Gravitational waves from the first order electroweak phase transition in the Z_3 symmetric singlet scalar model

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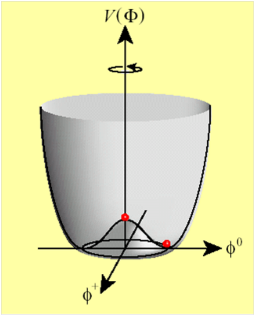
in collaborated with Zhaofeng Kang and Pyungwon Ko

Z. Kang, P. Ko and T. Matsui, arXiv:1706.09721 [hep-ph]

Motivation

- Discovery of the Higgs boson
  - Mass generation mechanism is confirmed
  - The standard model as an effective theory is established
- What is the nature of electroweak symmetry breaking?
  - SM have minimal Higgs potential…**no principle**
  - Higgs self-couplings **have not been measured**

    →We have not understood the shape of the Higgs potential



- Exploring the structure of the Higgs sector is important
  - New physics is required to solve BSM phenomena

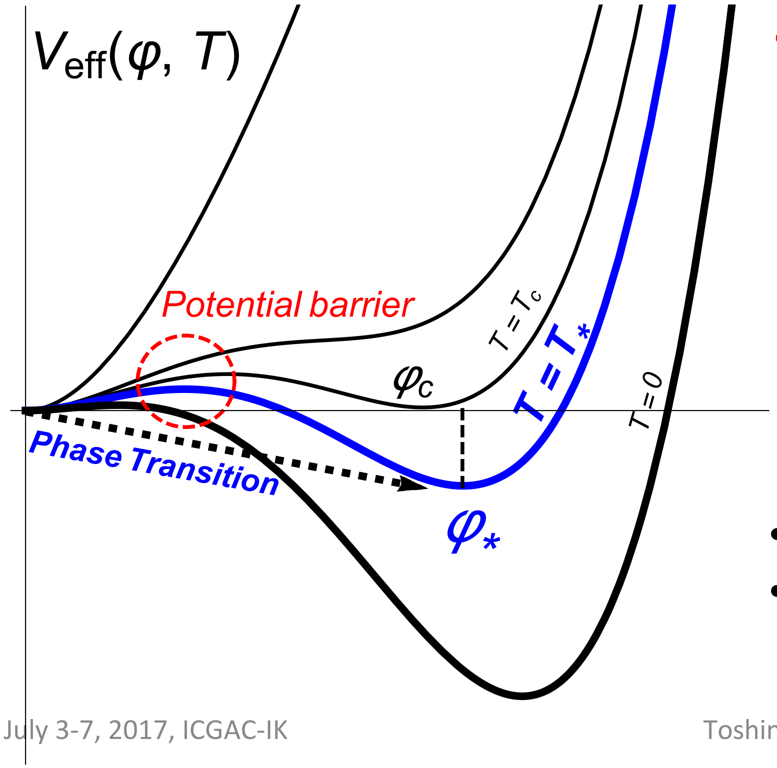
    Baryon asymmetry of the Universe, Existence of dark matter,…
  - BSM might be related to the extended Higgs sector

    EW baryogenesis, Radiative neutrino mass models, …

Electroweak Baryogenesisa

- Observed Baryon number: $n_B/s \simeq \mathcal{O}(10^{-10})$
- Sakharov's three conditions

  1. #B violation, 2. CP violation, 3. Departure from equilibrium



→Strongly 1st order phase transition

$$\varphi_*/T_* \gtrsim 1$$

- SM (m_h=125GeV) cannot satisfy these conditions.
- Strongly 1stOPT is realized by models with extended Higgs sector.

Strongly 1st order phase transition

～ Mechanisms to create the potential barrier - 1～

- Thermal loop effects (*E*)

Analytic formula (High temperature approximation)

The strength of phase transition

$$\varphi_c/T_c = 2E/\lambda(T_c) \gtrsim 1 \qquad V_{\rm eff} = D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda(T)}{4}\varphi^4$$

e.g. Two Higgs doublet model (2HDM)

$$m_\Phi^2 \simeq M^2 + \lambda_i v^2 \quad \Phi = H, A, H^\pm$$

$$E = \frac{1}{12\pi v^3}\left\{6m_{W^\pm}^3 + 3m_Z^3 + \sum_\Phi m_\Phi^3\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\left(1 + \frac{3}{2}\frac{M^2}{m_\Phi^2}\right)\right\}$$

Enhanced by $M \to 0$ limit (large λ_i)

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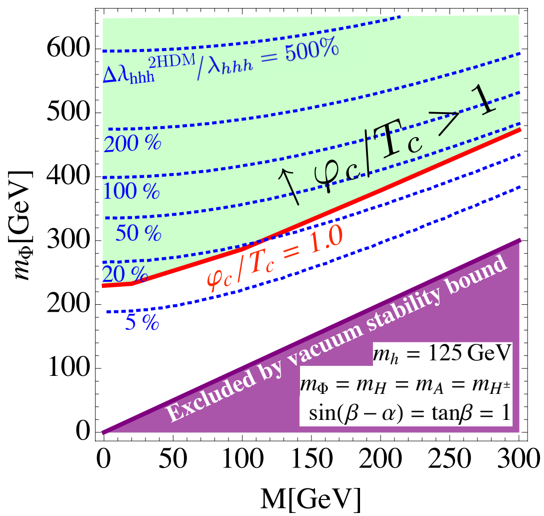

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$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}} \equiv \frac{\lambda_{hhh} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}}$$

Enhanced by *M*→0 limit (large λ_i)

$$\lambda_{hhh}^{\rm 2HDM} \equiv \frac{3m_h^2}{v}\left\{1 - \frac{m_t^4}{\pi^2 m_h^2 v^2} + \sum_\Phi \frac{m_\Phi^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\right\}$$

Kanemura, Okada, Senaha, PLB**606**, 361 (2005)
Kakizaki, Kanemura, TM, PRD 92, 115007 (2015)

The deviation in the Higgs boson couplings from the SM is required!

Strongly 1st order phase transition

～ Mechanisms to create the potential barrier - 2～

- Non-thermal tree level effects ($-e$)

Analytic formula (High temperature approximation)

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

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

Strongly 1st order phase transition

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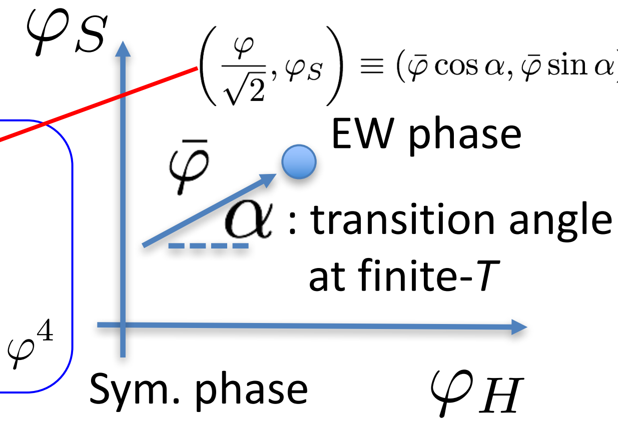

e.g. Higgs singlet model (HSM)

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

$$e = \left(\mu_{\Phi S}\cos^2\alpha + \frac{\mu_S'}{3}\sin^2\alpha\right)\sin\alpha \quad <0$$

Strongly 1st order phase transition

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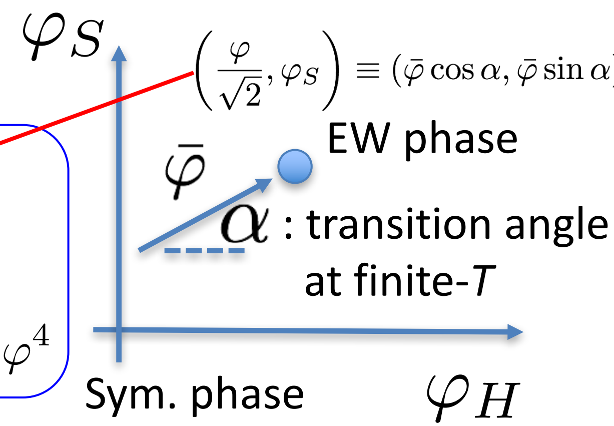
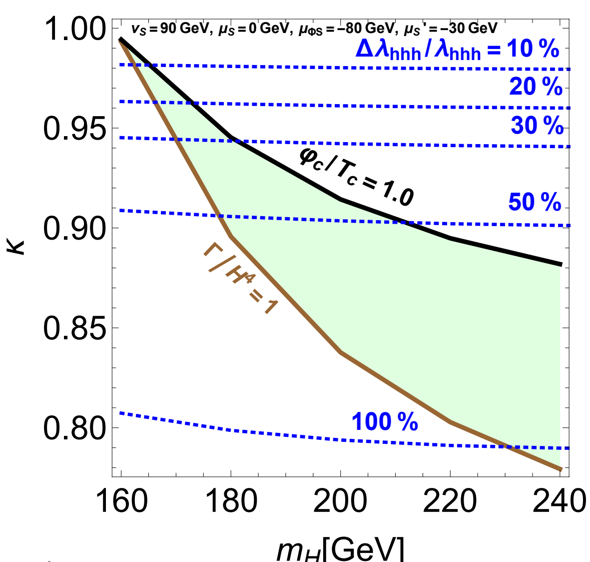


e.g. Higgs singlet model (HSM)



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$$e = \left(\mu_{\Phi S}\cos^2\alpha + \frac{\mu_S'}{3}\sin^2\alpha\right)\sin\alpha \quad <0$$

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

θ : mixing angle at zero-T

$$\lambda_{hhh}^{\rm HSM,tree} = 6\left(\lambda_\Phi v_\Phi c_\theta^3 + \frac{\mu_{\Phi S}}{2}s_\theta c_\theta^2 + \frac{\lambda_{\Phi S}}{2}s_\theta c_\theta(v_\Phi s_\theta + v_S c_\theta) + \left(\frac{\mu_S'}{3} + \lambda_S v_S\right)s_\theta^3\right)$$

$$\kappa_i \equiv g_{hii}/g_{hii}^{\rm SM}$$

$$\kappa \equiv \kappa_V = \kappa_F = \cos\theta$$

Fuyuto, Senaha, PRD **90**, no. 1, 015015 (2014)
Hashino, Kakizaki, Kanemura, TM, Ko, PLB **766**, 49 (2017)

Nightmare scenario

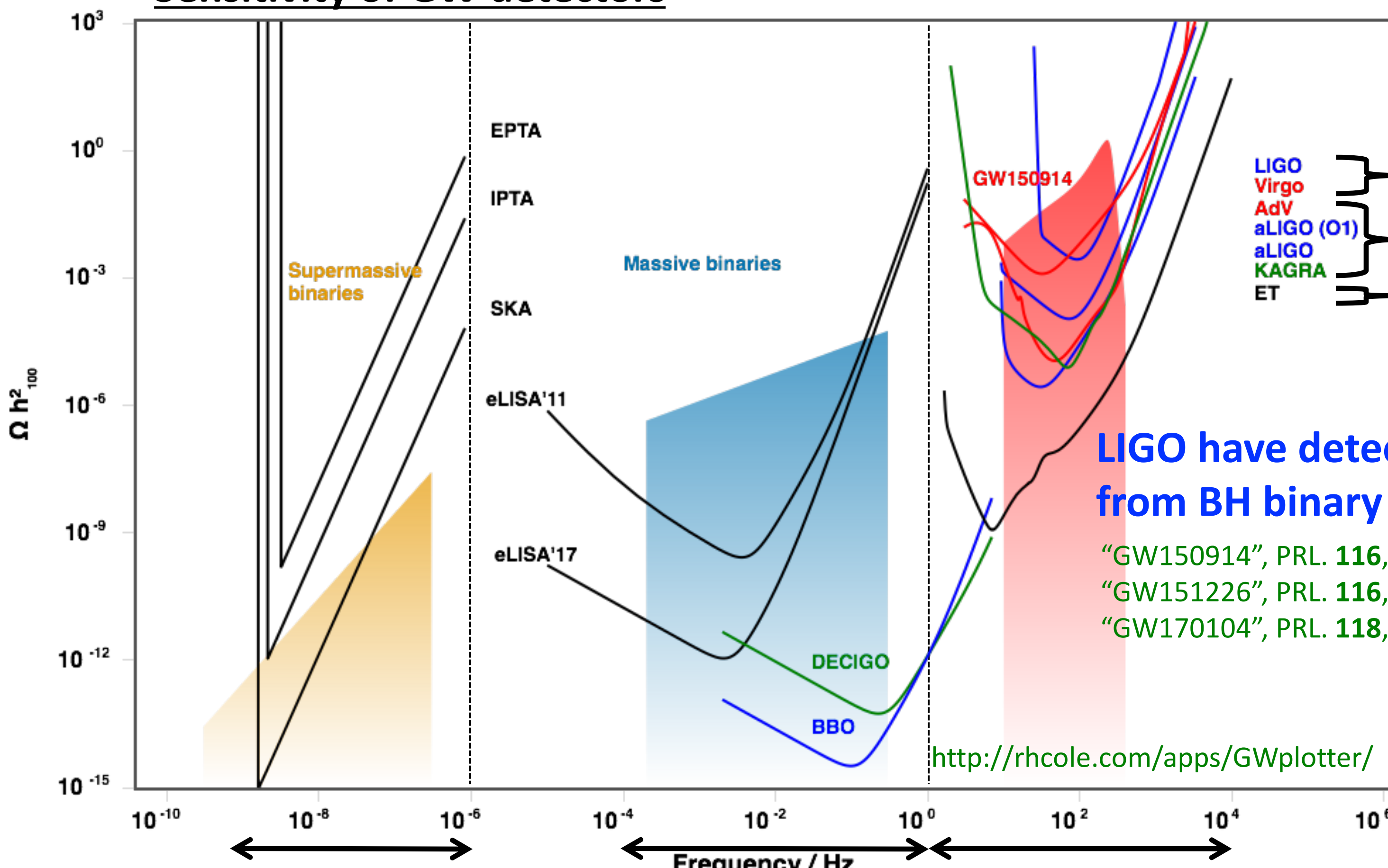
- However, even if the Higgs couplings do not deviate from SM, an alternative way to the desired tree level barrier is available in the symmetric limit where an additional scalar does not acquire VEV at T=0.
  - In the model with the unbroken discrete symmetry, the strongly 1stOPT can be realized by multi-step phase transition.
  - By the absence of the field mixing, it is difficult to test at colliders.

- We expect the observation of the gravitational waves as a new technique to detect the signal of the strongly 1stOPT.

Gravitational waves

～ Probing the Higgs potential by GW observations ～

Sensitivity of GW detectors



LIGO have detected GWs from BH binary directly!

"GW150914", PRL. **116**, 061102 (2016),
"GW151226", PRL. **116**, 241103 (2016),
"GW170104", PRL. **118**, 221101 (2017)

Pulsar Timing Array (PTA) | **Space-based interferometers** | **Ground-based interferometers**

Gravitational waves

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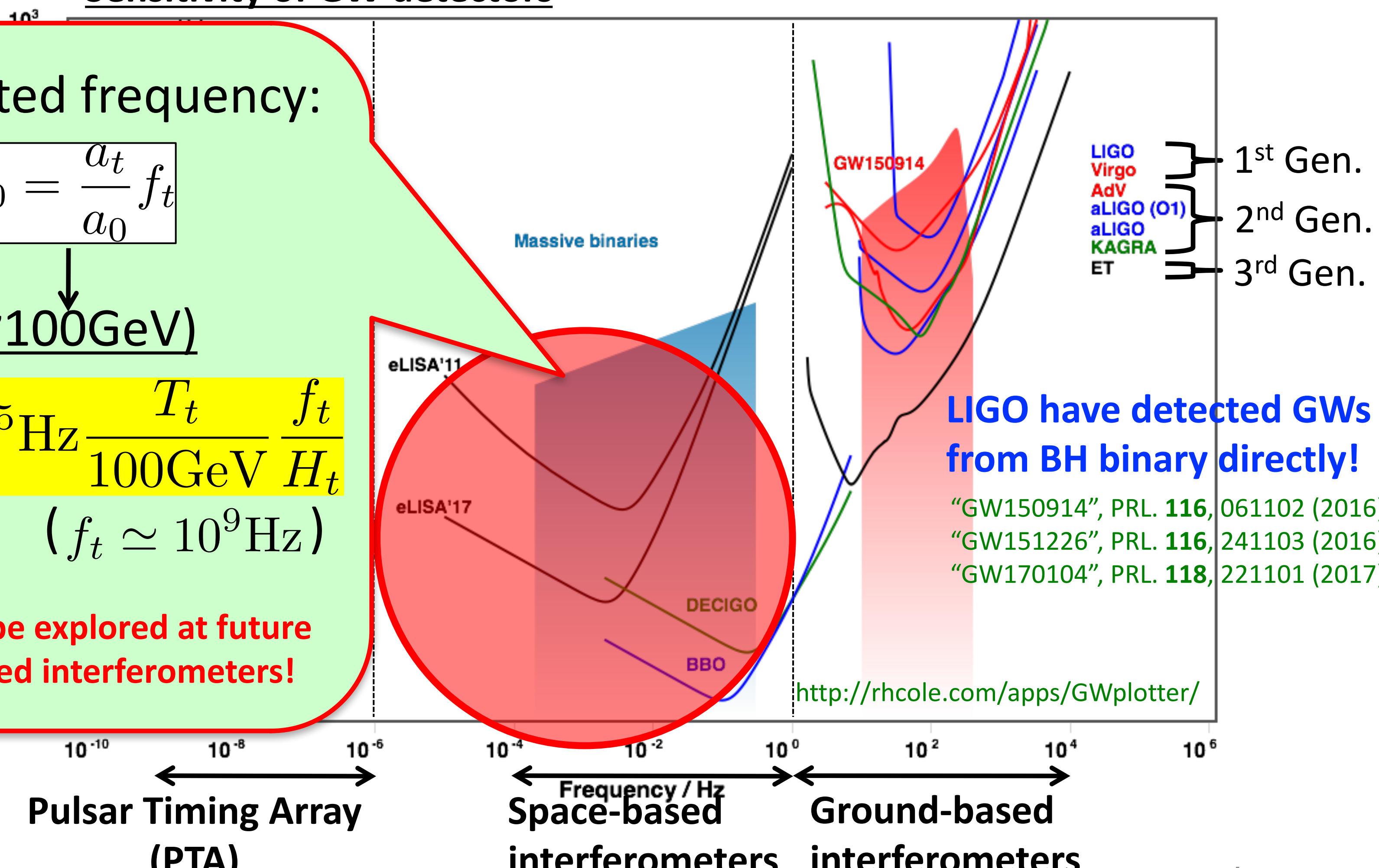

Red shifted frequency:

$$f_0 = \frac{a_t}{a_0} f_t$$

EWPT (~100GeV)

$$f_0 \simeq 10^{-5}\mathrm{Hz} \frac{T_t}{100\mathrm{GeV}} \frac{f_t}{H_t}$$

$$(f_t \simeq 10^9 \mathrm{Hz})$$

EWPT can be explored at future space-based interferometers!

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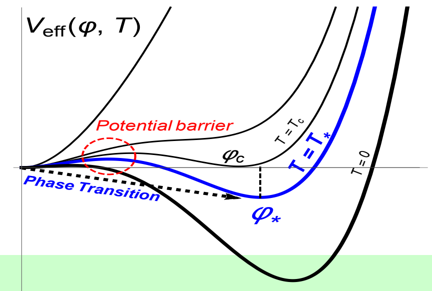
GWs from 1stOPT



Characteristic parameters of 1stOPT

"Normalized difference of the potential minima"

- α is defined as $\alpha \equiv \left.\frac{\epsilon}{\rho_{\rm rad}}\right|_{T=T_t}$. ($\rho_{\rm rad}$ is energy density of rad.)
  - Latent heat: $\epsilon(T) \equiv -\Delta V_{\rm eff}(\varphi_B(T),T) + T\frac{\partial \Delta V_{\rm eff}(\varphi_B(T))}{\partial T}$

"~How fast the minimum goes down"

- β is defined as $\beta \equiv \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_t}$. → $\tilde{\beta}\left(\equiv\frac{\beta}{H_t}\right) = T_t \left.\frac{d(S_3(T)/T)}{dT}\right|_{T=T_t}$
  - Bubble nucleation rate: $\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$
  - 3-dim. Euclidean action: $S_3(T) = \int dr^3 \left\{\frac{1}{2}\left(\vec{\nabla}\varphi\right)^2 + V_{\rm eff}(\varphi,T)\right\}$

Three sources of GWs (relic abundance @ peak frequency)

"Sound waves" (Compressional plasma)
"Bubble collision" (Envelope approximation)
"Magnetohydrodynamic turbulence in the plasma"

$V_{\rm eff}(\varphi,T)$ (Model)

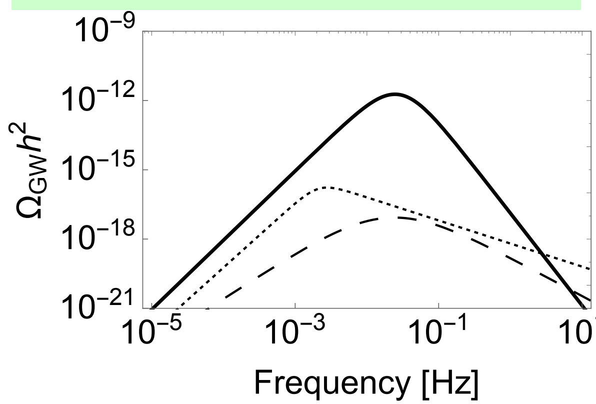
↓

$\alpha,\ \tilde{\beta}$ @T=T_t

↓ Prediction*

$\Omega_{\rm GW}(f)h^2$ (Observable)

(*) C. Caprini *et al.*, JCAP**1604**, 001 (2016)



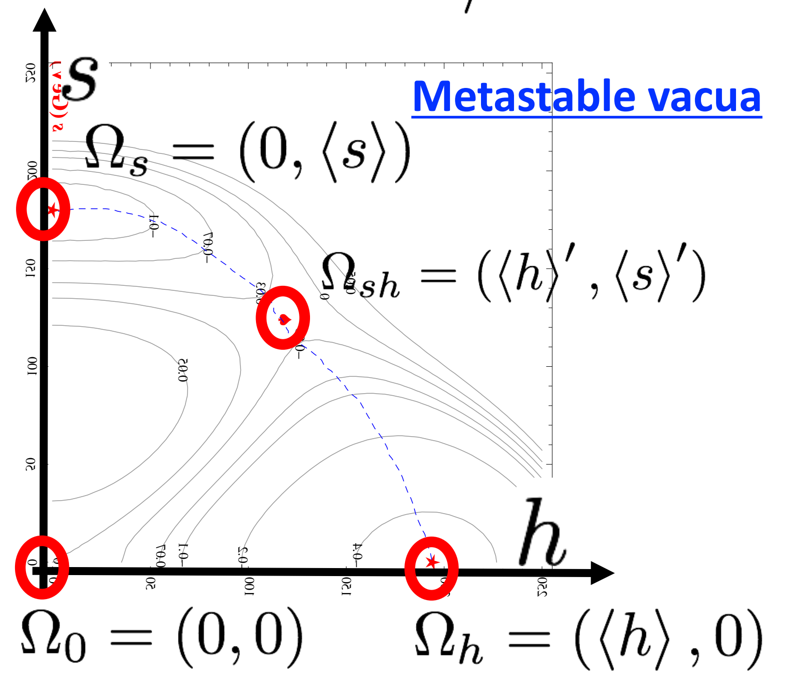
Z_3-symmetric model

- Higgs potential

$$V_0 = -\mu_h^2|H|^2 - \mu_s^2|S|^2 + \lambda_h|H|^4 + \lambda_s|S|^4 + \sqrt{2}\left(\frac{A_s}{3}S^3 + \text{h.c.}\right) + \lambda_{sh}|H|^2|S|^2$$

  – complex singlet scalar: $S \to e^{i2w}S$ with $w = \pi/3$

- Phase transition patterns
  – One-step ($\mu_s^2 > 0$, large λ_{sh})
    $\Omega_0 \to \Omega_h$
  – Two-step ($\mu_s^2 < 0$)
    $\Omega_0 \to \Omega_s \to \Omega_h$
  – Three-step
    $\Omega_0 \to \Omega_s \to \Omega_{sh} \to \Omega_h$



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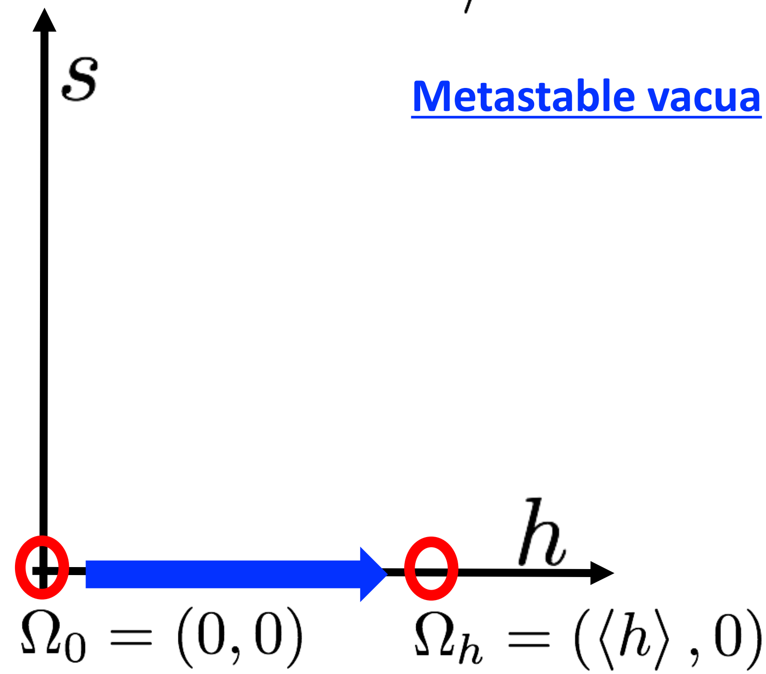

Metastable vacua

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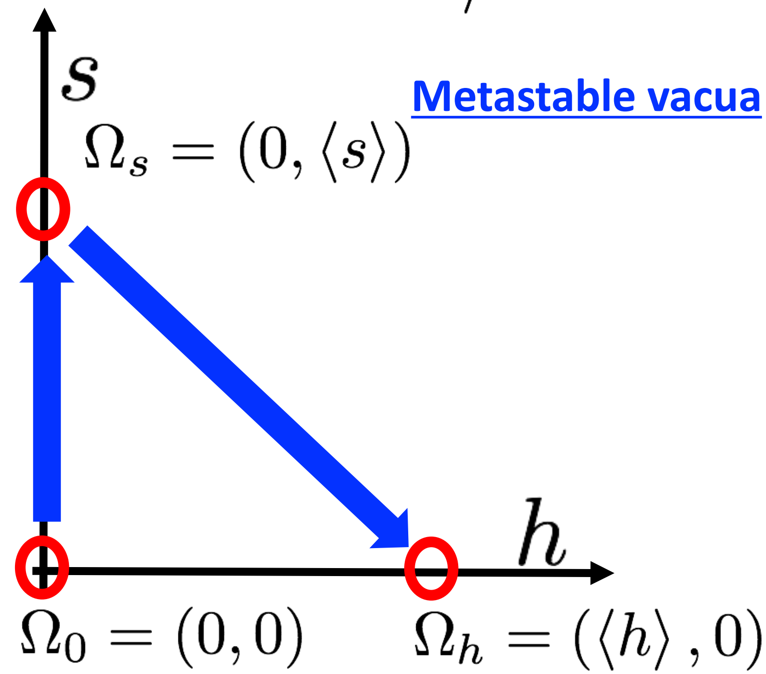

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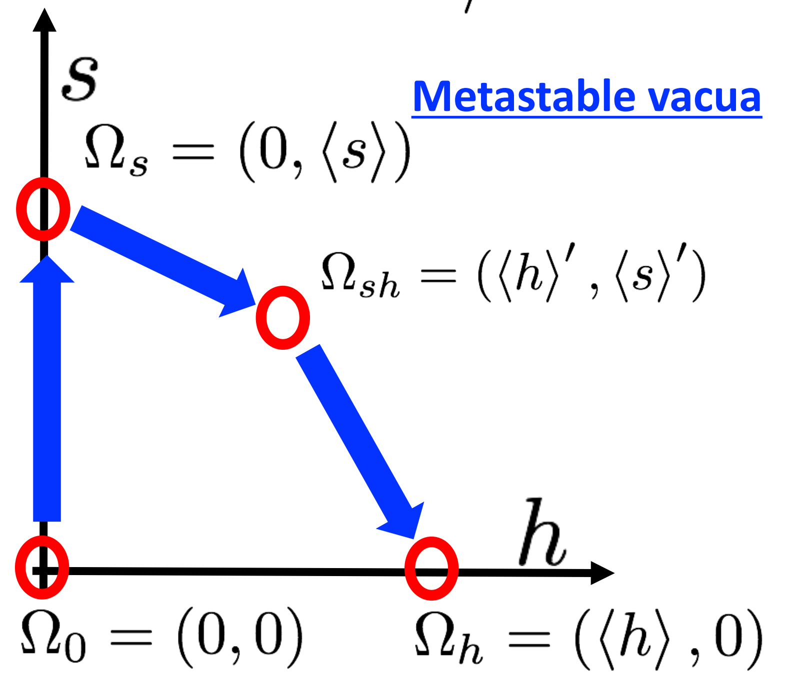
$$\Omega_0 \to \Omega_s \to \Omega_{sh} \to \Omega_h$$



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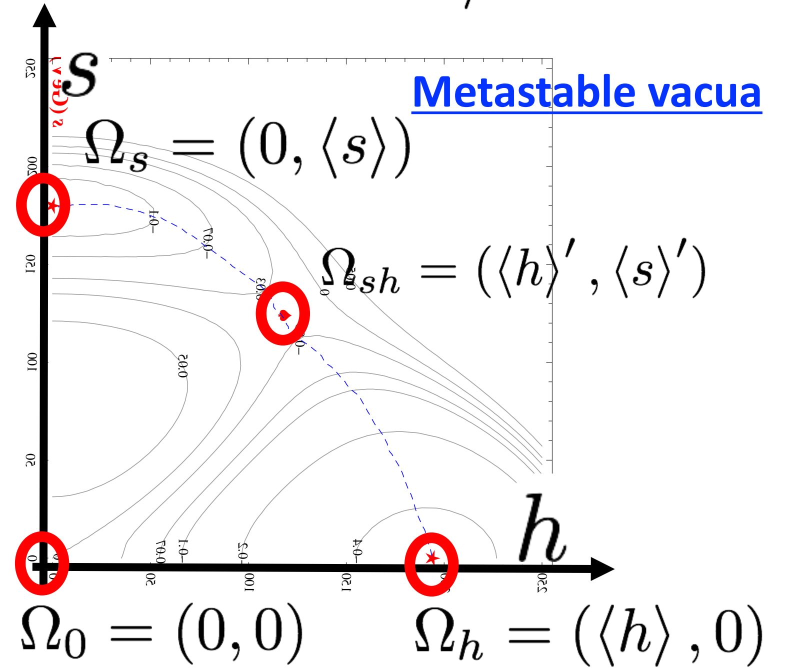
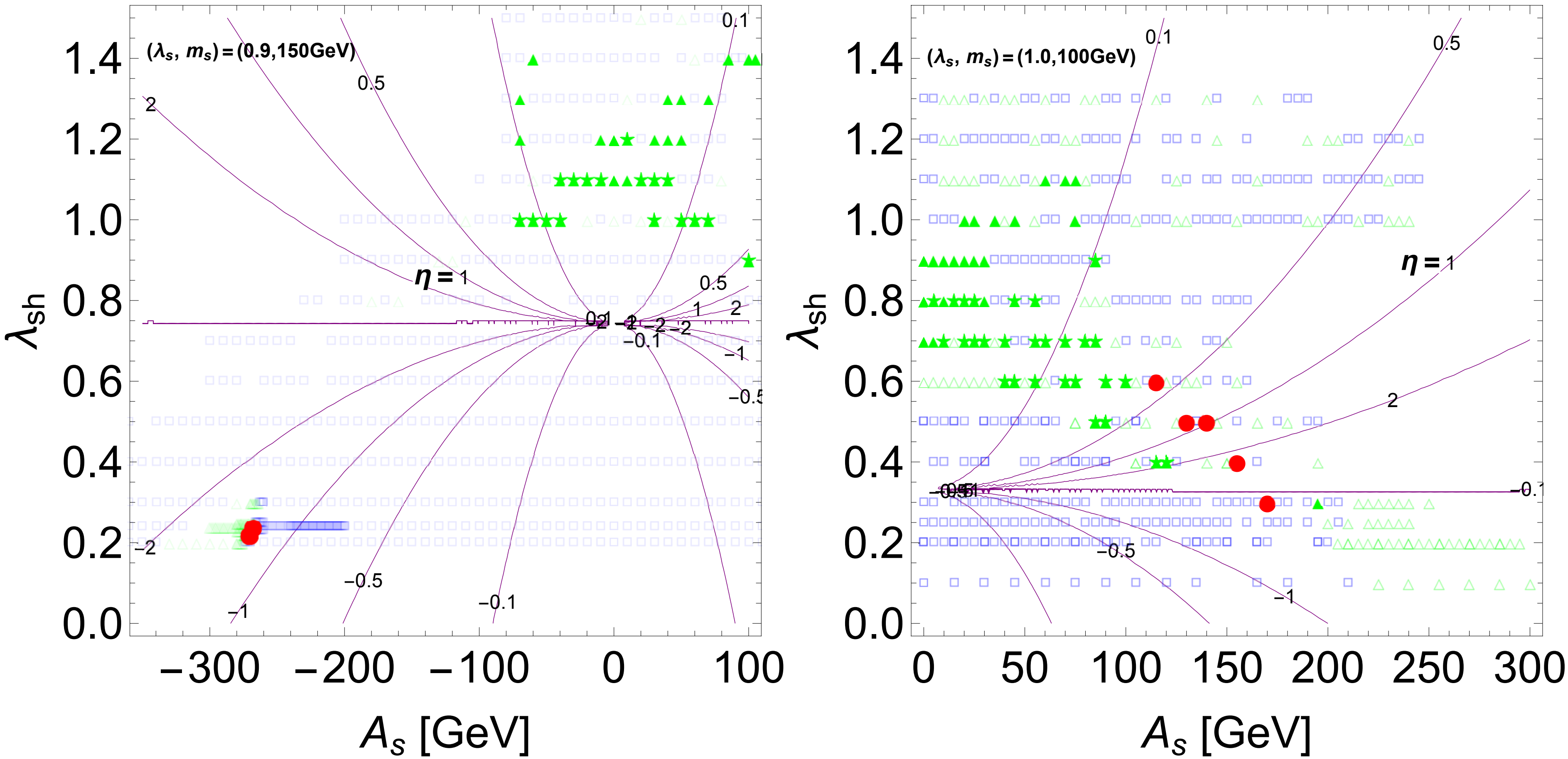


Allowed region of strongly 1st OPT via multi-step PT



<u>Strongly 1st order phase transitions with multi-step</u>

▲:Two-step PT (Z_2-like case), ★: Two-step PT (large A_s case), ●: Three-step PT

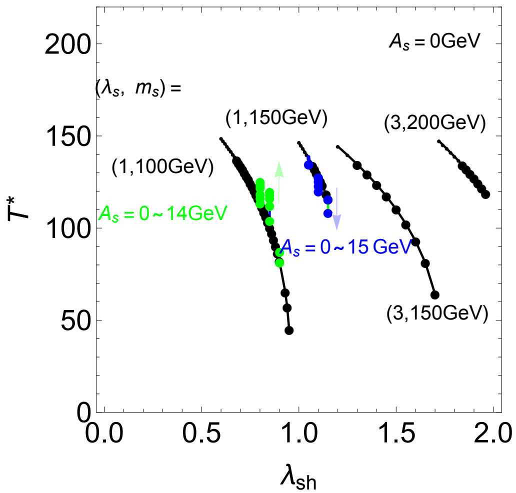
$\Omega_0 \xrightarrow{\text{2nd}} \Omega_s \xrightarrow{\text{1st}} \Omega_h$ $\qquad$ $\Omega_0 \xrightarrow{\text{1st}} \Omega_s \xrightarrow{\text{1st}} \Omega_h$ $\qquad$ $\Omega_0 \xrightarrow{\text{1st}} \Omega_s \xrightarrow{\text{2nd}} \Omega_{sh} \xrightarrow{\text{1st}} \Omega_h$

□: 2nd order EWPT (one-step)

Transition temperatures

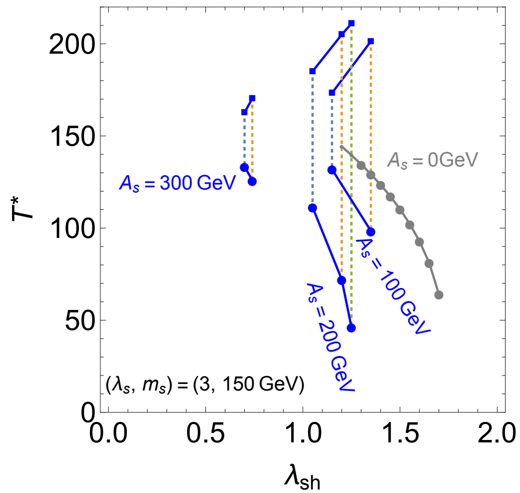
Two step PT (Z_2-like case)

$$\Omega_0 \xrightarrow{\text{2nd}} \Omega_s \xrightarrow[T_*]{\text{1st}} \Omega_h$$



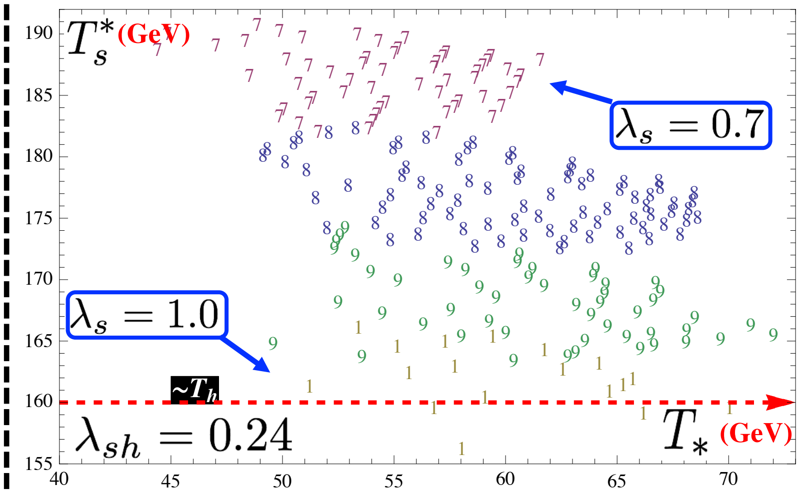
Two step PT (large A_s case)

$$\Omega_0 \xrightarrow[T_s^*]{\text{1st}} \Omega_s \xrightarrow[T_*]{\text{1st}} \Omega_h$$



Three step PT

$$\Omega_0 \xrightarrow[T_s^*]{\text{1st}} \Omega_s \xrightarrow{\text{2nd}} \Omega_{sh} \xrightarrow[T_*]{\text{1st}} \Omega_h$$



$$T_* \searrow \Longrightarrow \varphi_*/T_* \nearrow$$

Gravitational waves from 1^{st}OPT

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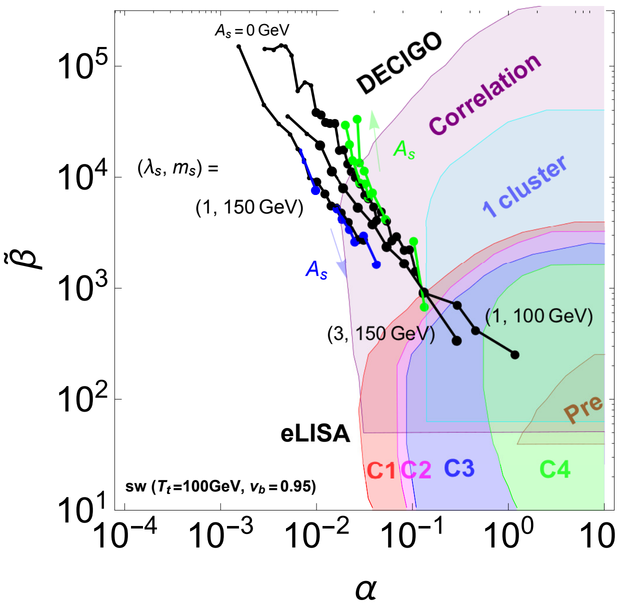

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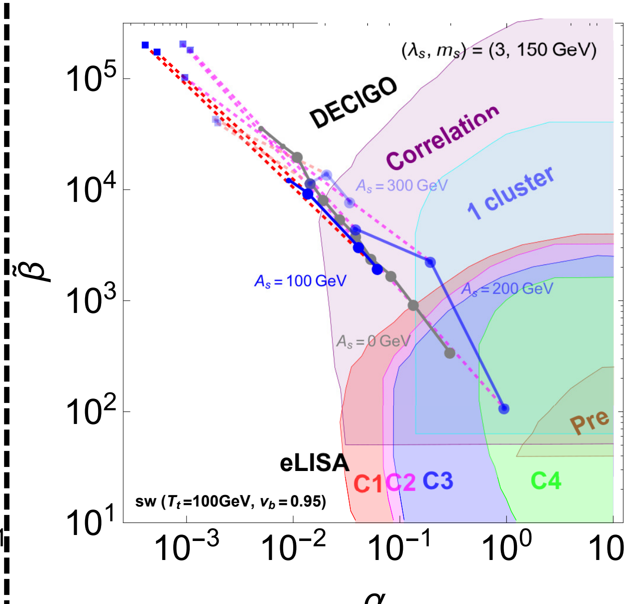
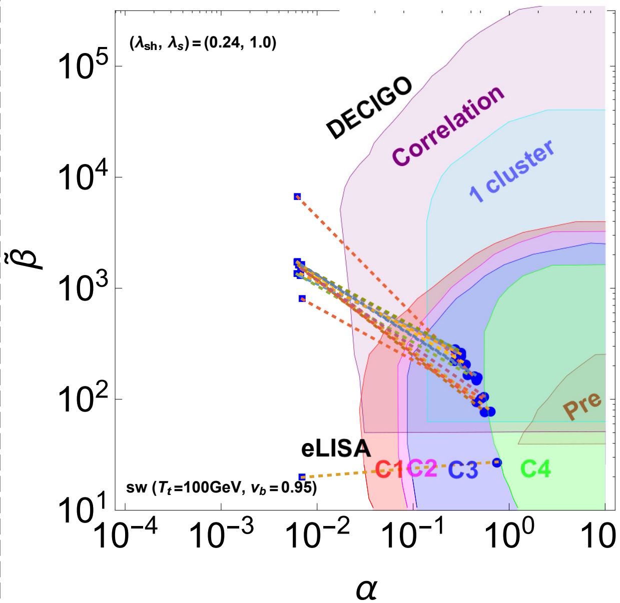


Three step PT

$$\Omega_0 \underset{T_s^*}{\xrightarrow{\text{1st}}} \Omega_s \xrightarrow{\text{2nd}} \Omega_{sh} \underset{T_*}{\xrightarrow{\text{1st}}} \Omega_h$$



Sensitivities

- DECIGO [S.Kawamura, et al., Class. Quant. Grav. 28, 094011 (2011)]
- eLISA [C.Caprini *et al.*, arXiv:1512.06239 [astro-ph.CO]]

Conclusions

- In general, the strongly 1stOPT can be realized by
  - The thermal loop coupling
  - The field mixing of the Higgs boson with additional scalar fields
- These cases can be tested at colliders.

- However, there is another case to hide such effects: "nightmare scenario"
- In this talk, we have focused on a model with unbroken discrete symmetry.
- The potential barrier is created by "the multi-step phase transition" on multi-field at finite temperature.
- We have shown that even if it is difficult to test at the colliders,
  - GWs is significantly enhanced by the strongly 1stOPT
  - GWs can be detected by future interferometers such as eLISA/DECIGO