Probing first-order electroweak phase transition via PBHs in the effective field theory

Masanori Tanaka

Osaka University → Peking University (Sep.~)

Collaborators: Shinya Kanemura (Osaka U.)
Tomo Takahashi (Saga U.)
Katsuya Hashino (Fukushima College)

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Introduction

- Standard model (SM) is consistent with LHC results

Unsolved problems: Baryon asymmetry of the Universe, dark matter, etc…

- Exploring the dynamics of electroweak symmetry breaking is important

Cf） EW baryogenesis [Kuzmin, et al. : PLB155 (1985)]

- How we can test the first order EW phase transition (EWPT)?

Precise measurement of hhh coupling	Gravitational waves from EWPT	Primordial black holes from EWPT
[Grojean et al., PRD 71 (2005), Kanemura et al. PLB 606 (2005)]	[Grojean and Servant, PRD 75 (2007)]	[Hashino, Kanemura and Takahashi, PLB 833 (2021)] [Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]

Outline

- Introduction
- Baryogenesis and EW phase transition
- Nearly aligned Higgs Effective Field Theory
- EW phase transition and PBHs
- Summary

Baryon asymmetry of the Universe

- Cosmic microwave background

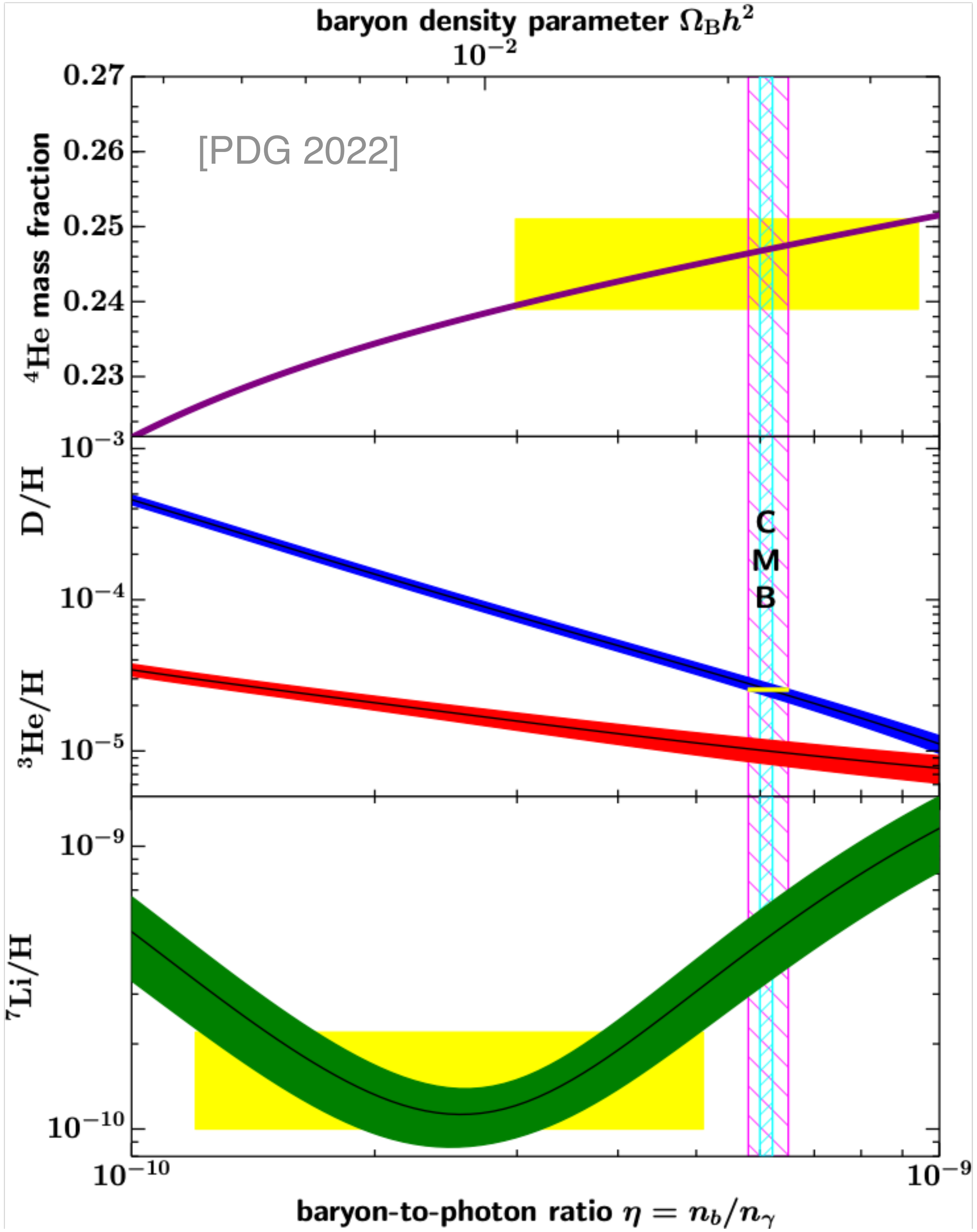
$$\eta_b = \frac{n_B}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

[Sakharov, Pisma Zh.Eksp.Teor.Fiz. 5 (1967)]

- Sakharov's condition

① Baryon number violation
② C and CP violation
③ Non thermal equilibrium

- Although the SM can satisfy the Sakharov's condition, η_b cannot be explained



Baryogeneis in the SM

- SM can satisfy the Sakharov's condition

  ① Baryon number violation: Sphaleron process

  ② CP violation: Cabbibo-Kobayashi-Maskawa (CKM) phase

  ③ Non thermal equilibrium: first order EW phase transition

- However…

  - EWPT in the SM is crossover (Not first order)
  - Too small CKM phase

$$\eta_B \propto J \frac{\Delta}{T_c^{12}} \sim 10^{-22} \ll 10^{-10}$$

$$\Delta \equiv (m_u^2 - m_c^2)(m_u^2 - m_t^2)(m_c^2 - m_t^2) \times (m_d^2 - m_s^2)(m_d^2 - m_b^2)(m_s^2 - m_b^2)\,.$$

Jarlskog invariant $J \simeq 3 \times 10^{-5}$ [Jarlskog, Phys. Rev. Lett 55 (1985)]

EW baryogenesis

- EW baryogenesis [Kuzmin, et al. : PLB155 (1985)]

  ① Sphaleron process
  ② CP violation in Higgs sectors
  ③ first order EW phase transition

Sakharov's condition

①Baryon number violation
②C and CP violation
③Non-thermal equilibrium

Vacuum bubbles nucleated by the EWPT

↓

Chiral asymmetry produced via interactions b/w plasma and vacuum bubble walls

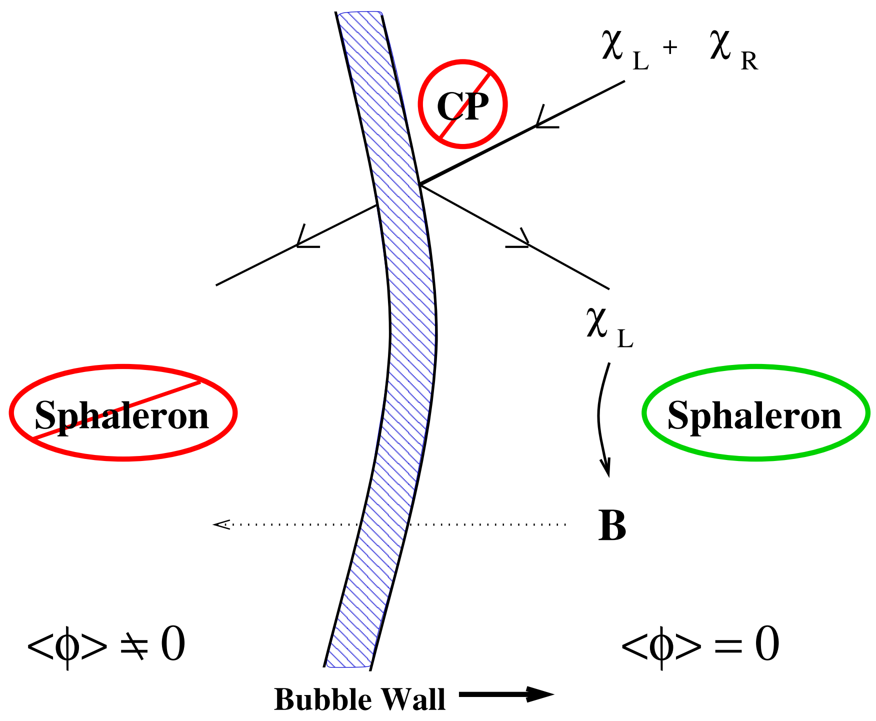
↓

Produced chiral asymmetry transferred into baryon asymmetry via sphaleron processes

↓

$$\eta_b = (6.12 \pm 0.04) \times 10^{-10}$$

[Morrissey and Ramsey-Musolf: NJP 14 (2012)]



Gravitational waves from FOPT

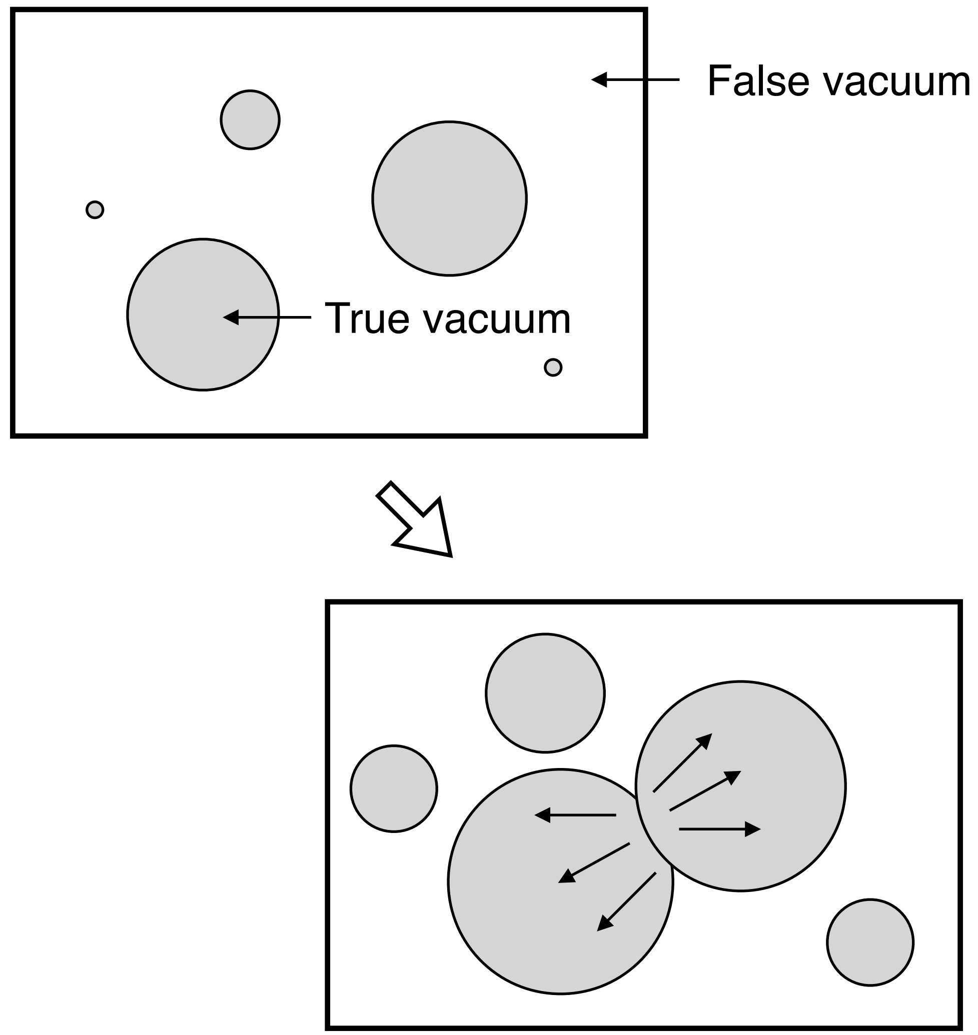
First order EWPT may be tested
by gravitational wave observations

- Sources of gravitational waves (GWs)

[Caprini et al., JCAP 04 (2016)]

①Collisions of vacuum bubbles
②Sound waves (compressive waves)
③Turbulence

[Grojean and Servant, PRD 75 (2007)]



- Parameters describing FOPT

T_n : Temperature starting FOPT

$\alpha_{\rm GW}$: Released latent heat

$\beta_{\rm GW}$: Duration of FOPT

v_b : vacuum bubble wall velocity

- Nucleation rate [Linde; Nucl. Phys. B216 (1983)]

$$\Gamma_{\rm bubble} \simeq A(T)\exp\left[-\frac{S_3(T)}{T}\right],$$

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

First order EWPT

- Effective potential at finite temperatures [Hall and Anderson: PRD 45 (1992)]

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

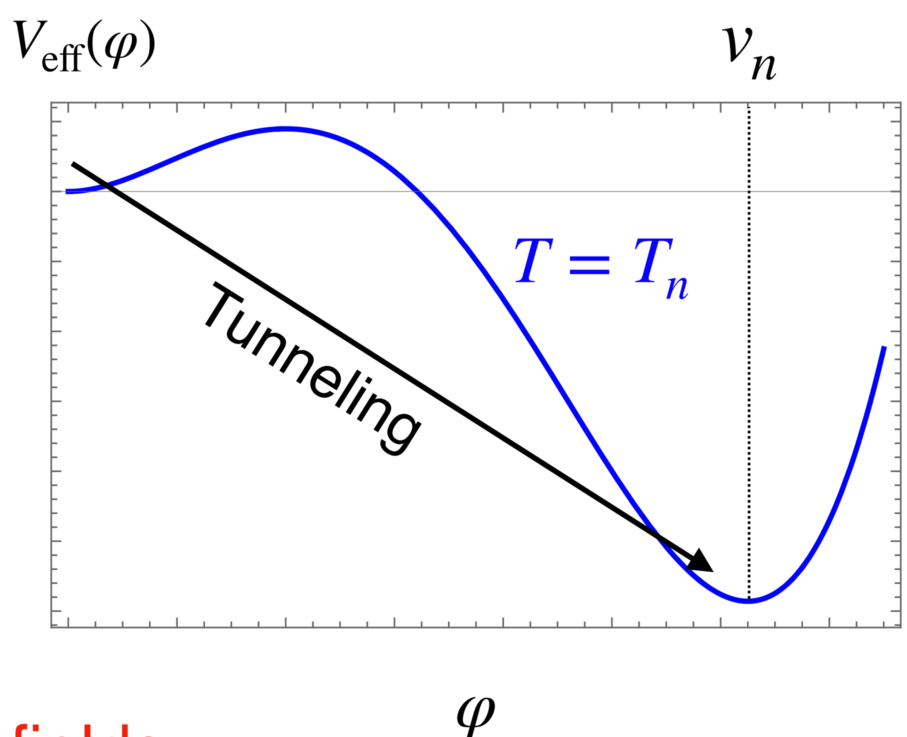
$$T_0^2 = \frac{1}{D}\left(\frac{1}{4}m_h^2 - 2Bv^2\right)$$

$$B = \frac{1}{64\pi^2 v^4}\left(m_h^2 + 6m_W^4 + 3m_Z^4 - 12m_t^4\right)$$

$$D = \frac{1}{24v^2}\left(m_h^2 + 6m_W^2 + 3m_Z^2 + 6m_t^2\right)$$

$$E = \frac{1}{12\pi v^3}\left(m_h^3 + 6m_W^3 + 3m_Z^3\right)$$ ← Only boson fields

$$\lambda_T = \frac{m_h^2}{2v^2}\left[1 - \frac{3}{8\pi^2 v^2 m_h^2}\left\{2m_W^4 \log\frac{m_W^2}{\alpha_B T^2} + m_Z^4 \log\frac{m_Z^2}{\alpha_B T^2} - 4m_t^4 \log\frac{m_t^2}{\alpha_F T^2}\right\}\right]$$



- Strength of first order EWPT : Important in EW baryogenesis

$$\frac{v_n}{T_n} \sim \frac{v_c}{T_c} \sim \frac{2E}{\lambda_{T_n}}$$

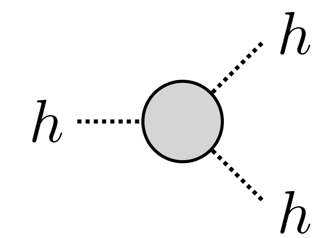
T_n: Nucleation temperature

$v(T_n)$: VEV at T=Tn

[Kuzmin, et al. : PLB155 (1985)]

Non-decoupling effect in hhh coupling

$$\left.\frac{\partial^3 V_{\rm eff}(\varphi)}{\partial \varphi^3}\right|_{\varphi=v} = \lambda_{hhh}^{\rm SM}\left(1+\frac{\Delta\lambda_{hhh}^{\rm new}}{\lambda_{hhh}^{\rm SM}}\right), \quad \Delta\lambda_{hhh}^{\rm new} = \lambda_{hhh}^{\rm new} - \lambda_{hhh}^{\rm SM}$$



Eg) Two Higgs doublet model: SM + Iso-doublet scalar field [Kanemura et al.: PRD 70 (2004)]

$$\frac{\Delta\lambda_{hhh}^{\rm 2HDM}}{\lambda_{hhh}^{\rm SM}} \simeq \sum_{\Phi=H,A,H^\pm}\frac{n_\Phi m_\Phi^4}{12\pi^2 m_h^2 v^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3 \simeq \begin{cases} \displaystyle\sum_\Phi \frac{n_\Phi \lambda_\Phi^3 v^4}{12\pi^2 m_h^2 m_\Phi^2} & (\lambda_\Phi v^2 \ll M^2) \quad \text{Decoupling} \\ \displaystyle\sum_\Phi \frac{n_\Phi m_\Phi^4}{12\pi^2 m_h^2 v^2} & (\lambda_\Phi v^2 \gtrsim M^2) \quad \text{Non-decoupling} \end{cases}$$

- Masses of additional scalars

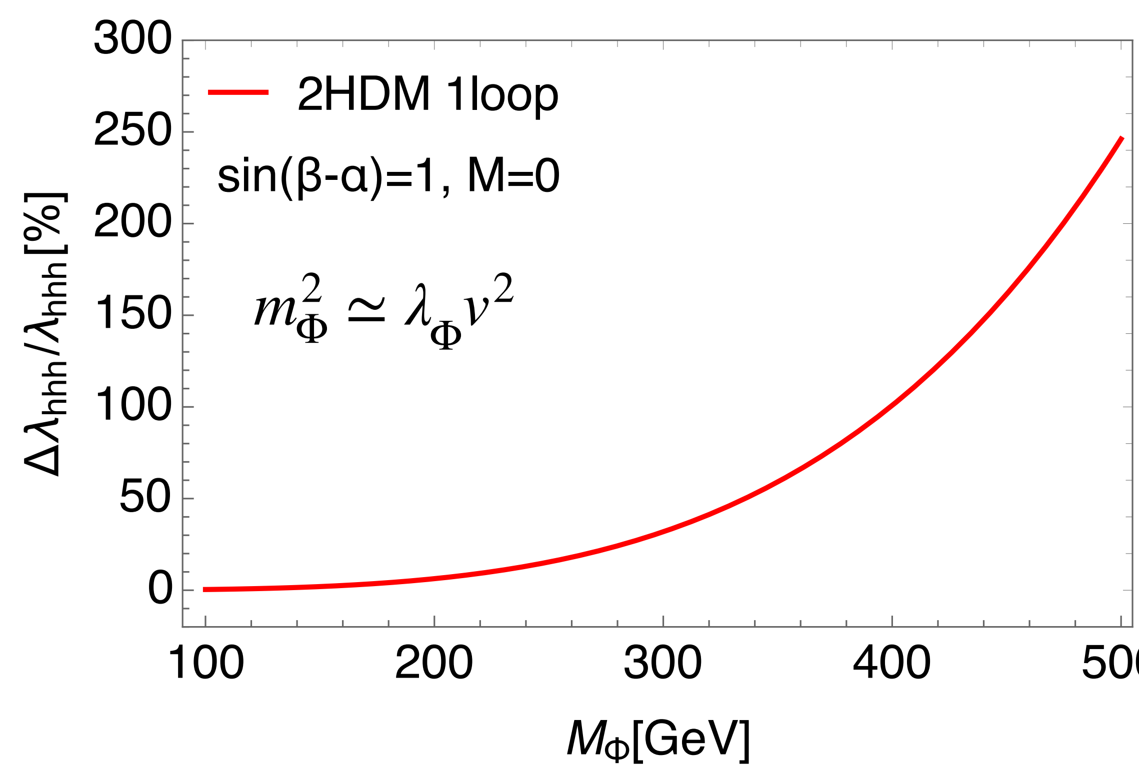
$$m_\Phi^2 \simeq M^2 + \lambda_\Phi v^2 \quad (\Phi = H, A, H^\pm)$$

λ_Φ: linear combinations of Higgs self-couplings

- hhh coupling is evaluated at the two loop level

[Braathen and Kanemura, PLB796 (2019)]

Non-decoupling effect is interesting!



Sphaleron decoupling condition

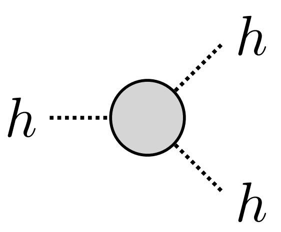
- Sphaleron decoupling condition: [Kuzmin, et al. : PLB155 (1985)]

$$\Gamma^{(b)}_{\rm sph}(T_n) = A(T_n) e^{-E_{\rm sph}(T_n)/T_n} < H_{\rm Hubble}(T_n) \quad \Rightarrow \quad \boxed{\frac{v_n}{T_n} > \zeta_{\rm sph}(T_n) \simeq 1}$$

- hhh coupling & sphaleron decoupling condition

Strongly first order EWPT

$$V_{\rm eff}(\varphi, T) \ni -ET\varphi^3 \quad \Leftrightarrow \quad \left.\frac{\partial^3 V_{\rm eff}(\varphi, T=0)}{\partial \varphi^3}\right|_{\varphi=v} =$$



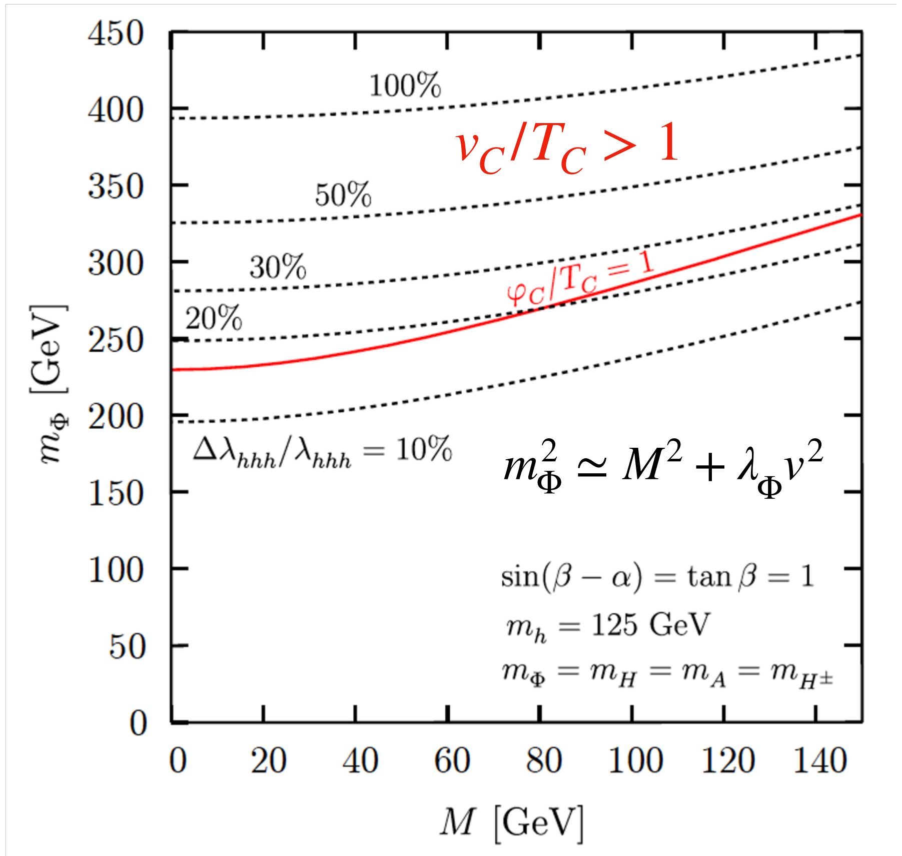
Eg) Two Higgs doublet model

[Kanemura, Okada and Senaha, PLB606 (2005)]

$$\frac{\Delta\lambda^{\rm 2HDM}_{hhh}}{\lambda^{\rm SM}_{hhh}} > 20 - 30\ \%$$

Large deviation in hhh coupling is required to realize first order EWPT

⇒ Non-decoupling effect is important



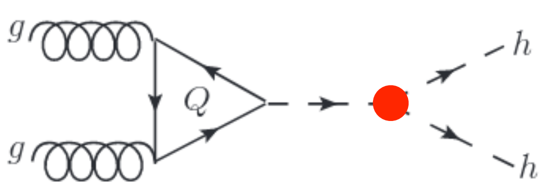
Status of hhh coupling measurements

- Current constrains from the LHC

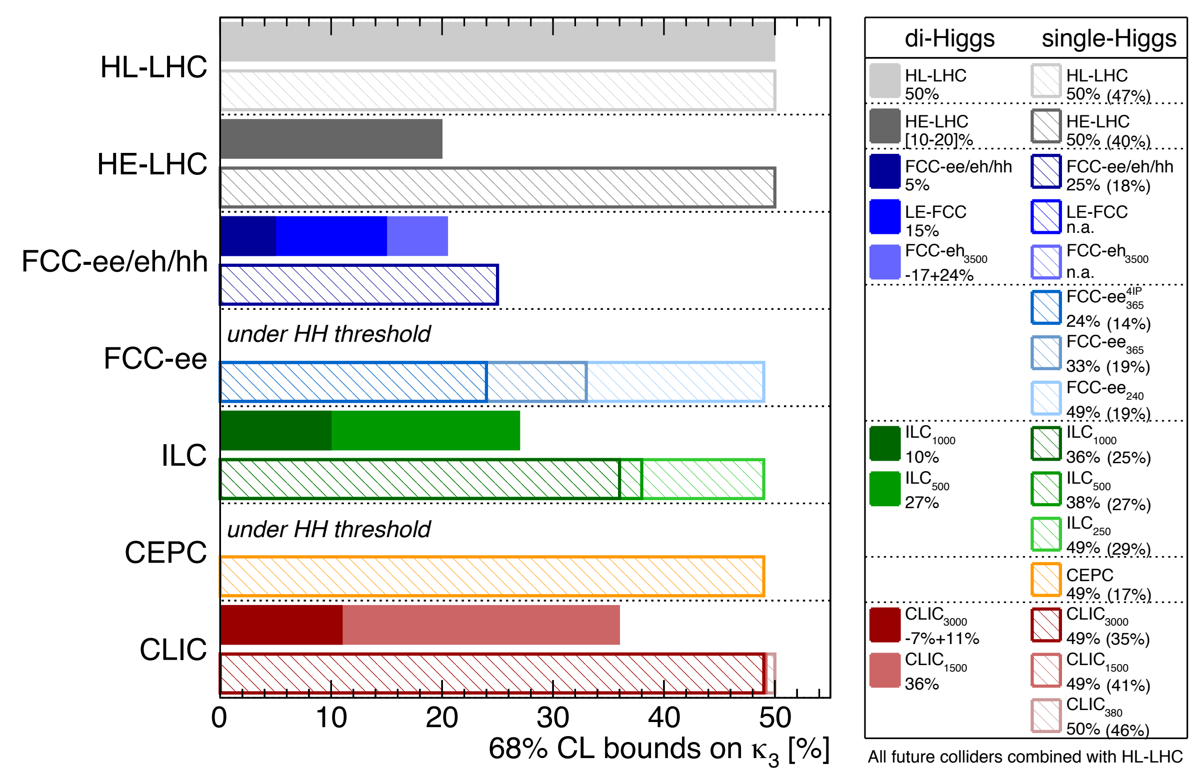
$$-1.4 < \frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}} < 5.3$$ [ATLAS, arXiv:2211.01216]

$$-2.24 < \frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}} < 5.49$$ [CMS, Nature 607 (2022)]

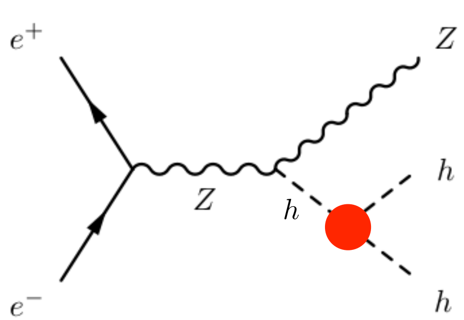
- Hadron colliders

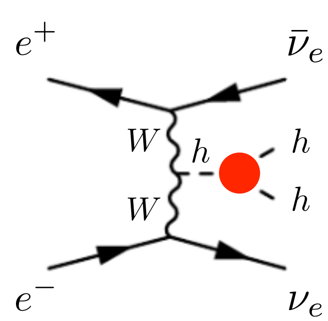


[de Blas et al., arXiv: 1905.03764]



- Lepton colliders





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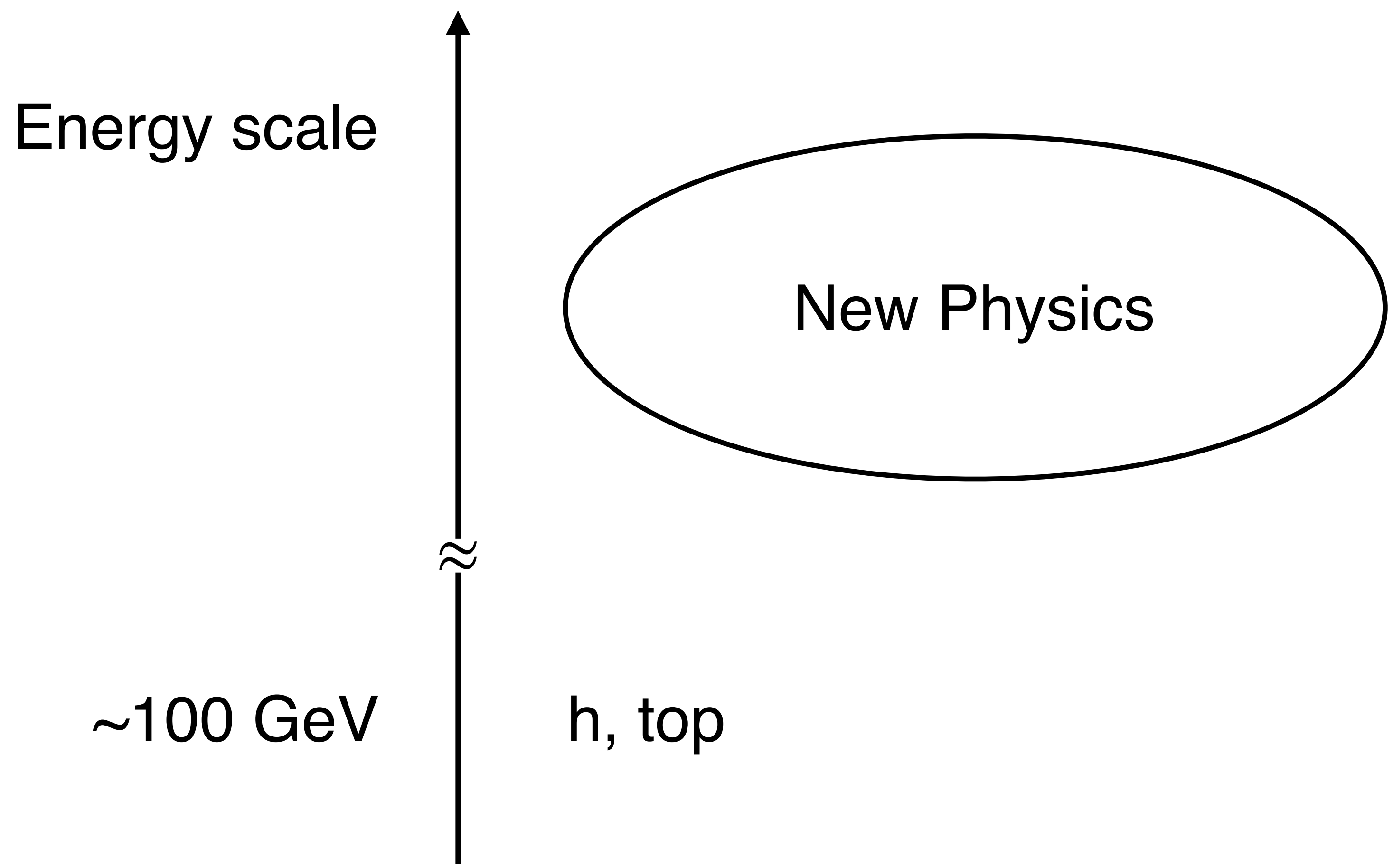
Effective field theory

Model independent properties of the EWPT

→ Effective field theory (EFT) is needed



Effects from heavy new particles are described by EFT frameworks

e.g., Standard Model Effective Field Theory (SMEFT), Higgs EFT

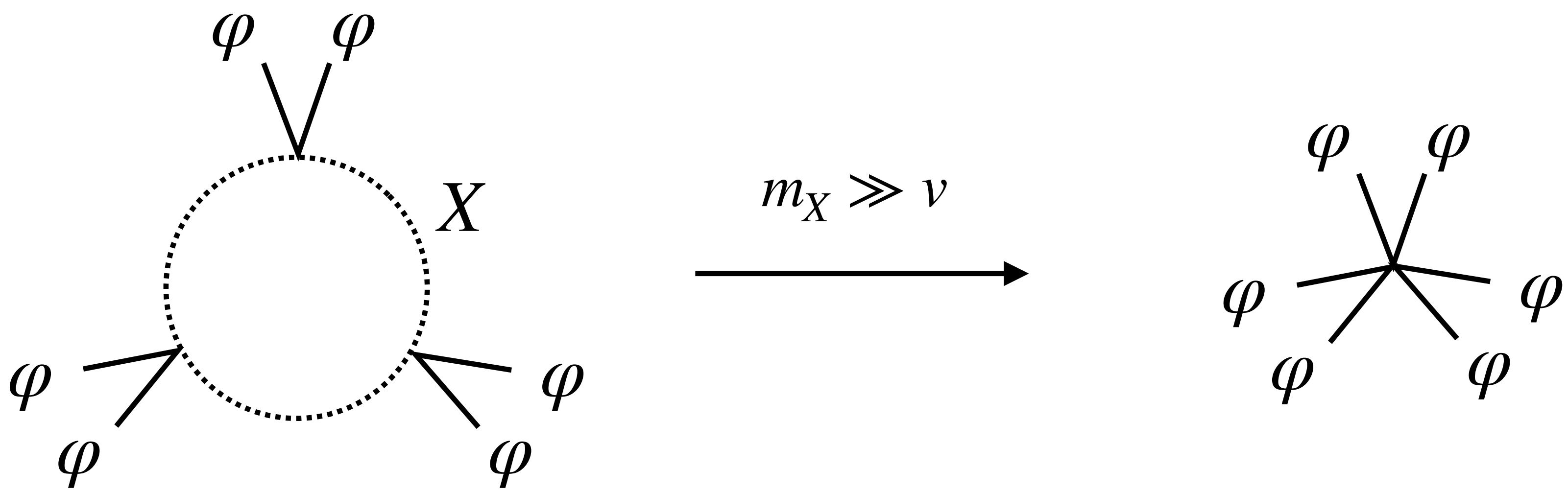
[Buchmuller and Wyler: Nucl. Phys. B268 (1986)] [Feruglio: Int. J. Mod. Phys. A 8 (1993)]
[Grzadkowski et al.: JHEP 10 (2010)]

Standard Model Effective Field Theory

Eg) Higgs potential in the SMEFT (up to dim.6)

[Buchmuller and Wyler: NPB 268 (1986)]
[Grzadkowski et al.: JHEP 10 (2010)]

$$V_{\rm SM} = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4$$



- Effective potential including effects from heavy new particles

$$V_{\rm SMEFT} = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \frac{c_6}{m_X^2}\varphi^6$$

SM + higher dim. operators→ Standard Model Effective Field Theory (SMEFT)

Useful in discussing model independent phenomenology

Nearly aligned Higgs EFT (naHEFT)

- Lagrangian [Kanemura and Nagai, JHEP 03 (2022)]

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

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

- 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)]

- Three free parameters

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

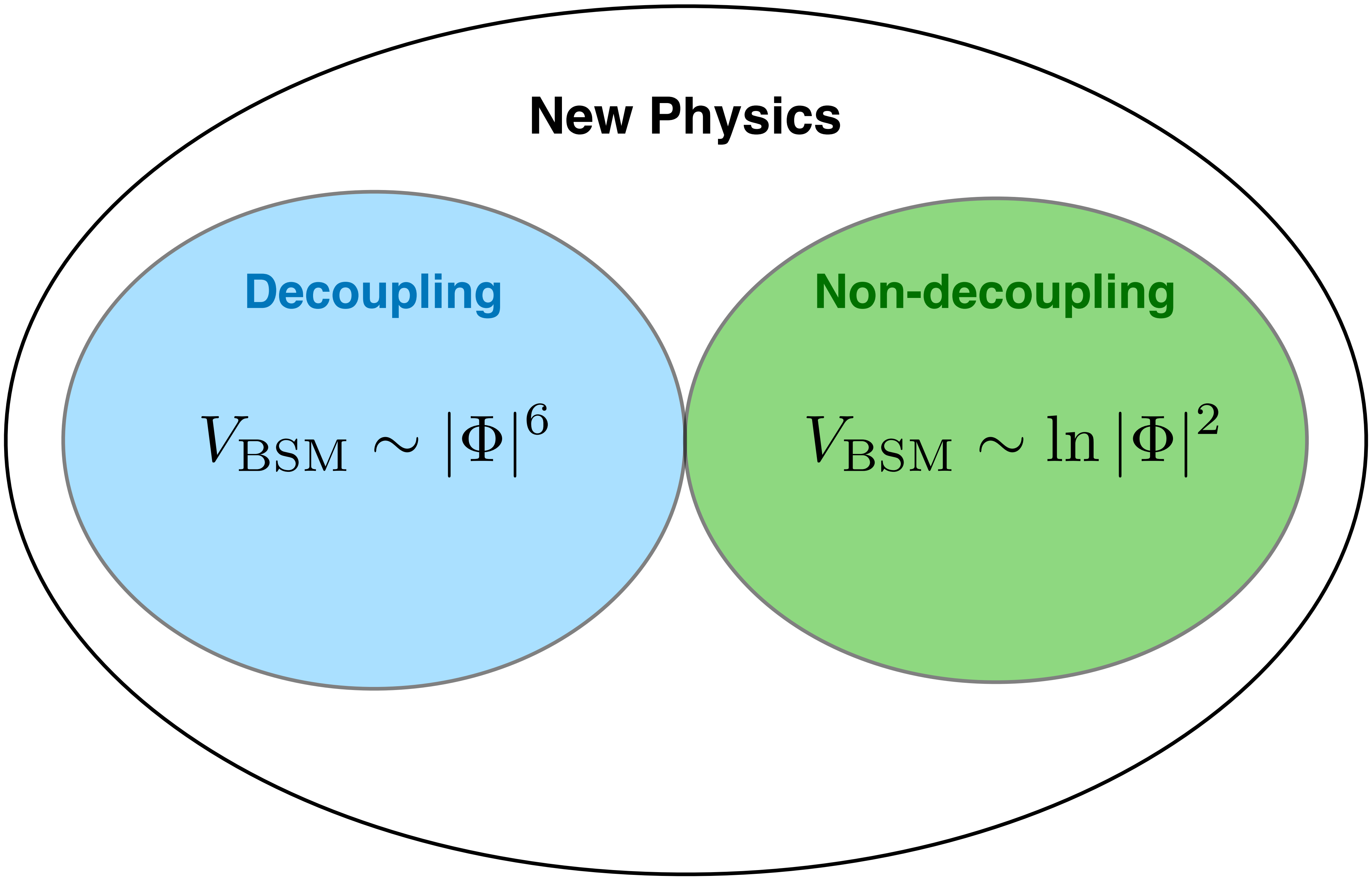
Mass of new particles d.o.f of new particles

r : non-decouplingness

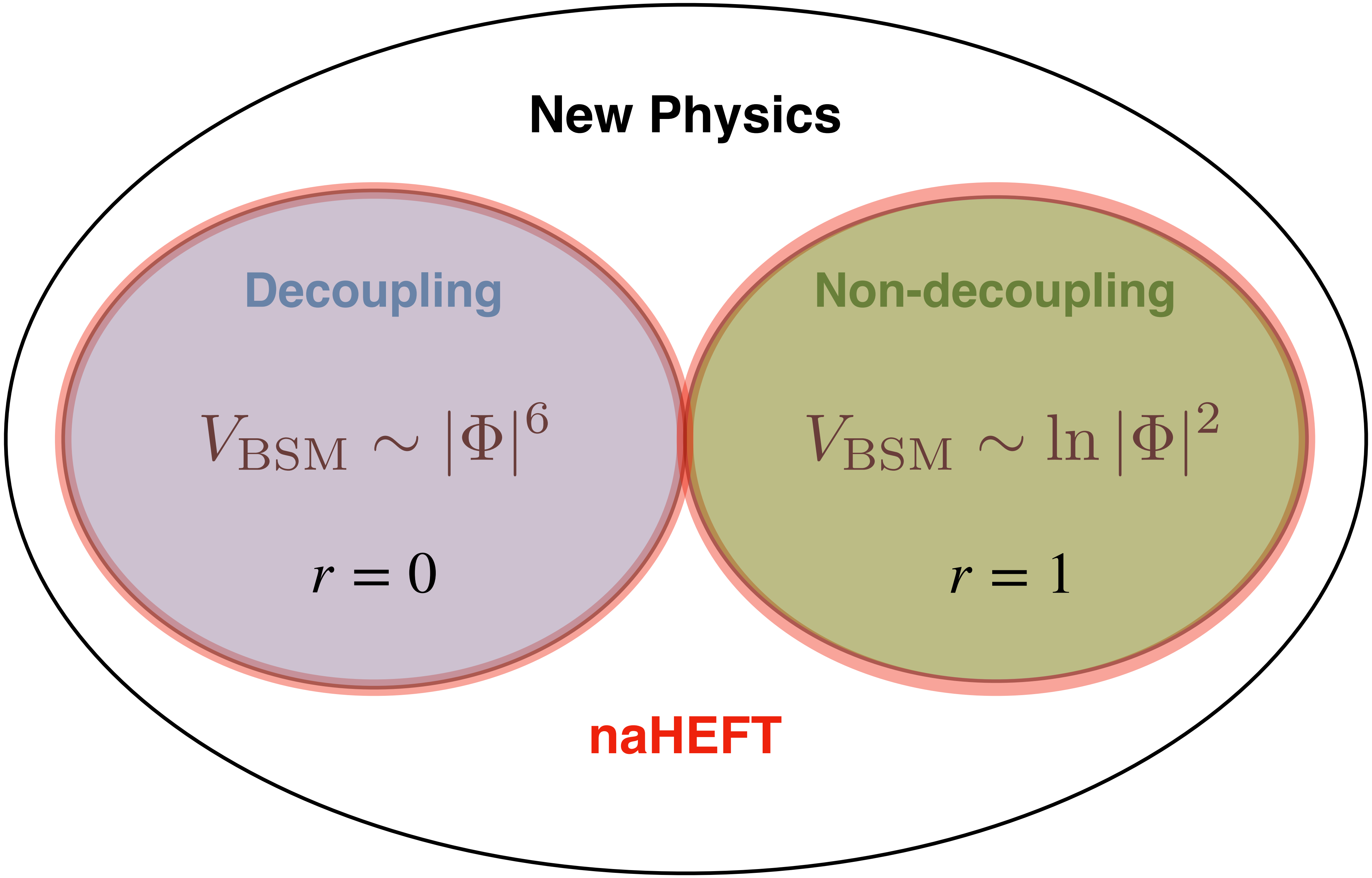
$r \sim 0 \Rightarrow M^2 \gg \frac{\kappa_p}{2}v^2$ Decoupling

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

Possibilities of new physics



Possibilities of new physics



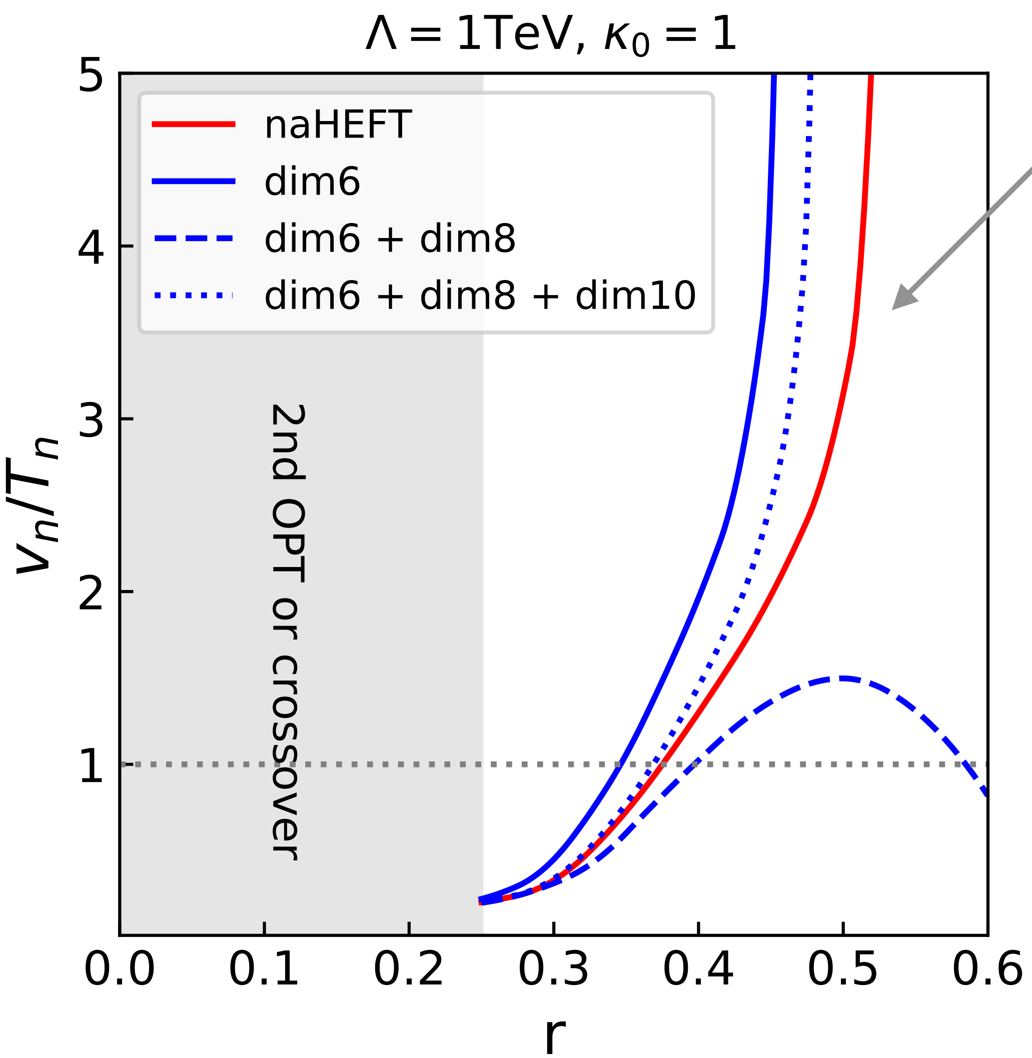
NaHEFT at finite temperatures

- The naHEFT at finite temperatures

[Kanemura, Nagai and Tanaka, JHEP 06 (2022)]

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

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



[Kanemura, Nagai and Tanaka, JHEP 06 (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

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

GWs from the first order EWPT

Predictions of GWs produced by the first order EWPT are also analyzed

- Nucleation rate [Linde; Nucl. Phys. B216 (1983)]

$$\Gamma_{\text{bubble}} \simeq A(T)\exp\left[-\frac{S_3(T)}{T}\right],$$

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

[Grojean and Servant, PRD 75 (2007)]

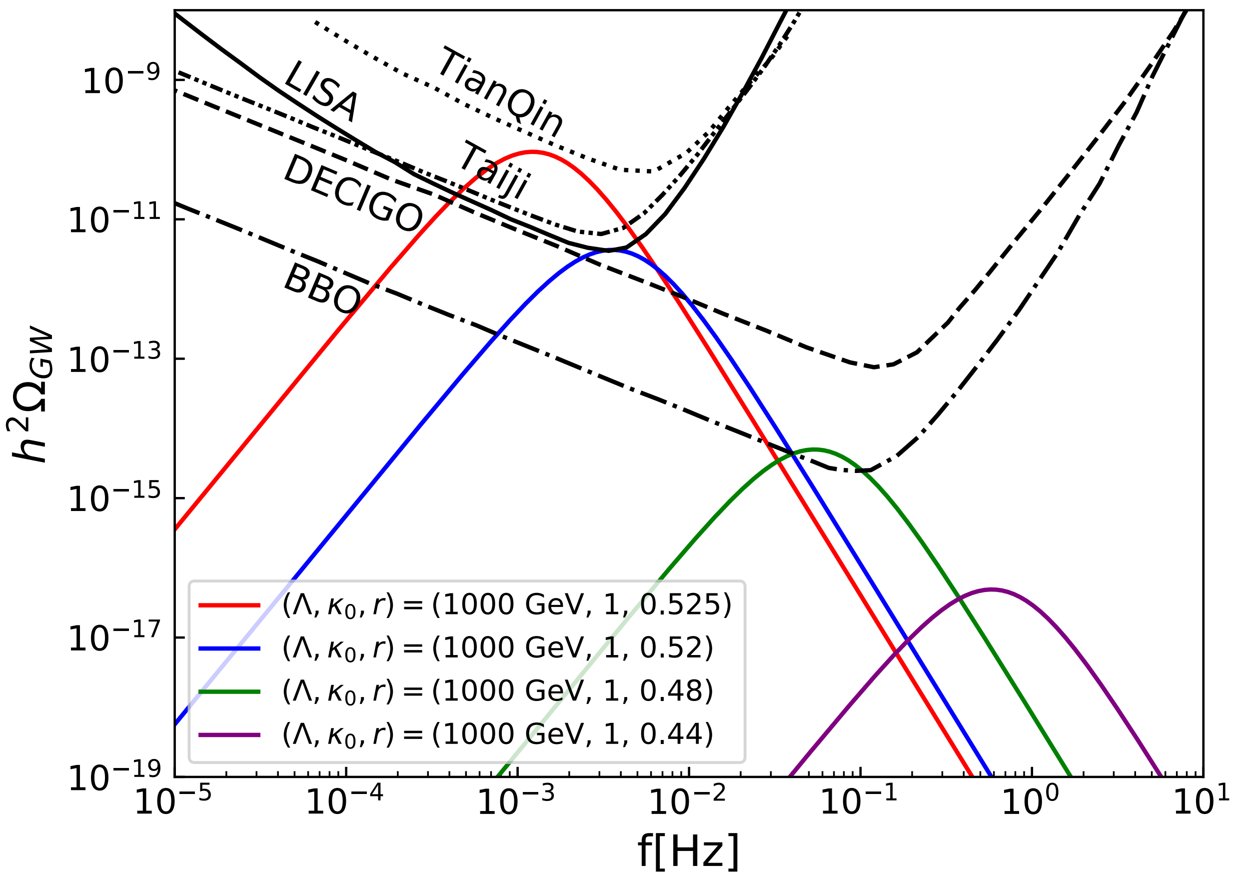
- Parameters describing FOPT

T_n : Temperature starting FOPT

α_{GW} : Released latent heat

β_{GW} : Duration of FOPT

[Kanemura, Nagai and Tanaka, JHEP 06 (2022)]



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Primordial black hole formation

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

- Condition for the PBH formation

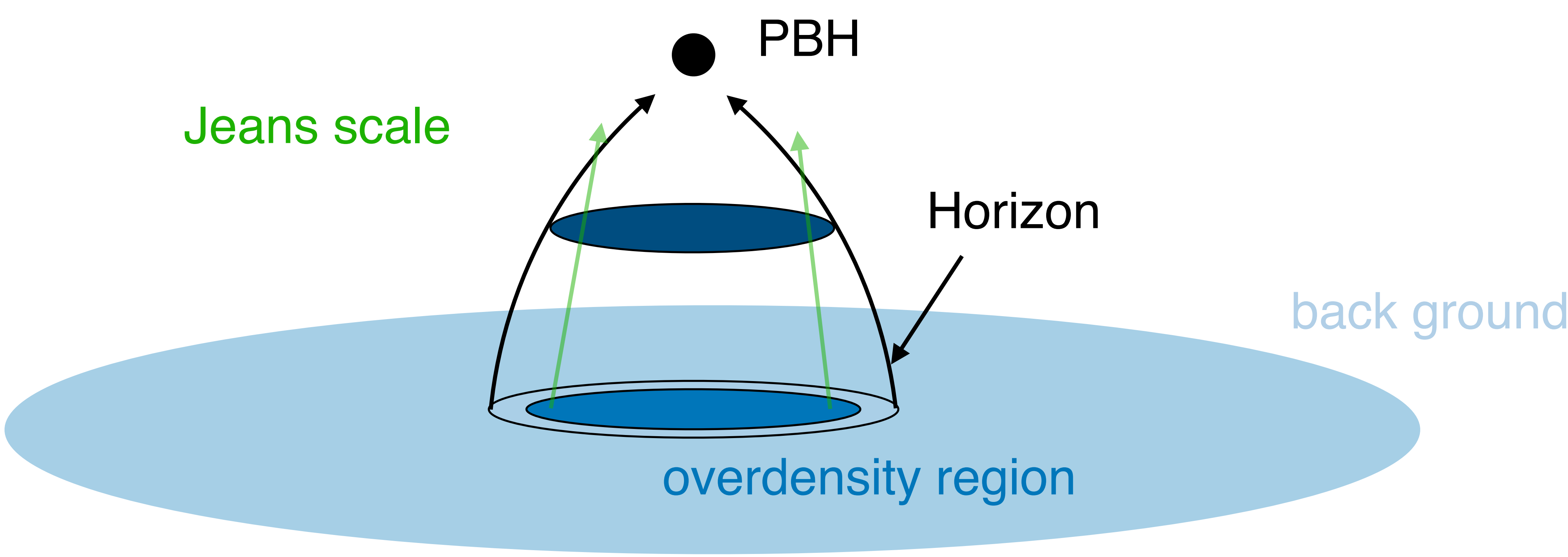
$$\delta = \frac{\rho_{\rm over} - \rho_{\rm back}}{\rho_{\rm back}} > \delta_C$$

[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)]



PBHs and first order phase transition

- Large density fluctuation can be realized b/w false and true vacua

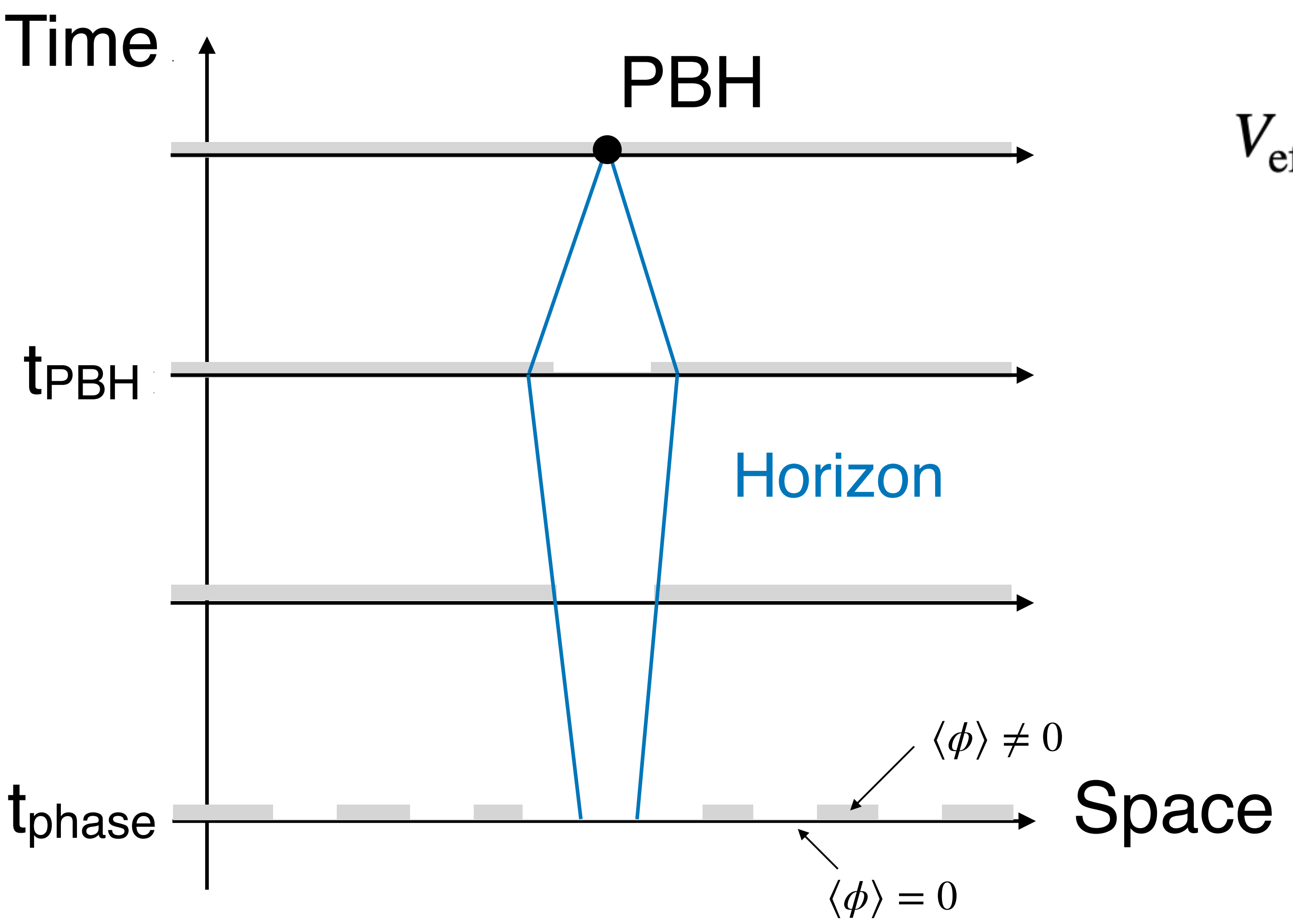
$$\delta = \frac{\rho_{\rm over} - \rho_{\rm back}}{\rho_{\rm back}} > \delta_C$$

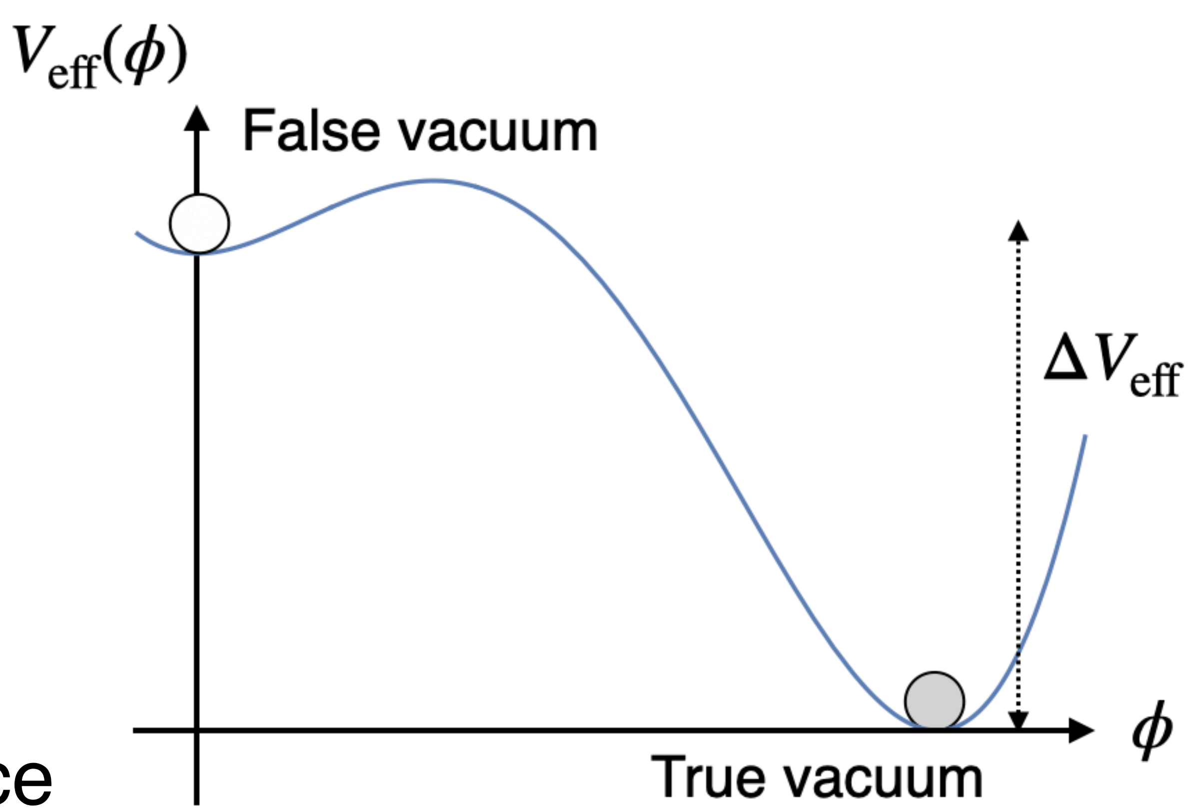
PBHs can be produced

[Liu et al., PRD 105 (2022)]

- We take $\delta_C = 0.45$ as often used

[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 produced by first order EWPT

- Properties of PBH produced by EWPT discussed in the SMEFT

[Hashino, Kanemura and Takahashi, PLB 833 (2021)]

We discussed the PBH formation in the naHEFT instead of the SMEFT

- PBH mass in the EWPT

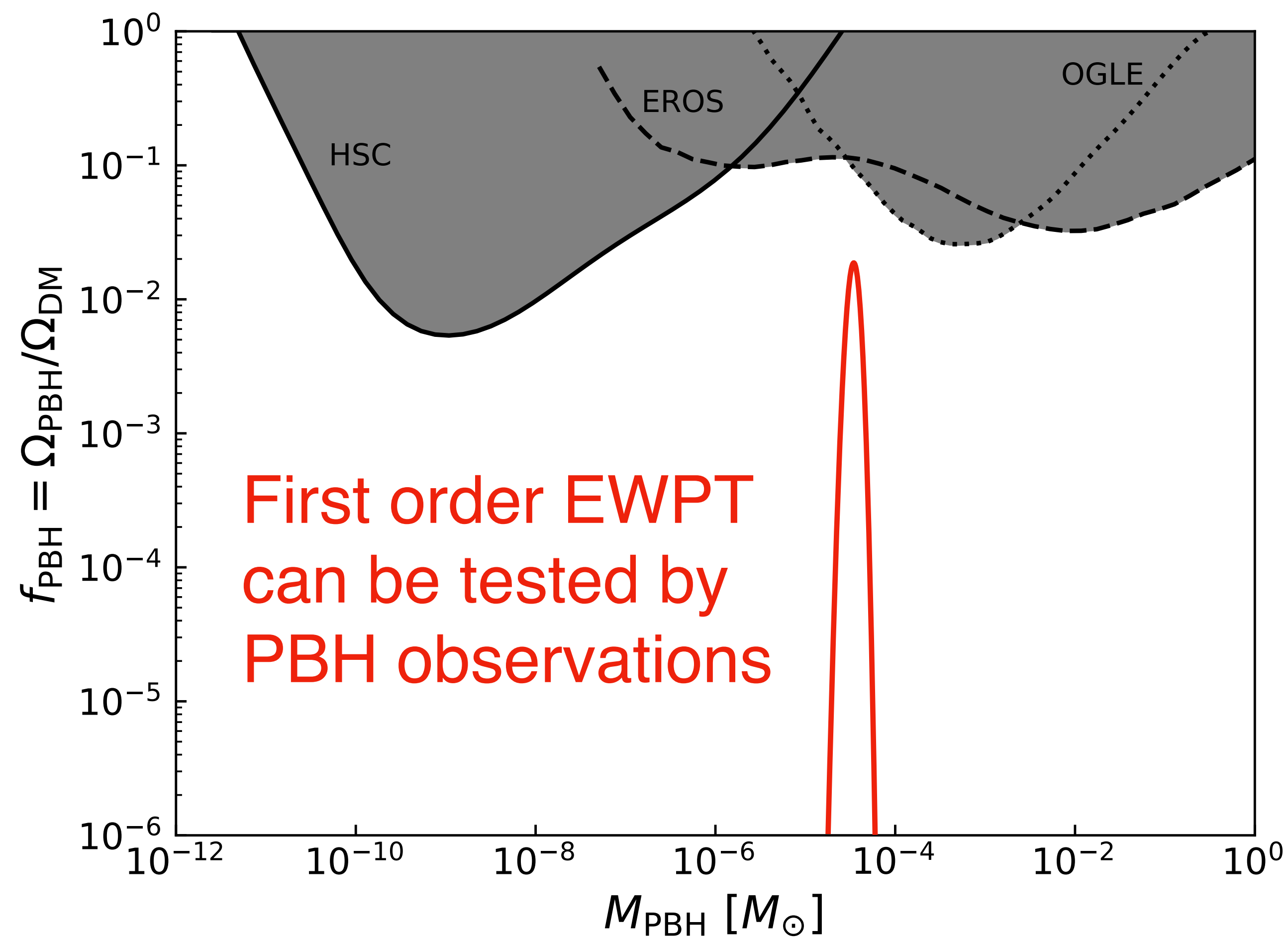
$$M_{\rm PBH} \sim 10^{-5} M_{\odot}$$

- Microlensing observations

  Subaru HSC, OGLE

  [HSC, https://hsc.mtk.nao.ac.jp/ssp/]

  [OGLE, http://ogle.astrouw.edu.pl]



- Future observations: PRIME, Roman

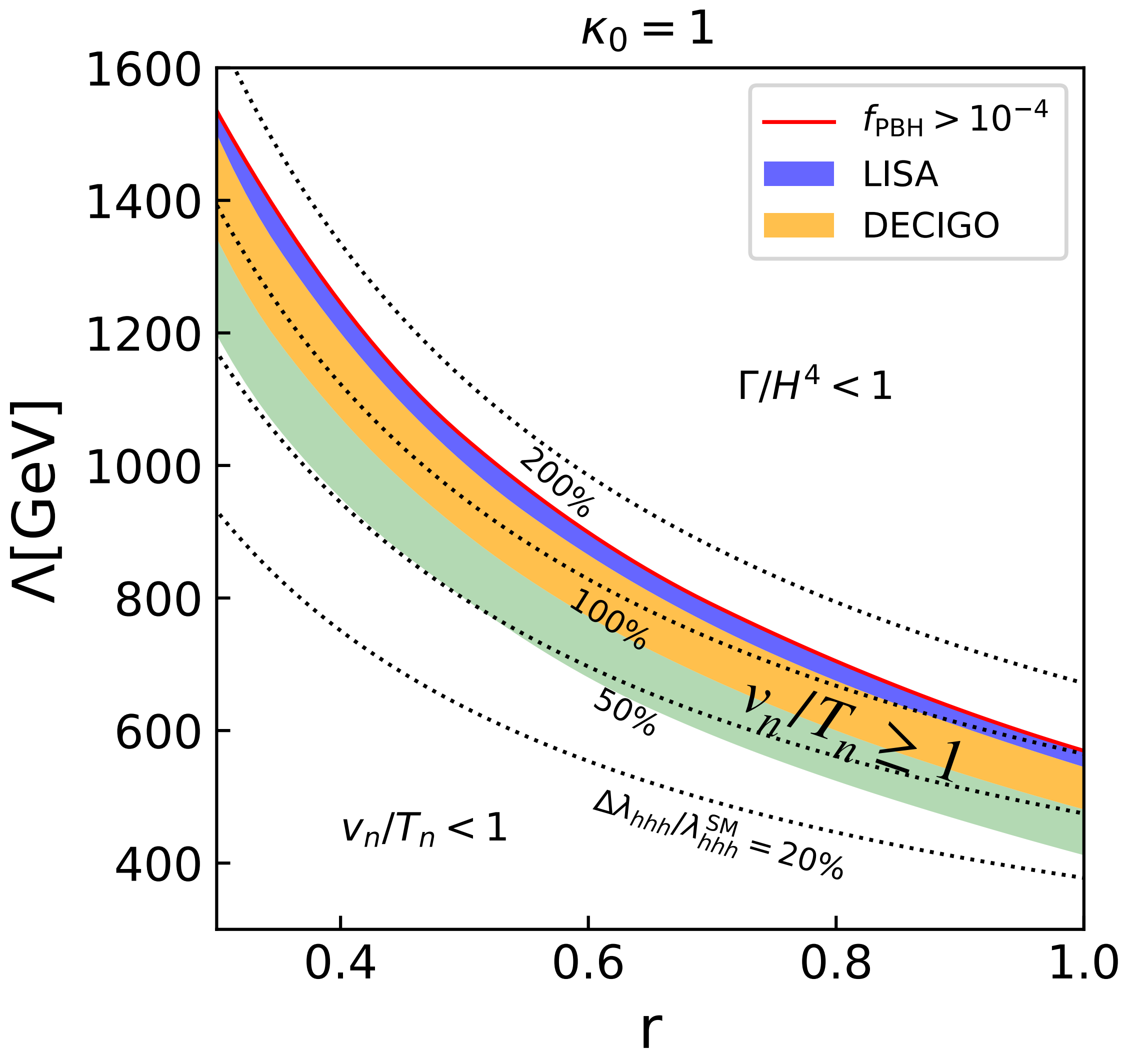
  $f_{\rm PBH}$ is constrained by 10^{-4}

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

Tests of the first order EWPT

How we can test the first order EWPT?

- hhh coupling measurement [Kanemura et al.: PRD 70 (2004)] [Kanemura et al., PLB606 (2005)] [Grojean et al., PRD71 (2005)]
- GW observations [Grojean and Servant, PRD 75 (2007)]
- PBH observations [Hashino, Kanemura and Takahashi, PLB 833 (2021)] [Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]



- Current and future observations

PBH: Subaru HSC, OGLE, PRIME, Roman

GWs: LISA, DECIGO Ongoing!

Colliders: ILC, HL-LHC

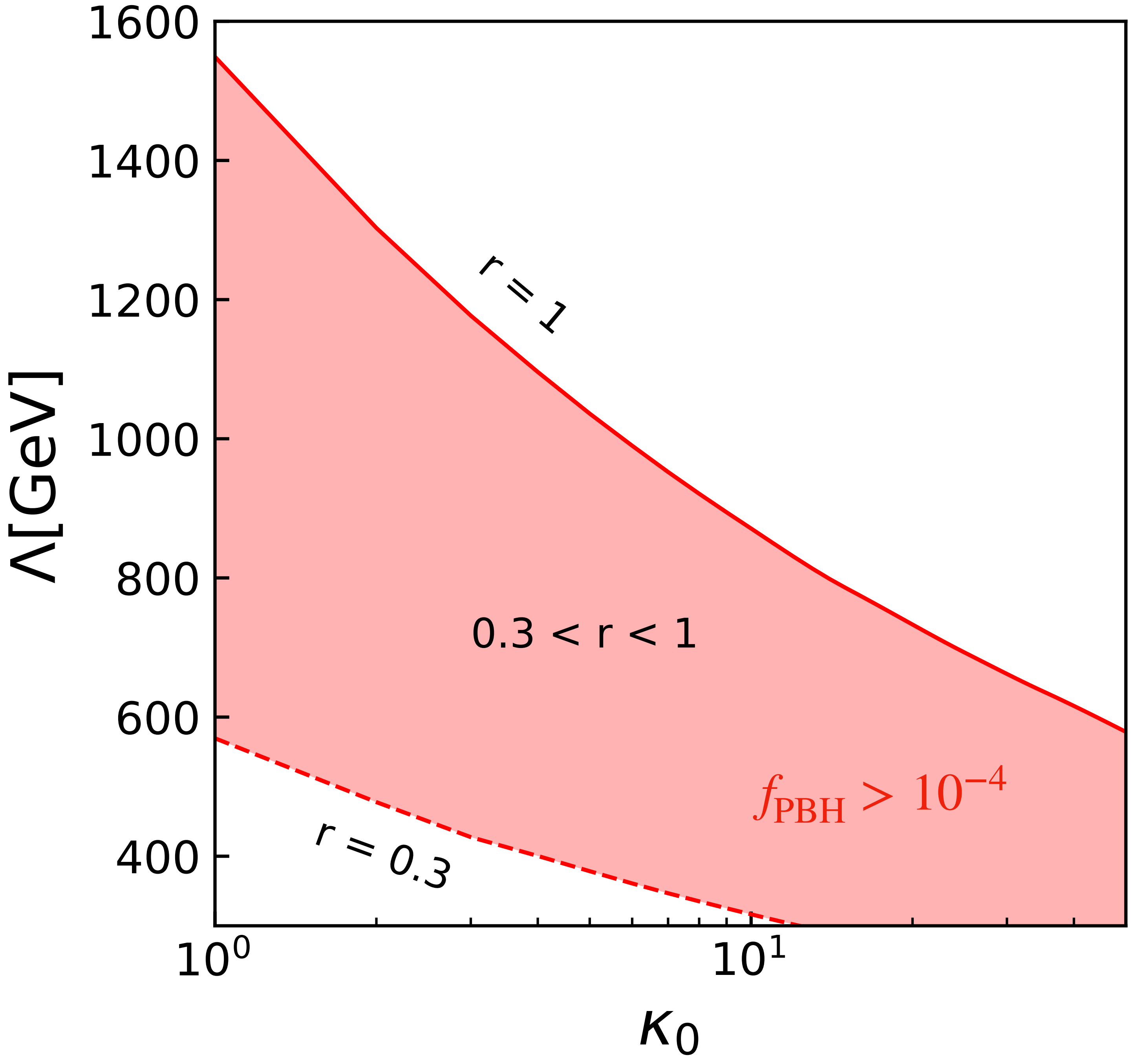
First order EWPT can be explored by PBH observations in addition to GW observations and collider experiments

[Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]

Parameter region explored by PBH obs.

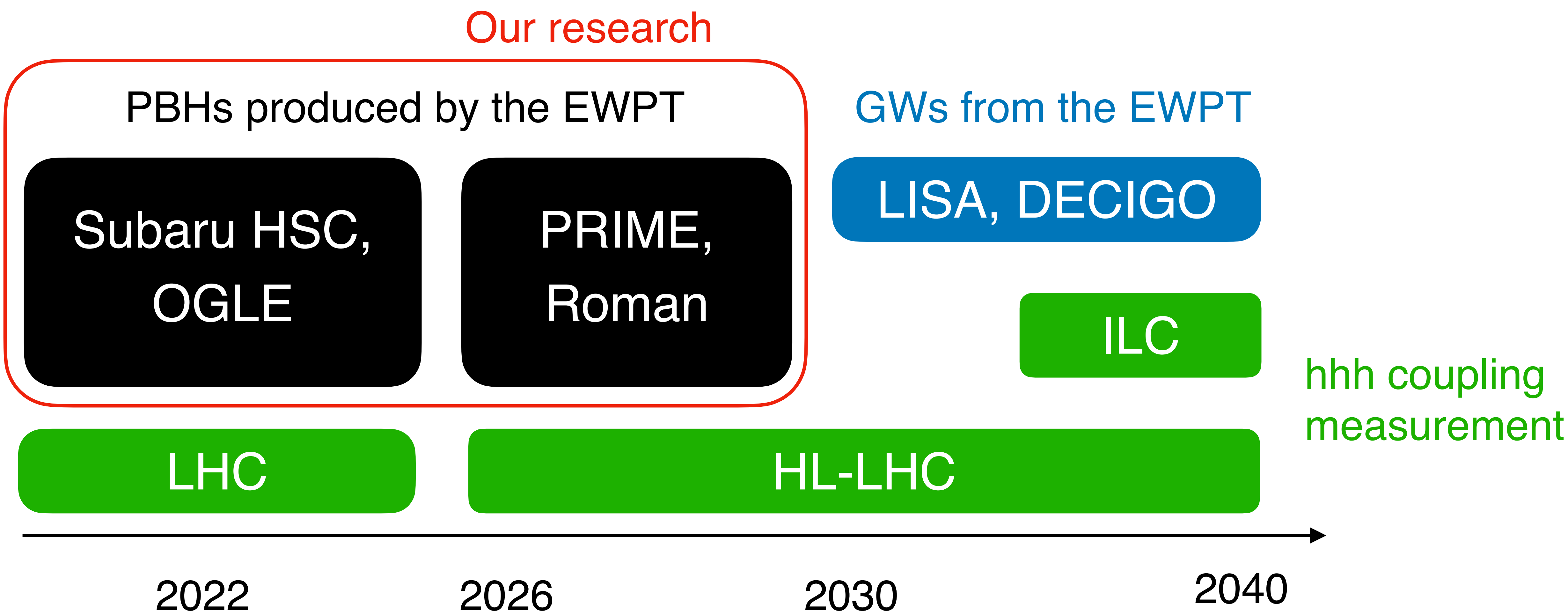
Wide parameter regions in new physics might be explored by PBH observations

[Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]



Timeline of experiments

Dynamics of the EWPT is thoroughly explored in the near future



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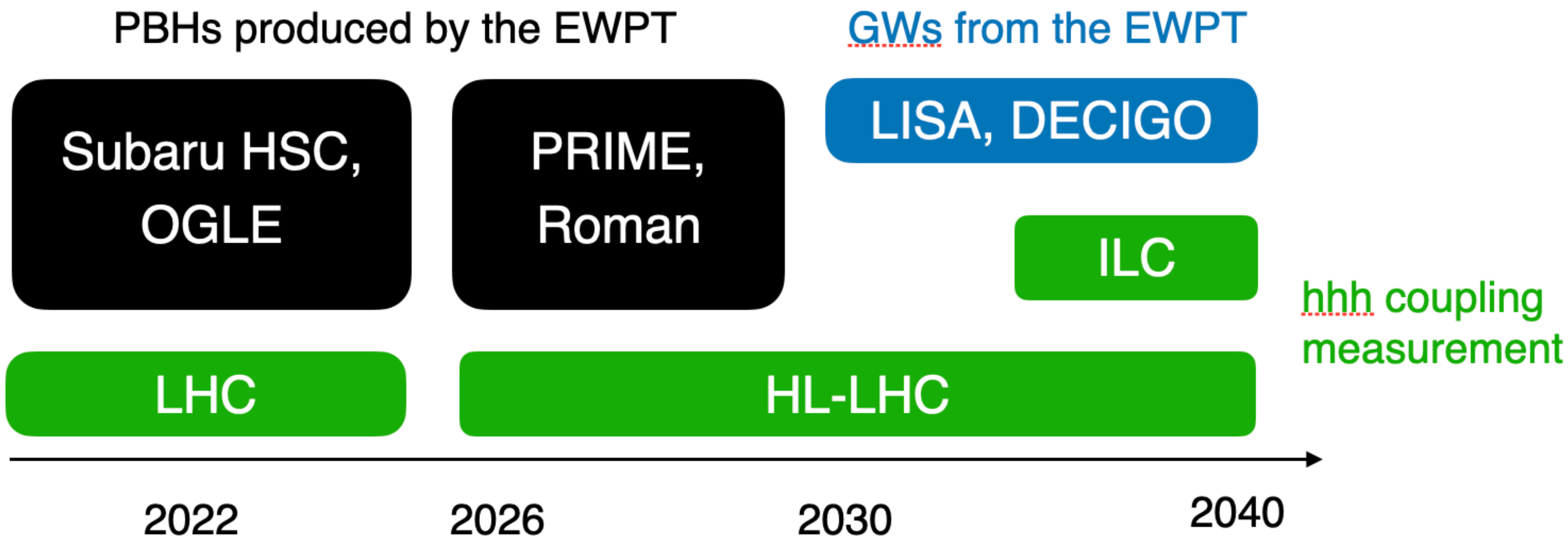
Summary

- We proposed the naHEFT which can appropriately describe the first order EWPT
- Strongly first order EWPT can be tested at current and future PBH observations like Subaru HSC, OGLE, PRIME and Roman telescope
- Wide parameter regions may be explored by PBH observations
- Colliders, GWs, PBHs → Dynamics of the EWPT is thoroughly explored



Backup

Nearly aligned Higgs EFT

naHEFTはノンデカップリング効果を記述できる　[Kanemura and Nagai, JHEP 03 (2022)]

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

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

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

: ヒッグス場の多項式

- 新粒子の場に依存する質量

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

簡単化のために次の形を仮定　$\mathcal{M}^2(h) = M^2 + \frac{\kappa_p}{2}(h+v)^2$

- 3つのパラメータ

r : non-decouplingness

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

新粒子の質量　新粒子の自由度

$r \sim 0 \Rightarrow M^2 \gg \frac{\kappa_p}{2}v^2$　デカップリング

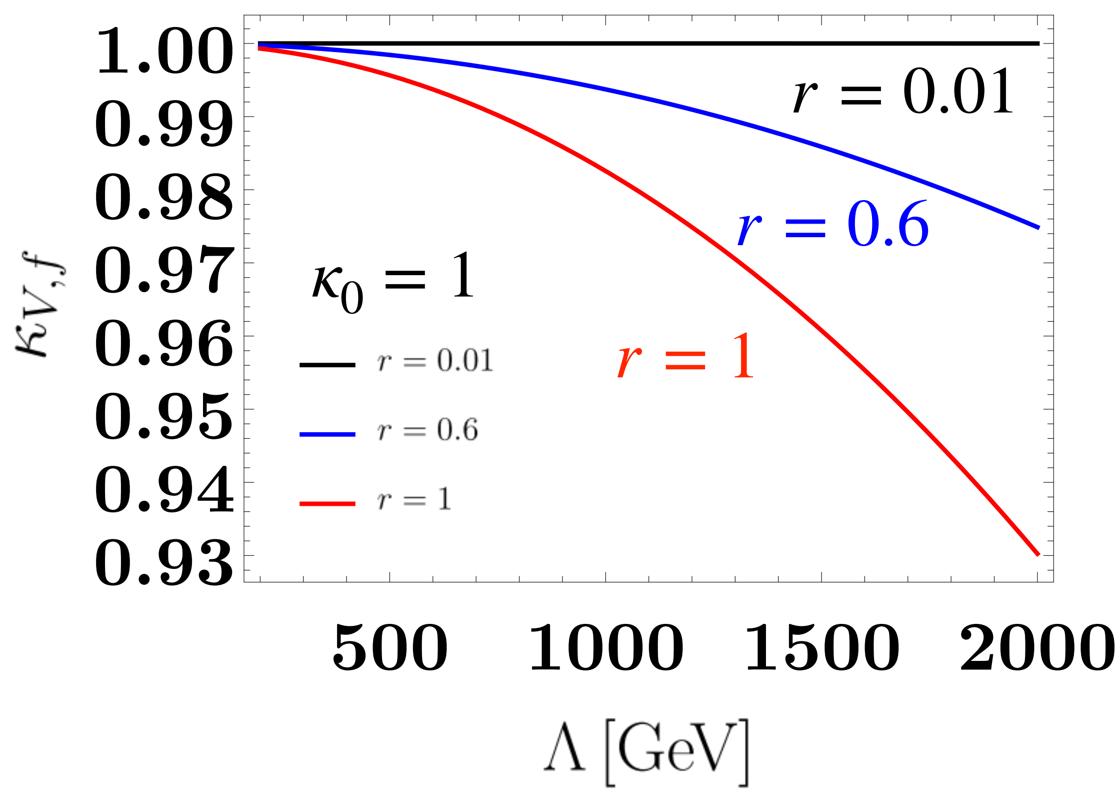
$r \sim 1 \Rightarrow M^2 \ll \frac{\kappa_p}{2}v^2$　ノンデカップリング

What is the meaning “nearly aligned”?

- The naHEFT in the canonical basis [Kanemura and Nagai, JHEP 03 (2022)]

$$\begin{aligned}\mathcal{L}_{\rm naHEFT} =& -\frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\ &+ \frac{v^2}{4}\left(1 + 2\kappa_V\frac{\hat{h}}{v} + \kappa_{VV}\frac{\hat{h}^2}{v^2} + \mathcal{O}\left(\hat{h}^3\right)\right) {\rm Tr}\left[D_\mu U^\dagger D^\mu U\right] \\ &+ \frac{1}{2}\left(\partial_\mu \hat{h}\right)\left(\partial^\mu \hat{h}\right) - \frac{1}{2}M_h^2\hat{h}^2 - \frac{1}{3!}\frac{3M_h^2}{v}\kappa_3\hat{h}^3 - \frac{1}{4!}\frac{3M_h^2}{v^2}\kappa_4\hat{h}^4 + \mathcal{O}\left(h^5\right) \\ &- \sum_{f=u,d,e} m_{f^i}\left[\left(\delta^{ij} + \kappa_f^{ij}\frac{h}{v} + \mathcal{O}\left(h^2,\pi^2\right)\right)\bar{f}^i_L f^j_R + h.c.\right],\end{aligned}$$

$$U = \exp\left(\frac{i}{v}\pi^a\tau^a\right)$$



The naHEFT can describe extended Higgs models without alignment ($\kappa_{V,f} \neq 1$)

$$\kappa_V = \frac{g_{hVV}^{\rm new}}{g_{hVV}^{\rm SM}}, \quad \kappa_f = \frac{g_{hff}^{\rm new}}{g_{hff}^{\rm SM}}$$

SMEFT and Higgs EFT

We only focus on the Higgs part

- SMEFT

$$\mathcal{L}_{\rm SMEFT} \ni A(|\Phi|^2)\,|\partial_\mu \Phi|^2 + B(|\Phi|^2)\left(\partial_\mu |\Phi|^2\right)^2 - V(\Phi) + O(\partial^4),$$

← $A(\Phi)$, $B(\Phi)$, $V(\Phi)$ are analytical at $|\Phi| = 0$

- Higgs EFT

V(h) is arbitrary

$$\mathcal{L}_{\rm HEFT} \ni \frac{1}{2}K(h)\partial_\mu h \partial^\mu h + \frac{v^2}{2}F(h){\rm Tr}\left[\partial_\mu U \partial^\mu U\right] + V(h),$$

← $K(h)$, $F(h)$, $V(h)$ can be non-analytical at $h \neq 0$

⇒ Higgs EFT is more general than SMEFT

In the naHEFT, it is assumed that V(h) has Coleman-Weinberg like structure

SMEFT and nearly aligned Higgs EFT

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

$$\mathcal{M}^2(\phi) = M^2 + \frac{\kappa_p}{2}\phi^2,$$

$$\mathcal{M}^2(v) \equiv \Lambda^2 \quad r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

$$\xi = \frac{1}{16\pi^2}$$

Expand the logarithmic part in terms of ϕ

- Up to dimension six

$$V_{\rm BSM}(\Phi) = \frac{1}{f^2}\left(|\Phi|^2 - \frac{v^2}{2}\right)^3, \quad \frac{1}{f^2} = \frac{2}{3}\,\xi\,\kappa_0 \frac{\Lambda^4}{v^6}\frac{r^3}{1-r}$$

- Up to dimension eight

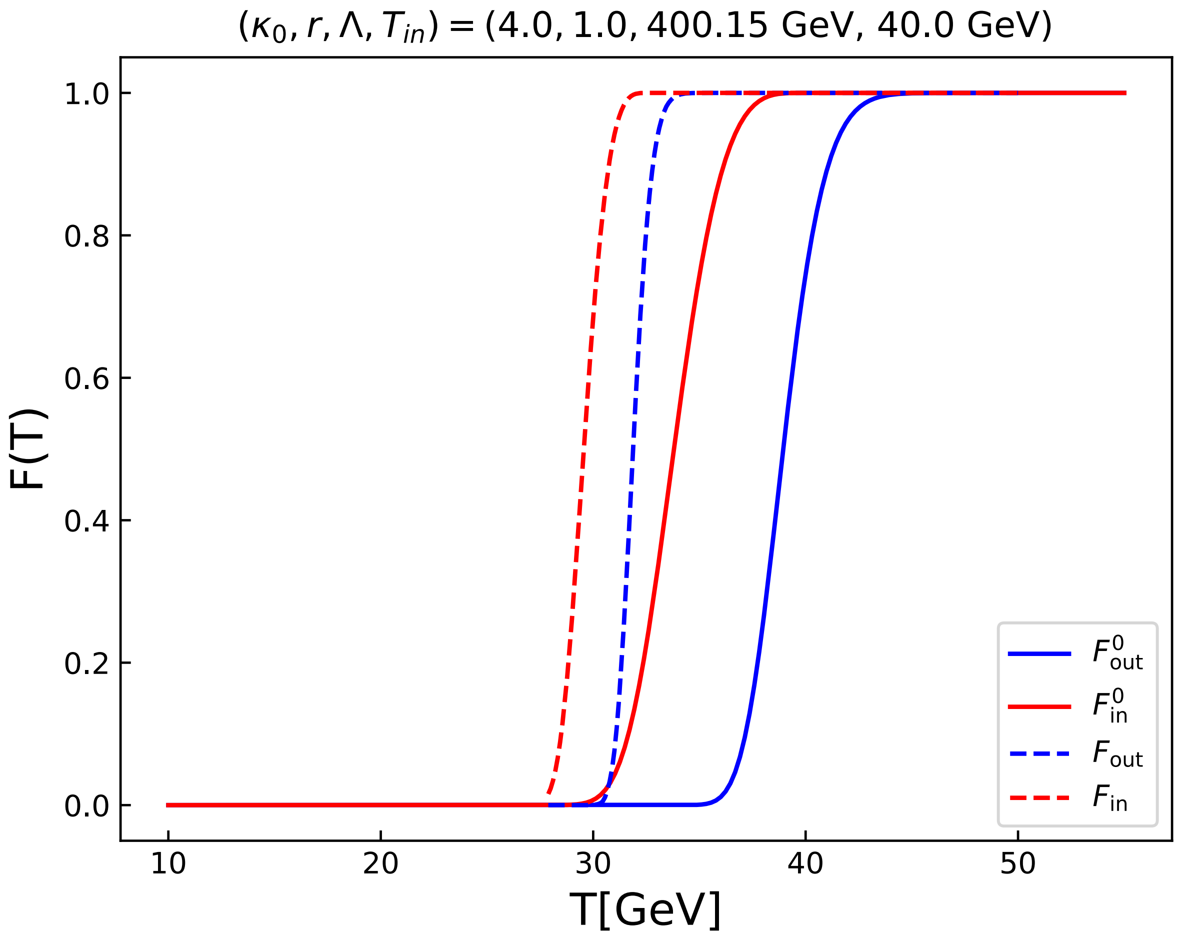
$$|\Phi|^2 = \phi^2/2$$

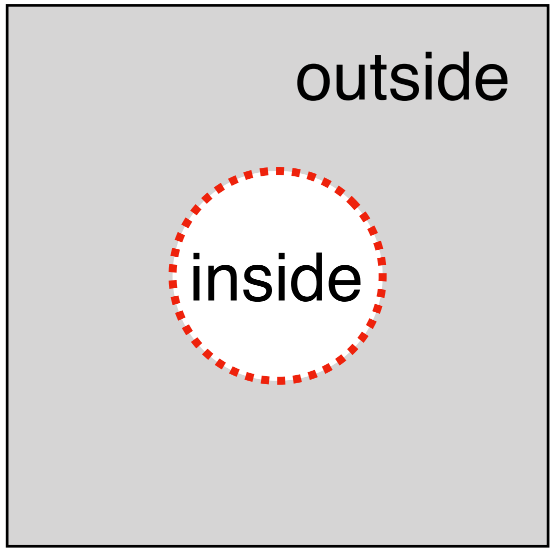
$$V_{\rm BSM}(\Phi) = \frac{1}{f_6^2}\left(|\Phi|^2 - \frac{v^2}{2}\right)^3 - \frac{1}{f_8^4}\left(|\Phi|^2 - \frac{v^2}{2}\right)^4$$

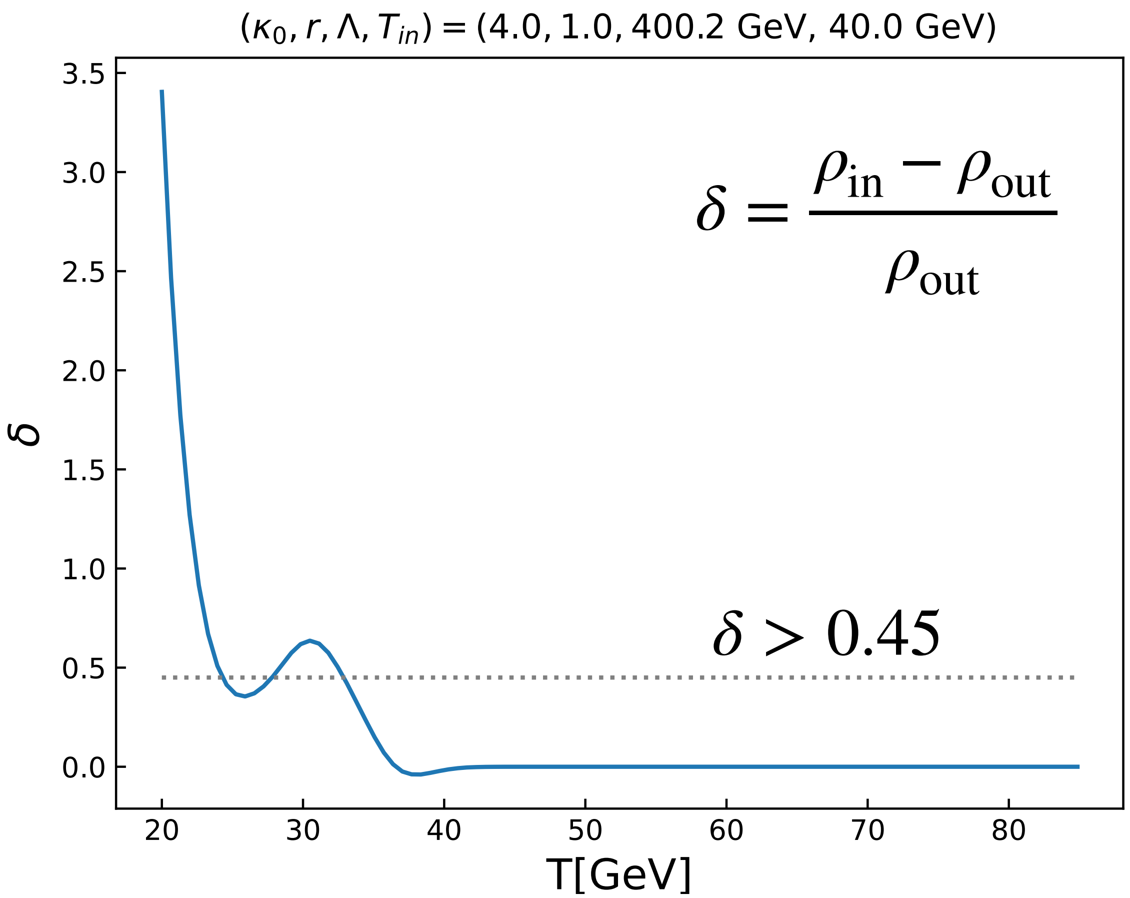
$$\frac{1}{f_6^2} = \frac{1}{f^2}\frac{1-2r}{1-r}, \quad \frac{1}{f_8^4} = \frac{1}{2f^2v^2}\frac{r}{1-r}$$

$r \to 1/2 \;\Rightarrow\; 1/f_8 \gg 1/f_6$ The expansion is not good at large r

Fraction of the false vacuum







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

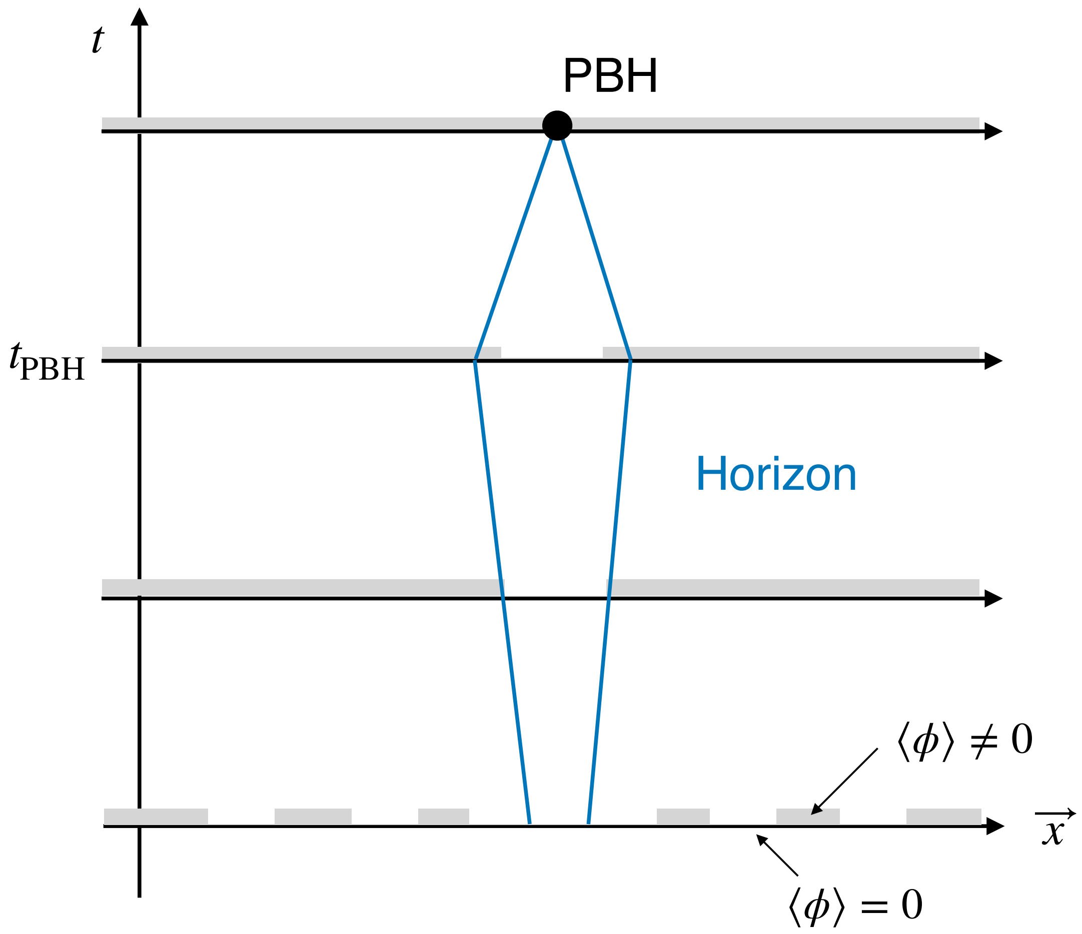
$$r(t, t') \equiv \int_{t'}^{t} \frac{v_w}{a(\tilde{t})} d\tilde{t}$$

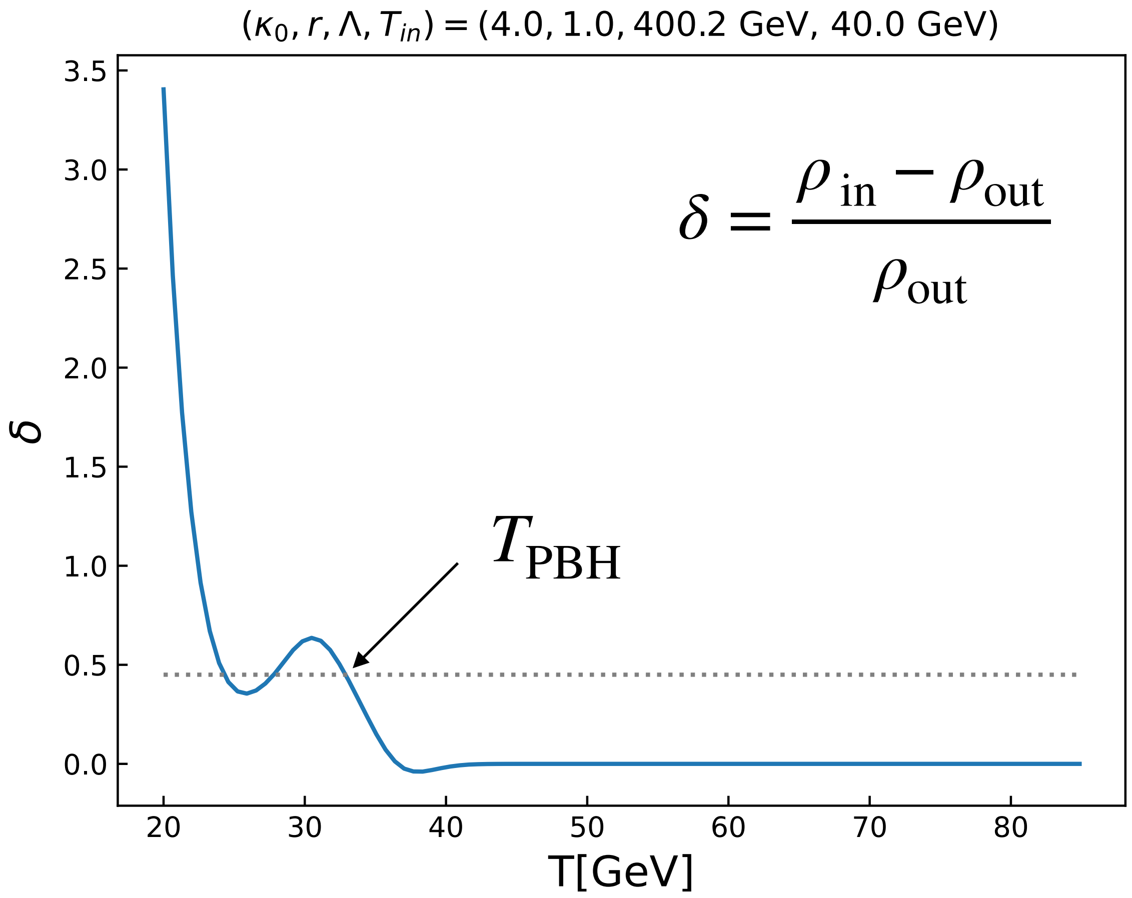
How to obtain PBH fraction?

1. Evaluate the possibility that the symmetry breaking is not broken in a Hubble volume

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

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

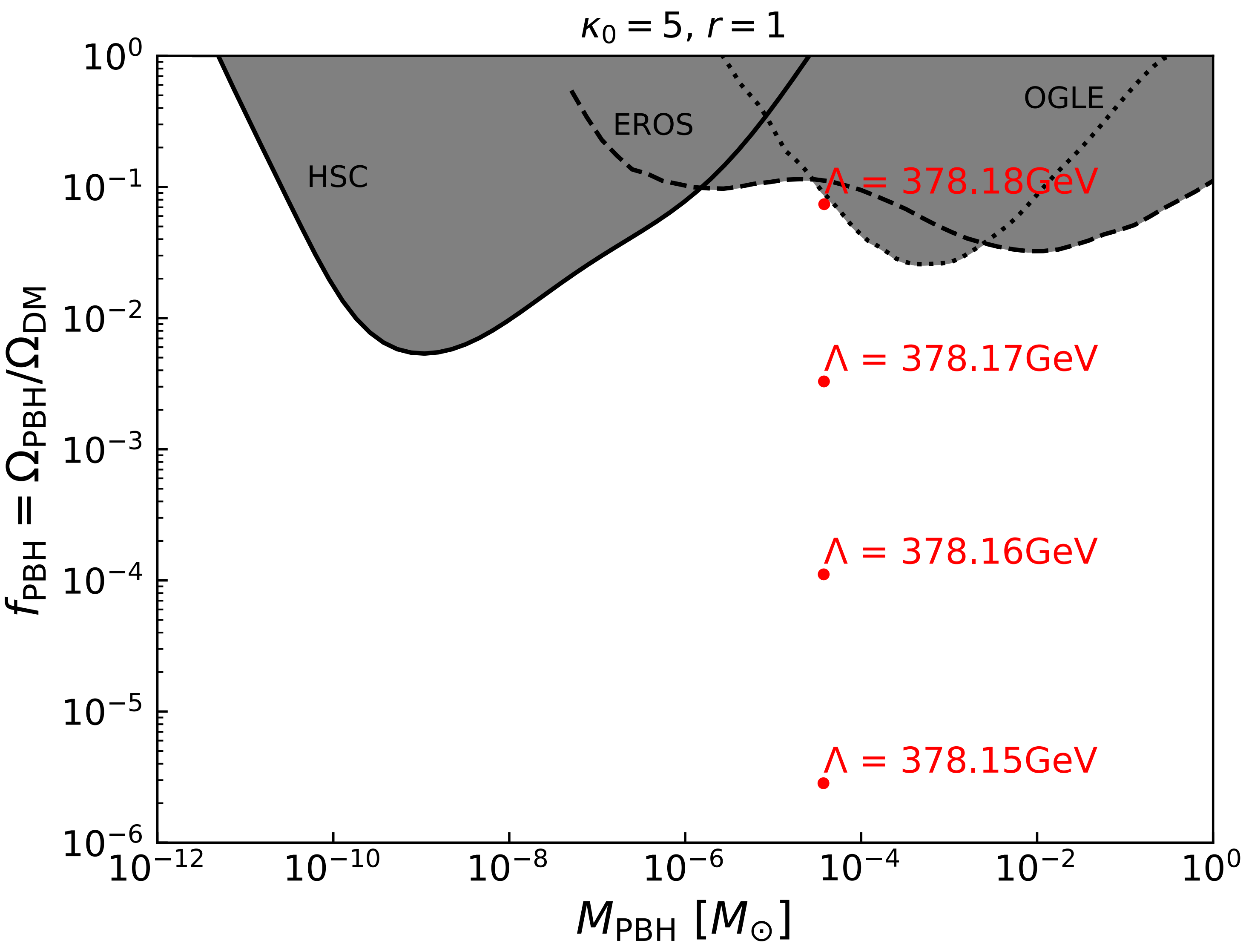




Fraction of primordial black holes

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

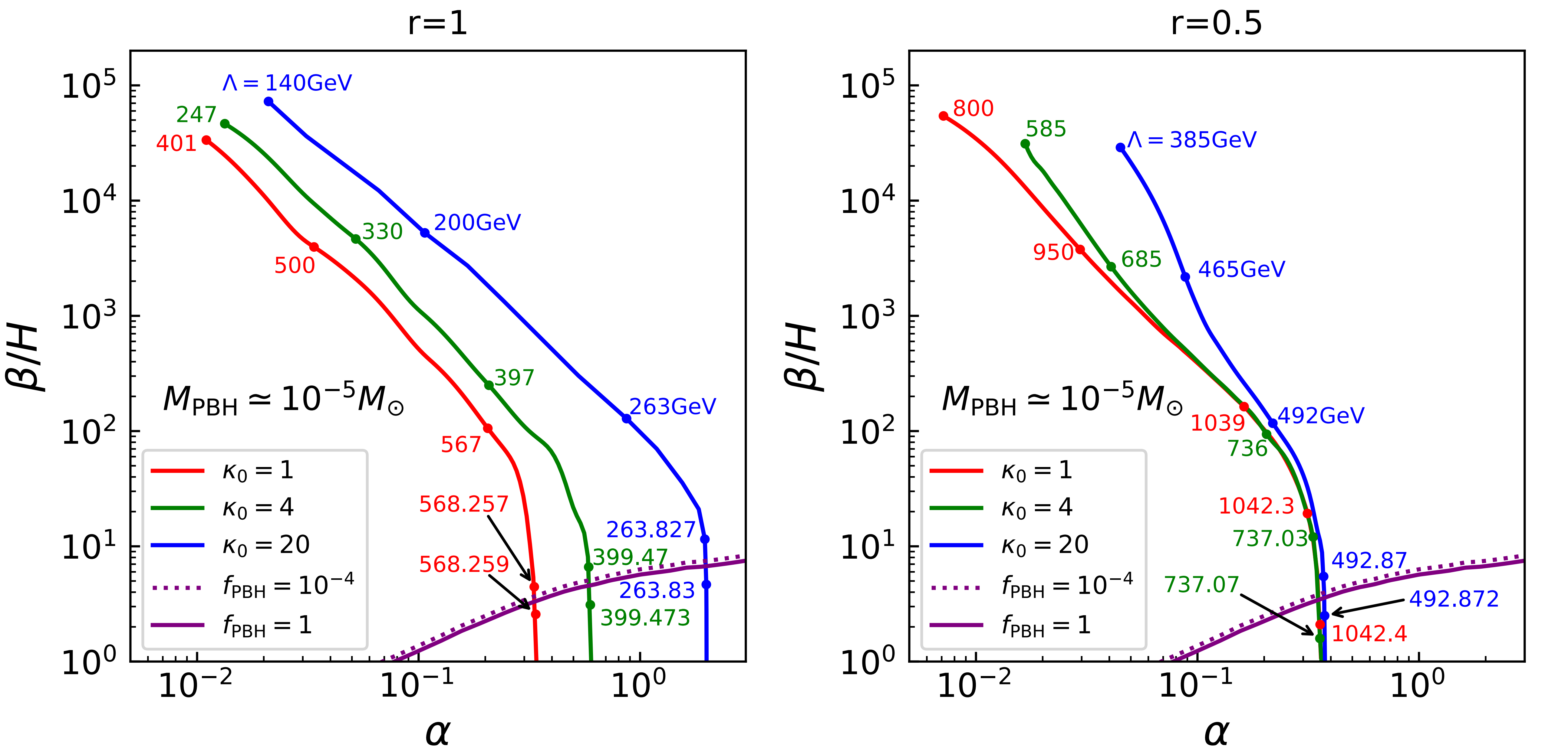
$$P(t_n) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t_n} \frac{a^3(t)}{a^3(t_{\rm PBH})}\frac{1}{H^3(t_{\rm PBH})}\Gamma(t)dt\right], \quad \Gamma_{\rm bubble}(T) \simeq T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left[-\frac{S_3(T)}{T}\right],$$



PBH fraction in naHEFT

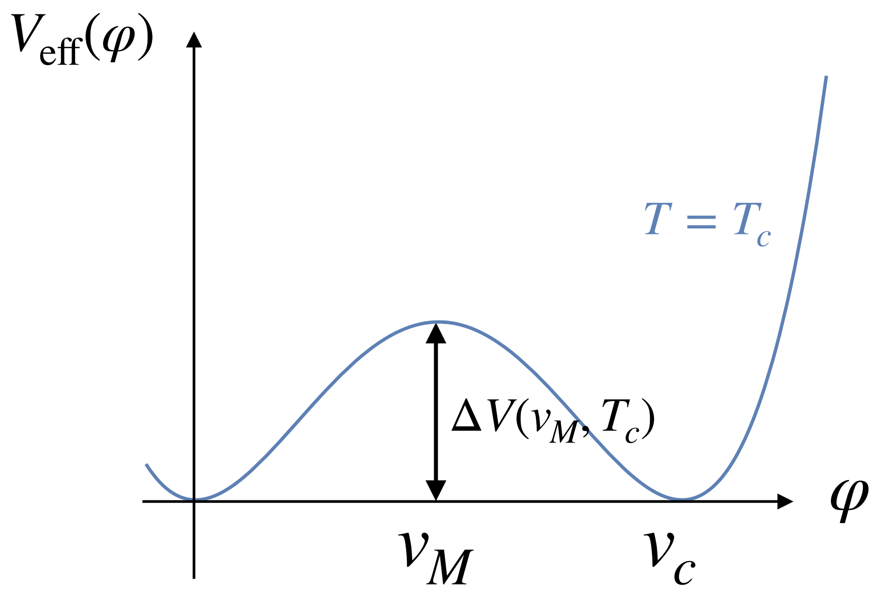
$f_{\rm PBH}$ is very sensitive to the parameters in the nearly aligned Higgs EFT

[Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]



Small beta and PBH formation

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



- Height of the effective potential

$$\Delta V(v_M, T_c) \propto \left(\frac{v_c}{T_c}\right)^3$$

→ Large vc/Tc favored to realize the strongly first-order

- β parameter (thin-wall approximation) [Eichhorn et al., JCAP 05 (2021)]

$$\frac{\beta}{H} \propto \left(\frac{v_c}{T_c}\right)^{-5/2}$$

→ When vc/Tc is large, β can be small

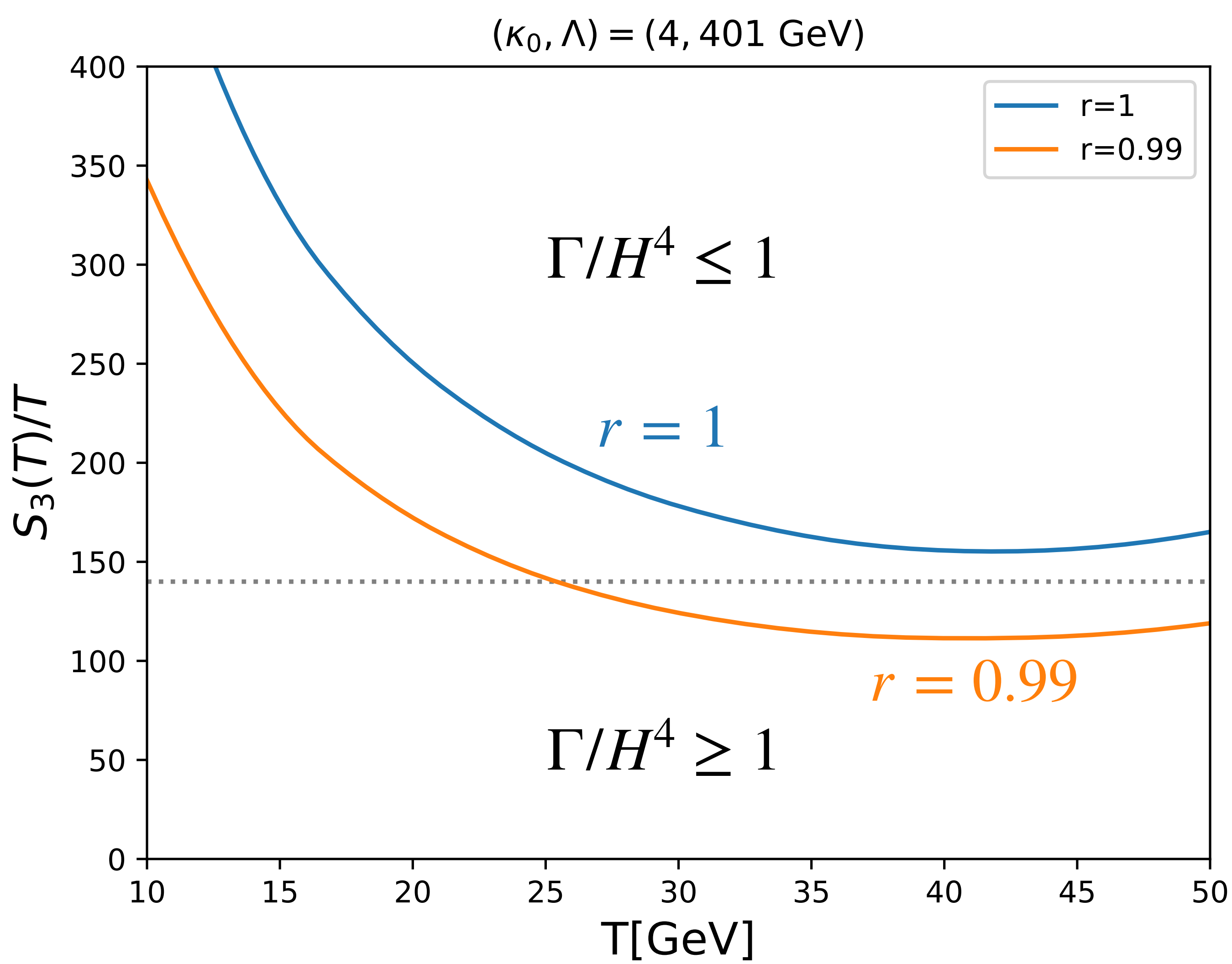
⇒ small β is preferred to delay the first-order phase transition

⇒ PBH formation requires small β

Bubble nucleation

- Nucleation rate of vacuum bubbles [Linde; Nucl. Phys. B216 (1983)]

$$\Gamma_{\rm bubble} \simeq A(T)\exp\left[-\frac{S_3(T)}{T}\right], \quad S_3(T) = \int d^3x \left[\frac{1}{2}\left(\nabla\varphi^b\right)^2 + V_{\rm eff}\left(\varphi^b, T\right)\right]$$



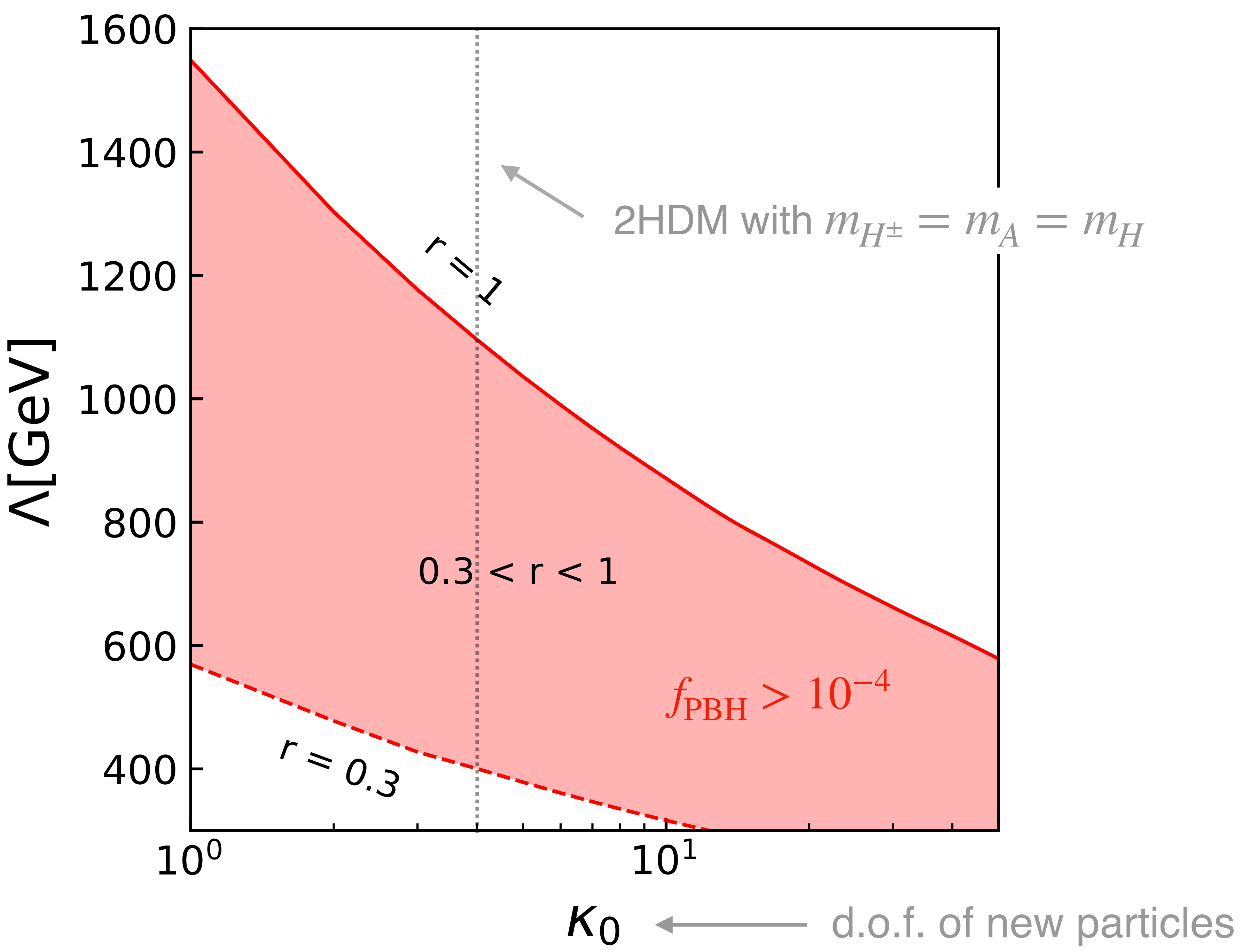
Non-decoupling effects are required to realize the delay of first-order EWPt

$$\Gamma/H^4 = 1 \quad \Leftrightarrow \quad S_3/T \sim 140$$

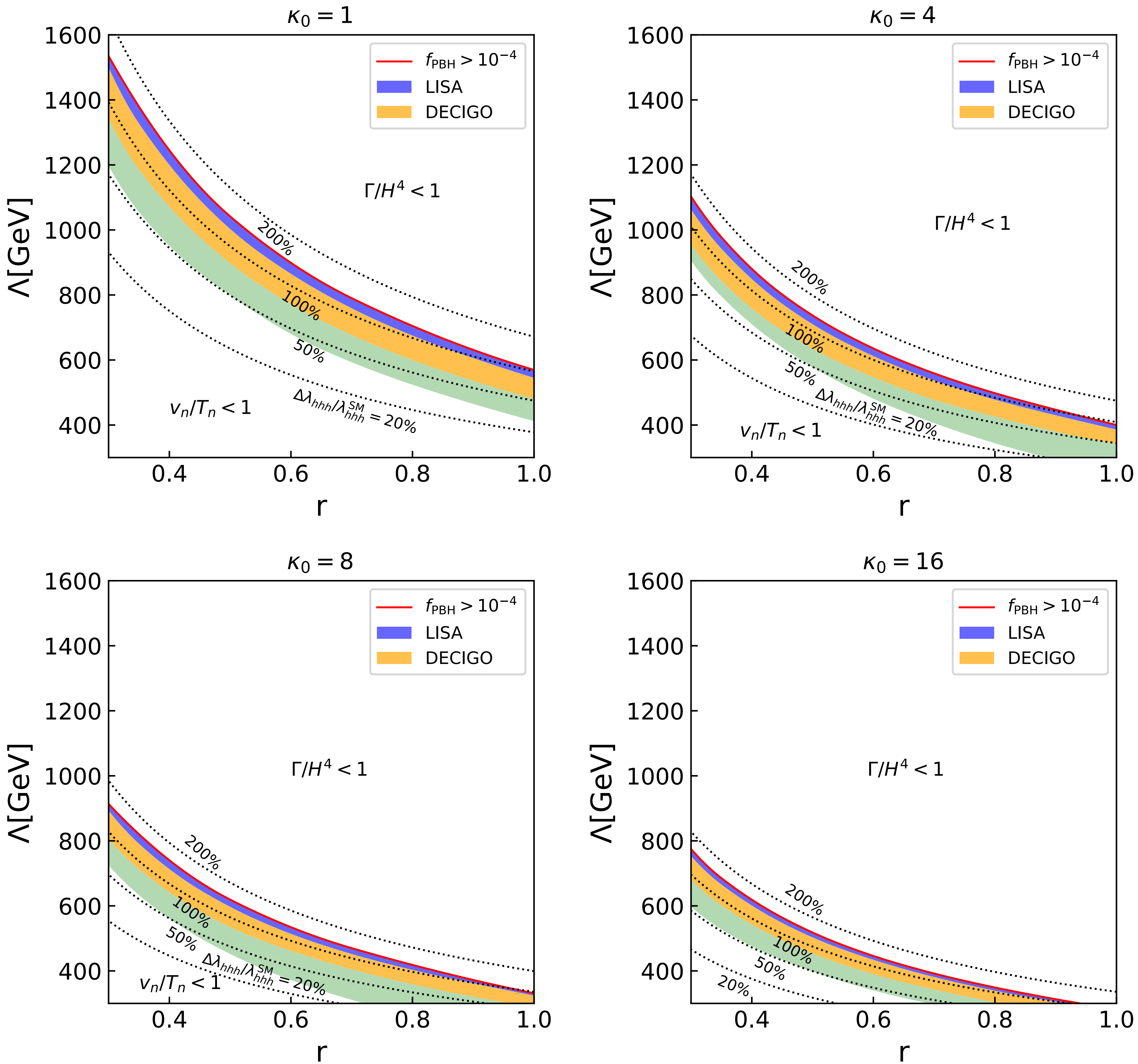
Parameter region explored by PBHs

Wide parameter region can be explored by PBH observations

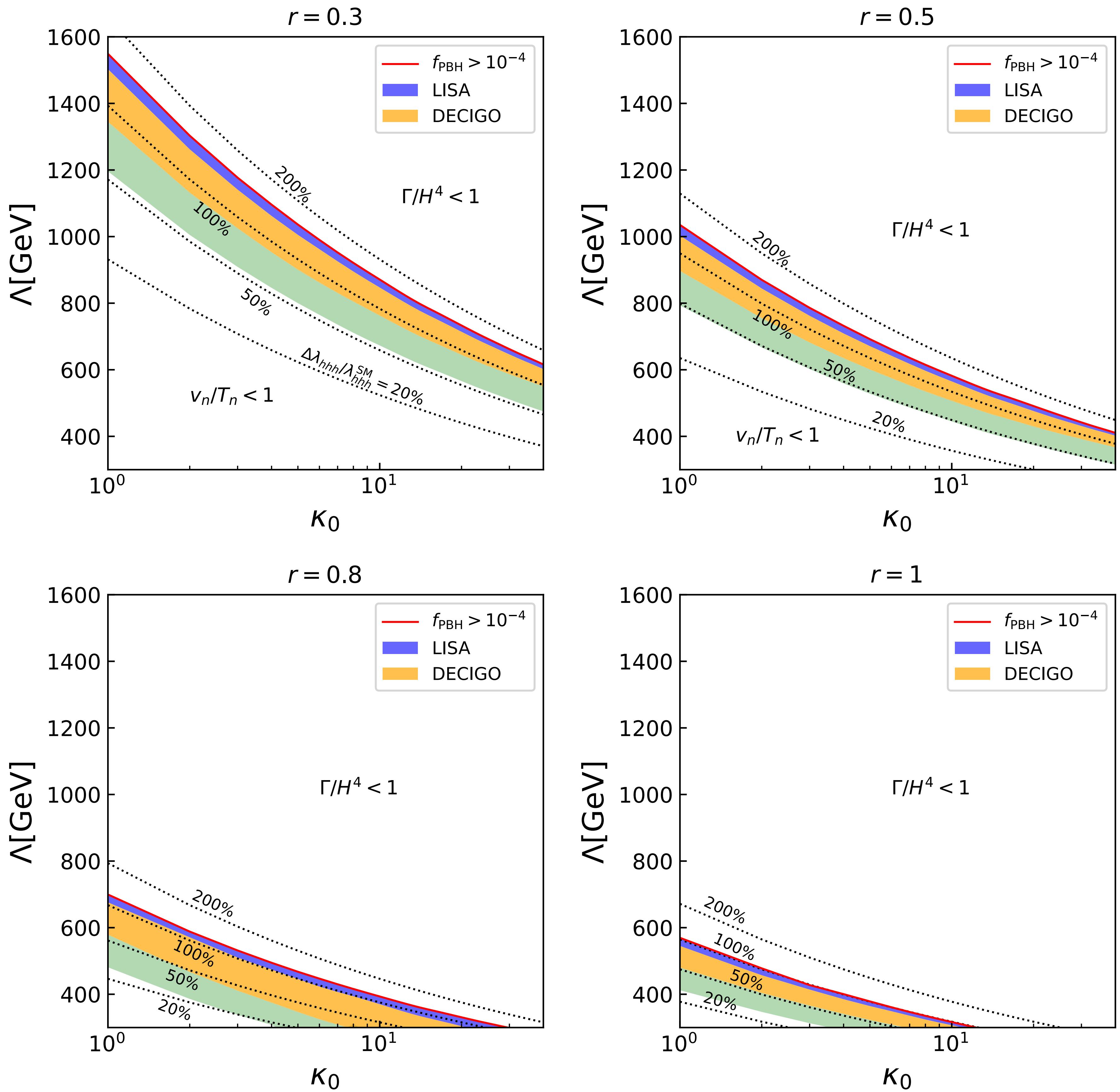
[Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]



Explored parameter regions



Explored parameter regions



Condition for PBH formations

- Condition $\delta > 0.45$ is derived in radiation dominant case

[Harada, Yoo and Kohri, PRD 88 (2013)

- PBH formation with $p = w\rho$ $(0.01 \leq w \leq 0.6)$ has been discussed

[Musco and Miller, Class. Quantum Grav. 30 (2013)]

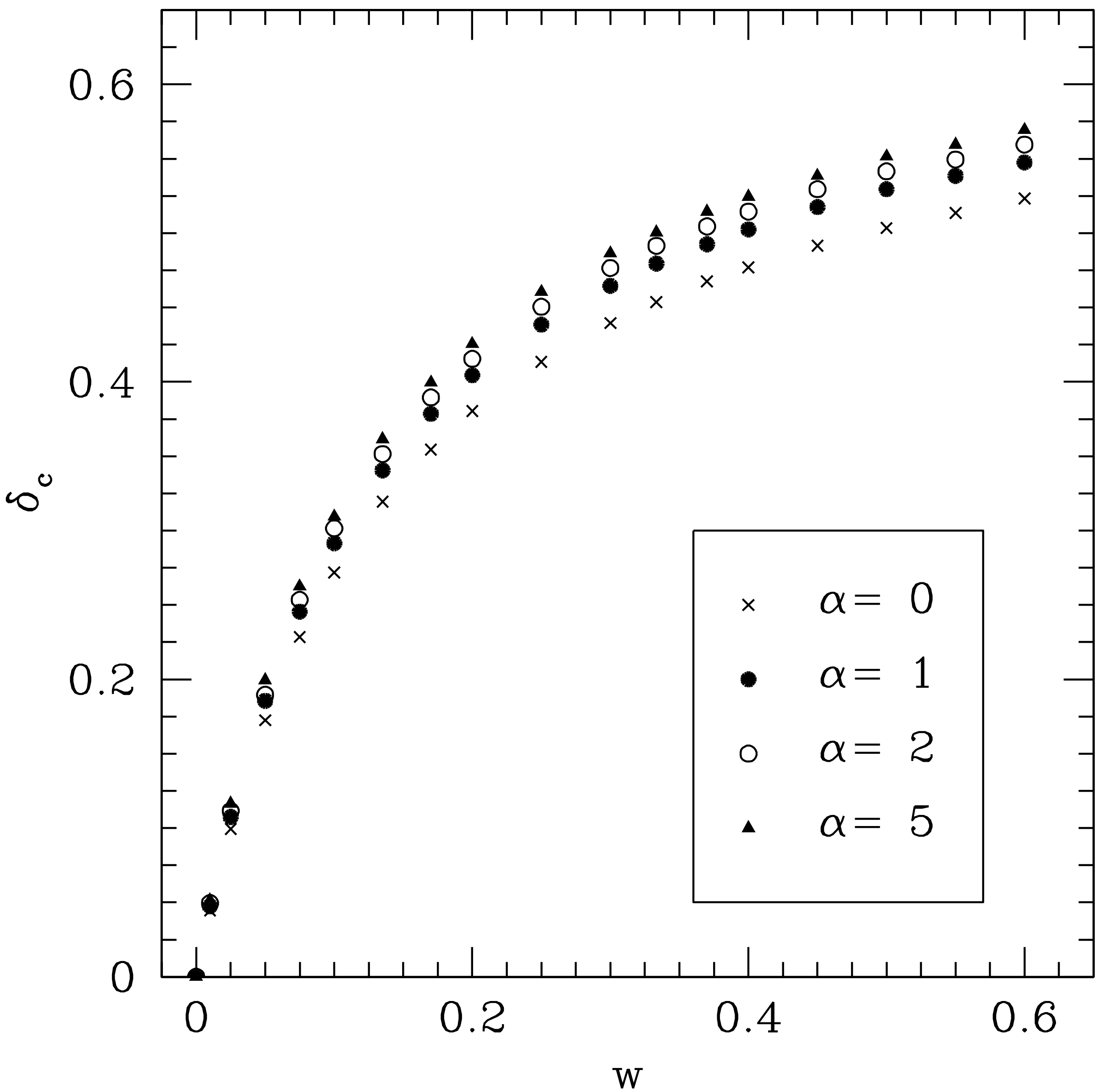
- PBH may be easily realized in vacuum energy dominant universe

∵ EoS $p = -\rho$

[Jedamzik and Niemeyer, PRD 59 (1999)

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

[Musco and Miller, Class. Quantum Grav. 30 (2013)]

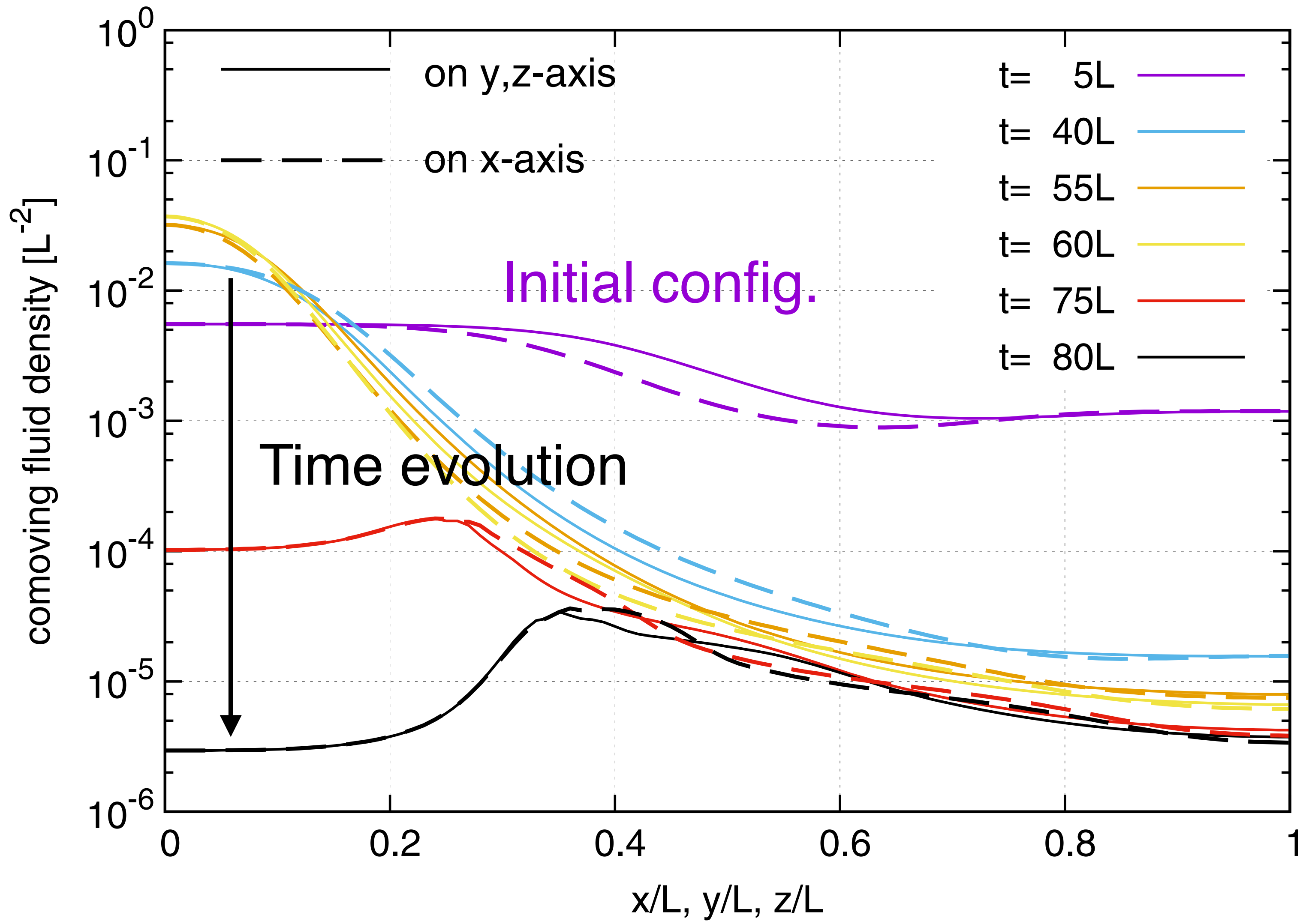


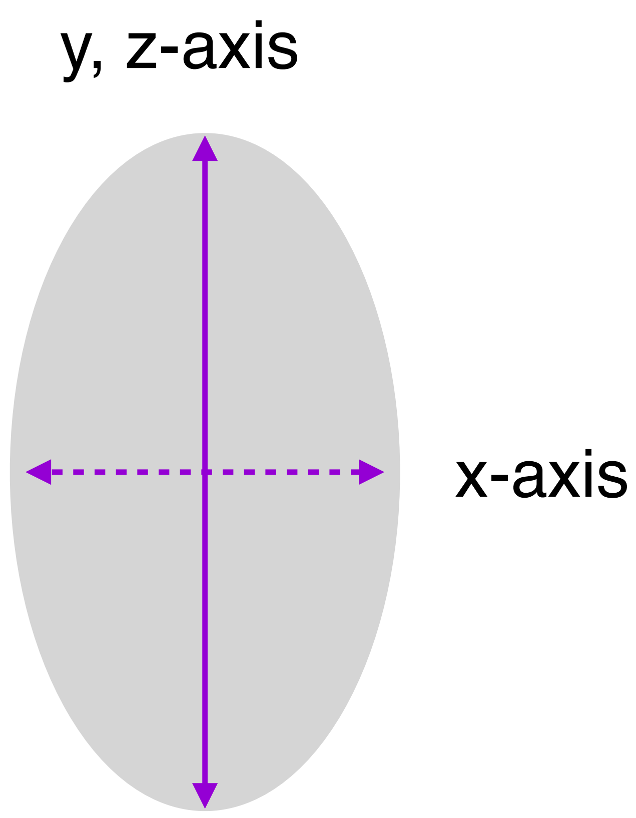
Spherical symmetry and PBH formation

- Non-spherical symmetric case

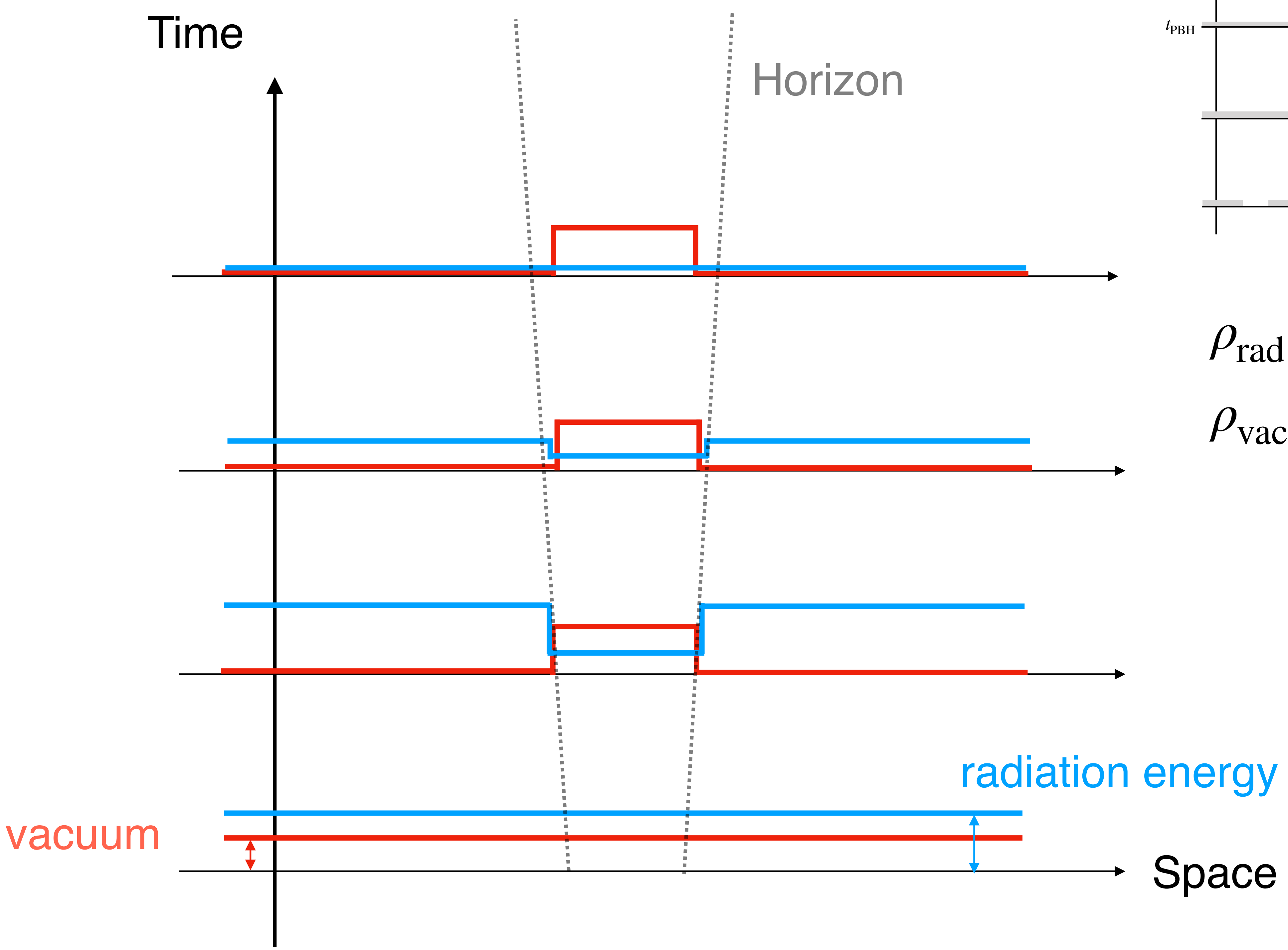
If the over density region does not respect the spherical symmetry, realization of PBH formation might be difficult

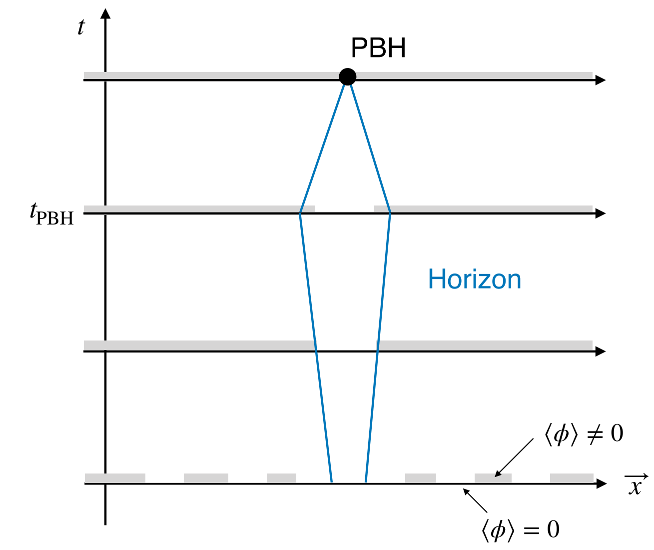
[Yoo, Harada and Okawa, PRD 102 (2020)





Spherical symmetry and PBH formation

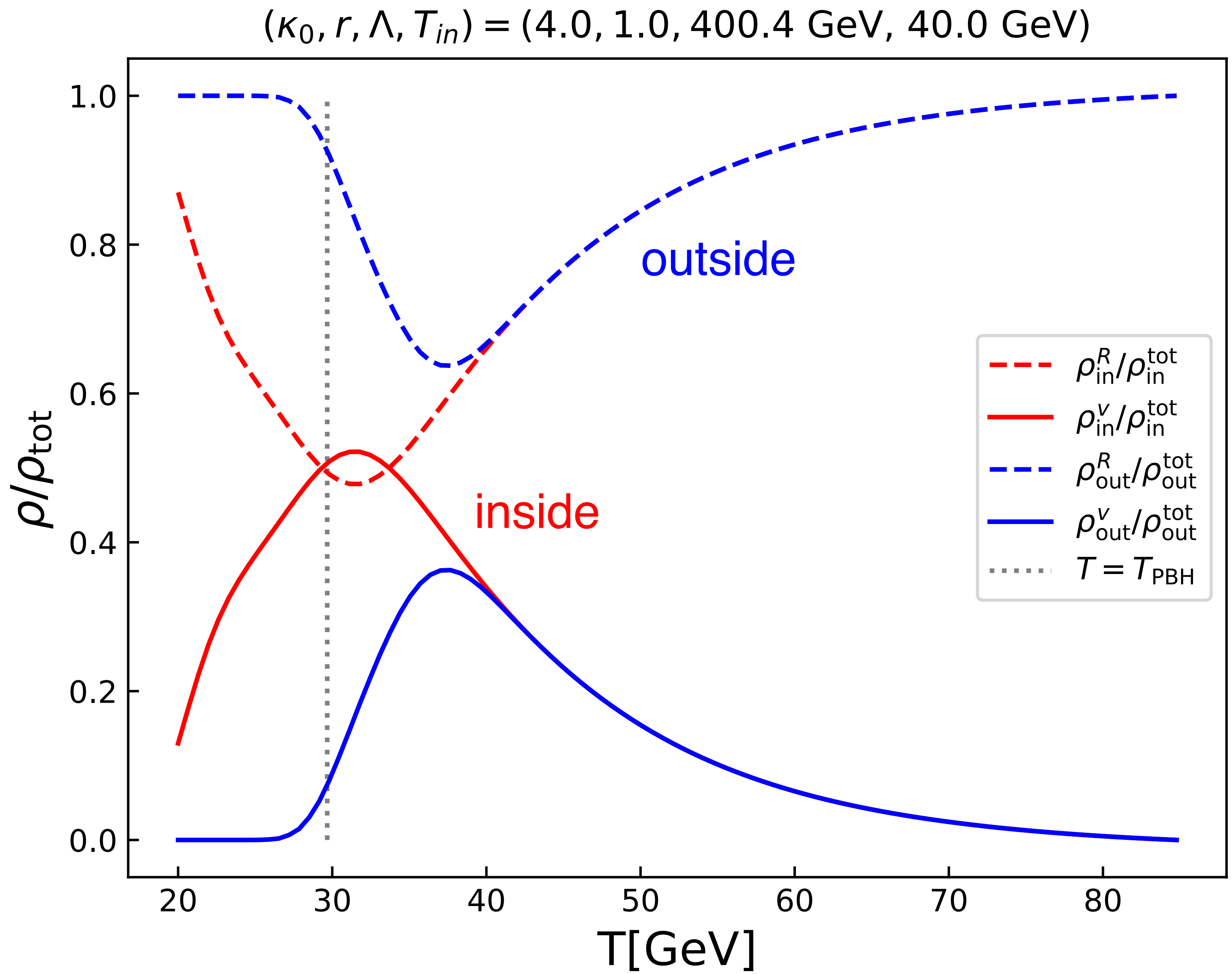


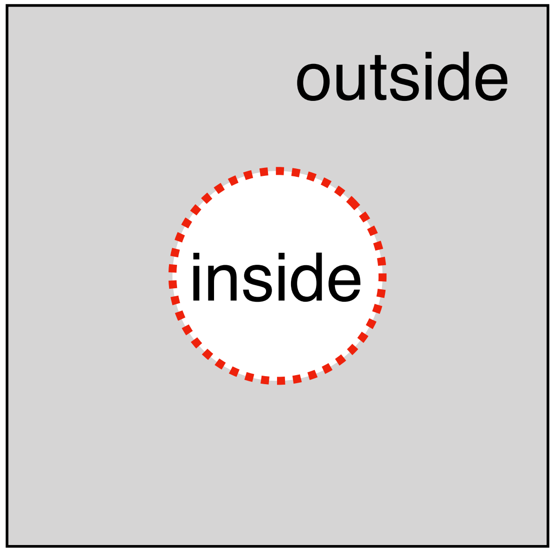


$$\rho_{\rm rad} \propto a^{-4}$$

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

Ratio of energy density



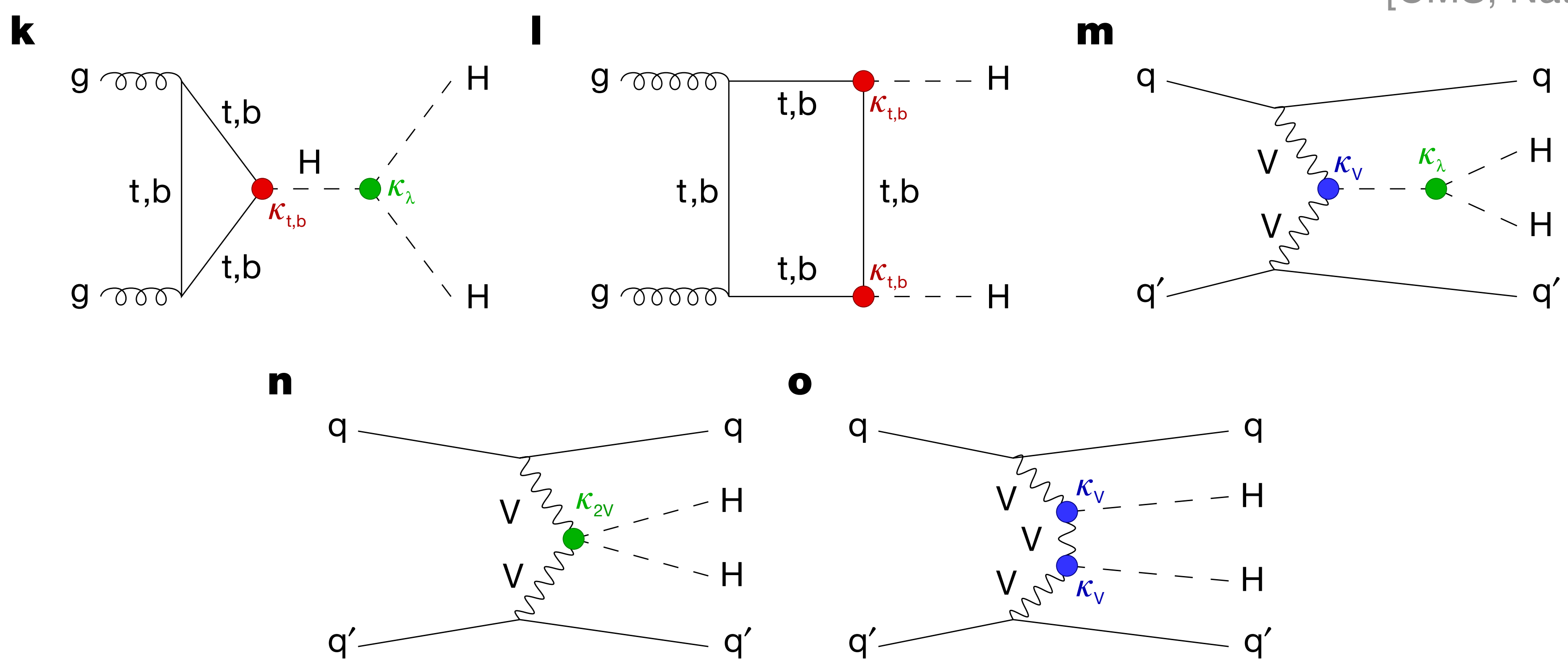


$$\rho_{\rm tot} = \rho_{\rm rad} + \rho_{\rm vac}$$

hhh coupling measurement at LHC

- Higgs pair-productionを通じてhhh結合が測定できる

[CMS, Nature 607 (2022)]



- 現在のLHC実験による制限

$$-1.4 < \frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} < 5.3$$ [ATLAS, arXiv:2211.01216 (2022)]

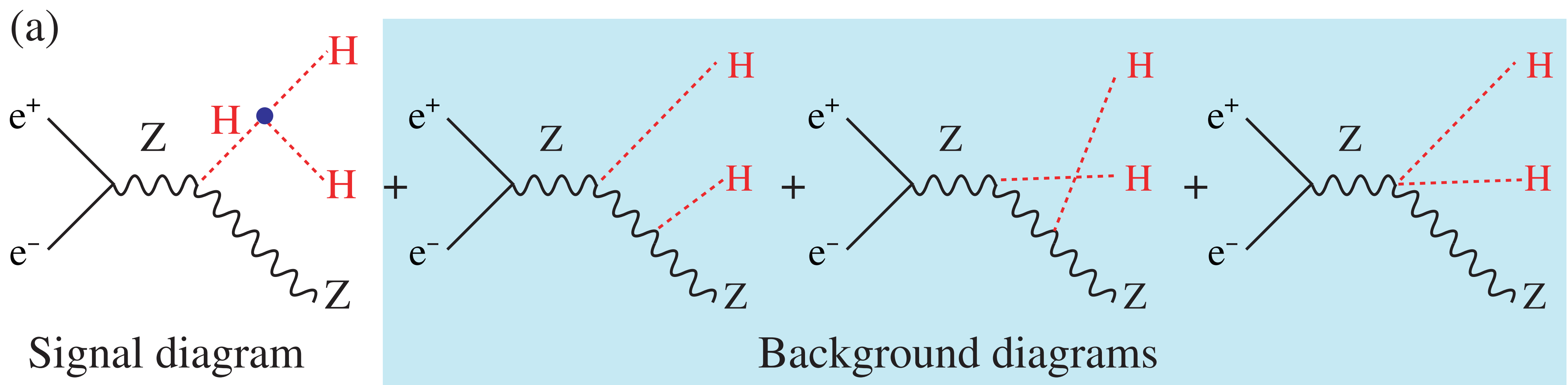
$$-2.24 < \frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} < 5.49$$ [CMS, Nature 607 (2022)]

- High-Luminocity LHCでは50%の精度で測定可能 [Cepeda et al., arXiv:1902.00134]

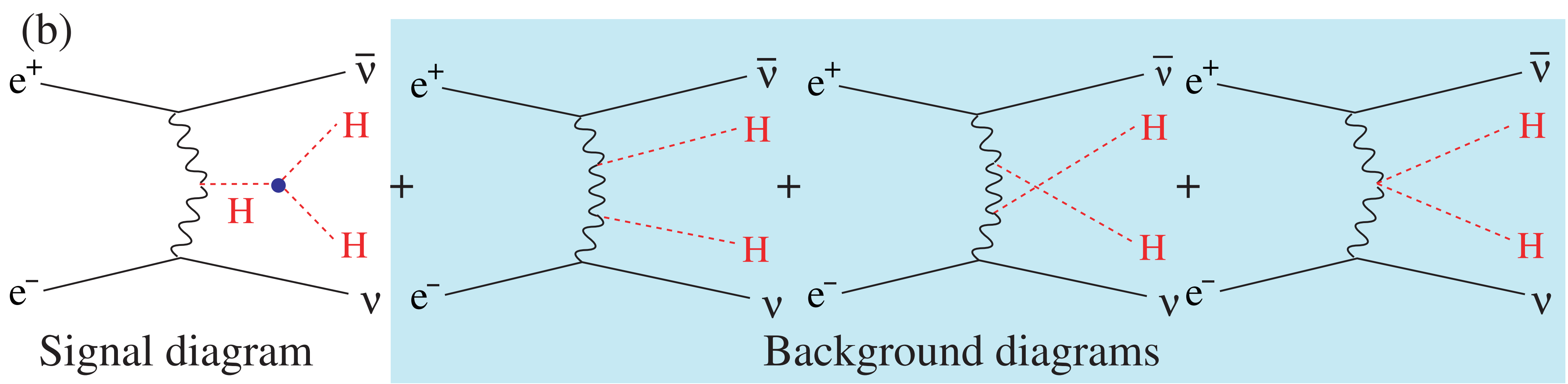
hhh coupling measurement at ILC

- ILC@500GeV

[Bambade et al., arXiv: 1906.01629]



- ILC@1TeV

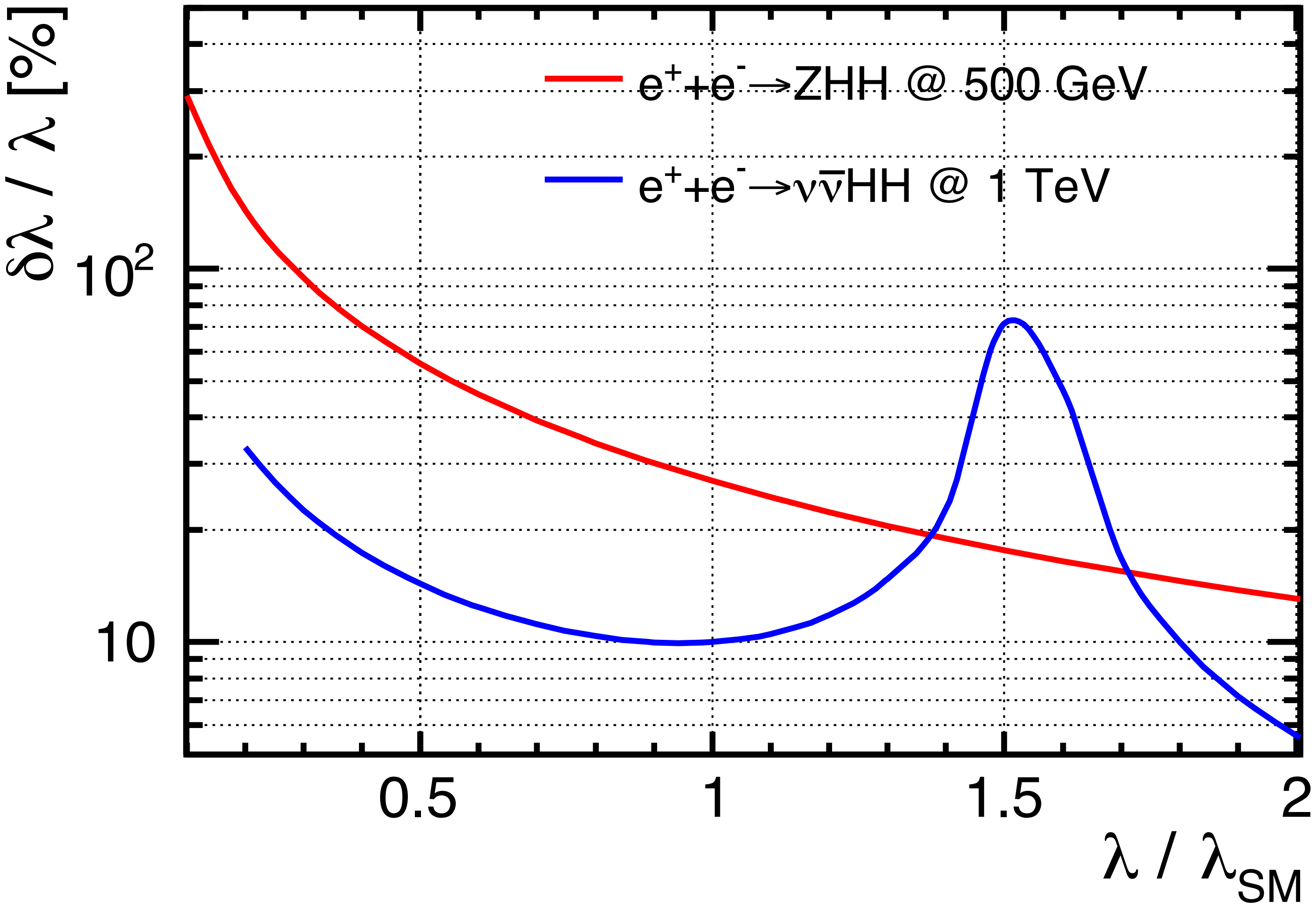


hhh coupling measurement at ILC

ILC@500GeV: hhh coupling can be measured with 27% accuracy

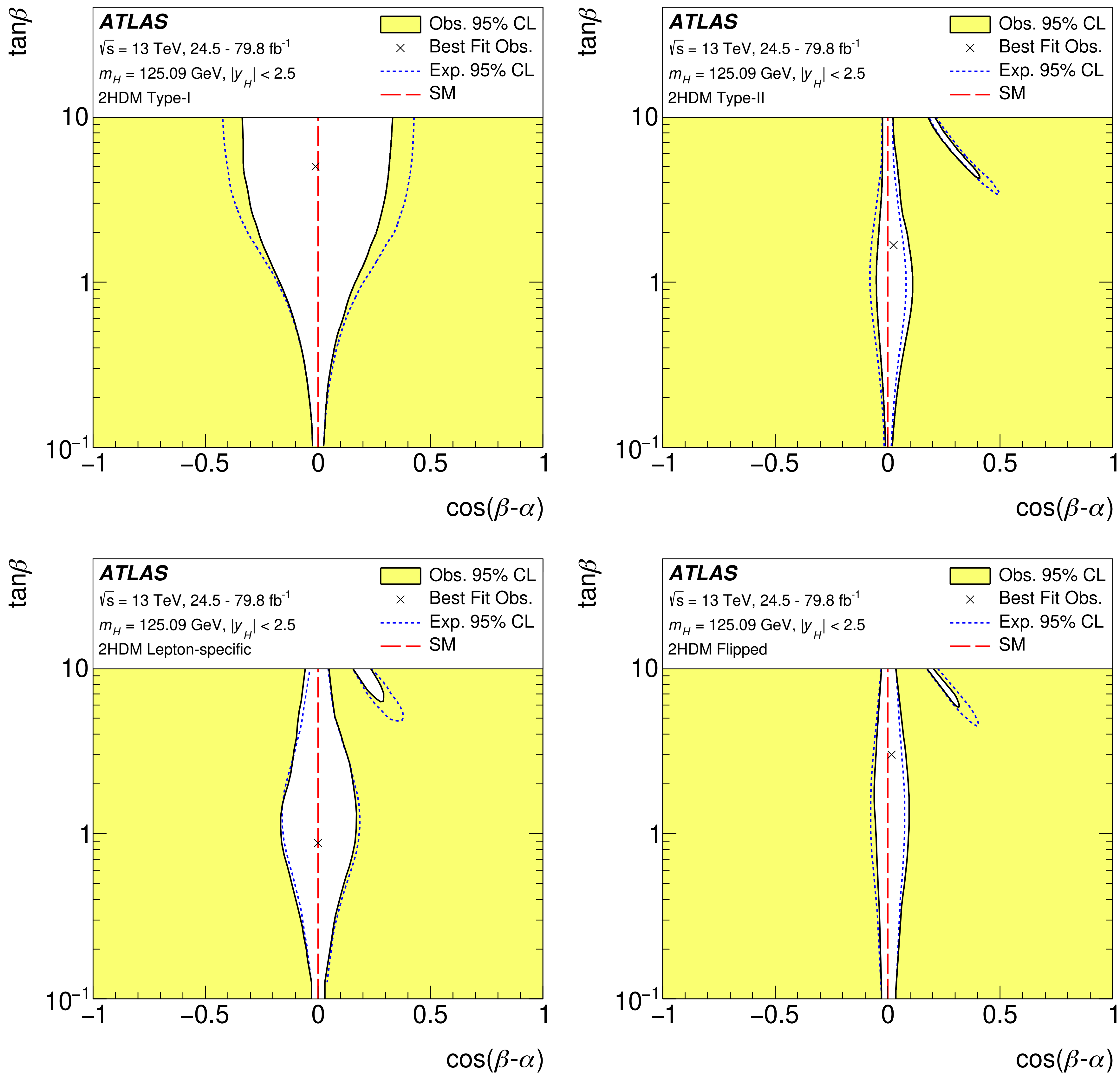
ILC@1TeV: hhh coupling can be measured with 10% accuracy

[Bambade et al., arXiv: 1906.01629]



Constraints on mixing angle in 2HDM

[ATLAS: 1909.02845]



Constraints on charged Higgs mass

[Haller et al.:Eur. Phys. J. C (2018)]