Reviving the Low-Mass Right Handed Neutrino Regime in Minimal Scotogenic Leptogenesis using Majoron Velocity

Based on:
arXiv:2608.12497 [hep-ph]

In collaboration with:
Hyun Min Lee, Jun-Ho Song

Arghyajit Datta
Department of Physics,
Chung-Ang University

Introduction:

Neutrino Mass

Dark Matter

Unresolved issues
in SM

Baryon asymmetry
of the Universe

Introduction:

Neutrino Mass

Scotogenic
Model

Dark Matter

[E. Ma, 1998,2006]

Baryon asymmetry
of the Universe

Neutrino mass:

Neutrino Mass
[one loop]

[E. Ma, 1998,2006]

Scotogenic Model

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Baryon asymmetry of the Universe

SM + $N_1, N_2, \ldots$ **+ inert doublet** $\begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$

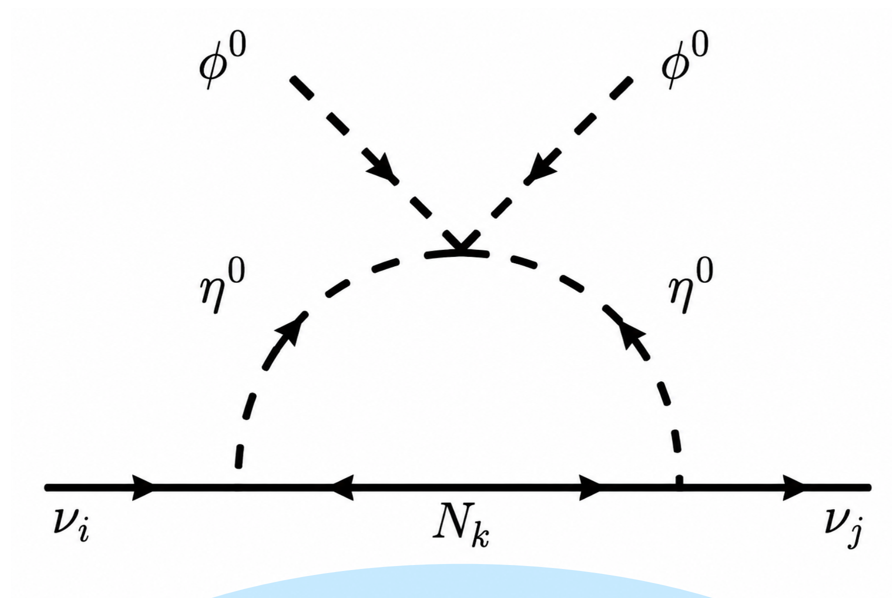
$\mathbb{Z}_2 :\ (+) \qquad (-) \qquad (-)$

$$-\mathcal{L} \supset Y^{\nu}_{\alpha i} \bar{\ell}_{L\alpha} \tilde{\eta} N_i + \frac{1}{2} M_i \bar{N}^c_i N_i + \mathrm{h.c.}$$

Neutrino mass:

Neutrino Mass
[one loop]

[E. Ma, 1998,2006]



Dark Matter

After EWSB

Baryon asymmetry of the Universe

Scotogenic Model

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Dark Matter:

See Huchan’s Talk

Neutrino Mass
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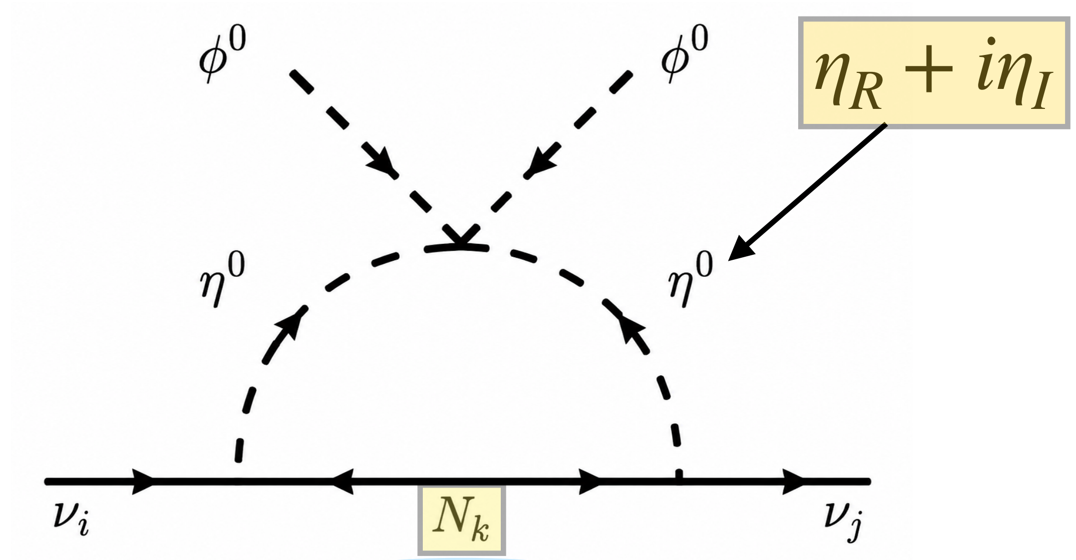

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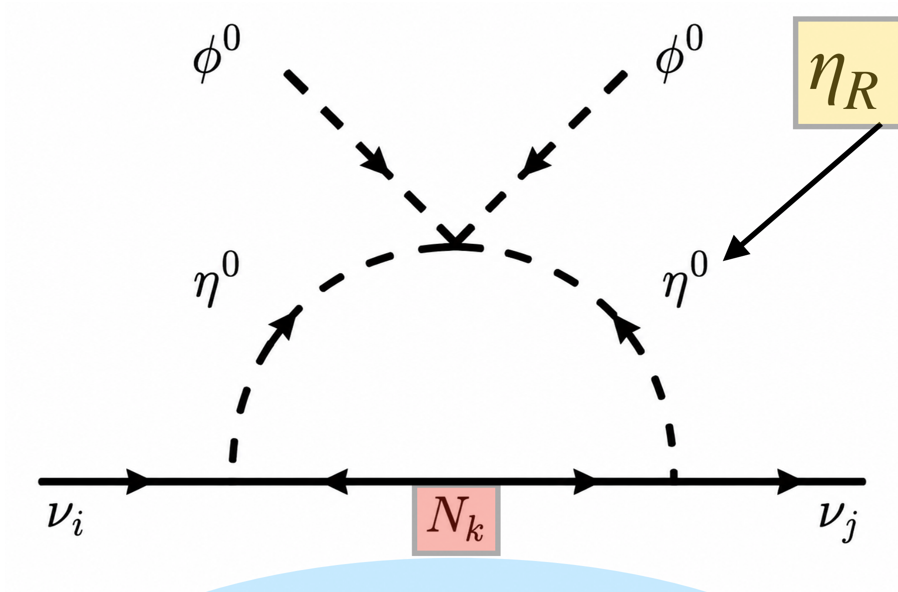

$\eta_R + i\eta_I$

Dark Matter

$M_i > m_\eta$

After EWSB

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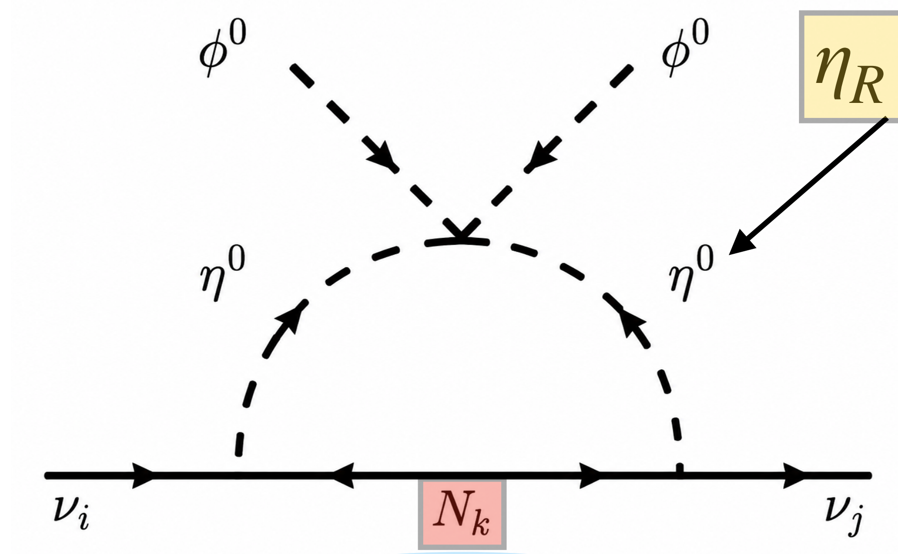

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many more….]

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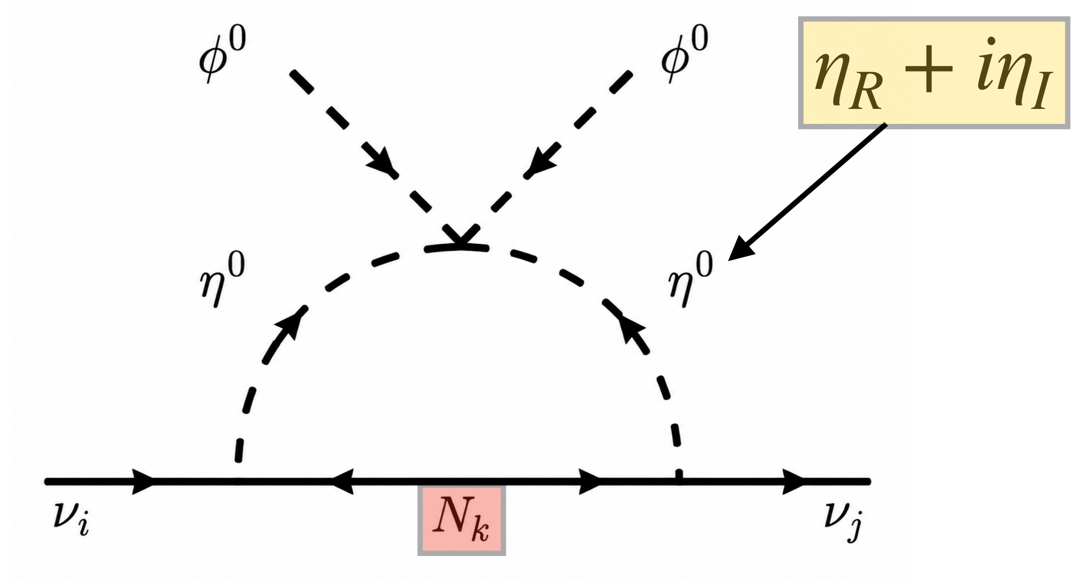

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After EWSB

$$550 \text{ GeV} \leq m_{\eta_I} \leq 1 \text{ TeV}$$

From Vanilla Scotogenic DM Pheno:

$$\lambda_5 \gtrsim 10^{-6}$$

* if $\Omega_{\eta_I} = 100\,\%\,\Omega_{\mathrm{DM}}$

Scotogenic Model

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Baryogenesis:

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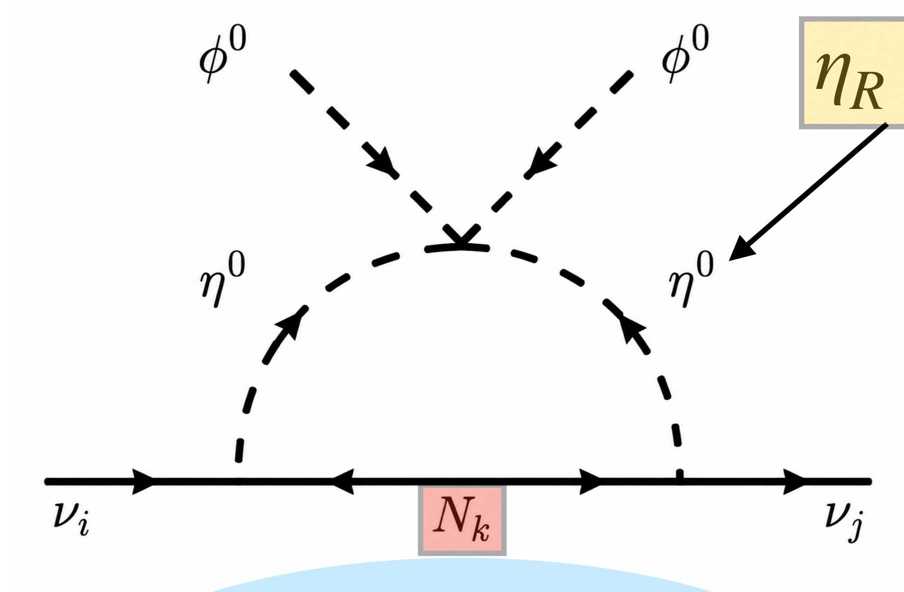

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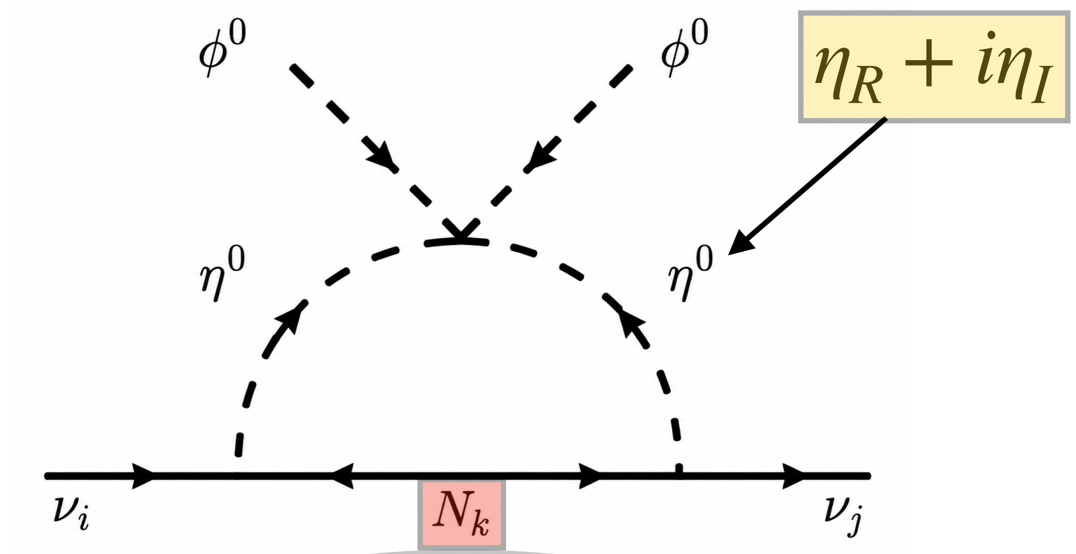

Dark Matter

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$M_i > m_\eta$

$N_i \to \ell_{L_\alpha} + \eta$

Before EWSB

Baryon asymmetry of the Universe
[via leptogenesis]

[Kashiwase, 2012, Kashiwase 2013, Racker 2013, Clarke 2015, Hugle 2018, Mahanta 2019]

Scotogenic Model

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Limitations:

1. Theoretical

The origin of the RHN Majorana scale remains unexplained.

Solution:

Natural possibility is to generate RHN mass dynamically

Scotogenic Model

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After SSB of $U(1)_{B-L}$: $\quad \varphi \to \frac{v_\varphi}{\sqrt{2}} \to M_i = Y_i^N v_\varphi/\sqrt{2}$

Scotogenic Model

$$\begin{array}{lcccc} & \textbf{SM} + & N_1, N_2, \ldots & + \textbf{ inert doublet} \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix} & + \ \varphi \\ \mathbb{Z}_2 : & (+) & (-) & (-) & (+) \\ U(1)_{B-L} : & & (-1) & (0) & (+2) \end{array}$$

[Global]

$$-\mathcal{L} \supset Y^\nu_{\alpha i} \bar{\ell}_{L\alpha} \tilde{\eta} N_i + \boxed{\frac{1}{2} Y_i^N \varphi \bar{N}_i^c N_i} + \text{h.c.}$$

Limitations:

2. Phenomenological

With two hierarchical RHN setup, Thermal Leptogenesis is high scale phenomena

$$-\mathcal{L} \supset Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{\eta}N_i + \frac{1}{2}M_i\bar{N}^c_i N_i + \text{h.c.} \qquad i = 1,2$$

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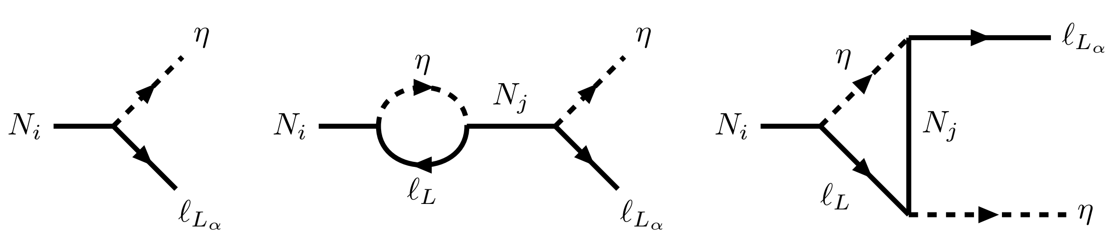
CP violation:

$$|\epsilon_1| \lesssim \frac{3}{8\pi}\xi_2^{-1}\frac{M_1}{v_\Phi^2}m_3,$$

$$\xi_i \equiv \frac{M_i^2}{16\pi^2 v_\Phi^2}\left[L^{(i)}_{\eta_R} - L^{(i)}_{\eta_I}\right], L^{(i)}_x = \frac{m_x^2}{m_x^2 - M_i^2}\ln\left(\frac{m_x^2}{M_i^2}\right).$$



Washout Factor: $K_1 = \Gamma_1/\mathcal{H}(M_1)$

$$K_1 = \frac{1}{4\pi v_\Phi^2}\xi_1^{-1}\sum_\alpha m_\alpha|R_{\alpha 1}|^2\frac{M_p}{0.33\sqrt{g_*(M_1)}}.$$

$$K_1 \gg 4$$

***Even for TeV scale RHN**

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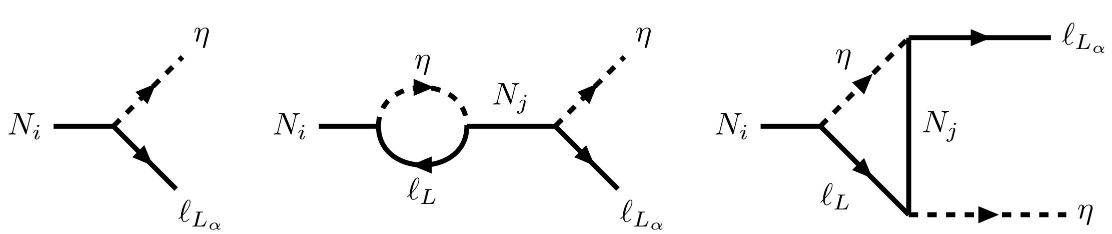

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***Even for TeV scale RHN**

$$M_1^{\min}(Y_B = 8.7 \times 10^{-11}) = 10^{11}\ \text{GeV}$$

***Even for $\lambda_5 = \lambda_5^{\max}$**

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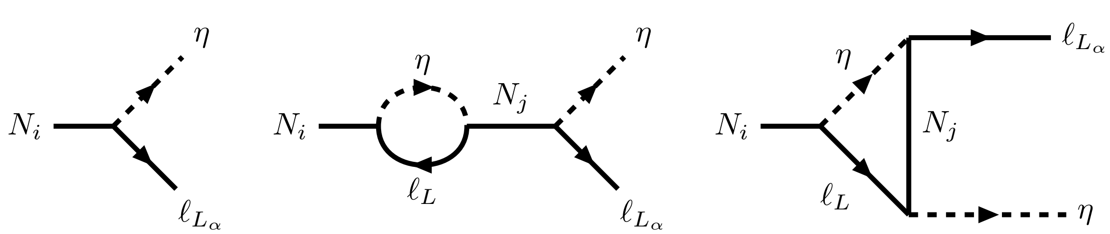

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***Even for TeV scale RHN**

How to remove this limitation?

$$M_1^{\min}(Y_B = 8.7\times 10^{-11}) = 10^{11}\ \text{GeV}$$

***Even for** $\lambda_5 = \lambda_5^{\max}$

Main topic of this talk

Minimal scotogenic Model

Conventional thermal leptogenesis typically prefers a very high RHN mass scale

What we ask in this talk

whether this conclusion can be relaxed if the RHN mass is generated dynamically
and can the associated Majoron field (for global symmetry breaking) play any important role here?

Solution: after global $U(1)_{B-L}$ SSB: $\varphi = \frac{1}{\sqrt{2}}(v_\varphi + h_\varphi)\exp\left[i\boxed{\frac{J(x)}{v_\varphi}}\right]$

$\frac{1}{2\sqrt{2}} Y_i^N v_\varphi e^{i\theta} \overline{N_i^c} N_i$ ⟶ Redefine $N_i \to e^{\theta/2} N_i$ ⟶ Redefine all fermions

[RHN mass term]

$$\partial_\mu \theta J^\mu_{B-L} \xrightarrow{(\dot{\theta},0,0,0)} \dot{\theta} n_{B-L} \longrightarrow \mu^{\text{eff}}_{B-L} = \dot{\theta}/2$$

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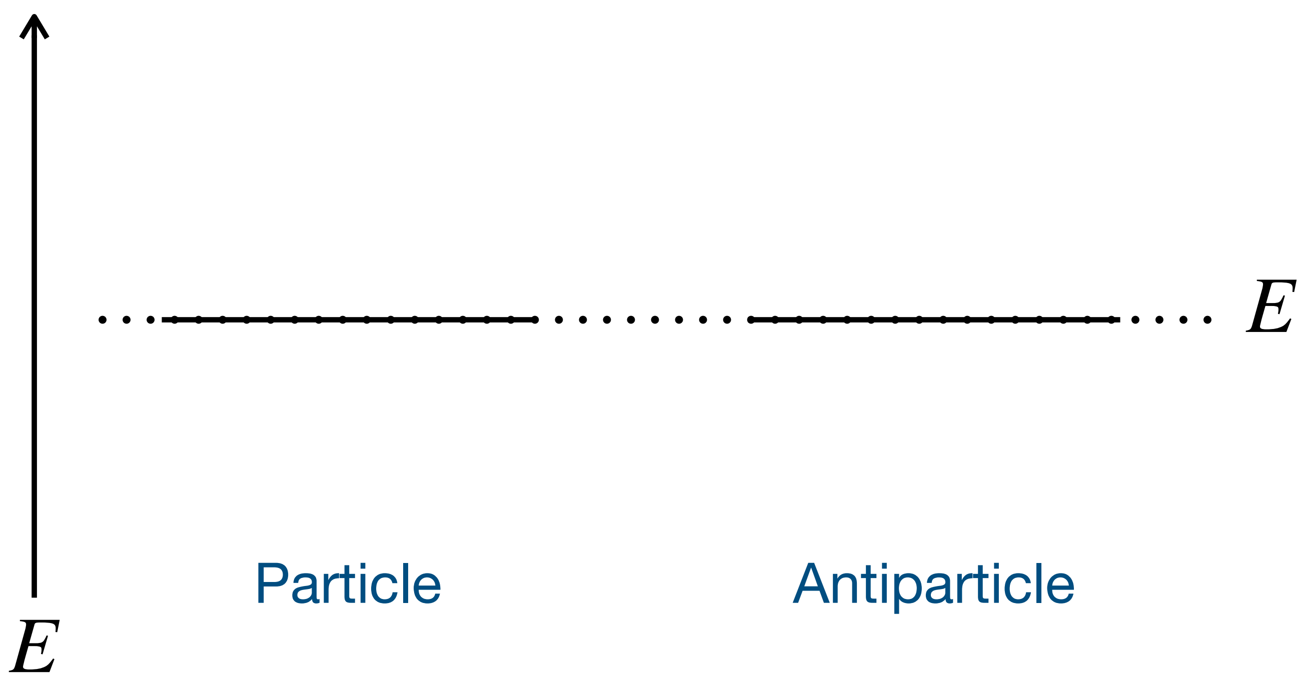
[RHN mass term]

$$\mu_{B-L}^{\text{eff}} = \dot{\theta}/2 \longleftarrow \dot{\theta} n_{B-L} \xleftarrow{(\dot{\theta},0,0,0)} \partial_\mu \theta J^\mu_{B-L}$$



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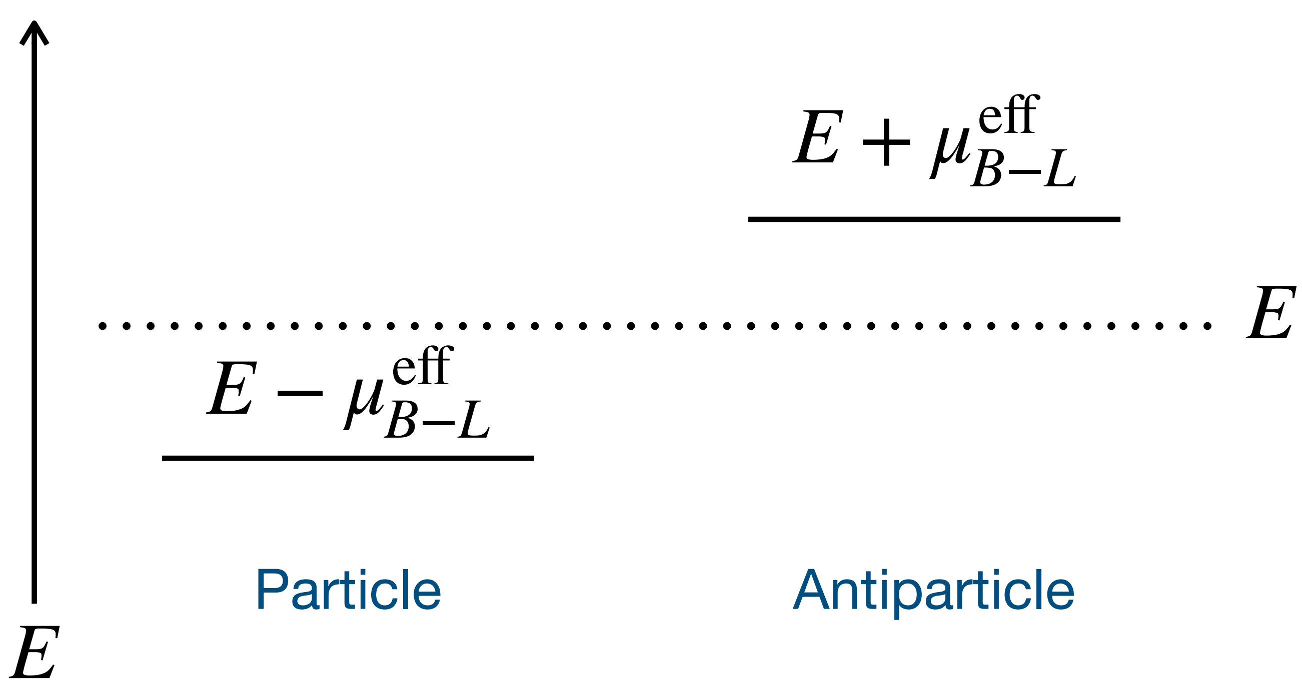

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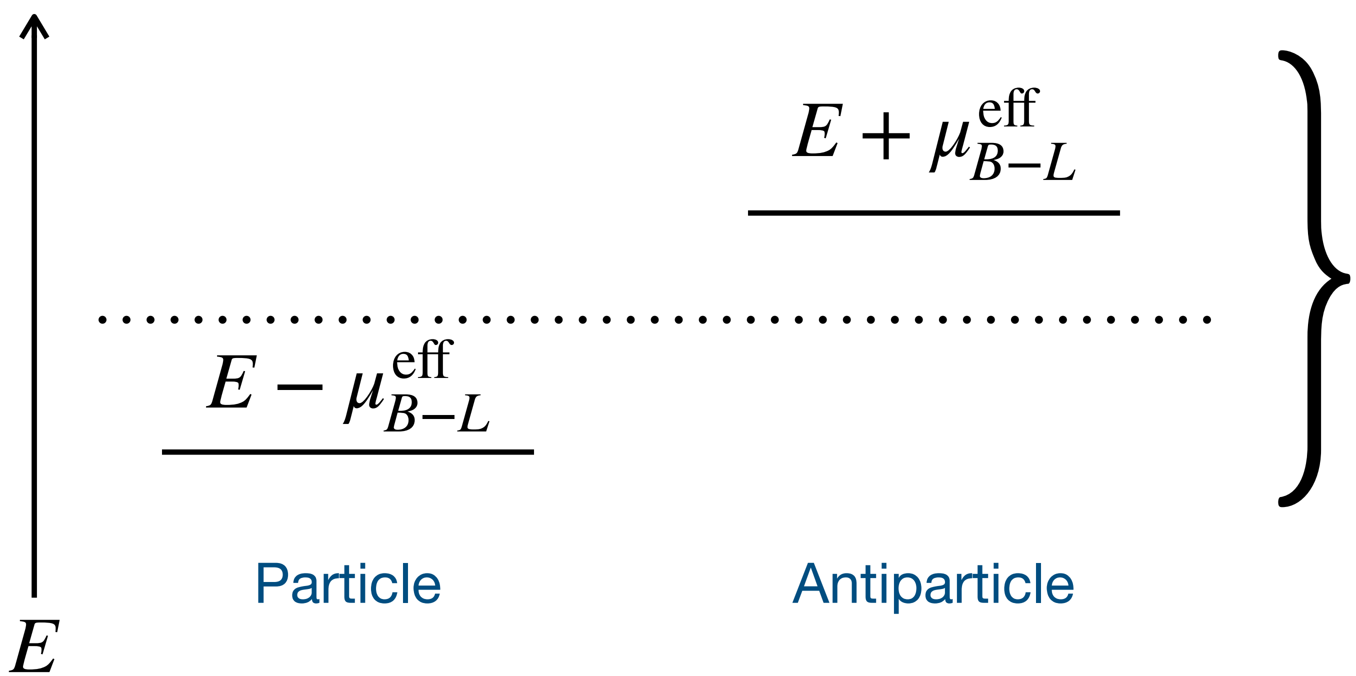

Biases equilibrium distribution function for particle and antiparticle

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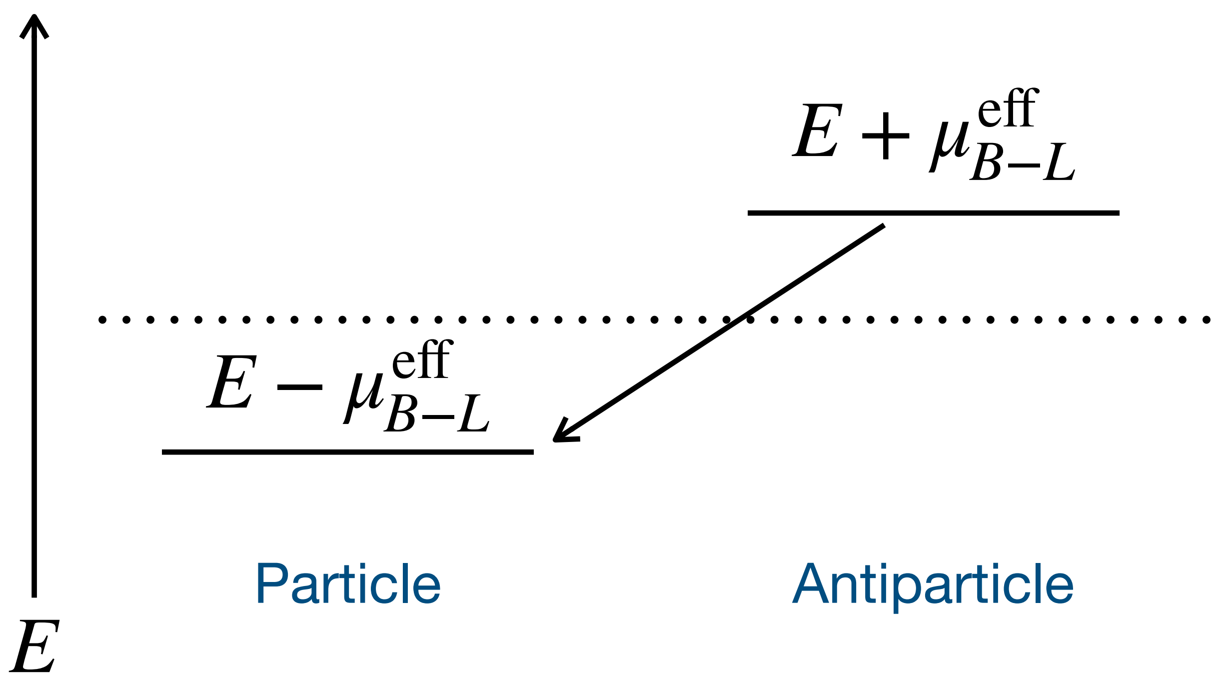

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presence of fast $B - L$ violating process

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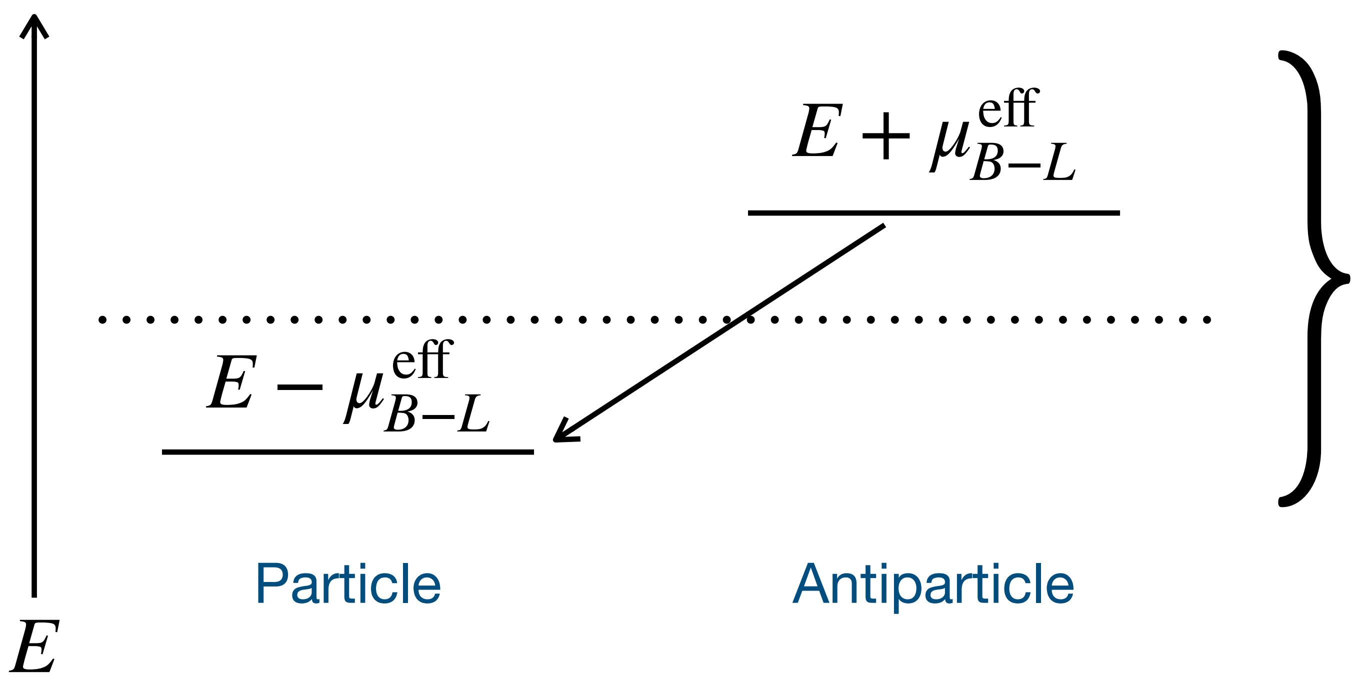

Biases equilibrium distribution function for particle and antiparticle

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presence of fast $B-L$ violating process

$Y_B^{\text{eq}} \neq 0 \xleftarrow{\text{Sphalerons}} \mu^{\text{eq}}_{B-L} = c_{B-L}\dot{\theta}$

[Cohen, 1987, Cohen, 1988]

Rolling Majoron gives rise to equilibrium baryon asymmetry in presence of fast $B-L$ violating interaction

Remember: For Minimal Scotogenic model with **two hierarchical RHNs**

Washout Factor: $K_1 = \Gamma_1/\mathcal{H}(M_1) >> 4$ $\quad M_1 \simeq 1$ TeV

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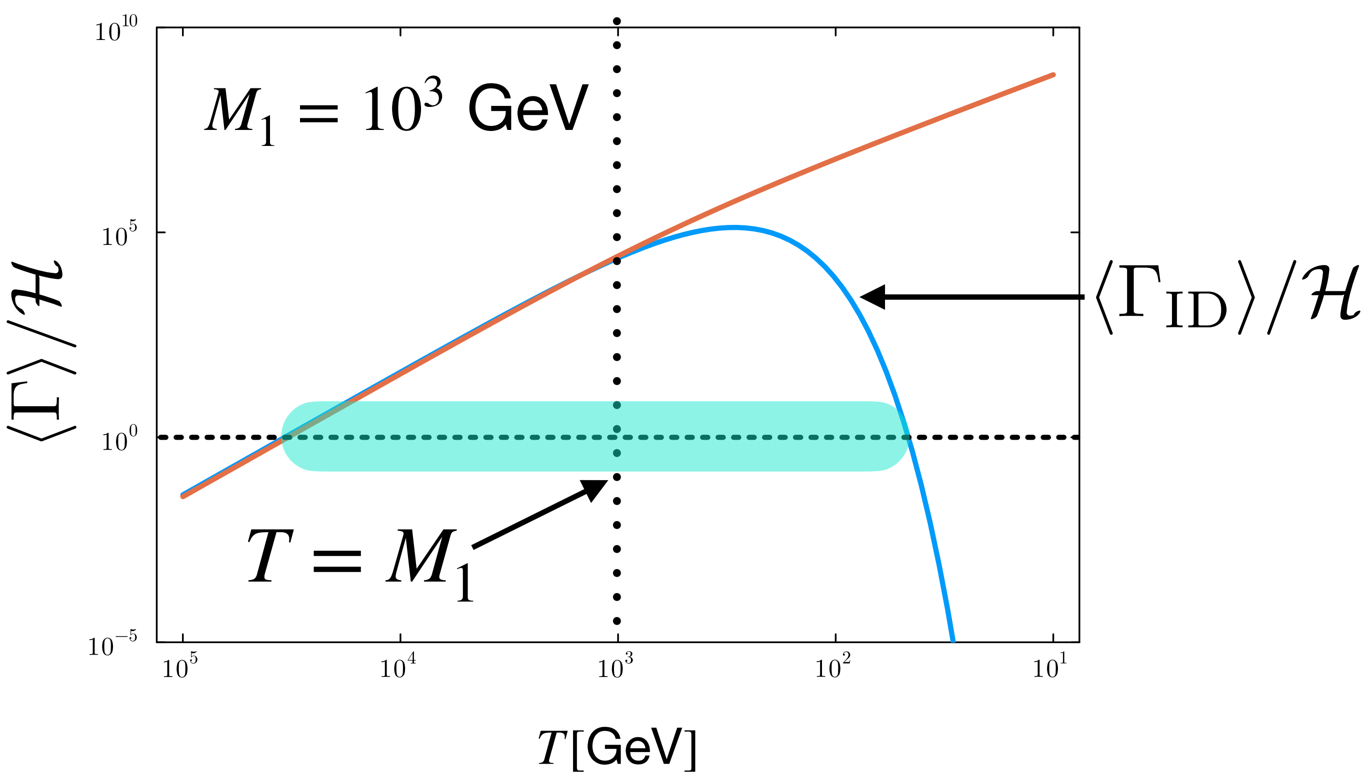

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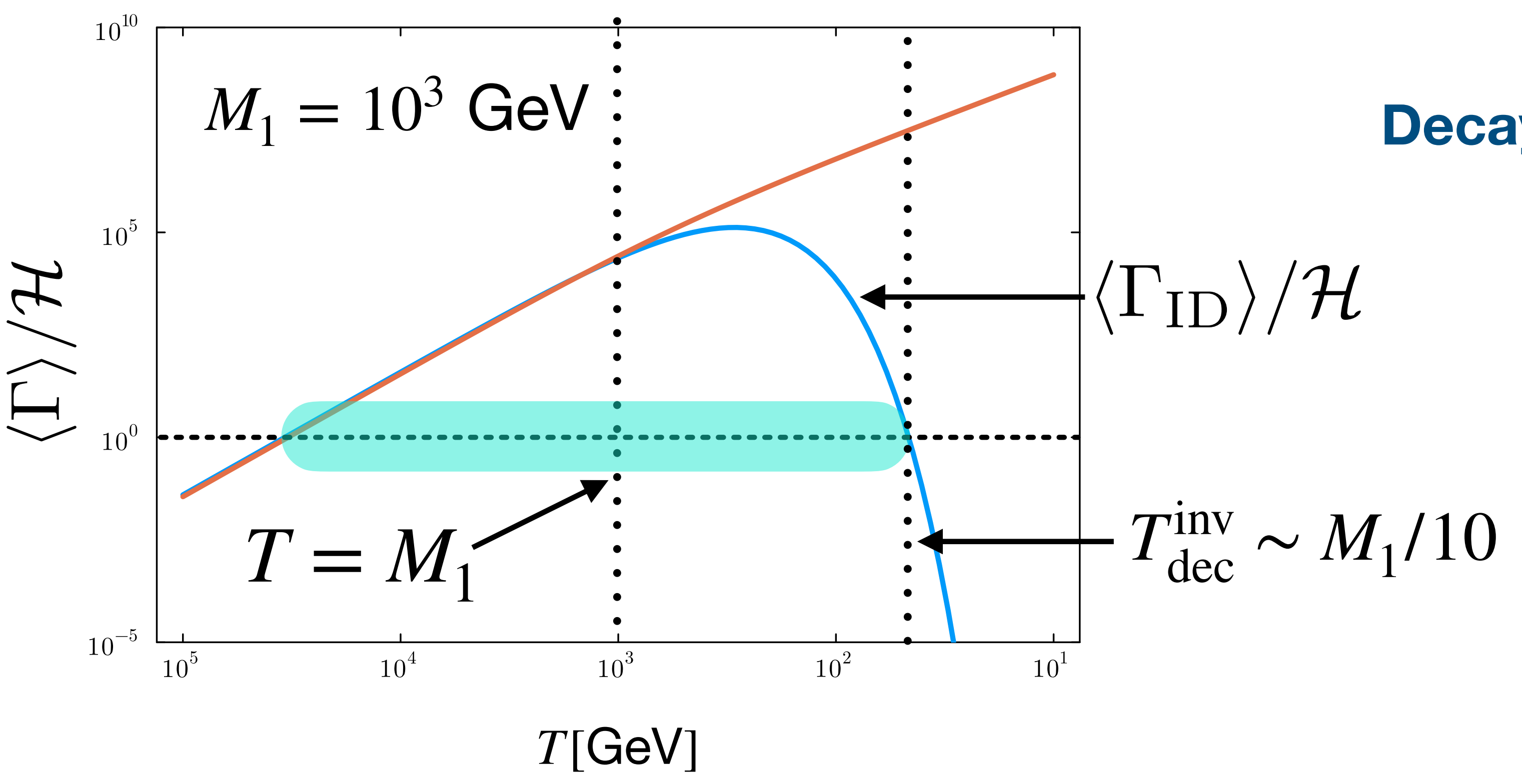

Decay and inverse decay remain in equilibrium for extended period of time

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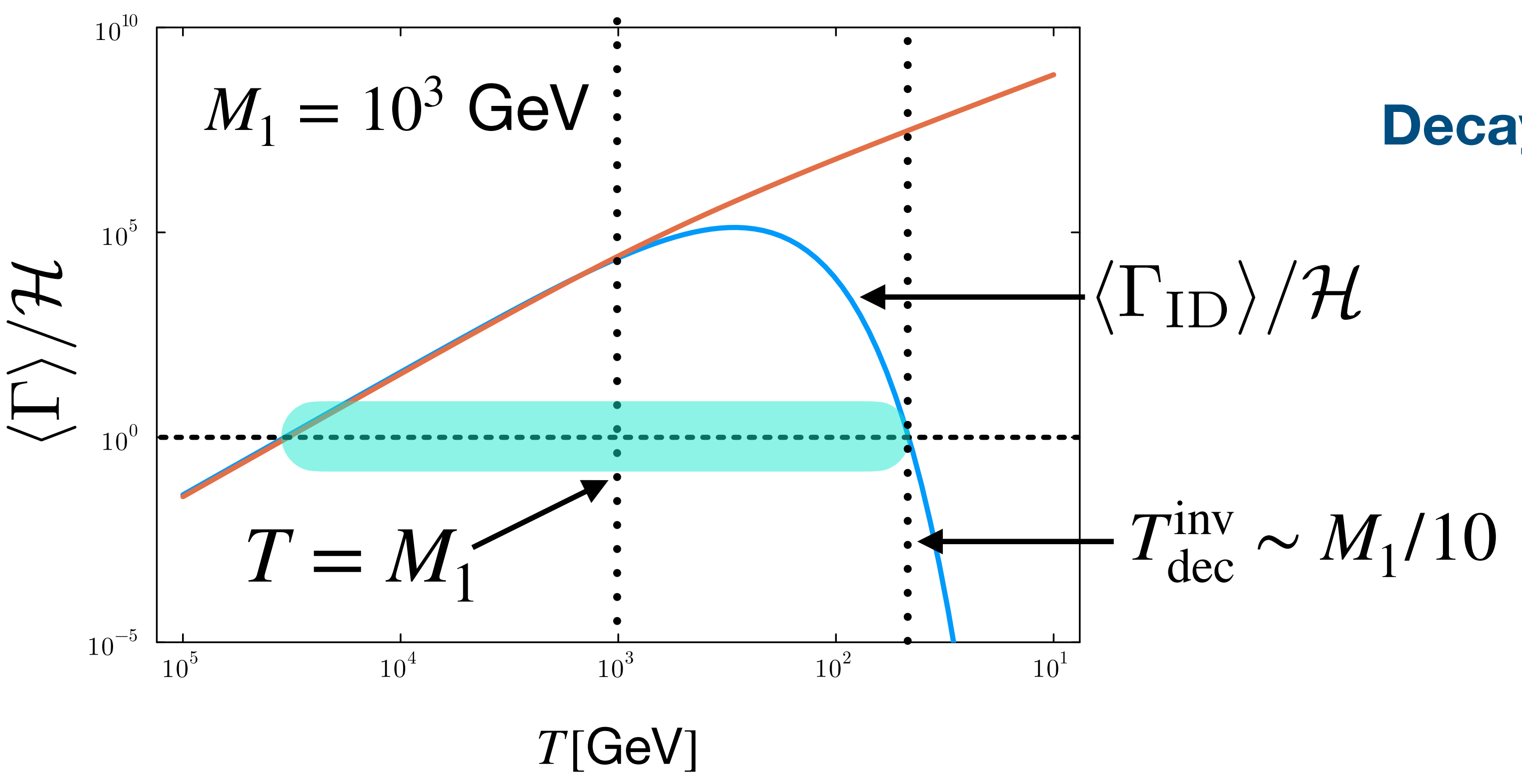

Decay and inverse decay remain in equilibrium for extended period of time

↓

Effectively $B-L$ violating process

↓ nonzero $\dot{\theta}$

Nonzero Y_{B-L}

Rolling Majoron gives rise to equilibrium baryon asymmetry in presence of fast $B-L$ violating interaction

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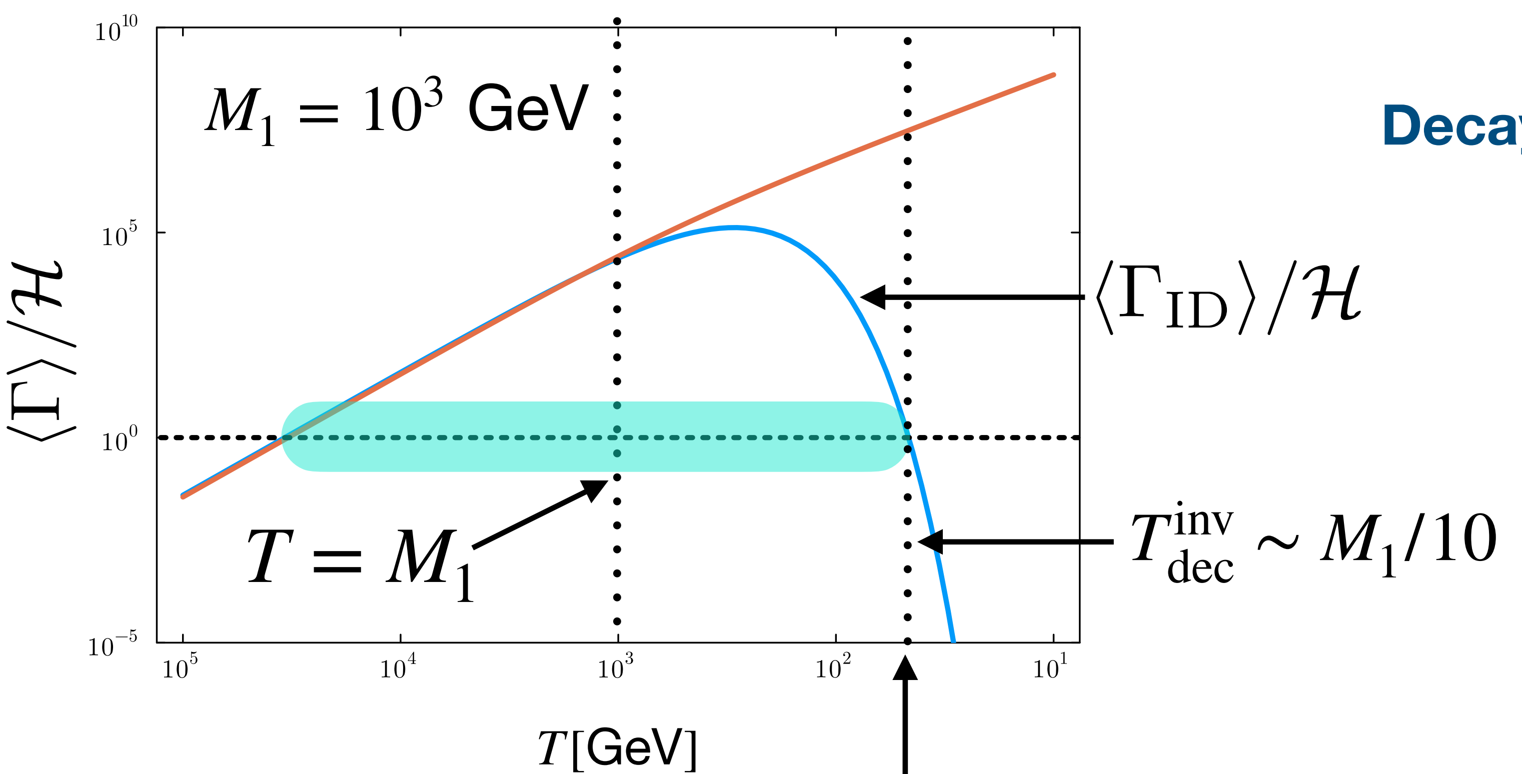

Y_{B-L} **saturates when** $\langle\Gamma_{\rm ID}\rangle < H$

Decay and inverse decay remain in equilibrium for extended period of time

↓

Effectively $B-L$ violating process

↓ nonzero $\dot{\theta}$

Nonzero Y_{B-L}

$$Y_B = \frac{c_B}{6} Y_\theta \left(\frac{M_1}{v_\varphi z_{\rm dec}}\right)^2$$

Rolling Majoron gives rise to equilibrium baryon asymmetry in presence of fast $B-L$ violating interaction

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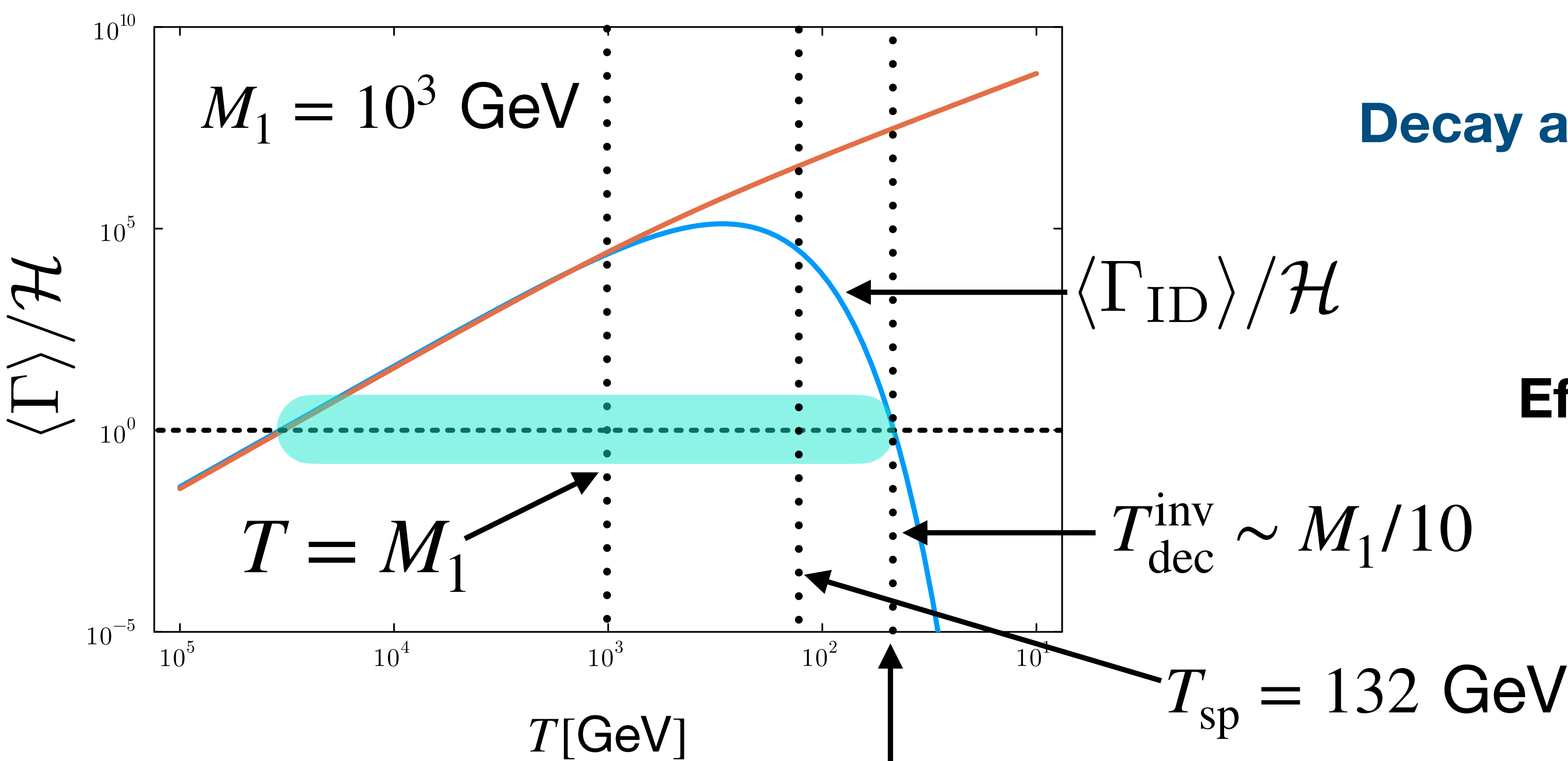


Decay and inverse decay remain in equilibrium for extended period of time

Effectively $B-L$ violating process

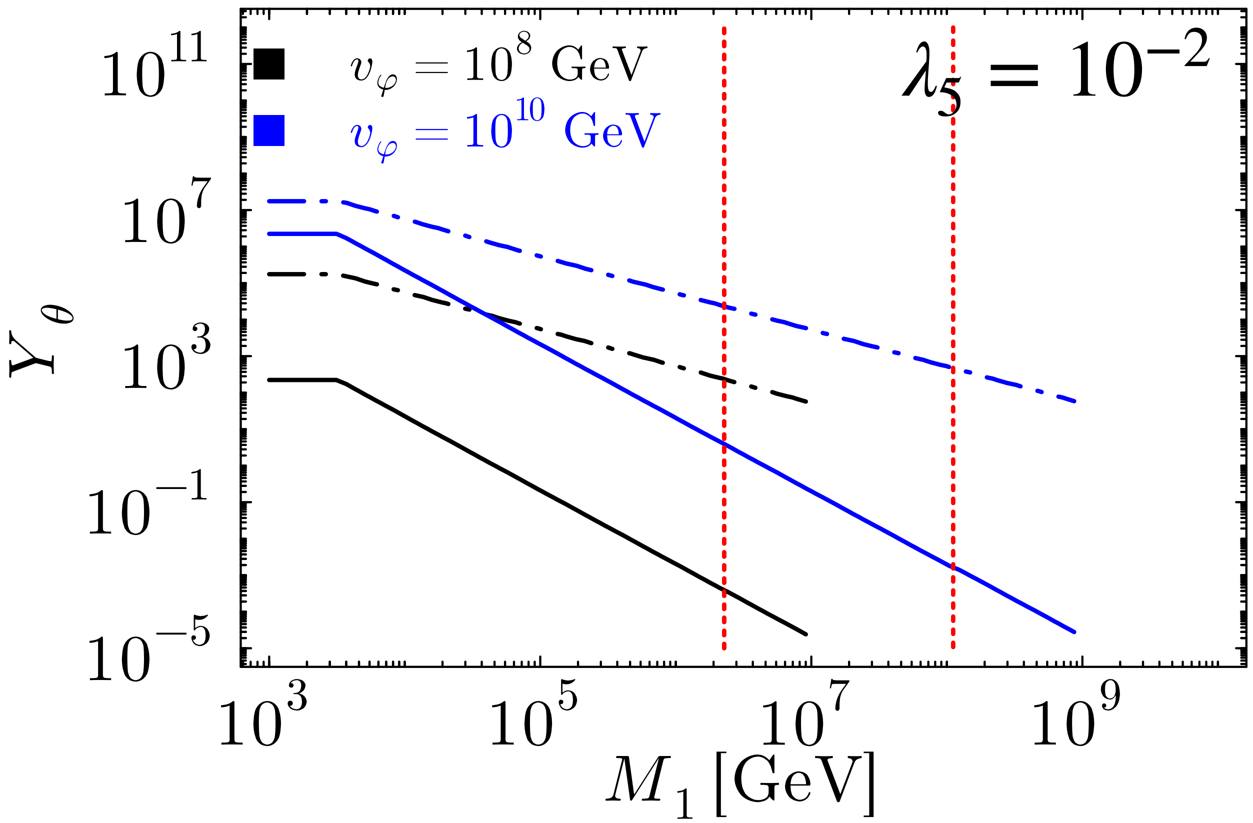
nonzero $\dot{\theta}$

Nonzero Y_{B-L}

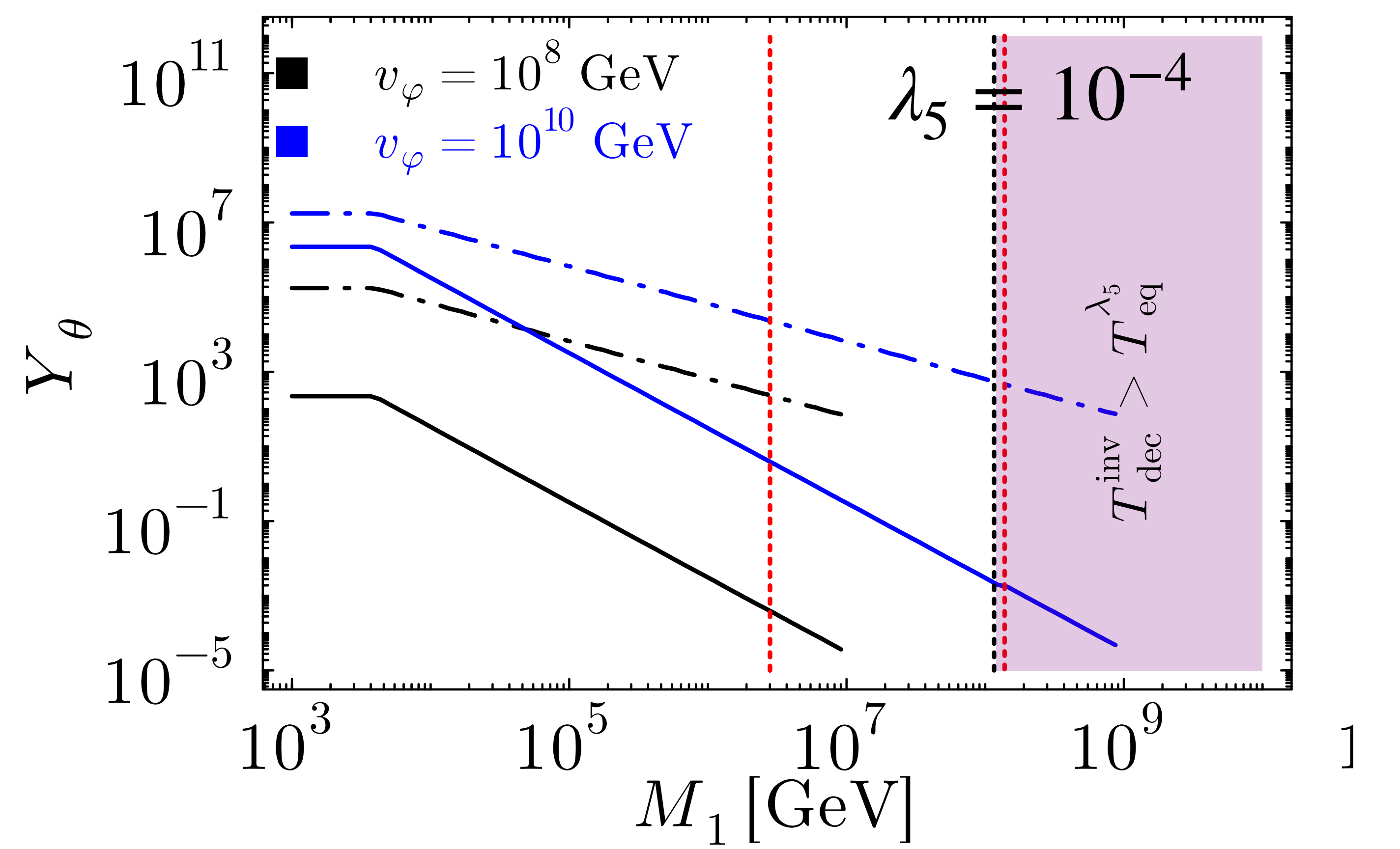
Y_{B-L} saturates when $\langle\Gamma_{\rm ID}\rangle < H$

Y_B saturates at $T = T_{\rm sp}$ $\longrightarrow$ $Y_B = \dfrac{c_B}{6} Y_\theta \left(\dfrac{M_1}{v_\varphi z_{\rm sp}}\right)^2$

parameter space for leptogenesis:



$$Y_B = \frac{c_B}{6} Y_\theta \left(\frac{M_1}{v_\varphi z_{\rm dec}} \right)^2$$



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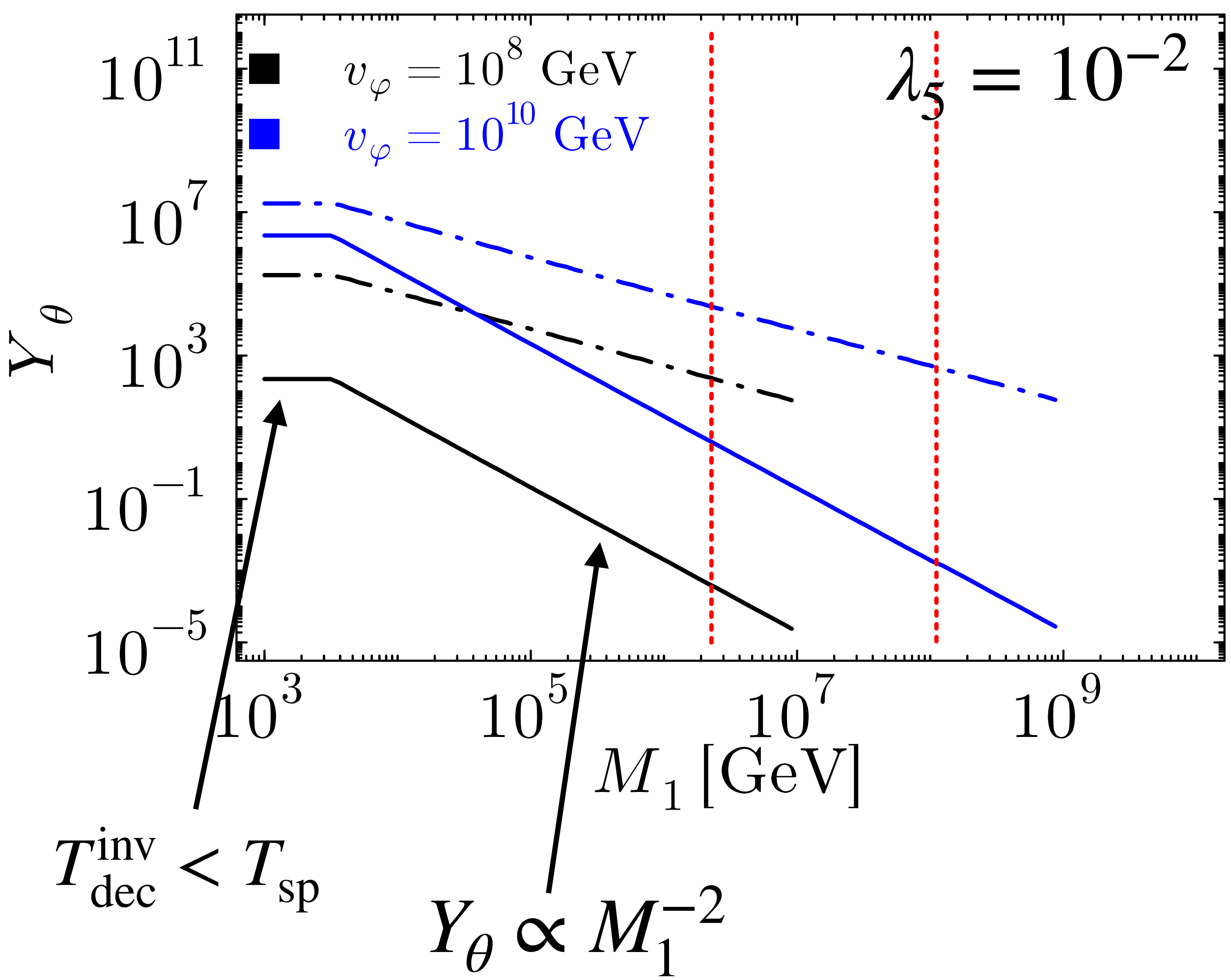

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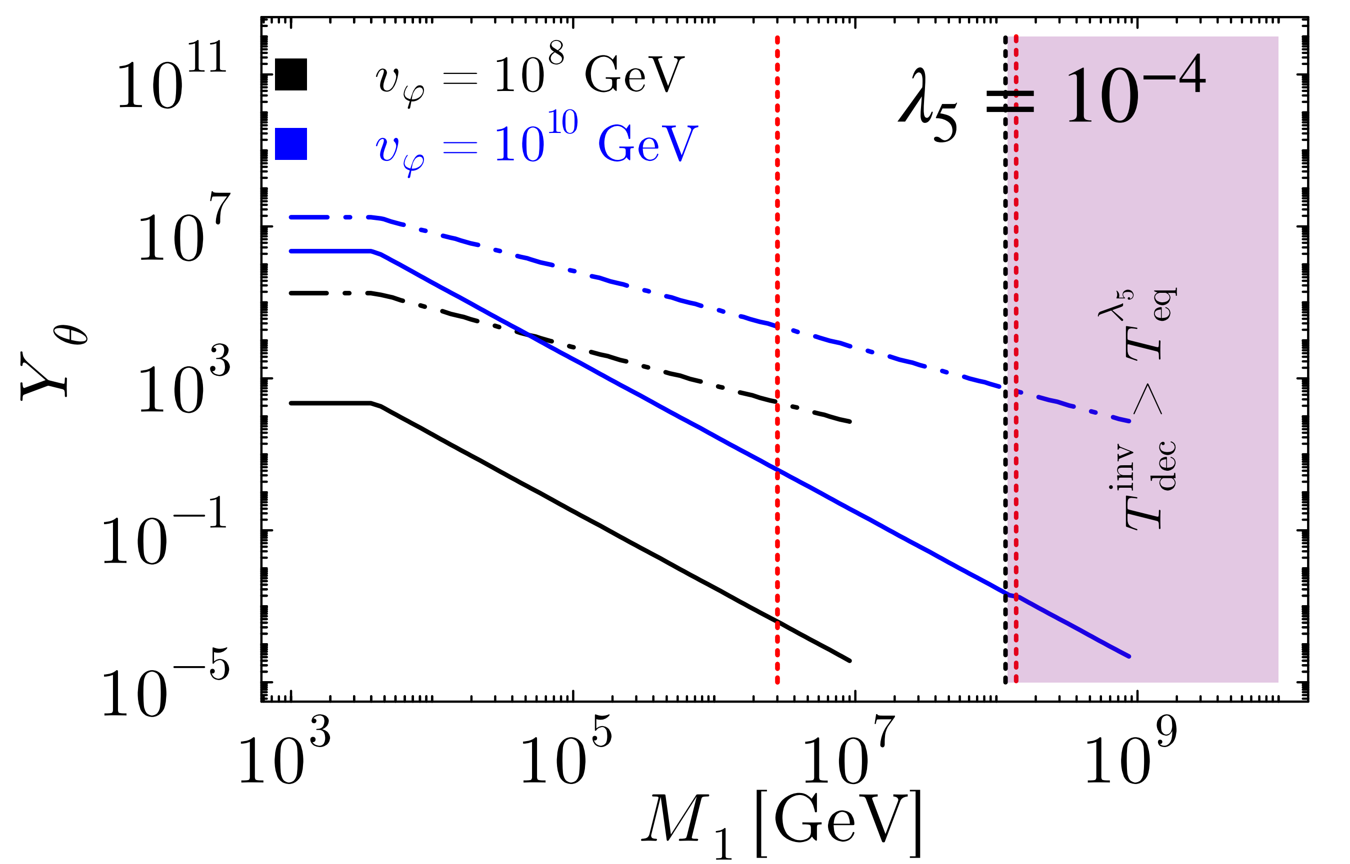

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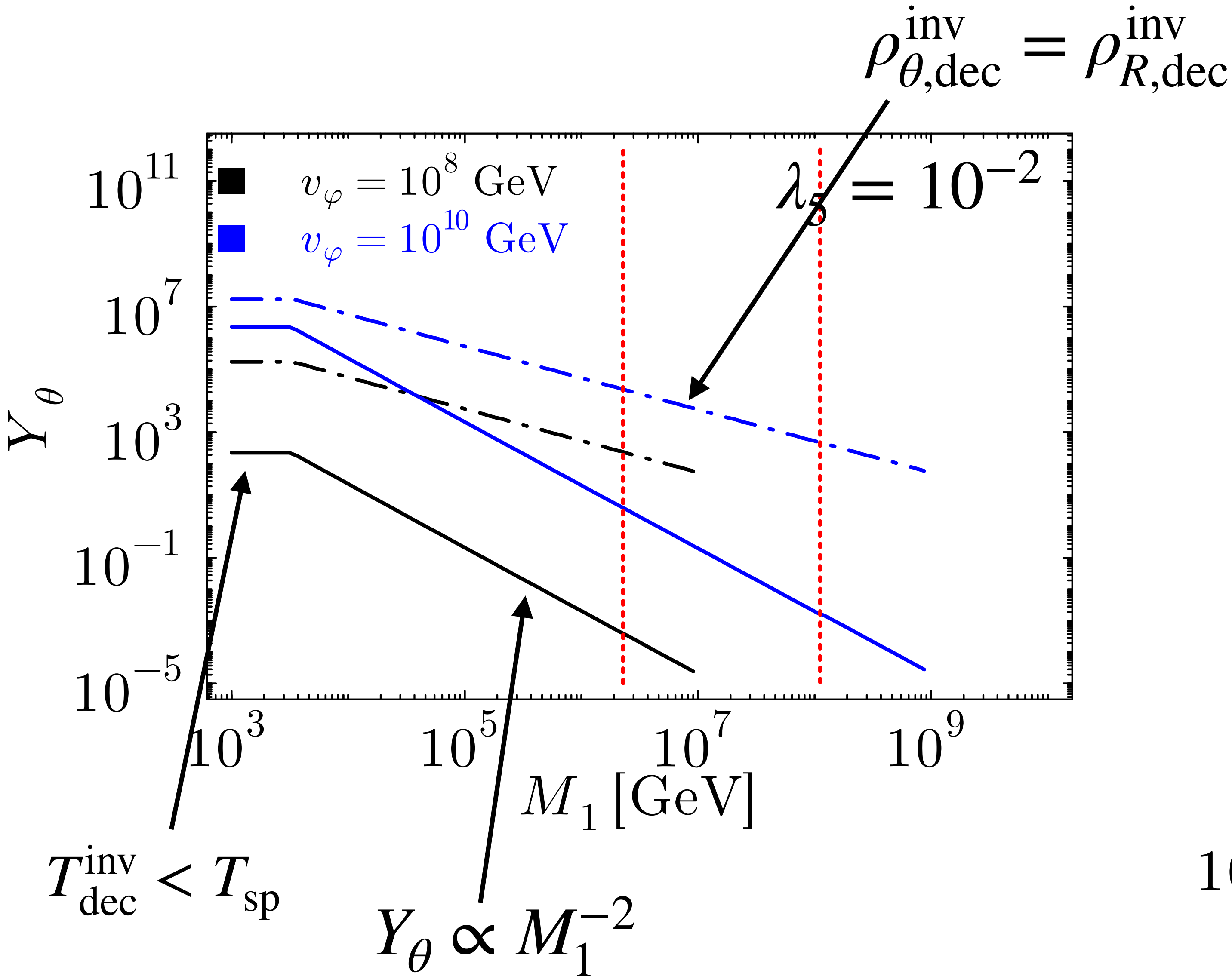

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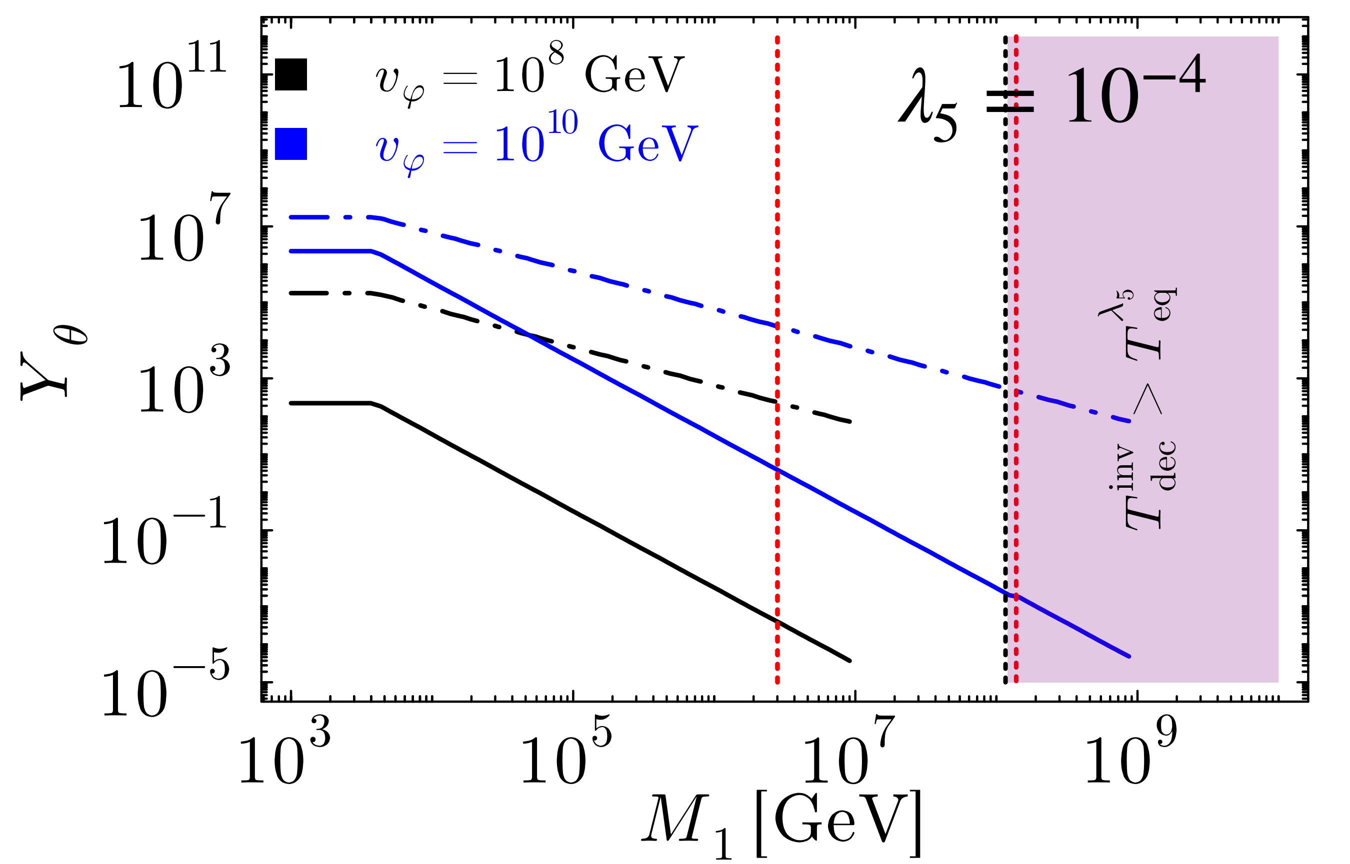
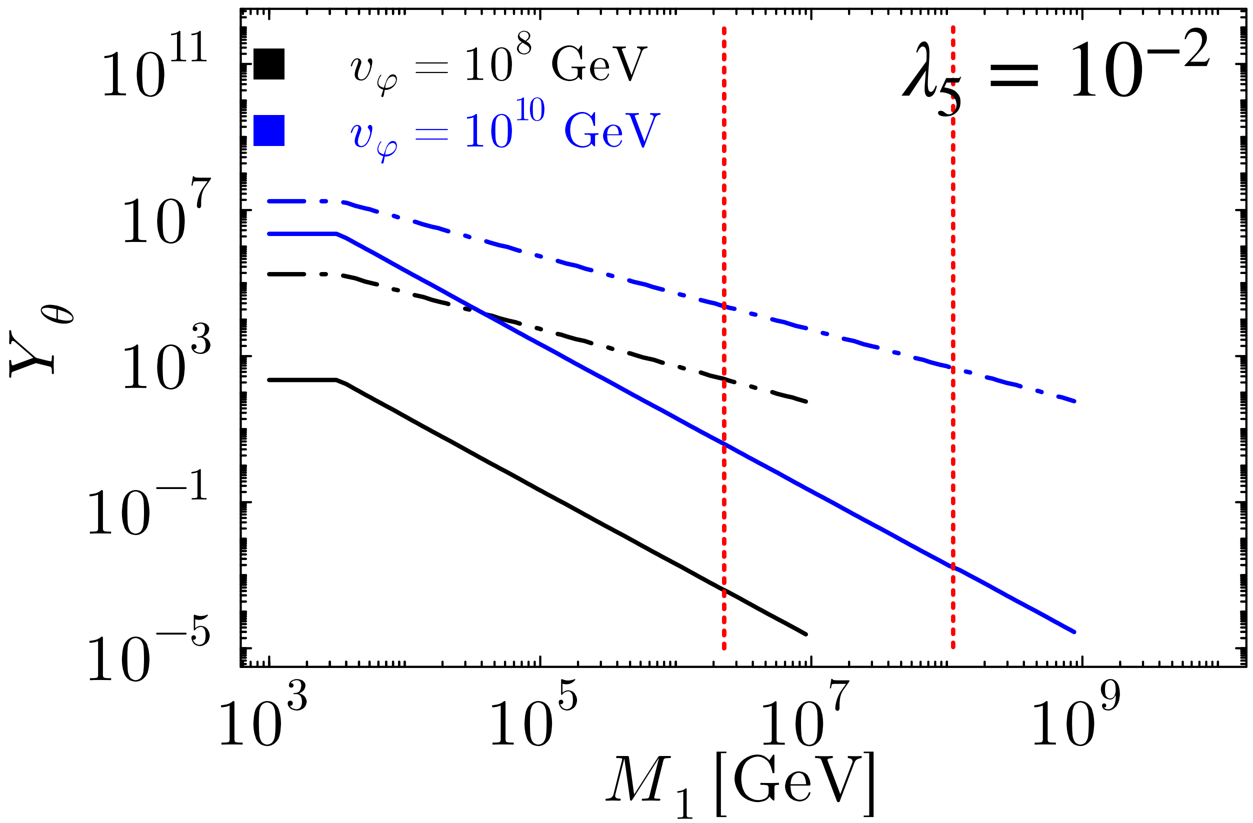


parameter space for leptogenesis:

$$\frac{\lambda_5}{2}\left[(\eta^\dagger\Phi)^2 + \mathrm{h.c}\right]$$



If in equilibrium (large λ_5), induces $\mu_\eta = \mu_\Phi$

Helps converting individual particle asymmetry to $B-L$ asymmetry

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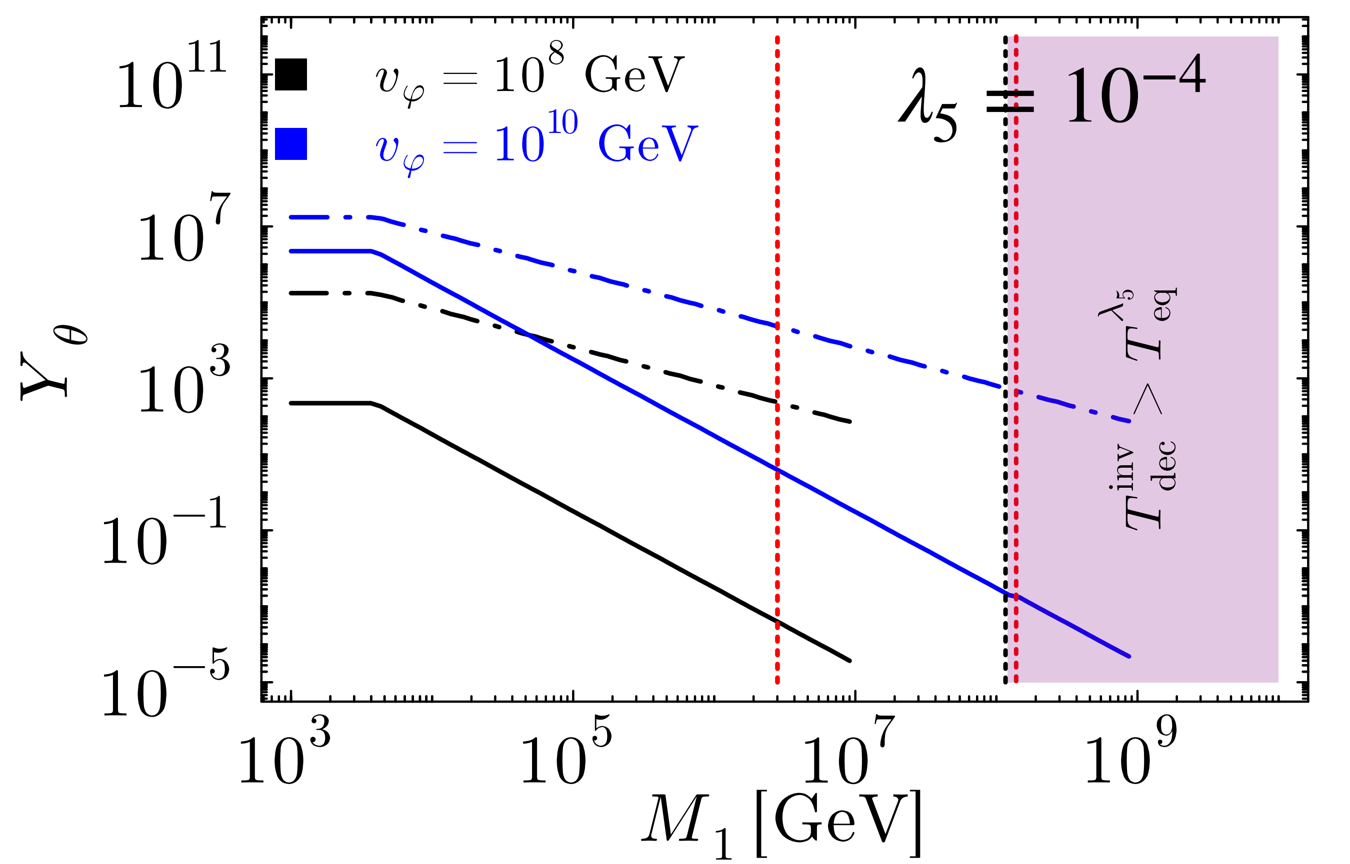
for small λ_5, interaction equilibrate late in time

If inverse decay decouples before equilibration of the λ_5 interaction μ_η is independent variable.



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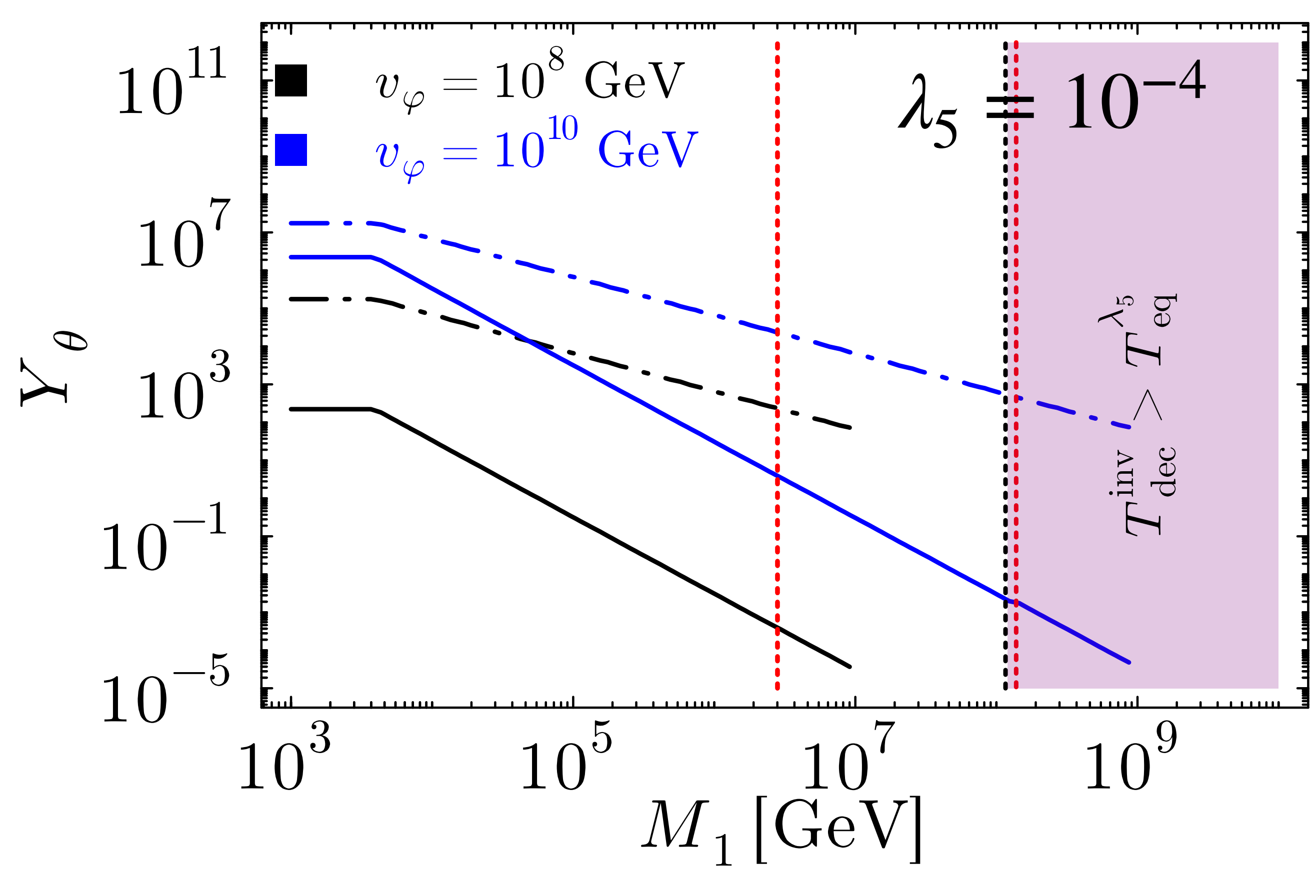
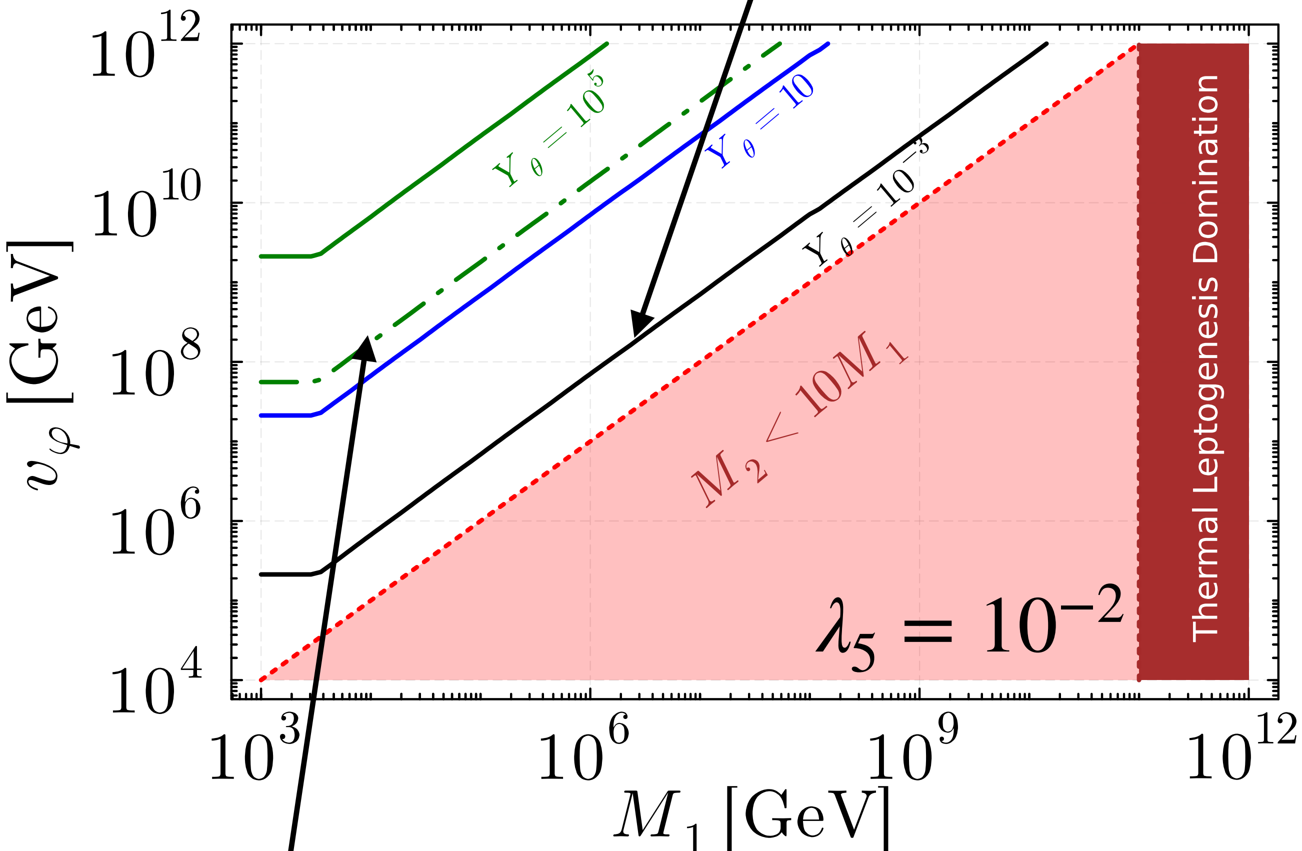
μ_η is independent variable.
For low scale leptogenesis
$\mu_\eta \simeq 0$



parameter space for leptogenesis:

$v_\varphi \propto M_1$



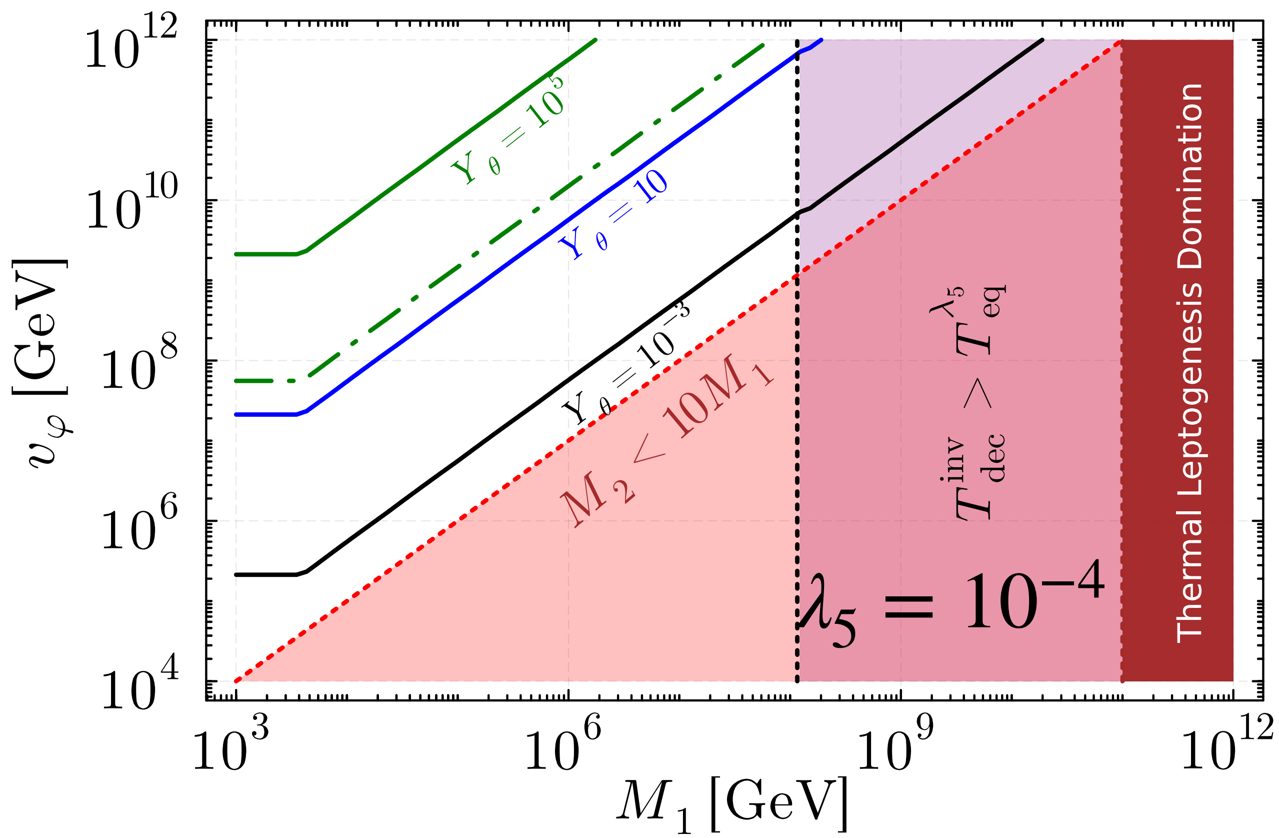
$\rho^{\rm inv}_{\theta,\rm dec} = \rho^{\rm inv}_{R,\rm dec}$

$$Y_B = \frac{c_B}{6} Y_\theta \left(\frac{M_1}{v_\varphi z_{\rm dec}} \right)^2$$

With fixed Y_θ, for a larger M_1 one needs larger v_φ to generate correct BAU

Low Y_θ can generate observed BAU for low M_1 and low v_φ

As long as $M_1 > m_\eta$ and $B-L$ violation is fast Y_B can be achieved



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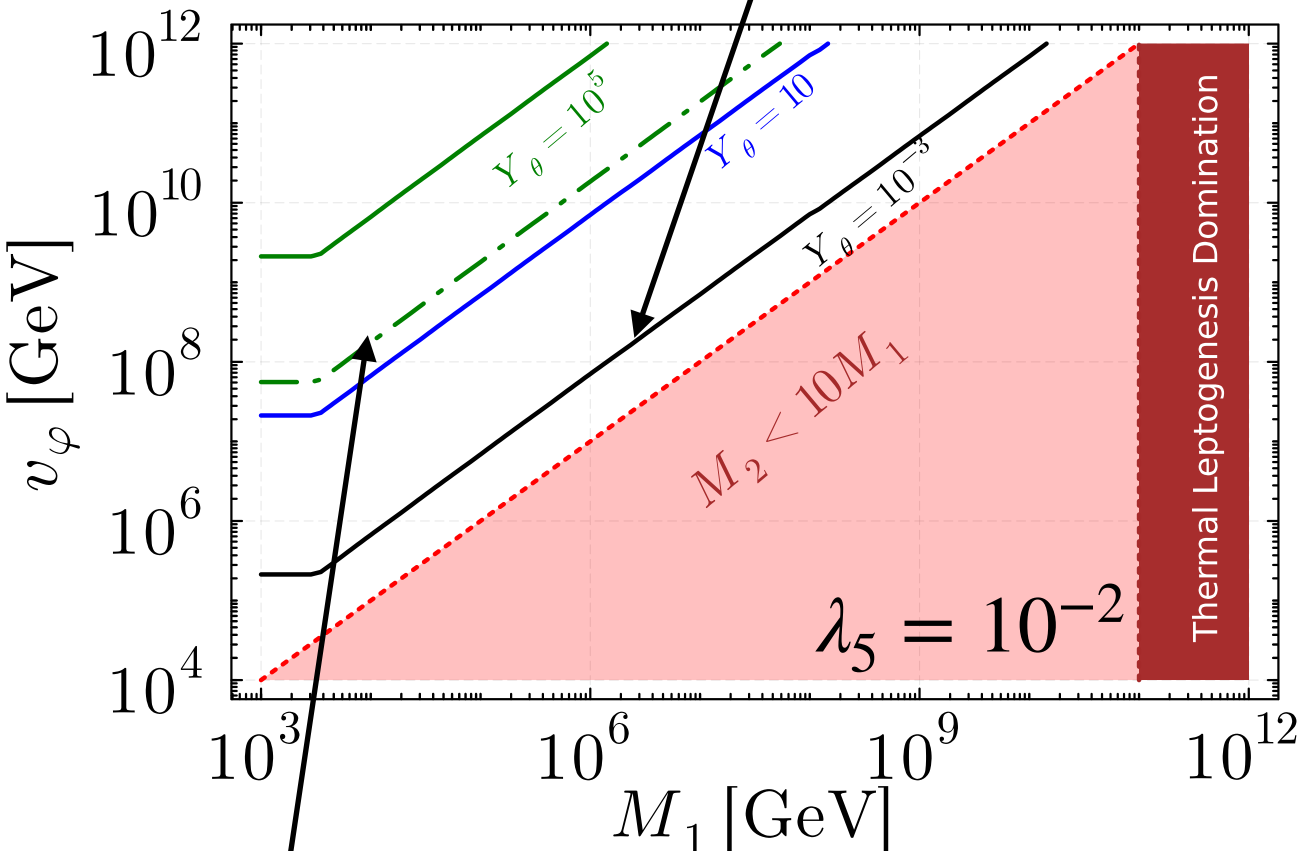

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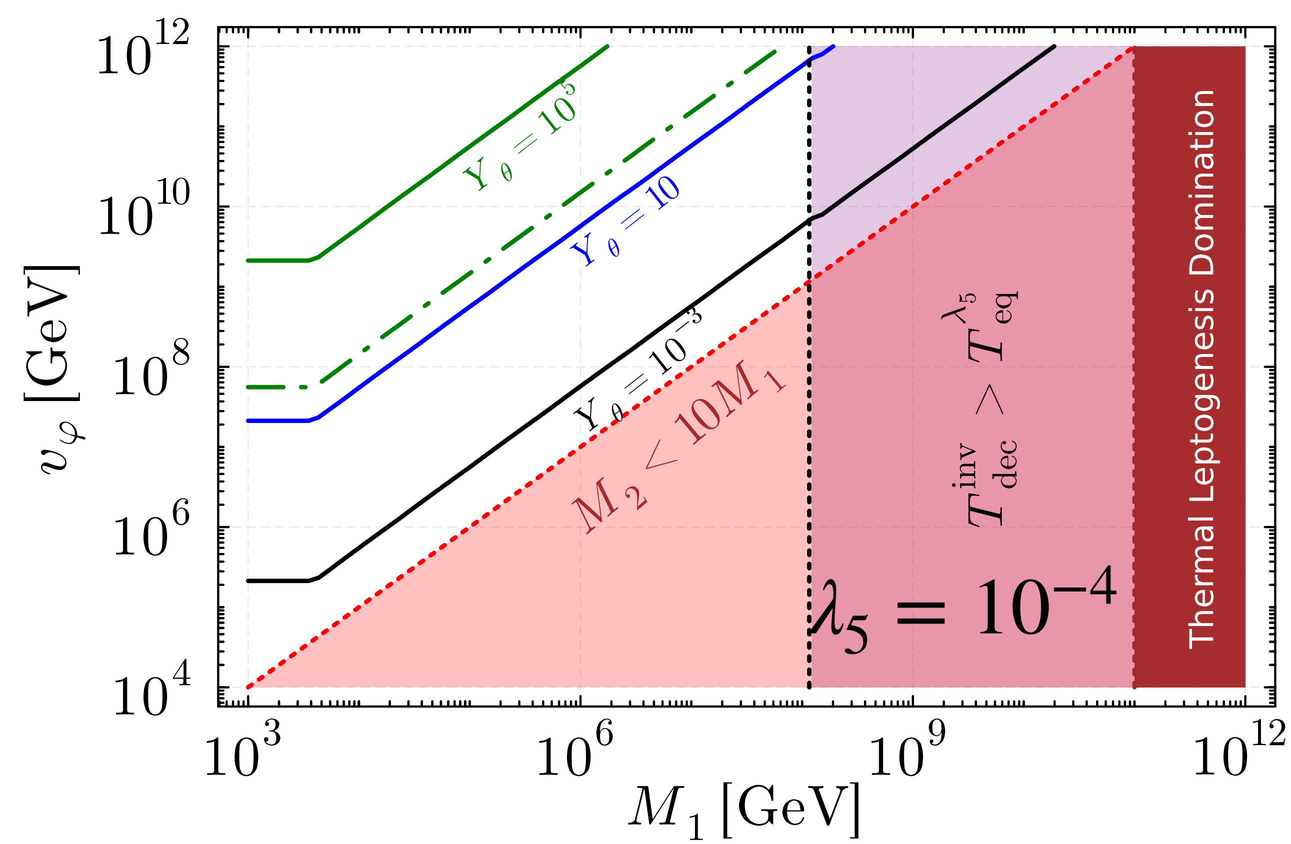
CP odd component of inert scalar: η_I

↓

100% DM

$$\lambda_5 > 10^{-6} \qquad \overbrace{\underbrace{m_{\eta_I} = [550 - 1000]\ \text{GeV}}}$$

$M_1 > \mathcal{O}(600)$ **GeV** ⟶ **observed Y_B**



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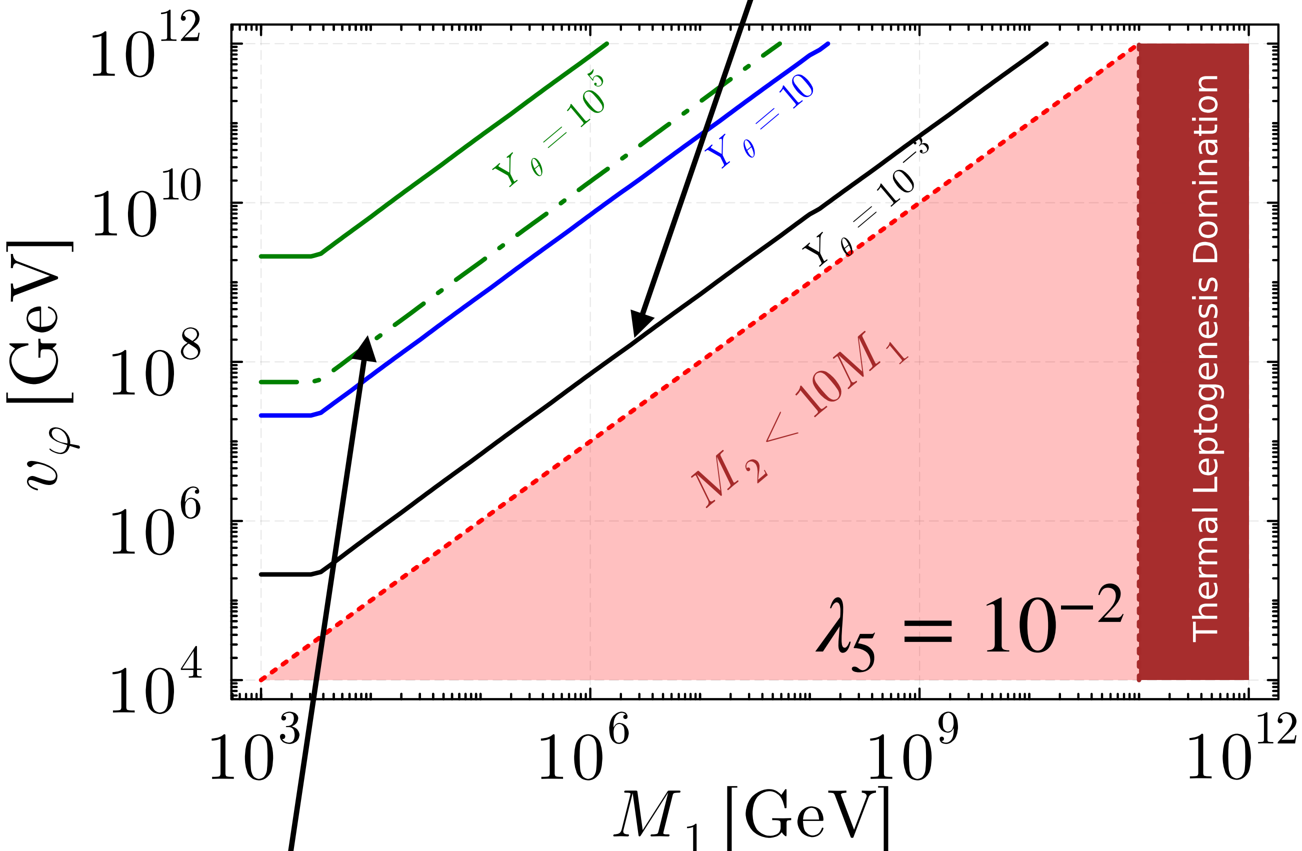

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Can we reduce the scale more??

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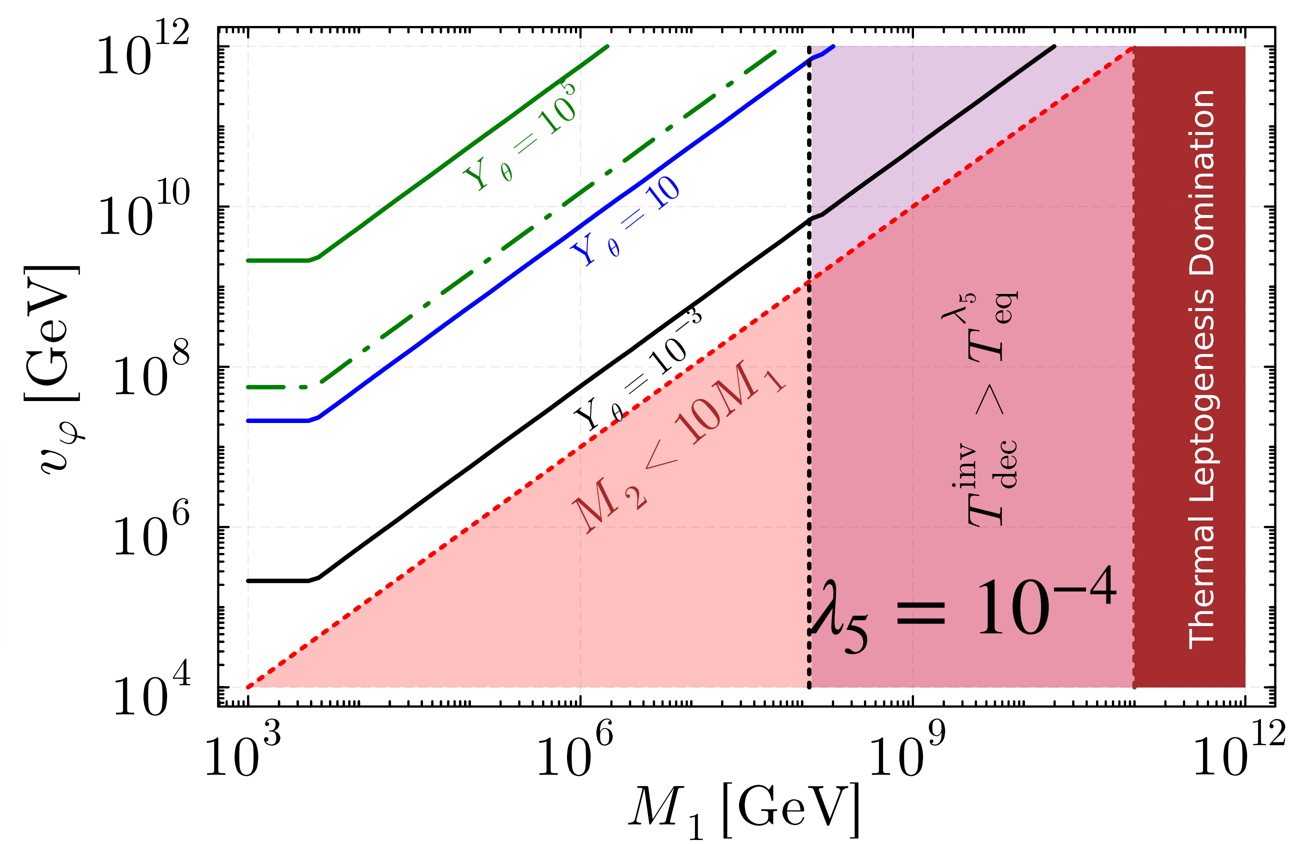

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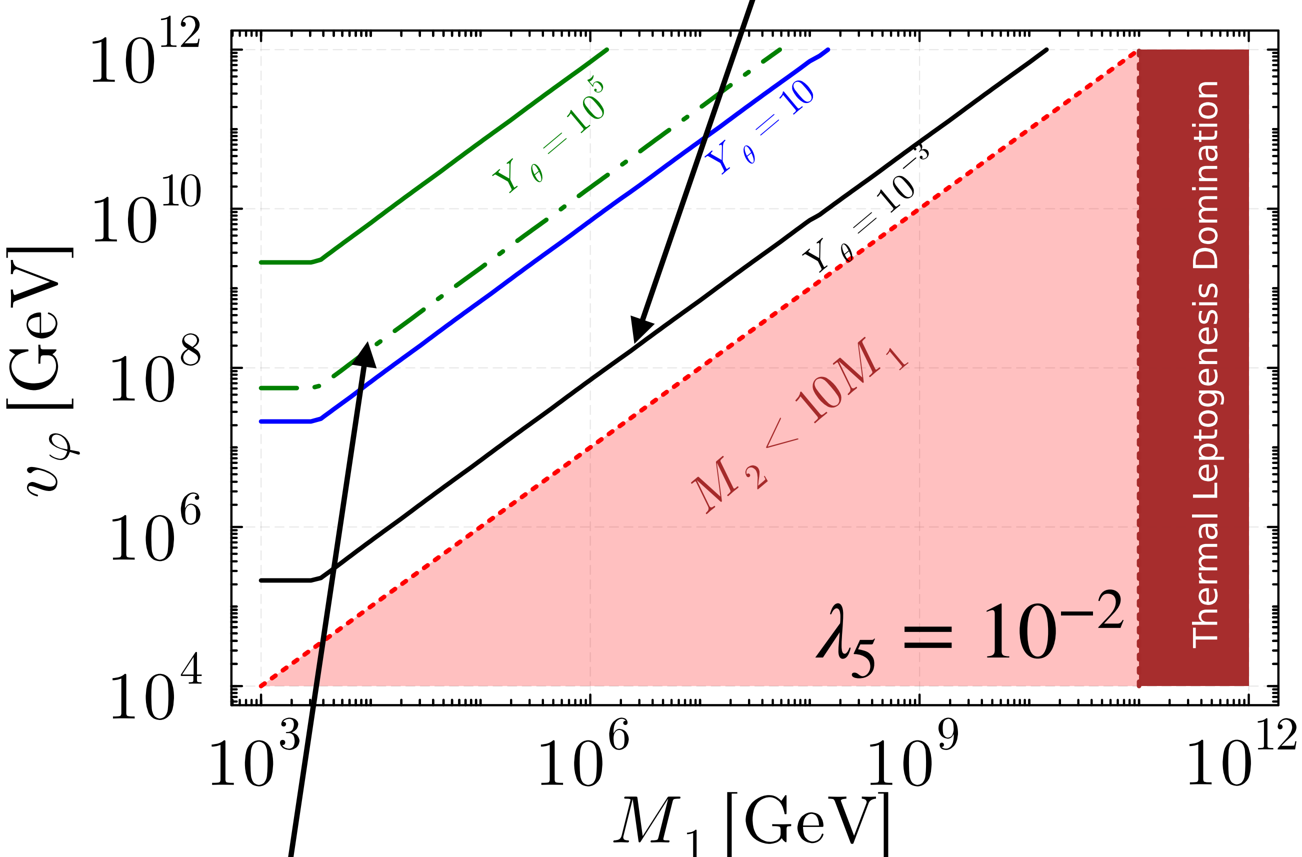

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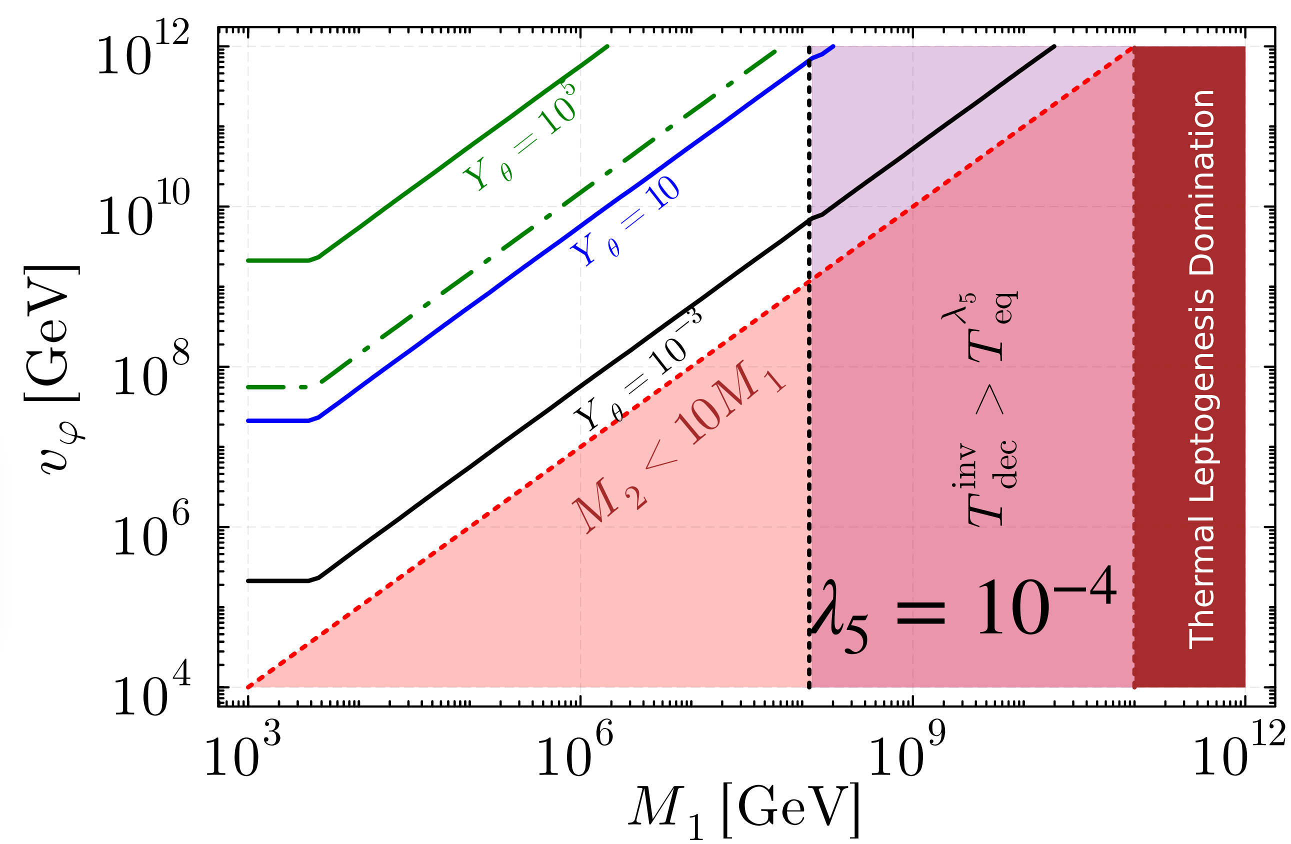
Subdominant DM $m_{\eta_I} < 550$ GeV

Can we reduce the scale more??

smaller M_1 can also explain observed Y_B



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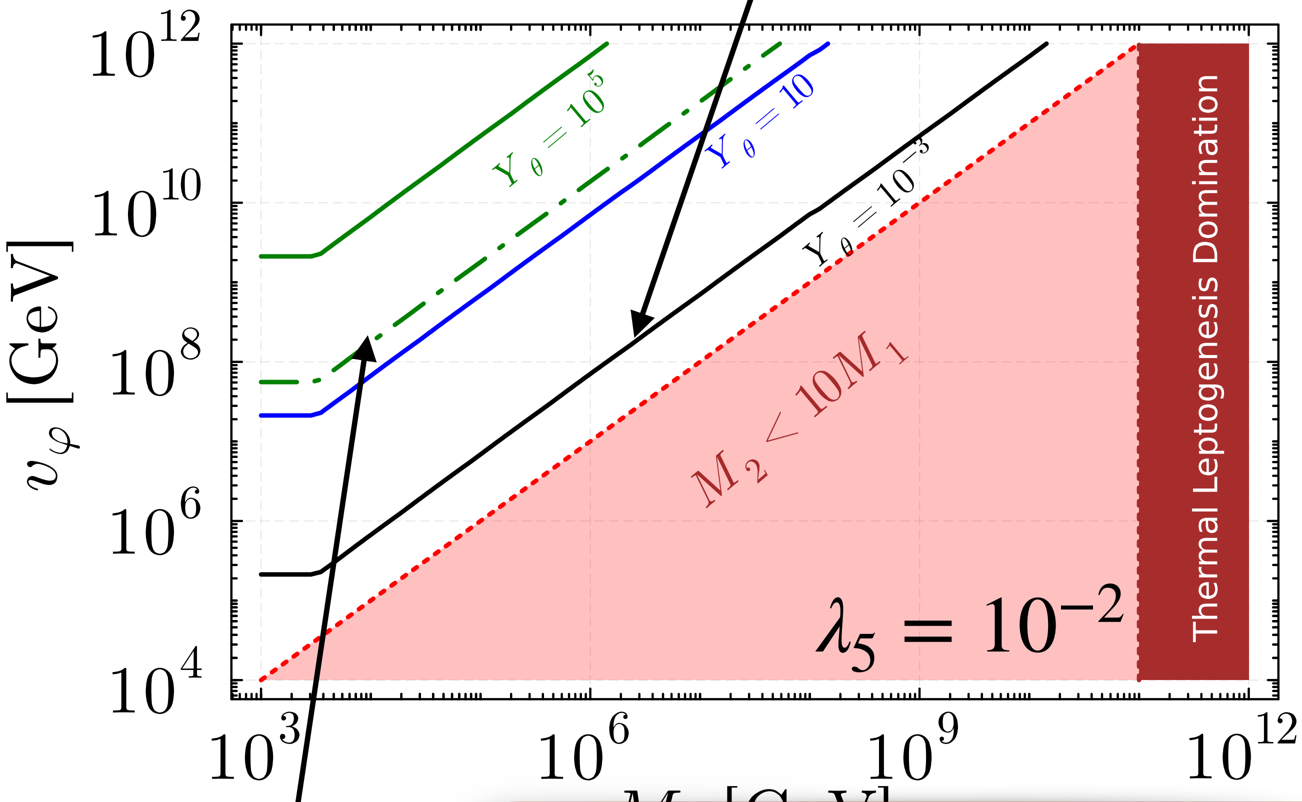

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How to produce Observed DM abundance?

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↓

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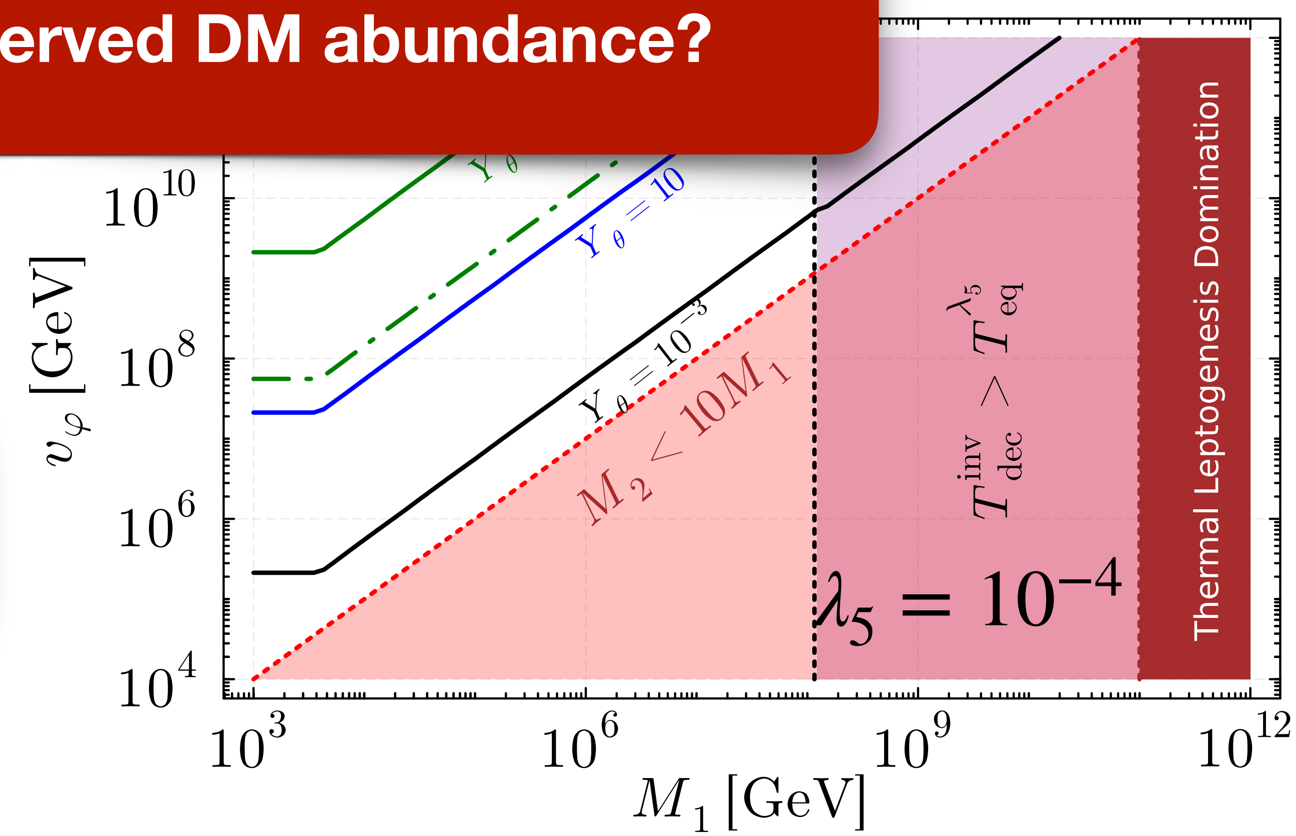

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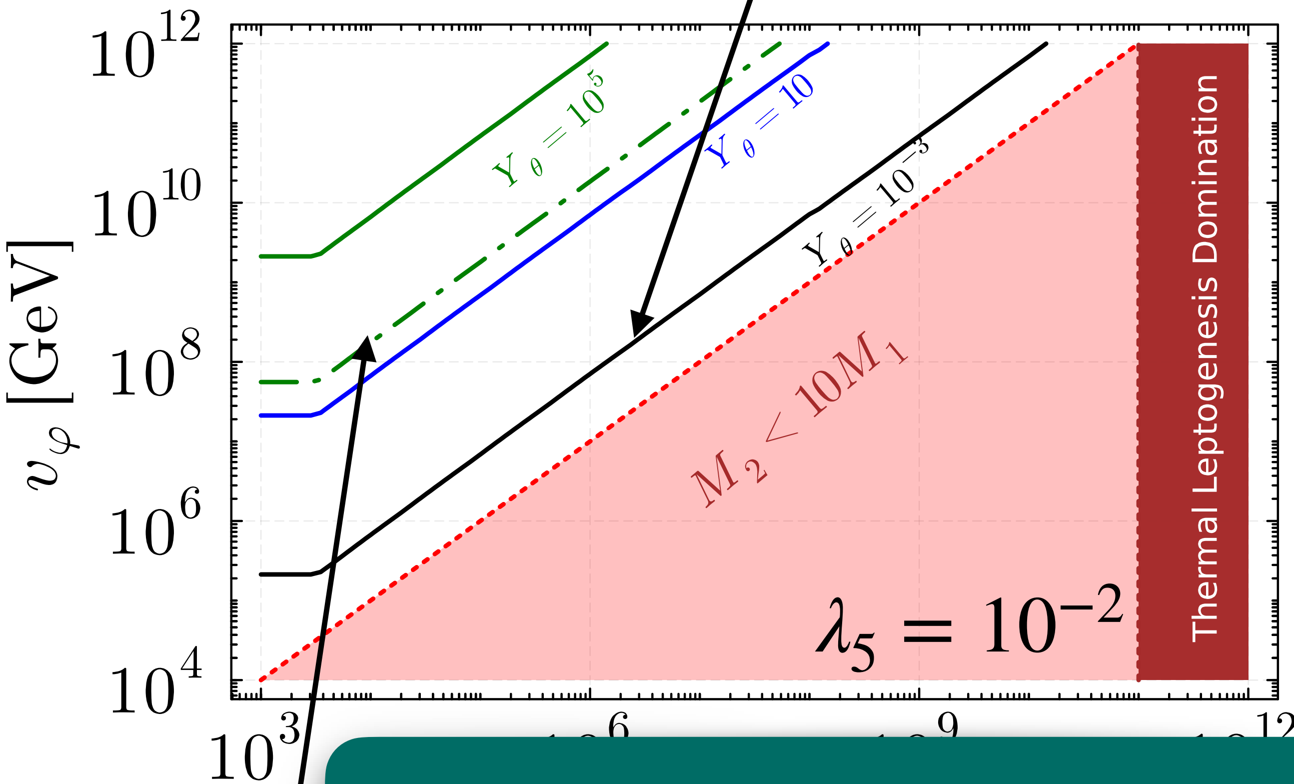

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Low Y_θ can generate observed BAU for low M_1 and low v_φ

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$\rho^{\mathrm{inv}}_{\theta,\mathrm{dec}} =$

Majoron can help !!

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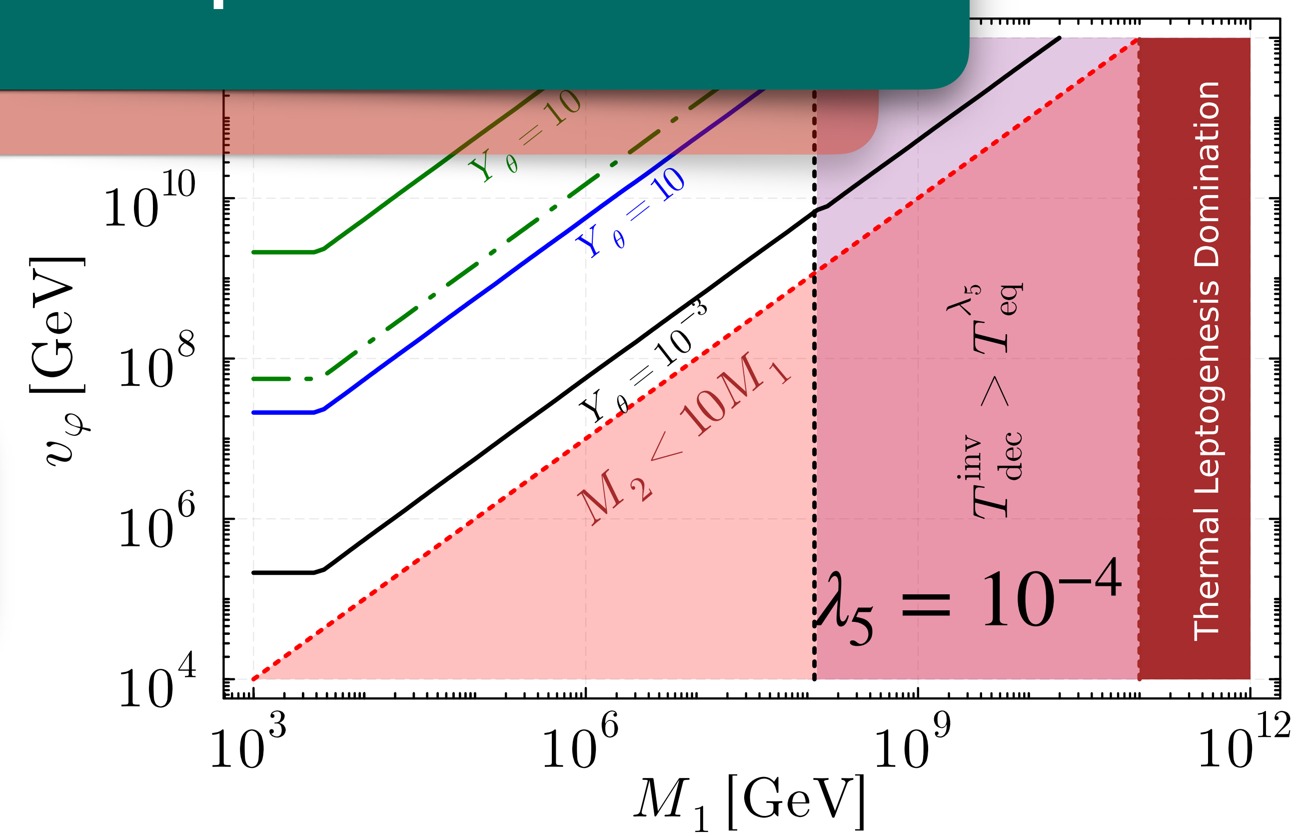
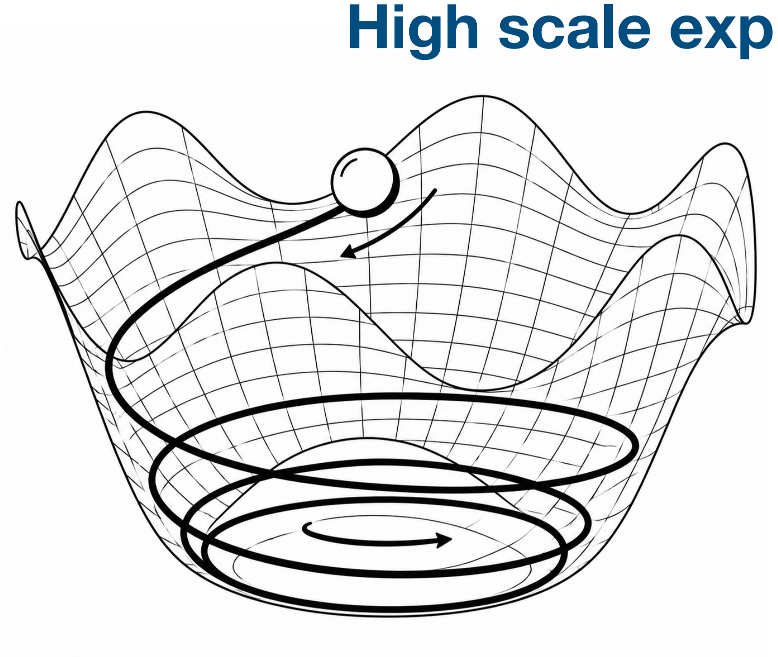


Origin of velocity:

High scale explicit breaking of the $U(1)_{B-L}$ can generate required $\dot{\theta}$



As Universe expands potential becomes subdominant
Y_θ becomes constant

Origin of Majoron DM:

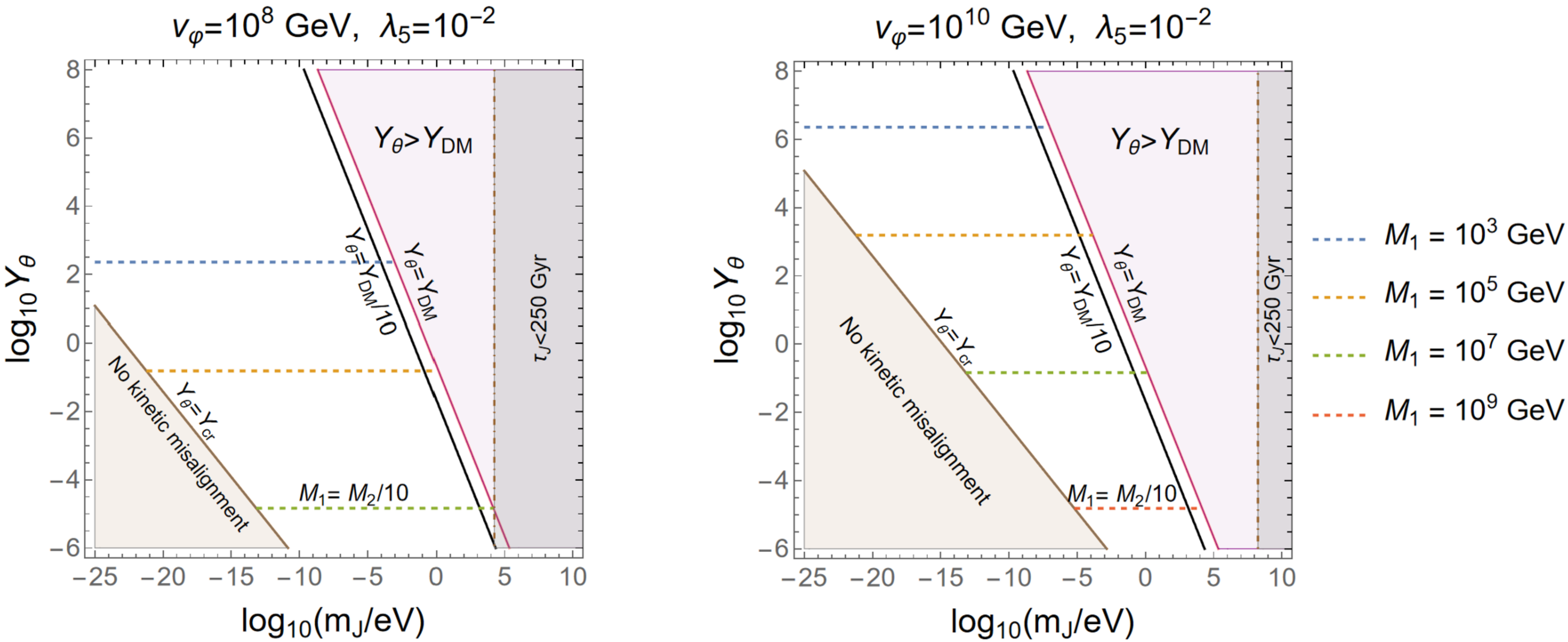
Same explicit breaking can give rise to Majoron mass

As Universe expands, Kinetic energy dilutes then it can get trapped in its potential
& start oscillating around its potential minima

while oscillating Majoron can act as cold condensate DM

Allowed parameter space:

$$V(J) = m_J^2 v_\varphi^2 \left[1 - \cos\left(\frac{J}{v_\varphi}\right)\right] ;$$



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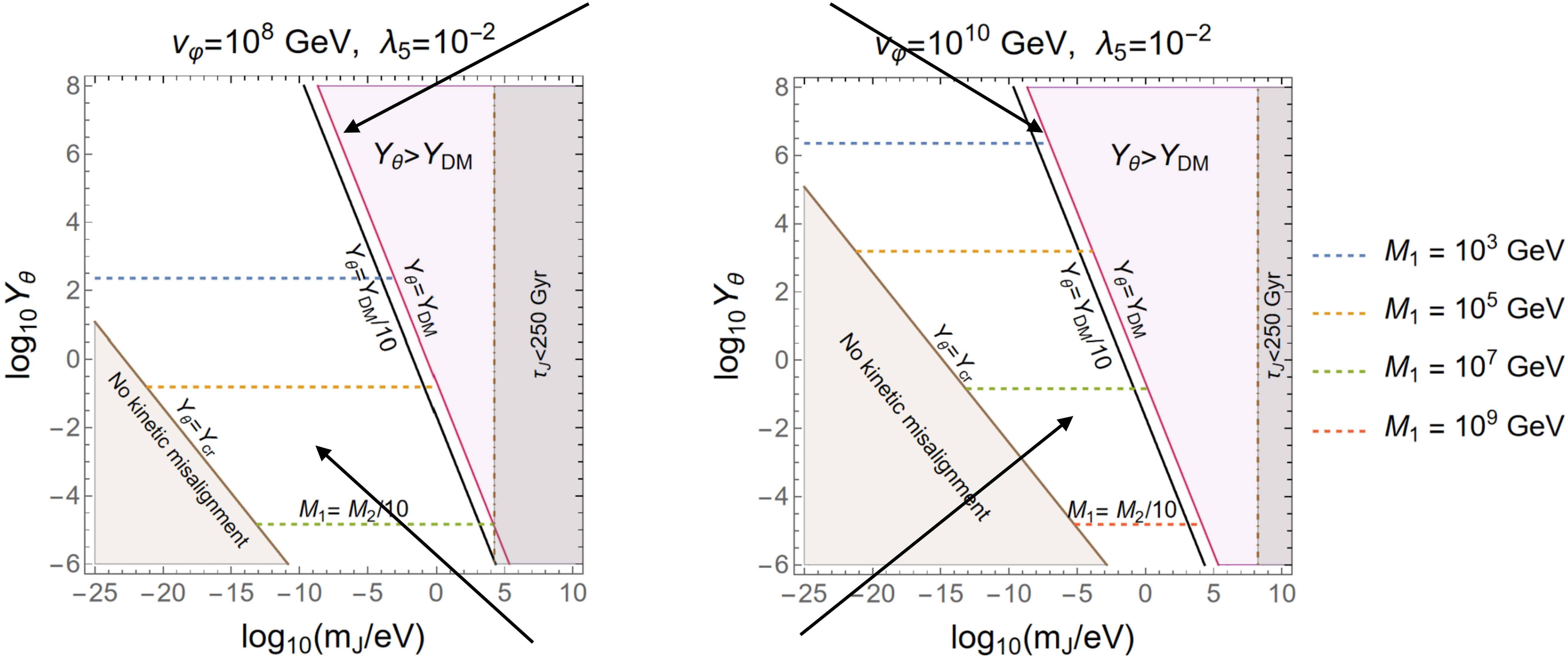
100% Majoron DM



subdominant Majoron DM

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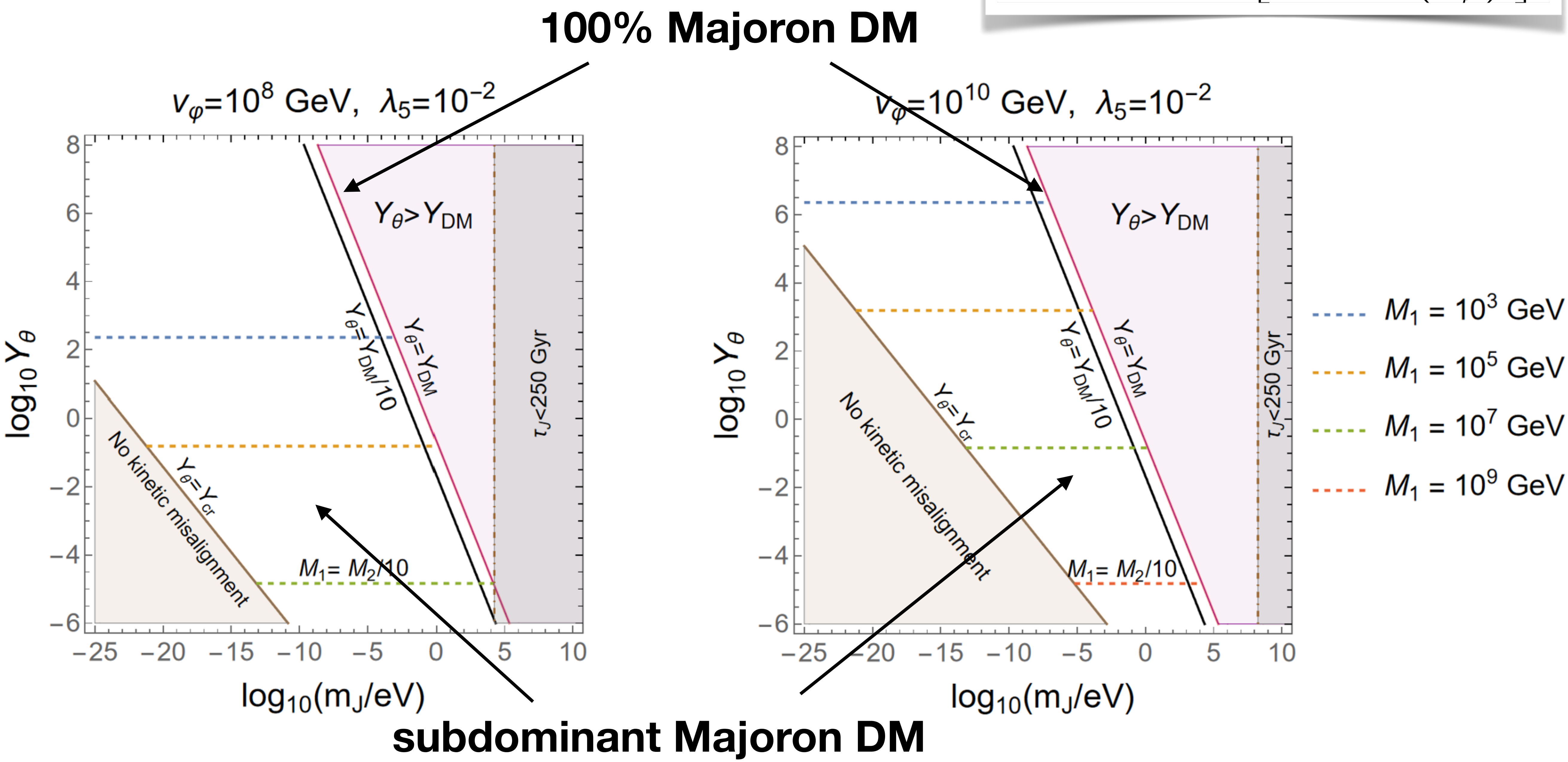

Conclusion:

Dynamical Scotogenic setup with two hierarchical RHN

neutrino mass

Multicomponent DM

Low scale leptogenesis with $M_1 \sim \mathcal{O}(\text{EW scale})$

Thank You for listening !!