcal{M}^2} + \frac{V}{\mathcal{M}^2} + \lambda\Big) \qquad \lambda = \lambda_0 + N\frac{\mathcal{Q}_A}{2} \qquad \kappa^2 = \kappa_0^2 + 2\mathcal{N}\mathcal{Q}_B$$

- So:

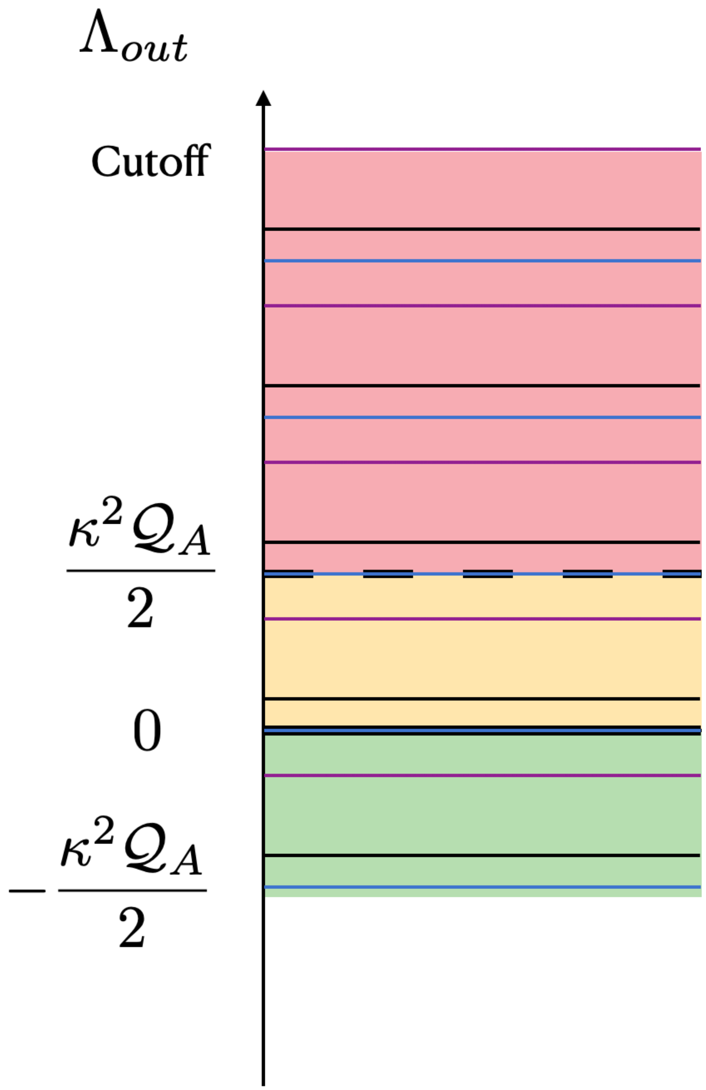
$$\Lambda_{\texttt{total}} = \big(\kappa_0^2 + 2\mathcal{N}\mathcal{Q}_B\big)\Big(\frac{\Lambda_0}{\mathcal{M}^2} + N\frac{\mathcal{Q}_A}{2}\Big)$$

- Thus the CC is unstable - BUT - to make it arbitrarily small eventually we must either take a tiny membrane charge or fine tune initial value

$$\big(\kappa_0^2 + 2\mathcal{N}\mathcal{Q}_B\big)\Lambda_0/\mathcal{M}^2$$

- This is the problem.

The Superselection Sectors in the Spectrum



Each color is a set of levels for a fixed superselection sector; they do not mix.

The Resolution: Add One More Charge

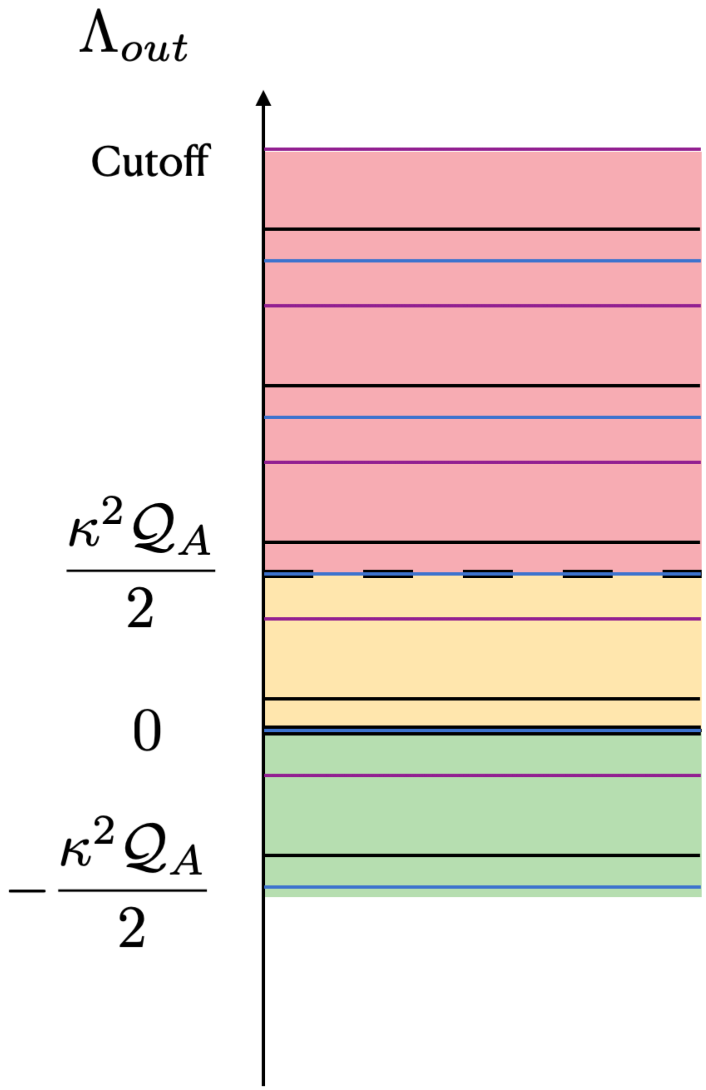
$$\mathcal{S} = S - \int d^4x\sqrt{g}\Big(\kappa^2\hat{\lambda} + \frac{\hat{\lambda}}{3}\epsilon^{\mu\nu\lambda\sigma}\partial_\mu \hat{\mathcal{A}}_{\nu\lambda\sigma}\Big) - \mathcal{T}_{\hat{A}}\int d^3\xi\sqrt{\gamma}_{\hat{A}} - \mathcal{Q}_{\hat{A}}\int \hat{\mathcal{A}}$$

$$\frac{\mathcal{Q}_{\hat{A}}}{\mathcal{Q}_A} = \omega \in \textbf{Irrational Numbers}$$

- As a result: $\Lambda_{\mathtt{total}} = (\kappa_0^2 + 2\mathcal{N}\mathcal{Q}_B)\Big(\frac{\Lambda_0}{\mathcal{M}^2} + \frac{\mathcal{Q}_A}{2}(N + \hat{N}\omega)\Big)$
- Here, $N, \hat{N}$ are any pair of integers; since the ratio of charges is irrational, $N, \hat{N}$ exist such that CC is arbitrarily close to zero!
- The idea is this is achieved by a long sequence of membrane nucleations/discharges where cc changes discretely from one to another, mediated by the `green' instantons, and continuing as long as CC is nonzero
- As CC approaches zero the nucleation rate becomes tiny since

$$S_{\mathtt{bounce}} \simeq \frac{24\pi^2\kappa^4_{\mathtt{eff}}}{\Lambda_{out}} \to \infty \quad \Rightarrow \quad \Gamma \to 0$$

Fine Structure of the Spectrum



Now all the superselection sectors mix together because there are two discharge channels and the CC=0 is the accumulation point since it is the only stable state in the spectrum

Approximate Density of States

- The evolution by discrete emissions realizes the density of states of the cosmological constant advocated by Hawking and Baum in 1984,

$$Z = \int e^{-S_E} \simeq e^{-S_{classical}} = \begin{cases} e^{24\pi^2 \frac{\kappa_{\tt eff}^4}{\Lambda}} = e^{\frac{A_{\tt horizon}}{4G_N}}\,, & \Lambda > 0\,; \\ e^{\Lambda \int d^4x \sqrt{g}} = 1\,, & \Lambda = 0\,; \\ e^{-|\Lambda| \int d^4x \sqrt{g}} \to 0\,, & \Lambda < 0\,, \quad \text{noncompact}\,. \end{cases}$$

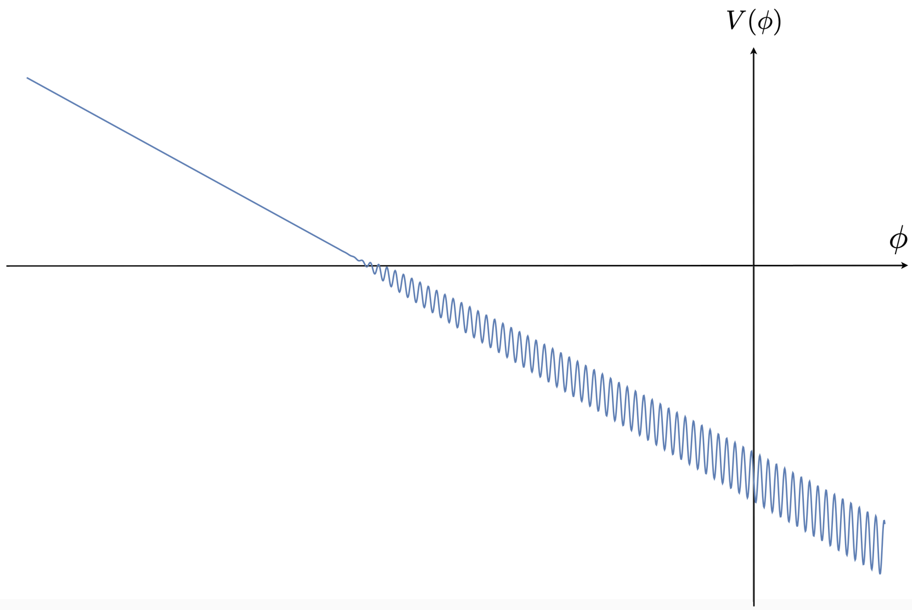
- This is in the leading order of the approximation which suffices here

- The conclusion is, that due to the imaginary ratio of charges and the evolution controlled by `green intantons' since $q < 1$

$$\frac{\Lambda}{\kappa_{\tt eff}^4} \to 0 \qquad \text{without anthropics!!!}$$

Abbott?

- With wisdom after the fact, this reminds one of Abbott 1985



- Abbot relaxed CC using a linear potential, with small bumps near the terminal value required to stop overshooting.
- However since the bumps were negligible at large values of CC his evolution was completely classical - so the field always dominated the geometry and generated the empty universe problem!
- We evade this problem since evolution is quantum Brownian drift and the terminal value is the asymptotic attractor!!!

Inflation?

- Because the evolution is by discrete jumps and CC=0 is the "semi-classical attractor" it is possible to have the jumps finish before the last stage of inflation, like in BP. There may also be interruptions that could yield observational signatures.
- It can also happen that a universe `restarts' itself by up-jumps; eg evolution brings it close to zero CC, and then a jump to a large value occurs; the universe recycles itself. In classical limit, this requires NEC violations, but in QM it is perfectly reasonable
- We do not have problems with wormholes etc in this order of approximation, since we have `stiff objects' (membranes) and gauge symmetries. This landscape is semiclassically safe; wormholes could still requires resolutions but this is true in any case.

Dark Energy?

- To have it be a CC we must fine tune since CC = 0 is the favored value. So what is it???
  - Transient quintessence?
  - A late stage phase transition?
  - The ratio of charges is a rational # but it is a fraction of two very large mutual primes - so a tiny value of CC exists but it is nonzero?
  - Even tho CC not zero seems unlikely, maybe using a different measure (than Hawking's) it is more likely; eg some argument related to inflation?
  - … ?

Summary

- GR IS A LANDSCAPE!
- In other words, properly understood, there is really infinitely many GRs and the one we use to describe the universe is an a posteriori fit. Each specific choice of parameters looks like a superselection sector, but dynamics induced by charges (fundamental, or “emergent”) mixes them up
- dS is unstable and decays to MInkowski - this is a good thing, since it can relax CC
- dS may be pretty long lived - a good thing too, inflation can work
- SM parameters may also be subject to such discrete variations, is there a connection?
- What is the UV completion/embedding into “proper” QG?

MERCI!