Fingerprinting models of first-order phase transitions by the synergy between collider and gravitational-wave experiments

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Introduction

- The gravitational waves (GWs) produce by the collison of bubbles of true vacuum, when the extended Higgs models can realize the first-order phase transition (1stOPT).

  → The spectrum of GW from the 1stOPT depend on the parameters in the extended Higgs model.

- Many authors use the GWs from the 1stOPT that are detectable to probe the extended Higgs model.

  → They did not quantify to what extent the model parameters can be measured once GWs are detected.

We quantitatively discuss a testability of the extended Higgs model (real Higgs singlet model) with the strong electroweak 1stOPT by the synergy between collider and GW experiments.

Real Higgs singlet model

- The Higgs potential at the tree level

$$V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu_S'}{3}S^3 + \frac{\lambda_S}{4}S^4$$

- Independent parameters in the model

$$v_\Phi(246\,GeV),\ m_h(125\,GeV),\ v_S,\ m_H,\ \theta,\ \mu_S,\ \mu_S',\ \mu_{\Phi S}$$

- The scaling factors for Higgs boson couplings

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

- Strong electroweak 1stOPT ($\phi_C/T_C > 1$)

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

Thermal (ET), Non-thermal (e)

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

We use "CosmoTransitions" to compute quantities regarding the 1stOPT in multi-field space.

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

The synergy between GW obsevations and collider experiments

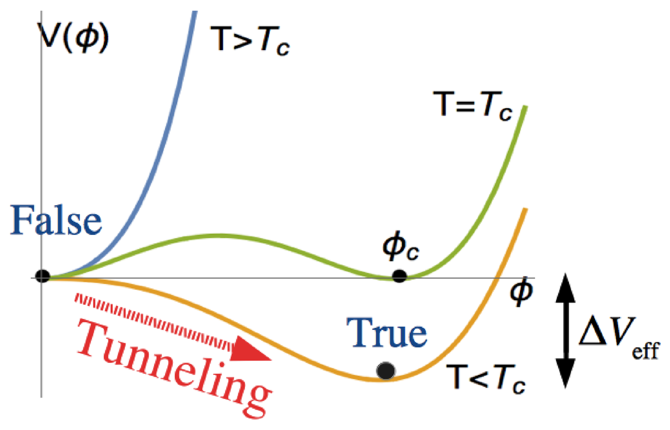
- The GW spectrum from the 1stOPT is characterized by T_t, v_w, α and $\tilde\beta$.

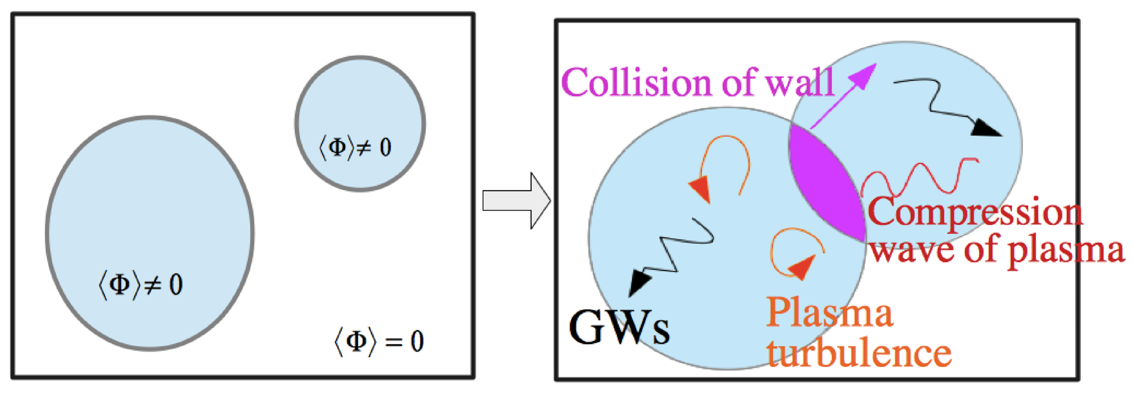
$$\Omega_{\rm peak}^{\rm Comp} \propto v_w \alpha^2 \tilde\beta^{-1},\quad f_{\rm peak}^{\rm Comp} \propto v_w^{-1} T_t \tilde\beta$$

α : Normalized latent heat released by 1stOPT, T_t : Transition temperature,

$\tilde\beta$: Normalized inverse of the duration of 1stOPT, v_w : Wall velocity

$$\Gamma/H^4|_{T=T_t} = 1 \qquad \alpha \equiv \frac{\epsilon(T_t)}{\rho_{\rm rad}(T_t)} \qquad \beta \simeq \frac{1}{\Gamma}\frac{d\Gamma}{dt}\Big|_{t=t_t} \qquad (\tilde\beta = \beta/H)$$



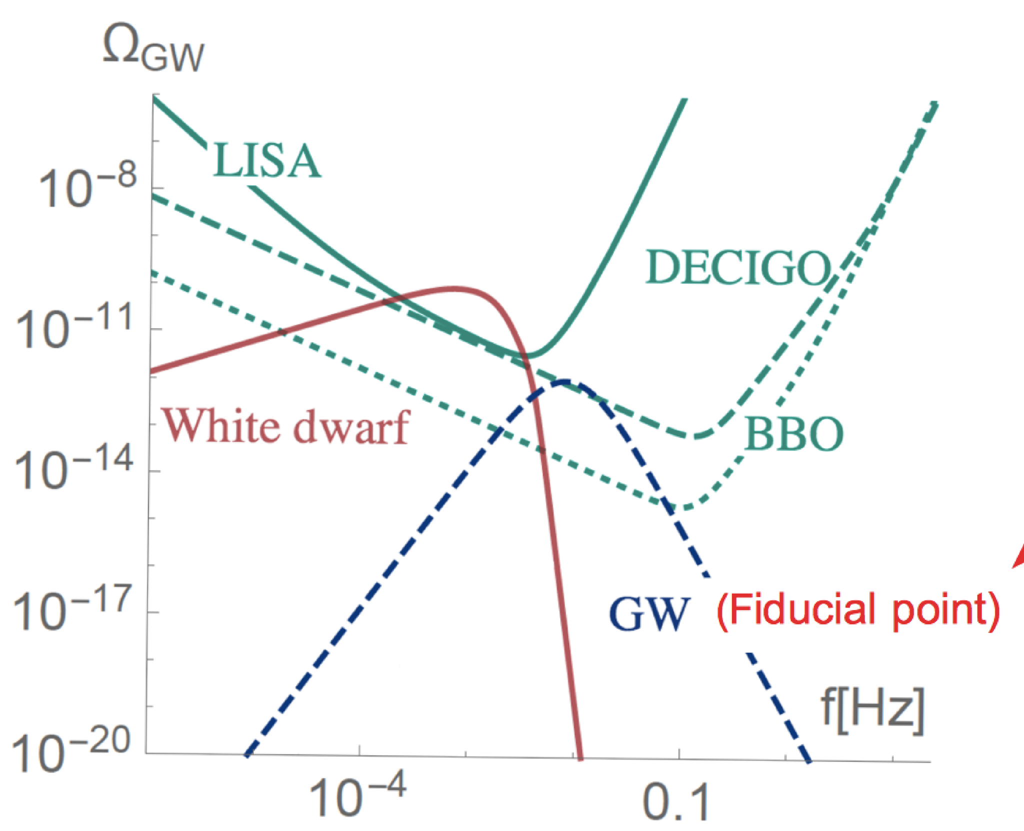


$$\epsilon(T) = \Delta V_{eff}(T) - T\frac{\partial \Delta V_{eff}}{\partial T} \qquad \Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}} \qquad S_3 \equiv \int d^3r \left[\frac{1}{2}(\vec\nabla\varphi)^2 + V_{\rm eff}(\varphi, T)\right]$$

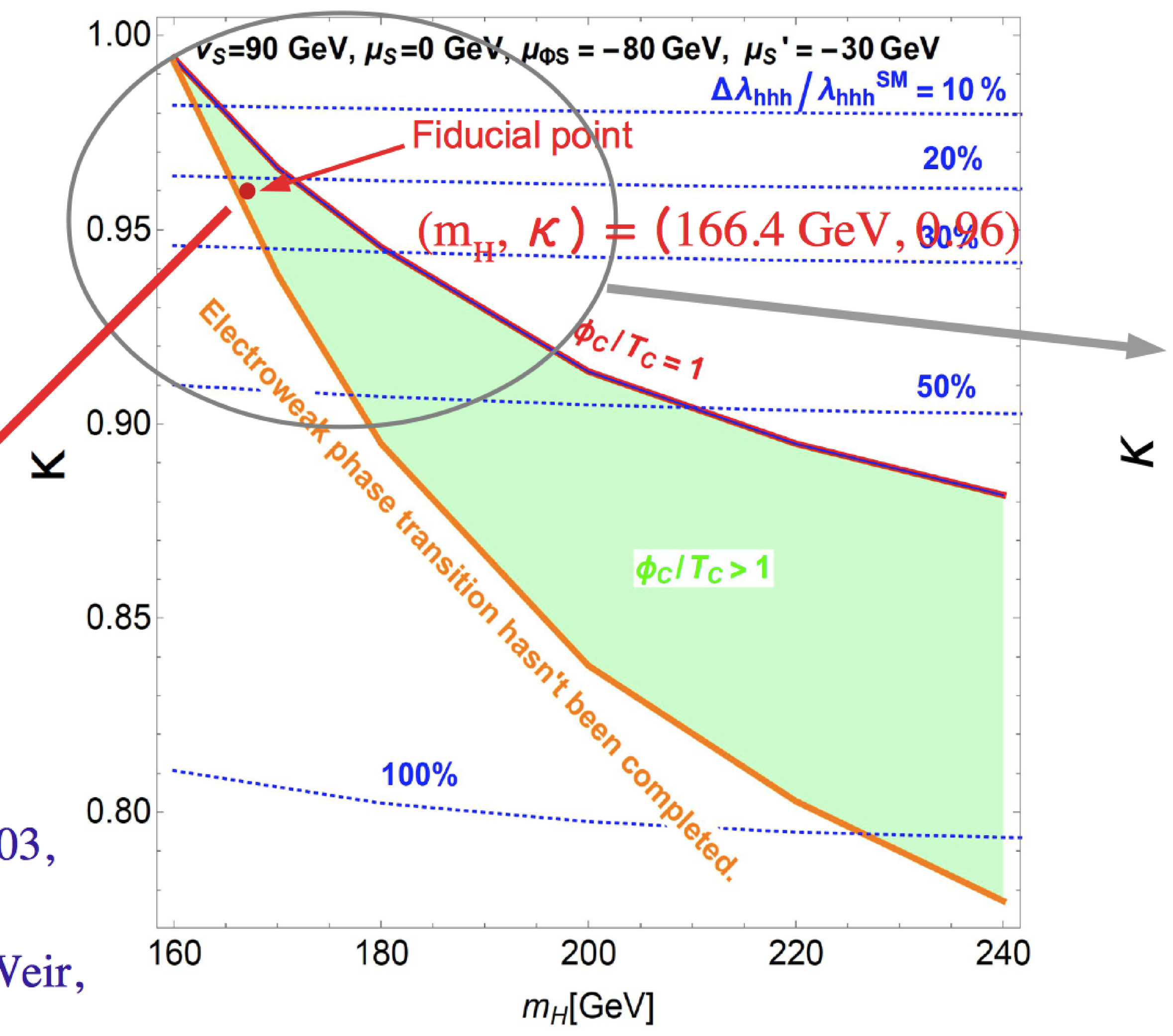
- We evaluate the expected uncertainty of the model parameters by using the Fisher matrix analysis, which is essentially a Gaussian approximation of the likelihood function.

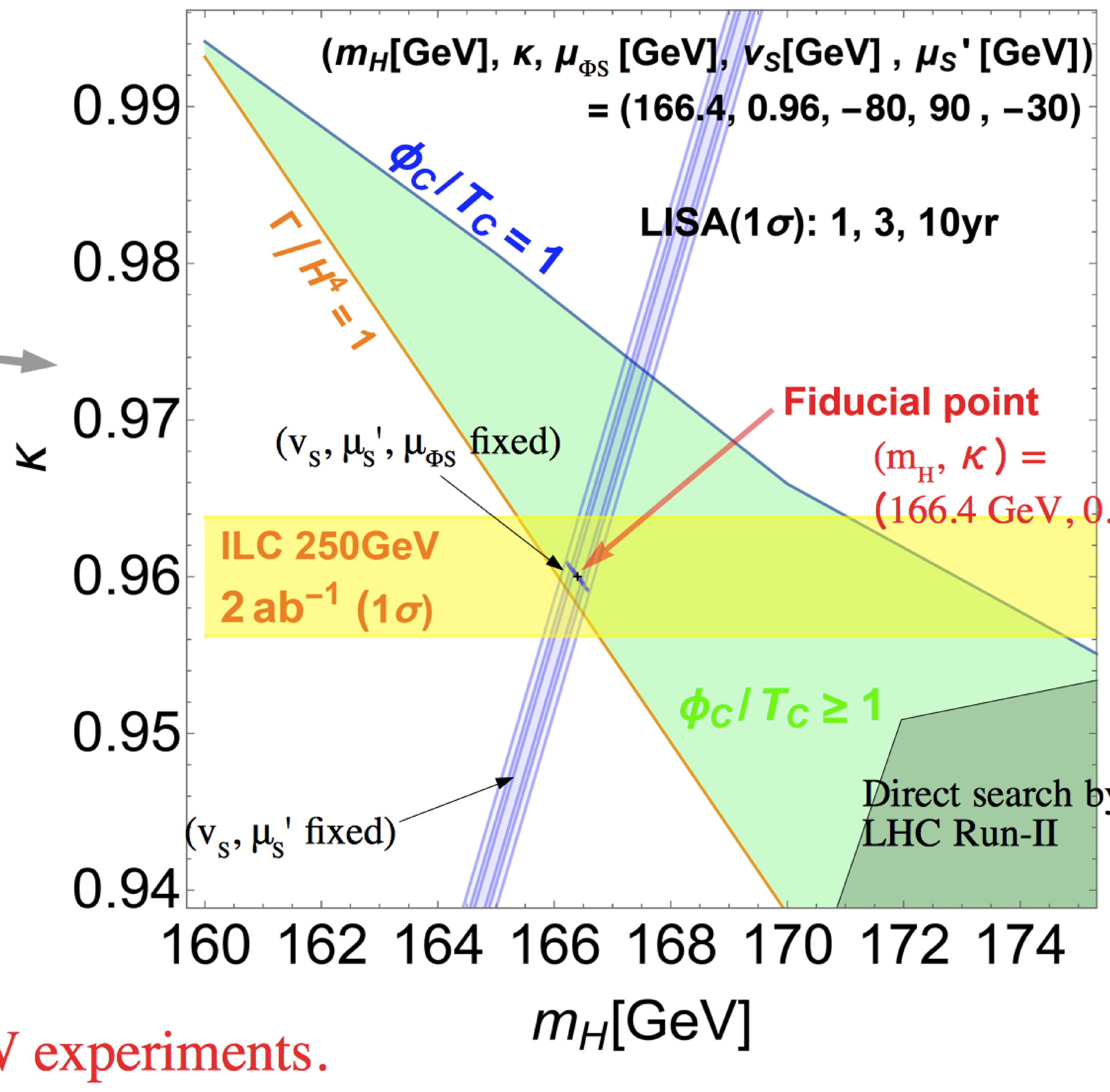
(We assume that we can apply the expression to one detector (LISA). E. Thrane and J. D. Romano, PRD 88 no. 12, (2013) 124032)

LISA: A. Klein et al., PRD93 no. 2, (2016) 024003
ILC : K. Fujii et al., arXiv:1710.07621 [hep-ex]
LHC Run-II : A. Ilnicka, T. Robens, and T. Stefaniak, Mod. Phys. Lett. A33 no. 10n11, (2018) 1830007



LISA, White dwarf : A. Klein et al., PRD 93 no. 2, (2016) 024003,
DECIGO, BBO : K. Yagi and N. Seto, PRD 83 (2011) 044011,
GW : M. Hindmarsh, S. J. Huber, K. Rummukainen, and D. J. Weir, PRD 96 no. 10, (2017) 103520





- We may be able to explore the model parameters by the synergy between collider and GW experiments.

K.H, R. Jinno, M. Kakizaki, S. Kanemura, T. Takahash and M. Takimoto, arXiv:1809.04994 [hep-ph]

Summary

- We have evaluated the expected constraints on the parameters of extended Higgs models with the strong electroweak first-order phase transition by using future space-based gravitational wave observations, such as LISA.

- We found that future gravitational wave observations can play complementary roles to future collider experiments. Fortunately, the LISA project and precision measurements of the Higgs boson couplings come around the same time in the future: a great synergy between collider and gravitational-wave experiments is awaiting us!