A model with an extended scalar sector for neutrino, DM and BAU

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Mayumi Aoki, Kazuki Enomoto, SK, PRD 107 (2023) 11, 115022
Kazuki Enomoto, SK, Sora Taniguchi, arxiv: 2403.13613

Extended Scalar Sectors from All Angles,
Oct 21-25, 2024 at CERN

Motivation to BSM

SM is a good description of the nature around the EW scale, however ….

Problems

- Gravity
- Unification
- Flavor
- No principle in the Higgs sector
  - Hierarchy
  - Strong CP
- Beyond SM phenomena
  - Neutrino Oscillation
  - Dark Matter
  - Baryon Asymmetry of Universe
  - …

SM must be replaced by a new more fundamental theory

Higgs sector is a probe of new physcs

Higgs sector remains unknown

Multiplet Structure
Higgs Potential　(Dynamics of EWSB, EWPT, …)
Yukawa Structure　(Flavor Physics, CPV, …)
Elementary or Composite? Hierarchy?

SM Higgs sector: no principle

Extension of the Higgs sector

⇨ BSM phenomena may be explained

Tiny neutrino mass
Phase Transition (1st Order)
CPV sources for baryogenesis
DM candidates
…

Testable at current and future experiments

New Physics and Multi-Higgs Models

Typical scenarios using TeV scale physics by extended Higgs

BAU	EW Baryogenesis
Neutrino mass	Radiative Seesaw
Dark Matter	WIMP

Can we combine these scenarios into a model?

This is the subject of this talk

Baryogenesis and Higgs

Sakharov Conditions

Kuzmin, Ruvakov, Shaposhnikov (1985)

1） B non-conservation ➡ **Sphaleron transition at high T**

2） C and CP violation ➡ **C violation (SM is a chiral theory)**
CP in extended Higgs sectors

3） Departure from thermal equilibrium ➡ **EWPT is strongly 1st OPT**

SM cannot satisfy the condition

Extended Higgs sectors
provide new sources of CPV and mechanisms of 1st OPT

Studied in 2HDMs, Singlet extensions, 2HDM+S, Triplet models, …

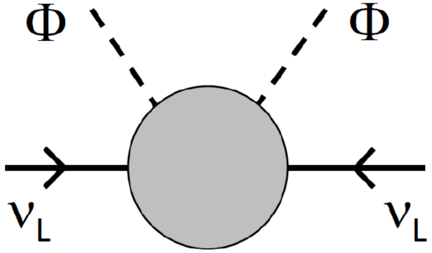
Rich phenomenology: Testable by experiments (colliders, EDM, flavor, GW, …)

Neutrino mass and Higgs

Neutrino Oscillation → Tiny mass （< eV)

Majorana mass

$$\boxed{\mathcal{L} = \frac{c}{\Lambda}(\phi\overline{\nu_L^c})(\nu_L\phi)}$$

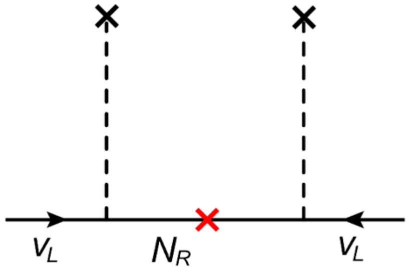


Seesaw Mechanism

$$m_\nu^{ij} = y_i y_j \frac{\langle\phi\rangle^2}{M_R}$$

← Large mass of Right-handed Neutrinos

Tiny mass



Seesaw

Mediated by RH neutirnos N_R

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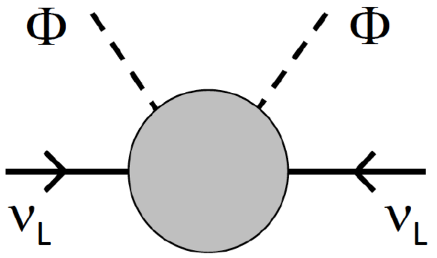
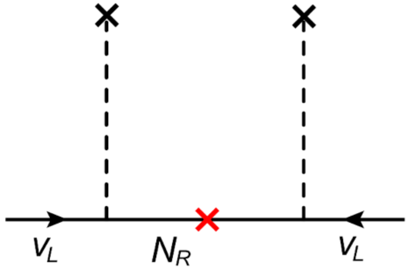


Seesaw Mechanism

$$m_\nu^{ij} = y_i y_j \frac{\langle\phi\rangle^2}{M_R} \leftarrow$$

Tiny mass

Large mass of Right-handed Neutrinos



Seesaw

Mediated by RH neutirnos N_R

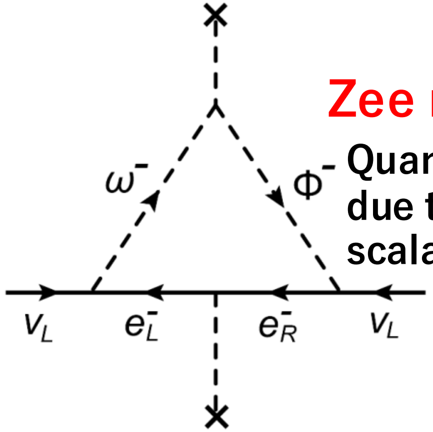
Alternative Scenario by quantum effects

$$m_\nu^{ij} = c_{ij}\left(\frac{1}{16\pi^2}\right)^N \frac{\langle\phi\rangle^2}{M_{\phi^+}}$$

Tiny mass

Quantum suppression

Mass around TeV scale



Zee model

Quantum effect due to additional scalar fields

Physics of specific extended Higgs sectors

Models of neutrino mass with DM

Introducing a discrete Z_2

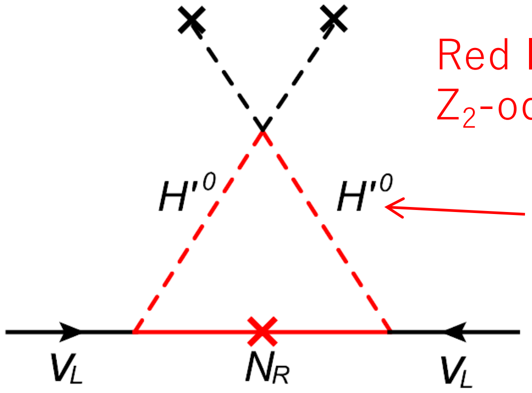
- Stability of new particle（DM）
- Loop induced masses

Tao-Ma model Tao 1996, Ma, 2006

SM+ H’ + N_R

1-loop induced ν -mass

Dark matter candidate [H’]



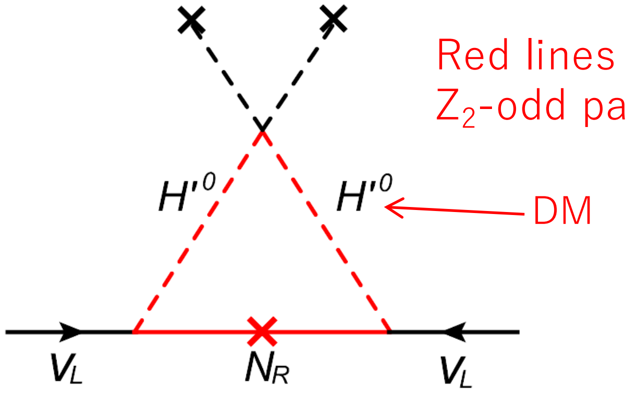
Red lines are Z_2-odd particles

DM

Models of neutrino mass with DM

Introducing a discrete Z_2

- Stability of new particle（DM）
- Loop induced masses



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Tao-Ma model　Tao 1996, Ma, 2006

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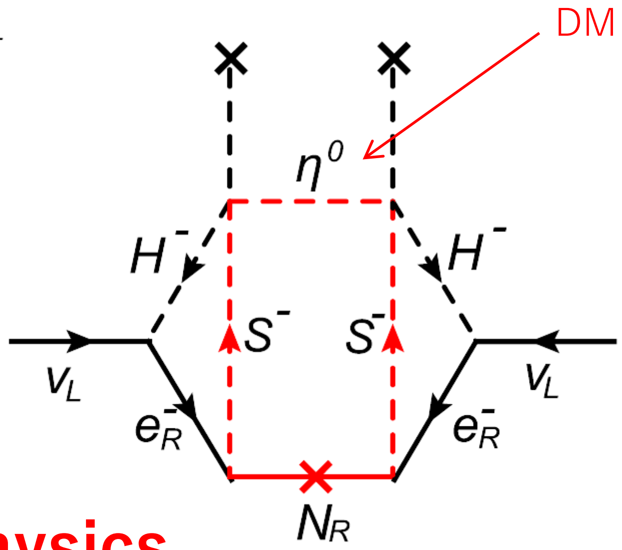


Model with higher loop effects　Aoki, SK, Seto, 2009

2HDM + η^0 + S^+ + N_R

ν -masses are 3-loop induced

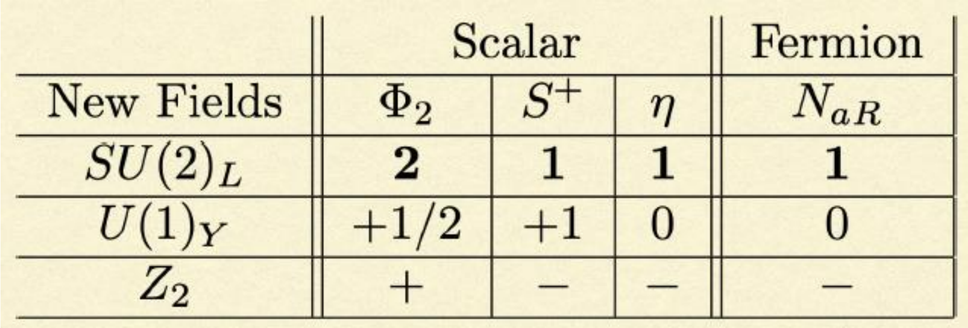
DM candidate [η^0]

EW Baryogenesis possible (CPV, 1stOPT)

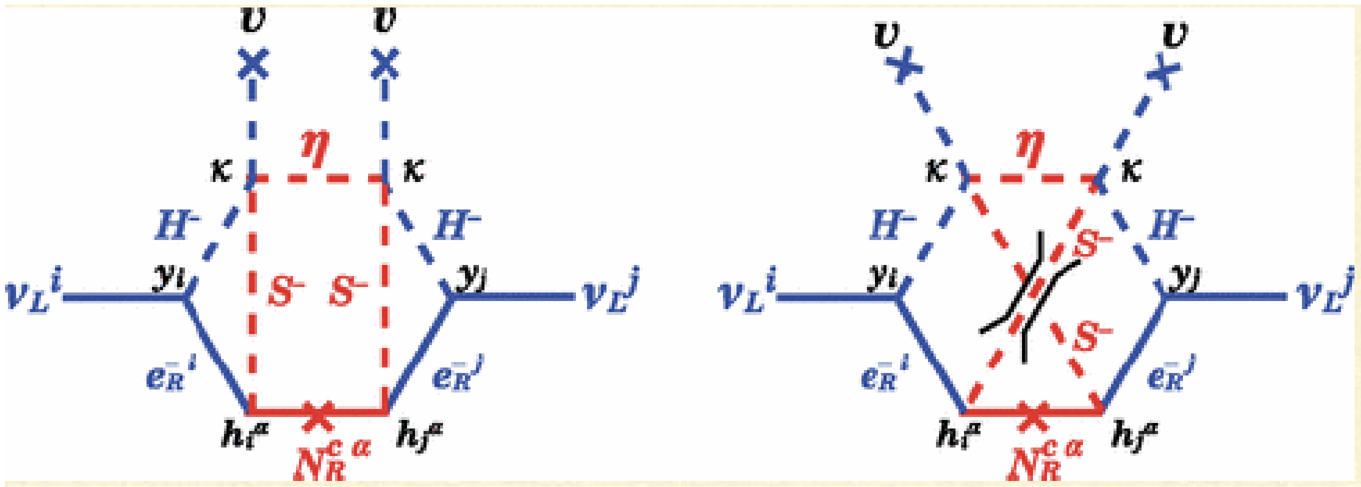
3 Problems can be explained by the TeV scale physics

Model (AKS2009)

M. Aoki, SK, O. Seto, PRL102, 051805 (2009)



New Fields	Scalar Φ_2	Scalar S^+	Scalar η	Fermion N_{aR}
$SU(2)_L$	**2**	**1**	**1**	**1**
$U(1)_Y$	$+1/2$	$+1$	0	0
Z_2	$+$	$-$	$-$	$-$

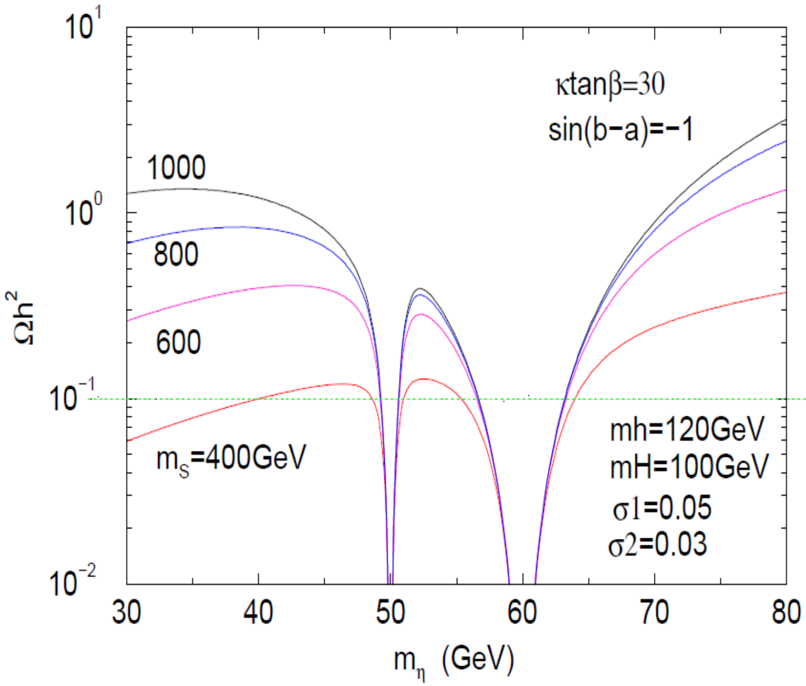


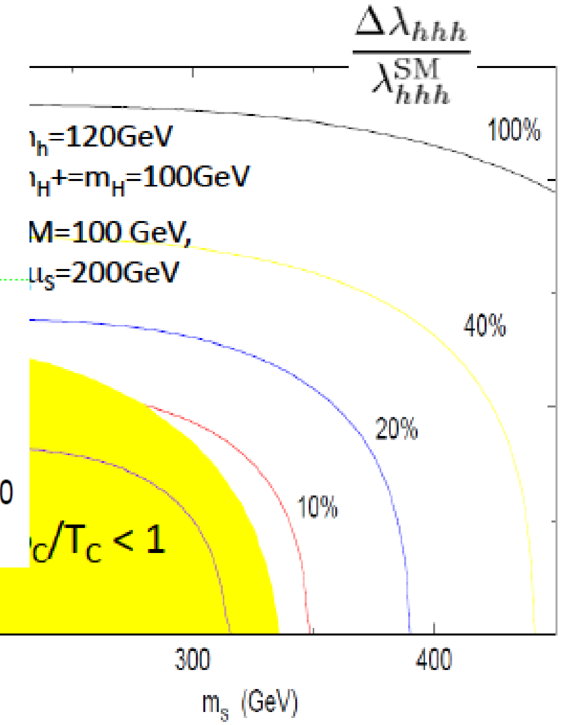
2HDM (Type X) + Z_2-odd scalars and RN

Neutrino mass at three loop
(smallness can be explained from TeV physics)

Dark Matter candidate with the mass mH/2

Strongly 1st OPT can be realized (EWBG)





However, CPV was not analyzed, and BAU was not evaluated

Recent Development of the model

M. Aoki, K. Enomoto, SK, PRD107 (2023)11, 115022

2HDM(Type X) ⇨ general 2HDM

$\lambda_6 \sim 0$ (Higgs alignment) (aligned 2HDM)
FCNC avoided by Yukawa alignment (Pich, Tuzon)
CPV phases in the Higgs potential and the Yukawa interactions

All current constraints from experimental data satisfied

Neutrino oscillation, DM data, LEP, LHC, EDM, LFV, B, ….
BAU is evaluated

A benchmark scenario is found, which explain Neutrino, DM and BAU

Model

Aoki, Enomoto, SK 2022

Z_2-even) $\Phi_1, \Phi_2 : (\mathbf{2}, +1/2)$

Z_2-odd) $S^+ : (\mathbf{1}, +1)$, $\eta : (\mathbf{1}, 0)$ real scalar

Scalar potential

$$\mathscr{V} = V_\Phi(\Phi_1, \Phi_2) + V_{S\eta}(\Phi_1, \Phi_2, S^+, \eta)$$

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H_1 + iG^0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H_2 + iH_3) \end{pmatrix}$$

$$M_{\mathrm{neutral}} \propto \begin{array}{c c} \begin{array}{ccc} H_1 & H_2 & H_3 \end{array} & \\ \begin{pmatrix} M_{11} & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ & M_{22} & \underset{\Phi_2}{\cancel{-\mathrm{Im}[\lambda_5]/2}} \\ & & M_{33} \end{pmatrix} & \begin{array}{c} H_1 \\ H_2 \\ H_3 \end{array} \end{array}$$

$\lambda_6 \to 0$ ➡ Mixings vanish [Higgs alignment]

(Higgs couplings coincide with SM ones)

3 CPV couplings in the Higgs potential

$$\mathscr{V}_{CPV} = \mathbf{Im}\Big[\overset{\lambda_6 = 0\ \text{(+ Stationary condition)}}{\cancel{\mu_{12}^2 \Phi_1^\dagger \Phi_2}} + (\Phi_1^\dagger \Phi_2)\Big\{\overset{\Phi_2}{\cancel{\frac{\lambda_5}{2}\Phi_1^\dagger \Phi_2}} + \overset{\lambda_6 = 0}{\cancel{\lambda_6 |\Phi_1|^2}} + \lambda_7 |\Phi_2|^2\Big\}$$

$$+ \rho_{12}(\Phi_1^\dagger \Phi_2)|S^+|^2 + \frac{\sigma_{12}}{2}(\Phi_1^\dagger \Phi_2)\eta^2 + \underset{S^\pm}{\cancel{2\kappa(\Phi_1^\dagger \Phi_2)S^- \eta}}\Big]$$

Yukawa interaction

Both Higgs doublets couple with the SM fermions.

$$\mathscr{L}_Y = \underbrace{-\frac{m_{fi}}{v}\overline{f_L^i}\, f_R^i H_1}_{\text{SM Yukawa}} + \underbrace{(y_2^f)_{ij}\overline{f_L^i}\, f_R^j (H_2 + iH_3)}_{\text{Non-diagonal } y_2^f} + \mathrm{h.c.}$$

$(i, j = 1,2,3)$

Non-diagonal y_2^f ➡ *FCNC!*

$$y_2^f = \underbrace{\frac{1}{v}\begin{pmatrix} m_{f^1} & 0 & 0 \\ 0 & m_{f^2} & 0 \\ 0 & 0 & m_{f^3} \end{pmatrix}}_{\text{SM Yukawa}} \begin{pmatrix} \zeta_{f^1} & 0 & 0 \\ 0 & \zeta_{f^2} & 0 \\ 0 & 0 & \zeta_{f^3} \end{pmatrix}$$

$\zeta_f^i \in \mathbb{C}$

For quarks,

$\zeta_{u^1} = \zeta_{u^2} = \zeta_{u^3} \equiv \zeta_u$

$\zeta_{d^1} = \zeta_{d^2} = \zeta_{d^3} \equiv \zeta_d$

Pich, Tuzon (2009)

Z_2-odd Majorana fermions: N_R^a $(a = 1,2,3)$

$$\frac{1}{2} m_{N^\alpha} \overline{(N_R^\alpha)^c} N_R^\alpha$$

Lepton # violating

$$\mathscr{L}_Y = -h_i^\alpha \overline{(N_R^\alpha)^c}\, \ell_R^i S^+ + \mathrm{h.c.}$$

Lepton flavor violating

Summary of the model

New particles: (Z_2-even) $H^\pm$, H_2, H_3 (Z_2-odd) $S^\pm$, η, N_R^a

Alignment: $\lambda_6 = 0$ & $(y_2^f)_{ij} \propto m_{fi}\zeta_{fi}\delta_{ij}$

(H_1 is the SM Higgs)   (No FCNC)

CP-violation: λ_7, ρ_{12}, σ_{12} & ζ_u, ζ_d, ζ_τ, ζ_μ, ζ_e, h_i^α

Benchmark scenario (BS)

Aoki, Enomoto, SK (2022)

Slide provided by Enomoto

Masses of New particle

Z_2 even: $m_{H^+} = 250$ GeV, $m_{H_2} = 420$ GeV, $m_{H_3} = 250$ GeV

Z_2 odd: $m_S = 400$ GeV, $m_\eta = 63$ GeV

$(m_{N_1}, m_{N_2}, m_{N_3}) = (3000, 3500, 4000)$ GeV

Scalar couplings

$$\mu_2^2 = (50\ \text{GeV})^2, \quad \mu_s^2 = (320\ \text{GeV})^2, \quad \mu_{12}^2 = 0$$

$$\lambda_2 = 0.1, \quad \lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \lambda_6 = 0, \quad |\lambda_7| = 0.82,$$

$$\rho_1 \simeq 1.90, \quad \sigma_1 = |\sigma_{12}| = 1.1 \times 10^{-3}, \quad \kappa = 2.0, \quad \theta_7 = -0.73, \quad \cdots$$

New Yukawa interactions

$$y_t|\zeta_u| = 0.17, \quad y_b|\zeta_d| = 4.2 \times 10^{-3}, \quad y_e|\zeta_e| = y_\mu|\zeta_\mu| = 2.5 \times 10^{-4},$$

$$y_\tau|\zeta_\tau| - 2.5 \times 10^{-3}, \quad \theta_e = \theta_\mu = \theta_\tau = -2.94, \quad \theta_u = \theta_d = 0.245$$

$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}, \quad \cdots$$

Constraints

Experimental constraints

$H^{\pm}$: (Direct) $H^{\pm} \to tb$ ATLAS (2021)

(Flavor) $B_d \to \mu^+\mu^-$ J. Haller, et al EPJC (2018)

$H_{2,3}$: (Direct) $H_{2,3} \to \tau\bar{\tau}$ ATLAS (2020)

$H_{2,3} \to t\bar{t}$ ATLAS (2018)

$S^{\pm}$: (Direct) $S^{\pm} \to H^{\pm}\eta \to tb\eta$ (from $Z^*, \gamma^* \to S^+S^-$) Weak constraints

(Flavor) Lepton flavor violating processes (Next slides)

N_R^{α} : (Direct) too heavy and weak constraints ($m_{N^\alpha} =$ 3-4 TeV)

(Flavor) Lepton flavor violating processes (Next slides)

η : Dark matter in the model

(DM searches) 3 Pages later

CP-violating phases : (EDM) 2 Pages later

We checked that all of these constraints can be avoided in the BS

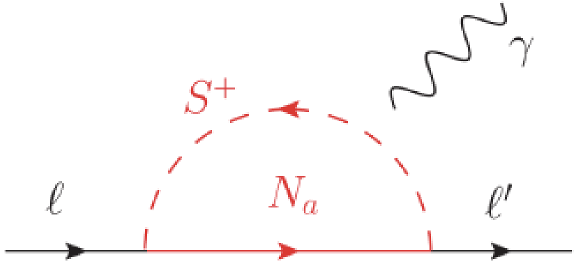
Lepton flavor violation

$m_S = 400$ GeV,

$M_N = \{3000, 3500, 4000\}$ GeV

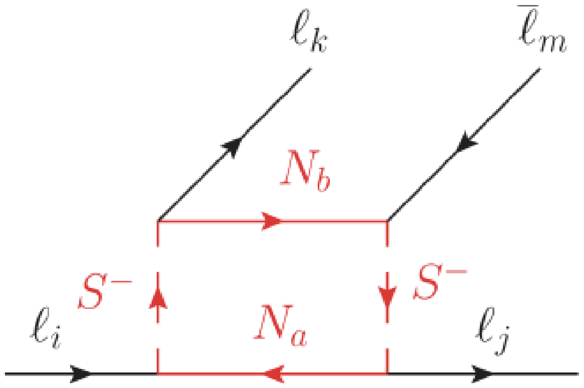
$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}$$

■ $\ell \to \ell' \gamma$



Processes	BR	Upper limits
$\mu \to e\gamma$	1.4×10^{-14}	4.2×10^{-13}
$\tau \to e\gamma$	5.3×10^{-10}	3.3×10^{-8}
$\tau \to \mu\gamma$	1.1×10^{-11}	4.4×10^{-8}

■ $\ell_i \to \ell_j \ell_k \overline{\ell}_m$

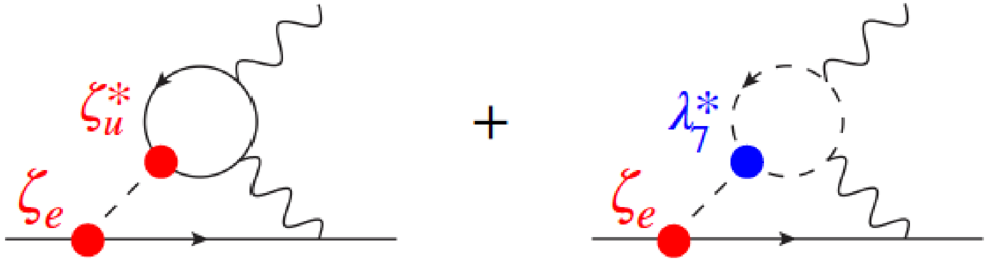


Processes	BR	Upper limits
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-12}
$\tau \to 3e$	6.2×10^{-10}	2.7×10^{-8}
$\tau \to 3\mu$	2.4×10^{-11}	2.1×10^{-8}
$\tau \to e\mu\bar{e}$	5.1×10^{-12}	1.8×10^{-8}
$\tau \to \mu\mu\bar{e}$	1.1×10^{-12}	1.7×10^{-8}
$\tau \to ee\bar{\mu}$	4.5×10^{-13}	1.5×10^{-8}
$\tau \to e\mu\bar{\mu}$	9.6×10^{-11}	2.7×10^{-8}

Electric dipole moment (EDM)

electron EDM (eEDM) $|d_e| < 4.0 \times 10^{-30}$ e cm Roussy, et al (2022)

eEDM can be small by **destructive interference**
SK, Kubota, Yagyu (2020)



$\propto \sin(\theta_u - \theta_e)$ $\propto \sin(\theta_7 - \theta_e)$

$m_{H_2} = 420$ GeV, $m_{H_3} = m_{H^\pm} = 250$ GeV
$\theta_7 = -2.34$, $\theta_u = 0.245$, $\theta_e = -2.94$

$\rightarrow$

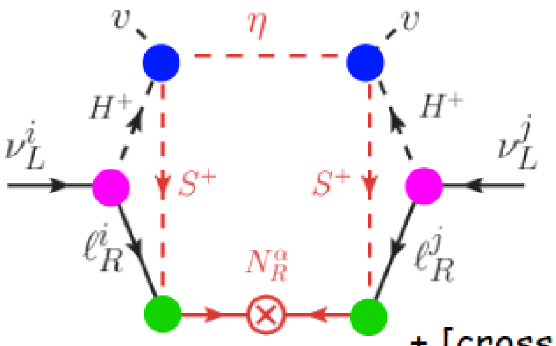
$|d_e| = 0.22 \times 10^{-30}$ e cm

neutron EDM (nEDM) $|d_n| < 1.8 \times 10^{-26}$ e cm

chromo EDM Barr, Zee (1990)
Weinberg ope. Weinberg (1989)
4 fermi interaction Khatsimovsky, Khriplovich, Yelkhovsky (1988)

In the BS, $|d_n| \sim 10^{-30}$ e cm

ν mass



+ [crossing $S^\pm$ lines]

$\kappa\,\tilde{\Phi}_1\Phi_2 S^-\eta$ $\quad h_i^\alpha\,\overline{(N_R^\alpha)^c}\,\ell_{iR}S^+$ $\quad \zeta_{\ell^i}y_{\ell^i}\,\overline{\ell_R^i}\nu_L^i H^-$

$(y_e|\zeta_e|,\, y_\mu|\zeta_\mu|,\, y_\tau|\zeta_\tau|) = (0.25, 0.25, 2.5)\times 10^{-3}$

$\theta_{\ell^i} = -2.94$

$\kappa = 2.0$

$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}$$

⬇

Normal ordering m_ν w/ $\quad m_{\nu 1} \simeq 0.006$ eV

$\delta \simeq 1.36\pi, \quad \alpha_1 \simeq 0, \quad \alpha_2 \simeq -\pi/2$

$m_{\beta\beta} \simeq 1$ meV, $\quad \Sigma m_{\nu^i} = 0.067$ eV

$m_{\beta\beta} < 35$ meV
KamLAND-Zen (2023)

$\Sigma m_{\nu^i} < 0.12$ eV
Planck (2018)

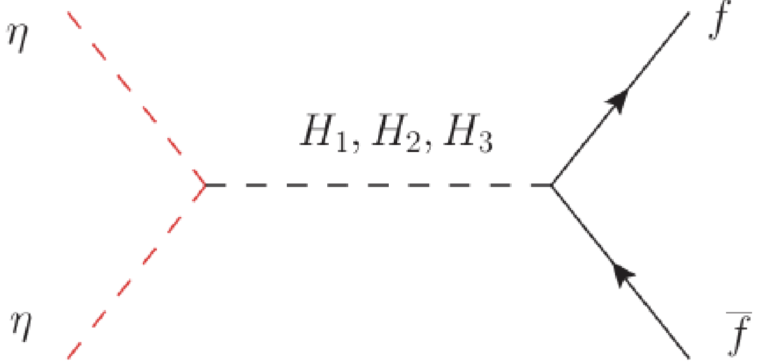
Dark matter (DM)

$m_\eta = 63$ GeV

$(M_{N_1}, M_{N_2}, M_{N_3}) = (3000,\ 3500,\ 4000)$ GeV

η: real scalar DM

dominant annihilation: $\eta\eta \to H_a^{(*)} \to f^i f^i$



$m_\eta = 63$ GeV, $m_{H_2} = 420$ GeV, $m_{H_3} = 250$ GeV

$\sigma_1 = |\sigma_{12}| = 1.1\times 10^{-3}, \quad \theta_\rho = -2.94$

⬇

$\Omega_\eta h^2 \simeq 0.12, \quad \sigma_{\rm SI} = 2.3\times 10^{-48}\ {\rm cm}^2$

$\Omega_{\rm DM}h^2 = 0.120(01)$
Planck (2018)

$\sigma_{\rm SI} \lesssim 10^{-47}$
LZ (2022)

Electroweak baryogenesis (EWBG)

The Sakharov conditions Sakharov (1967)

1. B-violation ←------ Sphaleron transition
2. C and CP violation ←------ CPV phases : $\lambda_7, \rho_{12}, \sigma_{12}, \zeta_u, \zeta_d, \zeta_\ell$
3. Departure from thermal equilibrium ←------ Strongly 1st order electroweak phase transition

Strongly 1st EWPT (EWPT = ElectroWeak Phase Transition)

Non-decoupling effect by $H_{2,3}$, $H^\pm$, $S^\pm$

$$m_{H^+}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2, \quad m_{H_{2,3}}^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)v^2, \quad m_S^2 = \mu_S^2 + \frac{1}{2}\rho_1 v^2$$

$$m_{H^+} = 250 \text{ GeV}, \quad m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = 250 \text{ GeV}, \quad m_S = 400 \text{ GeV}$$

$$\lambda_3 \simeq 1.98, \quad \lambda_4 \simeq 1.88, \quad \lambda_5 \simeq 1.88, \quad \rho_1 \simeq 1.90$$

We evaluated one-loop effective potential in Landau gauge Coleman, Weinberg (1973) Dolan, Jackiw (1974)

$(T = 0)$ Kanemura, et al (2003) Kanemura, et al (2004)

$$\Delta R \equiv \lambda_{hhh}/\lambda_{hhh}^{SM} - 1 = 38\ \%$$

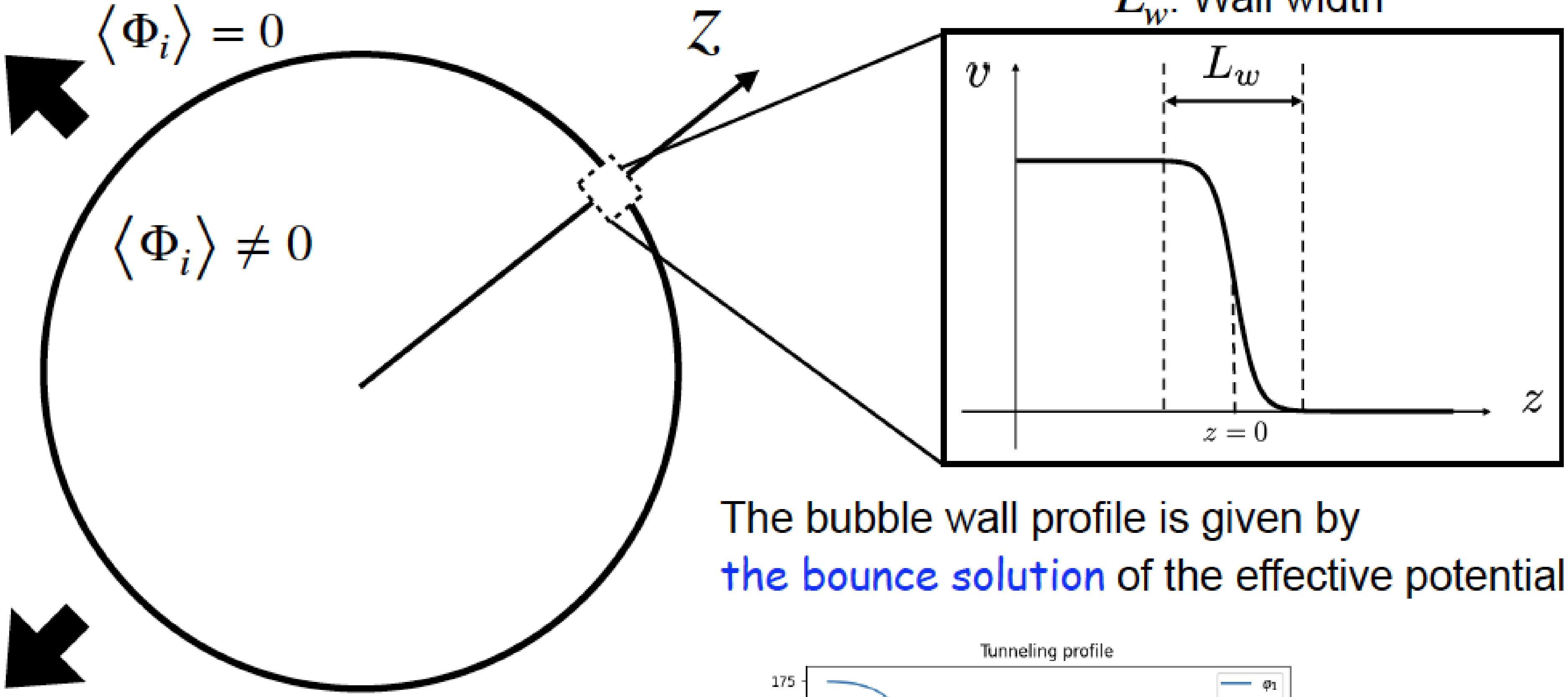
$(T \neq 0)$ thermal resummation Parwani (1992)

$$v_n/T_n = 1.74 > 1$$

Kuzmin, Rubakov, Shaposhnikov (1985)

Electroweak baryogenesis

L_w: Wall width

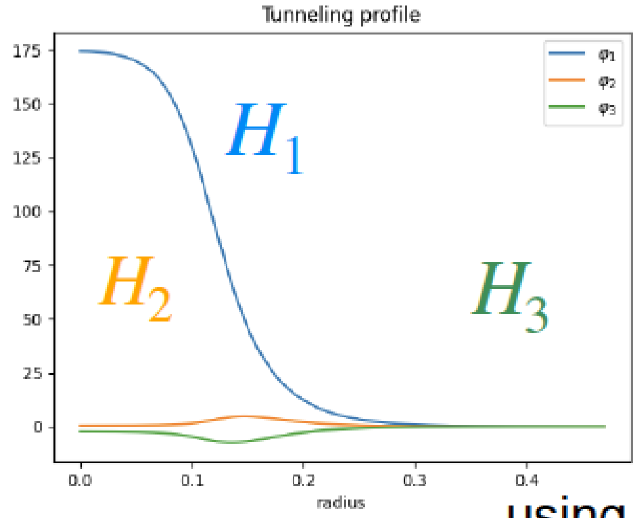


v_w: wall velocity

$\boxed{v_w = 0.1}$ is assumed

(In the case of the SM plasma, $v_w = O(0.1)$)

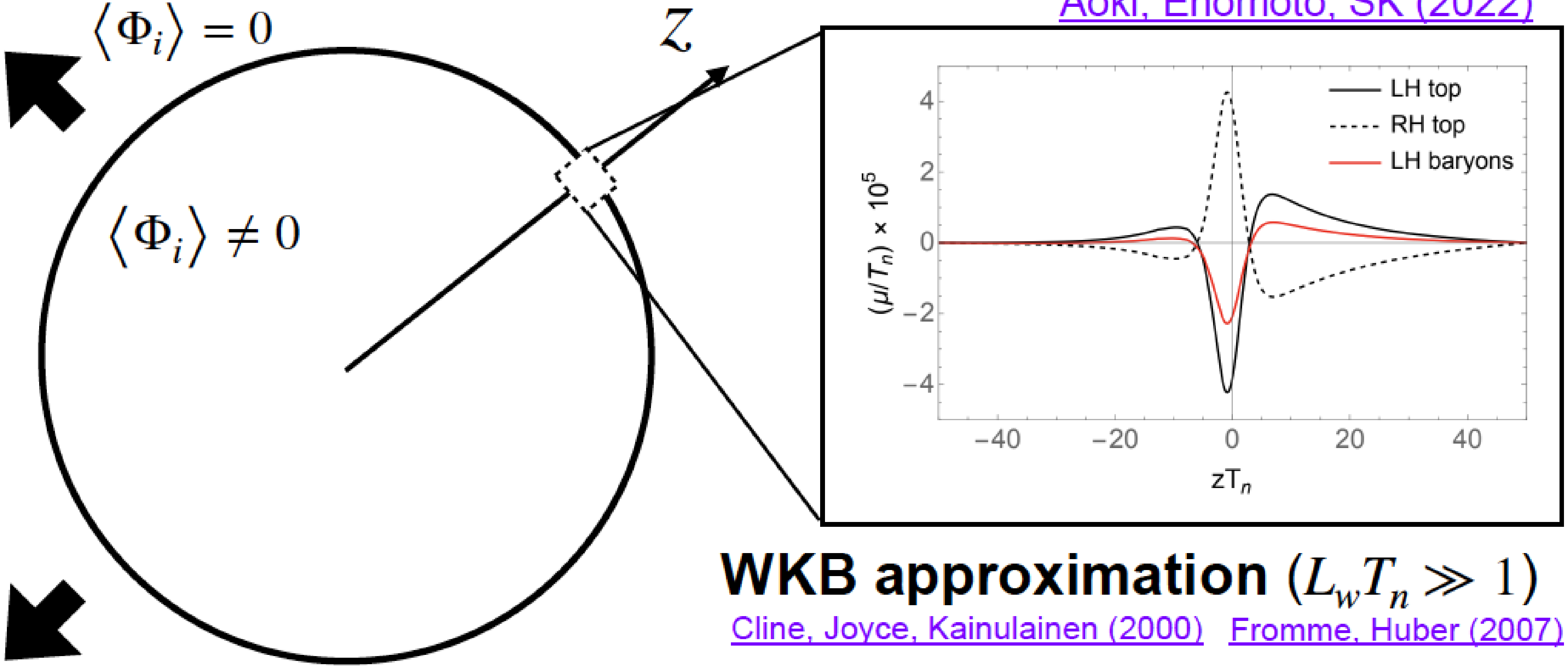
The bubble wall profile is given by
the bounce solution of the effective potential



using CosmoTransition

Electroweak baryogenesis

Aoki, Enomoto, SK (2022)



WKB approximation $(L_w T_n \gg 1)$

Cline, Joyce, Kainulainen (2000) Fromme, Huber (2007)

Cline, Kainulainen (2020)

v_w: wall velocity

$v_w = 0.1$ is assumed

Baryon-to-photon ratio

$$\boxed{\eta_B = \frac{n_B}{n_\gamma} \sim \Gamma_{ws} \int_0^\infty \mathrm{d}z\, \mu_{q_L} e^{-kz}}$$

BBN) $5.8 \times 10^{-10} \le \eta_B \le 6.5 \times 10^{-10}$

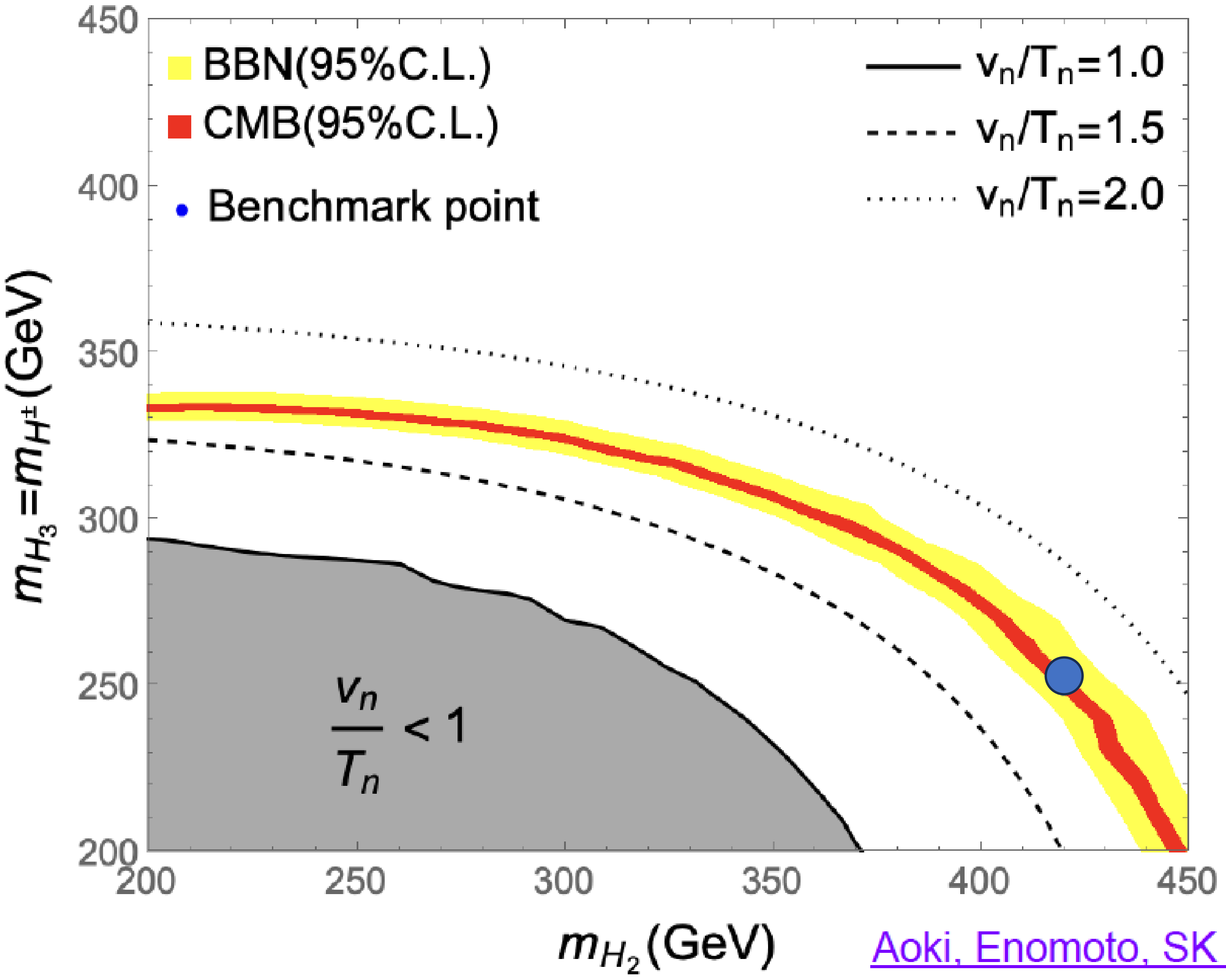
Fields, et al (2020)

CMB) $6.04 \times 10^{-10} \le \eta_B \le 6.20 \times 10^{-10}$

Planck (2018)

$\eta_B = 6.17 \times 10^{-10}$

Electroweak baryogenesis



Aoki, Enomoto, SK (2022)

Other parameters are the same with those in the BS

How to test the BS

EDM measurements

- One order improvement is expected in future ACME experiment ACME(2018)

Flavor experiments

- $B \to X_s\gamma$ or $B_d^0 \to \mu^+\mu^-$ in Belle-II experiments E. Kou, et al [Bell-II], arXiv:1808.10567 [hep-ex]
- CP violation in $B \to X_s\gamma\ (\Delta A_{CP})$ Benz, Lee, Neubert, Paz (2011); Watanuki et al [Belle] (2019)
- Lepton flavor violating decays $\mu \to e\gamma$ MEG-II $\mu \to 3e,\quad \tau \to 3e$ Belle-II

Collider experiments

- $gg \to H_2, H_3;\ gg \to H^\pm tb;\ q\overline{q} \to H_{2,3}H^\pm$ Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu (2021); SK, Takeuchi, Yagyu (2021)
- $q\overline{q} \to S^+S^-;\ e^+e^- \to S^+S^-;\ e^+e^- \to NN$ M. Aoki, SK, O. Seto (2009)
- Higgs triple coupling $\Delta R = \frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{SM}} = 38\ \%$

Sensitivity @ ILC ($\sqrt{s} = 500$ GeV)

$\Delta R = 27\ \%$ K. Fujii, et al, arXiv:1506.05992 [hep-ph]

- Azimuthal angle distribution of $H_{2,3} \to \tau\overline{\tau}$ at e^+e^- collider

SK, M. Kubota, K. Yagyu, JHEP (2021)

Dark matter direct detection

Observation of gravitational waves

Back to the original model AKS2009

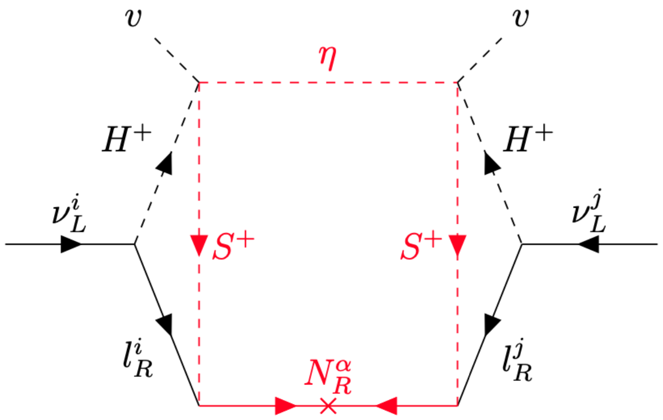
FCNC by softly broken Z_2

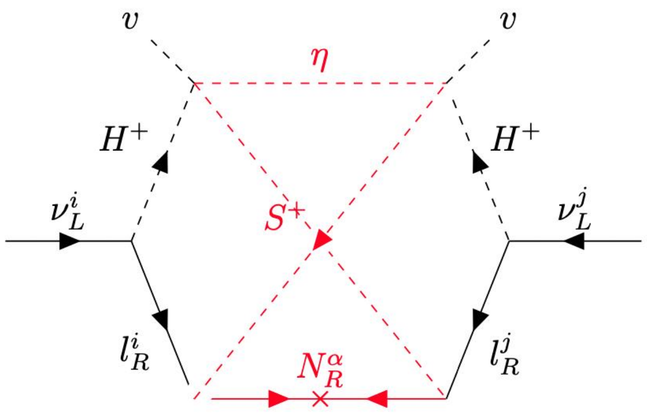
Smaller number of parameters

Type-X 2HDM + new Z2 odd $(N_R^\alpha, S^\pm, \eta)$

M. Aoki, K. Enomoto, SK, S. Taniguchi 2024

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Z_2	$\tilde{Z}_2$ (Softly broken)
Q^i	3	2	1/6	+	+
u_R^i	3	1	2/3	+	−
d_R^i	3	1	−1/3	+	−
L^i	1	2	−1/2	+	+
l_R^i	1	1	−1	+	+
ϕ_1	1	2	1/2	+	+
ϕ_2	1	2	1/2	+	−
N_R^α	1	1	0	−	+
S^+	1	1	1	−	+
η	1	1	0	−	+





$$M_{ij} \sim \underbrace{\left(\frac{1}{16\pi^2}\right)^3}_{\sim 10^{-6}} \times \underbrace{\left(\frac{m_l}{v}\right)^2}_{\sim 10^{-4}} \times \frac{v^2}{m_N}$$

Lagrangian

Stationary condition

$$\mathrm{Im}\left[\mu_{12}^2\right] - \frac{1}{2}\,\mathrm{Im}\left[\lambda_5\right] v_1 v_2 = 0$$

μ_{12}^2 and λ_5 are related

Type-X 2HDM + new Z2 odd ($N_R^\alpha, S^\pm, \eta$)

Higgs potential

$$\begin{aligned} V = & -\mu_1^2|\phi_1|^2 - \mu_2^2|\phi_2|^2 - \left(\boxed{\mu_{12}^2}\phi_1^\dagger\phi_2 + \mathrm{h.c.}\right) + \mu_S^2|S^+|^2 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 \\ & + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \left(\frac{\boxed{\lambda_5}}{2}(\phi_1^\dagger\phi_2)^2 + \mathrm{h.c.}\right) + \frac{\lambda_S}{4}|S^+|^4 + \frac{\lambda_\eta}{4!}\eta^4 + \frac{\xi}{2}|S^+|^2\eta^2 \\ & + \sum_{a=1}^{2}\left(\rho_a|\phi_a|^2|S^+|^2 + \frac{1}{2}\sigma_a|\phi_a|^2\eta^2\right) + \left(2\boxed{\kappa}\tilde{\phi}_1^\dagger\phi_2 S^-\eta + \mathrm{h.c.}\right) \end{aligned}$$

CP violating phase θ_5 ($\lambda_5 = |\lambda_5|e^{i\theta_5}$)

The phase of κ can be 0 by rephasing S^-

Additional Yukawa coupling with RHN

$$\mathcal{L} \supset -\boxed{h_i^\alpha}\,\overline{(N_R^\alpha)^c}\, l_R^i S^+ + \mathrm{h.c.}$$

$\alpha = 1,2,3,$ $i = 1,2,3,$ h_i^α are 3×3 matrix

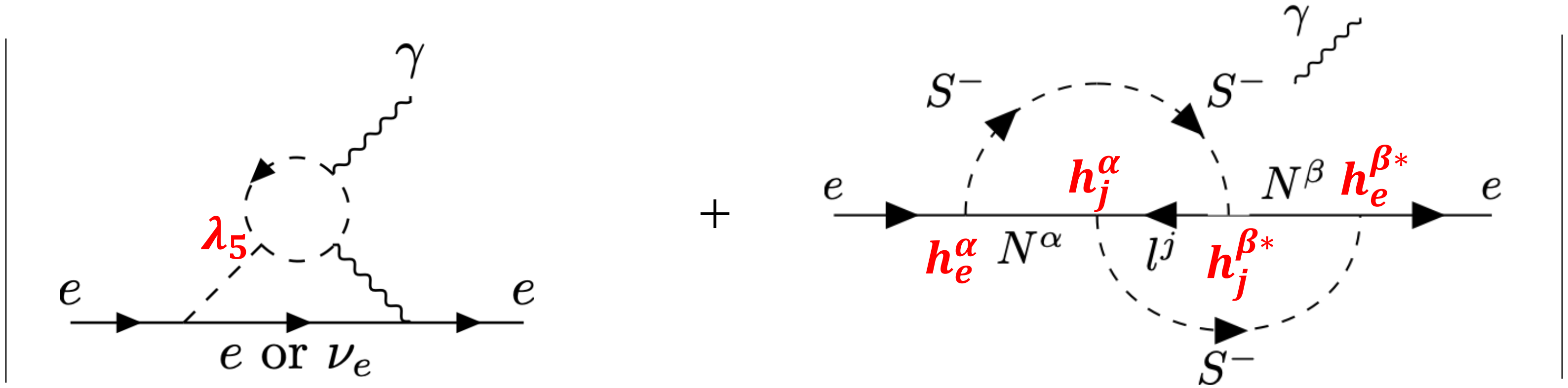
CPV

Electric dipole moment in our model

In the model, new CPV contribution from

$$\mathcal{L} \supset \; -\boxed{h_i^\alpha}\,\overline{(N_R^\alpha)^c}\, l_R^i S^+ + \text{h.c.}$$

By destructive interference Electron EDM can satisfy electron EDM



$< 4.1 \times 10^{-30}$ ecm

2HDM contribution

Barr, Zee (1990)

Altmannshofer, Gori, Hamer, Patel(2020)

Additional contribution
in our model

Benchmark scenario is found: K. Enomoto, SK, S. Taniguchi, arxiv:2403.13613

How about the UV theory?

The model (AKS2009) can satisfy all experimental results,
and explain Neutrino, Dark Matter, Baryogenesis by TeV scale physics

1st OPT. → Landau Pole Λ at 10-100TeV

What is the world above Λ?

An idea: New gauge theory with confinement.
Higgs is a realization as a meson formed
by the fundamental representation

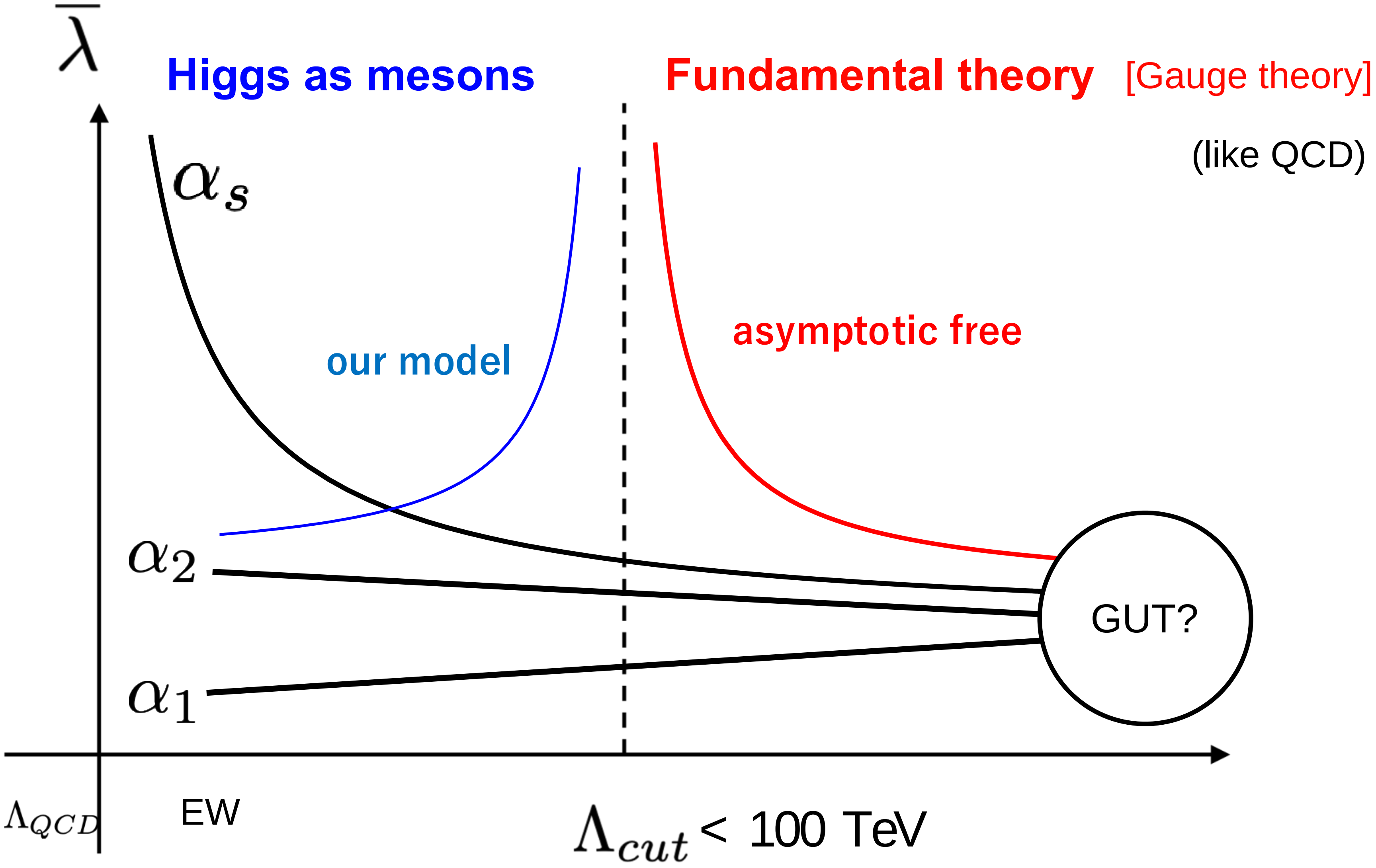
Higgs as mesons

$$M_{ij} = T_i T_j$$

Minimal SUSY Fat Higgs models
by Murayama et al 2004,
and many references

SK, T. Shindo, T. Yamada 2014

Landau pole and new physics



Higgs as mesons

our model

Fundamental theory [Gauge theory]

(like QCD)

asymptotic free

Minimal model for confinement ($N_c=2$, $N_f=3$)
→ 3 pairs of $SU(2)_H$ fundamental rep. T_i (i=1-6)

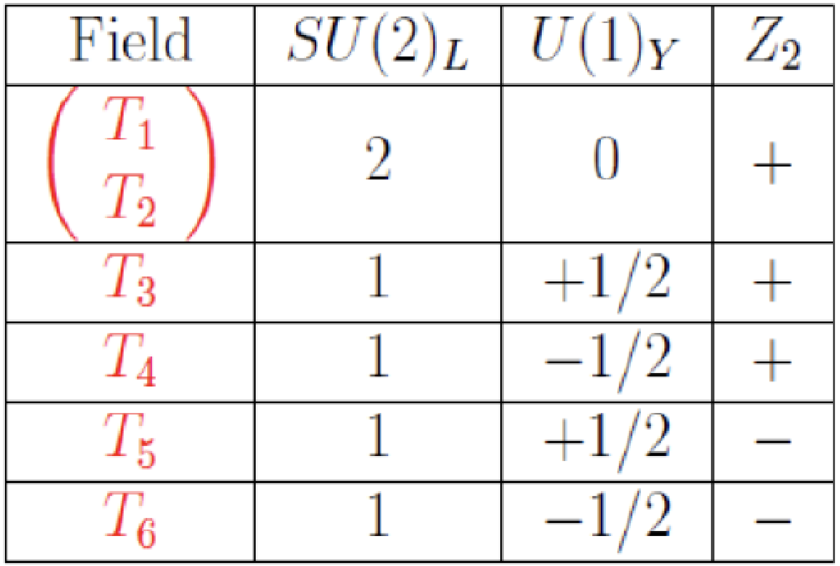
Minimal SUSY Fat Higgs models,
by Murayama et al 2004

Higgs as Meson

SU(2)H gauge theory

SK, Shindou, Yamada 2014

$$M_{ij} = T_i T_j$$



Field	$SU(2)_L$	$U(1)_Y$	Z_2
$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$	2	0	+
T_3	1	$+1/2$	+
T_4	1	$-1/2$	+
T_5	1	$+1/2$	−
T_6	1	$-1/2$	−

Additional Super-fields

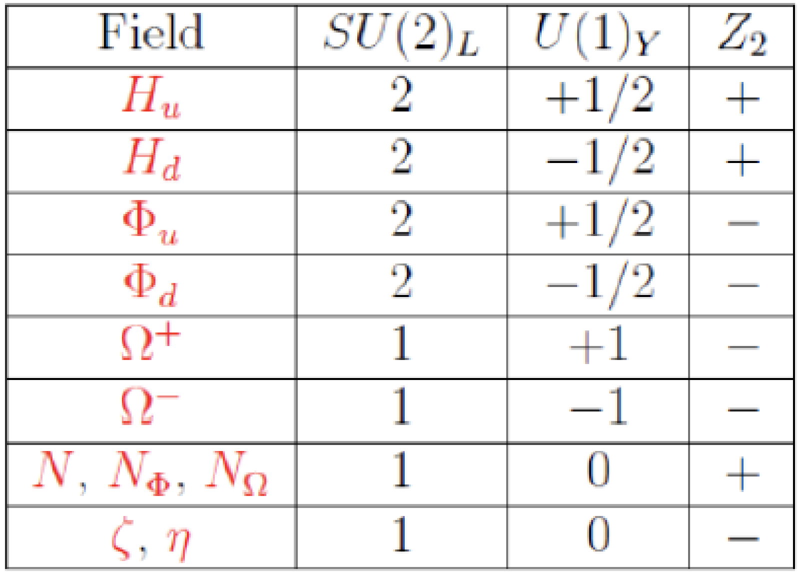
MSSM Higgs doublets

Extra Higgs doublets

Charged Higgs singlets

Z_2-even Higgs singlets

Z_2-odd Higgs singlets



Field	$SU(2)_L$	$U(1)_Y$	Z_2
H_u	2	$+1/2$	+
H_d	2	$-1/2$	+
Φ_u	2	$+1/2$	−
Φ_d	2	$-1/2$	−
Ω^+	1	$+1$	−
Ω^-	1	-1	−
$N,\ N_\Phi,\ N_\Omega$	1	0	+
$\zeta,\ \eta$	1	0	−

Intrilligator, Seiberg

Superpotential

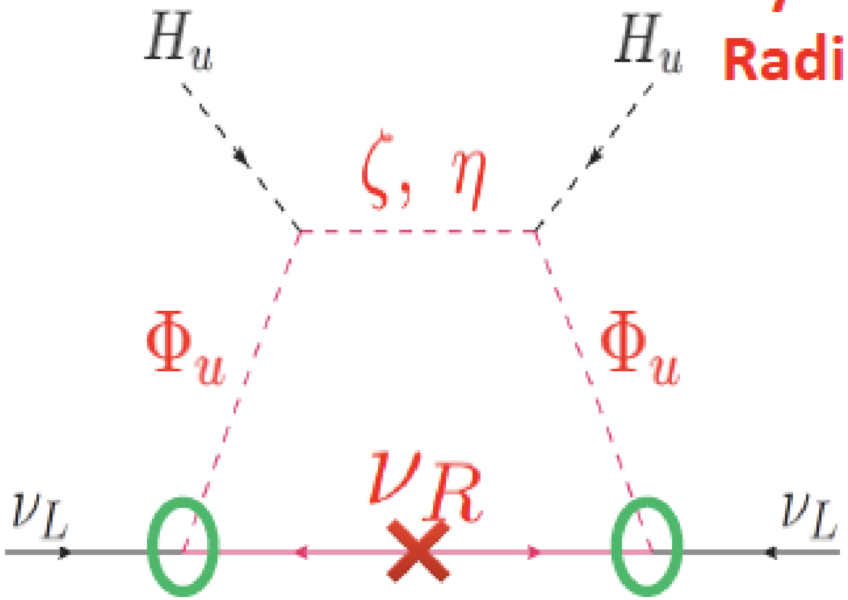
$$\begin{aligned} W_{eff} \;=\; \lambda\ \{ & N(H_u H_d + v_0^2) \;+\; N_\Phi(\Phi_u \Phi_d + v_\Phi^2) \;+\; N_\Omega(\Omega^+\Omega^- + v_\Omega^2) \\ & -\; N N_\Phi N_\Omega \;-\; N_\Omega \zeta \eta \;+\; \zeta H_d \Phi_u \;+\; \eta H_u \Phi_d \;-\; \Omega^+ H_d \Phi_d \;-\; \Omega^- H_u \Phi_u \ \} \end{aligned}$$

The low energy theory is 4HDM+Singlets but with a common λ !

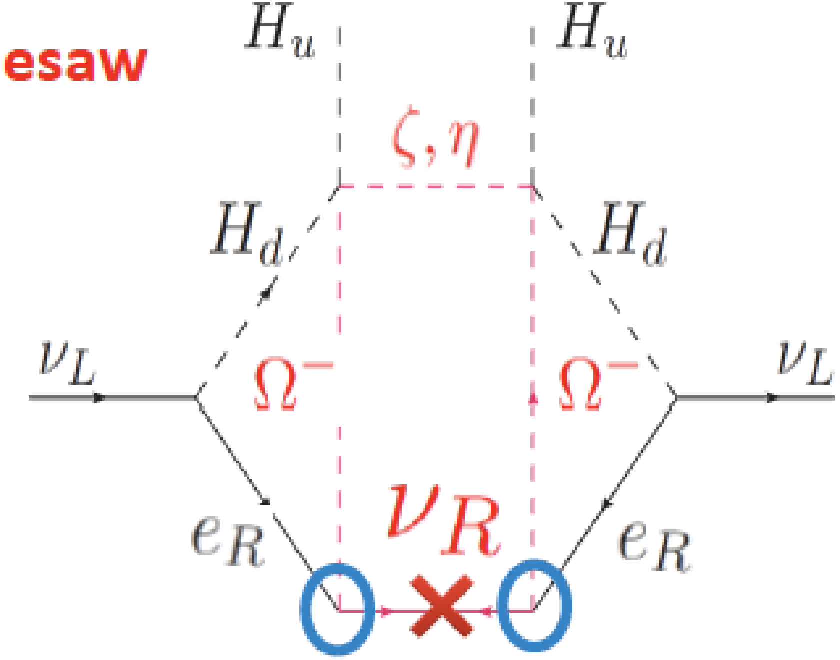
SK, Shindou, Yamada 2014

$$W^N_{\rm eff} = \frac{\kappa}{2} N \nu_R^c \nu_R^c + \boxed{y_N^i} \nu_R^c L_i \Phi_u + \boxed{h_N^i} \nu_R E_i^c \Omega^- + \frac{M}{2} \nu_R^c \iota$$

Hybrid mechanism of Radiative Seesaw



Ma Type diagram



AKS Type diagram

All particle contents are prepared from the $SU(2)_H$ gauge theory

Multiplet structure may be explained by the UV theory

Summary

- Higgs sector remains to be determined yet.
- Extended Higgs sector is used to explain physics of Neutrino, Dark Matter, Baryogenesis.

- A model which can explain neutrino, DM, BAU is revisited (AKS2009), and BAU was evaluated.
- Discussed viable benchmark scenarios
- The model is testable using various future experiments