Abbott model → string landscape + anthropic principle

- The anthropic principle can solve the emptiness problem in a rather trivial way:

No intelligent life in an empty universe.

- For this to happen the model has to be complicated enough:

There should be at list one trajectory that gives small CC in a hot universe.

- Abbott's model isn't complicated enough since there is only one trajectory.

↓

Abbott + anthropic reasoning = nothing

Anthropic principle and effective field theory reasoning

Life is an IR effect. IR physics by definition is most sensitive to relevant operators

↓

Anthropic principle is:

- Relevant for relevant operators.
- Marginally relevant for marginal operators.
- Irrelevant for irrelevant operators.

Anthropic principle and effective field theory reasoning

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Anthropic principle is more relevant for the CC problem than the θ_{QCD} problem.

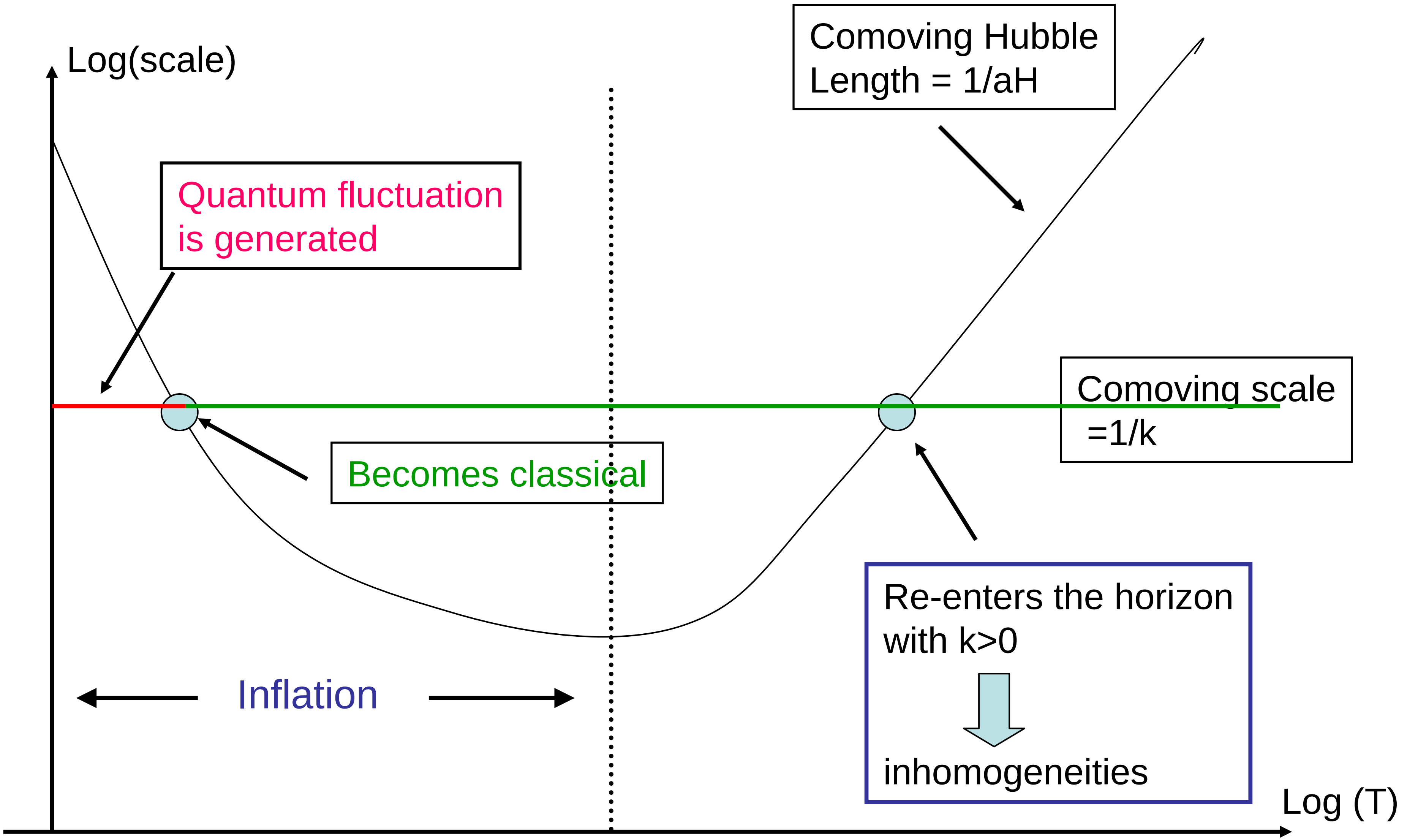
A common criticism: anthropic reasoning does not lead to any predictions.
However, back in 1987 Weinberg used anthropic reasoning to argue that the CC is

1- Small.
2- No vanishing.
3- Of the order of the matter energy density today.

Addressed all three CC problems when it was believed that there is only one!

- Weinberg's argument in short:

The CC has to be small enough to allow for structure formation, which is necessary for intelligent life.



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)

In a bit more details:

We know of structure formation at $Z \sim 4$ and that $\rho_m(Z = 4) = (1 + 4)^3 \rho_0$

The anthropic bound on the CC is at $\rho_v \sim (10 - 100)\rho_0$.

- A bit larger than the observed value but not exponentially larger.

In fact, might be smaller if we knew the “measure” of CC distribution.

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The anthropic bound on the CC is at $\rho_v \sim (10-100)\rho_0$.

• A bit larger than observed value but not exponentially larger.

• Leads to a prediction on quantum gravity:

There must be many (meta) stable solutions near zero CC.

• Possible with many fields, since the sum of many (positive and negative) numbers of order 1 can be much smaller than 1.

No need to correlate SUSY breaking scale with CC.

Does string theory have this property?

Not in 10/11 D.   What about 4D?

Two steps process to see that the answer might be “yes”:

1. Abbott → Brown and Teitelboim

A 4-form contribution to the action shifts the value of the CC:

The solution $F^{\mu\nu\rho\sigma} = c\epsilon^{\mu\nu\rho\sigma}$ gives an extra contribution to the CC

that scales like c^2.

Membrane nucleation reduces the CC just like in Abbott’s model.

- However, just like in Abbott the BT model is not complicated enough.

↓

BT + anthropic reasoning = nothing

- On top of the emptiness problem there is the gap problem: the charge of the membrane should be exponentially small.

2. Brown and Teitelboim → Bousso and Polchinski

The advantage of the BT model is that it can be realized in M-theory compactifications.
In fact we find J=1+N fluxes where N is the number of 3-cycles.

The J membranes in 4D: 1 M2 brane + N M5-branes that wraps a 3-cycles.

The CC is shifted in a more complicated fashion: $\lambda = \lambda_{\text{bare}} + \frac{1}{2}\sum_{i=1}^{J} n_i^2 q_i^2$

- Now that the model is more complicated (J –dimensional space)

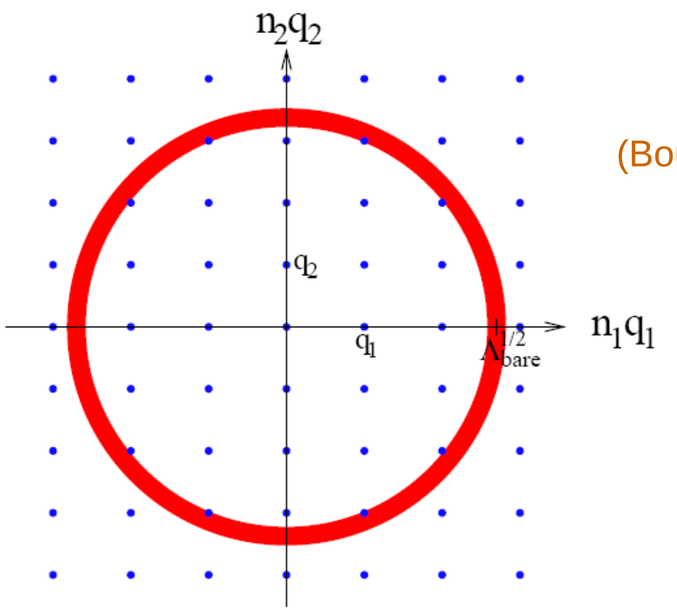
?

BP + anthropic reasoning = something

The gap problem is solved since there is no need for exponentially small charges:

we need to have $2|\lambda_{\rm bare}| < \sum_{i=1}^{J} n_i^2 q_i^2 < 2(|\lambda_{\rm bare}| + \Delta\lambda)$, which looks like

10^{-120}



(Bousso, Polchinski)

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With reasonably small charges need only J ~ 100.

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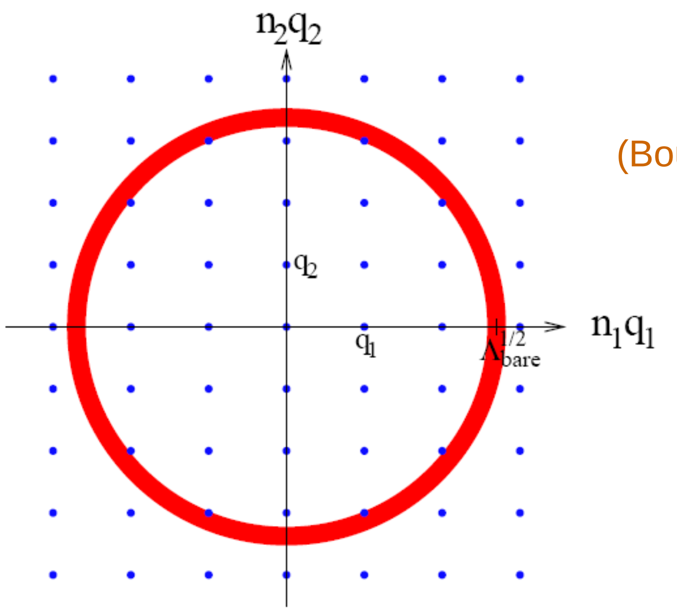

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Ex: Show this

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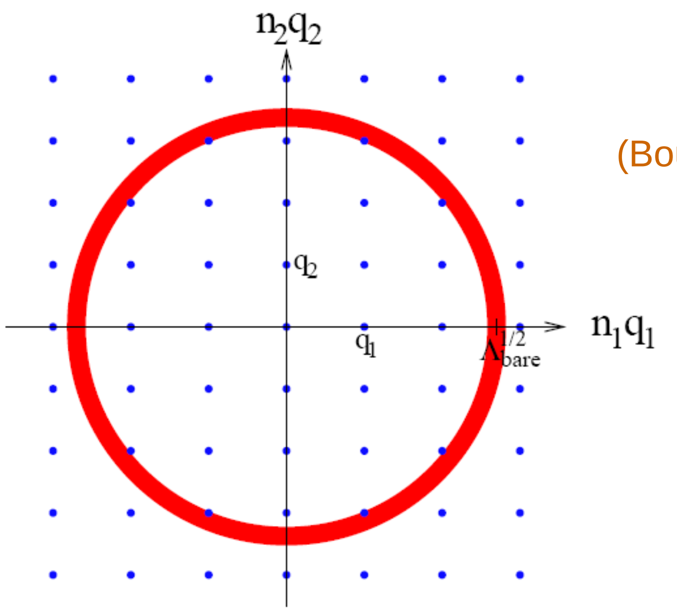

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With reasonably small charges need only J ~ 100.

What about the emptiness problem?

- In principle: no obstruction to solve the emptiness problem because, unlike in Abbott's model, the last drop in the vacuum energy is large.

- In practice: not known.

What about the clues?

1st clue: Antropic principle by itself does not imply a constant dark energy.

Current stringy ideas (KKLT) seems to imply that.

• No use of $\frac{(\mathrm{Tev})^2}{M_p} = 10^{-3} eV$.

2nd clue: Need inflation (or something like inflation) to generate large structure.

But, no need for a relation between SUSY and inflation scales.

• Main difficulty is that to make further progress we need detailed a knowledge of the landscape in regions that are relevant for our world while current techniques are valid in other regions.

• Hard even in field theory (K. Intriligator's talks):

We want

$$\Lambda_{QCD} < M_{SUSY}$$

But long lived when

$$\Lambda_{QCD} \gg M_{SUSY}$$

Is it possible that there is some effective field theory that takes advantage of BP approach to the emptiness problem?

In particular, last drop in energy is large.

Abbott model → The Bungee Jumping model

Let's modify Abbott's model in the following way:

$$S = S_{EH} \; + \; S_{\rm relaxation} \; + \; S_{\rm inflation}$$

The relaxation action is a simpler version of Abbott's action

$$S_{\rm relaxation} = \int d^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\psi)^2 - V_{\rm ren} - V(\psi)\right)$$

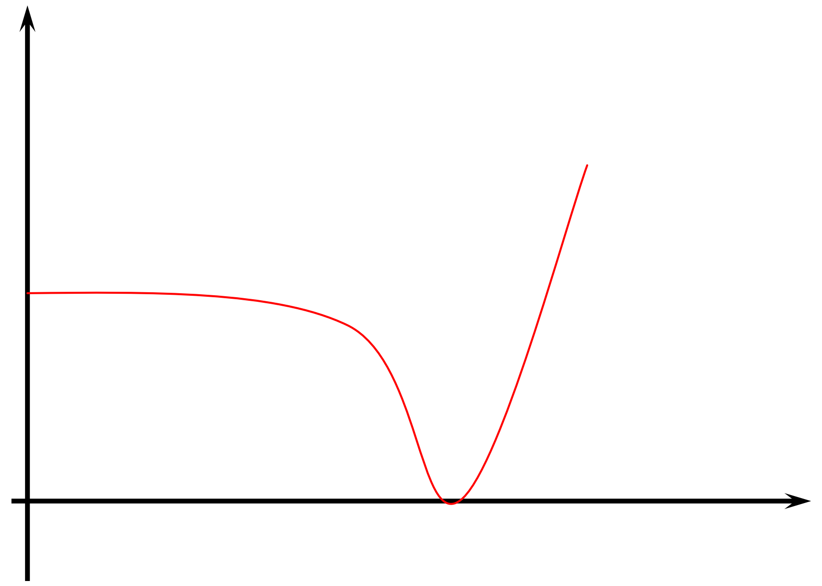
where $V(\psi) = \epsilon\,\psi$.

Much like in Abbott's case the vacuum energy is reduced slowly.

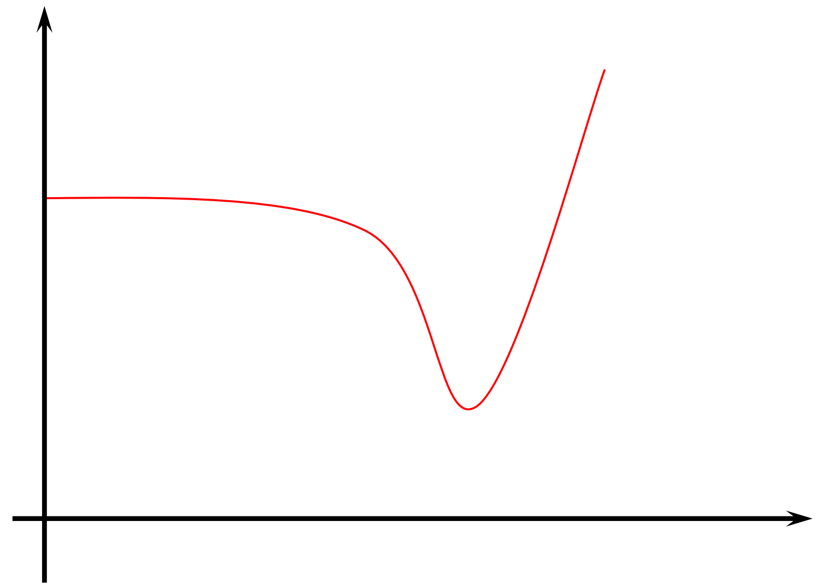
The challenge is to evade the emptiness problem by converting the potential energy into kinetic energy.

$S_{\rm inflation}$ is designed to fix that while making sure that the vacuum energy at the end of inflation is small.

That is $S_{\text{inflation}}$ makes sure that we have



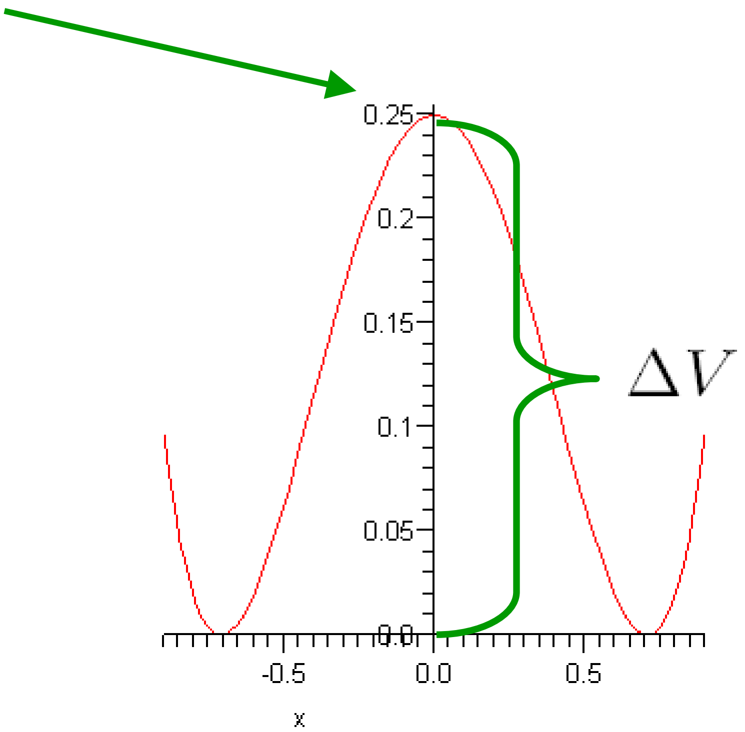
and not



We take $S_{EH} + S_{\text{inflation}} = \int d^4x\sqrt{-g}\left[\frac{1}{2}e^{-\phi^2}R - V(\phi)\right] + \int d^4x\mathcal{L}_{kin}$

The potential is designed to have the following properties:

$\gamma \equiv -\left.\frac{d^2V(\phi)}{d\phi^2}\right|_{\phi=0} > 0$ and $\Delta V \equiv V_{max} - V_{min} = \frac{\gamma}{4}$



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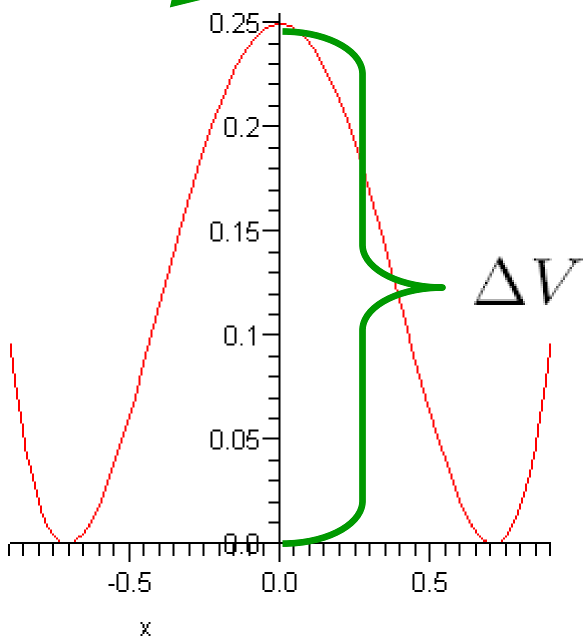


Similar to a bungee jump.


Is g = 9.8 a good
approximation?

Now the dynamics is more interesting:

The effective mass is $m_{\text{eff}}^2 = R - \gamma = 4V - \gamma$

↑

Slow roll approximation.

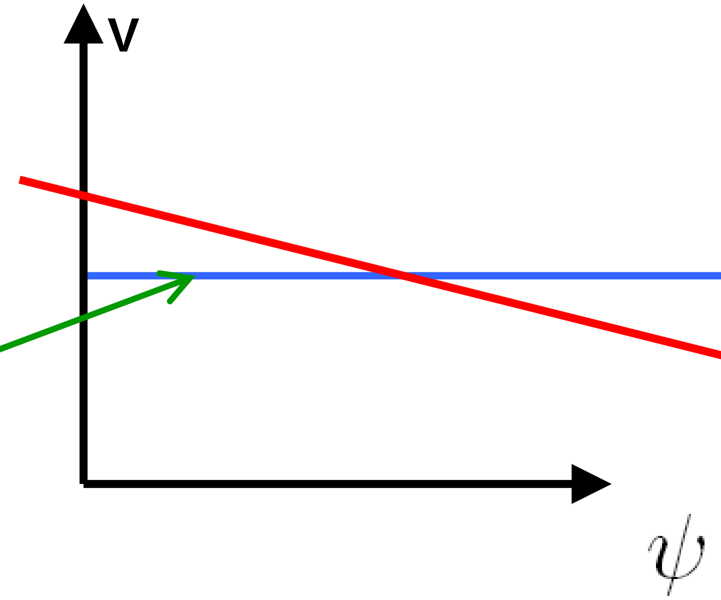
(This is where it is important that $\epsilon \ll 1$)

Now the dynamics is more interesting:

The effective mass is $m^2_{\text{eff}} = R - \gamma = 4V - \gamma$

Slow roll approximation

There is a phase transition:



For $V > \gamma/4$ ⇒ $m^2_{\text{eff}} > 0$

At the critical vacuum energy $V_c = \frac{\gamma}{4}$

an instability is developed and ϕ

acquires an expectation value.

$\Delta V \equiv V_{max} - V_{min} = \frac{\gamma}{4}$ ⇒ The end result is a flat space with plenty of kinetic energy.

Note that ϵ can be taken to be small so that on time scales of the age of the universe the vacuum energy density does not change significantly.

There are a couple of bounds on the T_r we can get this way:

1- Energy conservation: $T_r^4 \leq V_c$

2- Vacuum energy can be converted to kinetic energy only when

the slow-roll approximation is not valid: $T_r^4 < \gamma.$

In our case (1) and (2) are the same so an upper bound on T_r

is $T_r^4 \leq V_c$

What about quantum correction?

What about quantum correction?

Claim:

The present value of the vacuum energy

+

Technical naturalness of the model

- The upper bound on the reheating temperature is around the TeV scale.

- SUSY is broken at around the TeV scale.

- There is a fifth force deviation from GR at scales of the order of 100 microns.

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+

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- The upper bound on the reheating temperature is around the TeV scale.

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Let's consider the simplest potential $V(\phi) = -\frac{1}{2}m^2\phi^2 + \frac{1}{4}g\phi^4$

$$\Delta V = \frac{\gamma}{4} \Rightarrow m^2 = g$$

Quantum corrections to give non-vanishing vacuum energy, V_0, that should be at most 10^{-120}.

Because of the relevant term it is hard to control these quantum corrections without SUSY.

With SUSY we have $V_0 \sim g m^2 \sim m^4$

$$m \sim 10^{-30} \sim 10^{-3} eV$$

$$T_r \sim m^{1/2} \sim 10^{-15} \sim 1 \text{ TeV}$$

Fifth force at around 100 microns

When SUSY is broken these corrections are enhanced:

$$\delta m_\phi^2 \sim g\Delta m^2, \qquad \text{where} \qquad \Delta m^2 = m_\phi^2 - m_{\tilde{\phi}}^2$$

Δm^2 is at most of the order of 10^{-60}

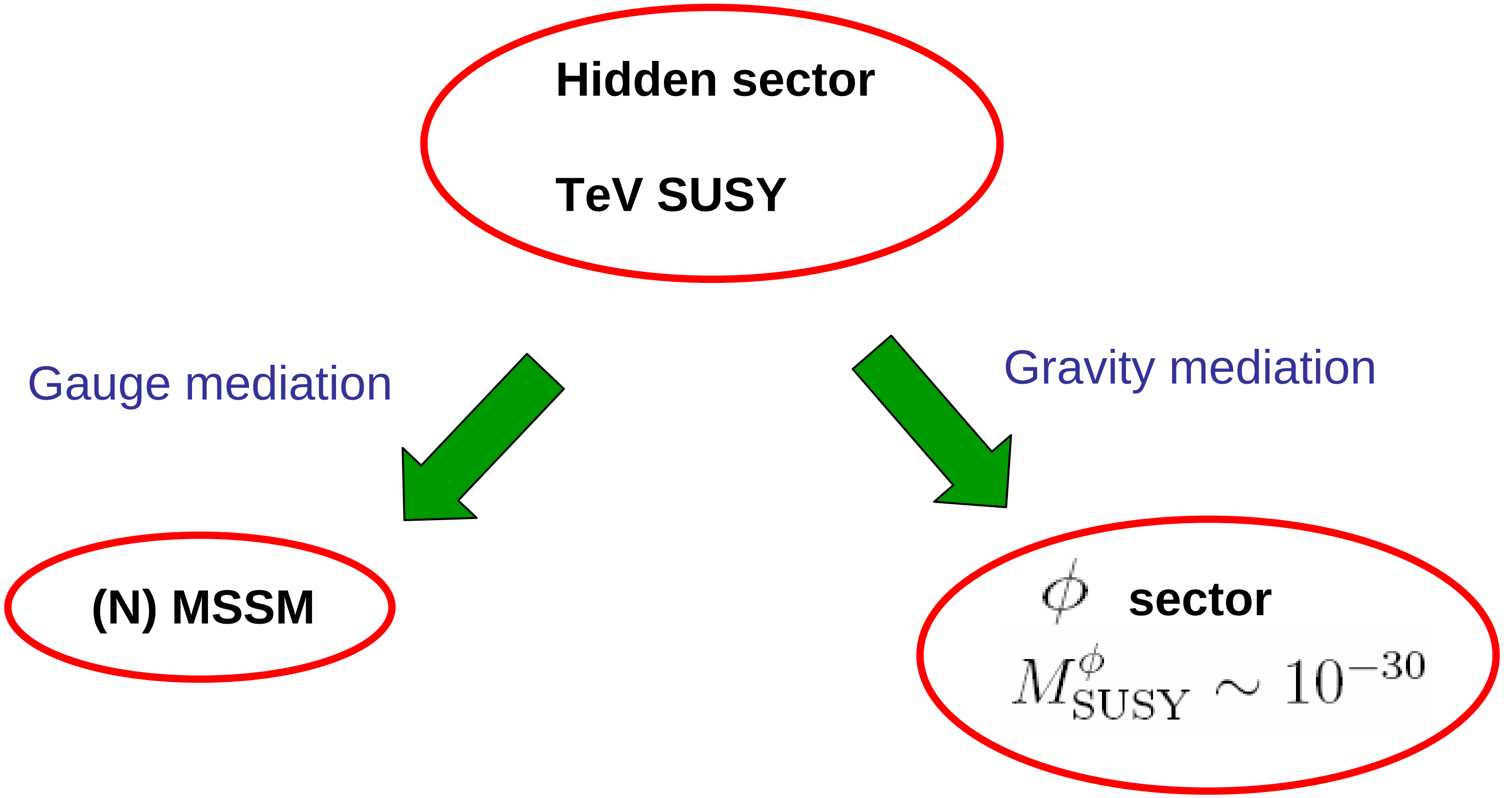
$$M_{\mathrm{SUSY}}^{\phi} \sim 10^{-30}$$

- Gravity always mediates SUSY breaking from one sector to the other:

$$M_{\mathrm{SUSY}}^{\phi} \sim M_{\mathrm{SUSY}}^{2}$$

$$M_{\mathrm{SUSY}} \sim \sqrt{M_{\mathrm{SUSY}}^{\phi}} \sim 10^{-15} \sim 1\mathrm{TeV}$$

So the picture is:



Natural question:
Can we find models that do not depend that on low scale SUSY?

The following model almost does that:

$$S_{EH} + S_{\text{inflation}} = \int d^4x\sqrt{-g}\left[\frac{1}{2}e^{-\phi^2}R - \frac{1}{2}(\partial\phi)^2 + \frac{1}{16\pi^2}\left(\frac{\phi}{f} - \pi\right)\text{Tr}(F \wedge F)\right]$$

Instantons give

$$V(\phi) = V_g \cos\left(\frac{\phi}{f}\right), \qquad \text{with} \qquad V_g = Ce^{-8\pi^2/g^2}$$

Without fine tuning only the order of magnitude of C can be fixed.

The nice feature of this model is that V_g drops out of the condition for the cancellation of the vacuum energy that takes the form $f^2 = \frac{1}{8}$.

The fact that g is not exponentially small does not matter since loops around the one-instanton background cannot modify f . The leading corrections to f come from two-instanton effects.

$$V_g \sim 10^{-60}$$

T_r is at the TeV scale.

So far we have not used SUSY at all !

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↓

$$V_g \sim 10^{-60}$$

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T_r is at the TeV scale.

So far we have not used SUSY at all !

Unfortunately, gravity loops spoil the naturalness of the model:

Several gravity effects:

1- R^2 effects: scale like $V_g^2 \sim 10^{-120}$ → is O. K.

2- Minimal coupling, respects $\phi \to \phi + 2\pi n f$ → is O. K.

3- Non-minimal coupling $e^{-\phi^2} R$ generates $\delta m^2 \sim \Lambda^4$

→ TeV SUSY is required to suppress these effects.

Interesting that only gravity loops cause problems while normally the CC problem is associated with field theory loops. Namely, even if we take

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

we still have the CC problem.

Out of the list of predictions:

(i) The upper bound on the reheating temperature is around the TeV scale.

(ii) SUSY is broken at around the TeV scale.

(iii) There is a fifth force deviation from GR at scales of the order of 100 microns.

- (iii) is the weakest since it depends on coupling of SM to ϕ .

- Perhaps (ii) also can be relaxed.

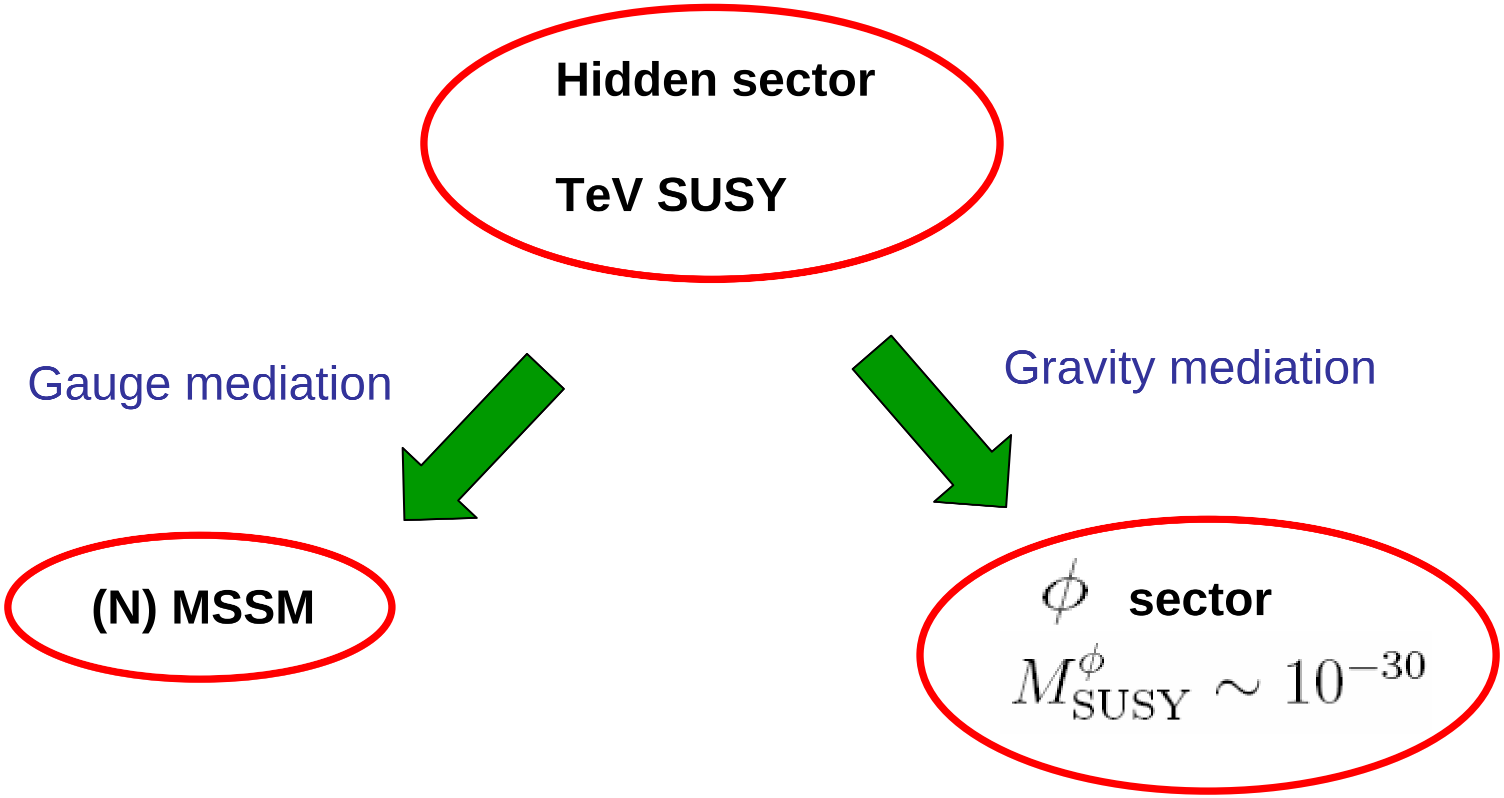
- Hard to see how to relax (i).

⇓

So the model implies low scale inflation.

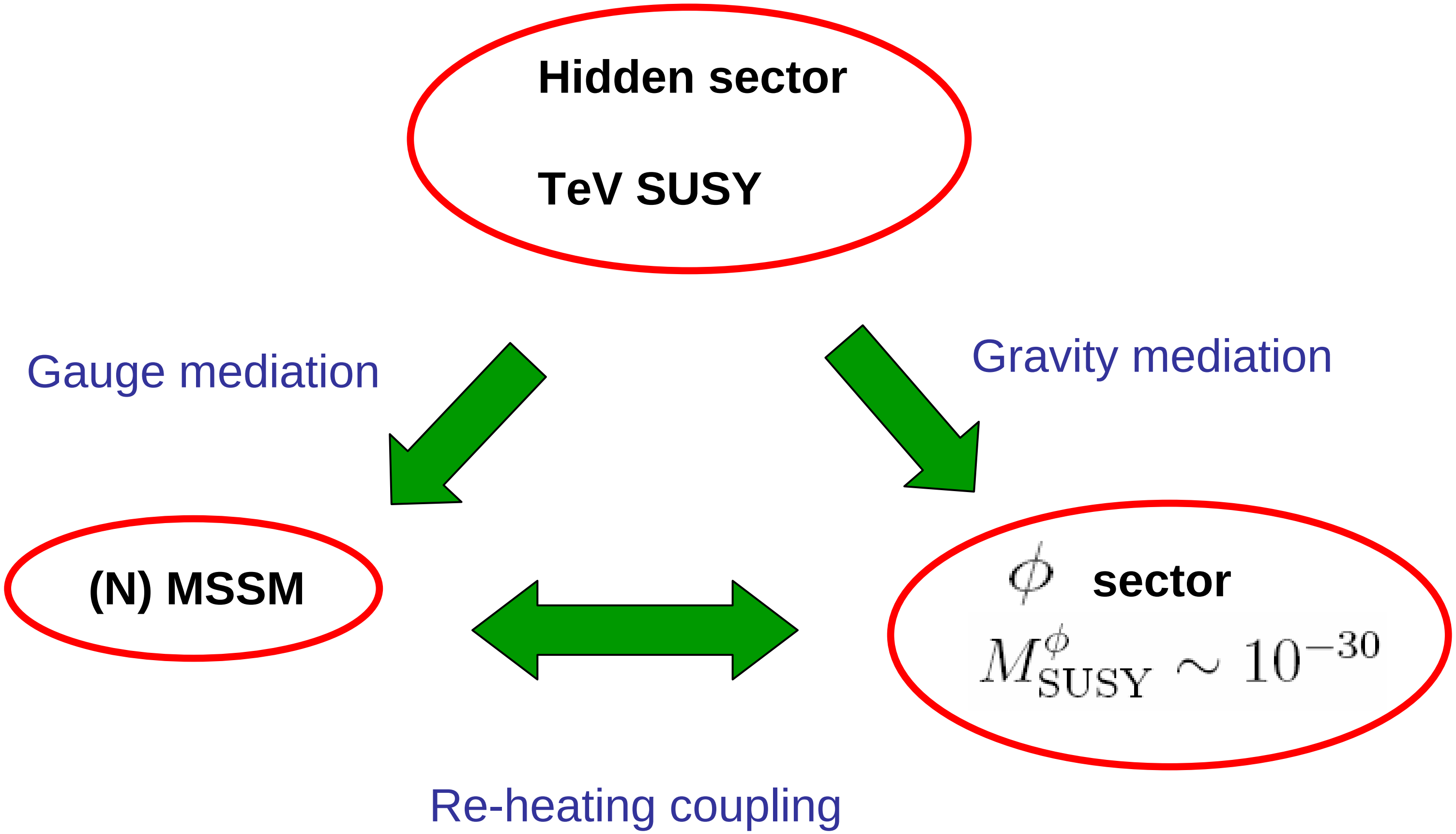
↳ The reheating should be very efficient.
Here even more tricky.

So far we talked about: vacuum energy → kinetic energy.



So far we talked about: vacuum energy → kinetic energy.

we should have: vacuum energy → kinetic energy → SM heat.



Can we re-heat without spoiling the naturalness of the model?

Two concrete ways to reheat:

1- In the axion like model derivatives coupling will not spoil the naturalness.

because of shift symmetry: $\phi \rightarrow \phi + 2\pi n f$

2- In the polynomial model ϕ can mix with another scalar $\tilde{\phi}$: $\Box \phi = m^2 \tilde{\phi}$

that decays to SM fields. (WIP: NI, D. Chang)

The process is:

ϕ Kinetic energy → $\tilde{\phi}$ Kinetic energy → SM heat

Resonance pre-heating

Standard coupling

Nice features:

- A relation between inflation and CC that takes advantage of $\frac{(\mathrm{Tev})^2}{M_p} = 10^{-3} eV$

  In fact, cannot solve the CC problem without inflation.

- Clear set-up where concrete calculations can be made.

  Can be proven wrong.

  For example by detection of tensor fluctuations, or absence of SUSY at LHC.

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- A relationship between inflation and CC problem:
  cannot solve the CC problem without inflation.

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Challenges:

- Meet all phenomenological constraints (baryogenesis, COBE normalization, etc).

- Stringy realization.

- Technical natural → natural.