Title: The anthropic solution to the strong CP problem and its cosmological implications.

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Abstract: We point out that the strong CP problem can be resolved by the anthropic principle. The key ideas are to allow explicit breaking(s) of the Peccei-Quinn symmetry which connects the problem to the cosmological constant problem, and to conjecture that the probability distribution of the vacuum energy in the landscape is hierarchical. The axion acquires a large mass from the explicit breaking, and does not contribute to the dark matter abundance. The axion may dominate the energy density of the universe after inflation and reheat the universe by the decay, possibly generating the density perturbations. On the other hand, the axion can be integrated out during inflation, if the explicit breaking is strong enough. All the cosmological problems of the (s)axion with a large Peccei-Quinn scale can be solved.

The Anthropic Solution to the Strong CP problem

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@PASCOS-08

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arXiv:0804.2478, F.T.

Basic idea:

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$$A + B = C$$

$$0 \leq A \leq 1$$
$$-\infty < B < +\infty$$

A and C are observable, but B is not.

Life can arise only if C is almost 0.

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(1) Dynamics of A.

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Solutions:

(1) Dynamics of A.

(2) The probability dist. of B may force A to take
the special value.

1. Introduction

Strong CP problem:

$$\mathcal{L} = \frac{g_s^2 \theta}{64\pi^2} \epsilon_{\mu\nu\rho\sigma} G^{(a)\mu\nu} G^{(a)\rho\sigma},$$

Experimental bound (from neutron EDM) reads

$$|\theta| < 10^{-(9-10)} \equiv \theta^{(\exp)}$$

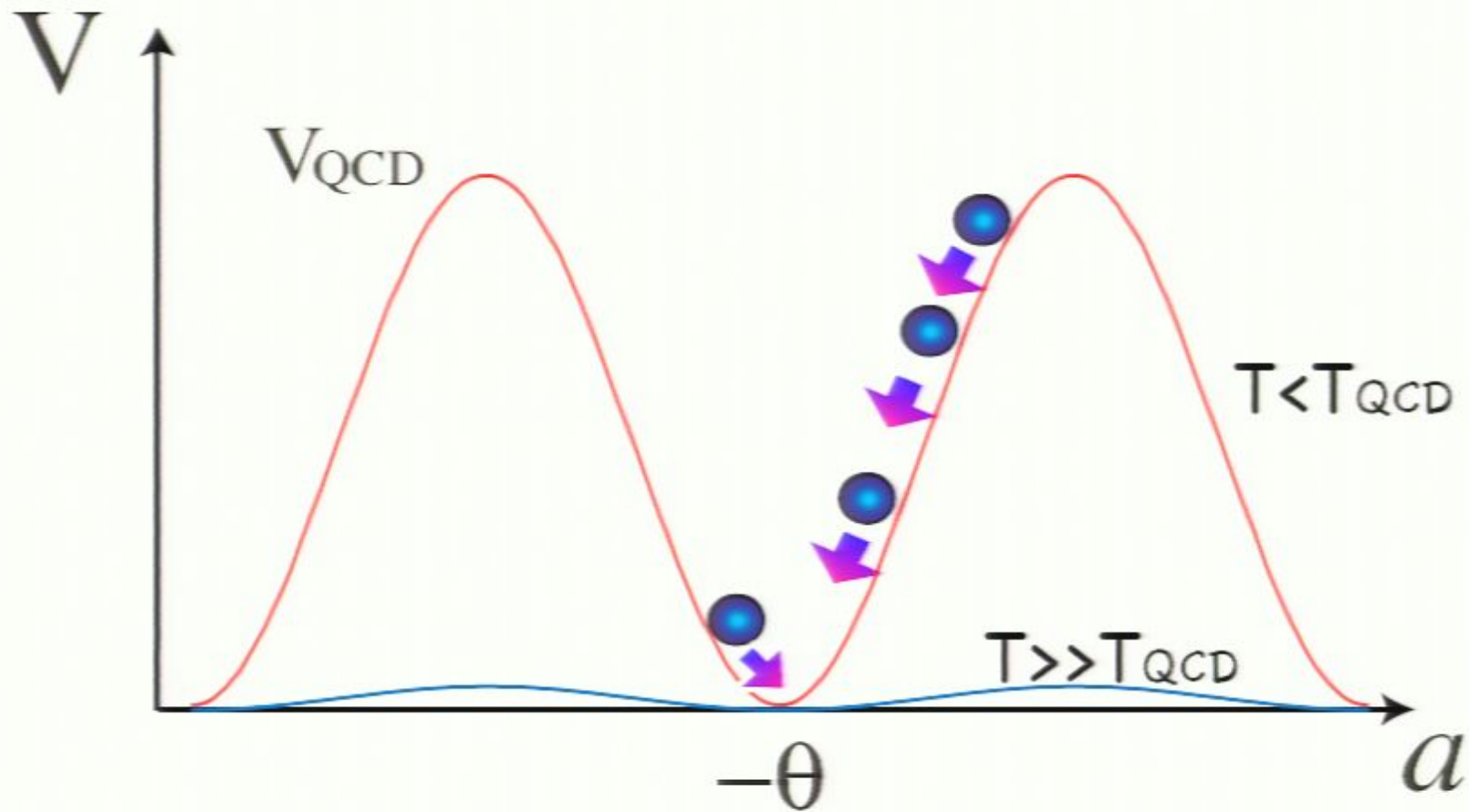## Why is θ so small??

The Peccei-Quinn (PQ) mechanism: (1977)

The axion, a , shifts as

$$a \rightarrow a + f_a\, \epsilon$$

under the PQ transformation, and has a coupling,

$$\mathcal{L} = \frac{g_s^2}{64\pi^2}\, a\, \epsilon_{\mu\nu\rho\sigma} G^{(a)\mu\nu} G^{(a)\rho\sigma} .$$

After the QCD phase transition, the axion is stabilized at $a + \theta = 0$.

In the PQ mechanism, the axion necessarily acquires non-vanishing energy density.

Axion models:

(1) DFSZ, KSVZ (or hadronic) axion models.

(2) string axion model $f_a = \mathcal{O}(10^{16})\mathrm{GeV}$

Astrophys. and
cosmological constraints:

$$10^9 \ \mathrm{GeV} \lesssim f_a \lesssim 10^{12} \ \mathrm{GeV}$$

Cosmological problem:
The axion abundance exceeds the observed
abundance of DM by many orders of magnitudes.

Theoretical issue:
The shift (or PQ) symmetry is explicitly violated.

The PQ mechanism

+

The string theory

$\Rightarrow$

Unconventional thermal history

or

Tuning of the initial displacement

The PQ~~~~chanism~~ mechanism
+
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⟹

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What we did:

We give up the dynamical solution to the strong CP problem.

We note that a large explicit breaking of the PQ symmetry relates the strong CP problem to the cosmological constant problem.

We show that the strong CP problem is solved by anthropic arguments, if the probability distribution of the vacuum energy has a mild pressure towards higher values.

The (s)axion cosmology is greatly improved!

2. Mechanism

The QCD instanton generates the potential,

$$V_{\text{QCD}}(a) = \Lambda^4_{\text{QCD}}(1 - \cos a),$$

Consider a large explicit breaking of the shift symmetry,

$$V_{inst}(a) = \Lambda^4_{inst}(1 - \cos(a - \psi))$$

with

$$\Lambda_{inst} \gg \Lambda_{\text{QCD}}$$

Using the relation, $\quad P(B|A) = \dfrac{P(A|B)\,P(B)}{P(A)}$

$P(|\psi| < \theta \,|\, \rho_\Lambda \lesssim \rho_\Lambda^{(\mathrm{aw})})$

$= P(\rho_{\mathrm{axion}} < \tfrac{1}{2}\theta^2 \Lambda_{\mathrm{QCD}}^4 \,|\, \rho_\Lambda \lesssim \rho_\Lambda^{(\mathrm{aw})})$

$$= \frac{\left(\int_0^{\rho_\Lambda^{(\mathrm{aw})}} d\rho_\Lambda \int_0^{\frac{1}{2}\theta^2 \Lambda_{\mathrm{QCD}}^4} d\rho_a \, \tilde{P}_A(\rho_a) P_L(\rho_\Lambda - \rho_a) \right) \cdot \left(\int_0^{\frac{1}{2}\theta^2 \Lambda_{\mathrm{QCD}}^4} d\rho_a \, P_A(\rho_a) \right)}{\left(\int_0^{\rho_\Lambda^{(\mathrm{aw})}} d\rho_\Lambda \int_0^{2\Lambda_{\mathrm{QCD}}^4} d\rho_a \, P_A(\rho_a) P_L(\rho_\Lambda - \rho_a) \right)}$$
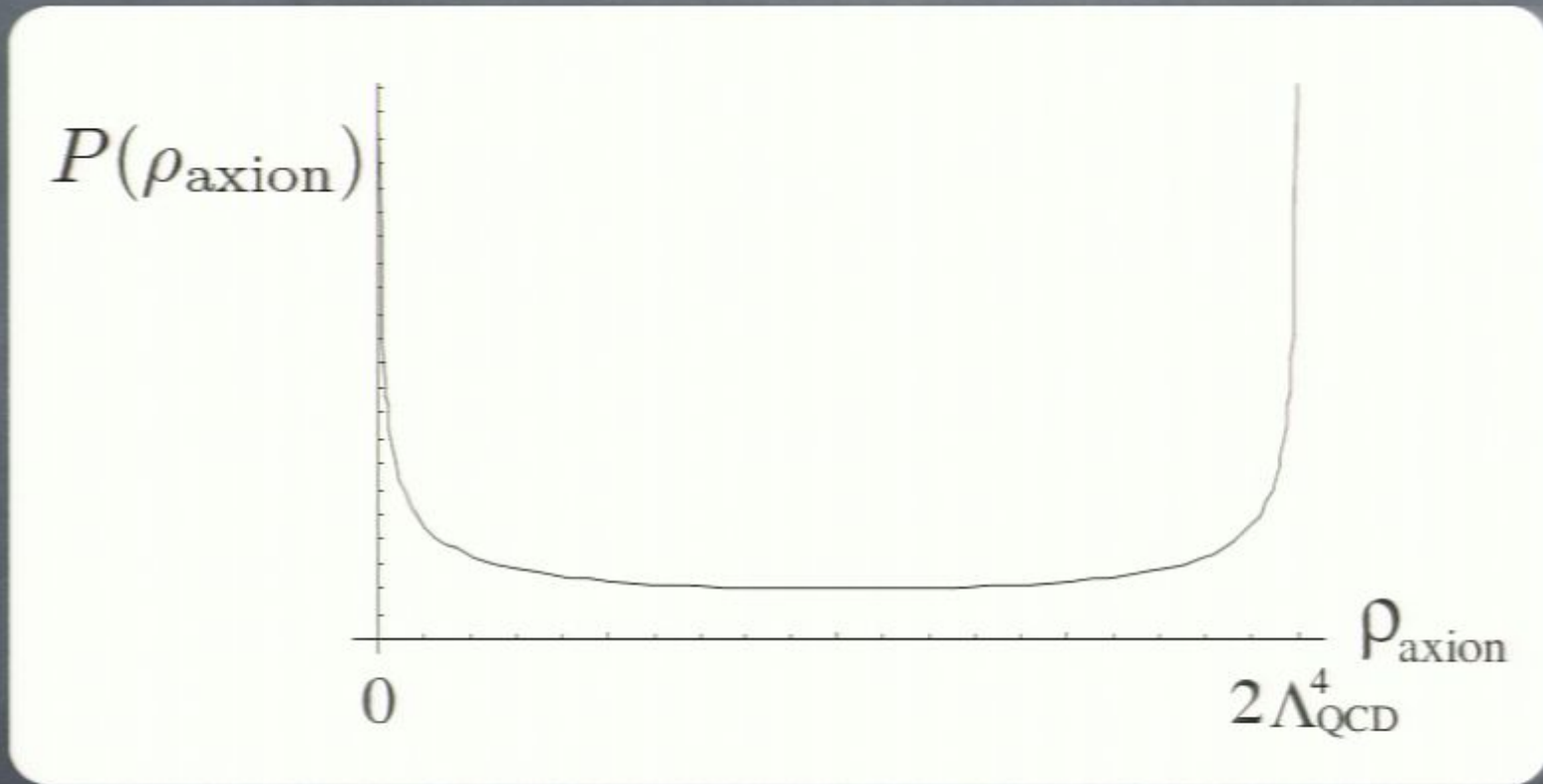
$\simeq \dfrac{X}{X+Y}$

$\quad X = \displaystyle\int_0^{\frac{1}{2}\theta^2 \Lambda_{\mathrm{QCD}}^4} d\rho_a \, P_A(\rho_a) P_L(\rho_\Lambda - \rho_a)$
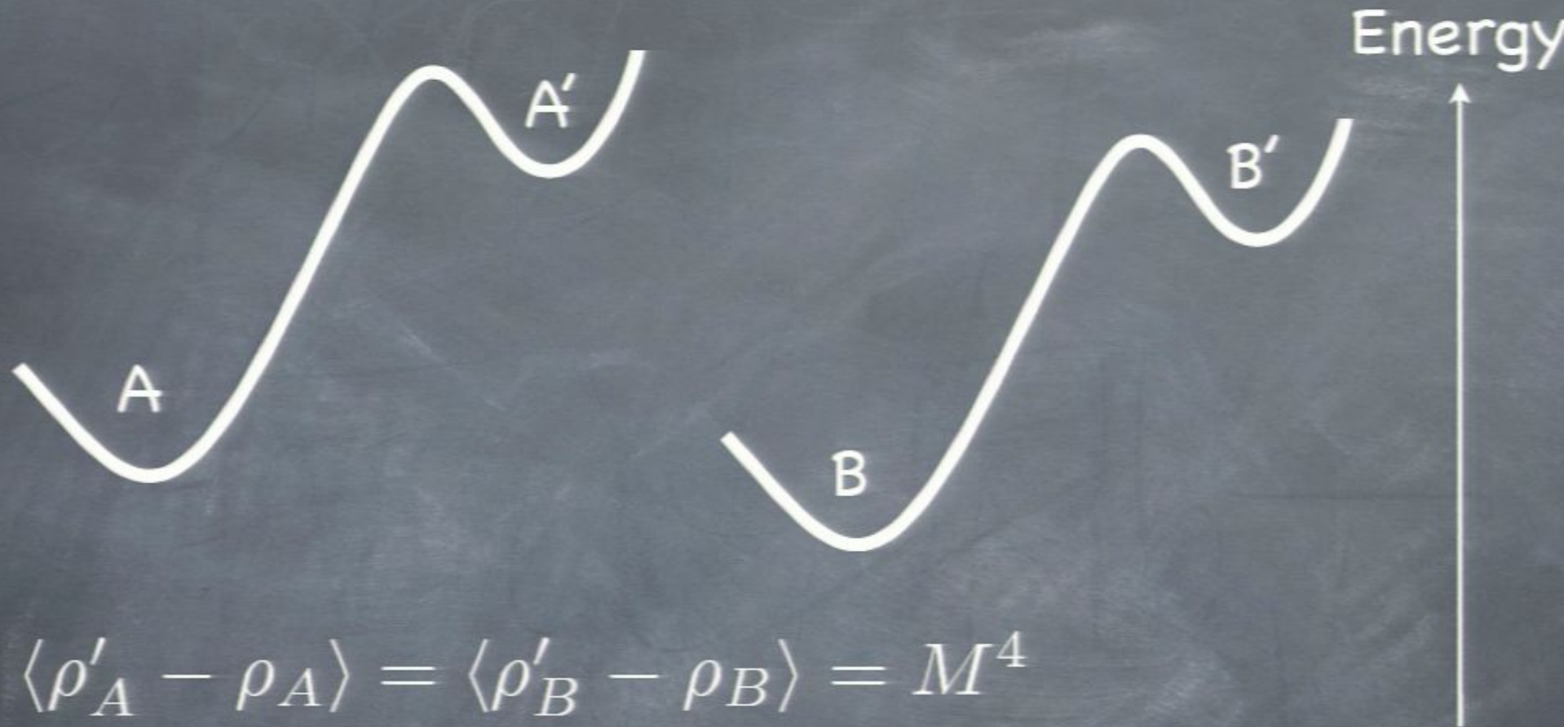
$\quad Y = \displaystyle\int_{\frac{1}{2}\theta^2 \Lambda_{\mathrm{QCD}}^4}^{2\Lambda_{\mathrm{QCD}}^4} d\rho_a \, P_A(\rho_a) P_L(\rho_\Lambda - \rho_a)$

The probability distribution of $\rho_{\text{axion}}(\psi) = \Lambda_{\text{QCD}}^4(1 - \cos\psi$

is given by

$$P(\rho_{\text{axion}}) = \frac{1}{\pi\Lambda_{\text{QCD}}^4}\left[2\left(\frac{\rho_{\text{axion}}}{\Lambda_{\text{QCD}}^4}\right) - \left(\frac{\rho_{\text{axion}}}{\Lambda_{\text{QCD}}^4}\right)^2\right]^{-\frac{1}{2}}$$

Energy

A'

B'

A

B

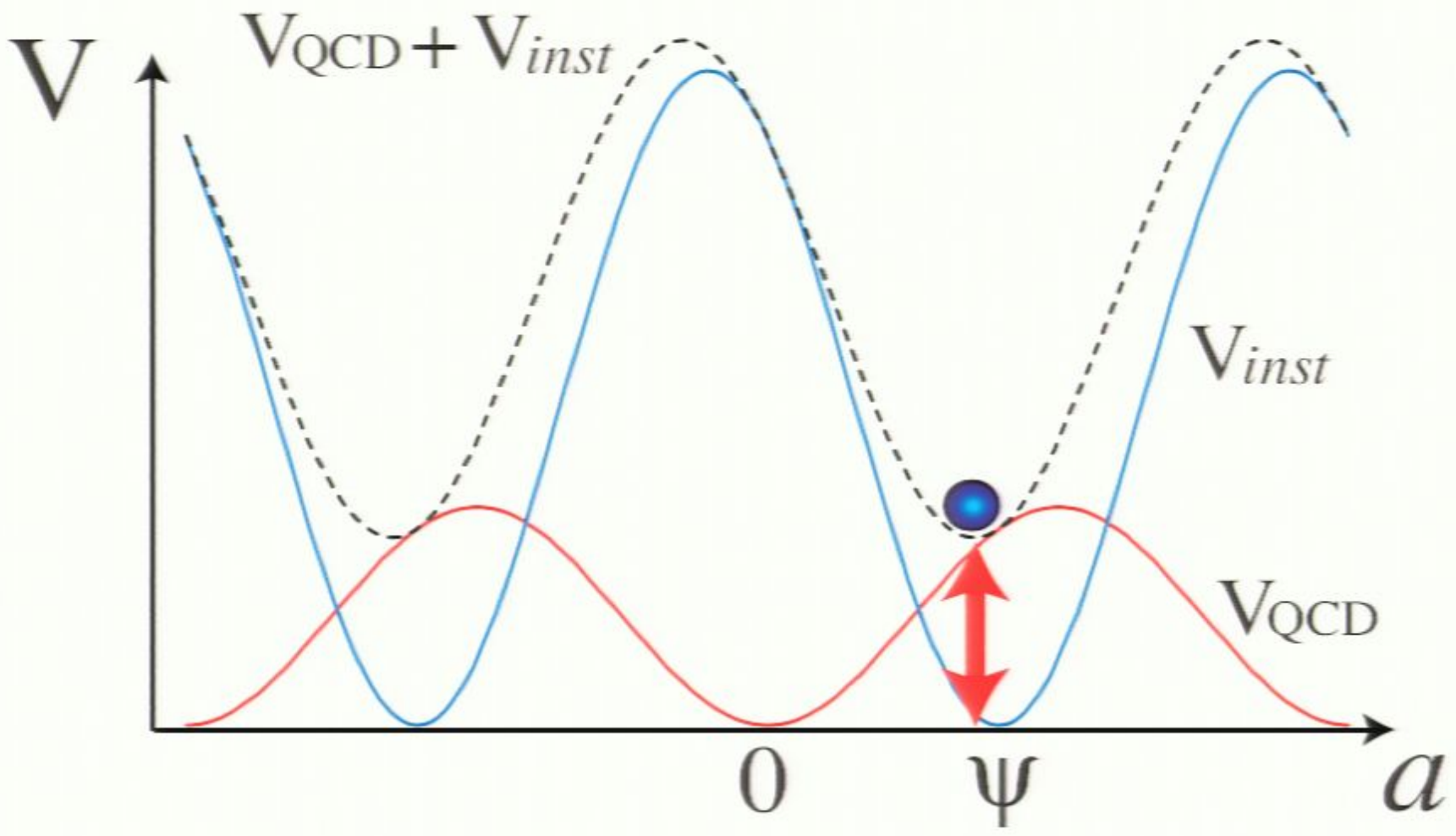$$\langle \rho'_A - \rho_A \rangle = \langle \rho'_B - \rho_B \rangle = M^4$$

$$\langle \rho'_A - \rho'_B \rangle = (\text{keV})^4$$

One needs to collect $N = \left[\left(\dfrac{M_P}{\text{keV}} \right)^4 \right]^2 = 10^{192}$ vacua.

(in the anthropic window

Also the old inflation must last long enough

What we did:

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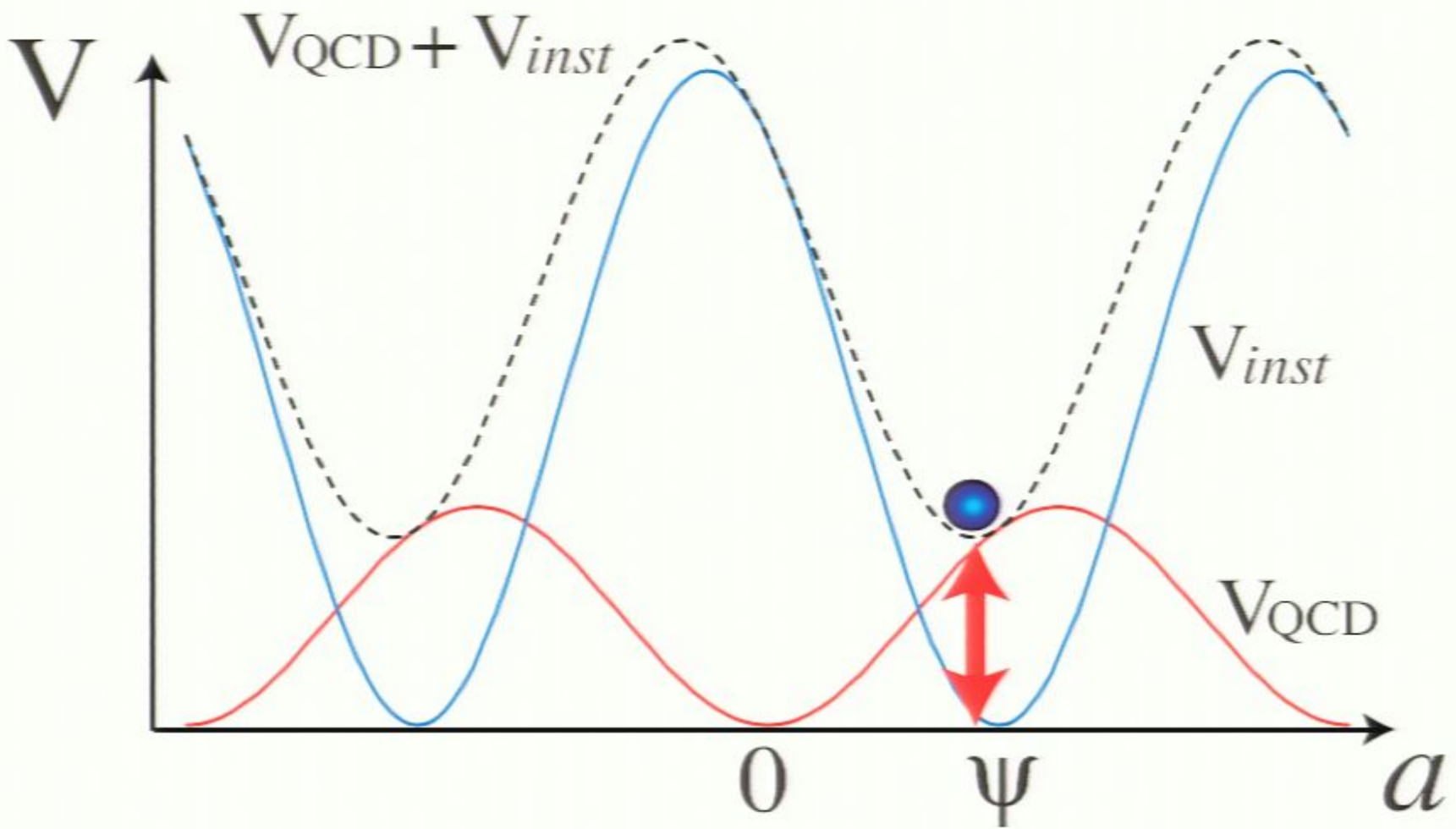$$V_{\mathrm{QCD}}(a) = \Lambda_{\mathrm{QCD}}^4 \left(1 - \cos a\right),$$

Consider a large explicit breaking of the shift symmetry,

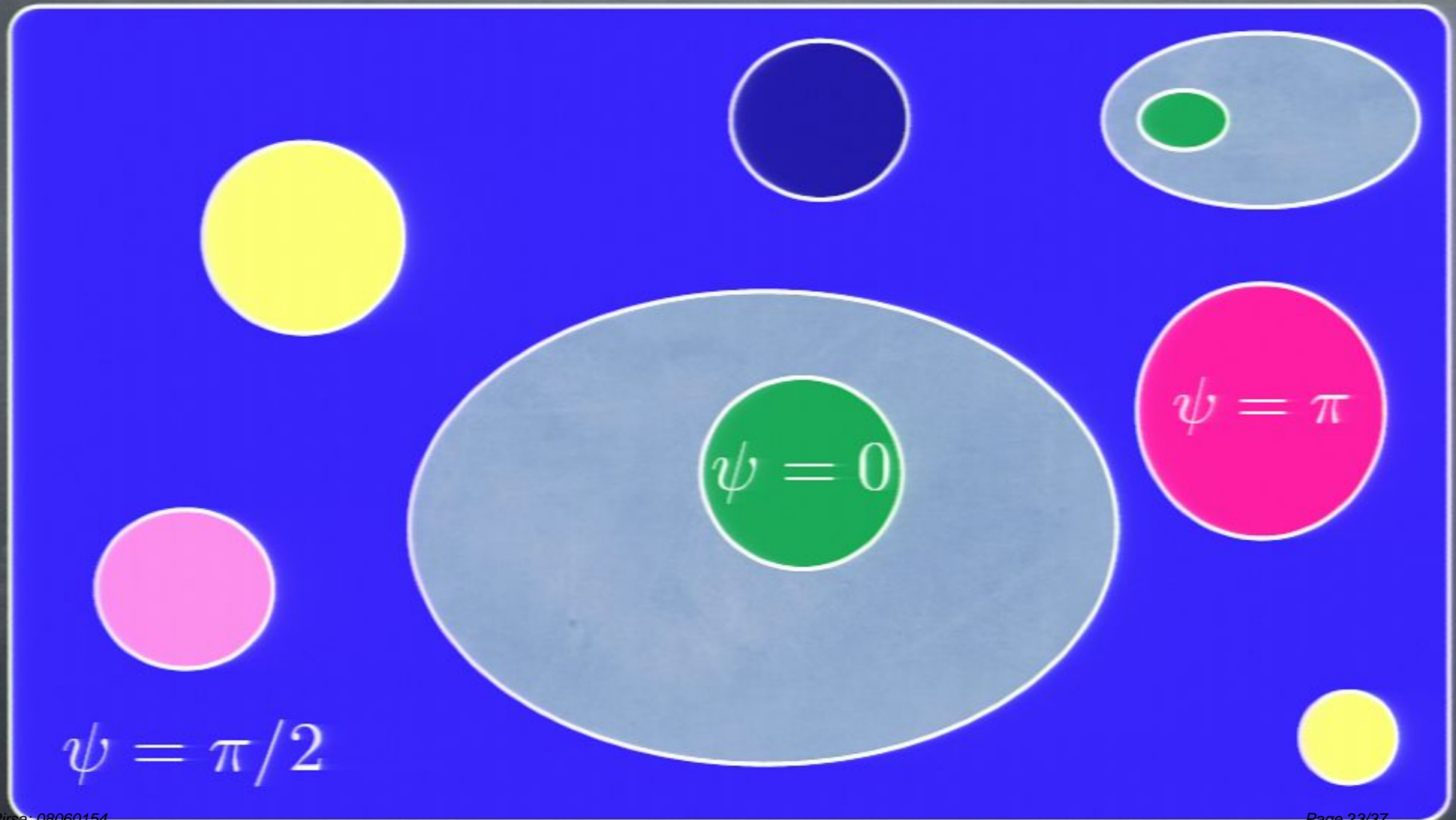$$V_{inst}(a) = \Lambda_{inst}^4 \left(1 - \cos\left(a - \psi\right)\right)$$

with

$$\Lambda_{inst} \gg \Lambda_{\mathrm{QCD}}$$

We assume that ψ is an environmental variable.

$\psi = \pi$

$\psi = 0$

$\psi = \pi/2$

$\Psi \neq 0$

$V_{QCD} + V_{inst}$

V

V_{inst}

V_{QCD}
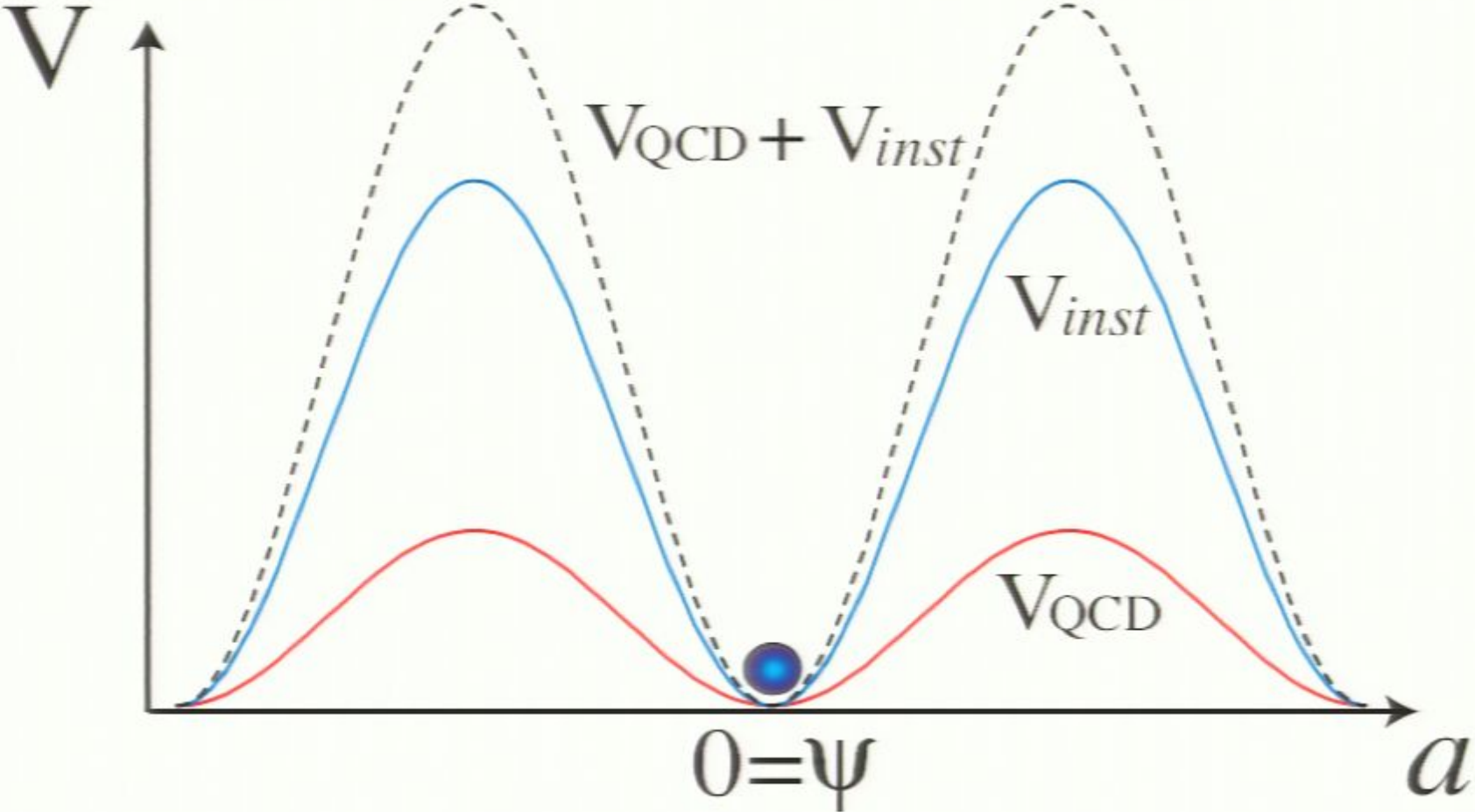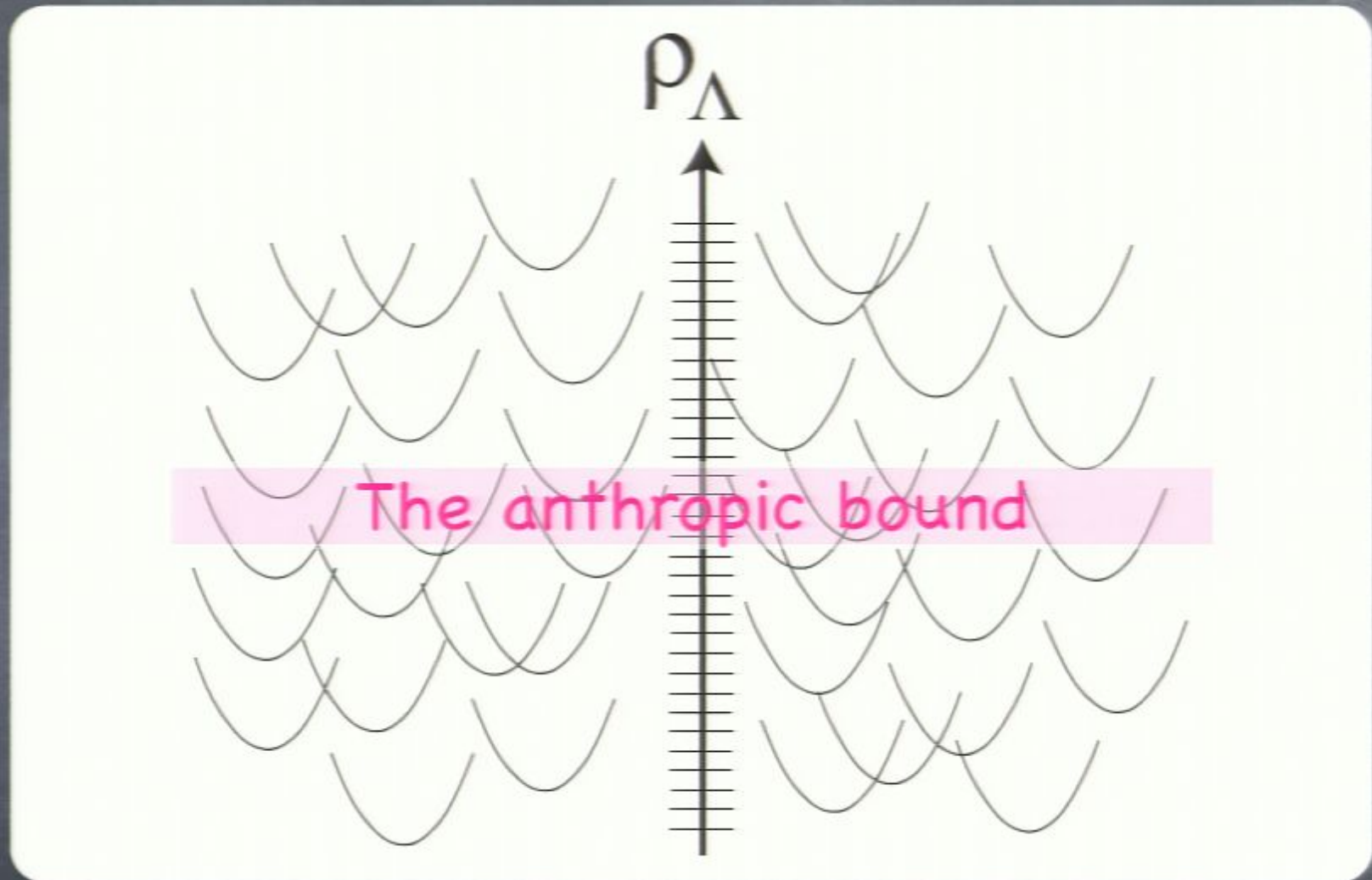
0 ψ a
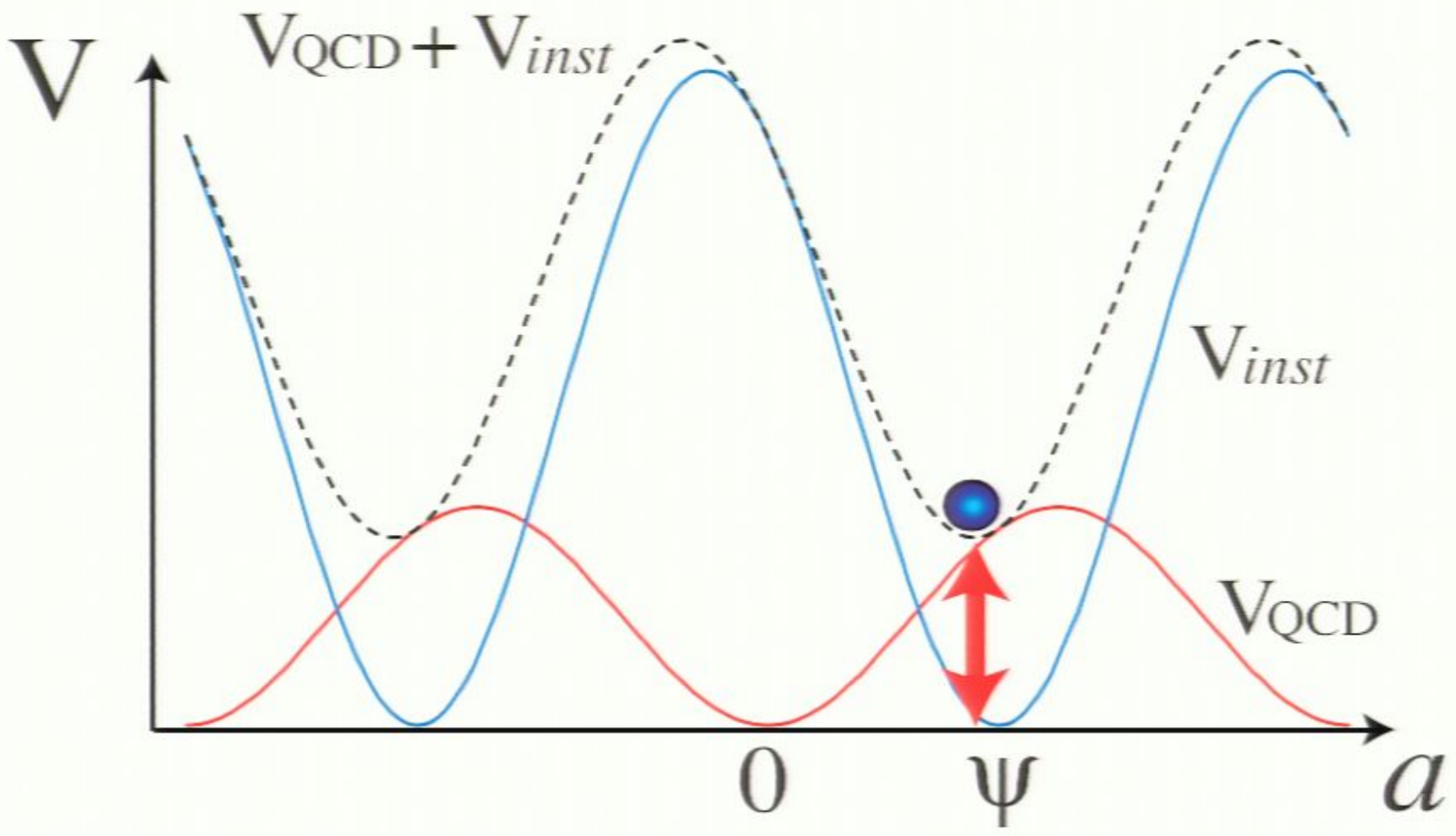
The CP conserving minimum ($\psi = 0$) is special in that it minimizes the contribution from the axion sector to the cosmological constant (CC).

However, there are many other contributions to the total CC.

The vacuum may not be special among those satisfying the anthropic bound on CC.

The anthropic constraint on CC Weinberg `87

Life arises in such universes satisfying

$$0 \leq \rho_\Lambda \lesssim \rho_\Lambda^{(\mathrm{aw})} \sim (1\,\mathrm{meV})^4$$

Let us now write the total CC as

$$\rho_{\mathrm{axion}}(\psi) + \rho_L = \rho_\Lambda$$

$\rho_{\mathrm{axion}}(\psi)$: the contribution from the axion sector

ρ_L : all the other contributions.

$$0 \leq \rho_{\mathrm{axion}} \leq 2\Lambda_{\mathrm{QCD}}^4$$

$$-M^4 < \rho_L < M^4$$

There can be many ways to cancel the terms to give $\quad 0 \leq \rho_\Lambda \lesssim \rho_\Lambda^{(\mathrm{aw})} \sim (1\,\mathrm{meV})^4$

Probability distributions.

We assume that there is no special feature in the axion sector, i.e., a priori, $\psi = 0$ is as likely as $\psi = 1$.
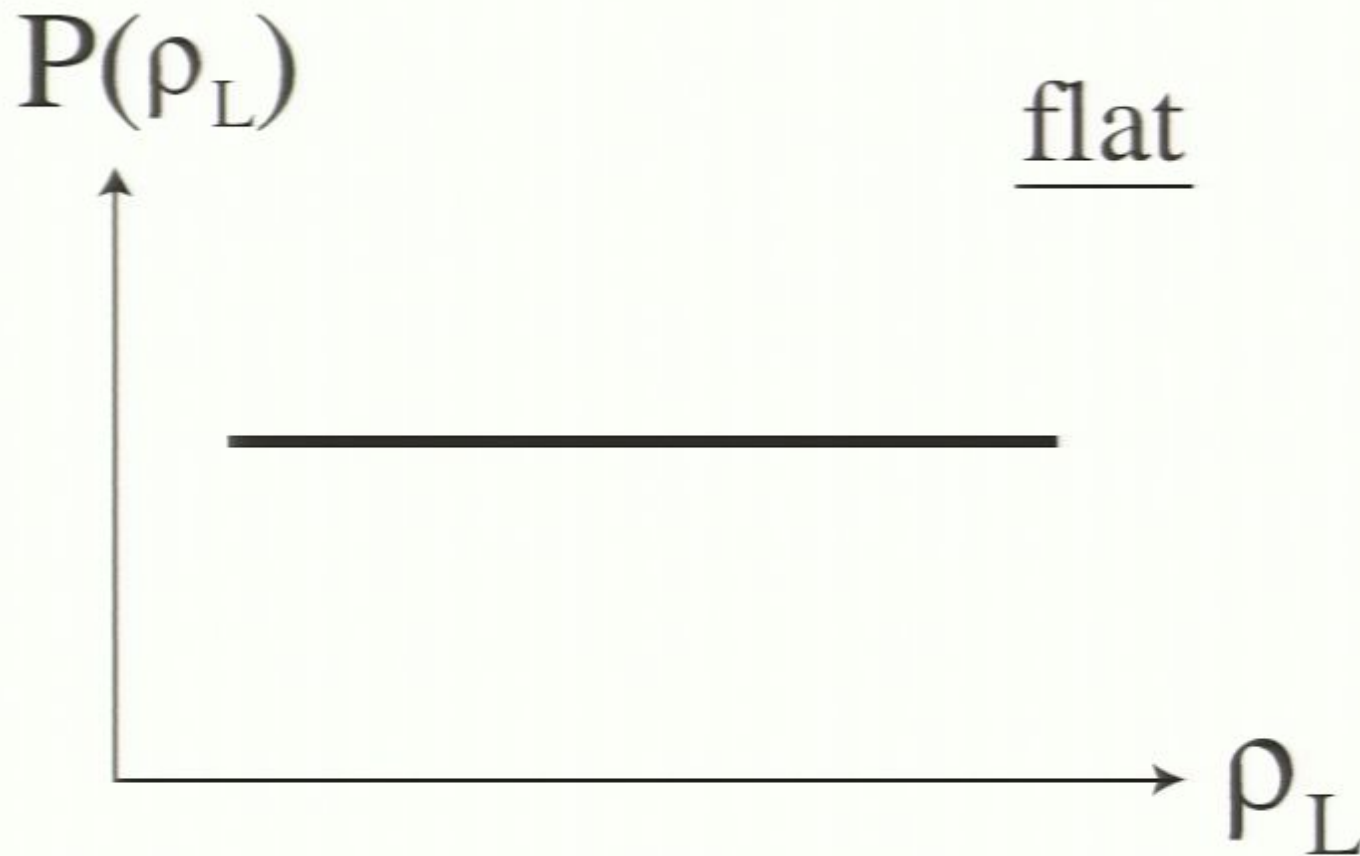
$$P(\psi) = \text{const.}$$

On the other hand, the probability distribution of all the other contributions may not be flat.
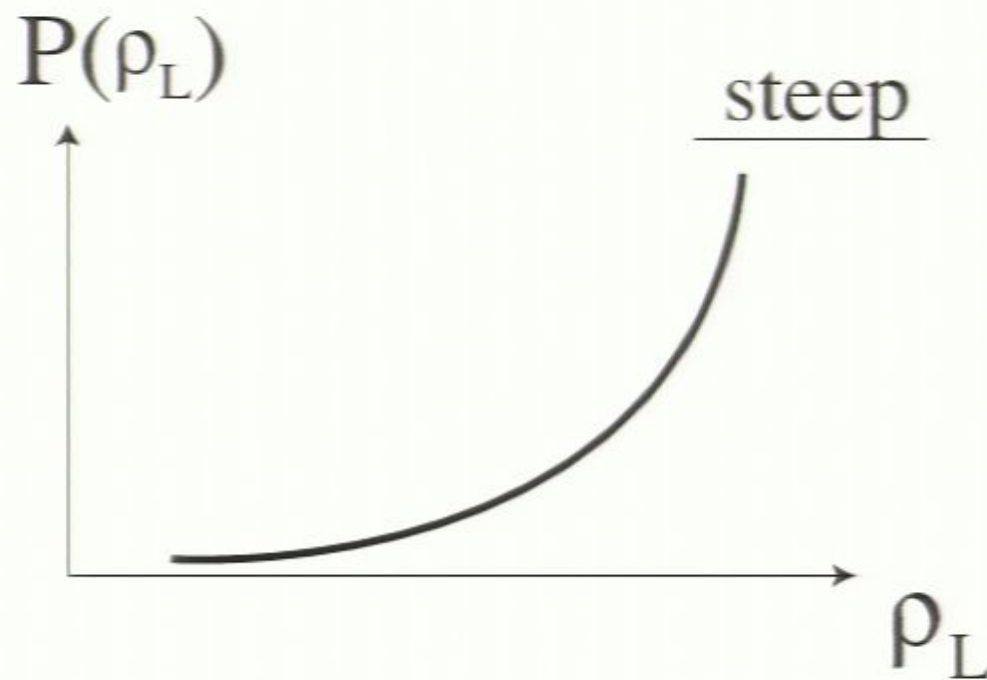
$$P(\rho_L) = ?? \qquad -M^4 < \rho_L < M^4$$

$P(\rho_L)$

ρ_L

If it is flat, $\psi = 0$ is not special at all.

$P(\rho_L)$

<u>flat</u>

ρ_L

$$\rho_\Lambda = \rho_L + \rho_{\mathrm{axion}}(\psi)$$

But, the situation significantly changes, if P_L has a pressure toward higher values.

$P(\rho_L)$

steep

ρ_L

$$\rho_\Lambda = \rho_L + \rho_{\mathrm{axion}}(\psi)$$

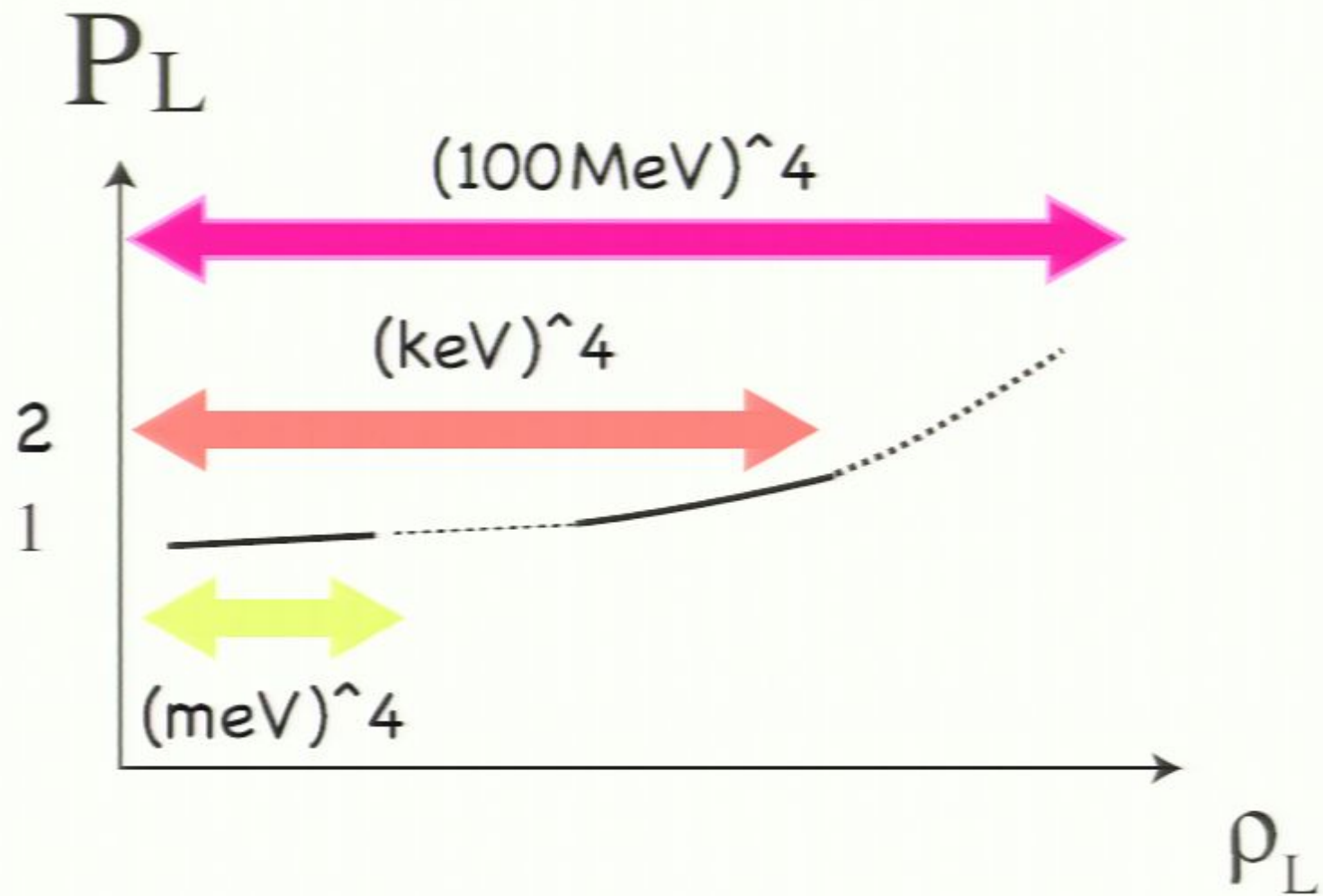Large ρ_L, i.e., smaller axion energy is favored.

We want to know

$$P(|\psi| < 10^{-9} \,|\, \rho_\Lambda \lesssim \rho_\Lambda^{(\mathrm{aw})})$$

If it is much smaller than unity, this is indeed a problem. If it is of O(0.1), it is not a problem.

$$\int_0^{\frac{1}{2}\theta^2\Lambda_{\mathrm{QCD}}^4} d\rho_a \, P_A(\rho_a) P_L(\rho_\Lambda - \rho_a) \gtrsim \int_{\frac{1}{2}\theta^2\Lambda_{\mathrm{QCD}}^4}^{2\Lambda_{\mathrm{QCD}}^4} d\rho_a \, P_A(\rho_a) P_L(\rho_\Lambda - \rho_a)$$

Roughly speaking, if $P(\rho_L)$ changes significantly over an energy scale of (O(1)keV)^4, the strong CP problem is solved.

$$\theta^{(\mathrm{exp})\,2}\Lambda_{\mathrm{QCD}}^4 \sim (\mathcal{O}(1)\mathrm{keV})^4$$

This pressure must last for a range of (100MeV)^4

3. Cosmology

We have implicitly assumed that the axion does not contribute to the DM density.

The axion acquires a large mass due to the large explicit breaking of the PQ symmetry.

The axion is actually unstable and decays into gluons!

Interesting scenarios arise!

(1) Axion-less universe;
The breaking is strong enough that the axion can be integrated out during inflation.

(2) Axion reheats the universe;
After inflation, the axion easily dominates the energy density, and reheats the universe.

(3) Axion curvaton;
For $H_{inf} = 10^{12}$ GeV with $f_a = 10^{16}$ GeV, the fluctuations of the axion can account for the density perturbations!

4. Conclusion

We have provided a possible solution to the strong CP problem, based on the bold assumption that the probability distribution of the vacuum energy has a pressure towards higher values.

Remaining issues:

    Cosmological measure problem.
    Similar effects on other variables?
    e.g., Higgs mass?