



Baryogenesis and Dark Matter from Rotating Axions

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IFT, UW

Seminar @ FUW

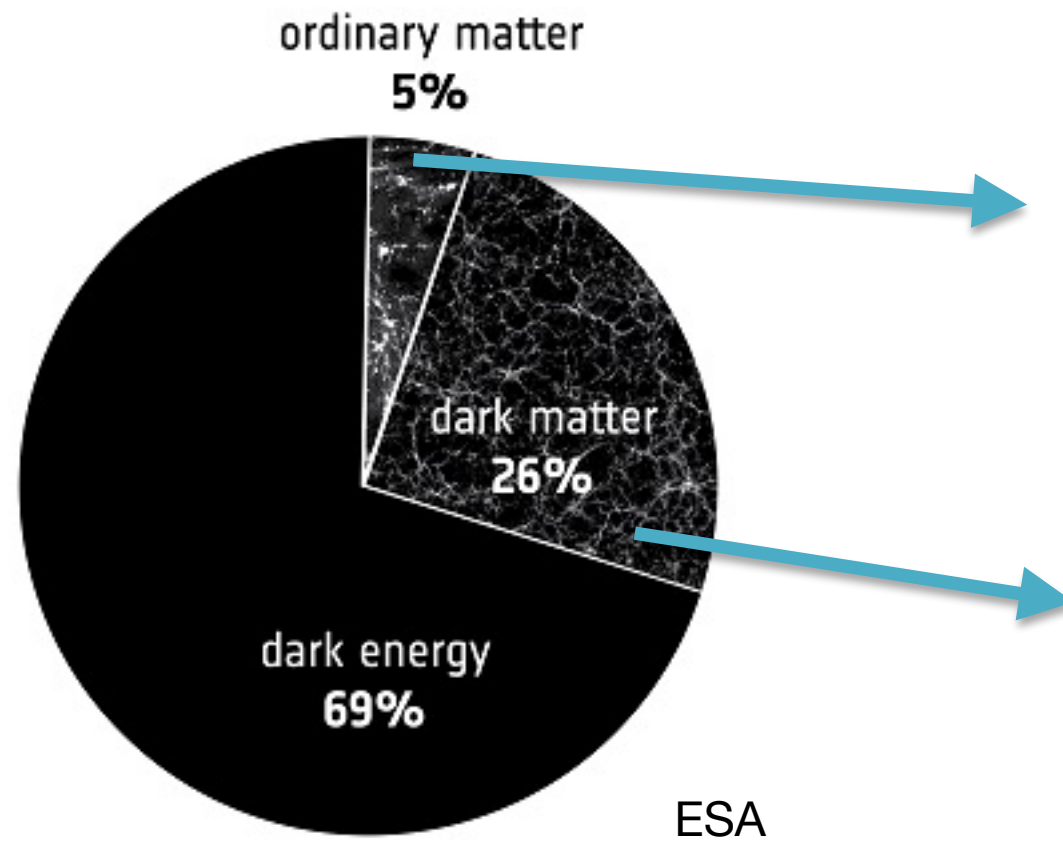
Based on:

2406.04180, PRD 2025 (E.J. Chun, **S.J. Das**, M. He, T.H. Jung, J. Sun)

2502.08720, EPJC 2025 (C. Chen, **S.J. Das**, K. Dimopoulos, A. Ghoshal)

Outline

- Introduction and Motivation.
- Rotation through symmetry non-restoration.
- Rotation through non-minimal coupling.
- Summary.

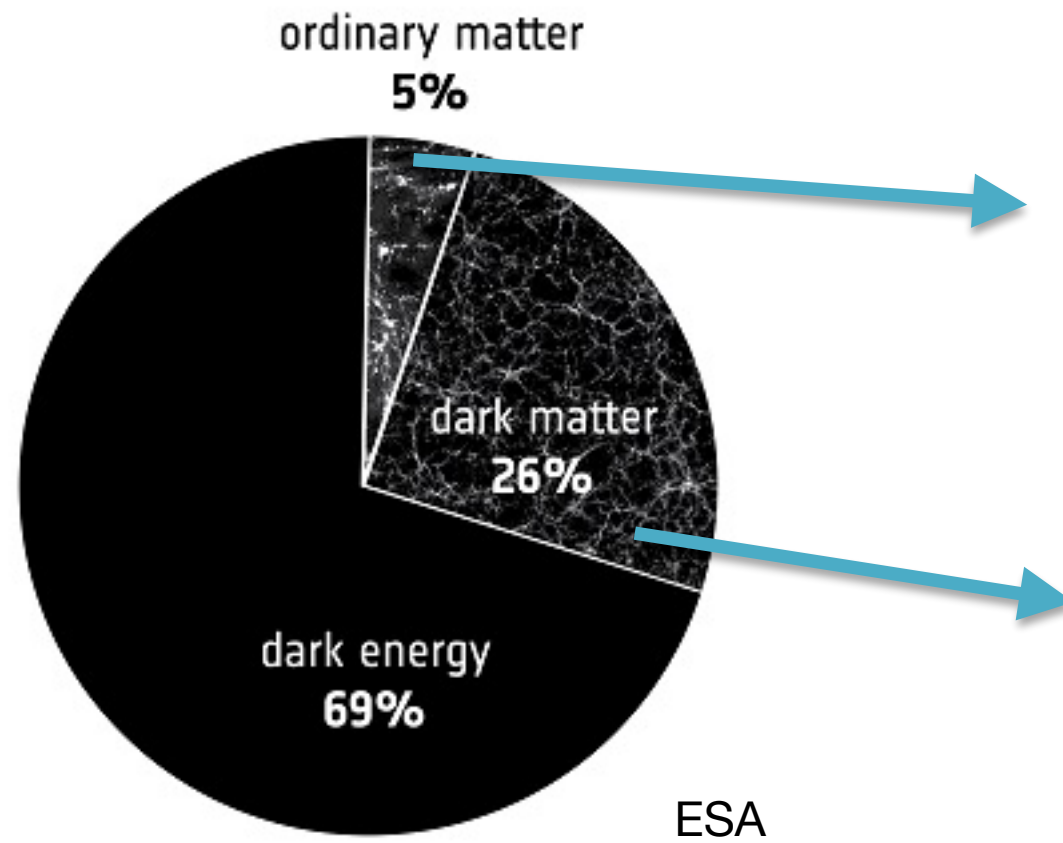


1) Baryon Asymmetry (from BBN and CMB):

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

2) Dark Matter abundance(from CMB):

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



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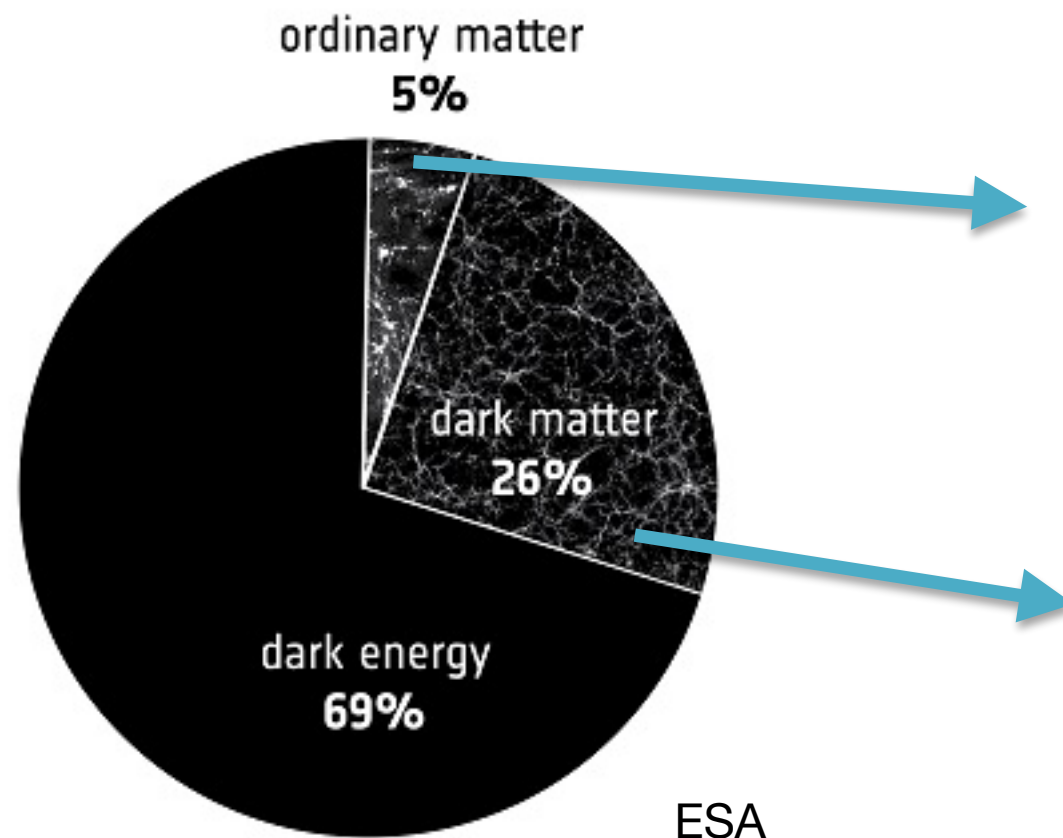
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Requires BSM physics

1) Leptogenesis, EW baryogenesis,
Spontaneous Baryogenesis

2) Freeze-out, freeze-in, PBH,
Misalignment mechanism



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Can a single field account for both?

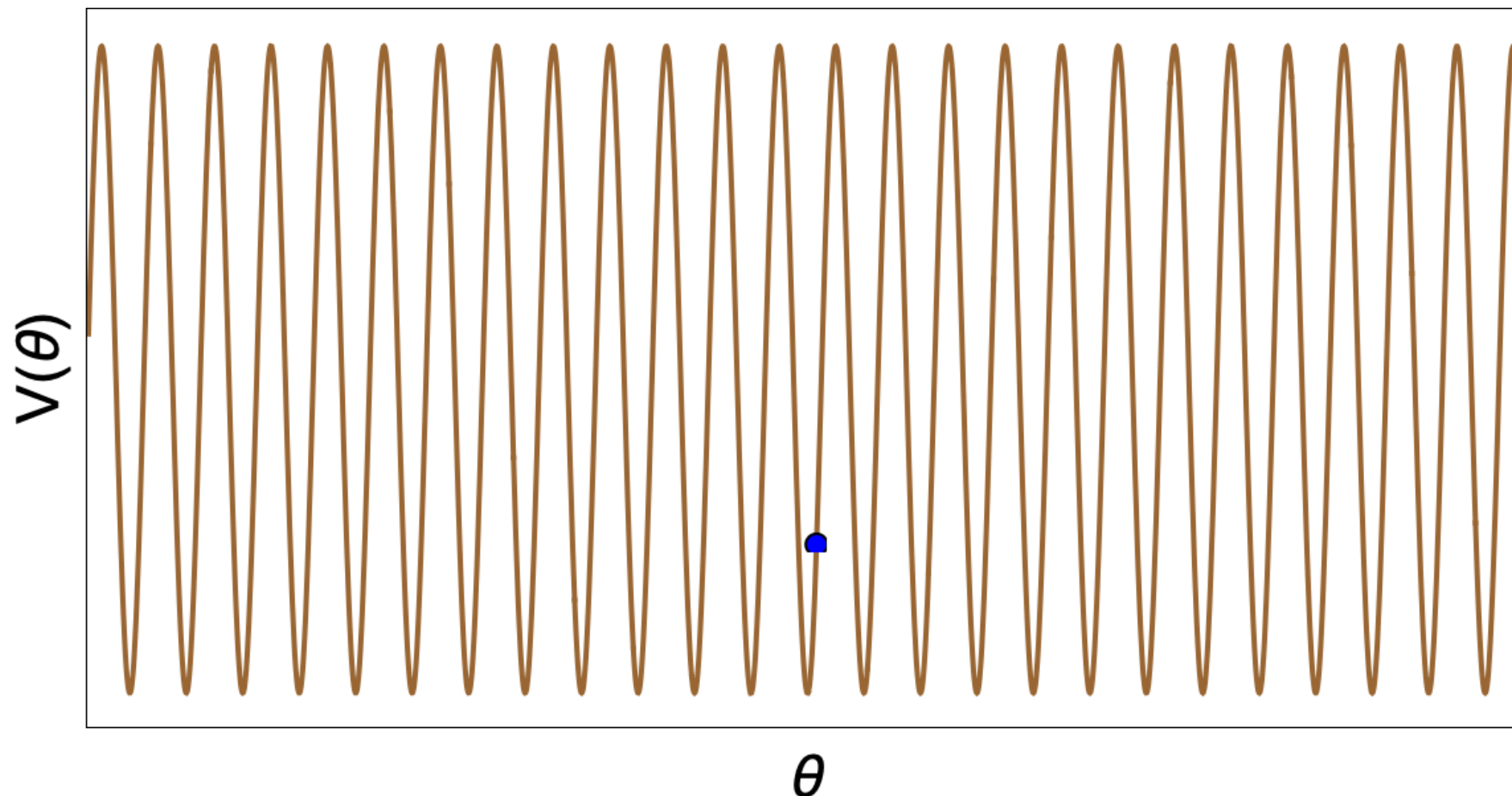
Axion-like particles:

- Pseudo-Nambu Goldstone boson of approximate global symmetry.

$$\Phi = \frac{f_a + \rho}{\sqrt{2}} e^{ia/f_a} \quad U(1) : \Phi \rightarrow e^{i\alpha} \Phi \implies a \rightarrow a + \alpha f_a$$

Examples: QCD axion, Majoron, Familon.....

- Small explicit symmetry breaking. $V(\theta) = m_a^2 f_a^2 (1 - \cos \theta)$ $\theta = \frac{a}{f_a}$



Coherent oscillation:
Dark Matter

How to generate asymmetry?

Sakharov '67

- B / 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:

$$\frac{c}{f_a}(\partial_\mu a) J_X^\mu \quad X = B, L \dots \quad \bar{\psi}\gamma^\mu\psi$$

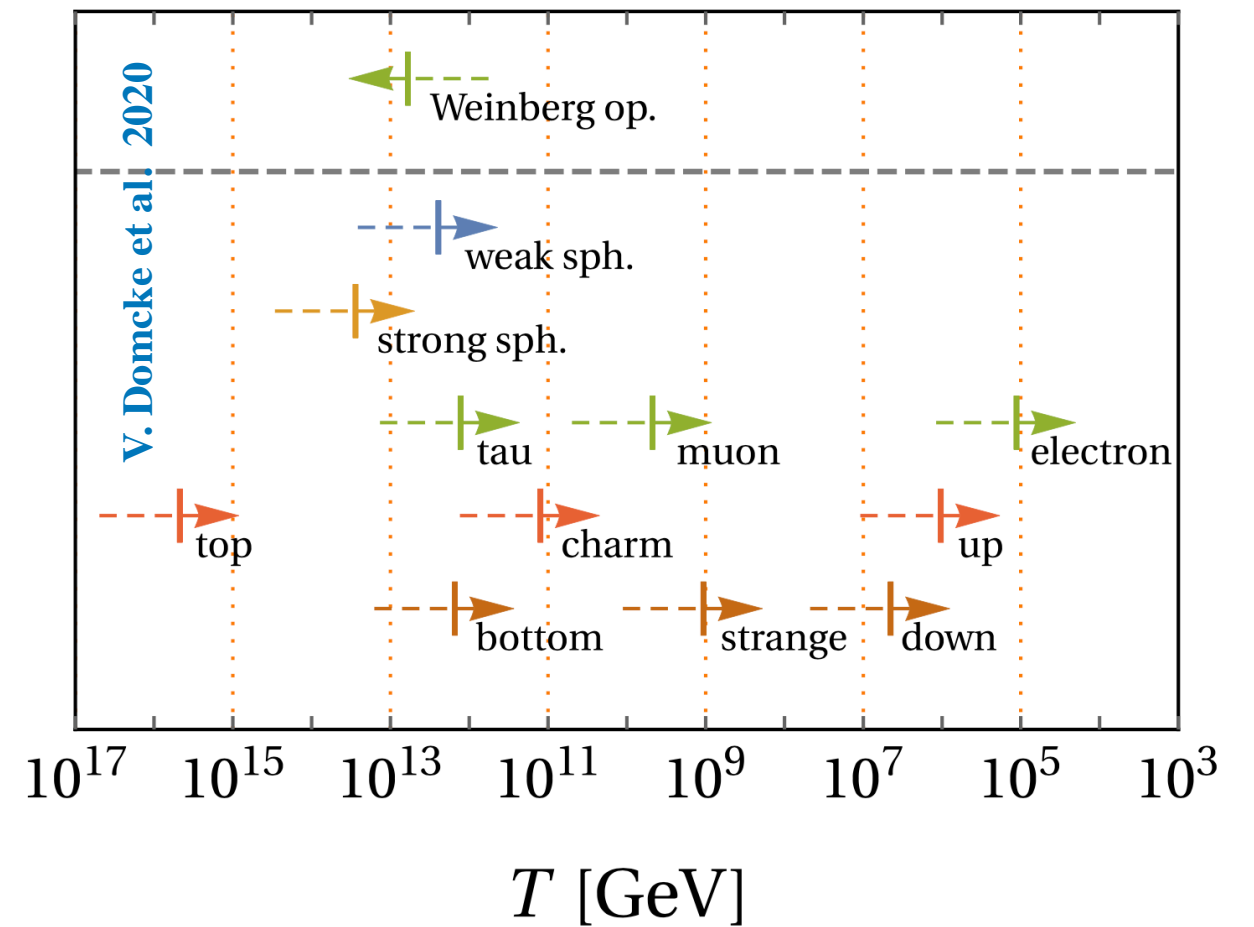
(natural in ALPs with shift symmetry)

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

Asymmetry redistributed



Interactions

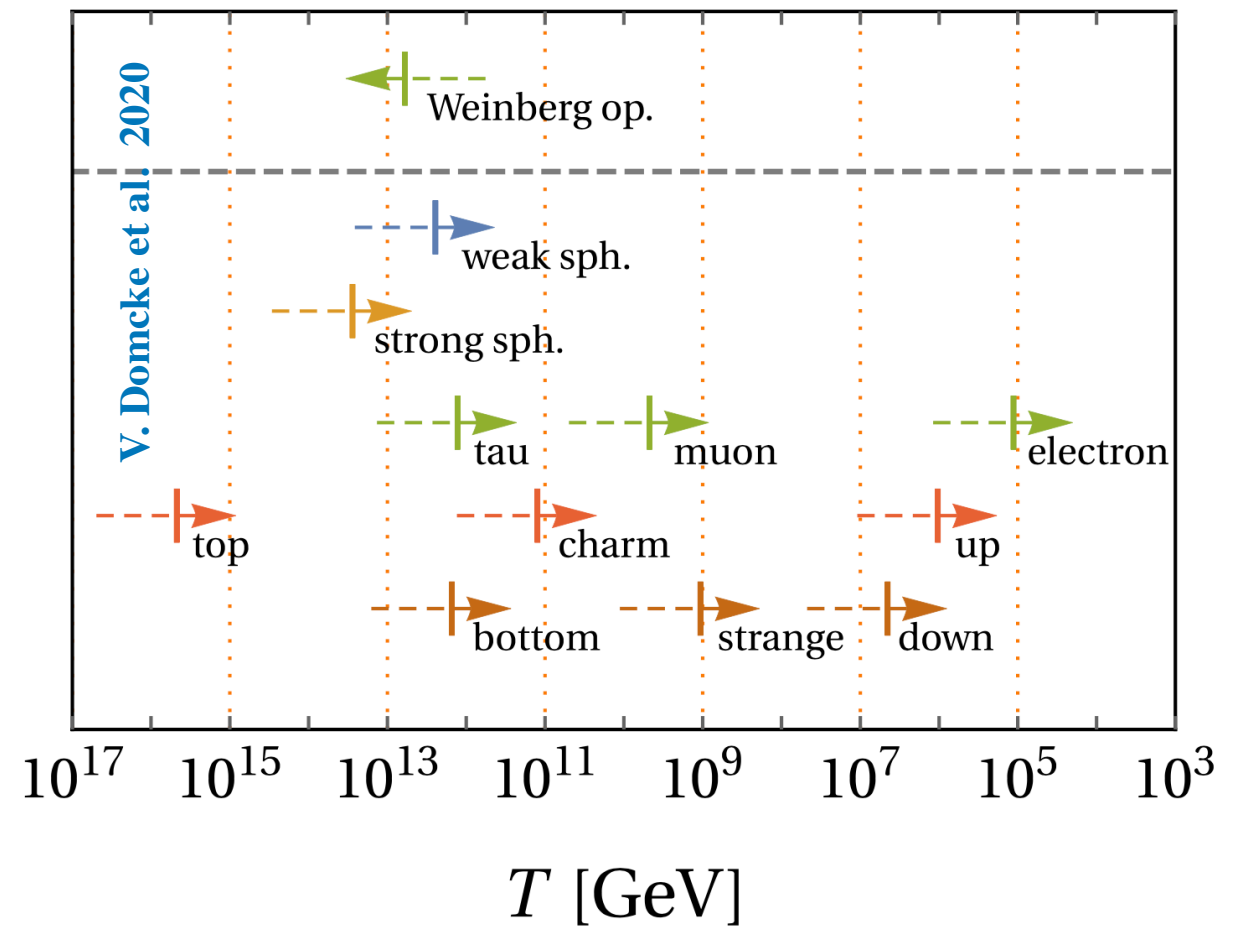


$$\frac{dn_i}{dt} = \text{Creation terms} - \text{Annihilation terms} + \text{bias terms} \rightarrow \text{proportional to } \dot{\theta}$$

Asymmetry redistributed



Interactions



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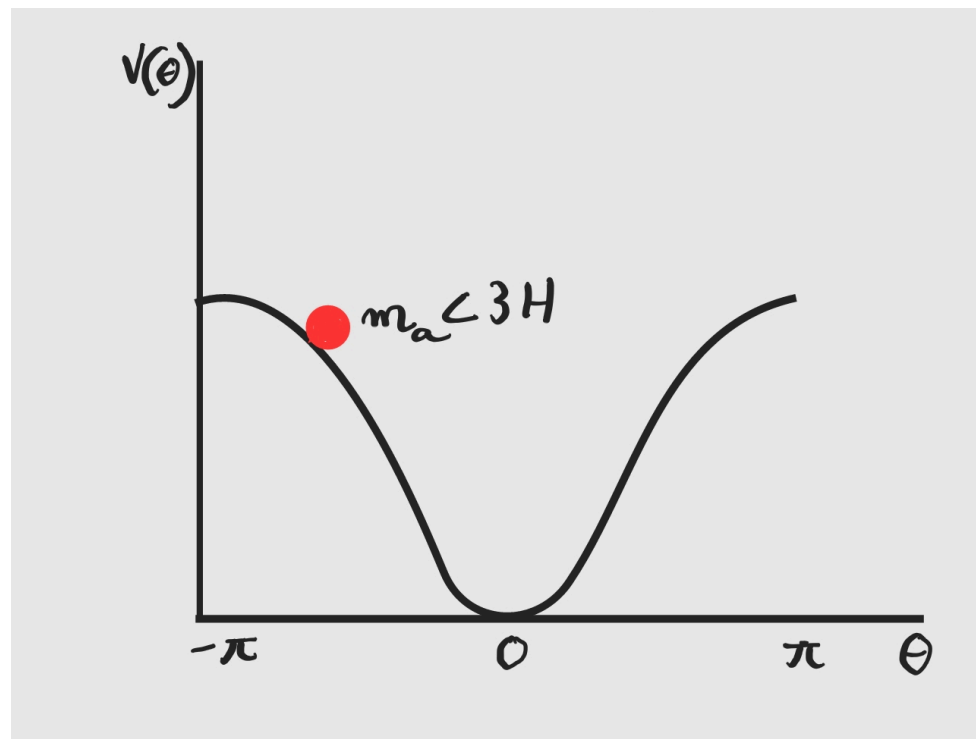
Final Asymmetry: $\frac{n_B}{s} \simeq \frac{\mu_B T^2}{s} \sim \frac{\dot{\theta}}{g_* T_{B-L}}$ at B,L violation decoupling

Dynamics of θ (Misalignment Mechanism)

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

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

Conventional misalignment

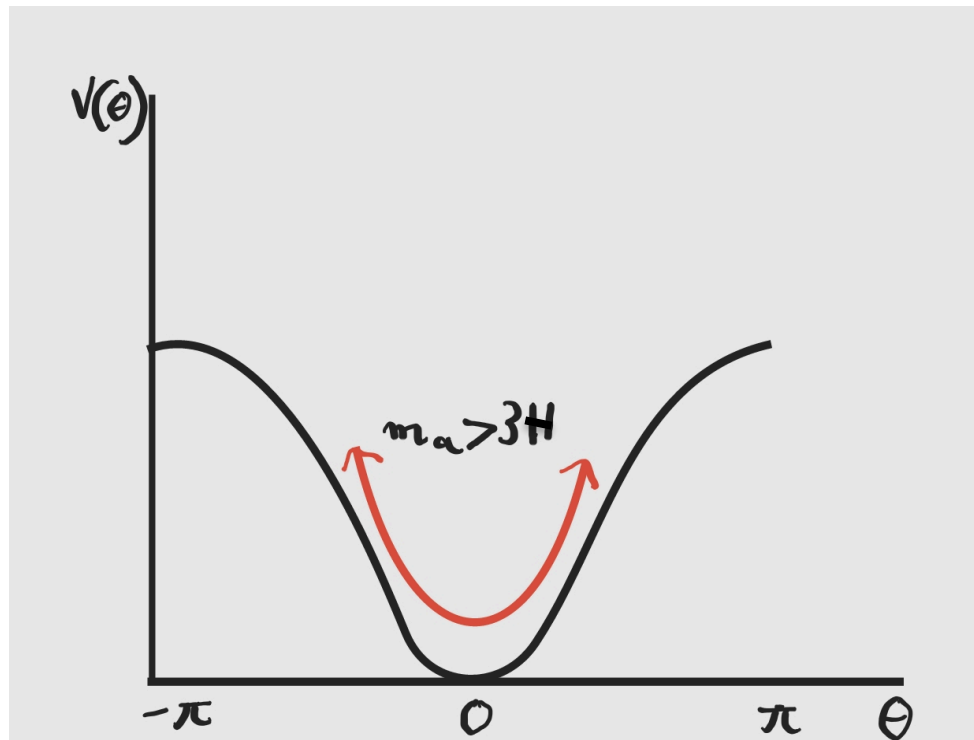


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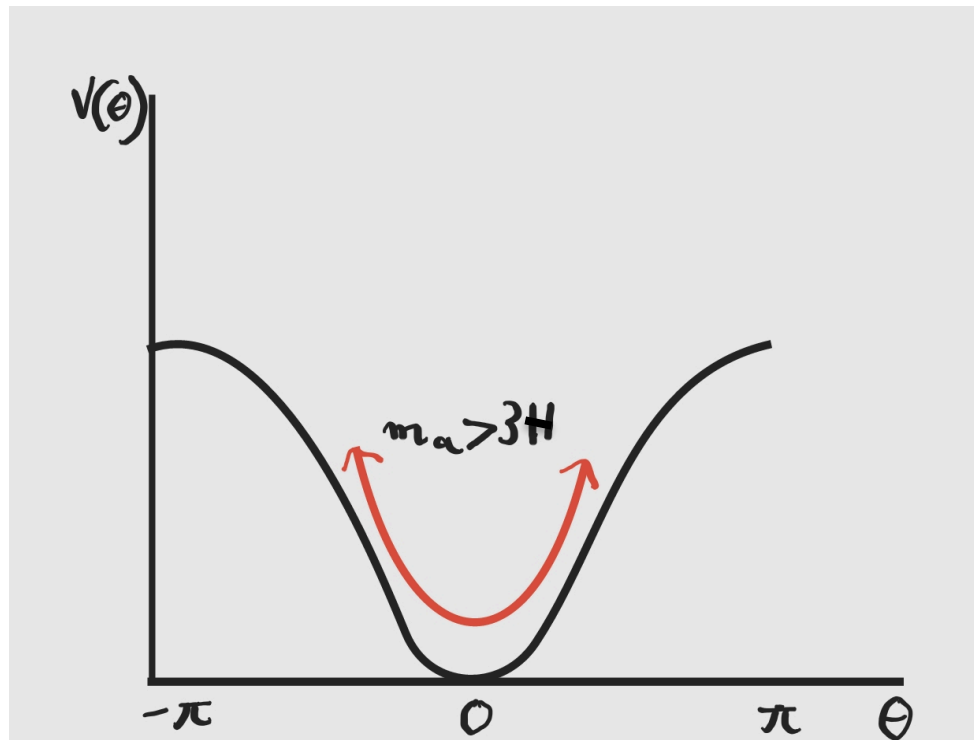


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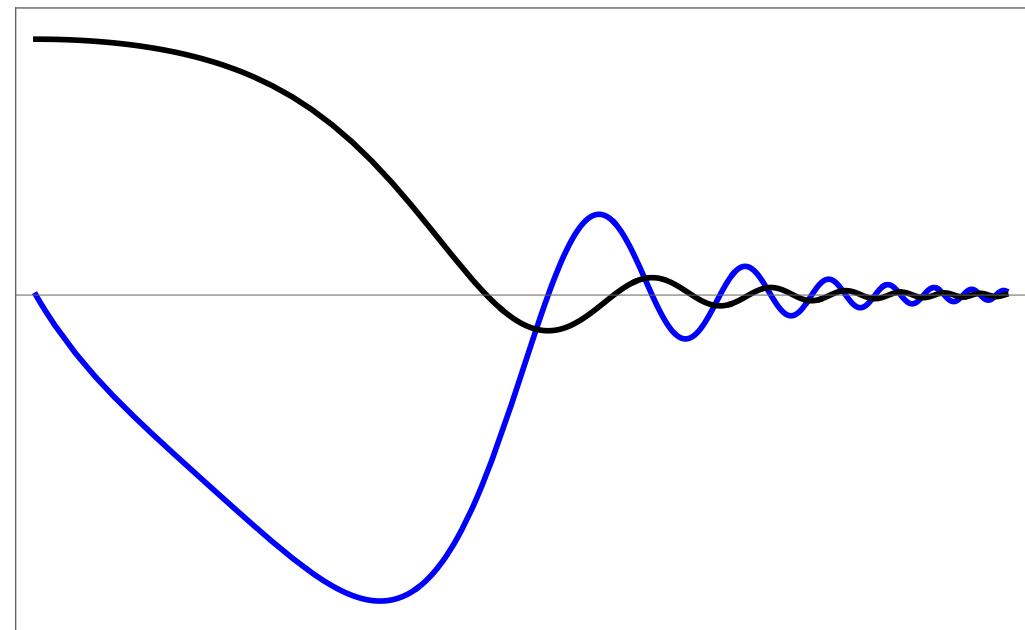
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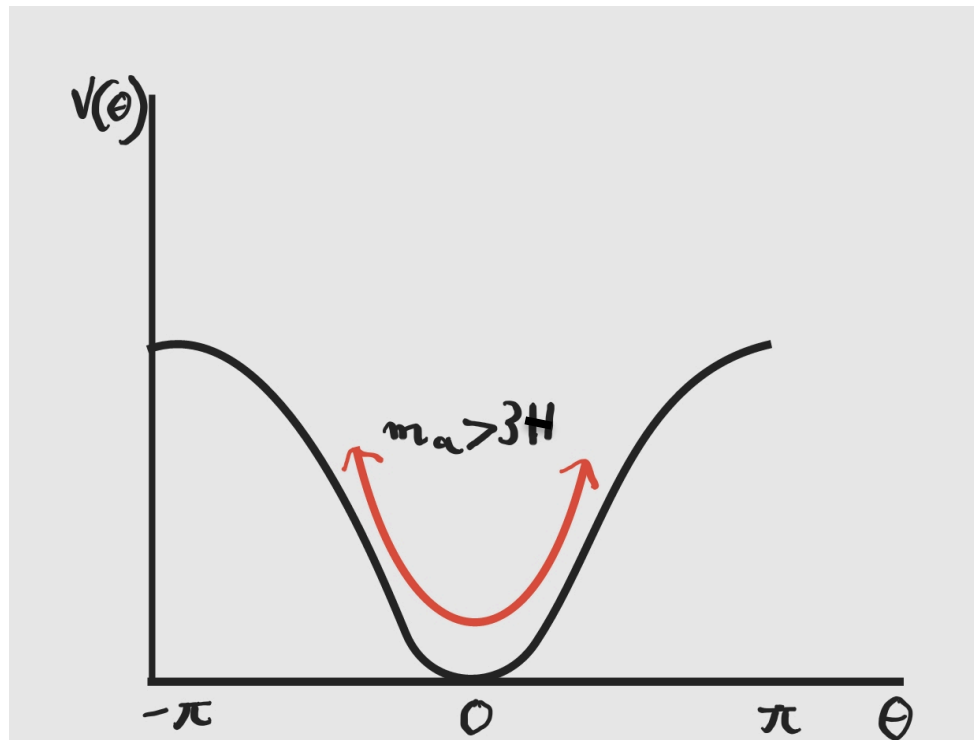
$\dot{\theta} =$ from 0 to m_a



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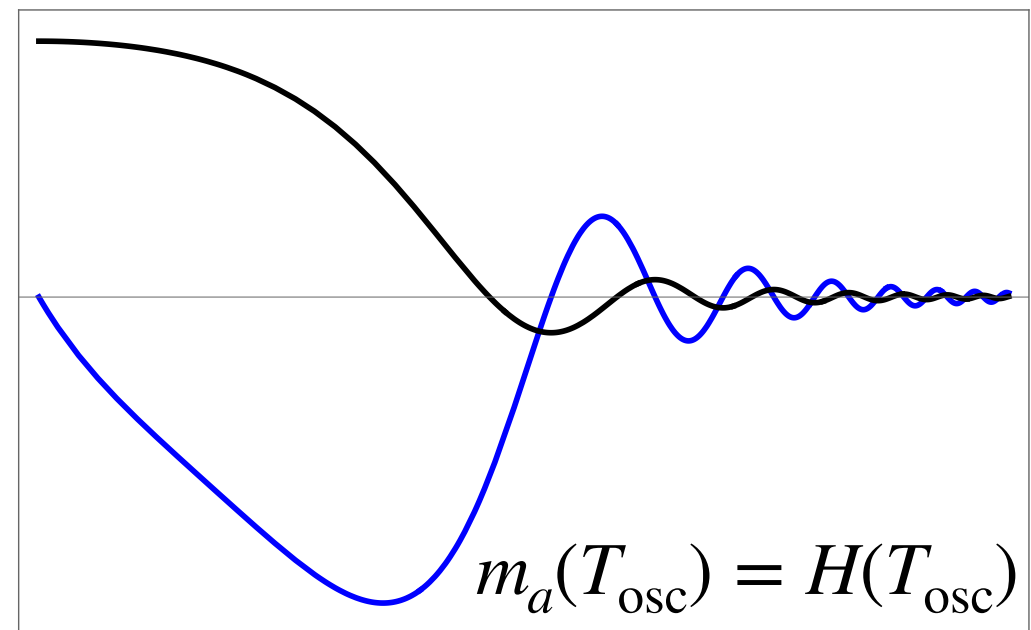
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Baryon Asymmetry:

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

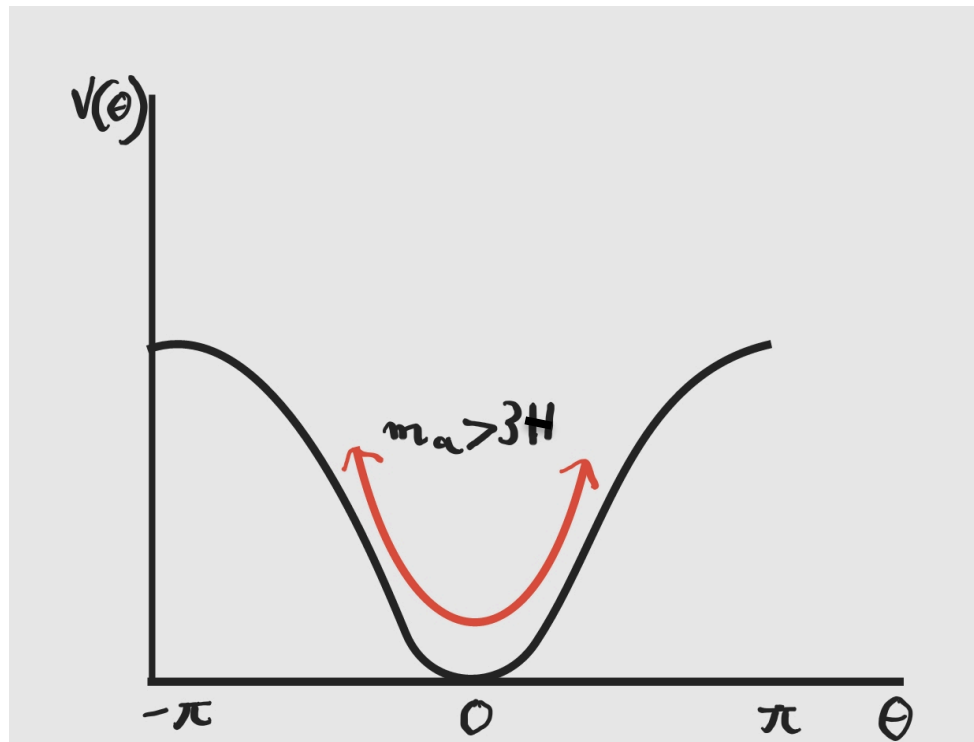
For $Y_B^{\text{observed}} \sim \frac{\dot{\theta}}{g_* T_{\text{osc}}} \sim 10^{-10}$ (observed)

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

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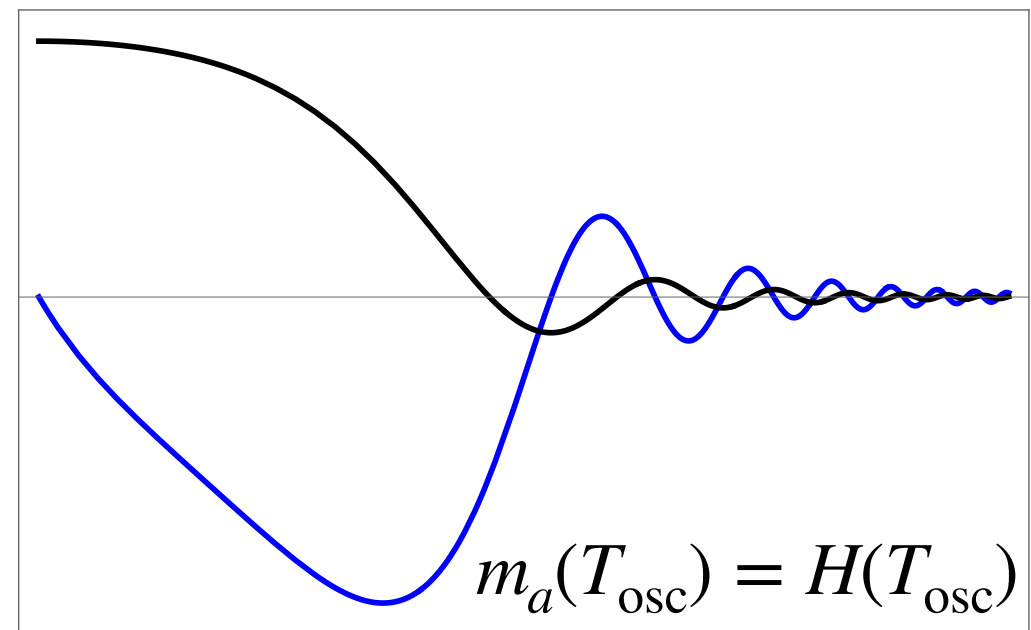
Dark Matter:

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

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

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

$\dot{\theta} = \text{from } 0 \text{ to } m_a$



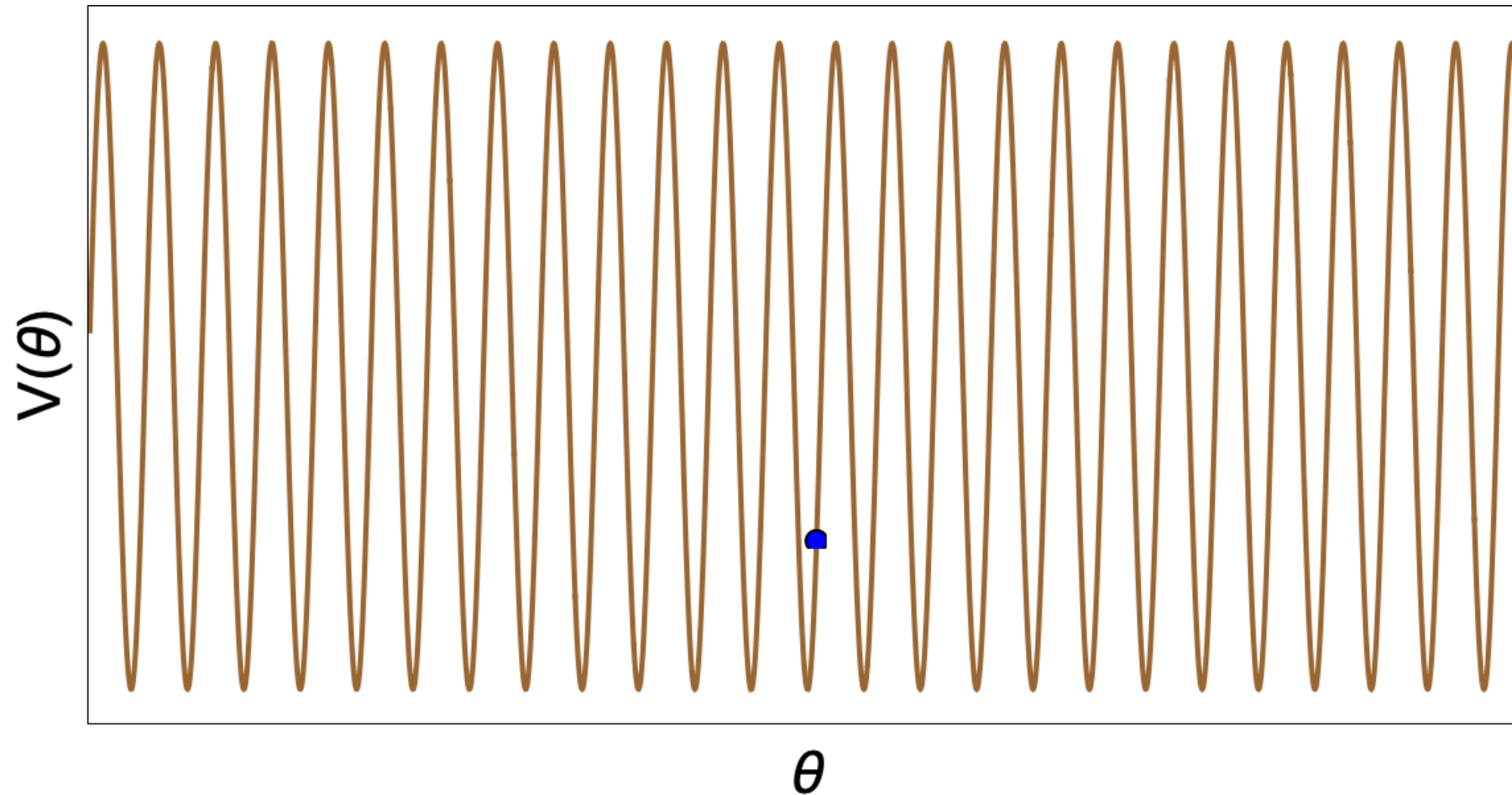
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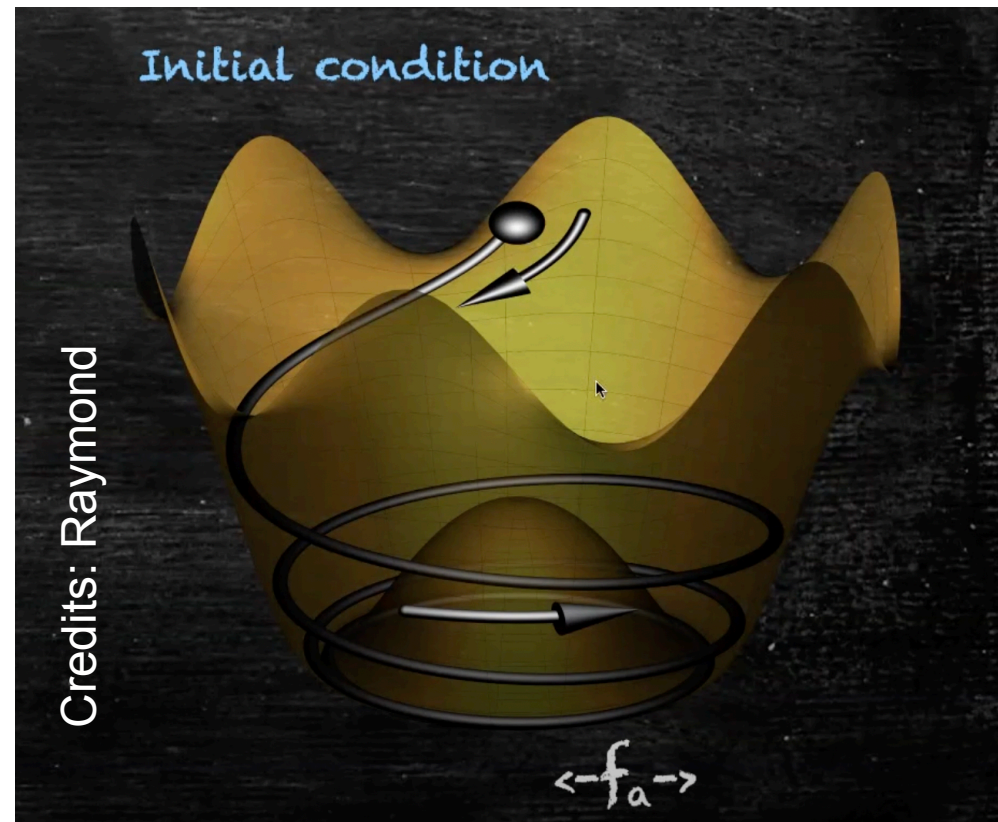
Rotating/Sliding ?



- 1) Delays oscillation, more parameter space for axion experiments.
- 2) Can source particle/anti-particle asymmetry via Spontaneous Baryogenesis.

How to generate rotation ?

- Kinetic Misalignment, radial field away from minimum $\rightarrow \dot{\theta}_i \neq 0$.



Affleck, Dine 1985

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

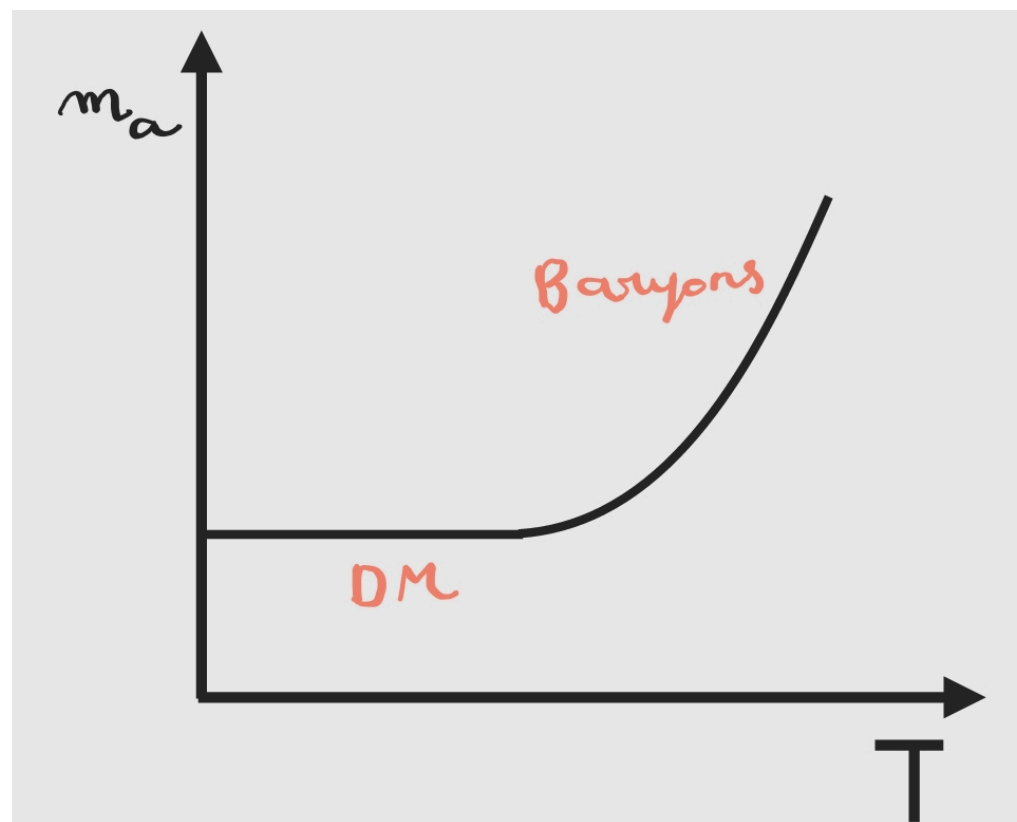
- With radial mode staying at minimum $\rightarrow \dot{\theta}_i \neq 0$?

+ cogenesis of
baryon and dark matter .

The core idea:

Early dynamics with $m_a(T) \gg m_a^{(0)}$

Separate out $T_{B-L} \gg T_{osc}$



- Time-dependent m_a .
- $\dot{\theta}$ large enough before T_{osc} .
- **Baryogenesis** at $T_{B-L} > T_{osc}$.
- Oscillation at low temperature: **DM**.

Rotation via **symmetry** **non-restoration**

Symmetry non-restoration

(S. Weinberg 1974)

Thermal corrections with **negative** contribution:

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

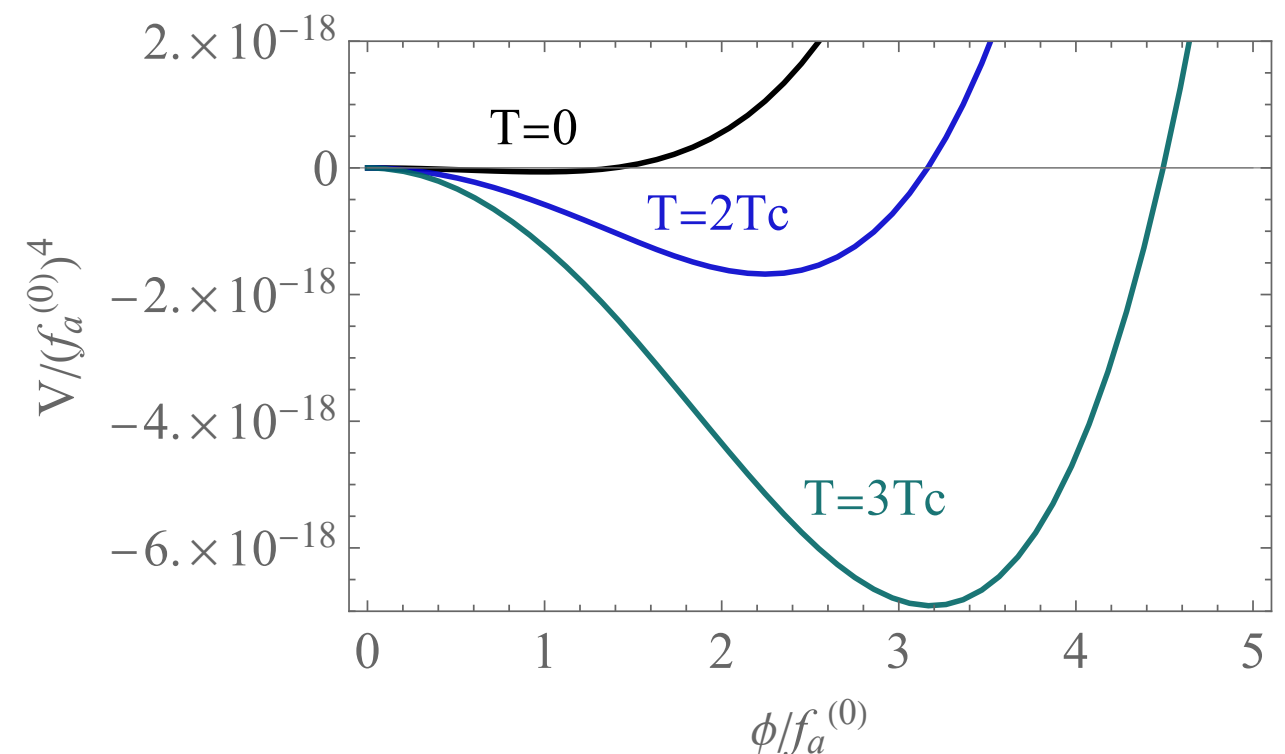
SM Higgs

Temp. Dependent V:

$$V_T(\phi) \simeq \frac{\lambda_\phi}{4} \phi^4 - \frac{1}{2}(m_0^2 + c T^2) \phi^2$$

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

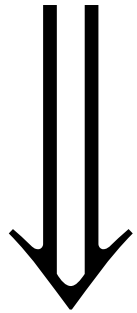
$$c_\lambda \simeq \lambda_{\text{mix}} / \lambda_\phi$$



Connection of axion mass with this vev f_a ?

Explicit breaking of U(1):

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



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

Mass of pNGB:

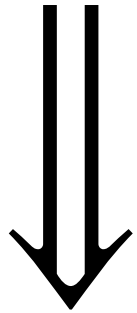
$$m_a^2(T) \sim \left(\frac{f_a(T)}{\Lambda} \right)^{n-4} f_a(T)^2.$$

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

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

X

pNGB Dynamics (n=5)

Modified E.O.M. :

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

$\swarrow$
 $-H$

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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

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

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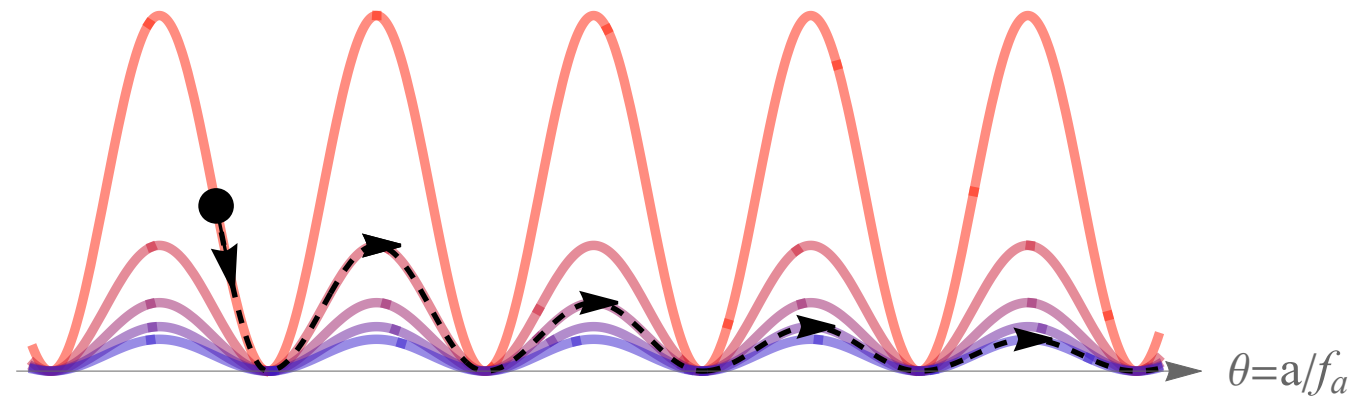
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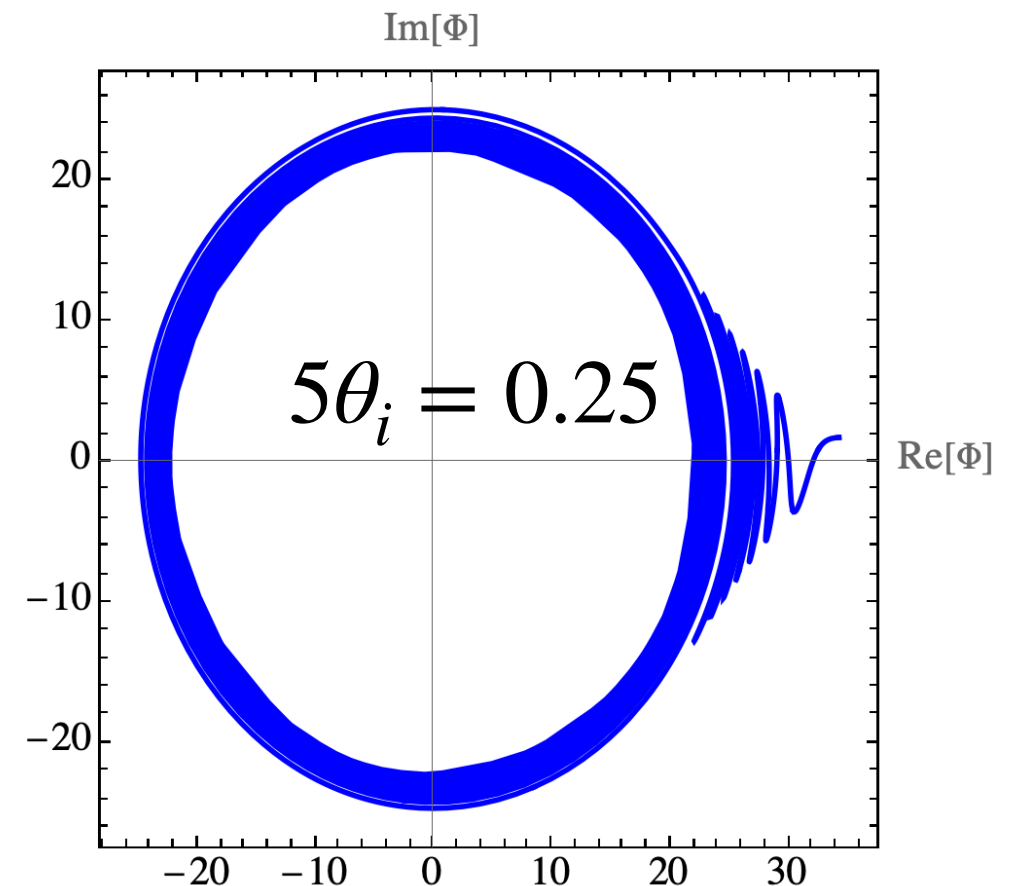
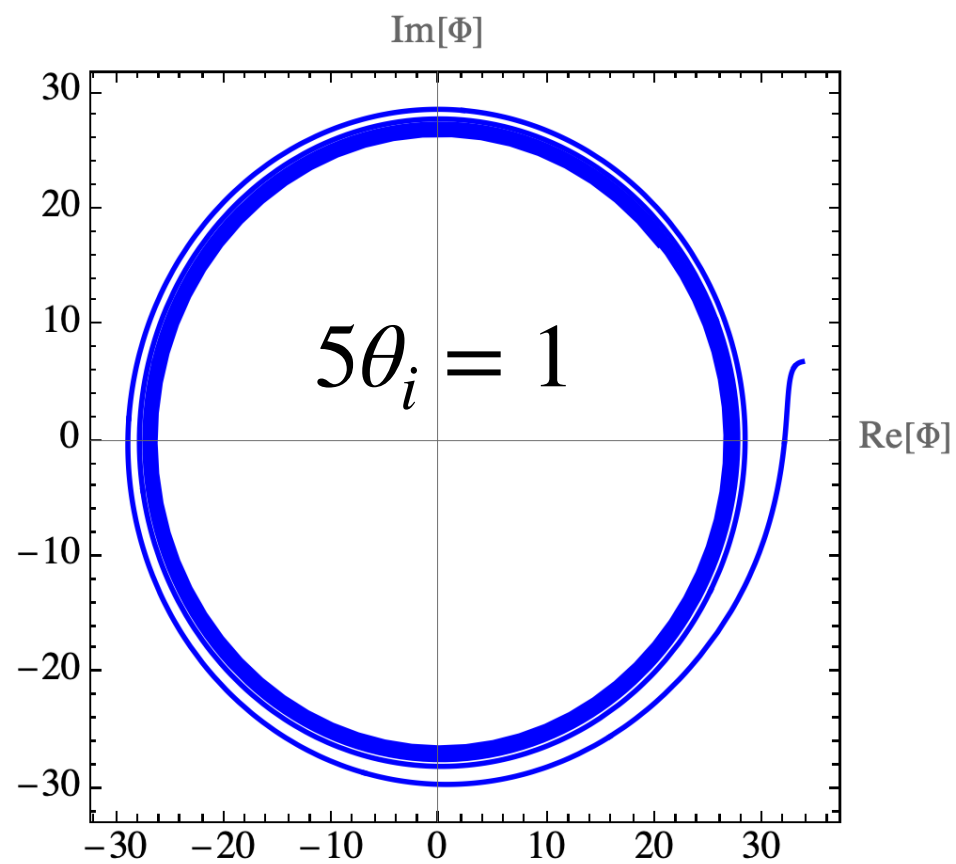
2nd epoch: $T < T_0$ Oscillation?

pNGB slides/rotates



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

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



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

From Spontaneous Baryo.

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

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

From Spontaneous Baryo.

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

3rd epoch: $T < T_c$

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

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

$$\ddot{\theta} + H\dot{\theta} = -\frac{1}{n}m_a^2(T)\sin(n\theta) \quad \text{Gives asymmetry} \quad \text{From Spontaneous Baryo.}$$

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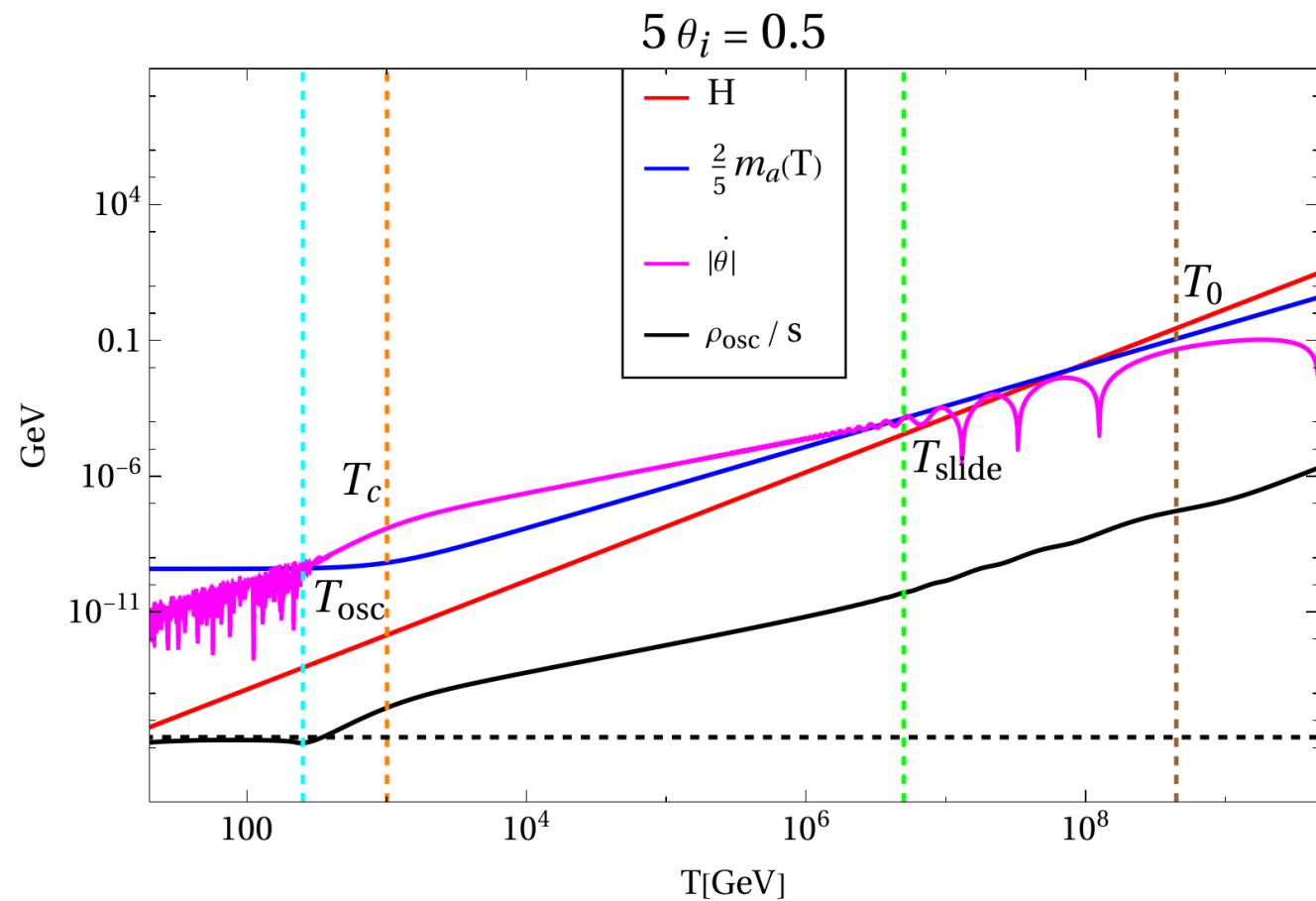
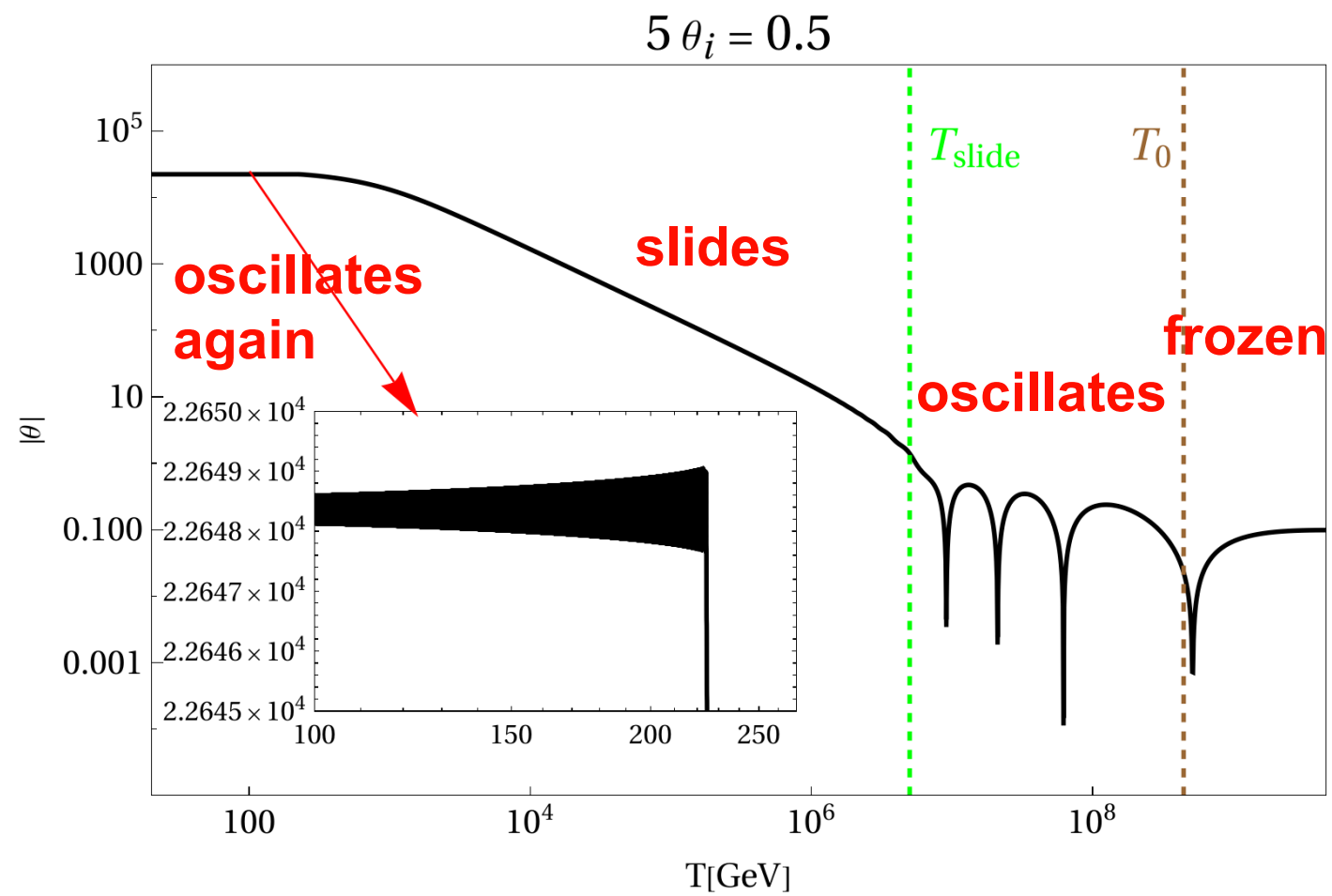
$$\dot{\theta} \propto T^3$$

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

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

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

$$\frac{\rho_{\text{osc}}}{s} \sim \frac{(m_a^{(0)} f_a^{(0)})^2}{s(T_{\text{osc}})} \quad \text{pNGB oscillates, gives DM}$$



Fluctuations of θ ?

$$\Theta(t, \mathbf{x}) = \theta(t) + \delta\theta(t, \mathbf{x})$$

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

periodic modulation

$\Rightarrow$ **Parametric Resonance if:** $| (k/R)^2 - \dot{\theta}^2 | \lesssim m_a^2$

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periodic modulation

$\Rightarrow$ **Parametric Resonance if:** $|(k/R)^2 - \dot{\theta}^2| \lesssim m_a^2$

$$\kappa = \frac{k}{m_a R}$$

$$|\kappa - \kappa_{\text{cr}}| \lesssim \delta\kappa_{\text{cr}}, \quad \kappa_{\text{cr}} \equiv \frac{n\langle\dot{\theta}^2\rangle^{1/2}}{2m_a}, \quad \delta\kappa_{\text{cr}} \equiv \frac{m_a}{2n\langle\dot{\theta}^2\rangle^{1/2}}$$

Modes grow as: $\exp(\mu_k t)$ $\mu_k \approx \left[\delta\kappa_{\text{cr}}^2 - (\kappa - \kappa_{\text{cr}})^2\right]^{1/2} m_a \stackrel{\kappa=\kappa_{\text{cr}}}{\simeq} \frac{m_a^2}{2n\dot{\theta}}$

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$$\left(\text{if } \frac{\text{Growth rate}}{\text{Hubble rate}} \sim \frac{m_a^2}{\dot{\theta}H} \gg 1 \right)$$

pNGB Fragmentation

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

periodic modulation

$\Rightarrow$ Parametric Resonance if: $(k/R)^2 - \dot{\theta}^2 \lesssim m_a^2$

$$\kappa = \frac{k}{m_a R}$$

Case I: Initial sliding $\dot{\theta} \propto T$

Case II: Constant mass $\dot{\theta} \propto T^3$

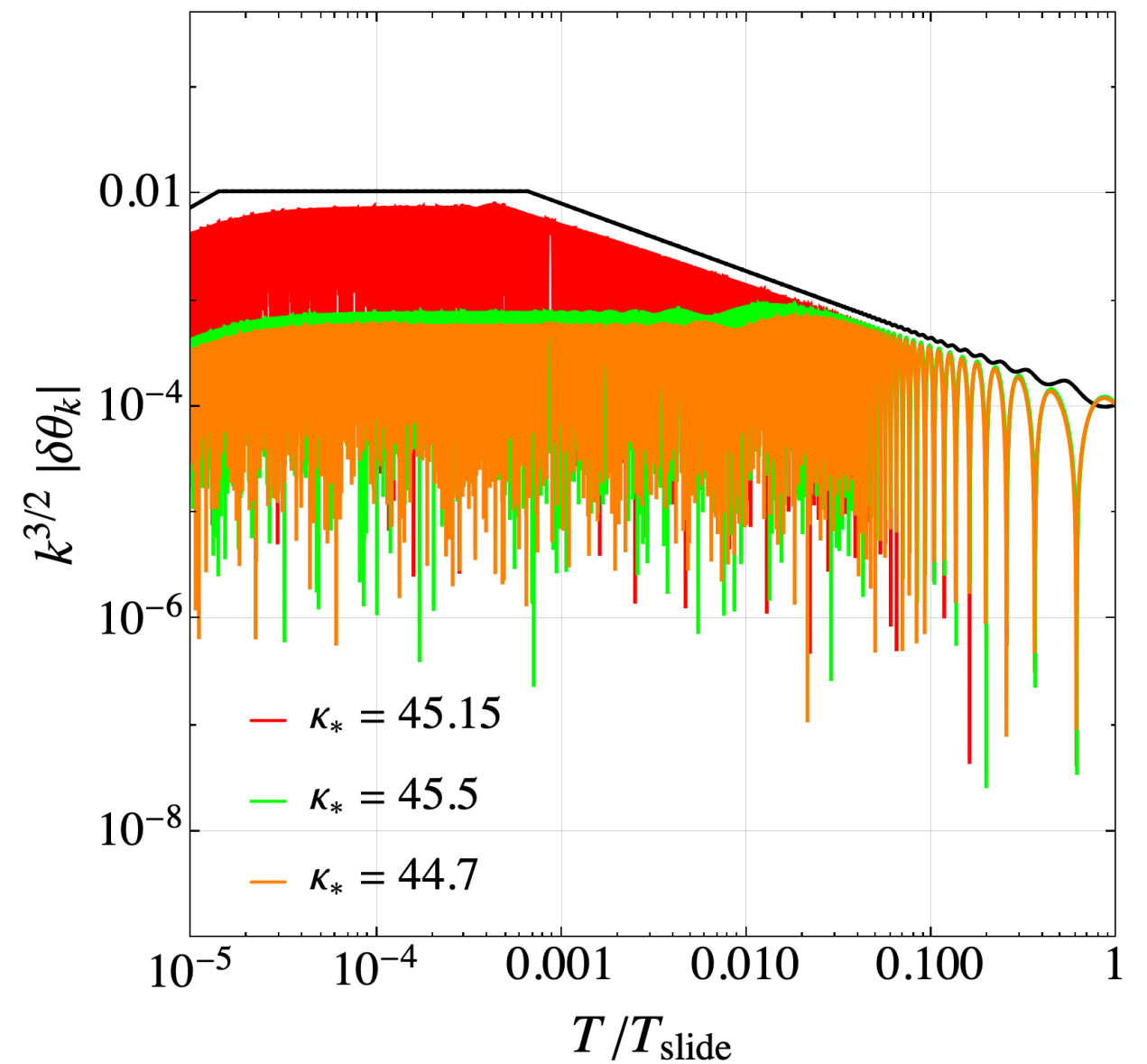
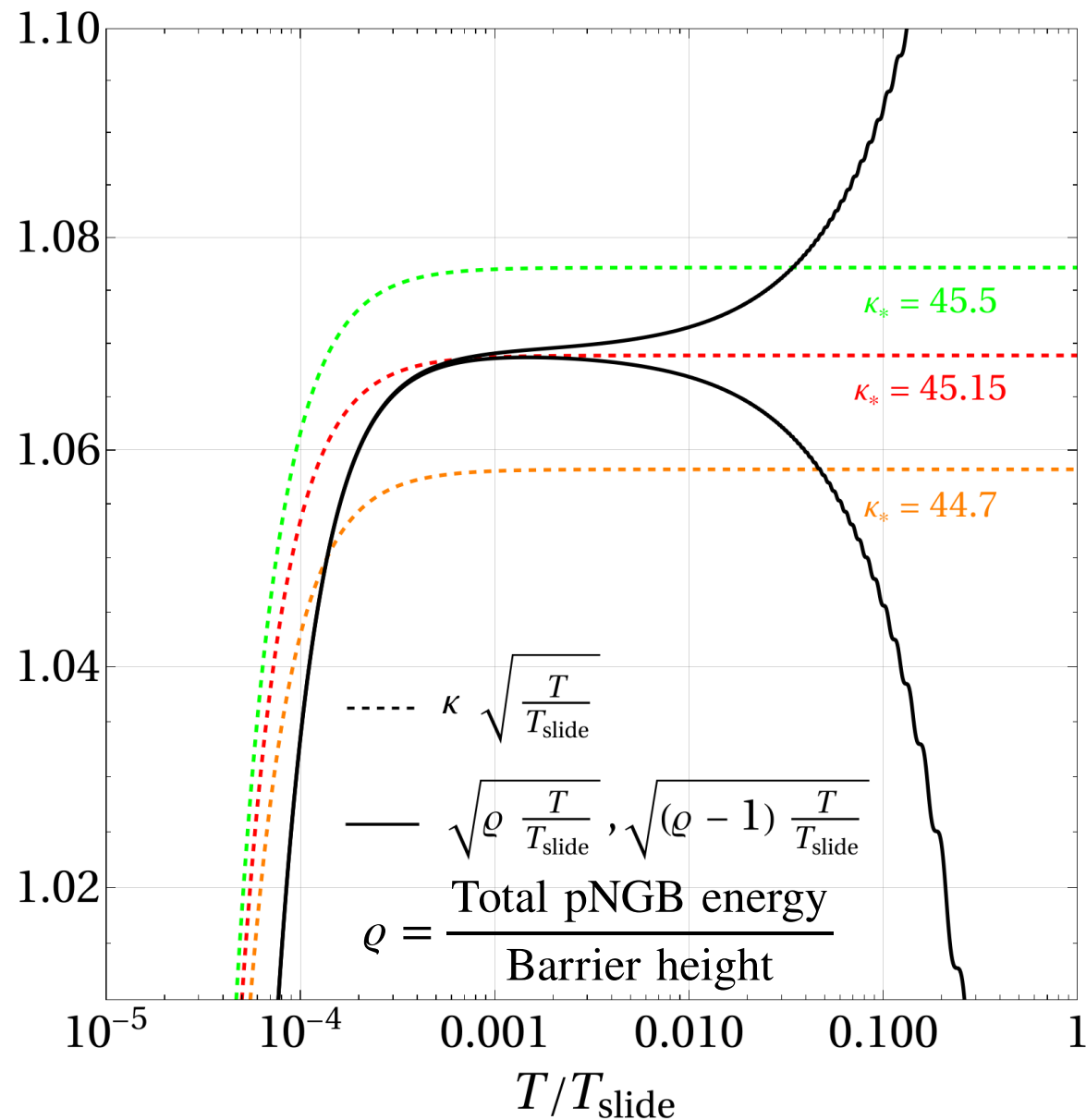
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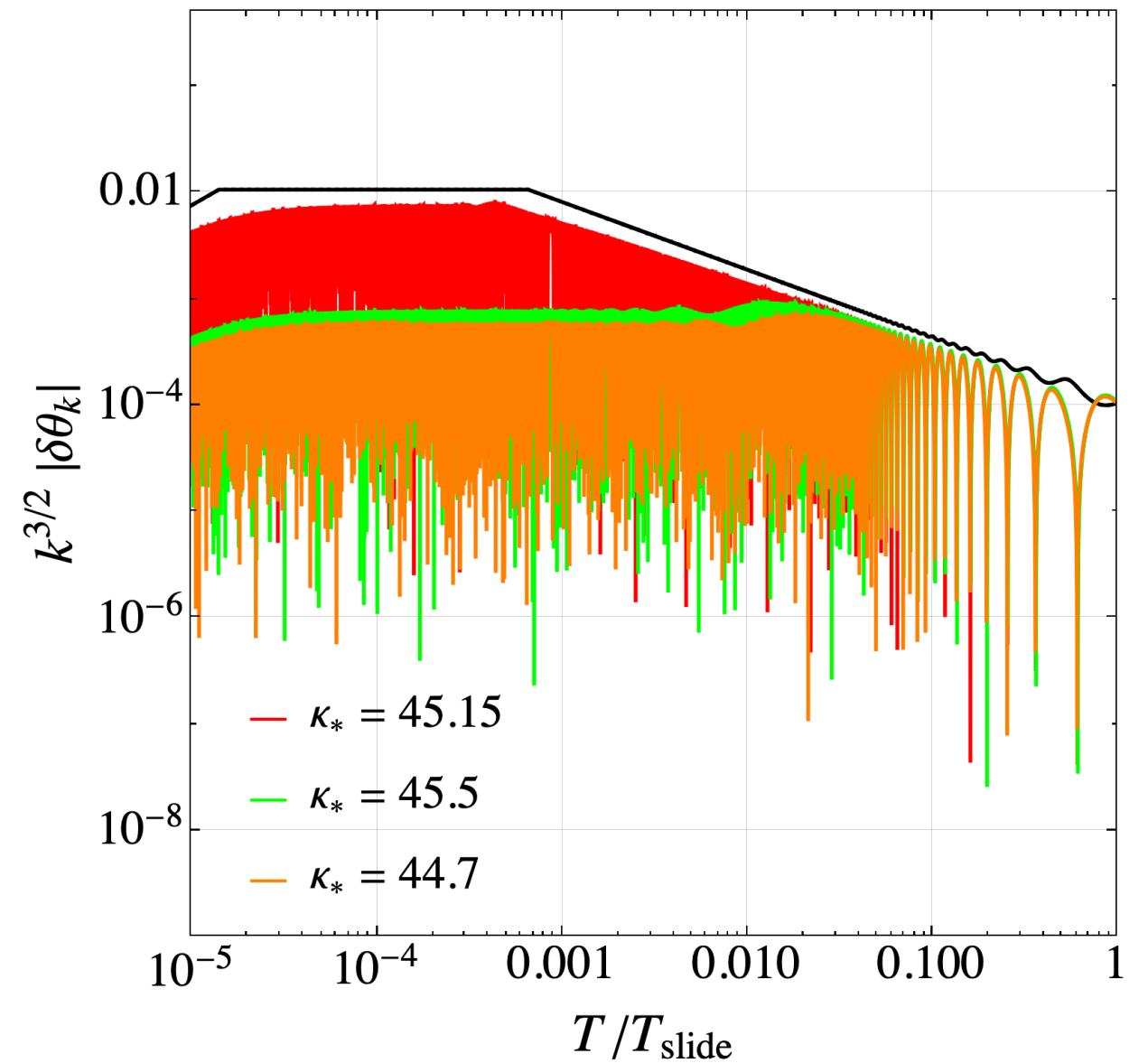
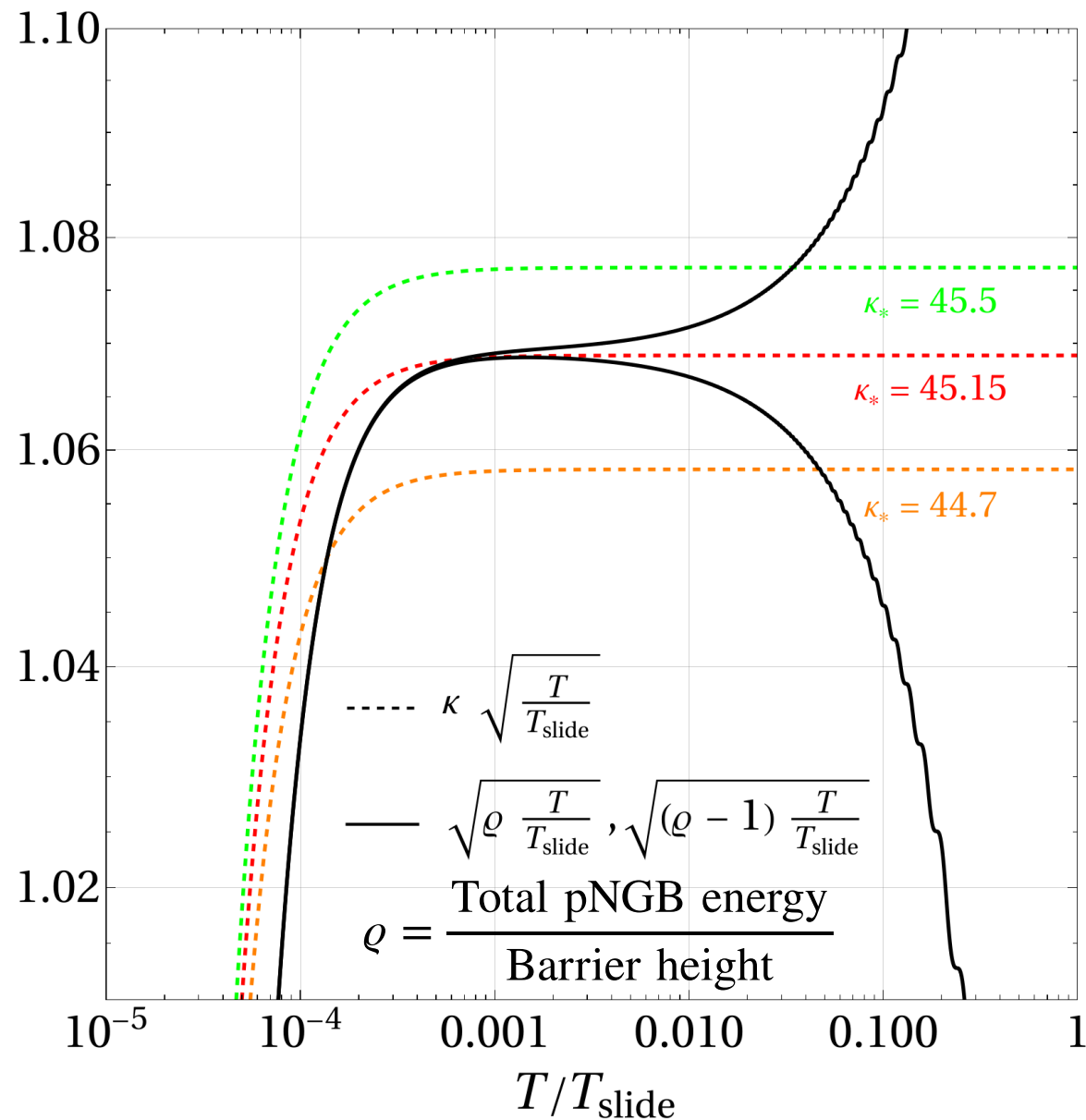
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pNGB Fragmentation

During Initial Sliding, $T > T_c$



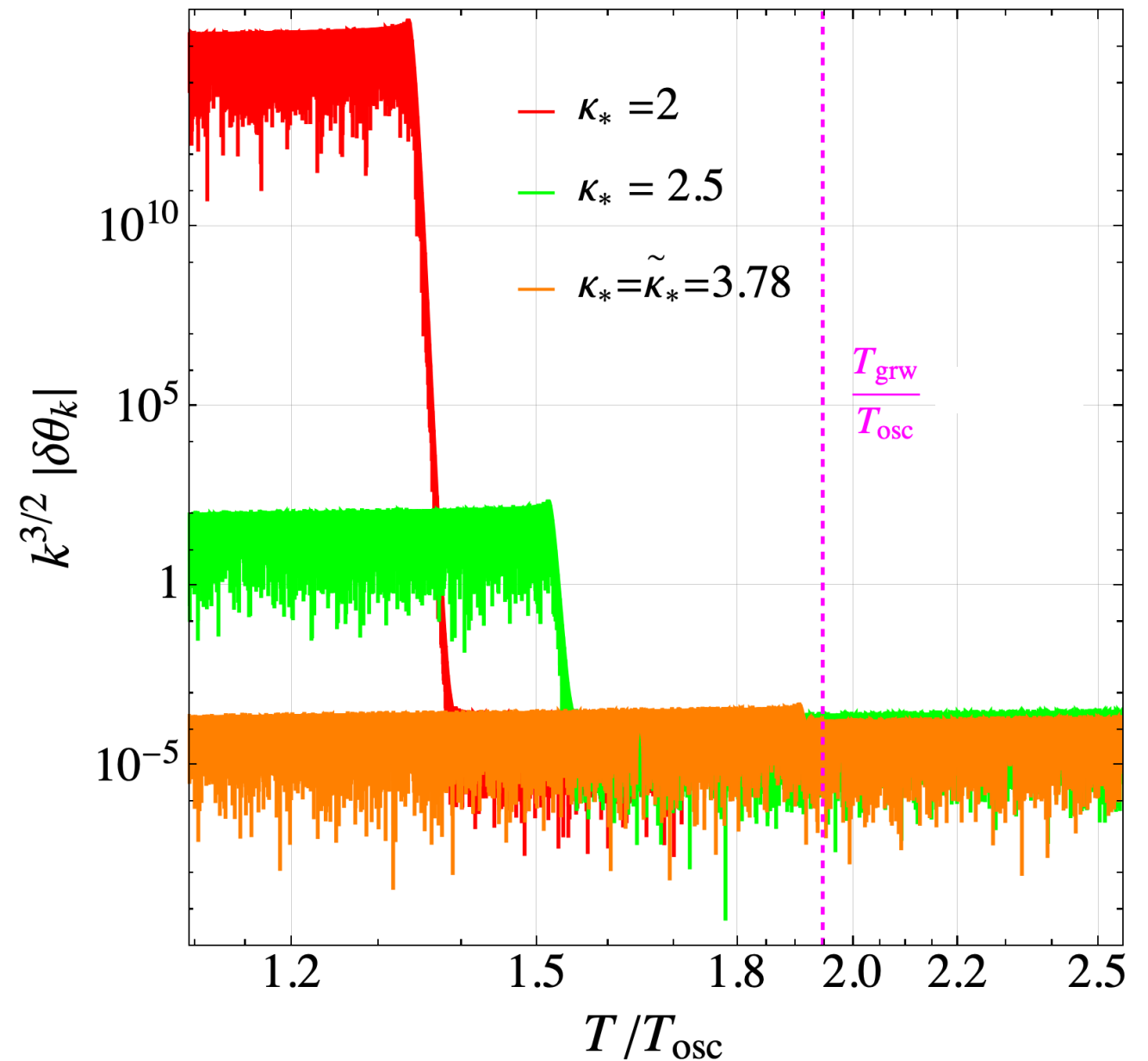
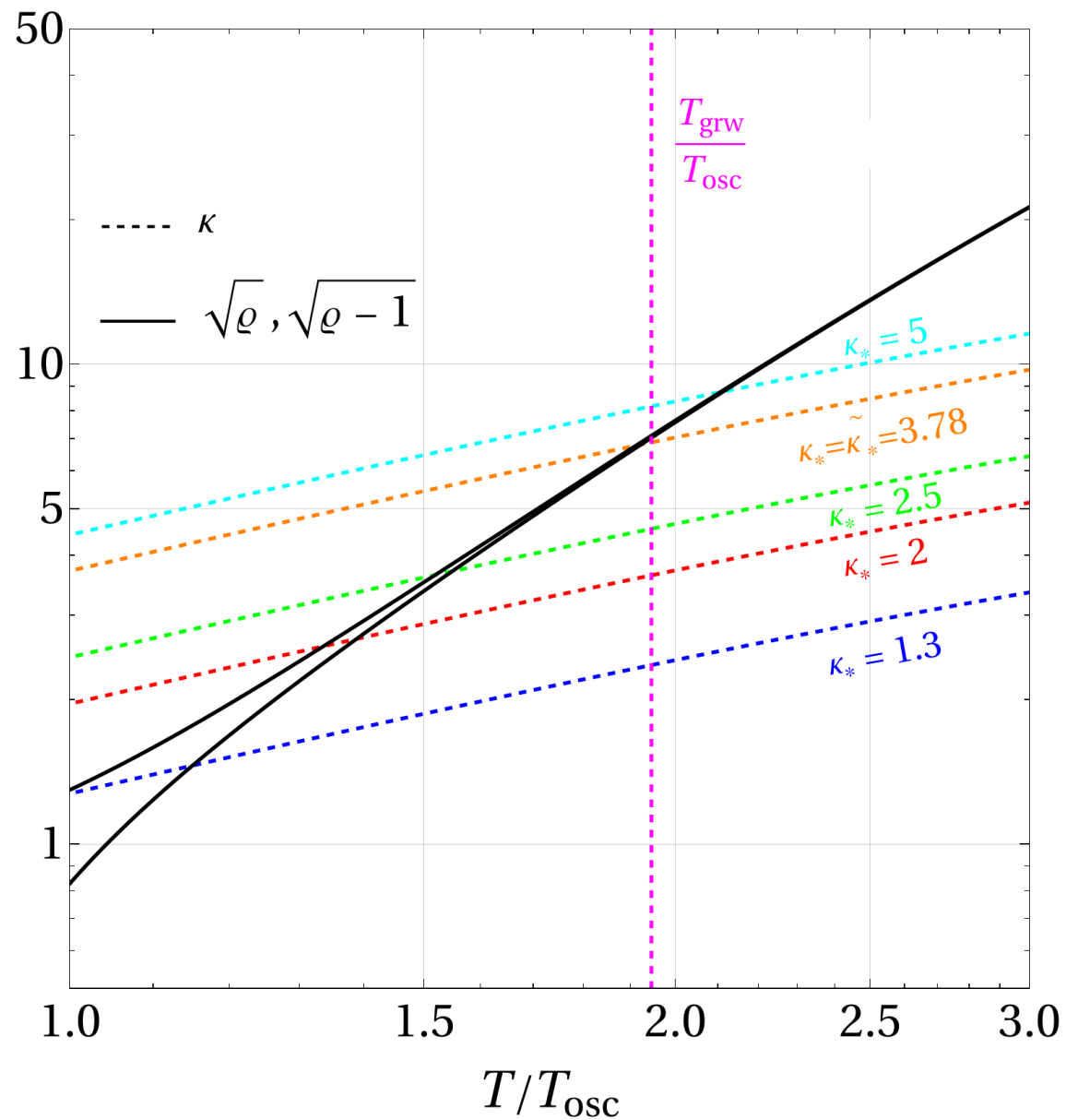
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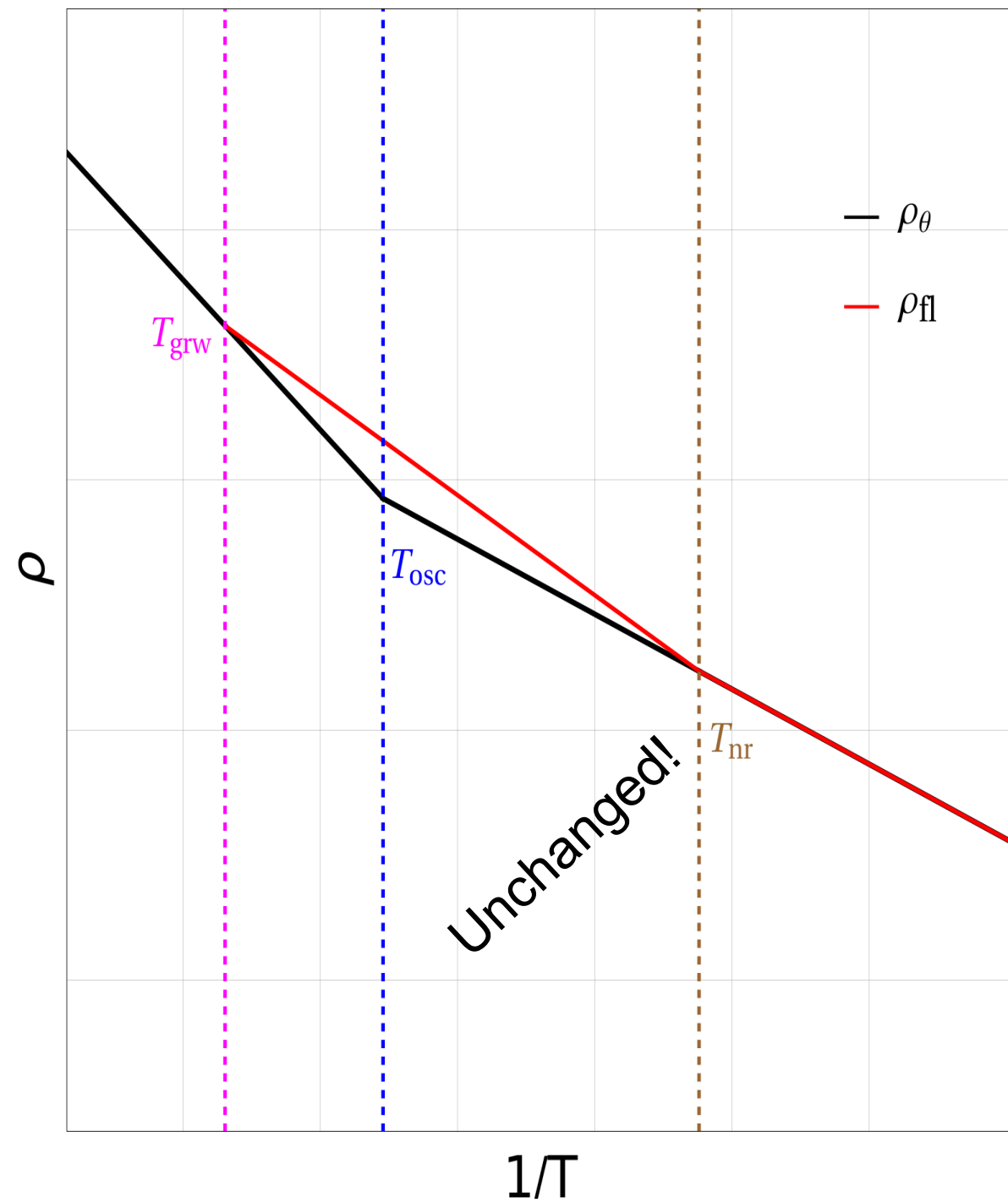
Growth not so large $\rho_{\text{fl}} \ll \rho_{\theta}$

During Sliding, $T < T_c$

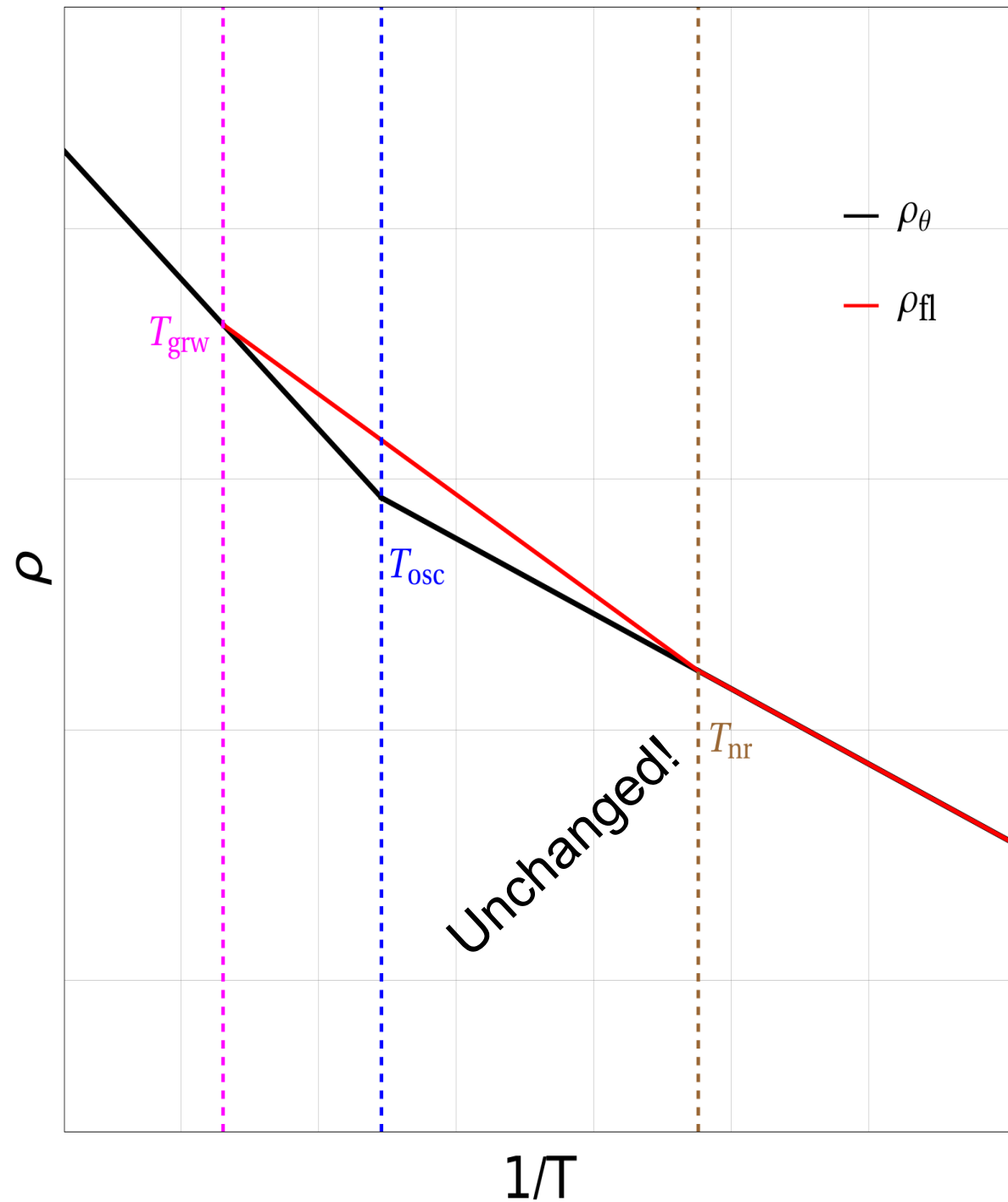
[similar to Kinetic Misalignment] [C. Eroncel et al. JCAP 2022](#)



Relic density?

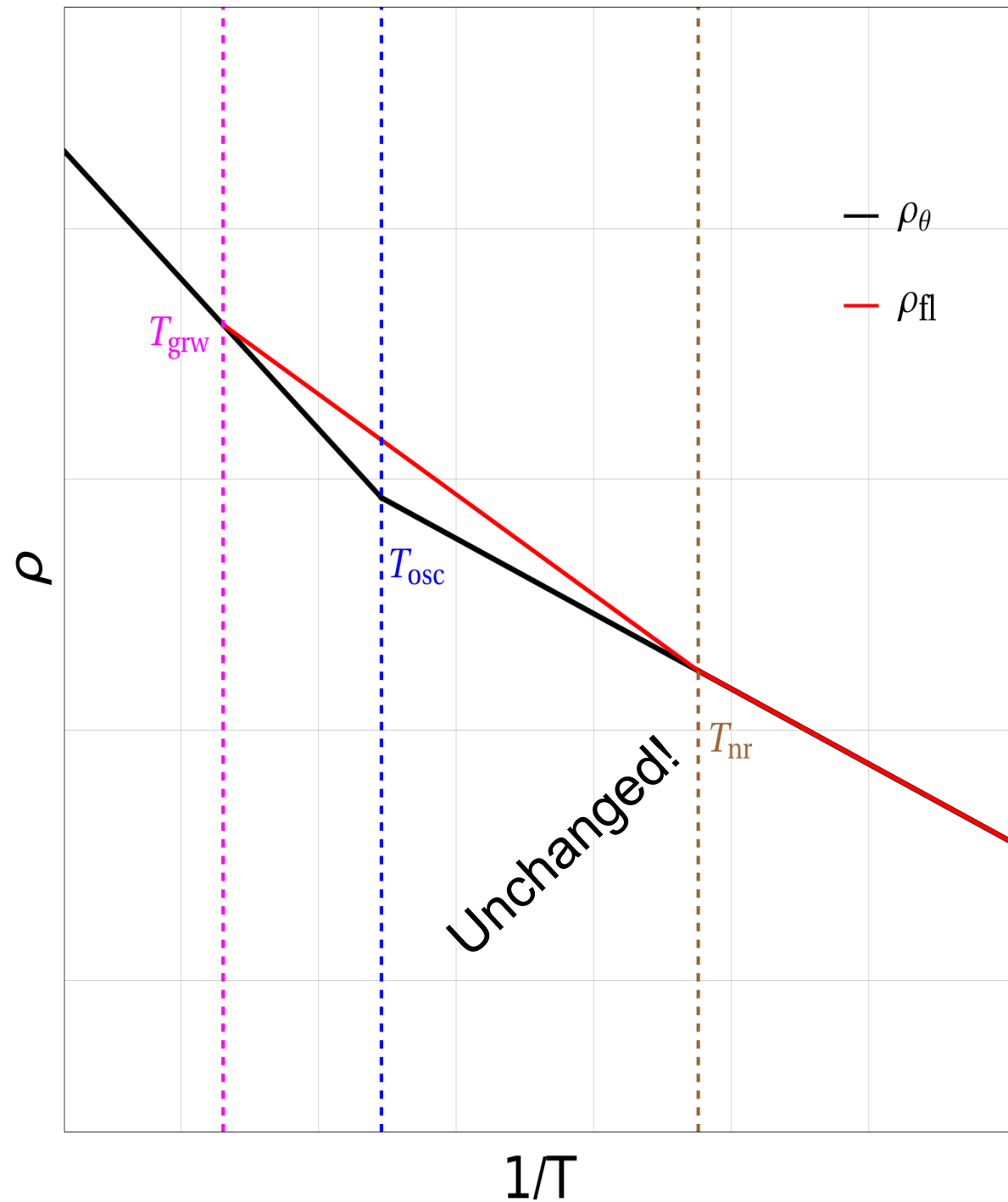


Relic density?



$$\begin{aligned}
 \rho_{\text{fl}}(T_f) &\simeq \rho_{\text{fl}}(T_{\text{nr}}) \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{fl}}(T_{\text{grw}}) \left(\frac{T_{\text{nr}}}{T_{\text{grw}}} \right)^4 \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{osc}}(T_{\text{osc}}) \left(\frac{T_{\text{grw}}}{T_{\text{osc}}} \right)^6 \left(\frac{T_{\text{nr}}}{T_{\text{grw}}} \right)^4 \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{osc}}(T_{\text{nr}}) \left(\frac{T_{\text{osc}}}{T_{\text{nr}}} \right)^3 \left(\frac{T_{\text{grw}}}{T_{\text{osc}}} \right)^6 \left(\frac{T_{\text{nr}}}{T_{\text{grw}}} \right)^4 \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{osc}}(T_f),
 \end{aligned}$$

Relic density?



$$\begin{aligned}
 \rho_{\text{fl}}(T_f) &\simeq \rho_{\text{fl}}(T_{\text{nr}}) \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{fl}}(T_{\text{grw}}) \left(\frac{T_{\text{nr}}}{T_{\text{grw}}} \right)^4 \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{osc}}(T_{\text{osc}}) \left(\frac{T_{\text{grw}}}{T_{\text{osc}}} \right)^6 \left(\frac{T_{\text{nr}}}{T_{\text{grw}}} \right)^4 \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{osc}}(T_{\text{nr}}) \left(\frac{T_{\text{osc}}}{T_{\text{nr}}} \right)^3 \left(\frac{T_{\text{grw}}}{T_{\text{osc}}} \right)^6 \left(\frac{T_{\text{nr}}}{T_{\text{grw}}} \right)^4 \left(\frac{T_f}{T_{\text{nr}}} \right)^3 \\
 &\simeq \rho_{\text{osc}}(T_f),
 \end{aligned}$$

pNGB is fragmented & DM density in the form of pNGB fluctuations

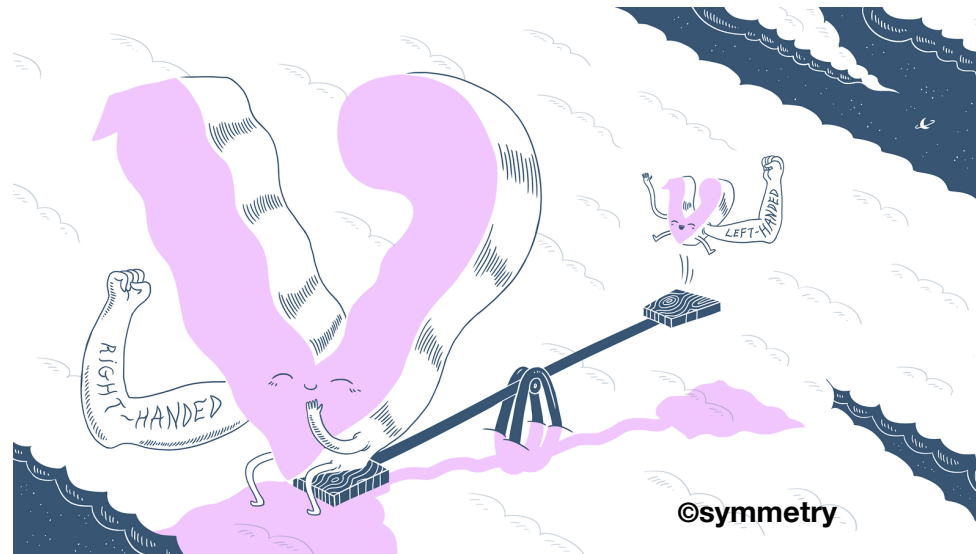
An explicit example: Majoron

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

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



right-handed neutrino



Type I seesaw:

$$m_\nu \sim \frac{Y_D^2 v^2}{M_N}$$

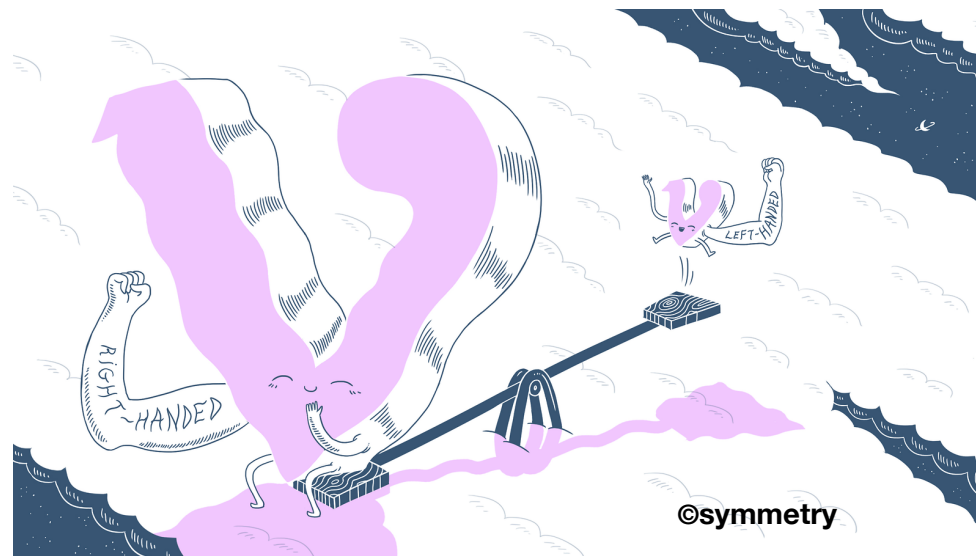
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Type I seesaw:

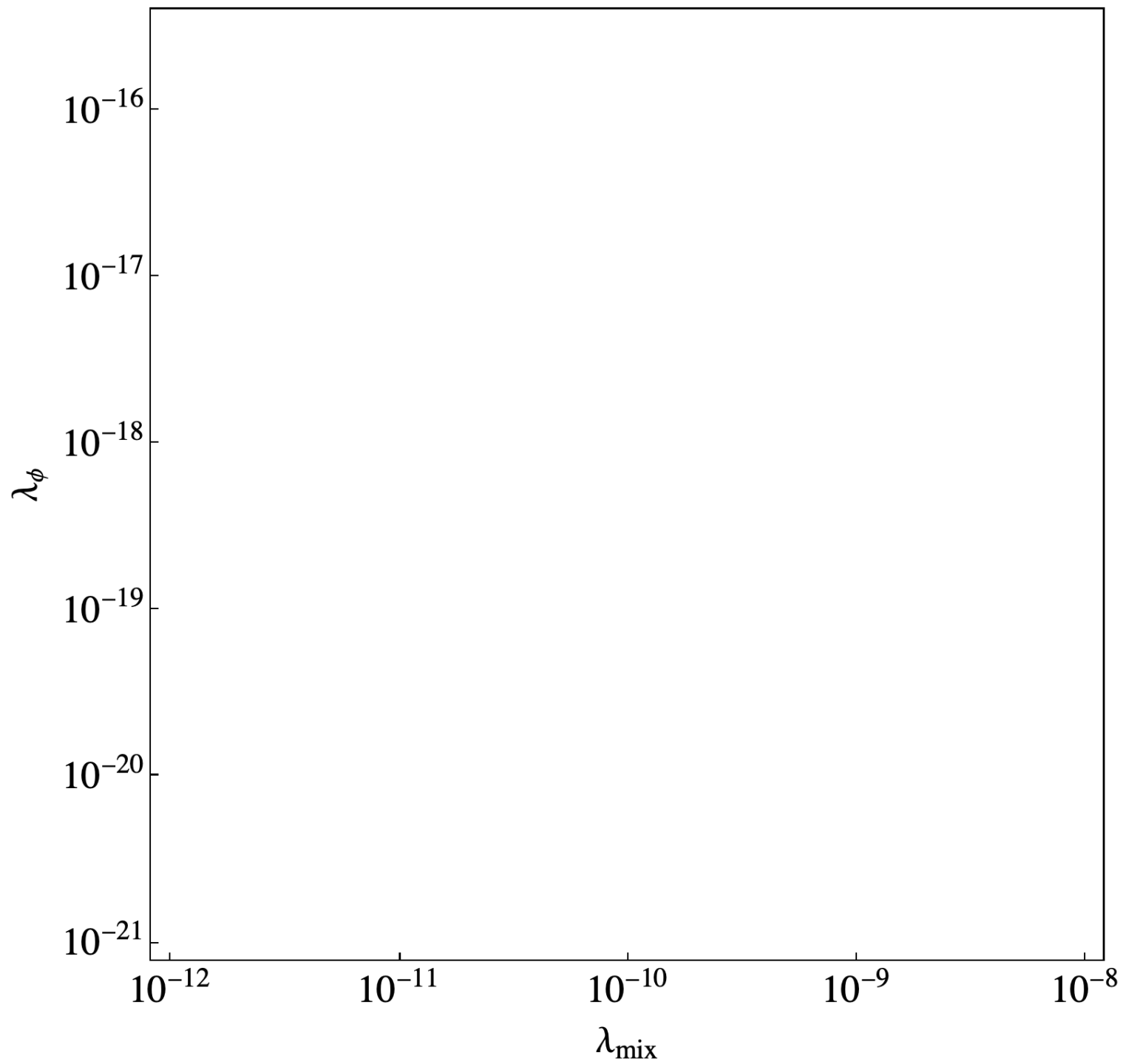
$$m_\nu \sim \frac{Y_D^2 v^2}{M_N}$$

- Lepton no. violating decays & inverse decays asymmetry in equilibrium.

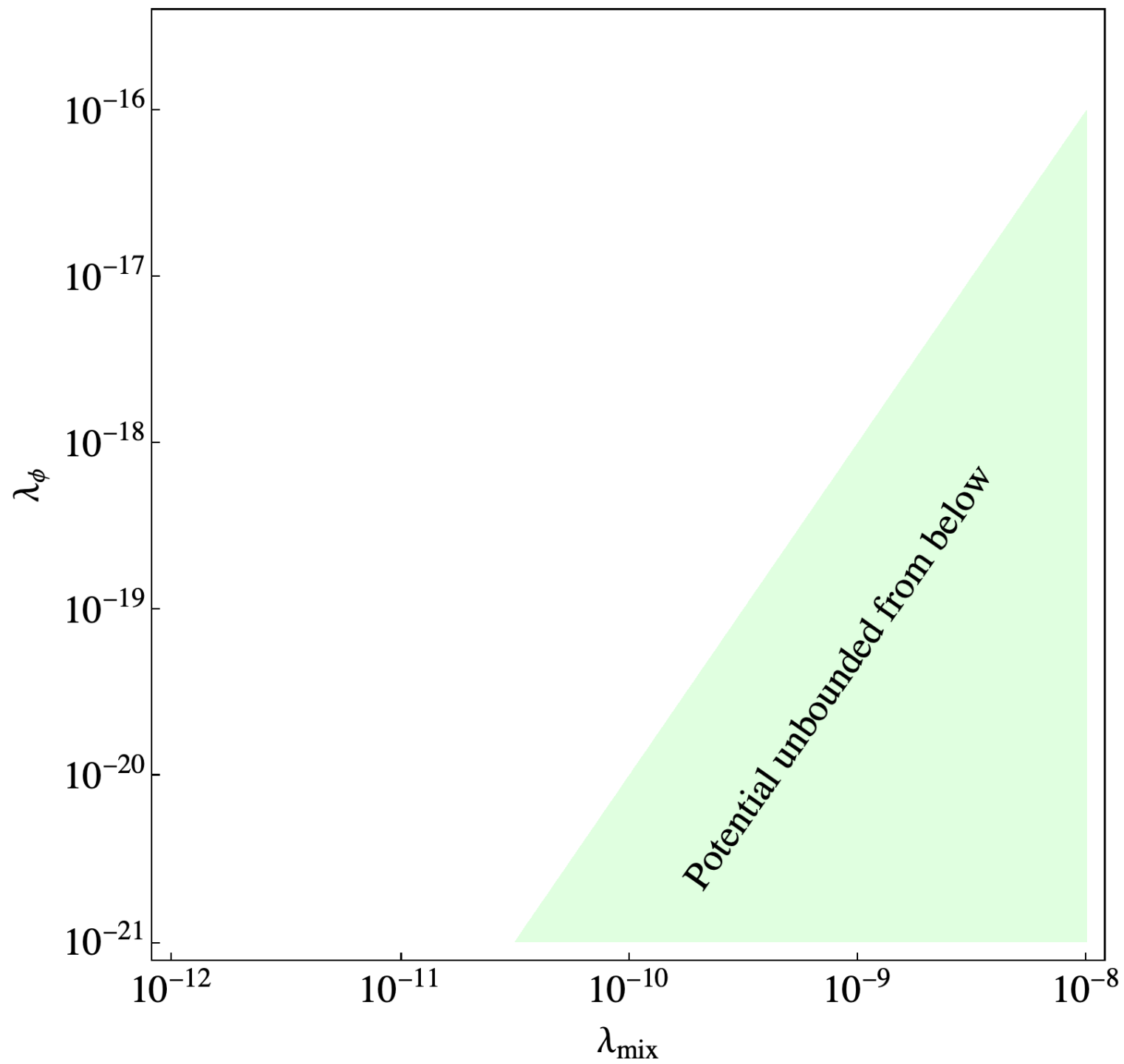
Non-zero $\dot{\theta}$

- Asymmetry effectively frozen at $T = T_{B-L} \sim \frac{M_N}{10}$

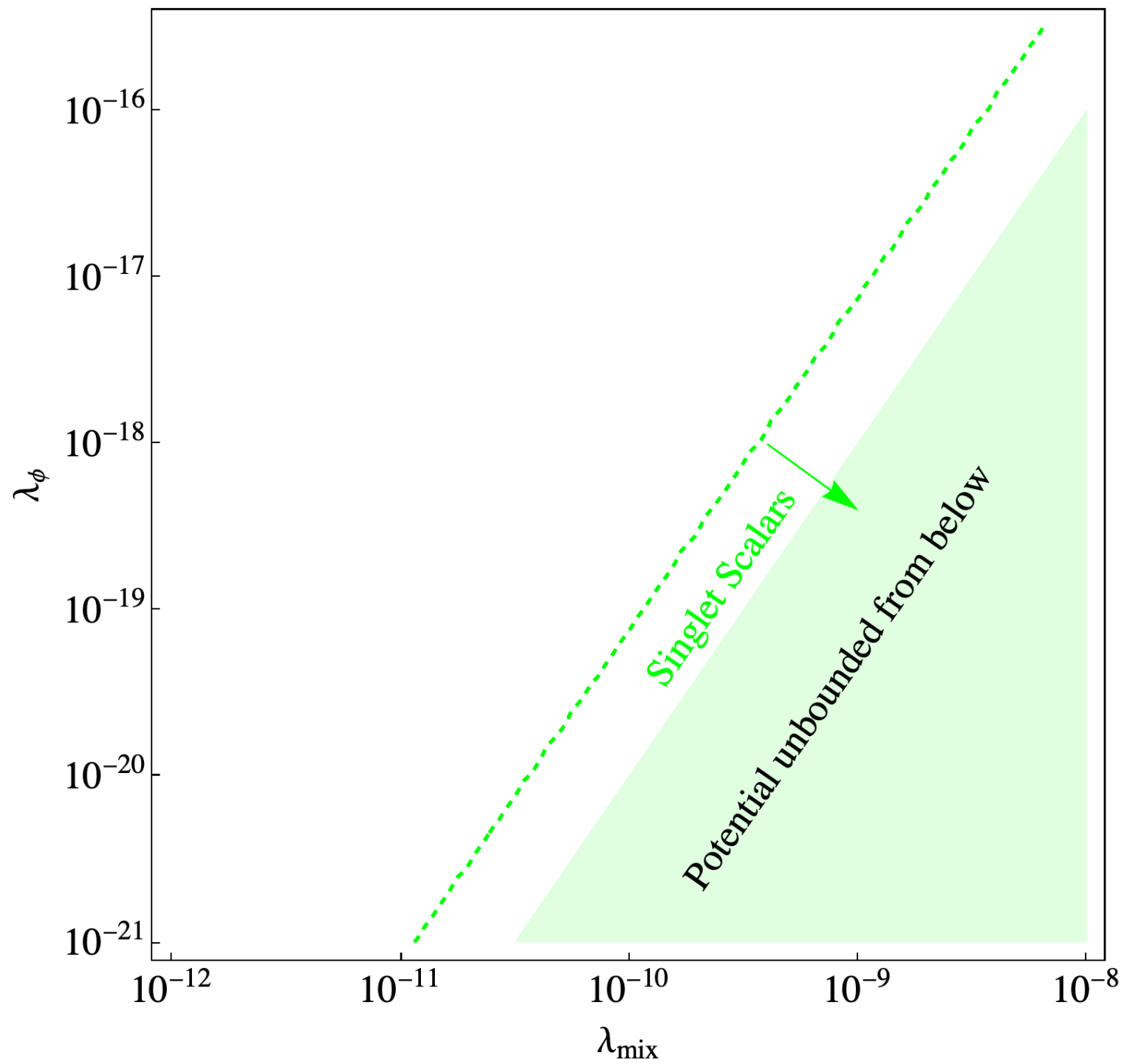
Predictions:



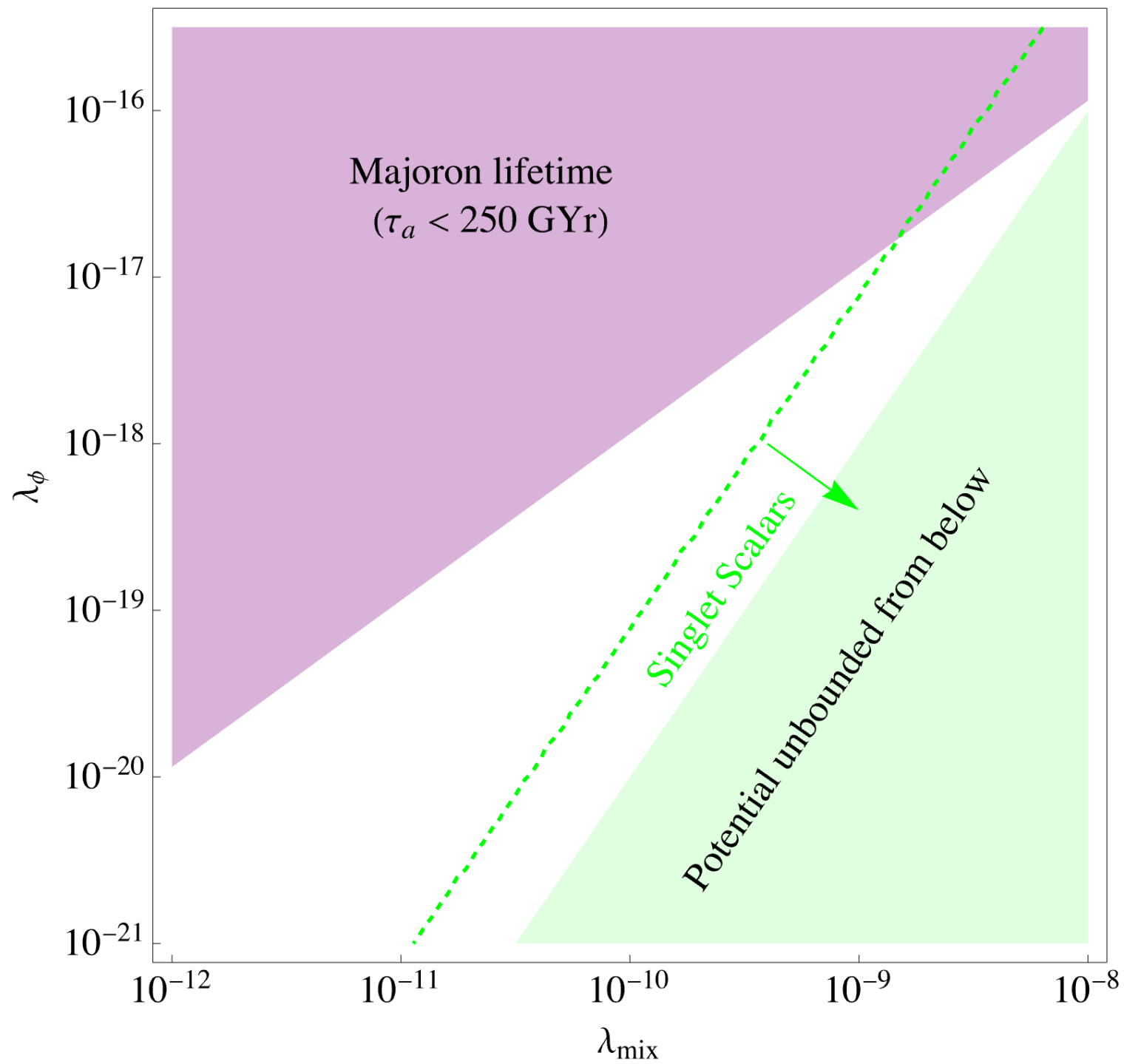
Predictions:



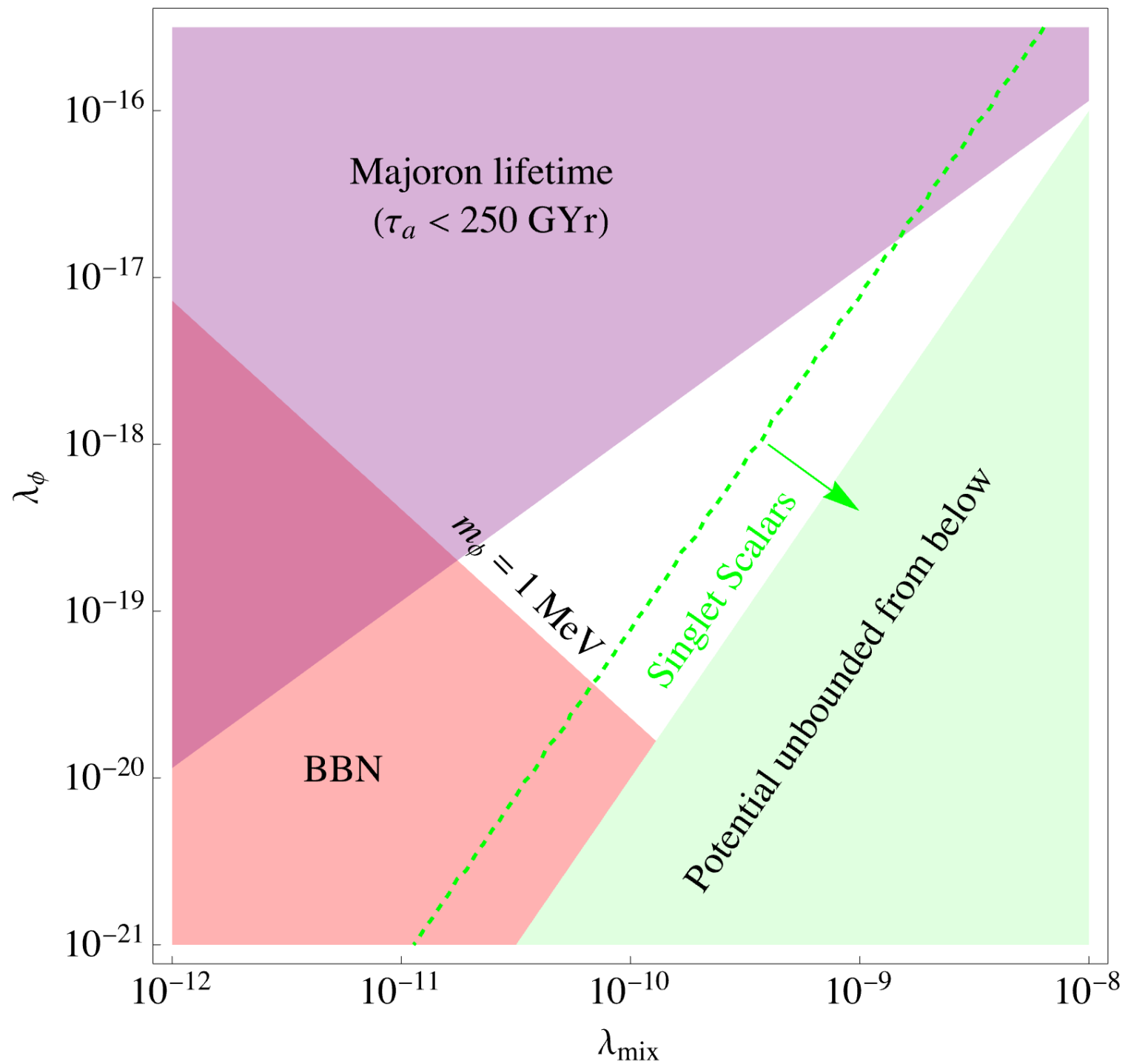
Predictions:



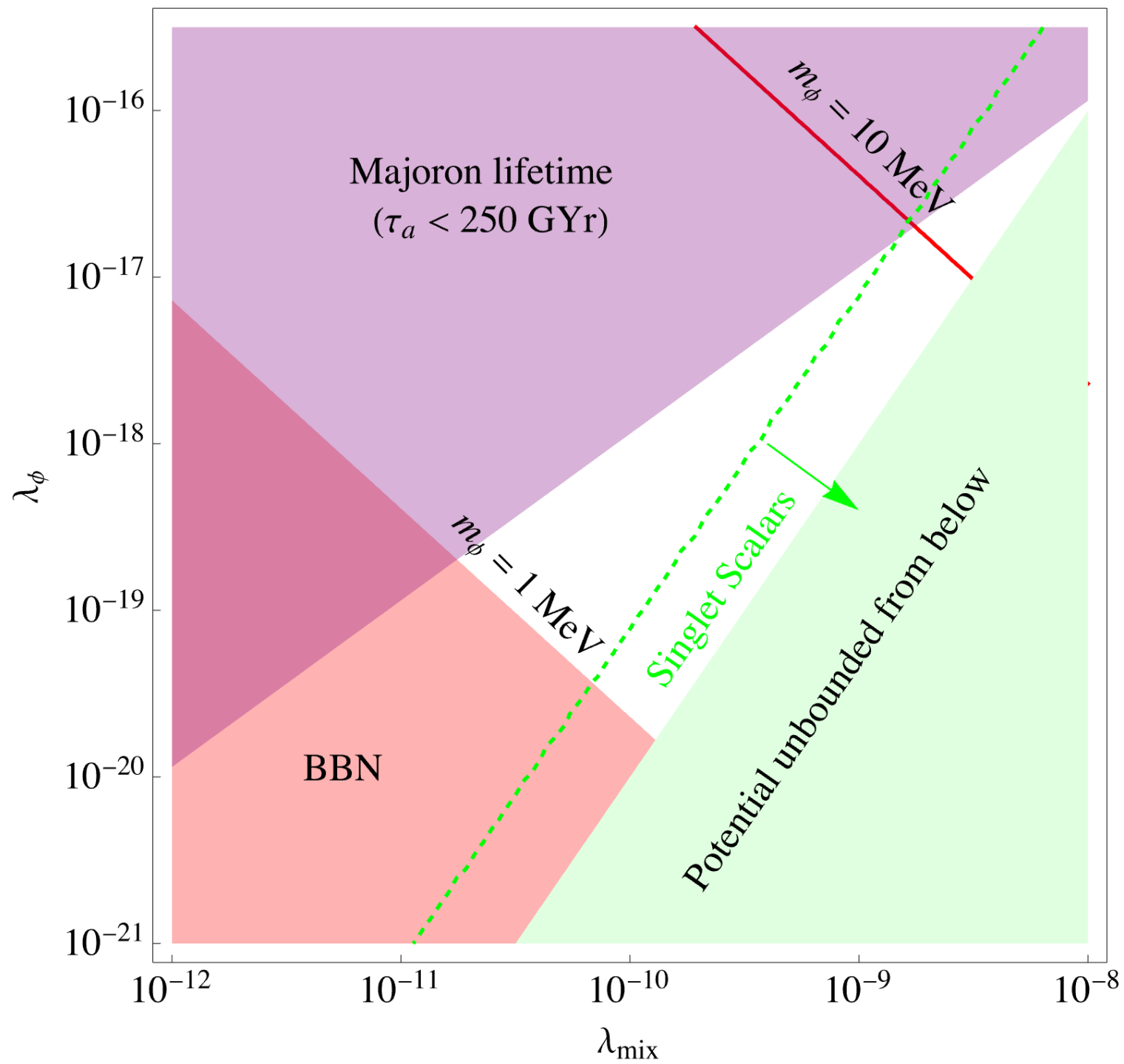
Predictions:



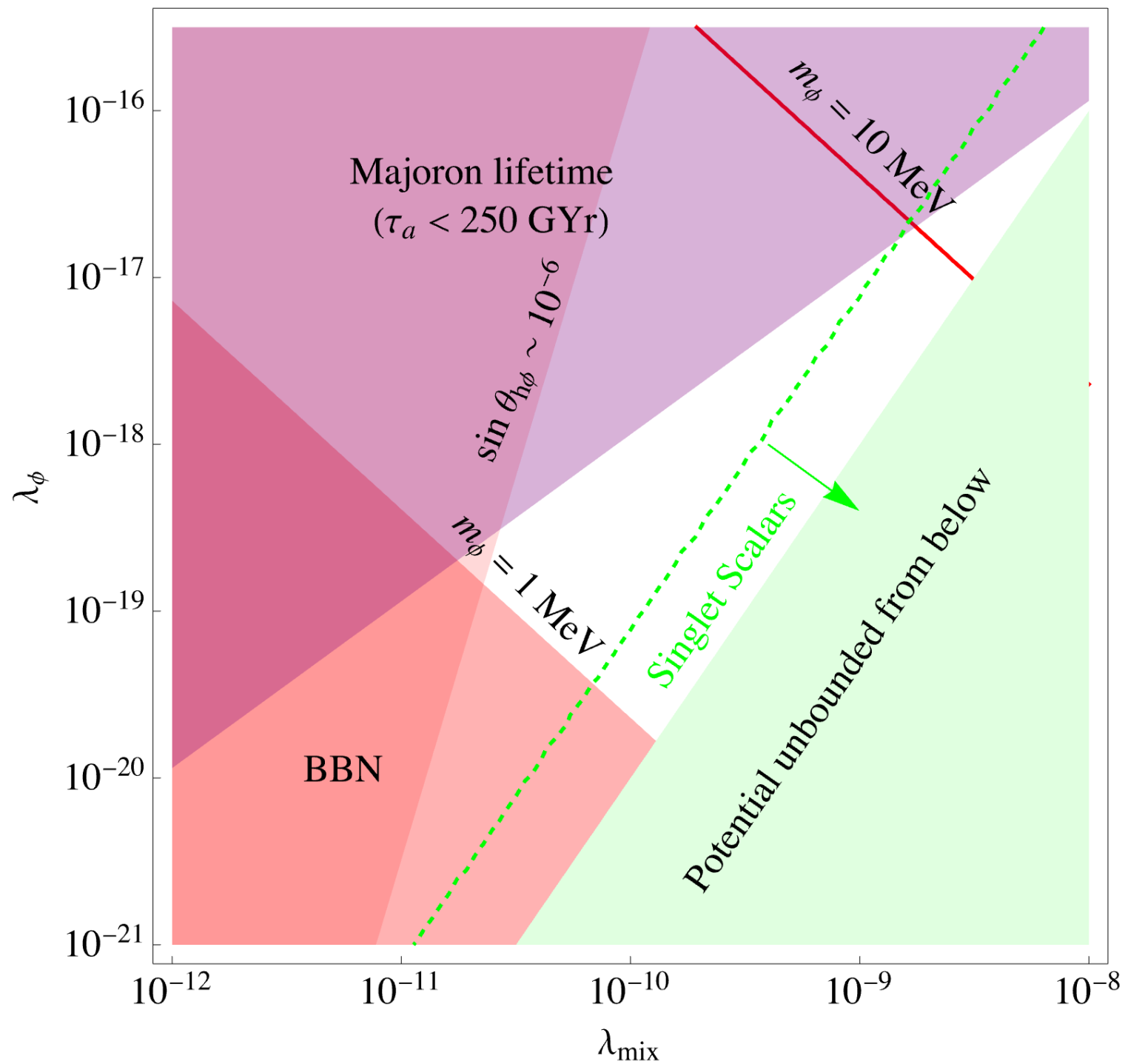
Predictions:



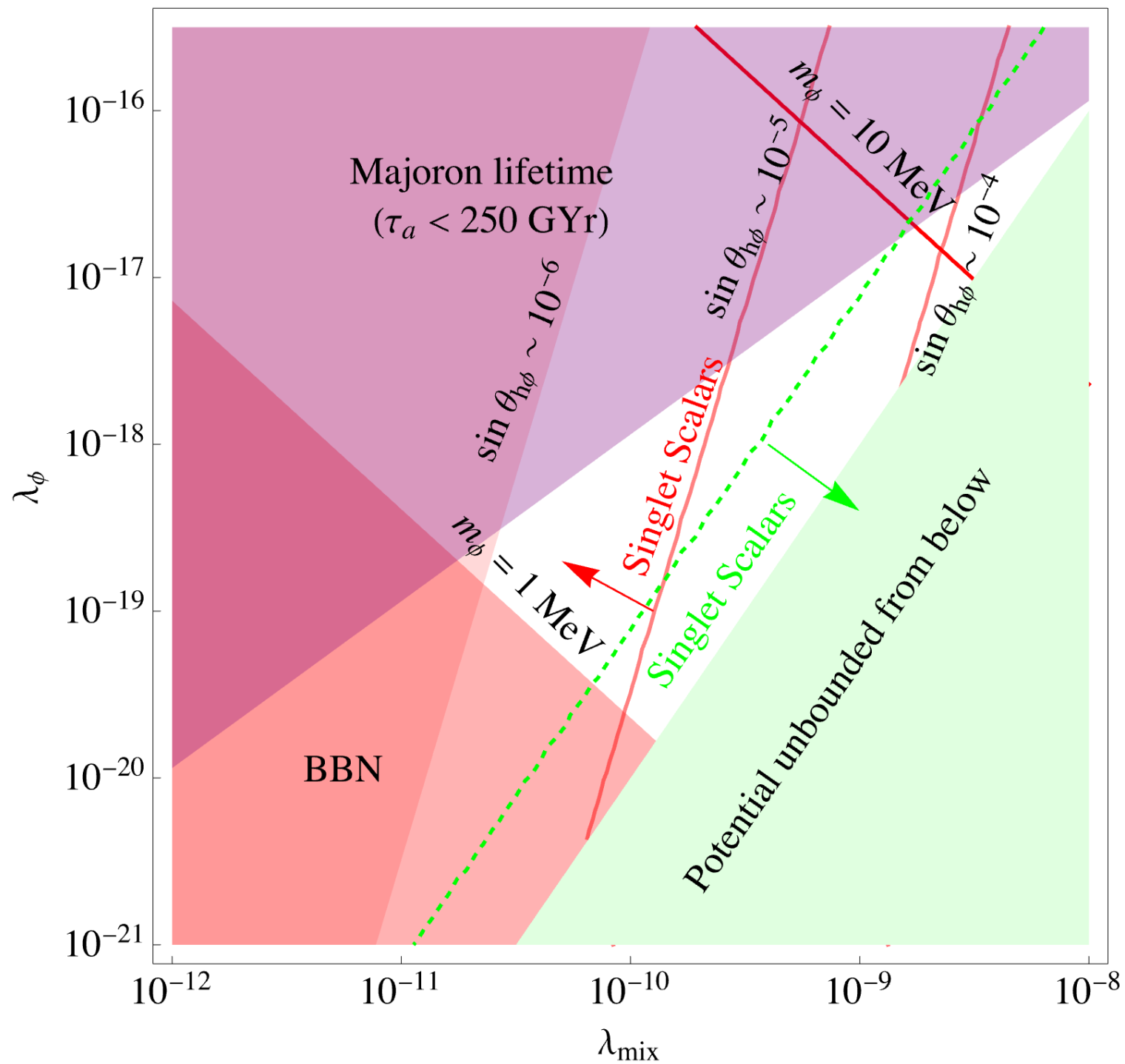
Predictions:



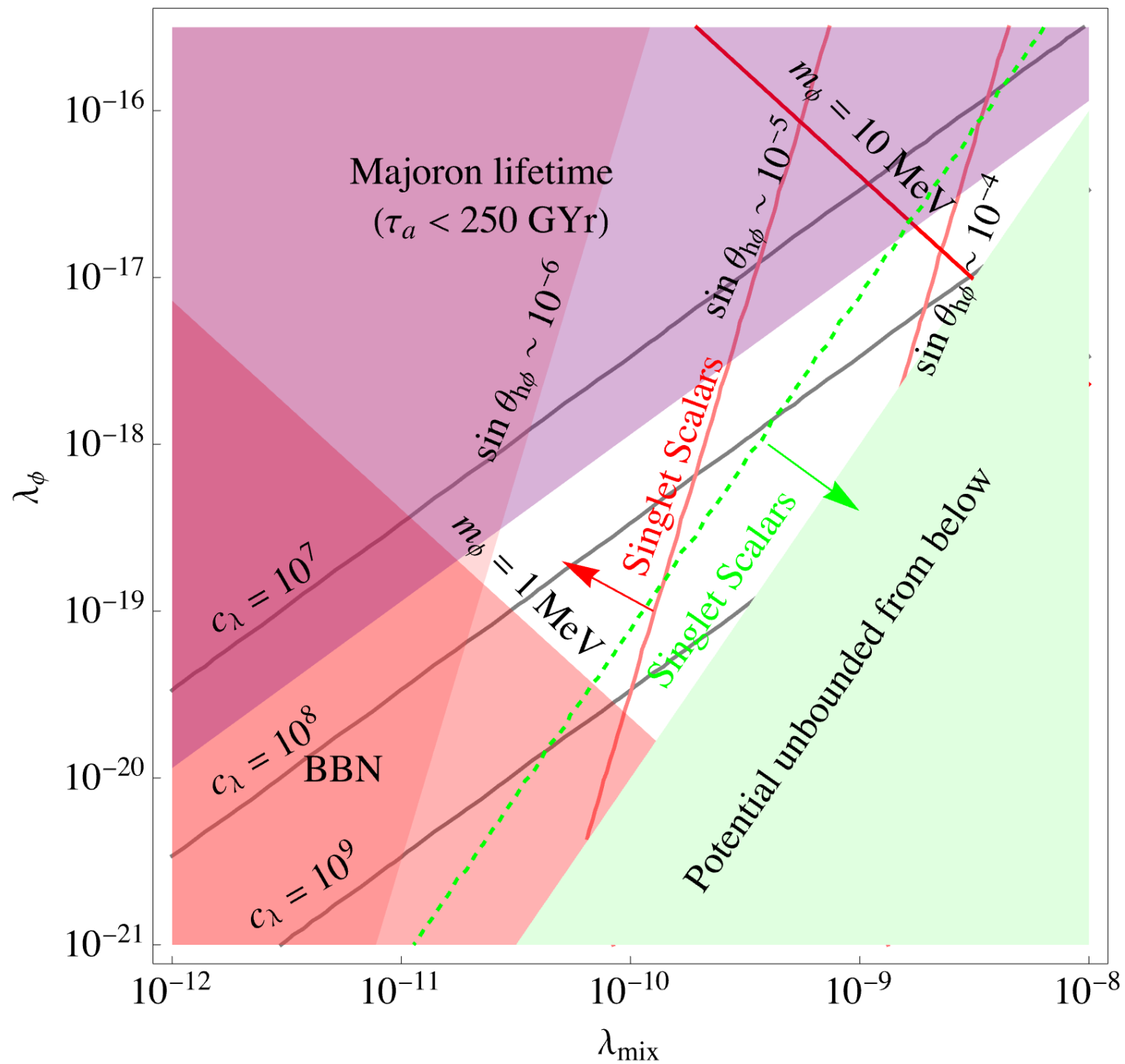
Predictions:



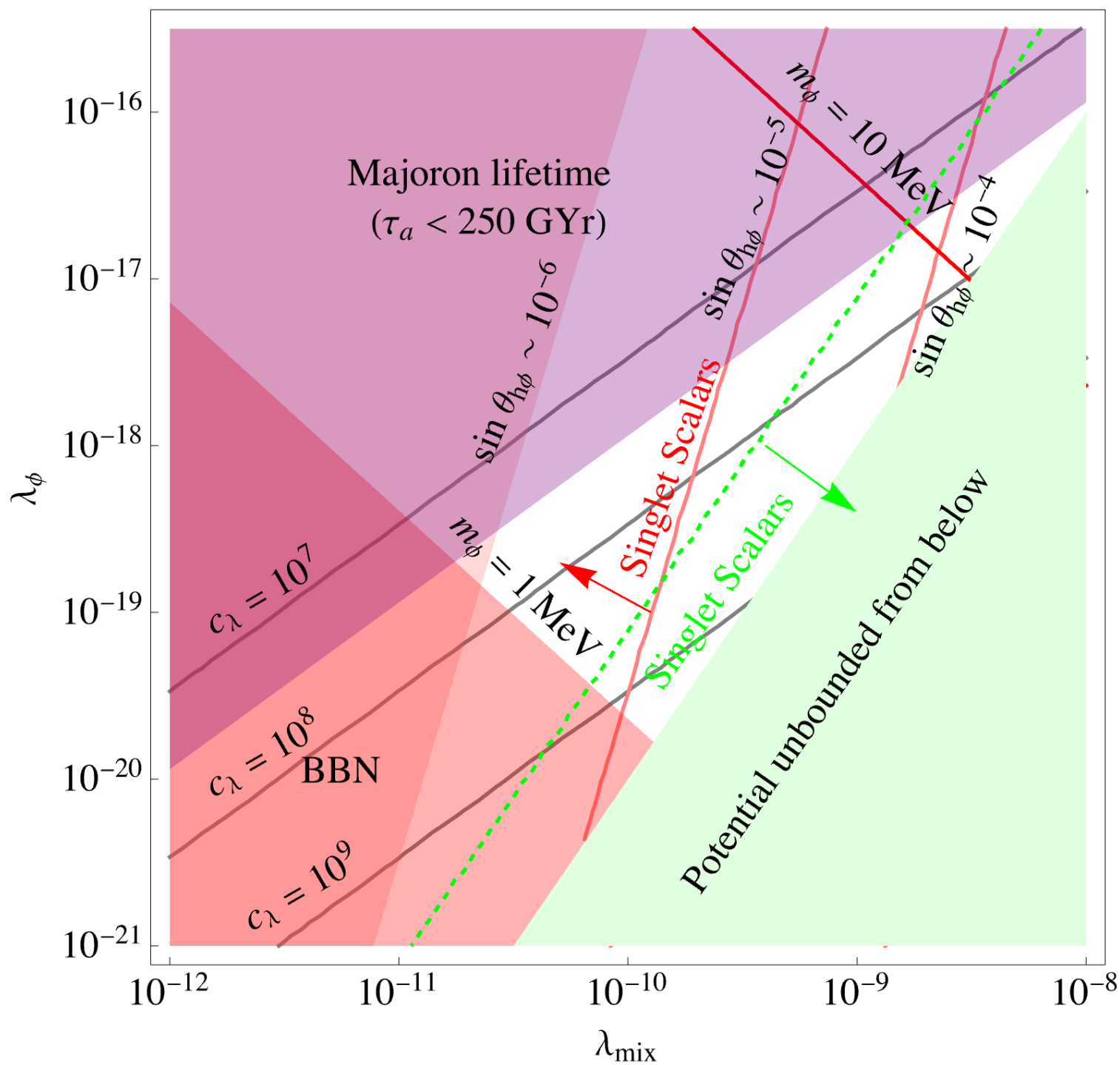
Predictions:



Predictions:



Predictions:



The Cogenesis Window

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

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

Rotation via **non-minimal** **coupling to gravity**

Periodic non-minimal coupling to gravity

R. Z. Ferreira, A. Notari, G. Simeon, JCAP 2018

$$\mathcal{L} = \frac{1}{2}m_P^2 R - \frac{1}{2}(\partial\phi)^2 - \left(\underset{\downarrow}{M^4} - \frac{1}{2}\xi \underset{\downarrow}{m_P^2 R} \right) [1 - \cos(\phi/f)]$$

$\downarrow$ $\downarrow$
 $m_\phi^2 f^2$ $R = 3(1 - 3w)H^2$

Periodic non-minimal coupling to gravity

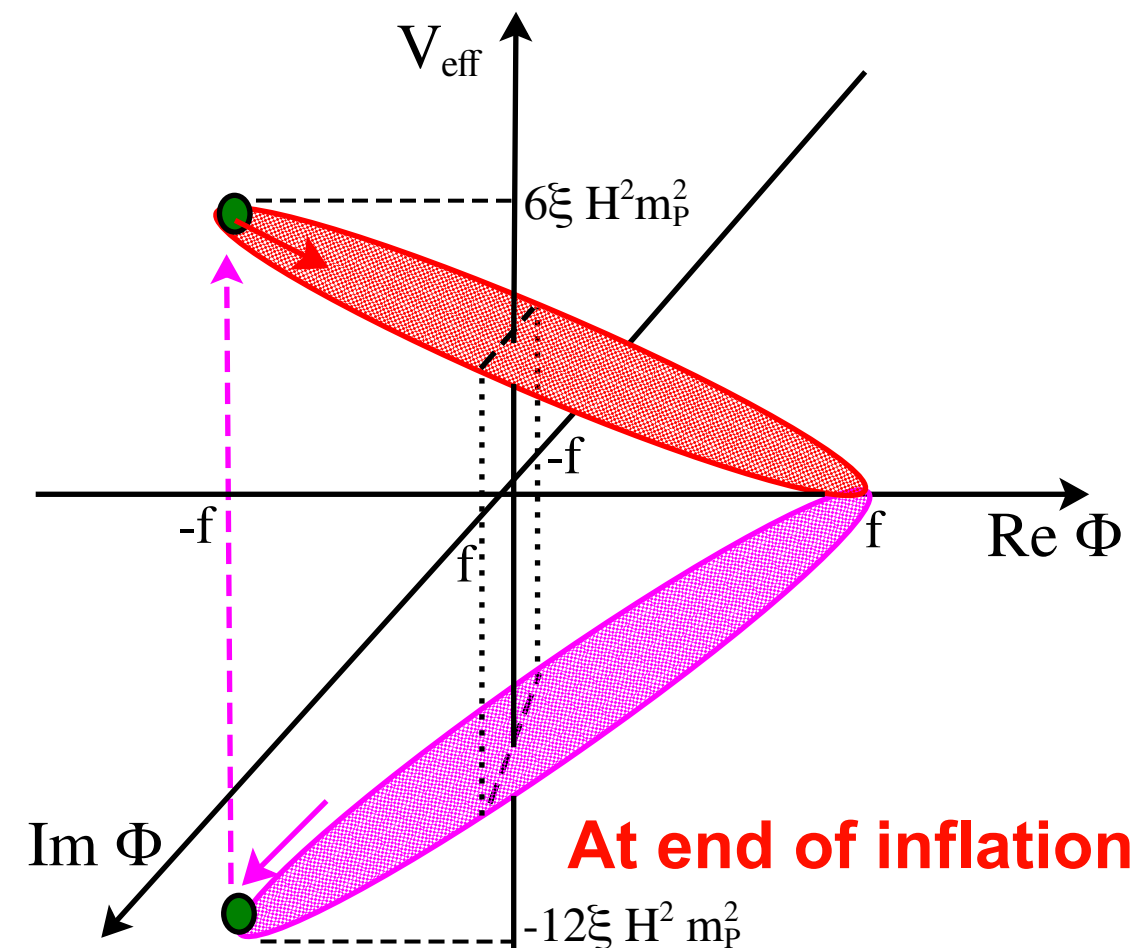
R. Z. Ferreira, A. Notari, G. Simeon, JCAP 2018

$$\mathcal{L} = \frac{1}{2}m_P^2 R - \frac{1}{2}(\partial\phi)^2 - \left(\underset{\substack{\downarrow \\ m_\phi^2 f^2}}{M^4} - \underset{\substack{\downarrow \\ \xi m_P^2 R}}{\frac{1}{2}} \right) [1 - \cos(\phi/f)]$$

$$R = 3(1 - 3w)H^2$$

Inflation followed by a Kination era?

$$V_{\text{eff}}(\phi) \simeq -6\xi m_P^2 H^2 [1 - \cos(\phi/f)] \longrightarrow V_{\text{eff}}(\phi) \simeq 3\xi m_P^2 H^2 [1 - \cos(\phi/f)]$$



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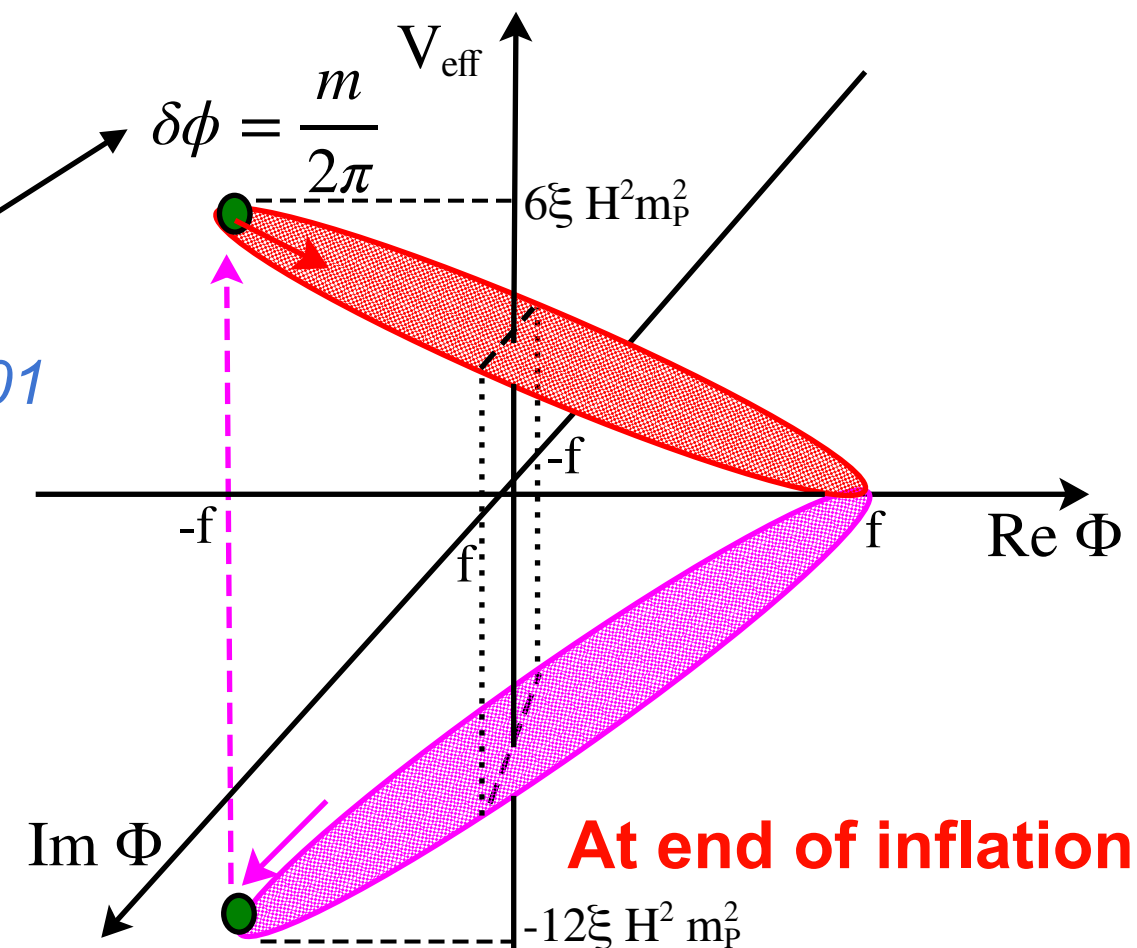
Inflation followed by a Kination era?

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$\dot{\theta}_i$ after the flip?

Quantum kick given by tachyonic mass

G.Felder, L. Kofman, A. Linde, 2001



Periodic non-minimal coupling to gravity

R. Z. Ferreira, A. Notari, G. Simeon, JCAP 2018

$$\mathcal{L} = \frac{1}{2}m_P^2 R - \frac{1}{2}(\partial\phi)^2 - \left(\underset{\substack{\downarrow \\ m_\phi^2 f^2}}{M^4} - \underset{\substack{\downarrow \\ \xi m_P^2 R}}{\frac{1}{2}} \right) [1 - \cos(\phi/f)]$$

$R = 3(1 - 3w)H^2$

Inflation followed by a Kination era?

$$V_{\text{eff}}(\phi) \simeq -6\xi m_P^2 H^2 [1 - \cos(\phi/f)] \longrightarrow V_{\text{eff}}(\phi) \simeq 3\xi m_P^2 H^2 [1 - \cos(\phi/f)]$$

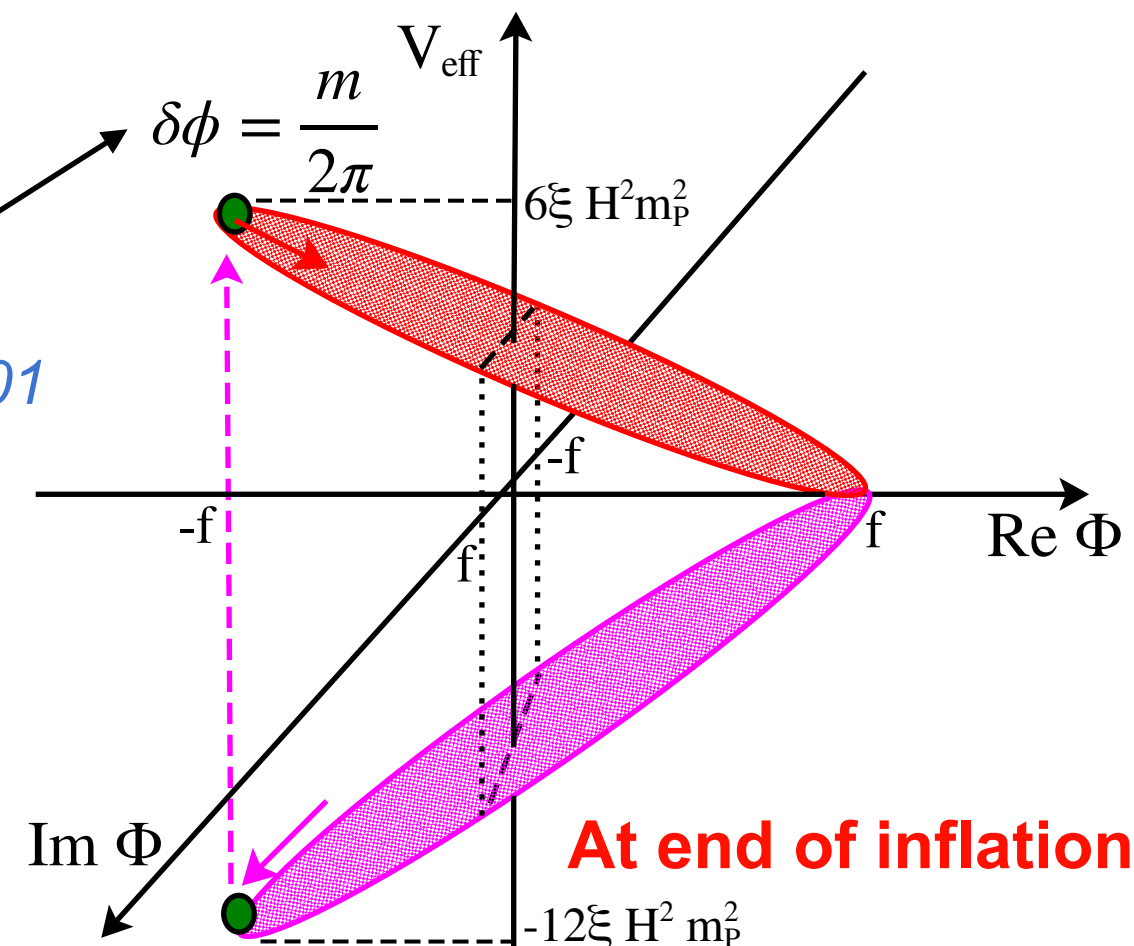
$\dot{\theta}_i$ after the flip?

Quantum kick given by tachyonic mass

G.Felder, L. Kofman, A. Linde, 2001

Maximum Kinetic energy (for large ξ) =

$$\frac{1}{2}f^2\dot{\theta}_m^2 \simeq 6\xi m_P^2 H_{\text{end}}^2$$

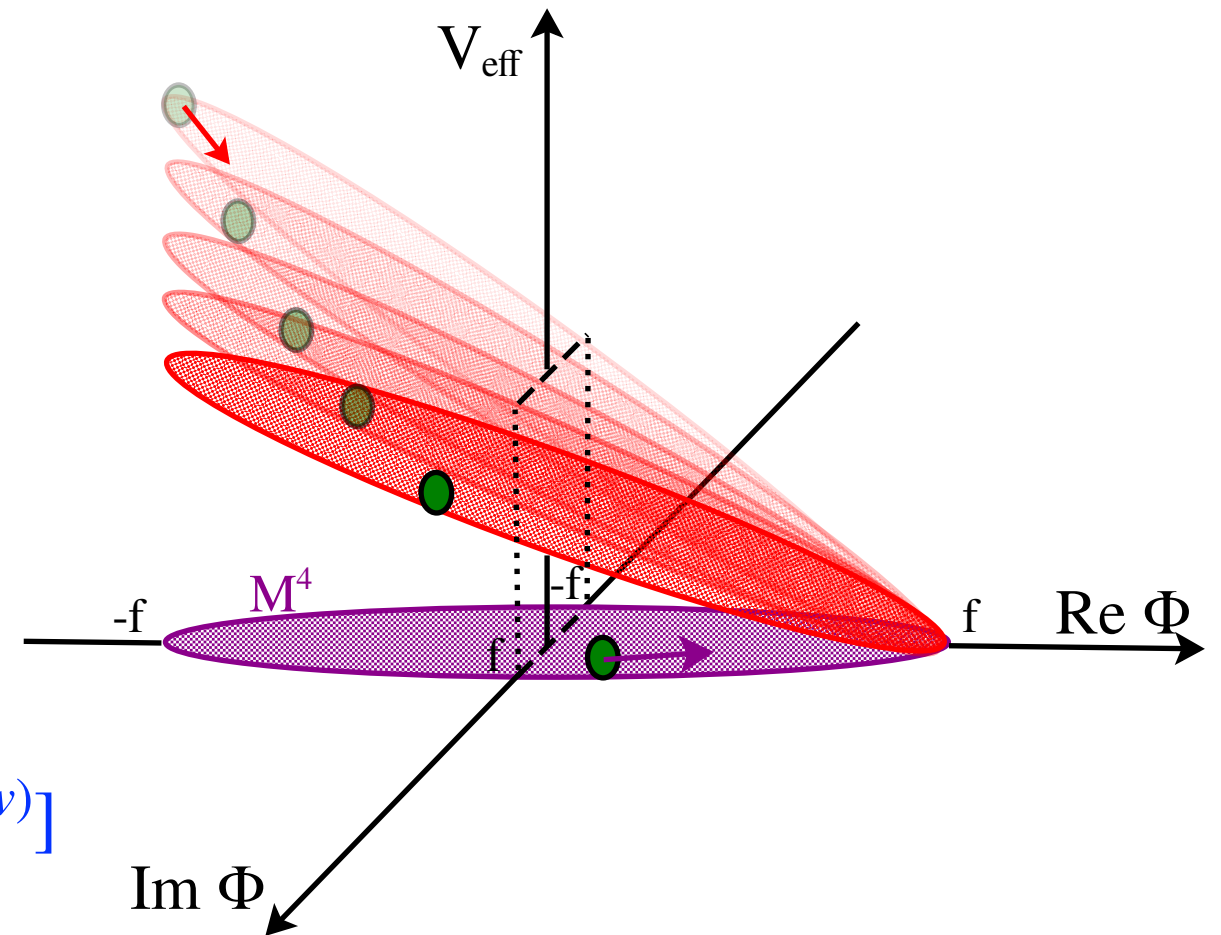


After inflation

Barrier height: $\propto H^2 \propto \frac{1}{t^2}$

in tandem with

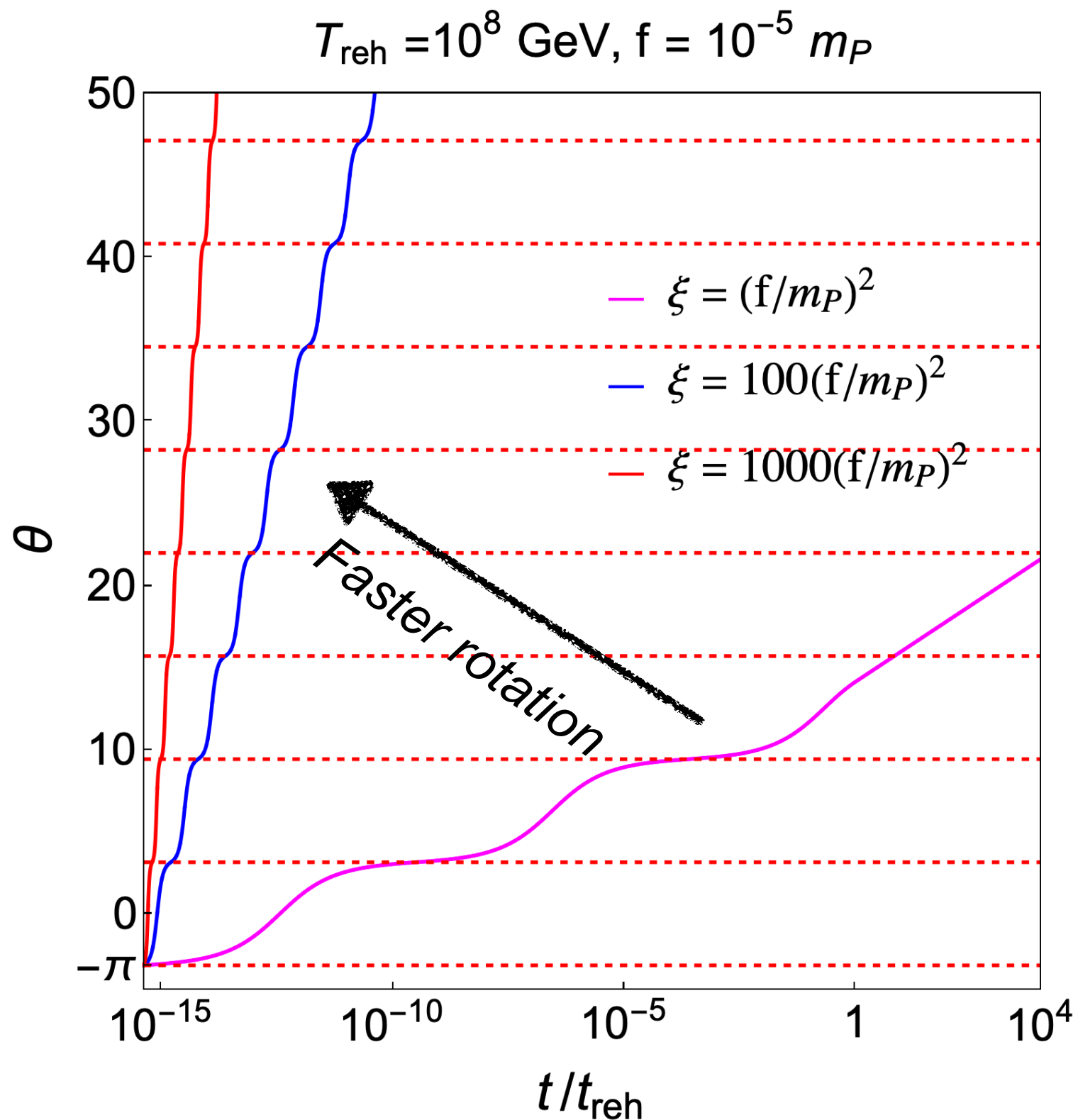
Kinetic Energy: $\propto \dot{\theta}^2 \propto \frac{1}{a^6} \propto \frac{1}{t^2}$
 $[a \propto t^{2/3(1+w)}]$



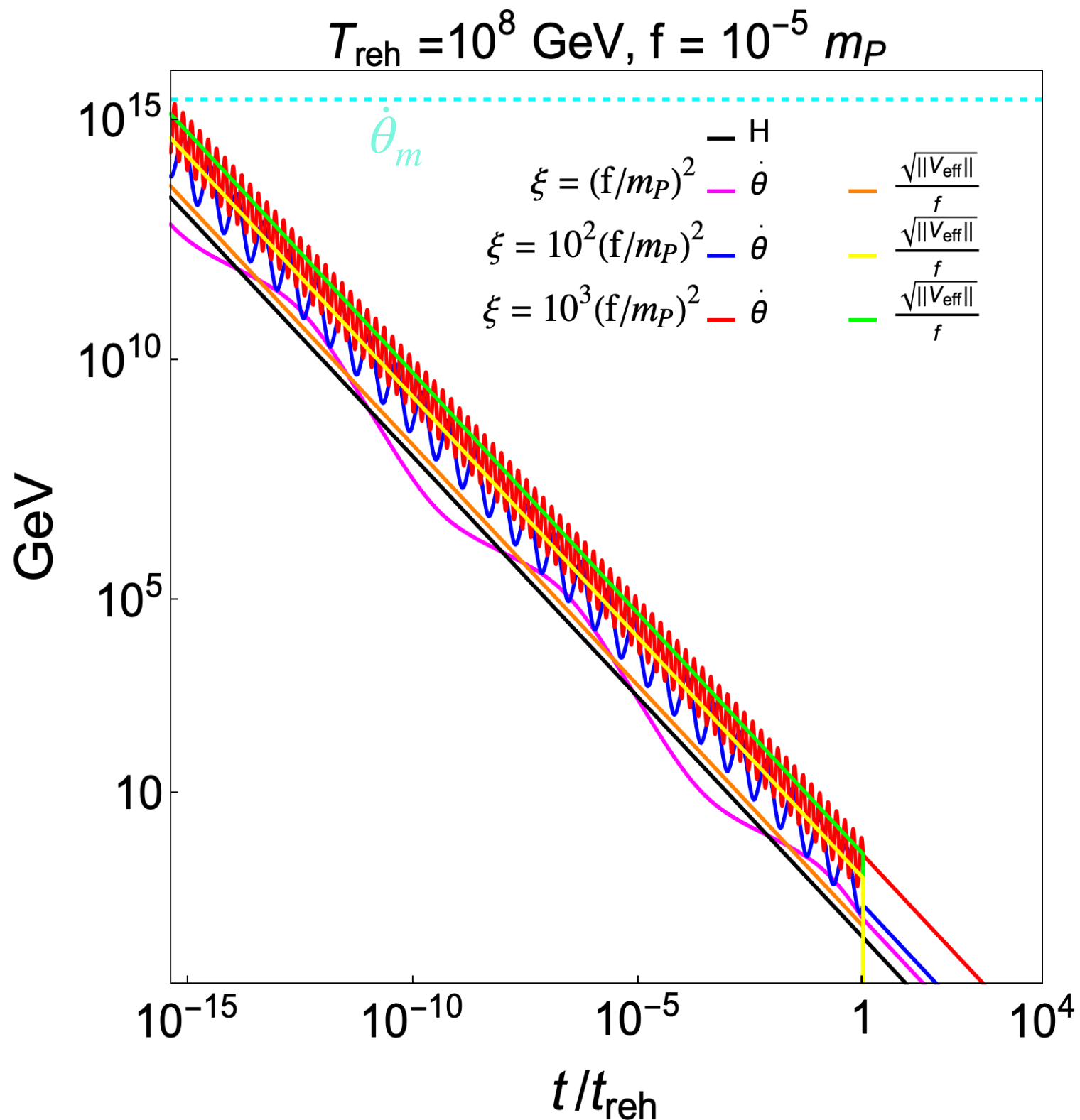
Range of ξ :

$$||V''_{\text{eff}}|| > H \longrightarrow \frac{3}{4} \left(\frac{f}{m_P} \right)^2 < \xi \ll \frac{1}{2} \longleftarrow \text{Axion remains sub-dominant}$$

Numerical solution



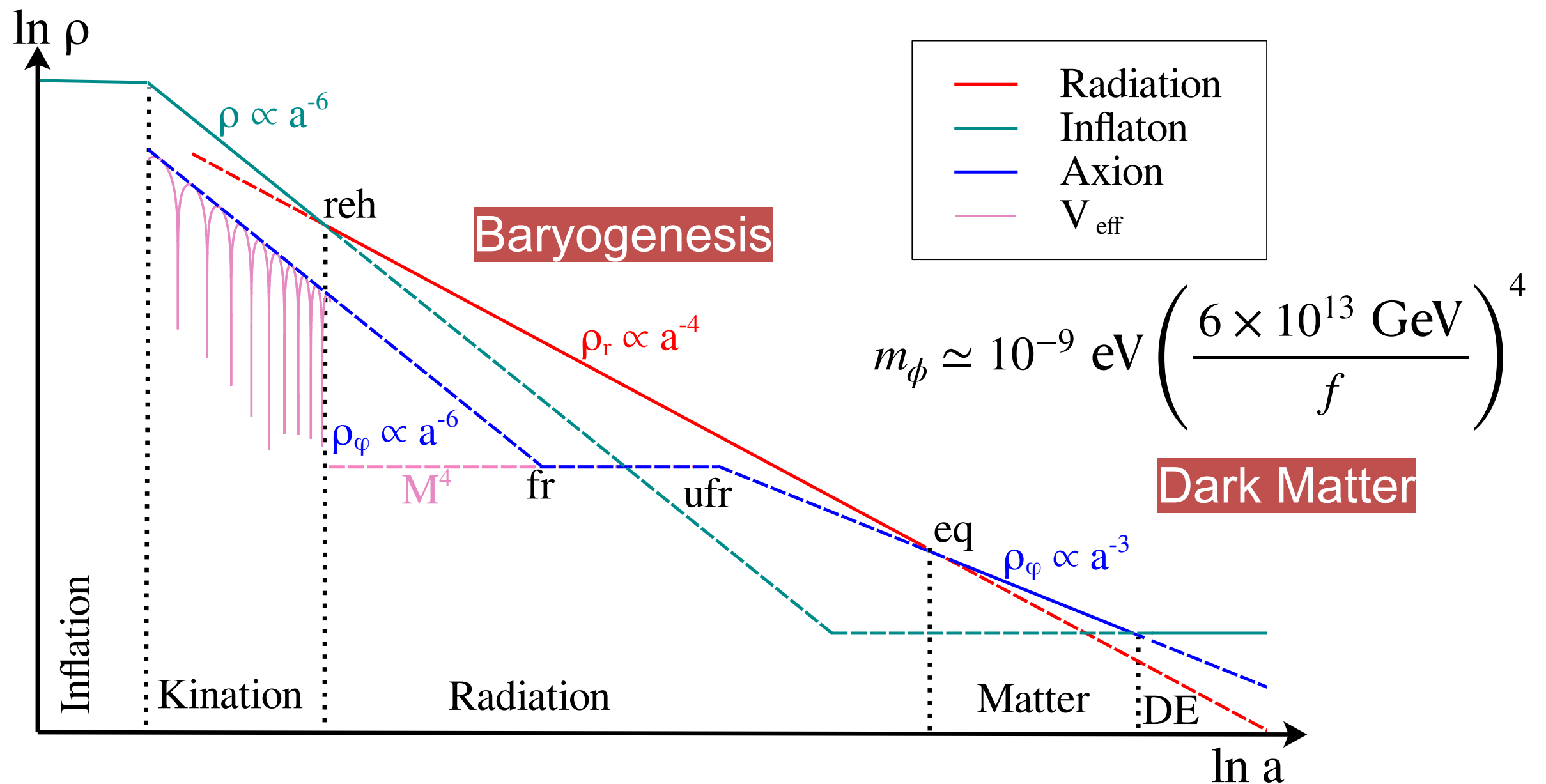
Numerical solution



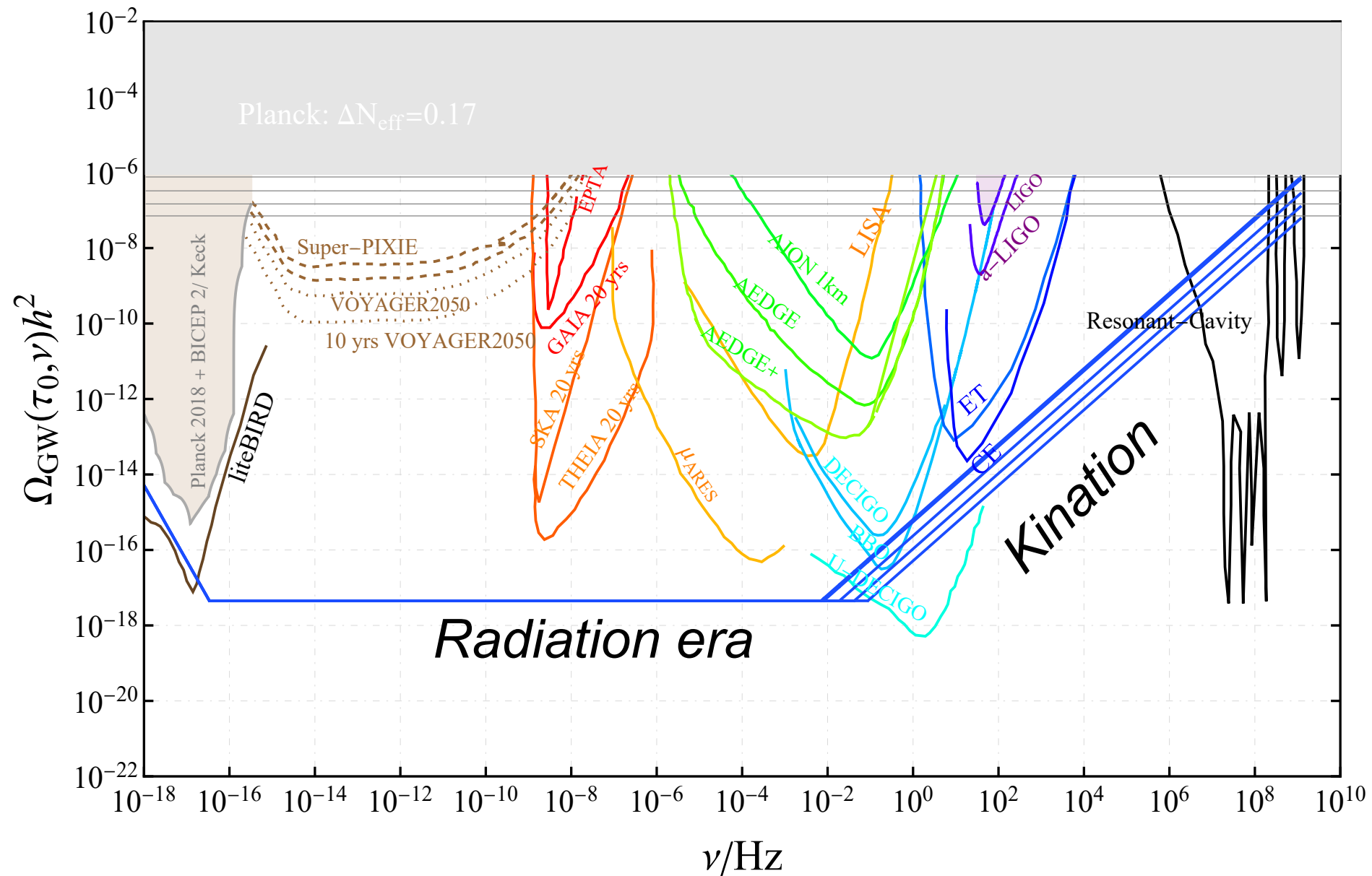
Spontaneous baryogenesis:

$$Y_B \sim \frac{\dot{\theta}_m}{g_{*s} T_{B-L}} \left(\frac{a_m}{a_{B-L}} \right)^3 \sim \frac{\sqrt{\xi}}{\sqrt{g^*}} \frac{T_{B-L}^2}{f T_{\text{reh}}}$$

Redshift

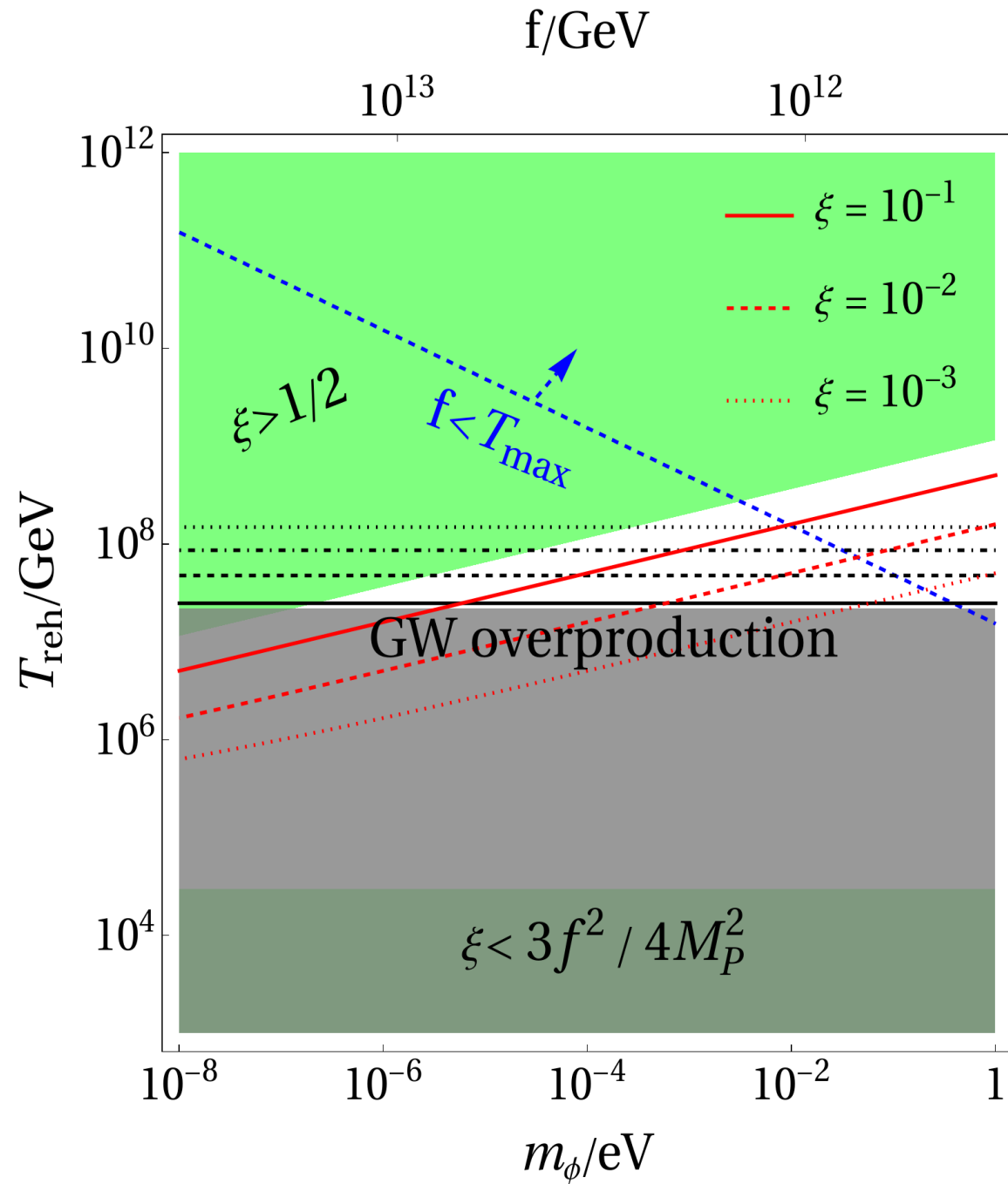


Primordial Gravitational waves from Inflation?



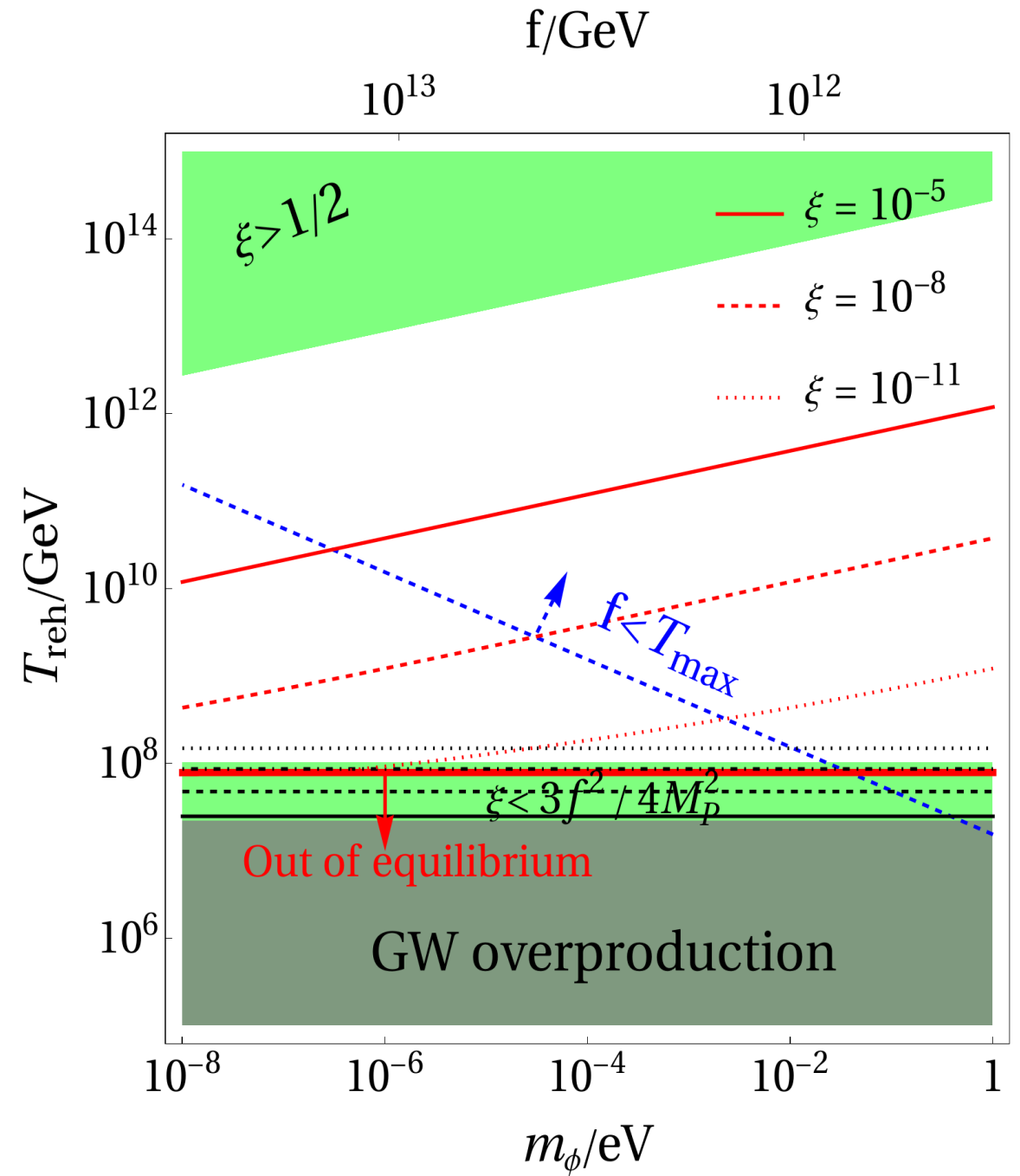
$$\Omega_{\text{peak}} h^2 \lesssim 5 \times 10^{-6} \Delta N_{\text{eff}} \implies T_{\text{reh}} \gtrsim \frac{6 \times 10^6 \text{ GeV}}{\Delta N_{\text{eff}}^{3/4}}$$

Predictions for Cogenesis (Majoron):



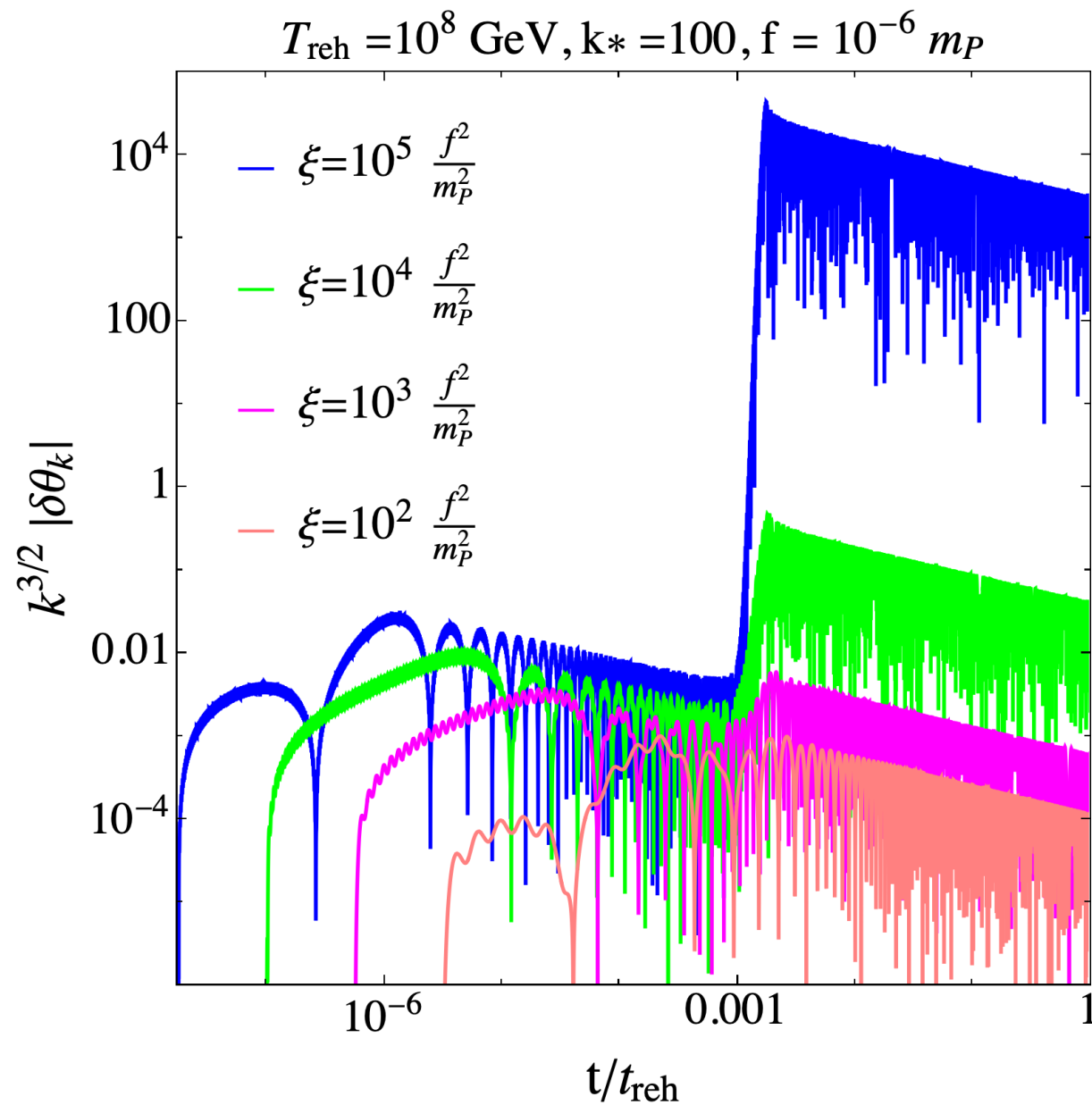
$$M_N = 10^7 \text{ GeV}$$

$$m_\nu \sim c_B^{1/2} \left(\frac{v}{246 \text{ GeV}} \right) \left(\frac{10}{z_{\text{fo}}} \right) \left(\frac{10^7 \text{ GeV}}{T_{\text{reh}}} \right)^{1/2} \left(\frac{Y_D}{6.3 \times 10^{-2}} \right)^2 \text{ eV}.$$



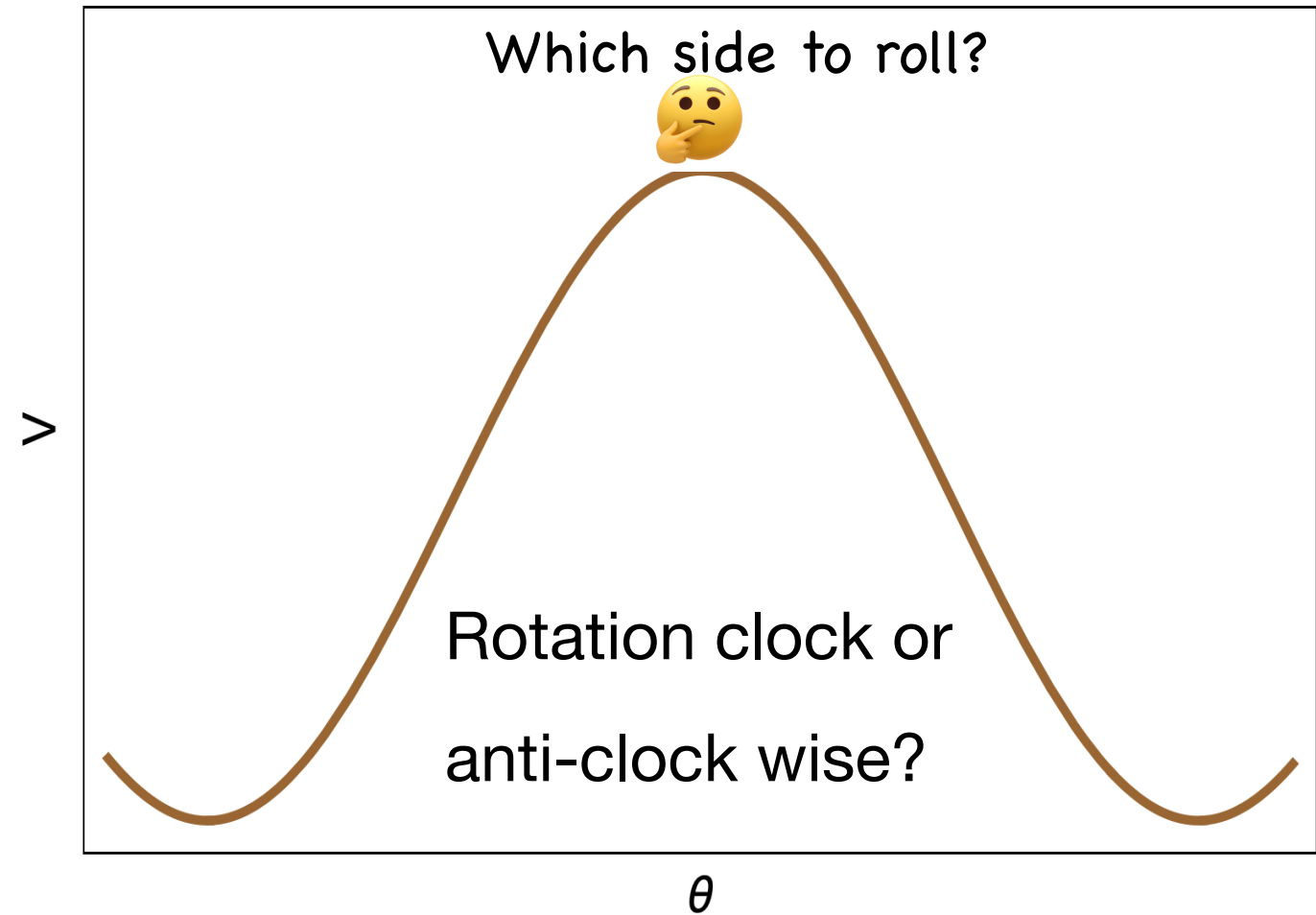
$$M_N = 5 \times 10^9 \text{ GeV}$$

Effects of Axion Fragmentation?



$$\xi \lesssim 10^3 \left(\frac{f}{m_P} \right)^2$$

Kibble Issue?



Slightly misaligned: $\langle \bar{\phi}^2 \rangle = \frac{3H^4}{8\pi^2 m_\phi^2} > \left(\frac{H}{2\pi} \right)^2$

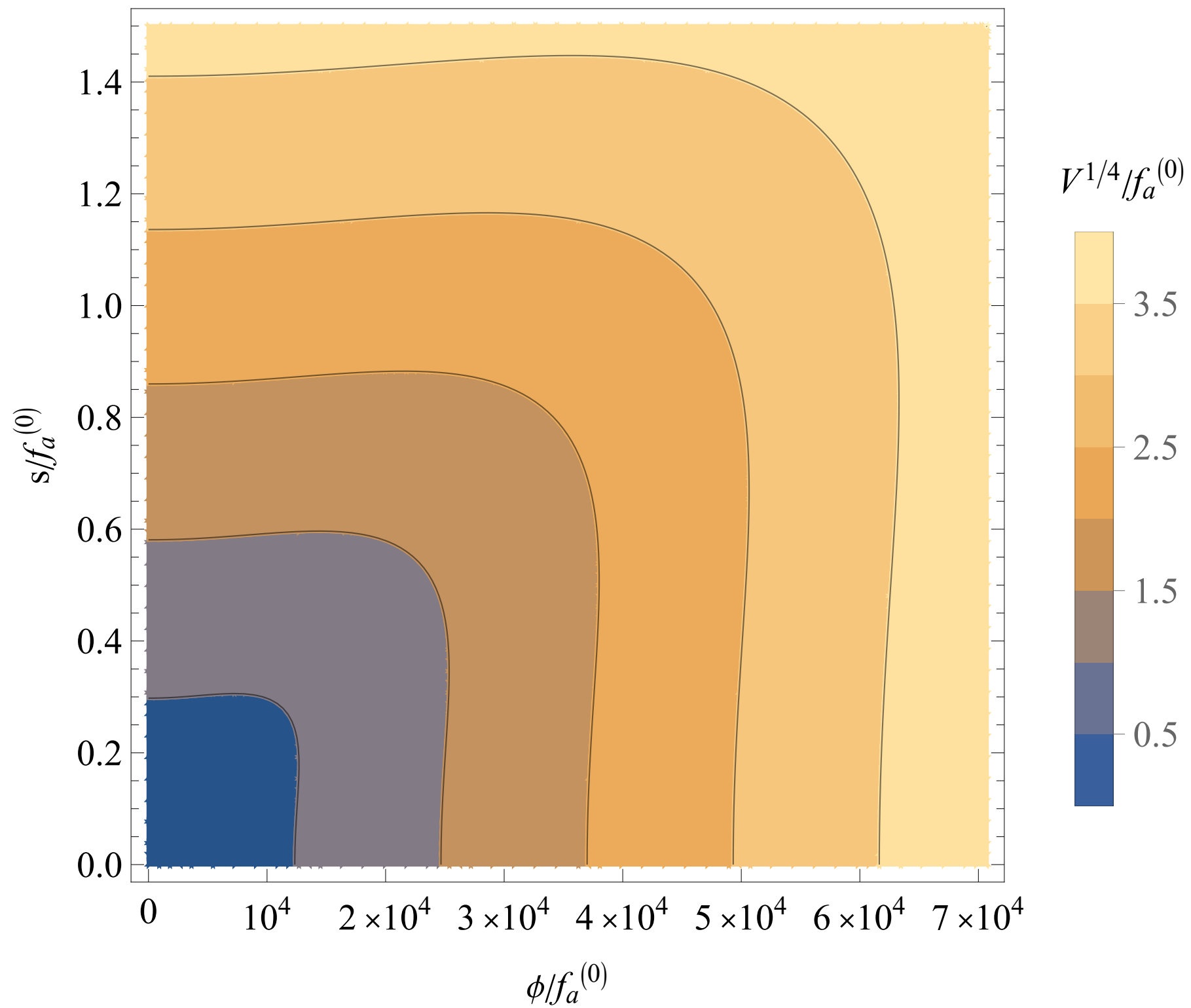
$$\xi \sim \left(\frac{f}{m_P} \right)^2$$

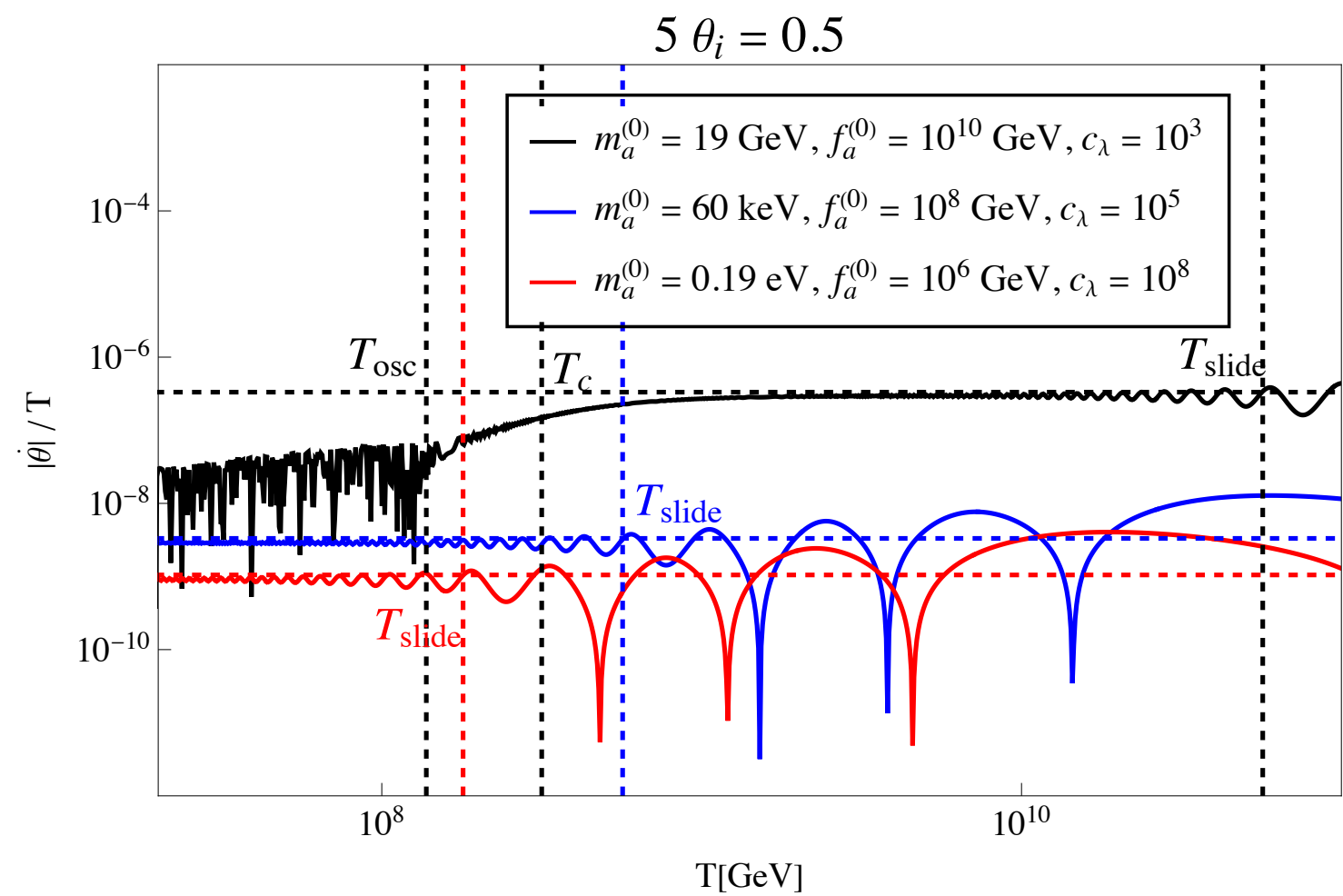
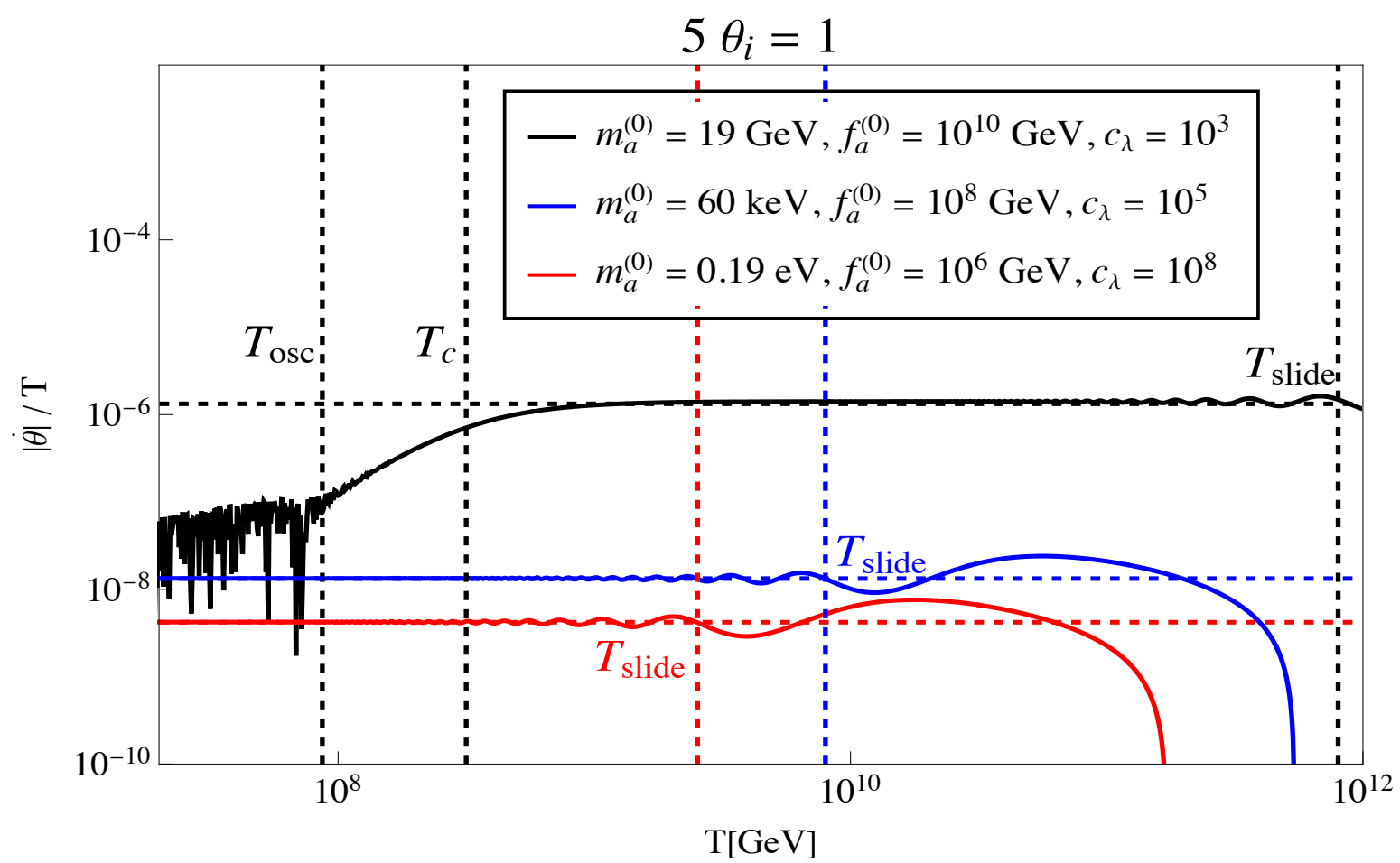
Key take aways...

- $\dot{\theta}_i = 0$ with **no radial dynamics** can lead to rotation/sliding and baryon & DM abundance.
- Baryon asymmetry at high temperatures **during sliding**, DM at low temperatures **during oscillation**.
- Via (a) Symmetry non-restoration, (b) Non-minimal coupling to gravity.
- Can be realized for **Majoron**, testable at (a) kaon experiments, colliders (b) GW.
- Extension of other D-operators, other scenarios?
- Observational consequences of rotation: GW anisotropies, CMB Birefringence and of fragmentation: Axion mini-clusters? GWs?

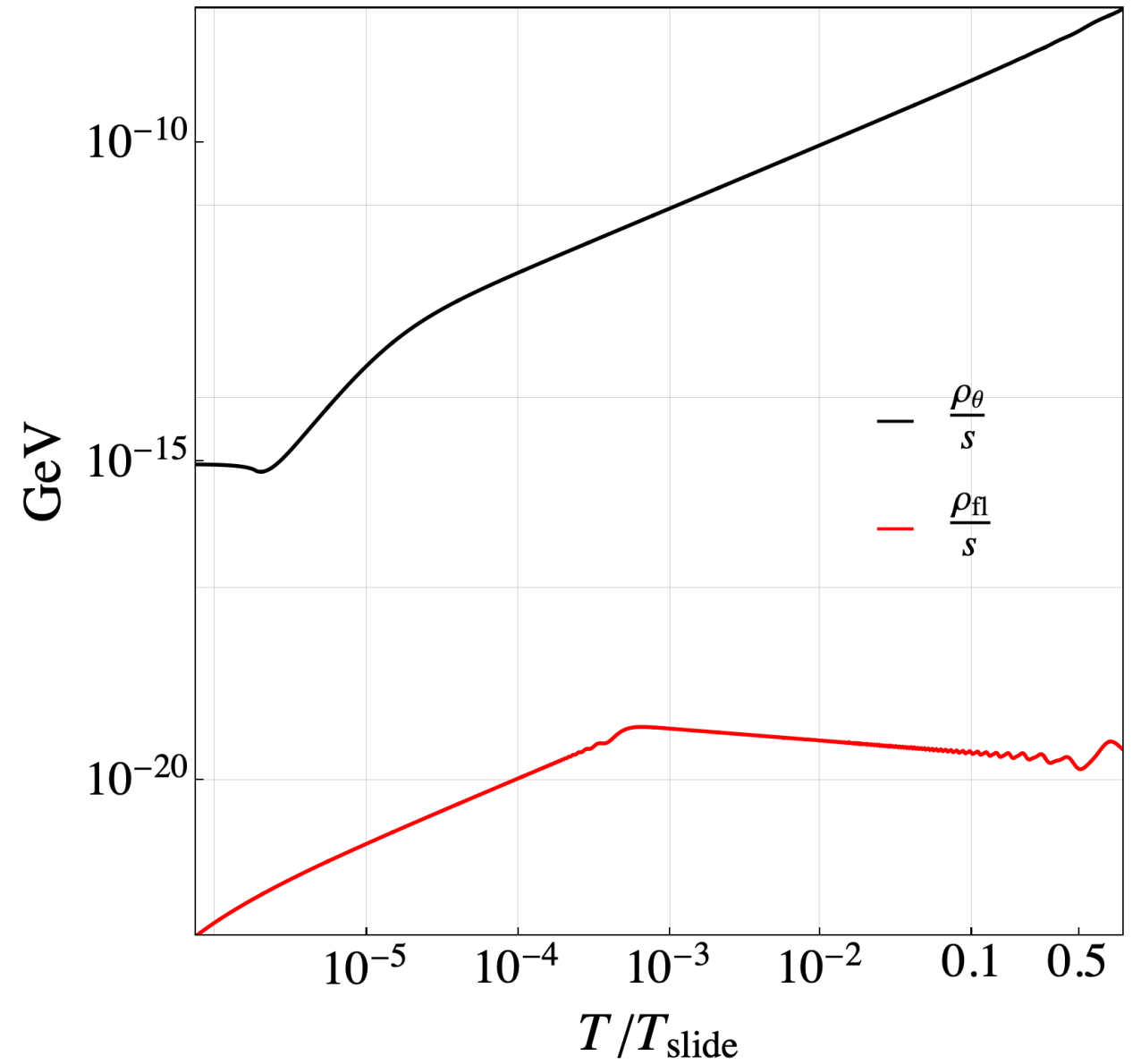
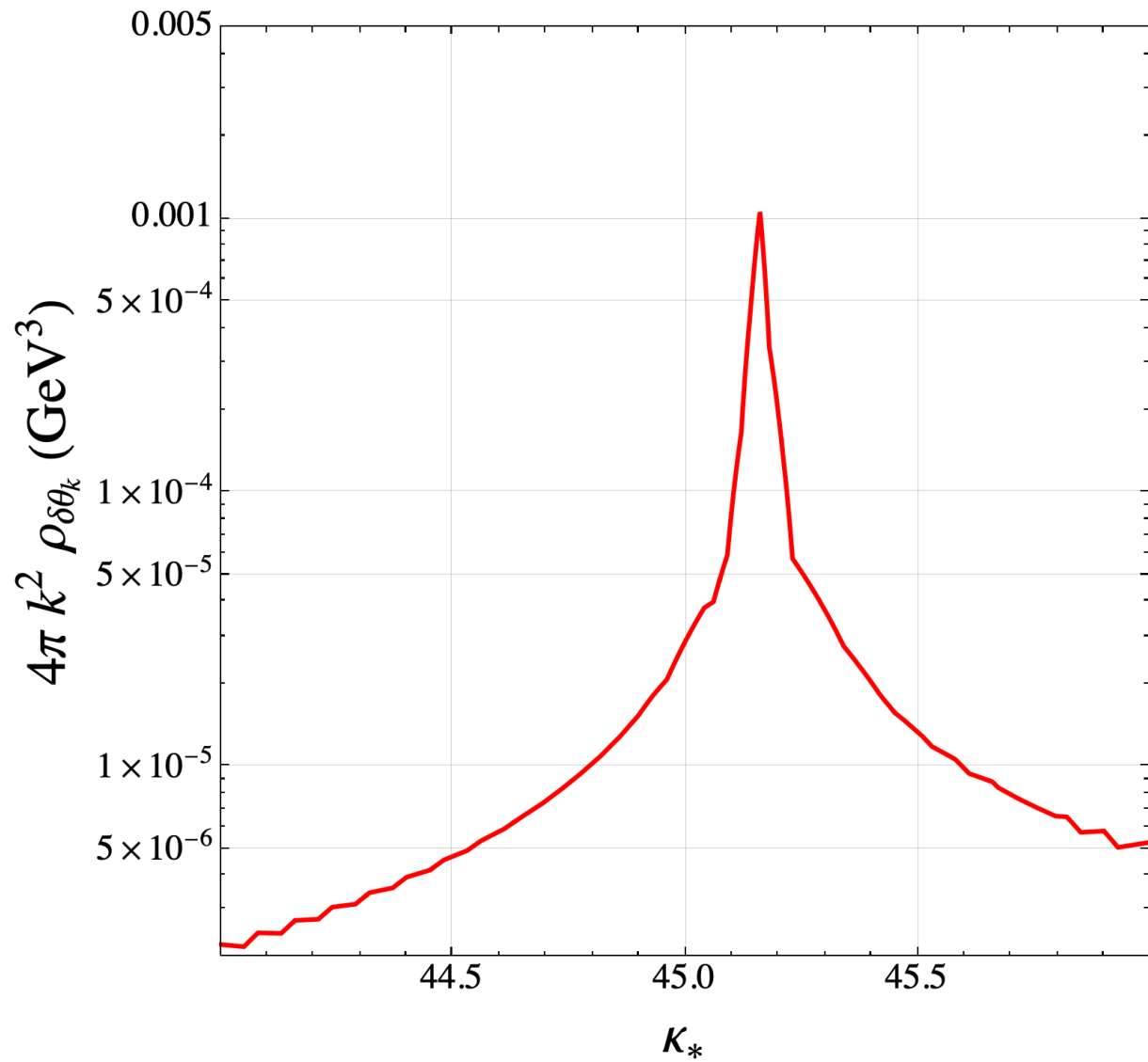
THANK YOU

Back Up



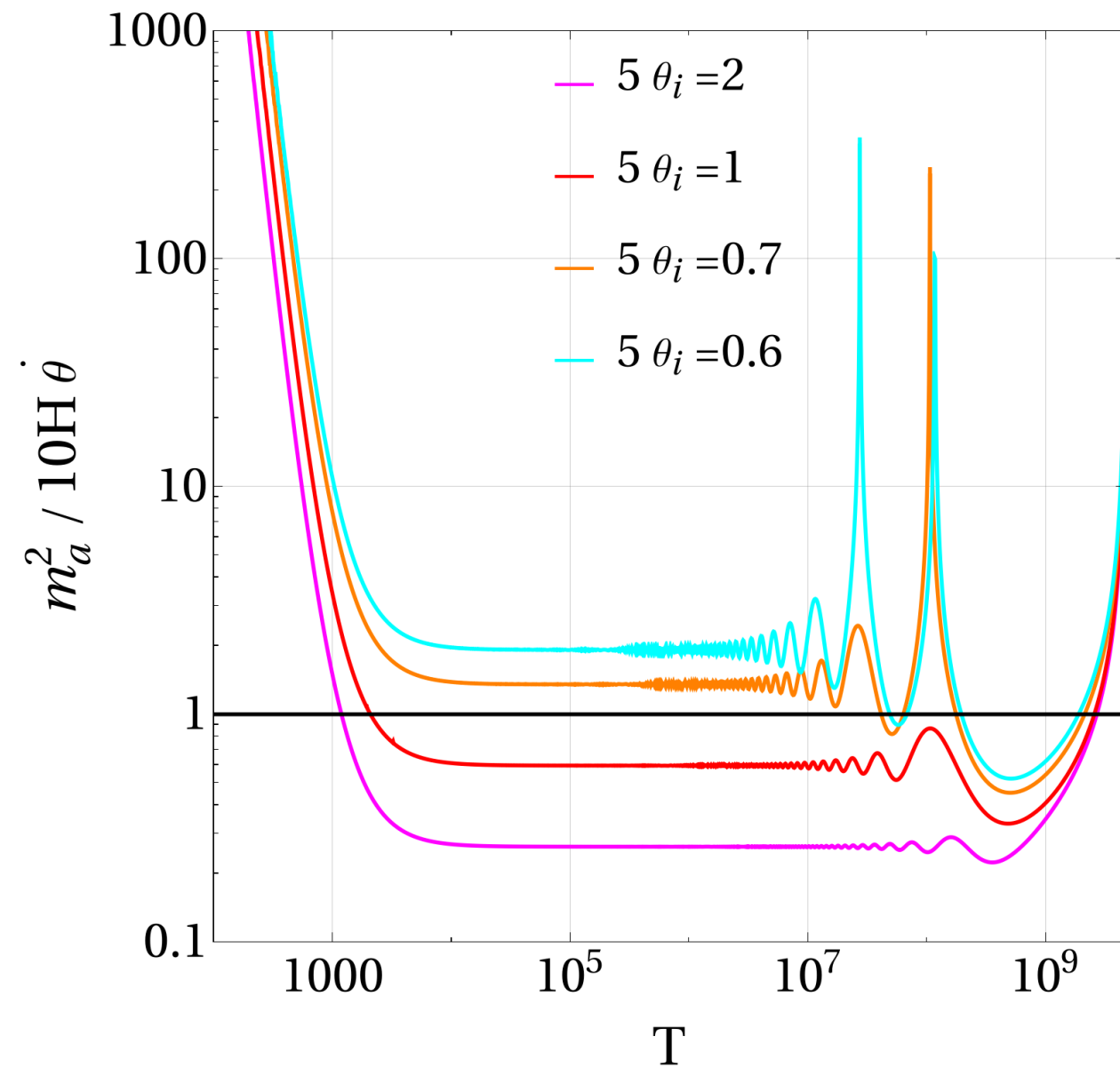


During Initial Sliding, $T > T_c$

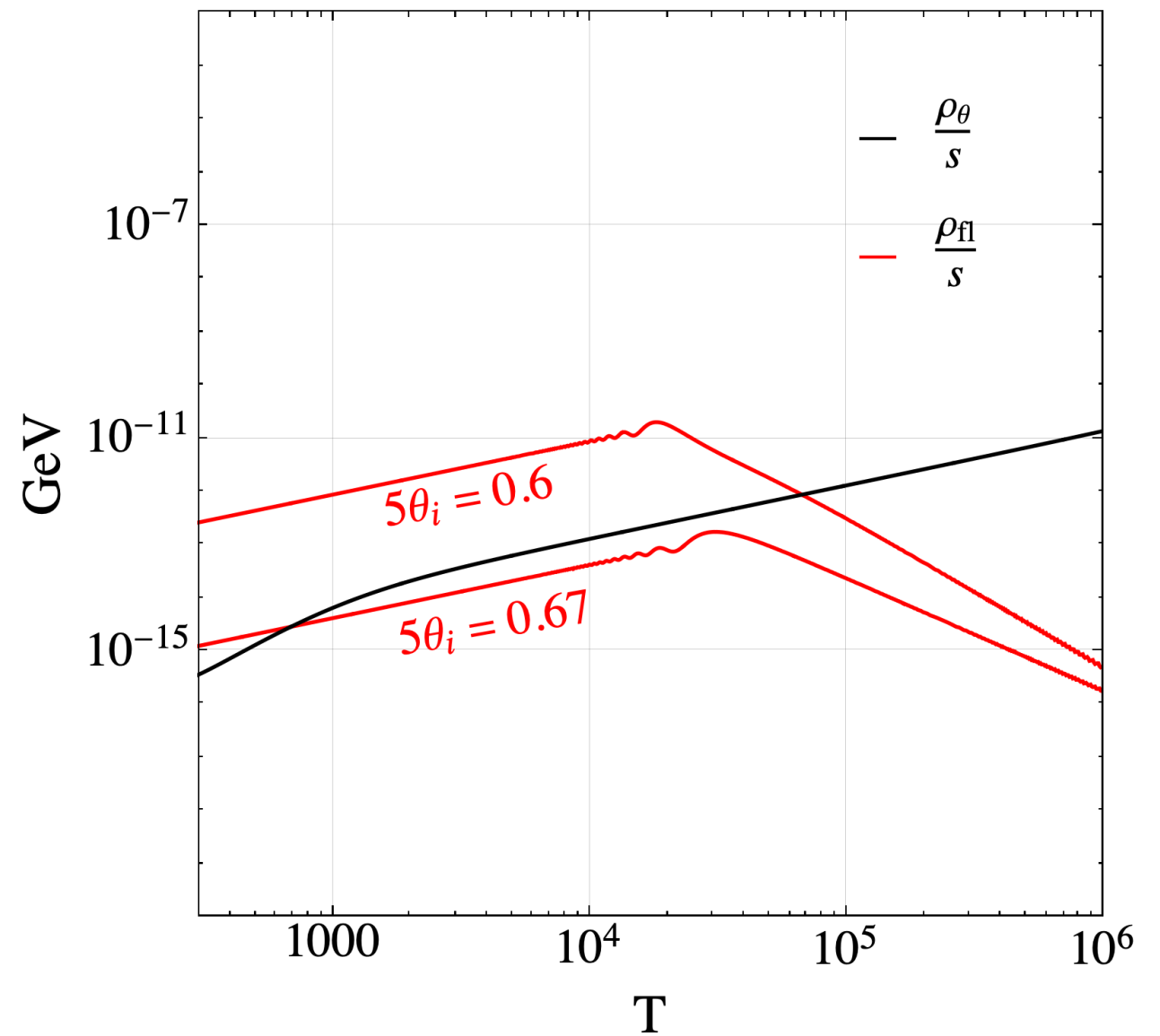


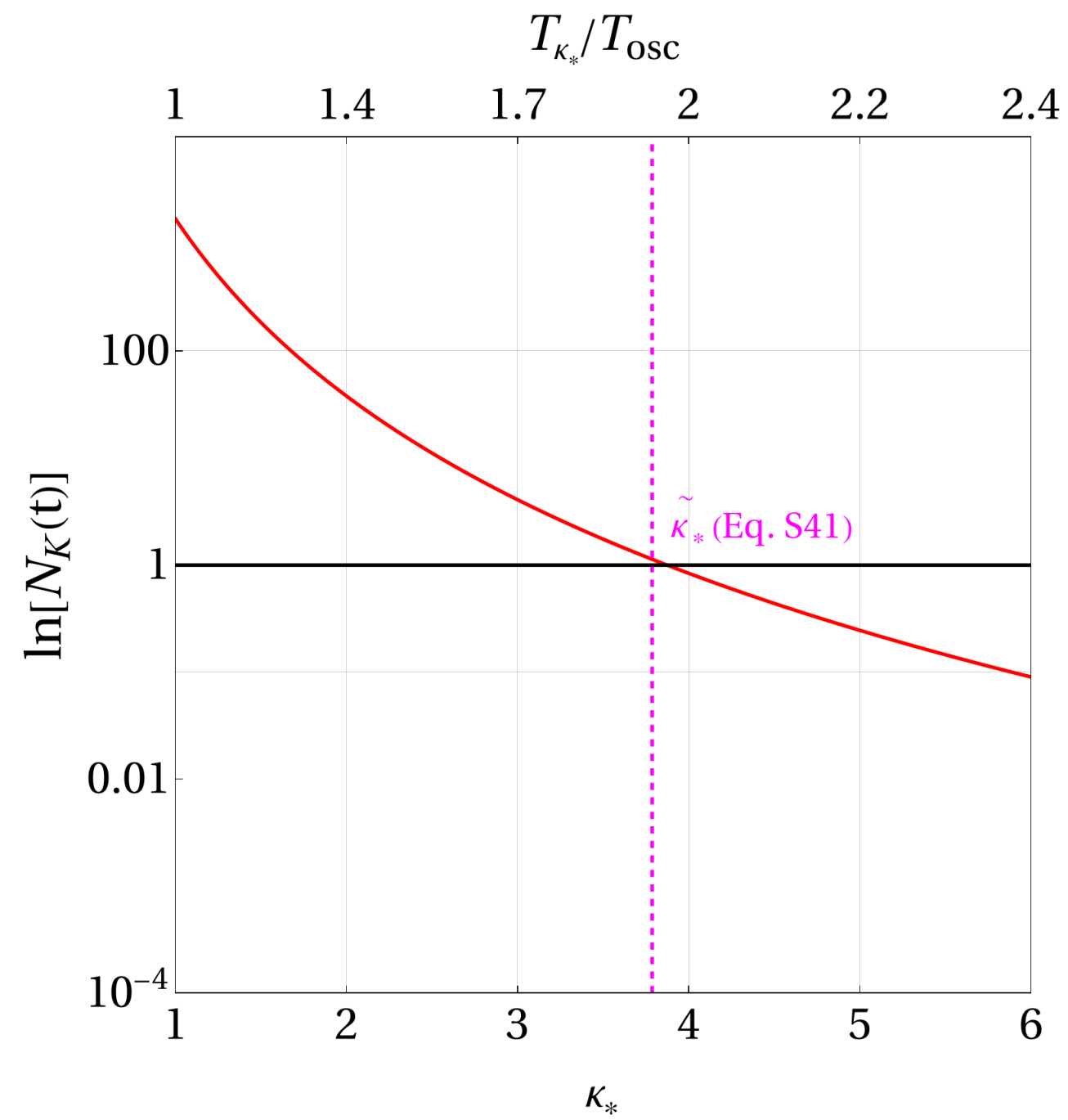
$$\rho_{\text{fl}} \ll \rho_\theta$$

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



Energy evolution





Sourced by tensor perturbations

$$ds^2 = a(\tau) \left[-d\tau^2 + (\delta_{ij} + h_{ij}) dx^i dx^j \right]$$

Transfer function

$$P_T(k) = r A_s(k_*) \left(\frac{k}{k_*} \right)^{n_T} \quad \Omega_{\text{GW}}(k) = \frac{1}{12 H_0^2} \left(\frac{k}{a_0} \right)^2 T_T^2(\tau_0, k) P_T(k)$$

Constrained from CMB

For single-field slow roll inflation models: $n_T = -r/8$

$$\Omega_{\text{GW}} h^2 \sim 10^{-16}$$

(too faint and scale-invariant...)

$$T_T^2(\tau_0, k) \text{ ?}$$