HIDDEN SECTOR NEUTRINOS & FREEZE-IN LEPTOGENESIS

based on I. Flood, R. Porto, J. Schlesinger, BS, M. Thum, 2109.10908, PRD 105 (2022)

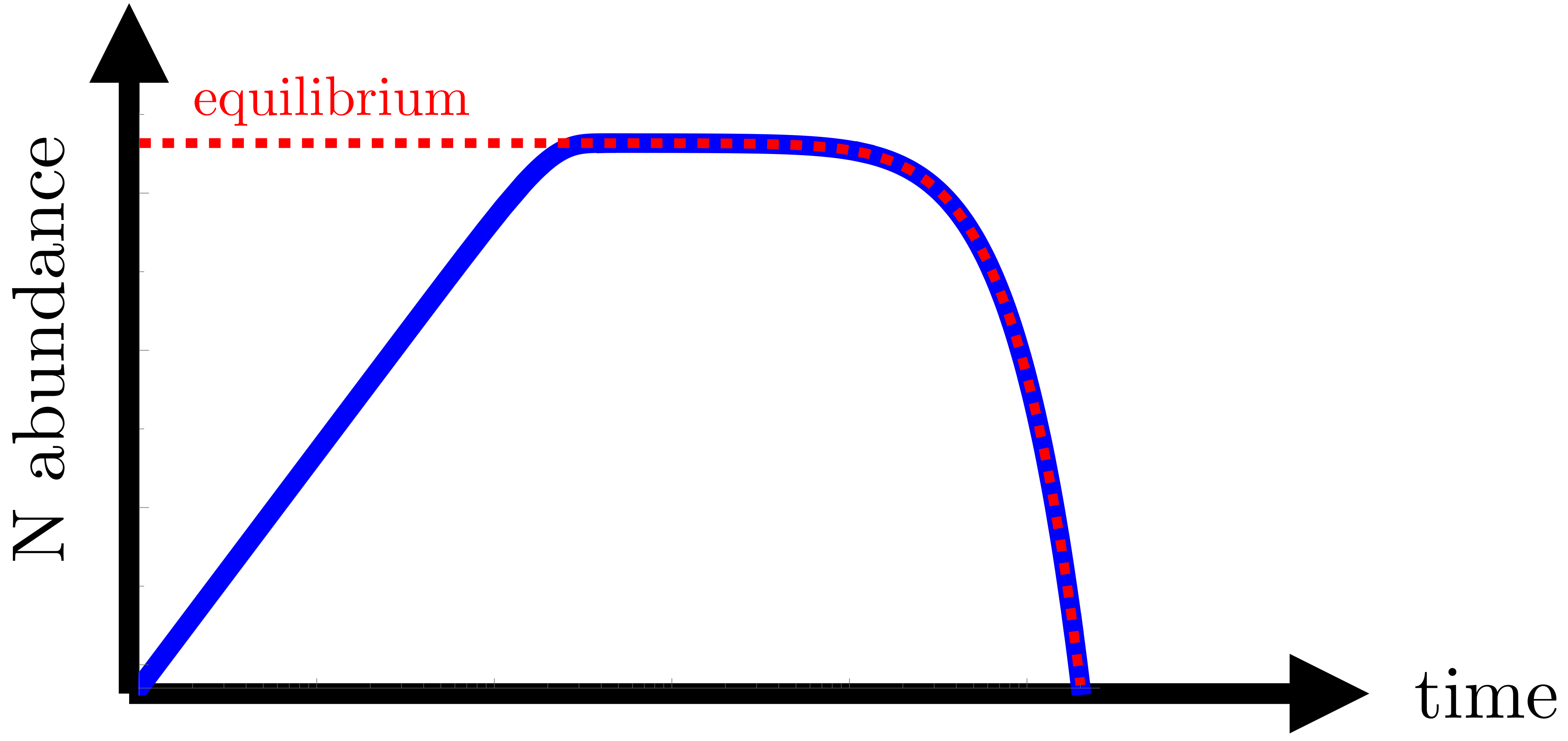
HARVEY MUDD COLLEGE

Brian Shuve

PPC 2022

STERILE NEUTRINOS

- Sterile neutrinos (*N*) can give rise to SM neutrino masses via seesaw mechanism
- Also good for leptogenesis when sterile neutrinos out of equilibrium!



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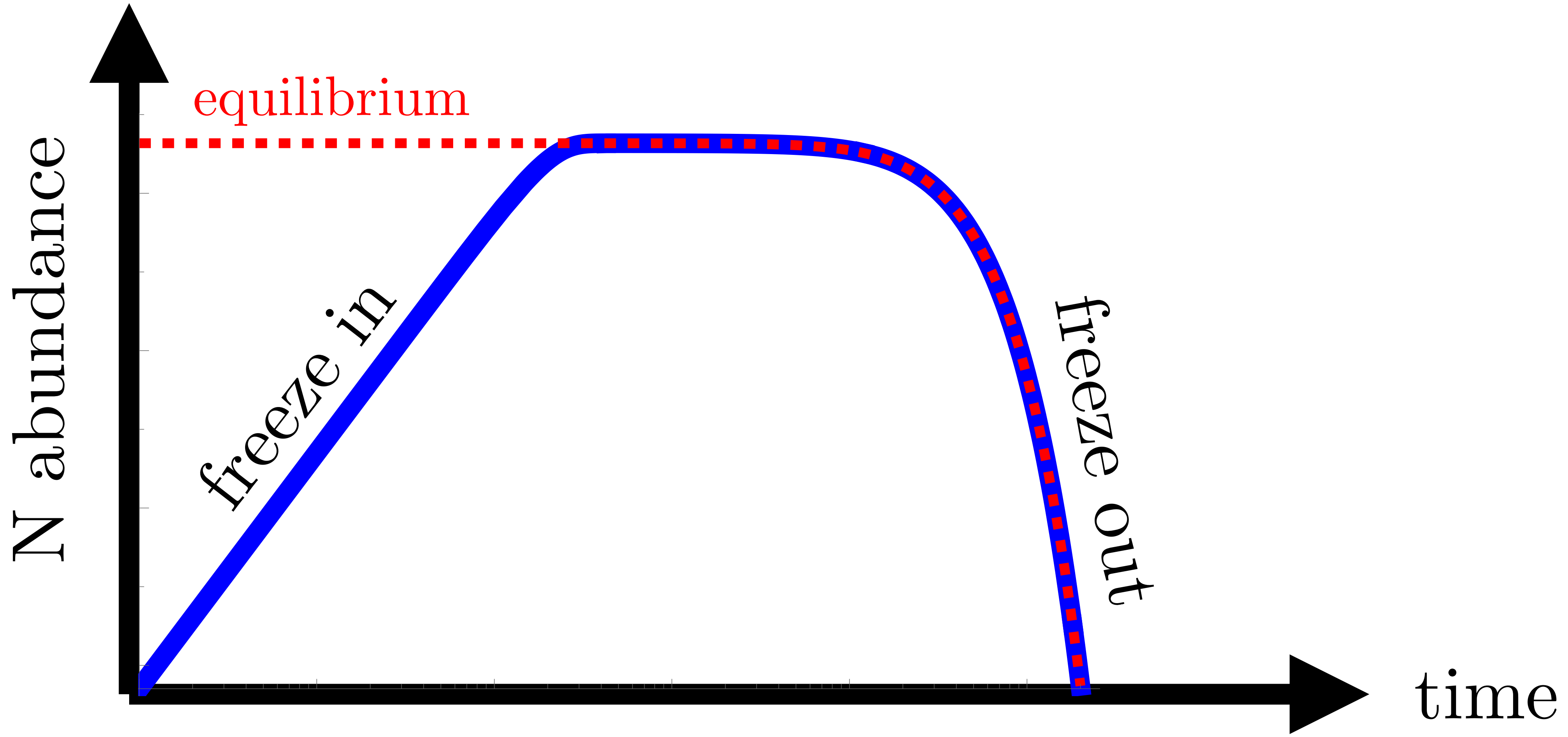
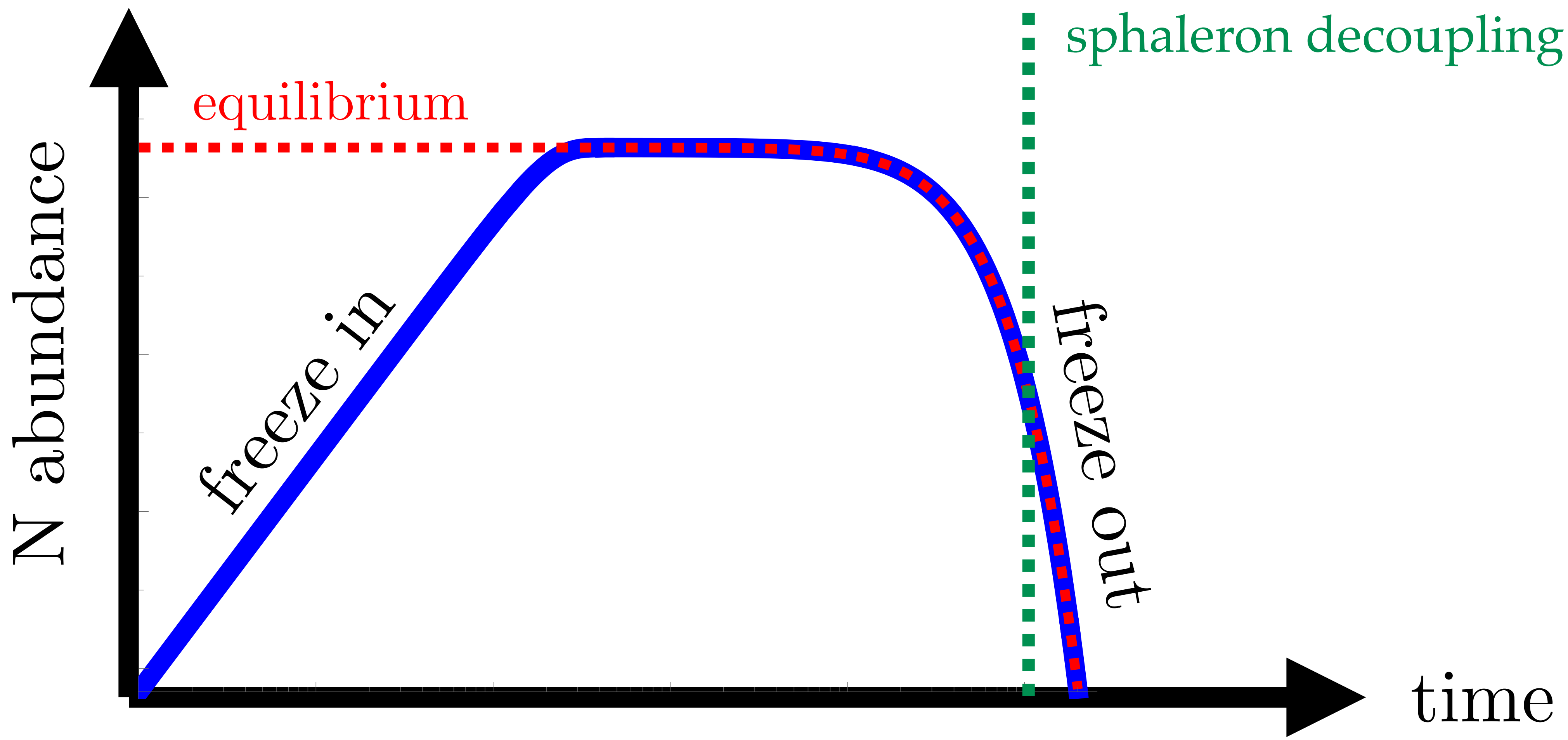


LEPTOGENESIS

- Lepton asymmetry shared with baryons via sphalerons
- Mechanism of baryogenesis depends on relative timing of sphaleron decoupling



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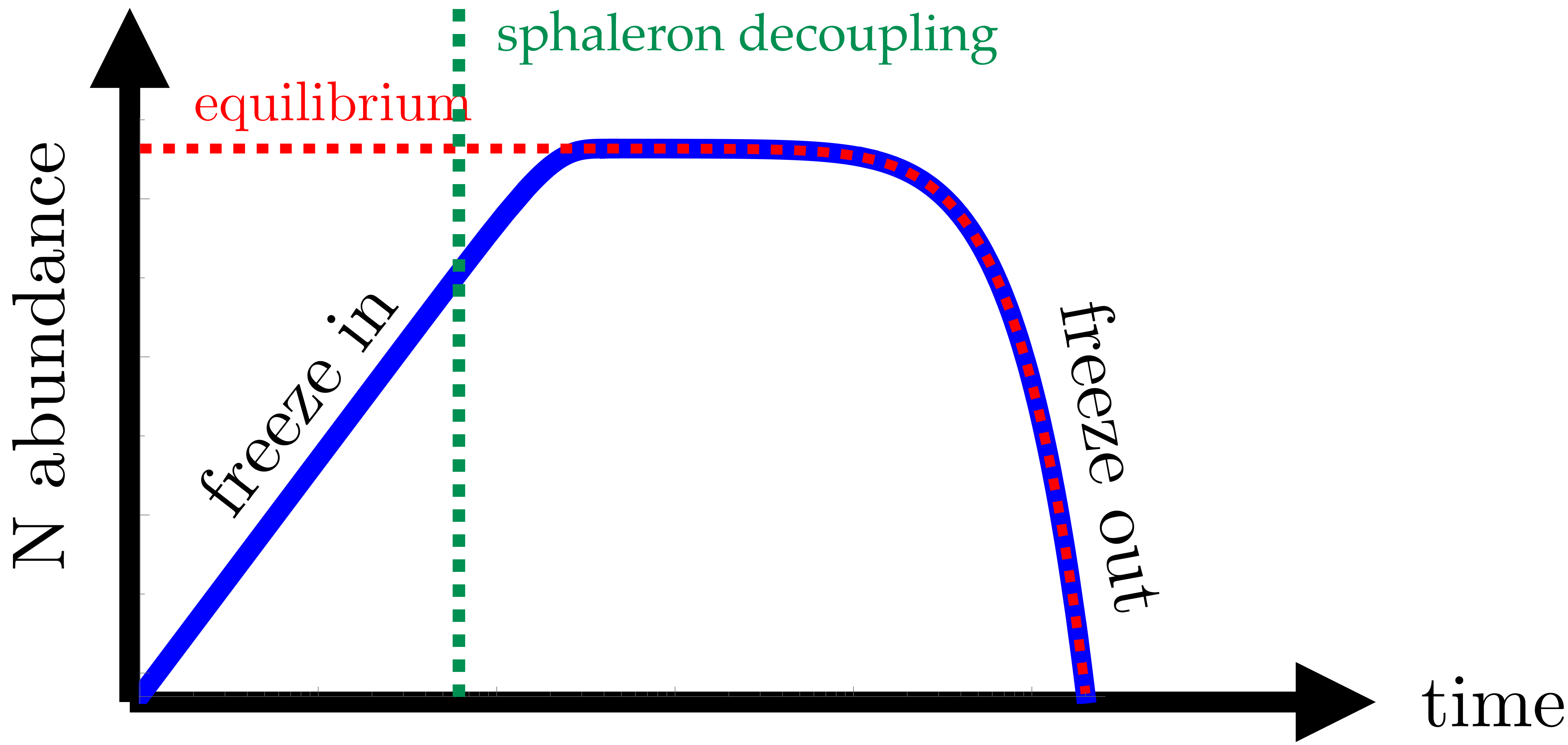
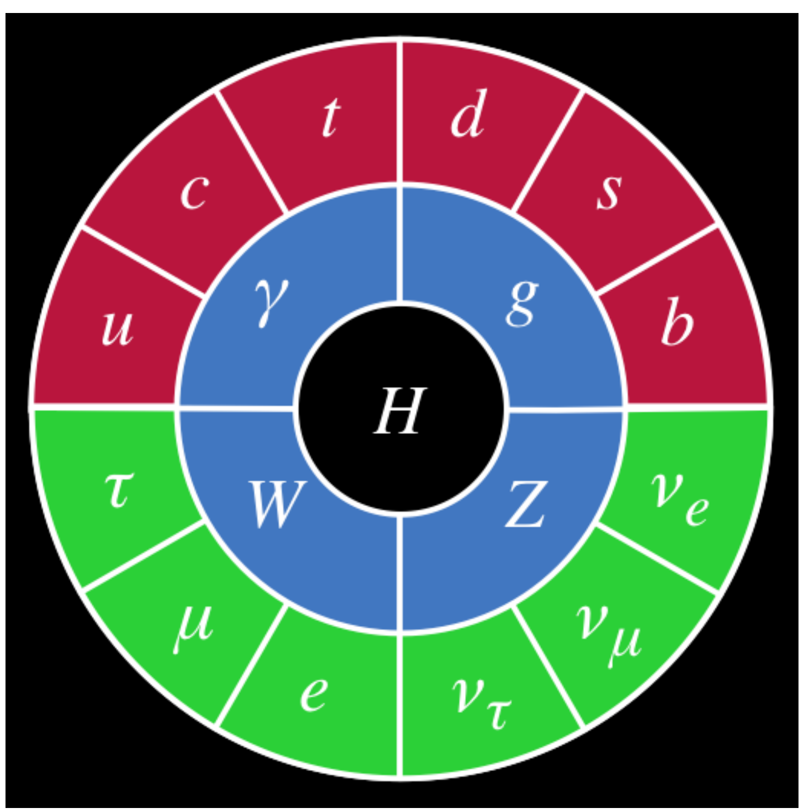
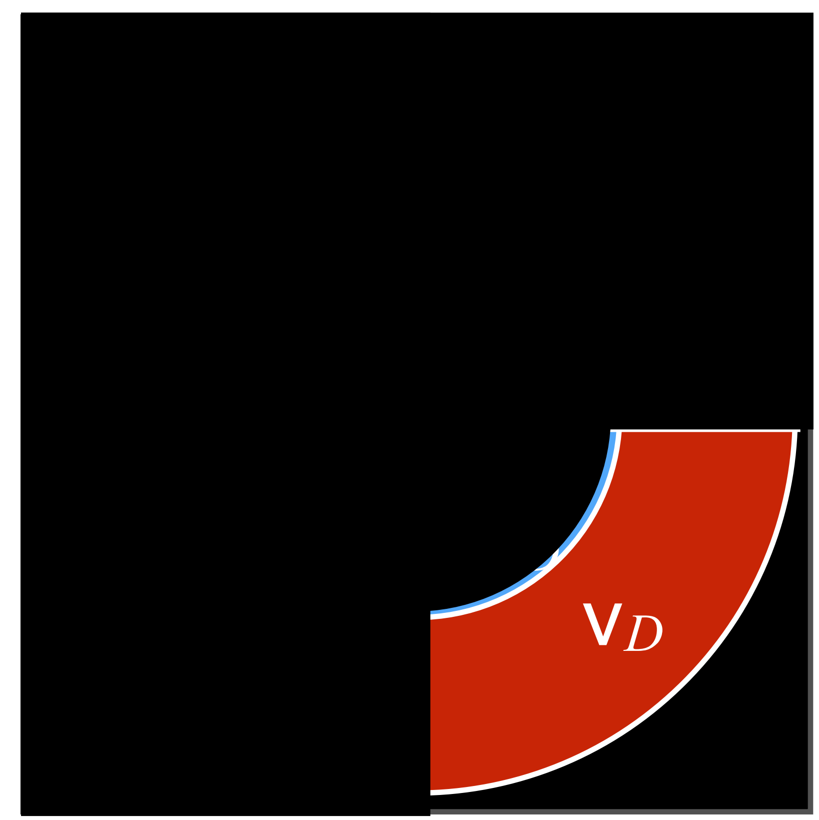


HIDDEN SECTORS

- Many models with sterile neutrinos contain other new particles, motivated by GUTs, dark matter, etc.
- Asymmetry from freeze-in depends crucially on hidden sector structure, since this dictates production & decay rates/modes





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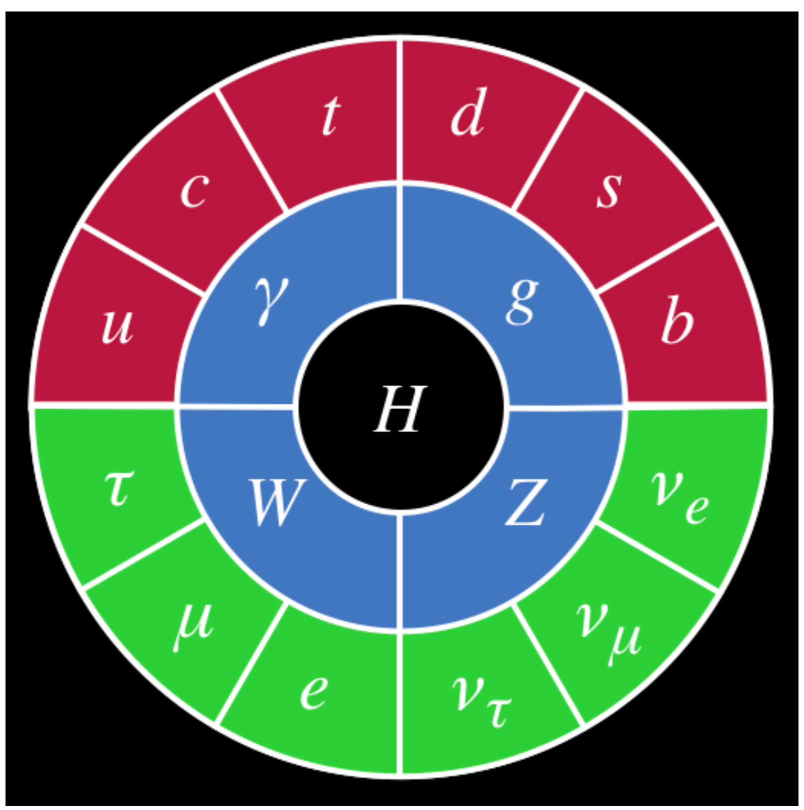
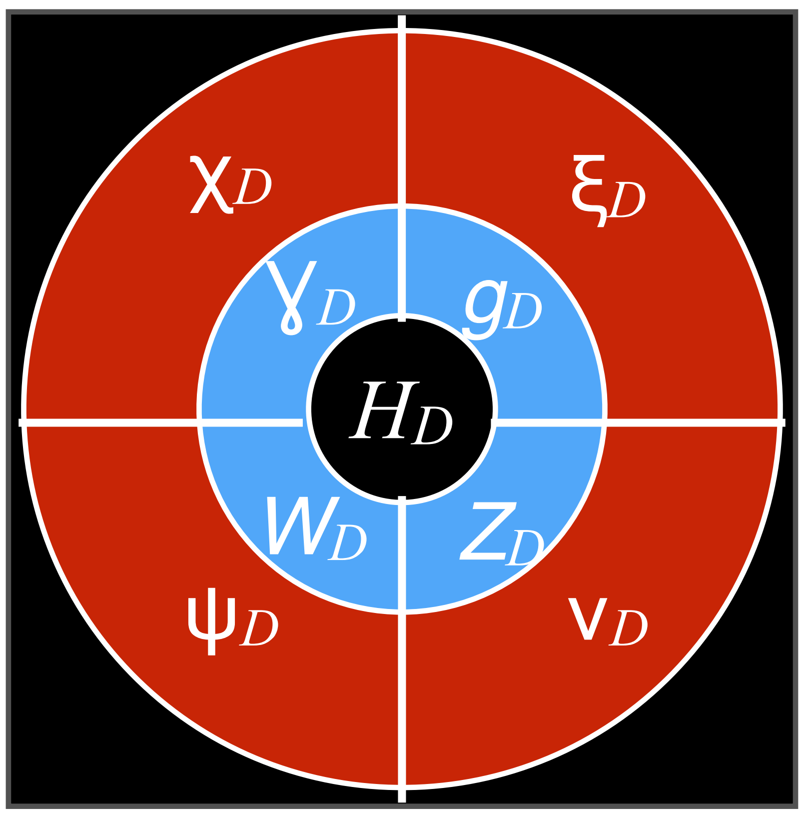
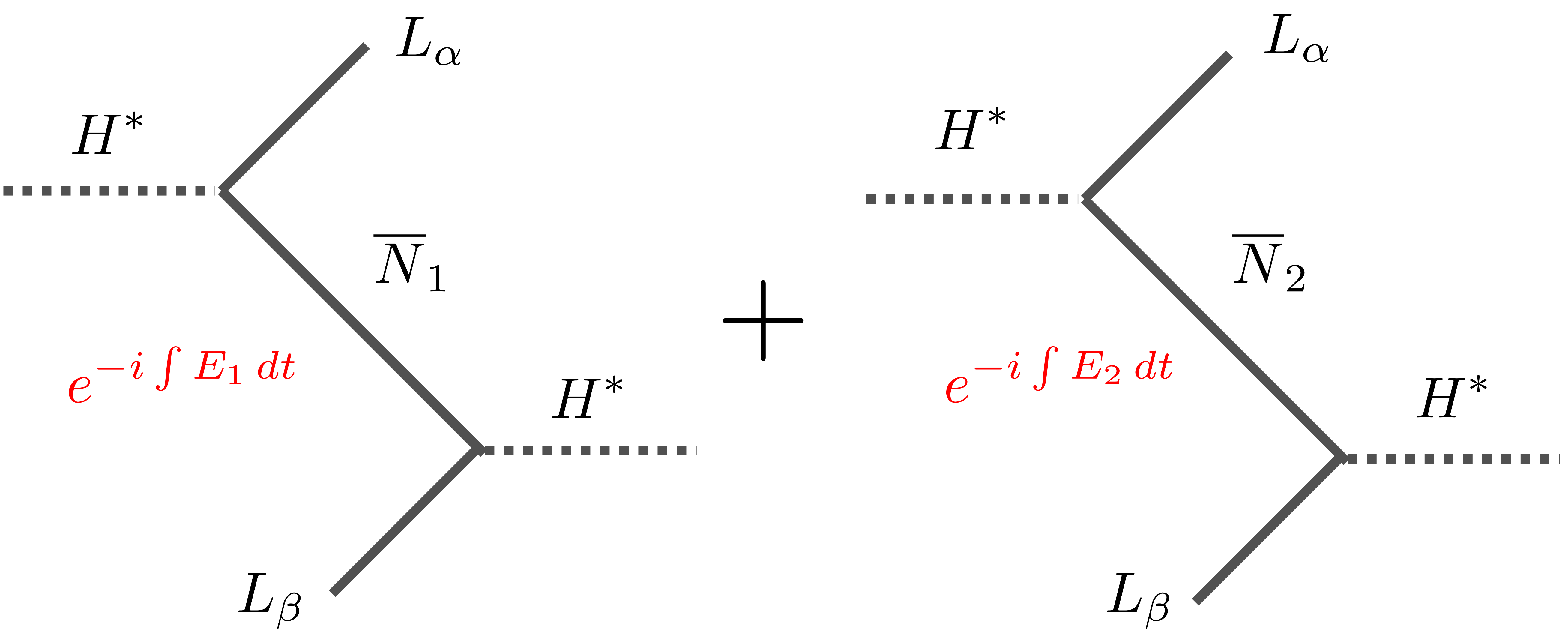




FREEZE-IN LEPTOGENESIS MECHANISM

- SM Higgs decays produce GeV-scale *N* + SM lepton
- Sterile neutrinos coherently propagate
- Inverse decay destroys SM lepton and sterile neutrino

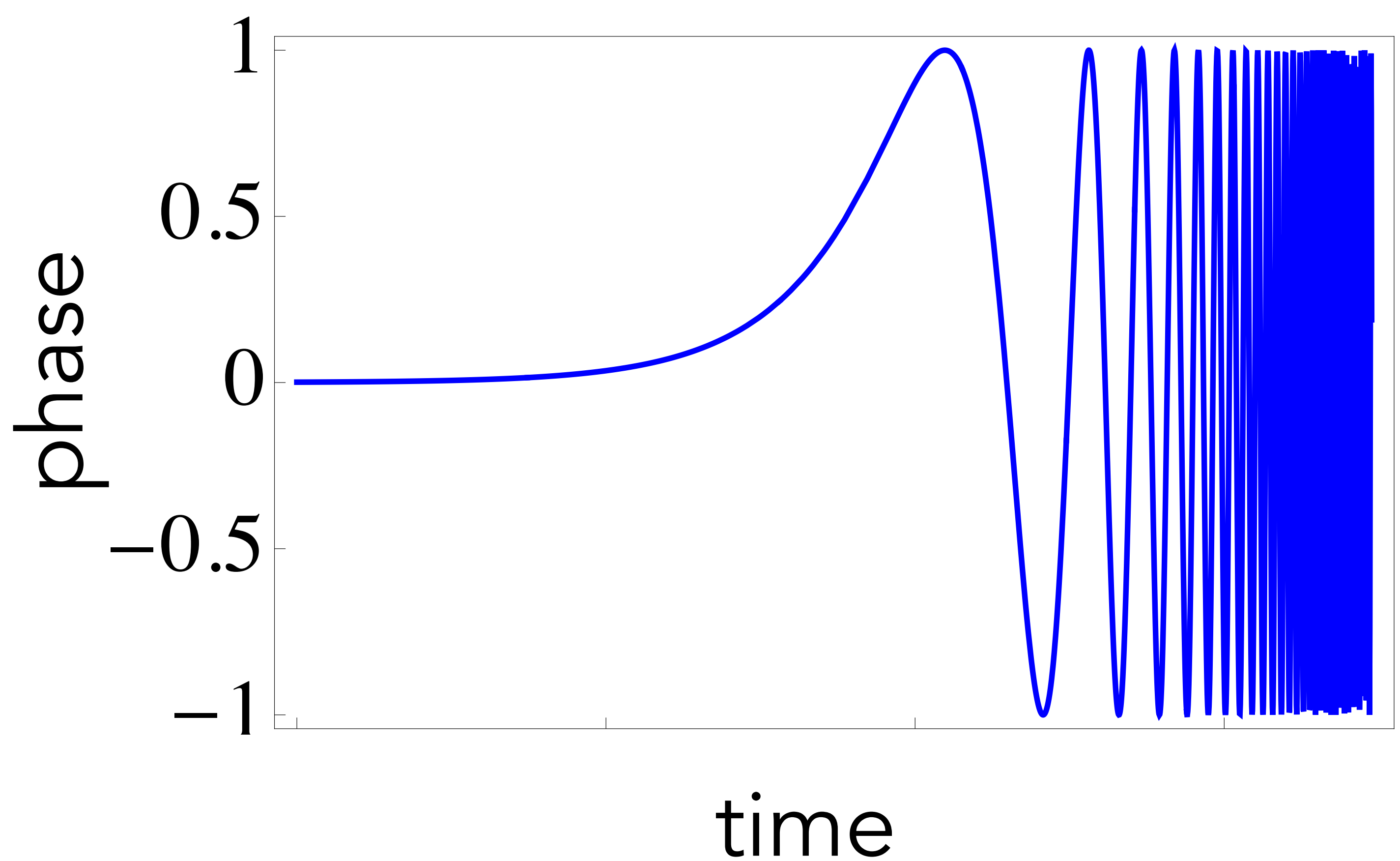


ASYMMETRY & HNL MASSES

- Asymmetry generation rate is proportional to

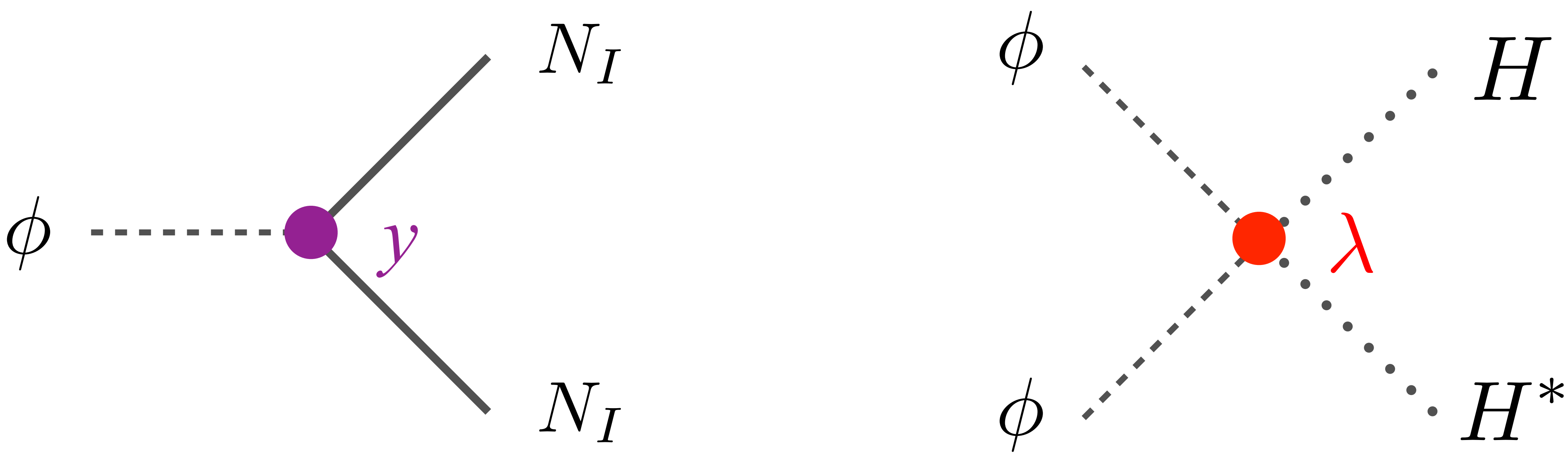
$$\sin\left[\int (E_2 - E_1)\, dt\right] \approx \sin\left[\int \frac{M_2^2 - M_1^2}{2p}\, dt\right]$$

- Asymmetry generation stops when N come into equilibrium



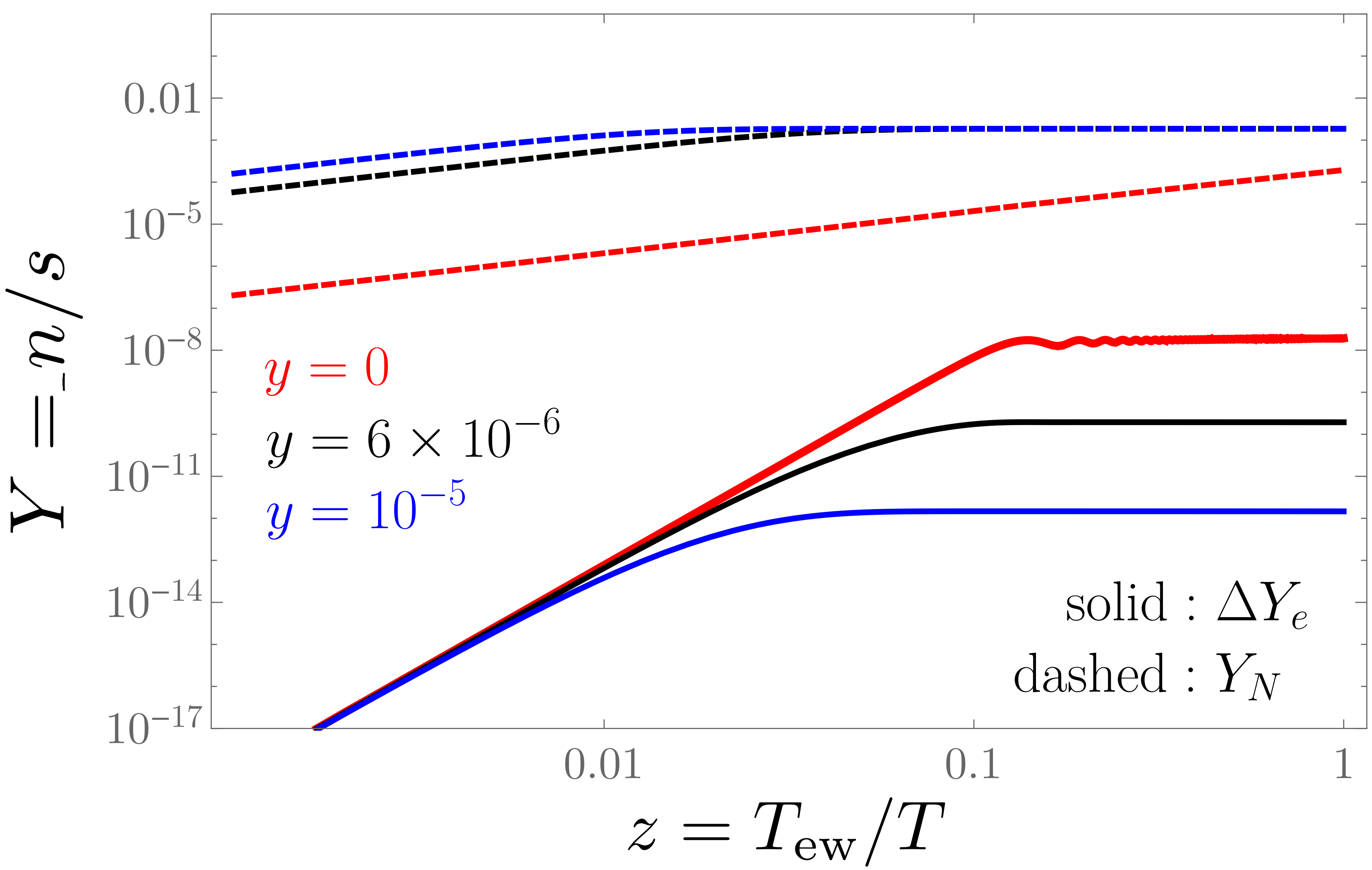
HIDDEN SECTOR MODEL

- Consider generic singlet scalar coupled to pairs of sterile neutrinos
- Results don't depend on details of model



ASYMMETRY SUPPRESSION

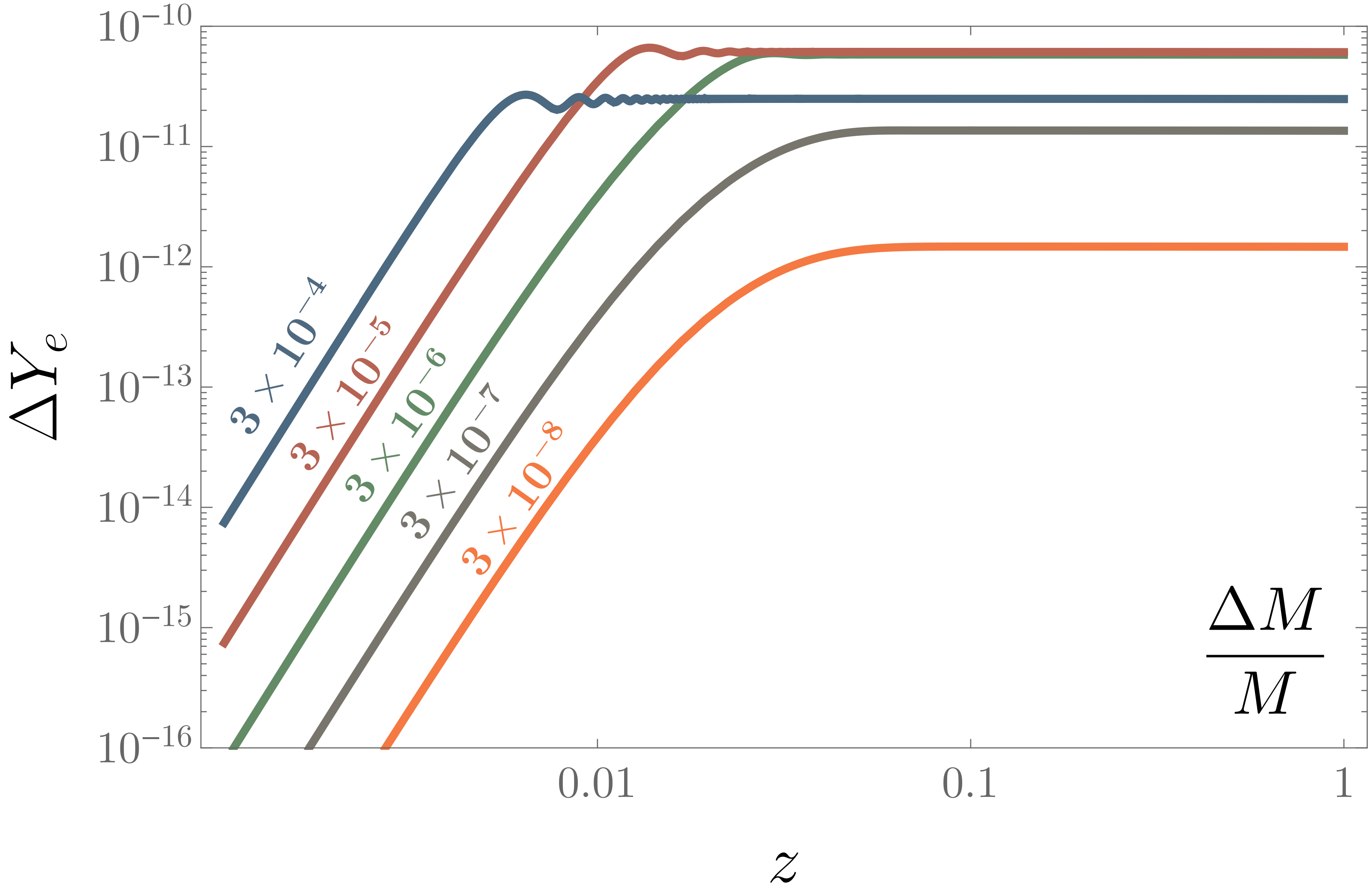
- To begin, assume $\lambda \gg y$ (ϕ always in equilibrium)
- Asymmetry suppressed by y^{-10} !!



$M_\phi = 1$ GeV
$M_1 = 1$ GeV
$\Delta M = 3 \times 10^{-8}$ GeV
$\lambda = 0.1$

ASYMMETRY SUPPRESSION

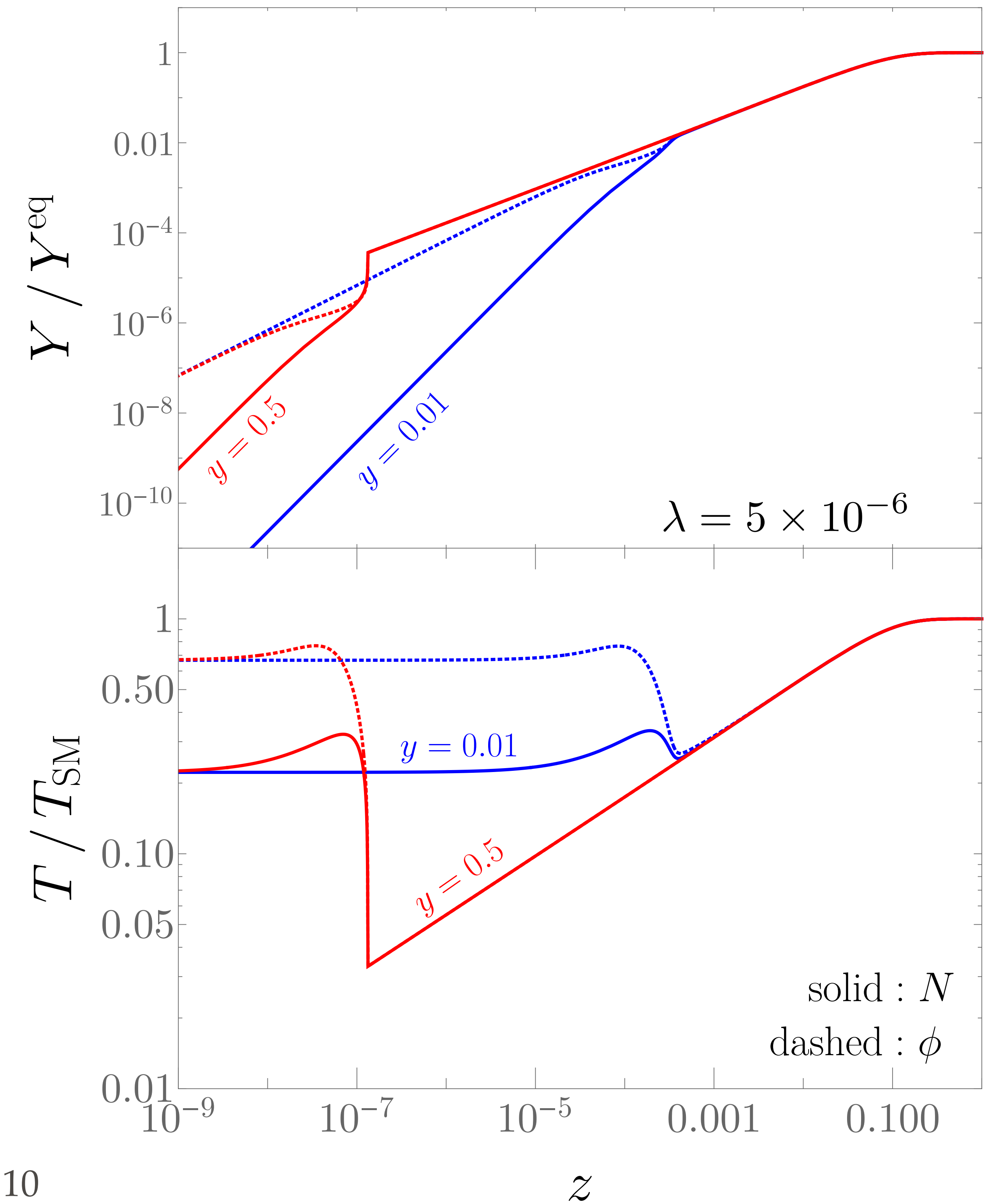
- Optimal mass splitting corresponds to onset of oscillations around sterile neutrino equilibration time



HIDDEN-SECTOR DYNAMICS

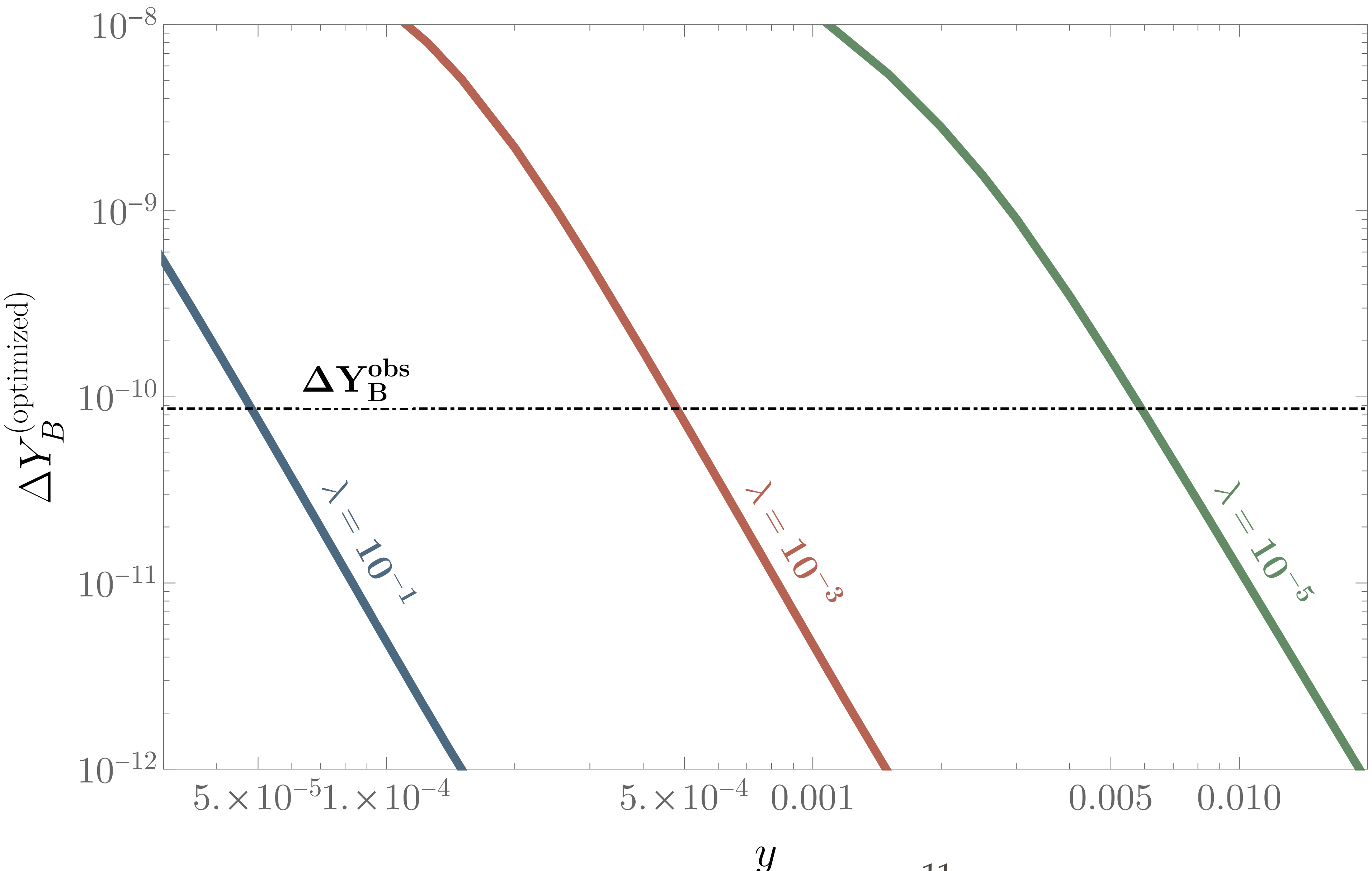
- Now, consider $y \gg \lambda$

- Interactions within the hidden sector change the number density **and** kinetic energy of hidden states $(T \neq T_{\rm SM})$



HIDDEN-SECTOR ASYMMETRY

- Optimize the asymmetry by picking the best mass splitting & overall scale of sterile neutrino Yukawa couplings

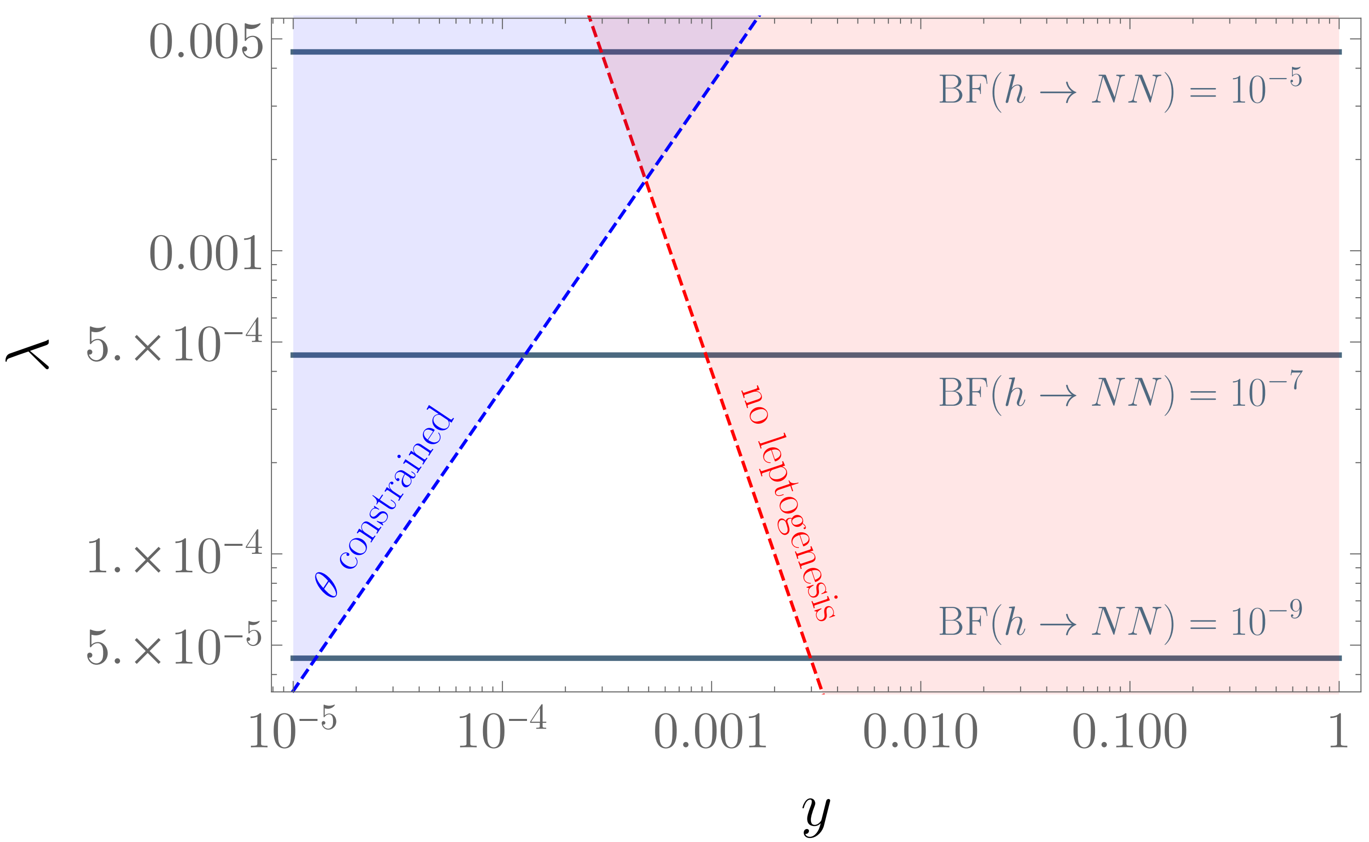


$$y\sqrt{\lambda} \lesssim 2 \times 10^{-5}$$

PHENOMENOLOGY

- Can connect with phenomenology, giving prospects for discovery or falsification of leptogenesis!

$$h \to NN$$



In both: $M_\phi = 15$ GeV
$M_N = 5$ GeV

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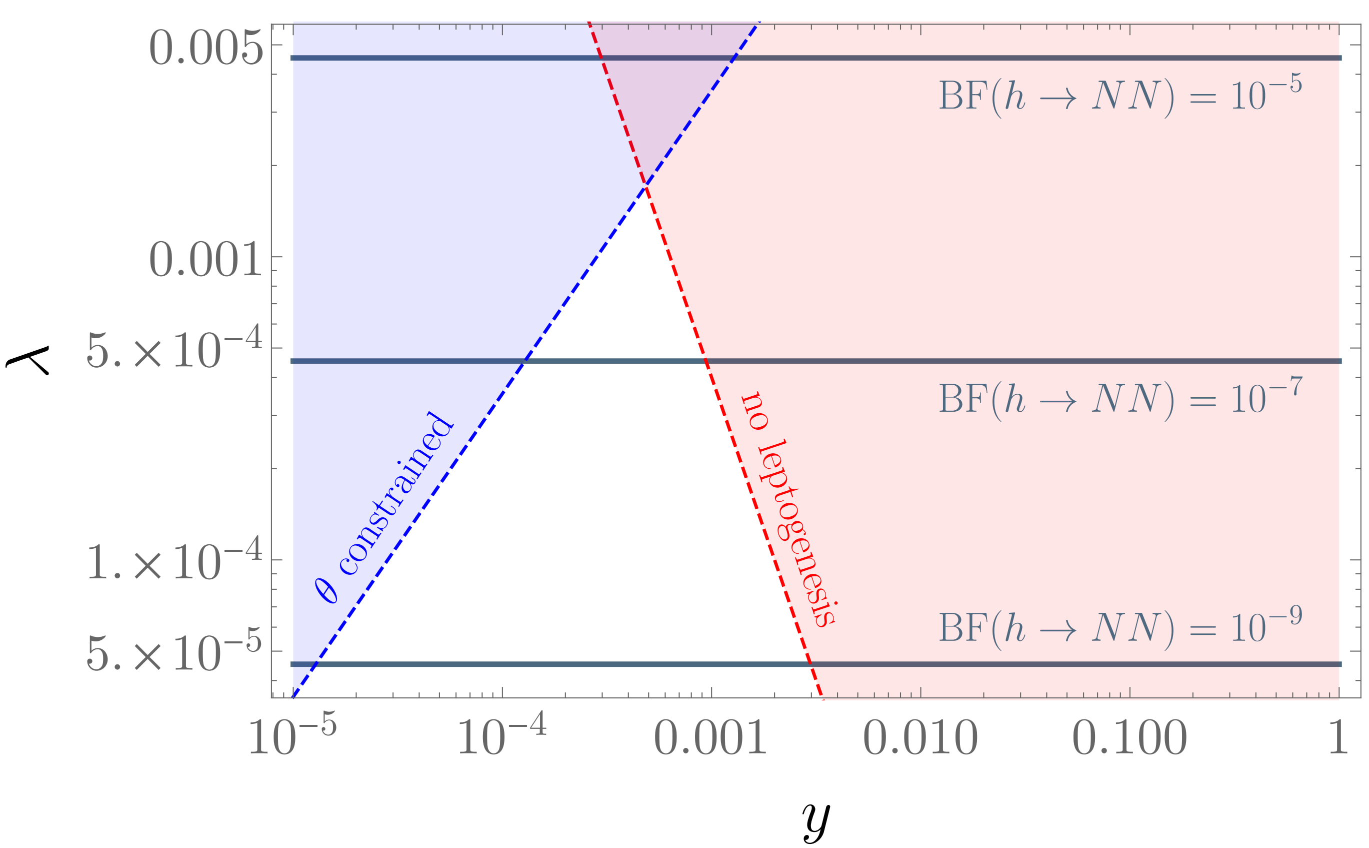
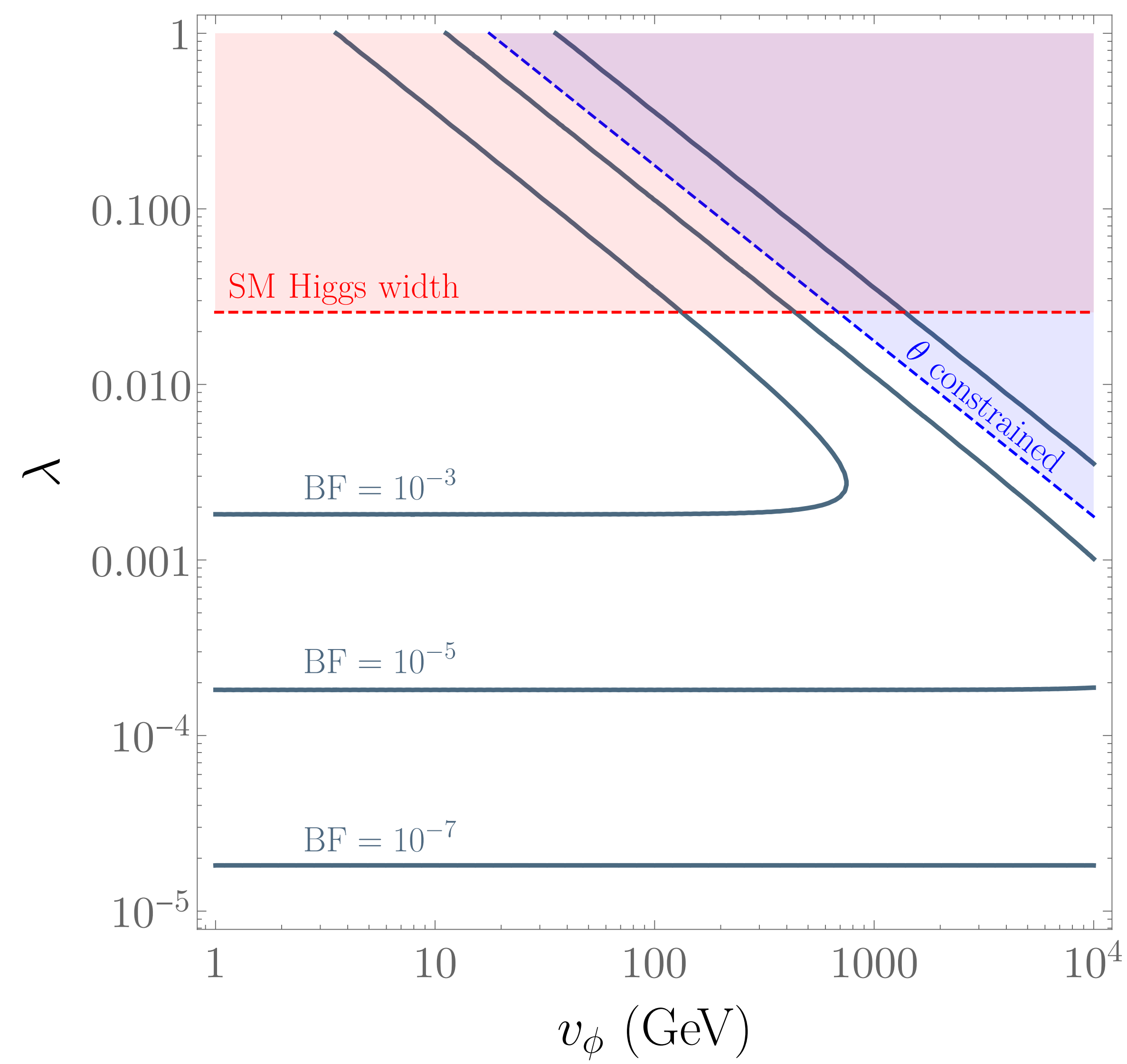


$h \to \phi\phi, \phi \to NN$



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SUMMARY

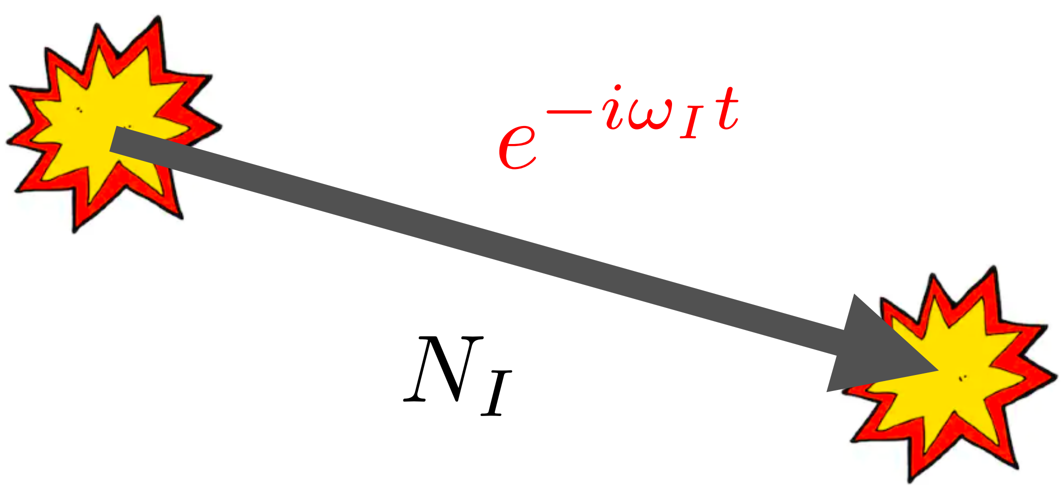
- Hidden-sector couplings to HNLs can severely suppress the asymmetry from leptogenesis
- Asymmetry suppression well modelled by simple analytic estimates
- We clarify the signals in conflict with & compatible with leptogenesis in a singlet scalar model
- Results easily generalized to other models of interest

BACKUP SLIDES

Akhmedov, Rubakov, Smirnov, hep-ph/9803255; Asaka, Shaposhnikov, hep-ph/0505013; …

THE MINIMAL PARADIGM

- Adding three sterile neutrinos/heavy neutral leptons (HNLs) can solve all three problems
- Heaviest two HNLs generate lepton asymmetry through freeze-in (ARS) leptogenesis, lightest HNL is a freeze-in DM candidate
- Neutrino minimal SM (or νMSM)



$$F \sim 10^{-7}$$

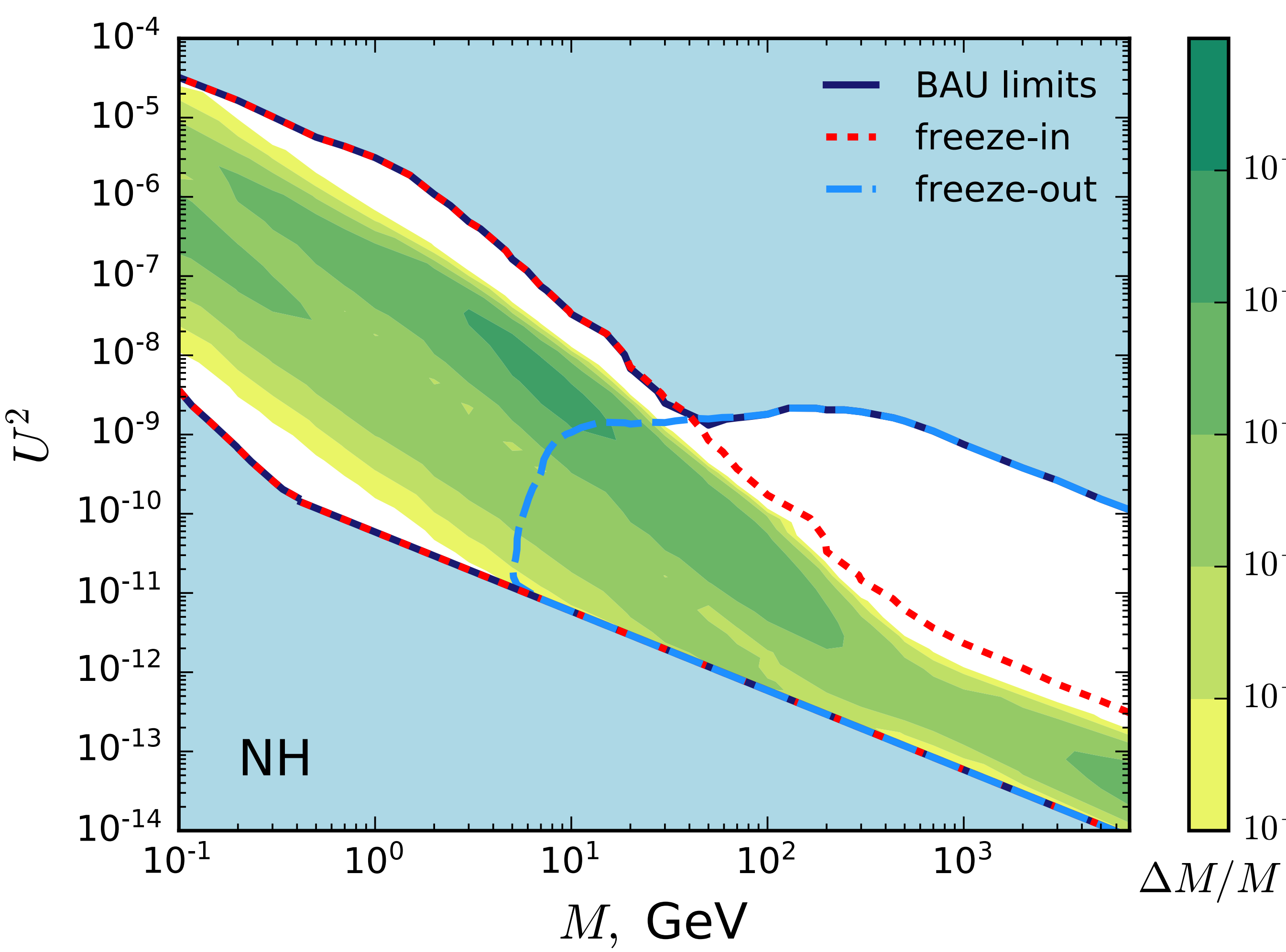
$$M_N \sim \mathrm{GeV}$$

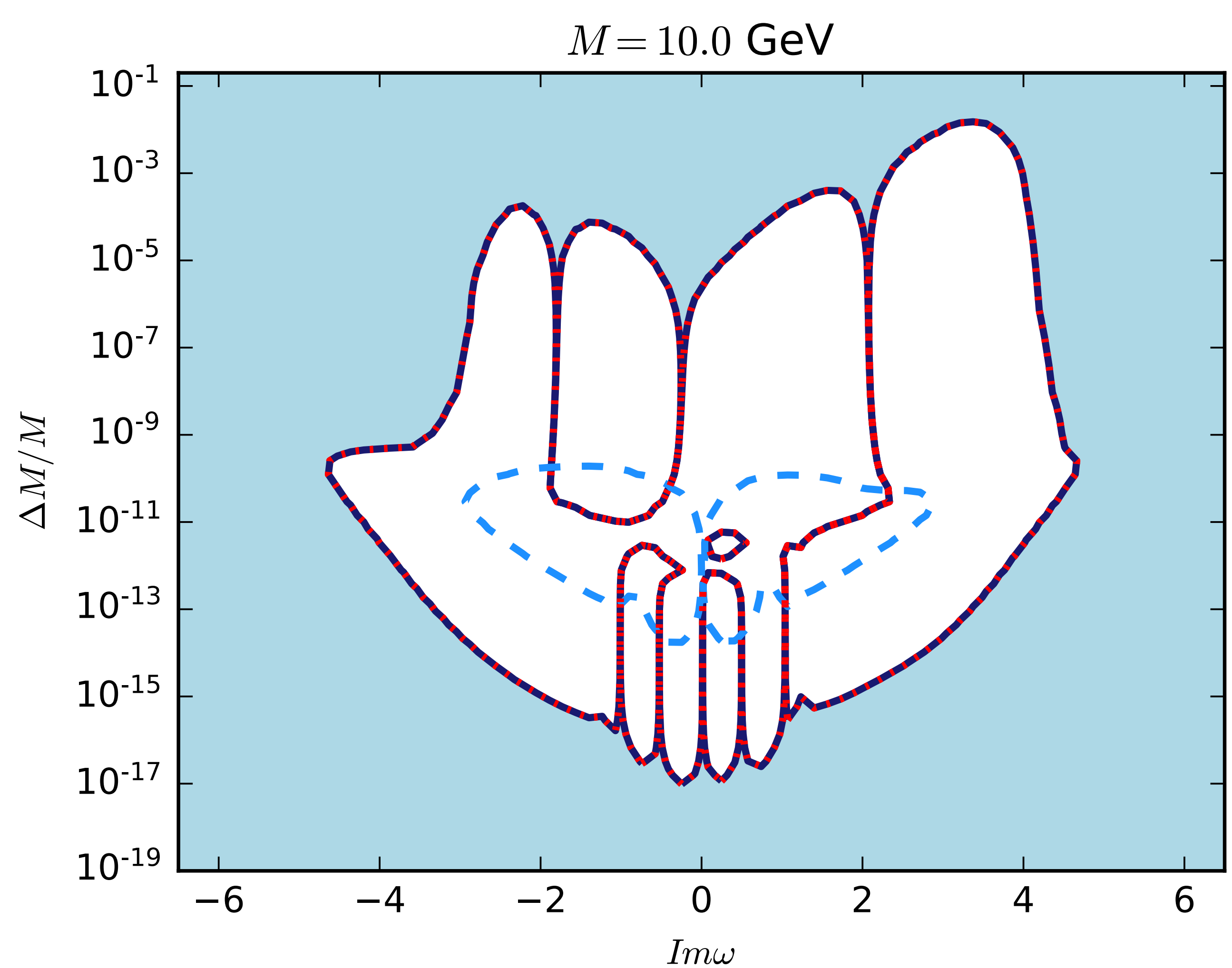
$$\Delta M_N \ll M_N$$

THE MINIMAL PARADIGM

- Often, although not always, mass degeneracies and/or enhancements in Yukawa couplings relative to naive see-saw
- Could be hallmark of approximate lepton number symmetry

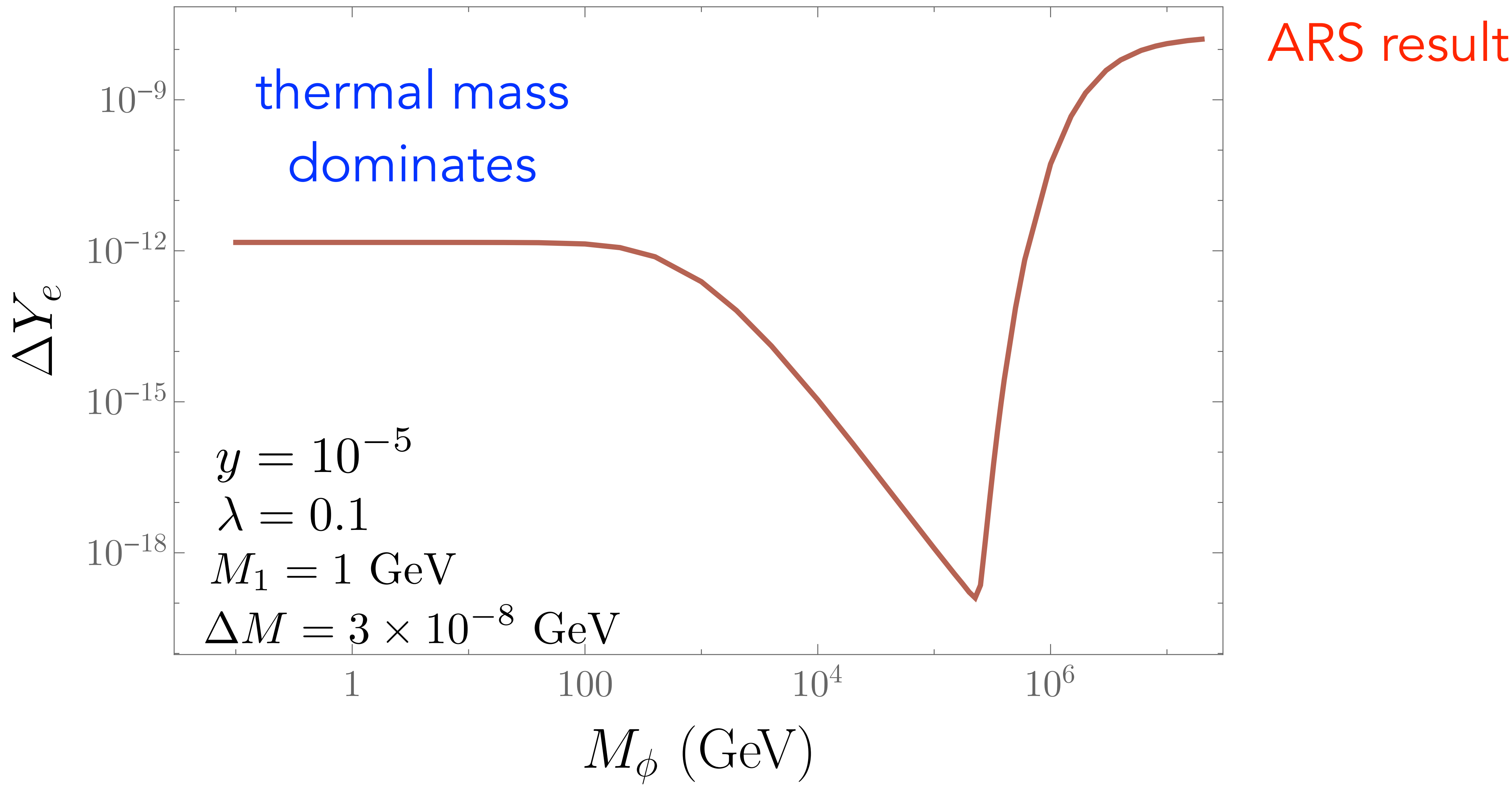
Shaposhnikov, hep-ph/0605047





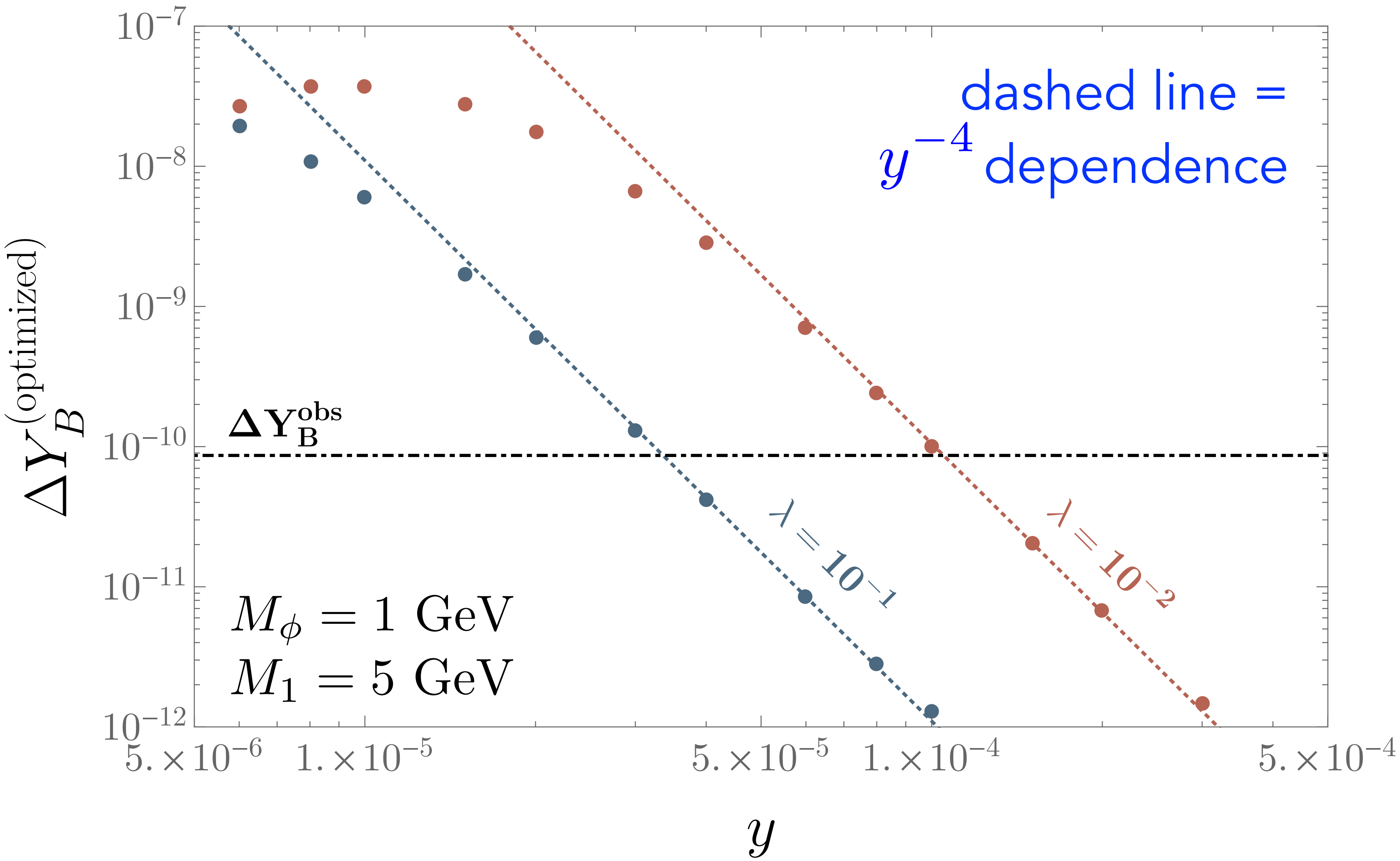
STERILE NEUTRINO RESULTS

- Scalar must be **very heavy** to avoid spoiling leptogenesis



STERILE: OPTIMAL ASYMMETRY

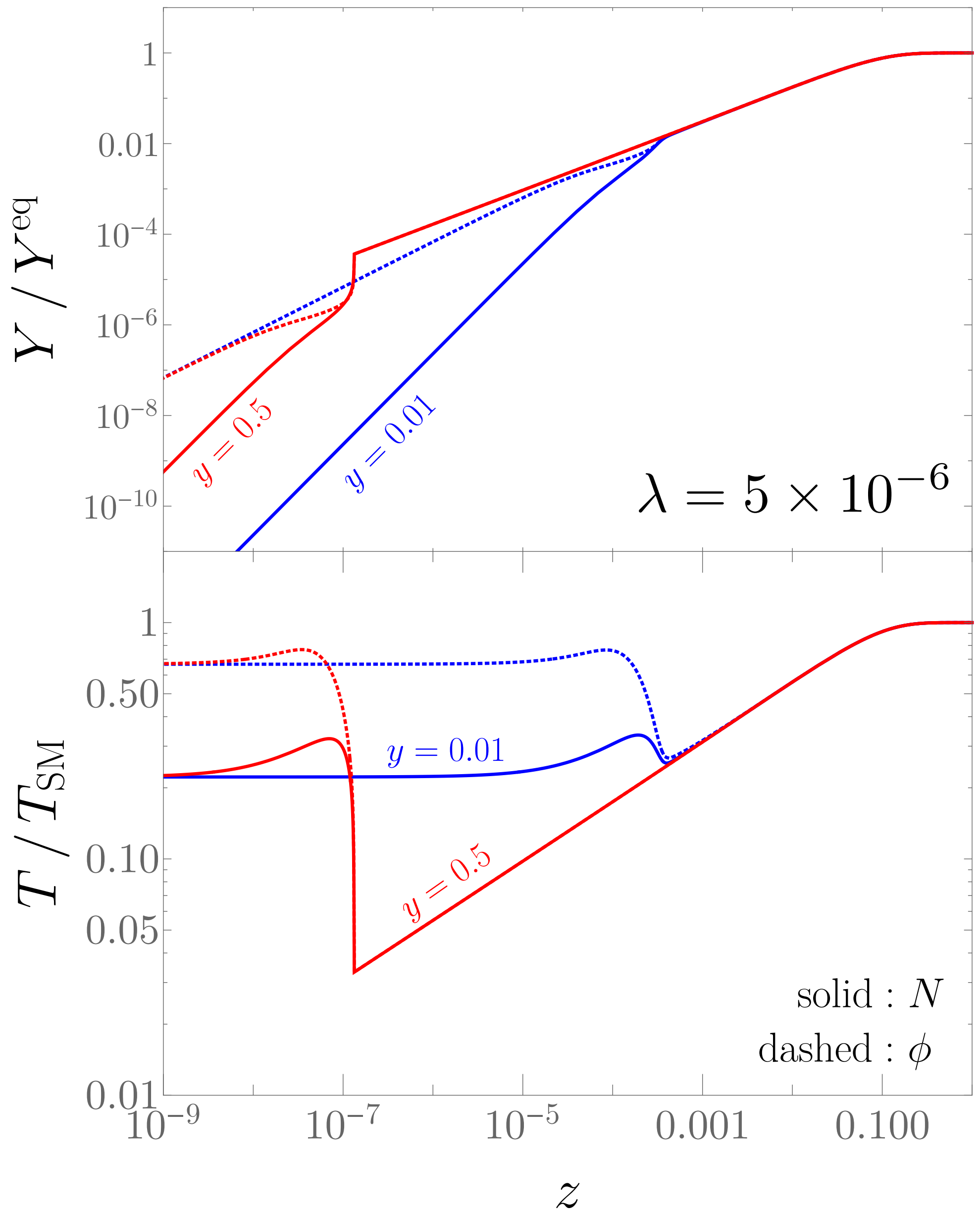
- Optimize the asymmetry by picking the optimal mass splitting & overall scale of sterile neutrino Yukawa couplings
- Agrees with analytic prediction

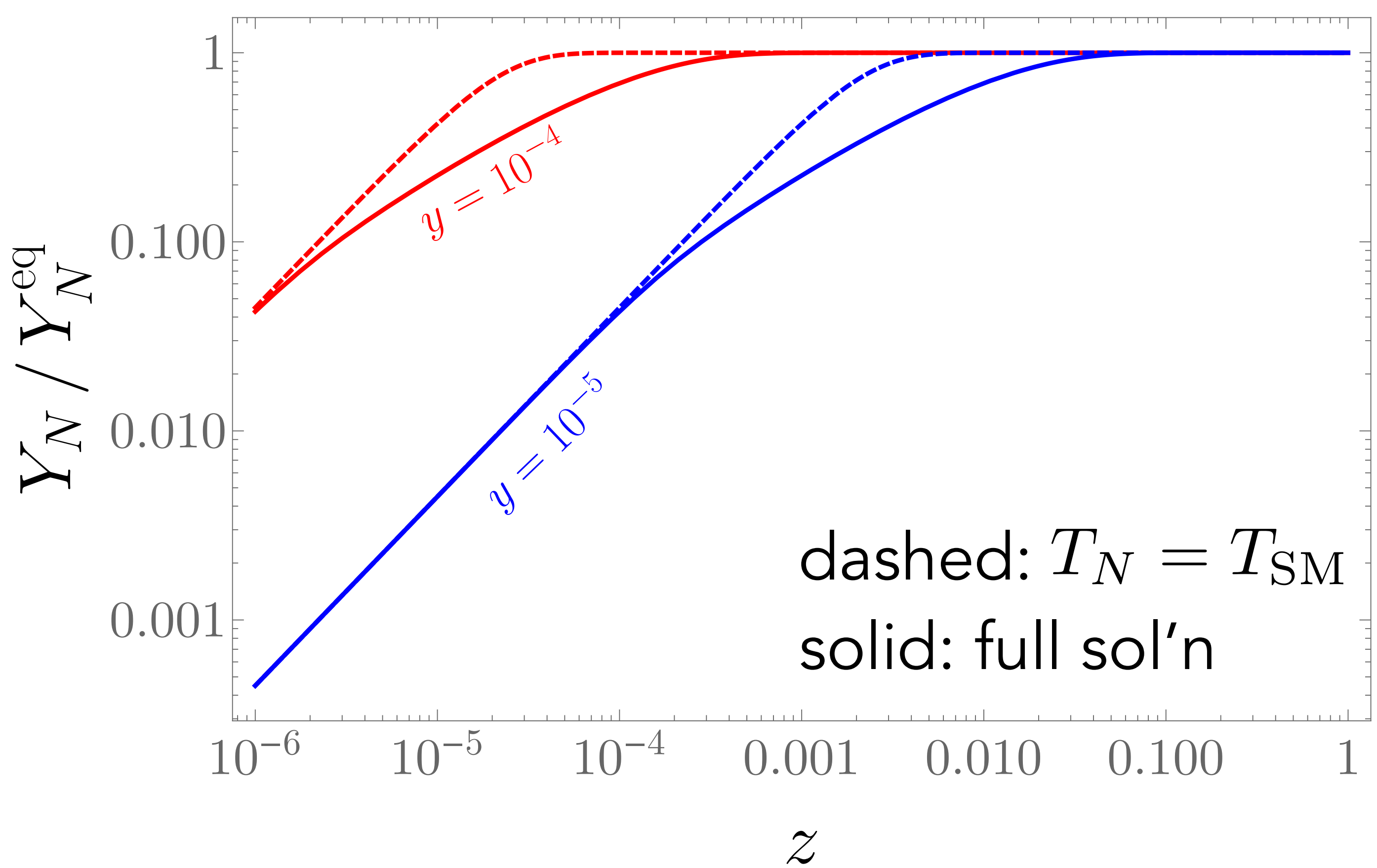


$$y\sqrt{\lambda} \lesssim 10^{-5}$$

HIDDEN-SECTOR DYNAMICS

- We start by simply characterizing the abundance & temperature of hidden-sector particles *without* determining asymmetry

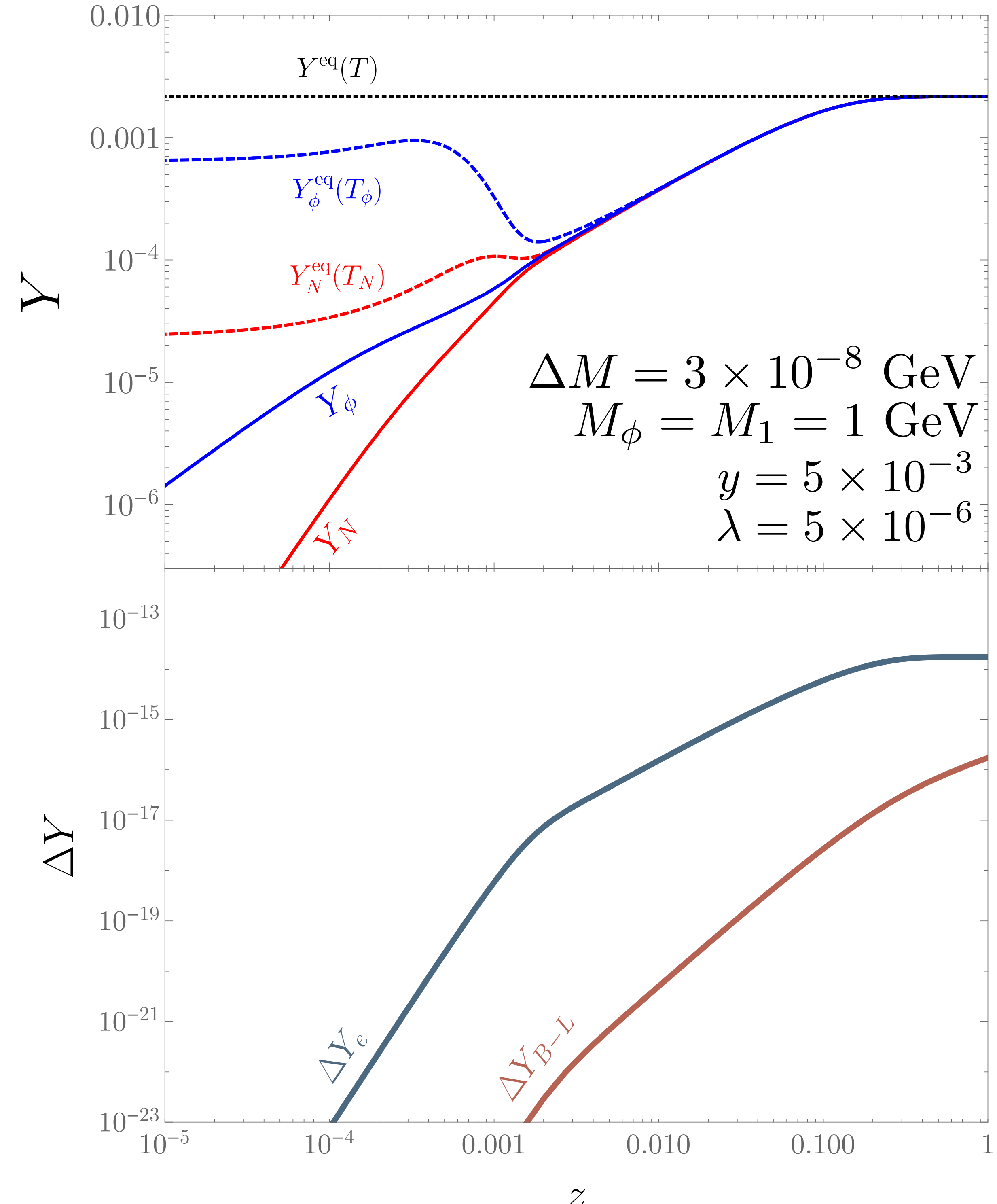




HIDDEN-SECTOR ASYMMETRY

- There is now a scenario where the hidden sector is internally in equilibrium but out of equilibrium with the SM

- Suppression of asymmetry when this happens!



HIDDEN-SECTOR ASYMMETRY

- To determine the lepton asymmetry, we model the HNL density matrix with two components:

$$\rho_N^{\mathrm{tot}} = \rho_N^{\mathrm{ARS}}(T) + \rho_{\tilde{N}}(T_N)$$

- We substitute this density matrix into the usual ARS equations, modify the collision terms to account for the fact that $\rho_{\tilde{N}}$ has a typical momentum associated with T_N

- We remove terms that are strictly internal to the hidden sector (i.e. that changes $\rho_{\tilde{N}}$ but not ρ_N^{ARS}

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$$n_N^{\text{h.s.}}\mathbb{I}$$

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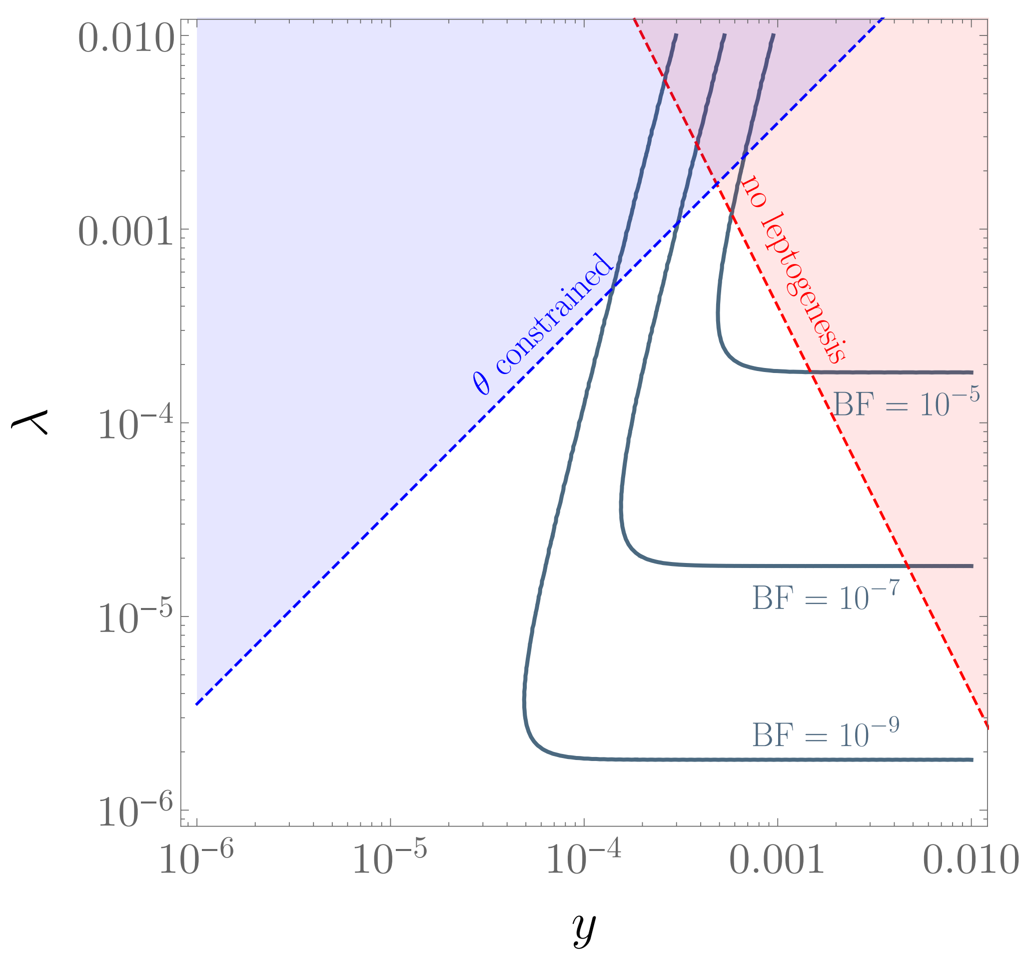
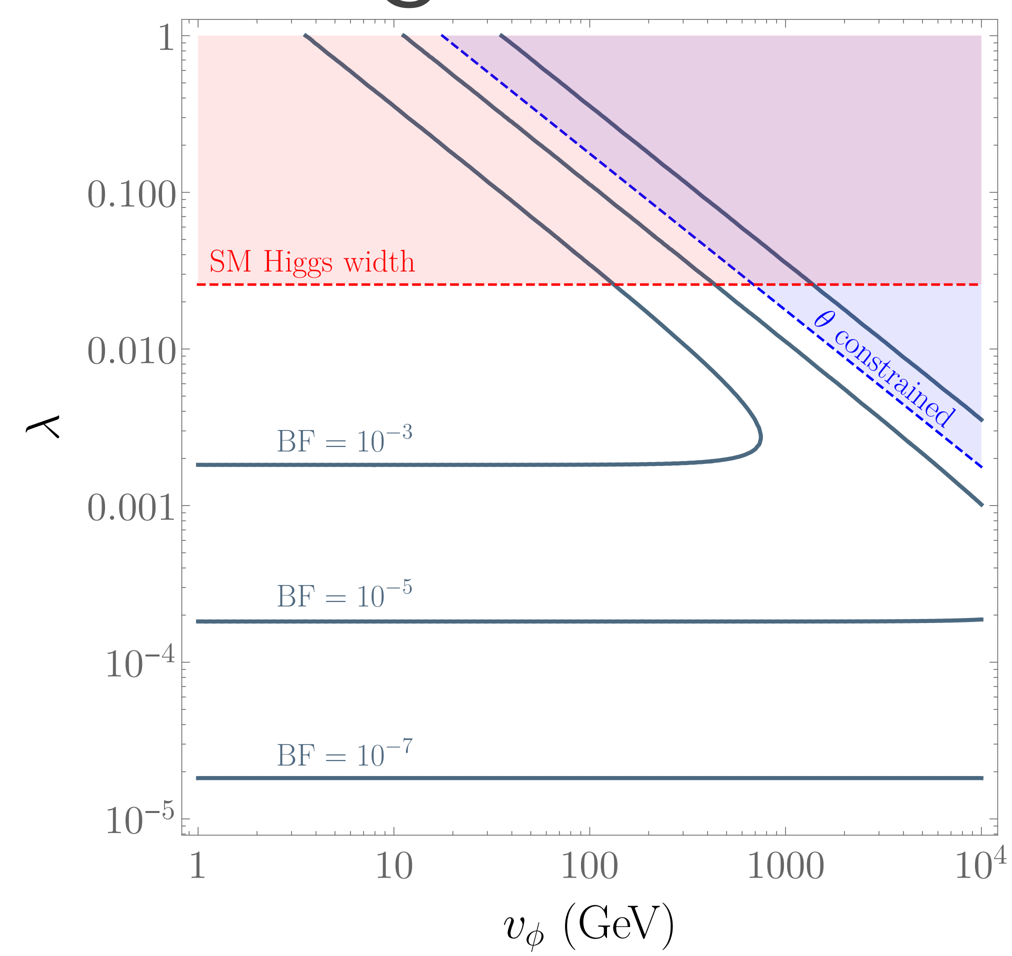
HIGGS DECAYS TO SCALARS

$$h \to \phi\phi, \phi \to NN$$

<u>dark Higgs</u>:



<u>generic</u>:



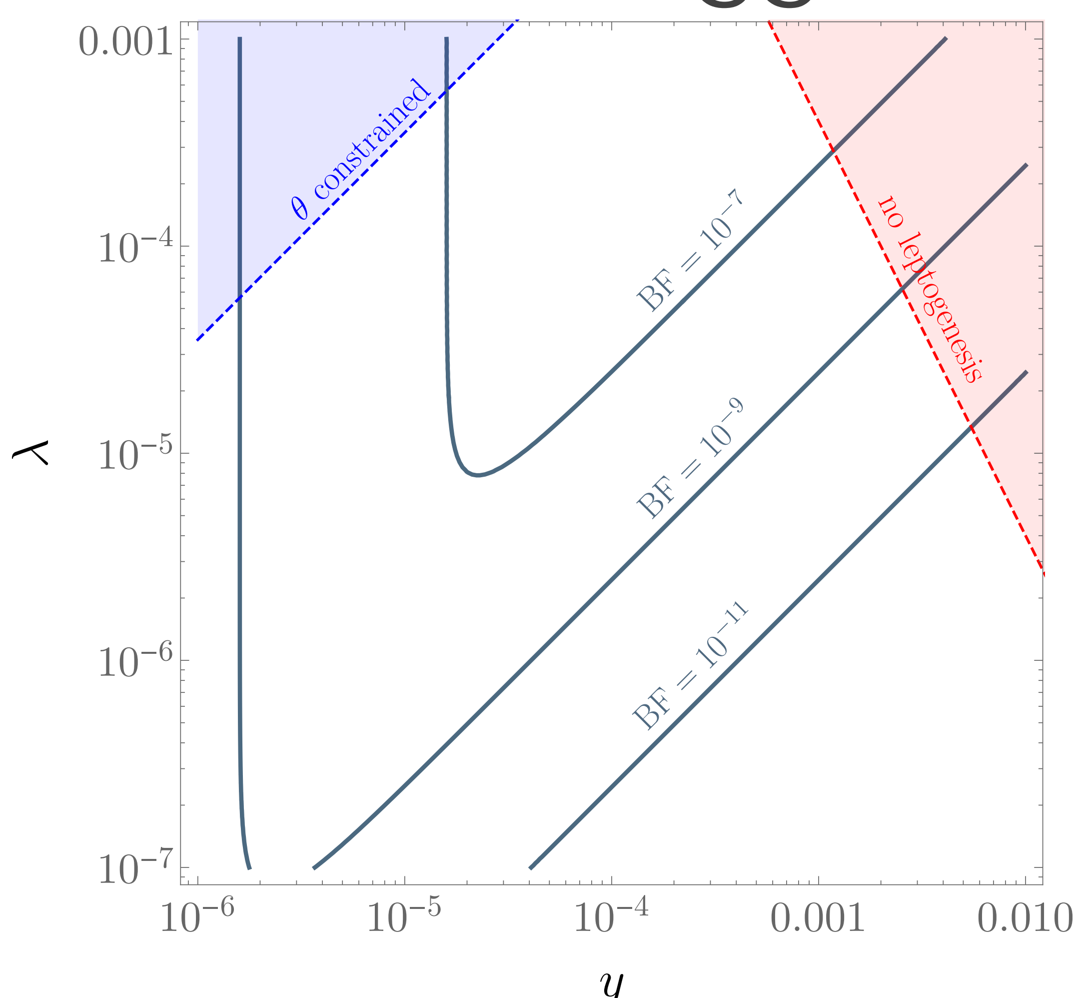
(set *y* to max allowed by leptogenesis)

In both: $M_\phi = 15$ GeV
$M_N = 5$ GeV

B DECAYS TO SCALAR

$$B \to K\phi, \phi \to NN$$

dark Higgs:



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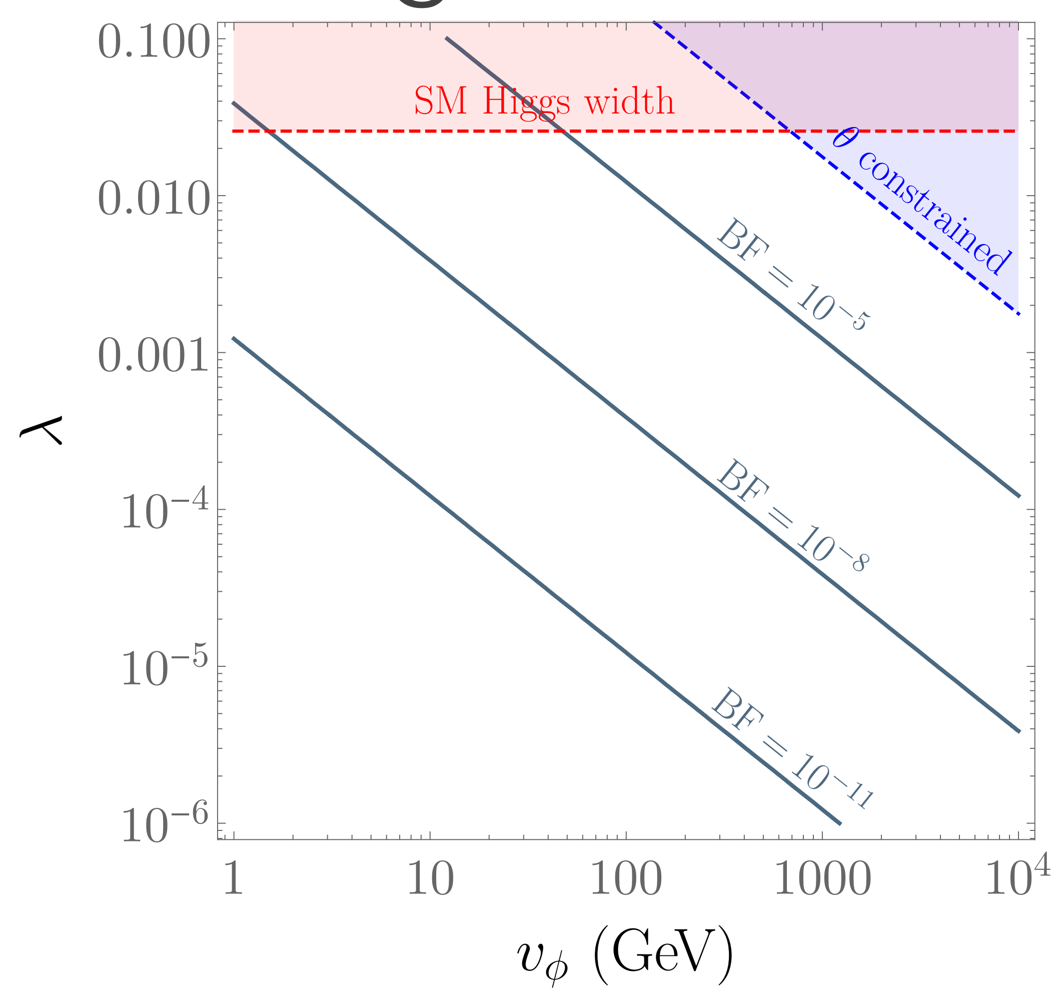


In both: $M_\phi = 2\ \mathrm{GeV}$
$M_N = 0.5\ \mathrm{GeV}$

(set y to max allowed by leptogenesis)

ARS QUANTUM KINETIC EQUATIONS

$$\frac{dR_N}{dz} = i\left[R_N, W_N\right] + 3iz^2\left[R_N, r\right] - \mathcal{C}^{(0)}\left\{R_N, W_N\right\} + 2\mathcal{C}^{(0)}W_N + \mathcal{C}^{(\mathrm{w.o.1})}o_\mu + \frac{1}{2}\mathcal{C}^{(\mathrm{w.o.2})}\left\{o_\mu, R_N\right\},$$

$$\frac{32T_{\mathrm{ew}}}{M_0}\frac{d\mu_{\Delta\alpha}}{dz} = -\mathcal{C}^{(0)}\left(FR_NF^\dagger - F^*R_{\overline{N}}F^{\mathrm{T}}\right)_{\alpha\alpha} + \mathcal{C}^{(\mathrm{w.o.1})}\left(FF^\dagger\right)_{\alpha\alpha}\mu_\alpha + \frac{\mathcal{C}^{(\mathrm{w.o.2})}}{2}\left(FR_NF^\dagger + F^*R_{\overline{N}}F^{\mathrm{T}}\right)_{\alpha\alpha}\mu_\alpha$$

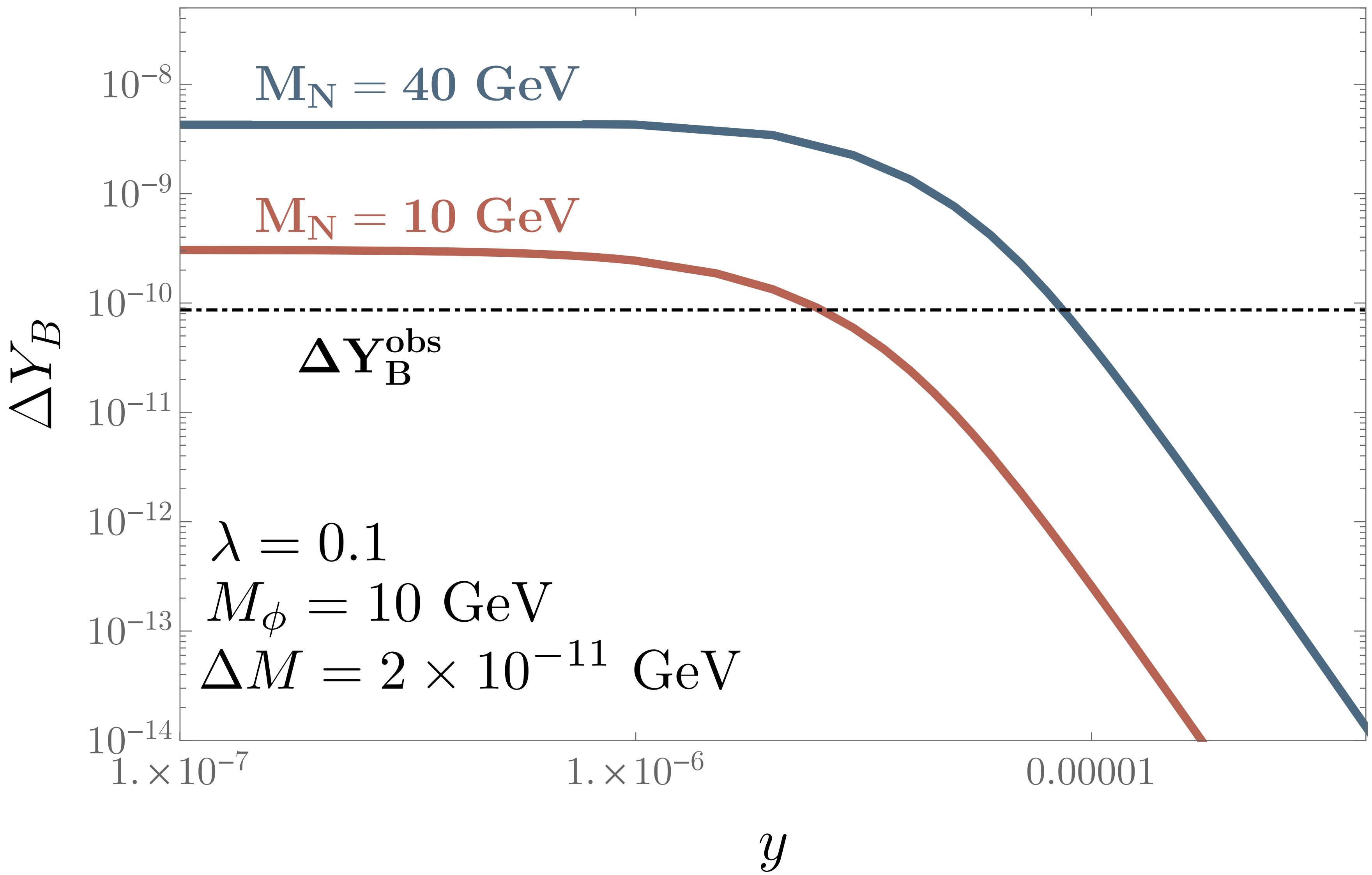
$$W_N = \frac{\pi^2 M_0}{144\zeta(3)T_{\mathrm{ew}}}F^\dagger F,$$

$$o_\mu = \frac{\pi^2 M_0}{144\zeta(3)T_{\mathrm{ew}}}F^\dagger \mu F,$$

$$r = \mathrm{diag}\left(0, \frac{\pi^2 M_0 \Delta M_{21}^2}{108\zeta(3)T_{\mathrm{ew}}^3}\right),$$

FREEZE-OUT LEPTOGENESIS

$$Y_N - Y_N^{\rm eq} \approx \frac{45 H Y_N^{\rm eq} z^2}{16\pi^4 g_{*S} \langle \Gamma_{\phi\to NN}\rangle Y_\phi^{\rm eq}} \left(\frac{M_N}{T_{\rm ew}}\right)^2 .$$



HIDDEN SECTOR BOLTZMANN EQUATIONS

$$\dot{n}_\phi + 3Hn_\phi = -2\left[\langle\sigma(\phi\phi \to HH^*)v\rangle_{T_\phi}\, n_\phi(t)^2 - \langle\sigma(\phi\phi \to HH^*)v\rangle_T\, n_\phi^{\rm eq}(T)^2\right]$$
$$- 2\sum_I \left[\langle\Gamma_{\phi\to N_I N_I}\rangle_{T_\phi} n_\phi(t) - \langle\Gamma_{\phi\to N_I N_I}\rangle_{T_N}\, n_\phi^{\rm eq}(T_N)\left(\frac{n_{N_I}(t)}{n_N^{\rm eq}(T_N)}\right)^2\right]$$
$$- 2\sum_I \left[\langle\sigma(\phi\phi \to \overline{N}_I N_I)v\rangle_{T_\phi}\, n_\phi(t)^2 - \langle\sigma(\phi\phi \to \overline{N}_I N_I)v\rangle_{T_N}\, n_\phi^{\rm eq}(T_N)^2 \left(\frac{n_{N_I}(t)}{n_{N_I}^{\rm eq}(T_N)}\right)^2\right],$$
$$\dot{n}_{N_I} + 3Hn_{N_I} = 2\left[\langle\Gamma_{\phi\to N_I N_I}\rangle_{T_\phi} n_\phi(t) - \langle\Gamma_{\phi\to N_I N_I}\rangle_{T_N}\, n_\phi^{\rm eq}(T_N)\left(\frac{n_{N_I}(t)}{n_N^{\rm eq}(T_N)}\right)^2\right]$$
$$+ \left[\langle\sigma(\phi\phi \to \overline{N}_I N_I)v\rangle_{T_\phi}\, n_\phi(t)^2 - \langle\sigma(\phi\phi \to \overline{N}_I N_I)v\rangle_{T_N}\, n_\phi^{\rm eq}(T_N)^2 \left(\frac{n_{N_I}(t)}{n_N^{\rm eq}(T_N)}\right)^2\right],$$

HIDDEN SECTOR BOLTZMANN EQUATIONS

$$
\begin{aligned}
\dot{\rho}_\phi + 4H\rho_\phi = &-\left[\langle\sigma(\phi\phi\to HH^*)vE_\phi\rangle_{T_\phi}\, n_\phi(t)^2 - \langle\sigma(\phi\phi\to HH^*)vE_\phi\rangle_T\, n_\phi^{\rm eq}(T)^2\right] \\
&- n_H^{\rm eq}(T) n_\phi(t)\langle\sigma(\phi H\to\phi H)vE_\phi\rangle_{T_\phi}\left(\frac{T_\phi}{T}-1\right) \\
&- 2\overline{M}_\phi\sum_I \Gamma_{\phi\to N_I N_I}\left[n_\phi(t) - n_\phi^{\rm eq}(T_N)\left(\frac{n_{N_I}(t)}{n_N^{\rm eq}(T_N)}\right)^2\right] \\
&- \sum_I\left[\langle\sigma(\phi\phi\to\overline{N}_I N_I)vE_\phi\rangle_{T_\phi}\, n_\phi(t)^2 - \langle\sigma(\phi\phi\to\overline{N}_I N_I)vE_\phi\rangle_{T_N}\, n_\phi^{\rm eq}(T_N)^2\left(\frac{n_{N_I}(t)}{n_N^{\rm eq}(T_N)}\right)^2\right] \\
&- \frac{2}{3} n_\phi(t)\sum_I n_{N_I}(t)\langle\sigma(\phi N_I\to\phi N_I)vE_\phi\rangle_{T_\phi}\left(\frac{T_\phi}{T_N}-1\right), \\
\dot{\rho}_{N_I} + 4H\rho_{N_I} = &\,\overline{M}_\phi\Gamma_{\phi\to N_I N_I}\left[n_\phi(t) - n_\phi^{\rm eq}(T_N)\left(\frac{n_{N_I}(t)}{n_N^{\rm eq}(T_N)}\right)^2\right] \\
&+ \frac{1}{2}\left[\langle\sigma(\phi\phi\to\overline{N}_I N_I)vE_\phi\rangle_{T_\phi}\, n_\phi(t)^2 - \langle\sigma(\phi\phi\to\overline{N}_I N_I)vE_\phi\rangle_{T_N}\, n_\phi^{\rm eq}(T_N)^2\left(\frac{n_{N_I}(t)}{n_N^{\rm eq}(T_N)}\right)^2\right] \\
&+ \frac{1}{3} n_\phi(t)\sum_I n_{N_I}(t)\langle\sigma(\phi N_I\to\phi N_I)vE_\phi\rangle_{T_\phi}\left(\frac{T_\phi}{T_N}-1\right),
\end{aligned}
$$

HIDDEN SECTOR QKES

$$\overline{T} \equiv \sqrt{T T_N}$$

$$\begin{aligned}
\frac{dR_N}{dz} &= i\,[R_N, W_N] + 3iz^2\,[R_N, r] - \mathcal{C}^{(0)}\left\{R_N + \frac{Y_{\tilde{N}}}{uY_N^{\rm eq}(T)}\mathbb{I}, W_N\right\} + 2\mathcal{C}^{(0)}W_N + \mathcal{C}^{(\rm w.o.1)}o_\mu \\
&+ \frac{1}{2}\mathcal{C}^{(\rm w.o.2)}\left\{o_\mu, R_N + \frac{Y_{\tilde{N}}}{uY_N^{\rm eq}(T)}\mathbb{I}\right\} - \frac{2}{zH}\langle\Gamma_{\phi\to N_I N_I}\rangle_{\overline{T}}\,\frac{Y_\phi^{\rm eq}(\overline{T})}{Y_N^{\rm eq}(\overline{T})^2}\,Y_{\tilde{N}}R_N \\
&- \frac{s}{zH}\langle\sigma(\phi\phi\to N_I\overline{N}_I)v\rangle_{\overline{T}}\,\frac{Y_\phi^{\rm eq}(\overline{T})^2}{Y_N^{\rm eq}(\overline{T})^2}\,Y_{\tilde{N}}R_N\,, \\
\frac{32T_{\rm ew}}{M_0}\frac{d\mu_{\Delta\alpha}}{dz} &= -\,\mathcal{C}^{(0)}\left(FR_NF^\dagger - F^*R_{\overline{N}}F^{\rm T}\right)_{\alpha\alpha} + \mathcal{C}^{(\rm w.o.1)}\left(FF^\dagger\right)_{\alpha\alpha}\mu_\alpha \\
&+ \frac{\mathcal{C}^{(\rm w.o.2)}}{2}\left(FR_NF^\dagger + F^*R_{\overline{N}}F^{\rm T} + \frac{2Y_{\tilde{N}}}{uY_N^{\rm eq}(T)}FF^\dagger\right)_{\alpha\alpha}\mu_\alpha.
\end{aligned}$$

THERMAL MASS OSCILLATIONS

- If HNL masses originate from spontaneous symmetry breaking, then they could be 0 at tree level in the early universe
- Dominant contribution now comes from **thermal contribution** to HNL energy differences due to hidden-sector couplings

$$\begin{aligned}\mathcal{A}(z_{\rm eq}) &= \int_0^{z_{\rm eq}} dz_2 \int_0^{z_2} dz_1 \, \sin\left[\frac{z_2 - z_1}{z_{\rm osc}}\right] \\ &\approx \frac{\Delta y^2 T_{\rm ew}^2}{288 a_N^3 y^6 M_0^2}.\end{aligned}$$

$$\mathcal{A}(z_{\rm eq})^{(\rm optimized)} = \frac{T_{\rm ew}^2}{6 a_N^2 M_0^2 y^4}$$

MOMENTUM AVERAGING

- Our QKEs average over momentum; however, in practice each momentum as its *own* oscillation time
- While we don't solve the full momentum-dependent QKEs in general, we can solve them *perturbatively*

$$z_{\rm osc}(q) = \left(\frac{6qT_{\rm ew}^3}{\Delta M_{21}^2 M_0}\right)^{1/3}$$

$$\mathcal{A}^{(\rm full)}(z_{\rm eq}) = \frac{\sqrt{\kappa}}{2K_1(2\sqrt{\kappa})}\int_0^\infty dq\,\frac{e^{-q-\kappa/q}}{q^2}\int_0^{z_{\rm eq}} dz_2 \int_0^{z_2} dz_1\,\sin\left[\frac{z_2^3 - z_1^3}{z_{\rm osc}(q)^3}\right]$$