The Cosmological Constant and the String Landscape

KITP Conference on Superstring Phenomenology

Aug. 28, 2006

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Why the cosmological constant problem is hard…

Three problems:

1. Why is ρ_Λ not large?
2. Why is ρ_Λ not zero?
3. Why does ρ_Λ have the same order of magnitude as the matter energy *today*? (Cosmic coincidence)

Why the cosmological constant problem is hard…

Two classes of solution:

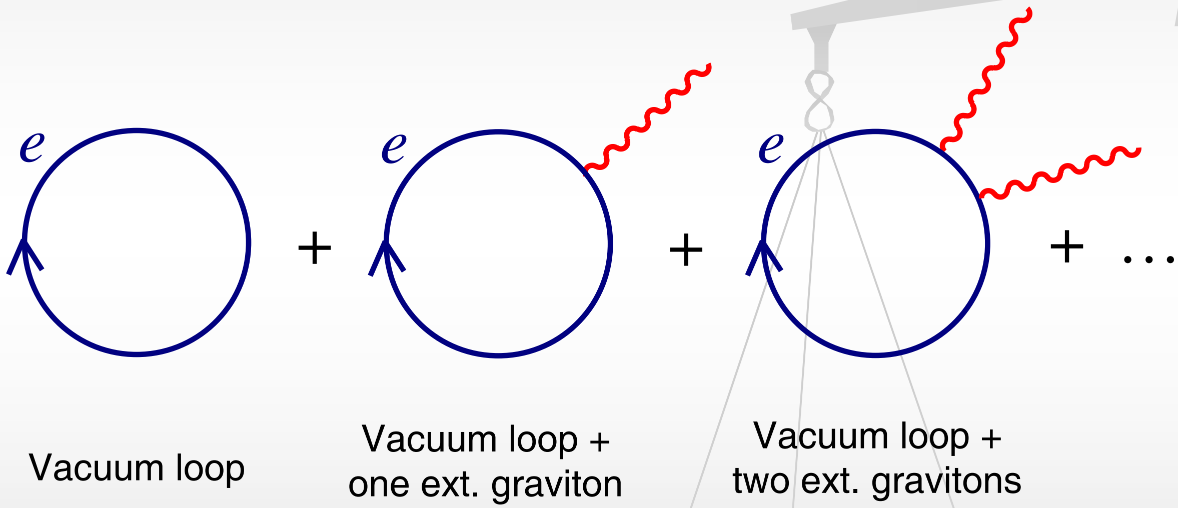
1) Those where the low energy effective theory (including the vacuum energy) is uniquely determined by the underlying theory.

2) Those where it is not unique determined, but adjustable in some way.

A litmus test for `unique' models

Stuff gravitates, and the vacuum is full of stuff.

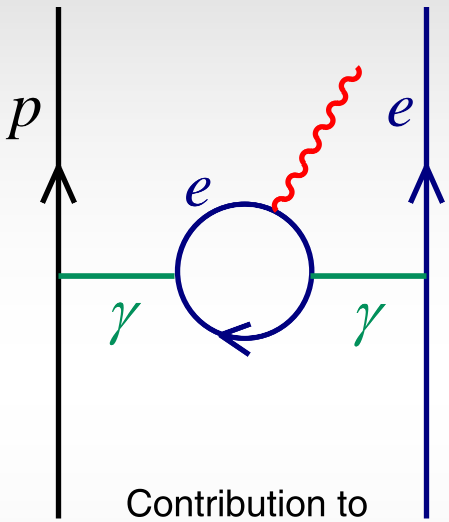
E.g., Electron zero point energy, up to scale *M*, e.g. 1 TeV.



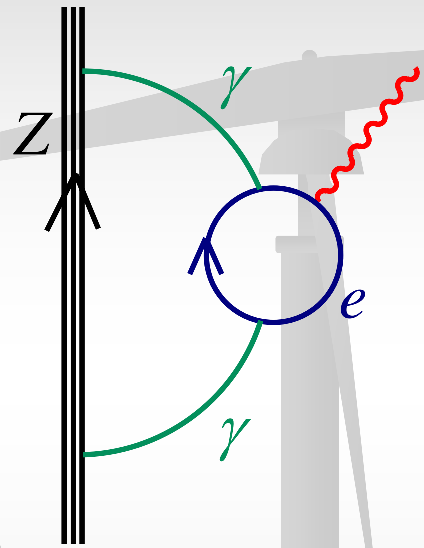
$$= \rho_\Lambda \sqrt{-g}$$

$$\rho_\Lambda = O(m_e^4 \ln M/m_e) + O(m_e^2 M^2) + O(M^4)$$

Moreover, we know that virtual electrons must gravitate (to accuracy 1 part in 10^6):



Contribution to Lamb shift



Electrostatic energy of nucleus, loop corr.

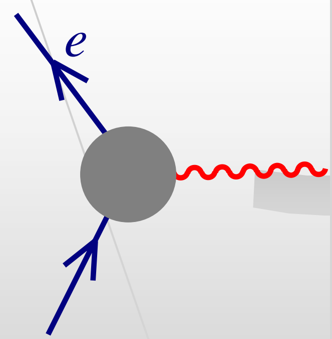
What is special about our vacuum, as compared to these environments? And, what about more symmetric states such as the $SU(2)$ x $U(1)$ symmetric state, for which the electron ZPE is different.

Example: `Technigravity' (Beane, Sundrum, Moffat, …)

What if gravity were composite at a 100 microns --- wouldn't this cut off the loop and produce $\Lambda \sim (100\ \mu)^{-4}$, just the right value?

No! We measure the c.c. with very long wavelength gravitons, not micron gravitons, and we already know (Lamb shift, nucleus) that these couple to virtual electrons.

Cf. effective vertex:
For c.c. the electron is off shell, not the graviton.



Other possibilities:

- OK, if we are measuring the c.c. with gravitons of cosmic wavelengths, can't we fix the problem by modifying gravity at very long distance?

  No: TeV scale c.c. gives centimeter scale curvature, we would have to modify gravity on *all* scales from cm to horizon. (cf. Arkani-Hamed, Dimopoulos, Dvali & Gabadazde).

- Holographic cutoff? Is there a consistent rule? Anyway, holography doesn't seem to work this way. E.g. for black holes, EFT gets energy densities right, holography shows up only in subtle phase correlations.

- An idea that might pass: $E \to -E$ symmetry, either exact (Linde) or approximate, not applying to gravity (Linde, Kaplan & Sundrum). Also, 't Hooft & Nobbenhuis …

Adjustable/environmental models:

Unimodular gravity.
Four-form potentials.
Wormholes.
Scalar potentials with many minima, or very long very flat potentials.
The string landscape.*
Self-tuning.
Explicit tuning.

Values of Λ are continuous or dense.

Note: $\Lambda = 0$ is not a minimum or special point in the distribution (else revert to earlier case).

Q: What is the adjustment principle?

Dynamical adjustment mechanisms

There are several mechanisms that appear to favor adjustment to a zero or small positive ρ_Λ:

Hartle-Hawking wavefunction: $|\Psi|^2 = e^{3/8G^2\rho_\Lambda}$

de Sitter entopy: $e^S = e^{3/8G^2\rho_\Lambda}$

Coleman-de Lucchia: tunnelling suppressed as $\rho_\Lambda \to 0^+$

Common problem: the empty universe. In our universe, ρ_Λ became dynamically `visible' only in the very recent past; it would have been dynamically negligible e.g. before nucleosynthesis. General problem: to measure the c.c. we need large volumes and times, and by then it is far too late.

Also applies to `static solution' selection.

Many of the attempted dynamical solutions succeed in populating states with all possible values of the vacuum energy, either sequentially in time, in distant patches of space (e.g. eternal inflation), or in branches of the wavefunction.

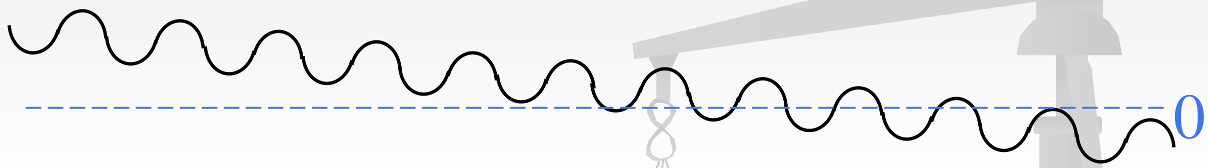
But this is all that is needed! Any observer in these theories will see a cosmological constant that is unnaturally small: in order to have any complex system one must have many `cycles' and many `bits'.

Solves the first c.c. problem, and solved second and third c.c. problems before they were even known to be problems (Banks 1984, Weinberg 1987).

• Additional dynamical selection may be present, but are not needed (and might spoil cosmic coincidence), at least as long as only the c.c. is varied…

Three recent ideas

1. **Steinhardt & Turok:** start with Abbott potential,



Due to Coleman-De Luccia effect, system can (for some parameter regimes) spend almost all its time in lowest positive minimum.

It takes a very long time to reach this minimum (empty universe problem) but then the cyclic universe can refill it!

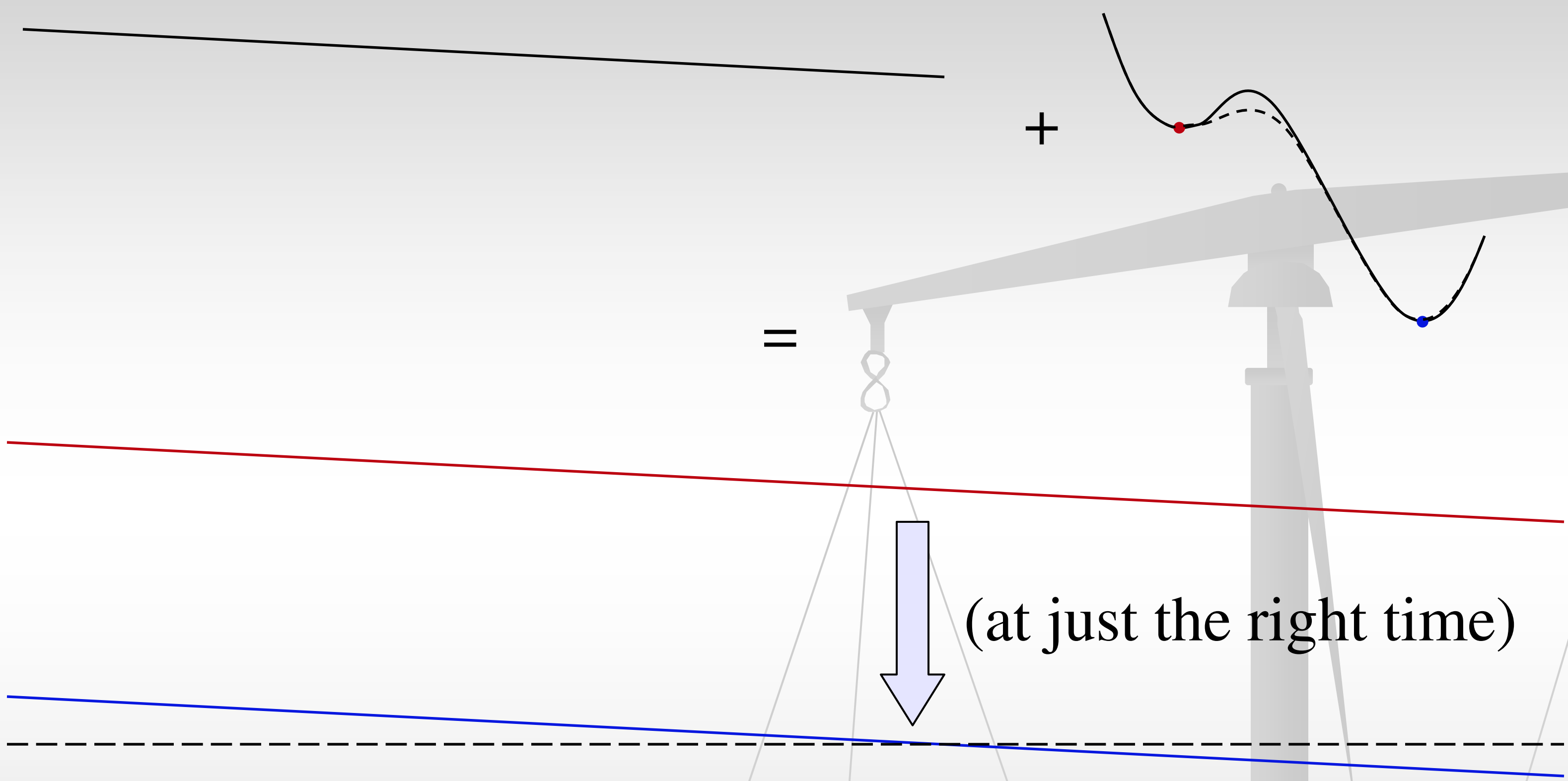
Steinhardt-Turok vs. Anthropic Landscape

1. Is the potential plausible?
   ST: Tiny steps ($\sim\Lambda_{now}$) might come from deep throat, but need many ($O(10^{60})$) steps to cancel Λ_{SM}: problematic.
   AL: Agrees with current understanding of string theory.

2. Is the cosmological dynamics plausible?
   ST: Ekpyrotic bounce is problematic (but still open).
   AL: Inflation + tunneling: ordinary physical processes.

3. Third c.c. problem?
   ST: Total coincidence.
   AL: Correct to 1 order of magnitude out of 120.

2. Itzhaki: two fields (slow roller and inflaton),



Banks (1984): Anthropic timing (didn't work?)

Itzhaki (2006): Classical fine tuning gives correct timing, stable against SM vacuum corrections!?!

3. Vilenkin: The Weinberg calculation requires $O(10^{120})$ vacua (less with SUSY) in order to have one likely in the allowed range. It assumes that the vacua all have equal probability, as seems to follow from the fact that $\Lambda=0$ is not a special point. However, some attempts to assign a measure to eternal inflation give an enormous *irregular* fluctuation that depends on the rate to tunnel into and out of a given bubble, so we are much more likely to find ourselves in a rare galaxy outside the anthropic range. (Also Steinhardt and Turok).

• Weinberg argument still works, but needs many more vacua.

• Depends on the measure for eternal inflation… there are large numbers of vacua, large spacetime volumes, large tunneling factors: do any of these really enter?

General lessons

#1: Compactifications of simple topology probably do not give enough vacua, need $O(100)$ handles.

Brane models may depend little on global structure, but what about e.g. heterotic? Are there any simple ways to think about manifolds with many handles, are there any general signatures?

#2: Stability: A generic non-SUSY compactification will decay in time $O(1)$ in Planck or other short-distance units. In our vacuum the decay amplitude e^{-B} (per spacetime volume) is less than e^{-550} in Planck units, and the number of decay channels is large (e.g. flux on each handle can decay).

Surprisingly, it does not seem so hard to stabilize *all* these decays. E.g. in KKLT most are stabilized by being close to supersymmetric AdS spaces ($B \propto 1/|w_0|^2$). In other solutions they may be stabilized by large volume of cycles (e.g. Balasubramanian, Berglund, Conlon & Quevedo) or weak coupling. So this is not so restrictive, but it does say that that our vacuum is likely close to one where we can calculate.

Conclusions

- All problems will be solved by later speakers.