The Evolving Cosmological Constant (Problem)

N. Itzhaki, (PU)

PiPT 2006

Outline

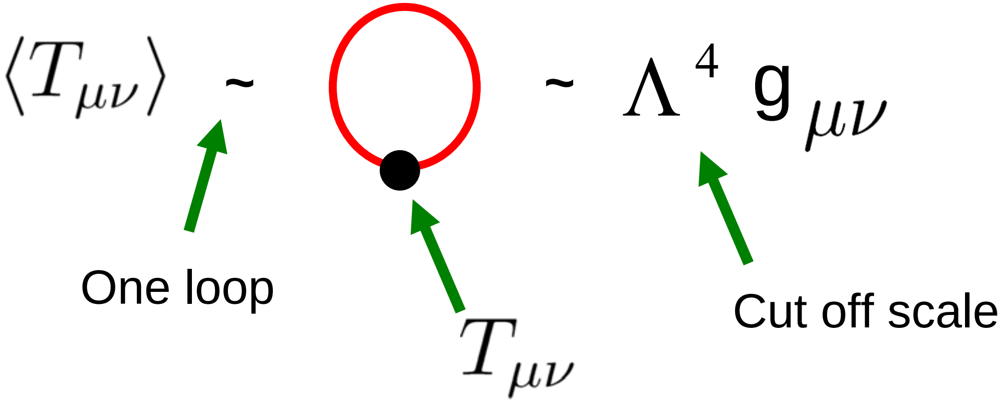
- The CC problem: then and now (experimental hints).
- Abbott's model (85).
- Abbott's model → string landscape + anthropic principle.
- Abbott's model → bungee jumping model.

The CC problem used to be a simple problem

The CC problem used to be a simple problem… to state:

Why is the CC vanishing?
The CC term is a relevant term that receives large quantum corrections:

Lorentz invariance + dim. analysis give



$$\langle T_{\mu\nu}\rangle \sim \bigcirc \sim \Lambda^4 g_{\mu\nu}$$

The goal was to find a way to get 0.

The CC problem seems to have little to do with particle physics and more to do with deep issues in quantum gravity.

- Old proposals to solve the CC problem:

1- Hawking’s wave function of the universe (most likely to have vanishing CC).

2- Coleman’s wormholes.

…

- Particle physics does not help much:

SUSY, that helps in a similar problem with the Higgs mass, gives at best

$$\Lambda^4 \sim (TeV)^4 \sim 10^{-60}$$

which is 10^{60} times larger than the total energy density in the universe.

The CC problem and IR

Suppose that we don’t quantized gravity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \langle T_{\mu\nu} \rangle$$

We still have the CC problem due to field theory loops.

The CC problem and IR

Suppose that we don’t quantized gravity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \langle T_{\mu\nu} \rangle$$

We still have the CC problem due to field theory loops.

- Two ways to think about this:

1- This is another reason why gravity must be quantized.

2- A clue that the CC problem is not a deep quantum gravity issue.

The CC problem and IR

Suppose that we don’t quantized gravity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \langle T_{\mu\nu} \rangle$$

We still have the CC problem due to field theory loops.

- Two ways to think about this:

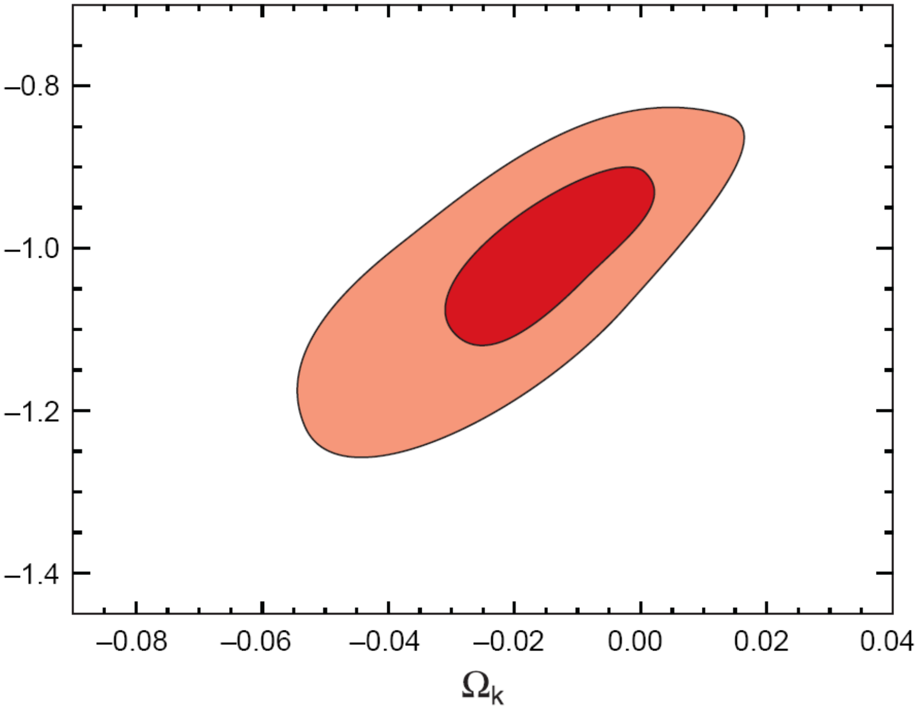
1- This is another reason why gravity must be quantized.

2- A clue that the CC problem is not a deep quantum gravity issue.

Luckily, more useful experimental hints have emerged.

1st clue: The universe is currently accelerating:

$$\frac{p}{\rho} =$$



(from WMAP3)

Agrees with dark energy as a cosmological constant.

Agrees with a flat universe.

- The bad news is that the CC problem evolved into three problems:

1- Why is the CC so small (in particle physics units)?

2- If so small why not zero?

3- Why now? Roughly when galaxies were formed the CC is of the order of the matter energy density in the universe.

- The bad news is that the CC problem evolved into three problems:

1- Why is the CC so small (in particle physics units)?

2- If so small why not zero?

3- Why now? Roughly when galaxies were formed the CC is of the order of the matter energy density in the universe.

- The good news is that we have a scale, $10^{-3}\, eV \sim 10^{-30}$ to work with.

Examples:

1- $\frac{(\mathrm{Tev})^2}{M_p} = 10^{-3} eV$ perhaps related to UV / IR mixing. (…, Banks, …)

2- Fifth force modification to gravity is not ruled out at $10^{-3} eV$.

⬇

Fat Gravity. (Beane; Sundrum)

3- Neutrinos: (Farbon, Nelson, Weiner)

Basic idea: promote the neutrino mass to a field.

$$V = m_\nu n_\nu + V_0(m_\nu).$$

The e. o. m. is $V' = n_\nu + V_0'(m_\nu) = 0.$

$$w + 1 = -\frac{V'(m_\nu)}{V m_\nu} = \frac{\Omega_\nu}{\Omega_\nu + \Omega_{DE}}$$

that is almost 0.

Does not address the CC problem.

2nd clue is Inflation

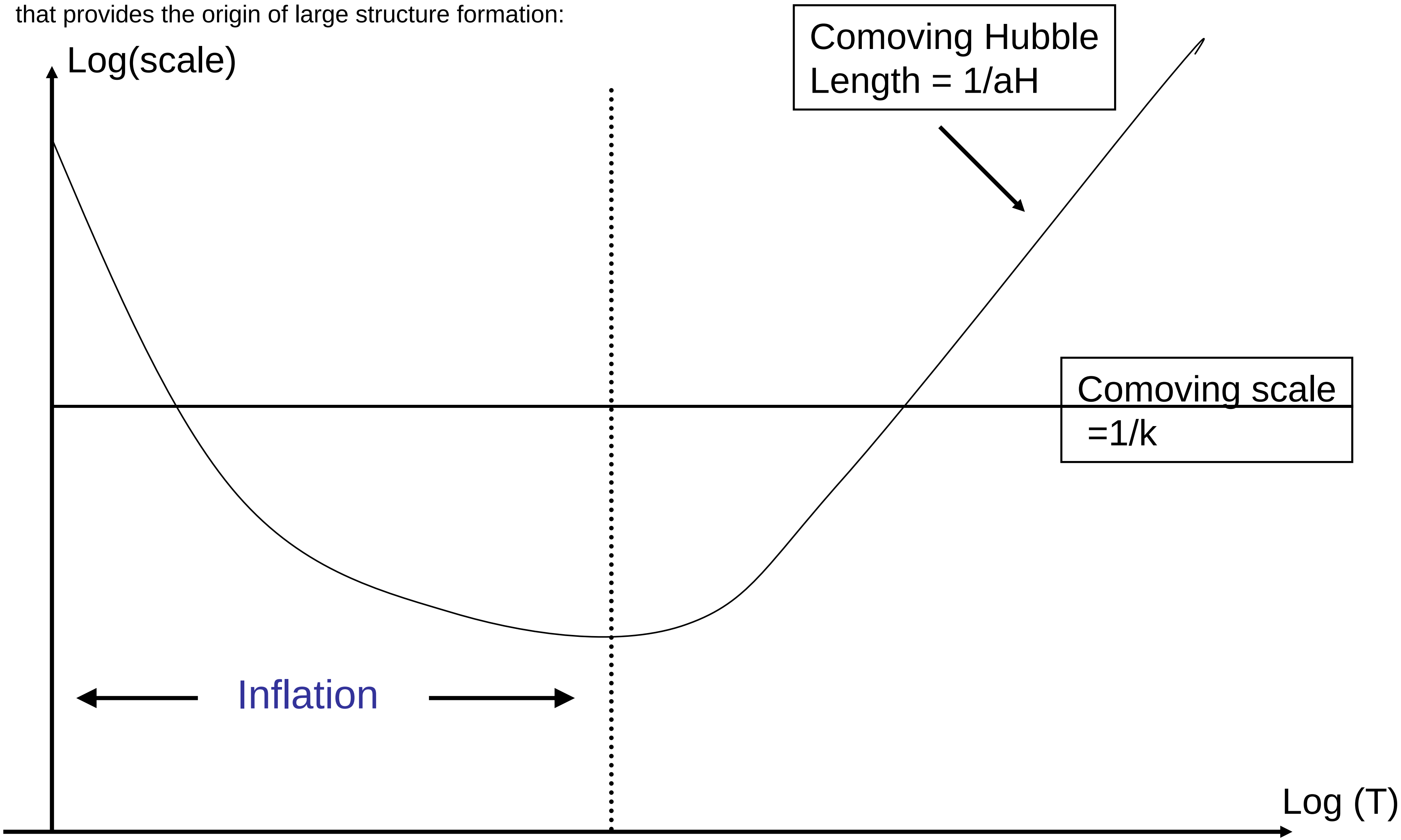
Originally was considered to be a wild idea designed to solved some problems (horizon, flatness, monopoles in GUT) in the big-bang model.

Now believed to be a crucial part in the modern “standard model” of cosmology that provides the origin of large structure formation:

2nd clue is Inflation

Originally was considered to be a wild idea that solved some problems (horizon, flatness, monopoles in GUT) with the big-bang model.

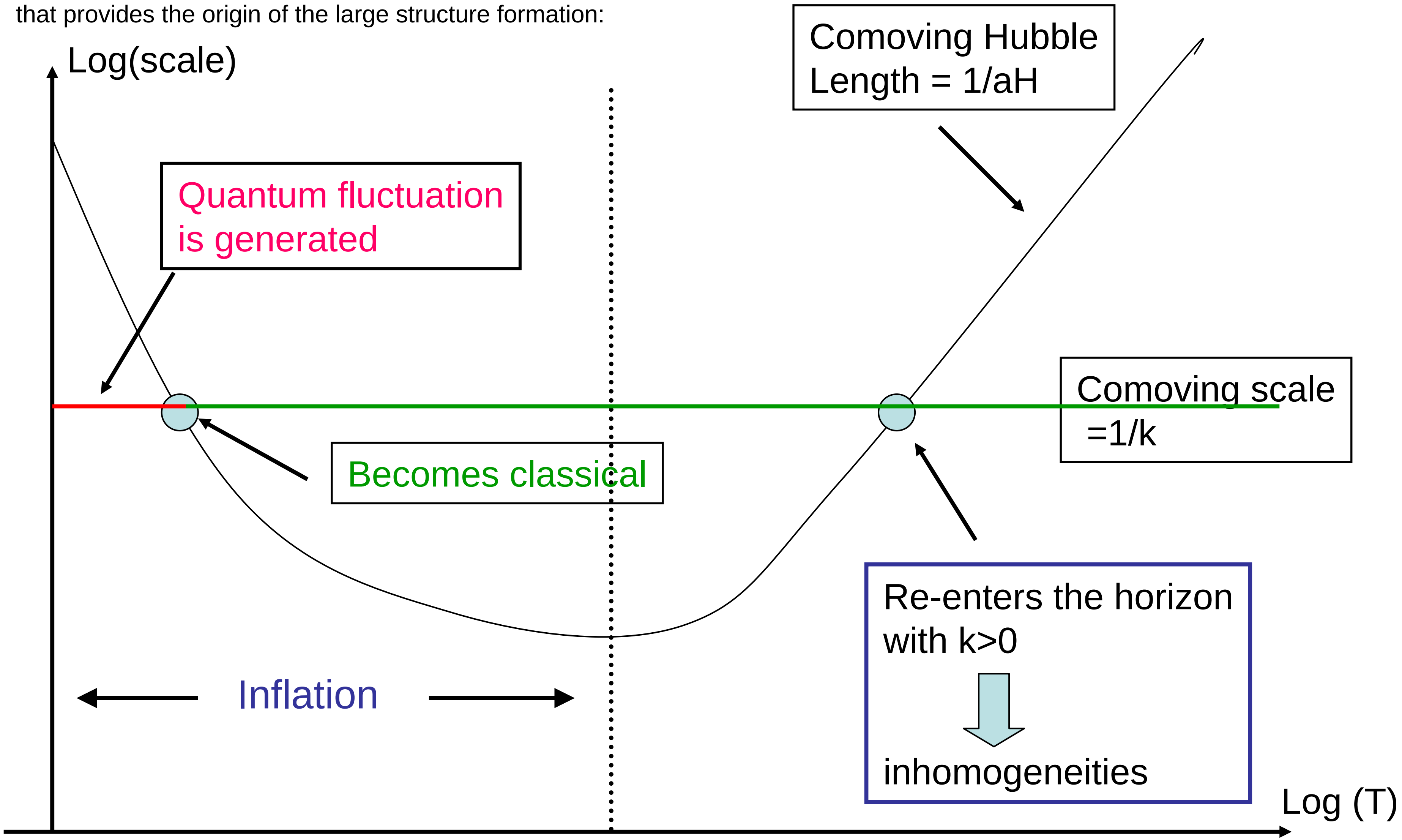
Now believed to be a crucial part in the “standard model” of cosmology that provides the origin of large structure formation:



2nd clue is Inflation

Originally was considered to be a wild idea that solved some problems (horizon, flatness, monopoles in GUT) with the big-bang model.

Now believed to be a crucial part in the “standard model” of cosmology that provides the origin of the large structure formation:



Log(scale)

Comoving Hubble Length = 1/aH

Quantum fluctuation is generated

Comoving scale =1/k

Becomes classical

Re-enters the horizon with k>0

inhomogeneities

Inflation

Log (T)

- Reasons to believe in inflation:

1- Hard to come up with alternatives to inflation.
2- WMAP3 seems to give direct evidence for inflation.

- Reasons to believe in inflation:

1- Hard to come up with alternatives to inflation.

2- WMAP3 seems to give direct evidence for inflation.

- Still we don’t know much about the details of inflation. In particular, we don’t even know the order of magnitude of value of the vacuum energy during inflation:

From nucleosynthesis we know for sure that

$$(10\ \mathrm{MeV})^4 < V_{\mathrm{inflation}}$$

Very reasonable to put a tighter bound

$$(10^2\ \mathrm{Gev})^4 < V_{\mathrm{inflation}} < (10^{16}\ \mathrm{Gev})^4$$

Baryogenesis

Slow roll + $\frac{\delta\rho}{\rho} \sim 10^{-5}$

- Most models assume large scale inflation, because COBE normalization gives

$$\frac{V^{3/2}}{V'} = 5.2 \times 10^{-4} \quad \Longleftrightarrow \quad V \sim \epsilon \, (10^{17} GeV)^4$$

where $\epsilon = \left(\frac{V'}{V}\right)^2$ is a slow roll parameter that should be smaller than 1.

How much smaller can it be?

- Most models assume large scale inflation, because COBE normalization gives

$$\frac{V^{3/2}}{V'} = 5.2 \times 10^{-4} \quad \Longleftrightarrow \quad V \sim \epsilon \left(10^{17} GeV\right)^4$$

where $\epsilon = \left(\frac{V'}{V}\right)^2$ is a slow roll parameter that should be smaller than 1.

How much smaller can it be?

- Currently there is no experimental evidence for this assumption.

- Detection of tensor fluctuations could fix $V_{\text{inflation}}$:

$$r \equiv \frac{\text{Tensor fluctuations}}{\text{Scalar fluctuations}} \sim 10\epsilon$$

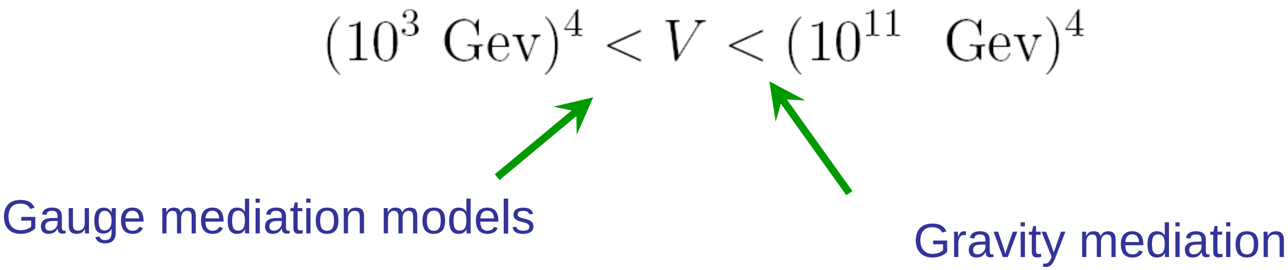
$$\Downarrow$$

Tensor fluctuations at large scale inflation.

The reason inflation can be viewed as a hint for the CC problem is that it is a reasonable to assume that there was no CC problem during inflation.

Loop corrections to the CC are within the inflation range:

In TeV SUSY theories the natural range of the vacuum energy is



$$(10^3 \ \mathrm{Gev})^4 < V < (10^{11} \ \ \mathrm{Gev})^4$$

Gauge mediation models

Gravity mediation

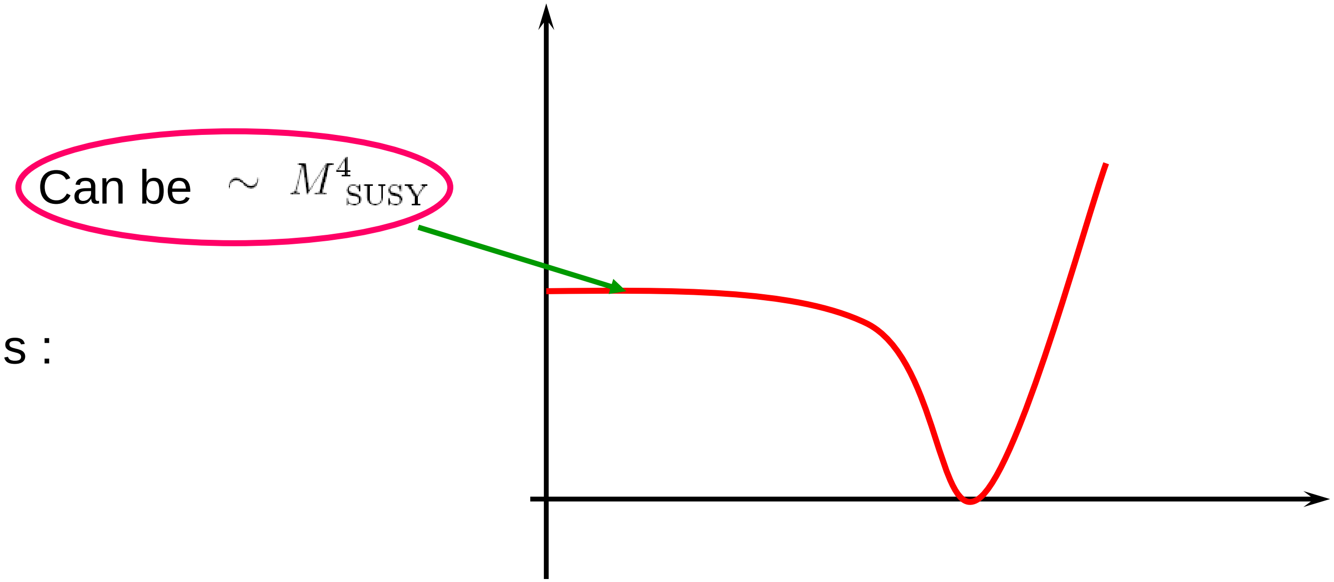
Which is within the inflation range

$$(10^2 \ \mathrm{Gev})^4 < V_{\mathrm{inflation}} < (10^{15} \ \ \mathrm{Gev})^4$$

- This assumption does not solve the CC problem, but if true it changes its nature:

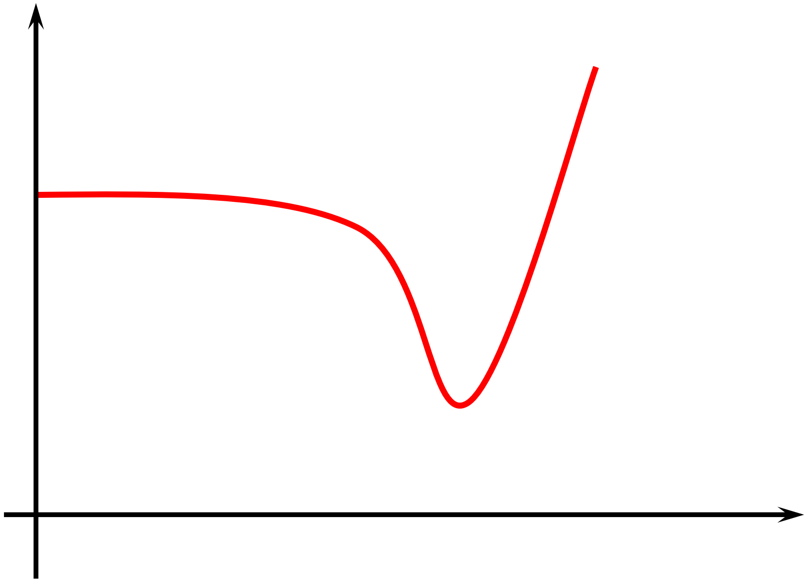
The question is now: why is the ratio of the vacuum energy during inflation to the current vacuum energy so large and yet not infinite?

Why it is :



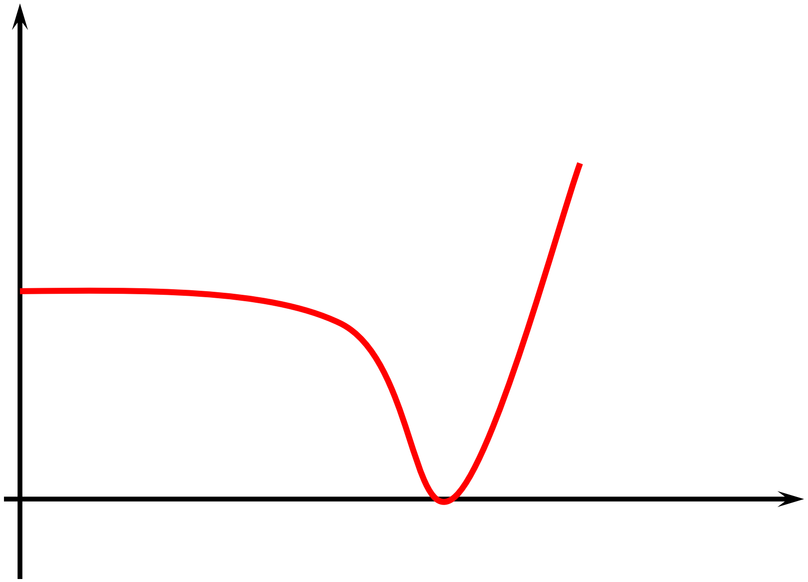
Can be $\sim M^4_{\text{SUSY}}$

and not

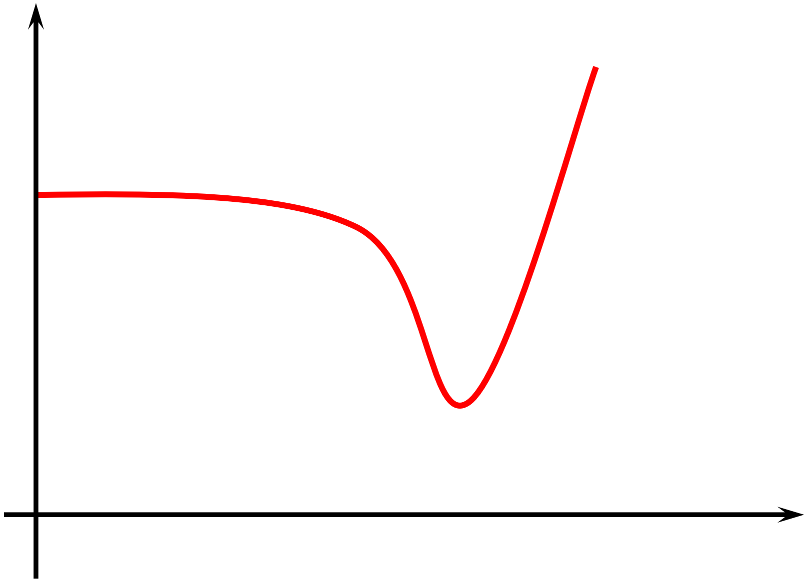


The question is: why is the ratio of the vacuum energy during inflation to the current vacuum energy so large and yet not infinite?

Why it is :



and not



The good thing is that we have to do it only once:

Temperature driven phase transitions (like the EW or QCD) will not change the vacuum energy.

Both clues might be misleading:

1st clue: The CC might not be a constant (quintessence).

2nd clue: The inflation energy scale need not be the SUSY scale.

Both clues can be misleading:

1st clue: The CC might not be a constant.

2nd clue: The inflation energy scale need not be the SUSY scale.

- In the rest of the talks I'll describe two approaches to the CC problem that take advantage on these clues:

  1- Antropic principle + string landscape uses mostly clue 1.

  2- The bungee jumping model uses mostly clue 2.

- Before we do that let's recall an old approach to the CC problem due to Abbott that can be viewed as the starting point to the more recent approaches.

Abbott's Model (85)

The action is $-\frac{1}{2}(\partial\phi)^2 + \epsilon\phi + \frac{1}{16\pi^2}\frac{\phi}{f}\mathrm{Tr}(F \wedge F)$

Instantons induce a potential: $V = \epsilon\phi + M^4 \cos(\phi/f) + V_{ren}$

The renormalized CC term

When $\epsilon = 0$ we have the symmetry $\phi \to \phi + 2\pi n f$

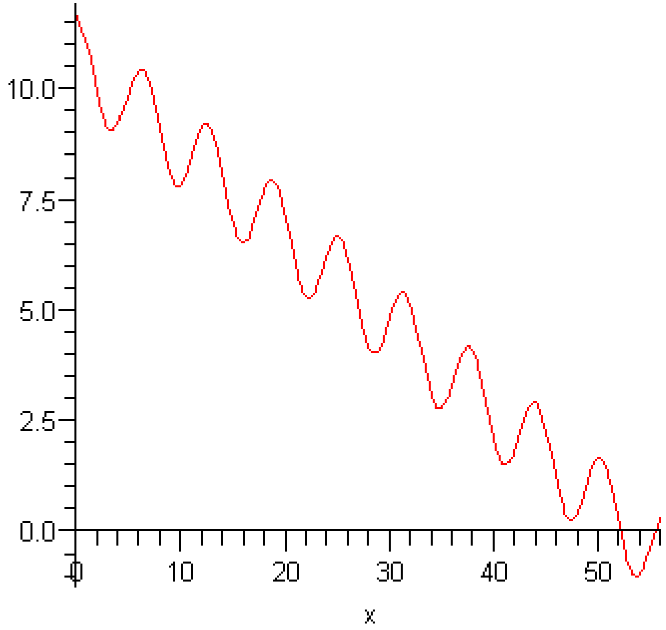
$$\Downarrow$$

$|\epsilon| \ll 1$ is technically natural. (similar to the mass of the electron)

- Small M is natural.

⇓

Also at the quantum level
the potential looks like:



- In quantum mechanics the local minima are on equal footing.

- Here the situation is more interesting:

Hawking temperature in de-Sitter is $T_H \sim \sqrt{V}$.

⇓

- For $V > M^2$ in effect there are no local minima.

- For $V < M^2$ we have tunneling.

The decay rate is $\Gamma \sim M^4 \exp(-1/V)$ ⇒ Most of the time at small CC.

↳ Regardless of $V_{\rm ren}$ we end up with a small CC

Regardless of $V_{\rm ren}$ we end up with a small CC

Unfortunately, we also end up with an empty universe.

This is known as the emptiness problem that appears also in other approaches to the CC problem.

We'll describe two different ways to address this emptiness problem.