Cogenesis by a sliding pNGB with symmetry non-restoration

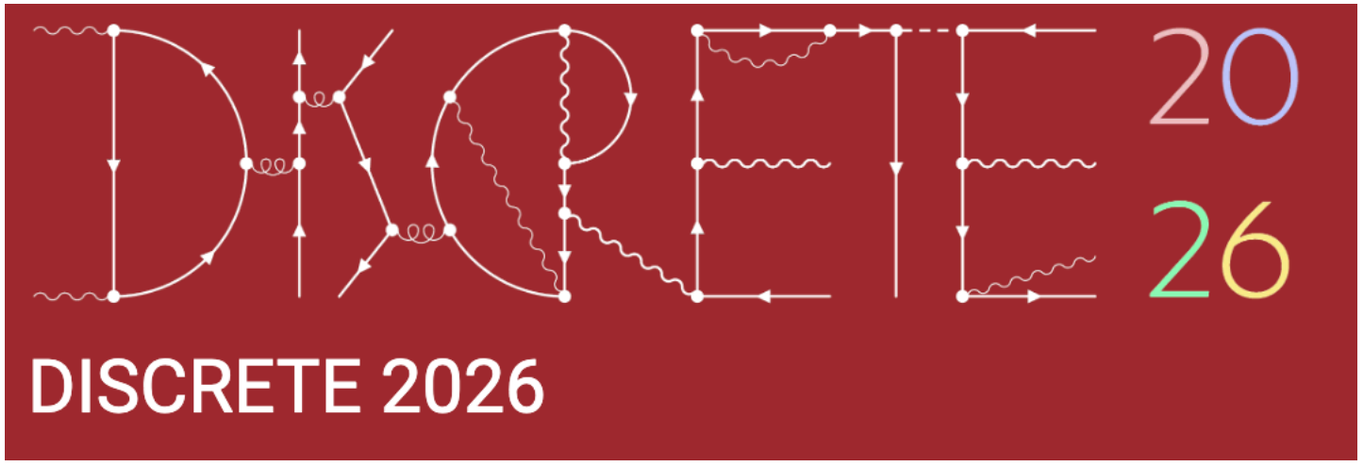
Suruj Jyoti Das

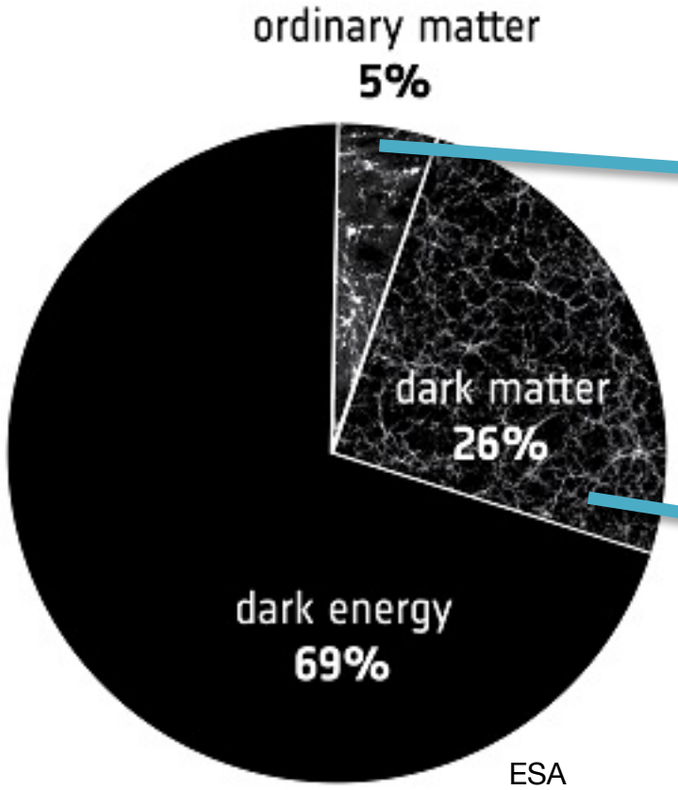
University of Warsaw



Based on:
arXiv: 2406.04180 (PRD 2025)

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





ESA

1) Baryon Asymmetry (from BBN and CMB):

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

2) Dark Matter abundance(from CMB):

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

This talk:

Generating the above via *Axions/ pNGB*

How to generate asymmetry?

Sakharov ’67

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

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Spontaneous baryogenesis Kohen, Kaplan ’87

- Background dynamics of scalar field (pNGB): spontaneously breaks CPT.

Source: $\frac{c}{f_a}(\partial_\mu a)\, J^\mu_X \qquad X = B, L \ldots \qquad \bar{\psi}\gamma^\mu\psi$

(natural in ALPs with shift symmetry)

$\theta = \frac{a}{f_a}$

- Effective chemical potential: $\mu_B^{\rm eff} \sim c\dot{\theta}$
- B/L violation in equilibrium $\Longrightarrow$ $n_B \sim \mu_B^{\rm eff} T^2$

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Final Asymmetry:

$$\frac{n_B}{s} \simeq \frac{\mu_B T^2}{s} \sim \frac{\dot{\theta}}{g_* T_{B-L}}$$

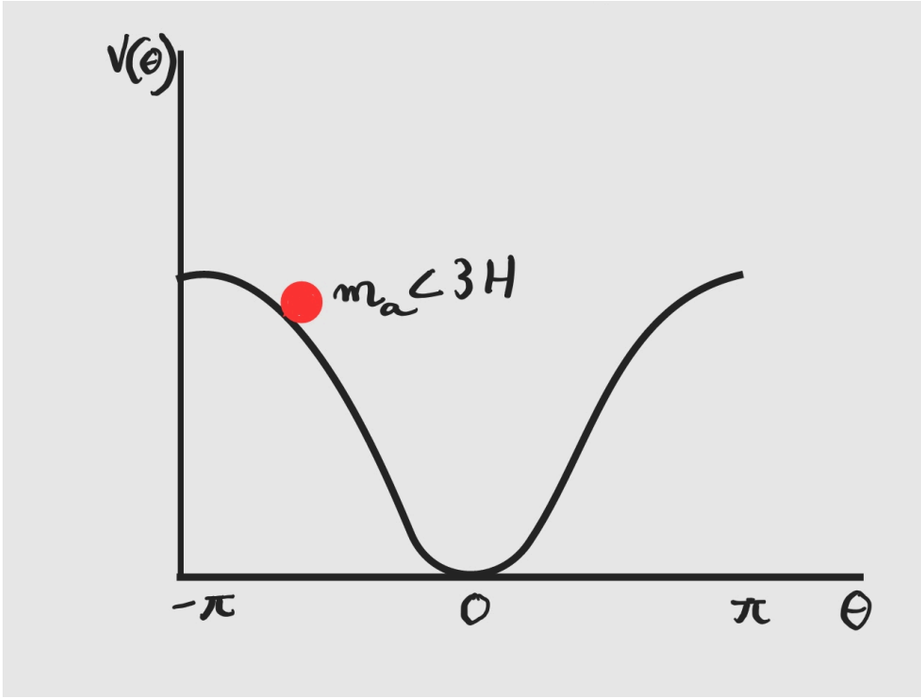
at B,L violation decoupling

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

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EOM: $\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$ Initial conditions: $\theta \neq 0 \quad \dot{\theta} = 0$

Conventional misalignment

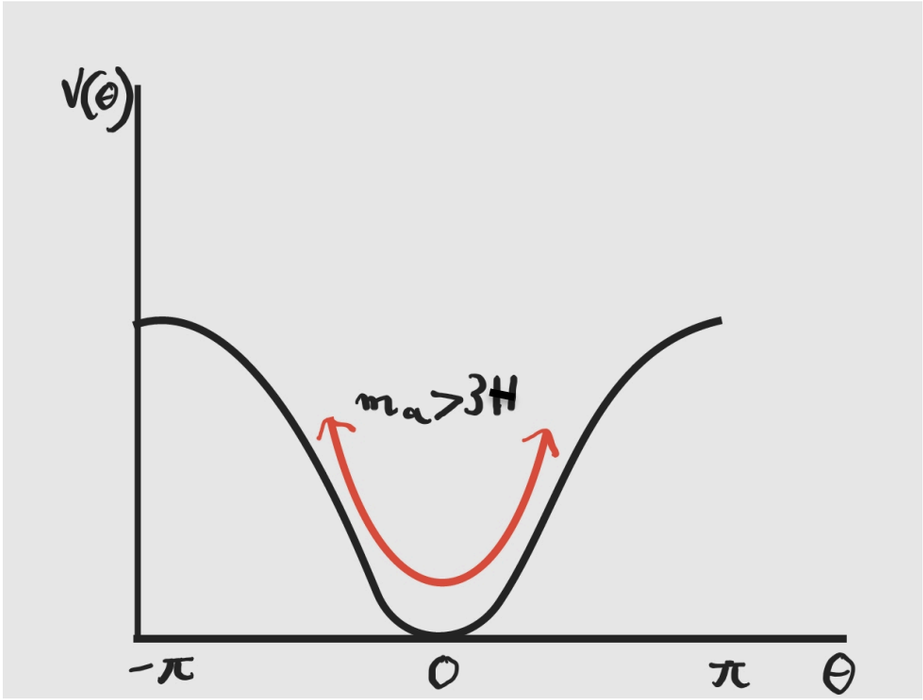


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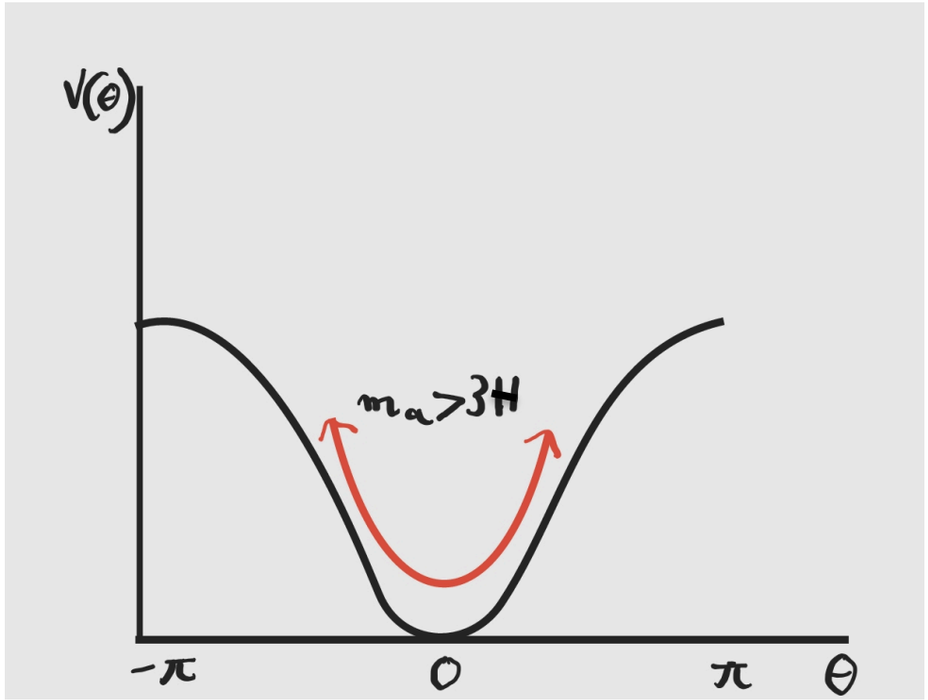
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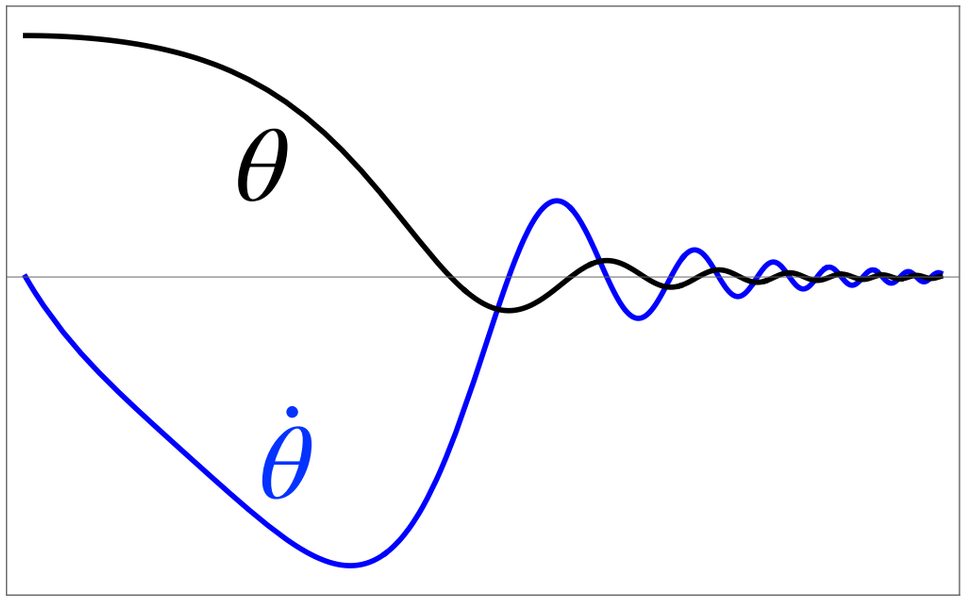
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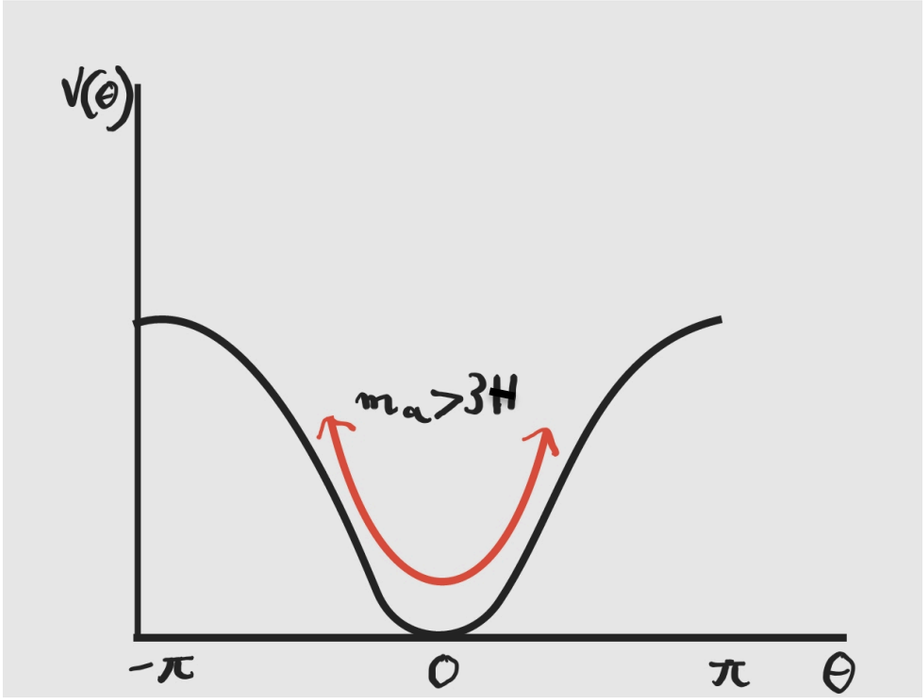


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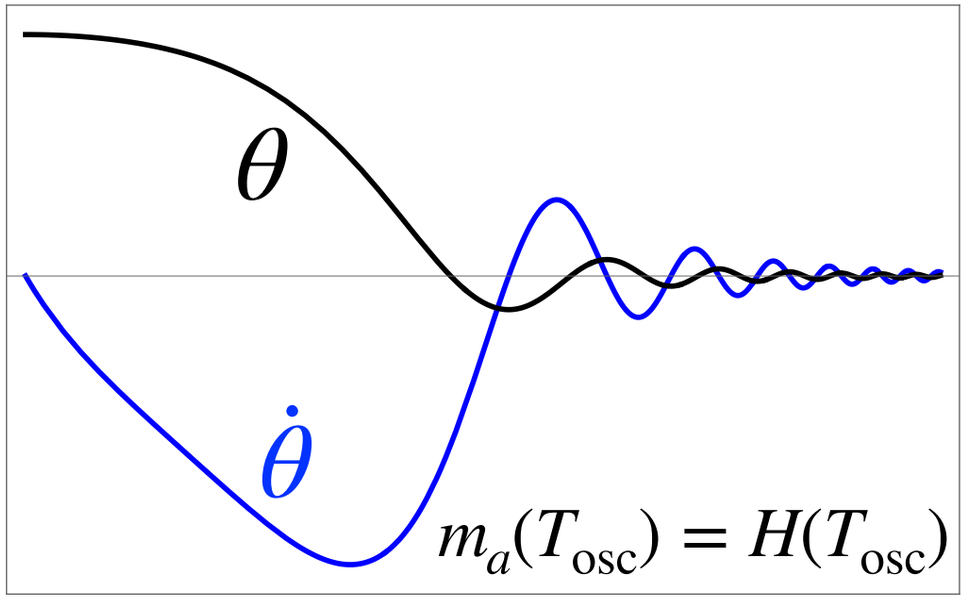
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Baryon Asymmetry:

$$T_{\rm B-L} \simeq T_{\rm osc} \simeq \sqrt{m_a M_P}$$

For $Y_B^{\rm observed} \sim \dfrac{\dot{\theta}}{g_* T_{\rm osc}} \sim 10^{-10}$ (observed)

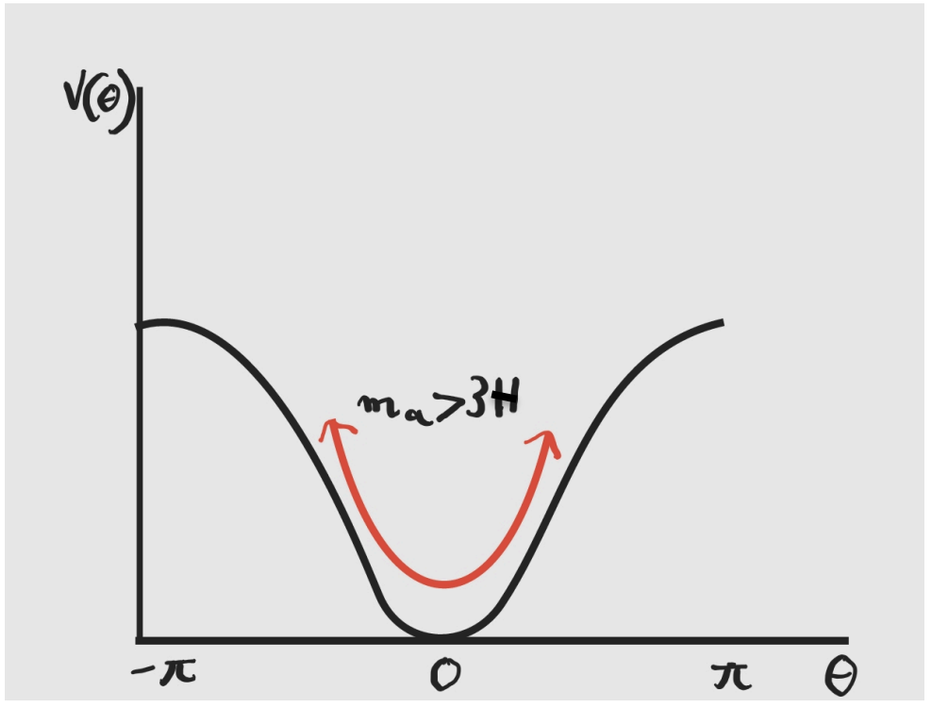
$$m_a \sim O(10^2) \text{ GeV}$$

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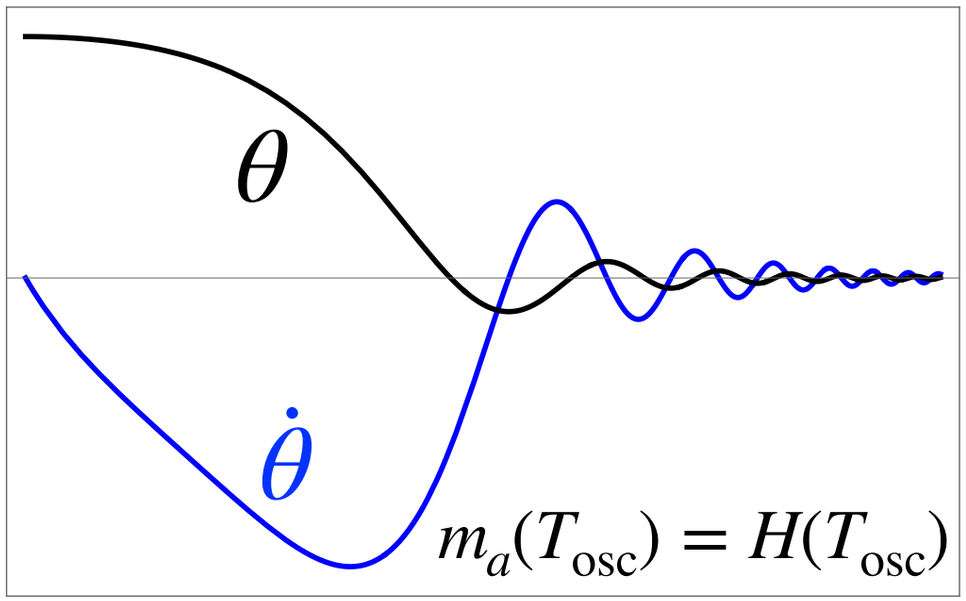
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Dark Matter:

$\rho_{\rm DM} \sim m_a \times \theta_i^2 m_a f_a^2$ (Mass X No. density)

$$\frac{\rho_{\rm DM}}{s} \sim \frac{m_a^2 f_a^2}{s} \sim \frac{m_a^2 T_{\rm osc}^2}{g_* T_{\rm osc}^3} \gg 0.44 \text{ eV (observed)}$$

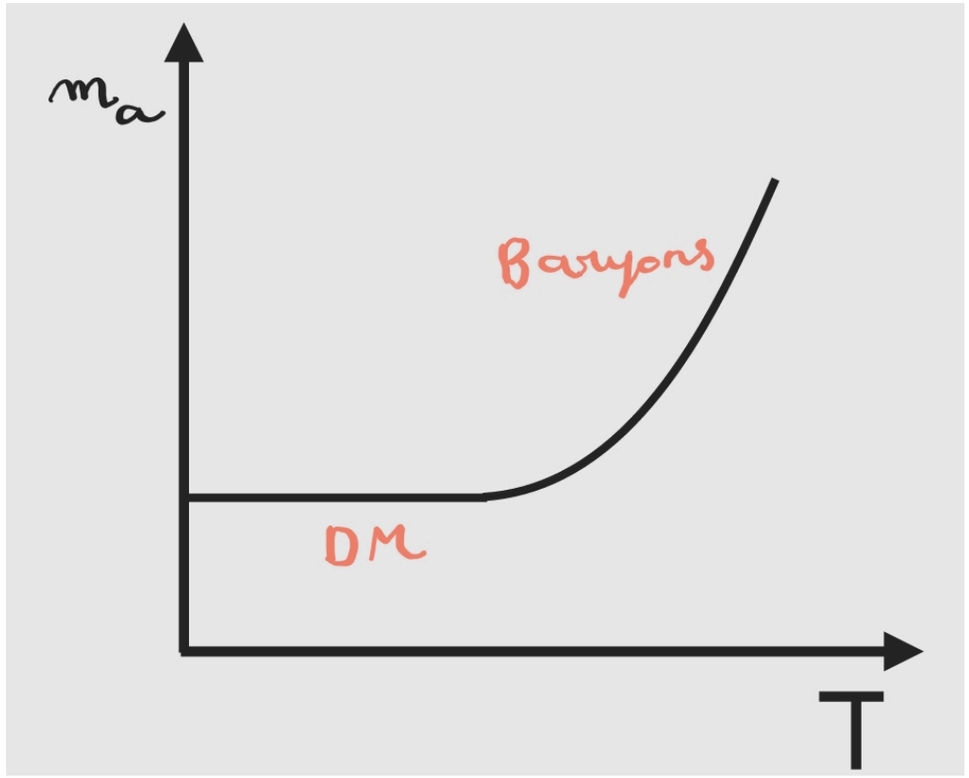
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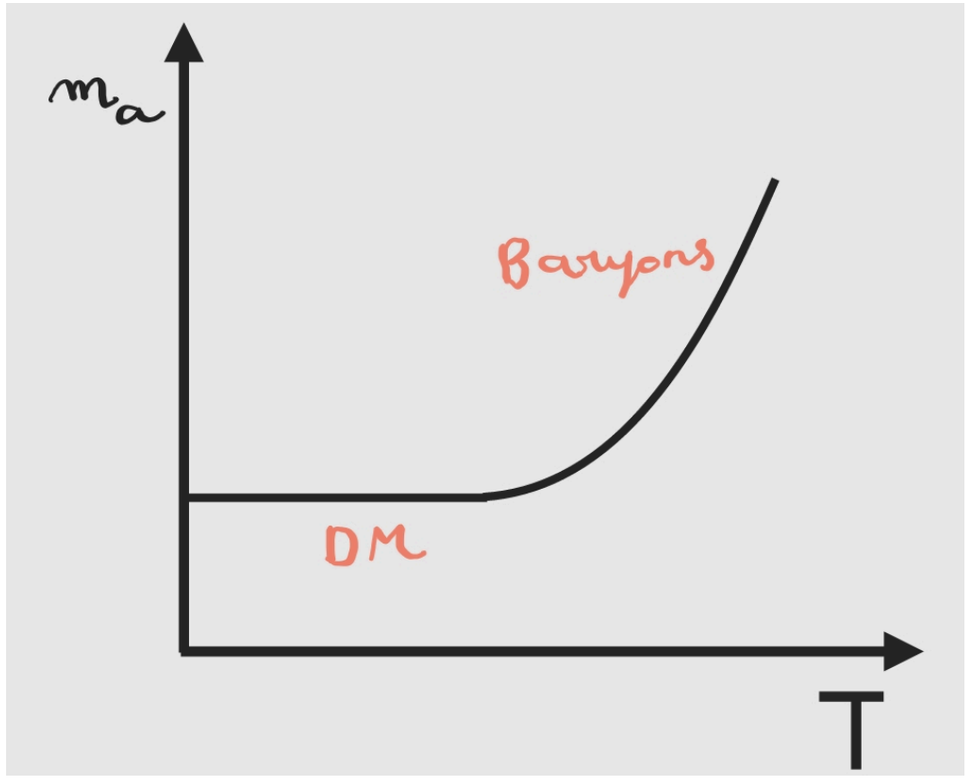
$\Longleftarrow$ $m_a \sim O(10^2)$ GeV

The key idea:



- Early dynamics with $m_a(T) \gg m_a^{(0)}$.
- Separate out $T_{\mathrm{B-L}} \gg T_{\mathrm{osc}}$.

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- Complementary to **Kinetic Misalignment**

  R.T. Co, L.J. Hall, K. Harigaya 2019

  here radial mode tracks the minimum.

Symmetry non-restoration

(S. Weinberg 1974)

Thermal corrections with **negative** contribution:

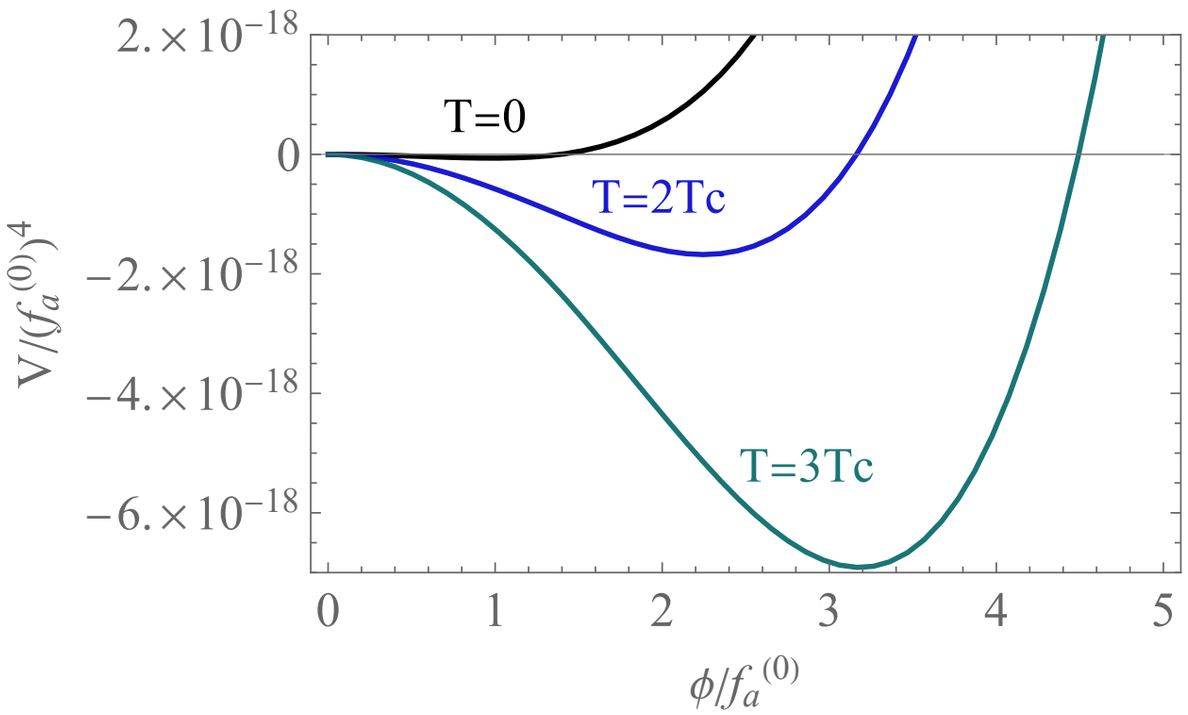
$$\Delta V = -2\lambda_{h\phi}\,|H|^2\,|\Phi|^2 \qquad \text{or} \qquad \Delta V = -\lambda_{\phi s_i}\,|\Phi|^2\,s_i^2$$

SM Higgs

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

$$f_a(T) = \sqrt{f_a^{(0)2} + c_\lambda T^2}$$

$$c_\lambda \simeq \lambda_{\rm mix}/\lambda_\phi$$



Connection of axion mass with this vev f_a ?

Explicit breaking of U(1):

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

$$\Downarrow$$

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

Mass of pNGB:

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

$$f_a(T) \propto T \qquad m_a(T) \propto T^{(n-2)/2}$$

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Thermal production? $\phi\phi \leftrightarrow aa \propto \frac{T^2}{f_a^4} \Longrightarrow$ $c_\lambda \gtrsim 10^7$ ✗

pNGB dynamics (n=5)

Modified E.O.M. :

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

$\dot{f}_a / f_a \to -H$

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

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

$H \to$ constant

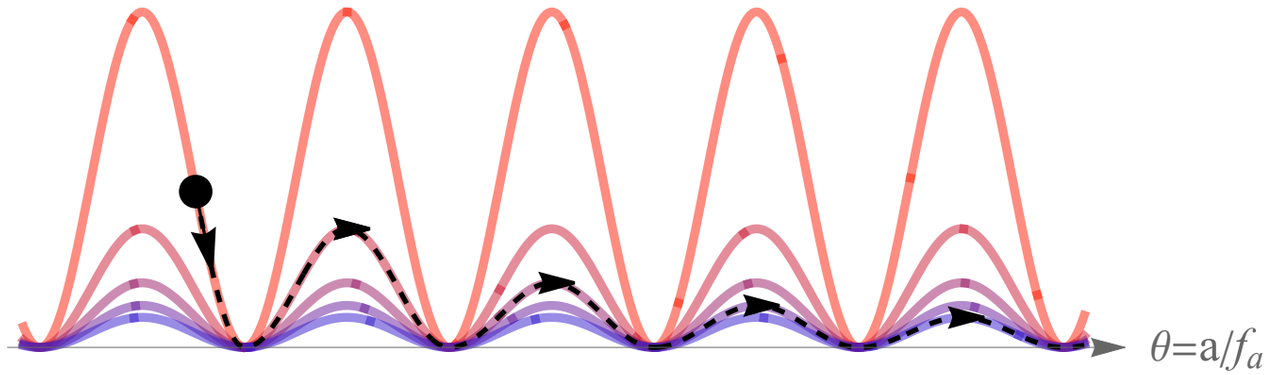
pNGB is frozen

until

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

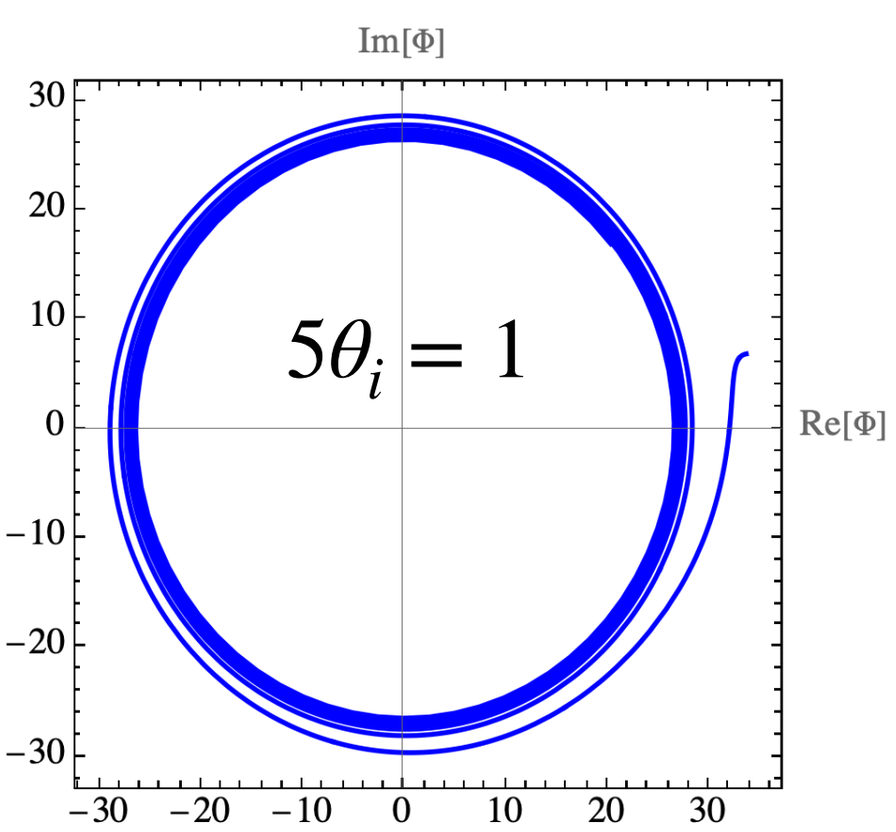
2nd epoch: T < T_0 **Oscillation?**

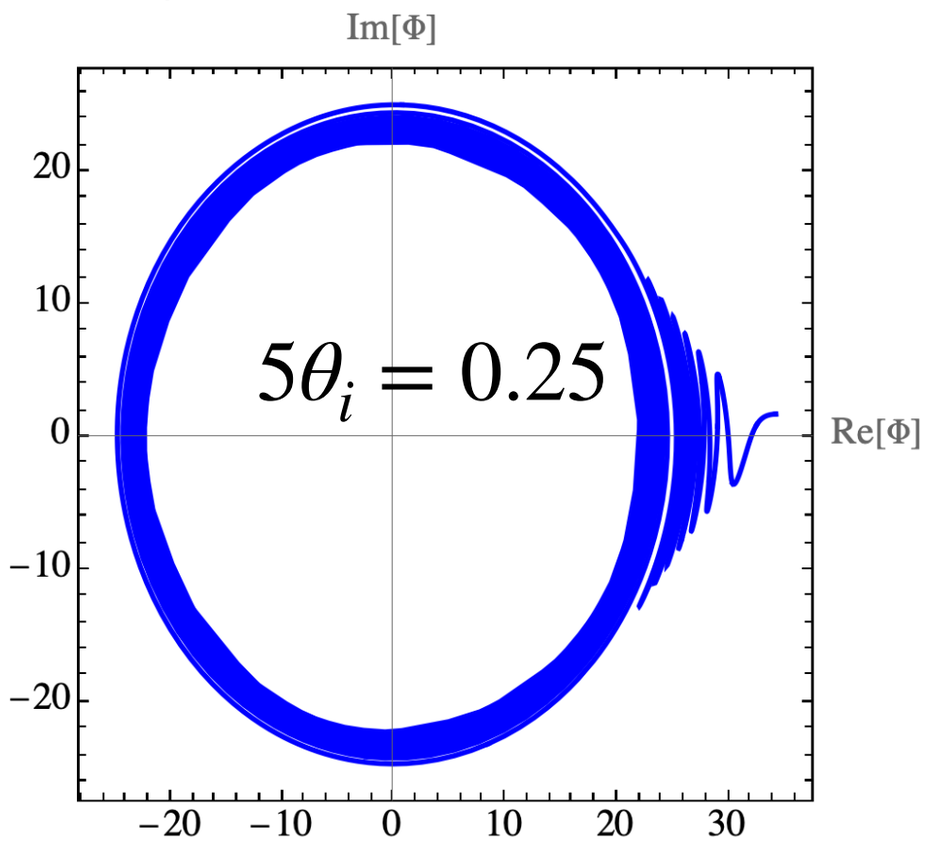
pNGB slides/rotates



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

$$T_{\rm slide} \sim T_0(1-\cos(5\theta_i))^2$$





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

Gives asymmetry

From Spontaneous Baryo.

$$\frac{\dot{\theta}}{T} = \text{constant}$$

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3rd epoch: $T < T_c$

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$f_a(T)$ **saturates**

$$\dot{\theta} \propto T^3$$

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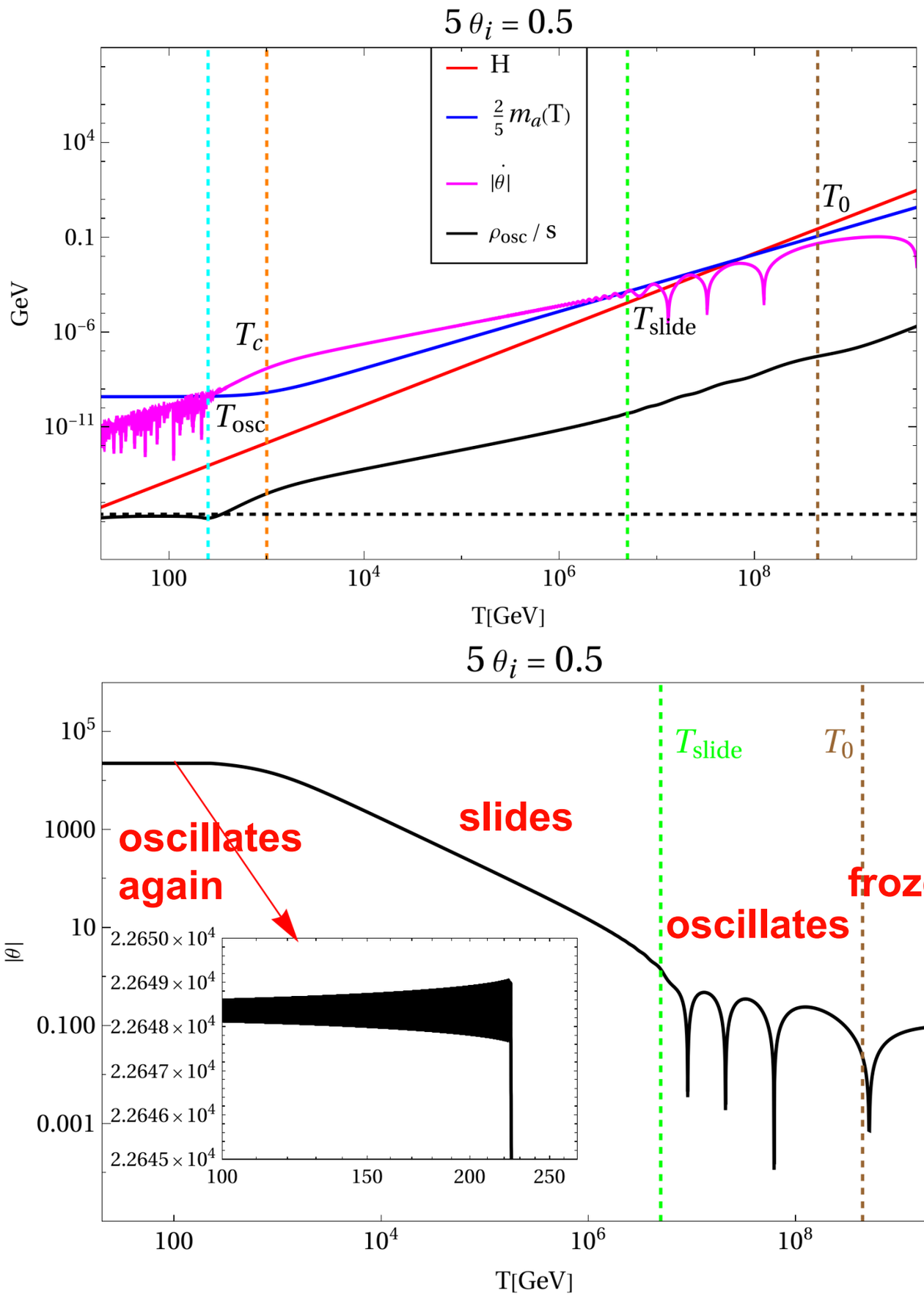
4th epoch: $T < T_{osc}$

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

Final oscillation: $\Longrightarrow$ $\dot{\theta}(T_{\rm osc}) \simeq \frac{2}{5} m_a^{(0)}$ ← **K.E. = Barrier**

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

pNGB oscillates, gives DM


5 $\theta_i = 0.5$
H
$\frac{2}{5} m_a(\mathrm{T})$
$|\dot{\theta}|$
ρ_{osc} / s
T_0
T_{slide}
T_c
T_{osc}
GeV
T[GeV]
5 $\theta_i = 0.5$
T_{slide}
T_0
slides
oscillates again
oscillates
frozen
$|\theta|$
T[GeV]

Fluctuations of θ ? $\Theta(t, \mathbf{x}) = \theta(t) + \delta\theta(t, \mathbf{x})$

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$$\delta\ddot{\theta}_k + \left(3H + 2\frac{\dot{f}_a}{f_a}\right)\delta\dot{\theta}_k + \left[\frac{k^2}{R^2} + m_a^2(T)\cos(n\theta)\right]\delta\theta_k = 0$$

periodic modulation

$$\Downarrow \quad |(k/R)^2 - \dot{\theta}^2| \lesssim m_a^2$$

Parametric Resonance

Fluctuations of θ ?

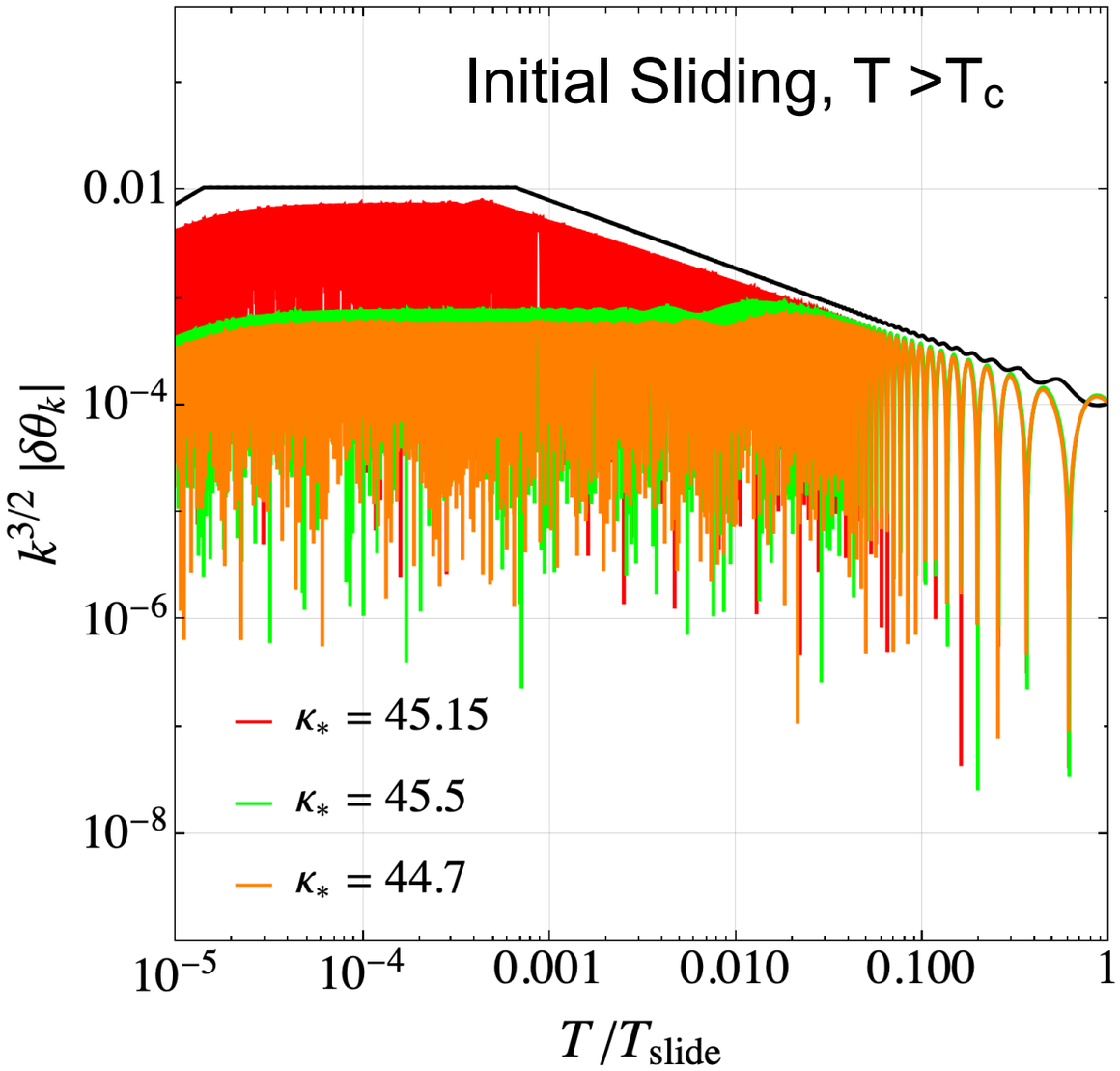
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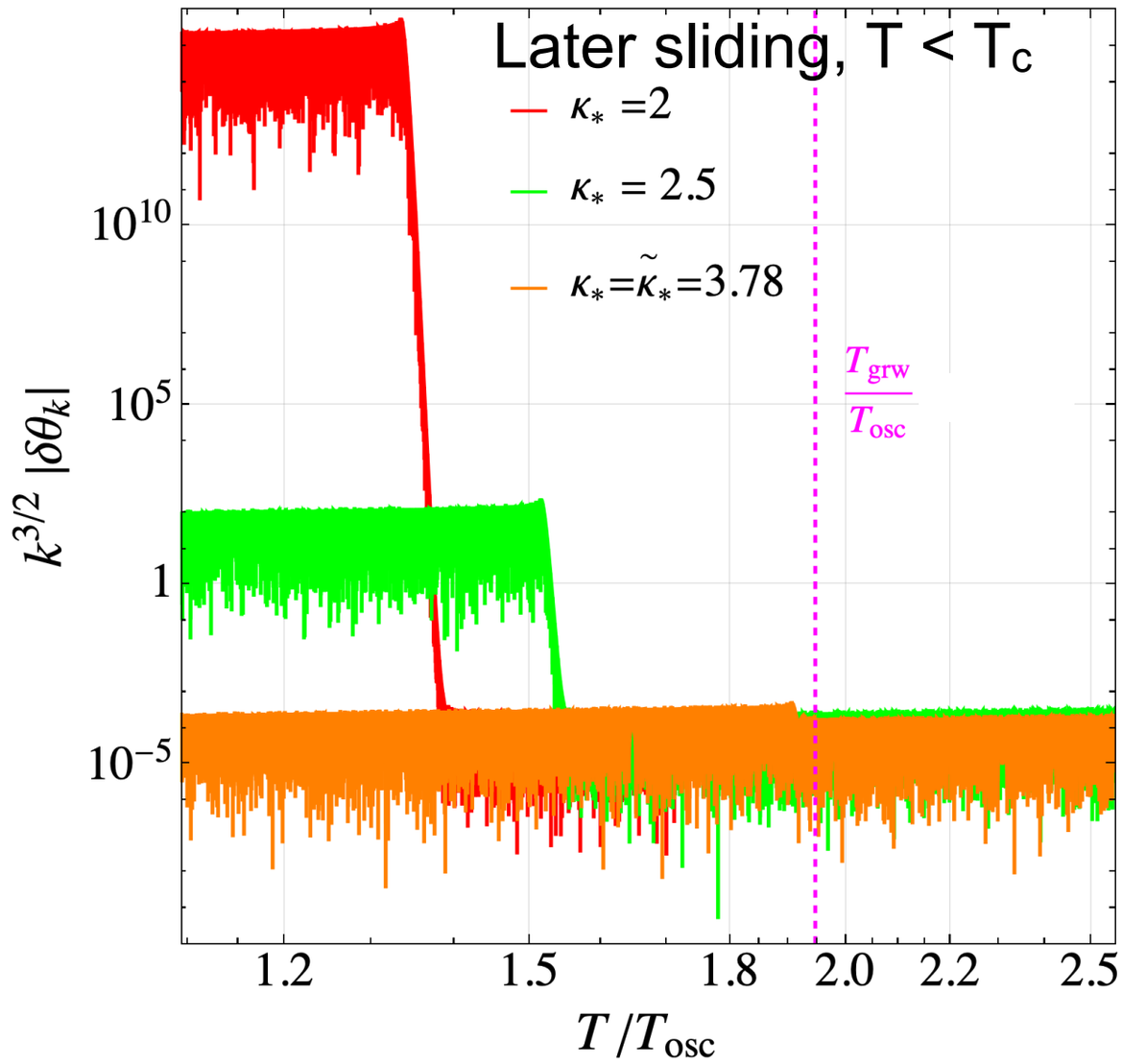
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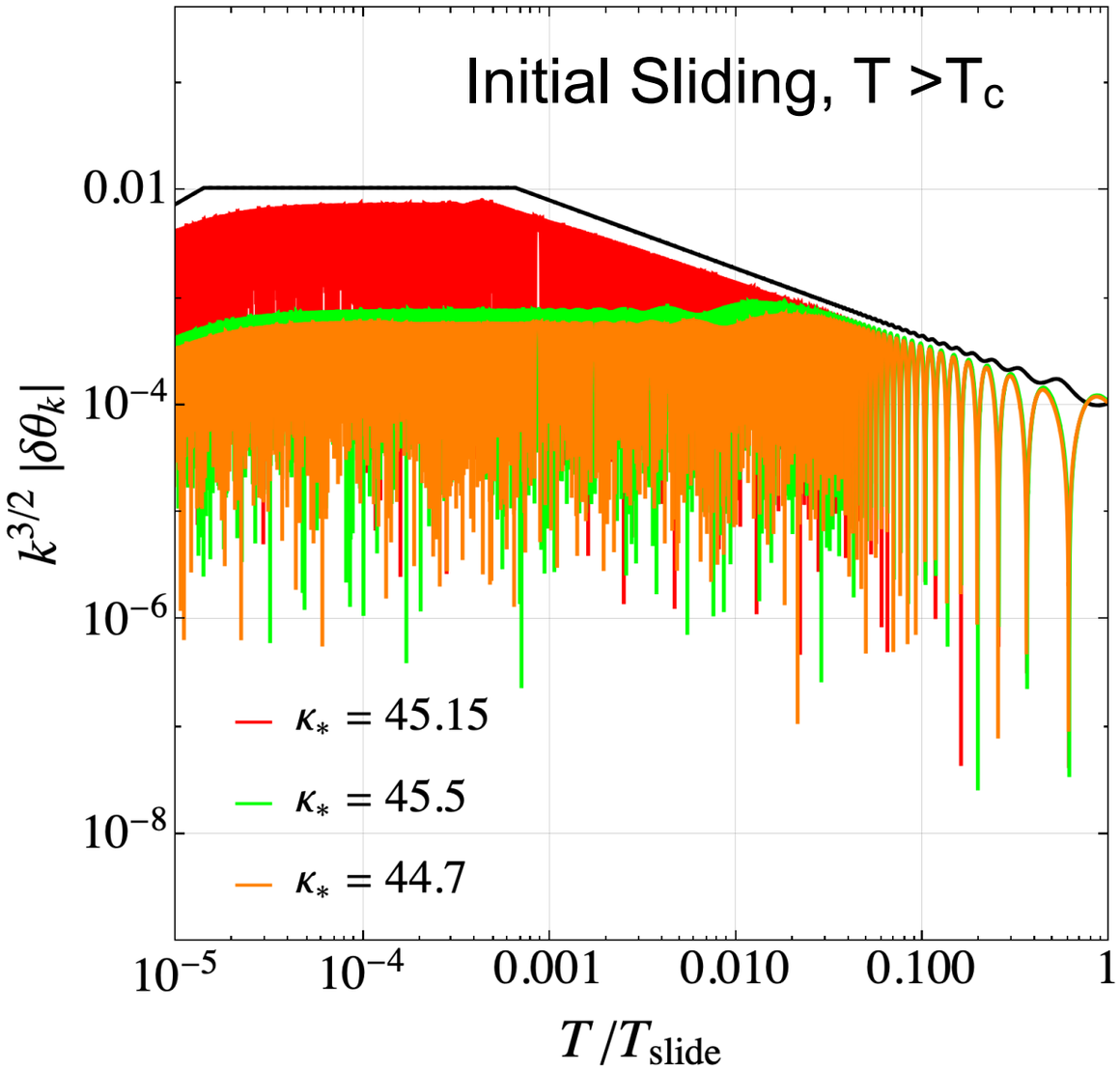
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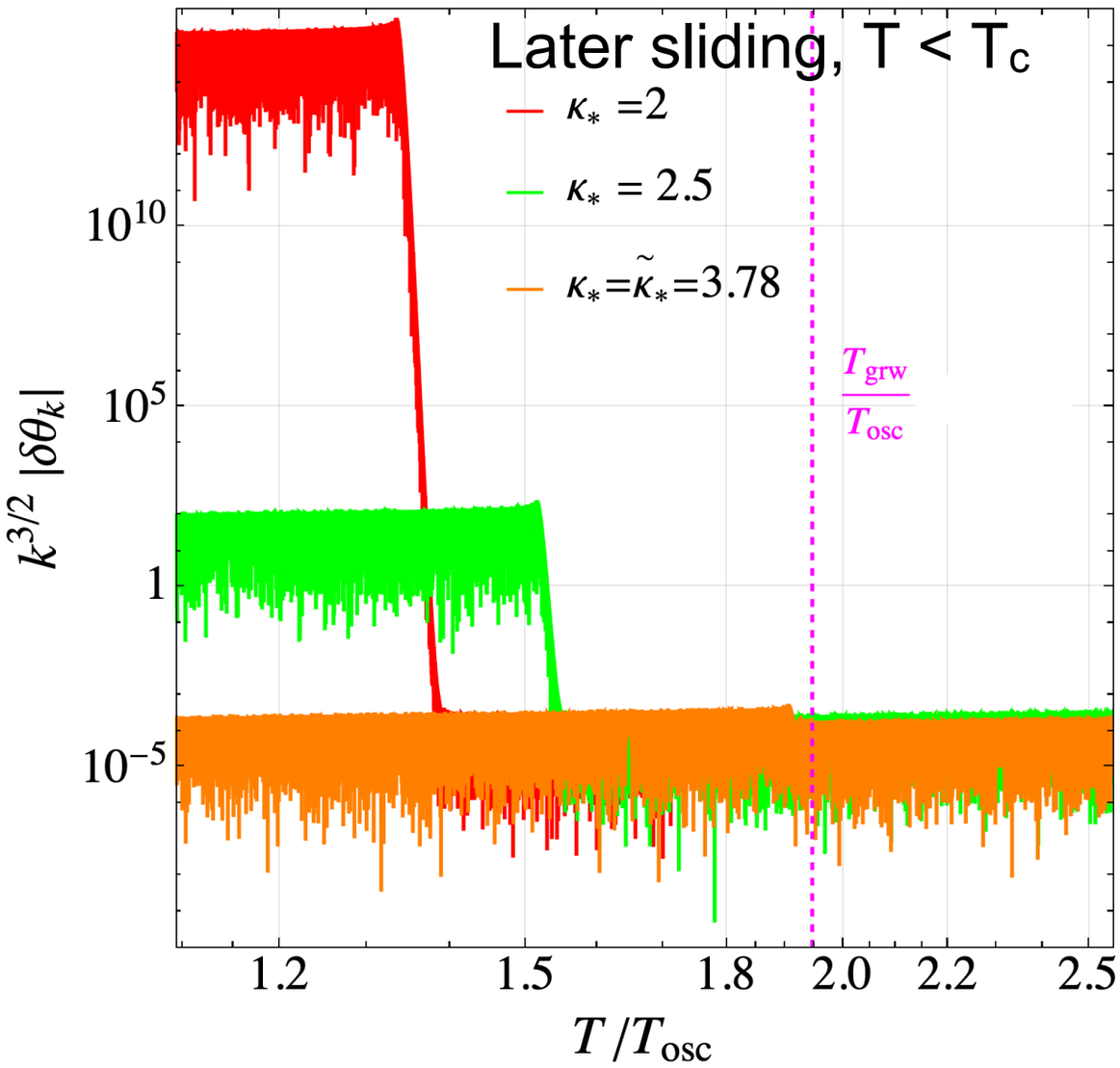
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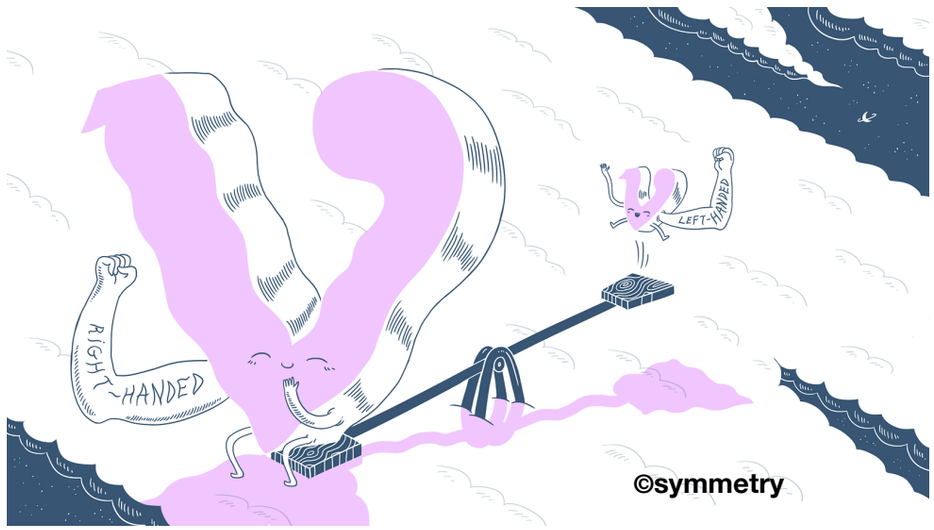
pNGB is **fragmented** & DM density(unchanged) in the form of pNGB fluctuations

An explicit example: Majoron

Spontaneous breaking of $U(1)_{B-L}$

$$-\Delta\mathscr{L} = (y\Phi N^c N^c + Y_D \bar{l}_\alpha \tilde{H} N^c + h.c.) + V(\Phi)$$

right-handed neutrino



Type I seesaw:

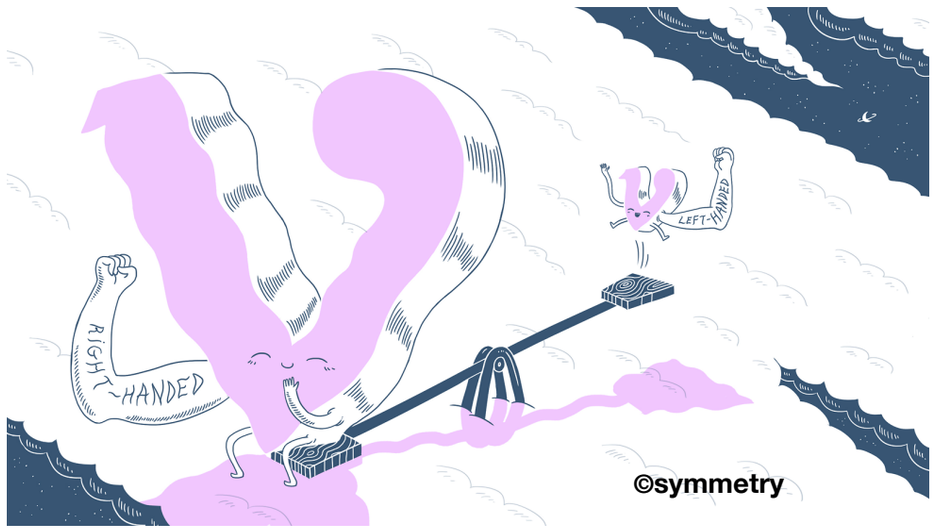
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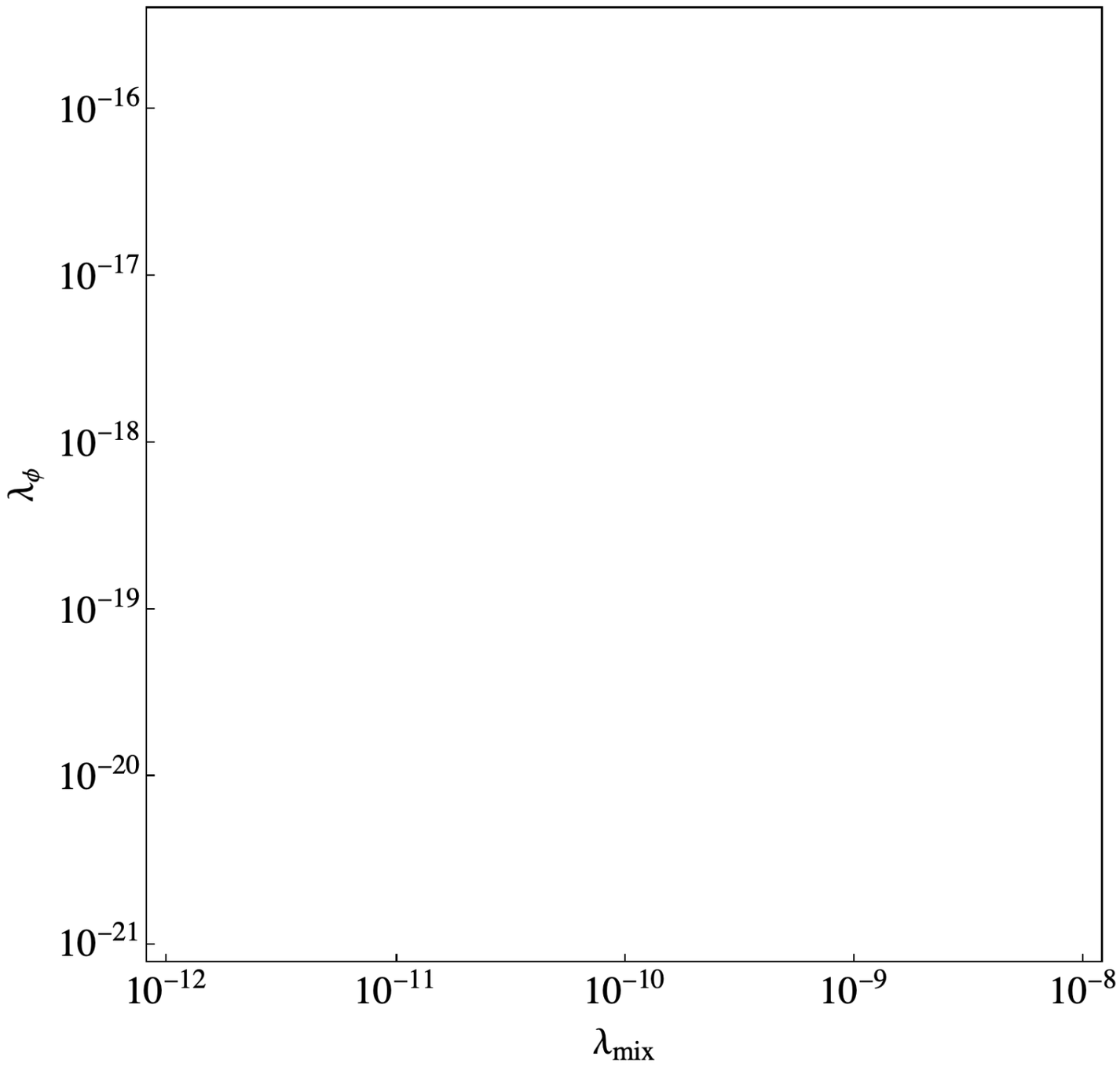


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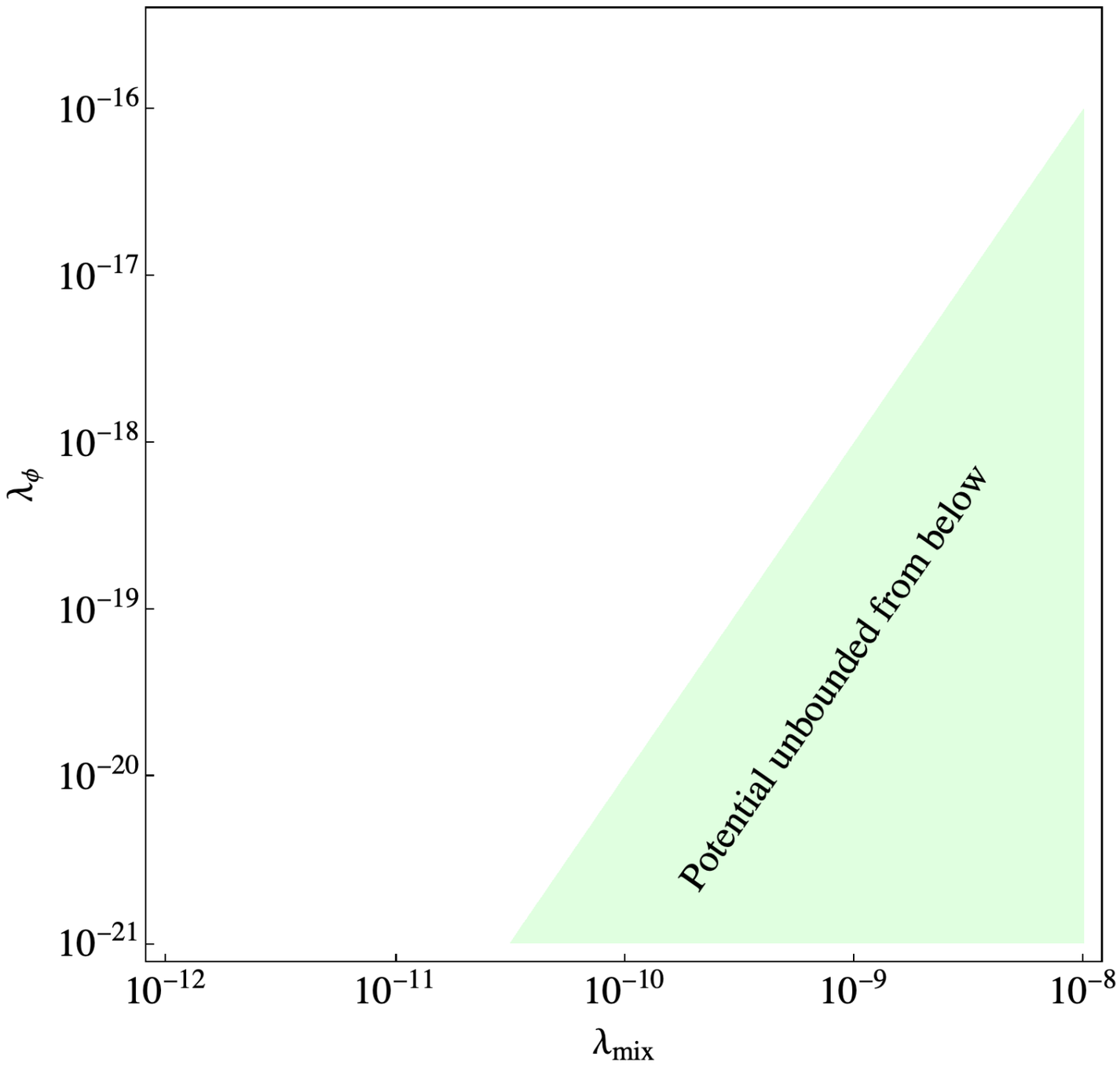
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- Lepton no. violating decays & inverse decays → Non-zero $\dot{\theta}$ asymmetry in equilibrium.
- Asymmetry effectively frozen at $T = T_{B-L} \sim \frac{M_N}{10}$.

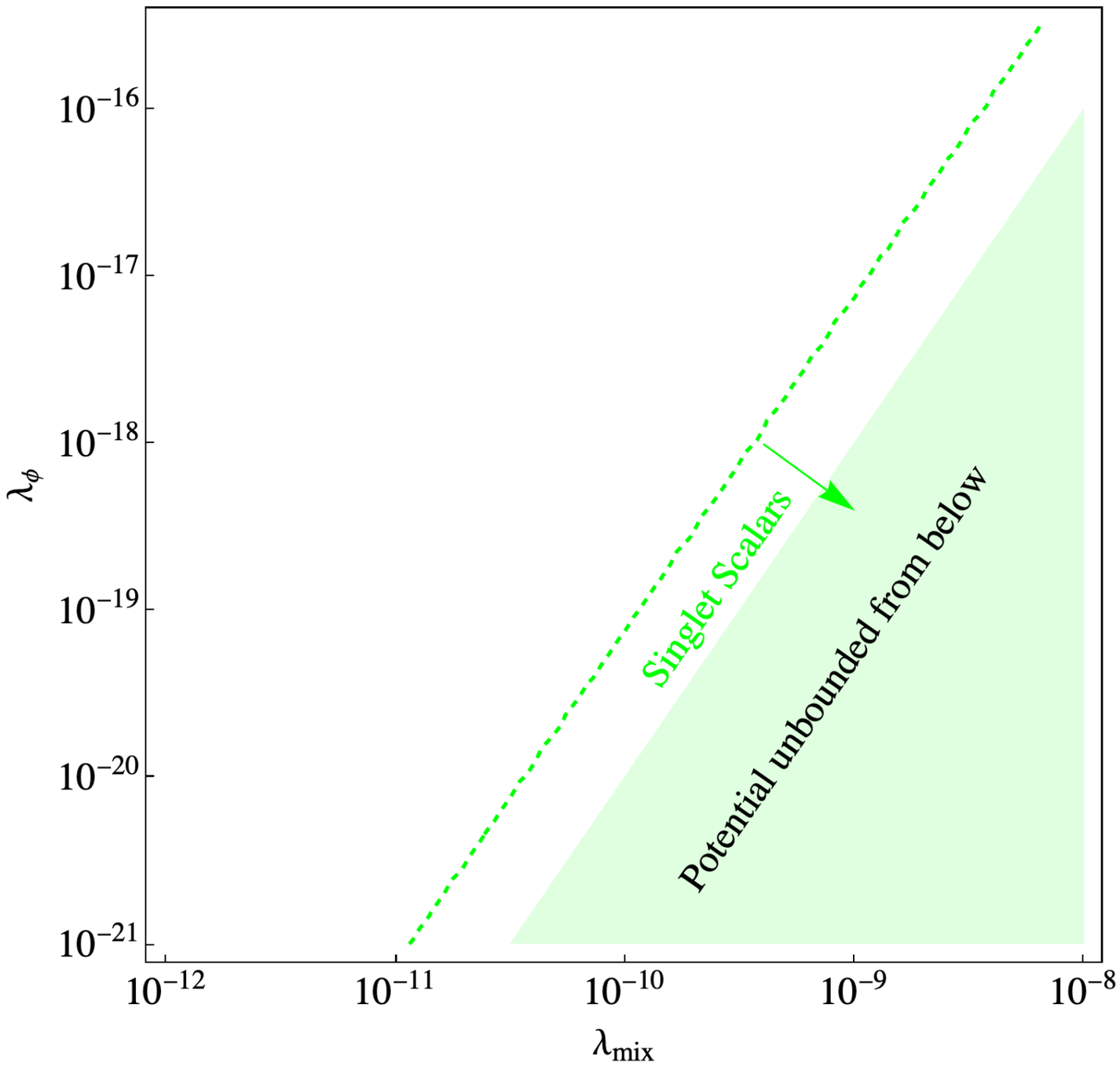
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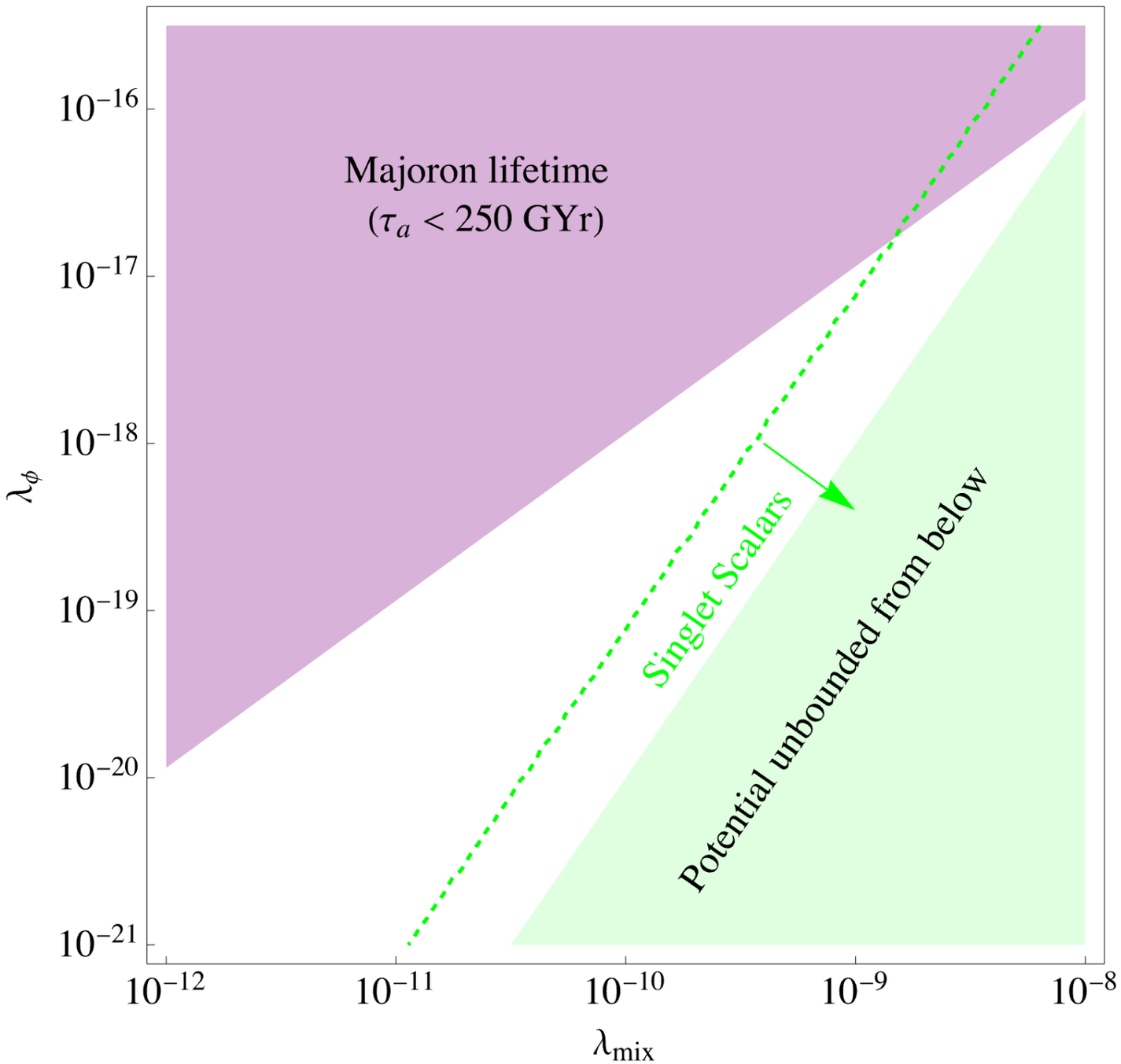
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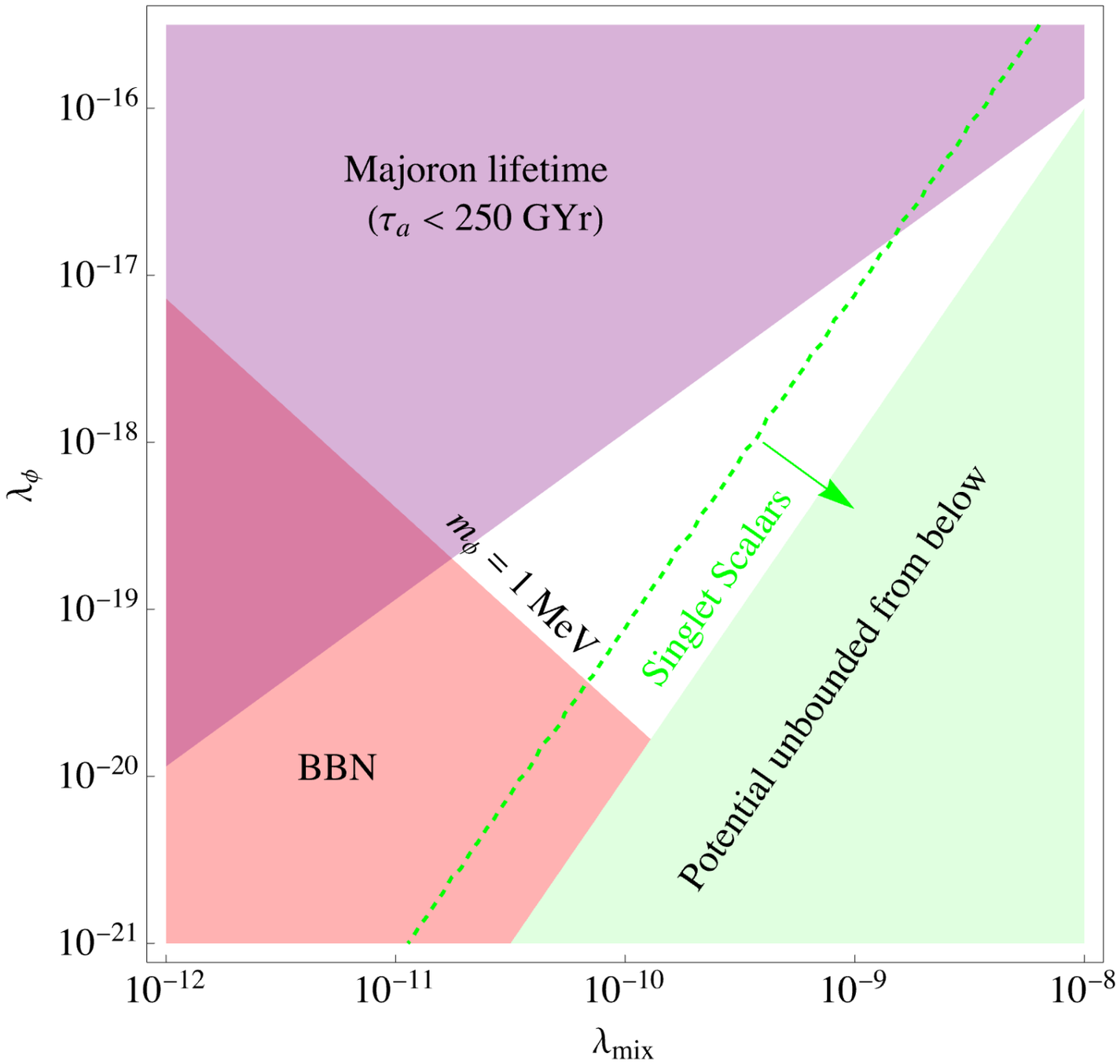
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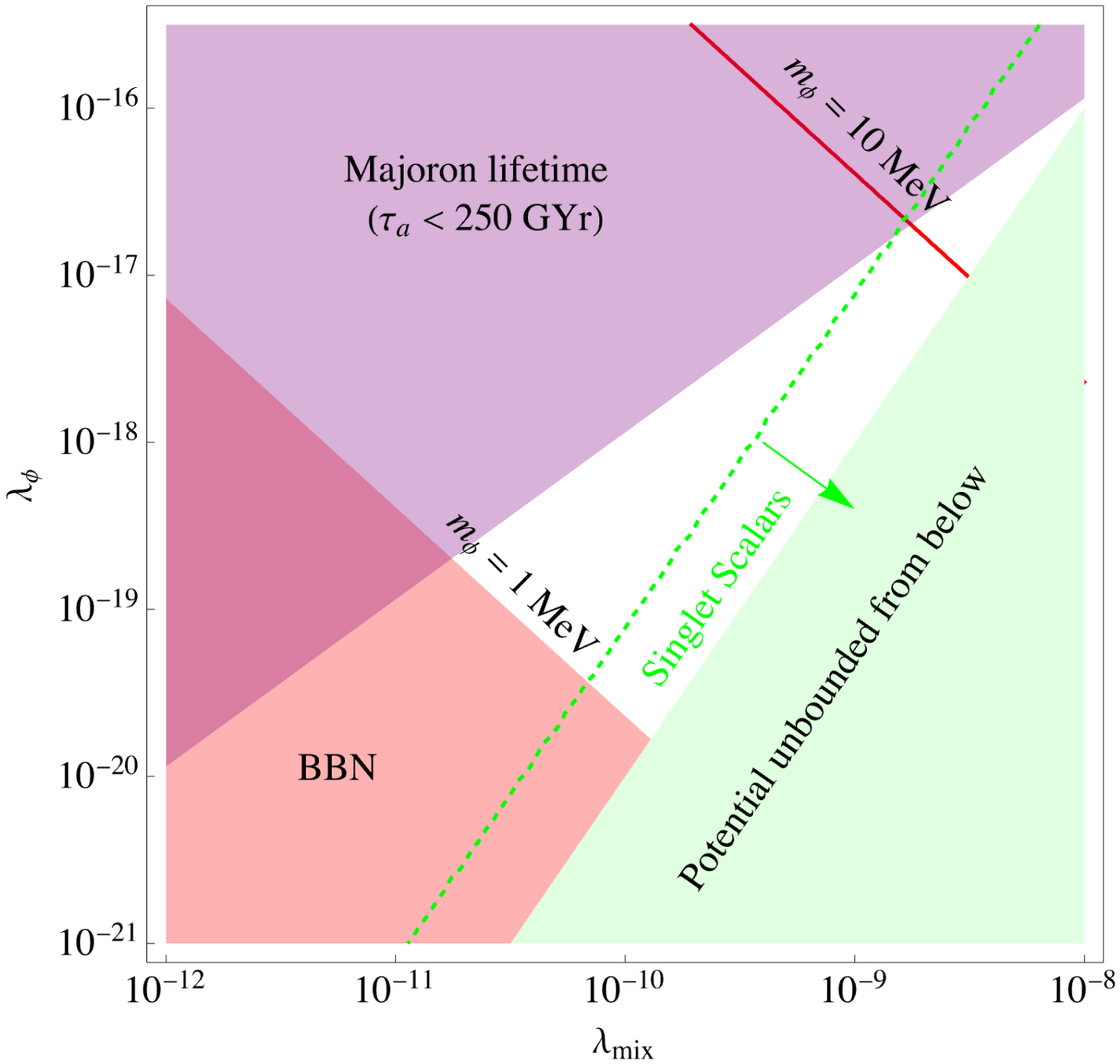
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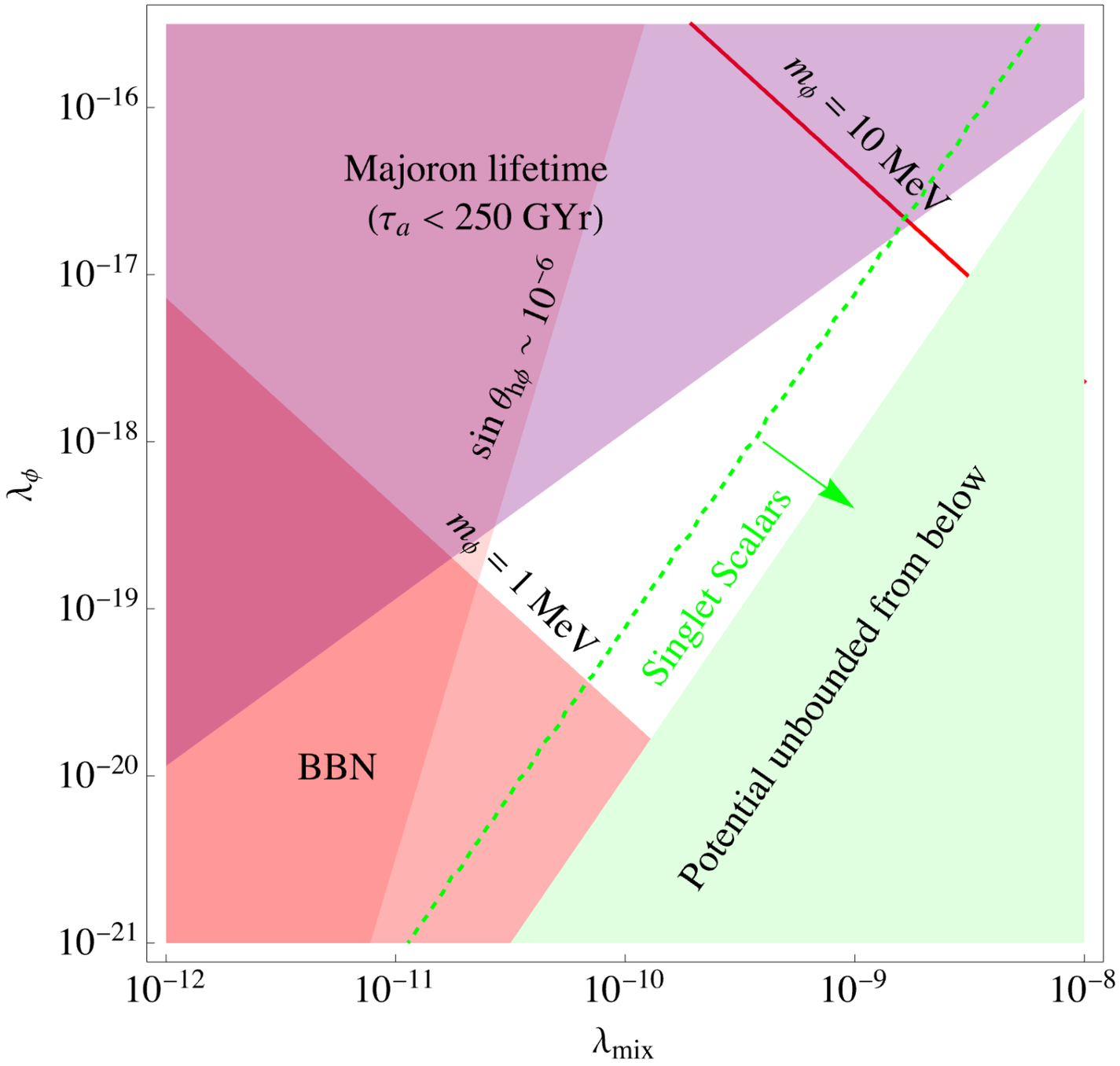
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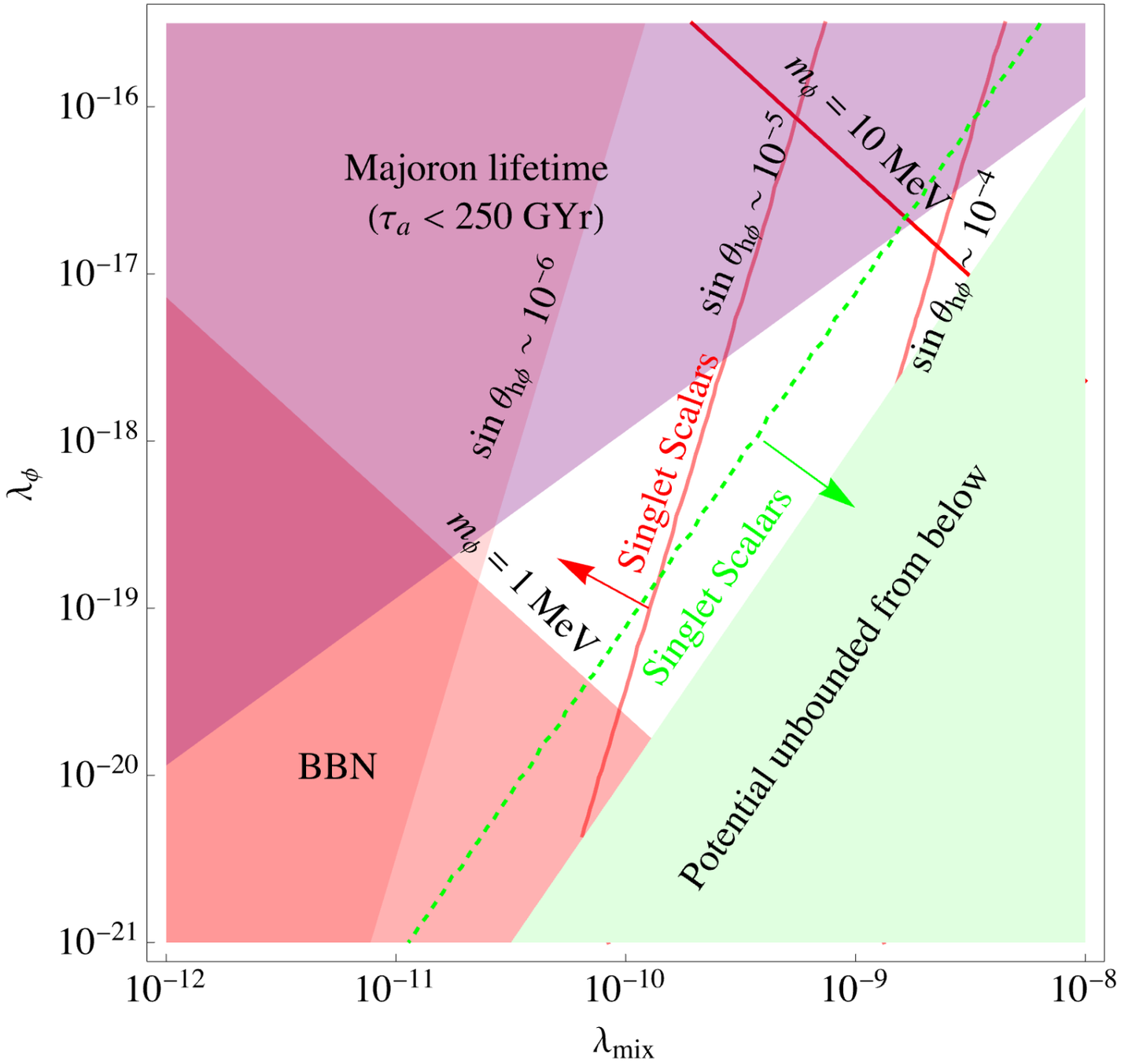
Predictions:



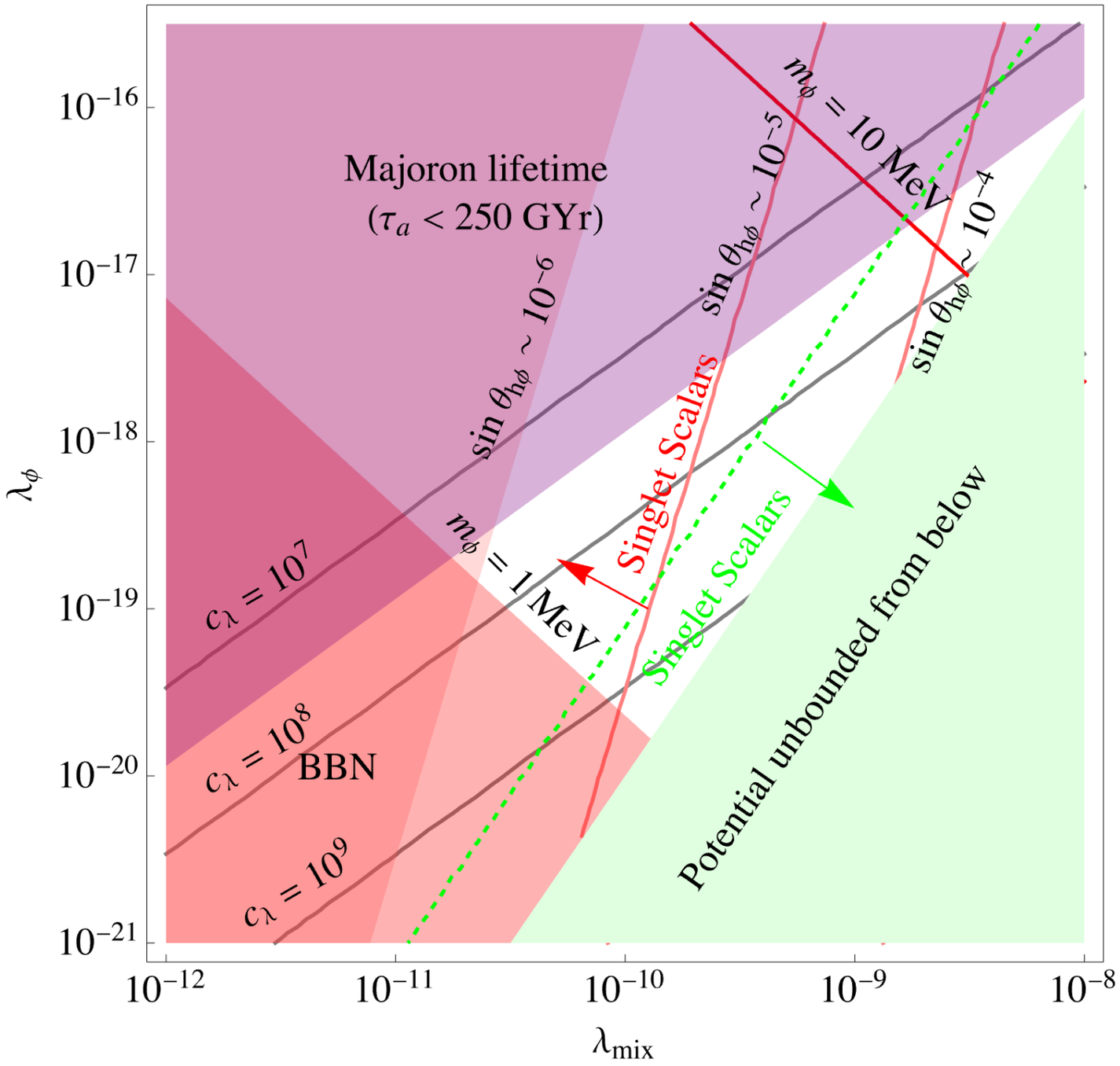
Predictions:



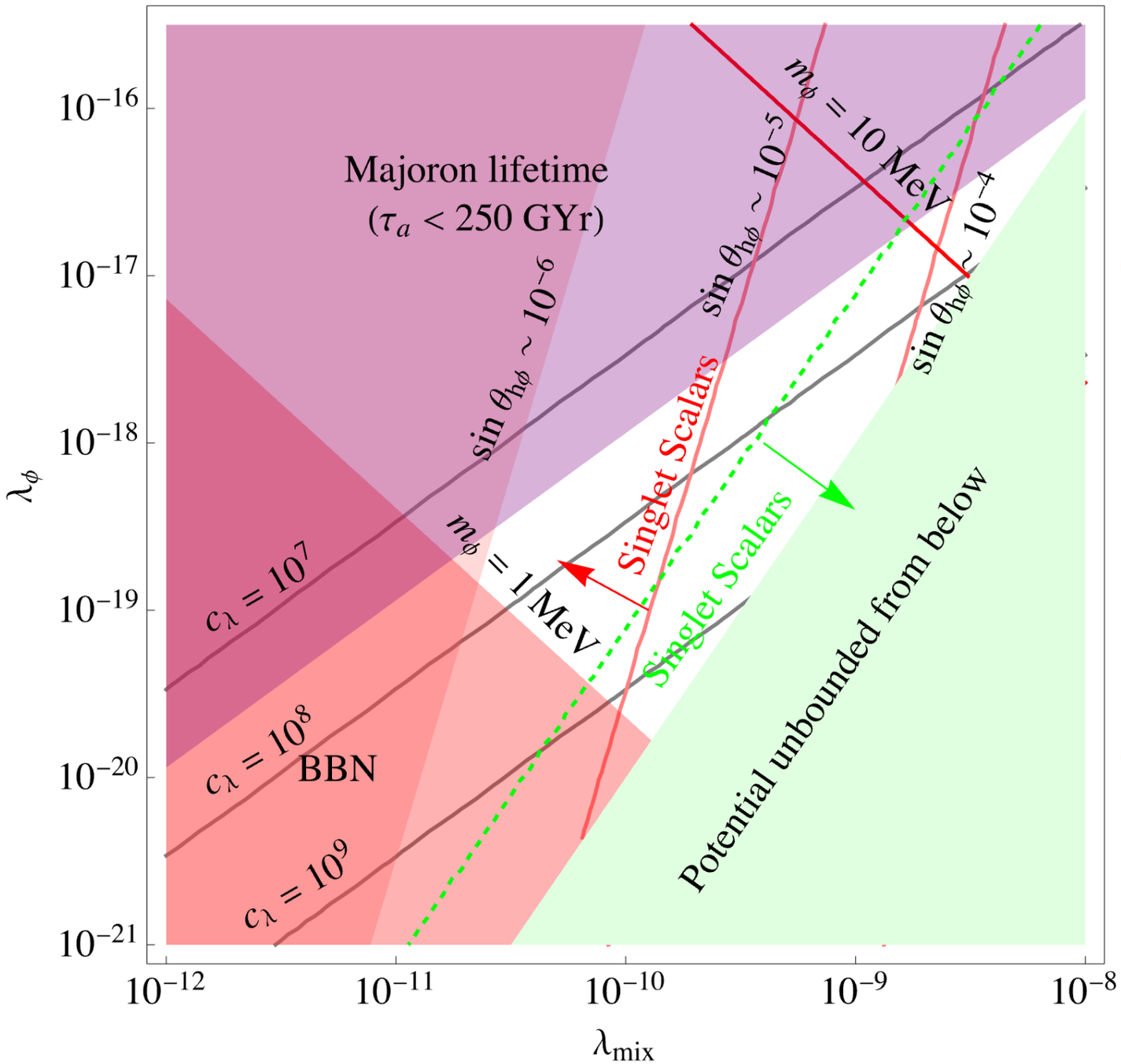
Predictions:



Predictions:



Predictions:



The Cogenesis Window

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

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

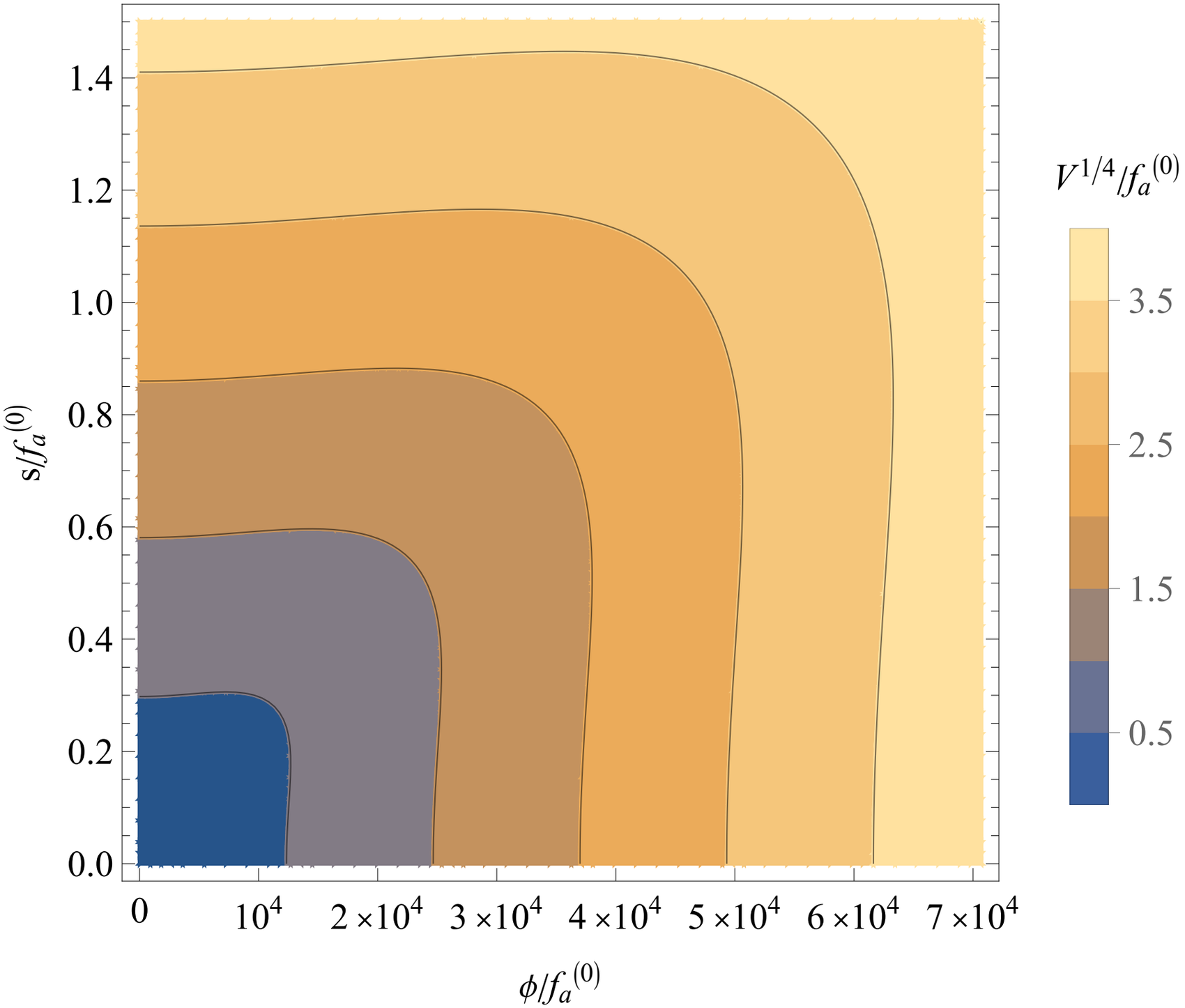
Summary

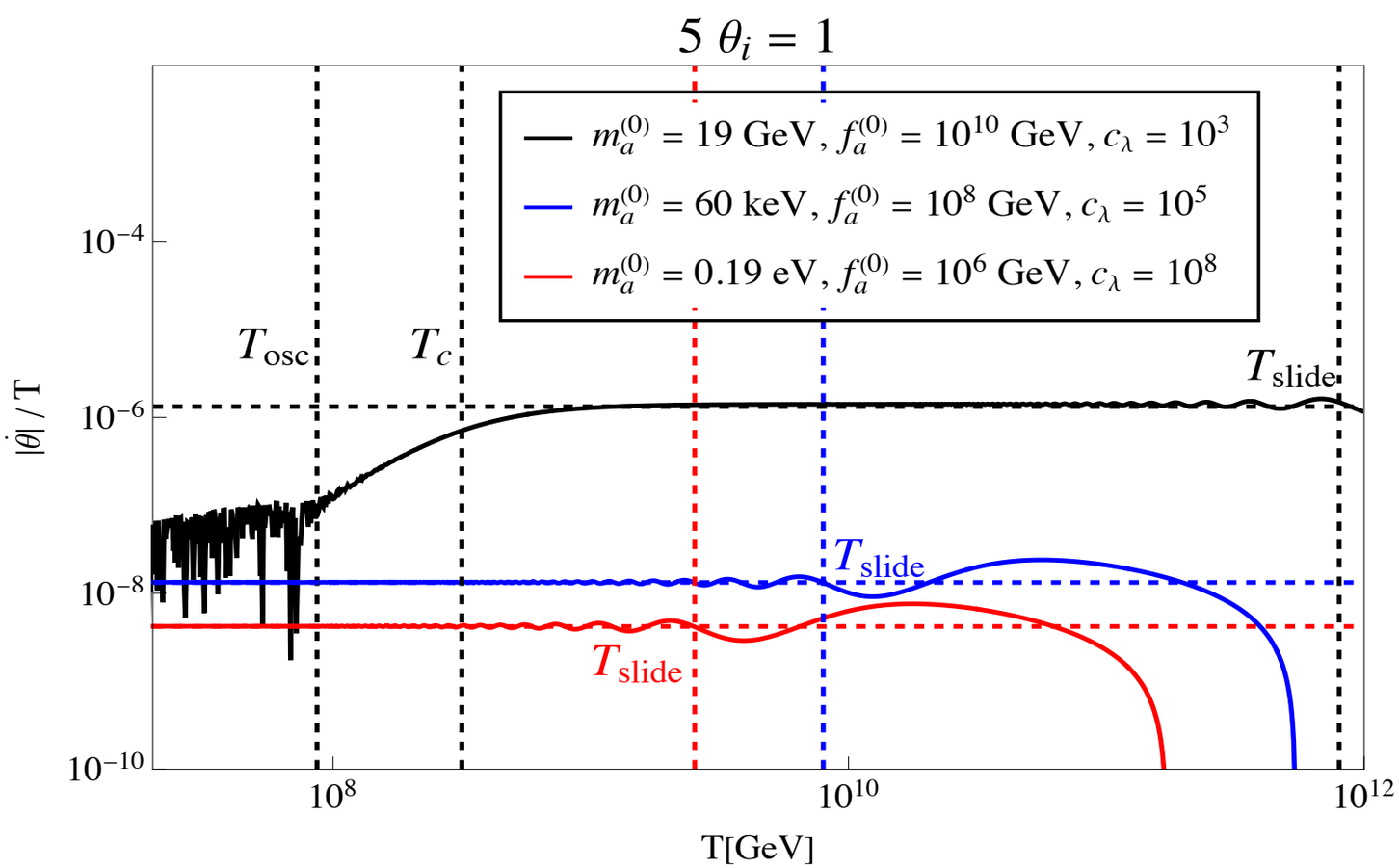
- Conventional misalignment: $\dot{\theta}_i = 0$, with no radial dynamics can lead to baryon & DM abundance.
- Baryon asymmetry at high temperatures during sliding, DM at low temperatures during oscillation.
- Decrease of pNGB potential via Symmetry non-restoration.
- Can be realized for Majoron.
- Predicts light RHN with $0.1\text{-}100$ GeV , testable at kaon experiments, colliders.

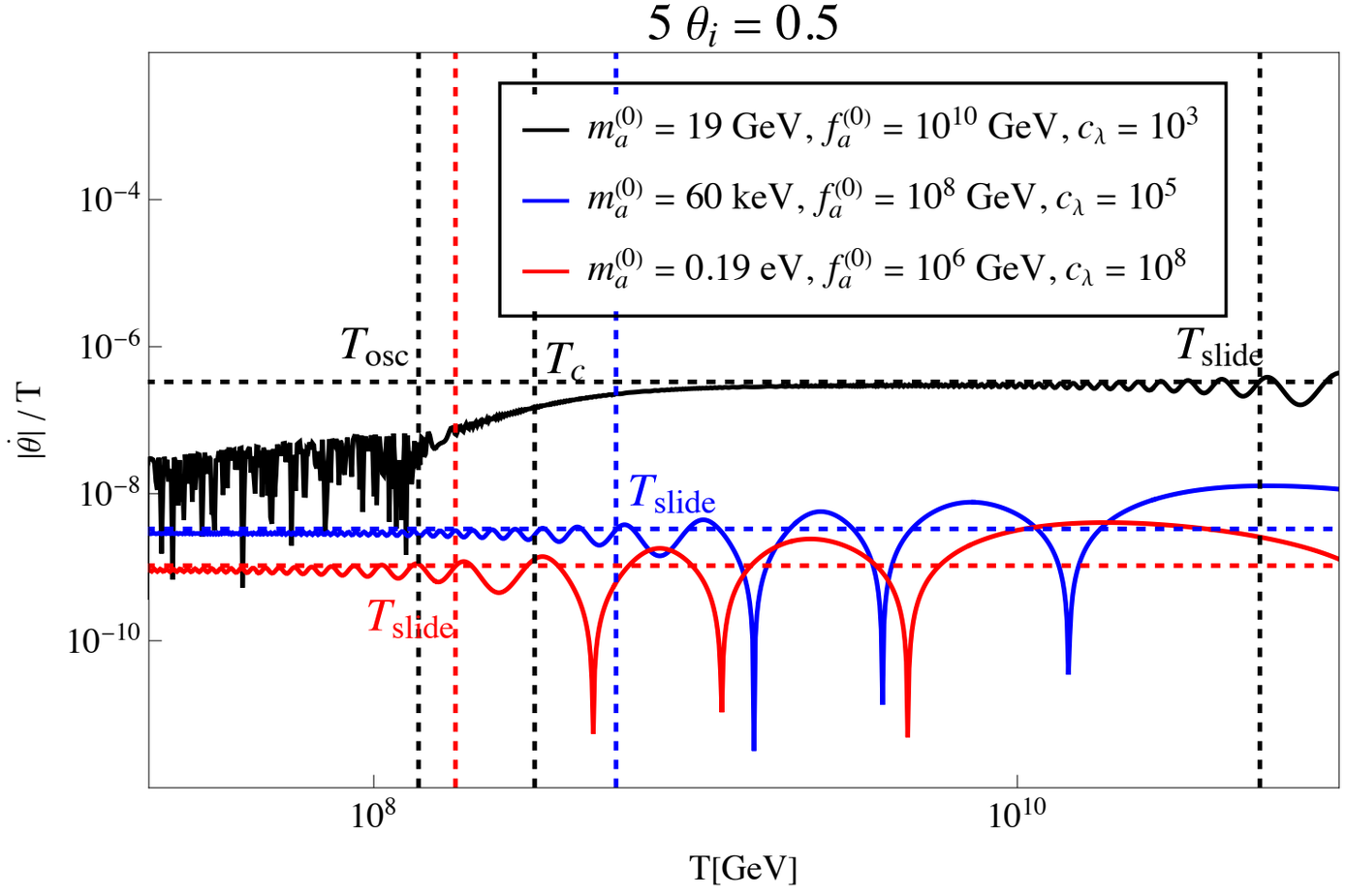
- Extension of other D-operators and other scenarios?
- Other avenues to explore for rotation: GW anisotropies, CMB Birefringence; fragmentation: Axion mini-clusters? GWs?

THANK YOU!

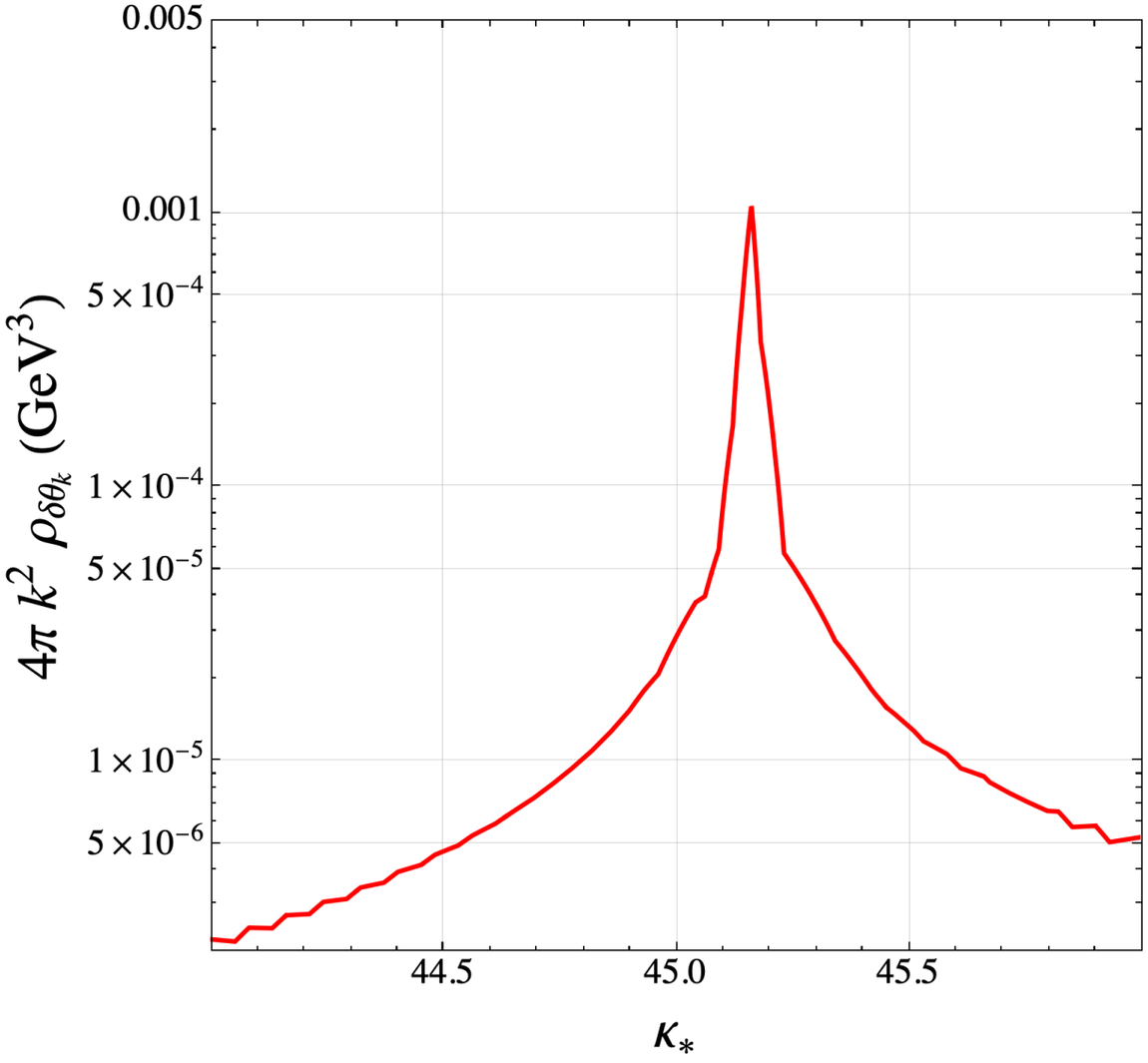
Back Up

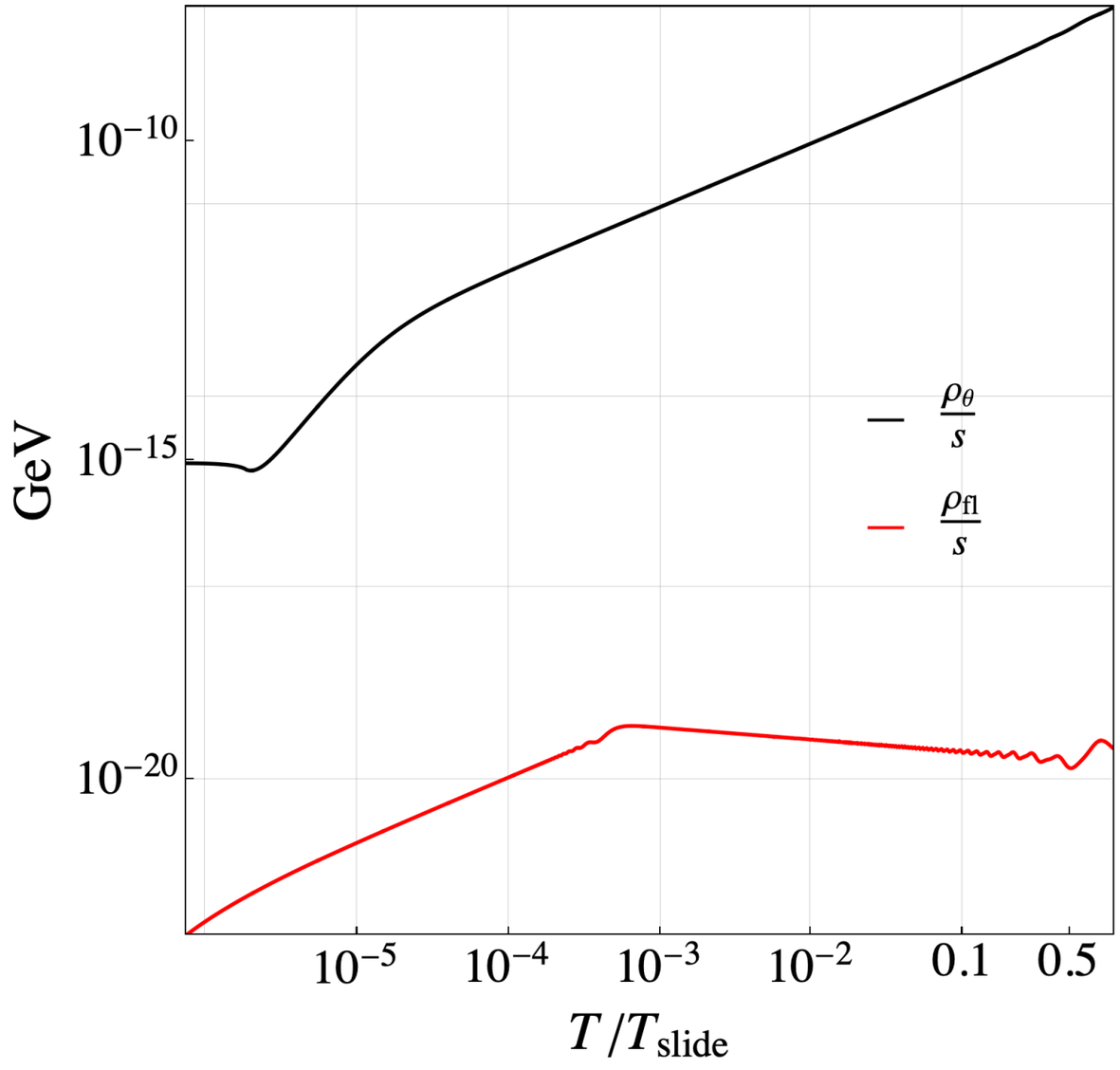

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$s/f_a^{(0)}$
0
10^4
2×10^4
3×10^4
4×10^4
5×10^4
6×10^4
7×10^4
$\phi/f_a^{(0)}$
$V^{1/4}/f_a^{(0)}$
3.5
2.5
1.5
0.5


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


$5\ \theta_i = 0.5$
$m_a^{(0)} = 19$ 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, $c_\lambda = 10^8$
$T_{\rm osc}$
T_c
$T_{\rm slide}$
$T_{\rm slide}$
$T_{\rm slide}$
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$|\dot{\theta}|\ /\ T$
10^8
10^{10}
T[GeV]

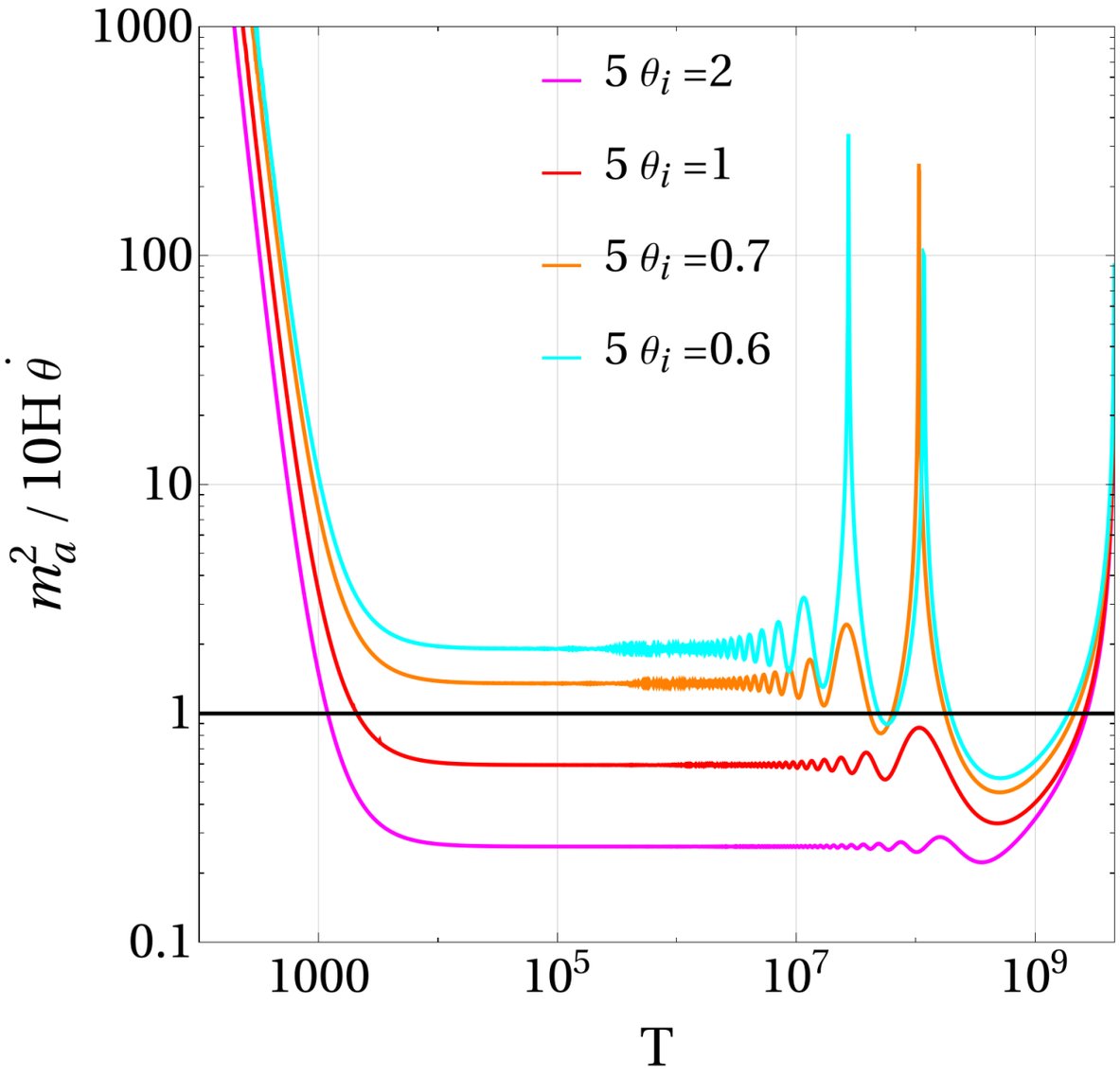
During Initial Sliding, $T > T_c$



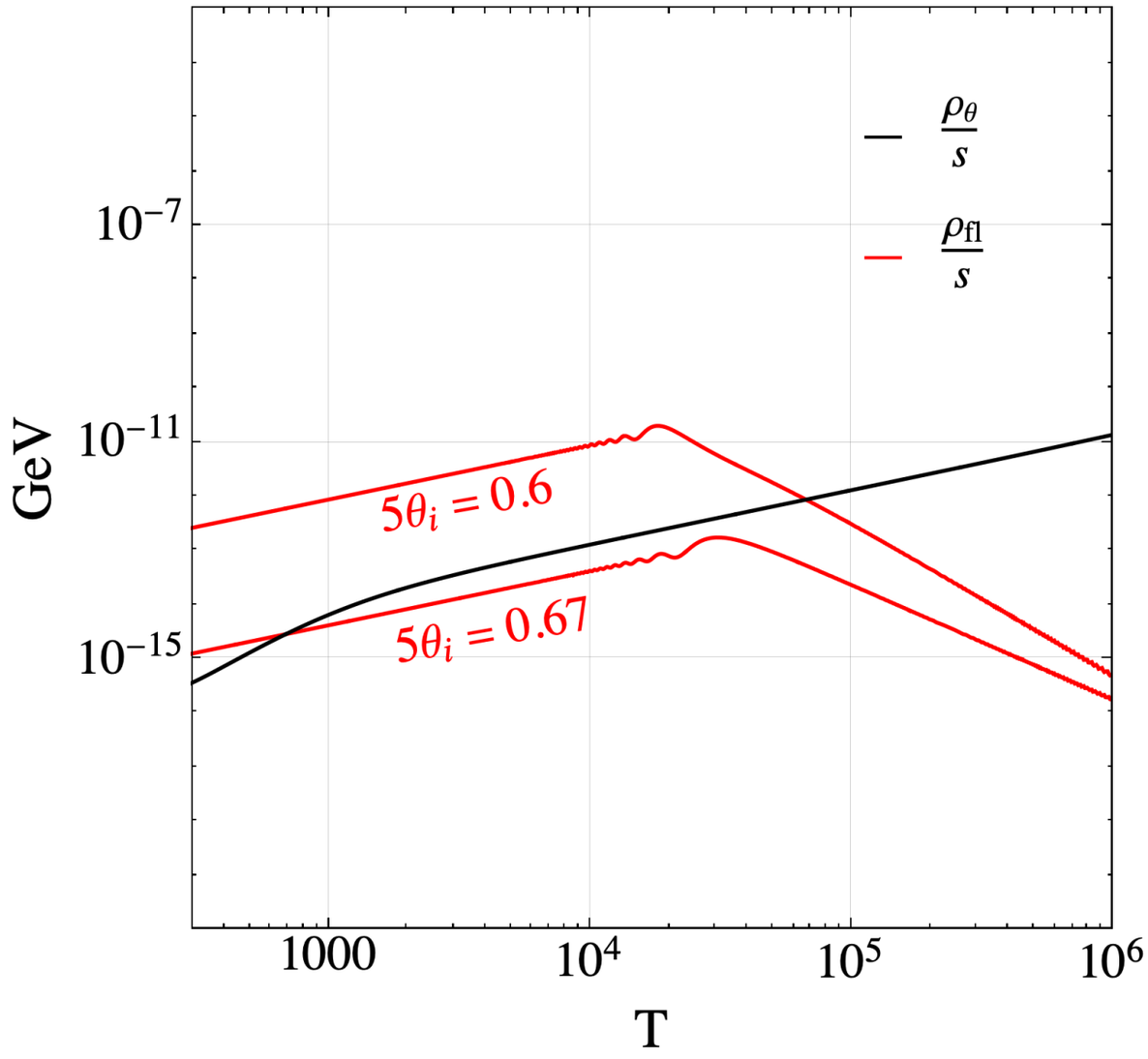


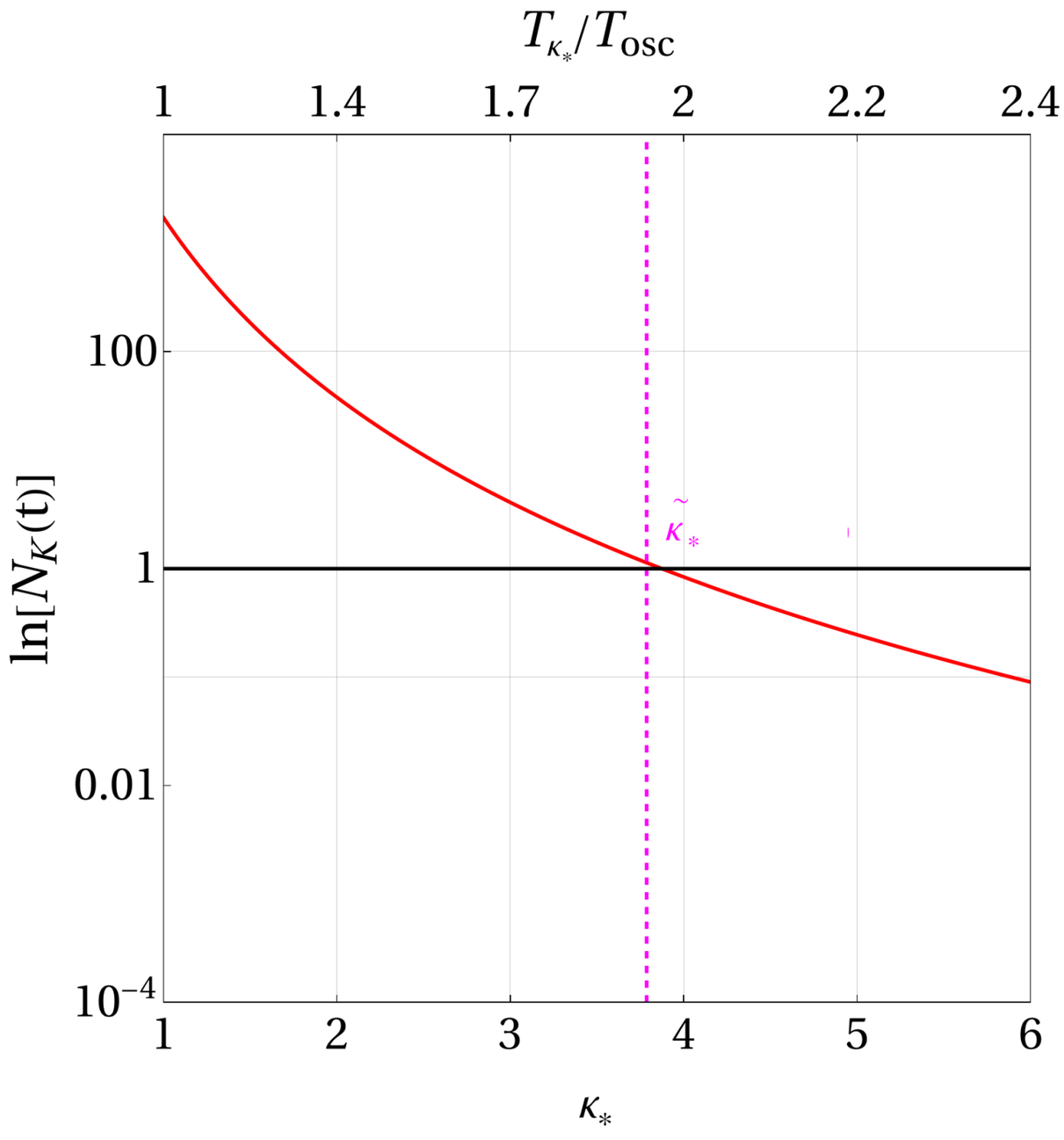
$$\rho_{\mathrm{fl}} \ll \rho_\theta$$

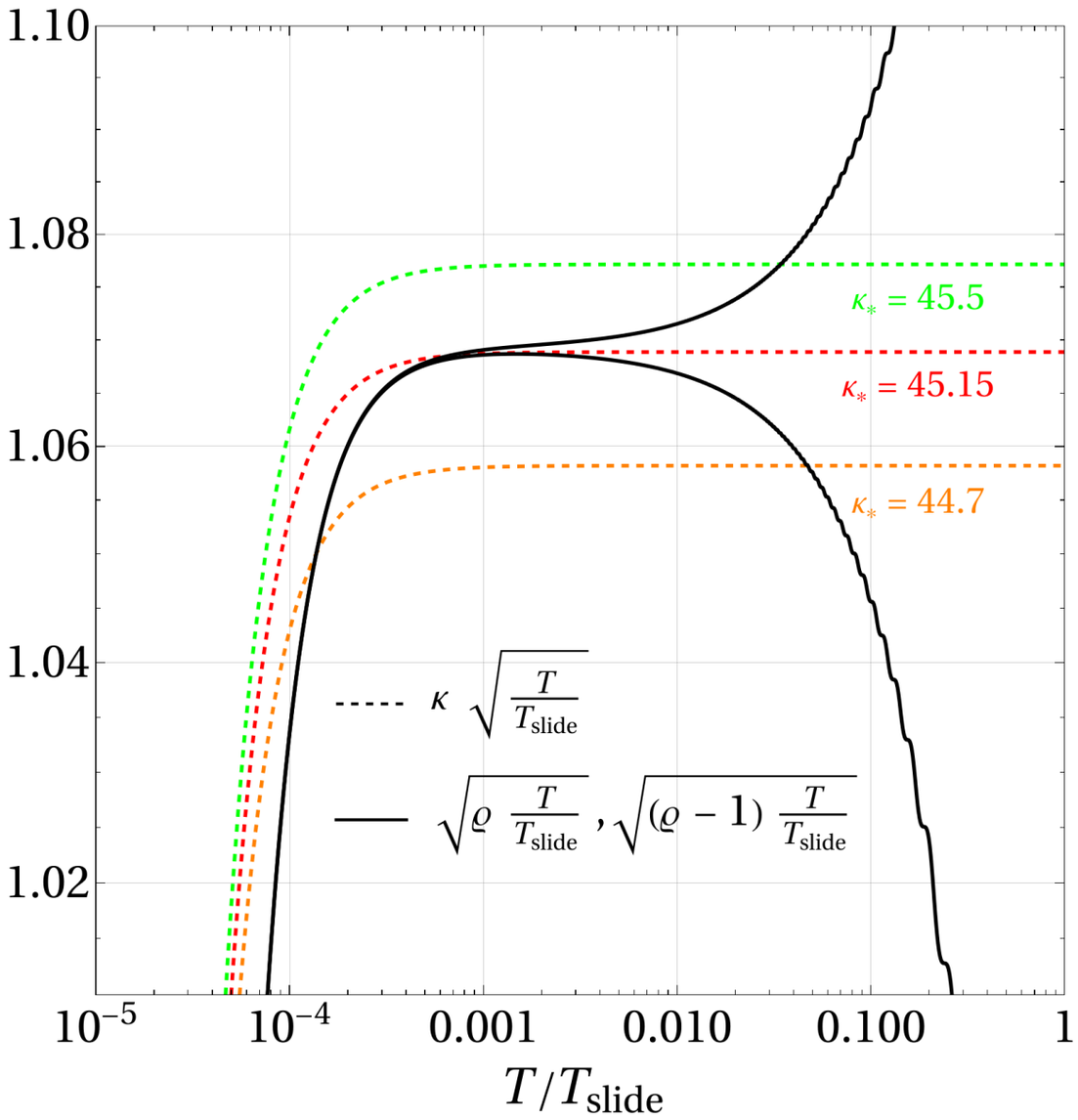
$$\frac{\text{Growth rate}}{\text{Hubble rate}} \propto (1-\cos(5\theta_i)^{-1})$$

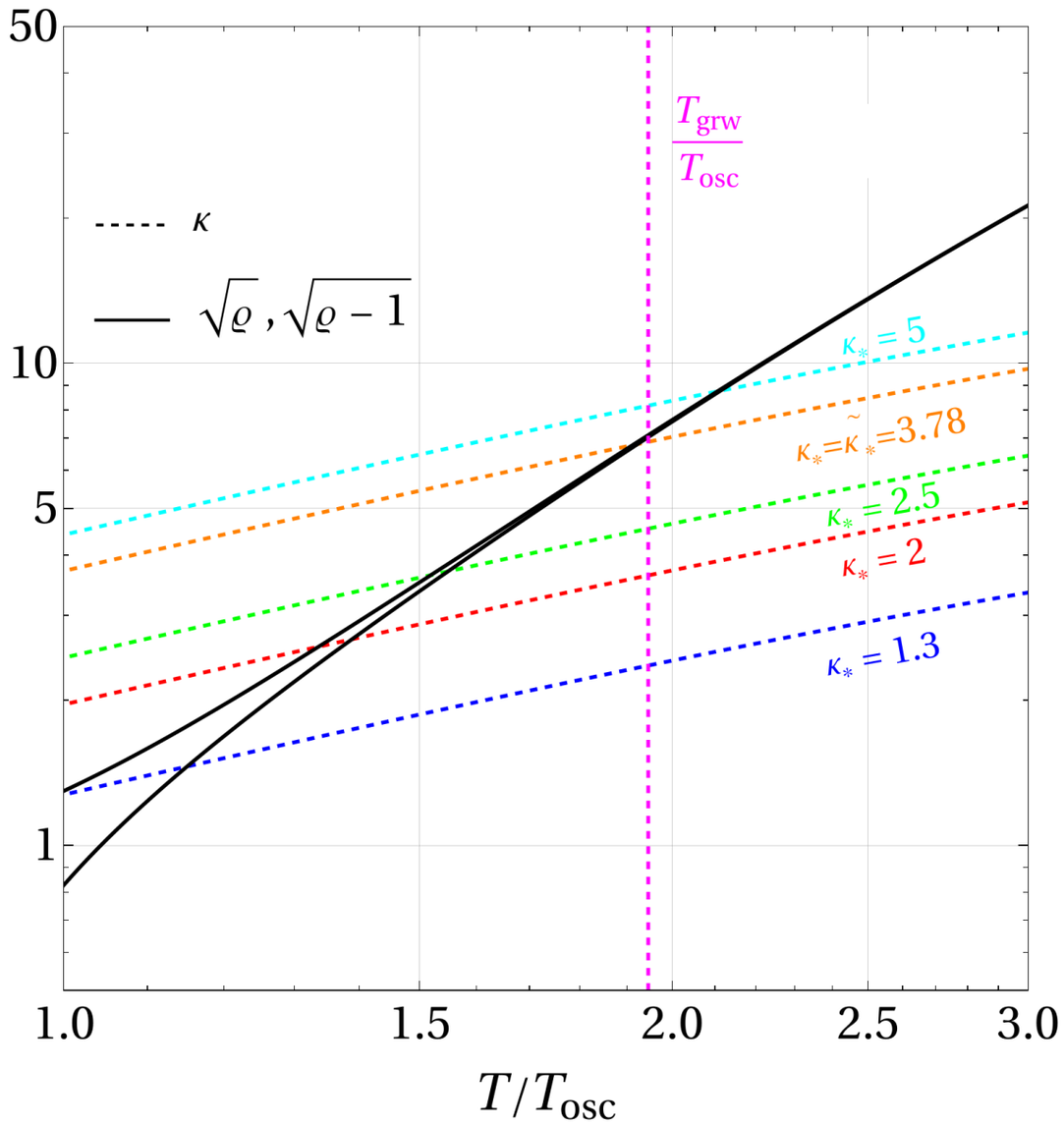


Energy evolution

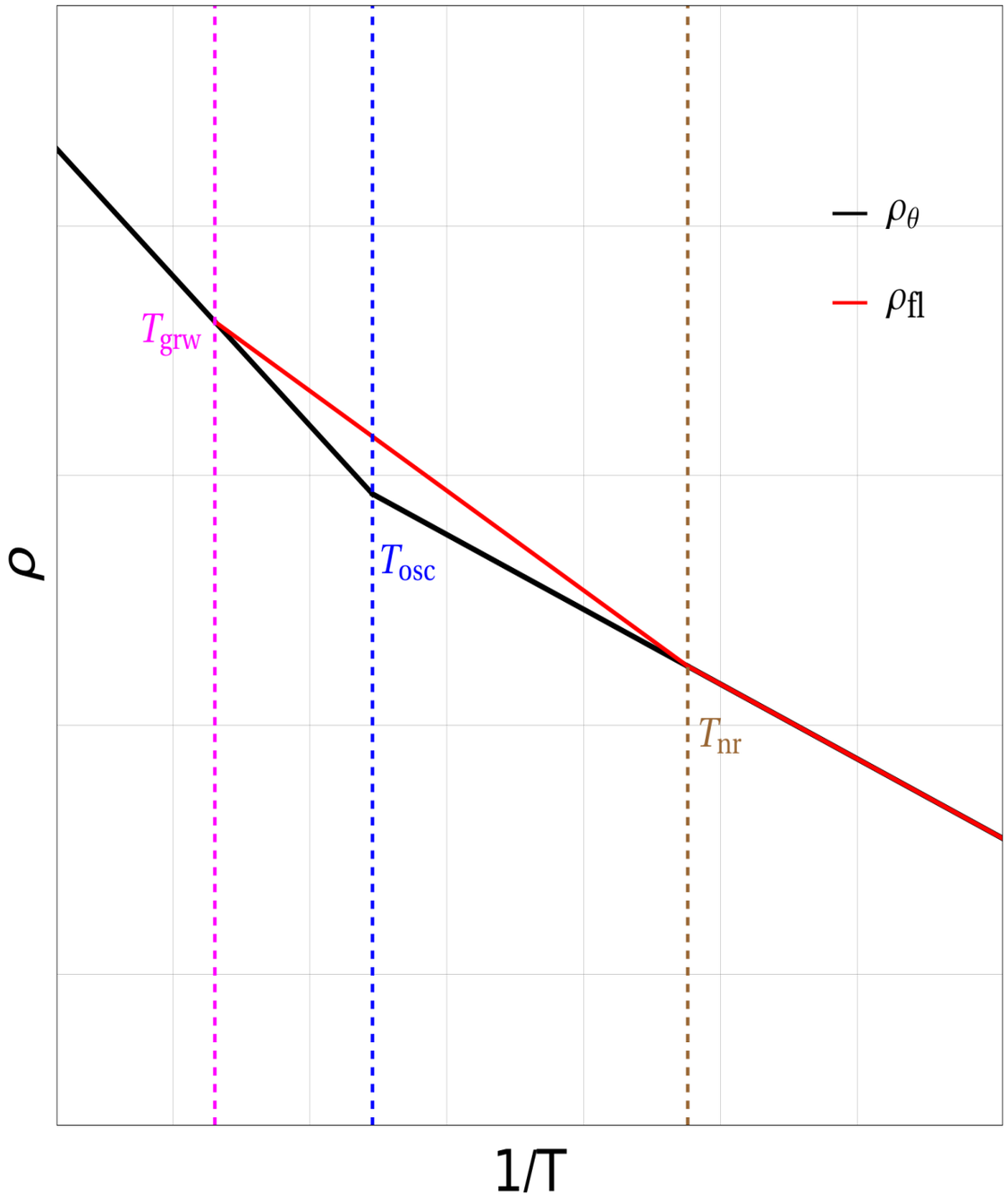



$T_{\kappa_*}/T_{\rm osc}$
1
1.4
1.7
2
2.2
2.4
100
1
0.01
10^{-4}
$\ln[N_K(t)]$
$\tilde{\kappa}_*$
1
2
3
4
5
6
κ_*


1.10
1.08
1.06
1.04
1.02
$\kappa_* = 45.5$
$\kappa_* = 45.15$
$\kappa_* = 44.7$
$\kappa \sqrt{\frac{T}{T_{\rm slide}}}$
$\sqrt{\varrho \frac{T}{T_{\rm slide}}}, \sqrt{(\varrho - 1) \frac{T}{T_{\rm slide}}}$
10^{-5}
10^{-4}
0.001
0.010
0.100
1
$T/T_{\rm slide}$


50
10
5
1
$\frac{T_{\rm grw}}{T_{\rm osc}}$
κ
$\sqrt{\varrho}, \sqrt{\varrho - 1}$
$\kappa_* = 5$
$\kappa_* = \tilde{\kappa}_* = 3.78$
$\kappa_* = 2.5$
$\kappa_* = 2$
$\kappa_* = 1.3$
1.0
1.5
2.0
2.5
3.0
$T/T_{\rm osc}$

Relic density



$$\rho_{\rm fl}(T_f) \simeq \rho_{\rm fl}(T_{\rm nr}) \left(\frac{T_f}{T_{\rm nr}}\right)^3$$

$$\simeq \rho_{\rm fl}(T_{\rm grw}) \left(\frac{T_{\rm nr}}{T_{\rm grw}}\right)^4 \left(\frac{T_f}{T_{\rm nr}}\right)^3$$

$$\simeq \rho_{\rm osc}(T_{\rm osc}) \left(\frac{T_{\rm grw}}{T_{\rm osc}}\right)^6 \left(\frac{T_{\rm nr}}{T_{\rm grw}}\right)^4 \left(\frac{T_f}{T_{\rm nr}}\right)^3$$

$$\simeq \rho_{\rm osc}(T_{\rm nr}) \left(\frac{T_{\rm osc}}{T_{\rm nr}}\right)^3 \left(\frac{T_{\rm grw}}{T_{\rm osc}}\right)^6 \left(\frac{T_{\rm nr}}{T_{\rm grw}}\right)^4 \left(\frac{T_f}{T_{\rm nr}}\right)^3$$

$$\simeq \rho_{\rm osc}(T_f)\,,$$