

The Higgs boson and cosmology

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U. Osaka
Dr. Wani
(mascot
character)

Higgs Hunting 2026, Paris on Sep. 18, 2026

HPNP2027

The 8th International Workshop on
“Higgs as a Probe of New Physics 2027”

24.-28. May 2027, University of Osaka, Japan

Organization
will start soon

LOC:

M. Aoki,
K. Enomoto
Y. Hamada
M. Kakizaki,
S. Kanemura
M. Kikuchi
T. Masubuchi
K. Oda
R. Sato
T. Shindou
K. Tsumura
K. Yagyu

Your participation
very welcome!



We also have Higgs 2027 in Nov 2027 in U. of Osaka

The Higgs

- Introduced for EW symmetry breaking
- Discovered at LHC in 2012, $m_h = 125\text{GeV}$, SM-like
- SM successful, but there are BSM phenomena (Neutrino, DM, BAU, ...)
- SM Higgs is just from assumption
- BSM scenarios predict extended Higgs sectors
- Higgs is a probe of new physics
- What is the next (solid) target?
- EW phase transition (thermal history)

Subject of my talk

How did the Universe reach today's EW vacuum?

$$SU(2)_I \times U(1)_Y \rightarrow U(1)_{\text{em}}$$

Symmetric Phase

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



Phase transition

Broken Phase (EWSB)

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

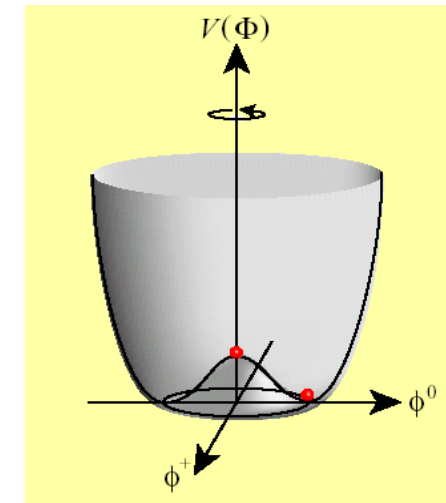
Early Universe before EWPT

By thermal effects
the gauge symmetry is restored

Today

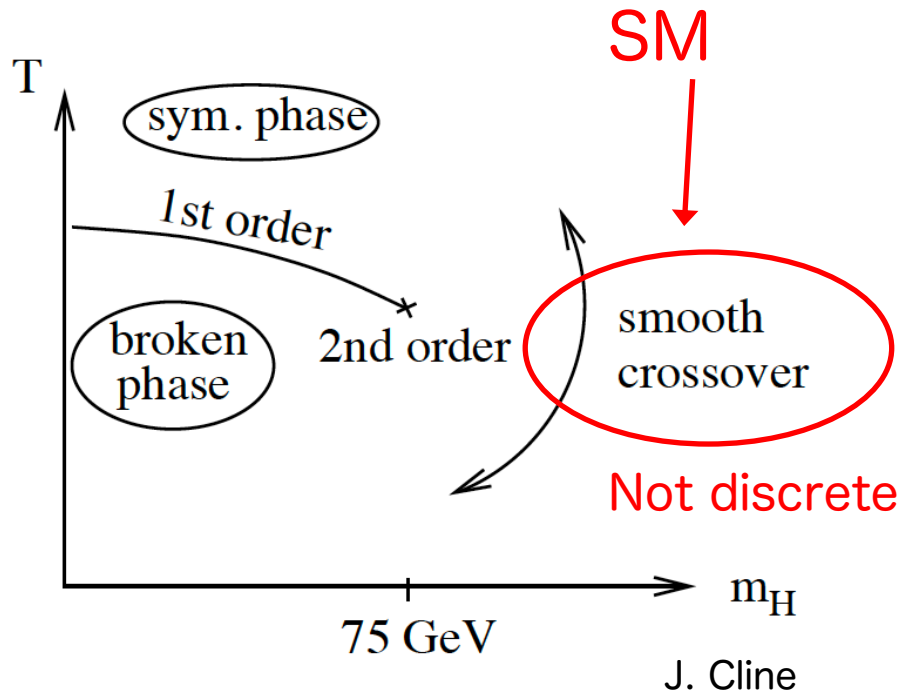
$$G_F \propto \frac{1}{v^2}$$

$$v = 246 \text{ GeV}$$



EW vacuum

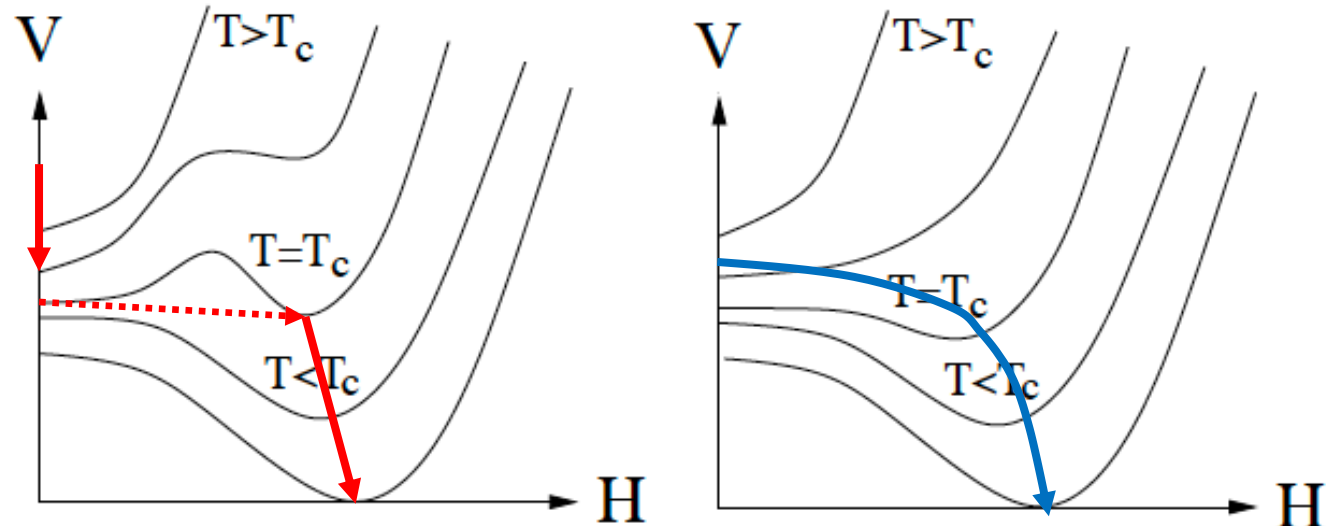
Crossover or First Order?



Cross Over

VEV is continuous
 VEV' is continuous

SM predicts crossover



VEV is discrete
 Bubble created

2nd OPT
 VEV is continuous
 VEV' is discrete

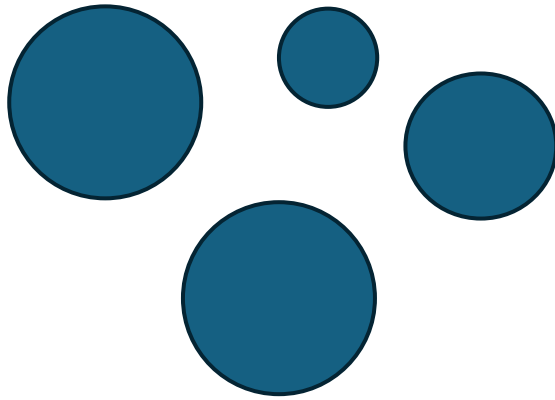
Some BSM scenarios predict 1st OPT

Higgs as a probe of early Universe

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

FOEWPT

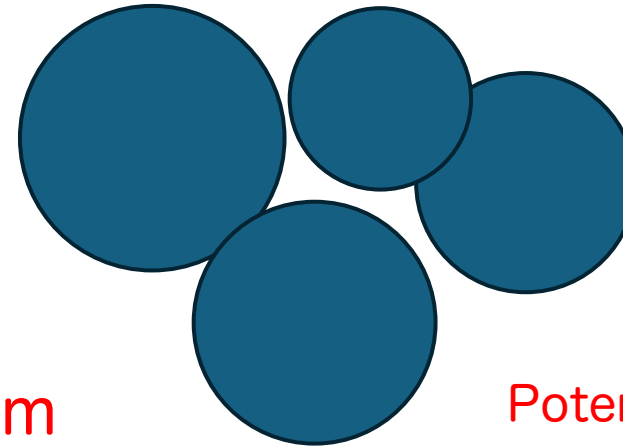
around T_c



Bubbles of broken phase



evolution



Non-equilibrium
process

Potentially observable relics
Higgs phenomenology
Gravitational waves
Primordial BH

Physics case: EW baryogenesis

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 $\Rightarrow$ Sphaleron transition at high T
- 2) C and CP violation $\Rightarrow$ C violation (SM is a chiral theory)
CP in BSM sectors
- 3) Departure from thermal equilibrium $\Rightarrow$ **EWPT is strongly 1st OPT**

Extension of the Higgs sector is required

Condition of Strongly First OPT

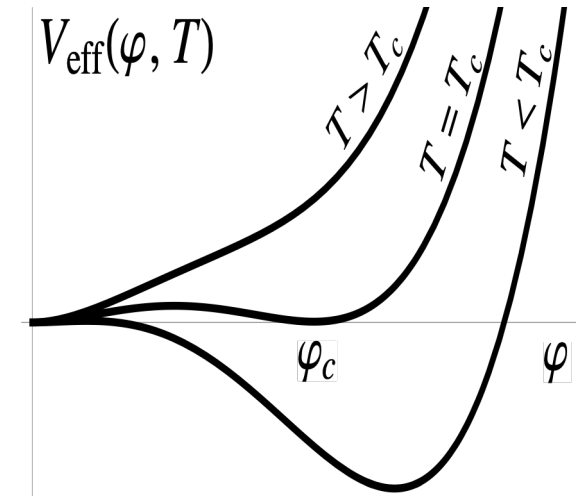
In the broken phase, sphaleron should quickly decouple to avoid wash out

$$\Gamma_{\text{sph}} < H$$



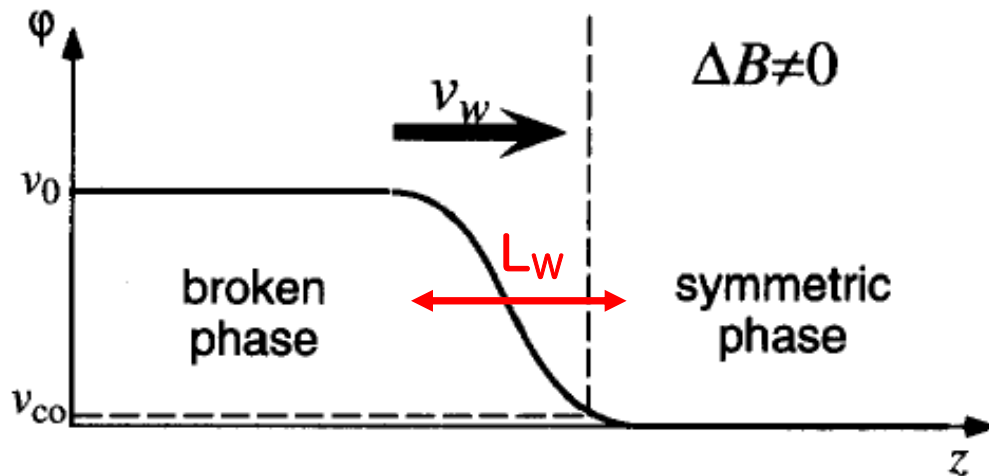
$$\frac{\varphi_c}{T_c} \gtrsim 1$$

Physics of Higgs potential



EW Baryogenesis

- 1st OPT $\Rightarrow$ bubbles of the broken phase



Profile
 Bounce solution
 $\Phi(z)$

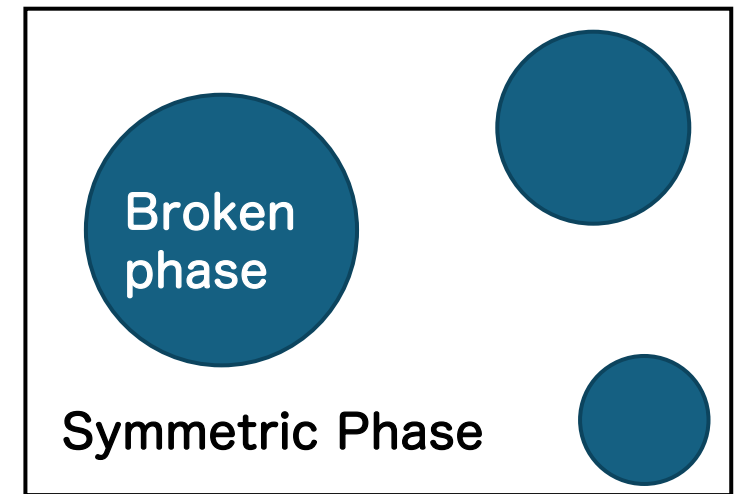
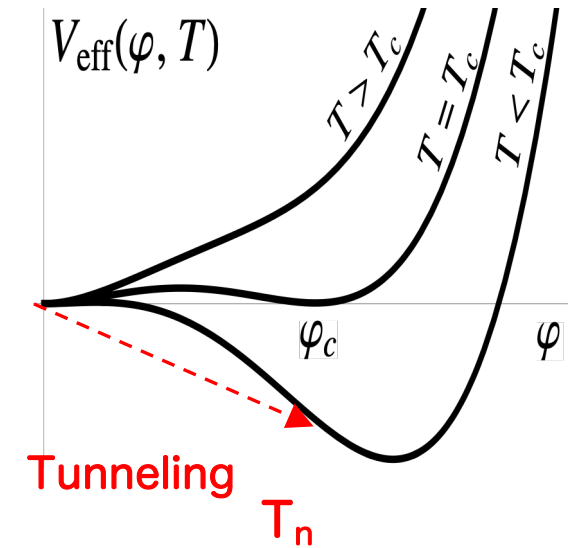


Figure by Funakubo 1996

EW Baryogenesis

- **1st OPT** $\Rightarrow$ bubbles of the broken phase
- **CPV** $\Rightarrow$ charge flow around the wall

Dirac equation solved by WKB method

Cline, Joyce, Kainulainen 2000

Boltzmann equation

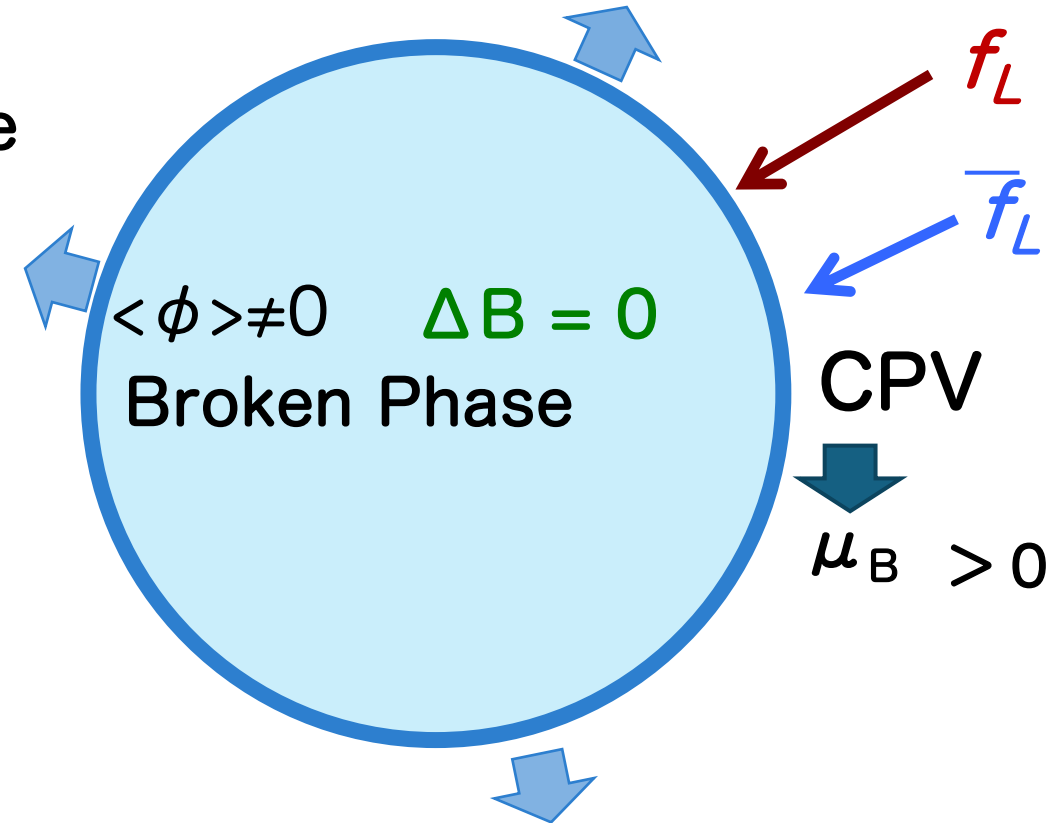
$$(\partial_t + \mathbf{v}_g \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}}) f_i = C[f_i, f_j, \dots]$$

Different sign between particle and anti-particle

Transport eq. for μ_i

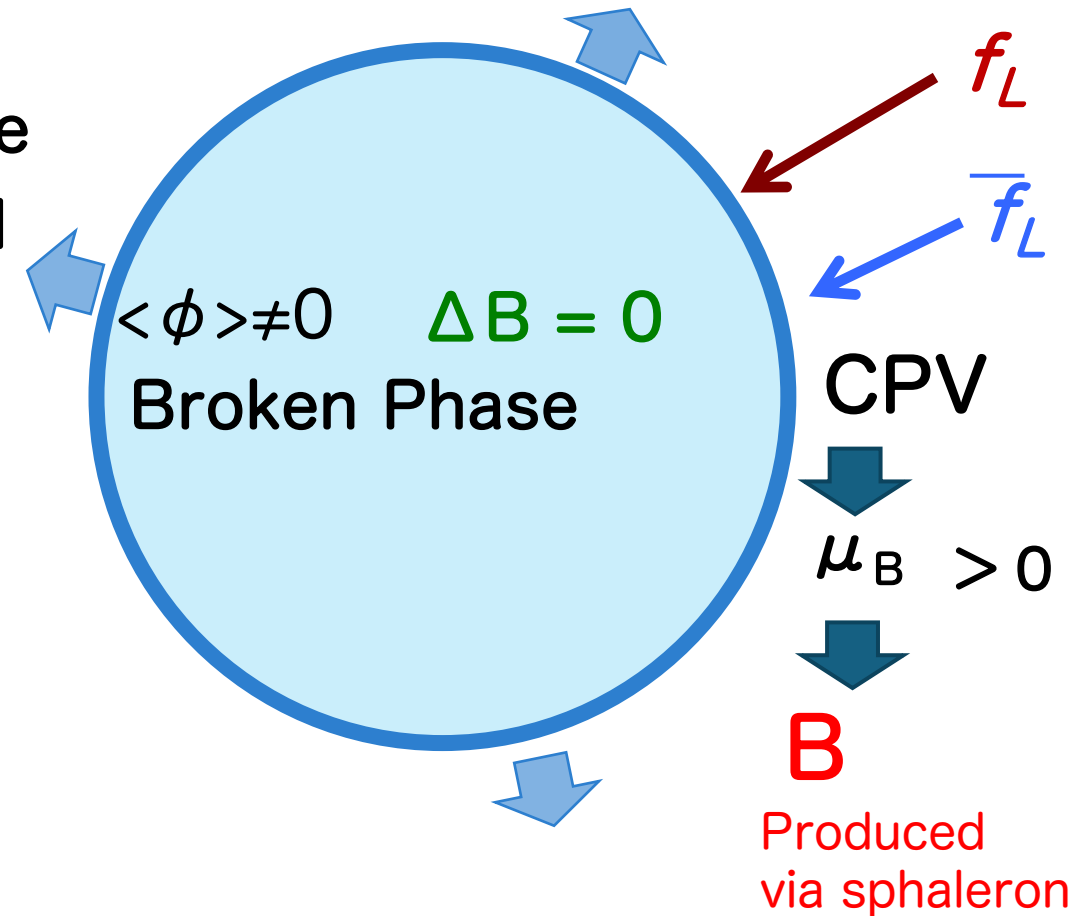
$$f_i = \frac{1}{e^{\beta[\gamma_w(E_i + v_w p_z) - \mu_i]} \pm 1} + \delta f_i$$

Symmetric Phase
 $\langle \phi \rangle = 0$ $\Delta B \neq 0$



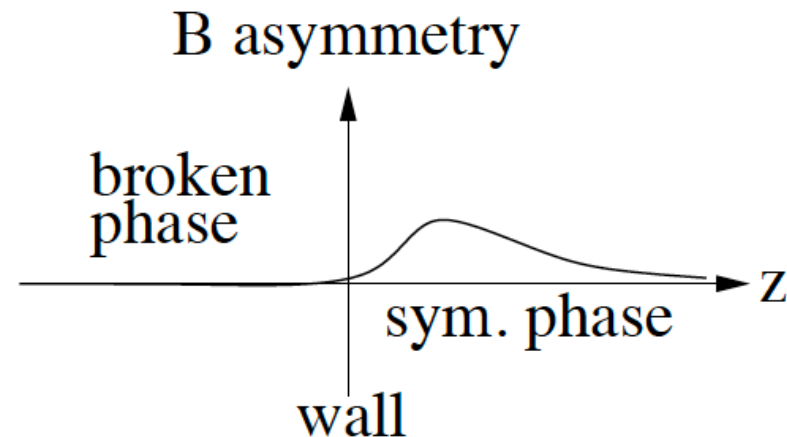
EW Baryogenesis

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



Chemical potential

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



EW Baryogenesis

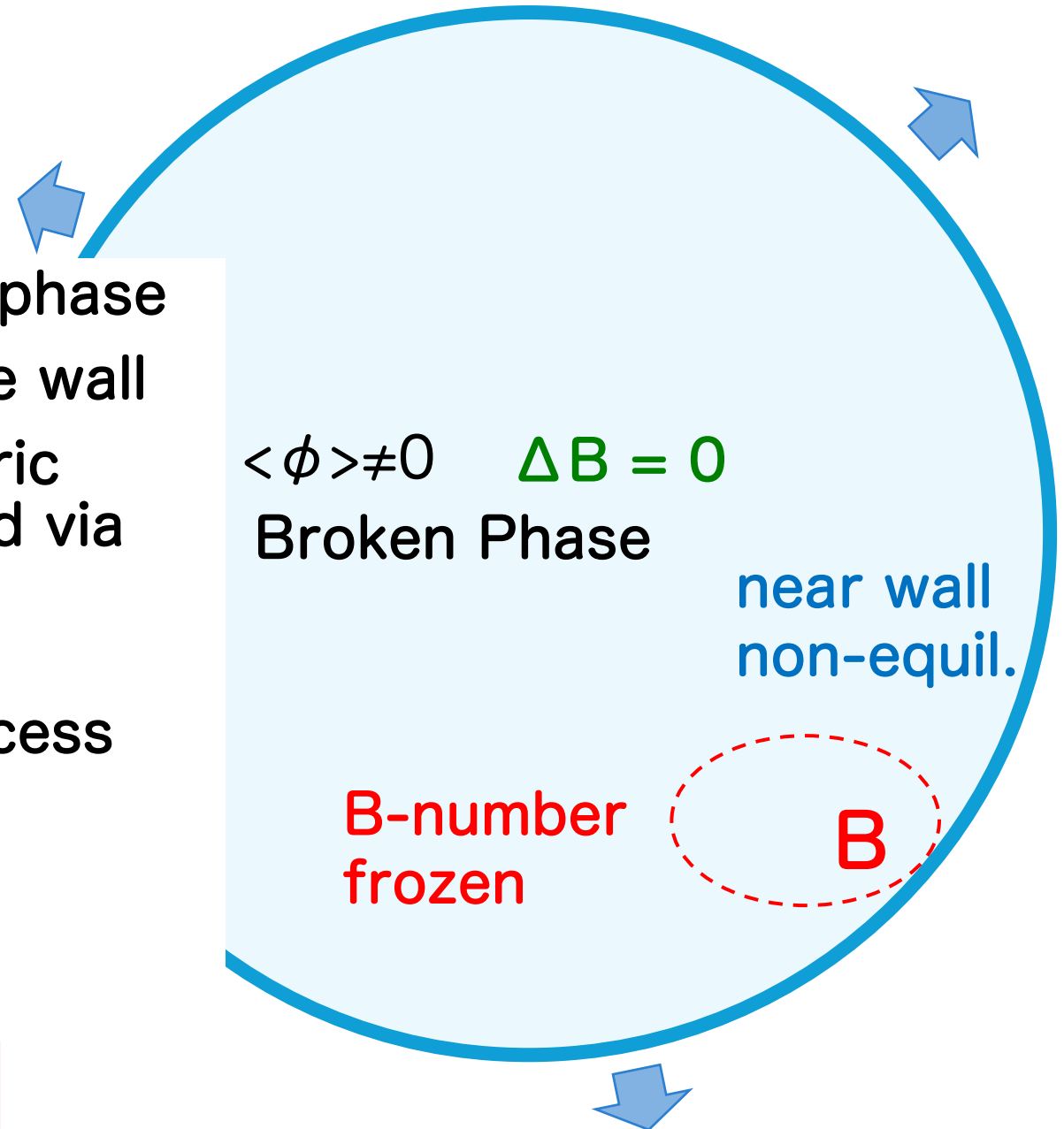
- **1st OPT** $\Rightarrow$ bubbles of the broken phase
- **CPV** $\Rightarrow$ charge flow around the wall
- By accumulated charge in symmetric phase, baryon number is generated via sphaleron
- In broken phase, produced baryon number is frozen, if sphaleron process decouples

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

- 1st OPT (Non-decoupling property)
- CP violation

2 Higgs doublet models
Singlet extension
Real triplet extension
...

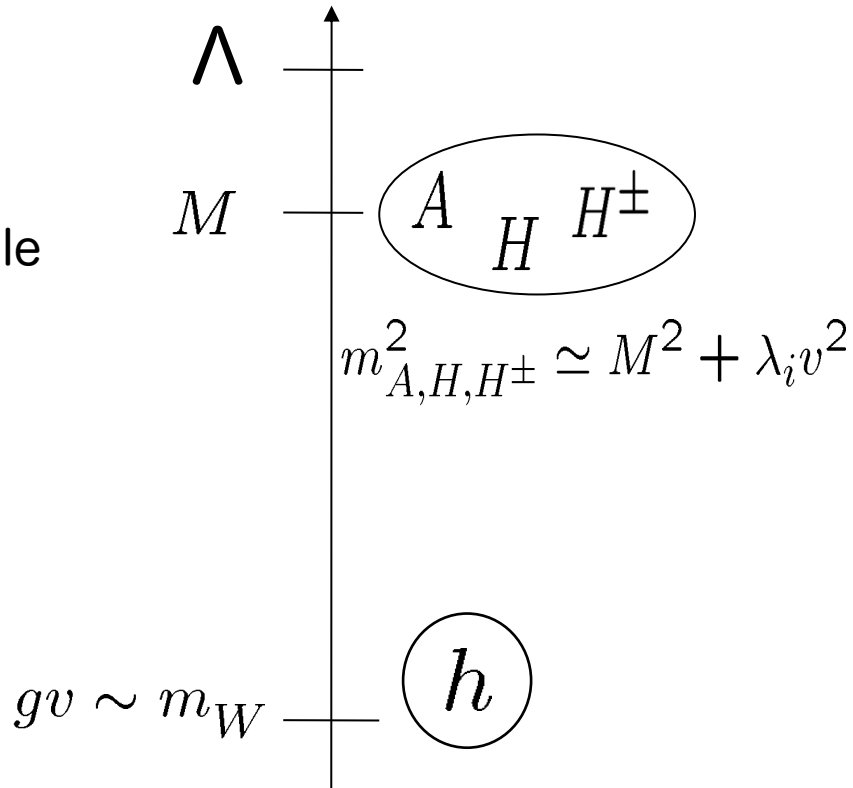
Constraints from current experimental data

EW Precision Tests
Flavor Changing Neutral Currents
EDMs
LHC

How SM-like is realized in extended Higgs sectors?

Λ : Cutoff

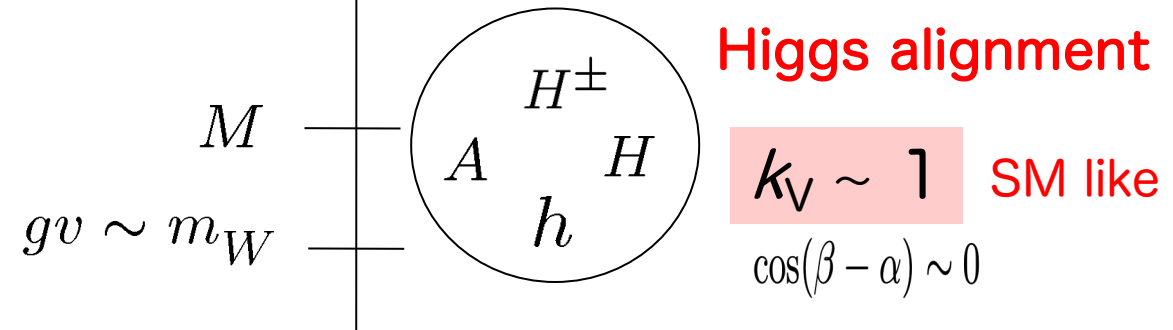
M : Mass scale
irrelevant
to VEV



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

Effective Theory is the SM
Decoupling

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



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

Effective Theory is an extended Higgs sector
Non-Decoupling

Higgs Potential

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

The hhh coupling is important to reconstruct the Higgs potential

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

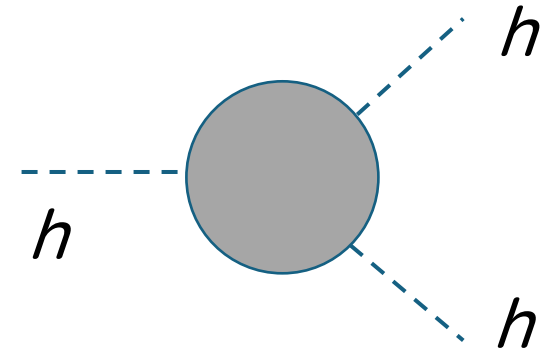
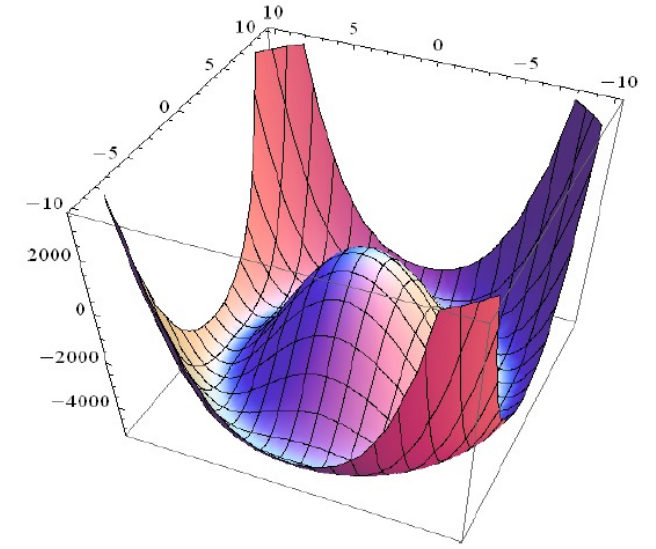
$$\lambda_{hhh}^{\text{SMloop}} \sim \frac{3m_h^2}{v} \left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \dots \right)$$

Non-decoupling effect

Top loop effect
in the SM

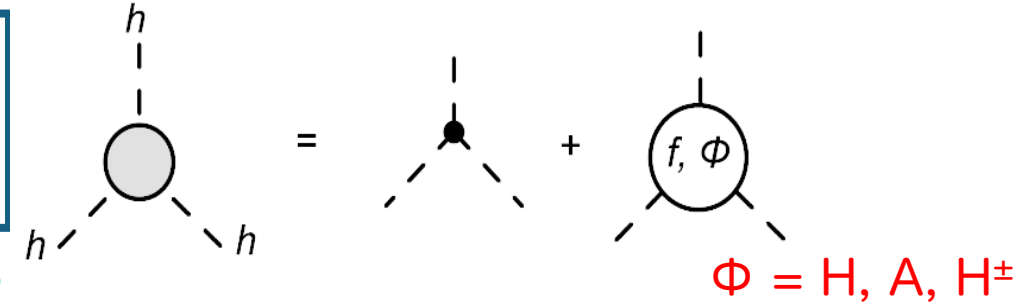
Sensitive to BSM physics too!

Physics of 1st OPT (EW Baryogenesis)



Ex) Case of extended Higgs sector

$$\lambda_{hhh}^{2\text{HDM}} \simeq \frac{3m_h^2}{v} \left[1 + \underbrace{\frac{m_\Phi^4}{12\pi^2 m_h^2} \left(1 - \frac{M^2}{m_\Phi^2}\right)^3}_{\text{Extra scalar loop}} - \underbrace{\frac{m_t^4}{\pi^2 v^2 m_h^2}}_{\text{Top loop}} \right]$$



Mass of extra Higgs bosons

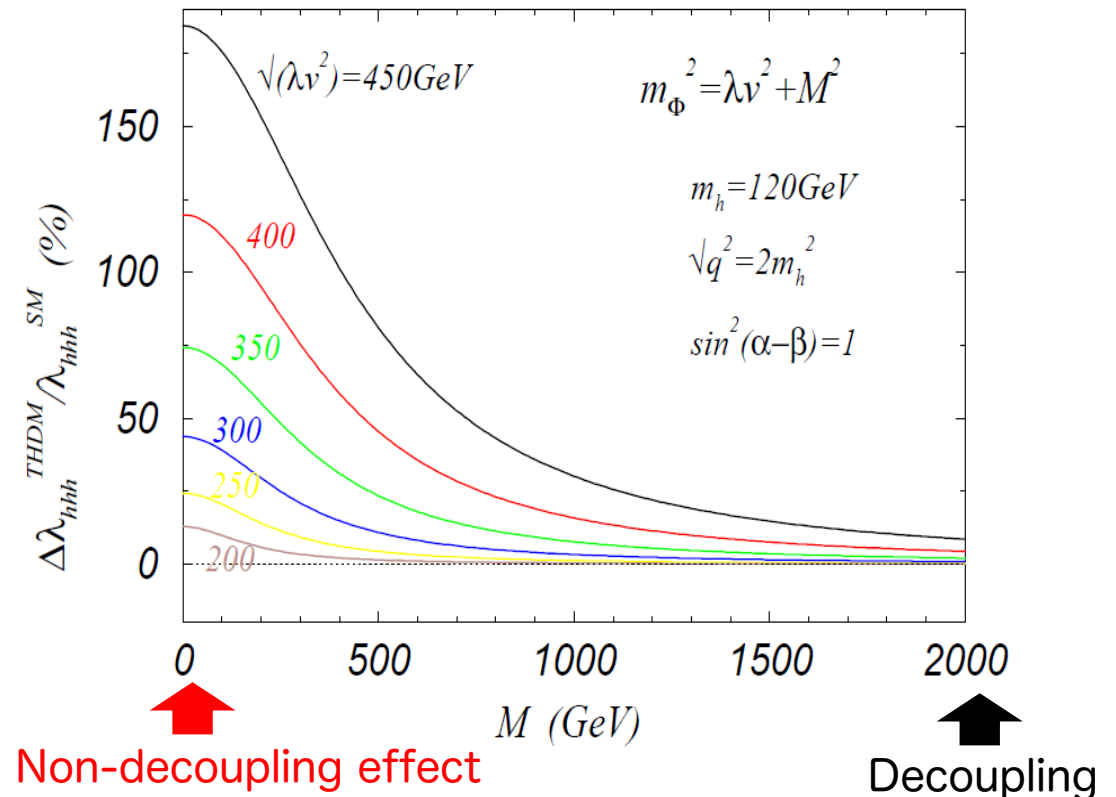
$$m_\Phi^2 = M^2 + \lambda_i v^2 \quad (\Phi = H, A, H^\pm)$$

- Consider the case: h is SM-like
- At 1-loop, powerlike effect m_Φ^4

Deviation can be large
 $\sim 100\%$

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

Physics of non-decoupling also affects 1st OPT



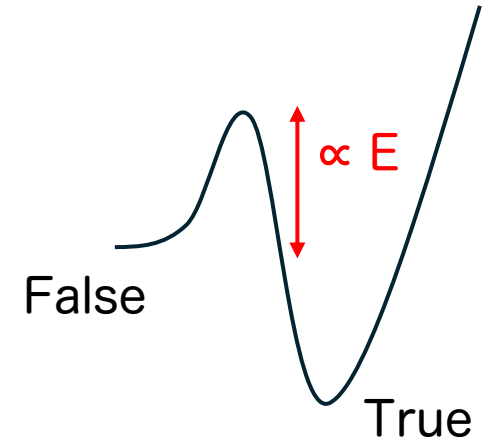
1st OPT by non-decoupling effect

Effective Potential at finite T (HTE)

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

Sphaleron decoupling condition

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



SM: The condition cannot be satisfied

$$\frac{\varphi_c}{T_c} = \frac{2E}{\lambda_T} \simeq \frac{6m_W^3 + 3m_Z^3 + \dots}{3\pi v m_h^2} \ll 1$$

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

$$\frac{\phi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2} \left\{ 6m_W^2 + 3m_Z^3 + \underbrace{\sum_{\Phi} n_{\Phi} m_{\Phi}^3 \left(1 - \frac{M^2}{m_{\Phi}^2} \right)^{3/2}}_{\text{Quantum effects of } \Phi (= H, A, H^+, \dots)} \right\} > 1 \quad (\text{when } M < m_{\Phi})$$

Same physics gives a large deviation in **the hhh coupling**

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

hhh from 1st OPT

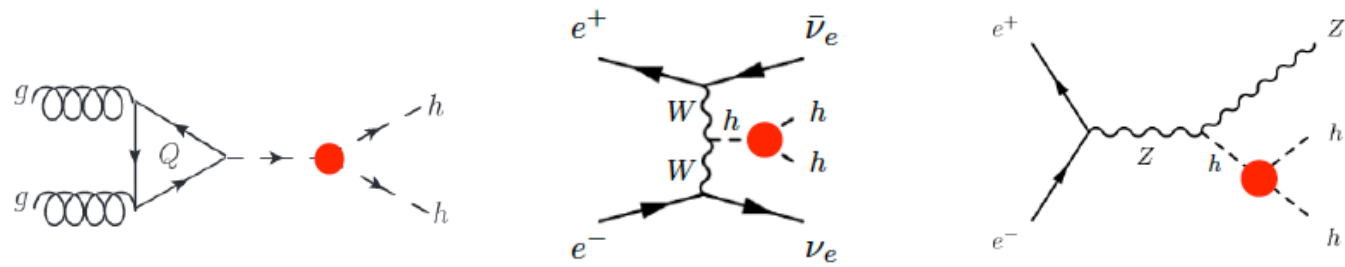
Example $\rightarrow$
 Aligned 2HDM:
 viable scenario
 of EWBG

Strongly 1st OPT

$\rightarrow$ A large deviation in the hhh coupling

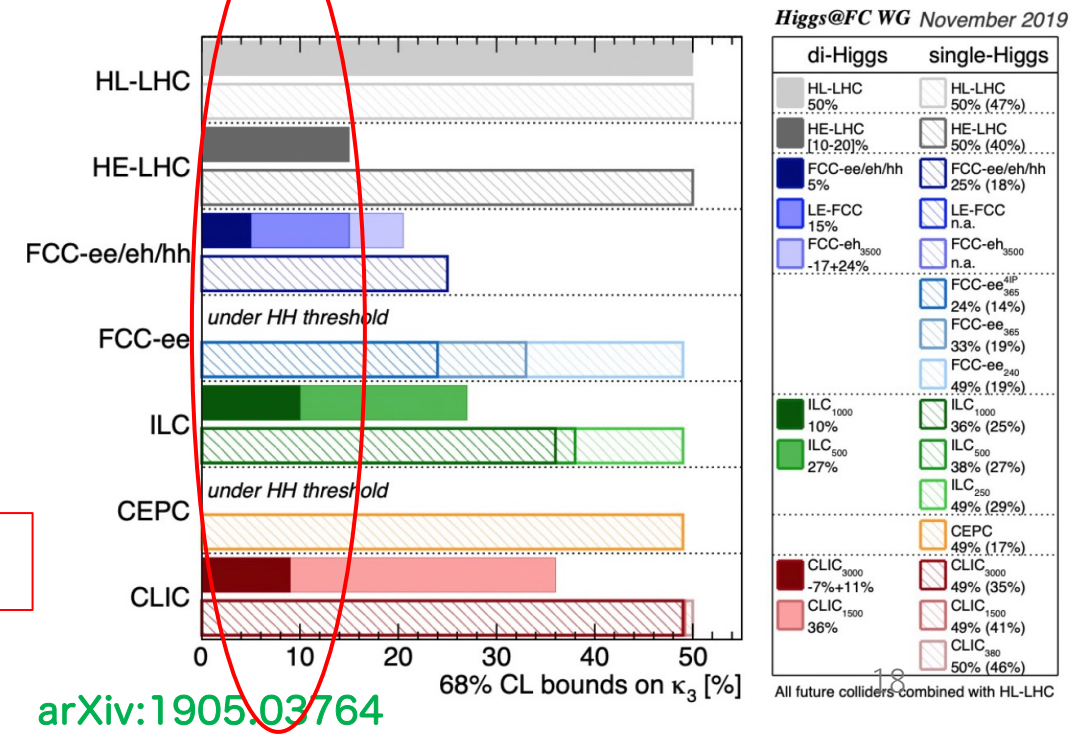
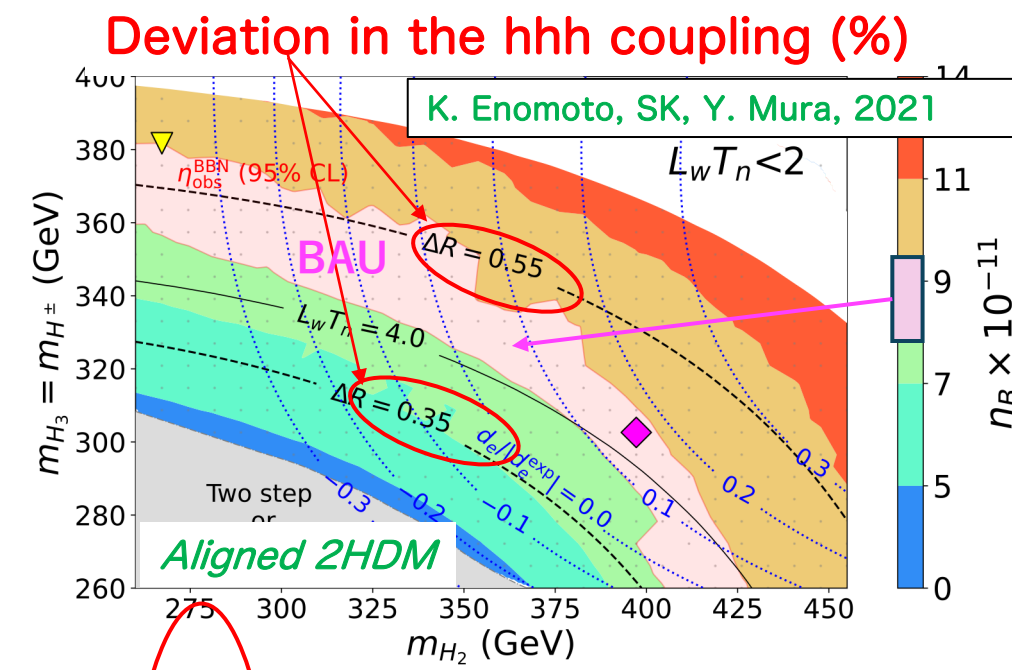
40 — 60%

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



Directly testable by the hhh measurement

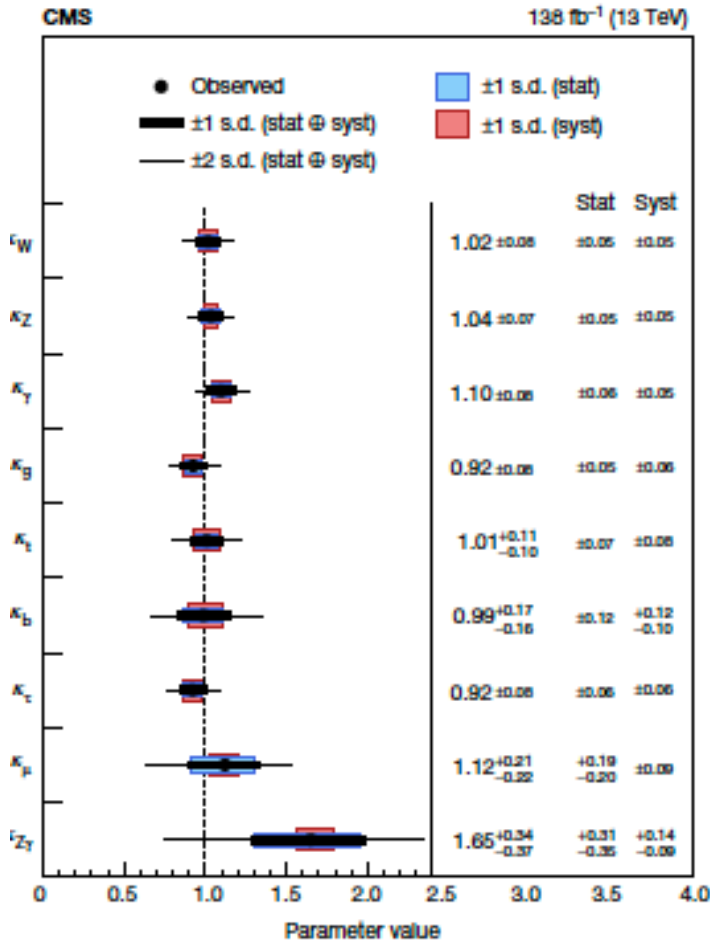
$h\gamma\gamma$ can also be sensitive to non-decoupling effects



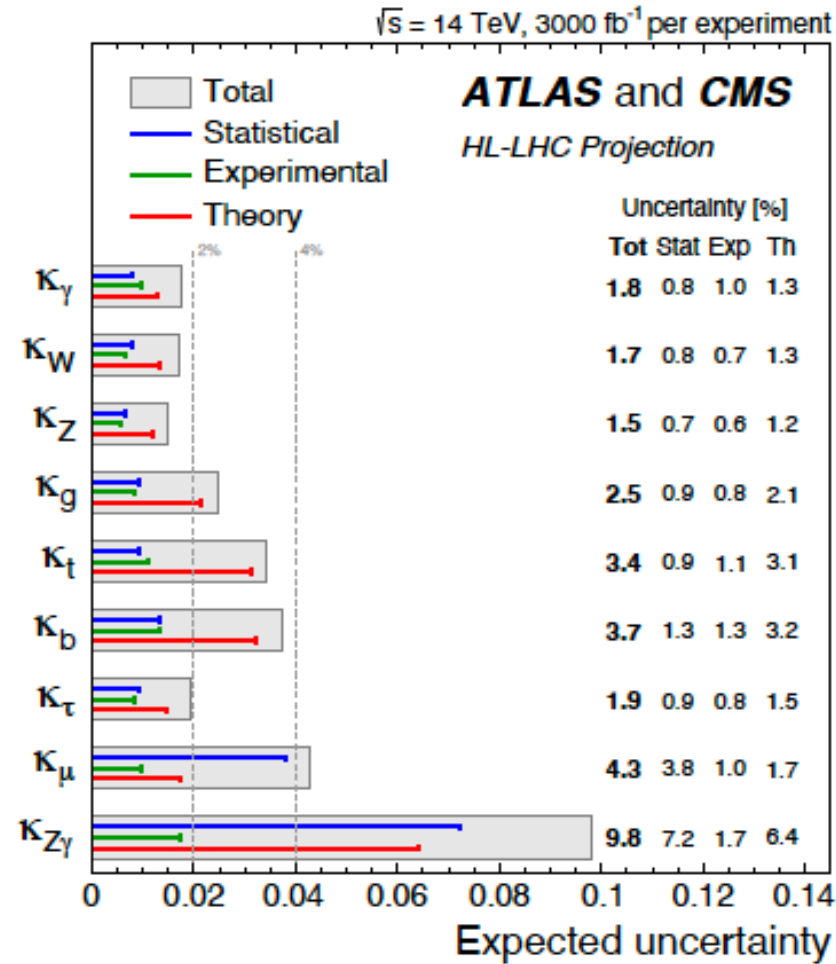
arXiv:1905.03764

Higgs coupling measurements

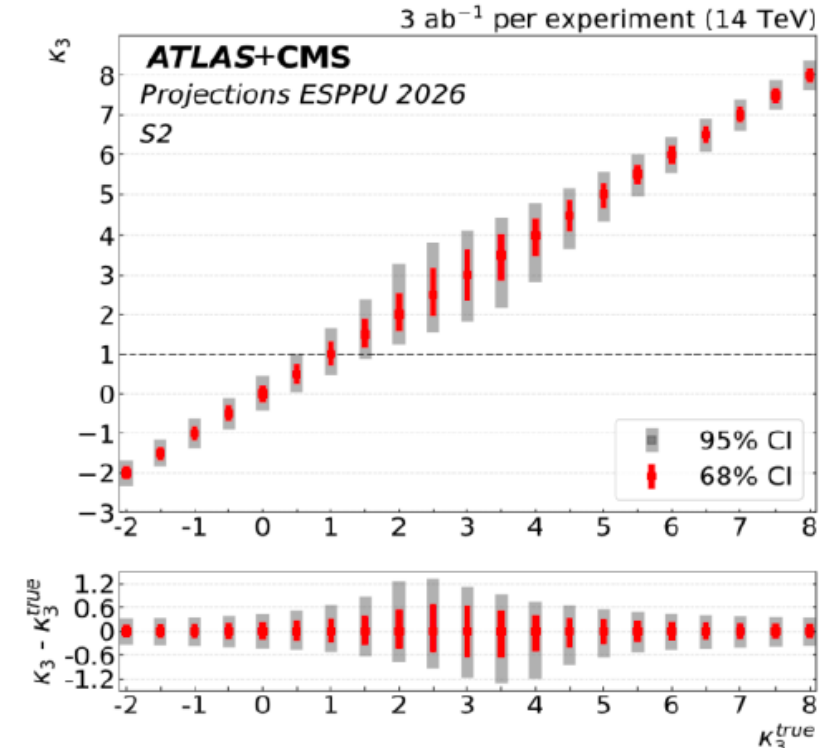
hhh



Today



Future



Future

Di-Photon decay of $h(125)$

Ex) Case of the inert doublet model

Loop induced

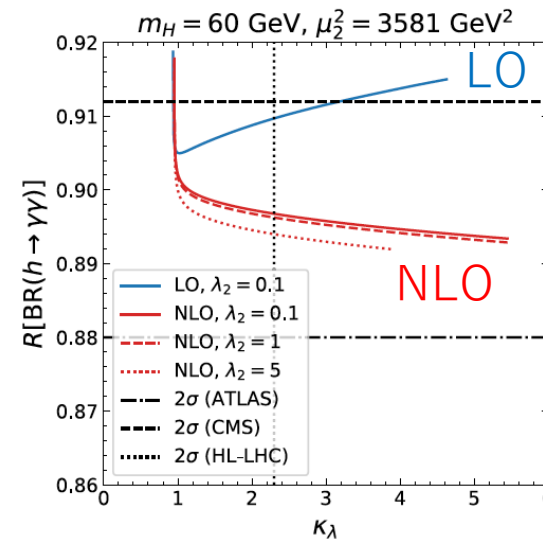
Small rate but sensitive to new charged particle loop effects

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

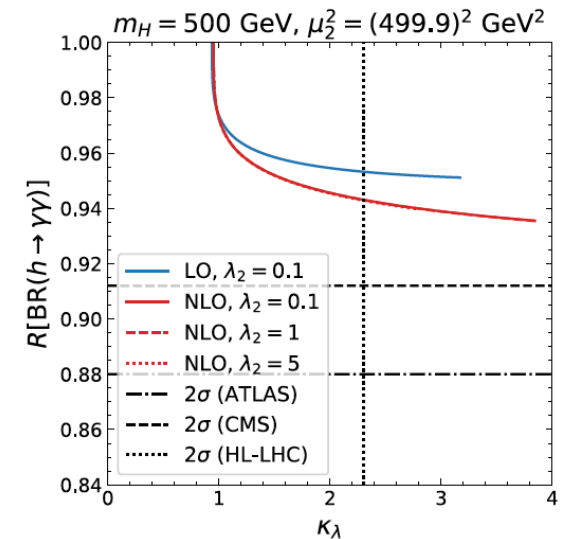
$h \rightarrow \gamma\gamma$, $gg \rightarrow hh$

Can give strong constraint on BSM models

Resonant DM scenario



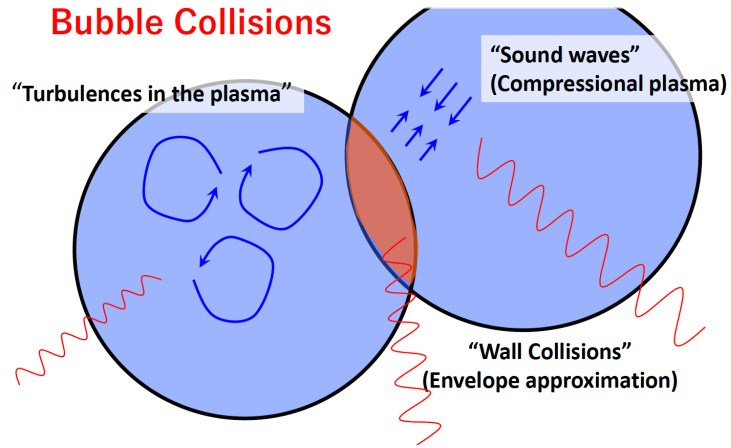
Heavy DM scenario



Aiko, Braathen, SK, 2023

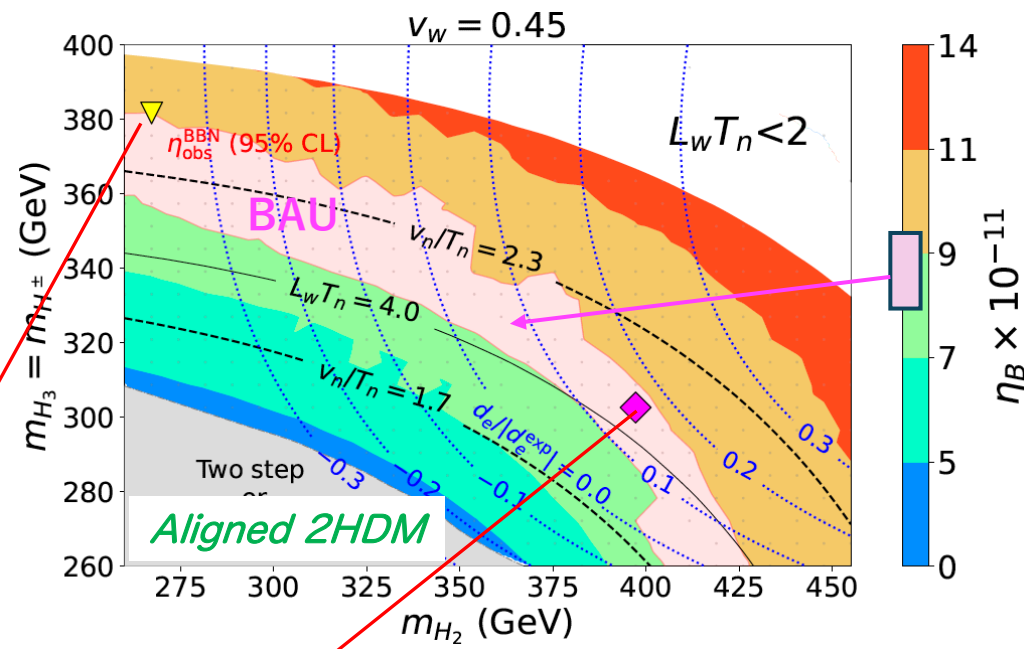
NLO (2 loop) correction is important

GW from 1stOPT

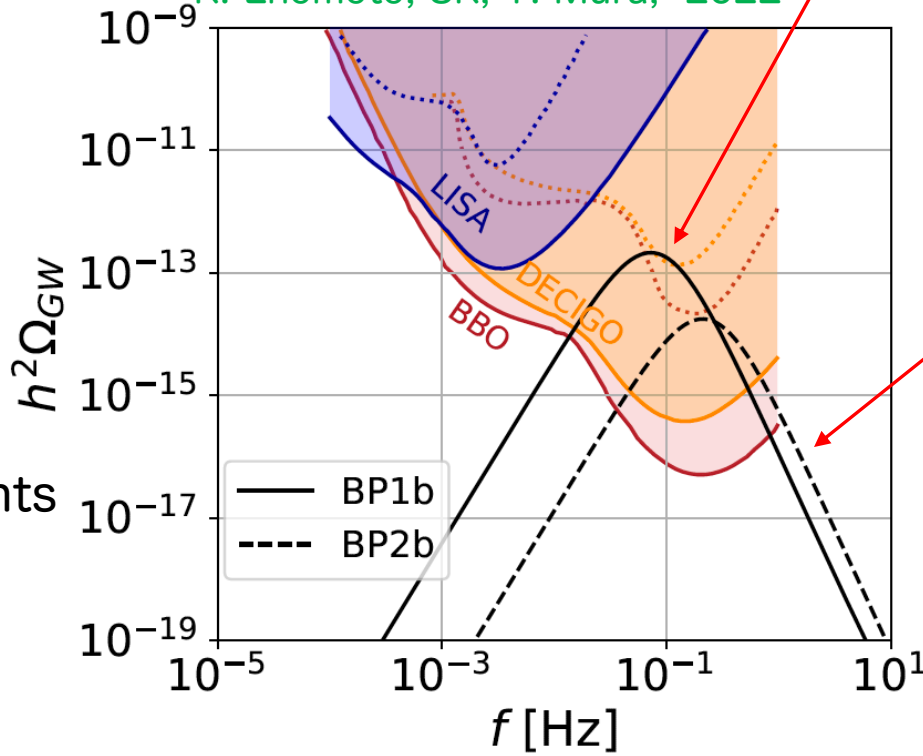


Example
Aligned 2HDM

K. Enomoto, SK, Y. Mura, 2022



K. Enomoto, SK, Y. Mura, 2022



GWs for benchmark
points of **BAU**

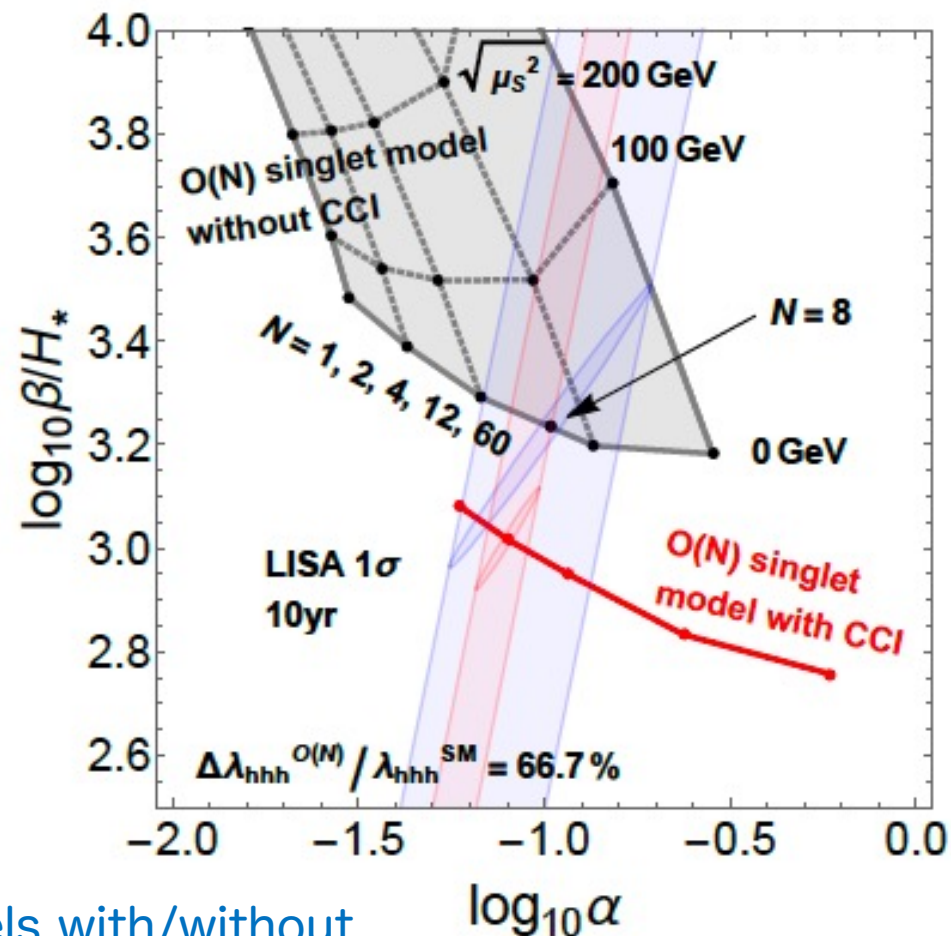
They may be tested
by future GW experiments

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

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

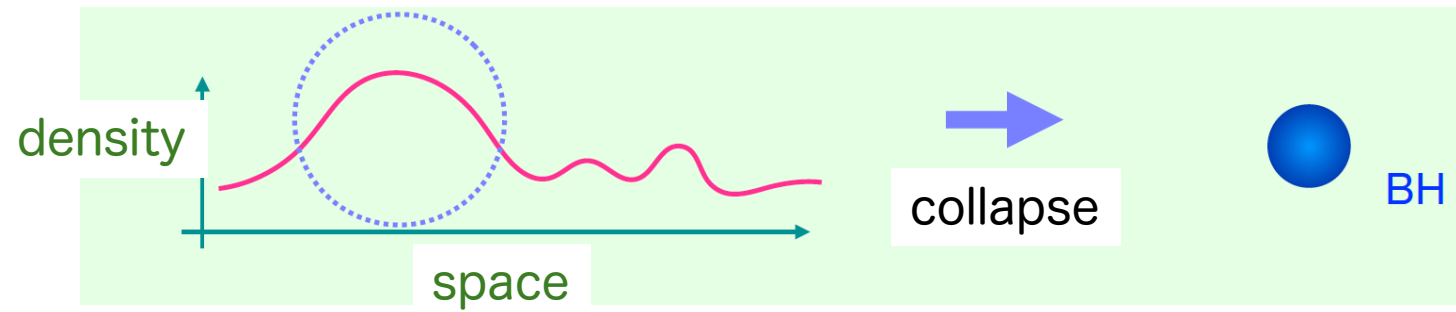
GW as a probe of models of SFO EWPT

- 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

PBH



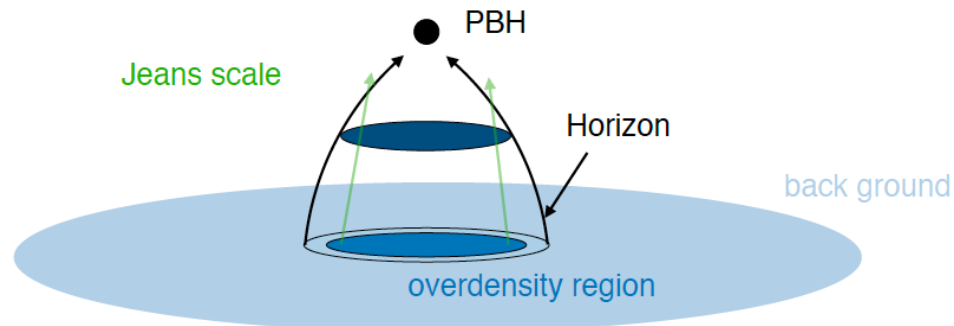
Primordial black holes (PBH) : BHs formed before the star formation

Condition for the PBH formation

$$\delta = \frac{\rho_{\text{over}} - \rho_{\text{back}}}{\rho_{\text{back}}} > \delta_c$$

[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)]

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

Why PBH is interesting for Higgs physics?

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

Subaru HSC, Ogle
PRIME, Roman Telescope

PBH from delayed FOEWPT

FOEWPT with small β



Delayed vacuum decay



Contrast δ grows



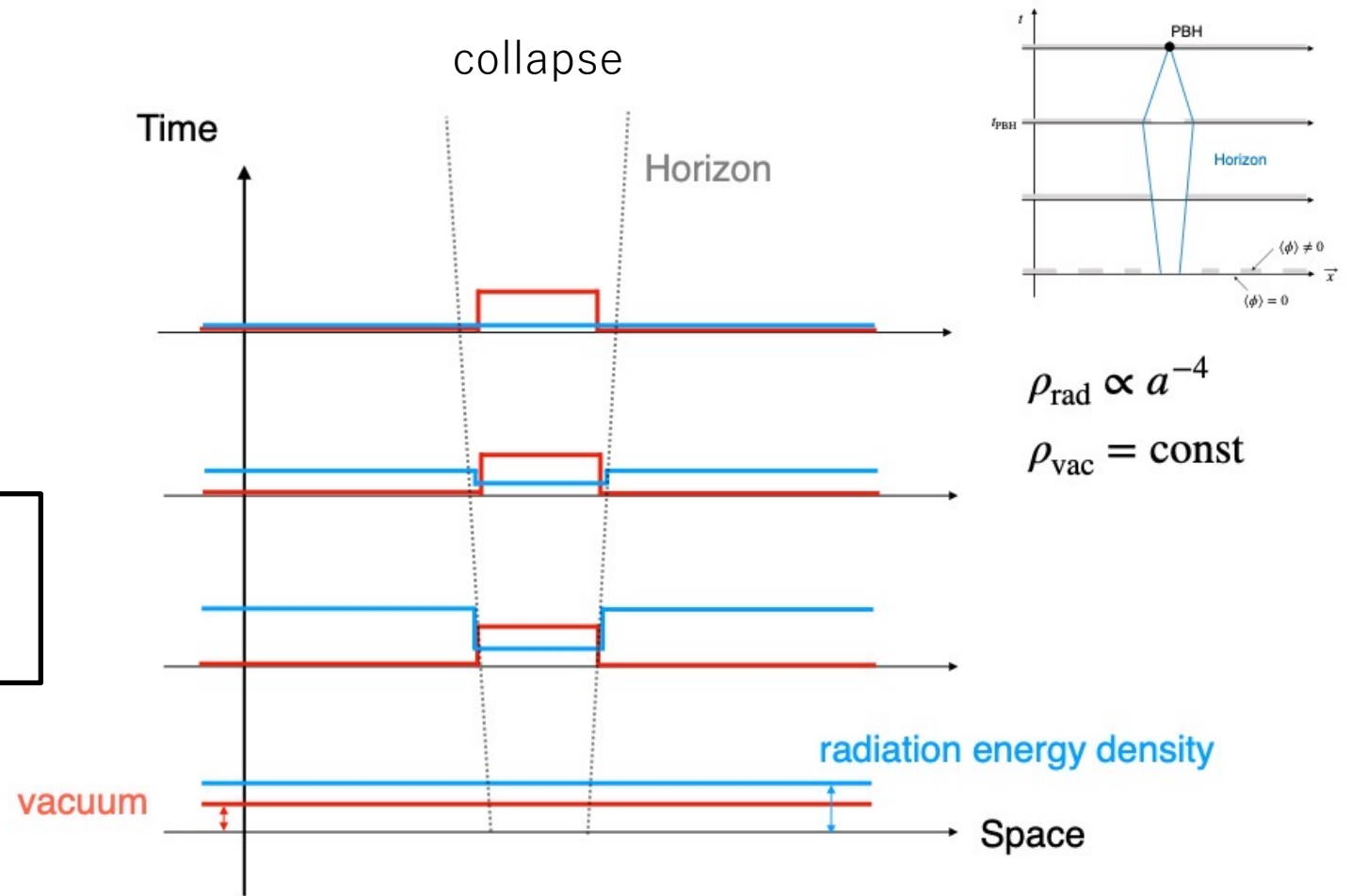
At the time t_{PBH}

$$\delta > \delta_c$$



PBH?

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



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.

The wall equation of motion yields two branches

Assumptions

Spherical symmetry
Thin wall approximation (tension σ)

Metric

Inside: Friedmann-Robertson-Walker (de Sitter)
Outside: Spherical symmetric metric

Israel junction condition

Equation of Motion

$$\ddot{\chi} + \underbrace{(4 - 3a^2\dot{\chi}^2)H\dot{\chi}}_{\text{friction}} + \underbrace{\frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2)}_{\text{curvature}} = \underbrace{\left(\frac{3\sigma}{4M_{pl}^2} - \frac{\rho_V}{\sigma} \right)}_{\text{Energy vacuum}} \frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$$

gravitational effect of the wall

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

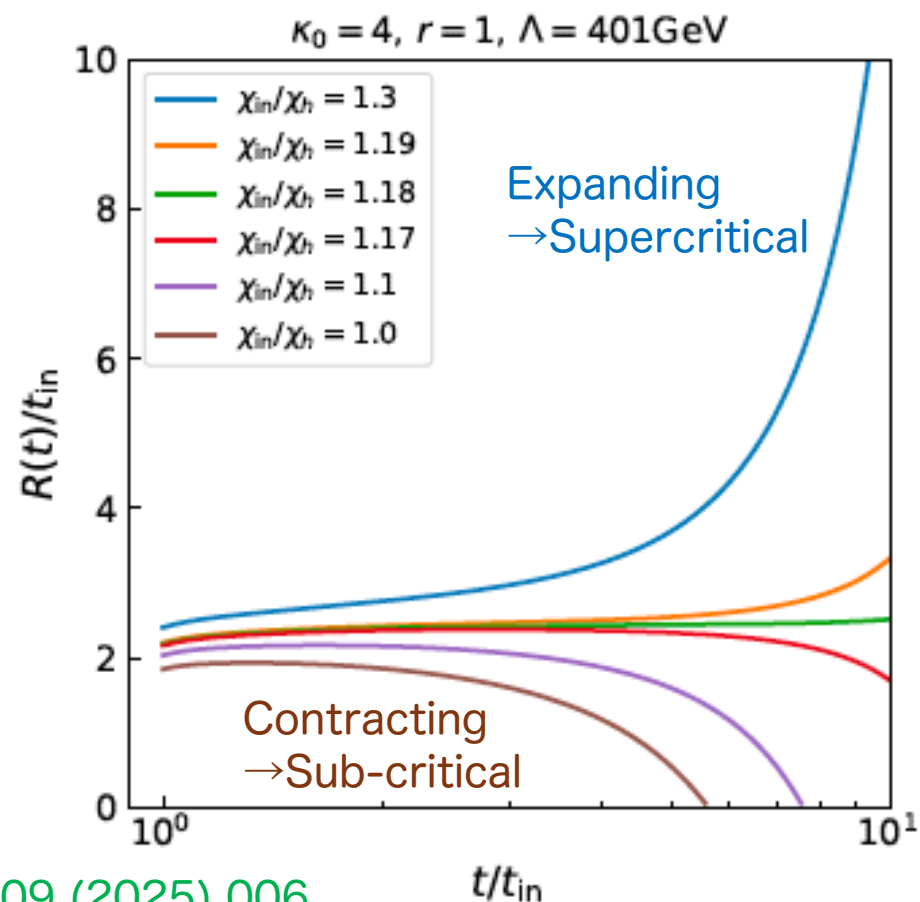
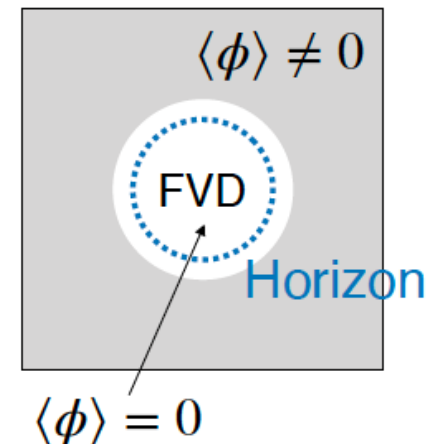
$$\chi_{in} = \chi(t_{in})$$

$$\chi_H = \chi(t_H)$$

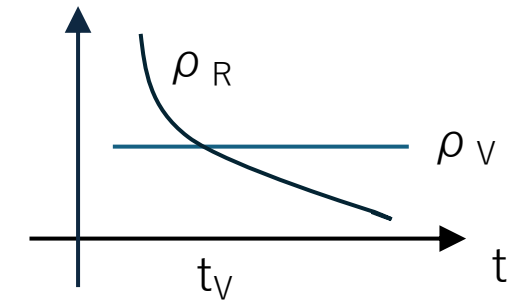
t_{in} : initial time defined by $F(t_{in}) = 0.7$

t_H : horizon-entry time of the FVD

$F(t)$: false-vacuum fraction



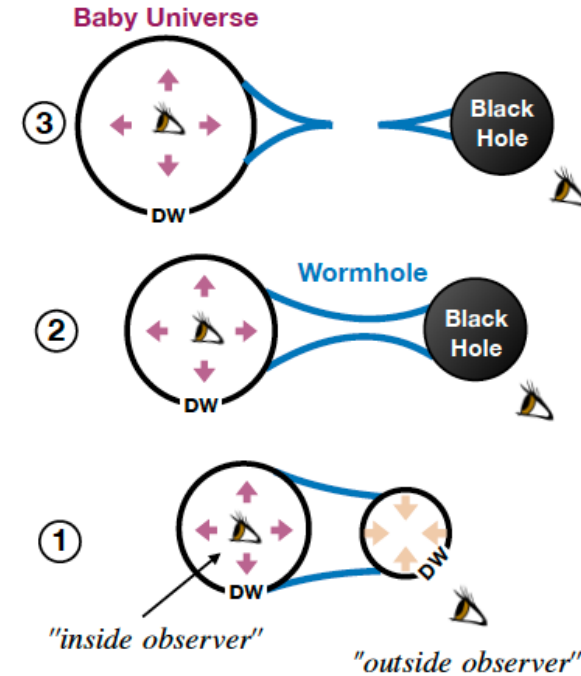
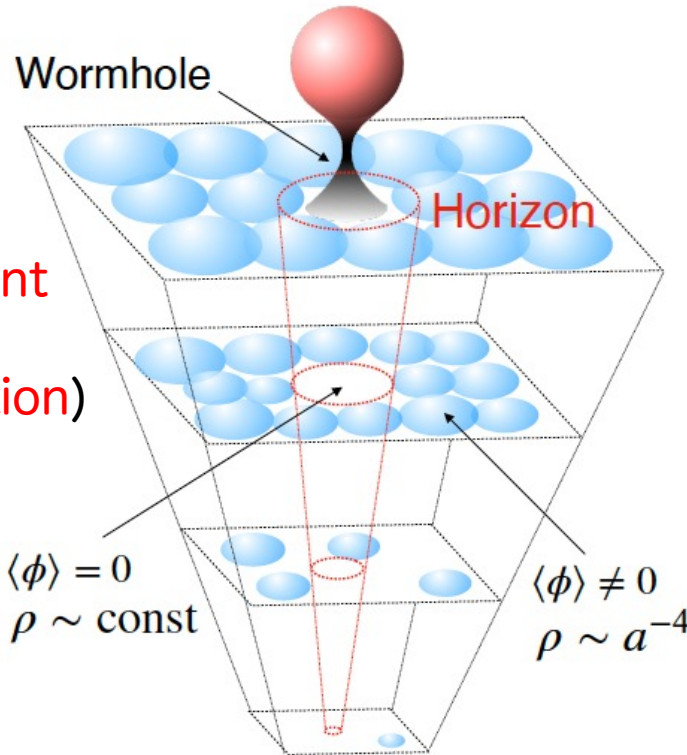
Two different solutions: Supercritical / Sub-critical



Supercritical

FVD formation

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



[Y. Gouttenoire et al, arXiv: 2501.16414]

FVD is seen as a PBH from outside

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

$$M_{\text{PBH}} \sim 4\pi M_{pl}^2 H(t_{\text{PBH}})^2 R(t_{\text{PBH}})^3 \sim 4\pi M_{pl}^2 H^{-1}(t_{\text{PBH}})$$

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

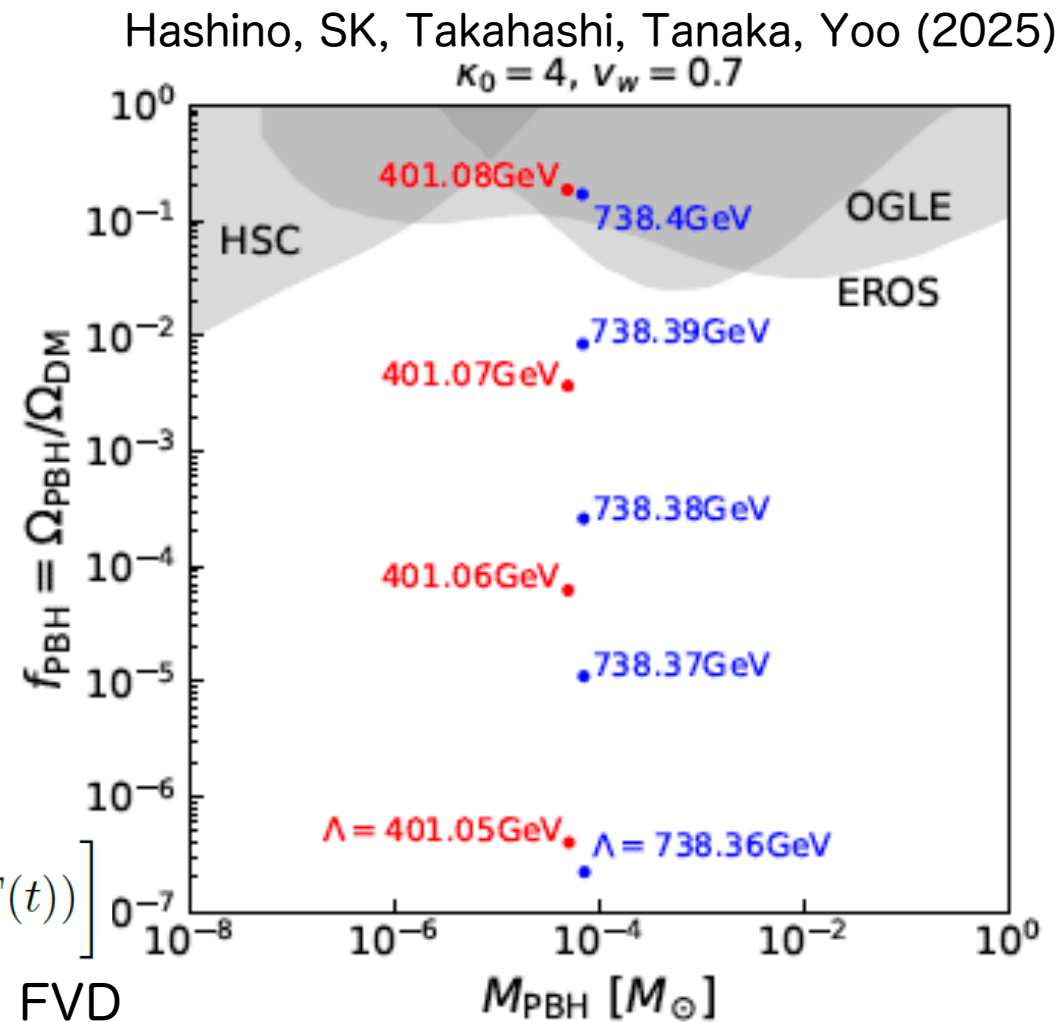
PBH abundance: determined by the probability of FVD formation

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

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

survival probability of a Hubble-sized FVD

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



Modeling the Higgs sector for the 1st OPT

$$V_{\text{naHEFT}}(\phi, T) = V_{\text{SM}}(\phi, T) + V_{T=0}^{\text{BSM}}(\phi) + V_T^{\text{BSM}}(\phi, T)$$

$$V_{T=0}^{\text{BSM}}(\phi) = \frac{\kappa_0}{64\pi^2} [M^2(\phi)]^2 \ln \frac{M^2(\phi)}{\mu^2} \quad M^2(\phi) = M^2 + \frac{\kappa_p}{2} \phi^2$$

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

Described by three parameters

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

r : decoupling property

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

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

Mass of new particles D. o. F. of new particles Decoupling parameter

Complementary probes of a strongly first-order EWPT

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

Sphaleron decoupling condition

$$v_n/T_n > 1$$

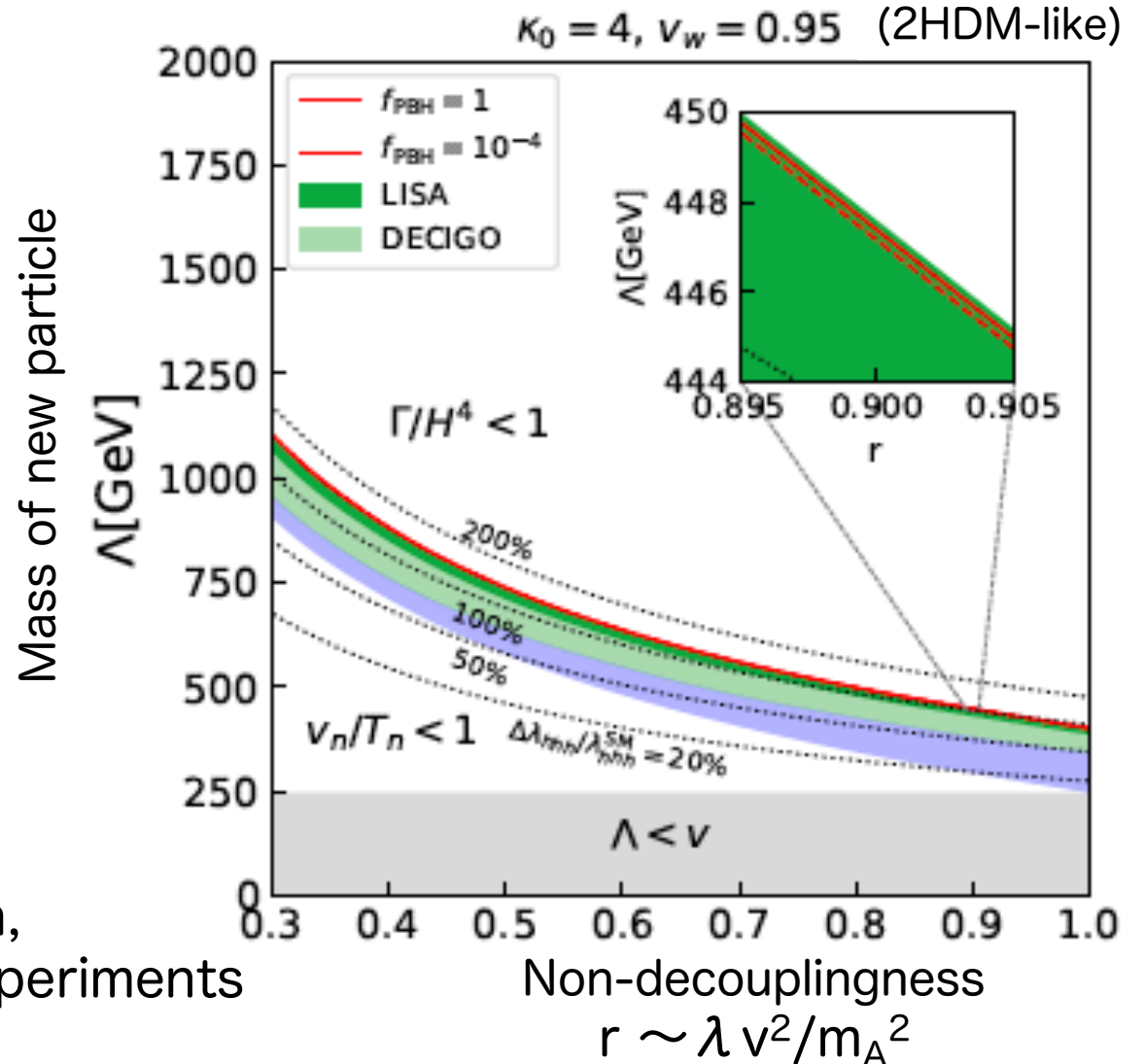
Bubble nucleation completion

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

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

Supercritical PBH

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

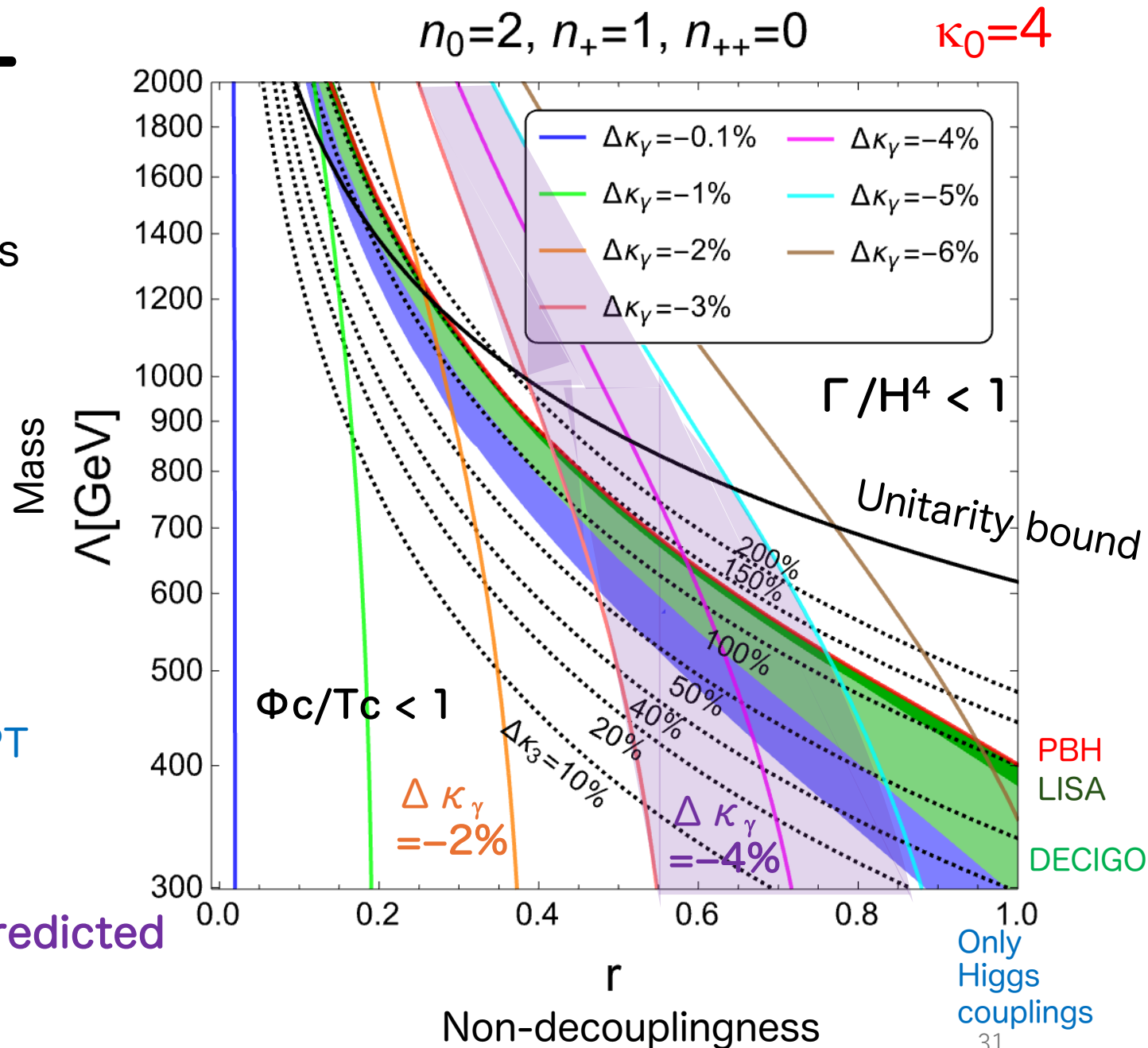
$$\left. \frac{\Gamma}{H^4} \right|_{T=T_t} \simeq 1$$

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

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

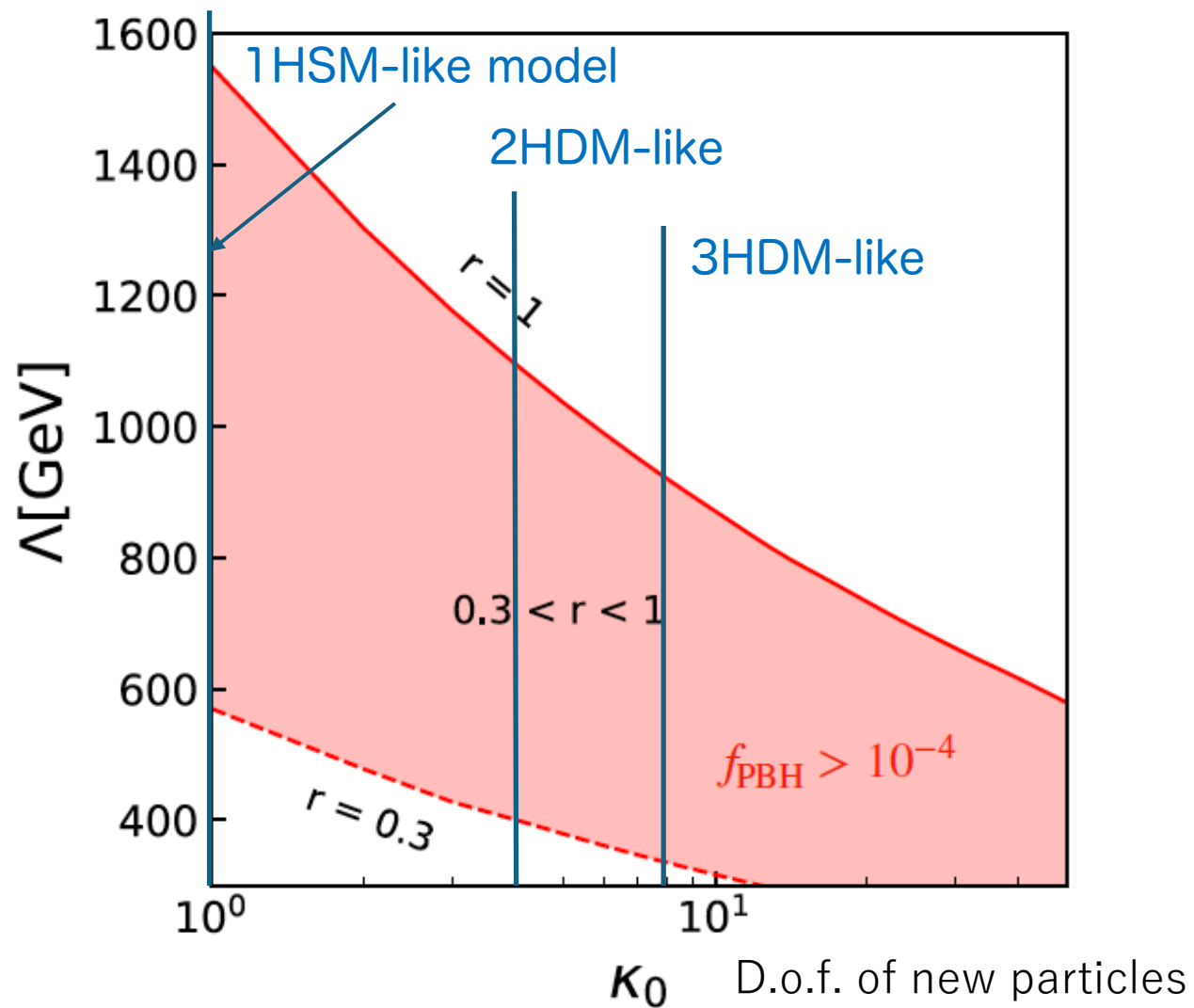
135% > ΔK₃ > 55%

GW, PBH can also be used



Parameter Regions testable by PBH

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

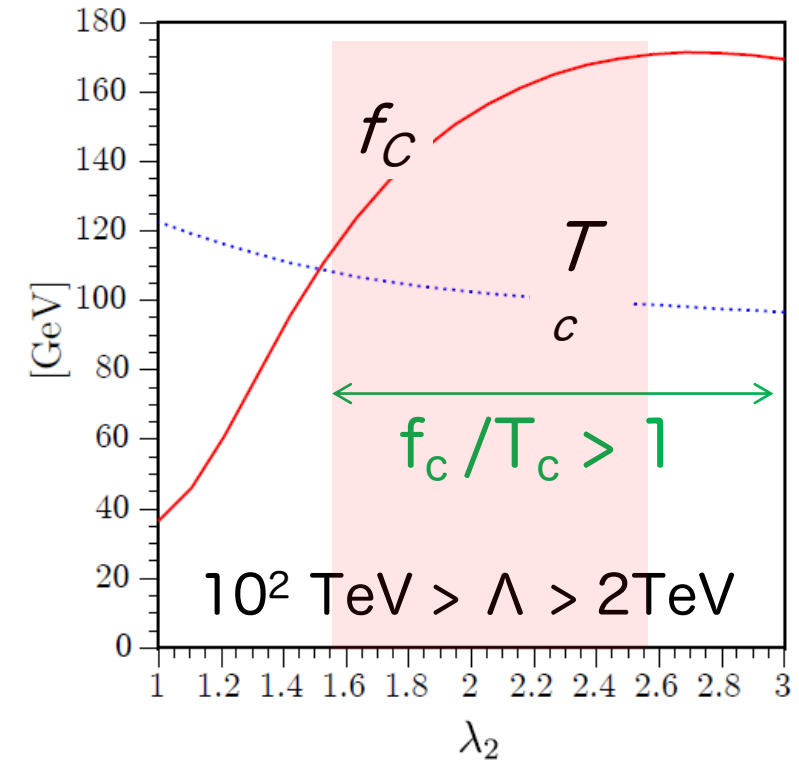
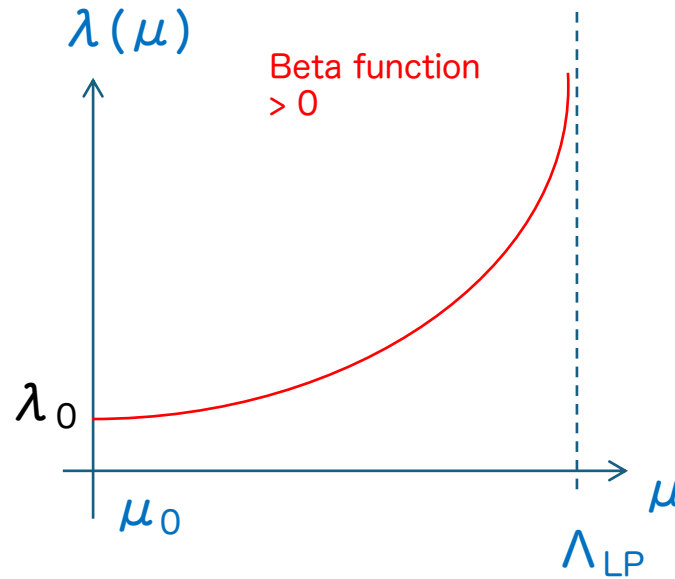


Landau pole and above

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

1st OPT $\rightarrow$ Landau pole

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



What is above ?

Higgs interaction
 $\rightarrow$ SU(N) gauge interaction

Higgs coupling
 $H_{ij} = T_i T_j$
 Higgs as "Meson"

New gauge coupling

UV theory

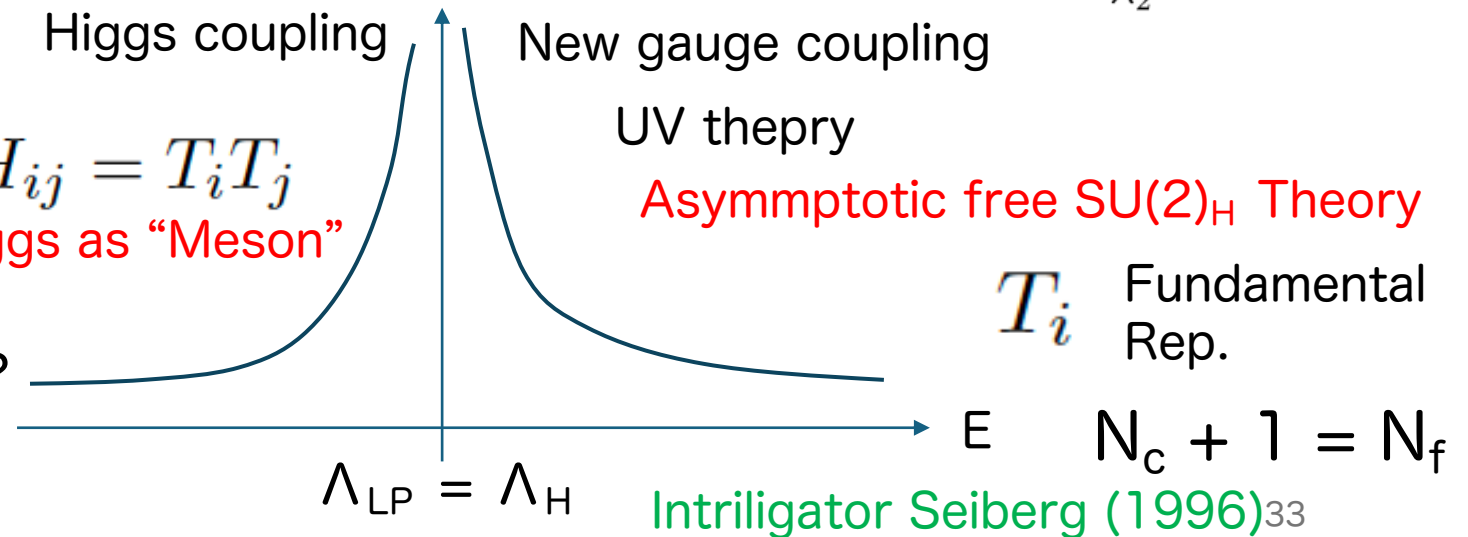
Asymptotic free SU(2)_H Theory

T_i Fundamental Rep.

SFOEWPT

$\Leftrightarrow$ Composite nature of Higgs boson?

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



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 ($h \rightarrow \gamma \gamma$) 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

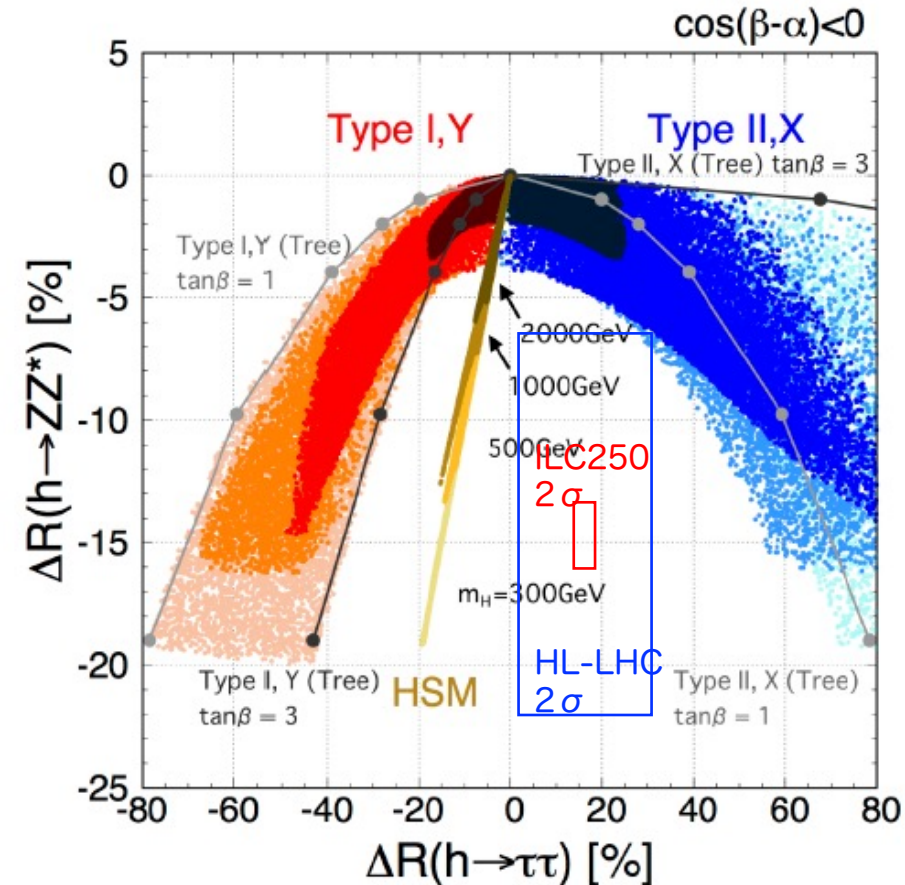
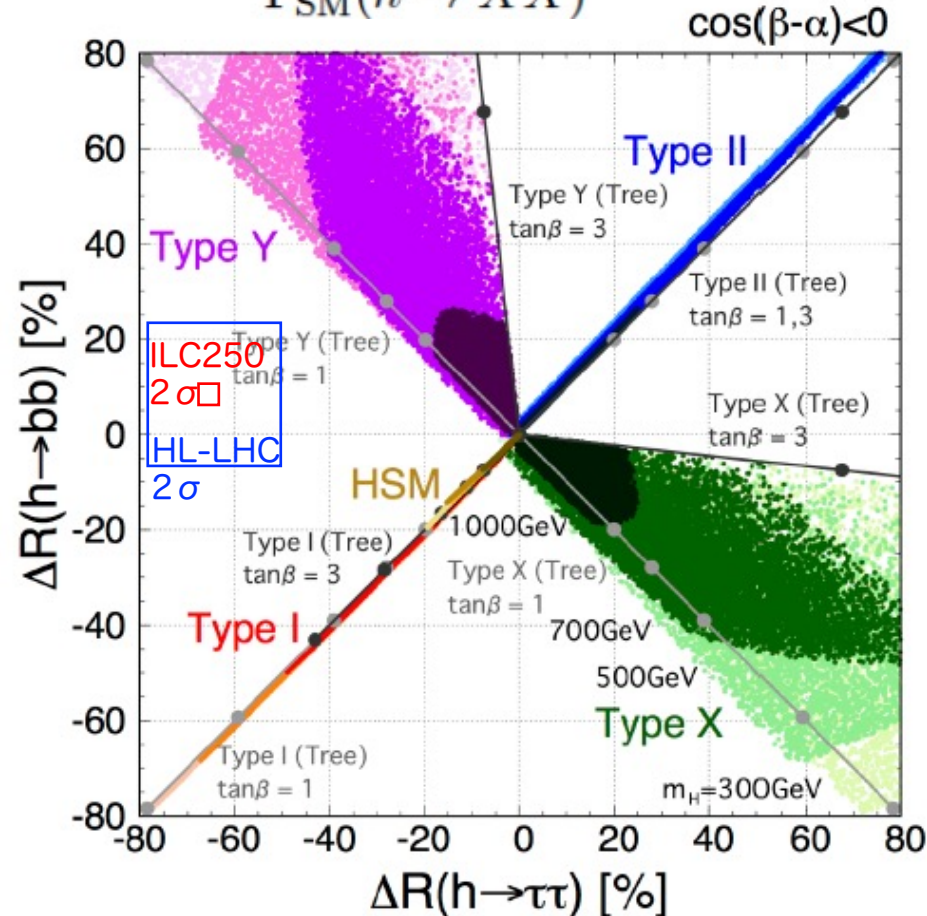
Thank you !

Backup slides

Fingerprinting

SK, Kikuchi, Mawatari, Sakurai, Yagyu 2018

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



Run2
 bb 130%
 $\tau\tau$ 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

2HDM Higgs alignment case

General Higgs potenshal

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

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

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

rephasing

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

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

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

Yukawa alignment
Pich and Tuzon (2009)

Multiple CPV phases

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

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 $\rightarrow |d_e| = O(10^{-28}) e \text{ cm}$

Barr-Zee diagram

Difficult

Observation

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

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); ...

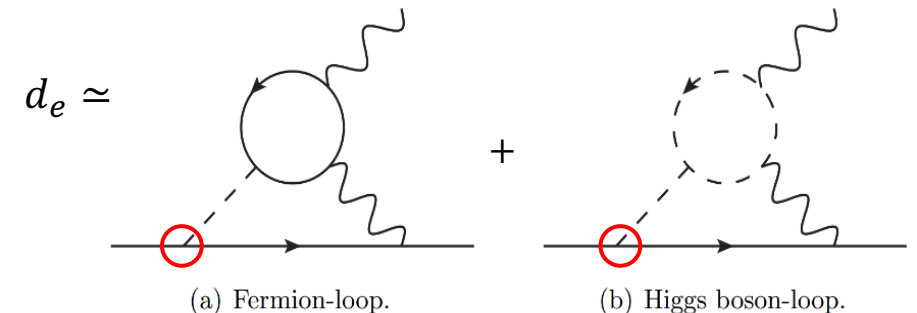
- Assuming the Yukawa alignment for avoiding FCNC

- Multiple CP phases

- EDM depends on the parameters not related to BAU.

EDM cancellation

Cancellation among Barr-Zee-type diagrams can be used



Is it really necessary?

No. It is possible to built a 2HDM without EDM cancellation Aiko, Endo, SK, Mura 2025

Starting from the general 2HDM

Most general potential

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

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 Yukawa sector

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

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.

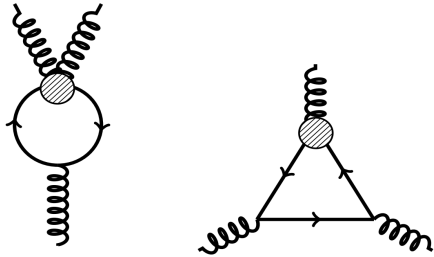
CPV rephasing invariants in the model $\Phi_2 \rightarrow e^{i\theta} \Phi_2$

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

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

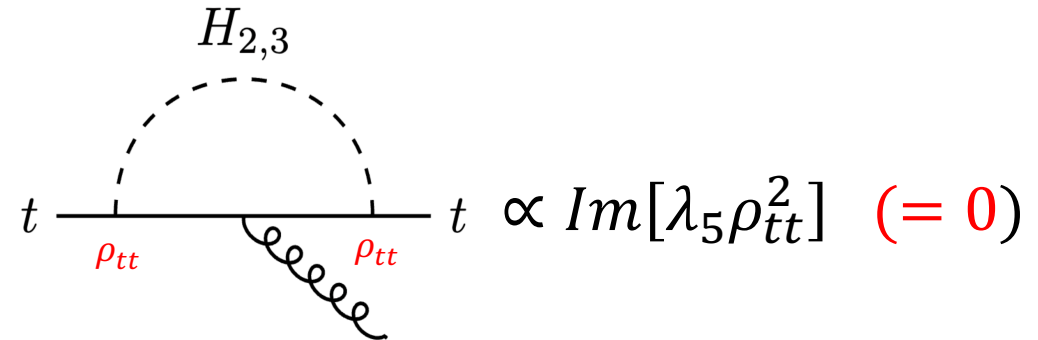
EDM in the minimal setup

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

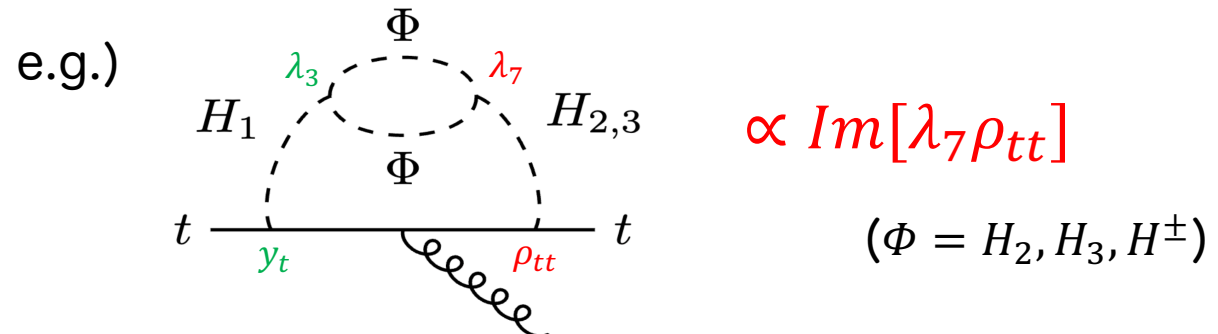


Kamenik et al. (2012);
Hisano, Tsumura and Yang (2012);
and more works

1 loop diagram for top CEDM e.g.)

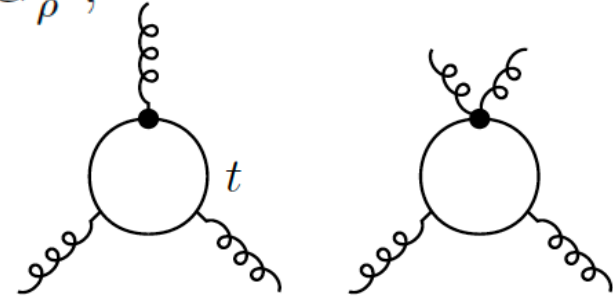


In our scenario, 2 loop diagrams are leading.



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

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



Induced Weinberg operator and EDMs

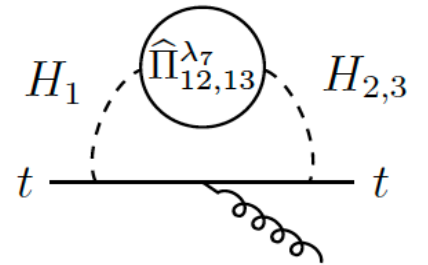
$$\delta w^{(t)} / g_S = \frac{g_S^2}{32\pi^2} \frac{\tilde{d}_t}{m_t}$$



RGE

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

hadronization scale $\mu_H = 2 \text{ GeV}$



QCD sum rule

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

Correlation between EDM and BAU in the minimal set up

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

Parameter scan

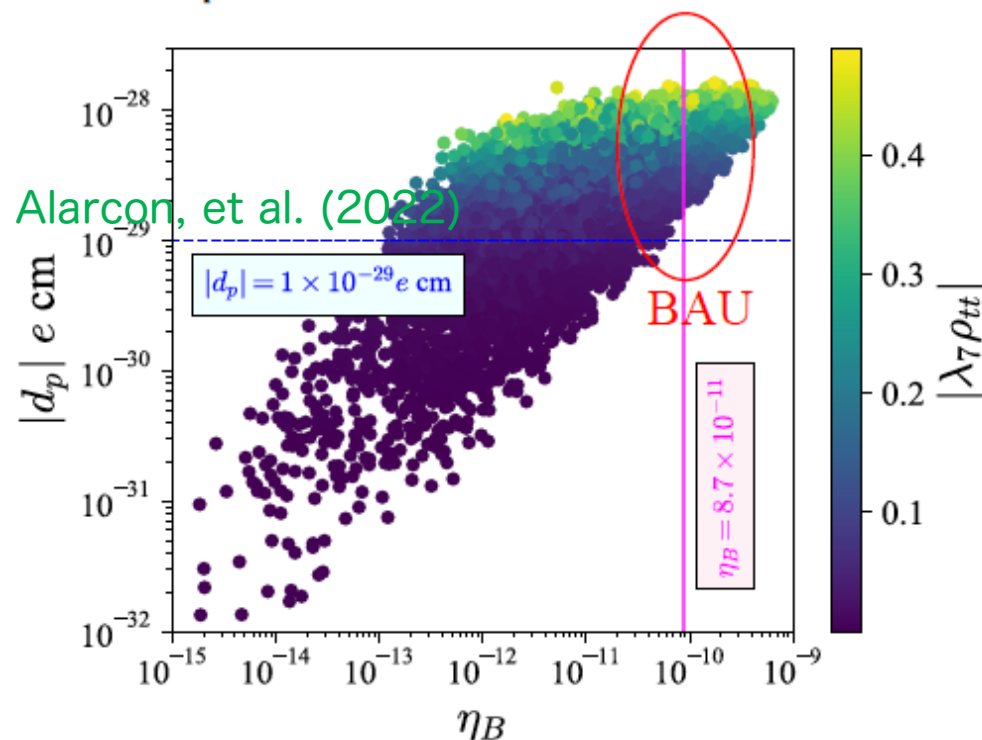
$$m_\Phi = [200, 500] \text{ GeV}, \mu_2^2 = [-m_\Phi^2, 0], |\rho_{tt}| = [0, 0.5]$$

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

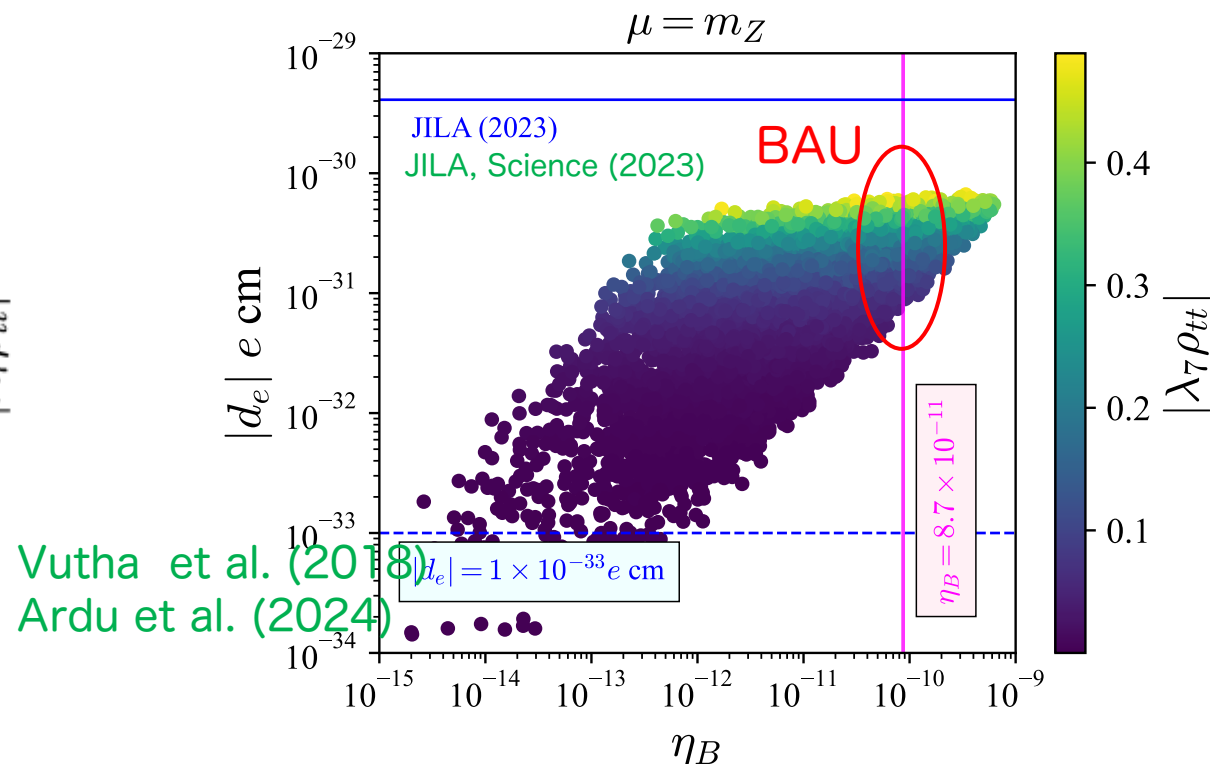
Neutron EDM

Sahoo, PRD (2017)

$$|d_p| < 2.1 \times 10^{-25} e \text{ cm (current)}$$



Electron EDM



Viable, and testable at future EDM experiments

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)

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

$$\mathcal{L}_{\text{BSM}} = \xi \left[-\frac{\kappa_0}{4} [\mathcal{M}^2(h)]^2 \ln \frac{\mathcal{M}^2(h)}{\mu^2} \right. \\ \left. + \frac{v^2}{2} \mathcal{F}(h) \text{Tr} [D_\mu U^\dagger D^\mu U] + \frac{1}{2} \mathcal{K}(h) (\partial_\mu h) (\partial^\mu h) \right. \\ \left. - v \left(\bar{q}_L^i U [\mathcal{Y}_q^{ij}(h) + \hat{\mathcal{Y}}_q^{ij}(h) \tau^3] q_R^j + h.c. \right) - v \left(\bar{l}_L^i U [\mathcal{Y}_l^{ij}(h) + \hat{\mathcal{Y}}_l^{ij}(h) \tau^3] l_R^j + h.c. \right) \right]$$

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

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

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

SK, R. Nagai (2021)

$$+ g^2 \mathcal{F}_W(h) \text{Tr} [\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}] + g'^2 \mathcal{F}_B(h) \text{Tr} [\mathbf{B}_{\mu\nu} \mathbf{B}^{\mu\nu}] \\ - gg' \mathcal{F}_{BW}(h) \text{Tr} [U \mathbf{B}_{\mu\nu} U^\dagger \mathbf{W}^{\mu\nu}]$$

Strongly 1st OPT

Colored region satisfies two conditions

Sphaleron decoupling

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

Bubble nucleation completion

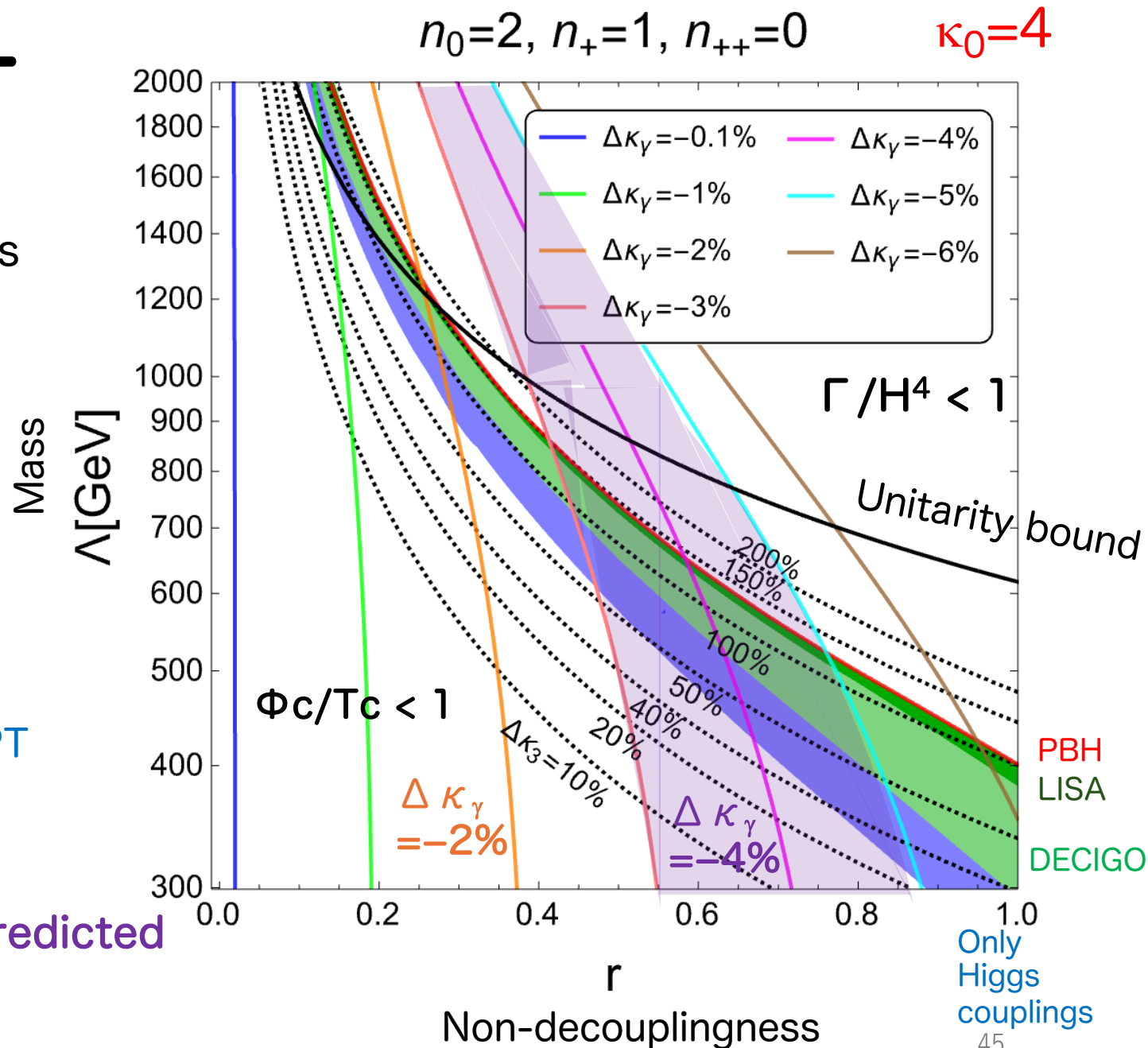
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($\Delta \lambda_3, \Delta \kappa_\gamma, \dots$)

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

135% > ΔK₃ > 55%

GW, PBH can also be used



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

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}

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

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

Microlensing observations

Subaru HSC <https://hsc.mtk.nao.ac.jp/ssp>

OGLE <http://ogle.astrouw.edu.pl/>

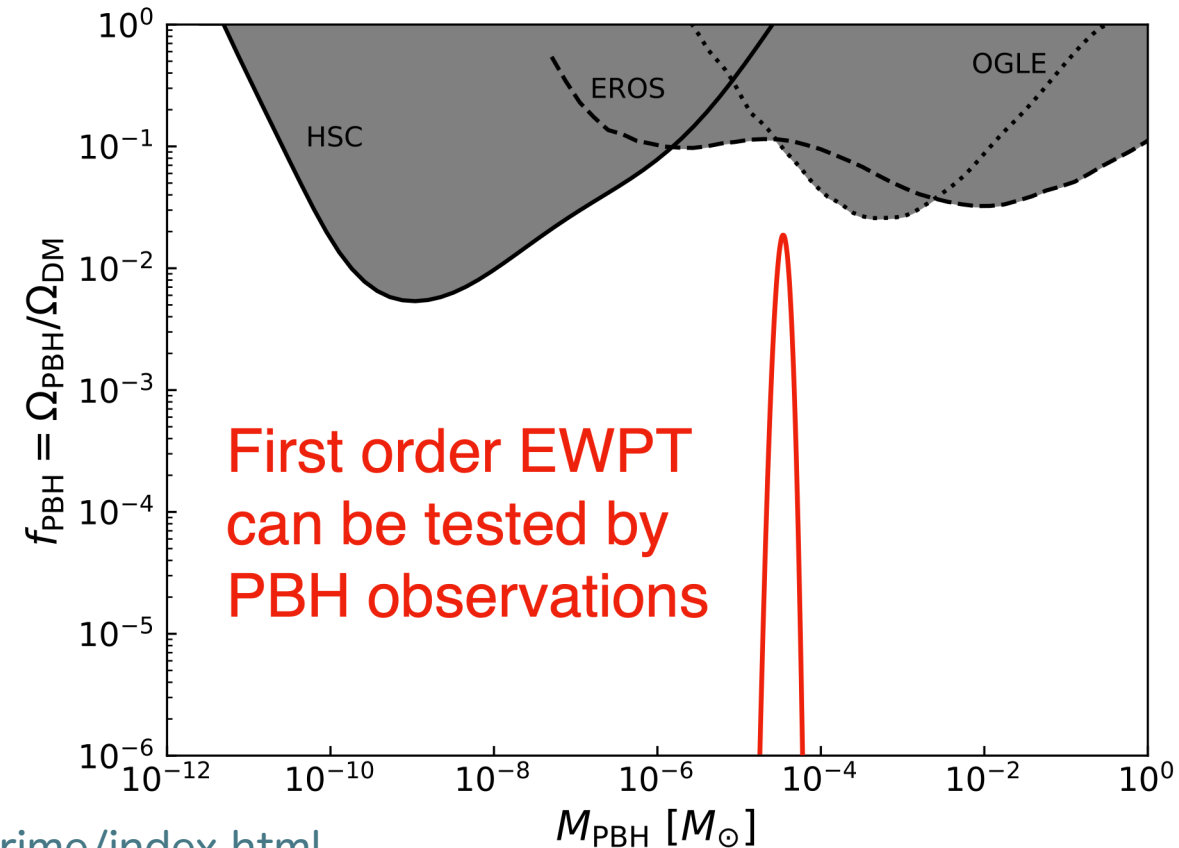
Future observations

PRIME 2023~ <http://www-ir.ess.sci.osaka-u.ac.jp/prime/index.html>

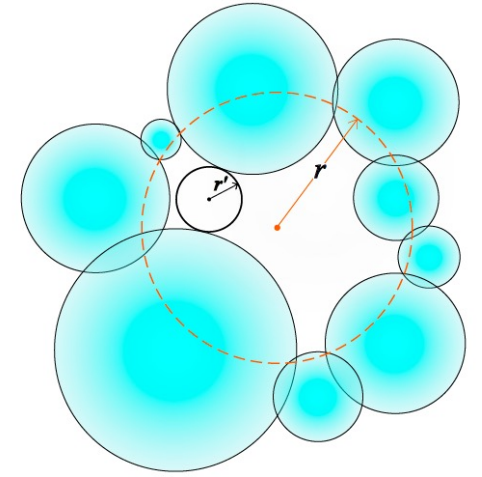
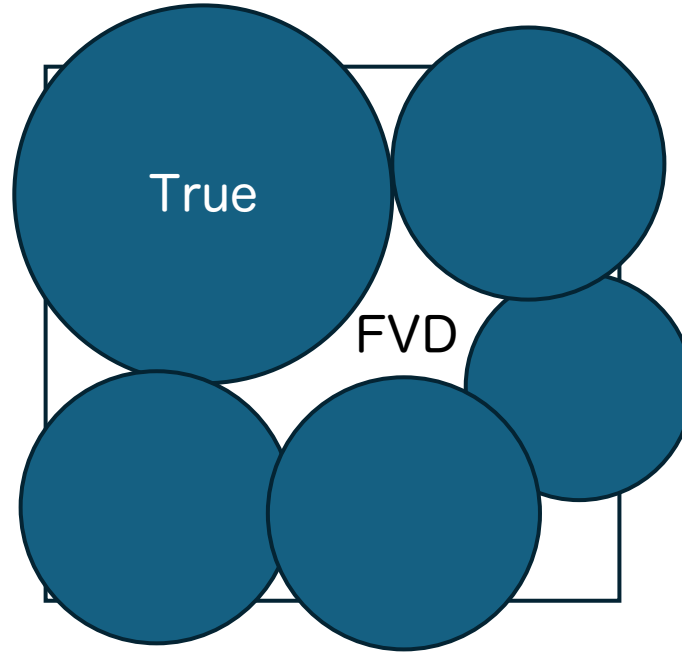
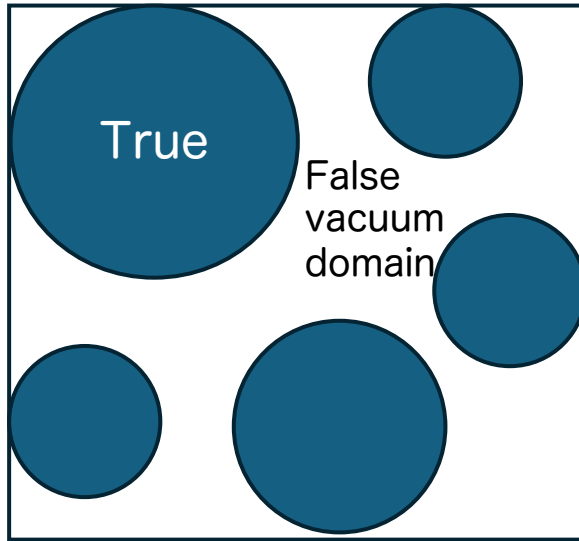
Roman 2026~ <https://roman.gsfc.nasa.gov>

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

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



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