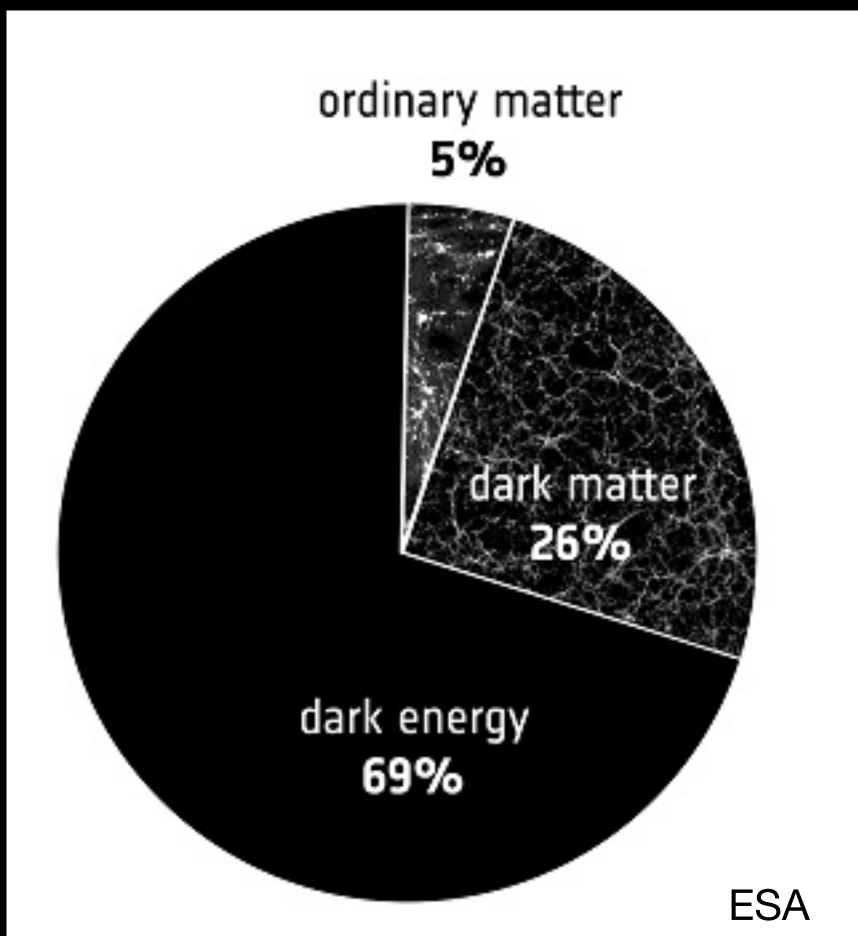
Dark World to Swampland:
9th IBS-IFT Workshop

Suruj Jyoti Das

Institute for Basic Science



Cogenesis by pNGB

Based on:
arXiv: 2406.04180

Collaborators:
Eung Jin Chun (KIAS),
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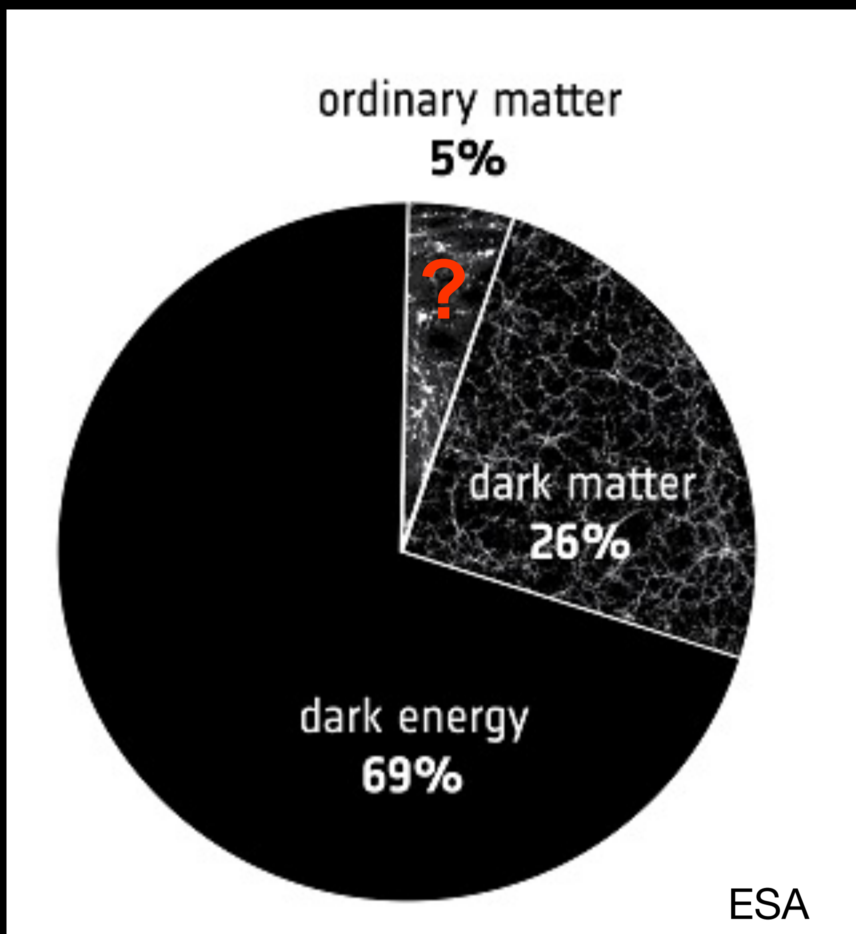

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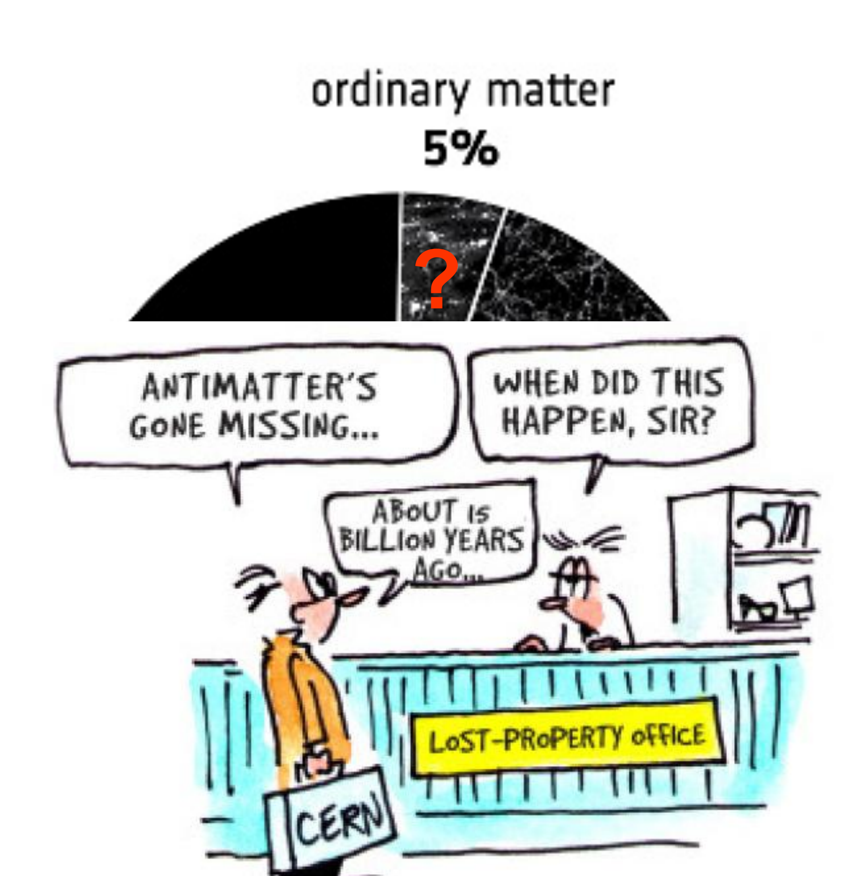

LHC Physics - CERN Bulletin

Cogenesis by pNGB

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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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Today's talk…..

- Introduction.
- Our idea of cogenesis.
- An explicit example.
- Summary.

How to generate asymmetry?

Conditions : Sakharov '67

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

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CPT is conserved

(Same energy levels for particles/anti-particles)

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How to generate asymmetry?

Conditions : Sakharov '67

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

} *CPT is conserved*

(Same energy levels for particles/anti-particles)

Spontaneous baryogenesis Kohen, Kaplan '87

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

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

- B,L violation in equilibrium.

Spontaneous Baryogenesis

- Energy shift of $\psi(\bar{\psi})$ by $\Delta E_{\psi(\bar{\psi})} \sim \pm c\dot{\theta}$
- In equilibrium $\Longrightarrow$ Chemical potential

$\theta = a/f_a$

$$\mu \propto \dot{\theta}$$

Spontaneous Baryogenesis

- Energy shift of $\psi(\bar{\psi})$ by $\Delta E_{\psi(\bar{\psi})} \sim \pm c\dot{\theta}$
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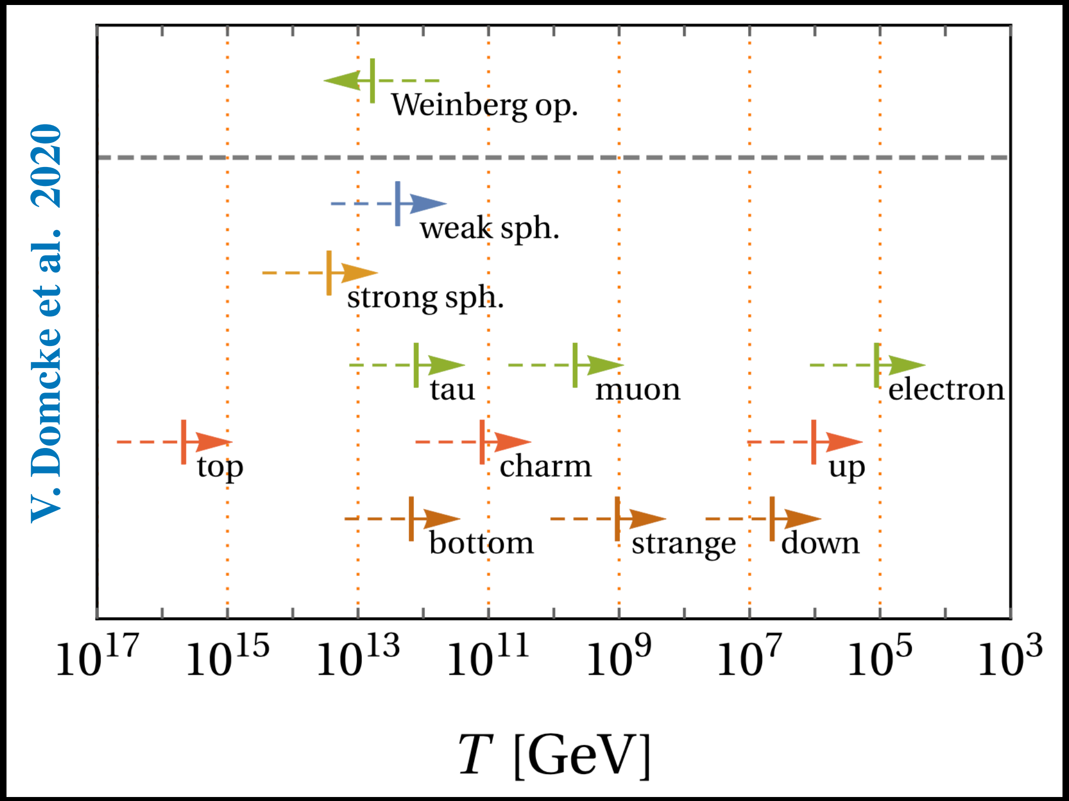
$$\mu \propto \dot{\theta}$$

Asymmetry redistributed

Interactions



Transport equation : $\dfrac{dn_i}{dt} =$ Creation terms - Annihilation terms + bias terms

i:Particle species

Spontaneous Baryogenesis

$$-\frac{d}{dlnT}\left(\frac{\mu_i}{T}\right) = -\frac{1}{g_i}\sum_\alpha n_i^\alpha \frac{\gamma_\alpha}{H}\left[\sum_j n_j^\alpha \left(\frac{\mu_j}{T}\right) - n_S^\alpha\left(\frac{\dot{a}/f}{T}\right)\right],$$

α:*Interactions*

V. Domcke et al. 2021

	T[GeV]	y_e	y_{ds}	y_d	y_s	y_{sb}	y_μ	y_c	y_τ	y_b	WS	SS	y_t
(v)	$(10^5, 10^6)$	q_e	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iv)	$(10^6, 10^9)$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iii)	$(10^9, 10^{11-12})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	✓	✓	✓	✓	✓	✓
(ii)	$(10^{11-12}, 10^{13})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	✓	✓
(i)	$(10^{13}, 10^{15})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	q_u	✓

$$q_X = n_X - n_{\bar{X}} = \mu_X T^2/6$$

#Conserved charges + # Interactions in equilibrium = # Particle species = 16 (in SM)

$$\boxed{\text{Final Asymmetry: } \frac{n_B}{s} \simeq \frac{\mu_B T^2}{s} \simeq c_B \frac{\dot{\theta}}{g_* T_B}}$$

c_B : *from transport eqns.*

at B,L violation decoupling

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So far....

$$\dot{\theta} \neq 0 \implies \text{Chemical potential} \implies \text{Asymmetry} \simeq \mathcal{O}(1)\frac{\dot{\theta}}{g_* T}$$

θ?

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

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θ?

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

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

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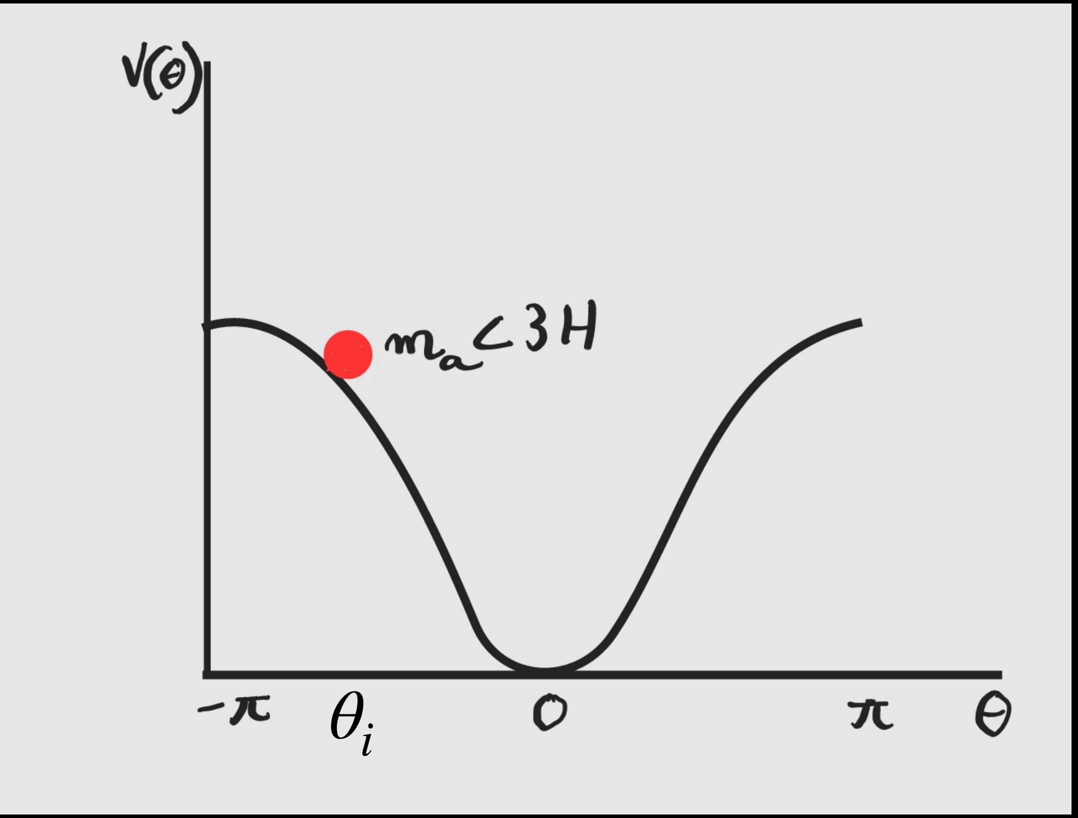
The Misalignment Mechanism

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

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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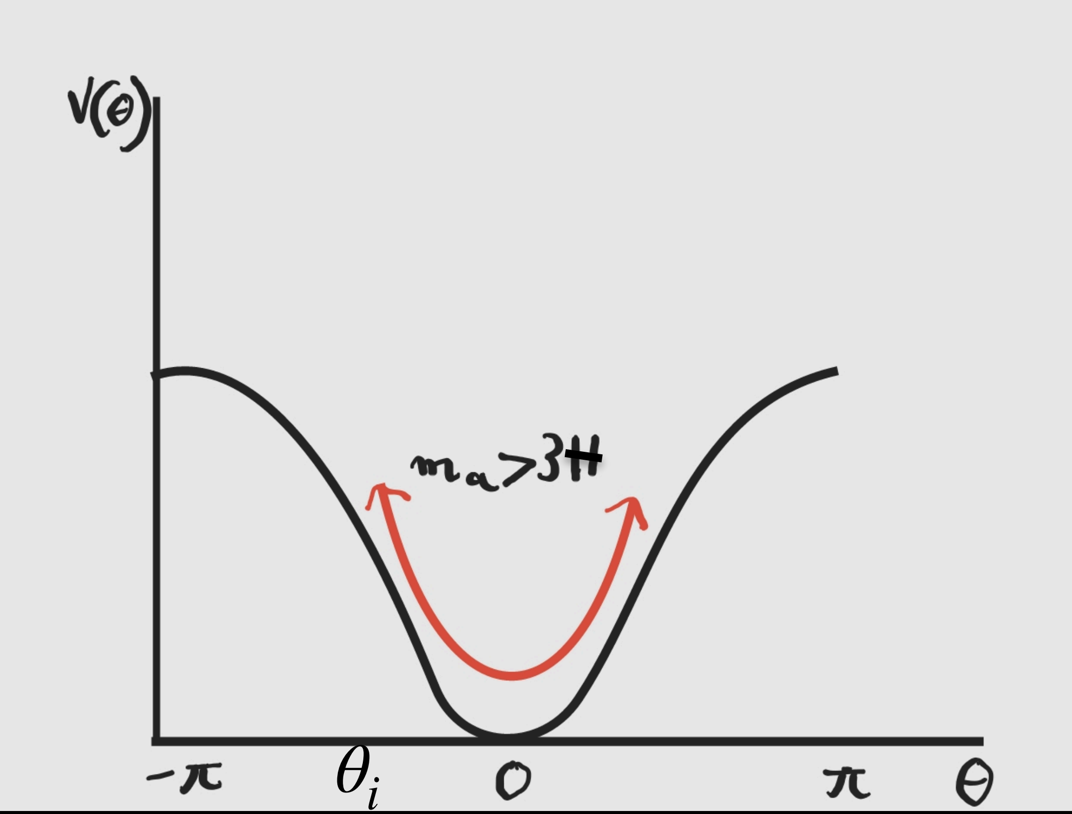


Oscillation:

- leads to non-zero

  $\dot{\theta}$ Asymmetry

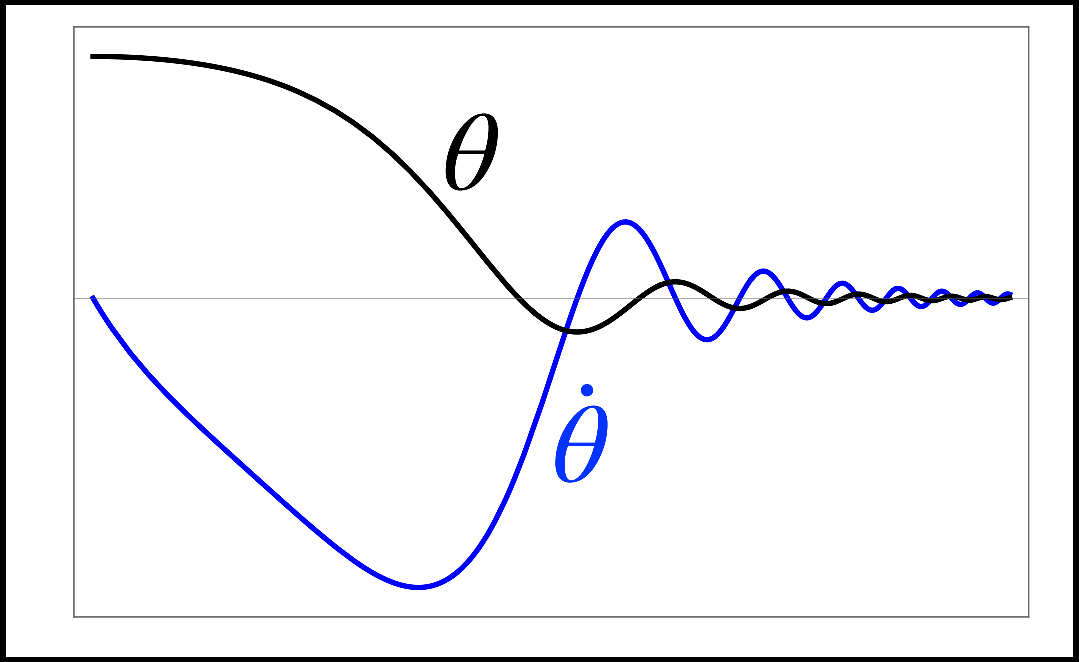
- Relic density

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

$$\sim \underbrace{\frac{1}{2} m_a^{(0)}}_{\text{Mass}} \underbrace{\theta_i^2 m_a^{\text{osc}} f_a^2}_{\text{No. density}} \underbrace{\left(\frac{a^{\text{osc}}}{a^{(0)}}\right)^3}_{\text{Redshift}}$$

Cogenesis in the conventional misalignment ?

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



Asymmetry:

$$\Longrightarrow \quad T_B \simeq T_{\rm osc} \simeq \sqrt{m_a M_P}$$

For $Y_B^{\rm observed} \sim \dfrac{\dot{\theta}}{g_* T_{\rm osc}} \sim \dfrac{\sqrt{m_a}}{g_* \sqrt{M_P}} \sim 10^{-10}$

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

$$\Downarrow$$

DM: $\dfrac{\rho_{\rm DM}}{s} \sim \dfrac{m_a^2 f_a^2}{s} \sim \dfrac{m_a^{1/2} f_a^2}{g_* M_P^{3/2}} \gg 0.44$ eV (observed)

Way out:

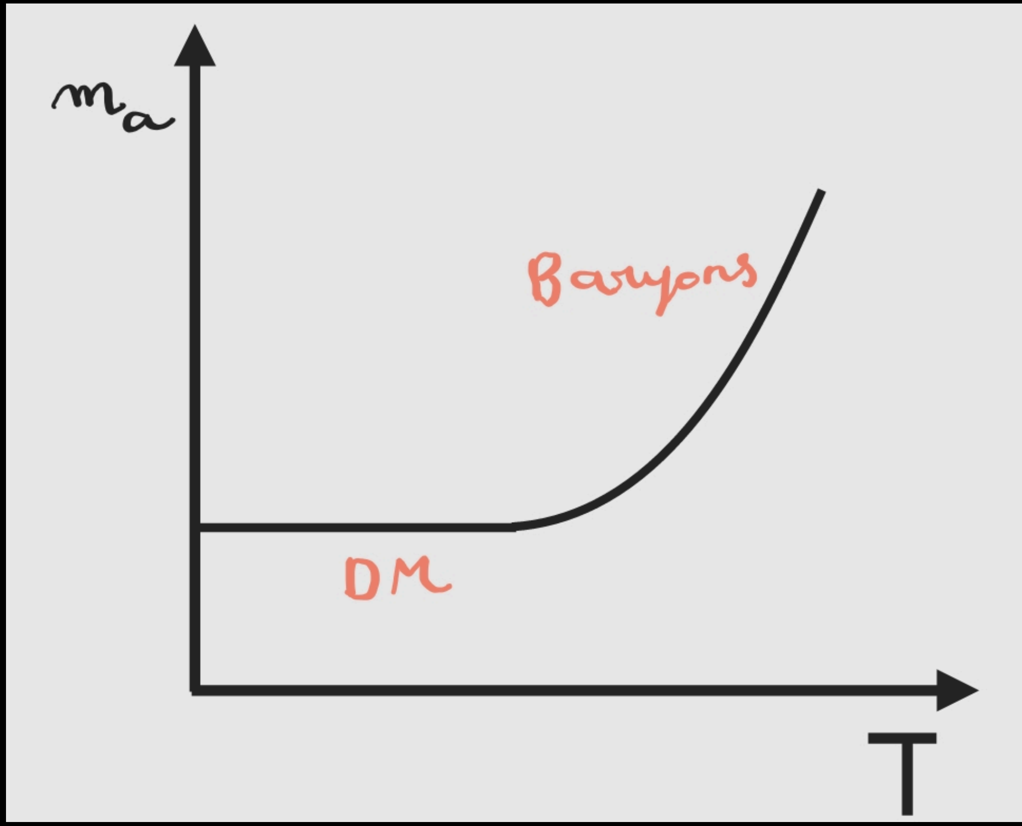
Early dynamics with $m_a(T) \gg m_a^{(0)}$

Separate out $T_B \gg T_{\rm osc}$

Our idea

- m_a and f_a time-dependent.

$$\Downarrow$$



- $\dot{\theta}/T$ large enough before $T_{osc.}$
- Baryogenesis at $T_B > T_{osc.}$
- Oscillation at low temperature : DM.

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The Setup

- 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):

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

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

$$\Downarrow$$

- Mass of pNGB:

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

How to realize f_a (T)?

Symmetry non-restoration

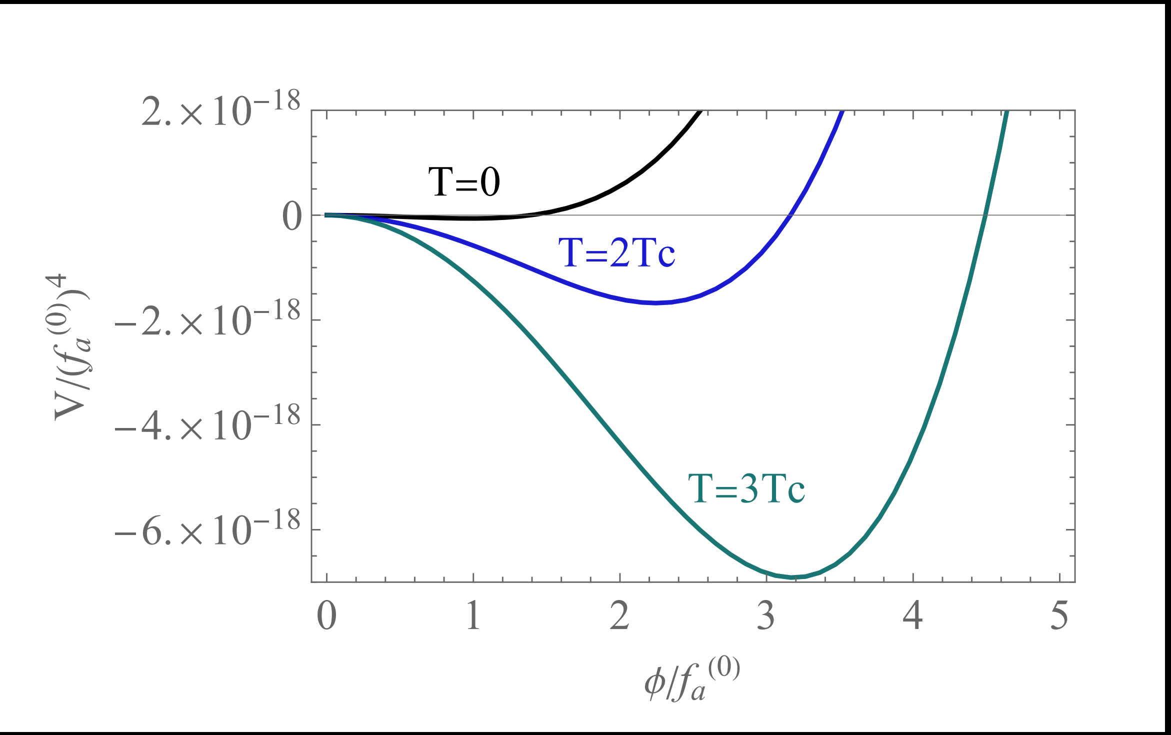
(S. Weinberg 1974)

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

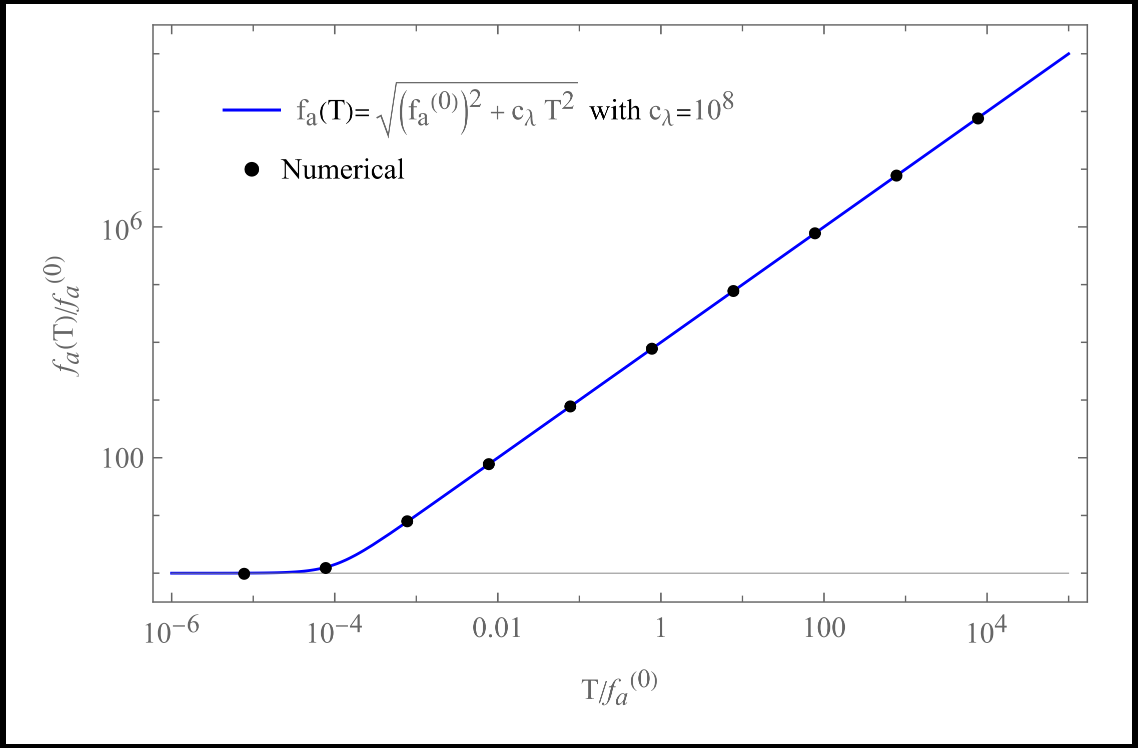


Symmetry non-restoration

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

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

$\lambda_{\rm mix} \equiv \lambda_{h\phi} + \sum_i \lambda_{\phi s_i}/4$



For $T > T_c \equiv f_a^{(0)} / \sqrt{c_\lambda}$

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

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Symmetry non-restoration

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

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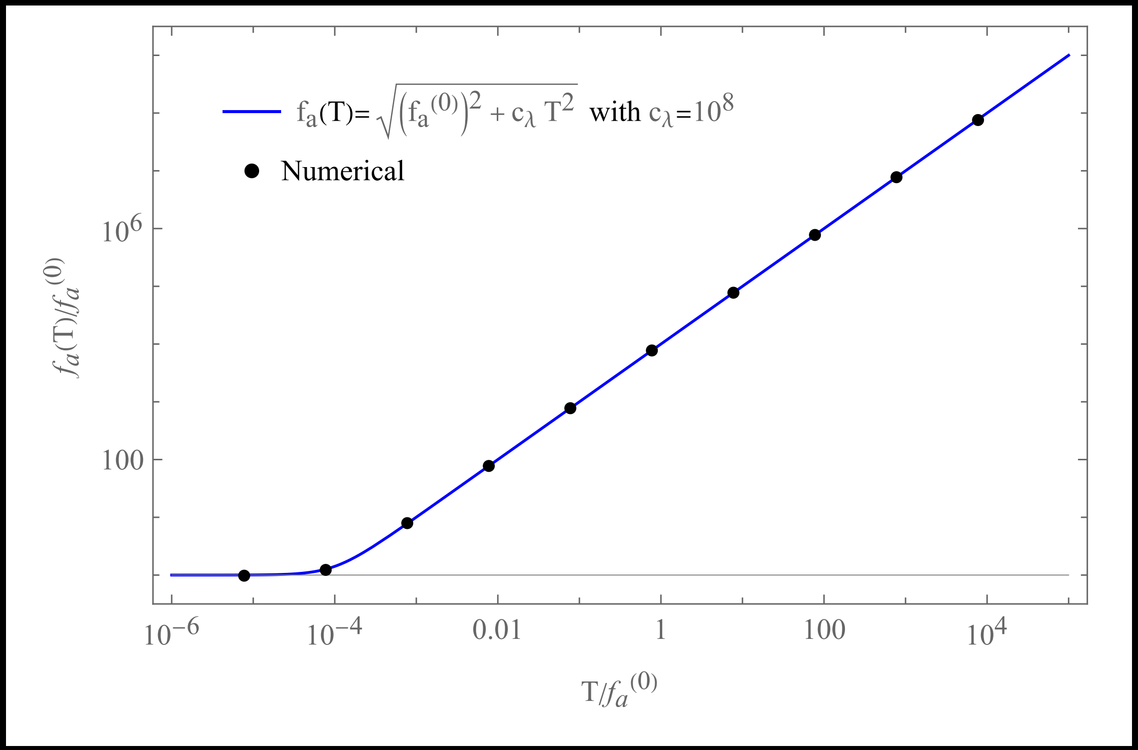

For $T > T_c \equiv f_a^{(0)} / \sqrt{c_\lambda}$

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

$$\phi\phi \leftrightarrow aa \propto \frac{T^2}{f_a^4} \implies \boxed{c_\lambda \gtrsim 10^7}$$

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pNGB Dynamics (n=5)

Modified E.O.M. :

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

$$-H$$

pNGB Dynamics (n=5)

Modified E.O.M. :

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

$$2\frac{\dot{f}_a}{f_a} \rightarrow -H$$

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

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

$\rightarrow$ constant

pNGB is frozen

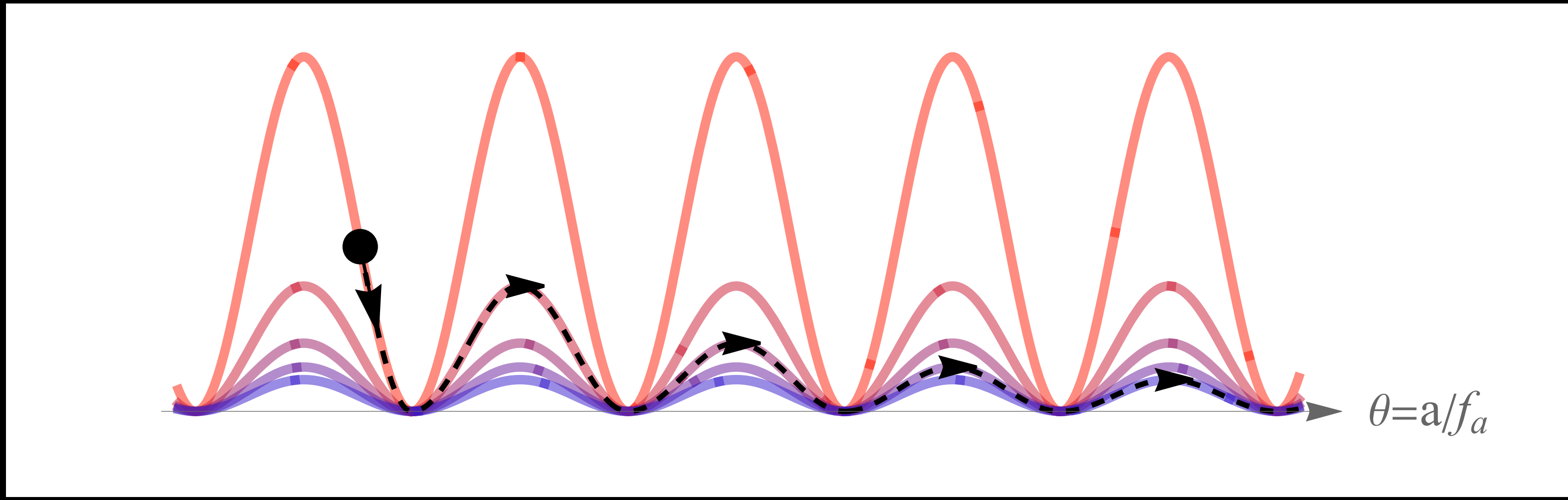
until….

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

2nd epoch: T < T_0

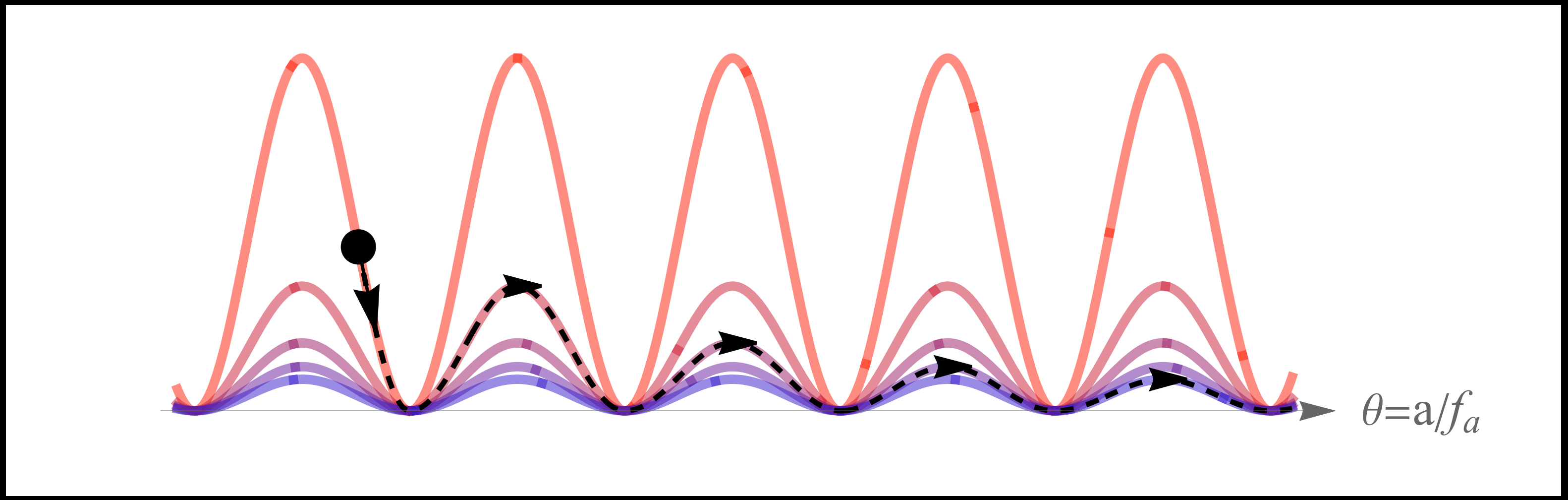
Oscillation?

pNGB slides



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

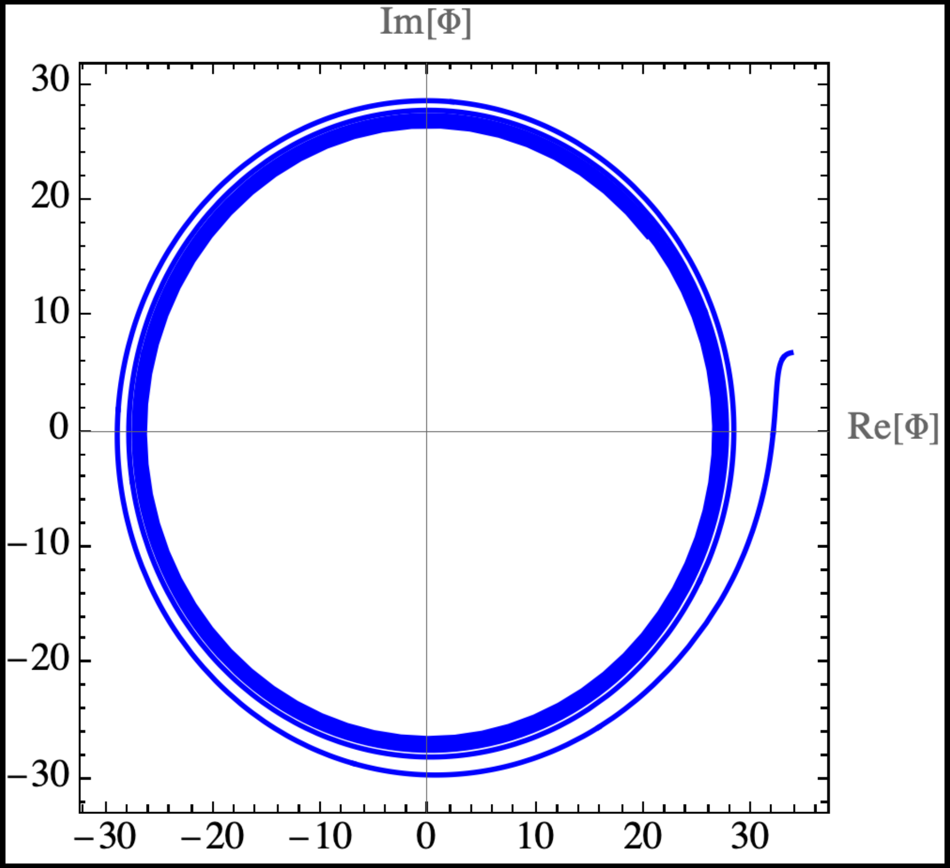
pNGB slides



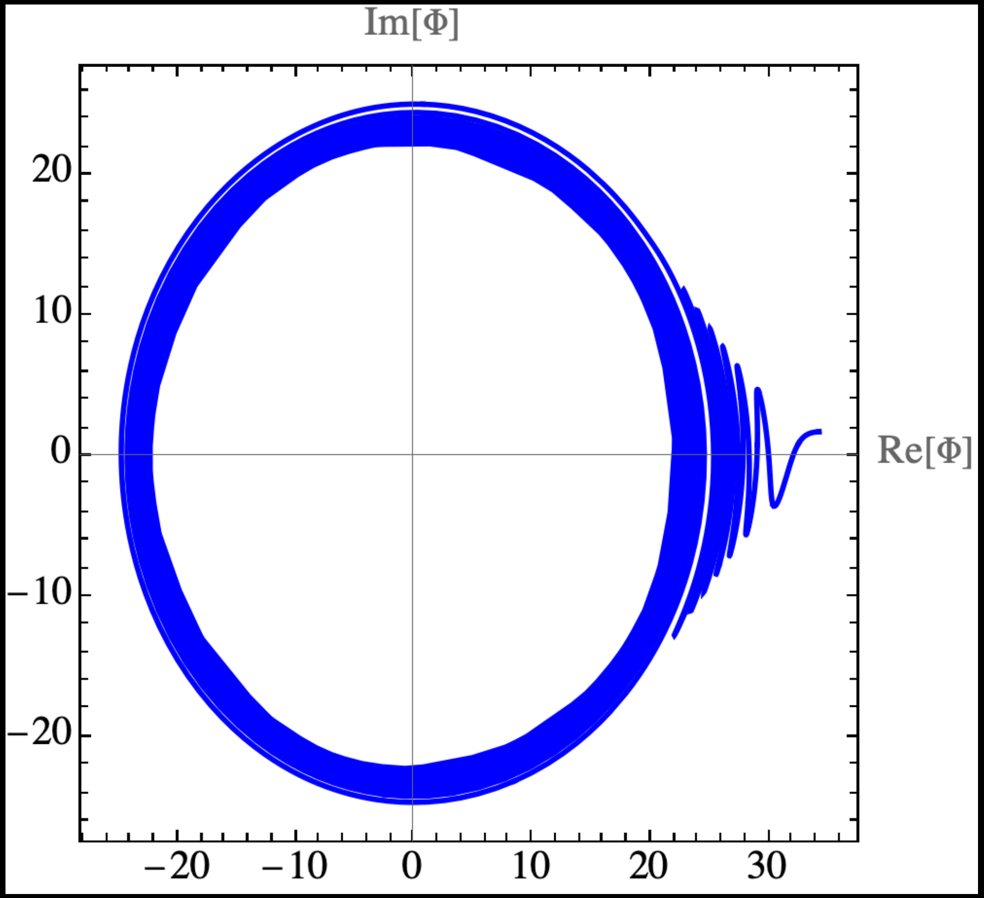
K.E. = Barrier $\Longrightarrow$ $\dot{\theta}(T_{\rm slide}) \simeq \frac{2}{5} m_a(T_{\rm slide})$

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

$5\theta_i = 1$



$5\theta_i = 0.25$



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

Gives asymmetry

From Spontaneous Baryo.

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

Gives asymmetry

From Spontaneous Baryo.

3rd epoch: T < T_c

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

$f_a(T)$ **saturates**

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

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

Gives asymmetry

From Spontaneous Baryo.

3rd epoch: **T < T$_c$**

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

$f_a(T)$ 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

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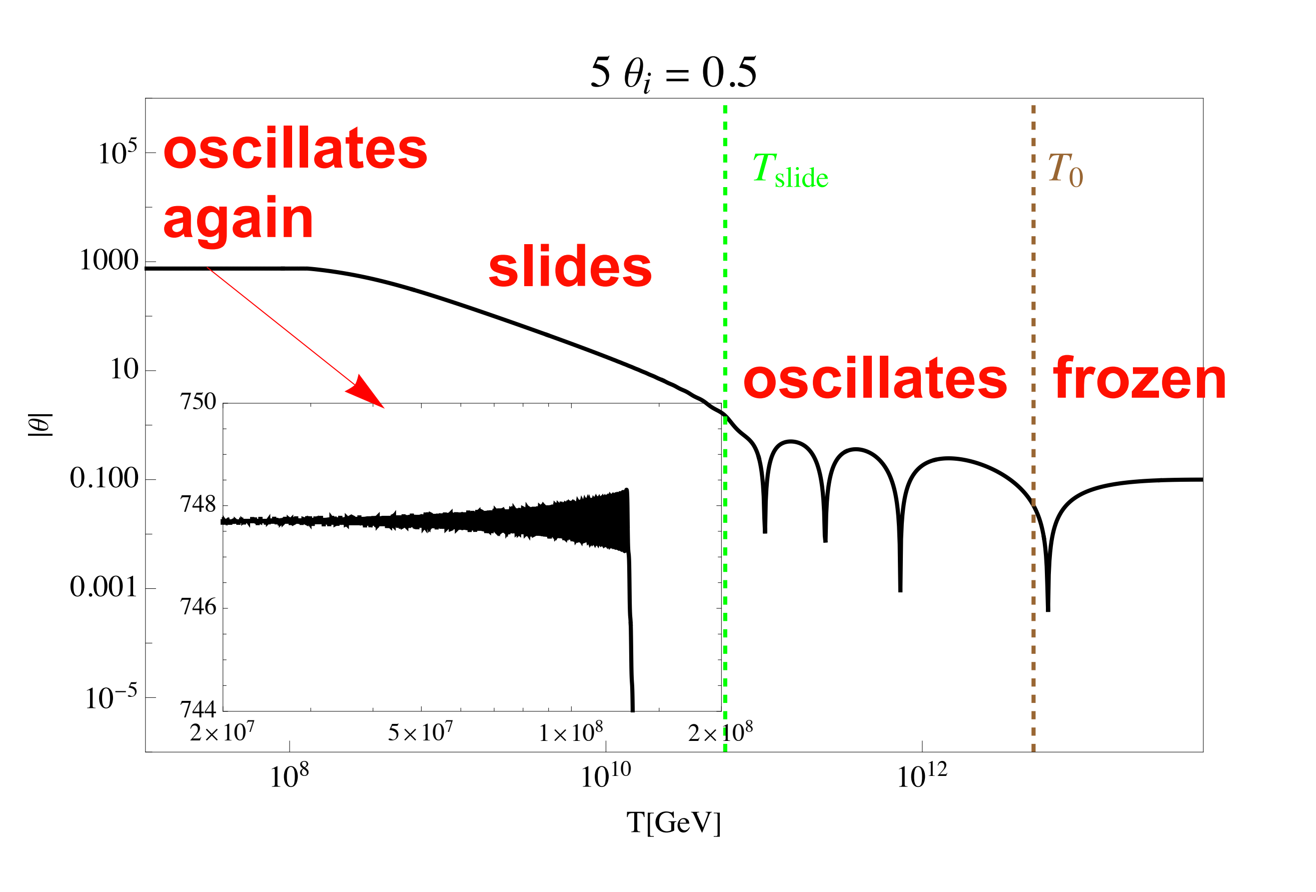
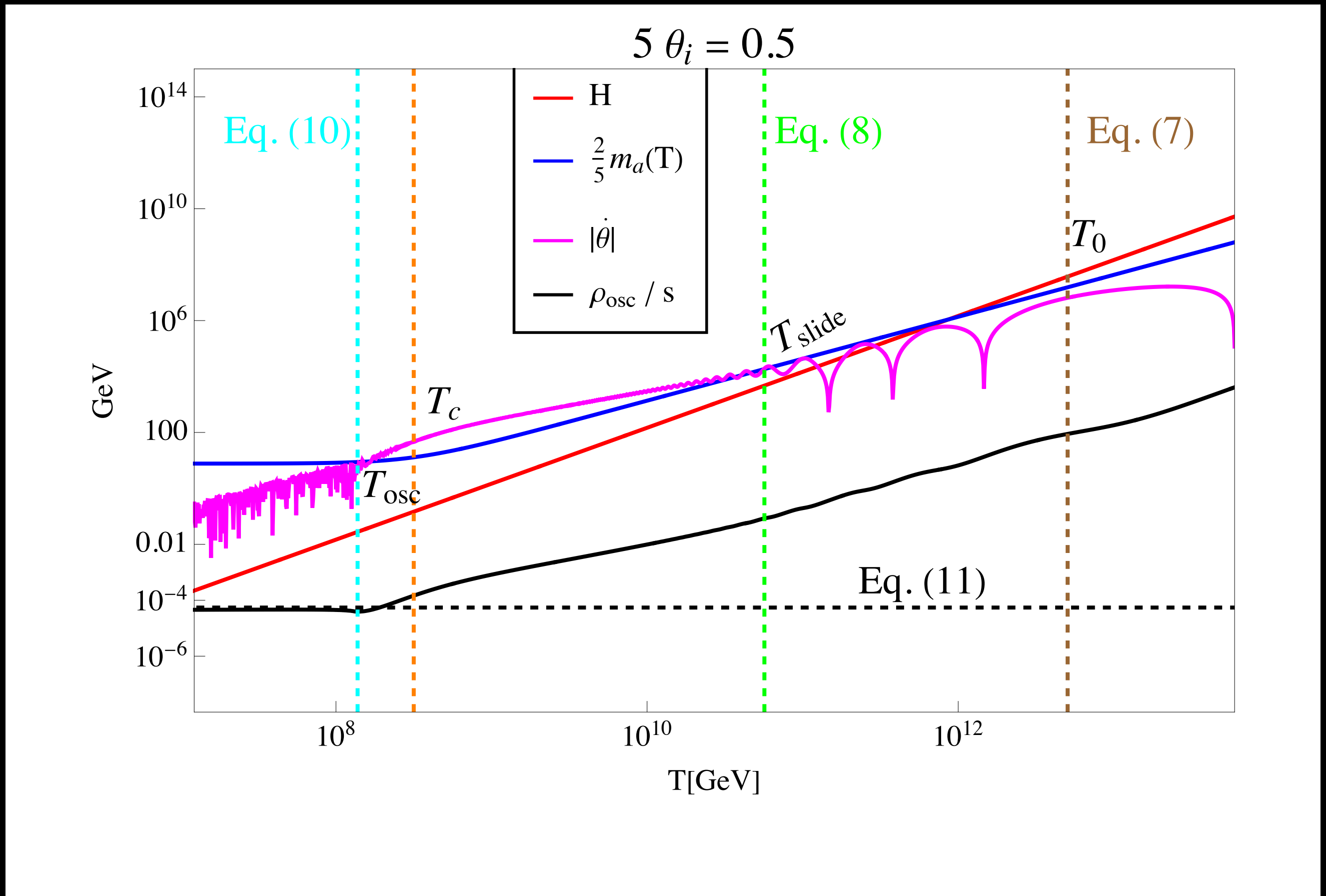
Numerical analysis:





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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:

$$M_N(T) \sim y\sqrt{c_\lambda}T$$

$$M_N^{(0)} \sim y f_a^{(0)} \sim T_c$$

- Lepton no. violating inverse decays (ID) in equilibrium.
- Asymmetry freezes out at sphaleron decoupling or ID decoupling.

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An Explicit Example (Type I seesaw)

Equilibrium conditions:

for $T \lesssim 10^5\text{GeV}$

$$\gamma_{Y_{u_i}} : \hat{\mu}_{q_i} + \hat{\mu}_{u_i^c} + \hat{\mu}_H = 0$$

$$\gamma_{Y_{d_i}} : \hat{\mu}_{q_i} + \hat{\mu}_{d_i^c} - \hat{\mu}_H = 0$$

$$\gamma_{Y_{e_i}} : \hat{\mu}_{\ell_i} + \hat{\mu}_{e_i^c} - \hat{\mu}_H = 0$$

$$\gamma_{EWS} : \sum_j \left(\hat{\mu}_{\ell_j} + 3\hat{\mu}_{q_j} \right) = 0$$

$$\gamma_{SS} : \sum_j \left(2\hat{\mu}_{q_j} + \hat{\mu}_{u_j^c} + \hat{\mu}_{d_j^c} \right) = 0$$

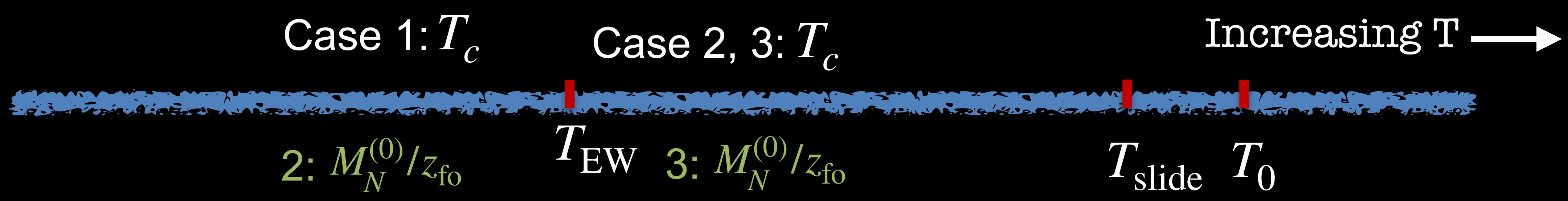
L-violation $\gamma_{Y_{ID}} : \hat{\mu}_{\ell_i} + \hat{\mu}_H - \frac{\dot{\theta}}{2T} = 0$

+

Hypercharge Y= 0

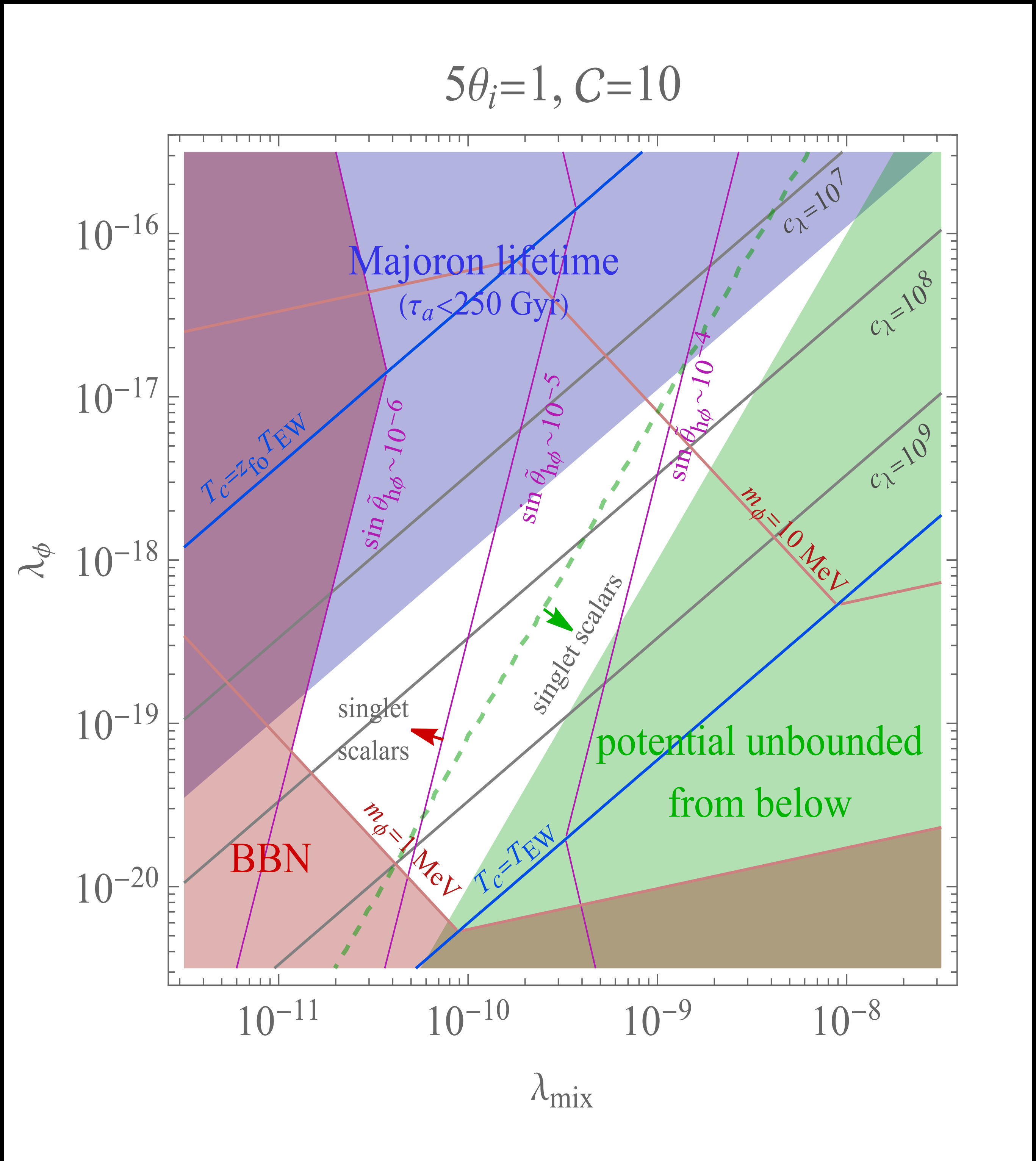
$$\hat{\mu}_{\mathrm{B-L}} = -\frac{79}{22}\frac{\dot{\theta}}{T}$$

An Explicit Example (Type I seesaw)



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

Predictions(for Majoron):

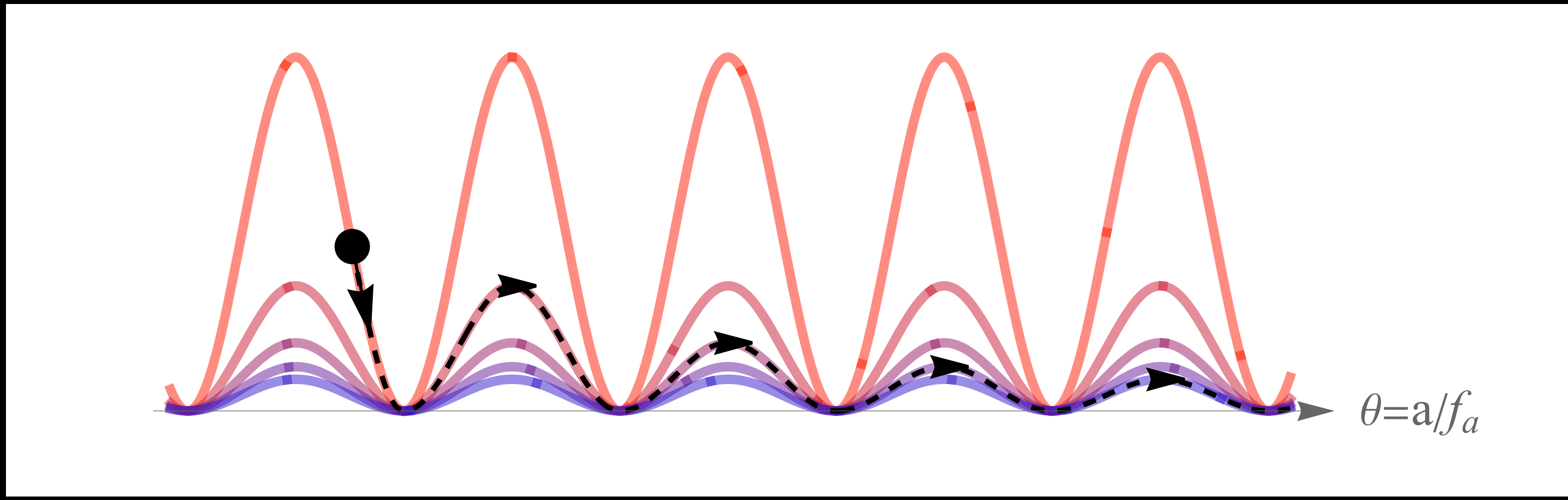


The Cogenesis Window

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

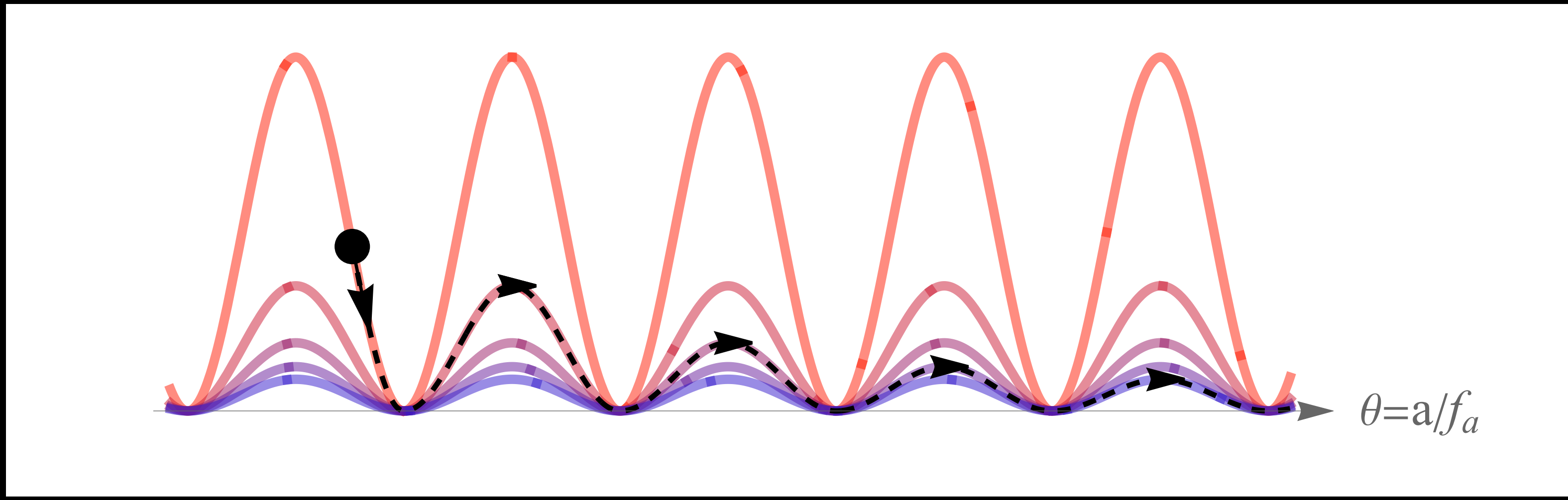
$$f_a^{(0)} = 3\times 10^6\text{ GeV}\, C^{1/18}(5\theta_i)^{2/9}\left(\frac{100}{g_*}\right)^{1/6}\left(\frac{c_\lambda}{10^8}\right)^{5/18}$$

Summary



- Conventional misalignment *can give* baryon and DM abundance.
- Baryon asymmetry at high temperatures during sliding, DM at low temperatures during oscillation.
- Can be realized for Majoron, with specific predictions.
- Testable at kaon experiments, colliders….
- Can be extended for other D-operators, other models..

Summary



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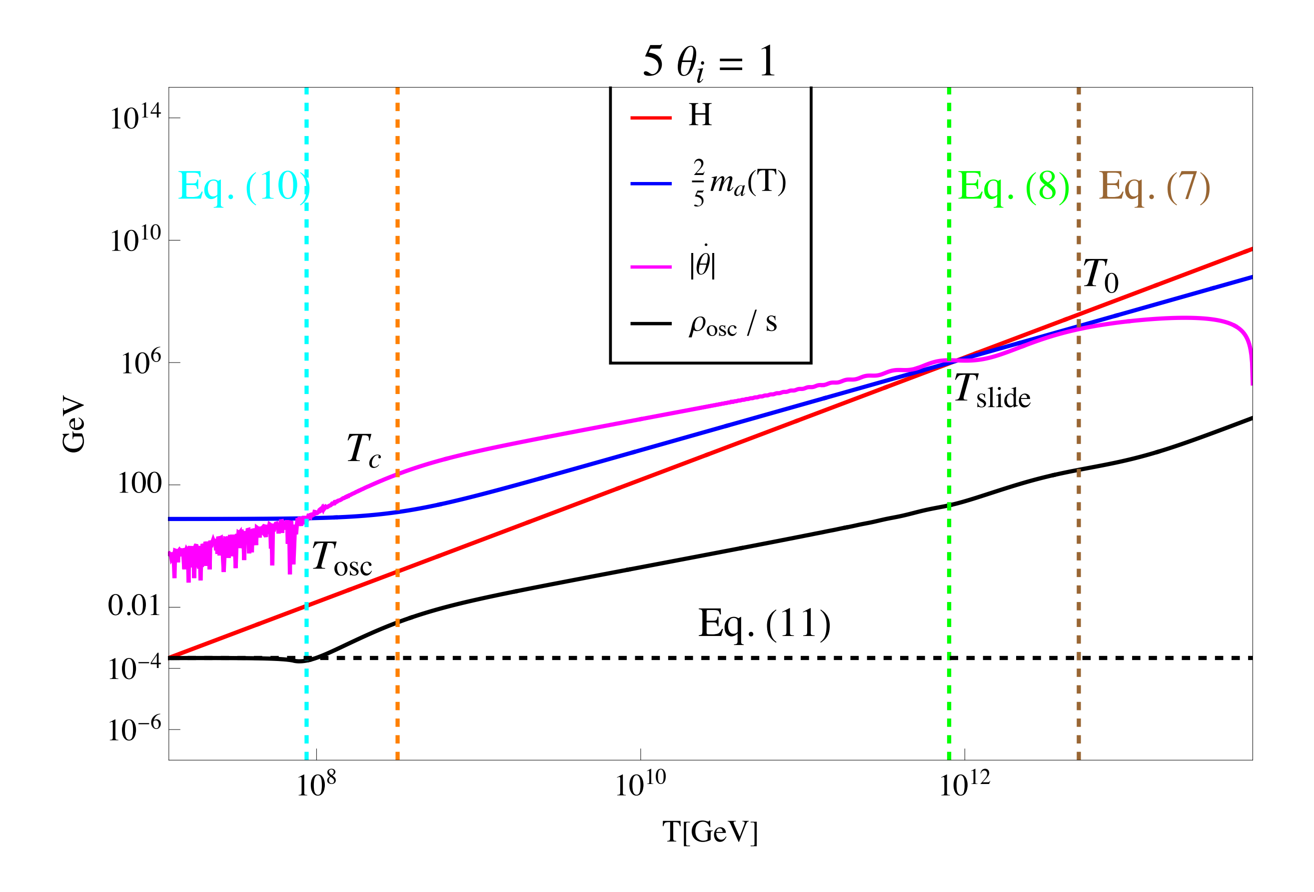
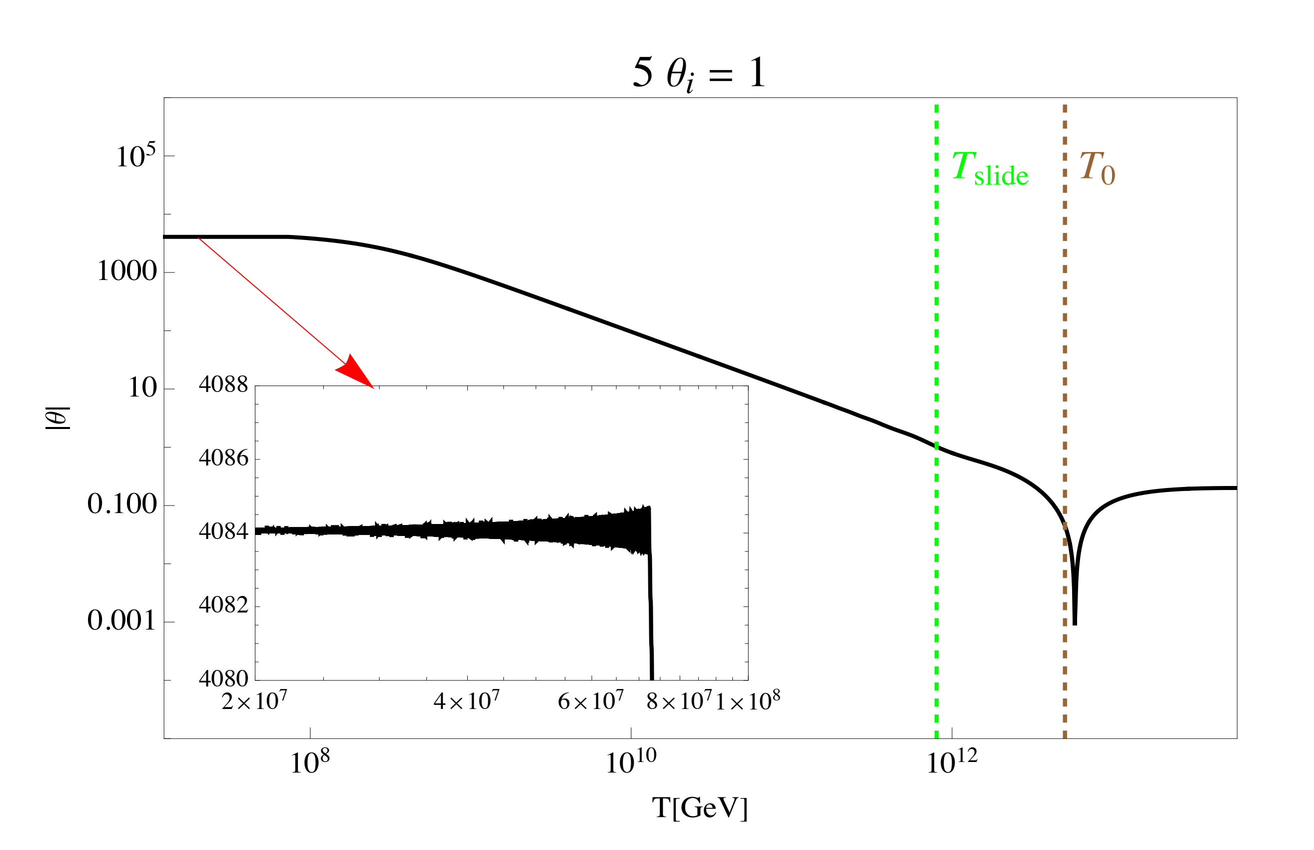
THANK YOU

BACK UP

Numerical analysis:





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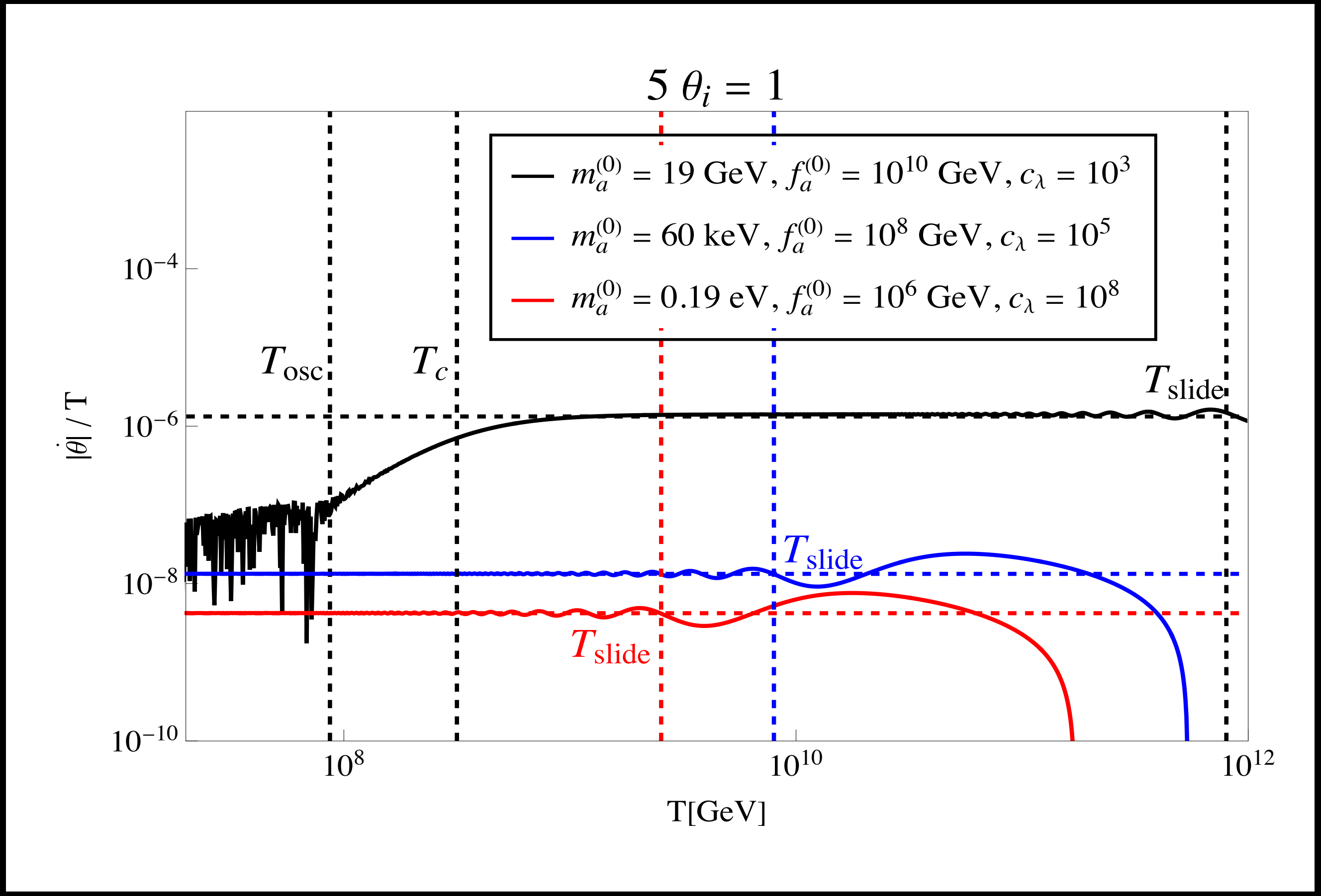
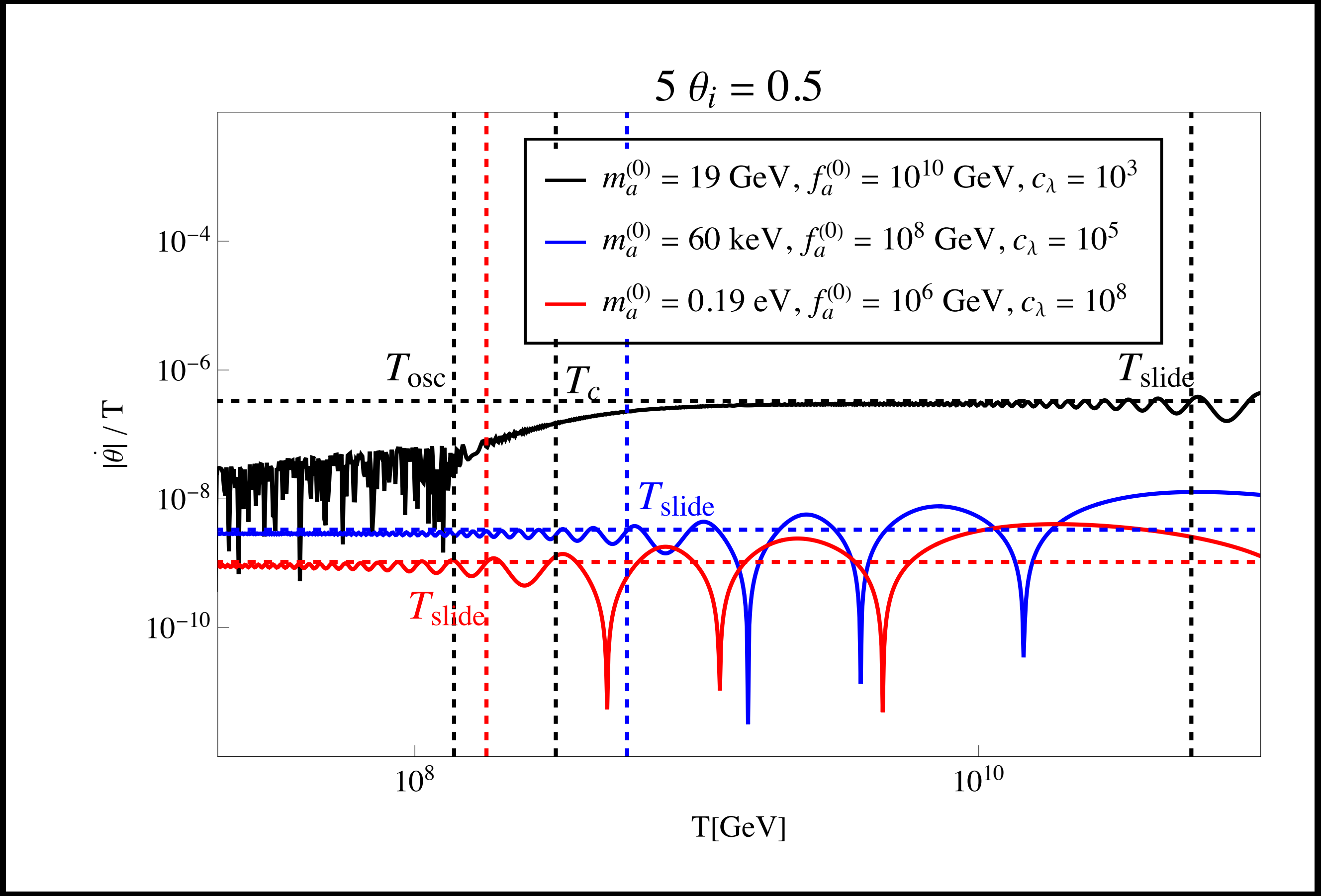

5 $\theta_i = 1$
$m_a^{(0)}$ = 19 GeV, $f_a^{(0)}$ = 10^{10} GeV, c_λ = 10^3
$m_a^{(0)}$ = 60 keV, $f_a^{(0)}$ = 10^8 GeV, c_λ = 10^5
$m_a^{(0)}$ = 0.19 eV, $f_a^{(0)}$ = 10^6 GeV, c_λ = 10^8
$T_{\rm osc}$
T_c
$T_{\rm slide}$
$T_{\rm slide}$
$T_{\rm slide}$
$|\dot{\theta}|$ / T
10^{-4}
10^{-6}
10^{-8}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


5 $\theta_i = 0.5$
$m_a^{(0)}$ = 19 GeV, $f_a^{(0)}$ = 10^{10} GeV, c_λ = 10^3
$m_a^{(0)}$ = 60 keV, $f_a^{(0)}$ = 10^8 GeV, c_λ = 10^5
$m_a^{(0)}$ = 0.19 eV, $f_a^{(0)}$ = 10^6 GeV, c_λ = 10^8
$T_{\rm osc}$
T_c
$T_{\rm slide}$
$T_{\rm slide}$
$T_{\rm slide}$
$|\dot{\theta}|$ / T
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^8
10^{10}
T[GeV]

Potential stability: