Primordial Black Holes as a probe of EW phase transition

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Higgs sector remains unknown

Non-minimal Higgs sectors

- Multi-plet structure
- Symmetries
- Strength of interaction

Important bound from data

vev, M_{h},

SM-like (nearly aligned)

…

Phase transition

CP Violation

⇒ BAU

DM candidate

Models for tiny neutrino masses

Inflatons

…

Rich Phenomenology

Example: 2HDM with softly broken Z_2

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

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

Φ_1 and Φ_2 $\Rightarrow$ $\underline{h, \quad H,} \quad A^0, \; H^\pm \oplus$ Goldstone bosons

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

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

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

masses

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

M_{soft}: soft breaking scale

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

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

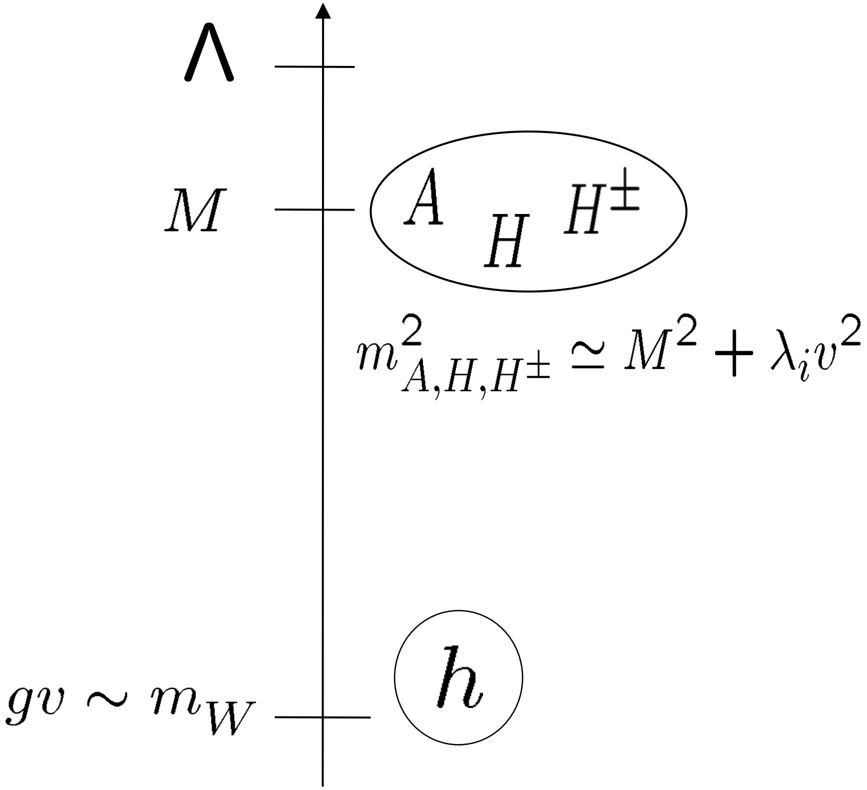
soft-breaking scale

of the discrete symm.

How SM-like is realized?

Λ : Cutoff

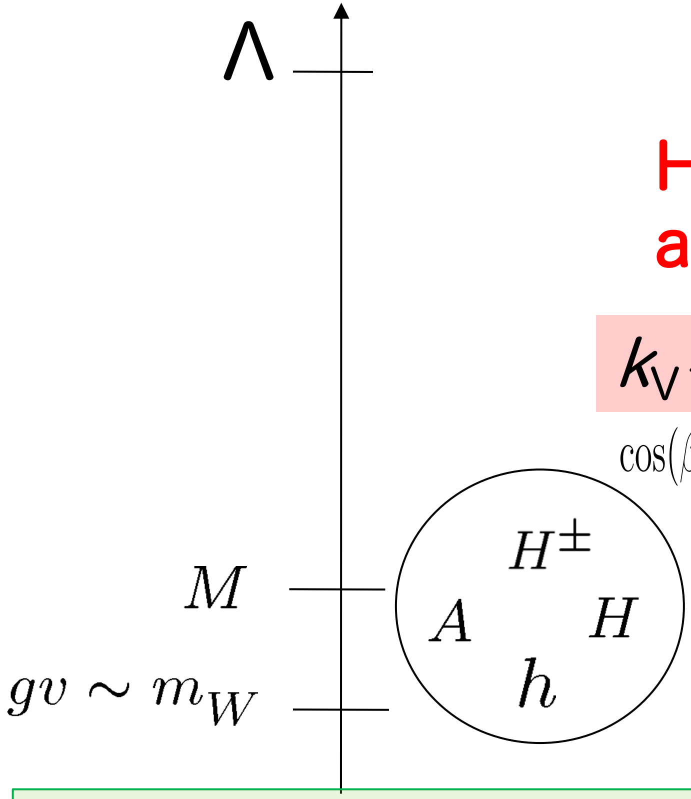
M : Mass scale irrelevant to VEV



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

Effective Theory is the SM

Decoupling



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

Alignment and non-decoupling case

- To study physics of this case is interesting
- New physics appears at TeV scale
- Testable at experiments

EWSB (Higgs physics)
WIMP
Hierarchy problem
EW Phase Transition
…

g-2, B-anomalies,
…

- 1st OPT for EW baryogenesis is a concrete example
- Today's subject

EW phase transition

EWSB

$\Longrightarrow$ EWPT exists in thermal history of Universe

Aspect of PT is crucial
for EW Baryogenesis

EW Baryogenesis

Sakharov Conditions

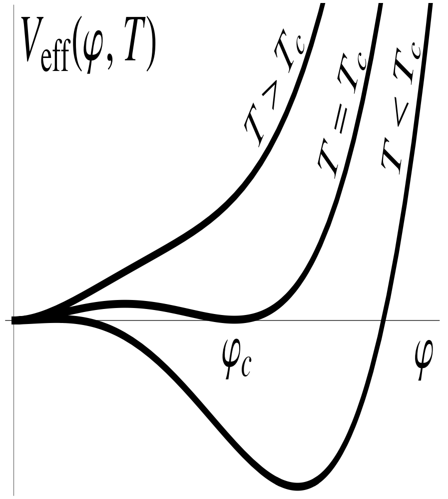
Kuzmin, Ruvakov, Shaposhnikov (1985)

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

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

Physics of Higgs potential

Extended Higgs can satisfy the condition

Effective Potential at finite T (HTE)

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

SM — The condition cannot be satisfied

$$\frac{\varphi_c}{T_c} = \frac{2E}{\lambda_T} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$$

Extended Higgs: Strong 1st OPT possible due to quantum effect

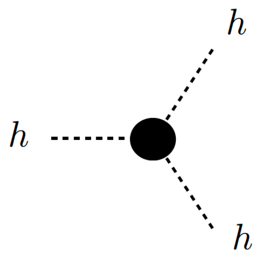
$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underbrace{\sum_\Phi m_\Phi^3 \left(1 - \frac{M^2}{m_\Phi^2}\right)^3 \left(1 + \frac{3M^2}{2m_\Phi^2}\right)}_{\text{Quantum effects of } \Phi (= H, A, H^+, \cdots)}\right\} > 1$$

Prediction: Large deviation in the hhh coupling

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

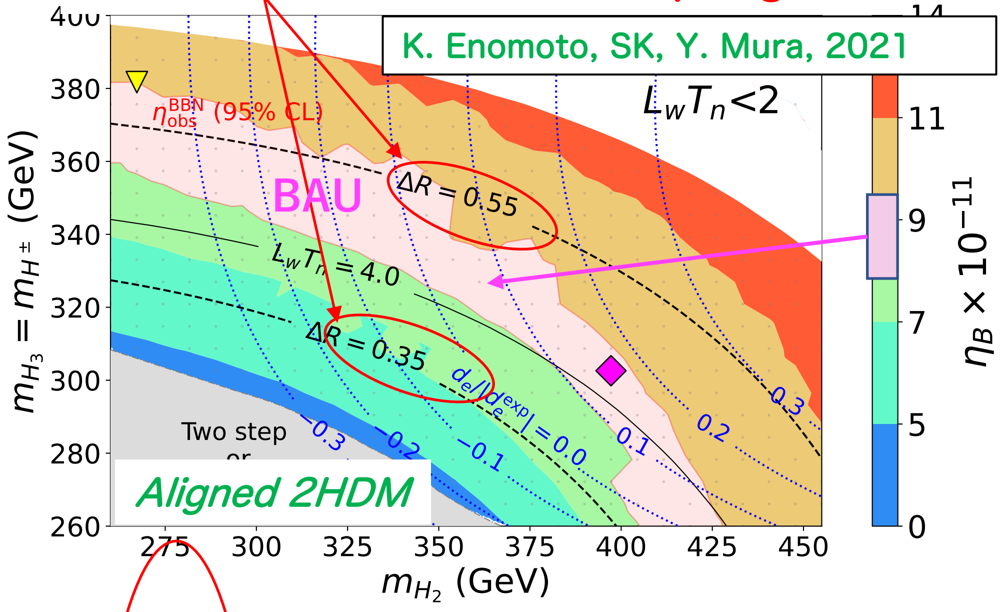
SK, Y. Okada, E. Senaha, 2005 Grojean, Servant, Wells, 2005

Test of strongly 1st OPT



Example
Aligned 2HDM

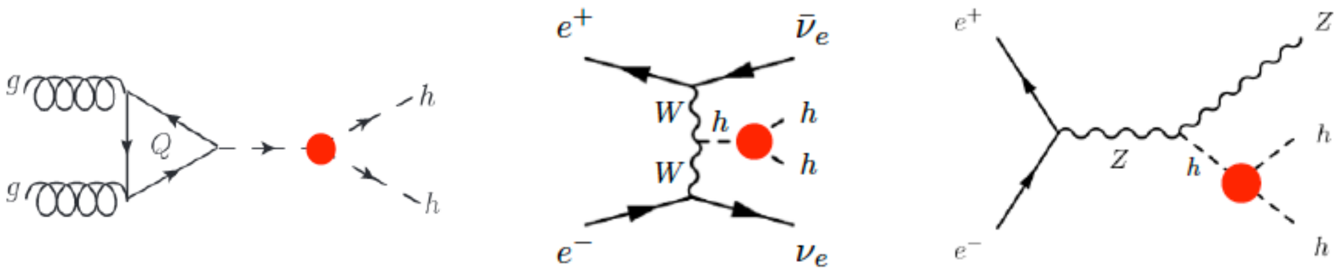
Deviation in the hhh coupling (%)

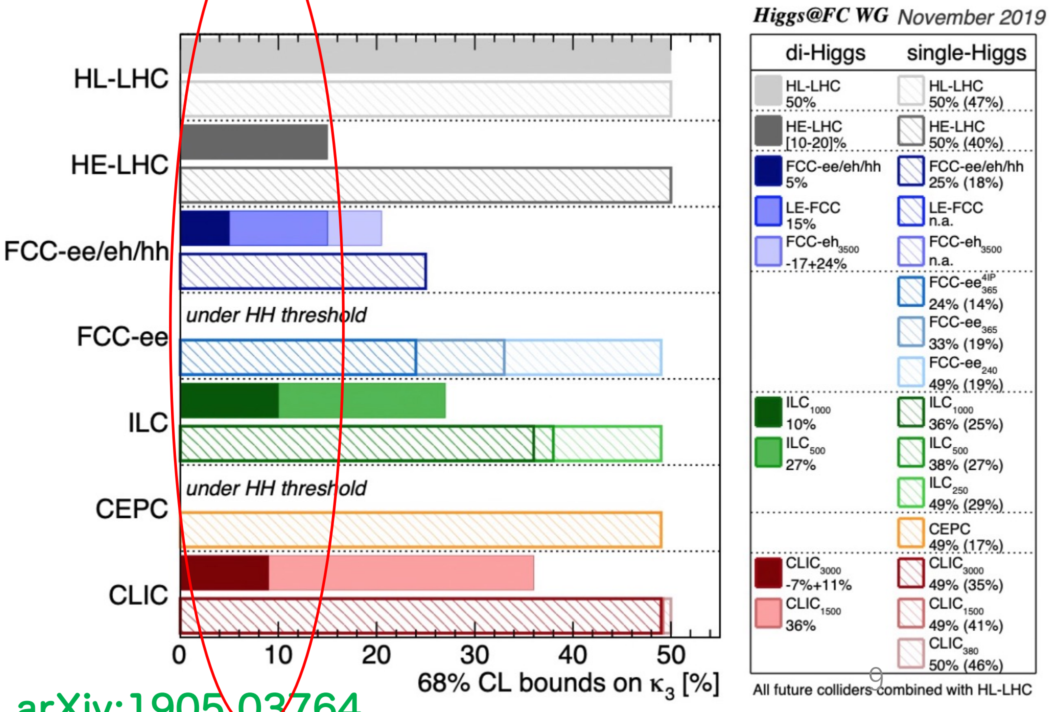


Stronlgly 1st OPT
→ A large deviation in the hhh coupling

SK, Y. Okada, E. Senaha, 2005

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

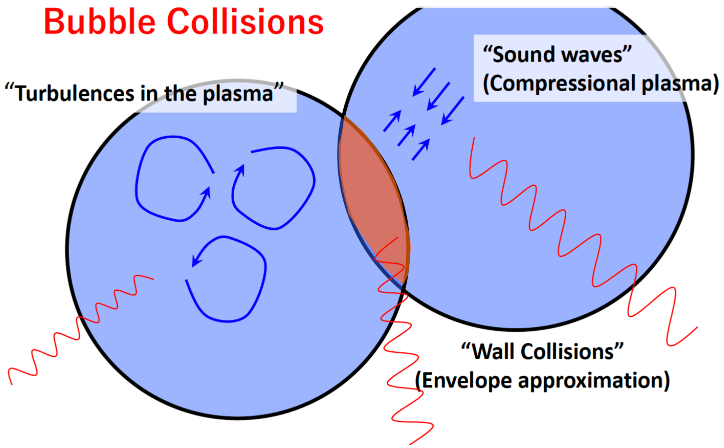




arXiv:1905.03764

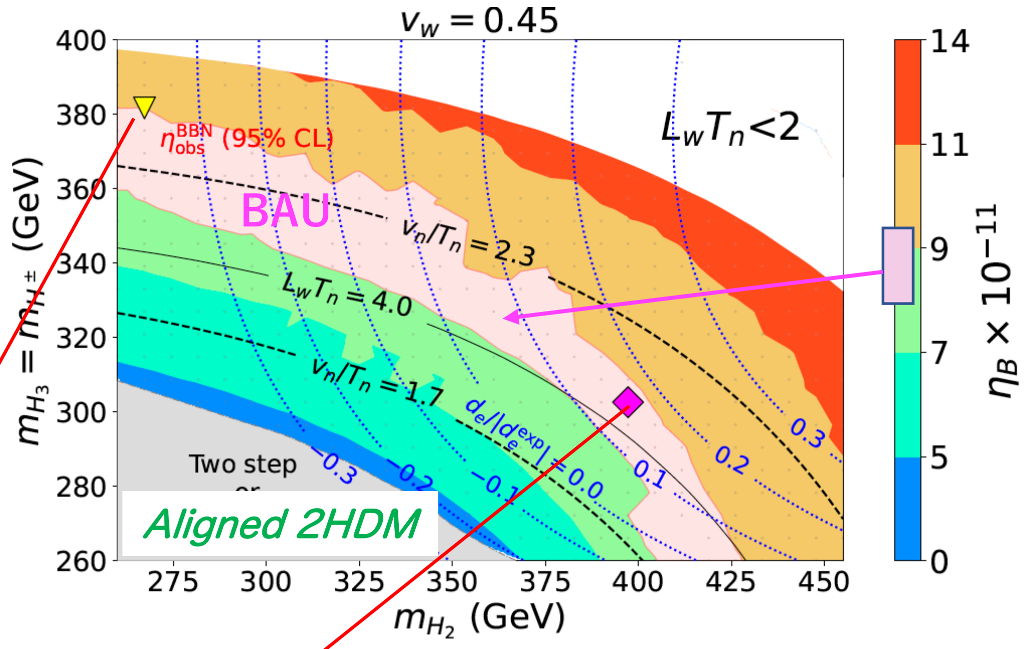
EW Baryogenesis can be directly tested by the hhh measurement

GW from 1stOPT

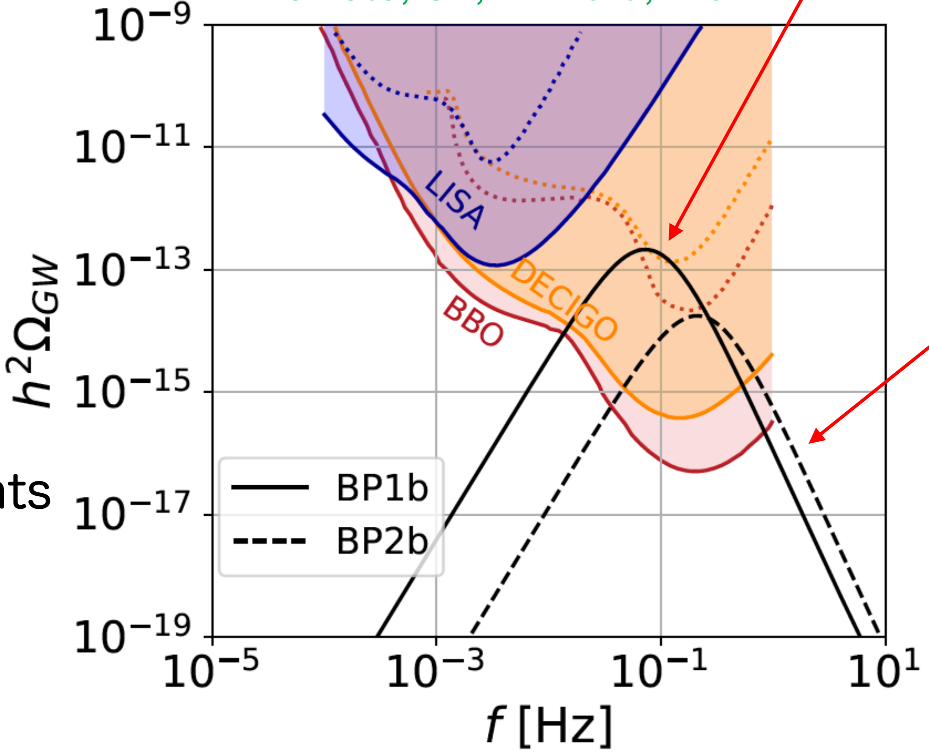


Example
Aligned 2HDM

K. Enomoto, SK, Y. Mura, 2022



K. Enomoto, SK, Y. Mura, 2022



GWs for benchmark points of BAU

They may be tested by future GW experiments

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

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

naHEFT (for describing non-decoupling property)

(nearly aligned)

SK, R. Nagai (2021)

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

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

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

$$V_{\text{BSM}}(\varphi) \simeq \frac{\lambda_\Phi^3}{64\pi^2 M^2}\varphi^6 = \frac{1}{\Lambda^2}\varphi^6$$ $\Rightarrow$ 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 Λ, κ_0, r

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

r : non-decouplingness

Mass of new particles

d.o.f of new particles

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

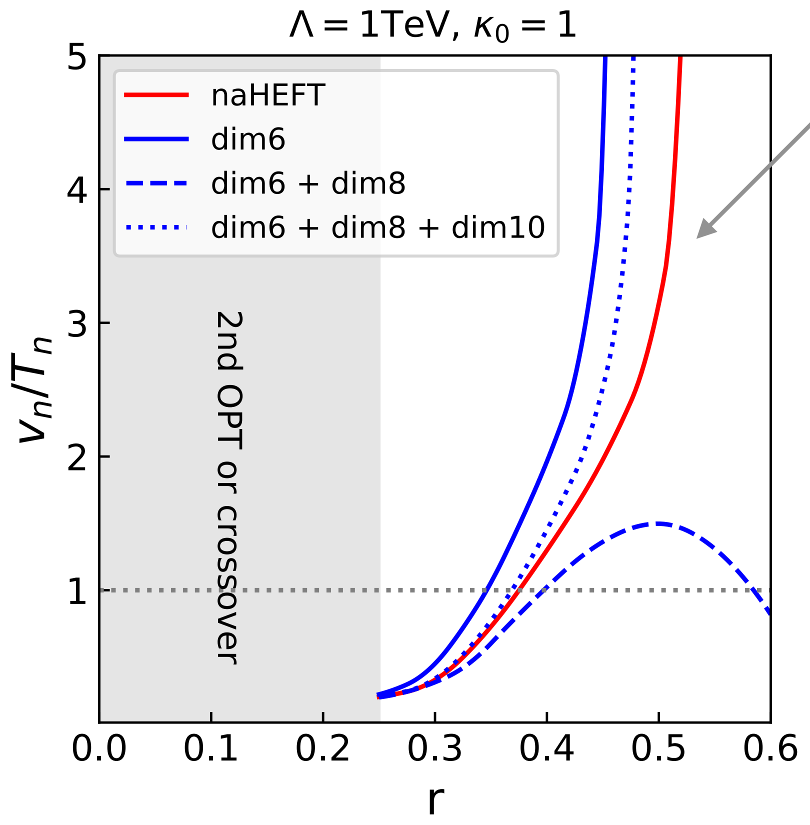
$r \sim 1 \Rightarrow M^2 \ll \frac{\kappa_p}{2}v^2$ Non-decoupling

• The naHEFT at finite temperatures

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

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

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



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

Consistent with results in the SM with a singlet

M. Kakizaki, SK, T.Matsui (2015)

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

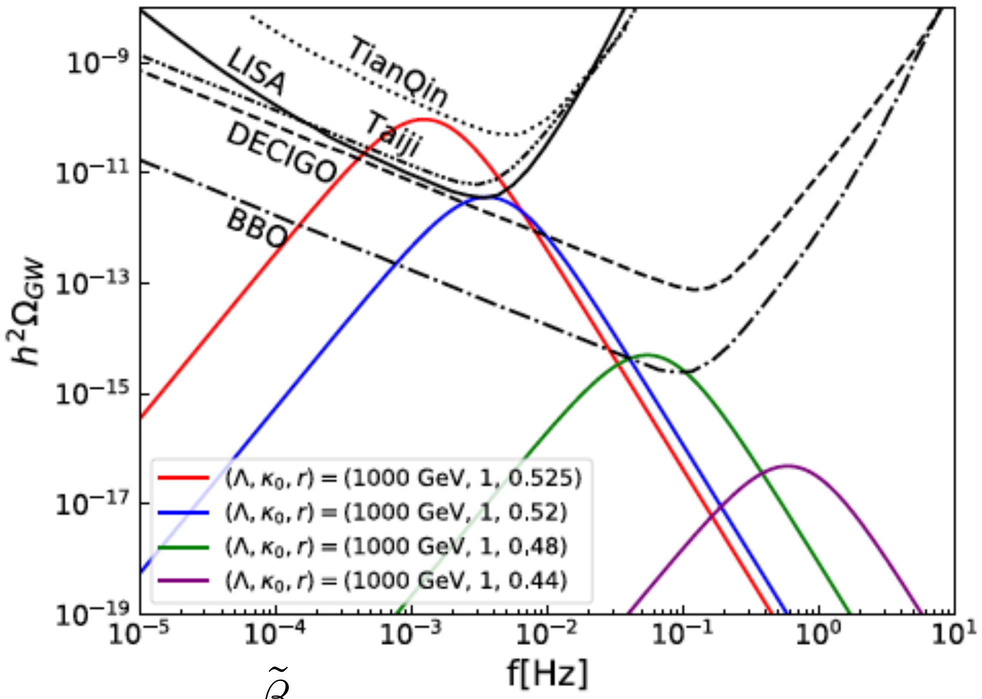
GW from 1st order EWPT in naHEFT

Nucleation rate $\quad \Gamma(T) \sim A(T)\exp\left(-\frac{S_3}{T}\right)$

Linde 1983

$$S_3(T) = \int d^3x \left[\frac{1}{2}(\vec{\nabla}\varphi^b)^2 + V_{\rm EFT}(\varphi^b, T; \Lambda, \kappa_0, r)\right]$$

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



Nucleation completion condition (→ transition temp T_t)

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

- α Latent heat (released *E* of false vacuum)
- β Inverse of duration of phase transition

GW Spectrum C.Caprini et al., arXiv:1512.06239

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

Test of EWPT

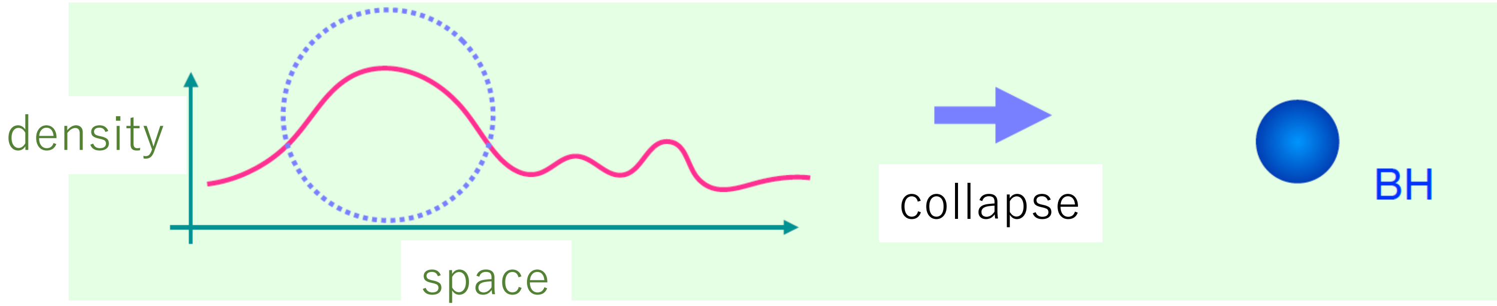
- Colliders (hhh, ⋯)

Colliders (hhh, ⋯)	HL-LHC	2028? ~
	ILC(500)	2040s??~
Space based GW interferometer	LISA	2037? ~
	DECIGO	2040s??~

A new possibility of testing EWPT by earlier experiment？

Primordial Black Holes?

PBH Formation



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

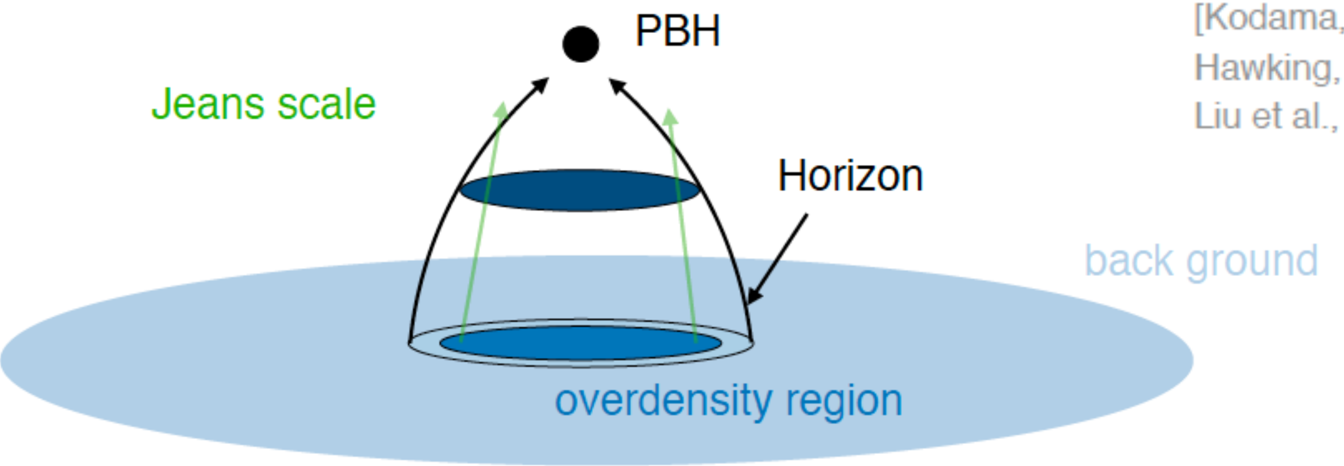
Condition for the PBH formation

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

[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

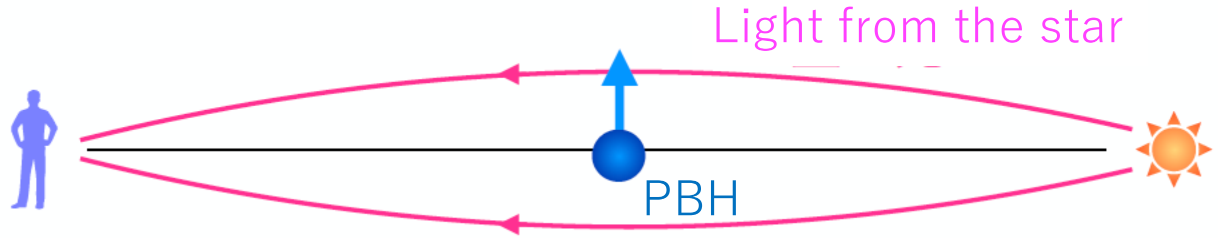
→ PBHs might be produced by the FOPT

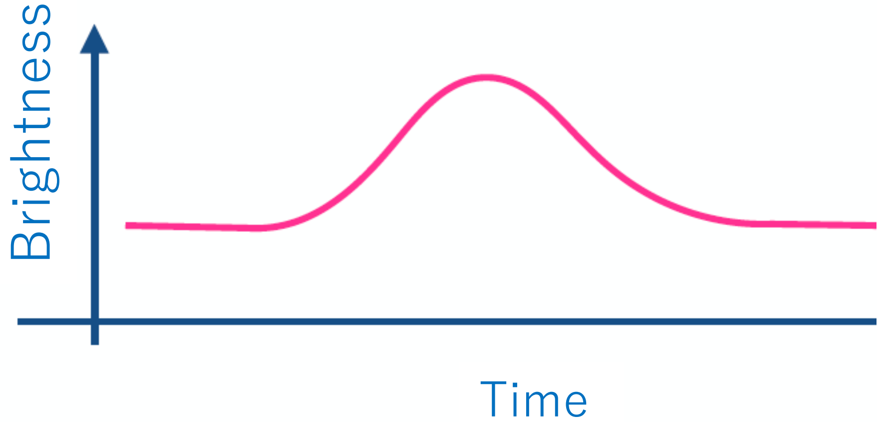


[Kodama, Sasaki and Sato, PTP 68 (1982);
Hawking, Moss and Stewart, PRD 26 (1982)
Liu et al., PRD105 (2022)]

PBH search

- Gravitational microlensing effect
- Brightness is up by passing PBH



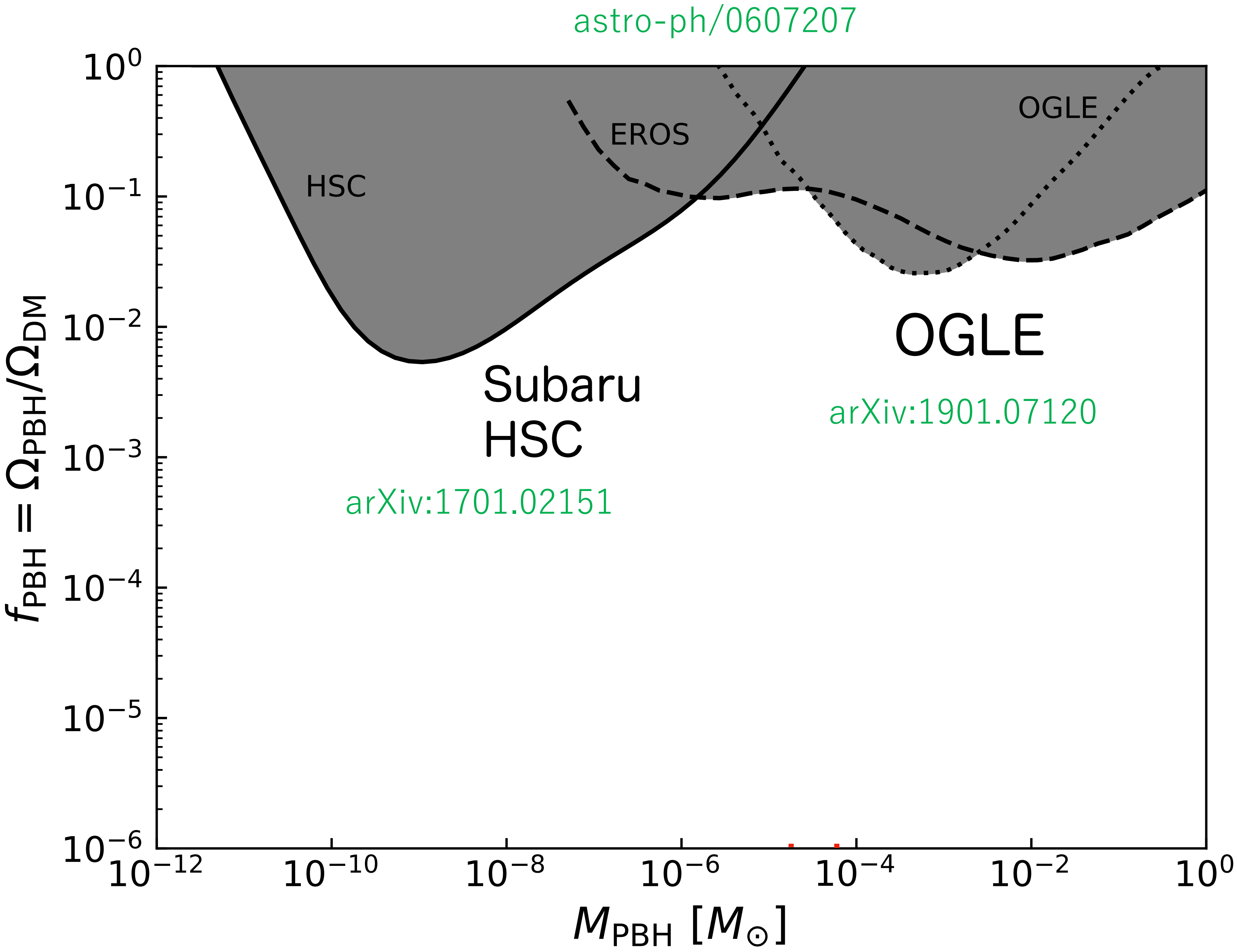


Non-observation → constraint on the PBH abundance

Subaru HSC、OGLE (Optical Gravitational Lensing Experiment)

Current Data have already constrained some mass regions

Microlensing effect of visible light



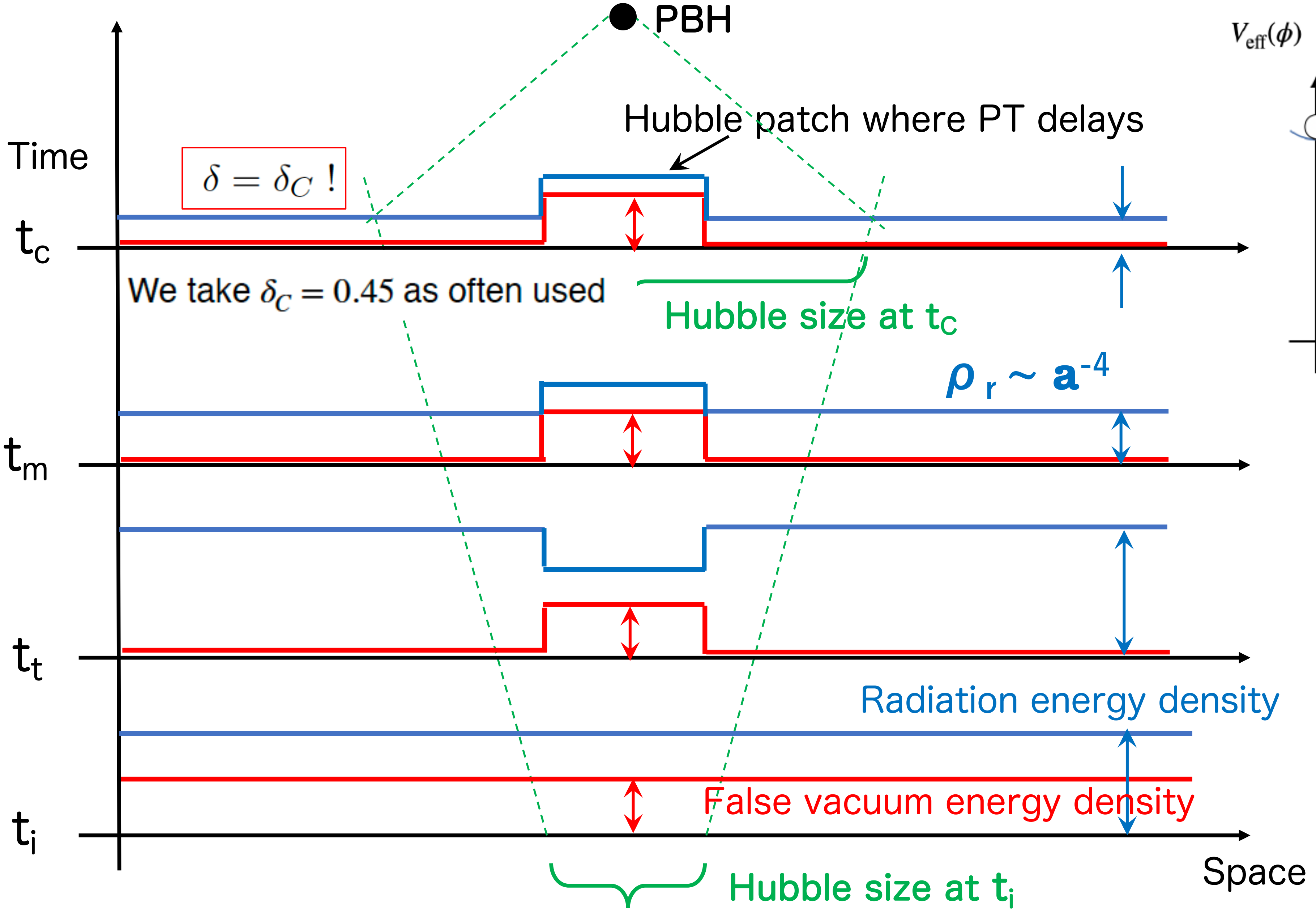
Improve in near future

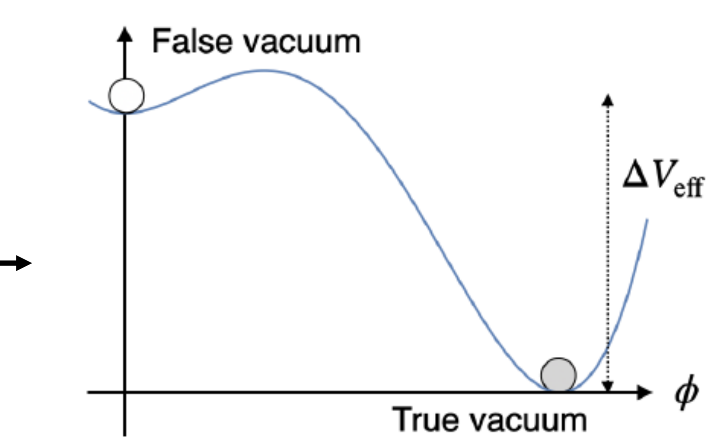
2023~ PRIME telescope
2026~ Roman telescope

PBH formation from the contrast

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

$$\delta_C = 0.45$$





False vacuum energy density

$$\rho_V \sim \text{const} \sim F(t)\,\Delta V$$

Radiation energy density

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

Liu, et al. 2021, more

Rate of staying at the symmetric phase in a Hubble volume

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

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

$$\rho_{\rm v} = F(t)\Delta V$$ vacuum energy density is constant

Radiation Dominant p = $\rho/3$

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

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

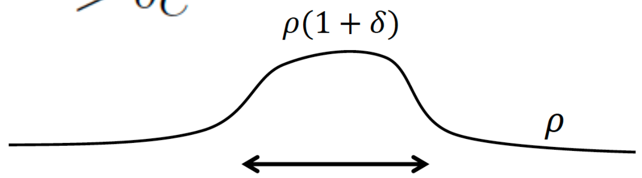
$\rho_{\rm w}$ $\propto a^{-4}(t)$

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

(v_w = 1)

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

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



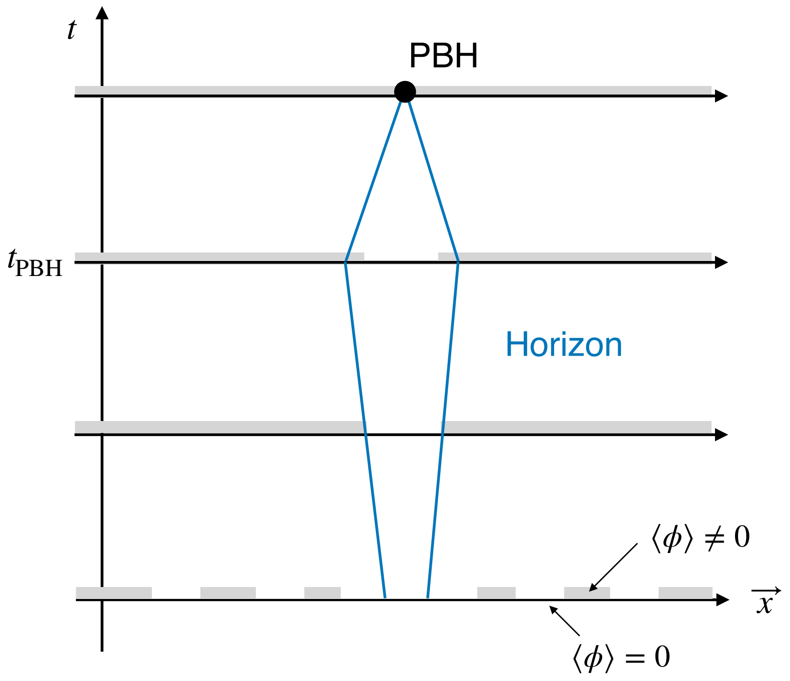
Then, from the criterion δc = 0.45,
T_{PBH} is determined

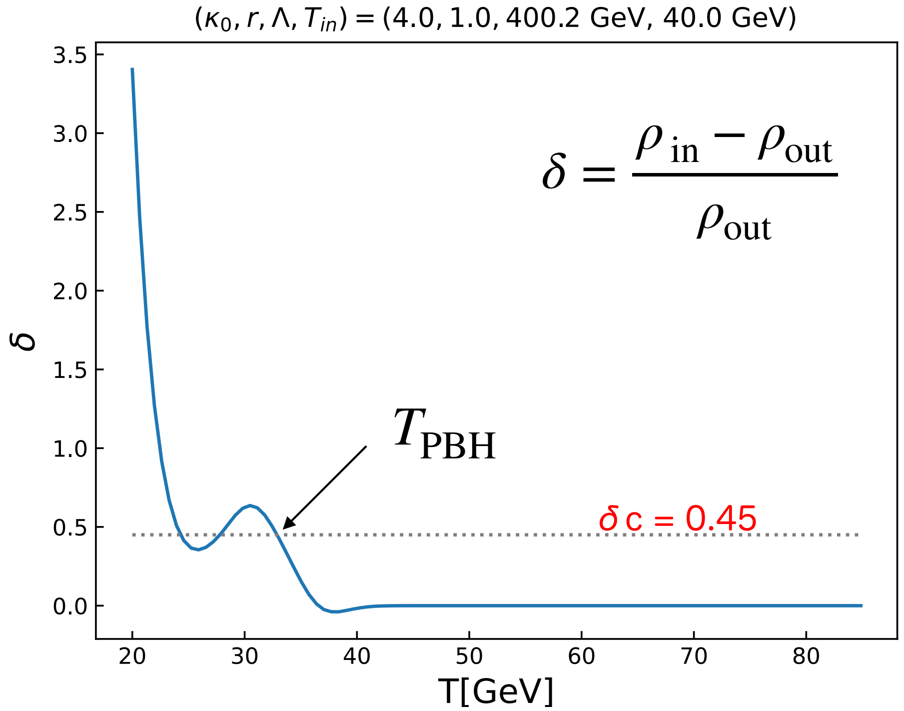
δ > 0.45 gravitational collapse!

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





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

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

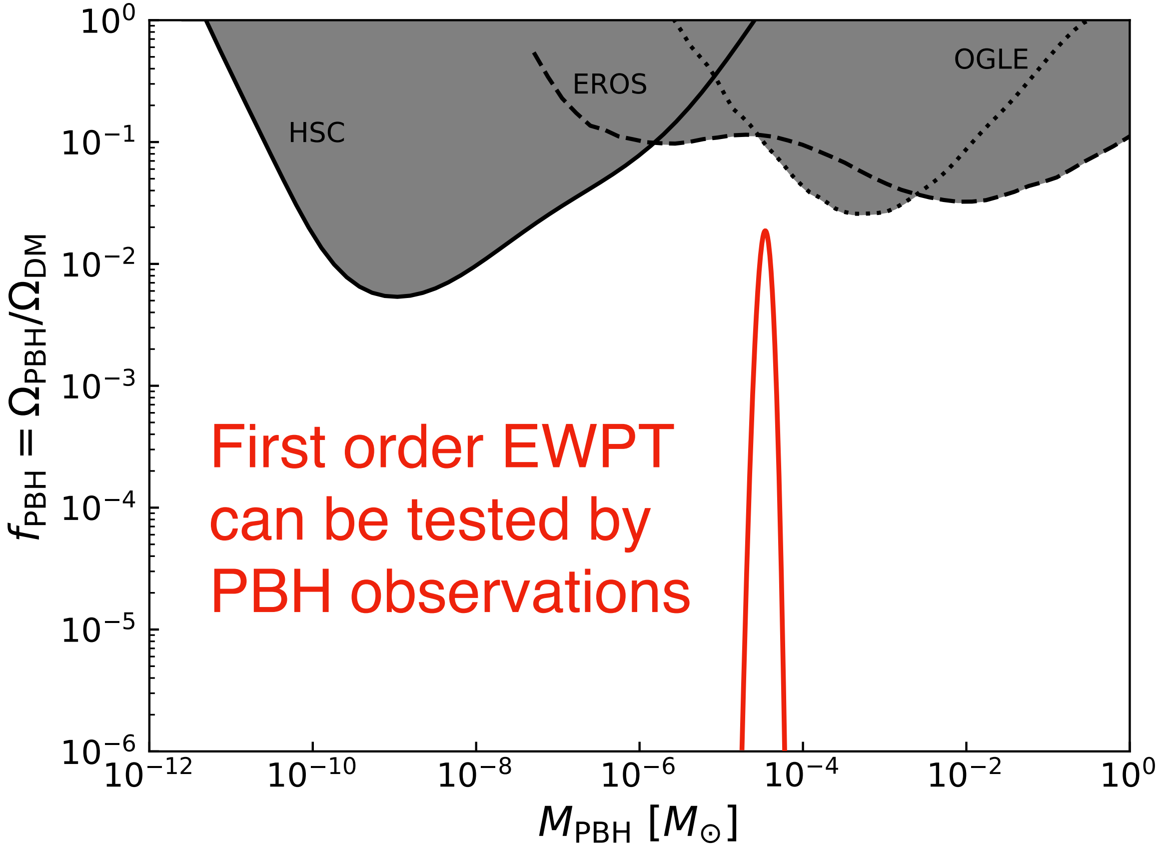
PBH from 1st OEWPT

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

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

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

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



Microlensing observations

Subaru HSC https://hsc.mtk.nao.ac.jp/ssp
OGLE http://ogle.astrouw.edu.pl/

Future observations

PRIME 2023~ http://www-ir.ess.sci.osaka-u.ac.jp/prime/index.html
Roman 2026~ https://roman.gsfc.nasa.gov

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

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

Theory prediction on α-β plane

Non-dec r =0.5

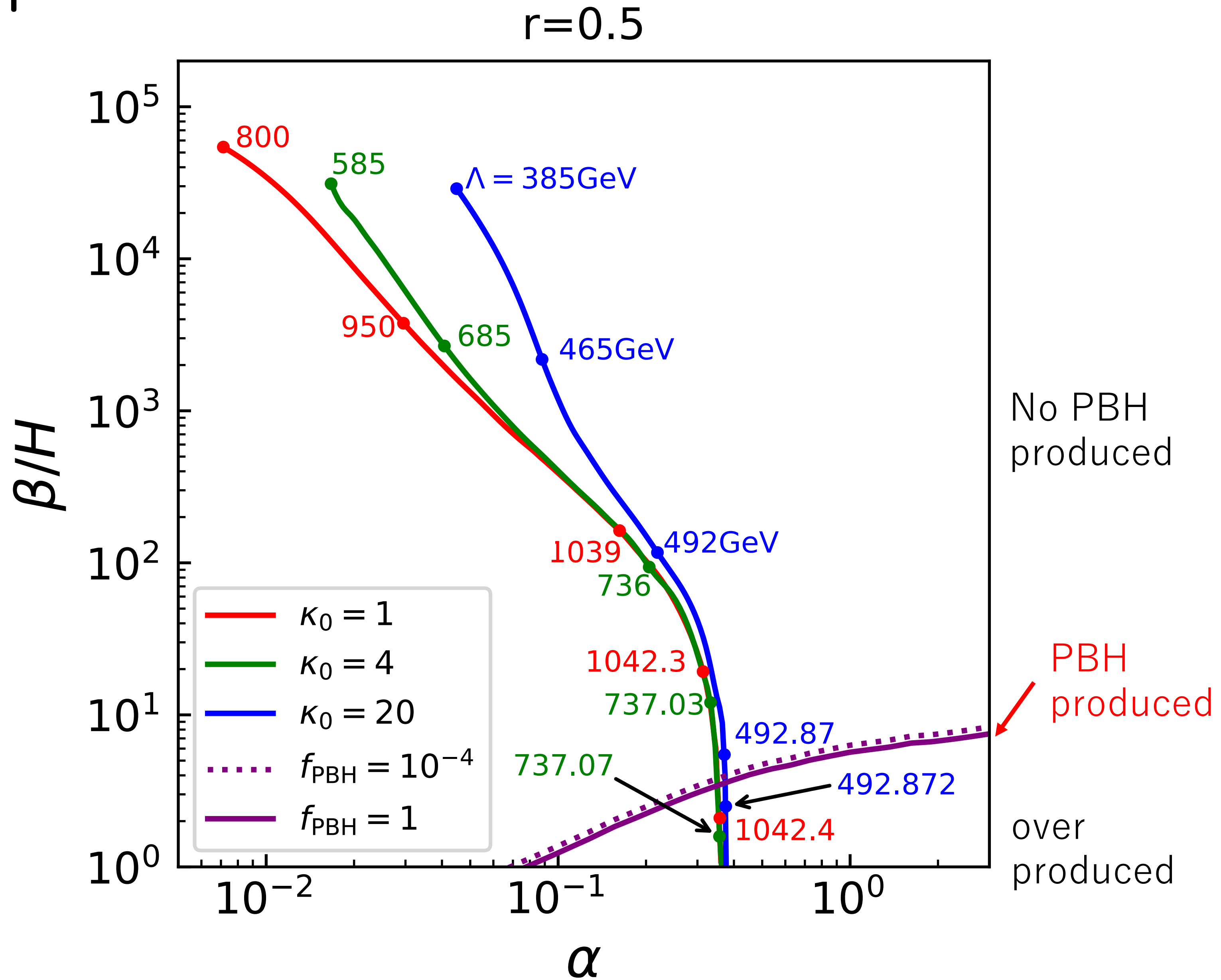
DOF κ_0 = 1, 4, 20

for various Λ

New scale

With contours of f_{PBH}

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



Strongly 1st OPT

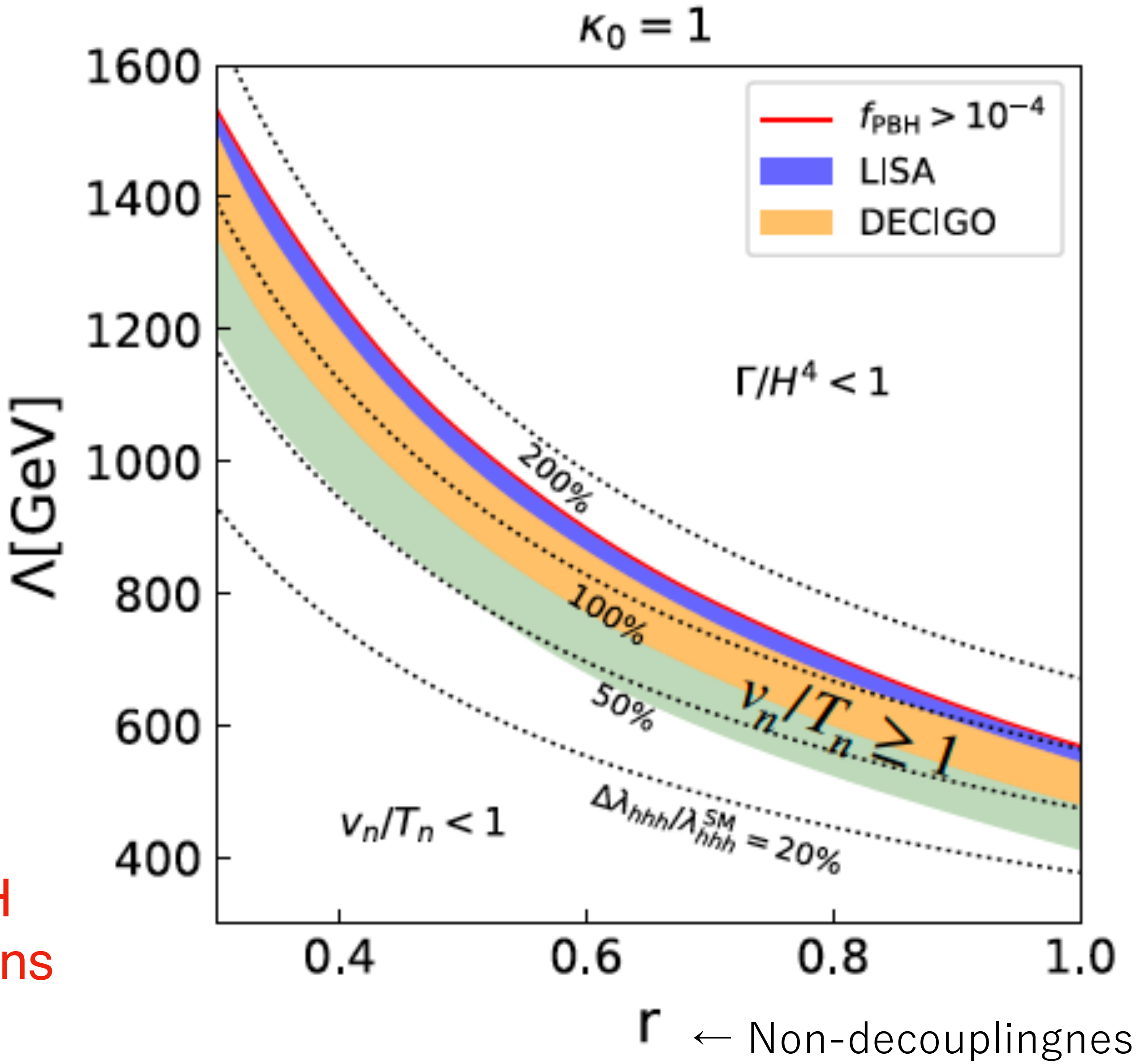
Parameter region

Sphaleron decoupling $\boxed{\dfrac{\varphi_c}{T_c} \gtrsim 1}$

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

- PBH (red)
- GW (LISA)
- GW (DECIGO)
- Only $\Delta\lambda_{hhh}$ (HL-LHC, ILC, ⋯)

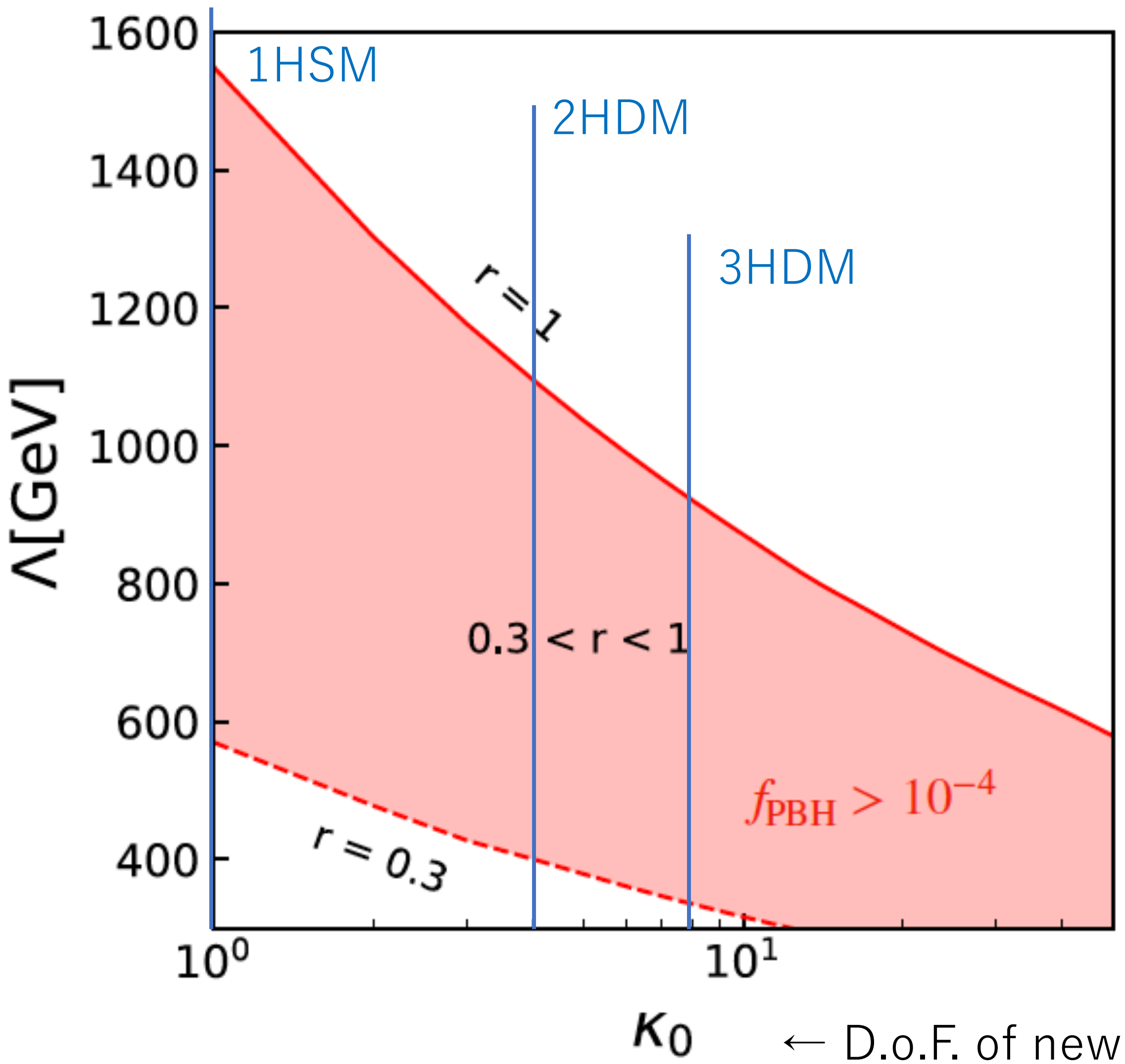
First order EWPT can be explored by PBH observations in addition to GW observations and collider experiments



← Non-decouplingness

Parameter Regions testable by PBH

Scale of new particles →

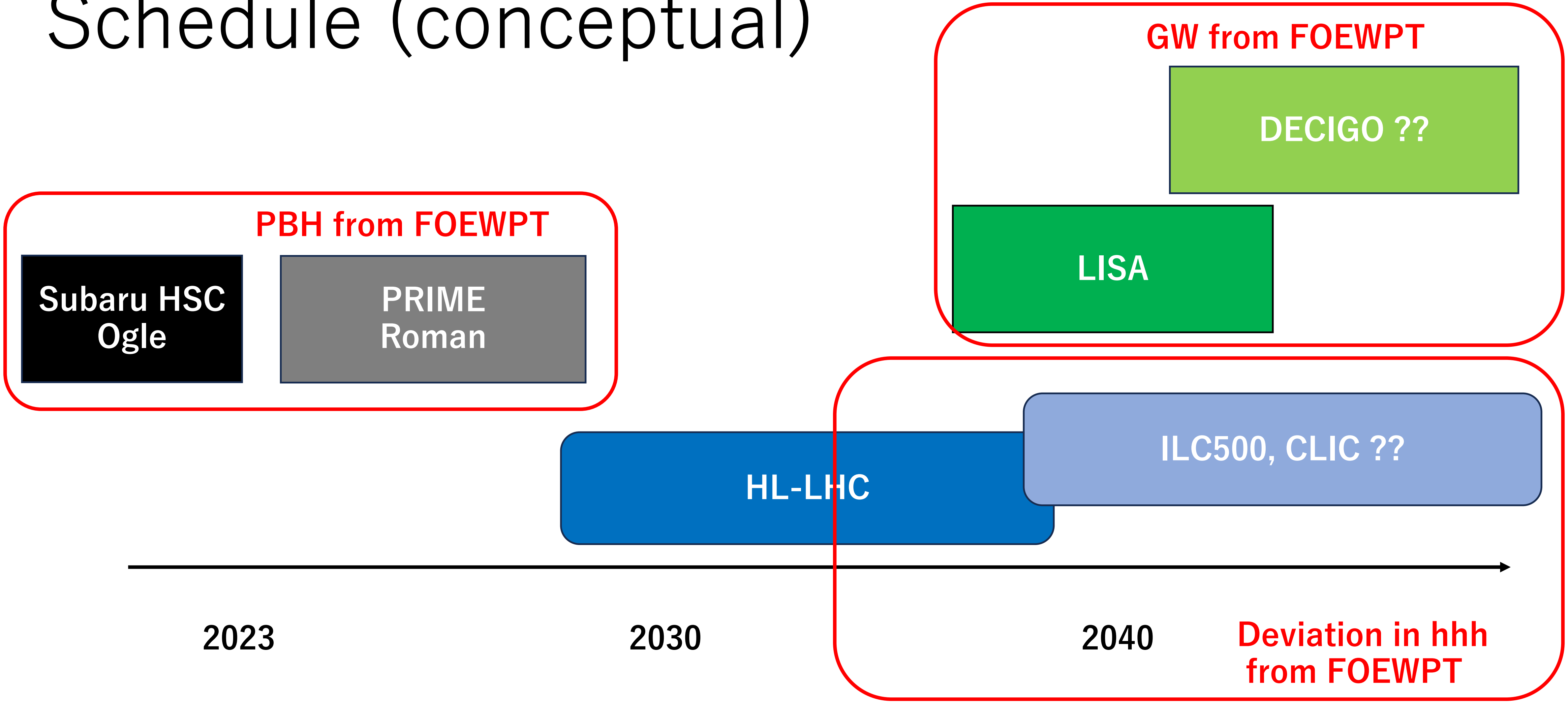


← D.o.F. of new particles

Non-decouplingness r scanned

0.3 < r < 1

Schedule (conceptual)



Complementary

Summary

- EWPT is the next target
- If non-decoupling property, EWPT can be strongly first order

EW baryogenesis

- Test of strong 1st order EWPT
  - $\Delta\lambda_{hhh}$ HL-LHC, ILC
  - GWs LISA late 2030s, DECIGO 2040 or after …

- Observation of PBH may also be used (in several years)

Interesting!

Will make it more matured

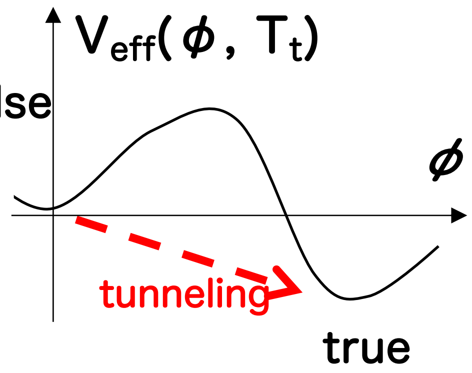
Thank you!

From bubble dynamics to GW spectrum

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

Linde 1983

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



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

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

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

β Inverse of duration of phase transition Speed of transition

$$\beta = -\left.\frac{dS_E}{dt}\right|_{t=t_t} \simeq \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_t} \qquad \tilde{\beta} = \frac{\beta}{H_t}$$

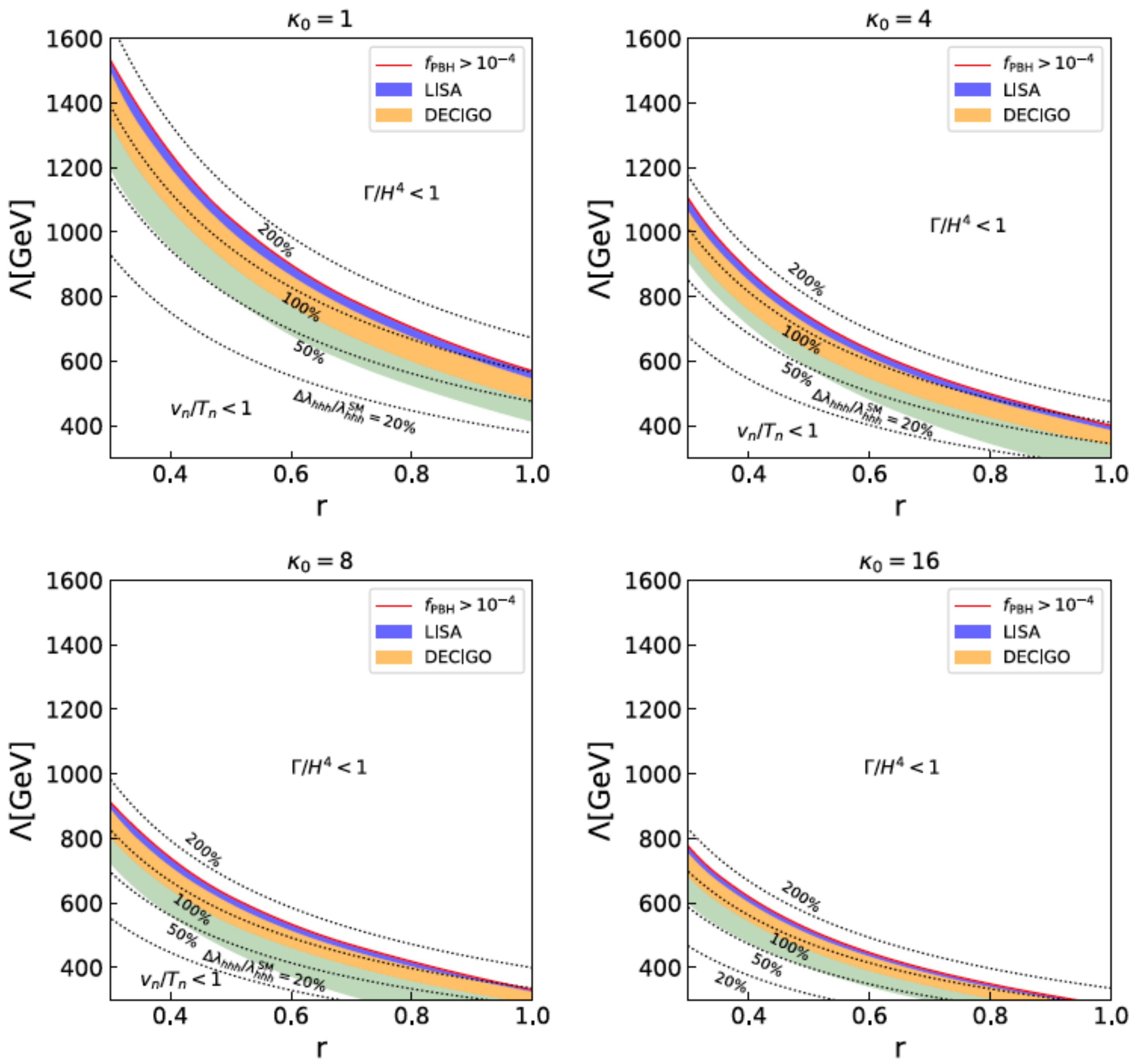
GW Spectrum is determined by T_t, α, β, v_b

C.Caprini et al., arXiv:1512.06239

ex) GW strength and peak frequency from sound waves (Fitting function)

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

v_b: wall velocity



$\kappa_0 = 1$
$\kappa_0 = 4$
$\kappa_0 = 8$
$\kappa_0 = 16$
$f_{\rm PBH} > 10^{-4}$
LISA
DECIGO
$\Gamma/H^4 < 1$
$v_n/T_n < 1$
$\Delta\lambda_{hhh}/\lambda_{hhh}^{\rm SM} = 20\%$
200%
100%
50%
20%
Λ[GeV]
r

Nearly aligned Higgs EFT

SK, R Nagai (2021)

Higgs EFT

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

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

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

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

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

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

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

arbitrary polinominals

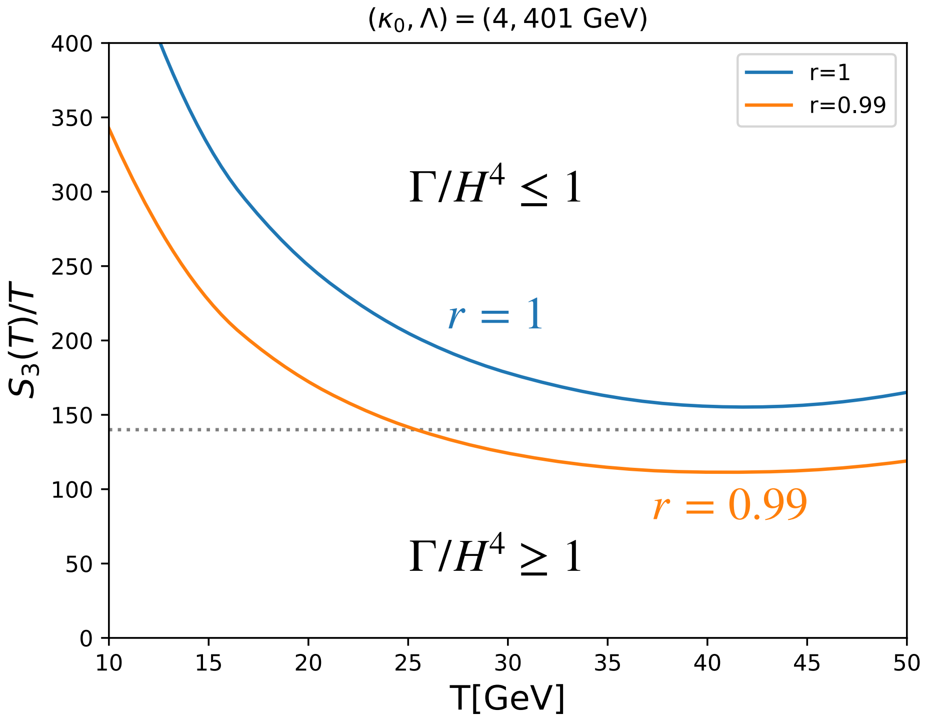
To describe non-decoupling effects
we put a CW type structure (1-loop)

Further assume the form $\quad \mathcal{M}^2(h) = M^2 + \frac{\kappa_p}{2}(h+v)^2$

Bubble nucleation

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

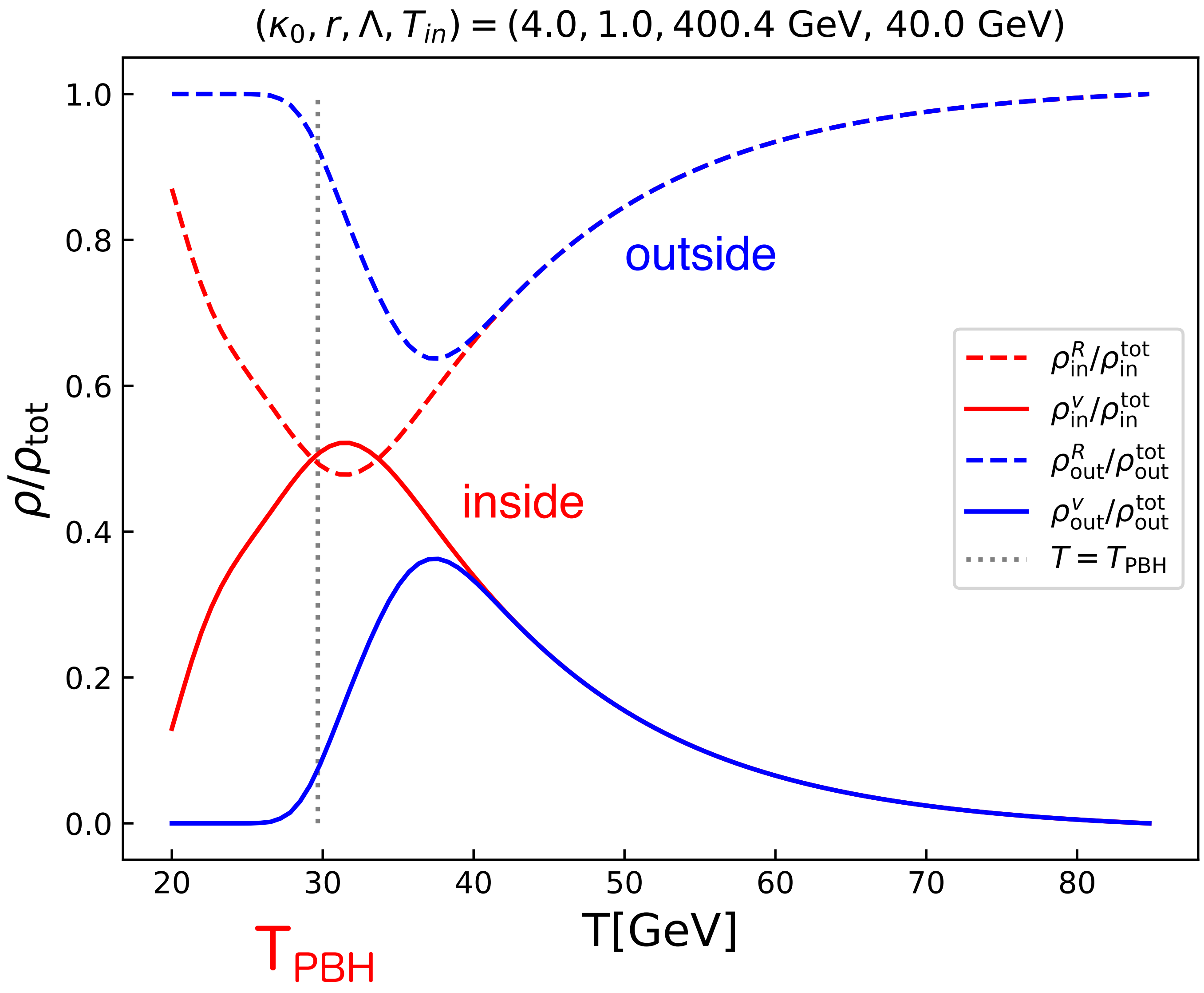
$$\Gamma_{\text{bubble}} \simeq A(T)\exp\left[-\frac{S_3(T)}{T}\right], \qquad S_3(T) = \int d^3x \left[\frac{1}{2}\left(\nabla\varphi^b\right)^2 + V_{\text{eff}}\left(\varphi^b, T\right)\right]$$

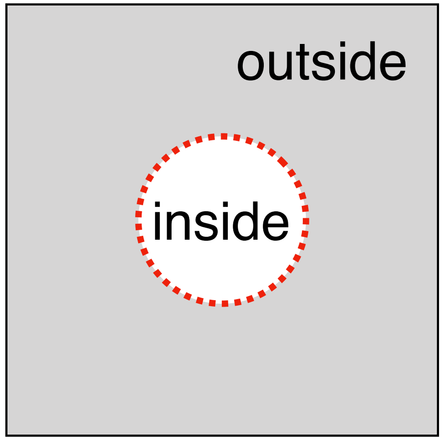


Non-decoupling effects are required to realize the delay of first-order EWPt

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

Ratio of energy density



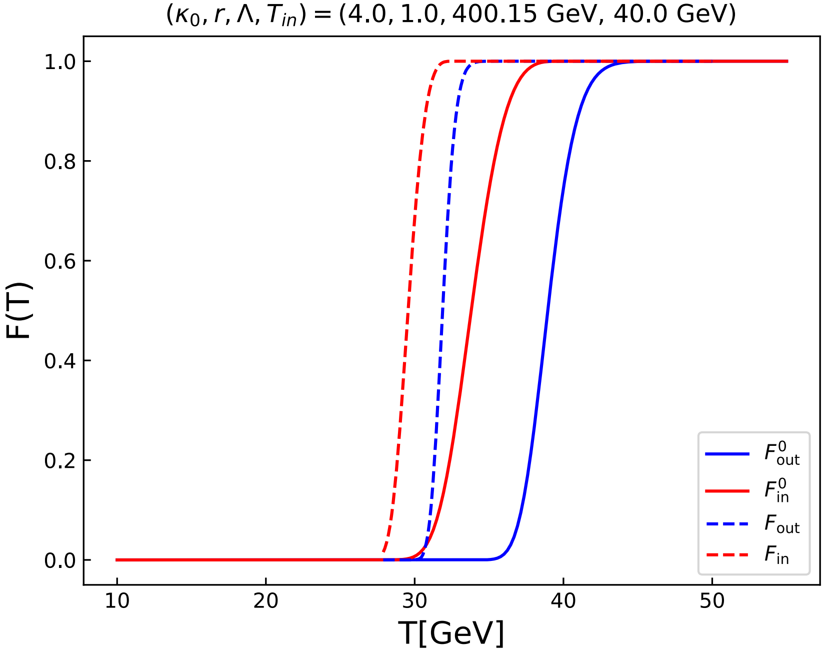


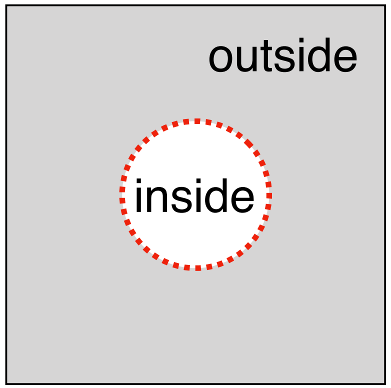
$$\rho_{\mathrm{tot}} = \rho_{\mathrm{rad}} + \rho_{\mathrm{vac}}$$

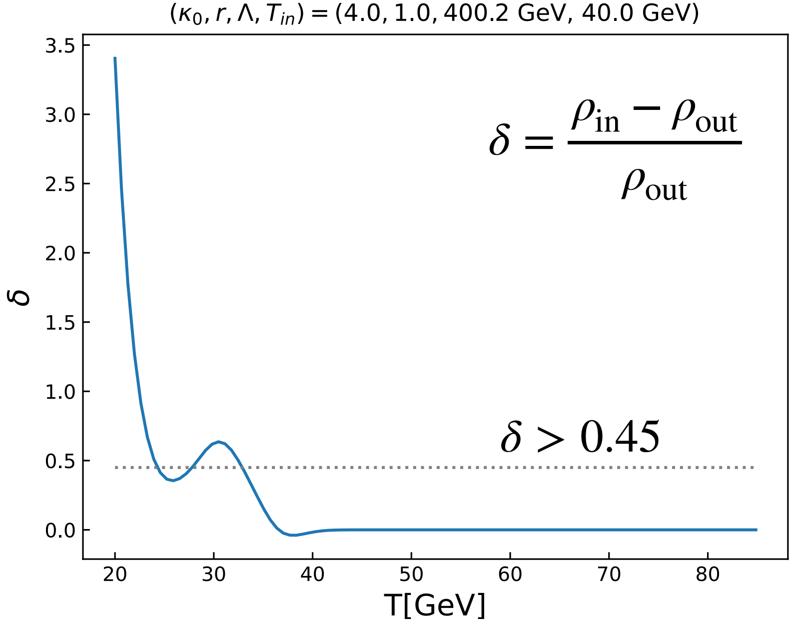
$$\delta = \frac{\rho_{\mathrm{over}} - \rho_{\mathrm{back}}}{\rho_{\mathrm{back}}} > \delta_C$$

δ c = 0.45

Fraction of the false vacuum







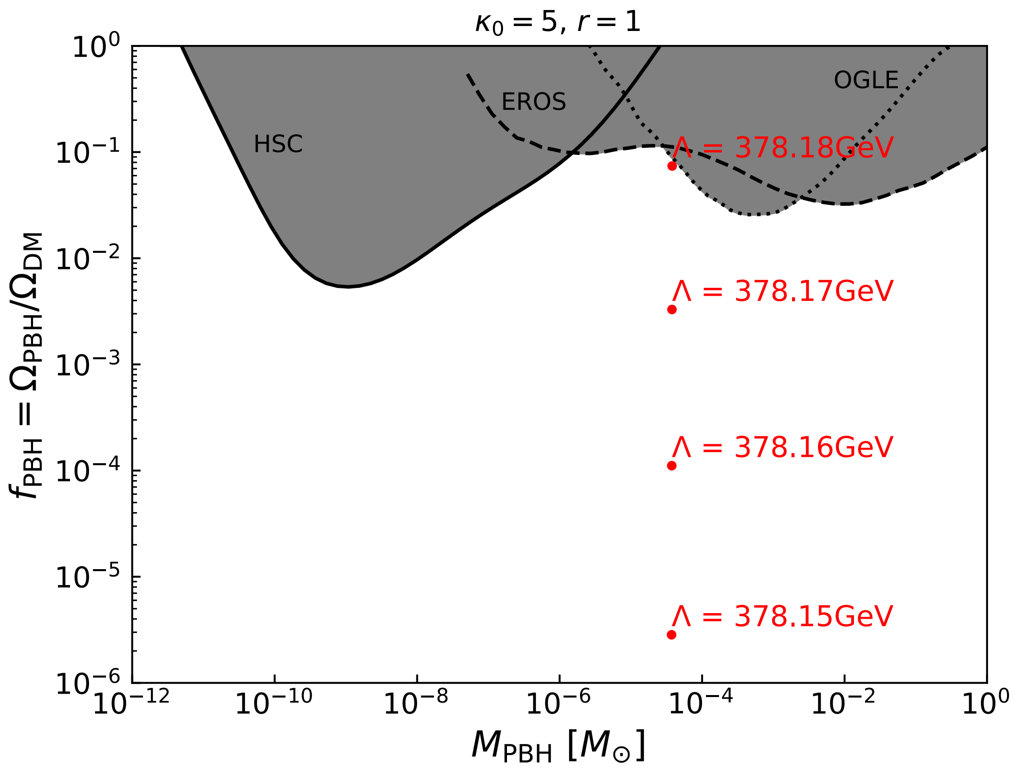
$$F(t) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t} dt'\Gamma(t')\, a^3(t) r^3(t,t')\right]$$

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

Fraction of PBH

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

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



General 2HDM

Most general Higgs potential

$$V = -\mu_1{}^2(\Phi_1{}^\dagger\Phi_1) - \mu_2{}^2(\Phi_2{}^\dagger\Phi_2) - \left(\mu_3{}^2(\Phi_1{}^\dagger\Phi_2) + h.c.\right)$$
$$+\frac{1}{2}\lambda_1(\Phi_1{}^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2{}^\dagger\Phi_2)^2 + \lambda_3(\Phi_1{}^\dagger\Phi_1)(\Phi_2{}^\dagger\Phi_2) + \lambda_4(\Phi_2{}^\dagger\Phi_1)(\Phi_1{}^\dagger\Phi_2)$$
$$+\left\{\left(\frac{1}{2}\lambda_5\Phi_1{}^\dagger\Phi_2 + \lambda_6\Phi_1{}^\dagger\Phi_1 + \lambda_7\Phi_2{}^\dagger\Phi_2\right)\Phi_1{}^\dagger\Phi_2 + h.c.\right\}, \quad (\mu_3, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

Most general Yukawa Interation

$$\mathcal{L}_y \supset \sum_{ij}\left\{\sum_{k=1}^{3} -\overline{f_{iL}}g^f_{k,ij}f_{jR}H_k\right.$$
$$\left. + \left\{\overline{u_{iR}}(\rho^{u\dagger}V_{\mathrm{CKM}})_{ij}d_{jL} - \overline{u_{iL}}(V_{\mathrm{CKM}}\rho^d)_{ij}d_{jR} - \overline{\nu_{iL}}\rho^e_{ij}e_{jR}\right\}H^+\right\} + \text{h.c.},$$

How we nallow down?

No principle

Use experimental data!
and basic requirements

Higgs alignment

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

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

Higgs potenshal

$$V = -\mu_1{}^2(\Phi_1{}^\dagger\Phi_1) - \mu_2{}^2(\Phi_2{}^\dagger\Phi_2) - \left(\mu_3{}^2(\Phi_1{}^\dagger\Phi_2) + h.c.\right)$$
$$+\frac{1}{2}\lambda_1(\Phi_1{}^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2{}^\dagger\Phi_2)^2 + \lambda_3(\Phi_1{}^\dagger\Phi_1)(\Phi_2{}^\dagger\Phi_2) + \lambda_4(\Phi_2{}^\dagger\Phi_1)(\Phi_1{}^\dagger\Phi_2)$$
$$+\left\{\left(\frac{1}{2}\lambda_5\Phi_1{}^\dagger\Phi_2 + \lambda_6\Phi_1{}^\dagger\Phi_1 + \lambda_7\Phi_2{}^\dagger\Phi_2\right)\Phi_1{}^\dagger\Phi_2 + h.c.\right\}, \quad (\mu_3, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

$$m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

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

Higgs Alignment (h: SM-like)

Mass matrix of neutral scalar bosons

$$\mathcal{M}^2 = v^2 \begin{pmatrix} \lambda_1 & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ \mathrm{Re}[\lambda_6] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + \mathrm{Re}[\lambda_5]) & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} \\ -\mathrm{Im}[\lambda_6] & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - \mathrm{Re}[\lambda_5]) \end{pmatrix} = \begin{pmatrix} m_h^2 & 0 & 0 \\ 0 & m_{H_2}^2 & 0 \\ 0 & 0 & m_{H_3}^2 \end{pmatrix}$$

rephasing

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

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

We work on this Higgs alignment scenario in the following discussion

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

2HDM (scenario 1)

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

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

Higgs potenshal

$$V = -\mu_1{}^2(\Phi_1{}^\dagger\Phi_1) - \mu_2{}^2(\Phi_2{}^\dagger\Phi_2) - \left(\mu_3{}^2(\Phi_1{}^\dagger\Phi_2) + h.c.\right)$$
$$+\frac{1}{2}\lambda_1(\Phi_1{}^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2{}^\dagger\Phi_2)^2 + \lambda_3(\Phi_1{}^\dagger\Phi_1)(\Phi_2{}^\dagger\Phi_2) + \lambda_4(\Phi_2{}^\dagger\Phi_1)(\Phi_1{}^\dagger\Phi_2)$$
$$+\left\{\left(\frac{1}{2}\lambda_5\Phi_1{}^\dagger\Phi_2 + \lambda_6\Phi_1{}^\dagger\Phi_1 + \lambda_7\Phi_2{}^\dagger\Phi_2\right)\Phi_1{}^\dagger\Phi_2 + h.c.\right\}, \quad (\mu_3, \lambda_5, \lambda_6, \lambda_7 \in \mathbb{C})$$

Higgs basis

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + ih_3) \end{pmatrix}$$

$$m_{H^\pm}^2 = M^2 + \frac{1}{2}\lambda_3 v^2$$

To satisfy LHC data、avoid mixing between *h* and heavy Higgs bosons: $\lambda_6 \sim 0$

Mass matrix of neutral scalar bosons

$$\mathcal{M}^2 = v^2\begin{pmatrix} \lambda_1 & \mathrm{Re}[\lambda_6] & -\mathrm{Im}[\lambda_6] \\ \mathrm{Re}[\lambda_6] & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 + \mathrm{Re}[\lambda_5]) & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} \\ -\mathrm{Im}[\lambda_6] & \cancel{-\frac{1}{2}\mathrm{Im}[\lambda_5]} & \frac{M^2}{v^2} + \frac{1}{2}(\lambda_3 + \lambda_4 - \mathrm{Re}[\lambda_5]) \end{pmatrix} = \begin{pmatrix} m_h^2 & 0 & 0 \\ 0 & m_{H_2}^2 & 0 \\ 0 & 0 & m_{H_3}^2 \end{pmatrix}$$

rephasing

Higgs alignment

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

Avoiding FCNC: Yukawa alignment is imposed by hand $y_f^2 = \zeta_f y_f^1 \quad (f = u, d, e)$

$$\mathcal{L}_y = -\overline{Q}_L\frac{\sqrt{2}M_u}{v}\left(\tilde{\Phi}_1 + \zeta_u^*\tilde{\Phi}_2\right)u_R - \overline{Q}_L\frac{\sqrt{2}M_d}{v}(\Phi_1 + \zeta_d\Phi_2)\,d_R - \overline{L}_L\frac{\sqrt{2}M_e}{v}(\Phi_1 + \zeta_e\Phi_2)\,e_R + h.c.$$

Yukawa alignment

Pich and Tuzon (2009)

Multiple CPV phases

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

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