# A new Dirac neutrino mass model with dark matter and electroweak baryogenesis

In preparation

Kodai Sakurai（University of Toyama）

Collaborators :
Shinya Kanemura（University of Toyama）
Hiroaki Sugiyama（ 〃 ）

RISE meeting, 6-7 March 2017

# Tiny neutrino masses

- It has been established that neutrinos have tiny masses because of the discovery of neutrino oscillations.

$$\Delta m_{21}^2 = 7.46\times10^{-5}\mathrm{eV}^2$$

SNO Collaboration, PRC 88 (2013) 025501

$$\left|\Delta m_{32}^2\right| = +2.51\times10^{-3}\mathrm{eV}^2$$

T2K Collaboration,PRD91 (2015) 072010

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

- In the Standard Model (SM), Quarks and Leptons obtain masses after electroweak symmetry breaking, but neutrino mass is zero.

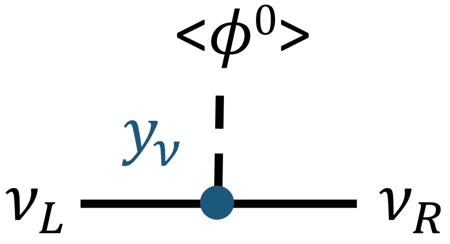
$$\frac{y_f}{\sqrt{2}}\bar{f}_L h f_R \to \frac{y_f}{\sqrt{2}}\langle h\rangle \bar{f}_L f_R$$

The SM don’t include $\nu_R$.

↳ What mechanism are neutrino masses $m_\nu$ generated by ?

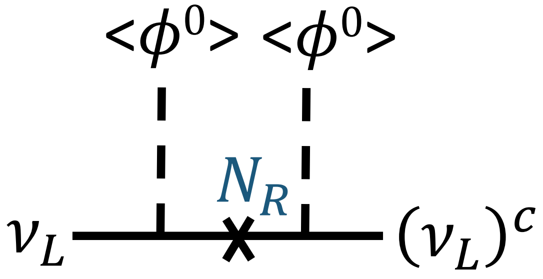
# Some mechanisms generating $\mathbf{m}_\nu$

① The same mechanism with quarks and leptons (Dirac mass)



$$\mathrm{m}_\nu = \frac{y_\nu}{\sqrt{2}} v$$

② Seesaw mechanism

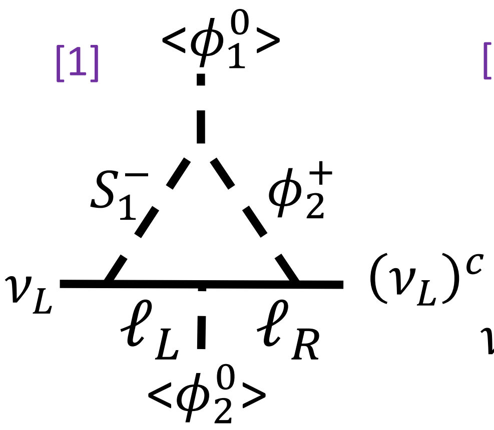


$$\mathrm{m}_\nu = \frac{\mathrm{y}_\nu^2 v^2}{M_{N_R}}$$

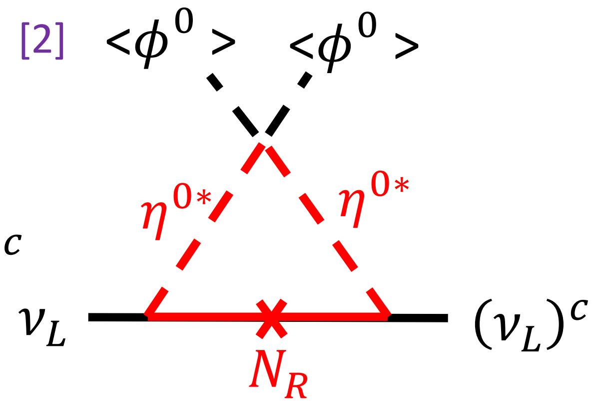
③ Radiative seesaw mechanism

[1] Zee, PLB93 (1980) 389. [2] Ma,PRD 73 (2006) 077301.
[3] Aoki, Kanemura, Seto, PRL 102 (2009) 051805.

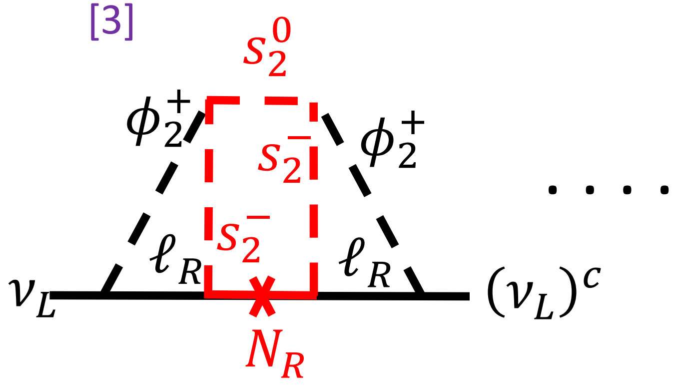
[1]



[2]



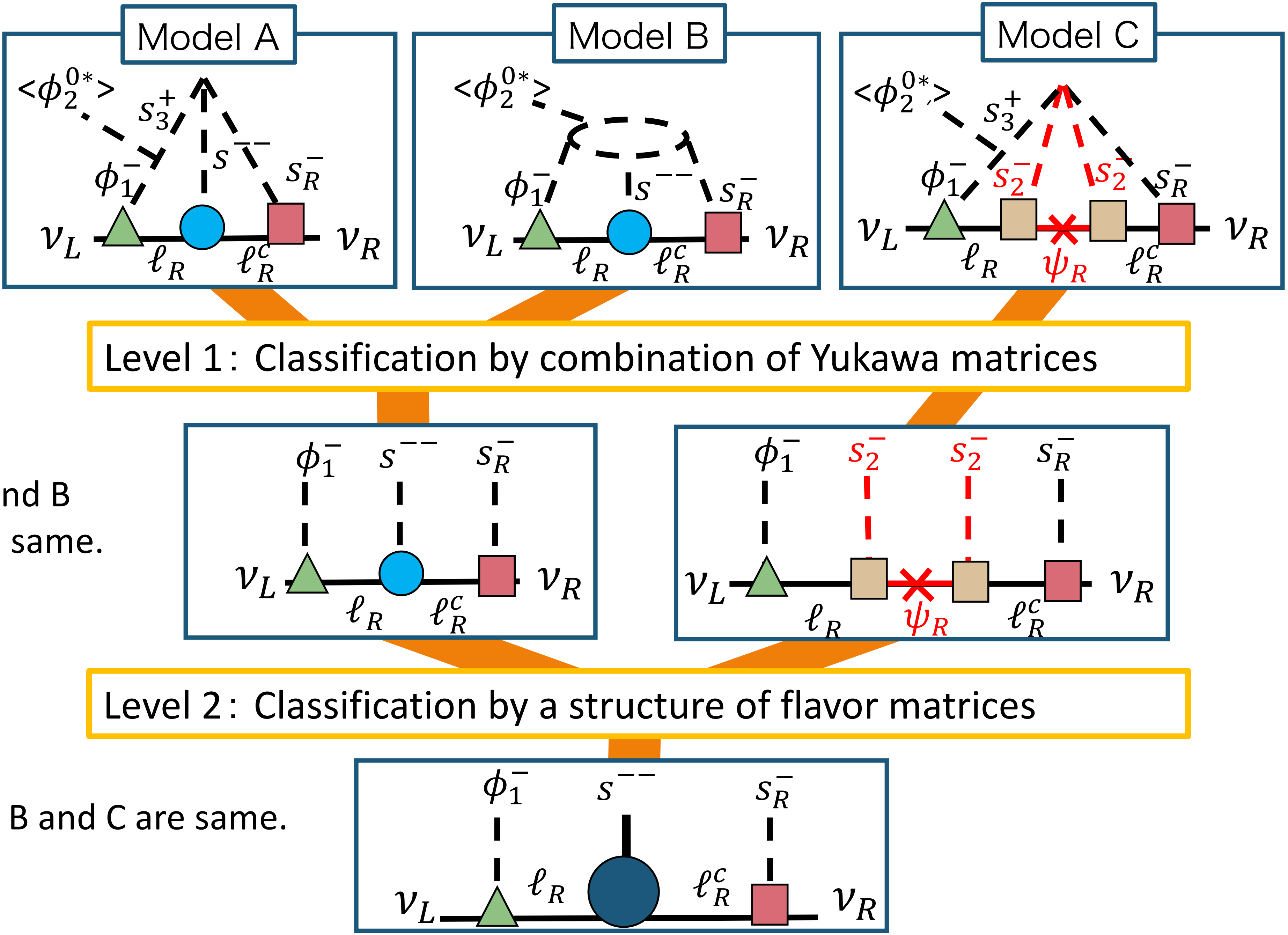
[3]



- There are many many models .
- In order to efficiently test models of $\mathrm{m}_\nu$, we classified the models into some groups, then, examined testability of the groups.

Kanemura, Sugiyama, PLB753 (2016) 161, Kanemura, Sugiyama, KS PLB758 (2016) 465.

# Classifications by flavor structure of $\mathbf{m}_\nu$



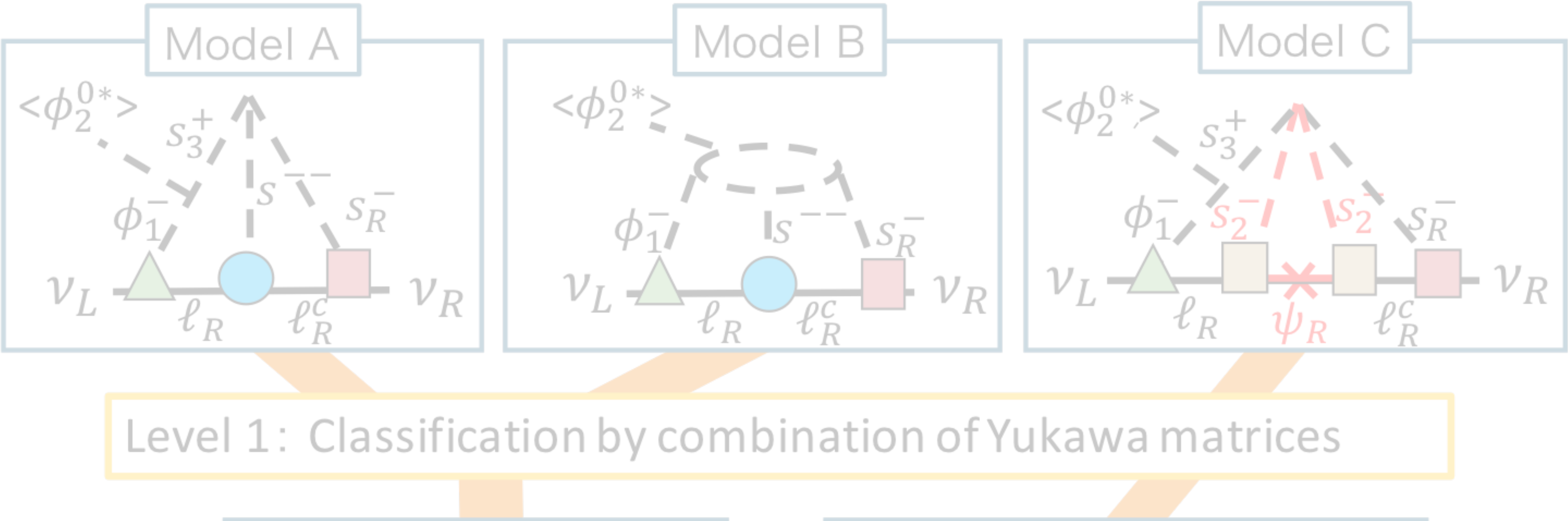
Level 1： Classification by combination of Yukawa matrices

A and B
are same.

Level 2： Classification by a structure of flavor matrices

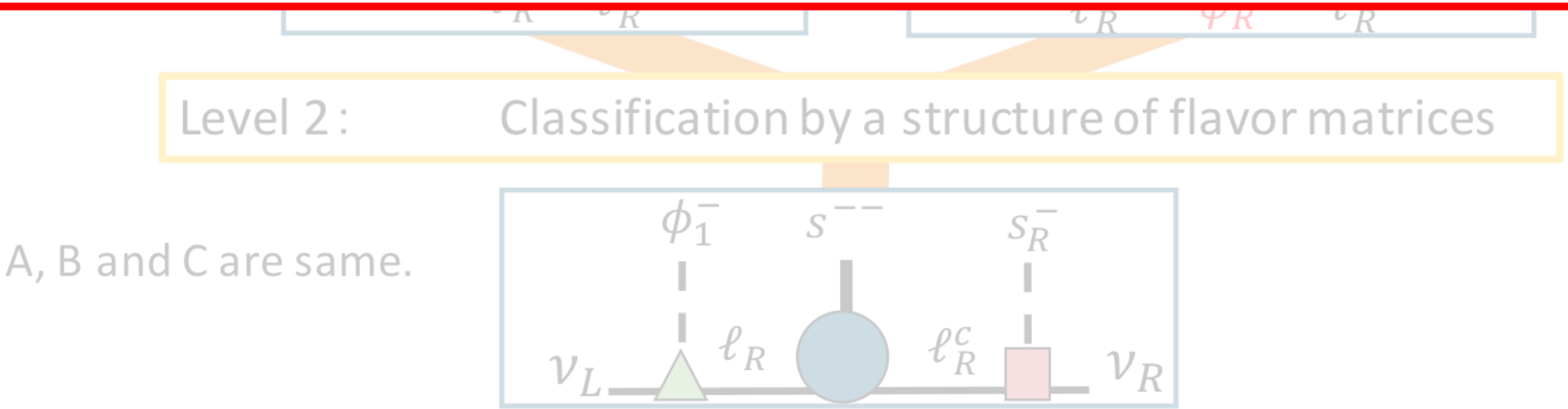
A, B and C are same.

# Classifications by flavor structure of $\mathbf{m}_\nu$



Level 1 : Classification by combination of Yukawa matrices

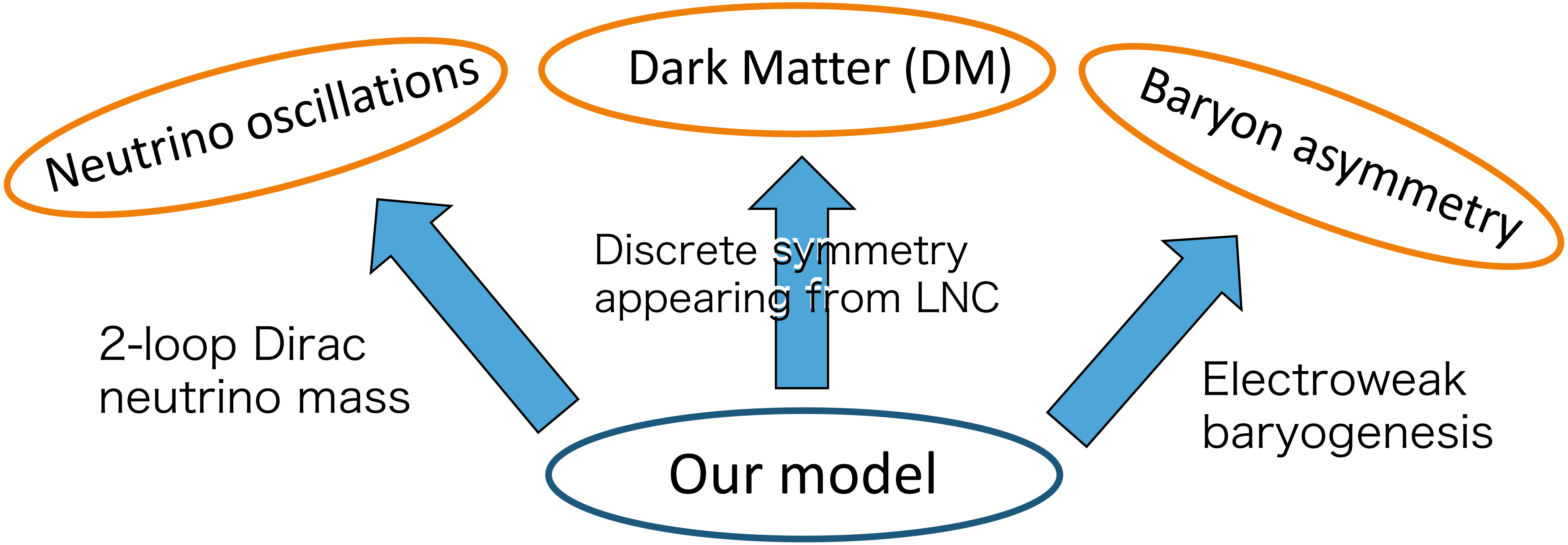
We discuss details of a new model which was found by our previous studies.



Level 2 : Classification by a structure of flavor matrices

A, B and C are same.

# Our model



Neutrino oscillations

Dark Matter (DM)

Baryon asymmetry

2-loop Dirac
neutrino mass

Discrete symmetry
appearing from LNC

Electroweak
baryogenesis

Our model

LNC : Lepton Number Conservation

We discuss whether or not there is a benchmark scenario which can simultaneously explain three Beyond the SM (BSM) phenomena.

# Setup

- New field in addition to SM field

$$\Phi_{1,2} = \begin{pmatrix} \omega^+_{1,2} \\ \frac{1}{\sqrt{2}}(v_{1,2} + \phi^0_{1,2} + iz_{1,2}) \end{pmatrix}$$

Higgs doublet : $\Phi_1, \Phi_2$

Scalar singlet : $s^0_1, s^+_2$, $s^+_3$

Gauge singlet fermion : $\psi_{R1}, \psi_{R2}, \psi_{R3}$

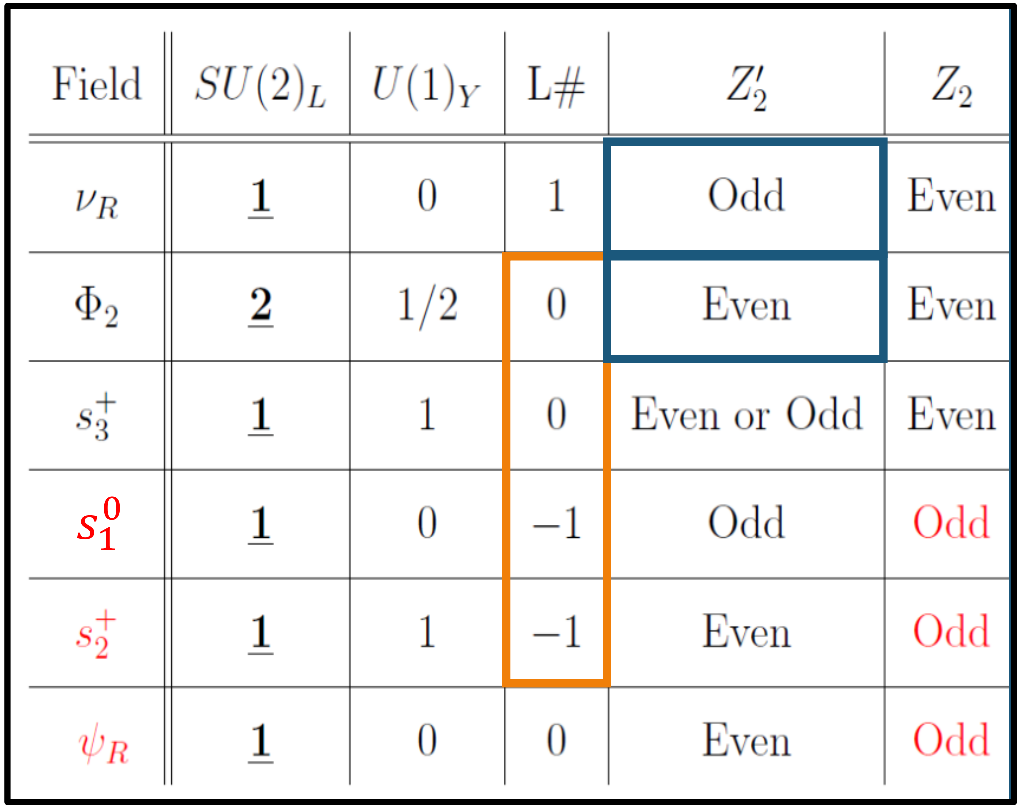
Right-handed neutrino : $\nu_{R1}, \nu_{R2}, \nu_{R3}$

Red character denote $Z_2$ odd particles.

$Z_2$ odd : $\psi_{Ra} \to -\psi_{Ra}, s^0_1 \to -s^0_1, s^+_2 \to -s^+_2$

$Z_2$ even : $\Phi_{1,2} \to +\Phi_{1,2}$, $s^+_3 \to +s^+_3, \nu_R \to +\nu_R$

- Symmetries: $Z'_2 \times U(1)_L \times Z_2$



| Field | $SU(2)_L$ | $U(1)_Y$ | L# | $Z'_2$ | $Z_2$ |
|---|---|---|---|---|---|
| $\nu_R$ | $\underline{\mathbf{1}}$ | 0 | 1 | Odd | Even |
| $\Phi_2$ | $\underline{\mathbf{2}}$ | 1/2 | 0 | Even | Even |
| $s_3^+$ | $\underline{\mathbf{1}}$ | 1 | 0 | Even or Odd | Even |
| $s_1^0$ | $\underline{\mathbf{1}}$ | 0 | $-1$ | Odd | Odd |
| $s_2^+$ | $\underline{\mathbf{1}}$ | 1 | $-1$ | Even | Odd |
| $\psi_R$ | $\underline{\mathbf{1}}$ | 0 | 0 | Even | Odd |

$U(1)_L$ : Lepton number conservation

$Z'_2$ : Prohibition for $Y_\upsilon \bar{L}\tilde{\Phi}\upsilon_R$

$Z_2$ : Stability for DM

- Physical states: $\nu_1, \nu_2, \nu_3, H_1^\pm, H_2^\pm, H, A, s_2^\pm, \underbrace{s_1^0, \psi_{R1}}, \psi_{R2}, \psi_{R3}$

the lightest $Z_2$ odd particle is dark mater candidate

# Lagrangian

- Scalar potential : we consider the CP conserving potential

$$\left.\begin{aligned} V = &\sum_{i=1}^{2}(m_i^2|\Phi_i|^2 + \frac{\lambda_i}{2}|\Phi_i|^4) - m_3^2(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) \\ &+ \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}] \end{aligned}\right\} \text{Two Higgs doublet model}$$

$$\left. + \sum_{i=1}^{3}\left(m_{s_i}^2|s_i|^2 + \frac{\lambda_{si}}{2}|s_i|^4\right) + \sum_{i<j}^{3}\lambda_{sisj}|s_i|^2|s_j|^2 \right\} \text{scalar singlet}$$

$$\left.\begin{aligned} &+ \left(\mu_3\Phi_2^\dagger\epsilon\Phi_1^* s_3^+ + h.c.\right) + \left(\mu_3' s_3^- s_2^+ s_1^0 + h.c.\right) \\ &+ \sum_{i=1}^{3}\left(\lambda_{\phi 1si}|\Phi_1|^2|s_i|^2 + \lambda_{\phi 2si}|\Phi_2|^2|s_i|^2\right) \end{aligned}\right\} \text{Interaction terms}$$

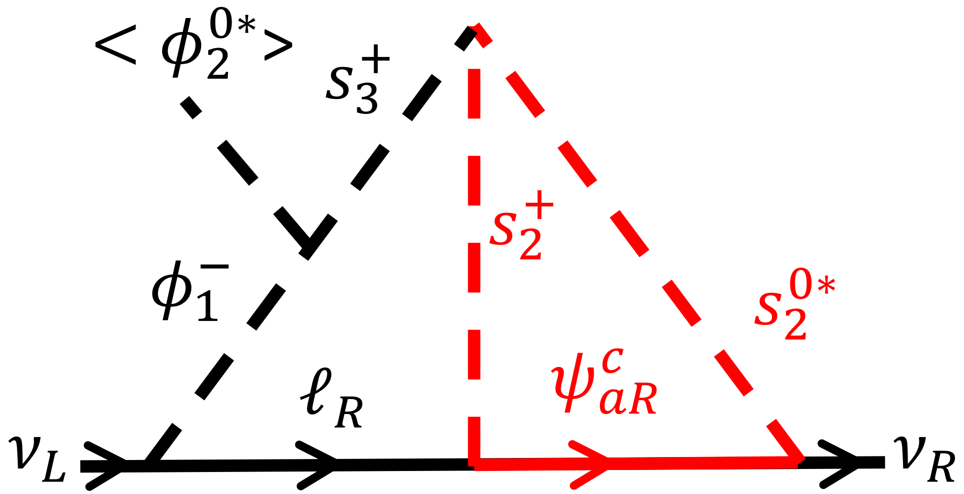
- Yukawa interactions: Additional $Z_2$ symmetry is imposed to prohibit FCNC.

$$\left. \mathcal{L}_Y = Y_\ell \overline{L}\Phi_1\ell_R + Y_u\overline{Q}\Phi_2 u_R + Y_d\overline{Q}\Phi_2 d_R \right\} \text{Type-X}$$

$$\left. + Y_\psi^0\left[\overline{(\nu_{iR})^c}\,\psi^0_{jR}s_1^0\right] + Y_\psi^+\left[\overline{(\ell_R)^c}\,\psi^0_{iR}\,s_2^+\right] + h.c. \right\} \text{New Yukawa}$$

# Neutrino mass

$$
\begin{aligned}
m_{\nu i \ell} = & (Y_\psi^{0*})_{ib} (Y_\psi^{+T})_{b\ell} \mu_3' \tan\beta \frac{\sqrt{2} m_\ell}{v} \frac{\sin 2\theta_+}{2} \\
& \times \left( \frac{1}{16\pi^2} \right)^2 F(m_{H_1^\pm}, m_{H_2^\pm}, m_{\psi_b}, m_{s_1^0})
\end{aligned}
$$

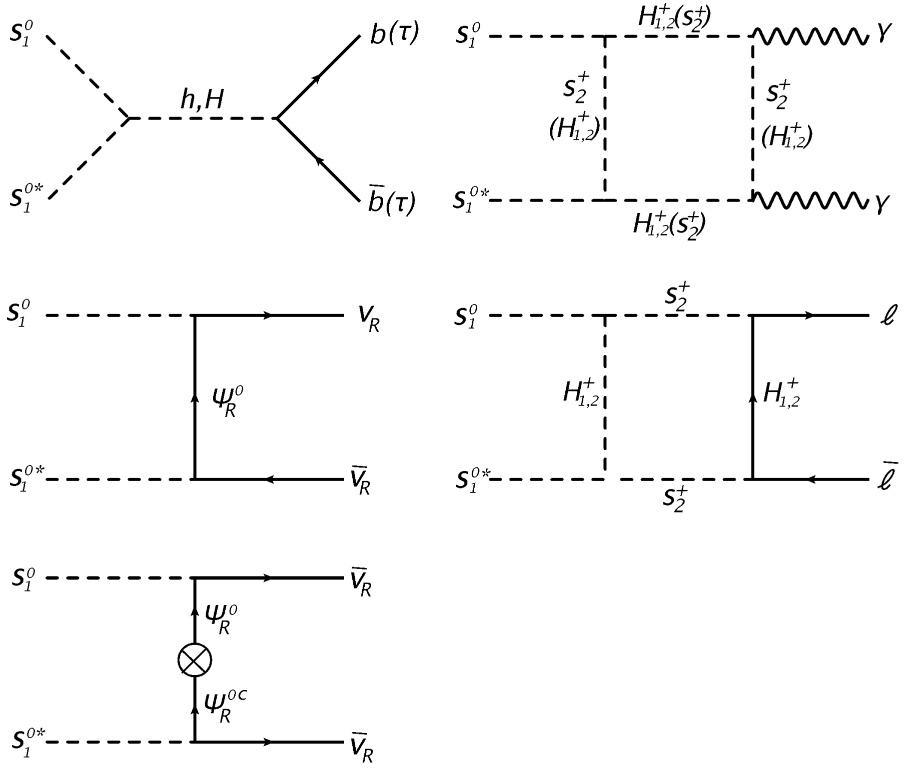


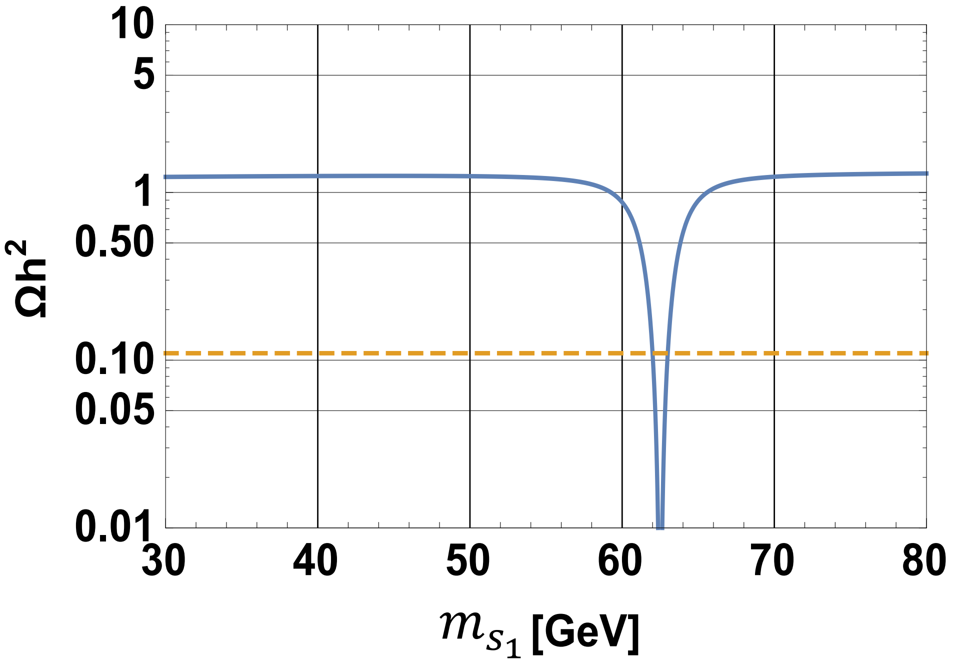
- $m_\nu$ is suppressed by 5 coupling constants + 2-loop suppression factor + a loop function F
- In order to satisfy the data of neutrino oscillations and constraint of LFV (Lepton Flavor Violation), the following Eq. is requried

$$
Y_\psi^+ \sim O(0.01),\ Y_\psi^0 \sim O(0.001),\ \underbrace{m_{\psi_{Ra}} \sim O(1)\text{TeV}}_{\text{A mass of heaviest particles}}
$$

# Relic abundance for DM

- $s_1^0$ is DM candidate.
- We foucus on a mass region $m_{DM} < 80$ GeV in which WW channel don’t open.
- There are 5 annihilation processes :





$$\Omega h^2 = 0.1199 \pm 0.0020$$

Plank, arXiv:1502.01589

$m_{S_1^0} = 62$ or 63 GeV are consistent with Plank exp. data.

# Electroweakbaryogenesis

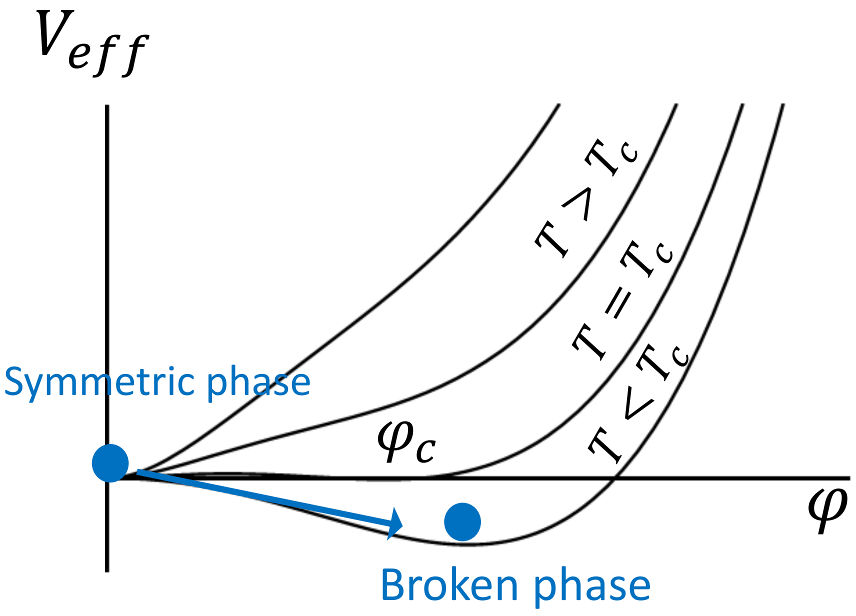
Sakharov's conditions

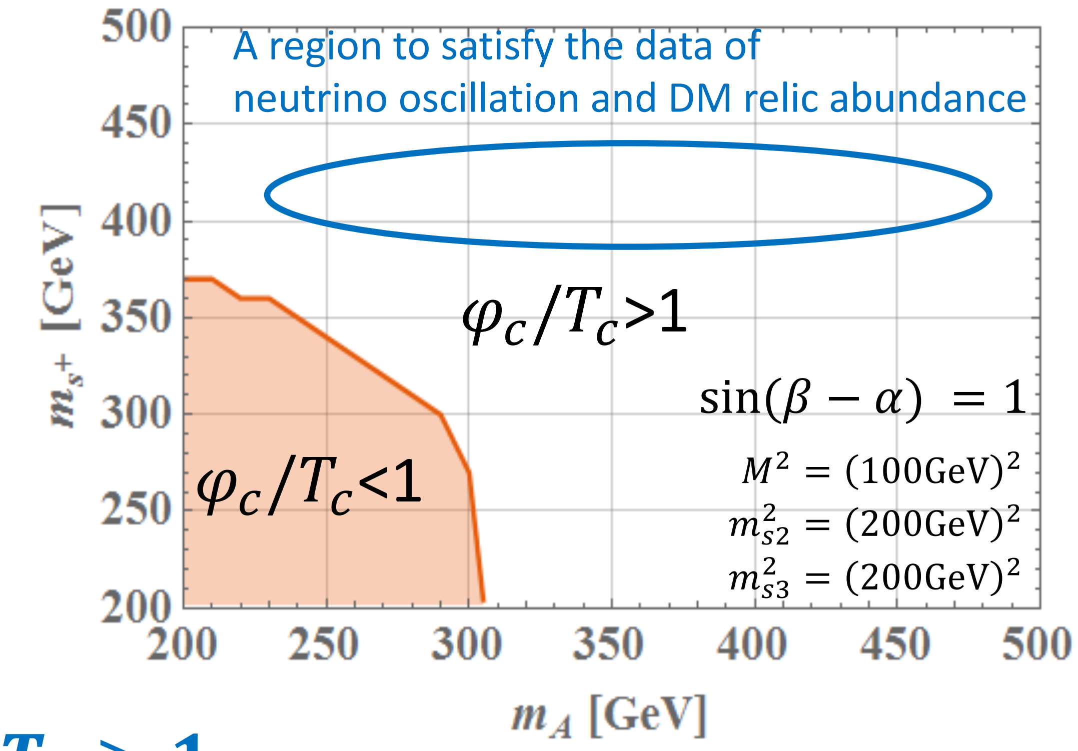
- B violation ← Sphaleron process
- C and CP violation ← CP phase in the Higgs sector
- Out of equilibrium ← Strong 1st Order phase Transition (1st OPT)

# Electroweakbaryogenesis

## Sakharov's conditions

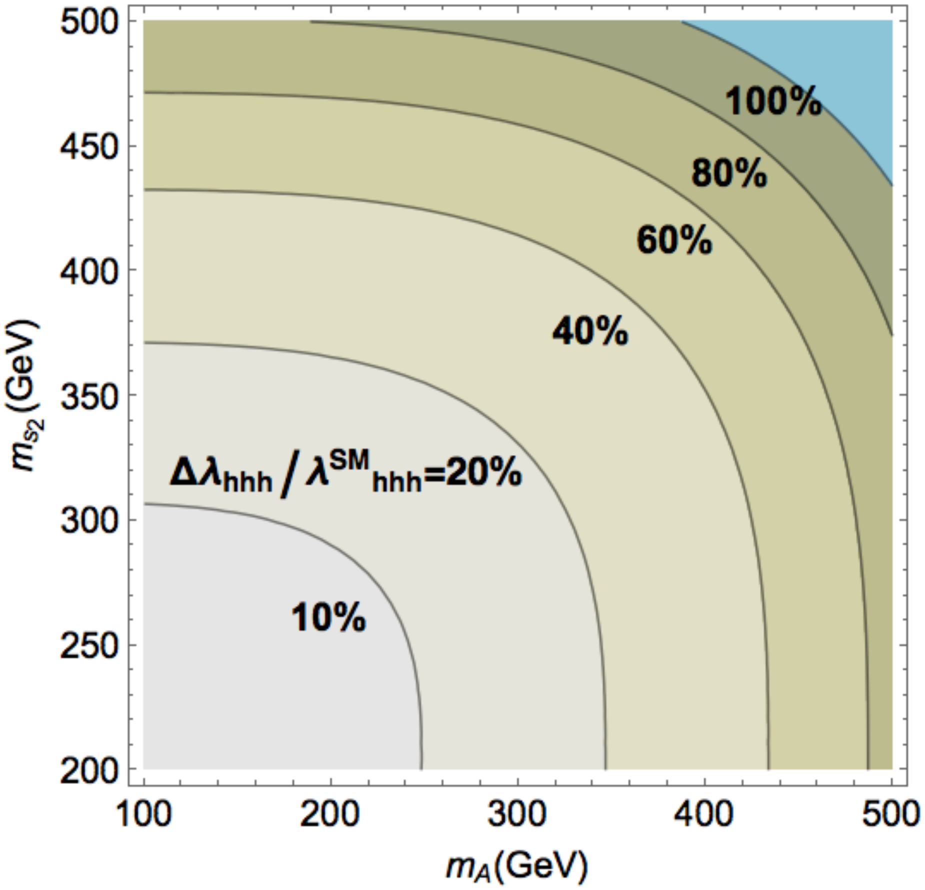
- B violation ← Sphaleron process
- C and CP violation ← CP phase in the Higgs sector
- Out of equilibrium ← Strong 1st Order phase Transition (1st OPT)





A condition to occur 1st OPT: $\boldsymbol{\varphi_c/T_c > 1}$

# Triple Higgs boson couplings



$$\Delta\lambda_{hhh} = \lambda_{hhh} - \lambda_{hhh}^{SM}$$

- We also evaluated triple Higgs boson coupling $\lambda_{hhh}$.
- Large deviation from the SM in $\lambda_{hhh}$ is occurred by non-decoupling effect of the additional scalar.

# A successful scenario

$\mu_3' = 50\text{GeV}, \quad \sin\theta_+ = 0.1, m_{\psi_{R_1}} = m_{\psi_{R2}} = m_{\psi_{R3}} = 5\text{TeV},$

$m_{H_1^\pm} = 200\text{GeV}, \quad m_{H_2^\pm} = 300\text{GeV}, \quad m_{s_2^\pm} = 400\text{GeV},$

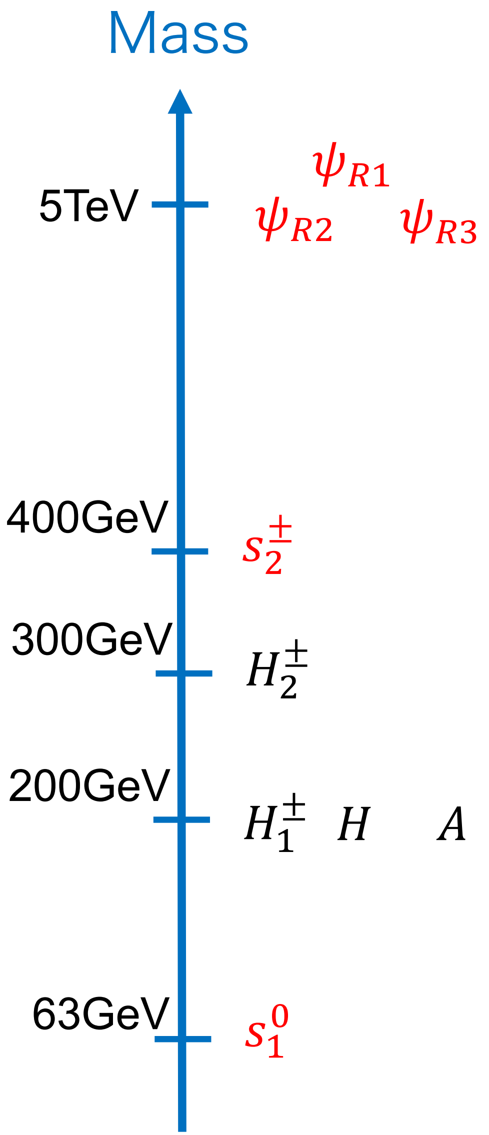
$m_{H,A} = 200\text{GeV}, \ m_{s_1^0} = 63\text{GeV},$

$$Y_\psi^+ = \begin{pmatrix} 1 & 0.01 & 0.01 \\ 0.01 & 1 & 0.01 \\ 0.01 & 0.01 & 1 \end{pmatrix}, \ Y_\psi^0 \cong \begin{pmatrix} 0.33 & -0.0041 & -0.0032 \\ 0.28 & -0.0014 & -0.0029 \\ 0.30 & 0.0040 & -0.0026 \end{pmatrix}$$

$\sin(\beta - \alpha) = 1, \tan\beta = 3, \ \lambda_{\phi 1 s0} = 0.02, \ \lambda_{\phi 2 s0} = 0.005,$

$M^2 = (100\text{GeV})^2, \ m_{s2}^2 = m_{s3}^2 = (200\text{GeV})^2$

- ✓ Neutrino oscillation
- ✓ DM relic density
- ✓ Strong 1st OPT
- ✓ LFV, LU
- ✓ DM direct detection
- ✓ S, T, U parameters



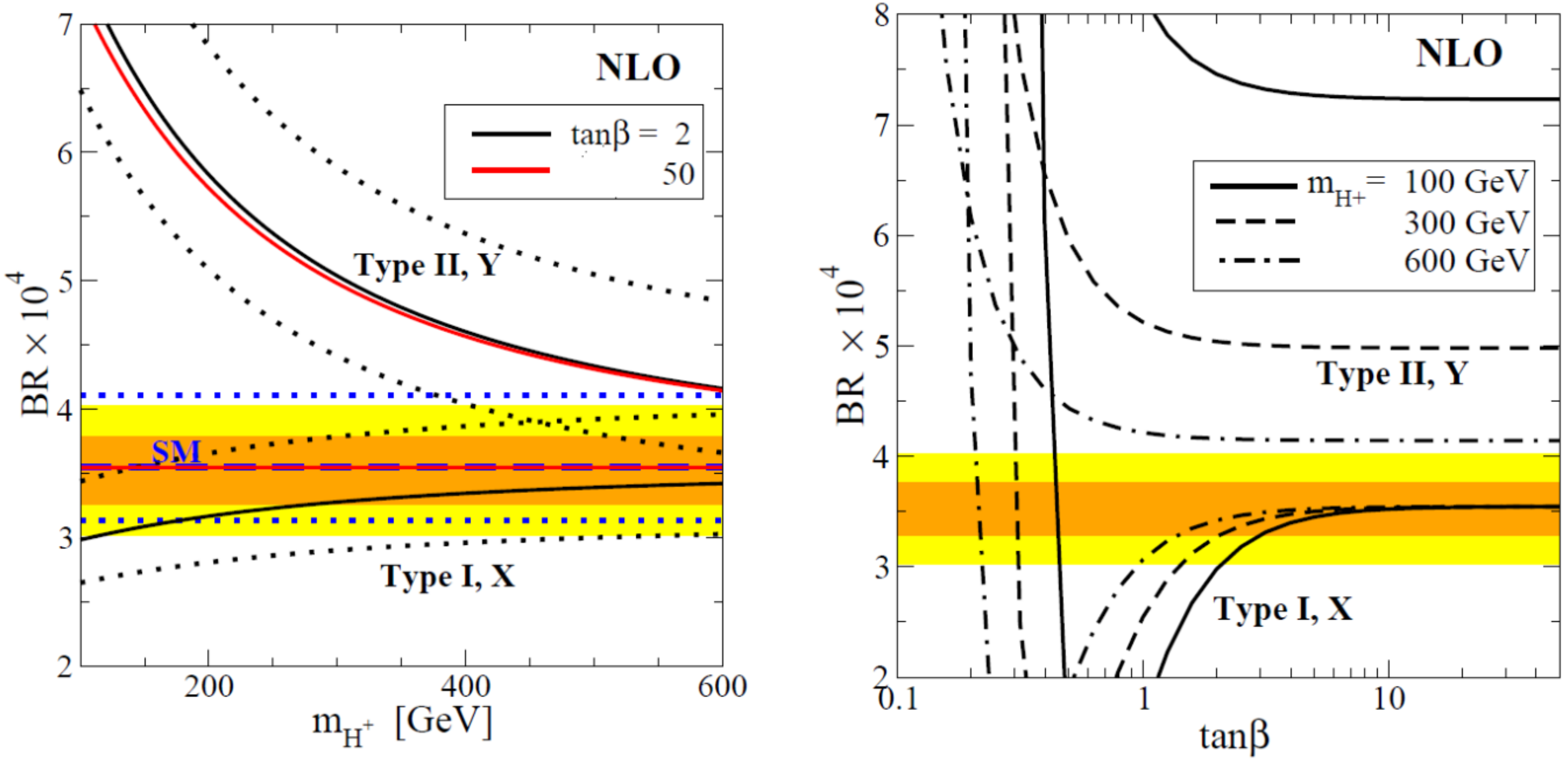
# Summary

- We proposed a new Dirac neutrino mass model which can explain dark matter and baryon asymmetry of the Universe
- This new model was found by classifications for neutrino mass model in our previous studies.
- We confirmed that there was a benchmark scenario explaining these three BSM phenomena.

# back up slides

# Constraint of $bs \to \gamma$（2HDM）

Aoki, Kanemura, Tsumura and Yagyu, Phys.Rev. D80 (2009) 015017

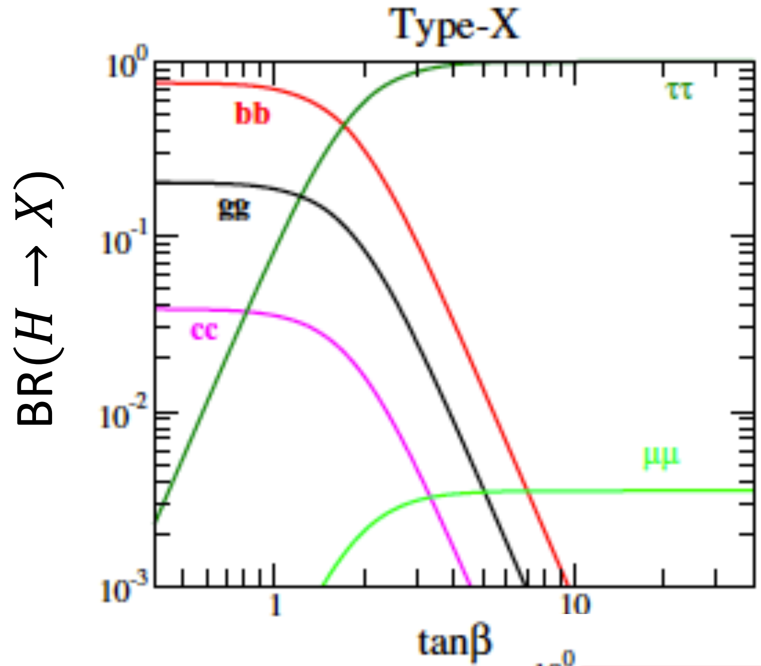


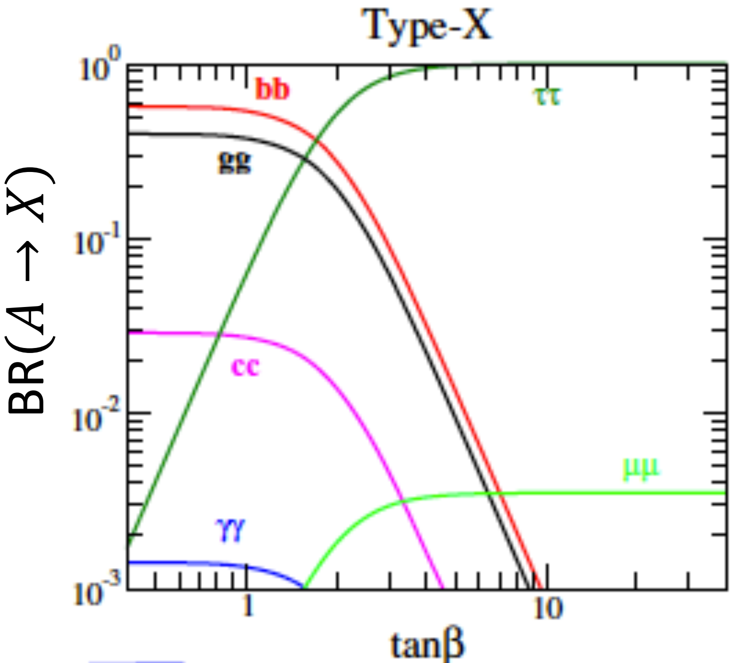
🟧 : allowed regions (1σ)

🟨 : allowed regions (2σ)

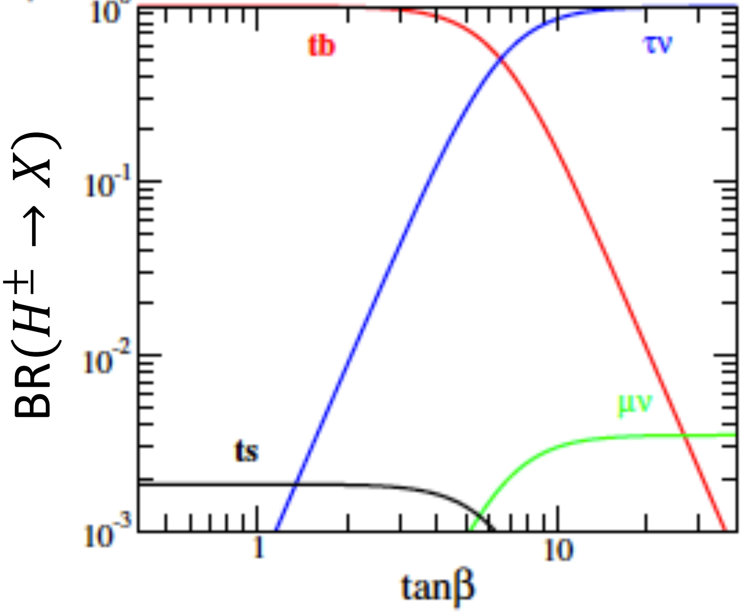
This is the reason why we adapt Type-X

# Branching ratio $H, A, H^{\pm}$ (Type-x THDM)





Kanemura, Tsumura, Yagyu,
Yokoya PRD 90, 075001 (2014)



$\mathrm{Sin}(\beta - \alpha) = 1$

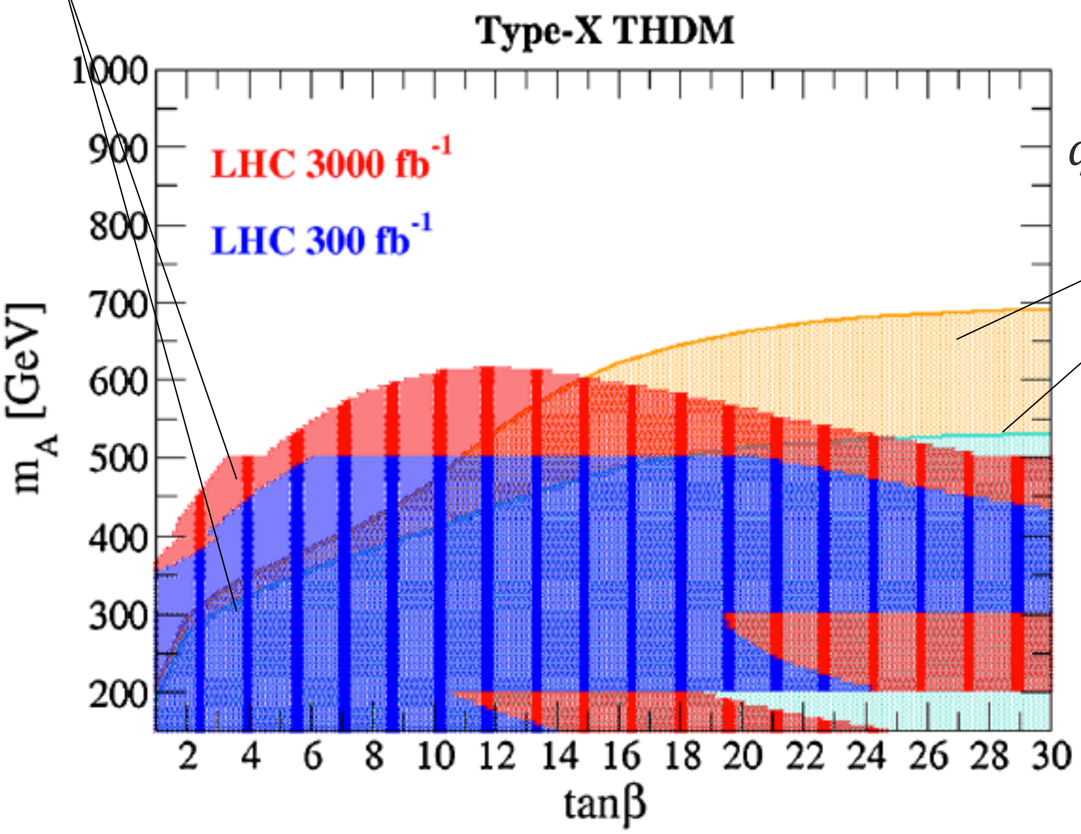
$m_{\Phi} = M = 200$ GeV

# Prospects of Direct search of *A* by the LHC(Type-x THDM)

Kanemura, Tsumura, Yagyu,
Yokoya PRD 90, 075001 (2014)

$gg \to \phi^0 \to \tau^+\tau^-, gg \to b^-b\phi^0 \to b^-b\tau^+\tau^-$

$(\phi^0 = H, A)$



$q^+q^- \to HA \to \tau^+\tau^-$

LHC 3000 fb$^{-1}$

LHC 300 fb$^{-1}$