TeV Scale Leptogenesis via Dark Sector Scattering

Sin Kyu Kang (Seoul Tech)

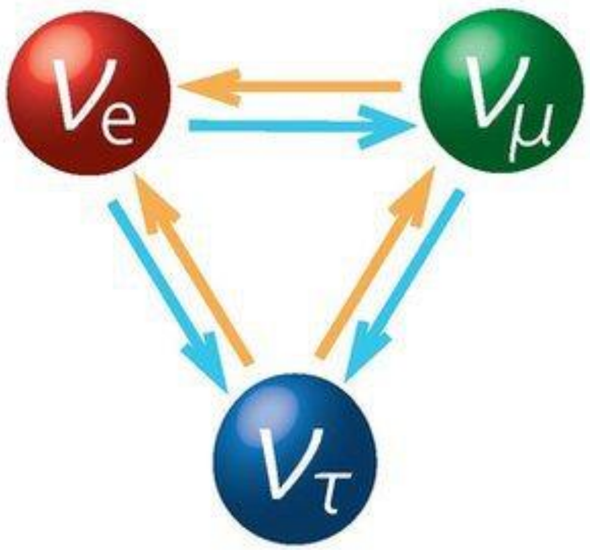
Based on work with Debasish Borah and Arnab Dasgupta,
arXiv:1811.02094;
& to appear soon

Outline

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

Problems in SM

- **SM cannot explain the observed Neutrino Mass and Mixing.**



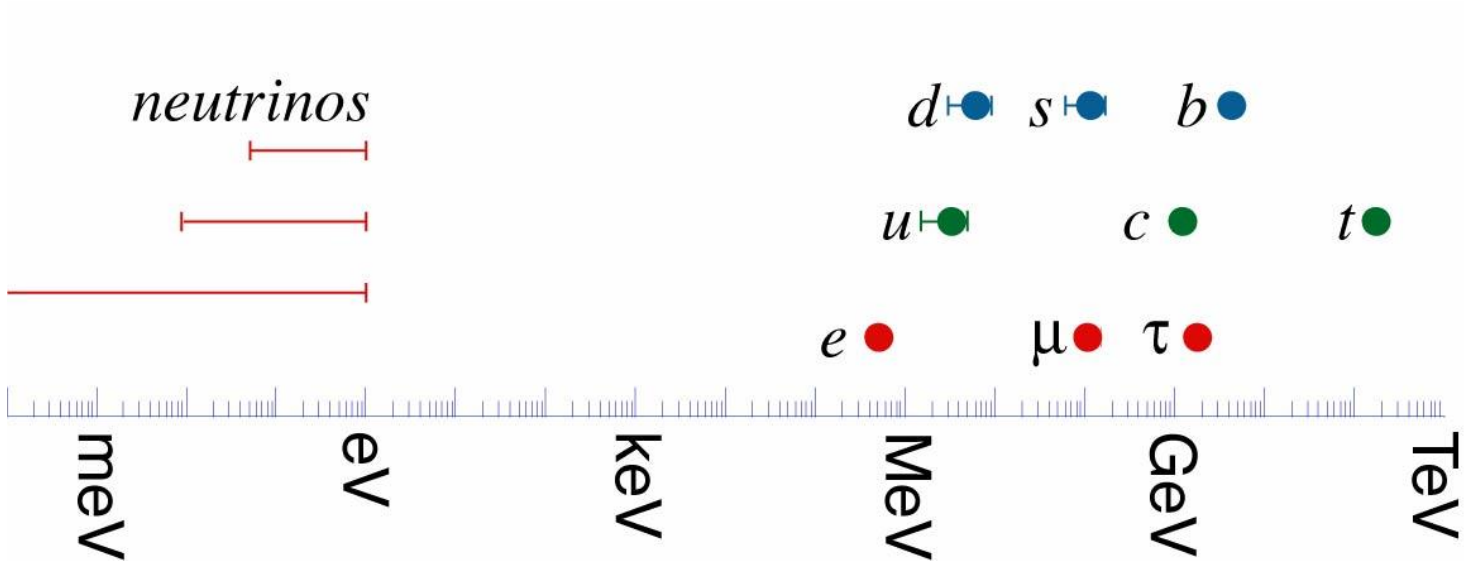
- **SM does not have a dark matter candidate.**

- **SM cannot explain the observed baryon asymmetry**

Neutrino Mass

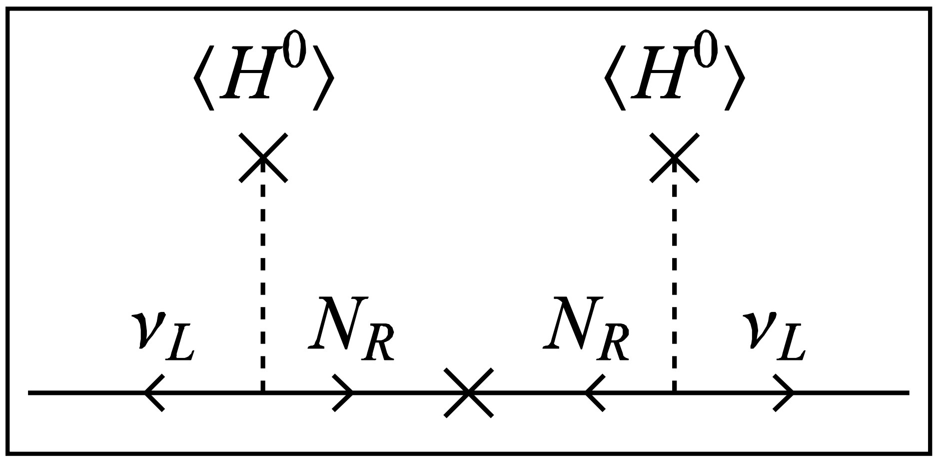
• **Neutrinos have masses that are (at least) a factor of 10^6 smaller than the one of the electron**

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

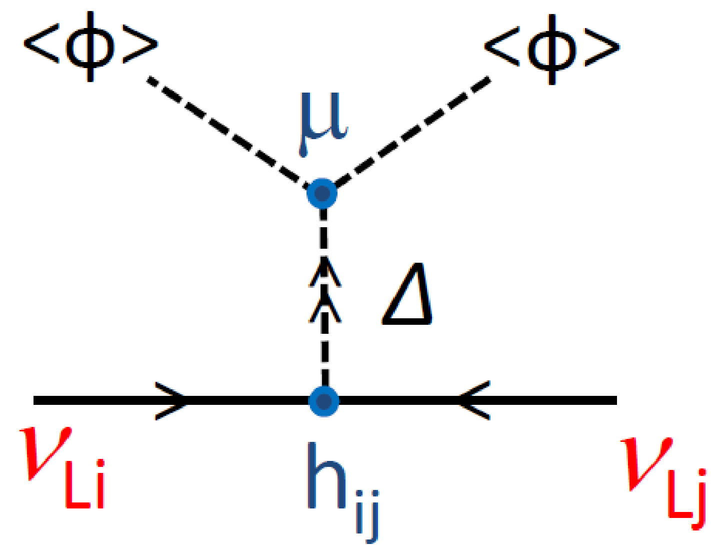


• **There are different possibilities to generate small neutrino masses**

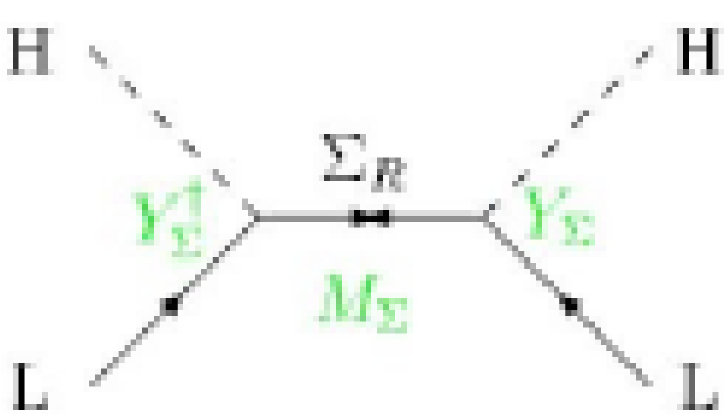
Tree level Mass



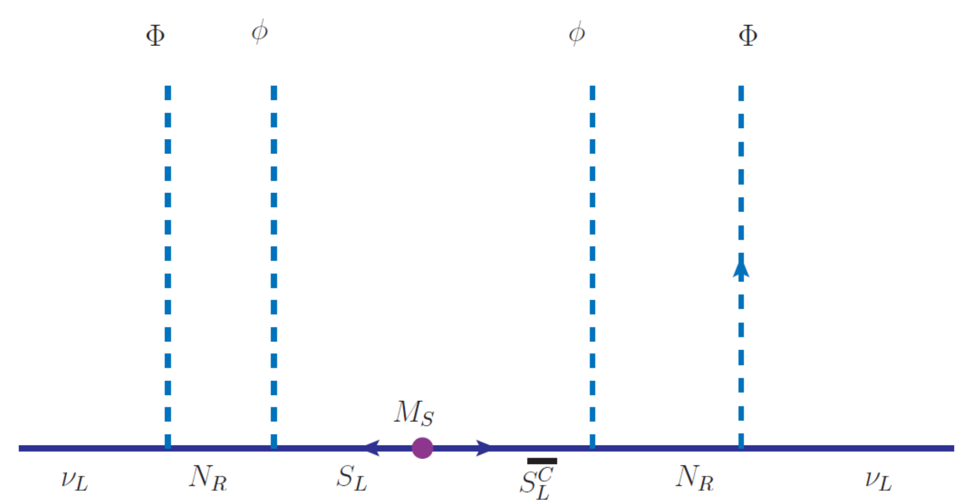
(Minkowski '77; Glashow'79; Yanagida '79; Gellman, Ramond, Slansky '80; Mohapatra, Senjanovic '80; Schechter, Valle '80)



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

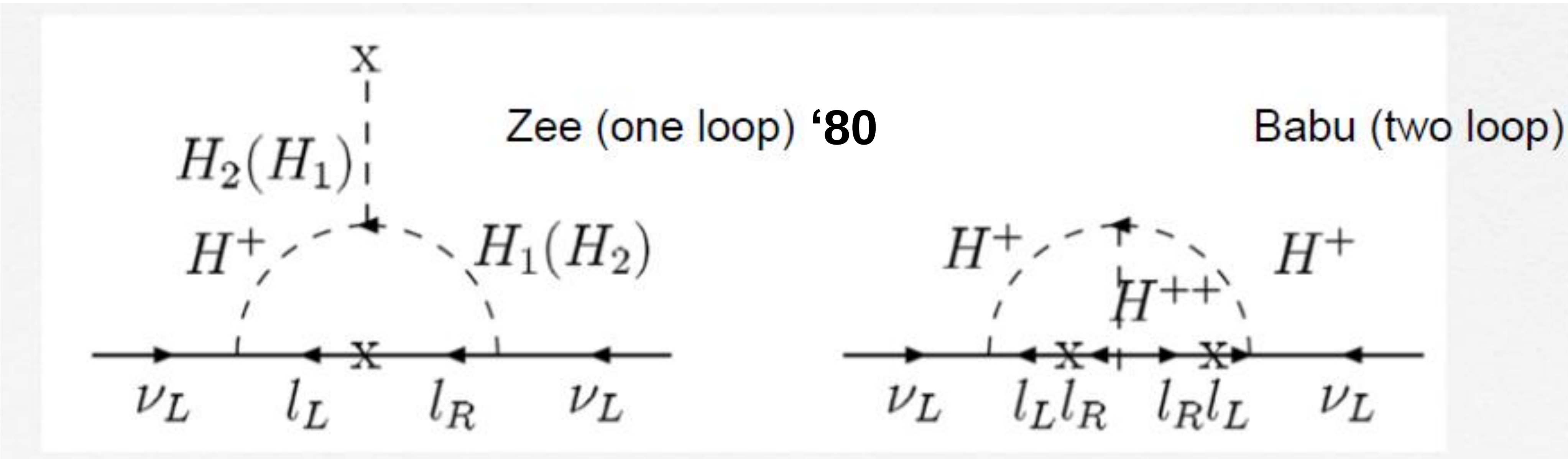


(Foot, Lew, He, Joshi '89)



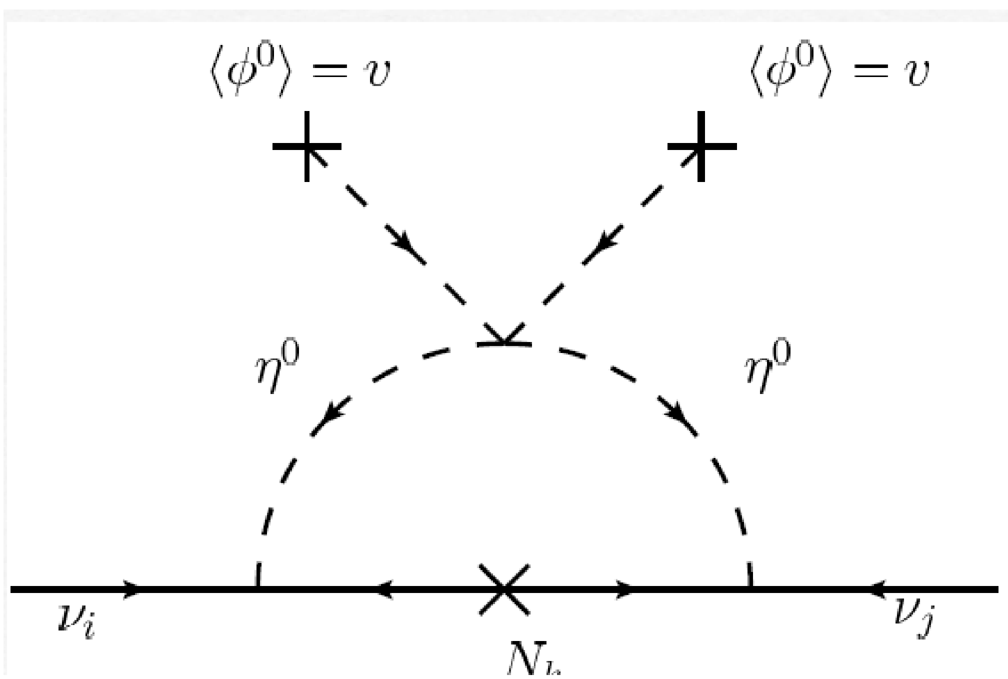
(Mohapatra'86; Mohapatra, Valle'86))

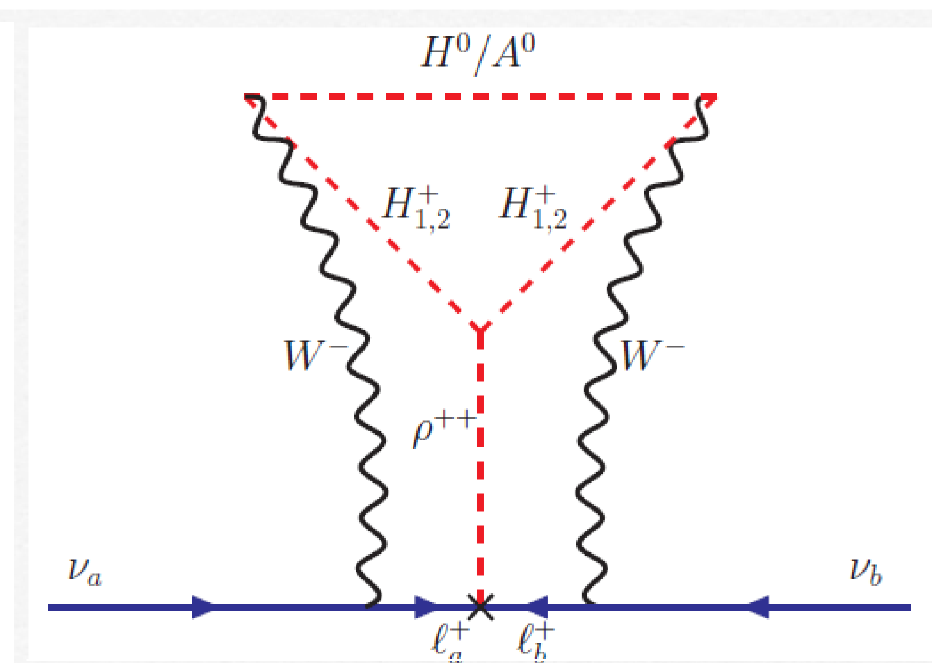
Loop level Mass



Zee (one loop) **'80**

Babu (two loop) **'88**





- Scotogenic (Ma) **'06**

Cocktail (Gustafusson et.al.'13)

- R-parity violating SUSY model

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

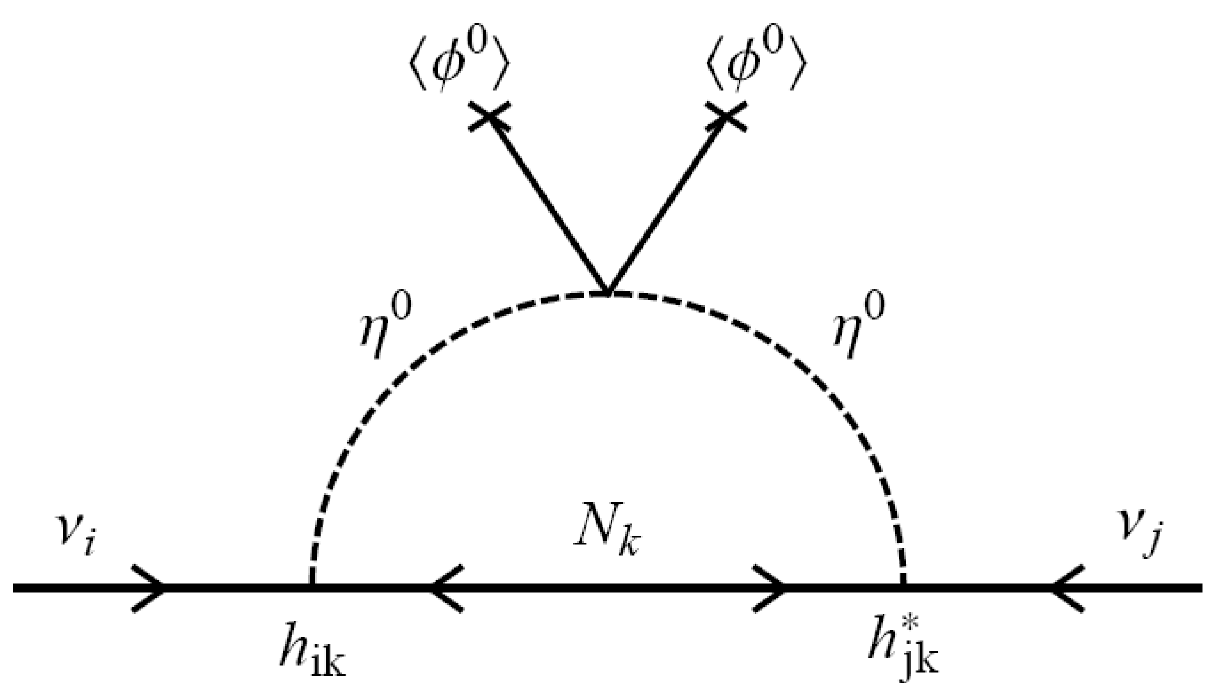
Scotogenic Model

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

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

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

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



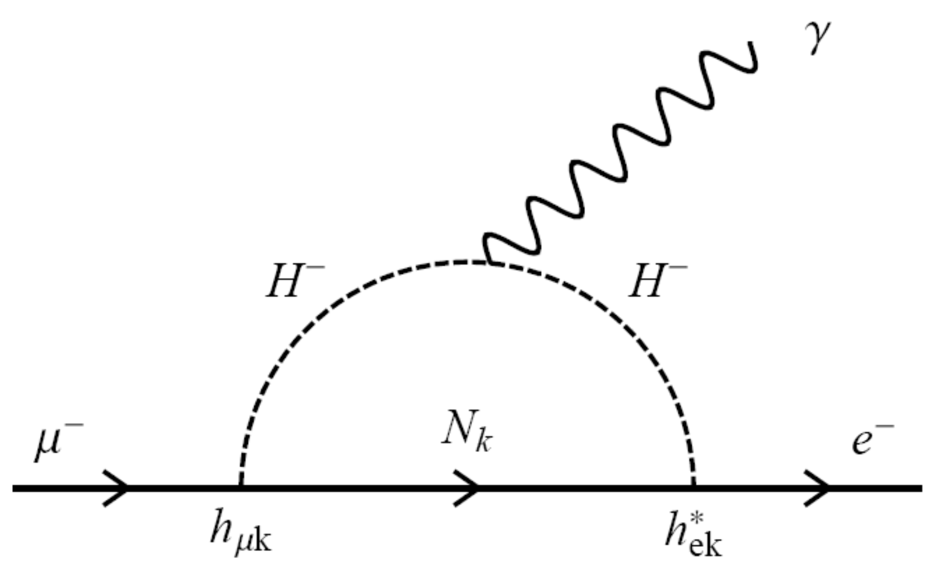
$$\boxed{\mathcal{M}_\nu = h^* \Lambda^{-1} h^\dagger} \qquad \Lambda_i := \frac{2\pi^2}{\lambda_5} \xi_i \frac{2M_i}{v^2}$$

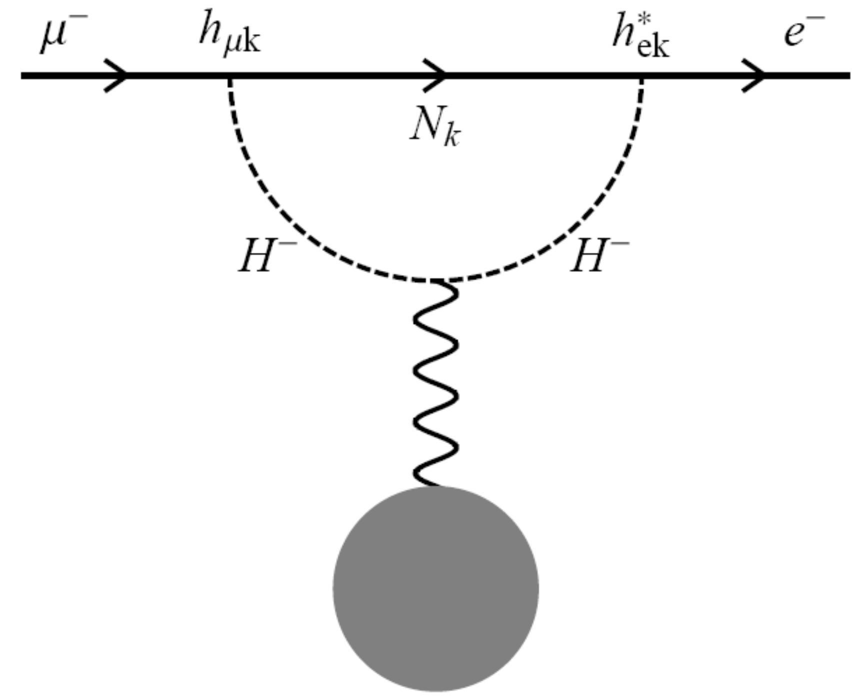
radiative seesaw

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

- **Tiny neutrino mass can be achieved by taking "natural" Yukawa couplings and TeV scale heavy neutrinos**

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





- **LFV-processes are constrained (MEGA experiment):**

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

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

$$\left|\sum_{k=1}^{3} h_{1k}^* h_{2k}\right| \lesssim 4.1 \times 10^{-5} \left(\frac{m_\eta}{100\ \mathrm{GeV}}\right)^2$$

Phys. Rev. **D79**, 013011 (2009)

Baryogenesis

(Planck, arXiv: 1502.01589)

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.15 \pm 0.25) \times 10^{-10}$$

CMB+BBN

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 equlibrium**

Leptogenesis

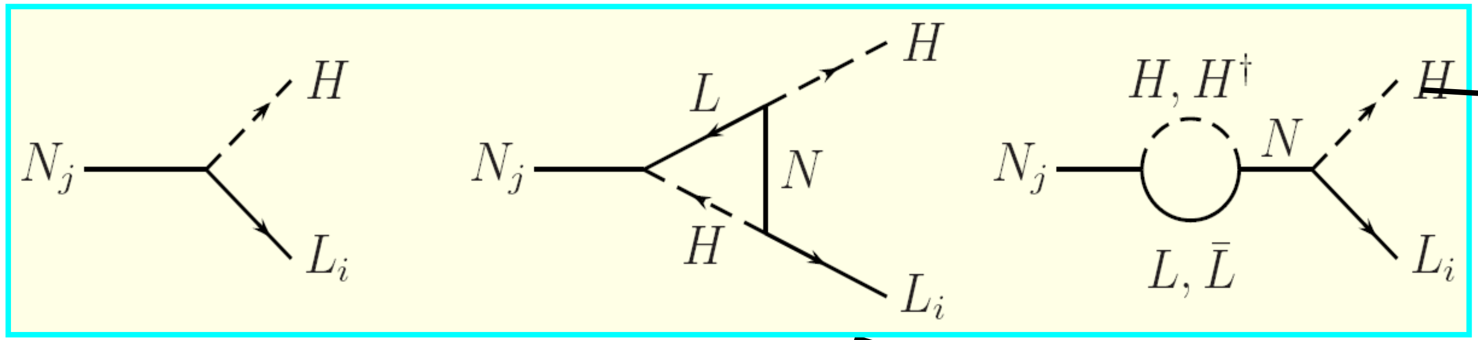
- Since the SM fails to satisfy Sakharov's conditions, new source of CP violation is necessarily required→BSM

- 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**



Liu & Segre '93

Fukugida & Yanagida '86

- CP Asymmetry:

$$\varepsilon_1 = \frac{\Gamma(N_1 \to L\Phi) - \Gamma(N_1 \to L^c\Phi^+)}{\Gamma(N_1 \to L\Phi) + \Gamma(N_1 \to L^c\Phi^+)}$$

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

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

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

Leptogenesis in Scotogenic Model

- **Since scotogenic model contains N_i, vanilla leptogenesis works.**
- **Vanilla leptogenesis requires heavy N_i ,$M_{N_1} \geq 5 \times 10^8 \left(\frac{v}{246\ GeV}\right)^2$**

(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}~10 TeV for successful leptogenesis can be obtained in scotogenic model** (Hugle et.al; 1804.09660).

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

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

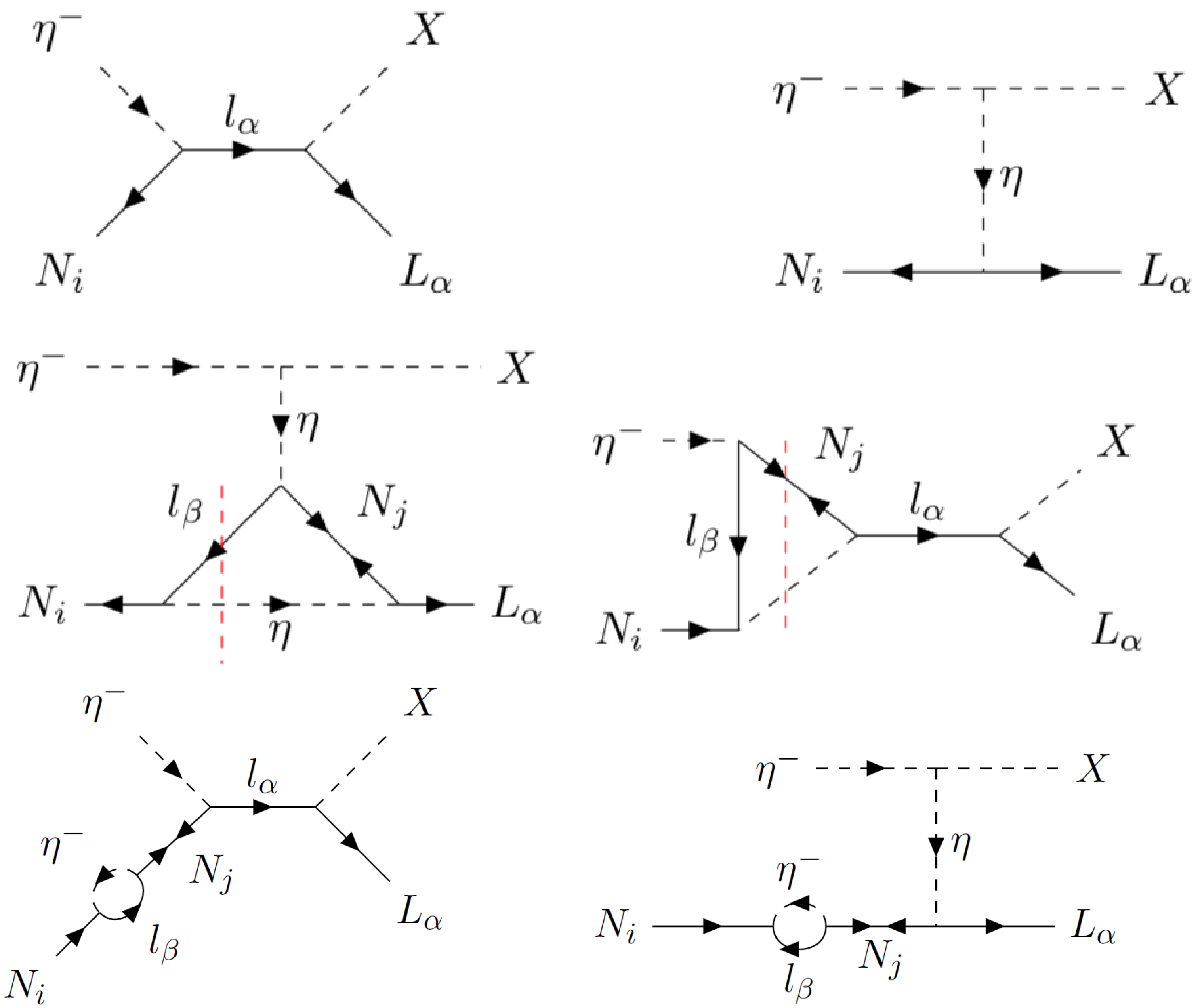
- L −violating scattering processes contributing to ΔL we consider
  - co-annihilations : $N_k \eta \to L, X(=\gamma, W, Z, h)$
  - annihilations : $\eta\eta \to LL$ through t-channel

- Contributions of L −violating processes depend on DM scenarios
  - Lightest N_i as a DM
  - Z_2 odd neutral scalar as a DM

Scalar Doublet η as Dark Matter

- **Scattering processes $\eta\eta \rightarrow LL$ through t-channel mediated by $\boldsymbol{N_i}$**
  → lead to zero CP asymmetry

- **co-annihilation processes $N_k\eta \rightarrow L, X(=\gamma, W, Z, h)$ lead to $\Delta \boldsymbol{L}$**



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

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

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

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

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

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

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

$$D = \sqrt{(r_i - r_j)\left(r_i + 4\sqrt{r_i} - r_j + 4\right)} \qquad r_l = \frac{M_{N_l}^2}{m_\eta^2}.$$

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

  - $\Delta L = 2$: $L\eta \to \bar{L}\eta, \quad \eta\eta \to LL$
  - $\Delta L = 1$: **there are two main sources of such wash-out**

    1. **Inverse decay of $N_k \to L\eta$,**
    2. **inverse process of co-annihilation $N_k\eta \to L, X(=\gamma, W, Z, h)$**

- **Boltzmann eqs.:**

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

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

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

BE for lepton asymmetry takes the following form:

$$\frac{dY_{\Delta L}}{dz} = \frac{1}{zH(z)} [\sum_i \epsilon_{N_i} (Y_{N_i} - Y_{N_i}^{\text{eq}}) \langle \Gamma_{N_i \to L_\alpha \eta} \rangle - Y_{\Delta L} r_{N_i} \langle \Gamma_{N_i \to L_\alpha \eta} \rangle - Y_{\Delta L} r_\eta s \langle \Gamma_{\eta \to N_1 L} \rangle$$

$$+ \sum_i \epsilon_{N_i \eta} s \langle \sigma v \rangle_{\eta N_i \to L \text{SM}} \left(Y_\eta Y_{N_i} - Y_\eta^{\text{eq}} Y_{N_i}^{\text{eq}} \right) - \frac{1}{2} Y_{\Delta L} Y_l^{\text{eq}} r_{N_i} r_\eta s \langle \sigma v \rangle_{\eta N_i \to \text{SM} \bar{L}}$$

$$- Y_{\Delta L} Y_l^{\text{eq}} r_\eta^2 s \langle \sigma v \rangle_{\eta\eta \to LL}^{wo}$$

$$- Y_{\Delta L} Y_\eta^{\text{eq}} s \langle \sigma v \rangle_{\eta L \to \eta \bar{L}}^{wo} - \sum_i Y_{\Delta L} Y_\eta^{\text{eq}} s \langle \sigma v \rangle_{\eta L \to N_i X}^{wo} - \sum_i Y_{\Delta L} Y_{N_i}^{\text{eq}} s \langle \sigma v \rangle_{N_i L \to \eta X}^{wo}],$$

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

- **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.**

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

Ex) $$R_{12} = \begin{pmatrix} \cos(\theta^R_{12} + i\theta^I_{12}) & \sin(\theta^R_{12} + i\theta^I_{12}) & 0 \\ -\sin(\theta^R_{12} + i\theta^I_{12}) & \cos(\theta^R_{12} + i\theta^I_{12}) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Numerical Results

- **Input values**

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

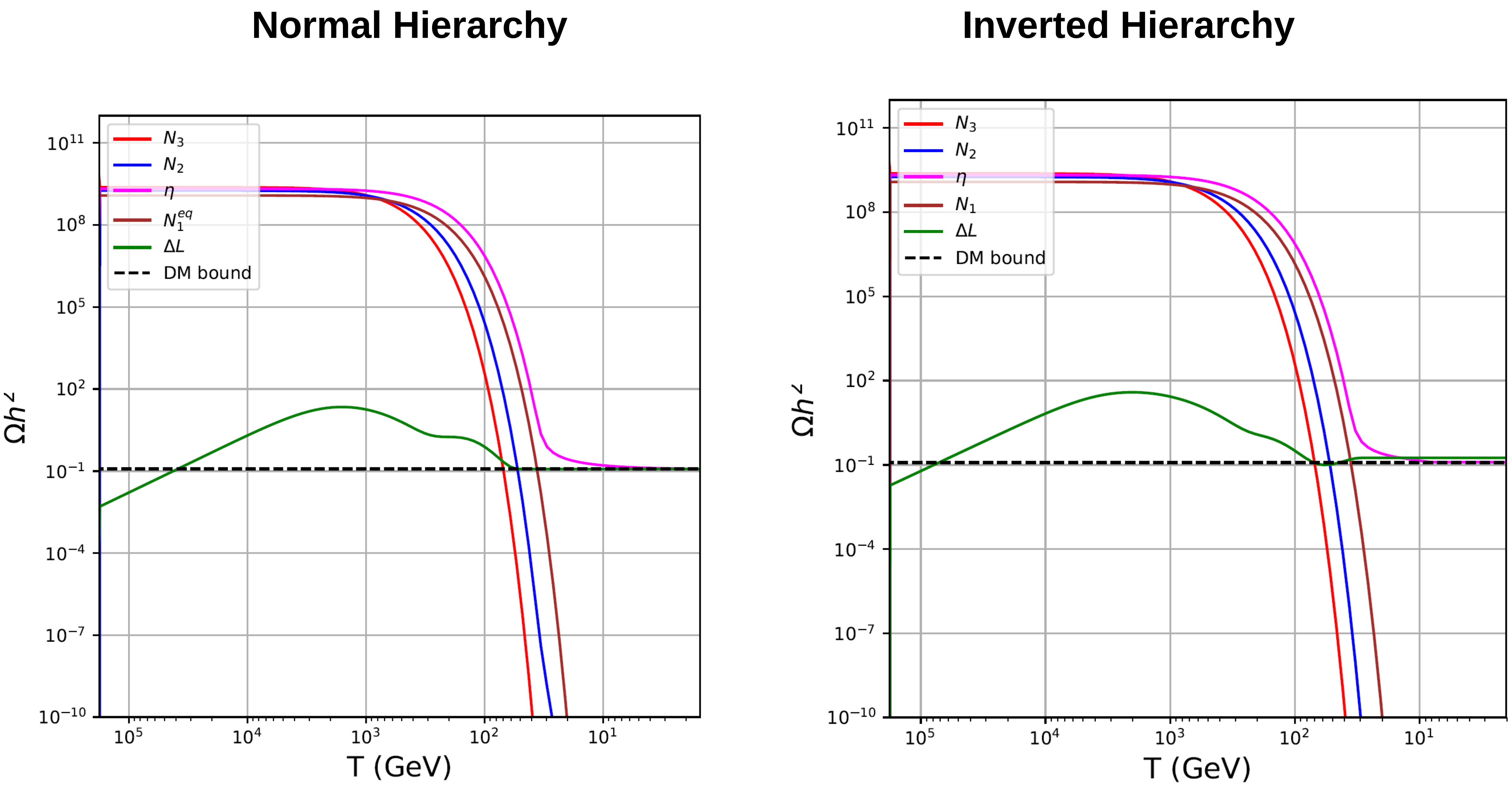
m_η=900 GeV M_{N_1}=1 TeV $\lambda_5 = -5 \times 10^{-5}$

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

$\theta^R_{ij} \sim \pi/4$, $\theta^I_{12} \sim 3\pi/4$, $\theta^I_{23} = \theta^I_{13} \sim \pi/4$

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

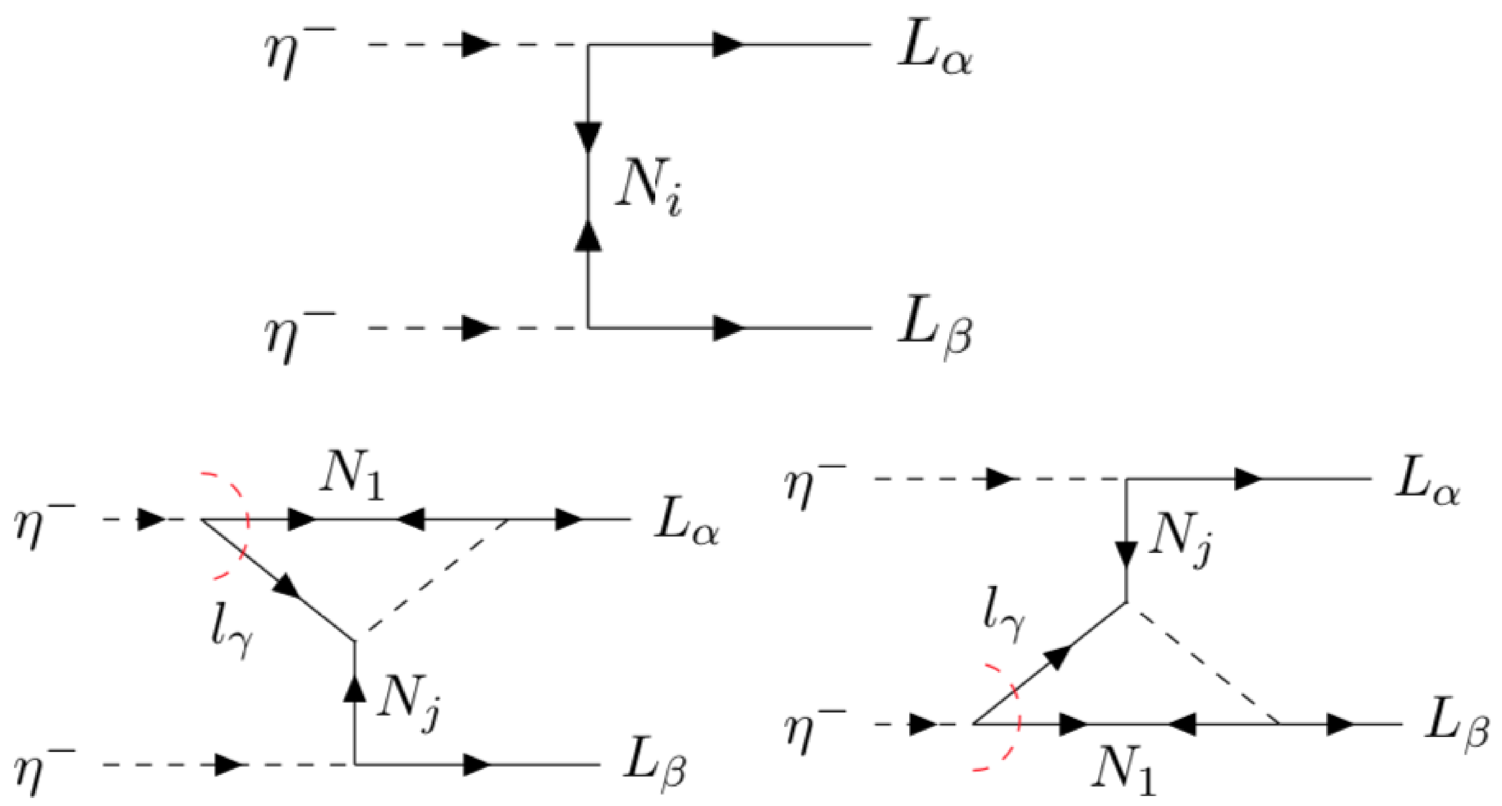
$$h|_{IH} = \begin{pmatrix} 8.52 - 13.8i & 5.78 + 0.25i & -5.66 - 0.20i \\ -4.89 - 12.8i & 4.54 - 3.93i & -4.42 + 4.03i \\ -17.18 - 3.51i & -2.6 - 6.78i & 2.71 + 6.60i \end{pmatrix} \times 10^{-3}$$



Normal Hierarchy
Inverted Hierarchy
N_3
N_2
η
N_1^{eq}
N_1
ΔL
DM bound
Ωh^2
T (GeV)

Right handed neutrino as dark matter

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



- **In this scenario, we require N_1 to be lighter than η whose annihilations are responsible for creating the asymmetry.**

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

$$\epsilon_{\eta\eta} = 8\sum_{ij}\left(\Im[(hh^\dagger)_{i1}(hh^\dagger)_{j1}(hh^\dagger)_{ij}]\right)\epsilon_{ij}^{ann}$$

$$= \sum_j \frac{m_1^4 - m_j^4}{\Lambda_1^4\Lambda_j^2}\left(\Delta m_{1j}^2 \sin(4\theta_{1j}^R) + (m_1^2 + m_j^2)\sinh(4\theta_{1j}^I)\right)\epsilon_{1j}^{ann}$$

$$\epsilon_{1j}^{ann} = \frac{1}{16\pi}\left[1 - r_1 - \frac{1}{2}(r_1 - 3)\ln\left[\frac{1+r_1}{3-r_1}\right]\right]\frac{\sqrt{r_j r_1}}{(1+r_j)(1+r_1)}\frac{1}{\mathcal{M}_{tree}}$$

$$\mathcal{M}_{tree} = \sum_{ij}(hh^\dagger)_{ij}^2 \frac{\sqrt{r_i}\sqrt{r_j}}{(1+r_i)(1+r_j)}.$$

- **The washout effects in this scenario are categorised as follows** :

  - $\Delta L = 2$: $L\eta \to \bar{L}\eta, \quad \eta\eta \to LL$
  - $\Delta L = 1$: **there are two main sources of such wash-out**

    1. **Inverse decay of** $N_k \to L\eta$, $\eta \to LN_k$
    2. **inverse process of co-annihilation** $N_k\eta \to L, X(=\gamma, W, Z, h)$

- **BEs for Z_2 odd particles take the following form:**

$$\frac{dY_{N_k}}{dz} = -\frac{1}{zH(z)}[(Y_{N_k} - Y_{N_k}^{\rm eq})\langle\Gamma_{N_k\to L_\alpha\eta}\rangle + (Y_{N_k}Y_\eta - Y_{N_k}^{\rm eq}Y_\eta^{\rm eq})s\langle\sigma v\rangle_{\eta N_k\to LSM}$$

$$+\sum_{l=1}^{3}(Y_{N_k}Y_{N_l} - Y_{N_k}^{\rm eq}Y_{N_l}^{\rm eq})s\langle\sigma v\rangle_{N_l N_k\to \rm SMSM}], \qquad \textit{for} \quad k = 2,3$$

$$\frac{dY_\eta}{dz} = \frac{1}{zH(z)}[\sum_{k=2}^{3}(Y_{N_k} - Y_{N_k}^{\rm eq})\langle\Gamma_{N_k\to L_\alpha\eta}\rangle - (Y_\eta - Y_\eta^{\rm eq})\langle\Gamma_{\eta\to L_\alpha N_1}\rangle$$

$$-2(Y_\eta^2 - (Y_\eta^{\rm eq})^2)s\langle\sigma v\rangle_{\eta\eta\to \rm SMSM} - \sum_{m=1}^{3}(Y_{N_m}Y_\eta - Y_{N_m}^{\rm eq}Y_\eta^{\rm eq})s\langle\sigma v\rangle_{\eta N_m\to LSM}]$$

$$\frac{dY_{N_1}}{dz} = \frac{1}{zH(z)}[(Y_\eta - Y_\eta^{\rm eq})\langle\Gamma_{\eta\to L_\alpha N_1}\rangle - (Y_{N_1}Y_\eta - Y_{N_1}^{\rm eq}Y_\eta^{\rm eq})s\langle\sigma v\rangle_{\eta N_1\to LSM}$$

$$-\sum_{l=1}^{3}(Y_{N_1}Y_{N_l} - Y_{N_1}^{\rm eq}Y_{N_l}^{\rm eq})s\langle\sigma v\rangle_{N_l N_1\to \rm SMSM}]$$

- **BE for lepton asymmetry takes the following form:**

$$\frac{dY_{\Delta L}}{dz} = \frac{1}{zH(z)}[\sum_i \epsilon_{N_i}(Y_{N_i} - Y_{N_i}^{\mathrm{eq}})\langle\Gamma_{N_i\to L_\alpha\eta}\rangle - Y_{\Delta L} r_{N_i}\langle\Gamma_{N_i\to L_\alpha\eta}\rangle - Y_{\Delta L} r_\eta s\langle\Gamma_{\eta\to N_1 L}\rangle$$

$$+2\epsilon_{\eta\eta} s\langle\sigma v\rangle_{\eta\eta\to LL}\left(Y_\eta^2 - (Y_\eta^{\mathrm{eq}})^2\right) - Y_{\Delta L} Y_l^{\mathrm{eq}} r_\eta^2 s\langle\sigma v\rangle_{\eta\eta\to LL}$$

$$+\sum_i \epsilon_{N_i\eta} s\langle\sigma v\rangle_{\eta N_i\to L\mathrm{SM}}\left(Y_\eta Y_{N_i} - Y_\eta^{\mathrm{eq}} Y_{N_i}^{\mathrm{eq}}\right) - \frac{1}{2} Y_{\Delta L} Y_l^{\mathrm{eq}} r_{N_i} r_\eta s\langle\sigma v\rangle_{\eta N_i\to \mathrm{SM}\bar{L}}$$

$$-Y_{\Delta L} Y_\eta^{\mathrm{eq}} s\langle\sigma v\rangle^{wo}_{\eta L\to\eta\bar{L}} - \sum_i Y_{\Delta L} Y_\eta^{\mathrm{eq}} s\langle\sigma v\rangle^{wo}_{\eta L\to N_i X} - \sum_i Y_{\Delta L} Y_{N_i}^{\mathrm{eq}} s\langle\sigma v\rangle^{wo}_{N_i L\to\eta X}],$$

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

- **The contribution of N_k annihilations to lepton asymmetry is suppressed compared to η annihilations as well as $\eta - N_k$ co-annihilations.**

Numerical Results

Input values

μ_η=850 GeV M_{N_1}=865 GeV $\lambda_5 = -1 \times 10^{-5}$

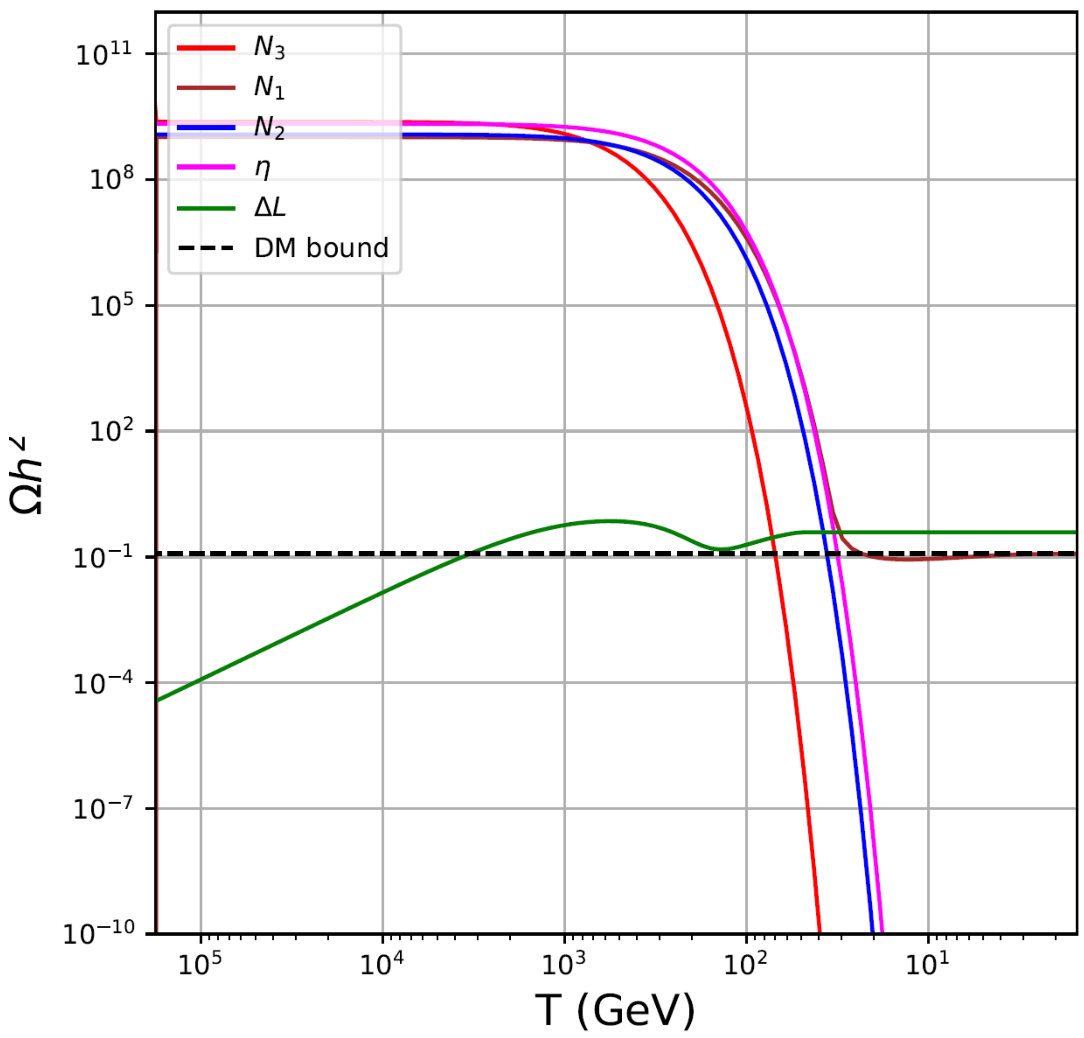
M_{N_2}=2 TeV M_3 =3 TeV $\lambda_1 \sim 0.2$, $\lambda_3 \sim 1.5$, $\lambda_4 \sim$-1.5 , $\lambda_2 \sim 1$

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

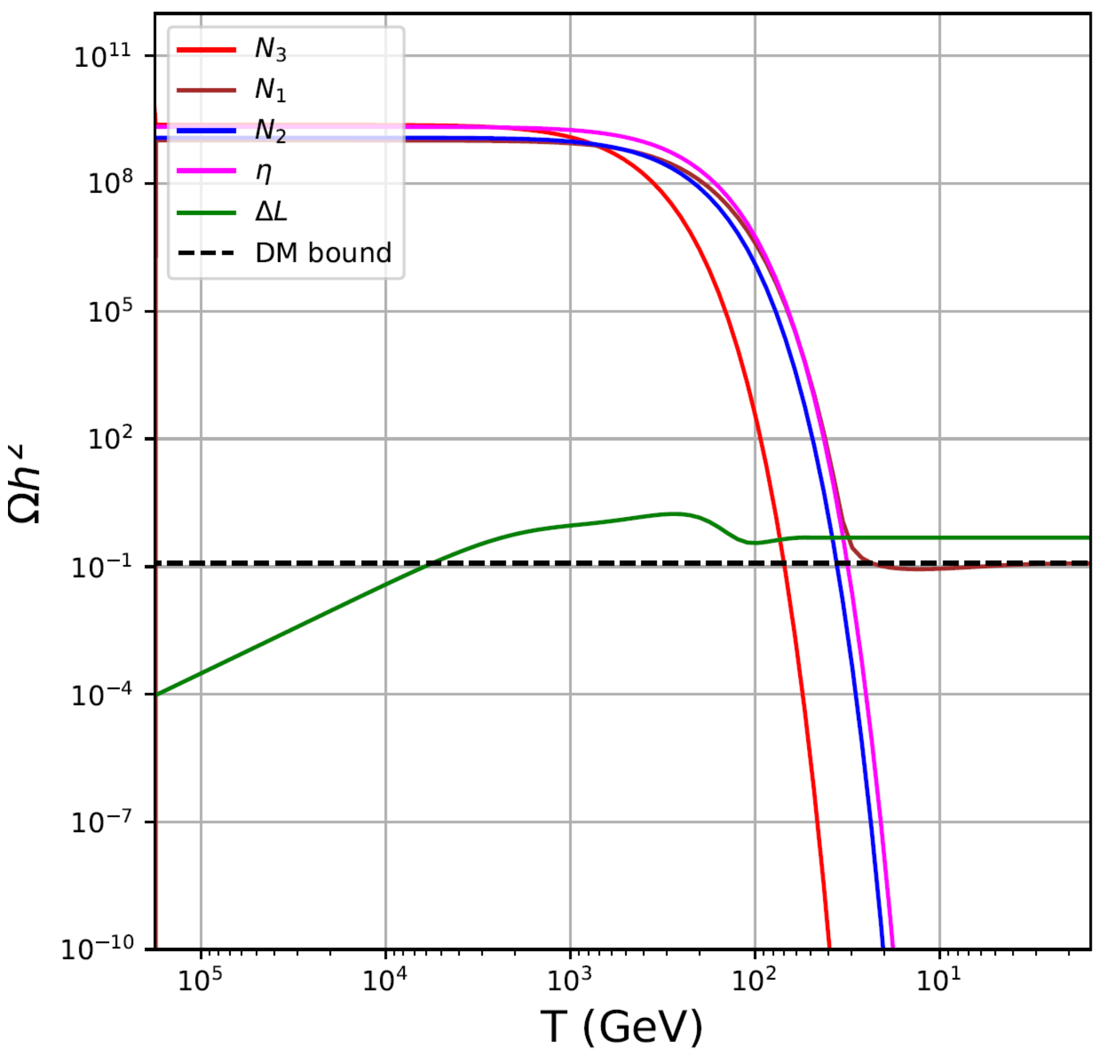
$$h|_{NH} = \begin{pmatrix} 1.01 - 1.14i & 2.43 + 1.09i & 1.44 + 1.8i \\ -0.15 - 1.21i & 1.92 - 9.29i & 1.67 + 0.13i \\ -1.40 - 0.61i & 2.55 - 2.6i & 1.37 - 1.81i \end{pmatrix} \times 10^{-2}$$

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

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