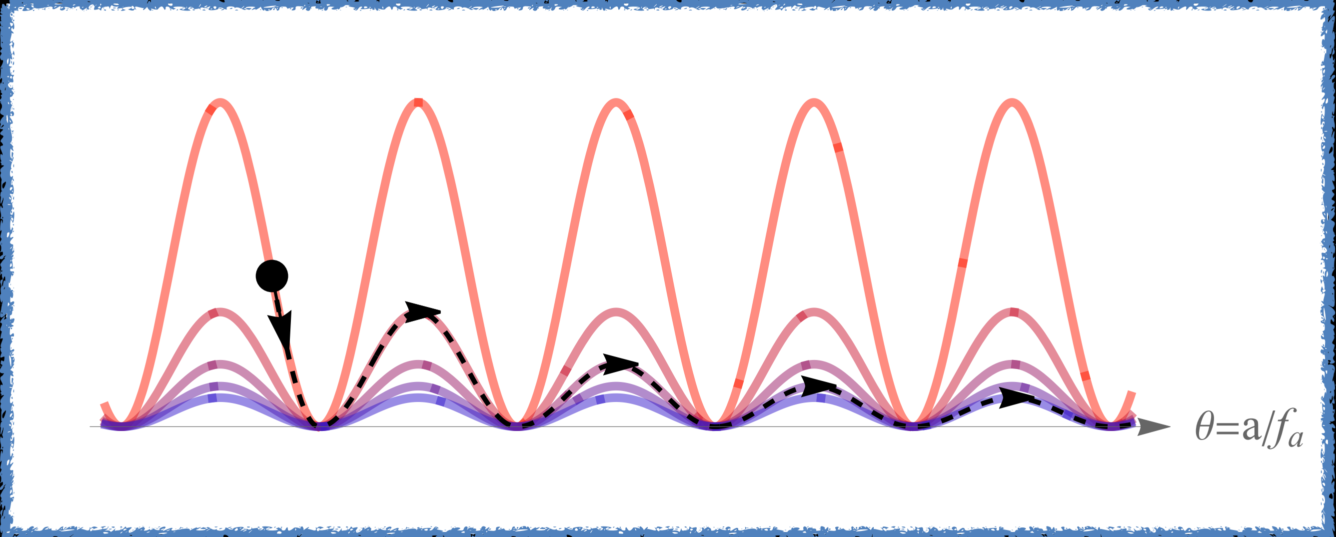
Cogenesis by a sliding pNGB with symmetry non-restoration



Suruj Jyoti Das

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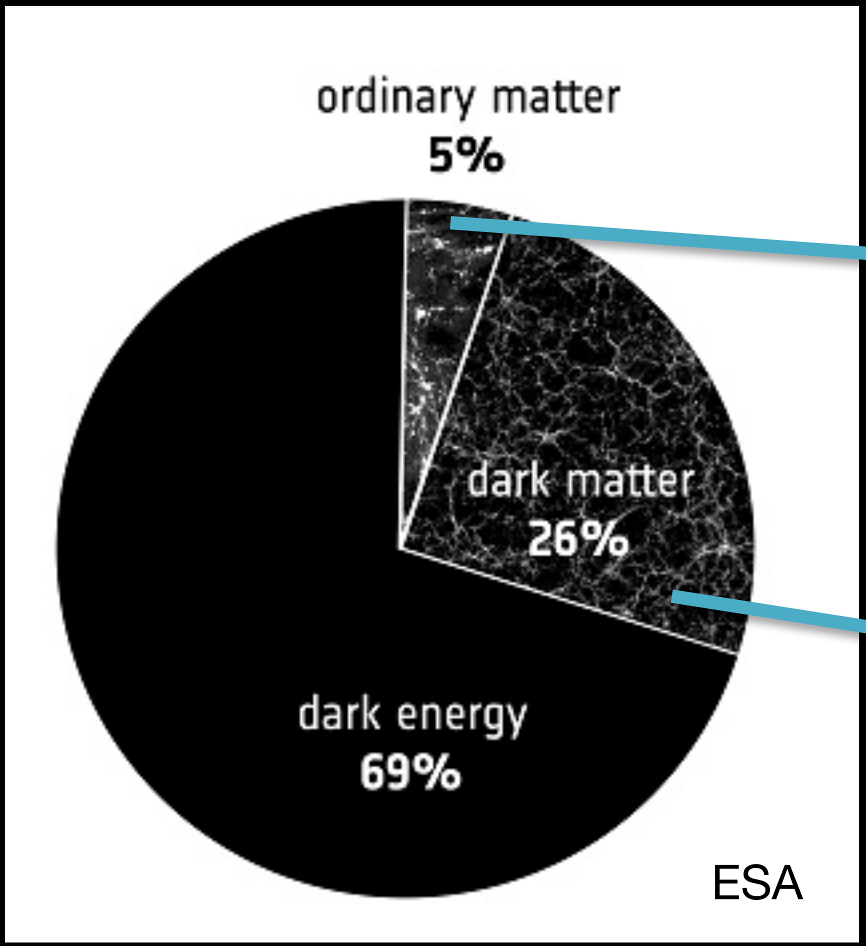
Light Dark World 2024

Based on:
arXiv: 2406.04180

Collaborators:
Eung Jin Chun (KIAS),
Minxi He, Tae Hyun Jung, Jin Sun (IBS)



Baryon Asymmetry (from BBN and CMB):

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = 8.7 \times 10^{-11}$$

Dark Matter abundance(from CMB):

$$\Omega_{DM} h^2 = \frac{\rho_{DM}}{\rho_{total}} h^2 = 0.12$$

Cogenesis of Baryon and Dark Matter?

Leptogenesis, EW baryogenesis,
Spontaneous Baryogenesis …

WIMP, FIMP,
Misalignment …

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Storyline…..

- Introduction.
- Our idea (with symmetry non-restoration).
- An explicit example.
- Summary.

How to generate asymmetry?

Sakharov conditions:

- B / L violation.
- C and CP violation.
- Departure from equilibrium.

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A pseudo Nambu Goldstone boson after spontaneous breaking of some global symmetry

Spontaneous baryogenesis

- CPT violation induced by background.
- External chemical potential for B,L.

Source: $(\partial_\mu \theta)\, J^\mu_{B,L}$

- Chemical potential: $\mu \propto \dot{\theta}$

Asymmetry: $n_B/s \propto \dot{\theta}/T$

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$\theta?$

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How to generate $\dot{\theta}$?

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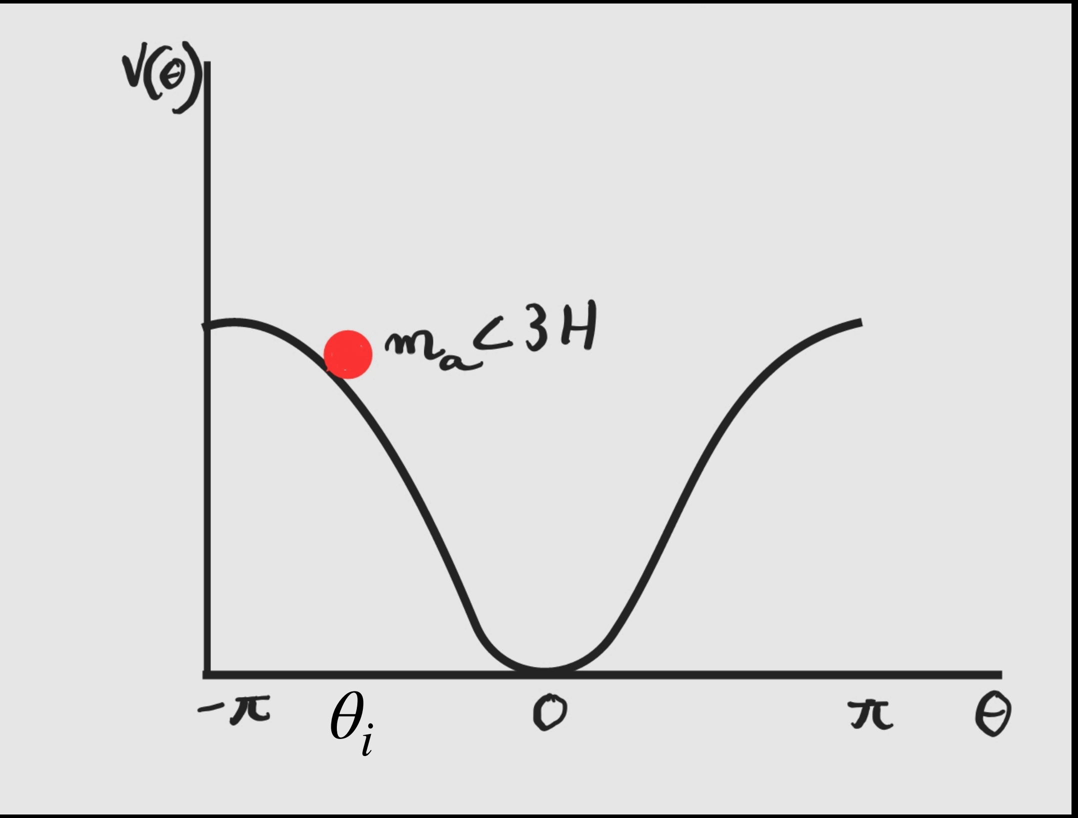
The Misalignment Mechanism

$$\mathscr{L} \supset f_a^2 \partial_\mu \theta \partial^\mu \theta - m_a^2(T) f_a^2 (1 - \cos(\theta))$$

EOM: $$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

Initial conditions: $\theta \neq 0 \quad \dot{\theta} = 0$



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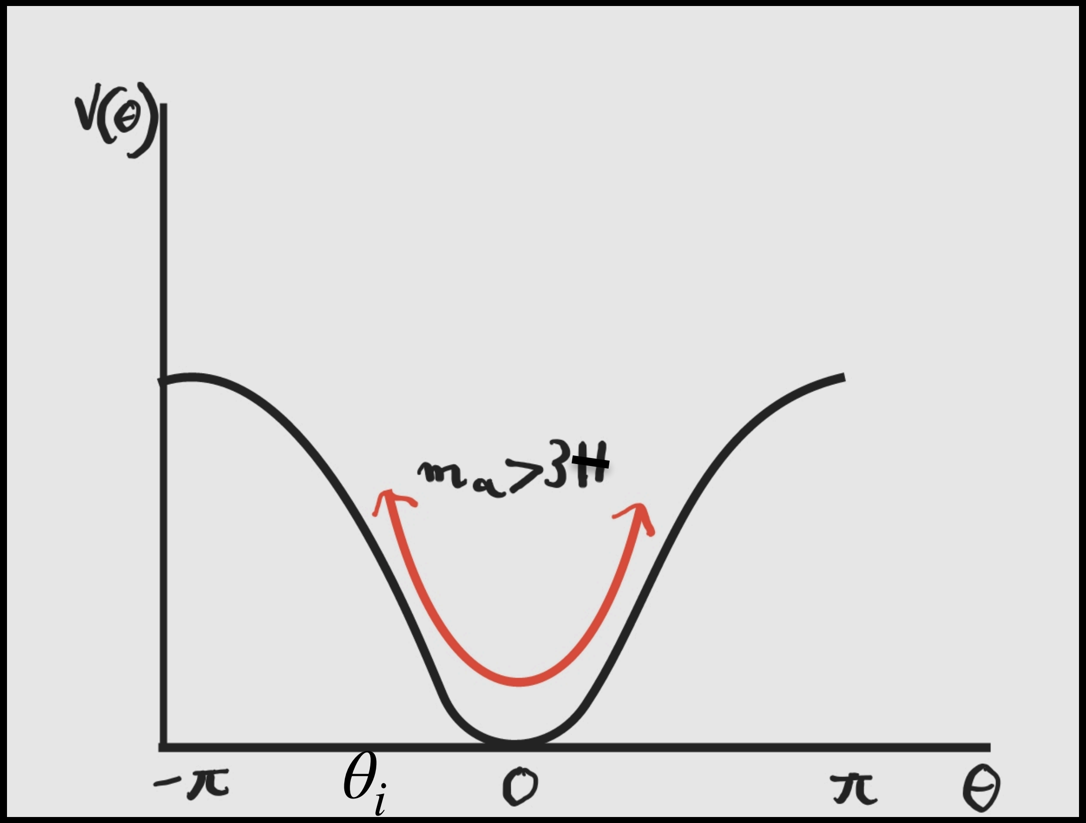

Oscillation:

- leads to non-zero

  $\dot{\theta}$ Asymmetry

- Relic density

$$\rho_\theta^{(0)} \simeq m_a^{(0)} n_a^{(0)}$$

$$\sim \frac{1}{2} m_a^{(0)} \theta_i^2 m_a^{\rm osc} f_a^2 \left(\frac{a^{\rm osc}}{a^{(0)}} \right)^3$$

DM

Cogenesis in the conventional misalignment ?

Problems

- $T_* \sim T_{osc}$
- $\rho_{osc} \gg \rho_{DM}$

T_* freezeout of asymmetry

Asymmetry:

$$n_B/s \approx \dot{\theta}(T_*)/g_* T_* \sim m_a/g_* T_{osc}$$

$$\Longrightarrow \; m_a \sim O(10^2) \text{ GeV}, \; T_{osc} \simeq \sqrt{m_a M_{Pl}} \sim O(10^{10}) \text{ GeV}.$$

Dark Matter:

$$\rho_{osc} / s \sim m_a^{1/2} f_a^2 / g_* M_{Pl}^{3/2} \gg \rho_{DM} / s \simeq 0.44 \text{ eV}$$

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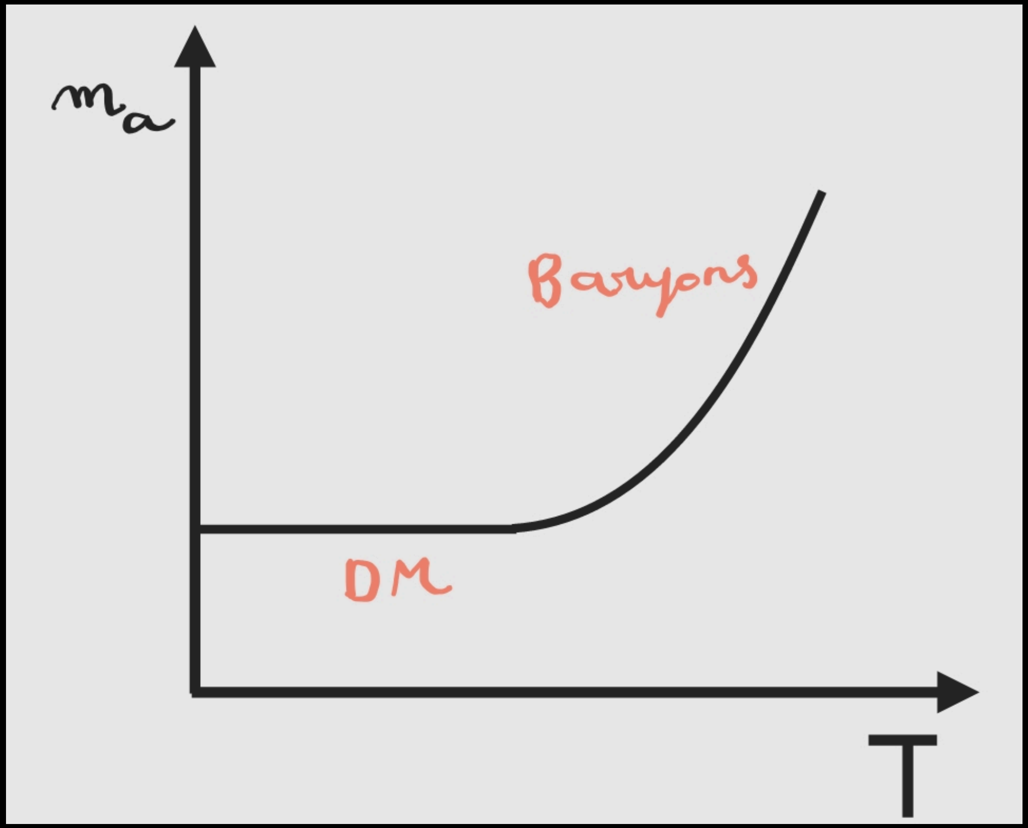
Our idea

- m_a and f_a time-dependent.

$$\Downarrow$$



- $\dot{\theta}/T$ sizable and constant before $T_{osc.}$
- Baryogenesis at $T_* > T_{osc.}$
- Oscillation at low temperature : DM.

Scalar potential:

$$V(\Phi) = \lambda_\phi |\Phi|^4 - m_0^2 |\Phi|^2 .$$

$$\Phi = \frac{1}{\sqrt{2}} \phi \, e^{ia/f_a}$$

pNGB

$$\langle |\Phi| \rangle = m_0 / \sqrt{2\lambda_\phi} \equiv f_a^{(0)} / \sqrt{2}$$

Explicit breaking of U(1):

$$\frac{\Phi^n}{\Lambda^{n-4}} \Rightarrow V_a(a) \simeq \frac{f_a^n}{\Lambda^{n-4}} \left(1 - \cos\left(\frac{na}{f_a}\right)\right)$$

$$\langle \phi \rangle_T = f_a(T)$$

⇓

Mass of pNGB:

$$m_a^2(T) \sim \left(\frac{f_a(T)}{\Lambda}\right)^{n-4} f_a(T)^2 .$$

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$$m_a^2(T) \sim \left(\frac{f_a(T)}{\Lambda}\right)^{n-4} f_a(T)^2 .$$

How to realize f_a (T)?

Symmetry non-restoration

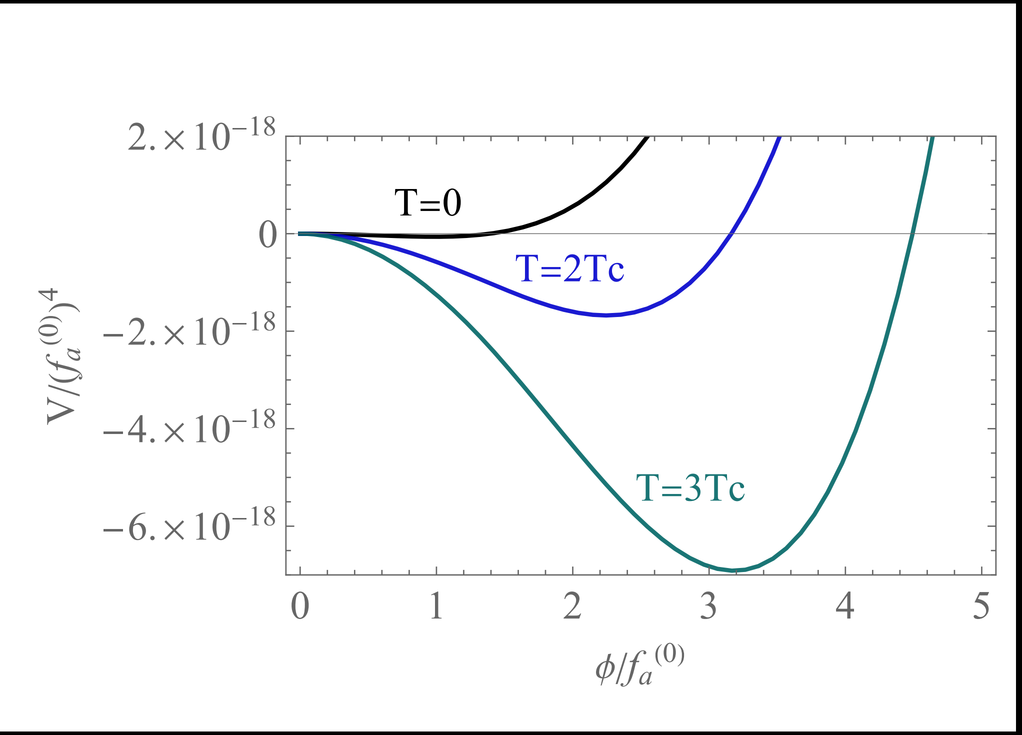
(S. Weinberg 1974)

Thermal corrections with **negative** contribution:

$$\Delta V = -2\lambda_{h\phi}|H|^2|\Phi|^2 \quad \text{or} \quad \Delta V = -\lambda_{\phi s_i}|\Phi|^2 s_i^2$$

SM Higgs

Temp. dependent V: $V_T(\phi) \simeq \frac{\lambda_\phi}{4}\phi^4 - \frac{1}{2}(m_0^2 + c\,T^2)\phi^2$



$$f_a(T) = \sqrt{f_a^{(0)2} + c_\lambda T^2} \qquad c_\lambda \equiv c/\lambda_\phi$$

For

$T > T_c \equiv f_a^{(0)} / \sqrt{c_\lambda}$ → $f_a(T) \propto T$ $\quad m_a(T) \propto T^{(n-2)/2}$

$c_\lambda \simeq \lambda_{\text{mix}}/3\lambda_\phi \qquad \lambda_{\text{mix}} \equiv \lambda_{h\phi} + \sum_i \lambda_{\phi s_i}/4$

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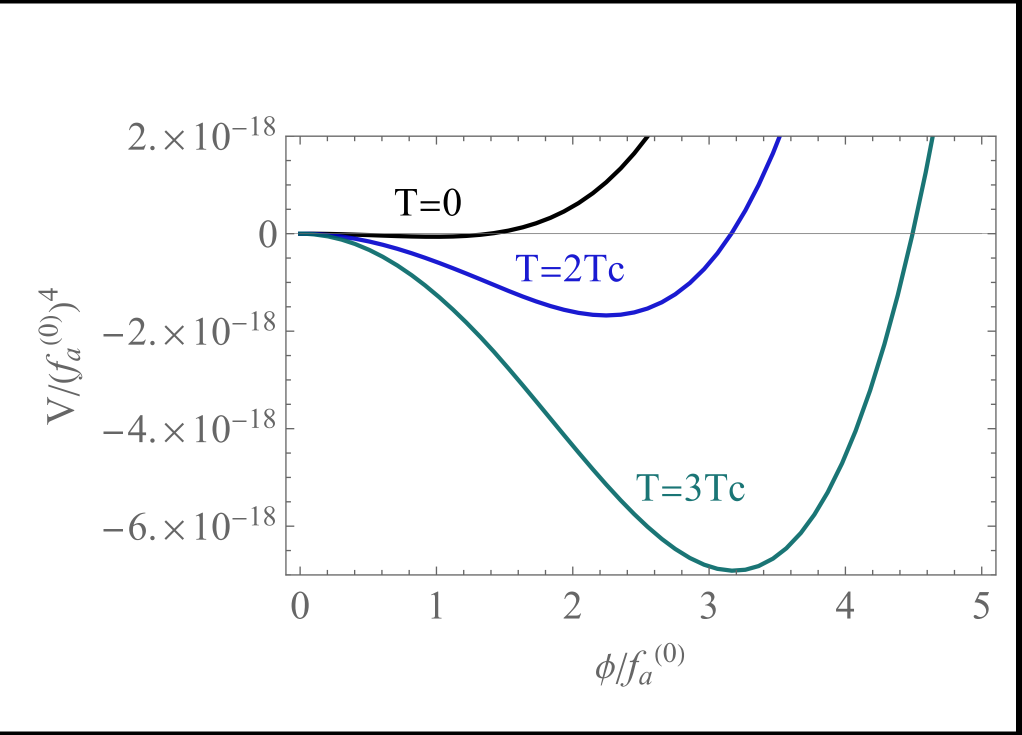

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$$\phi\phi \leftrightarrow aa \implies c_\lambda \gtrsim 10^7$$

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pNGB Dynamics (n=5)

Modified E.O.M. :

$$\ddot{\theta} + \left(3H + 2\frac{\dot{f}_a}{f_a} \right) \dot{\theta} = -\frac{1}{n} m_a^2(T) \sin(n\theta)$$

$-H$

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$-H$

1st epoch: H(T) > m(T)

$$\ddot{\theta} + H\dot{\theta} = -\frac{1}{n}m_a^2(T)\sin(n\theta)$$

constant

pNGB is frozen

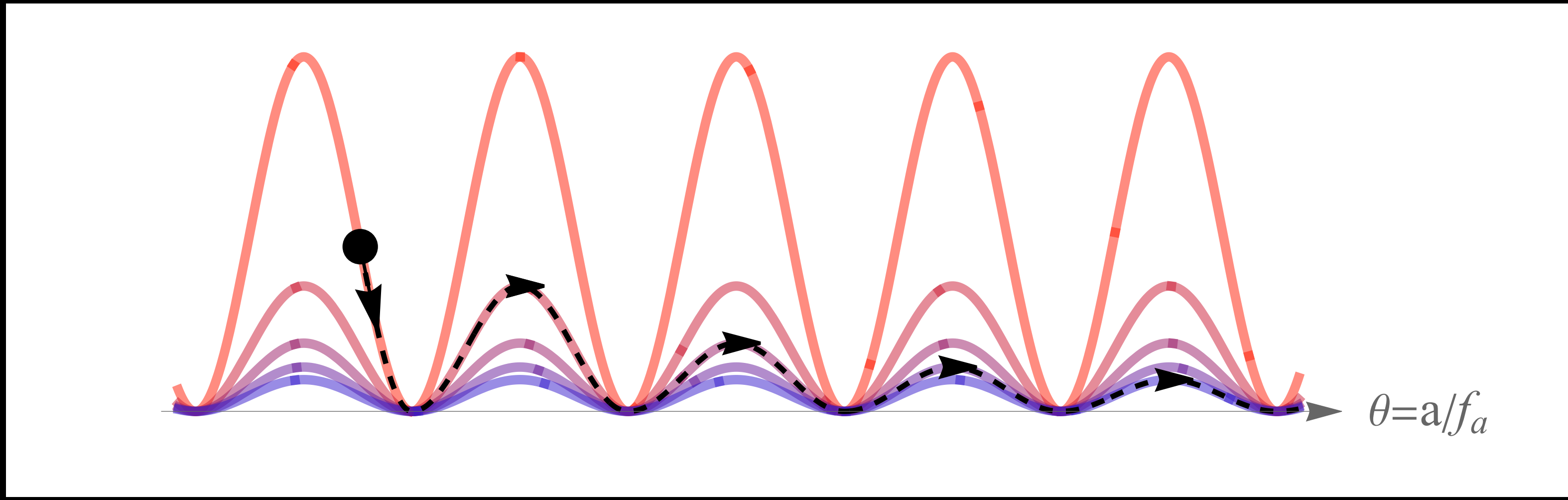
until….

$$H(T) = m(T) \implies T_0$$

2nd epoch: $T < T_0$

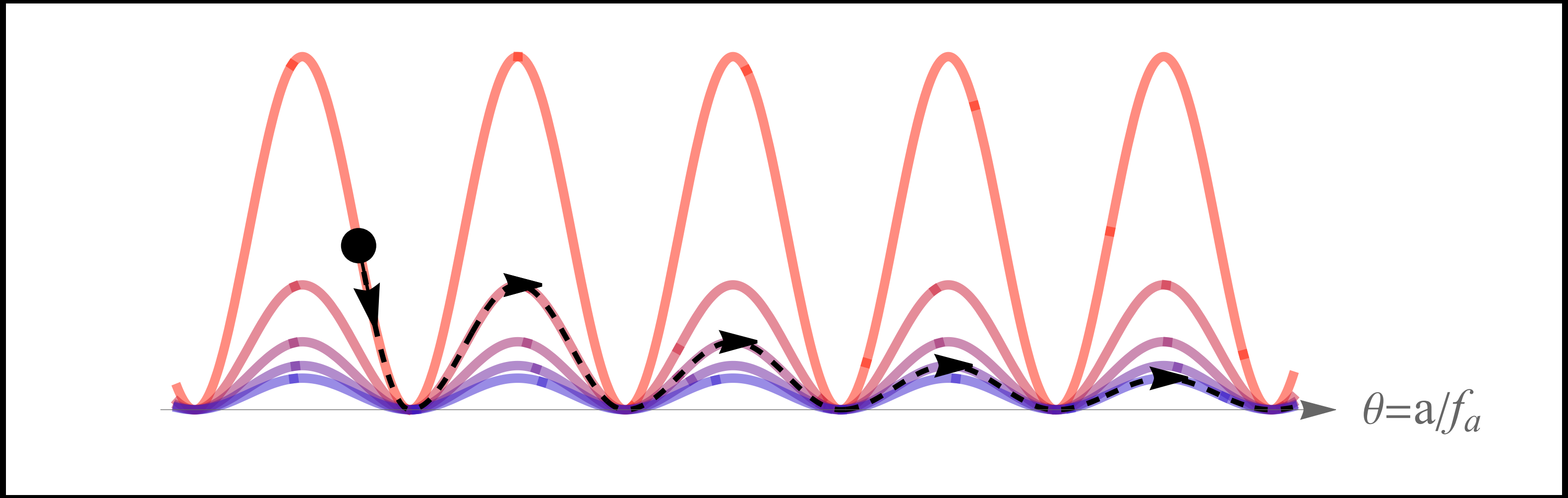
Oscillation?

pNGB slides



K.E. = Barrier $\Longrightarrow$ $\dot{\theta}(T_{\rm slide}) \simeq \frac{2}{5} m_a(T_{\rm slide})$

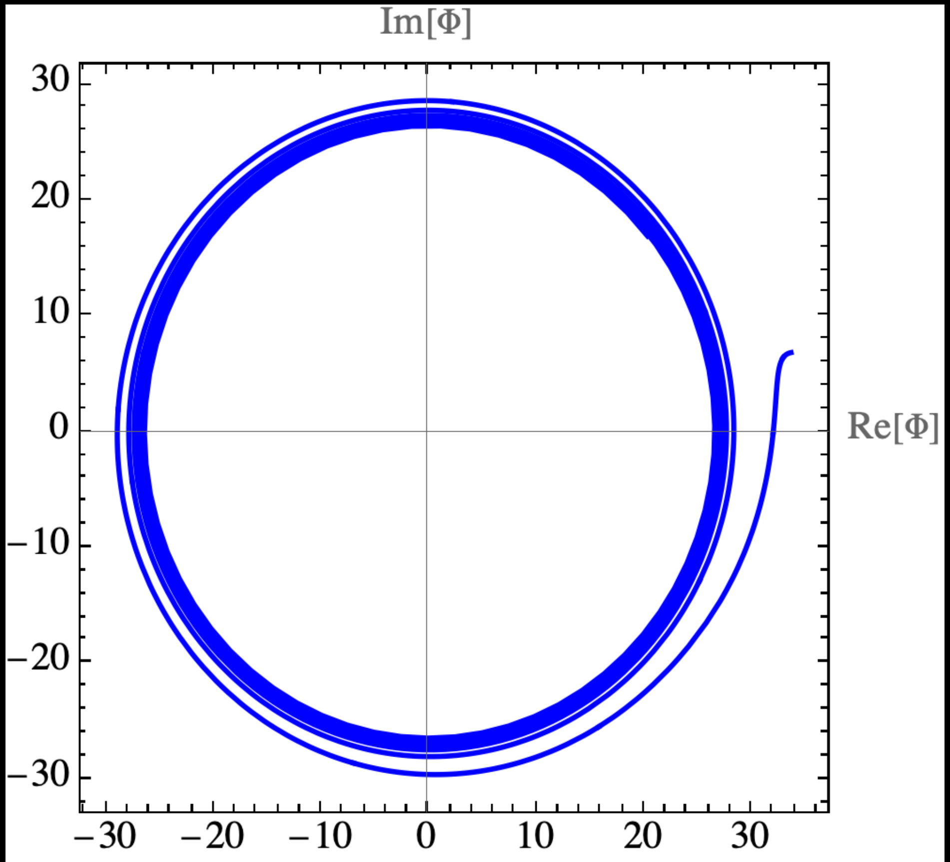
pNGB slides



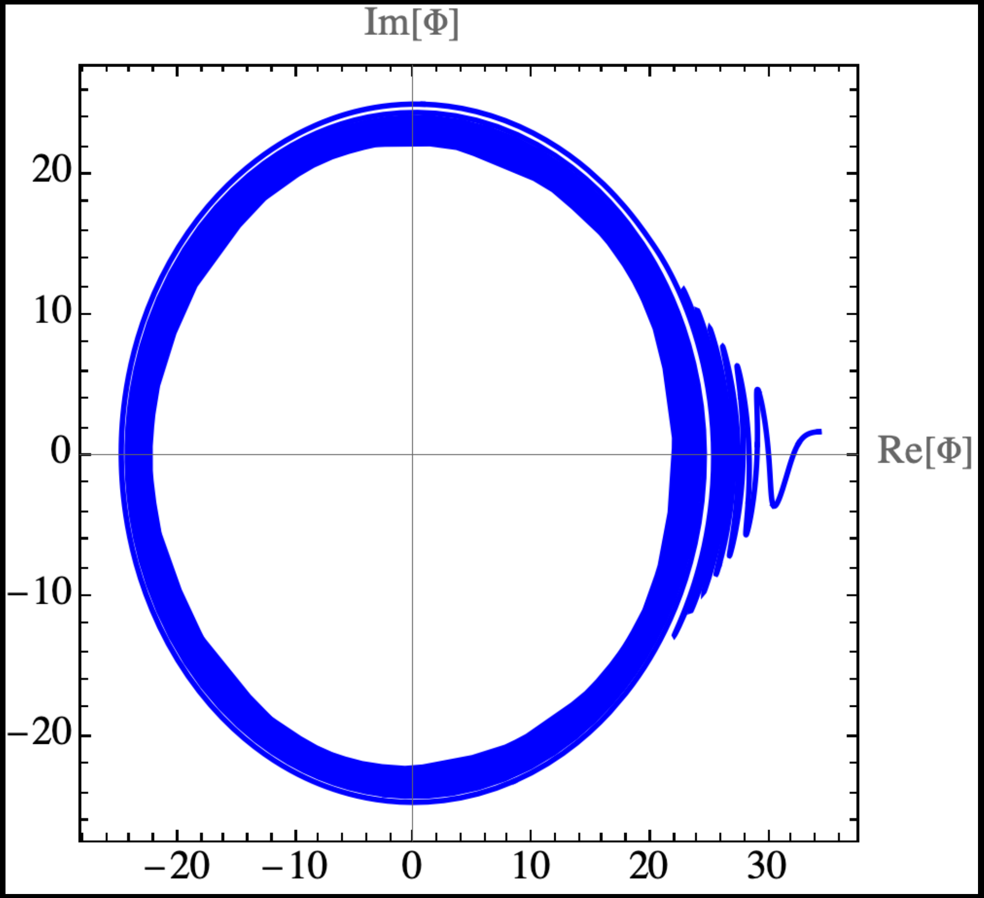
K.E. = Barrier $\Longrightarrow$ $\dot{\theta}(T_{\rm slide}) \simeq \frac{2}{5} m_a(T_{\rm slide})$

$$T_{\rm slide} \simeq C \frac{1}{4} T_0 (1 - \cos(5\theta_i))^2$$

$5\theta_i = 1$



$5\theta_i = 0.25$



$$\ddot{\theta} + H\dot{\theta} = -\frac{1}{n} m_a^2(T) \sin(n\theta)$$

Gives BAU

From Spontaneous Baryo.

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Gives BAU

From Spontaneous Baryo.

3rd epoch: T < T_c

$$\ddot{\theta} + \left(3H + 2\frac{\dot{f}_a}{f_a}\right)\dot{\theta} = -\frac{1}{n}m_a^2(T)\sin(n\theta)$$

$f_a(T)$ **saturates**

$$\dot{\theta}/T \propto T^2$$

$$\ddot{\theta} + H\dot{\theta} = -\frac{1}{n} m_a^2(T)\sin(n\theta)$$

Gives BAU

From Spontaneous Baryo.

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$$\ddot{\theta} + \left(3H + 2\frac{\dot{f}_a}{f_a}\right)\dot{\theta} = -\frac{1}{n} m_a^2(T)\sin(n\theta)$$

$f_a(T)$ saturates

$$\dot{\theta}/T \propto T^2$$

4th epoch: T < T_{osc}

$$\ddot{\theta} + 3H\dot{\theta} = -\frac{1}{n} m_a^{(0)2}\sin(n\theta)$$

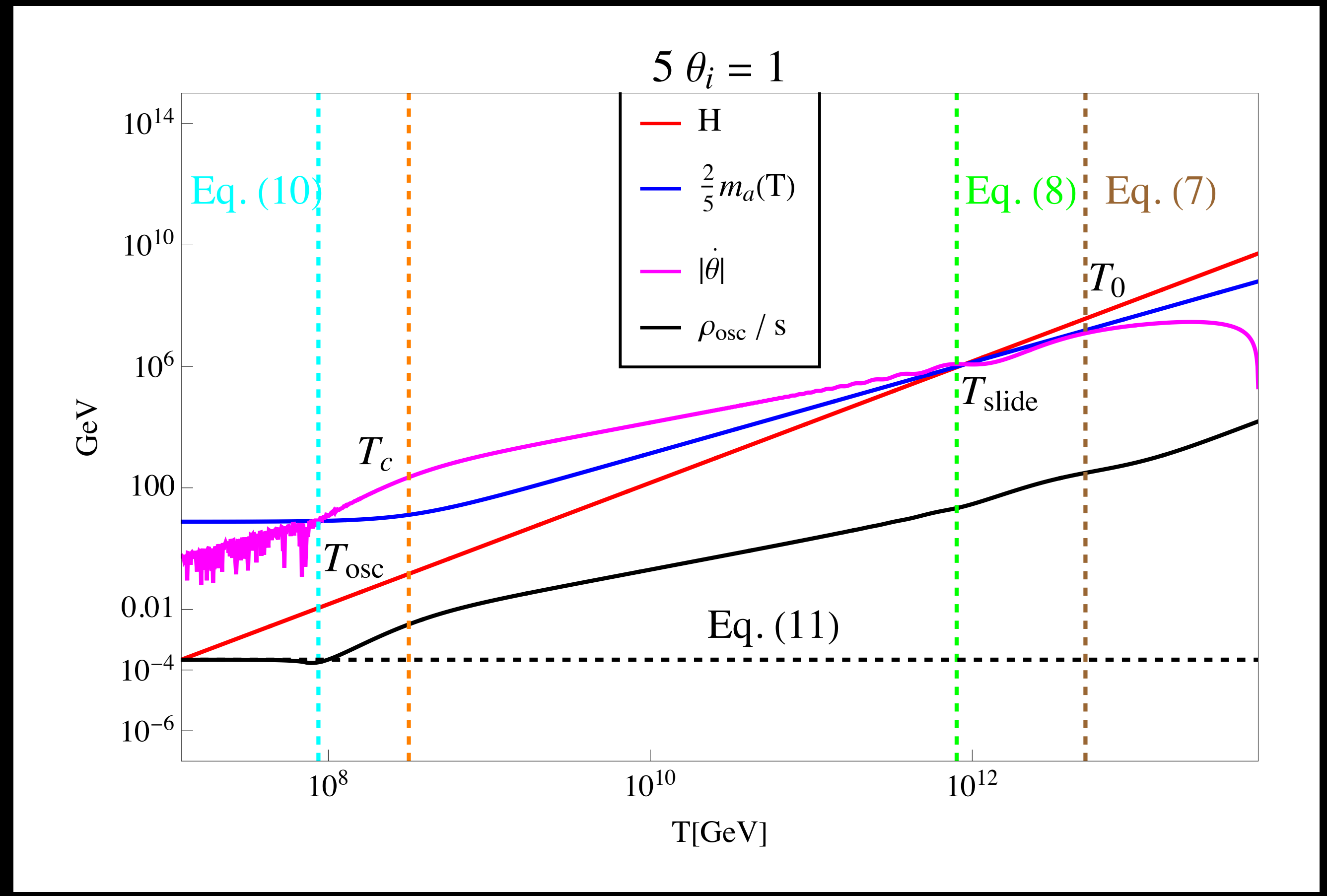
Final oscillation: $\Longrightarrow$ $\dot{\theta}(T_{\rm osc}) \simeq \frac{2}{5} m_a^{(0)}$

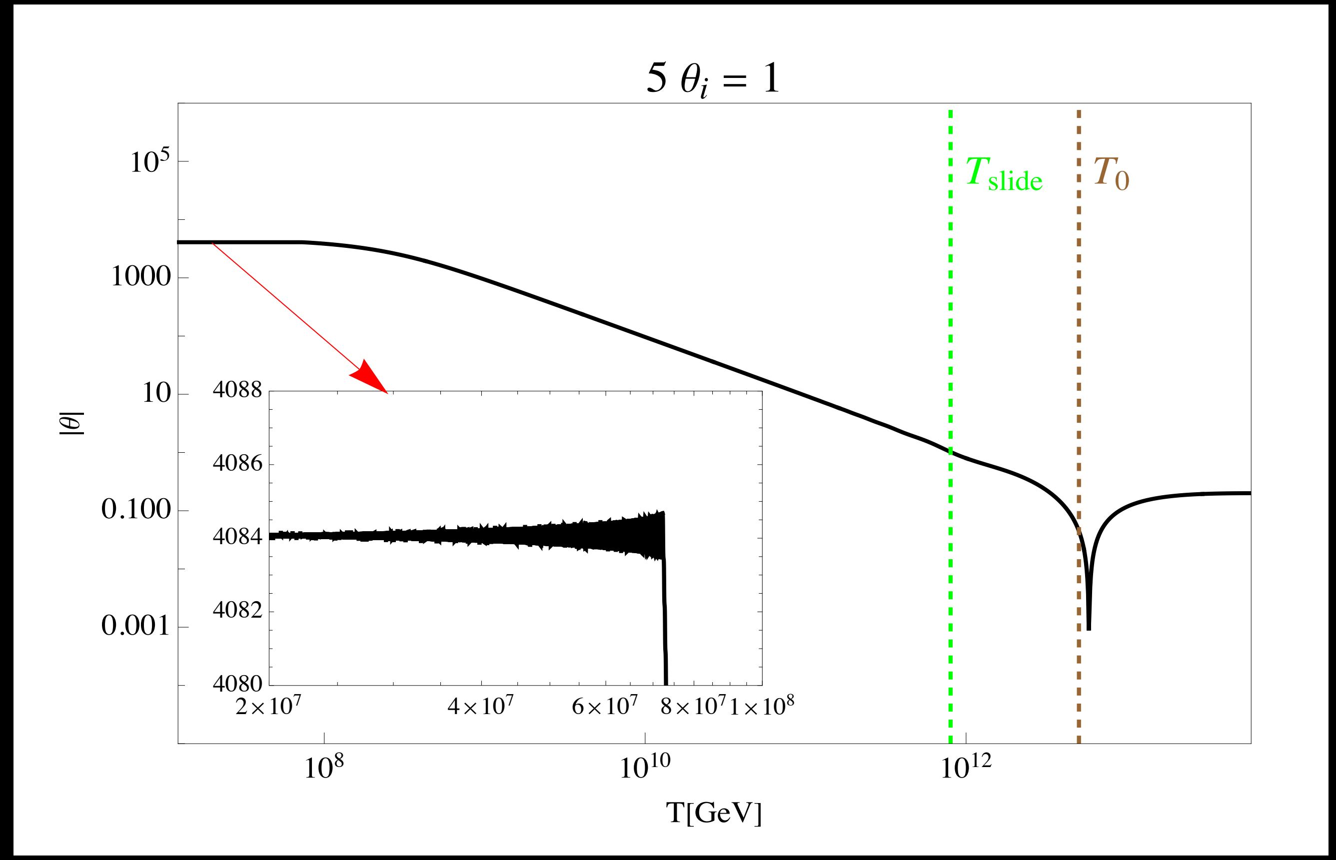
$$\frac{\rho_{\rm osc}}{s} \sim \frac{\left(m_a^{(0)} f_a^{(0)}\right)^2}{s(T_{\rm osc})}$$

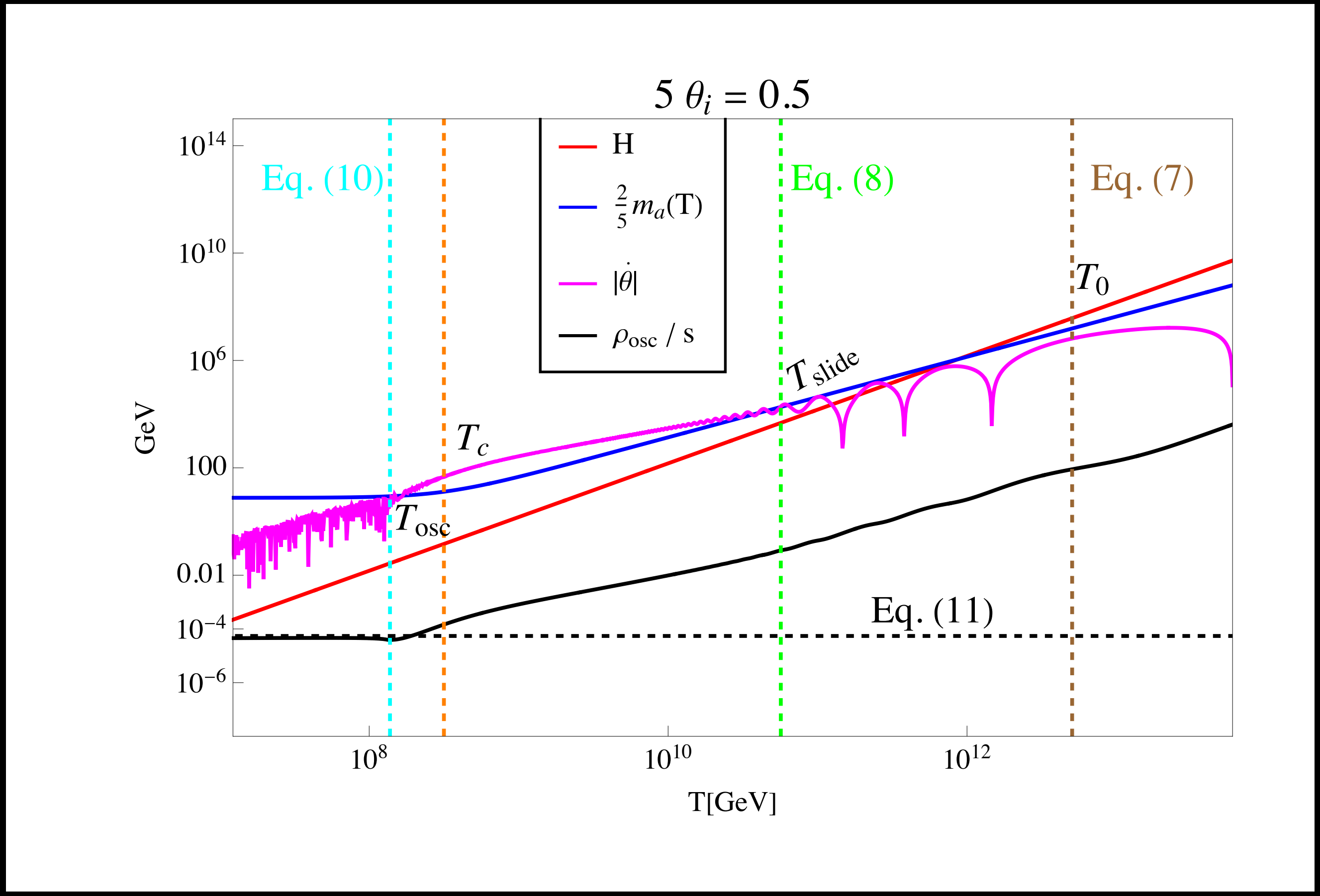
pNGB oscillates

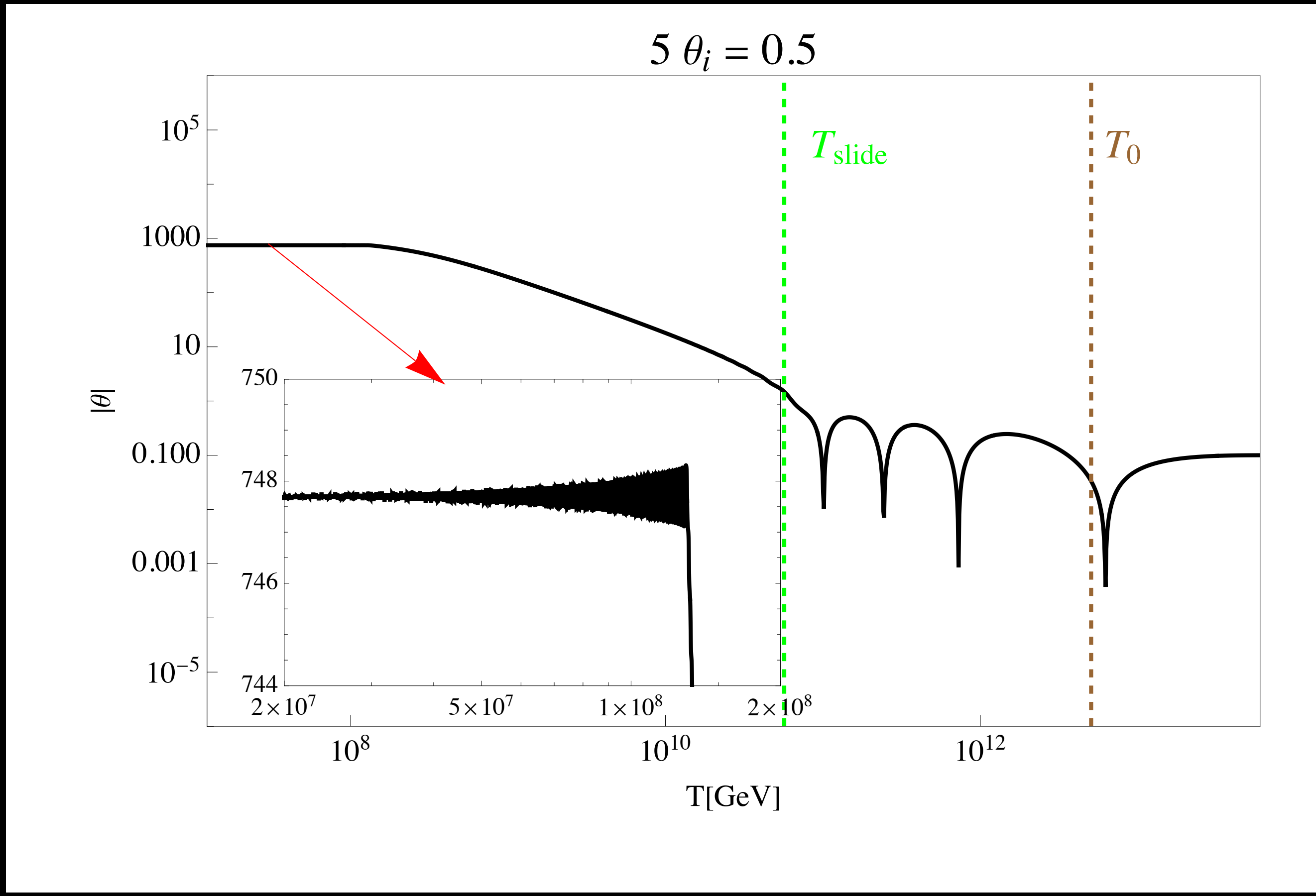
Gives DM

Numerical analysis:









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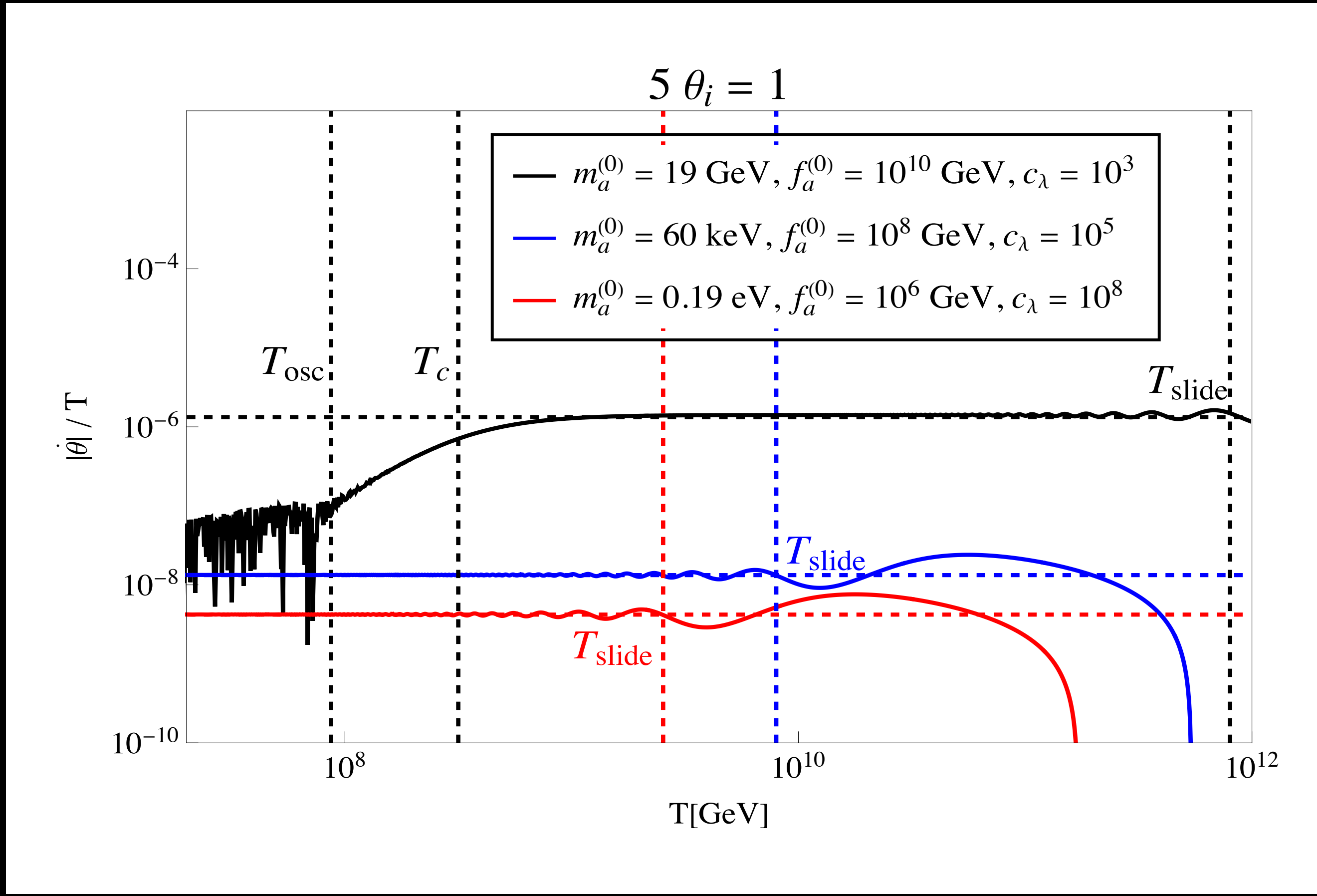
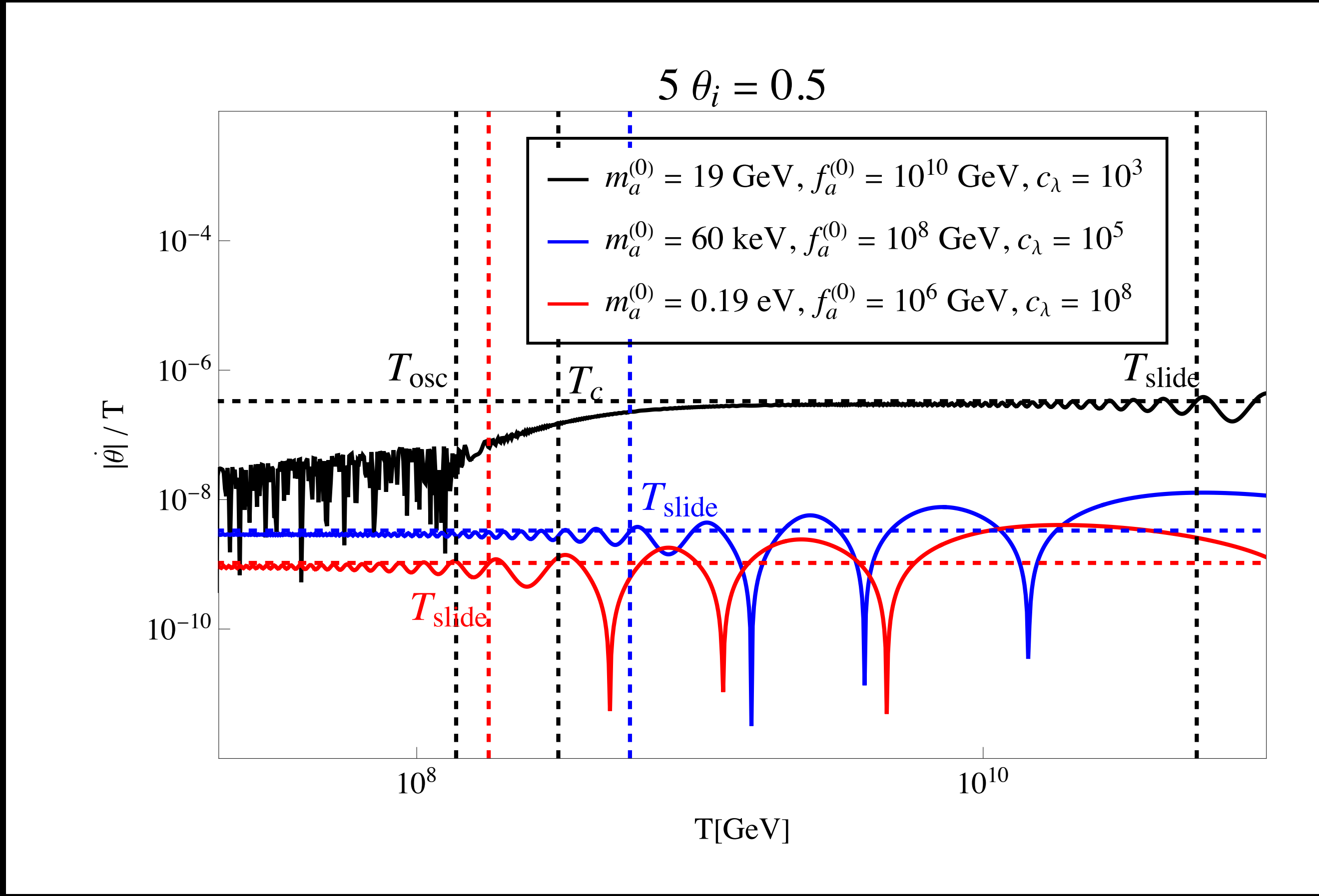


$5\ \theta_i = 1$
$m_a^{(0)} = 19$ GeV, $f_a^{(0)} = 10^{10}$ GeV, $c_\lambda = 10^3$
$m_a^{(0)} = 60$ keV, $f_a^{(0)} = 10^8$ GeV, $c_\lambda = 10^5$
$m_a^{(0)} = 0.19$ eV, $f_a^{(0)} = 10^6$ GeV, $c_\lambda = 10^8$
T_{osc}
T_c
T_{slide}
T_{slide}
T_{slide}
$|\dot\theta|$ / T
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^8
10^{10}
10^{12}
T[GeV]



$5\ \theta_i = 0.5$
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T_{osc}
T_c
T_{slide}
T_{slide}
T_{slide}
$|\dot\theta|$ / T
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^8
10^{10}
T[GeV]

An Explicit Example (Type I seesaw)

pNGB of B-L spontaneous symmetry breaking: Majoron

$$-\Delta\mathscr{L} = (y\Phi\nu^c\nu^c + Y_D H l \nu^c + h.c.) + V(\Phi)$$

right-handed neutrino

Mass of RHN:

$$M_N(T) \sim y\sqrt{c_\lambda}T \qquad M_N^{(0)} \sim y f_a^{(0)} \sim T_c$$

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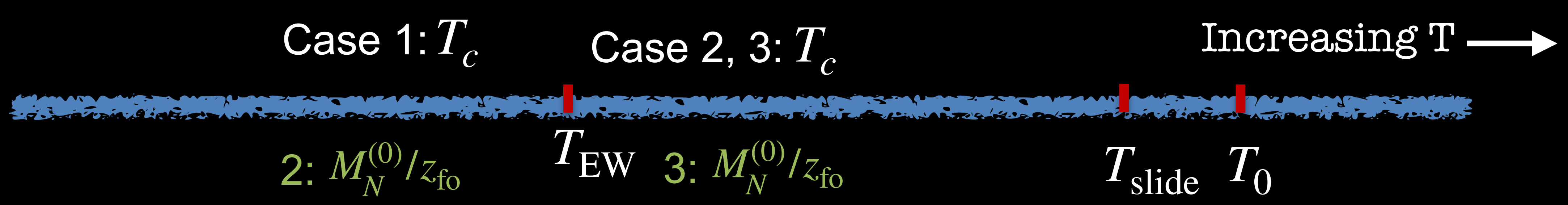
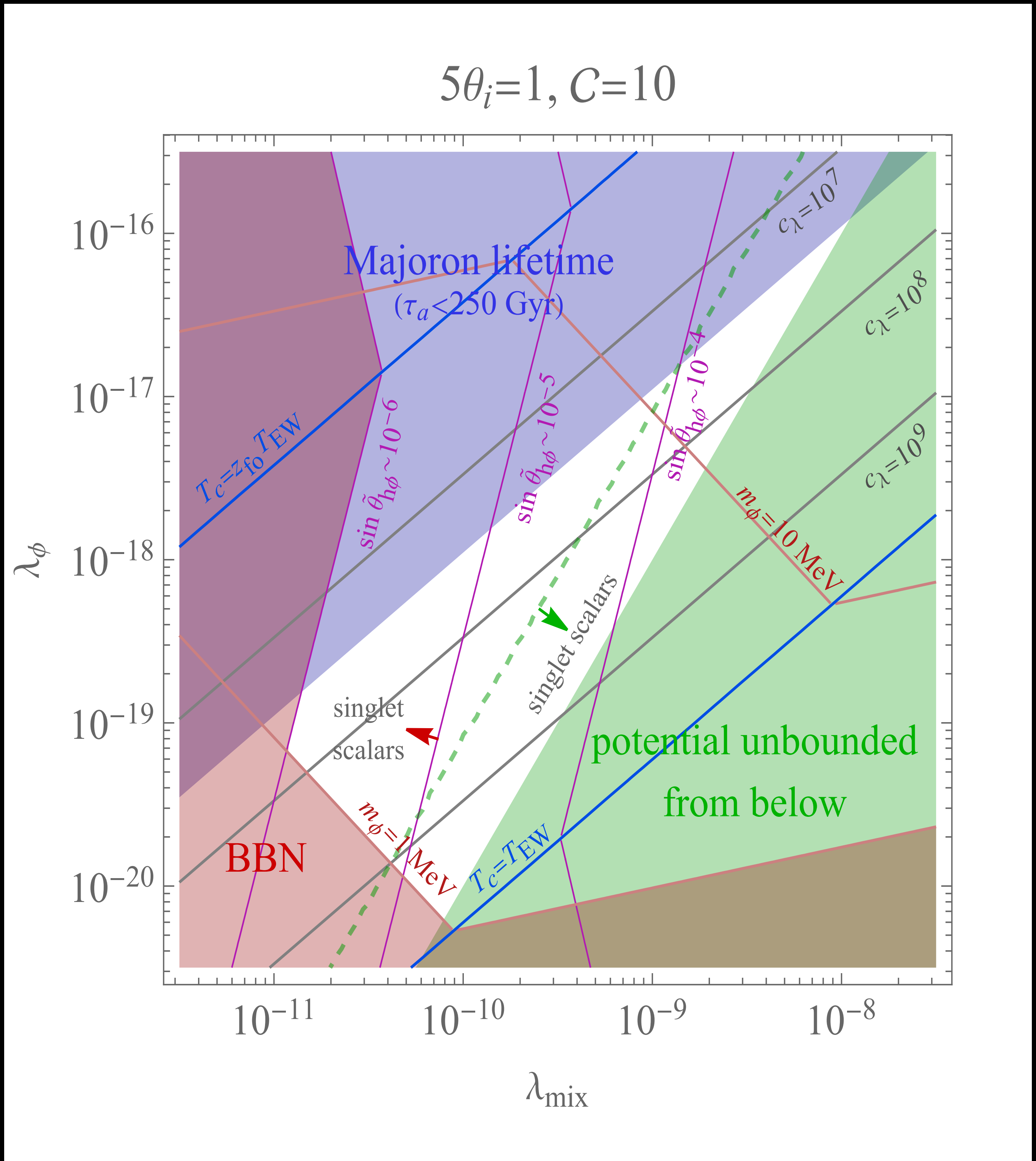


Asymmetry:
$$Y_B = \frac{45 c_B}{2\pi^2 g_*}\left(\frac{\dot\theta}{T}\right)_{\rm slide} \times \begin{cases} 1 & \text{for } T_{\rm EW} > T_c \\ \left(\frac{T_{\rm EW}}{T_c}\right)^2 & \text{for } M_N^{(0)}/z_{\rm fo} < T_{\rm EW} < T_c \\ \left(\frac{M_N^{(0)}}{z_{\rm fo} T_c}\right)^2 & \text{for } T_{\rm EW} < M_N^{(0)}/z_{\rm fo} \end{cases}$$

Predictions:



$$m_a^{(0)} = \frac{5\text{ eV}}{C^{1/9}(5\theta_i)^{4/9}}\left(\frac{g_*}{100}\right)^{1/3}\left(\frac{10^8}{c_\lambda}\right)^{5/9}$$

$$f_a^{(0)} = 3\times 10^6\text{ GeV}\, C^{1/18}(5\theta_i)^{2/9}\left(\frac{100}{g_*}\right)^{1/6}\left(\frac{c_\lambda}{10^8}\right)^{5/18}$$

Summary

- A new mechanism for cogenesis with the conventional misalignment.
- Decrease of pNGB potential via symmetry non-restoration.
- Baryon asymmetry at high temperatures during sliding, DM at low temperatures during oscillation.
- Can be realized for Majoron.
- Predicts RHN with mass 10-400 GeV, Majoron DM with mass eV.
- Testable at kaon experiments, colliders….

THANK YOU