



Landscape of Spontaneous CP Violation

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Based on: JHEP 04 (2022), 12 (2022), arXiv: 2510.23033 (to appear in JHEP)
with Fujikura, Girmohanta, Lee, Liu, Nakagawa, Sato, Suzuki, Yamada, Wang

60th Rencontres de Moriond, Electroweak session



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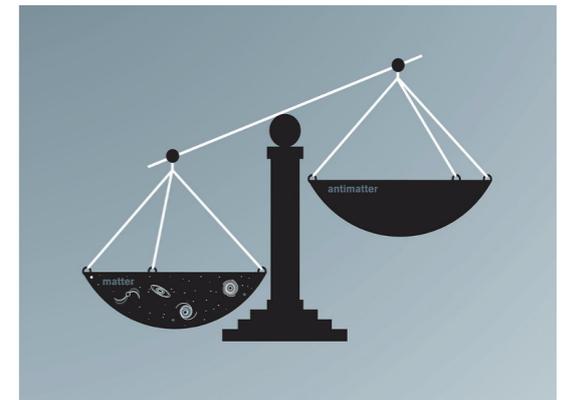
CP Violation

- **CP** turns a particle into its anti-particle with opposite helicity.
- **CP symmetry and its violation** stand *at the heart of modern particle physics.*



1. Question in Standard Model

“Why strong interaction respects CP symmetry while weak interaction does not?” (**strong CP Problem**)



2. Question in Cosmology

The Universe needs CP violation for **matter-antimatter asymmetry**.

3. Beyond Standard Model

CP violation in new physics can be probed through measurements of **electric dipole moments**.



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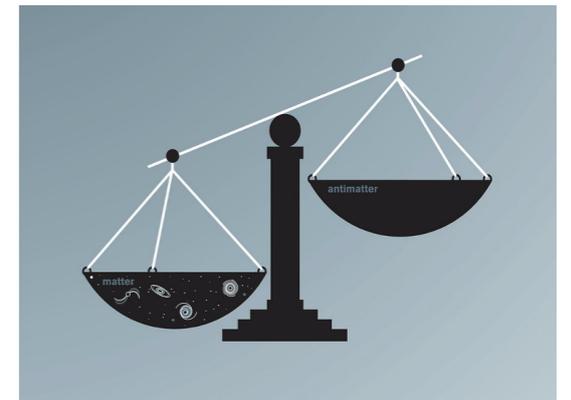


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Strong CP Problem

QCD Lagrangian for strong interactions allows

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$

explicitly violating **CP** symmetry.

The physical strong CP phase : $\bar{\theta} \equiv \theta - \arg \det (M_u M_d)$

The current upper bound on the neutron electric dipole moment

$$\rightarrow |\bar{\theta}| < 10^{-11}$$

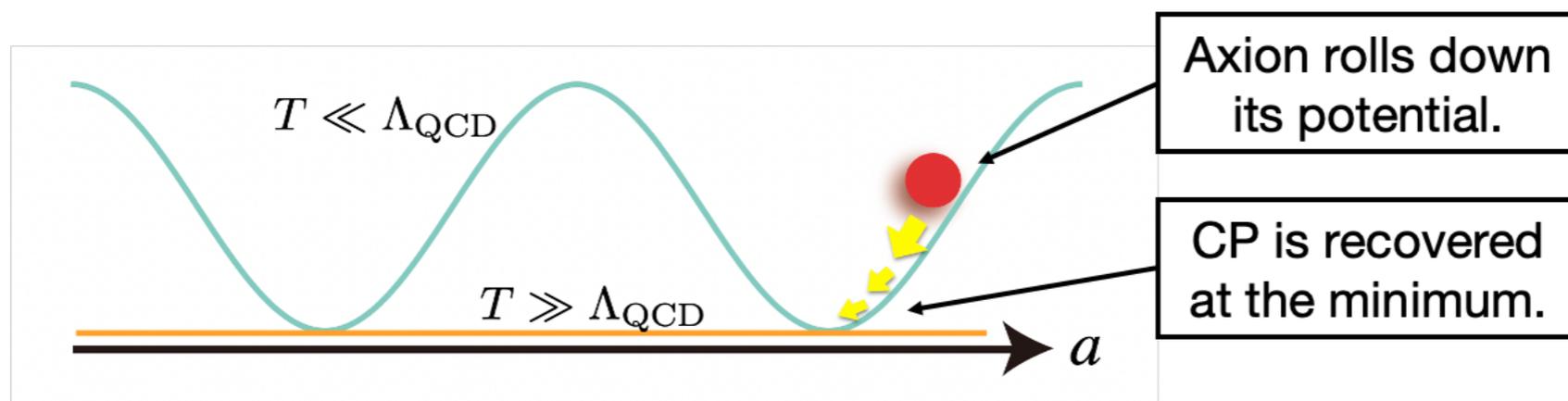
Why is $\bar{\theta}$ so small ??

Some shifts of $\bar{\theta}$ would not provide a visible change in our world.

Axion Solution

The most common explanation is **the Peccei-Quinn mechanism** that the strong CP phase is promoted to a dynamical variable.

$$\mathcal{L}_\theta = \left(\theta + \frac{a}{f_a} \right) \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$



The **axion a** dynamically cancels the strong CP phase.

Axion arises from spontaneous breaking of a global symmetry which must be preserved to an extraordinary high degree.



Incompatible with quantum gravity effects (**axion quality problem**)

Spontaneous CPV

- Spontaneous CP violation (SCPV) provides **an axionless solution** to the strong CP problem.
- CP is an exact symmetry of the Lagrangian but broken spontaneously at the vacuum

➔ Generation of the CKM phase without reintroducing a nonzero strong CP phase

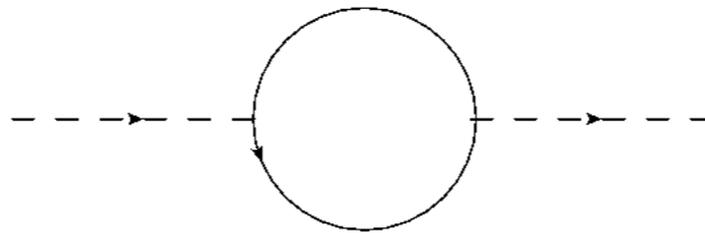
Nelson-Barr mechanism

A vector-like pair of heavy quarks is introduced, so that the extended quark mass matrix transmits SCPV into the CKM matrix.

$$\mathcal{L} = \underbrace{\mu \bar{q}q}_{\text{Heavy quarks}} + a_{a\bar{f}} \underbrace{\eta_a \bar{d}_{\bar{f}}q}_{\text{CP breaking field}} + y_{f\bar{f}} H Q_f \bar{d}_{\bar{f}} \quad \Rightarrow \quad \mathcal{M} = \begin{pmatrix} \mu & a_{a\bar{f}} \eta_a \\ \boxed{0} & m_d \end{pmatrix}$$

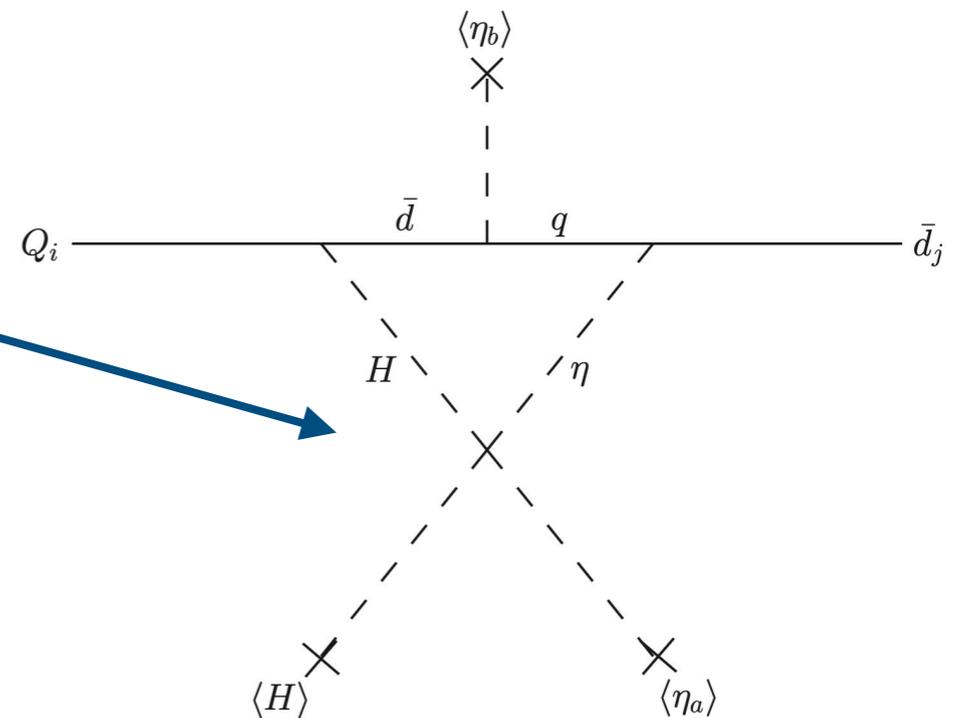
Challenges for SCPV

- **Naturalness problem:** the mechanism requires new scalar fields whose VEVs break CP much below the Planck scale.



- Sensitivity to **higher-dim. operators** and **radiative corrections**, regenerating a strong CP phase.

$$\mathcal{L} \supset \frac{\eta_b^*}{\Lambda} \eta_a \bar{q} q + \frac{\eta_a^*}{\Lambda} H Q \bar{q} + \underline{\gamma_{ab} \eta_a^* \eta_b H^\dagger H}$$



Dine, Draper (2015)

Challenges for SCPV

- **Naturalness problem:** the mechanism requires new scales whose VEVs break CP much below the Planck scale.

Supersymmetry (SUSY) offers a natural framework to address these difficulties !

- Sensitivity to **higher-dim. operators** and **radiative corrections**, regenerating a strong CP phase.

- ✓ SUSY stabilizes the SCPV scale in much the same way it stabilizes the EW scale.
- ✓ SUSY can forbid or strongly suppress dangerous higher-dim. operators.

It's reasonable to consider SCPV in SUSY.

For non-SUSY approach, see *e.g.* Girmohanta, Lee, YN, Suzuki (2022).

SCPV in SUSY

The physical strong CP phase :

$$\bar{\theta} \equiv \theta - \arg \det (M_u M_d) - 3 \arg (\underline{m_{\tilde{g}}})$$

Gluino mass

To set the cosmological constant to zero

$$\rightarrow \underline{\langle W \rangle} \sim \underline{m_{3/2}} M_{\text{Pl}}^2$$

↑
Gravitino mass

Complex phase generates a gluino mass phase via 1-loop anomaly med.

Constraint on $\bar{\theta}$ $\rightarrow \frac{\alpha_s}{4\pi} \frac{m_{3/2}}{m_{\tilde{g}}} < 10^{-10}$

Gravitino mass must be sufficiently small.

SCPV in SUSY

- **Flat directions** are ubiquitous in SUSY.
Valleys in field space along which the potential is exactly flat.
- Flat directions naturally contain a point to spontaneously break CP.

How to stabilize such a point ?

Giving positive masses for all scalar fields around the minimum.

- Two qualitatively different ways for the stabilization:
 - ✓ Purely in a **supersymmetric** way ← No low-energy prediction ...
 - ✓ Through **SUSY breaking effects**

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 - ✓ Through **SUSY breaking effects** ← **Let's focus !**

SCPV via ~~SUSY~~

Liu, Nakagawa, YN, Wang (2025)

- **Supersymmetric potential**

$$V_F = \lambda^2 |\phi_1 \phi_2 - v^2|^2 + \lambda^2 |X|^2 (|\phi_1|^2 + |\phi_2|^2)$$

Real parameter

➔ $\langle X \rangle = 0, \quad \langle \phi_1 \rangle = v_1 e^{i\theta}, \quad \langle \phi_2 \rangle = v_2 e^{-i\theta} \quad v_1 v_2 \equiv v^2$

Not uniquely determined **SCPV scale**

$$\phi_1(x) = \left(v_1 + \frac{\sigma_1(x)}{\sqrt{2}} \right) \exp \left[i \left(\theta + \frac{\pi_1(x)}{\sqrt{2}v_1} \right) \right], \quad \phi_2(x) = \left(v_2 + \frac{\sigma_2(x)}{\sqrt{2}} \right) \exp \left[i \left(-\theta + \frac{\pi_2(x)}{\sqrt{2}v_2} \right) \right]$$

Massless modes :

$$s(x) = \frac{1}{f_a} (v_1 \sigma_1(x) - v_2 \sigma_2(x)), \quad a(x) = \frac{1}{f_a} (v_1 \pi_1(x) - v_2 \pi_2(x))$$

$f_a \equiv \sqrt{v_1^2 + v_2^2}$

SCPV via ~~SUSY~~

Two terms with different periodicity are needed, e.g. $V = \mathcal{C} \cos \theta + \mathcal{D} \cos(2\theta)$

- **SUSY breaking**

$$V_{\text{soft}} = \left(\frac{1}{2} b_1 \phi_1^2 + \frac{1}{2} b_2 \phi_2^2 + \text{h.c.} \right) + m_1^2 \phi_1^* \phi_1 + m_2^2 \phi_2^* \phi_2$$

The potential is bounded from below. $\Rightarrow |b_1| \leq m_1^2, |b_2| \leq m_2^2$

- **Non-perturbative effect**

SU(N) dark QCD with quarks coupled to SCPV fields.

$$\Rightarrow V_{\text{dyn}} = \frac{(\kappa_1^2 + \kappa_2^2) \Lambda^{6 - \frac{2}{N}}}{|\kappa_1 \phi_1 + \kappa_2 \phi_2|^{2 - \frac{2}{N}}}$$

Real coupling constants

Λ : dark QCD dynamical scale

SCPV via ~~SUSY~~

$$V_{\text{tot}} = V_F + V_{\text{soft}} + V_{\text{dyn}}$$

$$= b_1 \left(v_1^2 + \frac{b_2 v^4}{b_1 v_1^2} \right) \frac{\cos(2\theta)}{\cos(2\theta)} + m_1^2 \left(v_1^2 + \frac{m_2^2 v^4}{m_1^2 v_1^2} \right) + \frac{(\kappa_1^2 + \kappa_2^2) \Lambda^{6 - \frac{2}{N}}}{[\kappa_1^2 v_1^2 + \kappa_2^2 v^4 / v_1^2 + 2\kappa_1 \kappa_2 v^2 \cos(2\theta)]^{1 - \frac{1}{N}}}$$

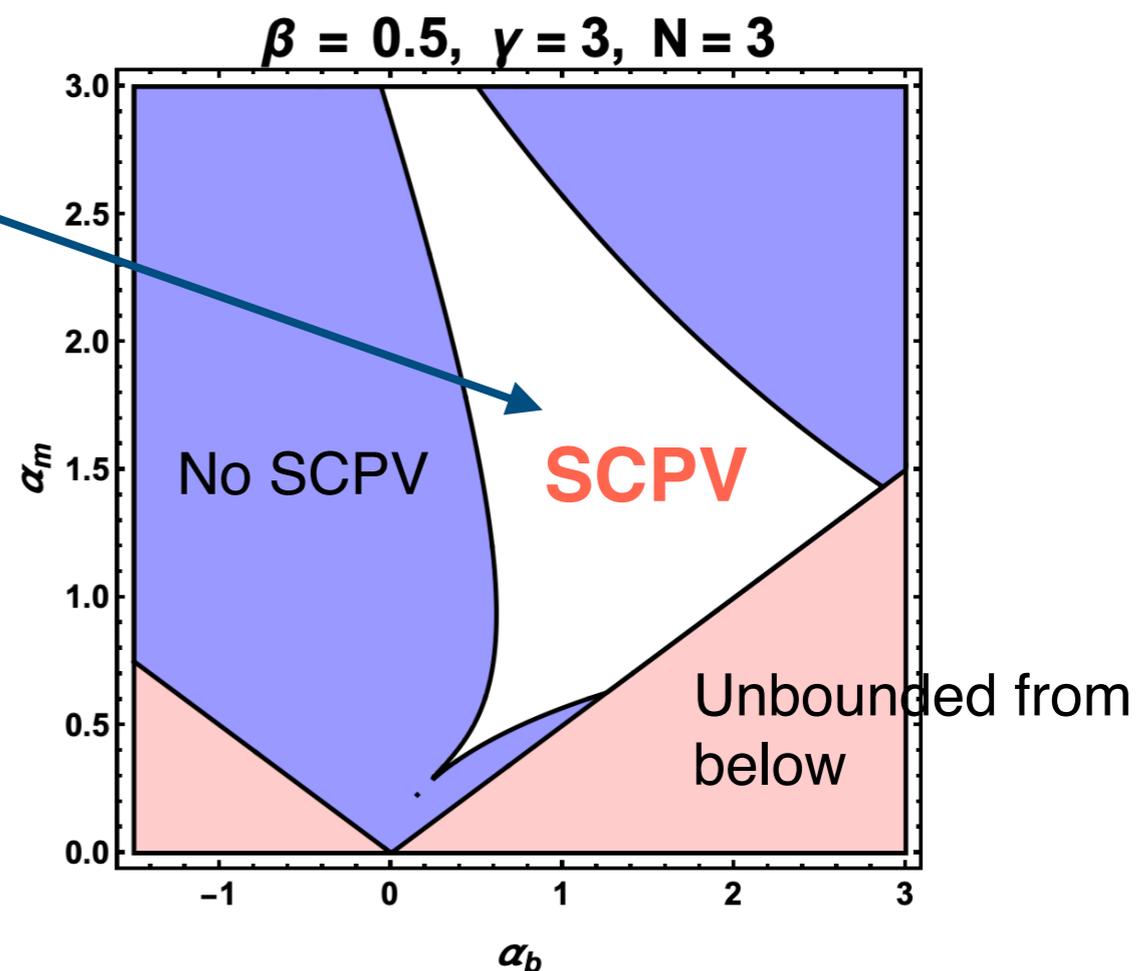
Stabilized at a non-trivial value ($\neq 0, \pi$)

All directions properly stabilized.

Existence of light modes :

$$m_a^2 \sim m_s^2 \lesssim m_{\text{soft}}^2$$

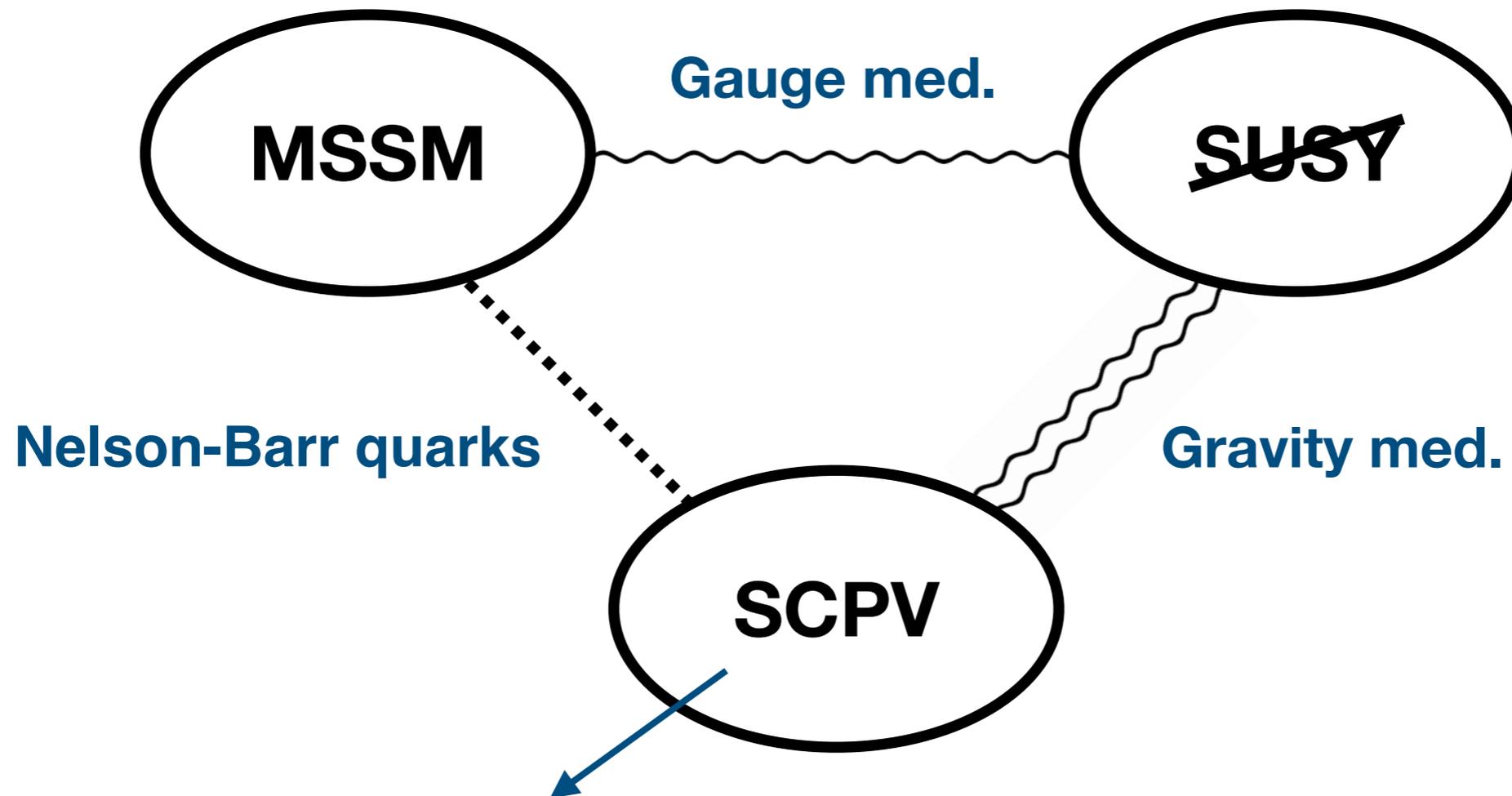
Much smaller than SCPV scale !



$$\alpha_b \equiv b_2/b_1, \alpha_m \equiv m_2^2/m_1^2, \beta \equiv b_1/m_1^2, \gamma \equiv \Lambda^{6 - \frac{2}{N}} / (m_1^2 v^{4 - \frac{2}{N}})$$

SCPV via ~~SUSY~~

Solving the strong CP problem via SCPV



$$m_a^2 \sim m_s^2 \sim m_{3/2}^2 < (10 - 100 \text{ keV})^2$$

Light particles feebly interacting with SM are predicted !

Detailed phenomenology & cosmology will be explored in a future study.

CP Violation

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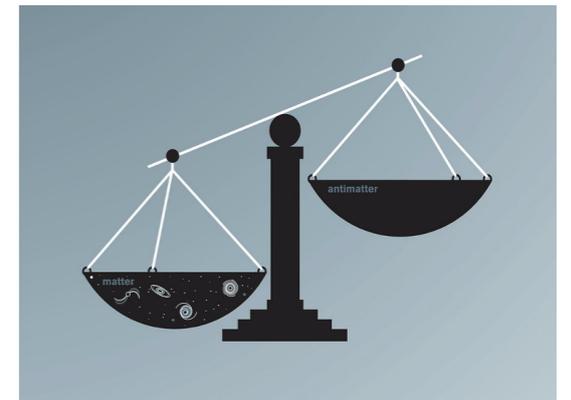


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Baryogenesis

Considering SCPV ...

Fujikura, YN, Sato, Yamada (2022)

- What is **the source of CPV** for baryogenesis?
- High reheating temperature for thermal leptogenesis causes **the overproduction of gravitinos.**

Affleck-Dine (AD) mechanism

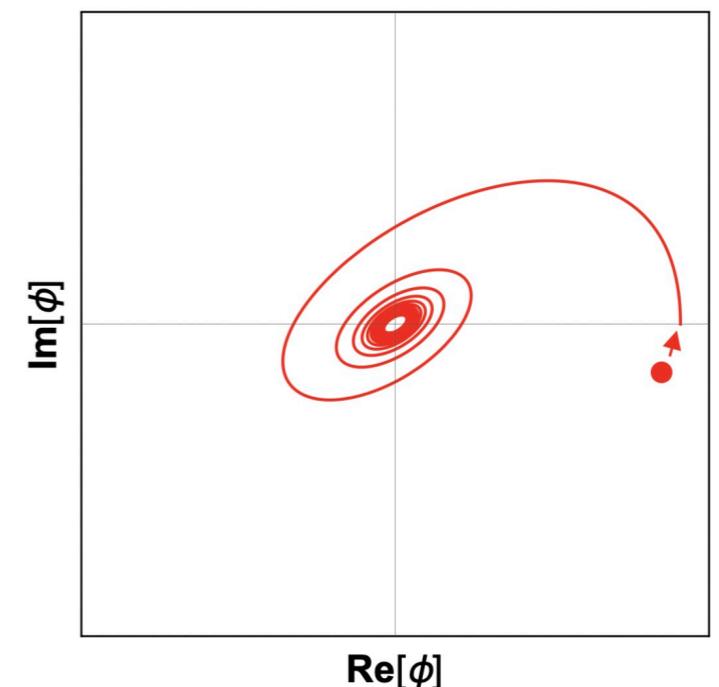
realized in SUSY and compatible with a low reheating temperature.

- ✓ **AD field** (ϕ) coherent rotational motion leads to baryon asymmetry.

$$\phi^3 \approx Q\bar{q}L$$

$$\phi = \frac{\varphi}{\sqrt{2}} e^{i\theta}, \quad n_{B-L} = q_{B-L} \varphi^2 \dot{\theta}$$

- ✓ Explicit CPV is not needed.



Baryogenesis

Fujikura, YN, Sato, Yamada (2022)

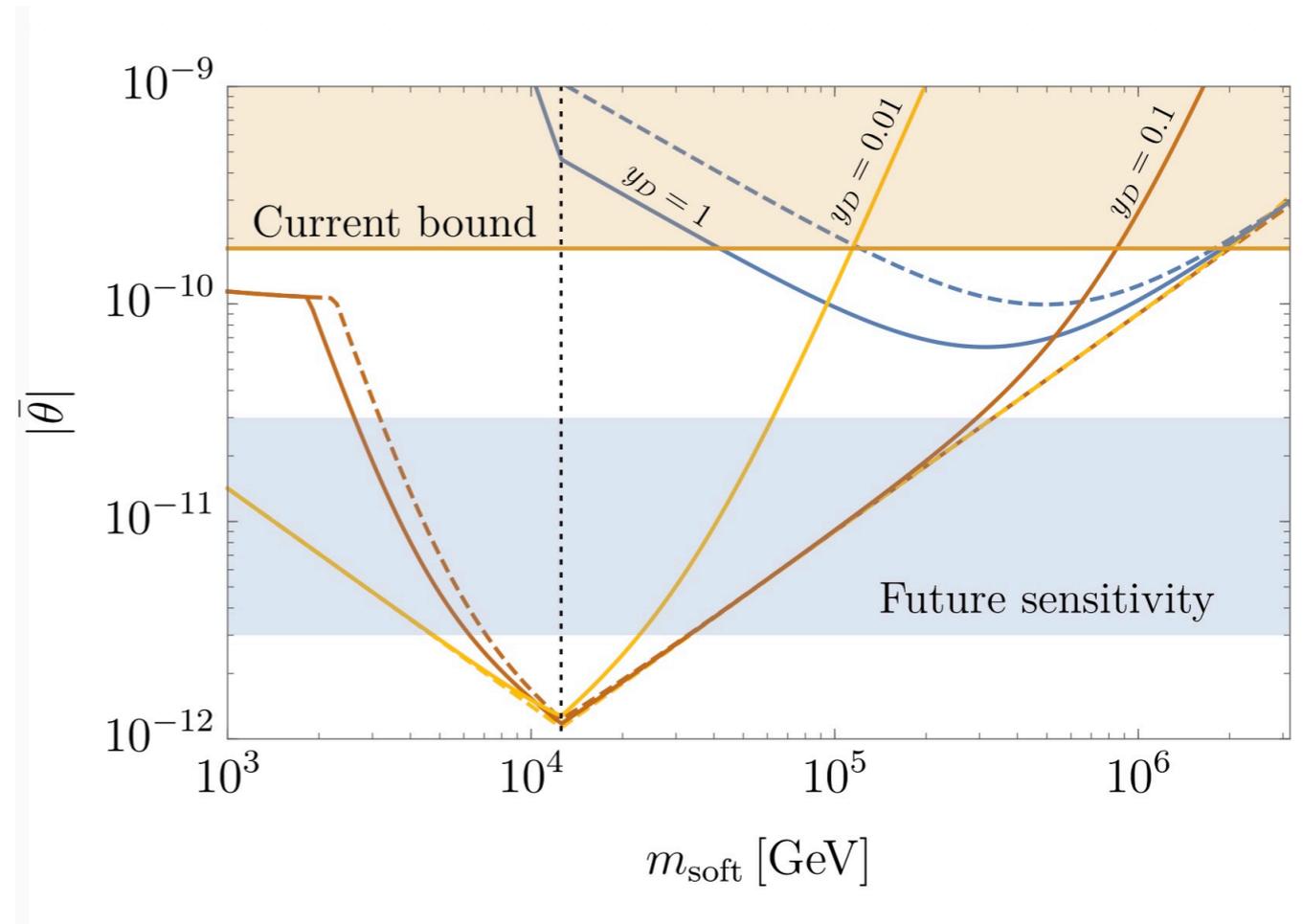
If **gravitino** gives DM ...

Lyman- α constraint $\rightarrow m_{3/2} \gtrsim 5.3 \text{ keV}$

Smallest value of $\bar{\theta}$

SCPV scale and reheating temperature are chosen to obtain the observed asymmetry and DM.

Consistency with SCPV via ~~SUSY~~ will be explored in a future study.



Neutron EDM is within the reach of near-future experiments !

Summary

- **Spontaneous CP violation (SCPV)** provides an axionless solution to the strong CP problem.
- It's reasonable to consider SCPV in **SUSY**, solving critical issues.
- SCPV vacuum stabilization via **SUSY breaking** predicts **light particles feebly interacting with SM**.
- **Affleck-Dine baryogenesis** is compatible with SCPV.
- **Neutron EDM** is within the reach of near-future experiments.

Thank you.