# Higgs as a probe of new physics

希格斯作为新物理学的探针

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International Workshop on New Opportunities for Particle Physics 2024
中国高能物理研究所 北京 July 19-21, 2024

# HPNP2025

$7^{th}$ international workshop
"Higgs as a probe of new Physics "


9-13 June 2025,
Osaka University, Japan

Your participation is very welcome!

大阪大学
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# Current Situation

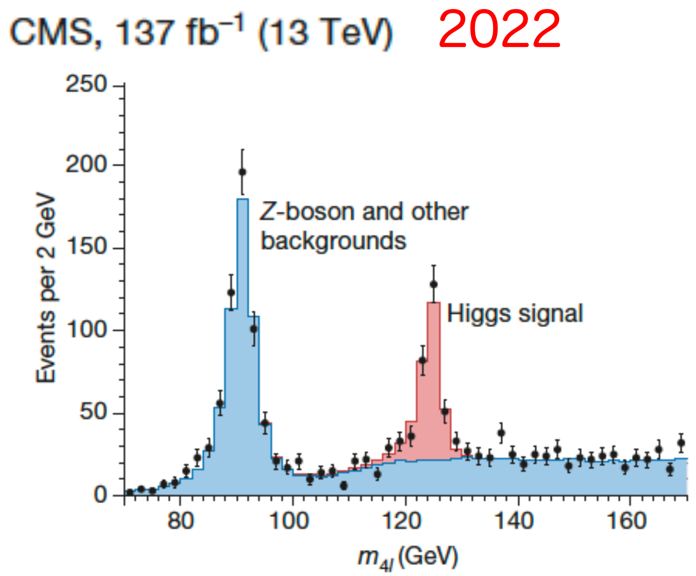
Higgs Discovery  2012

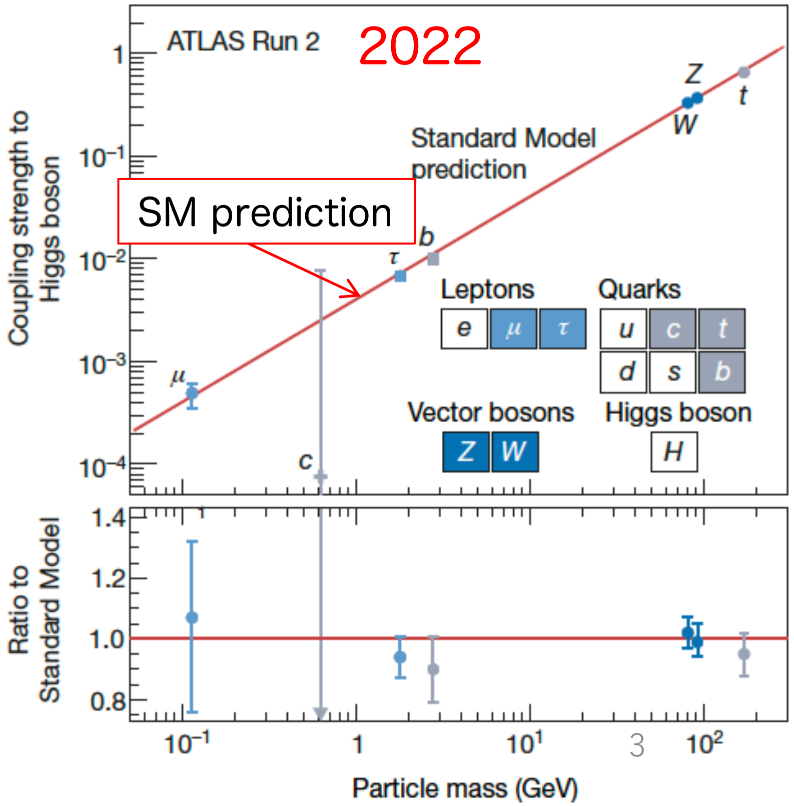
Mass 125 GeV

Spin・Parity

Agreement with SM prediction

No BSM particle found up to now



# SM is a tentative theory

SM is a good description of the nature around the EW scale, however ….

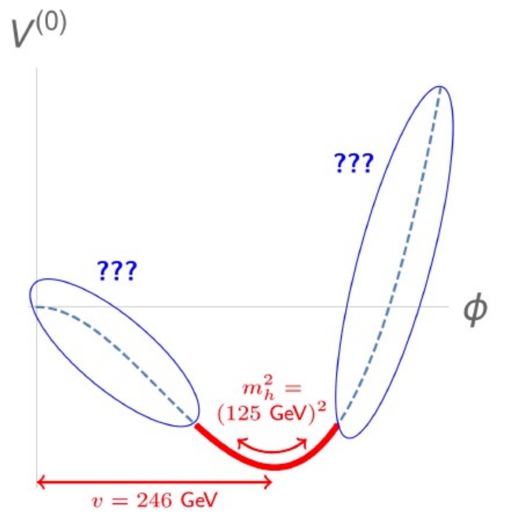
Problems
- Gravity
- Unification
- Flavor
- Higgs sector
  - Hierarchy Problem
  - Strong CP Problem
- Beyond SM phenomena
  - Neutrino oscillation
  - Dark matter
  - Baryon Asymmetry of Universe (BAU)
  - …

SM must be replaced by a new more fundamental theory

# Higgs sector is a probe of new physcs

Although the Higgs boson was found,
the Higgs sector remains unknown

Higgs potential (Dynamics of EWSB, EWPT, ⋯)
Yukawa structure (Flavor Physics, CPV, ⋯)
Elementary or Composite? Hierarchy? Multiplet structure?




SM Higgs sector: no principle

Extension of the Higgs sector
⇒ BSM phenomena may be explained

Tiny neutrino mass
DM candidates
Phase Transition (1st Order)
CPV sources for baryogenesis
…

Testable at current and future experiments

# Nature of the Higgs boson

| Higgs Nature | ⇔ | BSM Paradigm |
| --- | --- | --- |
| Elementary Scalar | | Supersymmetry |
| Composite of fermions | | Dynamical EW Symmetry Breaking |
| Vector field in extra D | | Gauge Higgs Unification |
| …… | | …… |

Each new paradigm predicts a specific Higgs sector

# Baryogenesis and Higgs

Baryon Number of the Universe

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

Baryogenesis

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

Sakharov's Condition

Sakharov 1967

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

SM cannot satisfy these conditions

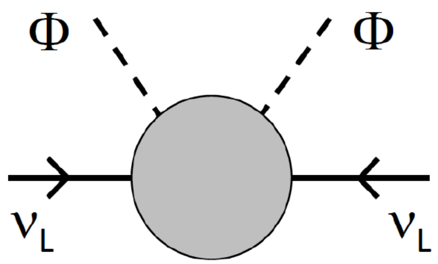
Extended Higgs models can satisfy them, and viable models for baryogenesis can be built

# Neutrino mass and Higgs

Neutrino Oscillation → Tiny mass ( < eV)

Majorana mass

$$\mathcal{L} = \frac{c}{\Lambda}(\phi\overline{\nu_L^c})(\nu_L\phi)$$

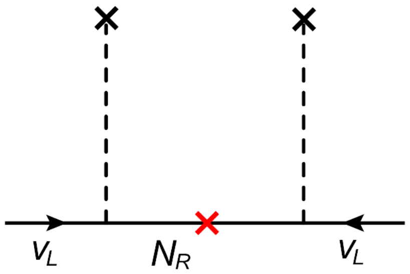



Seesaw Mechanism

$$m_\nu^{ij} = y_i y_j \frac{\langle\phi\rangle^2}{M_R}$$

Tiny mass

← Large mass of RH-Neutrinos




Seesaw

Mediated by RH neutirnos $N_R$

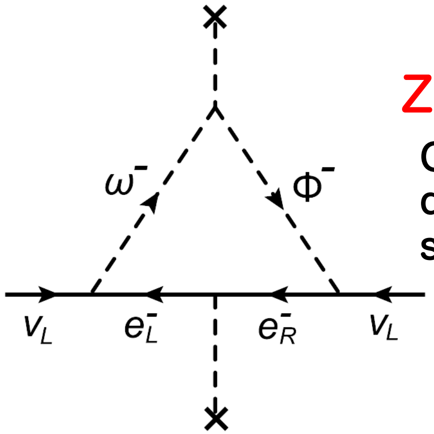
Alternative Scenario by quantum effects

$$m_\nu^{ij} = c_{ij}\left(\frac{1}{16\pi^2}\right)^N \frac{\langle\phi\rangle^2}{M_{\phi^+}}$$

Tiny mass

Quantum suppression

Mass around TeV scale

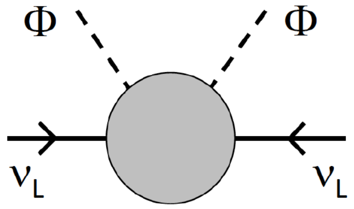



Zee model

Quantum effect due to additional scalar fields

Physics of specific extended Higgs sectors

# Models of neutrino mass with dark matter




Introducing a discrete symmetry

- Stability of new particle （DM)
- Loop induced masses

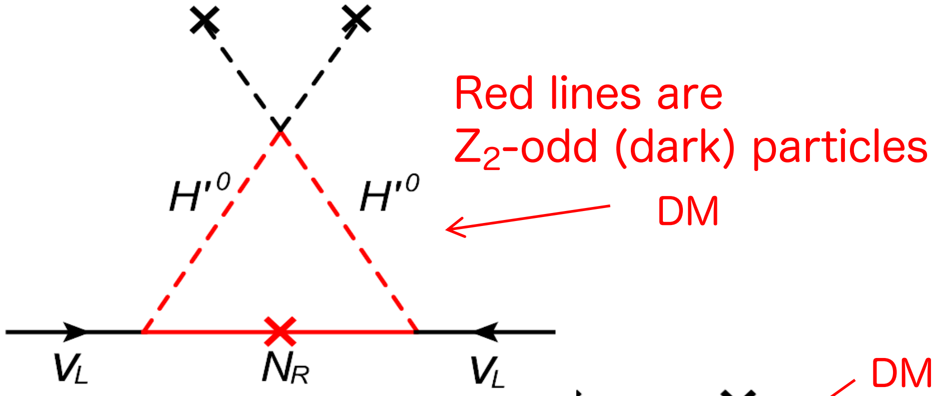
Stochastic model

Zhijian Tao 1996 (IHEP),
Earnest Ma, 2006

SM+ H’ + $N_R$

1-loop induced $\nu$-mass

Dark matter candidate [ H’ ]




Model with higher loop effects

Aoki, SK, Seto, 2008
Aoki, Enomoto, SK, 2023

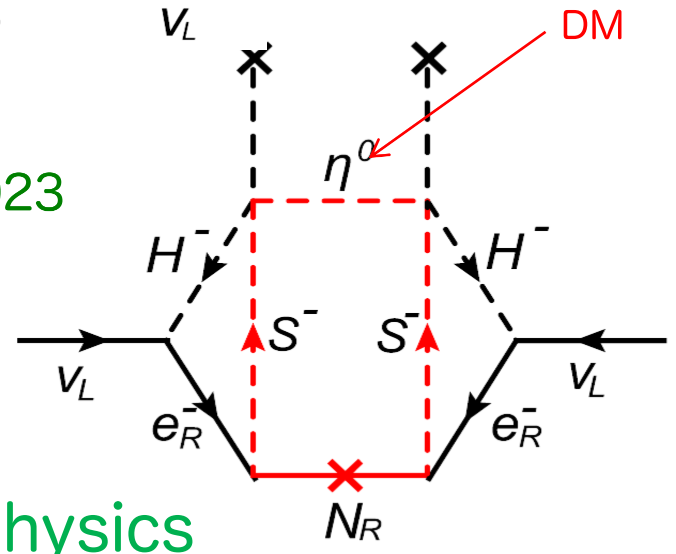
2HDM + $\eta^0$ + $S^+$ + $N_R$

$\nu$-masses are 3-loop induced

DM candidate [ $\eta^0$ ]

EW Baryogenesis possible (CPV, 1stOPT)

3 Problems can be explained by the TeV scale physics



# Higgs is a window to new physics

Higgs portal new physics scenarios

SUSY
Dynamical symmetry breaking
Higgs as a pNGB
Gauge Higgs Unification
CW mechanism (CSI)
Higgs portal dark matter
Inert scalar models
Radiative neutrino mass models
Electroweak baryogenesis
…

Experimental determination of the shape of the Higgs sector is crucial to narrow down new physics beyond SM

# Extended Higgs sector?

Multiplet Structure (with additional scalars)

$\Phi_{SM}$ + Isospin Singlet,
$\Phi_{SM}$ + Doublet (2HDM),
$\Phi_{SM}$ + 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

LHC data show **SM-like**

# Example: 2HDM with softly broken Z2

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

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

$\Phi_1$ and $\Phi_2 \Rightarrow h,\ H,\ A^0,\ H^\pm \oplus$ Goldstone bosons

↑ CPeven ↑ CPodd ↑charged

**Diagonalization**

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

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

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

masses

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

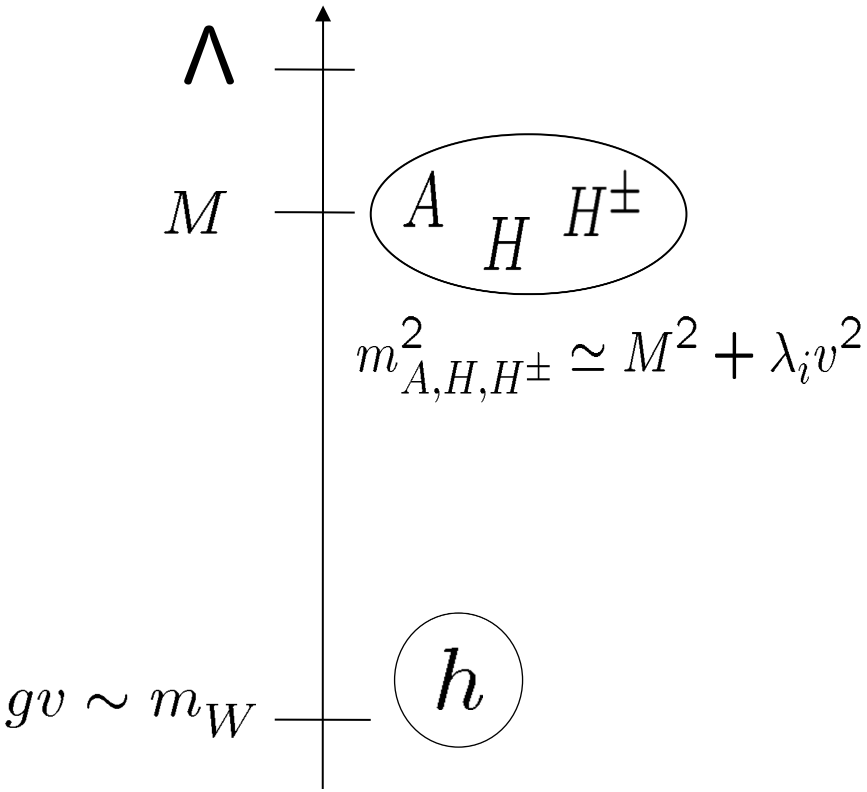
$$m_{A,H,H^\pm}^2 \simeq M^2 + \lambda_i v^2$$

$M_{\text{soft}}\ \left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$: soft-breaking scale of the discrete symm.

# How SM-like is realized?

$\Lambda$ : Cutoff

M : Mass scale irrelevant to VEV




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

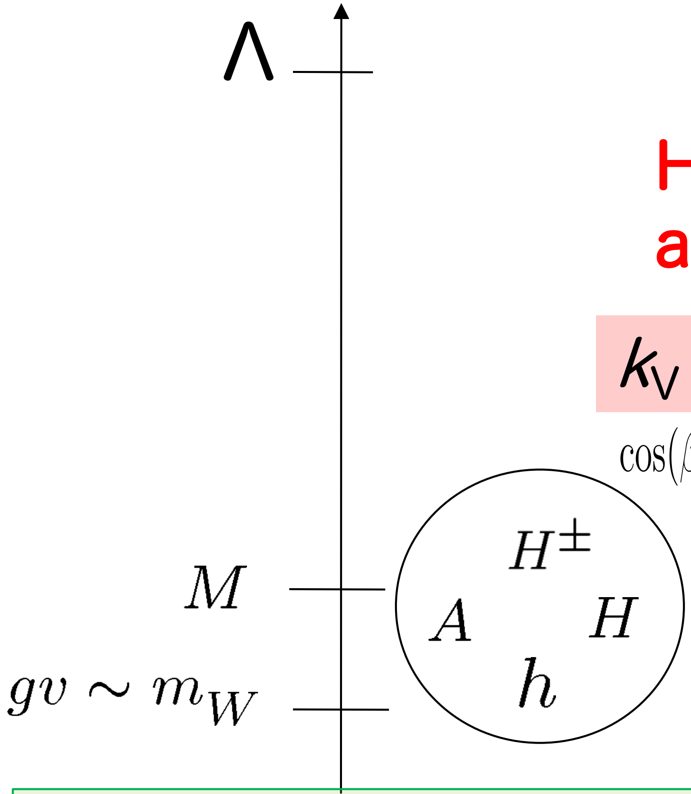
Effective Theory is the SM

Decoupling (M >> v)

Higgs alignment

$k_V \sim 1$ SM like

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



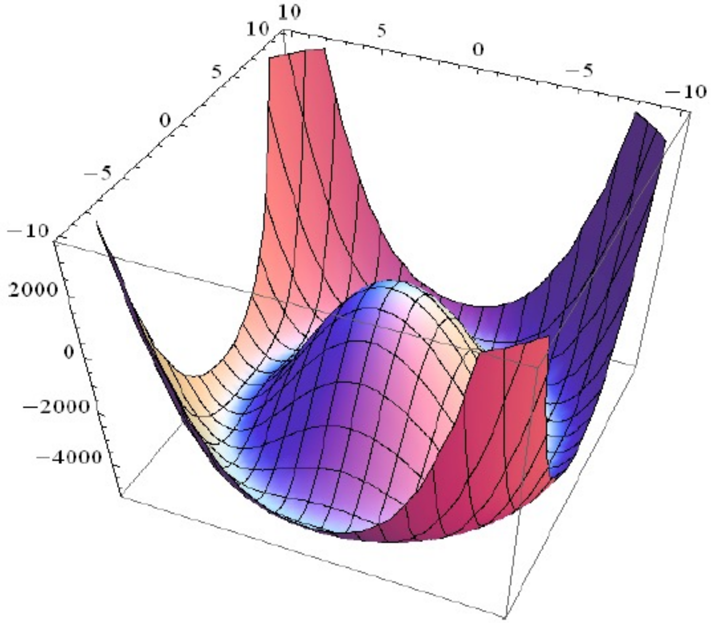

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm nonSM} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

Effective Theory is an extended Higgs sector

Alignment and Non-Decoupling (M ~ v)

# Higgs Potential

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



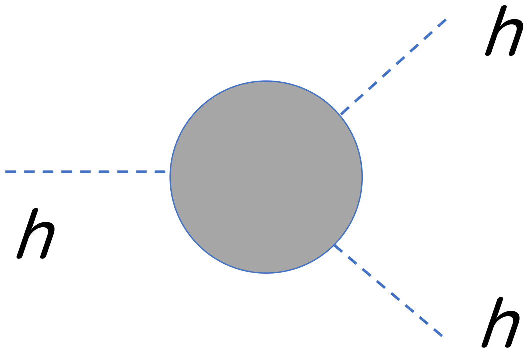

It is very important to know the *hhh* coupling
to reconstruct the Higgs potential

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

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

Top loop
effect
in the SM

Non-decoupling effect




Sensitive to the new physics!

The hhh measurement is crucial.

# EW phase transition

EWSB

⇒ EWPT exists in thermal history of Universe

Next target!

Aspect of PT is crucial for EW Baryogenesis

# EW Baryogenesis

Sakharov Conditions

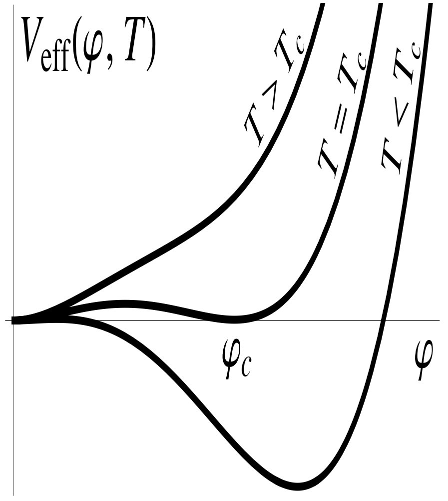
Kuzmin, Ruvakov, Shaposhnikov (1985)

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

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

Physics of Higgs potential

# 1st OPT by nondecoupling quantum effect

Effective Potential at finite T (HTE)

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

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

SM: The condition cannot be satisfied

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

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

(when $M \ll m_\Phi$)

Quantum effects of $\Phi$( = H, A, $H^+$, …)

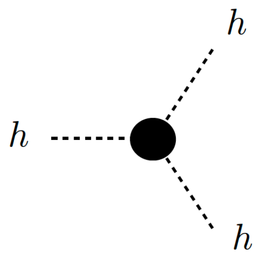
Prediction: Large deviation in the hhh coupling

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

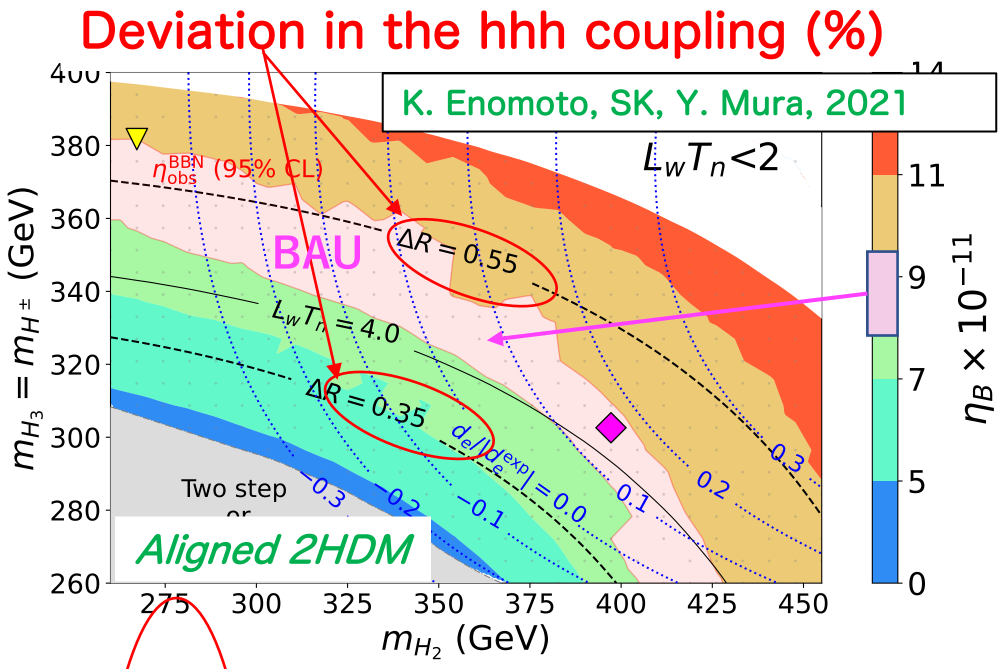
Grojean, Servant, Wells, 2005

SK, Y. Okada, E. Senaha, 2005

# Test of strongly 1st OPT




Example Aligned 2HDM: viable scenario of EWBG

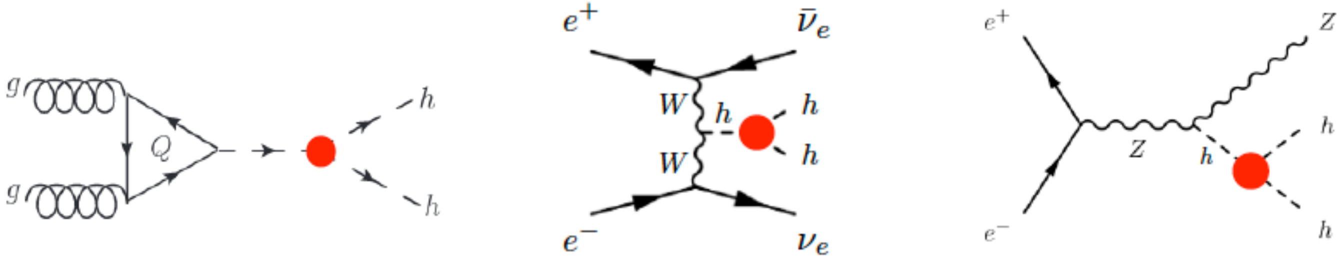


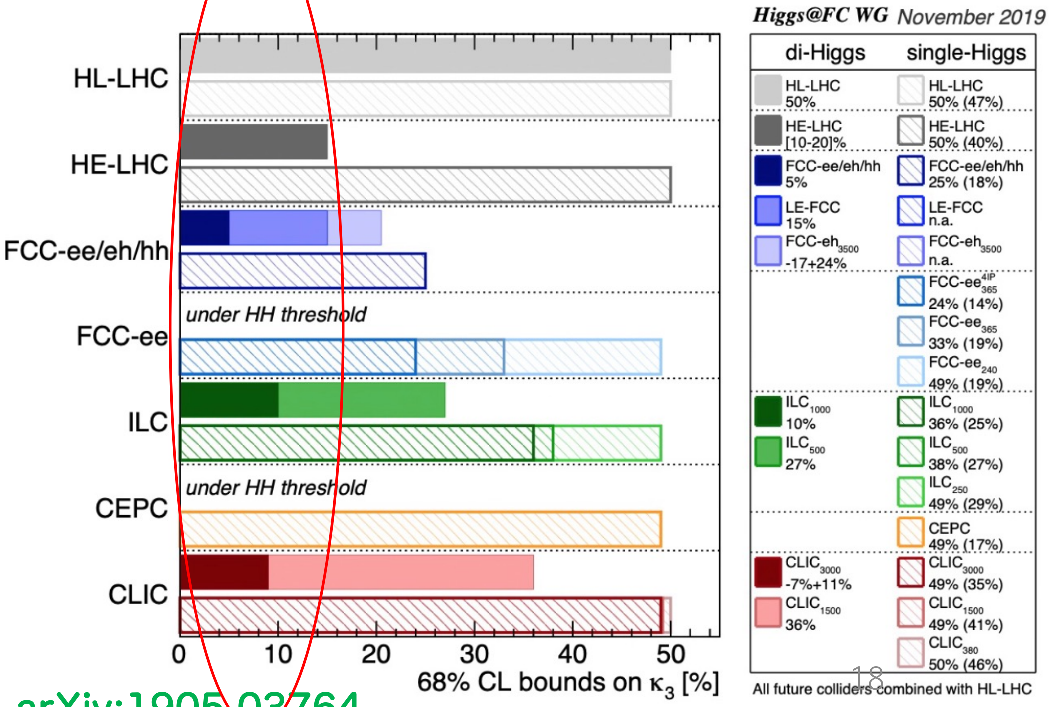

Strongly 1st OPT

→ 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



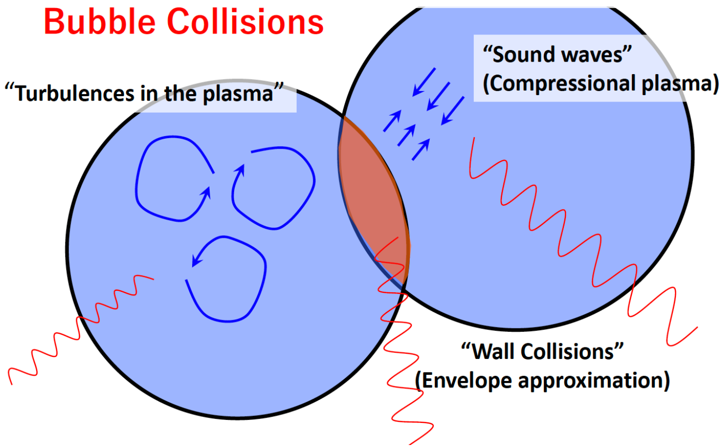




arXiv:1905.03764

**EW Baryogenesis can be directly tested by the hhh measurement**

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

# GW from 1stOPT

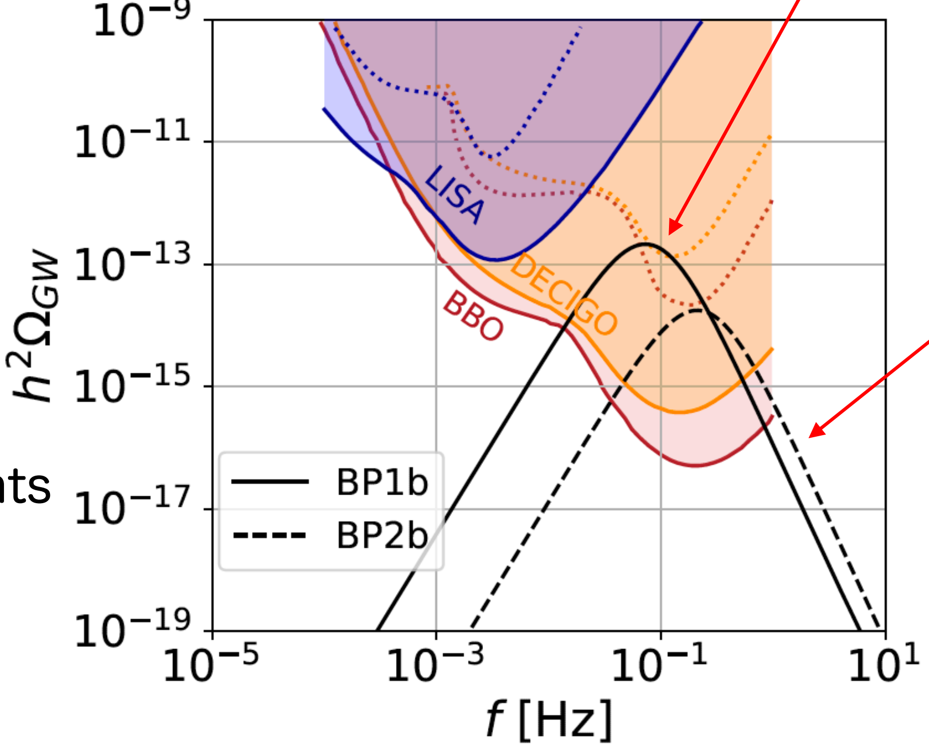



GWs for benchmark points of BAU

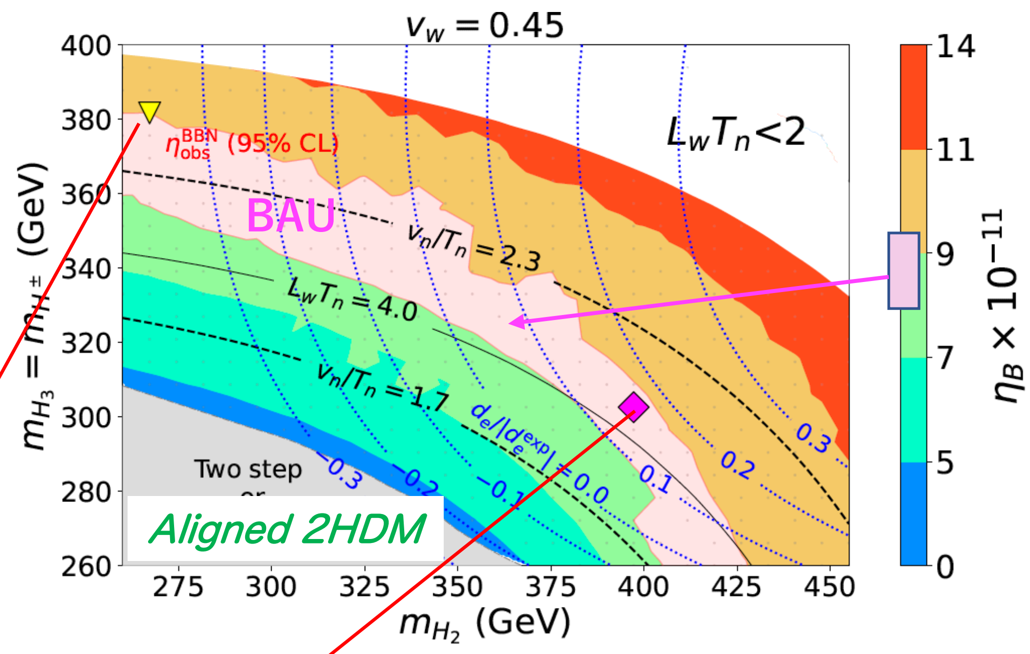
They may be tested by future GW experiments

Aligned 2HDM: viable scenario of EWBG

K. Enomoto, SK, Y. Mura, 2022




K. Enomoto, SK, Y. Mura, 2022




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

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

# How we can 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
  $\kappa_0$ (d.o.f. of new particle)
  $\Lambda$ (mass of new particle),
  r (non-decouplingness)

  $\kappa_0$: 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)

- How we can test 1st OPT by future experiments?

# Nearly aligned Higgs EFT

Higgs EFT

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

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

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

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

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

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

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

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

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

arbitrary polynomials

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

SK, R. Nagai (2021)

Buchalla, et al (2013)

# naHEFT (for describing non-decoupling property)

(nearly aligned)

SK, R. Nagai (2021)

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

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

Three free parameters $\Lambda$, $\kappa_0$, $r$

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

Non-decouplingness

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

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

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

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

$$V_{\rm BSM}(\varphi) \simeq \frac{\lambda_\Phi^3}{64\pi^2 M^2}\varphi^6 = \frac{1}{\Lambda^2}\varphi^6$$ ⇒ 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

$\Lambda$: mass of new particles
$\kappa_0$: d.o.f. of new particles
r: non-decouplingness

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

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

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

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

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

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

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

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

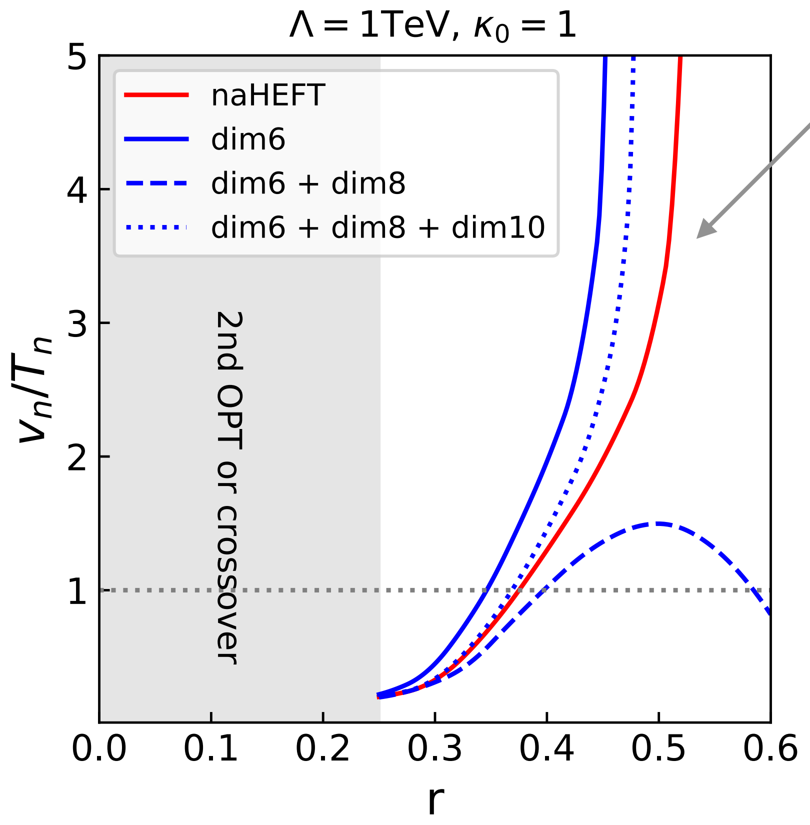
R. Florentino, S.K., M. Tanaka (2024)

# naHEFT at finite temperature

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

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

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




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 nearly aligned case

## 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, …

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

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

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

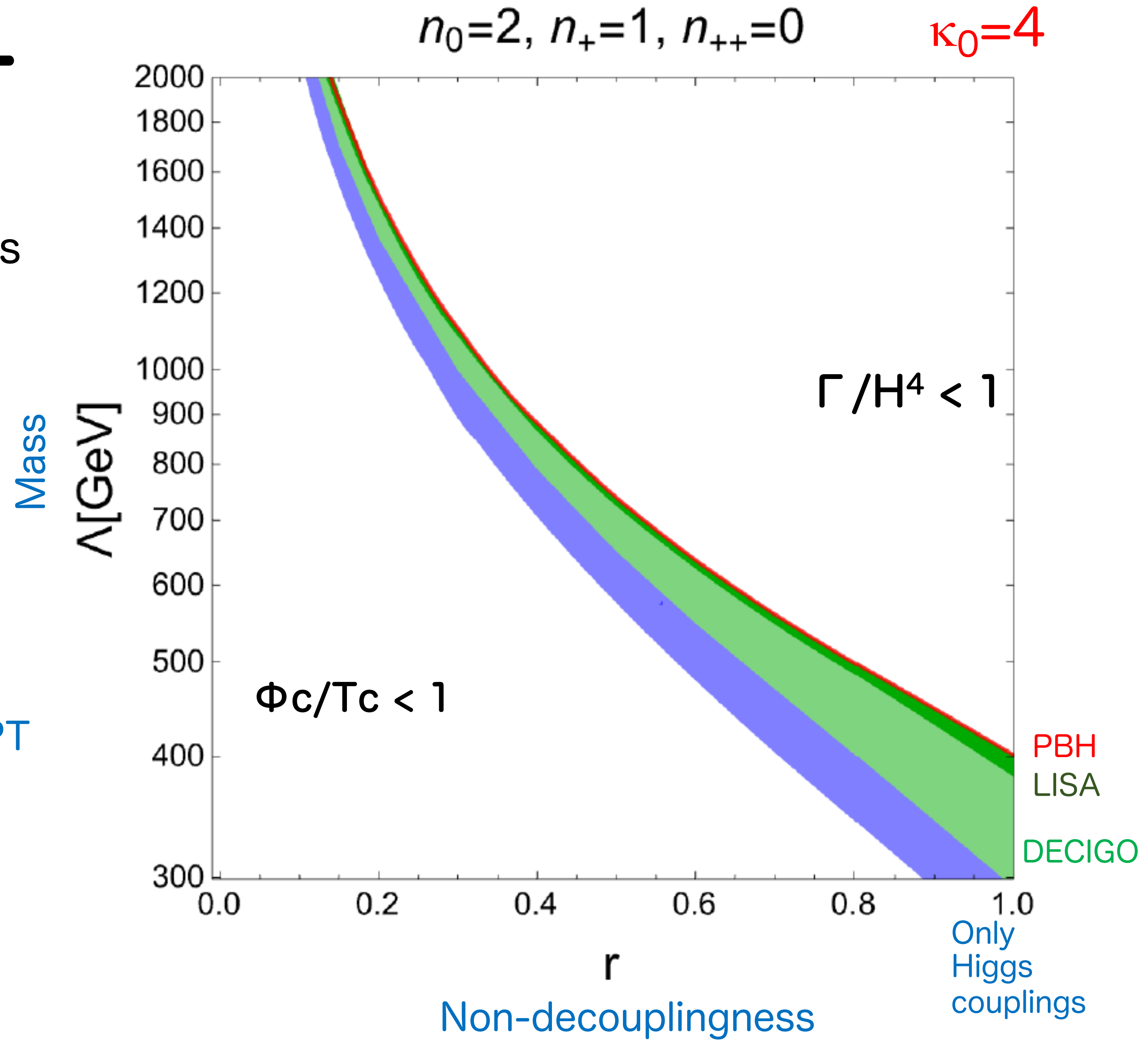
  PBH searches by microlensing: Subaru HSC, OGLE, Prime, Roman, …

# 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 ($\Delta\lambda_3$, $\Delta\kappa_\gamma$, …. )




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

# Strongly 1st OPT

Colored region satisfies two conditions

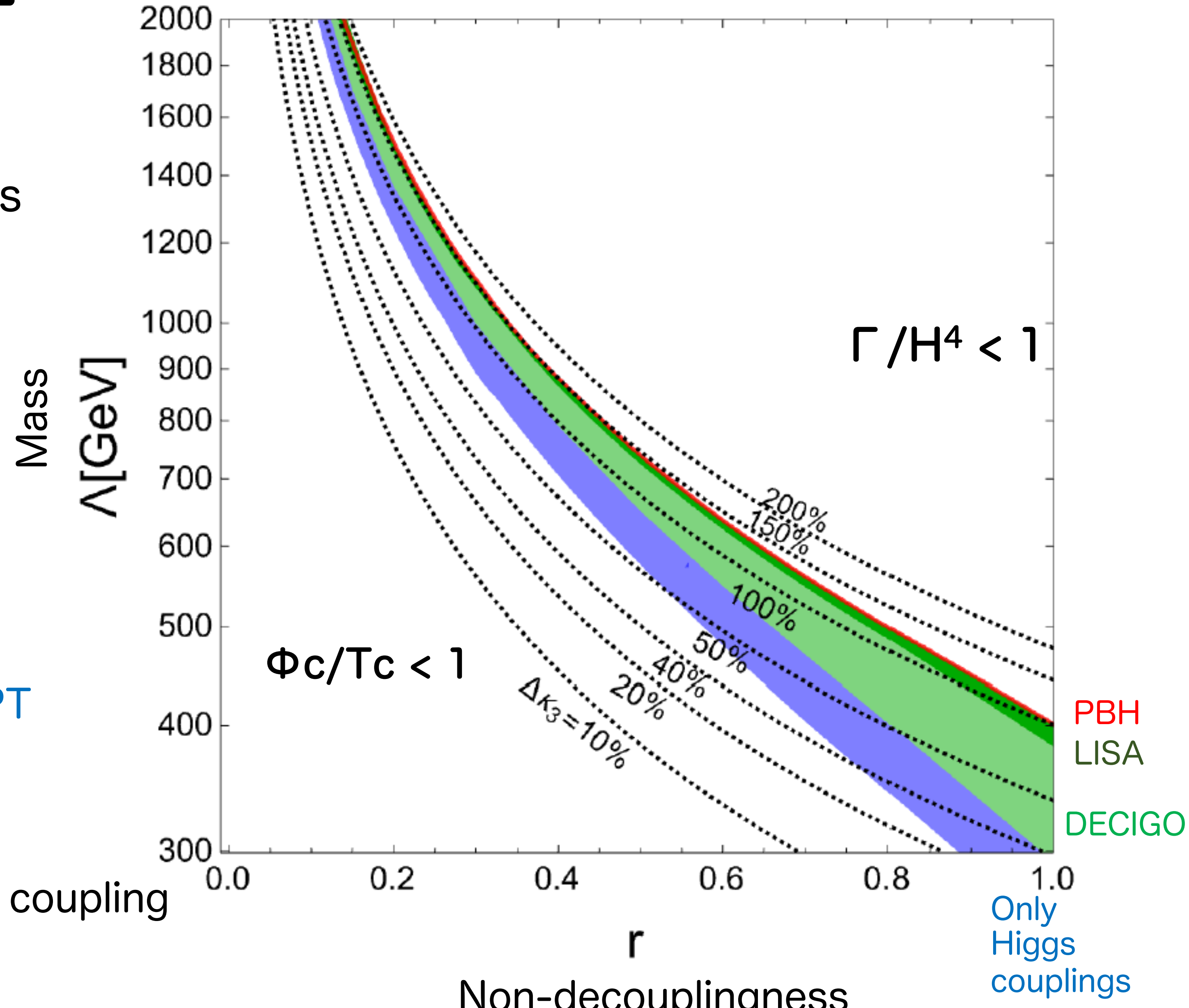
- Sphaleron decoupling $\frac{\varphi_c}{T_c} \gtrsim 1$
- Bubble nucleation completion $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1$

- 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

$n_0=2$, $n_+=1$, $n_{++}=0$ $\kappa_0=4$




Non-decouplingness

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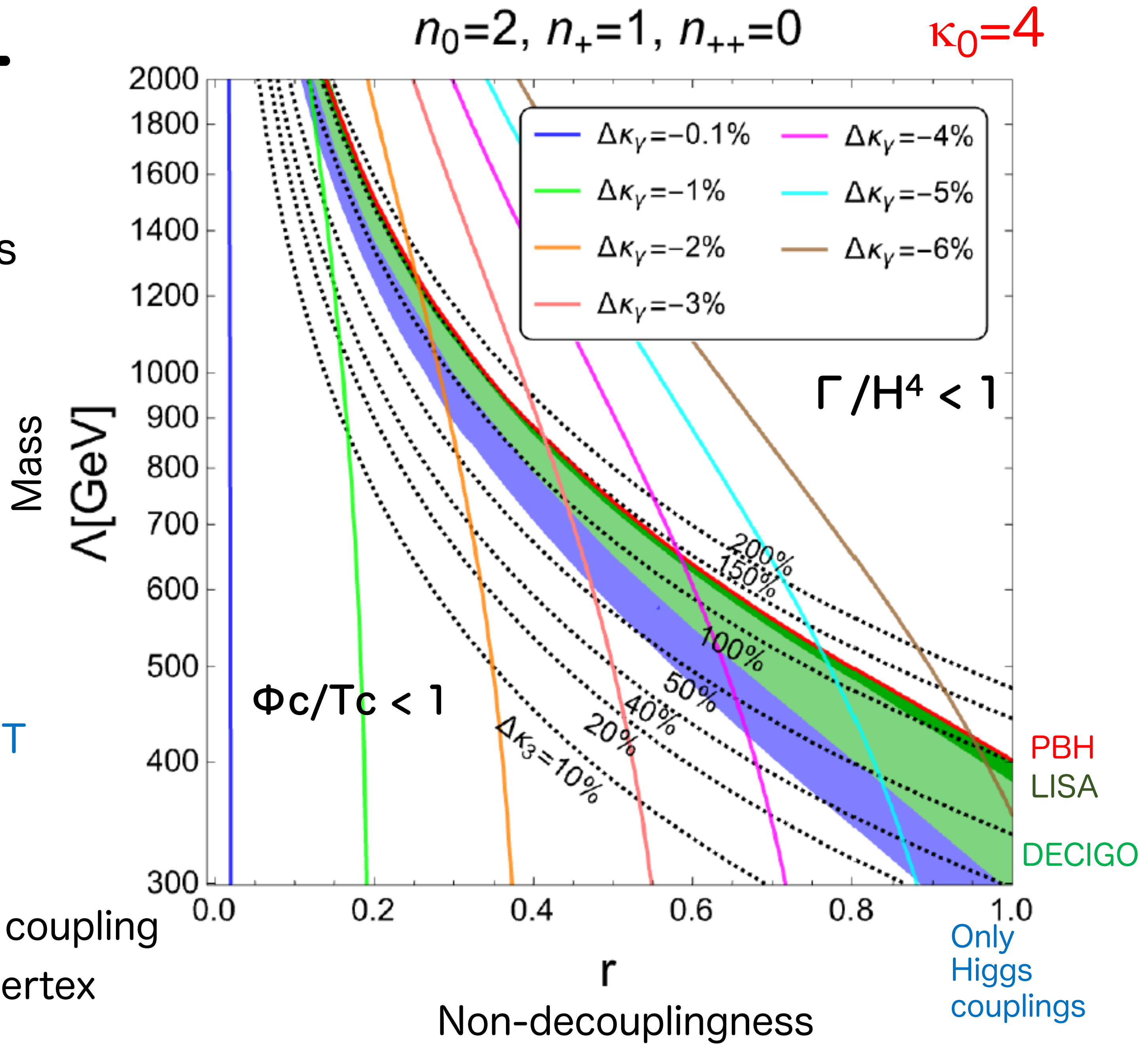


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## Contour plots

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

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

# Strongly $1^{st}$ OPT

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

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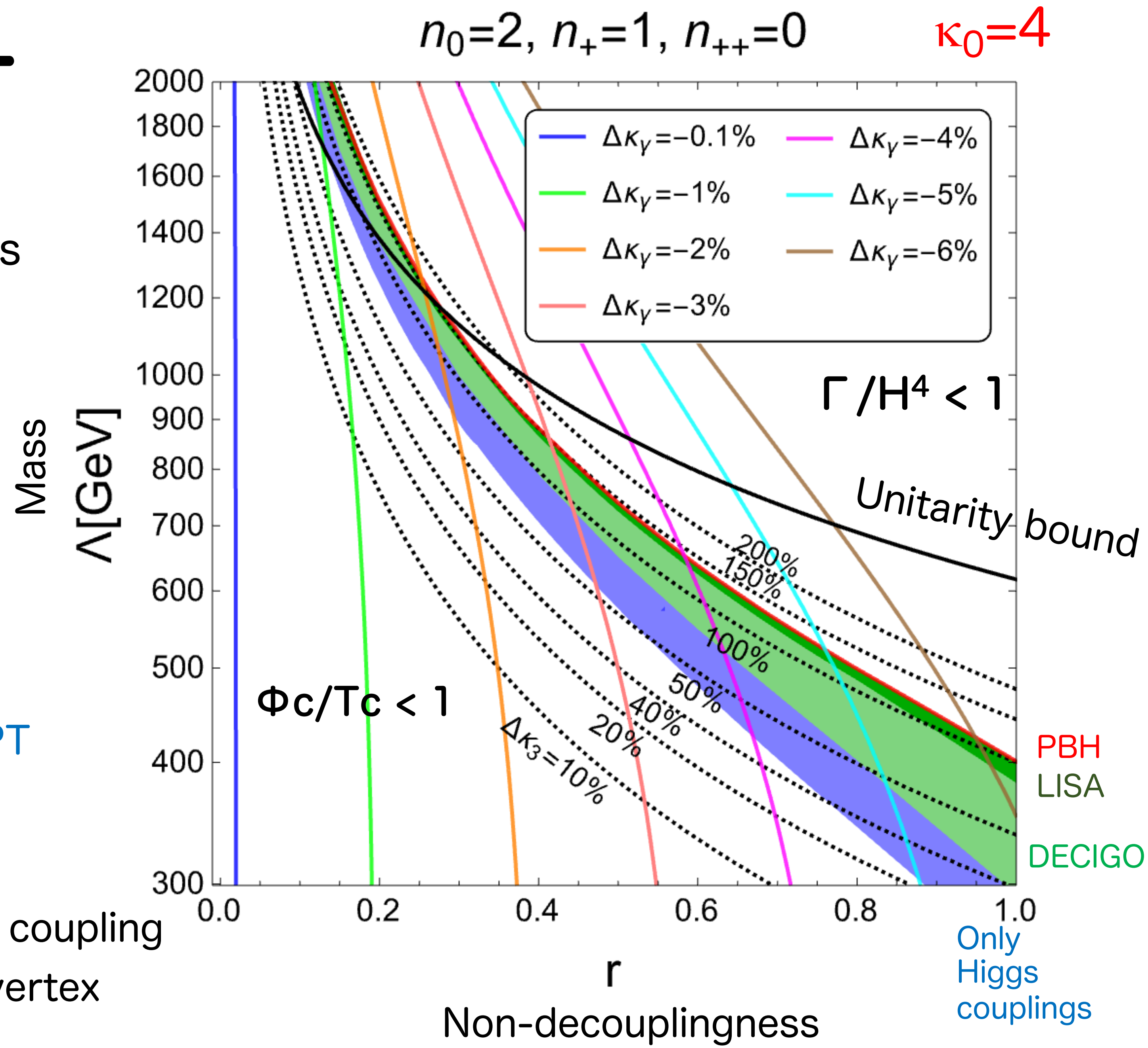
- GW (LISA detectable)
- GW (DECIGO detectable)
- Only Higgs couplings can test $1^{st}$ OPT
  ($\Delta\lambda_3$, $\Delta\kappa_\gamma$, .... )

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

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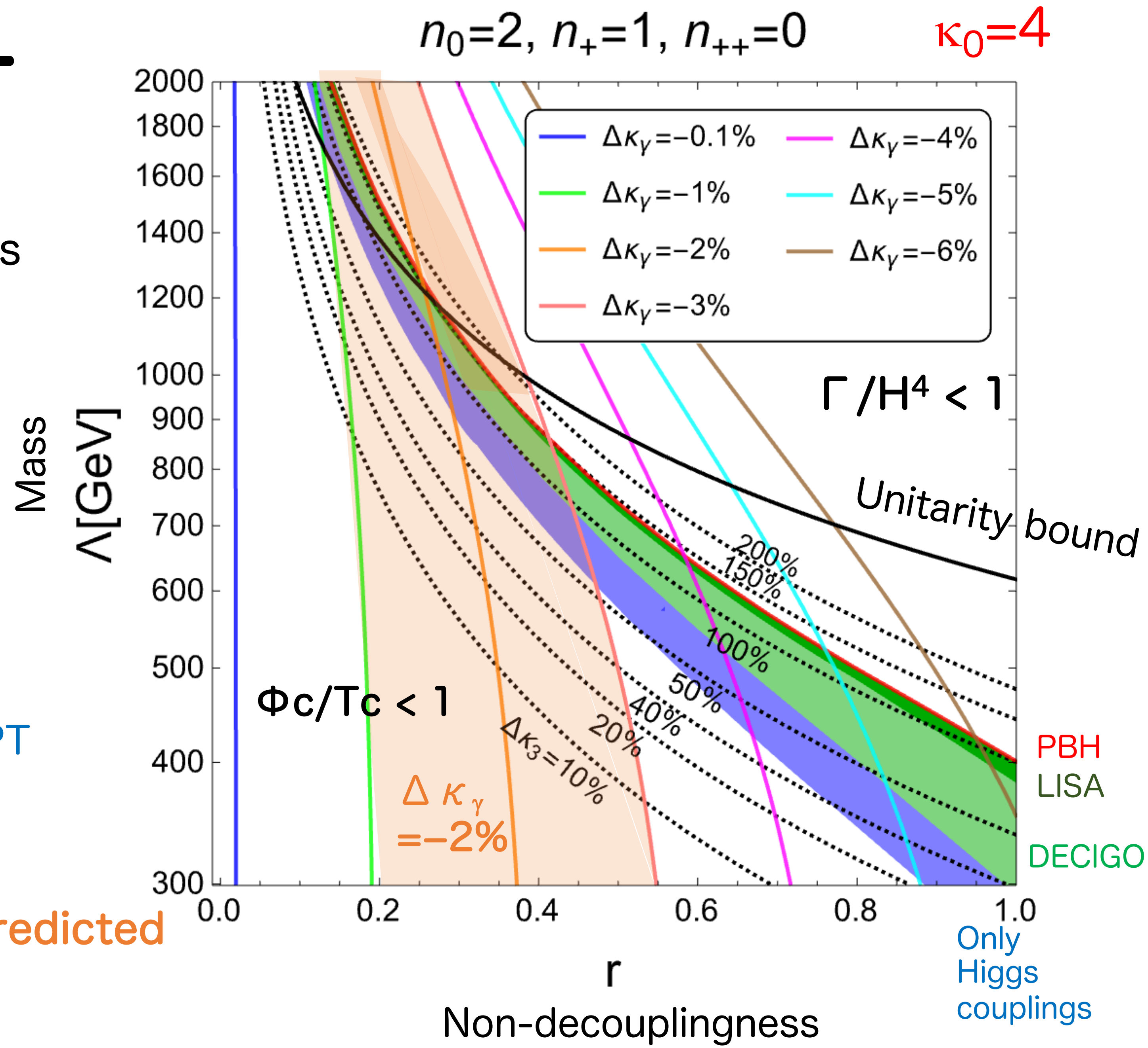


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If $\Delta\kappa_\gamma$ = -2% ± 1% (LHC+ILC), predicted

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

GW, PBH can also be used

# Strongly 1st OPT

Colored region satisfies two conditions

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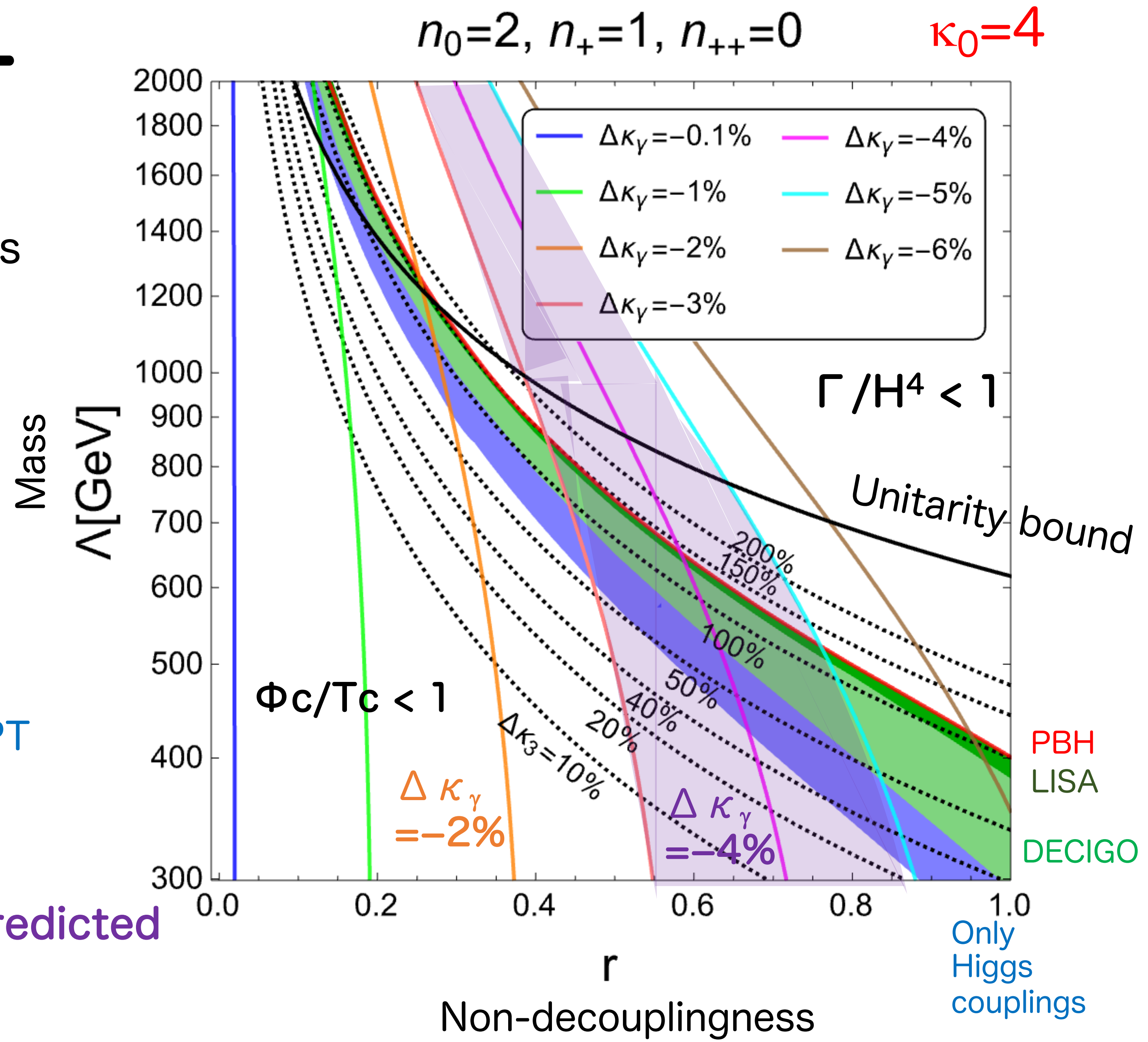
- PBH (Roman detectable $f_{PBH} > 10^{-4}$)
- GW (LISA detectable)
- GW (DECIGO detectable)
- Only Higgs couplings can test 1st OPT ($\Delta\lambda_3$, $\Delta\kappa_\gamma$, ....)

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

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

GW, PBH can also be used



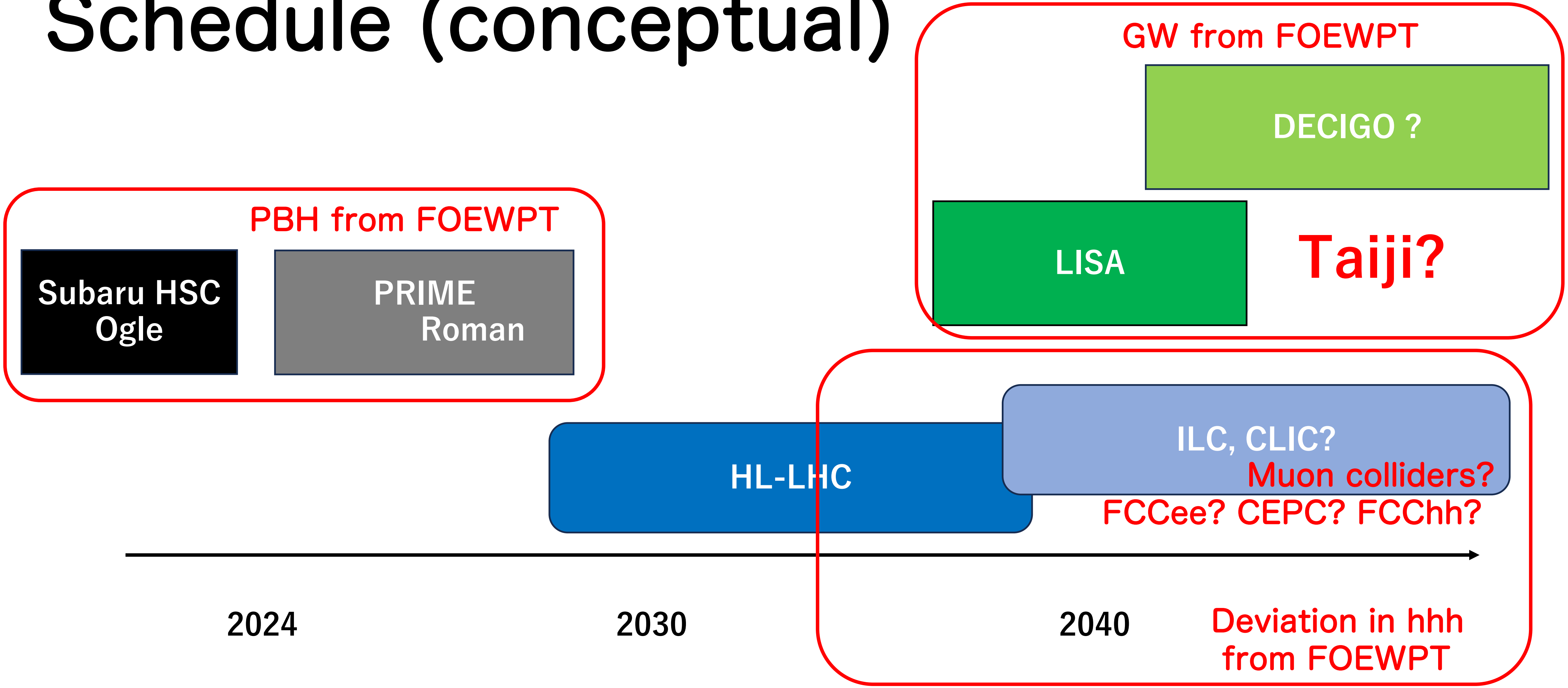

R. Florentino, S.K., M. Tanaka (2024)

# Summary

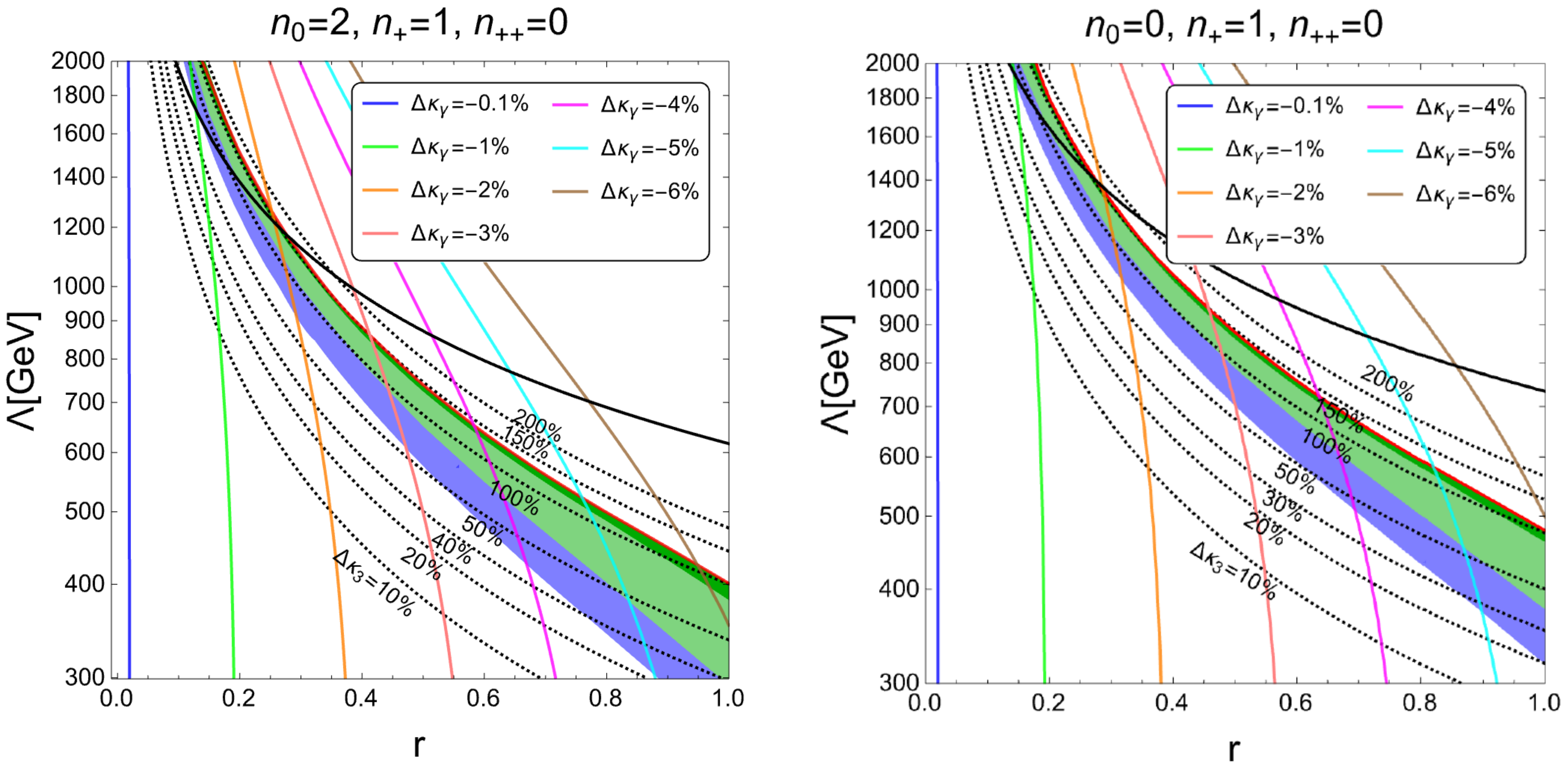
- Higgs sector is unknown
- Various possibility of extension
- Such extension can be connected to physics BSM
- Aspect of EWPT is a next global target
- Strongly 1st OPT is motivated by EW baryogenesis
- A simple mechanism for 1st OPT is the non-decoupling loop effect
- Described by the naHEFT
- Precision measurements of $h\gamma\gamma$ and hhh vertices, GW observation, PBH searches provide a complementary probe of EW 1stOPT

Thank you!

# Schedule (conceptual)

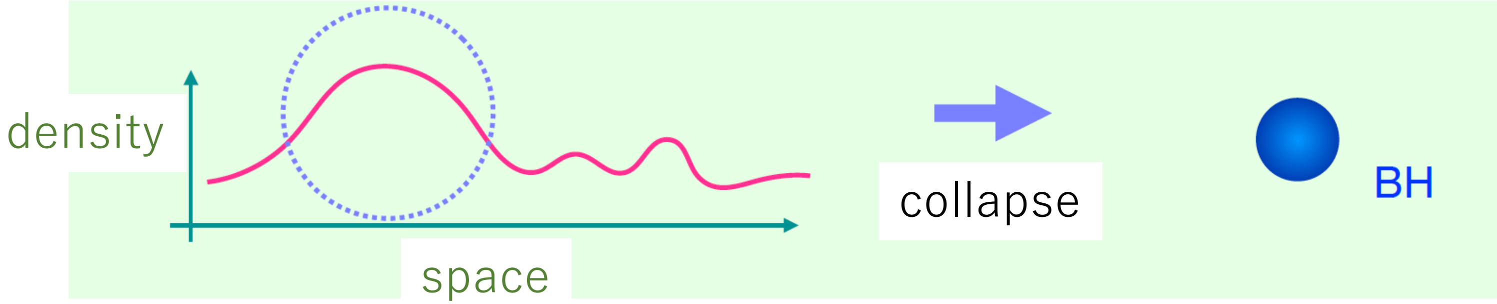



Complementary



$n_0$=2, $n_+$=1, $n_{++}$=0
$n_0$=0, $n_+$=1, $n_{++}$=0
Λ[GeV]
r
$\Delta\kappa_\gamma$=-0.1%
$\Delta\kappa_\gamma$=-1%
$\Delta\kappa_\gamma$=-2%
$\Delta\kappa_\gamma$=-3%
$\Delta\kappa_\gamma$=-4%
$\Delta\kappa_\gamma$=-5%
$\Delta\kappa_\gamma$=-6%
$\Delta\kappa_3$=10%
20%
30%
40%
50%
100%
150%
200%

# PBH Formation




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

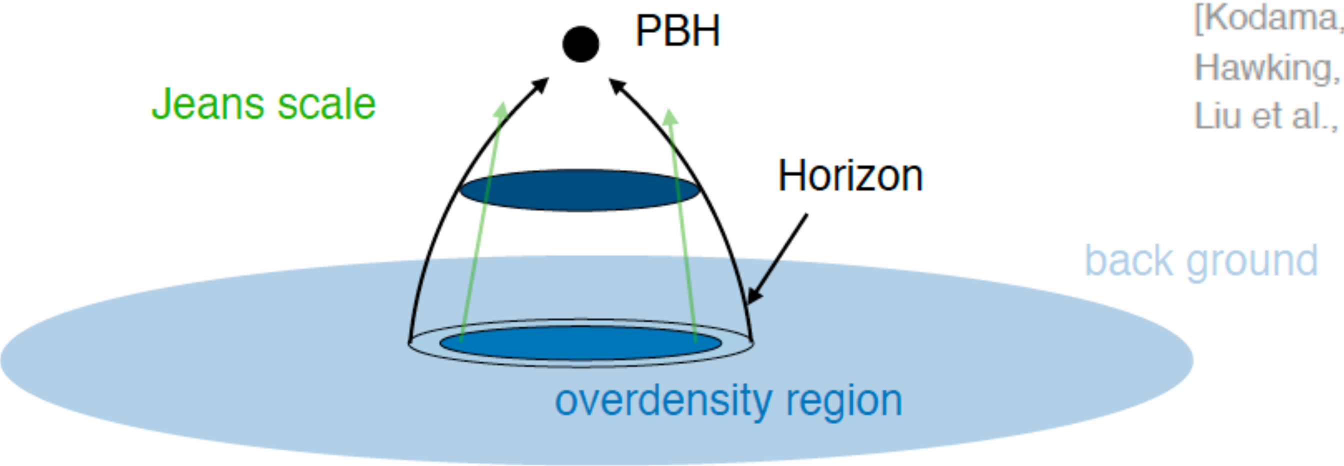
Condition for the PBH formation

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

[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 might be produced by the FOPT

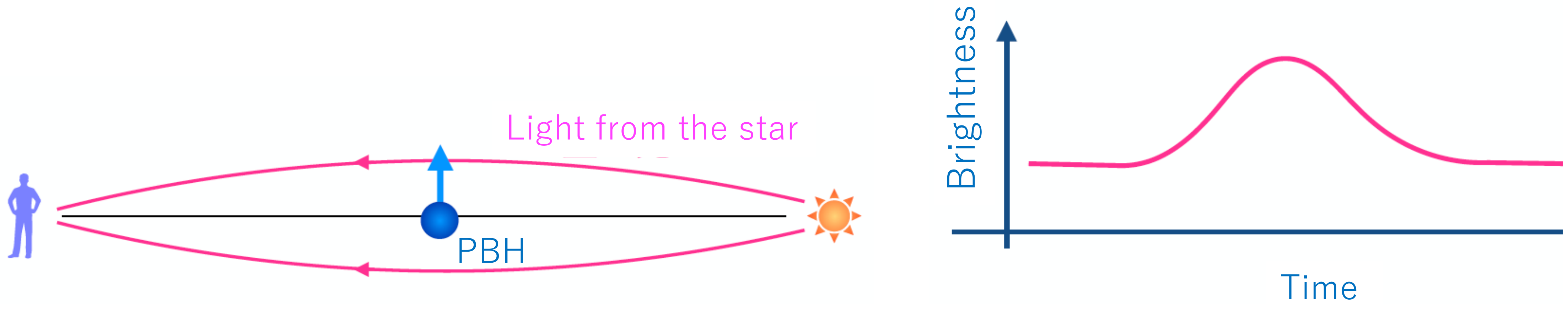



[Kodama, Sasaki and Sato, PTP 68 (1982);
Hawking, Moss and Stewart, PRD 26 (1982)
Liu et al., PRD105 (2022)]

Figure by Masanori Tanaka

# PBH search

- Gravitational microlensing effect
- Brightness is up by passing PBH




Non-observation → constraint on the PBH abundance

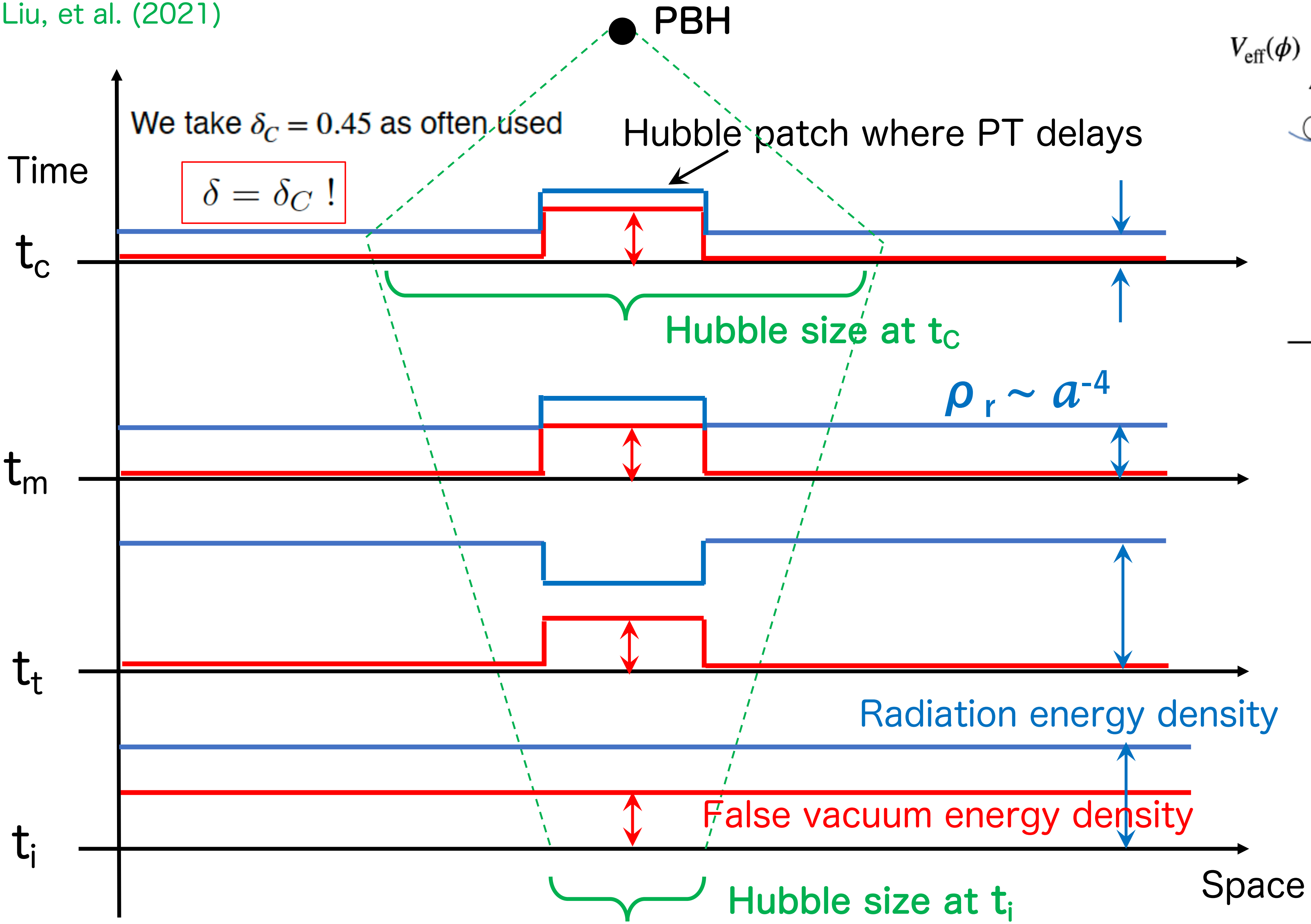
Subaru HSC、OGLE (Optical Gravitational Lensing Experiment)

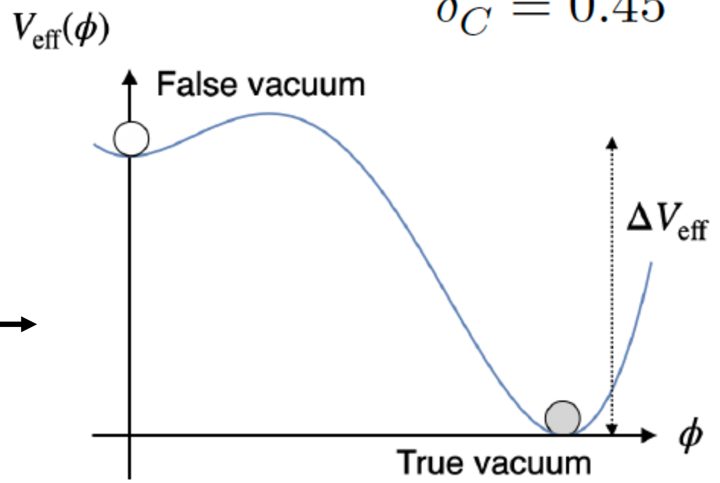
# PBH formation from the contrast

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

$$\delta_C = 0.45$$

J. Liu, et al. (2021)




False vacuum energy density

$\rho_V \sim$ **constant**

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

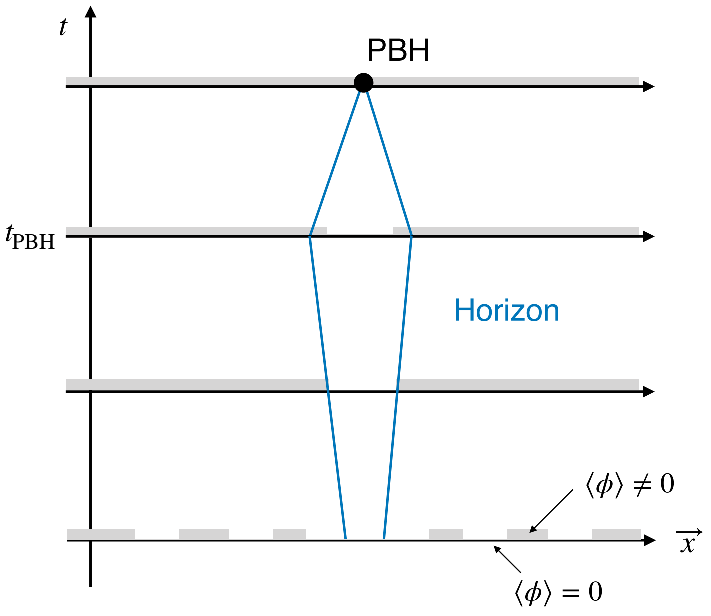
Radiation energy density

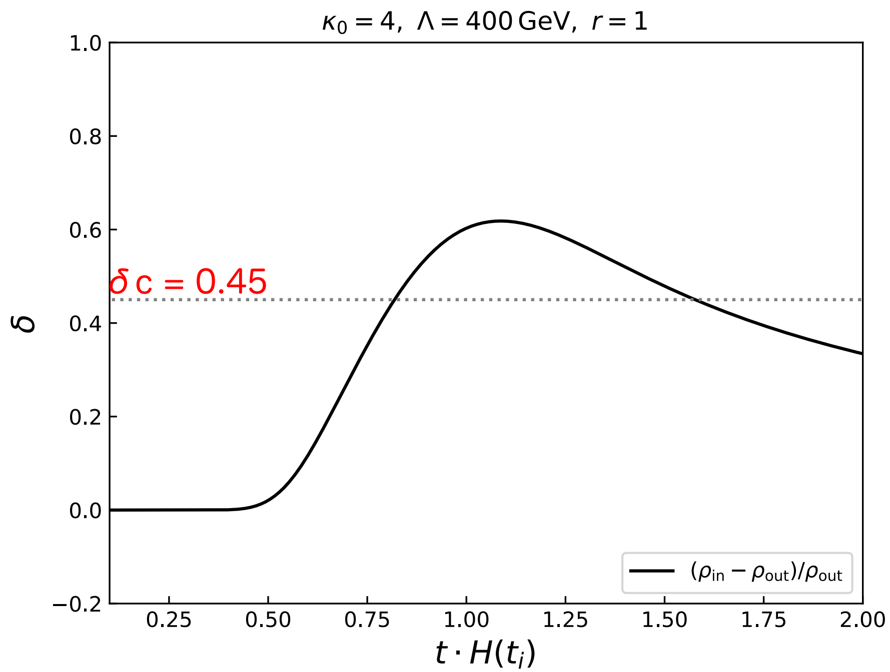
$\rho_r \sim a^{-4}$

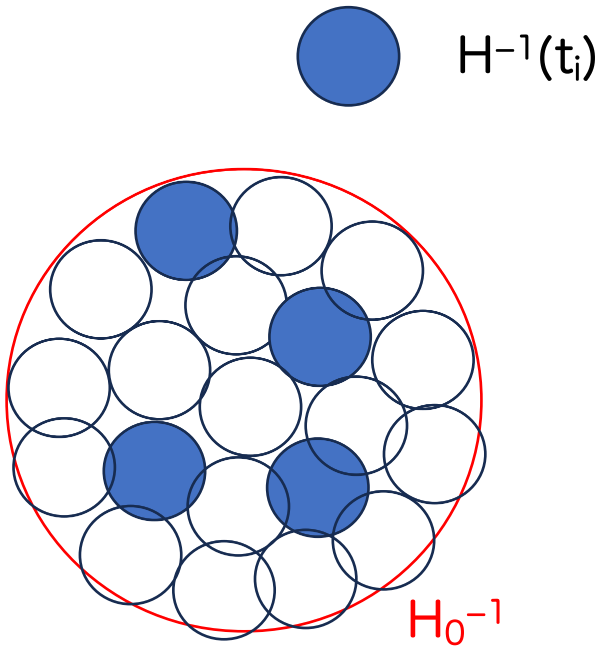
# How to calculate the fraction of PBH

1. Evaluate the possibility that the symmetry is not broken in a Hubble volume at $t_{PBH}$

2. Calculate how many Hubble patches at $t_{PBH}$ are included in the present Hubble volume




$$f_{\rm PBH}^{\rm EW} \equiv \frac{\Omega_{\rm PBH}^{\rm EW}}{\Omega_{\rm CDM}} \sim 1.49 \times 10^{11} \left(\frac{0.25}{\Omega_{\rm CDM}}\right)\left(\frac{T_{\rm PBH}}{100\,{\rm GeV}}\right) P(t_{\rm PBH})$$

$$P(t_n) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t_n} \frac{a^3(t)}{a^3(t_{\rm PBH})} H^{-3}(t_{\rm PBH})\Gamma(t)dt\right]$$

Prob. of Hubble patch of False

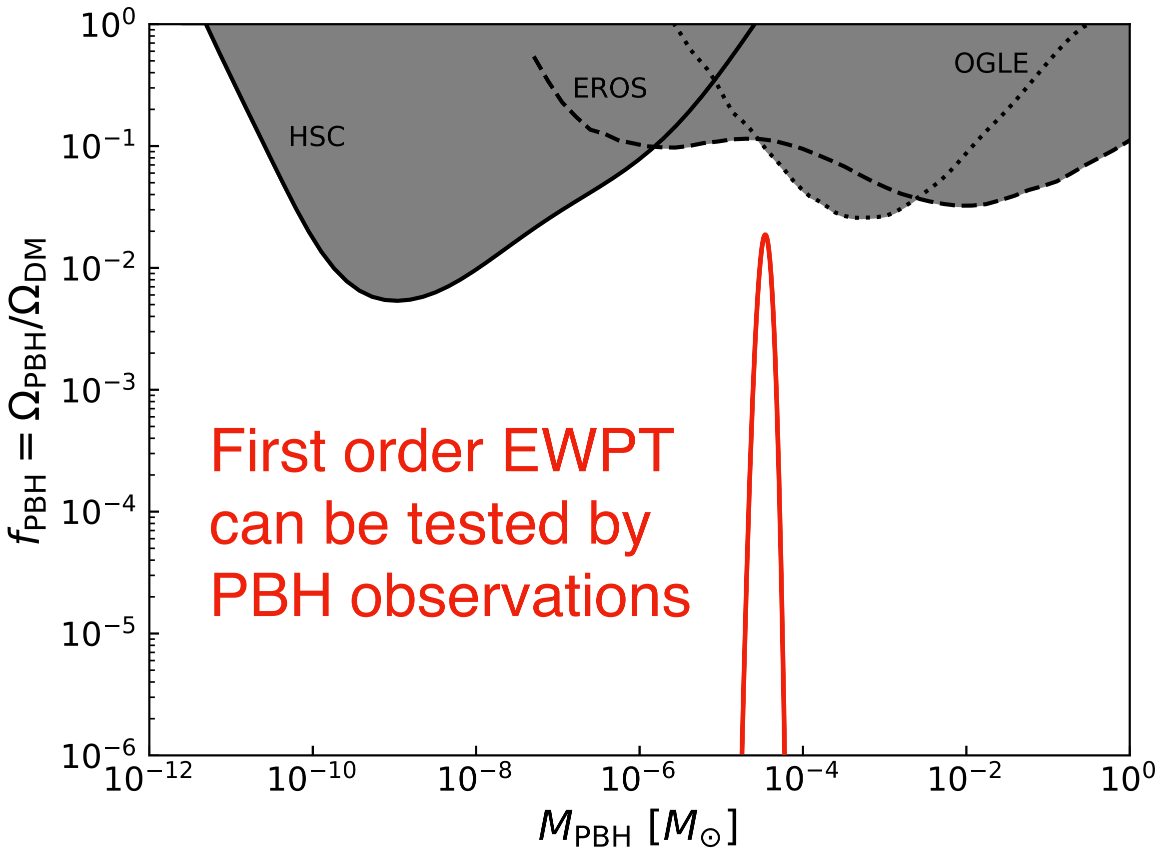
# PBH from 1st order EWPT

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

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

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

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




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 near infrared rays: sensitive to the microlensing from center galaxy

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

# Theory predictions on $\alpha$-$\beta$ 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 area