Leptogenesis and light DM in the Scotogenic model

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#DMLHC2018

PRISMA

JG|U

Scotogenic model spectrum I

E.Ma [hep-ph/0601225]

	$SU(2)_L$	$U(1)_Y$	Z_2
Σ	2	1/2	-
N_i	1	0	-
Φ	2	1/2	+
L	2	-1/2	+

Z_2 symmetry:

→ Forbids decays N_i to $\nu\gamma$

→ No vev for Σ

→ Radiative seesaw

→ Stable particle: N_1 → DM

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

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

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

Scotogenic model spectrum II

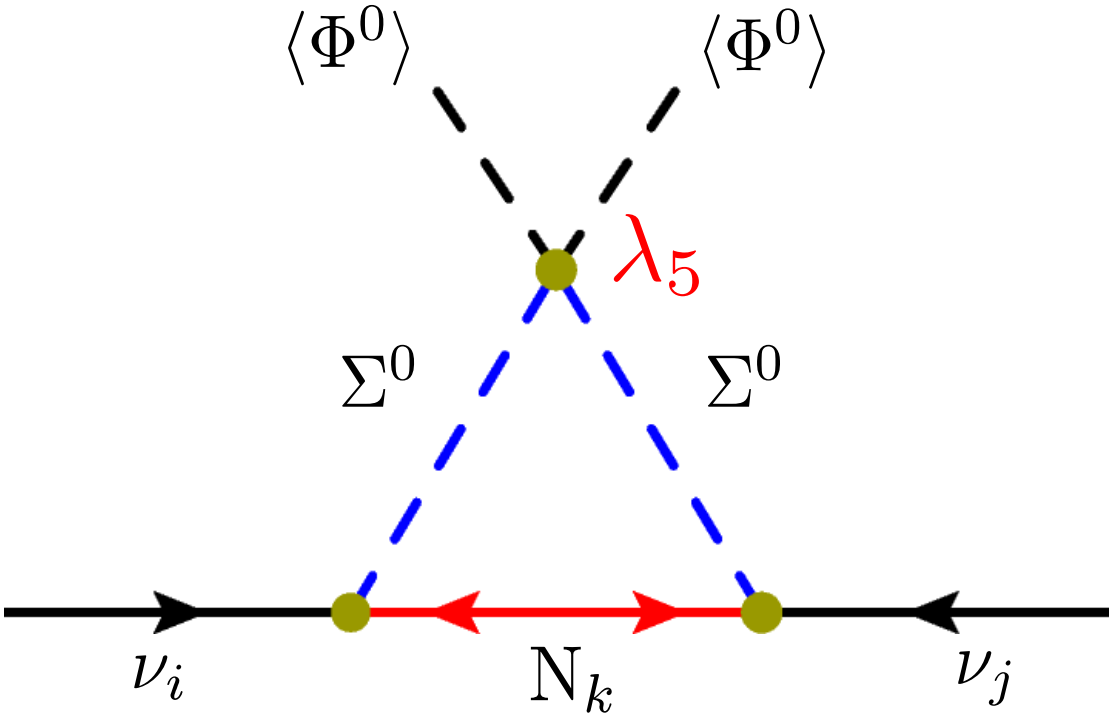
Scalar sector:

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

$$\Sigma = \begin{pmatrix} \sigma^+ \\ \frac{1}{\sqrt{2}}\left(S^0 + iA^0\right) \end{pmatrix}$$

$$\left.\begin{aligned} \mathrm{m}_\pm^2 &= \mu_2^2 + \tfrac{\lambda_3 v^2}{2} \\ \mathrm{m}_A^2 &= m_\pm^2 + \tfrac{(\lambda_4-\lambda_5)v^2}{2} \\ \mathrm{m}_S^2 &= m_A^2 + \lambda_5 v^2 \end{aligned}\right\} \leq 1\,\text{TeV}$$

Radiative neutrino masses



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

$$\downarrow$$

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

- Casas-Ibarra Parametrization:

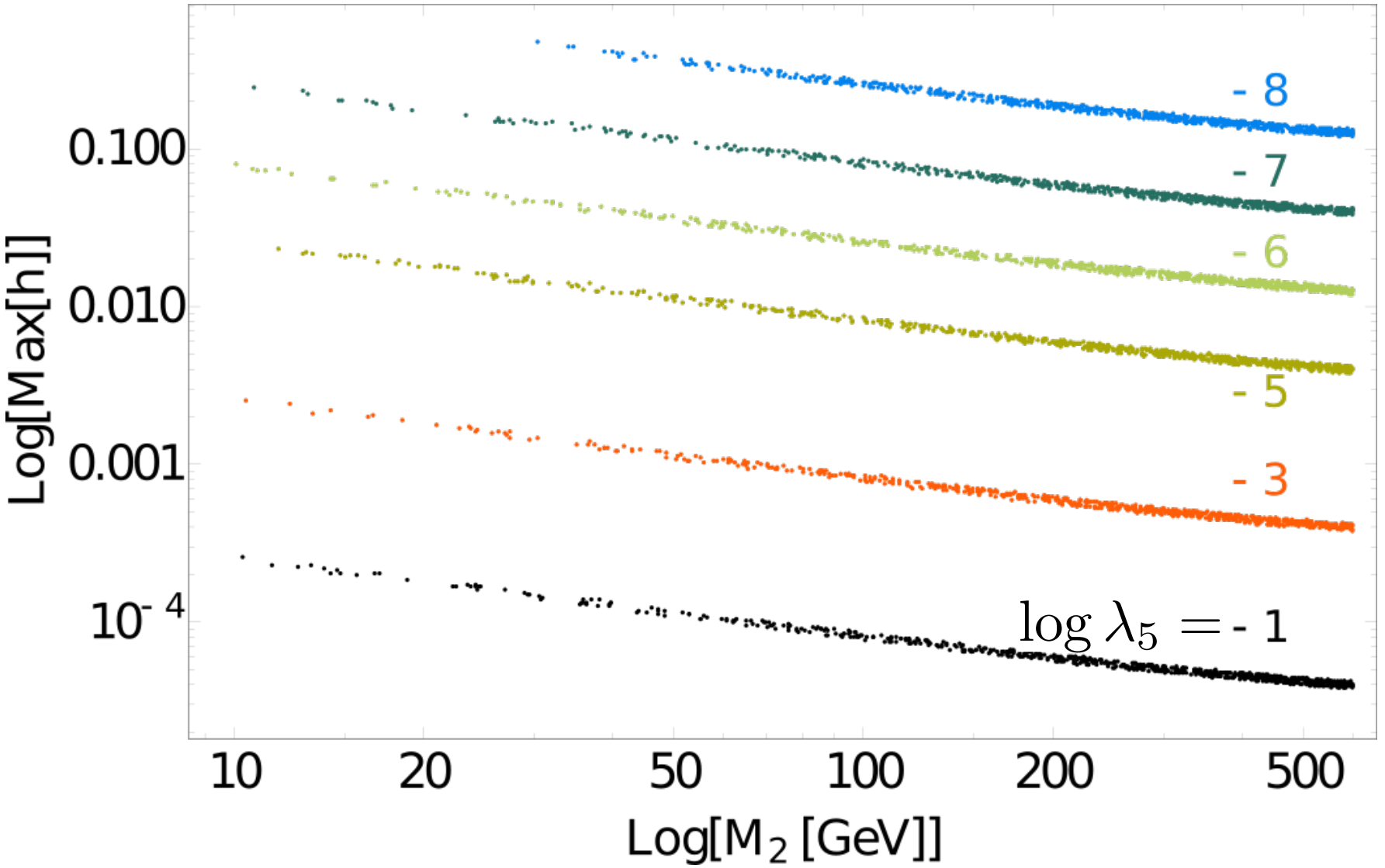
J.A. Casas, A. Ibarra [hep-ph/0103065]

$$\mathrm{h} = \sqrt{\Lambda^{-1}}\, R \sqrt{m_\nu}\, U_{\mathrm{PMNS}}^\dagger$$

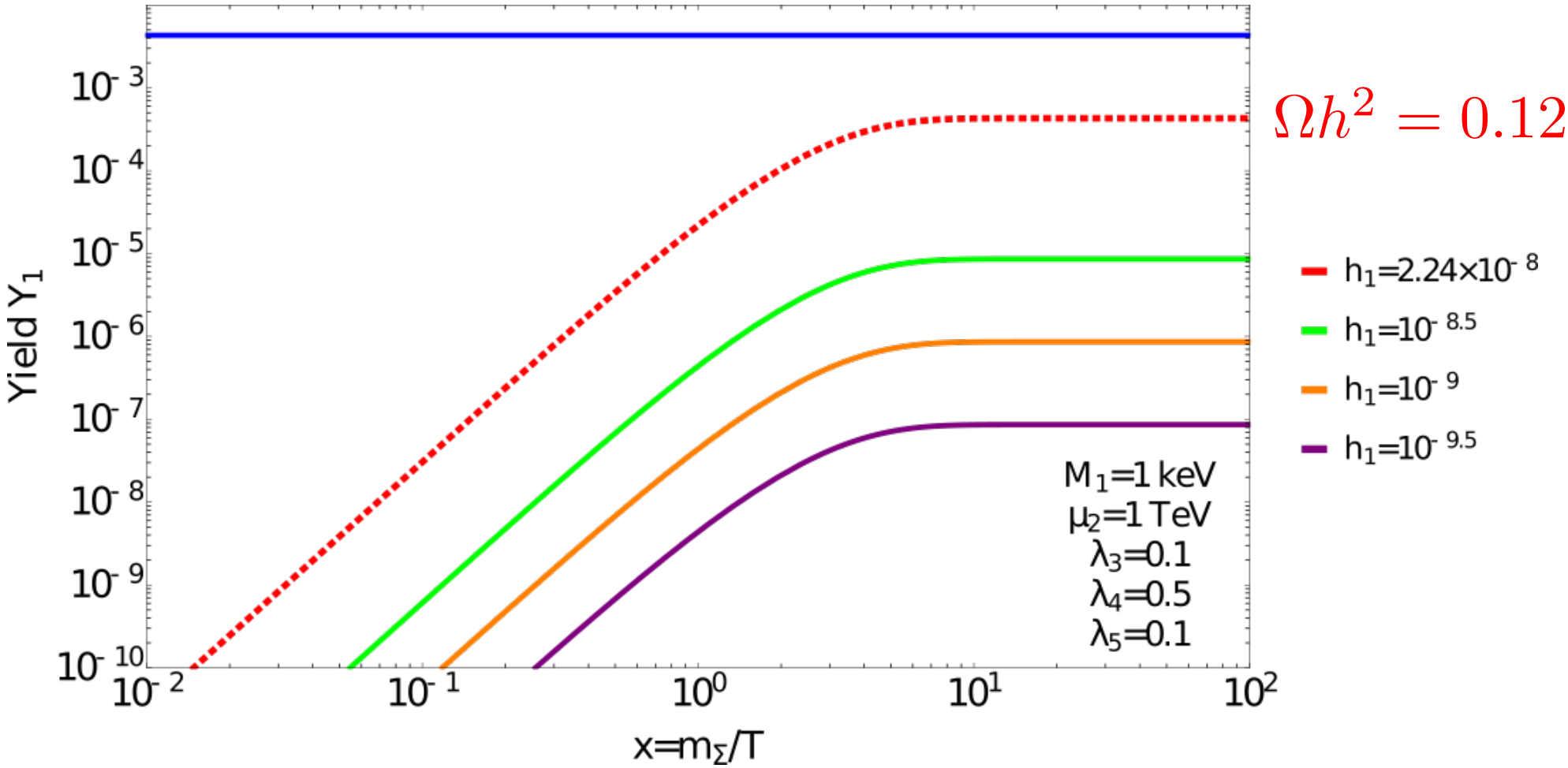
$$\mathrm{m}_\nu = \mathrm{Diag}(0, \sqrt{\Delta^2_{\mathrm{sol}}}, \sqrt{\Delta^2_{\mathrm{sol}} + \Delta^2_{\mathrm{atm}}})$$

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

DM I: impact of λ_5



DM II: N_1 Freeze-In

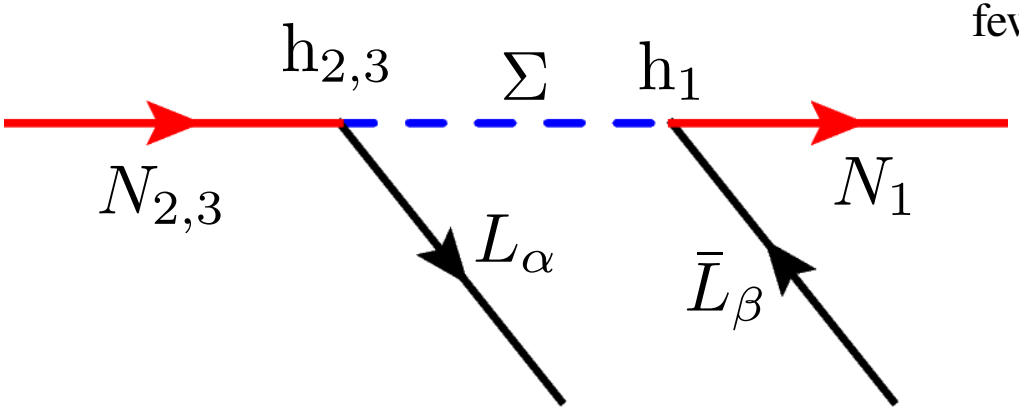


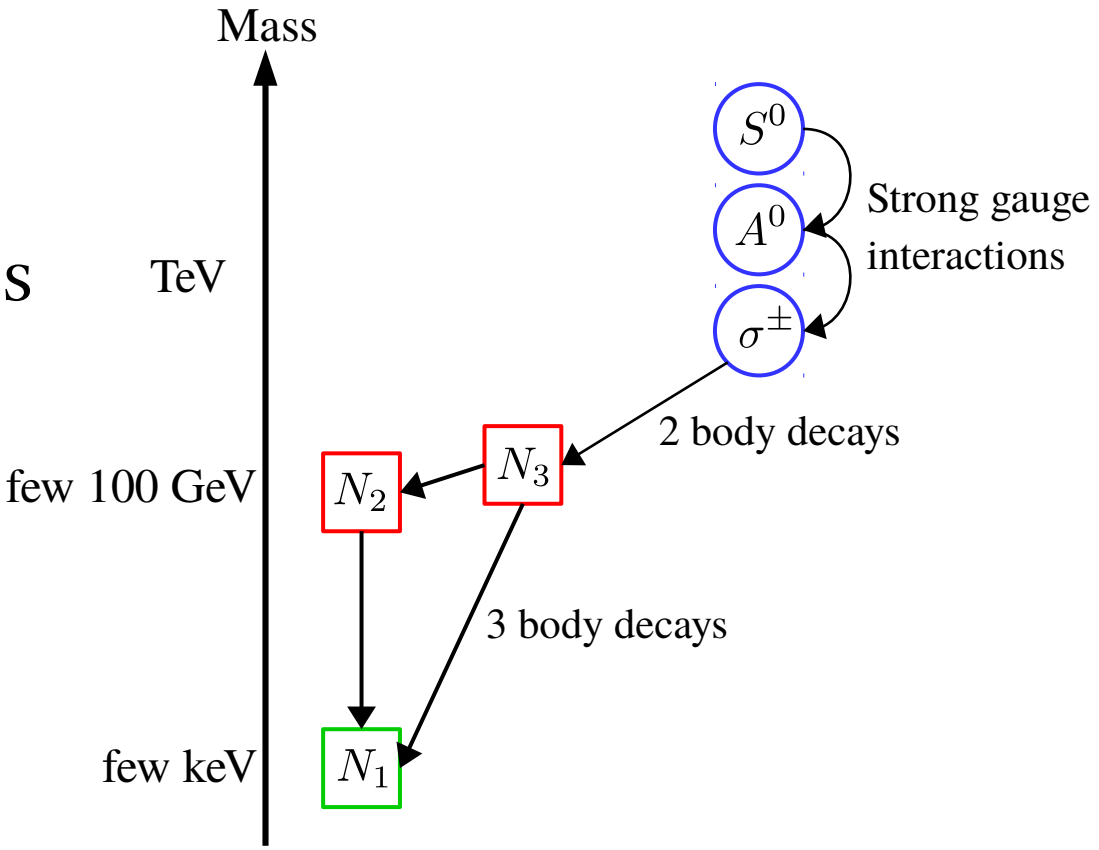
$$\Omega h^2 = 0.12$$

$$\Omega_{FI} h^2 = 2.75 \cdot 10^8 \, \frac{m_1}{\mathrm{GeV}} \, Y_1 \approx 0.12 \left(\frac{y_1}{10^{-7.86}} \right)^2 \left(\frac{m_1}{1\,\mathrm{keV}} \right) \left(\frac{1\mathrm{TeV}}{m_\pm} \right)$$

DM III: N_2 decay contributions

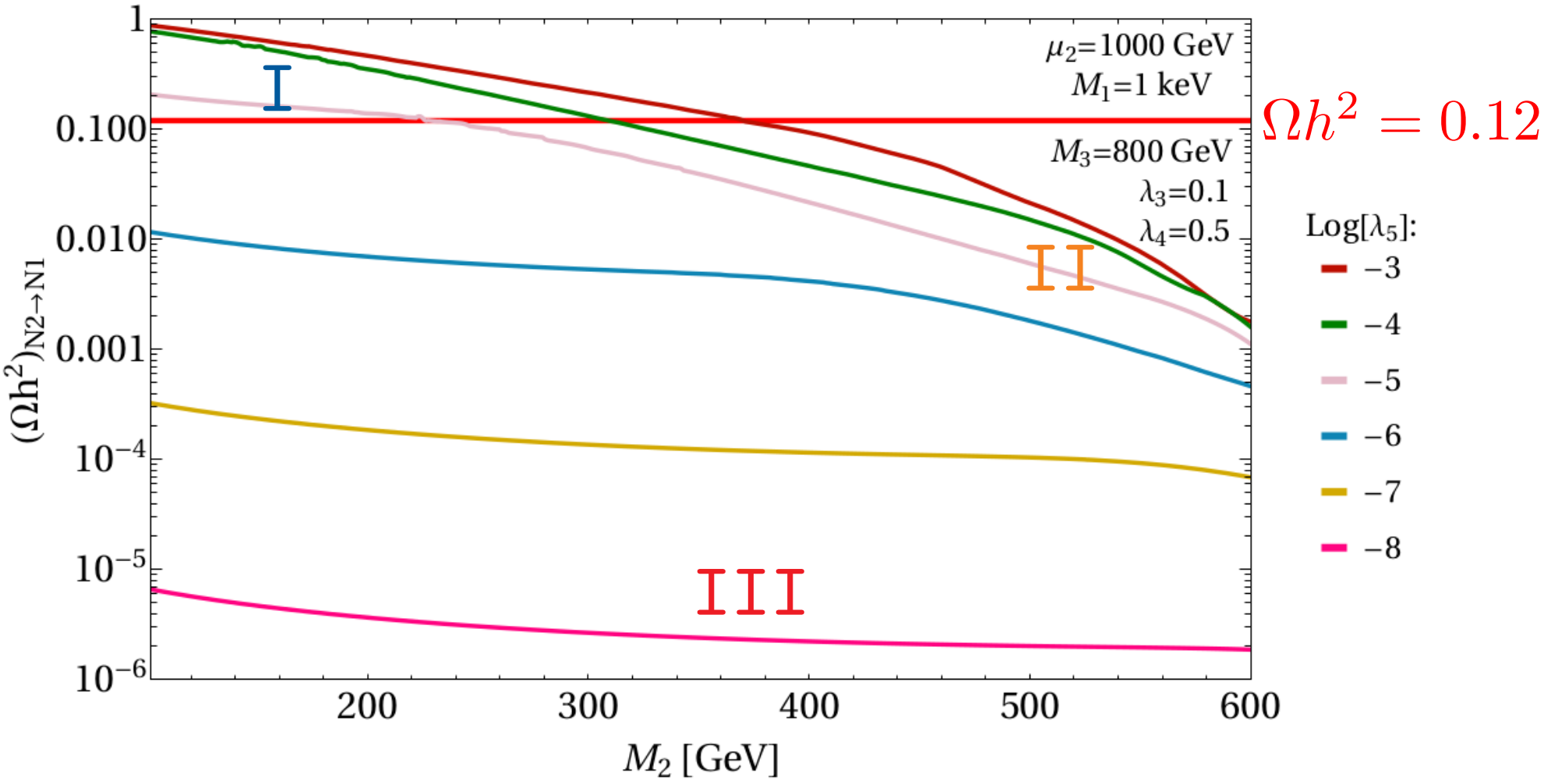
- $h_1 \ll 1$: Decouple N_1
- Decay of Z_2 odd particles into N_2
- Three body decay to N_1





$$\Omega h^2 = \Omega h^2_{\mathrm{FI}} + \Omega h^2_{\mathrm{N2\to N1}}$$

DM III: N_2 decay contributions



I + III: Only N_2 annihilation II: Additional scalar annihilation

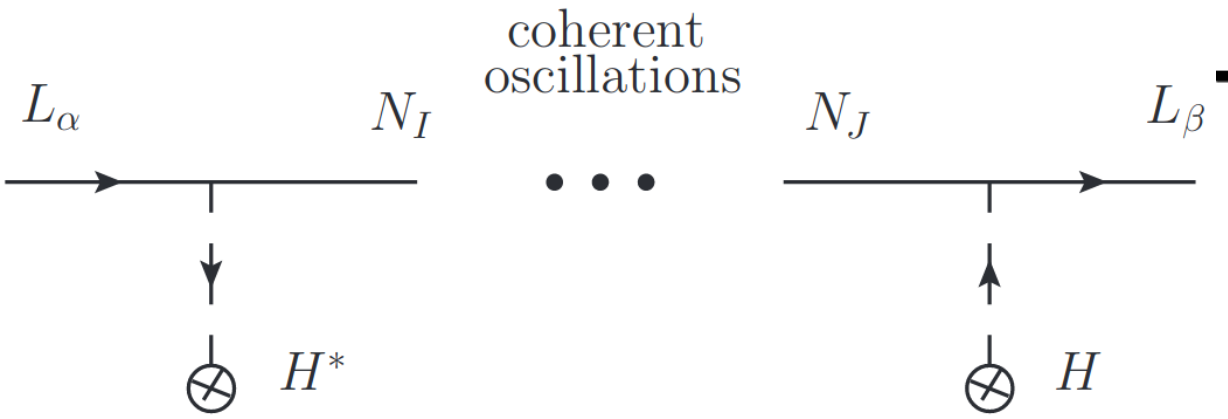
Leptogenesis I: Fundamentals

Goal: CP violation for lepton asymmetry

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

1) ARS:

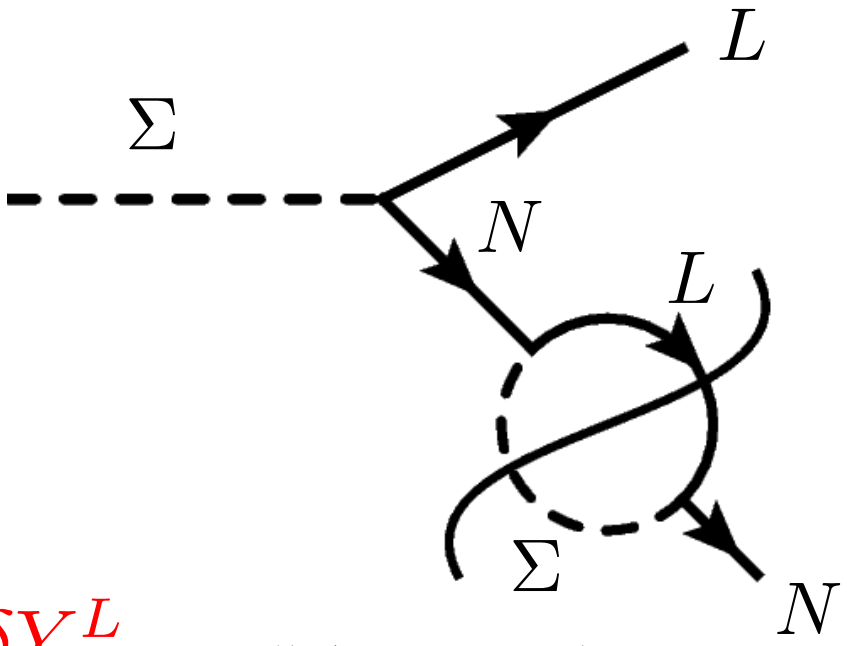
- Oscillations among N_i
- Asymmetry generation in each flavor



T.Hambye, D.Teresi [1606.00017]

2) Decays of $\Sigma \longrightarrow N\,L$

- Thermally induced on-shell particles



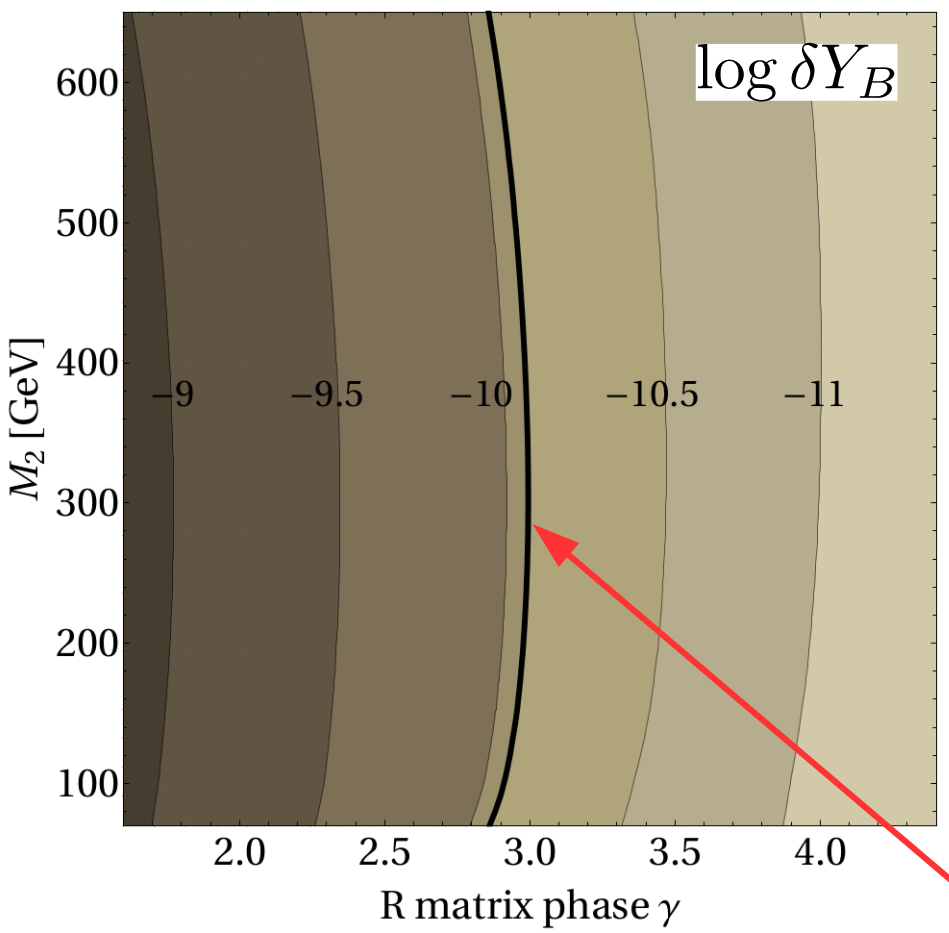
$$\delta Y_B = -\frac{2}{3}\sum_i \delta Y_i^L$$

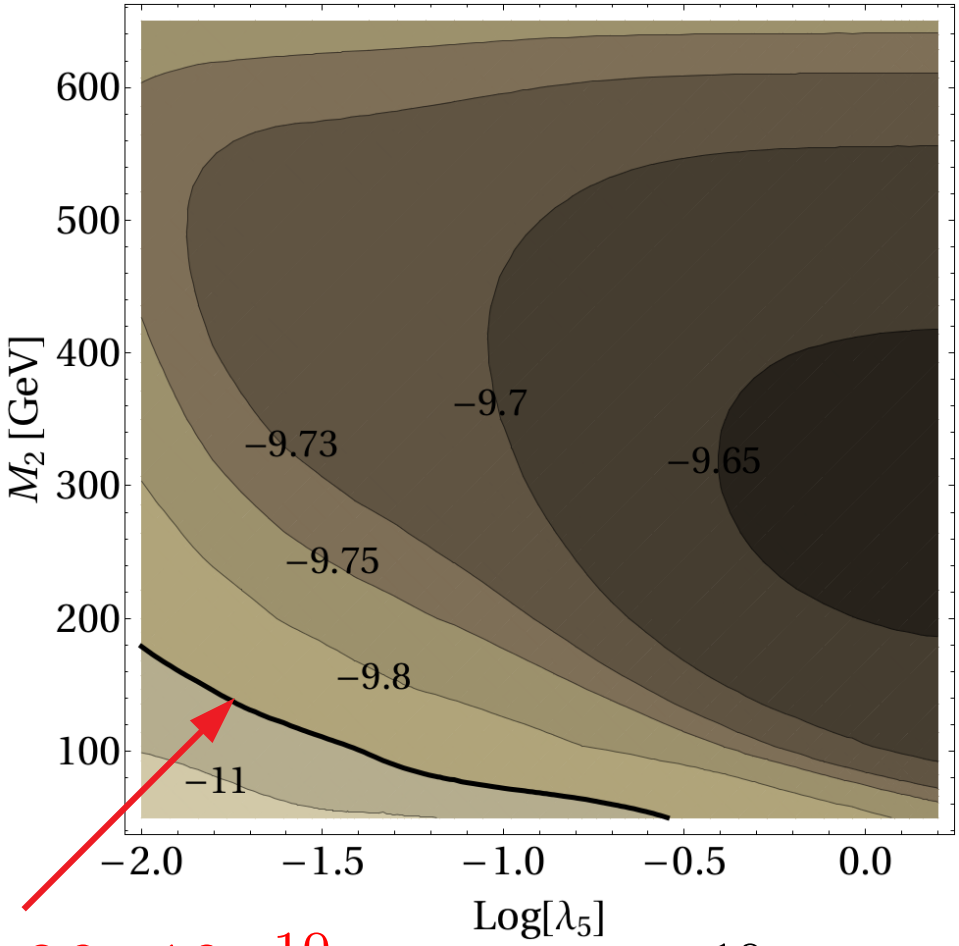
→ talk by K. Zurek

Leptogenesis II: results

$$\frac{d\,\delta Y_i^L}{dz} \approx S - \delta Y_i^L\, W$$

$\longrightarrow$ *Small* Yukawas required





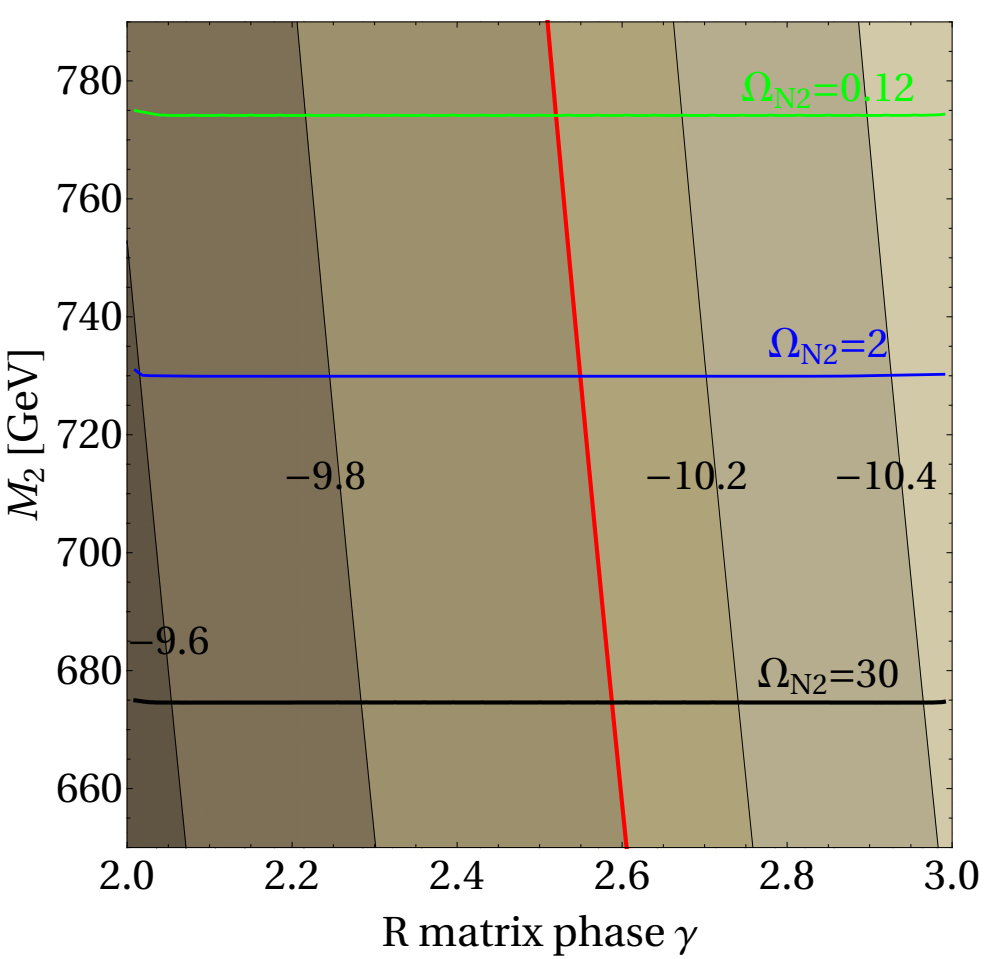
$$\delta Y_B = 0.86 \cdot 10^{-10}$$

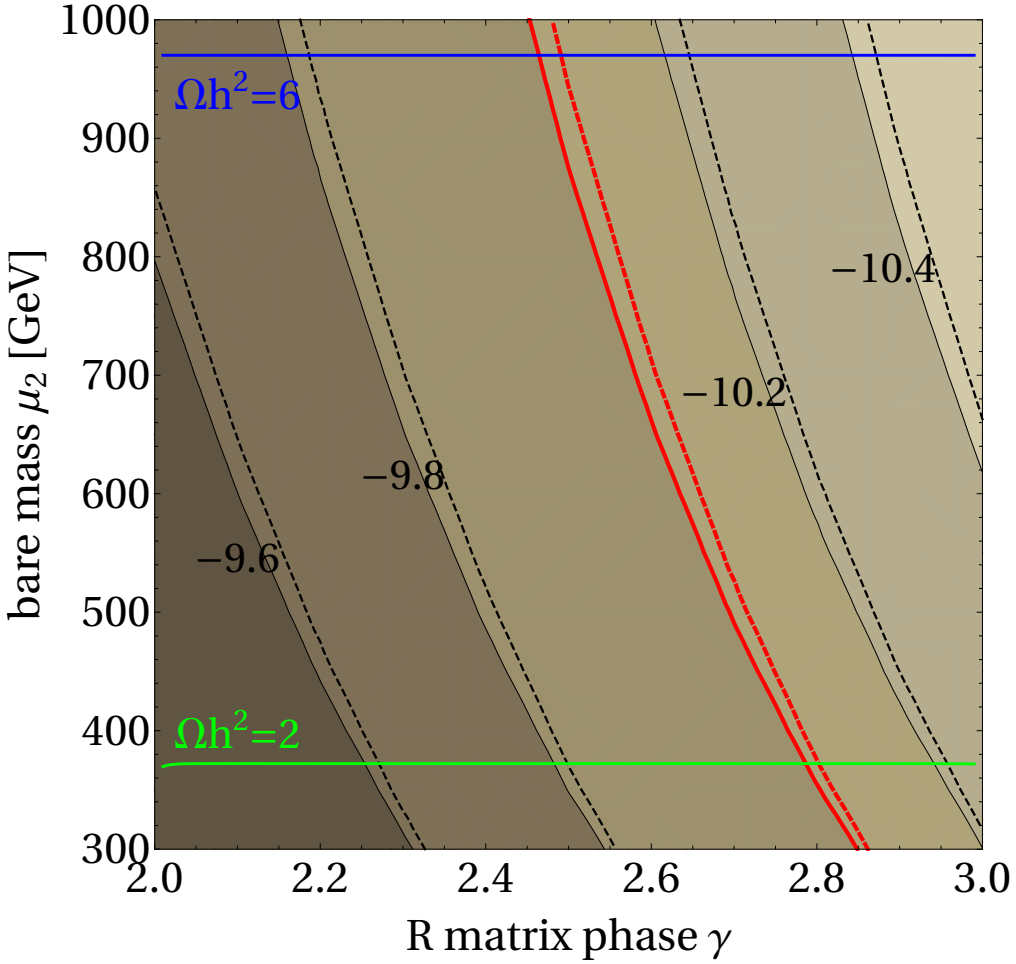
$$\delta M = 10^{-10}$$

$$\mu_2 = 800\,\mathrm{GeV}$$

Merging DM + Leptogenesis

Additional degeneracy between Σ and N_2 masses

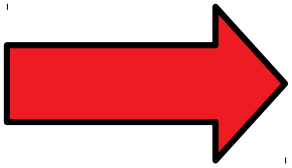




Preliminary results!

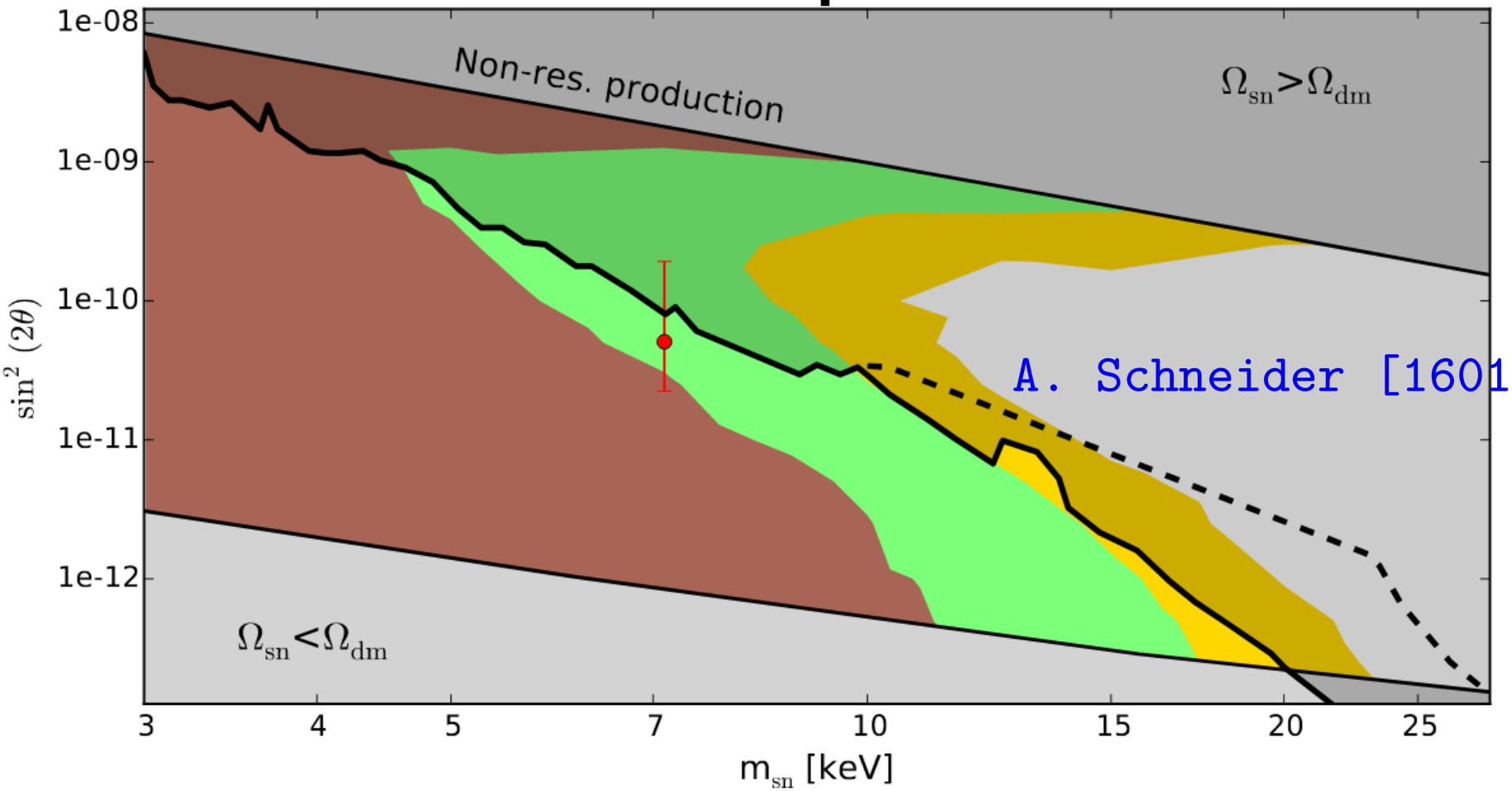
Summary

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

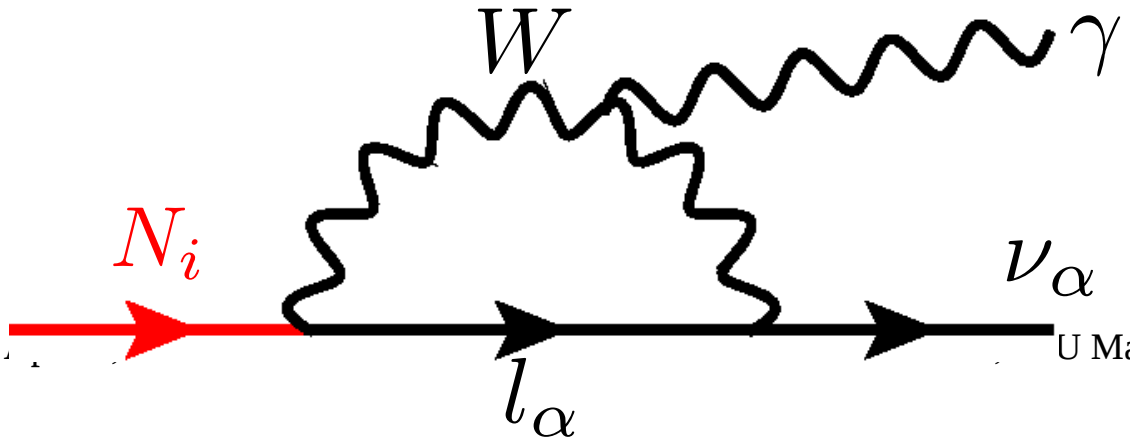


Parameter region for combination!

Backup slides

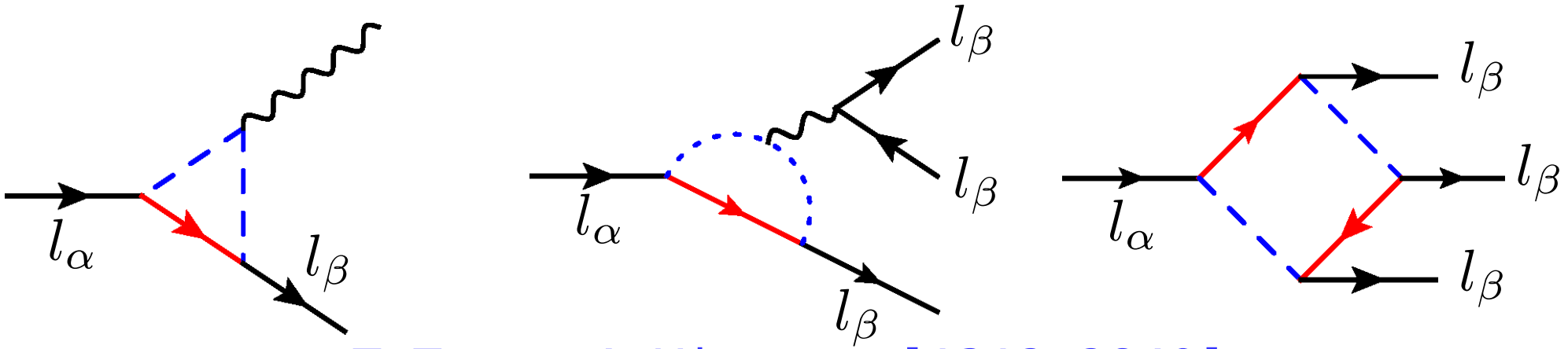


A. Schneider [1601.07553]



$$\Gamma \propto \sin(2\theta)^2 m_s^5$$

Backup slides



T.Toma, A.Vicente [1312.2840]

Process	BR bound
μ → e γ	$4.2 \cdot 10^{-13}$
τ → e γ	$3.3 \cdot 10^{-8}$
τ → mu γ	$4.4 \cdot 10^{-8}$
μ → 3 e	$1.0 \cdot 10^{-12}$
τ → 3 e	$2.7 \cdot 10^{-8}$
τ → 3 μ	$2.1 \cdot 10^{-8}$

→ *Upper bound* on Yukawa strength

Particle Data Group + 1605.05081

Backup slides

- Boltzmann equation for N_1

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

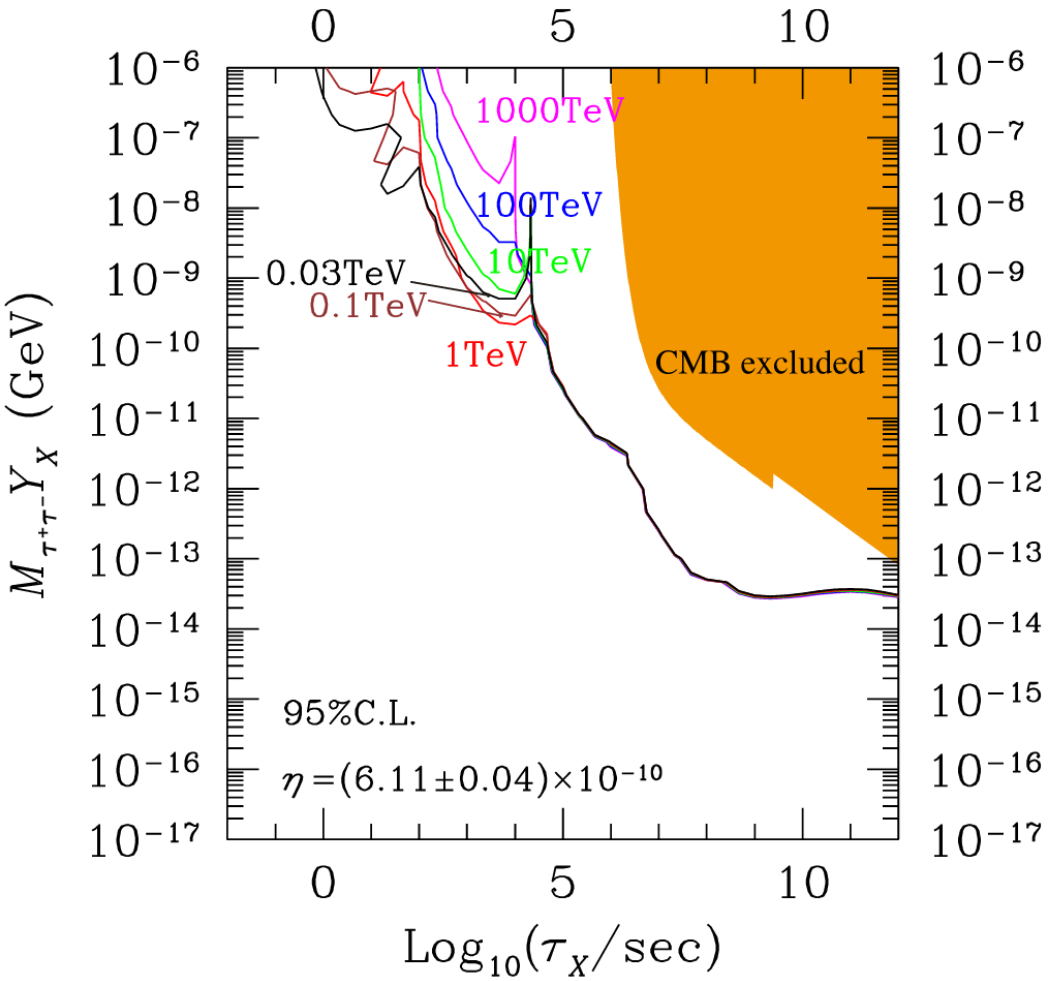
- Decay width $N_{2,3} \rightarrow N_1$:

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

E. Molinaro et. al. [1405.1259]

BBN bounds

$$(h_2)^2 \gtrsim 6.3 \cdot 10^{-7} \left(\frac{m_\Sigma}{1\,\mathrm{TeV}}\right)^4 \left(\frac{1\,\mathrm{TeV}}{M_2}\right)^5 \left(\frac{10^{-8}}{|h_1|}\right)^2 \left(\frac{1\,\mathrm{sec}}{\tau}\right)$$



- Naively: $t_{BBN} \sim 1$ sec
- Dominantly decays into τ pairs

  $\longrightarrow$ Small yield required

M.Kawasaki et.al. [1709.01211]

Backup slides

- Boltzmann equation for Leptogenesis:

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

$$+\frac{\delta n^L_l}{2n^L_{\rm eq}}\left((\gamma^{LC}_{WQ,l} - \gamma^{LV}_{WQ,l}) + \frac{1}{2}\left\{\gamma^{LC}_{WC,l} - \gamma^{LV}_{WC,l}, \frac{n^N}{n^N_{\rm eq}}\right\}\right)_{\alpha\beta}$$

$$\frac{d\bar{n}^N_{\alpha\beta}}{dt} = \frac{dn^N_{\alpha\beta}}{dt}(n \to \bar{n},\, \gamma \to \gamma^*, \delta n^L_l \to -\delta n^L_l)$$

$$\frac{d\delta n^L_l}{dt} = \frac{1}{n^N_{\rm eq}}{\rm tr}\left\{\left(\gamma^{LC}_l - \gamma^{LV}_l\right) n^N\right\} - (\gamma \to \gamma^*, n \to \bar{n})$$

$$-\frac{\delta n^L_l}{n^L_{\rm eq}}{\rm tr}\left\{\gamma^{LC}_{WQ,l} + \gamma^{LV}_{WQ,l}\right\}$$

$$-\frac{\delta n^L_l}{2n^L_{\rm eq}}\frac{1}{n^N_{\rm eq}}{\rm tr}\left\{n^N(\gamma^{LC}_{WC,l} + \gamma^{LV}_{WC,l})\right\} - (\gamma \to \gamma^*, n \to \bar{n})$$

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