Cogenesis by a sliding pNGB with global symmetry non-restoration

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Contents

Baryon asymmetry of the Universe

Observation: Our universe is made of matter, not antimatter.

$T_{BBN} \sim \mathrm{MeV}$

$T_{\mathrm{deu}} \sim 2\ \mathrm{MeV}/(\ln \eta_B^{-1})$

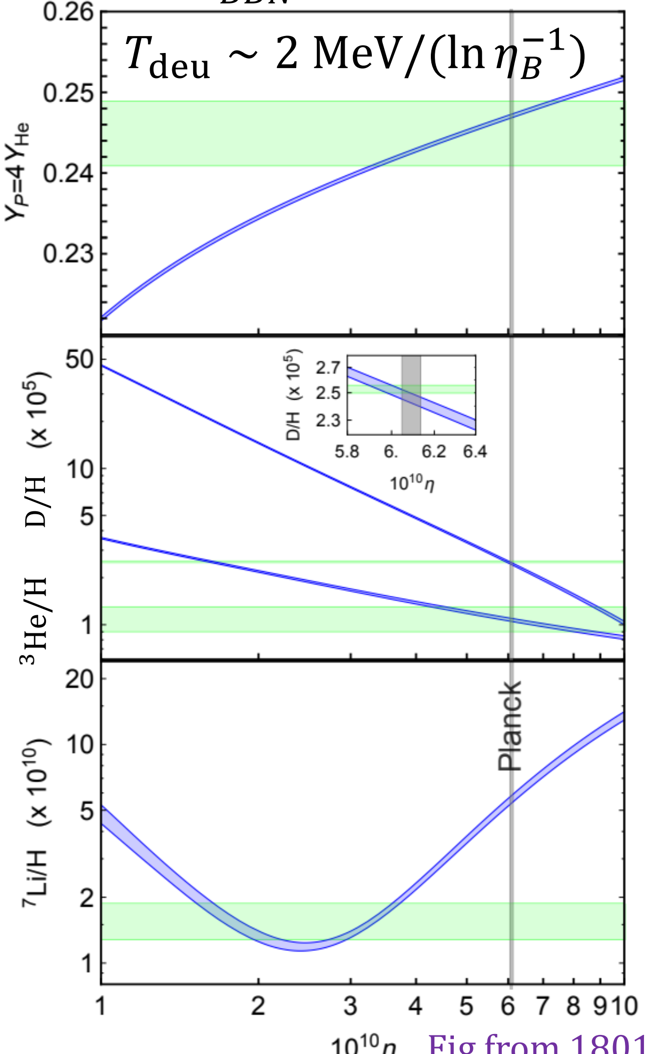
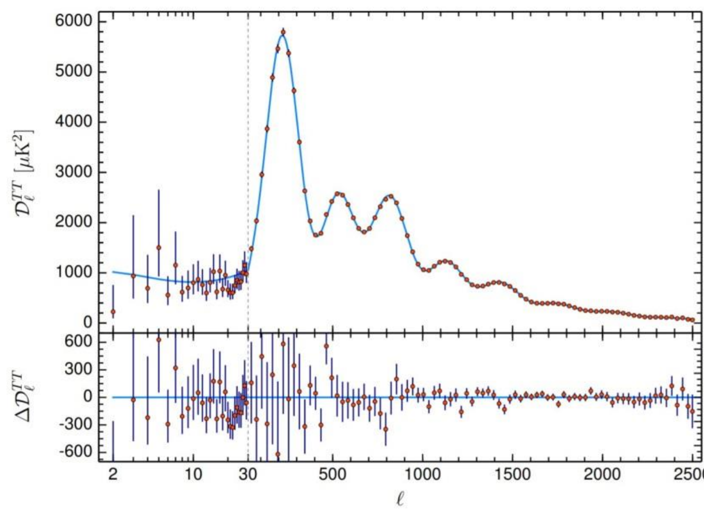


Fig from 1801.08023

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10}$$

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = 9 \times 10^{-11}$$

→ **Consistent with CMB fitting**



Planck 2018

$Y_B \sim 10^{-10}$ should be produced before BBN, **somehow**.

(main topic of this talk)

To generate baryon asymmetry...

<u>Sakharov conditions</u>

- **B number changing process**
  obvious

- **C and CP violation**
  no net effect if any of them is conserved

$$\begin{tikzcd}
\text{LH } B \arrow[d, leftrightarrow] \arrow[dr, leftrightarrow] & \text{RH } B \arrow[d, leftrightarrow] \\
\text{LH } \bar{B} \arrow[ur, leftrightarrow] & \text{RH } \bar{B}
\end{tikzcd}$$

- **Departure from thermal equilibrium**

$$\left(n_B = \sum_q \int \frac{d^3p}{(2\pi)^3} f_q(p)\right) = \left(n_{\bar{B}} = \sum_{\bar{q}} \int \frac{d^3p}{(2\pi)^3} f_{\bar{q}}(p)\right)$$

<u>In SM</u>

Weak sphaleron
SU(2) Chern-Simons number transition
$\rightarrow B + L$ transition

C violation: electroweak interaction
CP violation: CKM matrix (not enough)

EWPT (cross-over… not enough)
Some freeze-out process (… not enough)

We need new physics.
(there are many scenarios)

To generate baryon asymmetry...

Sakharov conditions

- **B number changing process**
  obvious

- **C and CP violation**
  no net effect if any of them is conserved

$$\begin{tikzcd}
\text{LH } B \arrow[d, leftrightarrow] \arrow[rd, leftrightarrow] & \text{RH } B \arrow[d, leftrightarrow] \arrow[ld, leftrightarrow] \\
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- **~~Departure from~~ thermal equilibrium**

$$\left(n_B = \sum_q \int \frac{d^3p}{(2\pi)^3} f_q(p)\right) \neq \left(n_{\bar{B}} = \sum_{\bar{q}} \int \frac{d^3p}{(2\pi)^3} f_{\bar{q}}(p)\right)$$

In SM

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Spontaneous baryogenesis/leptogenesis (Cohen, Kaplan, 87, 88)
$f_q \neq f_{\bar{q}}$ in the presence of CPT violation (due to background field dynamics)

Spontaneous baryogenesis/leptogenesis

- **Consider a pseudo-scalar field a with a current interaction**

$$L = \cdots + \frac{\partial_\mu a}{f_a}\,\psi^\dagger \bar{\sigma}^\mu \psi$$

$$(\psi^\dagger \bar{\sigma}^0 \psi = n_\psi - n_{\bar{\psi}})$$

and its homogenous motion:

$$\theta \equiv \frac{a}{f_a}, \qquad \dot{\theta} \neq 0 \;\Rightarrow\; H = \cdots - \int d^3x\,\dot{\theta}\,(n_\psi - n_{\bar{\psi}}) = \cdots - \dot{\theta}\,Q_\psi$$

$$\boxed{\Rightarrow \langle n_\psi - n_{\bar{\psi}} \rangle \sim \int dp\,p^2 \left(e^{-(E-\dot{\theta})/T} - e^{-(E+\dot{\theta})/T} \right) \sim c_\psi \dot{\theta}\,T^2}$$

- **Chemical equilibration (Charge transportation)**

Depending on what interactions are in the thermal bath, there are a series of chemical equilibrations, i.e. asymmetry re-distribution.

e.g. Top quark Yukawa $\rightarrow \mu_{q_3} + \mu_{t^c} + \mu_H = 0$

EW sphaleron $\rightarrow \sum_i (3\mu_{q_i} + \mu_{l_i}) = 0$

…

$$\frac{\mu_i}{T} \sim \frac{n_i - n_{\bar{i}}}{n_i + n_{\bar{i}}}$$

- **Scenario is specified by**
  - ✓ How its motion ($\dot{\theta} \neq 0$) is generated

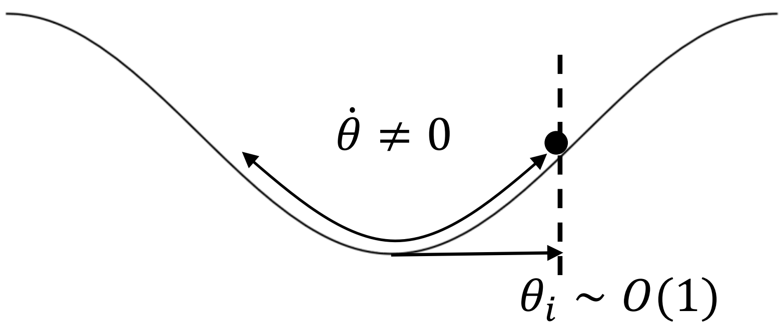
  e.g. coherent oscillation, kinetic misalignment, first-order phase transition, etc.

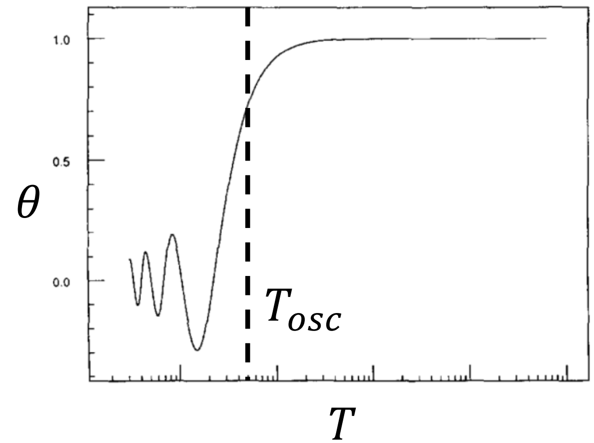
An example

Misalignment mechanism

Cohen, Kaplan, 87

- θ was stuck at O(1) initial misalignment angle, and starts oscillation when $H(T_{osc}) = m_a$.



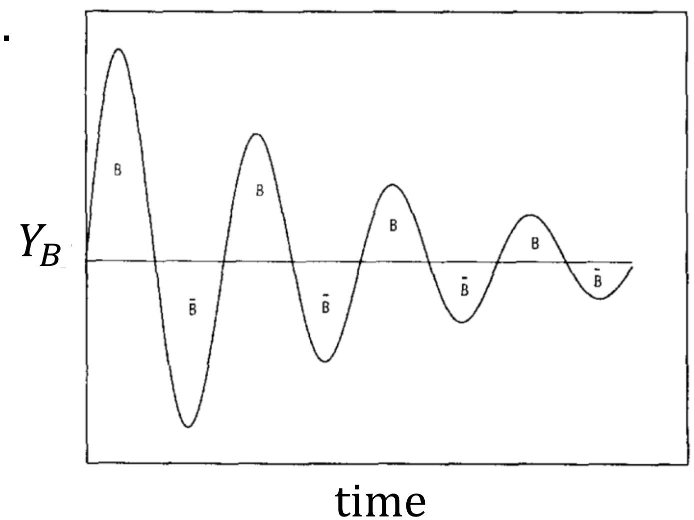


- $\dot{\theta}$ acts as a source term in the Boltzmann equation.

$$\dot{n}_B + 3H\, n_B = -\Gamma_B (n_B - c_B \dot{\theta}\, T^2)$$

$\downarrow$

T_{B*}: decoupling temperature of Γ_B



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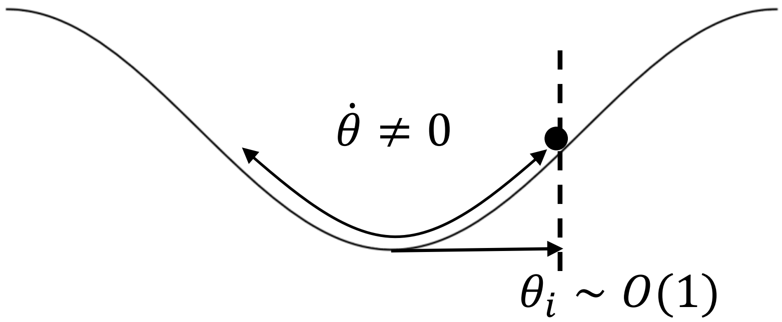

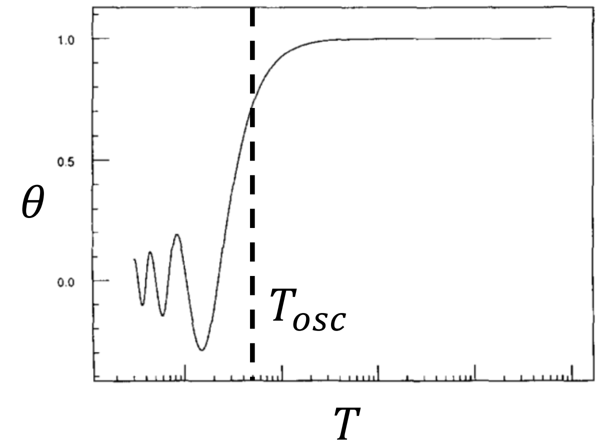

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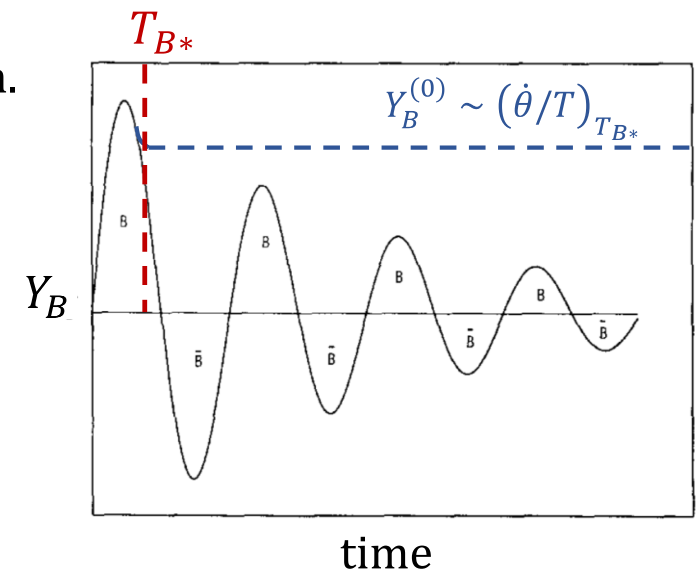

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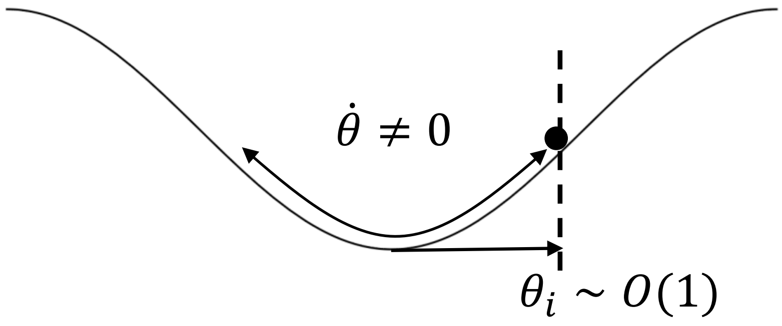

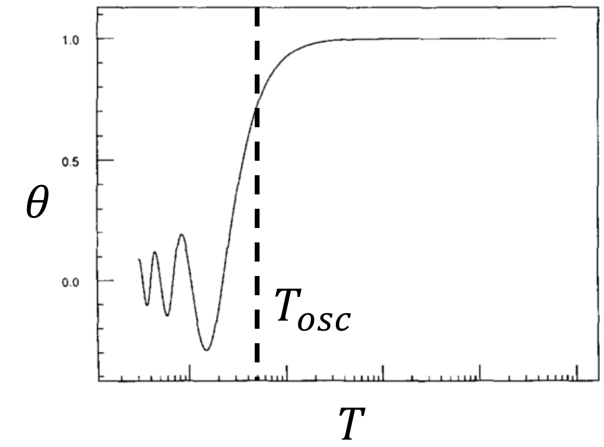

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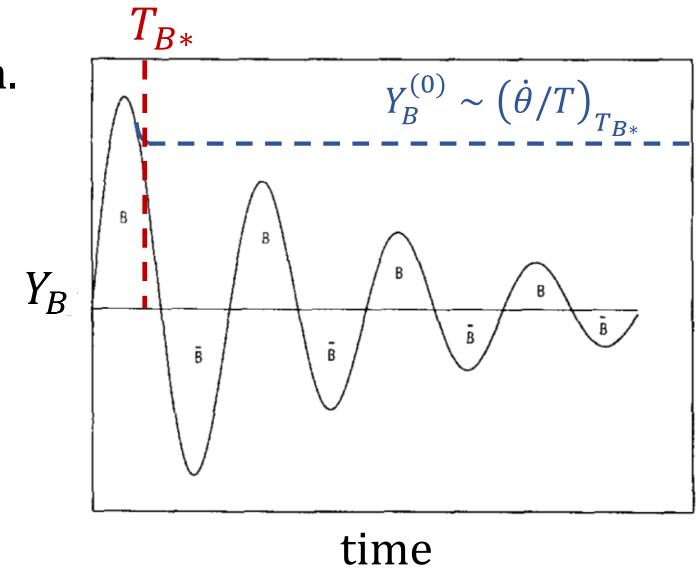


- **Q: can $\boldsymbol{\theta}$-oscillation also be DM?**

Is “co”genesis possible for standard misalignment?

Quick estimation

$$Y_B^{(0)} = \frac{n_B}{s}\Big|_{T_{B*}} \sim \frac{\dot{\theta}(T_{B*})}{g_* T_{B*}} \lesssim \frac{m_a}{g_* T_{osc}} \sim \frac{1}{g_*}\sqrt{\frac{m_a}{M_{\rm pl}}} \quad \Rightarrow \quad \begin{array}{c} \boldsymbol{m_a \gtrsim 100\ \mathrm{GeV}} \\ \boldsymbol{T_{osc} \gtrsim 10^{10}\ \mathrm{GeV}} \\ f_a \gg T_{osc} \end{array}$$

$\sim 10^{-10}$

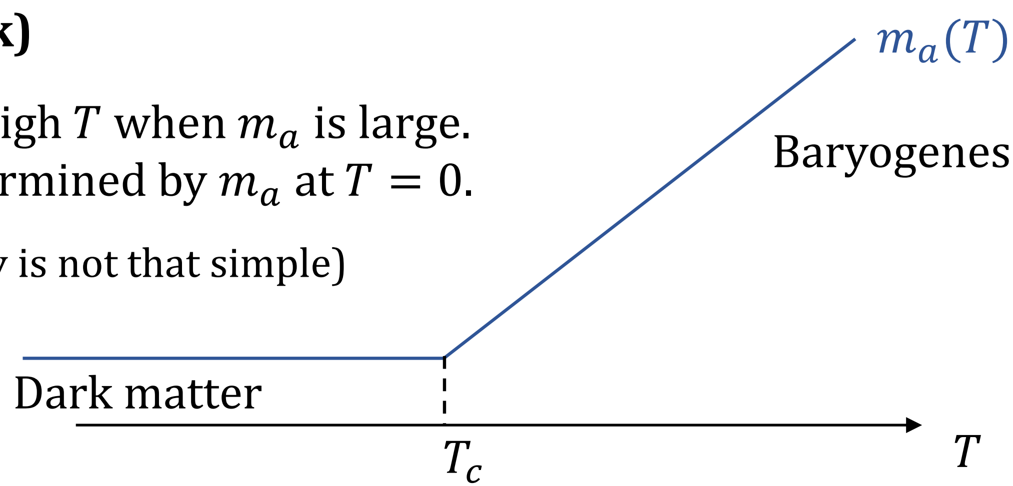
Tuning of $T_{osc} \sim T_{B*}$ is needed
to have the maximal value

$\Rightarrow$ $\boldsymbol{\theta}$ oscillation cannot be DM
(its energy density is too large)
(when m_a is constant)

What if $\boldsymbol{m_a(T) \propto T^{\#}}$? **(this work)**

Baryogenesis is completed at high T when m_a is large.
Dark matter abundance is determined by m_a at $T = 0$.

(original motivation… but the story is not that simple)



Realization of $m_a(T) \propto T^{\#}$ by symmetry non-restoration

A complex scalar field $\Phi = \frac{\phi}{\sqrt{2}} \exp[i\theta]$ whose axial mode is the pNGB for cogenesis.

$$V(\Phi) = \lambda_\phi |\Phi|^4 - m_0^2 \, |\Phi|^2 \qquad \Rightarrow f_a^{(0)} = \langle \phi \rangle = \frac{m_0}{\sqrt{\lambda_\phi}}$$

Thermal corrections

$$V_T(\phi) = \frac{1}{4}\lambda_\phi \phi^4 - \frac{1}{2} m_0^2 \, \phi^2 + \underbrace{(\mathrm{D}\ \mathrm{T}^2 \, \phi^2 - E \, T \, \phi^3 + \cdots)}_{\text{thermal corrections (high-}T\text{ expansion)}}$$

$$= \frac{1}{4}\lambda_\phi \phi^4 - \frac{1}{2}(m_0^2 - 2D \, T^2)\phi^2 + \cdots$$

$D \sim g^2 + y^2 + \lambda_{\text{mix}}$

coupling with SM Higgs
or additional scalars

- $D > 0$: Usual scenario with symmetry restoration at high T
- $\boldsymbol{D < 0}$ **: Symmetry non-restoration at high** $\boldsymbol{T}$

$$\langle \phi \rangle_T = f_a(T) \simeq \sqrt{\left(f_a^{(0)}\right)^2 + c_\lambda T^2} \simeq \begin{cases} f_a^{(0)} \quad , & T < T_c \equiv f_a^{(0)}/\sqrt{c_\lambda} \\ \boxed{\sqrt{c_\lambda}\, T \quad , \quad T > T_c} \end{cases}$$

with $c_\lambda = |D|/\lambda_\phi$

Realization of $m_a(T) \propto T^{\#}$ by symmetry non-restoration

- **VEV of radial mode increases as T above T_c**

$$D < 0 \qquad \boxed{f_a(T) \simeq \sqrt{c_\lambda}\, T} \quad , \qquad T > T_c \equiv f_a^{(0)}/\sqrt{c_\lambda}$$

- **An explicit $U(1)$ breaking operator to generate pNGB potential**

$$V_{\cancel{U(1)}} = \frac{1}{\Lambda}\Phi^5 + \mathrm{h.c.} \qquad \Rightarrow \boldsymbol{V_{\mathrm{pNGB}}(\theta) \sim \frac{\phi^5}{\Lambda}(1 - \cos(5\theta))}$$

$$\Rightarrow \boldsymbol{m_a(T) \sim \frac{f_a(T)^{3/2}}{\Lambda^{1/2}}} \simeq \begin{cases} m_a^{(0)} \quad , & T < T_c \equiv f_a^{(0)}/\sqrt{c_\lambda} \\ \boxed{m_a^{(0)}(\mathrm{T}/\mathrm{T_c})^{3/2} \quad , \quad T > T_c} \end{cases}$$

✓ In the end, we need $\Lambda \gg M_{\mathrm{Pl}}$.
This can be achieved by considering $V = \frac{1}{M_{\mathrm{Pl}}^2} X\, \Phi^5 \rightarrow \left(\Lambda = \frac{M_{\mathrm{Pl}}^2}{\langle X \rangle}\right)$
with a proper discrete symmetry to prevent higher dimensional operators from dominating.

Realization of $m_a(T) \propto T^{\#}$ by symmetry non-restoration

An explicit example: Φ with an additional complex scalar S

$$V(\Phi, \mathrm{S}) = \lambda_\phi |\Phi|^4 - 2\lambda_{\phi s}|\Phi|^2|S|^2 + \lambda_s|S|^4$$
$$-m_0^2\,|\Phi|^2 + m_s^2|S|^2$$

Stability condition: $\boldsymbol{\lambda_\phi \lambda_s > \lambda_{\phi s}^2}$

Consistency at one-loop: $\boldsymbol{\lambda > \frac{\lambda' \lambda''}{16\pi^2}}$ **for** $\boldsymbol{\lambda, \lambda', \lambda'' = \lambda_\phi, \lambda_s, \lambda_{\phi s}}$

$$V_T(\phi, s) = V + V_{CW} + \frac{T^4}{2\pi^2}\sum J_B\left(\frac{m_i^2(\phi)}{T^2}\right)$$

$$\simeq \frac{1}{4}\lambda_\phi \phi^4 - \frac{1}{2}\left(m_0^2 + \frac{1}{6}\lambda_{\phi s}\,T^2\right)\phi^2 + \cdots$$

Large $\boldsymbol{c_\lambda} = \frac{\lambda_{\phi s}}{6\lambda_\phi}$: $\lambda_s \sim O(1),\ \lambda_{\phi s} \sim \lambda_{\phi s}^2,\ \lambda_{\phi s} \ll 1$

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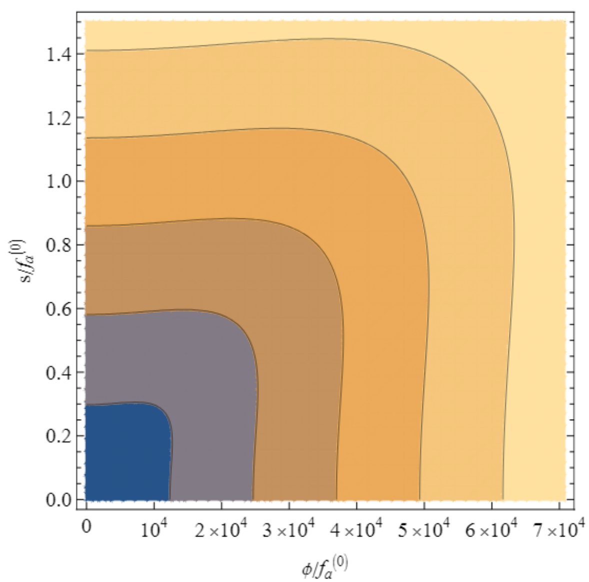

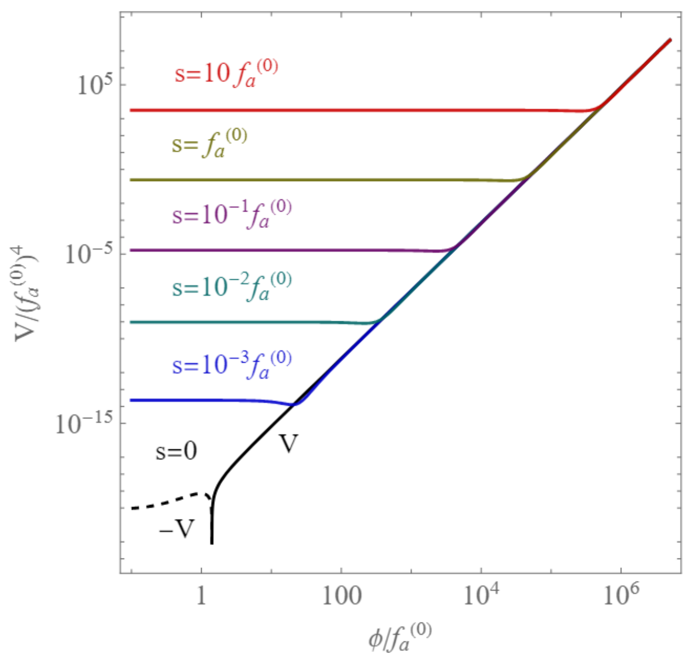

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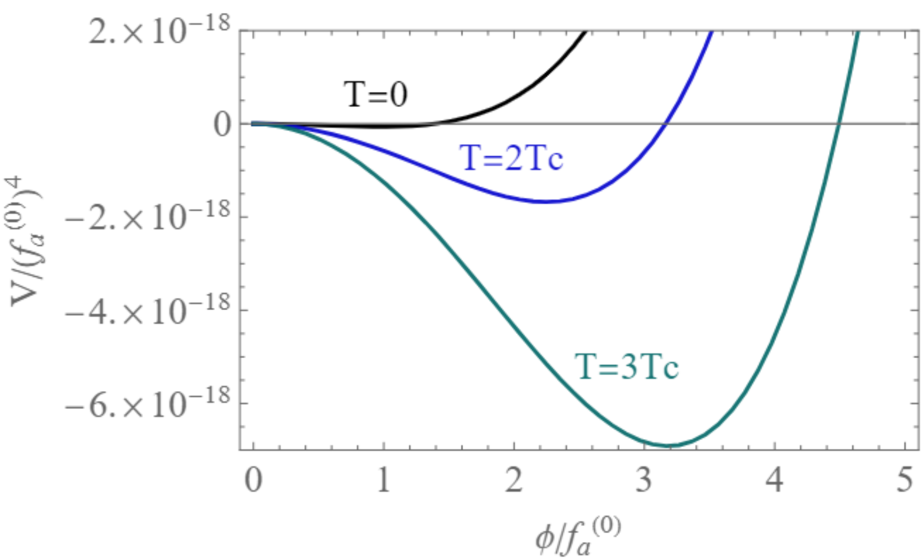
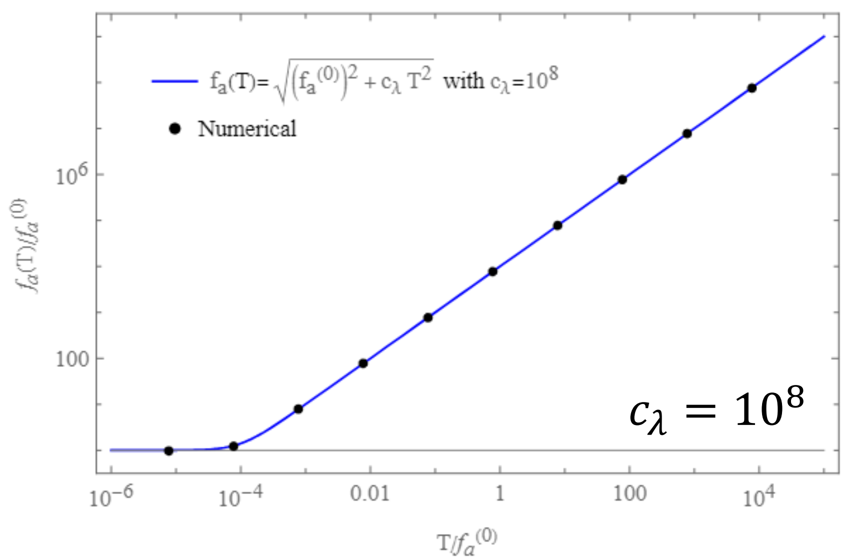


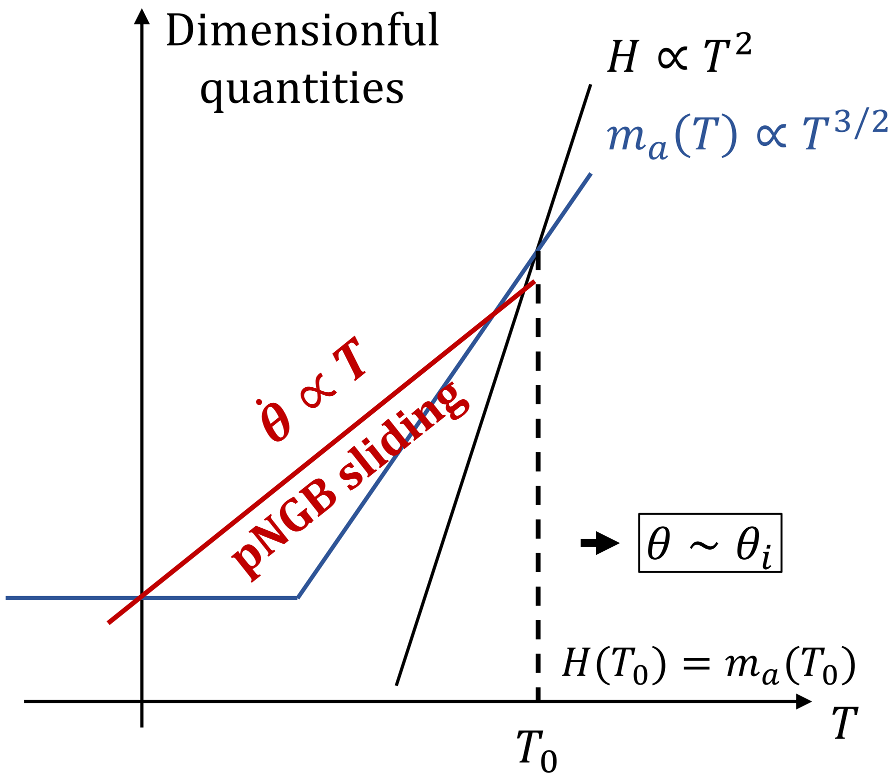


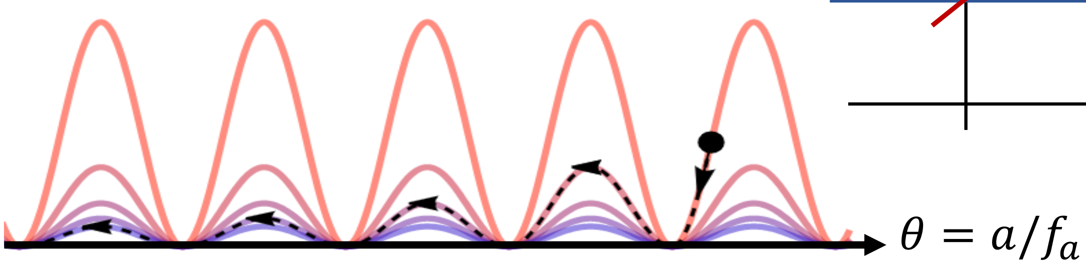
pNGB dynamics with symmetry non-restoration

- Assuming that ϕ follows its potential minimum (which must be justified later),

$$\ddot{\theta} + \underbrace{\left(3H + 2\frac{\dot{f}_a}{f_a}\right)}_{\simeq H \text{ for } T > T_c}\dot{\theta} = -\frac{1}{5} m_a^2(T) \sin 5\theta$$

- $H \propto T^2$ (radiation-dominated)
- $m_a \propto T^{3/2}$ for $T > T_c$
- At high T, $H(T) > m_a(T) \Rightarrow \theta \simeq \theta_i$.
- At T_0 ($H(T_0) = m_a(T_0)$), $\dot{\theta} \simeq m_a(T_0)$
- During the first dropping, potential barrier decreases faster than the redshift of K.E.





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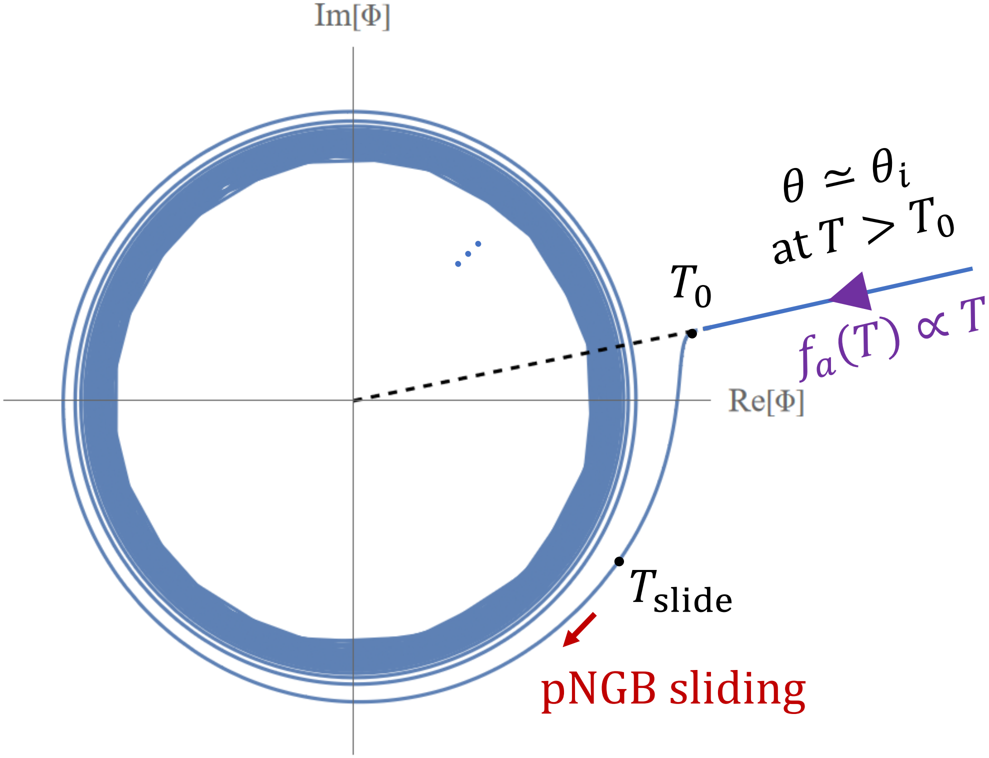

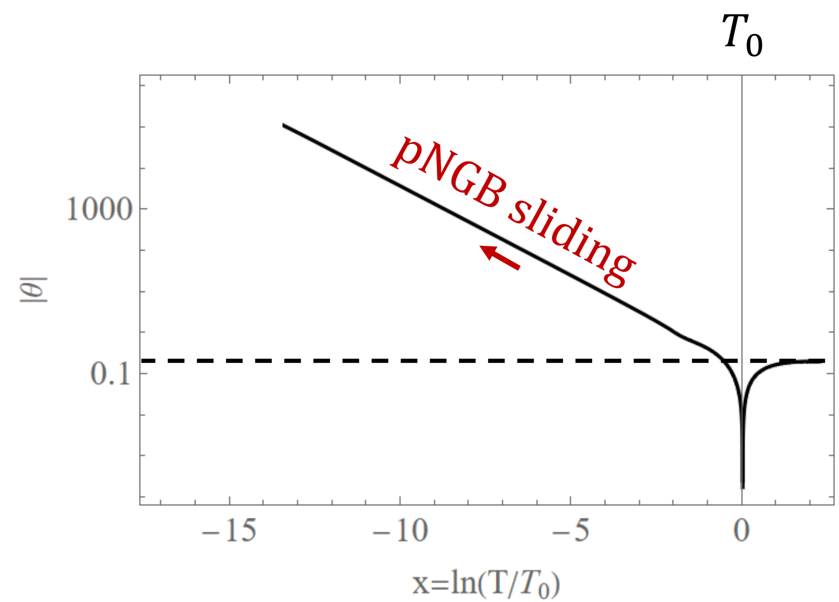

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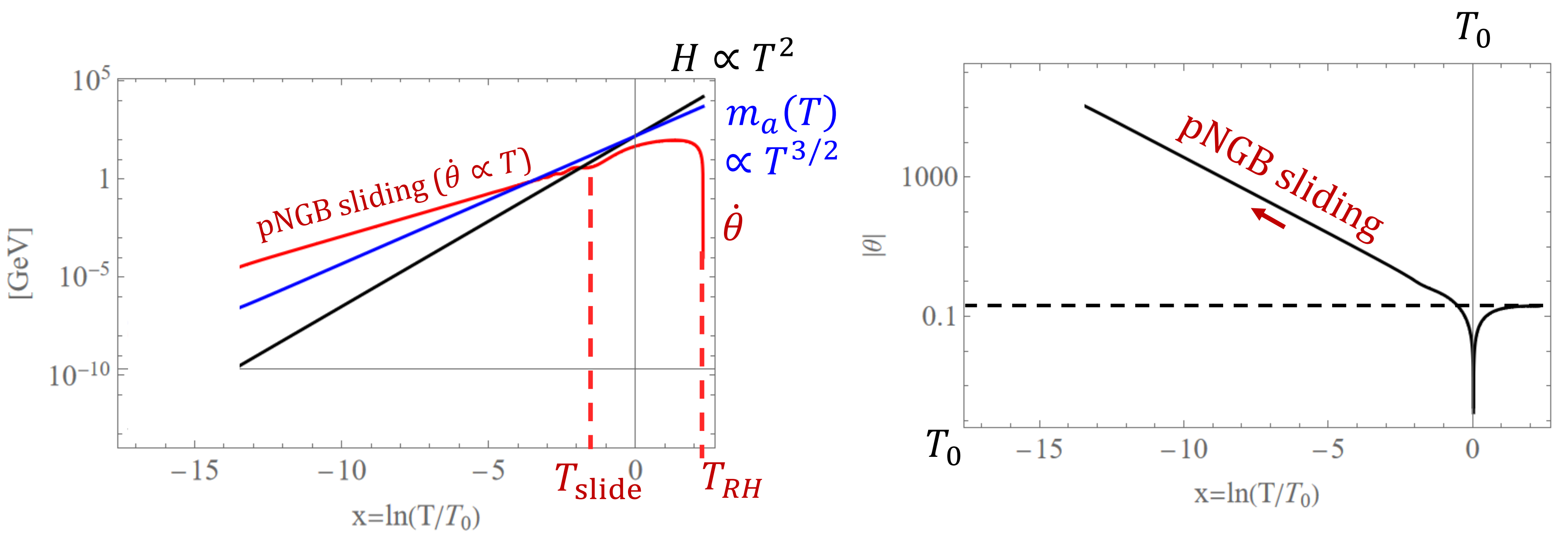

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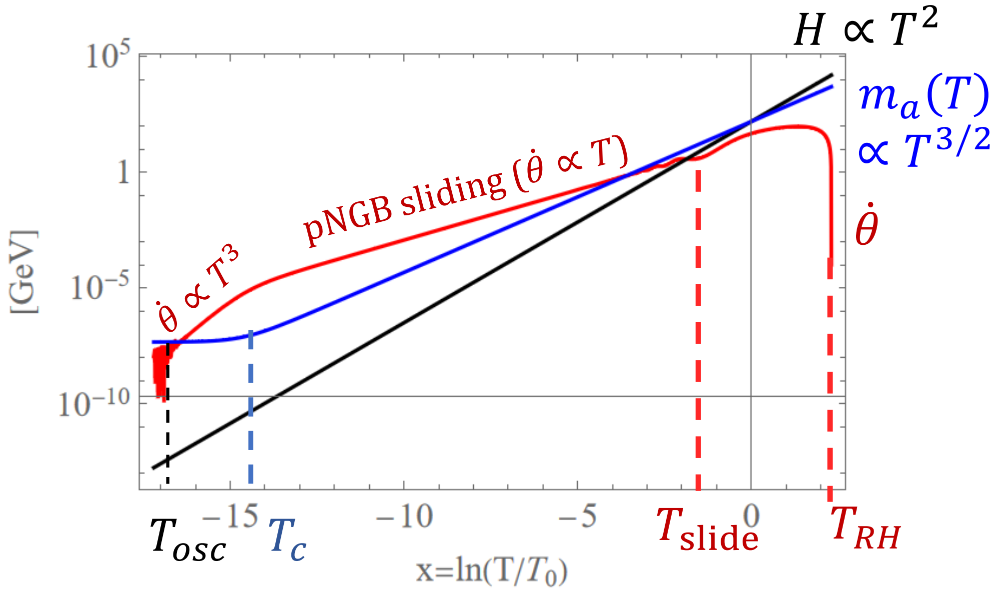
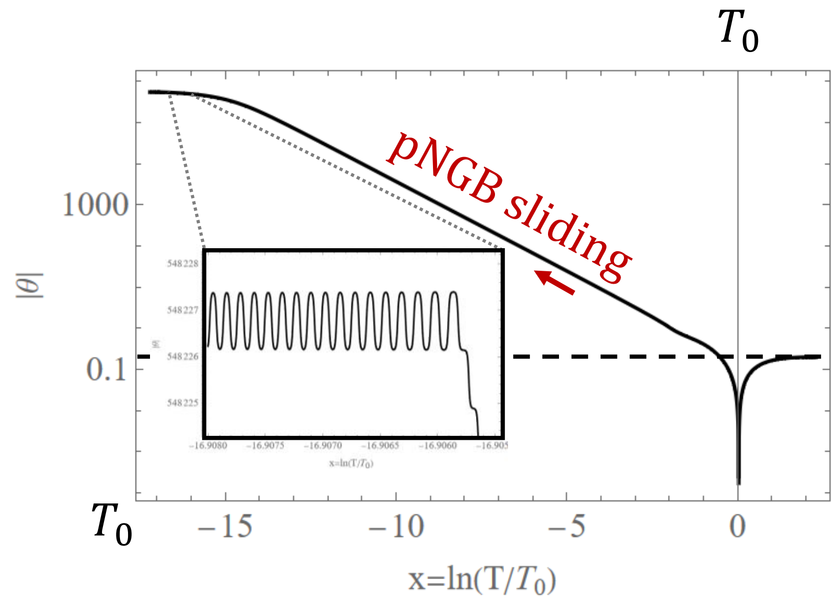


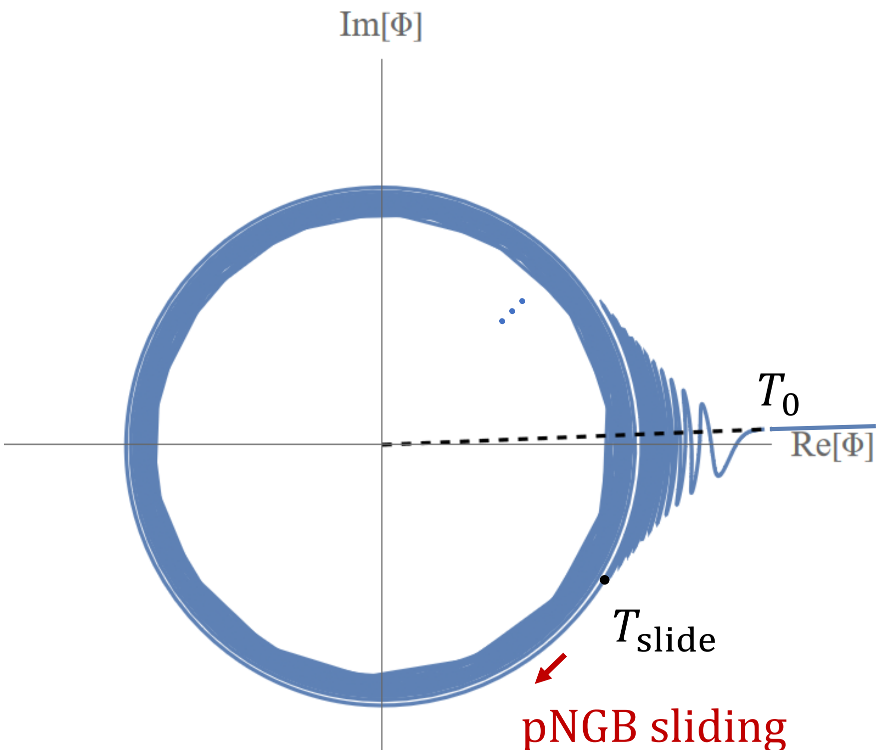


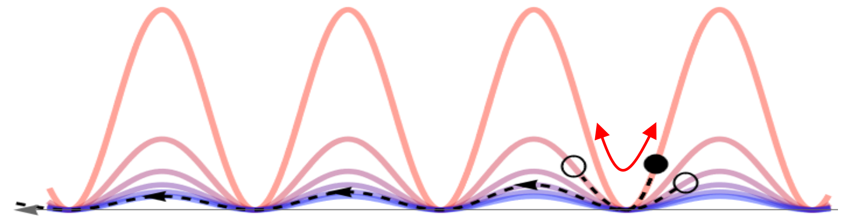
- At $T < T_c$, $\dot{f}_a \simeq 0$, so $\dot{\theta} \propto T^3$ until K.E < barrier height (i.e. the pNGB gets trapped).
- Then, pNGB starts oscillation ($T < T_{\text{osc}}$), and becomes dark matter.

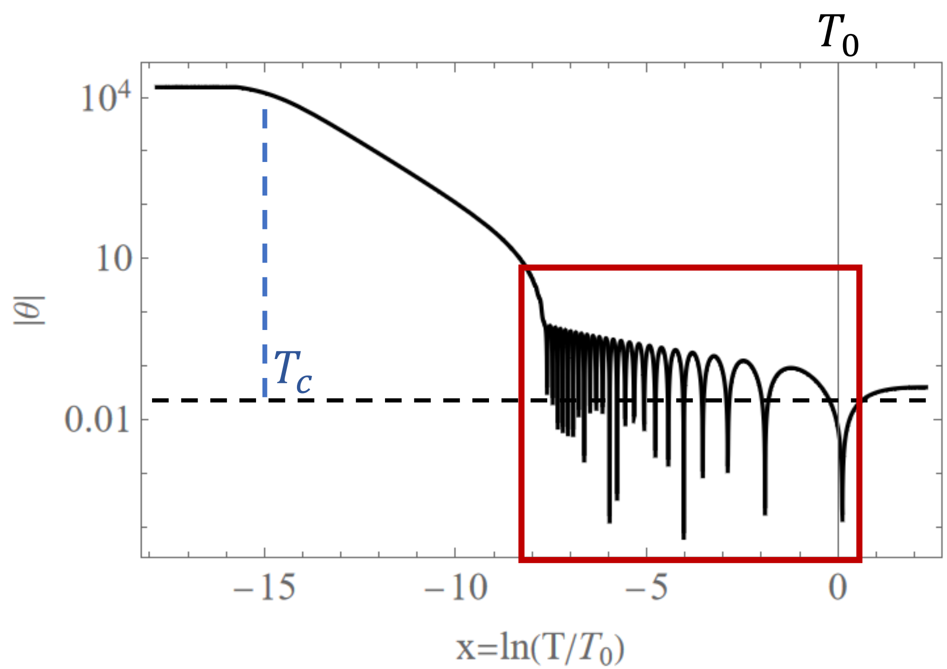
pNGB dynamics

$\boxed{\text{When } 5\theta_i \sim 0.2}$

$$\ddot{\theta} + \underbrace{\left(3H + 2\frac{\dot{f}_a}{f_a}\right)}_{\simeq H \ \text{ for } T > T_c} \dot{\theta} = -\frac{1}{5} m_a^2(T) \sin 5\theta$$







Summary of pNGB dynamics

$$\ddot{\theta} + \left(3H + 2\frac{\dot{f}_a}{f_a}\right)\dot{\theta} = -\frac{1}{5} m_a^2(T) \sin 5\theta$$

$\boldsymbol{T}$

$$\theta \simeq \theta_i$$

T_0 $\quad$ $H(T_0) = m_a(T_0)$

$$\theta(t) \sim A\,(t) \cos\left[\int^t dt'\, m_a(t')\right] \text{ with } A(t)^2 m_a(t) \propto \frac{1}{R(t)}$$

T_{slide} $\quad$ $\text{K. E.}\,(T_{\text{slide}}) = \text{Barrier}(T_{\text{slide}})$

$$\frac{\dot{\theta}}{T} \simeq \text{const} \simeq \frac{m_a(T_{\text{slide}})}{T_{\text{slide}}}$$

T_{c} $\quad$ $f_a \simeq f_a^{(0)}$ & $m_a \simeq m_a^{(0)}$

$$\dot{\theta} \propto \frac{1}{R(t)^3}$$

T_{osc} $\quad$ $\text{K. E.}\,(T_{\text{osc}}) = \text{Barrier}(T_{\text{osc}})$

$$\rho_{\text{osc}} \propto \frac{1}{R(t)^3}, \qquad \frac{\rho_{osc}}{s} = \text{const}$$

Summary of pNGB dynamics

$$\ddot{\theta} + \left(3H + 2\frac{\dot{f}_a}{f_a}\right)\dot{\theta} = -\frac{1}{5} m_a^2(T) \sin 5\theta$$

$\boldsymbol{T}$

$\theta \simeq \theta_i$

T_0

$\theta(t) \sim A\,(t) \cos\left[\int^t dt'\right.$

$T_{\rm slide}$

$\dfrac{\dot{\theta}}{T} \simeq$ con

$T_{\rm c}$

$\dot{\theta}$

$T_{\rm osc}$

$\rho_{\rm osc} \propto \dfrac{1}{R(t)^3}$ s

- **pNGB current interaction with fermions $\boldsymbol{\partial_\mu \theta\, \psi^\dagger \bar{\sigma}^\mu \psi}$**
  → generates external chemical potential
  → charge transport → baryon asymmetry

$$\boldsymbol{n_B = c_B \dot{\theta}\, T^2}$$

(model-dependent)

- **$\boldsymbol{T_{B*} > T_{osc}}$: baryon number is effectively frozen before oscillation**

$$\boldsymbol{Y_B^{(0)} = \frac{45\, c_B}{2\pi^2} \frac{\dot{\theta}(T_{B*})}{g_*\, T_{B*}} = 8.75 \times 10^{-10}}$$

- **Oscillation becomes DM**

$$\boldsymbol{\frac{\rho_{osc}}{s} = 0.44\ \mathrm{eV}}$$

Required conditions in the scalar sector

- **Conditions for $\boldsymbol{\phi}$**
  - ✓ Scalar field that gives $-|D|\,T^2\phi^2$ correction must be in the thermal bath.
    (Higgs or singlet scalars)

  - ✓ ϕ should be in the thermal bath → its relic abundance must decay before BBN.
  → mixing with the Higgs boson with $m_\phi^{(0)} > 2m_e \sim \mathrm{MeV}$ and $\sin\theta_{h\phi} > 10^{-5}$

  - ✓ ϕ must follow the potential minimum
    Time scale of ϕ dynamics is much shorter than others: $m_\phi(T) \gg m_a(T), H$
    Thermal friction → sufficiently large damping can be provided.

- **Conditions for $\boldsymbol{a}$**
  - ✓ "Particle" pNGB should not be produced (hot DM component).
  Estimation of freeze-in process of $\phi\phi \to a\, a \Rightarrow c_\lambda > 10^7$.

  - ✓ Lifetime of pNGB "DM" must be large enough. Depending on decay channel, there are several constraints.

Type-I seesaw with Majoron

- **Interaction lagrangian in the lepton sector**

$$-\Delta L = \left(\frac{1}{2} y\,\Phi\,\nu^c\nu^c + Y_D H l \nu^c + \mathrm{h.c.}\right)$$

$$\rightarrow \left(\frac{1}{2} M_N \nu^c\nu^c + Y_D H l \nu^c + \mathrm{h.c.}\right) + \frac{1}{2}\partial_\mu \theta\, J^\mu_{B-L}$$

$\boldsymbol{\psi \rightarrow e^{\frac{Q_{B-L}}{2} i\theta} \psi}$

generates external chemical potential $\propto \dot{\theta}$

$\boldsymbol{y\,\langle|\Phi|\rangle = M_N}$**,**

$\boldsymbol{a}$ = pNGB from spontaneous $U(1)_{B-L}$ breaking =**Majoron**

- **$\boldsymbol{B-L}$ changing process is required: any process involving $\boldsymbol{M_N}$,**
  e.g. inverse decay of ν^c, …

$$\dot{n}_B + 3H\,n_B = -\Gamma_B\left(n_B - c_B \dot{\theta}\,T^2\right)$$
$$\Gamma_\mathrm{B} = \min(\Gamma_{EW}, \Gamma_{M_N})$$

- **Inverse decay of $\boldsymbol{\nu^c}$ is active for**

$$\frac{M_N}{7} \lesssim T \lesssim 10 M_N$$

in our case $M_N = \frac{1}{\sqrt{2}} y\, f_a(T) = \frac{1}{\sqrt{2}} y\, c_\lambda^{1/2}\, T$ for $T > T_c$

$\Rightarrow$active at $\mathrm{T} > \mathrm{T}_c$ if $\frac{\sqrt{2}}{10\sqrt{c_\lambda}} \lesssim y \lesssim \frac{7\sqrt{2}}{\sqrt{c_\lambda}}$

Type-I seesaw with Majoron

$$\mathbf{0.1}\frac{\mathbf{1}}{\sqrt{\boldsymbol{c}_{\boldsymbol{\lambda}}}} \lesssim \boldsymbol{y} \lesssim \mathbf{10}\frac{\mathbf{1}}{\sqrt{\boldsymbol{c}_{\boldsymbol{\lambda}}}}$$

- **Potential terms in the scalar sector**

if needed

$$\Delta V = -2\,\lambda_{h\phi}|H|^2|\Phi|^2 - \left(2\lambda_{\phi s_i}|\Phi|^2|s_i|^2\right) + \cdots$$

$$\to c_\lambda \;=\; \frac{\frac{4}{12}\lambda_{h\phi} + \left(\frac{N_s}{12}\lambda_{\phi s_i}\right) - \frac{1}{12}y^2}{\lambda_\phi} \equiv \frac{\lambda_{\text{mix}}}{3\lambda_\phi}$$

- We ensure that $\boldsymbol{y}$ **does not spoil symmetry non-restoration,** i.e. no tuning of (large number) − (large number) is required.

$$\lambda_\phi \sim \lambda_{\text{mix}}^2, \qquad \lambda_{h\phi} \sim \lambda_{\phi s_i} \sim \lambda_{\text{mix}}, \qquad y \lesssim \sqrt{\lambda_{\text{mix}}}$$

- **Baryon number is frozen around $\boldsymbol{T_{EW}} \simeq$ 130 GeV** when electroweak sphaleron is decoupled.

Type-I seesaw with Majoron

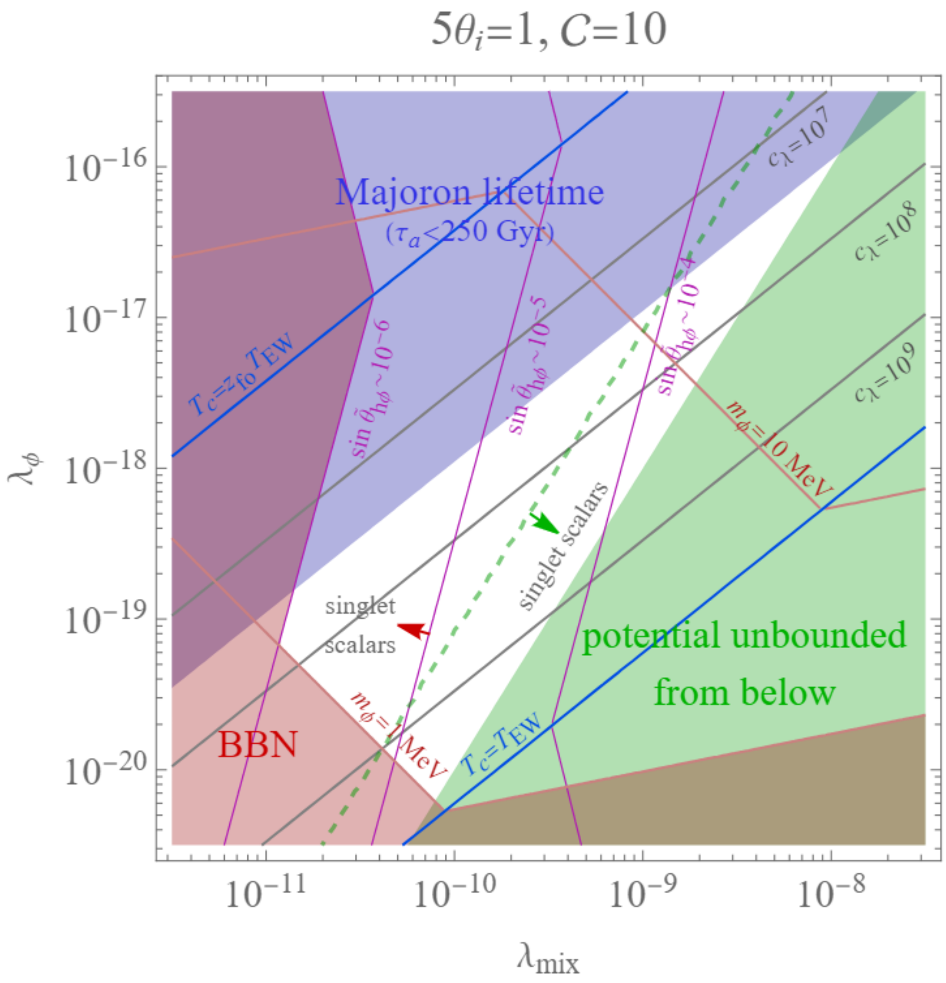
- **Free parameters:** $\boldsymbol{\lambda}_{\text{mix}}, \boldsymbol{\lambda}_{\boldsymbol{\phi}}, \boldsymbol{m}_{\boldsymbol{a}}^{(\mathbf{0})}, \boldsymbol{f}_{\boldsymbol{a}}^{(\mathbf{0})},\ (g_*, y, \theta_i),\ (T_{RH})$

$$
\begin{cases}
\boldsymbol{g}_* \sim 100 \\
0.1\dfrac{1}{\sqrt{c_\lambda}} \lesssim \boldsymbol{y} \lesssim 7\dfrac{1}{\sqrt{c_\lambda}} \\
5\boldsymbol{\theta}_{\boldsymbol{i}} \sim O(1) \\
\boldsymbol{T}_{\boldsymbol{RH}} > T_0
\end{cases}
$$

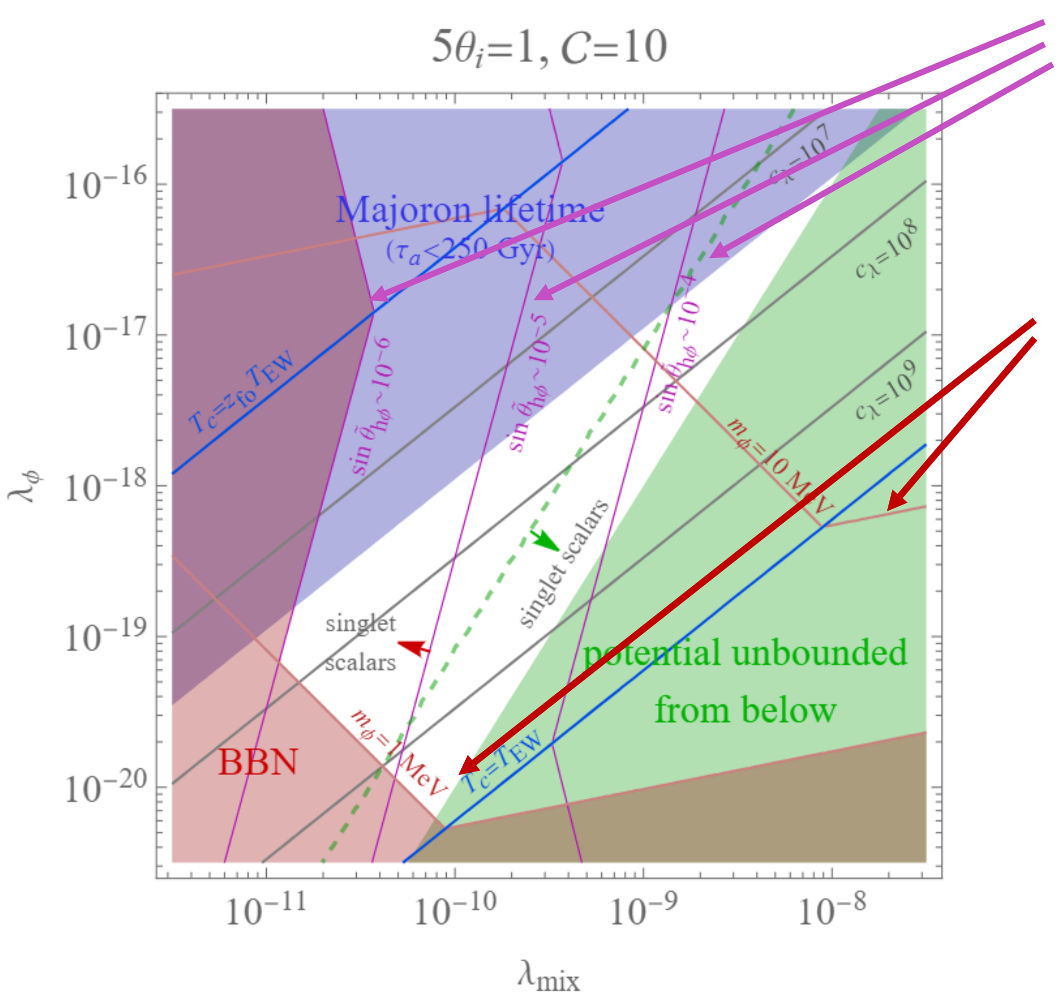
- **Two conditions for cogenesis: DM abundance and $\boldsymbol{Y}_{\boldsymbol{B}}$**

$$
\boxed{
\begin{aligned}
\boldsymbol{m}_{\boldsymbol{a}}^{(\mathbf{0})} &\simeq \mathbf{5\ eV} \left(\frac{\mathbf{10^8}}{\boldsymbol{c}_{\boldsymbol{\lambda}}}\right)^{\mathbf{5/9}} \\
\boldsymbol{f}_{\boldsymbol{a}}^{(\mathbf{0})} &\simeq \mathbf{3 \times 10^6\ GeV} \left(\frac{\mathbf{10^8}}{\boldsymbol{c}_{\boldsymbol{\lambda}}}\right)^{\mathbf{5/18}}
\end{aligned}
}
\qquad c_\lambda = \frac{\lambda_{\text{mix}}}{3\lambda_\phi}
$$

Viable parameter space



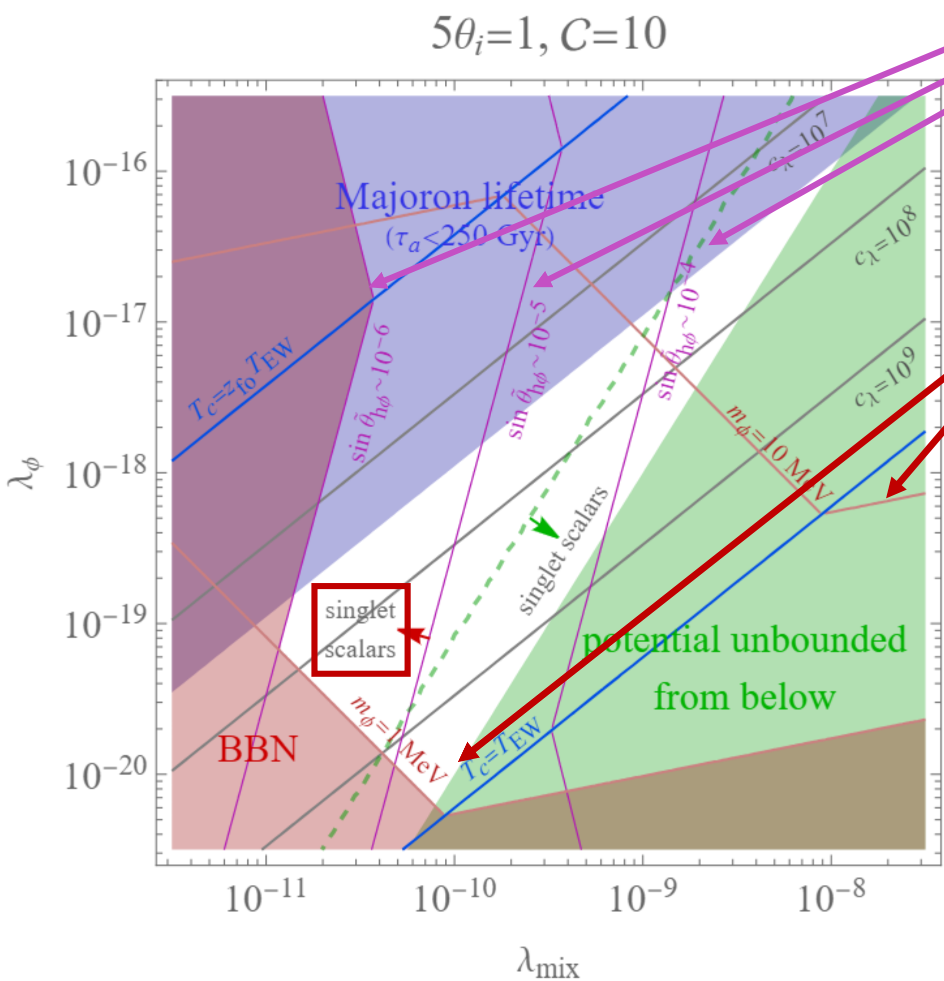
Viable parameter space



$\sin\tilde{\theta}_{h\phi}$ assuming no s_i

$m_\phi^{(0)}$

Viable parameter space

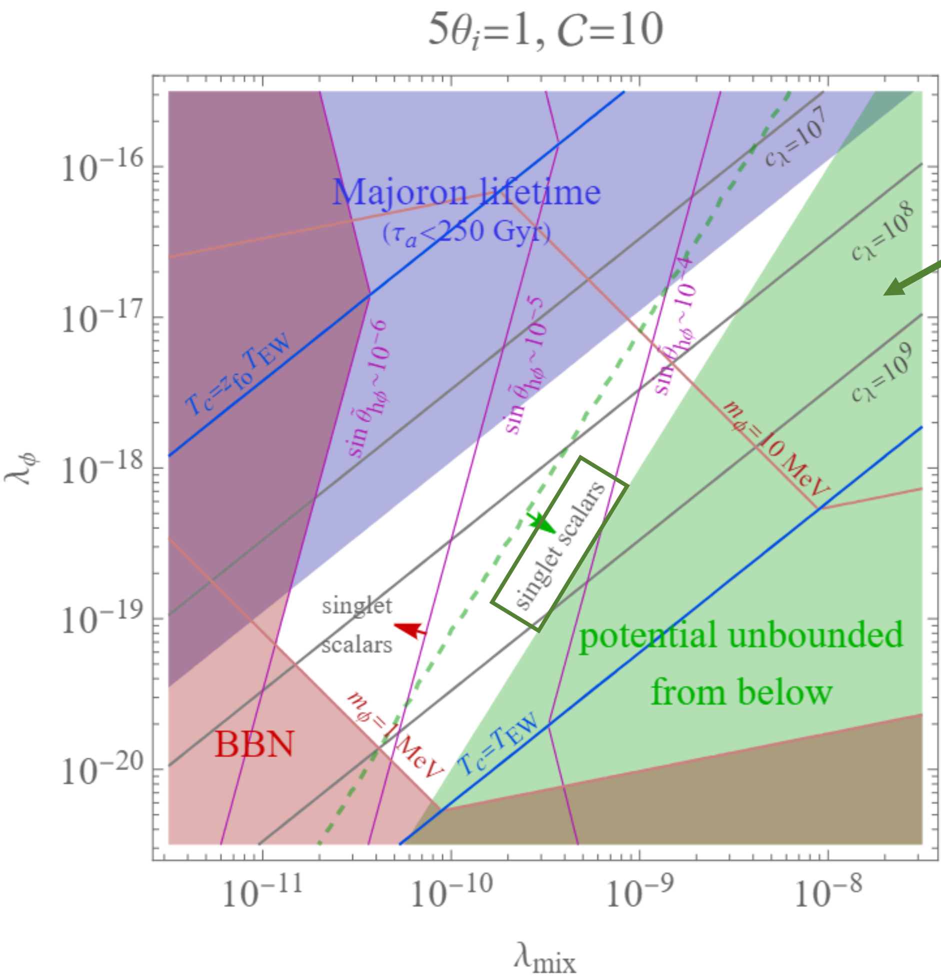


$\sin\tilde{\theta}_{h\phi}$ assuming no s_i

m_ϕ

- ϕ must decay before BBN through Higgs portal
  $\sin\theta_{h\phi} > 10^{-5}$ and $m_\phi > 2m_e$

Viable parameter space



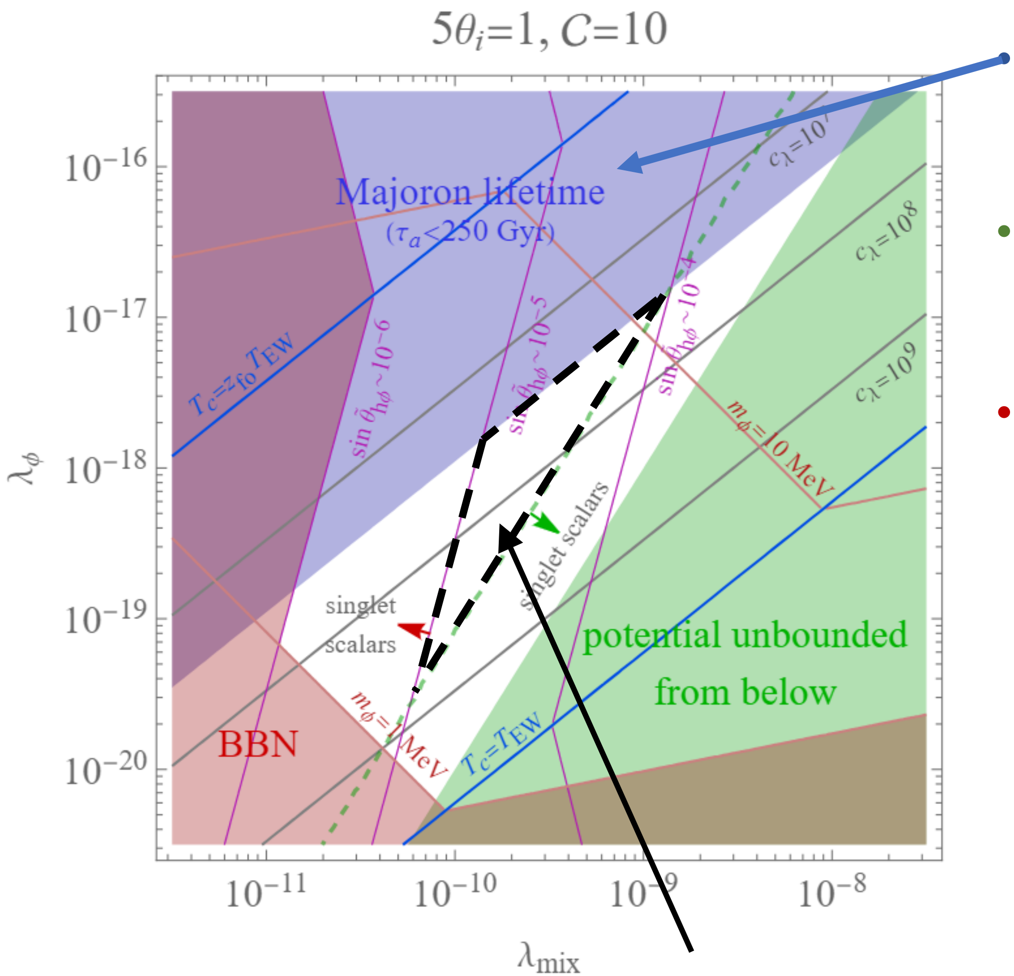
Potential unbounded from below

$\lambda_\phi\lambda_h < \lambda_{\rm mix}^2$ or $\lambda_\phi\lambda_s < \lambda_{\rm mix}^2$

- ϕ must decay before BBN through Higgs portal

  $\sin\theta_{h\phi} > 10^{-5}$ and $m_\phi > 2m_e$

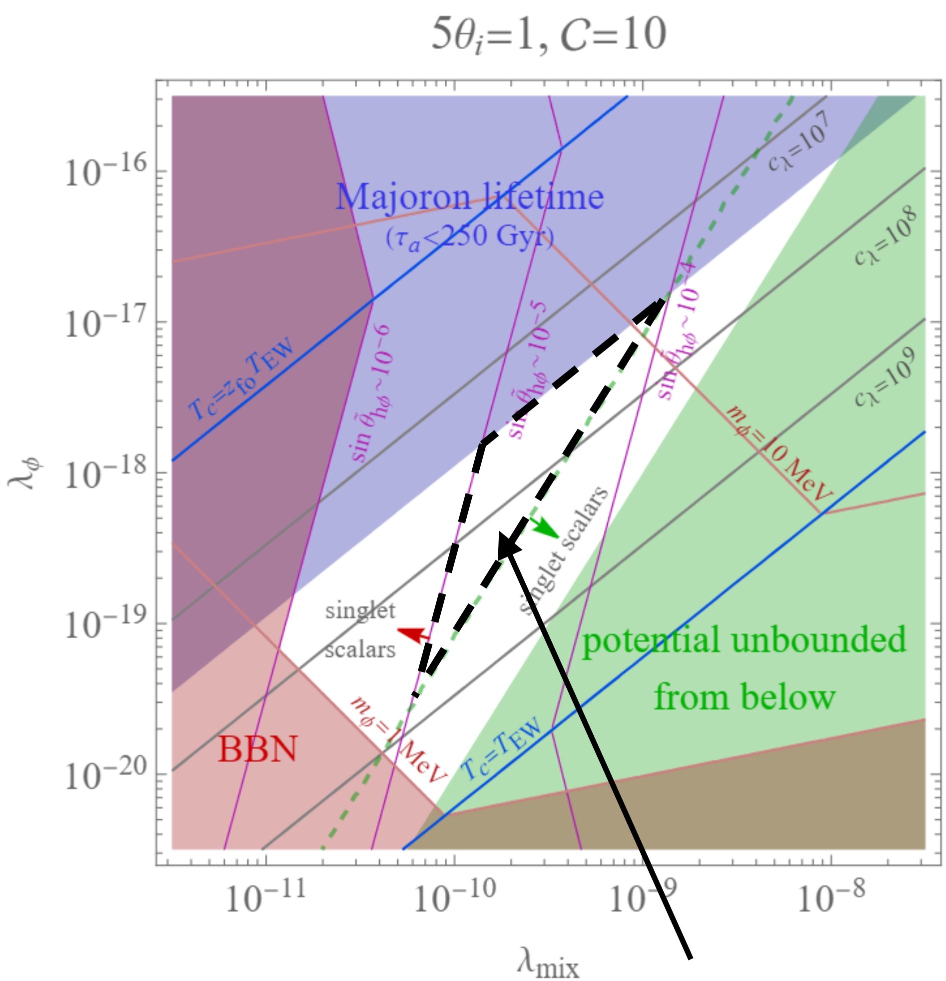
Viable parameter space



- a Lifetime constraint from CMB & BAO
  $\tau_a > 250$ Gyr
- Potential unbounded from below
  $\lambda_\phi \lambda_h < \lambda_{\rm mix}^2$ or $\lambda_\phi \lambda_s < \lambda_{\rm mix}^2$
- ϕ must decay before BBN through Higgs portal
  $\sin\theta_{h\phi} > 10^{-5}$ and $m_\phi > 2m_e$

Minimal Higgs portal works
without singlet scalars

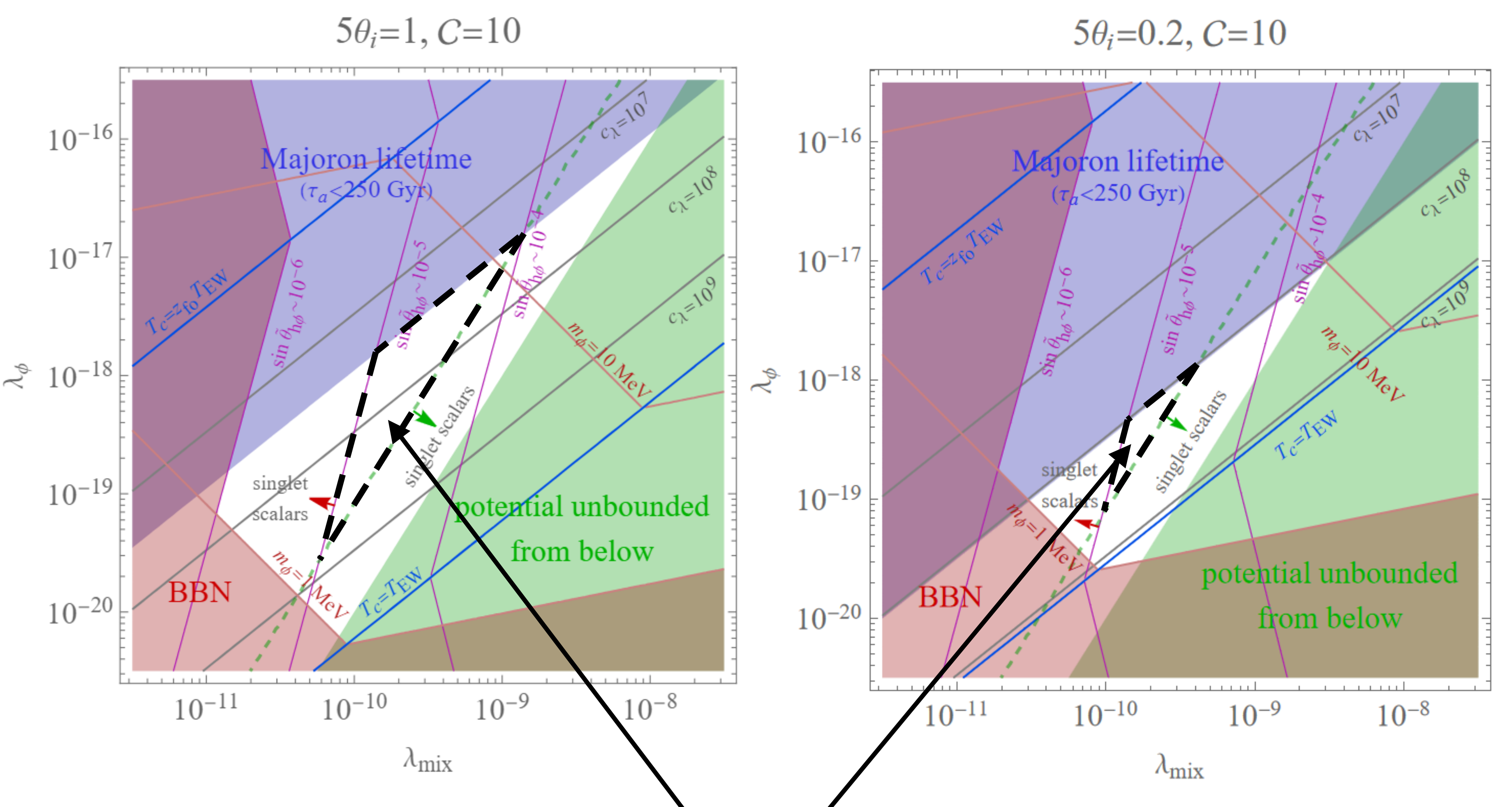
Viable parameter space



- a Lifetime constraint from CMB & BAO
  $$\tau_a > 250\ \mathrm{Gyr}$$
- Potential unbounded from below
  $$\lambda_\phi \lambda_h < \lambda_{\rm mix}^2 \ \text{ or } \ \lambda_\phi \lambda_s < \lambda_{\rm mix}^2$$
- ϕ must decay before BBN through Higgs portal
  $$\sin\theta_{h\phi} > 10^{-5} \quad \text{and} \quad m_\phi > 2m_e$$
- Singlet scalars are expected to be around EW scale to avoid tuning.
- $T_c \sim T_{EW}$ (accidentally!)
  $$\rightarrow M_N^{(0)} \sim 100\ \mathrm{GeV}$$

Minimal Higgs portal works
without singlet scalars

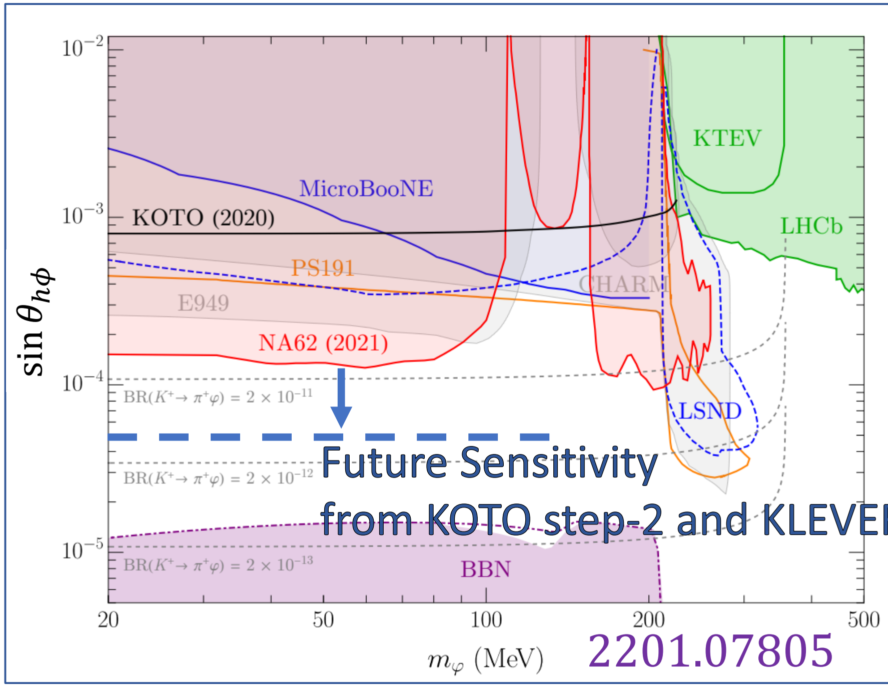
Viable parameter space



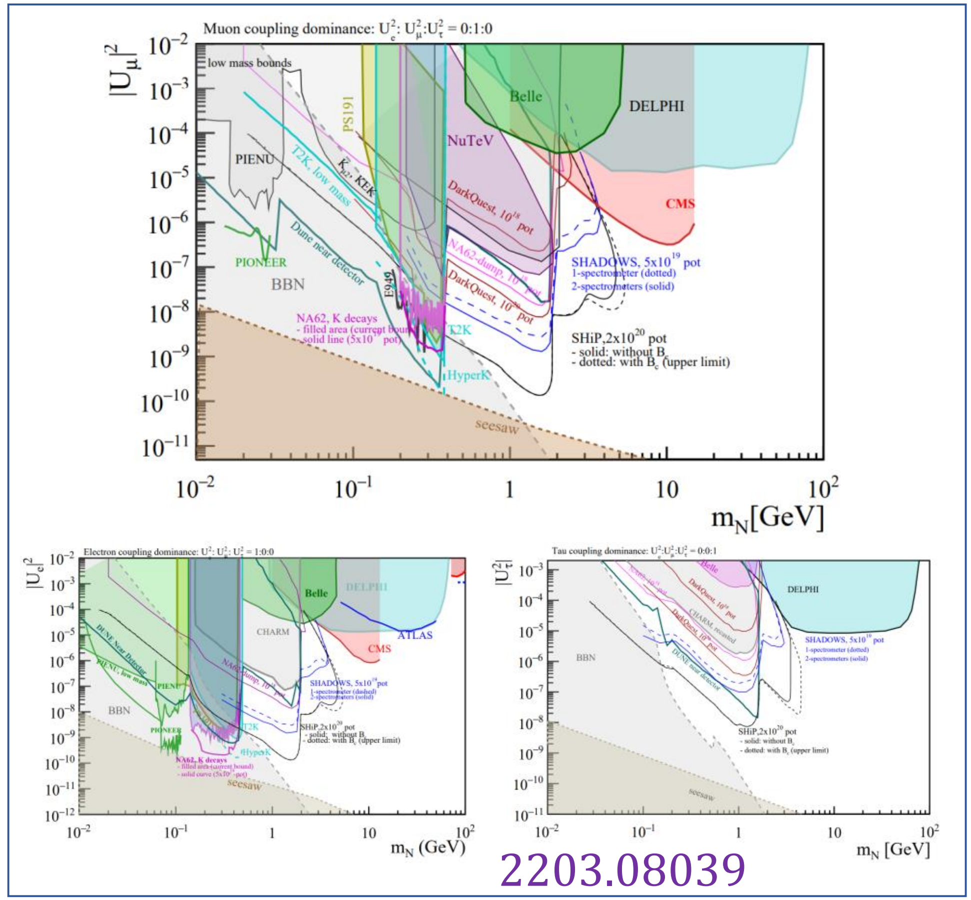
Minimal Higgs portal

Future sensitivity

Radial mode ϕ search
$(\mathrm{MeV} < m_\phi < 20\mathrm{MeV})$



Heavy Neutral Lepton search
heaviest $M_N^{(0)} \sim T_c \sim 100$ GeV



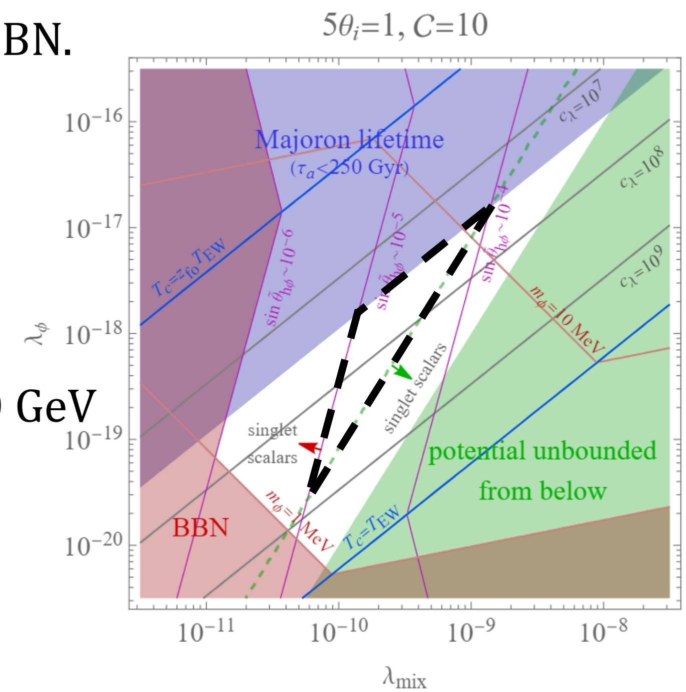
Summary

- (Global symmetry non-restoration) + (dim-5 explicit br operator) → pNGB sliding
- Cogenesis is possible when $m_a^{(0)} \sim 5$ eV and $f_a^{(0)} \sim 3 \times 10^6$ GeV.
- For the Majoron case, we find a viable parameter space.

✓ $\sin\theta_{h\phi} > 10^{-5}$ & $m_\phi > 2m_e$ is needed to avoid BBN.
→ Kaon experiments may test it.

✓ $M_N^{(0)} \lesssim 100$ GeV for the leptogenesis
→ HNL searches (beamdump, LHC, ...)

✓ Singlet scalars in non-minimal model around 100 GeV
→ LHC and future colliders may test it.



Thank you!

Thank you!

Lepton asymmetry generation

$$\dot{n}_{l_\alpha} + 3Hn_{l_\alpha} = \frac{n_N}{n_N^{(eq)}}\Gamma^{(eq)}(N \to l_\alpha H) - \frac{n_{l_\alpha} n_H}{n_{l_\alpha}^{(eq)} n_H^{(eq)}}\Gamma^{(eq)}(l_\alpha H \to N)$$

$$\wr \qquad\qquad\qquad\qquad \|$$

$$-\Big)\quad \dot{n}_{\bar{l}_\alpha} + 3Hn_{\bar{l}_\alpha} = \frac{n_N}{n_N^{(eq)}}\Gamma^{(eq)}(N \to \bar{l}_\alpha \bar{H}) - \frac{n_{\bar{l}_\alpha} n_{\bar{H}}}{n_{l_\alpha}^{(eq)} n_H^{(eq)}}\Gamma^{(eq)}(\bar{l}_\alpha \bar{H} \to N)$$

$$\dot{n}_{\Delta l_\alpha} + 3Hn_{\Delta l_\alpha} = O(\epsilon_{CP}) - \left(\frac{n_{\Delta l_\alpha}}{n_{l_\alpha}^{(eq)}} + \frac{n_{\Delta H}}{n_H^{(eq)}}\right)\Gamma^{(eq)}(l_\alpha H \to N)$$

Source term
in conventional
thermal leptogenesis

Wash-out term

$$\Big\downarrow \quad \dot{\theta} \neq 0: \ \mu_i \to \mu_i - \frac{(B-L)_i}{2}\dot{\theta}$$

$$\dot{n}_{\Delta l_\alpha} + 3Hn_{\Delta l_\alpha} = -\left(\left(\frac{n_{\Delta l_\alpha}}{n_{l_\alpha}^{(eq)}} - \frac{\dot{\theta}}{T}\right) + \frac{n_{\Delta H}}{n_H^{(eq)}}\right)\Gamma^{(eq)}(l_\alpha H \to N)$$

Source term: wash-in mechanism

pNGB dynamics

$\boxed{\text{When } 5\theta_i \sim 0.2}$

$$\ddot{\theta} + \underbrace{\left(3H + 2\frac{\dot{f}_a}{f_a}\right)}_{\simeq H \text{ for } T > T_c}\dot{\theta} = -\frac{1}{5} m_a^2(T) \sin 5\theta$$