

# Probing physics behind the electroweak symmetry breaking at future gravitational wave interferometers and future collider experiments

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- References:
  - MK, Kanemura, Matsui, PRD92, no.11,115007 (2015), arXiv:1509.08394
  - Hashino, MK, Kanemura, Matsui, PRD94, no.1, 015005 (2016), arXiv:1604.02069
  - Hashino, MK, Kanemura, Ko and Matsui, arXiv:1609.00297

# 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

## The Higgs sector is still vague

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

## Phenomena beyond the SM (BSM) reported

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

## 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) and Higgs boson couplings

## Sakharov's conditions for BAU

1<sup>st</sup> OPT

1. Baryon number violation ← Sphaleron
2. C and CP violation ← Extended Higgs sector
3. Departure from thermal equilibrium

Strongly first order phase transition  
(1<sup>st</sup> OPT):  $\varphi_c/T_c \gtrsim 1$

## SM Higgs sector w/ one doublet:

- Electroweak phase transition (EWPT) is NOT of 1<sup>st</sup> order for  $m_h = 125$  GeV  
e.g. Two Higgs doublet model (2HDM)

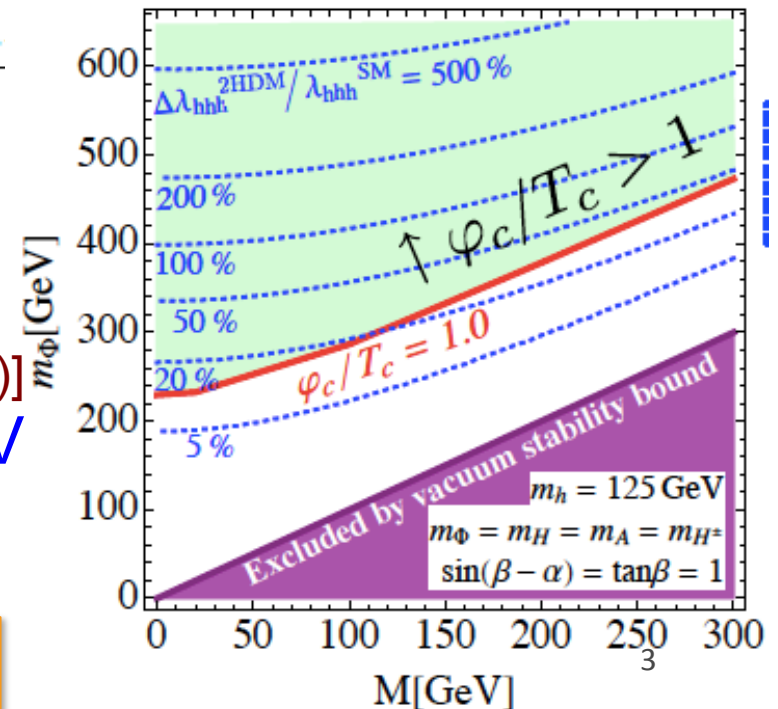
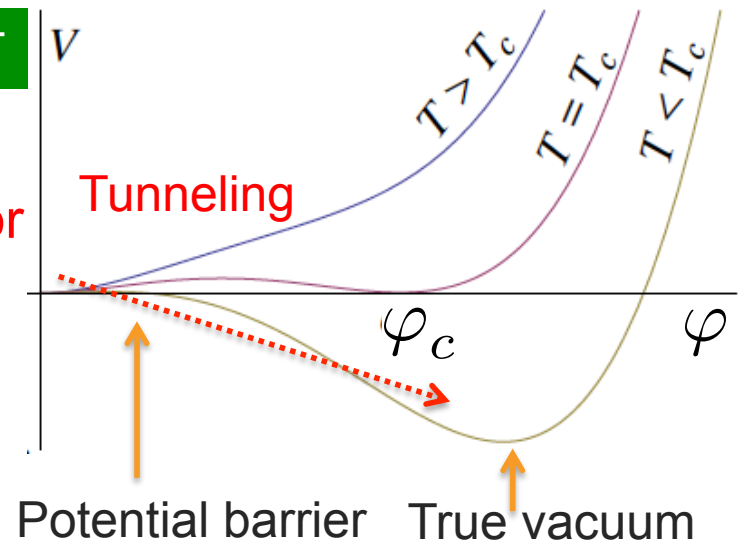
$$\varphi_c/T_c \gtrsim 1 \longrightarrow \Delta\lambda_{hhh}/\lambda_{hhh}^{\text{SM}} \gtrsim 10\%$$

[Kanemura, Okada, Senaha (2005)]

International Linear Collider (ILC) 1 TeV  
can measure  $\lambda_{hhh}$  at 10% accuracy

[Fujii et al. (2015)]

EWBG can be tested at future colliders



# Gravitational waves (GWs) as a probe of EWPT

## Ground-based interferometers (aLIGO, KAGRA, aVirgo)

- Targets: GWs from binary systems, supernovae, ...

- aLIGO made the first direct observation of GWs

➡ New era of GW astronomy [LIGO and Virgo (2016)]

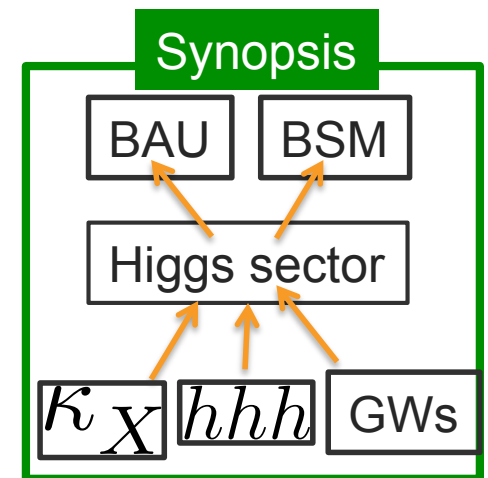
## Future space-based interferometers (eLISA, DECIGO, BBO)

- Sensitive to GWs from the early Universe  
(Strongly 1<sup>st</sup> OPT, cosmic inflation, ...)

➡ New era for fundamental physics

## Goal of our work:

- To investigate testability of models of EWSB using the synergy between the measurements of the GWs, Higgs boson couplings  $\kappa_X$  and the  $hhh$  coupling



# Model 1: Models with additional singlet scalars (without CSI)

Idea:

[MK, Kanemura, Matsui (2015)]

- To generally handle strongly 1<sup>st</sup> 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:  $V_0(\Phi, \vec{S}) = V_{\text{SM}}(\Phi) + \frac{\mu_S^2}{2} |\vec{S}|^2 + \frac{\lambda_S}{4} |\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2} |\Phi|^2 |\vec{S}|^2$

Singlet scalar boson mass:  $m_S^2 = \mu_S^2 + \frac{\lambda_{\Phi S}}{2} v^2$

Triple Higgs boson coupling:

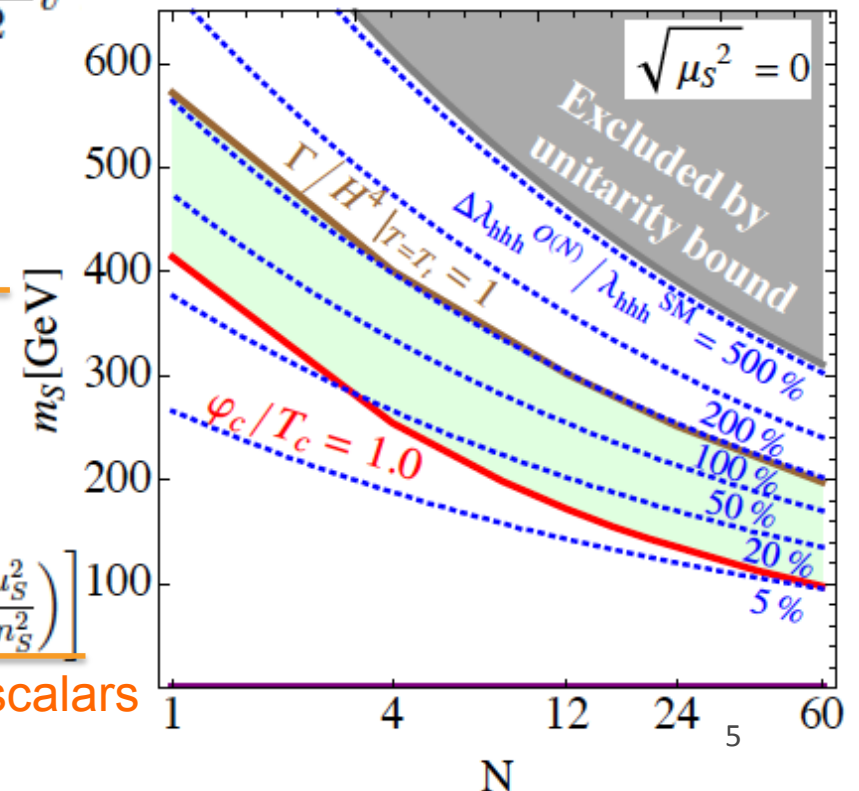
$$\lambda_{hhh}^{O(N)} = \frac{3m_h^2}{v} \left\{ 1 - \frac{1}{\pi^2} \frac{m_t^4}{v^2 m_h^2} + \frac{N}{12\pi^2} \frac{m_S^4}{v^2 m_h^2} \left( 1 - \frac{\mu_S^2}{m_S^2} \right)^3 \right\}$$

Finite temperature effective potential (high temperature expansion):

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

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

Non decoupling loop effect from additional scalars



# Model 2: 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

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

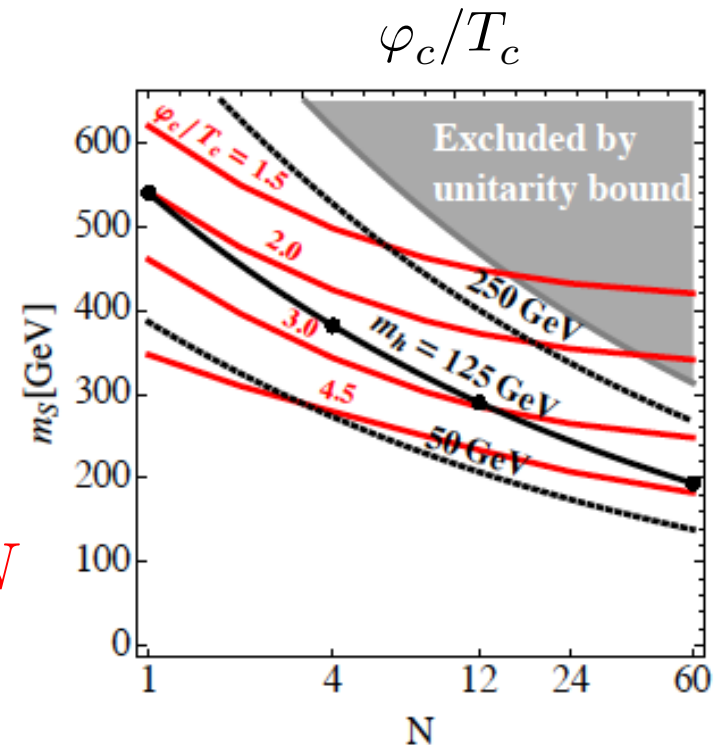
Singlet scalar boson mass

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

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)]



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

# Model 3: Higgs singlet model

## Idea

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

- To investigate EWPT caused by Higgs boson mixing by taking the extended model with a singlet Higgs boson  $S$

## Tree-level Higgs potential

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

## Higgs boson couplings to SM particles $\kappa_X = \frac{g_{hXX}}{g_{hXX}|_{\text{SM}}}$

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

## Triple Higgs boson couplings (effective potential approach)

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

## Finite temperature effective potential

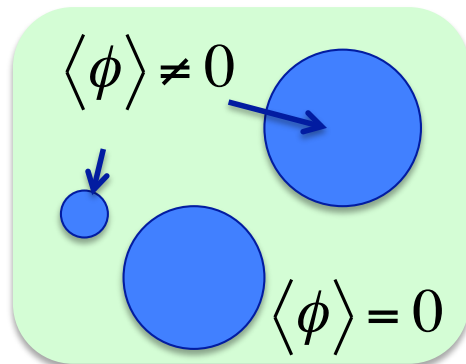
(high temperature expansion; one field approximation)

$$V_{\text{eff}} = D(T^2 - T_0^2)\varphi^2 - (ET - e)\varphi^3 + \frac{\lambda(T)}{4}\varphi^4 \quad \longrightarrow \quad \frac{\varphi_c}{T_c} = \frac{2E}{\lambda} \left(1 - \frac{e\lambda}{ET}\right)$$

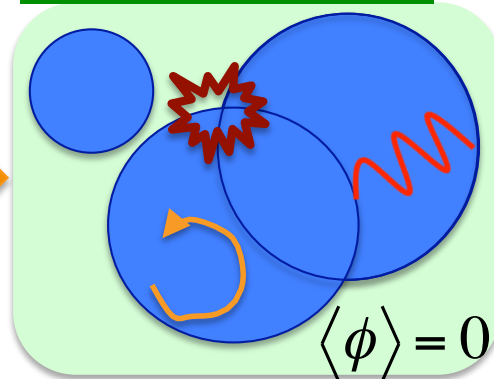
Effects from the Higgs boson mixing

# Important quantities for GW spectrum

## Bubble nucleation



## Bubbles collision



## Sources of GWs

1. Collision of bubble walls
  2. Compression wave of plasma
  3. Plasma turbulence
- GW spectrum is derived from finite temperature effective potential  $V_{\text{eff}}$

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  $T_t$  :  $\left. \frac{\Gamma}{H^4} \right|_{T=T_t} \simeq 1 \quad \longrightarrow \quad \frac{S_3(T_t)}{T_t} = 4 \ln(T_t/H_t) \simeq 140$

Released false vacuum energy (Latent heat)

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

Inverse of the duration of phase transition

$$\beta = - \left. \frac{dS_E}{dt} \right|_{t=t_t} \simeq \frac{1}{\Gamma} \left. \frac{d\Gamma}{dt} \right|_{t=t_t} \quad \text{Normalized parameter: } \tilde{\beta} = \frac{\beta}{H_t}$$

# GW spectrum

- Complicated numerical simulations are necessary
- Approximate fitting formula are available [Caprini et al. (2015)]

Collision of bubble walls (Envelope approximation):

$$\tilde{\Omega}_{\text{env}} h^2 \simeq 1.67 \times 10^{-5} \times \left( \frac{0.11 v_b^3}{0.42 + v_b^2} \right) \tilde{\beta}^{-2} \left( \frac{\kappa_\phi \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*^t} \right)^{1/3}$$
$$\tilde{f}_{\text{env}} \simeq 1.65 \times 10^{-5} \text{ Hz} \times \left( \frac{0.62}{1.8 - 0.1 v_b + v_b^2} \right) \tilde{\beta} \left( \frac{T_t}{100 \text{ GeV}} \right)$$

Sound waves (Compression waves of thermal plasma):

$$\tilde{\Omega}_{\text{sw}} h^2 \simeq 2.65 \times 10^{-6} v_b \tilde{\beta}^{-1} \left( \frac{\kappa_v \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*^t} \right)^{1/3} \quad \tilde{f}_{\text{sw}} \simeq 1.9 \times 10^{-5} \text{ Hz} \frac{1}{v_b} \tilde{\beta} \left( \frac{T_t}{100 \text{ GeV}} \right)$$

Magnetohydrodynamic (MHD) turbulence:

$$\tilde{\Omega}_{\text{turb}} h^2 \simeq 3.35 \times 10^{-4} v_b \tilde{\beta}^{-1} \left( \frac{\epsilon \kappa_v \alpha}{1 + \alpha} \right)^{3/2} \left( \frac{100}{g_*^t} \right)^{1/3} \quad \tilde{f}_{\text{turb}} \simeq 2.7 \times 10^{-5} \text{ Hz} \frac{1}{v_b} \tilde{\beta} \left( \frac{T_t}{100 \text{ GeV}} \right)$$

- $v_b$  : wall velocity
- $\kappa_\phi$  ,  $\kappa_v$  and  $\epsilon = 0.05$  : efficiency factors

# Model A vs. Model B: Predicted values of $\alpha$ and $\tilde{\beta}$ in models with singlet scalars with and without CSI

- Condition for strongly 1<sup>st</sup> OPT

➔ Constraints on  $\alpha$  and  $\tilde{\beta}$  for each model

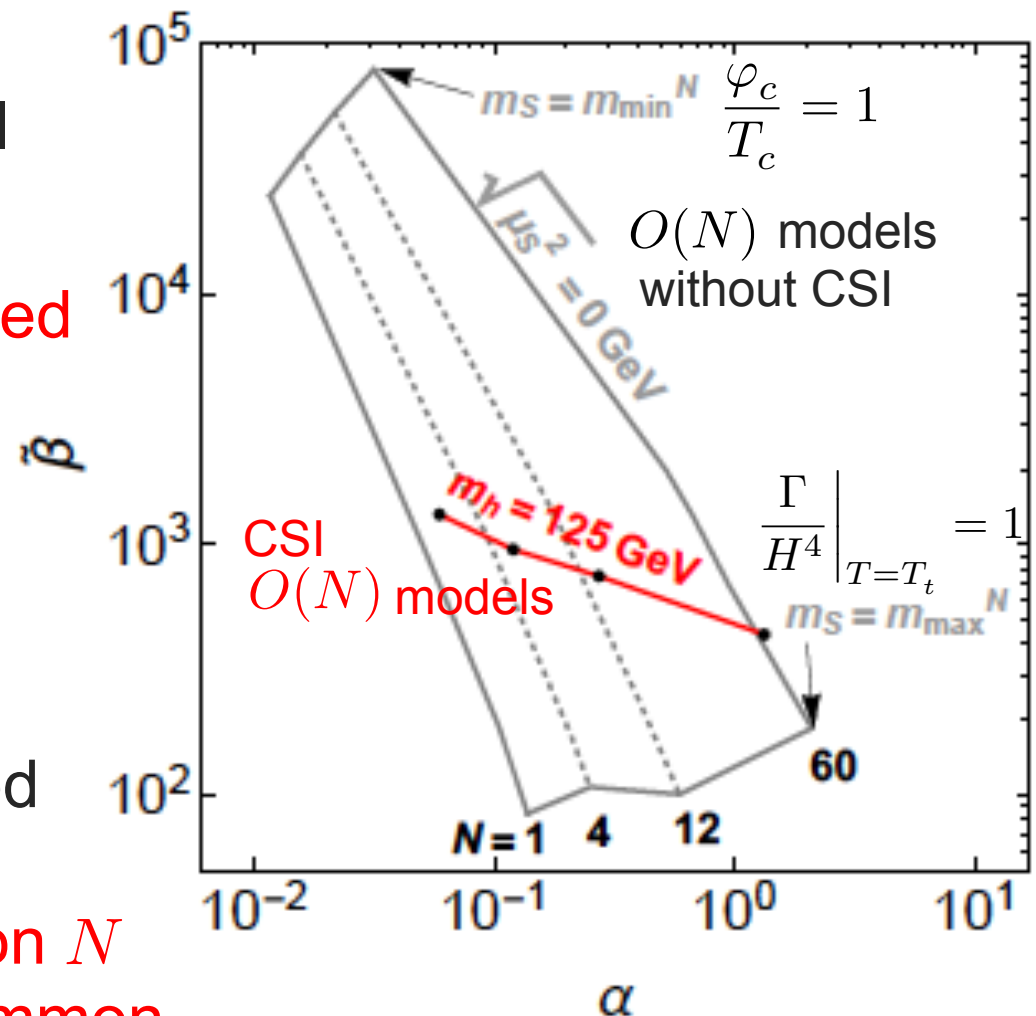
## $O(N)$ models without CSI

- $\alpha$  and  $\tilde{\beta}$  to be determined by GW observation are useful measures in determining  $N$  and  $m_S$

## CSI $O(N)$ models

- Scale invariance is violated at finite temperatures

➔  $\alpha$  and  $\tilde{\beta}$  depend on  $N$  though  $\lambda_{hhh}$  is common



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

# Testability of models with additional singlet scalars with and without CSI

- What if the  $h h h$  coupling is found to be

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

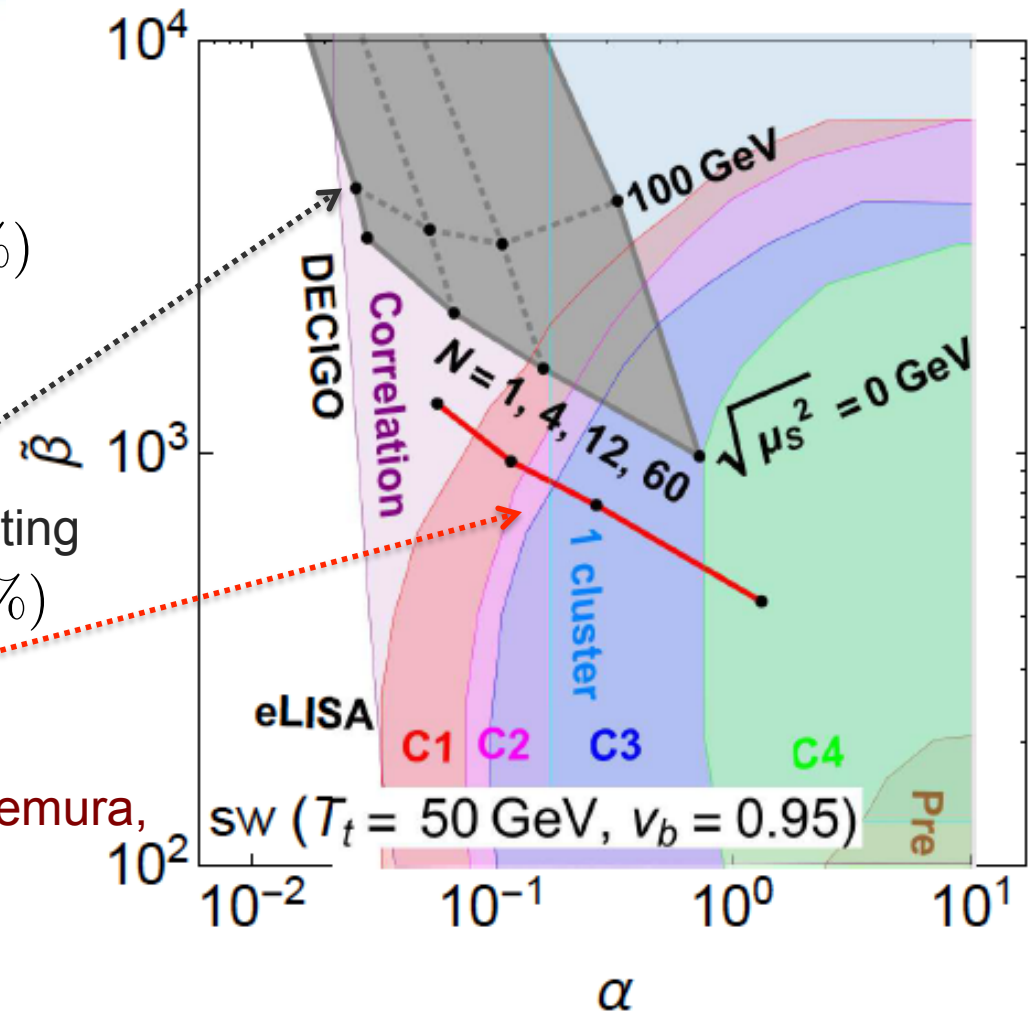
at future colliders?

- $O(N)$  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  $h h h$  coupling

# Testability of the Higgs singlet model

## Benchmark point

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

$v_\Phi$ [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]

- Implemented into CosmoTransitions  
[Wainwright (2012)]

## 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)]

- High-Luminosity LHC

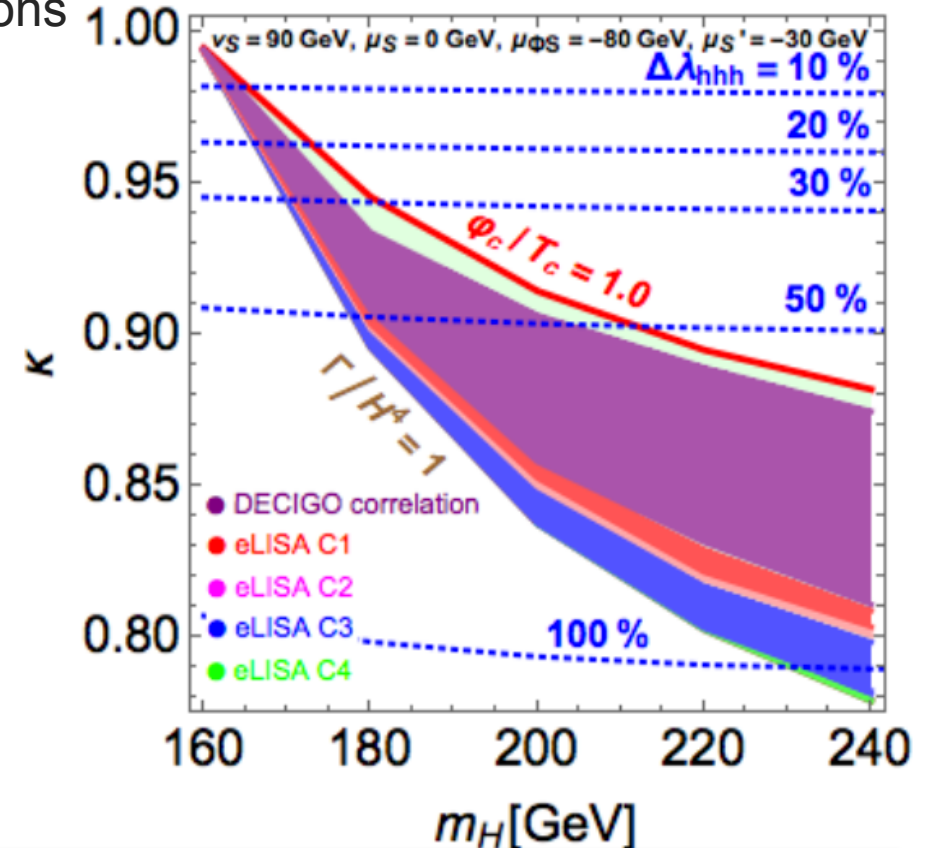
$$\kappa_V : 2\% \quad [\text{CMS (2013)}]$$

- ILC w/  $\sqrt{s} = 500$  GeV

$$\kappa_Z : 0.37\% \quad \kappa_W : 0.51\%$$

- ILC w/  $\sqrt{s} = 1$  TeV

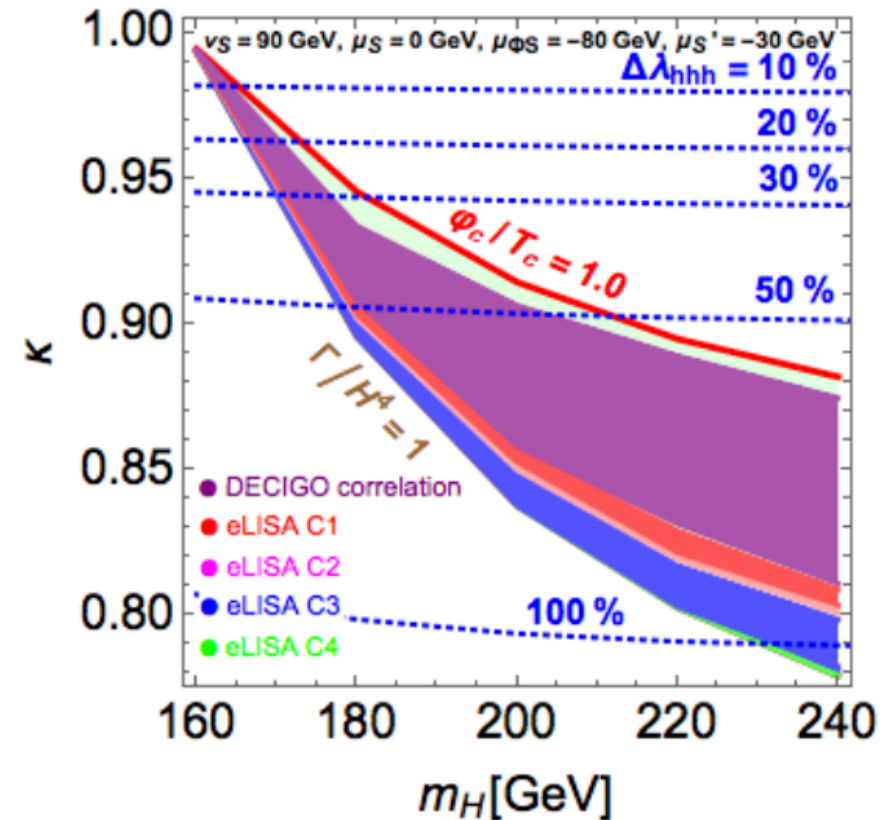
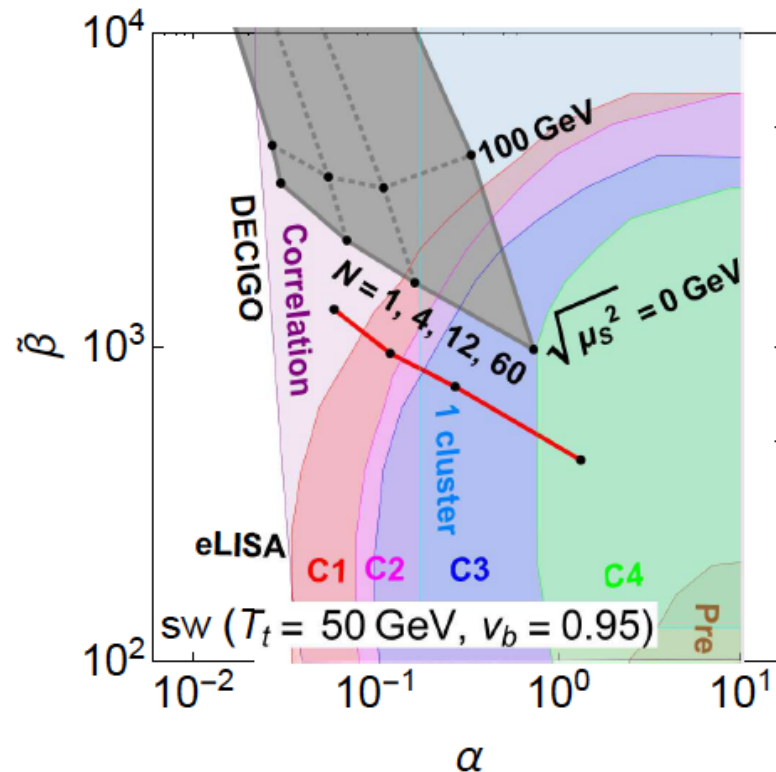
$$\Delta\lambda_{hhh} : 10\% \quad [\text{Fujii et al. (2015)}]$$



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

# Summary

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



- The strongly 1stOPT of the EWSB in extended Higgs sectors can be tested by the synergy of the measurements of Higgs boson couplings at the LHC, the  $hhh$  coupling at the ILC and GWs at future space-based interferometers

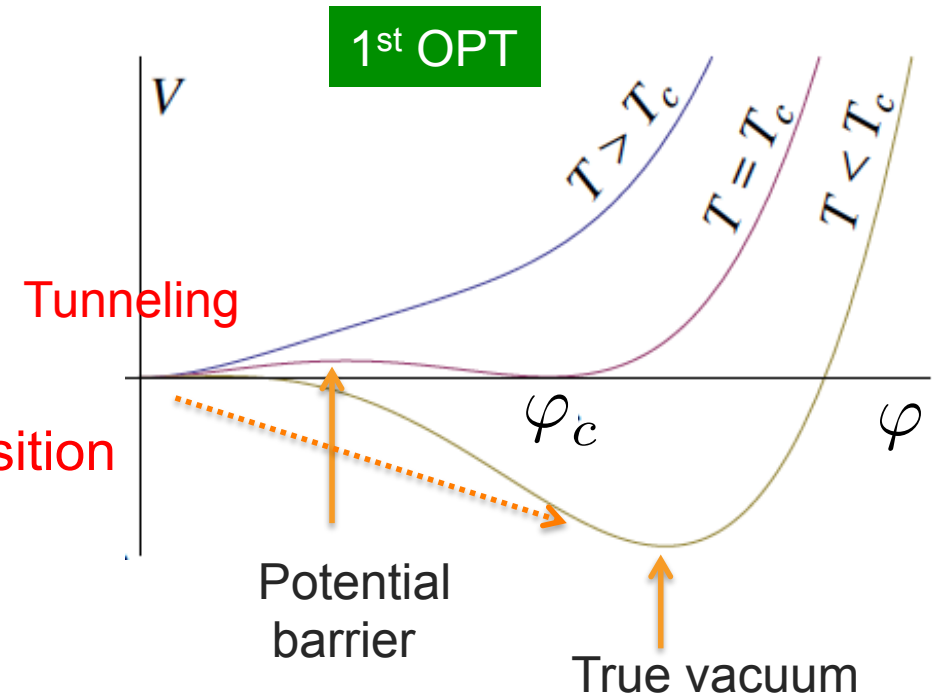
# Backup slides

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# Electroweak baryogenesis (EWBG) and Higgs boson couplings

## Sakharov's conditions for BAU

1. Baryon number violation  
    ↑ Sphaleron process
2. Violation of C and CP  
    ↑ Extended Higgs sector
3. Departure from thermal equilibrium  
    ↑ Strongly first order phase transition  
    (1<sup>st</sup> OPT):  $\varphi_c/T_c \gtrsim 1$



## SM Higgs sector w/ one doublet:

- Electroweak phase transition (EWPT) is NOT of 1<sup>st</sup> order for  $m_h = 125$  GeV

EWBG is an important physics case relating the Higgs sector to BSM phenomena

# Strongly 1<sup>st</sup> OPT and Higgs boson couplings

Models with extended Higgs sector

- 1<sup>st</sup> OPT is easily realized
- Signatures are testable at colliders

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

- Condition for strongly 1<sup>st</sup> OPT:

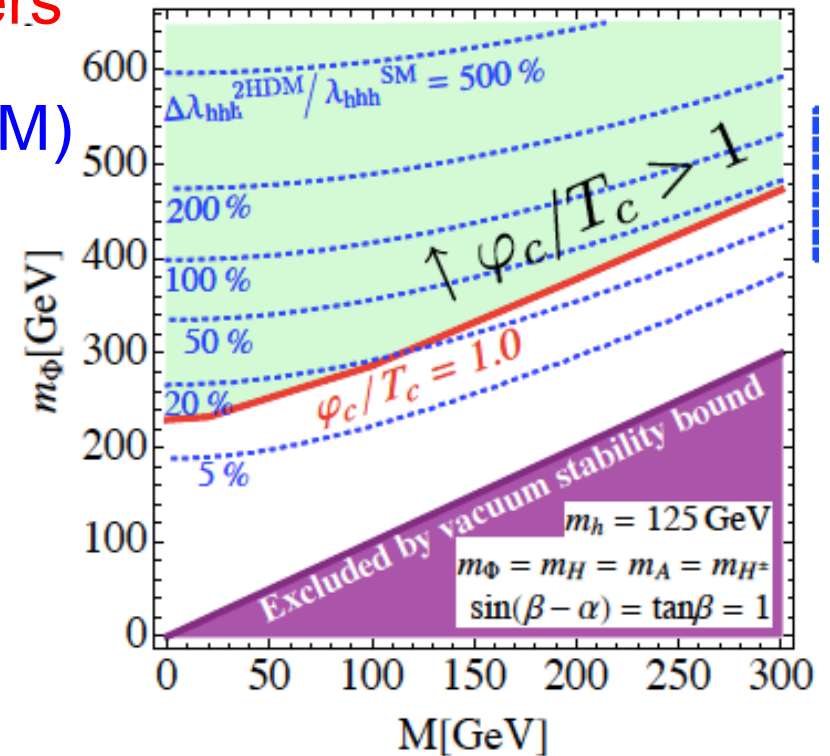
$$\varphi_c/T_c \gtrsim 1$$

➡ Large deviation in the triple Higgs boson coupling

$$(\Delta\lambda_{hhh}/\lambda_{hhh}^{\text{SM}} \gtrsim 10\%)$$

ILC 1 TeV can measure  $\lambda_{hhh}$   
at 10% accuracy [Fujii et al. (2015)]

EWBG can be tested at future colliders



[Kanemura, Okada,  
Senaha (2005)]

# Studies on the GWs from 1<sup>st</sup> order EWPT

## Model independent analysis

[Grojean, Servant (2007); Kikuta, Kohri, So (2014), ...]

## Higgs potential with higher order operators

[Delaunay, Grojean, Wells (2008); Huang, Wan, Wang, Cai, Zhang (2016), ...]

## Non-decoupling loop effects from hypothetical particles

- Light stop loop effects in the MSSM [Apreda, Maggiore, Nicolis, Riotto (2002), ...] n.b. Light stops are excluded by LHC

- Additional scalar loop effects

[MK, Kanemura, Matsui (2015); Hashino, MK, Kanemura, Matsui (2016), ...]

## Non-thermal effects even at the tree level

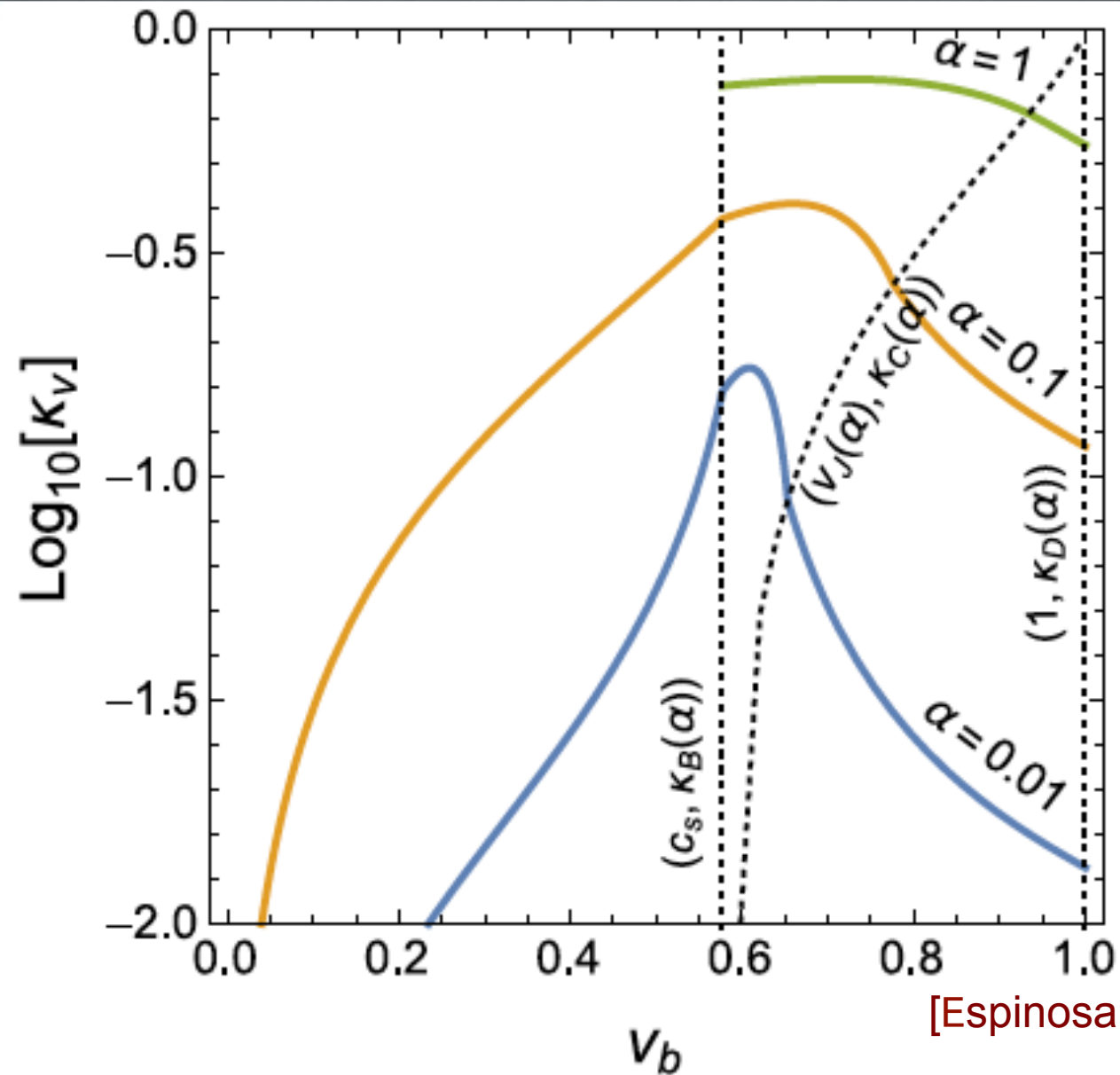
- Next-to-MSSM [Apreda, Maggiore, Nicolis, Riotto (2002), Huber, Konstandin, Nardini, Rues (2015), ...]

- Real singlet extension ← Today's topic

[Huang, Long, Wang (2016); Hashino, MK, Kanemura Ko, Matsui (2016), ....]

## Large GW signals compatible with EWBG: [No (2011), ...]

# Efficiency factor



[Espinosa et al. (2010)]

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

- Effective potential:

[MK, Kanemura, Matsui (2015)]

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

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

Non decoupling loop effect from additional scalars

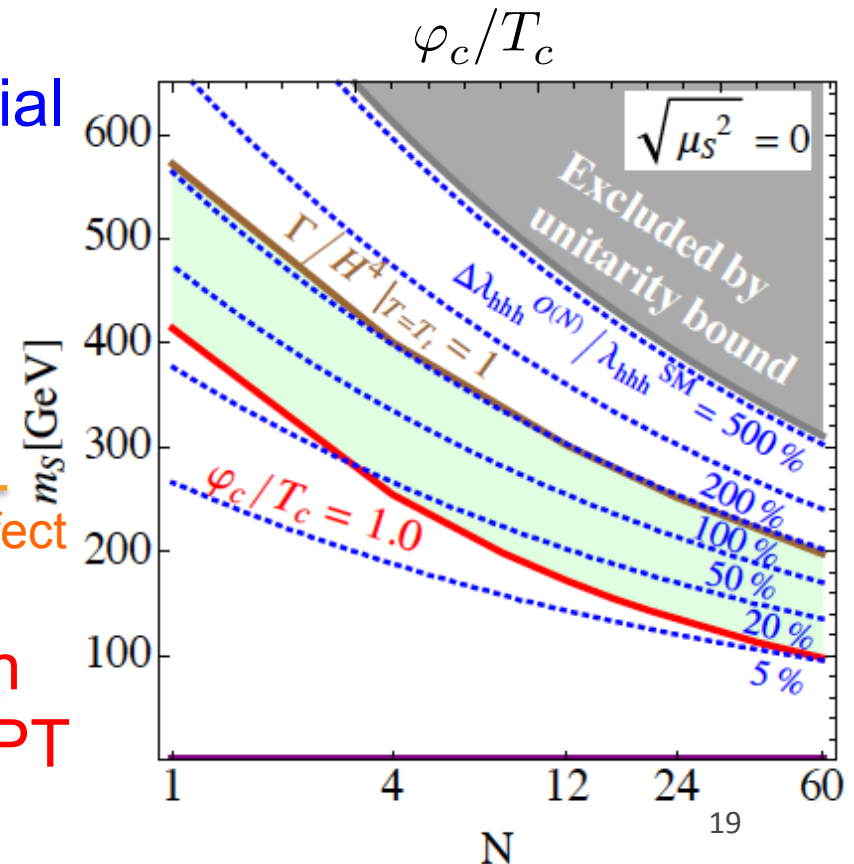
- Finite temperature effective potential (high temperature expansion):

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

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

Non decoupling loop effect from additional scalars

$\longrightarrow$  Typically  $\mathcal{O}(10)\%$  deviation in  $\lambda_{hhh}$  for strongly 1<sup>st</sup> OPT



# GW spectrum in CSI $O(N)$ models

- Contribution to GWs:

- Collision: ..... (dotted line)
- Sound wave: ——— (solid line)
- MHD Turbulence: - - - - (dashed line)

- Benchmark points:

$$N = 1, 4, 12, 60$$

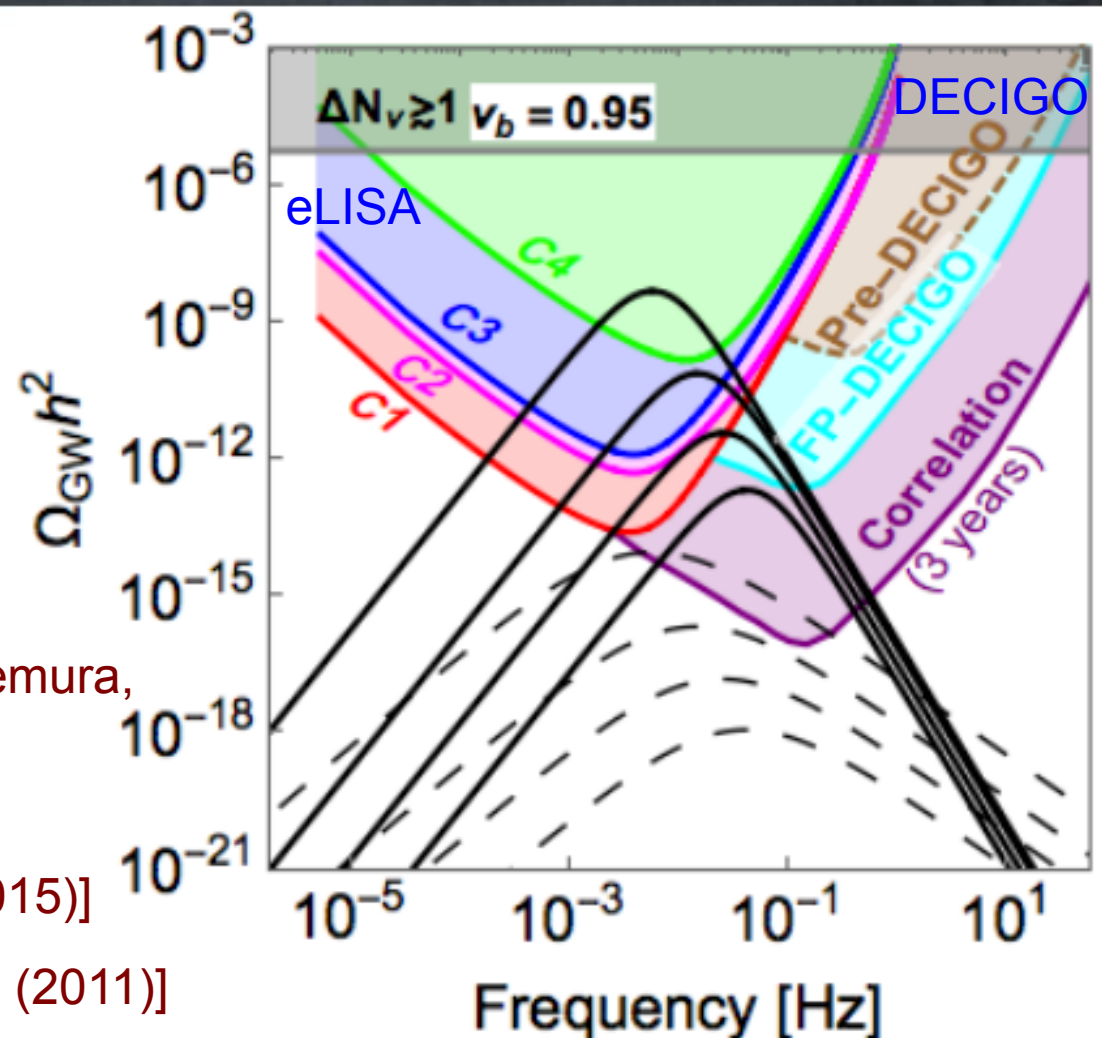
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[Hashino, MK, Kanemura,  
Matsui (2016)]

- Experimental prospects:

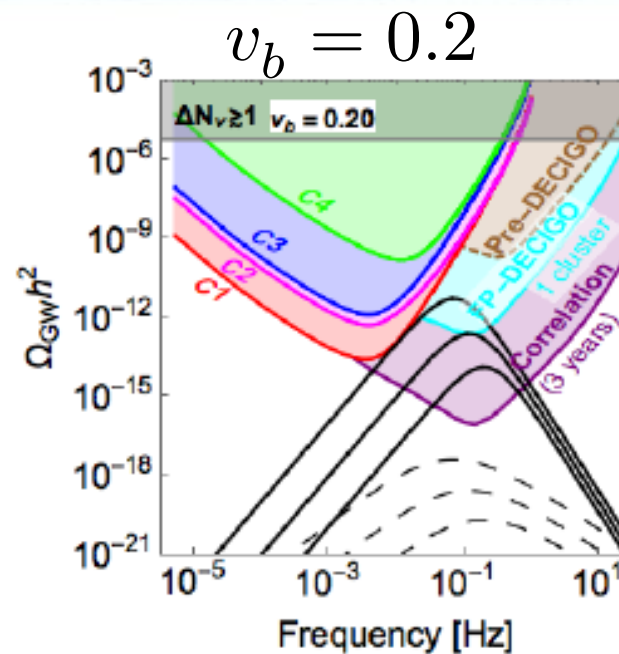
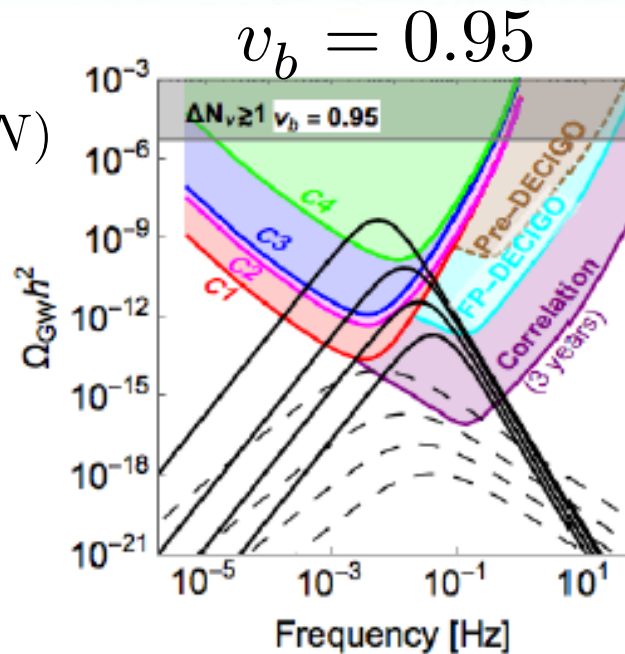
- eLISA: [Caprini et al. (2015)]
- DECIGO: [Kawamura et al. (2011)]

- Contribution from sound waves is dominant and detectable at future space-based interferometers, eLISA and DECIGO



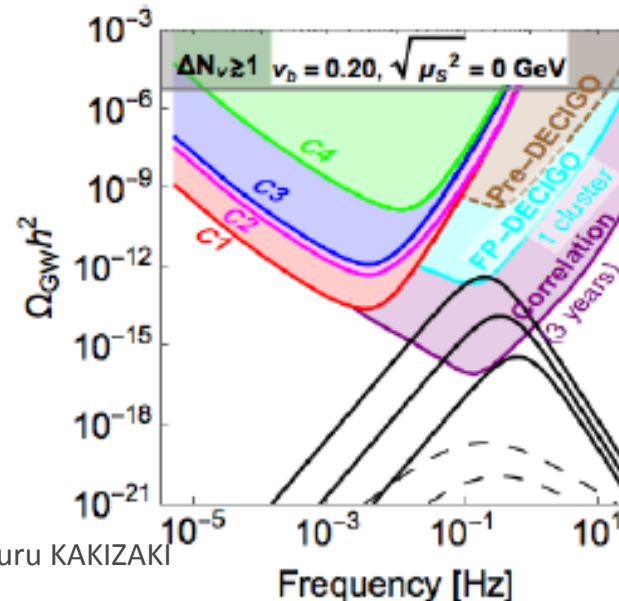
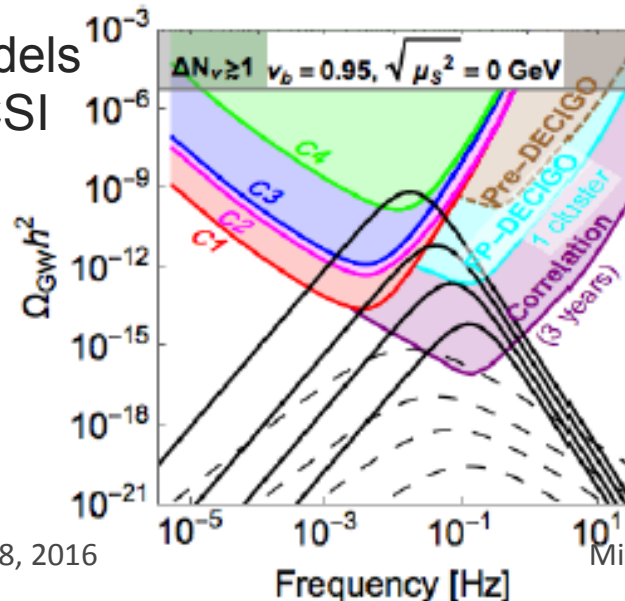
# Comparison of GW spectra

- CSI  $O(N)$  models



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

- $O(N)$  models without CSI  
 $\sqrt{\mu_S^2} = 0$



- N.B. subsonic wall velocity is preferred for EWBG but not necessarily  
[No (2011)]

# GW spectrum for $v_b = 1$

- Case of accelerating wall:

- For large  $\alpha$ , the bubble wall can accelerate without reaching a terminal velocity

- Contribution to GWs:

- Collision: .....  $\Omega_{\text{GW}} h^2$
- Sound wave: ———
- MHD Turbulence: - - - -

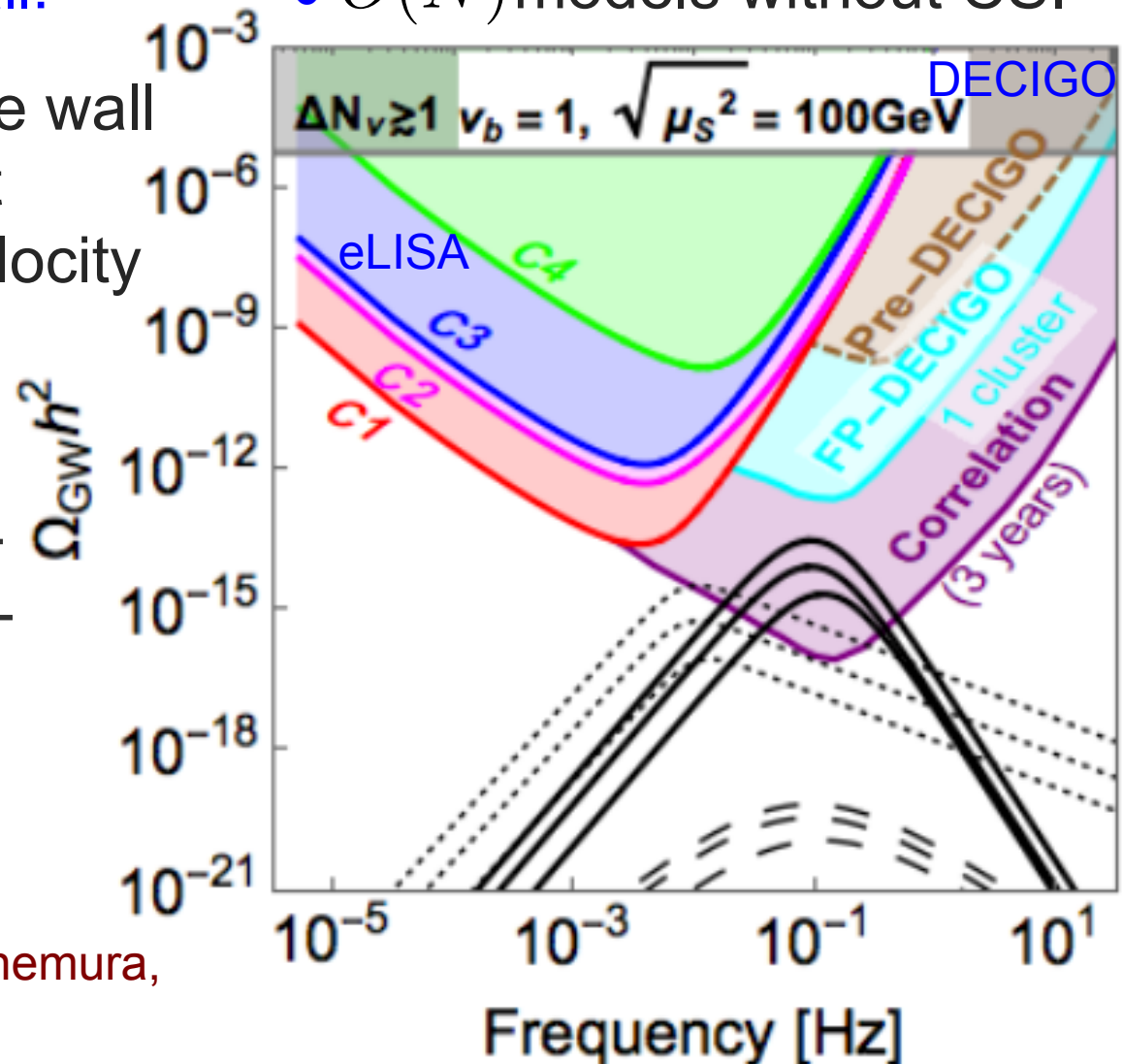
- Benchmark points:

$$N = 4, 12, 60$$

from the bottom

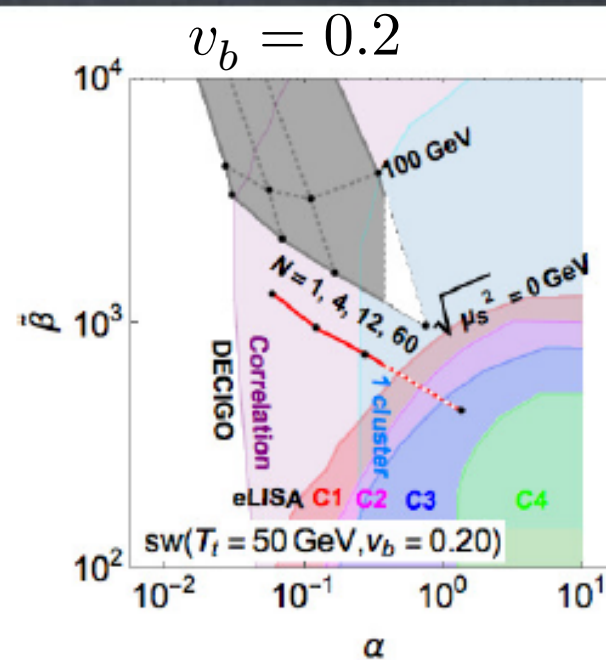
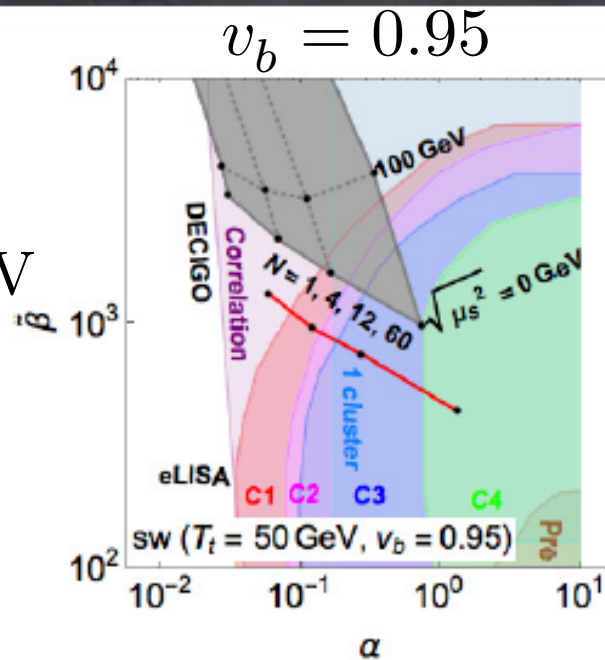
[Hashino, MK, Kanemura,  
Matsui (2016)]

- $O(N)$  models without CSI



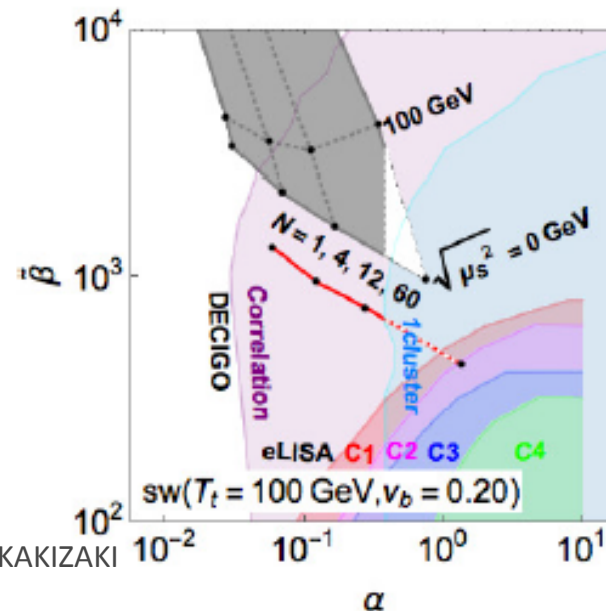
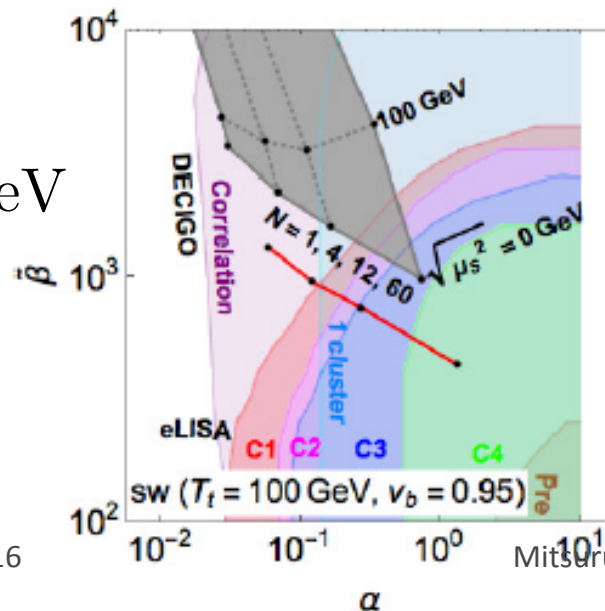
# Transition temperature and wall velocity dependence of detectability of GWs

$T_t = 50 \text{ GeV}$



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

$T_t = 100 \text{ GeV}$



# Predicted values of $\alpha$ and $\tilde{\beta}$

## Numerical results based on the two-field analysis

- Benchmark point

$v_\Phi$ [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]

- Condition for strongly 1<sup>st</sup> OPT

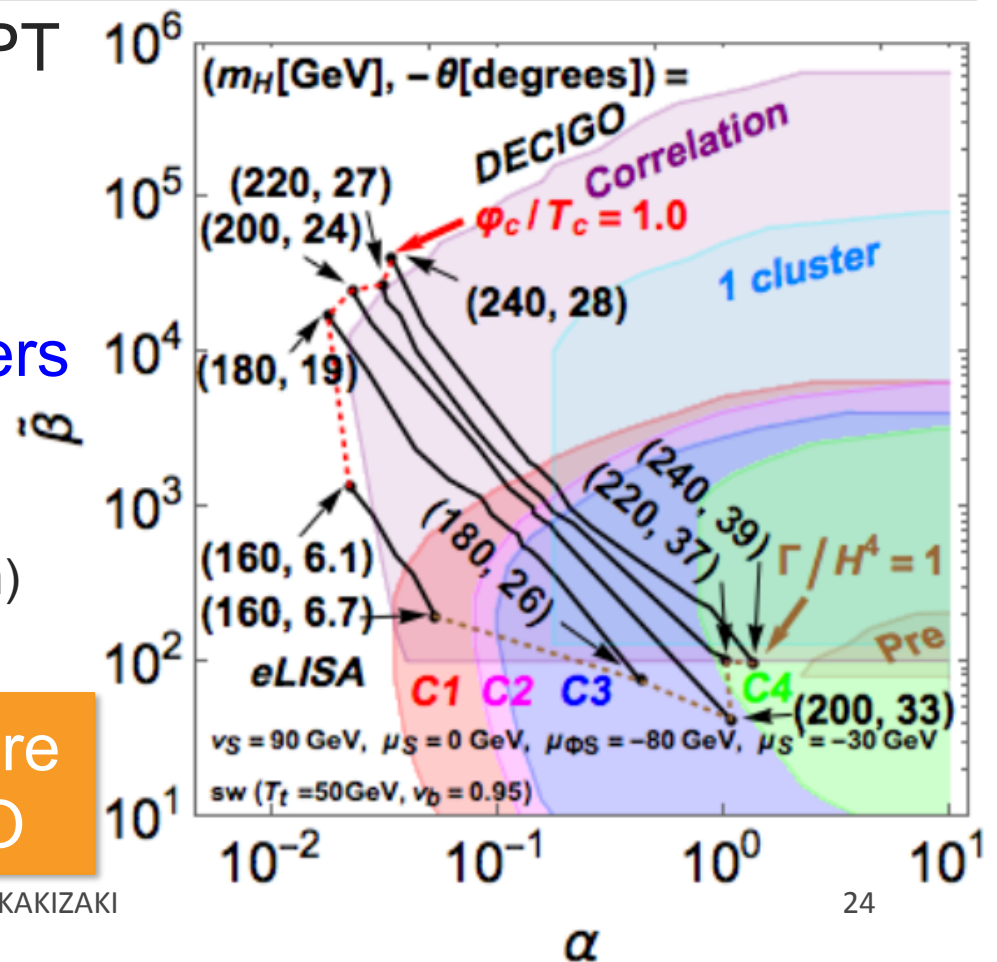
➔ Constraints on  $\alpha$  &  $\tilde{\beta}$

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

## Prospects of future interferometers

- eLISA (C1, C2, C3, C4):  
[Caprini et al. (2015)]
- DECIGO (Pre, 1 cluster, Correlation)  
[Kawamura et al. (2011)]

GWs from 1st OPT in the HSM are detectable at eLISA and DECIGO



# eLISA 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