New Mechanism for Baryon Asymmetry and Connection with Dark Matter

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Outline

- Introduction

  - brief review on baryon asymmetry of Universe (BAU)

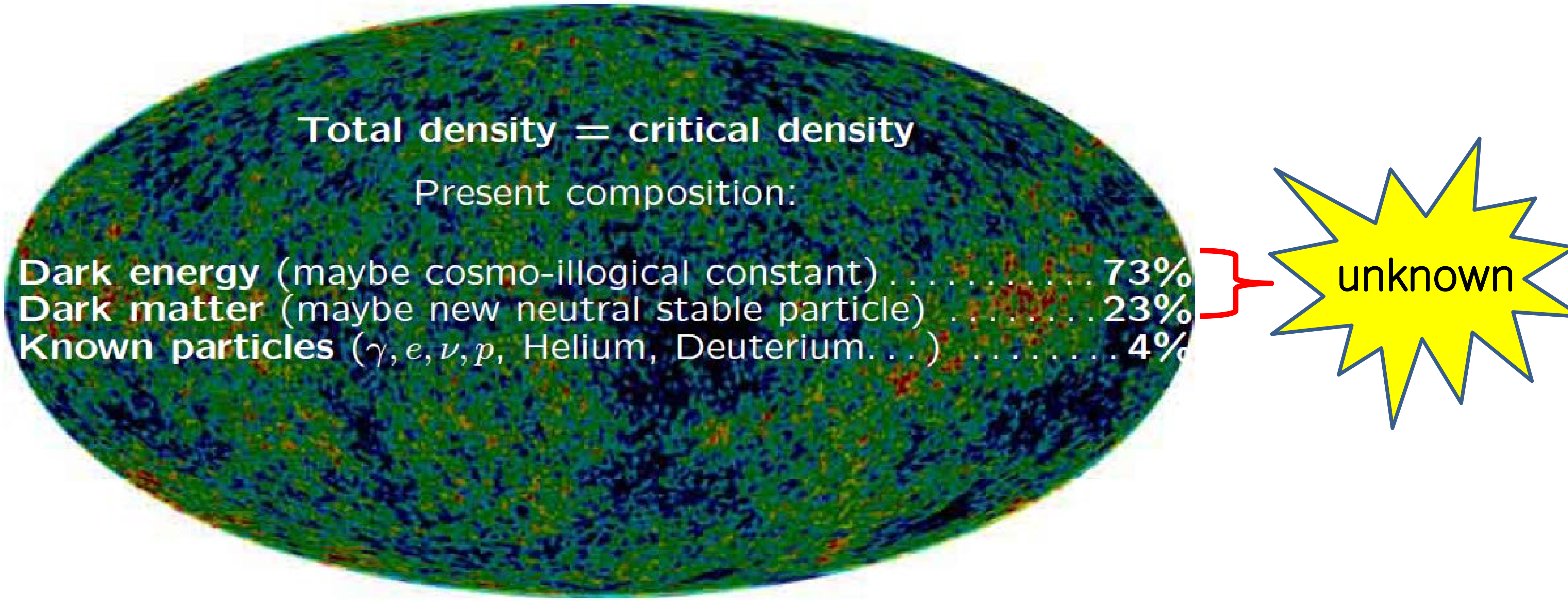
- Baryon asymmetry from scattering

  - WIMPy baryogensis/leptogensis

- New mechanism for baryon asymmetry

- Conclusion

Unsolved mysteries of the Universe



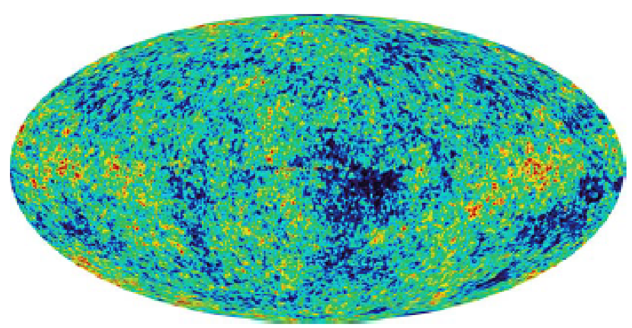
- Inflation explains $\rho = \rho_{cr}$
- Big-bang explains $n_e = n_p$, $n_{4He}/n_p = 0.25/4$,
  $n_D/n_p = 3\text{x}10^{-5}/2$, $n_n = 3n_\gamma/22$, etc.
- We do not understand n_B/n_γ

- Measuring $n_B / n_\gamma = 6 \cdot 10^{-10}$ $\quad$ $n_B \equiv n_B - n_{\bar{B}}$

  - T_{now} ~ 3K directly tells $n_\gamma \sim T^3_{now}$ ~ 400/cm³.
  - n_B ~ 1/m³ follows from

(1) Anisotropies in the cosmic microwave background:

$$n_B/n_\gamma = (6.3 \pm 0.3) \times 10^{-10}.$$



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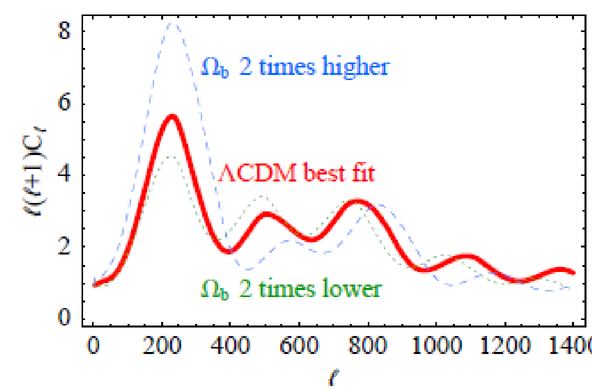


(2) Big Bang Nucleosynthesis: the D abundancy implies

$$n_B/n_\gamma = (6.1 \pm 0.5) \times 10^{-10}.$$

because many γ push in the ⟵ direction reactions like

$$p\ n \longleftrightarrow D\ \gamma$$

Their agreement makes the result trustable.

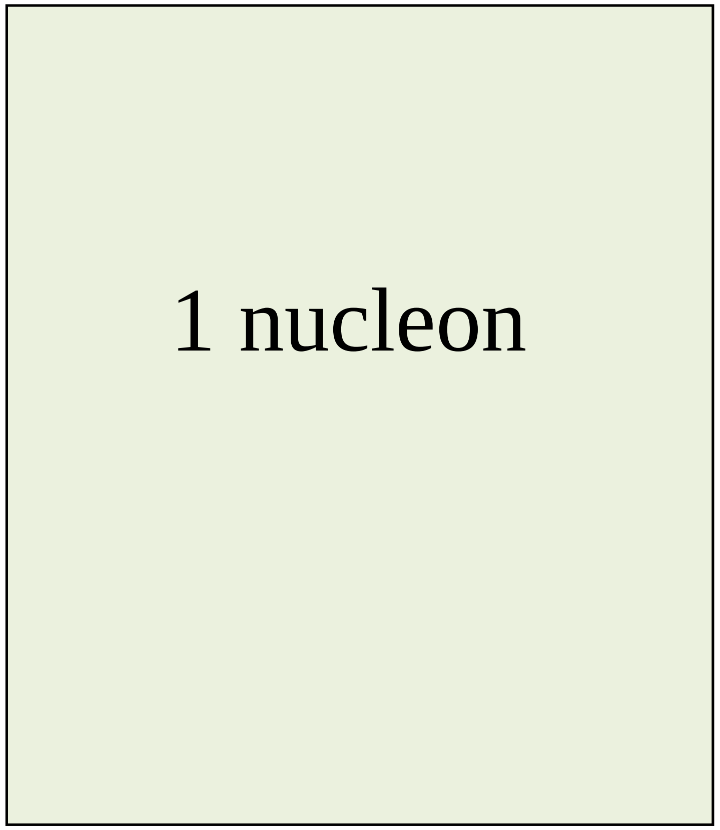
➡ Why is our present Universe matter dominated ?

$n_B/n_\gamma = 6 \cdot 10^{-10}$ is a strange number, because means that when the universe cooled below $T \sim m_p$, we survived to nucleon/antinucleon annihilations as

10,000,000,001 nucleons	10,000,000,000 anti-nucleons

Nucleons and anti-nucleons got together…

- They have all annihilated away except for the tiny difference.



- That created tiny excess of matter in the present universe

$$n_B/n_\gamma = 6 \cdot 10^{-10}$$

Sakharov's Conditions

Three basic ingredients necessary for dynamical generation of a net baryon asymmetry from an initially B symmetric Universe

- Baryon Number (B) violation
- C and CP violation.

$$\Gamma(X \to Y + B) \neq \Gamma(\overline{X} \to \overline{Y} + \overline{B})$$

$$\Gamma(X \to q_L + q_L) + \Gamma(X \to q_R + q_R) \neq \Gamma(\overline{q}_L + \overline{q}_L) + \Gamma(\overline{q}_R + \overline{q}_R)$$

- Departure from thermal equilibrium.

Leptogenesis

- The SM seems to fail to satisfy Sakharov's conditions.

  - insufficient CP violation in the quark sector

  - Higgs Mass is too large to support a strong first order electroweak phase transition.

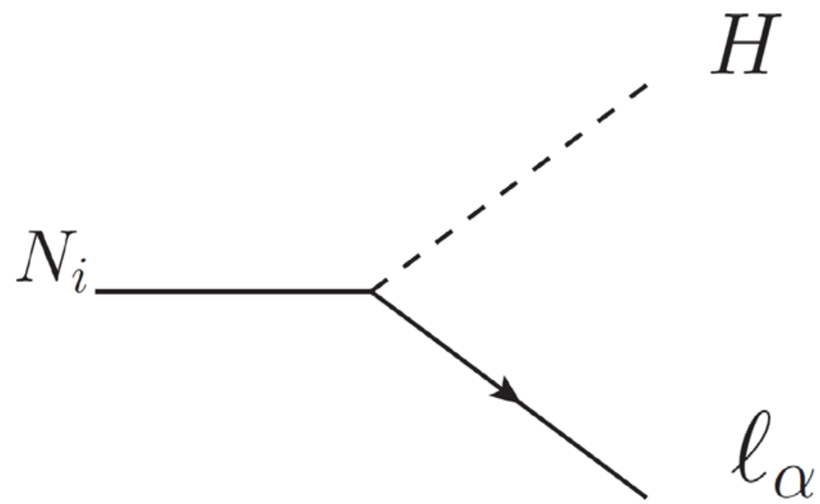
- New source of CP violation is necessarily required.

- Seesaw models provide a common framework to achieve tiny neutrino masses and baryon asymmetry of our universe.

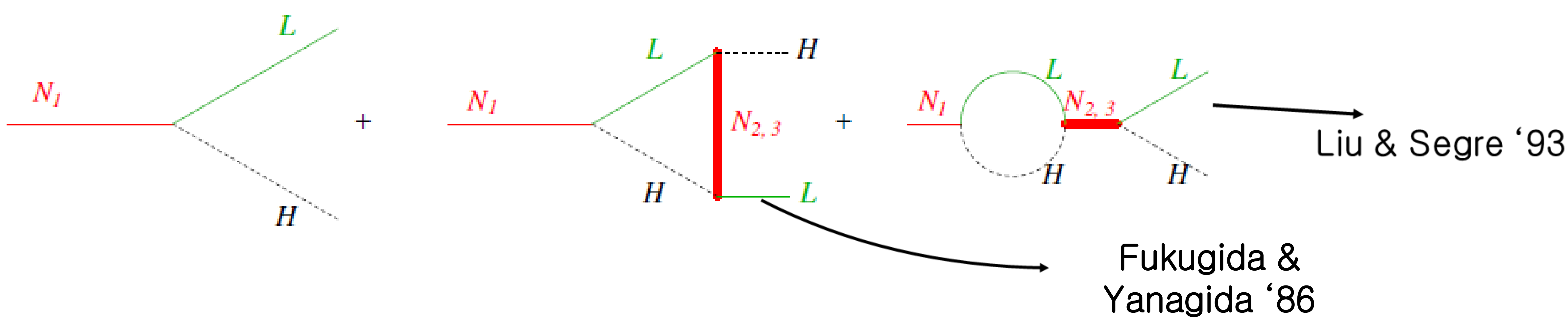
  → Baryogenesis through Leptogenesis (Fukugita, Yanagida 86):

Three basic steps

(1) Generation of L asymmetry by the decay of heavy Majorana neutrino



- CP asymmetry is produced by the interference between the tree and the loop diagrams for the decay of right-handed neutrino

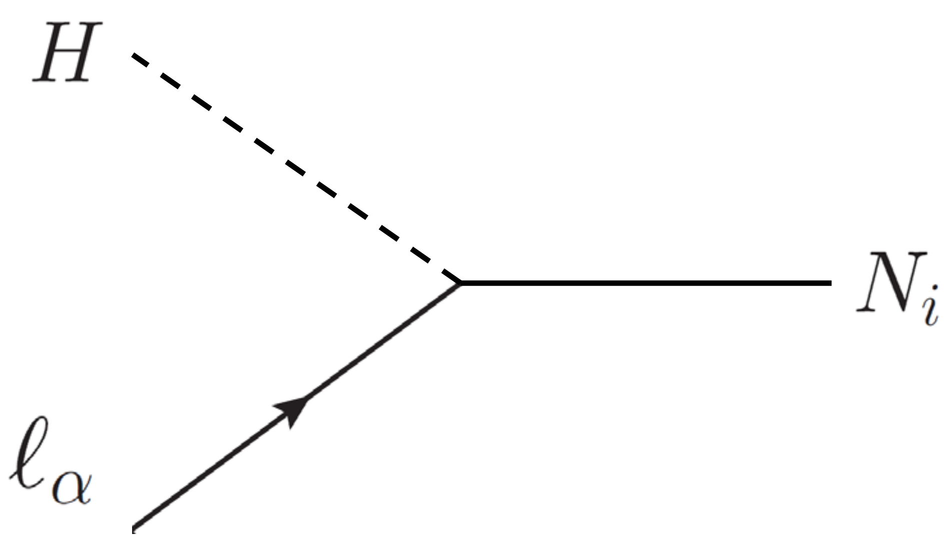


$$\varepsilon_1 = \frac{\Gamma(N_1 \to L\Phi) - \Gamma(N_1 \to L^c\Phi^+)}{\Gamma(N_1 \to L\Phi) + \Gamma(N_1 \to L^c\Phi^+)}$$

$$\eta_L \equiv \frac{n_L}{s} \sim \varepsilon_1 \frac{n_{N_1}}{s}$$

Three basic steps

(2) Partial washout of the asymmetry due to inverse decay and scattering



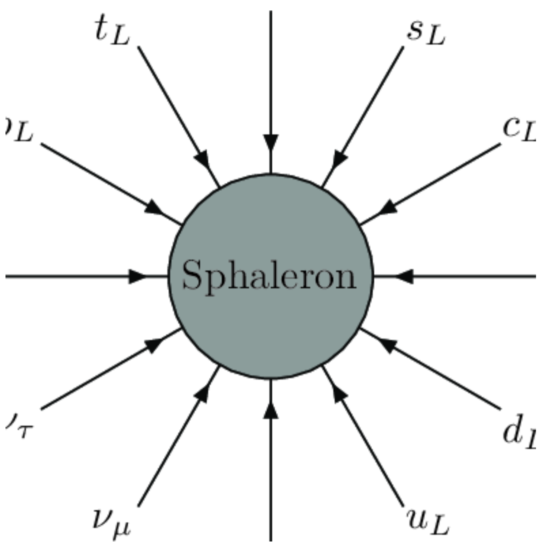
efficiency factor : κ

$$\eta_L \equiv \frac{n_L}{s} \sim \varepsilon_1 \frac{n_{N_1}}{s} \kappa$$

(3) Conversion of the left-over L asymmetry to

B asymmetry via sphaleron at $T > T_{sph}$.

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



Baryogenesis & Dark Matter

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

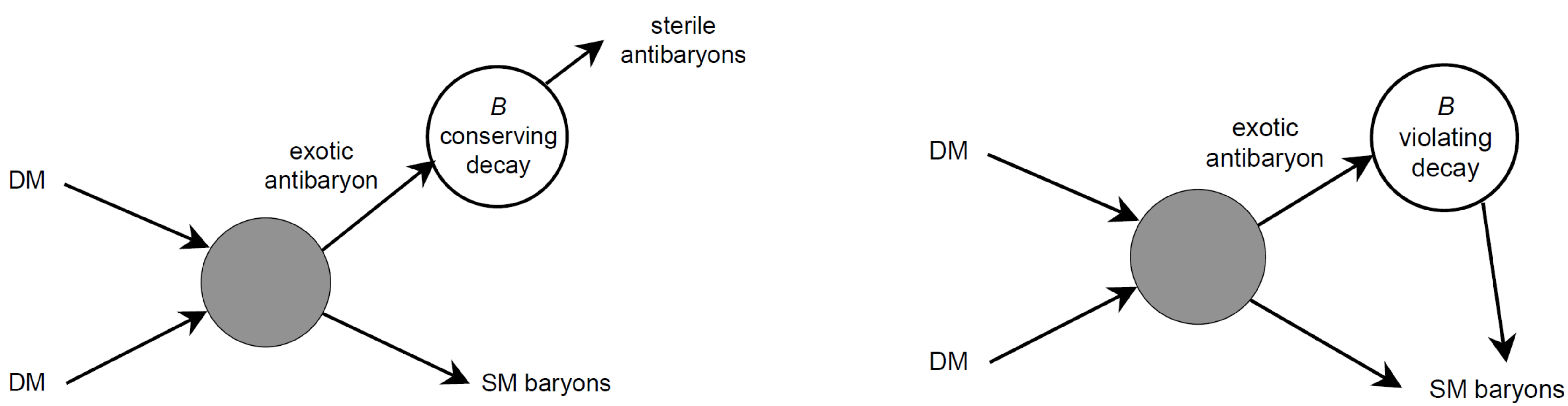
$$\Omega_{DM} \approx 5\Omega_B$$

- 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.
- While generic implementations of these scenarios tightly relate BAU & DM abundances, there exists other implementations too where the connections may be loose.

Baryon asymmetry from scattering

- WIMPy baryogenesis
- Baryon asymmetry can be obtained by B−violating dark matter scattering → cogenesis of baryon asymmetry and dark matter (two miracles happen in one framework !)

(Cui, Randall, Shuve, JHEP, 2012)



Baryon asymmetry from scattering

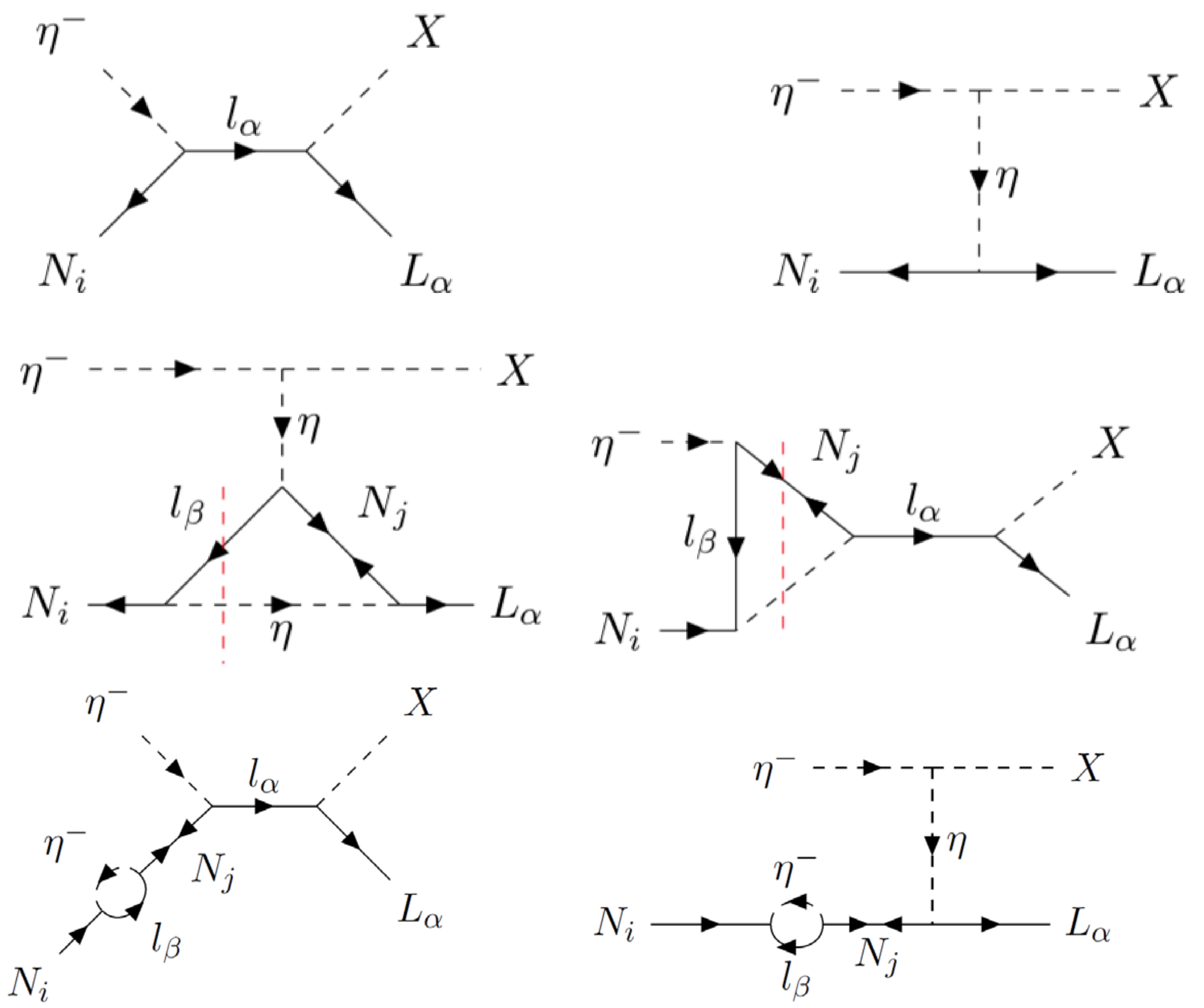
- WIMPy leptogenesis
- Baryon asymmetry can be obtained by L−violating dark sector scattering in scotogenic model (Borah, Dasgupta, SK, EPJC 2020)

  → SM+ 3N_k + inert SU(2) scalar doublet η (E. Ma, PRD73, 2006)

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

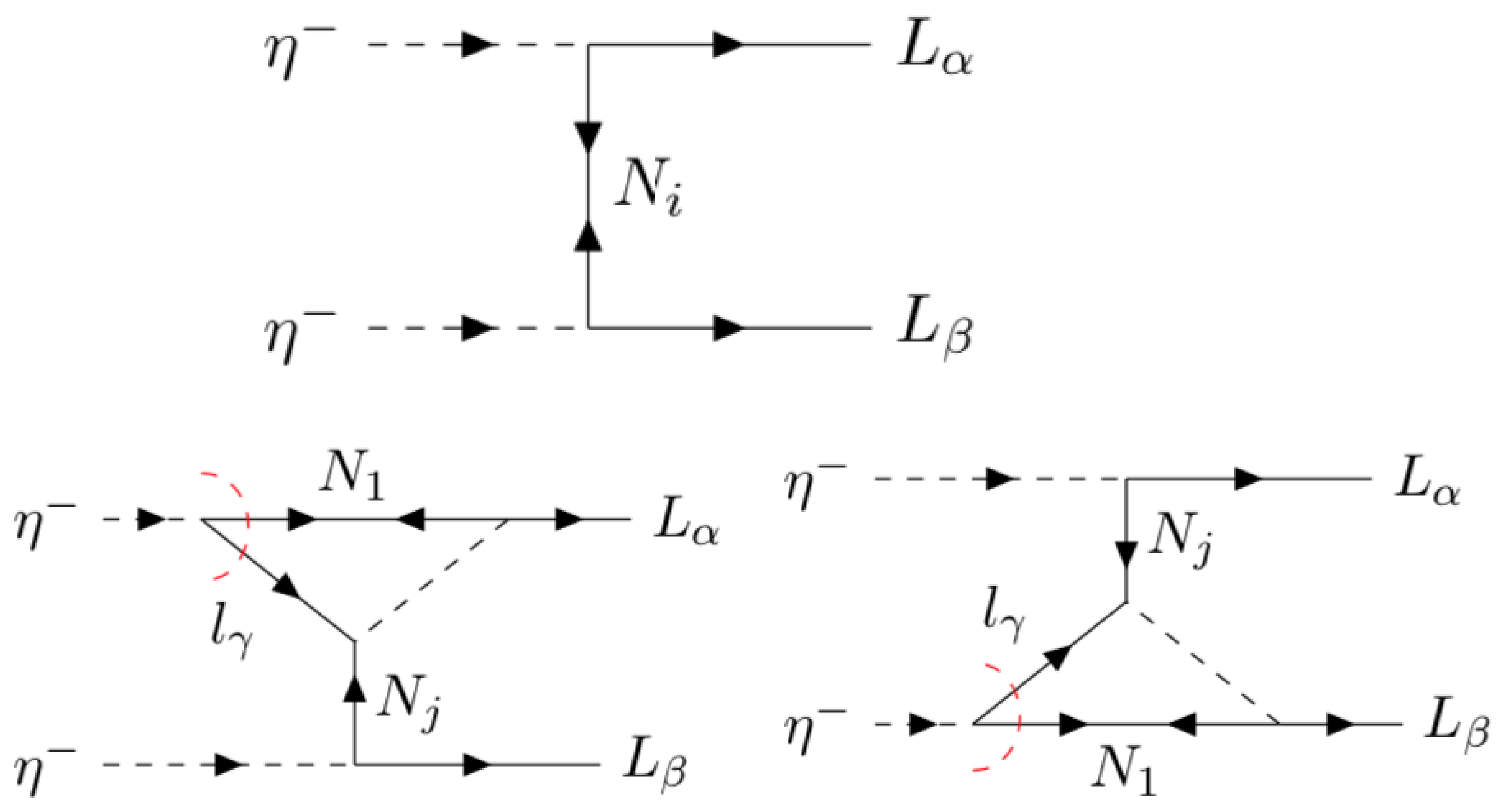
Scalar Doublet η as Dark Matter

- co-annihilation processes $N_k\eta \to L, X(=\gamma, W, Z, h)$ lead to ΔL



Right-handed neutrino as dark matter

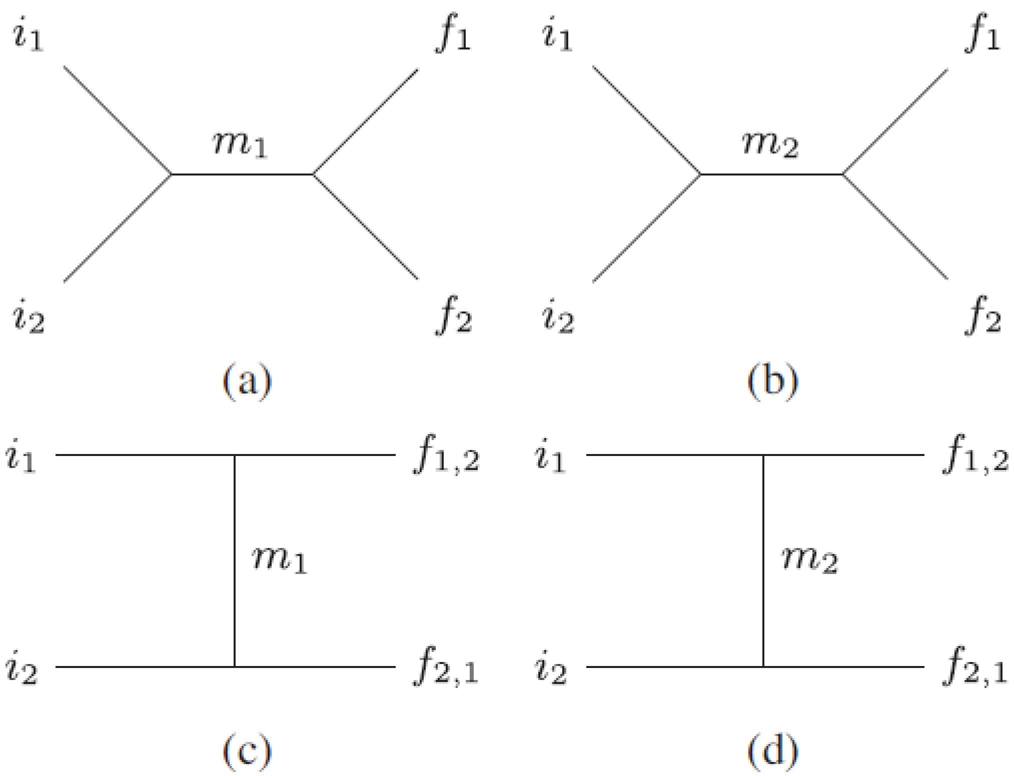
- co-annihilation processes $N_k\eta \to L, X(=\gamma, W, Z, h)$ lead to ΔL
- annihilation processes $\eta\eta \to LL$ through t-channel mediated by N_i

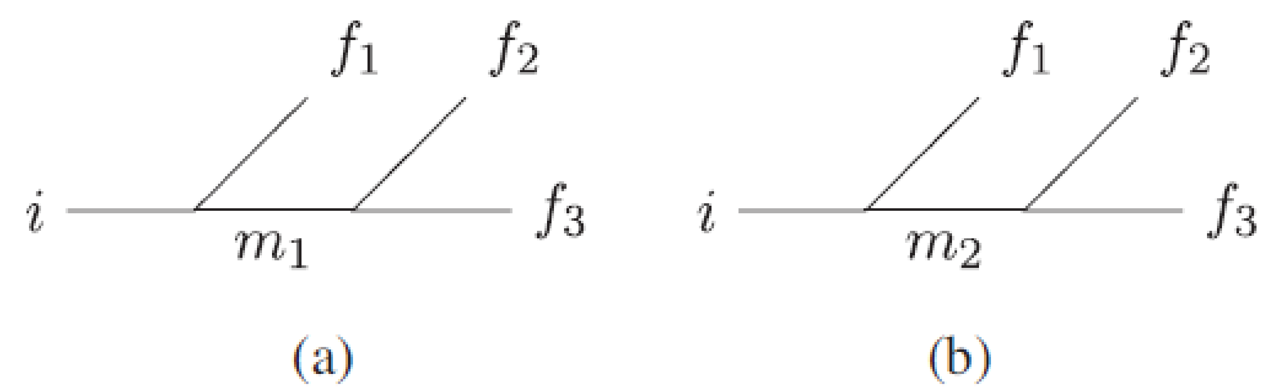


- In this scenario, we require N_1 to be lighter than η whose annihilations are responsible for creating the asymmetry.

New idea on L/B asymmetry

Interference between two sets of tree-level decay or scattering diagrams with the same $|i_i\rangle$ and $|f_i\rangle$





- A net nonzero L/B asymmetry between $|i_i\rangle$ and $|f_i\rangle$
- At least, one set of decay or scattering amplitude is complex such that

$$|\mathcal{M}(\boldsymbol{i} \to \boldsymbol{f})|^2 \neq \left|\mathcal{M}(\bar{\boldsymbol{\imath}} \to \bar{\boldsymbol{f}})\right|^2$$

- total amplitude for the process : $i_1 i_2 \to f_1 f_2$

$$\mathcal{M} = (\mathcal{C}_1 \mathcal{M}_1 + \mathcal{C}_2 \mathcal{M}_2)\mathcal{W}$$

$\mathcal{C}_i$ contain only the couplings,
$\mathcal{W}$ contains wave functions for the particles
$\mathcal{M}_i$ stand for the rest of the sub-amplitude

- total amplitude for the conjugate process : $\bar{i}_1 \bar{i}_2 \to \bar{f}_1 \bar{f}_2$

$$\bar{\mathcal{M}} = (\mathcal{C}_1^* \mathcal{M}_1 + \mathcal{C}_2^* \mathcal{M}_2)\mathcal{W}^*$$

- CP asymmetry is proportional to

$$\delta \equiv |\mathcal{M}|^2 - |\bar{\mathcal{M}}|^2$$

$$= -4\mathrm{Im}[\mathcal{C}_1 \mathcal{C}_2^*]\mathrm{Im}[\mathcal{M}_1 \mathcal{M}_2^*]|\mathcal{W}|^2$$

- Source of the complexity of $\mathcal{M}_i$:

imaginary part of Breit-Wigner propagator of unstable mediator

→ finite width of mediators

$$\mathcal{M}_j = \frac{A_j}{x_j - m_j^2 + i m_j \Gamma_j},$$

Then,

$$\mathrm{Im}[\mathcal{M}_1 \mathcal{M}_2^*] = \frac{A_1 A_2 [(x_1 - m_1^2) m_2 \Gamma_2 - (x_2 - m_2^2) m_1 \Gamma_1]}{[(x_1 - m_1^2)^2 + m_1^2 \Gamma_1^2][(x_2 - m_2^2)^2 + m_2^2 \Gamma_2^2]}$$

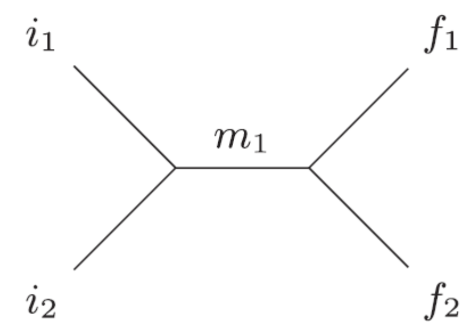
- To achieve L/B asymmetry, denominator should not be zero

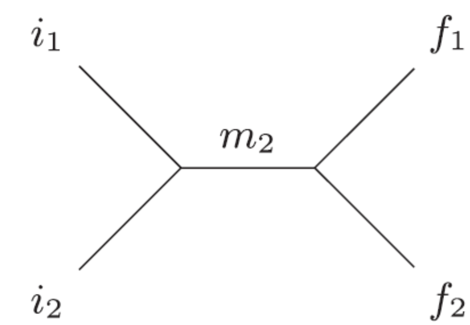
as well as $\mathrm{Im}[\mathcal{C}_1 \mathcal{C}_2^*] \neq 0$

- 3 possibilities for $\mathrm{Im}[\mathcal{M}_1\mathcal{M}_2^*] \neq 0$

  - Both processes in s−channel,
    $x_{1,2}$ replaced by *s*,
    δ can be enhanced in the vicinity of *s*,

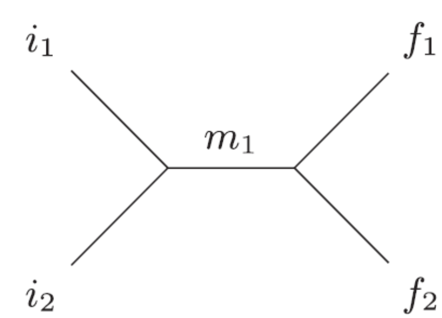
$$s - m_i^2 \simeq m_i\Gamma_i$$

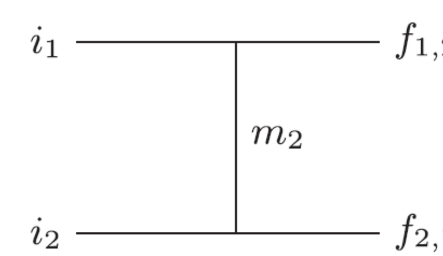




  - one in *s*−channel, the other in $t(u)$ −channel,
    δ can be enhanced at *s−channel,*

$$\mathrm{Im}[\mathcal{M}_1\mathcal{M}_2^*] \simeq -\frac{A_1A_2m_1\Gamma_1}{[(s-m_1^2)^2+m_1^2\Gamma_1^2](x-m_2^2)}$$

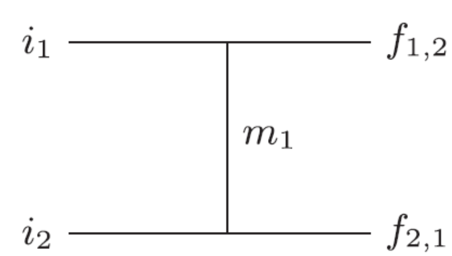


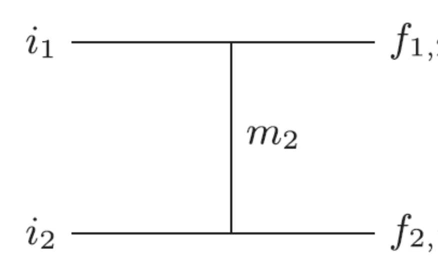


  - Both in $t(u)$−channel,
    width terms can be neglected,

$$\mathrm{Im}[\mathcal{M}_1\mathcal{M}_2^*] \simeq \frac{A_1A_2[(x_1-m_1^2)m_2\Gamma_2-(x_2-m_2^2)m_1\Gamma_1]}{(x_1-m_1^2)^2(x_2-m_2^2)^2}$$

    CP asymmetry is suppressed by $m_i\Gamma_i/(x_j-m_j^2)$





A model to realize the idea

- Scotogenic model with type II seesaw :
  - Z_2 odd : an inert SU(2) doublet scaler : $\eta = (\eta^+, \eta^0)$, 3 N_{R_i},
  - Z_2 even: a SU(2) triplet scalar $\Delta = (\Delta^{++}, \Delta^+, \Delta^0)$

- assumptions :
  - asymmetry generated by N_{R_i} or Δ is not relevant at T of interest
  - no mixing and CPV in N_{R_i} sector
  - η^0 DM candidate

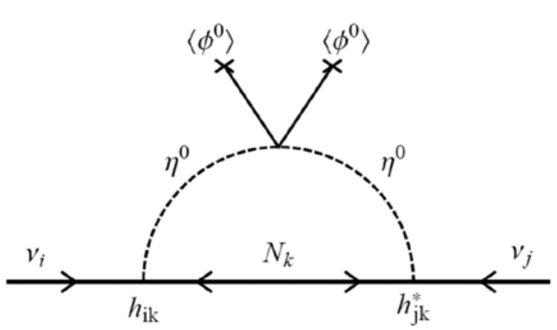
- Relevant Yukawa Lagrangian: $-\mathcal{L}_Y = Y^N_{i\alpha}\tilde{\eta}^\dagger L_\alpha N_i + Y^\Delta_{\alpha\beta}\overline{L^C_\alpha}\Delta L_\beta + \text{H.c.}$.

- The mass term $V \supset \mu_{\eta\Delta}\eta^\dagger\Delta^\dagger\tilde{\eta} + \text{H.c.}$ to be complex, crucial for CPV

- Neutrino masses : $m_\nu = (Y^N)^\mathsf{T}\Lambda Y^N + Y^\Delta v_\Delta$,

Tree mass(Type−II)

1−loop mass

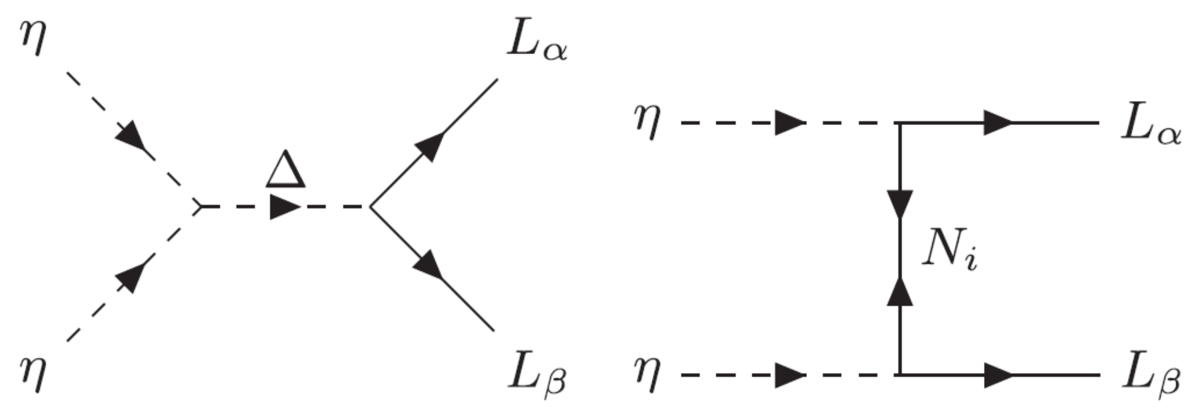


$$\Lambda_{ii} = \frac{m_{N_i}}{16\pi^2}\left[\frac{m^2_{\eta_R}}{m^2_{N_i} - m^2_{\eta_R}}\ln\left(\frac{m^2_{N_i}}{m^2_{\eta_R}}\right) - \frac{m^2_{\eta_I}}{m^2_{N_i} - m^2_{\eta_I}}\ln\left(\frac{m^2_{N_i}}{m^2_{\eta_I}}\right)\right]$$

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

Generation of L asymmetry

achieved by $2 \to 2$ $\Delta L = 2$ scattering : $\eta\eta \to L_\alpha L_\beta$



$$\delta = 4\sum_i \mathrm{Im}[\mu_{\eta\Delta}\{Y^N Y^{\Delta^*}(Y^N)^\mathsf{T}\}_{ii}]$$
$$\times \frac{s m_{N_i} m_\Delta \Gamma_\Delta}{(s-m_\Delta^2)^2 + m_\Delta^2\Gamma_\Delta^2}\left[\frac{1}{t-m_{N_i}^2} + \frac{1}{u-m_{N_i}^2}\right]$$

parameterizing

$$Y^N_{i\alpha} = F_\mathrm{I}^{1/2}(\Lambda^{-1/2}\mathcal{O}\hat{m}_\nu^{1/2}U^\dagger_\mathrm{PMNS})_{i\alpha},$$

$$Y^\Delta_{\alpha\beta} = F_\mathrm{II} v_\Delta^{-1}(U^*_\mathrm{PMNS}\hat{m}_\nu U^\dagger_\mathrm{PMNS})_{\alpha\beta},$$

$$\hat{m}_\nu = \{m_{\nu_1}, m_{\nu_2}, m_{\nu_3}\}$$

Boltzmann eqs.

Cogenesis of DM relic density and lepton asymmetry is governed by

$$\frac{\mathrm{d}Y_\eta}{\mathrm{d}z} = \frac{-s}{H(z)z}[(Y_\eta^2 - (Y_\eta^{\mathrm{eq}})^2)\langle\sigma v\rangle(\eta\eta \to \mathrm{SMSM})],$$

$$\frac{\mathrm{d}Y_{\Delta L}}{\mathrm{d}z} = \frac{s}{H(z)z}[(Y_\eta^2 - (Y_\eta^{\mathrm{eq}})^2)\langle\sigma v\rangle_\delta(\eta\eta \to LL)$$
$$- 2Y_{\Delta L}Y_\ell^{\mathrm{eq}} r_\eta^2 \langle\sigma v\rangle_{\mathrm{tot}}(\eta\eta \to LL)$$
$$- 2Y_{\Delta L}Y_\eta^{\mathrm{eq}}\langle\sigma v\rangle(\eta\bar{L} \to \eta L)],$$

$$z = m_\eta/T$$

$$H(z) = \sqrt{\frac{8\pi^3 g_*}{90}}\frac{m_\eta^2}{z^2 M_{\mathrm{Pl}}}$$

$$Y_{\Delta L} = Y_L - Y_{\bar{L}},$$

$$Y_i^{(\mathrm{eq})} \equiv n_i^{(\mathrm{eq})}/s$$

$$r_\eta = Y_\eta^{\mathrm{eq}}/Y_\ell^{\mathrm{eq}}$$

$$\langle\sigma v\rangle_{\mathrm{tot}}(\eta\eta \to LL) \equiv \langle\sigma v\rangle(\eta\eta \to LL) + \langle\sigma v\rangle(\eta^*\eta^* \to \bar{L}\,\bar{L})$$

$$\langle\sigma v\rangle_\delta(\eta\eta \to LL) \equiv \langle\sigma v\rangle(\eta\eta \to LL) - \langle\sigma v\rangle(\eta^*\eta^* \to \bar{L}\,\bar{L})$$

$\Omega_{\mathrm{DM}}h^2 = 2.755 \times 10^8 Y_\eta(m_\eta/\mathrm{GeV})$ at DM freeze out temperature $T_f \simeq m_\eta/20$

$Y_{\Delta B} = -(28/51)Y_{\Delta L}$ at sph. transition temperature $T_{\mathrm{sph}} = (131.7 \pm 2.3)\,\mathrm{GeV}$

A crucial criterion for achieving successful asymmetry:

washout of the asymmetry must freeze out
before the freeze-out of DM annihilations.

$$\langle \sigma v \rangle_{\rm tot}(\eta\eta \to LL) < \langle \sigma v \rangle(\eta\eta \to {\rm SMSM})$$

➡ Similar to WIMPy baryogenesis

- In WIMPy , both washout and DM freeze-out are governed by the same final states, so, one of the final states should be massive to satisfy the condition.
- But, in our mechanism, dominant process for DM freeze-out : $\eta\eta \to W^+W^-$
  & the dominant washout process : $\eta\eta \to LL$
- So, the freeze-out condition is satisfied for suitable choice of Yukawa couplings without requiring any of the final states to be massive.

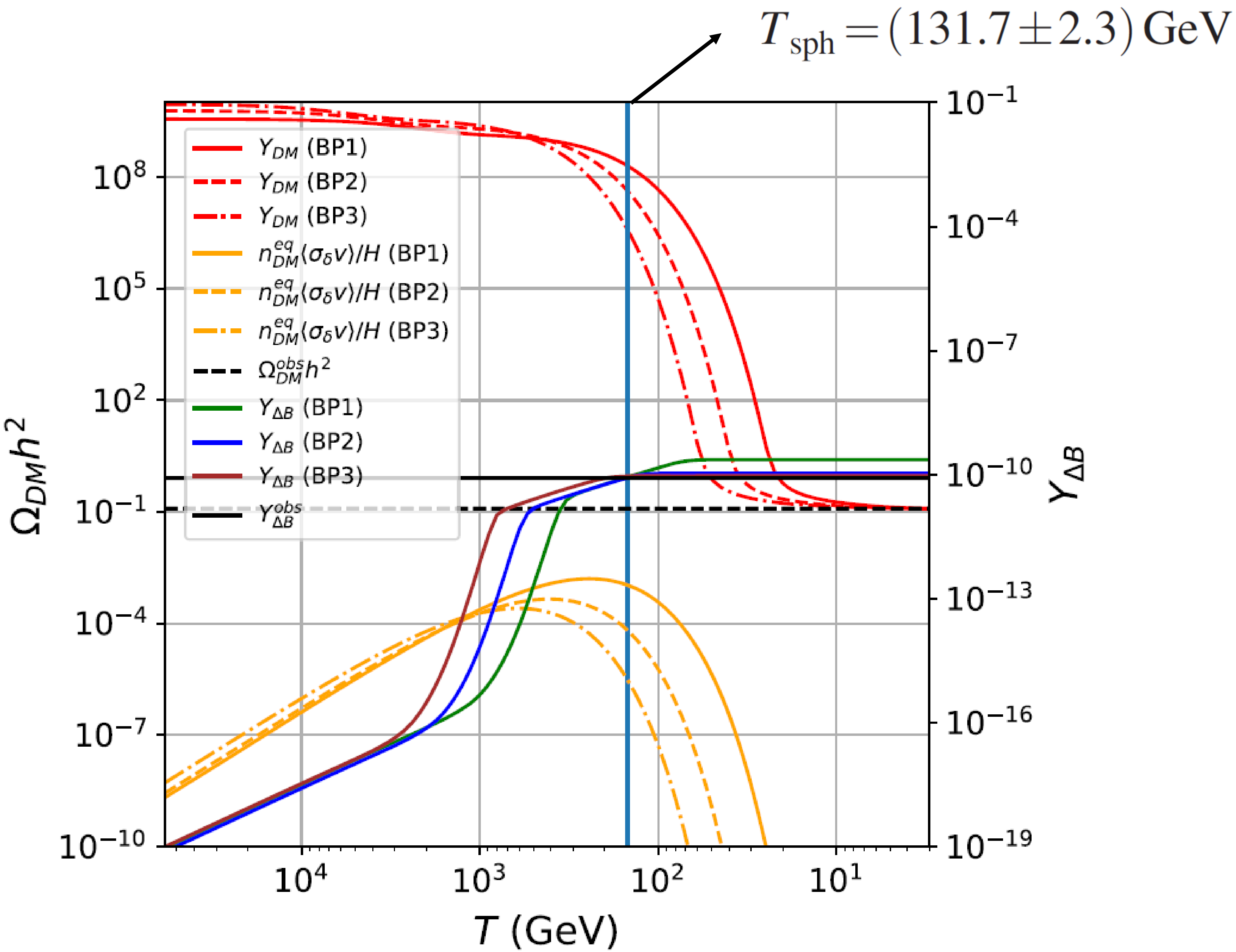
Numerical Results

3 benchmark points

	BP1	BP2	BP3
v_Δ	1 keV	1 keV	1 keV
μ_η	600 GeV	1 TeV	1.5 TeV
$\mu_{H\Delta}$	33.6 keV	93.5 keV	210 keV
$\mu_{\eta\Delta}$	$15i$ GeV	$7.1i$ GeV	$6i$ GeV
m_{N_1}	6 TeV	10 TeV	15 TeV
m_{N_2}	6.6 TeV	11 TeV	16.5 TeV
m_{N_3}	7.2 TeV	12 TeV	18 TeV
m_{η^0}	600 GeV	1 TeV	1.5 TeV
Δm_{η^0}	506 keV	300 keV	200 keV
$m_{\eta^\pm}$	606 GeV	1 TeV	1.5 TeV
m_{Δ^0}	1.2 TeV	2 TeV	3 TeV
$m_{\Delta^\pm}$	1.2 TeV	2 TeV	3 TeV
$m_{\Delta^{\pm\pm}}$	1.2 TeV	2 TeV	3 TeV
λ_H	0.253	0.253	0.253
$\lambda_{H\eta}$	0.19	0.56	0.91
$\lambda'_{H\eta}$	−0.19	−0.56	−0.91
$\lambda''_{H\eta}$	1×10^{-5}	1×10^{-5}	1×10^{-5}

$$\Delta m_{\eta^0} = m_{\eta_R} - m_{\eta_I}$$

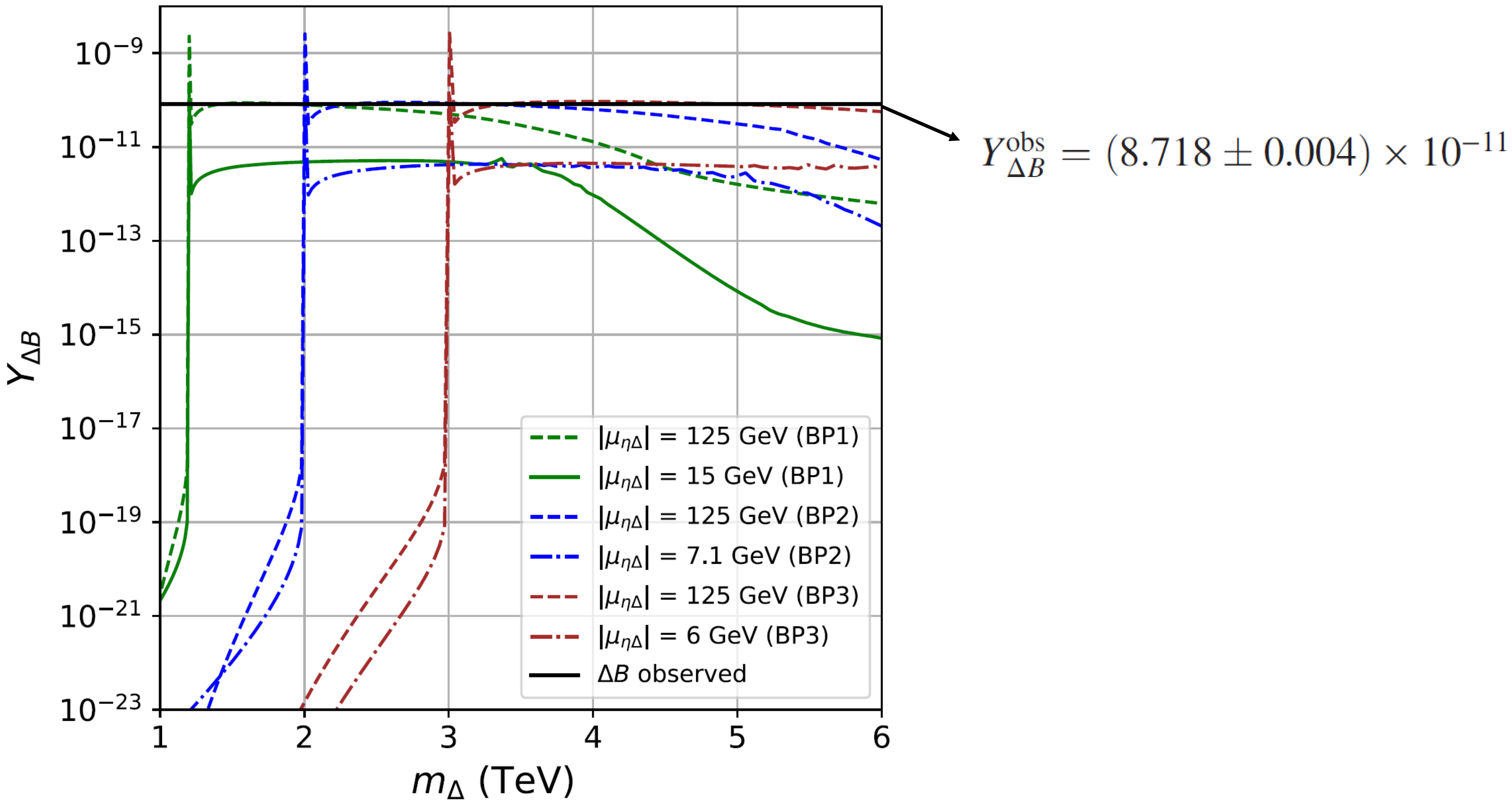
- We solve the BEs numerically for 3BPs in Table.
- ΔL coming from the standard decay of N_i will not come into play. (taking yukawa matrix appropriately)
- N_i are taken to be much heavier than η to avoid the wash-out of ΔL from the inverse decay $L_\alpha \eta \to N_i$



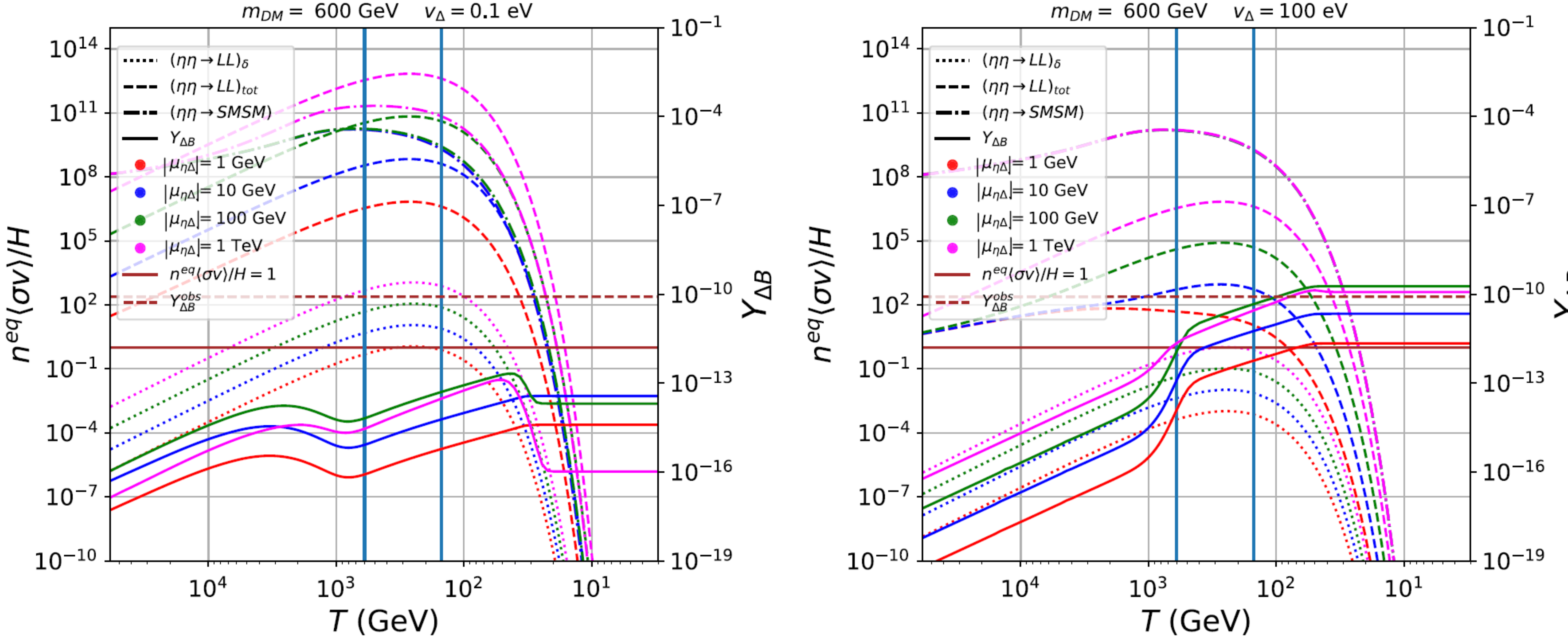
Net baryon number density $Y_{\Delta B}$, DM density $\Omega_{DM}h^2$, $n_{DM}^{eq}\langle\sigma v\rangle_\delta/H$
as a function of T for 3 BPs

Solid black line : $Y_{\Delta B}^{\rm obs} = (8.718 \pm 0.004) \times 10^{-11}$

dashed black line : $\Omega_{\rm DM}^{\rm obs}h^2 = 0.120 \pm 0.001$



Net baryon number density $Y_{\Delta B}$ as a function of m_Δ for 3 BPs

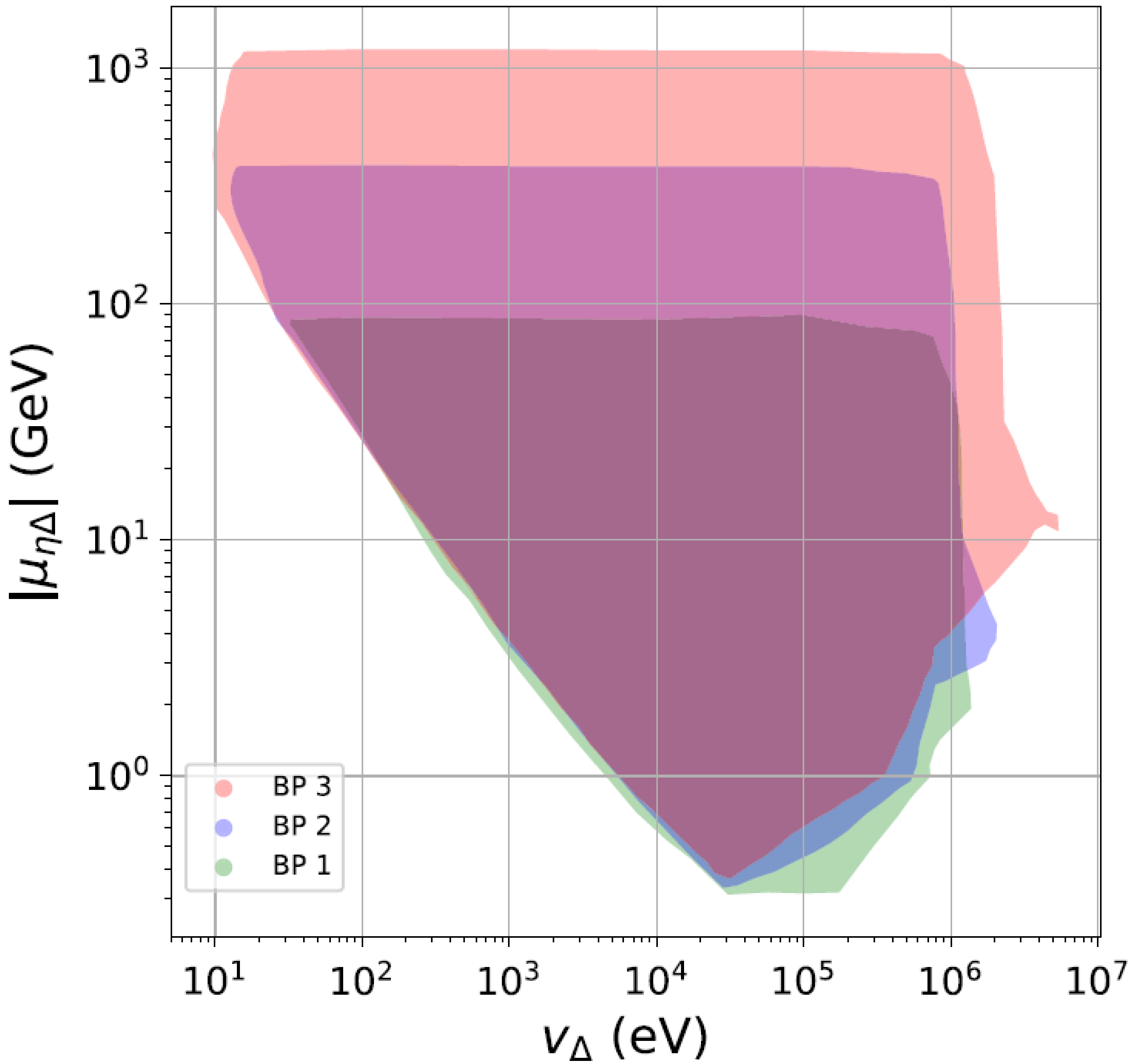


Net baryon number density $Y_{\Delta B}$ and $n^{\rm eq}\langle\sigma v\rangle/H$ for the processes

$(\eta\eta \to LL)_\delta$, $(\eta\eta \to LL)_{\rm tot}$ and $(\eta\eta \to {\rm SMSM})$

for $|\mu_{\eta\Delta}| = 1$ GeV, 10 GeV, 100 GeV and 1 TeV for the BP1

$v_\Delta = 0.1$ eV (left) $v_\Delta = 100$ eV (right)



$$\mathrm{BP1:}\ 40\,\mathrm{eV} \lesssim v_\Delta \lesssim 1.5\ \mathrm{MeV}, \quad 0.3\,\mathrm{GeV} \lesssim |\mu_{\eta\Delta}| \lesssim 80\,\mathrm{GeV},$$

$$\mathrm{BP2:}\ 20\,\mathrm{eV} \lesssim v_\Delta \lesssim 1.2\ \mathrm{MeV}, \quad 0.3\,\mathrm{GeV} \lesssim |\mu_{\eta\Delta}| \lesssim 380\,\mathrm{GeV},$$

$$\mathrm{BP3:}\ 10\,\mathrm{eV} \lesssim v_\Delta \lesssim 20\,\mathrm{MeV}, \quad 0.3\,\mathrm{GeV} \lesssim |\mu_{\eta\Delta}| \lesssim 1.2\,\mathrm{TeV}.$$

Collider signature

- The allowed range of v_Δ corresponding to $5 \times 10^{-9} \lesssim Y_\Delta \lesssim 3 \times 10^{-3}$ gives rise to prompt dilepton signals in the Δ^{++} decays for the triplet masses given in Table.

- The charged scalars $\eta+$ can be produced in association with the neutral DM particle η^0 through the W boson

$$pp \to W^* \to \eta^\pm \eta^0 \to \eta^0 \eta^0 W^{(*)}$$

- For our chosen BPs, N_i are heavier than η and can only be produced at high-energy colliders from the off-shell decay

$$\eta^{\pm *} \to \ell_\alpha^\pm N_i$$

$$\hookrightarrow \ell_\alpha^\pm \eta^{\mp(*)} \to \ell_\alpha^\pm \eta^0 W^{\mp(*)}$$

→ same sign leptons but with missing energy due to η^0

Conclusion

- We have shown a new mechanism for generation of baryon asymmetry from the interference between two tree processes containing BW propagators of unstable mediators.
- The interesting feature of this mechanism is that the baryon asymmetry depends on the decay width of the unstable dark sectors.
- The model we consider is readily testable in next generation colliders

Thank You