Synergy of collider and gravitational waves to explore the Higgs sector

Shinya KANEMURA

大阪大学
OSAKA UNIVERSITY

Multi Higgs Models 2018, Sep 2-7, 2018, Lisbon

Higgs as a Probe of New Physics 2019

HPNP2019

The 4th International Workshop on
“Higgs as a Probe of New Physics”

18.-22. February 2019, Osaka University, Japan

OSAKA

International Advising Committee

Fawzi Boudjema (Annecy, LAPTH)
Christophe Grojean (DESY)
Junji Hisano (Nagoya U.)
Stefano Moretti (U. of Southampton)
Yasuhiro Okada (KEK)
Chengwei Chiang (NTU)
Howard E. Haber (UC Santa Cruz)
Pyungwon Ko (KIAS)
Mihoko Nojiri (KEK / Kavli IPMU)
Michael Peskin (SLAC)

Local Organizing Committee

Mayumi Aoki (Kanazawa U.)
Shinya Kanemura (Osaka U.), Chair
Kin-ya Oda (Osaka U.)
Hiroaki Sugiyama (Toyama Pref. U.)
Kei Yagyu (Seikei U.)
Mitsuru Kakizaki (U. of Toyama)
Kentarou Mawatari (Osaka U.)
Tetsuo Shindou (Kogakuin U.)
Koji Tsumura (Kyoto U.)

Contact

Ai Sato (Secretary)
Email : hpnp2019@het.phys.sci.osaka-u.ac.jp
URL : http://www3.u-toyama.ac.jp/theory/HPNP2019/

Introduction

Although a Higgs boson was found at LHC, the origin of EWSB remains mystery. Unlike the gauge sector, the Higgs sector is not uniquely determined from the theory.

(Dirty! Expecting a beautiful principle for EWSB behind)

There can still be many possibilities for non-minimal Higgs sectors. Phenomena beyond the SM may be related to such an extended Higgs sector

At LHC, measured production and decay of the Higgs boson are consistent with the SM predictions. SM is a good description of nature below 100 GeV.

Introduction

SM is enough?

Of course not. There are many reasons to consider BSM.

- **Hierarchy, Nature of Higgs, Strong CP, GUT, Gravity, …**
- **Dark matter, Baryogenesis, Neutrino mass, Inflation, …**

The SM Higgs sector causes the hierarchy problem. Paradigms such as SUSY have been proposed, but new particles such as SUSY particles have not been discovered yet. …

New physics must exist. But we do not know at which scale it appears. How we can approach to new physics?

Higgs sector is Key

In addition to direct searches of new particles at LHC,

we can measure Higgs couplings precisely at a Higgs factory

Precision of the measured Higgs couplings

hVV, hff, hgg, hγγ, hZγ*

10-20 % (Run 2) → several % (HL-LHC)

sub % (ILC250)

Higgs potential (remains untested)

hhh → O(100)% (HL-LHC)

→ impossible (ILC250)

→ O(10) % (ILC1TeV)

Instead of *hhh* coupling, we may use gravitational waves (GWs)

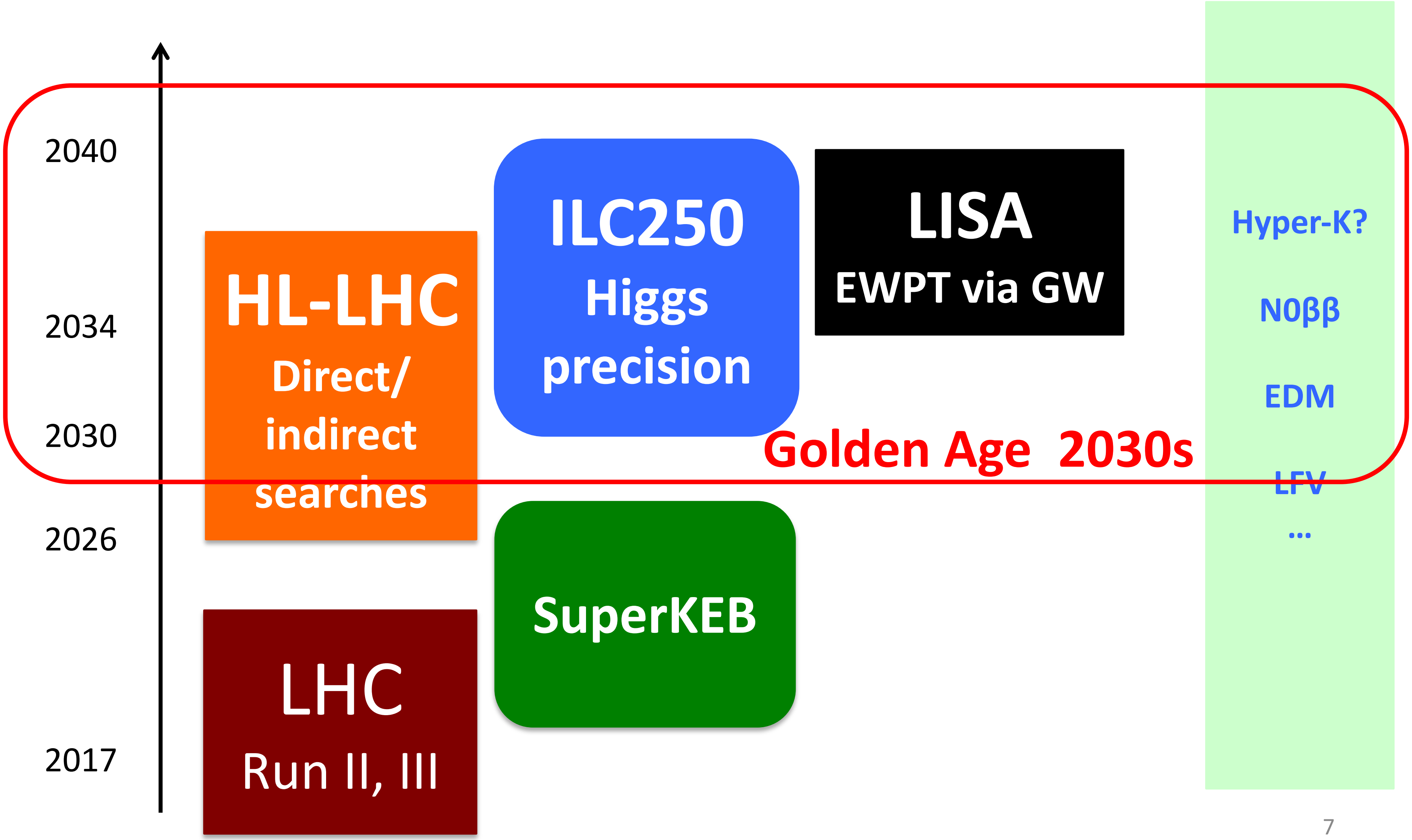
EW phase transition via GW (LISA/DECIGO/BBO)

Main Points

Slide by Hitoshi Yamamoto for the status of ILC

- ILC has been designed to lead the new era of particle physics opened up by the discovery of Higgs.
- ILC250 Higgs Factory reduces the cost by up to 40%.
- For precision Higgs measurements, ILC ~ several tens of HL-LHC running simultaneously.
- New particles: at LHC, ~1 million Higgs were produced and then discovered. At ILC, a handful will do.
- Japanese government is about to finish evaluating the case for ILC (ILC 250 Higgs Factory).
- The deadline for inputs to the European Strategy Discussion is the end of this year – important that a positive statement comes from Japanese government in that time scale.

Future experiments



2040

2034

2030

2026

2017

HL-LHC

Direct/ indirect searches

ILC250

Higgs precision

LISA

EWPT via GW

Golden Age 2030s

SuperKEB

LHC

Run II, III

Hyper-K?

N0ββ

EDM

LFV

…

Contents

Introduction (done)

Fingerprinting of extended Higgs sectors
by precision measurements

Higgs potential (GW from EW phase transition)

Physics case of probing a model using the synergy of
HL-LHC, ILC250 and LISA in 2030s

Summary

Extended Higgs sectors

Multiplet Structure (with additional scalars)

Φ_{SM}+Isospin Singlet,
Φ_{SM}+Doublet (2HDM),
Φ_{SM}+Triplet, …

Additional Symmetry

Discrete or Continuous?
Exact or Softly broken?

Interaction

Weakly coupled or Strongly Coupled?

Hint for BSM models

Era of Precision Measurement again

Direct search at LHC

reach 1-2TeV → 3 TeV (HL-LHC)

at most a factor improvement

Indirect test

10-30% → 1% (ILC, other Higgs factories)

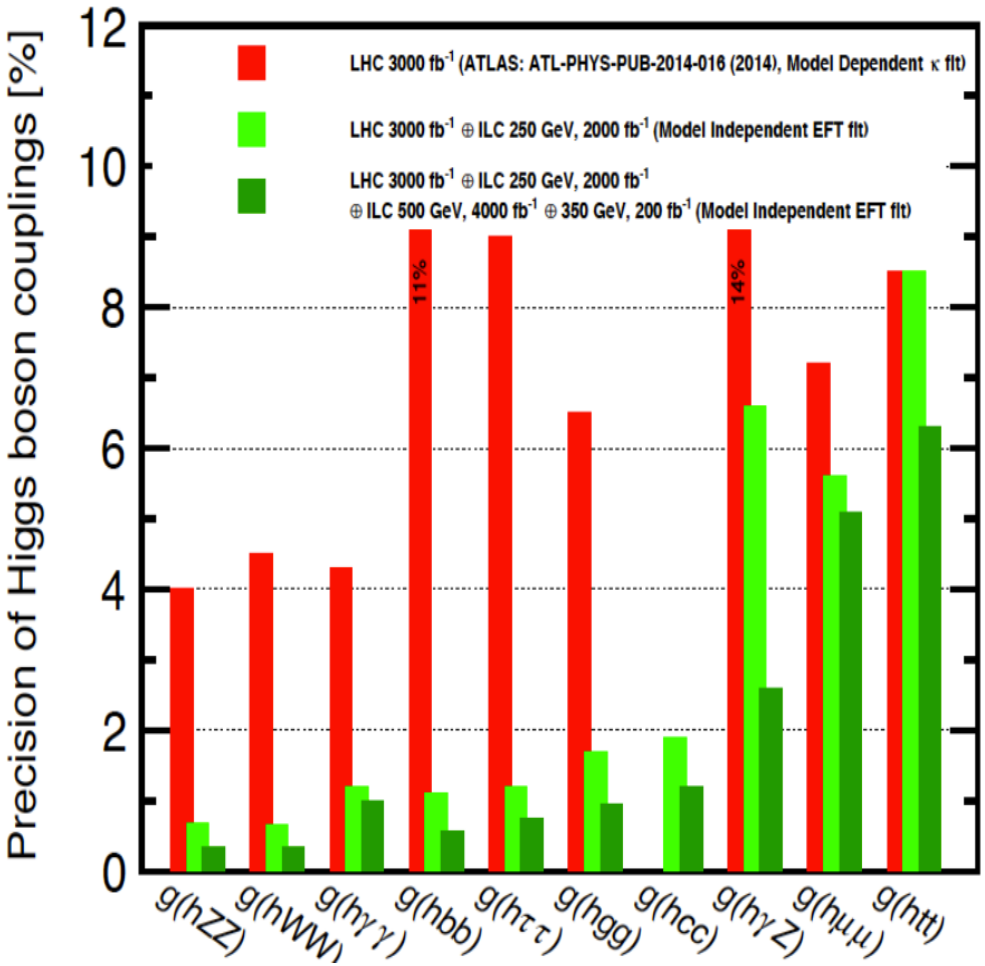
at least 1 order improvements

Higgs factory: lepton collider [ILC, CEPC, FCCee, CLIC]

With such future precision studies, we try to find deviation from SM.
Once detected, we can determine the Higgs sector
and get information for direction of new physics

Higgs Precision at HL-LHC, ILC250, …

[K. Fujii, et al., arXiv:1710.07621]



Deviation = New Physics Scale

Scaling factor κ_i : factor of deviation from the SM value

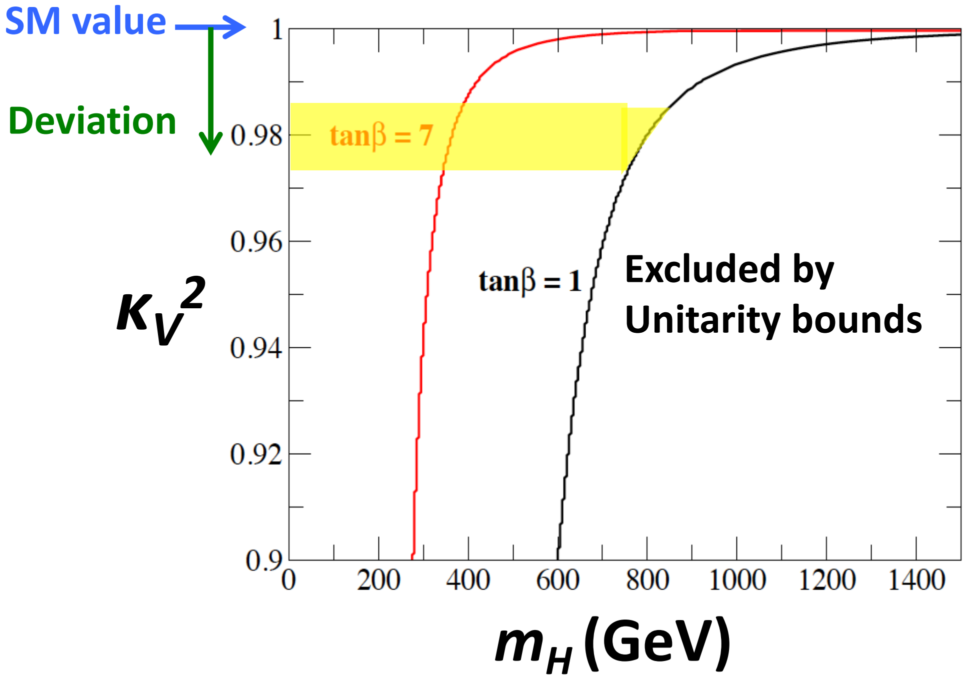
Coupling of h(125) and weak bosons
V (=W, Z) hVV

$$\kappa_V^2 = \sin^2(\beta-\alpha)$$

If a 2% deviation in κ_V^2

The second Higgs H must be lighter than 800 GeV

Ex) 2HDM



Precision test has the similar power to the direct search

Patterns of deviations

$\cos(\beta-\alpha) < 0$

	Gauge couplings	**Yukawa couplings**		
	hVV	$h\tau\tau$	hbb	hcc
	κ_V	κ_τ	κ_b	κ_c
Type-I	↓	↓	↓	↓
Type-II	↓	↑	↑	↓
Type-X	↓	↑	↓	↓
Type-Y	↓	↓	↑	↓

Direction of deviation in each coupling

We can fingerprint extended Higgs models from the pattern of deviation in Higgs couplings

SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014

Fingerprinting the model

$$\boxed{\kappa_V \equiv \frac{g_{hVV(2HDM)}}{g_{hVV(SM)}} = \sin(\beta - \alpha)}$$

$x = \cos(\beta - \alpha)$ **SM-like: $|x| \ll 1$**

$\kappa_V = 1 - (1/2)\, x^2 + \ldots$

When a Fermion couples to Φ_1

$$\kappa_f = 1 + \cot\beta\, x + \cdots$$

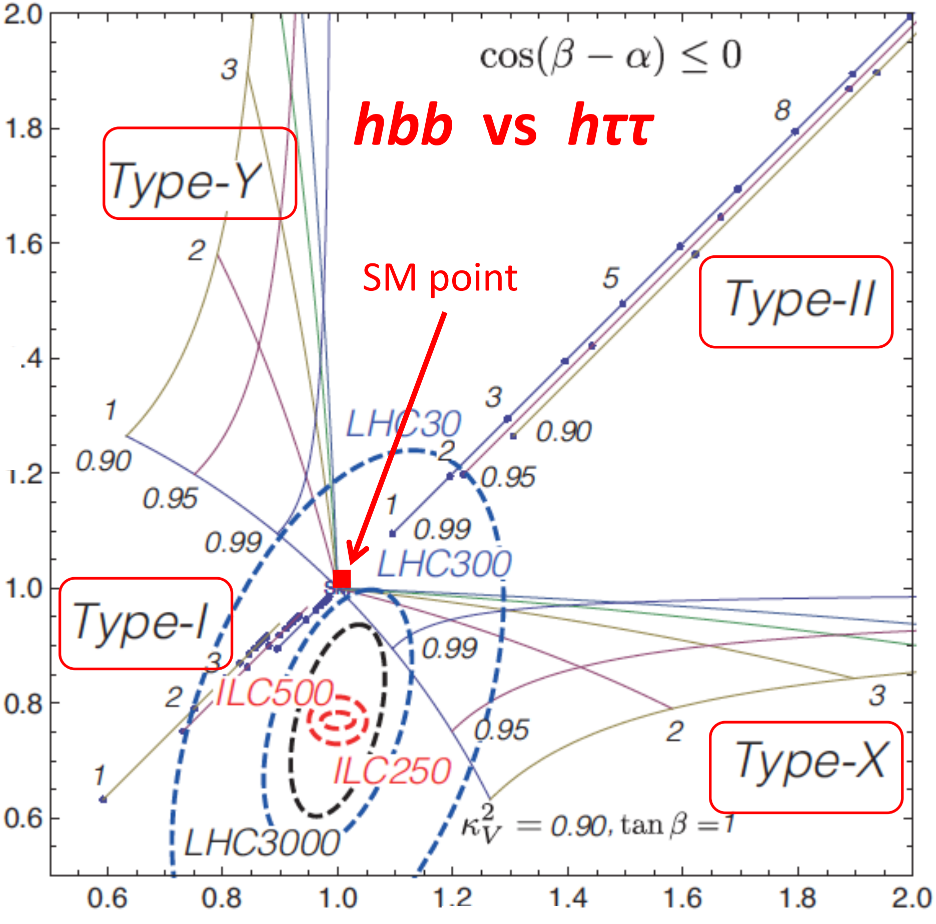
and if it couples to Φ_2

$$\kappa_f = 1 - \tan\beta\, x + \cdots$$

If deviation in κ^2_V can be large enough to be detected at future collider

4-models can be separated by looking at deviations in Yukawa couplings κ_τ, κ_b, κ_c, …

SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014



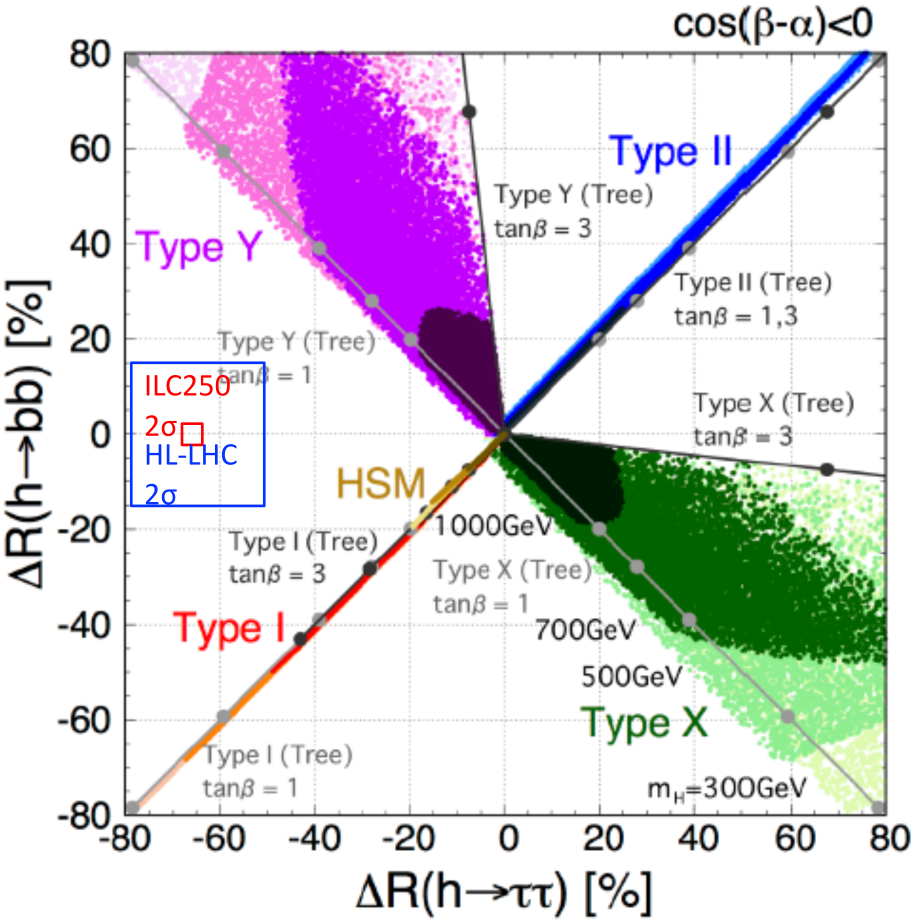
Ellipse = 68.27% CL

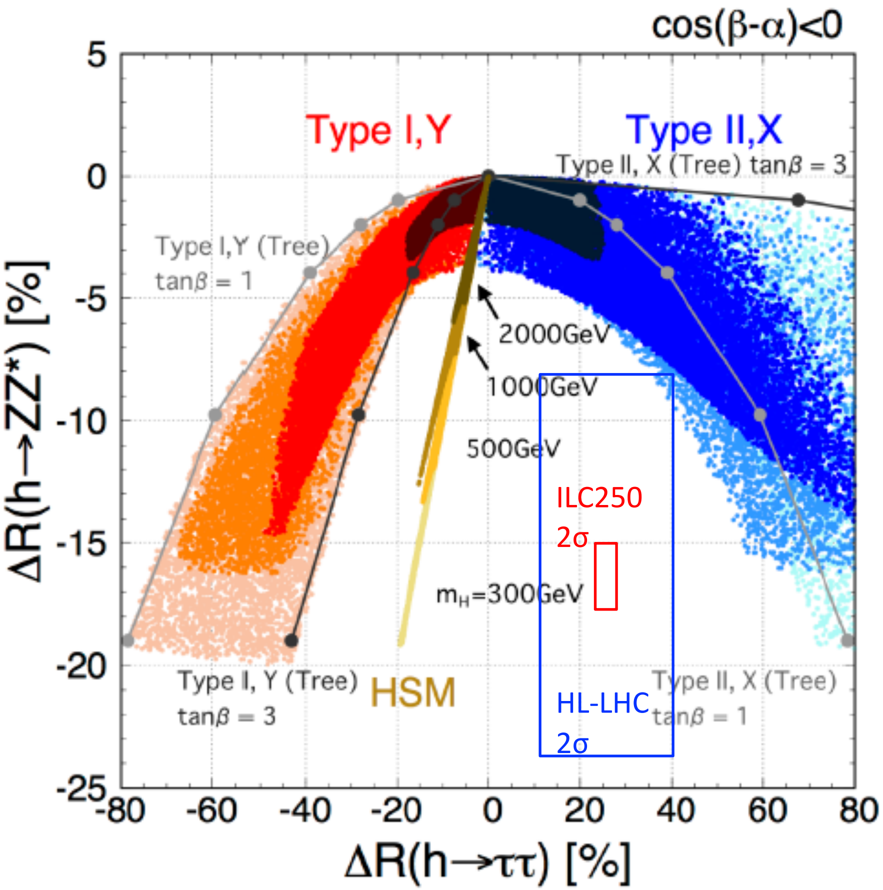
$$\Delta R(h \to XX) = \frac{\Gamma_{\mathrm{NP}}(h \to XX)}{\Gamma_{\mathrm{SM}}(h \to XX)} - 1$$

H-COUP Project

SK, Kikuchi, Mawatari, Sakurai, Yagyu 2018

See also Sakurai's talk.





Full set of 1-loop corrections (EW + QCD + Higgs) to the decay rates in various Higgs sectors and future precision measurements at ILC250 make us possible to fingerprint models and also to get information of inner parameters such as mass of the second Higgs boson

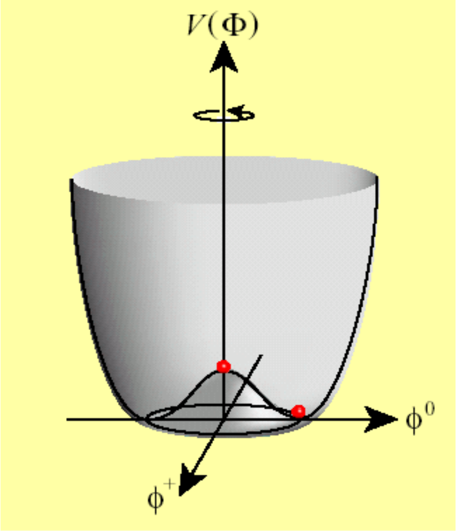
Higgs potential

Most important part for the EW symmetry breaking
(Yet to be tested)

$$V(\Phi) = +\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

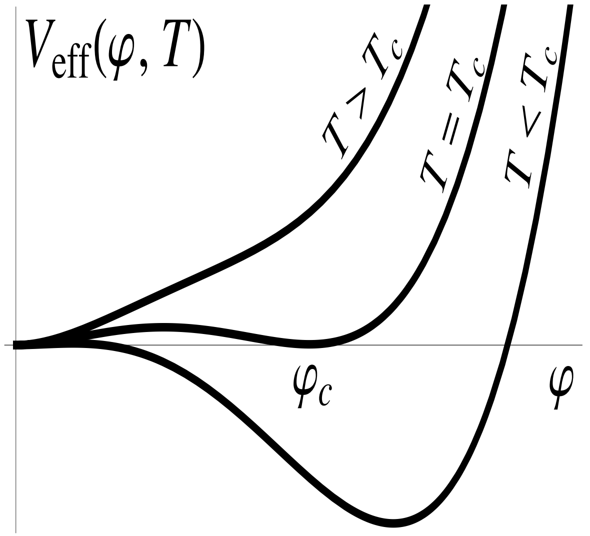
- **Physics behind EWSB**
  - Where come from $\mu^2 < 0$
  - What is the origin of λ
  - Dynamics, nature

- **Electroweak Phase Transition**
  - Aspect of Transition, 1st order or not?
  - Mechanism of Phase Transition
  - Relation to EW baryogenesis



Electroweak Baryogenesis

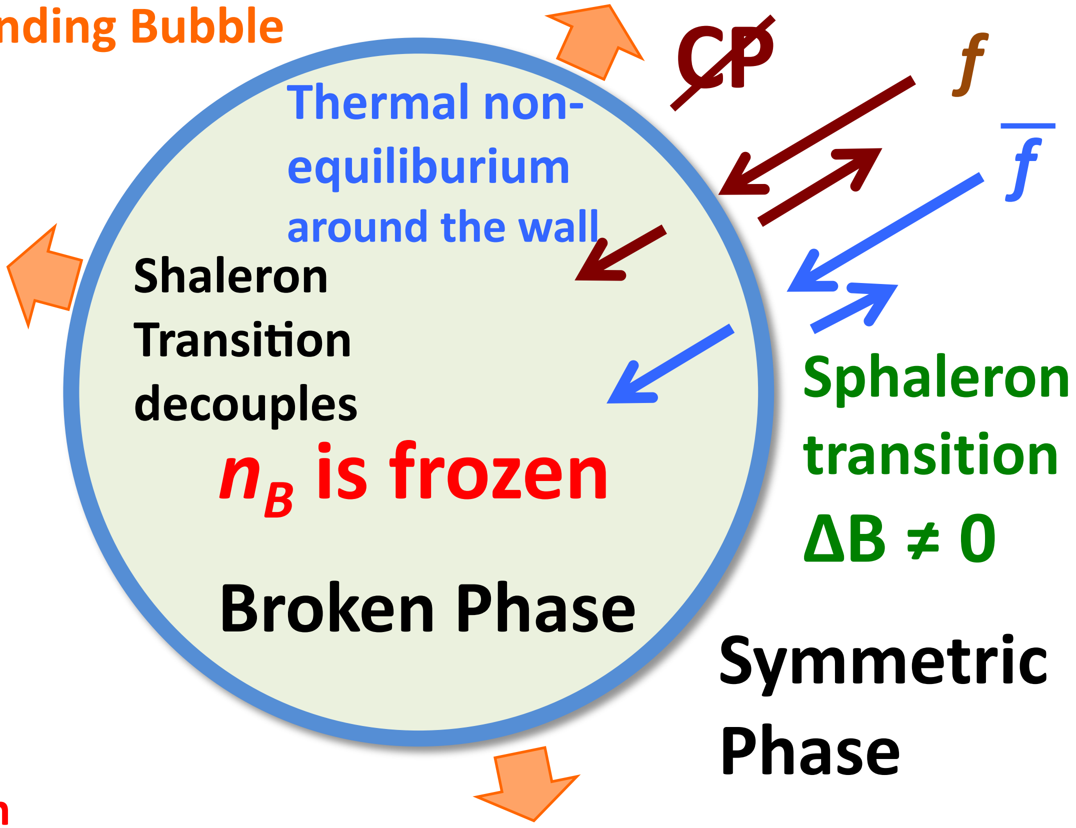
1^{st} OPT is required



Sakharov 3^{rd} condition

Departure from Thermal Equilibrium

Expanding Bubble



$\cancel{CP}$

f

$\overline{f}$

Thermal non-equiliburium around the wall

Shaleron Transition decouples

n_B **is frozen**

Broken Phase

Sphaleron transition

$\Delta B \neq 0$

Symmetric Phase

Sphaleron Decoupling

$$\boxed{\Gamma_{sph} < H(T_c)}$$

$$\Gamma_{sph} \sim e^{-E_{sph}/T_c}$$
$$\sim e^{-\alpha' \varphi_c/T_c}$$

$$\Longrightarrow \quad \boxed{\frac{\varphi_c}{T_c} \gtrsim 1}$$

Physics of the Higgs potential

1^{st} OPT possible in extended Higgs

Potential at finite temperatures (HTE)

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

SM **1^{st} OPT not realized**

$$\frac{\varphi_C}{T_C} = \frac{2E}{\lambda_T} = \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$$

1st OPT possible in extended Higgs

Potential at finite temperatures (HTE)

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

SM 1st OPT not realized

$$\frac{\varphi_C}{T_C} = \frac{2E}{\lambda_T} = \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$$

Extended Higgs: Strongly 1st OPT possible

Quantum effect of additional Scalar field Φ (= *H, A, H*$^+$, …)

Realized by Quantum Effect by Φ (= *H, A, H*$^+$, …)

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underline{\sum_\Phi m_\Phi^3 \left(1 - \frac{M^2}{m_\Phi^2}\right)^3 \left(1 + \frac{3M^2}{2m_\Phi^2}\right)}\right\} > 1$$

1st OPT possible in extended Higgs

Potential at finite temperatures (HTE)

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

SM 1st OPT not realized

$$\frac{\varphi_C}{T_C} = \frac{2E}{\lambda_T} = \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1$$

Extended Higgs: Strongly 1st OPT possible

Quantum effect of additional Scalar field Φ (= *H, A, H*$^+$, ...)

Realized by Quantum Effect by Φ (= *H, A, H*$^+$, ...)

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underline{\sum_\Phi m_\Phi^3\left(1 - \frac{M^2}{m_\Phi^2}\right)^3\left(1 + \frac{3M^2}{2m_\Phi^2}\right)}\right\} > 1$$

Prediction: a large deviation on the *hhh* coupling

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \underline{\sum_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3}\right\} > \lambda_{hhh}^{SM}$$

1st OPT and the *hhh* coupling

Strong 1st OPT (Φ_c/T_c >1)
⇔ Deviation in the *hhh* coupling

EW Baryogenesis can be tested by detecting a large deviation in the *hhh* coupling

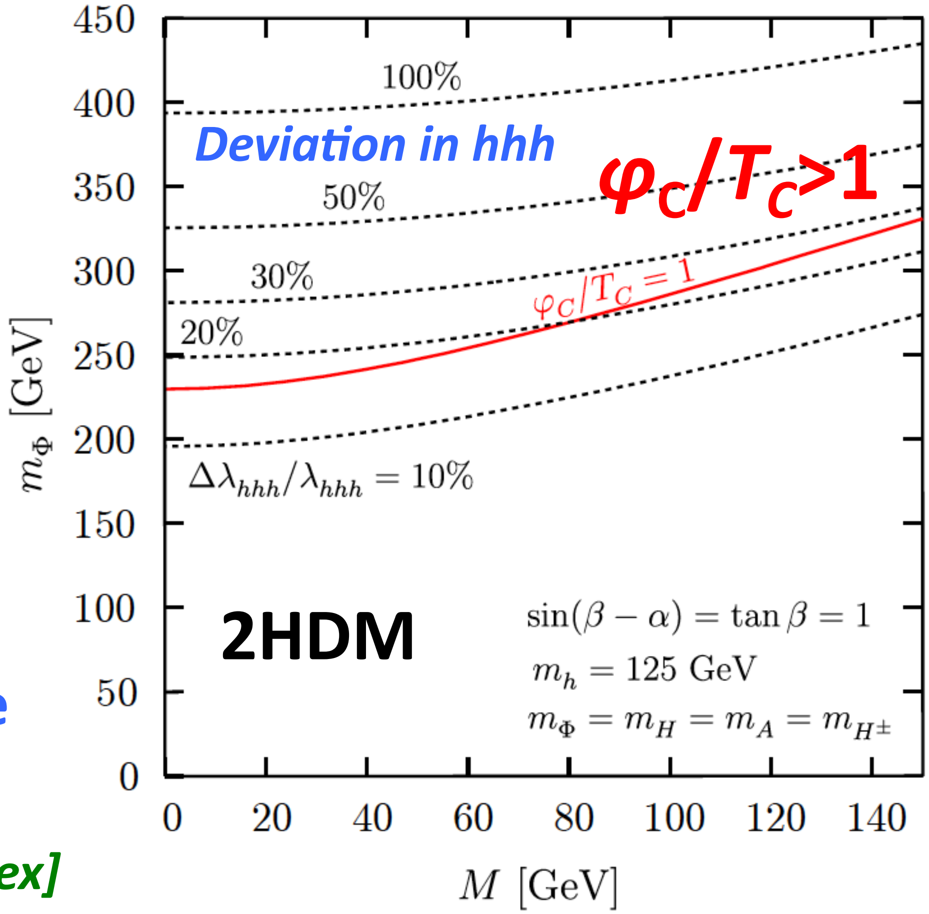
Which collider?

(HL-)LHC cannot do it

ILC(1 TeV) [and CLIC] can measure it by O(10) %

K.Fujii et al., arXiv:1506.05992 [hep-ex]

S.K., Y. Okada, E. Senaha (2005)

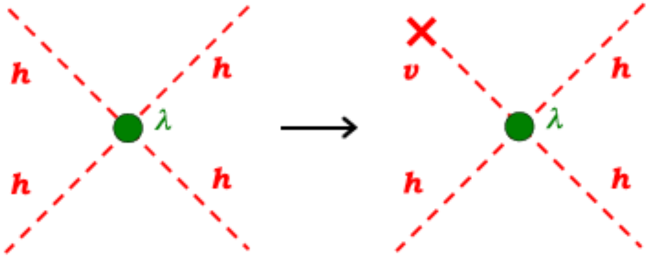


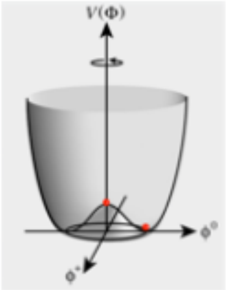
Clearly, ILC250 is not useful for this purpose

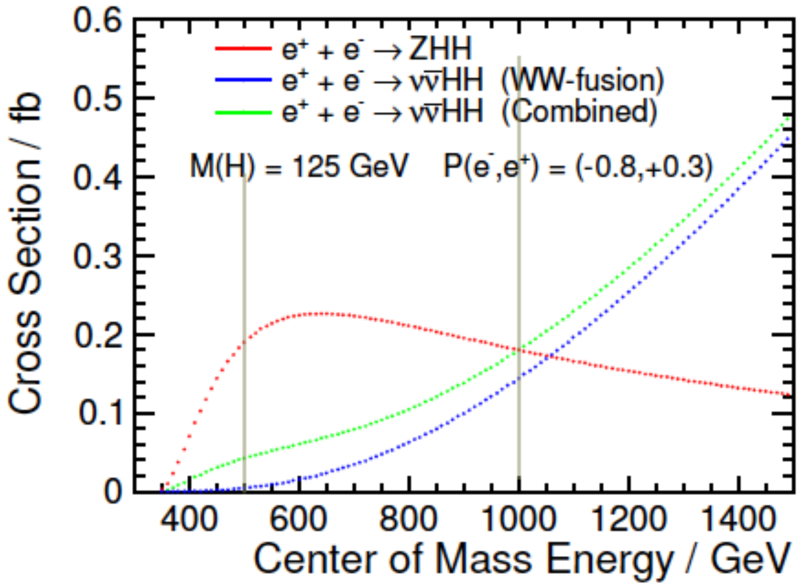
Higgs Self-Coupling

Slide by Keisuke Fujii

hhh coupling =
consequence of vacuum condensation



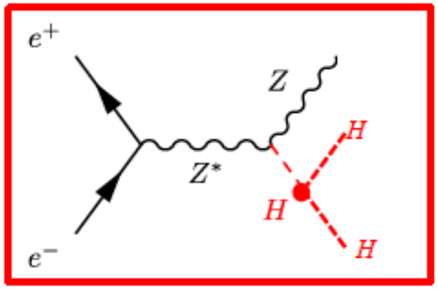


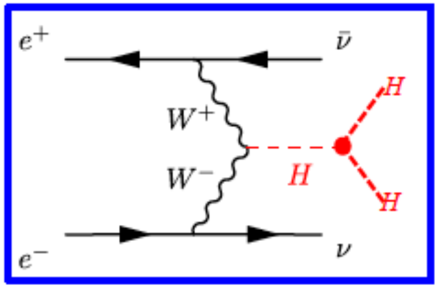


Challenging measurement because of:

- Small cross section (Zhh 0.2 fb at 500 GeV)
- Many jets in the final state
- ***Presence of irreducible BG diagrams***

arXiv:1310.0763	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%
λ	83%	46%	21%	13%





Ongoing analysis improvements ***towards O(10)% measurement***

See J.Tian's Poster

Alternative tool to explore EWPT

At HL-LHC, ILC250, FCCee, …

the *hhh* coupling cannot be measured efficiently

We cannot test the Higgs potential in the near future?

Fortunately,

Gravitational Waves can be a new tool to explore physics at the early Universe

(Inflation, EW phase transition, Topological defects …)

Higgs potential via GWs

In 2016, LIGO reported the first direct observation of GWs from merge of a BH Binary (～100 Hz) → Era of GW astronomy started

Ground based experiments

aLIGO, KAGRA, aVirgo…

GW Physics

GW from 1st OPT: homogeneous, isotropic, stationary, unpolarized

Relic GWs are characterized only by frequency

Transition temperature gives typical frequencies

T_t= 100GeV → $f = 10^{-1} - 10^{-3}$ Hz

Out of sensitivity at LIGO/KAGRA (10-10^3Hz)

Future space based GW experiments

LISA Sensitivity around 10^{-3} (mili) Hz (will start in 2034)

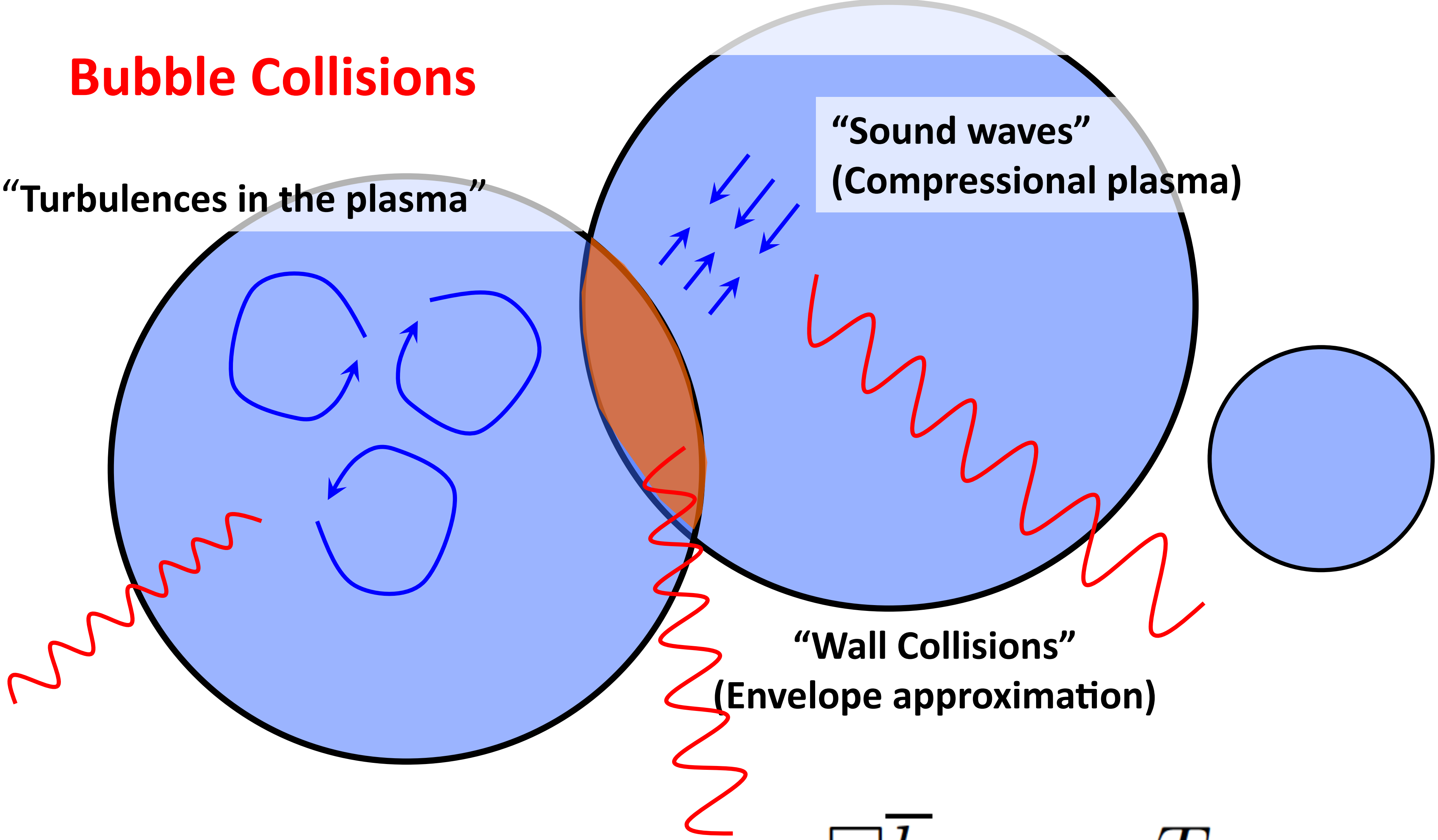
DECIGO Sensitivity around 10^{-1} (deci) Hz

We can explore GWs from the early Universe!

Grojean, Survant, …

GWs from 1st OPT

Bubble Collisions



“Turbulences in the plasma”

“Sound waves”
(Compressional plasma)

“Wall Collisions”
(Envelope approximation)

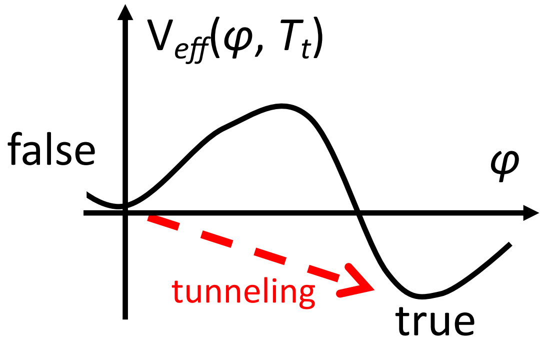
Spherical symmetry is violated by bubble collisions → GW occurs

$$\Box \bar{h}_{\mu\nu} = \kappa \underline{T_{\mu\nu}}$$

Source of GW

From bubble dynamics to GW spectrum

Bubble Nucleation Rate **$\Gamma(T) = \Gamma_0 \exp(-S_3/T)$**



With the phase transition condition

$\Gamma(T)/H^4 = 1$ we can determine

α Latent heat（released energy from the PT） **Depth of the potential**

β Inverse of the time variation of 1stOPT **Speed of phase transition**

$$\alpha = \frac{\epsilon(T_*)}{\rho_{\rm rad}(T_*)} \qquad \beta = -\left.\frac{dS_E}{dt}\right|_{t=t_*} \simeq \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_*}$$

From these parameters we can calculate GW spectra.

Ex）GW spectrum from Sound Wave (Compressional wave)

$$\widetilde{\Omega}_{\rm sw}h^2 \simeq 2.65\times 10^{-6}\frac{v_b}{\tilde{\beta}}\left(\frac{\kappa(v_b,\alpha)\alpha}{1+\alpha}\right)^2 \qquad \tilde{f}_{\rm sw} \simeq 1.9\times 10^{-5}{\rm Hz}\frac{\tilde{\beta}}{v_b}$$

C.Caprini et al., arXiv:1512.06239

Various models for 1st OPT

Thermal loop effect ↓

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

Non-thermal effect ↑

- **1st OPT by thermal loop effects**
  - MSSM (excluded)
  - N-Scalar singlets (incl. 2HDM) *Kakizaki, SK, Matsui, 2015*
  - Those with classical scale invariance *Hashino, Kakizaki, SK, Matsui, 2016*

- **1st OPT by non-thermal mixing effects**
  - Doublet-Singlet mixing model *Hashino, Kakizaki, SK, Ko Matsui, 2017*
  - NMSSM (underway)

See also Hashino’s talk

Ex) Higgs model with *N* singlet scalars

M. Kakizaki, SK, T. Matsui, Phys. Rev. D92 (2015) no.11,115007

Imposed O(*N*) for simplicity $S^{\mathrm{T}} = (S_1, \cdots, S_N)$

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

Mass of scalar fields: $\boxed{m_S^2 = \mu_S^2 + \frac{c}{2}v^2}$

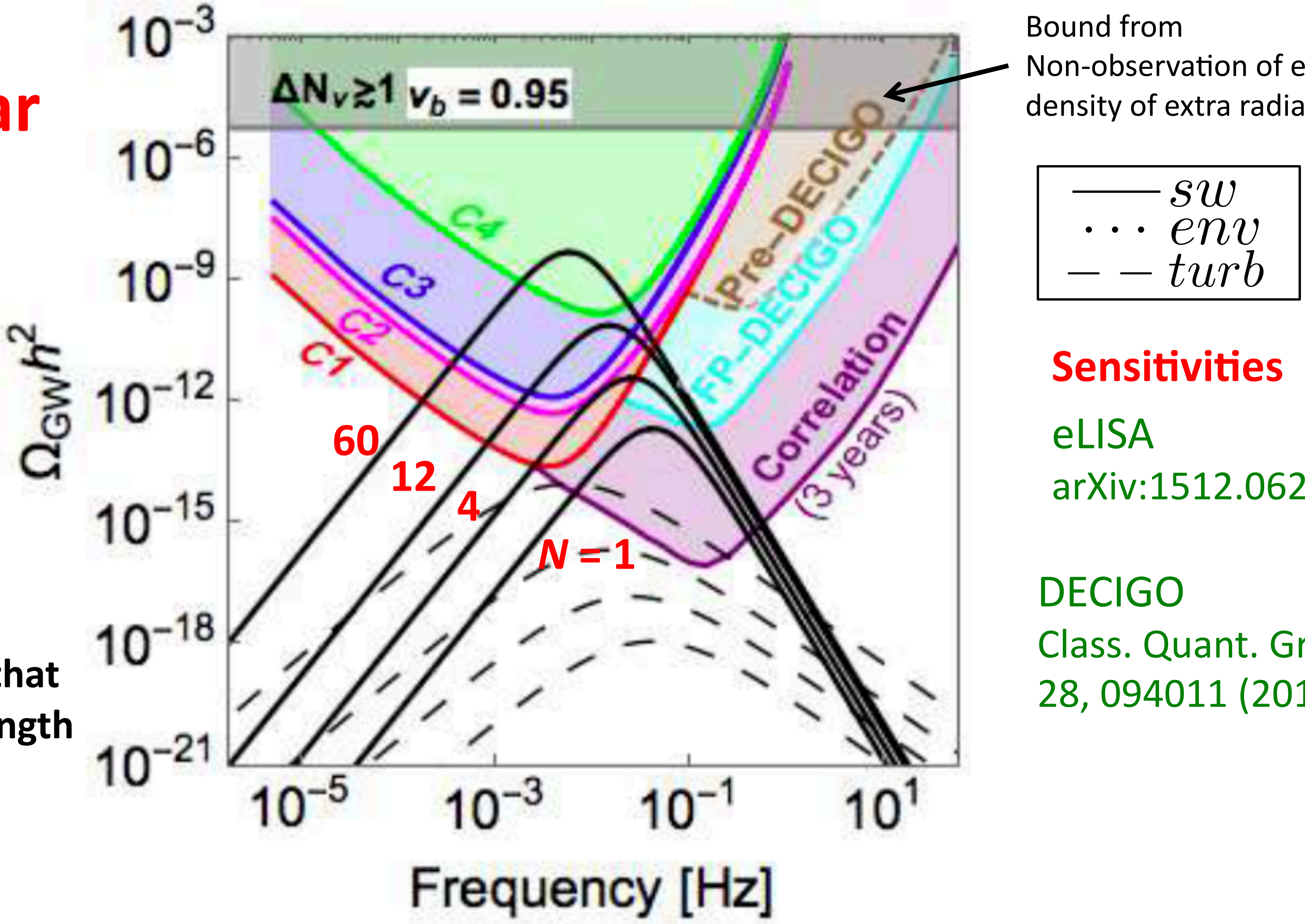
$\varphi_c/T_c > 1$ is satisfied by the nondecoupling effect of the singlet fields（compatible with m_h=125GeV）

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underline{N m_S^3\left(1-\frac{\mu_S^2}{m_S^2}\right)^3\left(1+\frac{3\mu_S^2}{2m_S^2}\right)}\right\} > 1$$

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

GW spectrum from 1st OPT

***N* scalar model**



Bound from Non-observation of energy density of extra radiation

Sensitivities

eLISA
arXiv:1512.06239

DECIGO
Class. Quant. Grav. 28, 094011 (2011)

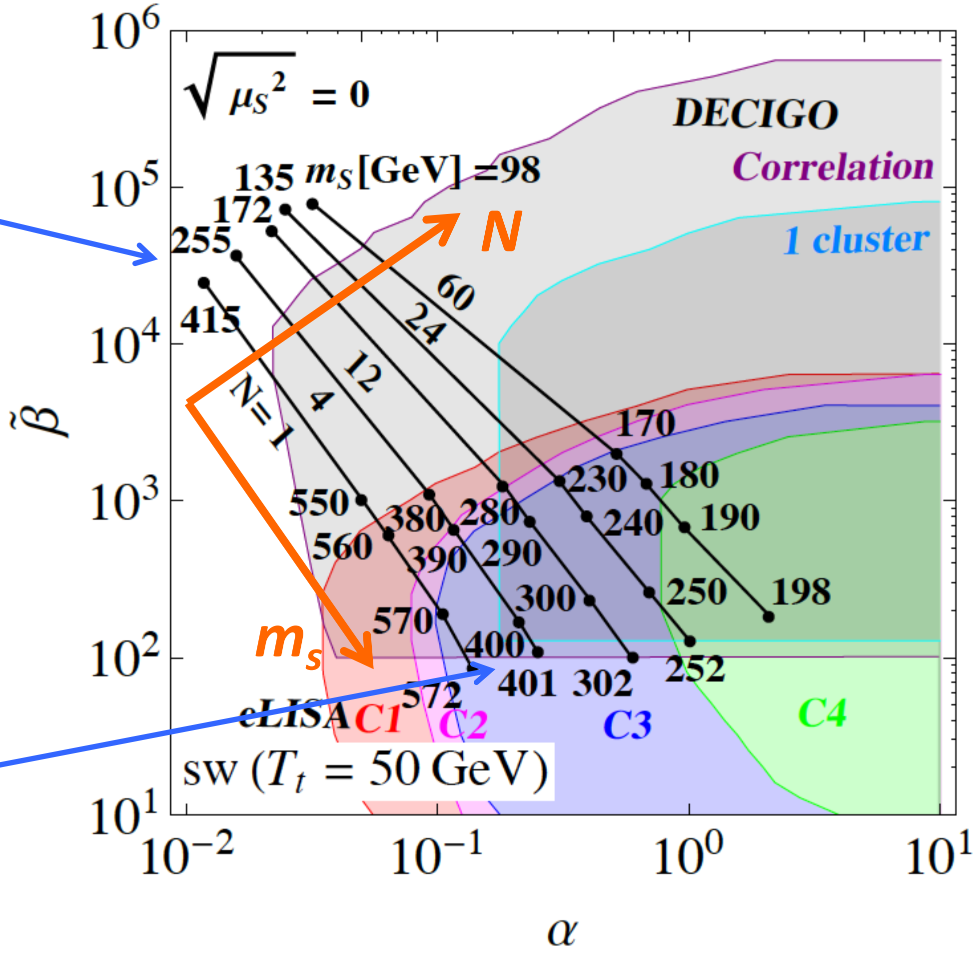
Mass m_s is chosen such that the peak strength is maximal

M. Kakizaki, S.K., T. Matsui, Phys. Rev. D92 (2015) no.11,115007

(N, m_s) may be determined from GWs

O(N) singlet model with the mass m_s

For smaller m_s
$\varphi_c/T_c>1$
cannot be satisfied



Sensitivities

eLISA
arXiv:1512.06239

DECIGO,
Class. Quant. Grav.
28, 094011 (2011)

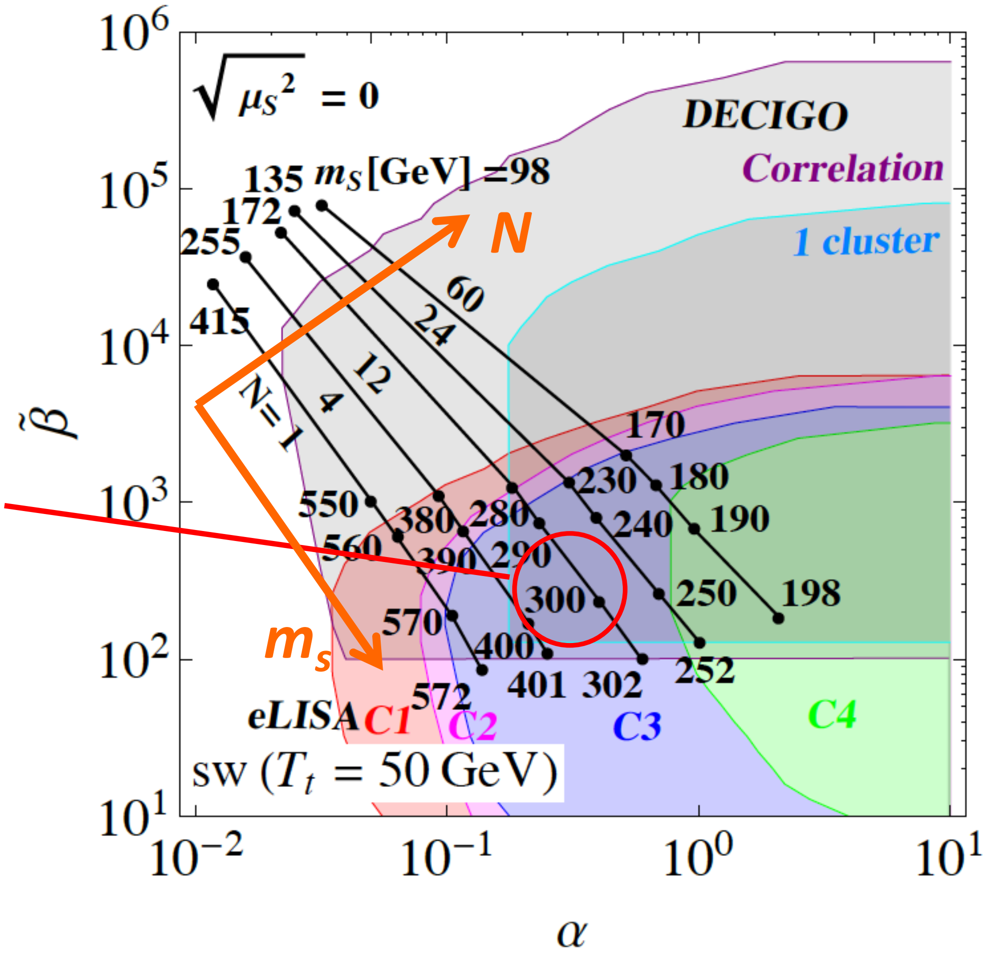
For larger m_s
$\Gamma/H^4 = 1$ cannot
be satisfied

M. Kakizaki, SK, T. Matsui, Phys. Rev. D92 (2015) no.11,115007

(N, m_s) may be determined from GWs

O(N) singlet model with the mass m_S

If α and β are determined with a resolution,
We may be able to fingerprint the model with (N, m_S)



Sensitivities

eLISA
arXiv:1512.06239

DECIGO,
Class. Quant. Grav.
28, 094011 (2011)

M. Kakizaki, SK, T. Matsui, Phys. Rev. D92 (2015) no.11,115007

Fisher Analysis

Likelihood function

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

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

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

Observation period

Effective sensitivity of interferometer

⬇ Taylor expansion at $\{p\} = \{\hat{p}\}$

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

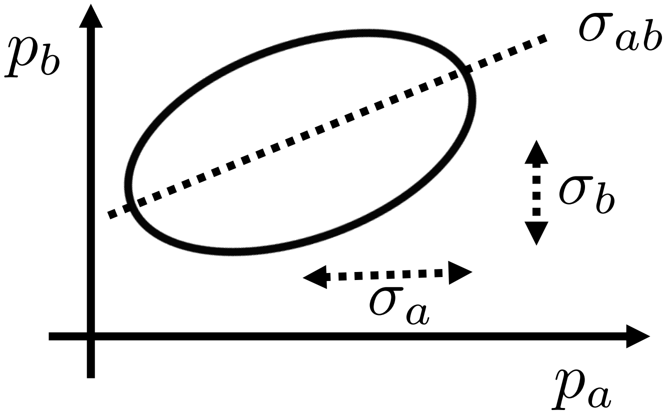
Fisher information matrix

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

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

Confidence ellipse

Inclination: σ_{ab}



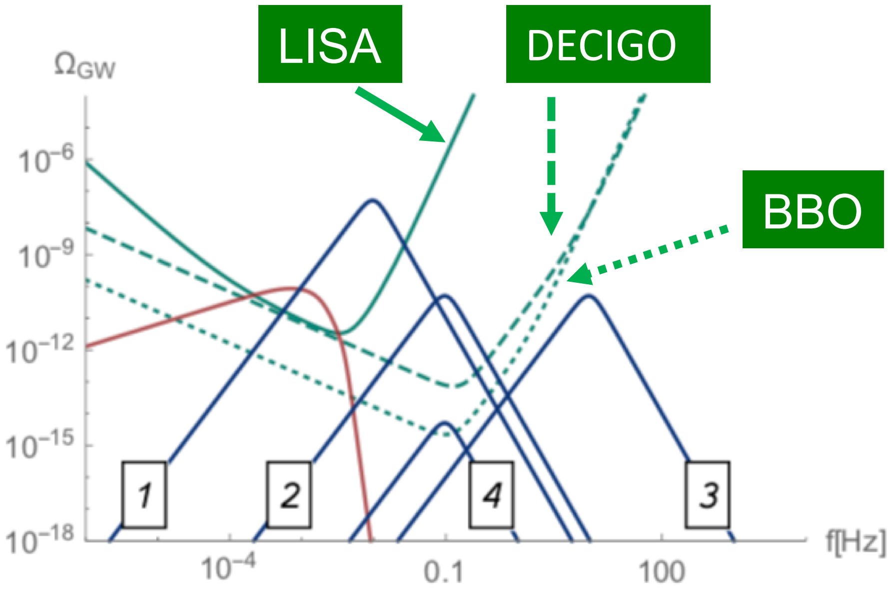
We assume that these expressions are applicable to a single-detector like LISA

Hashino, Jinno, Kakizaki, SK, Takahashi, Takimoto, work in progress

Constraints on the shape of spectrum

GW spectrum

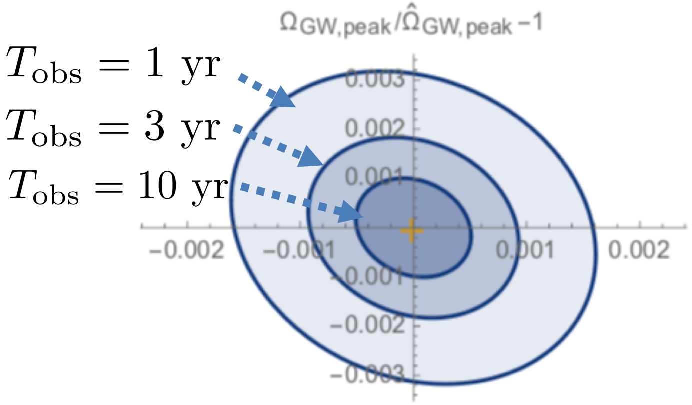
- Fiducial values
  - Point 1: $(f_{\rm peak}, \Omega_{\rm peak}) = (10^{-2}\ {\rm Hz}, 10^{-7})$,
  - Point 2: $(f_{\rm peak}, \Omega_{\rm peak}) = (10^{-1}\ {\rm Hz}, 10^{-10})$,
  - Point 3: $(f_{\rm peak}, \Omega_{\rm peak}) = (10\ {\rm Hz}, 10^{-10})$,
  - Point 4: $(f_{\rm peak}, \Omega_{\rm peak})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



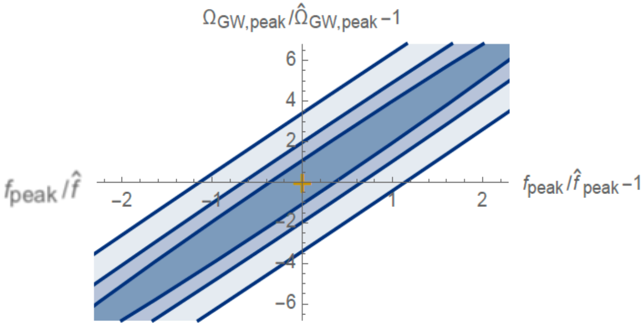
Expected constraints on the GW spectrum

LISA

1σ confidence ellipse in $(f_{\rm peak}, \Omega_{\rm peak})$ for P1 and P2



Point 1



Point 2

A physics case for the synergy of HL-LHC, ILC250 and LISA

Constraints on the model parameters
Case of the singlet-doublet mix model

Thermal loop effect ↓

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

Non-thermal effect ↑

Higgs singlet model

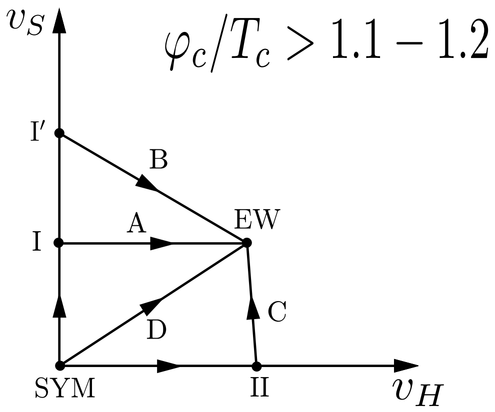
$$V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu_S'}{3}S^3 + \frac{\lambda_S}{4}S^4$$

$$\Phi = \left(\begin{array}{c} G^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi_1 + iG^0) \end{array}\right), \quad S = v_S + \phi_2 \qquad (\phi_1, \phi_2) \rightarrow \ (h, H) \text{ with } \theta$$

Multi-field analysis of EWPT is necessary

$$(v_\Phi, v_S)$$

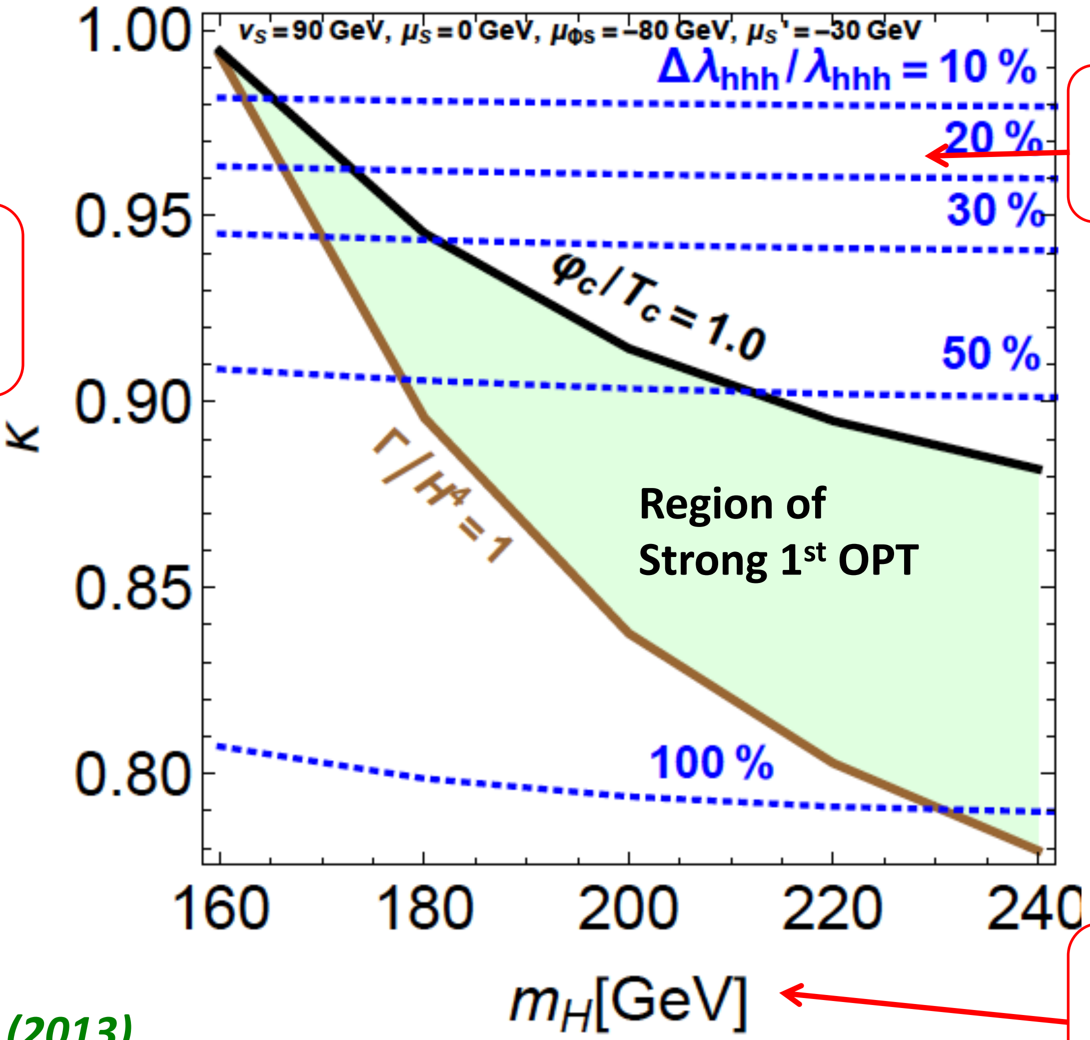
Public tool "CosmoTransition" is used.



$\kappa = \kappa_V = \kappa_f$

$= \cos\theta$

Precision measurement at ILC/LHC



Region of Strong 1st OPT

Self-coupling *hhh* measurement at ILC

Direct searches of the second Higgs at LHC

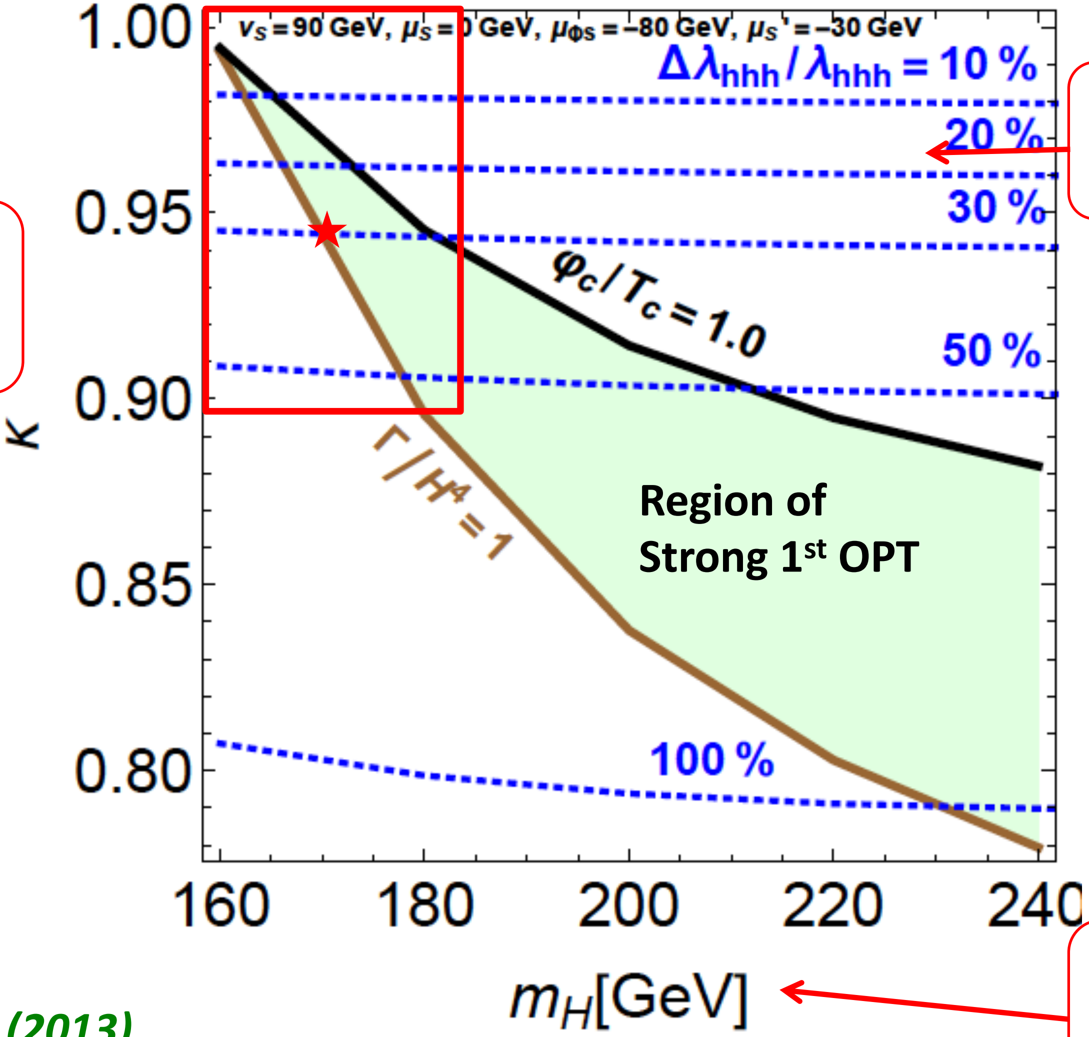
Fuyuto, Senaha (2013)

K. Hashino, M. Kakizaki, S.K., T. Matsui, P. Ko, Phys. Lett. B 766, 49 (2017)

$\kappa = \kappa_V = \kappa_f$

$= \cos\theta$

Precision measurement at ILC/LHC



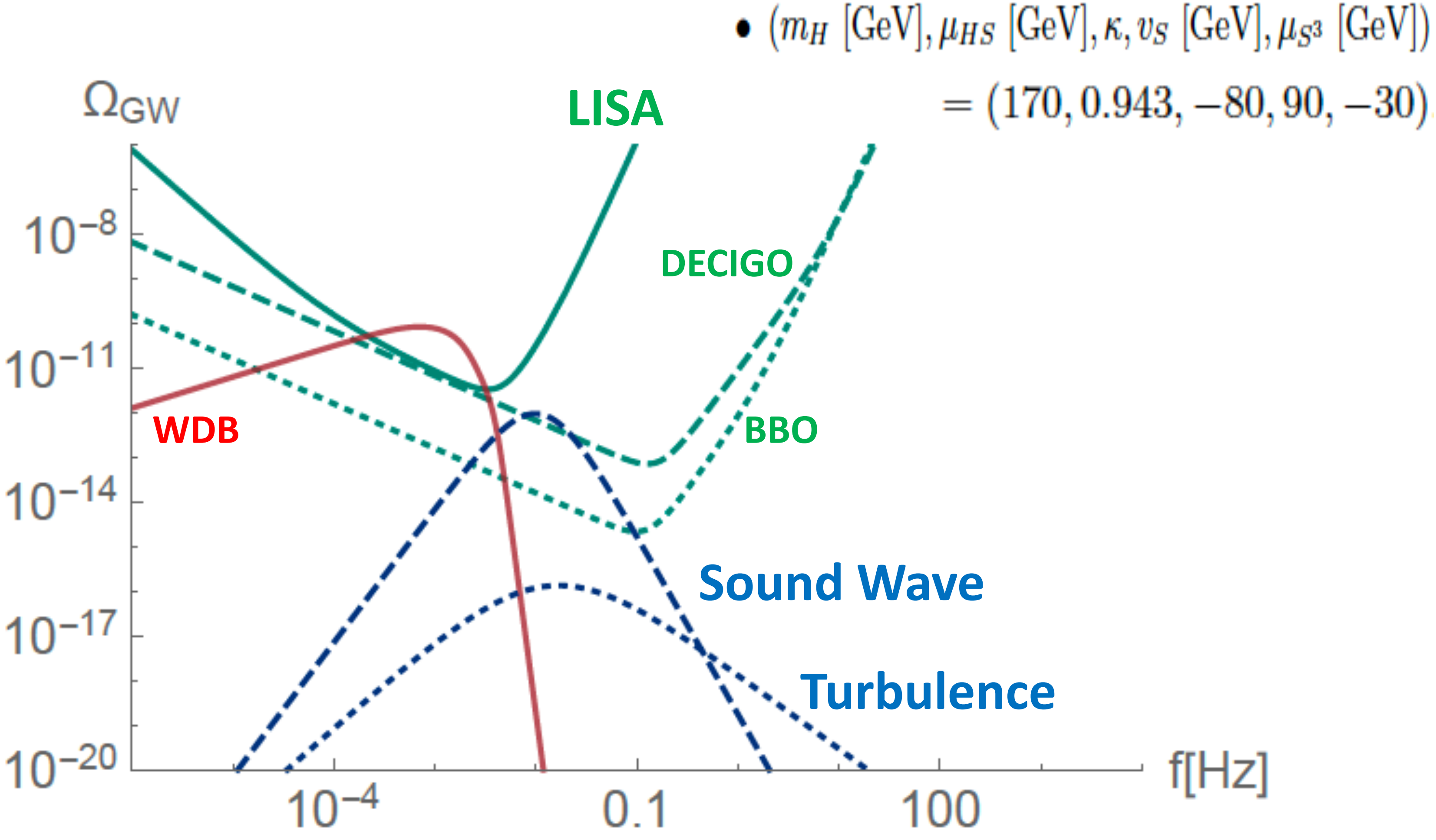
Self-coupling *hhh* measurement at ILC

Direct searches of the second Higgs at LHC

Fuyuto, Senaha (2013)

K. Hashino, M. Kakizaki, S.K., T. Matsui, P. Ko, Phys. Lett. B 766, 49 (2017)

Calculated Spectrum of GW at a fiducial point (DS mixing model)



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

Doublet-Singlet Mixing model

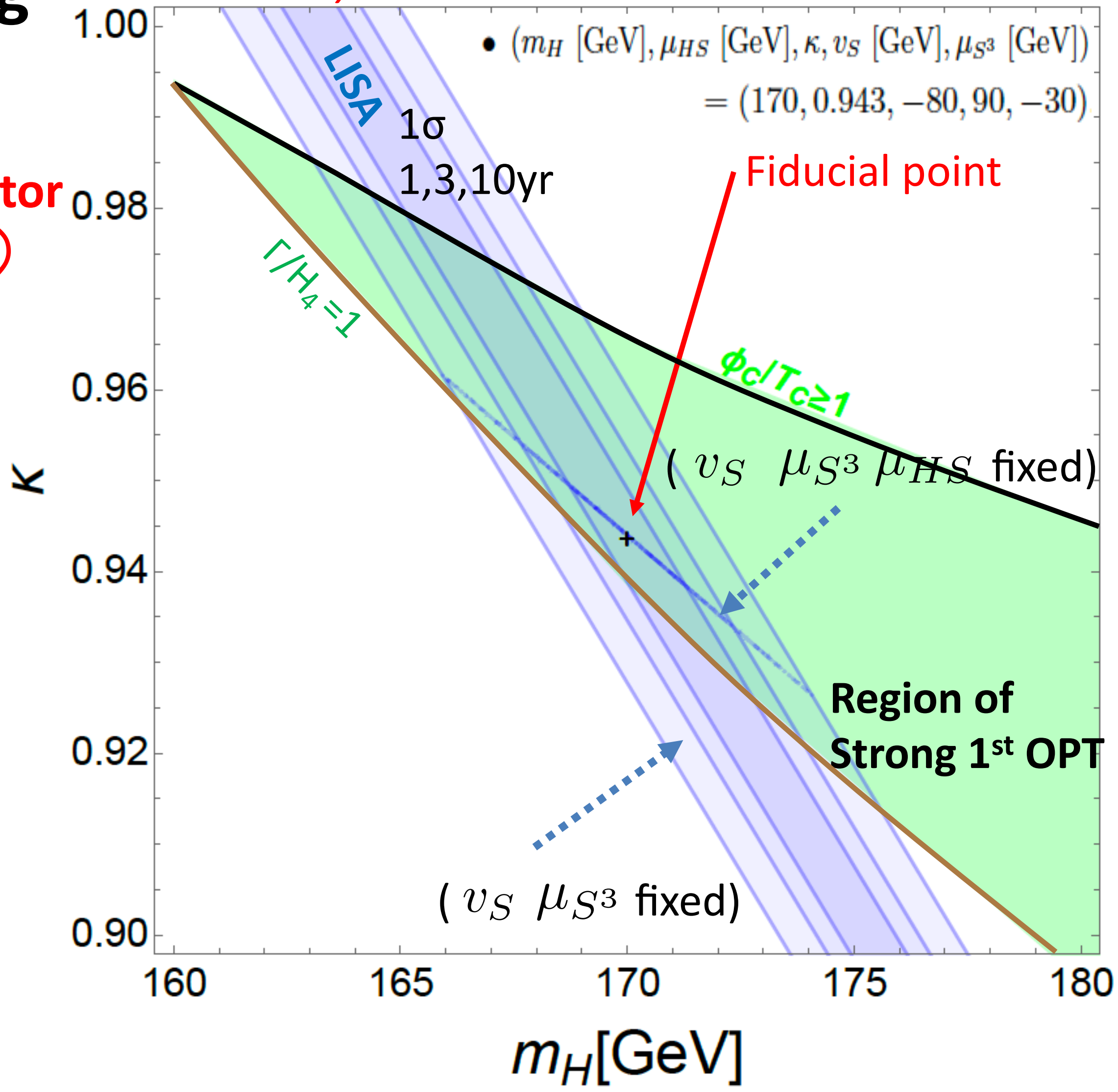
K (= K_f = K_V = cosθ): Scaling Factor

m_H : Mass of the 2nd Higgs（H）

Green:
area where 1st OPT is strongly enough for EW baryogenesis

Blue: Constrained area from GW at LISA

By Hashino, Jinno, Kakizaki, SK, Takahashi, Takimoto
Preliminary



Doublet-Singlet Mixing model

By Hashino, Jinno, Kakizaki, SK, Takahashi, Takimoto
Preliminary

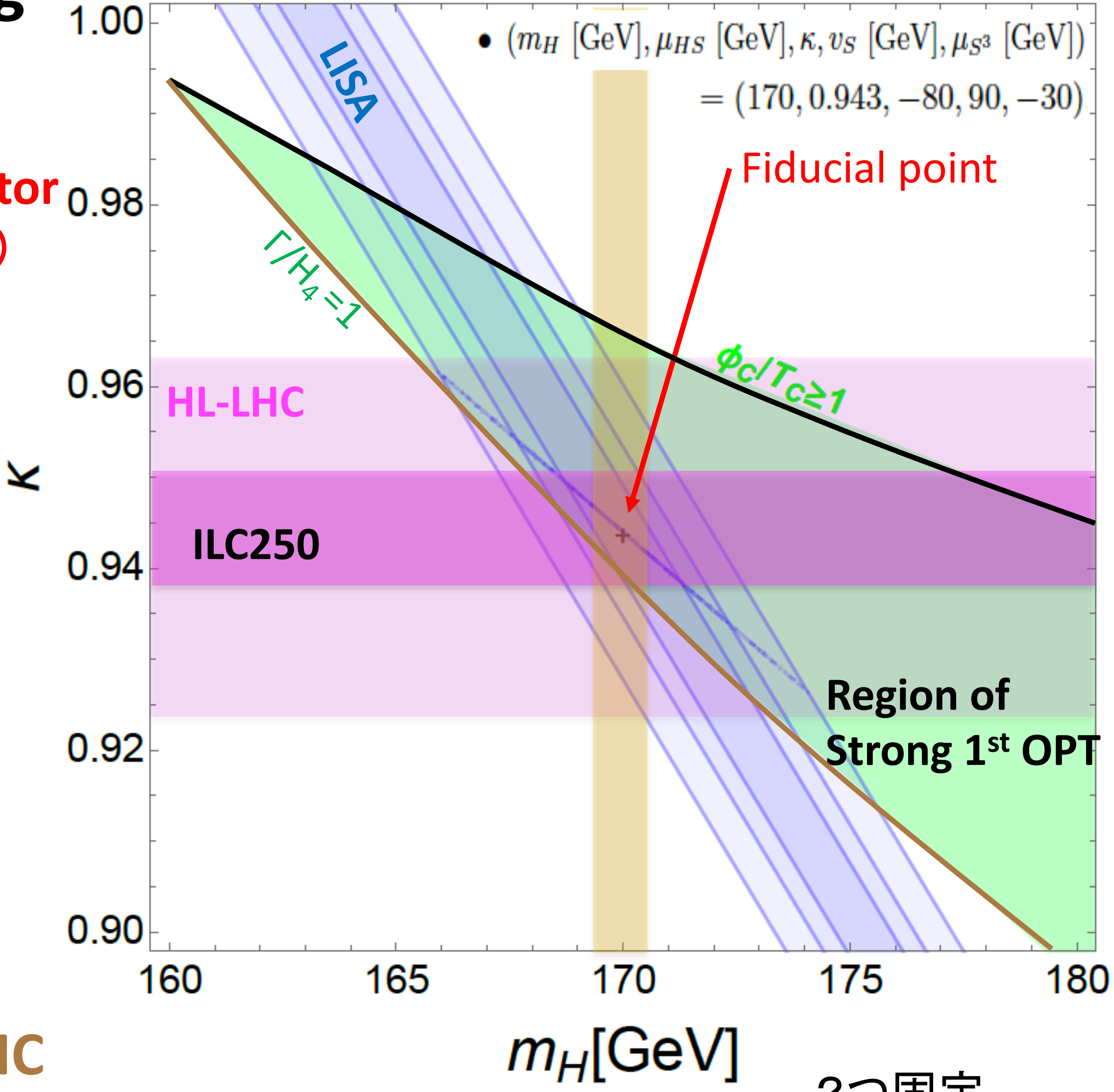
K (= K_f = K_V = cosθ): Scaling Factor
m_H: Mass of the 2nd Higgs（H）

Green:
area where 1st OPT is strongly enough for EW baryogenesis

Blue: Constrained area from GW at LISA

Δκ ~ 2 % (HL-LHC)
0.6 % (ILC250)

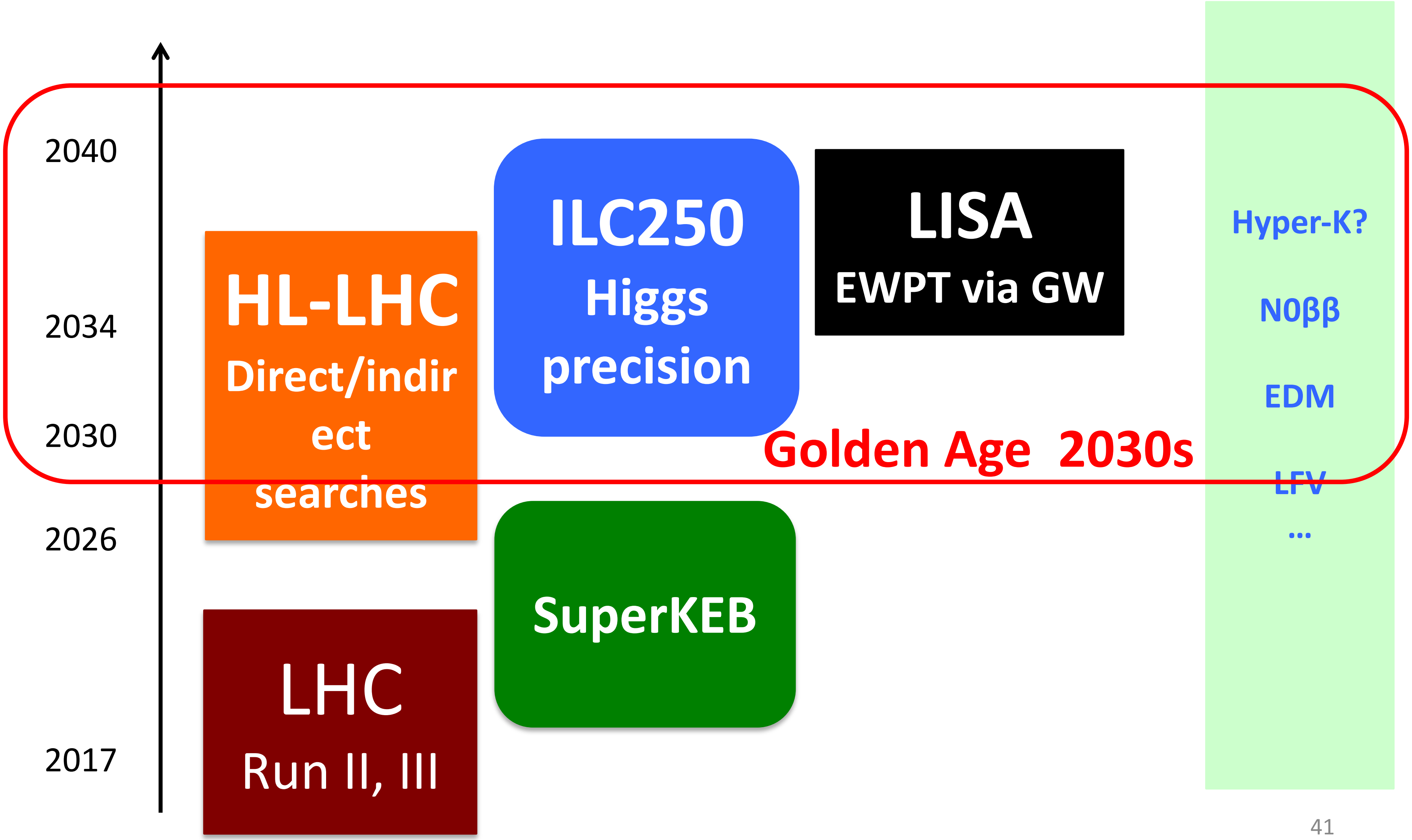
Δm_H ~ 1 GeV(?) at (HL-)LHC



2つ固定
と3つ固定

The model can be well tested by the synergy of HL-LHC, ILC250 and LISA

Future experiments



2040

2034

2030

2026

2017

HL-LHC
Direct/indirect searches

ILC250
Higgs precision

LISA
EWPT via GW

Golden Age 2030s

SuperKEB

LHC
Run II, III

Hyper-K?

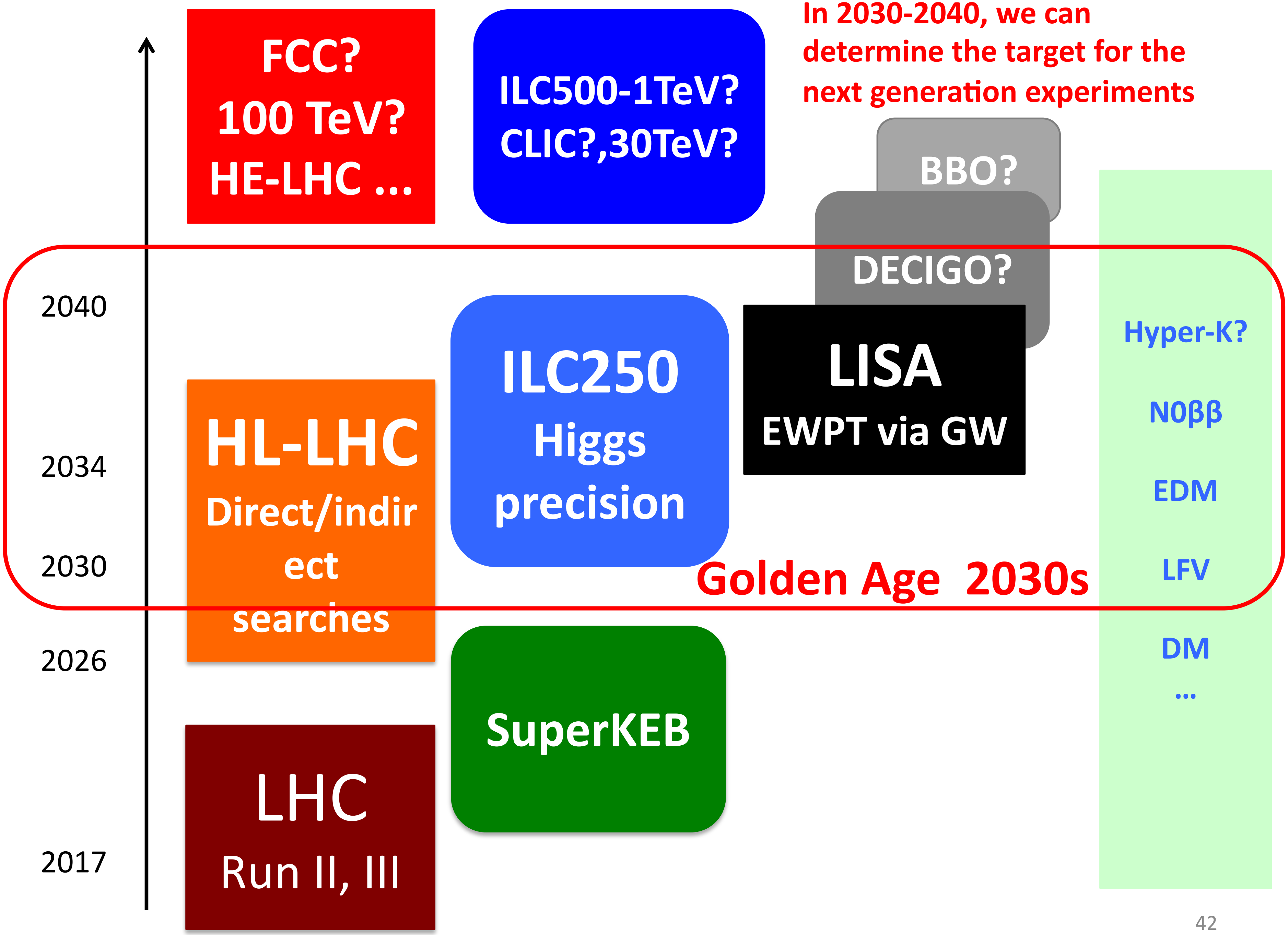
N0ββ

EDM

LFV

…

In 2030-2040, we can determine the target for the next generation experiments



2040

2034

2030

2026

2017

FCC?
100 TeV?
HE-LHC ...

ILC500-1TeV?
CLIC?,30TeV?

BBO?

DECIGO?

LISA
EWPT via GW

HL-LHC
Direct/indirect searches

ILC250
Higgs precision

Golden Age 2030s

SuperKEB

LHC
Run II, III

Hyper-K?
N0ββ
EDM
LFV
DM
…

Summary

Although a Higgs boson was found in 2012, the origin of EW symmetry breaking remains unknown. (Dynamics, nature, physics behind, …)

The non-minimal Higgs sector might be related to phenomena which cannot be explained in the SM.

→ Higgs sector is an important probe of new physics.

By the synergy of

1. Search of the 2nd Higgs bosons at HL-LHC (Hadron Collider),
2. Precision studies of Higgs sectors at ILC250 (Lepton Collider),
3. gravitational wave experiments at LISA

we can thoroughly explore the detail of the Higgs sector in 2030-40s.

→ We showed physics case (an extended Higgs model for 1st OPT)

By knowing the Higgs sector, we can approach to new physics beyond SM.

Summary

Although a Higgs boson was found in 2012, the origin of EW symmetry breaking remains unknown. (Dynamics, nature, physics behind, …)

The non-minimal Higgs sector might be related to phenomena which cannot be explained in the SM.

→ Higgs sector is an important probe of new physics.

By the synergy of

1. **Search of the 2nd Higgs bosons at HL-LHC (Hadron Collider),**
2. **Precision studies of Higgs sectors at ILC250 (Lepton Collider),**
3. **gravitational wave experiments at LISA**

we can thoroughly explore the detail of the Higgs sector in 2030-40s.

→ We showed physics case (an extended Higgs model for 1st OPT)

By knowing the Higgs sector, we can approach to new physics beyond SM.

We need ILC

Back up slides

Higgs singlet extension (HSM)

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

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi_1 + iG^0) \end{pmatrix}, \quad S = v_S + \phi_2$$

$(\phi_1, \phi_2) \rightarrow$ (h, H) with θ

Two Higgs doublet model (2HDM)

$$V_{\rm THDM} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - (m_3^2\Phi_1^\dagger\Phi_2 + {\rm h.c.}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+ \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \lambda_6|\Phi_1|^2\Phi_1^\dagger\Phi_2 + \lambda_7|\Phi_2|^2\Phi_1^\dagger\Phi_2 + {\rm h.c.}],$$

$$\Phi_i = \begin{pmatrix} \omega_i^\pm \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad (i = 1, 2)$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} H \\ h \end{pmatrix} \qquad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} z \\ A \end{pmatrix}$$

$$\begin{pmatrix} \omega_1^\pm \\ \omega_2^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} \omega^\pm \\ H^\pm \end{pmatrix}$$

$$\underset{\overset{\uparrow}{h(125)}}{h} \quad \underbrace{H \quad \overset{\text{CP-odd}}{A} \quad \overset{\text{Charged}}{H^\pm}}_{\text{Additional bosons}}$$

With the softly broken Z_2 symmetry (FCNC) $\lambda_6 = \lambda_7 = 0$

4 types of Yukawa interaction (Type I, II, X, Y)

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$	$\tan\beta$	$-\cot\beta$

TABLE II: The mixing factors in each type of Yukawa interactions in the THDMs [40].

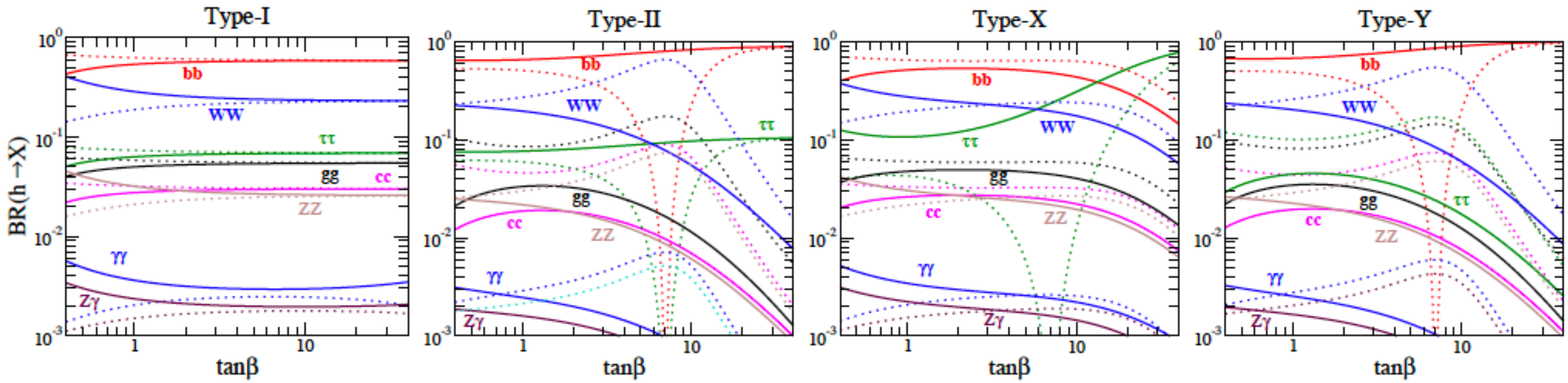
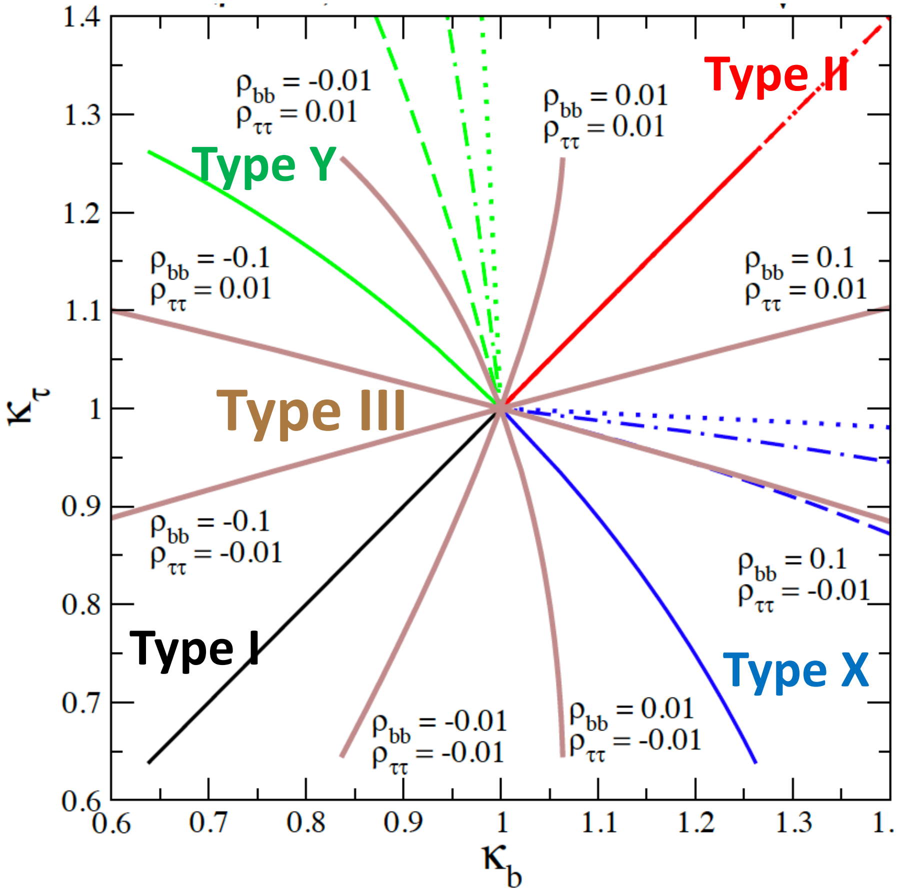


FIG. 6: Decay branching ratios for h as a function of $\tan\beta$ in the case of $m_\Phi = M = 200$ GeV and $\sin(\beta-\alpha) = 0.99$. The solid and dashed curves respectively show the cases with $\cos(\beta-\alpha) < 0$ and $\cos(\beta-\alpha) > 0$.

General 2HDM without the Z_2 symmetry (Type III)

$$\mathcal{L}_Y = -\bar{Q}_{L,i}\tilde{\Phi}\kappa^{0,u}_{ij}u^0_{R,j} - \bar{Q}_{L,i}\Phi\kappa^{0,d}_{ij}d_{R,j} - \bar{Q}_{L,i}\tilde{\Phi}'\rho^{0,u}_{ij}u^0_{R,j} - \bar{Q}_{L,i}\Phi'\rho^{0,d}_{ij}d_{R,j} + h.c.$$

Models	κ_V	κ_c	κ_b	κ_τ
Type-I	$s_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$
Type-II	$s_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} - \tan\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} - \tan\beta c_{\beta-\alpha}$
Type-X	$s_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} - \tan\beta c_{\beta-\alpha}$
Type-Y	$s_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} - \tan\beta c_{\beta-\alpha}$	$s_{\beta-\alpha} + \cot\beta c_{\beta-\alpha}$
Type-III	$s_{-\gamma}$	$s_{-\gamma} + \frac{v}{\sqrt{2}m_c}\rho_{cc}c_\gamma$	$s_{-\gamma} + \frac{v}{\sqrt{2}m_b}\rho_{bb}c_\gamma$	$s_{-\gamma} + \frac{v}{\sqrt{2}m_\tau}\rho_{\tau\tau}c_\gamma$

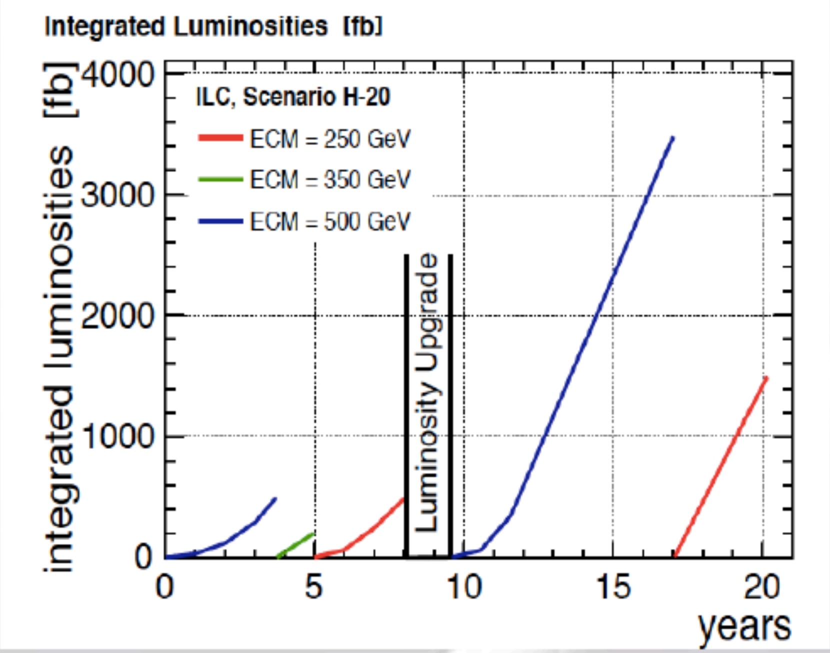


Mariko Kikuchi

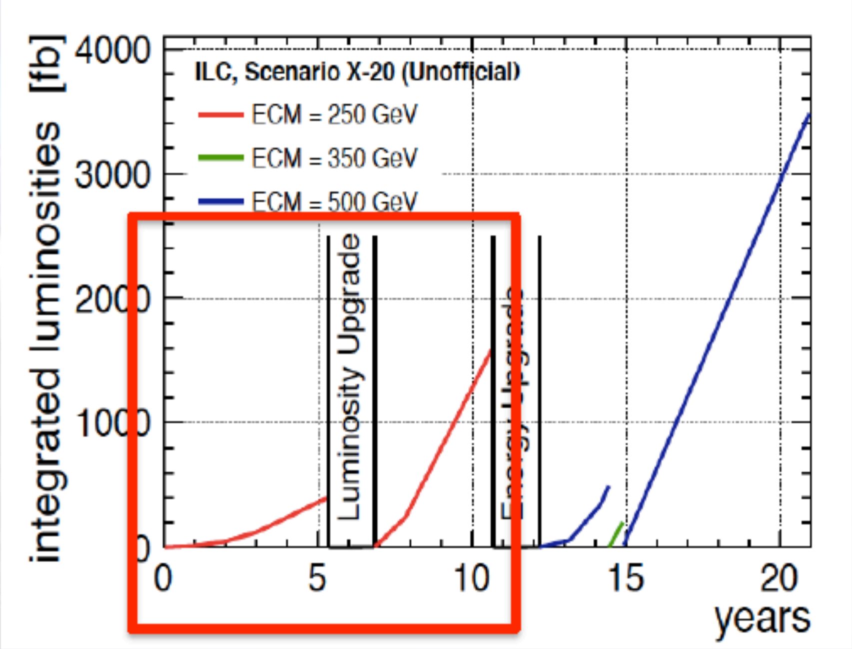
Slide by Hitoshi Yamamoto

Staging：ILC250 Higgs Factory

Up to Dec. 2016　(LCWS Morioka)
500 GeV start sample scenario



After Dec. 2016
Generally agreed by ILC community
To be formalized this fall



ILC250 Higgs Factory

Build the ILC250 Higgs factory as the first stage ‘program’

Slide by
Hitoshi Yamamoto

Main Points

- ILC has been designed to lead the new era of particle physics opened up by the discovery of Higgs.
- ILC250 Higgs Factory reduces the cost by up to 40%.
- For precision Higgs measurements, ILC ~ several tens of HL-LHC running simultaneously.
- New particles: at LHC, ~1 million Higgs were produced and then discovered. At ILC, a handful will do.
- Japanese government is about to finish evaluating the case for ILC (ILC 250 Higgs Factory).
- The deadline for inputs to the European Strategy Discussion is the end of this year – important that a positive statement comes from Japanese government in that time scale.

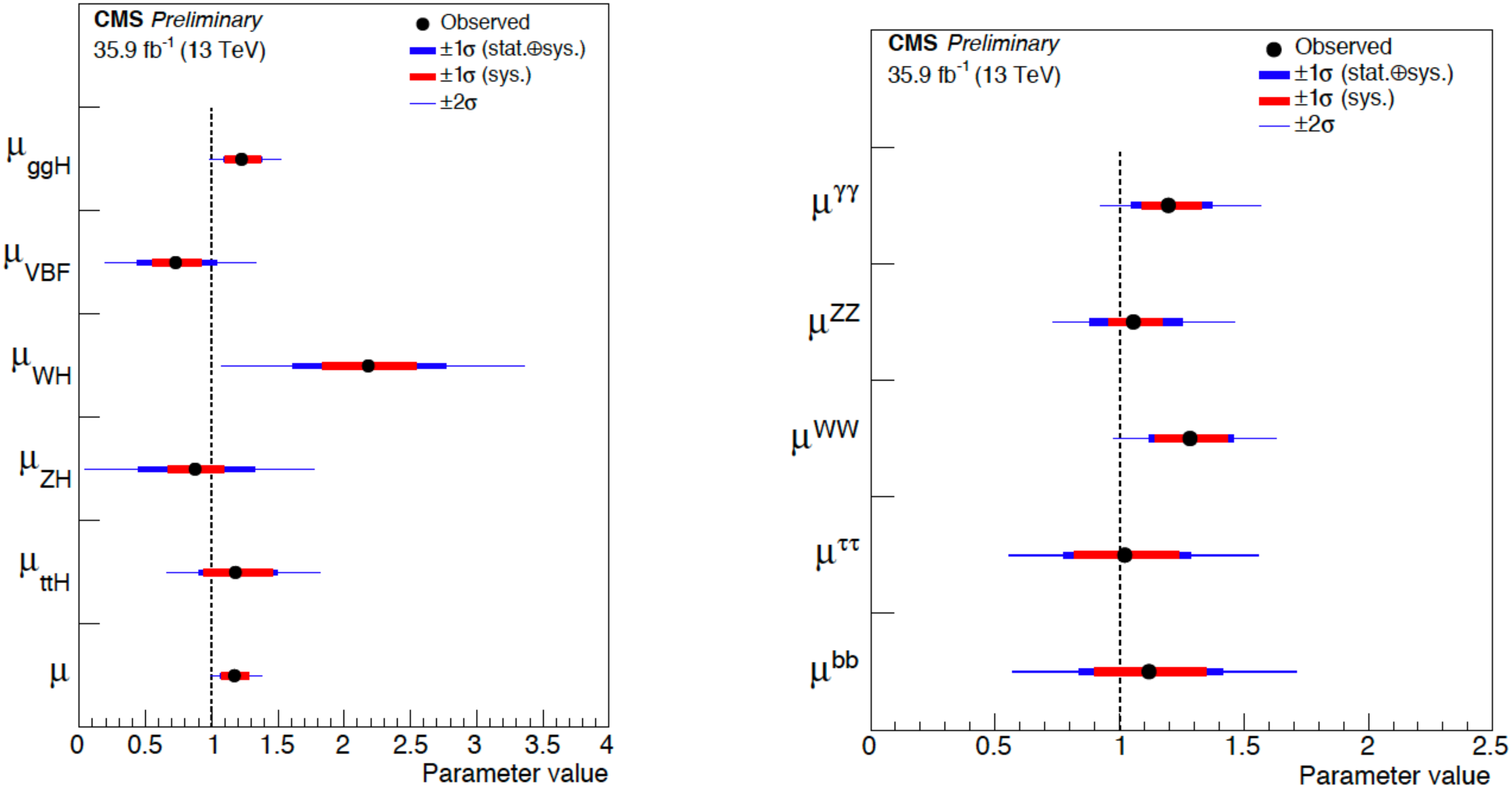


Figure 5: Summary plot of the fit to the per-production mode (left) and per-decay mode (right) signal strength modifiers μ_i. The thick and thin horizontal bars indicate the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively. Also shown are the $\pm 1\sigma$ systematic components of the uncertainties. The last point in the per-production mode summary plot is taken from a separate fit and indicates the result of the combined overall signal strength μ.

1^{st} Order Phase Transition

Effective potential at one-loop

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

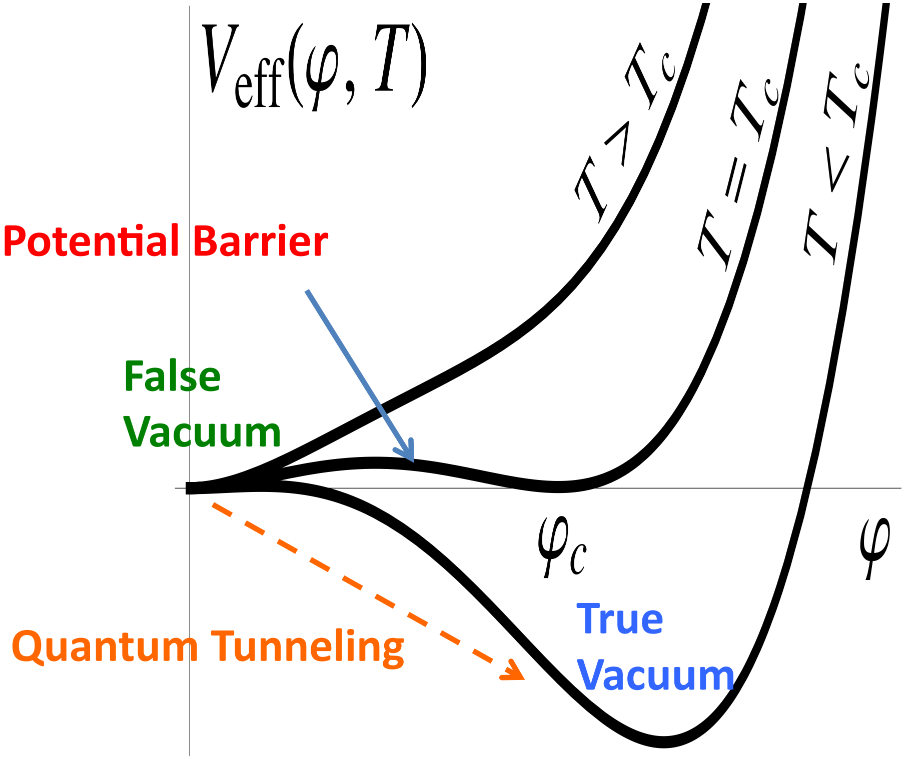
Finite temperature parts

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

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

High temperature expansion

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



Bosonic loop contribute to the cubic term → 1^{st} OPT stronger

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

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

$$\boxed{\varphi_c/T_c \propto E}$$

$$\log\alpha_B = 2\log 4\pi - 2\gamma_E$$
$$\log\alpha_F = 2\log\pi - 2\gamma_E$$
$$\gamma_E = 0.5772\cdots$$

Constraints on transition parameters

Constraining parameters

- The GW spectrum is determined by $f_{\rm peak}$, $\Omega_{\rm peak}$

➡ Our Fisher analysis generically constrain
2 combinations of underlying parameters

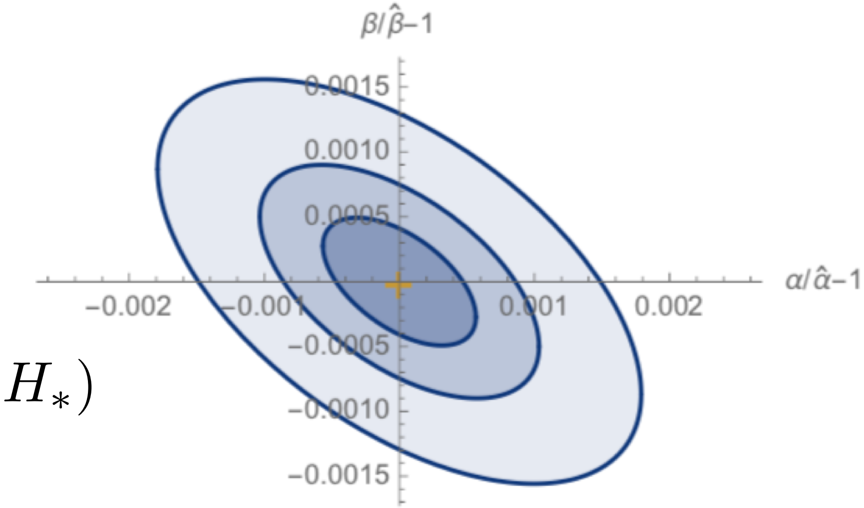
Quantities describing transition dynamics

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

Expected constraints on the transition parameters

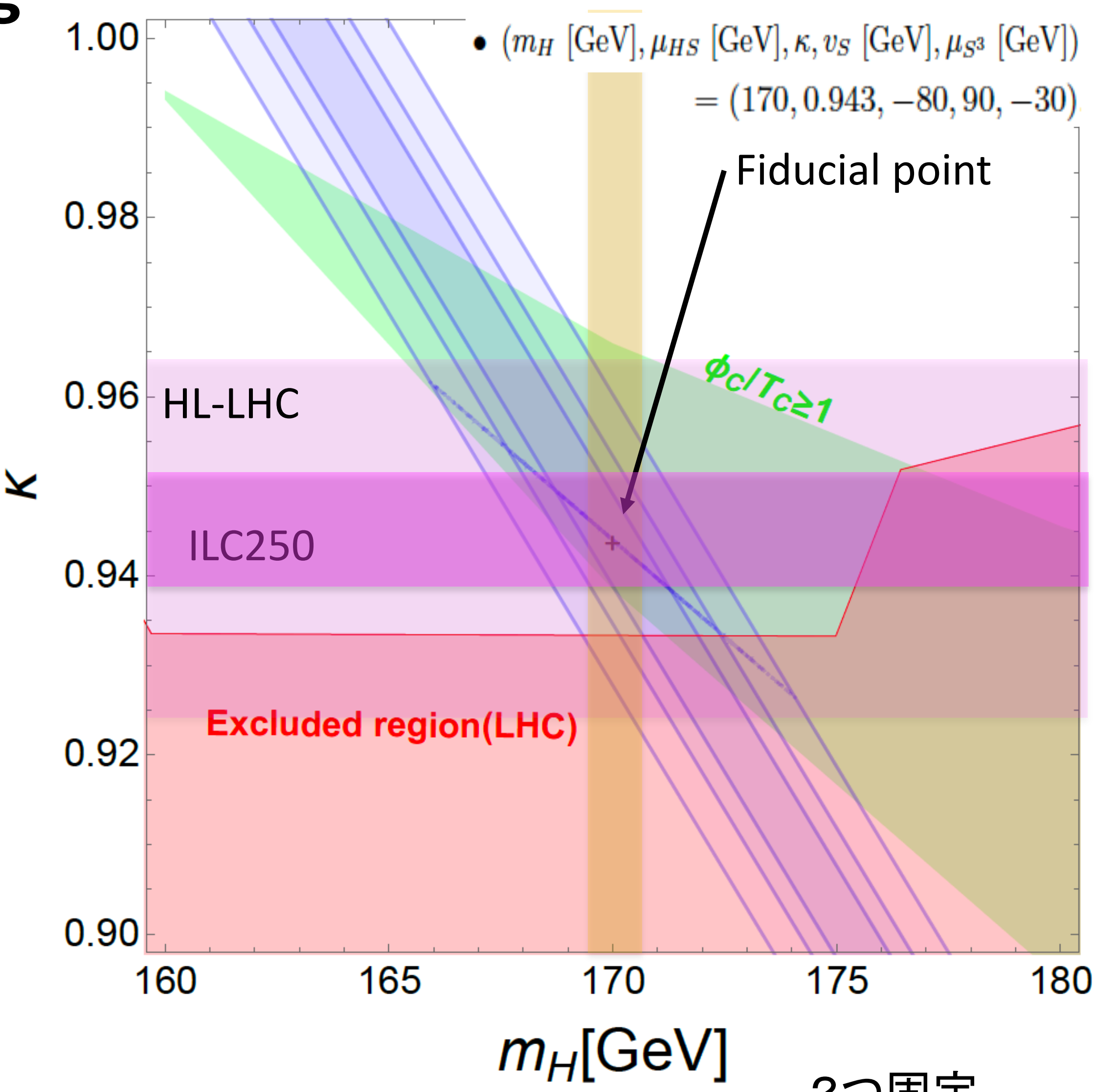
- Fiducial values
  $(\alpha, \beta/H_*, v_w, T_*) = (1, 100, 1, 100 \text{ GeV})$
- $1\ \sigma$ confidence ellipse in $(\alpha, \beta/H_*)$
  for fixed T_* and v_w

LISA



Doublet-Singlet Mixing model

Hashino, Jinno, Kakizaki, SK, Takahashi, Takimoto



K (= cosθ): Scaling Factor
m_H: Mass of the 2nd Higgs H

Green:
area where 1st OPT is strongly enough for EW baryogenesis

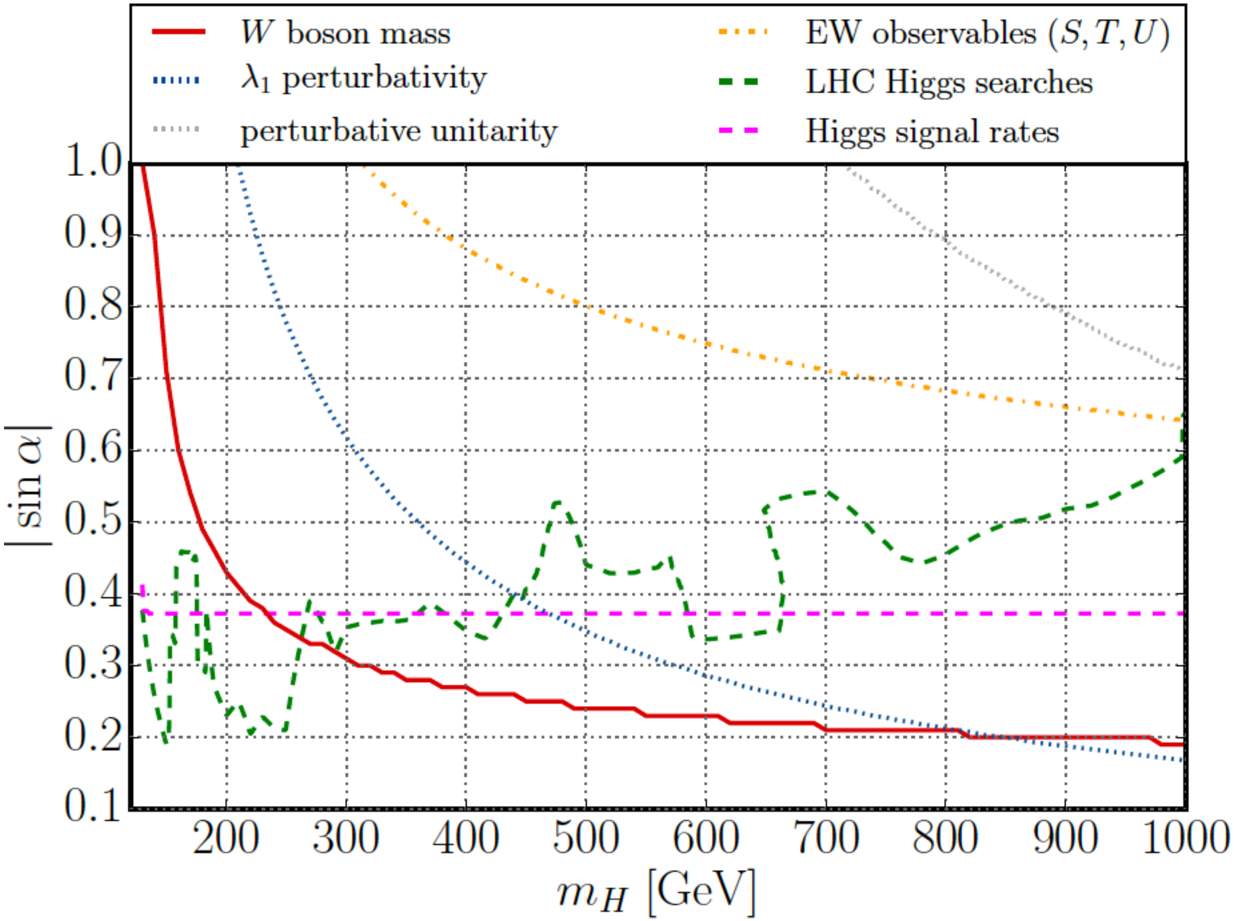
Blue: Constrained area from GW at LISA

Δκ ~ 2 % (HL-LHC)
0.6 % (ILC250)

Δm_H ~ 1 GeV(?) at HL-LHC

2つ固定
と3つ固定

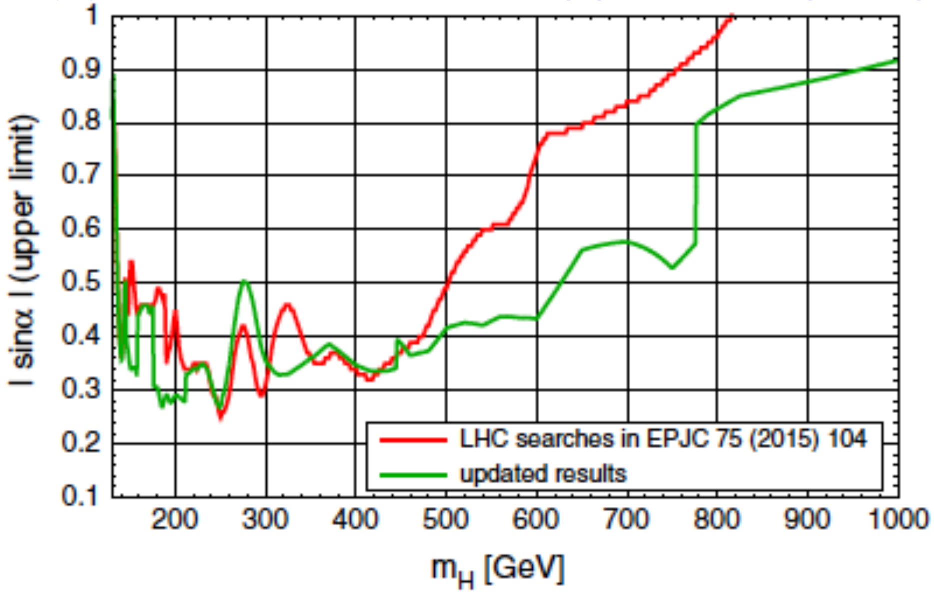
The model can be well tested by the synergy of HL-LHC, ILC250 and LISA

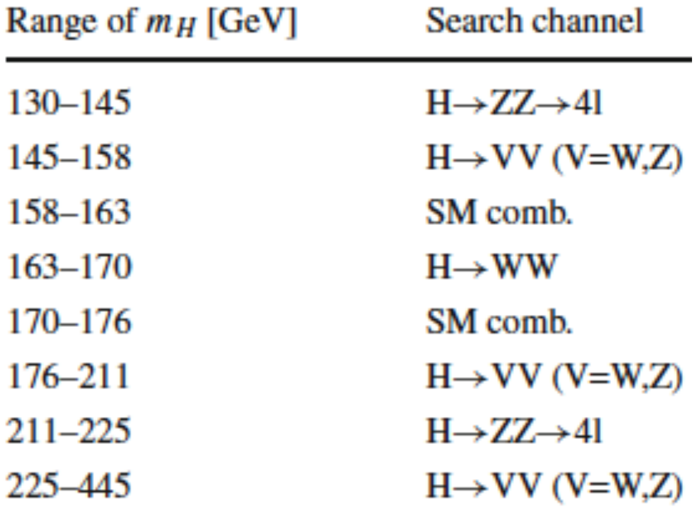

W boson mass
λ_1 perturbativity
perturbative unitarity
EW observables (S, T, U)
LHC Higgs searches
Higgs signal rates
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$|\sin\alpha|$
200
300
400
500
600
700
800
900
1000
m_H [GeV]

Direct searches for the additional Higgs boson in the HSM at the LHC

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

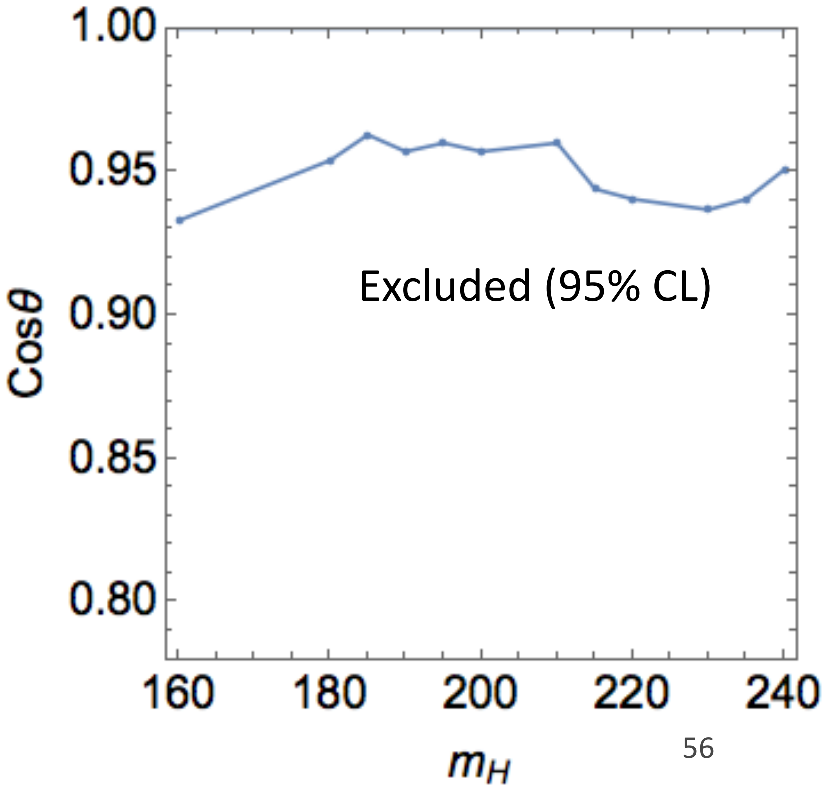
[Robens, Stefaniak (2016)]





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

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



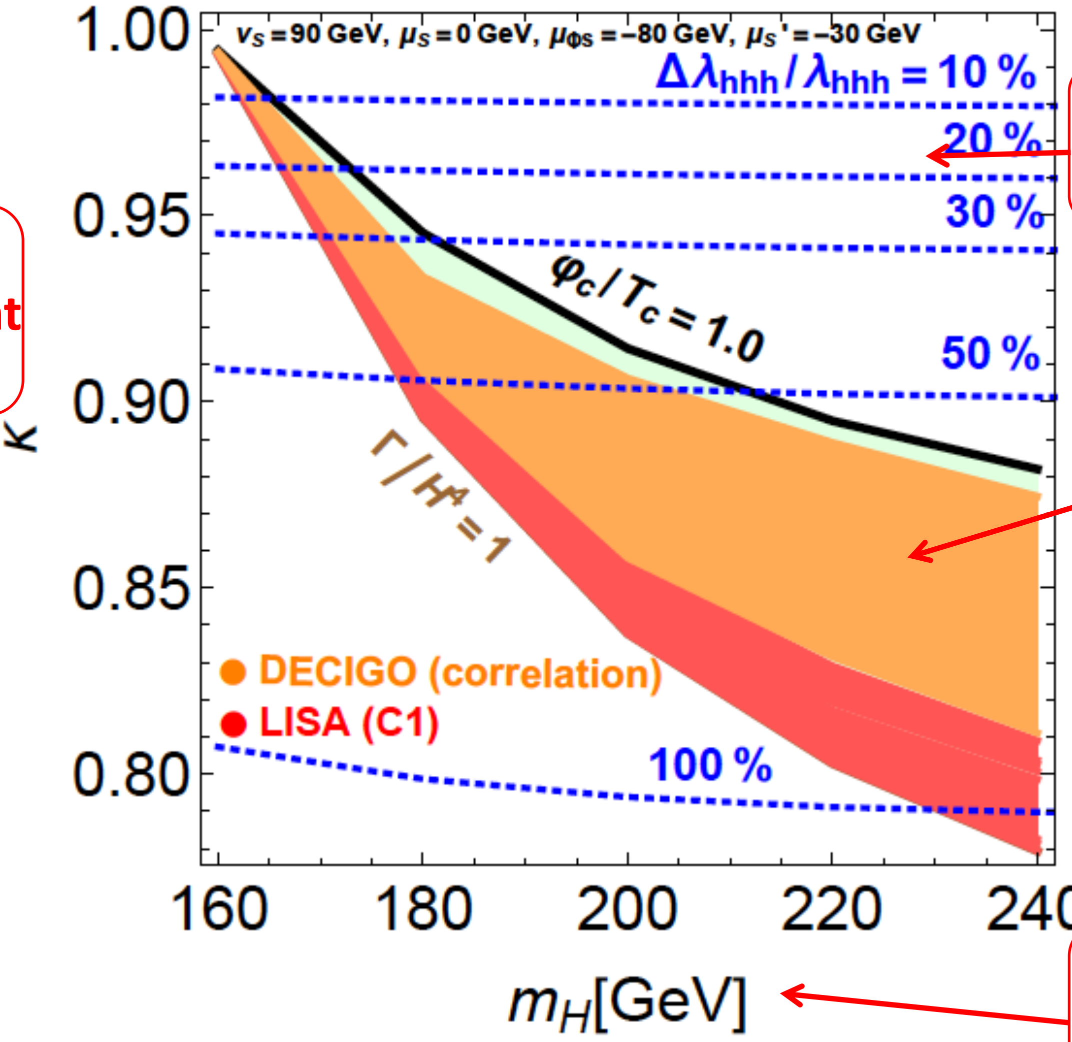
Excluded (95% CL)

Model of EW Baryogenesis will be well tested by the synergy of HL-LHC, ILC250, LISA/DECIGO, ….

$\kappa = \kappa_V = \kappa_f$

$= \cos\theta$

Precision measurement at ILC250



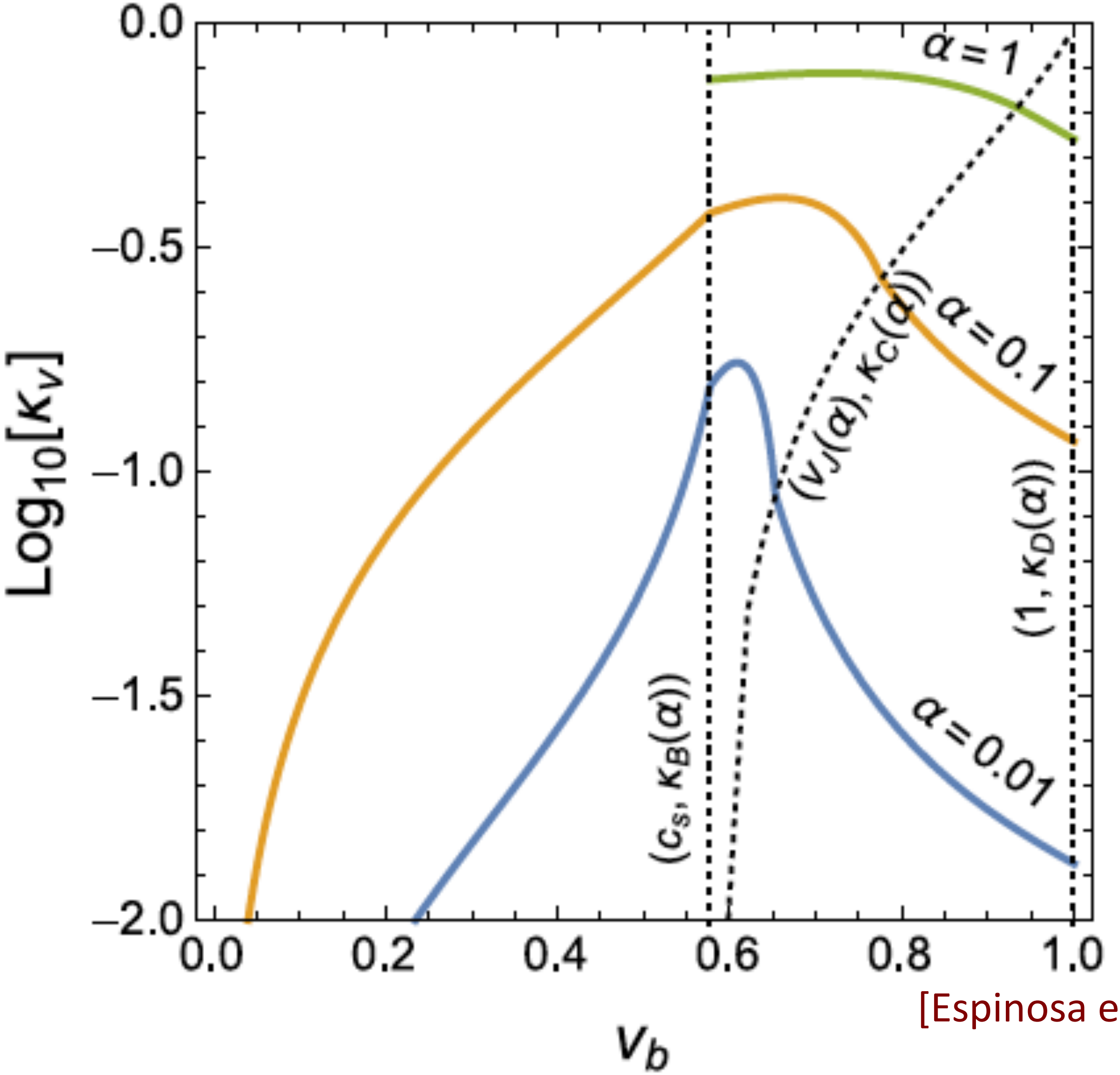
Self-coupling *hhh* measurement at ILC

Measurement of Gravitational Waves at LISA/DECIGO

Direct searches of the second Higgs at LHC

K. Hashino, M. Kakizaki, S.K., T. Matsui, P. Ko, Phys. Lett. B 766, 49 (2017)

Efficiency factor



[Espinosa et al. (2010)]

Red-shifted frequency

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

a_t: scale factor
f_t: frequency
at the transition

Conservation of the entropy per comoving volume

$$sa^3 = \frac{2\pi^2}{45} g_s T^3 a^3 = \mathrm{const}$$

$$\frac{a_t}{a_0} = \left(\frac{g_{s0}}{g_s^t}\right)^{1/3} \frac{T_0}{T_t}$$

Radiation dominant Universe

$$H = \sqrt{\frac{4\pi^3}{45}} g_*^{1/2} \frac{T^2}{M_{\rm Pl}}$$

We obtain

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

f_t/H_t must be > 1, typically 10^2 (10^2-10^4)

$1/f_t$ Wavelength of GWs at the PT
$1/H_t$ Size of the universe (horizon) at the PT

$$\boxed{f_0 = 10^{-3}\text{-}10^{-1}\ \mathrm{Hz}}$$

Characteristic GW Abundance from the strong EW 1st OPT

Normalized energy density

$$\Omega_{\mathrm{GW}}(f) \equiv \frac{1}{\rho_{\mathrm{c}}} \frac{d\rho_{\mathrm{GW}}}{d\ln f}$$

$$\begin{cases} \rho_{\mathrm{GW}} = \dfrac{1}{32\pi G}\langle \dot{h}_{ij}\dot{h}_{ij}\rangle \\ \rho_c = \dfrac{3H_0^2}{8\pi G} \end{cases}$$

$$h_{\mu\nu}^{\mathrm{TT}} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Transverse-Traceless gauge

Red shifted abundance

Scaling $\rho_{\mathrm{GW}} = \left(\dfrac{a_t}{a_0}\right)^4 \rho_{\mathrm{GW}}^t \quad \rho_c = \left(\dfrac{H_0}{H_t}\right)^2 \rho_c^t$

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

Characteristic GW Abundance from the strong EW 1st OPT

At the phase transition, we have

$$\rho^t_{\rm GW} \sim \frac{\dot{h}^2_{ij}}{G} \qquad \rho^t_c \sim \frac{H^2_t}{G}$$

Einstein Equation

$$\Box h_{ij} \sim G T_{ij}$$

$$\beta^2 h_{ij} \sim G T_{ij}$$

Typical duration of the phase transition: 1/β

$$\dot{h}_{ij} \sim \beta h_{ij} \sim \frac{G T_{ij}}{\beta}$$

Eenergy density at PT

$$\Omega^t_{\rm GW} = \frac{\rho^t_{\rm GW}}{\rho^t_c} \sim \frac{H^2_t}{\beta^2}\frac{T^2_{ij}}{(\rho^t_c)^2} \sim \frac{H^2_t}{\beta^2}\frac{\rho^2_{\rm kin}}{(\rho_{\rm vac}+\rho^t_{\rm rad})^2}$$

$$\Omega^t_{\rm GW} \sim \frac{H^2_t}{\beta^2}\frac{\kappa^2\alpha^2}{(1+\alpha)^2}$$

$$\alpha = \rho_{\rm vac}/\rho^t_{\rm rad}$$

$$\kappa = \rho_{\rm kin}/\rho_{\rm vac}$$

Characteristic GW Abundance from the strong EW 1st OPT

Abundance of GWs

$$\Omega_{\rm GW} h^2 \simeq 1.7 \times 10^{-5} \; \frac{H_t^2}{\beta^2} \frac{\kappa^2 \alpha^2}{(1+\alpha)^2}$$

$$\alpha = \rho_{\rm vac} / \rho_{\rm rad}^t \qquad \kappa = \rho_{\rm kin} / \rho_{\rm vac}$$

Energy density of false vacuum released by PT

Efficiency of kinetic energy of walls in the release energy.

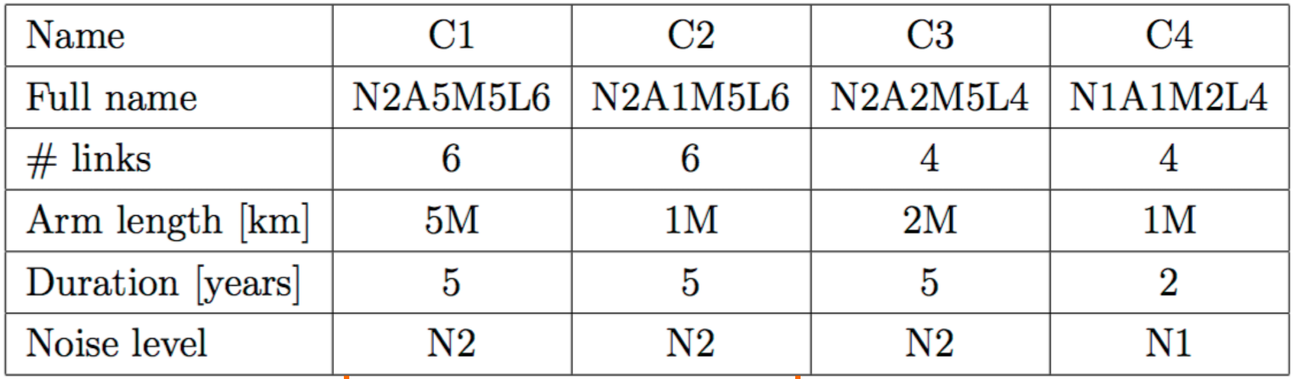
The spectrum is determined by
α (latent heat), β (duration of PT), κ (Efficiency)
They can be basically calculated if a model is given.

This rough estimation is applicable to GWs from the wall collision.
However, Ωh^2 is enhanced by β/H_t for GWs from the motion of thermal plasma fluid (sound waves and turbulence). ***Hindmarsh***

Laser interferometer space antena

Properties of the representative LISA configurations

C.Caprini *et al.*, arXiv:1512.06239



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

LISA has been approved in 2016
It will start from 2034

FP (Fabry-Perot)-DECIGO

1 cluster (arm length 1000km)
Correlation between 2 cluster

S. Kawamura et al, Class. Quant. Grav. 28, 094011 (2011)