Dynamical Relaxation of Axion Misalignment in the Early Universe

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Background

Why QCD Axion Dark Matter?

- Three questions for any dark matter (DM) candidate:
  - **Does it solve other problems in physics?**

  - **Can it be produced in the early universe?**
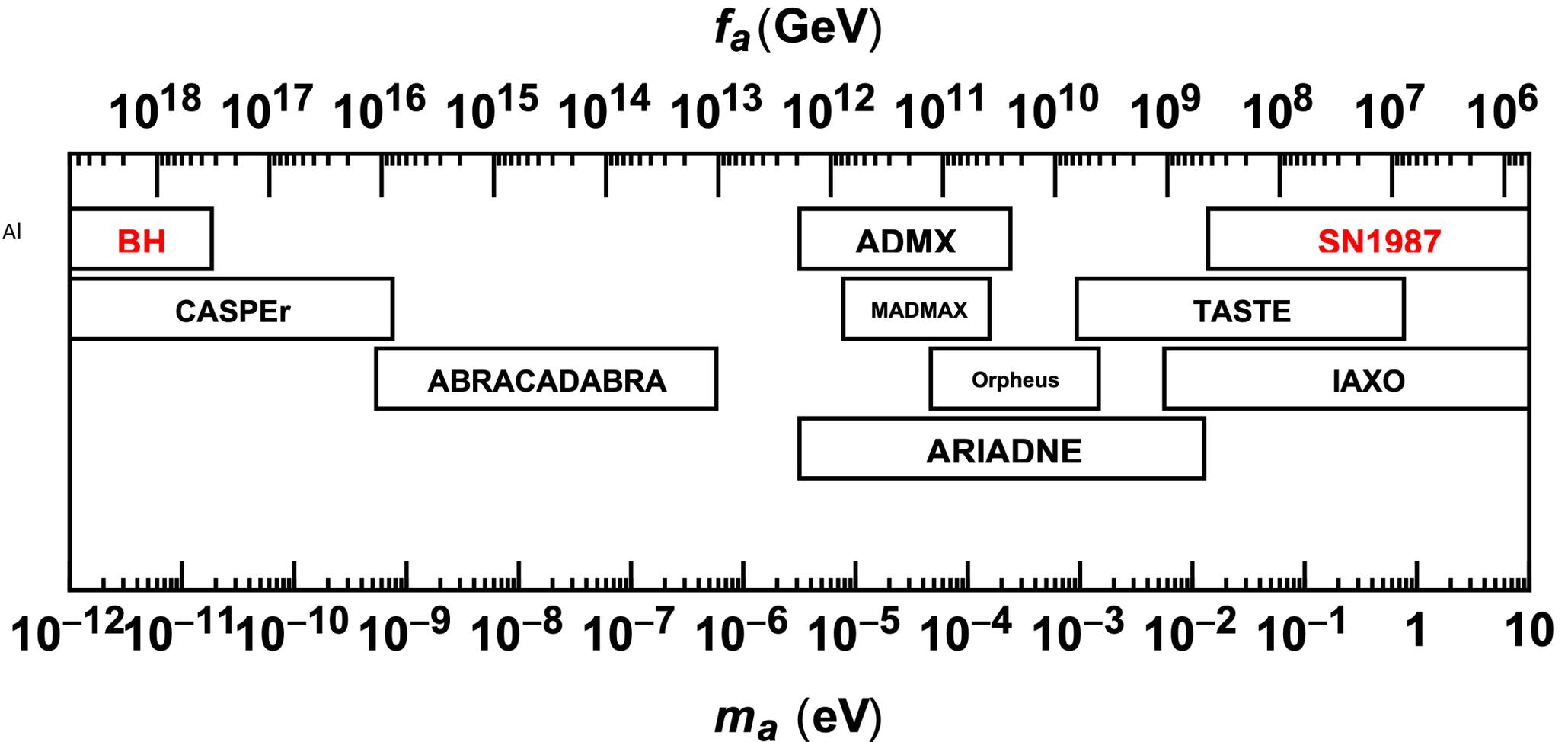
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  - QCD Axion DM can be produced non-thermally
    - Misalignment, Topological Defects
  - **Is it detectable?**

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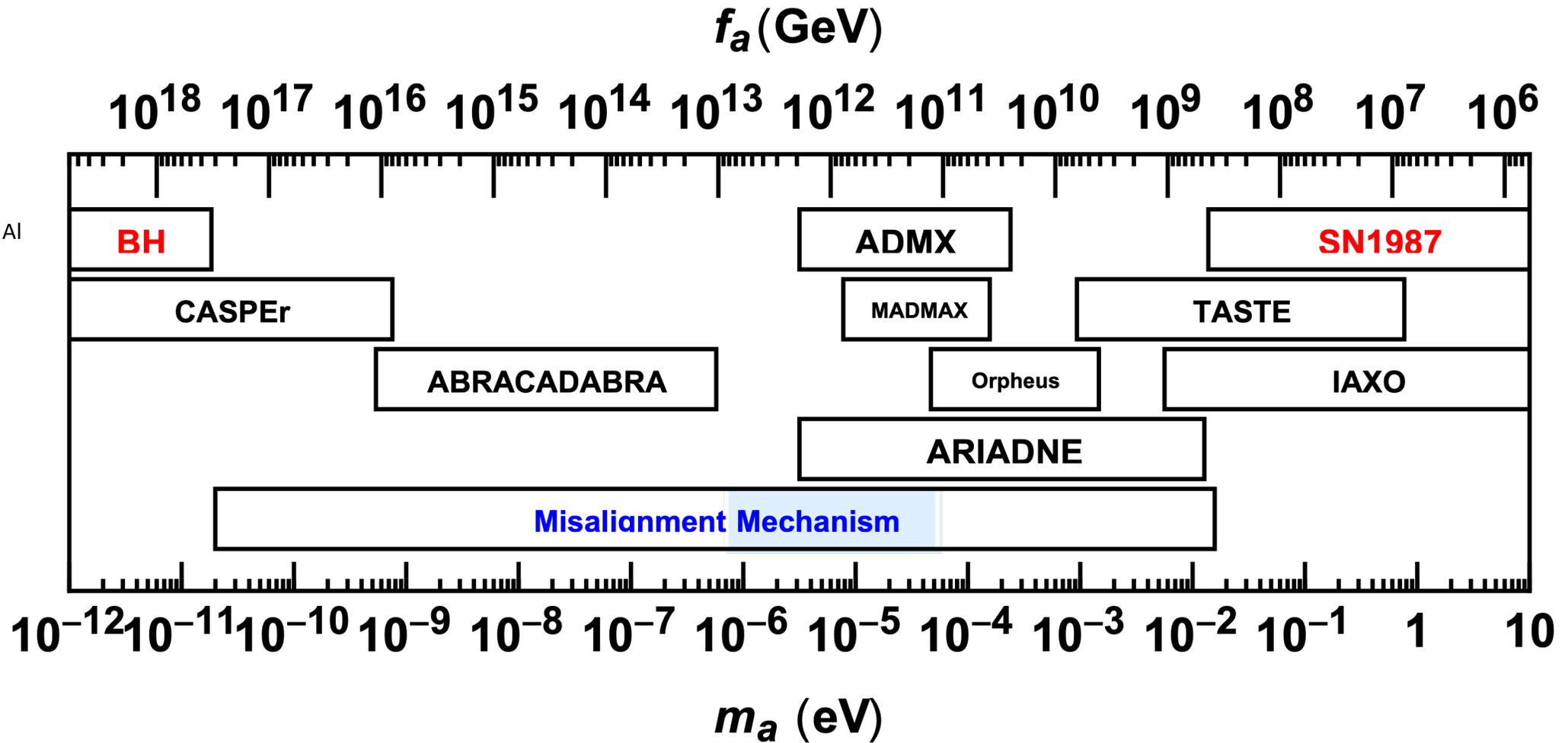 - **Is it detectable?**
  - Many experiments, current and planned.

QCD Axion Experiments

$$f_a \, (\text{GeV})$$

$10^{18} \quad 10^{17} \quad 10^{16} \quad 10^{15} \quad 10^{14} \quad 10^{13} \quad 10^{12} \quad 10^{11} \quad 10^{10} \quad 10^{9} \quad 10^{8} \quad 10^{7} \quad 10^{6}$

Arvanitaki et. Al
1411.2263

Raffelt
0611350

BH **ADMX** **SN1987**

CASPEr **MADMAX** **TASTE**

ABRACADABRA Orpheus **IAXO**

ARIADNE

$10^{-12} \, 10^{-11} \, 10^{-10} \, 10^{-9} \quad 10^{-8} \quad 10^{-7} \quad 10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \quad 10$

$$m_a \, (\text{eV})$$

Co, EG, Harigaya (1812.11186,
1812.11192)

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7

Misalignment Mechanism (Pre-Inflationary PQ Breaking)

f_a (GeV)

10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^9 10^8 10^7 10^6

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8

Standard Misalignment Mechanism

$$\ddot{\theta}_a + 3H\,\dot{\theta} = -m_a^2 \sin\theta_a$$

$H > m_a$ axion is frozen

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$H < m_a$ axion oscillates

$$\Omega_a h^2 = 0.12\,\theta_{mis}^2\,\mathcal{F}(\theta_{mis})\left(\frac{f_a}{5 \times 10^{11}\,\mathrm{GeV}}\right)^{\frac{7}{6}}$$
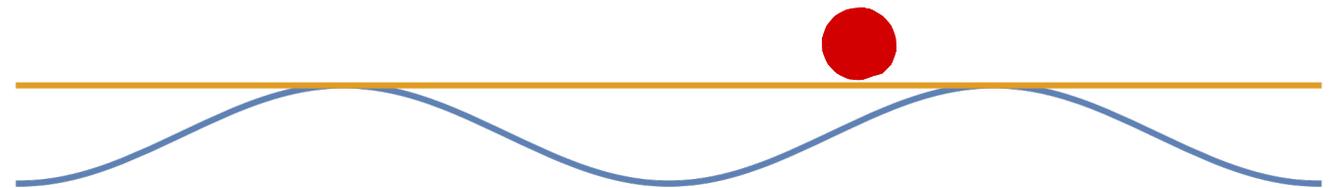
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Case 1
Large Decay Constant

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Standard Misalignment Mechanism

Assumed same potential
in early universe:

No Early Universe
Dynamics
in Standard picture

$H > m_a$ axion is frozen

New Early Universe Axion Dynamics

Lift Assumption:

Axion can relax in Early Universe

Lifted assumption provides scenario where $\theta_{mis} \ll 1$

$H > m_a$ axion is frozen

$H < m_a$ axion oscillates

Axion Mass and Λ_{QCD}

$$m_a \propto \frac{\Lambda_{\mathrm{QCD}}^2}{f_a}$$

$$\mu_r \frac{d}{d\mu_r} \frac{8\pi^2}{g^2} = 3N - F$$

$$\mathcal{L} \subset \lambda_u u^c Q \phi_u + \lambda_d d^c Q \phi_d$$

Early Universe α_s

Today's α_s

Renormalization Scale [GeV]

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Λ_{QCD} and the Higgs VEV

$$m_a \propto \frac{\Lambda_{\text{QCD}}^2}{f_a}$$

$$\Lambda_{\text{QCD}}^3 \propto \langle \phi \rangle^2$$

Dvali 9505253
Banks and Dine 9608197

Hubble Induced Mass

$$\Delta K \sim \frac{|X|^2}{M^2}|\phi|^2 - \frac{|X|^2}{M^4}|\phi|^4$$

$$V_\phi \sim (m_\phi^2 - cH_I^2)|\phi|^2$$
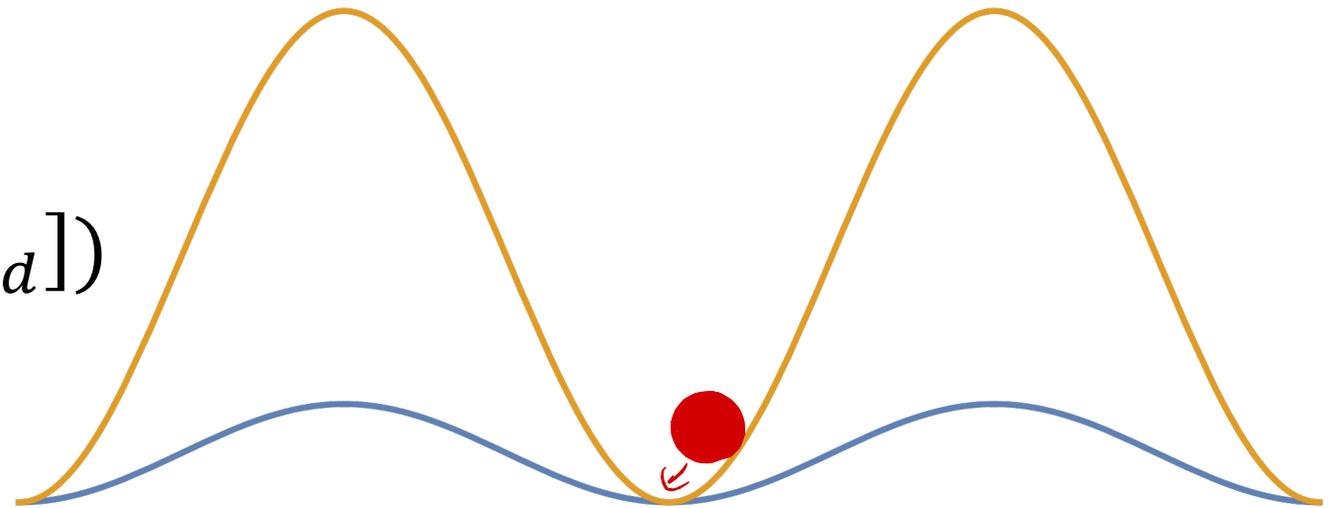$$+ \frac{cH_I^2}{M^2}|\phi|^4 + \cdots$$

—— Early Universe V_ϕ

—— Low Temp. V_ϕ

Phase of the Axion Potential

$$\bar{\theta} = \theta_{\text{QCD}} + \arg(\det[m_u m_d]) + \cdots$$

$$\bar{\theta}_{\text{MSSM}} = \theta_{\text{QCD}} + \arg(\det[\lambda_u \lambda_d])$$
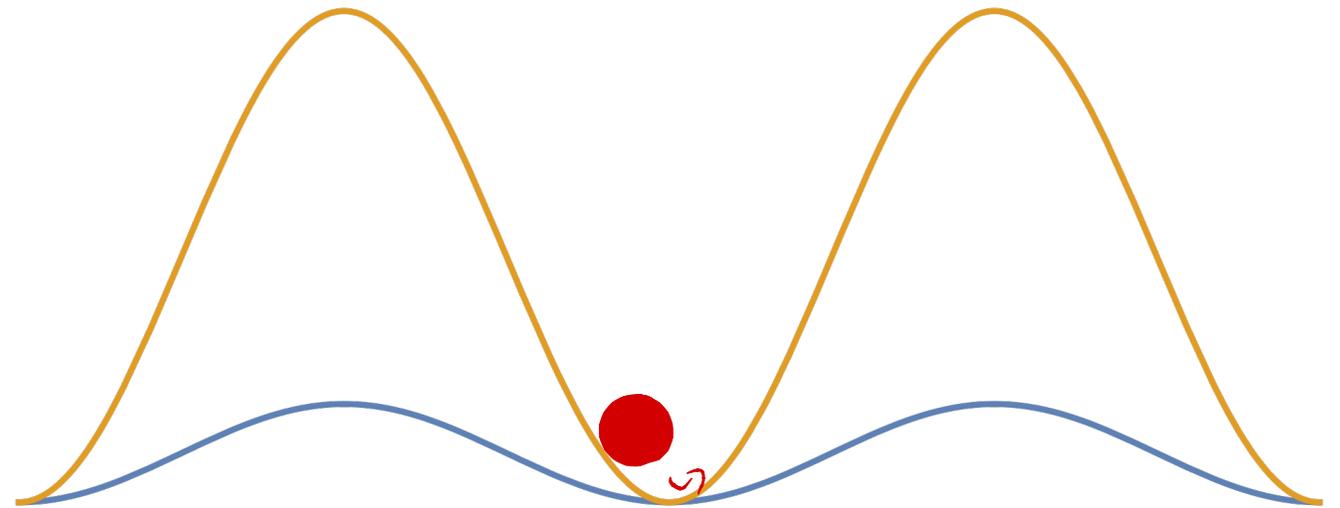$$+3\arg(B\mu) + \cdots$$

Legend: Early Universe V_a — Low Temp. V_a

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Dynamical Axion Misalignment Production

Two criteria for DAMP:

1) Axion must relax
in the early universe

2) CP structure relates
Early/Late axion
potential minima

— Early Universe V_a

— Low Temp. V_a

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Case 2
Small Decay Constant

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Phase of the Axion Potential

$$\bar{\theta}_{\mathrm{MSSM}} = \theta_{\mathrm{QCD}} + \arg(\det[\lambda_u \lambda_d])$$
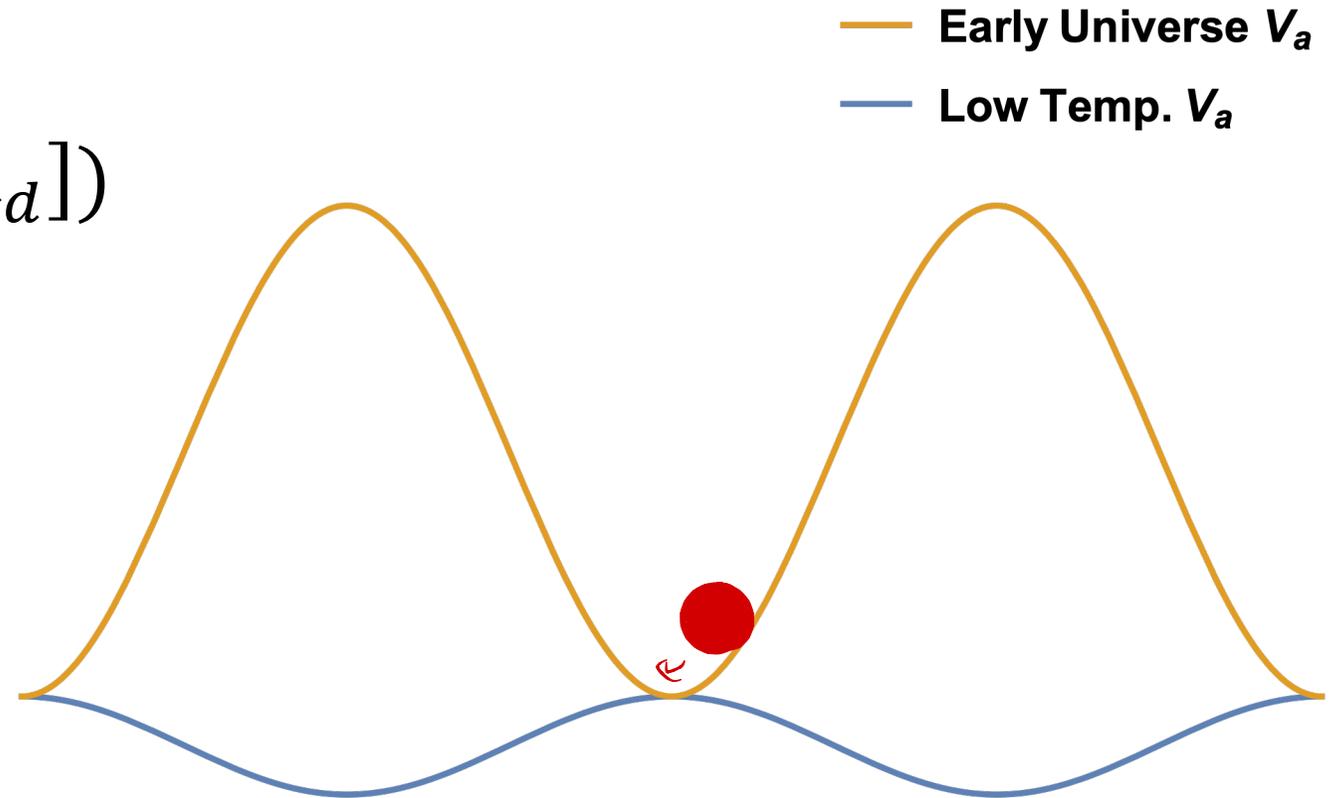$$+3\arg(B\mu)$$

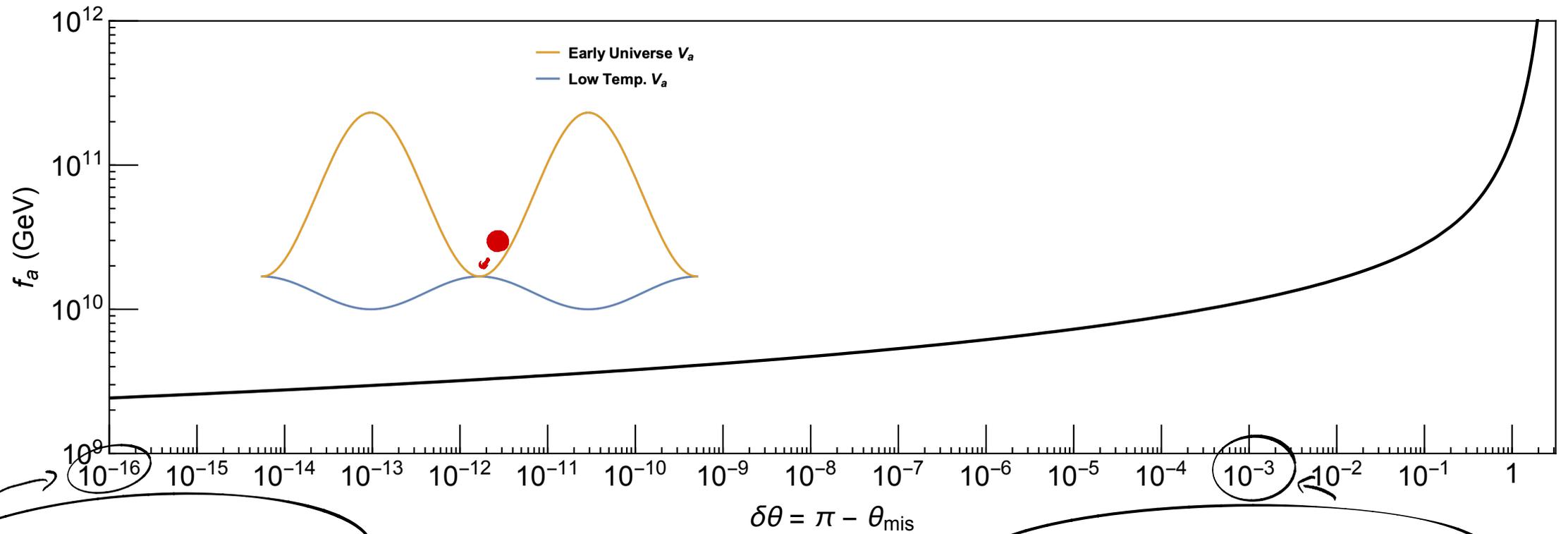Eric Gonzalez

Mass of the Higgs Phase

$$\bar{\theta}_{\mathrm{MSSM}} = \theta_{\mathrm{QCD}} + \arg(\det[\lambda_u \lambda_d])$$
$$+3\arg(B\mu)$$

$$V_\phi \sim (B\mu - cH_I^2)\phi_u\phi_d$$

Shifting the Potential

$$\bar{\theta}_{\mathrm{MSSM}} = \theta_{\mathrm{QCD}} + \arg(\det[\lambda_u \lambda_d])$$
$$+3\arg(B\mu)$$

$$V_\phi \sim (B\mu - cH_I^2)\phi_u\phi_d$$
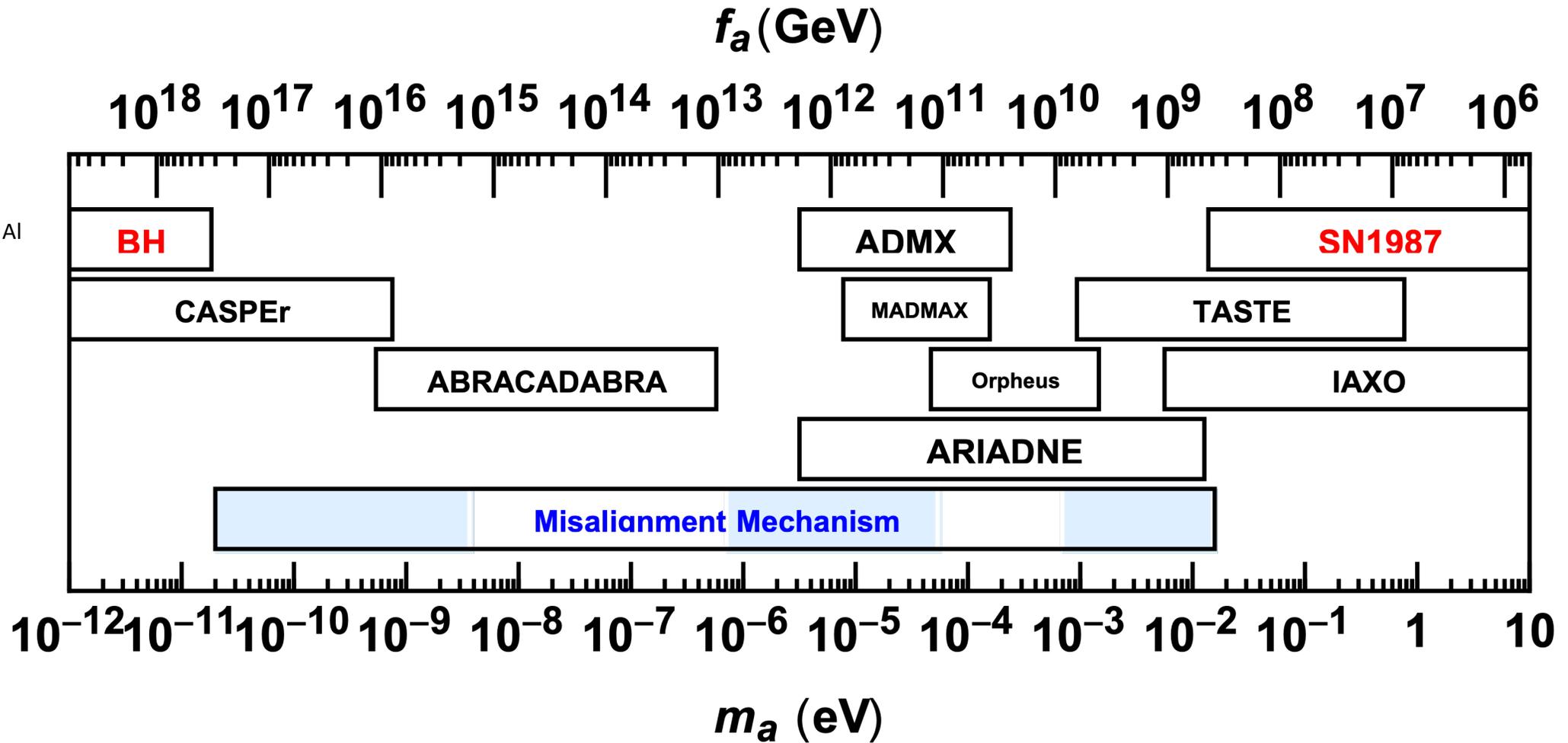
π shift if $B\mu < cH_I^2$

— Early Universe V_a
— Low Temp. V_a

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Anharmonic Effect

CPV from Yukawa Couplings

Electron EDM in TeV scale SUSY

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New Motivated Regions

Summary Table

$\textbf{DAMP}_0$	$\textbf{DAMP}_\pi$
$\boldsymbol{\theta_i \to 0}$	$\boldsymbol{\theta_i \to \pi}$
Decay constant predicted by CP structure	
Isocurvature perturbations are suppressed. Jeong and Takahashi 1308.8131	
$f_a \gtrsim 10^{16}$ GeV typical string axion scale. Svrcek and Witten 0605206	Anharmonic effect could enhance structure formation. Greene, Kofman, and Starobinsky 9808477

Early Universe V_a
Low Temp. V_a

Co, EG, Harigaya (1812.11186, 1812.11192)

Thank you!

Cosmology Bounds

Early Universe Axion Dynamics

$$\bar{\theta} = \theta_{\mathrm{QCD}} + \arg(\det[m_u m_d]) + \cdots$$

$$\mathcal{L} \subset \lambda_u u^c Q \phi_u + \lambda_d d^c Q \phi_d$$

$$\bar{\theta}_{\mathrm{MSSM}} = \theta_{\mathrm{QCD}} + \arg(\det[\lambda_u \lambda_d]) + 3\arg(B\mu)$$

Legend:
— Early Universe V_a
— Low Temp. V_a

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