Cogenesis of Dark Matter and Baryon Asymmetries in Scotogenic Model

(work in progress)

Saitama University M1

Yuhei Sakai

Collaborator : Kento Asai , Joe Sato , Yasutaka Takanishi

・ Motivation

○ Scotogenic Model

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

・ Neutrino masses
・ Dark Matter

○ Asymmetric Dark Matter (ADM) Model

D. E. Kaplan, M. A. Luty, K. M. Zurek, Phys. Rev. D **79** (2009) 115016

・ $\Omega_{\mathrm{DM}} \cong 5\Omega_{\mathrm{B}}$

Combine ADM scenario with Scotgenic Model and explain Neutrino masses , Dark Matter , Baryon Asymmetry simultaneously

• Model

Standard Model

Scotogenic Model

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

+ σ (singlet real scalar)

DM

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

Table 1 : Z_2 symmetry assignment

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

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

Focus on this

- # Model

Neutrino mass

$$\eta = (\eta^+, (\eta_R + i\eta_I)/\sqrt{2})^T$$

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

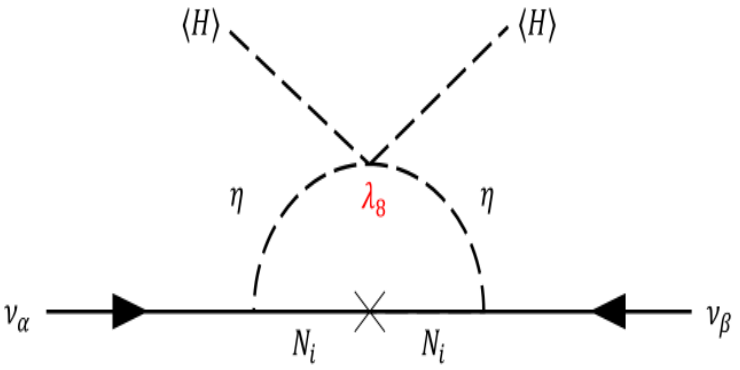


Fig.1 : One-loop diagram

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

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

$$U^T \mathcal{M}_\nu U = \mathrm{diag}(m_1, m_2, m_3) \equiv D_\nu$$

U : Maki-Nakagawa-Sakata(MNS)matrix

Casas-Ibarra parametrization

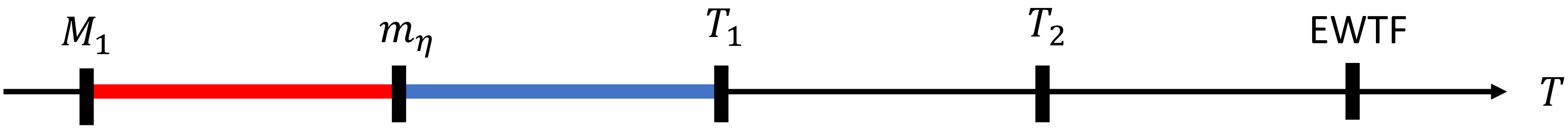
$$h_{\alpha i} = \left(U\, D_\nu^{\frac{1}{2}}\, R^\dagger\, D_\Lambda^{\frac{1}{2}} \right)_{\alpha i}$$

R : complex orthogonal matrix

Yukawa matrix depends on λ_8 , M_i

• Cogenesis

○ Story of the generation of dark matter



- $M_1 > T > m_\eta$

The lightest heavy neutrino N_1 decays into L_α and η

$$n_{L-\bar{L}} \cong n_{\eta-\bar{\eta}}$$

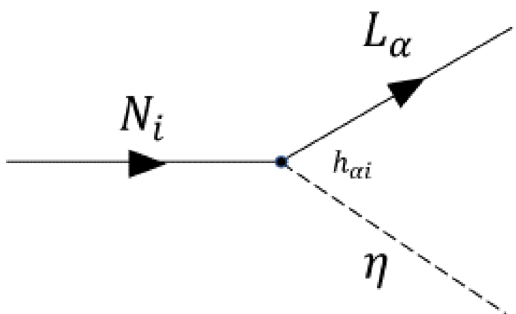


Fig.2 : The decay of N_i

- $m_\eta > T > T_1$

The inert higgs η annihilates into SM particle

$$n_\eta \cong n_{\eta-\bar{\eta}} \gg n_{\bar{\eta}}$$

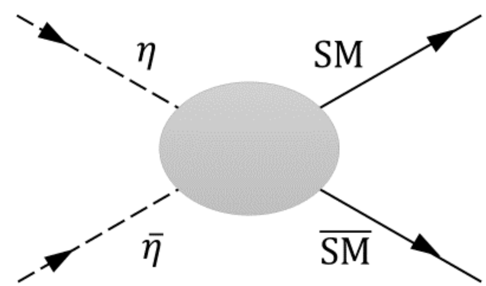
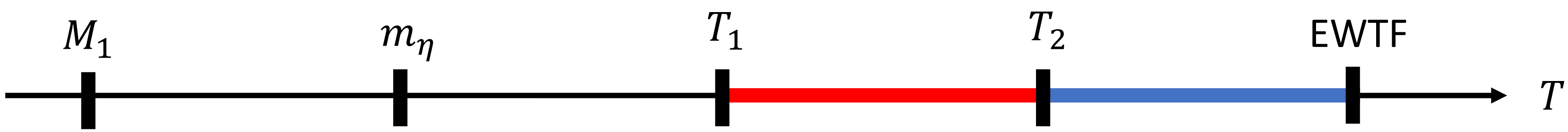


Fig.3 : The annihilation of η

- # Cogenesis
  - Story of the generation of dark matter



- $T_1 > T > T_2$

The inert higgs η decays into Dark Matter σ

$$n_{\eta-\bar{\eta}} \to n_{\mathrm{DM}}$$

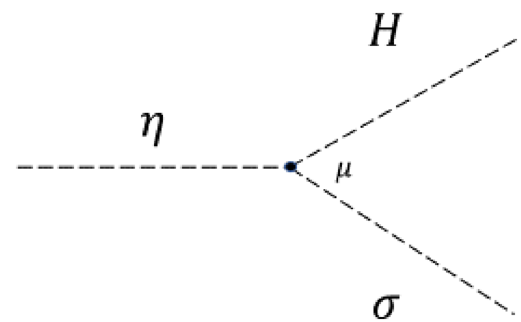


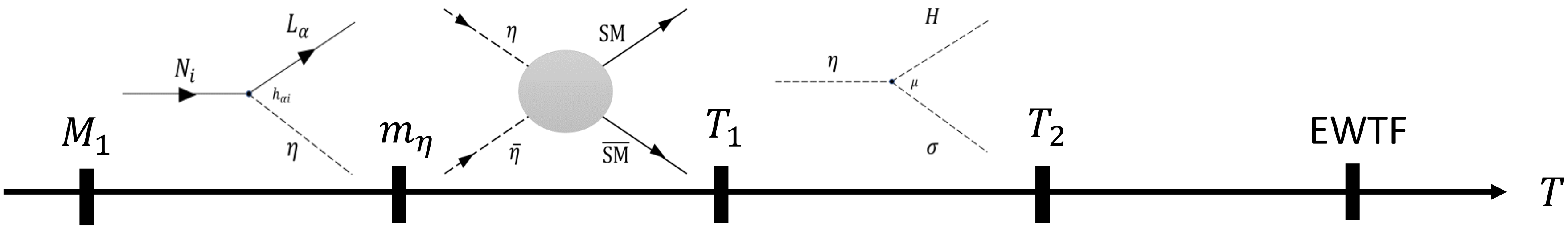
Fig.4 : The decay of η

- $T_2 > T > 10^2\mathrm{GeV}$

The decay of inert higgs η completes at this era

$$n_{\eta-\bar{\eta}} \cong 0 \text{ and } n_{L-\bar{L}} \cong n_{\mathrm{DM}}$$

• Cogenesis



$\eta\eta \to HH$ should be out of equilibrium from M_1 to T_2

If it occurs

$$n_{L-\bar{L}} \neq n_{\eta-\bar{\eta}}$$

Interactions

Interactions	m_η – T_1	T_1 – T_2	T_2 – EWTF
$\bar\eta\,\eta \to \overline{\rm SM}\,{\rm SM}$	○	×	×
$\eta \to \sigma H$ $\bar\eta \to \sigma \bar H$	×	○	○
$\eta\eta \to HH$ $\bar\eta\bar\eta \to \bar H \bar H$	×	×	○

• Cogenesis

The Yukawa matrix and the interaction of $\eta\eta \to HH$ depend on λ_8

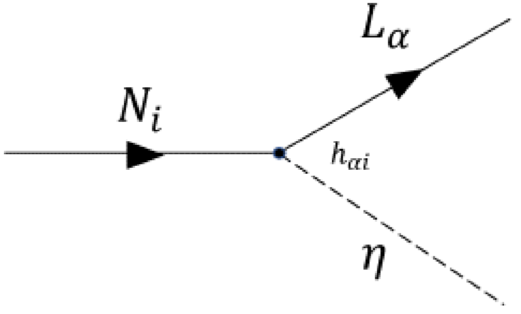


Fig.2 : The decay of N_i

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

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

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

○ Condition for λ_8

$$\Gamma_{\eta\eta\to HH} < H \text{ (Hubble parameter)}$$

$$\therefore\ \lambda_8 < 3.4 \times 10^{-8} \sqrt{m_\eta/[\mathrm{GeV}]}$$

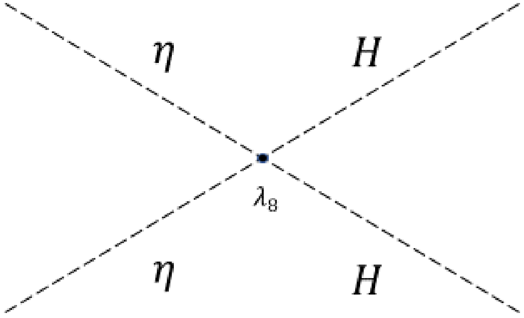


Fig.5 : $\eta\eta \to HH$

⇒ Calculate Lepton asymmetry under this condition

・Calculation

○ Calculate baryon to photon ratio η_B in a standard Leptogenesis

$$\eta_B \approx -0.01\epsilon_1\kappa_1$$

ϵ_1 : asymmetry parameter
κ_1 : efficiency factor

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

$$F\left(r_{ji},\eta_i\right) = \sqrt{r_{ji}}\left[f\left(r_{ji},\eta_i\right) - \frac{\sqrt{r_{ji}}}{r_{ji}-1}\left(1-\eta_i\right)^2\right]$$

$$f\left(r_{ji},\eta_i\right) = \sqrt{r_{ji}}\left[1 + \frac{\left(1-2\eta_i+r_{ji}\right)}{\left(1-\eta_i\right)^2}\ln\left(\frac{r_{ji}-\eta_i^2}{1-2\eta_i+r_{ji}}\right)\right]$$

$$\eta_i = m_\eta^2/M_i^2$$

$$r_{ji} = M_j^2/M_i^2$$

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

This approximation holds in the range: $10 < K_1 < 50$

$$K_1 = \frac{1}{8\pi}\sqrt{\frac{90}{8\pi^3 g_*}}\frac{M_{\mathrm{Pl}}}{M_1}\left(h^\dagger h\right)_{11}\left(1-\eta_1\right)^2$$
$$= \frac{2\pi^2}{\lambda_5}\xi_1\sqrt{\frac{45}{64\pi^5 g_*}}\frac{M_{\mathrm{Pl}}}{v^2}\left(RD_{\mathcal{M}_\nu}R^\dagger\right)_{11}\left(1-\eta_1\right)^2$$

K_1 : decay parameter

・Result

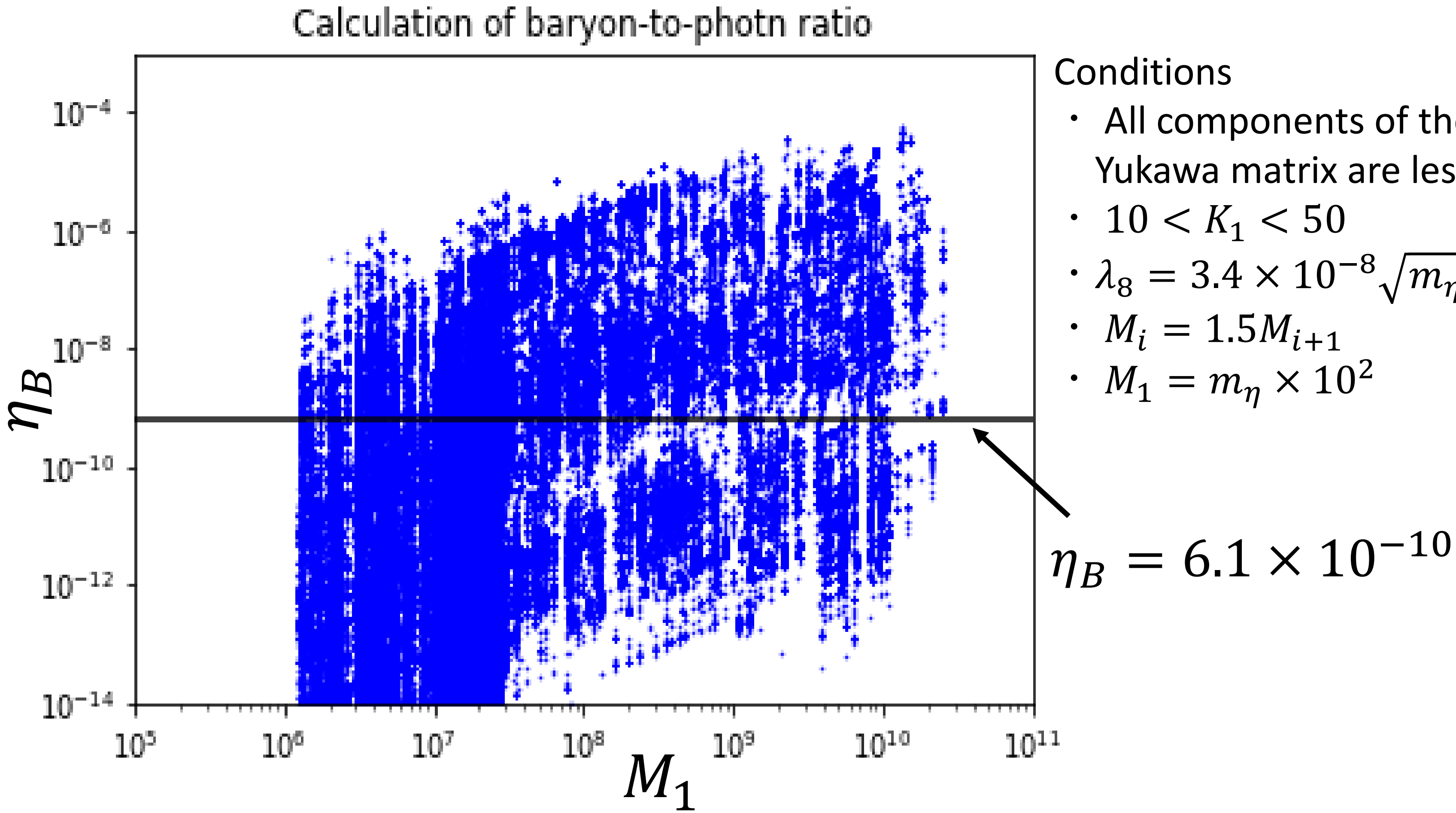


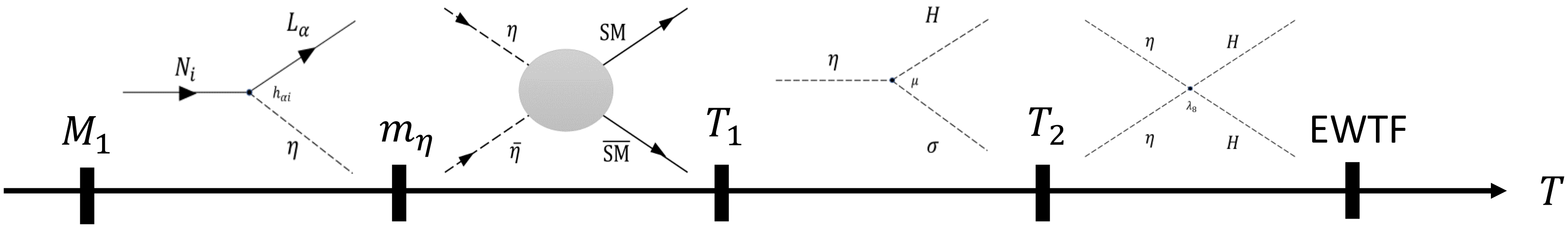
Fig.6 : Result of calculation

Conditions

- All components of the Yukawa matrix are less than 1
- $10 < K_1 < 50$
- $\lambda_8 = 3.4 \times 10^{-8} \sqrt{m_\eta/[\mathrm{GeV}]}$
- $M_i = 1.5 M_{i+1}$
- $M_1 = m_\eta \times 10^2$

・Summary

○ Combine ADM scenario to Scotgenic Model



- λ_8 is involved in the the Yukawa matrix and the interaction of $\eta\eta \to HH$.

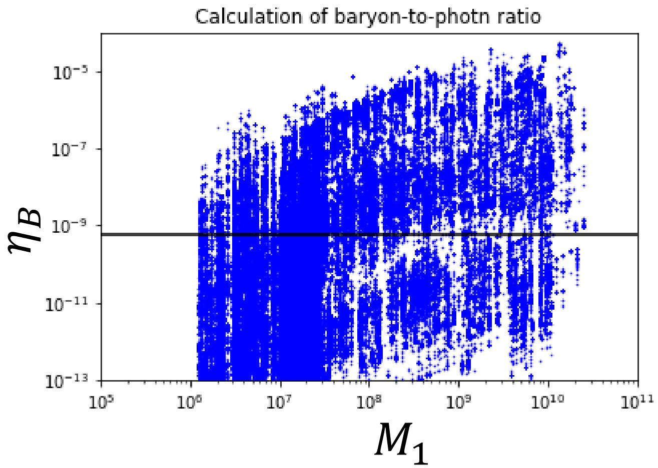
- There are parameters that satisfy under these conditions.

○ As a future prospect, we will verify whether there are parameters that satisfy other conditions

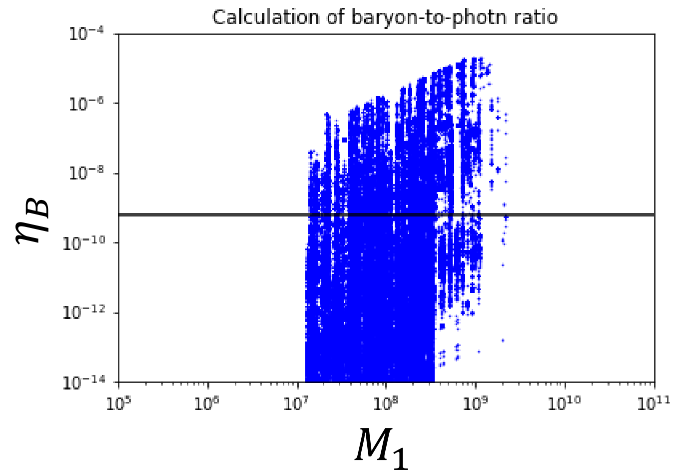
Thank you for your attention.

Appendix

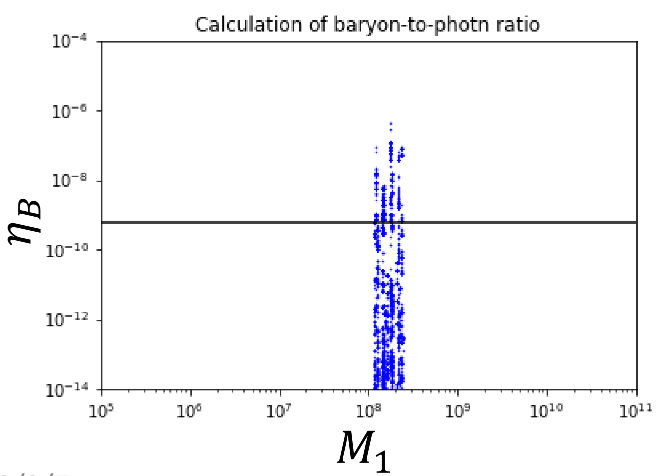
- $\lambda_8 = 3.4 \times 10^{-8}\sqrt{m_\eta/[\mathrm{GeV}]}$
- $M_1 = m_\eta \times 10^2$



- $\lambda_8 = 1.0 \times 10^{-8}\sqrt{m_\eta/[\mathrm{GeV}]}$
- $M_1 = m_\eta \times 10^2$



- $\lambda_8 = 3.4 \times 10^{-9}\sqrt{m_\eta/[\mathrm{GeV}]}$
- $M_1 = m_\eta \times 10^2$



- $\lambda_8 = 3.4 \times 10^{-8}\sqrt{m_\eta/[\mathrm{GeV}]}$
- $M_1 = m_\eta \times 10^3$