# Test of the model by collider and gravitational wave observation experiments

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(1. IBS, 2. KEK, 3. Univ. of Toyama, 4. Osaka Univ. , 5. Saga Univ. , 6. Weizmann Institute of Science)

K. H, R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi and M. Takimoto, Phys. Rev. D 99, no. 7, 075011 (2019)

# Introduction

- Higgs boson which is predicted in the Standard Model(SM) was detected at the Large Hadron Collider(LHC).

- Measurements of Higgs boson couplings

The relation between the mass of particle and Higgs coupling in the SM

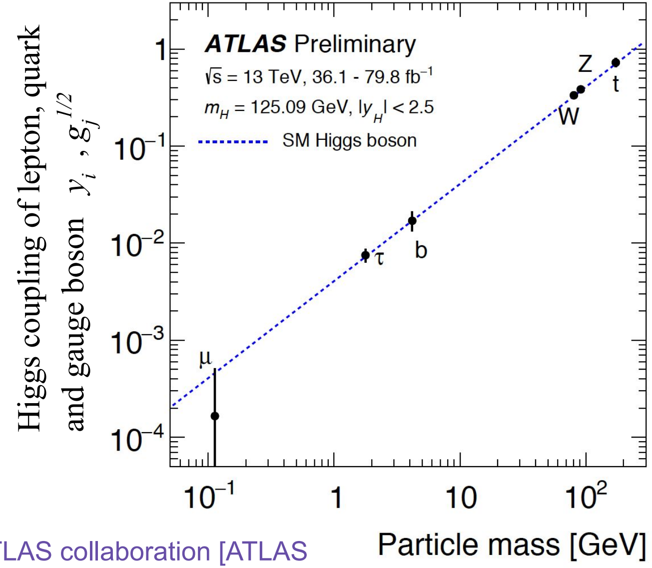
$$m_i \sim y_i v$$
$$m_j \sim g_j^{1/2} v$$

$m_i$ : Mass of particle $i$ (quark and lepton)

$m_j$ : Mass of gauge boson $j$

$y_i$ : Yukawa interaction for fermion $i$

$g_j$ : Higgs couplings for gauge boson $j$




[The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2018-031]

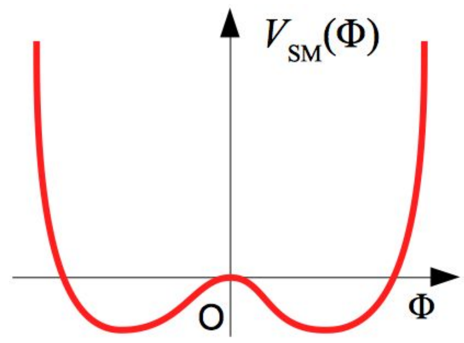
The SM can explain the current results of the collider experiments below O(1) TeV.

# Introduction

❖ However, phenomena beyond the SM have been reported.

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

→ The SM has to be extended.




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

$(\mu^2 < 0)$

❖ The Higgs sector is still vague.

- The number of the Higgs field ?
- The Higgs field is elementary or composed ?
- Dynamics of the electroweak symmetry breaking (EWSB) ?

→ We can consider the various extended Higgs models

❖ The extended Higgs models can explain phenomena beond the SM.

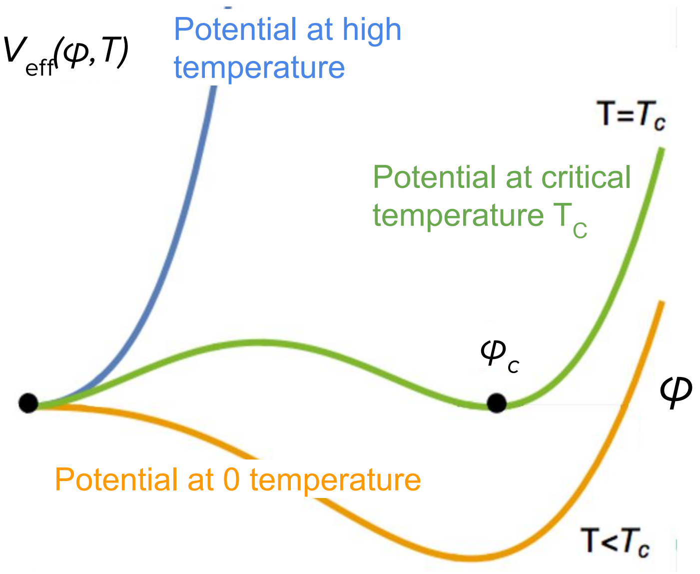
# Introduction

❖ Electroweak Baryogenesis (EWBG) is a 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
  → Extended Higgs sector
- Departure from equilibrium
  → Strongly first order electroweak phase transition (1st EWPT) $(\varphi_c / T_c \gtrsim 1)$




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

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

$E$ : 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 1st EWPT by extended Higgs models.

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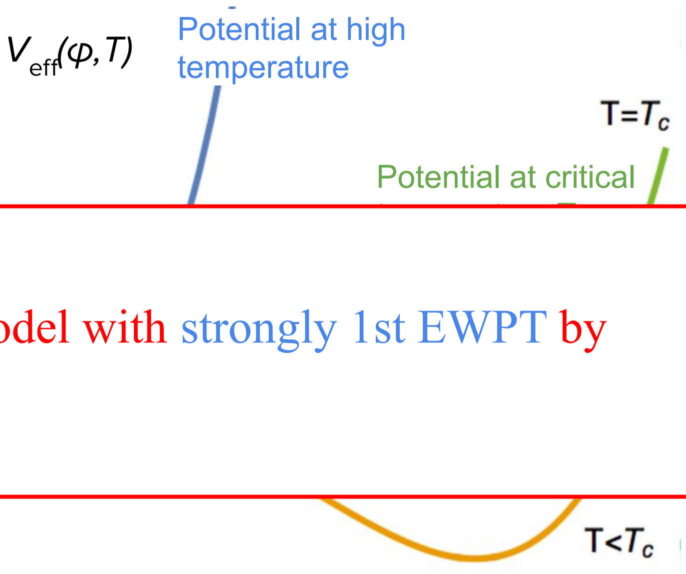


In this talk, we discuss the testability of extended Higgs model with strongly 1st EWPT by collider and gravitational wave observation experiments.

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# Contents

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

- We discuss the testability of 2 Higgs doublet model with $\varphi_c / T_c \gtrsim 1$ by collider experiments.

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

Input parameters : $m_1^2,\ m_2^2,\ m_3^2,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5$

$$\rightarrow v,\ M^2(=2m_3^2/\sin\beta),\ m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \tan\beta = \langle\Phi_2\rangle/\langle\Phi_1\rangle,\ \sin(\beta-\alpha)$$

Vacuum expectation value (246GeV) | Masses of new scalars | Mixing angle for mass matrix for *h* and *H*

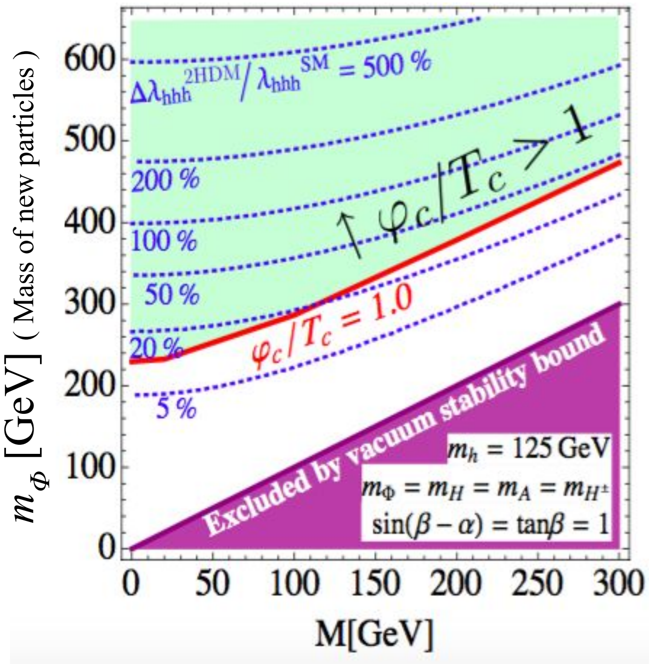
- The model can realize strongly 1st EWPT when *hhh* coupling is about 10% larger than the SM one. [S. Kanemura, Y. Okada, E. Senaha, Physics Letters B 606 361 (2005)]

- ILC with $\sqrt{s} = 1$ TeV and $L$=5000 fb$^{-1}$ can measure the *hhh* coupling at about 10% accuracy. [K. Fujii et al. , arXiv:1506.05992]

- However, the center of mass energy of ILC is 250 GeV under the current plan. (*hhh* coupling will be precisely measured in the distant future.)

$$m_\Phi^{\ 2} \sim \lambda_i v^2 + M^2$$

$$\Delta\lambda_{hhh}^{2HDM}/\lambda_{hhh}^{SM} \equiv (\lambda_{hhh}^{2HDM} - \lambda_{hhh}^{SM})/\lambda_{hhh}^{SM}$$



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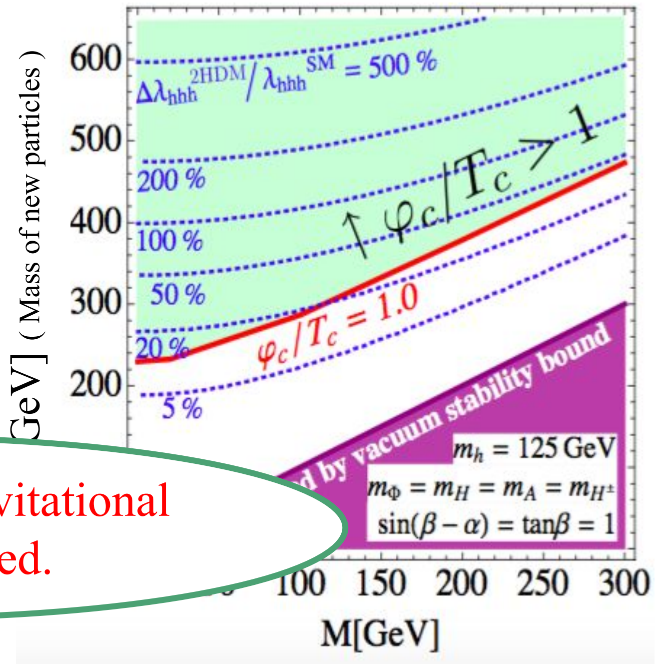
- ❖ ILC with $\sqrt{s} = 1$ TeV and $L$=5000 fb$^{-1}$ ca... about 10% accuracy. [K. Fujii et al. , arXiv:15...
- ❖ However, the center of mass energy of ILC is 25... plan. (*hhh* coupling will be precisely measured in the distant future.)

Measurements of gravitational wave can be substituted.

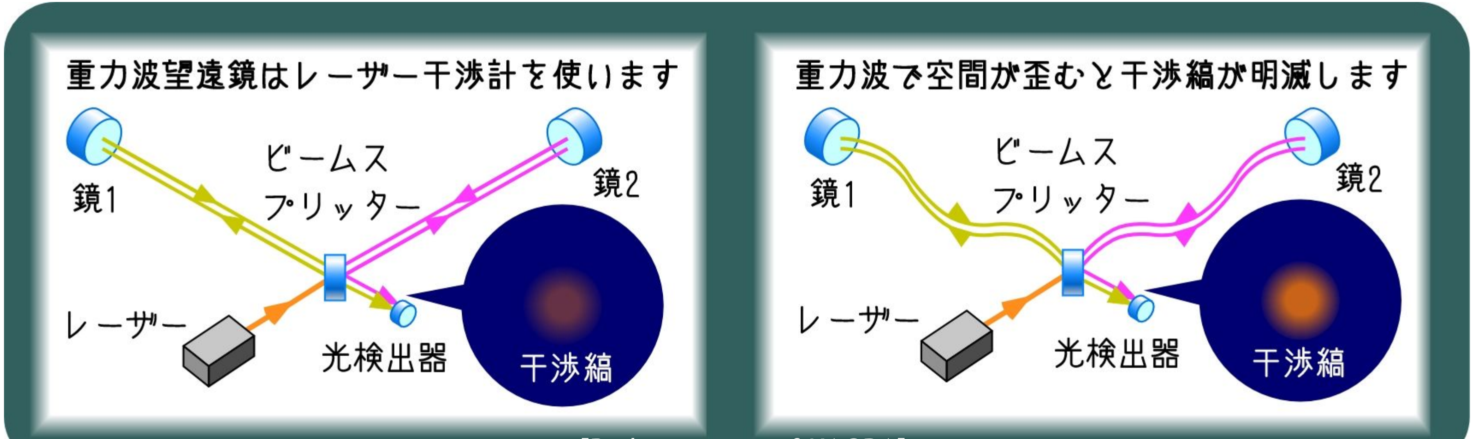


# Measurement of gravitational wave

❖ If the model realizes first-order phase transition in the early universe, the gravitational waves (GWs) are produced by the phase transition.

★ What is the GW? → GW is disturbance in the curvature of spacetime.

The disturbance can be observed by difference in phase change of laser for the interferometer.

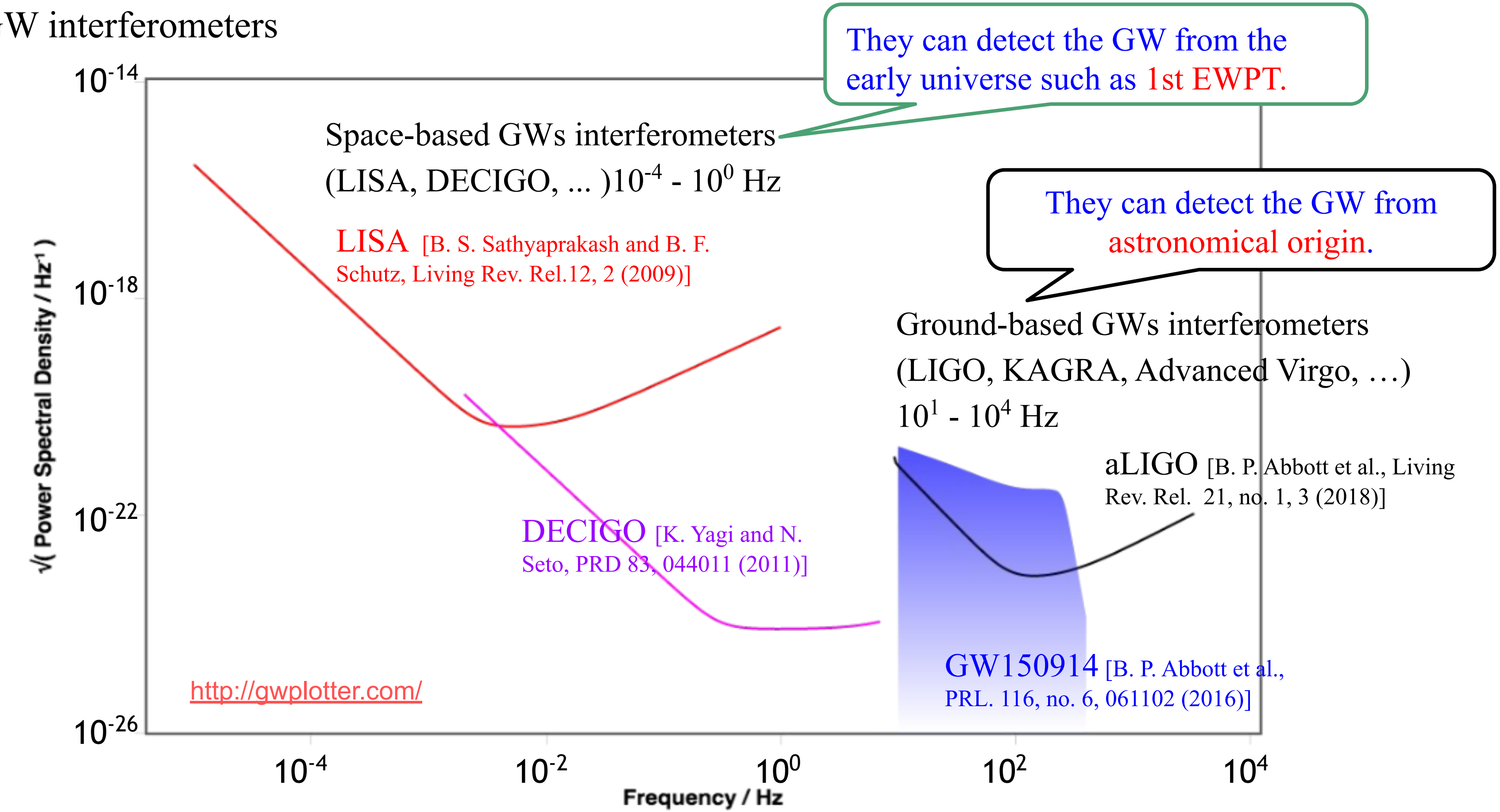



[By homepage of KAGRA]

If GWs come to the interferometers, the interfered fringe changes by extending and shrinking the lengths of the arms.

# Measurement of gravitational wave

- GW interferometers



# Measurement of gravitational wave

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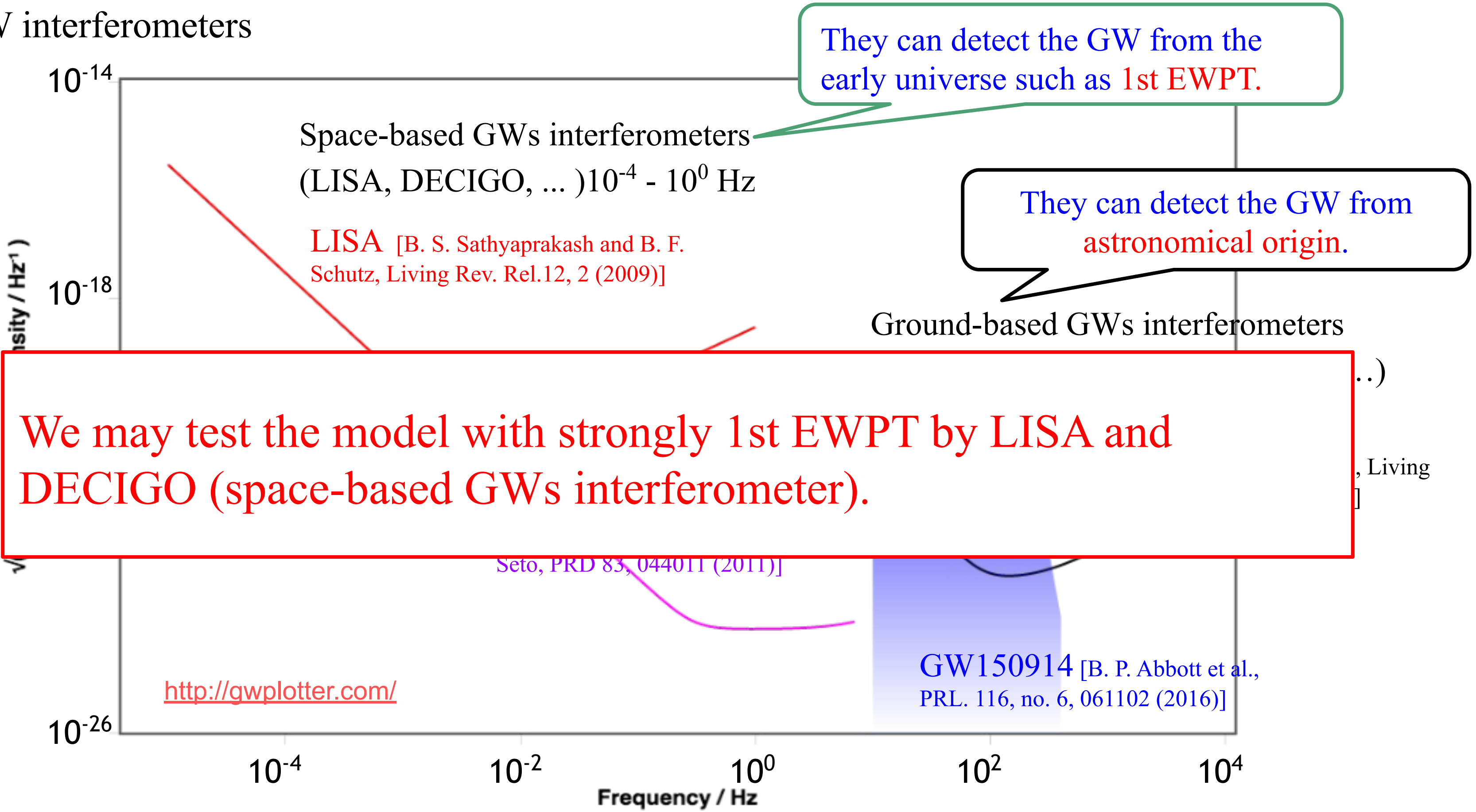
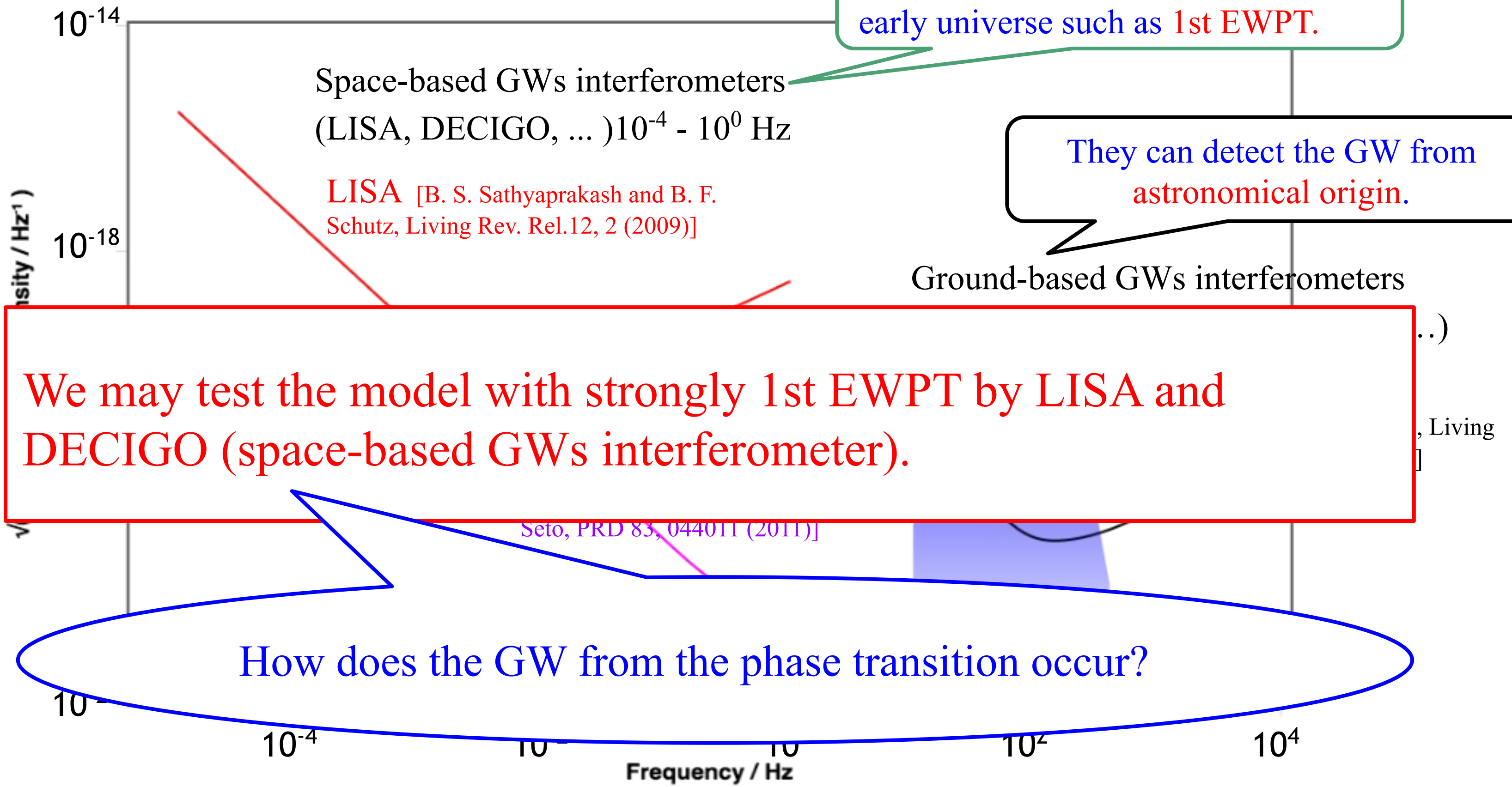



We may test the model with strongly 1st EWPT by LISA and DECIGO (space-based GWs interferometer).

# Measurement of gravitational wave

❖ GW interferometers




They can detect the GW from the early universe such as 1st EWPT.

They can detect the GW from astronomical origin.

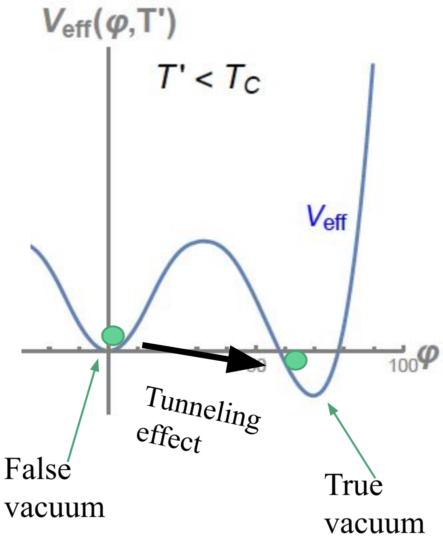
We may test the model with strongly 1st EWPT by LISA and DECIGO (space-based GWs interferometer).

How does the GW from the phase transition occur?

# GW from 1st EWPT

❖ What is 1st EWPT?

The order parameter $\varphi$ discontinuously moves from the origin of the potential to the bottom (from false vacuum to true vacuum).

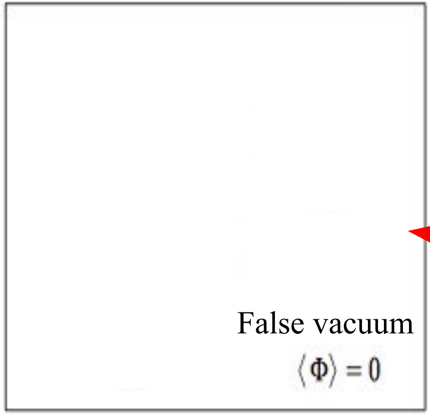



• Nucleation rate of one critical bubble per unit time and per unit volume

[S. Coleman, "Aspects of Symmetry" ], [C. Grojean and G. Servant, Phys. Rev. D 75, 043507 (2007)]

$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}} \qquad \left( S_3 = \int d^3r \left[ \frac{1}{2}(\vec{\nabla}\varphi_b)^2 + V_{\text{eff}}(\varphi_b, T) \right] \right)$$

It depends on the theory.




The space filled with the false vacuum ($\langle\varphi\rangle=0$).

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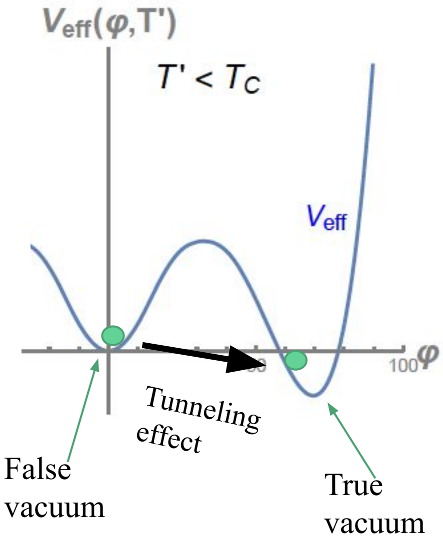


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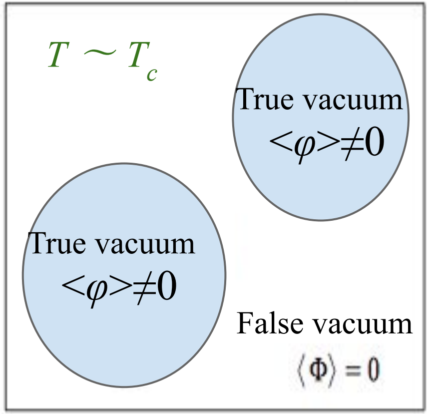


The bubble for true vacuum ($<\varphi>\neq 0$) nucleates in the space filled with false vacuum ($<\varphi>=0$) by the tunneling effect.

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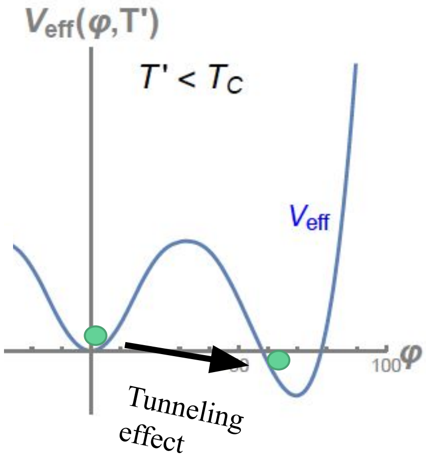


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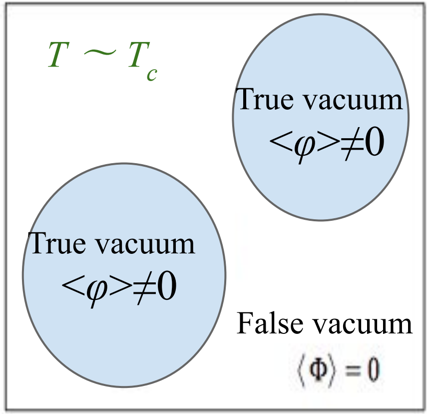
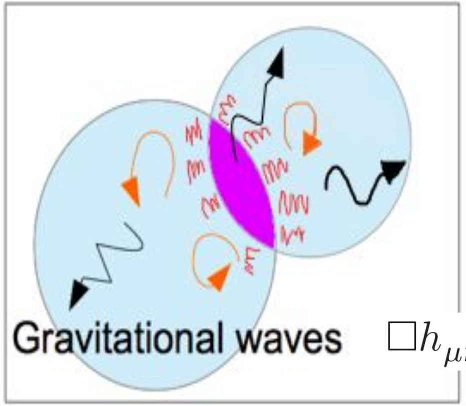



$$\Box h_{\mu\nu} \sim T_{\mu\nu}$$

**Sources of GWs**

1. Compression wave of plasma
2. Plasma turbulence
3. Collision of wall

GWs occur by collision of bubbles.

# Parameters characterizing GWs from 1st EWPT

- Velocity of bubble wall $v_b$ (In this time, we take it as a free parameter.)
- Transition temperature $T_t$ (Temperature where EWPT is complete)

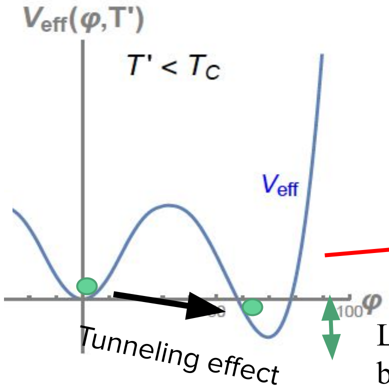
$$\Gamma/H^4|_{T=T_t} = 1$$

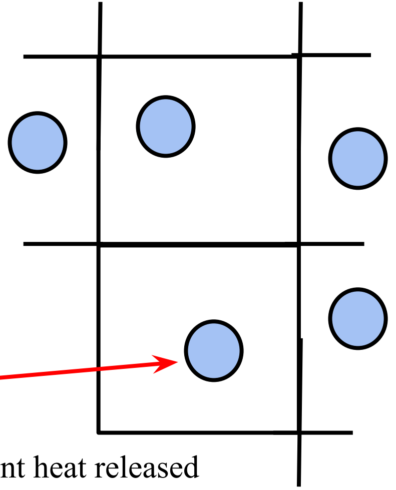
(H : the Hubble parameter)

- α and β parameter

α ≃ Normalized latent heat released by EWPT,

β ≃ 1/(Duration of the EWPT )



Latent heat released by EWPT

$$\alpha \equiv \frac{\epsilon(T_t)}{\rho_{\rm rad}(T_t)} \qquad \beta \simeq \frac{1}{\Gamma}\frac{d\Gamma}{dt}\bigg|_{t=t_t}$$

Latent heat : $\epsilon(T) = \Delta V_{eff}(T) - T\frac{\partial \Delta V_{eff}}{\partial T}$ $\quad U = F - T\frac{\partial F}{\partial T}$

Radiative energy density : $\rho_{rad}$

$T_t$, α and β parameters can be fixed by the potential (These depend on the model).

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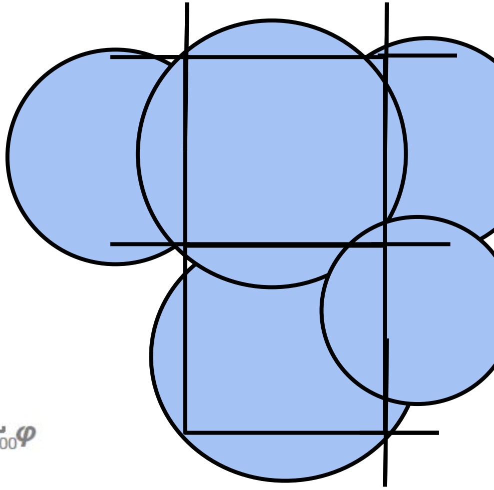

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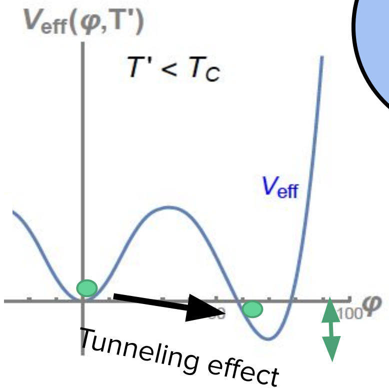


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Radiative energy density : $\rho_{rad}$

$T_t$, α and β parameters can be fixed by the potential (These depend on the model).

# GW from 1st EWPT

- The GW spectrum from 1stOPT need complicated numerical simulations.

→ We use apploximately fitting formula.

For example… Compression wave of thermal plasma

[C. Caprini, et al., J.Cosmol. Astropart. Phys. 1604(04)(2016) 01.]

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

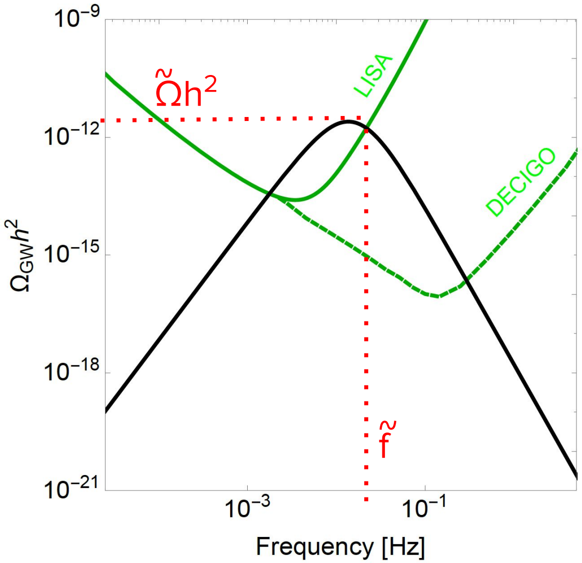
Peak of the spectrum

$$\tilde{\Omega}_{\rm comp}h^2 \simeq 2.65 \times 10^{-6} v_b \tilde{\beta}^{-1} \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*^t}\right)^{1/3},$$

Peak of frequency

$$\tilde{f}_{\rm comp} \simeq 1.9 \times 10^{-5}\ {\rm Hz} \frac{1}{v_b} \tilde{\beta} \left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

$\tilde{\beta} \equiv \beta/H$ $\kappa_v$ : efficiency factor




The sensitivity regions LISA: [arXiv:1512.06239 [astro-ph.CO]], DECIGO: [Class. Quant. Grav. 28, 094011(2011)]

$T_t$, α and β can be fixed by the observation of the GW spectrum → Model information can be obtained by the measurement!

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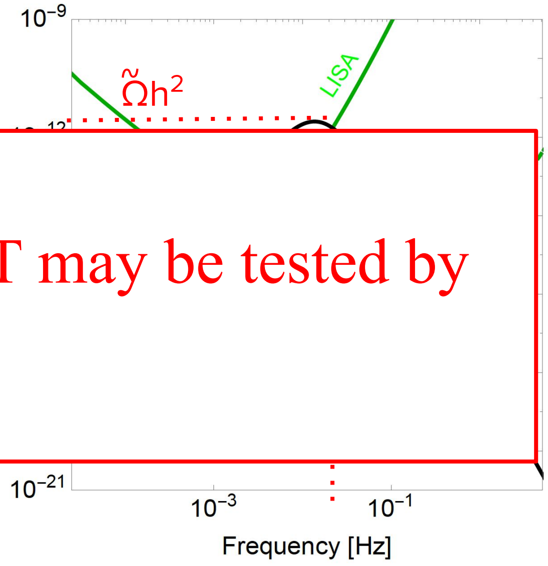


The extended Higgs model with strongly 1st EWPT may be tested by collider and GW observation experiments.

$\tilde{\beta} \equiv \beta/H$ $\kappa_v$ : efficiency factor

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# Contents

# Strongly 1st EWPT for extended Higgs model

❖ Model with strongly 1st EWPT

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

e : tree-level effects

E : thermal loop effect of bosons

(Potential with high temperature approximation)

$$\frac{\varphi_C}{T_C} = \frac{2}{\lambda(T_C)}\left(\underline{E} - \frac{e}{\underline{T_C}}\right)$$

- The model in which the loop effects of bosons E is mainly related to 1st EWPT
- The model in which the mixing effects e at tree-level is mainly related to 1st EWPT

We discuss the model with one real isospin singlet scalar field *S* as an example (this model is one of the simplest model with small e effects).

# Model with a real isospin singlet scalar field

[K. H. , M. Kakizaki, S. Kanemura, P. Ko and T. Matsui, Phys. Lett. B766 (2017) 49 ]

❖ This model is the SM with one isospin singlet scalar field *S*.

❖ Higgs potential

$$V_0 = \underbrace{-\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4}_{\text{The SM parts}} + \underbrace{\mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu'_S}{3}S^3 + \frac{\lambda_S}{4}S^4}_{\text{An additional scalar boson parts}}$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\phi_1 + i\phi_0) \end{pmatrix} \qquad S = \phi_2 \qquad \langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}v \end{pmatrix} \quad \langle S\rangle = v_S$$

- Stationary condition of the potential

$$\left.\frac{\partial V}{\partial \phi_i}\right|_{\phi_1=v,\phi_2=v_S} = 0, \ (i = 1, 2)$$

# Model with a real isospin singlet scalar field

[K. H. , M. Kakizaki, S. Kanemura, P. Ko and T. Matsui, Phys. Lett. B766 (2017) 49 ]

- Diagonalized mass matrix for SM-like Higgs *h* and additional scalar *H*

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\begin{pmatrix} m_h^2 & 0 \\ 0 & m_H^2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} m_{11}^2 & m_{12}^2 \\ m_{21}^2 & m_{22}^2 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

Mass matrix for *h* and *H*

Mass matrix for $\phi_1$ and $\phi_2$ $m_{ij}^2 = \left.\frac{\partial^2 V_{\mathrm{eff},T=0}}{\partial\varphi_i \partial\varphi_j}\right|_{\phi_1=v,\phi_2=v_S}$

- Independent parameters of the model

$\mu_\Phi, \lambda_\Phi, \mu_{\Phi S}, \lambda_{\Phi S}, \mu_S, m_S, \mu'_S, \lambda_S \rightarrow$ $v\,(246GeV), m_h(125GeV), v_S, m_H, \theta, \mu_S, \mu'_S, \mu_{\Phi S}$

(Parameters in tree-level potential)

# Model with a real isospin singlet scalar field

[K. H. , M. Kakizaki, S. Kanemura, P. Ko and T. Matsui, Phys. Lett. B766 (2017) 49 ]

❖ Scaling factors of the Higgs boson coupling

$$\kappa_X \equiv \frac{g_{hXX}}{g_{hXX}^{\rm SM}}, \quad \kappa = \kappa_V = \kappa_F = \cos\theta$$

$g_{hXX}$ : Higgs coupling for $X$,

$V$ : gauge boson,

$F$ : fermion

(It is the ratio between the coupling of the real Higgs singlet model and one of the SM.)

❖ The deviation for *hhh* coupling

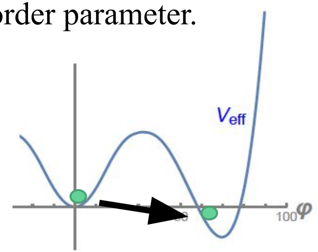
$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{SM}} = \frac{\lambda_{hhh} - \lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}} \quad \lambda_{hhh} = c_\theta^3 \left\langle \frac{\partial^3 V_{\text{eff},T=0}}{\partial \varphi_\Phi^3} \right\rangle + c_\theta^2 s_\theta \left\langle \frac{\partial^3 V_{\text{eff},T=0}}{\partial \varphi_\Phi^2 \partial \varphi_S} \right\rangle + c_\theta s_\theta^2 \left\langle \frac{\partial^3 V_{\text{eff},T=0}}{\partial \varphi_\Phi \partial \varphi_S^2} \right\rangle + s_\theta^3 \left\langle \frac{\partial^3 V_{\text{eff},T=0}}{\partial \varphi_S^3} \right\rangle$$

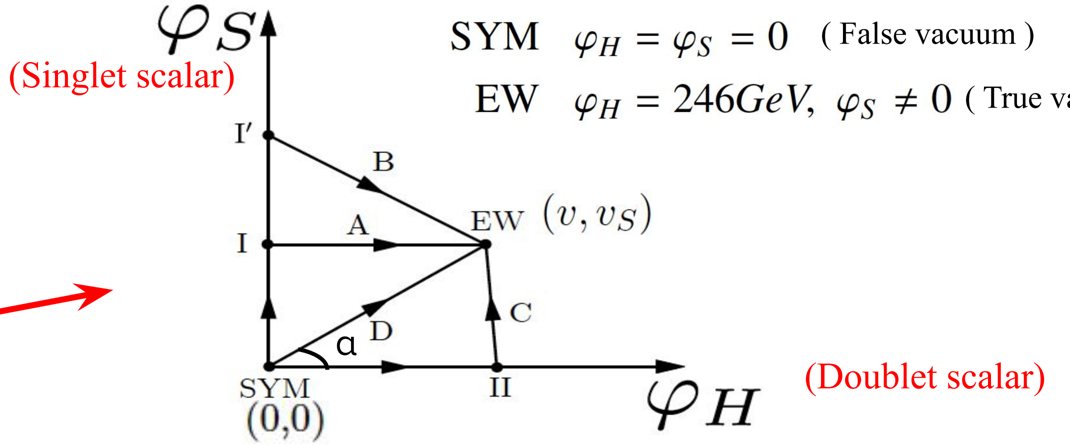
These Higgs couplings can be precisely measured by future collider experiments.

# EWPT of the model with one singlet scalar field

❖ EWPT occurs in the space of two order parameters for doublet and singlet scalar.

It is the EWPT for one order parameter.




SYM $\varphi_H = \varphi_S = 0$ ( False vacuum )

EW $\varphi_H = 246GeV,\ \varphi_S \neq 0$ ( True vacuum )

❖ $\phi_c / T_c$ of the model with one singlet scalar field for Path A and B.

[S. Profumo, M. J. Ramsey-Musolf and G. Shaughnessy, JHEP 0708, 010 (2007)]

$$\phi_C/T_C \ni -\frac{2}{\lambda(T_C)}\left(\mu_{\Phi S}\cos^2\alpha + \frac{\mu'_S}{3}\sin^2\alpha\right)\sin\alpha/T_C$$

These are tree-level effects.

# Model with a real isospin singlet scalar field

❖ The benchmark point and scanned range

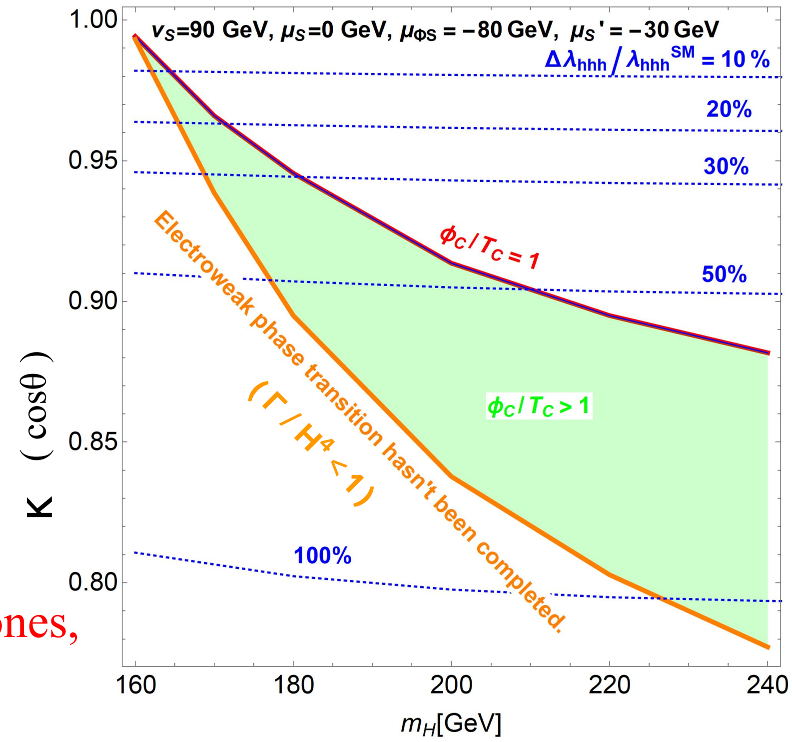
| $v_\Phi$ [GeV] | $v_S$ [GeV] | $m_h$ [GeV] | $\mu_{\Phi S}$ [GeV] | $\mu'_S$ [GeV] | $\mu_S$ [GeV] | $m_H$ [GeV] | $\theta$ [degrees] |
|---|---|---|---|---|---|---|---|
| 246.2 | 90 | 125.5 | −80 | −30 | 0 | [160, 240] | [−45, 0] |

[K. Fuyuto and E. Senaha, Phys. Rev. D 90, 015015 (2014)]

(We analyze the EWPT in multi-field space by public code "CosmoTransitions".)

[C. L. Wainwright, Comput. Phys. Commun. 183, 2006 (2012)]

$$\Delta\lambda_{hhh} = \frac{\lambda_{hhh}^{\rm HSM} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}}, \quad \kappa_X \equiv \frac{g_{hXX}}{g_{hXX}^{\rm SM}}, \quad \kappa = \kappa_V = \kappa_F = \cos\theta$$



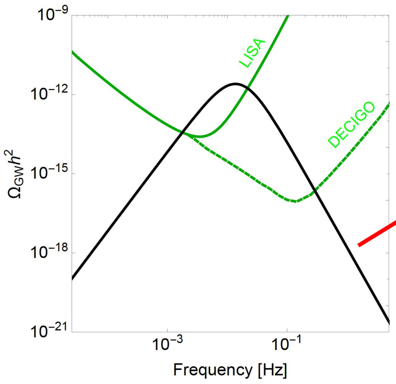

( Mass of new particle )

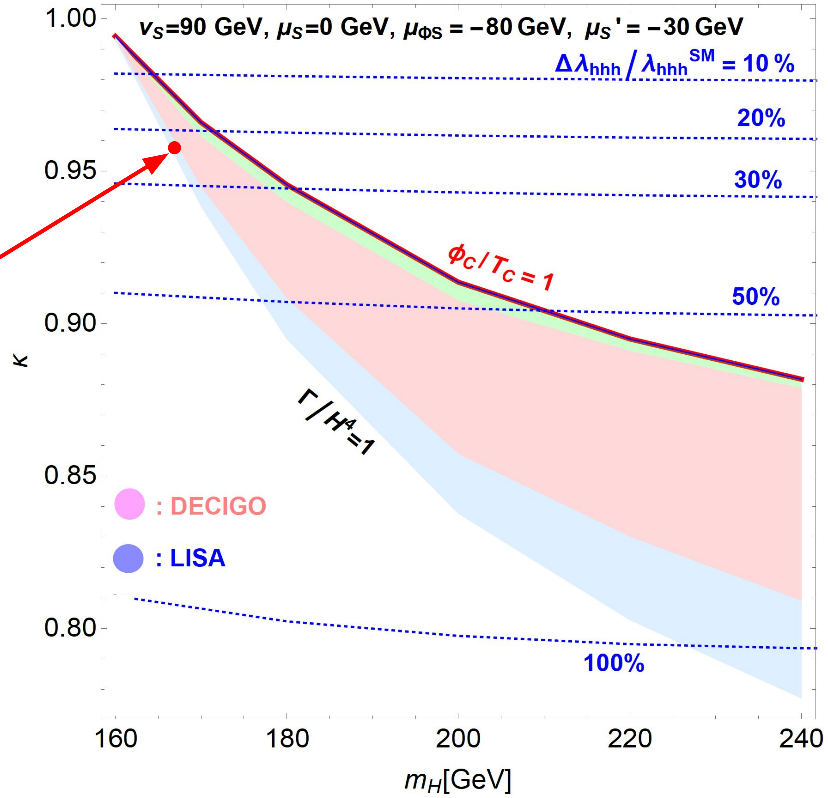
❖ The Higgs boson couplings deviate from the SM ones, when the model can realize strongly 1st EWPT.

Also detectable GWs from the EWPT may be able to occur.

# Model with a real isospin singlet scalar field

❖ We show the parameter region where the detectable GW spectrum occurs.




❖ We conclude that the model with strongly 1st EWPT can be complementarily tested by the measurements of hff and hVV couplings at LHC, ones of hhh coupling at ILC and ones of the spectrum of the GW at DECIGO and LISA.

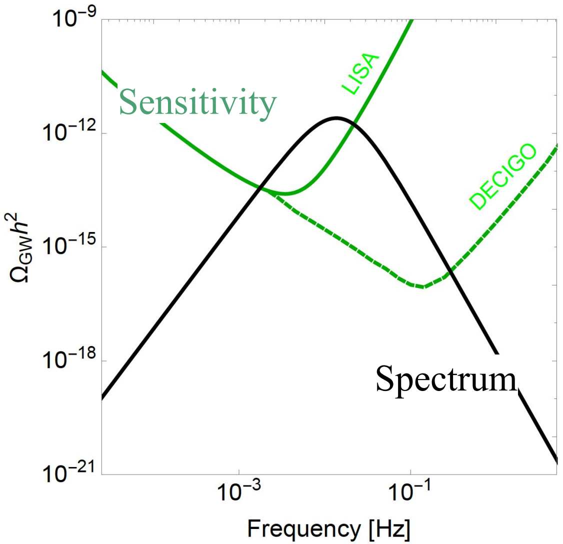
[K. H. , M. Kakizaki, S. Kanemura, P. Ko and T. Matsui, Phys. Lett. B766 (2017) 49 ]

# Testability of the model by measurements of GW

❖ We use the measurements of GW spectrum to examine the model parameters.

**However...**

We assume that **"the information can be completely obtained by the measurements of GWs when the peak of the spectrum is in the sensitivity region".**



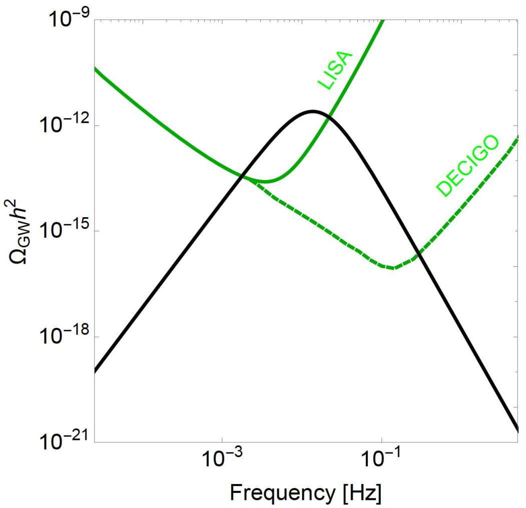

❖ We can quantitatively discuss the expected uncertainties in future space-based interferometers for parameters of the extended models by the Fisher matrix analysis.

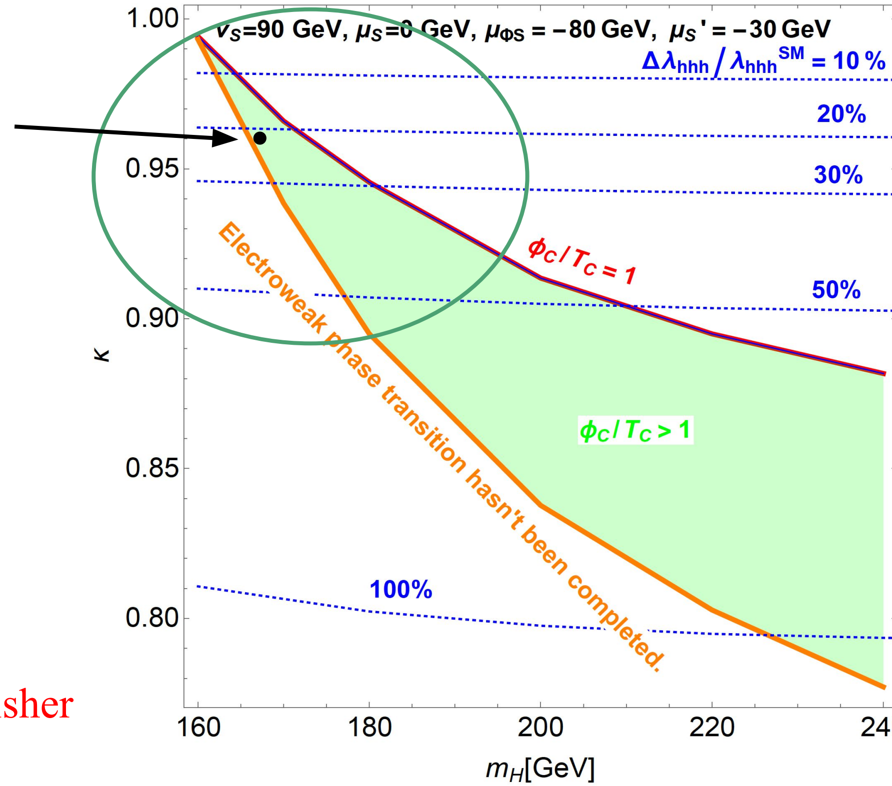
[K. H. , R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi and M. Takimoto, Phys. Rev. D 99, no. 7, 075011 (2019)

(The Fisher matrix corresponds to the inverse of the covariance matrix.)

# Testability of real Higgs singlet model

❖ Fiducial point $(m_H, \kappa) = (166.4\text{ GeV}, 0.96)$




❖ We can estimate the expected constraints by the Fisher matrix analysis, which is essentially a Gaussian approximation of the likelihood function.

# Testability of real Higgs singlet model

- ❖ $\Delta\lambda_{hhh}/\lambda_{hhh}^{SM}$ and detectable GWs are described in scaling factors ($\kappa_F$ and $\kappa_V$) and $m_H$.

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{SM}} = \frac{\lambda_{hhh}-\lambda_{hhh}^{SM}}{\lambda_{hhh}^{SM}}, \quad \kappa_X \equiv \frac{g_{hXX}}{g_{hXX}^{\rm SM}}, \quad \kappa = \kappa_V = \kappa_F = \cos\theta$$

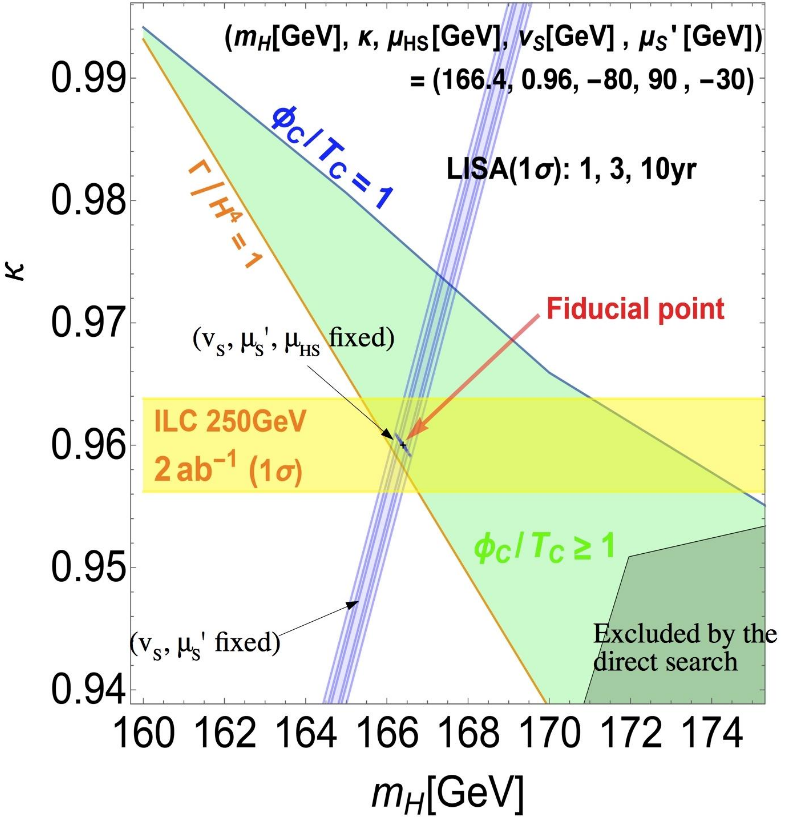
- ❖ Fiducial point ($m_H$, $\kappa$) = (166.4 GeV, 0.96)

ILC : $\Delta\kappa_Z \sim 0.38\%$ [K. Fujii et al., arXiv:1710.07621 [hep-ex]]

Direct searches by LHC Run-II :

[A. Ilnicka, T. Robens, and T. Stefaniak, Mod. Phys. Lett. A33 no. 10n11, (2018) 1830007]

- ❖ We may be able to test the model by the synergy between measurements of the Higgs boson couplings and the spectrum of GW.




[K. H, R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi and M. Takimoto, Phys. Rev. D 99, no. 7, 075011 (2019)]

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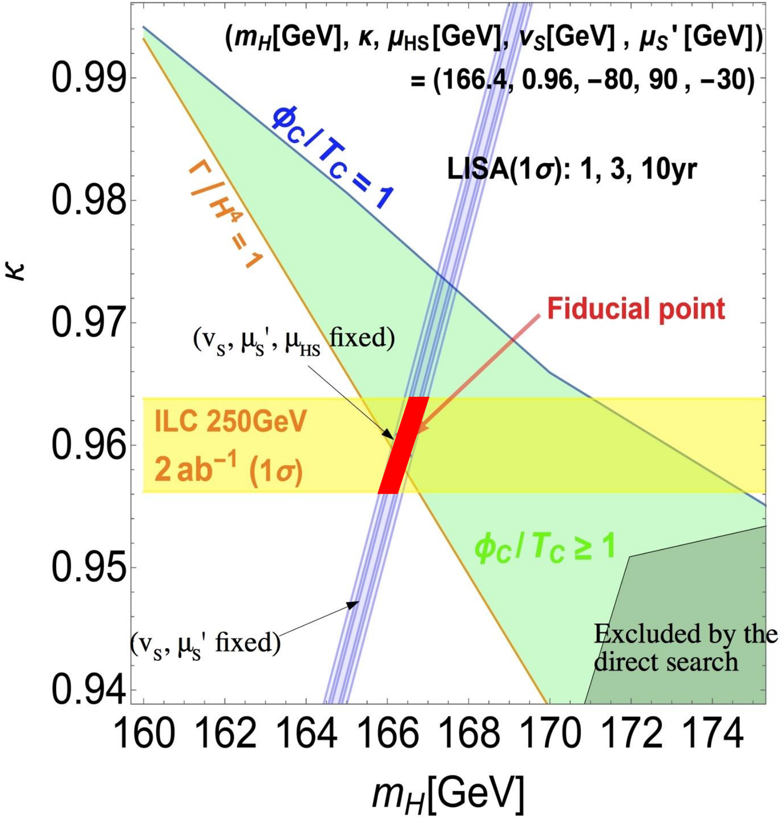


[K. H, R. Jinno, M. Kakizaki, S. Kanemura, T. Takahashi and M. Takimoto, Phys. Rev. D 99, no. 7, 075011 (2019)]

# Summary

- The extended Higgs model can explain the phenomena beyond the Standard model, such as baryon asymmetry of the university.

- We have quantitatively discussed the testability of the model with strongly first-order electroweak phase transition by the collider and gravitational wave observation experiments.

- We can complementarily test the models by the measurements of the various Higgs boson couplings and direct search of new boson at the collider experiments and the spectrum of gravitational wave at the future space-based interferometers.