The Golden Age 2030s

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“Scalars 2017”, University of Warsaw, 29 Nov. 2017

In deepest sympathy

I would like to thank
Maria Krawczyk
for her kind supports
and friendship
for almost 20 years

We pray that
her soul may rest in peace

Maria in TOYAMA at HPNP Meeting

This talk

- Introduction
  - Higgs as a probe of new physics
  - In the future we have the golden age to explore Higgs physics

    HL-LHC, ILC250, LISA, … in 2030s

- Precision study of Higgs sectors at ILC250 (Higgs Factory)

- Gravitational Waves
  - LIGO, Virgo, KAGRA → LISA (approved), DECIGO, BBO
  - A new tool to access the Higgs Potential/Phase transition

- Summary

Introduction

The LHC data show . . .

No contradiction with the SM prediction

No signal for new BSM phenomena

The SM is enough?

There are many reasons to consider BSM

Unification of Law

- **Paradigm of Grand Unification**
- **Yukawa structure (flavor physics)**

Problem in the SM Higgs

- **Hierarchy Problem, Shape of Higgs sector, Nature, …**

BSM Phenomena

- **Dark Matter, Neutrino mass and mixing**
- **Baryon Asymmetry of Universe, Inflation, Dark Energy, Gravity,…**

New Physics must exist!

Higgs: a key to new physics

Although Higgs boson was found, Higgs sector is unknown

- **Nature of Higgs boson**

$$\delta m_H^2 = \frac{\Lambda_{cutoff}^2}{16\pi^2}$$

Hierarchy Problem

New paradigm of New Physics

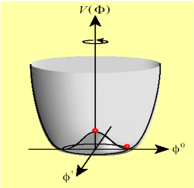
- **Structure**

Only one Higgs?

Multiplet structure, Symmetry, …

Relation to new paradigms and BSM phenomena

- **Higgs Potential**



$\mu^2 < 0$

EW Symmetry Breaking

Dynamics of EWSB

EW Phase Transition

By the discovery of *h*(125), these problems became frontier

Higgs sector is a probe of new physics

Extended Higgs sectors?

<u>Multiplet Structure (with additional scalars)</u>

Φ_{SM}+Isospin Singlet,

Φ_{SM}+Doublet (2HDM),

Φ_{SM}+Triplet, …

<u>Additional Symmetry</u>

Discrete or Continuous?

Exact or Softly broken?

<u>Interaction</u>

Weakly coupled or Strongly Coupled?

Hint for BSM models

Simplest Extension

2 Higgs doublet model (2HDM)

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

Sharing the VEV $\quad v = 246 \text{ GeV} = \sqrt{v_1^2 + v_2^2} \qquad \tan\beta = \frac{v_2}{v_1}$

Field Mixing

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

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

New Particles $\quad h \quad H \quad A \quad H^\pm$

CP-odd: A Charged: $H^\pm$

h ↑ *h*(125)

H, A, $H^\pm$: Additional bosons

Other three are unphysical Nambu-Goldstone bosons

Deviation in the couplings of *h*(125)

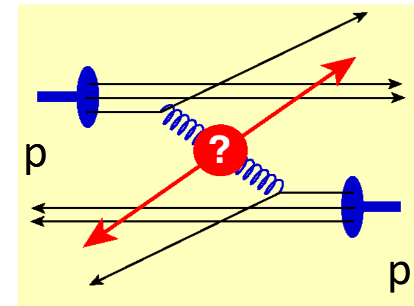
	SM		2HDM
hVV	1	→ *hVV*	sin(β−α)

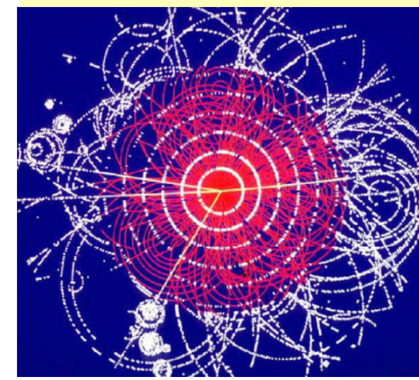
LHC: Hadron Collider

Run1	7-8 TeV	20fb^{-1}
Run 2,3	13-14 TeV	300fb^{-1}
HL-LHC	14 TeV	3000fb^{-1}

Machine for discovery

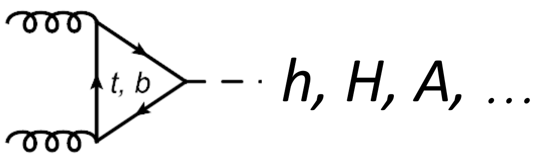
At some probability, elementary process with very large energy can occur





- **Direct searches of additional Higgs bosons**

  h*(125), *H, A, H^+, H^{++}, …

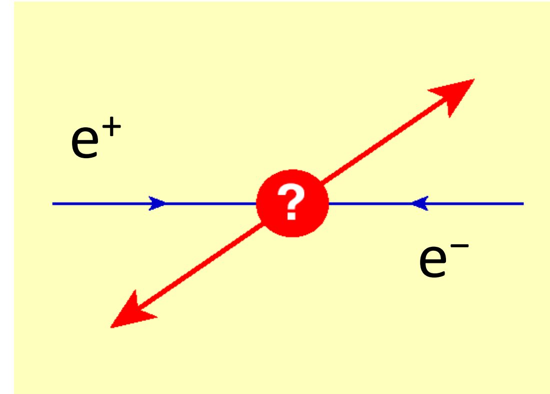


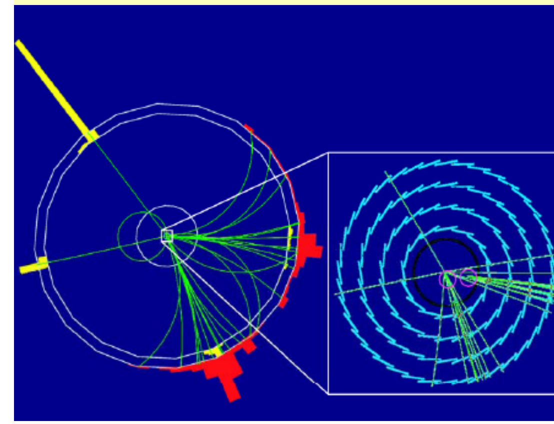
- **Indirect test by finding deviations from SM**

  Couplings of *h*(125) ***hWW, hZZ, hγγ, hff, hhh, …***

Precision rather limited by huge QCD backgrounds etc

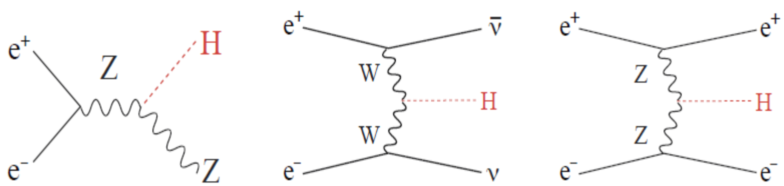
Lepton Collider



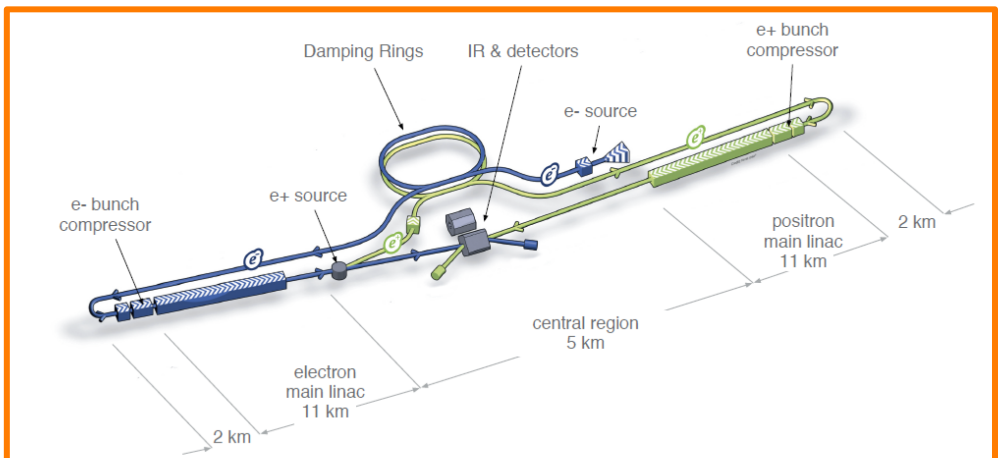


Machine for precision measurements!

- Simple Kinematics
- Low QCD backgrounds
- Beam polarization (linear collider)
- Energy Scan (linear collider)



International Linear Collider (ILC)



Next Generation Linear Collider
Energy 250-500 GeV, 1TeV)

- TDR published
- Technically ready
- Waiting for approval
- Hosted by Japan (Iwate)

New proposal (ILC250)

~~ILC (TDR) 250GeV→500GeV, and 1TeV~~

It takes time for making decision (due to the cost!)

ILC250 as Higgs Factory (proposed in 2017)

- Collision Energy *E* = 250GeV (40% cost reduction)
- Run in the similar time to HL-LHC (2030s)
- Accumulate 2ab^{-1} by running for 10 years
- Possibility of a future energy extension

ILC250 Valueable?

Slide from ILC250 Committee

Committee on the Scientific Case of ILC250 Higgs Factory

July 22, 2017 Report to the HEP community (V1)

Shoji Asai* (U. Tokyo), Junichi Tanaka (ICEPP, U. Tokyo), Yutaka Ushiroda (KEK), Mikihiko Nakao (KEK), Junping Tian (ICEPP, U.Tokyo), Shinya Kanemura (Osaka U.), Shigeki Matsumoto (Kavli IPMU, U.Tokyo), Satoshi Shirai (Kavli IPMU, U. Tokyo), Motoi Endo (KEK), Mitsuru Kakizaki (Toyama U.)
***chair**

Commissioned by the Japan Association of High Energy Physicists
An independent review of the scientific case of the ILC by ATLAS, Belle II, Theory members

Commissioned by the Japan Association of HEP. July 26.

In light of the recent outcomes of LHC Run 2, JAHEP proposes to promptly construct ILC as a Higgs factory with the center-of-mass energy of 250 GeV in Japan.

Physics Case for the 250 GeV Stage of the ILC

K. Fujii, C. Grojean, M. Peskin, et al. arXiv:1710.07621

ICFA statement. Nov. 8, 2017 (Extracts)

ICFA welcomes the efforts by the Linear Collider Collaboration on cost reductions for the ILC, which indicate that up to 40% cost reduction relative to the 2013 Technical Design Report (500 GeV ILC) is possible for a 250 GeV collider.

ICFA thus supports the conclusions of the Linear Collider Board (LCB) in their report presented at this meeting and very strongly encourages Japan to realize the ILC in a timely fashion as a Higgs boson factory with a center-of-mass energy of 250 GeV as an international project, led by Japanese initiative.

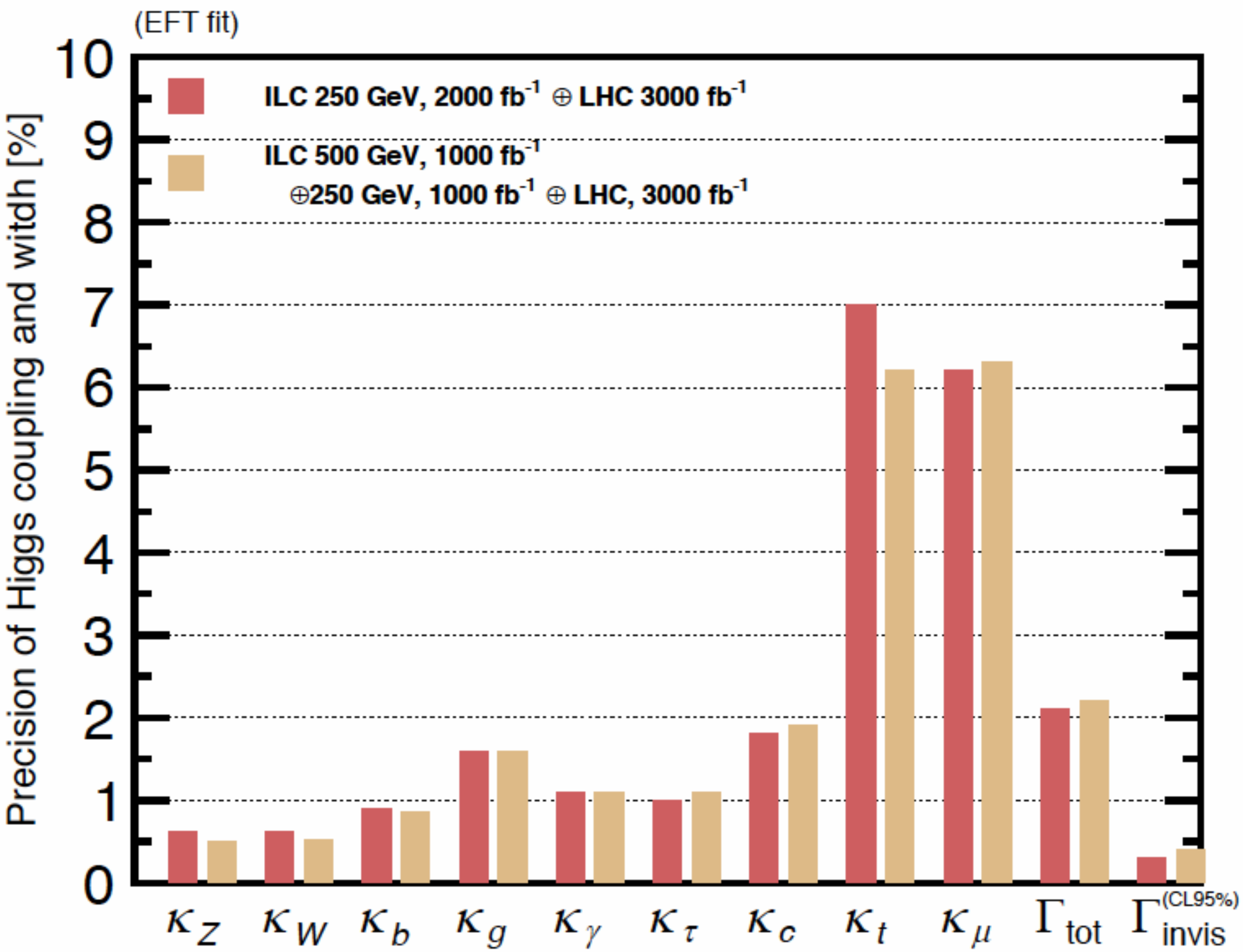
ICFA: International Committee for Future Accelerators

Slide from ILC250 Committee

Synergy is Key

Challenging tasks for ILC250	Solutions with Synergy
Higgs Full Width	HL-LHC: custodial symmetry ($K_W/K_Z = 1$) Replace Γ_{HZZ} with Γ_{HWW} $\Gamma_{total}=\Gamma_{HWW}/Br(H\to WW)$ → comparable with ILC500 precision
Self-coupling HHH (challenging with ILC500)	Baryon number violation → EWBG or LG (T2K, double beta decay) EW baryogenesis HL-LHC, ILC250, SuperKEKB, Gravitational waves ILC250 possible
Higgs coupling	HL-LHC (Yt) Lattice (mb,mc,αs uncertainty) → comparable with ILC500 SuperKEKB (Lattice examination)
Search	Electroweak gaugino search based on naturalness Higgsino mass < ~200GeV Dark matter search (<62GeV)
Top mass	HL-LHC(0.2~0.3GeV) SM precision sufficient Precision sufficient for vacuum stability discussion (if a detailed probe of high scale physics needed, upgrade to ILC350)

Slide from ILC250 Committee



ILC250 precision is comparable to ILC500
Synergy with LHC is key

With HL-LHC

No big difference is observed between ILC 250GeV and ILC 500GeV

1.1 Higgs coupling

Model Independent
coupling measurement precision ILC250+HL-LHC

Slide from ILC250 Committee

coupling Δg/g	500 fb-1	2000 fb-1
HZZ	1.1%	0.63%
HWW	1.1%	0.63%
Hbb	1.7%	0.89%
Hcc	3.5%	1.8%
Hgg	3.1%	1.6%
Hττ	2.0%	1.0%
Hγγ	1.5%	1.1%
Hμμ	27%	13%
Γ_H	4.1%	2.1%
BR(H->inv.) (95% CL)	0.61%	0.31%

Effective Field Theory approach

Used as input for theory models

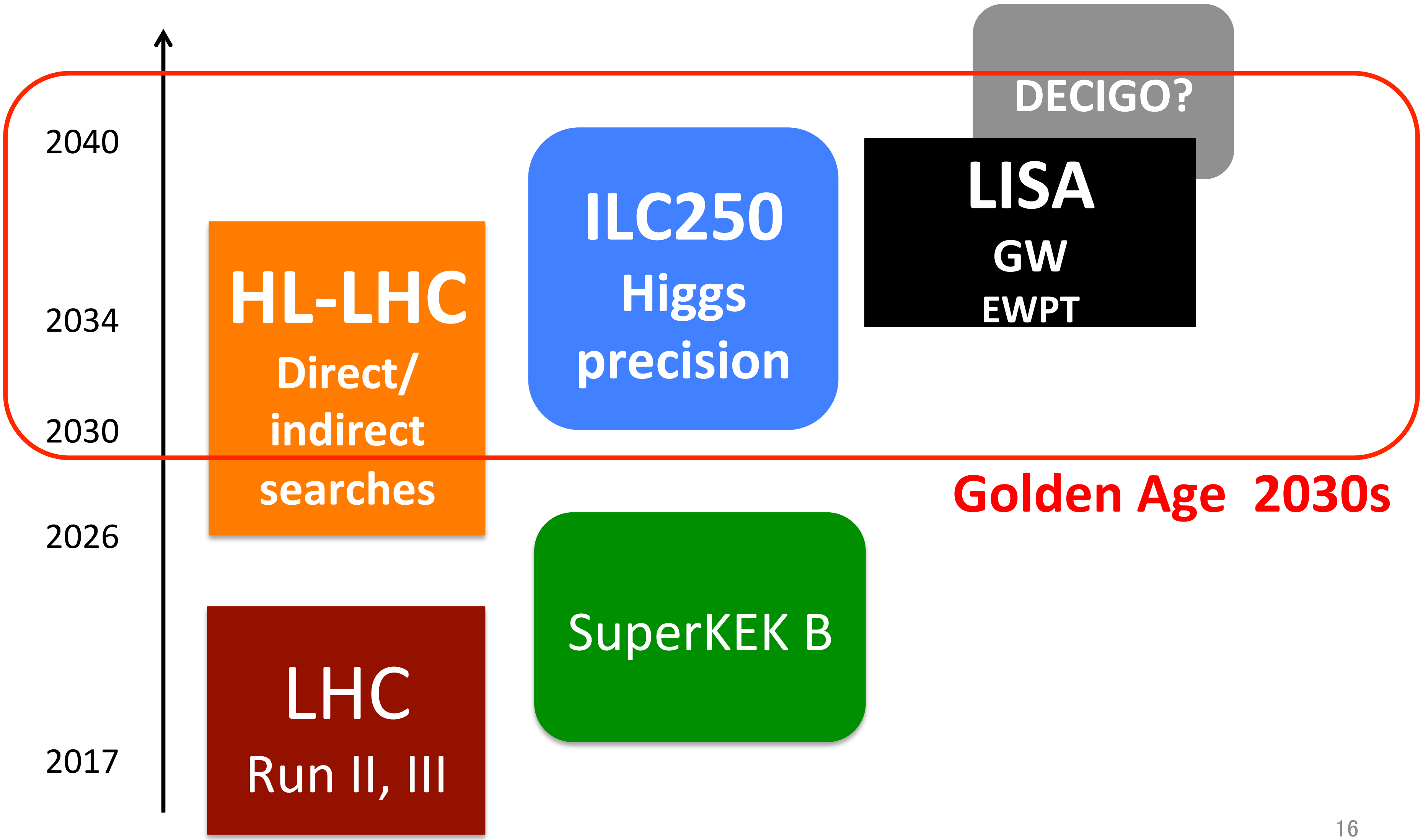
Systematic uncertainty is key

α_s	0.08%
m_b	0.1%
m_c	0.7%
b-tag	0.1%

1) HL-LHC W/Z custodial symmetry → improve precision
2) Use HL-LHC (e.g. Higgs coupling with top, μ, γ)

1) Coupling to Fermion : ~1.5% (top: ~7%)
2) Coupling to Z/W : ~0.6%
3) Coupling to γ/g : 1-2%
4) Coupling to 2nd gen. : 2-7 %

Future experiments



Precision study at ILC250
a Higgs factory

Deviation = New Physics scale

Scaling factor κ_i : factor of deviation from the SM value

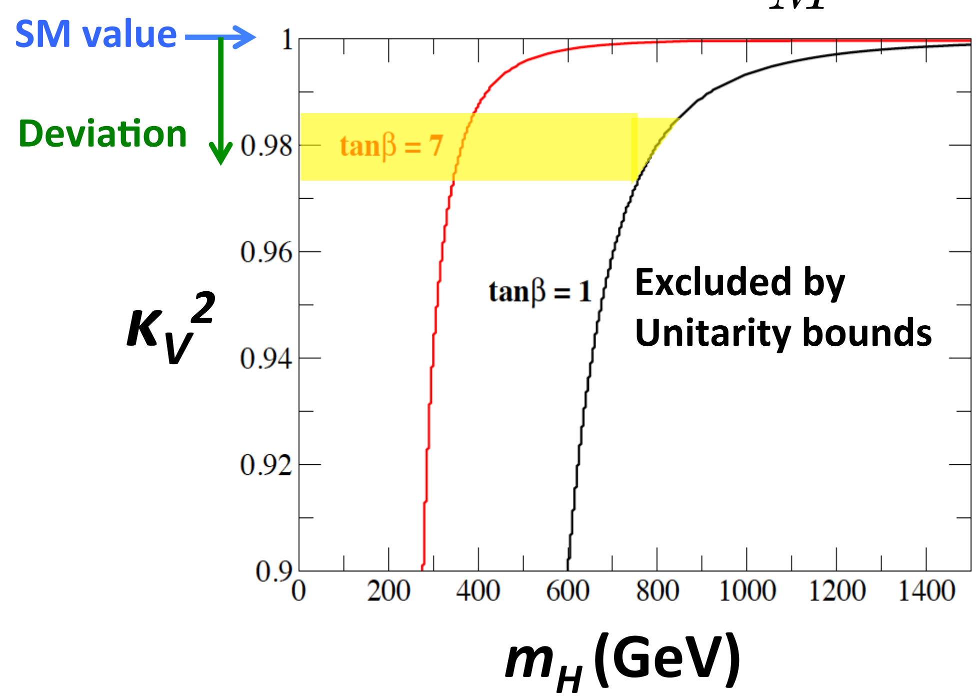
Coupling of h(125) and weak bosons
V (=W, Z) hVV

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

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

If a 2% deviation in κ_V^2

The second Higgs H must be lighter than 800 GeV



Precision test has the similar power to the direct search

Patterns of deviations in 2HDM

Gauge couplings | Yukawa couplings

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

	hVV	hττ	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

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

x = cos(β−α) **SM-like: |x| <<1**

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

When a Fermion couples to Φ_1

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

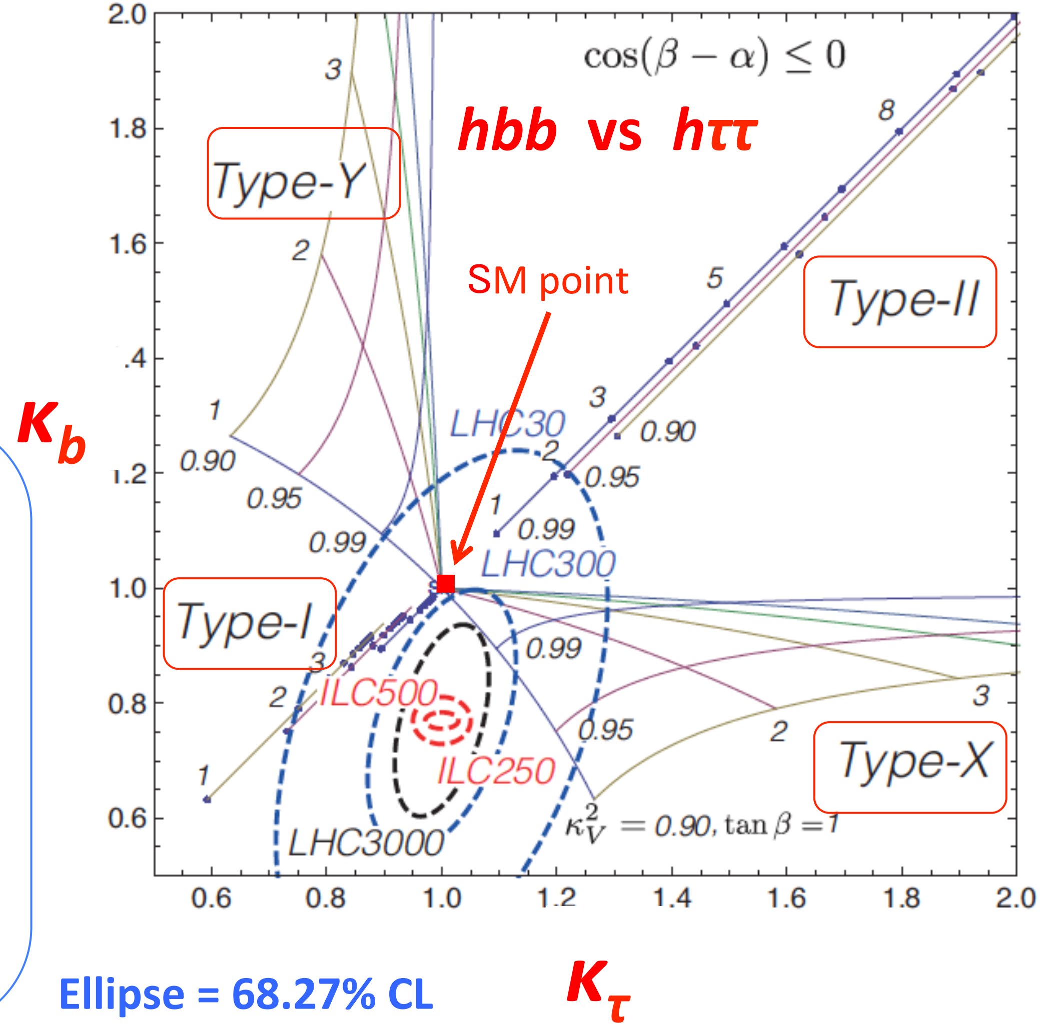
and if it couples to Φ_2

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

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, …

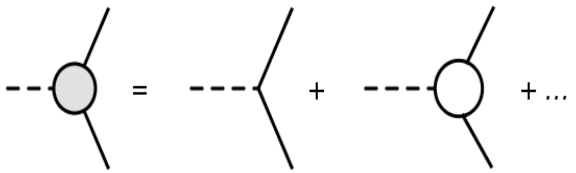
SK, K. Tsumura, K. Yagyu, H. Yokoya, 2014



Ellipse = 68.27% CL

Radiative Corrections

Higgs couplings *$h\gamma\gamma$, hgg, hWW, hZZ, $h\tau\tau$, hbb, htt, …*
will be measured thoroughly in the future



Analyses with radiative corrections are necessary

Accurate Theory Predictions × **Future Precision Measurements**

⬇

New Physics!

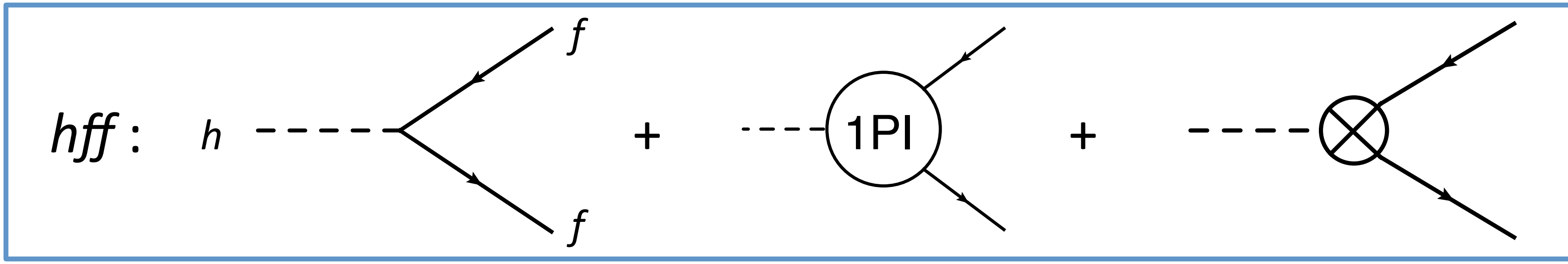
H-COUP Project *SK, Kikuchi, Sakurai, Yagyu (2017)*

Full set of Fortran codes to systematically calculate quantum corrections to Higgs couplings in various extended Higgs models

Program H-COUP ver. 1 has been completed
[Manual arXiv: 1710.04603]

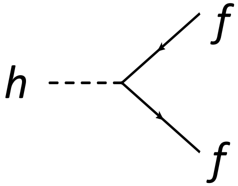
Models
- Additional Singlet
- 2HDM (I)
- 2HDM (II)
- 2HDM (X)
- 2HDM (Y)
- Inert doublet/singlet
- Triplet model

For example: renormalized *hff* coupling



tree level 1-loop level counter term

tree level



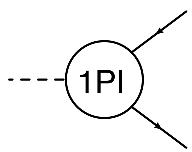
$$= -\frac{m_f}{v}\xi_h^f$$

$$\xi_h^f = \sin(\beta-\alpha) + \xi_f \cos(\beta-\alpha)$$

α : mixing angle for CP-even Higgs *H,h*

β : mixing angle for CP-odd Higgs *A,G⁰*

1-loop level



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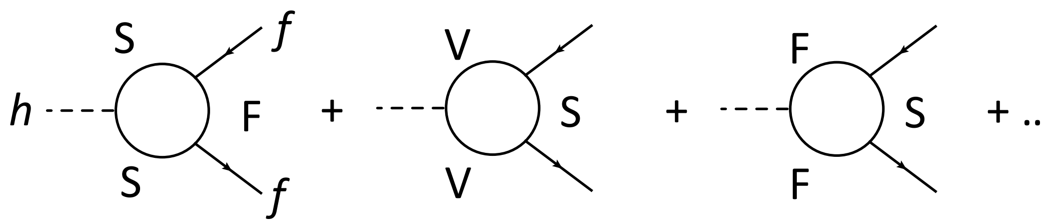
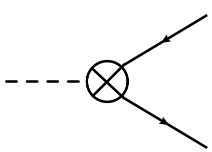


counter term



$$= -\frac{m_t}{v}\xi_h^f\left[\frac{\delta m_f}{m_f} - \frac{\delta v}{v} + \frac{1}{2}\delta Z_h + \delta Z_f + \frac{\delta \xi_h^f}{\xi_h^f} + \frac{\xi_H^f}{\xi_h^f}(\delta C_h + \delta\alpha)\right]$$

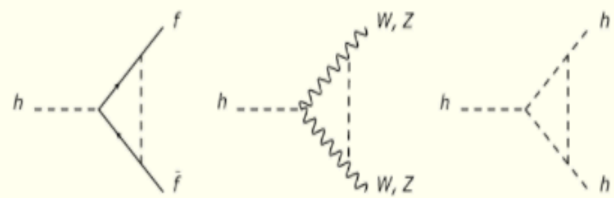
counter term parameters : $\delta m_f, \delta v, \delta\alpha, \delta\xi_h^f, \delta Z_h, \delta Z_f, \delta C_h$

these are determined by relevant renormalization conditions.

H-COUP

www-het.phys.sci.osaka-u.ac.jp/~kanemu/HCOUP_HP1013/HCOUP_HP.html

H-COUP



H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The impolved on-shell renormalization scheme is adopted, where the gauge depdence is eliminated.

Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 1.0 can be taken on arXiv:1710.04603 [hep-ph].

Downloads

- H-COUP version 1.0 : [HCOUP-1.0.zip] [The manual is here]

In order to run H-COUP version 1.0, you need to install LoopTools (www.feynarts.de/looptools/).

History

Contact

One can download the H-COUP program and the manual on this website

$\Delta\Gamma(h \to \tau\bar{\tau})$ vs $\Delta\Gamma(h \to b\bar{b})$

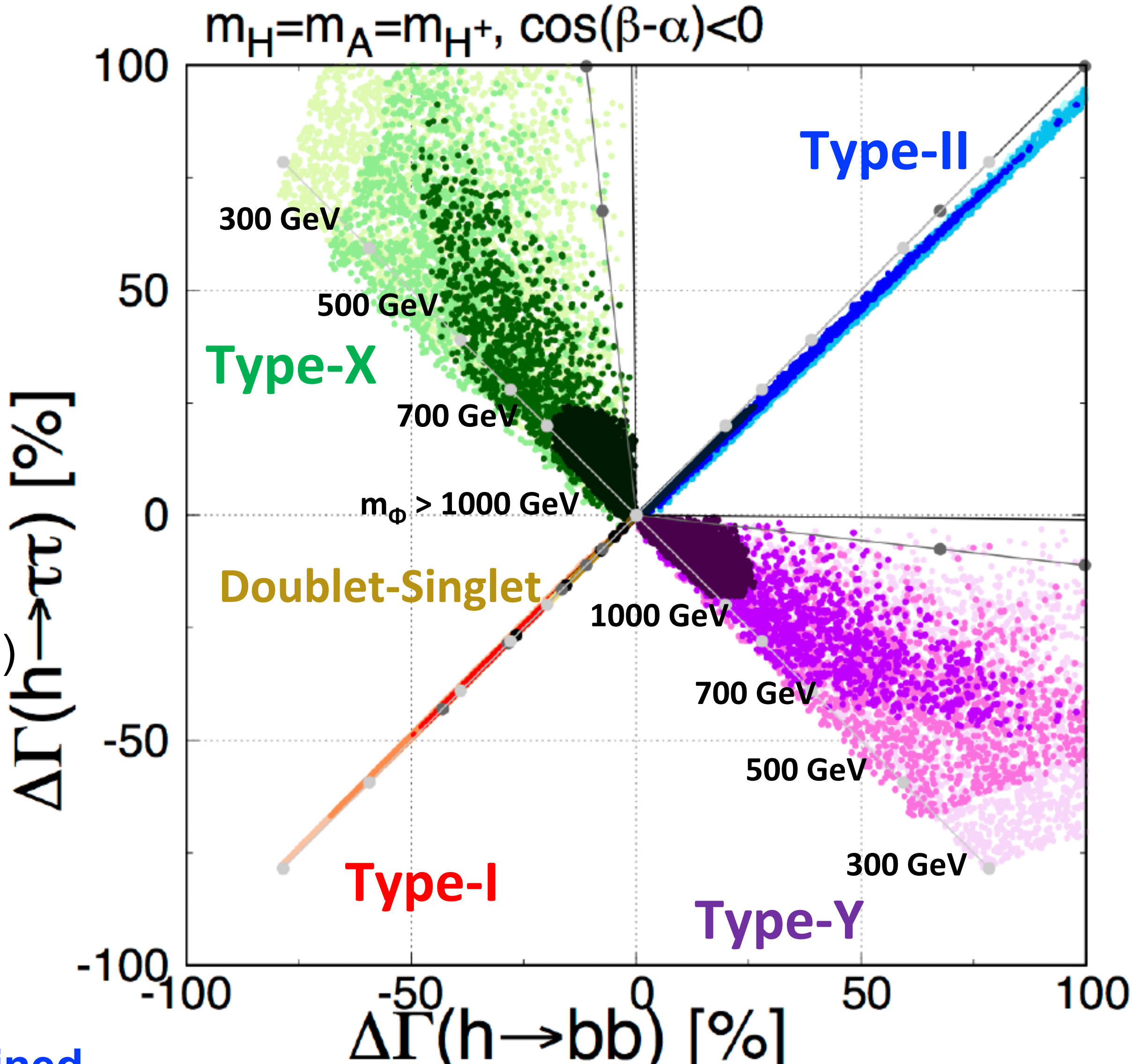
Deviations from the SM

$$\Delta\Gamma(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$

- Color plot : predictions at the 1-loop level
- Color gradation : upper bound on the mass m_Φ ($=m_H=m_A=m_{H+}$) of additional Higgs bosons

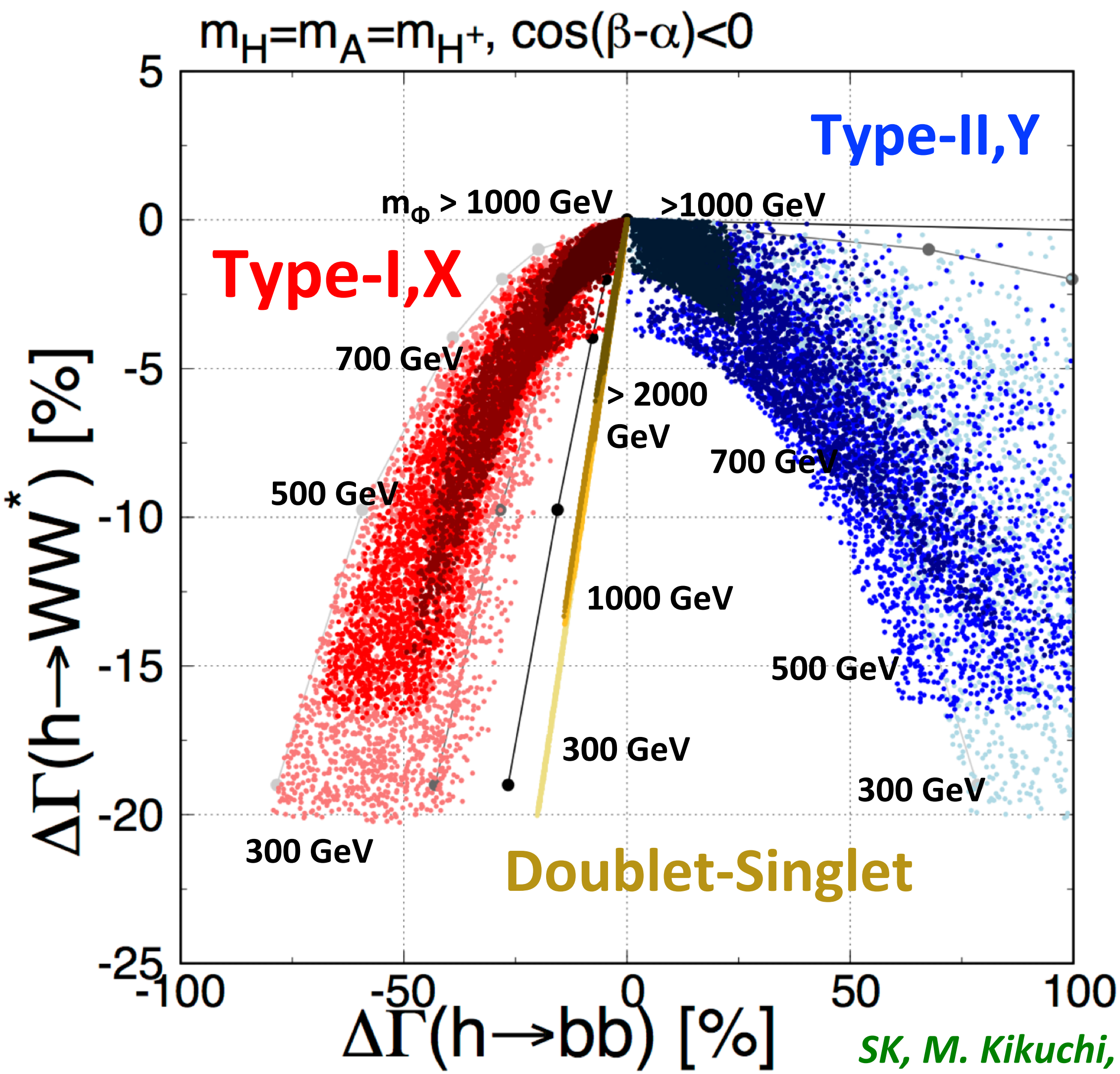
4 types of the 2HDMs can be discriminated.

Information of inner parameters such as m_Φ, tanβ, α, … can be obtained



SK, M. Kikuchi, K. Mawatari, K. Sakurai, K. Yagyu
In preparation

$\Delta\Gamma(h \to WW^*)$ vs $\Delta\Gamma(h \to b\bar{b})$



Deviations from the SM :

$$\Delta\Gamma = \frac{\Gamma_{EX}}{\Gamma_{SM}} - 1$$

SK, M. Kikuchi, K. Mawatari, K. Sakurai, K. Yagyu, In preparation

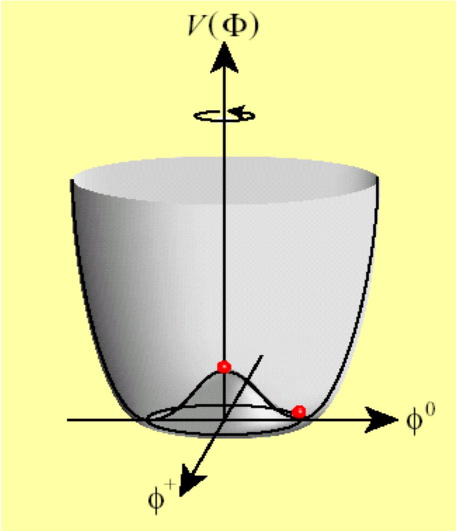
Doublet-Singlet model can be separated from 2HDM-I

Higgs potential

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

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

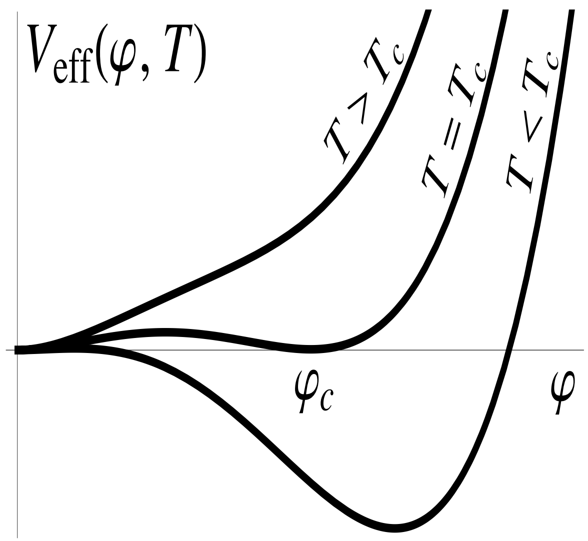
- **Physics behind EWSB**
  - Where come from $\mu^2 < 0$
  - What is the origin of λ
  - Dynamics

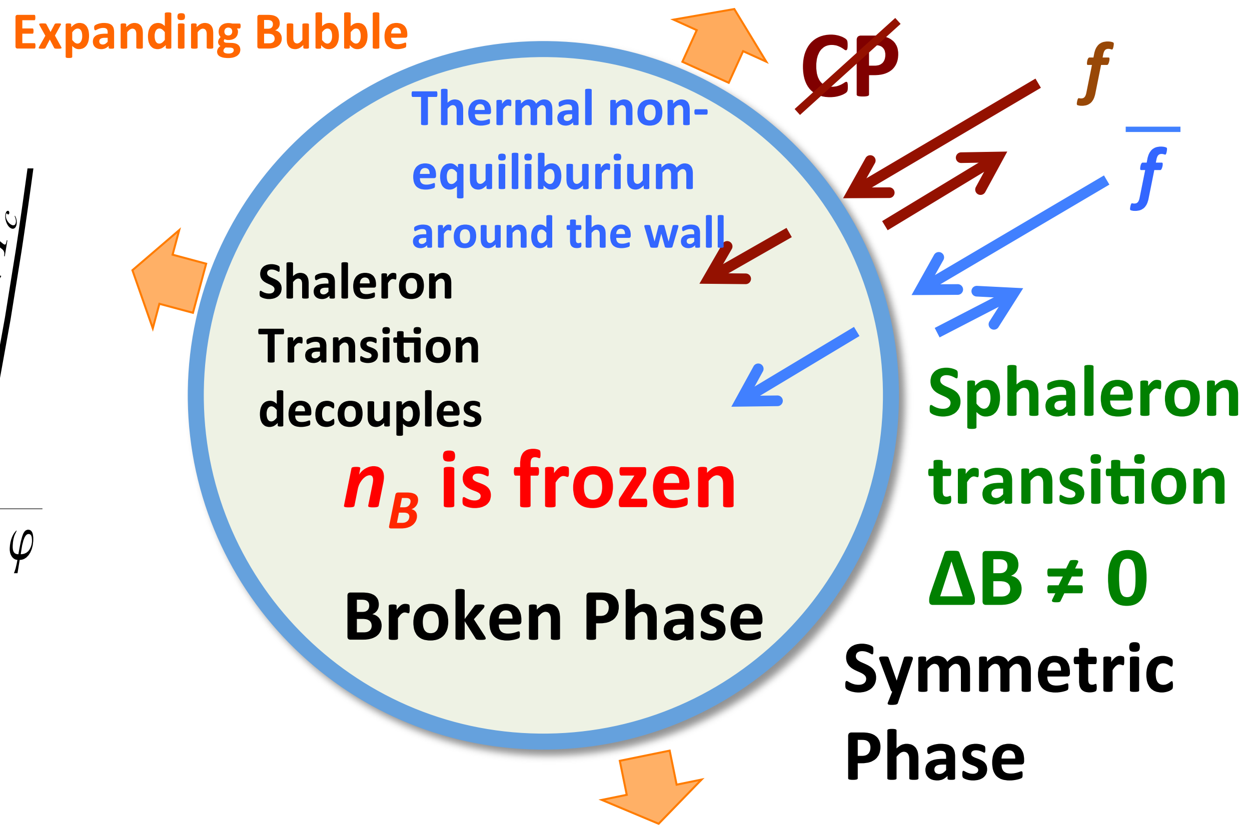


- **Electroweak Phase Transition**
  - Aspect of Transition, 1st order or not?
  - Relation to EW baryogenesis
  - Mechanism of Phase Transition

Electroweak Baryogenesis

1^{st} OPT is required





Sakharov 3rd condition

Departure from Thermal equilibrium

Sphaleron Decoupling
(strongly 1^{st} OPT)

$$\frac{\varphi_c}{T_c} \gtrsim 1$$

Physics of the
Higgs potential

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

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

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

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

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

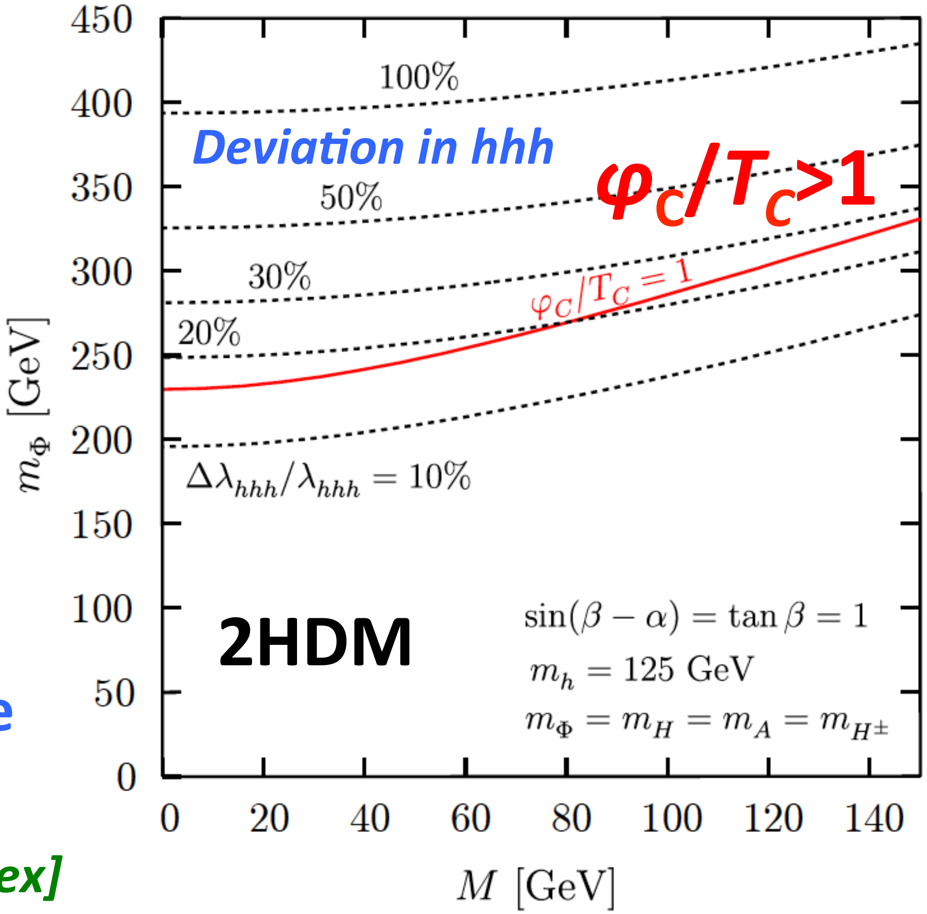
Which collider?

(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)



But now ILC(1TeV) became out of plan!

New tool

At ILC250, FCCee,… the *hhh* coupling cannot be measured

We cannot test the Higgs potential so long?

<u>Fortunately,</u>

the situation has changed by the discovery of GWs

GW can be a new tool to explore physics of EWPT (Higgs potential)

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 experimetns

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

$T = 100\text{GeV} \rightarrow f = 10^{-1} - 10^{-3}$ Hz

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

Future space based GW experiments

LISA — Sensitivity around mili Hz (approved 2034–)

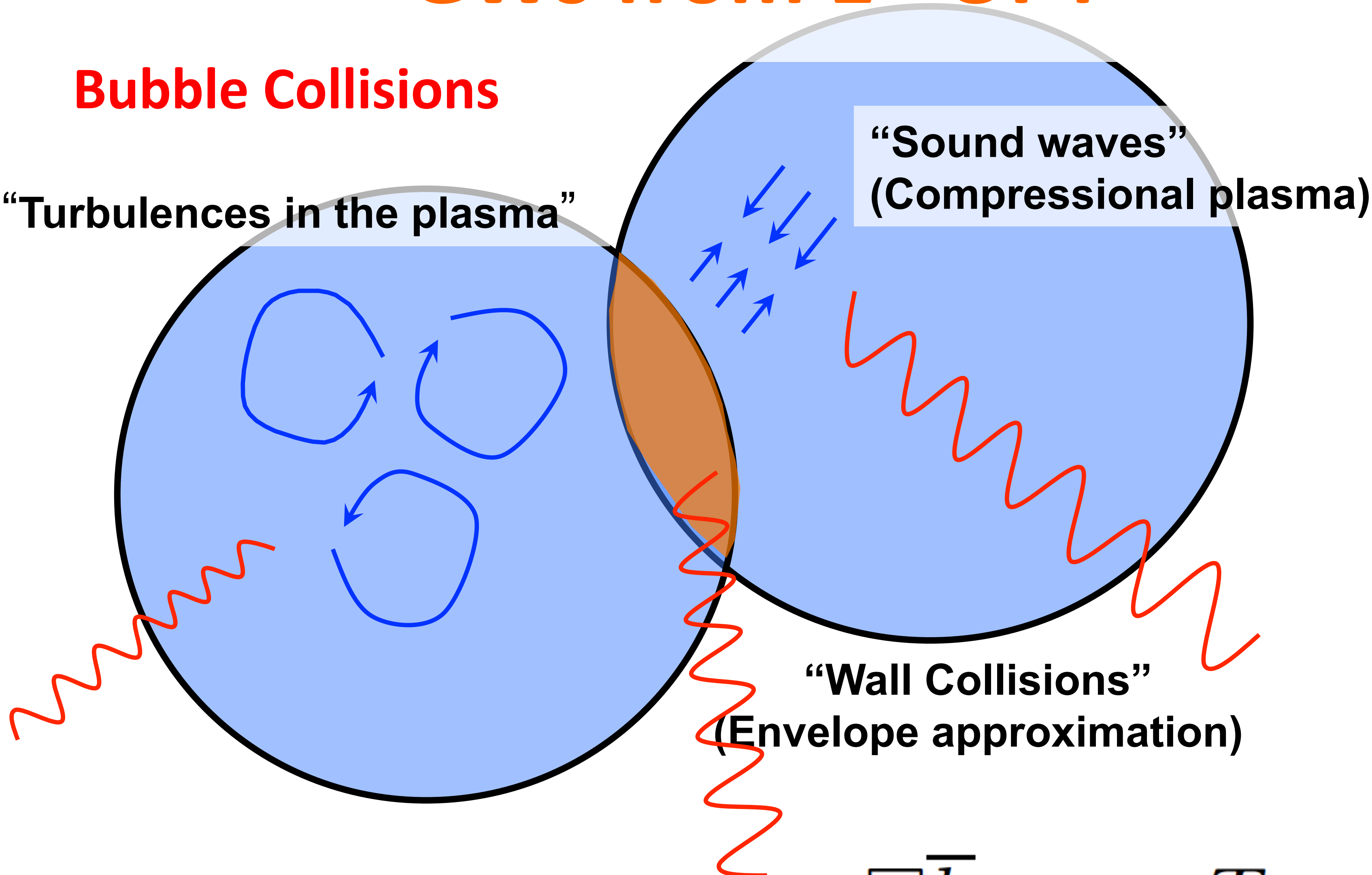
DECIGO — Sensitivity around deci Hz

We can explore GWs from the early Universe!

Grojean, Survant, …

GWs from 1st OPT

Bubble Collisions

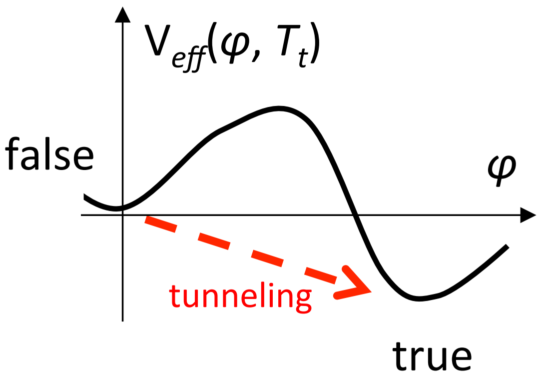


Spherical symmetry is violated by bubble collisions → GW occurs

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

Source of GW

From bubble dynamics to GW spectrum



$\Gamma(T) = \Gamma_0 \exp(-S_3/T)$

With the phase transition condition
$\Gamma(T)/H^4 = 1$ we can determine

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

Bubble nuclitization（inverse of β） β — **Speed of phase transition**

From these parameters we can calculate GW spectra.

Ex）Sound Wave (Compressional wave)のGW spectrum

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

C.Caprini et al., arXiv:1512.06239

Higgs model with *N* singlet fields

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: $m_S^2 = \mu_S^2 + \frac{c}{2}v^2$

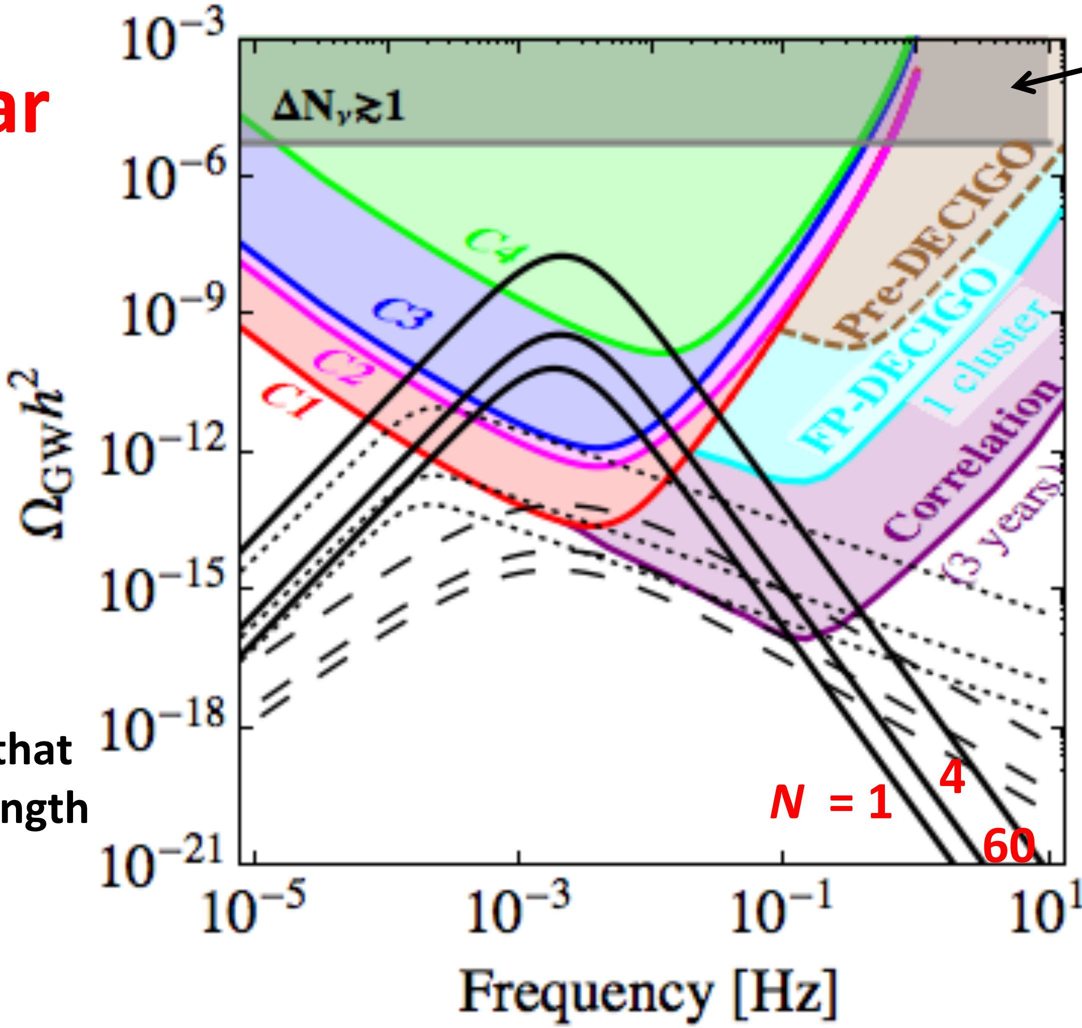
φ_c/T_c > 1 is satisfied by the nondecoupling effect of the singlet fields（compatible with m_h=125GeV）

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

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

GW spectrum from 1st OPT

***N* scalar model**



Bound from Non-observation of energy density of extra radiation

Mass m_s is chosen such that the peak strength is maximal

Sensitivities

eLISA
arXiv:1512.06239

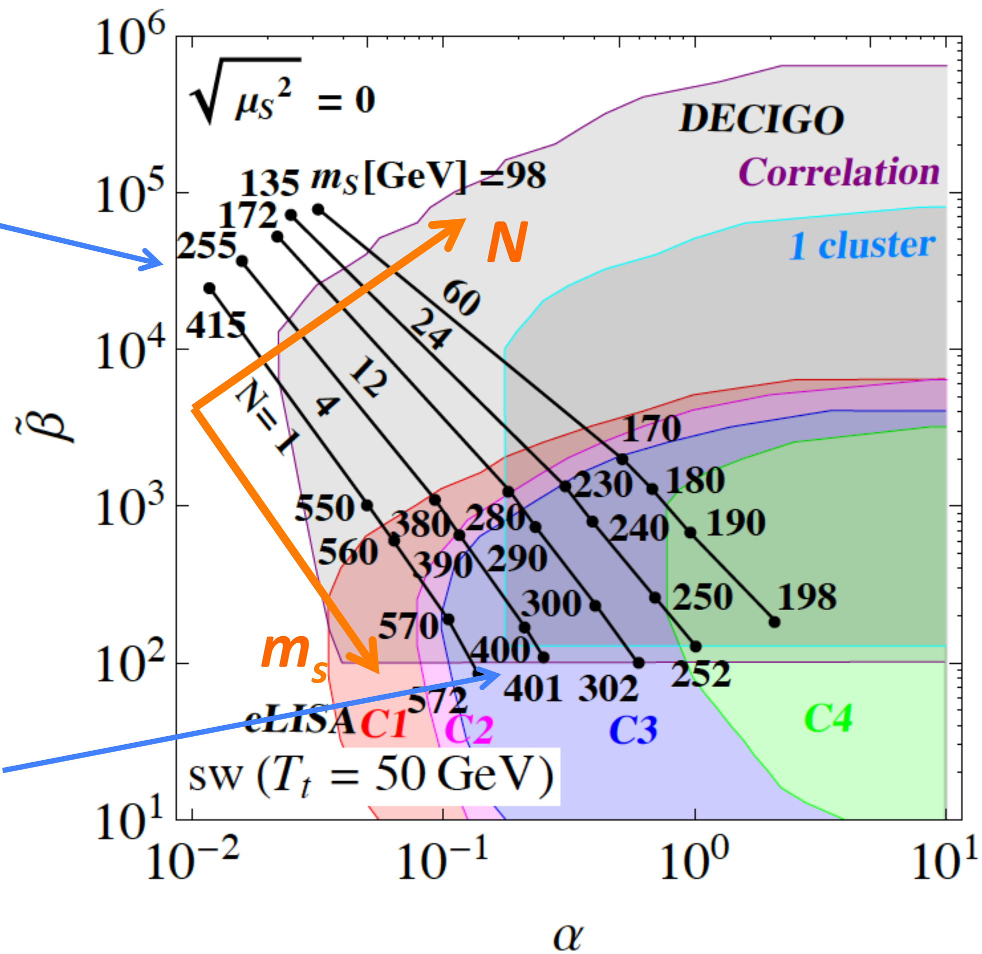
DECIGO
Class. Quant. Grav. 28, 094011 (2011)

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



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

Sensitivities

eLISA
arXiv:1512.06239

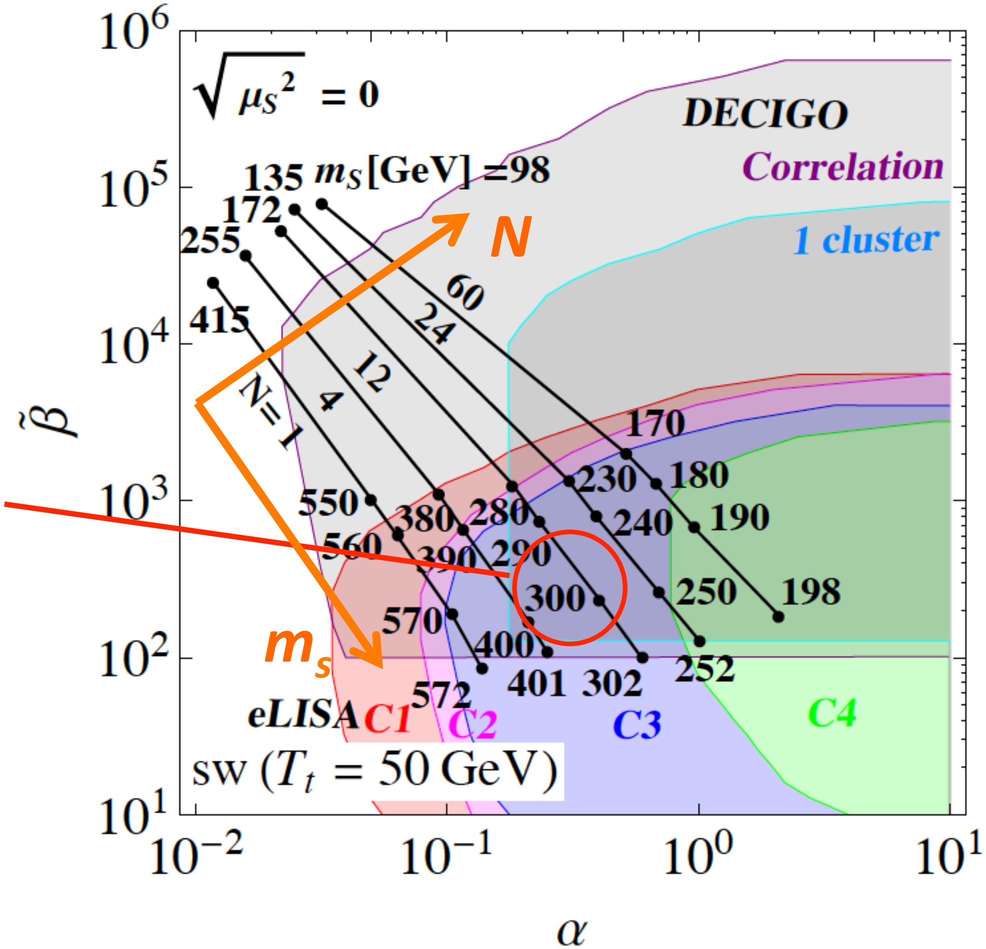
DECIGO,
Class. Quant. Grav. 28, 094011 (2011)

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

Final Example: Strongly 1st OPT by non-thermal mixing effect

Thermal loop effect ↓

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

Non-thermal effect ↑

Higgs singlet model

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

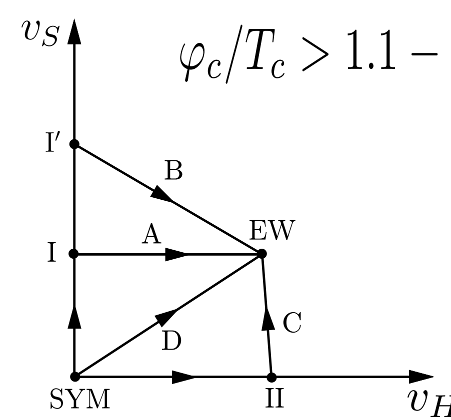
$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + \phi_1 + iG^0) \end{pmatrix}, \quad S = v_S + \phi_2$$

$(\phi_1, \phi_2) \to$ (h, H) with θ

Multi-field analysis of EWPT is necessary

$$(v_\Phi, v_S)$$

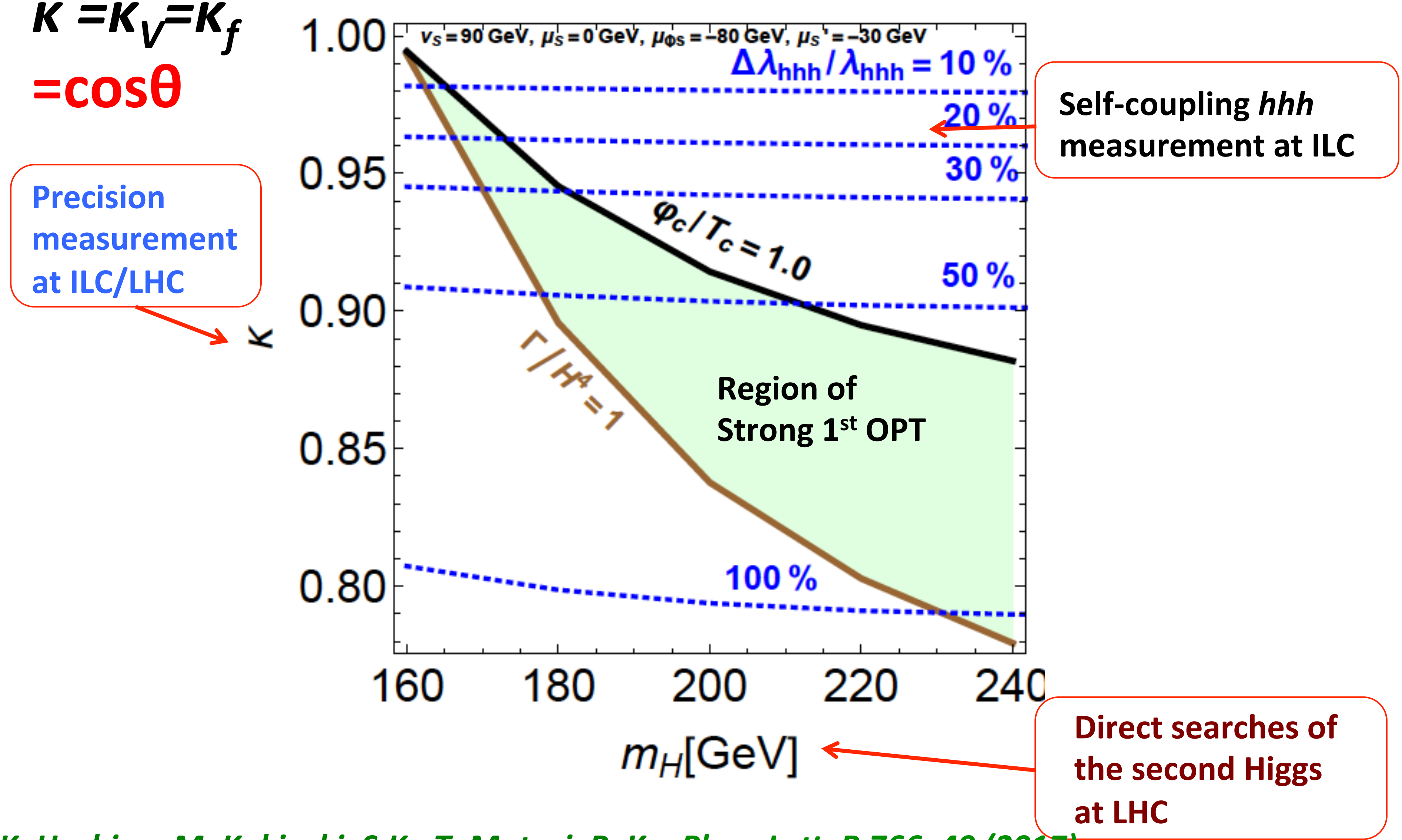
$\varphi_c/T_c > 1.1 - 1.2$



Public tool "CosmoTransition" (Python code) is used.

$\kappa = \kappa_V = \kappa_f$

$= \cos\theta$



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

$\kappa = \kappa_V = \kappa_f$

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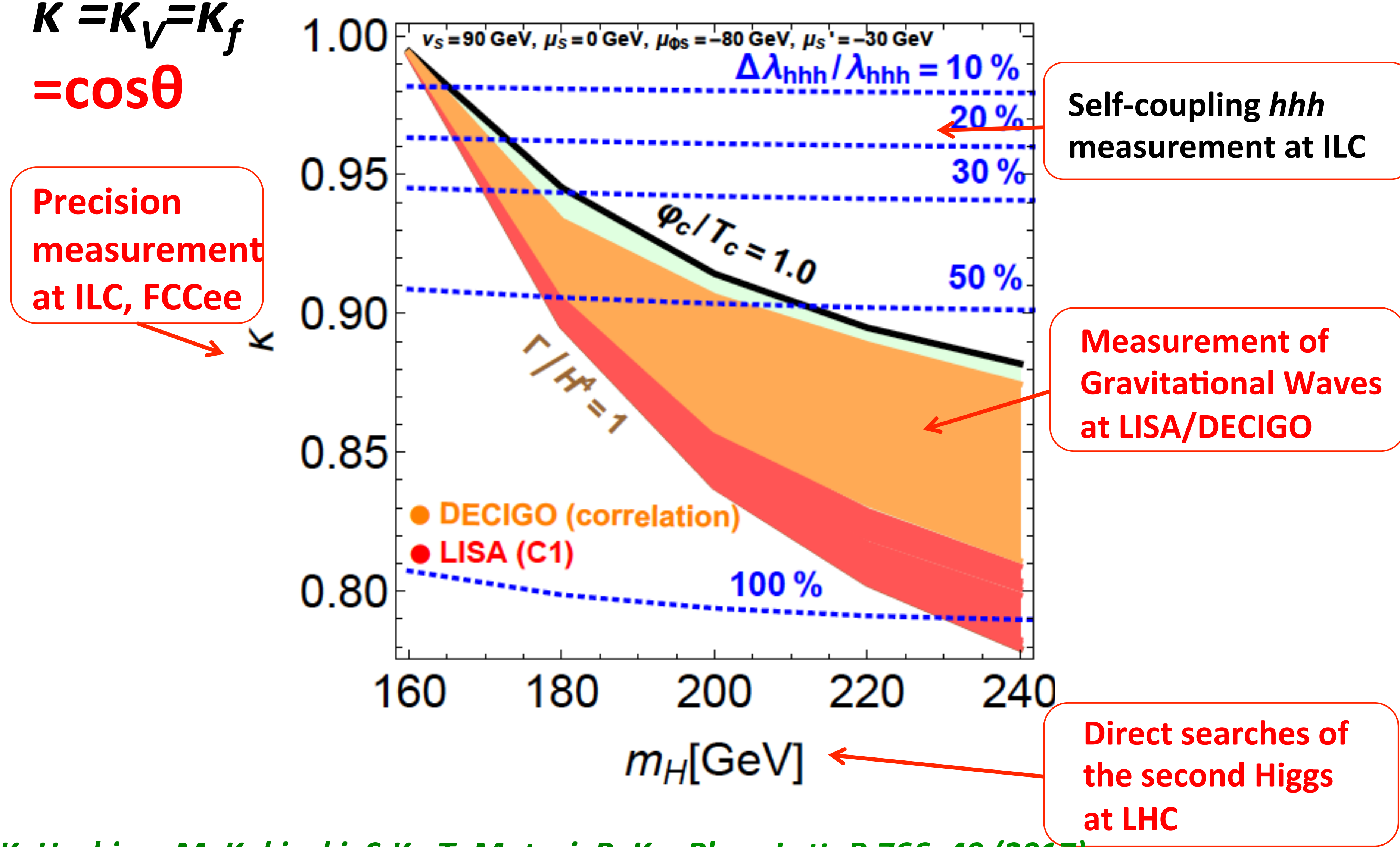
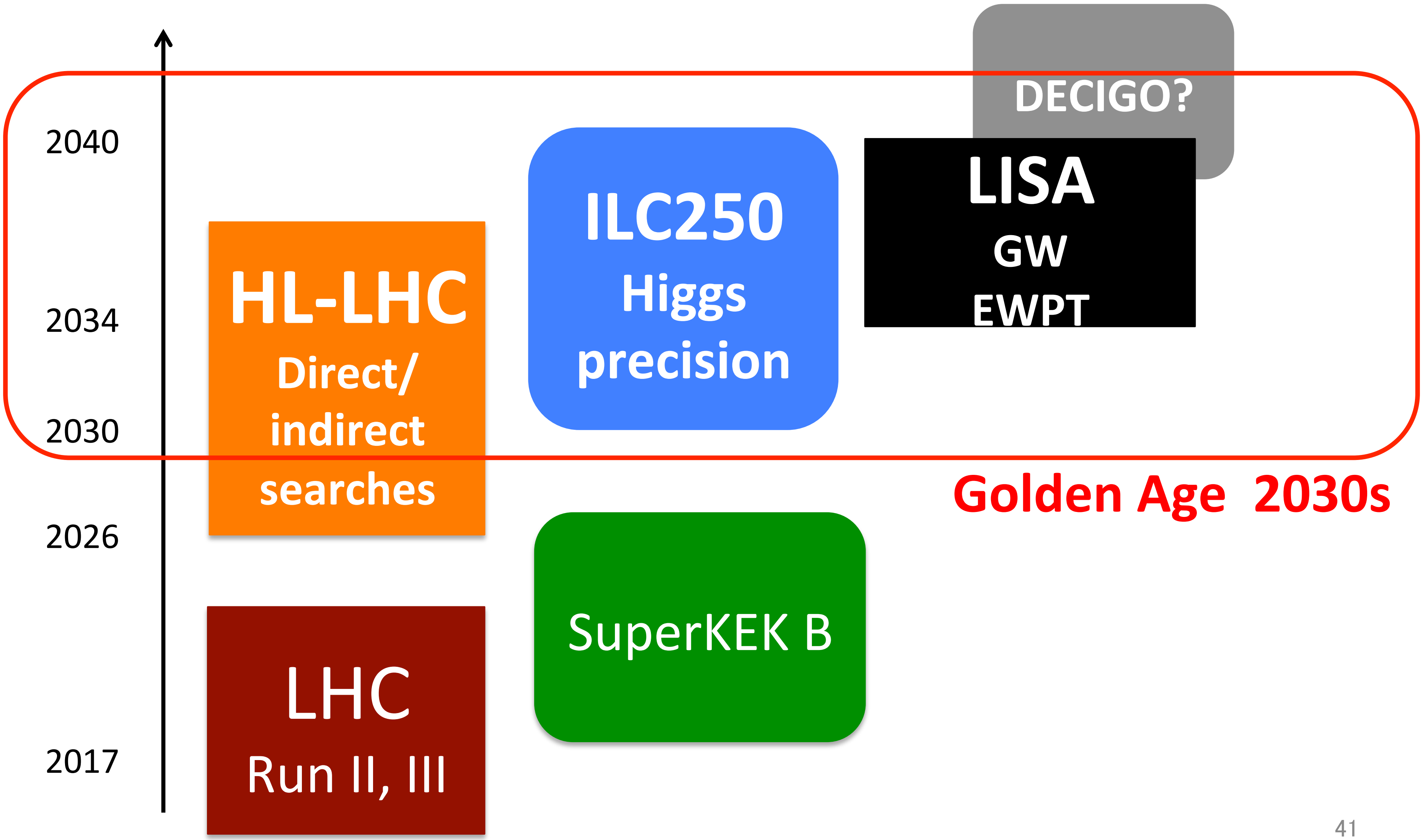


K. Hashino, M. Kakizaki, S.K., T. Matsui, P. Ko, Phys. Lett. B 766, 49 (2017)

Future experiments



Summary

In 2030-40s, three experiments will be run at the same time!

- **Hadron Collider（HL-LHC）** **Direct searches of new particles**
- **Lepton Collider （ILC250）** **Higgs factory** **Precision Study**
- **Space based GW tests（LISA/DECIGO）** **EWPT, Higgs potential**

The details of the Higgs sector can be determined,
and the direction of new physics will be clarified

Then, we may get more information for the new physics scale to be examined thereafter.

LC upgrades or next generation hadron collider?

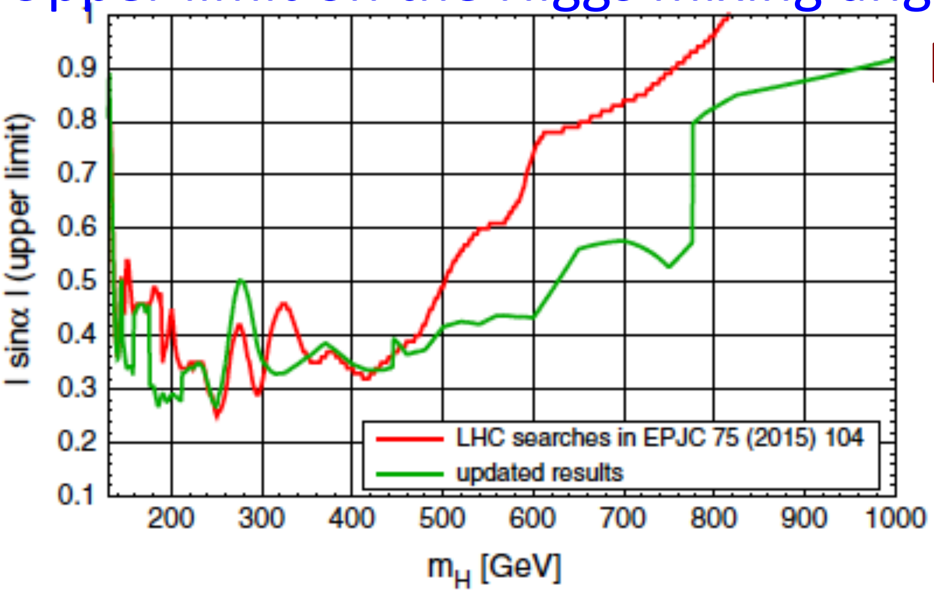
The golden age will have come!

Back up slides

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

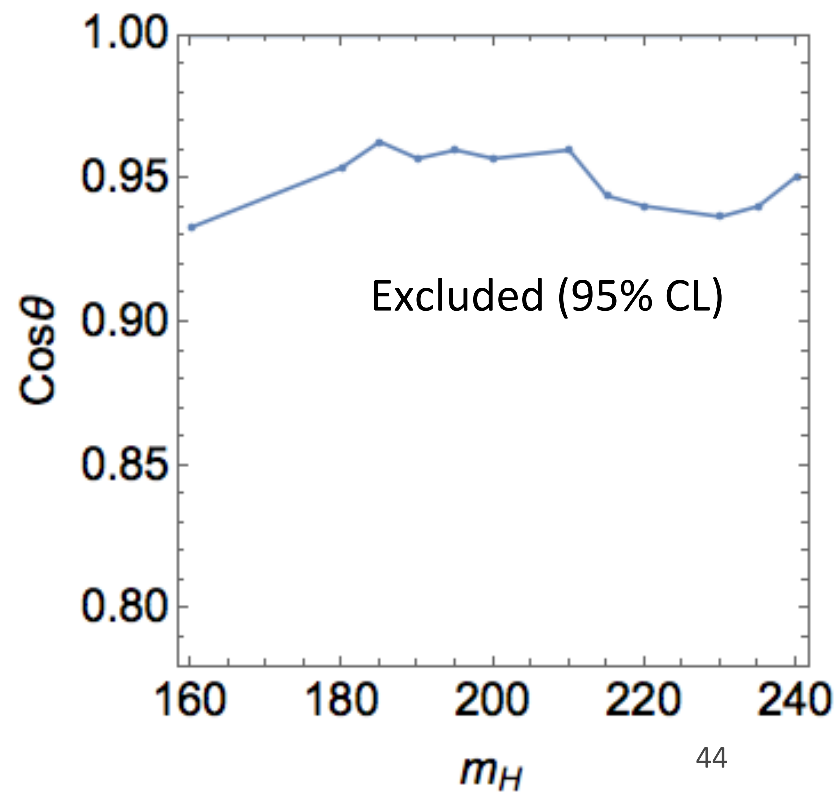
Upper limit on the Higgs mixing angle $|\sin\theta|$

[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 $\kappa(=\cos\theta)$



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

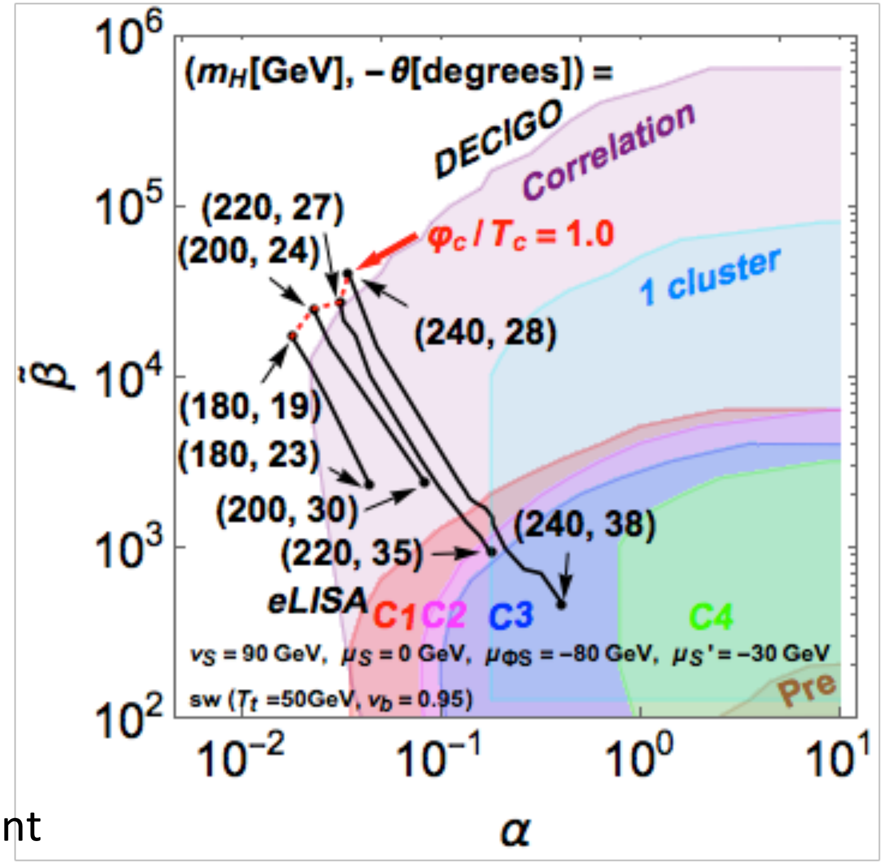
FP (Fabry-Perot)-DECIGO

1 cluster (arm length 1000km)

Correlation between 2 cluster

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

K.Hashino, M.Kakizaki, S.K., T.Matsui, P.Ko, arXiv1608.00297



LISA (C1-C4):
[Caprini et al. (2015)]

DECIGO
(Pre, 1 cluster, Correlation)
[Kawamura et al. (2011)]

Benchmark point

v_Φ [GeV]	v_S [GeV]	m_h [GeV]	$\mu_{\Phi S}$ [GeV]	μ'_S [GeV]	μ_S [GeV]	m_H [GeV]	θ [degrees]
246.2	90	125.5	−80	−30	0	[160, 240]	[−45, 0]

LISA and DECIGO are capable of detecting GWs from 1[st] OPT in the HSM.

Signal strength current data

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.14^{+0.19}_{-0.18}$ $\left(^{+0.18}_{-0.17}\right)$	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$
μ^{ZZ}	$1.29^{+0.26}_{-0.23}$ $\left(^{+0.23}_{-0.20}\right)$	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$
μ^{WW}	$1.09^{+0.18}_{-0.16}$ $\left(^{+0.16}_{-0.15}\right)$	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$
$\mu^{\tau\tau}$	$1.11^{+0.24}_{-0.22}$ $\left(^{+0.24}_{-0.22}\right)$	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$
μ^{bb}	$0.70^{+0.29}_{-0.27}$ $\left(^{+0.29}_{-0.28}\right)$	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$
$\mu^{\mu\mu}$	$0.1^{+2.5}_{-2.5}$ $\left(^{+2.4}_{-2.3}\right)$	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$

JHEP08,045

Definition of μ^f

$$\mu^f = \frac{\mathrm{BR}_{EX}}{\mathrm{BR}_{SM}}$$

Signal strength by ILC (prospect)

ArXiv: 1310.8361

	ILC 250/500/1000 GeV		ILC LumiUp[‡] 250/500/1000 GeV	
	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$
Inclusive	2.6/3.0/–%	–	1.2/1.7/–%	–
$H \to \gamma\gamma$	29-38%	–/20-26/7-10%	16/19/–%	–/13/5.4%
$H \to gg$	7/11/–%	–/4.1/2.3%	3.3/6.0/–%	–/2.3/1.4%
$H \to ZZ^*$	19/25/–%	–/8.2/4.1%	8.8/14/–%	–/4.6/2.6%
$H \to WW^*$	6.4/9.2/–%	–/2.4/1.6%	3.0/5.1/–%	–/1.3/1.0%
$H \to \tau\tau$	4.2/5.4/–%	–/9.0/3.1%	2.0/3.0/–%	–/5.0/2.0%
$H \to b\bar{b}$	1.2/1.8/–%	11/0.66/0.30%	0.56/1.0/–%	4.9/0.37/0.30%
$H \to c\bar{c}$	8.3/13/–%	–/6.2/3.1%	3.9/7.2/–%	–/3.5/2.0%
$H \to \mu\mu$	–	–/–/31%	–	–/–/20%
	$t\bar{t}H$		$t\bar{t}H$	
$H \to b\bar{b}$	–/28/6.0%		–/16/3.8%	

ILC250 reach in various new physics models

In MSSM, NMSSM [hbb/hWW ~ 0.64%] 1.6 TeV

In general two Higgs doublet models (unitarity bound)

[hZZ~0.38%] 1 TeV

[hbb/hWW~0.64%] 2HDM Type II, Y 3 TeV

[hττ/hWW~0.84%] 2HDM Type II, X 2.7 TeV

Full coverage up to 1.5-3 TeV

In the Higgs doublet and singlet model (unitarity bound)

[hZZ~0.38%] 5 TeV

In Minimal Composite Higgs Model ($\xi=\sin^2(v/f)$)

[hZZ~0.38%] MCHM4 2.8 TeV

[hbb/hWW~0.64%] MCHM5, MCHM10 3.8 TeV

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ILC250検証委員会スライドより

From Higgs sector to new physics

When at ILC250 the structure of the Higgs sector（1DM, 2HDM, Singlets, exotic, …）is clarified, it will be important information for new physics

New paradigm (SUSY or others)
Baryogenesis（CPV, 1st Order Phase Transition）
Neutrino （radiative seesaw, triplet）
Dark Matter (Higgs portal, Inert scalar models),
…

Synergy among experiment is important

Baryogenesis and Higgs

Baryon Number of the Universe

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} (= (5-7)\times 10^{-10})$$

Baryogenesis What is the mechanism to generate the baryon asymmetric Universe from the symmetric one?

Sakharov's Condition

Sakharov 1967

1. ΔB ≠ 0 — Sphaleron process
2. C and CP violation — Chiral gauge theory, KM phase
3. Departure from thermal equilibrium — Strongly first order phase transition

SM could satisfy these conditions but excluded by the data

Scenario of Baryogenesis

1. Electroweak Baryogenesis — Physics of (extended) Higgs sector
2. Leptogenesis — New physics at very high scales

CPV and EW Baryogenesis

Type 3 of 2HDM

Tau got mass from two Higgs doublets

- **Flavor changing interaction**
- **CP violation**

Can explain electroweak baryogenesis

Chiang, Fuyuto, Senaha, 2016

Blue curves are EDM bounds

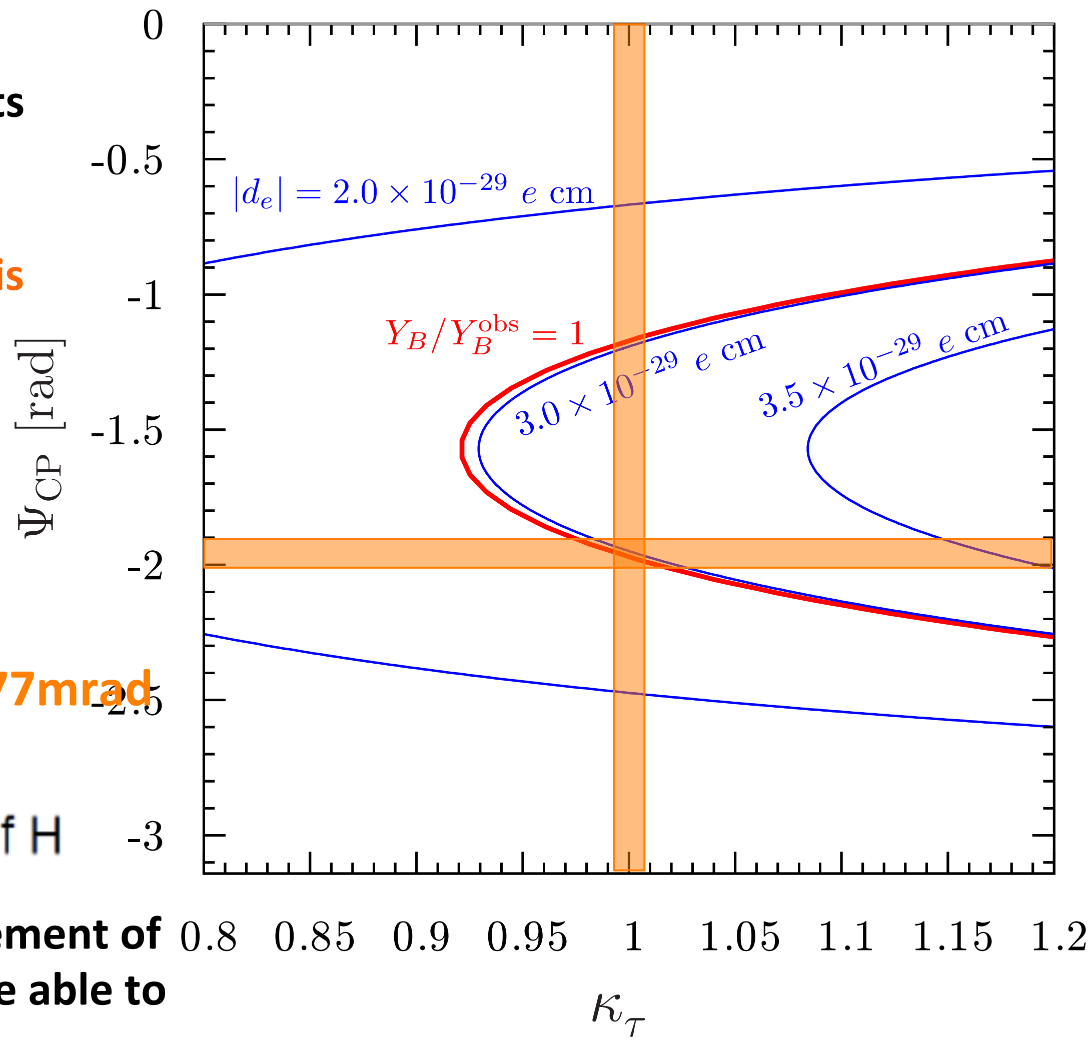
Current $|d_e| < 8.7 \times 10^{-29}$ e cm

ILC250 ***D. Jeans, et al 2016***

CP phase can be determined by 77mrad

Tau Yukawa (κ_τ/κ_V) 0.84%

$$\mathcal{L} \sim g\,\bar{f}\,(\cos\psi_{CP} + i\,\gamma^5 \sin\psi_{CP})\,f\,H$$



Inner parameter fixed as $\Delta\tan\beta$=0.05, v_w=0.1

By combination of precision measurement of Yukawa coupling and CPV, we may be able to distinguish (or identify) model

Important synergy with CPV, g-2, LFV, EDM experiments

1^{st} Order Phase Transition

Effective potential at one-loop

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

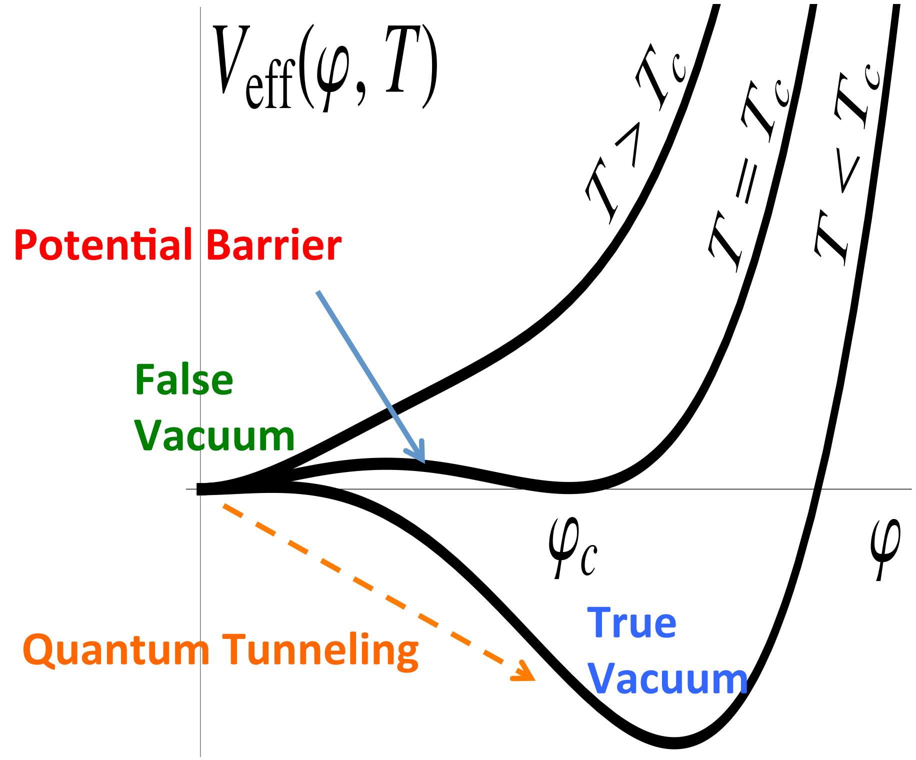
Finite temperature parts

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

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

High temperature expansion

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



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

$$\varphi_c / T_c \propto E$$

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

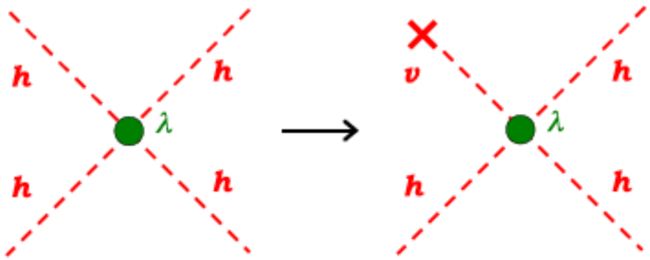
$$I_F(a^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{32}\left(\ln\frac{a^2}{\alpha_F} - 3/2\right) + \mathcal{O}(a^6)$$

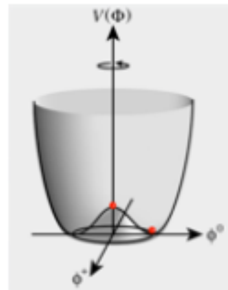
$$\log\alpha_B = 2\log 4\pi - 2\gamma_E$$
$$\log\alpha_F = 2\log\pi - 2\gamma_E$$
$$\gamma_E = 0.5772\cdots$$

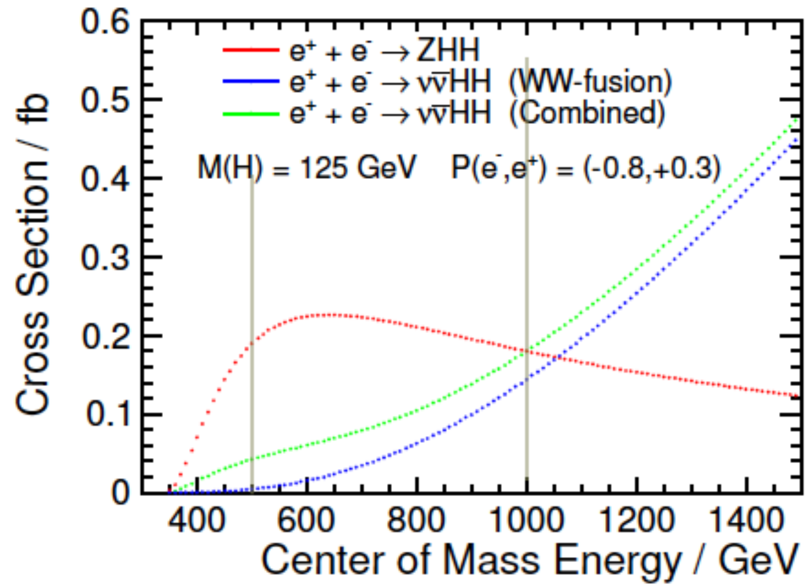
Higgs Self-Coupling

Slide by Keisuke Fujii

hhh coupling =
consequence of vacuum condensation

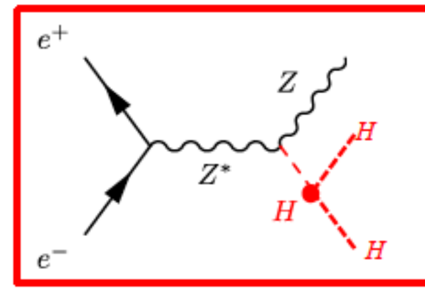


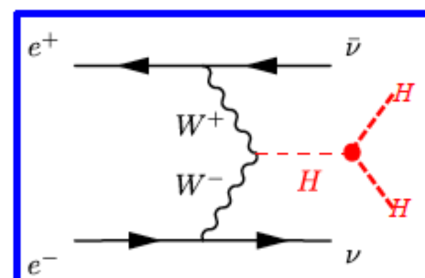




Challenging measurement because of:

- 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	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$
$P(e^-,e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$
$\sigma(ZHH)$	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

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

$$sa^3 = \frac{2\pi^2}{45} g_s T^3 a^3 = \text{const} \qquad \frac{a_t}{a_0} = \left(\frac{g_{s0}}{g_s^t}\right)^{1/3} \frac{T_0}{T_t}$$

Radiation dominant Universe

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

We obtain

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

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

$f_0 = 10^{-3}$-10^{-1} Hz

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

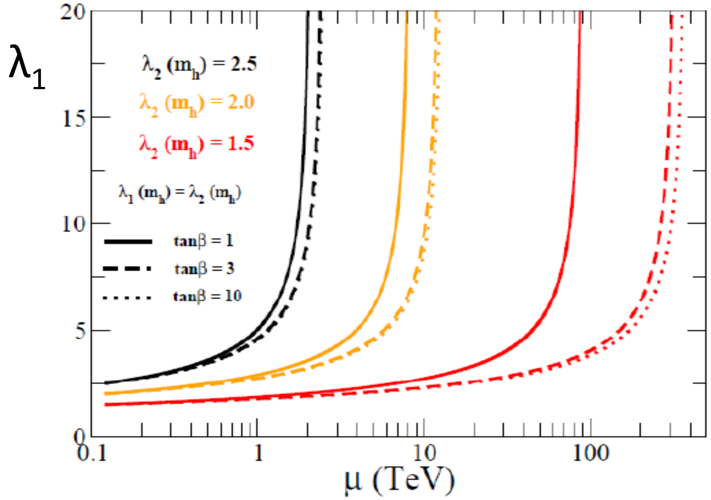
1 cluster (arm length 1000km)
Correlation between 2 cluster

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

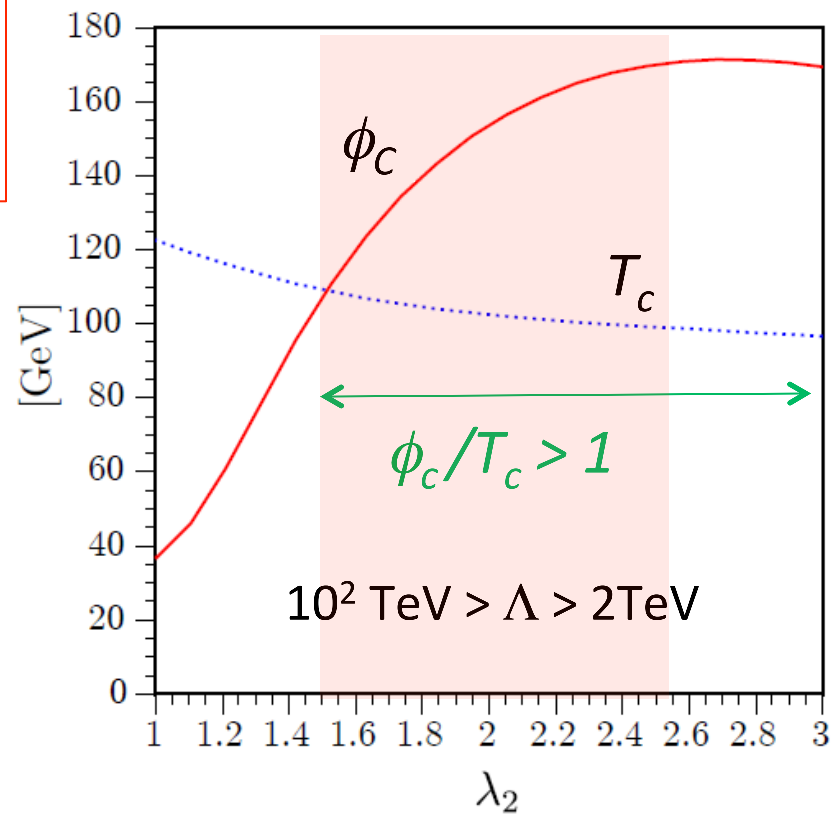
Landau pole and EW baryogenesis

Strong 1st OPT
→ RGE analysis λ'
→ **Landau pole**

$W = \lambda_1\ H_u H_u'\Omega_1 + \lambda_2\ H_d H_d'\Omega_2$



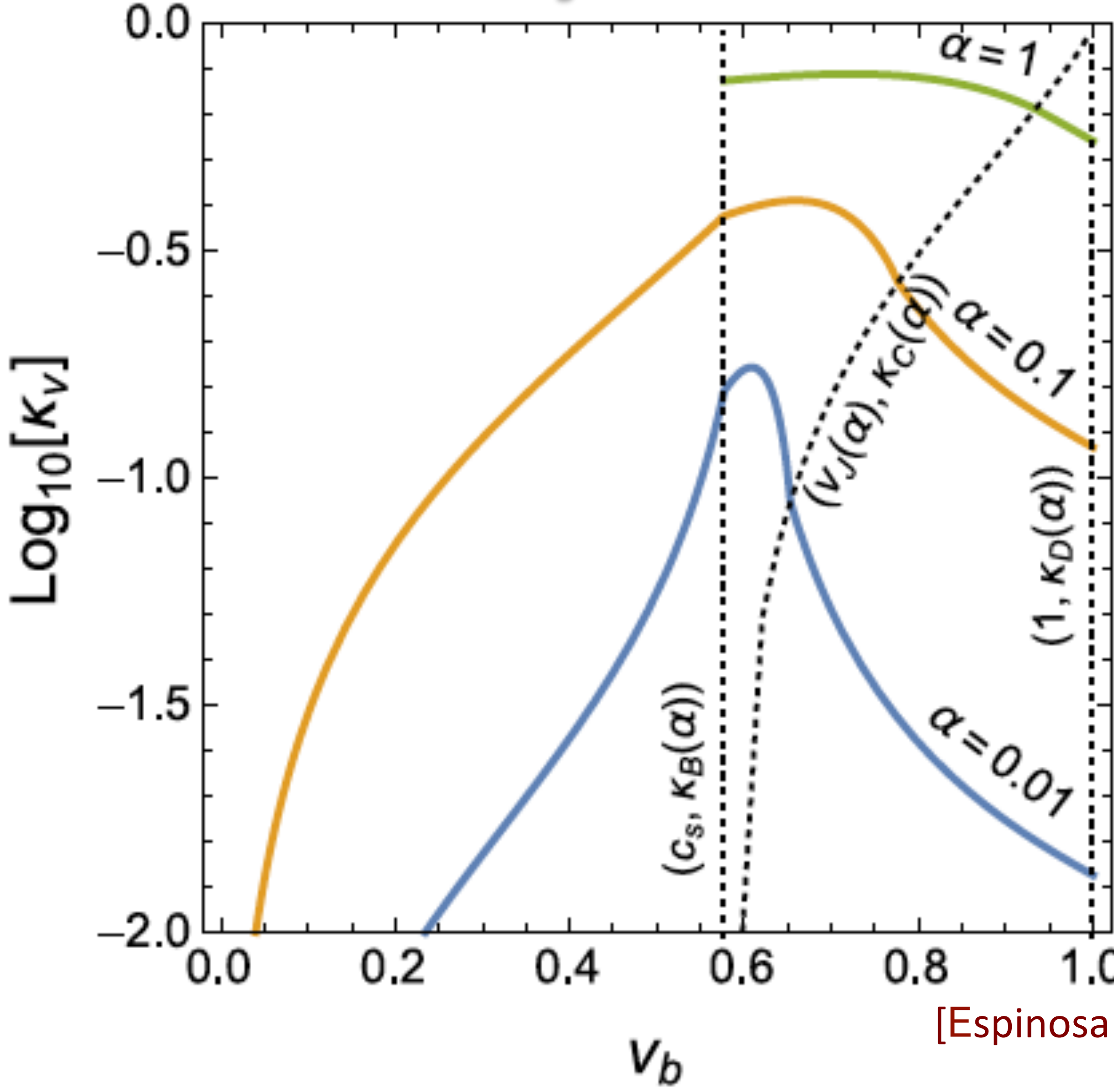
S.K., E. Senaha, T. Shindou 2011



$$\varphi_c/T_c > 1 \ \ \Rightarrow \Lambda_{cutoff} < O(100)\ \text{TeV}$$

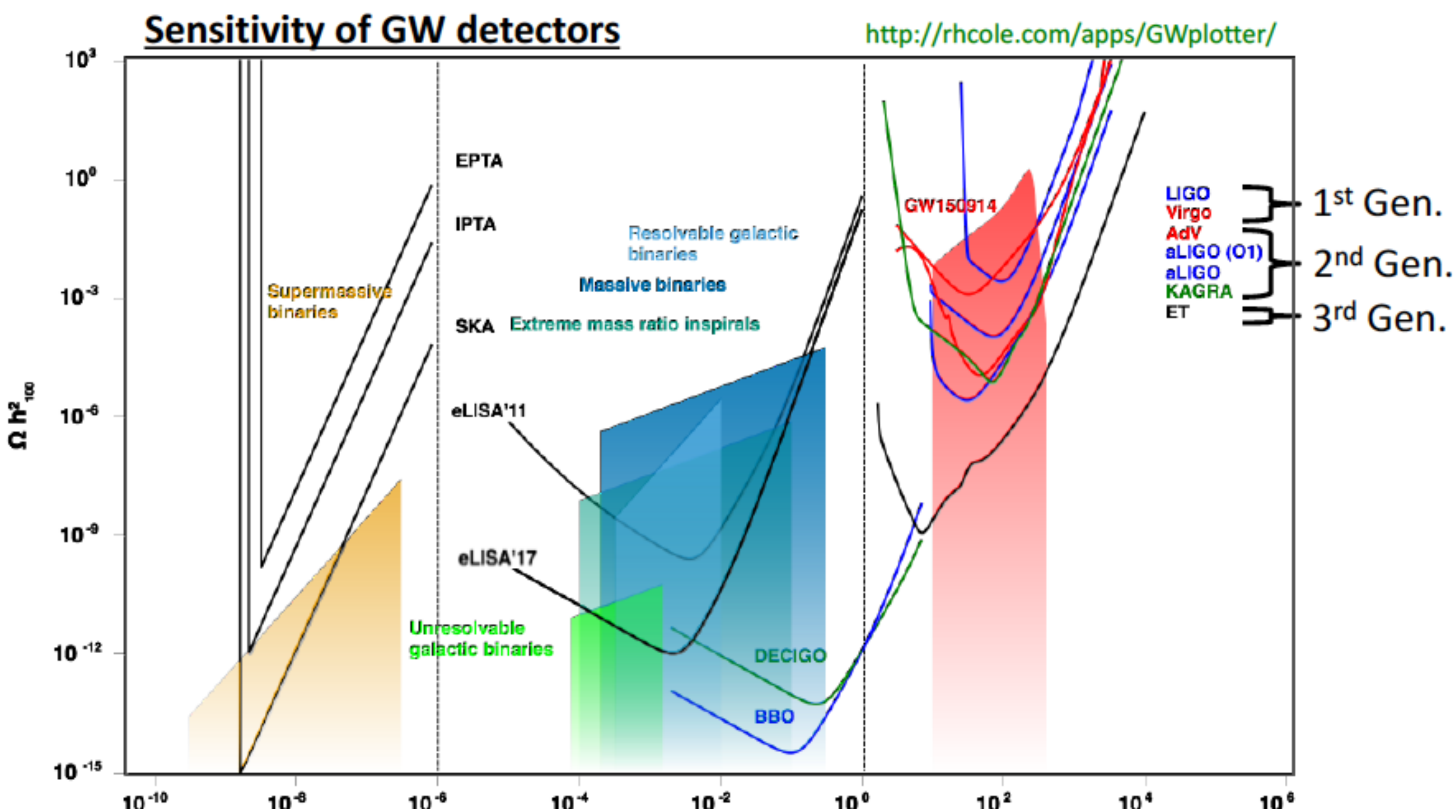
Above the Landau pole it is a new world

Efficiency factor



[Espinosa et al. (2010)]

~ Probing the Higgs potential by GW observations ~



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

$$sa^3 = \frac{2\pi^2}{45} g_s T^3 a^3 = \text{const} \qquad \frac{a_t}{a_0} = \left(\frac{g_{s0}}{g_s^t}\right)^{1/3} \frac{T_0}{T_t}$$

Radiation dominant Universe

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

We obtain

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

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

$f_0 = 10^{-3}$-10^{-1} Hz

Characteristic GW Abundance from the strong EW 1st OPT

Normalized energy density

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f}$$

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

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

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

Transverse-Traceless gauge

Red shifted abundance

Scaling $\rho_{\rm GW} = \left(\frac{a_t}{a_0}\right)^4 \rho_{\rm GW}^t \qquad \rho_c = \left(\frac{H_0}{H_t}\right)^2 \rho_c^t$

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

Characteristic GW Abundance from the strong EW 1st OPT

At the phase transition, we have

$$\rho_{\rm GW}^t \sim \frac{\dot{h}_{ij}^2}{G} \qquad \rho_c^t \sim \frac{H_t^2}{G}$$

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

$$\Omega_{\rm GW}^t = \frac{\rho_{\rm GW}^t}{\rho_c^t} \sim \frac{H_t^2}{\beta^2} \frac{T_{ij}^2}{(\rho_c^t)^2} \sim \frac{H_t^2}{\beta^2} \frac{\rho_{\rm kin}^2}{(\rho_{\rm vac} + \rho_{\rm rad}^t)^2}$$

$$\Omega_{\rm GW}^t \sim \frac{H_t^2}{\beta^2} \frac{\kappa^2 \alpha^2}{(1+\alpha)^2}$$

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

Characteristic GW Abundance from the strong EW 1st OPT

Abundance of GWs

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

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

Energy density of false vacuum released by PT

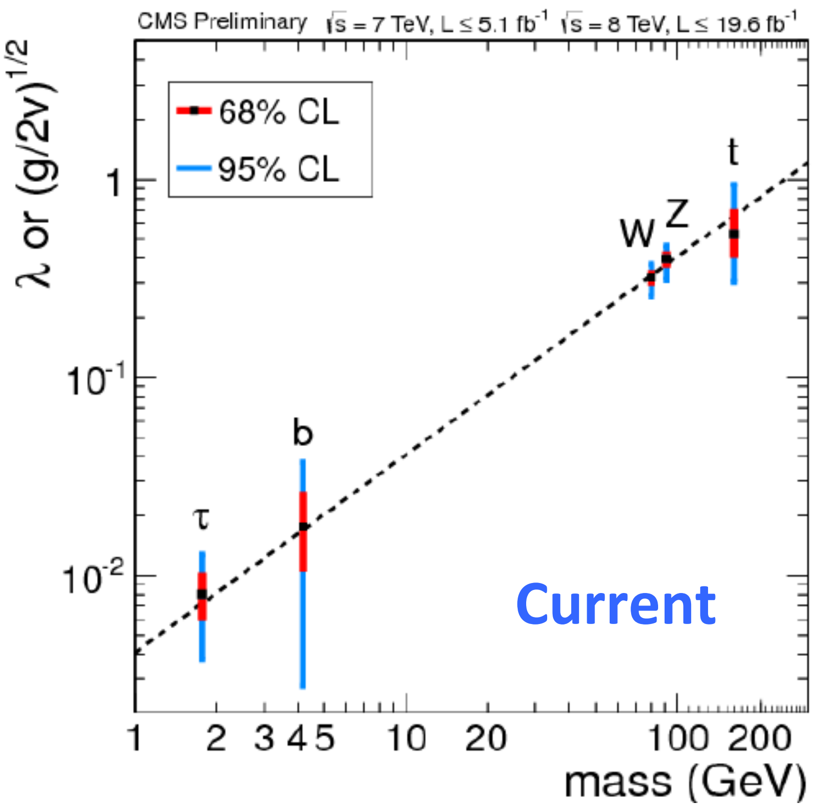
$\kappa = \rho_{\rm kin}/\rho_{\rm vac}$

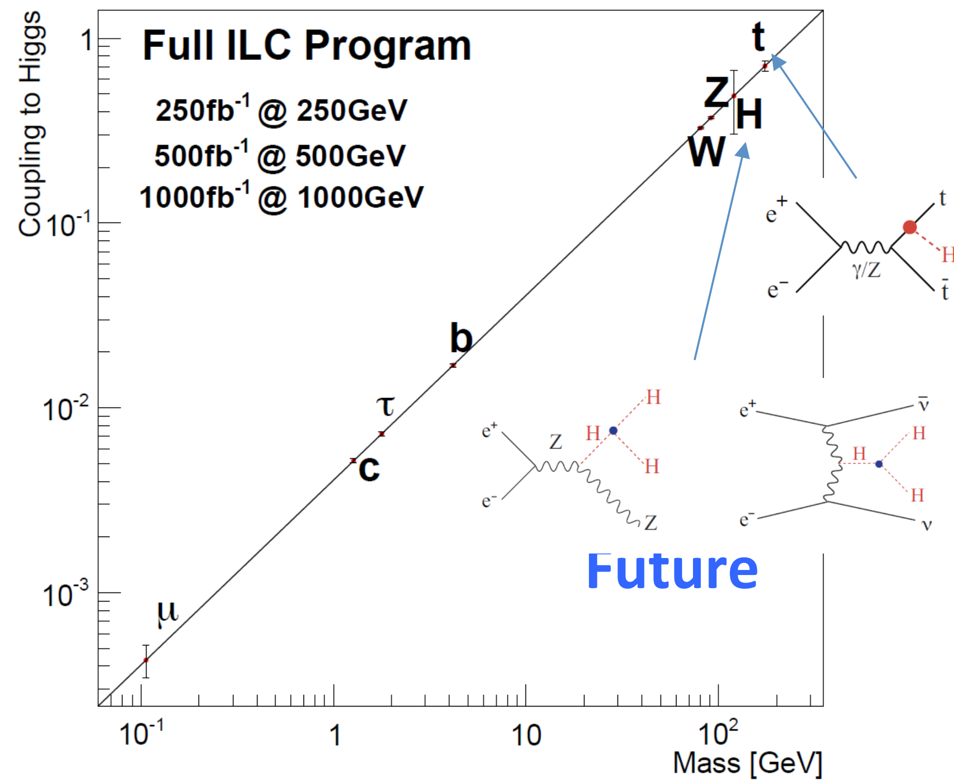
Efficiency of kinetic energy of walls in the release energy.

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).

Higgs coupling measurements





Measurement accuracy at ILC (500-up)

***hVV* coupling by about 0.4%** **(95% CL)**

Yukawa coupling by a few % **(95% CL)**

Snowmass Higgs Working Group Report 2013