Electroweak baryogenesis in the 3-loop neutrino mass model with dark matter

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Collaborators

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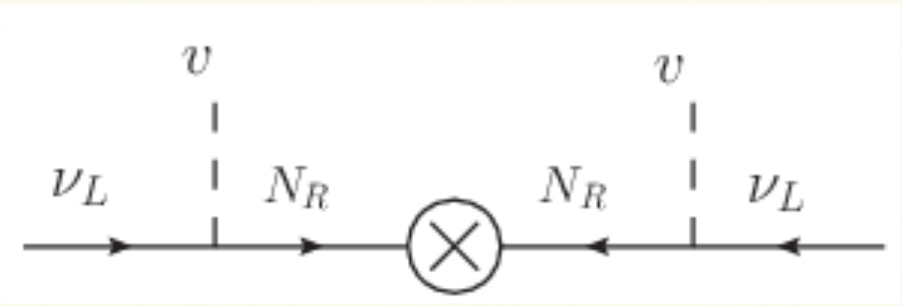
Paper in preparation

Introduction

What is the origin of tiny neutrino mass?

■ **Seesaw mechanism** Minkowski (1977); Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic (1980); Schechter, Valle (1980)

Right-handed Majorana ν's: N_R



$$(m_\nu)_{\ell\ell'} \propto \frac{v^2}{M_N} \quad \mathcal{O}(M_N) = \text{GUT scale}$$

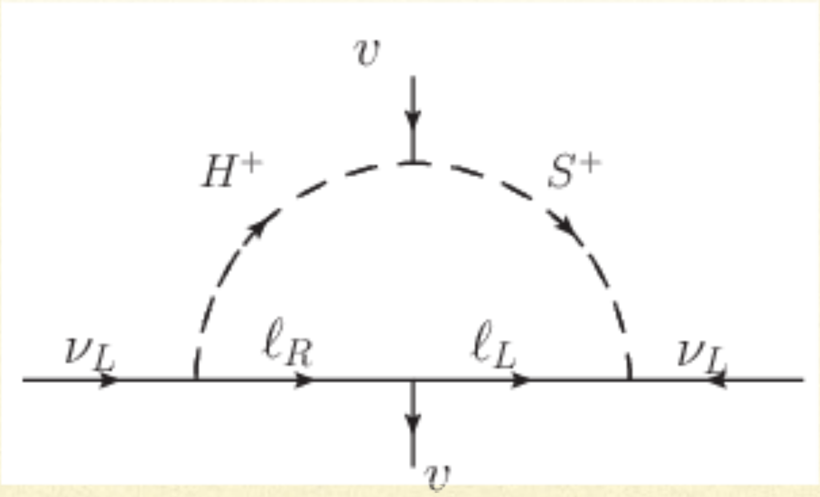
Difficult to test

■ **Radiative seesaw** (quantum effects)

e.g.) Zee model A. Zee (1980)

$\phi_2 : (\mathbf{2}, +1/2)$

$S : (\mathbf{1} + 1)$



The loop suppression

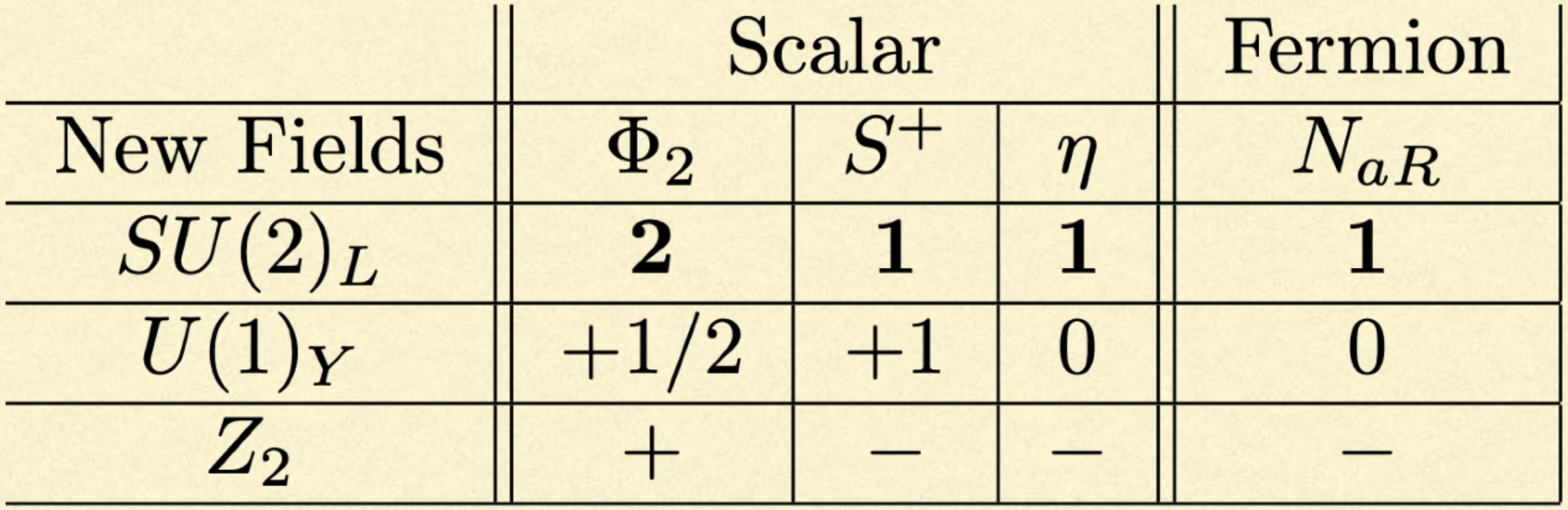
$$\left(\frac{1}{16\pi^2}\right)^n$$

Can be tested

Introduction

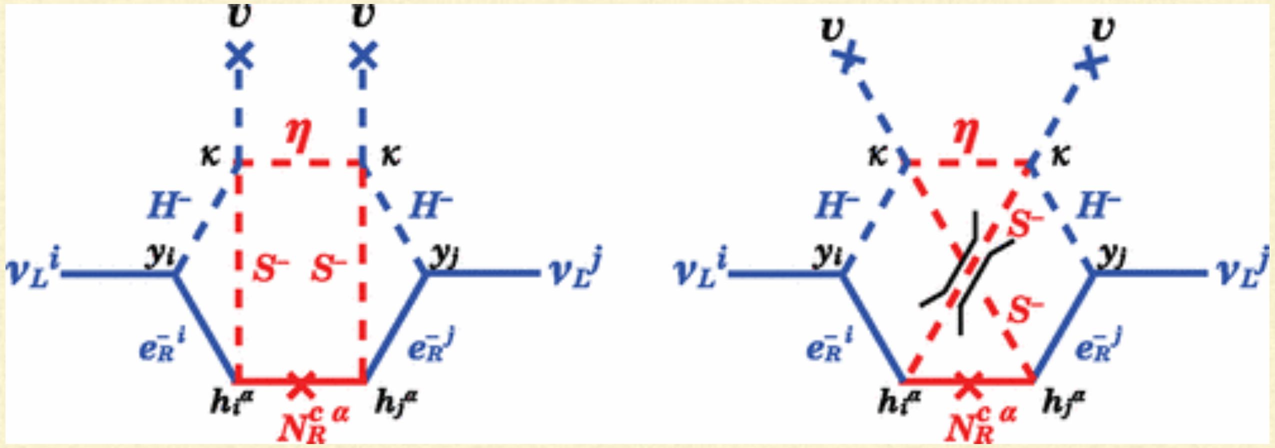
A radiative seesaw model

proposed in M. Aoki, S. Kanemura, O. Seto (2009)



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

$(a = 1{,}2{,}3)$



- ●ν masses：3-loop diagram
- ●DM： Unbroken Z_2 symmetry
- ●BAU： Electroweak baryogenesis by extended Higgs sector

(BAU = Baryon Asymmetry of the Universe)

Introduction

In the previous works, Aoki, Kanemura, Seto (2009)
Aoki, Kanemura, Yagyu (2011)

CP-violation was neglected

for simplicity

→ BAU has not been evaluated.

(They have evaluated ν mass and DM.)

Q. Can this model explain ν mass, DM, and BAU simultaneously?

Our work Aoki, KE, Kanemura (2022) in preparation

Revisit (and extend) the model considering CPV phases.

→ New benchmark scenario

The model

Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Scalar Bosons

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

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

Extension of 2-Higgs doublet model

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

CP-violation

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

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

6 CP-violating couplings

The model

Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Mass of Neutral Higgs Bosons

Higgs basis

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

$$M_{\mathrm{neutral}} \propto \begin{array}{cccc} H_1 & H_2 & H_3 & \\ \left(\begin{matrix} M_{11} \\ \\ \\ \end{matrix}\right. & \begin{matrix} \mathrm{Re}[\lambda_6] \\ M_{22} \\ \\ \end{matrix} & \left.\begin{matrix} -\mathrm{Im}[\lambda_6] \\ \underset{\Phi_2}{\cancel{-\mathrm{Im}[\lambda_5]/2}} \\ M_{33} \end{matrix}\right) & \begin{matrix} H_1 \\ H_2 \\ H_3 \end{matrix} \end{array}$$

In the limit

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

(Higgs couplings coincide with SM ones)

The model

Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Higgs alignment scenario

Simple scenario $\lambda_6 = 0$

Kanemura, Kubota, Yagyu (2020), (2021)
KE, Kanemura, Mura (2021)
Kanemura, Takeuchi, Yagyu (2021)

- H_1, H_2, H_3 are mass eigenstates w/o mixing

(H_1 is 125GeV Higgs boson)

- 3 CPV couplings in the Higgs potential

$\lambda_6 = 0$
(+ Stationary condition)

Φ_2

$\lambda_6 = 0$

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

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

$S^\pm$

The model Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Yukawa interaction

Both Higgs doublets couple with the SM fermions.

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

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

SM Yukawa

Non-diagonal y_2^f ➡ *FCNC!*

To avoid FCNC,

(FCNC = Flavor Changing Neutral Current)

- In AKS(2009): Softly broken Z_2 Glashow, Weinberg (1977)
- **Current Work: Flavor Alignment**

$$y_2^f = \underbrace{\frac{1}{v}\begin{pmatrix} m_{f1} & 0 & 0 \\ 0 & m_{f2} & 0 \\ 0 & 0 & m_{f3} \end{pmatrix}}_{\text{SM Yukawa}} \begin{pmatrix} \zeta_{f1} & 0 & 0 \\ 0 & \zeta_{f2} & 0 \\ 0 & 0 & \zeta_{f3} \end{pmatrix}$$

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

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)

The model

Aoki, Kanemura, Seto (2009); Aoki, KE, Kanemura in preparation

Yukawa interaction

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

$$\frac{1}{2} M_{N^a} \overline{(N_R^a)^c} N_R^a$$

Lepton # violating

$$\mathscr{L}_Y = -(Y_N)_{ai} \overline{(N_R^a)^c} \ell_R^i S^+ + \mathrm{h.c.}$$

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

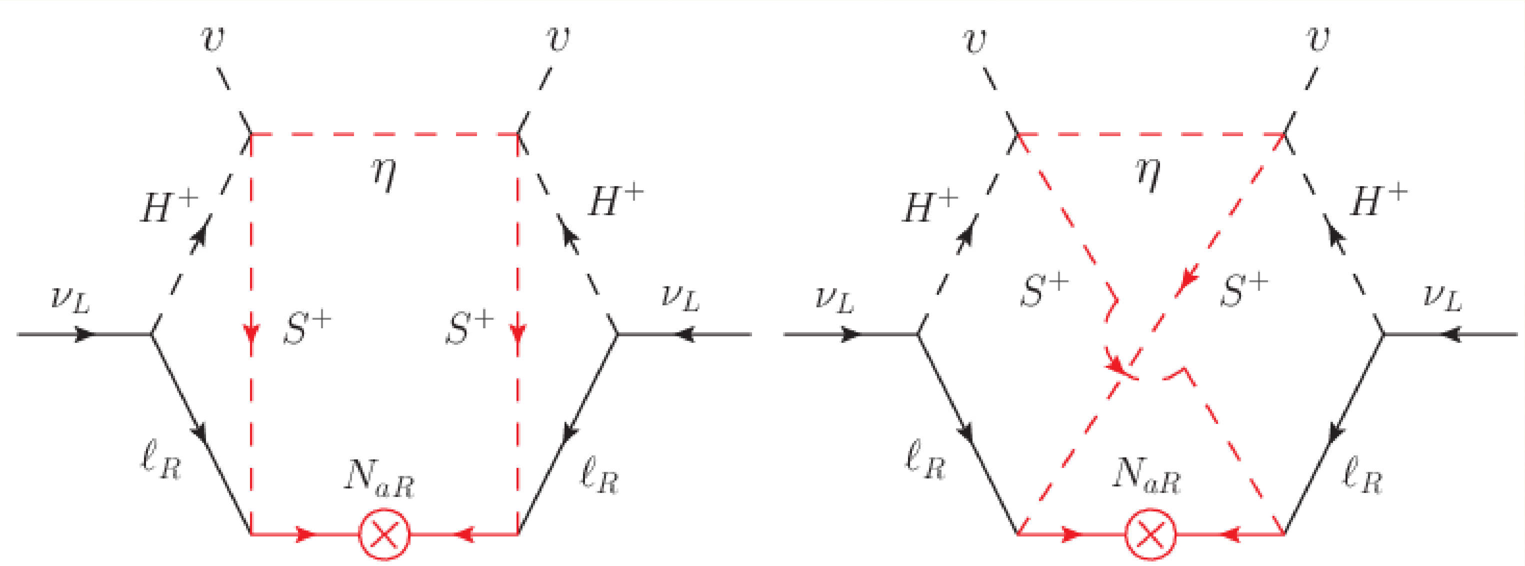
Alignment: $\lambda_6 = 0$ (H_1 is the SM Higgs) & $(y_2^f)_{ij} \propto m_{fi} \zeta_{fi} \delta_{ij}$ (No FCNC)

CP-violation: $\lambda_7, \rho_{12}, \sigma_{12}$ & $\zeta_u, \zeta_d, \zeta_\tau, \zeta_\mu, \zeta_e, (Y_N)_{ai}$

Neutrino masses

🚫 $\overline{L_{iL}}\tilde{\Phi}_1 N_{aR}$ (N_{aR} is Z_2-odd)

Neutrino masses are generated via 3-loop diagrams



$$\kappa\,\tilde{\Phi}_1\Phi_2\,S^-\eta$$

$$(Y_N)_{ai}\,\overline{N^c_{aR}}\,\ell_{iR}\,S^+$$

$$\zeta_e\frac{\sqrt{2}m_{\ell_i}}{v}\,\overline{L_{iL}}\,\Phi_2\,\ell_{iR}$$

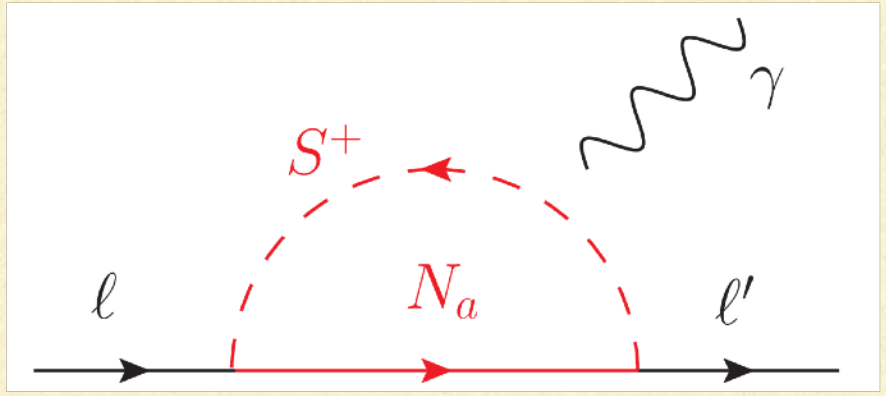
Input parameters

Input parameters in the benchmark scenario

LFV decays (LFV = Lepton Flavor Violating)

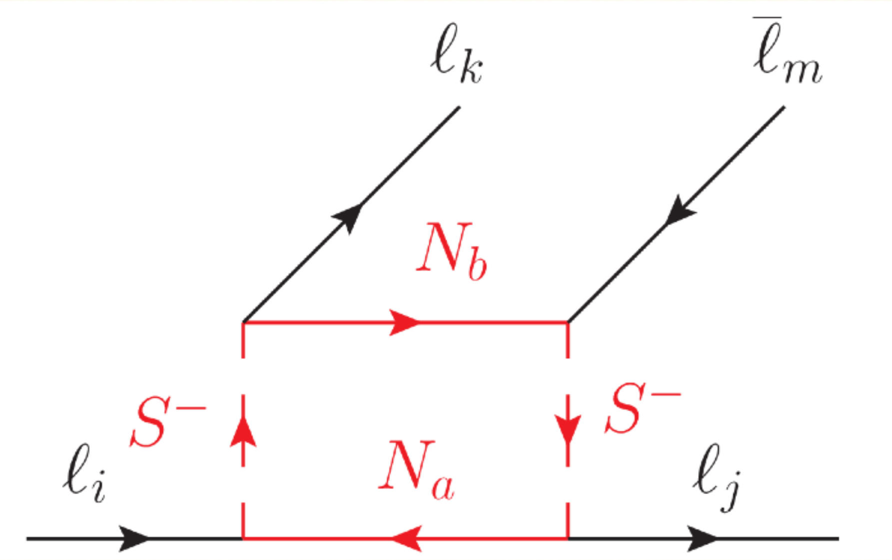
Input parameters in the benchmark scenario

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



Processes	BR	Upper limits
$\mu \to e\gamma$	7.18×10^{-16}	4.2×10^{-13}
$\tau \to e\gamma$	2.37×10^{-12}	3.3×10^{-8}
$\tau \to \mu\gamma$	1.31×10^{-12}	4.4×10^{-8}

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

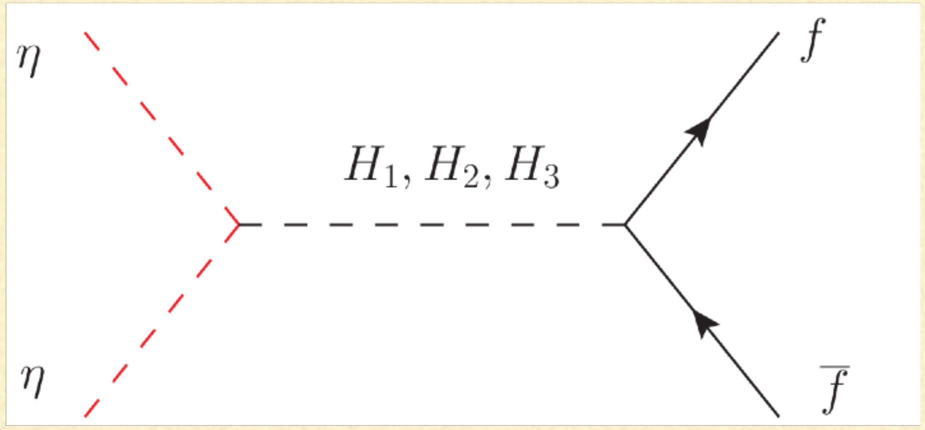


Processes	BR	Upper limits
$\mu \to 3e$	1.35×10^{-15}	1.0×10^{-12}
$\tau \to 3e$	1.68×10^{-11}	2.7×10^{-8}
$\tau \to 3\mu$	5.14×10^{-15}	2.1×10^{-8}
$\tau \to e\mu\bar{e}$	4.11×10^{-10}	1.8×10^{-8}
$\tau \to \mu\mu\bar{e}$	2.60×10^{-13}	1.7×10^{-8}
$\tau \to ee\bar{\mu}$	7.17×10^{-14}	1.5×10^{-8}
$\tau \to e\mu\bar{\mu}$	7.63×10^{-13}	2.7×10^{-8}

Dark matter

DM candidates：real scalar η, Majorana fermion N_a

In the benchmark scenario, DM is η.



$$\frac{\sigma_1}{2}|\Phi_1|^2\eta^2 + \left(\frac{\sigma_{12}}{2}(\Phi_1^\dagger\Phi_2)\eta^2 + \mathrm{h.c.}\right)$$

Input parameters

in the benchmark scenario

Relic abundance

$$\Omega_{\eta 0}h^2 = 0.12$$

Planck (2018) $\Omega_{DM}h^2 = 0.1200 \pm 0.0012$

Direct detection

$$\sigma(\eta N \to \eta N) = 2.3 \times 10^{-48}\ \mathrm{cm}^2$$

XENON1T (2018)
PANDAX-4T (2022)

$$\sigma \lesssim 10^{-47}\ \mathrm{cm}^2$$

Electroweak baryogenesis

Kuzmin, Rubakov, Shaposhnikov (1985)

The Sakharov conditions

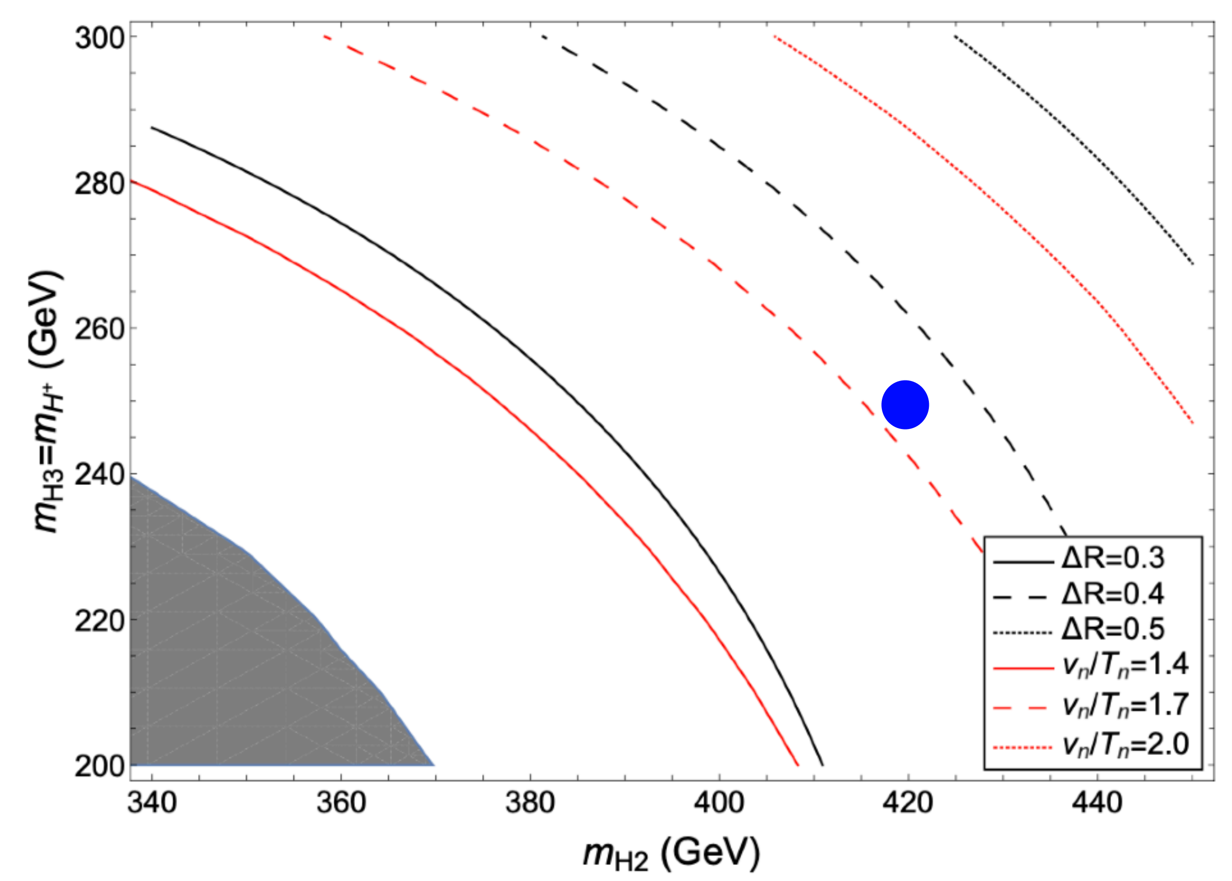
Sakharov (1967)

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)

Aoki, KE, Kanemura, in preparation



Blue point : Benchmark scenario

$$m_{H^\pm} = m_{H_3} = 250\ \mathrm{GeV},$$
$$m_{H_2} = 420\ \mathrm{GeV},\ m_S = 400\ \mathrm{GeV}$$

Sphaleron decoupling condition

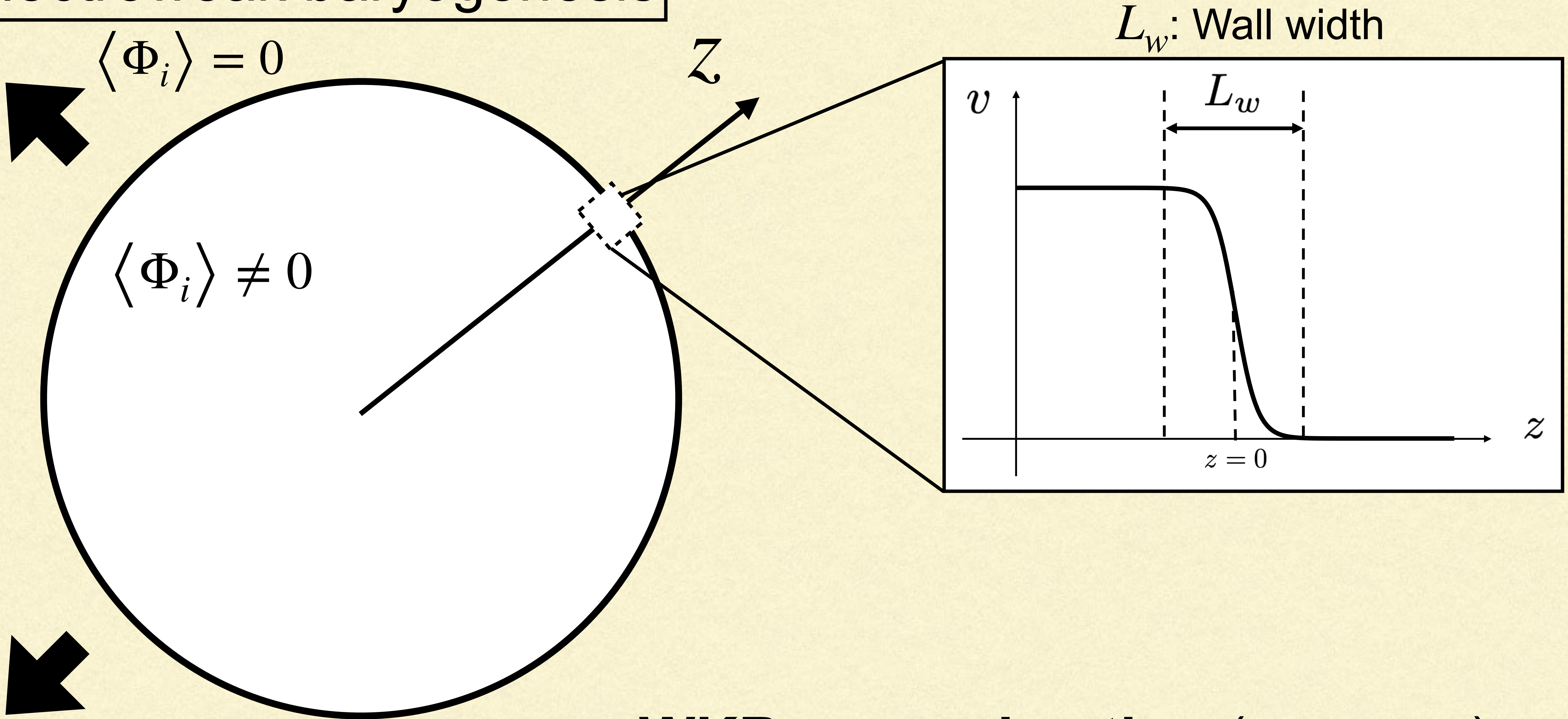
$$v_n/T_n = 1.74$$

Triple Higgs coupling

Kanemura, Okada, Senaha (2005)

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

Electroweak baryogenesis



v_w: wall velocity

$v_w = 0.1$ is assumed

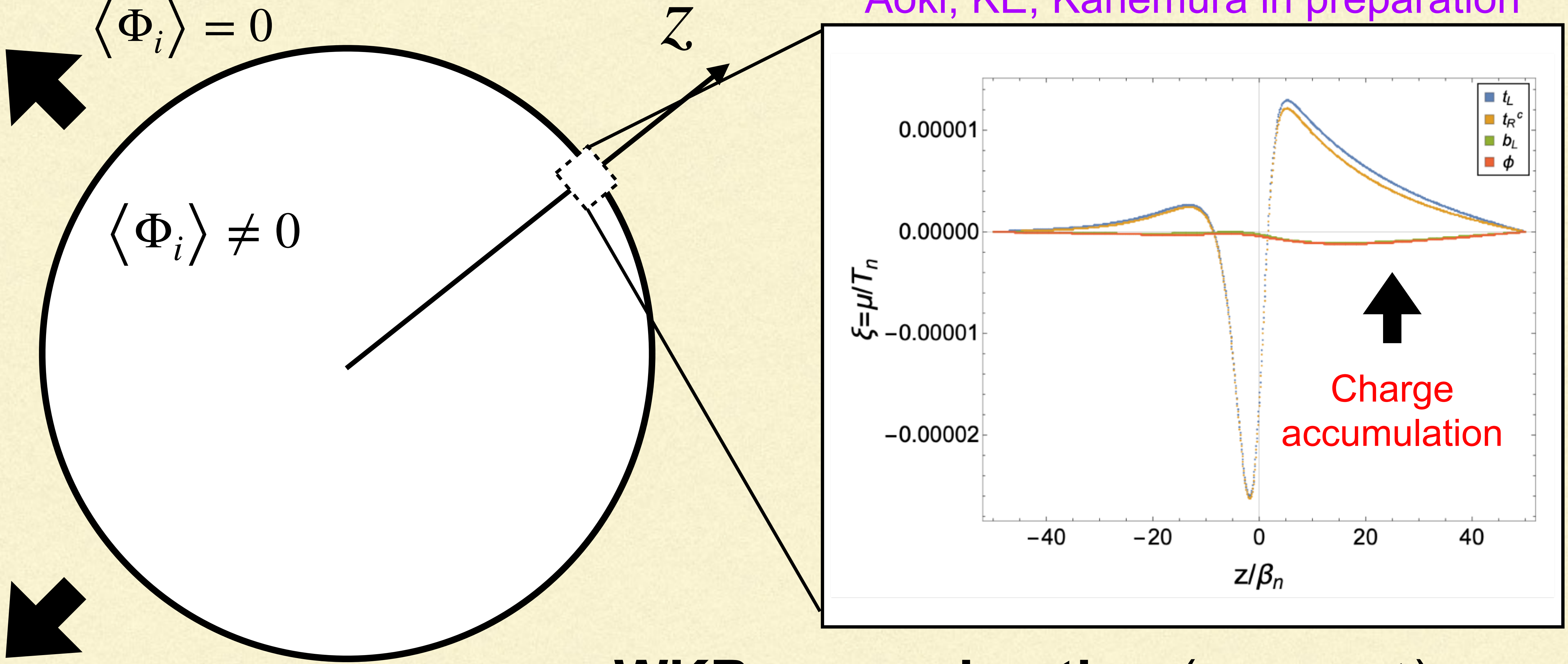
WKB approximation $(L_w T_n \gg 1)$

Joyce, Prokopec, Turok (1995);
Cline, Joyce, Kainulainen (2000); Cline, Kainulainen (2020)

Electroweak baryogenesis

Chemical potential

Aoki, KE, Kanemura in preparation



WKB approximation $(L_w T_n \gg 1)$

Joyce, Prokopec, Turok (1995);
Cline, Joyce, Kainulainen (2000); Cline, Kainulainen (2020)

v_w: wall velocity

$v_w = 0.1$ is assumed

$$\eta_B \simeq \Gamma_{ws} \int_0^\infty \mathrm{d}z \, \mu_{q_L} e^{-kz} = 6.18 \times 10^{-10}$$

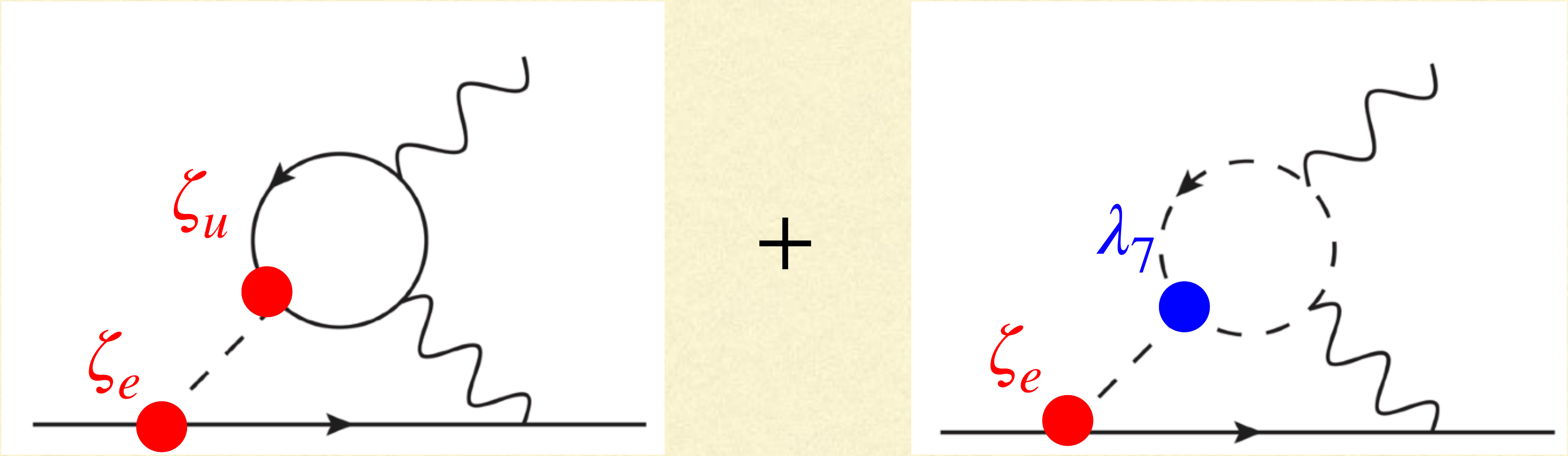
Experimental value **Explained !!!**

BBN) $5.8 \times 10^{-10} \leq \eta_B \leq 6.5 \times 10^{-10}$
CMB) $6.04 \times 10^{-10} \leq \eta_B \leq 6.20 \times 10^{-10}$

electron Electric Dipole Moment (eEDM)

Two kinds of Barr-Zee type diagrams Barr, Zee (1990)

Fermion loop **Scalar loop**



eEDM can be small by **destructive interference**

S. Kanemura, M. Kubota, K. Yagyu, JHEP(2020)

Input parameters
in the benchmark scenario

In our benchmark scenario,

$$|d_e| = 4.5 \times 10^{-30}\ \mathrm{ecm}$$

ACME (2018)

$$|d_e| < 1.0 \times 10^{-29}\ \mathrm{ecm}$$

How to test the benchmark scenario

EDM measurements

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

Flavor experiments

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

Collider experiments

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

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

S. Kanemura, M. Kubota, K. Yagyu, JHEP (2021)

Dark matter direct detection

Observation of gravitational waves

Details of these are currently under investigation.

Summary of this talk

- The SM cannot explain some observed phenomena (tiny ν masses, DM, BAU), therefore, we need physics beyond the SM.

- In the previous work, the authors proposed a model where tiny ν masses, DM, and BAU can be explained simultaneously at TeV-scale. However, they neglected CPV phases for simplicity.

- We have revisited the model and found a new benchmark scenario including CPV phases, where tiny ν masses, dark matter, and BAU can be explained under the constraints from the current experiments. (LFV, EDM, …) .

- This benchmark scenario includes some new particles at a few hundred GeV scale, and they would be testable at various future experiments.

Thank you for listening!