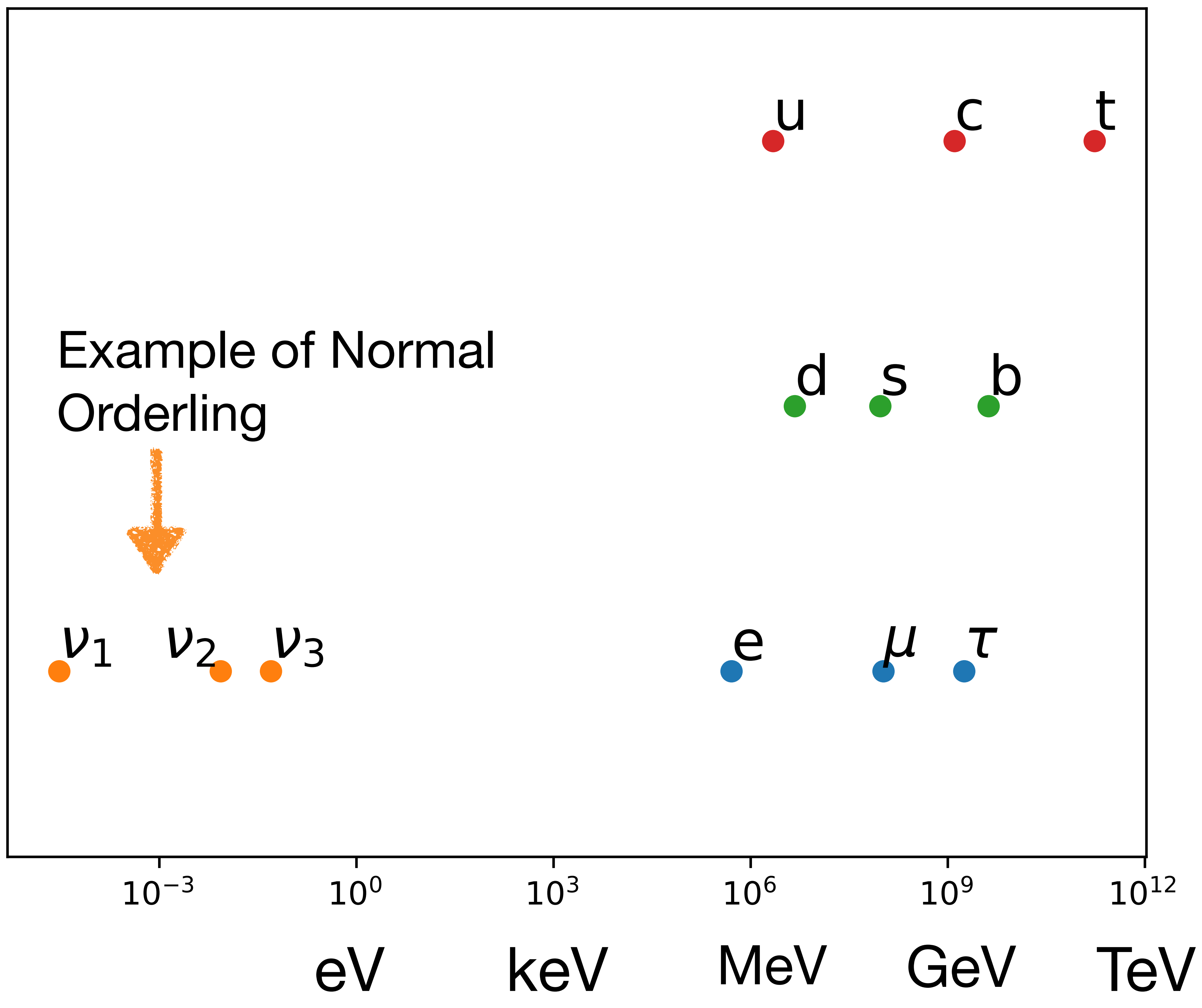
# Leptogenesis via scalar doublet decay in the Scotogenic model

Yurika Sekikawa
(Yokohama National University)

In collaboration with
Joe Sato, Kento Asai, Masato Yamanaka

work in progress

# Why neutrino mass so small?




Neutrinos are extremely light compared to charged leptons and quarks

Some mechanism?

**neutrinos are Dirac fermions?**
**(SM+right handed neutrino)**

Neutrino mass

$$y_\nu \bar{L}\tilde{\Phi}\nu_R + \text{ h.c.} \longrightarrow \mathcal{M}_\nu = y_\nu \frac{v}{\sqrt{2}}$$

$\mathcal{O}(0.1)eV$ needs $y_\nu \sim 10^{-13}$

**Seesaw mechanism?**
**(right-handed neutrinos are Majorana)**

$$y_\nu \bar{L}\tilde{\Phi}\nu_R + \frac{1}{2}M\bar{\nu}_R^c\nu_R + \text{ h.c.}$$

$$\longrightarrow \mathcal{M}_\nu \simeq \frac{y_\nu^2 v^2}{M}$$

Requires very heavy Majorana masses

# Neutrino mass generated radiatively

## Radiative Seesaw Model

Suppression from loop factors and couplings

- massless at tree level
- generated neutrino mass radiatively at one or more loops

### Scotogenic Model

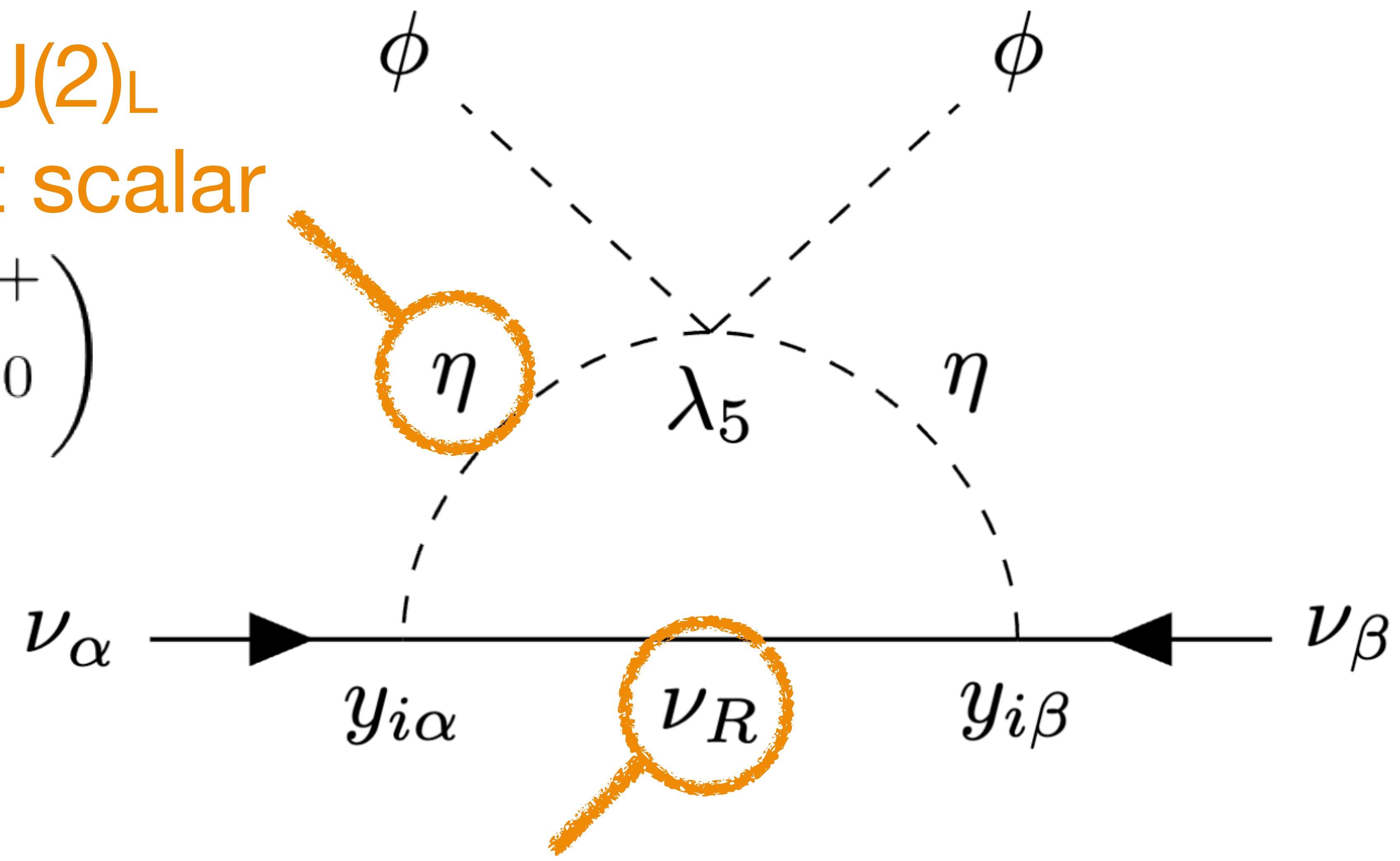
✦ Generate neutrino masses via dark sector (η) radiatively

Neutrino mass

$$[\mathcal{M}_\nu]_{\alpha\beta} = \frac{\lambda_5 v^2}{16\pi^2} \sum_i \frac{y_{i\alpha} y_{i\beta} M_i}{m_\eta^2 - M_i^2} \left[ 1 - \frac{M_i^2}{m_\eta^2 - M_i^2} \log \frac{m_\eta^2}{M_i^2} \right]$$

New $SU(2)_L$ doublet scalar

$$\eta = \begin{pmatrix} \eta^+ \\ \eta^0 \end{pmatrix}$$




Right-handed neutrino (i=1,2,3)

E. Ma, Phys.Rev.D.73.077301 (2006)    Z. Tao, Phys.Rev.D.54.5693 (1996)

# Neutrinos as window into BSM physics

## Cosmological issues suggesting BSM

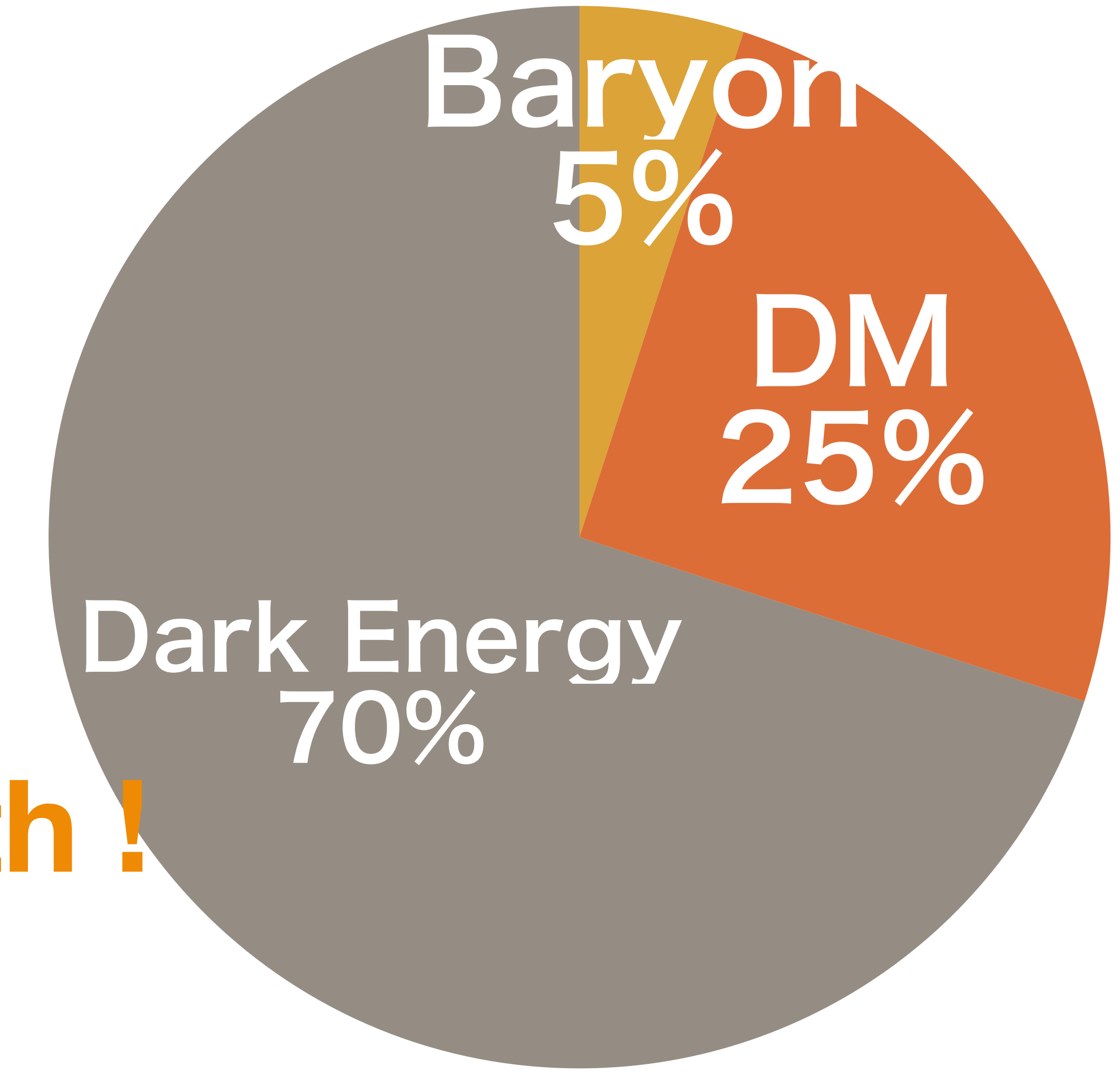
- **Matter–antimatter asymmetry**

Pair creation in the early universe

Only matter remains today

why did particles remain, while antiparticles disappeared?

- **Dark Matter** Massive, long-lived, weakly interacting particle




**Scotogenic model has the potential to explain them both !**

# Scenario

- ✦ **DM candidate → $N_1$ or η**

η as DM candidate $m_\eta < M_1 < M_2 < M_3$

✔ Neutrino masses
✔ DM abundance
✔ Baryon asymmetry

$N_1$ as DM candidate

$M_1 < m_\eta < M_2 < M_3$

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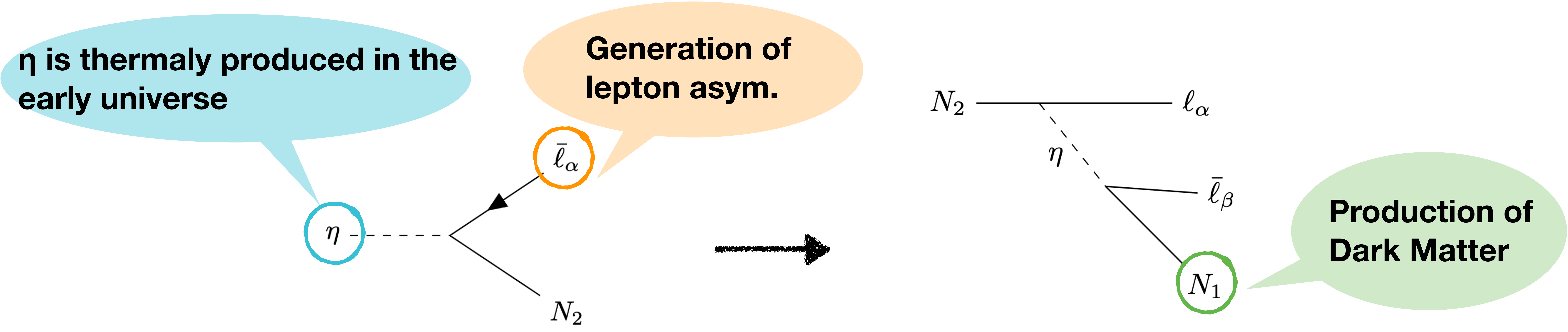


# Baryon asymmetry from $\eta$ decay

Baryon-asymmetry : the differences of the number of baryon and anti-baryon $B = n_b - n_{\bar{b}}$

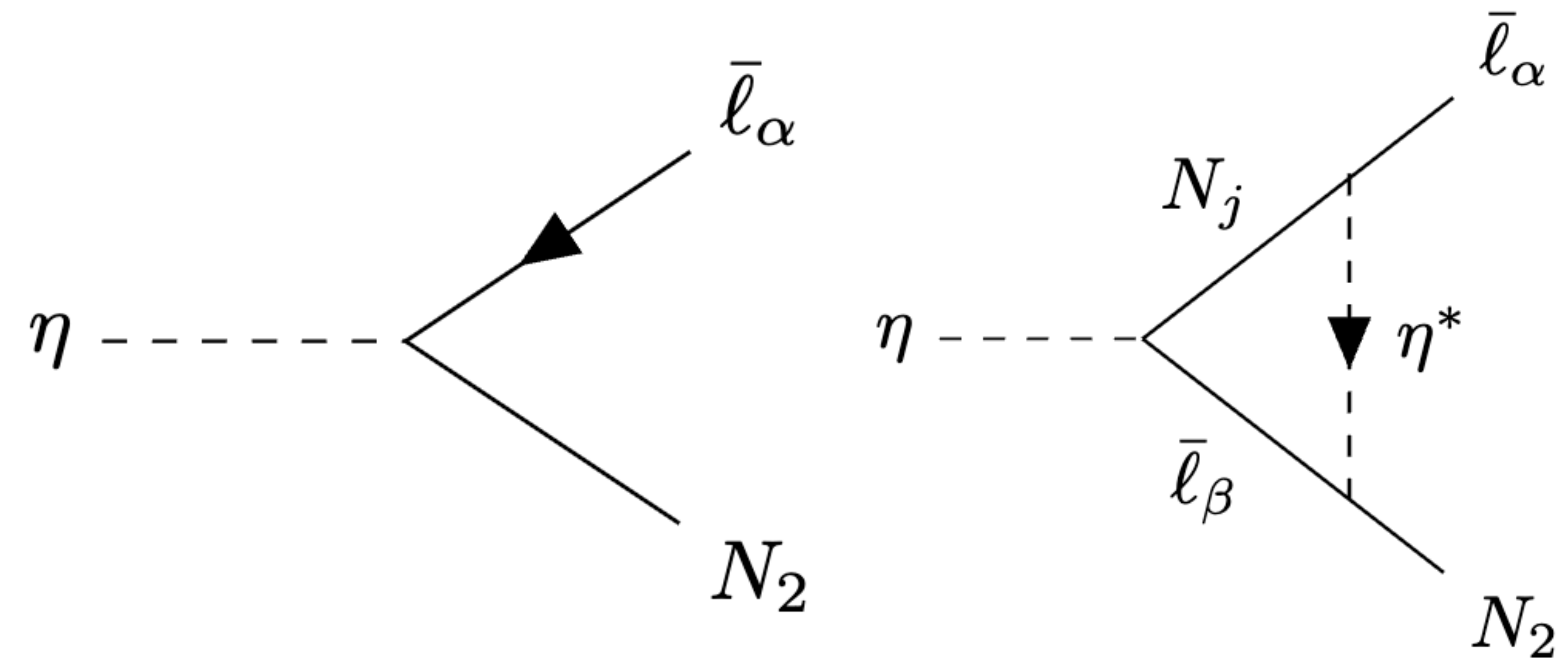
**Leptogenesis**

Lepton asym. → Baryon asym.
sphaleron process

CP is conserved→no asymmetry

$$X \to A + B$$
$$\bar{X} \to \bar{A} + \bar{B}$$

- **Need CP violation**
- **CP asym. from interference of tree and 1-loop**




CP asym. in this scenario

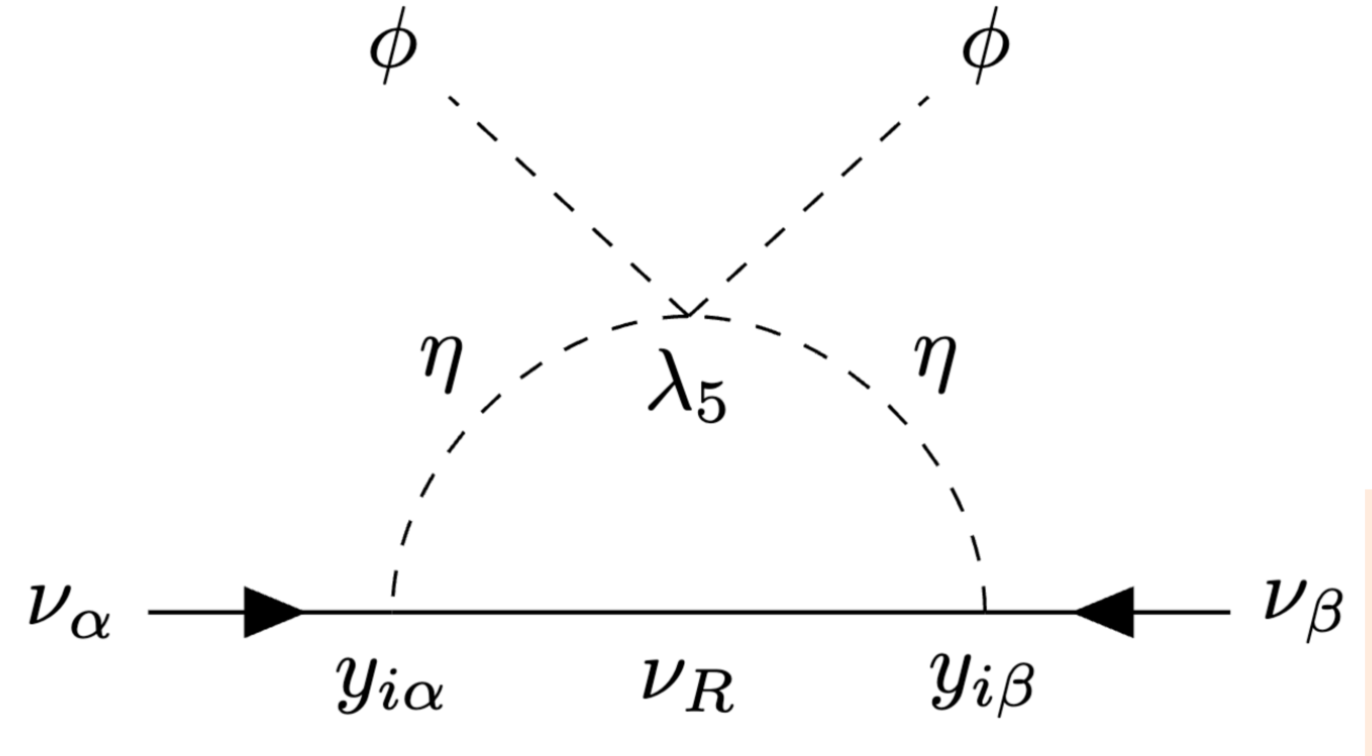
$$\epsilon_{i\alpha} = \frac{\Gamma(\eta \to N_i \bar{\ell}_\alpha) - \Gamma(\bar{\eta} \to N_i \ell_\alpha)}{\Gamma(\eta \to N_i \bar{\ell}_\alpha) + \Gamma(\bar{\eta} \to N_i \ell_\alpha)}$$

$$= \frac{1}{8\pi} \sum_{\beta,j} \frac{Im[Y^*_{i\alpha} Y^*_{i\beta} Y_{j\alpha} Y_{j\beta}]}{|Y_{\alpha i}|^2} \frac{M_i M_j}{m_\eta^2 - M_i^2} \left\{ 1 - \left( 1 + \frac{m_\eta^2 - M_j^2}{m_\eta^2 - M_i^2} \right) \log \left( \frac{m_\eta^2 - M_i^2}{m_\eta^2 - M_j^2} + 1 \right) \right\}$$

# A parameter for Neutrino mass

**Neutrino masses from radiative seesaw**

$$[\mathcal{M}_\nu]_{\alpha\beta} = \frac{\lambda_5 v^2}{16\pi^2} \sum_i \frac{y_{i\alpha} y_{i\beta} M_i}{m_\eta^2 - M_i^2} \left[ 1 - \frac{M_i^2}{m_\eta^2 - M_i^2} \log \frac{m_\eta^2}{M_i^2} \right]$$




**Right handed neutrino and η masses**

$$M_1 = 1\,\mathrm{MeV}$$
$$M_2 = 9.5 \times 10^9\,\mathrm{GeV}$$
$$M_3 = 9.8 \times 10^9\,\mathrm{GeV}$$
$$m_\eta = 10^{10}\,\mathrm{GeV}$$

**Coupling**

$$\lambda_5 = 1$$

$$y_{i\alpha} = \begin{pmatrix} 6.03 \times 10^{-7} + 1.06 \times 10^{-6} i & -1.71 \times 10^{-6} + 2.29 \times 10^{-6} i & -1.96 \times 10^{-6} - 5.23 \times 10^{-7} i \\ -1.17 \times 10^{-2} + 5.93 \times 10^{-3} i & -2.34 \times 10^{-2} - 2.21 \times 10^{-2} i & 6.87 \times 10^{-3} - 2.22 \times 10^{-2} i \\ -1.33 \times 10^{-2} - 5.85 \times 10^{-5} i & 4.14 \times 10^{-2} - 1.23 \times 10^{-2} i & 4.17 \times 10^{-2} + 3.60 \times 10^{-3} i \end{pmatrix}$$

⇨ **neutrino masses and mixing can be reproduced !**

$$m_1 = 1.00 \times 10^{-31} eV$$
$$m_2 = 8.65 \times 10^{-3} eV$$
$$m_3 = 5.03 \times 10^{-2} eV$$

$$\sin\theta_{12}^2 = 0.307$$
$$\sin\theta_{23}^2 = 0.561$$
$$\sin\theta_{13}^2 = 0.02195$$
$$\delta_{CP}/^\circ = 177$$

(From NuFit6.0)

# Calculation of Lepton asym.

- **L-asym. is calculated by solving Boltzmann equation**

equation of time evolution of number density

$$\frac{dn_L}{dt} + 3Hn_L = -\left\{n_{\Delta\eta} + n_\eta^{eq}\frac{n_L}{n_\ell^{eq}}\frac{n_N}{n_N^{eq}}\right\}\langle\Gamma_\eta\rangle - \left\{n_+ - n_+^{eq}\frac{n_N}{n_N^{eq}}\right\}\epsilon\langle\Gamma_\eta\rangle$$
$$+\left\{n_{\Delta\eta}n_+ - n_\eta^{eq}n_+^{eq}\frac{n_L}{n_\ell^{eq}}\right\}C_{spec}\langle\sigma v\rangle_{\eta\eta\to\phi\phi}$$

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

$n^{eq}$ : number density in thermal equilibrium

$C_{spec}$ : Coefficient converting Higgs asym. to lepton asym.

solve a set of three coupled differential equations numerically

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$$\frac{dn_+}{dt} + 3Hn_+ = -\left\{n_+ + n_+^{eq}\frac{n_N}{n_N^{eq}}\right\}\langle\Gamma_\eta\rangle - \frac{1}{2}\left\{n_+^2 - n_+^{eq2}\right\}\epsilon\langle\Gamma_\eta\rangle_{\eta\eta\to\phi\phi,\eta\eta\to AA}$$

$$\frac{dn_{N_2}}{dt} + 3Hn_{N_2} = \langle\Gamma_\eta\rangle\left\{n_\eta - \frac{n_{N_2}}{n_{N_2}^{eq}}\frac{n_\ell}{n_\ell^{eq}}n_\eta^{eq}\right\}$$

solve a set of four coupled differential equations numerically

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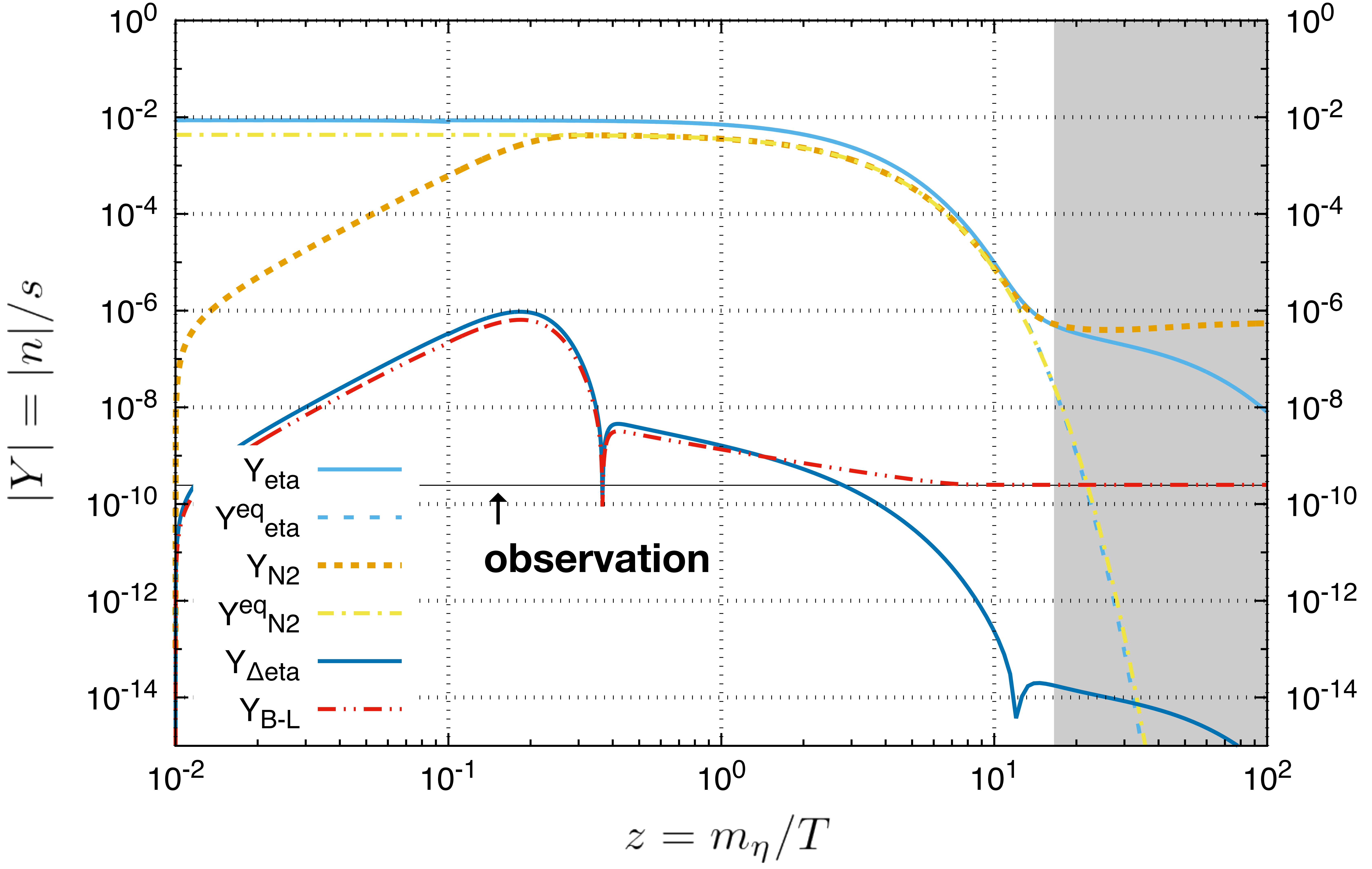
# L asym. time evolution




- ✦ **Unified framework for $m_\nu$, mixing, DM, Baryon Asym.**
- ✦ **The favored parameter space is completely different from the scenario with η as the DM candidate.**

# Summary

- **The radiative seesaw model is an attractive scenario that explains the smallness of neutrino masses through one or more loops.**
- **Scotogenic model generate neutrino mass via dark sector.**
- **In this model, neutrino masses, the baryon asymmetry, and DM abundance can all be explained in unified framework when the lightest right-handed neutrino is the DM candidate.**
- **The favored parameter space is completely different from the scenario with η as the DM candidate.**