Primordial black holes as a probe of electroweak phase transition

Masanori Tanaka (Osaka University)

Collaborator: Katsuya Hashino (Tokyo University of science)
Shinya Kanemura (Osaka U.)
Tomo Takahashi (Saga U.)

arXiv: 2211.16225

KEK-PH 2022, 30/11/2022

Introduction

- A Higgs boson was discovered at LHC in 2012

  ← Dynamics of the electroweak (EW) symmetry breaking is unknown

- EW symmetry breaking occurred at the early Universe: EW phase transition (EWPT)

- In the standard model (SM), EWPT is crossover not 1st order phase transition

[Kajantie, Laine, Rummukainen and Shaposhnikov, Nucl. Phys. B 466 (1996)]
[Laine and Rummukainen, Nucl. Phys. 73 (1999)]

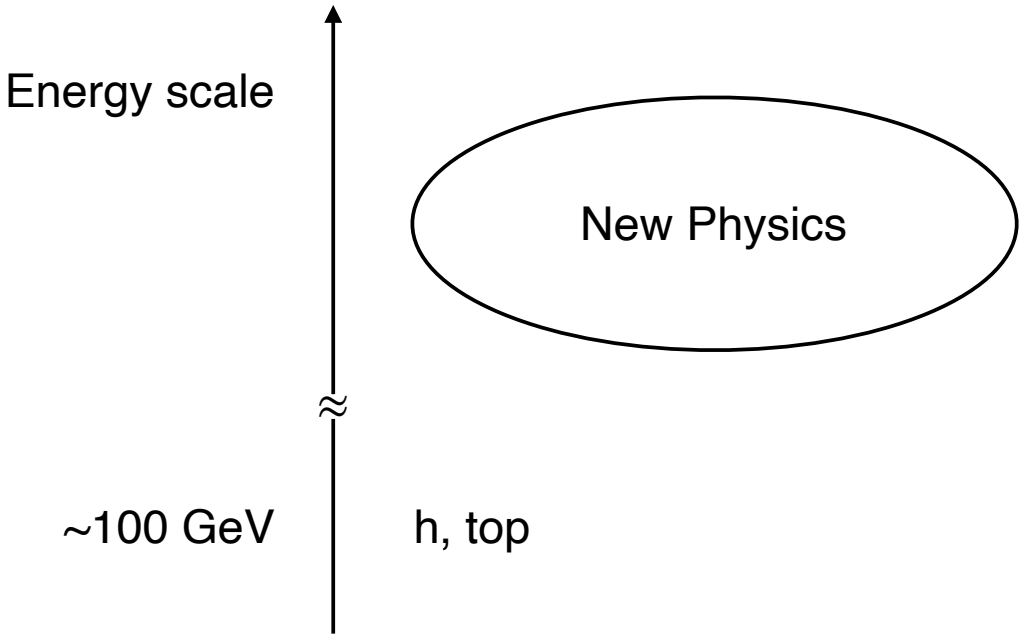
- What can we expect when the EWPT is 1st order?

Large deviation in the hhh coupling	Gravitational waves from 1st order phase transition	Primordial black holes from 1st order EWPT
[Grojean et al., PRD 71 (2005), Kanemura et al. PLB606 (2005)]	[Grojean and Servant, PRD 75 (2007)]	[Hashino, Kanemura and Takahashi, PLB 833 (2021)] [Hashino, Kanemura, Takahashi and Tanaka, arXiv: 2211.16225 (2022)]

Effective field theory

The SM is consistent with the result in LHC

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



Contributions from heavy new particles can be described by EFT frameworks

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

[Buchmuller and Wyler: Nucl. Phys. B268 (1986)]
[Grzadkowski et al.: JHEP 10 (2010)]

[Feruglio: Int. J. Mod. Phys. A 8 (1993)]

Effective field theory

- The framework of the SMEFT is often used [Buchmuller and Wyler: Nucl. Phys. B268 (1986)] [Grzadkowski et al.: JHEP 10 (2010)]

  → SMEFT is a good EFT for the decoupling new physics

  [Appelquist and Carazzone, PRD 11 (1975)]

- Heavy particles can arise large quantum effects (non-decoupling effects)

  [Kanemura et al.: PRD 70 (2004)]

  → SMEFT does not work well in such the case

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

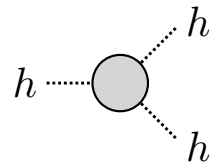
- HEFT can describe the new physics with the large quantum effects

  [Feruglio: Int. J. Mod. Phys. A 8 (1993)]

We discuss a phenomenology by using an extended HEFT

Non-decoupling effects 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 (2HDM) [Kanemura et al.: PRD 70 (2004)]

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

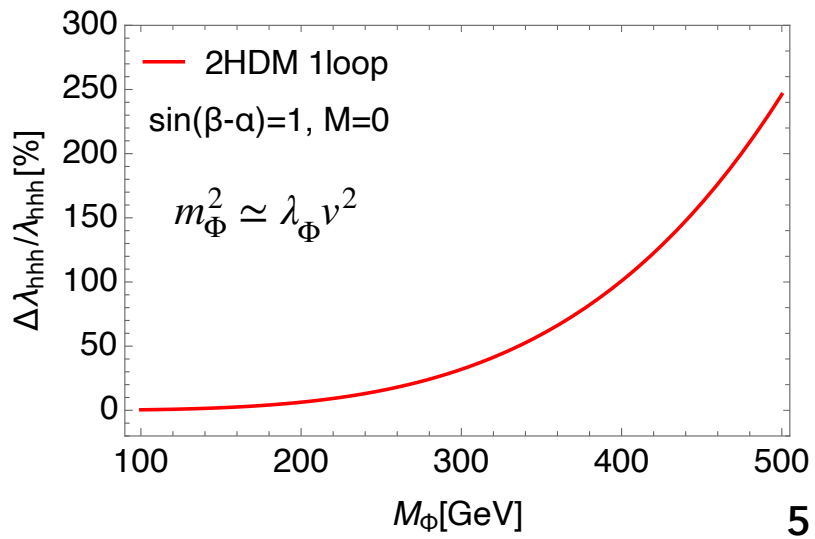
- Masses of additional Higgs bosons

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

- In recent, the hhh coupling at two-loop level has been evaluated

[Braathen and Kanemura, PLB796 (2019)]

The non-decoupling effect is interesting



The strongly 1st OPT and hhh coupling

To realize the EW baryogenesis, the sphaleron process should be decoupled

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

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

Strongly 1st order EWPT

Eg) Two Higgs doublet model (2HDM)

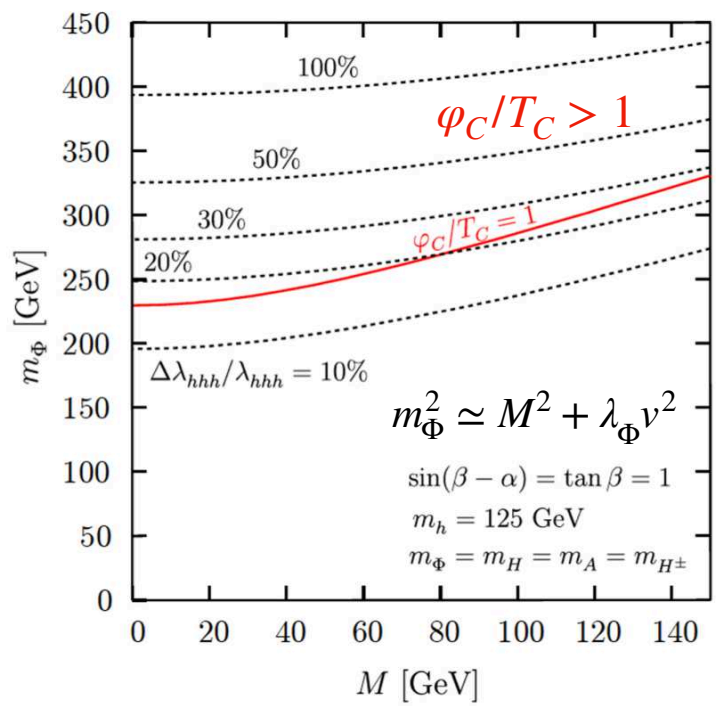
[Kanemura, Okada and Senaha, PLB606 (2005)]

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

Large deviation in the hhh coupling is important to realize EW baryogenesis

[Grojean, Servant and Wells, PRD 71 (2005), Kanemura, Okada and Senaha, PLB606 (2005)]

The non-decoupling effect is very important



Nearly aligned Higgs EFT (naHEFT)

naHEFT can describe the non-decoupling effects [Kanemura and Nagai, JHEP 03 (2022)]

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

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

: polynomial in terms of h

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

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

- Field dependent mass of new particles

For simplicity, we take $\mathcal{M}^2(h) = M^2 + \frac{\kappa_p}{2}(h+v)^2$

- 3 Free parameters in the naHEFT

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

Mass of new particle d.o.f. of new particle

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

Nearly aligned Higgs EFT (naHEFT)

naHEFT can describe the non-decoupling effects [Kanemura and Nagai, JHEP 03 (2022)]

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

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

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

: polynomial in terms of h

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

- Field dependent mass of new particles

For simplicity, we take $\mathcal{M}^2(h) = M^2 + \frac{\kappa_p}{2}(h+v)^2$

- 3 Free parameters in the naHEFT

r : non-decouplingness

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

Mass of new particle d.o.f. of new particle

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

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

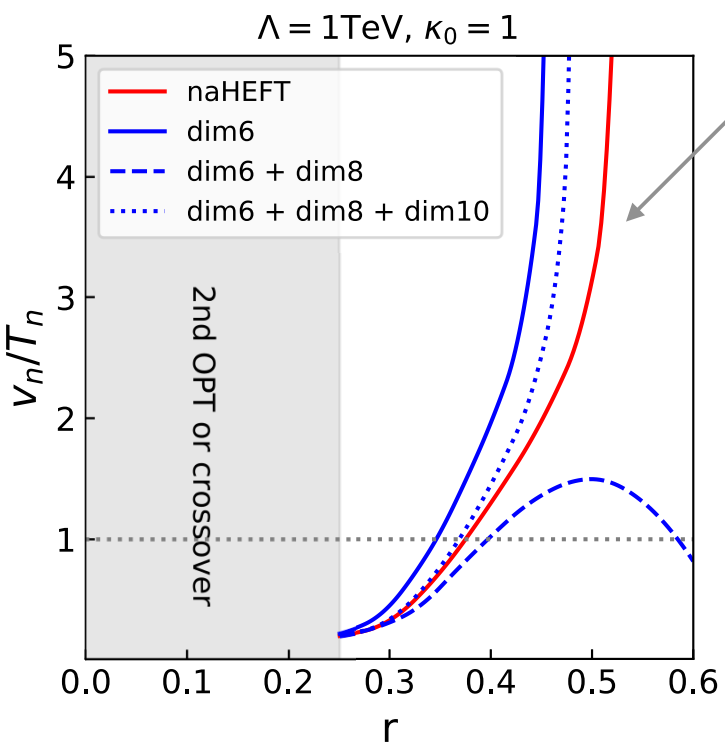
new Higgs EFT at the finite temperature

- naHEFT at finite temperature system

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

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

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



consistent with the result in the SM with a singlet scalar

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

There is a large discrepancy b/w the prediction on v_n/T_n in the new EFT and the SMEFT

⇩

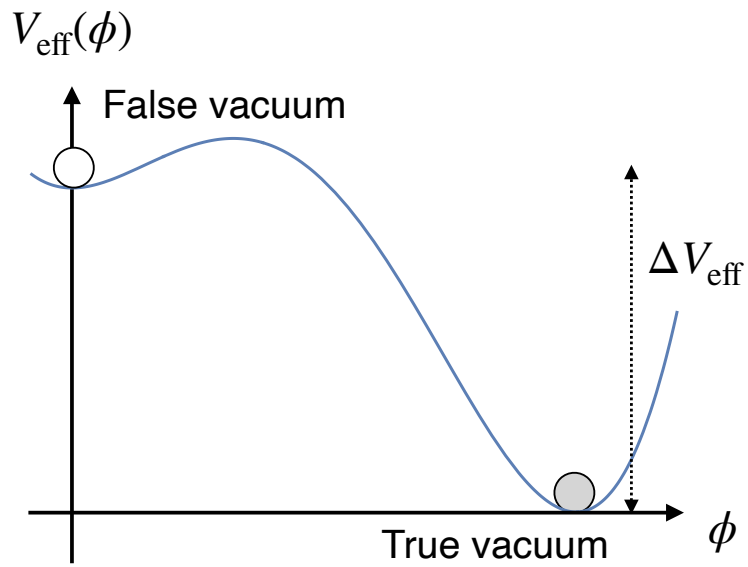
SMEFT may not be appropriate when we discuss the strongly 1st order EWPT

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

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

Gravitational waves from 1st OPT

Strongly 1st order EWPT may be tested by gravitational wave (GW) observations



[Linde; Nucl. Phys. B216 (1983)]

- Nucleation rate of the vacuum bubbles

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

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

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

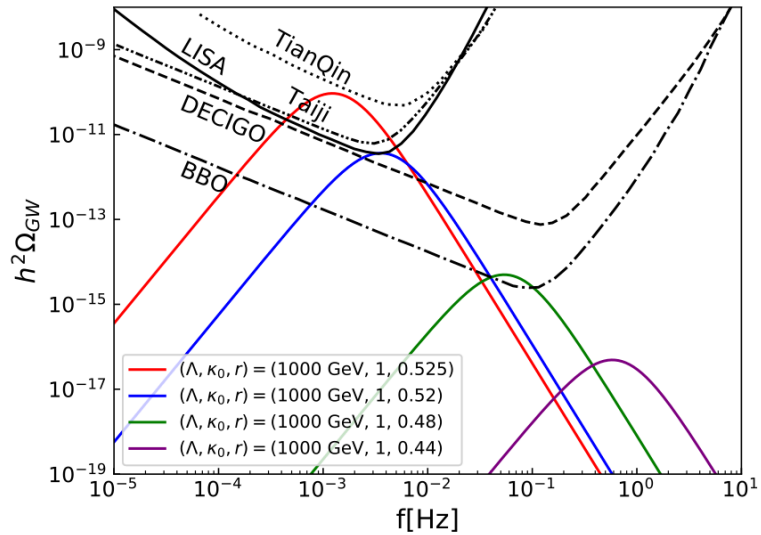
[Grojean and Servant, PRD 75 (2007)]

- Parameters characterizing 1st OPT

T_n : Temperature starting 1st OPT

$\alpha_{\rm GW}$: Latent heat released by 1st OPT

$\beta_{\rm GW}$: Duration of 1st OPT



Primordial black holes from 1st OPT

- Primordial black hole (PBH): Black hole formed at very early Universe

  before the star formation

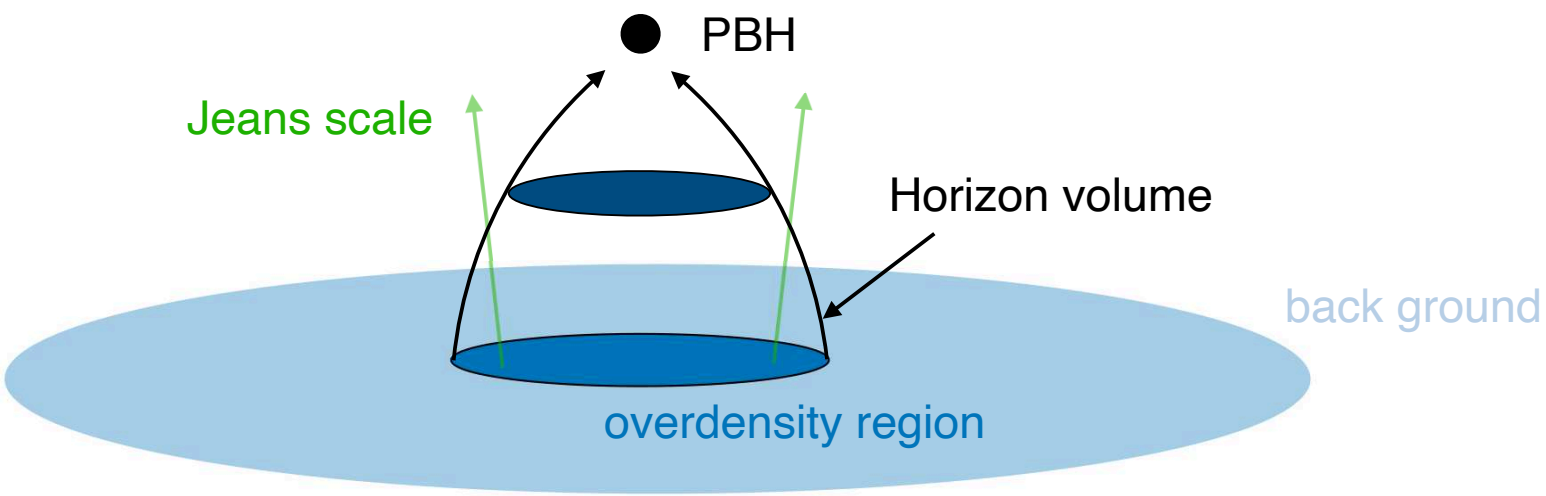
- To realize the PBH formation,

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

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

- When the 1st order phase transition occurs, $\delta > 0.45$ can be satisfied

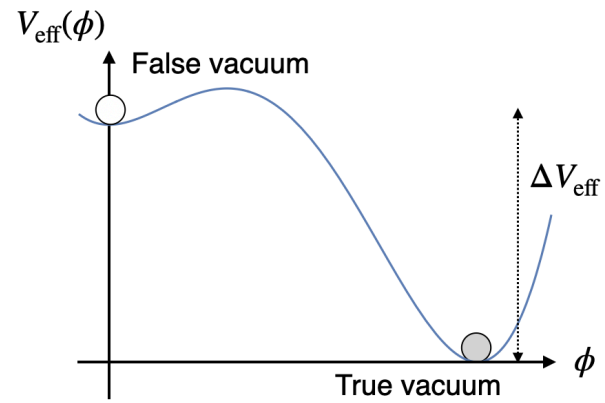
  → PBHs can be formed by 1st order phase transition [Liu et al., PRD105 (2022)]



PBHs and 1st order phase transition

- We focus on a region where the phase transition delays [Liu et al., PRD105 (2022)]

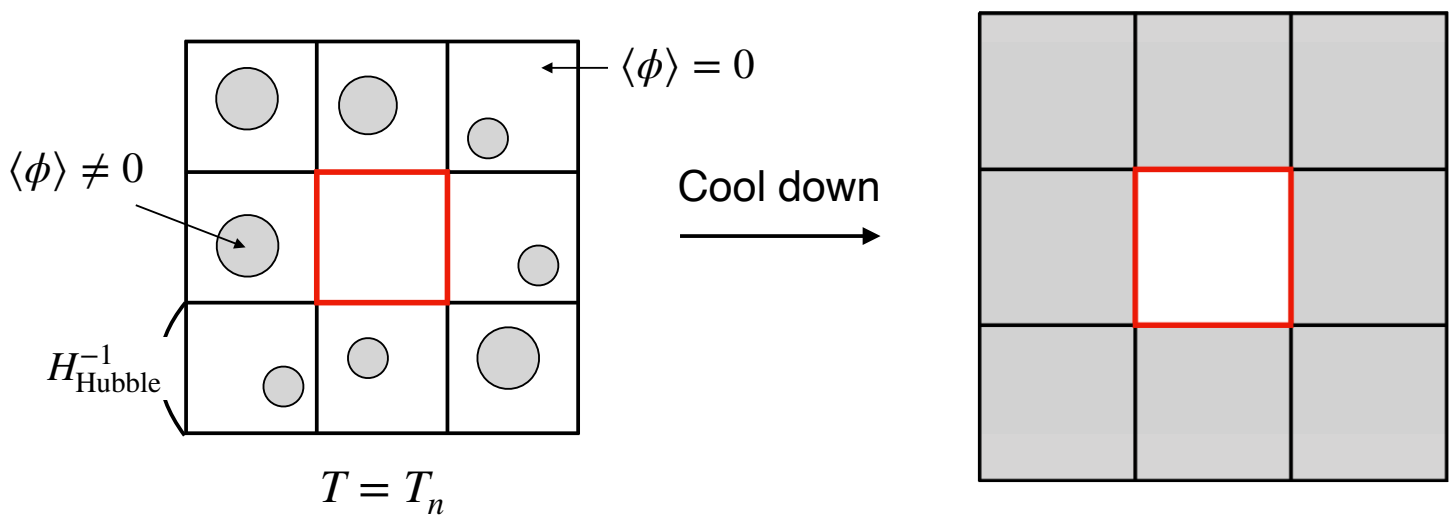
$$\Gamma_{\rm bubble}(T) \simeq A(T)\exp[-S_3(T)/T]$$



- Large energy density fluctuation can be realized b/w the false and true vacuum

PBHs can be produced from the 1st OPT

← $f_{\rm PBH}$ can be evaluated in any models which realize the 1st OPT



PBHs from 1st order EWPT

- PBHs from 1st order EWPT is discussed in the SMEFT

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

We discuss PBH production in the naHEFT instead of the SMEFT

- Typical mass of PBHs from EWPT

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

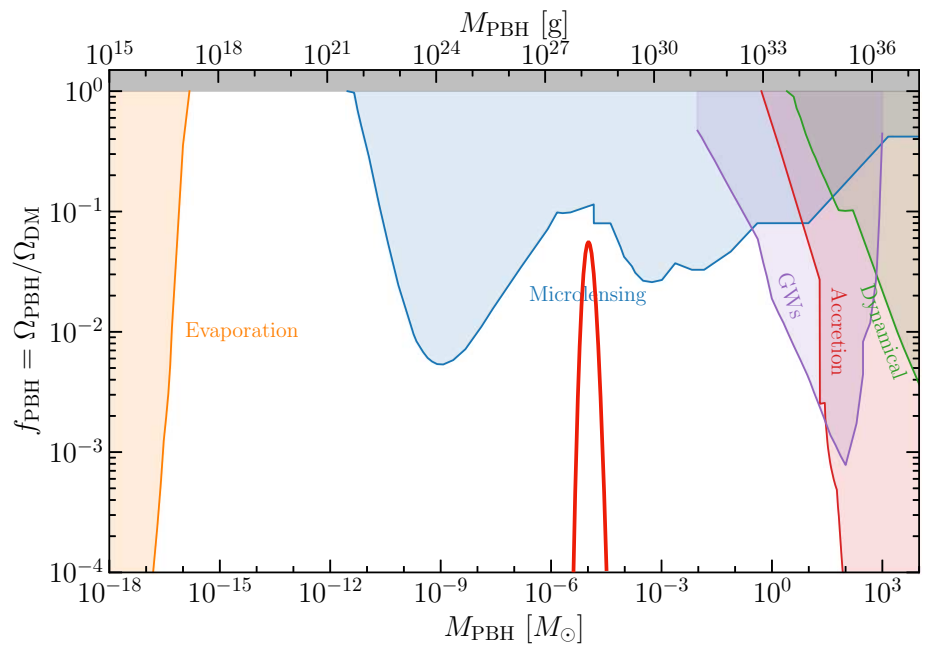
1st order EWPT can be tested by PBH observations

- Current microlensing observations

Subaru HSC, OGLE

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

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



[Green and Kavanagh, J. Phys. G: Nucl. Part. Phys. 48 (2021)]

- Future observations: PRIME, Roman

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

[PRIME: http://www-ir.ess.sci.osaka-u.ac.jp/prime/index.html]

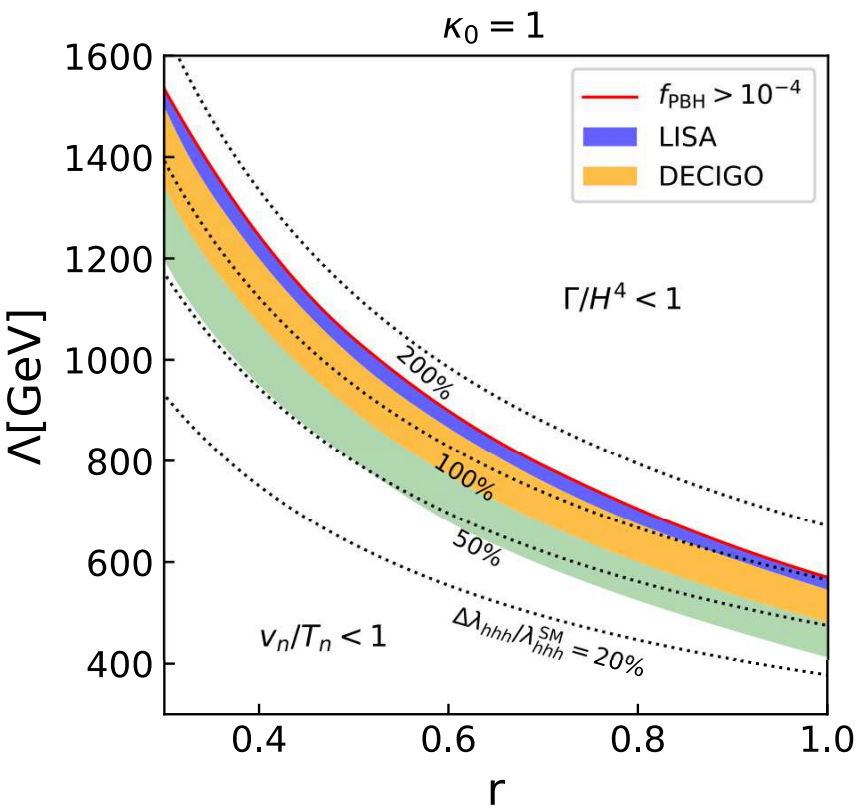
[Roman: https://roman.gsfc.nasa.gov]

Probing the strongly first-order EWPT

How can we test the strongly 1st order EWPT?

- hhh coupling [Kanemura et al.: PRD 70 (2004)] [Kanemura et al., PLB606 (2005)] [Grojean et al., PRD71 (2005)]
- GWs from 1st order phase transition [Grojean and Servant, PRD 75 (2007)]
- Primordial black hole formations from the 1st order EWPT

[Hashino, Kanemura and Takahashi, PLB833 (2021)]
[Hashino, Kanemura, Takahashi and Tanaka, arXiv: 2211.16225]



- Current or future experiments

  Collider: ILC, HL-LHC

  GWs: LISA, DECIGO

  PBH observations: Subaru HSC, OGLE

  Current observations!

We can test 1st order EW phase transition by using colliders, GW observations and PBH observations

[Hashino, Kanemura, Takahashi and Tanaka, arXiv: 2211.16225]

Summary

- Strongly first-order phase transition can be tested via
  - measurement of the triple Higgs boson coupling
  - gravitational wave observations
  - primordial black hole observations

- Typical mass of PBHs from the 1st order EW phase transition

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

Strongly 1st order EW phase transition may be tested by the PBH observations at the microlensing experiments (e.g., Subaru HSC, OGLE, PRIME, Roman)

- We discussed the PBH production by using the naHEFT

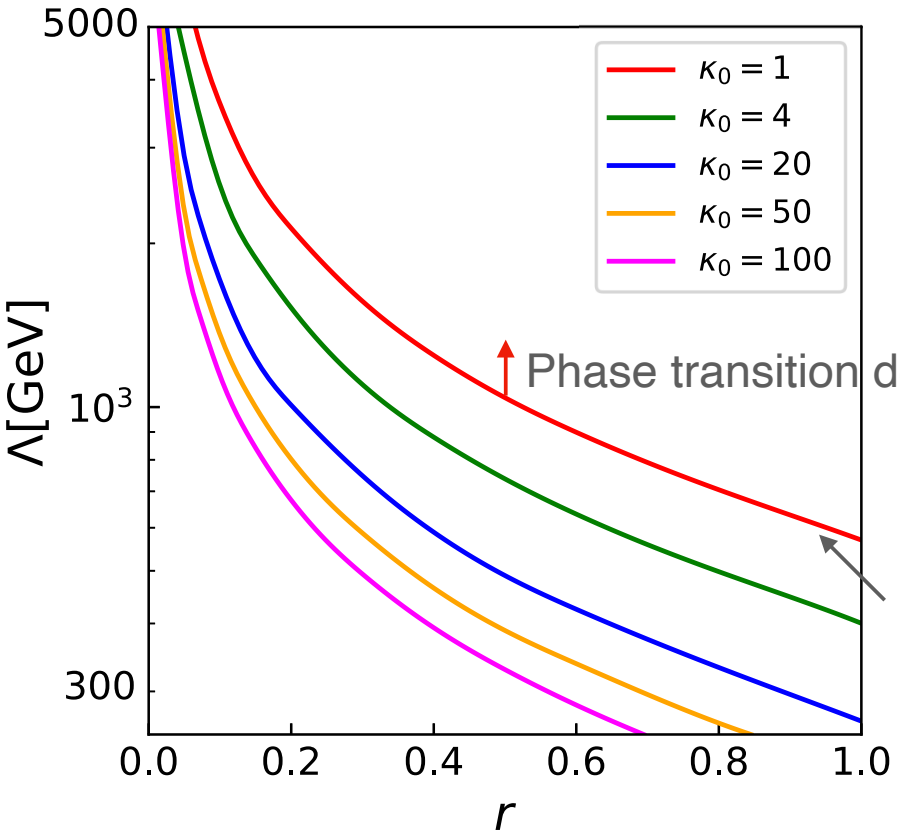
We might be able to test the wide parameter region in extended Higgs models with the strongly first-order phase transition by the PBH observations

Back up

PBH formation in the naHEFT

We might be able to test the wide parameter region by using PBH observations

[Hashino, Kanemura, Takahashi and Tanaka, arXiv: 2211.16225]



Phase transition does not finish

PBH can be produced

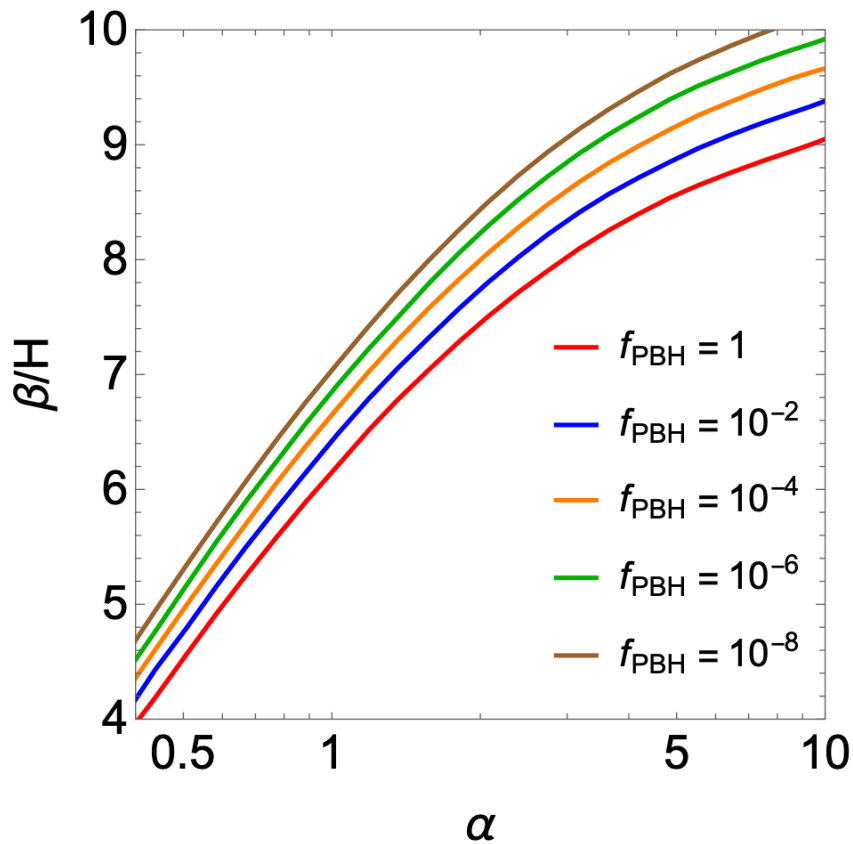
$$V_{\rm EFT} = V_{\rm SM} + \frac{\kappa_0}{64\pi^2}\left[\mathcal{M}^2(\phi)\right]^2 \ln\frac{\mathcal{M}^2(\phi)}{\mu^2}\,.$$

$$\Lambda^2 = \mathcal{M}^2(h=0) = M^2 + \frac{\kappa_p}{2}v^2, \quad r = \frac{\kappa_p v^2}{2}/\Lambda^2$$

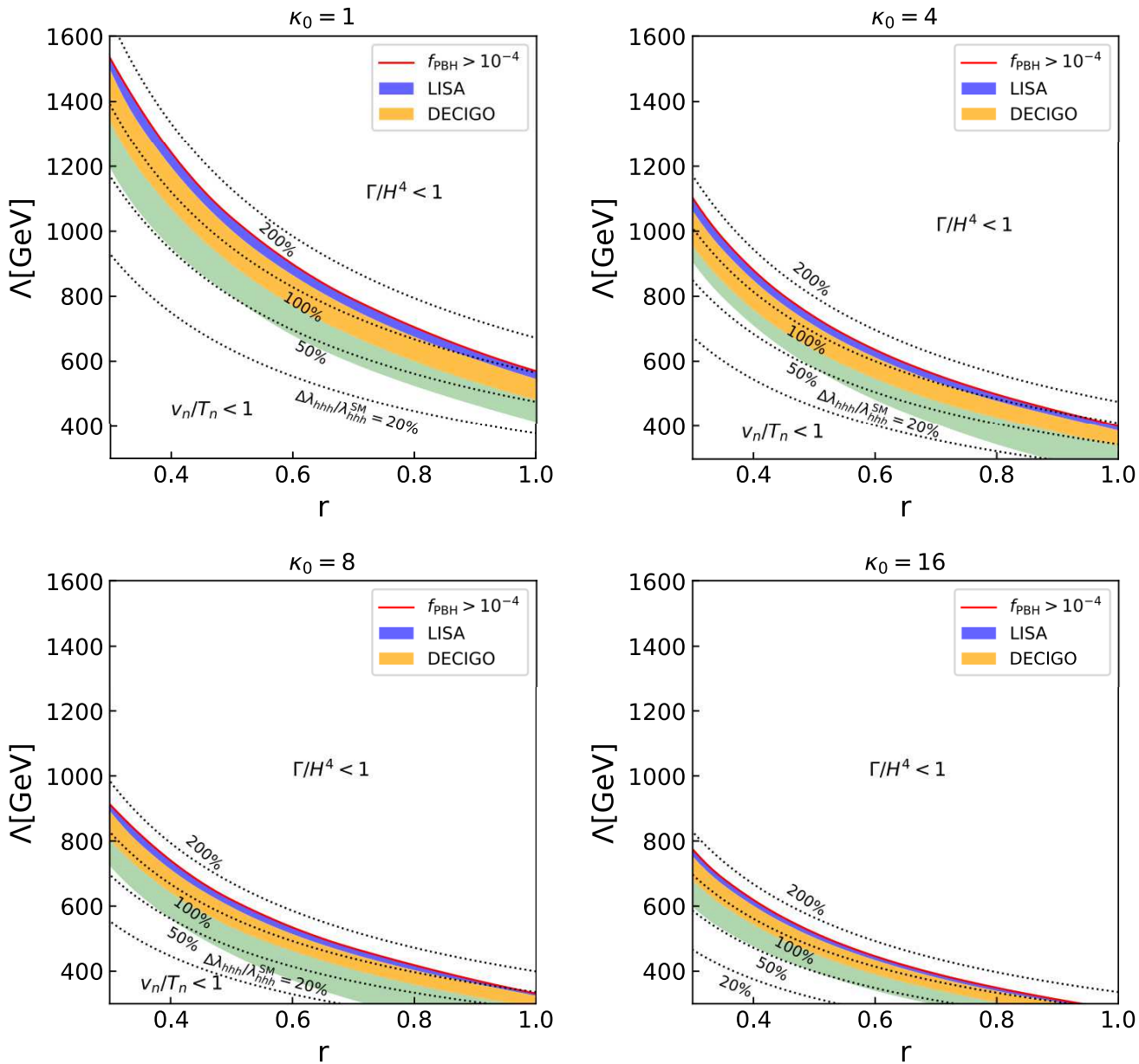
The fraction of PBHs and GW parameters

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

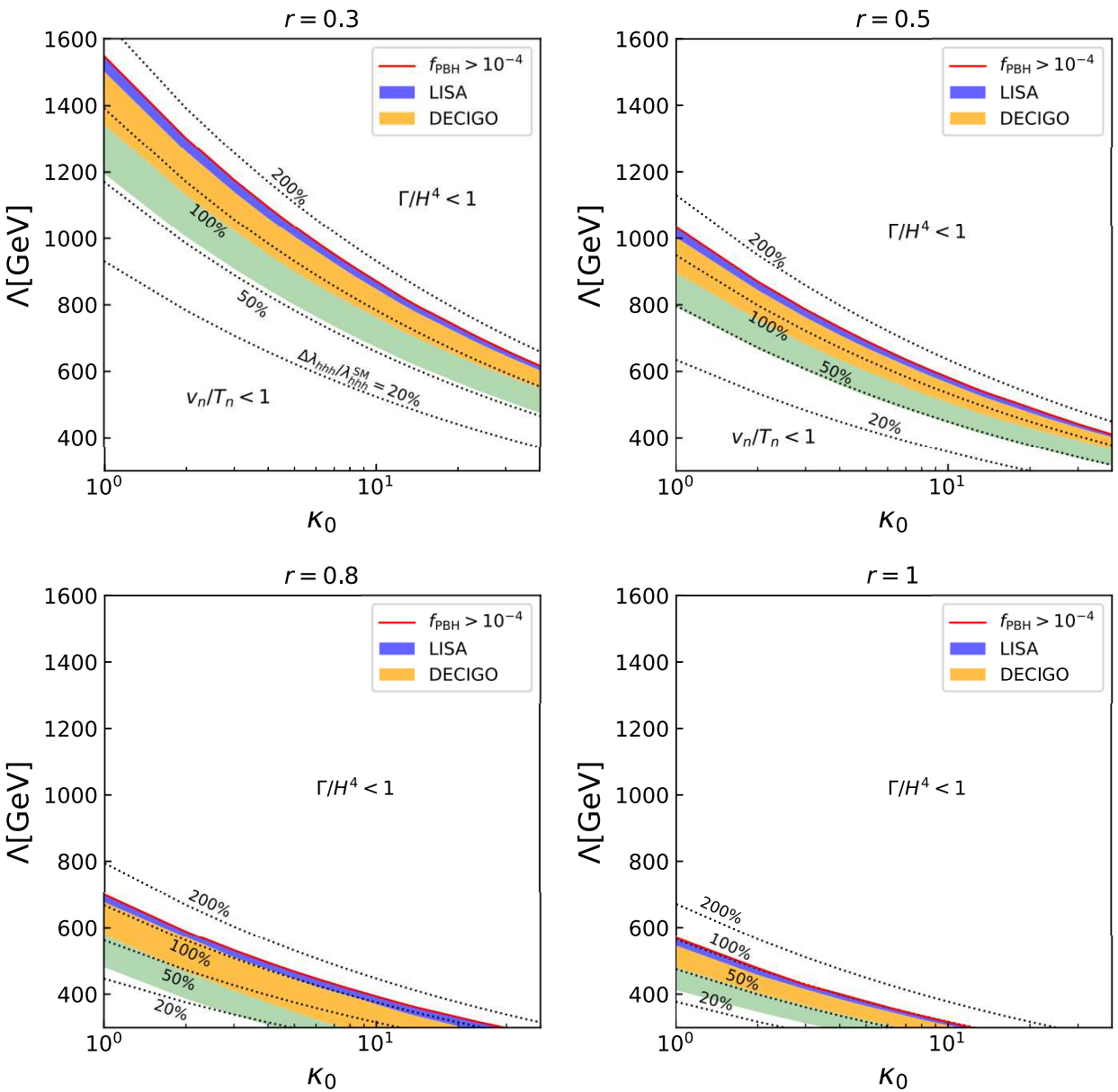
[Hashino, Kanemura, Takahashi and Tanaka, arXiv: 2211.16225]



PBH formation in the naHEFT



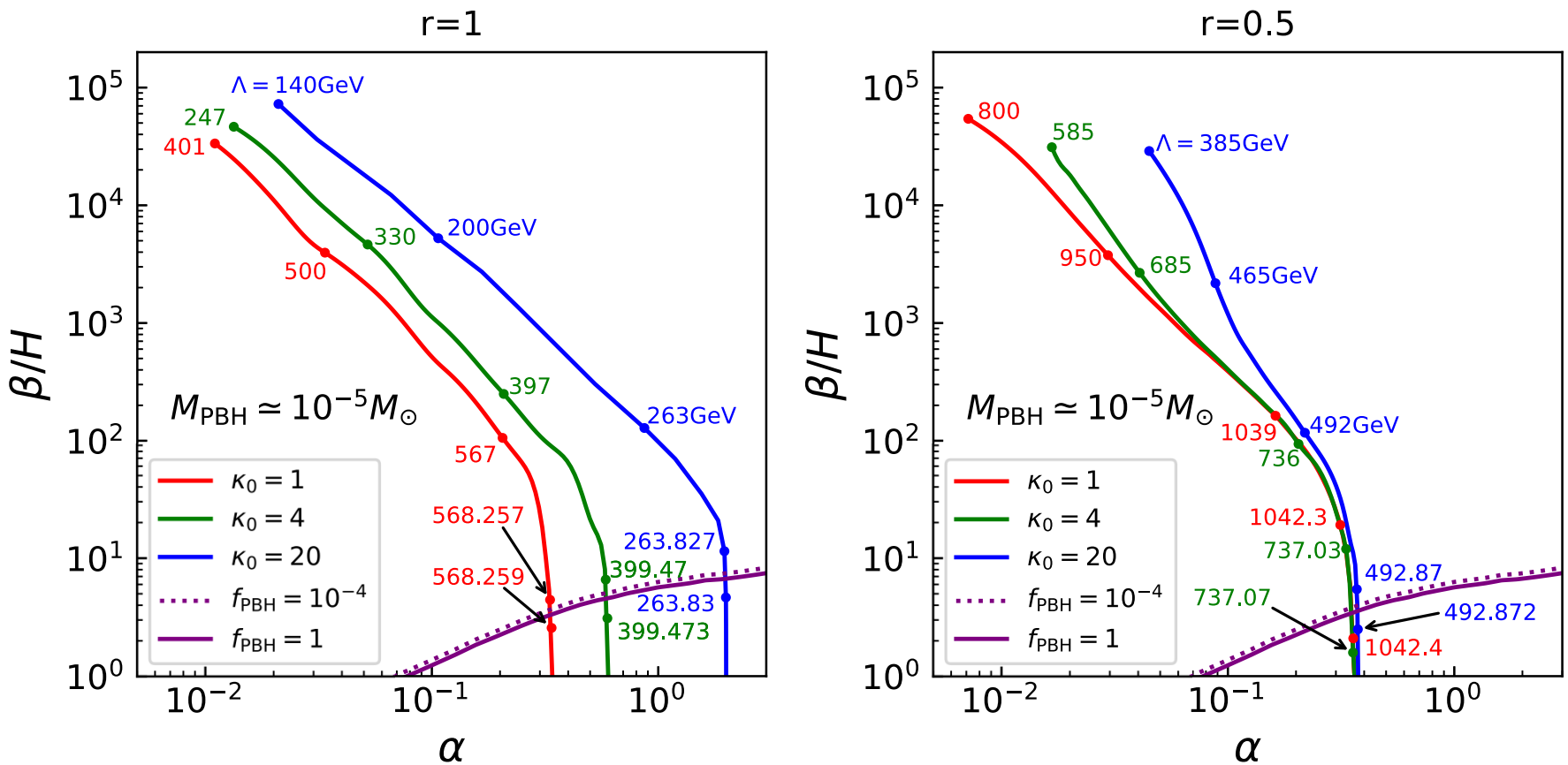
PBH formation in the naHEFT



Fraction of the primordial black holes

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

[Hashino, Kanemura, Takahashi and Tanaka, arXiv: 2211.16225]



What is the meaning of “nearly aligned”?

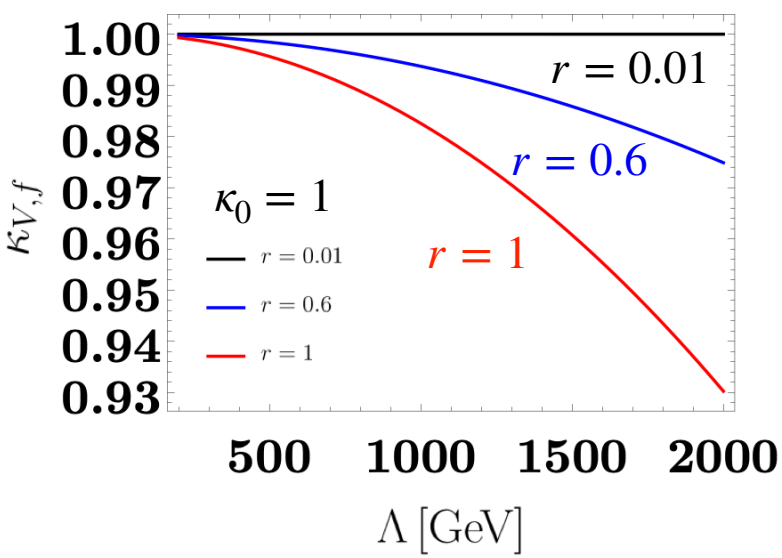
- The naHEFT in the canonical basis [Kanemura and Nagai, JHEP 03 (2022)]

$$\mathcal{L}_{\rm naHEFT} = -\frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \qquad U = \exp\left(\frac{i}{v}\pi^a\tau^a\right)$$

$$+\frac{v^2}{4}\left(1+2\kappa_V\frac{\hat{h}}{v}+\kappa_{VV}\frac{\hat{h}^2}{v^2}+\mathcal{O}\left(\hat{h}^3\right)\right)\mathrm{Tr}\left[D_\mu U^\dagger D^\mu U\right]$$

$$+\frac{1}{2}\left(\partial_\mu\hat{h}\right)\left(\partial^\mu\hat{h}\right)-\frac{1}{2}M_h^2\hat{h}^2-\frac{1}{3!}\frac{3M_h^2}{v}\kappa_3\hat{h}^3-\frac{1}{4!}\frac{3M_h^2}{v^2}\kappa_4\hat{h}^4+\mathcal{O}\left(h^5\right)$$

$$-\sum_{f=u,d,e} m_{f^i}\left[\left(\delta^{ij}+\kappa_f^{ij}\frac{h}{v}+\mathcal{O}\left(h^2,\pi^2\right)\right)\bar{f}_L^i f_R^j + h.c.\right],$$



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 naHEFT

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

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

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

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

Expand the logarithmic part in terms of ϕ

- Up to dimension six

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

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

- Up to dimension eight

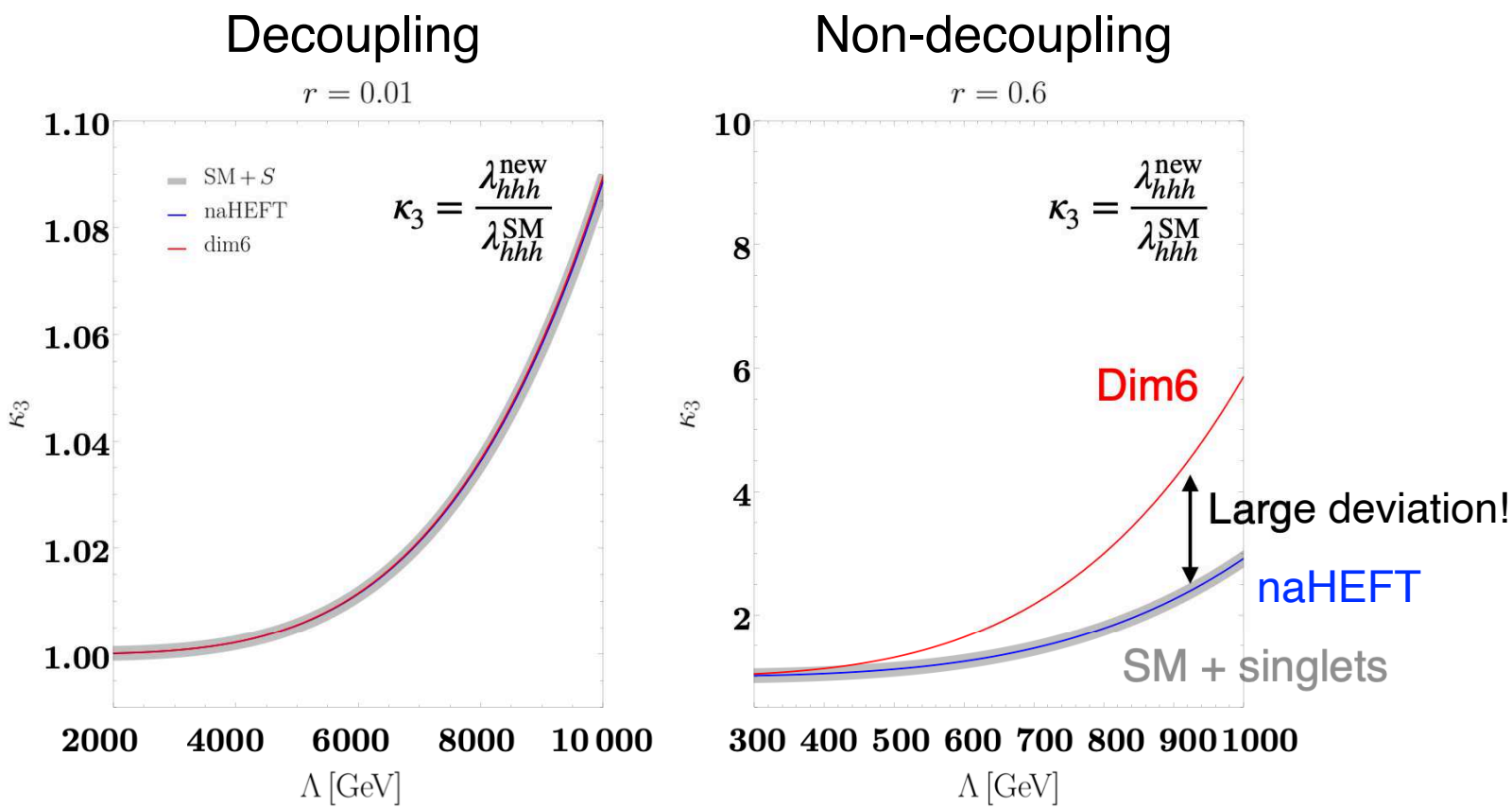
$$V_{\rm BSM}(\Phi) = \frac{1}{f_6^2}\left(|\Phi|^2 - \frac{v^2}{2}\right)^3 - \frac{1}{f_8^4}\left(|\Phi|^2 - \frac{v^2}{2}\right)^4$$

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

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

SMEFT vs naHEFT: hhh coupling

[Kanemura and Nagai, JHEP 03 (2022)]



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

NaHEFT and SM with singlets

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

[Kanemura and Nagai, JHEP 03 (2022)]

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

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

- We consider the SM with singlets $\vec{S} = (S_1, S_2, \cdots S_N)\,, \quad \langle S_i \rangle = 0\,.$

$$V(\Phi, \vec{S}) = m^2 |\Phi|^2 + \lambda |\Phi|^4 + \frac{M^2}{2} (\vec{S} \cdot \vec{S}) + \frac{\kappa_{\rm p}}{2} |\Phi|^2 (\vec{S} \cdot \vec{S}) + \frac{\lambda_S}{4} (\vec{S} \cdot \vec{S})^2$$

- Form factors

$$\mathcal{M}^2(h) = \Lambda^2 + \kappa_{\rm p} \left(|\Phi|^2 - \frac{v^2}{2} \right), \qquad \kappa_0 = \kappa_2 = N$$

$$\mathcal{K}(h) = \kappa_2 \frac{\Lambda^2}{3v^2} r \left[1 - \frac{M^2}{\mathcal{M}^2(h)} \right],$$

$$\mathcal{F}(h) = \mathcal{Y}^{ij}(h) = \hat{\mathcal{Y}}^{ij}(h) = 0\,,$$

NaHEFT and SM with singlets

- Predictions

$$\kappa_V = 1 - \kappa_2 \frac{\xi}{6} \frac{\Lambda^2}{v^2} r^2 ,$$

$$\kappa_u^{ij} = \kappa_d^{ij} = \kappa_e^{ij} = \kappa_V \delta_{ij} ,$$

$$\kappa_{VV} = 1 - \kappa_2 \frac{\xi}{6} \frac{\Lambda^2}{v^2} r^2 (3 - 2r) ,$$

$$\kappa_3 = 1 + \frac{4\xi}{3} \frac{\Lambda^4}{v^2 M_h^2} \left[\kappa_0 r^3 - \kappa_2 \frac{M_h^2}{8\Lambda^2} r^2 (3 - 2r) \right] ,$$

$$\kappa_4 = 1 + \frac{16\xi}{3} \frac{\Lambda^4}{v^2 M_h^2} \left[\kappa_0 r^3 \frac{(3 - r)}{2} - \kappa_2 \frac{M_h^2}{16\Lambda^2} r^2 \frac{(25 - 38r + 16r^2)}{3} \right]$$

Form factor

$$\mathcal{M}^2(h) = \Lambda^2 + \kappa_{\rm p} \left(|\Phi|^2 - \frac{v^2}{2} \right) ,$$

$$\mathcal{K}(h) = \kappa_2 \frac{\Lambda^2}{3v^2} r \left[1 - \frac{M^2}{\mathcal{M}^2(h)} \right] ,$$

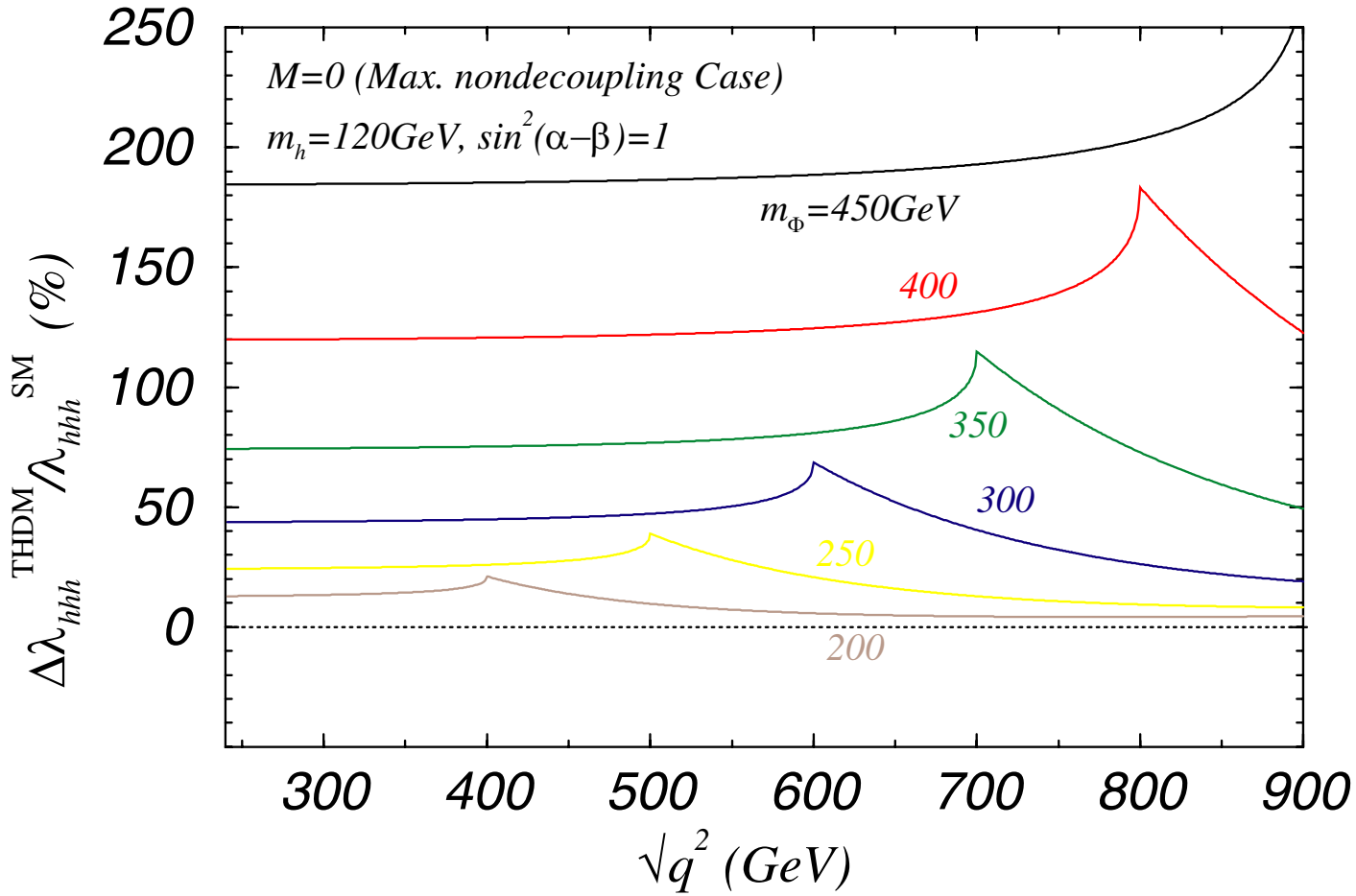
$$\mathcal{F}(h) = \mathcal{Y}^{ij}(h) = \hat{\mathcal{Y}}^{ij}(h) = 0 ,$$

By measuring κ, we can estimate the structure of form factors

Nearly aligned Higgs Effective Field Theory is very useful !

Momentum dependence on hhh coupling

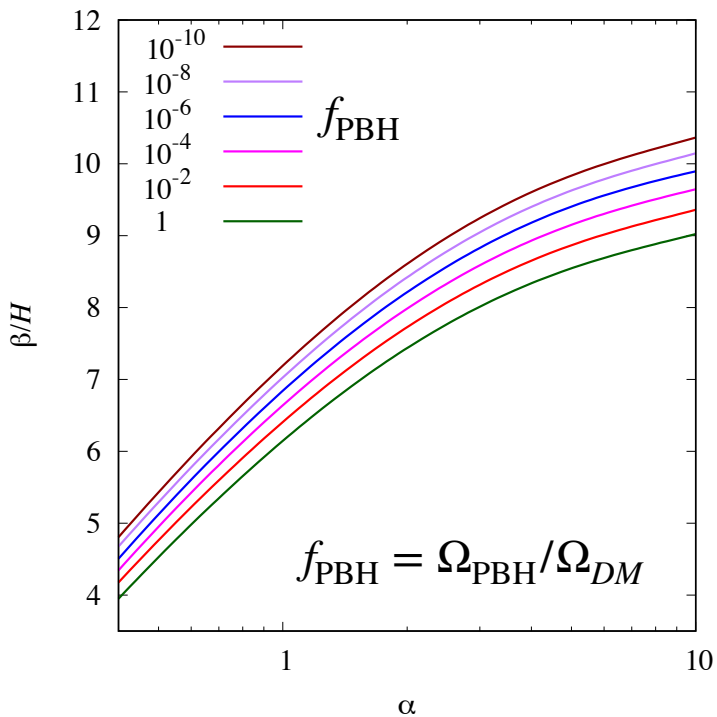
[Kanemura, Okada, Senaha and Yuan, PRD 70 (2004)]

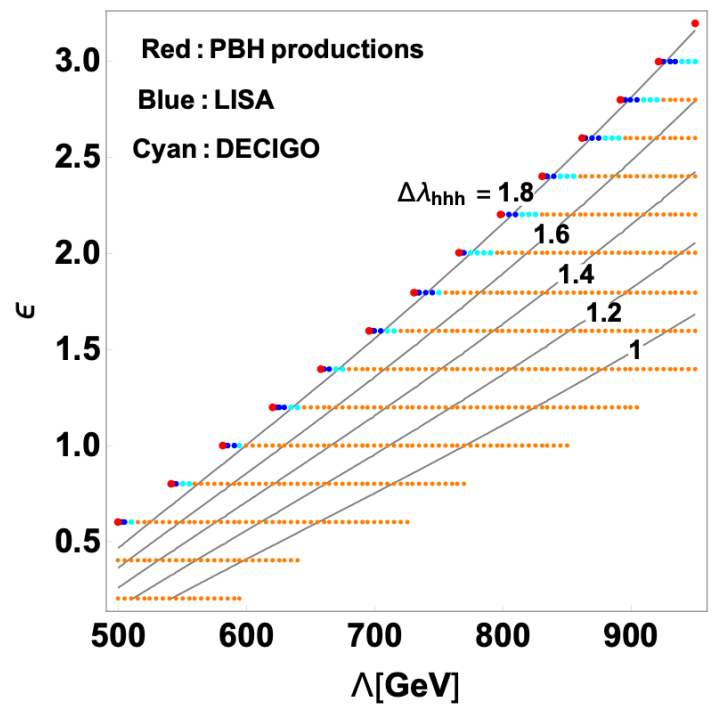


PBH production in the standard model EFT

- Effective potential in the SMEFT [Hashino, Kanemura and Takahashi, PLB 833 (2021)]

$$V_{eff}(\varphi, T) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \frac{\epsilon}{8\Lambda^2}\varphi^6 + \frac{1}{16\Lambda^4}\varphi^8 + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi)\left(\ln\left(\frac{M_i^2(\varphi)}{Q^2}\right) - c_i\right) + \Delta V_T$$





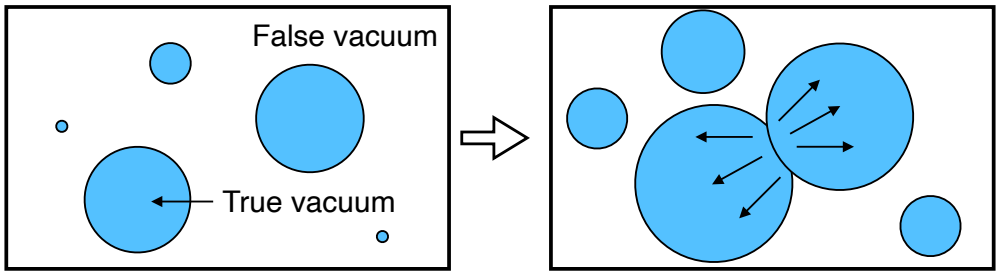
Gravitational waves from 1st OPT

Origin of the gravitational waves (GWs) from 1st OPT [Caprini et al., JCAP 04 (2016)]

①Bubble collisions

②Compression wave of plasma

③Plasma turbulence



Eg) Compression wave (leading contribution)

PTPlot used [Caprini et al., JCAP 03 (2020) 024]

[LISA: arXiv:1702.00786]

$$\Omega_{\rm SW}(f)h^2 = \tilde{\Omega}_{\rm SW}^{\rm peak} h^2 \times \left(f/\tilde{f}_{\rm SW}\right)^3 \left(\frac{7}{4+3\left(f/\tilde{f}_{\rm SW}\right)^2}\right)^{7/2}$$

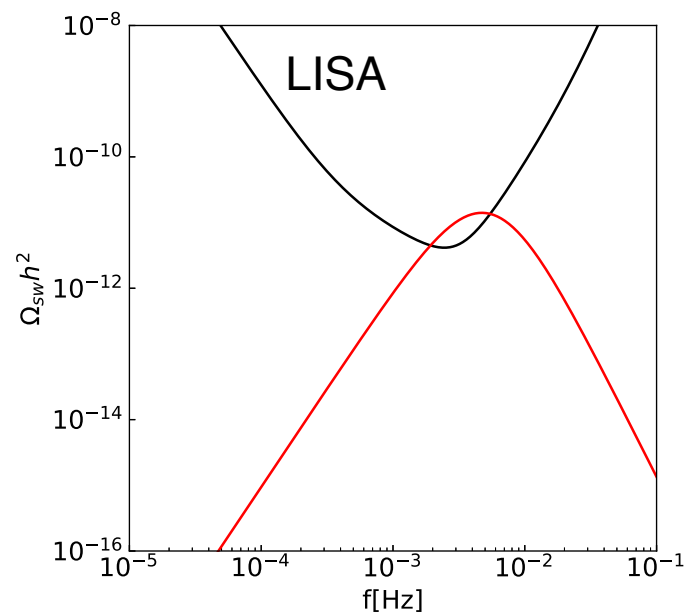
The peak height

$$\tilde{\Omega}_{\rm sw}^{\rm peak} h^2 \simeq 2.65\times 10^{-6} v_b \tilde{\beta}_{\rm GW}^{-1} \left(\frac{\kappa_{\rm sw}\alpha_{\rm GW}}{1+\alpha_{\rm GW}}\right)^2 \left(\frac{100}{g_*}\right)^{1/3}$$

The peak frequency

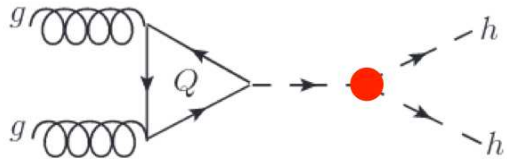
$\kappa_{\rm sw}$: efficiency factor

$$\tilde{f}_{\rm sw} \simeq 1.9\times 10^{-2} \frac{1}{v_b} \tilde{\beta}_{\rm GW} \left(\frac{T_n}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6} \ {\rm mHz}$$

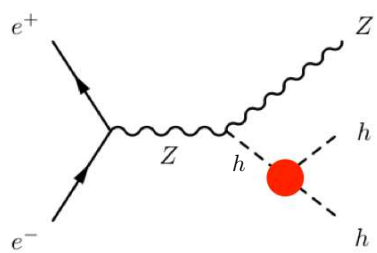


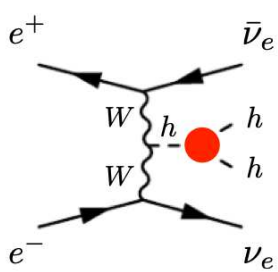
hhh measurement at future colliders

- Hadron colliders



- Lepton colliders





[de Blas et al., arXiv: 1905.03764]