Higgs as a Probe of New Physics

Shinya KANEMURA

大阪大学
THE UNIVERSITY OF OSAKA

U. Osaka
Dr. Wani
(mascot
character)

Seminar at Institute of Nuclear Physics PAN, September 25, 2025

This talk

I would like to emphasize importance of Higgs physics as a probe of new physics

- Deviation in h(125) couplings at NLO and fingerprinting
- Decays of heavy Higgs bosons at NLO
- Higgs Potential/EW phase transition/EW baryogenesis

Current Situation

Higgs Discovery 2012

Mass 125 GeV Spin・Parity

Good agreement with SM prediction

No BSM evidence found up to now

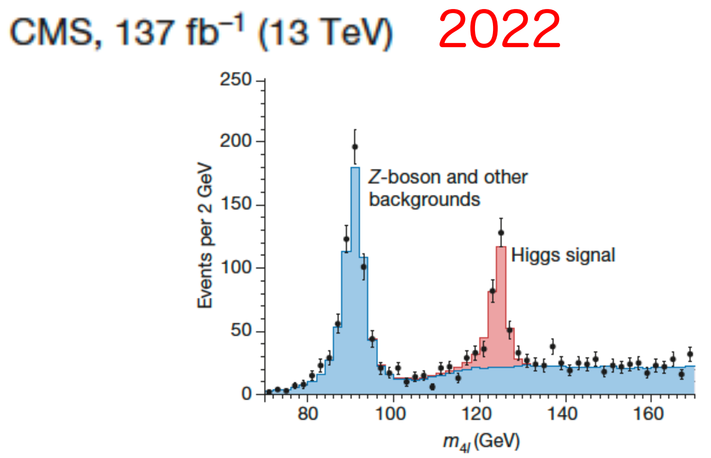
But big questions → BSM

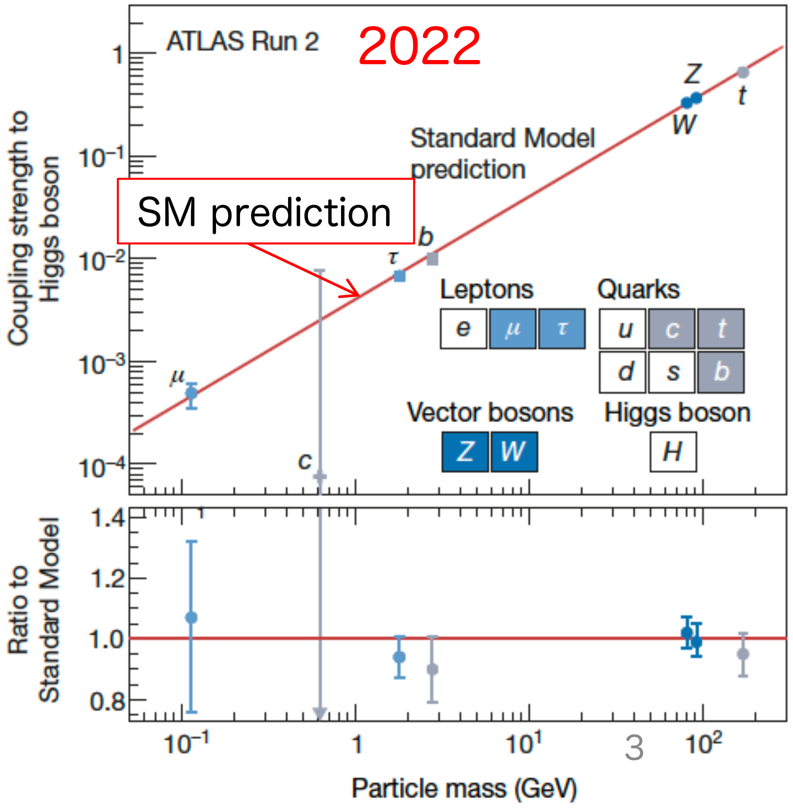
<u>Where is new physics?</u>

Low scale?

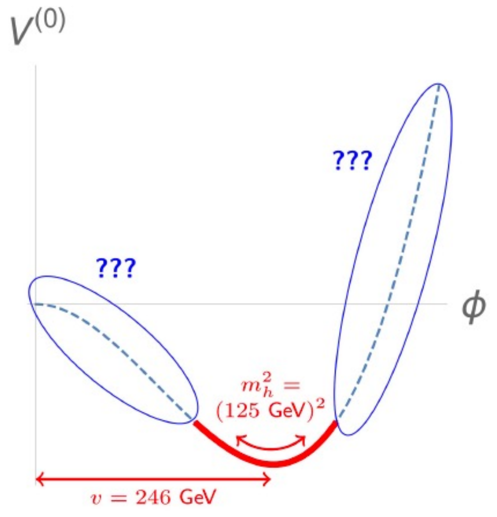
TeV Scale?

High Scale?





Higgs: window to new physics



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
SUSY, DSB, GHU,
…

TeV scale: testable at current and future experiments

Extended Higgs sectors?

Multiplet Structure (with additional scalars)

Φ_{SM} + Isospin Singlet,
Φ_{SM} + Doublet (2HDM),
Φ_{SM} + Triplet,
…

Additional Symmetry

Discrete or Continuous?
Exact or Approximate or Softly broken?

Interaction

Weakly coupled or strongly coupled?

Hint for BSM models

Rho parameter ➡ Multi-doublet (and singlet) structures
FCNC Suppression ➡ Strong constraint on the Yukawa sector
Higgs alignment ➡ Strong constraint on mixing angles

Example: 2HDM with softly broken Z2

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

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

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

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}\begin{bmatrix} H \\ h \end{bmatrix} \qquad \begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

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

masses

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

M_{soft}: soft breaking scale

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

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

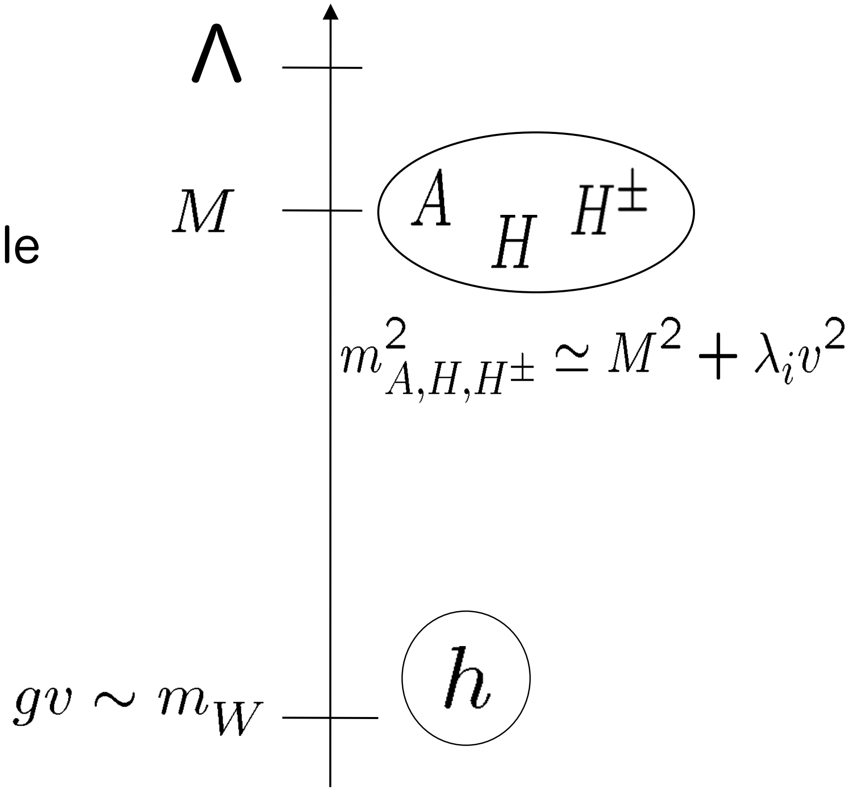
soft-breaking scale

of the discrete symm.

How SM-like is realized?

Λ : Cutoff

M : Mass scale irrelevant to VEV

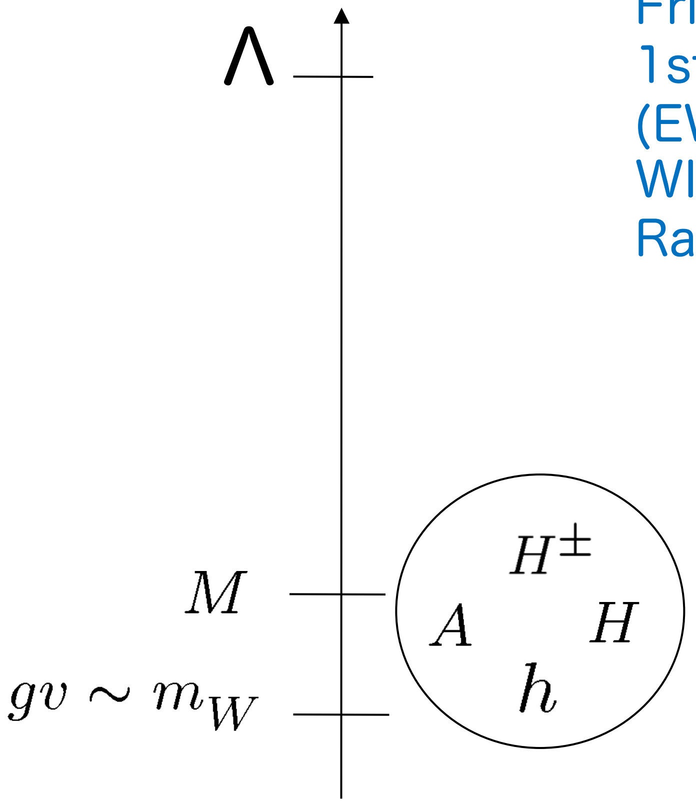


$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM

Decoupling

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



Higgs alignment

$k_V \sim 1$ SM like

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

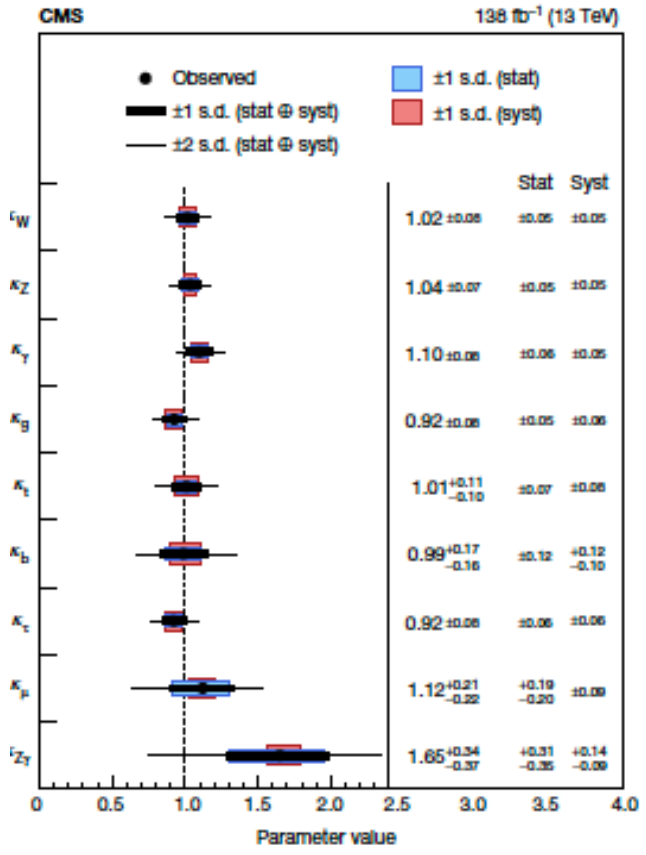
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm nonSM} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

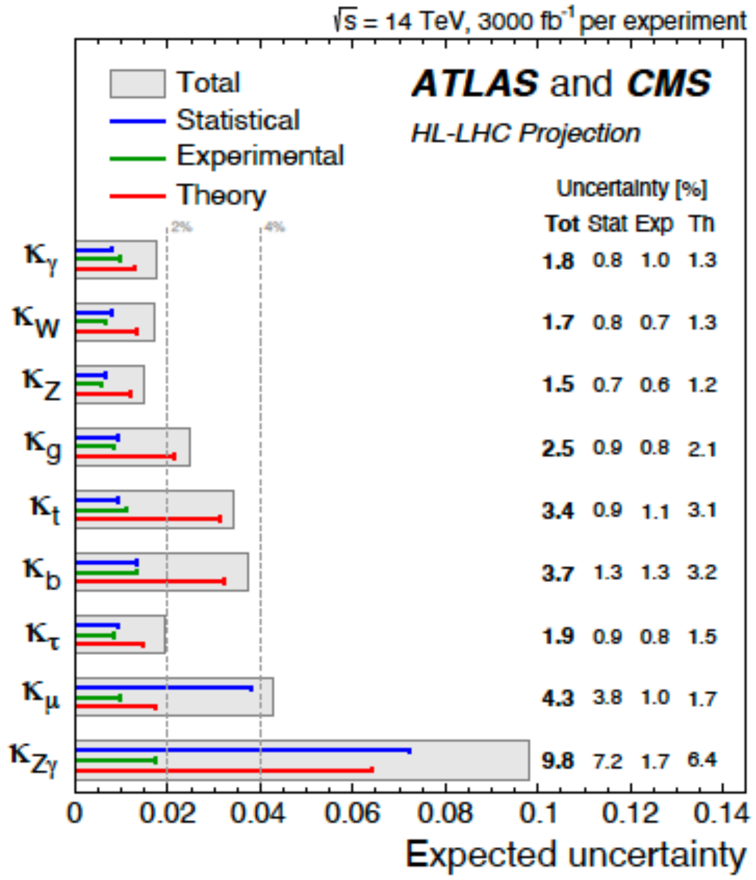
Effective Theory is an extended Higgs sector

Alignment and Non-Decoupling

Higgs couplings

hWW, hZZ, h$\tau\tau$,
htt, hbb, ⋯ ,
h$\gamma\gamma$, hZγ, hhh





BSM effect can be described by

SMEFT (decoupling)   HEFT (w/wo decoupling)

Extended Higgs models (w/wo decoupling)

Each concrete BSM model

Small deviation ($\kappa_V \neq 1$) = New Scale

No-Lose Theorem Lee, Quigg, Thacker 1977

Unitarity:	$M_H < 1$ TeV, otherwise, BSM appears below 1TeV

Motivation to build SSC, LHC

h(125) discovery!

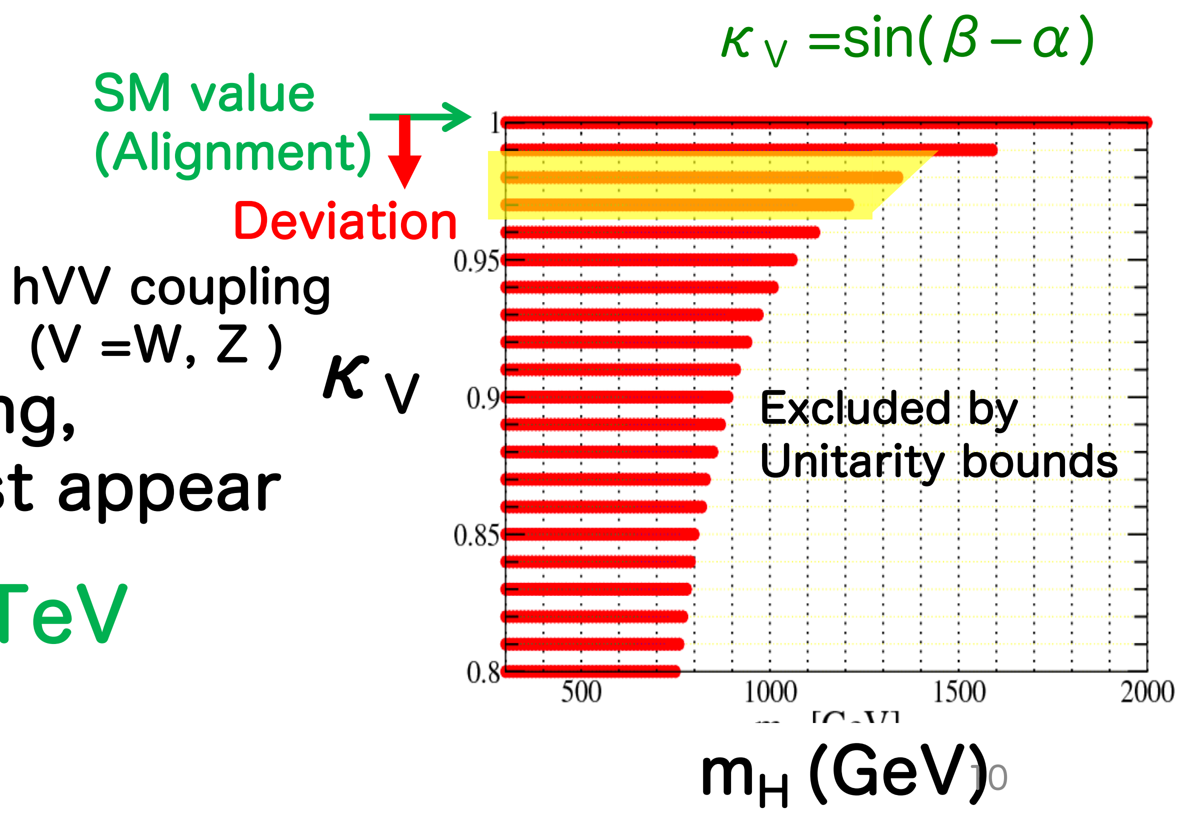
Small deviation ($\kappa_V \neq 1$) = New Scale

<u>No-Lose Theorem</u> Lee, Quigg, Thacker 1977

Unitarity: $M_H < 1$ TeV, otherwise, BSM appears below 1TeV

Motivation to build SSC, LHC

h(125) discovery!



New No-Lose Theorem

If deviation appears in a Higgs coupling,
the second Higgs H or New Phys must appear

$$\Delta \kappa_V = 2\ \% \quad \rightleftarrows \quad m_H < 1.4\ \text{TeV}$$

Deviation is necessary

Yukawa Couplings

Multi-doublet models: FCNC appears via Higgs mediation

<u>In two Higgs doublet models:</u>

to avoid FCNC, give different charges to Φ_1 and Φ_2

Discrete sym. $\Phi_1 \rightarrow +\Phi_1$, $\Phi_2 = -\Phi_2$

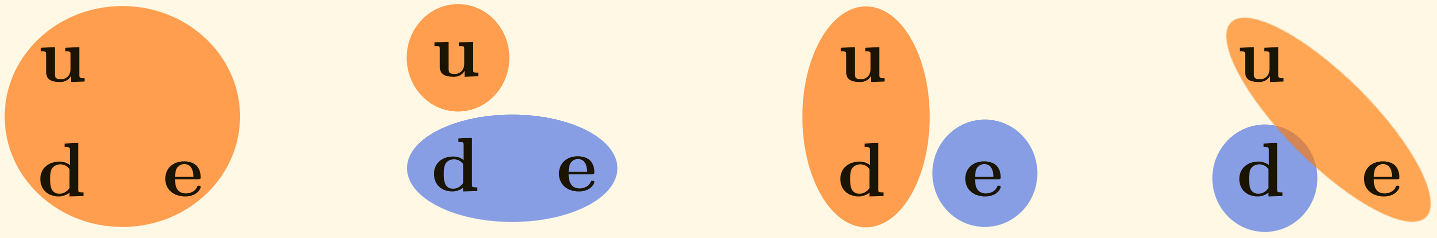
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

Four Types of Yukawa coupling

Barger, Hewett, Phillips

Classified by Z_2 charge assignment



Type-I — Neutrinophilic, Inert

Type-II — SUSY

Type-X — Radiative Seesaw, Lepton specific

Type-Y

Pattern of deviations separates models

Couplings of h(125) to quarks and leptons are different in different Higgs models

Simple example: 2HDM

	κ_V	κ_τ	κ_b	κ_c
Type-I	↓	↓	↓	↓
Type-II	↓	↑	↑	↓
Type-X	↓	↑	↓	↓
Type-Y	↓	↓	↑	↓

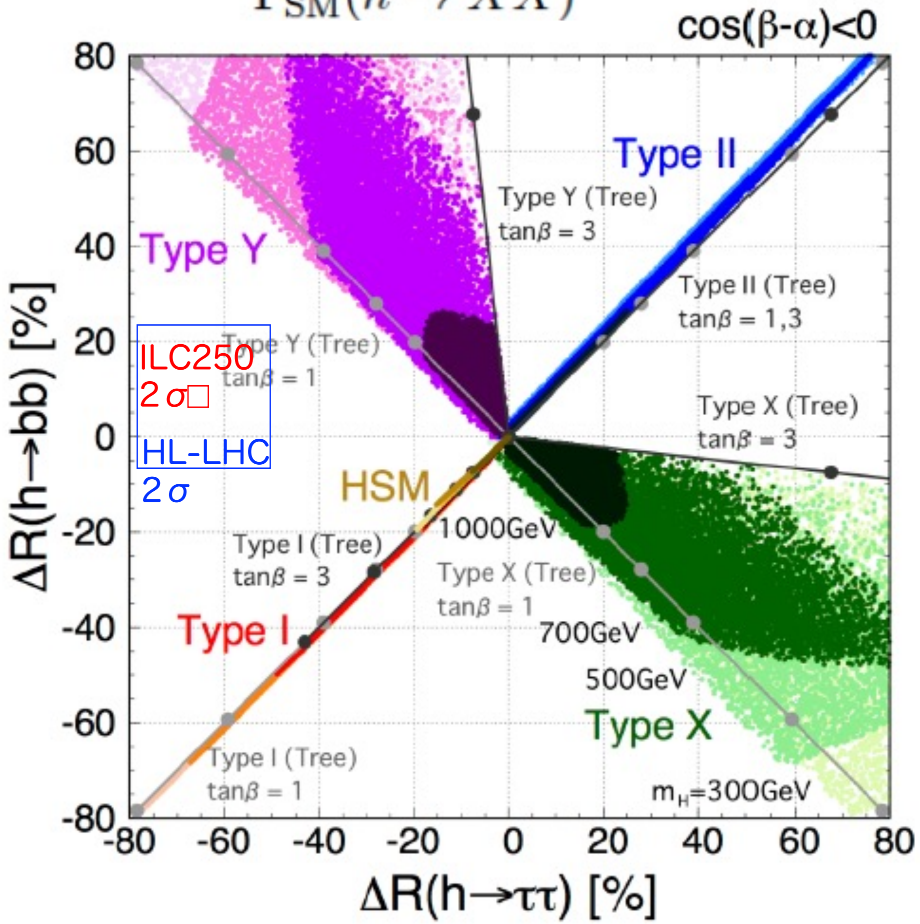
Direction of deviation in each coupling

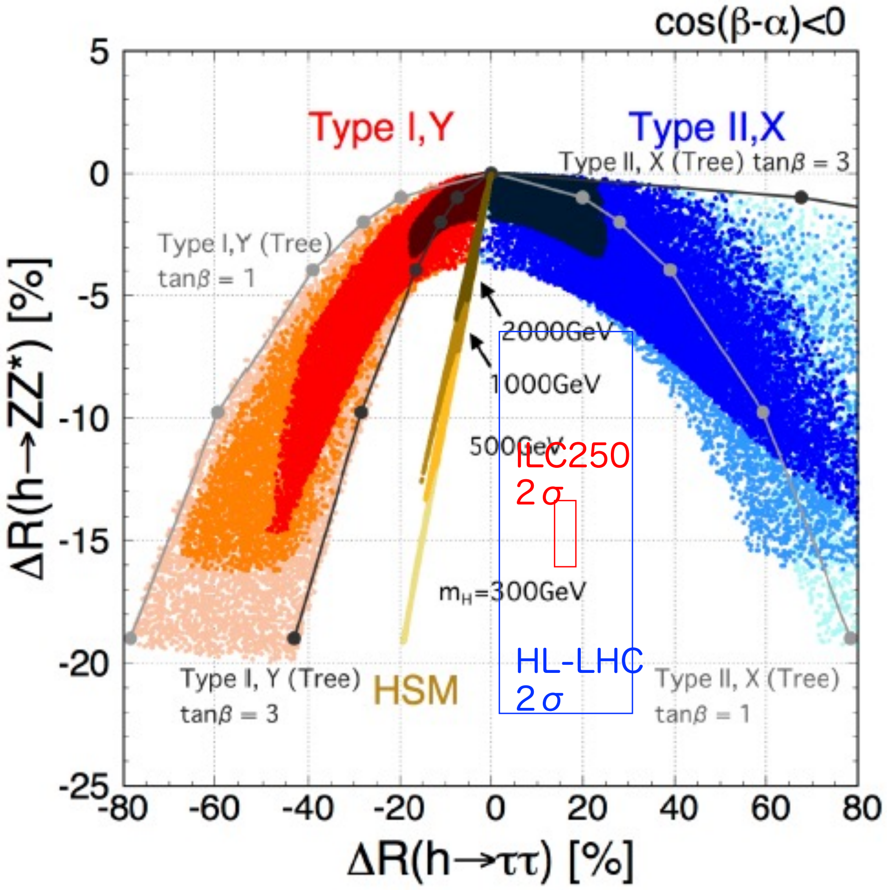
We can fingerprint the BSM model from pattern of deviations in couplings

Fingerprinting

SK, Kikuchi, Mawatari, Sakurai, Yagyu 2018

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





Run2

bb	130%
$\tau\tau$	64%
ZZ*	56%

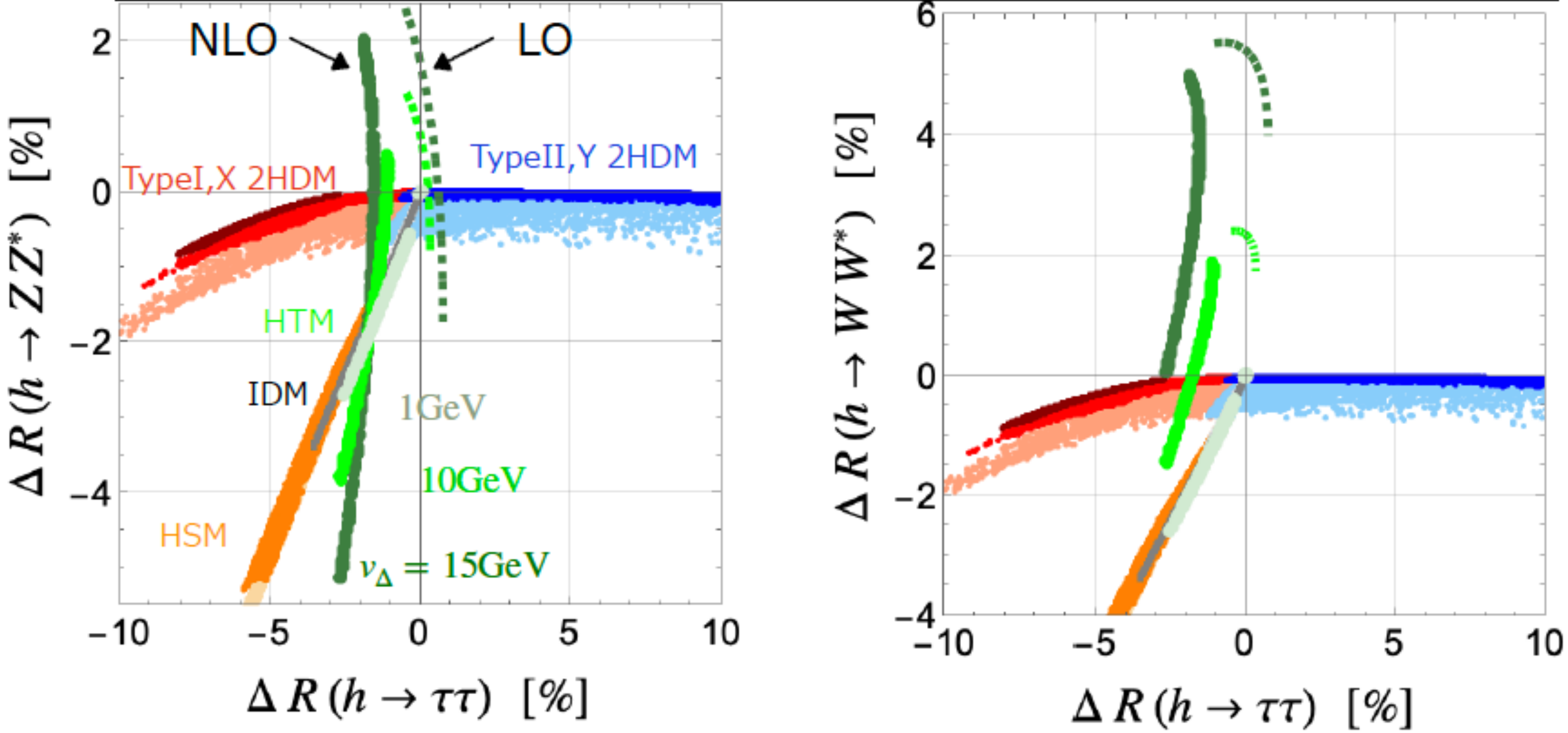
Full set of 1-loop corrections (EW + QCD + Higgs) to the decay rates in various Higgs sectors and future precision measurements make us possible to fingerprint models and also to get information of inner parameters such as mass of the second Higgs boson

Decay rates of h

[Aiko, Kanemura, Kikuchi, KS, Taniguchi, Yagyu, preliminary]

$$\Delta R \equiv \frac{\Gamma(h \to XX)^{\mathrm{HTM}}}{\Gamma(h \to XX)^{\mathrm{SM}}} - 1$$

$m_H = m_A = 300\mathrm{GeV},\ 0 < \Delta m(= m_{H^\pm} - m_A) < 150\mathrm{GeV},\ 0 < \sin\alpha < 0.18$



$\tan\beta = \frac{\sqrt{2}v_\Delta}{v_\phi}$

$\tan\beta' = \frac{2v_\Delta}{v_\phi}$

Higgs Triplet Model (type II seesaw)

Slide Kodai Sakurai at HPNP2025

- At LO, the deviation arises by Higgs mixings :

  $c_{hZZ} = c_{\beta'}c_\alpha + 2s_{\beta'}s_\alpha,\ c_{hWW} = c_\beta c_\alpha + \sqrt{2}s_\beta s_\alpha,\ c_{hff} = c_\alpha/c_\beta$

  Positive $\Delta R_{h\to ZZ^*}, \Delta R_{h\to WW^*}$ are clear sign for HTM.

- Due to the loop corrections, ΔR deviate from LO by with-2~-5%.

  ⟷ $\Gamma(h \to ZZ^*)$~1.5% , $\Gamma(h \to WW^*)$~5.2%, $\Gamma(h \to \tau\tau)$~7.6%

  [K. Fujii, C. Grojean, M. E. Peskin, et. al.,1710.07621]

α : mixing angle for (h,H)

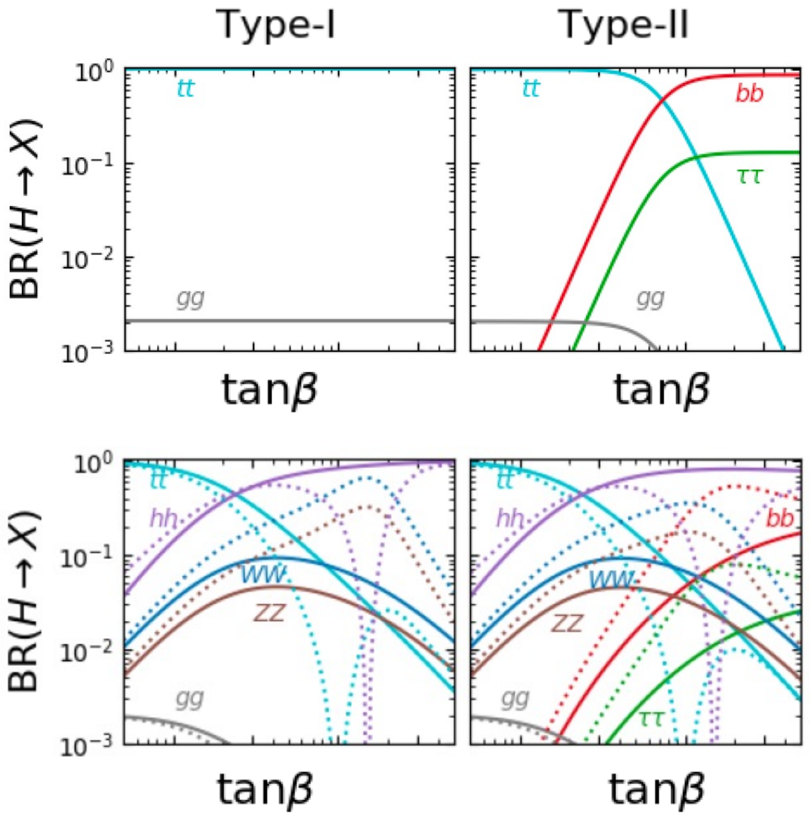
$\beta^{(\prime)}$: mixing angle for charged (CP-odd) Higgs bosons

Constraints:
- Vacuum stability
- Perturbative unitarity
- EW parameters (m_W, ρ, s_W^2)

Decay of Heavy Higgs bosons

H, A, H+, ..

Exact and near κ_V=1 are drastically different

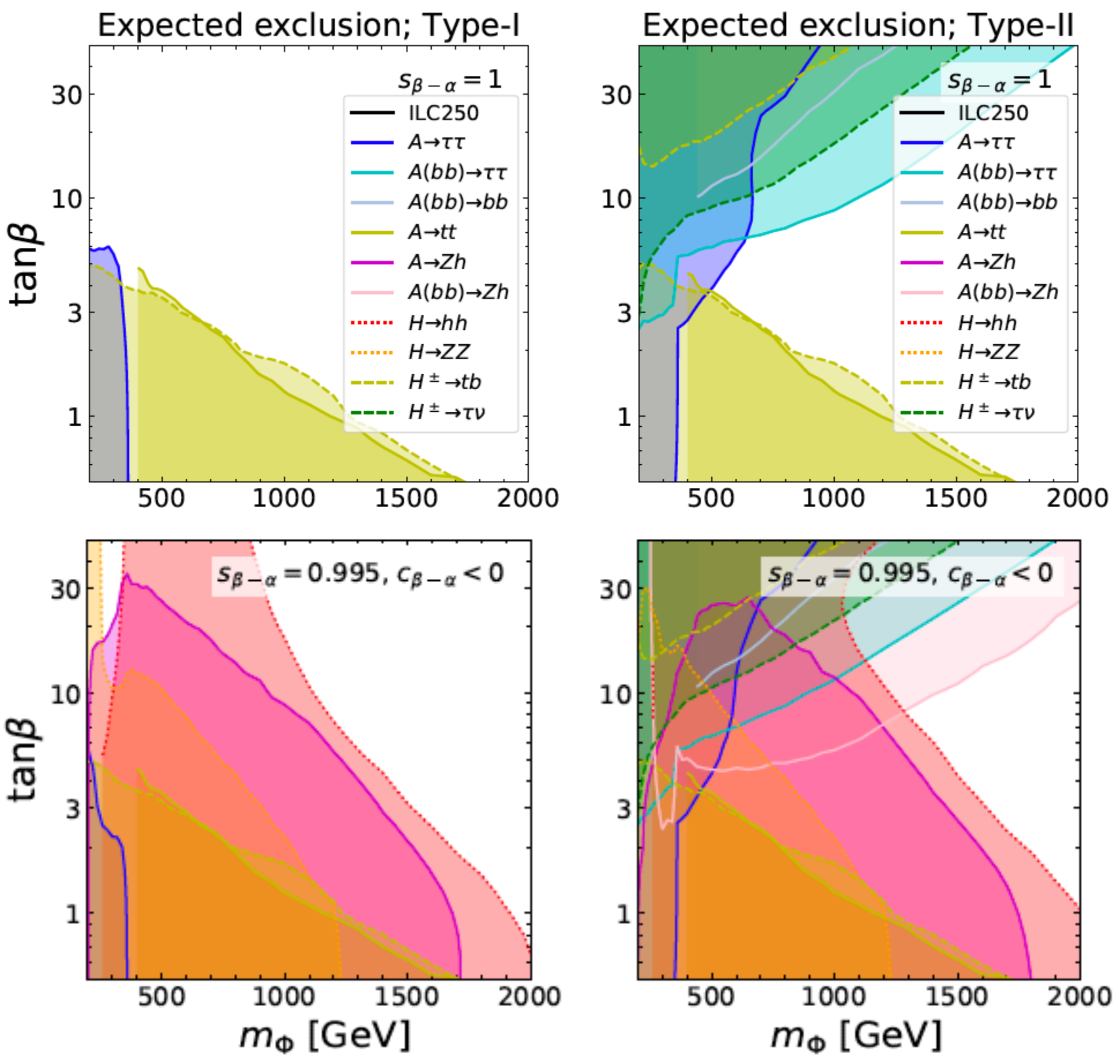


Kv =1
Alignment

Kv =0.995
Near alignment

H to H decays become important
for the near alignment case

Expected excluded region at HL-LHC
using current LHC data

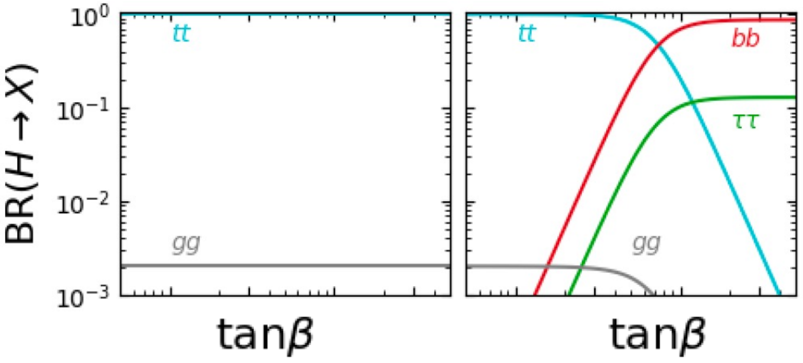


Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu, 2020

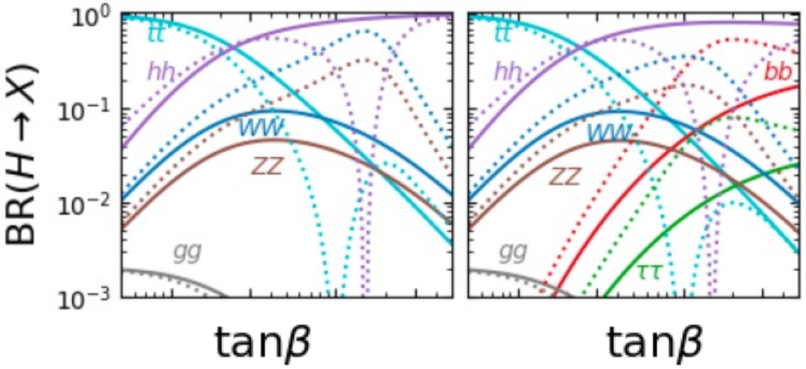
Decay of Heavy Higgs bosons
H, A, H+, ..

Aiko, SK, Kikuchi, Mawatari, Sakurai, Yagyu, 2020

Exact and near κ_V=1 are drastically different

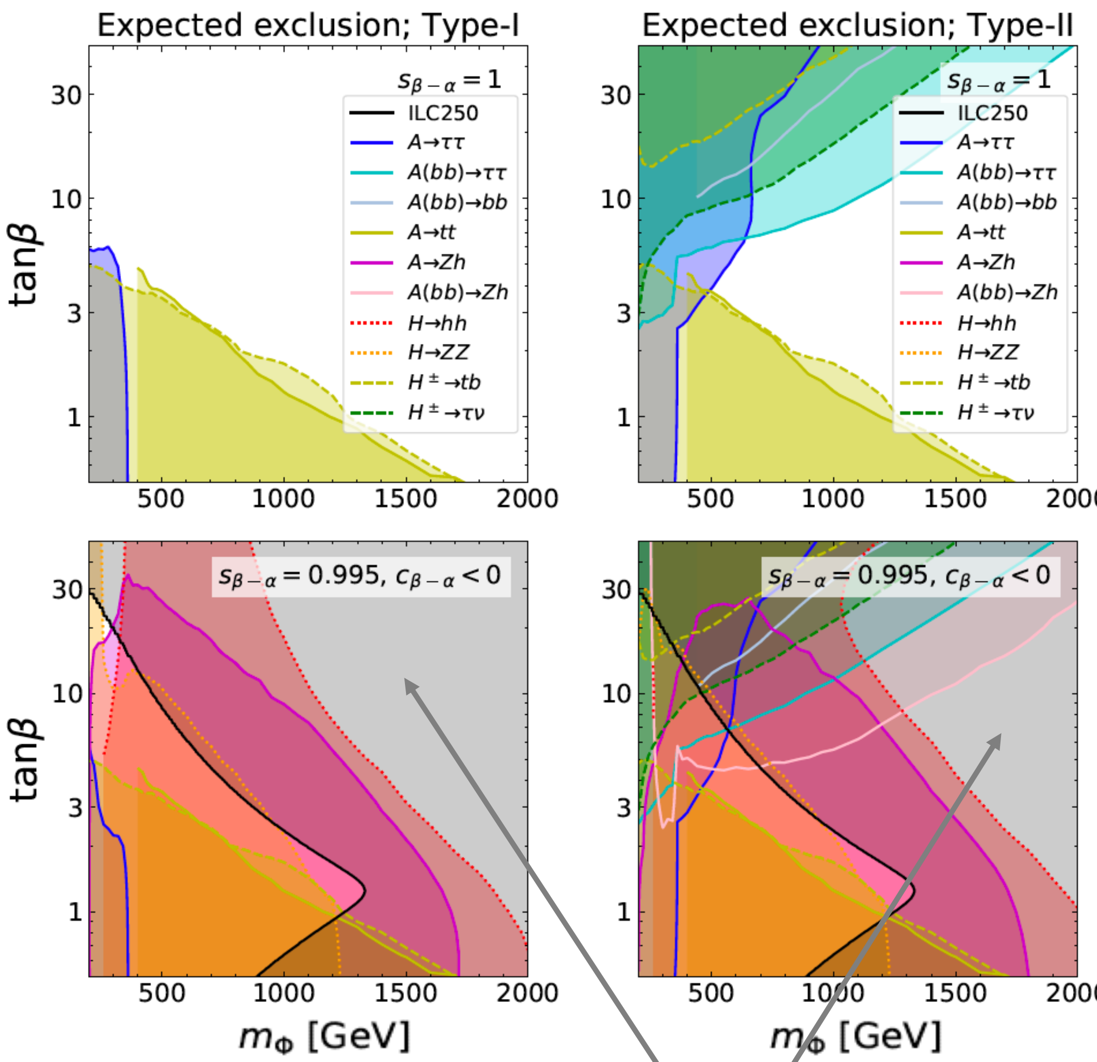


Kv =1
Alignment



Kv =0.995
Near alignment

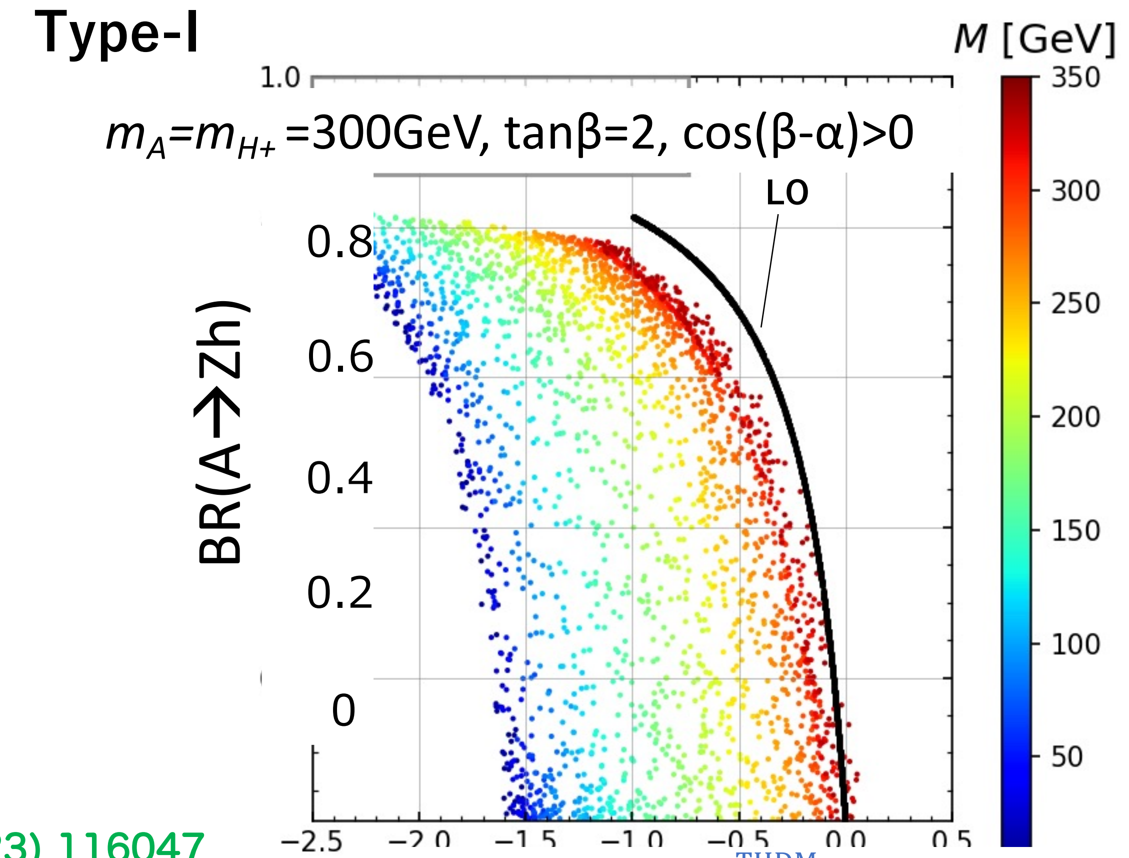
H to H decays become important for the near alignment case



For near alignment cases, all parameter regions can be excluded

By the new no-lose theorem

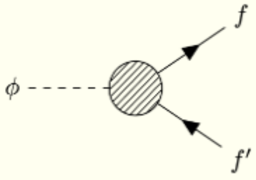
NLO calculation can change the LO analysis

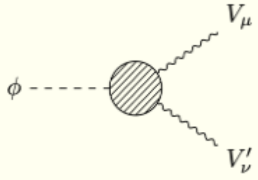


$$\Delta R[h_{125} \to ZZ^*] = \frac{\Gamma^{\mathrm{THDM}}_{\mathrm{NLO}}[h_{125} \to ZZ^*]}{\Gamma^{\mathrm{SM}}_{\mathrm{NLO}}[h_{125} \to ZZ^*]} - 1$$

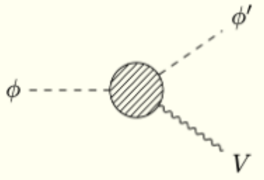
NPB 986 (2023) 116047
Aiko, SK, Sakurai

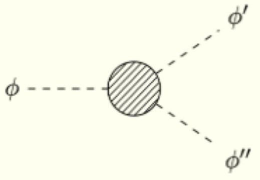
Correlations between “Higgs to Higgs decays” and h_{125}→VV*
are significantly different from LO results.





H-COUP





Fortran program for decay BRs of Higgs bosons with loop corrections in extended Higgs models.

You can obtain H-COUP at ⇒ http://www-het.phys.sci.osaka-u.ac.jp/~hcoup/

【 Characteristics of H-COUP】

- Various extended Higgs models : Higgs singlet model, THDMs (Type-I, II, X, Y) , Inert doublet model
- Full set of decay processes of all Higgs bosons:

  Ver.1 (2017) : Renormalized vertices of h_{125}. SK, Kikuchi, Sakurai, Yagyu, CPC.233(2018)134

  Ver.2 (2019) : Two- and Three-body decays of h_{125}. SK, Kikuchi, Mawatari, Sakurai, Yagyu, CPC 257(2020) 107512

  Ver.3 (2023) : Two-body decays of additional Higgs bosons (H, A, $H^{\pm}$) Aiko, SK, Kikuchi, Sakurai, Yagyu, CPC 301 (2024) 109231

  ⇒ Evaluate correlations between behavior of various decay processes.

- Loop corrections : EW and scalar-NLO
  - UV div. → On-shell renormalizations
  - Gauge dependence → Remove by Pinch technique
  - IR div. via photon loop → Cancel by real photon emission

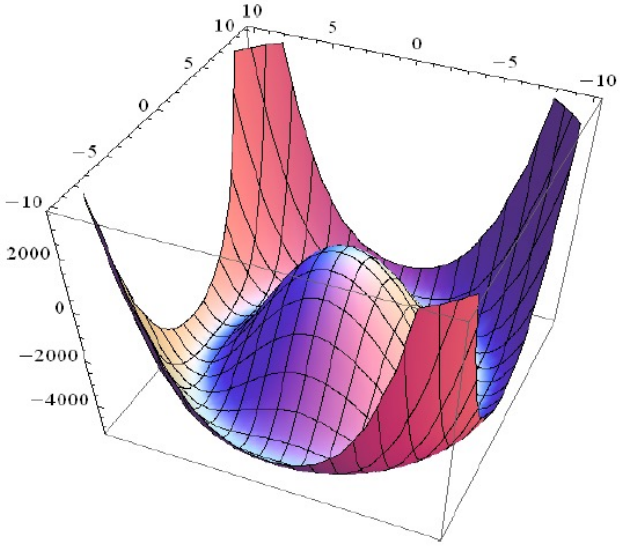
  QCD (NNLO, NLO) corrections (MS-bar scheme).

  A. Djouadi, Phys. Rept., 457, 1 (2008),
  B. M. Spira, Prog. Part. Nucl. Phys., 95, 98 (2017),
  K. G. Chetyrkin, A. Kwiatkowski, Nucl. Phys., B461, 3 (1996)

- Constraints : Vacuum stability (tree level, RGE improved), Tree-level unitarity, Triviality, True vacuum, ST parameters

Higgs Potential

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



It is very important to know the *hhh* coupling
to reconstruct the Higgs potential

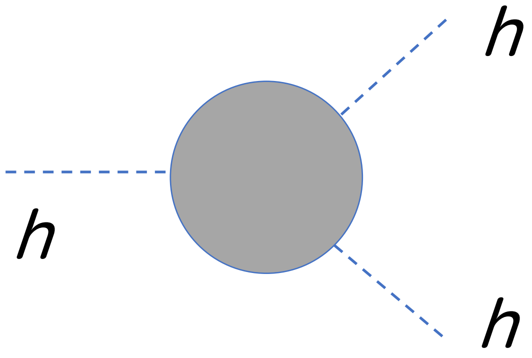
$$\boxed{V_{\rm Higgs} = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\underline{\lambda_{hhh}}h^3 + \frac{1}{4!}\lambda_{hhhh}h^4 + \cdots}$$

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

Top loop
effect
in the SM

SK, Okada, Senaha, Yuan, 04

Non-decoupling effect



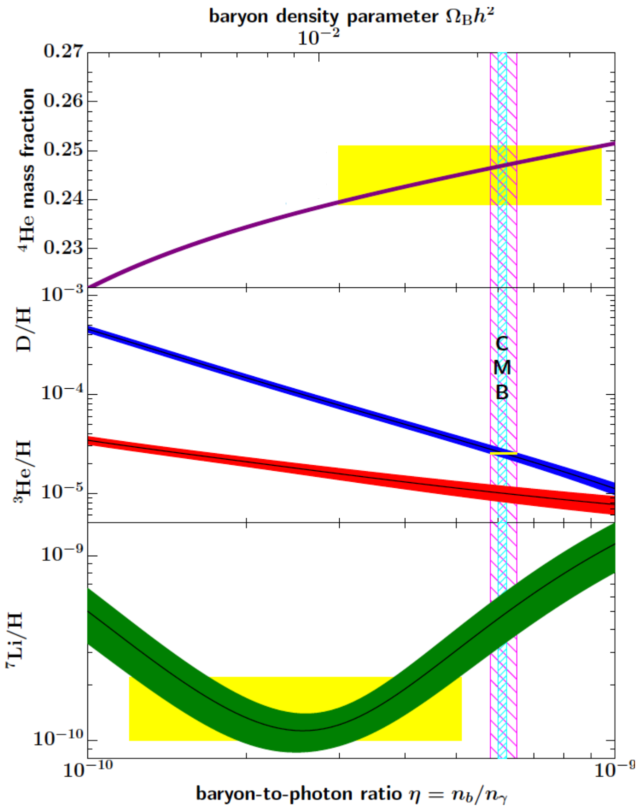
Sensitive to BSM physics too!

Effect of BSM Higgs can enhance the hhh by O(30-100) %

Physics of 1st OPT (EW Baryogenesis)

BAU and Baryogenesis

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



Particle Data Group

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

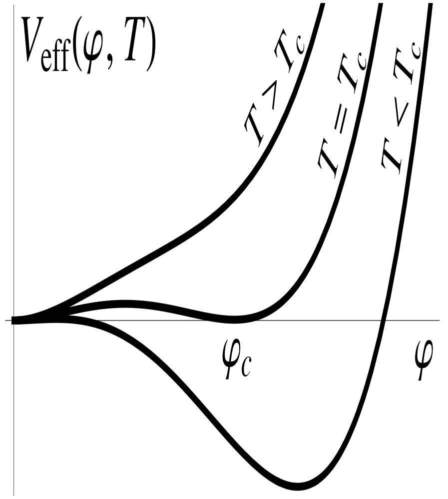
Kuzmin, Ruvakov, Shaposhnikov (1985)

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

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

Physics of Higgs potential

1st OPT by nondecoupling quantum effect

Effective Potential at finite T (HTE)

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

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

SM: The condition cannot be satisfied

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

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

(when $M \ll m_\Phi$)

Quantum effects of Φ(= H, A, H+, …)

Prediction: Large deviation in the hhh coupling

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

SK, Okada, Senaha, Yuan, 04

Grojean, Servant, Wells, 2005

SK, Y. Okada, E. Senaha, 2005

Higgs alignment

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

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

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、need to avoid mixing between *h* and heavy Higgs bosons: $\lambda_6 \sim 0$

Higgs Alignment (h: SM-like)

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

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

Physical Phase in the Higgs potential : $\arg[\lambda_7] \equiv \theta_7$

We work on this Higgs alignment scenario in the following discussion

$\boxed{\text{Simply } \lambda_6 = 0}$

Constraint from eEDM

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

T violation if ≠ 0 ⇄ CPV (CPT theorem)

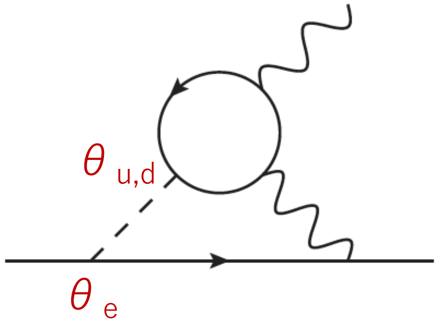
$$\mathcal{L}_{\rm EDM} = -\frac{d_f}{2} \bar{f} \sigma^{\mu\nu} (i\gamma^5) f F_{\mu\nu}$$

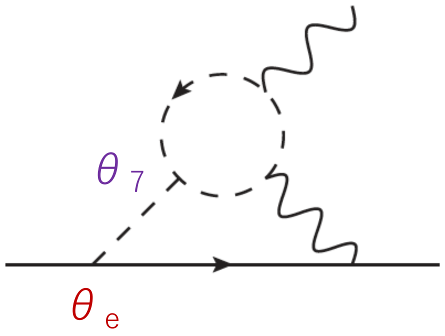
$|d_e| < 4.1 \times 10^{-30}\ e$ cm

Roussy *et al.* [Cornell Group]
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 $\zeta_e = \zeta_u = \zeta_d$

<u>Aligned 2HDM</u>

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

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

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

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

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

Baryon asymmetry

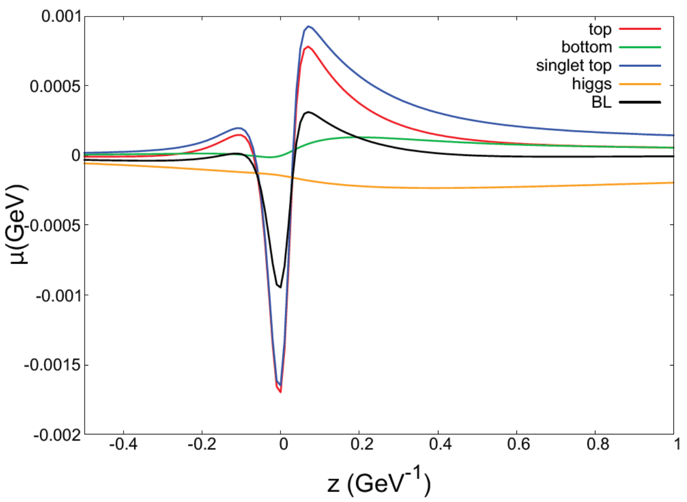
L_w Wall Thickness
T_n Transition Temp

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

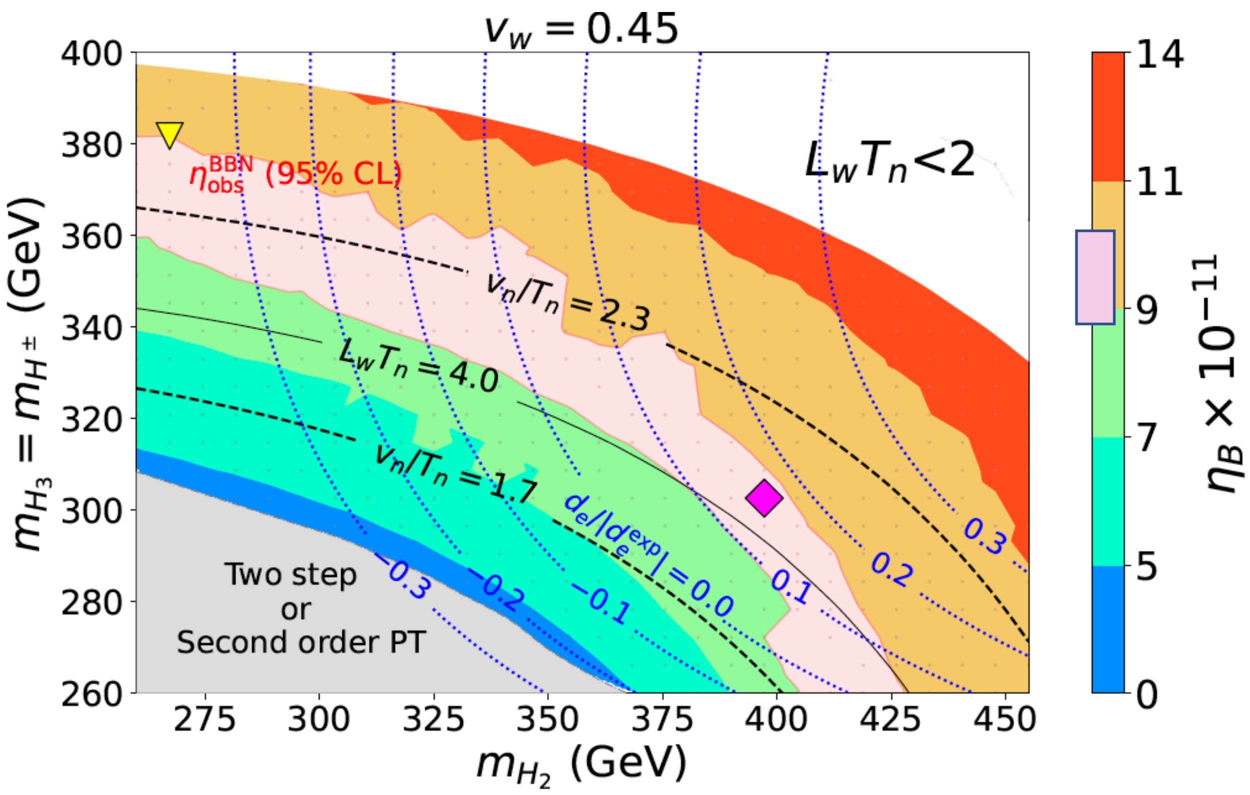
K. Enomoto, SK, Y. Mura, arXiv: 2207.00060

Aligned 2HDM

Chemical potential



Top transport scenario



In the sym. phase, baryon # generated via shpaleron

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

Frozen in the broken phase

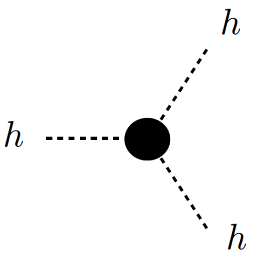
Cline, Kainulein, ⋯

BAU observed value
(Pink region)

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

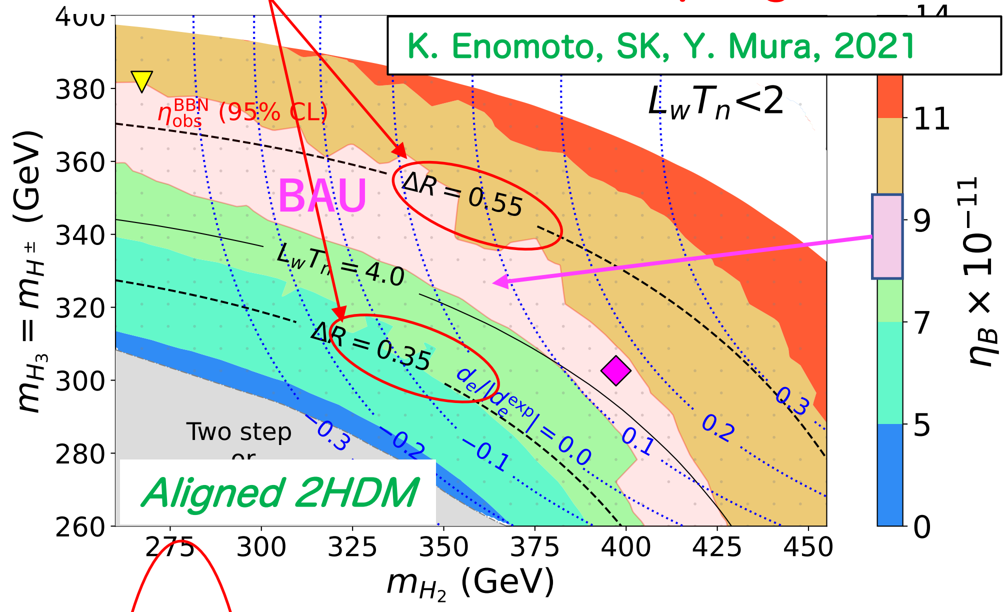
$$s = 0.74 n_\gamma$$

hhh from 1st OPT



Example Aligned 2HDM: viable scenario of EWBG

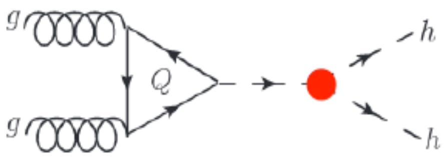
Deviation in the hhh coupling (%)

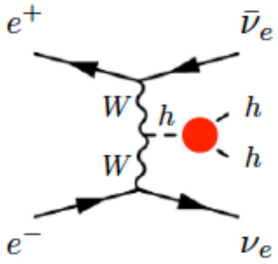


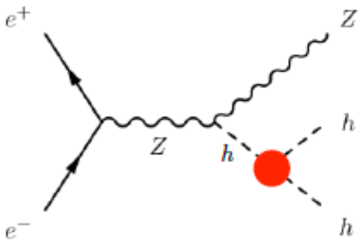
Strongly 1st OPT
→ A large deviation in the hhh coupling

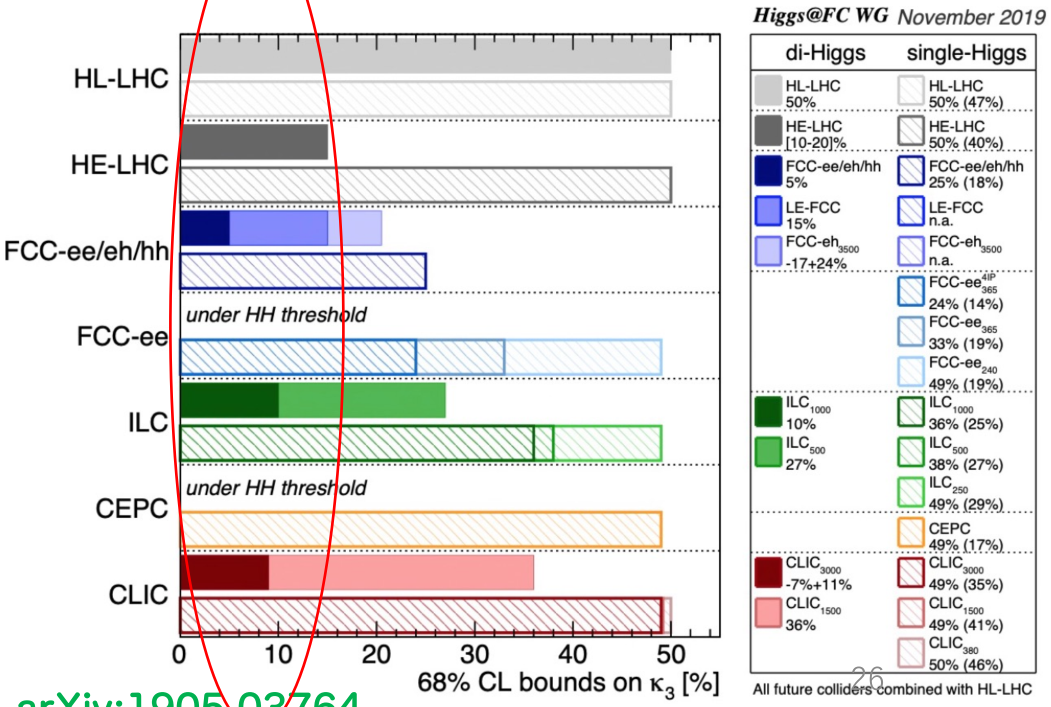
SK, Y. Okada, E. Senaha, 2005

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







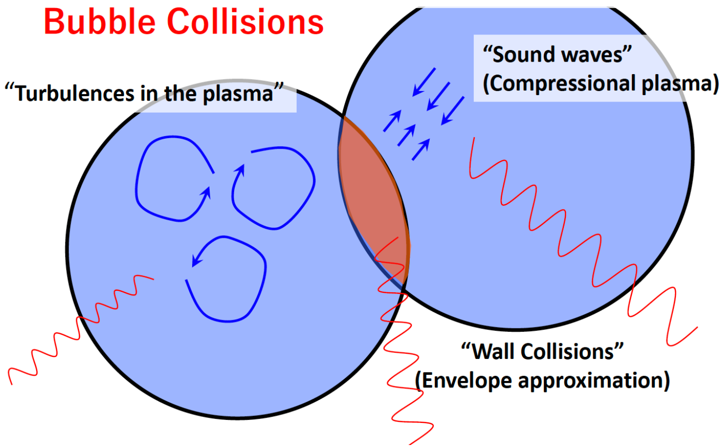


arXiv:1905.03764

EW Baryogenesis can be directly tested by the hhh measurement

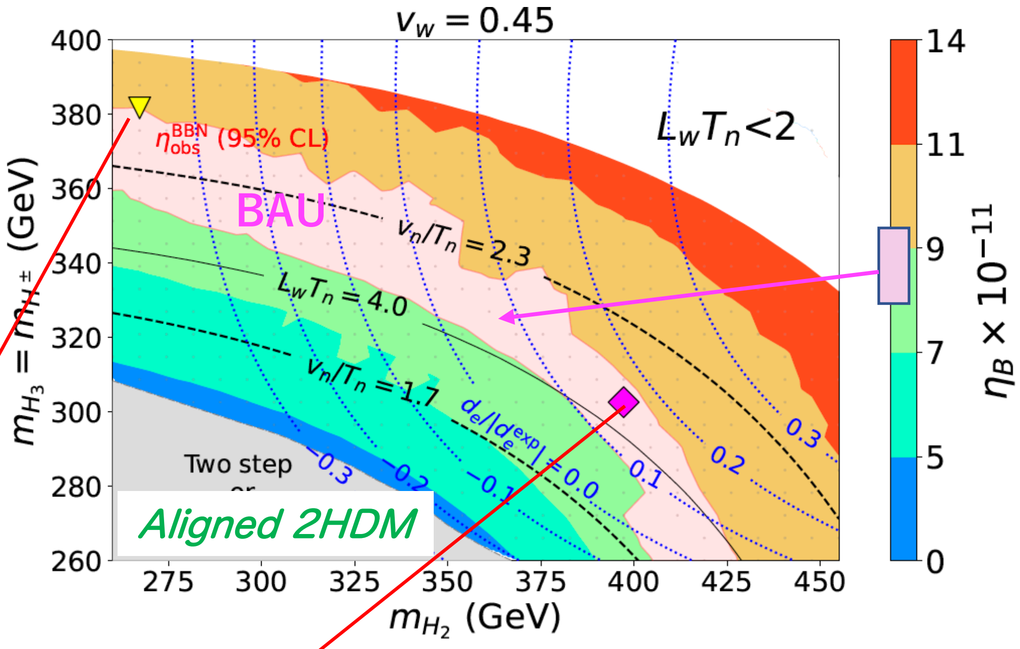
Hγγ can also be sensitive to the non-decoupling effects

GW from 1stOPT



Example
Aligned 2HDM

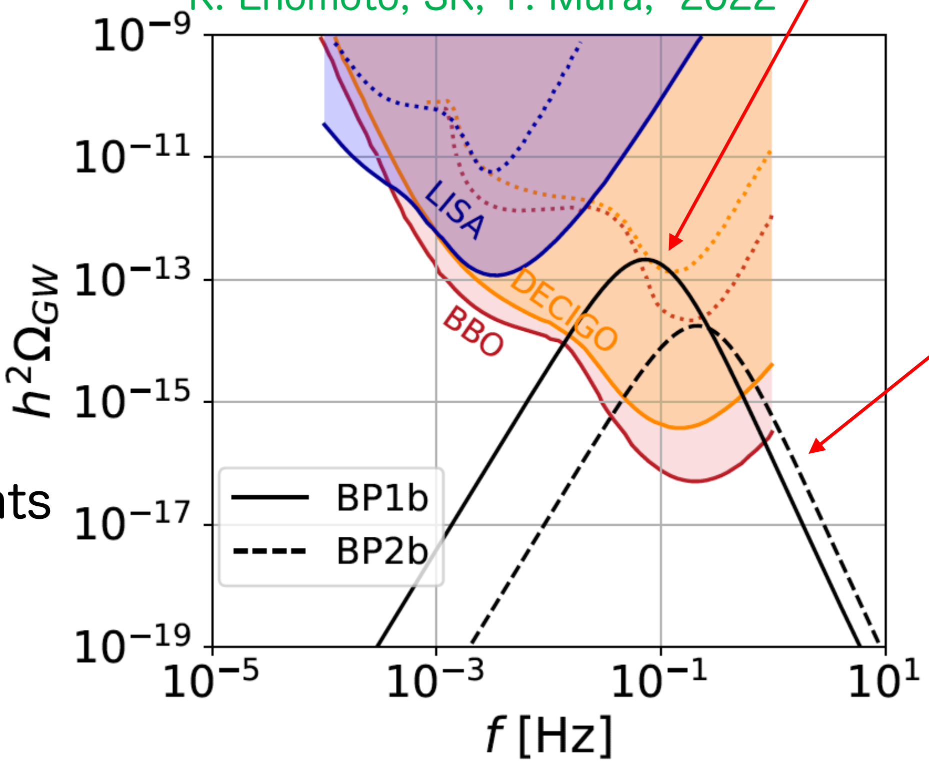
K. Enomoto, SK, Y. Mura, 2022



GWs for benchmark points of BAU

They may be tested by future GW experiments

K. Enomoto, SK, Y. Mura, 2022



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

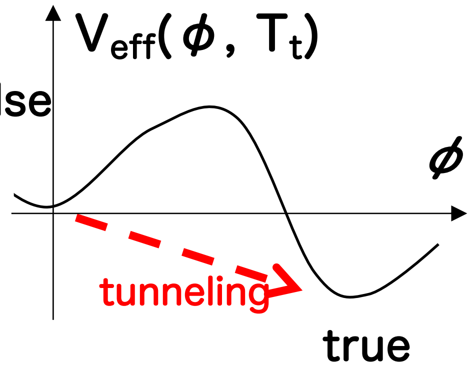
Solid curves: $h^2\Omega_{PISC}$ [SNR criterion]
J. Cline et al., arXiv: 2102.12490

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 $\boxed{\left.\dfrac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1}$ ➡ $\dfrac{S_3(T_t)}{T_t} = 4\ln(T_t/H_t) \simeq 140$

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

How we test models of 1st OPT?

- We discuss how to test the strongly 1st OPT using Higgs EFT with some assumptions

- Nearly aligned HEFT
  (SM-like: assuming small mixing and deviation in Higgs couplings mainly comes from quantum effects of BSM)

- Simply EWPT can be described by parameters
  κ_0 (d.o.f. of new particle)
  Λ (mass of new particle),
  r (non-decouplingness)

κ_0: d.o.f of new particles with non-decoupling property

$$\kappa_0 = n_0 + 2\, n_+ + 2\, n_{++} + \cdots$$

(n_0, n_+, n_{++} : # of neutral/charged/doubly-charged particles)

naHEFT (for describing non-decoupling property)

(nearly aligned)

SK, R. Nagai (2021)

$$\boxed{\mathcal{L}_{\mathrm{naHEFT}} = \mathcal{L}_{\mathrm{SM}} - \frac{\kappa_0}{64\pi^2}[\mathcal{M}^2(\varphi)]^2 \ln \frac{\mathcal{M}^2(\varphi)}{\mu^2}}$$

$$\mathcal{M}^2(h) = M^2 + \frac{\kappa_p}{2}\varphi^2 = M^2 + \frac{\kappa_p}{2}(h+v)^2$$

Three free parameters Λ, κ_0, r

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

Non-decouplingness

$$\begin{cases} r \sim 0 \Rightarrow M^2 \gg \dfrac{\kappa_p}{2}v^2 & \text{Decoupling} \\ r \sim 1 \Rightarrow M^2 \ll \dfrac{\kappa_p}{2}v^2 & \text{Non-decoupling} \end{cases}$$

Mass of New particles   d.o.f of new pariticles

In the decoupling region ($M^2 \gg \kappa_p v^2$),

$$V_{\mathrm{BSM}}(\varphi) \simeq \frac{\lambda_\Phi^3}{64\pi^2 M^2}\varphi^6 = \frac{1}{\Lambda^2}\varphi^6 \quad \Rightarrow \text{SMEFT is a good approximation}$$

SMEFT is not good in the non-decoupling region ($M^2 < \kappa_p v^2$)

[Falkowski, Rattazzi, JHEP 10 (2019), Cohen et. al, JHEP 03 (2021)]

Higgs couplings in naHEFT

<u>Nearly aligned case:</u>
small mixing and Higgs couplings can deviate mainly by quantum corrections

Λ: mass of new particles
κ_0: d.o.f. of new particles
r: non-decouplingness

$\kappa_0 = n_0 + 2\, n_+ + 2\, n_{++} + \cdots$

$$b = (n_+ + 4n_{++})/3$$

$$\xi = 1/(4\pi)^2$$

$$F_{\rm SM} = 6.492$$

$$G_{\rm SM} = 11.65$$

$$\kappa_V = \kappa_f = 1 - \kappa_0 \frac{\xi}{6}\frac{\Lambda^2}{v^2} r^2,$$

$$\kappa_3 = 1 + \kappa_0 \frac{4\xi}{3}\frac{\Lambda^4}{v^2 m_h^2}\left[r^3 - \frac{m_h^2}{8\Lambda^2} r^2 (3-2r)\right],$$

$$\kappa_{\gamma\gamma}^2 \simeq \left|\kappa_V - \frac{br}{F_{\rm SM}}\right|^2,$$

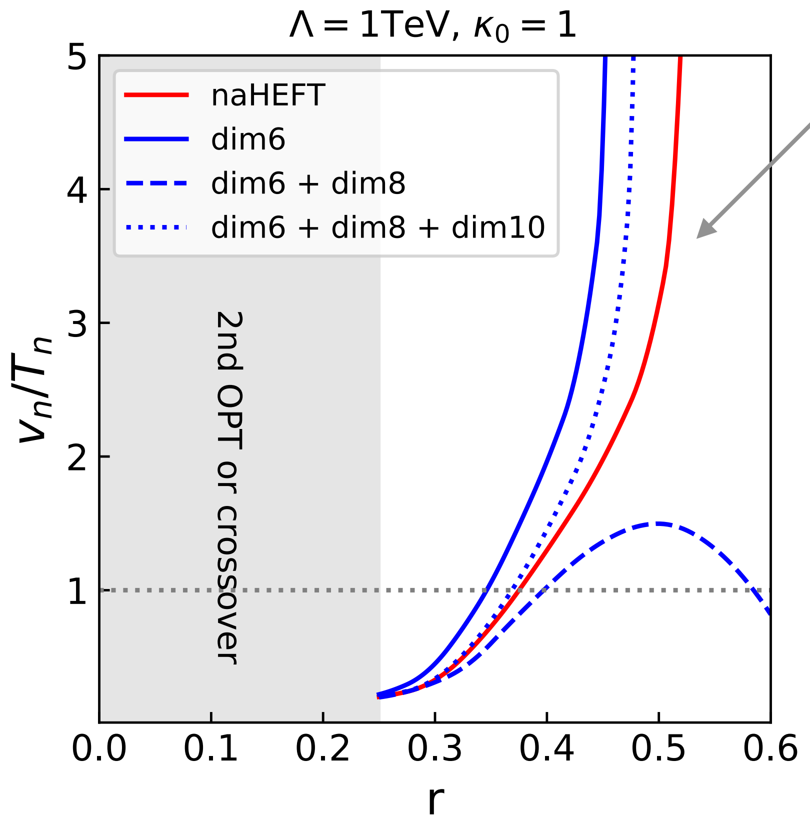
R. Florentino, S.K., M. Tanaka (2024)

naHEFT at finite temperature

SK, R. Nagai, M. Tanaka (2022)

$$V_{\rm EFT} = V_{\rm SM} + \frac{\kappa_0}{64\pi^2}\left[\mathcal{M}^2(\phi)\right]^2 \ln\frac{\mathcal{M}^2(\phi)}{\mu^2} + \frac{\kappa_0}{2\pi^2} T^4 J_{\rm BSM}\left(\frac{\mathcal{M}^2(\phi)}{T^2}\right)$$

$$J_{\rm BSM}(a^2) = \int_0^\infty dk^2 k^2 \ln\left[1 - {\rm sign}\,(\kappa_0)\, e^{-\sqrt{k^2+a^2}}\right] \quad \mathcal{M}^2(\phi) = M^2 + \frac{\kappa_p}{2}\phi^2$$



SK, R. Nagai, M. Tanaka (2022)

Consistent with results in the SM with a singlet

[Kakizaki et al., PRD 92 (2015), Hashino et al., PRD 94 (2016)]

Large deviation in v_n/T_n exists b/w the SMEFT and naHEFT

⇩

SMEFT may not be appropriate when we discuss the strongly first order EWPT

$$r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

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

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

Testing EW 1st OPT in naHEFT

Strongly 1st OPT ($\phi/T > 1$)

- Sensitive to the hhh coupling, and also (if charged BSM) to the $h\gamma\gamma$ coupling
  - HL-LHC ⊕ ILC etc $\Delta\kappa_\gamma$ measured with 1% accuracy
  - HL-LHC (ILC1000) $\Delta\kappa_3$ measured with about 50% (10%)
- Gravitational Waves (with 10^{-3} to 10^{-1} Hz)

  LISA, DECIGO, BBO, …

Liu et al (2021)
Hashino, SK, Takahashi (2021)

- Primordial Blackholes ($M_{PBH} = 10^{-5} M_{solar}$ for EW 1st OPT)

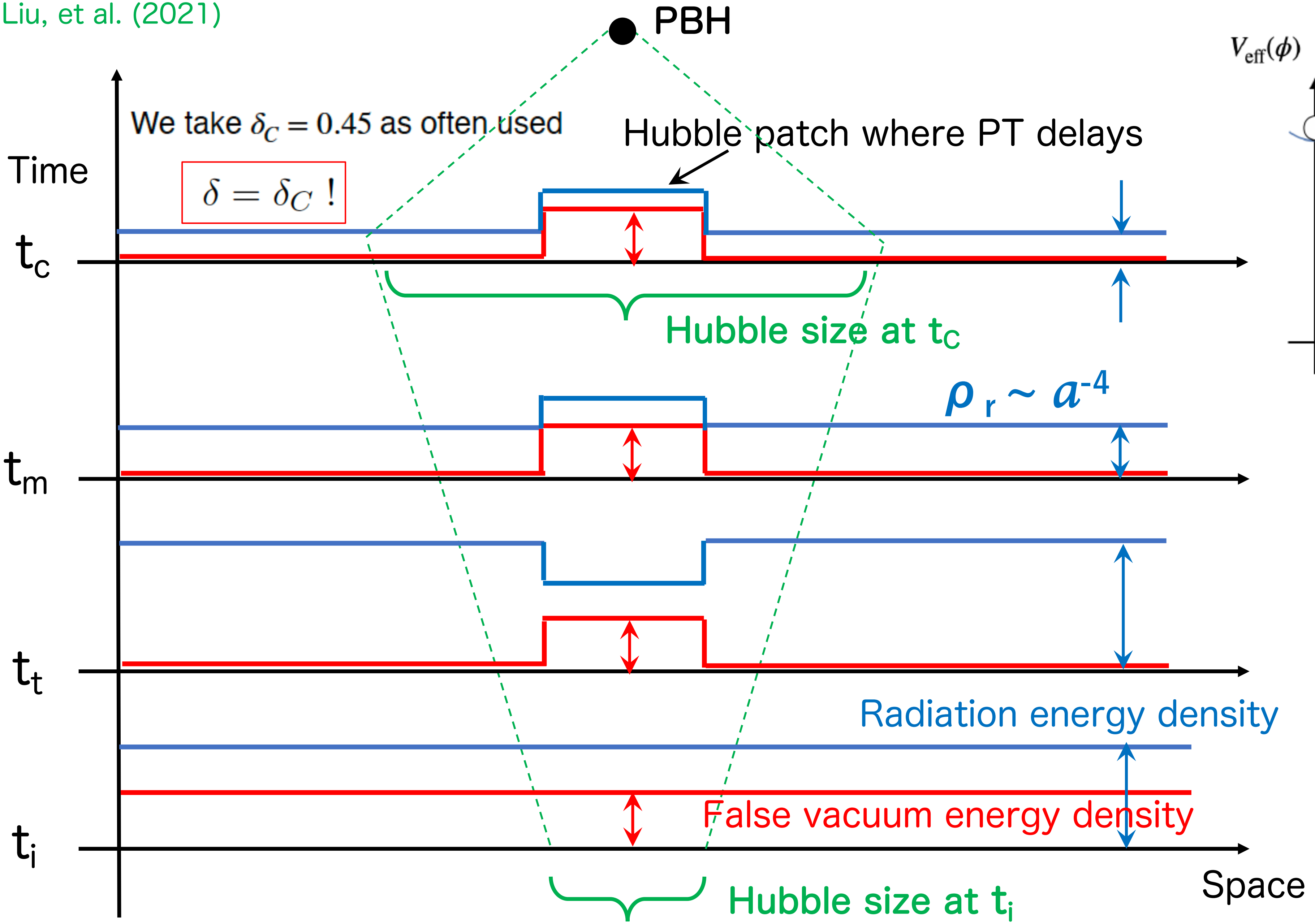
  PBH may be formed at the 1st EWPT by the contrast of the PT time around Tc (depending on the Higgs potential) .

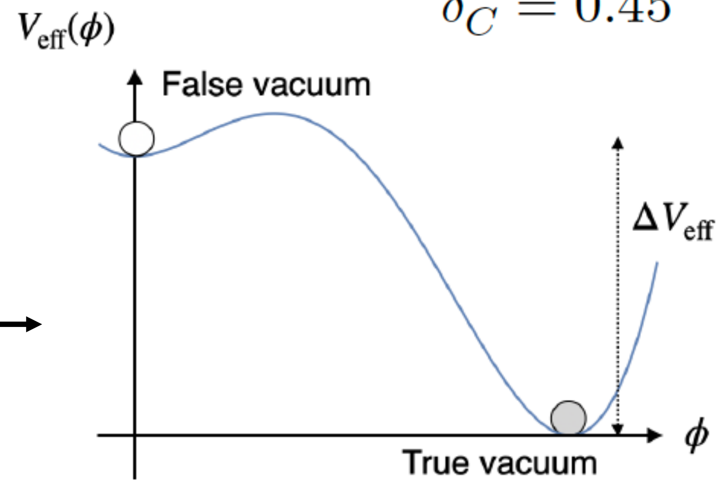
  PBH searches by microlensing: Subaru HSC, OGLE, Prime, Roman, …

PBH formation from the contrast

$$\delta = \frac{\rho_{\rm over} - \rho_{\rm back}}{\rho_{\rm back}} > \delta_C \qquad \delta_C = 0.45$$

J. Liu, et al. (2021)





False vacuum energy density

$\rho_V \sim$ **constant**

$\sim F(t)\ \Delta V_{\rm eff}$

Radiation energy density

$\rho_r \sim a^{-4}$

J. Liu, L. Bian, R.-G. Cai, Z.-K.Guo, S.-J. Wang (2021)

Rate of staying at the symmetric phase in a Hubble volume

$$F(t) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t} \mathrm{d}t'\Gamma\left(t'\right) a^3\left(t'\right) r^3\left(t, t'\right)\right]$$

$$r(t,t') \equiv \int_{t'}^{t} a^{-1}(\tau) d\tau$$

$$\rho_{\mathrm{v}} = F(t)\Delta V$$

vacuum energy density is constant

Radiation Dominant p = $\rho/3$

Friedmann eq $$H^2 = \frac{\rho_{\mathrm{v}} + \rho_{\mathrm{r}} + \rho_{\mathrm{w}}}{3}$$

Conservation $$\frac{d(\rho_{\mathrm{r}} + \rho_{\mathrm{w}})}{dt} + 4H(\rho_{\mathrm{r}} + \rho_{\mathrm{w}}) = \left(-\frac{d\rho_{\mathrm{v}}}{dt}\right)$$

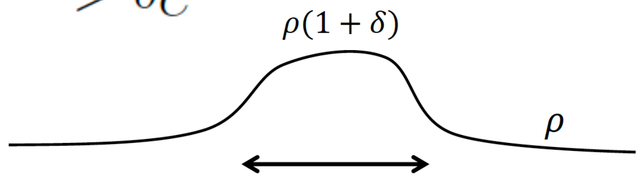
ρ_{r} Radiation (wall) energy density

ρ_{w} $\propto a^{-4}(t)$

(v_w = 1)

$\rho_r(t)$, H(t) are determined

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



Then, from the criterion δ_c = 0.45,
T_{PBH} is determined

δ > 0.45 gravitational collapse

PBH from 1st order EWPT

K. Hashino, SK, T. Takahashi, 2021

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

K. Hashino, SK, T. Takahashi, M. Tanaka, C.M. Woo 2025

Mass of PBH from EWPT is determined by t_{PBH}

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

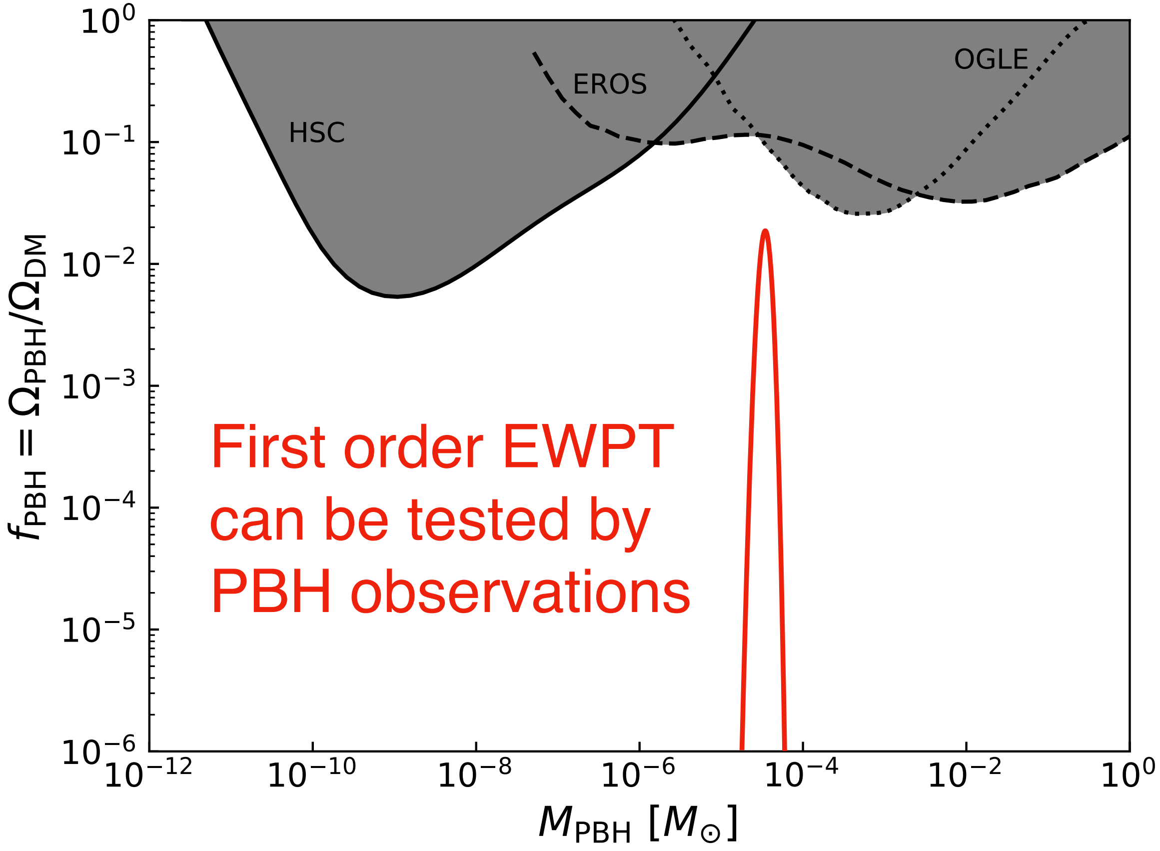
$$\boxed{M_{\rm PBH} \sim 10^{-5} M_\odot}$$

← Important prediction

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

$f_{\rm PBH}$ is constrained by 10^{-4}

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

Theory predictions on α-β plane

Non-dec. DOF $r = 0.5$

$\kappa_0 =$ 1, 4, 20

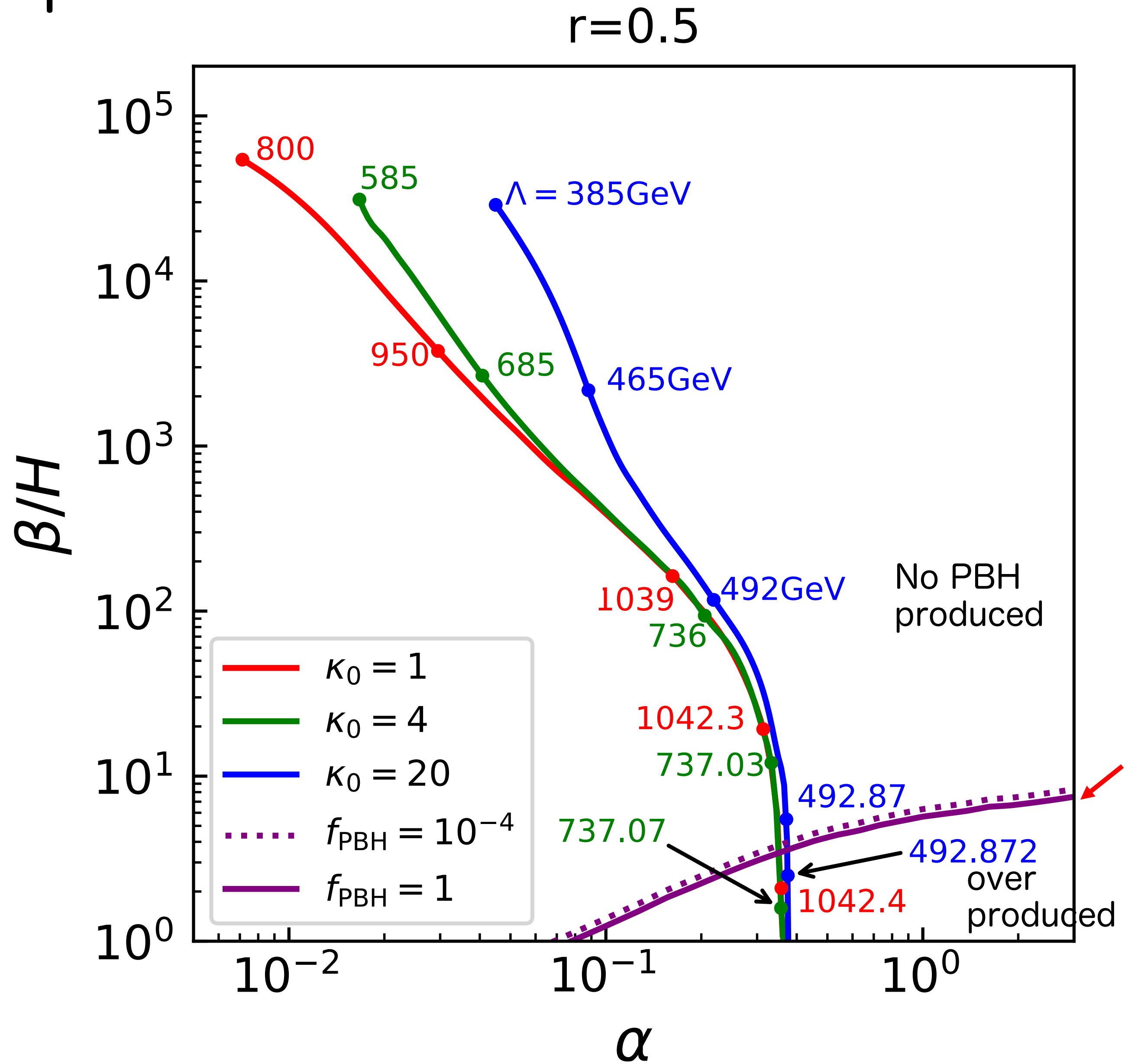
for various Λ

New scale

Contours of f_{PBH}

$10^{-4} < f_{PBH} < 1$

PBH can be produced in this nallow area



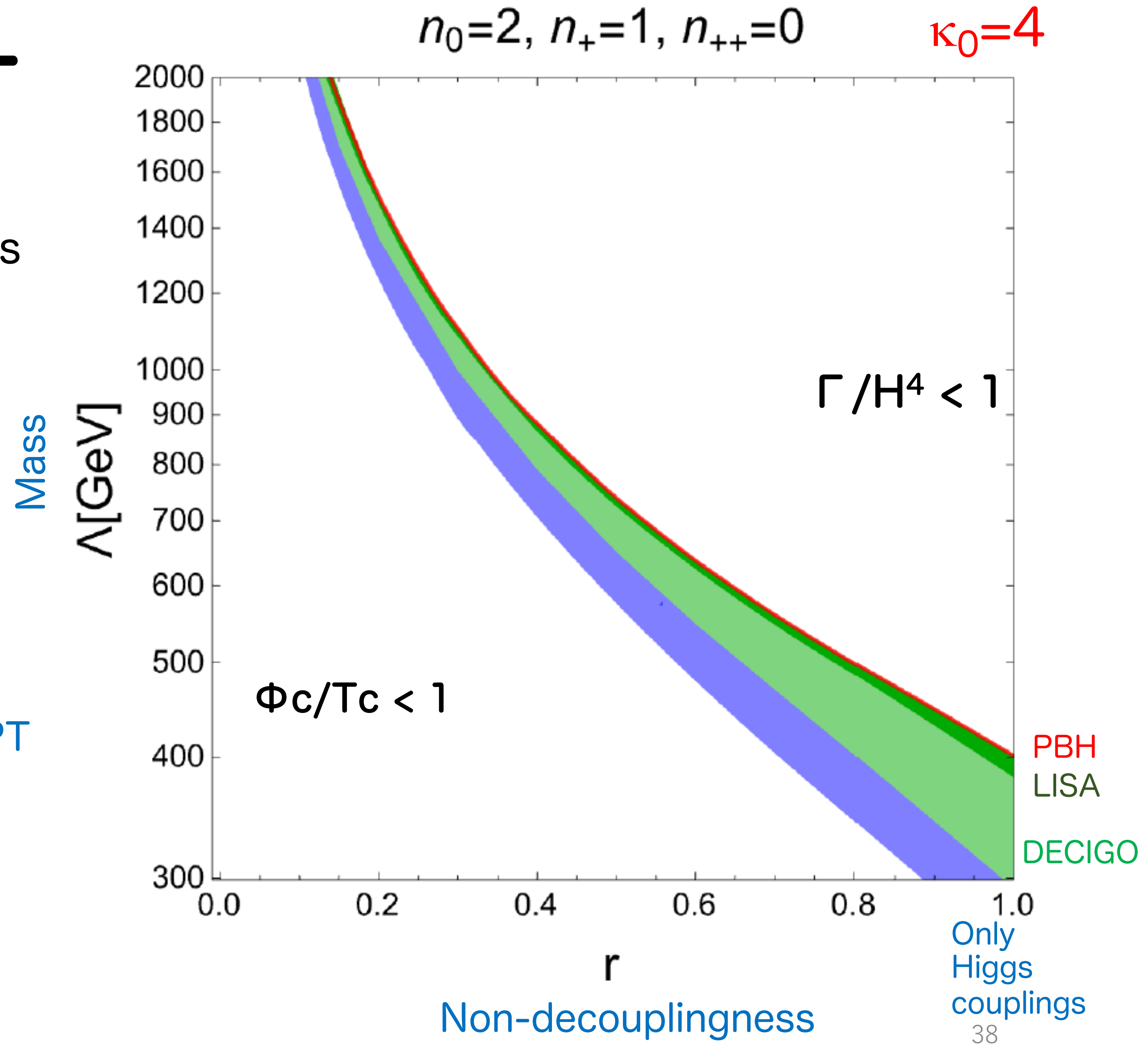
PBHs are produced Here!

Strongly 1st OPT

Colored region satisfies two conditions

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

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



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

Strongly 1st OPT

Colored region satisfies two conditions

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

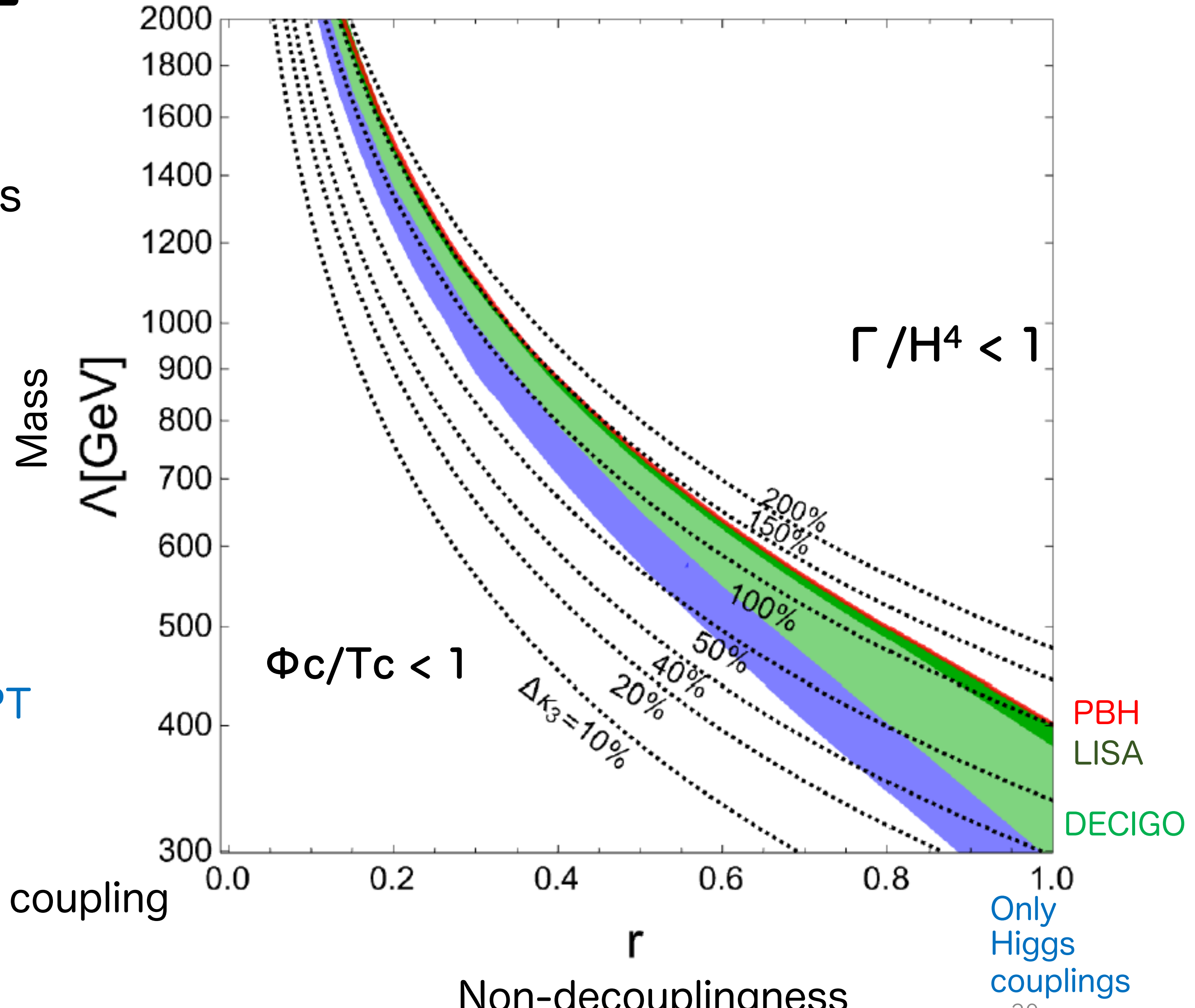
Bubble nucleation completion $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

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

Contour plots

Dotted curves: $\Delta\kappa_3$ deviation in the hhh coupling

n_0=2, n_+=1, n_{++}=0 κ_0=4



Non-decouplingness

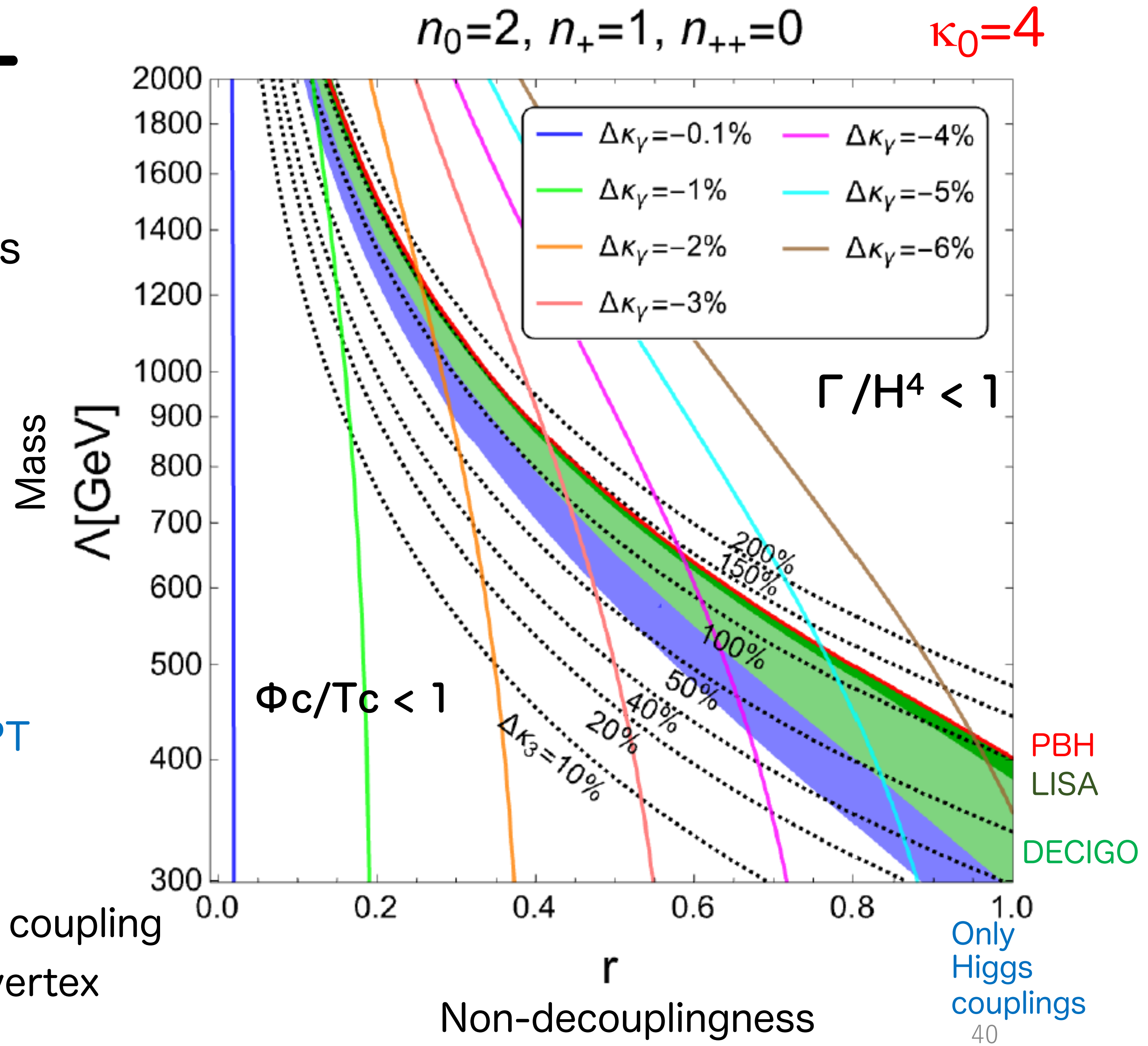
R. Florentino, S.K., M. Tanaka (2024)

Strongly 1st OPT

Colored region satisfies two conditions

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

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



Contour plots

Dotted curves: $\Delta\kappa_3$ deviation in the hhh coupling

Colored curves : $\Delta\kappa_\gamma$ deviation in the $h\gamma\gamma$ vertex

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

Strongly 1^{st} OPT

Colored region satisfies two conditions

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

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

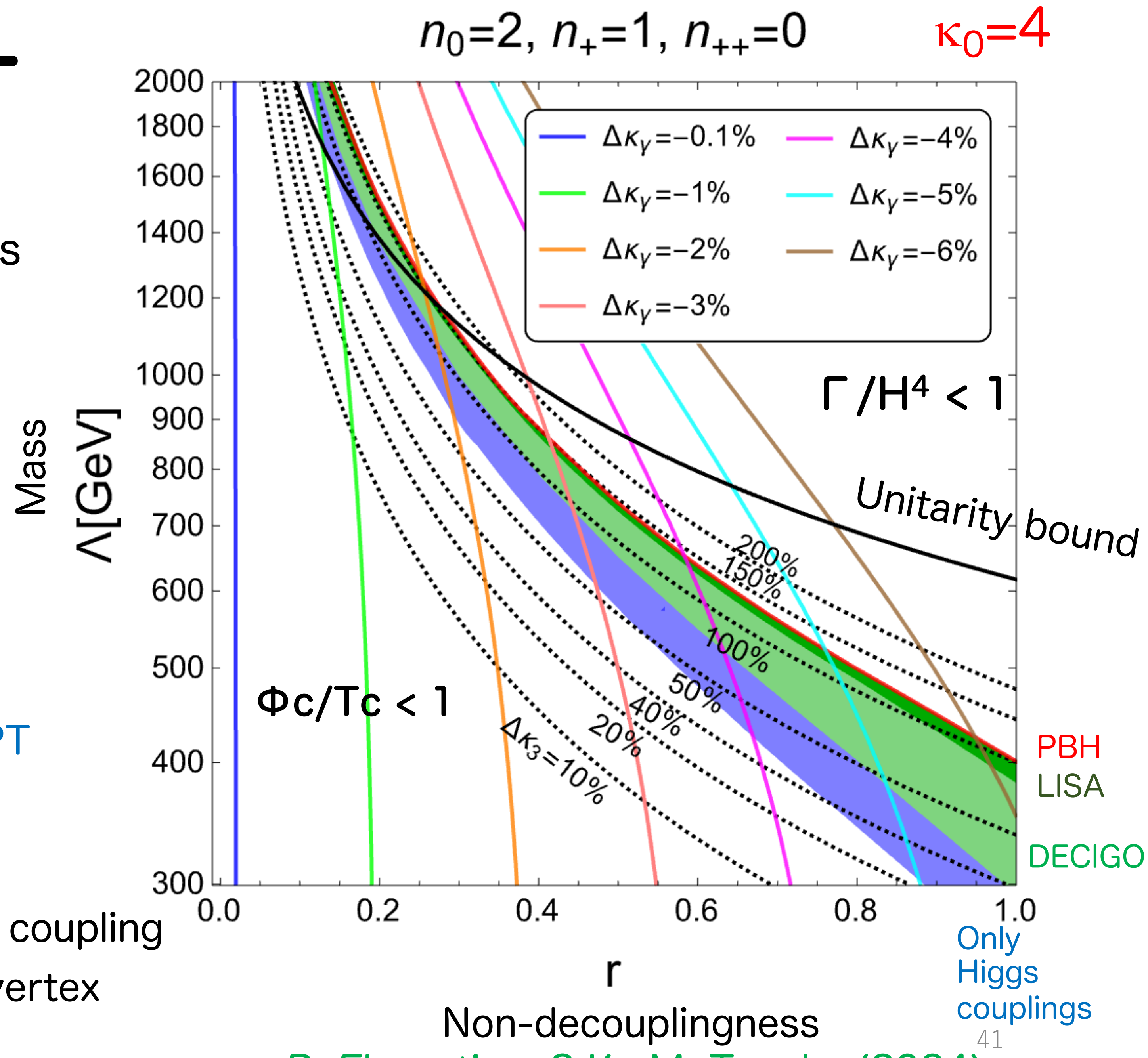
- PBH (Roman detectable $f_{PBH} > 10^{-4}$)
- GW (LISA detectable)
- GW (DECIGO detectable)
- Only Higgs couplings can test 1^{st} OPT
  ($\Delta\lambda_3$, $\Delta\kappa_\gamma$, ...)

Contour plots

Dotted curves: $\Delta\kappa_3$ deviation in the hhh coupling

Colored curves : $\Delta\kappa_\gamma$ deviation in the h$\gamma\gamma$ vertex

Black solid curve: unitarity bound



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

Strongly 1st OPT

Colored region satisfies two conditions

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

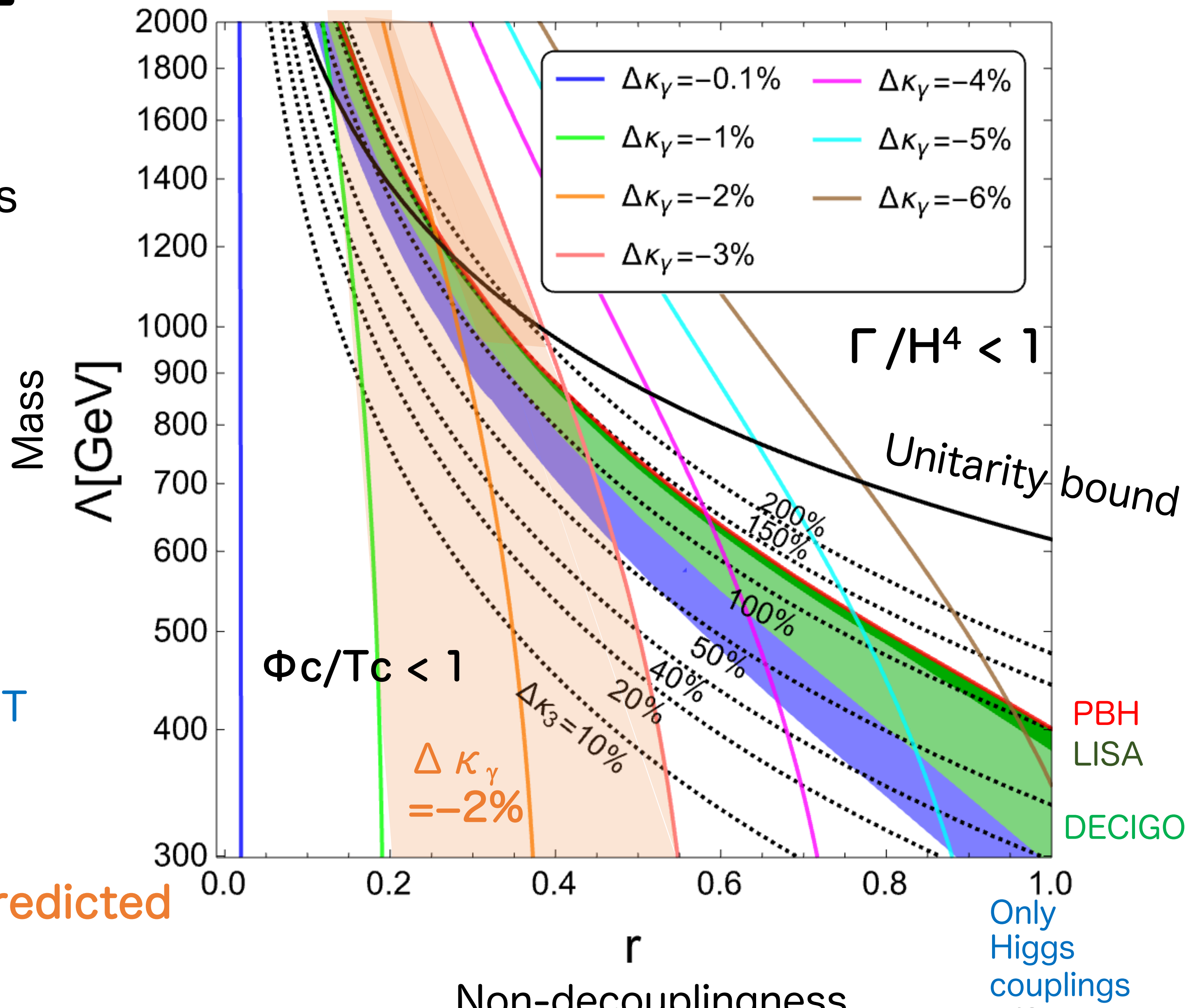
- PBH (Roman detectable $f_{PBH} > 10^{-4}$)
- GW (LISA detectable)
- GW (DECIGO detectable)
- Only Higgs couplings can test 1st OPT ($\Delta\kappa_3$, $\Delta\kappa_\gamma$, ...)

If $\Delta\kappa_\gamma$ = -2% ± 1% (LHC+ILC), predicted

150% > $\Delta\kappa_3$ > 72%

GW, PBH can also be used

n_0=2, n_+=1, n_{++}=0 κ_0=4



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

Strongly 1st OPT

Colored region satisfies two conditions

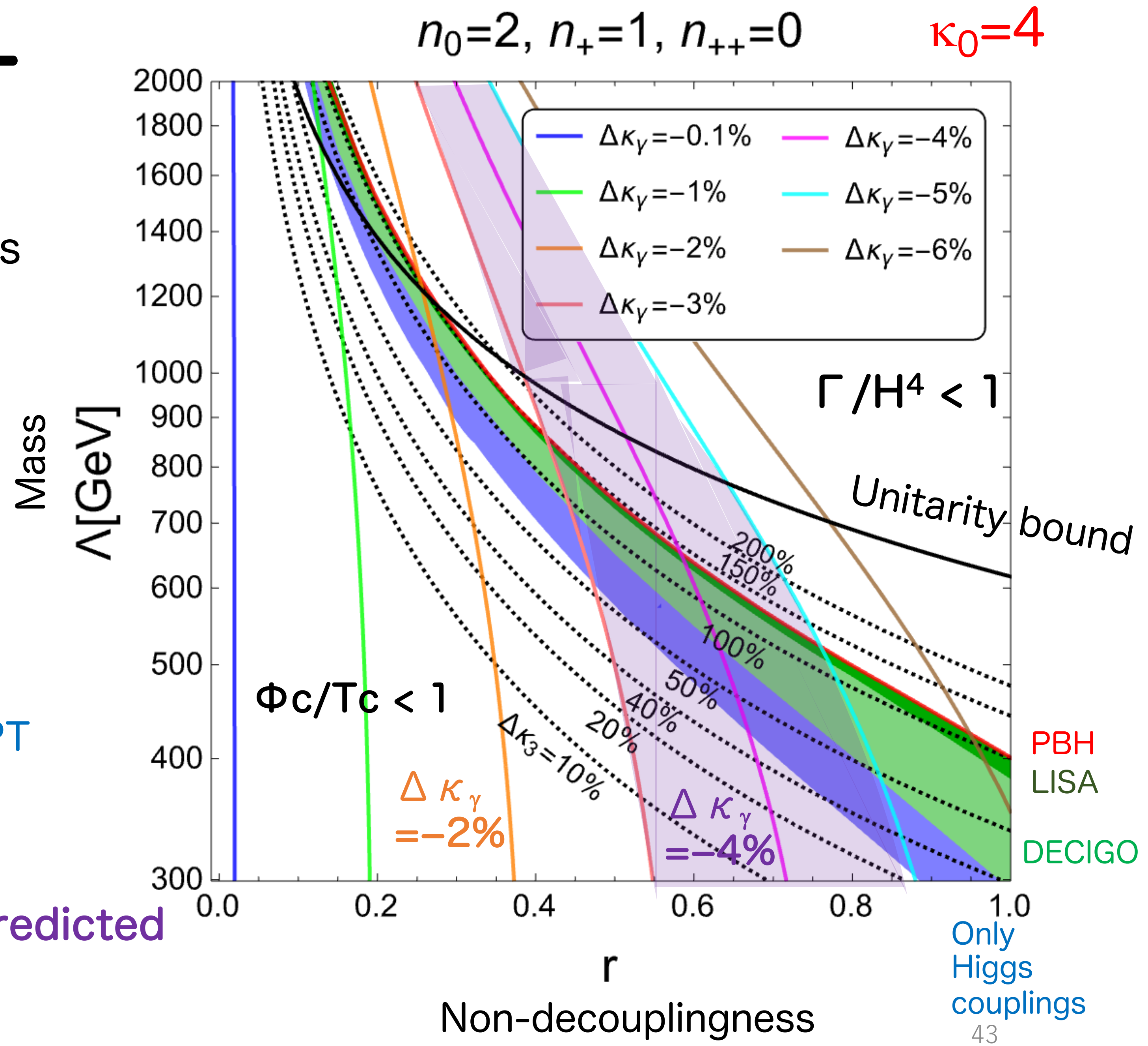
- Sphaleron decoupling $\frac{\varphi_c}{T_c} \gtrsim 1$
- Bubble nucleation completion $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

- 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)

Summary

- Higgs sector unknown. BSM introduces non-minimal Higgs sectors

- Precision measurement of h(125) important
  - Fingerprinting BSM models

- Direct searches of extra Higgs bosons (H, A, H^+, …)
  - Importance of Higgs to Higgs decays A→Zh, H→hh, …
  - Systematic study with radiative corrections important

- Higgs potential EWSB/EWPT unknown
  - V(ϕ): important of measuring hhh, hhhh
  - Phys of 1st OPT: $h\gamma\gamma$, hhh, GW, PBH

- Synergy gives important hint for new physics

Thank you!

Backup slides

Available tools

- **H-COUP** [M. Aiko, S. Kanemura, M. Kikuchi, KS, K. Yagyu, CPC301(2024),109231], [S. Kanemura, M. Kikuchi, K. Mawatari, K. Sakurai, K. Yagyu, CPC257(2020),107512], [S. Kanemura, M. Kikuchi, K. Sakurai, K. Yagyu,CPC233(2018),134-144]
  - 2-body and 3-body decays with NLO EW and NNLO QCD corrections, loop corrected Higgs couplings
  - 2HDMs, IDM, HSM
- **2HDECAY, sHDECAY, NHDECAY** [M. Krause, M. Mühlleitner, 1904.02103] [M. Krause, M. Mühlleitner, M. Spira, CPC 246 (2020) 106852], [F. Egle, M. Mühlleitner, ,R. Santos,J. Viana, JHEP 11 (2023) 116]]
  - 2-body decays of all Higgs boson with NLO EW and the state of the art QCD corrections.
  - Model: THDMs (2HDECAY), the Singlet extension of the SM with Z_2 (sHDECAY), THDMs + real singlet (NHDECAY)
- **PROPHECY4F** [L. Altenkamp, S. Dittmaier, H. Rzehak,JHEP 1803 (2018) 110]
  - CP-even Higgs decays into 4fermions with NLO EW and QCD corrections.
  - Model: THDMs, the Singlet extension of the SM with Z_2.
- **Flexibledecay** [P. Athron, A. Büchner, et. al., Comput.Phys.Commun. 283, (2023) 108584]
  - 2-body decays of neutral Higgs bosons with SM QCD/EW corrections in HSM, Type II 2HDM, CMSSM,MRMSSM.
  - BSM effect is at LO.
- **anyH3** [H. Bahl, J. Braathen, G. Weiglein,EPJC 83 (2023) 12, 1156]
  - 1-loop corrections to Higgs trilinear couplings.

Di-Photon decay of h(125)

Loop induced

Small rate but sensitive to new charged particles

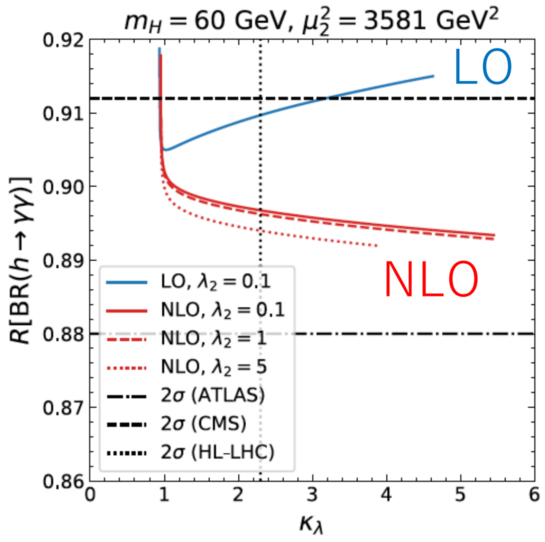
Large deviation from new physics models especially for models with non-decoupling property

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

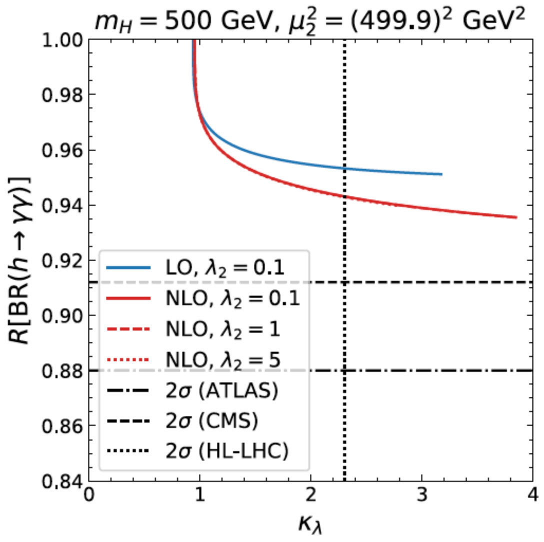
Can give strong constraint on BSM models

Ex) Case of the inert doublet model

Resonant DM scenario



Heavy DM scenario

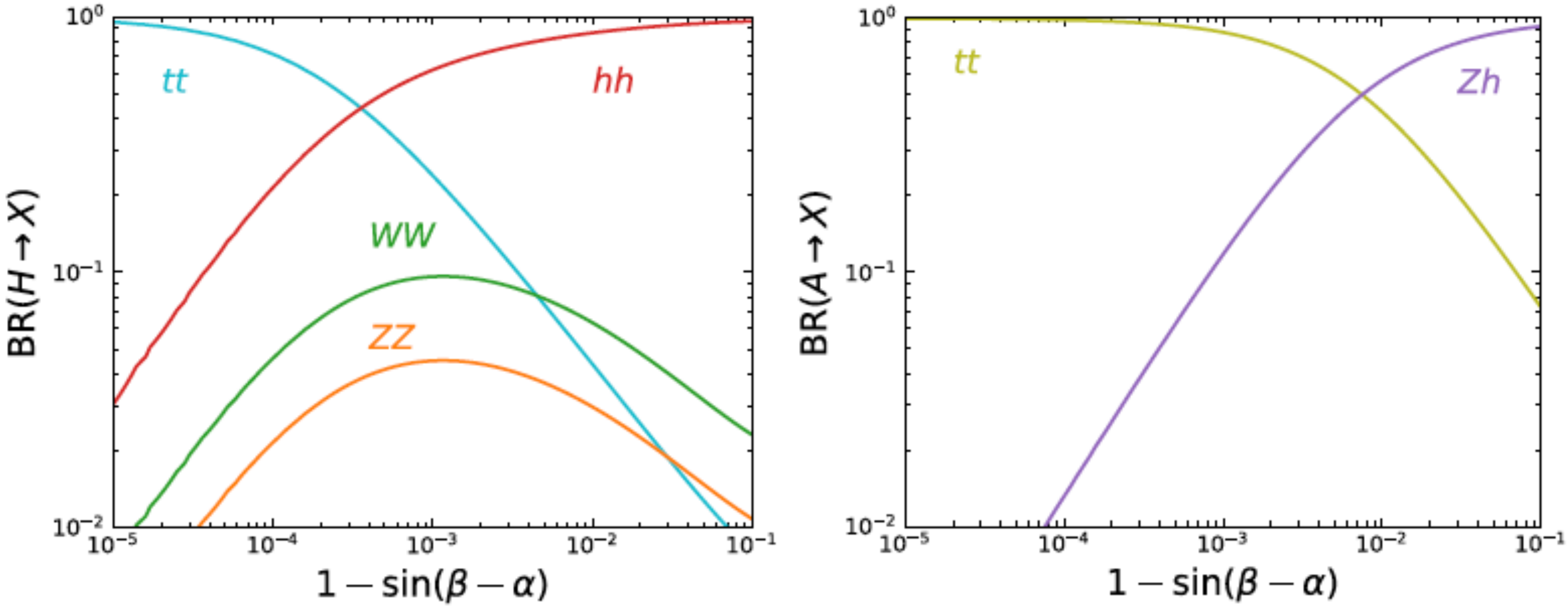


Aiko, Braathen, SK, 2023

NLO (2 loop) correction is important

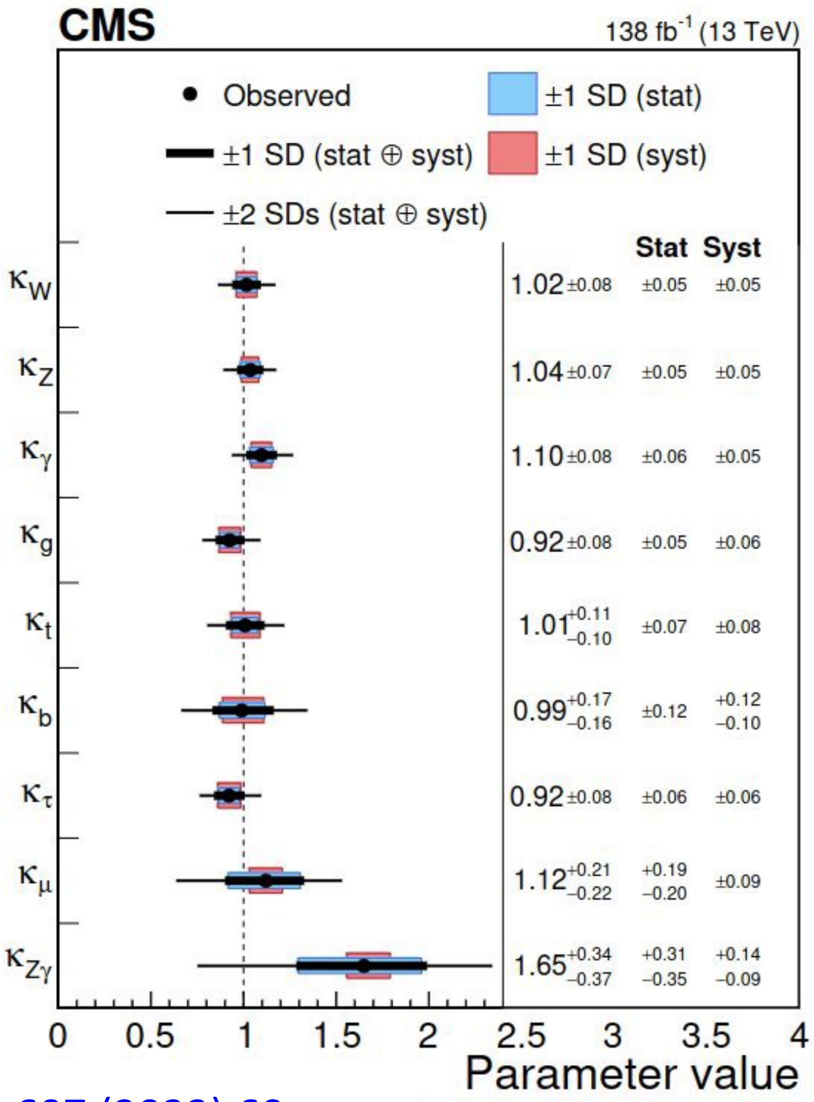
Decay patterns

Type-I 2HDM: $m_\Phi = m_H = m_A = m_{H^\pm} = 400$ GeV, $\tan\beta = 10$

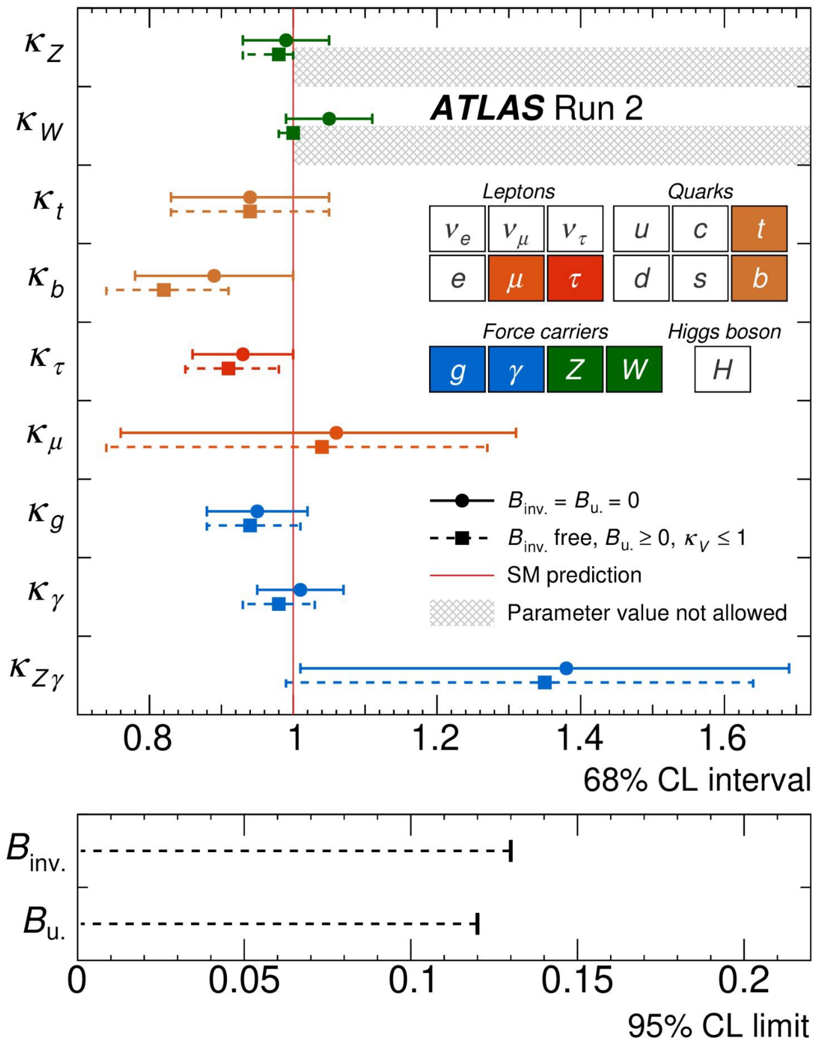


Higgs-to-Higgs decays can be dominant if $s_{\beta-\alpha} \neq 1$

Combined scale factor results



Nature 607 (2022) 60



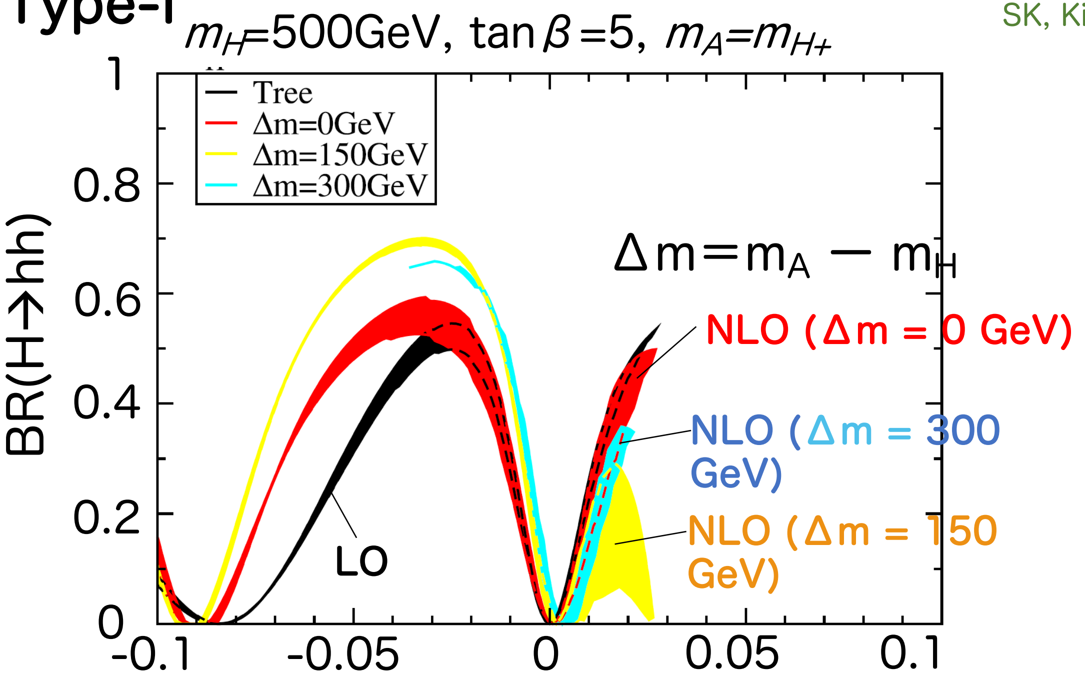
Nature 607 (2022) 52

Correlation between H→hh and h→WW*

NPB 983(2022)115906
SK, Kikuchi, Yagyu

Slide by Kikuchi

Type-I



$$\Delta\mu[h \to WW^*] = \frac{\mathrm{BR}^{\mathrm{THDM}}_{\mathrm{NLO}}[h \to WW^*]}{\mathrm{BR}^{\mathrm{SM}}_{\mathrm{NLO}}[h \to WW^*]} - 1$$

$$\Gamma^{\mathrm{THDM}}_{\mathrm{LO}}[h \to WW^*] \propto \sin^2(\beta-\alpha)$$

$$\Rightarrow \quad \Gamma^{\mathrm{THDM}}[h \to WW^*] \lesssim \Gamma^{\mathrm{SM}}[h \to WW^*]$$

If cos($\beta-\alpha$)>0 ・・・ $\Gamma^{\mathrm{THDM}}_{h,\mathrm{total}} > \Gamma^{\mathrm{SM}}_{h,\mathrm{total}}$

If cos($\beta-\alpha$)<0 ・・・ $\Gamma^{\mathrm{THDM}}_{h,\mathrm{total}} < \Gamma^{\mathrm{SM}}_{h,\mathrm{total}}$

⇒ Decrease in $\Gamma^{\mathrm{THDM}}_{\mathrm{partial}}$ is canceled by decrease in $\Gamma^{\mathrm{THDM}}_{\mathrm{h,total}}$.

Correlation between BR($H \to hh$) and BR($h \to WW^*$) is changed from LO by O(10)%.

It is important to evaluate both *h*-decays and *H*-decays with loop corrections simultaneously.

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

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

Higgs alignment

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、need to avoid mixing between *h* and heavy Higgs bosons: $\lambda_6 \sim 0$

Higgs Alignment (h: SM-like)

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

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

Physical Phase in the Higgs potential : $\arg[\lambda_7] \equiv \theta_7$

We work on this Higgs alignment scenario in the following discussion

$\boxed{\text{Simply } \lambda_6 = 0}$

Constraint from eEDM

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

T violation if ≠ 0 ⇄ CPV (CPT theorem)

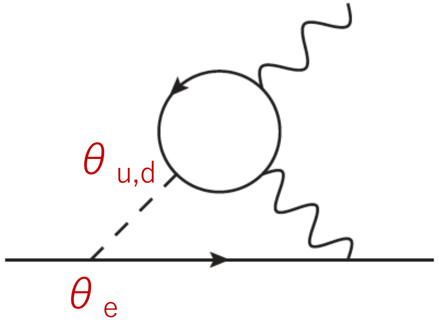
$$\mathcal{L}_{\rm EDM} = -\frac{d_f}{2}\bar{f}\sigma^{\mu\nu}(i\gamma^5)fF_{\mu\nu}$$

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

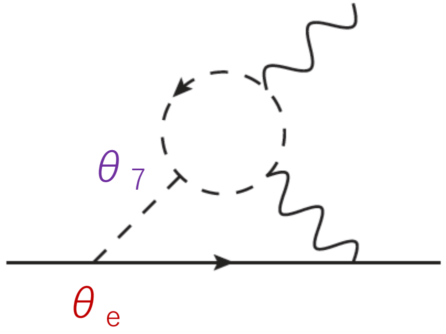
Roussy *et al.* [Cornell Group]
arXiv:2212.11841

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 $\zeta_e = \zeta_u = \zeta_d$

<u>Aligned 2HDM</u>

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

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

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

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

Evaluation of BAU

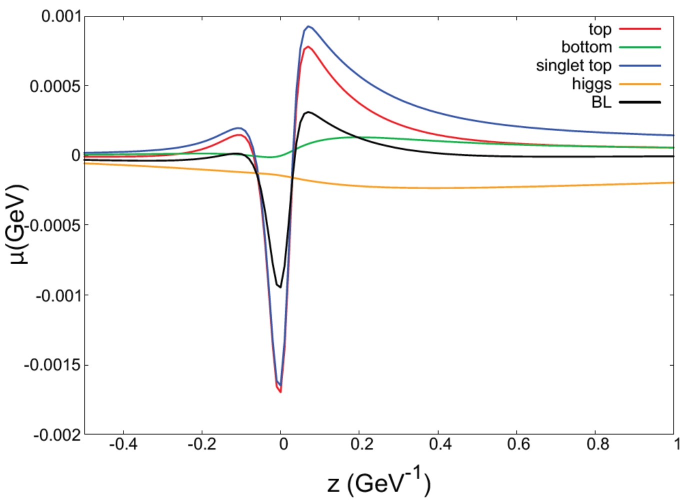
L_w : wall width
T_n : nucleation temp

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

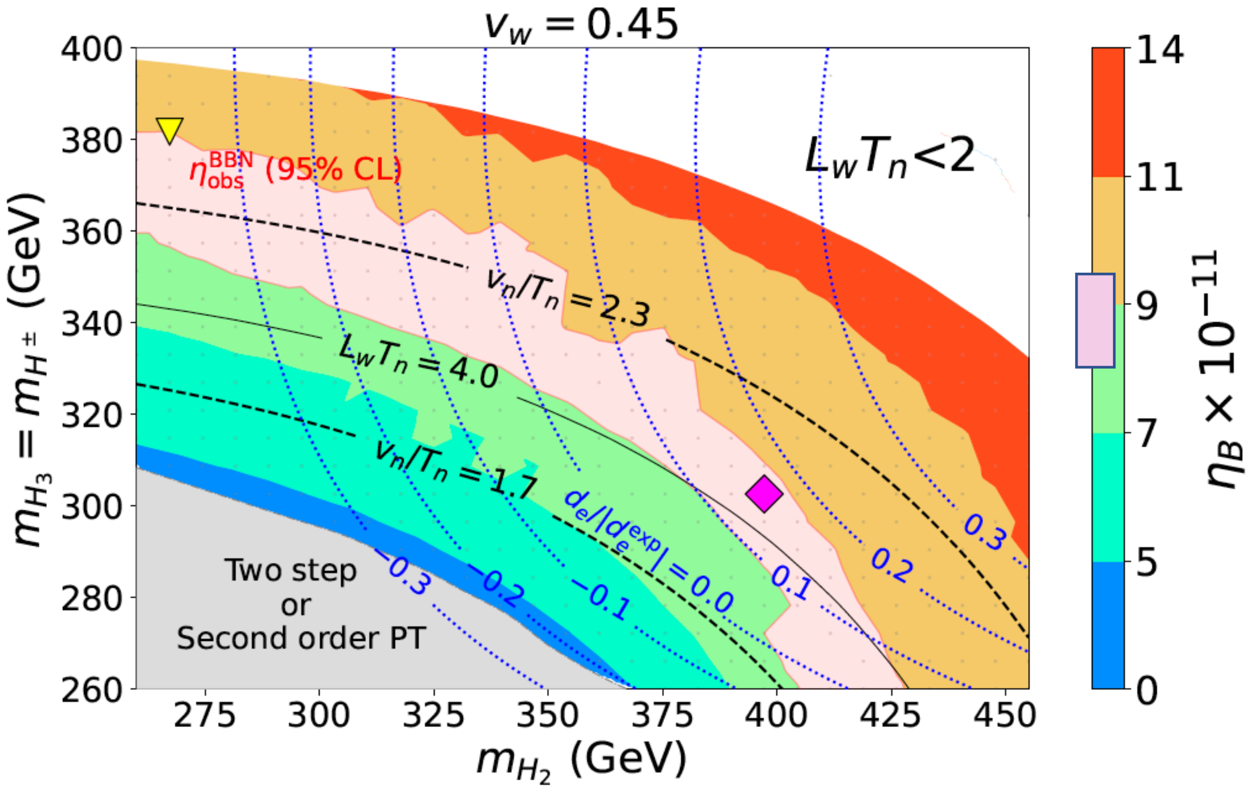
K. Enomoto, SK, Y. Mura, arXiv: 2207.00060

Aligned 2HDM

Chemical potential



Top transport scenario



In symmetric phase, B is produced by sphaleron

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

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

Cline, Kainulainen, …

BAU data reproduced (pink region)

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

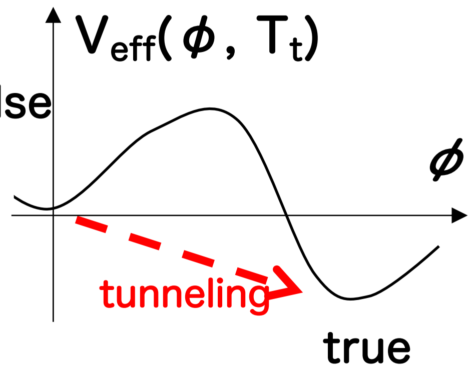
$$s = 0.74 n_\gamma$$

From bubble dynamics to GW spectrum

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

Linde 1983

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



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

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

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

- 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)

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

v_b: wall velocity

Nearly aligned Higgs EFT

Higgs EFT

Fergulio (1993),
Giudice, et al (2007), …

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

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

$$\mathcal{L}_{\rm BSM} = \xi\Bigg[-\frac{\kappa_0}{4}\left[\mathcal{M}^2(h)\right]^2 \ln\frac{\mathcal{M}^2(h)}{\mu^2}$$

$$+\frac{v^2}{2}\mathcal{F}(h)\,{\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] + \frac{1}{2}\mathcal{K}(h)\left(\partial_\mu h\right)\left(\partial^\mu h\right)$$

$$-v\left(\bar{q}^i_L U\left[\mathcal{Y}^{ij}_q(h) + \hat{\mathcal{Y}}^{ij}_q(h)\tau^3\right]q^j_R + h.c.\right) - v\left(\bar{l}^i_L U\left[\mathcal{Y}^{ij}_l(h) + \hat{\mathcal{Y}}^{ij}_l(h)\tau^3\right]l^j_R + h.c.\right.$$

$$+ g^2\mathcal{F}_W(h)\,{\rm Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}] + g'^2\mathcal{F}_B(h)\,{\rm Tr}[\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu}]$$

$$- gg'\mathcal{F}_{BW}(h)\,{\rm Tr}[U\mathbf{B}_{\mu\nu}U^\dagger\mathbf{W}^{\mu\nu}]\Big]$$

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

arbitrary polynomials

To describe non-decoupling effects
we put a CW type structure (1–loop)

SK, R. Nagai (2021)

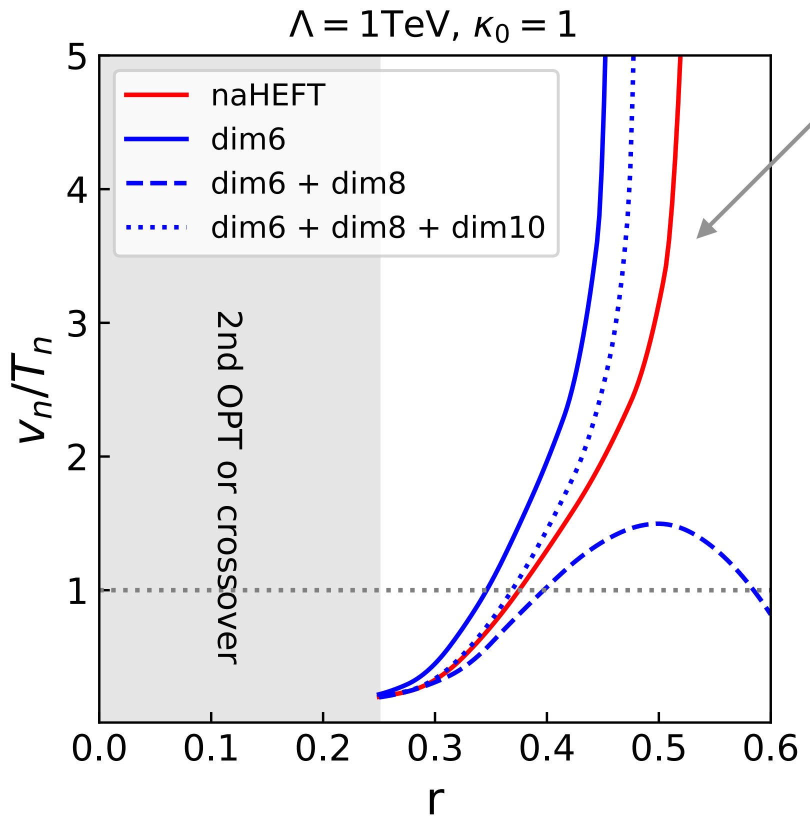
Buchalla, et al (2013)

naHEFT at finite temperature

SK, R. Nagai, M. Tanaka (2022)

$$\boxed{V_{\rm EFT} = V_{\rm SM} + \frac{\kappa_0}{64\pi^2}\left[\mathcal{M}^2(\phi)\right]^2 \ln\frac{\mathcal{M}^2(\phi)}{\mu^2} + \frac{\kappa_0}{2\pi^2} T^4 J_{\rm BSM}\left(\frac{\mathcal{M}^2(\phi)}{T^2}\right)}$$

$$J_{\rm BSM}(a^2) = \int_0^\infty dk^2 k^2 \ln\left[1 - {\rm sign}\,(\kappa_0)\, e^{-\sqrt{k^2+a^2}}\right] \quad \mathcal{M}^2(\phi) = M^2 + \frac{\kappa_p}{2}\phi^2$$



SK, R. Nagai, M. Tanaka (2022)

Consistent with results in the SM with a singlet

[Kakizaki et al., PRD 92 (2015), Hashino et al., PRD 94 (2016)]

Large deviation in v_n/T_n exists b/w the SMEFT and naHEFT

⇩

SMEFT may not be appropriate when we discuss the strongly first order EWPT

$$r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

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

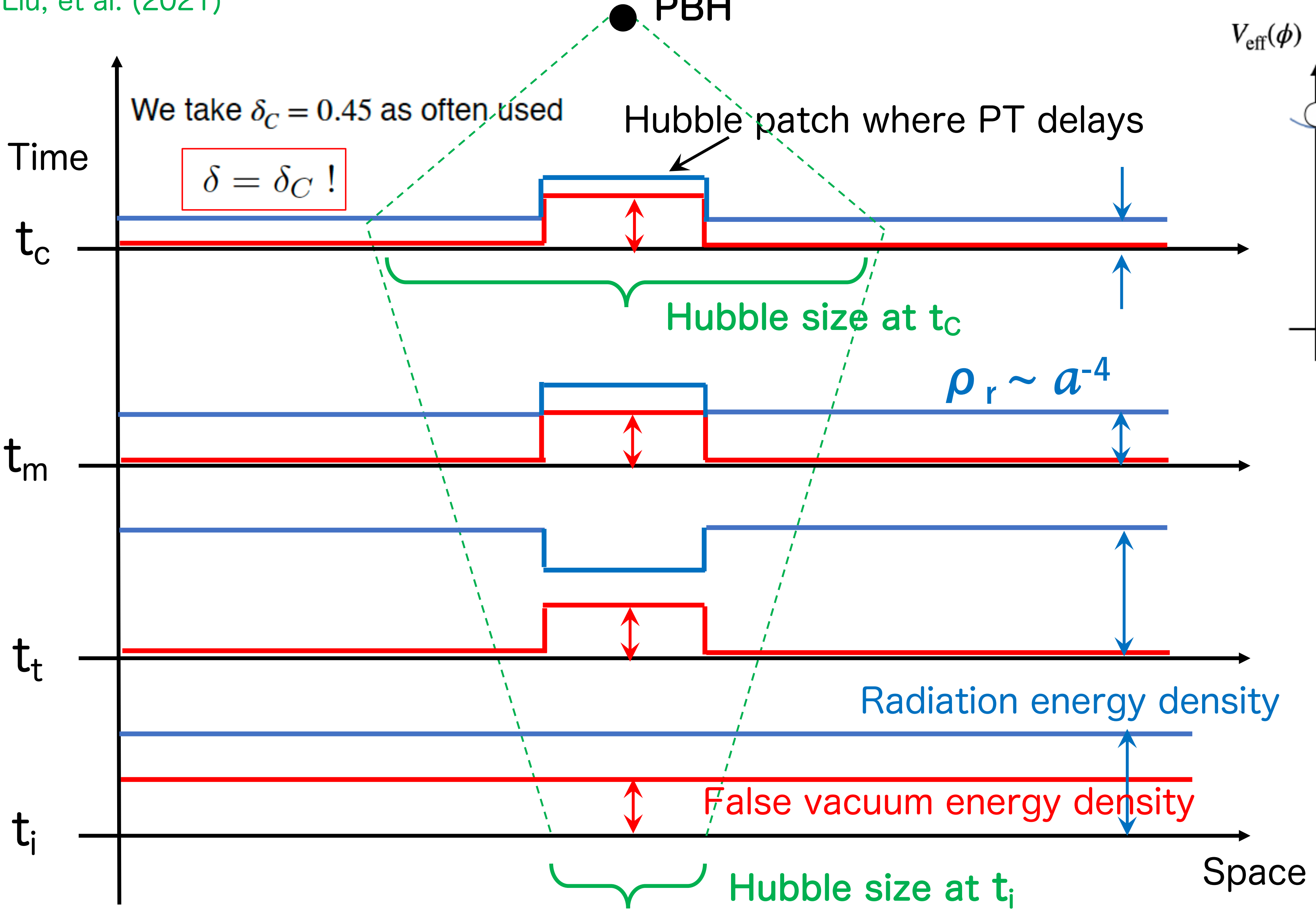
$r \sim 1 \Rightarrow M^2 \ll \frac{\kappa_p}{2}v^2$ Non-decoupling

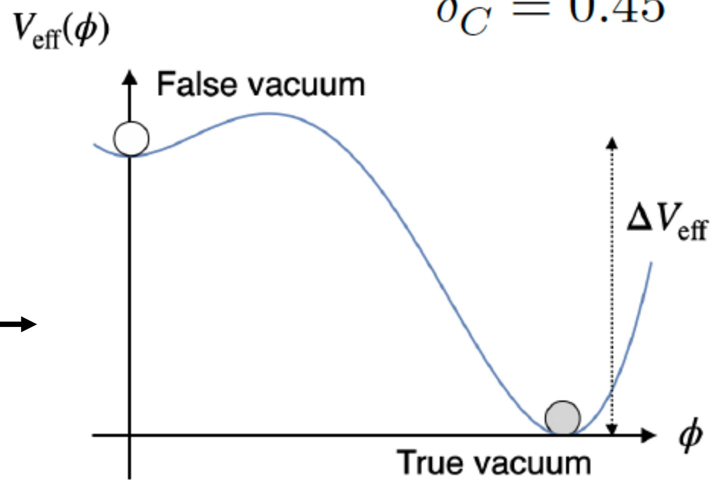
PBH formation from the contrast

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

$$\delta_C = 0.45$$

J. Liu, et al. (2021)





False vacuum energy density

$\rho_V \sim$ **constant**

$\sim F(t)\ \Delta V_{\mathrm{eff}}$

Radiation energy density

$\rho_r \sim a^{-4}$

Originally by J. Liu, L. Bian, R.-G. Cai, Z.-K.Guo, S.-J. Wang (2021)

Rate of staying at the symmetric phase in a Hubble volume

$$F(t) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t} \mathrm{d}t'\Gamma(t')\,a^3(t')\,r^3(t,t')\right]$$

$$r(t,t') \equiv \int_{t'}^{t} a^{-1}(\tau)d\tau$$

$$\rho_{\rm v} \;=\; F(t)\Delta V$$

vacuum energy density is constant

Radiation Dominant p = $\rho/3$

Friedmann eq $$H^2 = \frac{\rho_{\rm v}+\rho_{\rm r}+\rho_{\rm w}}{3}$$

Conservation $$\frac{d(\rho_{\rm r}+\rho_{\rm w})}{dt} + 4H(\rho_{\rm r}+\rho_{\rm w}) = \left(-\frac{d\rho_{\rm v}}{dt}\right)$$

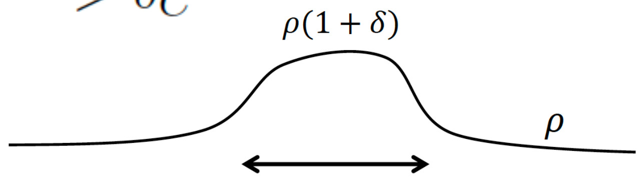
$\rho_{\rm r}$ Radiation (wall) energy density

$\rho_{\rm w}$ $\propto \; a^{-4}(t)$

(v_w = 1)

ρ_r(t), H(t) are determined

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



Then, from the criterion δ_c = 0.45,
T_{PBH} is determined

δ > 0.45 gravitational collapse

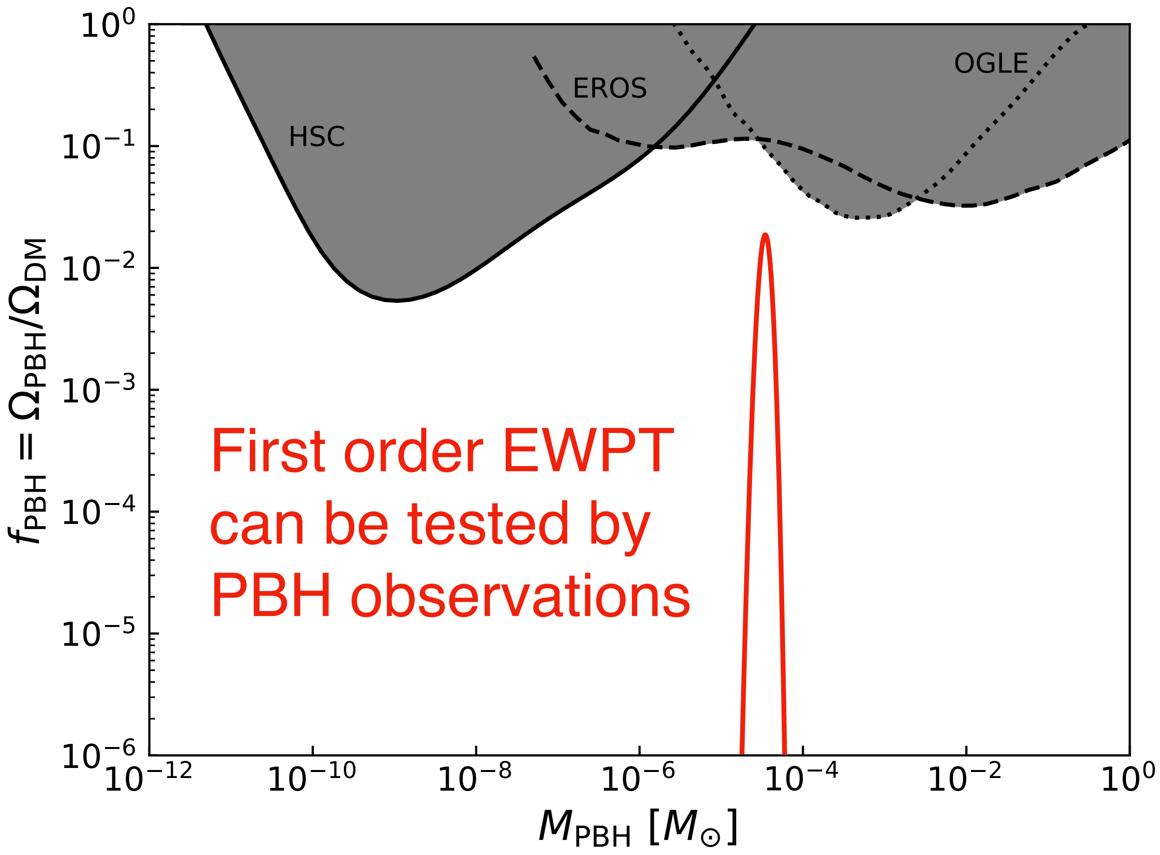
PBH from 1st order EWPT

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

Mass of PBH from EWPT is determined by t_{PBH}

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

$\boxed{M_{\rm PBH} \sim 10^{-5} M_\odot}$ ← Important prediction



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

$f_{\rm PBH}$ is constrained by 10^{-4}

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

Theory predictions on α-β plane

Non-dec. r = 0.5

DOF κ_0 = 1 , 4, 20

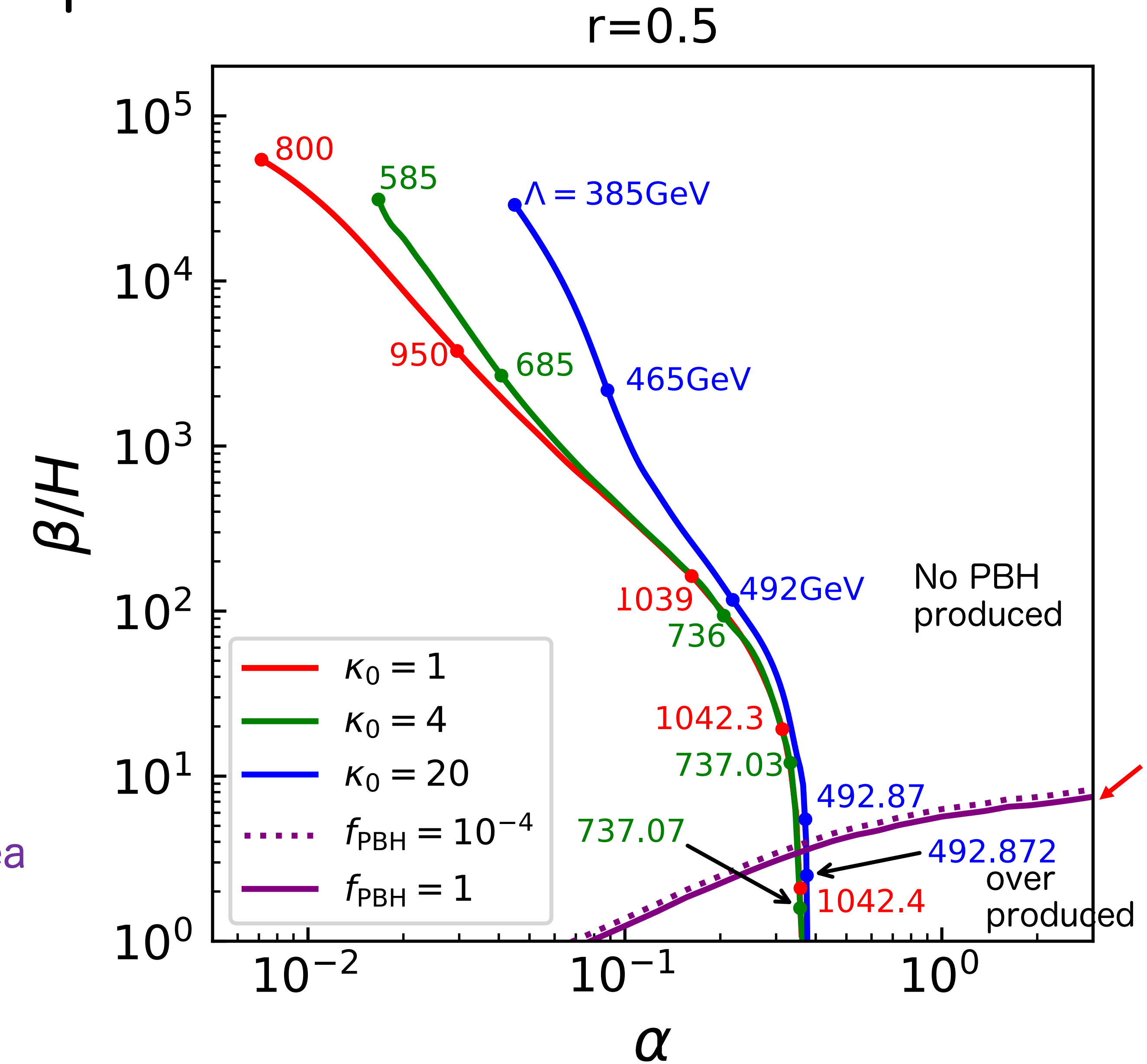
for various Λ

New scale

Contours of f_{PBH}

$10^{-4} < f_{PBH} < 1$

PBH can be produced in this area



PBHs are produced Here!

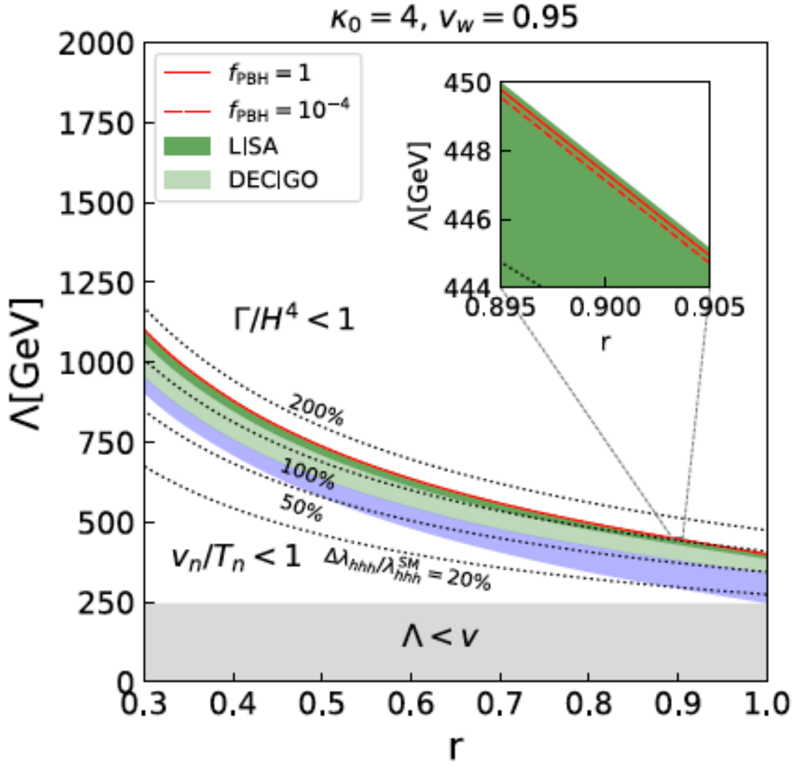
Exploring FOEWPT via PBHs

- 1st order EWPTs can be tested by
  - hhh coupling
  - Gravitational waves
  - PBH observations

- PBH observations already have data

  1st OPTs can be tested by a fact that no PBH is observed

- More precise observations will start in near future



Hahino, SK, Takahashi, Tanaka, Yoo, arXiv: 250111040

PRIME & Roman telescope explore regions with $f_{\rm PBH} > 10^{-4}$