

Probing electroweak phase transition via the synergy between colliders and gravitational wave observations

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- References:
- Hashino, Jinno, MK, Kanemura, Takahashi and Takimoto, paper in preparation

Contents

1. Introduction
2. Gravitational waves from first order phase transition
3. Expected constraints on model parameters
4. Summary

Motivation

Discovery of the 125 GeV Higgs boson h at the CERN LHC

- The Standard Model (SM) has been established as a low-energy effective theory below $O(100)$ GeV

This is not the end of the story

Puzzles in the Higgs sector

- Guiding principle?
- Shape of the Higgs potential (multiplets, symmetries, ...)?
- Dynamics behind the electroweak symmetry breaking (EWSB)?

Phenomena beyond the SM (BSM)

- Baryon asymmetry of the Universe (BAU)
- Existence of dark matter
- Cosmic inflation
- Neutrino oscillations

Idea: Higgs sector = Window to New Physics

- The structure of the Higgs sector is related to BSM models

Information on new physics can be obtained by investigating the properties of the Higgs sector

Electroweak baryogenesis (EWBG) relates the Higgs sector and BSM phenomena

Sakharov's conditions for BAU

1. Baryon number violation \leftarrow Sphaleron
2. C and CP violation \leftarrow Extended Higgs sector
3. Departure from thermal equilibrium
 \uparrow Strongly first order phase transition
 $(1^{\text{st}} \text{ OPT}): \varphi_c/T_c \gtrsim 1$

SM Higgs potential w/ one doublet:

- PT is NOT of 1st order for $m_h = 125$ GeV
- e.g. Two Higgs doublet model (2HDM)

$$\varphi_c/T_c \gtrsim 1 \rightarrow \Delta\lambda_{hhh}/\lambda_{hhh}^{\text{SM}} \gtrsim 10\%$$

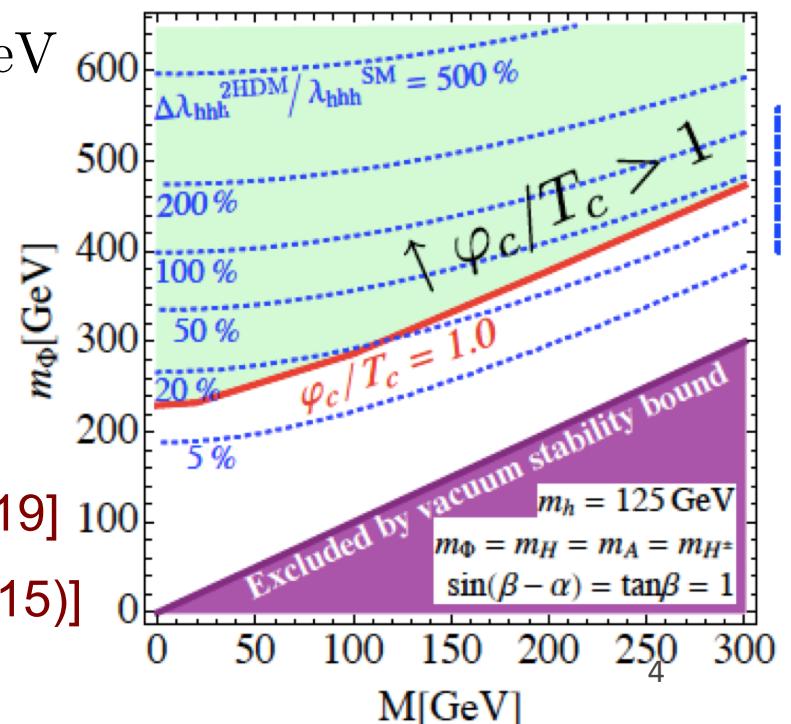
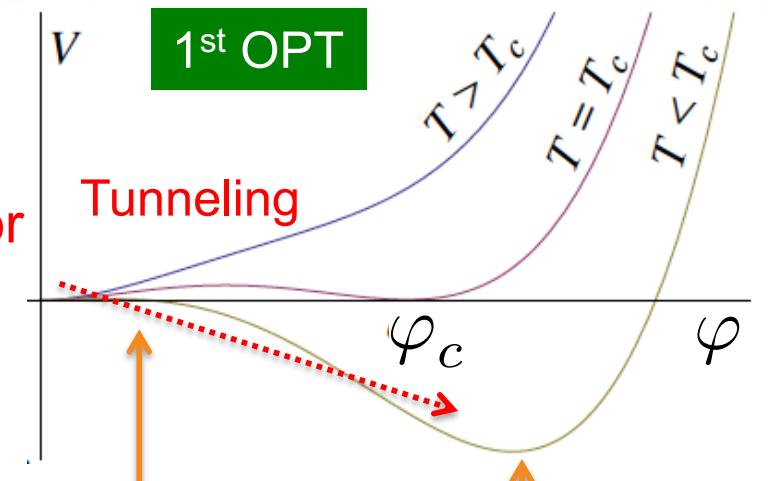
[Kanemura, Okada, Senaha (2005)]

Future accuracy:

- High-Luminosity LHC:

$$-1.3 \lesssim \Delta\lambda_{hhh}/\lambda_{hhh}^{\text{SM}} \lesssim 8.7 \quad [\text{ATL-PHYS-PUB-2014-019}]$$

- ILC 1 TeV: $\Delta\lambda_{hhh} : 10\%$ [Fujii et al. (2015)]



Gravitational waves (GWs) as a probe of EWPT

Ground-based interferometers:

advanced LIGO, advanced Virgo, KAGRA, ...

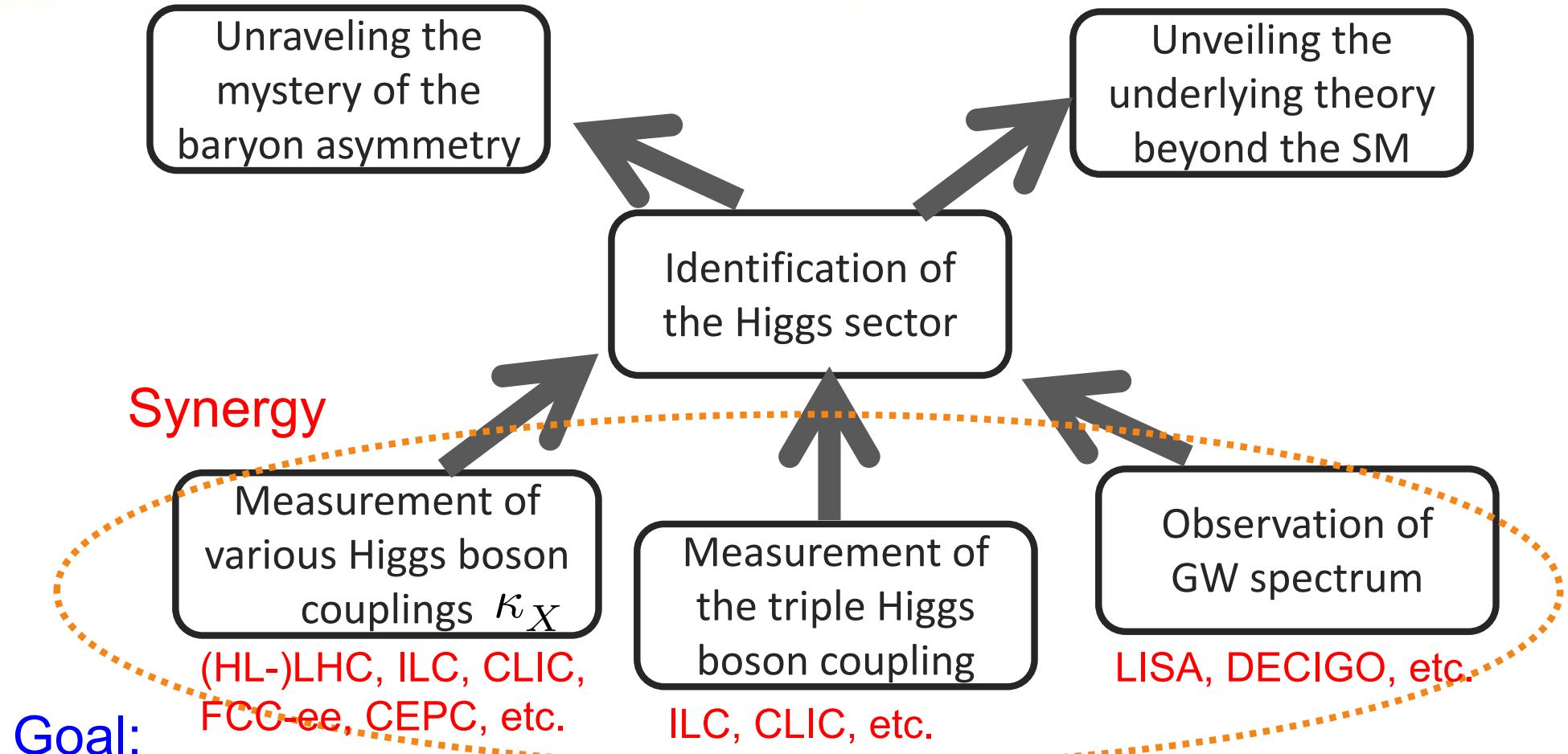
- Main targets: GWs from binary systems, supernovae, ...
- aLIGO made the first direct observation of GWs
→ New era of GW astronomy [LIGO and Virgo (2016)]

Future space-based interferometers:

LISA (2034-), DECIGO, ...

- Sensitive to GWs from the early Universe
(Strongly 1st OPT, cosmic inflation, ...)
→ New era for fundamental physics

Synopsis

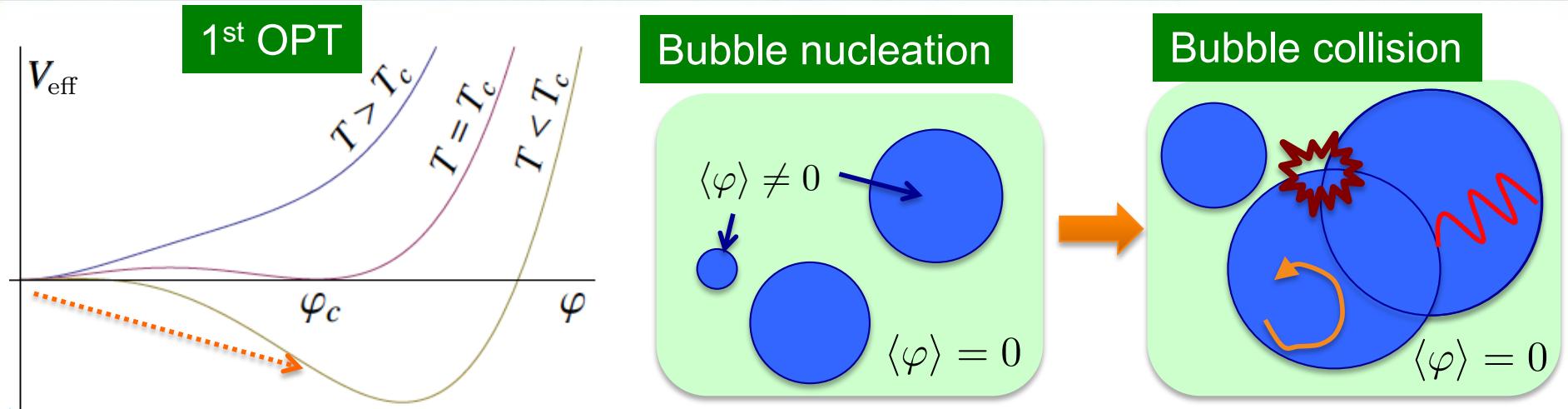


- We investigate expected precision for the parameters of models with 1st OPT using future space-based GW observations to maximize the synergy with colliders

Contents

1. Introduction
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GWs from 1st OPT



Linearized Einstein equation for the metric perturbation $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

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

Sources of GWs

1. Collision of bubble walls
2. Sound wave
3. Plasma turbulence

- GW spectrum is derived from finite temperature effective potential V_{eff}

Important quantities for GW spectrum

Bubble nucleation rate per unit volume per unit time:

$$\Gamma(t) = \Gamma_0(t) \exp[-S_E(t)] \quad S_E(T) = S_3(T)/T, \quad S_3 = \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi_b)^2 + V_{\text{eff}}(\varphi_b, T) \right]$$

Transition temperature T_*

$$\left. \frac{\Gamma}{H^4} \right|_{T=T_*} \sim 1 \quad \rightarrow \quad \frac{S_3(T_*)}{T_*} = 4 \ln(T_*/H_*) \sim 140$$

Released false vacuum energy (Latent heat)

$$\epsilon(T) = -V_{\text{eff}}(\varphi_B(T), T) + T \frac{\partial V_{\text{eff}}(\varphi_B(T), T)}{\partial T} \quad \text{Normalized parameter: } \alpha = \frac{\epsilon(T_*)}{\rho_{\text{rad}}(T_*)}$$

Inverse of the duration of phase transition

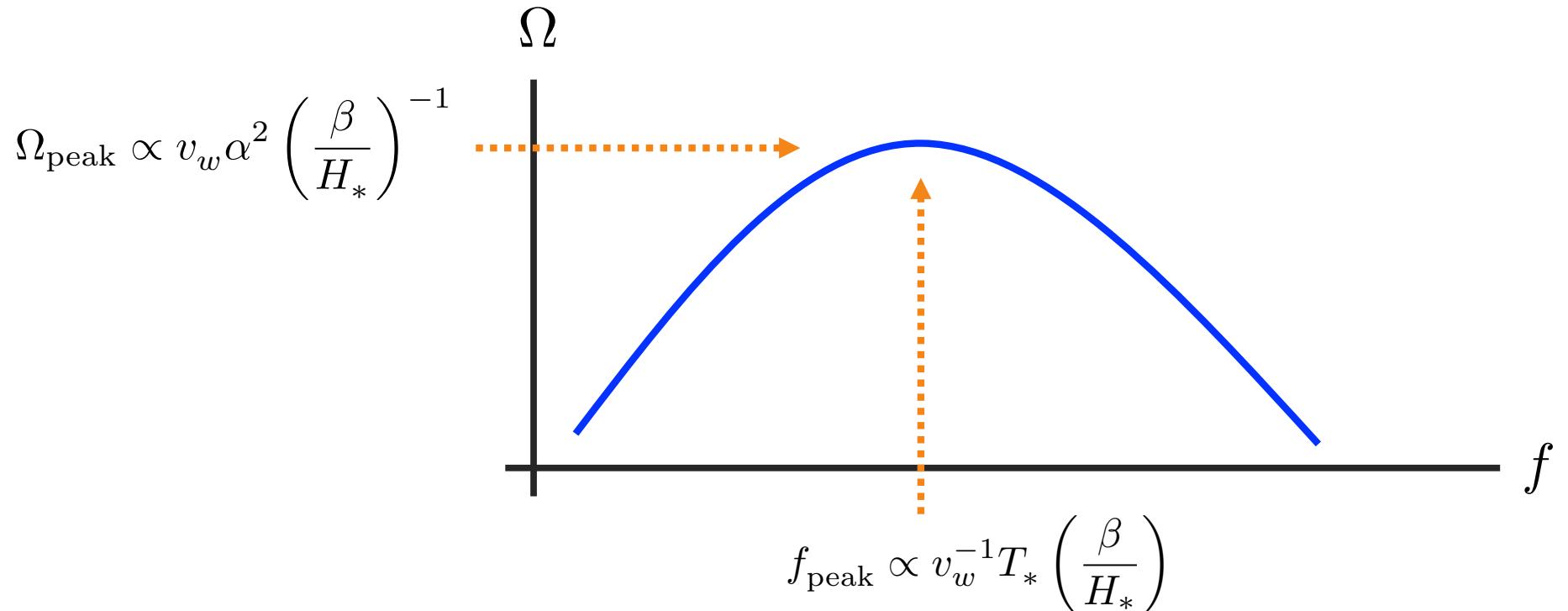
$$\beta = - \left. \frac{dS_E}{dt} \right|_{t=t_*} \simeq \left. \frac{1}{\Gamma} \frac{d\Gamma}{dt} \right|_{t=t_*}$$

Normalized parameter: $\frac{\beta}{H_*} (= \tilde{\beta})$

Wall velocity v_w

GW spectrum

Rough spectrum from the dominant sound wave contribution



- Complicated numerical simulations are necessary
- Our analysis relies on the approximate fitting formula provided by Caprini et al. [Caprini et al. (2015)]

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Fisher Analysis

Likelihood function

$$\delta\chi^2(\{p\}, \{\hat{p}\}) = 2T_{\text{obs}} \int_0^\infty df \frac{[S_h(f, \{p\}) - S_h(f, \{\hat{p}\})]^2}{[S_{\text{eff}}(f) + S_h(f, \{\hat{p}\})]^2}$$

Observation period

\downarrow Taylor expansion w.r.t. $\{p\} = \{\hat{p}\}$

$$\delta\chi^2(\{p\}, \{\hat{p}\}) \simeq \mathcal{F}_{ab}(p_a - \hat{p}_a)(p_b - \hat{p}_b)$$

Fisher information matrix

$$\mathcal{F}_{ab} = 2T_{\text{obs}} \int_0^\infty df \frac{\partial_{p_a} S_h(f, \{\hat{p}\}) \partial_{p_b} S_h(f, \{\hat{p}\})}{[S_{\text{eff}}(f) + S_h(f, \{\hat{p}\})]^2}$$

The inverse \mathcal{F}_{ab}^{-1} is the covariance matrix

n.b.: we assume that these expressions are applicable to a single-detector like LISA

GW spectrum for parameter set $\{p\}$

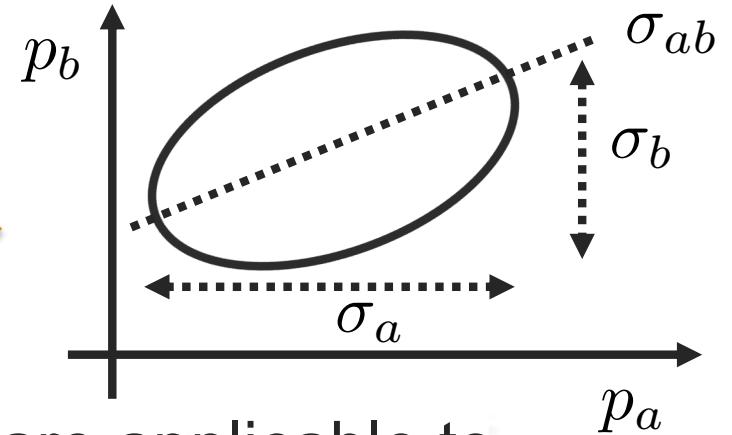
GW spectrum for fiducial parameter set $\{\hat{p}\}$

$$[S_h(f, \{p\}) - S_h(f, \{\hat{p}\})]^2$$

Effective sensitivity of interferometer

Confidence ellipse

Inclination:

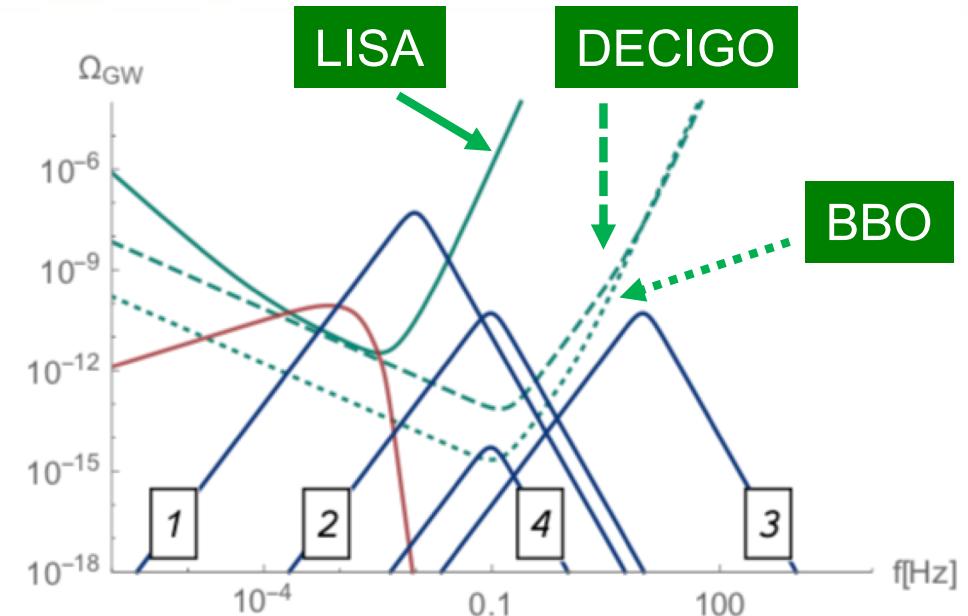


Constraints on the shape of GW spectrum

GW spectrum

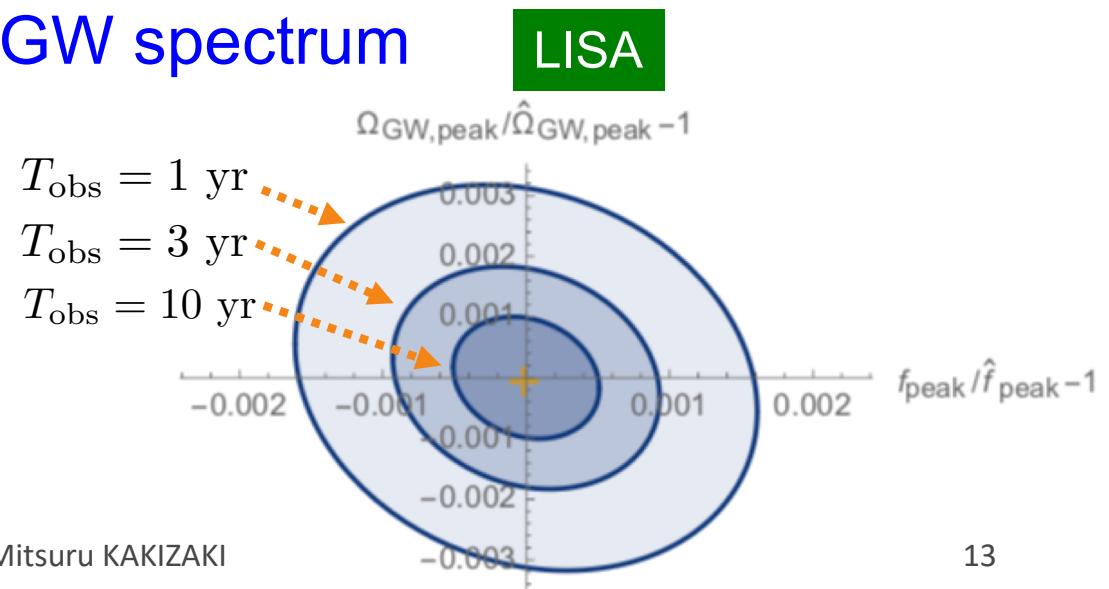
- Fiducial values

- Point 1: $(f_{\text{peak}}, \Omega_{\text{peak}}) = (10^{-2} \text{ Hz}, 10^{-7})$,
- Point 2: $(f_{\text{peak}}, \Omega_{\text{peak}}) = (10^{-1} \text{ Hz}, 10^{-10})$,
- Point 3: $(f_{\text{peak}}, \Omega_{\text{peak}}) = (10 \text{ Hz}, 10^{-10})$,
- Point 4: $(f_{\text{peak}}, \Omega_{\text{peak}}) = (10^{-1} \text{ Hz}, 10^{-14})$.



Expected constraints on the GW spectrum

- 1σ confidence ellipse in $(f_{\text{peak}}, \Omega_{\text{peak}})$ for Point 1



Constraints on transition parameters

Constraining parameters

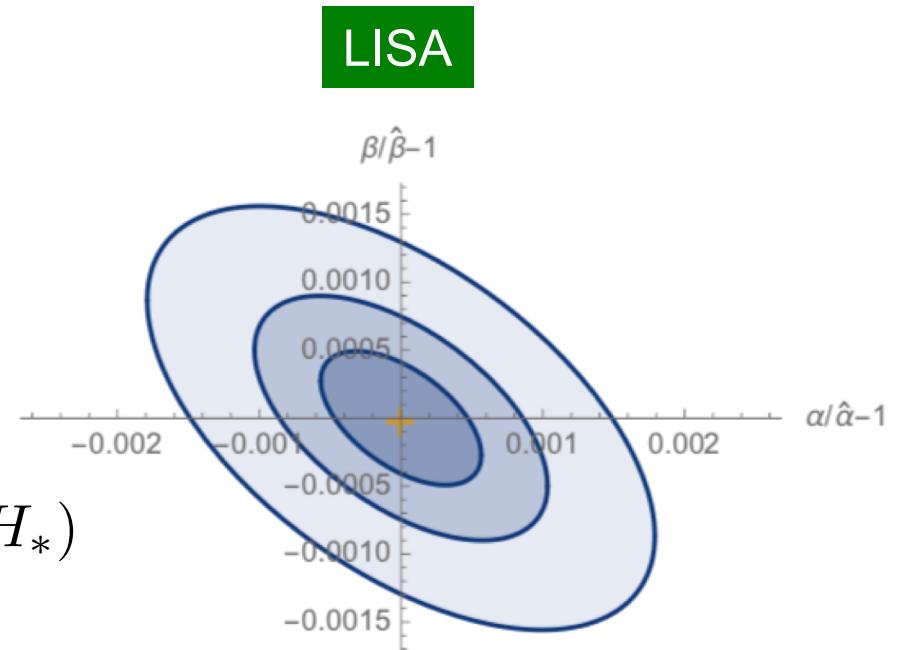
- The GW spectrum is determined by f_{peak} , Ω_{peak}
→ Our Fisher analysis generically constrain 2 combinations of underlying parameters

Quantities describing transition dynamics

$$T_*, \quad v_w, \quad \alpha, \quad \frac{\beta}{H_*}$$

Expected constraints on the transition parameters

- Fiducial values
 $(\alpha, \beta/H_*, v_w, T_*) = (1, 100, 1, 100 \text{ GeV})$
- 1σ confidence ellipse in $(\alpha, \beta/H_*)$ for fixed T_* and v_w



Models with $O(N)$ symmetry with and without CSI

Typical examples for 1st OPT from thermal loop effects

- Models with CSI

- Tree-level Higgs potential

$$V_0 = \lambda_\Phi |\Phi|^4 + \frac{\lambda_S}{4} |\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2} |\Phi|^2 |\vec{S}|^2$$

Φ :Higgs doublet
 $\vec{S} = (S_1, \dots, S_N)$

- Fiducial parameters

- $(N, \lambda_S) = (4, 0.1)$
- $(\alpha, \beta/H_*, T_* [\text{GeV}]) \simeq (0.12, 890, 74)$

- Models without CSI

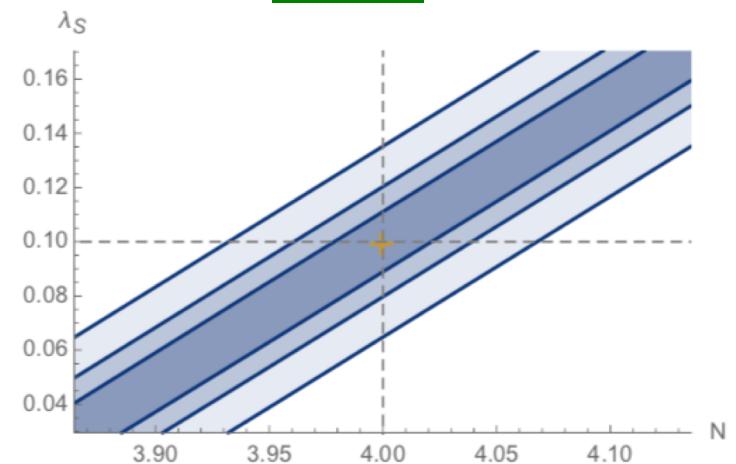
- Tree-level Higgs potential

$$V_0 = -\mu^2 |\Phi|^2 + \mu_S^2 |\vec{S}|^2 + \lambda_\Phi |\Phi|^4 + \frac{\lambda_S}{4} |\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2} |\Phi|^2 |\vec{S}|^2$$

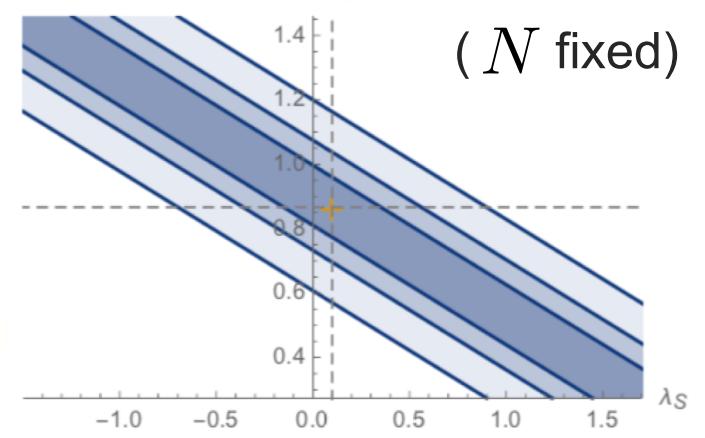
- Fiducial parameters

- $(N, \lambda_S, m_S [\text{GeV}], \mu_S [\text{GeV}]) = (4, 0.1, 385, 0)$
- $(\alpha, \beta/H_*, T_* [\text{GeV}]) \simeq (0.10, 800, 77)$

LISA



$\Delta \lambda_{hh}/\lambda_{SM}$



Higgs singlet model

Typical example for 1st OPT from tree-level mixing

- Expected constraints on the Higgs singlet model

- Tree-level Higgs potential

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

- Fiducial parameters

- $(m_H \text{ [GeV]}, \mu_{HS} \text{ [GeV]}, \kappa, v_S \text{ [GeV]}, \mu_{S^3} \text{ [GeV]}) = (170, 0.943, -80, 90, -30)$

➡ • $(\alpha, \beta/H_*, T_* \text{ [GeV]}) \simeq (0.10, 800, 77)$

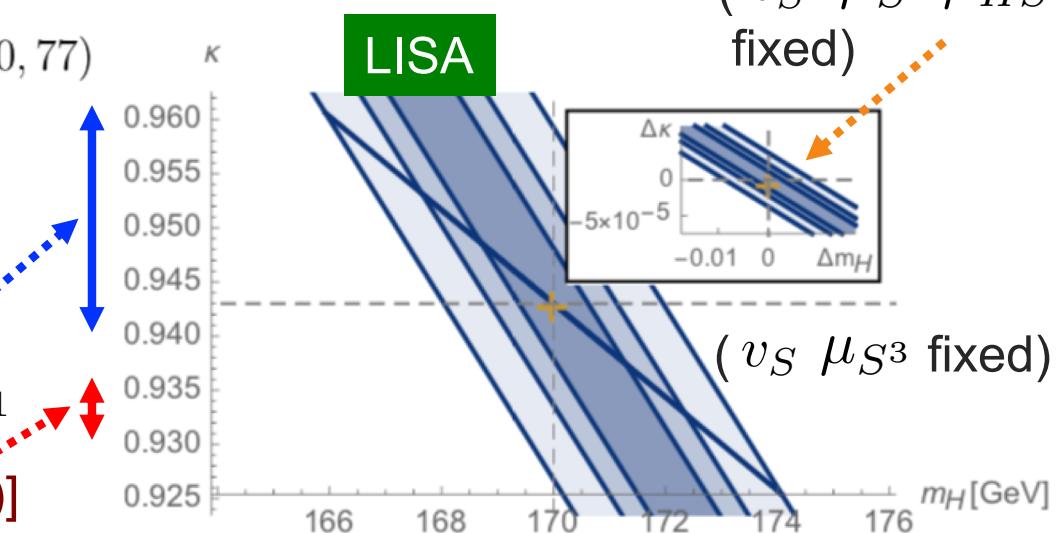
- Future colliders

- HL-LHC

$\Delta\kappa_V : 2\% \text{ [ATLAS, CMS (2013)]}$

- ILC w/ $\sqrt{s} = 250 \text{ GeV}$ $L = 2 \text{ ab}^{-1}$

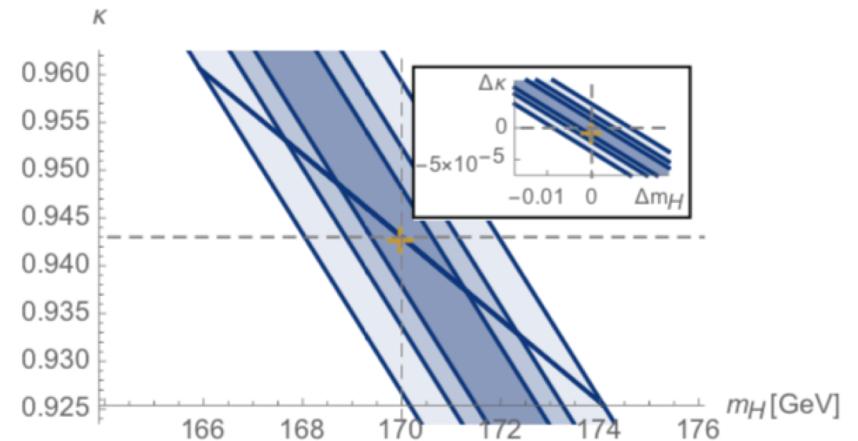
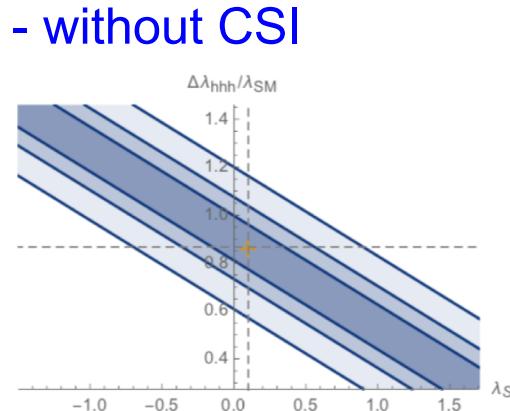
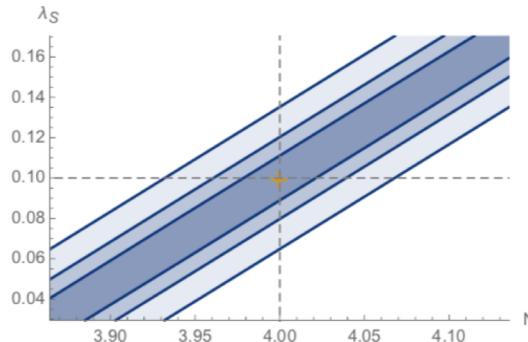
$\Delta\kappa_V : 0.6\% \text{ [Durieux et al. (2017)]}$



The synergy between colliders and GW observations can narrow down the allowed parameter space

Summary

- Models with additional singlet scalars
 - with CSI
 - without CSI
- Higgs singlet model



- We have evaluated the expected constraints on the parameters of new physics models with 1st OPT using future space-based GW observations
- We have shown that the synergy between future colliders and GW observations can play complementary roles in determining model parameters

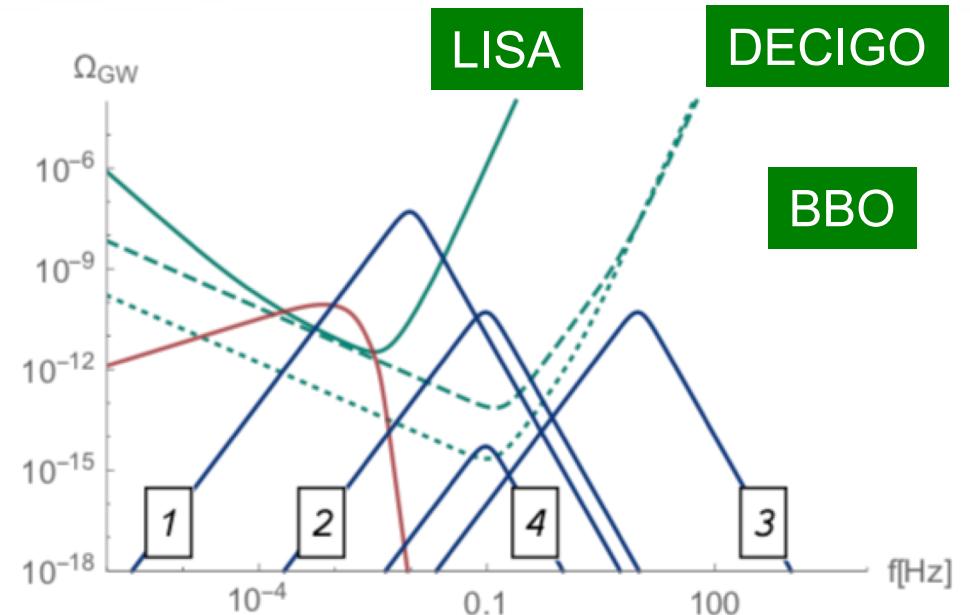
Backup slides

Constraints on the shape of GW spectrum

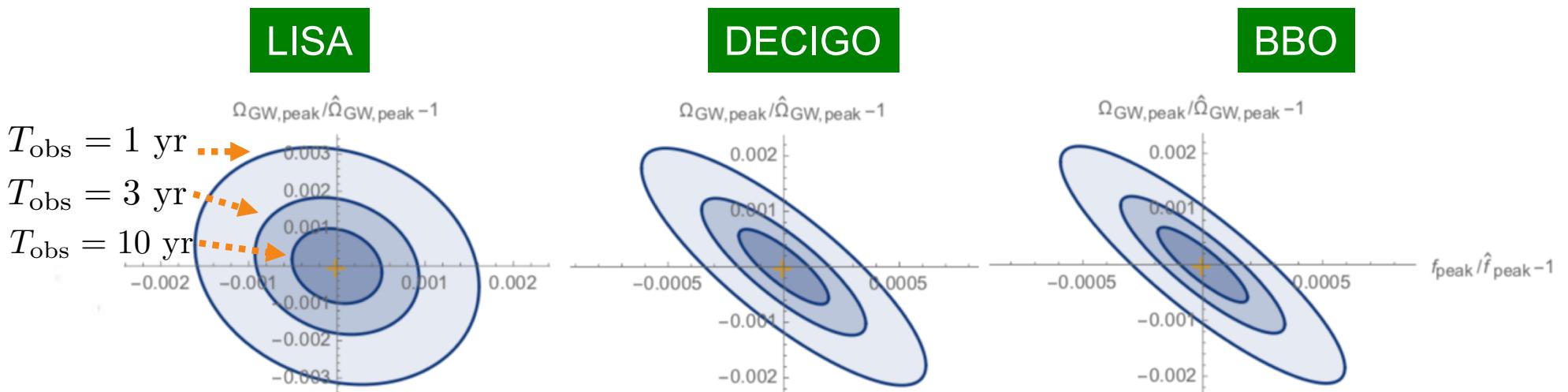
GW spectrum

- Fiducial values

- Point 1: $(f_{\text{peak}}, \Omega_{\text{peak}}) = (10^{-2} \text{ Hz}, 10^{-7})$,
- Point 2: $(f_{\text{peak}}, \Omega_{\text{peak}}) = (10^{-1} \text{ Hz}, 10^{-10})$,
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- Point 4: $(f_{\text{peak}}, \Omega_{\text{peak}}) = (10^{-1} \text{ Hz}, 10^{-14})$.



Expected constraints on the GW spectrum for Point1



Model A: Models with additional singlet scalars (without CSI)

Idea:

[MK, Kanemura, Matsui (2015)]

- To generally handle strongly 1st OPT via thermal loop, N isosinglet scalars S_i ($i = 1, \dots, N$) are introduced
- For simplicity, $O(N)$ symmetry is imposed

Tree-level scalar potential:

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

Φ : SM Higgs doublet $\vec{S} = (S_1, S_2, \dots, S_N)^T$

Singlet scalar boson mass:

$$m_S^2 = \mu_S^2 + \frac{\lambda_{\Phi S}}{2} v^2$$

Undetermined parameters responsible for EWPT:

μ_S, m_S for each $O(N)$ model

Models with additional singlet scalars (without CSI) (contd.)

- Effective potential:

[MK, Kanemura, Matsui (2015)]

$$V_{\text{eff}}(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi) \left(\ln \frac{M_i^2(\varphi)}{Q^2} - \frac{3}{2} \right)$$

$$\rightarrow \lambda_{hhh}^{O(N)} = \frac{3m_h^2}{v} \left\{ 1 - \frac{1}{\pi^2} \frac{m_t^4}{v^2 m_h^2} + \frac{N}{12\pi^2} \frac{m_S^4}{v^2 m_h^2} \left(1 - \frac{\mu_S^2}{m_S^2} \right)^3 \right\}$$

Non decoupling loop effect from additional scalars

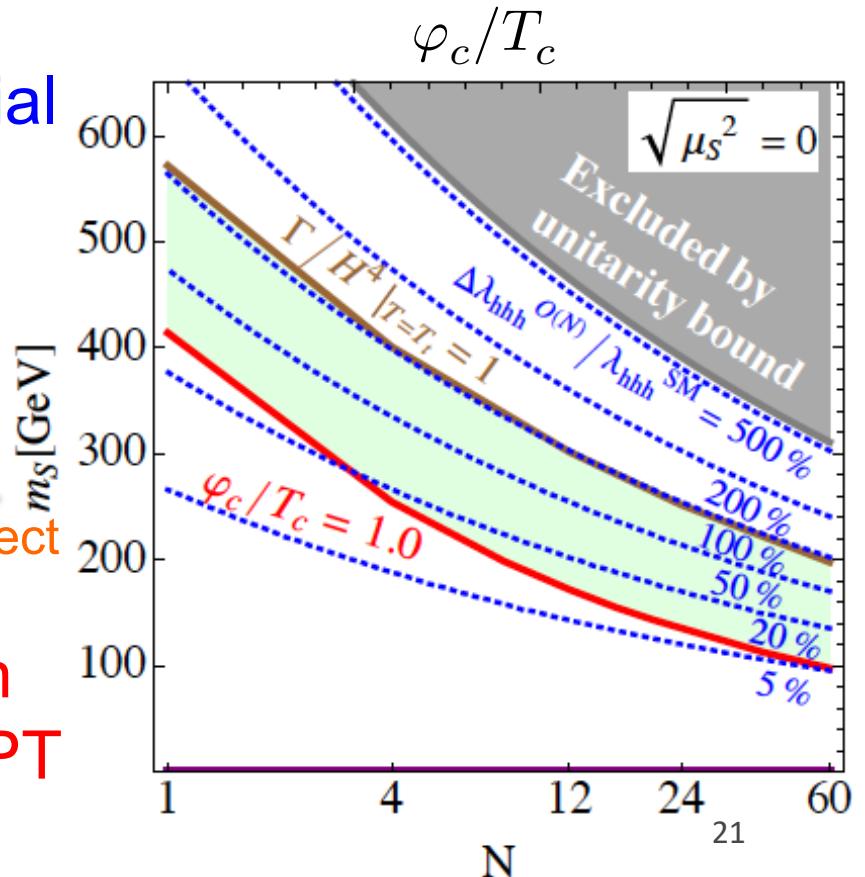
- Finite temperature effective potential (high temperature expansion):

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \dots$$

$$\frac{\varphi_c}{T_c} \propto E = \frac{1}{12\pi v^3} \left[6m_W^3 + 3m_Z^3 + Nm_S^3 \left(1 - \frac{\mu_S^2}{m_S^2} \right)^3 \left(1 + \frac{3\mu_S^2}{2m_S^2} \right) \right]$$

Non decoupling loop effect from additional scalars

\rightarrow Typically $\mathcal{O}(10)\%$ deviation in λ_{hhh} for strongly 1st OPT



Model B: CSI models with additional singlet scalars

Idea [Hashino, Kanemura, Orikasa (2015)]

- Mass parameters are absent in the original Lagrangian due to Classical Scale Invariance (CSI) [Bardeen (1995)]
- EWSB is directly caused by thermal loop effects

Tree-level scalar potential

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

Effective potential along the flat direction

$$V_1(\varphi) = \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi) \left(\ln \frac{M_i^2(\varphi)}{Q^2} - c_i \right) \quad c_i = 3/2$$

Singlet scalar boson mass

$$Nm_S^4 = 8\pi^2 v^2 m_h^2 - 6m_W^4 - 3m_Z^4 + 12m_t^4$$

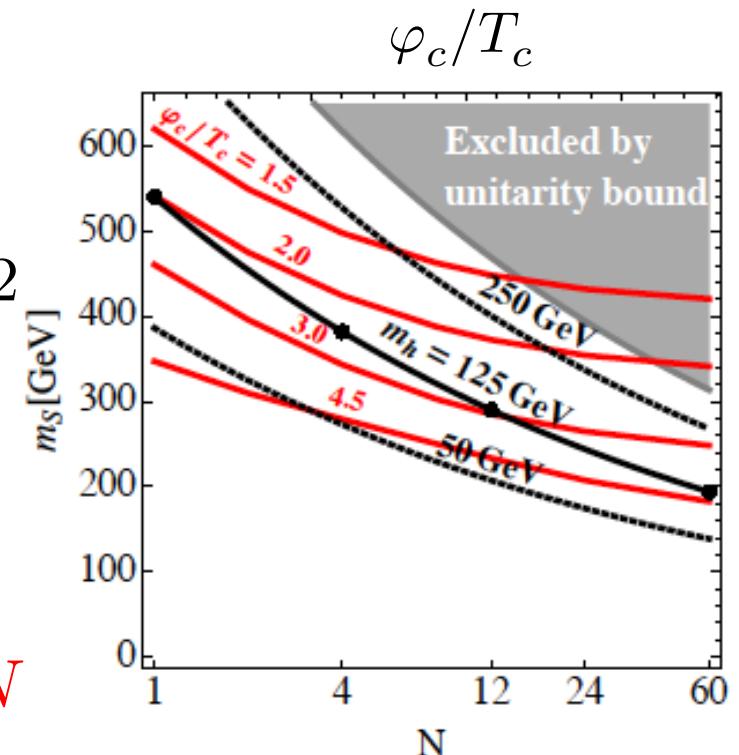
Triple Higgs boson coupling

$$\frac{\Delta \lambda_{hhh}}{\lambda_{hhh}^{\text{SM(tree)}}} = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\text{SM(tree)}}} - 1 = \frac{2}{3} \quad \text{independent of } N$$

[Hashino, Kanemura, Orikasa (2015)]

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[Hashino, MK, Kanemura, Matsui (2015)]

22

Model C: Higgs singlet model

Idea

[Hashino, MK, Kanemura, Ko, Matsui (2016)]

- To investigate strongly 1st OPT and Higgs couplings induced through Higgs field mixing (at least 2 classical fields needed)
- For simplicity, we introduce a singlet Higgs field S

Tree-level Higgs potential

$$V_0 = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \mu_{\Phi S} |\Phi|^2 S + \frac{\lambda_{\Phi S}}{2} |\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2} S^2 + \frac{\mu'_S}{3} S^3 + \frac{\lambda_S}{4} S^4$$
$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \varphi_\Phi \end{pmatrix} : \text{SM Higgs doublet} \qquad \qquad \langle S \rangle = \varphi_S : \text{Higgs singlet}$$

Effective potential:

$$V_{\text{eff}, T=0}(\varphi_\Phi, \varphi_S) = V_0(\varphi_\Phi, \varphi_S) + \sum_i n_i \frac{M_i^4(\varphi_\Phi, \varphi_S)}{64\pi^2} \left(\ln \frac{M_i^2(\varphi_\Phi, \varphi_S)}{Q^2} - c_i \right) \quad c_F = c_S = 5/6 \\ c_V = 5/6$$

Higgs boson masses and mixing

$m_h (= 125 \text{ GeV})$: Mass of the discovered Higgs boson

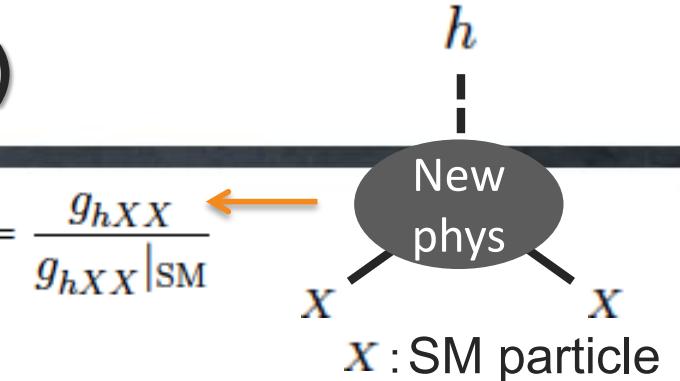
m_H : Mass of the additional Higgs boson

θ : Higgs mixing angle

Model C: Higgs Singlet Model (contd.)

Higgs boson couplings to SM particles

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



Triple Higgs boson couplings (effective potential approach)

$$\Delta\lambda_{hhh} = \frac{\lambda_{hhh}^{\text{HSM}} - \lambda_{hhh}^{\text{SM}}}{\lambda_{hhh}^{\text{SM}}}$$

$$\lambda_{hhh}^{\text{SM}} = \frac{3m_h^2}{v_\Phi} \left[1 + \frac{9m_h^2}{32\pi^2 v_\Phi^2} + \sum_{i=W^\pm, Z, t, b} n_i \frac{m_i^4}{12\pi^2 m_h^2 v_\Phi^2} \right]$$

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

Finite temperature effective potential in one direction
(high temperature expansion)

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

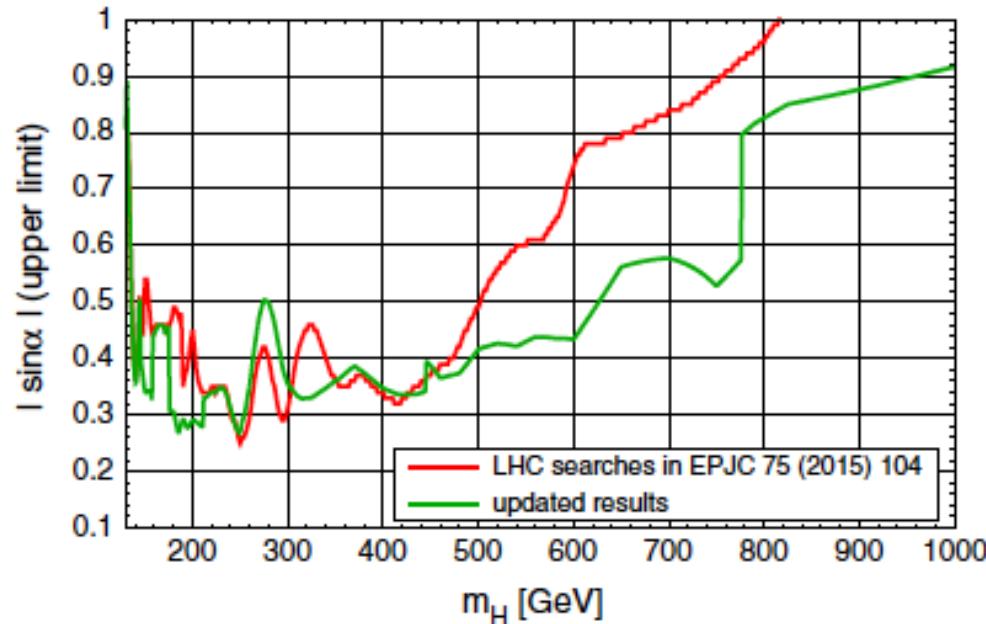
$$\rightarrow \frac{\varphi_c}{T_c} = \frac{2E}{\lambda} \left(1 - \frac{e\lambda}{ET} \right)$$

Effects from the Higgs boson mixing

The Higgs boson mixing gives considerable contributions to deviation in the Higgs boson couplings and to phase transition

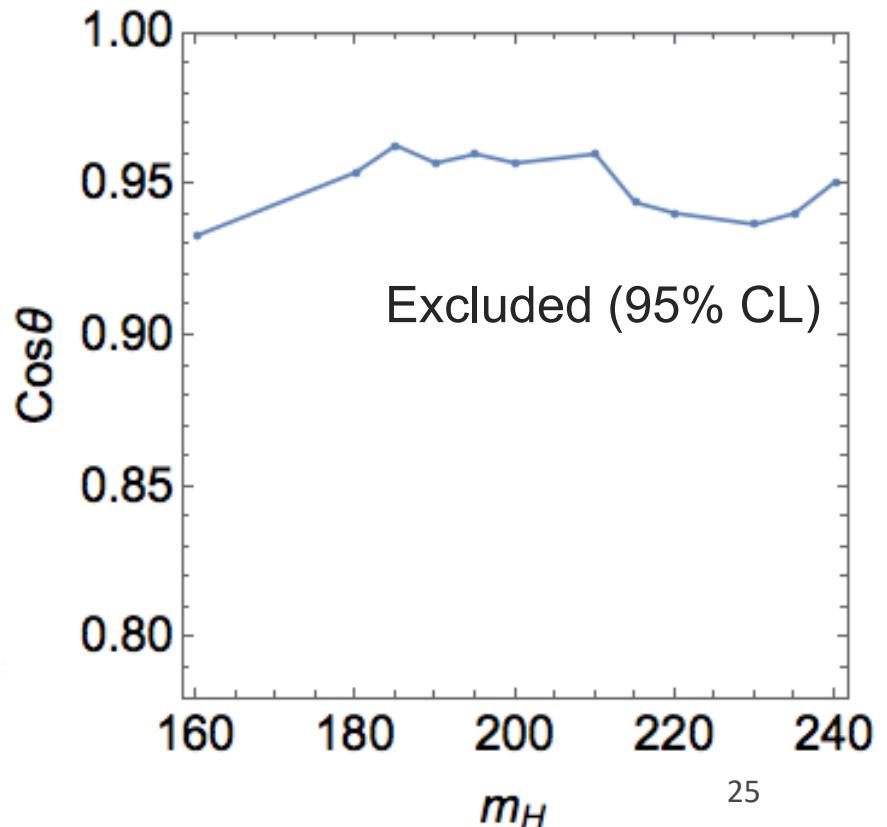
Model C: Direct searches for the additional Higgs boson in the HSM at the LHC

Upper limit on the Higgs mixing angle $|\sin \theta|$



[Robens, Stefaniak (2016)]

→ Constraints on the Higgs boson coupling $\kappa (= \cos \theta)$



Range of m_H [GeV]	Search channel
130–145	$H \rightarrow ZZ \rightarrow 4l$
145–158	$H \rightarrow VV$ ($V=W,Z$)
158–163	SM comb.
163–170	$H \rightarrow WW$
170–176	SM comb.
176–211	$H \rightarrow VV$ ($V=W,Z$)
211–225	$H \rightarrow ZZ \rightarrow 4l$
225–445	$H \rightarrow VV$ ($V=W,Z$)

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Sketch of first order phase transition

Effective potential at one-loop level:

$$V_{\text{eff}}(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi) \left(\ln \frac{M_i^2(\varphi)}{Q^2} - \frac{3}{2} \right)$$

Contribution at finite-temperatures:

$$\Delta V_T(\varphi, T) = \frac{T^4}{2\pi^2} \left[\sum_{i=\text{bosons}} n_i I_B(a^2) + \sum_{i=\text{fermions}} n_i I_F(a^2) \right]$$

$$I_{B/F}(a^2) = \int_0^\infty dx x^2 \ln \left(1 \mp e^{-\sqrt{x^2+a^2}} \right) \quad a^2 = \frac{M^2(\varphi, T)}{T^2}$$

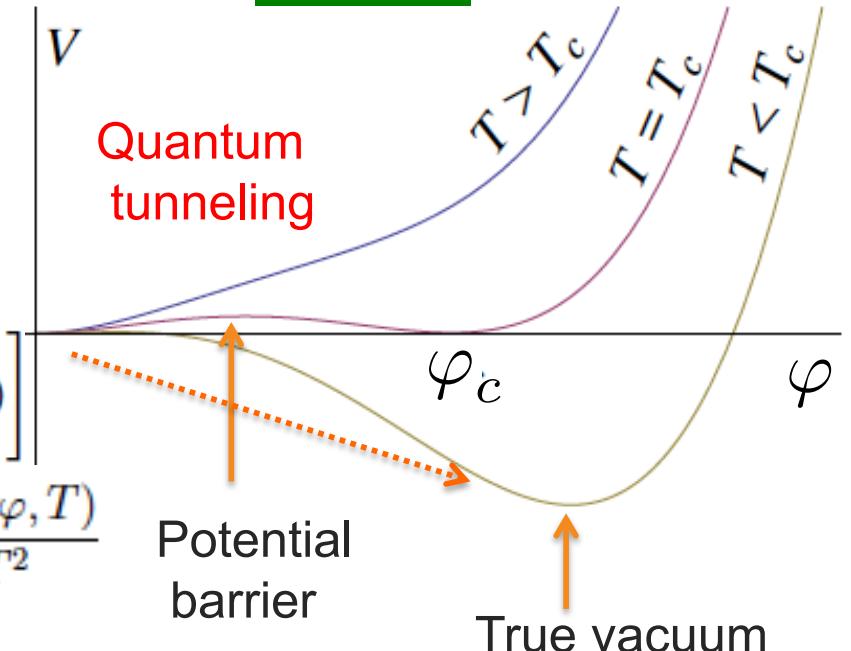
High-temperature expansion:

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - \underline{ET\varphi^3} + \frac{\lambda_T}{4}\varphi^4 + \dots \quad \varphi_c/T_c \propto E$$

$$I_B(a^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{32} \left(\ln \frac{a^2}{\alpha_B} - 3/2 \right) + \mathcal{O}(a^6)$$

$$I_F(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{32} \left(\ln \frac{a^2}{\alpha_F} - 3/2 \right) + \mathcal{O}(a^6)$$

1st OPT



Bosonic loop contribute
to the cubic term

Strongly 1st OPT ($\varphi_c/T_c \gtrsim 1$) can be achieved by adding bosons

Necessary for successful electroweak baryogenesis

Gravitational waves

Properties of gravitational waves

- GWs propagate at the speed of light
- GWs are transverse to the direction of propagation
- Spin 2
- 2 polarization modes: Plus mode h^+ & Cross mode $h\times$

Weak-field approximation:

- Metric close to flat: $g_{\mu\nu}(x) = \eta_{\mu\nu} + \underline{h_{\mu\nu}(x)}$ $|h_{\mu\nu}| \ll 1$
Linearized Einstein eq. in vacuum: $\square h_{\mu\nu} = 0$ Wave eq.!

Interactions of gravitational waves

- Reaction rate: $\Gamma = n\sigma v$ $n \sim T^3$ $\sigma \sim G^2 T^2 = \frac{T^2}{M_{Pl}^4}$ $v \sim 1$
 - Expansion rate of the Universe: $H \sim \frac{T^2}{M_{Pl}}$
- $\frac{\Gamma}{H} \sim \frac{T^3}{M_{Pl}^3}$: GWs decouple below the Planck scale M_{Pl}

GWs convey information on the time when produced

Relic gravitational waves

Characteristics of relic gravitational waves

- Homogeneous
- Isotropic
- Static
- Unpolarized

→ Relic GWs are characterized only by frequency

Energy density of relic gravitational waves

$$\rho_{\text{GW}} = \frac{1}{32\pi G} \langle \dot{h}_{ij} \dot{h}_{ij} \rangle$$

- Normalized Energy density per unit logarithmic interval of frequency f

$$\Omega_{\text{GW}}(f) \equiv \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}}{d \ln f} \quad \rho_c = \frac{3H_0^2}{8\pi G} \quad : \text{Critical density}$$

Typical frequency of relic gravitational waves

Gravitational waves produced with frequency f_t , abundance Ω_{GW}^t are red-shifted due to the expansion of the Universe

- Frequency and energy density scale as $f \propto \frac{1}{a}$ $\rho_{\text{GW}} \propto \frac{1}{a^4}$
- Conservation of entropy: $sa^3 = \text{const.}$ a : scale factor

→ Red-shifted GW relic abundance observed today:

$$\Omega_{\text{GW}} h^2 \simeq 1.7 \times 10^{-5} \left(\frac{100}{g_*^t} \right)^{1/3} \Omega_{\text{GW}}^t$$

Red-shifted typical frequency observed today:

$$f_0 \simeq 1.7 \times 10^{-5} \left(\frac{g_*^t}{100} \right)^{1/6} \left(\frac{T_t}{100 \text{ GeV}} \right) \frac{f_t}{H_t} \text{ Hz}$$

For typical electroweak phase transition:

$$T_t \sim 100 \text{ GeV} \quad f_t/H_t \sim 10^2 - 10^4 \rightarrow f_0 \sim 10^{-3} - 10^{-1} \text{ Hz}$$

Range for future space-based interferometers

Model A: Predicted values of α and $\tilde{\beta}$

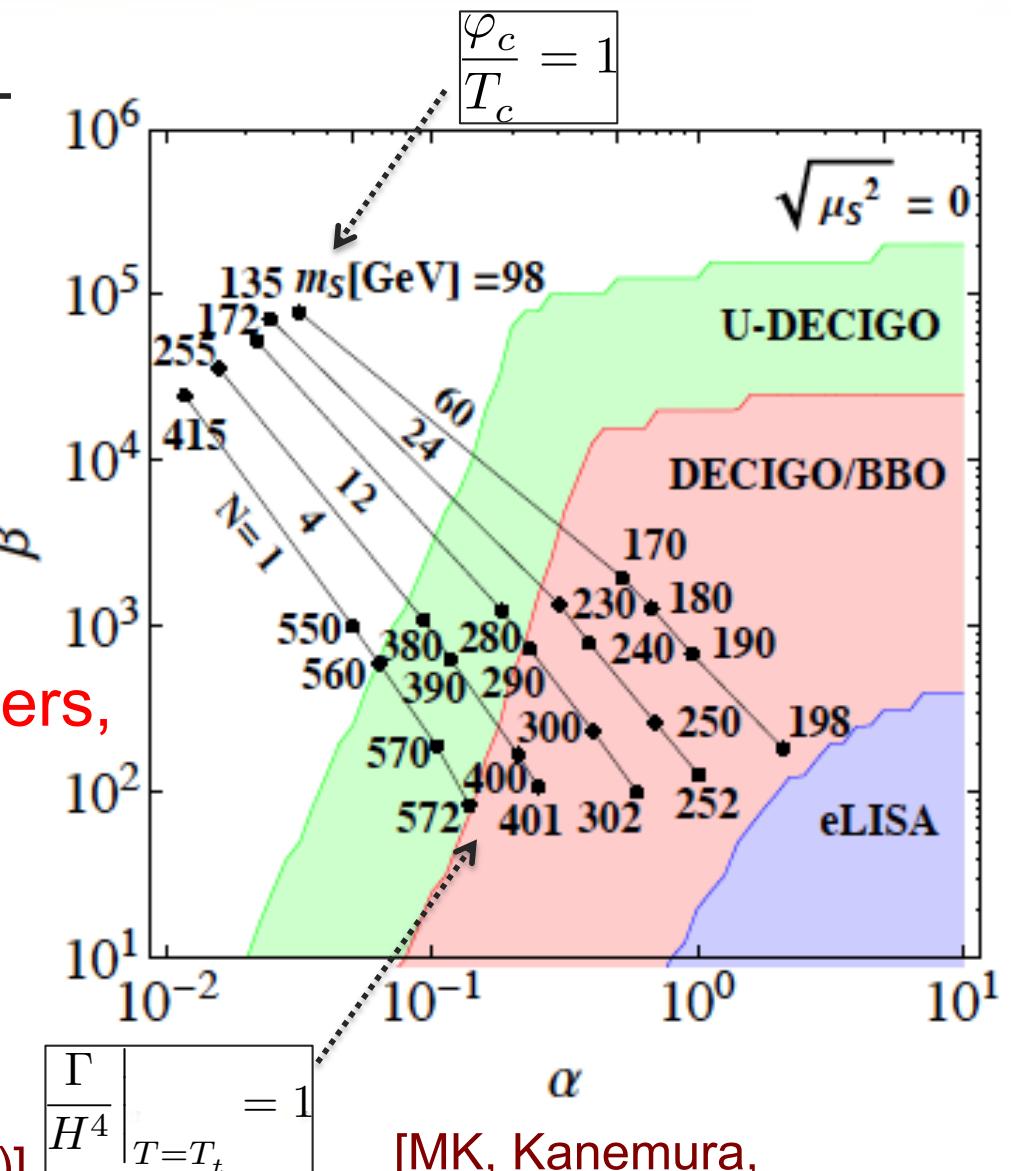
- Condition for strongly 1st OPT
➡ Constraints on α and $\tilde{\beta}$ for each model

[MK, Kanemura, Matsui (2015)]

- α and $\tilde{\beta}$ to be determined by GW observation are useful in determining model parameters, such as N and m_S

n.b.: The experimental prospects are estimated based on the traditional GW spectrum

[See e.g. Grojean, Servant (2007)]



Testability of models with additional singlet scalars with and without CSI

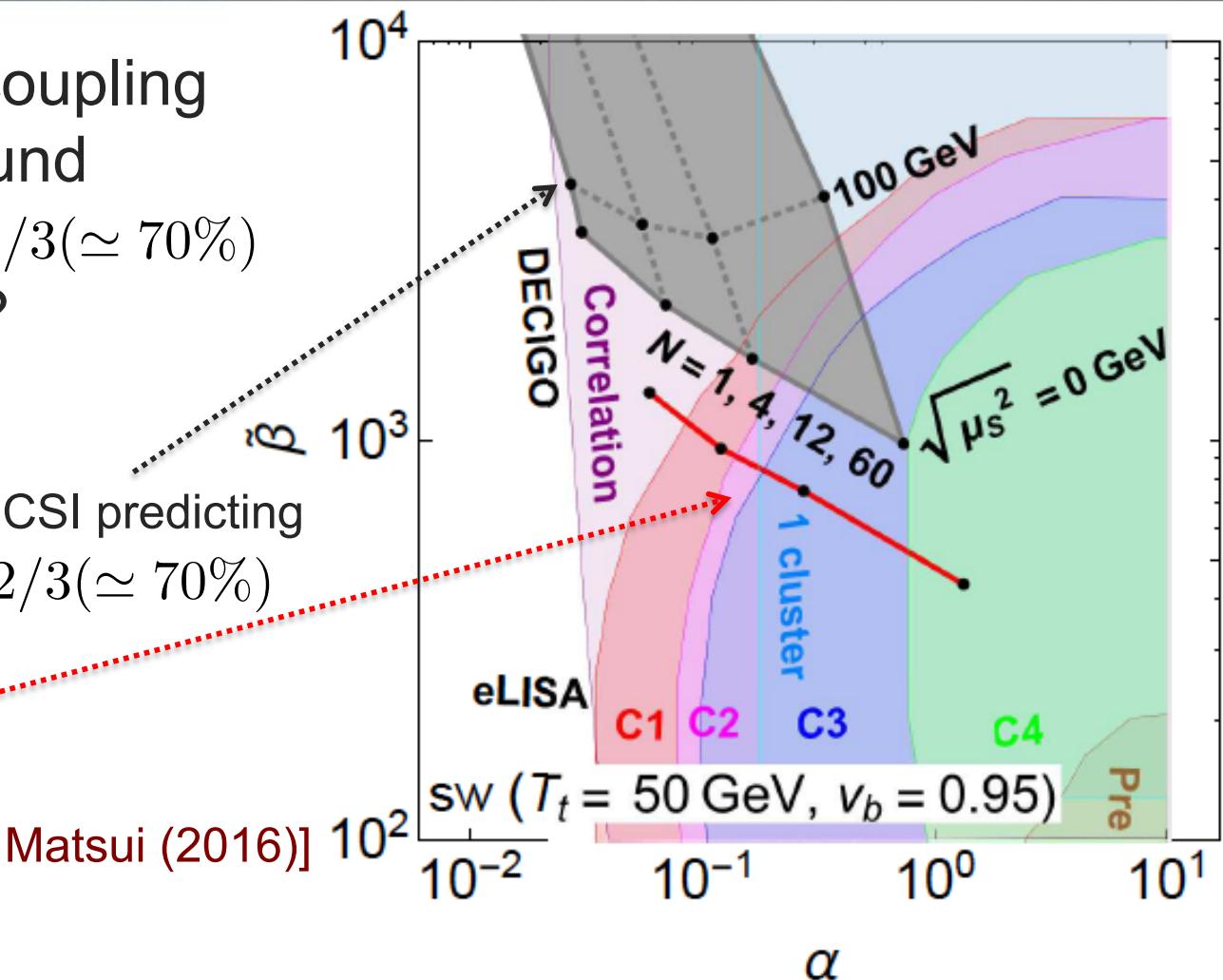
- What if the hhh coupling is found to be around

$$\Delta\lambda_{hhh}/\lambda_{hhh}^{\text{SM}} = 2/3 (\simeq 70\%)$$

at future colliders?

- $O(N)$ models without CSI predicting
 $\Delta\lambda_{hhh}/\lambda_{hhh}^{\text{SM}} = 2/3 (\simeq 70\%)$
- CSI $O(N)$ models

[Hashino, MK, Kanemura, Matsui (2016)]



Models with and without CSI can be distinguished at future GW interferometers even if they share common hhh coupling

Model C: Synergy of measurements of various Higgs boson couplings and GWs in the HSM

[Hashino, MK, Kanemura,
Ko, Matsui (2016)]

Collider experiments

- LHC Run I results

$\kappa_Z = 1.03^{+0.11}_{-0.11}$, $\kappa_W = 0.91^{+0.10}_{-0.10}$
[ATLAS, CMS (2016)]

- HL-LHC

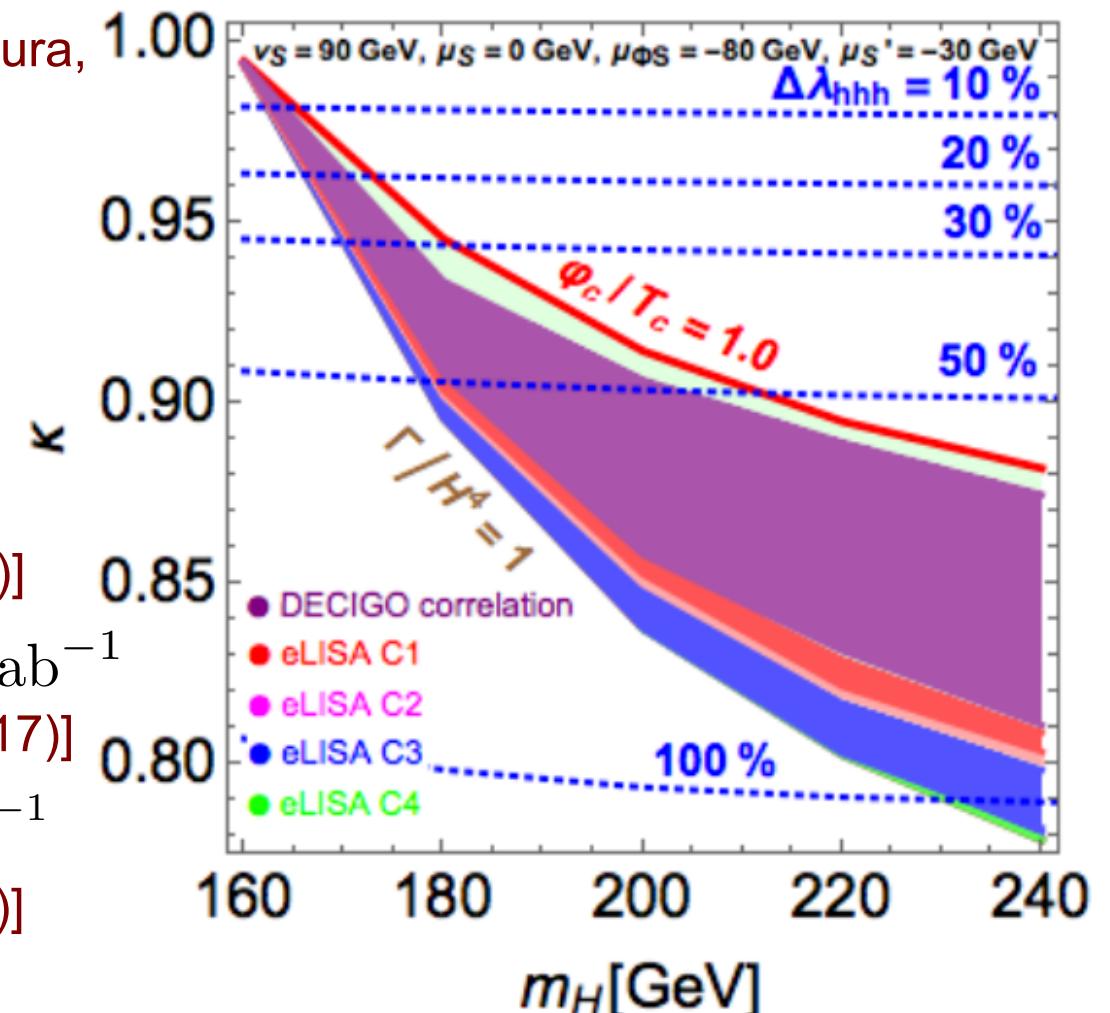
$\Delta\kappa_V : 2\%$ [ATLAS, CMS (2013)]

- ILC w/ $\sqrt{s} = 250$ GeV $L = 2 \text{ ab}^{-1}$

$\Delta\kappa_V : 0.6\%$ [Durieux et al. (2017)]

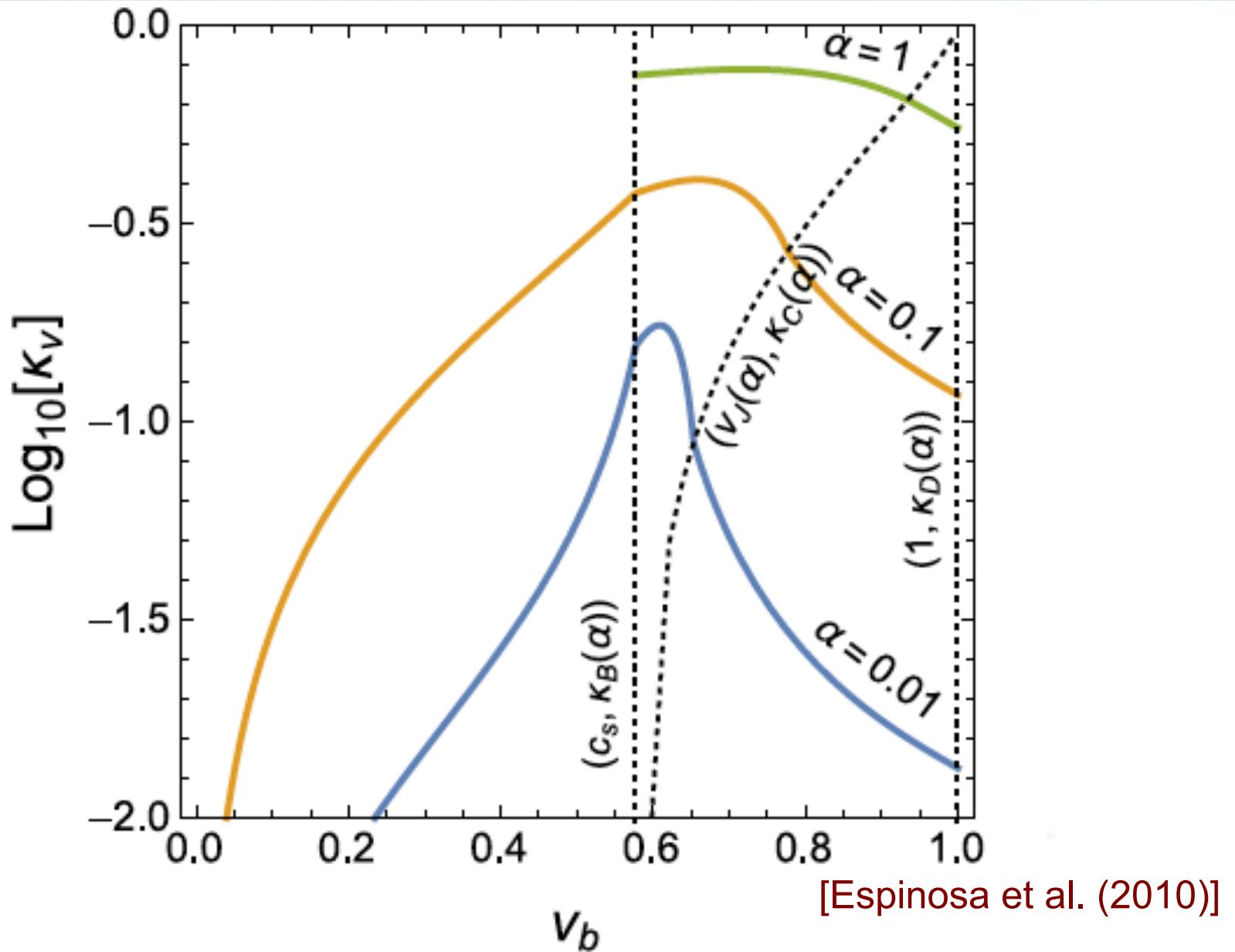
- ILC w/ $\sqrt{s} = 1$ TeV $L = 5 \text{ ab}^{-1}$

$\Delta\lambda_{hhh} : 10\%$ [Fujii et al. (2015)]



The synergy between the Higgs boson coupling measurements and GW observations is important for the HSM Higgs potential

Efficiency factor



Landau pole in CSI model

- Large scalar couplings at the EW scale
→ Landau pole near the EW scale

N	1	4	12	60
Q	381 GeV	257 GeV	188 GeV	119 GeV
$\Lambda(\lambda_S = 0)$	5.4 TeV	17 TeV	28 TeV	33 TeV
$\Lambda(\lambda_S = 0.1)$	5.3 TeV	16 TeV	23 TeV	13 TeV
$\Lambda(\lambda_S = 0.2)$	5.2 TeV	15 TeV	19 TeV	5.4 TeV
$\Lambda(\lambda_S = 0.3)$	5.0 TeV	14 TeV	15 TeV	2.7 TeV

[Hashino, MK, Kanemura, Matsui
(2016)]

LISA design

[Caprini et al (2015)]

Name	C1	C2	C3	C4
Full name	N2A5M5L6	N2A1M5L6	N2A2M5L4	N1A1M2L4
# links	6	6	4	4
Arm length [km]	5M	1M	2M	1M
Duration [years]	5	5	5	2
Noise level	N2	N2	N2	N1