

TeV Scale Leptogenesis via Dark Sector



Sin Kyu Kang (Seoul Tech)



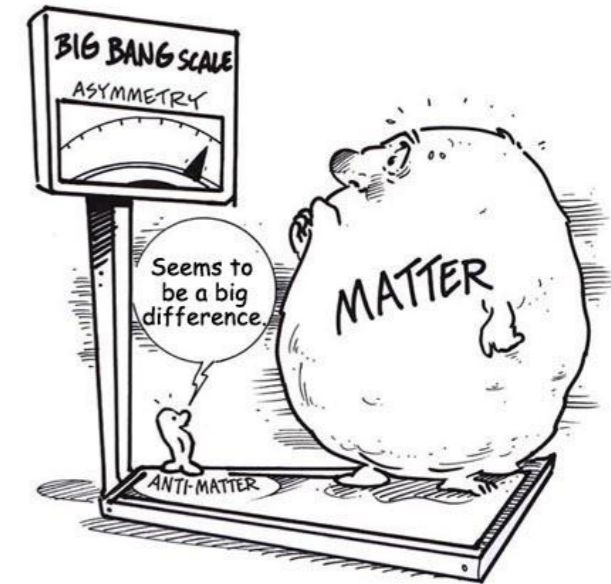
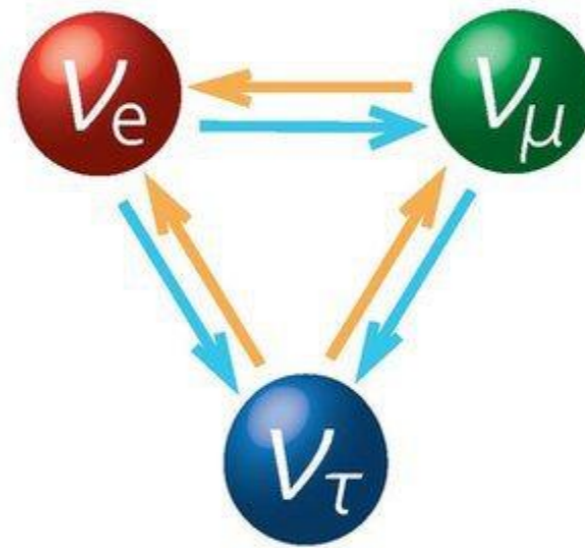
Based on work with Debasish Borah and Arnab Dasgupta,
arXiv:1811.02094;
to appear soon

Outline

- Introduction
- Review on scotogenic model
- Leptogenesis from the Dark Sector
- Conclusion

Problems in SM

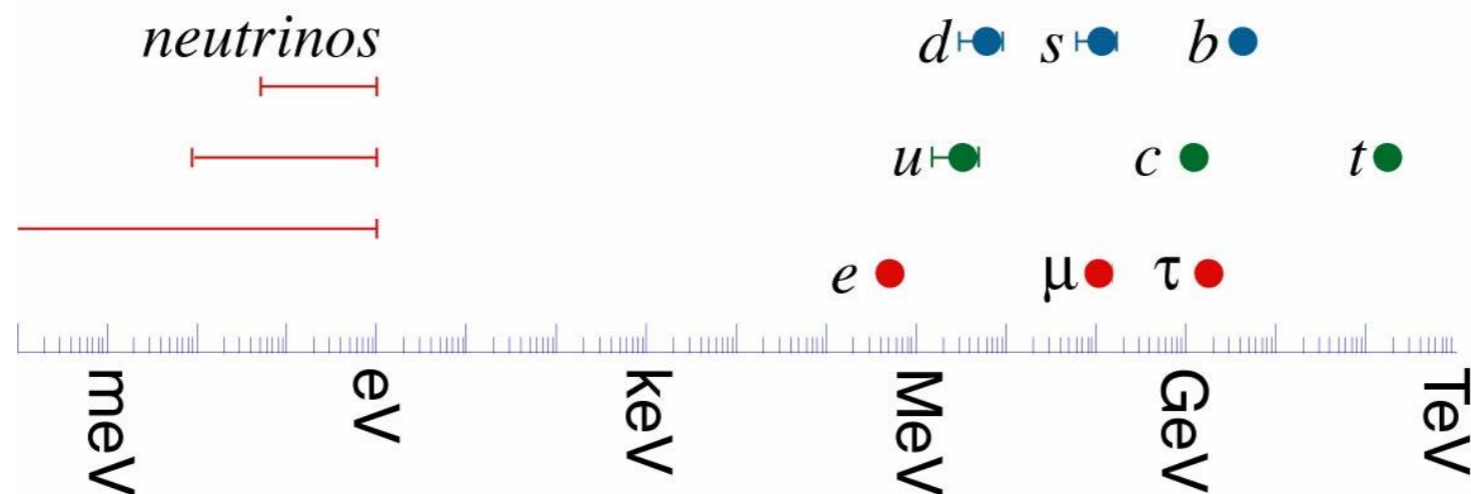
- SM cannot explain the observed Neutrino Mass and Mixing.
- SM does not have a dark matter candidate.
- SM cannot explain the observed baryon asymmetry



Neutrino Mass

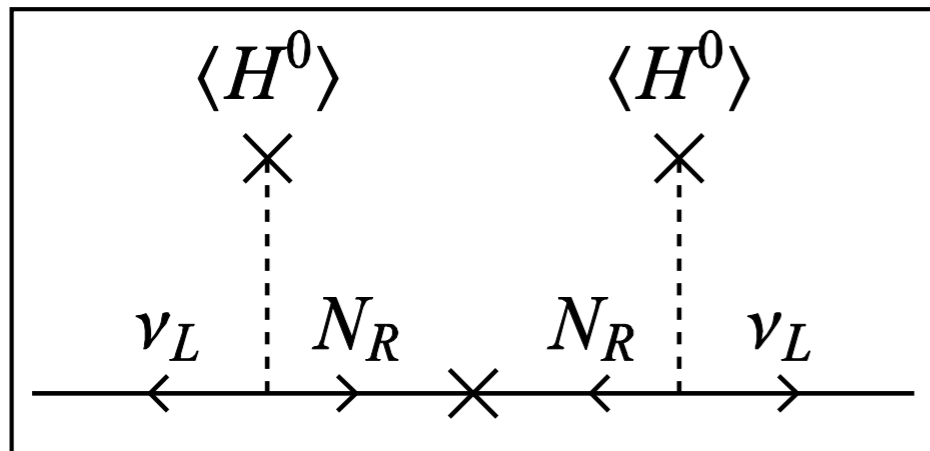
- Neutrinos have masses that are (at least) a factor of 10^6 smaller than the one of the electron

→ do not seem to have the same origin as the other masses

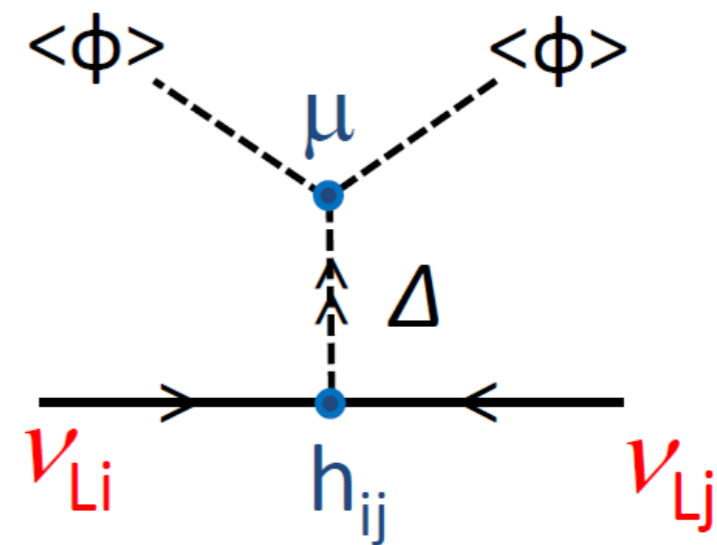


- There are different possibilities to generate small neutrino masses

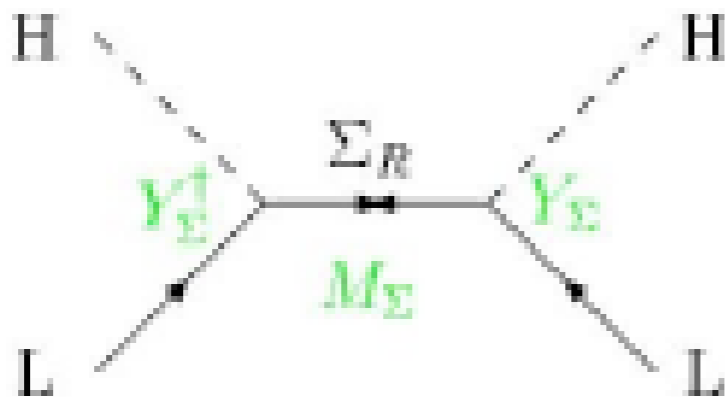
Tree level Mass



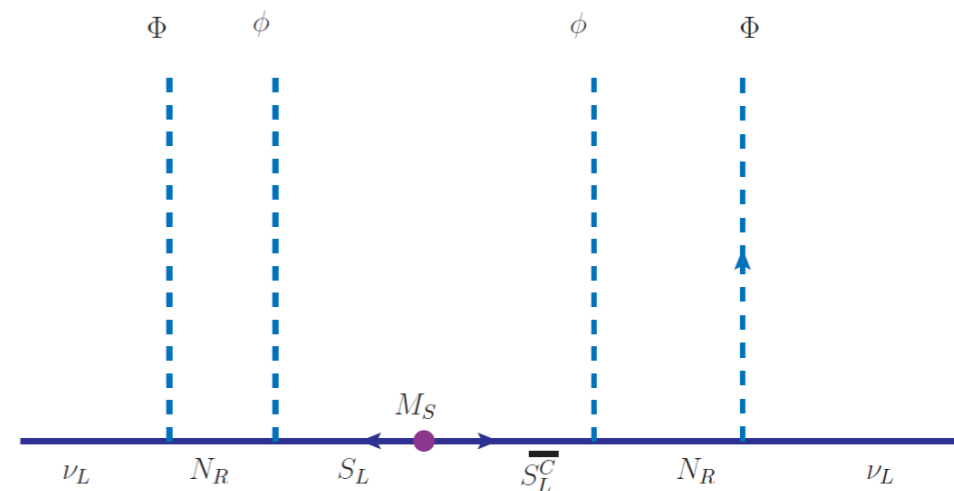
(Minkowski '77; Glashow'79; Yanagida '79; Gellman, Ramond, Slansky '80; Mohapatra, Senjanovic '80; Schechter, Valle '80)



(Magg, Wetterich'80; Cheng, Li '80; Schechter, Valle '80; Lazarides, Shafi; Wetterich'81; Mohapatra, Senjanovic'81)

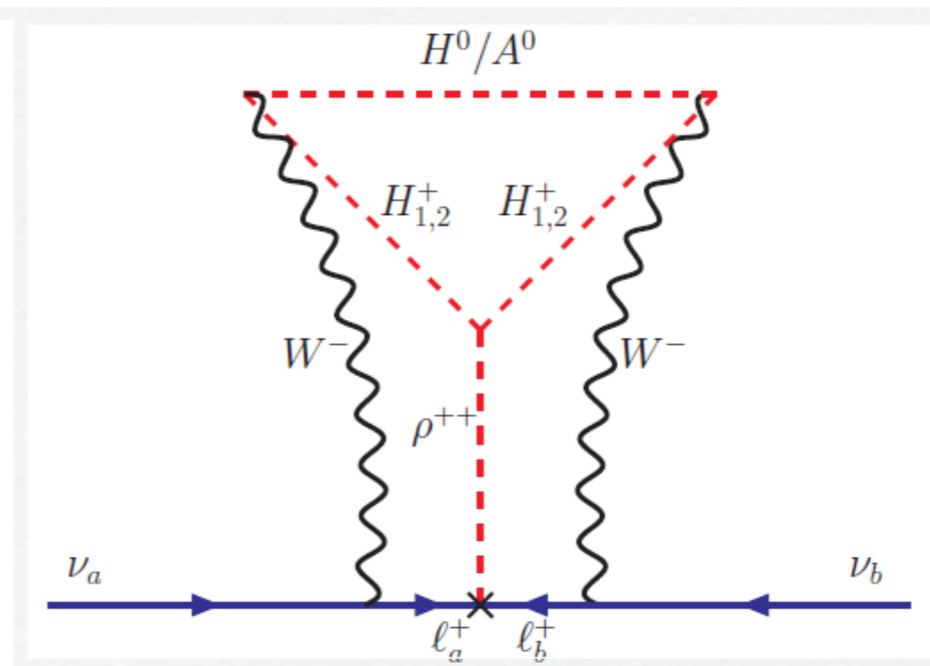
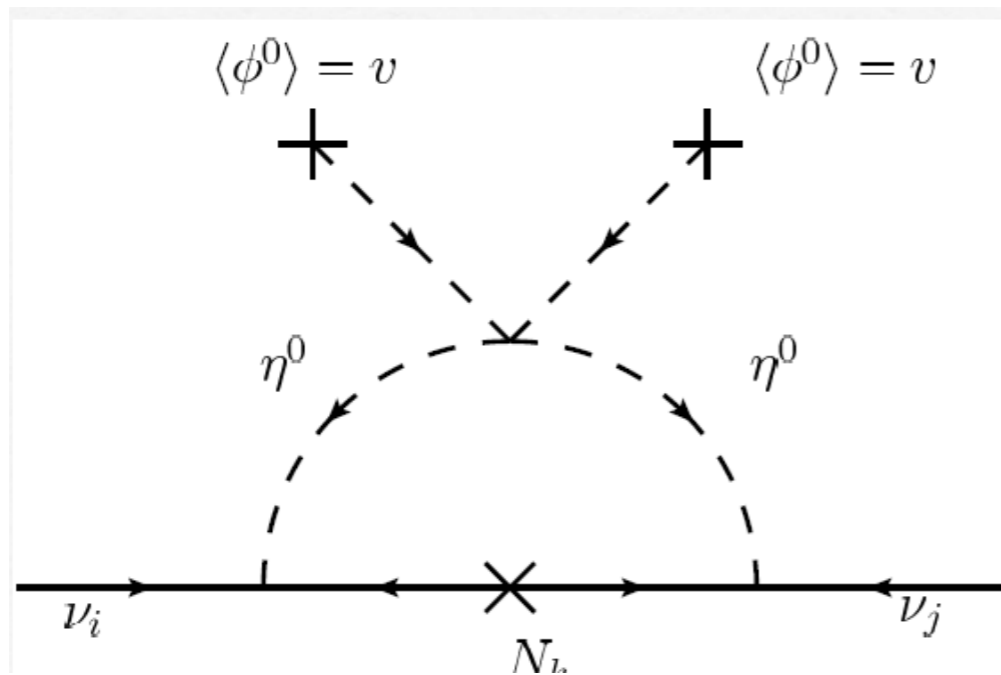
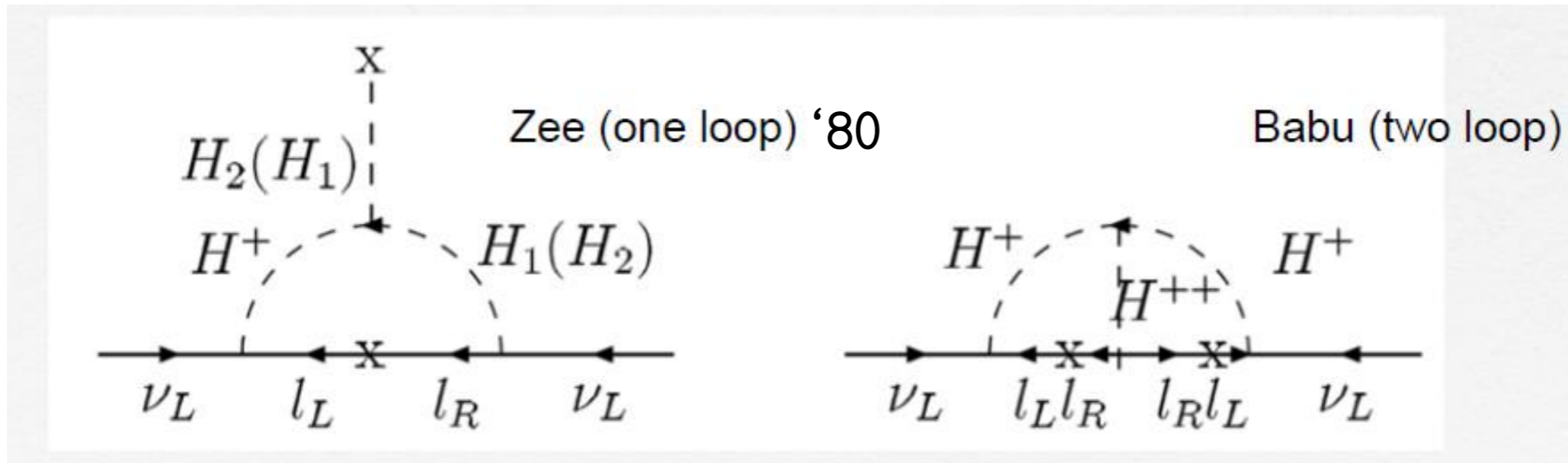


(Foot, Lew, He, Joshi '89)



(Mohapatra'86; Mohapatra, Valle'86))

Loop level Mass



- Radiogenic (Ma) '06
- R-parity violating SUSY model

Cocktail (Gustafsson)

Scotogenic Model

E. Ma, Phys. Rev. D73, 077301 (2006)

- **Ingredients apart from the SM:**
 - 3 heavy right-handed Majorana neutrinos N_k
 - second Higgs doublet η without VEV (inert doublet)
 - additional Z_2 parity, under which N_k and η are odd
 - **stable Dark matter candidates:**
 - neutral scalar η_0 or lightest heavy Neutrino N_1

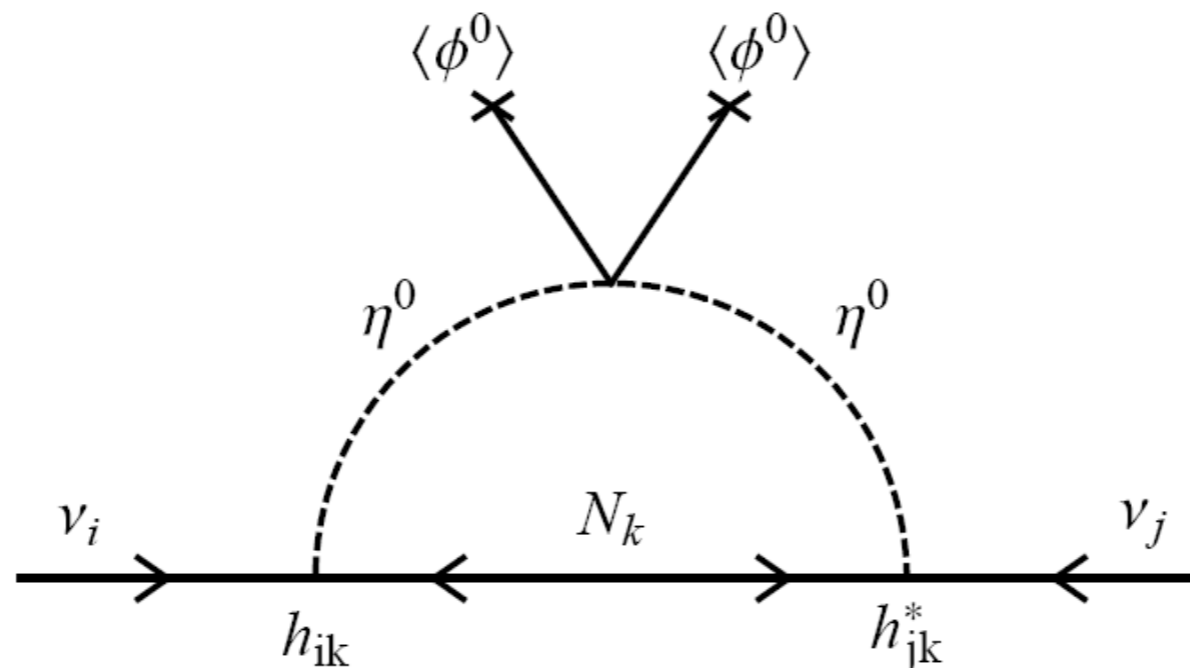
Scotogenic Model

E. Ma, Phys. Rev. D73, 077301 (2006)

$$V = m_1^2 \phi^+ \phi + m_2^2 \eta^+ \eta + \frac{\lambda_1}{2} (\phi^+ \phi)^2 + \frac{\lambda_2}{2} (\eta^+ \eta)^2 + \lambda_3 (\phi^+ \phi)(\eta^+ \eta) \\ + \lambda_4 (\phi^+ \eta)(\eta^+ \phi) + \frac{\lambda_5}{2} [(\phi^+ \eta)^2 + \text{h.c.}]$$

$$\mathcal{L}_Y = f_{ij} (\phi^- \nu_i + \phi^{0*} l_i) e_j^c + h_{ij} (\eta^0 \nu_i - \eta^+ l_i) N_j + \text{h.c.}$$

- Due to Z_2 symmetry, $\langle \eta^0 \rangle = 0$.
- Tree-level neutrino mass vanishes, but generated at 1 loop



$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^3 h_{ik} h_{jk} \Lambda_k$$

$$\Lambda_k = \frac{M_k}{16\pi^2} \left[\frac{m^2(H^0)}{m^2(\underbrace{H^0}_{\sqrt{2} \operatorname{Re} \eta^0}) - M_k^2} \ln \left(\frac{m^2(H^0)}{M_k^2} \right) - \frac{m^2(A^0)}{m^2(\underbrace{A^0}_{\sqrt{2} \operatorname{Im} \eta^0}) - M_k^2} \ln \left(\frac{m^2(A^0)}{M_k^2} \right) \right]$$

Higgs masses:

$$m^2(h^0) = 2\lambda_1 v^2$$

$$m^2(H^0) = m_2^2 + (\lambda_3 + \lambda_4 + \lambda_5) v^2$$

$$m^2(A^0) = m_2^2 + (\lambda_3 + \lambda_4 - \lambda_5) v^2$$

- “natural” Yukawa couplings
- loop suppression : $\frac{1}{16\pi^2}$
- TeV scale heavy neutrinos

$$\mathcal{M}_\nu = h^* \Lambda^{-1} h^\dagger$$

$$\Lambda_i := \frac{2\pi^2}{\lambda_5} \xi_i \frac{2M_i}{v^2} \quad \text{radiative seesaw}$$

$$\xi_i := \left(\frac{1}{8} \frac{M_i^2}{m_{\eta_R}^2 - m_{\eta_I}^2} [L(m_{\eta_R}^2) - L(m_{\eta_I}^2)] \right)^{-1} \quad L(m^2) := \frac{m^2}{m^2 - M_i^2} \ln \left(\frac{m^2}{M_i^2} \right)$$

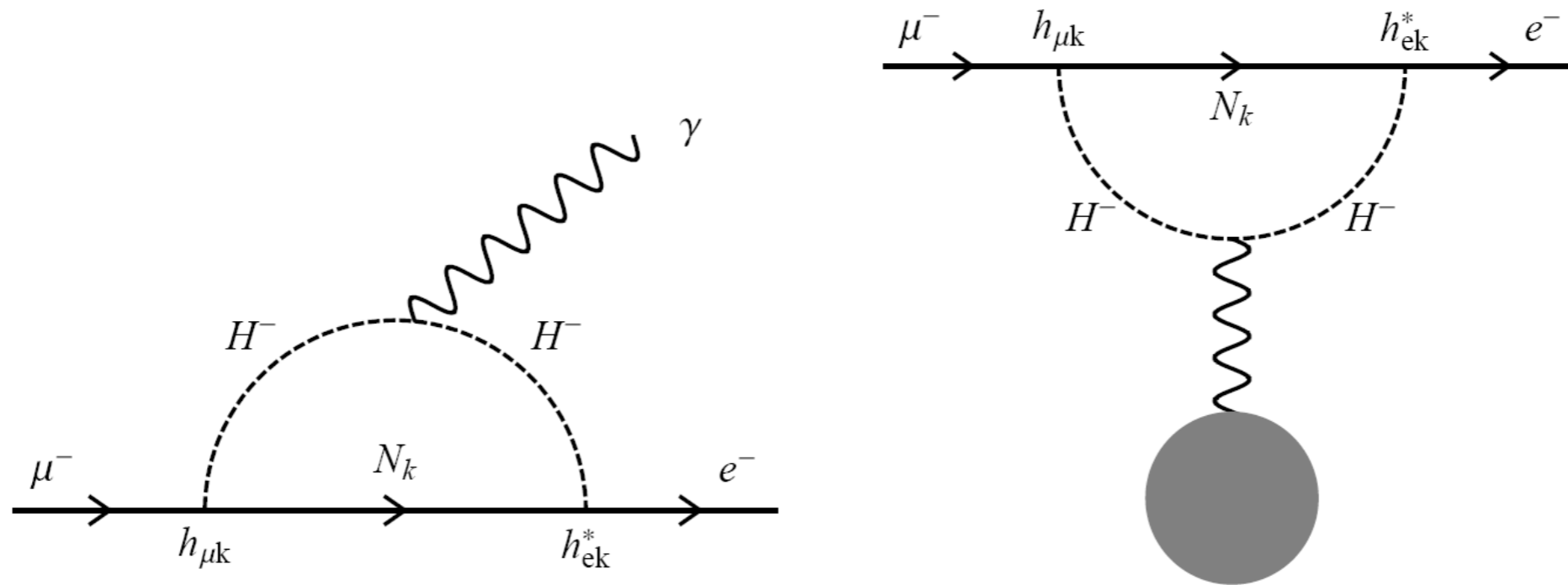
If $m_R^2 - m_I^2 = 2\lambda_5 v^2$ is small compared to $m_0^2 = (m_R^2 + m_I^2)/2$

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2} \sum_k \frac{h_{ik} h_{jk} M_k}{m_0^2 - M_k^2} \left[1 - \frac{M_k^2}{m_0^2 - M_k^2} \ln \frac{m_0^2}{M_k^2} \right]$$

$$\text{If } M_k^2 \gg m_0^2, \text{ then} \quad (\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2} \sum_k \frac{h_{ik} h_{jk}}{M_k} \left[\ln \frac{M_k^2}{m_0^2} - 1 \right]$$

$$\text{If } m_0^2 \gg M_k^2, \text{ then} \quad (\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2 m_0^2} \sum_k h_{ik} h_{jk} M_k$$

- The Yukawa coupling that enters into the neutrino mass also generates LFV processes



- LFV-processes are constrained (MEGA experiment):

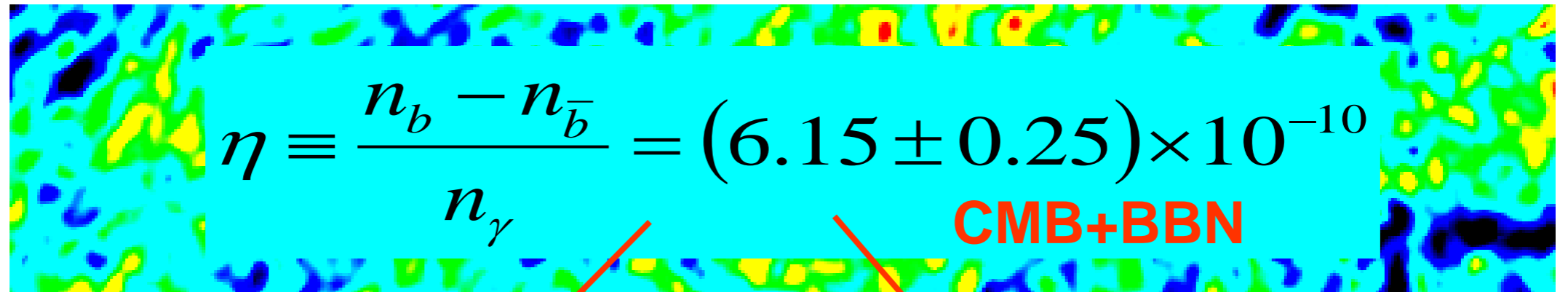
$$\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$$

$$\text{Br}(\mu \rightarrow e\gamma) \simeq \frac{\Gamma(\mu \rightarrow e\gamma)}{\Gamma(\mu \rightarrow e\bar{\nu}_e\nu_\mu)} = \frac{\alpha}{24\pi G_F^2} \frac{\left| \sum_{k=1}^3 h_{1k}^* h_{2k} \right|^2}{m_\eta^4}$$

$$\left| \sum_{k=1}^3 h_{1k}^* h_{2k} \right| \lesssim 4.1 \times 10^{-5} \left(\frac{m_\eta}{100 \text{ GeV}} \right)^2 \quad \text{Phys. Rev. D79, 013011 (2009)}$$

Baryogenesis

(Planck, arXiv: 1502.01589)



after Giudice et al., hep-ph/0310123

**always present in
the Universe
(initial condition)**

**generated dynamically
during the expansion**

Sakharov conditions:

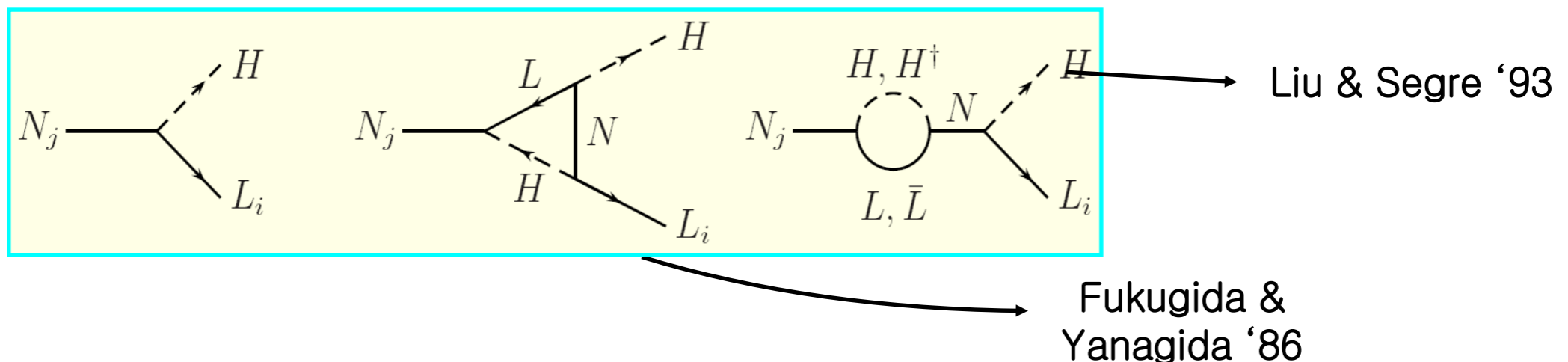
- **B violation**
- **C and CP violation**
- **departure from
thermal equilibrium**

Leptogenesis

- Since the SM fails to satisfy Sakharov's conditions, **new source of CP violation is necessarily required** → BSM
- Type-I Seesaw model provides a common framework to achieve tiny neutrino masses and baryon asymmetry of our universe.

→ Baryogenesis through Leptogenesis (Fukugita, Yanagida '86):

- Decay of heavy right-handed neutrino is responsible for lepton number violation
- CP violation is achieved by the interference between the tree and the loop diagrams for the decay of right-handed neutrino



- **CP Asymmetry:**
$$\varepsilon_1 = \frac{\Gamma(N_1 \rightarrow L\Phi) - \Gamma(N_1 \rightarrow L^c\Phi^+)}{\Gamma(N_1 \rightarrow L\Phi) + \Gamma(N_1 \rightarrow L^c\Phi^+)}$$

$$\varepsilon_1 \approx \frac{1}{8\pi v^2 (m_D^+ m_D)_{11}} \sum_{i=2,3} \text{Im}[(m_D^+ m_D)_{i1}^2] \times \left[f_V \left(\frac{M_i^2}{M_1^2} \right) + f_S \left(\frac{M_i^2}{M_1^2} \right) \right]$$

- **Out-of-equilibrium condition :**
$$\Gamma_{N_1} \leq H(T = M_{N_1})$$

- **The efficiency factor (due to washout)**

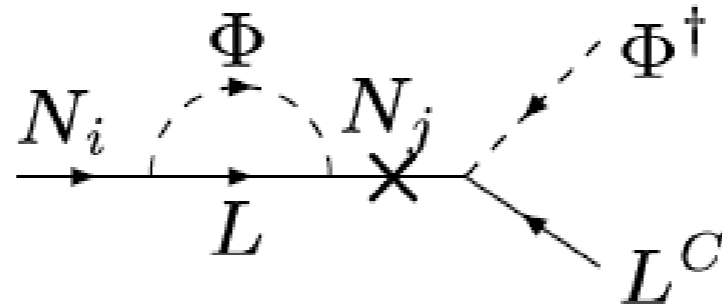
$$\frac{n_L}{s} \approx \frac{\varepsilon_1}{g_*} \kappa \equiv \eta_L$$

- **Conversion L into B via Sphaleron process**

- ▶ **conversion factor :**
$$\eta_B = -\left(\frac{28}{79}\right)\eta_L$$

Resonant Leptogenesis (Pilaftsis)

If $M_1 \cong M_2$, resonant effects can enhance ϵ_1



$$\epsilon_{N_i} = \frac{\text{Im} (h^{\nu\dagger} h^\nu)_{ij}^2}{(h^{\nu\dagger} h^\nu)_{ii} (h^{\nu\dagger} h^\nu)_{jj}} \frac{(m_{N_i}^2 - m_{N_j}^2) m_{N_i} \Gamma_{N_j}^{(0)}}{(m_{N_i}^2 - m_{N_j}^2)^2 + m_{N_i}^2 \Gamma_{N_j}^{(0)2}}$$

Resonant condition :

$$m_{N_2} - m_{N_1} \sim \frac{1}{2} \Gamma_{N_{1,2}}^{(0)}$$

- No more lower limit on M_{N_i} for successful leptogenesis
➔ possible TeV scale leptogenesis

Leptogenesis in Scotogenic Model

- Since scotogenic model contains N_i , vanilla leptogenesis works.
- Vanilla leptogenesis requires heavy N_i , $M_{N_1} \geq 5 \times 10^8 \left(\frac{v}{246 \text{ GeV}} \right)^2$
(Davidson & Ibarra'02)
- Such large scale is undesirable in scotogenic model & naturalness problem
- Resonant leptogenesis remedies these problem (Pilaftsis '97, B Dev et. al '13)
- For three hierarchical N_i , a lower bound on $M_{N_1} \sim 10 \text{ TeV}$ for successful leptogenesis can be obtained in scotogenic model (Hugle et.al; 1804.09660).

$$M_1^{\text{min}} \approx \frac{\xi_1}{\xi_3} \frac{m_l}{m_h} 2 \cdot 10^{11} \text{ GeV}$$

Baryogenesis & Dark Matter

- The observed BAU and DM abundance are of the same order

$$\Omega_{DM} \approx 5\Omega_B$$

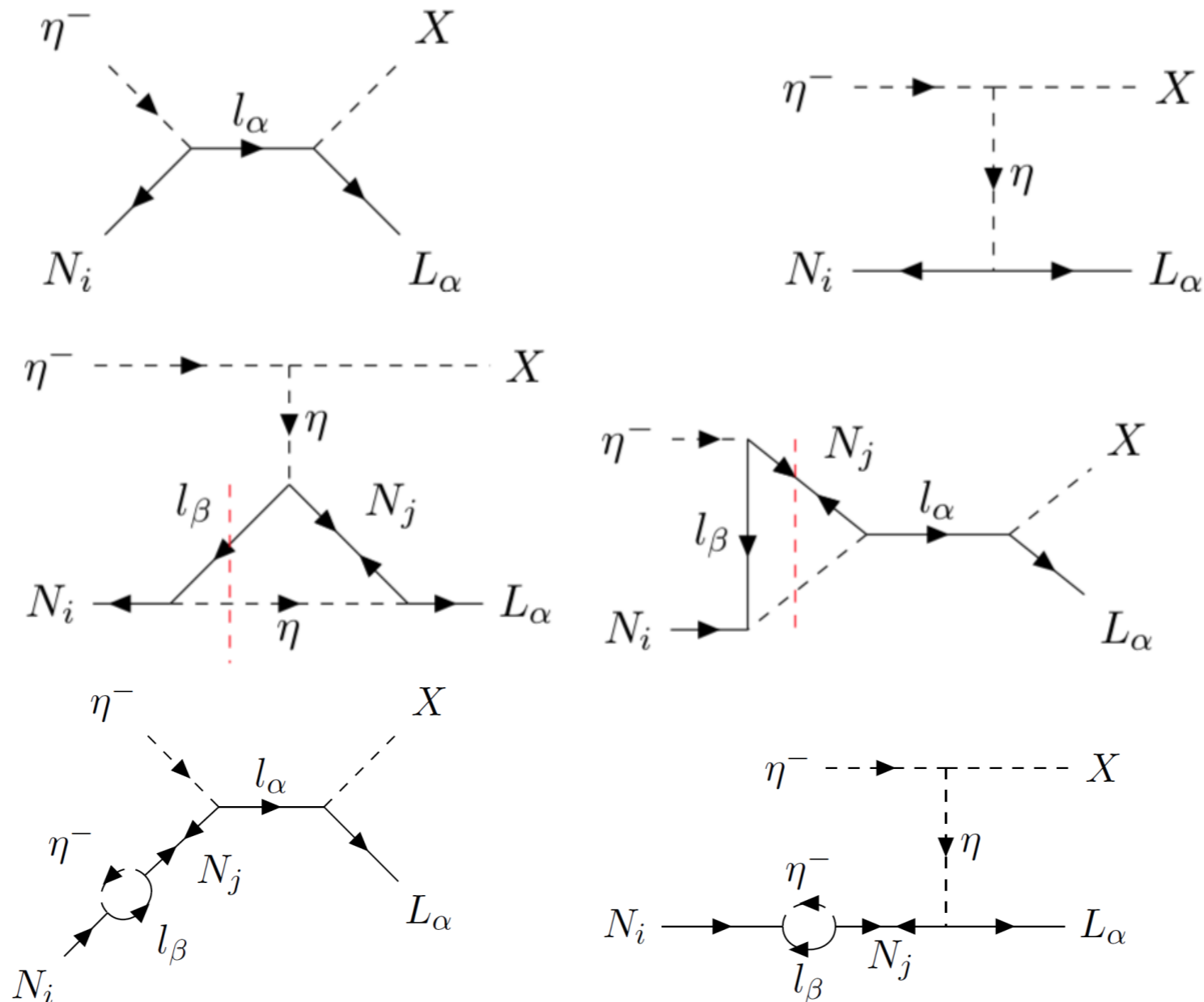
- Although this could be just a coincidence, it has motivated several studies trying to relate their origins.
- Asymmetric DM, WIMPy Baryogenesis etc are some of the scenarios proposed so far.
- It is hard to realize WIMPy Baryogenesis in scotogenic model, our scenario for leptogenesis has some correlation between DM and baryogenesis

Leptogenesis from scattering

- **L –violating scattering processes can play an important (dominant) role in achieving TeV-scale leptogenesis**
- **L –violating scattering processes contributing to ΔL we consider**
 - **co-annihilations : $N_k \eta \rightarrow L, X (= \gamma, W, Z, h)$**
 - **annihilations : $\eta\eta \rightarrow LL$ through t-channel**
- **Contributions of L –violating processes depend on DM scenarios**
 - **Lightest N_i as a DM**
 - **Z_2 odd neutral scalar as a DM**
- **Although there exist 3 body decays of N_i at the same order $\mathcal{O}(Y^4 g^2)$.But, contributions are suppressed by phase space.**

Scalar Doublet η as Dark Matter

- Scattering processes $\eta\eta \rightarrow LL$ through t-channel mediated by N_i \rightarrow lead to zero CP asymmetry
- co-annihilation processes $N_k\eta \rightarrow L, X (= \gamma, W, Z, h)$ lead to ΔL



- The CP asymmetry arising from interference between tree and 1-loop diagrams can be estimated as

$$\epsilon_{N_i\eta} = \frac{1}{4\pi(hh^\dagger)_{ii}} \sum_j \Im[(hh^\dagger)_{ij}^2] \tilde{\epsilon}_{ij}$$

$$\tilde{\epsilon}_{ij} = \frac{\sqrt{r_j}}{6r_i \left(-r_i^{3/2} + r_i(r_j - 2) + \sqrt{r_i}r_j + 1 \right)^2 (\sqrt{r_i} - 3)} \left(r_i^{7/2}(3r_j + 1) + \sqrt{r_i}(3r_j + 5) + 1 \right.$$

$$\left. -3r_i^{5/2}(r_j(D + (r_j - 3)r_j + 4) - 3D - 2) - 3r_i^{3/2} \left(2(D + 3) + r_j(r_j(D + r_j + 1) - D - 4) \right) \right.$$

$$\left. -r_i^4 + f^3(3D + 3r_j^2 + 11) - 3r_i^2(r_j(D + 2(r_j - 1)r_j + 2) - D + 6) + r_i(1 - 3r_j(D + r_j - 4)) \right)$$

$$+ \frac{\sqrt{r_j}}{4r_i} \left(\sqrt{r_i} - 1 + \frac{\sqrt{r_j}}{(1 + \sqrt{r_i})^2} (\sqrt{r_i} - 1 + r_j) \left(\log \left(\frac{1 + \sqrt{r_i}r_j}{r_i(1 + \sqrt{r_i})} \right) - \log \left(\frac{1 + r_i + r_i^{3/2} + \sqrt{r_i}r_j}{r_i(1 + \sqrt{r_i})} \right) \right) \right.$$

$$\left. + \log \left(1 + \frac{1 + \sqrt{r_i}}{\sqrt{r_i}(\sqrt{r_i} - 1 + r_i + r_j)} \right) \right)$$

$$D = \sqrt{(r_i - r_j)(r_i + 4\sqrt{r_i} - r_j + 4)}$$

$$r_l = \frac{M_{N_l}^2}{m_\eta^2}$$

- wash-out processes in this scenario, categorized as follows:

- $\Delta L = 2 : L\eta \rightarrow \bar{L}\eta, \quad \eta\eta \rightarrow LL$

- $\Delta L = 1$:there are two main sources of such wash-out

1. Inverse decay of $N_k \rightarrow L\eta$,

2. inverse process of co-annihilation $N_k\eta \rightarrow L, X(= \gamma, W, Z, h)$

- Boltzmann eqs.:

BEs for number density of Z_2 odd particles take the following form:

$$\frac{dY_{N_k}}{dz} = -\frac{1}{zH(z)} [(Y_{N_k} - Y_{N_k}^{\text{eq}})\langle\Gamma_{N_k \rightarrow L\alpha\eta}\rangle + (Y_{N_k}Y_\eta - Y_{N_k}^{\text{eq}}Y_\eta^{\text{eq}})s\langle\sigma v\rangle_{\eta N_k \rightarrow LSM} + \sum_{l=1}^3 (Y_{N_k}Y_{N_l} - Y_{N_k}^{\text{eq}}Y_{N_l}^{\text{eq}})s\langle\sigma v\rangle_{N_l N_k \rightarrow SMSM}]$$

$$\frac{dY_\eta}{dz} = \frac{1}{zH(z)} [(Y_{N_k} - Y_{N_k}^{\text{eq}})\langle\Gamma_{N_i \rightarrow L\alpha\eta}\rangle - 2(Y_\eta^2 - (Y_\eta^{\text{eq}})^2)s\langle\sigma v\rangle_{\eta\eta \rightarrow SMSM} - \sum_{m=1}^3 (Y_{N_m}Y_\eta - Y_{N_m}^{\text{eq}}Y_\eta^{\text{eq}})\langle\sigma v\rangle_{\eta N_m \rightarrow LSM}]$$

BE for lepton asymmetry takes the following form:

$$\begin{aligned}
\frac{dY_{\Delta L}}{dz} = & \frac{1}{zH(z)} \left[\sum_i \epsilon_{N_i} (Y_{N_i} - Y_{N_i}^{\text{eq}}) \langle \Gamma_{N_i \rightarrow L\alpha\eta} \rangle - Y_{\Delta L} r_{N_i} \langle \Gamma_{N_i \rightarrow L\alpha\eta} \rangle - Y_{\Delta L} r_{\eta} s \langle \Gamma_{\eta \rightarrow N_1 L} \rangle \right. \\
& + \sum_i \epsilon_{N_i \eta} s \langle \sigma v \rangle_{\eta N_i \rightarrow LSM} \left(Y_{\eta} Y_{N_i} - Y_{\eta}^{\text{eq}} Y_{N_i}^{\text{eq}} \right) - \frac{1}{2} Y_{\Delta L} Y_l^{\text{eq}} r_{N_i} r_{\eta} s \langle \sigma v \rangle_{\eta N_i \rightarrow SM\bar{L}} \\
& - Y_{\Delta L} Y_l^{\text{eq}} r_{\eta}^2 s \langle \sigma v \rangle_{\eta\eta \rightarrow LL}^{\text{wo}} \\
& \left. - Y_{\Delta L} Y_{\eta}^{\text{eq}} s \langle \sigma v \rangle_{\eta L \rightarrow \eta\bar{L}}^{\text{wo}} - \sum_i Y_{\Delta L} Y_{\eta}^{\text{eq}} s \langle \sigma v \rangle_{\eta L \rightarrow N_i X}^{\text{wo}} - \sum_i Y_{\Delta L} Y_{N_i}^{\text{eq}} s \langle \sigma v \rangle_{N_i L \rightarrow \eta X}^{\text{wo}} \right],
\end{aligned}$$

$$H = \sqrt{\frac{4\pi^3 g_*}{45} \frac{M_{\chi}^2}{M_{\text{PL}}}}, \quad s = g_* \frac{2\pi^2}{45} \left(\frac{M_{\chi}}{z} \right)^3, \quad r_j = \frac{Y_j^{\text{eq}}}{Y_l^{\text{eq}}}, \quad \langle \Gamma_{j \rightarrow X} \rangle = \frac{K_1(M_j/T)}{K_2(M_j/T)} \Gamma_{j \rightarrow X},$$

- In our calculation we have used the Casas-Ibarra parameterisation

$$h_{i\alpha} = \sqrt{\Lambda_i}^{-1} R \sqrt{m_\nu} U_{PMNS}^+$$

- Now, if $R = I$, or it contains only real parameters, the asymmetry is vanished. So we parameterize it to contain complex entries.

$$R_{\alpha\beta} = \begin{pmatrix} \cos(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) & \cdots & \sin(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) \\ \vdots & \ddots & \vdots \\ -\sin(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) & \cdots & \cos(\theta_{\alpha\beta}^R + i\theta_{\alpha\beta}^I) \end{pmatrix}$$

$$\text{Ex) } R_{12} = \begin{pmatrix} \cos(\theta_{12}^R + i\theta_{12}^I) & \sin(\theta_{12}^R + i\theta_{12}^I) & 0 \\ -\sin(\theta_{12}^R + i\theta_{12}^I) & \cos(\theta_{12}^R + i\theta_{12}^I) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Numerical Results

- Input values

For three neutrino mixing angles, we take the best fit values obtained from the recent global fit analysis.

$$m_\eta = 900 \text{ GeV} \quad M_{N_1} = 1 \text{ TeV} \quad \lambda_5 = -5 \times 10^{-5}$$

$$M_{N_2} = 2 \text{ TeV} \quad M_3 = 3 \text{ TeV} \quad \lambda_1 \sim 0.2, \lambda_3 \sim 0.5, \lambda_4 \sim -0.5, \lambda_2 \sim 1$$

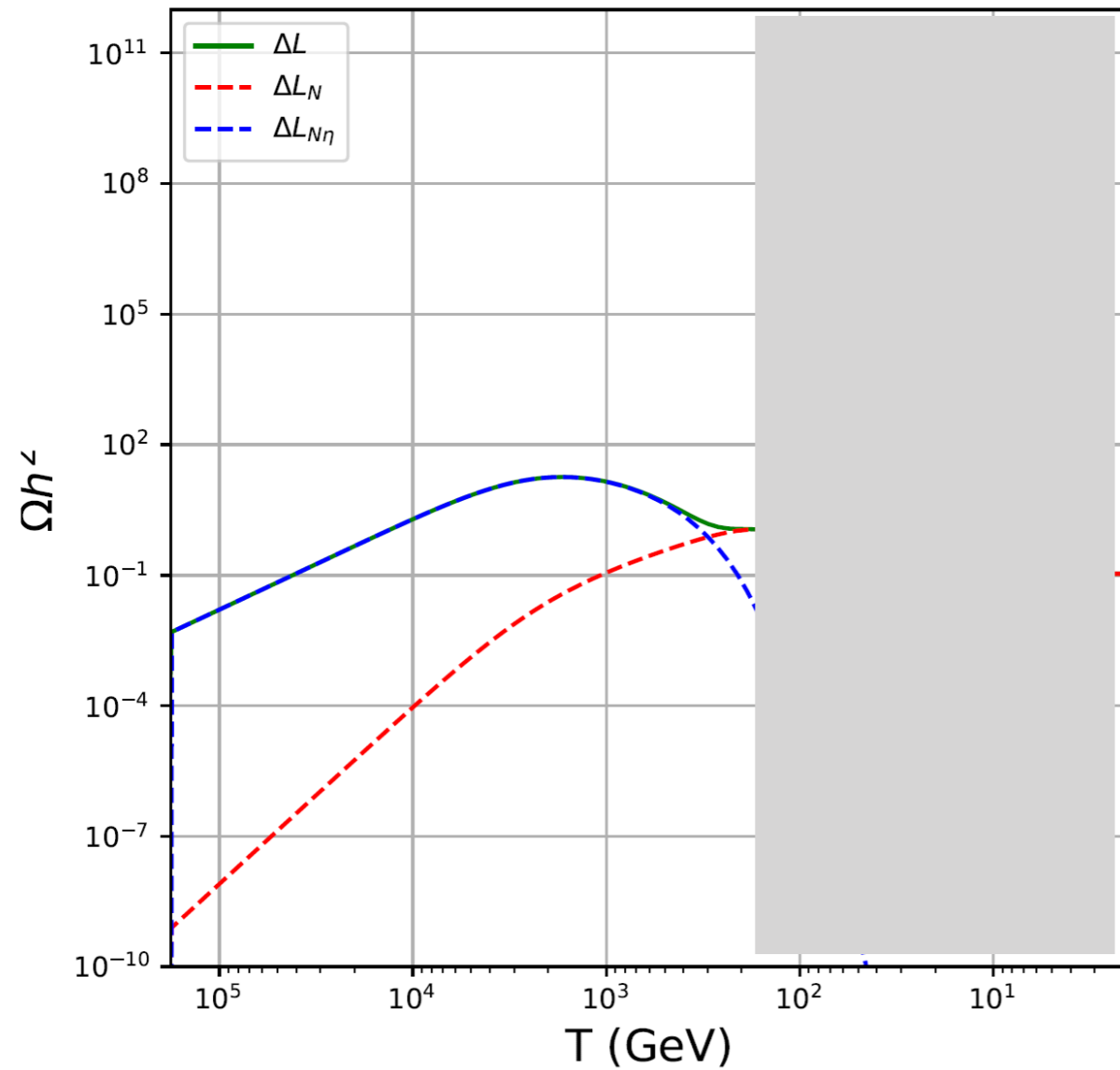
$$\theta_{ij}^R \sim \pi/4, \theta_{12}^I \sim 3\pi/4, \theta_{23}^I = \theta_{13}^I \sim \pi/4$$



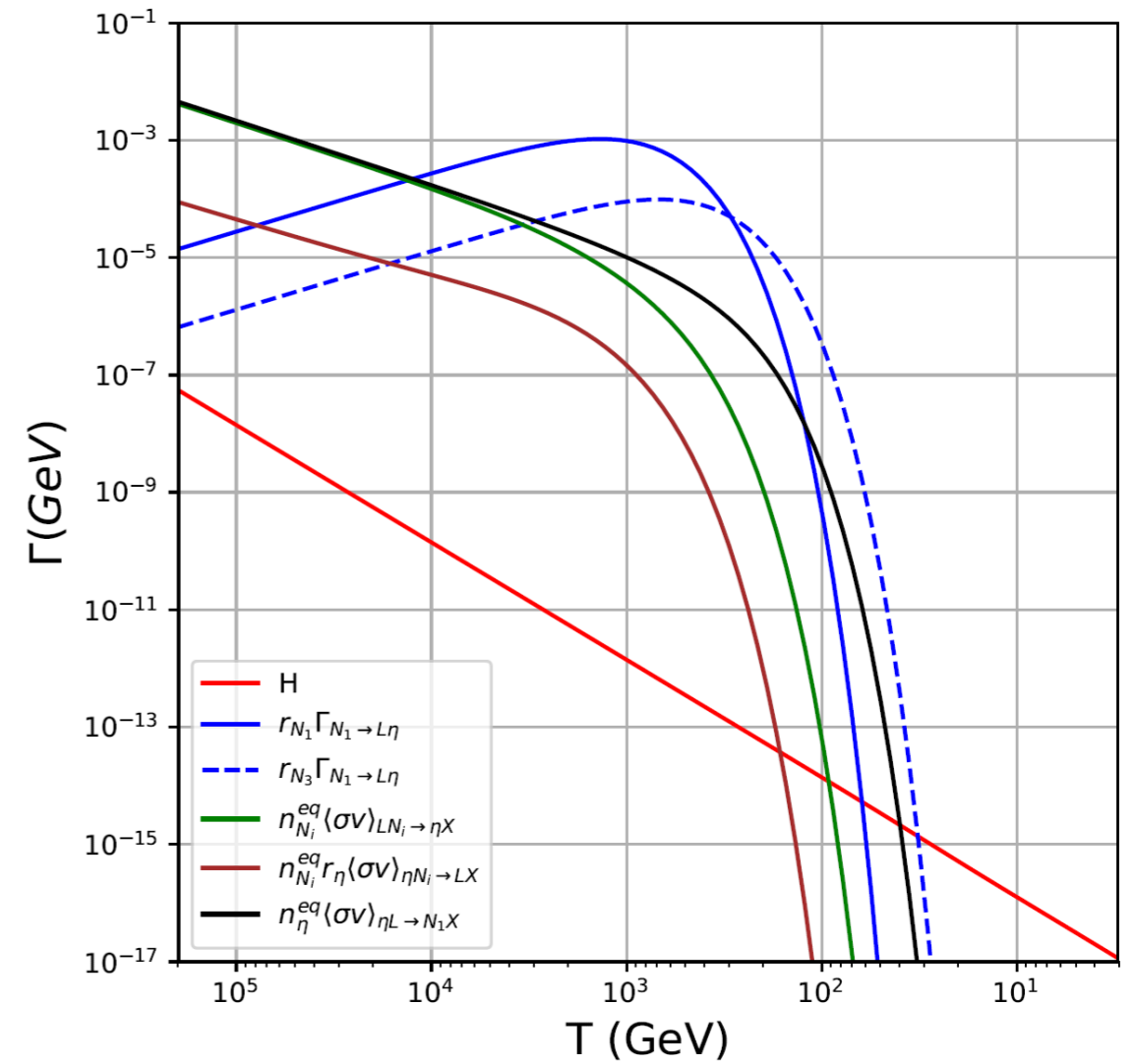
$$h|_{NH} = \begin{pmatrix} 4.47 - 5.04i & 10.7 + 4.77i & 6.35 + 7.96i \\ -0.66 - 5.30i & 8.38 - 4.06i & 7.29 + 0.59i \\ -6.34 - 2.74i & 1.15 - 11.7i & 6.20 - 8.20i \end{pmatrix} \times 10^{-3}$$

$$h|_{IH} = \begin{pmatrix} 8.52 - 13.8i & 5.78 + 0.25i & -5.66 - 0.20i \\ -4.89 - 12.8i & 4.54 - 3.93i & -4.42 + 4.03i \\ -17.18 - 3.51i & -2.6 - 6.78i & 2.71 + 6.60i \end{pmatrix} \times 10^{-3}$$

Numerical Results

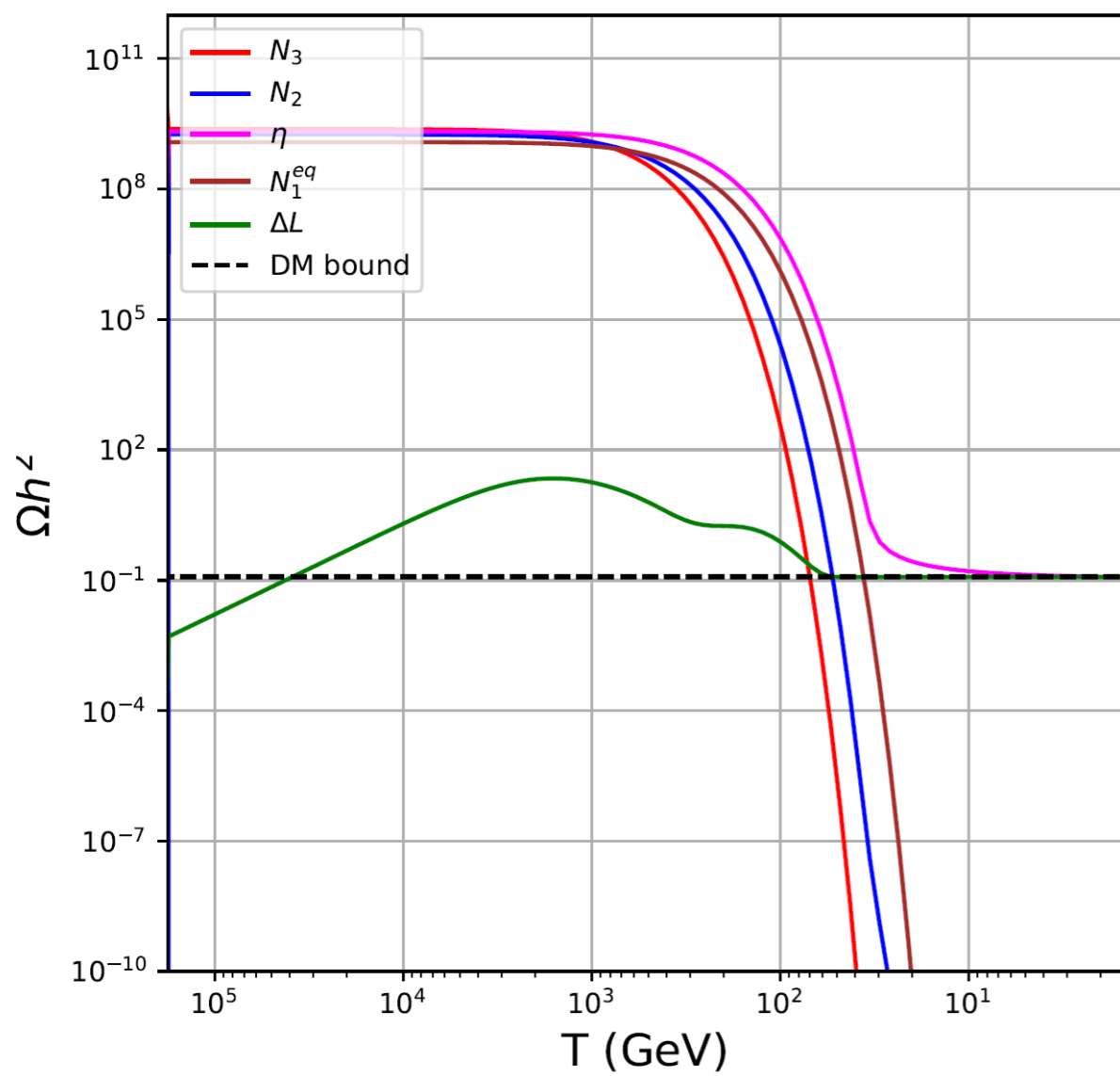


Contributions to lepton asymmetry

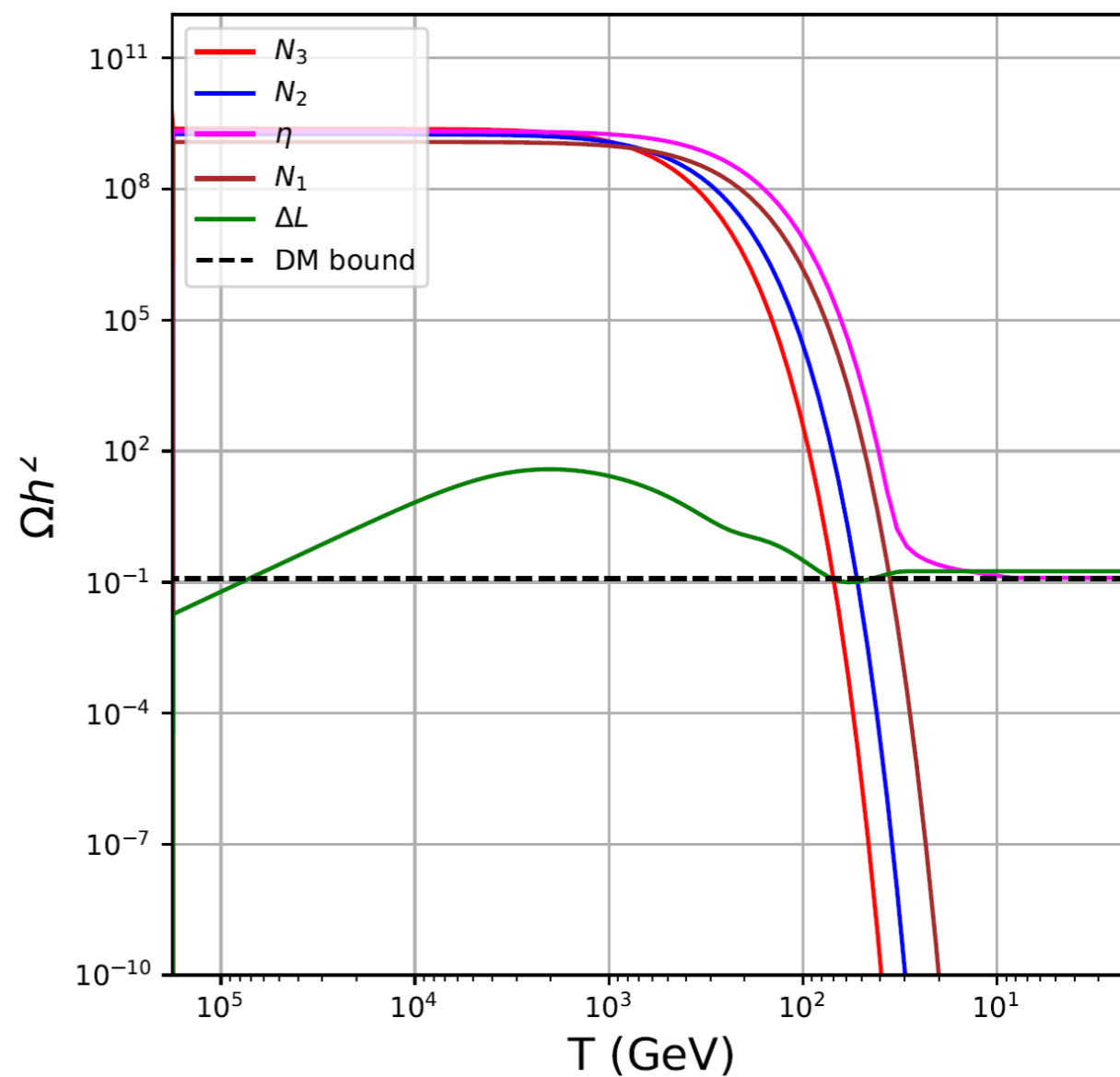


Contributions to wash-out

Normal Hierarchy



Inverted Hierarchy



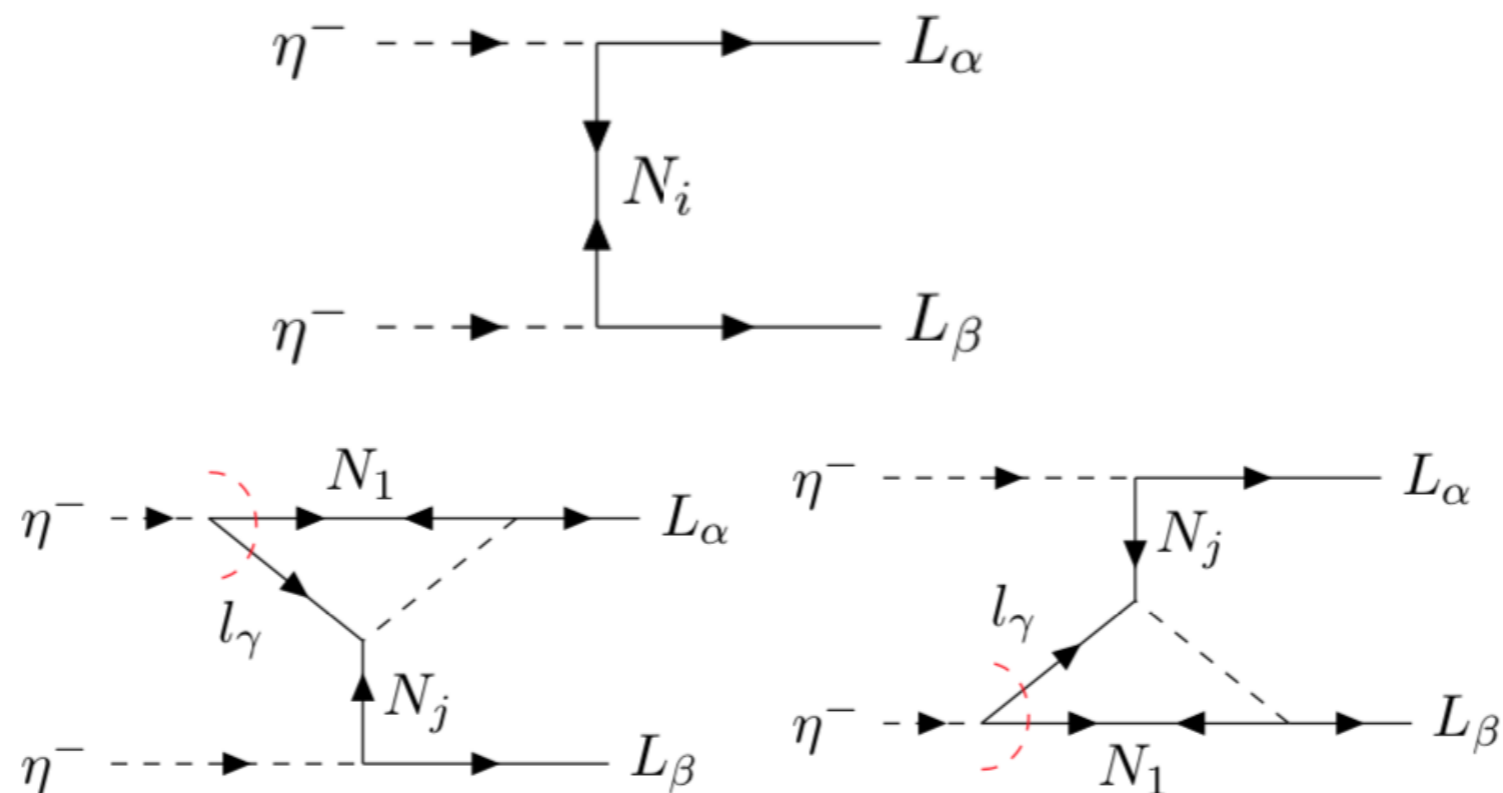
- Considering the limits on the parameter λ_5 , keeping all the other parameters same as shown on above table
 - $m_R^2 - m_I^2 = 2\lambda_5 v^2$ should more than approximately 100 keV, in order to avoid Z mediated inelastic direct detection scattering of DM off nucleons, $\eta_R n \rightarrow \eta_I n$

$$|\lambda_5| \geq 3 \times 10^{-6}$$

- While the lepton asymmetry gets converted into the baryon asymmetry before electroweak phase transition, it takes a while for DM to freeze out.

Right handed neutrino as dark matter

- **co-annihilation processes** $N_k \eta \rightarrow L, X (= \gamma, W, Z, h)$ lead to ΔL
- **annihilation processes** $\eta\eta \rightarrow LL$ through t-channel mediated by N_i



- **On top of the co-annihilation contributions discussed earlier, the annihilation channels shown above also contribute to the asymmetry**

- The CP asymmetry coming from previous diagrams are given as:

$$\begin{aligned}
\epsilon_{\eta\eta} &= 8 \sum_{ij} (\Im[(hh^\dagger)_{i1}(hh^\dagger)_{j1}(hh^\dagger)_{ij}]) \epsilon_{ij}^{ann} \\
&= \sum_j \frac{m_1^4 - m_j^4}{\Lambda_1^4 \Lambda_j^2} (\Delta m_{1j}^2 \sin(4\theta_{1j}^R) + (m_1^2 + m_j^2) \sinh(4\theta_{1j}^I)) \epsilon_{1j}^{ann} \\
\epsilon_{1j}^{ann} &= \frac{1}{16\pi} \left[1 - r_1 - \frac{1}{2} (r_1 - 3) \ln \left[\frac{1 + r_1}{3 - r_1} \right] \right] \frac{\sqrt{r_j r_1}}{(1 + r_j)(1 + r_1)} \frac{1}{\mathcal{M}_{tree}} \\
\mathcal{M}_{tree} &= \sum_{ij} (hh^\dagger)_{ij}^2 \frac{\sqrt{r_i} \sqrt{r_j}}{(1 + r_i)(1 + r_j)}.
\end{aligned}$$

- The washout effects in this scenario are categorised as follows :
 - $\Delta L = 2$: $L\eta \rightarrow \bar{L}\eta$, $\eta\eta \rightarrow LL$
 - $\Delta L = 1$: there are two main sources of such wash-out
 1. Inverse decay of $N_k \rightarrow L\eta$, $\eta \rightarrow LN_k$
 2. inverse process of co-annihilation $N_k\eta \rightarrow L, X (= \gamma, W, Z, h)$

- BEs for Z_2 odd particles take the following form:

$$\frac{dY_{N_k}}{dz} = -\frac{1}{zH(z)} [(Y_{N_k} - Y_{N_k}^{\text{eq}})\langle\Gamma_{N_k \rightarrow L_\alpha \eta}\rangle + (Y_{N_k} Y_\eta - Y_{N_k}^{\text{eq}} Y_\eta^{\text{eq}})s\langle\sigma v\rangle_{\eta N_k \rightarrow \text{LSM}} + \sum_{l=1}^3 (Y_{N_k} Y_{N_l} - Y_{N_k}^{\text{eq}} Y_{N_l}^{\text{eq}})s\langle\sigma v\rangle_{N_l N_k \rightarrow \text{SMSM}}], \quad \text{for } k = 2,3$$

$$\frac{dY_\eta}{dz} = \frac{1}{zH(z)} \left[\sum_{k=2}^3 (Y_{N_k} - Y_{N_k}^{\text{eq}})\langle\Gamma_{N_k \rightarrow L_\alpha \eta}\rangle - (Y_\eta - Y_\eta^{\text{eq}})\langle\Gamma_{\eta \rightarrow L_\alpha N_1}\rangle - 2(Y_\eta^2 - (Y_\eta^{\text{eq}})^2)s\langle\sigma v\rangle_{\eta\eta \rightarrow \text{SMSM}} - \sum_{m=1}^3 (Y_{N_m} Y_\eta - Y_{N_m}^{\text{eq}} Y_\eta^{\text{eq}})s\langle\sigma v\rangle_{\eta N_m \rightarrow \text{LSM}} \right]$$

$$\frac{dY_{N_1}}{dz} = \frac{1}{zH(z)} \left[(Y_\eta - Y_\eta^{\text{eq}})\langle\Gamma_{\eta \rightarrow L_\alpha N_1}\rangle - (Y_{N_1} Y_\eta - Y_{N_1}^{\text{eq}} Y_\eta^{\text{eq}})s\langle\sigma v\rangle_{\eta N_1 \rightarrow \text{LSM}} - \sum_{l=1}^3 (Y_{N_1} Y_{N_l} - Y_{N_1}^{\text{eq}} Y_{N_l}^{\text{eq}})s\langle\sigma v\rangle_{N_l N_1 \rightarrow \text{SMSM}} \right]$$

- BE for lepton asymmetry takes the following form:

$$\begin{aligned} \frac{dY_{\Delta L}}{dz} = & \frac{1}{zH(z)} \left[\sum_i \epsilon_{N_i} (Y_{N_i} - Y_{N_i}^{\text{eq}}) \langle \Gamma_{N_i \rightarrow L\alpha\eta} \rangle - Y_{\Delta L} r_{N_i} \langle \Gamma_{N_i \rightarrow L\alpha\eta} \rangle - Y_{\Delta L} r_{\eta} s \langle \Gamma_{\eta \rightarrow N_1 L} \rangle \right. \\ & \left. + 2\epsilon_{\eta\eta} s \langle \sigma\nu \rangle_{\eta\eta \rightarrow LL} (Y_{\eta}^2 - (Y_{\eta}^{\text{eq}})^2) - Y_{\Delta L} Y_l^{\text{eq}} r_{\eta}^2 s \langle \sigma\nu \rangle_{\eta\eta \rightarrow LL} \right. \\ & \left. + \sum_i \epsilon_{N_i\eta} s \langle \sigma\nu \rangle_{\eta N_i \rightarrow LSM} (Y_{\eta} Y_{N_i} - Y_{\eta}^{\text{eq}} Y_{N_i}^{\text{eq}}) - \frac{1}{2} Y_{\Delta L} Y_l^{\text{eq}} r_{N_i} r_{\eta} s \langle \sigma\nu \rangle_{\eta N_i \rightarrow SM\bar{L}} \right. \\ & \left. - Y_{\Delta L} Y_{\eta}^{\text{eq}} s \langle \sigma\nu \rangle_{\eta L \rightarrow \eta\bar{L}}^{\text{wo}} - \sum_i Y_{\Delta L} Y_{\eta}^{\text{eq}} s \langle \sigma\nu \rangle_{\eta L \rightarrow N_i X}^{\text{wo}} - \sum_i Y_{\Delta L} Y_{N_i}^{\text{eq}} s \langle \sigma\nu \rangle_{N_i L \rightarrow \eta X}^{\text{wo}} \right], \end{aligned}$$

$$H = \sqrt{\frac{4\pi^3 g_*}{45} \frac{M_{\chi}^2}{M_{\text{PL}}}}, \quad s = g_* \frac{2\pi^2}{45} \left(\frac{M_{\chi}}{z} \right)^3, \quad r_j = \frac{Y_j^{\text{eq}}}{Y_l^{\text{eq}}}, \quad \langle \Gamma_{j \rightarrow X} \rangle = \frac{K_1(M_j/T)}{K_2(M_j/T)} \Gamma_{j \rightarrow X},$$

- In this scenario, we require N_1 to be lighter than η whose annihilations are responsible for creating the asymmetry.
- The contribution of N_k annihilations to lepton asymmetry is suppressed compared to η annihilations as well as $\eta - N_k$ co-annihilations.
- It is worthwhile to note that the η annihilations shown above cannot contribute to lepton asymmetry in the scalar DM scenario due to the absence of "on-shell" condition for loop particles.

Numerical Results

Input values

$$\mu_\eta = 850 \text{ GeV} \quad M_{N_1} = 865 \text{ GeV} \quad \lambda_5 = -1 \times 10^{-5}$$

$$M_{N_2} = 2 \text{ TeV} \quad M_3 = 3 \text{ TeV} \quad \lambda_1 \sim 0.2, \lambda_3 \sim 1.5, \lambda_4 \sim -1.5, \lambda_2 \sim 1$$

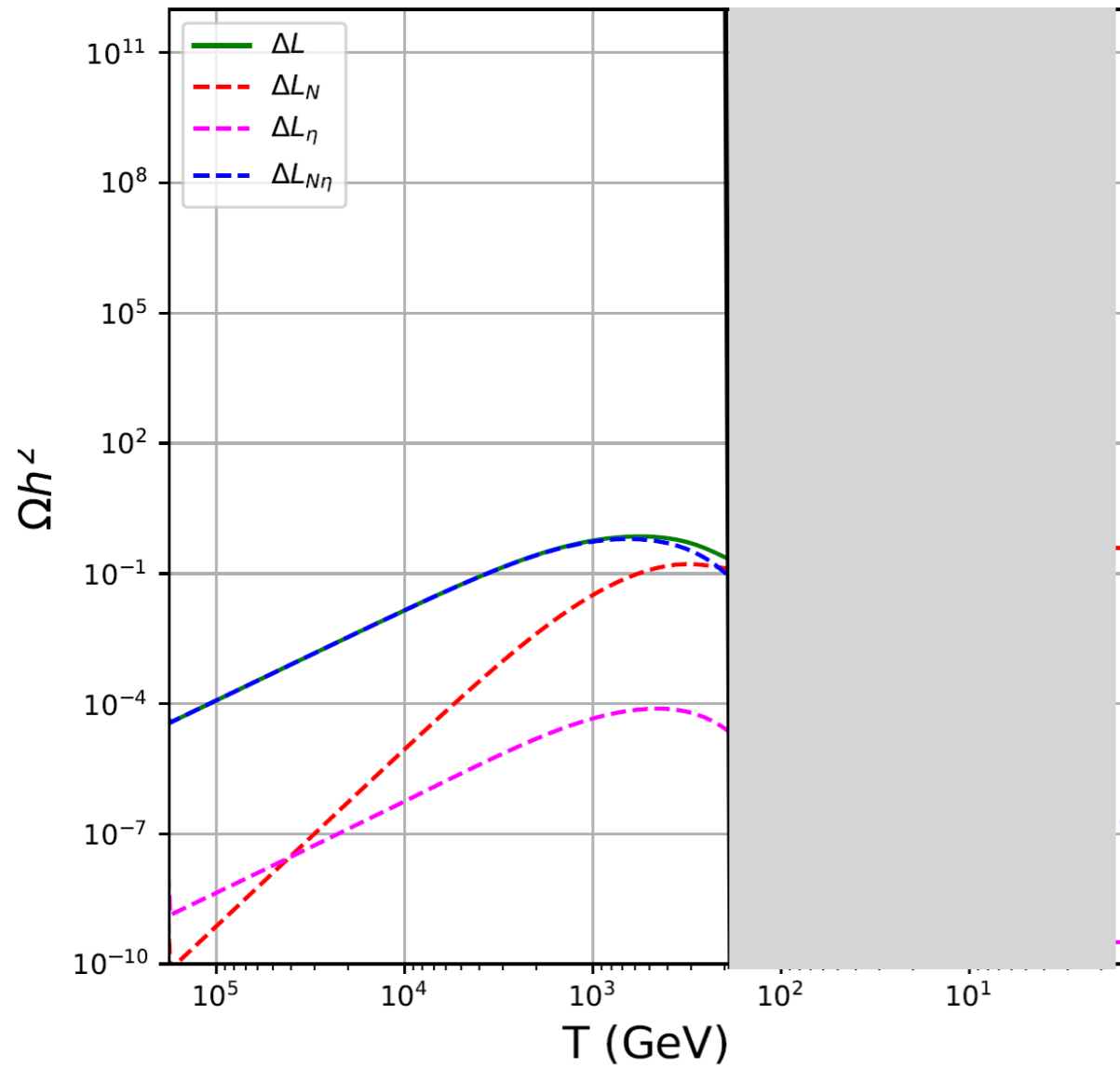
$$\theta_{ij}^R \sim \pi/4, \theta_{12}^I \sim 3\pi/4, \theta_{23}^I = \theta_{13}^I \sim \pi/4$$



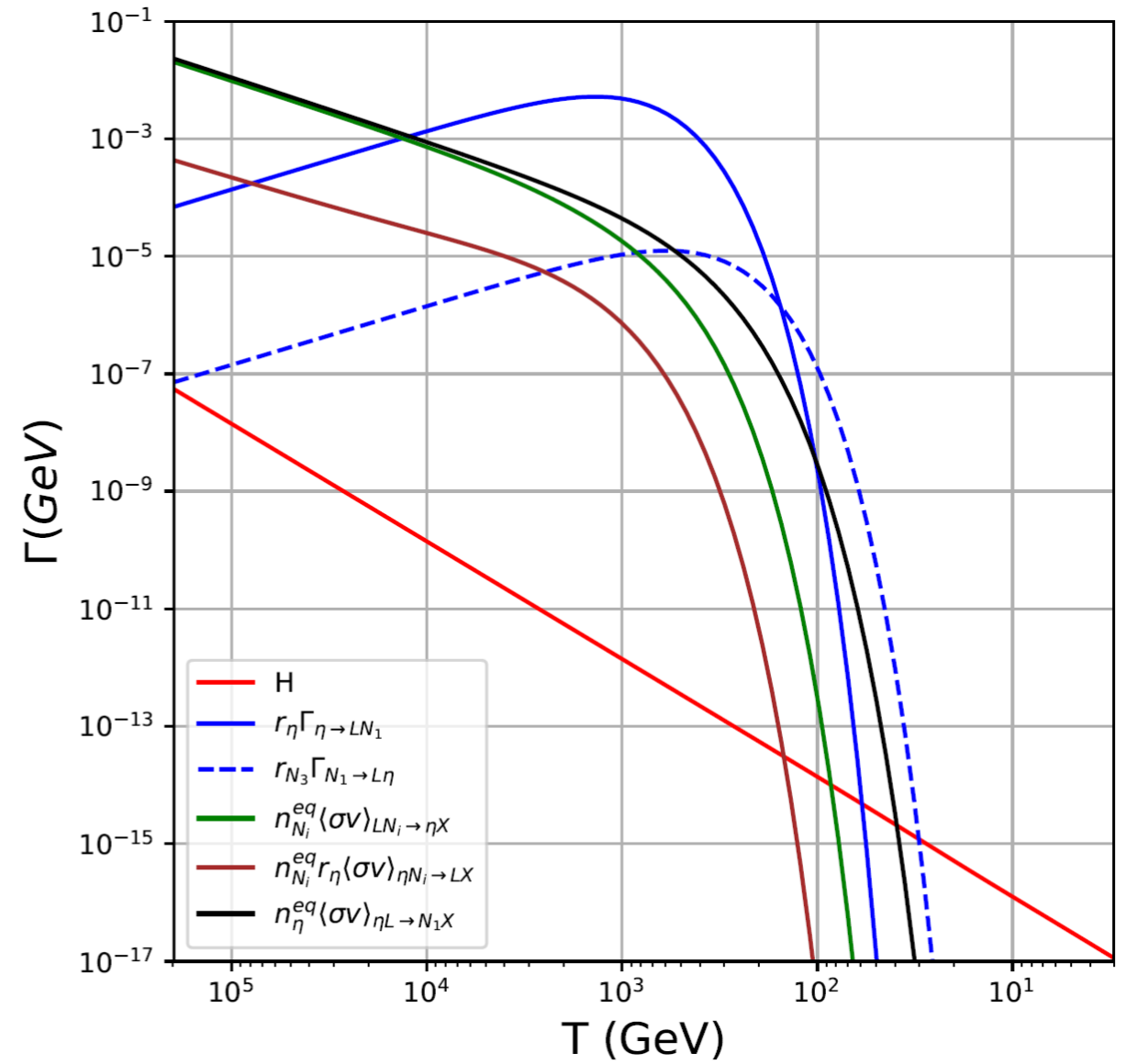
$$h|_{NH} = \begin{pmatrix} 1.01 - 1.14i & 2.43 + 1.09i & 1.44 + 1.8i \\ -0.15 - 1.21i & 1.92 - 9.29i & 1.67 + 0.13i \\ -1.40 - 0.61i & 2.55 - 2.6i & 1.37 - 1.81i \end{pmatrix} \times 10^{-2}$$

$$h|_{IH} = \begin{pmatrix} 1.88 - 3.05i & 1.28 + 0.55i & -1.25 - 0.45i \\ -1.12 - 2.92i & 1.04 - 0.9i & -1.01 + 0.92i \\ -3.87 - 0.79i & -0.59 - 1.53i & 0.61 + 1.49i \end{pmatrix} \times 10^{-2}$$

Numerical Results

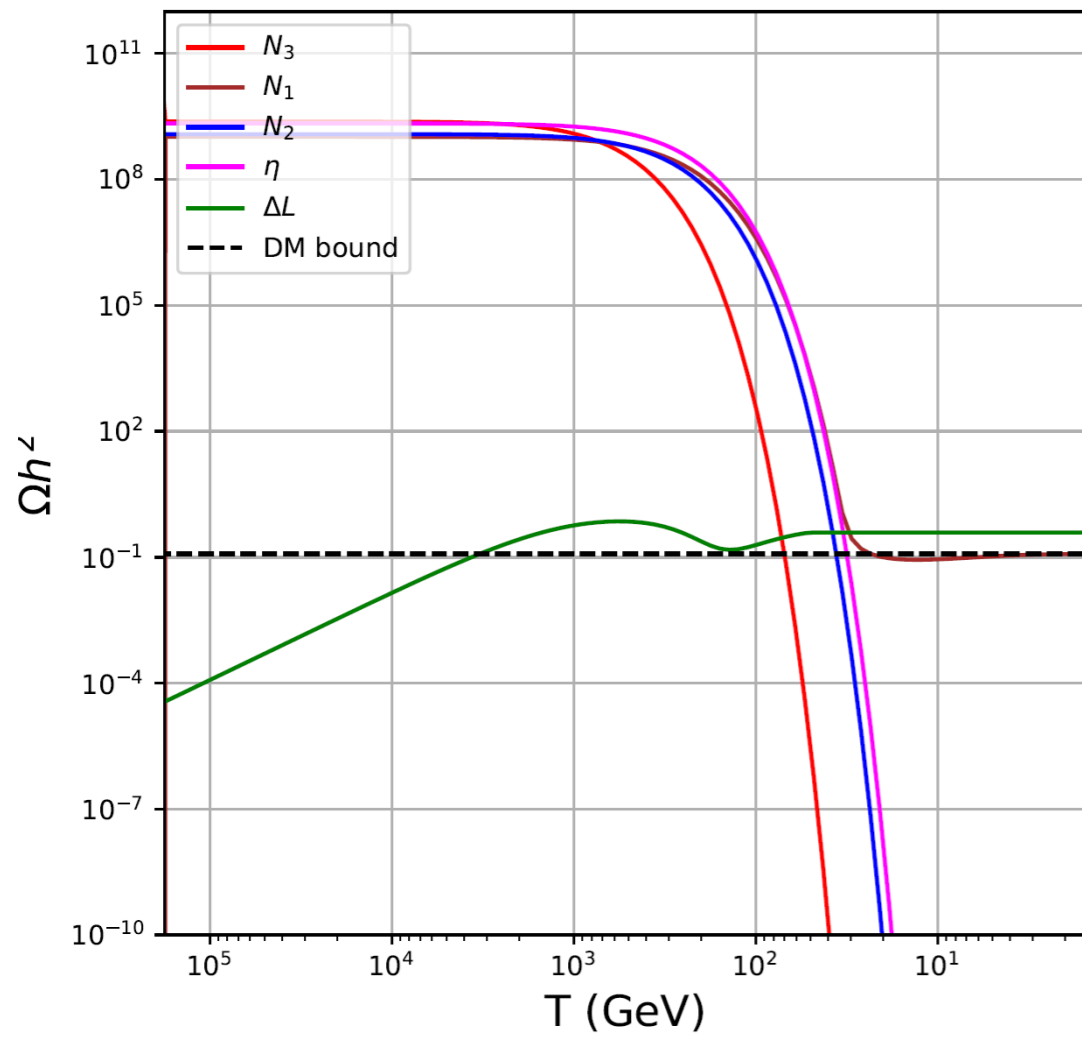


Contributions to lepton asymmetry

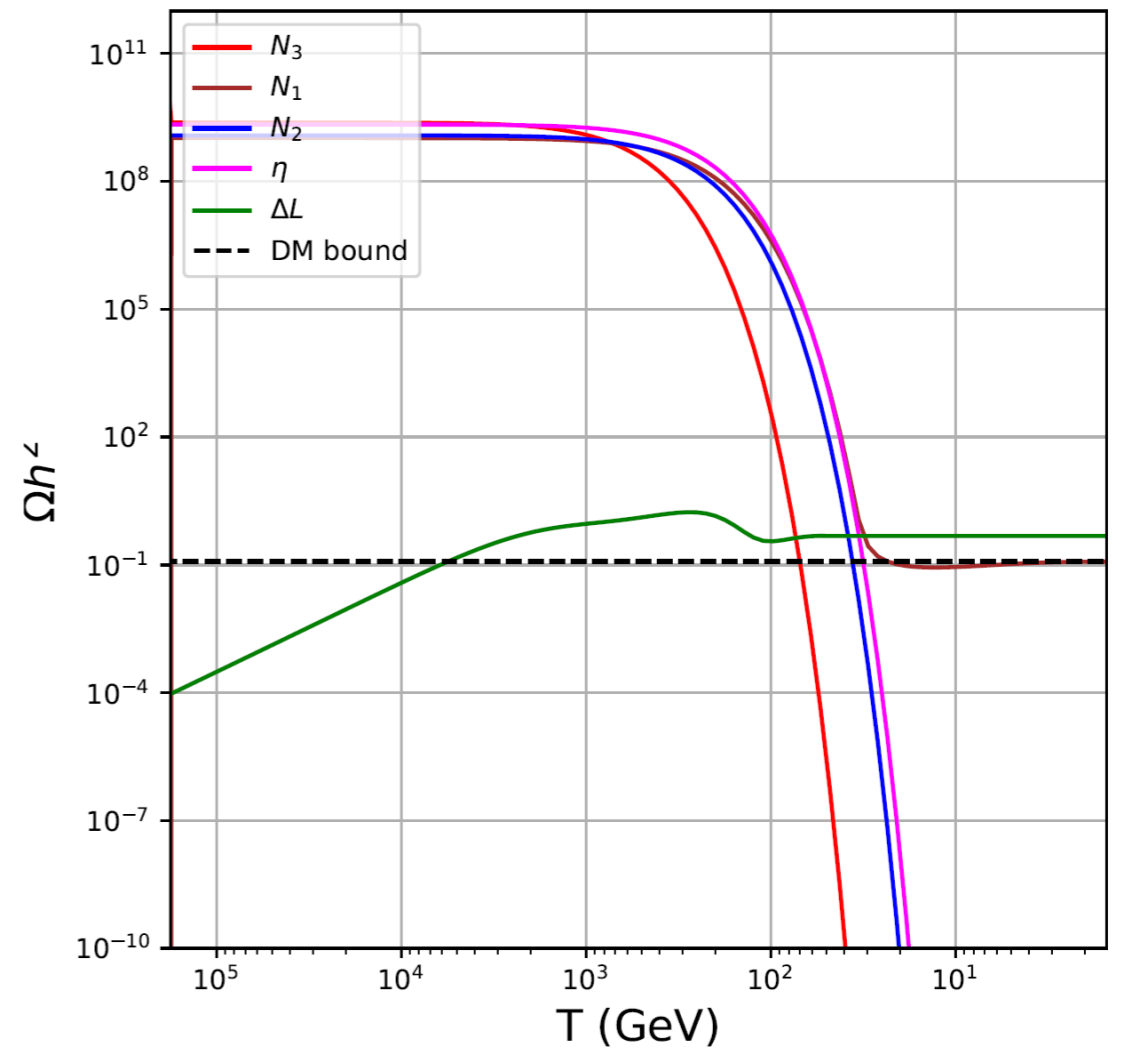


Contributions to wash-out

Normal Hierarchy



Inverted Hierarchy



Conclusion

- 3 well known problems in SM can be resolved in scotogenic model.
- We have shown that scattering processes such as co-annihilation of $N_k - \eta$ can play an important role in achieving TeV leptogenesis.
- In our scenarios, generation of baryon asymmetry can be related with generation of dark matter abundance.

Thank You