Asymmetric Mediator in Scotogenic Model

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New perspectives on flavor and symmetries in particle physics
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Based on **K. Asai**, Y. Sakai, J. Sato, Y. Takanishi, and M. Yamanaka, PLB 836 (2023) 137627, arXiv:2209.08257
K. Asai, S. Enomoto, T. Hirose, and M. Yamanaka, arXiv:2512.14271

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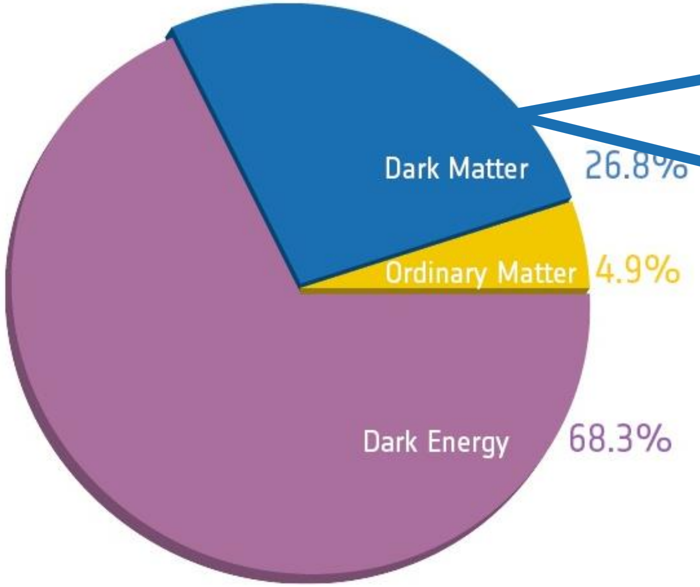
Motivation of BSM

Measurement of Cosmic Microwave Background (CMB) suggests existence of dark matter and baryon asymmetry



<u>Dark matter</u>

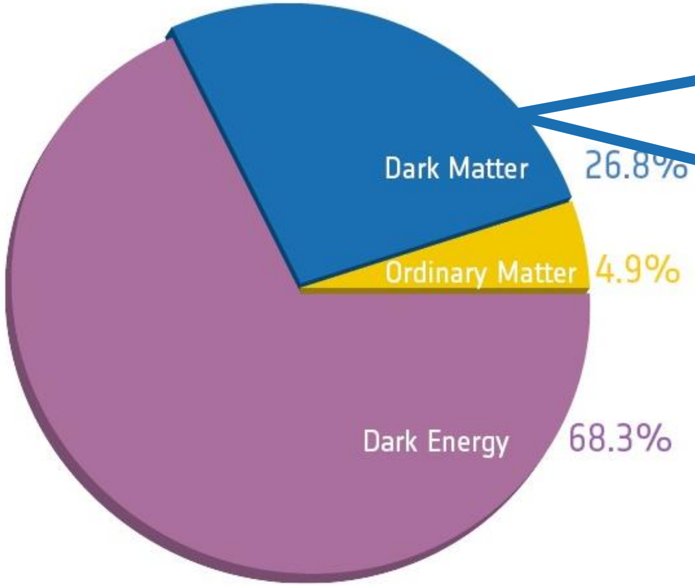
Conditions should be satisfied

・non-baryon ・massive ・zero EM charge

➡ Neutrinos ?

Motivation of BSM

Measurement of Cosmic Microwave Background (CMB) suggests existence of dark matter and baryon asymmetry



<u>Dark matter</u>

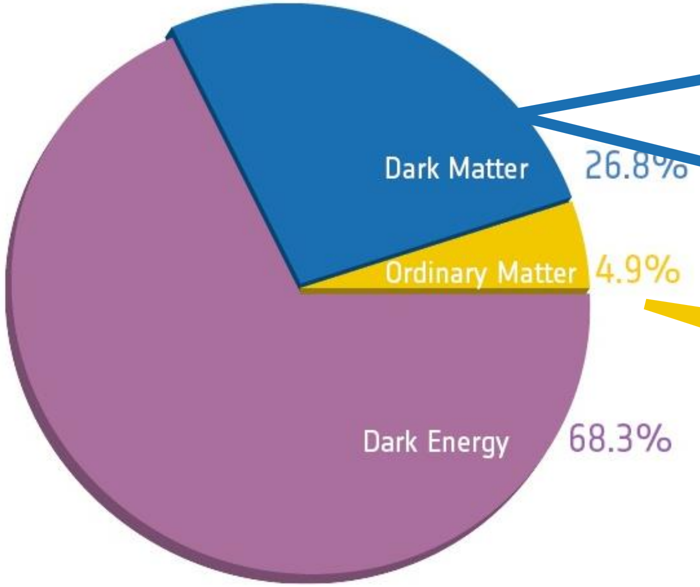
Conditions should be satisfied

・non-baryon ・massive ・zero EM charge

➡ ~~Neutrinos ?~~ Too long free-streaming scale (hot DM)

Motivation of BSM

Measurement of Cosmic Microwave Background (CMB) suggests existence of dark matter and baryon asymmetry



Dark matter

Conditions should be satisfied

・non-baryon ・massive ・zero EM charge

⇒ Neutrinos ? ✗ Too long free-streaming scale (hot DM)

Baryon asymmetry

SM does not satisfy Sakharov's three conditions

・Baryon number violation ✅
・C & CP violation ❌
・Departure from thermal equilibrium ❌

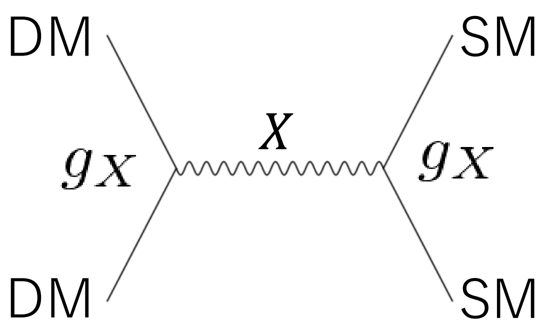
⇒ ~~Electroweak baryogenesis~~

Dark matter

Candidate in BSM model

- Weakly Interacting Massive Particle (WIMP)
- Strongly Interacting Massive Particle (SIMP)
- Axion / Axion-like Particle (ALP)
- Sterile Neutrino

⋮



DM production scenario

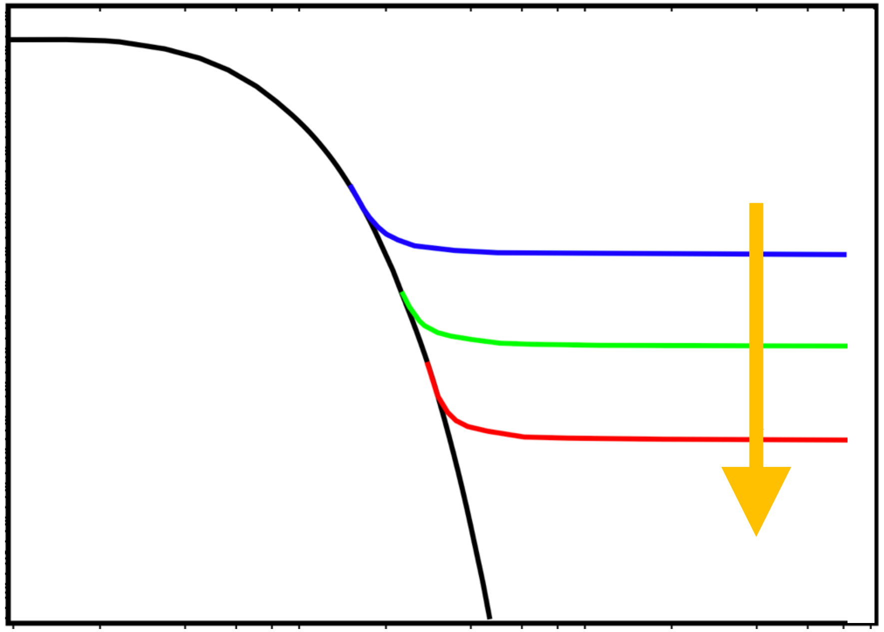
e.g.)

- Thermal freeze-out mechanism

  DM is produced at a breath and reduced by **annihilation**

  int. rate ↗ ➡ DM relic density ↘

$$\Omega_{\rm DM} \propto m_{\rm DM} n_{\rm DM} \simeq 0.1 \times \left(\frac{10^{-9}\,{\rm GeV}^2}{\langle \sigma_{\rm ann} v \rangle} \right)$$



Baryogenesis

Candidate in BSM model

- Electroweak baryogenesis
- Leptogenesis
- Affleck-Dine baryogenesis
- baryogenesis via neutrino oscillations

⋮

Leptogenesis scenario

Heavy Majorana neutrino

⬇ CP-violating decay

Lepton asymmetry

⬇ Sphaleron process

Baryon asymmetry

$$\Omega_{\mathrm{B}} \propto \frac{n_{\mathrm{B}}}{n_\gamma} \simeq -0.01\epsilon\kappa$$

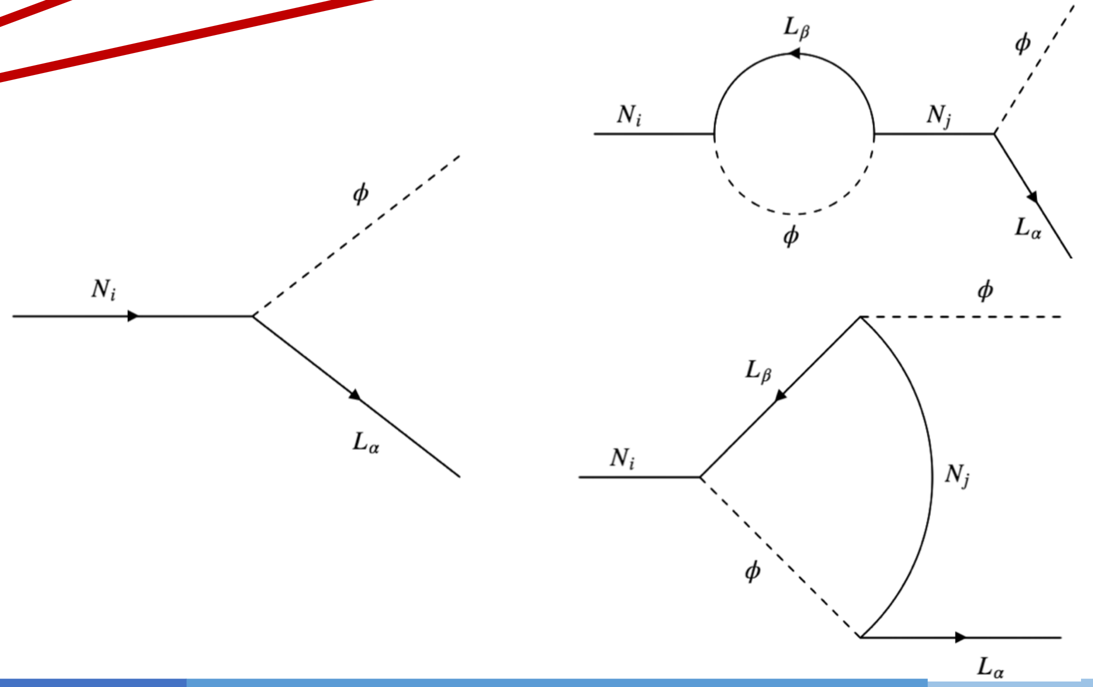
Dirac mass term

➡ Non-zero ν mass

Seesaw mechanism

P. Minkowski (1977); T. Yanagida (1979); M. Gell-Mann, P. Ramond, and R. Slansky (1979); R. N. Mohapatra and G. Senjanovic (1980)

➡ Lightness of active ν



Coincidence Problem

Energy densities of baryon and dark matter are close each other

$$\Omega_{\rm DM} : \Omega_B \sim 5 : 1$$

➡ Dark matter and baryon asymmetry are individually generated by different mechanism

➡ Why are $\Omega_{\rm DM}$ and $\Omega_{\rm B}$ close each other ?

Coincidence Problem

Why are Ω_{DM} and Ω_{B} close each other ?

Answer 1 :

No theoretical reason. Accidentally.

Answer 2 :

Anthropic requirement. Too small $\Omega_{\mathrm{B}}/\Omega_{\mathrm{DM}}$ cause failed star formation

Tegmark, Aguirre, Ree, Wilczek (2006)

Answer 3 :

Mechanism connecting DM and baryon generation

➡ Asymmetric dark matter

Barr, Chivukula, Farhi (1990); Kaplan (1992); Kaplan, Luty, Zurek (2009);

Asymmetric DM

Basic idea

DM relic density is realized by DM-anti DM annihilation

$$\eta_{\rm DM} = \left(n_{\rm DM} - n_{\overline{\rm DM}}\right)/n_\gamma, \qquad \eta_{\rm B} = \left(n_{\rm B} - n_{\overline{\rm B}}\right)/n_\gamma$$

DM relic density = DM asymmetry

- DM & baryon asymmetries have a common origin, and then

$$\eta_{\rm DM}/\eta_{\rm B} = \mathcal{O}(1)$$

- DM mass is $\sim 5\,{\rm GeV}$,

Why $m_{\rm DM} = \mathcal{O}(1)\,{\rm GeV}$?

$$\Omega_{\rm DM}/\Omega_{\rm B} = m_{\rm DM} n_{\rm DM}/m_{\rm B} n_{\rm B}$$
$$= (m_{\rm DM}/m_{\rm B}) \times (\eta_{\rm DM}/\eta_{\rm B}) \sim 5$$

Coincidence problem is partially solved

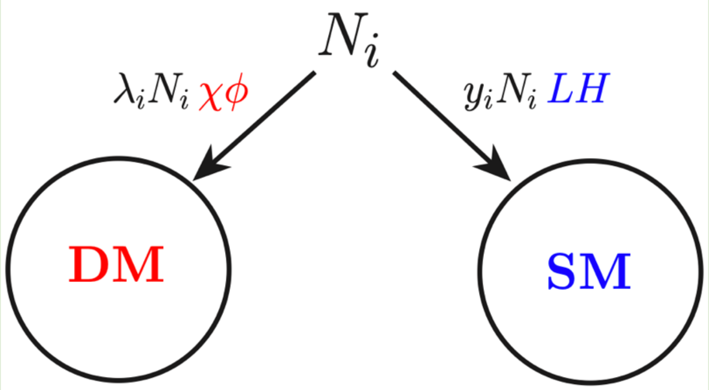
Cogenesis

Cogenesis in leptogenesis scenario

Falkowski, Ruderman, Volansky (2011)

heavy ν decay → $B-L$ asymmetry —sphaleron→ B asymmetry
heavy ν decay → DM asymmetry

Asymmetries of lepton and DM are generated by CP-violating heavy neutrino decays



○ Lagrangian

$$\mathcal{L} = y_i N_i^c (L\cdot H) + \lambda_i N_i^c \chi\phi + \frac{1}{2} M_i N_i^c N_i^c + \text{H.c.}$$

where $y_1, \lambda_1 \in \mathbb{R}, \quad y_2 = |y_2| e^{i\phi_l}, \quad \lambda_2 = |\lambda_2| e^{i\phi_\chi}$

e.g.) standard leptogenesis

$$\Omega_B \propto \frac{n_B}{n_\gamma} \simeq -0.01\epsilon\kappa$$

○ Asymmetry parameter (asymmetry generation per one N_R decay)

$$\frac{\epsilon_l}{\epsilon_\chi} \simeq \frac{2r\sin(2\phi_l) + \sin(\phi_l + \phi_\chi)}{2r^{-1}\sin(2\phi_\chi) + \sin(\phi_l + \phi_\chi)} \sim r$$

where $r = y_1 |y_2| / (\lambda_1 |\lambda_2|)$

Condition for $\Omega_{DM}/\Omega_B = \mathcal{O}(1)$

- $m_{DM}/m_B, r = \mathcal{O}(1)$
- $r = \mathcal{O}(1)$
- washout factor : $\kappa_l \sim \kappa_\chi$

Cogenesis

Cogenesis in leptogenesis scenario

Falkowski, Ruderman, Volansky (2011)

heavy ν decay → $B-L$ asymmetry —sphaleron→ B asymmetry
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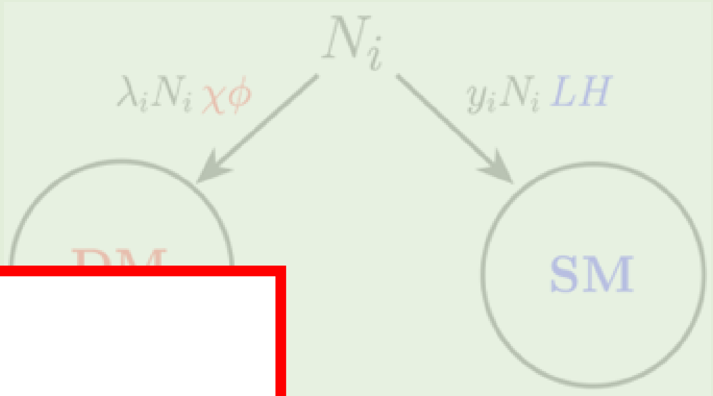


Asymmet…
by CP-vi…

○ Lagrangian

$\mathcal{L} = y_i N_i^c$ …

where $y_1, \lambda_1 \in \mathbb{R}, \quad y_2 = |y_2| e^{i\phi_l}, \quad \lambda_2 = |\lambda_2| e^{i\phi_\chi}$

…ard leptogenesis

$\frac{n_B}{n_\gamma} \simeq -0.01\epsilon\kappa$

Too many conditions

➡ **More simple and natural realization of $\Omega_{\rm DM}/\Omega_{\rm B} = \mathcal{O}(1)$ by cogenesis ?**

○ Asymmetry parameter (asymmetry generation per one N_R decay)

$$\frac{\epsilon_l}{\epsilon_\chi} \simeq \frac{2r\sin(2\phi_l) + \sin(\phi_l + \phi_\chi)}{2r^{-1}\sin(2\phi_\chi) + \sin(\phi_l + \phi_\chi)} \sim r$$

where $r = y_1|y_2|/(\lambda_1|\lambda_2|)$

Condition for $\Omega_{\rm DM}/\Omega_{\rm B} = \mathcal{O}(1)$

- $m_{\rm DM}/m_{\rm B}, r = \mathcal{O}(1)$
- washout factor : $\kappa_l \sim \kappa_\chi$

New idea

Motivation

We want to realize cogenesis in more simple and natural model

Idea

SM fields (Z_2 even)

+ right-handed neutrinos (Z_2 odd) : N_R

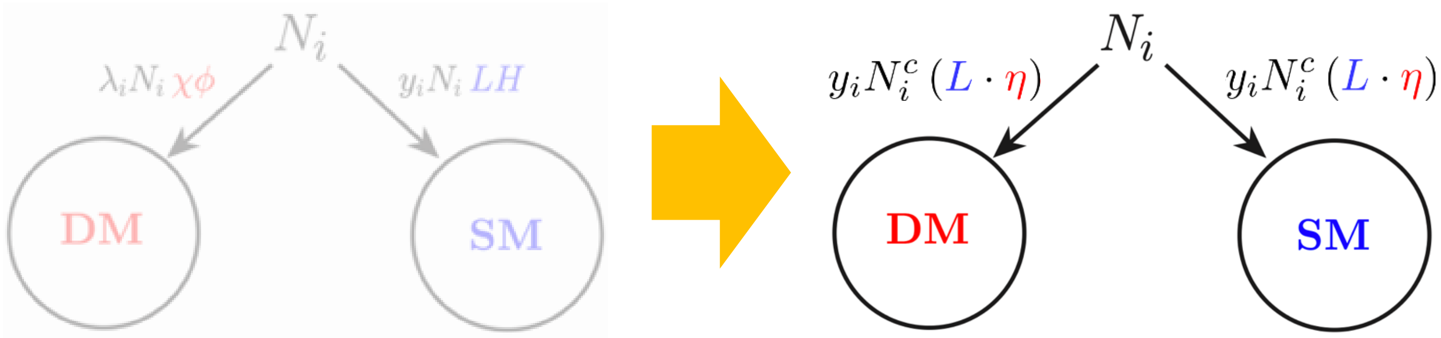
+ neutrinophilic $\mathrm{SU(2)}_L$ doublet scalar (Z_2 odd) : η

Z_2 symmetry

- prohibit $y_i N_i^c (L \cdot H)$
- DM stability

○ Lagrangian

$$\mathcal{L} = y_i N_i^c (L \cdot \eta) + \frac{1}{2} M_i N_i^c N_i^c$$

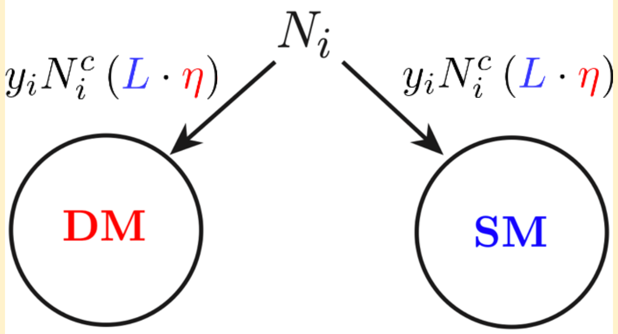


New idea

○ Cogenesis

N_i decay → $B-L$ asymmetry $\xrightarrow{\text{sphaleron}}$ B asymmetry

N_i decay → η (DM) asymmetry



$$\eta_{\rm B} = \frac{28}{79}\eta_{\rm B-L} = \frac{28}{79}\eta_{\rm DM}$$

➡ $\eta_{\rm B} \sim \eta_{\rm DM}$ is naturally realized

$$\Omega_{\rm DM} : \Omega_B \sim 5 : 1$$

$$m_{\rm DM} = \left(\frac{\Omega_{\rm DM}}{\Omega_{\rm B}}\right)\left(\frac{\eta_{\rm DM}}{\eta_{\rm B}}\right)^{-1} m_B \simeq 5 \times \left(\frac{79}{28}\right)^{-1} \times 1\,{\rm GeV} \simeq 2\,{\rm GeV}$$

Field contents

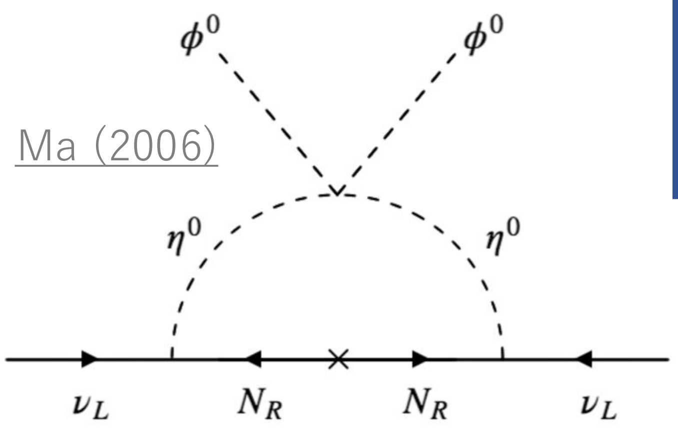
SM fields (Z_2 even)

+ right-handed neutrinos (Z_2 odd) : N_R

+ neutrinophilic $SU(2)_L$ doublet scalar (Z_2 odd) : η

➡ Same fields and symmetry as scotogenic (Ma) model

Scotogenic model



Ma (2006)

○ Field contents

SM fields (Z_2 even)

+ three (or two) right-handed neutrinos (Z_2 odd) : N_R

+ neutrinophilic $SU(2)_L$ doublet scalar (Z_2 odd) : η

$$\eta = \begin{pmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}(\eta_R + i\eta_I) \end{pmatrix}$$

○ Lagrangian

$$\mathcal{L}_Y = \mathcal{L}_{\rm SM} + \left(\bar{L}_\alpha h_{\alpha i} \tilde{\eta}^c N_i - \frac{1}{2} M_i N_i^T N_i + h.c. \right) - V_{\rm scalar}(\phi, \eta)$$

$$V_{\rm scalar}(\phi,\eta) = m_\phi^2 \phi^\dagger \phi + m_\eta^2 \eta^\dagger \eta + \frac{1}{2}\lambda_1 (\phi^\dagger\phi)^2 + \frac{1}{2}\lambda_2(\eta^\dagger\eta)^2 + \lambda_3(\phi^\dagger\phi)(\eta^\dagger\eta)$$
$$+\lambda_4(\phi^\dagger\eta)(\eta^\dagger\phi) + \frac{1}{2}\lambda_8\left[(\phi^\dagger\eta)^2 + h.c.\right]$$

$U(1)_L$ lepton number symmetry is violated ➡ Neutrino mass

But…

Scalar mass

Z_2-odd scalar mass

$$m^2(\eta^\pm) = m_\eta^2 + \lambda_3 v^2 \equiv m_+^2$$

$$m^2(\eta_R^0) = m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_8) v^2 \equiv m_R^2$$

$$m^2(\eta_I^0) = m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_8) v^2 \equiv m_I^2$$

Experimental bound

- Slepton search

$\eta^+ \to \tau^+ \nu_\tau$ ➡ $m(\eta^+) \gtrsim 350\,\mathrm{GeV}$

$\eta^+ \to \mu^+ \nu_\mu$ ➡ $m(\eta^+) \gtrsim 550\,\mathrm{GeV}$

- Z, W boson decay

$$\min(m_R + m_I, 2m_+) < m_Z$$

$$\min(m_R + m_+, m_I + m_+) < m_W$$

- Triviality bound

$$|\lambda_i| < 4\pi$$

Solution ?

$(m_+, m_R, m_I) = (1\,\mathrm{TeV}, 900\,\mathrm{GeV}, 2\,\mathrm{GeV})$

➡ $(\lambda_4, \lambda_8) \simeq (-9.8, 6.7)$

Failed cogenesis (I explain later)

Asymmetric mediator model

K. Asai, Y. Sakai, J. Sato, Y. Takanishi, and M. Yamanaka, PLB 836 (2023) 137627,
arXiv:2209.08257

Extended scotogenic model

○ Field contents

SM fields

+ three right-handed neutrinos : N_R

+ neutrinophilic $SU(2)_L$ doublet scalar : η

+ singlet scalar DM : σ

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

○ Lagrangian

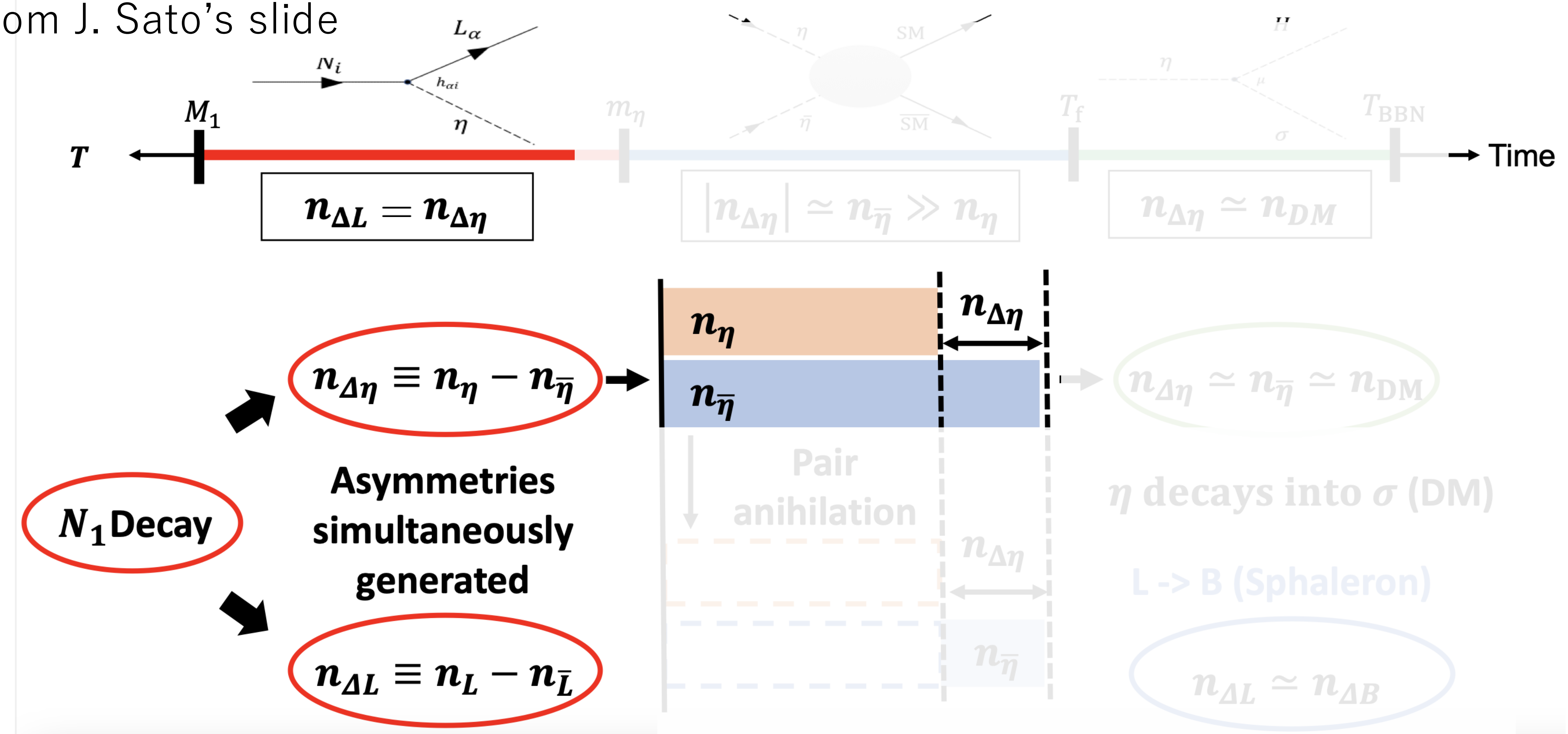
$$\mathcal{L} \supset -h_{\alpha i}\bar{L}_\alpha \tilde{\eta} N_i + \frac{1}{2} M_i \bar{N}_i N_i^c + \text{H.c.} \ ,$$

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

Important for cogenesis

Tales of Cogenesis

From J. Sato's slide



Tales of Cogenesis

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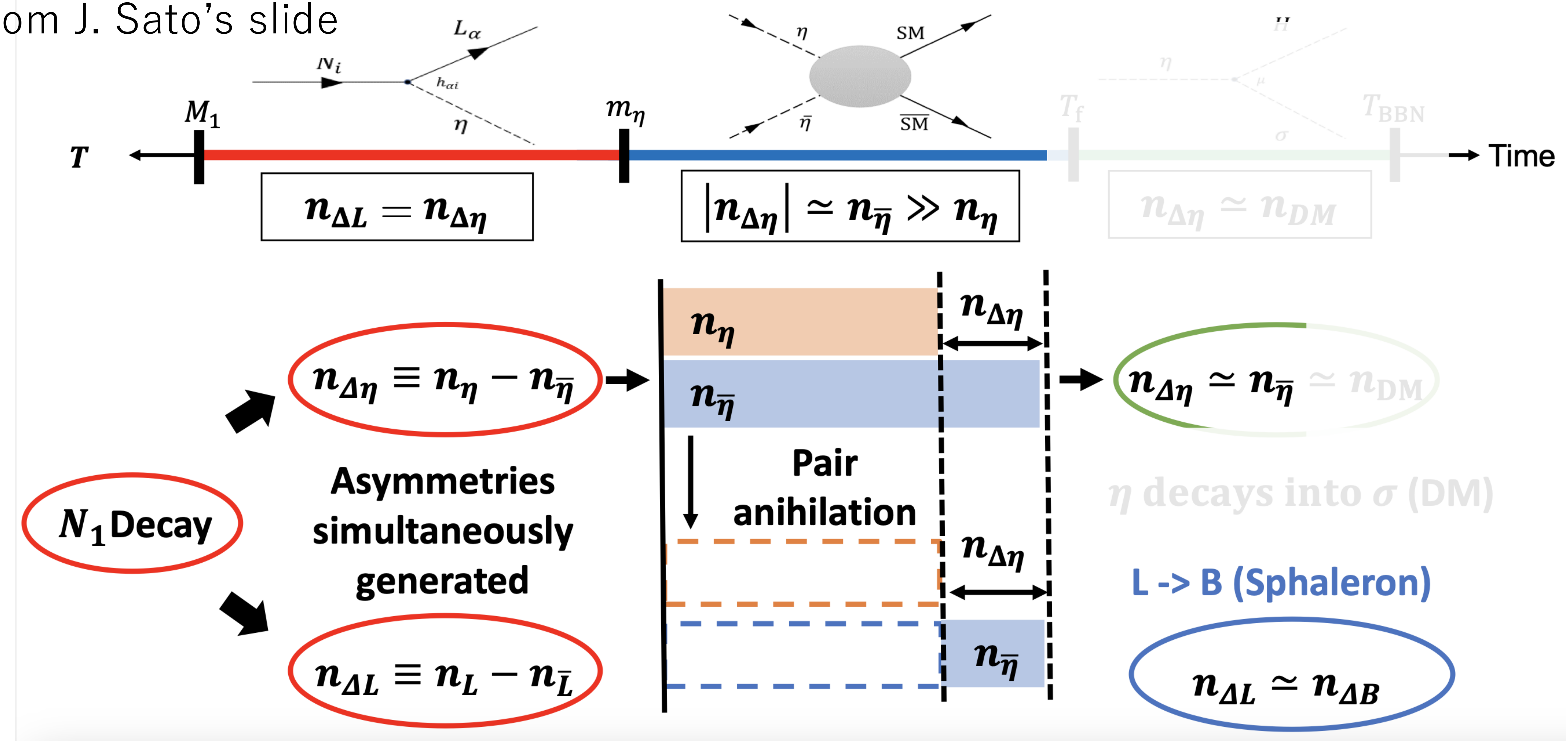

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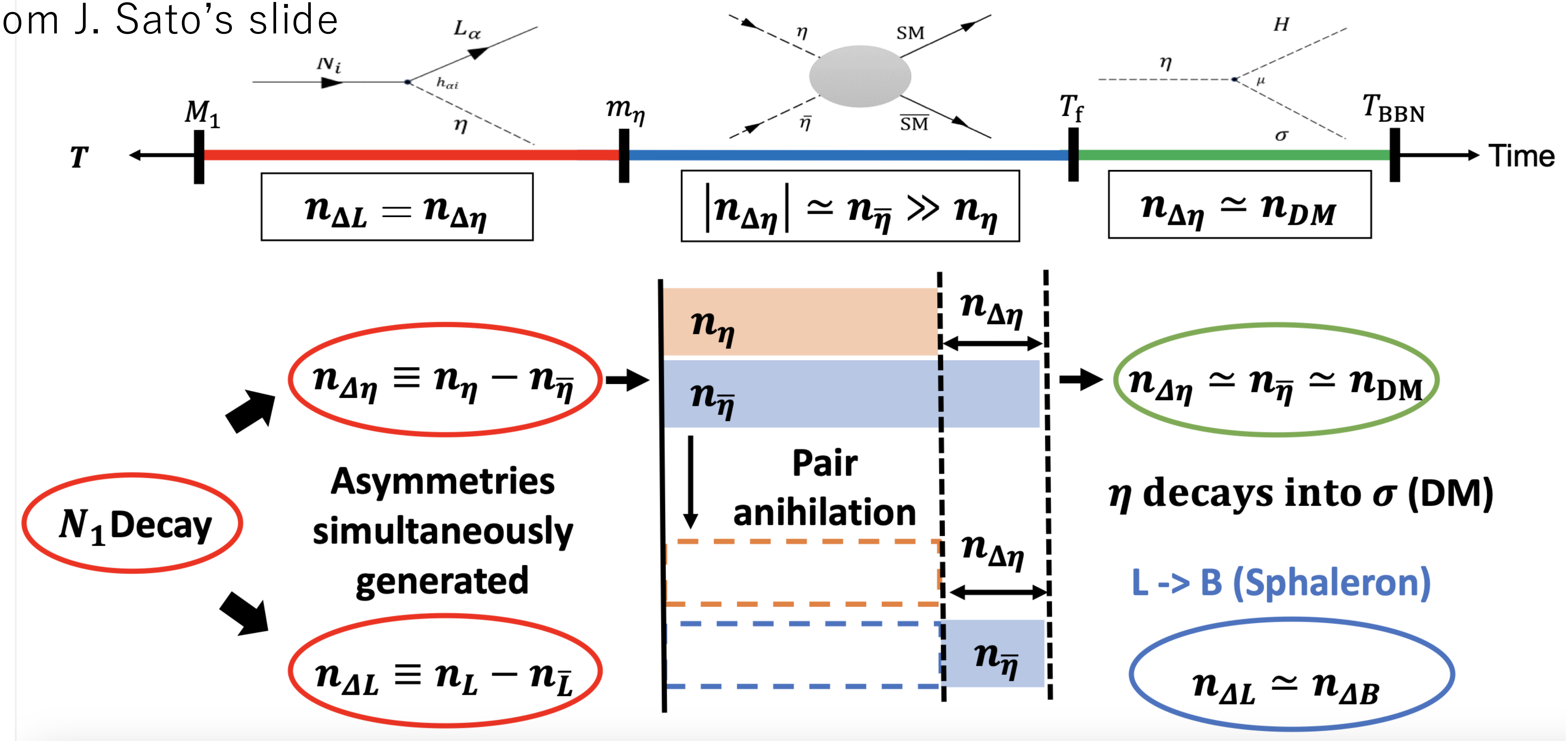

Tales of Cogenesis

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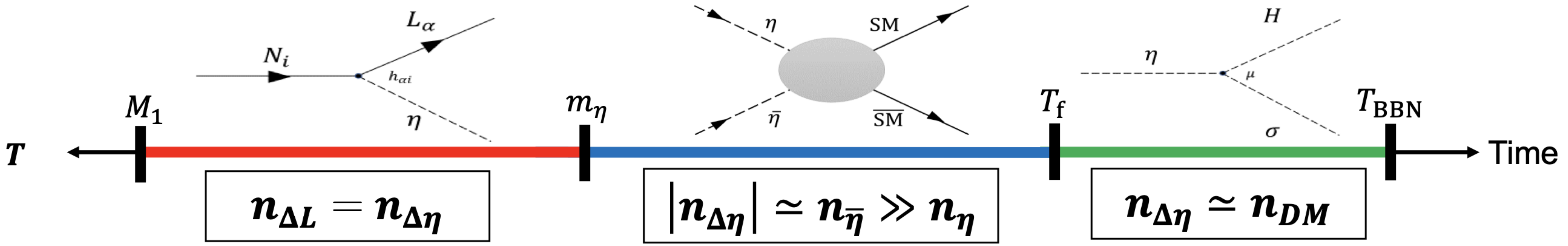


Finally

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

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

➡ **Asymmetric Mediator**

Cogenesis of lepton & mediator asymmetries

(Lepto+Mediato)genesis

Asymmetry parameter

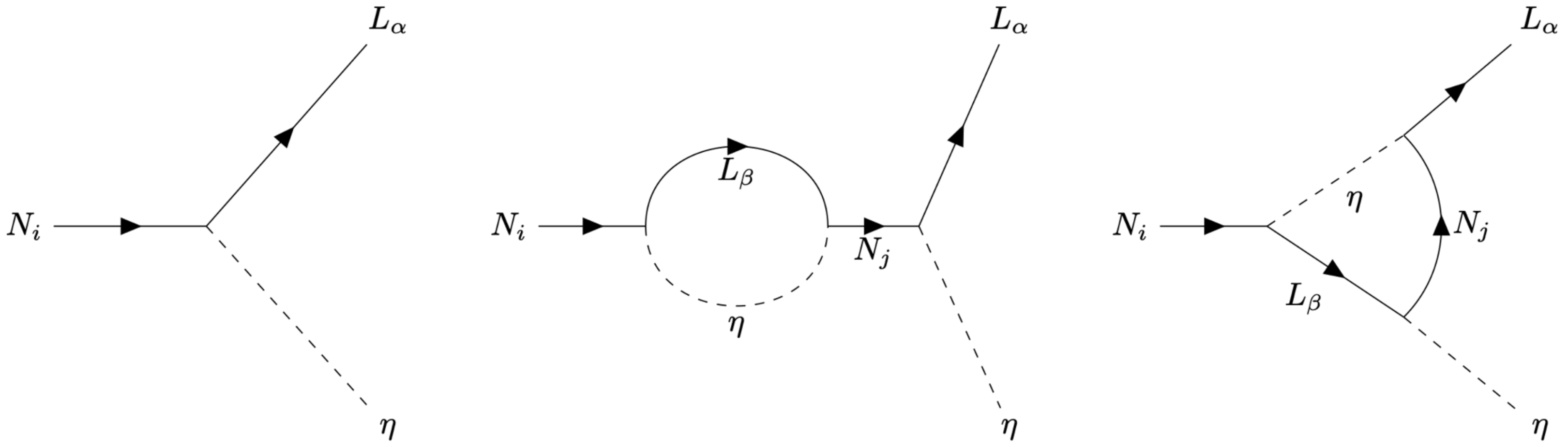
Hugle, Platscher, Schmitz (2018)

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

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

with $\eta_i \equiv m_\eta^2 / M_i^2$, $r_{ji} \equiv M_j^2 / M_i^2$

$$F(x, y) = \sqrt{x}\left[1 + \frac{1 + x - 2y}{(1-y)^2} \ln\left(\frac{x - y^2}{1 + x - 2y}\right) - \frac{1}{x-1}(1-y)^2\right]$$



(Lepto+Mediato)genesis

Decay parameter

Hugle, Platscher, Schmitz (2018)

$$K_1 \equiv \Gamma_1 / H(T = M_1)$$
$$= \frac{2\pi^2}{\lambda_8}\xi_1\sqrt{\frac{45}{64\pi^5 g_*}}\frac{M_{\rm Pl}}{v^2}\,\widetilde{m}_{11}\,(1-\eta_1)^2$$
$$\simeq 15 \cdot \frac{10^{-7}}{\lambda_8}\left(\frac{-10}{\ln(\eta_1)}\right)\frac{\widetilde{m}_{11}}{10^{-10}\,\mathrm{eV}},$$

with
$$\eta_i \equiv m_\eta^2 / M_i^2$$
$$r_{ji} \equiv M_j^2 / M_i^2$$
$$\widetilde{m} \equiv R D_\nu R^\dagger.$$

In this model, lepton asymmetry is generated via strong wash-out regime

Efficiency parameter

Buchmuller, Bari, Plumacher (2005)

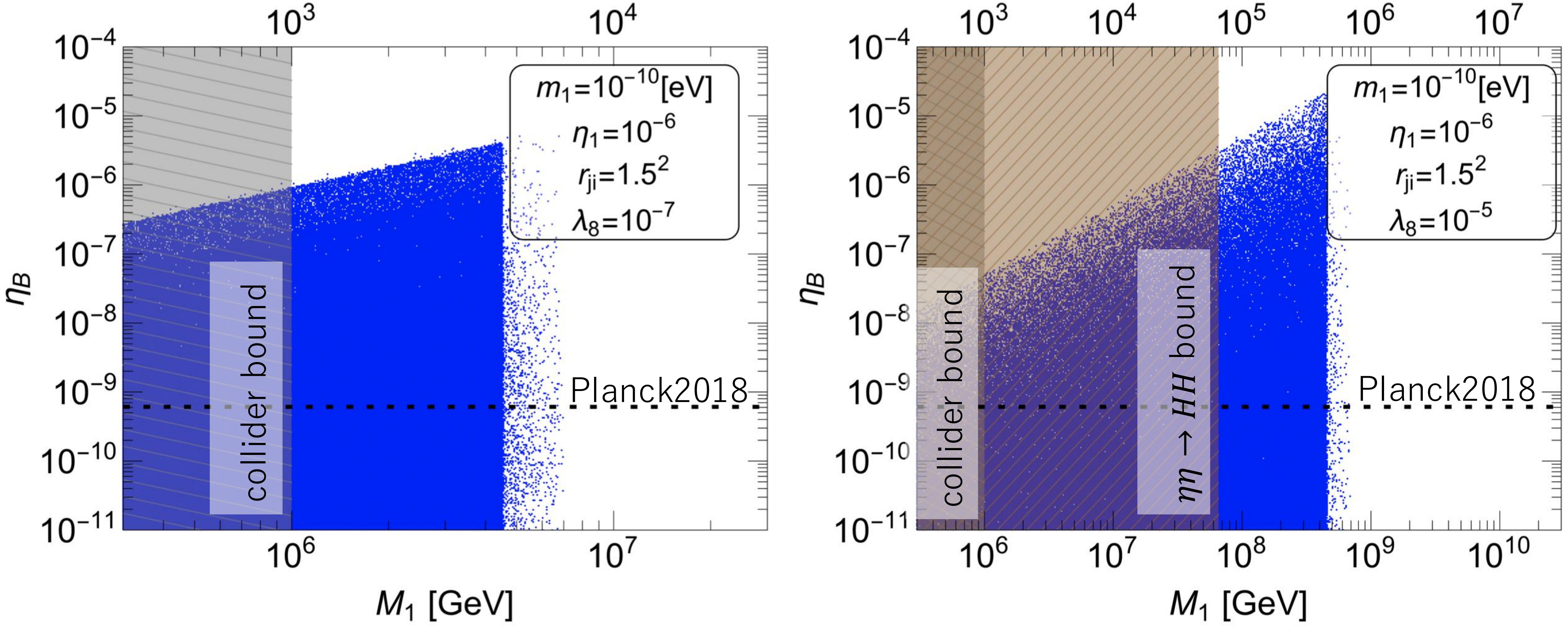
$$\kappa_1(K_1) = \frac{1}{1.2 K_1 [\ln K_1]^{0.8}}$$

Baryon asymmetry

All points satisfy
$\sum m_i < 0.16\,\mathrm{eV}, |h_{\alpha i}| < 1, K_1 > 10$

Result

$\eta_i \equiv m_\eta^2/M_i^2 \quad r_{ji} \equiv M_j^2/M_i^2$



Baryon asymmetry

All points satisfy
$\sum m_i < 0.16\,\mathrm{eV}, |h_{\alpha i}| < 1, K_1 > 10$

Large-η_B boundary

Larger asymmetry

↑

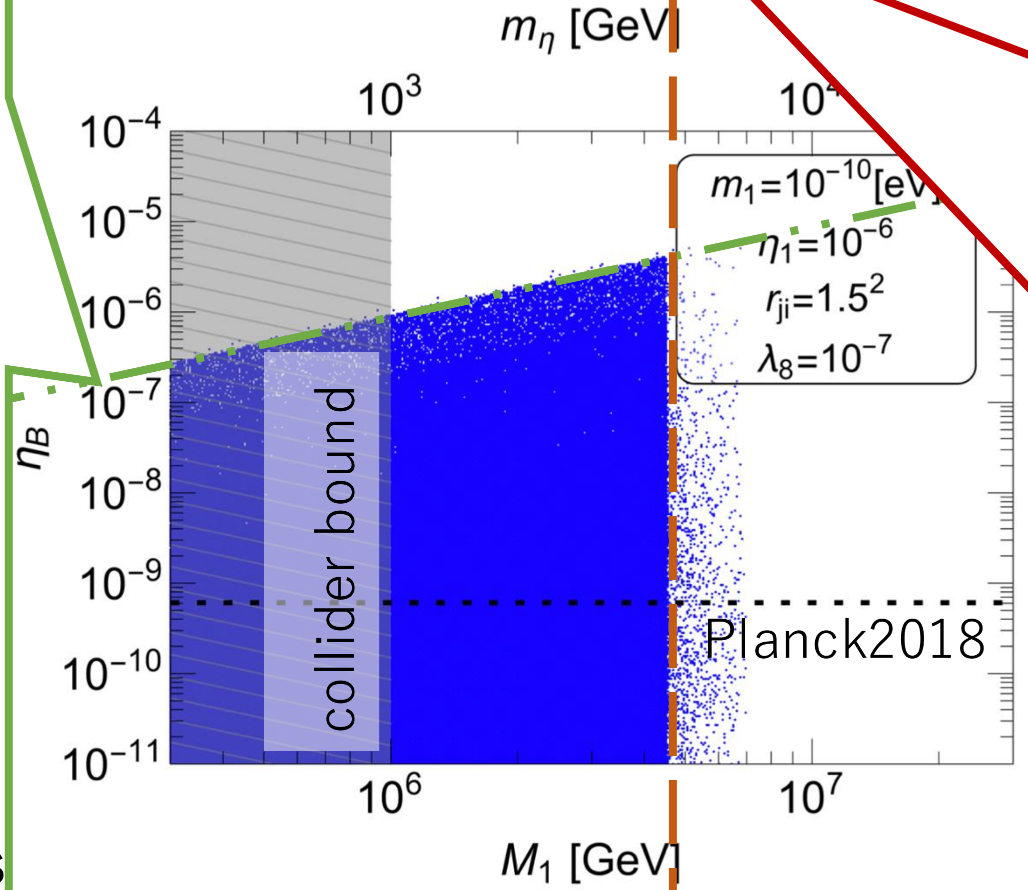
Larger Yukawa coupling

↓

Heavier neutrino mass

↕ tension

Bound on neutrino mass
$\sum m_i < 0.16\,\mathrm{eV}$



Heavy-M_1 boundary

Heavier M_1

↓

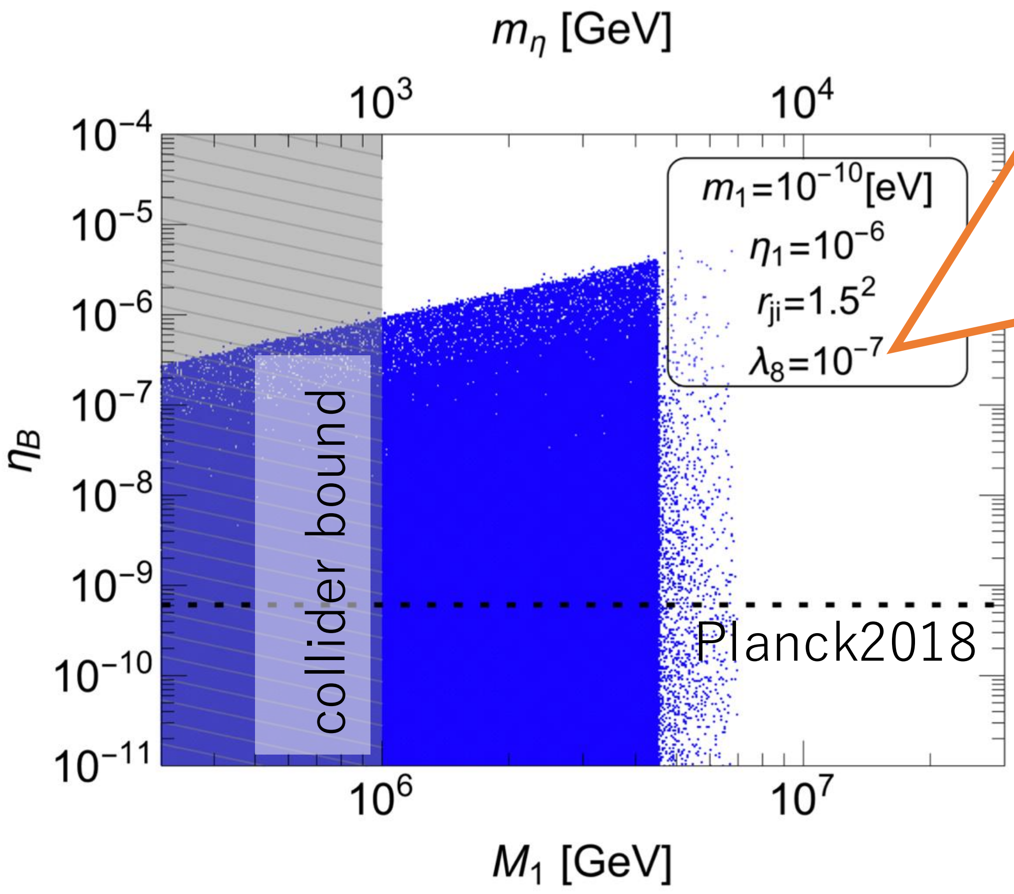
Larger ν Yukawa coupling needs for enough large m_i

↕ tension

Triviality bound
$|h_{\alpha i}| < 1$

Baryon asymmetry

All points satisfy
$\sum m_i < 0.16\,\mathrm{eV}, |h_{\alpha i}| < 1, K_1 > 10$



Small-λ_8 boundary

Smaller λ_8

↓

Lighter M_1 needs for enough large neutrino mass

↓

Mediator mass m_η needs to be lighter

↕ tension

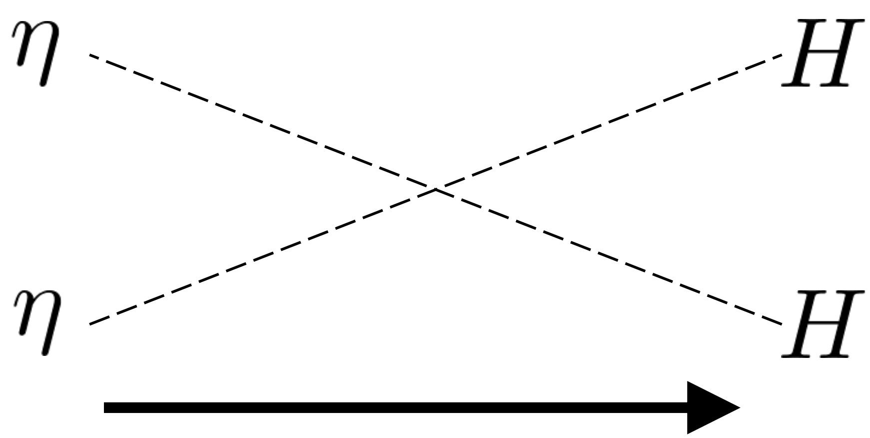
Collider bound on mediator : $m_\eta > 1\,\mathrm{TeV}$

⇒ Too small λ_8 is disfavored

λ_8 bound

λ_8 interaction washes out mediator asymmetry $n_{\Delta\eta}$

$$(\sigma v)_{\eta\eta\to HH} = (\sigma v)_{\eta^\dagger\eta^\dagger\to H^\dagger H^\dagger} = \frac{3\lambda_8^2}{128\pi T^2}$$



Violate important relation

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

λ_8 interaction should be suppressed

$$(\sigma v_{\rm rel})_{\eta\eta\to HH}\, n_{\eta^0} < H(T)$$

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

Reminder

Solution ?

$(m_+, m_R, m_I) = (1\,\mathrm{TeV}, 900\,\mathrm{GeV}, 2\,\mathrm{GeV})$

$\Rightarrow (\lambda_4, \lambda_8) \simeq (-9.8, 6.7)$

Failed cogenesis (I explain later)

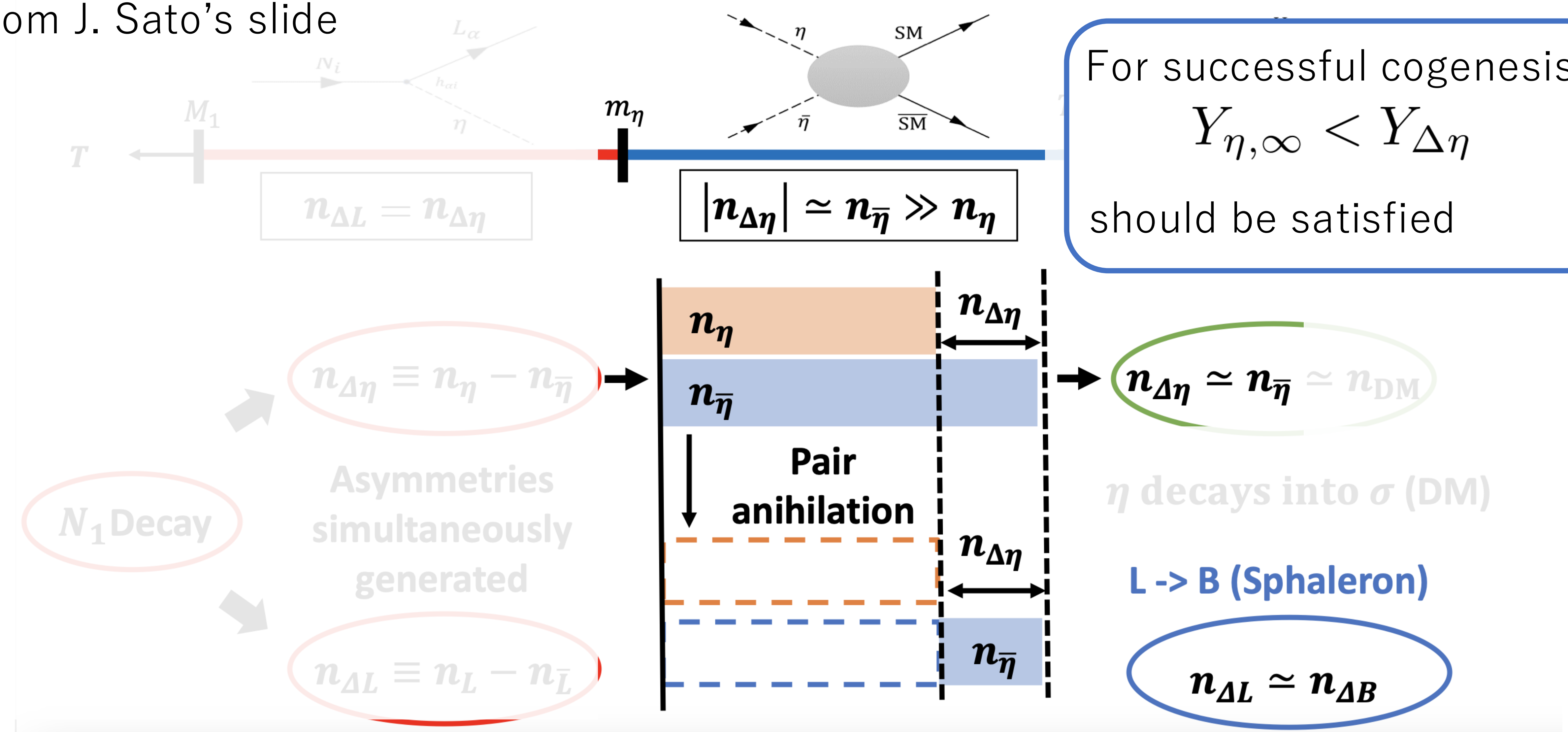
Dark matter abundance

K. Asai, Y. Sakai, J. Sato, Y. Takanishi, and M. Yamanaka, PLB 836 (2023) 137627, arXiv:2209.08257

Precise evaluation → **K. Asai**, S. Enomoto, T. Hirose, and M. Yamanaka, arXiv:2512.14271

Tales of Cogenesis

From J. Sato's slide



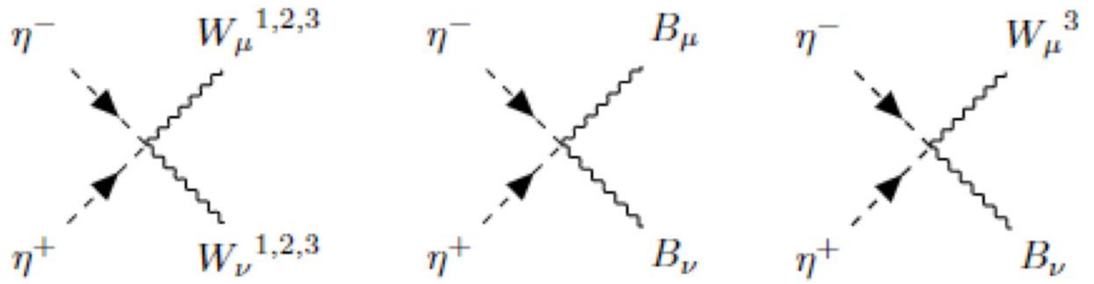
For successful cogenesis,

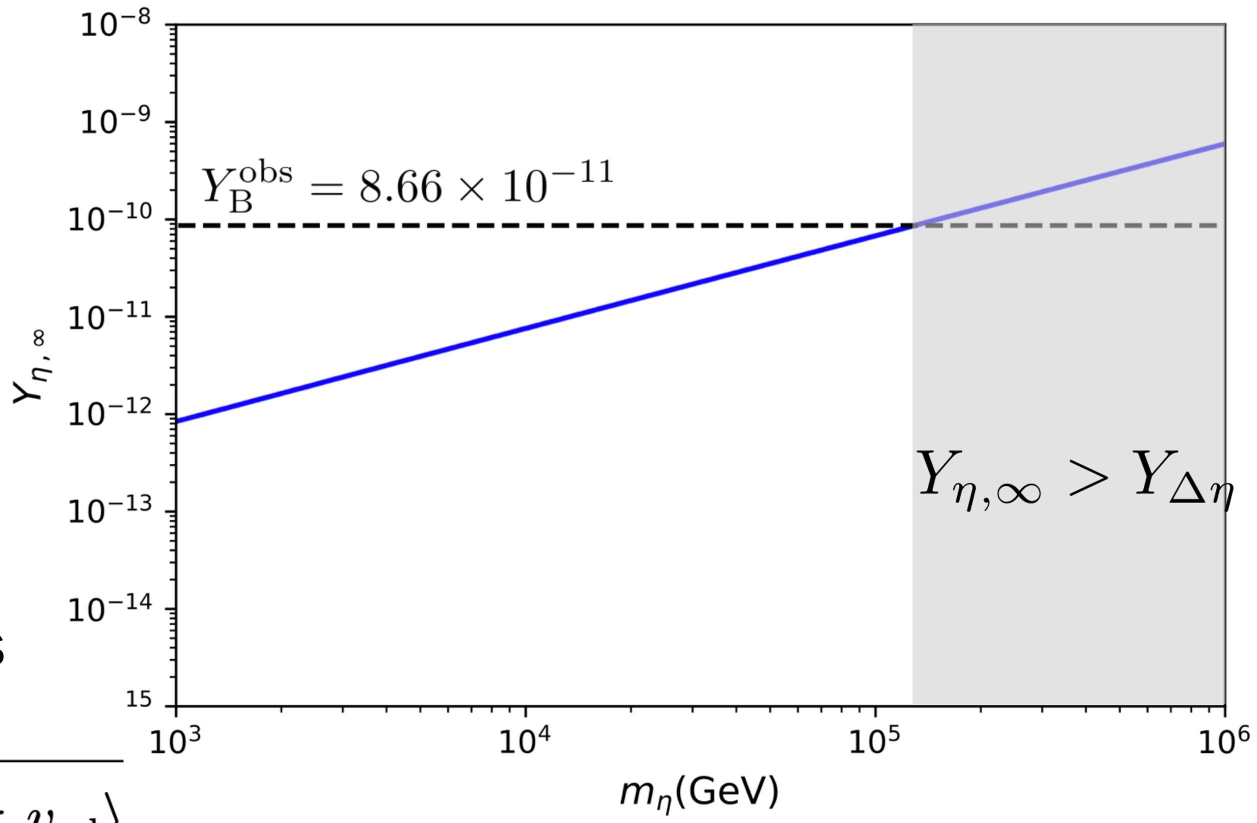
$$Y_{\eta,\infty} < Y_{\Delta\eta}$$

should be satisfied

Mediator annihilation

Symmetric component of mediator should annihilate before decays into DM





Relic density of η

When only symmetric component exists

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

with $x_f \equiv \frac{m_\eta}{T_f} = \ln\left[0.038\left(g/g_*^{1/2}\right) M_{Pl} m_\eta \langle \sigma_g v_{rel}\rangle\right] - \frac{1}{2}\ln\left\{\ln\left[0.038\left(g/g_*^{1/2}\right) M_{Pl} m_\eta \langle \sigma_g v_{rel}\rangle\right]\right\}$

Tales of Cogenesis

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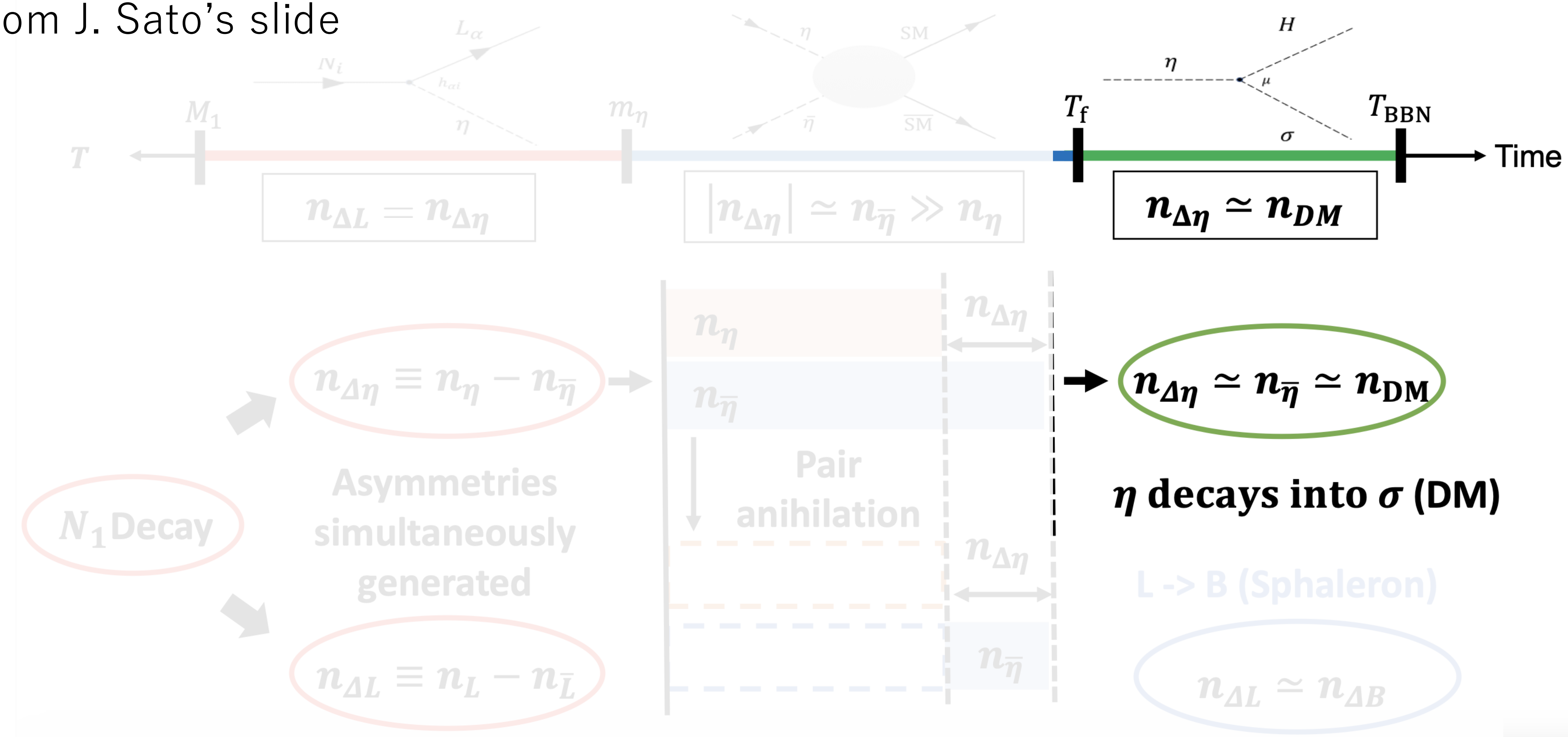
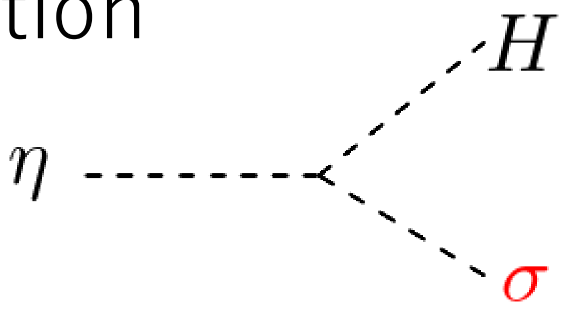


DM production

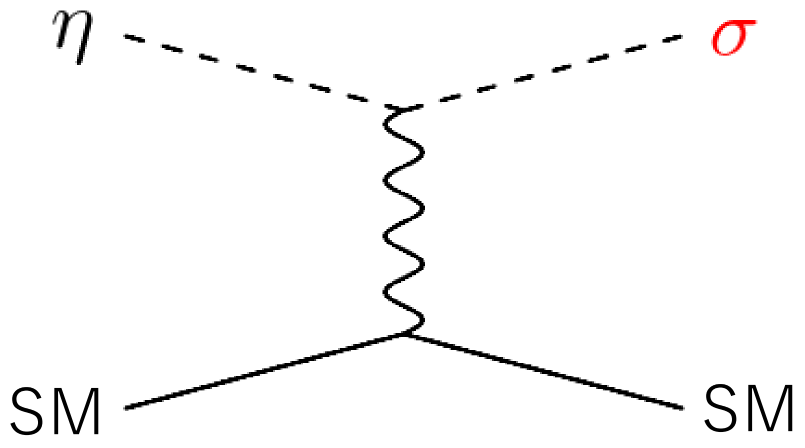
Mediator decay

Mediator should decay into DM after annihilation of symmetric component



Mediator scattering

Scattering between mediator & SM particle also produce DM



Early-time decay

Condition of mediator lifetime

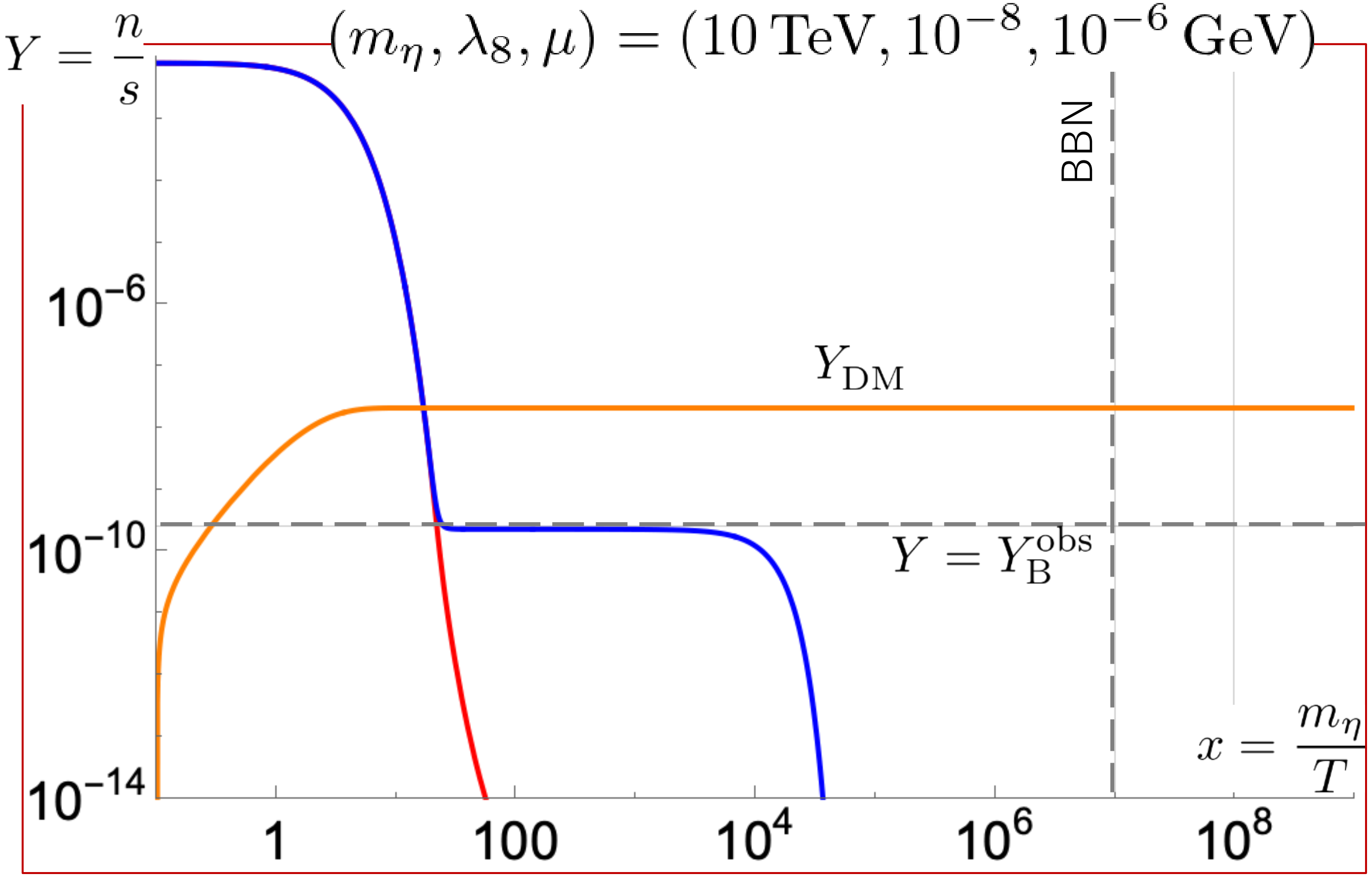
1, Decay should start after annihilation of symmetric component

Too short lifetime

➡ Symmetric component also decays into DM

➡ $|n_{\Delta\eta}| \ll n_\eta + n_{\eta^\dagger} \sim n_{\rm DM}$

DM overabundance



Late-time decay

Condition of mediator lifetime

2, Decay should finish before big-bang nucleosynthesis

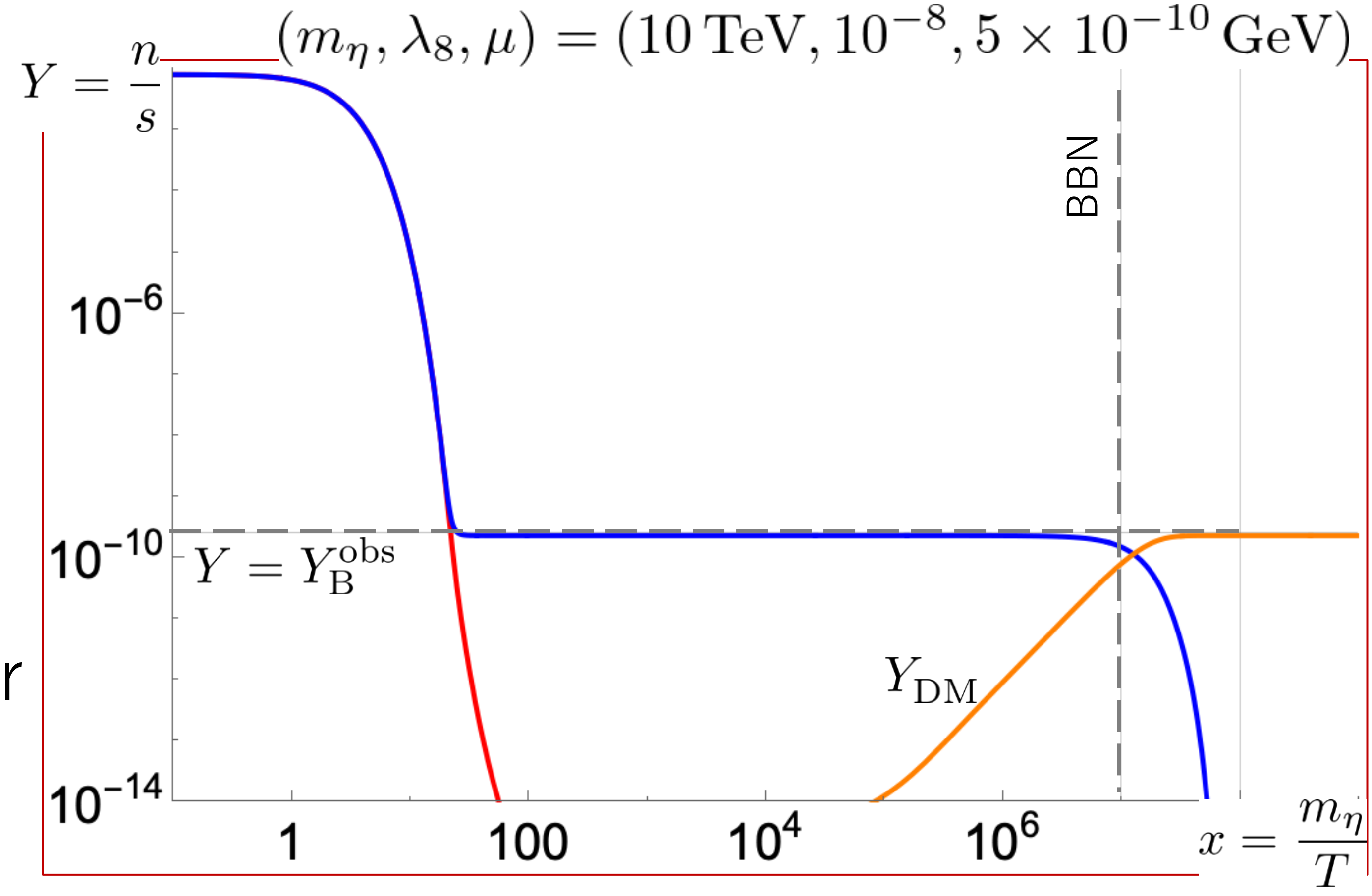
Too long lifetime

➡ Mediator decays into DM & SM particle

e.g.) $\eta^+ \to W^+ + \sigma,\ \eta_R^0 \to h + \sigma$

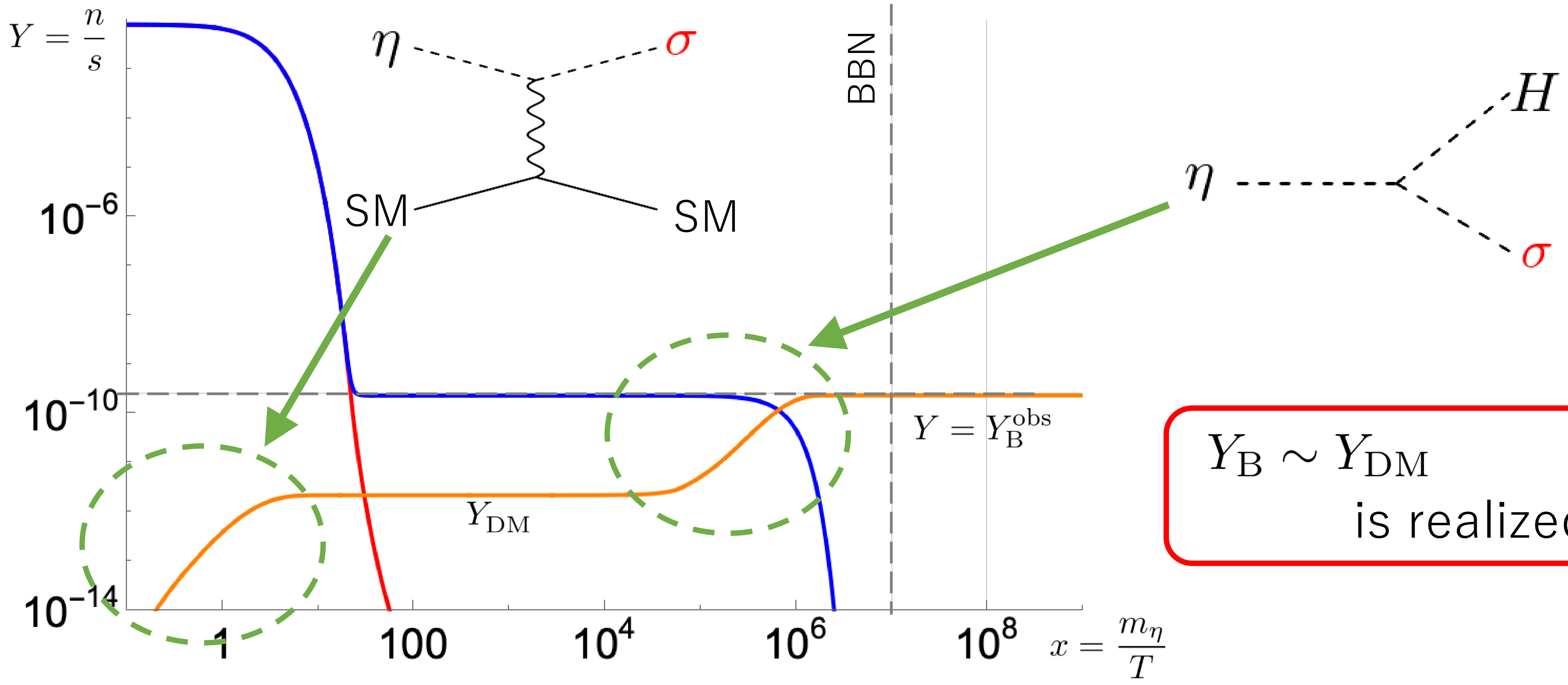
➡ SM particle decays create high energy hadronic shower

Failed BBN



Successful cogenesis

$$(m_\eta, \lambda_8, \mu) = (10\,\mathrm{TeV}, 10^{-8}, 10^{-8}\,\mathrm{GeV})$$



$Y_B \sim Y_{DM}$
is realized !

Cosmological bounds

K. Asai, S. Enomoto, T. Hirose, and M. Yamanaka, arXiv:2512.14271

BBN bound

Mediator decay during BBN spoils successful BBN through following three effects

① proton-neutron interconversion $(\tau_\eta \lesssim 100\,\mathrm{sec})$

Charged pions from η decay change proton-neutron ratio

$$n + \pi^+ \to p + \pi^0, \quad p + \pi^- \to n + \pi^0$$

② hadrodissociation $(100\,\mathrm{sec} \lesssim \tau_\eta \lesssim 10^{4-6}\,\mathrm{sec})$

Hadron particles from η decay break light elements

③ photodissociation $(\tau_\eta \gtrsim 10^{4-6}\,\mathrm{sec})$

Low-energy photons from η decay break light elements

BBN bound

Pioneering work M. Kawasaki, K. Kohri, T. Moroi, PRD 71 (2005) 083502

In early stage of BBN, bound on helium/baryon ratio $\mathbf{Y_p}$ is the most severe

observed value (old) :

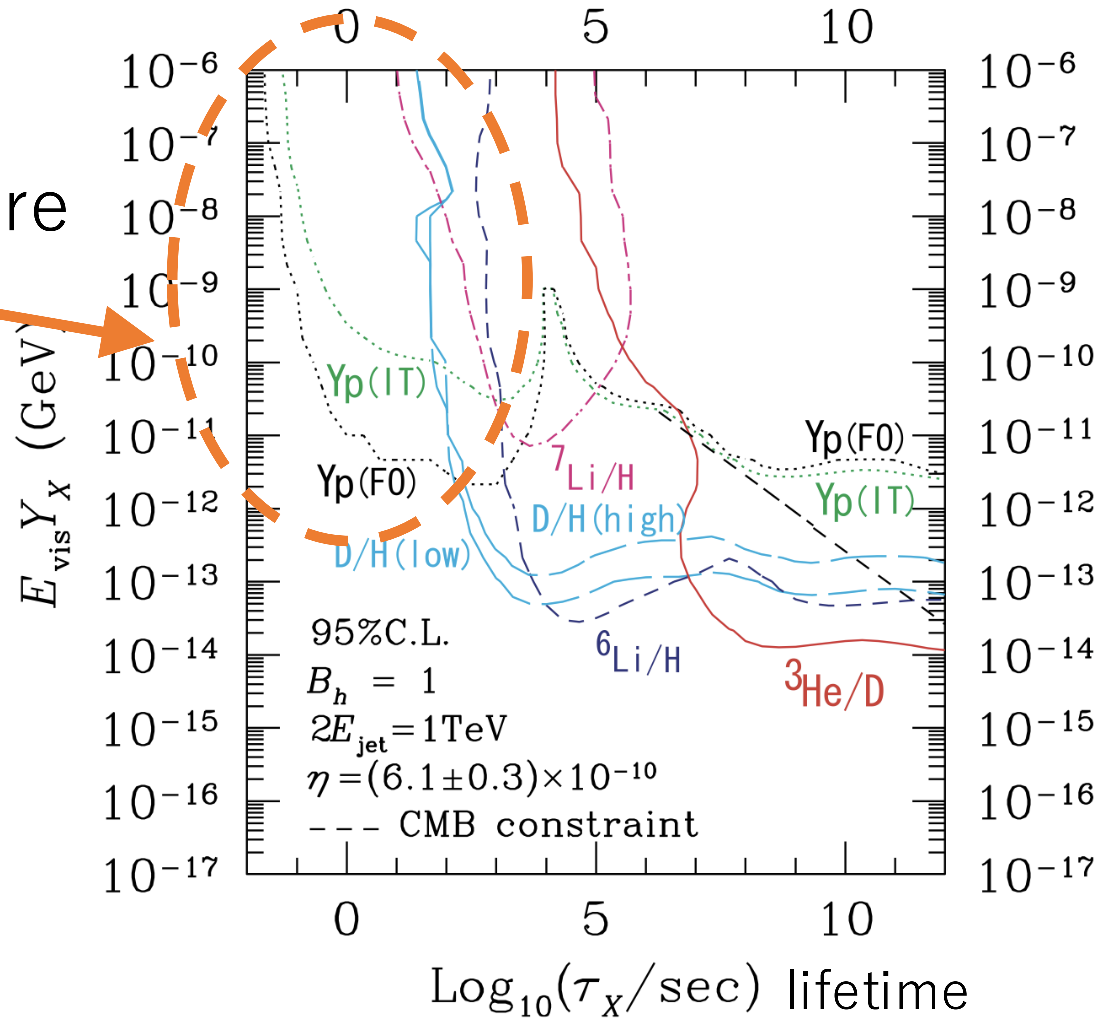
$$Y_p^{\rm obs}({\rm FO}) = 0.238 \pm (0.002)_{\rm stat} \pm (0.005)_{\rm syst} \ ,$$

$$Y_p^{\rm obs}({\rm IT}) = 0.242 \pm (0.002)_{\rm stat} \ (\pm(0.005)_{\rm syst})$$

observed value (current) :

$$Y_p^{\rm obs}({\rm EMPRESS}) = 0.2370^{+0.0034}_{-0.0033}$$

We used FO's bound

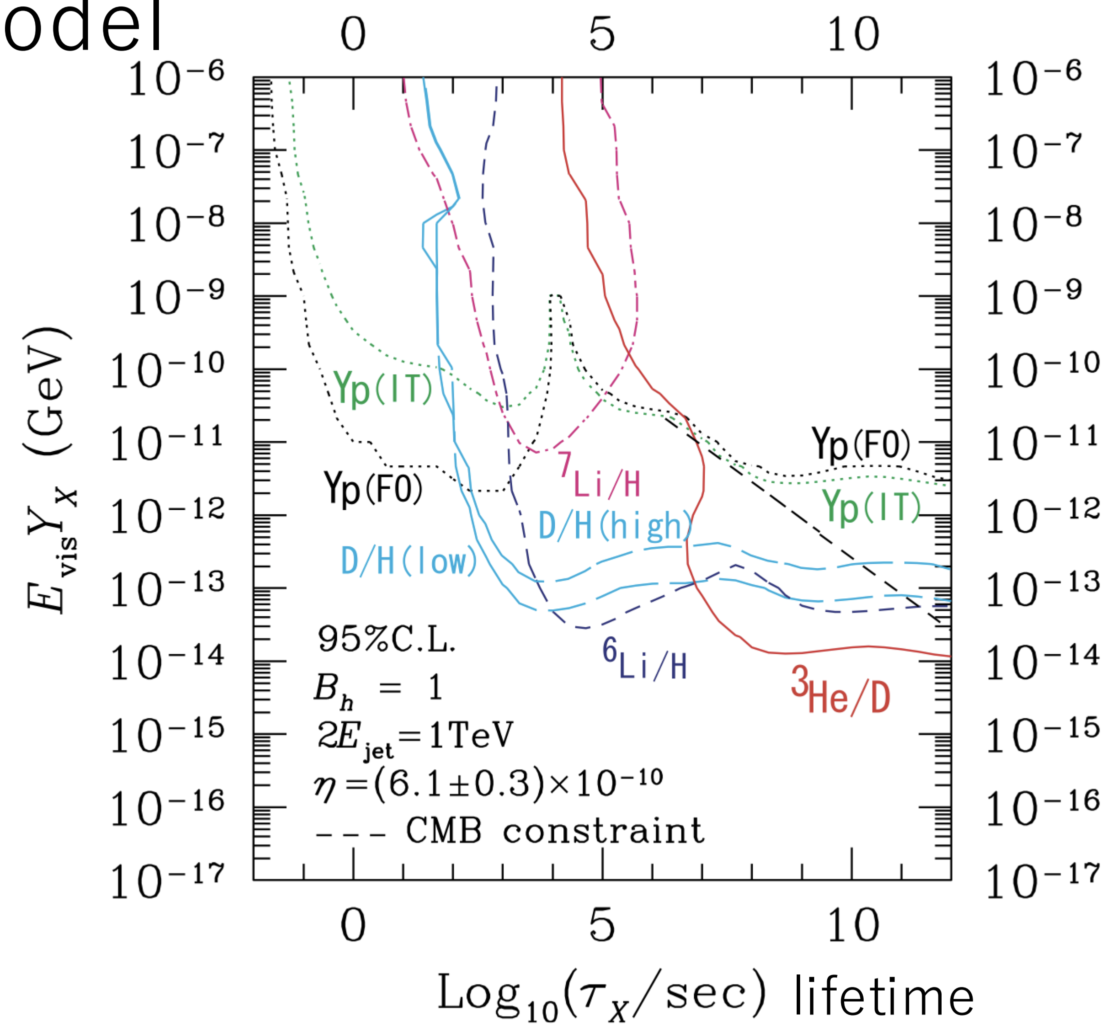


Recasting BBN bound

◯ Challenges in applying to our model

- bound plots are given for a few benchmark values of m_X & $\mathrm{Br}_{\mathrm{hadron}}$
- evaluating η -decay effect on BBN is very difficult

We found simple recasting method to obtain BBN bound on long-lived particle



M. Kawasaki, K. Kohri, T. Moroi, PRD 71 (2005) 083502

Recasting BBN bound

○ Equality-time

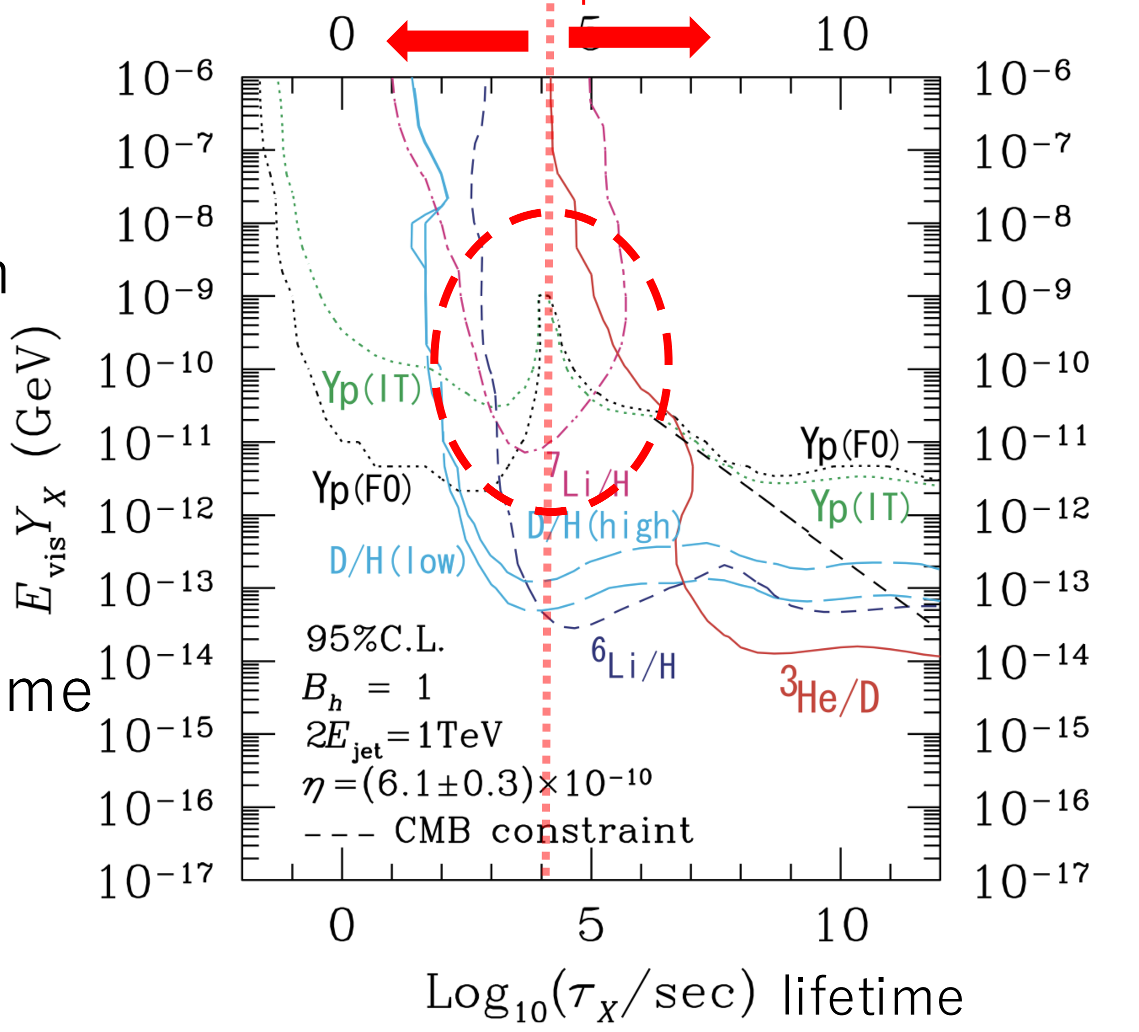
We define equality-time t_{eq} as the time at which the contributions of "pn-interconversion + hadrodissociation" and "photodissociation" become comparable

Equality-time can be determined from the lifetime at which the bound curve locally weakens

$$t_{\rm eq}[Y_p(\mathrm{FO})] = 10^4\,\mathrm{s}, \qquad t_{\rm eq}[\mathrm{D/H(low)}] = 10^8\,\mathrm{s},$$

$$t_{\rm eq}[^6\mathrm{Li/H}] = 10^8\,\mathrm{s}$$

hadron-effects dominate | photon-effect dominates



M. Kawasaki, K. Kohri, T. Moroi, PRD 71 (2005) 083502

Recasting BBN bound

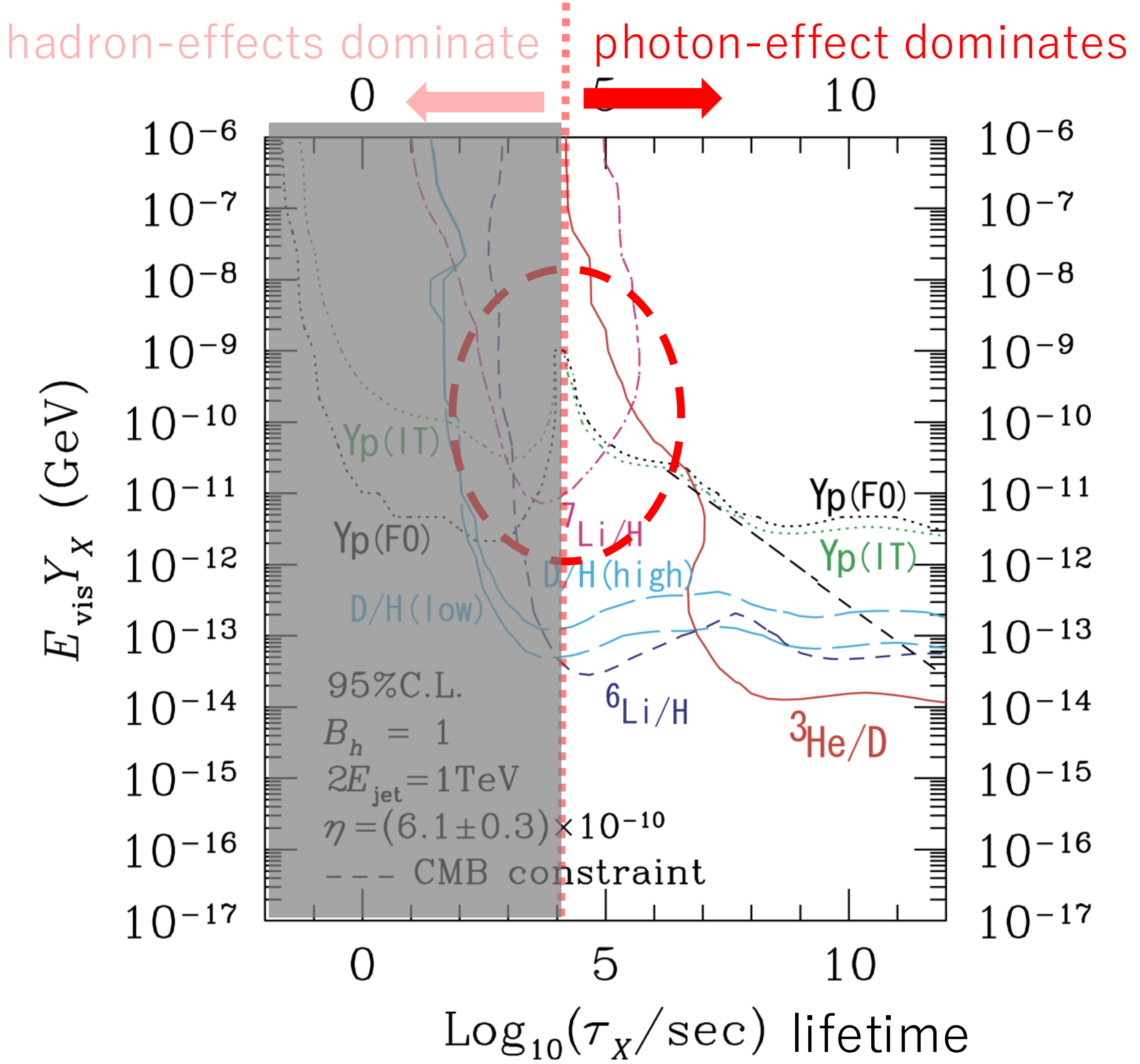
○ $t > t_{\mathrm{eq}}$ (photon-effect dominated era)

Strength of bounds is

- independent of $\mathrm{BR_{had}}$
- proportional to energy emitted from η-decay (mass of η)

$$(Y_\eta)_{\rm our} < 2\times 10^{-3}\left(\frac{m_\eta}{1\,\mathrm{TeV}}\right)^{-1}\frac{(E_{\rm vis}Y_X)^{\rm upper\ bound}_{\rm KKM}}{\rm GeV}$$

with $Y_\eta \equiv Y_{\eta^+} + Y_{\eta^-} + Y_{\eta^0} + Y_{\eta^{0*}}$



M. Kawasaki, K. Kohri, T. Moroi, PRD 71 (2005) 083502

Recasting BBN bound

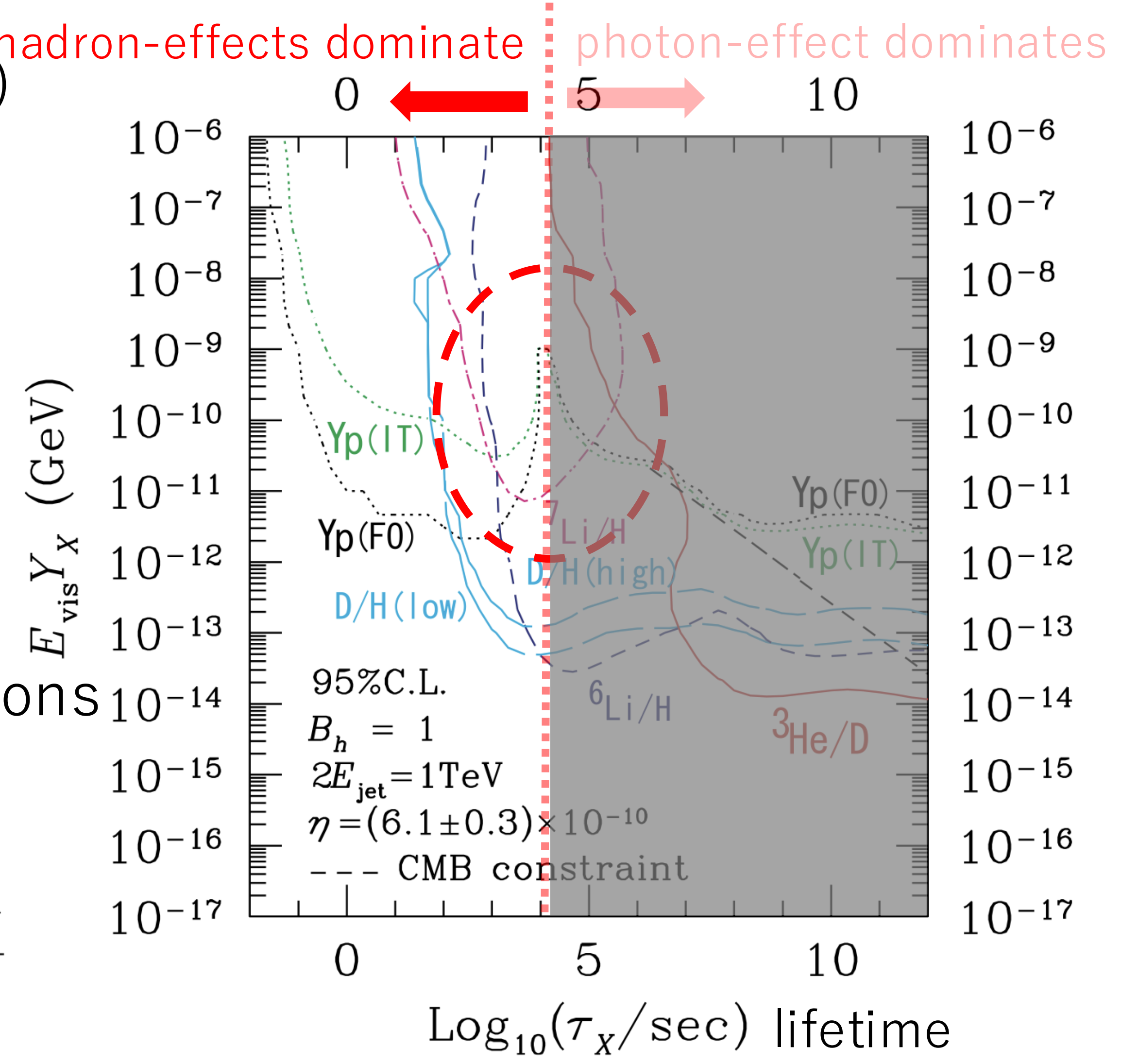
○ $t < t_{\mathrm{eq}}$ (hadron-effects dominated era)

Strength of bounds is proportional to # of hadrons from η-decay, which is

- proportional to $\mathrm{BR_{had}}$
- proportional to $(E^{\eta}_{\mathrm{had}})^{0.3}$

  with E^{η}_{had} being energy converted into hadrons

$$(Y_\eta)^{\text{upper bound}}_{\text{our}} = 2 \times 10^{-3} \left(\frac{m_\eta}{1\,\mathrm{TeV}}\right)^{-1} \left(\frac{E^{\eta}_{\mathrm{had}}}{1\,\mathrm{TeV}}\right)^{-\delta} \frac{(E_{\mathrm{vis}} Y_X)^{\text{upper bound}}_{\mathrm{KKM}}}{\mathrm{GeV}}$$



M. Kawasaki, K. Kohri, T. Moroi, PRD 71 (2005) 083502

Structure formation bound

Too late-time η-decay derives DM with large momentum during structure formation era

➡ DM erases small-scale structure below free-streaming length

… physical distance that particles can travel without colliding

$$\lambda_{\mathrm{FS}} = \int_{a_D}^{a_{\mathrm{eq}}} da\, \frac{v_\sigma(a)}{a^2 H(a)} \sim \frac{a_{\mathrm{NR}}}{H_0\sqrt{\Omega_{r0}}a_0^2}\left(1 - \frac{a_D}{a_{\mathrm{NR}}} + \ln\frac{a_{\mathrm{eq}}}{a_{\mathrm{NR}}}\right)$$

$$\sim 4.85\,\mathrm{kpc} \times F(m_\eta,\mu)\,(11.2 - \ln F(m_\eta,\mu))$$

with $$F(m_\eta,\mu) = \left(\frac{m_\eta}{1\,\mathrm{TeV}}\right)^{3/2}\frac{10^{-9}\,\mathrm{GeV}}{\mu}$$

Structure formation bound

○ Constraints on free-streaming length

(1) typical intergalactic distance is 1 Mpc

$\lambda_{\rm FS} > 1\,{\rm Mpc}$ ➡ DM inhibits large scale structure formation

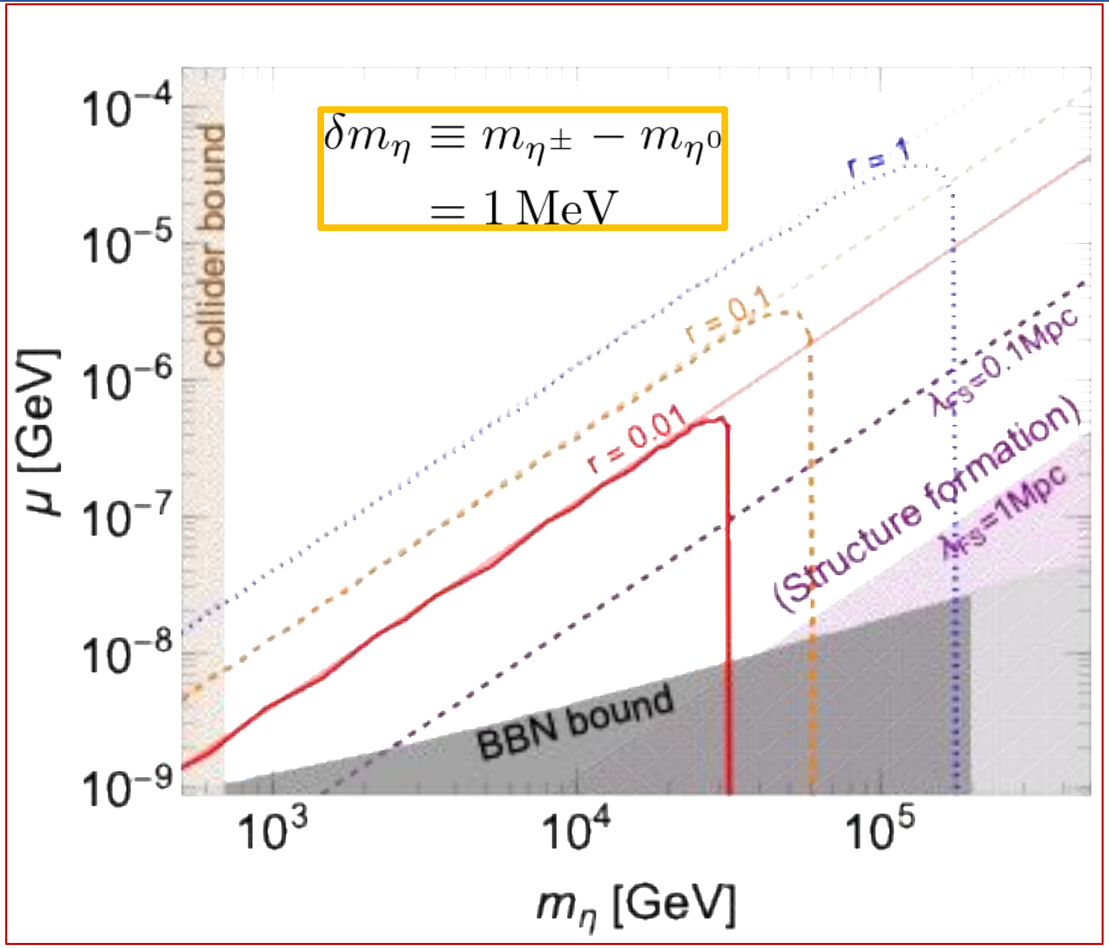
(2) cut-off scale of matter power spectrum of Lyman-α observation at redshift is $\mathcal{O}(1)\,{\rm Mpc}$ or $0.1\,{\rm Mpc}$

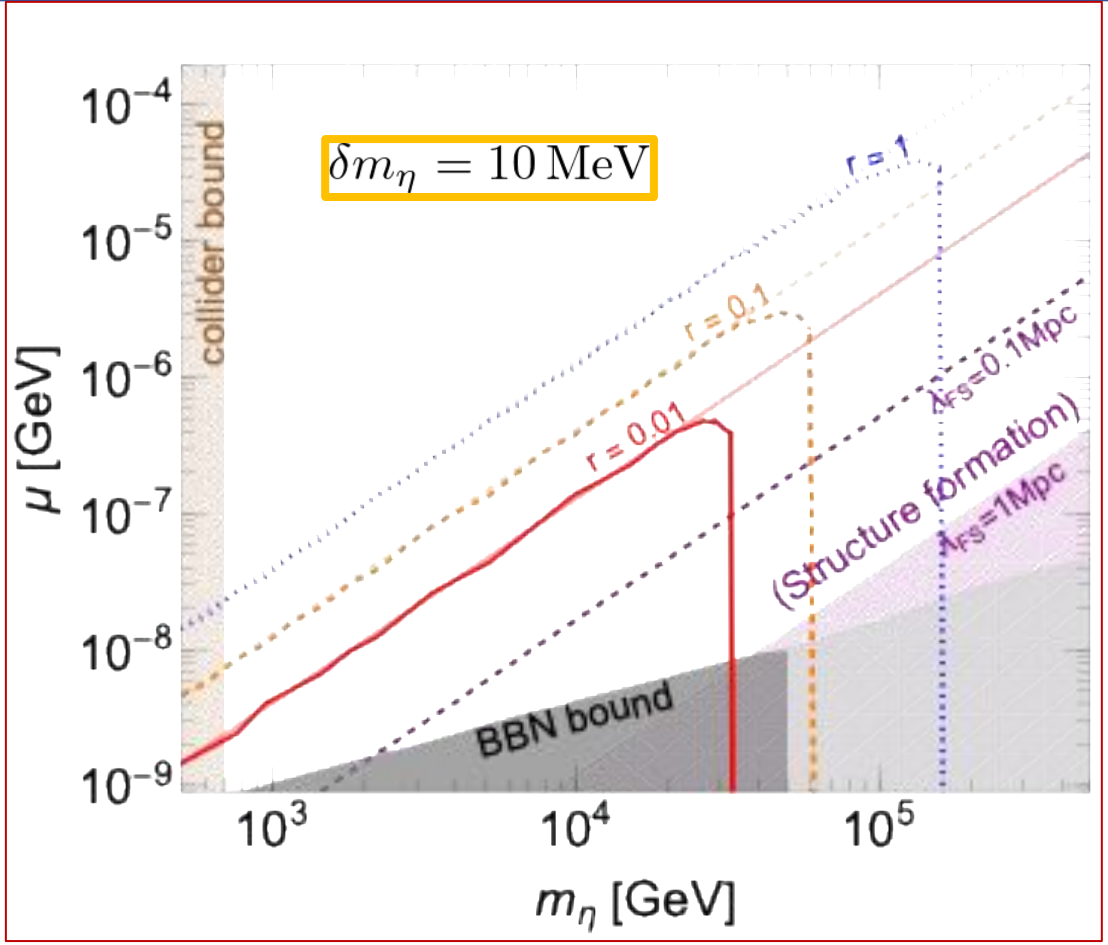
$\lambda_{\rm FS} > 0.1 - 1\,{\rm Mpc}$ ➡ DM erase small scale

Result

coincidence index

$$r \equiv (Y_\sigma - Y_{\Delta L})/Y_{\Delta L}$$





Viable parameter region is bounded by collider (light m_η) and cosmology (heavy m_η & small μ)

Summary

- We have studied a scotogenic model with a singlet scalar and explored a possibility of realization of cogenesis.
- Asymmetries of B-L and dark sector are generated by common process and mediator asymmetry is converted into DM
- We have evaluated cosmological bounds (BBN bound & structure formation) and found viable parameter region for successful scenario

Thank you for your attention !

Appendix

Asymmetric DM

How does $\eta_{\rm DM} \sim \eta_{\rm B}$ realize ?

Sharing mechanism

Primordial asymmetry is shared by SM and DM sectors through portal interaction

? $\longrightarrow$ X asymmetry $\rightarrow$ $B-L$ asymmetry $\xrightarrow{\text{sphaleron}}$ B asymmetry

X asymmetry $\rightarrow$ DM asymmetry

Cogenesis

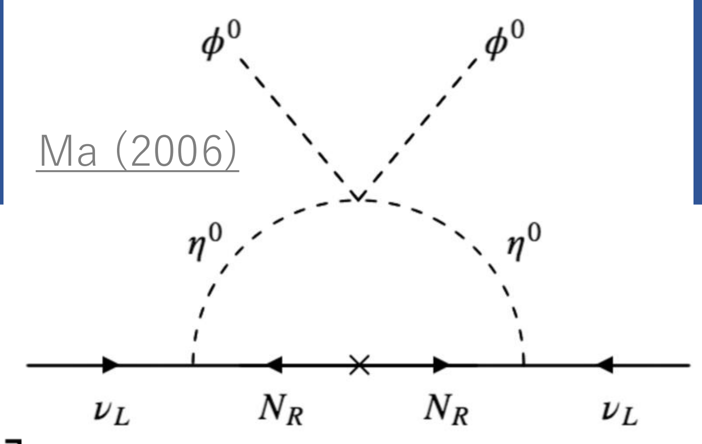
Asymmetries in SM and DM sectors are generated through same process

? $\rightarrow$ $B-L$ asymmetry $\xrightarrow{\text{sphaleron}}$ B asymmetry

? $\rightarrow$ DM asymmetry

➡ We have focused on this mechanism

Scotogenic model



Neutrino mass is generated by one-loop diagram

$$(\mathcal{M})_{\alpha\beta} = \sum_i \frac{h_{\alpha i} h_{\beta i} M_i}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_i^2} \ln \frac{m_R^2}{M_i^2} - \frac{m_I^2}{m_I^2 - M_i^2} \ln \frac{m_I^2}{M_i^2} \right]$$

For $M_i^2 \gg m_R^2 \simeq m_I^2$,

$$(\mathcal{M})_{\alpha\beta} \simeq \frac{\lambda_8 v^2}{8\pi^2} \sum_i \frac{h_{\alpha i} h_{\beta i}}{M_i} \left[\ln \frac{M_i^2}{m_0^2} - 1 \right]$$

where $m_0^2 \equiv (m_R^2 + m_I^2)/\sqrt{2}$

Neutrino mass is proportional to coefficient of $U(1)_L$-breaking term

$$\frac{1}{2}\lambda_8 \left[(\phi^\dagger \eta)^2 + h.c. \right]$$

Davidson-Ibarra bound

Davidson, Ibarra (2002)

Thermal leptogenesis & neutrino mass

$M_1 > 10^{8\text{-}9}$ GeV

Yukawa coupling can be large

Davidson-Ibarra bound is alleviated by λ_8

Neutrino mass

Mass matrix

Hugle, Platscher, Schmitz (2018)

$$\mathcal{M}_\nu = h^* \mathcal{D}_\Lambda^{-1} h^\dagger \ , \ (\mathcal{D}_\Lambda)_{ii} = \frac{2\pi^2}{\lambda_8} \xi_i \frac{2M_i}{v^2} \equiv \Lambda_i$$

with

$$\xi_i \equiv \left\{ \frac{1}{8} \frac{M_i^2}{m_{\eta_R}^2 - m_{\eta_I}^2} \left(\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_i^2} \ln \frac{m_{\eta_R}^2}{M_i^2} - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_i^2} \ln \frac{m_{\eta_I}^2}{M_i^2} \right) \right\}^{-1}$$

$$\approx \frac{8}{[\ln (M_i^2/m_0^2) - 1]}$$ for $\lambda_8 v^2 \ll m_\eta^2$ and $m_\eta \ll M_i$

Casas-Ibarra parametrization

Casas, Ibarra (2001)

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

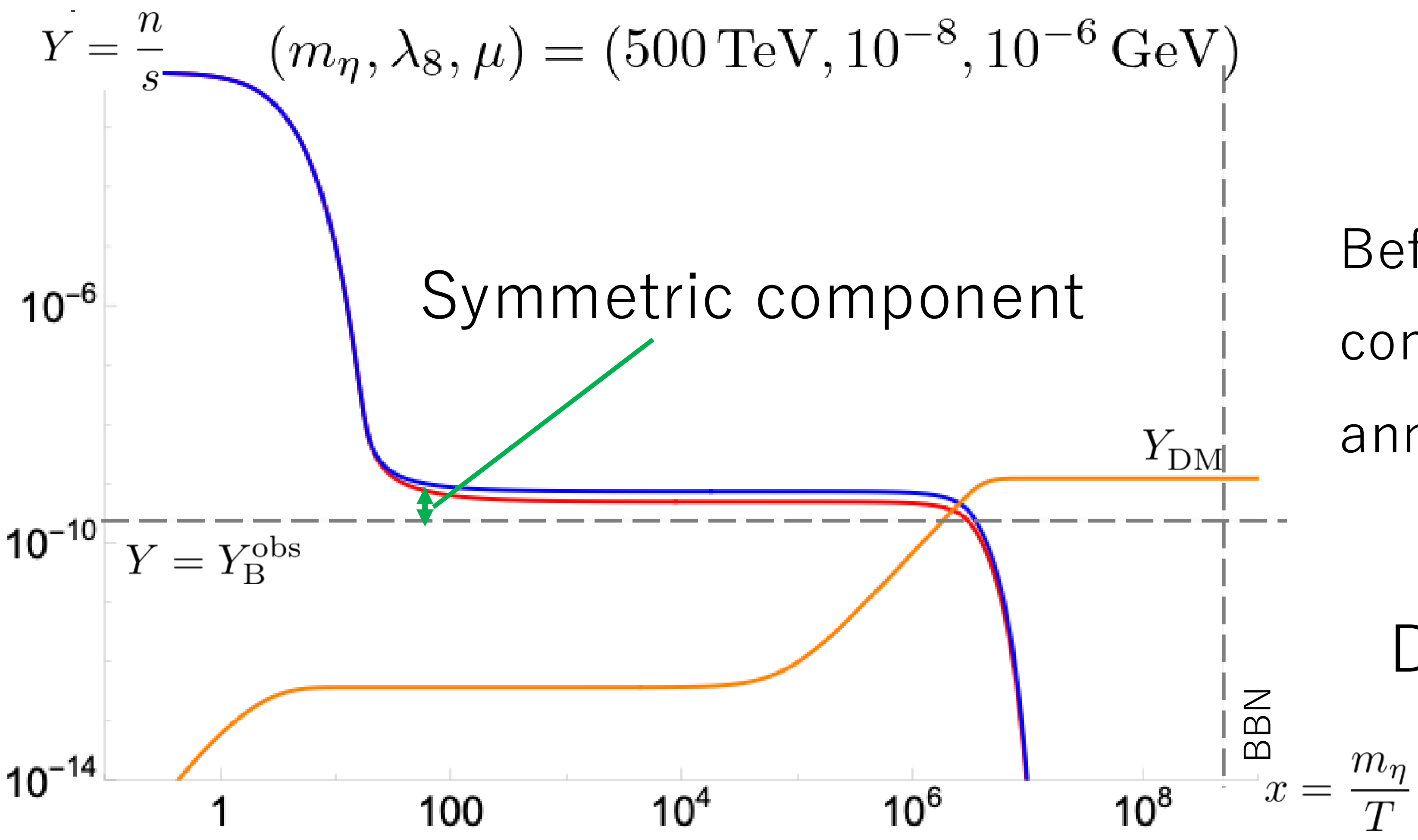
where $D_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$

arbitrary complex orthogonal matrix : $R \ (RR^T = 1)$

PMNS unitary matrix : $U \ (UU^\dagger = 1)$

Mediator annihilation

If $m_\eta > 10^5\,\mathrm{GeV}$,



Before symmetric component completely annihilate, annihilation process freeze-out

DM overabundance