TeV Scale Leptogenesis from Annihilations via t-channel and Co-annihilations Processes

Based on with
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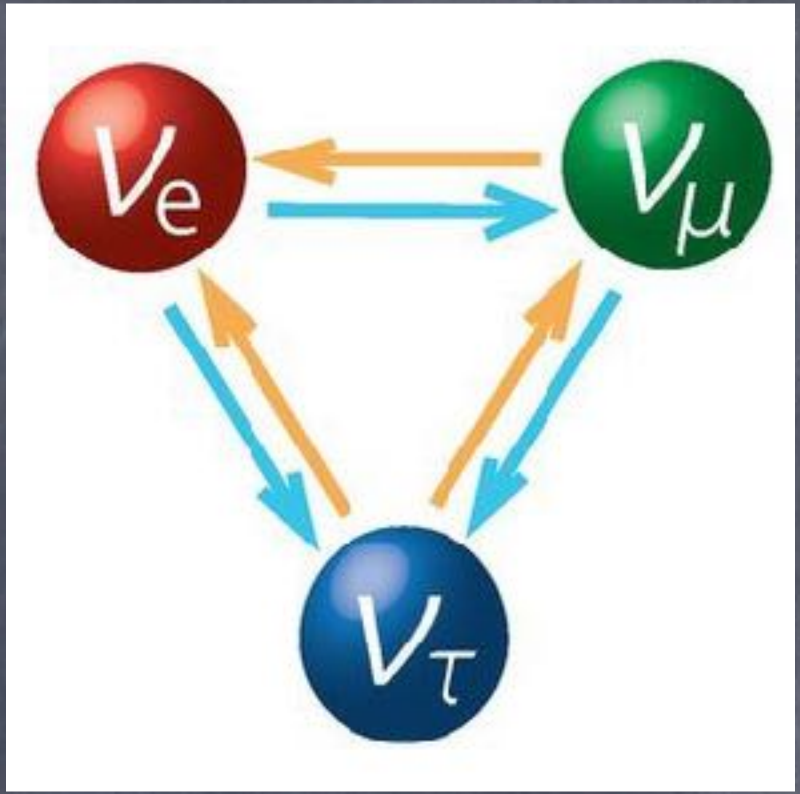
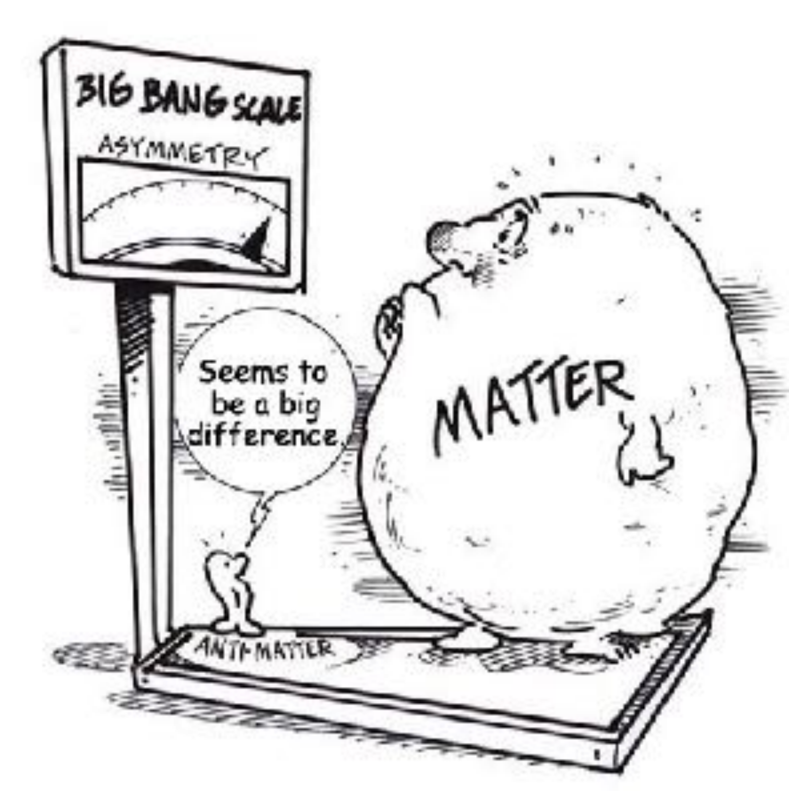
Outline

- Introduction Dark Matter (DM)
- Baryon Asymmetry of Universe (BAU)
- Towards a Common Origin of DM and BAU
- Baryogenesis from DM annihilation and co-annihilation in Scotogenic Model
- Conclusion

Problems in the SM





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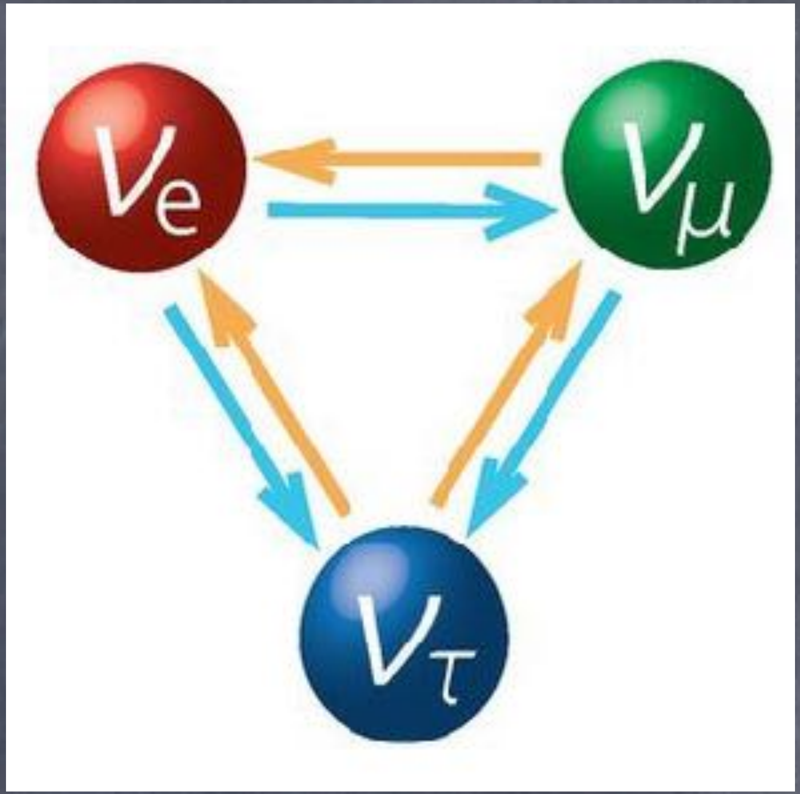

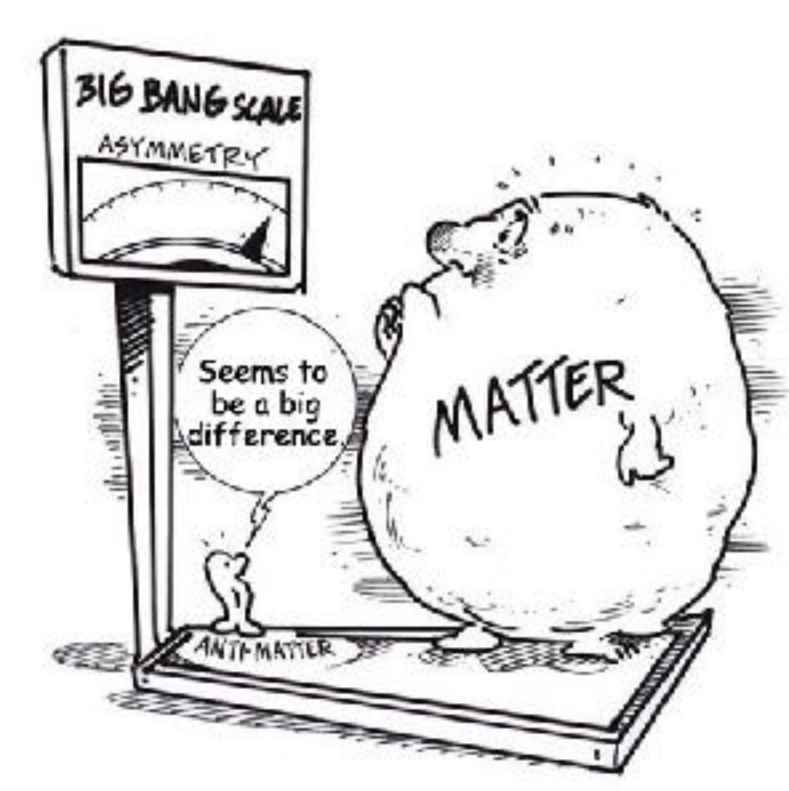

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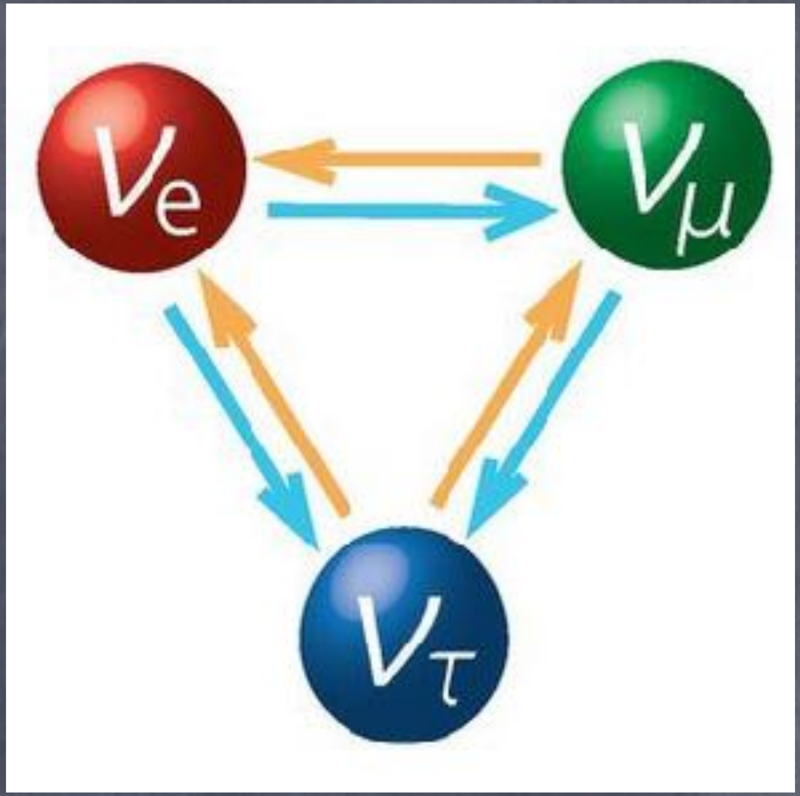

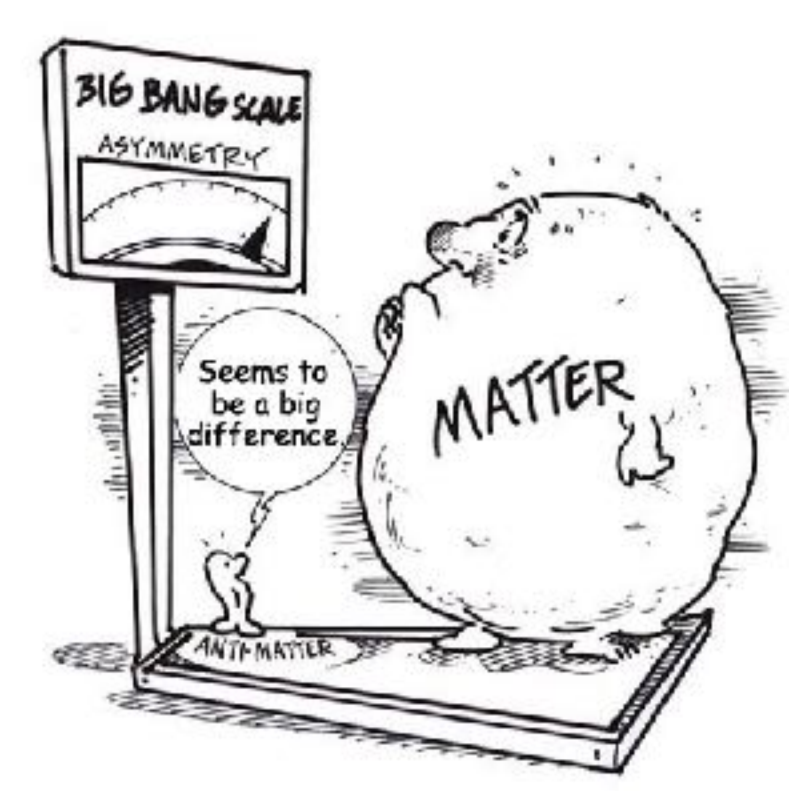

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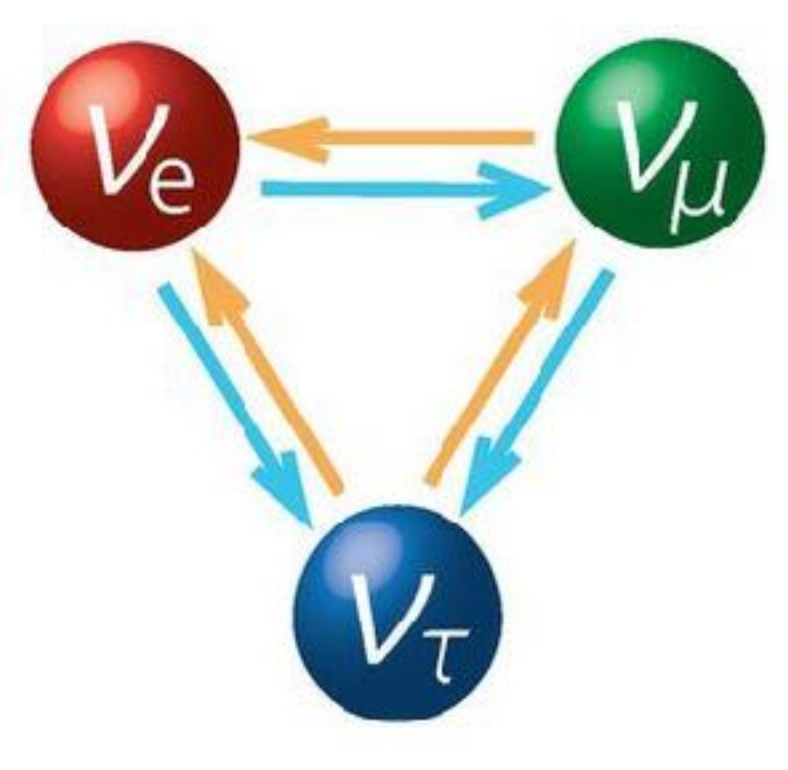
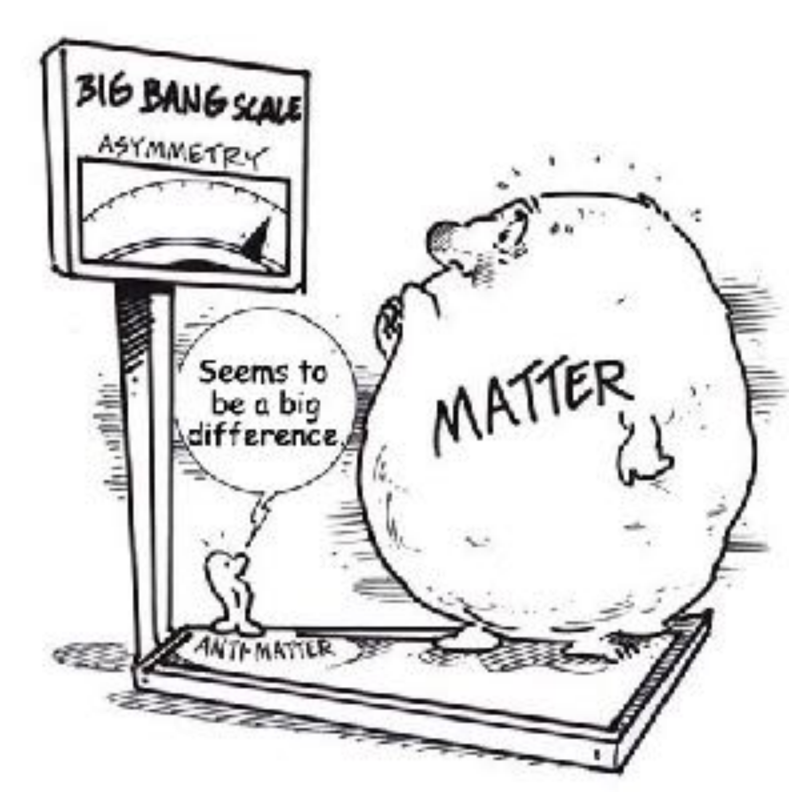
- SM cannot explain the observed baryon asymmetry





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- The prediction for this ratio from Big Bang Nucleosynthesis (BBN) agrees well with the observed value from Cosmic Microwave Background Radiation (CMBR) measurements (Planck, arXiv: 1502.01589).

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- Departure from thermal equilibrium.

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- Leptogenesis provide a common framework to explain neutrino mass, mixing and baryon asymmetry of the Universe.

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- Asymmetric DM, WIMPy Baryogenesis etc are some of the scenarios proposed so far.
- While generic implementations of these scenarios tightly relate BAU & DM abundances, there exists other implementations too where the connections may be loose.

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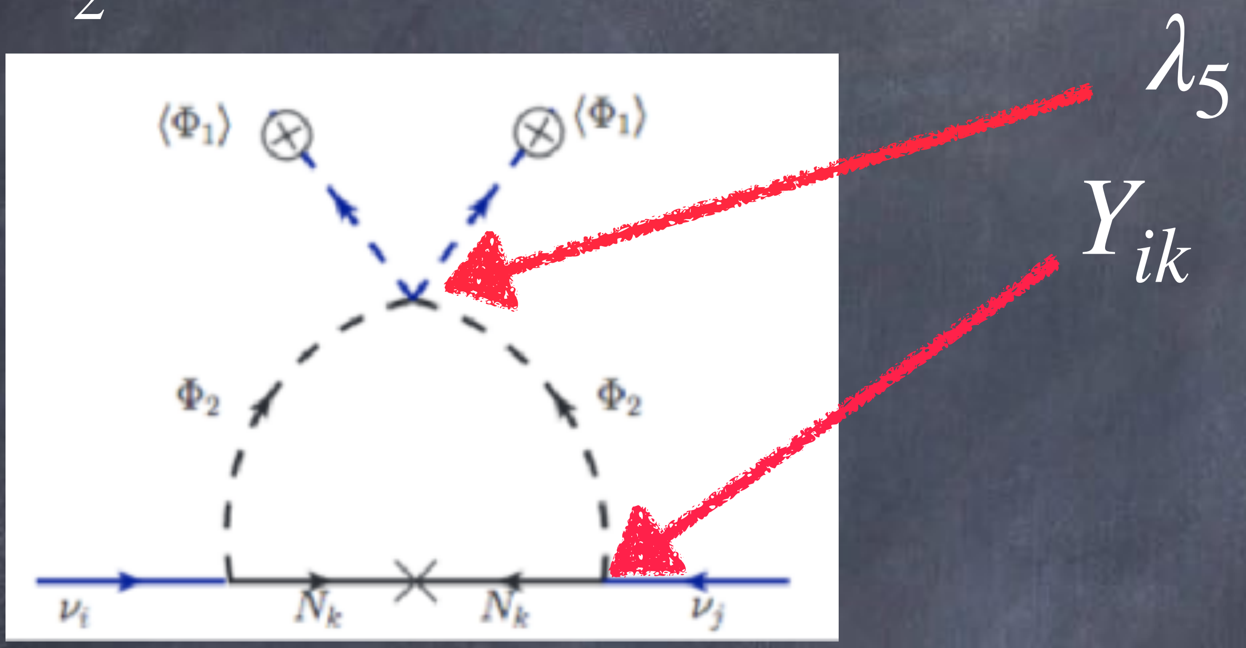
- Lightest RHN DM (1710.03824).
- Neutrino Mass arises at one-loop level.

Scotogenic Model

$$V(\Phi_1,\Phi_2) = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi^\dagger\Phi|^2 + \left\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2) + h.c\right\}$$

$$\mathscr{L} \supset \frac{1}{2}(M_N)_{ij}N_iN_j + (Y_{ij}\bar{L}\tilde{\Phi}_2N_j + h.c)$$



$$m_h^2 = \lambda_1 v^2$$

$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2,$$

$$m_H^2 = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right)v^2$$

$$m_A^2 = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right)v^2$$

One loop neutrino mass : $(m_\nu)_{ij} = \sum_k \frac{Y_{ik}Y_{jk}M_k}{16\pi^2}\left(\frac{m_R^2}{m_R^2 - M_k^2}\ln\frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2}\ln\frac{m_I^2}{M_k^2}\right)$

Which under the approximation $m_H^2 + m_A^2 \approx M_k^2$ boils down to

$$(m_\nu)_{ij} \approx \sum_k \frac{\lambda_5 v^2}{32\pi^2}\frac{Y_{ik}Y_{jk}}{M_k} = \sum_k \frac{m_A^2 - m_H^2}{32\pi^2}\frac{Y_{ik}Y_{jk}}{M_k}$$

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- But one may notice that the tree level process for particle and anti-particle are the same.

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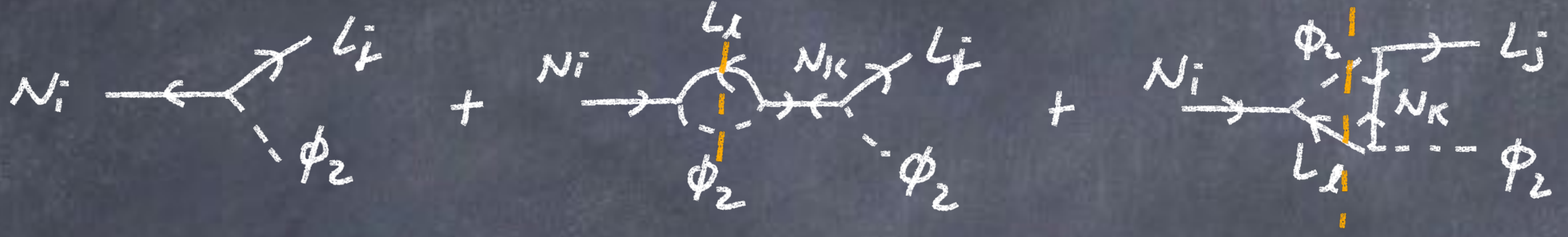

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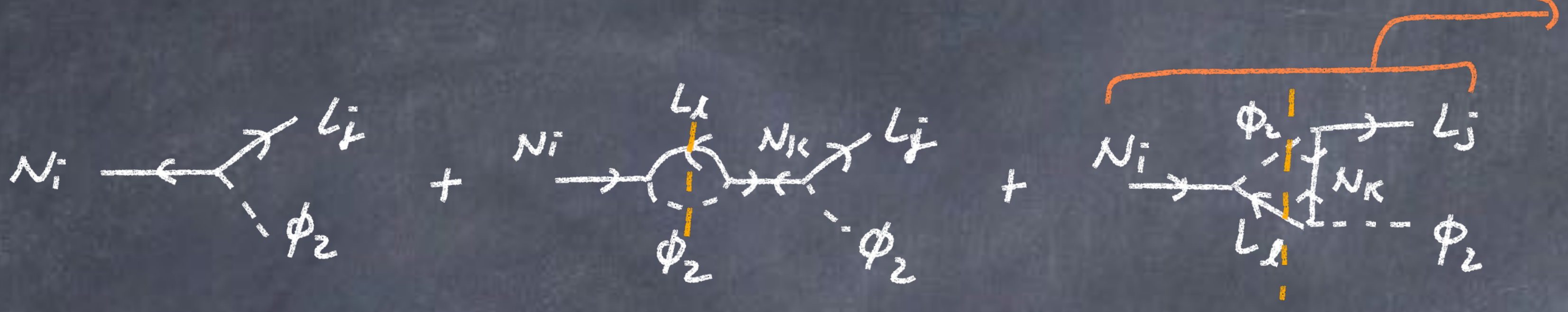

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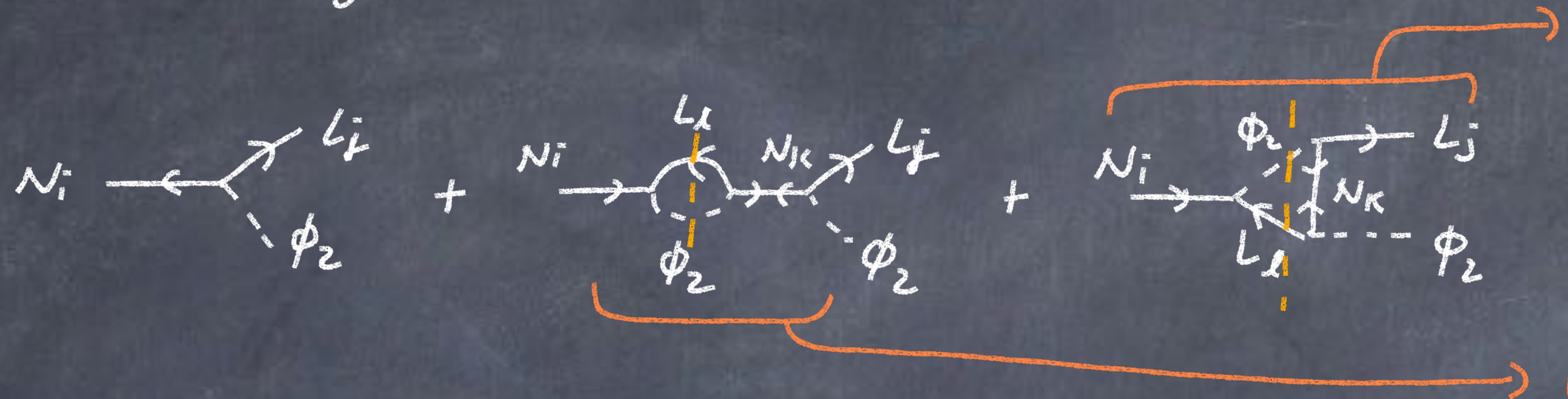

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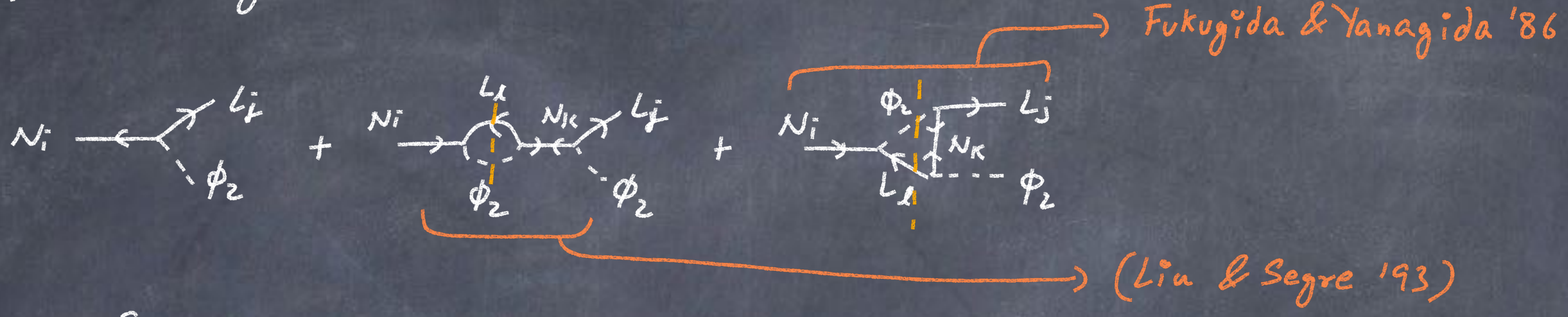

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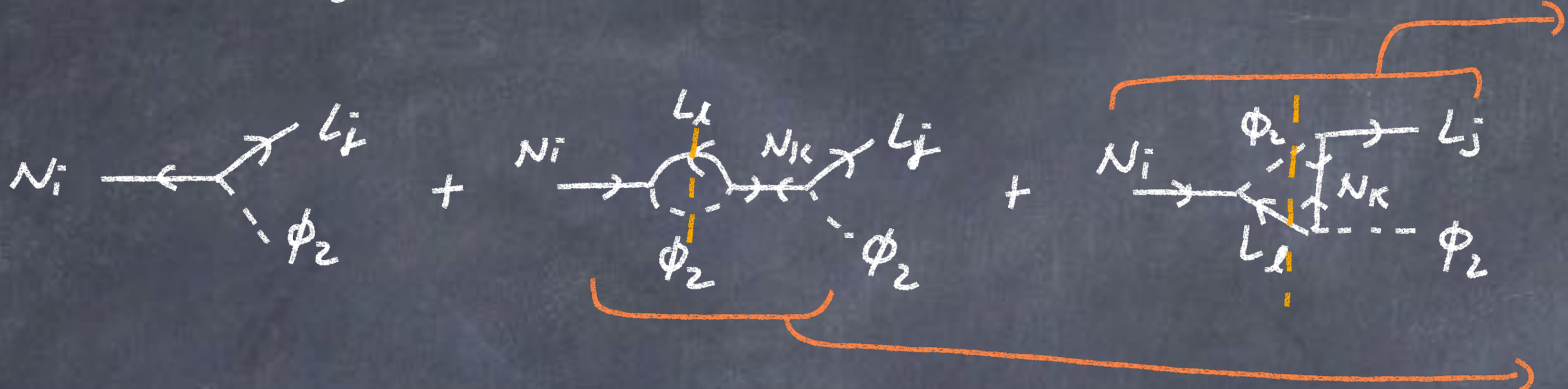

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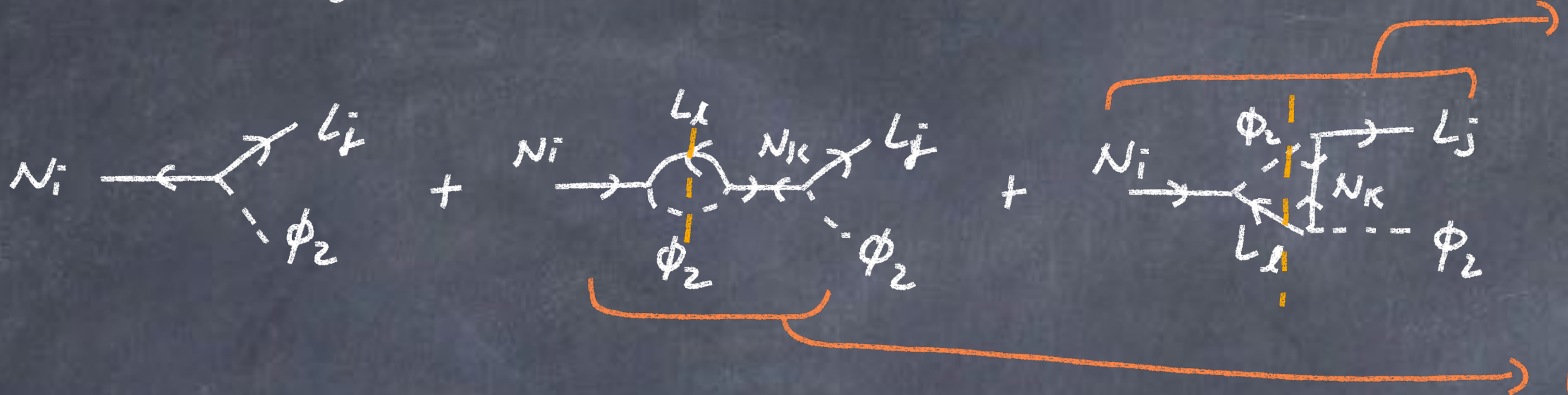

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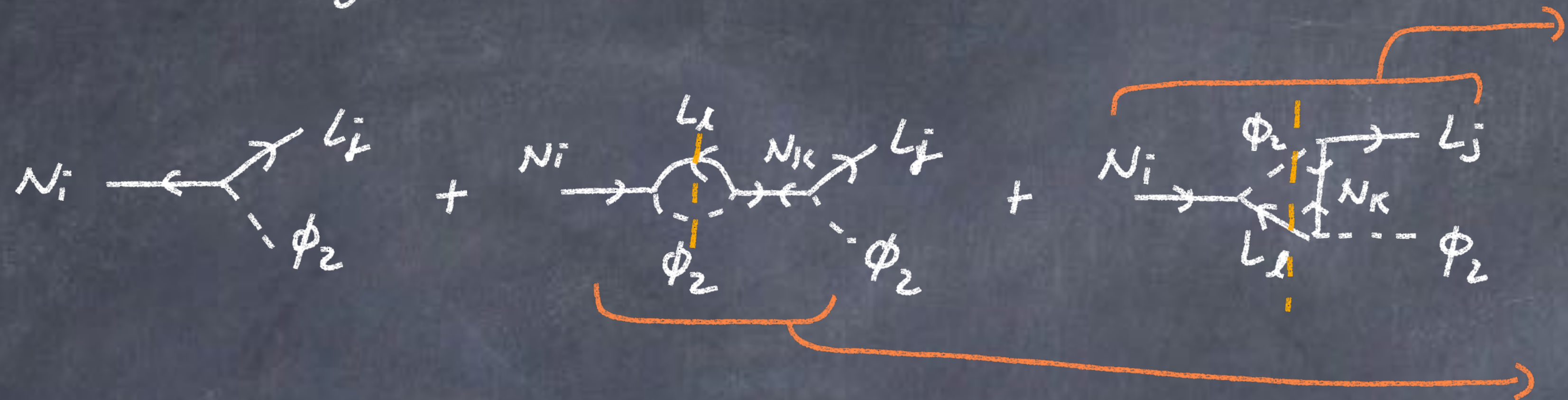

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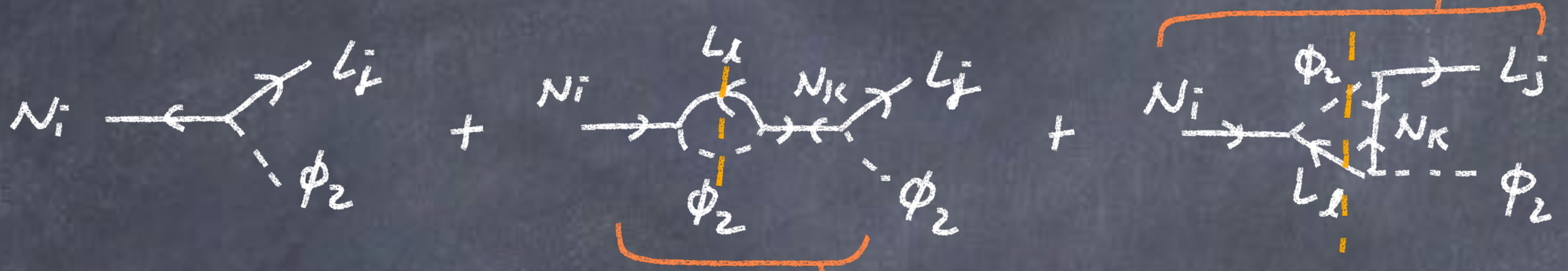

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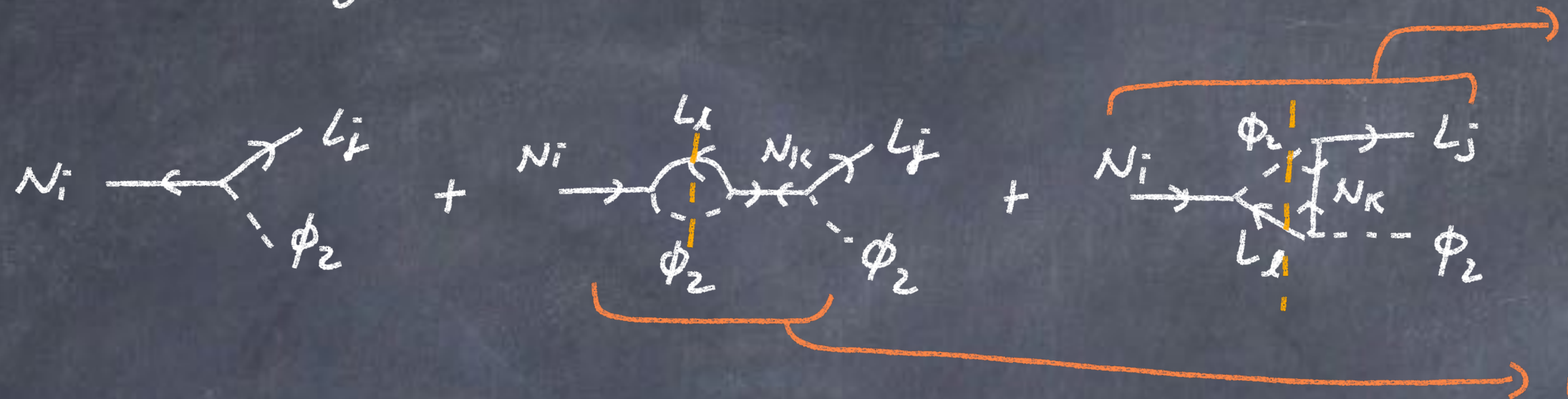

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- In this scenario atleast 2 N's are needed to get the CP violation from the interference term.

Vanilla Leptogenesis in Scotogenic Model

- The asymmetry freezes out at $T \ll M_i$
- The lepton asymmetry gets converted into baryons asymmetry through electroweak sphalerons (Khlebnikov & Shaposhnikov'88).

$$\frac{n_{\Delta B}}{s} = -\frac{28}{79}\frac{n_{\Delta L}}{s}$$

- The same right handed neutrinos also generate light neutrino masses at one-loop, along with scalar dark matter going inside the loop.

Leptogenesis in Scotogenic Model

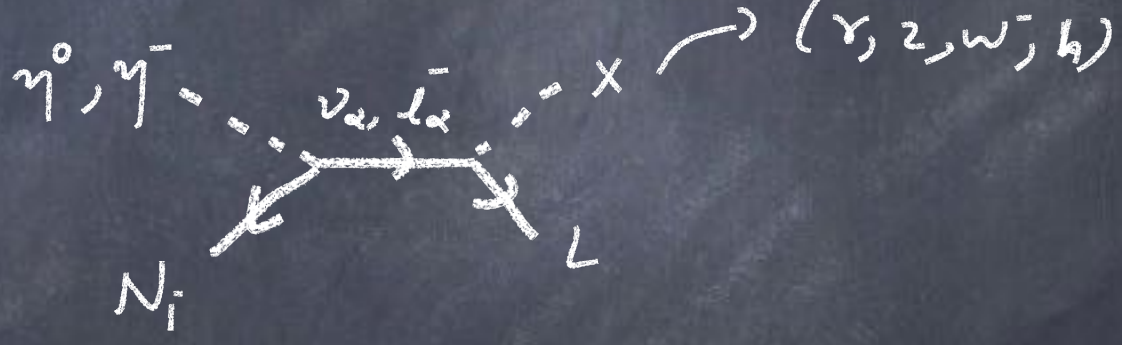
- Smaller values of λ_5 requires larger Yukawa for correct neutrino mass and vice versa.
- Large Yukawa results in more wash-outs. Small Yukawa will produce small asymmetry.
- For TeV scale RHN, one requires very small values of λ_5 to satisfy neutrino mass and baryon asymmetry requirements.
- TeV scale leptogenesis is not possible for hierarchal RHN, unless the lightest RHN is heavier than 10 TeV (1804.09660).
- Resonant leptogenesis can work (Pilaftsis 1997, B Dev et al 2013)

TeV Leptogenesis from DM annihilation

- In, order to generate leptonic asymmetry around TeV scale we would need the following L violating processes

t-channel (Annihilation)

s-channel (Co-annihilation)



- Now, if we consider scalars as Dark Matter the t-channel process do not produce asymmetry.

- And to have a successful leptogenesis one would require the Yukawa's to be of $\mathcal{O}(1)$

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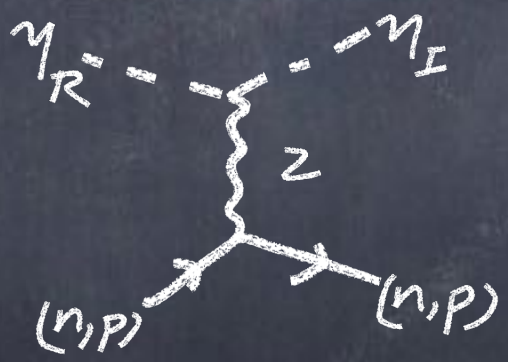
- This opens up the channel for inelastic scattering in Direct Detection through Z



⇒ This gives a real stringent bound on Direct Detection.

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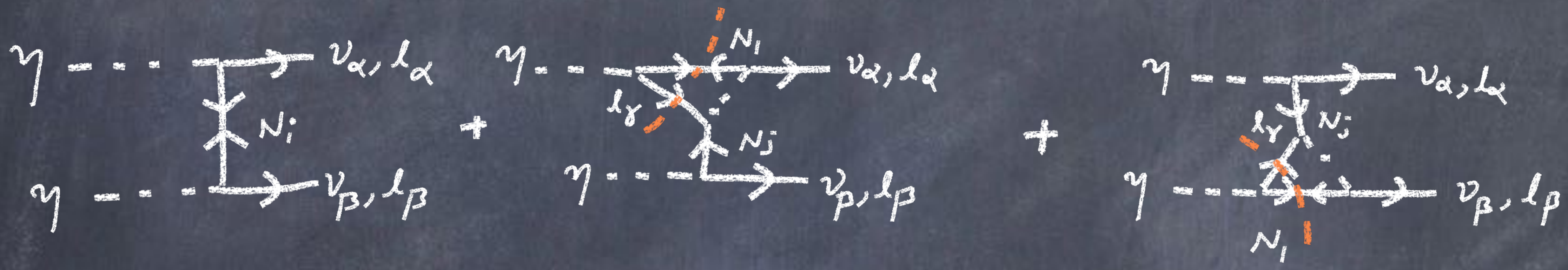
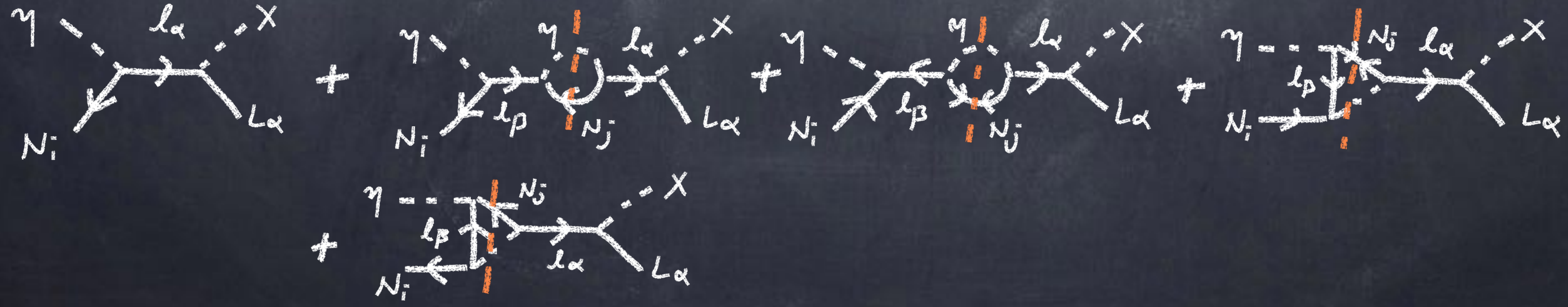
  - In this scenario one can reach as low as $M_{N_1} \sim 500$ GeV

Details of Leptogenesis

- For t-channel to contribute one would require atleast one of the RHN to be lightest making it the Dark Matter candidate.



- For asymmetry arising from s-channel the required diagrams are



- The asymmetry coming Co-annihilation (s-channel)

$$\epsilon_{\eta L} = \frac{1}{16\pi}\left[2(1+\sqrt{\gamma_i})^2\gamma_i\gamma_j + \frac{1}{2}(1+2\sqrt{\gamma_i}+\gamma_i-\gamma_j)(1+2\sqrt{\gamma_i}+\gamma_i+\gamma_j+2\gamma_i\gamma_j)\right]$$

$$\times\ \frac{1}{(1+\sqrt{\gamma_i})^2}$$

$$\gamma_i = \frac{M_{N_i}^2}{M_\eta^2}$$

$\Rightarrow$ Showing the contribution from bubble diagram.

- And then the assymetry coming from (t-channel)

$$\epsilon_{\eta\eta} = \frac{1}{16\pi}\left[1-\gamma_1+\frac{1}{2}(3-\gamma_1)\ln\left[\frac{1+\gamma_1}{3-\gamma_1}\right]\right]\sum_{j\neq 1}\frac{\sqrt{\gamma_j\gamma_1}}{(1+\gamma_j)(1+\gamma_1)} \times \frac{1}{\sum_i \frac{\gamma_i}{(1+\gamma_i)^2}}$$

The Boltzmann Equations

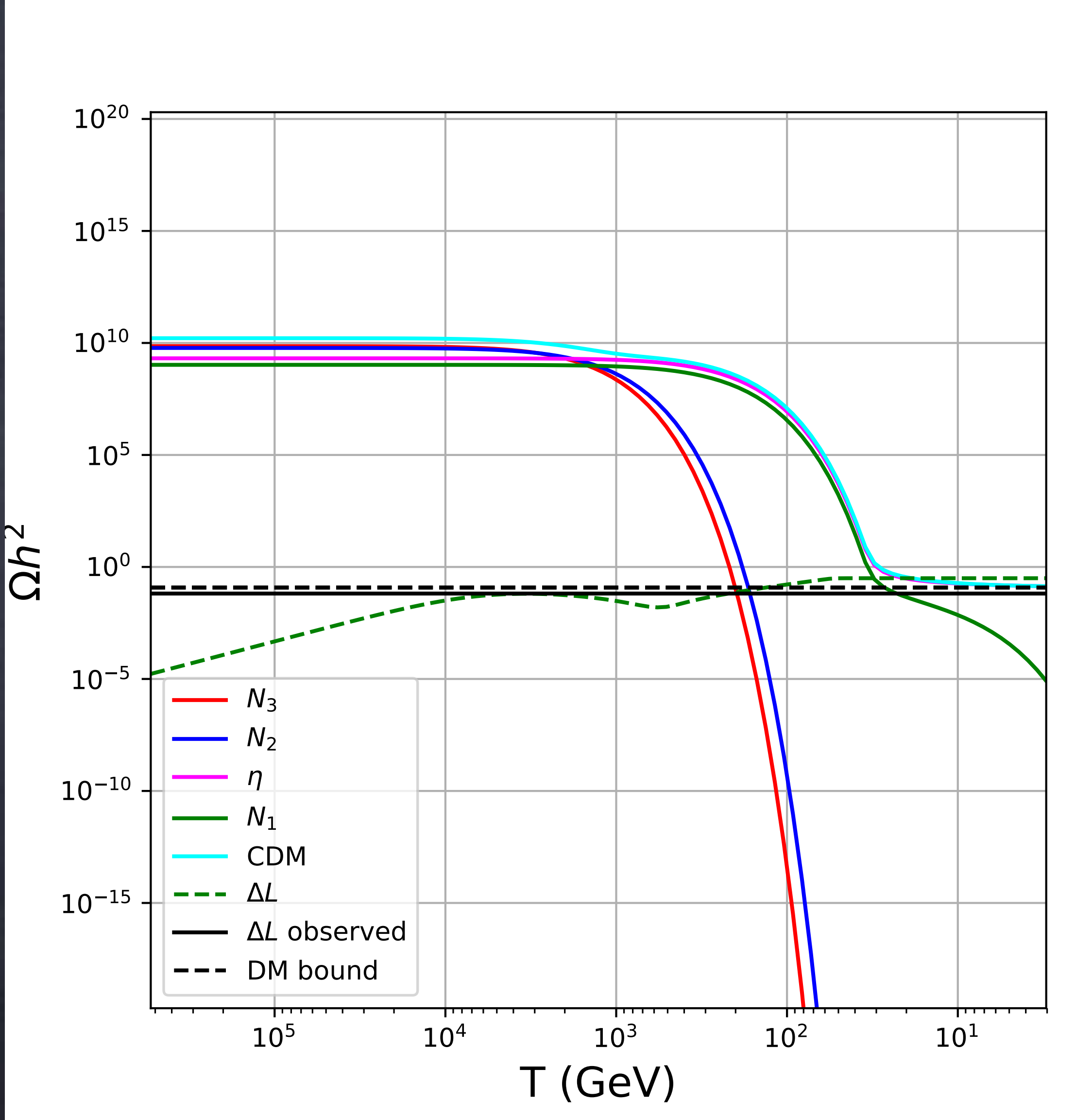
$$\frac{dY_{DM}}{dz} = -\frac{2zs}{H(M_{DM})}\langle\sigma v\rangle_{DMDM\to SMSM}\left(Y_{DM}^2 - (Y^{eq})_{DM}^2\right)$$

$$\begin{aligned}\frac{dY_{\Delta L}}{dz} = \frac{2zs}{H(M_{N_3})}\Bigg[&\sum_i \epsilon_{N_i}(Y_{N_i}^2 - (Y_{N_i}^{eq})^2)\langle\Gamma_{N_i\to L_\alpha\eta}\rangle - Y_\Delta r_i\langle\Gamma_{N_i\to L_\alpha\eta}\rangle\\ &+\epsilon_{\eta\eta}\langle\sigma v\rangle_{\eta\eta\to LL}\left(Y_\eta^2 - (Y_\eta^{eq})^2\right) - Y_{\Delta L}Y_l^{eq}r_\eta^2\langle\sigma v\rangle_{\eta\eta\to LL}\\ &+\sum_i \epsilon_{N_i\eta}\langle\sigma v\rangle_{\eta N_i->LSM}\left(Y_\eta Y_{N_i} - Y_\eta^{eq}Y_{N_i}^{eq}\right) - \frac{1}{2}Y_{\Delta L}Y_l^{eq}r_{N_i}r_\eta\langle\sigma v\rangle_{\eta N_i\to SM\bar{L}}\\ &-Y_{\Delta L}Y_\eta^{eq}\langle\sigma v\rangle_{\eta L\to\eta\bar{L}}^{wo} - Y_{\Delta L}r_\eta\langle\Gamma_{\eta\to N_1 l}\rangle\Bigg]\end{aligned}$$

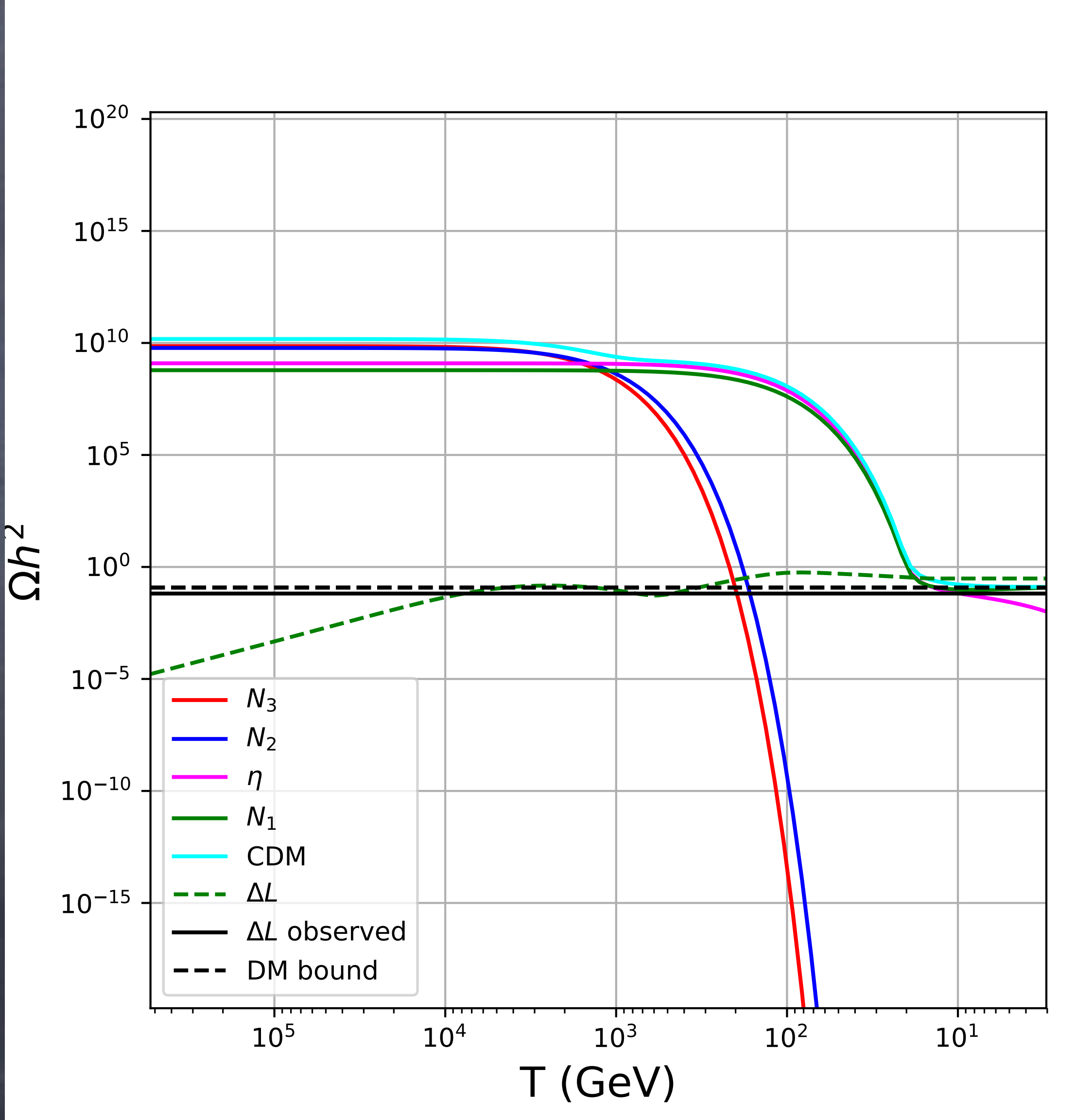
$$H = \sqrt{\frac{4\pi^3 g_*}{45}}\frac{M_{DM}^2}{M_{Pl}}, \quad s = g_*\frac{2\pi^2}{45}\left(\frac{M_{DM}}{z}\right)^3 \qquad r_j = \frac{Y_j^{eq}}{Y_l^{eq}} \qquad \langle\Gamma_{j->X}\rangle = \frac{K_1(M_j/T)}{K_2(M_j/T)}\Gamma_{j\to X}$$

Results

η as Dark Matter



N_1 as the Dark Matter



	BP1 (η DM)	BP2 (N_1 DM)
M_η	850 GeV	500 GeV
M_{N_1}	895 GeV	507.1 GeV
M_{N_2}	5 TeV	5 TeV
M_{N_3}	6 TeV	6 TeV
λ_1	0.253	0.253
λ_3	0.5	0.5
λ_4	-0.5	0.3
λ_5	3×10^{-10}	1×10^{-10}
λ_2	1.0	1.0

Yukawa Structure and LFV

For η as Dark Matter

$$\begin{pmatrix} 9.9\times10^{-2} & -6.036\times10^{-2} & 3.27\times10^{-2} \\ 2.047\times10^{-1} & 2.12\times10^{-1} & -2.29\times10^{-1} \\ 1.41\times10^{-1} & 6.028\times10^{-1} & 6.837\times10^{-1} \end{pmatrix}$$

For N_1 as Dark Matter

$$\begin{pmatrix} 1.366\times10^{-1} & -8.32\times10^{-2} & 4.51\times10^{-2} \\ 3.086\times10^{-1} & 3.196\times10^{-1} & -3.45\times10^{-1} \\ 2.148\times10^{-1} & 9.174\times10^{-1} & 1.04 \end{pmatrix}$$

The Yukawa's are obtained by Casas-Ibarra parametrization.

$$\frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to e\gamma)_{\rm expt}} = 0.35$$

$$\frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to e\gamma)_{\rm expt.}} = 0.74$$

arXiv:1312.2840,1412.2545

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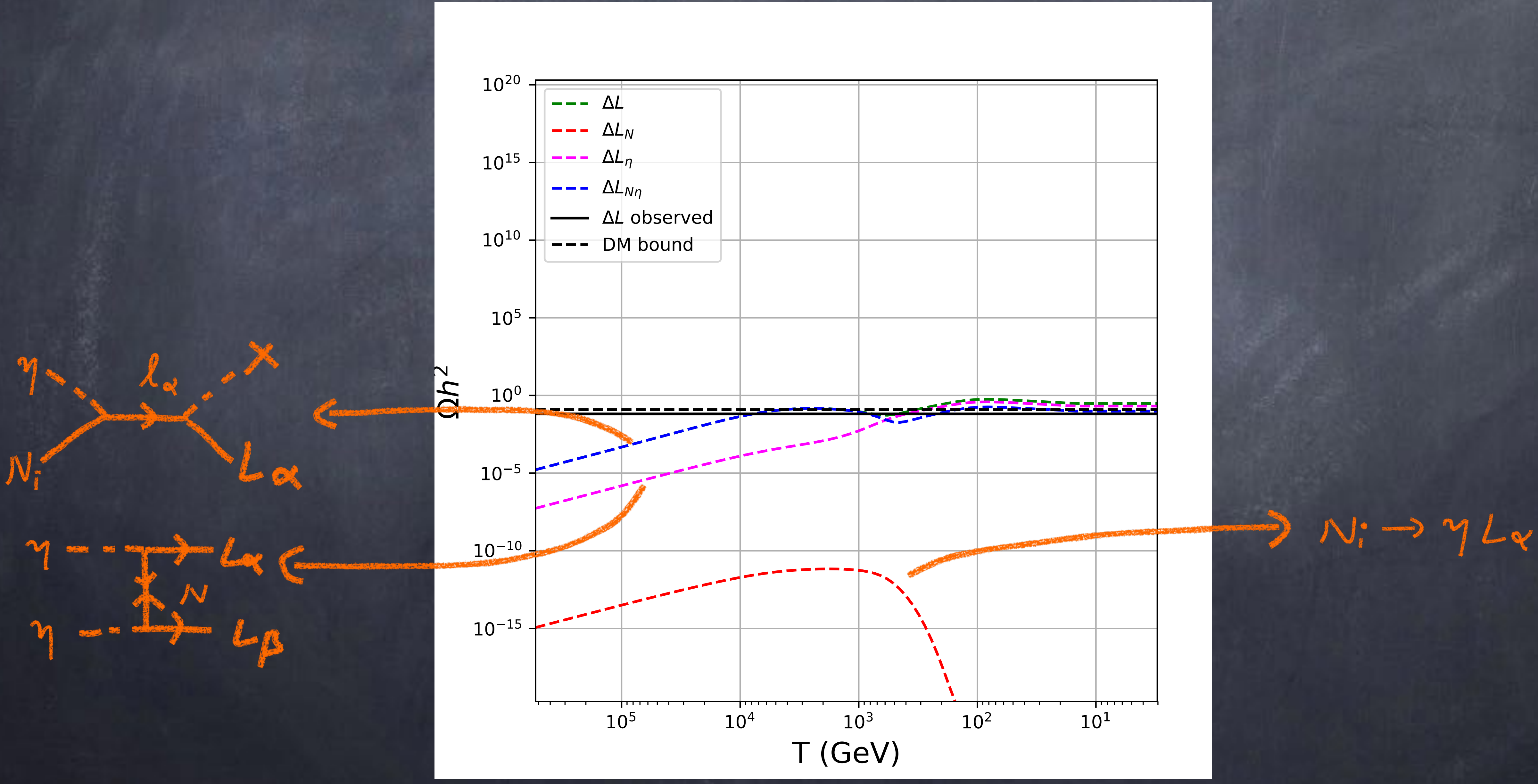
- In order to see the individual contributions of asymmetry sources



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- The model can however be tested at rare decay experiments looking for the lepton flavour violation.
- The prospects at the direct/indirect dark matter detection experiments remain weak.

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- In this case another channel opens up through the t-channel giving additional channel for asymmetry.

Thank You