Primordial black holes, gravitational waves and the *hhh* coupling as a probe of strongly first-order electroweak phase transition

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[In preparation]

Introduction

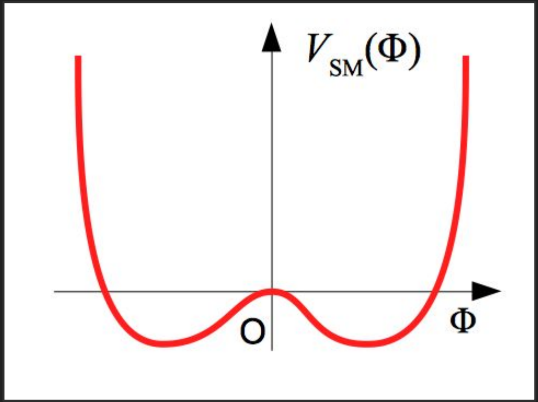
★ Phenomena beyond the SM have been reported.

- Dark matter
- Neutrino oscillations
- Baryon asymmetry of the Universe (BAU)

→ The SM has to be extended.

★ The shape of Higgs potential is still undetermined.

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



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

The EWPT is related to the phenomena beyond the SM, such as BAU.

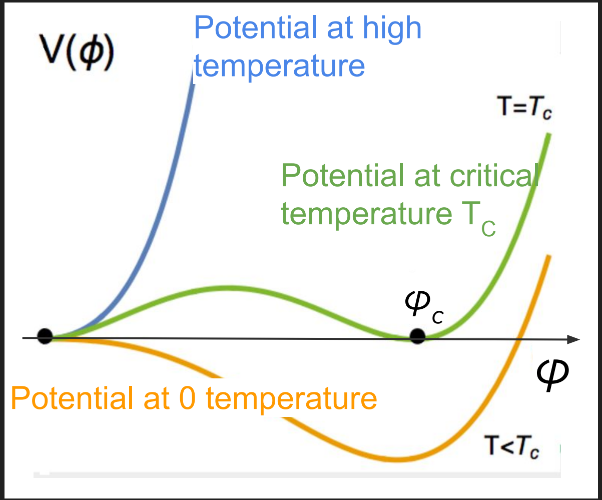
Introduction

★ Electroweak Baryogenesis is one of senario explaining BAU.

Sakharov's conditions

[A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967)]

- Baryon number violation
  → Sphaleron process
- C and CP violation
  → Model extension
- Departure from equilibrium
  → Strongly first order electroweak phase transition (1st EWPT) $(\varphi_c / T_c \gtrsim 1)$



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

$$\frac{\phi_C}{T_C} = \frac{2E}{\lambda}\left(1 - \frac{e\lambda}{ET}\right)$$

E : Loop effects of bosons

e : Mixing effects at the tree level

The SM cannot satisfy the condition of strongly 1st EWPT $\varphi_c / T_c \gtrsim 1$.

[Y. Aoki, F. Csikor, Z. Fodor and A. Ukawa, Phys. Rev. D 60, 013001 (1999)]

We can realize strongly first-order EWPT in the new physics model beyond the SM.

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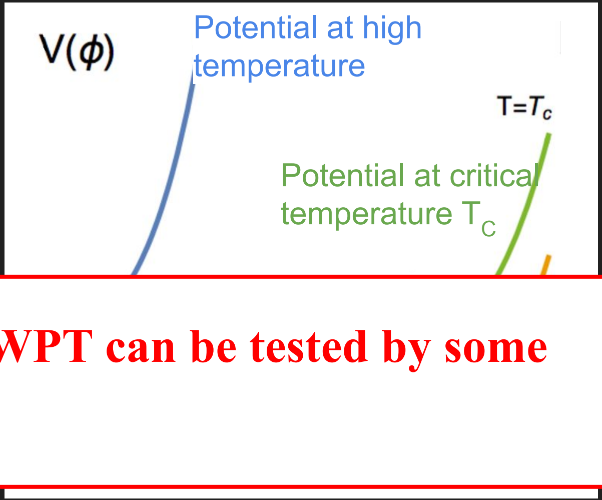

The new physics models with strongly first-order EWPT can be tested by some experiments.

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Testability of the model with $\varphi_c / T_c \gtrsim 1$

New physics models with strongly first-order EWPT

The *hhh* coupling measurement

The model with strongly first-order EWPT can have the *hhh* coupling is **about 10%** larger than the SM one.

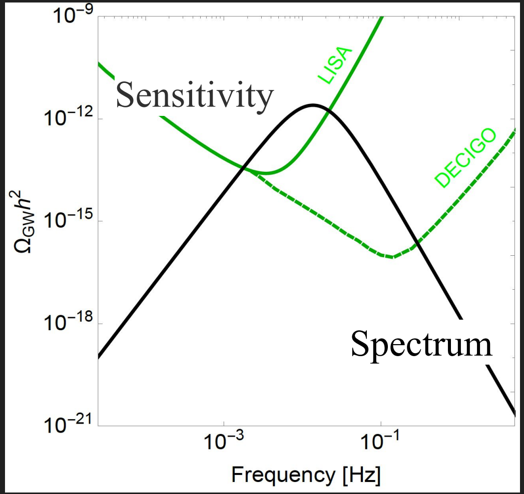
S. Kanemura, Y. Okada, E. Senaha, PLB 606 361 (2005)

Measurements of gravitational wave (GW) spectrum from first-order EWPT

The peak of GW spectrum from first-order EWPT depends on the model parameters.

C. Grojean and G. Servant, PRD 75 (2007), 043507

Correlation



LISA: A. Klein et al., PRD93 no. 2, (2016) 024003
DECIGO: K. Yagi and N. Seto, PRD83 (2011) 044011

So far, we used this correlation between the *hhh* coupling and GW spectrum measurements to discuss the testability of the new physics models.

K. H, R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi and M. Takimoto, PRD 99, no. 7, 075011 (2019) and so on

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Correlation

Measurements of Primordial black holes (PBHs) from first-order EWPT

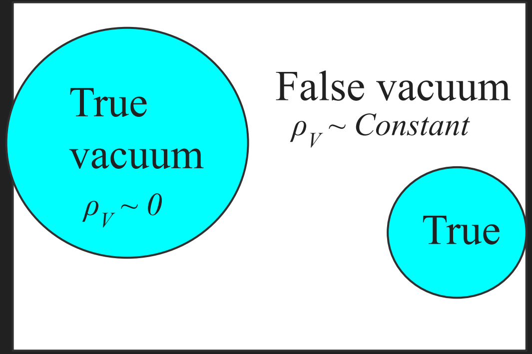
We can evaluate the PBHs from first-order phase transition by model-independently (phase transition parameters).

J. Liu, L. Bian, R. G. Cai, Z. K. Guo and S. J. Wang, [arXiv:2106.05637 [astro-ph.CO]].

New correlation

We can use the stronger correlation to discuss the testability of the model with strongly first-order EWPT. [K. H., Shinya Kanemura, Tomo Takahashi, In preparation]

Primordial black holes from first-order phase transition



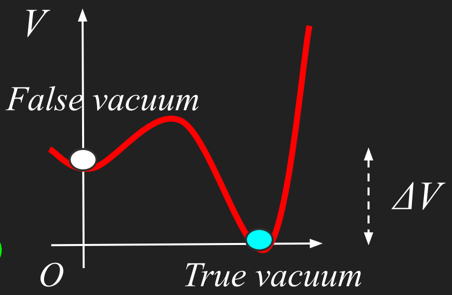
★ The PBHs can be produced during the first-order phase transition model-independently.

J. Liu, L. Bian, R. G. Cai, Z. K. Guo and S. J. Wang, [arXiv:2106.05637 [astro-ph.CO]].

Vacuum energy density $\rho_V \sim \Delta V$

Radiative energy density $\rho_r \propto a(t)^{-4}$

(We assume the true vacuum sits at V = 0)



★ The delay of vacuum decay results in an increase of the total energy density in false vacuum space.

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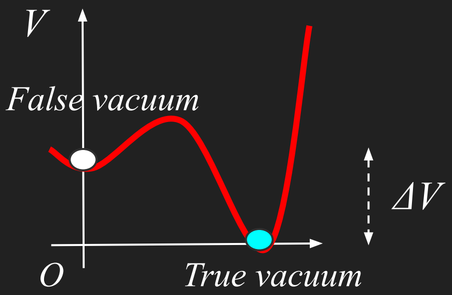
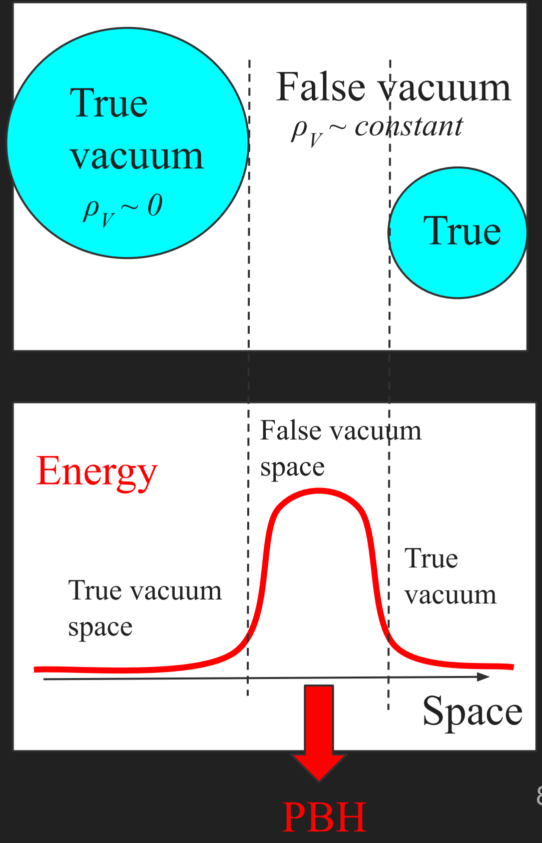




★ The delay of vacuum decay results in an increase of the total energy density in false vacuum space.

It is the source of large energy fluctuation.

→ The mass in the false vacuum space collapse into PBH.

Primordial black holes from first-order phase transition

★ The PBH mass from first-order EWPT is related to the time when the EWPT starts.

$$M_{PBH} \sim 10^{-5}\, M_{SUN}$$

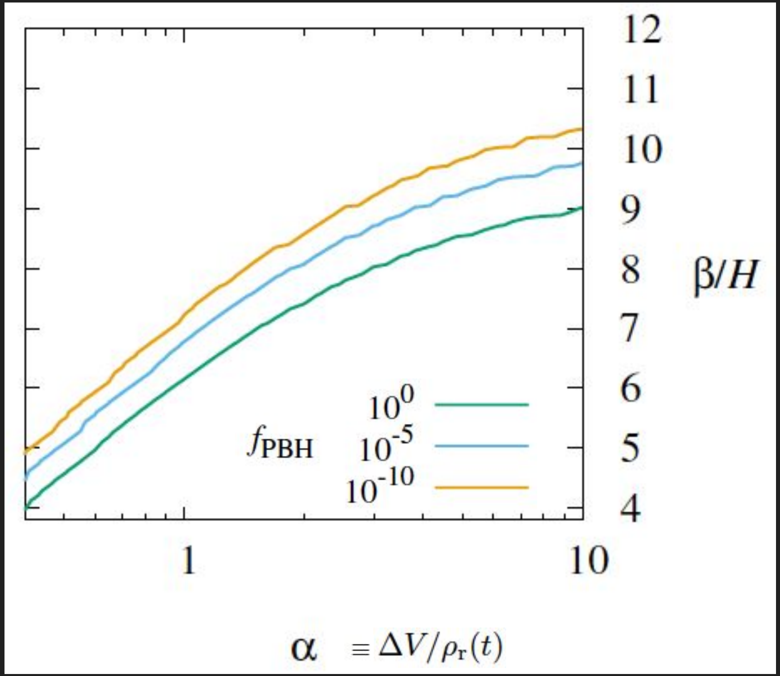
Such a PBH can be detected by OGLE, PRIME and Roman experiments.

★ The PBH abundance f_{PBH} is proportional to the probability of delayed vacuum decay.

$$\Gamma(t) = \Gamma_0 e^{\beta t}$$

The β^{-1} parameter corresponds the duration time of phase transition.

The PBH abundance f_{PBH} is very sensitive to the beta parameter.



[K. H., Shinya Kanemura, Tomo Takahashi, In preparation]

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As an example, we focus on the model with dimension 6 and 8 operators and discuss the PBHs, GW and the *hhh* coupling in the model.

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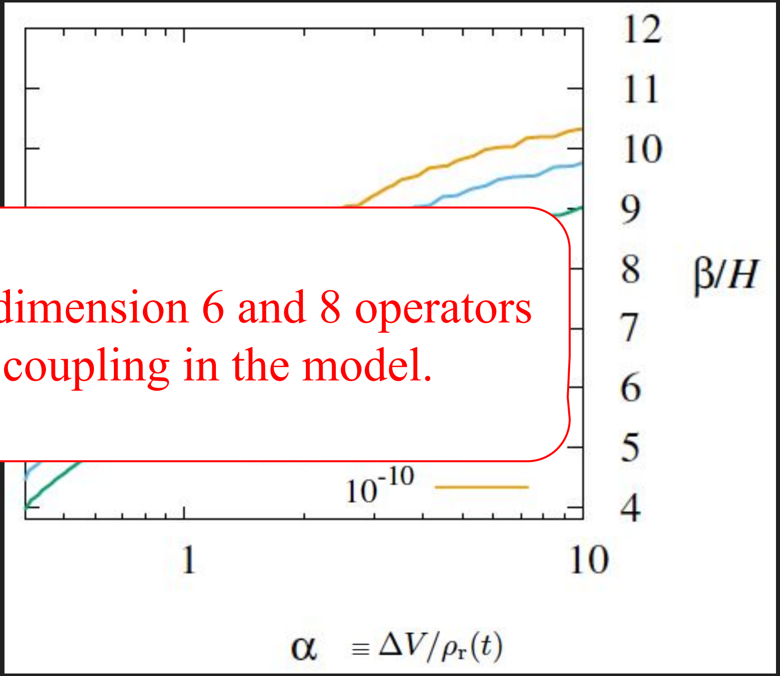


[K. H., Shinya Kanemura, Tomo Takahashi, In preparation]

Model with high dimensional operators

★ As an example, we focus on the model with dimension 6 and 8 operator and discuss the testability of it by the correlation.

★ Tree-level potential

$$V_{EFT}(H) = \mu^2|H|^2 + \lambda|H|^4 + a_6|H|^6 + a_8|H|^8,$$

$$H = \begin{pmatrix} G^{\pm}, \\ \frac{1}{\sqrt{2}}\left(h + iG^0\right) \end{pmatrix}$$

★ Effective potential with finite temperature effects

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

$$a_6 = \epsilon/\Lambda^2,\ a_8 = 1/\Lambda^4$$

ΔV_T : Finite temperature effects

★ The deviation in the *hhh* coupling from the SM prediction value

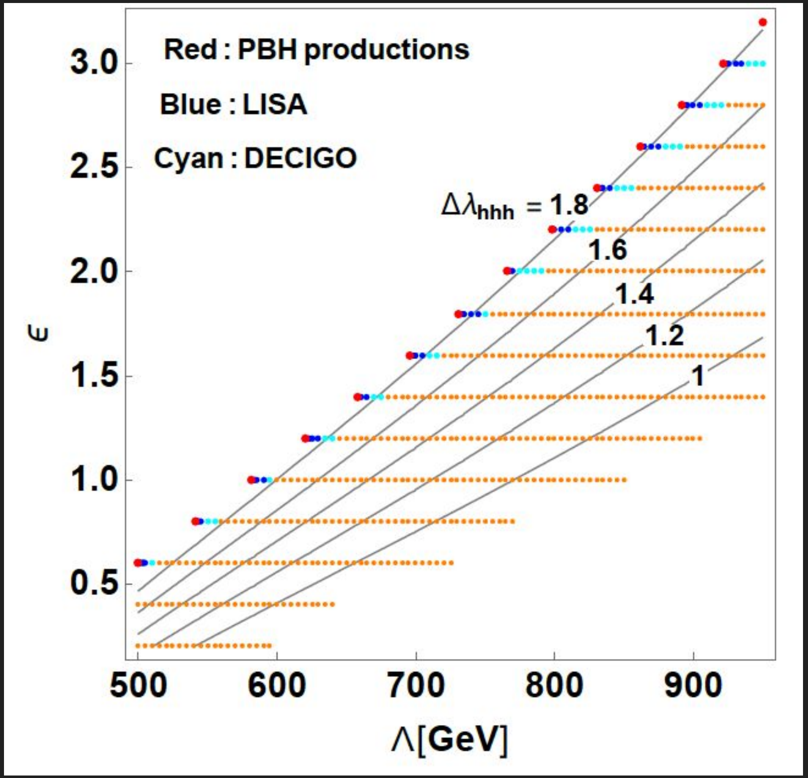
$$\Delta\lambda_{hhh} \equiv \frac{\lambda_{hhh} - \lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}}, \quad \lambda_{hhh} \equiv \left.\frac{\partial^3 V_{eff}}{\partial h^3}\right|_{h=v}$$

The correlation in the model with high dimensional operators

★ We show the correlation in the model:

- Red points: PBHs can be produced and f_{PBH} can be tested.
- Blue points: The GW spectrum can be detected at LISA experiment
- Cyan points: The GW spectrum can be detected at DECIGO experiment
- Black contours: Deviation in the *hhh* coupling

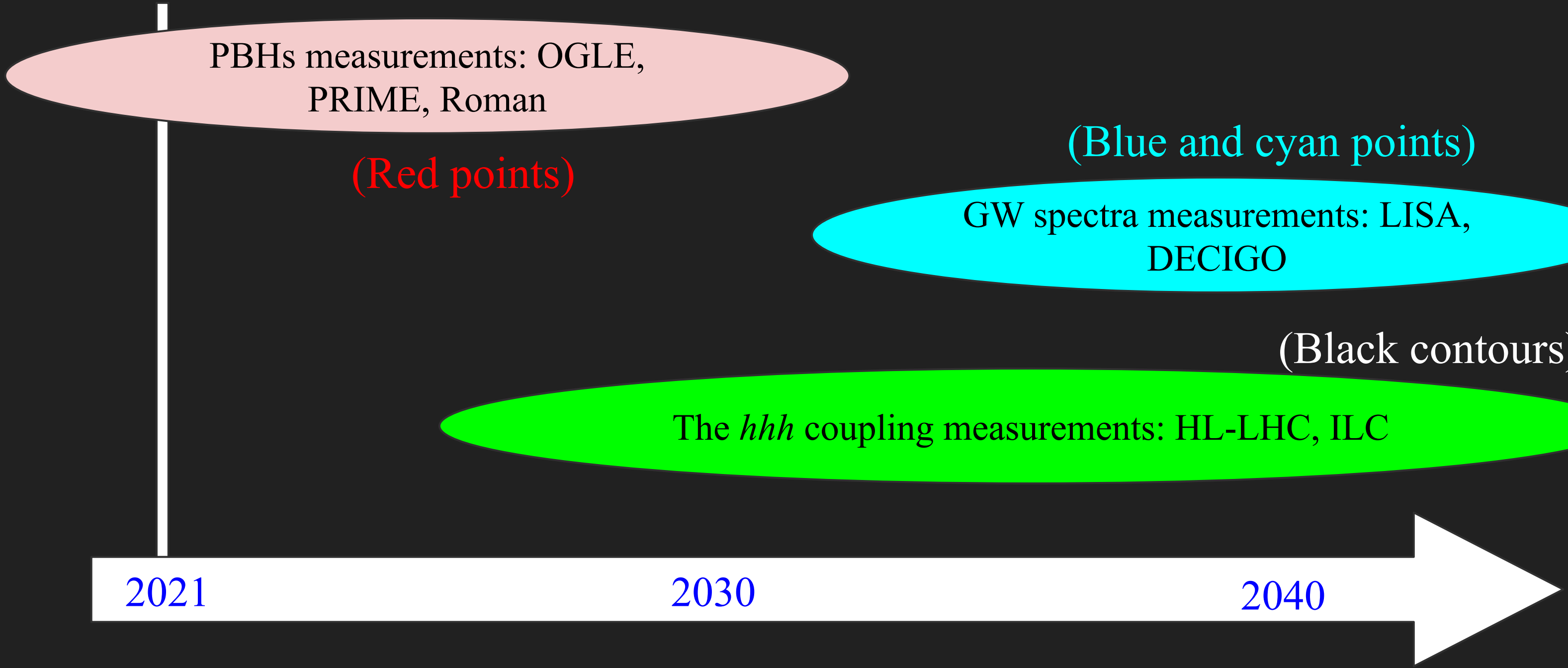
$$\Delta\lambda_{hhh} \equiv \frac{\lambda_{hhh} - \lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}},$$



We can use the stronger correlation to discuss the testability of the model with strongly first-order EWPT.

[K. H., Shinya Kanemura, Tomo Takahashi, In preparation]

Measurements of PBHs, GW, the *hhh* coupling



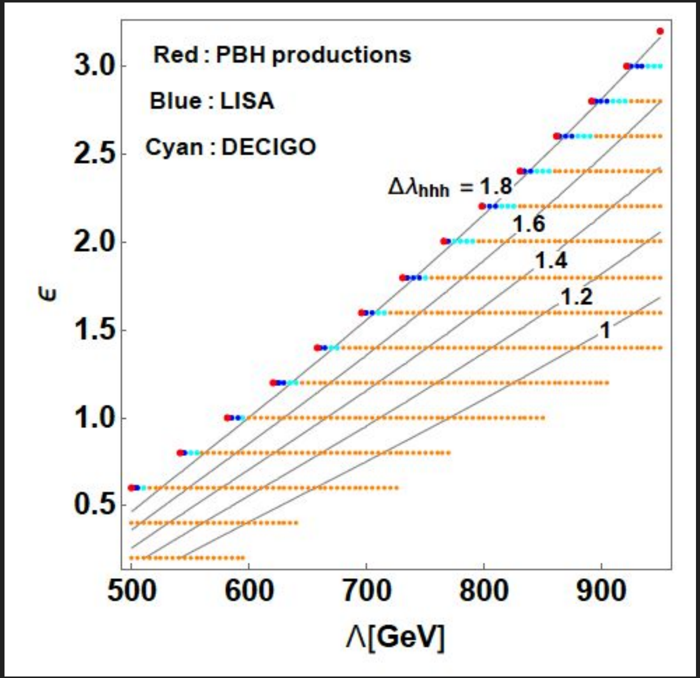
We can test the model with strongly first-order EWPT steadily!

Summary

★ The model with strongly first-order electroweak phase transition can be tested by some experiments.

★ In this time, we used the correlation among the measurements of hhh coupling, gravitational wave spectrum and primordial black holes to discuss the testability.

★ As an example, we focused on the model with dimension 6 and 8 operators and discuss the testability of it.



We showed that the model with strongly first-order electroweak phase transition can be comprehensively tested by the stronger correlation than before.