Probing first-order electroweak phase transition via primordial black holes

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Introduction

- Standard Model (SM) is consistent with the result in LHC

  Unsolved problems: baryon asymmetry of the Universe (BAU), dark matter …

- Exploring dynamics of EW phase transition (EWPT) is important

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

- How can we test first-order EWPT?

  - hhh coupling measurement [Kanemura et al., PLB606 (2005), Grojean et al., PRD71 (2005)]

  - Gravitational wave observations [Grojean and Servant, PRD 75 (2007), Kakizaki et al., PRD 92 (2015)]

  - Primordial black hole observations [Hashino, Kanemura and Takahashi, PLB 833 (2021), Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]

- We focus on an extended Higgs EFT to obtain model independent results

  [Kanemura and Nagai, JHEP 03 (2022); Kanemura, Nagai and Tanaka, JHEP 06 (2022)]

Nearly aligned Higgs EFT (naHEFT)

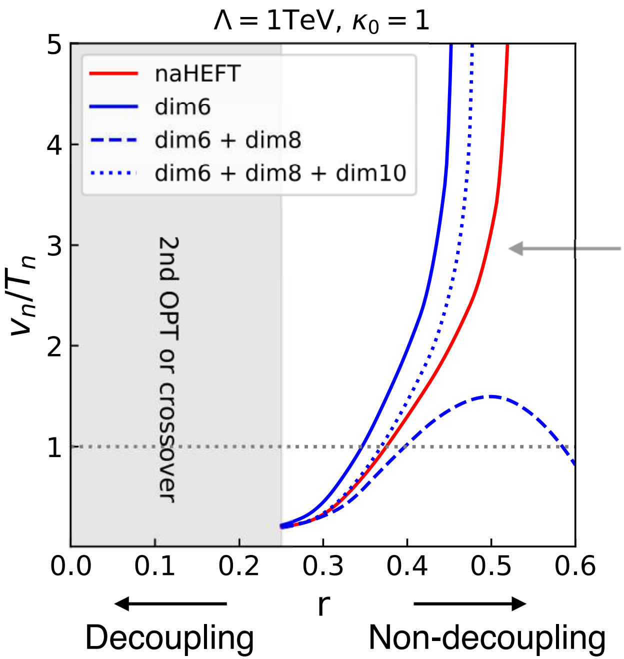
$$V_{\rm EFT} = V_{\rm SM} + \frac{\kappa_0}{64\pi^2}\left[\mathcal{M}^2(\phi)\right]^2 \ln\frac{\mathcal{M}^2(\phi)}{\mu^2} + \frac{\kappa_0}{2\pi^2} T^4 J_{\rm BSM}\left(\frac{\mathcal{M}^2(\phi)}{T^2}\right)$$

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

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

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

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



consistent with results in SM with a singlet scalar

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

Large discrepancy b/w SMEFT and naHEFT

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

Primordial black holes (PBHs)

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

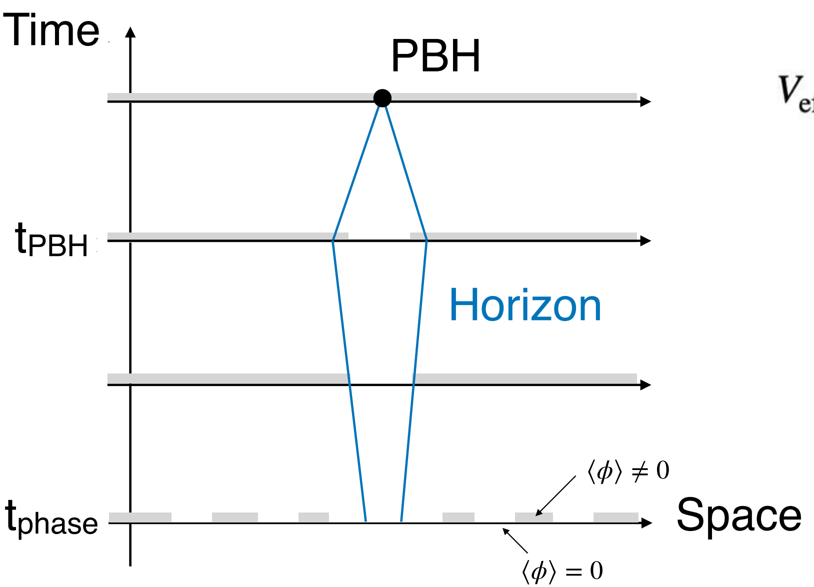
[Liu et al., PRD 105 (2022)]

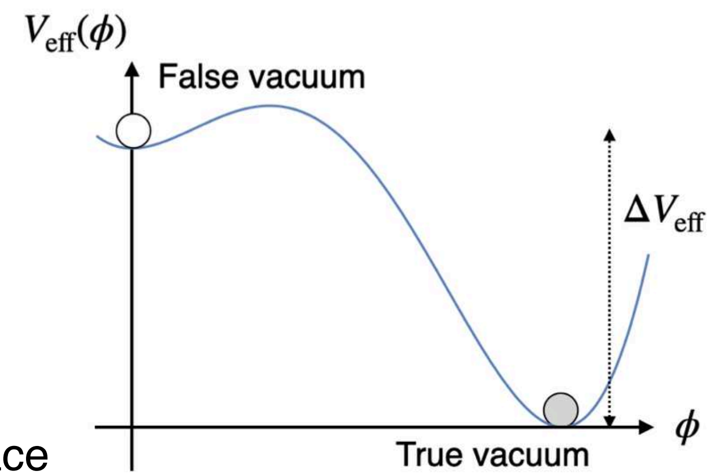
$$\delta = \frac{\rho_{\rm over} - \rho_{\rm back}}{\rho_{\rm back}} > \delta_C$$

PBHs can be formed by 1st order phase transition

- 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 formed by first-order EWPT

- PBH formation is discussed in SMEFT [Hashino, Kanemura and Takahashi, PLB 833 (2021)]

We discuss PBH properties by using the naHEFT instead of the SMEFT

- Mass of PBH formed by EWPT

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

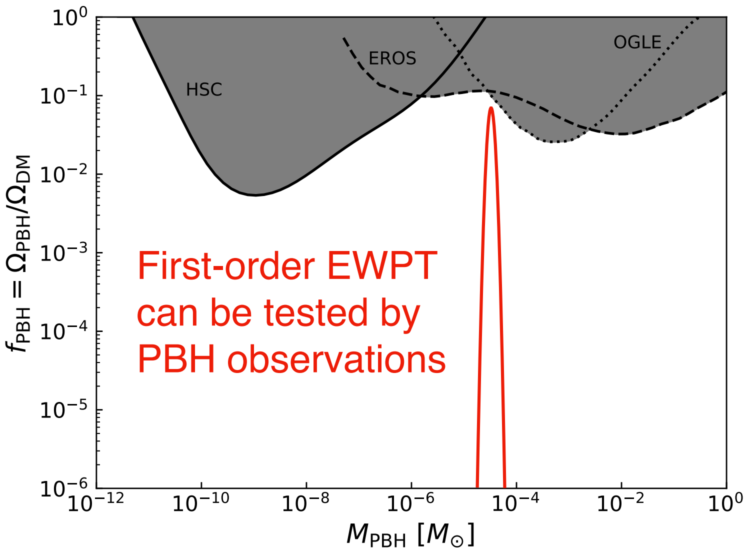
- Microlensing observations

Subaru HSC, OGLE, EROS

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

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

[EROS, http://eros.in2p3.fr]



- Future observations: PRIME, Roman

$f_{\rm PBH} > 10^{-4}$ will be constrained

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

Testing first-order EWPT

How can we test the first-order EWPT?

- hhh coupling measurement [Grojean et al., PRD71 (2005), Kanemura et al., PLB606 (2005)]
- GWs from the EWPT [Grojean and Servant, PRD 75 (2007), Kakizaki et al., PRD 92 (2015)]
- PBHs formed by the EWPT [Hashino, Kanemura and Takahashi, PLB 833 (2021), Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]

- Current and future experiments

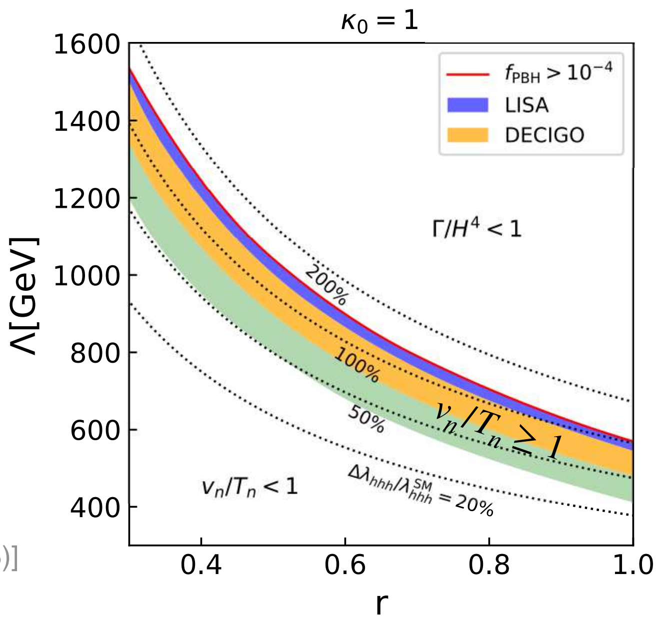
PBH: Subaru HSC, OGLE, PRIME, Roman

GWs: LISA, DECIGO On going!

Colliders: ILC, HL-LHC

In addition to collider and GW observations, we can test the first-order EWPT via PBH observations!

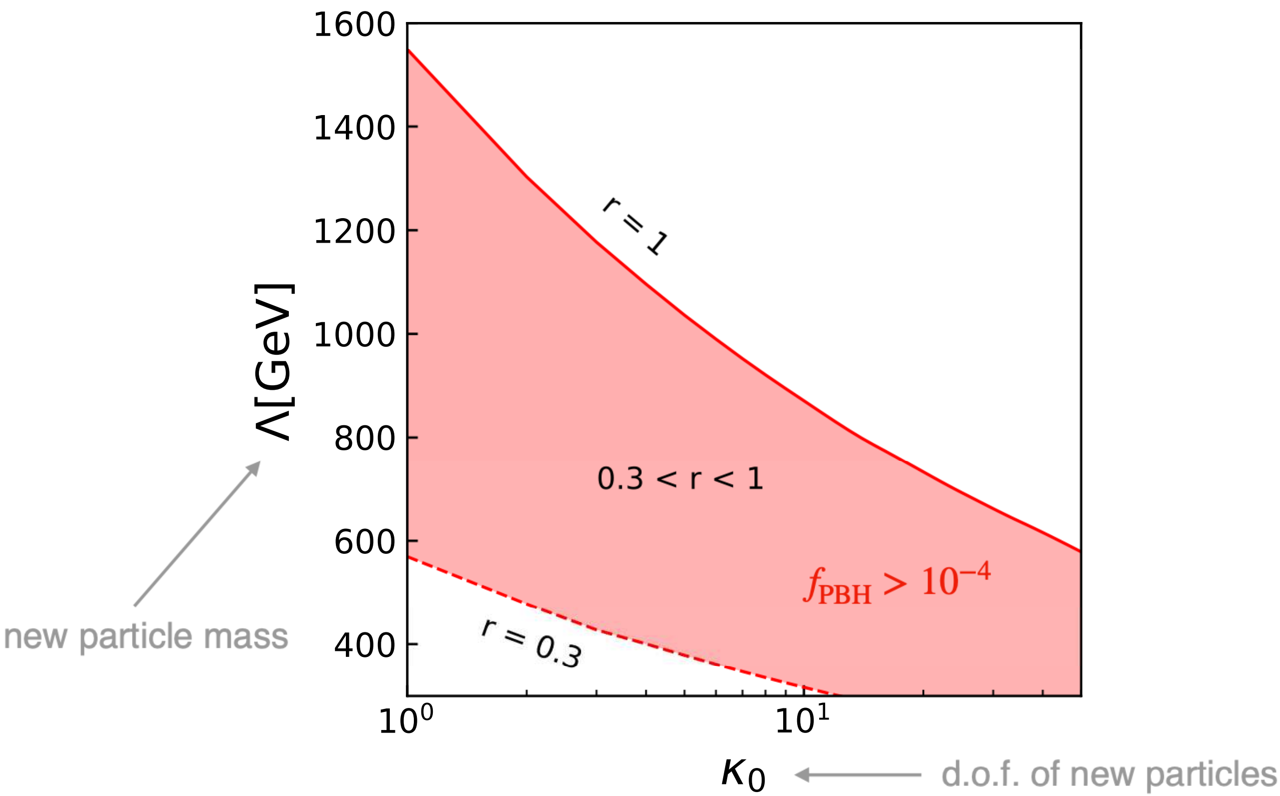
[Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]



Parameter region explored by PBHs

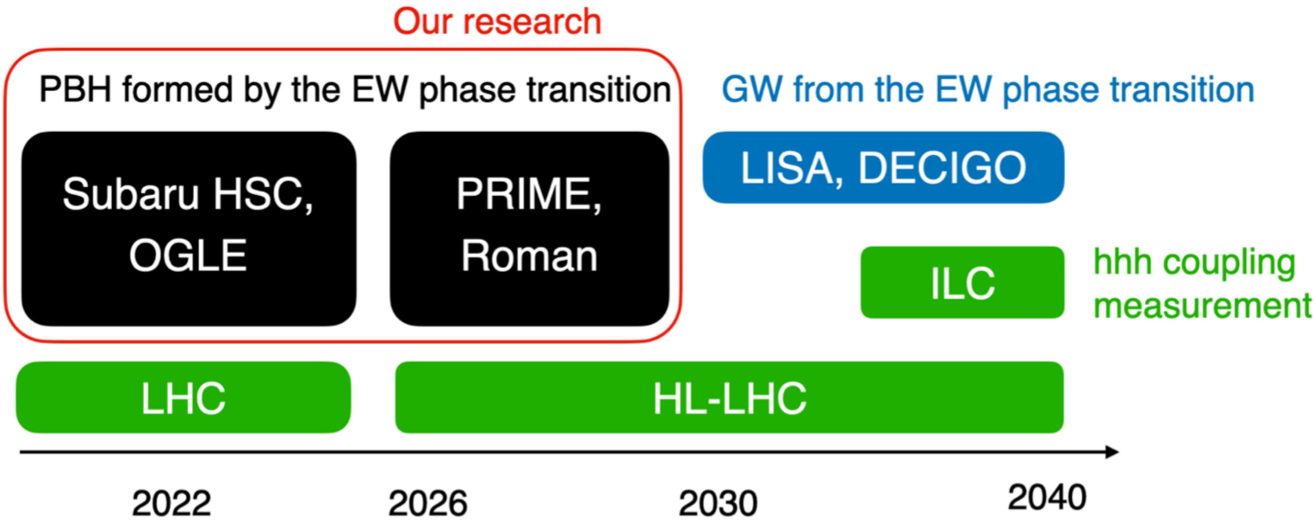
Wide parameter region can be explored by PBH observations

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



Summary

- naHEFT can appropriately describe new physics with first-order EWPT
- First-order EWPT can be tested by PBH observations
- Wide parameter regions of new physics can be explored by PBH observations



Back up

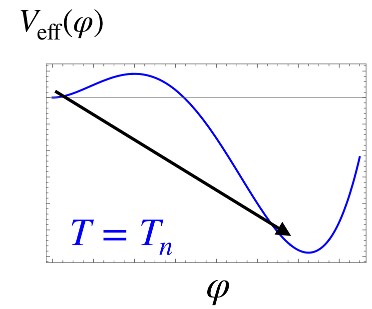
Sphaleron decoupling condition

- EW baryogenesis requires strongly 1st order EW phase transition (EWPT)

→ 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 EW phase transition (EWPT)

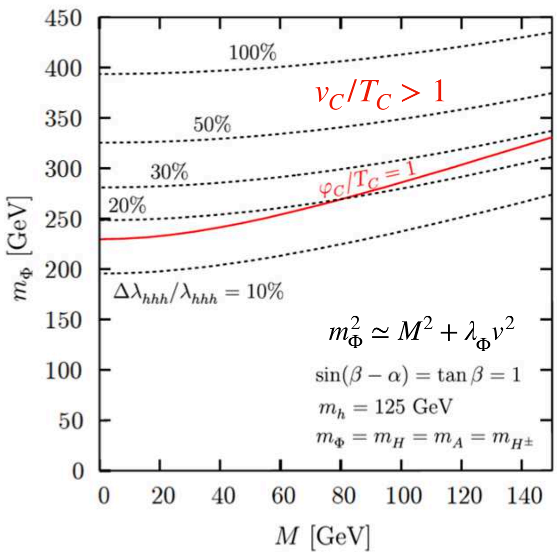


Eg) Two Higgs doublet model

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

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

Non-decoupling effect is important!



Gravitational waves (GWs)

Predicted GW spectrum from the first-order EWPT is also discussed

- Nucleation rate for the vacuum bubbles [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)]

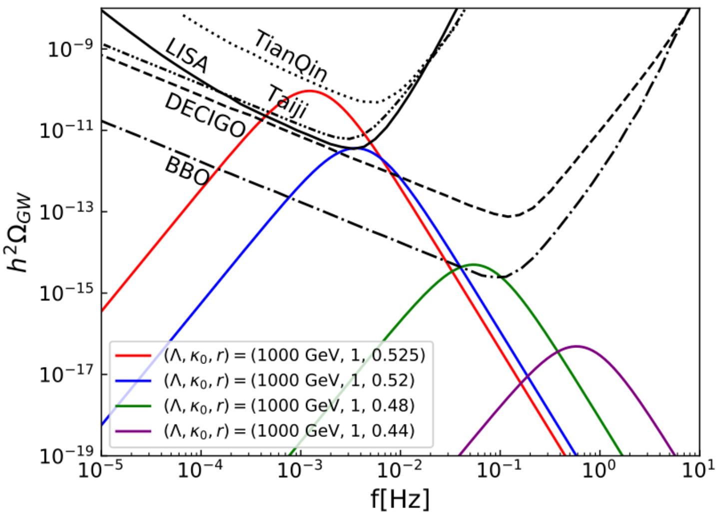
- Parameters characterizing first-order phase transition

T_n : temperature starting the phase transition

α_{GW} : released latent heat

β_{GW} : duration of the phase transition

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



Introduction

- Quantum corrections to the effective potential [Coleman and Weinberg: PRD 7 (1973)]

$$V_{\rm CW}(\varphi) = \frac{[M^2(\varphi)]^2}{64\pi^2}\ln\frac{M^2(\varphi)}{Q^2} \qquad \ln\frac{M^2(\varphi)}{Q^2} = \ln\frac{M^2}{Q^2} + \ln\left(1+\frac{\lambda_\Phi\varphi^2}{M^2}\right)$$

- Assume $M^2(\varphi) = M^2 + \lambda_\Phi\varphi^2$ $(M^2 \gg \lambda_\Phi v^2)$ [Buchmuller and Wyler: Nucl. Phys. B268 (1986)] [Grzadkowski et al.: JHEP 10 (2010)]

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

$\Rightarrow$ SMEFT is a good approximation

- In non-decoupling case ($M^2 \lesssim \lambda_\Phi v^2$), $V_{\rm CW}$ cannot be expanded in terms of φ

$\Rightarrow$ SMEFT may not be able to describe non-decoupling new physics

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

- Higgs EFT can describe non-decoupling effects [Feruglio: Int. J. Mod. Phys. A 8 (1993)]

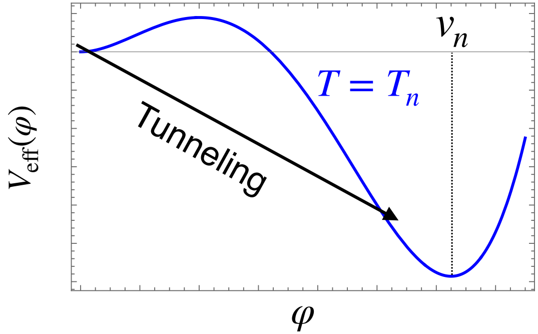
Extension of Higgs EFT is promising!

First-order EW phase transition

- Effective potential (high temperature)

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

Only boson loops contribute



- Strength of the phase transition:

$$\frac{v_n}{T_n} \sim \frac{v_c}{T_c} \sim \frac{2E}{\lambda(T_c)}$$

  - large E: extended Higgs models with the non-decoupling effects
  - small λ: standard model effective field theory (SMEFT)

- Sphaleron decoupling condition:

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

$$\zeta_{\rm sph}(T_n) = \frac{v_n}{E_{\rm sph}(T_n)}\left[43.5 + 7\ln\frac{v_n}{T_n} - \ln\left(\frac{T_n}{100{\rm GeV}}\right)\right]$$

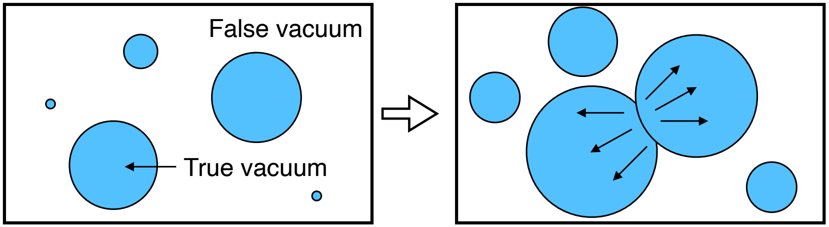
Gravitational waves

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)

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

The peak height

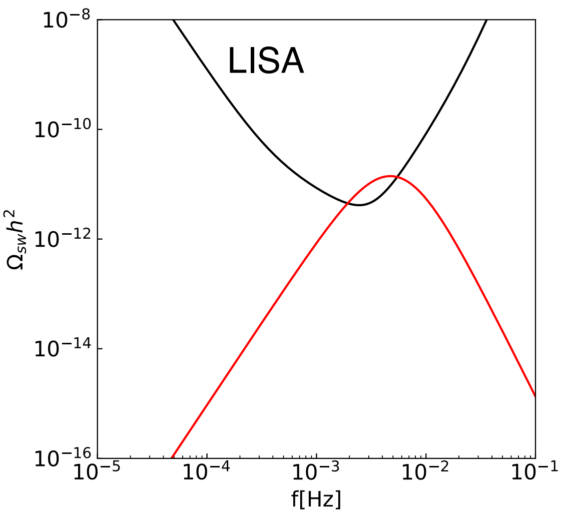
$$\tilde{\Omega}^{\rm peak}_{\rm sw}h^2 \simeq 2.65\times 10^{-6} v_b \tilde{\beta}^{-1}_{\rm GW}\left(\frac{\kappa_{\rm sw}\alpha_{\rm GW}}{1+\alpha_{\rm GW}}\right)^2\left(\frac{100}{g_*}\right)^{1/3}$$

The peak frequency

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

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

[LISA: arXiv:1702.00786]

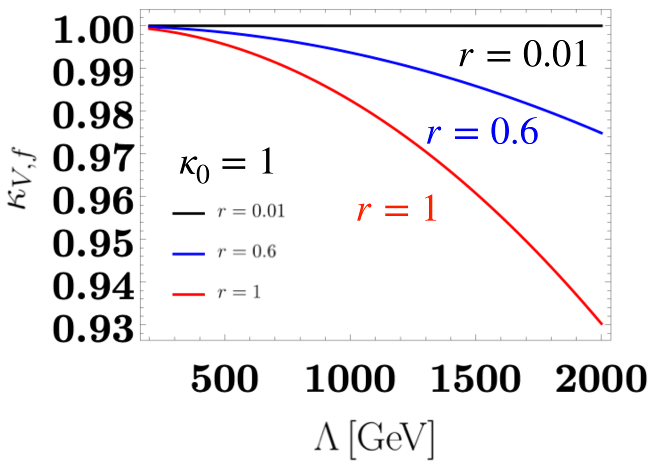


What is the meaning “nearly aligned”?

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

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

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



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

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

← $K(h)$, $F(h)$, $V(h)$ 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

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

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

- 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

Primordial black holes

Primordial black holes

- Primordial black holes (PBH)：BH formed at the early Universe

Before the star formation

- Condition for the PBH formation

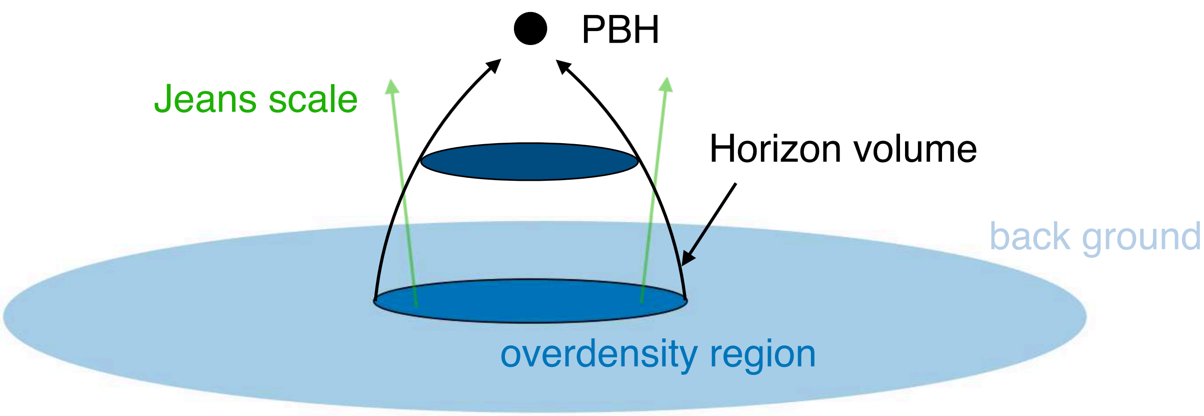
$$\delta = \frac{\rho_{\rm over} - \rho_{\rm back}}{\rho_{\rm back}} > 0.45$$

[Hawking, Mon. Not. Roy. Astron. Soc. 152 (1971),
Hawking and Carr, Mon. Not. Roy. Astron. Soc. 168 (1974),
Harada, Yoo and Kohri, PRD 88 (2013)]

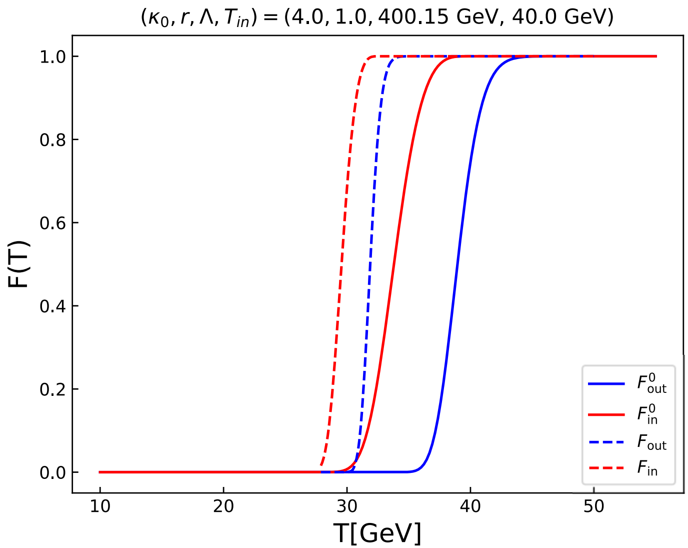
- $\delta > 0.45$ can be satisfied when a first-order phase transition occurs

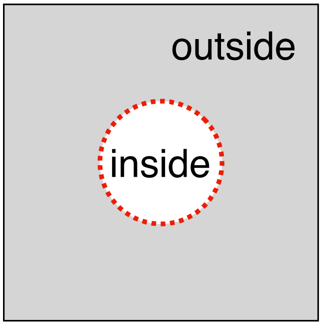
→ PBH formed by a first-order phase transition

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



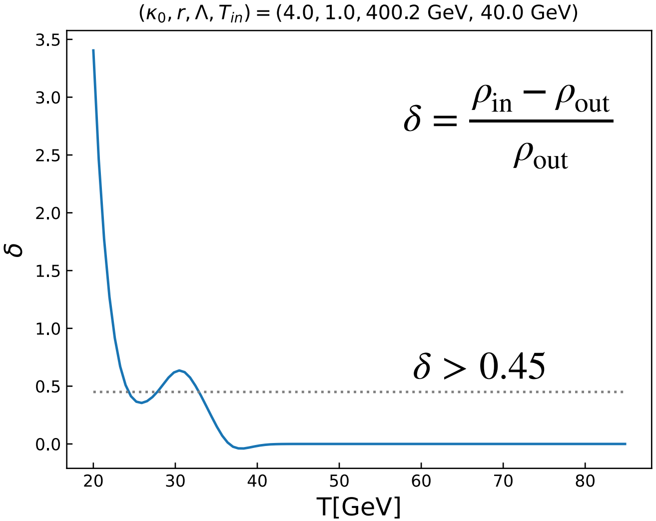
Fraction of the false vacuum





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

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

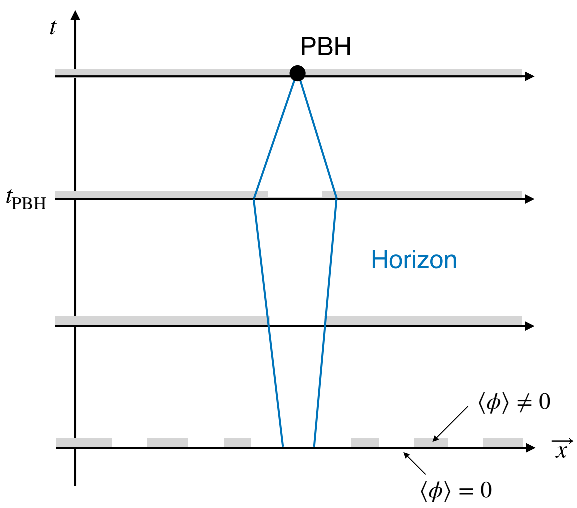


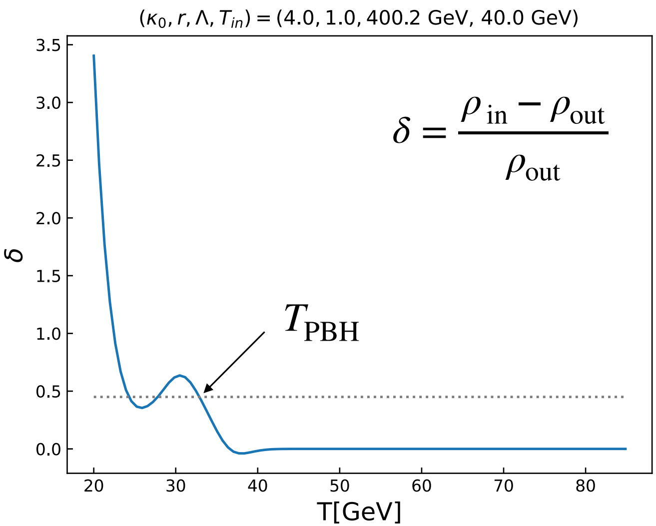
How to obtain PBH fraction?

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

2. Calculate how many Hubble patches at $t_{\rm PBH}$ are included in those at present

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

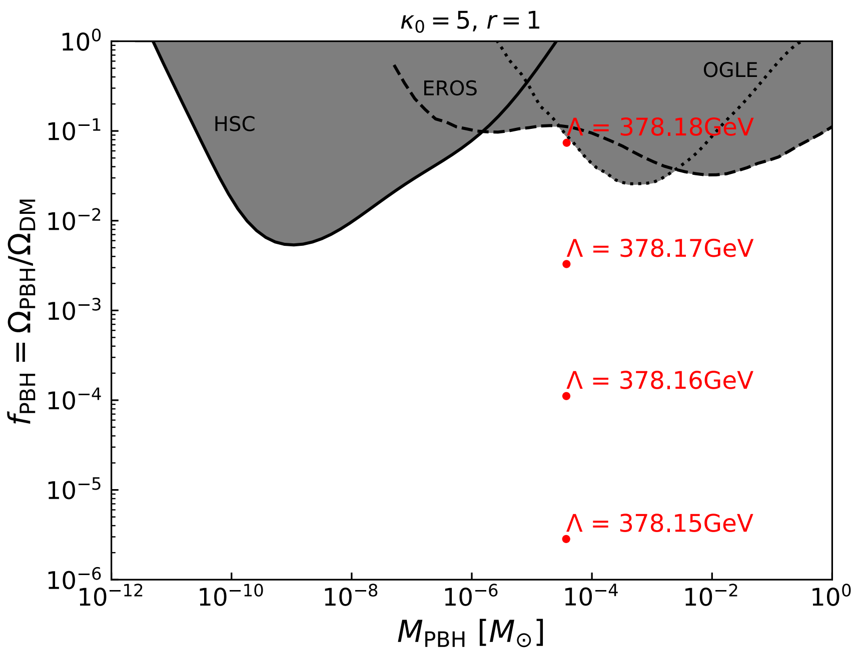




Fraction of primordial black holes

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

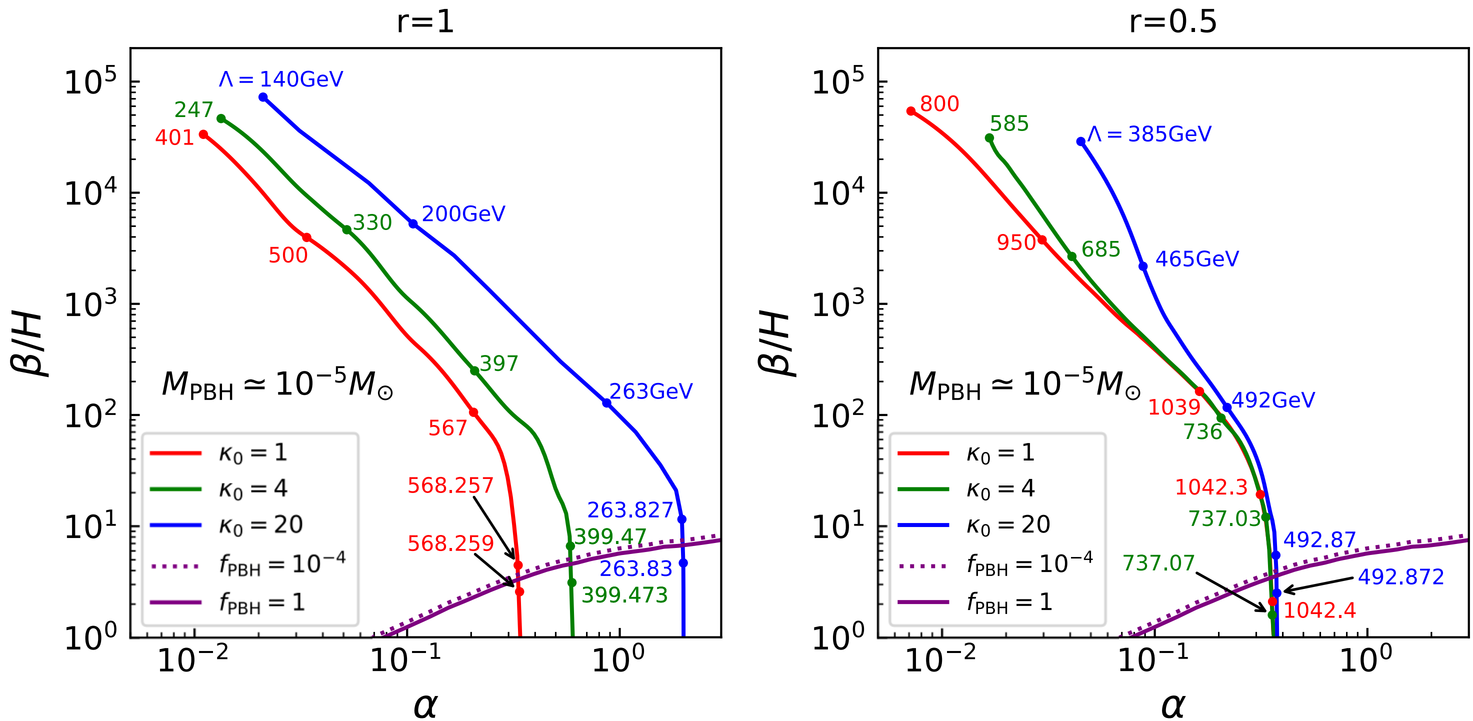
$$P(t_n) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t_n} \frac{a^3(t)}{a^3(t_{\rm PBH})}\frac{1}{H^3(t_{\rm PBH})}\Gamma(t)dt\right], \quad \Gamma_{\rm bubble}(T) \simeq T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left[-\frac{S_3(T)}{T}\right],$$



PBH fraction in naHEFT

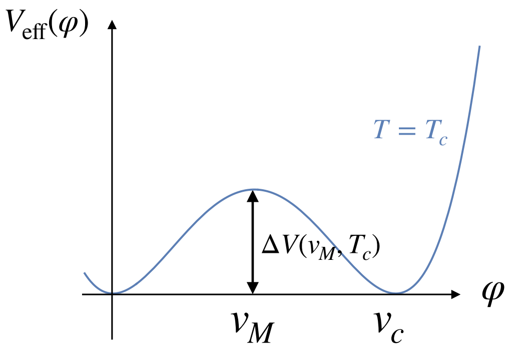
$f_{\rm PBH}$ is very sensitive to the parameters in the nearly aligned Higgs EFT

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



Small beta and PBH formation

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



- 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

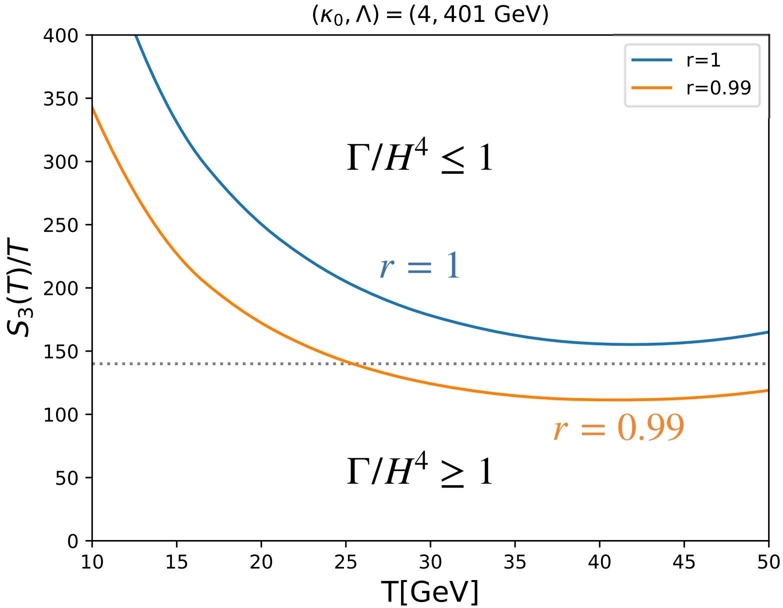
⇒ small β is preferred to delay the first-order phase transition

⇒ PBH formation requires small β

Bubble nucleation

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

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



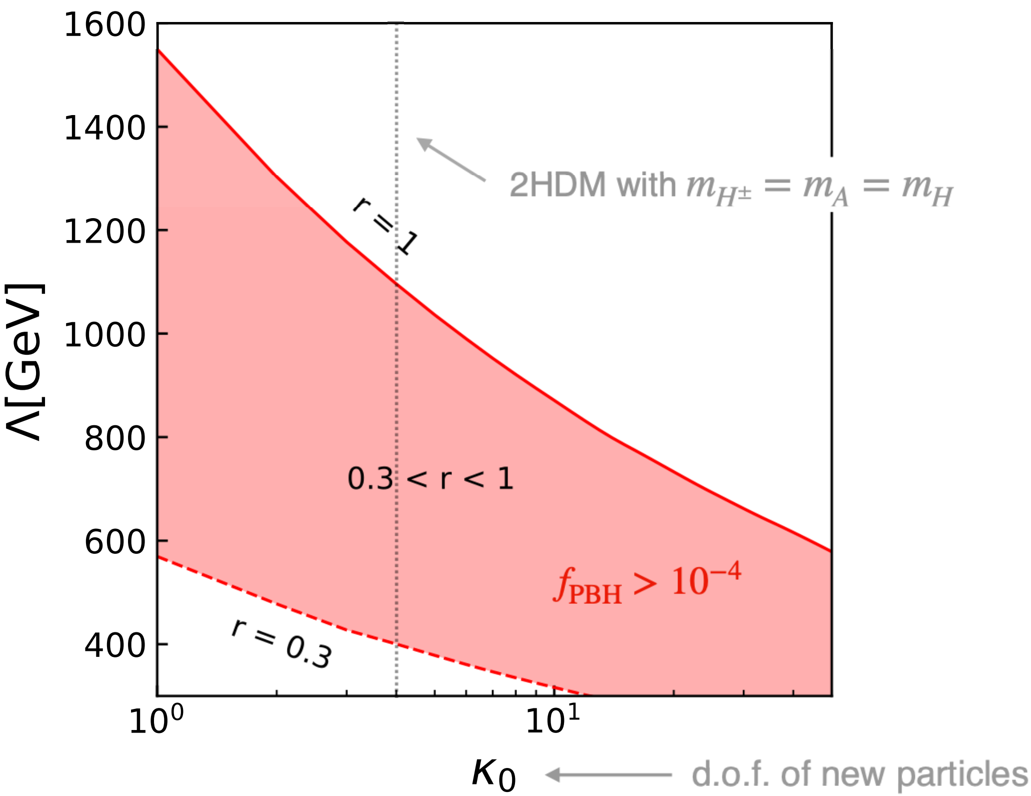
Non-decoupling effects are required to realize the delay of first-order EWPt

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

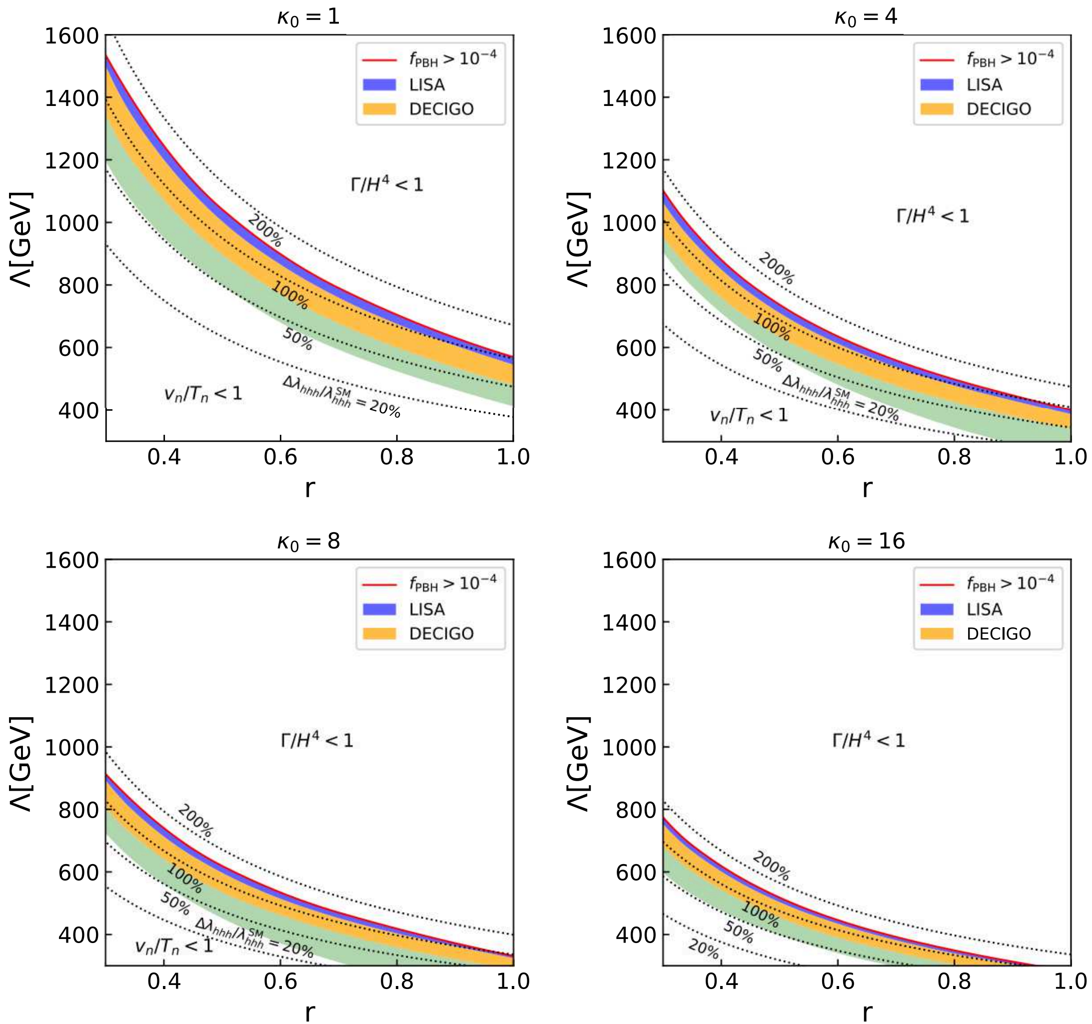
Parameter region explored by PBHs

Wide parameter region can be explored by PBH observations

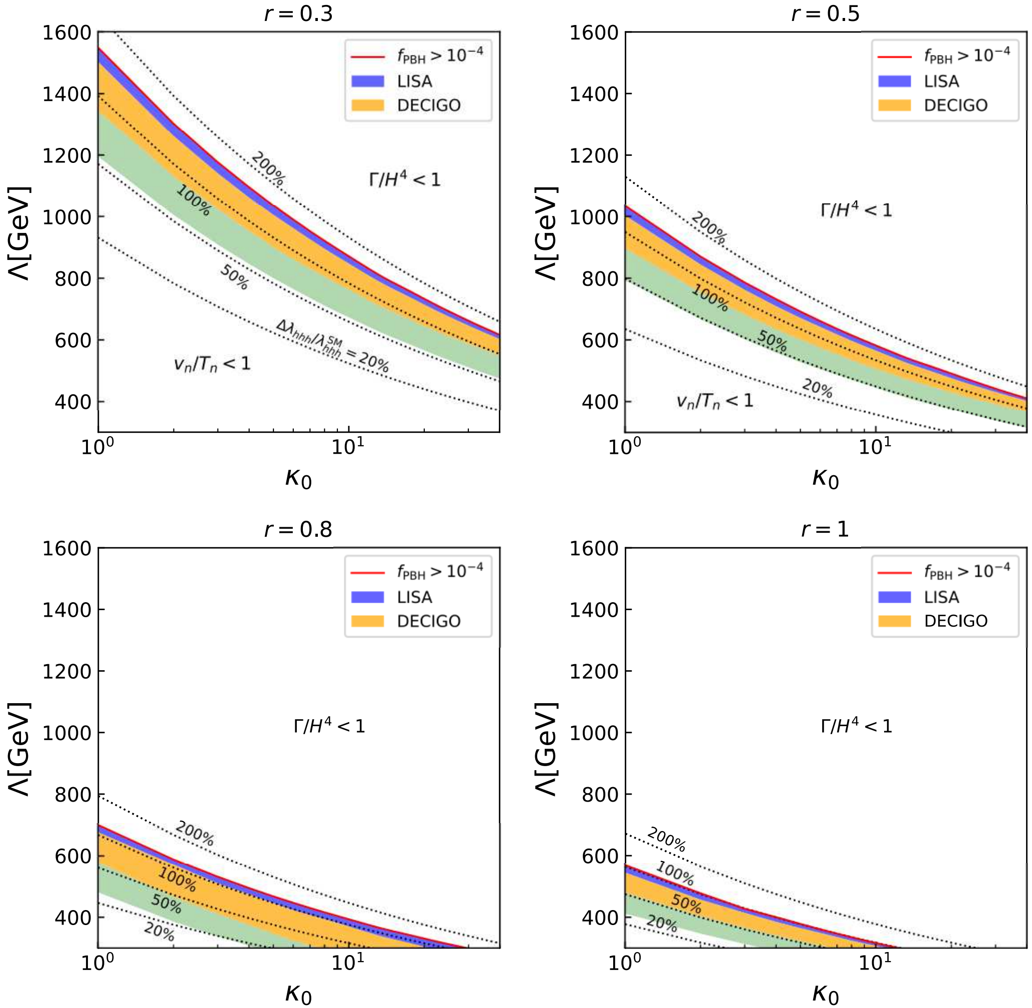
[Hashino, Kanemura, Takahashi and Tanaka, PLB 838 (2023)]



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)]

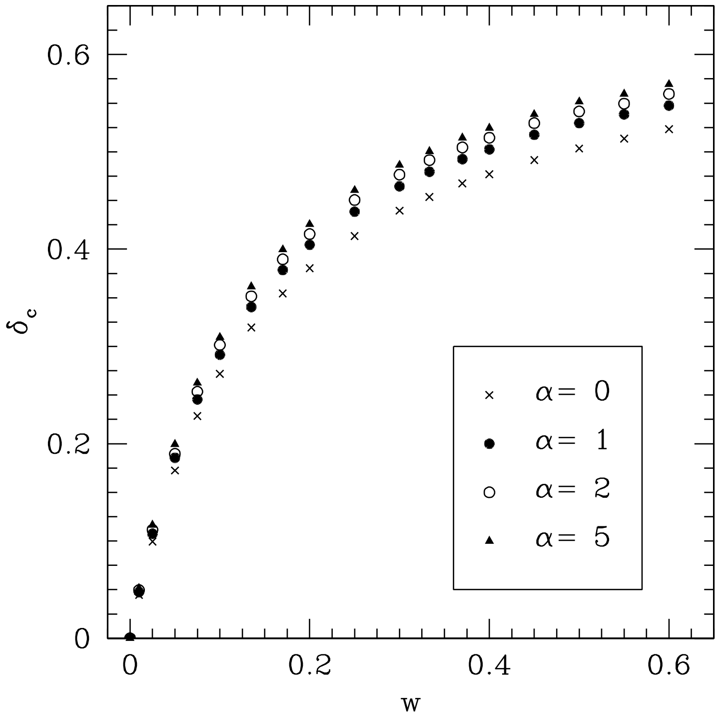
- PBH may be easily realized in vacuum energy dominant universe

$\because$ EoS $\quad p = -\rho$

[Jedamzik and Niemeyer, PRD 59 (1999)

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

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

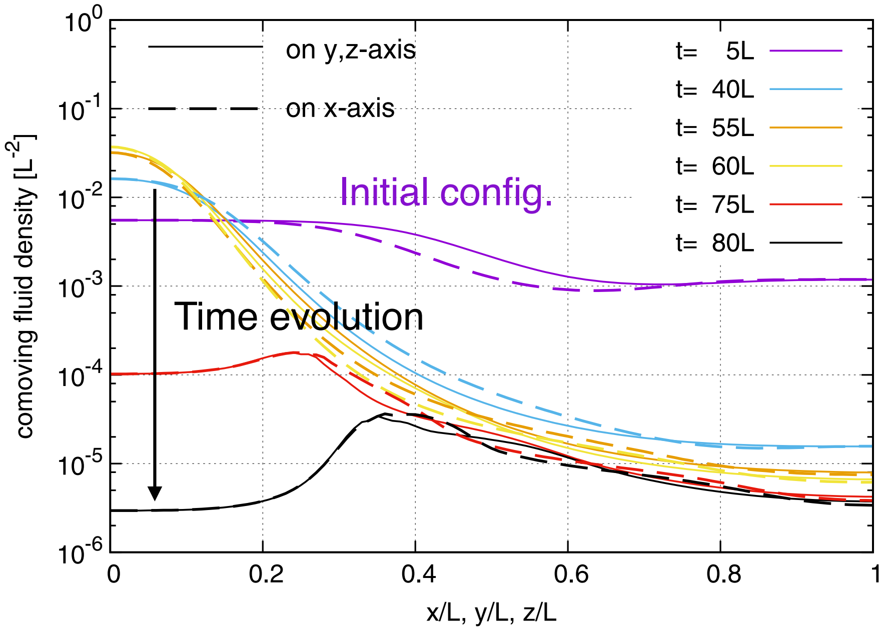


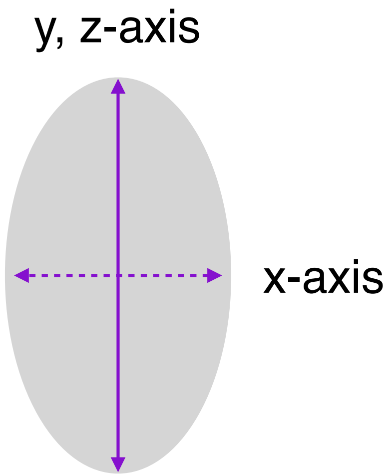
Spherical symmetry and PBH formation

- Non-spherical symmetric case

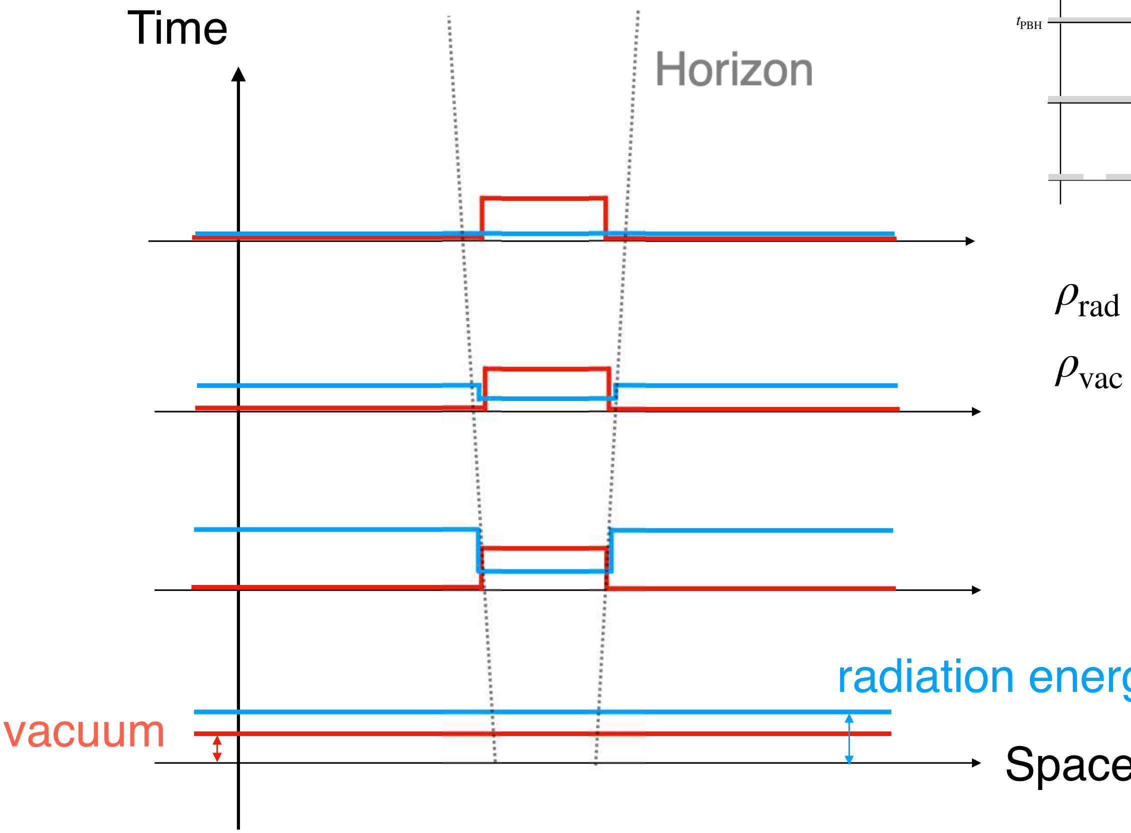
If the over density region does not respect the spherical symmetry, realization of PBH formation might be difficult

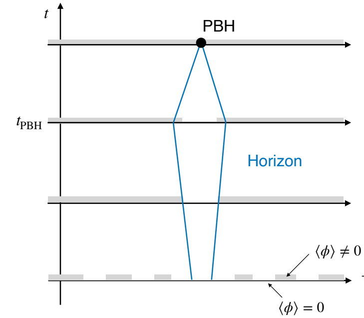
[Yoo, Harada and Okawa, PRD 102 (2020)





Spherical symmetry and PBH formation

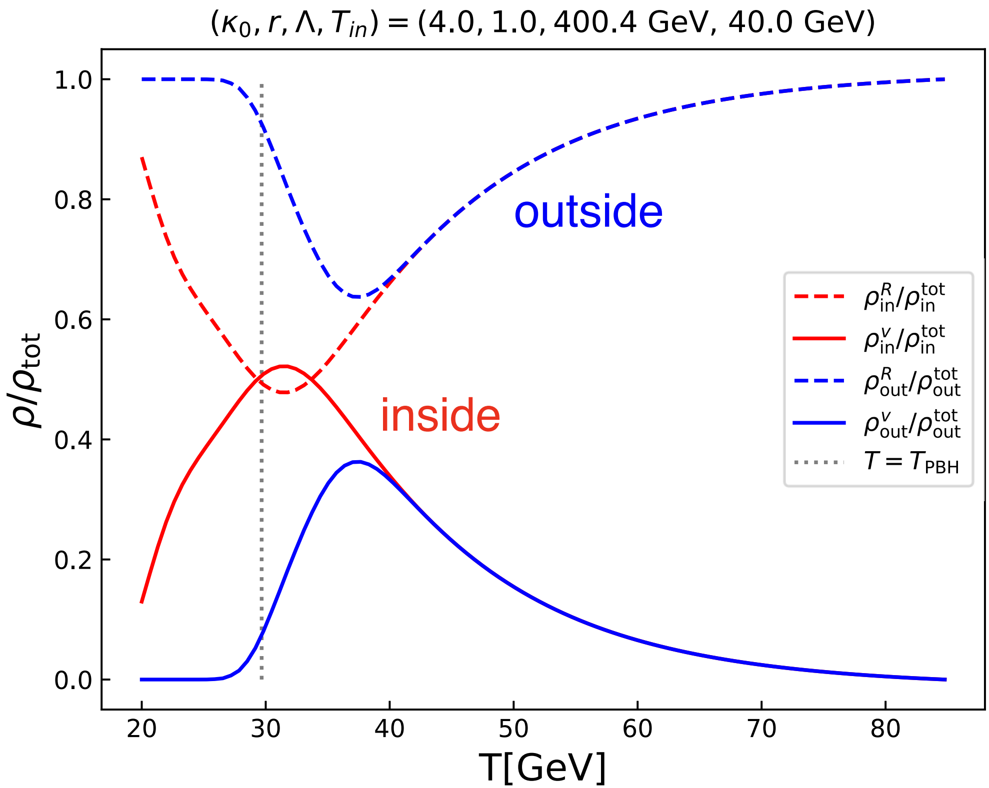


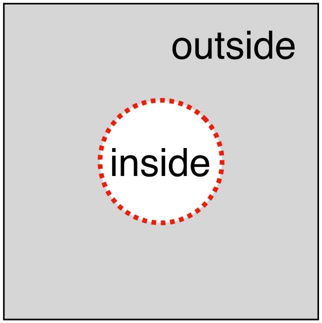


$$\rho_{\rm rad} \propto a^{-4}$$

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

Ratio of energy density





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