# Testability of models with the deviation in the *hhh* coupling

---

Katsuya Hashino

(Tokyo University of Science)

# Contents

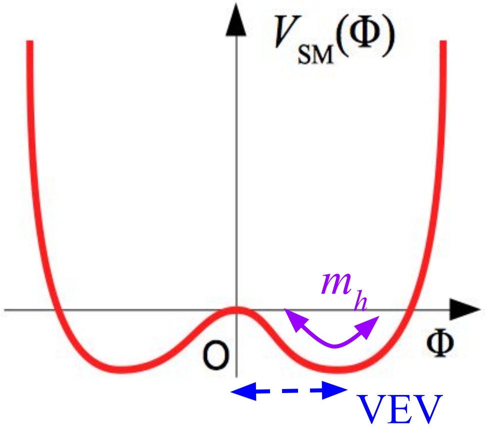
# Introduction

★ The shape of Higgs potential is still undetermined.

$$V_{SM}(\phi)=\mu^2|\phi|^2+\lambda|\phi|^4$$

We only know the vacuum expectation value and Higgs boson mass.

★ It is important to explore the details of shape of Higgs potential.



The electroweak phase transition (EWPT) is governed by the shape of Higgs potential.

**The first-order EWPT is related to some phenomena.**

# Introduction

★ For example, the SM cannot explain baryon asymmetry of the universe (BAU).

**Electroweak Baryogenesis** is one of senario explaining BAU.

**Sakharov's conditions**

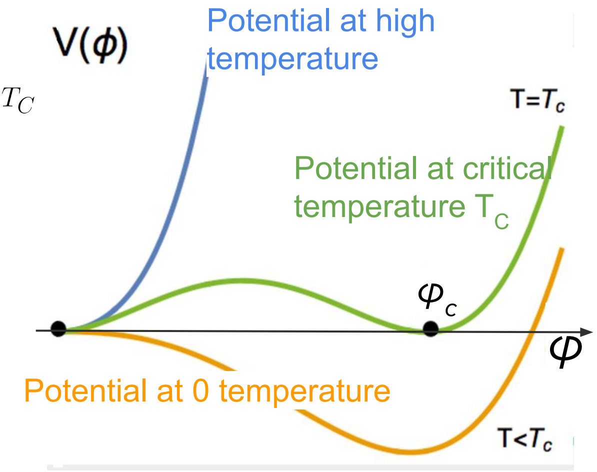
- Baryon number violation

  → Sphaleron process $\Gamma_{\mathrm{sph}} \sim e^{-\alpha' \varphi_C / T_C}$
- C and CP violation

  → Model extension
- Departure from equilibrium

  → Strongly first order electroweak phase transition (EWPT)

  $(\varphi_c / T_c > 1)$



**The strongly first-order EWPT is required to explain the BAU.**

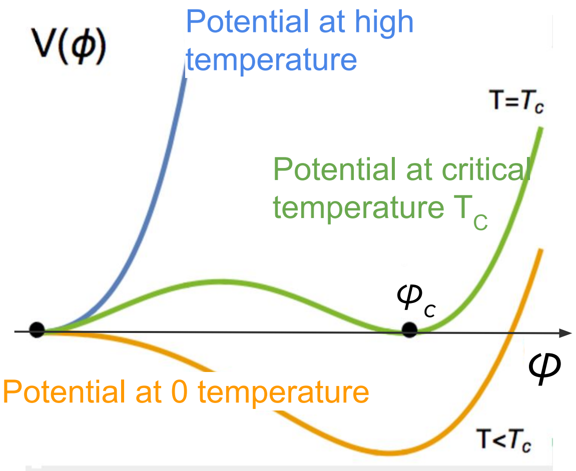
# First-order electroweak phase transition

★ The effective potential under high temperature approximation.

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

$$V_{eff}(0,T_C)=V_{eff}(\varphi_C,T_C),\qquad \left.\frac{\partial V_{eff}(\varphi,T_C)}{\partial\varphi}\right|_{\varphi=\varphi_C}=0 \quad\Rightarrow\quad \boxed{\frac{\varphi_C}{T_C}=\frac{E}{2\lambda_T}}$$

$E$ : Loop effects of bosons



★ The effective potential in the SM

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

There is no sizable barrier in the potential of the SM to realize the first-order EWPT.

The SM cannot satisfy the condition of strongly 1st EWPT $\varphi_c/T_c>1$ . [Y. Aoki, F. Csikor, Z. Fodor and A. Ukawa, Phys. Rev. D 60, 013001 (1999)]

**We can realize strongly first-order EWPT by new physics effects beyond the SM.**

# The *hhh* coupling

- ★ **A large deviation from the SM prediction in the triple Higgs boson (*hhh*) coupling is required to realize the first-order EWPT.** [S. Kanemura, Y. Okada, E. Senaha, PLB 606 361 (2005)]

- ★ Two Higgs doublet model

$$\begin{aligned} V_{\rm tree} &= m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + {\rm h.c.}) \\ &+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + {\rm h.c.}\right] \end{aligned}$$

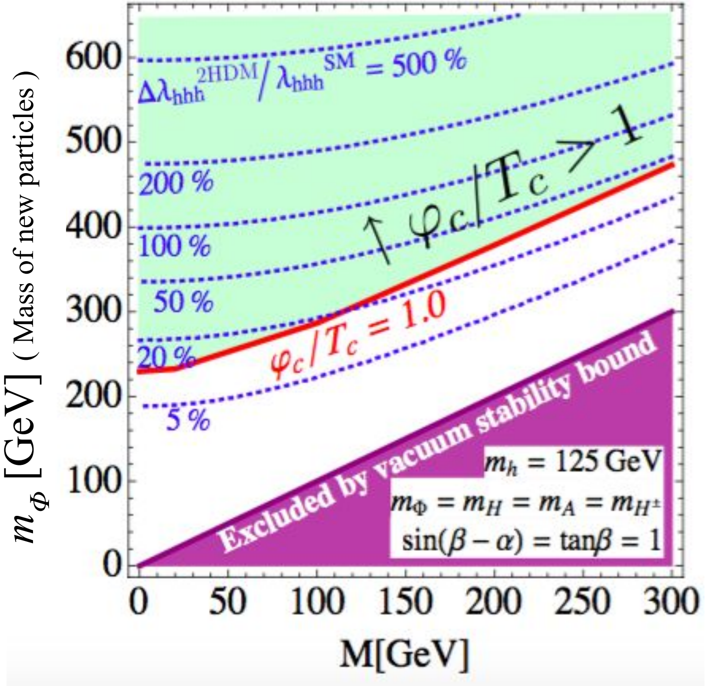
(The masses of scalar bosons: $m_\Phi{}^2 \sim M^2 + \lambda_i v^2$ )

- ★ The *hhh* coupling

$$\Delta\lambda_{hhh} \equiv \lambda_{hhh}^{\rm 2HDM} - \lambda_{hhh}^{\rm SM} \qquad \Delta\lambda_{hhh} \sim \frac{1}{12\pi^2 m_h^2 v^2}(m_H^4 + m_A^4 + 2m_{H^\pm}^4)$$

- ★ The strength of the EWPT

$$\frac{\varphi_C}{T_C} = \frac{E}{2\lambda_T} \qquad E \sim \frac{1}{12\pi^2 v^3}(m_H^3 + m_A^3 + 2m_{H^\pm}^3)$$



# The *hhh* coupling

- ★ **A large deviation from the SM prediction in the triple Higgs boson (*hhh*) coupling is required to realize the first-order EWPT.** [S. Kanemura, Y. Okada, E. Senaha, PLB 606 361 (2005)]

- ★ Two Higgs doublet model

$$V_{\text{tree}} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.})$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$

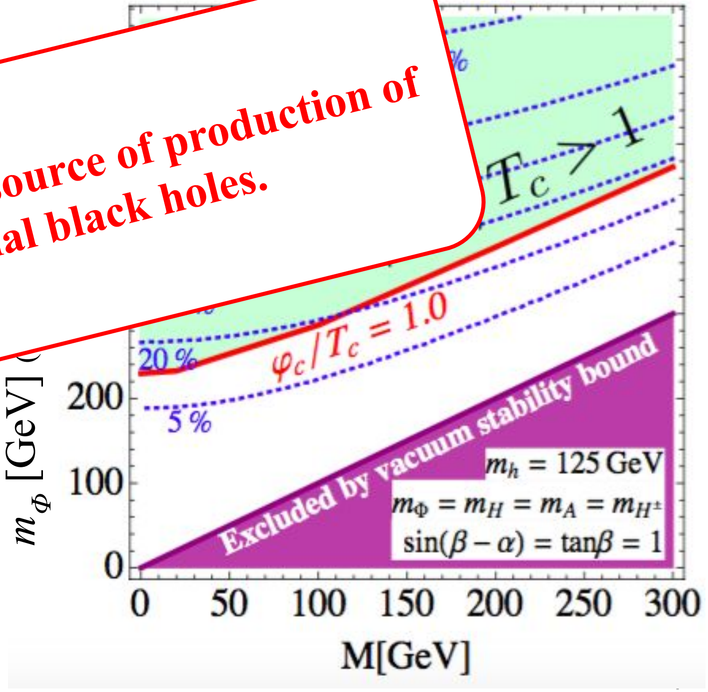
(The mass

- ★ The

$$\Delta\lambda_{hhh} \quad m_A^4 + 2m_{H^\pm}^4)$$

- ★ The stre EWPT

$$\frac{\varphi_C}{T_C} = \frac{E}{2\lambda_T} \qquad E \sim \frac{1}{12\pi^2 v^3}(m_H^3 + m_A^3 + 2m_{H^\pm}^3)$$

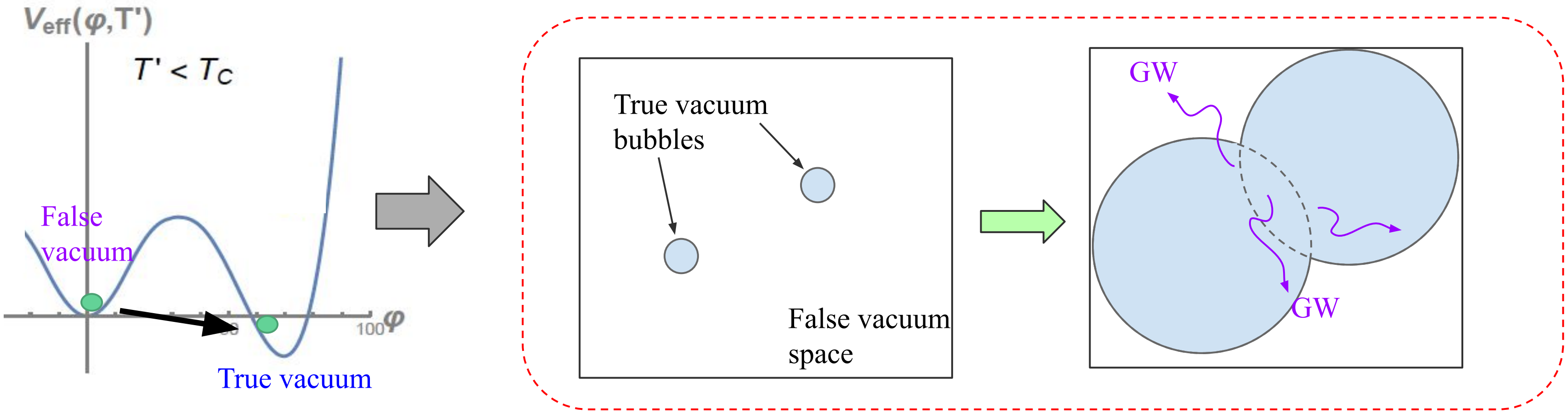


**The large deviation in the hhh coupling is the source of production of the gravitational waves and primordial black holes.**

# Contents

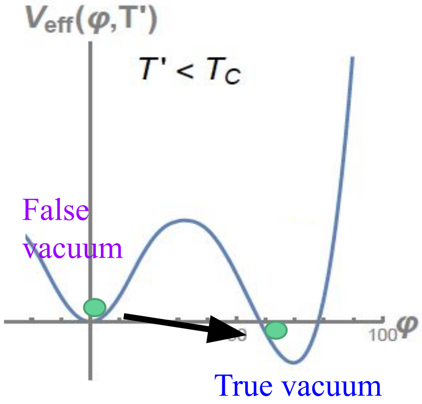
# Gravitational waves from first-order phase transition

★ If the first-order phase transition occurs in the early Universe, the gravitational waves (GWs) are produced by collision of bubbles from the phase transition.



The GW spectrum depends on the phase transition parameters: $T_t$, $\alpha$, $\beta/H$ and $v_b$.

# Gravitational waves from first-order phase transition



**(1)** **$T_t$ : Transition temperature** (The temperature of the Universe just after the phase transition.)

$$\Gamma/H^4|_{T=T_t} = 1$$

$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$$

($H$ : Hubble parameter)

**(2)** **$\alpha$ ∼ Normalized latent heat released by EWPT**

$$\alpha \equiv \frac{\epsilon(T_t)}{\rho_{\mathrm{rad}}(T_t)}$$

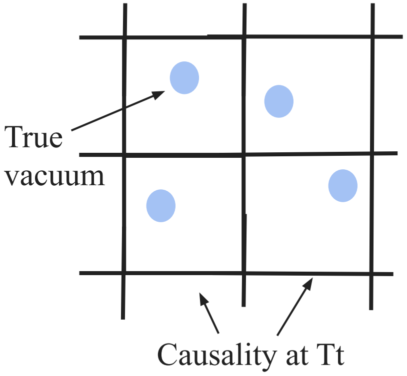
$$\epsilon(T) = \Delta V_{eff}(T) - T\frac{\partial \Delta V_{eff}}{\partial T}$$

$\rho_{\mathrm{rad}}$ : Radiative energy density

**(3)** **$\beta/H$ ∼ 1 / (Duration of EWPT)**

$$\frac{\beta}{H_n} = T\frac{d(S_3(T)/T)}{dT}|_{T=T_t}$$

**(4)** **$v_b$ : Bubble wall velocity**



# Gravitational waves from first-order phase transition

- ★ Fitting function of the GW spectrum from sound wave of plasma.

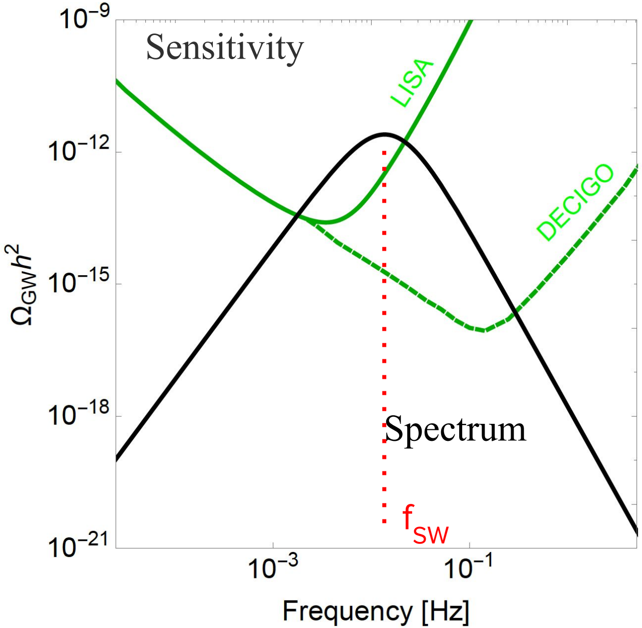
[M. Hindmarsh, S. J. Huber, K. Rummukainen and D. J. Weir, PRD 96, no.10, 103520 (2017)[erratum: PRD 101, no.8, 089902 (2020)], H. K. Guo, K. Sinha, D. Vagie and G. White, JHEP 06, 164 (2021)]

$$h^2\Omega_{\rm GW}(f) = 8.5\times10^{-6}\left(\frac{100}{g_n}\right)^{1/3}\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{H_n}{\beta}\right)v_w S_{\rm SW}(f)$$

$$S_{\rm SW}(f) = \left(\frac{f}{f_{\rm SW}}\right)^3\left[\frac{7}{4+3(f/f_{\rm SW})^2}\right]^{7/2} \qquad f_{\rm SW} = 1.9\times10^{-5}\frac{1}{v_w}\left(\frac{\beta}{H_n}\right)\left(\frac{T_n}{100\ \text{GeV}}\right)\left(\frac{g_n}{100}\right)^{1/6}\text{Hz.}$$

$\kappa$ : efficiency factor

- ★ The GW from the first-order EWPT can be observed by the future space-based GW interferometers, such as LISA and DECIGO experiments.



(Sensitivity lines)
LISA [arXiv:1512.06239]
DECIGO [Class. Quant. Grav. 28, 094011 (2011)]

# Gravitational waves from first-order phase transition

- ★ Typically, large α and small β/H are required to produce the detectable GW spectrum.

$$V_0(\Phi, \vec{S}) = V_{\rm SM}(\Phi) + \frac{\mu_S^2}{2}|\vec{S}|^2 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2$$

$$\vec{S} = (S_1, S_2, \cdots, S_N)^T$$

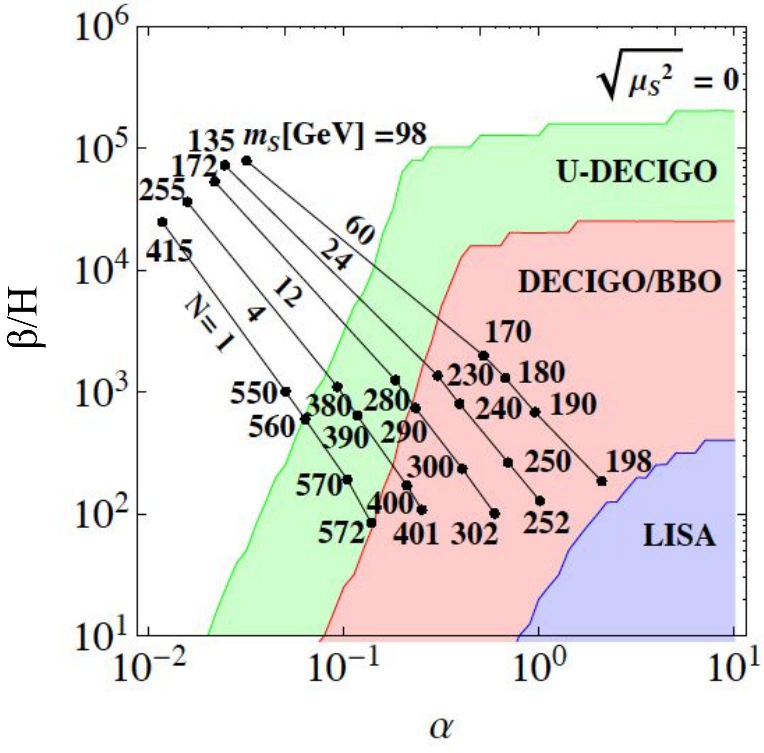
M. Kakizaki, S. Kanemura and T. Matsui, Phys. Rev. D 92 (2015) no.11, 115007 [arXiv:1509.08394 [hep-ph]].

- ★ $\alpha \propto (\varphi_C/T_C)^2$ and $\beta/H \propto (\varphi_C/T_C)^{-5/2}$

[J. R. Espinosa, T. Konstandin, J. M. No and G. Servant, JCAP 06 (2010), 028 [arXiv:1004.4187 [hep-ph]], A. Eichhorn, J. Lumma, J. M. Pawlowski, M. Reichert and M. Yamada, JCAP 05 (2021), 006 [arXiv:2010.00017 [hep-ph]].

The large deviation from the SM prediction in the *hhh* coupling is required to realize the strongly first-order EWPT.

**The detectable GW spectrum can be produced in the model with the large deviation in the *hhh* coupling.**



# Contents

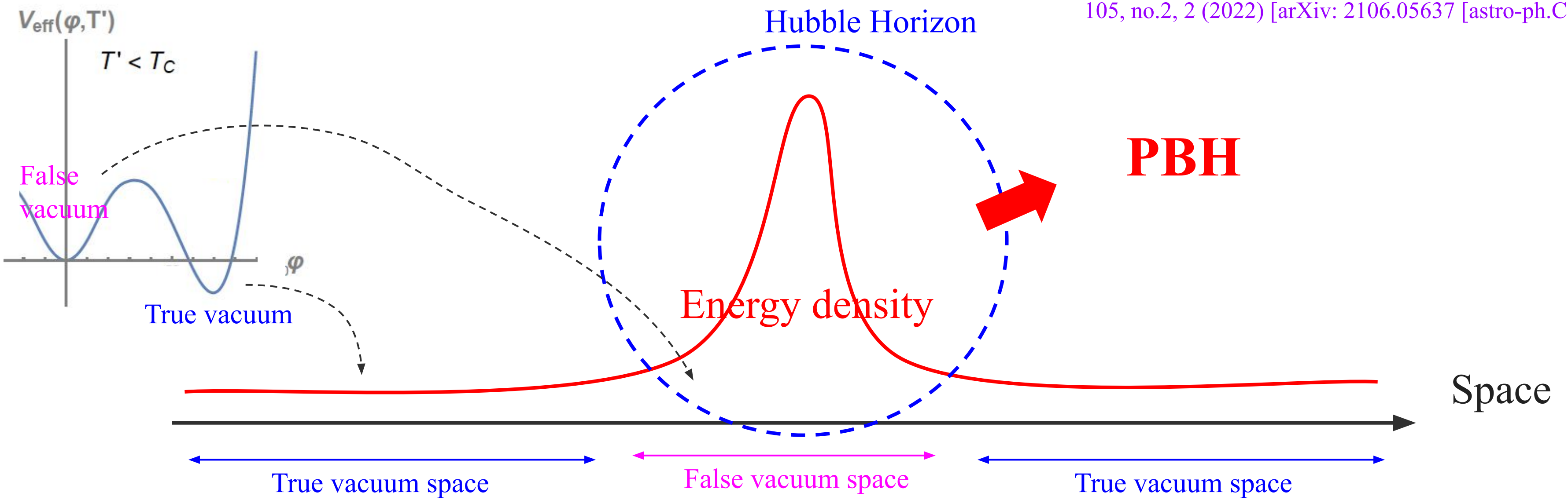
1. Introduction
2. Gravitational waves from first-order phase transition
3. Primordial black holes from first-order phase transition
4. Testability of the model with a deviation in the *hhh* coupling
5. Summary

# Primordial black holes from first-order phase transition

★ Primordial black holes (PBHs) can be produced via large density contrast.

The large density contrast can be realized by the postponed vacuum decay.

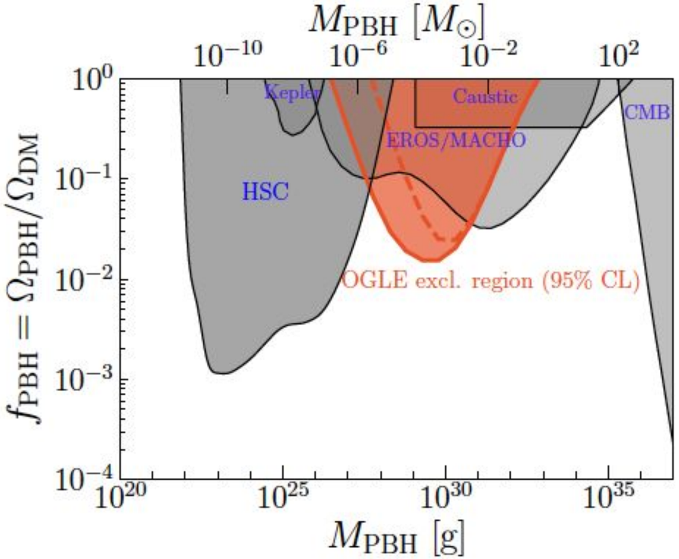
J. Liu, L. Bian, R. G. Cai, Z. K. Guo and S. J. Wang, PRD 105, no.2, 2 (2022) [arXiv: 2106.05637 [astro-ph.CO]].



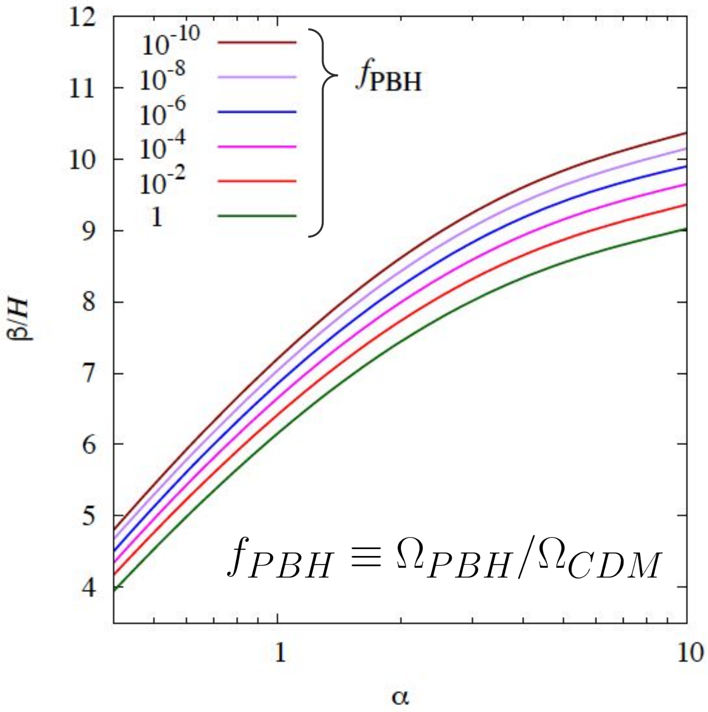
# Primordial black holes from first-order phase transition

★ Mass of PBH from first-order EWPT

$$M_{PBH} \sim 4\pi H^{-1} \sim 10^{-5} M_{SUN}$$



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

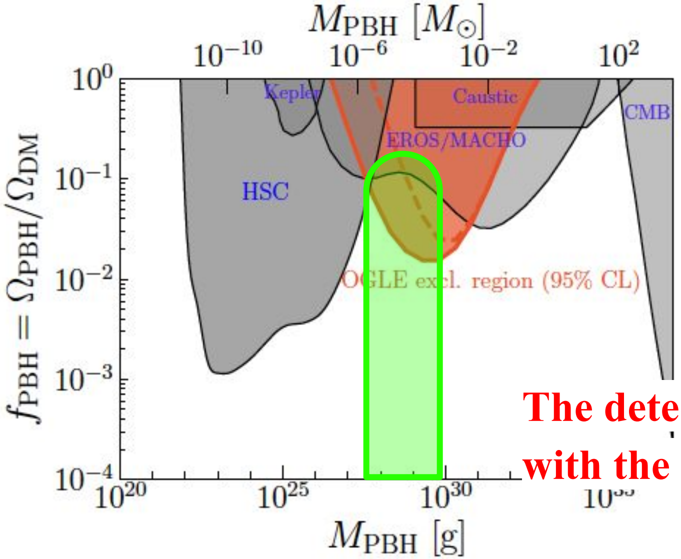


[K. H., S. Kanemura, T. Takahashi, PLB, Volume 833, 137261, arXiv:2111.13099]

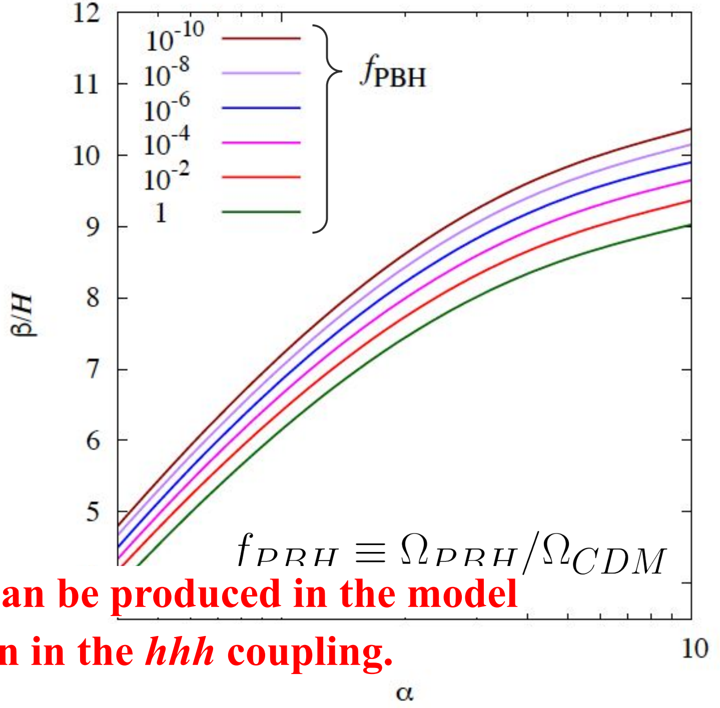
# Primordial black holes from first-order phase transition

★ Mass of PBH from first-order EWPT

$$M_{PBH} \sim 4\pi H^{-1} \sim 10^{-5} M_{SUN}$$



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



**The detectable PBHs can be produced in the model with the large deviation in the *hhh* coupling.**

[K. H., S. Kanemura, T. Takahashi, PLB, Volume 833, 137261, arXiv:2111.13099]

# Contents

# Nearly aligned Higgs effective field theory

★ Effective potential

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

[S. Kanemura and R. Nagai, JHEP 03 (2022), 194, arXiv:2111.12585 [hep-ph]]

This effective field theory can parameterize quantum non-decoupling effects.

★ Free parameters

$$\kappa_0,\ \kappa_P,\ M \ \longrightarrow\ \kappa_0,\ r,\ \Lambda$$

$$\Lambda^2 = M^2 + \frac{\kappa_{\rm p}}{2}v^2, \qquad r \sim 0 \Rightarrow M^2 \gg \frac{\kappa_p}{2}v^2$$ **Decoupling**

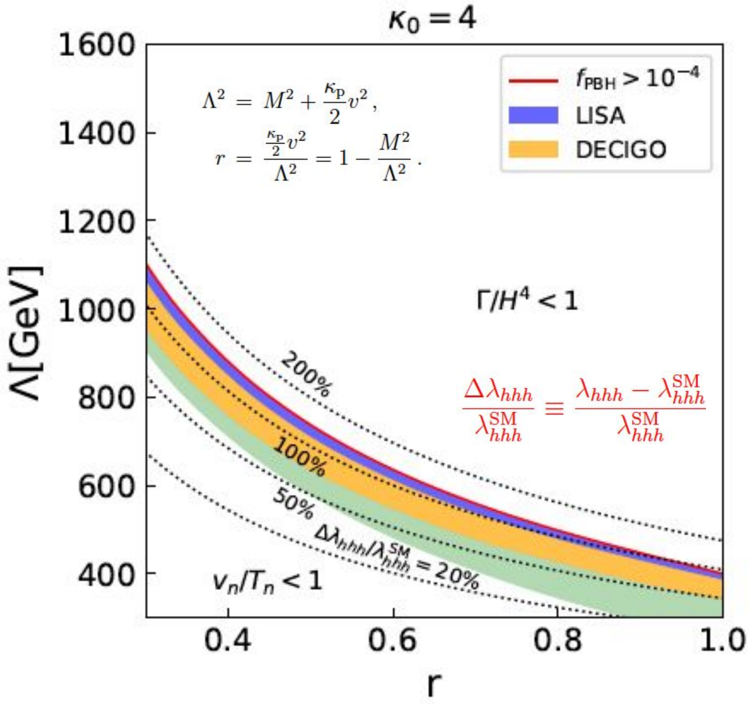
$$r = \frac{\frac{\kappa_{\rm p}}{2}v^2}{\Lambda^2} = 1 - \frac{M^2}{\Lambda^2}. \qquad r \sim 1 \Rightarrow M^2 \ll \frac{\kappa_p}{2}v^2$$ **Non-decoupling**

Large $\varphi_c/T_c$ requires non-decoupling effects, which can be controlled by $r$ parameter.

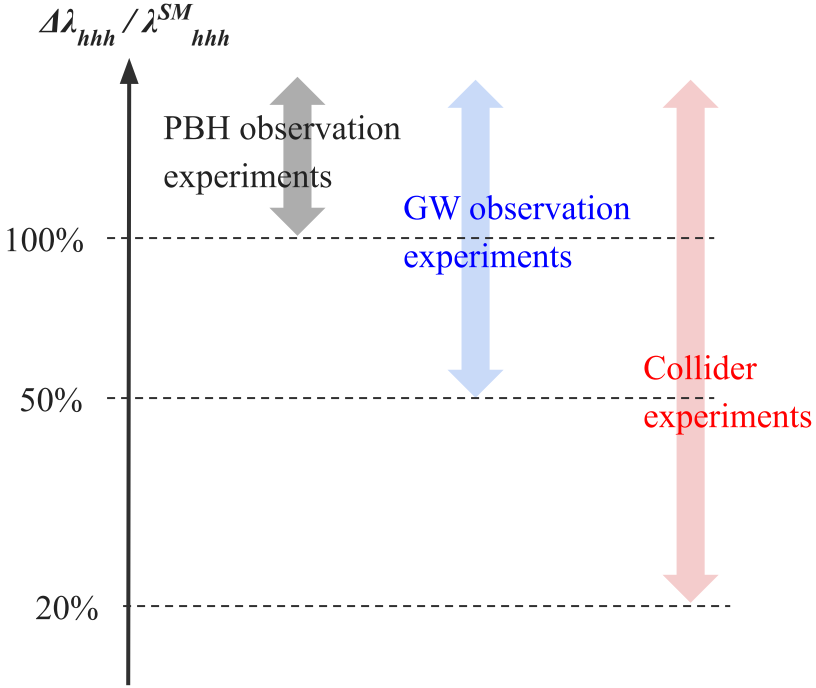
S. Kanemura, R. Nagai and M. Tanaka, JHEP 06 (2022), 027, [arXiv:2202.12774 [hep-ph]]

# Nearly aligned Higgs effective field theory

$$V_{\rm BSM}(\Phi) = \frac{\xi}{4}\kappa_0 [\mathcal{M}^2(\Phi)]^2 \ln\frac{\mathcal{M}^2(\Phi)}{\mu^2}$$



[K. Hashino, S. Kanemura, T. Takahashi and M. Tanaka, Phys. Lett. B 838 (2023), 137688 [arXiv:2211.16225 [hep-ph]].]



$\Delta\lambda_{hhh} / \lambda^{SM}_{hhh}$

PBH observation experiments

GW observation experiments

Collider experiments

100%

50%

20%

The parameter region with the deviation in the *hhh* coupling can be comprehensively tested by some experiments.

# Summary

★ A large deviation in the *hhh* coupling is the source of the first-order EWPT.

★ GWs and PBHs can be produced by the first-order EWPT.

These are detectable in the model with the large deviation in the *hhh* coupling.

We can steadily test the model with the large deviation in the *hhh* coupling by these three experiments.