A TeV-Scale 3-loop Neutrino Mass model with Dark Matter and Baryogenesis

Shinya KANEMURA
OSAKA University

Osaka Univ.
Dr. Wani

Multi Higgs Models, Sep 6, 2024 at IST, Lisbon

大阪大学
OSAKA UNIVERSITY

Machikane-Wani

Osaka University
Official Mascot Character
"Dr. Wani”

ウィキペディア

1964 discovered on Campus of Osaka Univ.

Japan's first crocodile fossil

about 400,000 years ago（7 m）
Japanese:　Machikane-Wani
Scientific name:　*Toyotamaphimeia machikanensis*

D. Wani
When he was
School of
Science

Machikane-Wani is a member of Osaka University’s
It is popular as a symbolic presence

HPNP2025

Higgs as a Probe of New Physics 2025

9 -13 June, 2025

Nambu Yoichiro Hall
The University of OSAKA
Japan

Announcement will come soon!

Expo 2025 in Osaka

Expo 2025 Osaka Kansai
Period: 184 days, from Sunday, April 13 to Monday, October 13, 2025

Introduction

Current Situation

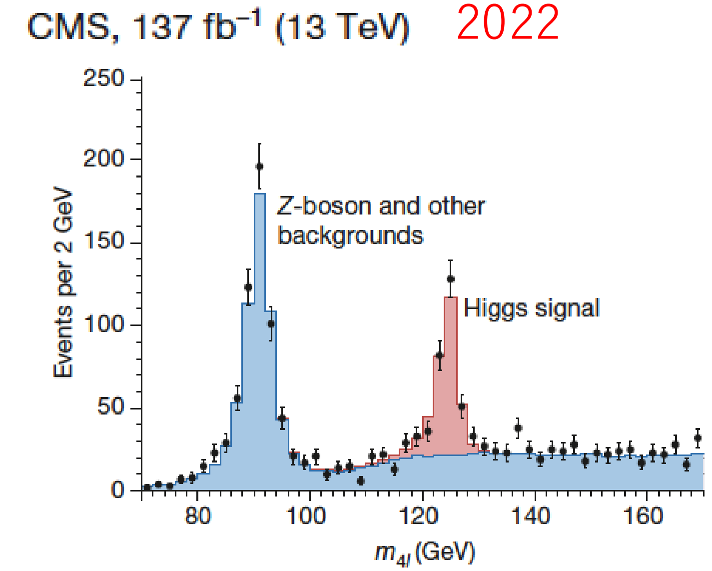
Higgs Discovery 2012

Mass 125 GeV

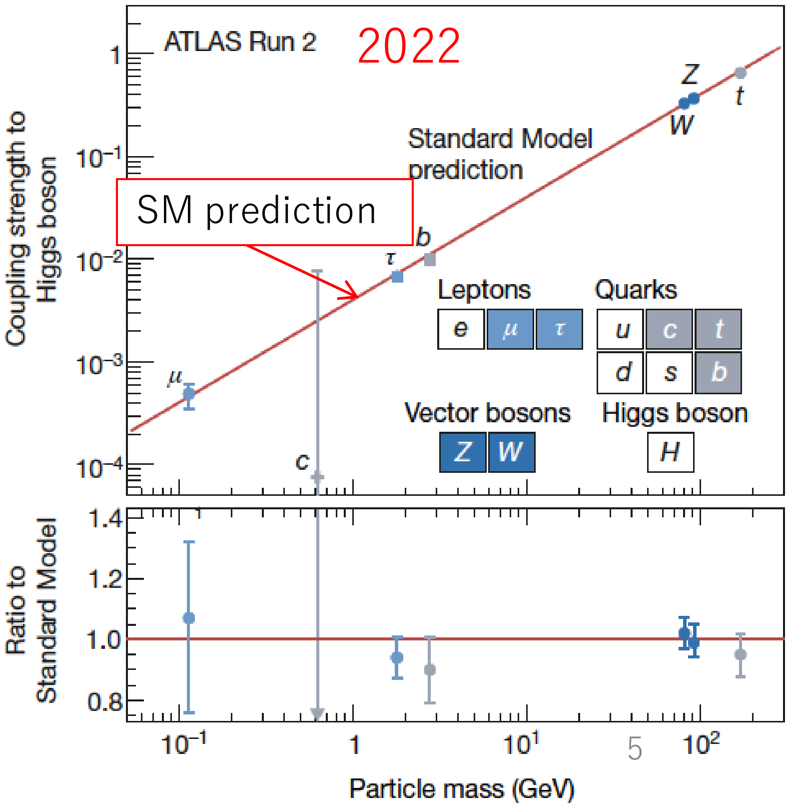
Spin・Parity

Good agreement with SM prediction

No BSM particle has found up to now



2022



2022

SM prediction

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

Standard Model:

Lagrangian

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\ &+\overline{Q}_L i\gamma^\mu D_\mu Q_L + \overline{L}_L i\gamma^\mu D_\mu L_L \\ &+\overline{u}_R i\gamma^\mu D_\mu u_R + \overline{d}_R i\gamma^\mu D_\mu d_R + \overline{e}_R i\gamma^\mu D_\mu e_R \\ &-\left\{\boxed{Y_u} Q_L \tilde{\Phi} u_R + \boxed{Y_d} Q_L \Phi d_R + \boxed{Y_e} Q_L \Phi e_R + (\text{h.c.})\right\} \\ &+|D_\mu \Phi|^2 - \boxed{V(\Phi)}\end{aligned}$$

Yukawa couplings

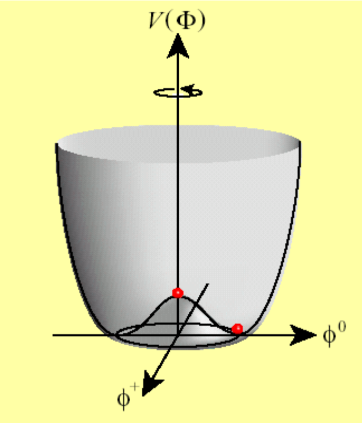
Higgs Potential

Gauge interactions

Beautiful being determined by the gauge principle

EWSB for mass

Yukawa interactions
Kinetic term of Higgs
Higgs potential



No principle, by hand

Perhaps a beautiful principle behind?

Higgs is a probe of new physics!

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	CPV, 1stOPT
• Neutrino mass	Loop induced	RHN, Z_2
• Dark Matter	WIMP	Z_2

Can we combine these scenarios into a model?

EW Baryogenesis

EW Baryogenesis

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 them

Extension of the Higgs sector is required

SK, M. Kubota, K. Yagyu (2020)
K. Enomoto, SK, Y. Mura (2021)

2HDM (viable scenario)

Higgs potenshal

$$V = -\mu_1{}^2(\Phi_1{}^\dagger\Phi_1) - \mu_2{}^2(\Phi_2{}^\dagger\Phi_2) - \left(\mu_3{}^2(\Phi_1{}^\dagger\Phi_2) + h.c.\right)$$
$$+\frac{1}{2}\lambda_1(\Phi_1{}^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2{}^\dagger\Phi_2)^2 + \lambda_3(\Phi_1{}^\dagger\Phi_1)(\Phi_2{}^\dagger\Phi_2) + \lambda_4(\Phi_2{}^\dagger\Phi_1)(\Phi_1{}^\dagger\Phi_2)$$
$$+\left\{\left(\frac{1}{2}\lambda_5\Phi_1{}^\dagger\Phi_2 + \lambda_6\Phi_1{}^\dagger\Phi_1 + \lambda_7\Phi_2{}^\dagger\Phi_2\right)\Phi_1{}^\dagger\Phi_2 + h.c.\right\}, \quad (\mu_3, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

$$m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

To satisfy LHC data、 avoid mixing between *h* and heavy Higgs bosons: $\lambda_6 \sim 0$

Mass matrix of neutral scalar bosons

$$\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ \mathrm{Re}[\lambda_6] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + \mathrm{Re}[\lambda_5]) & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} \\ -\mathrm{Im}[\lambda_6] & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - \mathrm{Re}[\lambda_5]) \end{pmatrix} = \begin{pmatrix} m_h^2 & 0 & 0 \\ 0 & m_{H_2}^2 & 0 \\ 0 & 0 & m_{H_3}^2 \end{pmatrix}$$

rephasing

Higgs alignment
$\arg[\lambda_7] \equiv \theta_7$

Avoiding FCNC: Yukawa alignment is imposed by hand $y_f^2 = \zeta_f y_f^1 \quad (f = u, d, e)$

$$\mathcal{L}_y = -\overline{Q}_L \frac{\sqrt{2}M_u}{v}\left(\tilde{\Phi}_1 + \zeta_u^*\tilde{\Phi}_2\right)u_R - \overline{Q}_L \frac{\sqrt{2}M_d}{v}\left(\Phi_1 + \zeta_d\Phi_2\right)d_R - \overline{L}_L \frac{\sqrt{2}M_e}{v}\left(\Phi_1 + \zeta_e\Phi_2\right)e_R + h.c.$$

Yukawa alignment
Pich and Tuzon (2009)

Multiple CPV phases

Higgs potential $\arg[\lambda_7] \equiv \theta_7$
Yukawa couplings $\arg[\zeta_u] \equiv \theta_u$, $\arg[\zeta_d] \equiv \theta_d$, $\arg[\zeta_e] \equiv \theta_e$

Constraint from eEDM

$$\boxed{H_{\mathrm{EDM}} = -d_f \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E}}$$

T violation if ≠ 0 ⇄ CPV (CPT theorem)

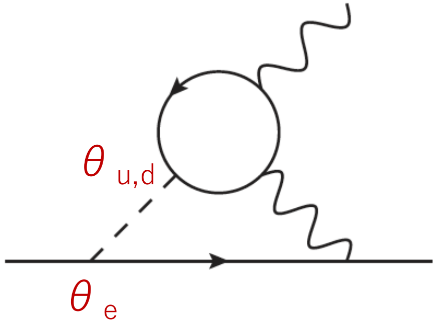
Barr-Zee type diagrams

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{d_f}{2} \bar{f} \sigma^{\mu\nu} (i\gamma^5) f F_{\mu\nu}$$

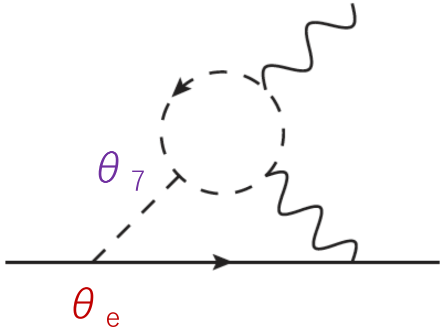
$$|d_e| < 4.1 \times 10^{-30}\, e\ \mathrm{cm}$$

Roussy *et al.* [Cornell Group]
arXiv:2212.11841

$d_e \simeq$



$|\zeta_u||\zeta_e|\sin(\theta_u - \theta_e)$



$|\lambda_7||\zeta_e|\sin(\theta_7 - \theta_e)$

10^{-29} e cm

when $\zeta_e = \zeta_u = \zeta_d$

Aligned 2HDM

Higgs potential $\arg[\lambda_7] \equiv \theta_7$

Yukawa couplings $\arg[\zeta_u] \equiv \theta_u$, $\arg[\zeta_d] \equiv \theta_d$, $\arg[\zeta_e] \equiv \theta_e$

S.K., M. Kubota, K. Yagyu (2022)

eEDM data can be satisfied by destructive interference of multiple CPV phsses

$$d_f = d_f(\mathrm{fermion}) + d_f(\mathrm{Higgs}) + d_f(\mathrm{gauge})$$

Evaluation of BAU

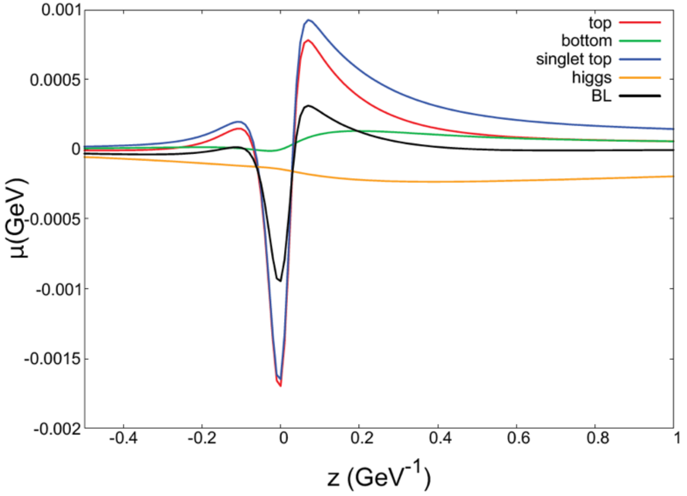
L_w : wall width
T_n : nucleation temp

$$M = 30\ \mathrm{GeV},\quad \lambda_2 = 0.1,\quad |\lambda_7| = 0.8,\quad \theta_7 = -0.9,$$
$$|\zeta_u| = |\zeta_d| = |\zeta_e| = 0.18,\quad \theta_u = \theta_d = -2.7,\quad \delta_e = -0.04$$

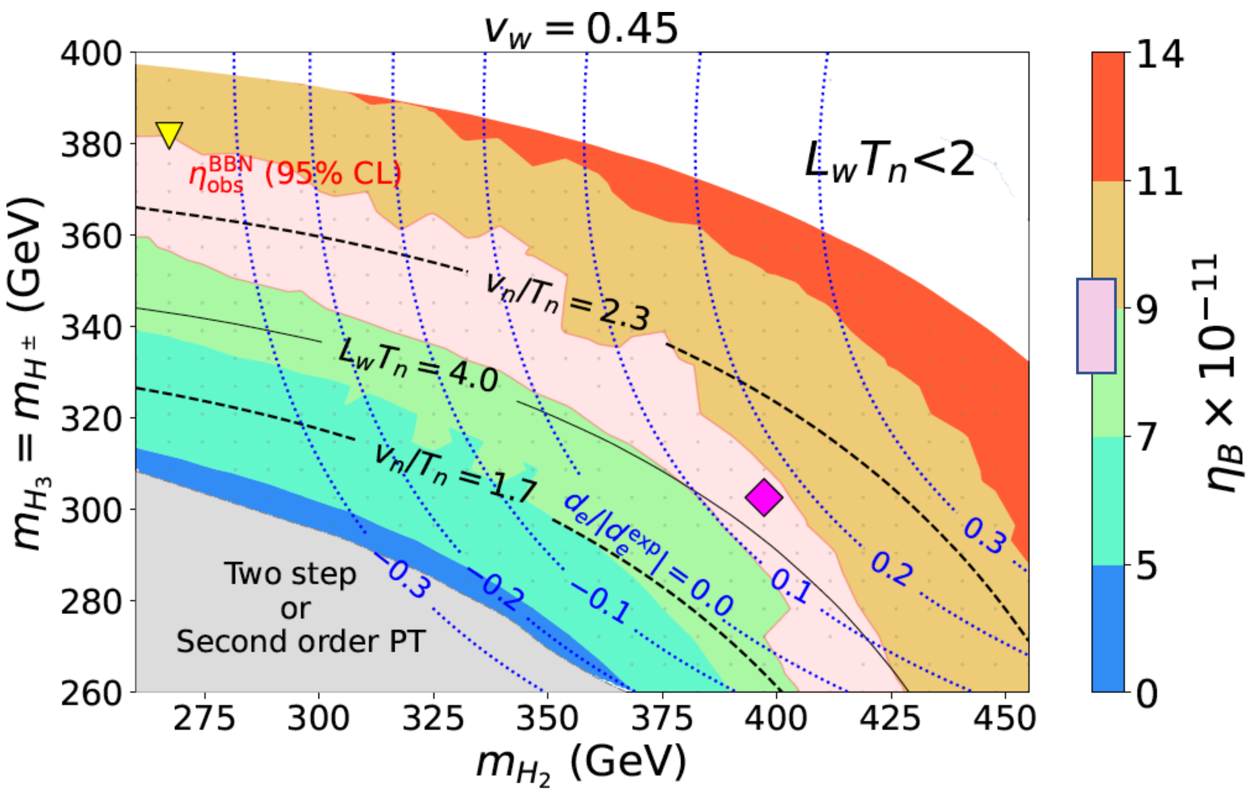
K. Enomoto, SK, Y. Mura, arXiv: 2207.00060

Aligned 2HDM

Chemical potential



Top transport scenario



In symmetric phase, B is produced by sphaleron

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 v_w g_* T}\int_0^\infty dz\ \mu_{B_L} f_{\rm sph} e^{-45\Gamma_{\rm sph} z/(4v_w)}$$

Frozen at the Broken phase when $v_n/T_n > 1$

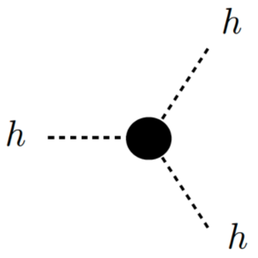
Cline, Kainulainen, …

BAU data reproduced（pink region）

$$\eta^{\rm BBN}_{obs} \equiv \frac{n_B}{s} = 8.2\text{–}9.2 \times 10^{-11}$$

$$s = 0.74 n_\gamma$$

Test of strongly 1st OPT



Stronlgly 1st OPT

→ **A large deviation in the hhh coupling**

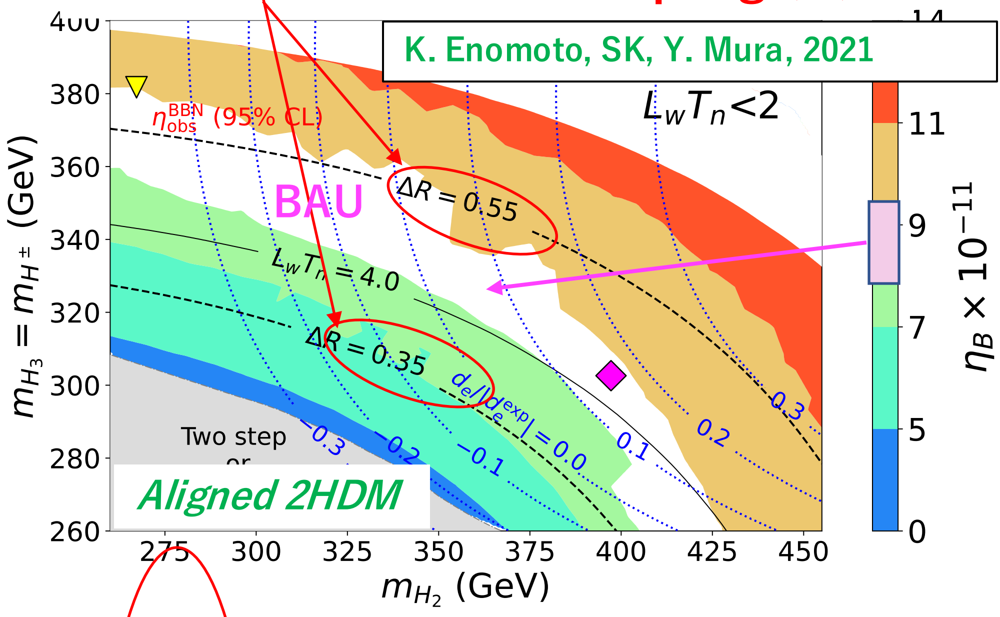
SK, Y. Okada, E. Senaha, 2005

Example ➡

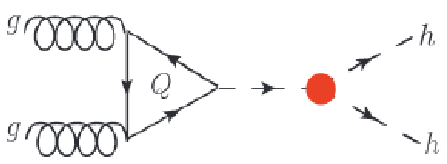
Aligned 2HDM

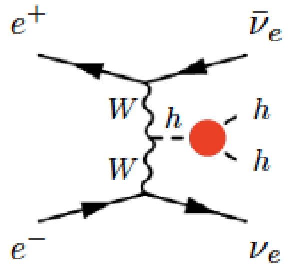
Deviation in the hhh coupling (%)

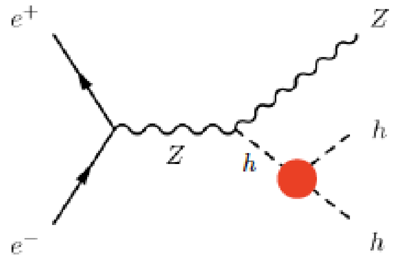
K. Enomoto, SK, Y. Mura, 2021

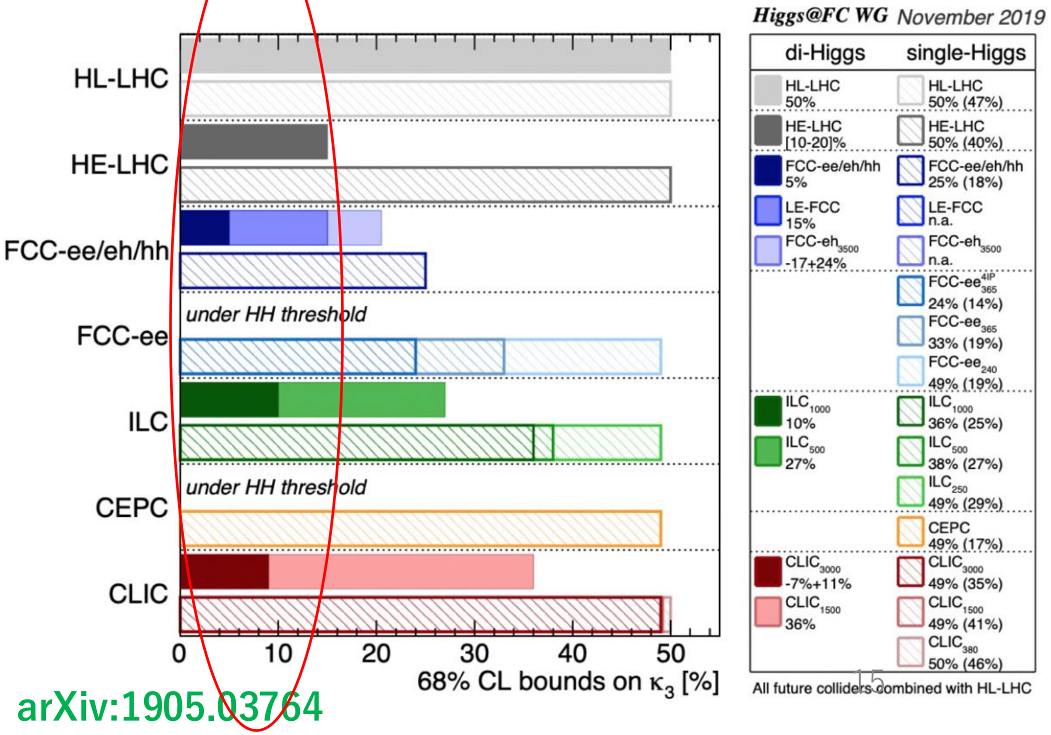


The hhh coupling can be measured at HL-LHC, or future e$^+$e$^-$ colliders







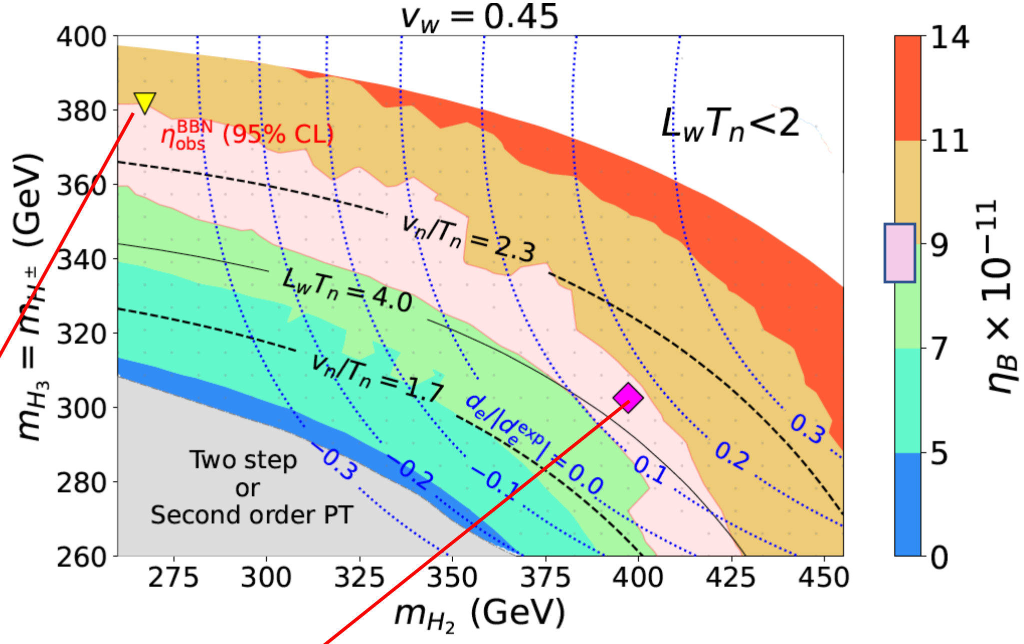


arXiv:1905.03764

EW Baryogenesis can be tested by the hhh measurement

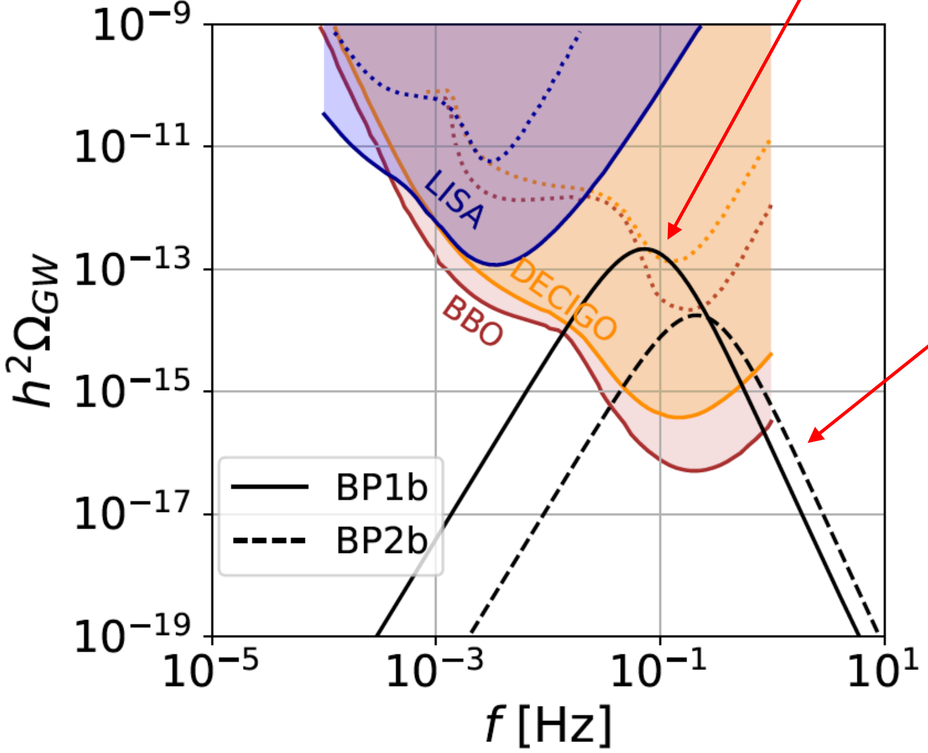
K. Enomoto, SK, Y. Mura, arXiv: 2207.00060

Case of aligned 2HDM



GW spectrum for the benchmark points to reproduce BAU, which satisfy current constraints from collider, flavor and EDM data

BP1 and BP2 may be tested by future GW experiments



Dotted curves: Sensitivity Curve
M. Breitbach et al., arXiv: 1811.11175

Solid curves: $h^2\Omega_{\rm PISC}$ [SNR criterion]
J. Cline et al., arXiv: 2102.12490

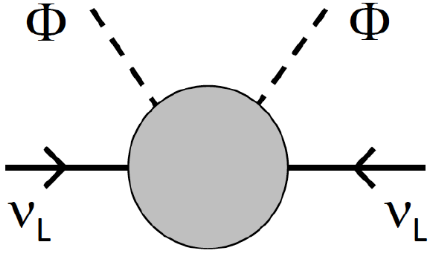
Neutrino mass, DM problem

Neutrino mass and Higgs

Neutrino Oscillation → Tiny mass （$< \mathrm{eV}$)

Majorana mass

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

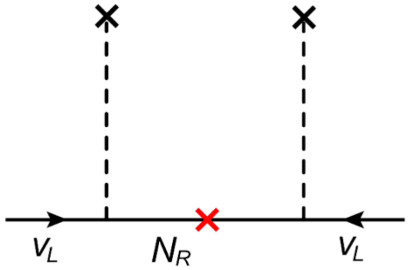


Seesaw Mechanism

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

Tiny mass

← Large mass of Right-handed Neutrinos



Seesaw

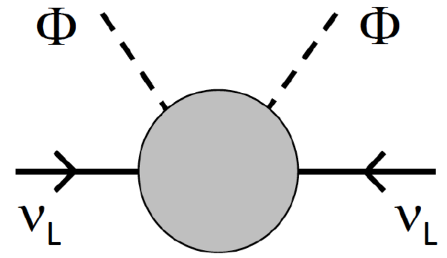
Mediated by RH neutirnos N_R

Neutrino mass and Higgs

Neutrino Oscillation → Tiny mass （$< \mathrm{eV}$)

Majorana mass

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

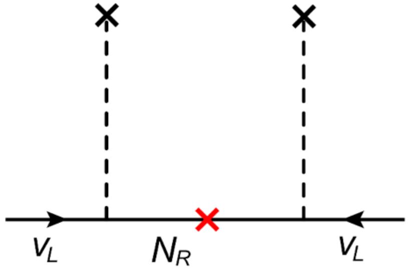


Seesaw Mechanism

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

Tiny mass

Large mass of Right-handed Neutrinos



Seesaw

Mediated by RH neutirnos N_R

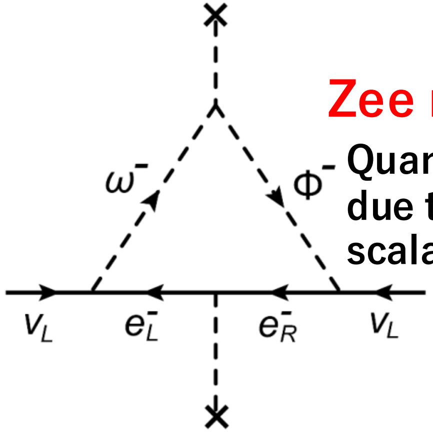
Alternative Scenario by quantum effects

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

Tiny mass

Quantum suppression

Mass around TeV scale



2HDM+S$^+$

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

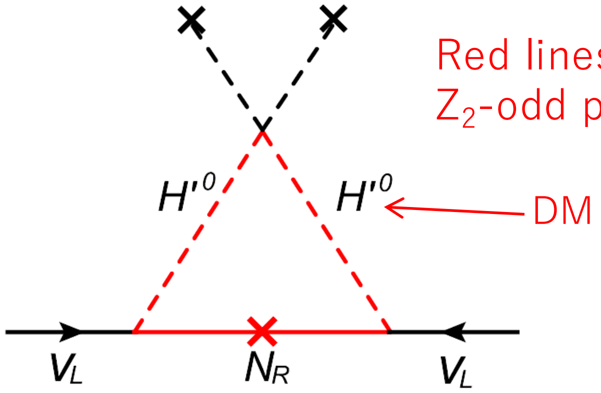
<u>Ma model</u>

Ma, 2006

SM+ H’ + N_R

1-loop induced ν -mass

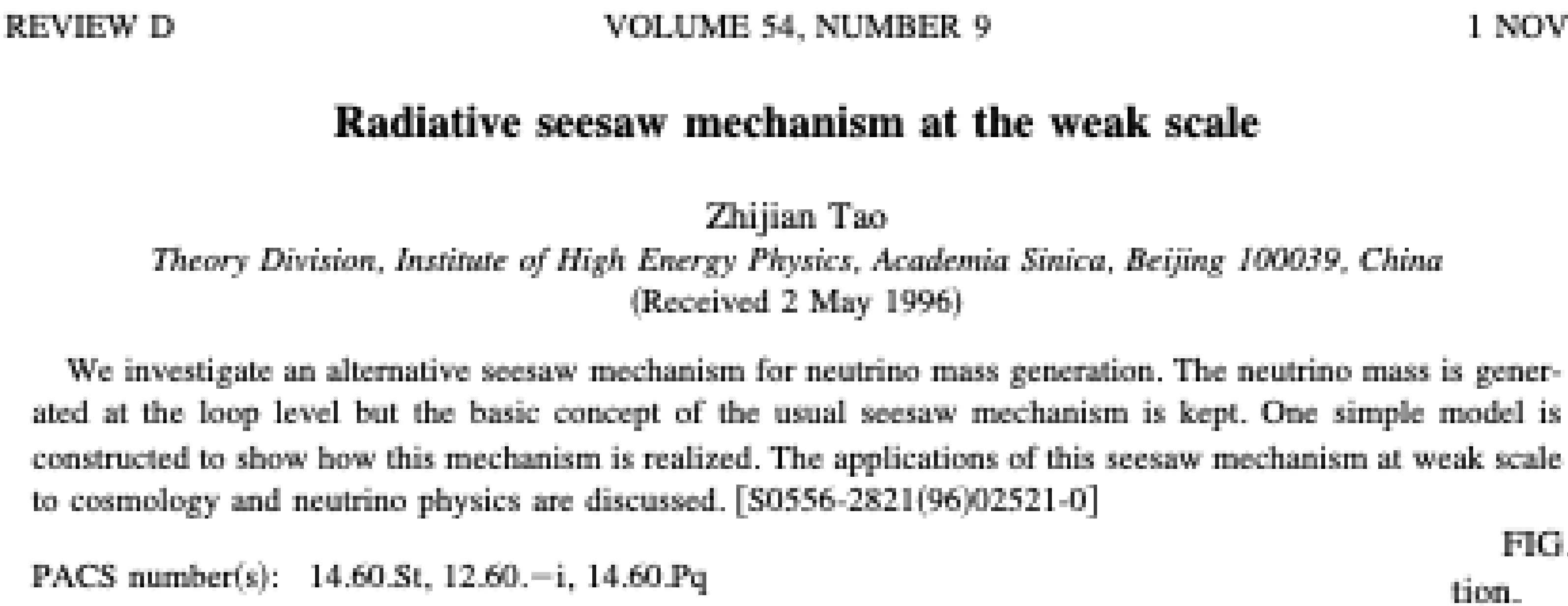
Dark matter candidate [H’]



Red lines are Z_2-odd particles

Recent discovery

Same model
Same motivation
Same results



REVIEW D VOLUME 54, NUMBER 9 1 NOVEMBER 1996

Radiative seesaw mechanism at the weak scale

Zhijian Tao
Theory Division, Institute of High Energy Physics, Academia Sinica, Beijing 100039, China
(Received 2 May 1996)

We investigate an alternative seesaw mechanism for neutrino mass generation. The neutrino mass is generated at the loop level but the basic concept of the usual seesaw mechanism is kept. One simple model is constructed to show how this mechanism is realized. The applications of this seesaw mechanism at weak scale to cosmology and neutrino physics are discussed. [S0556-2821(96)02521-0]

PACS number(s): 14.60.St, 12.60.−i, 14.60.Pq

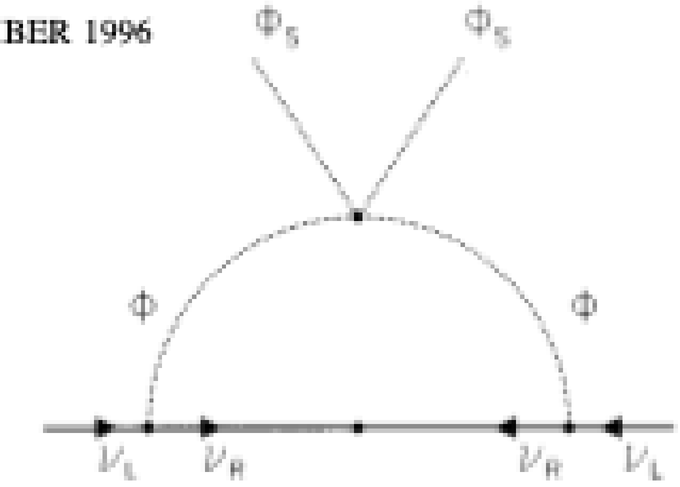
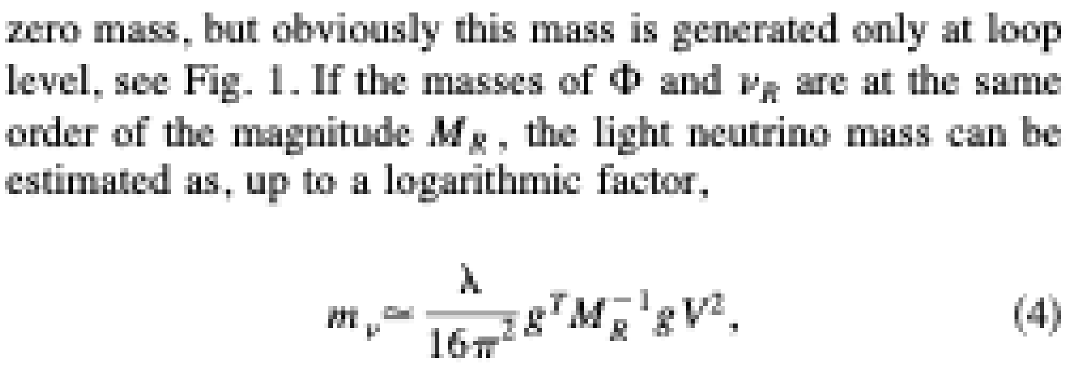


FIG. 1. The one-loop diagram for light neutrino mass generation.



zero mass, but obviously this mass is generated only at loop level, see Fig. 1. If the masses of Φ and ν_R are at the same order of the magnitude M_R, the light neutrino mass can be estimated as, up to a logarithmic factor,

$$m_\nu \simeq \frac{\lambda}{16\pi^2} g^T M_R^{-1} g V^2, \tag{4}$$

1996 Zhi-jian Tao Citation 0 before 2022
2006 Earnest Ma Citation ＞ 1500

We shoud call this model
Tao-Ma model instead of Ma model

Models of neutrino mass with DM

Introducing a discrete Z_2

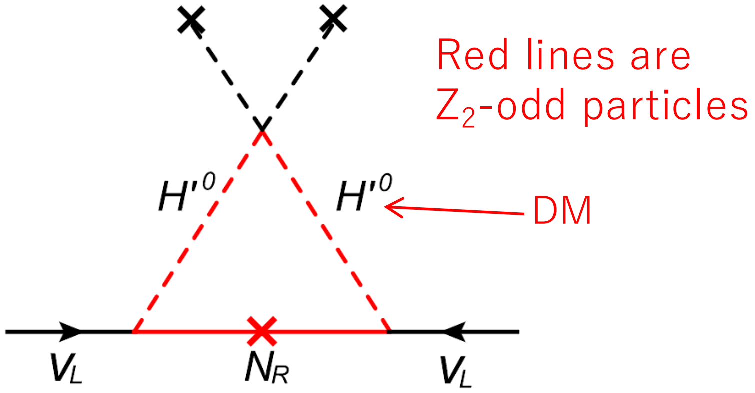
- Stability of new particle（DM）
- Loop induced masses

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

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Tao-Ma model Tao 1996, Ma, 2006

SM+ H’ + N_R

1-loop induced ν -mass

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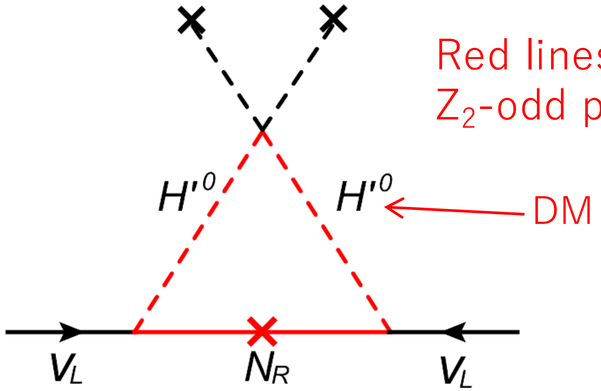


Red lines are Z_2-odd particles

DM

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

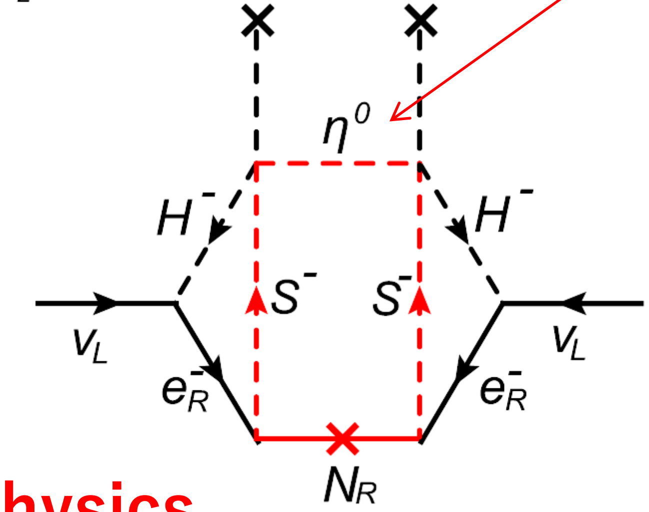
2HDM + η^0 + S^+ + N_R

ν -masses are 3-loop induced

DM candidate [η^0]

EW Baryogenesis possible (CPV, 1stOPT)

DM

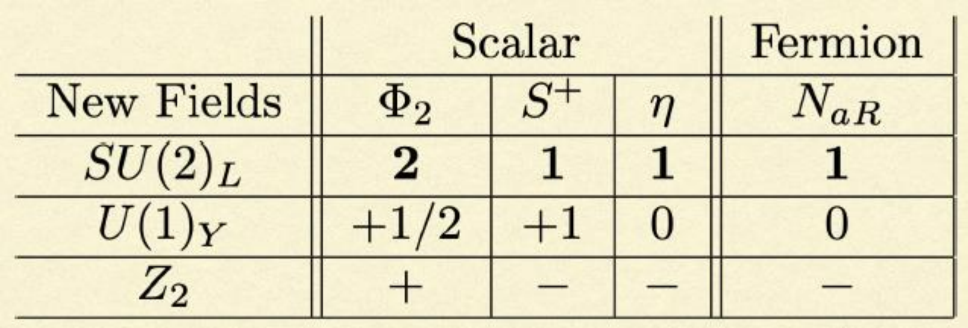


3 Problems can be explained by the TeV scale physics

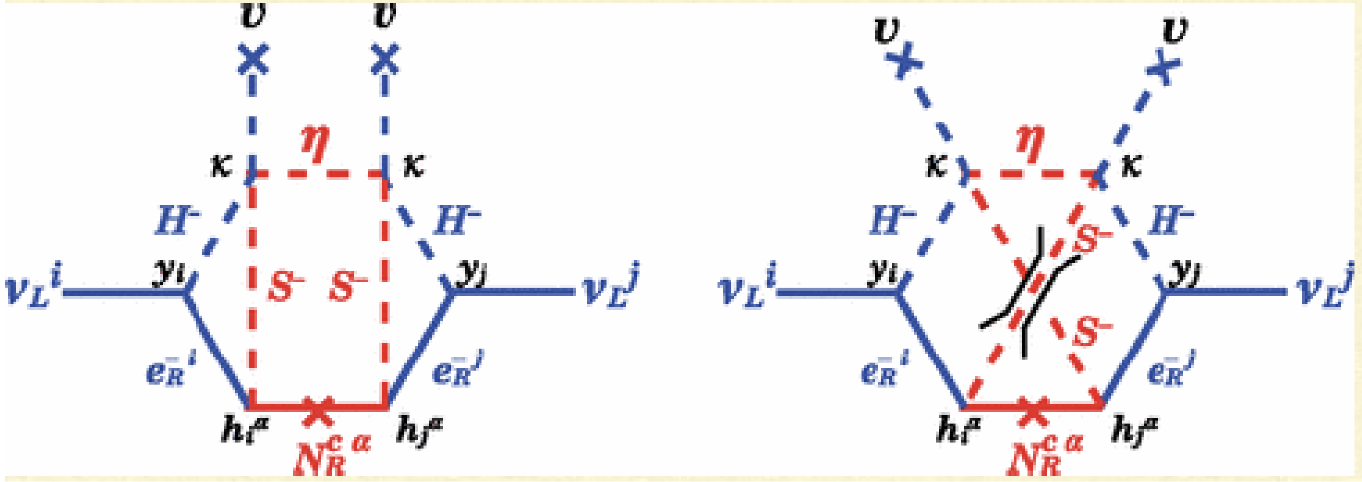
AKS2009
(The model discussed today)

Model (AKS2009)

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



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

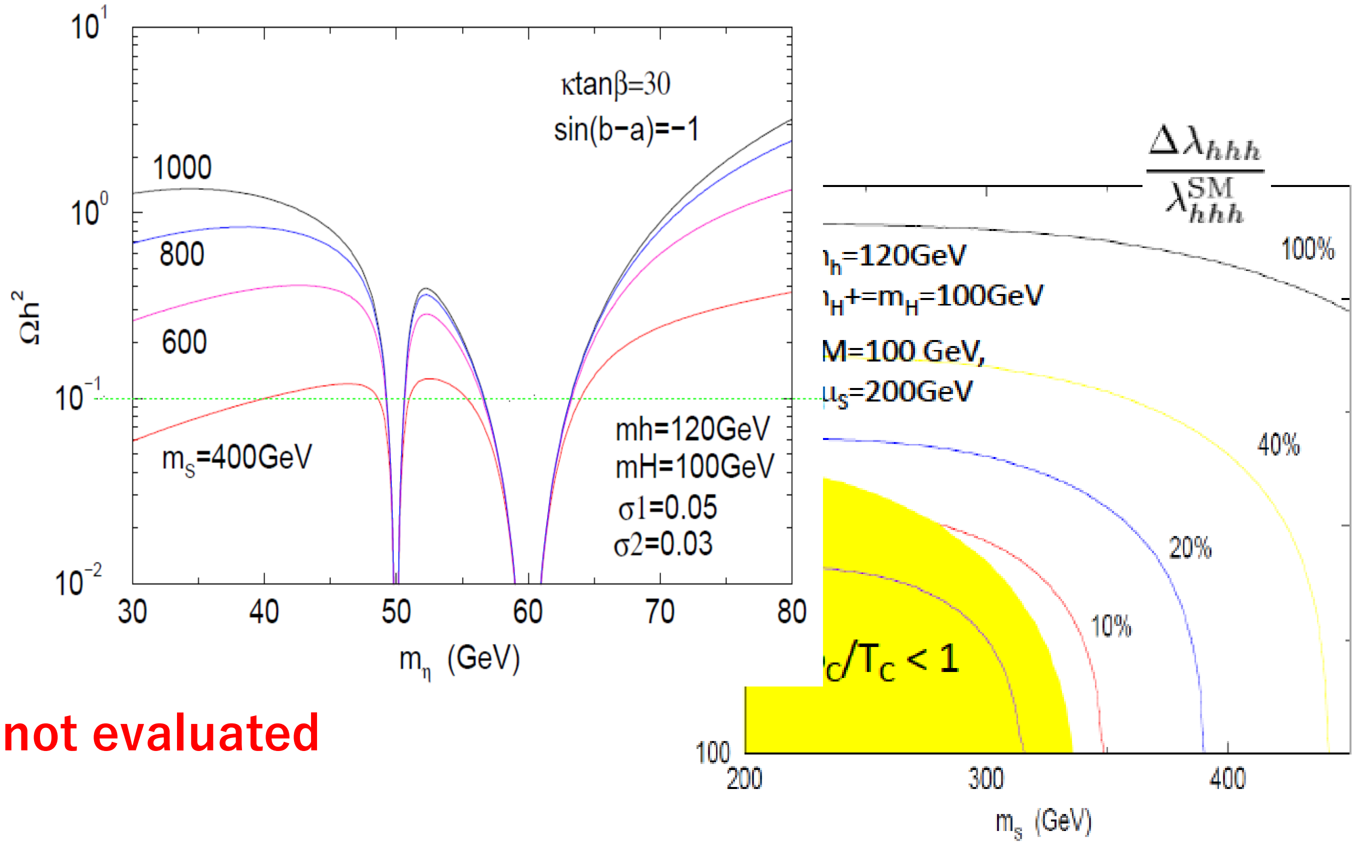


2HDM (Type X) + **Z_2-odd scalars and RN**

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 but **Aligned 2HDM**

$\lambda_6 = 0$ (Higgs alignment)
FCNC avoided by Yukawa alignment (Pich, Zuzon)
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 was evaluated

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

Constraints

Slide by Enomoto

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

Benchmark scenario (BS) Aoki, Enomoto, SK (2022)

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

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

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

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

New Yukawa interactions

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

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

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

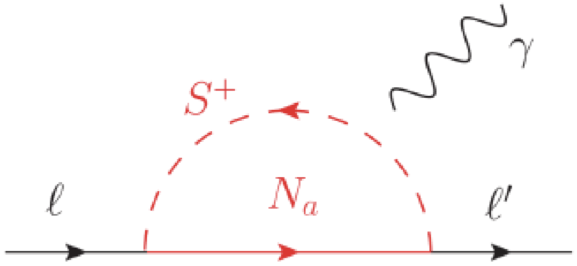
Lepton flavor violation

$m_S = 400$ GeV,

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

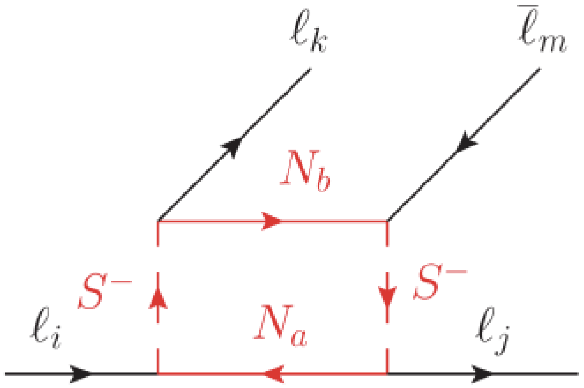
$$h_i^\alpha \simeq \begin{pmatrix} 1.0\,e^{-0.31i} & 0.2\,e^{0.30i} & 1.0\,e^{-2.4i} \\ 1.1\,e^{-1.9i} & 0.21\,e^{-1.8i} & 1.1\,e^{2.3i} \\ 0.45\,e^{2.7i} & 1.3\,e^{-0.033i} & 0.10\,e^{0.63i} \end{pmatrix}$$

- $\ell \to \ell'\gamma$



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}

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

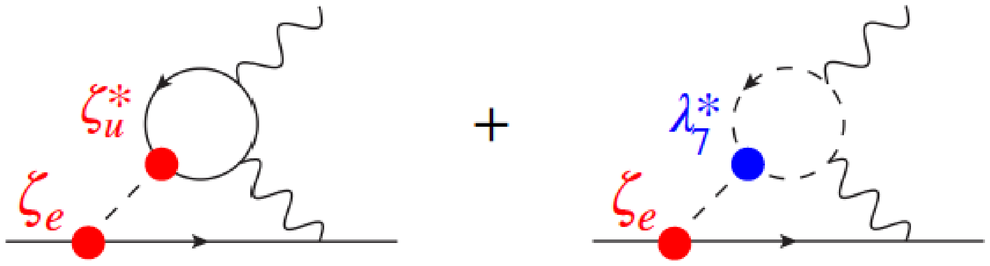


Processes	BR	Upper limits
$\mu \to 3e$	1.0×10^{-13}	1.0×10^{-12}
$\tau \to 3e$	6.2×10^{-10}	2.7×10^{-8}
$\tau \to 3\mu$	2.4×10^{-11}	2.1×10^{-8}
$\tau \to e\mu\bar{e}$	5.1×10^{-12}	1.8×10^{-8}
$\tau \to \mu\mu\bar{e}$	1.1×10^{-12}	1.7×10^{-8}
$\tau \to ee\bar{\mu}$	4.5×10^{-13}	1.5×10^{-8}
$\tau \to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



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

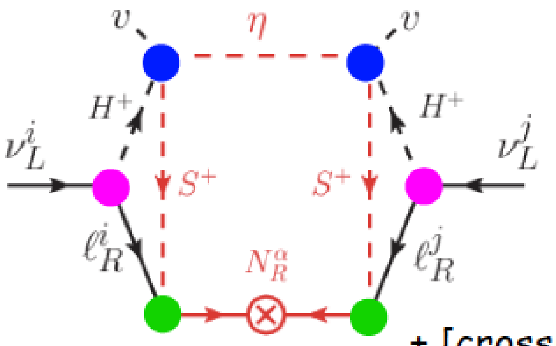
$$\boxed{\begin{array}{l} m_{H_2} = 420 \text{ GeV}, \quad m_{H_3} = m_{H^\pm} = 250 \text{ GeV} \\ \theta_7 = -2.34, \quad \theta_u = 0.245, \quad \theta_e = -2.94 \end{array}} \Rightarrow \boxed{|d_e| = 0.22 \times 10^{-30} \text{ e cm}}$$

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, $\boxed{|d_n| \sim 10^{-30} \text{ e cm}}$

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/ $m_{\nu 1} \simeq 0.006$ 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)

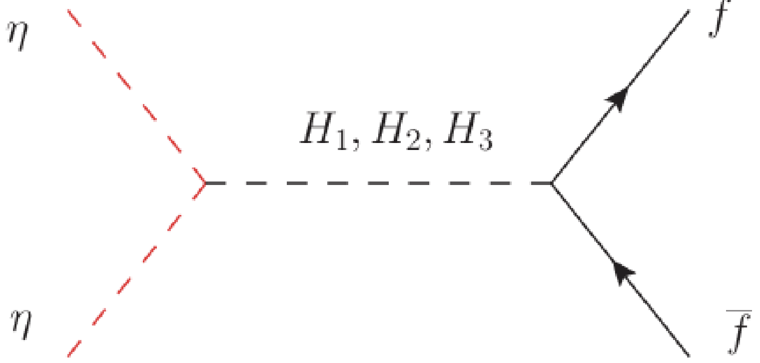
Dark matter (DM)

$m_\eta = 63$ 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)

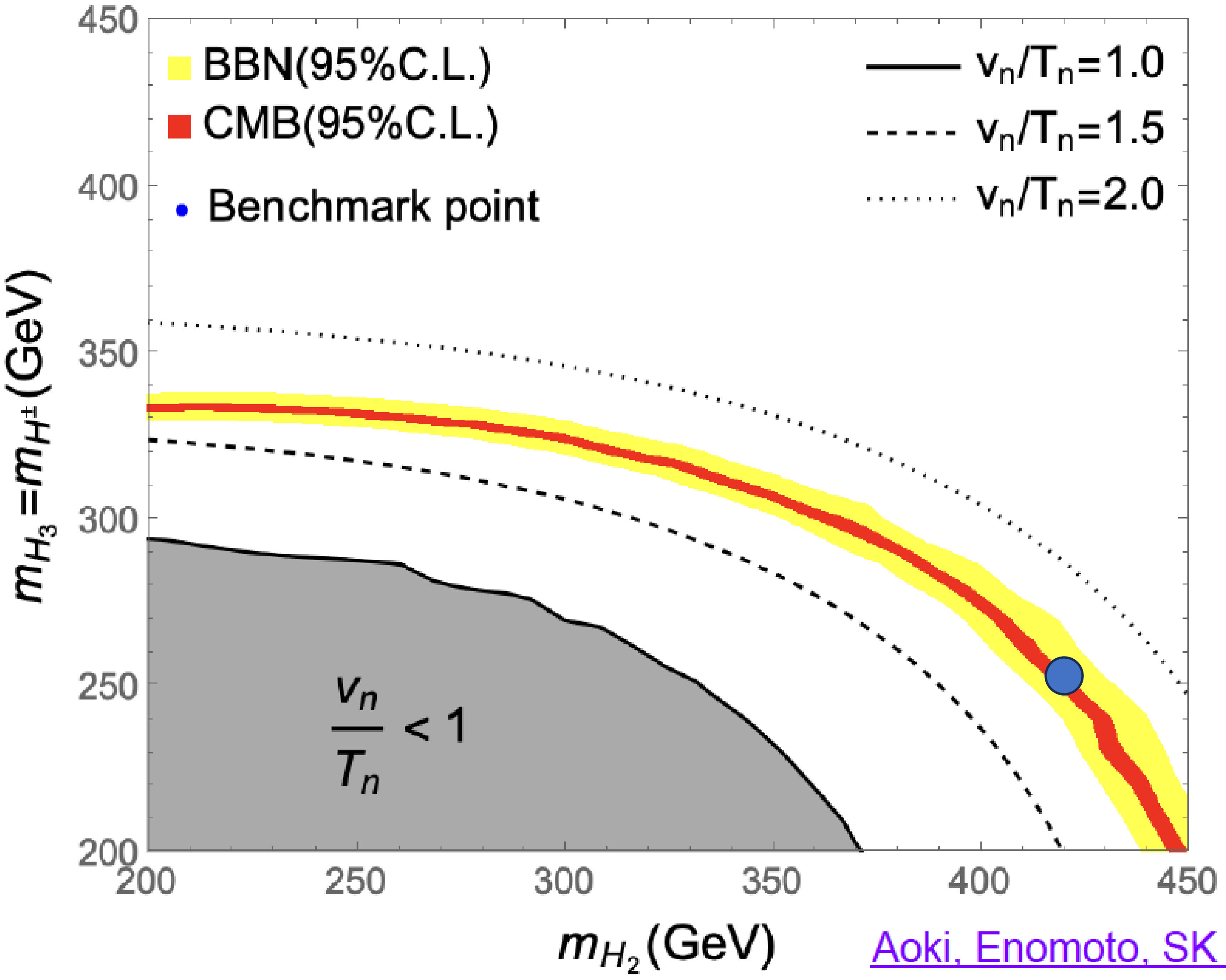
$(T \neq 0)$ thermal resummation Parwani (1992)

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

$$v_n/T_n = 1.74 > 1$$

Kuzmin, Rubakov, Shaposhnikov (1985)

Electroweak baryogenesis



Aoki, Enomoto, SK (2022)

Other parameters are the same with those in the BS

Get back to the original model AKS2009

FCNC by softly broken Z2
Smaller number if parameters

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

Particle content

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

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	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	$-$	$+$

$i = 1,2,3$

$\alpha = 1,2,3$

Dark matter candidate

Lagrangian

Stationary condition

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

μ_{12}^2 and λ_5 are related

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

Higgs potential

$$V = -\mu_1^2|\phi_1|^2 - \mu_2^2|\phi_2|^2 - (\boxed{\mu_{12}^2}\phi_1^\dagger\phi_2 + \mathrm{h.c.}) + \mu_S^2|S^+|^2 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4$$

$$+ \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \left(\frac{\boxed{\lambda_5}}{2}(\phi_1^\dagger\phi_2)^2 + \mathrm{h.c.}\right) + \frac{\lambda_S}{4}|S^+|^4 + \frac{\lambda_\eta}{4!}\eta^4 + \frac{\xi}{2}|S^+|^2\eta^2$$

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

$$+ \sum_{a=1}^{2}\left(\rho_a|\phi_a|^2|S^+|^2 + \frac{1}{2}\sigma_a|\phi_a|^2\eta^2\right) + (2\boxed{\kappa}\tilde{\phi}_1^\dagger\phi_2 S^-\eta + \mathrm{h.c.})$$

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

Only θ_5 in the Higgs potential

Additional Yukawa coupling with RHN

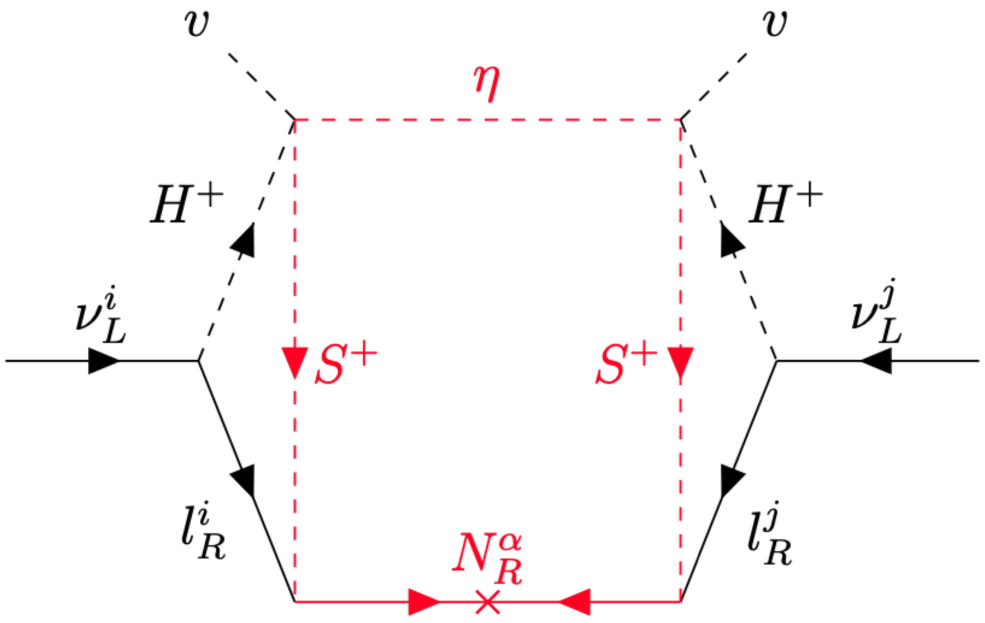
$$\mathcal{L} \supset -\boxed{h_i^\alpha}\,\overline{(N_R^\alpha)^c}\, l_R^i S^+ + \mathrm{h.c.}$$

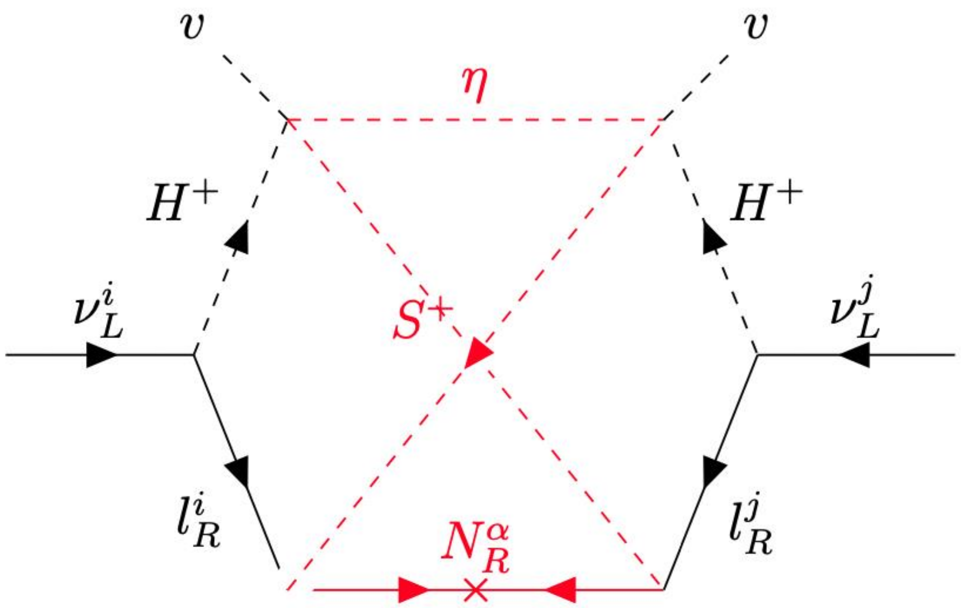
$\alpha = 1,2,3,$ $i = 1,2,3,$ h_i^α are 3×3 matrix

CPV

Neutrino mass

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





Three loop effects

→**Natural $h_e^\alpha \sim O(1)$ and $m_N \sim O(1)$ TeV**

Benchmark scenarios

DM Abundance
DM Directsearch Ex
Neutirno Data
BAU

LEP
LHC (ALTAS, CMS)
Electron EDM, neutron EDM
Various LFV experiment

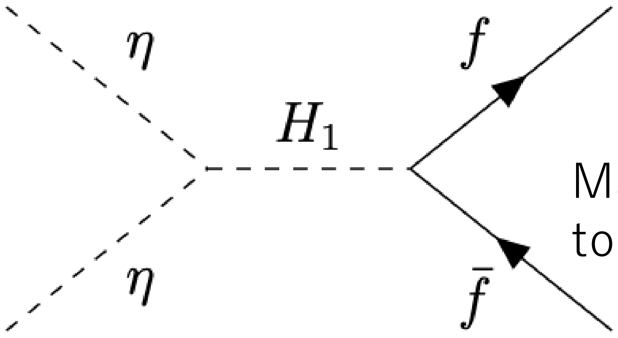
Explore a benchmark point which satisfy every thing

Benchmark scenarios

K. Enomoto, S.Kanemura, ST (2024)

Two benchimark scenario (Neutrino mass is assumed normal order)

- **Scenario 1(resonant)**



Main contribution to the abundance

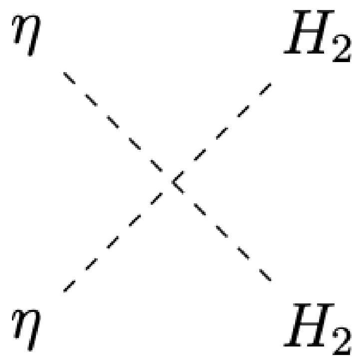
$m_{H^1} \simeq 125$ GeV, $m_{H^2} \simeq 224$ GeV, $m_{H^3} \simeq 391$ GeV
$m_{H^\pm} \simeq 391$ GeV, $m_S = 325$ GeV, $m_\eta = 63$ GeV
$(m_{N^1}, m_{N^2}, m_{N^3}) = (2500, 3000, 3500)$ GeV
$m_{\nu^1} = 4.76$ meV, $\kappa \tan\beta = 30, \tan\beta = 18,$
$\theta_5 \simeq -0.990$

$$h_i^\alpha \simeq \begin{pmatrix} 2.9e^{0.96\pi i} & 0.010e^{0.39\pi i} & 0.0024e^{-0.072\pi i} \\ 2.3e^{-0.44\pi i} & 0.019e^{-0.93\pi i} & 0.0021e^{-0.73\pi i} \\ 2.0e^{-0.48\pi i} & 0.054e^{-0.029\pi i} & 0.0022e^{-0.083\pi i} \end{pmatrix}$$

$|d_e| \simeq 3 \times 10^{-31}$ ecm $< 4.1 \times 10^{-30}$ ecm

$\Omega h^2 \simeq 0.12$

- **Scenario 2(heavy WIMP)**



Main contribution to the abundance

$m_{H^1} \simeq 125$ GeV, $m_{H^2} \simeq 224$ GeV, $m_{H^3} \simeq 391$ GeV
$m_{H^\pm} \simeq 391$ GeV, $m_S = 325$ GeV, $m_\eta = 250$ GeV
$(m_{N^1}, m_{N^2}, m_{N^3}) = (2500, 3000, 3500)$ GeV
$m_{\nu^1} = 7.17$ meV, $\kappa \tan\beta = 30, \tan\beta = 18, \theta_5 \simeq -0.999$

$$h_i^\alpha \simeq \begin{pmatrix} 2.7e^{0.96\pi i} & 0.014e^{-0.22\pi i} & 0.0016e^{-0.85\pi i} \\ 2.8e^{0.66\pi i} & 0.044e^{0.76\pi i} & 0.0017e^{-0.91\pi i} \\ 2.6e^{-0.10\pi i} & 0.059e^{-0.88\pi i} & 0.0021e^{0.97\pi i} \end{pmatrix}$$

$|d_e| \simeq 1 \times 10^{-30}$ ecm $< 4.1 \times 10^{-30}$ ecm

$\Omega h^2 \simeq 0.12$

Dark matter direct detection

$$V \supset + \sum_{a=1}^{2}\left(\rho_a|\phi_a|^2|S^+|^2 + \underbrace{\frac{1}{2}\sigma_a|\phi_a|^2\eta^2}_{\text{DM-Higgs interaction}}\right)$$

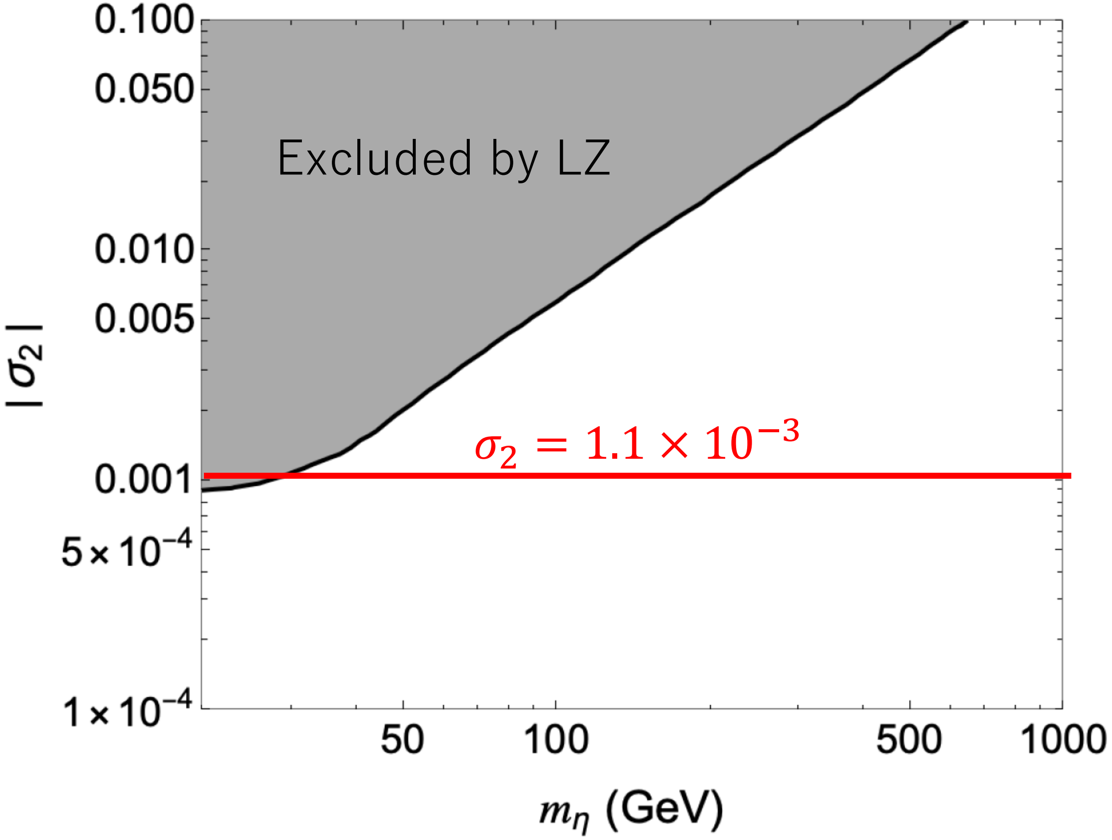
η : dark matter

The process $\eta N \to \eta N$ depens on $(\sigma_1 \cos\beta + \sigma_2 \sin\beta)$ and m_η

For large $\tan\beta$, $(\sigma_1 \cos\beta + \sigma_2 \sin\beta) \simeq \sigma_2$
Direct detection does not depend on σ_1

$\to \sigma_2 = 1.1 \times 10^{-3}$

$\sigma_{SI}(\eta N \to \eta N)$



K. Enomoto, S.Kanemura, ST (2024)

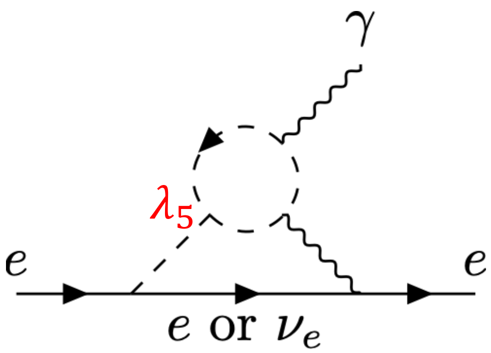
Electric dipole moment in our model

In the model AKS, new contributions from

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

appear.

By destructive interference Electron EDM can satisfy electron EDM

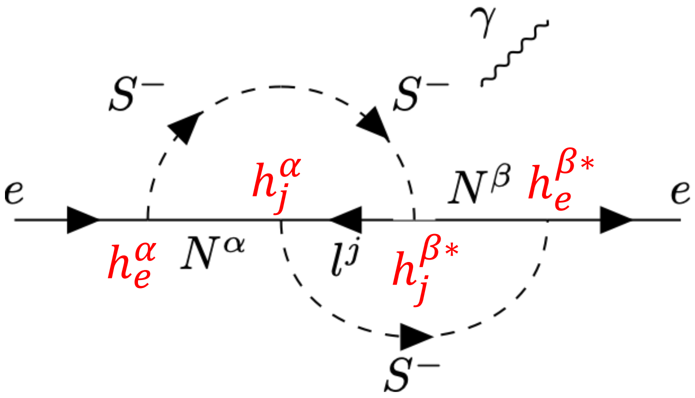


2HDM contribution

Barr, Zee (1990)

Altmannshofer, Gori, Hamer, Patel(2020)

$+$



Additional contribution in our model

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

Lepton flavor violation(LFV)

$Br(\mu \to e\gamma) < 3.1 \times 10^{-13}$ Afanaciev et al. MEG-II (2023)
$Br(\mu \to 3e) < 1.0 \times 10^{-12}$ Perez et al. Mu3e (2023)
$\cdots$

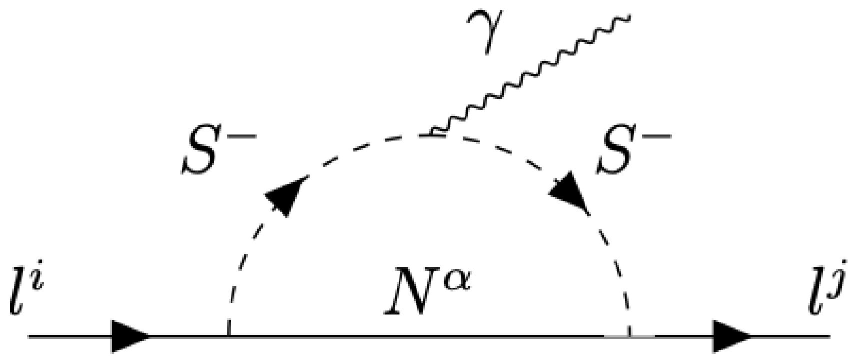
In the model,

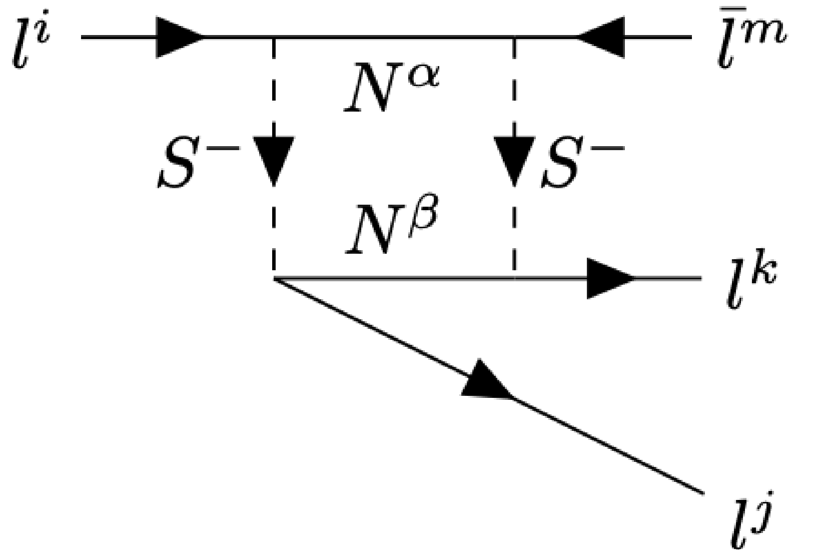
$$\mathcal{L} \supset -h_i^\alpha \overline{(N_R^\alpha)^c} l_R^i S^+ + \text{h.c.}$$

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

causes LFV processes.

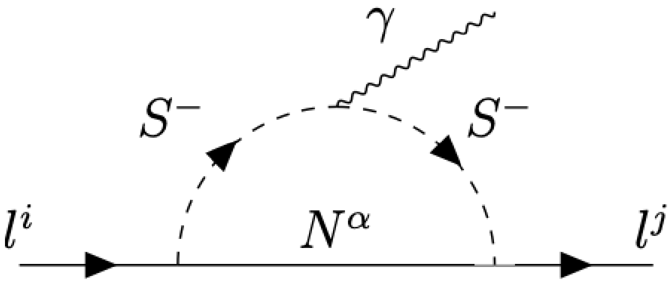
→ **LFV can test the model**



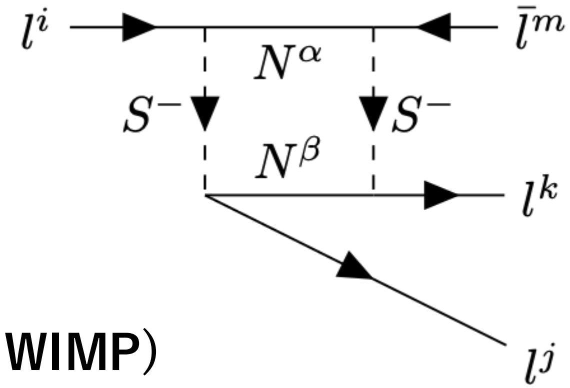


Constaraints from lepton flavor violation

$l^i \to l^j \gamma$



$l^i \to l^j \, l^k \, \bar{l}^m$



- **Scenario 1(Resonant)**

	Prediction	Exp. bounds
$\mu \to e\gamma$	2.95×10^{-14}	3.1×10^{-13}
$\tau \to e\gamma$	4.73×10^{-15}	3.3×10^{-8}
$\tau \to \mu\gamma$	2.49×10^{-18}	4.4×10^{-8}
$\mu \to 3e$	4.68×10^{-13}	1.0×10^{-12}
$\tau \to 3e$	4.84×10^{-10}	2.7×10^{-8}
$\tau \to 3\mu$	4.88×10^{-20}	2.1×10^{-8}
$\tau \to e\mu\bar{e}$	1.14×10^{-16}	1.8×10^{-8}
$\tau \to \mu\mu\bar{e}$	5.77×10^{-17}	1.7×10^{-8}
$\tau \to ee\bar{e}$	1.46×10^{-13}	1.5×10^{-8}
$\tau \to e\mu\bar{\mu}$	1.14×10^{-16}	2.7×10^{-8}

- **Scenario 2(Heavy WIMP)**

	Prediction	Exp. bounds	
$\mu \to e\gamma$	5.08×10^{-14}	3.1×10^{-13}	MEG-II(2024)
$\tau \to e\gamma$	1.56×10^{-15}	3.3×10^{-8}	BaBar(2010)
$\tau \to \mu\gamma$	1.33×10^{-18}	4.4×10^{-8}	BaBar(2010)
$\mu \to 3e$	2.79×10^{-13}	1.0×10^{-12}	Mu3e(2023)
$\tau \to 3e$	1.50×10^{-10}	2.7×10^{-8}	BaBar(2010)
$\tau \to 3\mu$	7.76×10^{-20}	2.1×10^{-8}	Belle (2010)
$\tau \to e\mu\bar{e}$	1.60×10^{-16}	1.8×10^{-8}	Belle (2010)
$\tau \to \mu\mu\bar{e}$	2.62×10^{-17}	1.7×10^{-8}	Belle (2010)
$\tau \to ee\bar{e}$	6.95×10^{-13}	1.5×10^{-8}	Belle (2010)
$\tau \to e\mu\bar{\mu}$	1.60×10^{-16}	2.7×10^{-8}	Belle (2010)

K. Enomoto, S.Kanemura, ST (2024)

Test of our benchmark scenario

	Prediction Scenario 1	Prediction Scenario 2	Expected sensitivity	
$\mu \to e\gamma$	2.95×10^{-14}	5.08×10^{-14}	6×10^{-14}	MEG-II
$\mu \to 3e$	4.68×10^{-13}	2.79×10^{-13}	1×10^{-16}	Mu3e
$\tau \to 3e$	4.84×10^{-10}	1.50×10^{-10}	4×10^{-10}	Belle-II

Future LFV experiments may confirm/exclude the model

Furue Electron EDM experiments

ACME-III try to explore CPV by $|d_e| < 10^{-30}$ ecm

- **Scenario 1(resonant)** $|d_e| \simeq 3 \times 10^{-31}$ ecm
- **Scenario 2(Heavy)** $|d_e| \simeq 1 \times 10^{-30}$ ecm

→Scenario 2 can be tested by ACME-III

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

- $gg \to H_2, H_3;\ gg \to H^\pm tb;\ q\bar{q} \to H_{2,3}H^\pm$ Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu (2021); SK, Takeuchi, Yagyu (2021)
- $q\bar{q} \to S^+S^-;\ e^+e^- \to S^+S^-;\ e^+e^- \to NN$ 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 $H_{2,3} \to \tau\bar{\tau}$ at e^+e^- collider

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

Dark matter direct detection

Observation of gravitational waves

The detailed study is a work in progress.

UV theory?

What is the world above Landau Pole?

Why so various scalar fields appear at low energy?

SK, T. Shindo, T. Yamada 2014

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

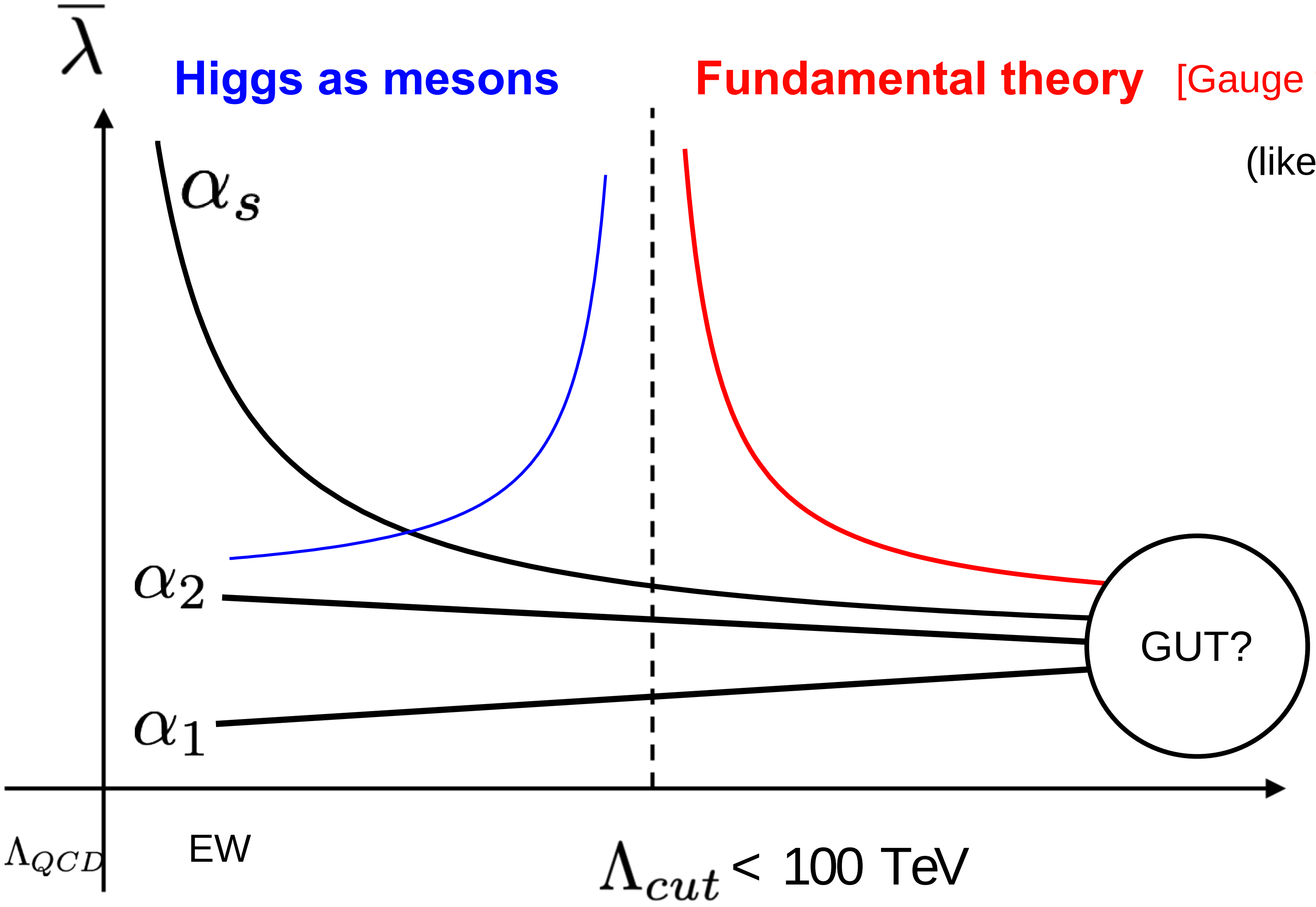
What is the world above Λ?

Higgs as mesons

$$M_{ij} = T_i T_j$$

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

Landau pole and new physics



Higgs as mesons

Fundamental theory [Gauge theory]

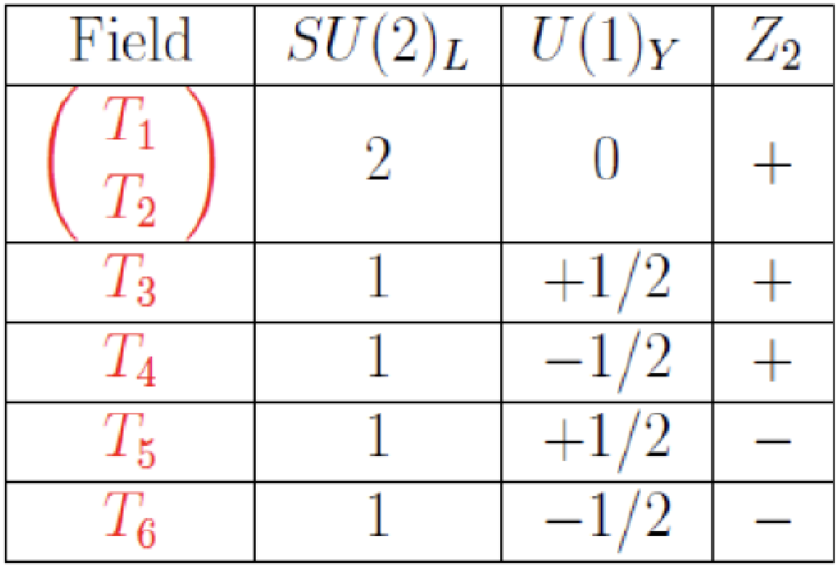
(like QCD)

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

SK, Shindou, Yamada 2014

Higgs as Meson

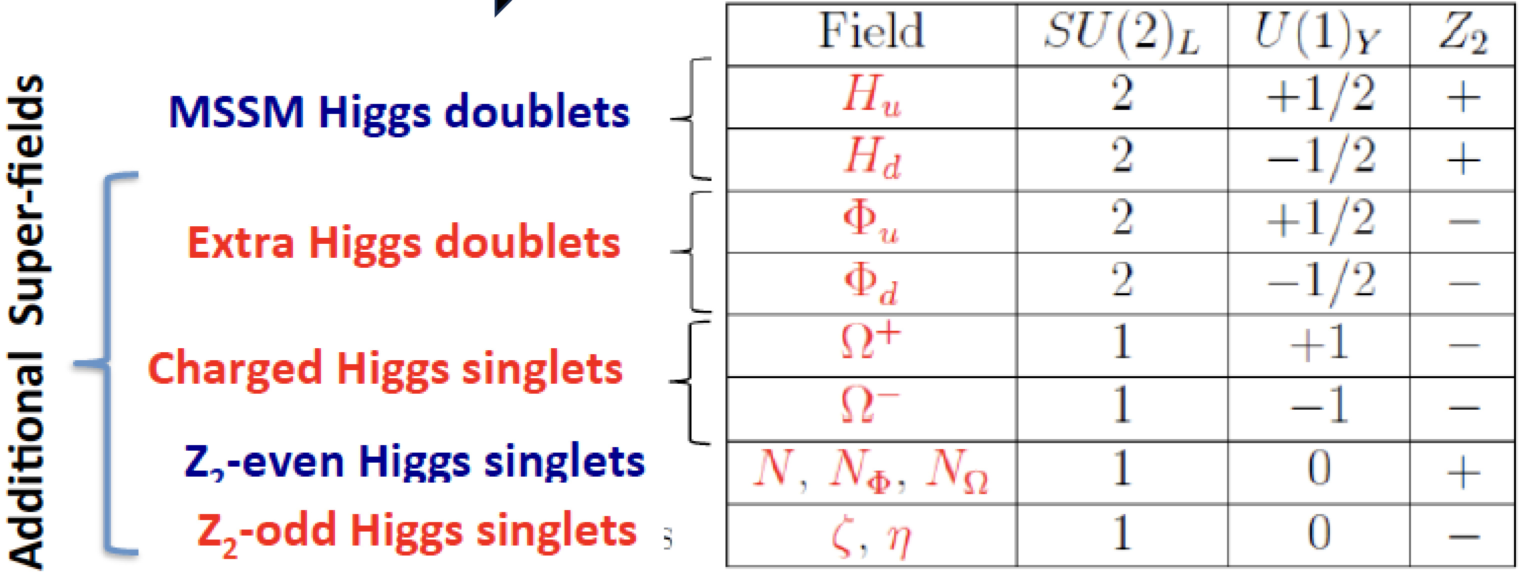
SU(2)H gauge theory



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	$-1/2$	−

Intrilligator, Seiberg

$$M_{ij} = T_i T_j$$



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	−

Superpotential

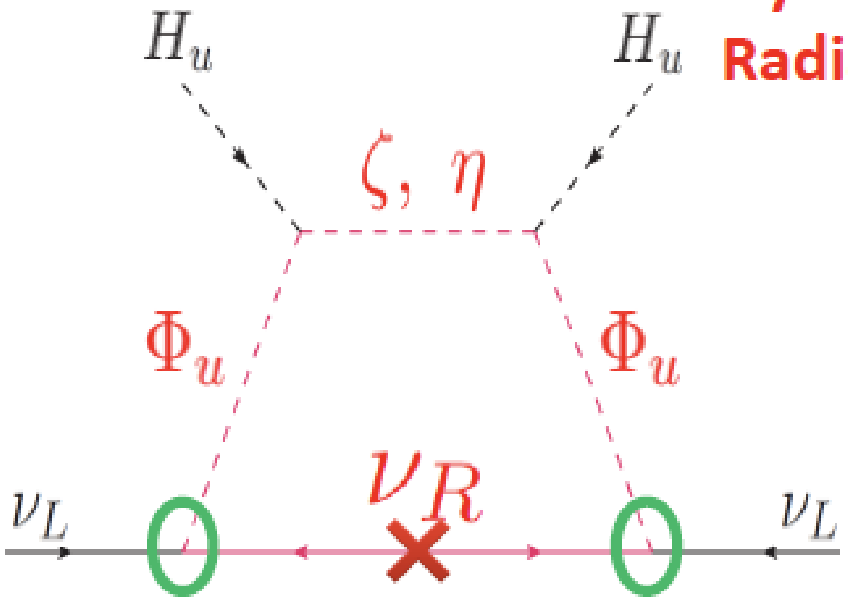
$$\begin{aligned} W_{eff} \ = \ \lambda \ \{ & N(H_u H_d + v_0^2) \ + \ N_\Phi(\Phi_u \Phi_d + v_\Phi^2) \ + \ N_\Omega(\Omega^+ \Omega^- + v_\Omega^2) \\ & - \ N N_\Phi N_\Omega \ - \ N_\Omega \zeta \eta \ + \ \zeta H_d \Phi_u \ + \ \eta H_u \Phi_d \ - \ \Omega^+ H_d \Phi_d \ - \ \Omega^- H_u \Phi_u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

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

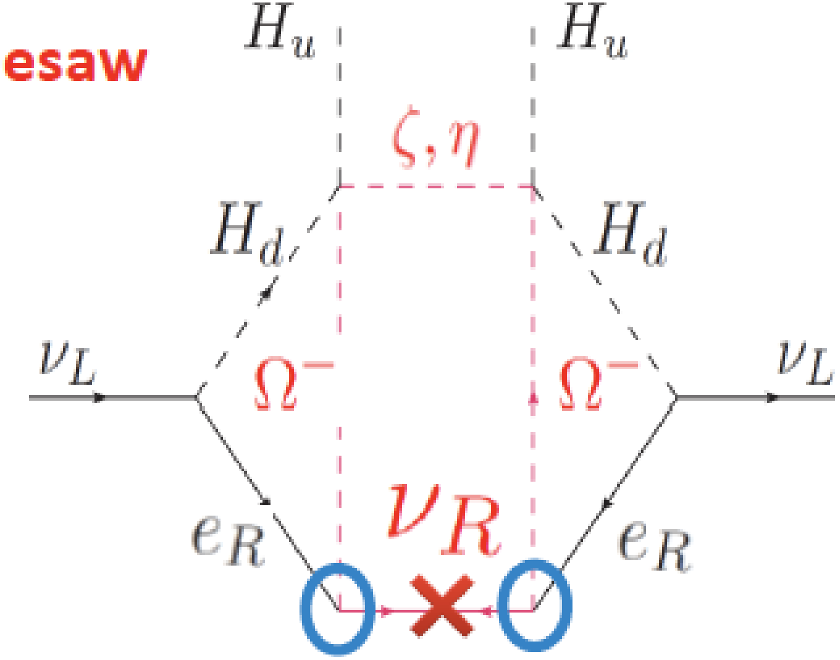
SK, Shindou, Yamada 2014

$$W^N_{\rm eff} = \frac{\kappa}{2} N \nu^c_R \nu^c_R + y^i_N \nu^c_R L_i \Phi_u + h^i_N \nu_R E^c_i \Omega^- + \frac{M}{2} \nu^c_R \iota$$

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 also 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

- To consider the UV structure of the model is interesting

HPNP2025

Higgs as a Probe of New Physics 2025

9 -13 June, 2025

Nambu Yoichiro Hall
The University of OSAKA
Japan

大阪大学
公式マスコットキャラクター
「ワニ博士」

Your participation is welcome!

Announcement will come soon!

Expo 2025 in Osaka

Expo 2025 Osaka Kansai
Period: 184 days, from Sunday, April 13 to Monday, October 13, 2025