The Higgs: A Window on New Physics and the Early Universe

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THE UNIVERSITY OF OSAKA

U. Osaka Dr. Wani (mascot character)

Colloquium at APC, Paris on Sep. 16, 2026

University of Osaka

Founded in 1724 (Kaitokudo)
in 1838 (Tekijuku)

Re-established as
Osaka Imperial University
before WW2

University of Osaka after WW2

Old Campus (Downtown Osaka)
School of Science
Osaka Imperial University

New Campus (Toyonaka City)
School of Science
University of Osaka

Historical Physicists at the Univ of Osaka

Hideki Yukawa

大阪大学湯川記念室

Ph. D（U. Osaka）

Meson Theory
1935

Ryoyu Utiyama

窮理舎 龍雄先生の冒険より

Ph. D（U. Osaka）

General Gauge Theory
1954

Yoichiro Naumbu

commons.wikimedia.org

Ph. D（U. of Tokyo）

Distinguished professor

Symmetry Breaking 1961
Color, String Theory

Standard Model:

Lagrangian

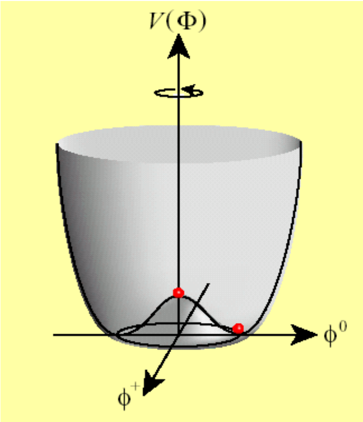
$$\mathcal{L} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+\overline{Q}_L i\gamma^\mu D_\mu Q_L + \overline{L}_L i\gamma^\mu D_\mu L_L$$
$$+\overline{u}_R i\gamma^\mu D_\mu u_R + \overline{d}_R i\gamma^\mu D_\mu d_R + \overline{e}_R i\gamma^\mu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

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

Perhaps a beautiful principle behind?
Non-minimal shape? Many possibilities.

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

This talk

1. The Higgs: a window on new physics
2. The electroweak phase transition: the next target
3. Electroweak baryogenesis (as a case study)
4. Testing the Higgs potential at colliders
5. Complementary tests of the early Universe
6. Probing the thermal history of the Universe

1. The Higgs: a window on new physics

What have we learned, and what remains unknown?

What we have learned

Higgs Discovery 2012

Mass 125 GeV   Spin・Parity

Good agreement with SM prediction

No evidence of new physics up to now

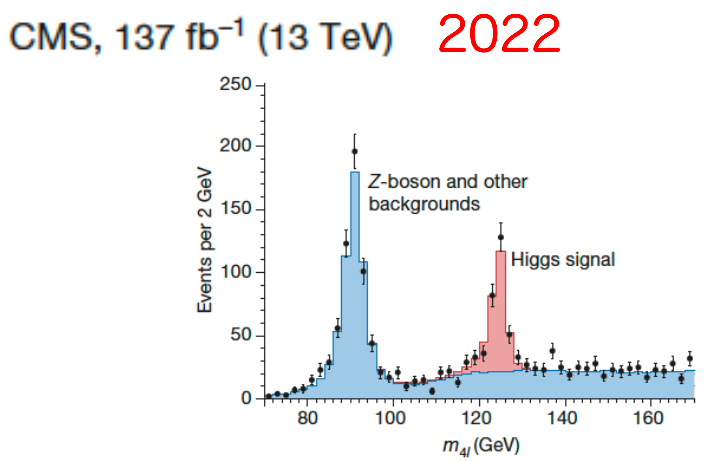
BSM phenomena → New physics must exist

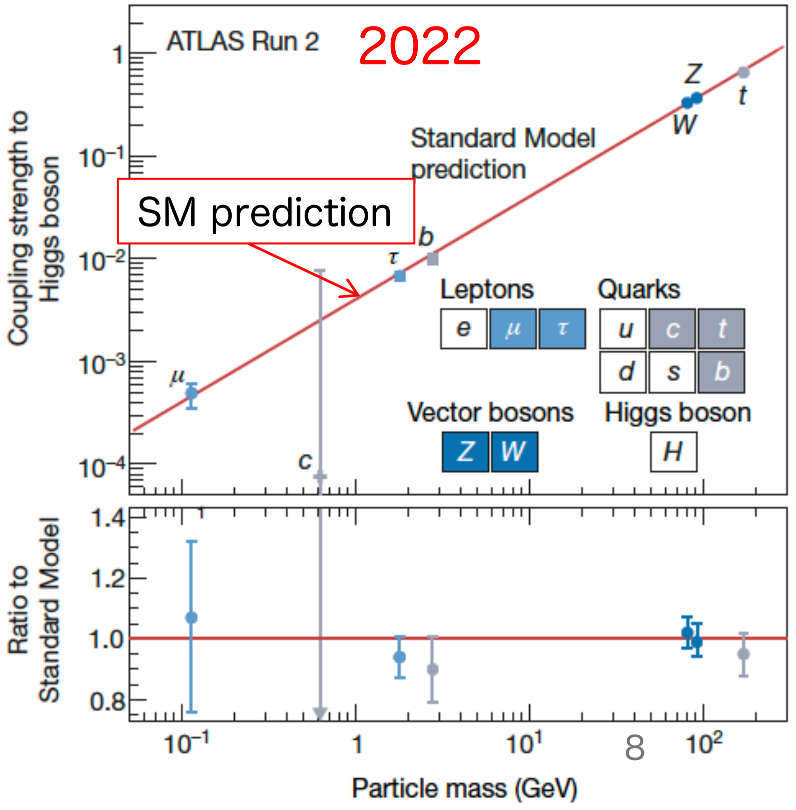
<u>Where is new physics?</u>

Low scale?

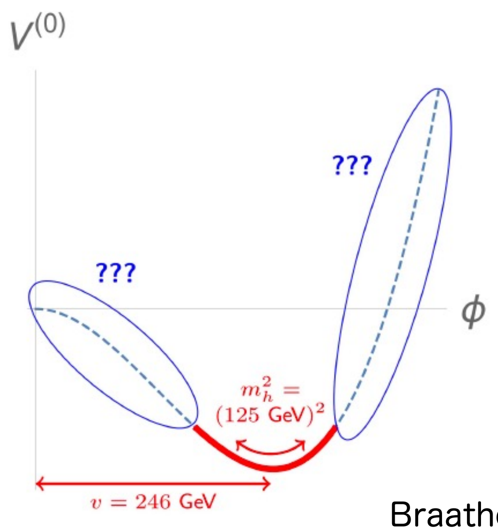
TeV Scale?

High Scale?





Higgs: window to new physics



Braathen

Higgs sector remains unknown

- Multiplet structure (# of fields, symmetry, couplings, ⋯)
- Higgs potential (dynamics of EWSB, EWPT, ⋯)
- Yukawa Structure (flavor, CPV, ⋯)
- Elementary or Composite? Hierarchy?

SM Higgs sector: no principle

Extension of the Higgs sector

⇒ BSM phenomena may be explained

Radiative seesaw models
DM candidates
Phase Transition (1st Order)
CPV sources for baryogenesis
Supersymmetry
Dynamical symmetry breaking,
Composite Higgs models, ⋯

TeV scale: testable at current and future experiments

2. The EW phase transition: the next target

Crossover or first order? Implications for the early Universe

How did the Universe reach today's EW vacuum?

$$SU(2)_I \times U(1)_Y \to U(1)_{\rm em}$$

Symmetric Phase

$$\langle \varphi(T) \rangle = 0$$

Phase transition

Broken Phase (EWSB)

$$\langle \varphi(0) \rangle \neq 0$$

Early Universe before EWPT

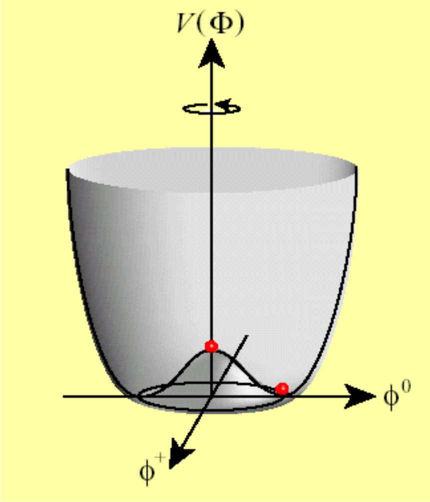
By thermal effects

The gauge symmetry is restored

Today

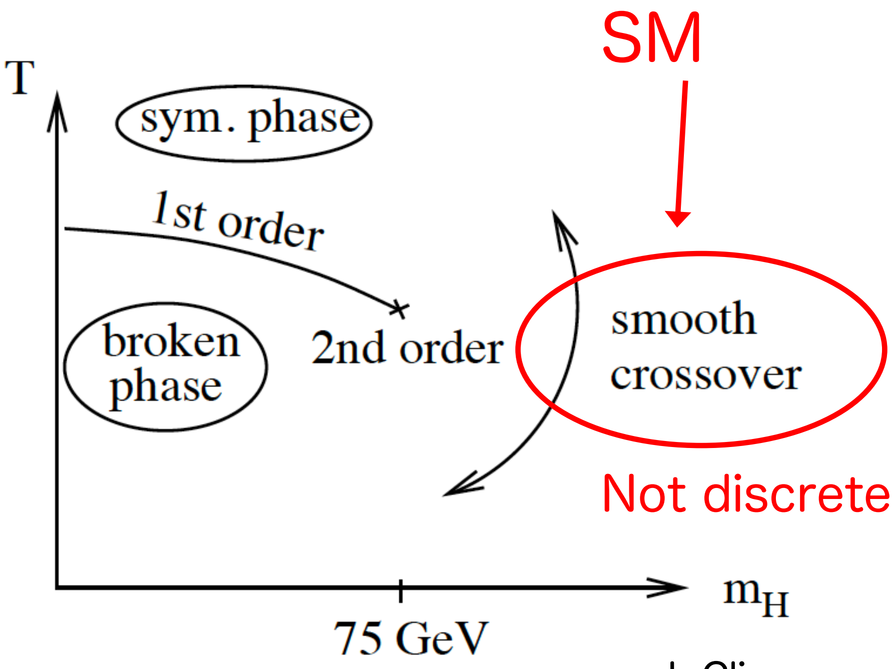
$$G_F \propto \frac{1}{v^2}$$

v = 246GeV



EW vacuum

Crossover or First Order?

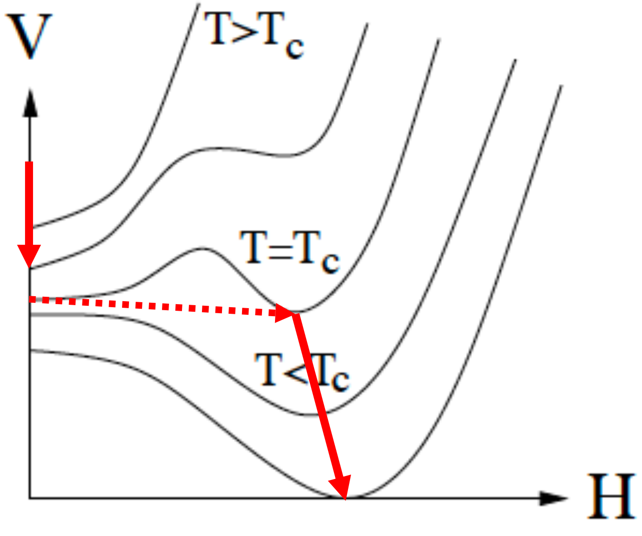


J. Cline

Cross Over

VEV is continuous

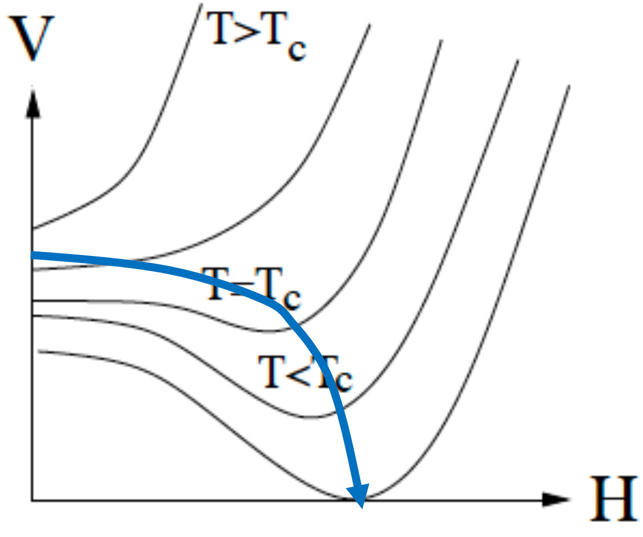
VEV' is continuous



1st OPT

VEV is discrete

Bubble created



2nd OPT

VEV is continuous

VEV' is discrete

SM predicts crossover

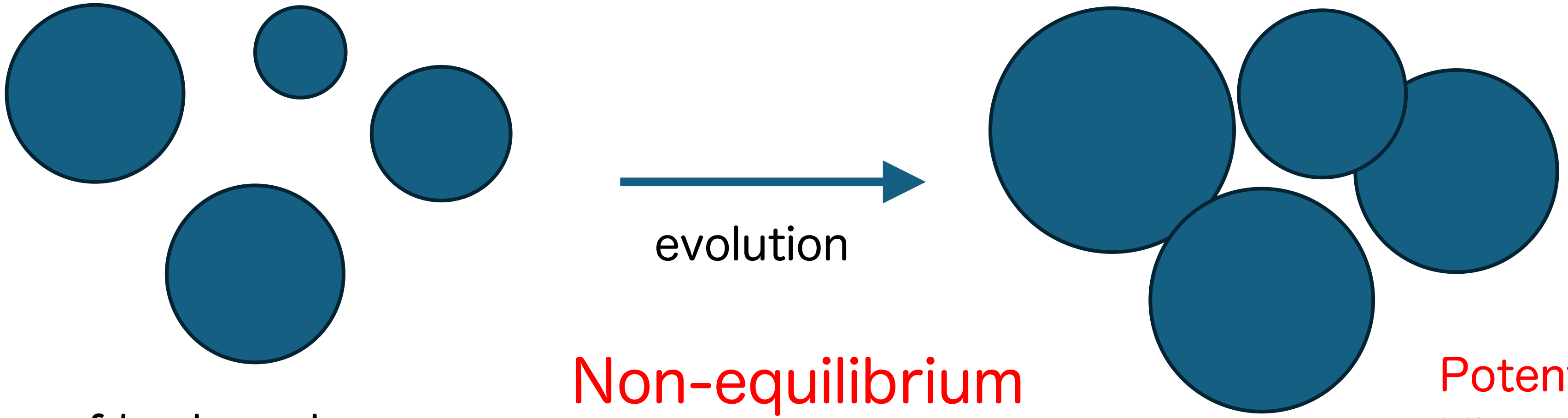
Some BSM scenarios predict 1st OPT

Higgs as a probe of early Universe

Understanding the nature of the phase transition reveals the history of the Universe.

FOEWPT

around *Tc*



Bubbles of broken phase

Non-equilibrium process

Potentially observable relics

Higgs pheno.
Gravitational waves
Primordial BH

Physics case: EW baryogenesis

3 Electroweak baryogenesis

SFOEWPT and new CP violation

Baryon Asymmetry of 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

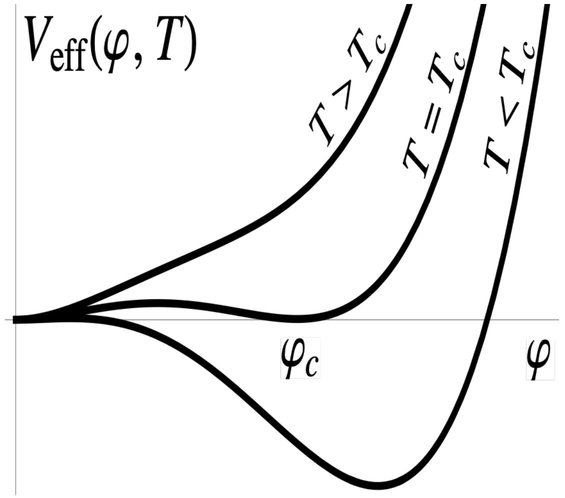
Kuzmin, Ruvakov, Shaposhnikov (1985)

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

2) C and CP violation ➡ C violation (SM is a chiral theory)
CP in BSM sectors

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

Extension of the Higgs sector is required



Condition of Strongly First OPT

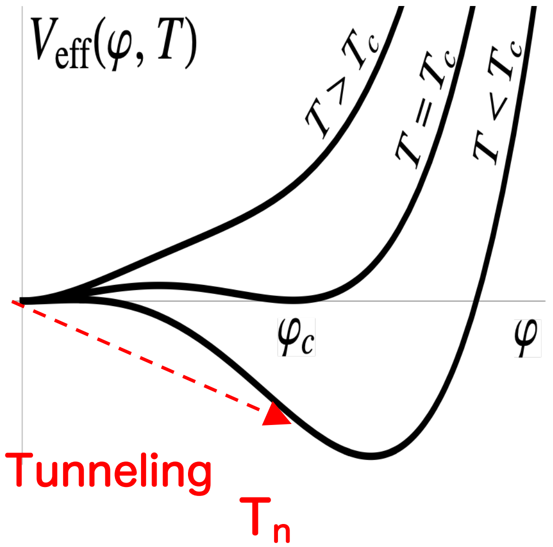
In the broken phase, sphaleron should quickly decouple to avoid wash out

$\Gamma_{sph} < H$ ➡ $\dfrac{\varphi_c}{T_c} \gtrsim 1$

Physics of Higgs potential

EW Baryogenesis

- 1st OPT ⇒ bubbles of the broken phase



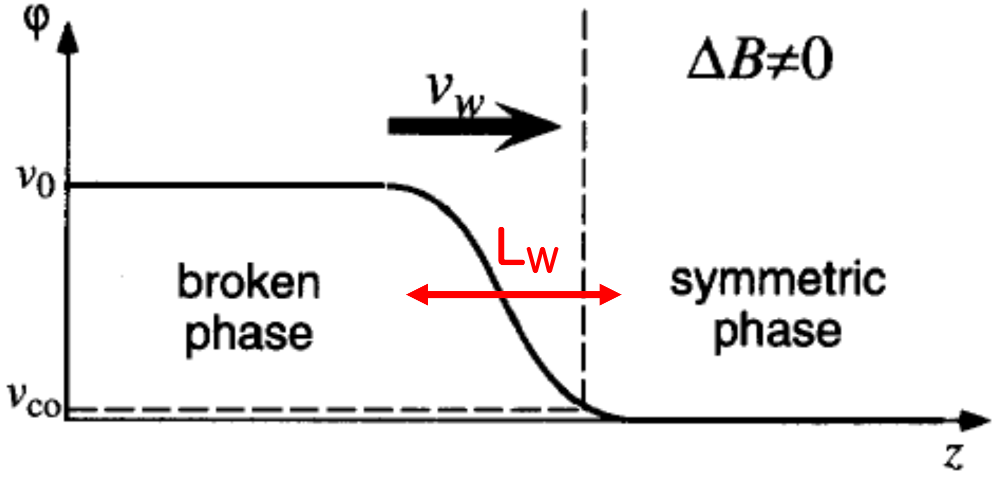
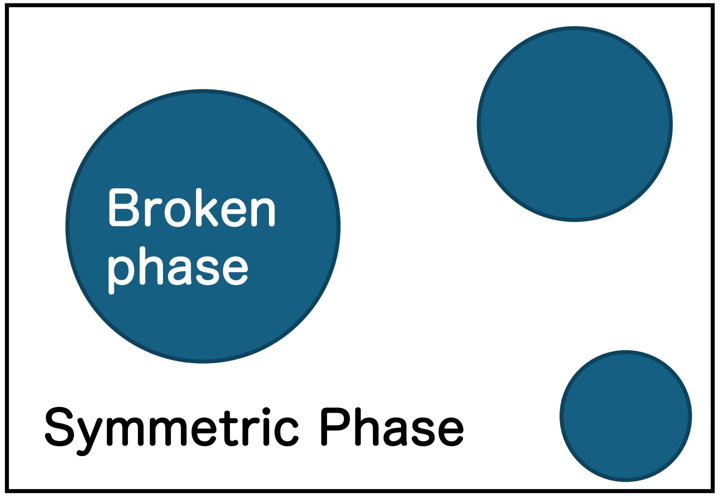


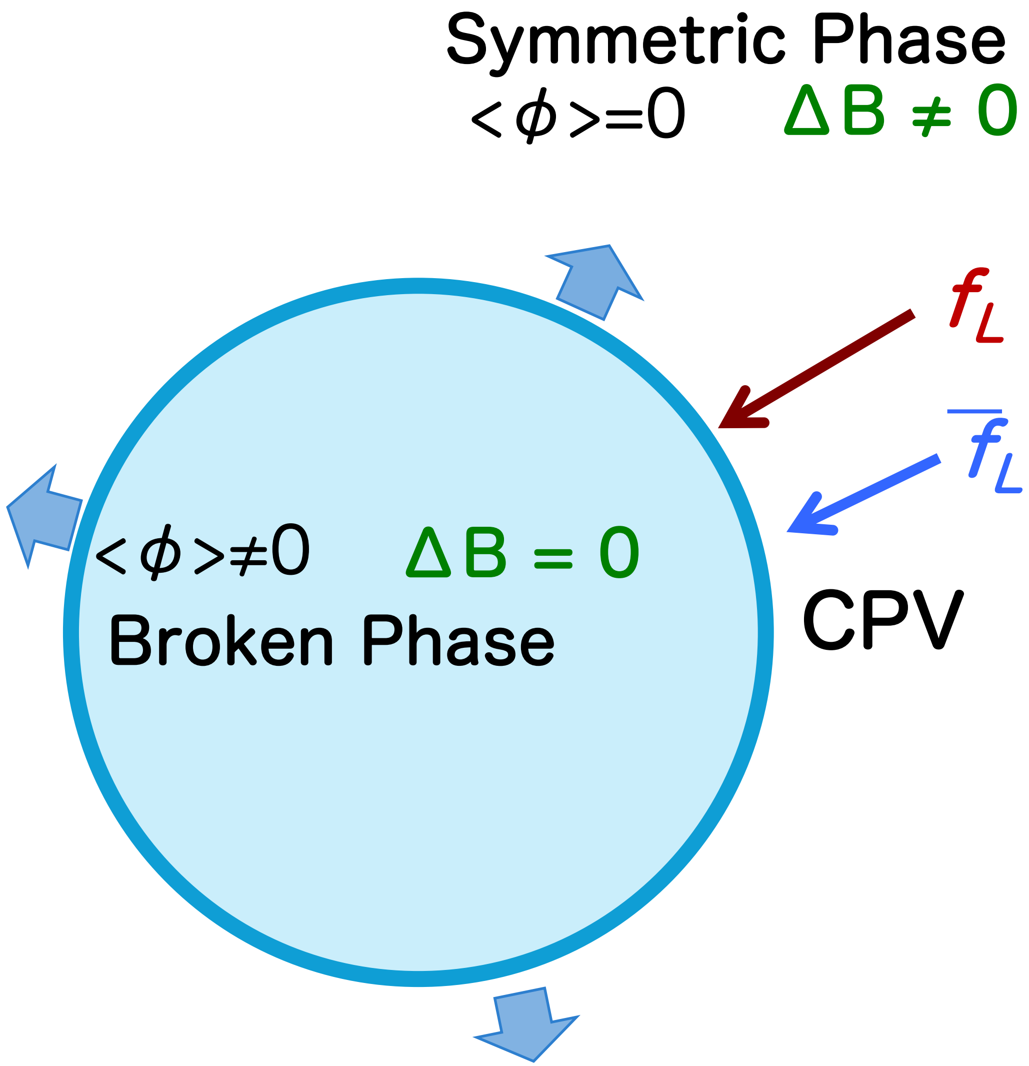
Figure by Funakubo 1996

Profile
Bounce solusion
Φ(z)



EW Baryogenesis

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



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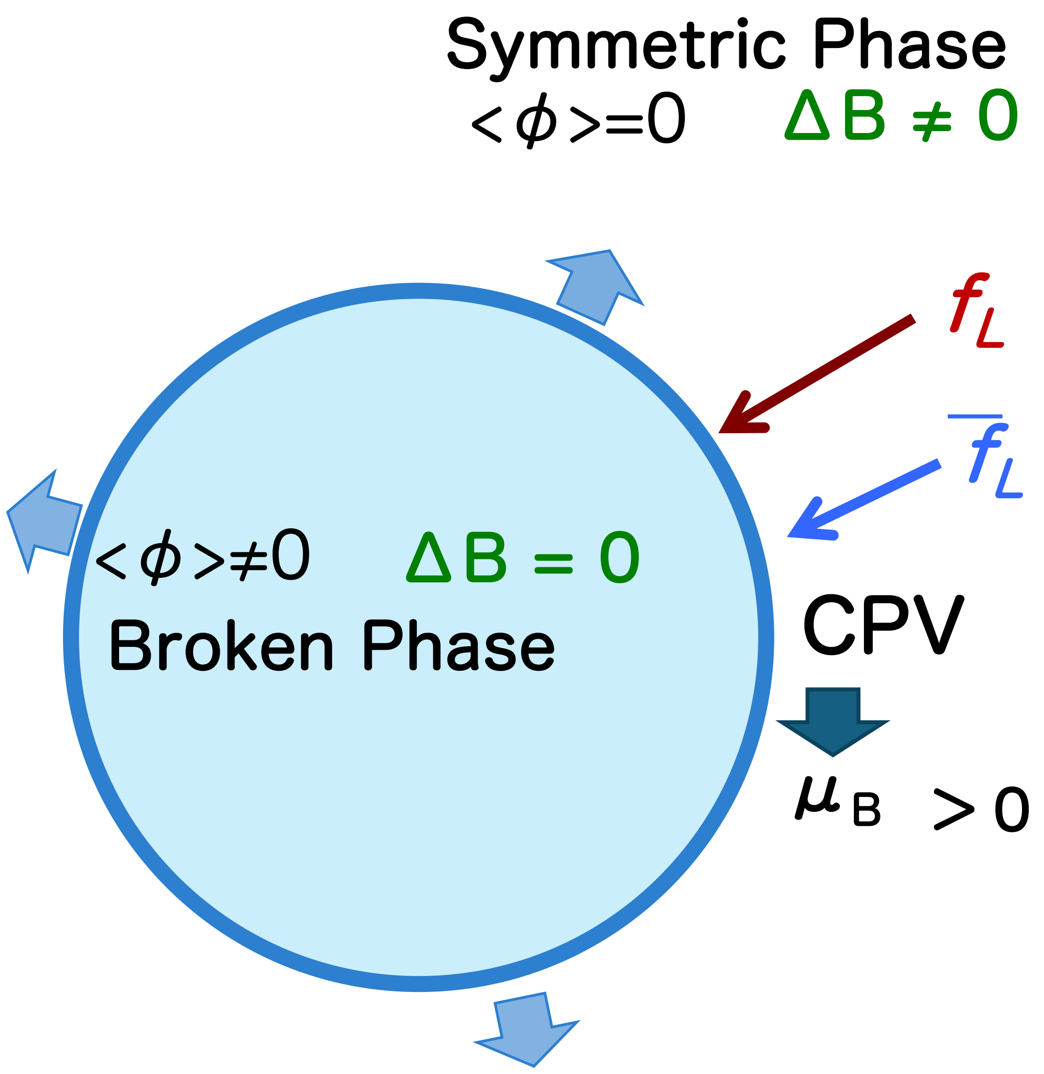


Dirac equation solved by WKB method
Cline, Joyce, Kainulainen 2000

Boltzmann equation

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

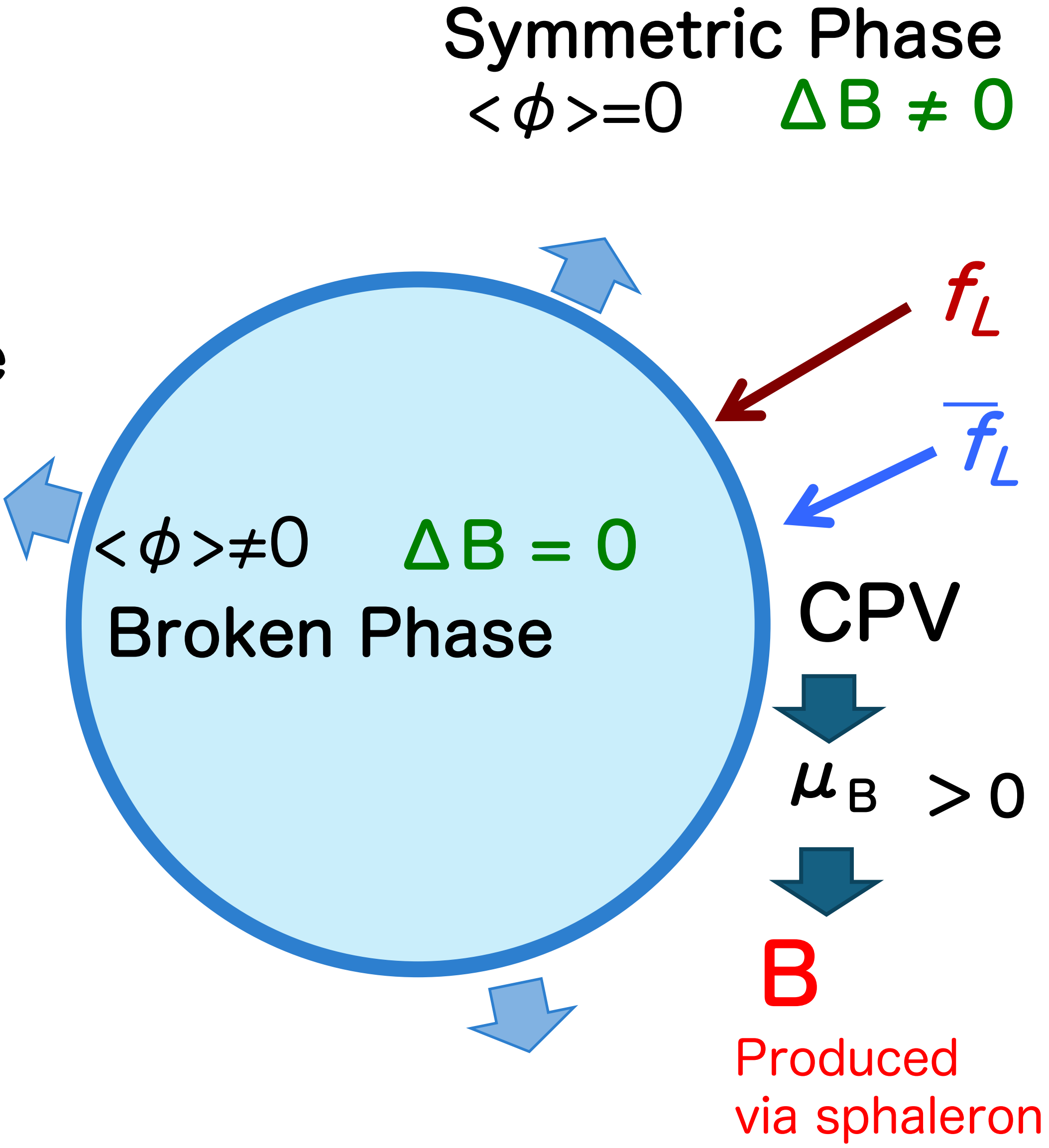
Different sign between particle and anti-particle

⇒ Transport eq. for μ_i

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

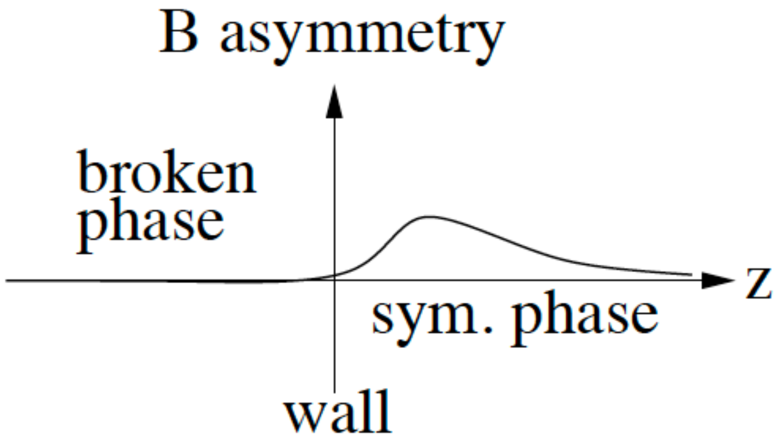
EW Baryogenesis

- 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



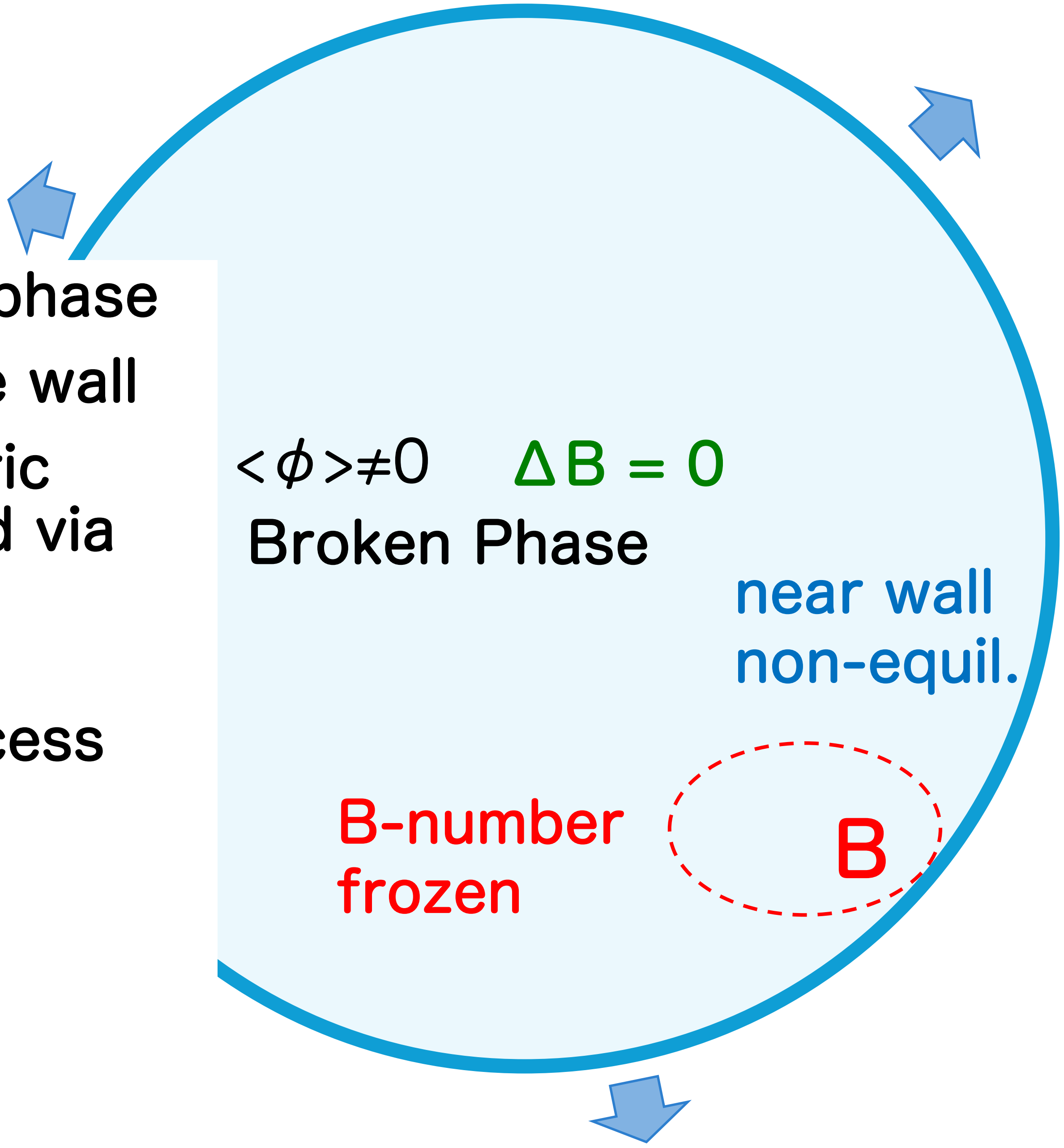
Chemical potential

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



EW Baryogenesis

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



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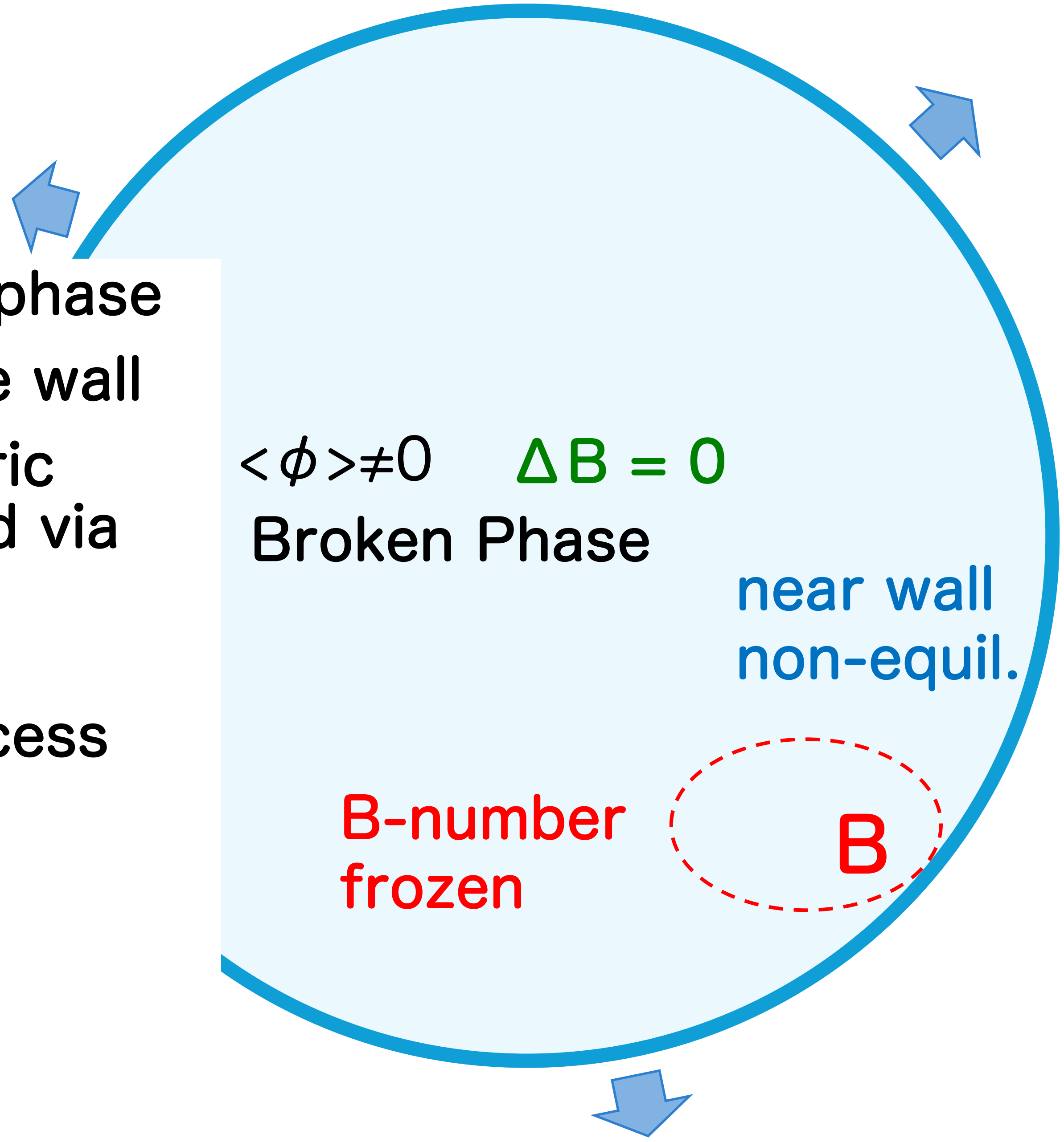
Sphaleron decoupling in broken phase $\frac{\varphi_c}{T_c} \gtrsim 1$



EW Baryogenesis

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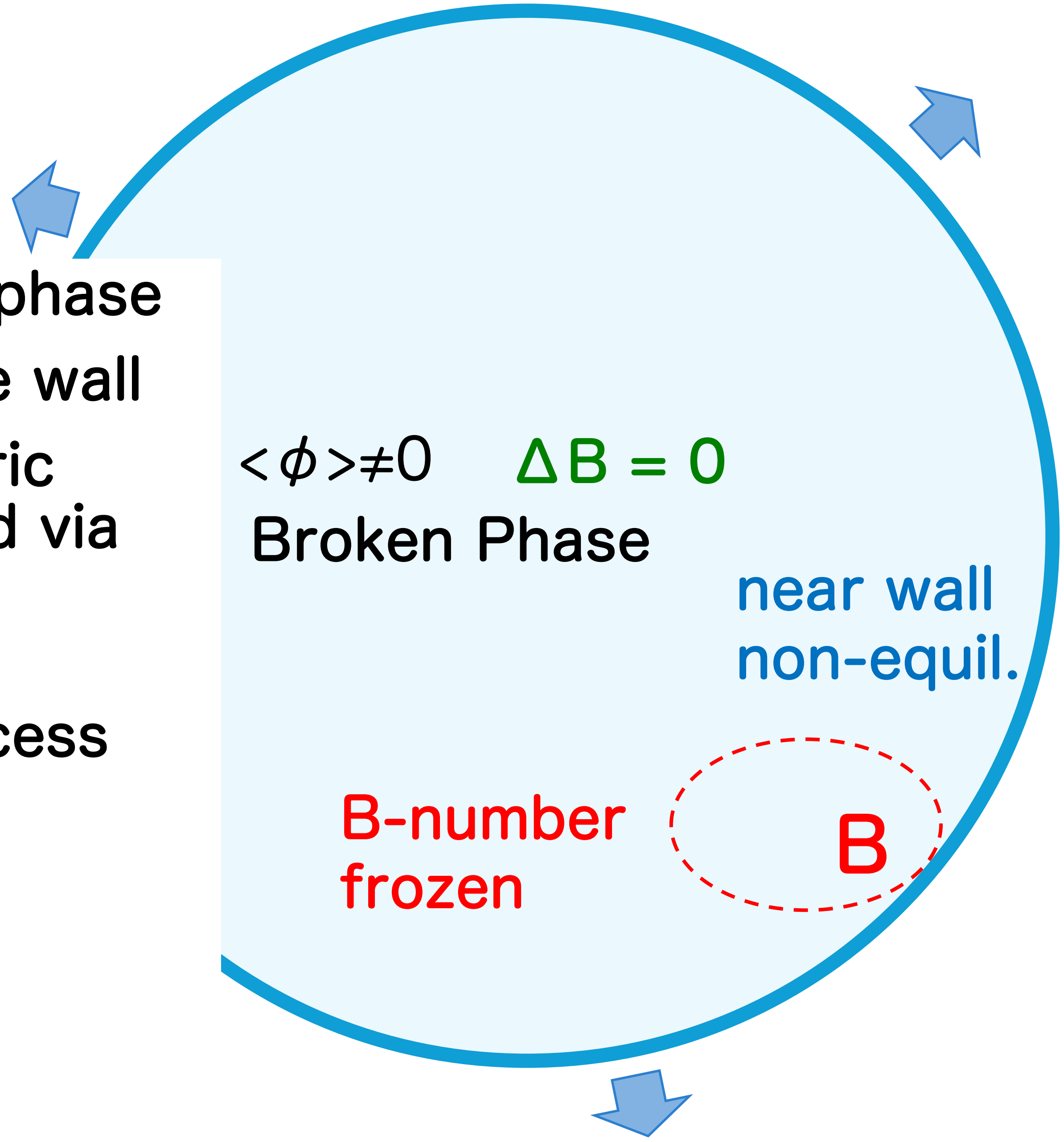


Sphaleron decoupling in broken phase $\frac{\varphi_c}{T_c} \gtrsim 1$

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

What kind of the Higgs sector can lead EW Baryogenesis?

An extended Higgs sector, which realizes

- 1^{st} OPT (Non-decoupling property)
- CP violation

2 Higgs doublet models
Singlet extension
Real triplet extension
…

Constraints from current experimental data

EW Precision Tests
Flavor Changing Neutral Currents
EDMs
LHC

Example: 2HDM

$$V_{\text{THDM}} = +m_1^2 |\Phi_1|^2 + m_2^2 |\Phi_2|^2 - \underline{m_3^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right)}$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2$$
$$+\lambda_4 \left|\Phi_1^\dagger \Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + (\text{h.c.})\right]$$

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + i a_i) \end{bmatrix} \quad (i = 1, 2)$$

Φ_1 and $\Phi_2 \Rightarrow \underline{h, \quad H,} \quad A^0, H^\pm \oplus$ Goldstone bosons

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix}$$

$$\begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

$$\begin{bmatrix} w_1^\pm \\ w_2^\pm \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} w^\pm \\ H^\pm \end{bmatrix}$$

masses

$$m_h^2 = v^2 \left(\lambda_1 \cos^4\beta + \lambda_2 \sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$
$$m_H^2 = M_{\text{soft}}^2 + v^2 (\lambda_1 + \lambda_2 - 2\lambda)\sin^2\beta\cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$
$$m_{H^\pm}^2 = M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2} v^2,$$
$$m_A^2 = M_{\text{soft}}^2 - \lambda_5 v^2.$$

M_{soft}: soft breaking scale

$$\frac{v_2}{v_1} \equiv \tan\beta$$

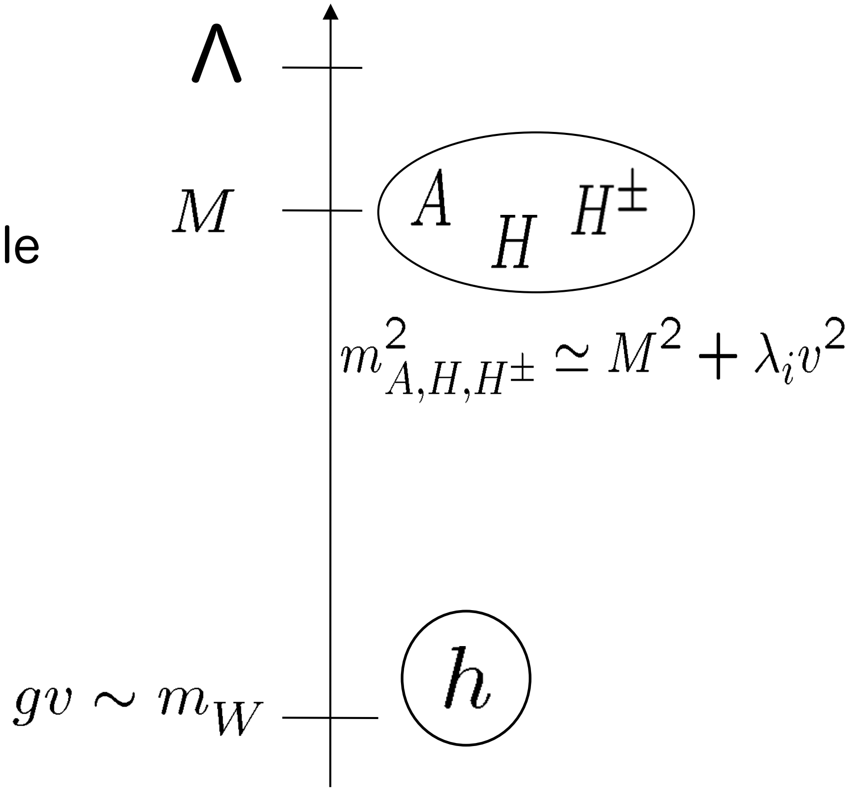
$M_{\text{soft}} \;\left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$:

soft-breaking scale of the discrete symm.

How SM-like is realized in extended Higgs sectors?

Λ : Cutoff

M : Mass scale irrelevant to VEV

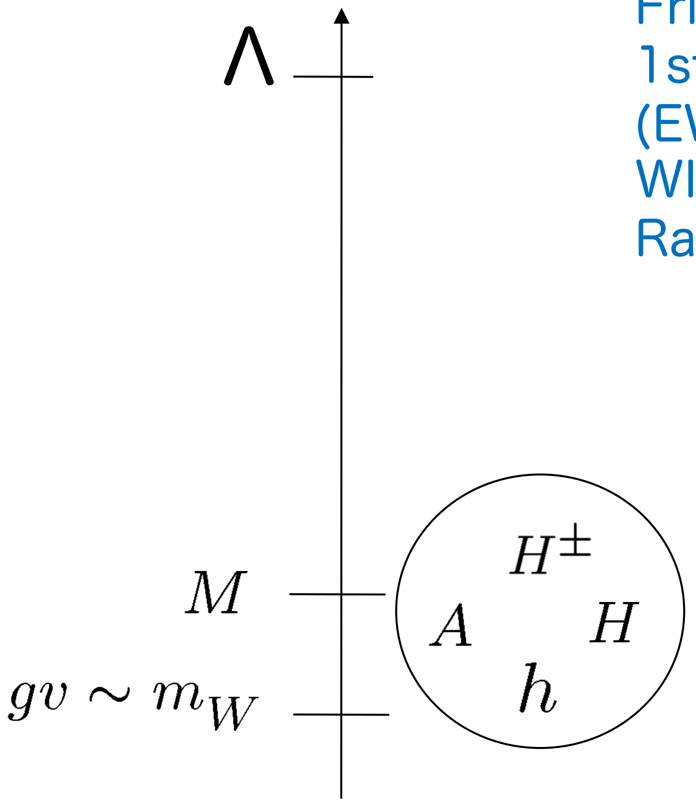


$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM

Decoupling

Friendly with
1st OPT
(EW Baryogenesis)
WIMP
Radiative seesaw



Higgs alignment

$k_V \sim 1$ SM like

$\cos(\beta - \alpha) \sim 0$

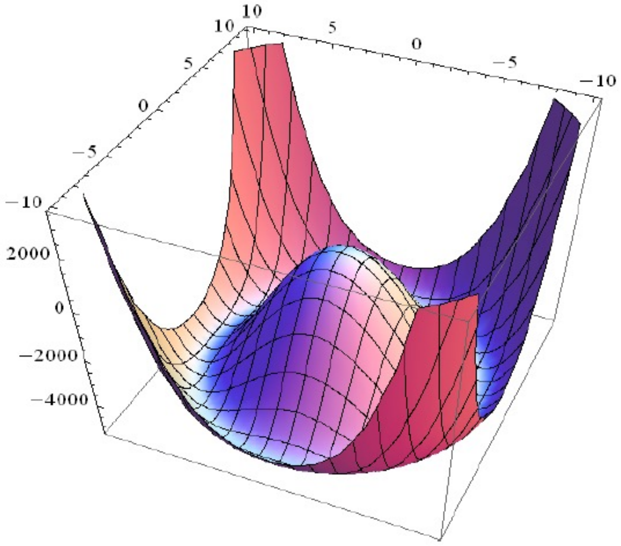
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{nonSM}} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

Effective Theory is an extended Higgs sector

Non-Decoupling

Higgs Potential

Dynamics of EWSB $SU(2)_I \times U(1)_Y \to U(1)_{\rm em}$



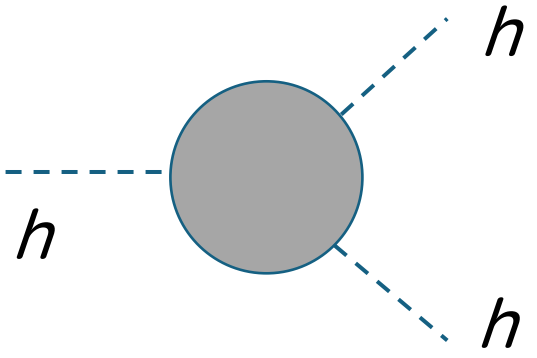
The hhh coupling is important to reconstruct the Higgs potential

$$V_{\rm Higgs} = \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \underline{\lambda_{hhh}} h^3 + \frac{1}{4!} \lambda_{hhhh} h^4 + \cdots$$

$$\lambda_{hhh}^{\rm SMloop} \sim \frac{3m_h^2}{v} \left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots \right)$$

Top loop effect in the SM

Non-decoupling effect



Sensitive to BSM physics too!

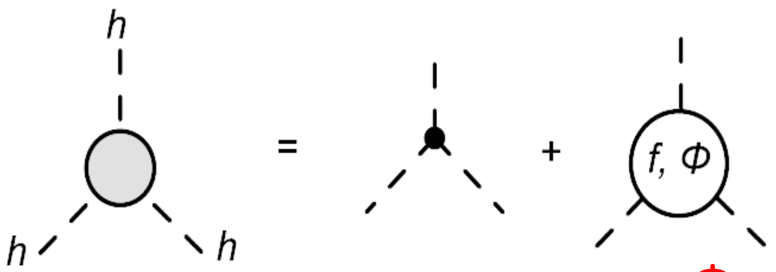
Physics of 1st OPT (EW Baryogenesis)

Ex) Case of extended Higgs sector

$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1 + \frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3 - \frac{m_t^4}{\pi^2 v^2 m_h^2}\right]$$

Extra scalar loop

Top loop



Φ = H, A, $H^\pm$

Mass of extra Higgs bosons

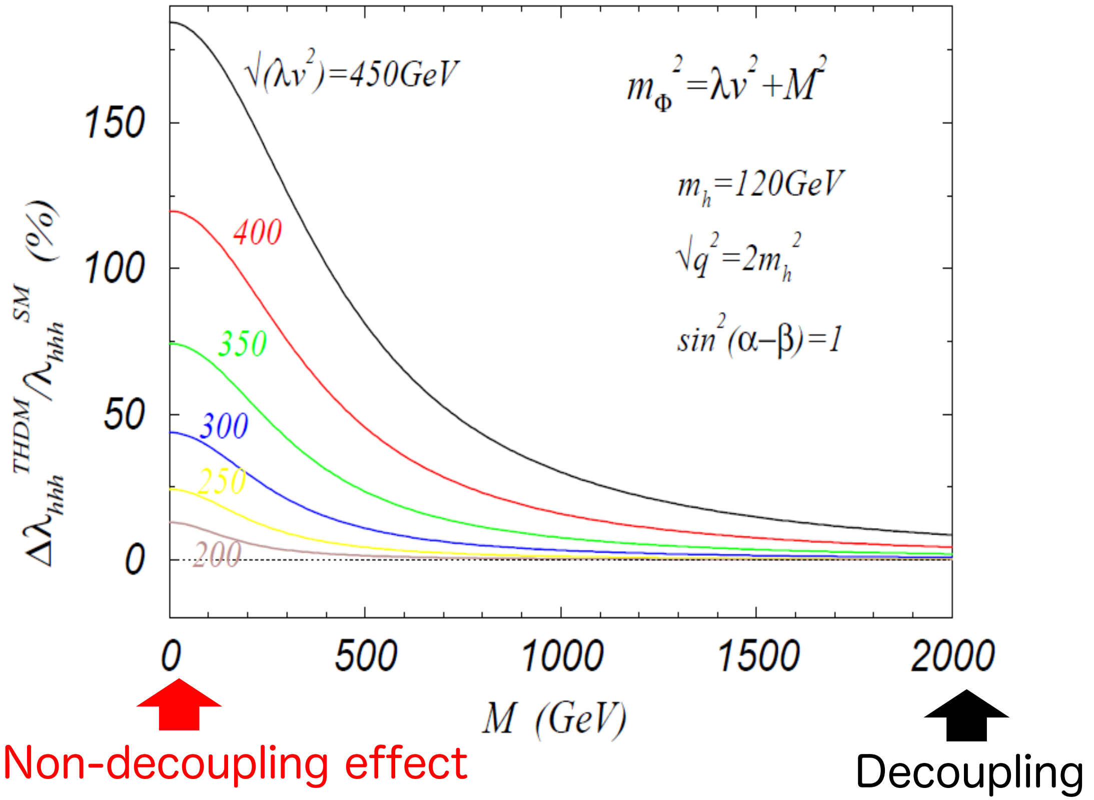
$$m_\Phi^2 = M^2 + \lambda_i v^2 \qquad (\Phi = H, A, H^\pm)$$

- Consider the case: h is SM-like
- At 1-loop, powerlike effect $m_\Phi{}^4$

Deviation can be large ~ 100%

SK, Kiyoura, Okada, Senaha, Yuan, 2003
Braathen, SK (2019)

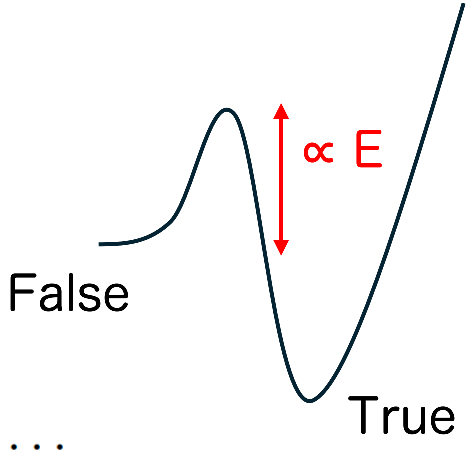
Physics of non-decoupling also affects 1st OPT



1st OPT by non-decoupling effect

Effective Potential at finite T (HTE)

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - \underline{ET\varphi^3} + \frac{\lambda_T}{4}\varphi^4 + \cdots$$



Sphaleron decoupling condition $\boxed{\frac{\varphi_c}{T_c} > 1}$ $\quad \frac{\varphi_c}{T_c} \propto E$

SM: The condition cannot be satisfied $\frac{\varphi_c}{T_c} = \frac{2E}{\lambda_T} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$

Non-minimal Higgs can satisfy it due to non-decoupling quantum effects

$$\frac{\phi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^2 + 3m_Z^3 + \underline{\sum_\Phi n_\Phi m_\Phi^3 \left(1 - \frac{M^2}{m_\Phi^2}\right)^{3/2}}\right\} > 1 \quad \text{(when } M < m_\Phi\text{)}$$

Quantum effects of Φ(= H, A, H+, …)

Same physics gives a large deviation in the hhh coupling

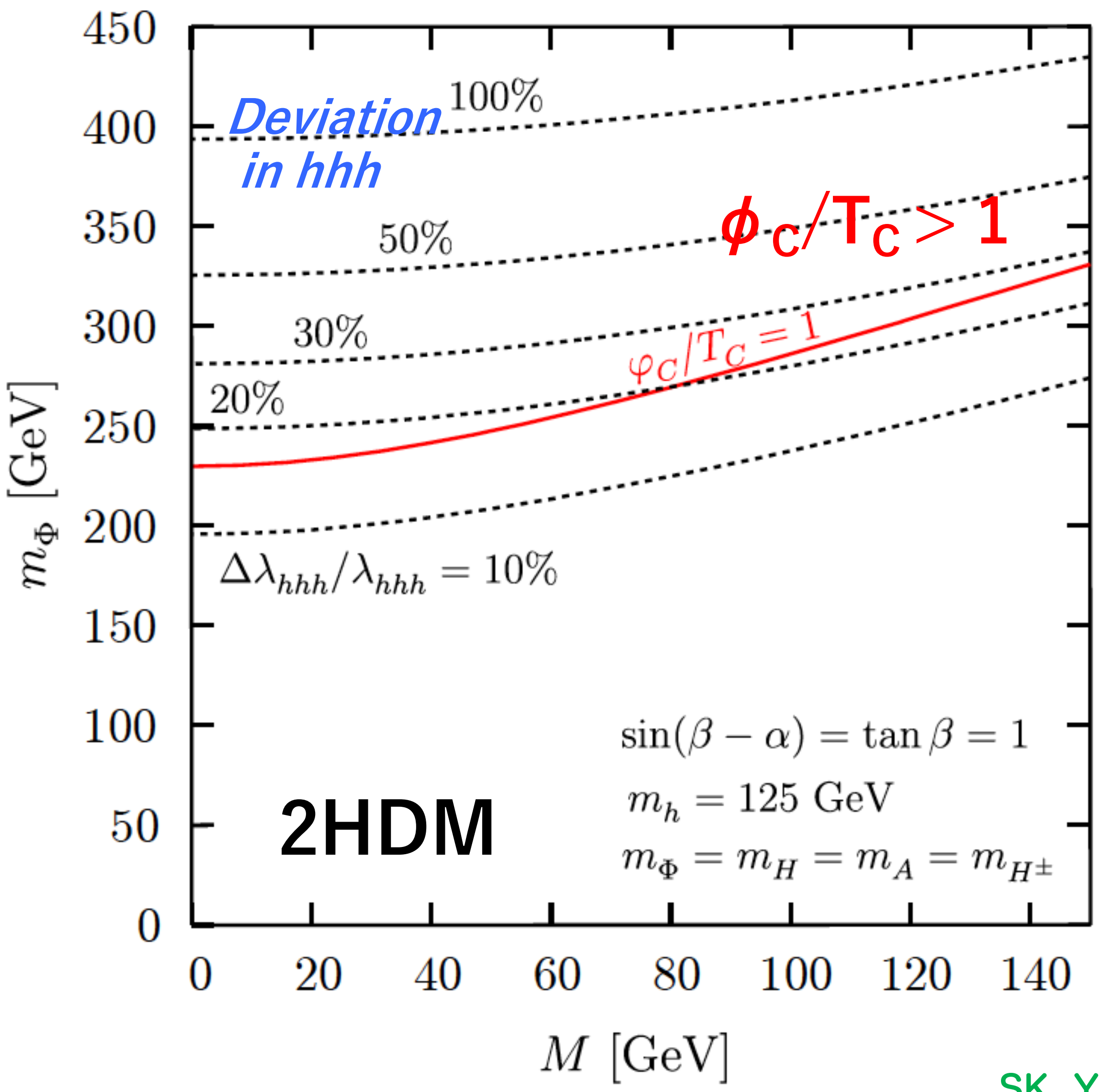
$$\lambda_{hhh} \simeq \frac{3m_h^2}{v}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \underline{\sum_\Phi n_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3}\right\} > \lambda_{hhh}^{SM}$$

SK, Y. Okada, E. Senaha, 2005

SFOEWPT

v.s.

Deviation
in the hhh coupling

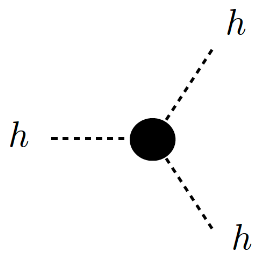


SK, Y. Okada, E. Senaha, 2005

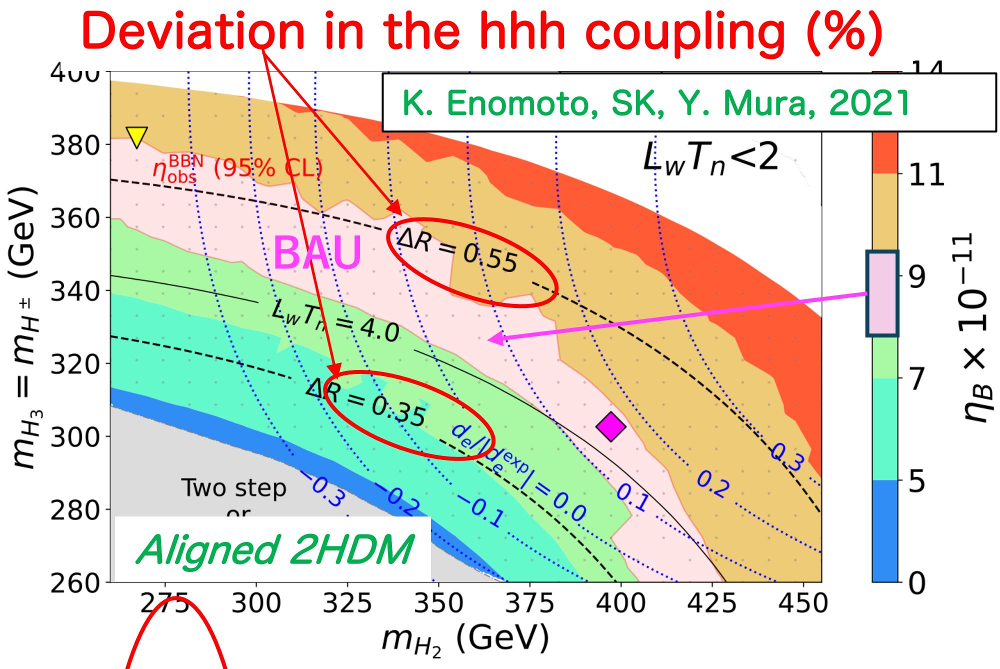
4. Testing the Higgs potential at colliders

Higgs self-coupling (hhh) and the diphoton decay (h$\gamma\gamma$)

hhh from 1st OPT



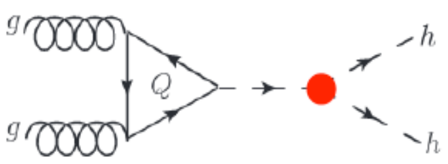
Example ➡ Aligned 2HDM: viable scenario of EWBG

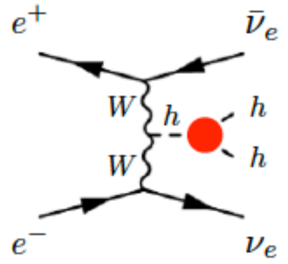


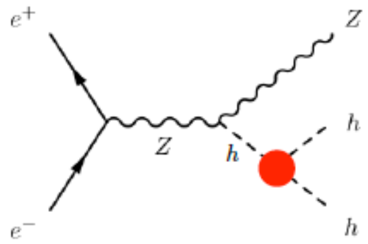
Strongly 1st OPT
→ A large deviation in the hhh coupling

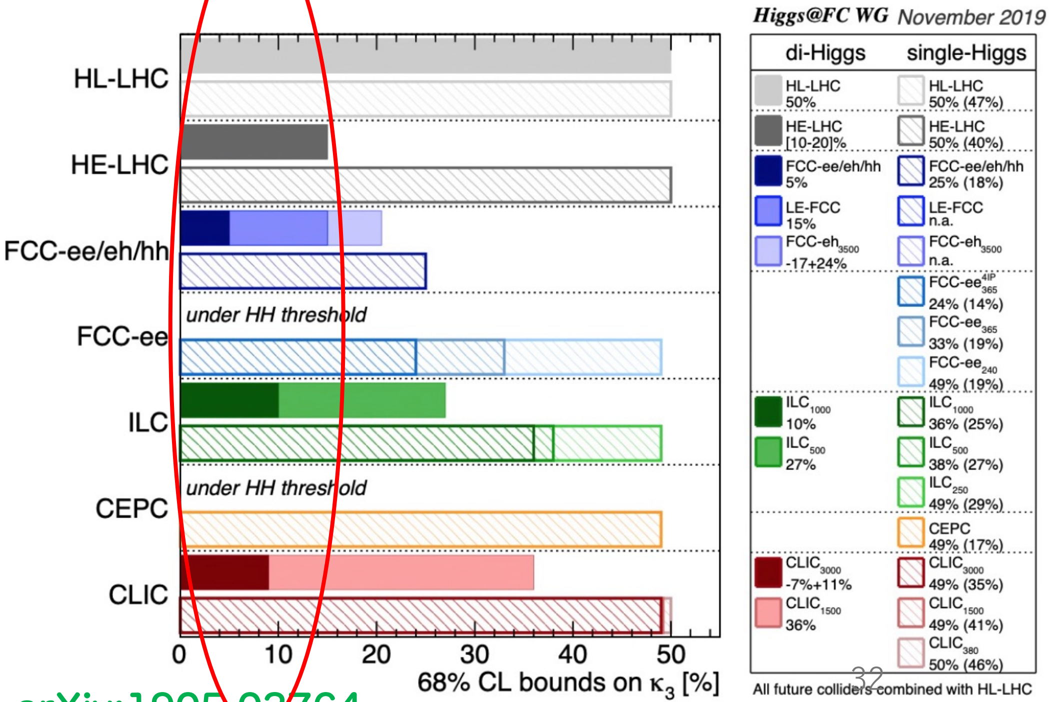
40 — 60%

The hhh coupling can be measured at HL-LHC, or future lepton colliders







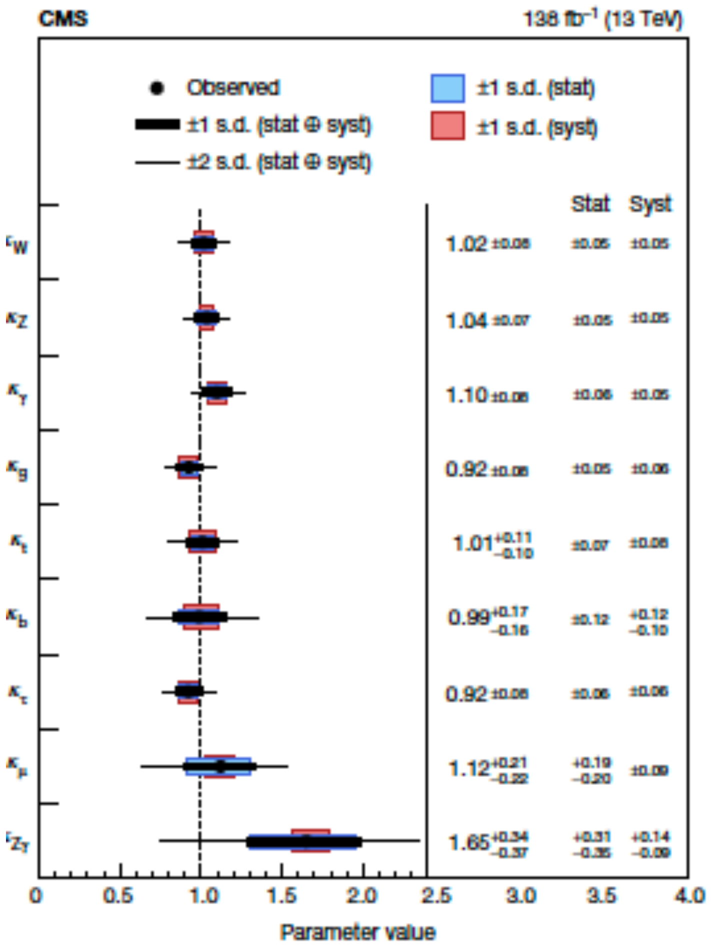


arXiv:1905.03764

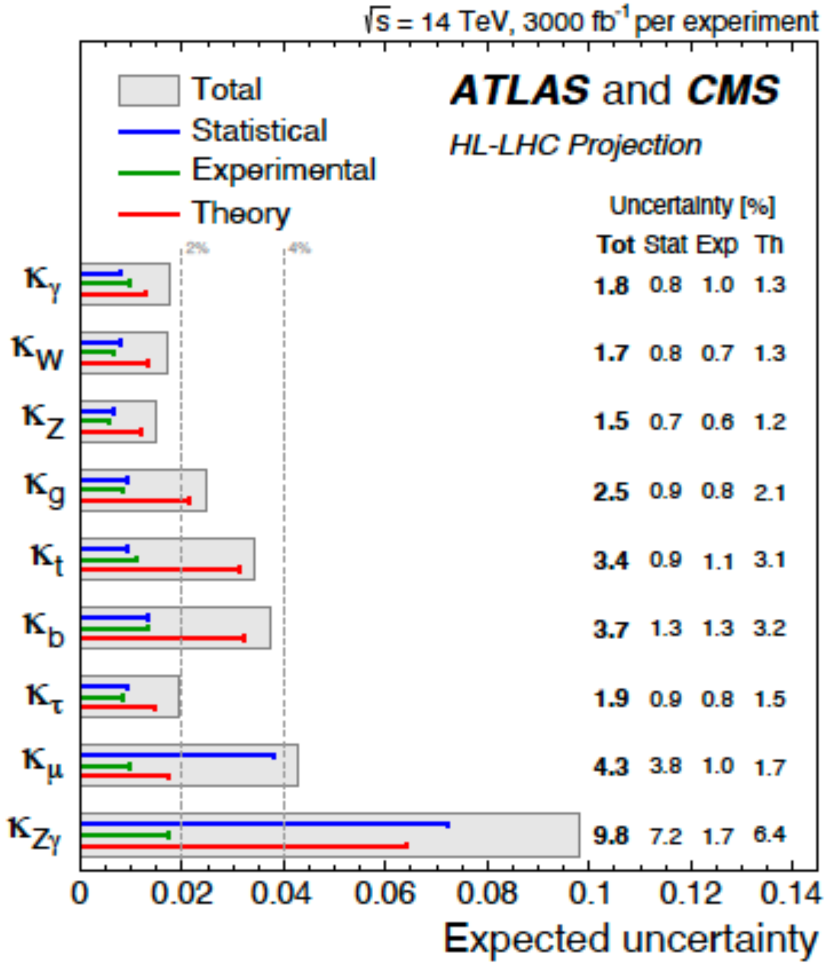
EW Baryogenesis can be directly tested by the hhh measurement

Hγγ can also be sensitive to non-decoupling effects

Higgs coupling measurements

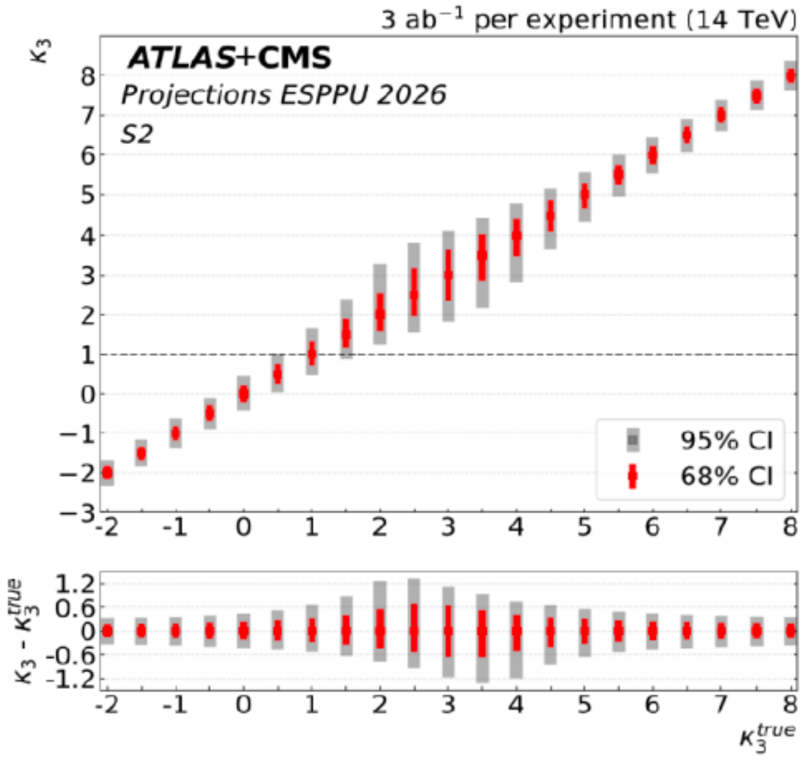


Today



Future

hhh



Future

Di-Photon decay of h(125)

Ex) Case of the inert doublet model

Loop induced

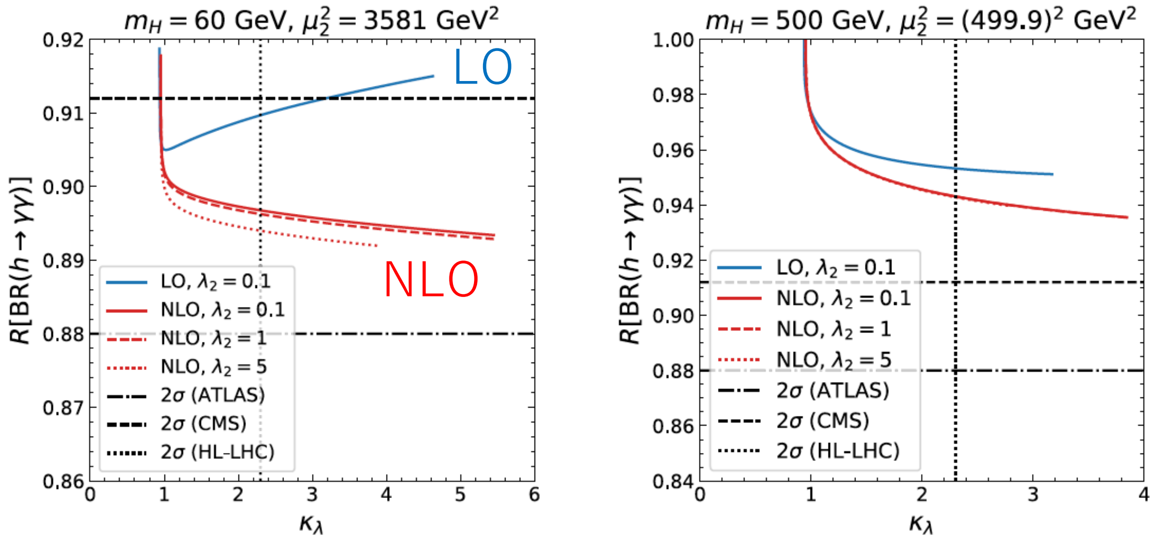
Small rate but sensitive to new charged particles

Large deviation from new physics models especially for models with non-decoupling property

$h \to \gamma\gamma$, $gg \to hh$

Can give strong constraint on BSM models

Resonant DM scenario　　Heavy DM scenario



Aiko, Braathen, SK, 2023

NLO (2 loop) correction is important

CPV: EDM in EW baryogenesis models

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

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

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

Barr-Zee diagram

Difficult

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

- **General 2HDM** Viable EWBG as the aligned 2HDM, but ⋯

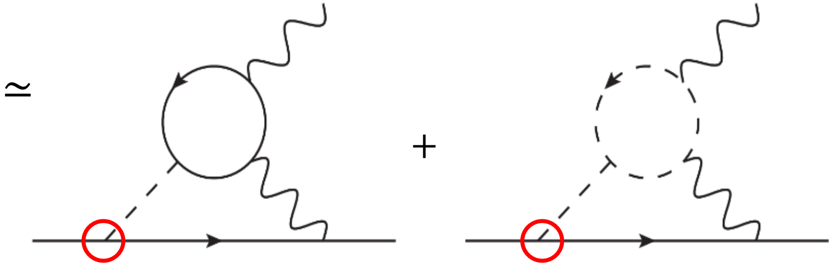
Fuyuto, et al. (2019); SK Kubota and Yagyu (2020), Enomoto, SK and Mura (2021), (2022); ⋯

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

Cancellation among Barr-Zee-type diagrams can be used

EDM cancellation

$d_e \simeq$



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

Is it really necessary?
No. It is possible to built a 2HDM without EDM cancellation   Aiko, Endo, SK, Mura 2025

Correlation between EDM and BAU in the minimal set up

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

Parameter scan

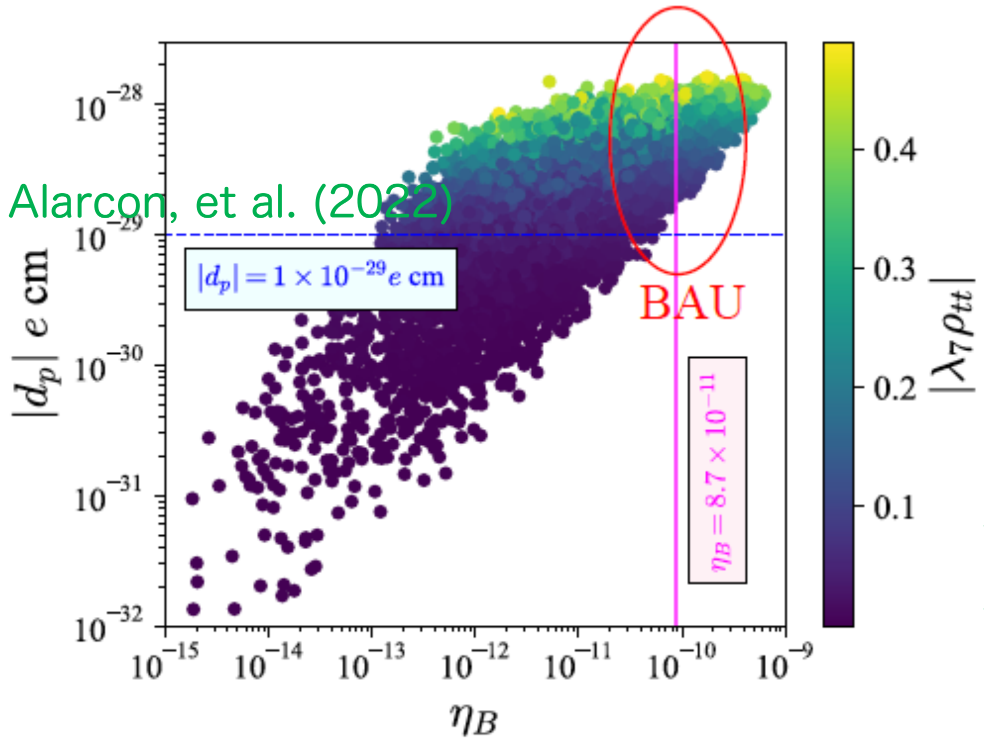
$m_\Phi = [200, 500]\ \mathrm{GeV}, \mu_2^2 = [-m_\Phi^2, 0], |\rho_{tt}| = [0, 0.5]$

$|\lambda_7| = [0,1], \lambda_2 = [0,1], \arg[\lambda_7 \rho_{tt}] = -\pi/2, v_w = [0.1, 1/\sqrt{3}]$

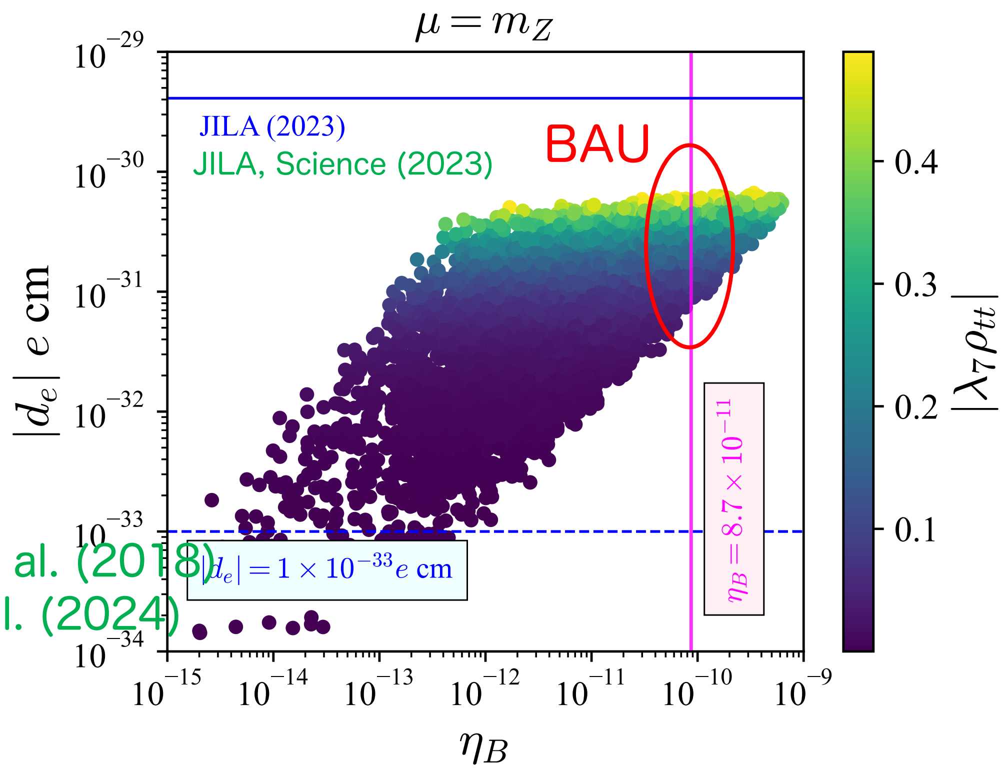
Neutron EDM

Sahoo, PRD (2017)

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



Electron EDM

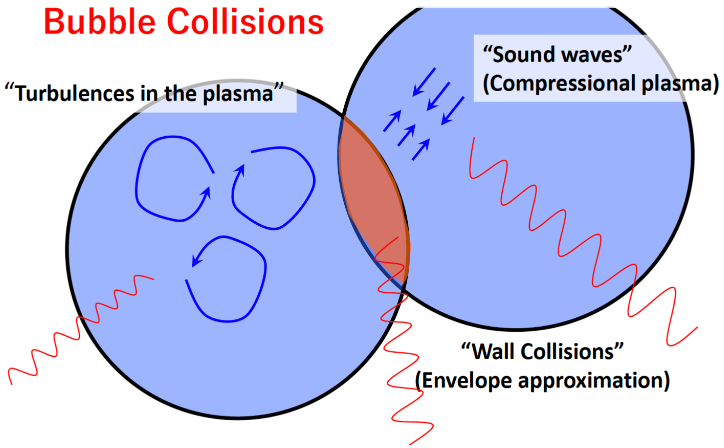


Viable, and testable at future EDM experiments

5. Complementary tests of the early Universe

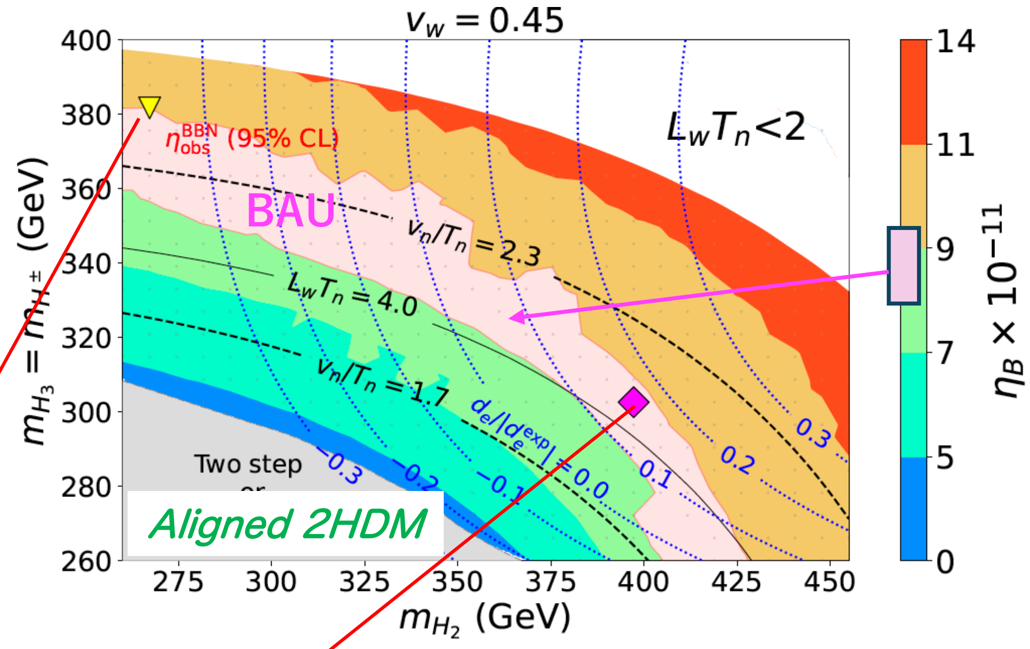
Phase-transition signatures in gravitational waves and PBH

GW from 1stOPT

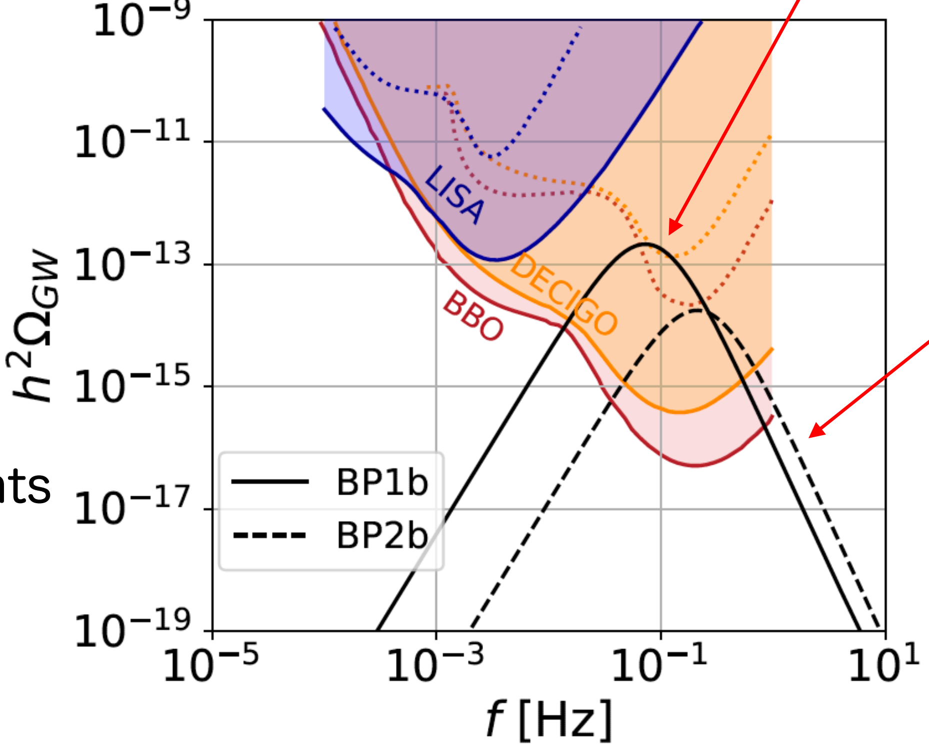


Example
Aligned 2HDM

K. Enomoto, SK, Y. Mura, 2022



K. Enomoto, SK, Y. Mura, 2022



GWs for benchmark points of BAU

They may be tested by future GW experiments

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

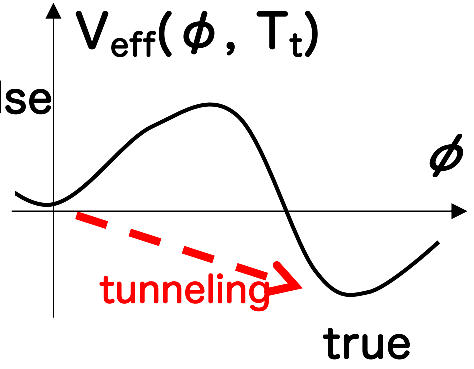
Solid curves: $h^2\Omega_{PISC}$ [SNR criterion]
J. Cline et al., arXiv: 2102.12490

From bubble dynamics to GW spectrum

Nucleation rate per time and volume $\Gamma(T) = \Gamma_0 \exp(-S_3/T)$

Linde 1983

$$S_3 = \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi_b)^2 + V_{\rm eff}(\varphi_b, T)\right]$$



T_t transition temp is determined by $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$ ➡ $\frac{S_3(T_t)}{T_t} = 4\ln(T_t/H_t) \simeq 140$

- α Latent heat (released E of False vacuum) — Depth of the potential

$$\alpha = \frac{\epsilon(T_t)}{\rho_{\rm rad}(T_t)} \qquad \epsilon(T) = -V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial V_{\rm eff}(\varphi_B(T), T)}{\partial T}$$

- β Inverse of duration of phase transition — Speed of transition

$$\beta = -\left.\frac{dS_E}{dt}\right|_{t=t_t} \simeq \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_t} \qquad \tilde{\beta} = \frac{\beta}{H_t}$$

GW Spectrum is determined by T_t, α, β, v_b

C.Caprini et al., arXiv:1512.06239

ex) GW strength and peak frequency from sound waves (Fitting function)

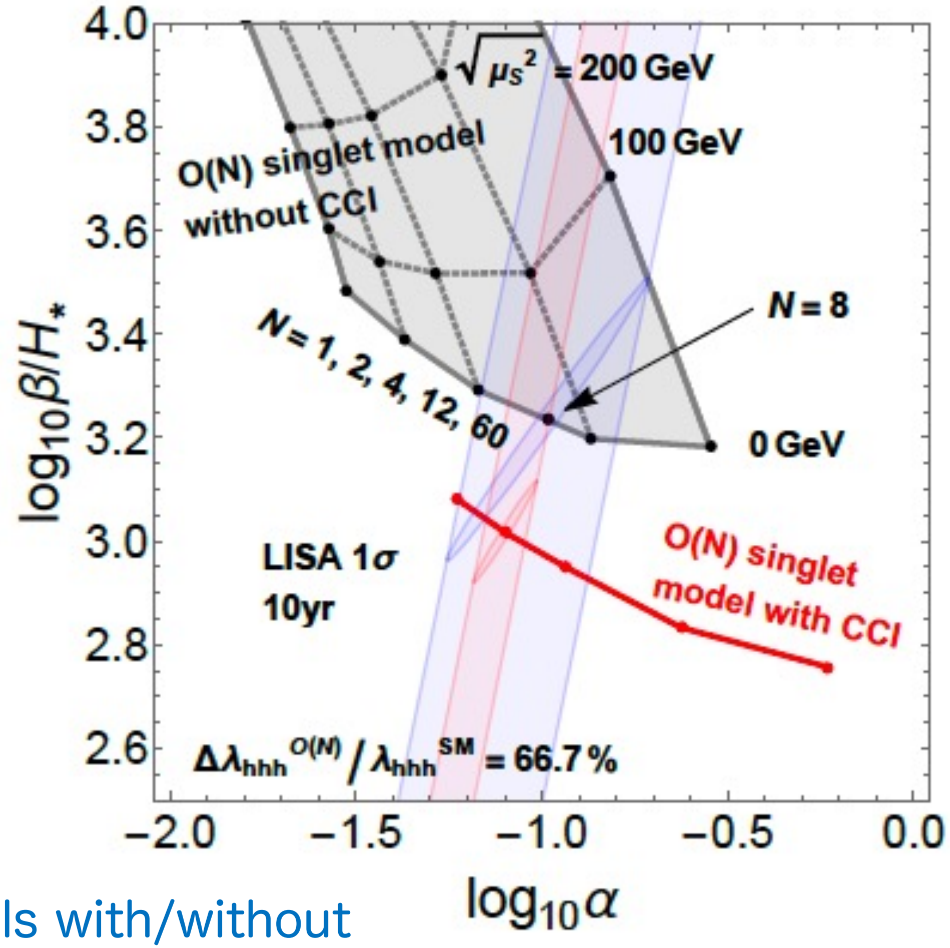
$$\tilde{\Omega}_{\rm sw}h^2 \simeq 2.65 \times 10^{-6}\frac{v_b}{\tilde{\beta}}\left(\frac{\kappa(v_b,\alpha)\alpha}{1+\alpha}\right)^2 \qquad \tilde{f}_{\rm sw} \simeq 1.9 \times 10^{-5}{\rm Hz}\frac{\tilde{\beta}}{v_b}$$

v_b: wall velocity

GW as a probe of models of SFO EWPT

- Detailed measurements of GW (Ω_{GW}, f_{peak}, ⋯)
- Parameter space of 1st OPT (α, β, ⋯)
- Fingerprinting the Higgs models of 1st OPT!

(# of fields, mass, ⋯)



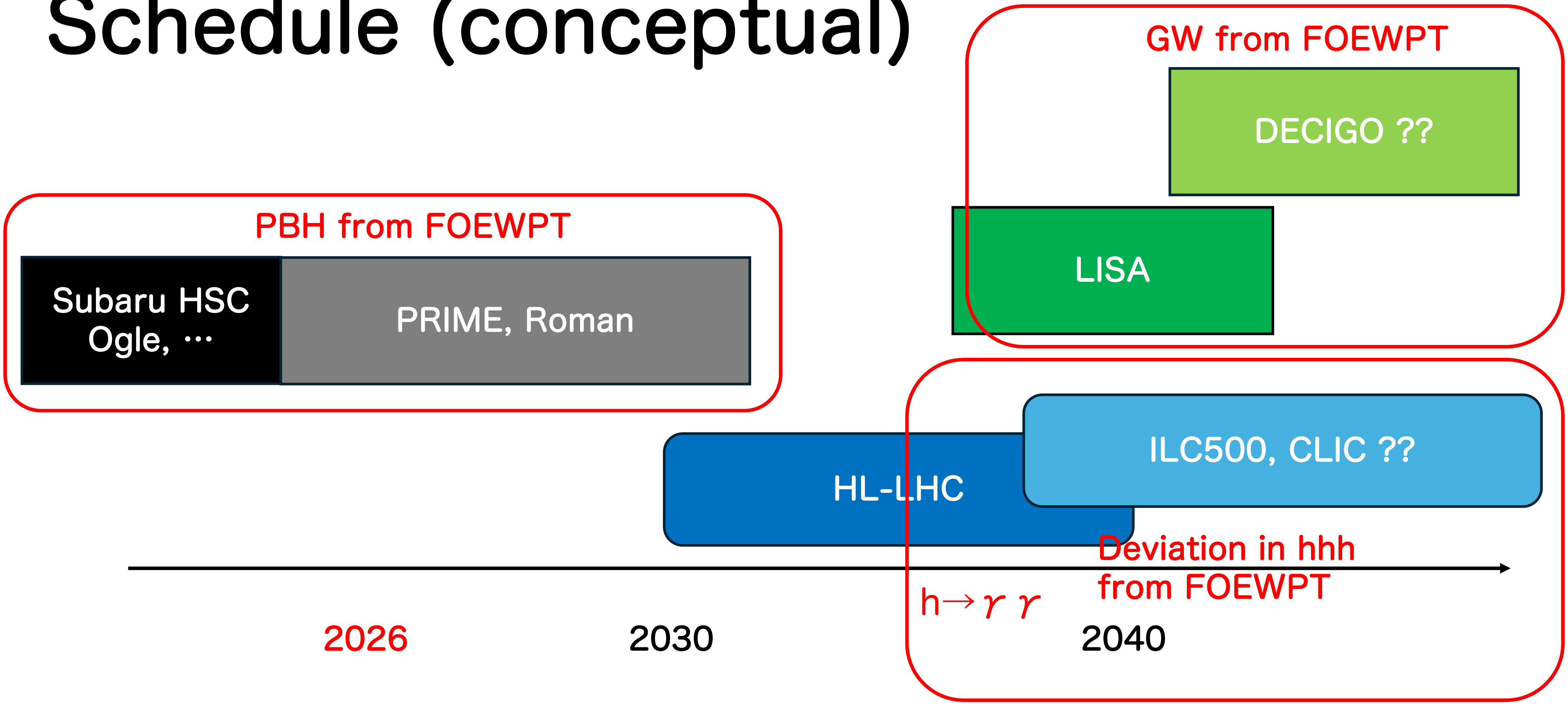
O(N) scalar models with/without the classical conormal invariance

Hashino, Jinno, Kakizaki, SK, Takahashi, Takimoto (2018)

Why PBH is interesting for Higgs physics?

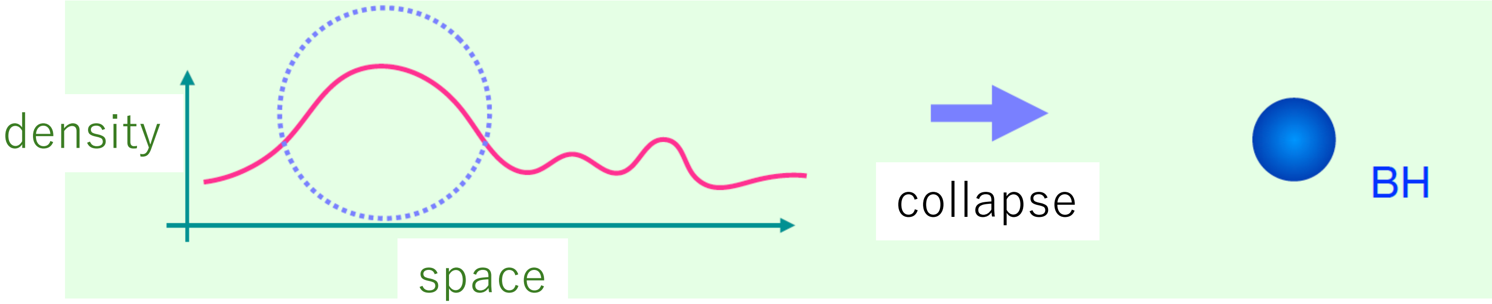
1. Can PBHs provide another probe?
2. Microlensing observations underway

Schedule (conceptual)



Complementarity

PBH



Primordial black holes (PBH)：BHs formed before the star formation

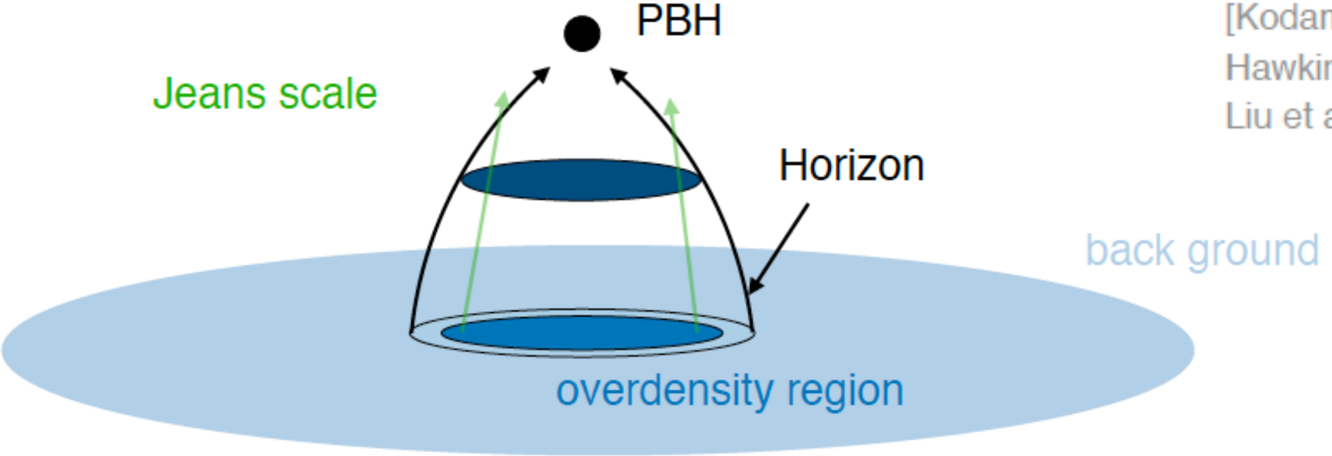
Condition for the PBH formation

$$\delta = \frac{\rho_{\rm over} - \rho_{\rm back}}{\rho_{\rm back}} > \delta_C$$

[Hawking, Mon. Not. Roy. Astron. Soc. 152 (1971),
Hawking and Carr, Mon. Not. Roy. Astron. Soc. 168 (1974),
Harada, Yoo and Kohri, PRD 88 (2013)]

$\delta > \delta_C$ can be satisfied when the FOPT occurs

PBHs may be produced by density fluctuation of EWPT in spacetime



[Kodama, Sasaki and Sato, PTP 68 (1982);
Hawking, Moss and Stewart, PRD 26 (1982)
Liu et al., PRD105 (2022)]

Figure by Masanori Tanaka

PBH from delayed FOEWPT

FOEWPT with small β

↓

Delayed vacuum decay

↓

Contrast δ grows

↓

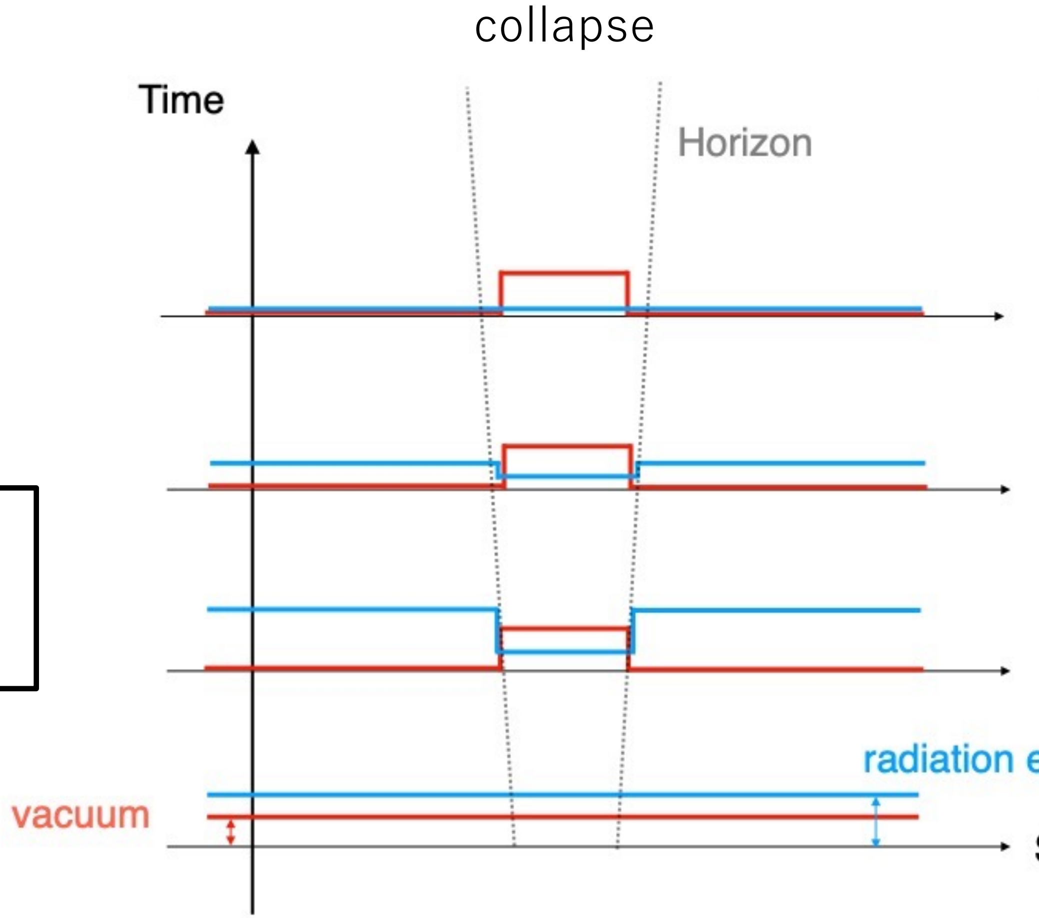
At the time t_{PBH}

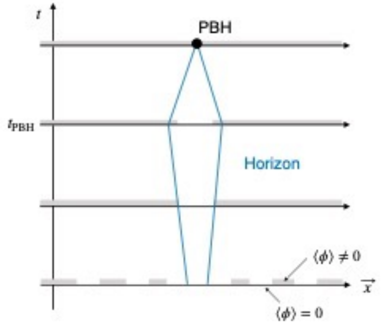
$\delta > \delta_c$

$$\delta = \frac{\rho_{\rm in}(t_H) - \rho_{\rm out}(t_H)}{\rho_{\rm out}(t_H)}$$

↓

PBH?





$\rho_{\rm rad} \propto a^{-4}$

$\rho_{\rm vac} = {\rm const}$

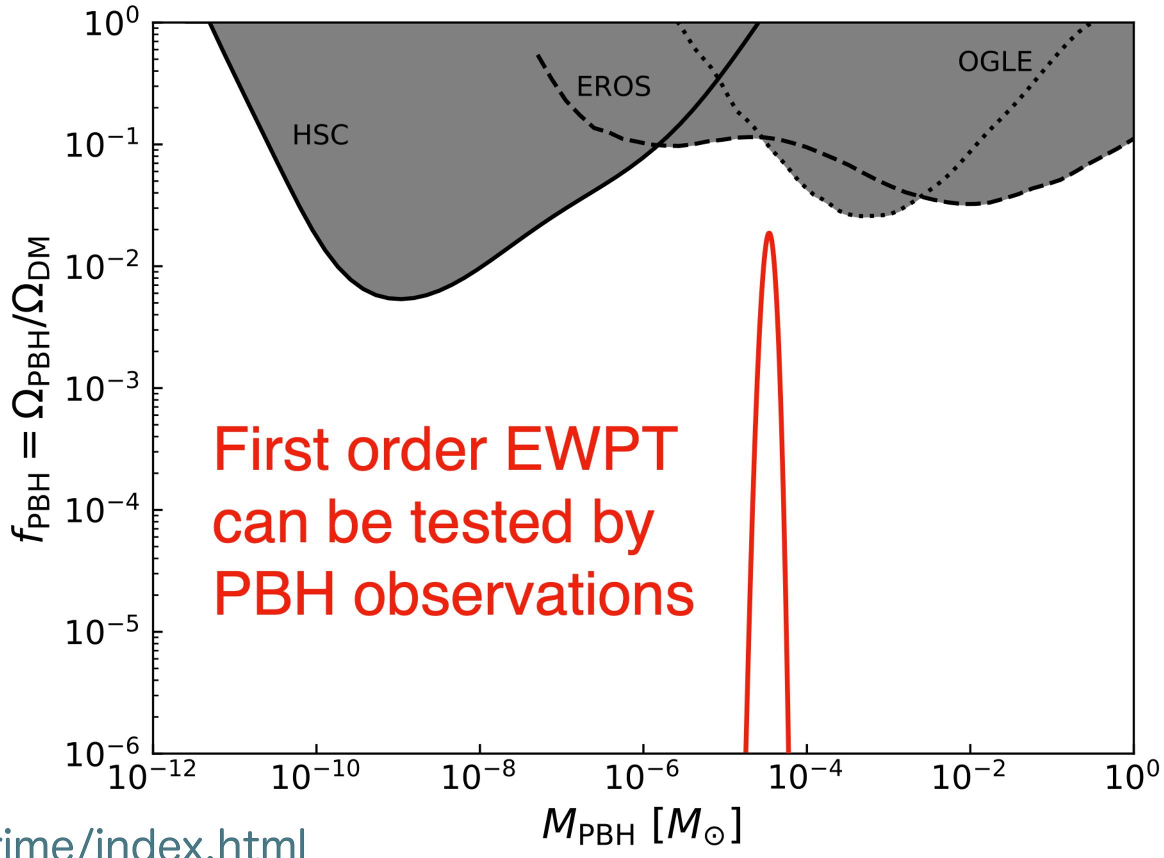
PBH from SFOEWPT

K. Hashino, SK, T. Takahashi, 2021
K. Hashino, SK, T. Takahashi, M. Tanaka 2023

Mass of PBH is determined by t_{PBH}

$$M_{PBH} \approx \frac{4\pi}{3} H^{-3}(t_{PBH})\rho_c = 4\pi H^{-1}(t_{PBH})$$

$$M_{PBH} \sim 10^{-5} M_\odot$$



Microlensing observations

Subaru HSC https://hsc.mtk.nao.ac.jp/ssp
OGLE http://ogle.astrouw.edu.pl/

Future observations

PRIME 2023~ http://www-ir.ess.sci.osaka-u.ac.jp/prime/index.html
Roman 2026~ https://roman.gsfc.nasa.gov

Using far infrared rays:
sensitive to the microlensing
from center galaxy

f_{PBH} is constrained by 10^{-4}

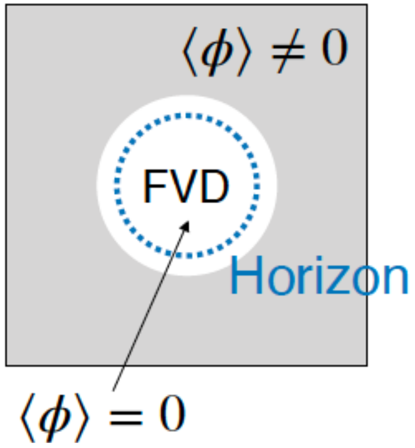
Is the conventional density-contrast criterion applicable to FVD?

- $\delta > \delta_c$ ($\delta_c = 0.45$): collapse threshold for a radiation overdensity
- Delayed EWPT: false-vacuum domain + wall
- Does ($\delta > \delta_c$) really imply PBH formation?

We therefore solve the gravitational dynamics of the false-vacuum domain and its wall.

Hashino, SK, Takahashi, Tanaka, Yoo, JCAP 09 (2025) 006

The wall equation of motion yields two branches



Assumptions: Spherical symmetry; Thin wall approximation (tension σ)

Metric: Inside: Rriedman-Robertson-Walker (de Sitter); Outside: Spherical symmetric metric

Israel junction condition

Equation of Motion

$$\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = \left(\frac{3\sigma}{4M_{p\ell}^2} - \frac{\rho_V}{\sigma}\right)\frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$$

friction; curvature; gravitational effect of the wall; Energy vacuum

$R(t)=a(t)\chi(t)$

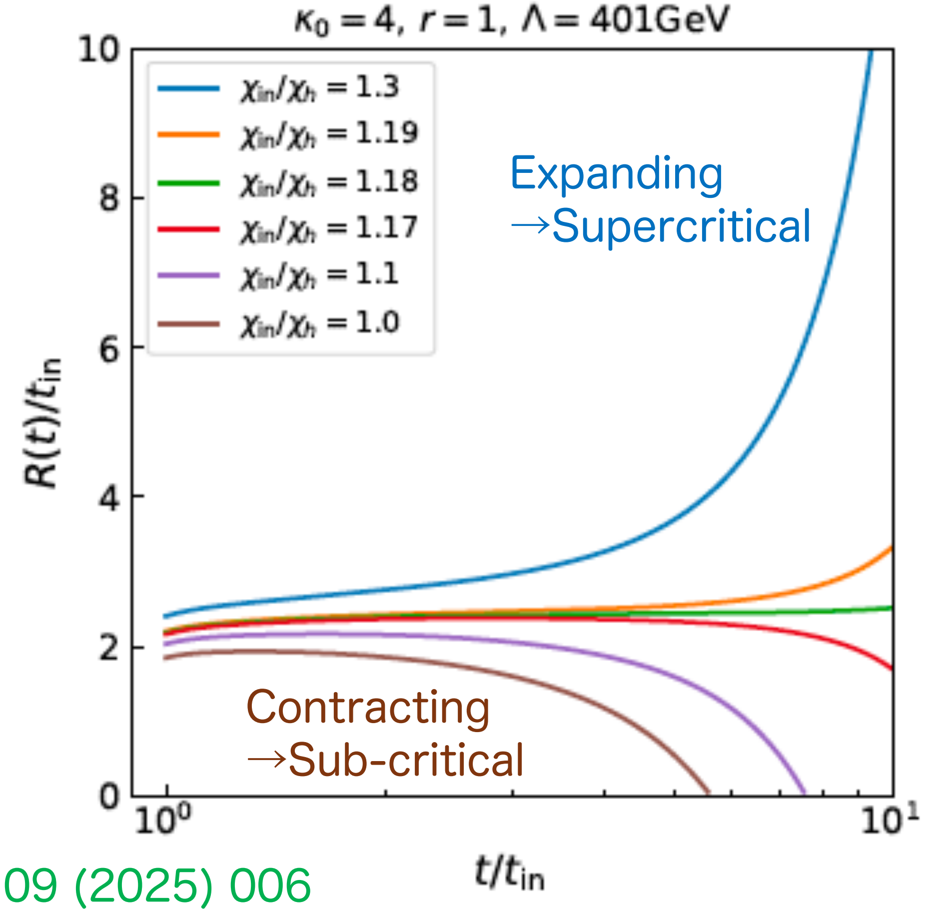
$\chi_{in} = \chi(t_{in})$

$\chi_H = \chi(t_H)$

t_{in}: initial time defined by $F(t_{in})=0.7$

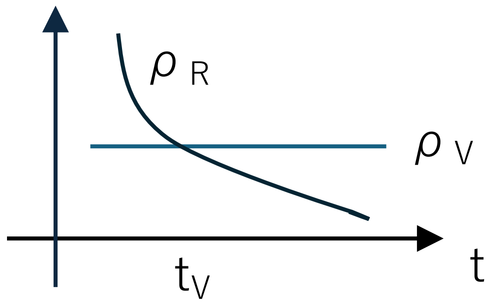
t_H: horizon-entry time of the FVD

$F(t)$: false-vacuum fraction



Hashino, SK, Takahashi, Tanaka, Yoo, JCAP 09 (2025) 006

Two different solutions: Supercritical / Sub-critical



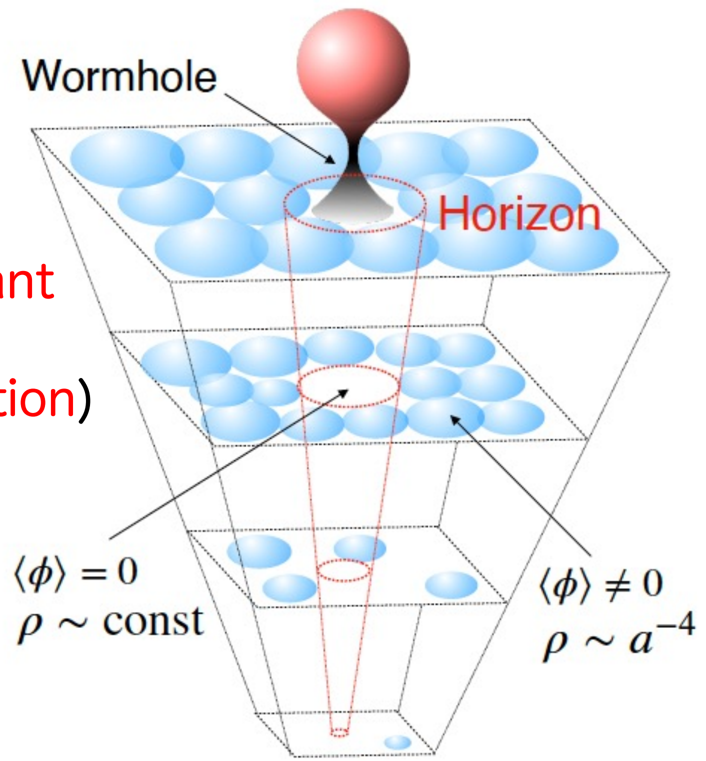
Supercritical

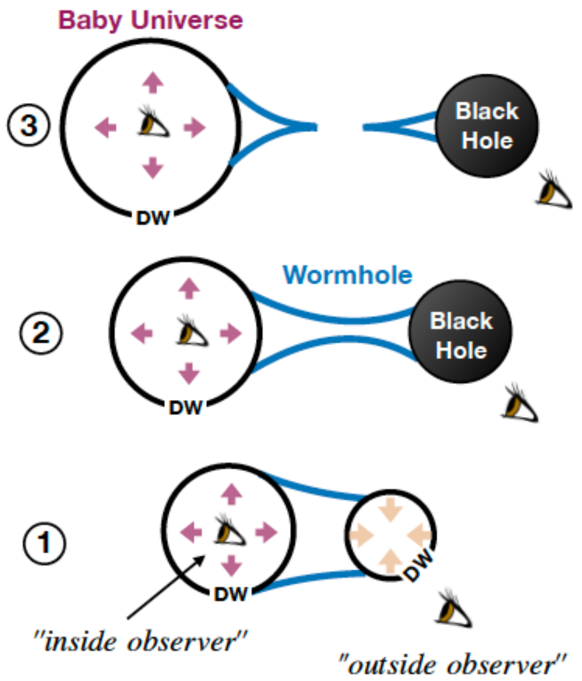
FVD formation

t_V FVD vacuum dominant
($\rho_V > \rho_R$)
De Sitter (local inflation)

t_H Horizon re-entry

FVD is seen as a PBH from outside





[Y. Gouttenoire et al, arXiv: 2501.16414]

Sub-critical

FVD formation

t_H Horizon re-entry

t_V FVD Collapse

Collapse

PBH not guaranteed

PBH mass, fraction

PBH mass: determined by the formation scale

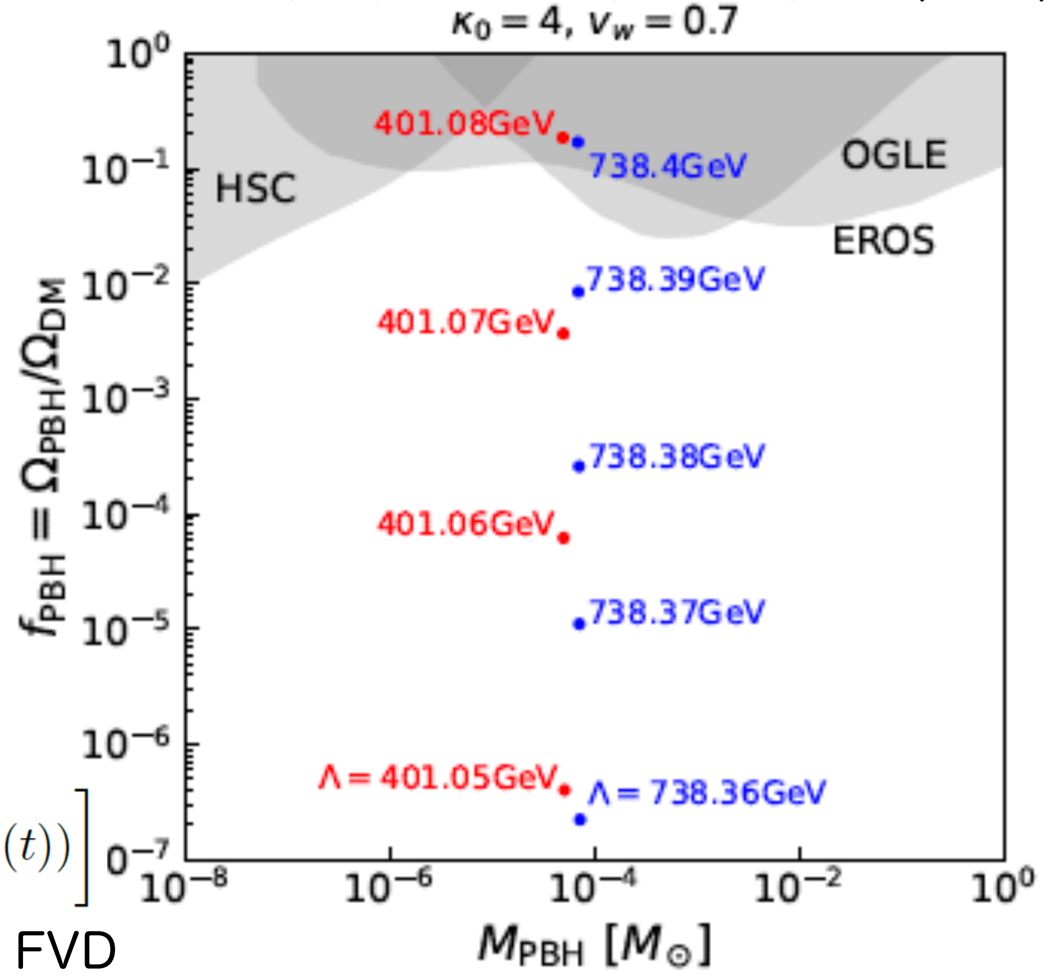
$$M_{\rm PBH} \sim 4\pi M_{p\ell}^2 H(t_{\rm PBH})^2 R(t_{\rm PBH})^3 \sim 4\pi M_{p\ell}^2 H^{-1}(t_{\rm PBH})$$

$$M_{\rm PBH} \sim 10^{-5} M_\odot$$

PBH abundance: determined by the probability of FVD formation

$$f_{\rm PBH} \sim 1.49 \times 10^{11} \left(\frac{0.25}{\Omega_{\rm DM}}\right) \left(\frac{T(t_{\rm PBH})}{100\,{\rm GeV}}\right) P(\chi_{\rm th})$$

Hashino, SK, Takahashi, Tanaka, Yoo (2025)



$$P(\chi_{\rm in}) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t_V} dt \frac{a^3(t)}{a^3(t_{\rm in})} R(t_{\rm in})^3 \Gamma(T(t))\right]$$

survival probability of a Hubble-sized FVD

The PBH abundance is exponentially sensitive to the phase-transition dynamics.

6. Probing the thermal history of the Universe

Modeling the Higgs sector for the 1st OPT

$$V_{\rm naHEFT}(\phi,T) = V_{\rm SM}(\phi,T) + V^{\rm BSM}_{T=0}(\phi) + V^{\rm BSM}_{T}(\phi,T)$$

$$V^{\rm BSM}_{T=0}(\phi) = \frac{\kappa_0}{64\pi^2}\left[M^2(\phi)\right]^2 \ln\frac{M^2(\phi)}{\mu^2} \qquad M^2(\phi) = M^2 + \frac{\kappa_p}{2}\phi^2$$

$$V^{\rm BSM}_{T}(\phi,T) = \frac{\kappa_0}{2\pi^2}T^4\int_0^\infty dk k \ln\left(1-\exp\left[-\sqrt{k+M^2(\phi)/T^2}\right]\right)$$

Described by three parameters

$$\Lambda = \sqrt{M^2+\frac{\kappa_p}{2}v^2},\quad \kappa_0,\quad r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

Mass of new particles (Λ)

D. o. F. of new particles (κ_0)

Decoupling parameter (r)

r: decoupling property

$r \sim 0 \Rightarrow M^2 \gg \frac{\kappa_p}{2}v^2$ Decoupling

$r \sim 1 \Rightarrow M^2 \ll \frac{\kappa_p}{2}v^2$ Non-decoupling

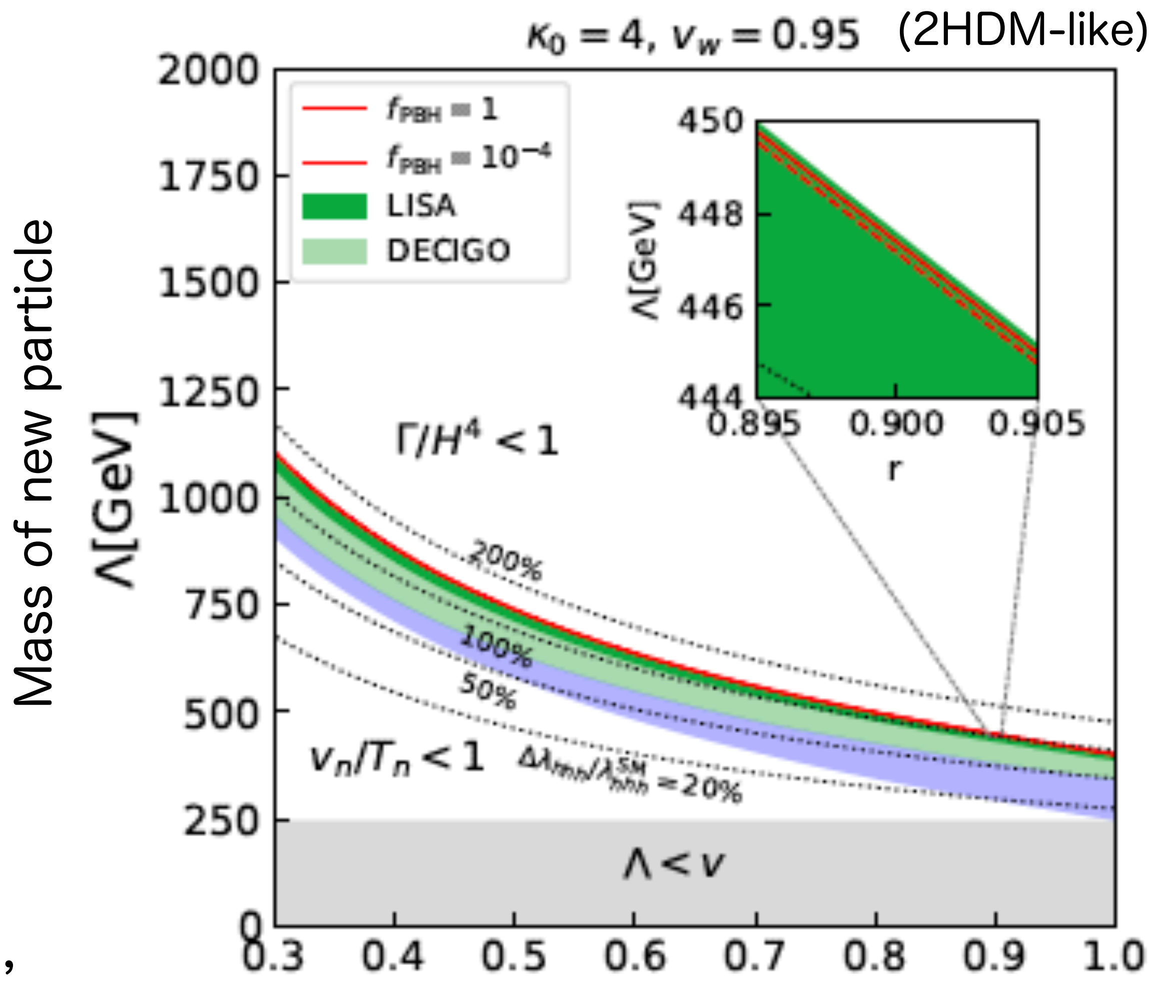
Complementary probes of a strongly first-order EWPT

Hashino, SK, Takahashi, Tanaka, Yoo (2025)

Sphaleron decoupling condition $v_n/T_n > 1$

Bubble nucleation completion $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

- PBH (red) — Supercritical PBH
- GW (LISA)
- GW (DECIGO)
- Only $\Delta\lambda_{hhh}$ (HL-LHC, ILC, …)



FOEWPT can be explored by PBH observation, in addition to GW observations and collider experiments

Strongly 1st OPT

Colored region satisfies two conditions

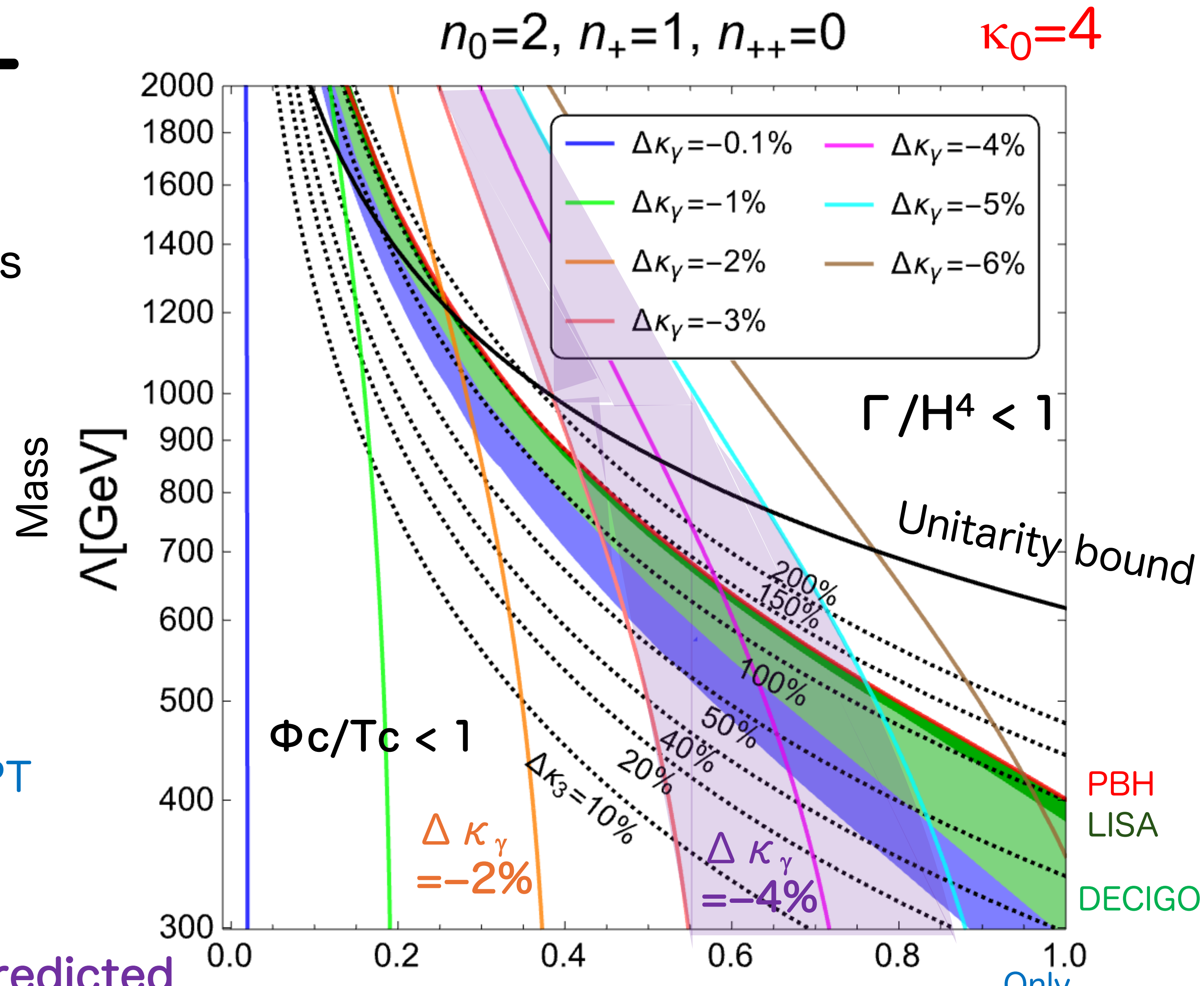
- Sphaleron decoupling $\frac{\varphi_c}{T_c} \gtrsim 1$
- Bubble nucleation completion $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

- PBH (Roman detectable $f_{PBH} > 10^{-4}$)
- GW (LISA detectable)
- GW (DECIGO detectable)
- Only Higgs couplings can test 1st OPT
  ($\Delta\lambda_3$, $\Delta\kappa_\gamma$, ...)

If $\Delta\kappa_\gamma$ = -4% ± 1% (LHC+ILC), predicted

135% > $\Delta\kappa_3$ > 55%

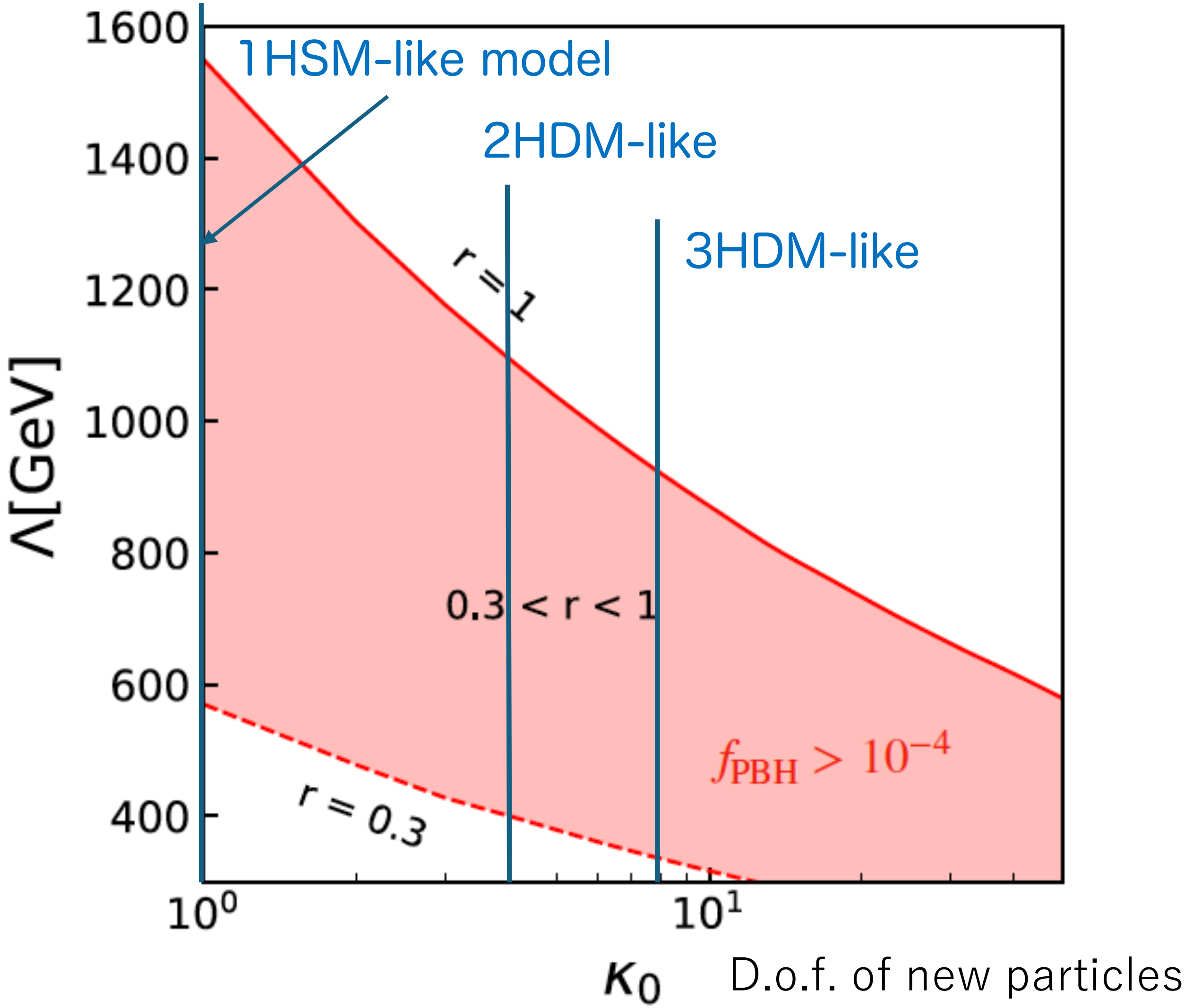
GW, PBH can also be used



R. Florentino, S.K., M. Tanaka (2024)

Parameter Regions testable by PBH

Scanning the non-decoupling parameter r substantially enlarges the region testable by PBH searches.

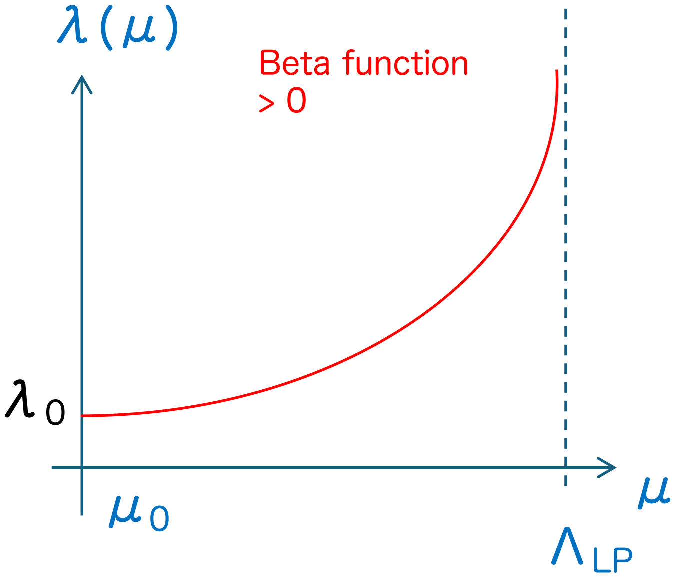


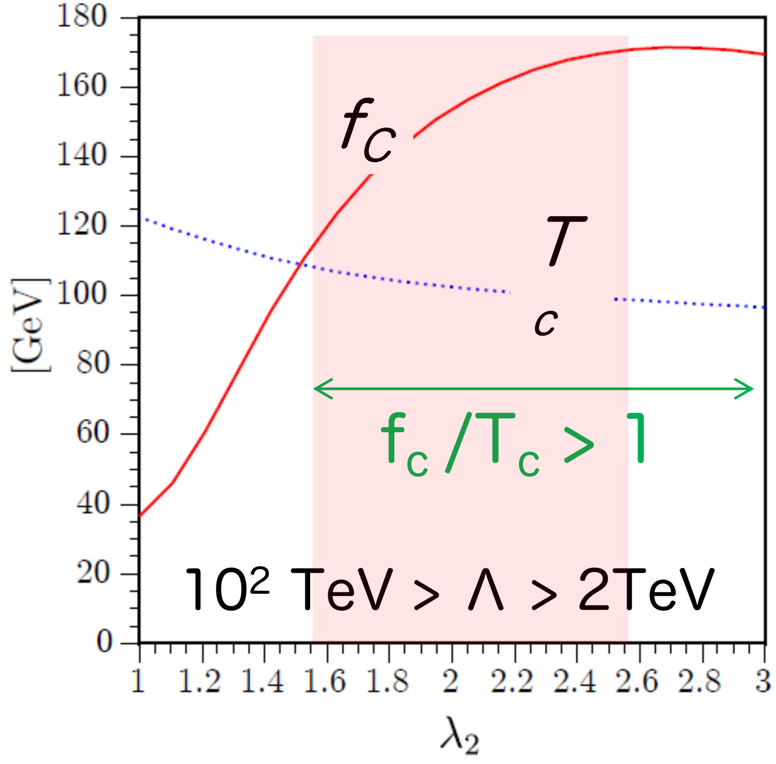
Landau pole and above

S.K., E. Senaha, T. Shindou 2011

1st OPT → Landau pole

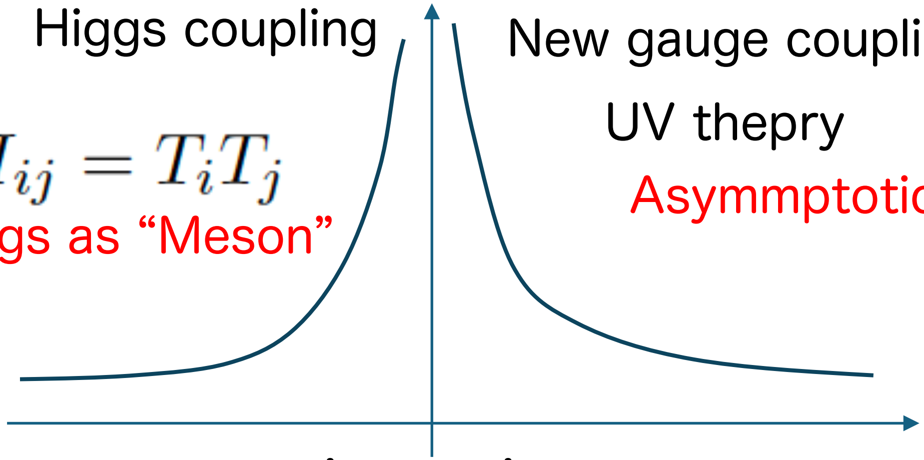
$$\frac{\varphi_c}{T_c} > 1 \Leftrightarrow \Lambda_{LP} = \mathcal{O}(10)\mathrm{TeV}$$





<u>What is above ?</u>

Higgs interaction
→ SU(N) gauge interaction



UV thepry

$$H_{ij} = T_i T_j$$

Higgs as "Meson"

Asymmptotic free $SU(2)_H$ Theory

T_i Fundamental Rep.

$N_c + 1 = N_f$

SFOEWPT
⇄ Composite nature of Higgs boson?

SK, T. Shindou, T. Yamada (2012)

Intriligator Seiberg (1996)

Summary

- **The Higgs discovery opened a new question about our cosmic history**
  How did the Universe reach today's electroweak vacuum?

- **The nature of the electroweak transition is a key target**
  The SM predicts a crossover, while electroweak baryogenesis requires a strong first-order transition and new CP violation.

- **Higgs measurements can probe the physics behind this transition**
  The self-coupling (hhh) and the diphoton decay ($h \to \gamma\gamma$) provide complementary tests of extended Higgs sectors.

- **Laboratory experiments and cosmic observations test different aspects**
  - EDMs probe CP violation
  - gravitational waves probe transition dynamics.
  - Primordial black holes may provide an additional probe, depending on their formation dynamics.

Together, these observations may reveal the Higgs sector and the thermal history of the early Universe.

Dr. Wani
Osaka Univ. official mascot

Thank you !

Modeling the Higgs sector for the 1st OPT

naHEFT(nearly aligned Higgs EFT)

Higgs EFT Fergulio (1993), Giudice, et al (2007), … Buchalla, et al (2013)

$$\mathcal{L}_{\rm naHEFT} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm BSM},$$

$$\begin{aligned}\mathcal{L}_{\rm BSM} = \xi \Bigg[& -\frac{\kappa_0}{4}\left[\mathcal{M}^2(h)\right]^2 \ln\frac{\mathcal{M}^2(h)}{\mu^2} \\ & + \frac{v^2}{2}\mathcal{F}(h)\,{\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] + \frac{1}{2}\mathcal{K}(h)\,(\partial_\mu h)\,(\partial^\mu h) \\ & - v\left(\bar{q}_L^i U\left[\mathcal{Y}_q^{ij}(h) + \hat{\mathcal{Y}}_q^{ij}(h)\tau^3\right] q_R^j + h.c.\right) - v\left(\bar{l}_L^i U\left[\mathcal{Y}_l^{ij}(h) + \hat{\mathcal{Y}}_l^{ij}(h)\tau^3\right] l_R^j + h.c.\right)\Bigg] \\ & + g^2\mathcal{F}_W(h)\,{\rm Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}] + g'^2\mathcal{F}_B(h)\,{\rm Tr}[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}] \\ & - gg'\mathcal{F}_{BW}(h)\,{\rm Tr}[U\mathbf{B}_{\mu\nu}U^\dagger\mathbf{W}^{\mu\nu}]\end{aligned}$$

$$\xi = \frac{1}{16\pi^2} \qquad U = \exp\left(\frac{i}{v}\pi^a\tau^a\right)$$

$\mathcal{M}^2(h),\ \mathcal{F}(h),\ \mathcal{K}(h),\ \mathcal{Y}_\psi^{ij}(h),\ \hat{\mathcal{Y}}_\psi^{ij}(h)$

arbitrary polynomials

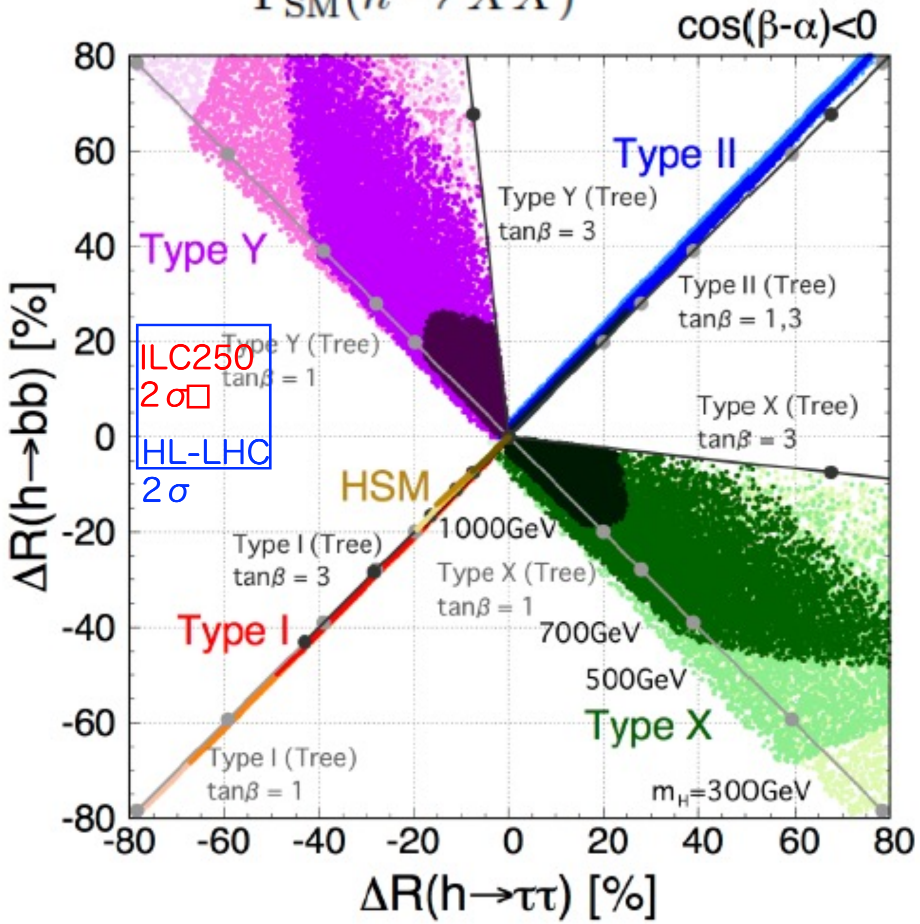
Describing leading non-decoupling effects
Coleman-Weinberg type structure (1 loop)

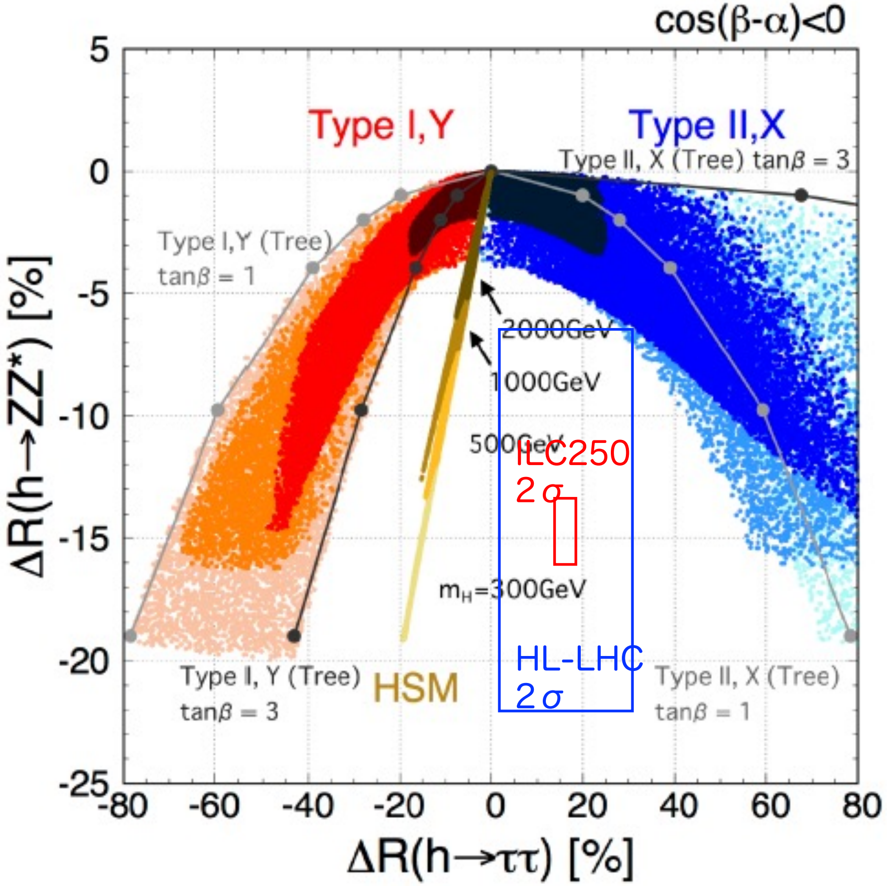
SK, R. Nagai (2021)

Fingerprinting

SK, Kikuchi, Mawatari, Sakurai, Yagyu 2018

$$\Delta R(h \to XX) = \frac{\Gamma_{NP}(h \to XX)}{\Gamma_{SM}(h \to XX)} - 1$$

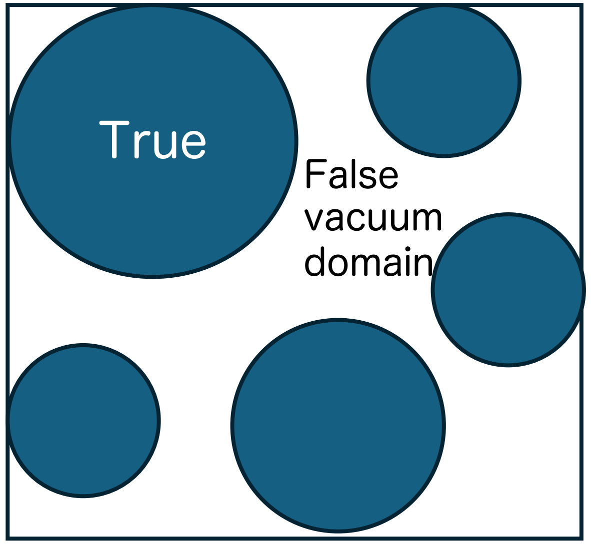


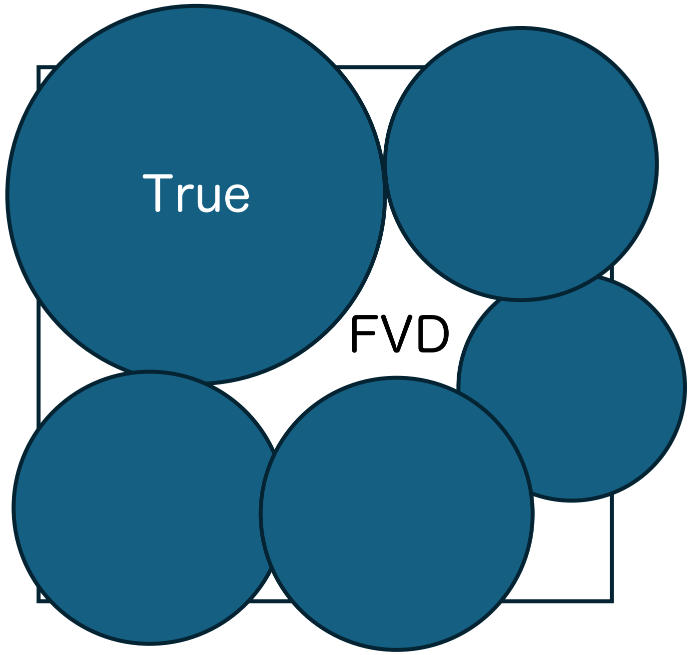


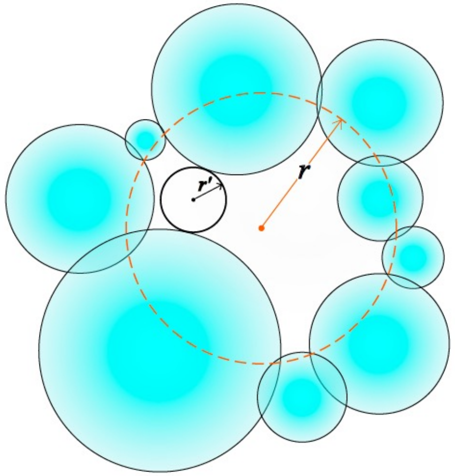
Run2
bb 130%
τ τ 64%
ZZ* 56%

Full set of 1-loop corrections (EW + QCD + Higgs) to the decay rates in various Higgs sectors and future precision measurements make us possible to fingerprint models and also to get information of inner parameters such as mass of the second Higgs boson

Beyond spherical symmetry







Non-sphericity: phenomenologically modeled by Lewicki et al., following the work of Kodama, Sasaki and Sato

Full gravitational dynamics beyond spherical symmetry remains open.

It is important to study the case without the spherical assumption

2HDM Higgs alignment case

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

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

General 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

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

rephasing

Higgs alignment

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

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

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

Yukawa alignment

Pich and Tuzon (2009)

Multiple CPV phases

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

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

Starting from the general 2HDM

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)

Most general potential

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

Most general Yukawa sector

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

Yukawa coupling Y_2 for the additional doublet Φ_2 is a 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.

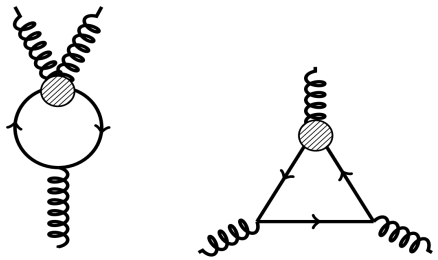
CPV rephasing invariants in the model $\mathbf{\Phi_2} \to e^{i\theta}\mathbf{\Phi_2}$

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)

EDM in the minimal setup

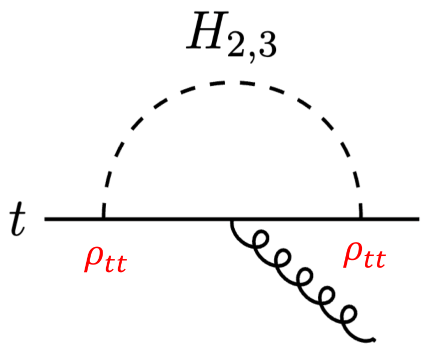
Top chromo EDM induces Weinberg operators and light fermion EDMs by RGE



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

1 loop diagram for top CEDM

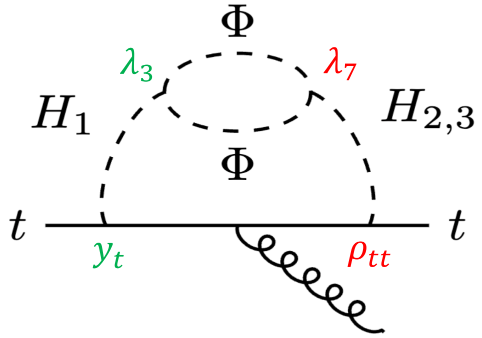
e.g.)



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

In our scenario, 2 loop diagrams are leading.

e.g.)

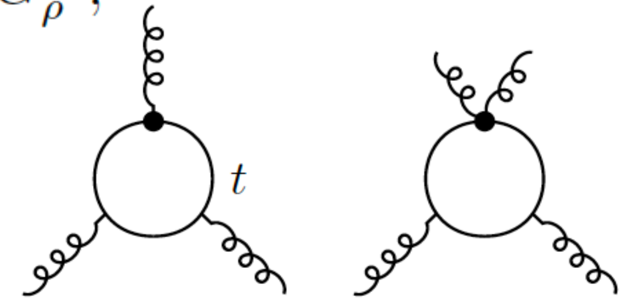


$\propto Im[\lambda_7 \rho_{tt}]$

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

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

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



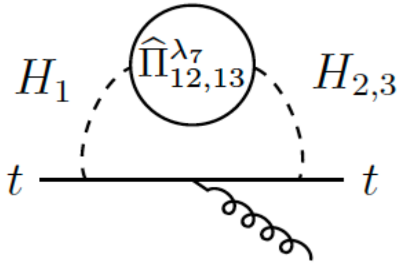
Induced Weinberg operator and EDMs

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

RGE

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

hadronization scale $\mu_H = 2$ GeV



QCD sum rule

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