

# Leptogenesis and light DM in the Scotogenic model

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Based on [arXiv:1806.06864](https://arxiv.org/abs/1806.06864)

With Vedran Brdar and Pedro Schwaller



**PRISMA**

DESY Theory  
Workshop 2018



# Scotogenic model spectrum I

E.Ma [hep-ph/0601225]

	$SU(2)_L$	$U(1)_Y$	$Z_2$
$\Sigma$	2	1/2	-
$N_k$	1	0	-
$\Phi$	2	1/2	+
$L$	2	-1/2	+

$Z_2$  symmetry:

→ **Forbids** decays  $N_k \rightarrow \nu\gamma$

→ **No** vev for  $\Sigma$

→ **Radiative** seesaw

→ Stable particle:  $N_1$  as **DM**

$$\mathcal{L} \supset y_{ki} \bar{N}_k \tilde{\Sigma}^\dagger L_i - \frac{1}{2} \bar{N}_k^c M_k N_k + \text{h.c.}$$

$$M_1 = \mathcal{O}(\text{keV}) \longrightarrow \textit{Freeze-In}$$

$$M_{2,3} = \mathcal{O}(\text{few } 100 \text{ GeV}) \longrightarrow \textit{Freeze-Out}$$

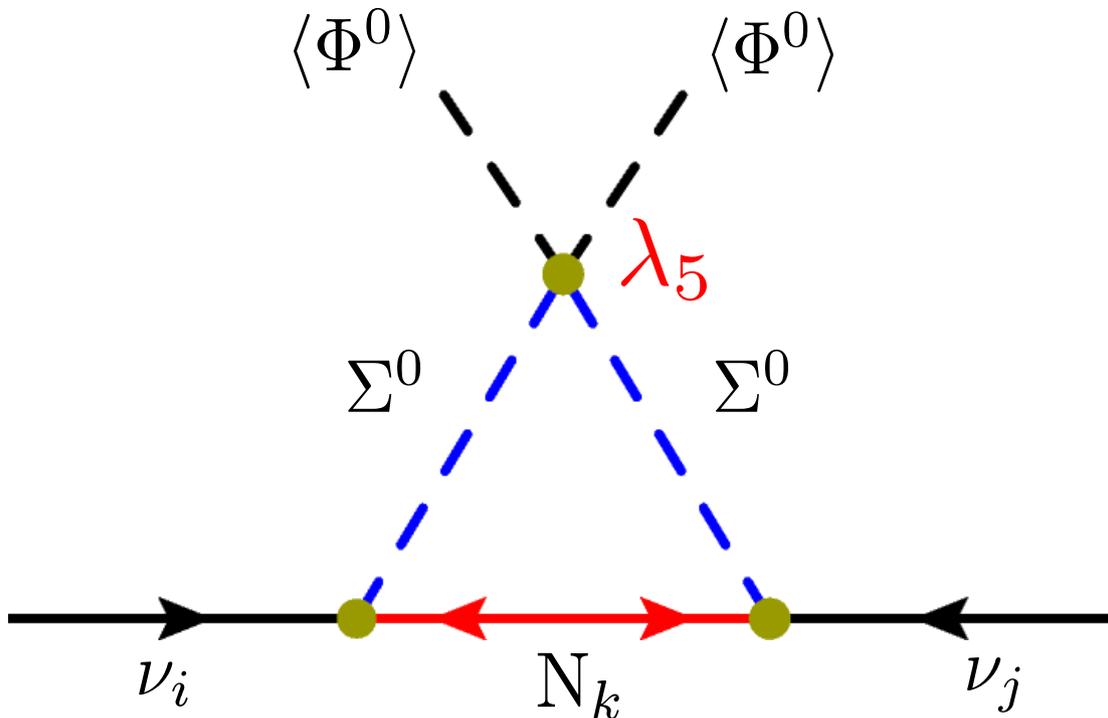
# Scotogenic model spectrum II

## Scalar sector:

$$V(\Phi, \Sigma) = \mu_1^2 \Phi^\dagger \Phi + \mu_2^2 \Sigma^\dagger \Sigma + \frac{\lambda_1}{2} (\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2} (\Sigma^\dagger \Sigma)^2 \\ + \lambda_3 (\Phi^\dagger \Phi) (\Sigma^\dagger \Sigma) + \lambda_4 (\Phi^\dagger \Sigma) (\Sigma^\dagger \Phi) + \frac{\lambda_5}{2} \left( (\Phi^\dagger \Sigma)^2 + \text{h.c.} \right)$$

$$\Sigma = \begin{pmatrix} \sigma^+ \\ \frac{1}{\sqrt{2}} (S^0 + iA^0) \end{pmatrix} \left. \begin{array}{l} m_{\pm}^2 = \mu_2^2 + \frac{\lambda_3 v^2}{2} \\ m_A^2 = m_{\pm}^2 + \frac{(\lambda_4 - \lambda_5) v^2}{2} \\ m_S^2 = m_A^2 + \lambda_5 v^2 \end{array} \right\} \leq 1 \text{ TeV}$$

# Radiative neutrino masses



$$m_0^2 \equiv \frac{m_S^2 + m_A^2}{2} \gg M_k^2$$

$$\downarrow$$

$$(m_\nu)_{ij} \approx \frac{\lambda_5 v^2}{8\pi^2} \frac{y_{ki} y_{kj}}{m_0^2} M_k$$

Casas-Ibarra Parametrization:

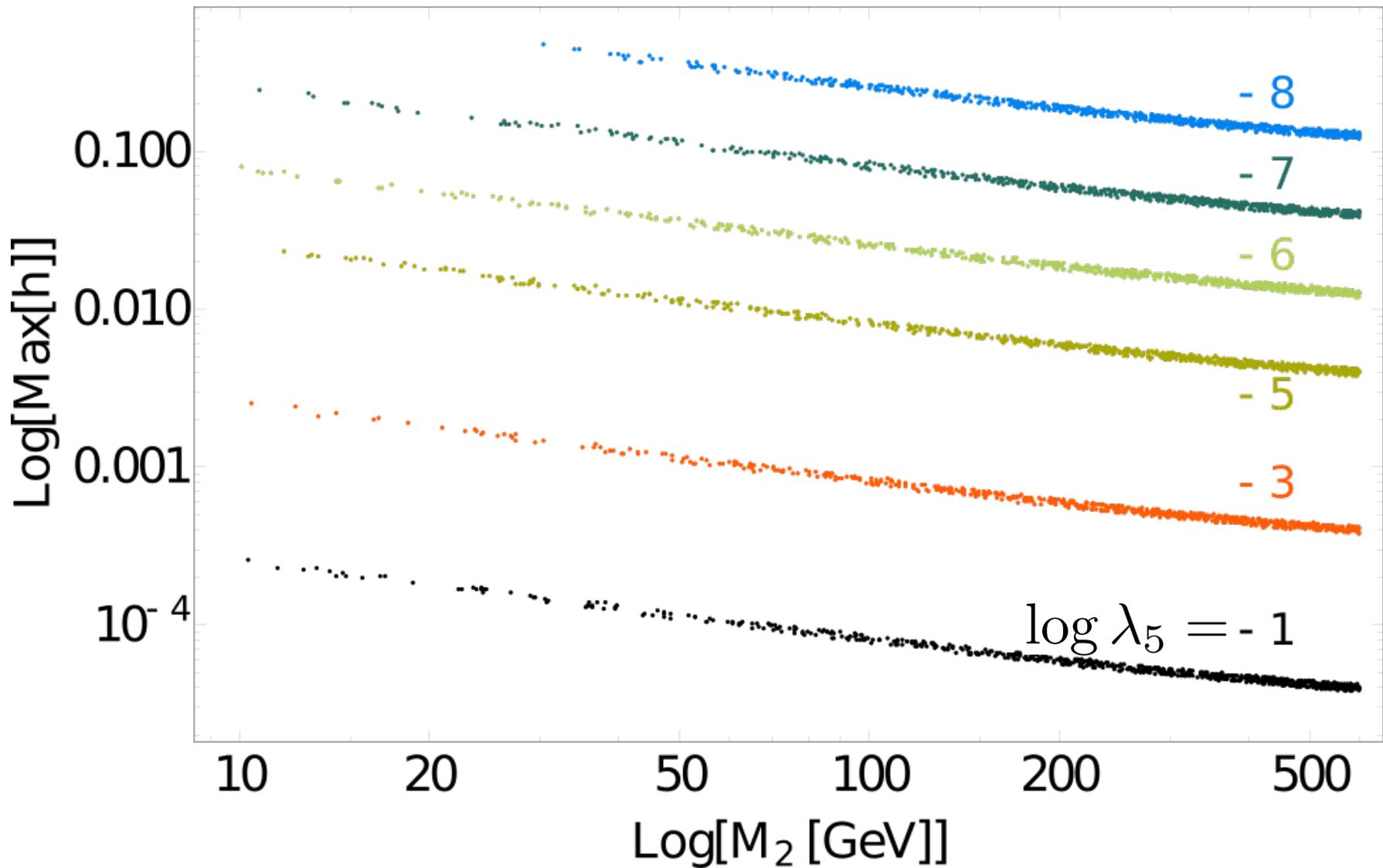
J.A. Casas, A. Ibarra  
[hep-ph/0103065]

$$y = \sqrt{\Lambda^{-1}} R \sqrt{m_\nu} U_{\text{PMNS}}^\dagger$$

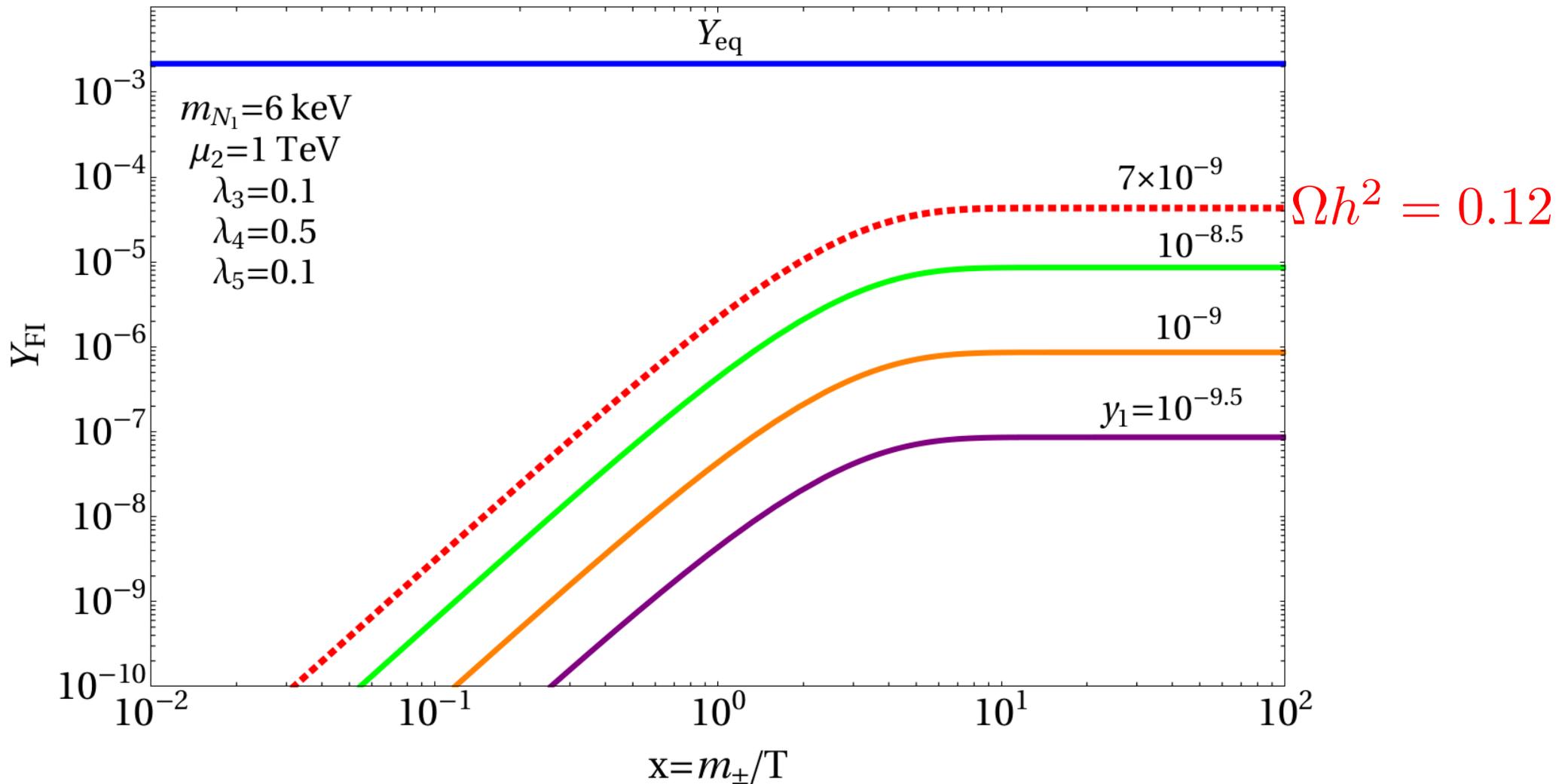
$$m_\nu = \text{Diag}(0, \sqrt{\Delta_{\text{sol}}^2}, \sqrt{\Delta_{\text{sol}}^2 + \Delta_{\text{atm}}^2})$$

$$R = \begin{pmatrix} 0 & \cos(w + i\xi) & \sin(w + i\xi) \\ 0 & -\sin(w + i\xi) & \cos(w + i\xi) \end{pmatrix}$$

# Impact of $\lambda_5$



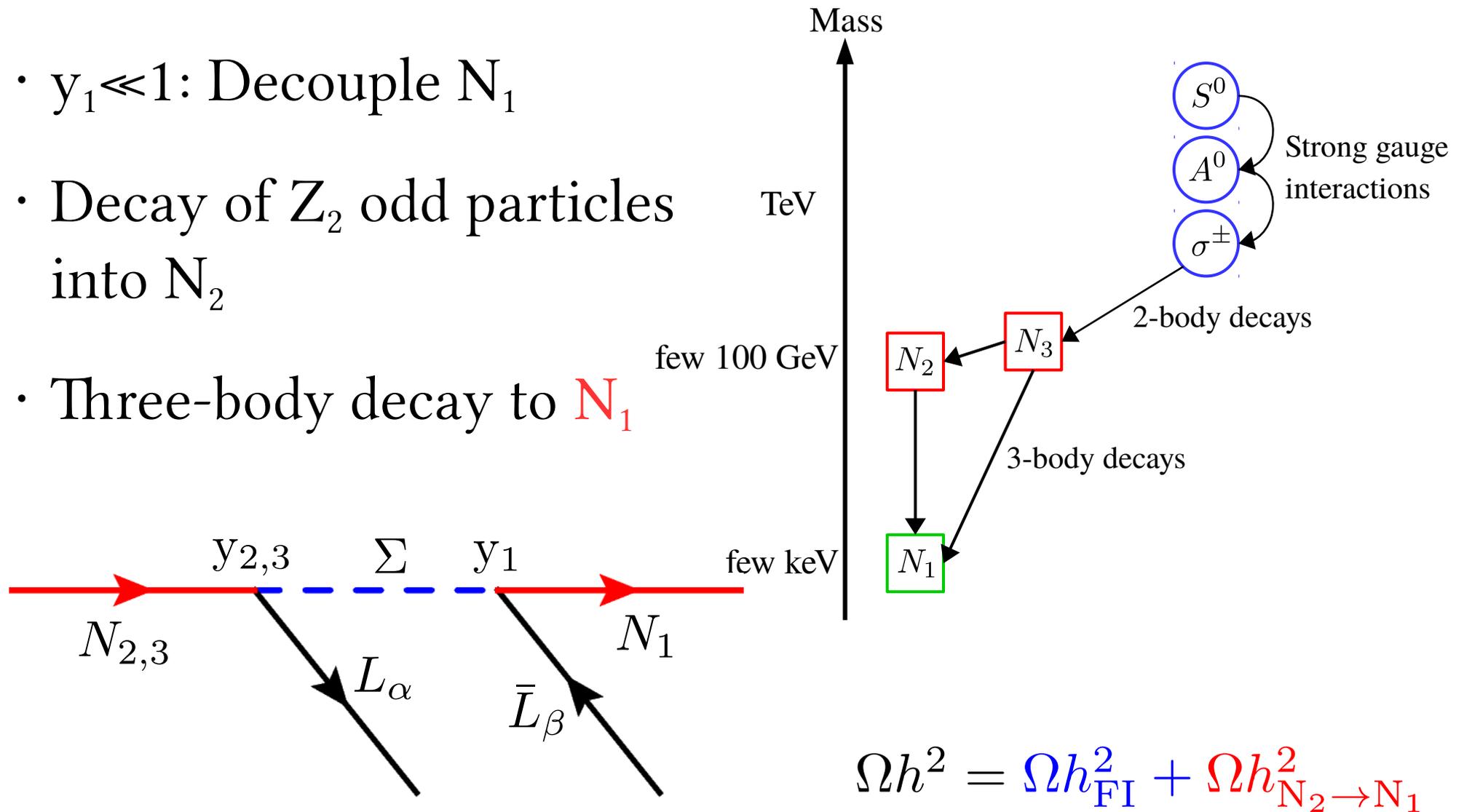
# DM I: $N_1$ Freeze-In



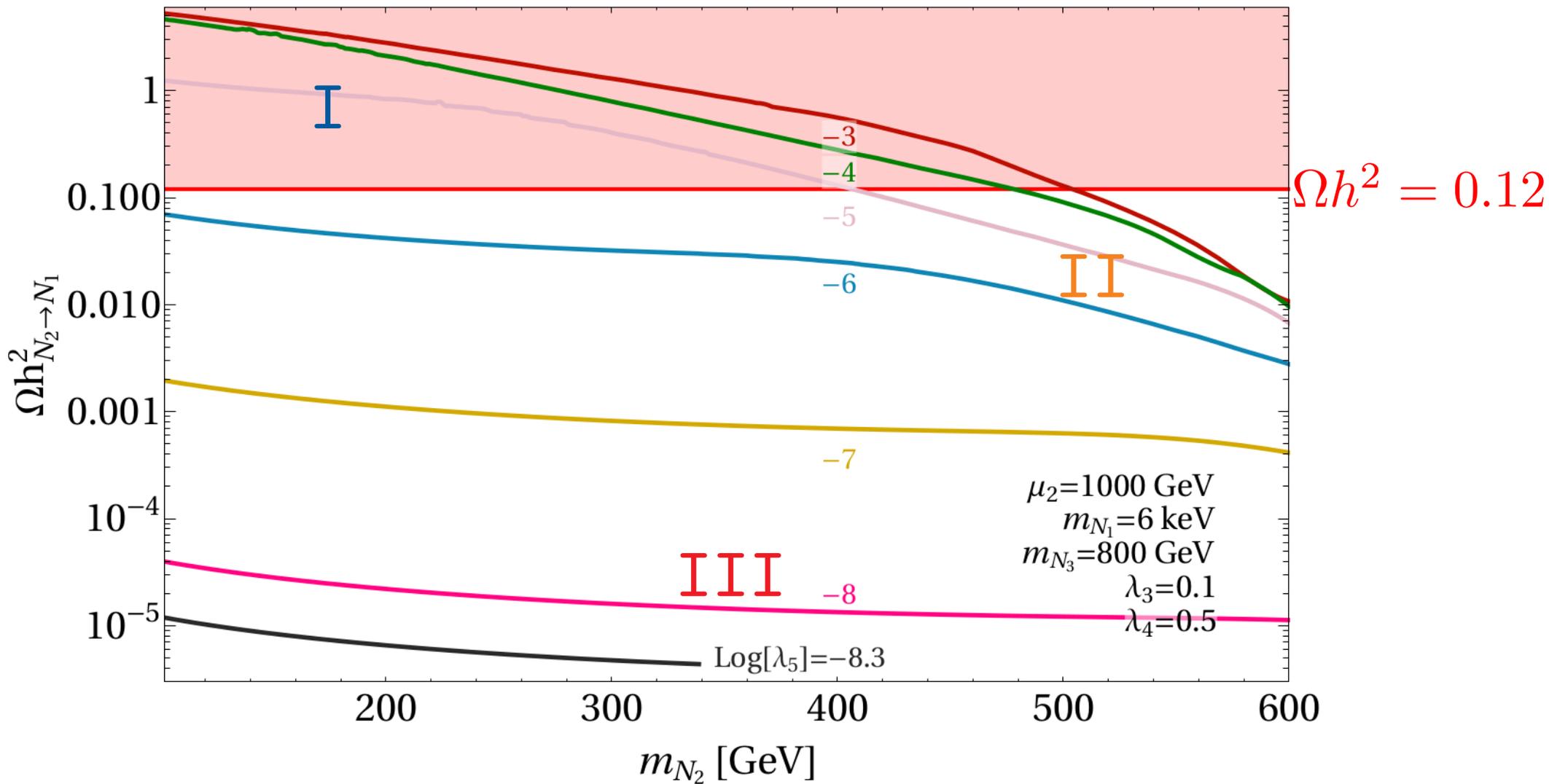
$$\Omega_{\text{FI}} h^2 = 2.75 \cdot 10^8 \frac{M_1}{\text{GeV}} Y_1 \approx 0.12 \left( \frac{y_1}{6 \cdot 10^{-9}} \right)^2 \left( \frac{M_1}{6 \text{ keV}} \right) \left( \frac{1 \text{ TeV}}{m_{\pm}} \right)$$

# DM II: $N_2$ decay contributions

- $y_1 \ll 1$ : Decouple  $N_1$
- Decay of  $Z_2$  odd particles into  $N_2$
- Three-body decay to  $N_1$



# DM II: $N_2$ decay contributions



**I + III:** Only  $N_2$  annihilation

**II:** Additional annihilation channels

# Leptogenesis I: Fundamentals

Goal: *CP violation* for lepton asymmetry

Akhmedov, Rubinov, Smirnov [hep-ph/9803255]

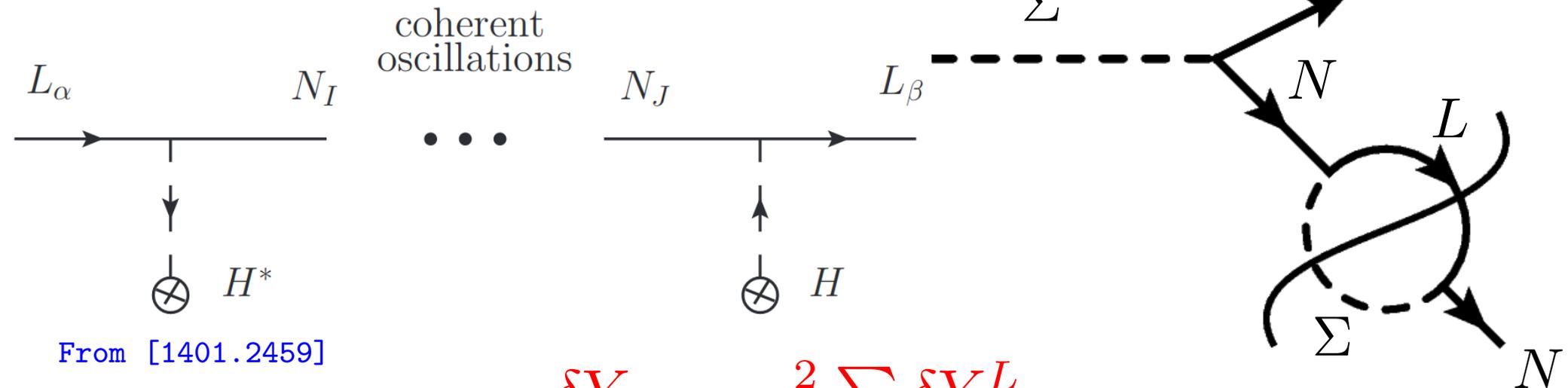
T.Hambye, D.Teresi [1606.00017]

## 1) ARS:

- Oscillations among  $N_k$
- Asymmetry generation in each flavor

## 2) Decays $\Sigma \rightarrow N L$

- Thermally induced on-shell particles

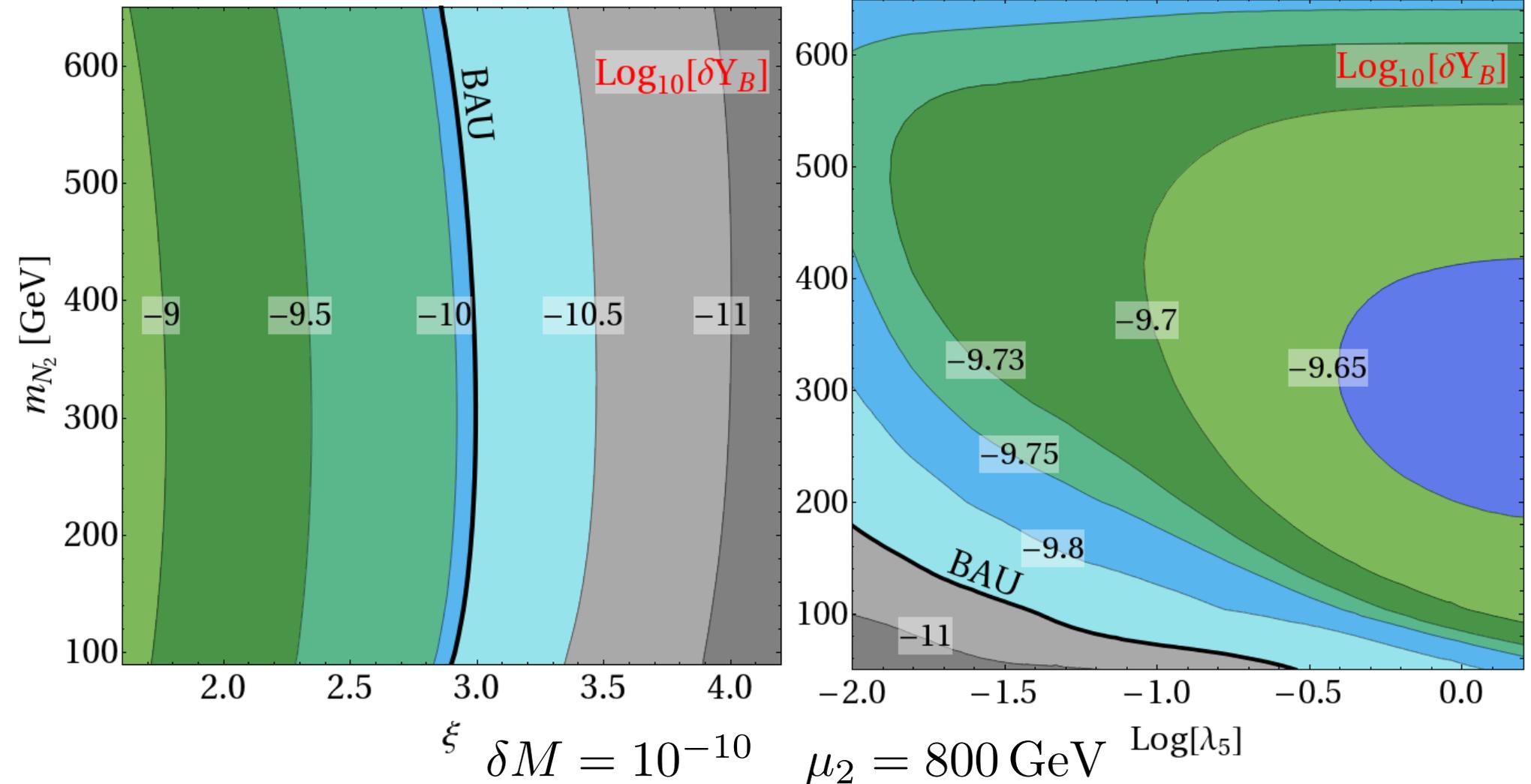


From [1401.2459]

$$\delta Y_B = -\frac{2}{3} \sum_i \delta Y_i^L$$

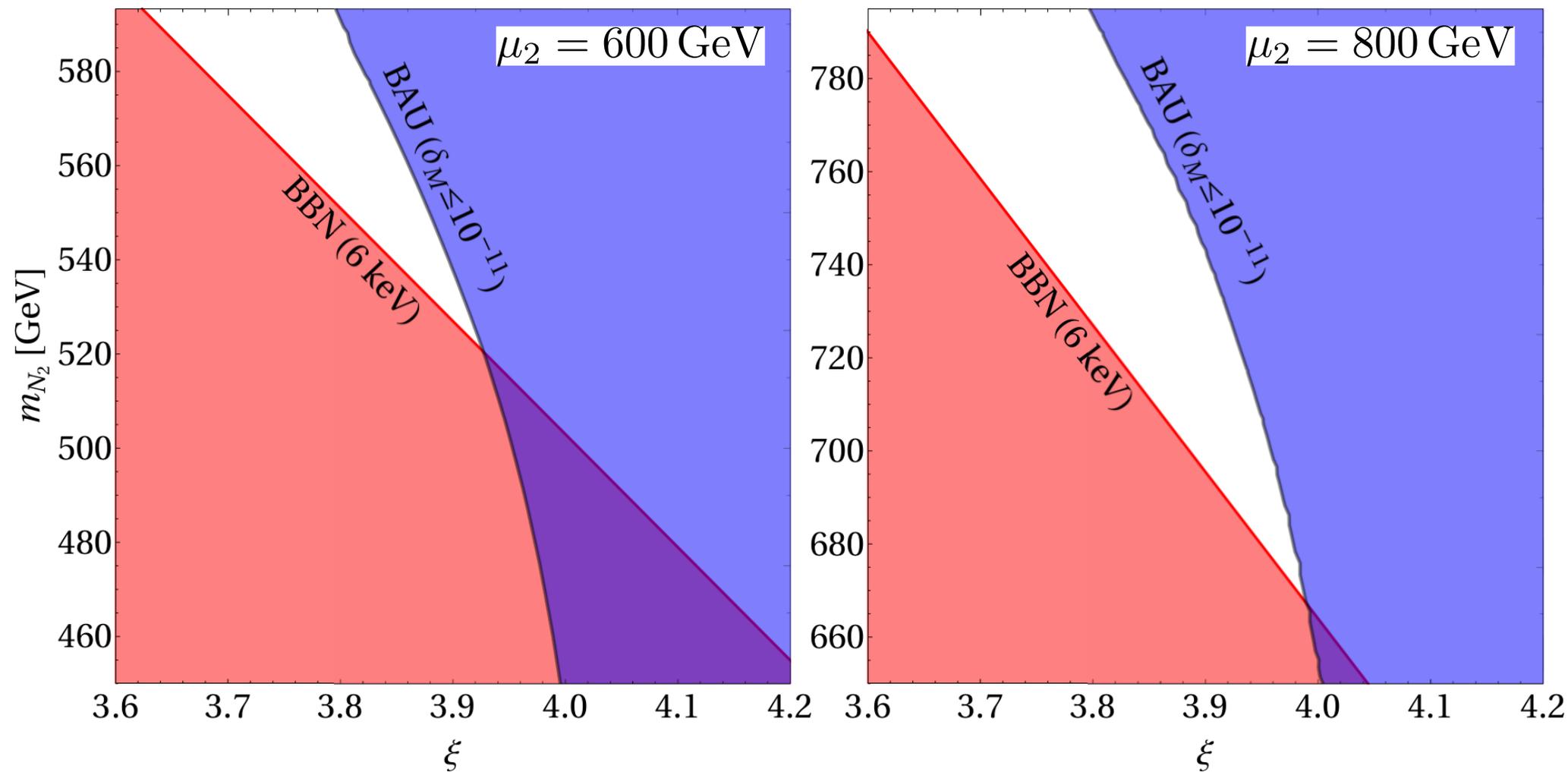
# Leptogenesis II: Results

$$\frac{d \delta Y_i^L}{dz} \approx S - \delta Y_i^L W \rightarrow \textit{Small Yukawas required}$$



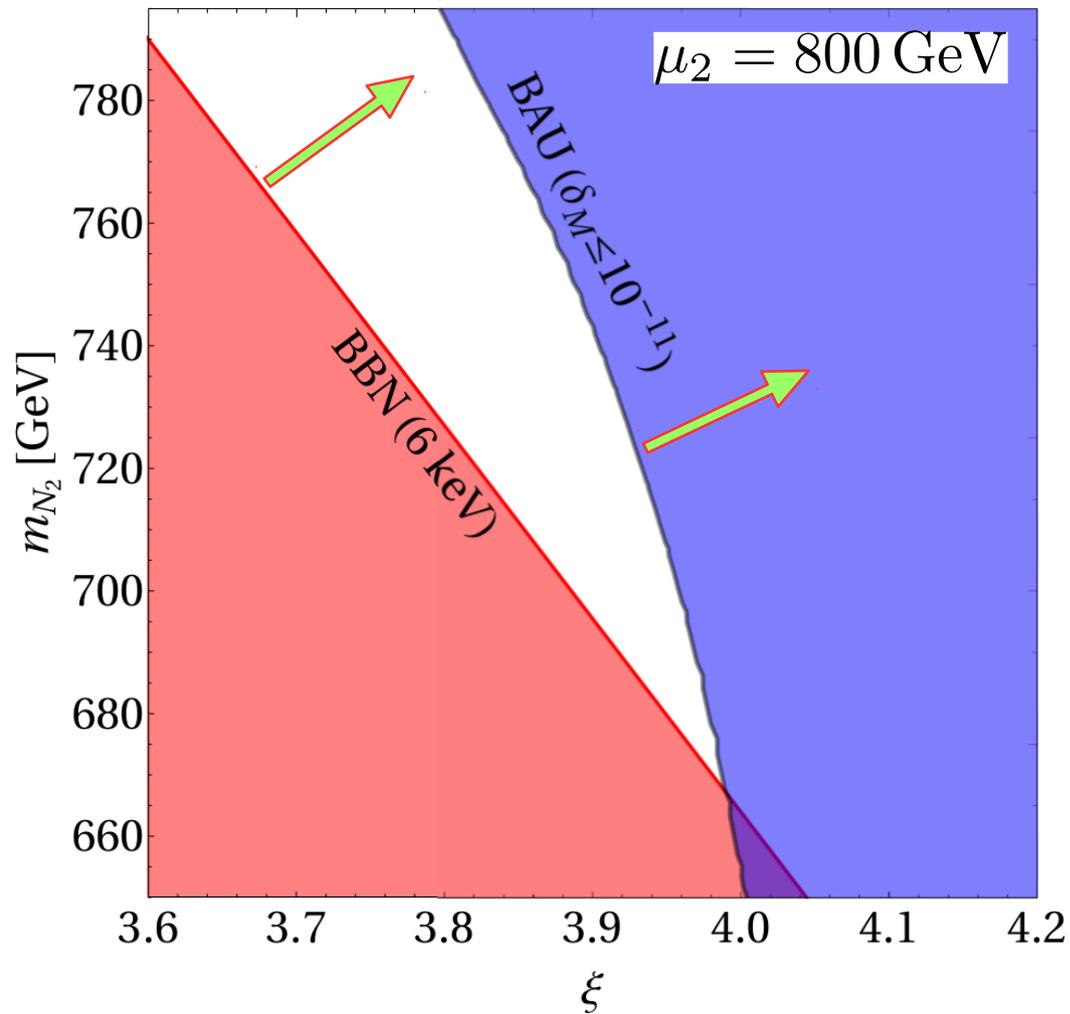
# Merging DM + Leptogenesis

Decrease splitting between  $\Sigma$  and  $N_2$  masses



# Merging DM + Leptogenesis

Possible to extend parameter region?



Larger degeneracy of  $N_2 + N_3$   
→ more efficient Leptogenesis

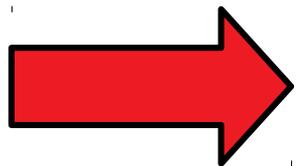
Saturation at  $\delta M \sim 10^{-12}$

Yields an **upper bound** for  
light DM:

**~20 keV**

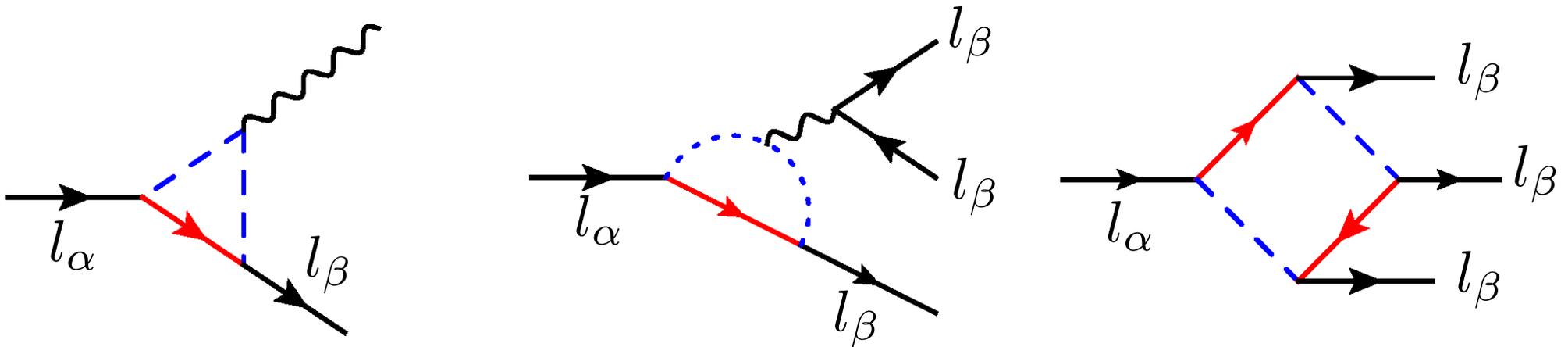
# Summary

- **Sub TeV** realization of Scotogenic model
- Successful DM density:
  - Freeze-In of  $N_1$
  - $N_2$  decay contribution
- Significant baryon asymmetry from Leptogenesis



Parameter region for combination!

# Backup slides



T.Toma, A.Vicente [1312.2840]

Process	BR bound
$\mu \rightarrow e \gamma$	$4.2 \cdot 10^{-13}$
$\tau \rightarrow e \gamma$	$3.3 \cdot 10^{-8}$
$\tau \rightarrow \mu \gamma$	$4.4 \cdot 10^{-8}$
$\mu \rightarrow 3 e$	$1.0 \cdot 10^{-12}$
$\tau \rightarrow 3 e$	$2.7 \cdot 10^{-8}$
$\tau \rightarrow 3 \mu$	$2.1 \cdot 10^{-8}$

→ *Upper bound* on Yukawa strength

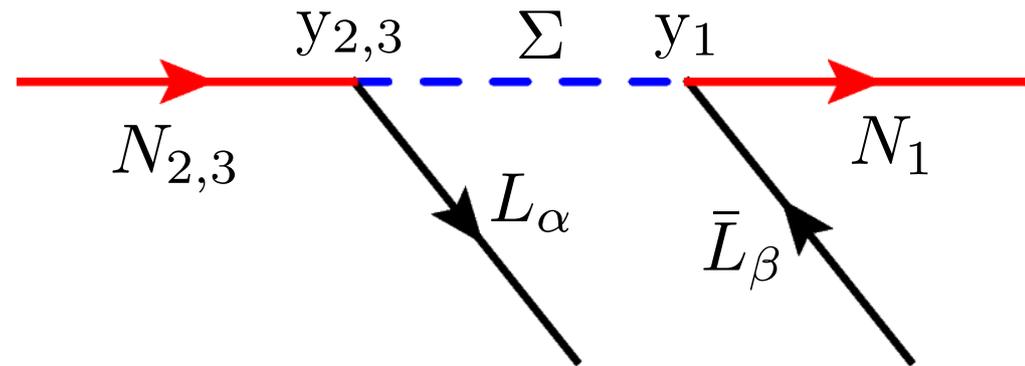
Particle Data Group +  
1605.05081

# Backup slides

- Boltzmann equation for  $N_1$

$$Y'_1(x) = 6 \sum_{i=\pm,S} \frac{45 M_{\text{Pl}} y_1^2}{32\pi^4 \cdot 1.66 (g_*)^{3/2}} \frac{m_i^3}{m_1^4} x^3 \cdot K_1 \left( \frac{m_i}{m_1} x \right)$$

- Decay width  $N_{2,3} \rightarrow N_1$ :



$$\Gamma(N_{2,3} \rightarrow N_1 \bar{l}_\alpha l_\beta) = \frac{M_{2,3}^5}{6144\pi^3 m_S^4} (|y_{1\beta}|^2 |y_{2,3\alpha}|^2 + |y_{1\alpha}|^2 |y_{2,3\beta}|^2)$$

E. Molinaro et. al. [1405.1259]

# Backup slides

- Boltzmann equation for  $N_2$

J. Edsjo, P. Gondolo [hep-ph/9704361]

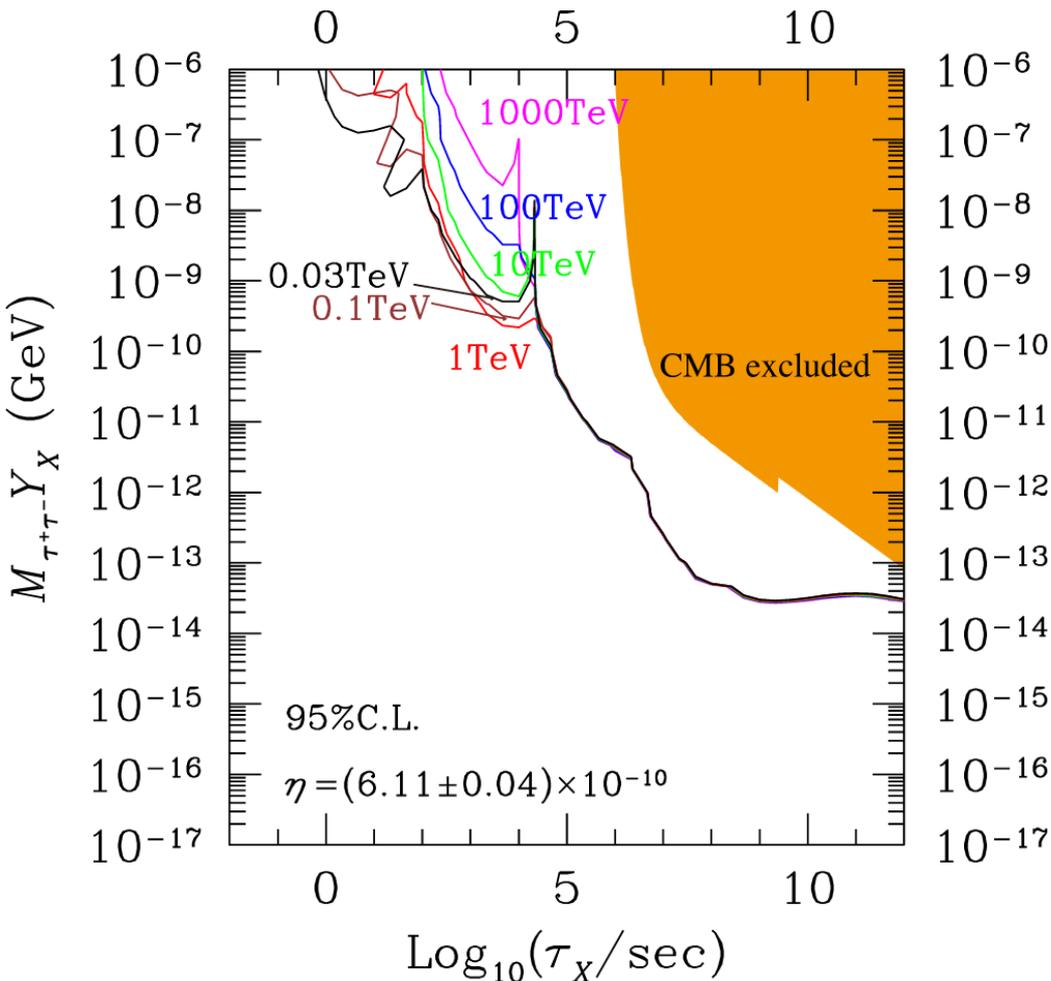
$$\begin{aligned} \frac{dn_i}{dt} + 3Hn_i = & - \sum_{j=1}^N \langle \sigma_{ij} v_{ij} \rangle (n_i n_j - n_i^{\text{eq}} n_j^{\text{eq}}) \\ & - \sum_{j \neq 1}^N \left( \langle \sigma'_{Xij} v_{ij} \rangle (n_i n_X - n_i^{\text{eq}} n_X^{\text{eq}}) - \langle \sigma'_{Xji} v_{ij} \rangle (n_j n_X - n_j^{\text{eq}} n_X^{\text{eq}}) \right) \\ & - \sum_{j \neq 1}^N \left( \Gamma_{ij} (n_i - n_i^{\text{eq}}) - \Gamma_{ji} (n_j - n_j^{\text{eq}}) \right) \end{aligned} \quad \begin{array}{l} I = N_{2,3}, A^0, S^0, \Sigma^\pm \\ X = \text{SM particles} \end{array}$$

Where 
$$n_i^{\text{eq}} = \frac{T}{2\pi^2} \sum_i g_i m_i^2 K_2 \left( \frac{m_i}{T} \right)$$

# Backup slides

- BBN bounds

$$(h_2)^2 \gtrsim 6.3 \cdot 10^{-7} \left( \frac{m_\Sigma}{1 \text{ TeV}} \right)^4 \left( \frac{1 \text{ TeV}}{M_2} \right)^5 \left( \frac{10^{-8}}{|y_1|} \right)^2 \left( \frac{1 \text{ sec}}{\tau} \right)$$



- Naively:  $t_{\text{BBN}} \sim 1 \text{ sec}$
- Dominantly decays into  $\tau$  pairs  
 → Small yield required

M.Kawasaki et.al. [1709.01211]

# Backup slides

- Boltzmann equation for Leptogenesis:

$$\frac{dn_{\alpha\beta}^N}{dt} = -i[E_N, n^N(\mathbf{k})]_{\alpha\beta} - \frac{1}{2} \left\{ \gamma^{LC} + \gamma^{LV}, \frac{n^N}{n_{\text{eq}}^N} - I \right\}_{\alpha\beta}$$

$$+ \frac{\delta n_l^L}{2n_{\text{eq}}^L} \left( (\gamma_{WQ,l}^{LC} - \gamma_{WQ,l}^{LV}) + \frac{1}{2} \left\{ \gamma_{WC,l}^{LC} - \gamma_{WC,l}^{LV}, \frac{n^N}{n_{\text{eq}}^N} \right\} \right)_{\alpha\beta}$$

$$\frac{d\bar{n}_{\alpha\beta}^N}{dt} = \frac{dn_{\alpha\beta}^N}{dt} (n \rightarrow \bar{n}, \gamma \rightarrow \gamma^*, \delta n_l^L \rightarrow -\delta n_l^L)$$

$$\frac{d\delta n_l^L}{dt} = \frac{1}{n_{\text{eq}}^N} \text{tr} \{ (\gamma_l^{LC} - \gamma_l^{LV}) n^N \} - (\gamma \rightarrow \gamma^*, n \rightarrow \bar{n})$$

$$- \frac{\delta n_l^L}{n_{\text{eq}}^L} \text{tr} \{ \gamma_{WQ,l}^{LC} + \gamma_{WQ,l}^{LV} \} \quad \delta Y_B = -\frac{2}{3} \sum_i \delta Y_i^L$$

$$- \frac{\delta n_l^L}{2n_{\text{eq}}^L} \frac{1}{n_{\text{eq}}^N} \text{tr} \{ n^N (\gamma_{WC,l}^{LC} + \gamma_{WC,l}^{LV}) \} - (\gamma \rightarrow \gamma^*, n \rightarrow \bar{n})$$