Electroweak Baryogenesis in 2HDM without EDM cancellation

大阪大学
THE UNIVERSITY OF OSAKA

Shinya Kanemura

U. Osaka
Dr. Wani

M. Endo (KEK), M. Aiko (Miyakonojo), S. K. (U. Osaka), Y. Mura (KEK)

JHEP 07 (2025) 236

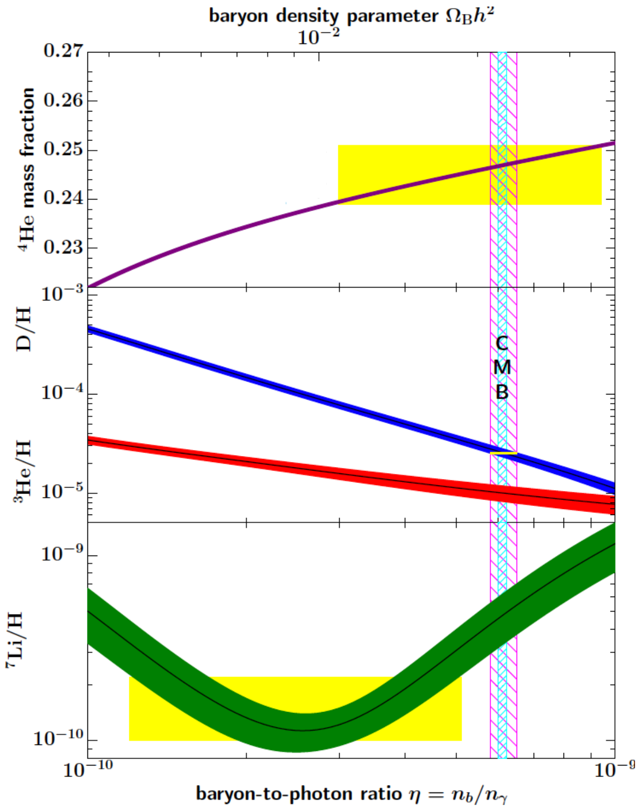
Sep 23, 2025, Scalars 2025: Higgs bosons and cosmology, Warsaw

This talk

- Introduction
  - EW Baryogenesis
  - A viable Model (aligned 2HDM) with EDM cancellation
- Alternative Scenario (Minimal 2HDM scenario for EWBG)
  - Set up of the model
  - EWBG without EDM cancellation
  - Results
- Summary

Introduction

BAU and Baryogenesis



Particle Data Group

Baryon Number
of the Universe

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} (= (5-7) \times 10^{-10})$$

Baryogenesis

What is the mechanism to generate the baryon asymmetric Universe from the symmetric one?

Sakharov's
Condition

Sakharov 1967

1. $\Delta B \neq 0$
2. C and CP violation
3. Departure from thermal equilibrium

SM cannot satisfy these conditions

EW Baryogenesis

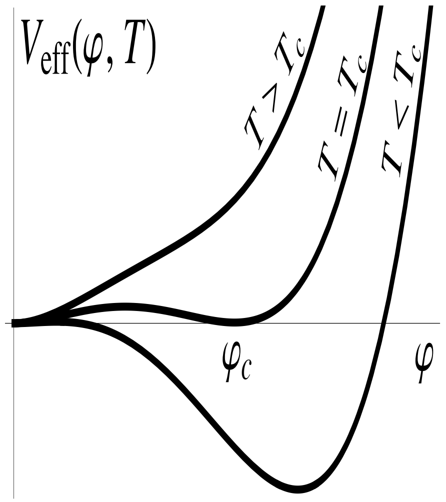
Sakharov Conditions

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 : KM phase not enough, EWPT not 1st order … EWBG not viable

Extension of the Higgs models: new CPV and EWPT being 1st OPT …. EWBG possible!

Strongly First order PT

In the broken phase, sphaleron should quickly decouple to avoid wash out

$$\boxed{\frac{\varphi_c}{T_c} \gtrsim 1}$$

In one-step EWPT scenario, non-decoupling quantum effect of additional bosons make it possible

2HDM etc

EDM in 2HDM

- **2HDM with softly broken Z2 symmetry**

Fromme, Huber and Seniuchi (2006);
Dorsch et al. (2017);Basler et al. (2021), and more

  - Suppressed FCNC
  - One CP phase
  - CP violation for observed BAU → $|d_e| = O(10^{-28})\ e$ cm

Difficult

Observation
$|d_e| < 4.1\times10^{-30}\ e$ cm
Roussy et al. 2022

- **General 2HDM**

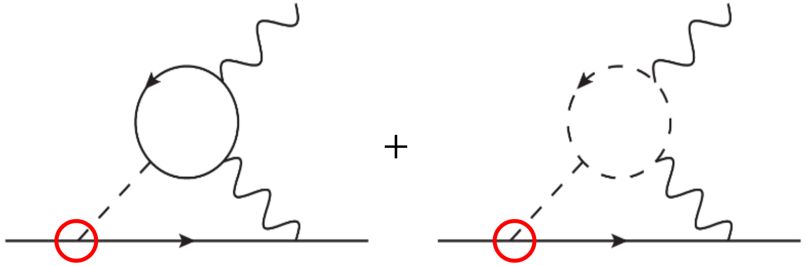
Viable EWBG as the aligned 2HDM, but …

Fuyuto, Hou and Senaha (2019); SK Kubota and Yagyu (2020); Enomoto, SK and Mura (2021), (2022); Idegawa and Senaha (2023); and more

  - Assuming the Yukawa alignment for avoiding FCNC
  - Multiple CP phases
  - EDM depends on the parameters not related to BAU.

EDM cancellation

$d_e \simeq$



(a) Fermion-loop. (b) Higgs boson-loop.

EDM in 2HDM

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EDM cancellation

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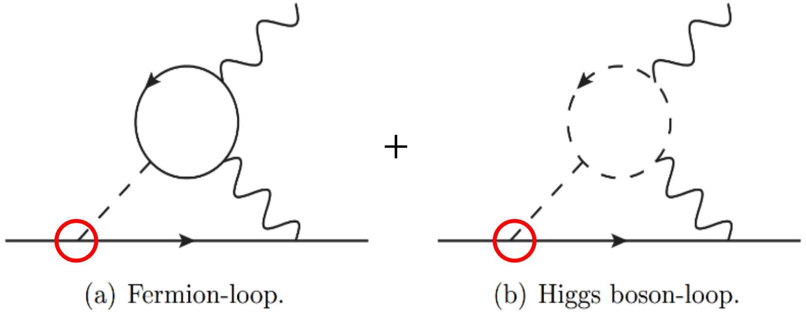

(a) Fermion-loop. + (b) Higgs boson-loop.

Is such cancellation really neessary?

SK, M. Kubota, K. Yagyu (2020)

K. Enomoto, SK, Y. Mura (2021)

Aligned 2HDM (a viable scenario)

General Higgs potential in the 2HDM

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

Higgs basis

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

Davidson and Haber (2005)

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

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

$$y_f^2 = \zeta_f y_f^1 \quad (f = u, d, e)$$

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

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

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

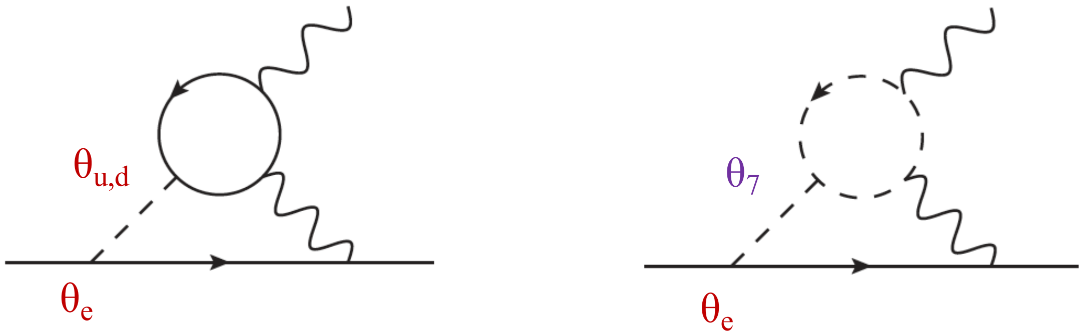
T violation if $\neq 0$ ⇄ CPV (CPT theorem)

$$|d_e| < 4.1\times10^{-30}\ e\ \mathrm{cm}$$

Roussy *et al.* arXiv:2212.11841

Barr-Zee type diagrams

$$d_e \simeq$$



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

10^{-29} e cm

when $\zeta_e = \zeta_u = \zeta_d$

Aligned 2HDM

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

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

eEDM data can be satisfied by destructive interference (cancellation) among multiple CPV phases

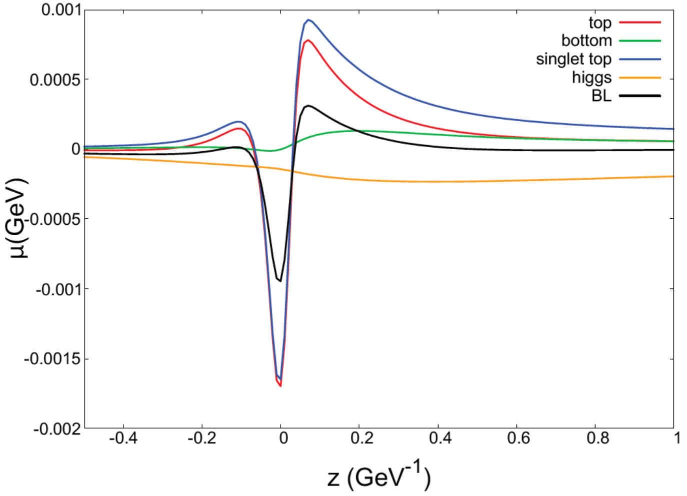
$$d_f = d_f(\mathrm{fermion}) + d_f(\mathrm{Higgs}) + d_f(\mathrm{gauge})$$

Fuyuto, Hou and Senaha (2019); SK Kubota and Yagyu (2020);
Enomoto, SK and Mura (2021), (2022); Idegawa and Senaha (2023); and more

Evaluation of BAU

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, Joyce, Kainulainen

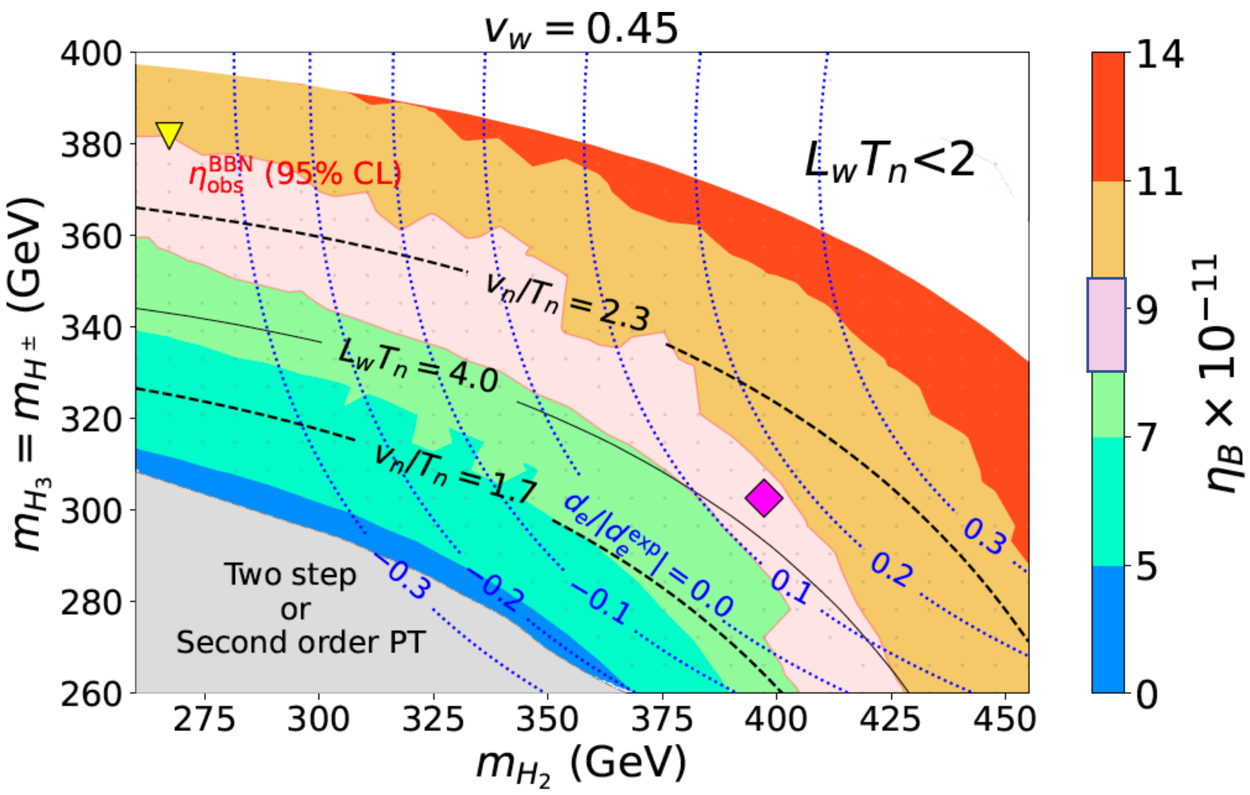
L_w : wall width

T_n : nucleation temp

$$M = 30\ \text{GeV},\quad \lambda_2 = 0.1,\quad |\lambda_7| = 0.8,\quad \theta_7 = -0.9,$$

$$|\zeta_u| = |\zeta_d| = |\zeta_e| = 0.18,\quad \theta_u = \theta_d = -2.7,\quad \delta_e = -0.04$$

K. Enomoto, SK, Y. Mura, 2022

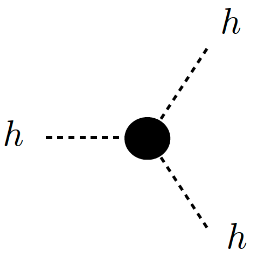


BAU data reproduced (pink region)

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

$$\boxed{s = 0.74 n_\gamma}$$

Test of strongly 1st OPT

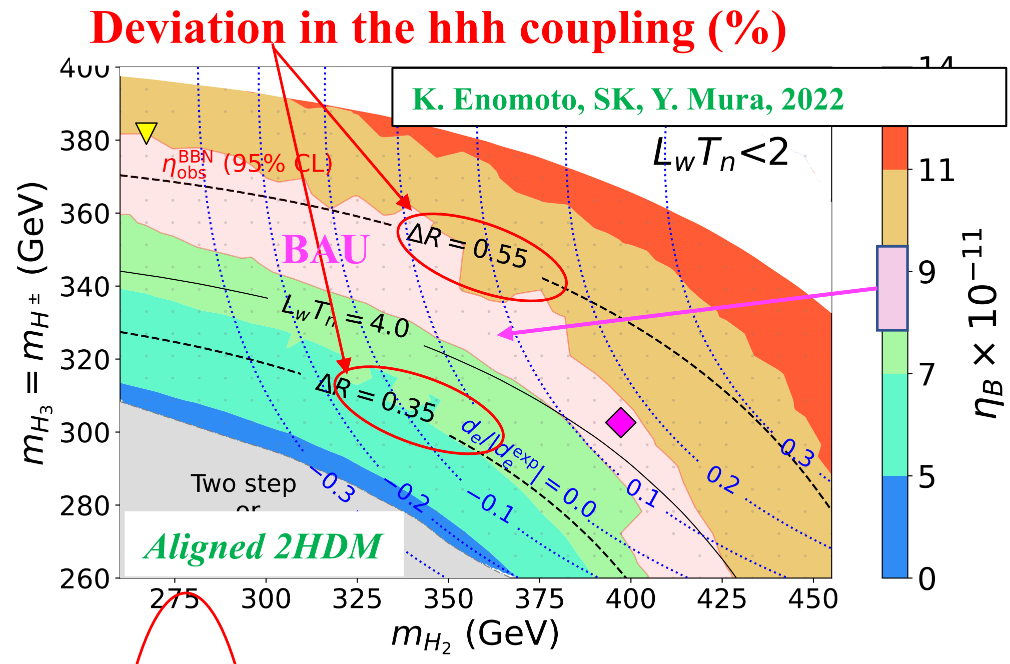


Example → Aligned 2HDM

Stronlgly 1st OPT

→ A large deviation in the hhh coupling

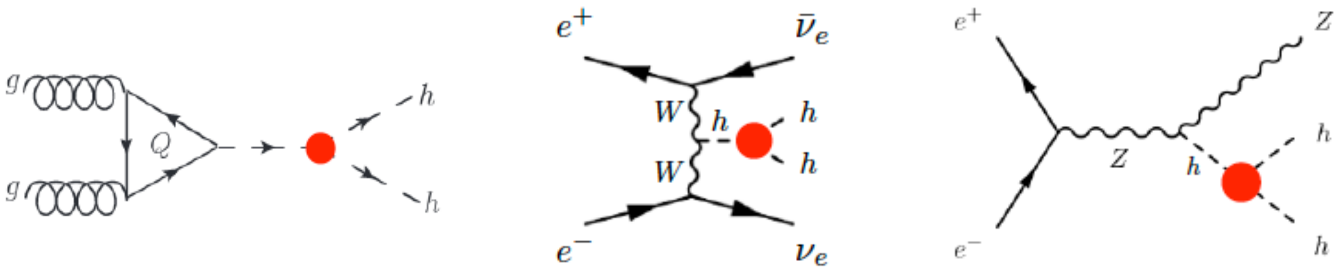
SK, Y. Okada, E. Senaha, 2005

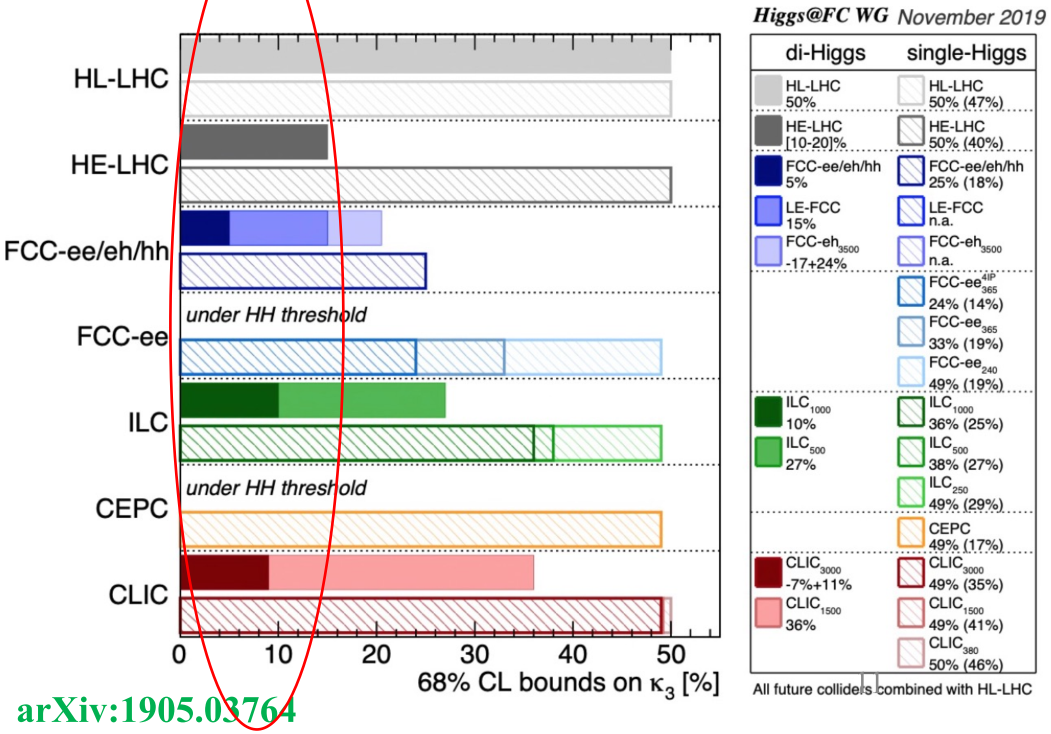


Deviation in the hhh coupling (%)

K. Enomoto, SK, Y. Mura, 2022

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



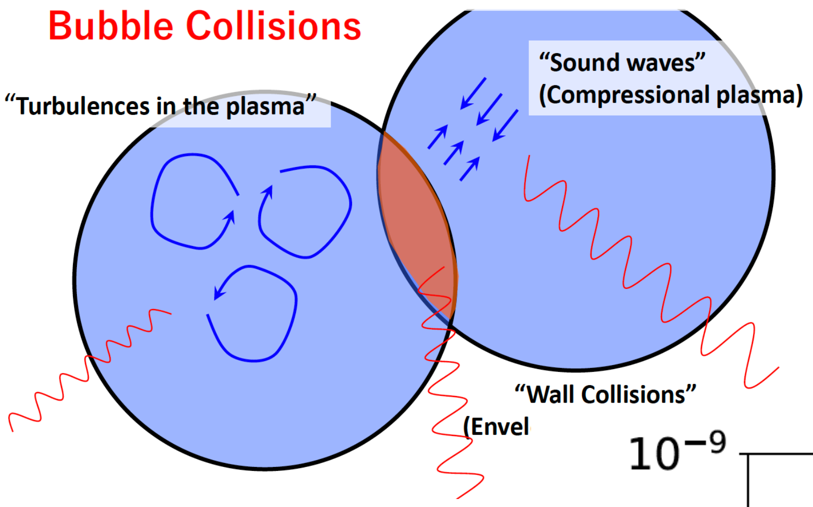


arXiv:1905.03764

EW Baryogenesis can be tested by the hhh measurement

Test of strongly 1st OPT

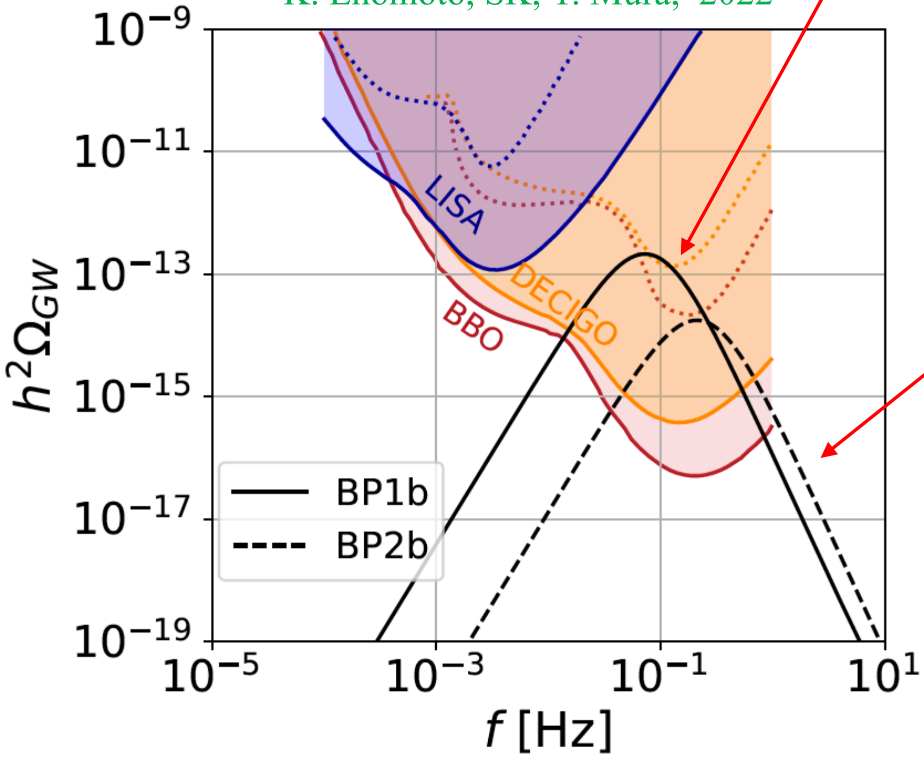
Example
Aligned 2HDM



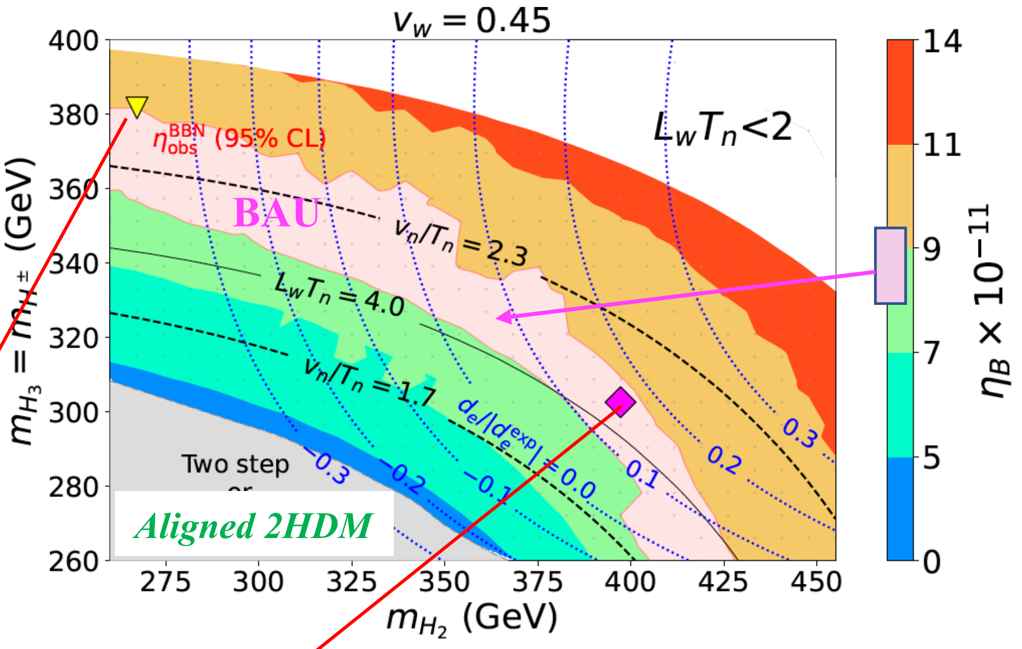
GWs for benchmark points of BAU

They may be tested
by future GW experiments

K. Enomoto, SK, Y. Mura, 2022



K. Enomoto, SK, Y. Mura, 2022

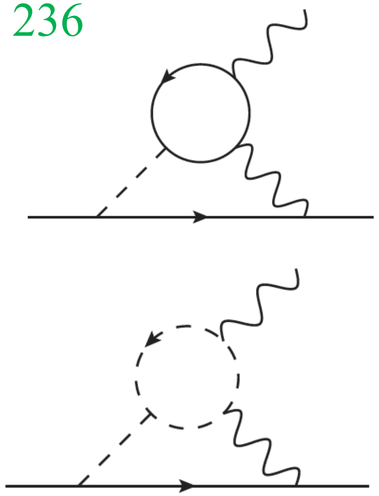


Dotted curves: Sensitivity Curve
M. Breitbach et al., arXiv: 1811.11175

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

Alternative scenario for EWBG in 2HDM without EDM cancellation?

M. Endo, M. Aiko, S.K., Y. Mura, JHEP 07 (2025) 236



- This old scenario (aligned 2HDM) relies on the cancellation of Barr-Zee-type EDM diagrams due to multiple CPV phases

- Barr-Zee type diagrams are given by light fermion couplings with Higgs bosons. If we just switch off them, EDMs via the BZ diagrams vanish, while the CPV phase in top Yukawa can generate BAU.

- Still, the CPV phase of the top coupling for EWBG can lead the top-quark (C)EDM, which causes n, p, e EDMs.

- We examine whether this scenario works well or not under all theoretical and experimental constraints.

- The scenario is viable under current experimental bounds, and also testable at future EDM experiments as well as other experiments.

Minimal 2HDM Scenario for EWBG

M. Endo, M. Aiko, S.K., Y. Mura, JHEP 07 (2025) 236

Starting from the general 2HDM

- **Most general potential**

Higgs basis

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

Davidson and Haber (2005)

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

- **Most general Yukawa sector**

$$\mathcal{L}_Y = -\sum_{k=1,2} \left(\overline{Q_L} Y_{k,u}^\dagger \widetilde{\Phi}_k u_R + \overline{Q_L} Y_{k,d} \Phi_k d_R + \overline{L_L} Y_{k,l} \Phi_k e_R + h.c.\right)$$

$$Y_{1,u} = diag(y_u, y_c, y_t) \qquad Y_{1,d} = diag(y_d, y_s, y_b) \qquad Y_{1,l} = diag(y_e, y_\mu, y_\tau)$$

- **Y_2 is general complex matrix**

e.g.) Up type

$$Y_{2,u} = \begin{pmatrix} \rho_{uu} & \rho_{cu} & \rho_{tu} \\ \rho_{uc} & \rho_{cc} & \rho_{tc} \\ \rho_{ut} & \rho_{ct} & \rho_{tt} \end{pmatrix}$$

FCNC couplings are bounded
to satisfy experimental constraints.

General two Higgs doublet model

- **Stationary conditions and mass spectra**

$$\frac{\partial V}{\partial h_i} = 0 \;\Leftrightarrow\; \mu_1^2 = \frac{1}{2}\lambda_1 v^2,\; \mu_3^2 = \frac{1}{2}\lambda_6 v^2$$

$$\frac{\partial^2 V}{\partial h_i \partial h_j} = \mathcal{M}_{ij}^n = \begin{pmatrix} \lambda_1 v^2 & \mathrm{Re}[\lambda_6]v^2 & -\mathrm{Im}[\lambda_6]v^2 \\ \mathrm{Re}[\lambda_6]v^2 & M^2 + \frac{1}{2}(\lambda_3+\lambda_4+\lambda_5)v^2 & -\frac{1}{2}\mathrm{Im}[\lambda_5] \\ -\mathrm{Im}[\lambda_6]v^2 & -\frac{1}{2}\mathrm{Im}[\lambda_5] & M^2 + \frac{1}{2}(\lambda_3+\lambda_4-\lambda_5)v^2 \end{pmatrix}$$

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

- **Mass eigenstate for neutral scalar bosons**

125 GeV Higgs

Orthogonal matrix R $\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$, $\quad R^T \mathcal{M}^n R = \mathrm{diag}(m_{H_1}, m_{H_2}, m_{H_3})$

- **CPV rephasing invariants in the model** $\boldsymbol{\Phi}_2 \rightarrow e^{i\theta}\boldsymbol{\Phi}_2$

Potential: $\mathrm{Im}[\lambda_5^*\lambda_6^2]$, $\mathrm{Im}[\lambda_5^*\lambda_7^2]$, $\mathrm{Im}[\lambda_6^*\lambda_7]$

Yukawa: $\mathrm{Im}[\lambda_5\rho_{tt}^2]$, $\mathrm{Im}[\lambda_6\rho_{tt}]$, $\mathrm{Im}[\lambda_7\rho_{tt}]$ (and other ρ_{ij} related invariants)

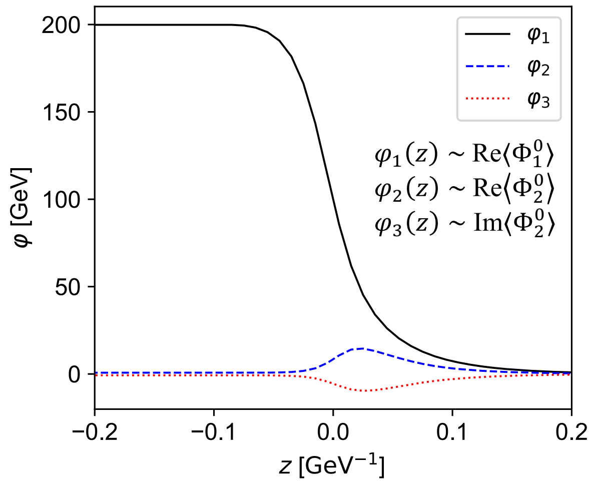
Our scenario

- **Discovered 125GeV Higgs is SM like**

ATLAS, Nature (2022);
CMS, Nature (2022);

e.g.) H_1ZZ coupling $\kappa_Z \simeq 1$ ➡ $|\lambda_6| \ll 1$

➡ $\mathrm{Im}[\lambda_5^*\lambda_7^2]$, $\mathrm{Im}[\lambda_5\rho_{tt}^2]$, $\mathrm{Im}[\lambda_7\rho_{tt}]$.



- **From Yukawa interaction of top quark, we get**

$$m_t^2\theta_t' \sim \frac{y_t|\rho_{tt}|}{2}\{(\varphi_1\varphi_2' - \varphi_2\varphi_1')\sin(\arg[\rho_{tt}]) + (\varphi_3\varphi_1' - \varphi_1\varphi_3')\cos(\arg[\rho_{tt}])\}$$

Top transport scenario

- **For sufficient BAU, $\mathrm{Im}[\lambda_7\rho_{tt}]$ is necessary.**
  - If $\lambda_6 \simeq \lambda_7 \simeq 0$, tree level potential approximately has $\mathbb{Z}_2$ symmetry ($\boldsymbol{\Phi_2} \to -\boldsymbol{\Phi_2}$).
    ⇨ $\varphi_2, \varphi_3 \ll 1$

- **See essential effects: we consider Minimal Setup for EWBG in 2HDM**

$\rho_{ij} = 0$ (except for ρ_{tt}) and $\lambda_4 = \lambda_5 = \lambda_6 = 0$ ($\lambda_4 = \lambda_5$ is for T parameter)

➡ $m_{H_2} = m_{H_3} = m_{H^\pm} \equiv m_\Phi$ One available CP phase: $\arg[\lambda_7\rho_{tt}]$

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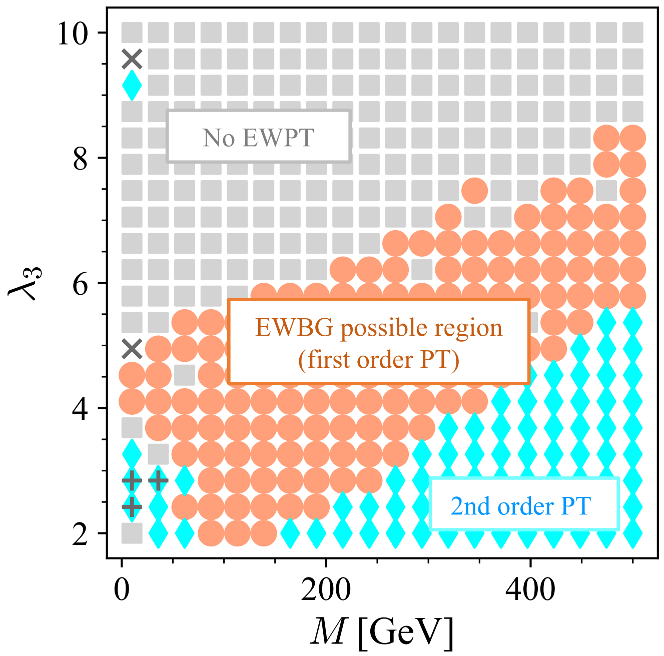
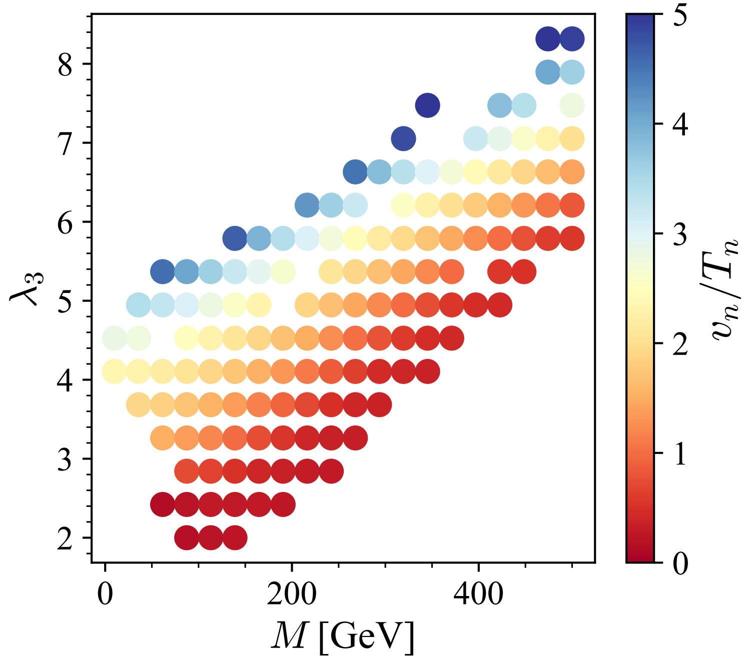
Electroweak phase transition

(Used Cosmotransitions)

Wainwright (2011)

- Several fates of the vacuum





- For successful EWBG, at least,
  - O(1) large λ_3 coupling
  - Satisfying $v_n/T_n > 1$

are needed.

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

and

$$m_{H_2} = m_{H_3} = m_{H^\pm}$$

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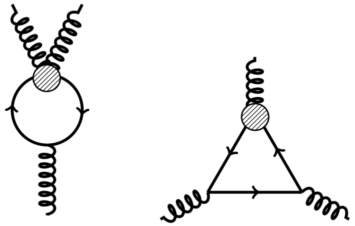
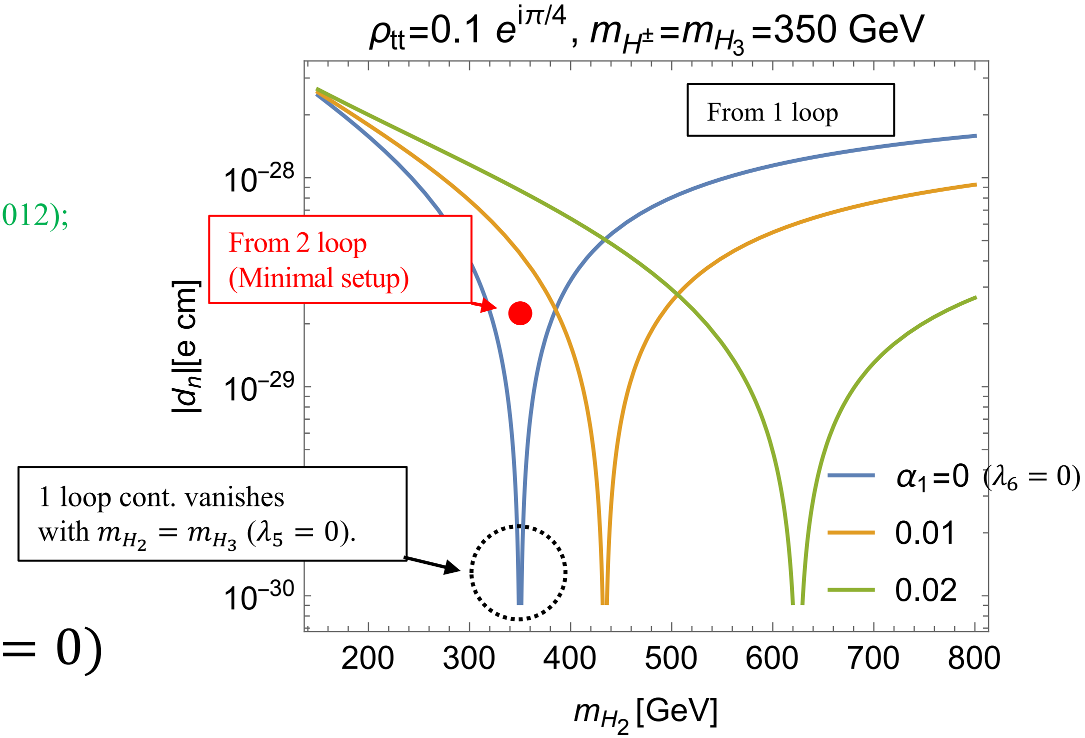
EDMs in the minimal setup

- Top chromo EDM induces Weinberg op. and light fermion EDMs by RGE running.



Kamenik et al. (2012);
Hisano, Tsumura and Yang (2012);
and more works



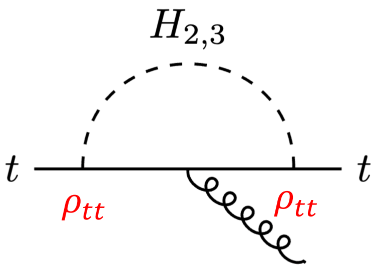
From 1 loop

From 2 loop
(Minimal setup)

1 loop cont. vanishes
with $m_{H_2} = m_{H_3}$ ($\lambda_5 = 0$).

- At 1 loop level

e.g.)



$\propto Im[\lambda_5\rho_{tt}^2]$ (= 0)

- With the minimal setup, 2 loop diagrams are leading.

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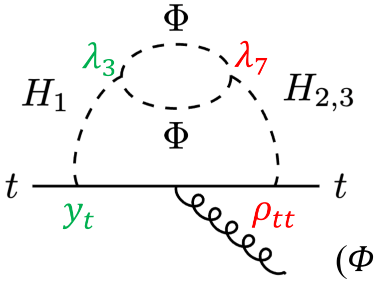
JHEP 07 (2025) 236

e.g.)



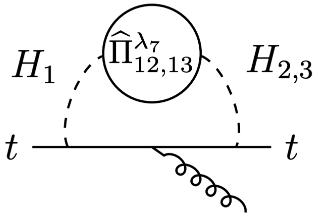
($\Phi = H_2, H_3, H^\pm$)

$\propto Im[\lambda_7\rho_{tt}]$

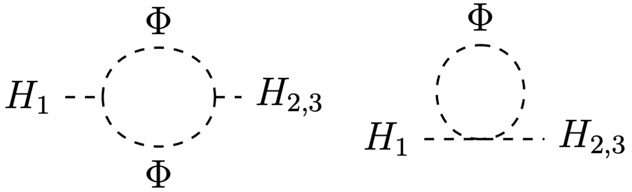
At the red point,
$\lambda_7 = e^{i\pi/4}, -\mu_2^2 = 30^2\ GeV^2$ are taken.

Renormalization

- UV divergence in mixing-self-energy diagrams



$\Pi^{\lambda_7}_{12,13} =$



- Effective potential renormalization

$$\left.\frac{\partial V}{\partial \varphi_i}\right|_{\varphi=v_{EW}} = 0, \quad \left.\frac{\partial^2 V}{\partial \varphi_i \partial \varphi_j}\right|_{\varphi=v_{EW}} = \mathcal{M}_{ij} \quad \Rightarrow \quad \begin{array}{l} \Gamma_i^{(1)}(p^2=0) + \delta\Gamma_i^{(1)} = 0 \\ \Gamma_{ij}^{(2)}(p^2=0) + \delta\Gamma_{ij}^{(2)} = 0 \end{array}$$

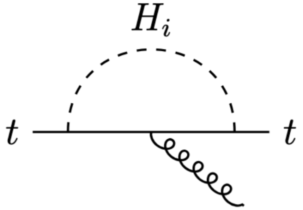
- Other renormalization schemes?

e.g.) $\overline{\text{MS}}$ scheme $\quad d_t^{\overline{MS}} = d_t^{EP} + \Delta d_t$

- Scheme conversion $\quad \lambda_6^{\overline{MS}} = \lambda_6^{EP} + \Delta\lambda_6^{EP}$

$\lambda_6^{EP} = 0$ does not mean $\lambda_6^{\overline{MS}} = 0$.

$$d_t^{\overline{MS}} = d_t^{EP} + \Delta d_t \underbrace{- \Delta d_t}_{\text{from one-loop}} + O(\hbar^3)$$



Other scheme (MS bar)

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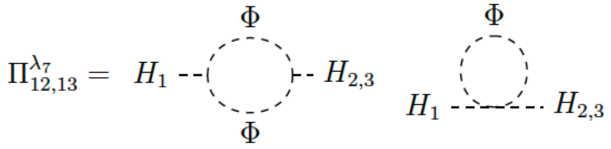
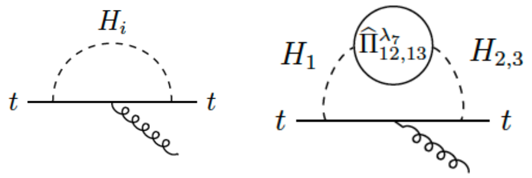


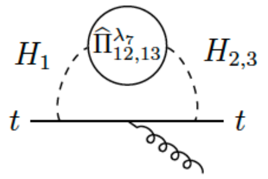
$$\boxed{\lambda_6^{\overline{\rm MS}} = \lambda_6 - \frac{3}{16\pi^2}\lambda_3\lambda_7 \log\frac{\mu^2}{m_\Phi^2} + \dots \Big|_{\rm EP}}$$

$\lambda_6^{EP} = 0$ does not mean $\lambda_6^{\overline{MS}} = 0$.

$$\tilde{d}_t^{(1),\overline{\rm MS}} + \tilde{d}_t^{(2),\overline{\rm MS}} = \tilde{d}_t^{(2)} + \mathcal{O}(\hbar^3)\Big|_{\rm EP}$$



MS bar



EP scheme

In the on-shell scheme, we also confirmed the similar relation

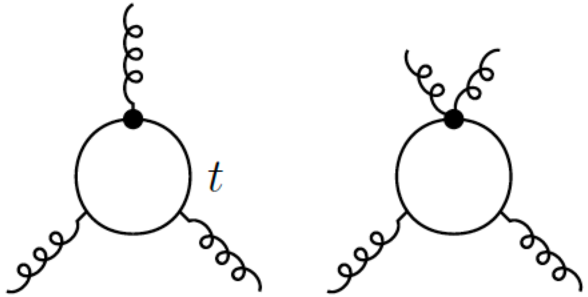
$$\tilde{d}_t^{(2),\overline{\rm MS}} = \tilde{d}_t^{(2)} + \Delta\tilde{d}_t^{(2),\overline{\rm MS}},$$

$$\Delta\tilde{d}_t^{(2),\overline{\rm MS}} = \frac{{\rm Im}[\lambda_7\rho_{tt}]}{\sqrt{2}}\frac{3\lambda_3 v}{(16\pi^2)^2}\frac{2m_t^2}{m_\Phi^2 - m_{H_1}^2}\Big(C_{11}[\Phi,t,t] - C_{11}[H_1,t,t]\Big)\log\frac{\mu^2}{m_\Phi^2}\Big|_{\overline{\rm MS}}$$

$$\tilde{d}_t^{(1),\overline{\rm MS}} = \frac{{\rm Im}[\lambda_6\rho_{tt}]}{\sqrt{2}}\frac{v}{16\pi^2}\frac{2m_t^2}{m_\Phi^2 - m_{H_1}^2}\Big(C_{11}[\Phi,t,t] - C_{11}[H_1,t,t]\Big)\Big|_{\overline{\rm MS}}$$

e, n, p EDMs from top (C)EDM from $\mathrm{Im}[\lambda_7 \rho_{tt}]$

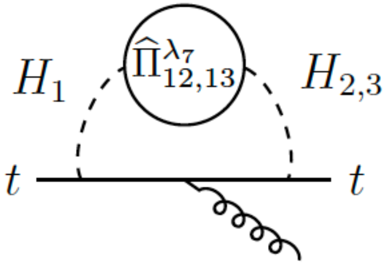
$$\mathcal{L}_{\rm CPV} = -\frac{1}{2} d_\psi \overline{\psi} \sigma_{\mu\nu} i\gamma^5 \psi F^{\mu\nu} - \frac{1}{2} g_S \tilde{d}_q \overline{q} \sigma_{\mu\nu} i\gamma^5 T^a q G^{a\mu\nu} + \frac{1}{3} w f_{abc} G^a_{\mu\nu} \tilde{G}^{b\nu\rho} G^{c\mu}_{\rho},$$



Induced Weinberg operator and EDMs

$$\delta w^{(t)}/g_S = \frac{g_S^2}{32\pi^2} \frac{\tilde{d}_t}{m_t}$$

$$\begin{aligned} d_u &= 1.8 \times 10^{-9}\ e\ \tilde{d}_t, \quad d_d = -2.0 \times 10^{-9}\ e\ \tilde{d}_t, \\ \tilde{d}_u &= -8.0 \times 10^{-9}\ \tilde{d}_t, \quad \tilde{d}_d = -1.7 \times 10^{-8}\ \tilde{d}_t, \\ w &= -1.4 \times 10^{-5}\ \mathrm{GeV}^{-1}\ \tilde{d}_t, \end{aligned}$$



hadronization scale $\mu_H = 2$ GeV

QCD sum rule

$$\begin{aligned} d_n &= 0.73 d_d - 0.18 d_u + e(0.20\tilde{d}_d + 0.10\tilde{d}_u) + 23 \times 10^{-3}\ \mathrm{GeV}\ ew, \\ d_p &= 0.73 d_u - 0.18 d_d - e(0.40\tilde{d}_u + 0.049\tilde{d}_d) - 33 \times 10^{-3}\ \mathrm{GeV}\ ew, \end{aligned}$$

Experimental Bounds on Electric dipole moments (EDMs)

Current bounds

• Electron EDM	$\lvert d_e \rvert < 4.1\times10^{-30}\ e\ \mathrm{cm}$	JILA, Science (2023)
• Neutron EDM	$\lvert d_n \rvert < 1.8\times10^{-26}\ e\ \mathrm{cm}$	Abel et al. PRL (2020)
• Proton EDM	$\lvert d_p \rvert < 2.1\times10^{-25}\ e\ \mathrm{cm}$	Sahoo, PRD (2017)

Expected sensitivities in the future

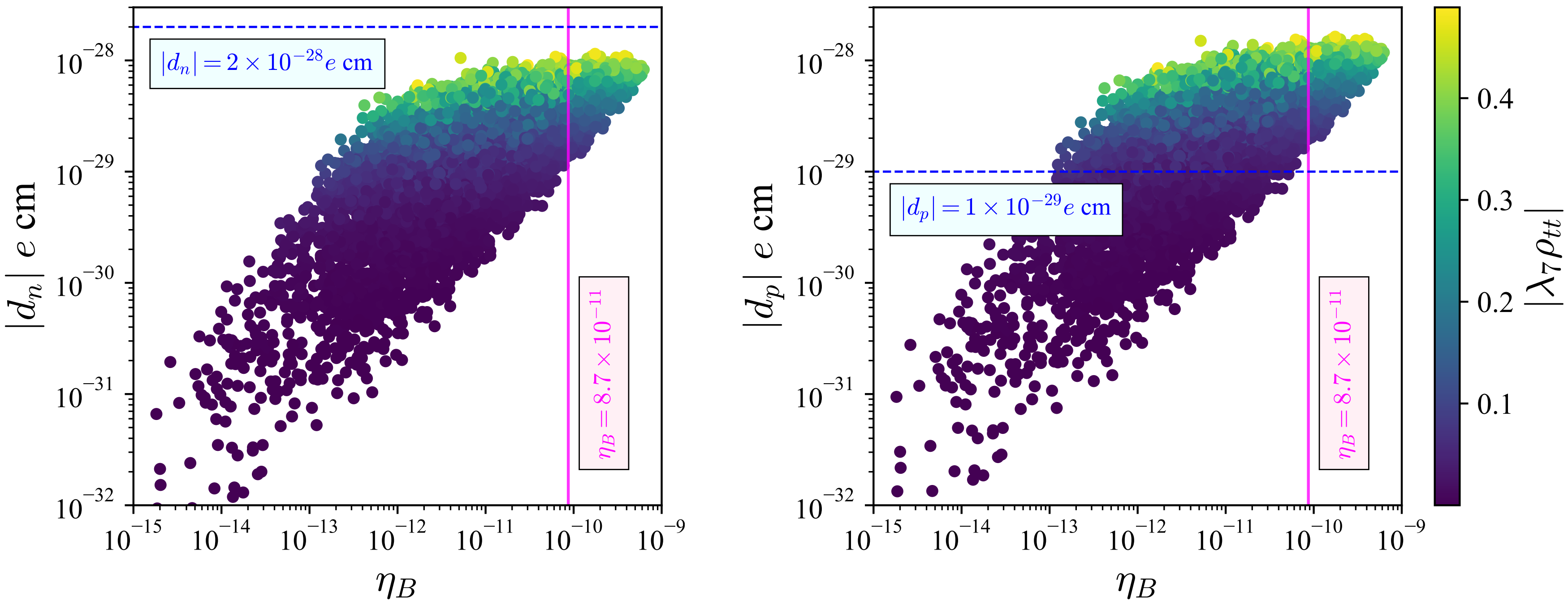
$\lvert d_e \rvert \sim 10^{-33}\ e\ \mathrm{cm}$	Vutha et al. (2018) Ardu et al. (2024)
$\lvert d_n \rvert \sim 10^{-28}\ e\ \mathrm{cm}$	nEDM (2019)
$\lvert d_p \rvert \sim 10^{-29}\ e\ \mathrm{cm}$	Alarcon, et al. (2022)

Correlation between EDMs and BAU

- **Scanning parameter space**

$$m_\Phi = [200{,}500]\ \mathrm{GeV}, \mu_2^2 = \left[-m_\Phi^2, 0\right], |\rho_{tt}| = [0{,}0.5]$$
$$|\lambda_7| = [0{,}1], \lambda_2 = [0{,}1], \arg[\lambda_7\rho_{tt}] = -\pi/2\,, v_w = \left[0.1, 1/\sqrt{3}\right]$$

- **Neutron and proton EDMs**



$|d_n| < 1.8\times10^{-26}$ e cm (current)

$|d_p| < 2.1\times10^{-25}$ e cm (current)

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Correlation between EDMs and BAU

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$$m_\Phi = [200{,}500]\,\mathrm{GeV}, \mu_2^2 = \left[-m_\Phi^2, 0\right], |\rho_{tt}| = [0{,}0.5]$$
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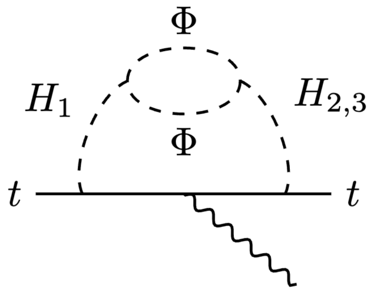
- **Electron EDM induced by top EDM**

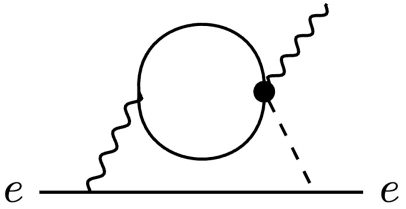
Cirigliano et al. (2016), Fuyuto and Ramsey-Musolf (2017)

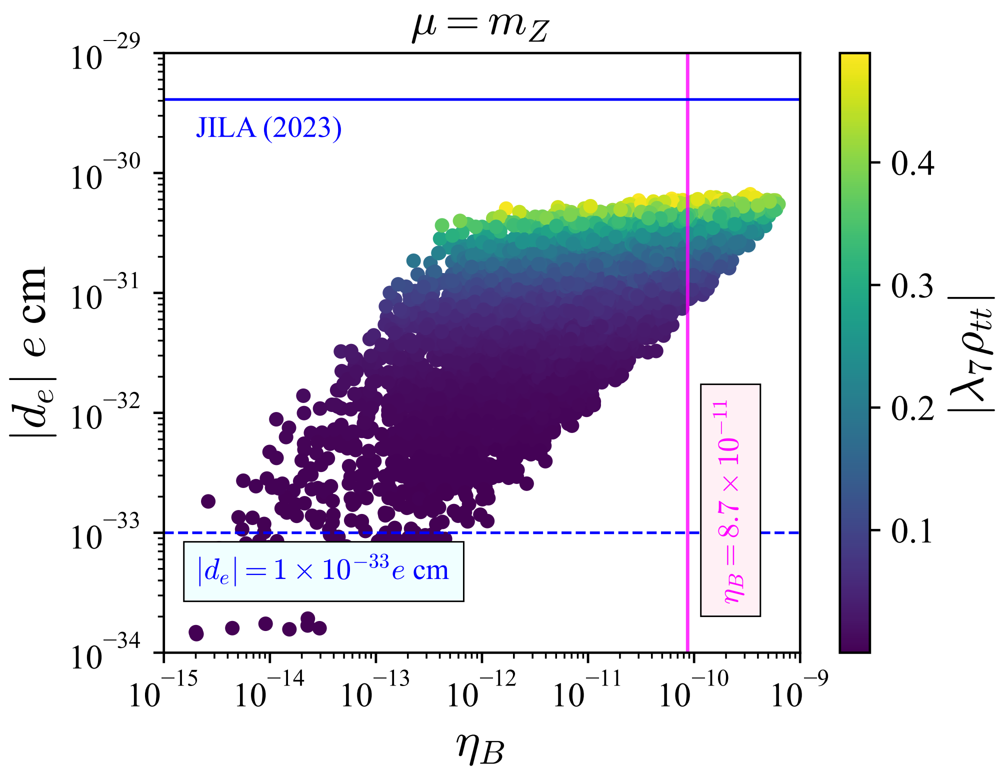
e.g.)

- Dipole operators for top are induced below $\Lambda \simeq m_\Phi$.



- Matching to d_e at $\mu \sim m_Z$, where top, Higgs, W and Z are integrated out.





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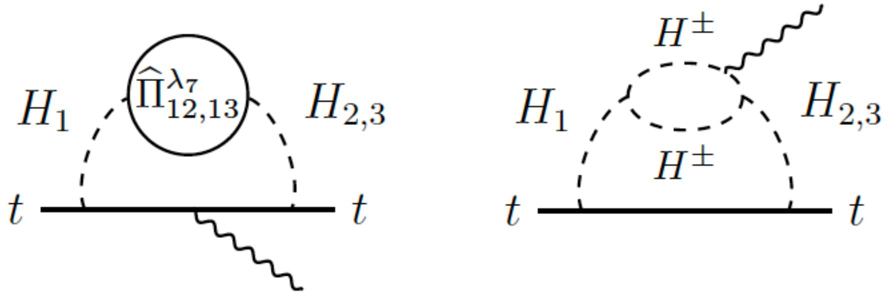
eEDM from the top EDM from $\mathrm{Im}[\lambda_7 \rho_{tt}]$



Effective operators below the scale Λ (= m_Φ)

$$\mathcal{L}_{\rm eff} = -\frac{1}{\Lambda^2}\left(\frac{g'}{\sqrt{2}}C_{tB}\overline{Q_L}\sigma^{\mu\nu}t_R\tilde{\Phi}_1 B_{\mu\nu} + \frac{g}{\sqrt{2}}C_{tW}\overline{Q_L}\sigma^{\mu\nu}t_R\tau^a\tilde{\Phi}_1 W^a_{\mu\nu} + \text{h.c.}\right)$$

$$d_t^{B_\mu} = \frac{g_1 v}{\Lambda^2}\mathrm{Im}[C_{tB}], \quad d_t^{W^3_\mu} = \frac{g_2 v}{\Lambda^2}\mathrm{Im}[C_{tW}]$$

After RGE flow, by integrating out t, W, and Z at the scale μ, eEDM is obtained

$$d_e = -\frac{e}{2v}\left(\frac{v}{\Lambda}\right)^2\left(\log\frac{\Lambda}{\mu}\right)^2\Big[(A_e - D_e)\mathrm{Im}[C_{tB}] + (B_e - E_e)\mathrm{Im}[C_{tW}]\Big]$$

$$A_e = \mathcal{Y}_e(15g_1^2 + 3g_2^2), \quad B_e = 10\mathcal{Y}_e g_2^2,$$
$$D_e = -6\mathcal{Y}_e g_1^2, \quad E_e = -5\mathcal{Y}_e(g_1^2 + g_2^2),$$
$$\mathcal{Y}_e = N_c y_e y_t/(4\pi)^4$$

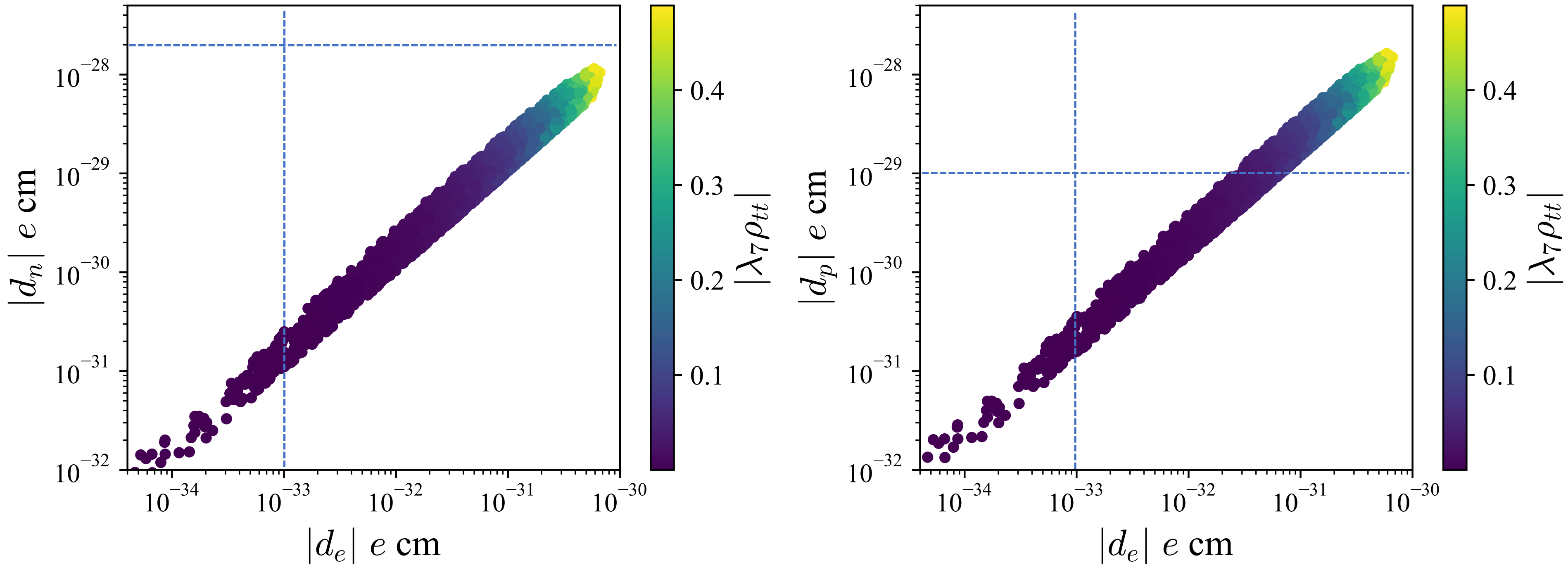
Λ = mΦ

μ = mt, mh, mZ

Correlation among EDMs

M. Endo, M. Aiko, S.K., Y. Mura, arXiv: 2504.07705

- Strong correlation among EDMs (dashed: future prospect bounds)



- All of CPV quantities are correlated by $\mathrm{Im}[\lambda_7 \rho_{tt}]$.
  ⇨. Characteristic prediction of our scenario

- Null results of EDM in the future experiment
  ⇨. We need to start considering a cancellation mechanism.

Phenomenology

1st OPT

Deviation in the di-photon decay and in the hhh coupling, gravitational waves, …

CPV

eEDM, nEDM, pEDM, Colliders ($gg \to H_2/H_3 \to tt$, $H^+ \to W^- Z$, …)

Shape of the 2HDM

Deviation pattern in decays of h(125) via the quantum effect

Detect heavy Higgs bosons $H_{2,3} \to tt$, $H^{\pm} \to tb$

Detailed study to be done

Summary

For BAU, additional CP violation is necessary, strongly 1st OPT is realized

- In the SM, insufficient CP violation, Smooth Cross Over
- In 2HDM, additional CP violation can be introduced, and 1st OPT is realized

  Rich predictions, but severely constrained by eEDM data (B-Z type)

We have considered a Minimal scenario for EWBG in general 2HDM

- take $\rho_{ij} = 0$ except for ρ_{tt} to avoid constraints from B-Z type eEDM.
- $\mathrm{Im}[\lambda_7 \rho_{tt}]$ is the most important rephasing invariant for EWBG.
- In the minimal setup, only $\mathrm{Im}[\lambda_7 \rho_{tt}]$ causes EDM and BAU.

No EDM cancellation necessary

Two loop EDMs and BAU with the minimal setup

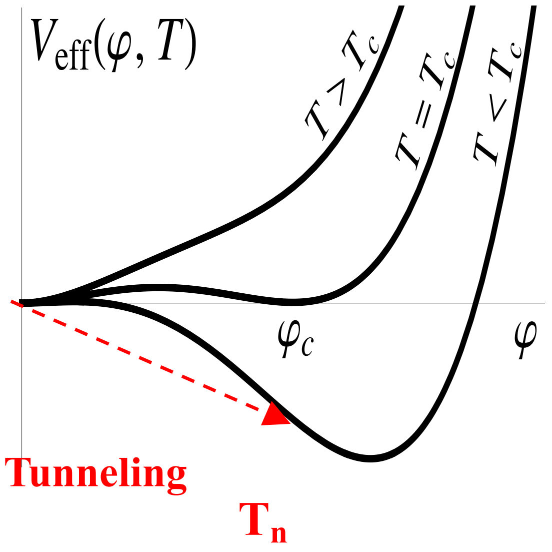
- We evaluated leading 2 loop top EDMs in the minimal setup.
- Correlation between EDMs (n, p, e) and BAU.
- Our scenario is viable under current bounds, and would be testable in the future.

Thank you

U. Osaka
Dr. Wani

EW Baryogenesis

- **1st OPT ⇨ bubbles of the broken phase**



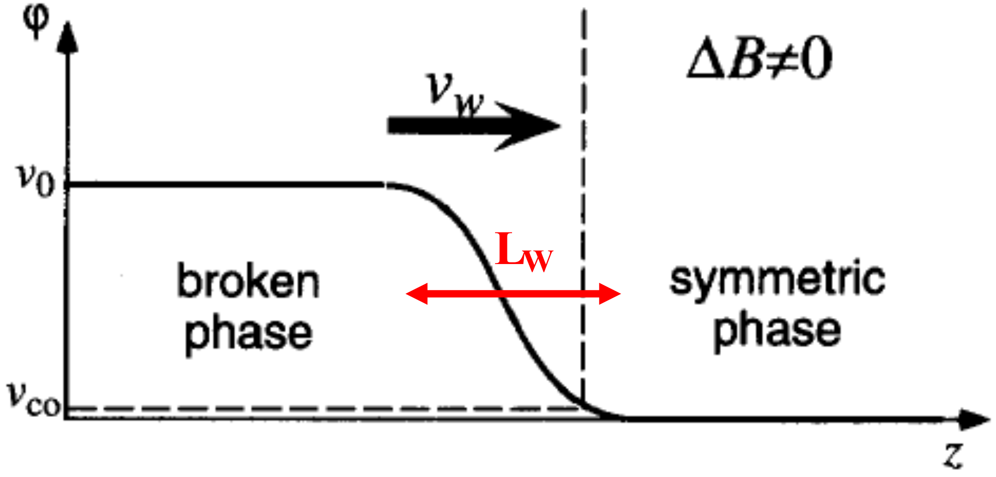
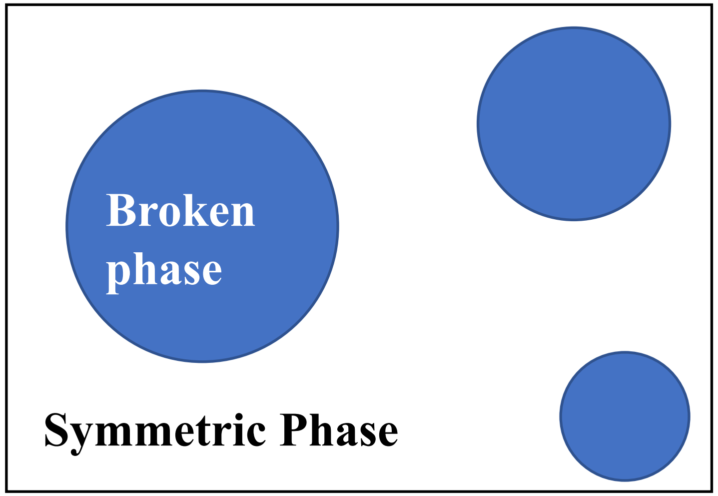


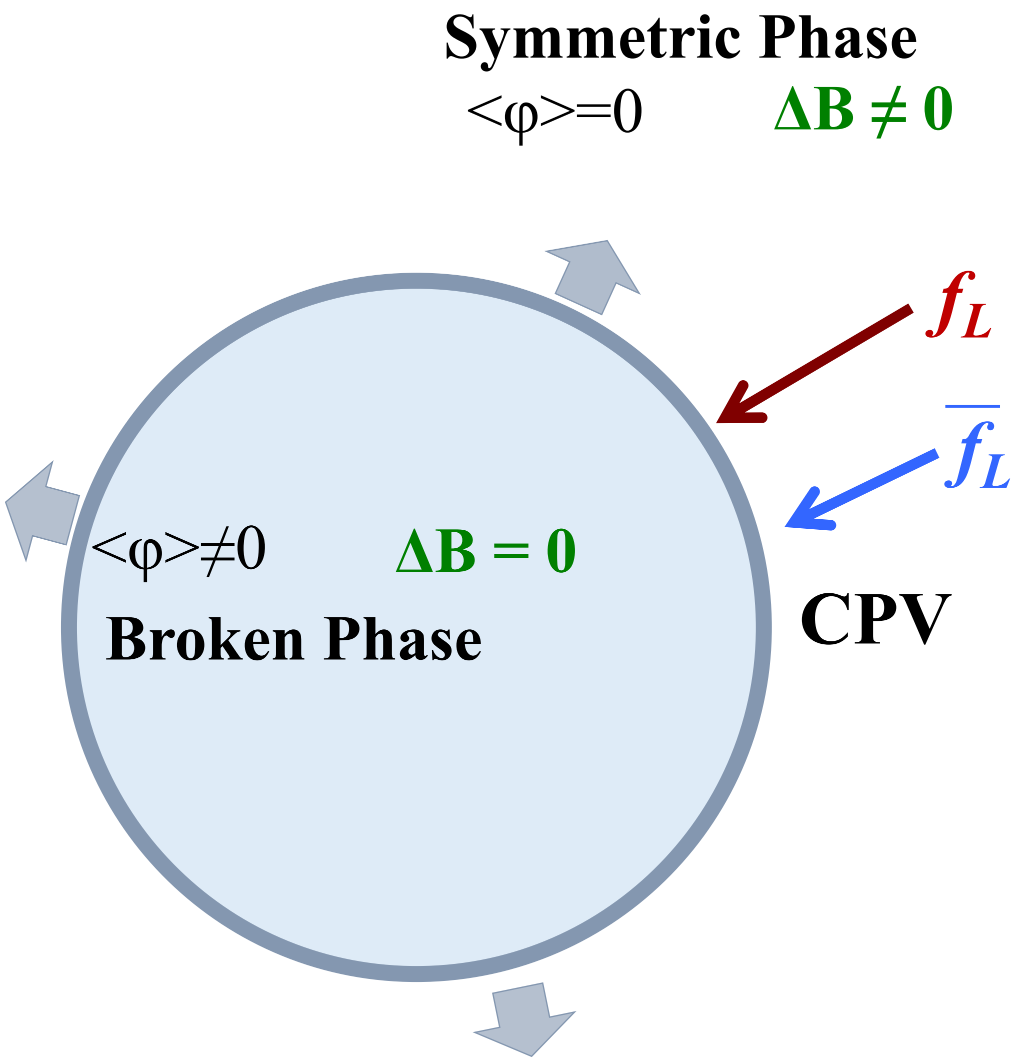
Figure by Funakubo 1996

Profile
Bounce solusion
Φ(z)



EW Baryogenesis

- 1st OPT ⇨ **bubbles of the broken phase**
- CPV ⇨ **charge flow around the wall**



EW Baryogenesis

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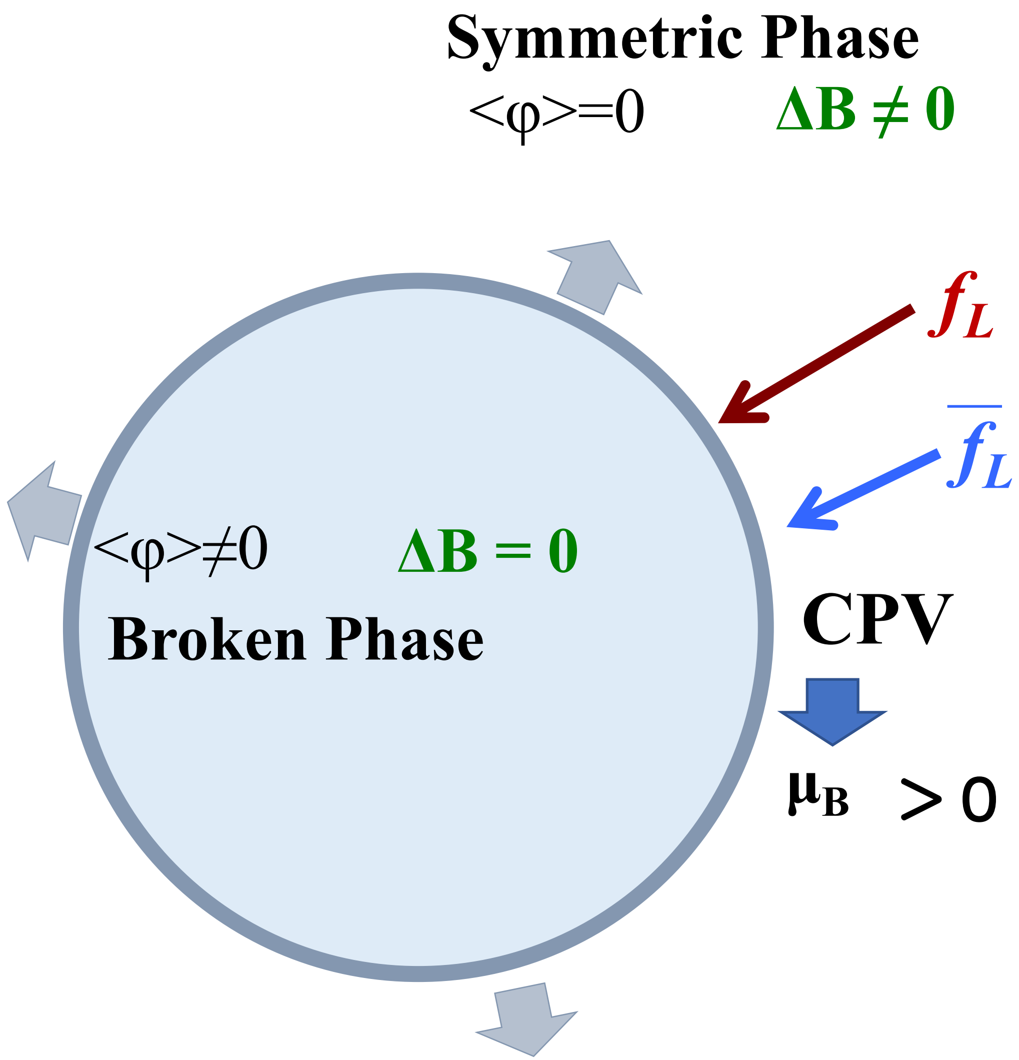


Symmetric Phase

<φ>=0 **ΔB ≠ 0**

f_L

$\overline{f_L}$

<φ>≠0 **ΔB = 0**

Broken Phase

CPV

$\mu_B > 0$

Dirac equation solved by WKB method

Cline, Joyce, Kainulainen 2000

Boltzmann equation

$$(\partial_t + \boldsymbol{v}_g \cdot \partial_{\boldsymbol{x}} + \boldsymbol{F} \cdot \partial_{\boldsymbol{p}}) f_i = C[f_i, f_j, \ldots]$$

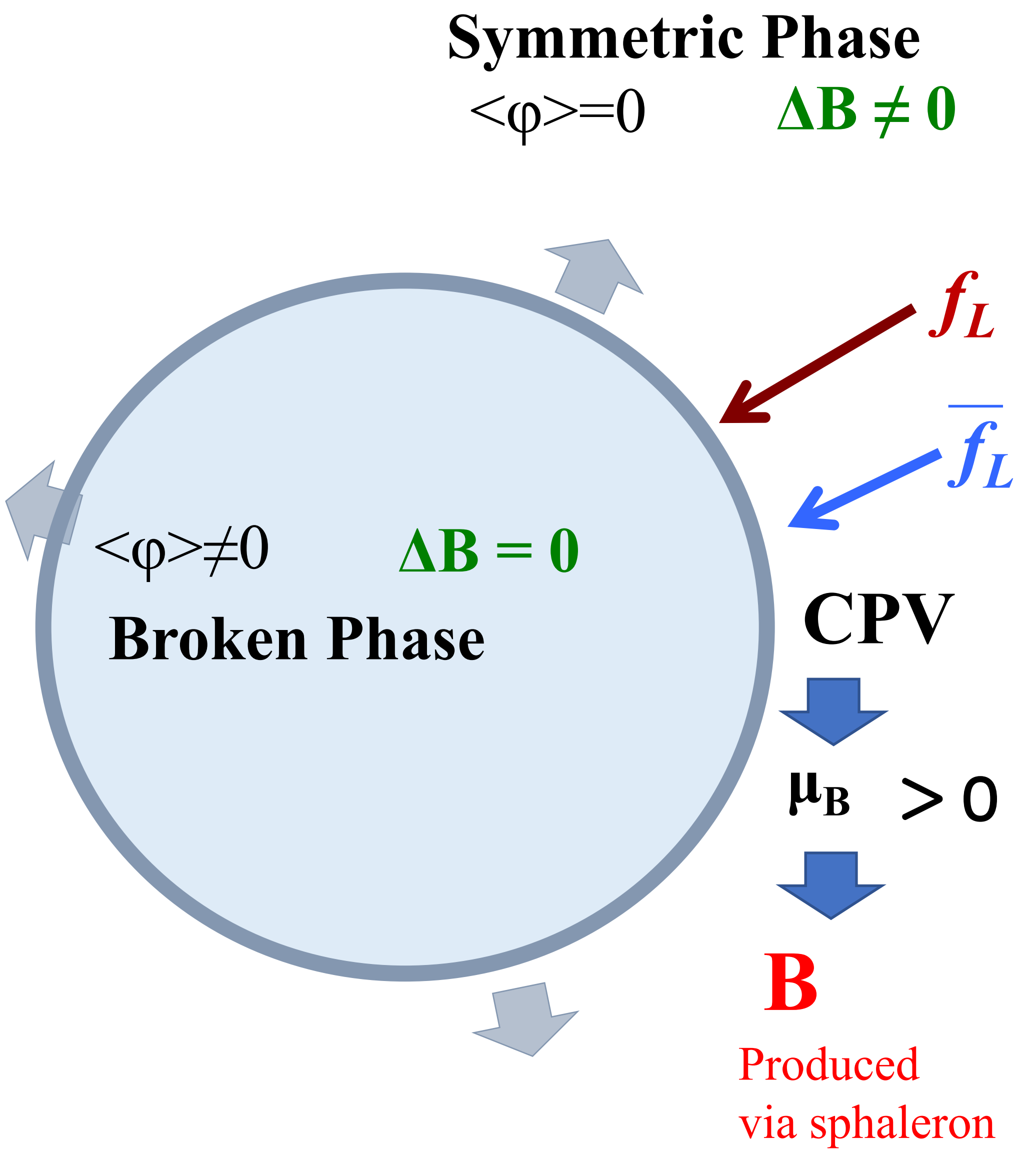
Different sign between particle and anti-particle

$$f_i = \frac{1}{e^{\beta[\gamma_w(E_i + v_w p_z) - \mu_i]} \pm 1} + \delta f_i$$

⇨ Transport eq for μ_i

EW Baryogenesis

- **1st OPT ⇨ bubbles of the broken phase**
- **CPV ⇨ charge flow around the wall**
- **By accumulated charge in symmetric phase, baryon number is generated via sphaleron**



Symmetric Phase

<φ>=0 **ΔB ≠ 0**

f_L

$\overline{f_L}$

<φ>≠0 **ΔB = 0**

Broken Phase

CPV

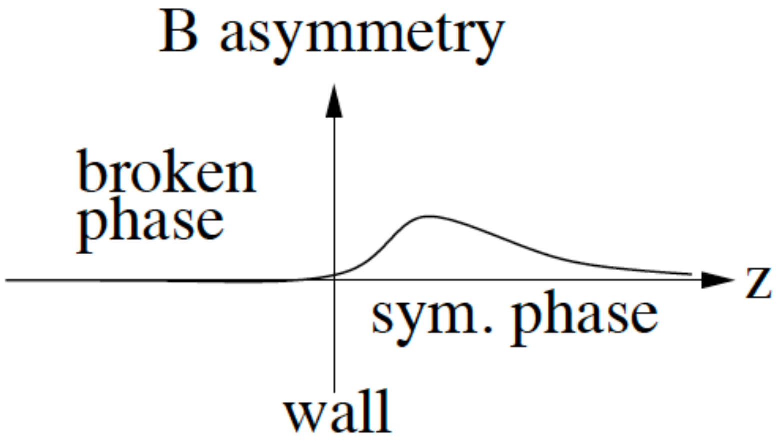
$\mu_B > 0$

B

Produced via sphaleron

Chemical potential

$$\boxed{\dot{n}_B \simeq -\frac{\mu_B \Gamma_{\rm sph}}{T}}$$



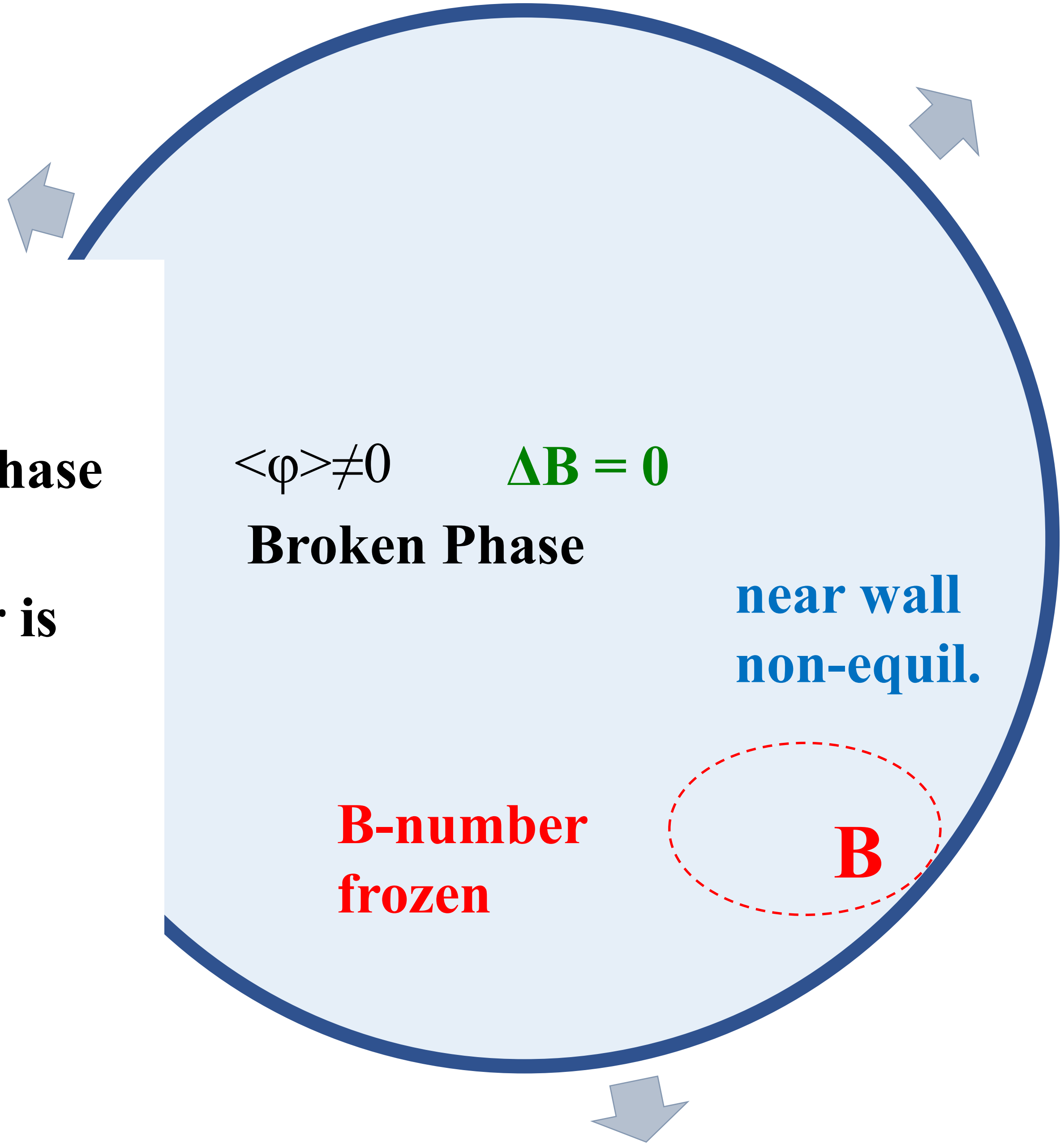
EW Baryogenesis

- **1st OPT** ⇨ **bubbles of the broken phase**
- **CPV** ⇨ **charge flow around the wall**
- **By accumulated charge in the symmetric phase baryon number is generated via sphaleron**
- **In broken phase, produced baryon number is frozen, if sphaleron process decouples**

Sphaleron decoupling
in broken phase

$$\boxed{\frac{\varphi_c}{T_c} \gtrsim 1}$$

BAU $\boxed{\eta \sim 10^{-10}}$



<φ>≠0 **ΔB = 0**

Broken Phase

near wall
non-equil.

B-number
frozen

B

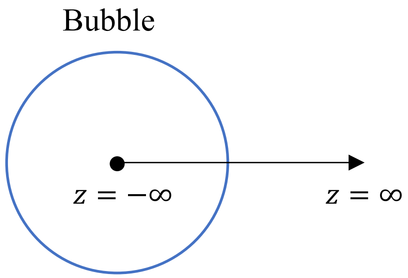
WKB method

Cline, Joyce, and Kainulainen (2000);
Fromme and Huber (2007); and more

- **Transport equation for chemical potential**

$$C_1\ \mu''(z) + C_2\ \mu'(z) + C_3\ \mu(z) = S_{\mathrm{CPV}}$$

where, $\mu(z) = \mu_\psi - \mu_{\overline{\psi}}$



- **By solving Dirac eq. for ψ with WKB approximation, we have**

$$S_{\mathrm{CPV}} = C_4\left(m_\psi^2\theta_\psi'\right)' + C_5\ m_\psi^2\theta_\psi'\left(m_\psi^2\right)'.$$

C_i are functions of z, T, m, and v_w.

- **Final BAU:** $$\eta_B \simeq (\text{const.})\ \Gamma_{\text{sph}}^{\text{sym}} \int_0^\infty dz\ \mu_{B_L} \underbrace{e^{-(\text{const.})\ \Gamma_{\text{sph}}^{\text{sym}}\ z}}_{\boxed{\text{washout}}}$$

- **Comments on VEV-Insertion-Approximation (VIA) method**

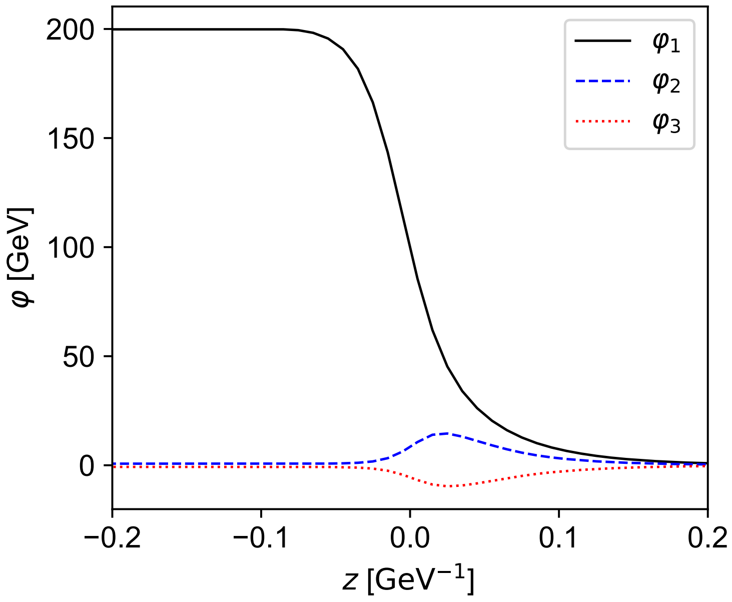
Riotto (1996) (1998);

  - BAU evaluated by VIA method tends to be larger than that by WKB method.
  - Main difference: CPV source is derived by SK formalism.

Cline and Laurent (2021); Basler (2023);
and more

  - LO-term used as the CPV source vanishes by correct resummation.

Kainulainen (2021); Postma et al. (2022);



We evaluate BAU using semi-classical force method with WKB approximation.

CPV source term in the transport equation

$$S_{f_i} = -\gamma v_w \left(m_{f_i}^2 \theta'_{f_i}\right)' Q_{f_i}^8 + \gamma v_w m_{f_i}^2 \theta'_{f_i} \left(m_{f_i}^2\right)' Q_{f_i}^9$$

Top transport scenario

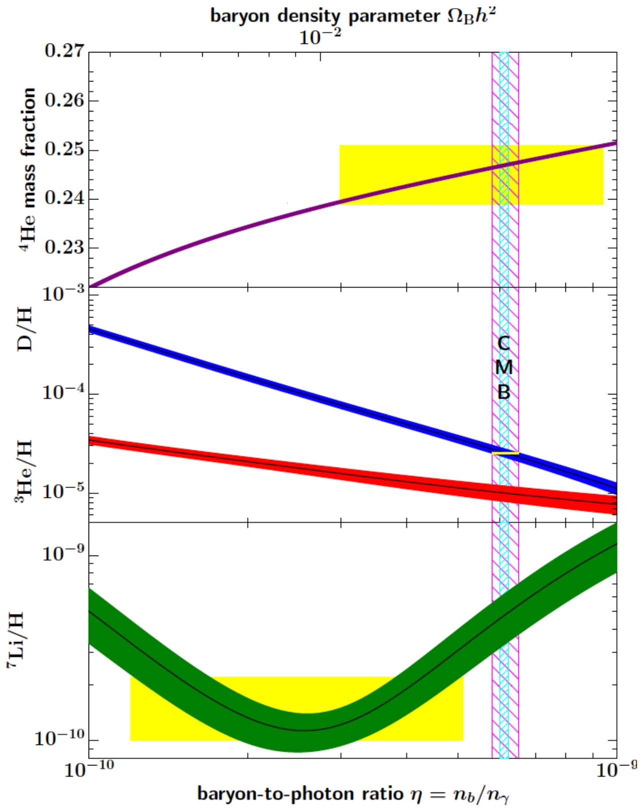
In the Minimal setup, the local mass and the phase for the top quark are given

$$m_t^2 = \frac{1}{2}\Big(y_t^2\varphi_1^2 + |\rho_{tt}|^2(\varphi_2^2+\varphi_3^2) + 2y_t|\rho_{tt}|\varphi_1\big(\varphi_2\cos\theta_{tt} + \varphi_3\sin\theta_{tt}\big)\Big),$$

$$m_t^2\theta_t' = \frac{1}{2}\Big\{y_t|\rho_{tt}|\Big((\varphi_3\varphi_1' - \varphi_1\varphi_3')\cos\theta_{tt} + (\varphi_1\varphi_2' - \varphi_2\varphi_1')\sin\theta_{tt}\Big)$$

$$+ |\rho_{tt}|^2(\varphi_3\varphi_2' - \varphi_2\varphi_3')\Big\} + \frac{m_t^2}{\varphi_1^2+\varphi_2^2+\varphi_3^2}(\varphi_3\varphi_2' - \varphi_2\varphi_3'),$$

BAU and Baryogenesis



Particle Data Group

Baryon Number
of the Universe

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} (= (5-7) \times 10^{-10})$$

Baryogenesis

What is the mechanism to generate the baryon asymmetric Universe from the symmetric one?

Sakharov's Condition

Sakharov 1967

1. $\Delta B \neq 0$
2. C and CP violation
3. Departure from thermal equilibrium

SM cannot satisfy these conditions