Asymmetric Mediator in Scotogenic Model

今週arXivに投稿します！

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Motivation

- Neutrino masses
- Dark Matter (DM)

  ○ Scotogenic Model

  E. Ma , Phys. Rev. D **73** (2006) 077301

- Baryon asymmetry of the universe (BAU)

  ○ Leptogenesis

  M. Fukugita and T. Yanagida Phys.Lett.B174(1986)45-47

T. Hugle, M. Platscher, and K. Schmitz, Phys. Rev. D **98** (2018) 023020

- $\Omega_{\mathrm{DM}} / \Omega_{\mathrm{B}} \cong 5$

  ○ Asymmetric Dark Matter Model (ADM)

  K. Petraki and R. R. Volkas, Int. J. Mod. Phys. A 28(2013) 1330028

Combine ADM scenario with Scotogenic Model and explain Neutrino masses , DM , BAU , and $\Omega_{\mathrm{DM}} / \Omega_{\mathrm{B}} \approx 5$ simultaneously

・Model

Original Scotogenic Model

Standard Model
+ $N_i (i = 1,2,3)$ (singlet fermion)
+ η (doublet complex scalar)

This model

Original Scotogenic Model
+ σ (singlet real scalar : DM)

Role of η
・Connect SM and DM

Mediator !

$$\mathcal{L} \supset -h_{\alpha i}\bar{L}_\alpha \tilde{\eta} N_i + \frac{1}{2} M_i \bar{N}_i N_i^c + h.c.$$

$$\begin{aligned} V(H,\eta,\sigma) = & m_H^2 |H|^2 + m_\eta^2 |\eta|^2 + m_\sigma^2 \sigma^2 \\ & + \frac{1}{2}\lambda_1 |H|^4 + \frac{1}{2}\lambda_2 |\eta|^4 + \frac{1}{2}\lambda_3 \sigma^4 \\ & + \lambda_4 |H|^2 |\eta|^2 + \lambda_5 |H^\dagger \eta|^2 + \lambda_6 |H|^2 \sigma^2 + \lambda_7 |\eta|^2 \sigma^2 \\ & + \underline{\frac{\lambda_8}{2}\left[(H^\dagger \eta)^2 + h.c.\right]} + \frac{\mu}{\sqrt{2}}\left[\sigma(H^\dagger \eta) + h.c.\right] \end{aligned}$$

field	fermion			scalar		
	L	e_R	N	H	η	σ
$SU(2)_L$	**2**	**1**	**1**	**2**	**2**	**1**
Z_2	+	+	−	+	−	−

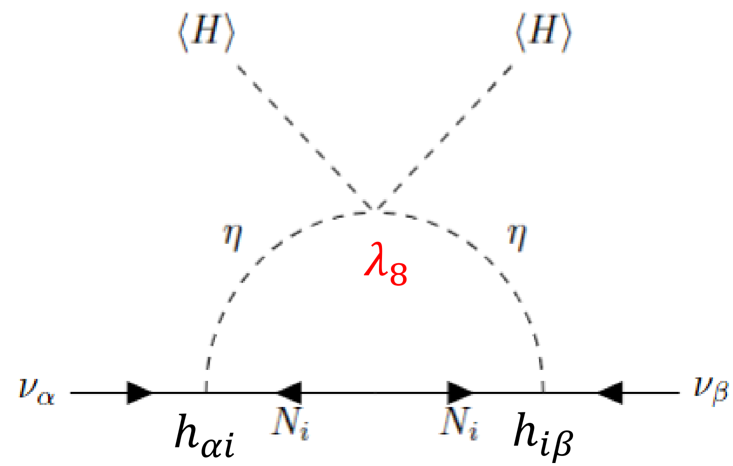
Z_2 symmetry assignment

・Model

Neutrino mass matrix

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h^*_{\alpha i} h^*_{\beta i}}{32\pi^2} M_i \left[\frac{m^2_{\eta_R}}{m^2_{\eta_R} - M_i^2} \ln \frac{m^2_{\eta_R}}{M_i^2} - \frac{m^2_{\eta_I}}{m^2_{\eta_I} - M_i^2} \ln \frac{m^2_{\eta_I}}{M_i^2} \right]$$

$$\simeq \frac{\lambda_8 v^2}{32\pi^2} \sum_i \frac{h^*_{\alpha i} h^*_{\beta i}}{M_i} \left[\ln \frac{M_i^2}{m_\eta^2} - 1 \right]$$



λ_8 is an important parameter related to neutrino mass

Casas-Ibarra parametrization

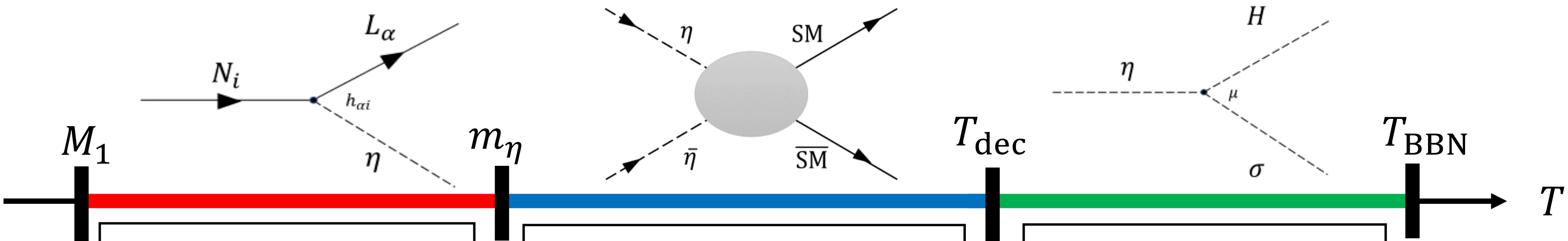
$$h_{\alpha i} = \left(U \, D_\nu^{\frac{1}{2}} \, R^\dagger \, D_\Lambda^{\frac{1}{2}} \right)_{\alpha i}$$

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

$$(\mathcal{D}_\Lambda)_{ii} = \frac{2\pi^2}{\lambda_8} \xi_i \frac{2M_i}{v^2}$$

Yukawa matrix depends on λ_8 , M_i

・Cogenesis



$n_{L-\bar{L}} = n_{\eta-\bar{\eta}}$ | $n_{\eta-\bar{\eta}} \cong n_{\bar{\eta}} \gg n_\eta$ | $n_{\eta-\bar{\eta}} \cong n_{\text{DM}}$

The number density of the DM has the same order as those of the SM lepton and baryon

$$n_{B-\bar{B}} \sim n_{L-\bar{L}} \cong n_{\eta-\bar{\eta}} \cong n_{\text{DM}}$$

Interactions — M_1, m_η, T_{dec}, T_{BBN} → T

$N_i \to \eta\, L_\alpha \,, \bar{\eta}\, \bar{L}_\alpha$	○	○	×	×	×
$\bar{\eta}\, \eta \to \overline{\text{SM}}\ \text{SM}$	○	○	○	×	×
$\eta \to \sigma\, H \,, \bar{\eta} \to \sigma\, \bar{H}$	×	×	×	○	×
$\eta\eta \to HH \,, \bar{\eta}\bar{\eta} \to \bar{H}\bar{H}$	×	×	×	×	×

- # Calculation

  - ## Condition for λ_8

$\eta\eta \to HH$ should be out of equilibrium !

If it occurs → $$n_{L-\bar{L}} \neq n_{\eta-\bar{\eta}}$$ ← This model is not work !

Decouple condition : $\Gamma_{\eta\eta\to HH} < H(T = m_\eta)$

$$\therefore \ \lambda_8 < 3.9 \times 10^{-8} \sqrt{m_\eta/\mathrm{GeV}}$$ ← λ_8 is so small !

Neutrino mass matrix

$$(\mathcal{M}_\nu)_{\alpha\beta} \simeq \frac{\lambda_8 v^2}{32\pi^2} \sum_i \frac{h^*_{\alpha i} h^*_{\beta i}}{M_i} \left[\ln \frac{M_i^2}{m_0^2} - 1 \right]$$

If λ_8 is small, neutrino mass cannot be created.

→ Calculate Baryon asymmetry under this condition

- # Calculation

  - Calculate baryon to photon ratio η_B in a standard Leptogenesis

$$\boxed{\eta_B \approx -0.01\epsilon_1\kappa_1}$$

ϵ_1 : asymmetry parameter
κ_1 : efficiency factor

$$\epsilon_i = \frac{\sum_\alpha \left[\Gamma(N_i \to L_\alpha \eta) - \Gamma(N_i \to \bar{L}_\alpha \eta^\dagger)\right]}{\sum_\alpha \left[\Gamma(N_i \to L_\alpha \eta) + \Gamma(N_i \to \bar{L}_\alpha \eta^\dagger)\right]}$$

$$\kappa_1(K_1) \simeq \frac{1}{1.2K_1\left[\ln K_1\right]^{0.8}}$$

This approximation holds in the range: $1 \ll K_1$

$$K_1 \equiv \frac{\Gamma_1}{H(T = M_1)}$$

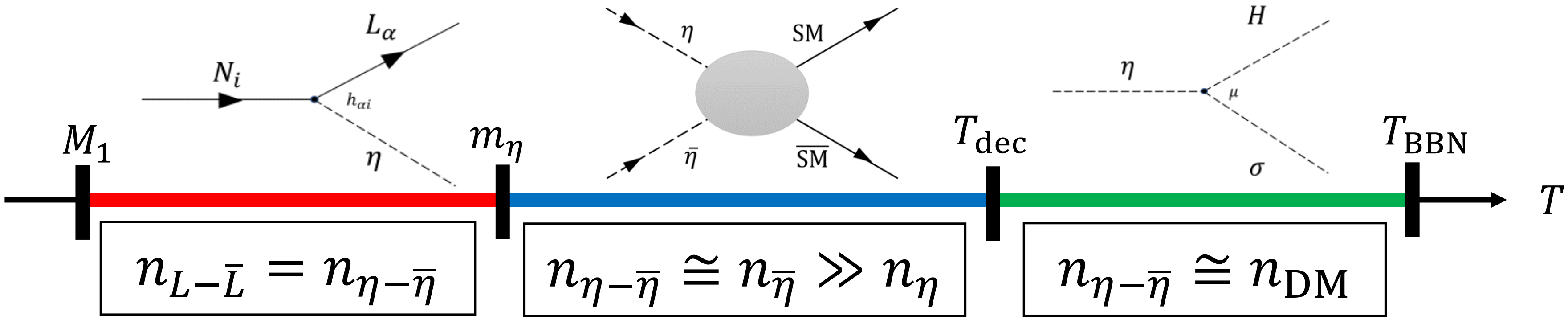
K_1 : decay parameter

> In this model, K_1 is much larger than 1 and the lepton asymmetry is generated via the strong wash-out regime

  - Condition for η_B

$$\eta_B = \eta_{\mathrm{B}}^{\mathrm{obs}} \qquad \eta_B^{obs} = 6.1 \times 10^{-10}$$

• Calculation

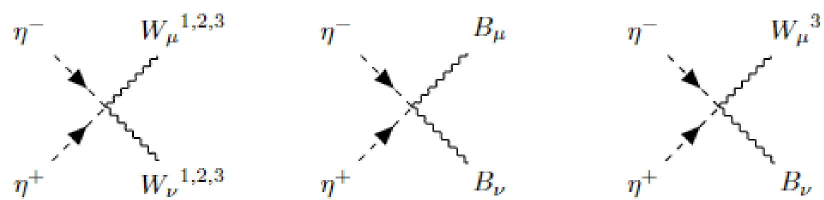


○ Evaluate the relic abundance of η

$$Y_{\eta,\infty} \equiv \frac{n_{\eta,\infty}}{s} = 2 \times \frac{3.80\, x_f}{\left(g_{*s}/g_*^{1/2}\right) M_{\mathrm{Pl}} m_\eta \langle \sigma_{\mathrm{g}} v_{\mathrm{rel}} \rangle}$$

The thermally averaged annihilation cross section is approximated by its non-relativistic limit

$$\langle \sigma_{\mathrm{g}} v_{\mathrm{rel}} \rangle \simeq \frac{(g_1)^4 + 6 \cdot (g_1 g_2)^2 + 3 \cdot (g_2)^4}{256 \pi {m_\eta}^2}$$



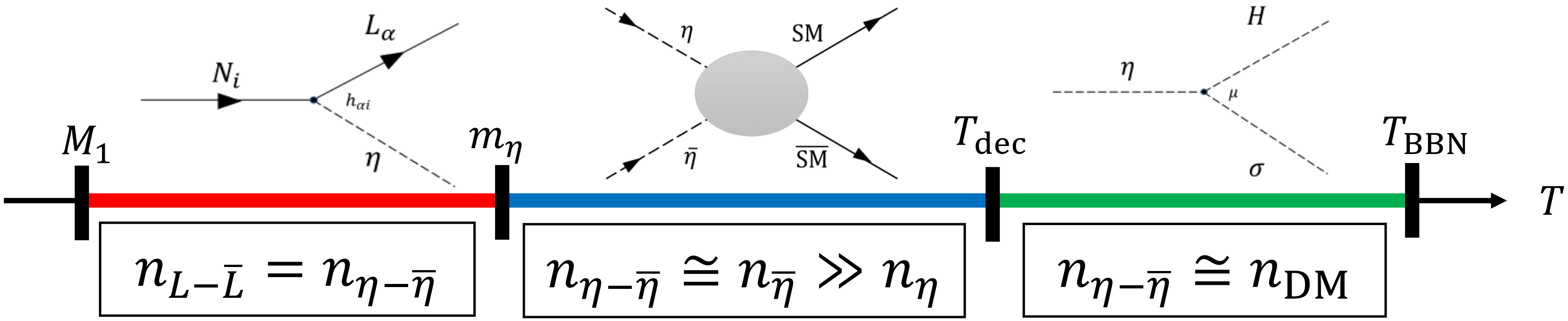
○ Condition for $Y_{\eta,\infty}$

$Y_{\eta,\infty}$ should be smaller than $Y_{\mathrm{B}}^{\mathrm{obs}}$

$$Y_{\eta,\infty} \lesssim Y_{\mathrm{B}}^{\mathrm{obs}} \qquad Y_{\mathrm{B}}^{\mathrm{obs}} = 8.66 \times 10^{-11}$$

• Calculation

○ Condition for μ



The mediator decays after the annihilation of the symmetric component

$$T_{\mathrm{dec}} < T_f \qquad \left(\Gamma_{\eta\to\sigma H} = H(T_{\mathrm{dec}})\right)$$

The mediator decay during or after the Big-Bang Nucleosynthesis (BBN) is cosmologically dangerous

$$\Gamma_{\eta\to\sigma H} > H(T_{\mathrm{BBN}})$$

$$\therefore 8.41\times10^{-12}\,\frac{T_{\mathrm{BBN}}}{1[\mathrm{MeV}]}\sqrt{\frac{m_\eta}{[\mathrm{GeV}]}} < \frac{\mu}{\mathrm{Gev}} < 8.41\times10^{-9}\,\frac{T_f}{[\mathrm{GeV}]}\sqrt{\frac{m_\eta}{[\mathrm{GeV}]}}$$

- # Result

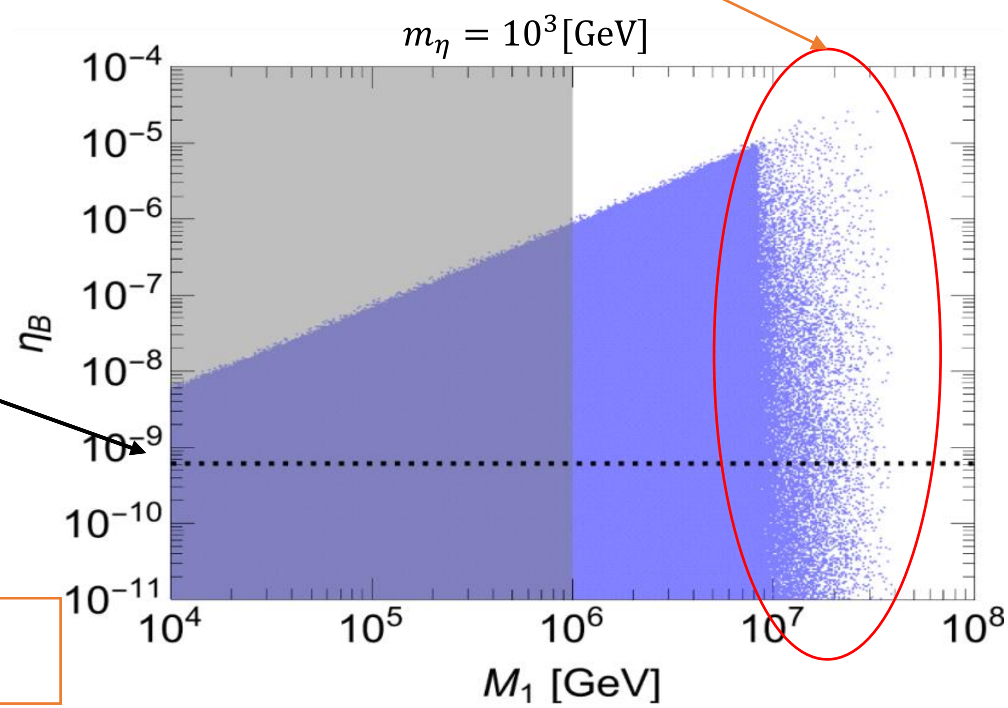
Neutrino mass matrix

$$\mathcal{M}_\nu \simeq 0.05\,\mathrm{eV} \times h^* h^\dagger \sqrt{\frac{10^7\,\mathrm{GeV}}{M_1}}$$

Conditions

- $|h_{\alpha i}| \leq 1$
- $10 < K_1$
- $\lambda_8 = 2.0 \times 10^{-9} \sqrt{m_\eta/[\mathrm{GeV}]}$
- $M_{i+1}/M_i = 1.5$
- $M_1/m_\eta = 10^3$
- $m_1 = 10^{-10}\mathrm{eV}$

$\eta_B^{obs} = 6.1 \times 10^{-10}$

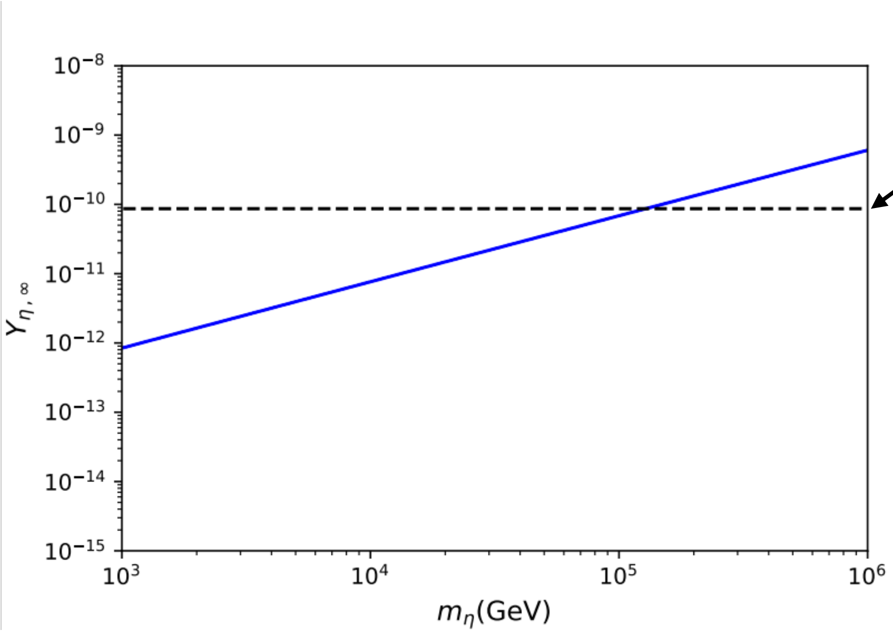


The baryon-to-photon ratio

The range of m_η

$$10^3\mathrm{GeV} < m_\eta < 10^4\mathrm{GeV}$$

• Result



$Y_B^{obs} = 8.66 \times 10^{-11}$

The range of m_η

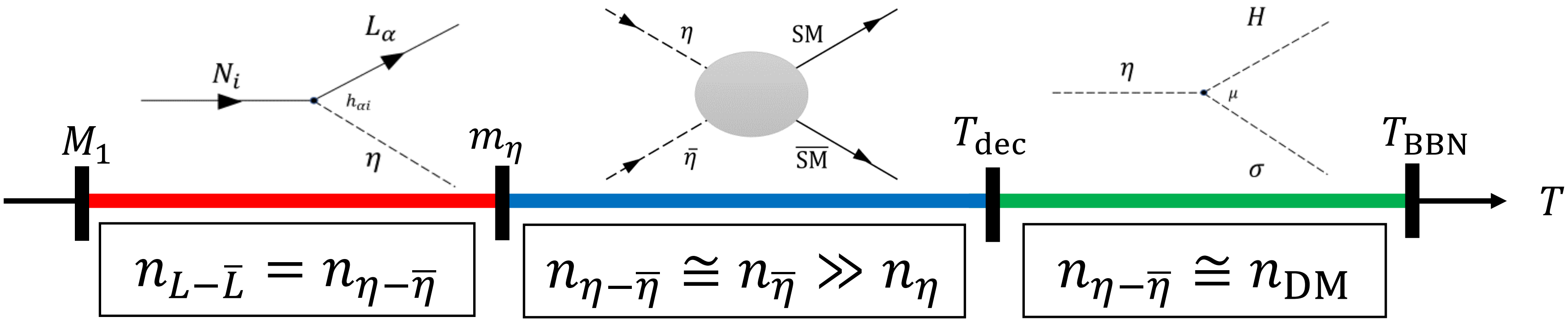
$$m_\eta < 10^5 \mathrm{GeV}$$

This model can realize the coincidence between the number densities of baryon and DM

$$\lambda_8 < 10^{-8}\sqrt{m_\eta/[\mathrm{GeV}]}\,, 1\mathrm{TeV} < m_\eta < 10\mathrm{TeV}$$

$$10^{-11}\sqrt{\frac{m_\eta}{[\mathrm{GeV}]}} < \frac{\mu}{\mathrm{Gev}} < 10^{-10}\left(\frac{m_\eta}{[\mathrm{GeV}]}\right)^{3/2}$$

- # Summary
  - ## Combine ADM scenario to Scotgenic Model



This model can realize the coincidence between the number densities of baryon and DM

$$\lambda_8 < 10^{-8}\sqrt{m_\eta/[\mathrm{GeV}]}\,, 1\mathrm{TeV} < m_\eta < 10\mathrm{TeV}$$

$$10^{-11}\sqrt{\frac{m_\eta}{[\mathrm{GeV}]}} < \frac{\mu}{\mathrm{Gev}} < 10^{-10}\left(\frac{m_\eta}{[\mathrm{GeV}]}\right)^{3/2}$$

- ## As a future prospect, we will explore the parameter area in more detail

  e.g. Solve the Boltzmann equation

Thank you for your attention.

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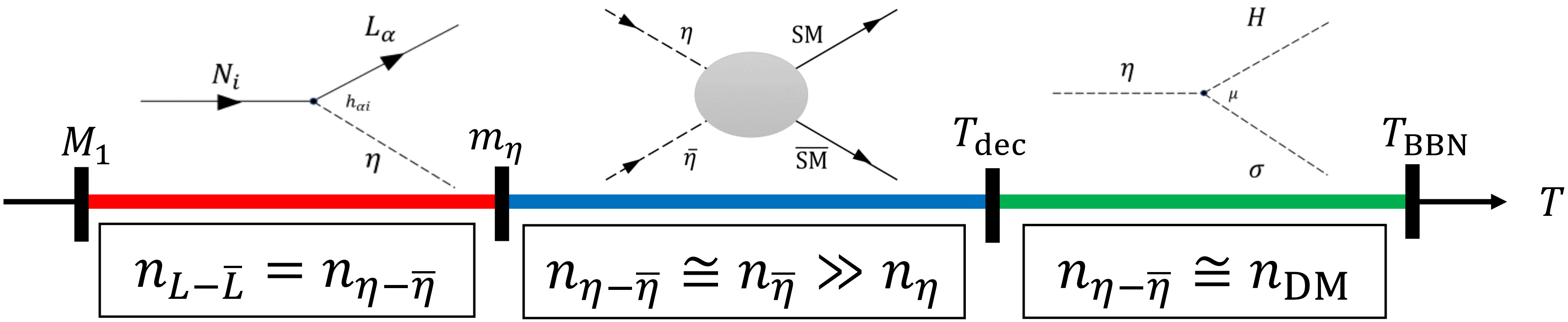
preparation

・preparation



1. The Lepton asymmetry $L - \bar{L}$ and mediator asymmetry $\eta - \bar{\eta}$ are simultaneously produced.

2. The annihilation process makes n_η become much smaller than $n_{\bar{\eta}}$ and the hierarchy of the number densities is realized as $n_{\eta-\bar{\eta}} \cong n_{\bar{\eta}} \gg n_\eta$.

The important thing is mediator asymmetry $\eta - \bar{\eta}$ during the annihilation process

3. $n_{\eta-\bar{\eta}}$ is converted into the DM number density n_{DM}

Role of η

- Connect SM and DM
- Transmit the asymmetry

} Asymmetric Mediator !

- preparation
  - Mediator asymmetry $\eta - \bar{\eta}$

$$n_{\eta-\bar{\eta}} = n_\eta - n_{\bar{\eta}}$$

○ Annihilation

$n_{\bar{\eta}}$ and n_η decrease simultaneously

⇒ Preserve asymmetry $\eta - \bar{\eta}$

○ $\eta\eta \to HH$, $\bar{\eta}\bar{\eta} \to \bar{H}\bar{H}$

Either $n_{\bar{\eta}}$ or n_η changes biased

⇒ Break asymmetry $\eta - \bar{\eta}$