Asymmetric Mediator in Scotogenic Model

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1． Introduction -- Motivation

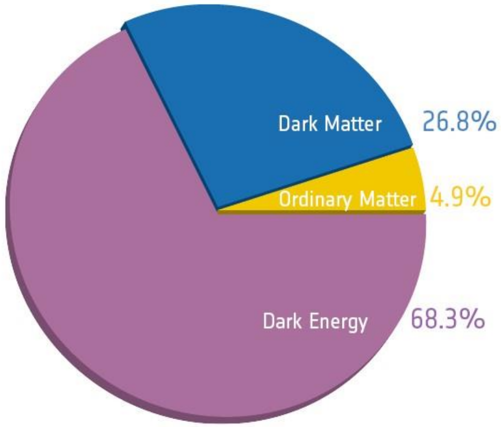
Abundance of Dark Matter

$$\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$$

$$\Omega_{\mathrm{B}} h^2 = 0.0224 \pm 0.0001$$

➡ $\boldsymbol{\Omega_{\mathrm{DM}} \,/\, \Omega_B \simeq 5}$

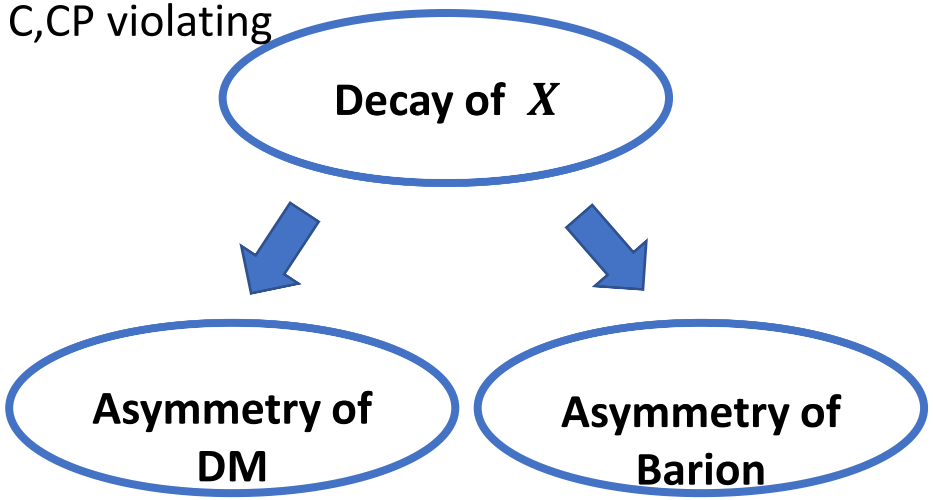
Accidental？



Ingredient

https://sci.esa.int/s/8o9qJ0w

ADM in cogenesis scenario



No, There is a relation !!!

Asymmetric Dark Matter (ADM)

Asymmetries are generated simultaneously

Same origin for DM and Baryon

1. Introduction – goal for the work

- Dark Matter
- Neutrino Oscillation
- Baryon Asymmetry
- $\Omega_{\mathrm{DM}} / \Omega_B \simeq 5$

Scotogenic Model (Dark Matter, Neutrino Oscillation)
E. Ma , Phys. Rev. D **73** (2006) 077301

Leptogenesis (Neutrino Oscillation, Baryon Asymmetry)
M. Fukugita and T. Yanagida, Phys. Lett. B**174** (1986)45-47

Scotogenic Model + Leptogenesis: T. Hugle, M. Platscher, and K. Schmitz, Phys. Rev. D **98** (2018) 023020

Asymmetric Dark Mater
David E. Kaplan, Markus A. Luty, and Kathryn M. Zurek,Phys. Rev.D.**79**. (2009) 115016

Goal

Scotogenic Model
+
ADM

➡ Construction of a model to ecplain them simultaneously

2. Our Model

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

Standard Model
+ $N_i (i = 1,2,3)$ (RH neutrinos)
+ η ($\mathrm{SU}(2)_L$ doublet scalar)

extension →

Our Model

Scotogenic Model
+ σ (real scalar: DM candidate)

σ is assumed to be a few GeV

- **Symmetry**

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathbb{Z}_2$$

$\mathbb{Z}_2$: Stability for DM σ
Radiative ν mass

場	フェルミオン場 L	e_R	N	スカラー場 H	η	σ
$\mathrm{SU}(2)_L$	**2**	**1**	**1**	**2**	**2**	**1**
Z_2	+	+	−	+	−	−

- **Lagrangian**

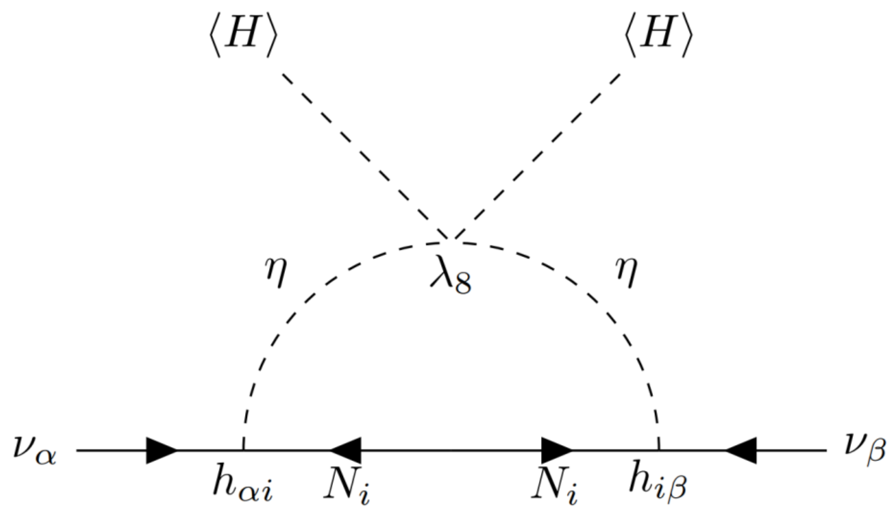
$$\mathcal{L} \supset -\underbrace{h_{\alpha i}\bar{L}_\alpha \tilde{\eta} N_i}_{\text{Yukawa}} + \underbrace{\frac{1}{2} M_i \bar{N}_i N_i^c}_{\text{Majorana mass}}$$

$$V(H,\eta,\sigma) \supset \underbrace{\frac{\lambda_8}{2}\left[(H^\dagger \eta)^2 + h.c.\right]}_{\text{Radiative seesaw}} + \underbrace{\frac{\mu}{\sqrt{2}}\left[\sigma(H^\dagger \eta) + h.c.\right]}_{\text{DM}}$$

2. Our Model

$\mathbb{Z}_2$ forbid Dirac mass instead coupling with η

× : $h_{\alpha i}\,\overline{L_\alpha}\,\tilde{H}\,N_i$ ⟶ ○ : $h_{\alpha i}\,\overline{L_\alpha}\,\tilde{\eta}\,N_i$



⇒ **Mass generation at1-loop**

Radiative generation

- **Neutrino mass matrix**

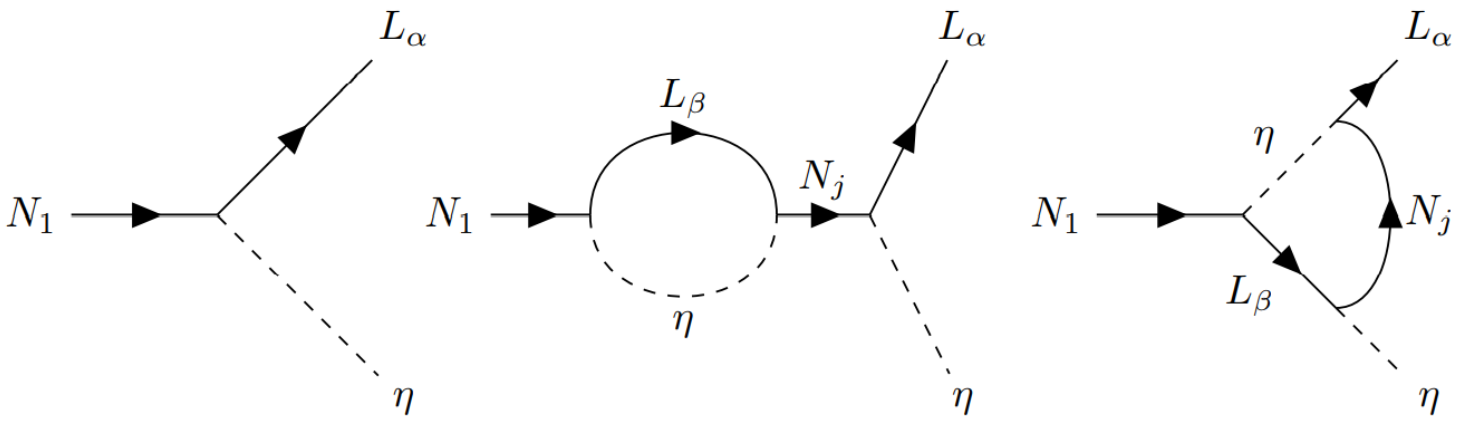
$$(\mathcal{M}_\nu)_{\alpha\beta} \simeq \frac{\lambda_8 v^2}{32\pi^2} \sum_i \frac{h^*_{\alpha i} h^*_{\beta i}}{M_i} \left[\ln \frac{M_i^2}{m_\eta^2} - 1 \right]$$

M_i : RH neutrino mass
m_η : $SU(2)_L$ doublet mass
v : Higgs VEV

λ_8 is key to generate neutrino mass

2. Our Model

Leptogenesis：**Lepton Number creation with RH ν Decay**



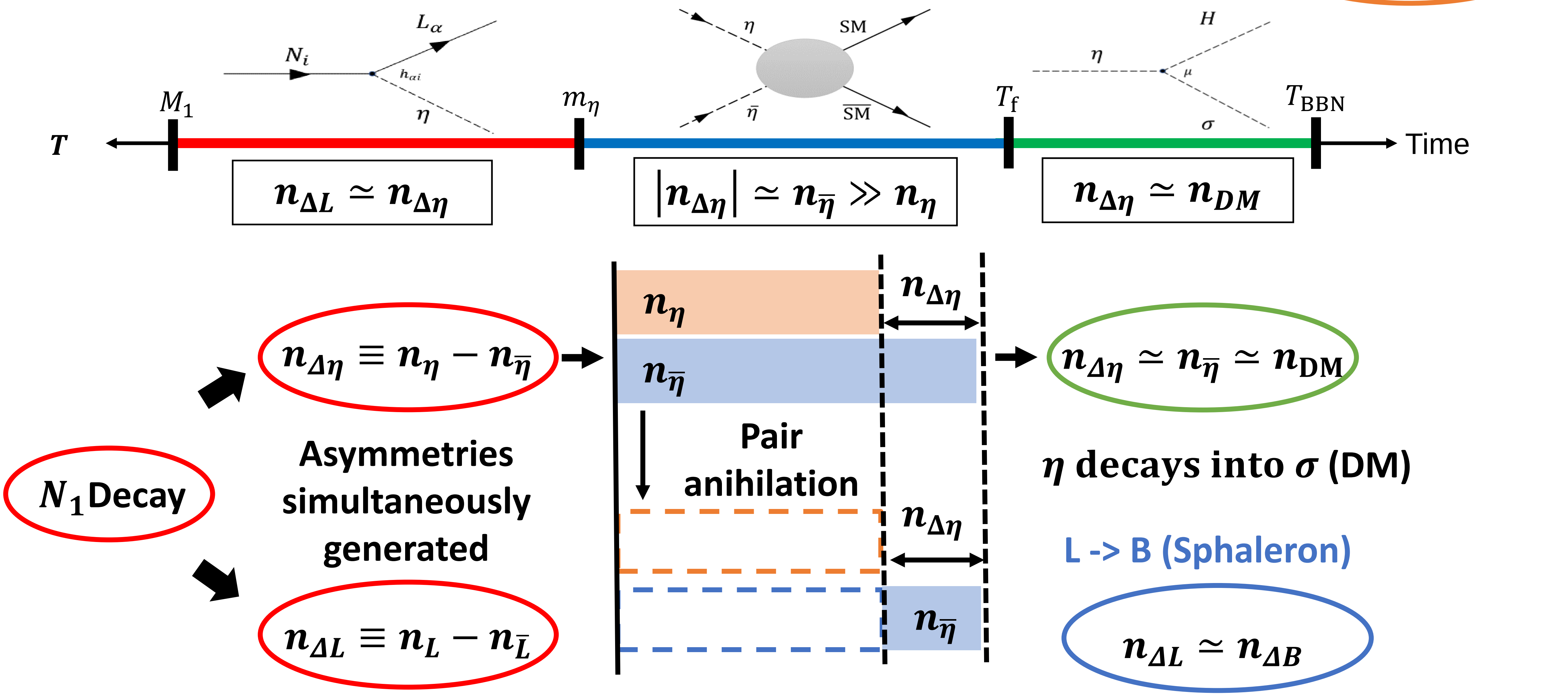
$$\mathcal{L} \supset -h_{\alpha i}\bar{L}_\alpha \tilde{\eta} N_i + \frac{1}{2} M_i \bar{N}_i N_i^c$$

$$V(H,\eta,\sigma) \supset \frac{\lambda_8}{2}\left[(H^\dagger \eta)^2 + h.c.\right] + \frac{\mu}{\sqrt{2}}\left[\sigma(H^\dagger \eta) + h.c.\right]$$

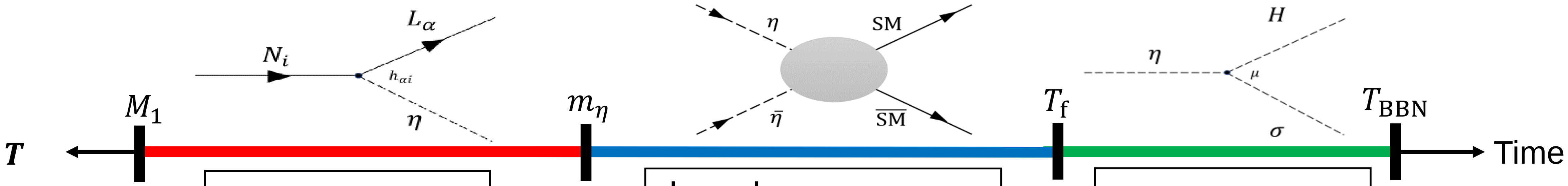
➡ **Violation of Lepton and η number！**

3． How to “create” Dark Matter

Important !



3. How to “create” Dark Matter



$$n_{\Delta L} \simeq n_{\Delta\eta}$$

$$|n_{\Delta\eta}| \simeq n_{\bar{\eta}} \gg n_\eta$$

$$n_{\Delta\eta} \simeq n_{DM}$$

Finally

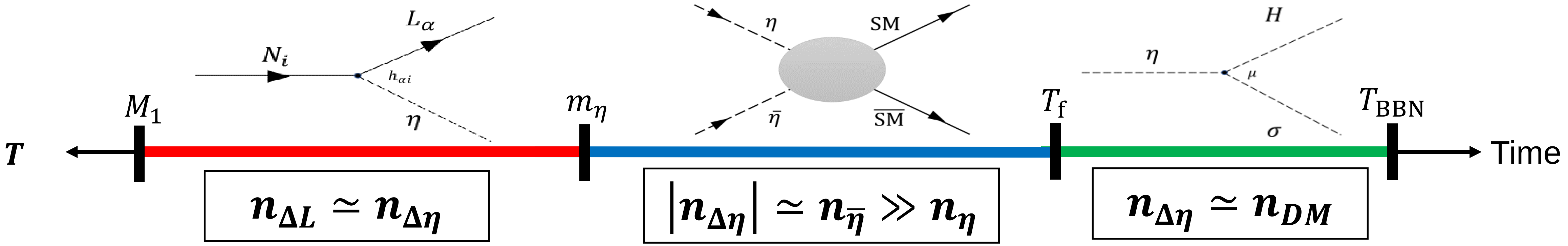
$$n_{\Delta B} \simeq \underline{n_{\Delta L} \simeq n_{\Delta\eta} \simeq n_{\bar{\eta}}} \simeq n_{\text{DM}}$$

Connecting Baryon # and DM # via $\Delta\eta$

➡ **Asymmetric Mediator**

Mass of $\boldsymbol{\sigma}$ $\sim\mathbf{GeV}$

3． How to “create” Dark Matter



Finally

$$n_{\Delta B} \simeq \underline{n_{\Delta L} \simeq n_{\Delta\eta}} \simeq n_{\bar{\eta}} \simeq n_{\mathrm{DM}}$$

Important thing :To keep $n_{\Delta L} \simeq n_{\Delta\eta}$

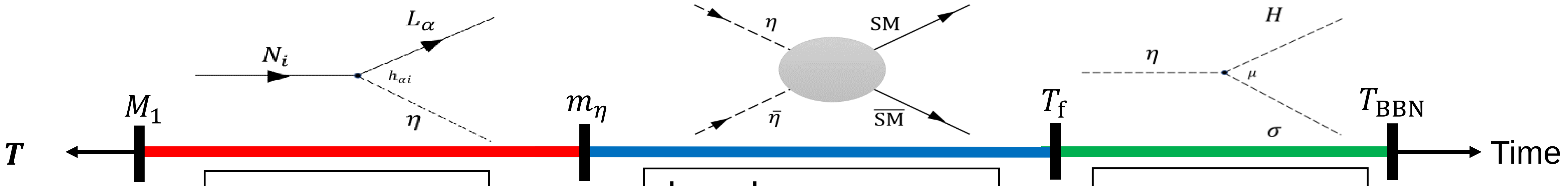
Interactions — M_1, m_η, T_f, T_dec, T_BBN → Time

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

Changing $n_{\Delta\eta}$

No process $\eta\eta \to HH$

What are important in our scenario



$n_{\Delta L} \simeq n_{\Delta\eta}$ | $|n_{\Delta\eta}| \simeq n_{\bar{\eta}} \gg n_\eta$ | $n_{\Delta\eta} \simeq n_{DM}$

①No $\eta\eta \to HH$

②Complete pair anihilation η

③ σ created finally

$$\lambda_8 < 3.9 \times 10^{-8}\sqrt{m_\eta/\text{GeV}}$$

$Y_\eta^{\text{f}} \ll Y_{\Delta\eta}$

Y_η^{f} : entropy ratio

$T_{\text{f}} > T > T_{\text{BBN}}$

T_{f} : freezeout T

T_{BBN} : Big-bang Nucleosynthesis T

λ_8 relevant with ν mass
Baryon number depends on too
Not too be small

Conditions ①②③ are satidfied ?

4． Condition for Baryon Number

Approcimation for B #

$$\eta_B \simeq -0.01\,\epsilon_1\,\kappa_1$$

ϵ_1 : asymmetry parameter
κ_1 : efficiency factor

ϵ_1 and κ_1 are calculated by Yukawa

Casas-Ibarra parametrization

$$h_{\alpha i} = \left(U\, D_\nu^{\frac{1}{2}}\, R^\dagger\, D_\Lambda^{\frac{1}{2}}\right)_{\alpha i} \qquad (\mathcal{D}_\Lambda)_{ii} = \frac{2\pi^2}{\lambda_8}\xi_i \frac{2M_i}{v^2}$$

R complex orthogonal matrix

ϵ_1 is given by ($r_{ij} = M_j/M_i$, $\eta_i = m_\eta/M_i$)

$$\epsilon_i = \frac{1}{8\pi}\frac{1}{(h^\dagger h)_{ii}}\sum_{j\neq i}\mathrm{Im}\left[\left\{(h^\dagger h)_{ij}\right\}^2\right]\frac{1}{\sqrt{r_{ji}}}F(r_{ji},\eta_i)$$

κ_1 is given by

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

$$K_1 = \frac{1}{8\pi}\sqrt{\frac{90}{8\pi^3 g_*}}\frac{M_{\mathrm{Pl}}}{M_1}\left(h^\dagger h\right)_{11}(1-\eta_1)^2$$

if $K_1 > 1$, this is well satisfied

4． Condition for Baryon Number

①No $\eta\eta \to HH$

<-> $\Gamma_{\eta\eta\to HH} < H(T = m_\eta)$

<-> $\lambda_8 < 3.9 \times 10^{-8}\sqrt{m_\eta/\mathrm{GeV}}$

$\lambda_8$contributes neutrino masses

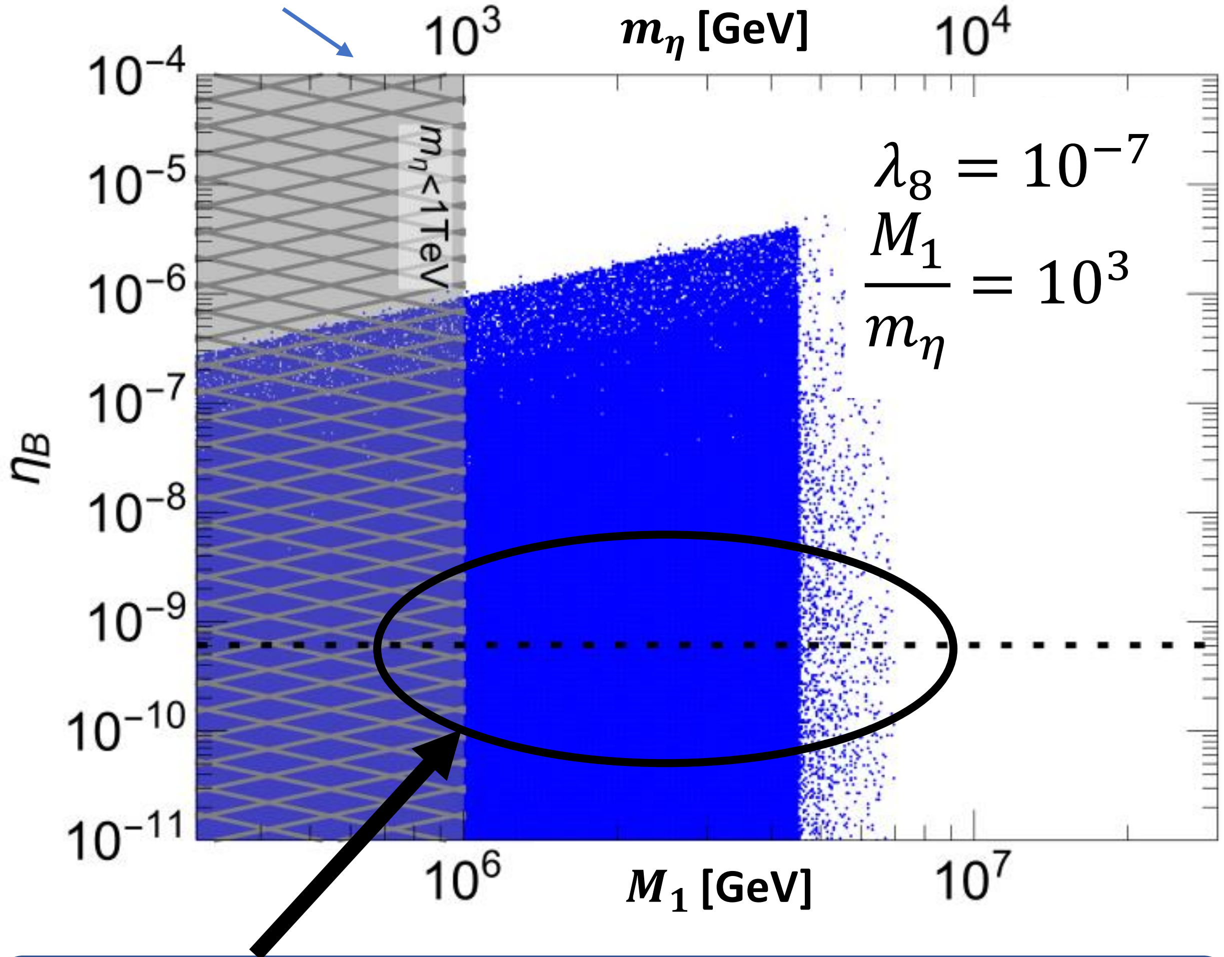
$$(\mathcal{M}_\nu)_{\alpha\beta} \simeq \frac{\lambda_8 v^2}{32\pi^2}\sum_i \frac{h^*_{\alpha i}h^*_{\beta i}}{M_i}\left[\ln\frac{M_i^2}{m_\eta^2} - 1\right]$$

Select parameters so that neutrino oscillation can be explained

Blue： η_B

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

Constraint from accelarator



$\eta_B = \eta_B^{\mathrm{obs}}$ Baryon # can be explained

4． Conditions for pair annihilation of η

② η pair-annihilates sufficiently

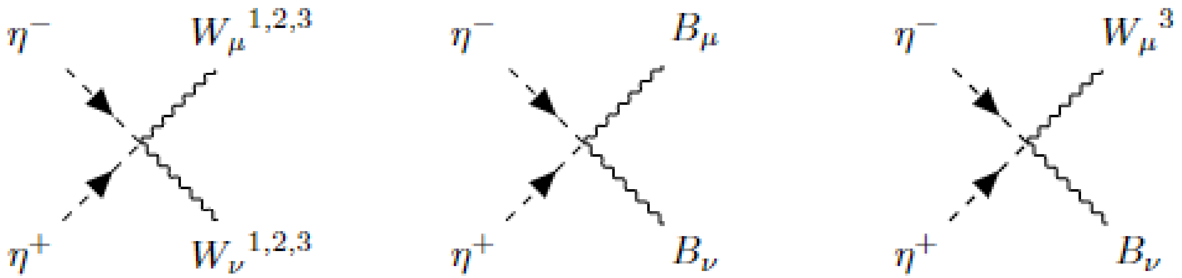
$$Y_\eta^{\mathrm{f}} \ll Y_{\Delta\eta}$$

Note $n_\eta < n_{\bar{\eta}}$

Estimate with following approximation

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

$$x_{\mathrm{f}} \equiv \frac{m_\eta}{T_{\mathrm{f}}} = \ln\left[0.038 \left(g/g_*^{1/2}\right) M_{\mathrm{Pl}} m_\eta \langle \sigma_{\mathrm{g}} v_{\mathrm{rel}} \rangle\right] - \frac{1}{2} \ln\left\{\ln\left[0.038 \left(g/g_*^{1/2}\right) M_{\mathrm{Pl}} m_\eta \langle \sigma_{\mathrm{g}} v_{\mathrm{rel}} \rangle\right]\right\}$$



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

4． Condition for pair annihilation of η

② η pair-annihilates sufficiently

$$Y_\eta^{\mathrm{f}} \ll Y_{\Delta\eta}$$

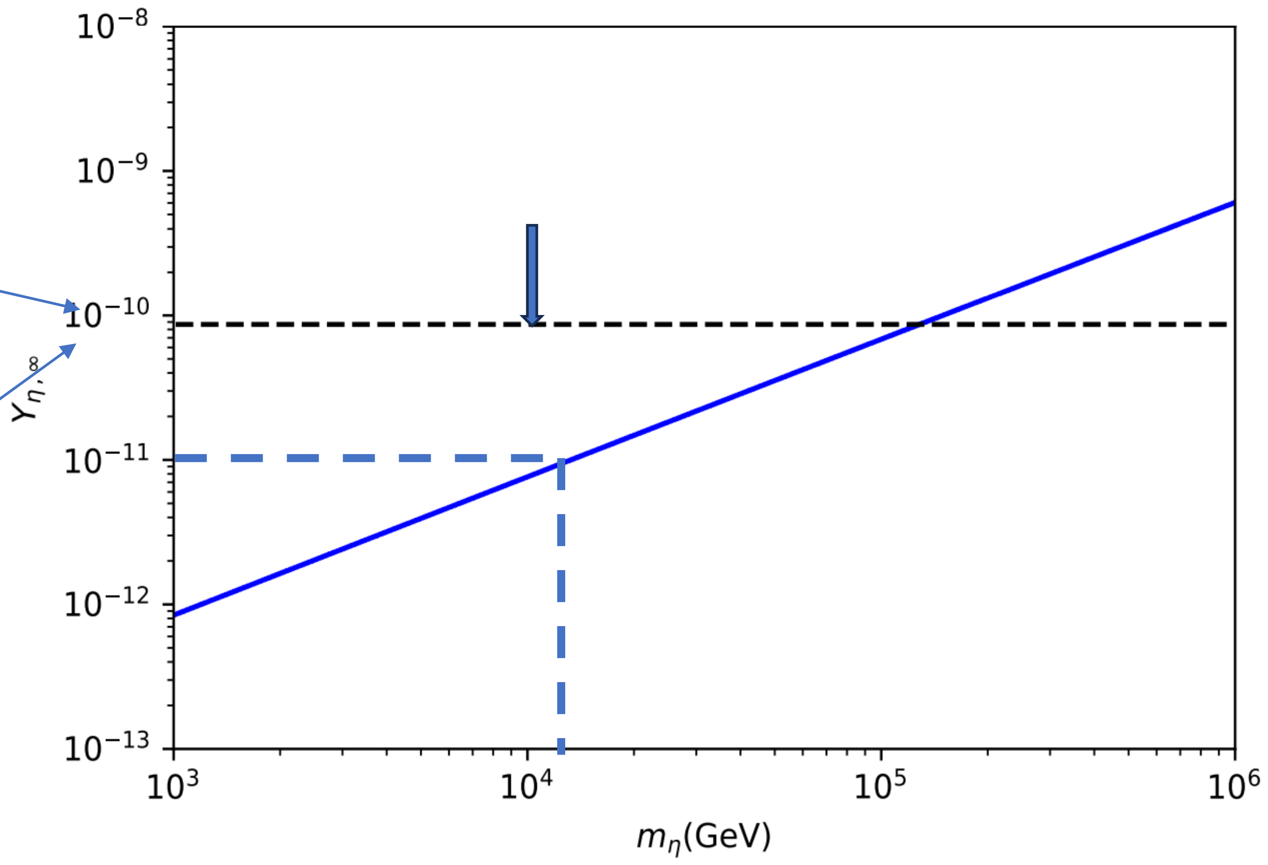
Under this line

Note $n_{\Delta\eta} \simeq n_{\Delta B}$

$$\Rightarrow \quad Y_\eta^{\mathrm{f}} \ll Y_{\mathrm{B}}^{\mathrm{obs}}$$

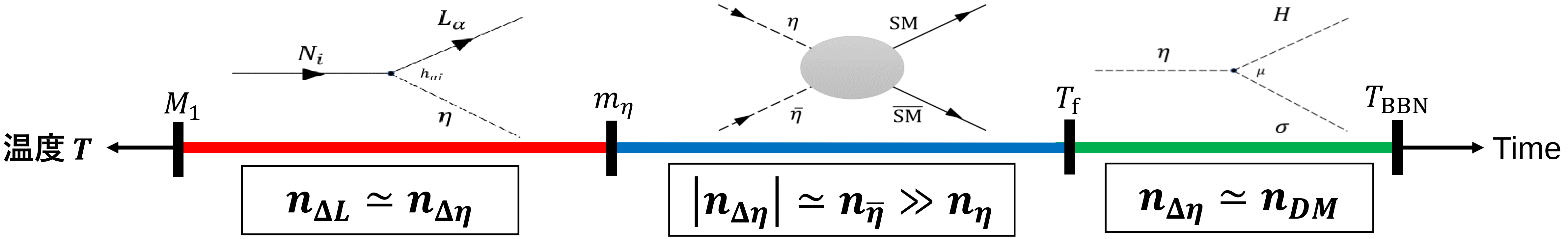
Blue：final Y_η^{f}

Black：$Y_B^{\mathrm{obs}} = 8.7 \times 10^{-11}$



$$m_\eta \sim 10^4\ \mathrm{GeV}$$

4. Condition for asymmetric Dark Matter



③ σ is produced finally by decay of η

$T_{\text{f}} > T > T_{\text{BBN}}$

$$\Rightarrow \quad 8.4 \times 10^{-12} \sqrt{\frac{m_\eta}{[\text{GeV}]}} < \frac{\mu}{\text{Gev}} < 3.8 \times 10^{-10} \frac{T_{\text{f}}}{m_\eta / 22} \left(\frac{m_\eta}{\text{GeV}}\right)^{\frac{3}{2}}$$

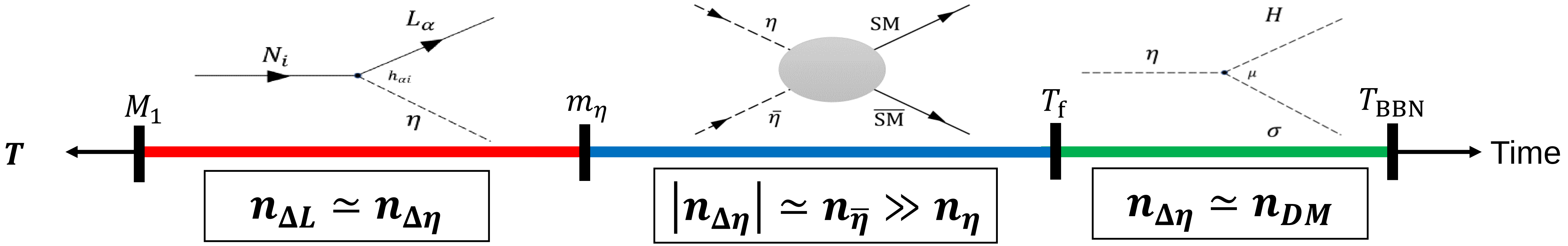
T_{f} : freez-out of pair annih.

T_{BBN} : Big-bang Nuclepsynthesis

As a whole

$$m_\eta \sim 10^4 \text{GeV}, \quad \lambda_8 < 10^{-8} \left(\frac{m_\eta}{\text{GeV}}\right)^{\frac{1}{2}}, \quad 10^{-11} \left(\frac{m_\eta}{\text{GeV}}\right)^{\frac{1}{2}} < \frac{\mu}{\text{Gev}} < 10^{-10} \left(\frac{m_\eta}{\text{GeV}}\right)^{\frac{3}{2}}$$

5． Summary



We study a Scotogenic Model with a real scalar

① **Decay of RH N_1 : Lepton # generation**

② **The mediator η pair-annihilate with keeping asymmetry $n_{\Delta\eta}$**

③ **DM σ is produced by η decay**

Summay

「Dark Matter」 「Neutrino Oscillation」
「Baryon Asymmetry」 「Asymmetric DM condition $\Omega_{\rm DM} / \Omega_B \simeq 5$ 」

can be simultaneously explained in one framework !