Electroweak and Higgs physics

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Plan of the Lectures

1 EW Symmetry Breaking in the Standard Model (SM)

2 Physics of non-Minimal Higgs sectors

3 Higgs as a Probe of New Physics

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1 EW Symmetry Breaking in the Standard Model (SM)

2 Physics of non-Minimal Higgs sectors

3 Higgs as a Probe of New Physics
  3-1: Higgs problem and new paradigms
  3-2: BSM Phenomena and Higgs
  3-4: EW Baryogenesis and Higgs self-coupling
  3-5: Gravitational Waves as a probe of
  1st Order Phase Transition
  3-6: Towards 2030s: Golden Age of Synergy

3 Higgs as a Probe of new physics

3-1 Higgs Problem and new paradigms

Nature of Higgs

Higgs Nature	⇔	BSM Paradigm
– Elementary Scalar		SUSY
– Composite of fermions		Dynamical Symmetry Breaking
– A vector field in extra D		Gauge Higgs Unification
– Pseudo NG Boson		Minimal Composite Models
– ……		……

Each new paradigm predicts a specific Higgs sector
(eg. MSSM: two Higgs doublets,
Gauge-Higgs Uni.: Higgs couplings are weaker)

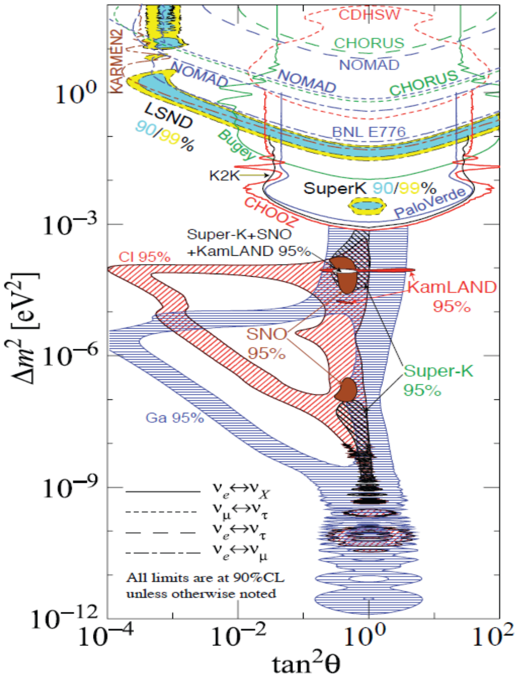
Introduction

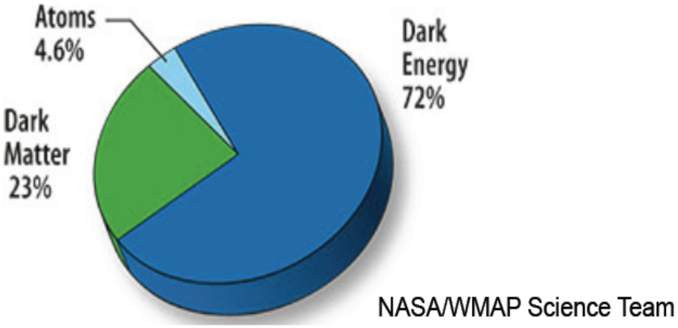
- Higgs sector remains unknown
  - Minimal/Non-minimal Higgs sector?
  - Higgs Search is the most important issue to complete the SM particle contents.
- We already know BSM phenomena:
  - Neutrino oscillation

    $\Delta m^2 \sim 8\times 10^{-5}\,\mathrm{eV}^2,\ \Delta m^2 \sim 3\times 10^{-3}\,\mathrm{eV}^2$
  - Dark Matter

    $\Omega_{DM}h^2 \sim 0.1$
  - Baryon Asymmetry of the Universe

    $n_B/s \sim 9\times 10^{-11}$





NASA/WMAP Science Team

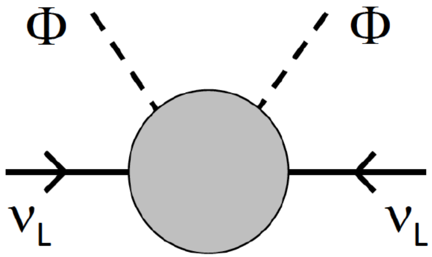
To understand these phenomena, we need to go beyond-SM

Neutrino mass and Higgs

Neutrino Oscillation → Tiny mass (< eV)

Majorana mass

$$\boxed{\mathcal{L} = \frac{c}{\Lambda}(\phi\overline{\nu_L^c})(\nu_L\phi)}$$

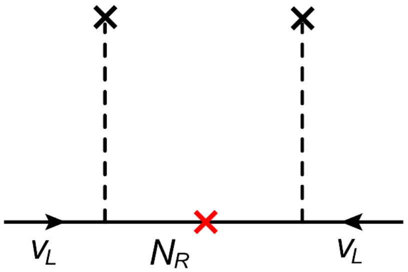


Seesaw Mechanism

$$m_\nu^{ij} = y_i y_j \frac{\langle\phi\rangle^2}{M_R} \leftarrow$$

Large mass of Right-handed Neutrinos

Tiny mass



Seesaw

Mediated by RH neutrinos N_R

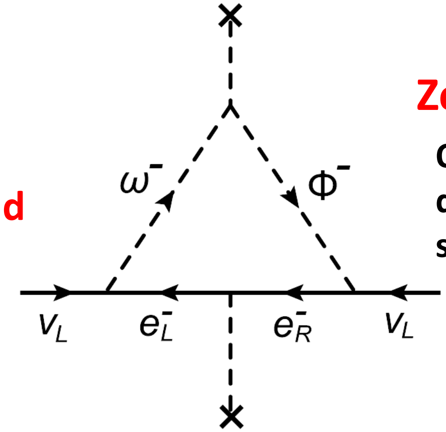
Alternative Scenario by quantum effects

$$m_\nu^{ij} = c_{ij}\left(\frac{1}{16\pi^2}\right)^N \frac{\langle\phi\rangle^2}{M_{\phi^+}}$$

Tiny mass

Quantum suppression

Mass around TeV scale



Zee model

Quantum effect due to additional scalar fields

Physics of specific extended Higgs sectors

Baryogenesis and Higgs

Baryon Number of the Universe

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

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

Sakharov's Condition

Sakharov 1967

1. $\Delta B \neq 0$	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

Higgs is a window to new physics

Higgs portal new physics scenarios

- SUSY
- Dynamical symmetry breaking
- Higgs as a pNGB
- Gauge Higgs Unification
- CW mechanism
- Higgs portal dark matter
- Inert scalar models
- Radiative neutrino mass models
- Electroweak baryogenesis
- …

It is important to experimentally determine
the Higgs sector to explore new physics beyond SM

3-2 BSM Phenomena and Higgs

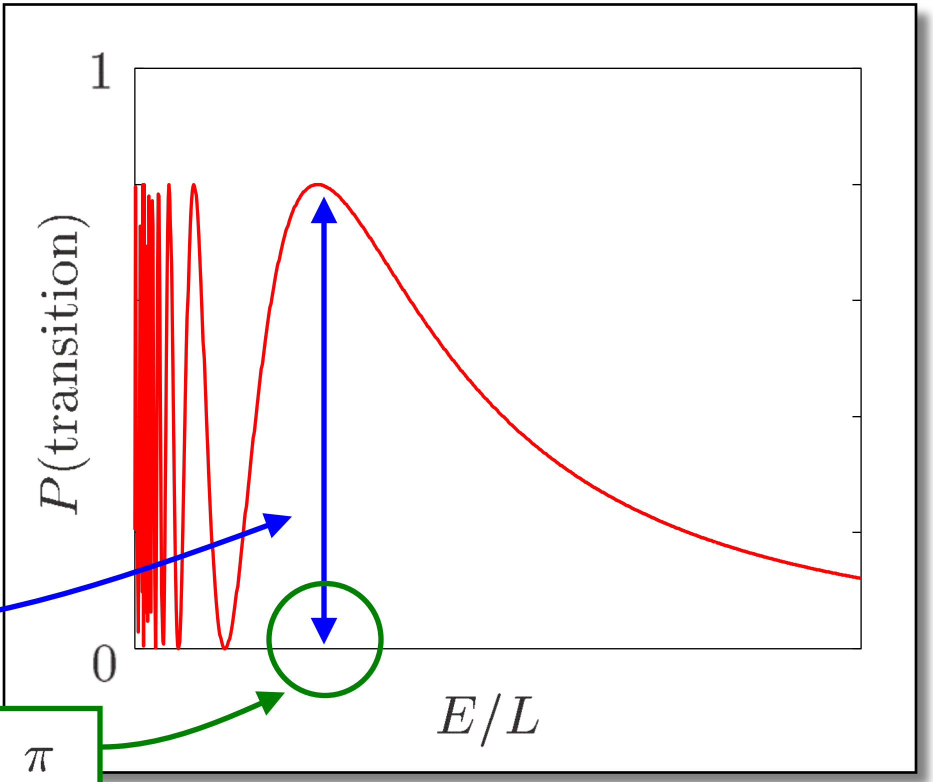
Two-flavor oscillation

$$U_{\mathrm{MNS}} \equiv \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

$$\Downarrow$$

$$\boxed{P = \underbrace{\sin^2 2\theta}_{}\ \sin^2 \underbrace{\left(\frac{\Delta m^2 L}{4E}\right)}_{}}$$

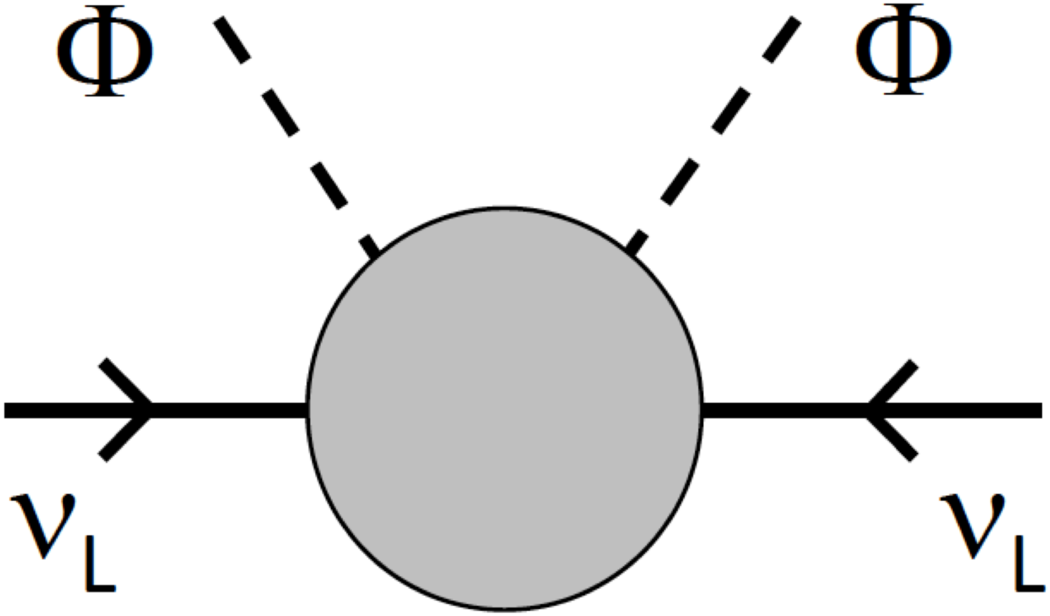


$$\boxed{\frac{\Delta m^2 L}{4E} = \frac{\pi}{2}}$$

First oscillation maximum

$$\frac{\Delta m^2 L}{4E} = 1.27\,\frac{\Delta m^2(\mathrm{eV}^2)\ L(\mathrm{m})}{E(\mathrm{MeV})}$$

Neutrinos have masses



This is a clear signature of BSM

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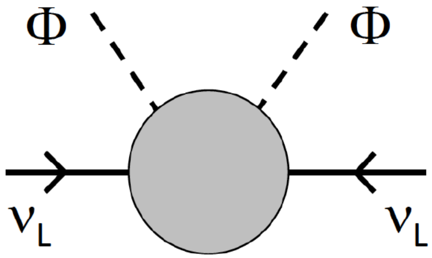

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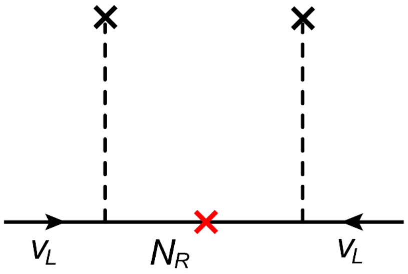

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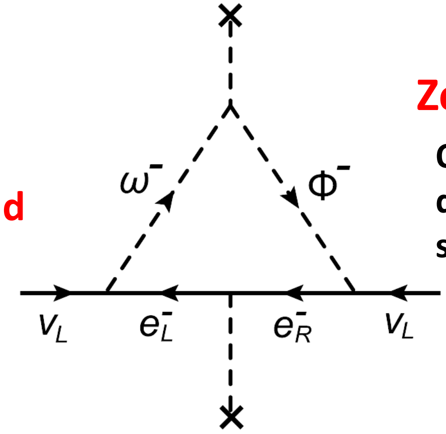


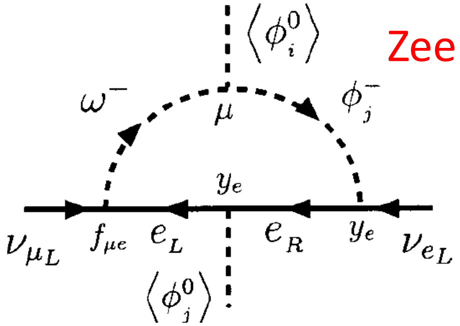
Zee model

Quantum effect due to additional scalar fields

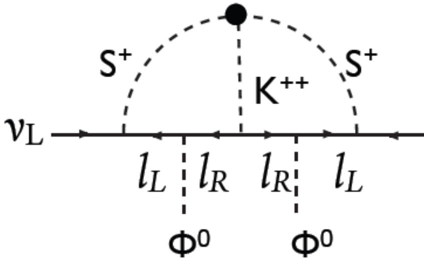
Physics of specific extended Higgs sectors

Scenario of radiative $\nu\nu\phi\phi$ generation

- Tiny ν-Masses come from loop effects
  - Zee (1980, 1985)
  - Zee, Babu (1988)
  - Krauss-Nasri-Trodden (2002)
  - Ma (2006), …..



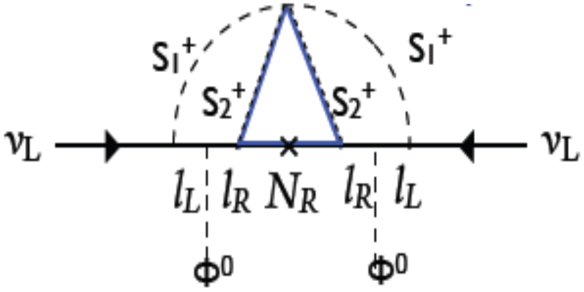
Zee



Babu

- Merit
  - Super heavy particles are not necessary

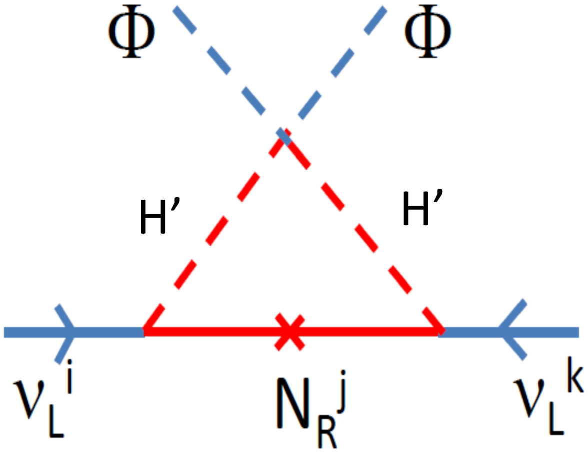
    Size of tiny m_ν can naturally be deduced from TeV scale by higher order perturbation
  - Physics at TeV: Testable at collider experiments



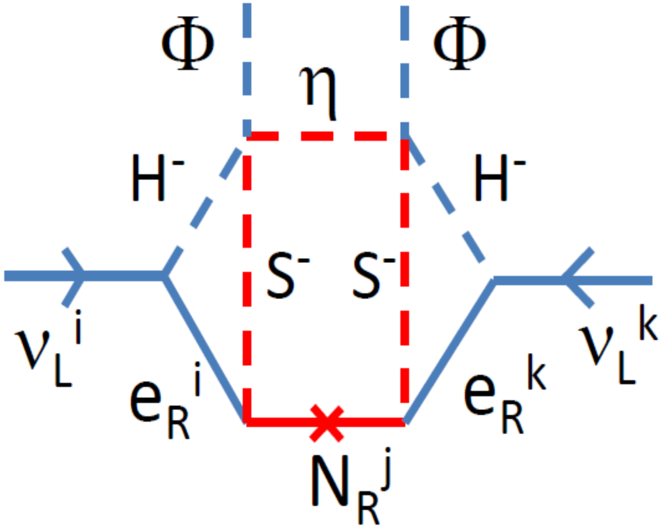
Krauss et al

Radiative seesaw with Z_2

- 1-loop (Ma)
  - Simplest model
  - SM + NR + Inert doublet (H')
  - DM candidate [H' or NR]
    - H' case
    - NR   (LFV and MN not compatible)

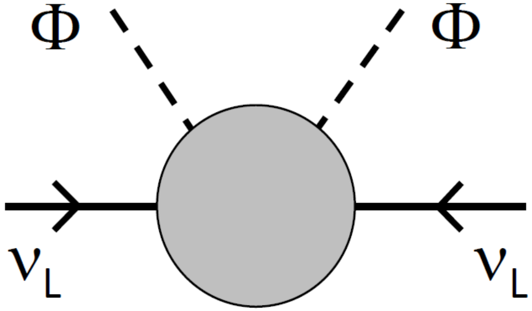


- 3-loop (Aoki-Kanemura-Seto)
  - Neutrino mass from O(1) coupling.
  - Electroweak Baryogenesis
  - 2HDM + η^0 + S^+ + NR
  - DM candidate [η^0 (or NR)]



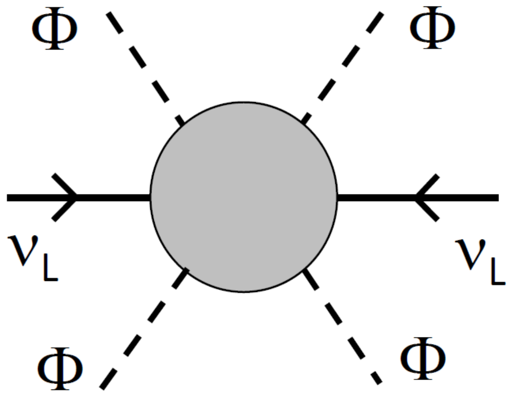
Higher Order Effect

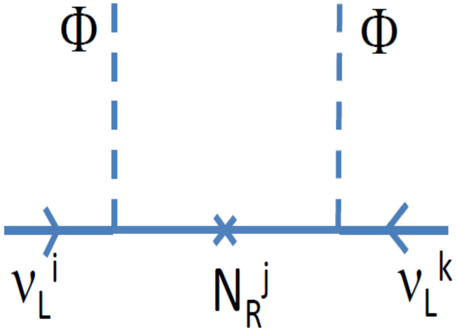
- Majorana mass of LH neutrinos may be generated from dim > 5 operators



- For dim-(5+n) operators, additional suppression $LL\varphi\varphi/\Lambda \times (\varphi\varphi/\Lambda^2)^n$

- Discrete symmetries forbid lower order operators

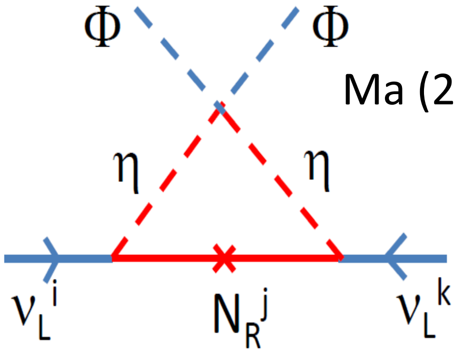




Yanagida;
Gell-Mann;
Minkowski

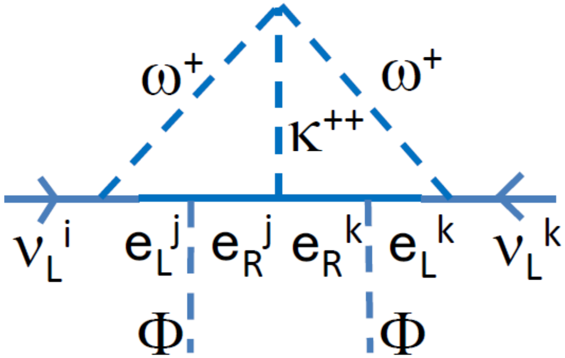
(*m*, *n*)=(0, 0)

Ma (2006)



(1, 0)

Zee; Babu

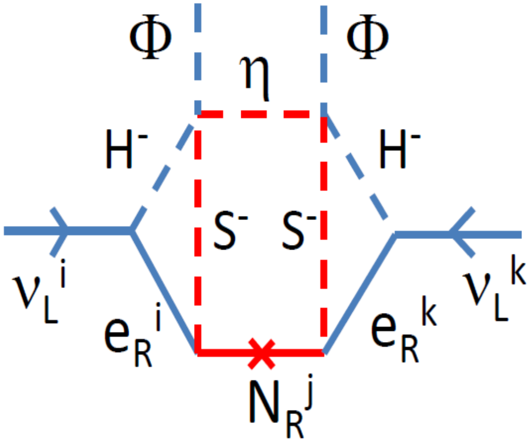


(2, 0)

$$m_\nu \sim c' \left(\frac{1}{16\pi^2}\right)^m \left(\frac{v}{\Lambda}\right)^{2n+1} v$$

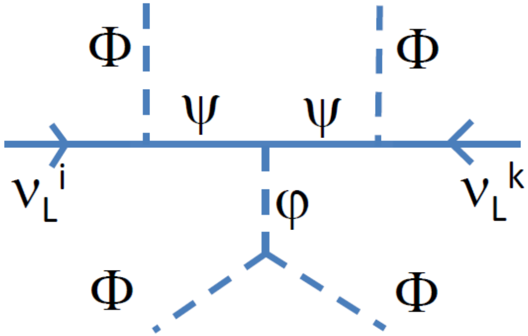
Dim 5+*n* Operator
m-loop induced

Aoki, SK,
Seto (2008)



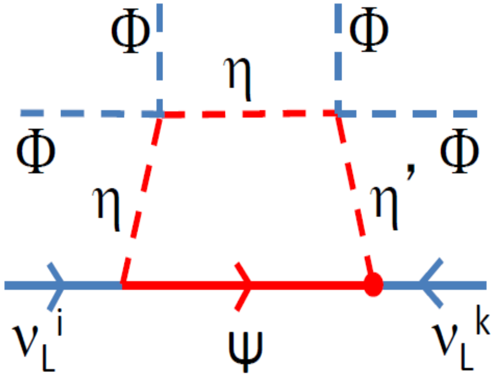
(3, 0)

Bonnet, et al. (2009)



(0, 1)

SK, Ota (2010)



(1, 1)

3-3 EW Phase Transition and Higgs self-coupling

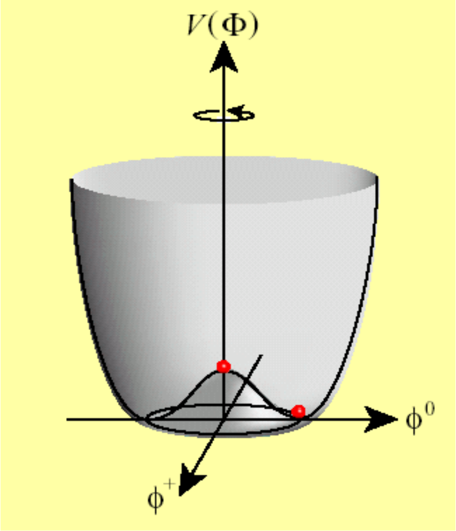
Higgs potential

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

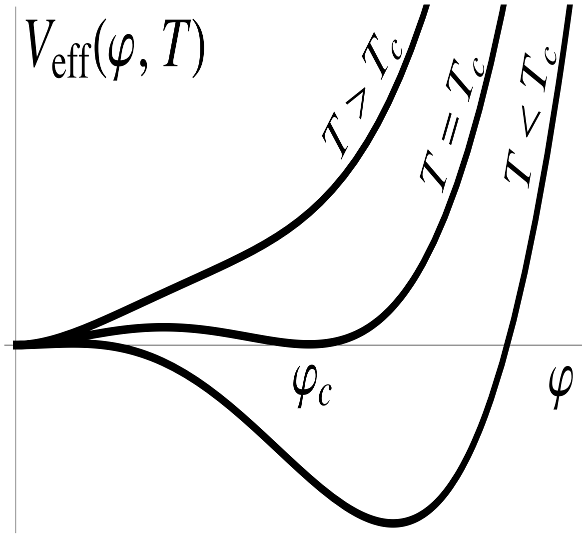
$$V(\Phi) = +\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

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

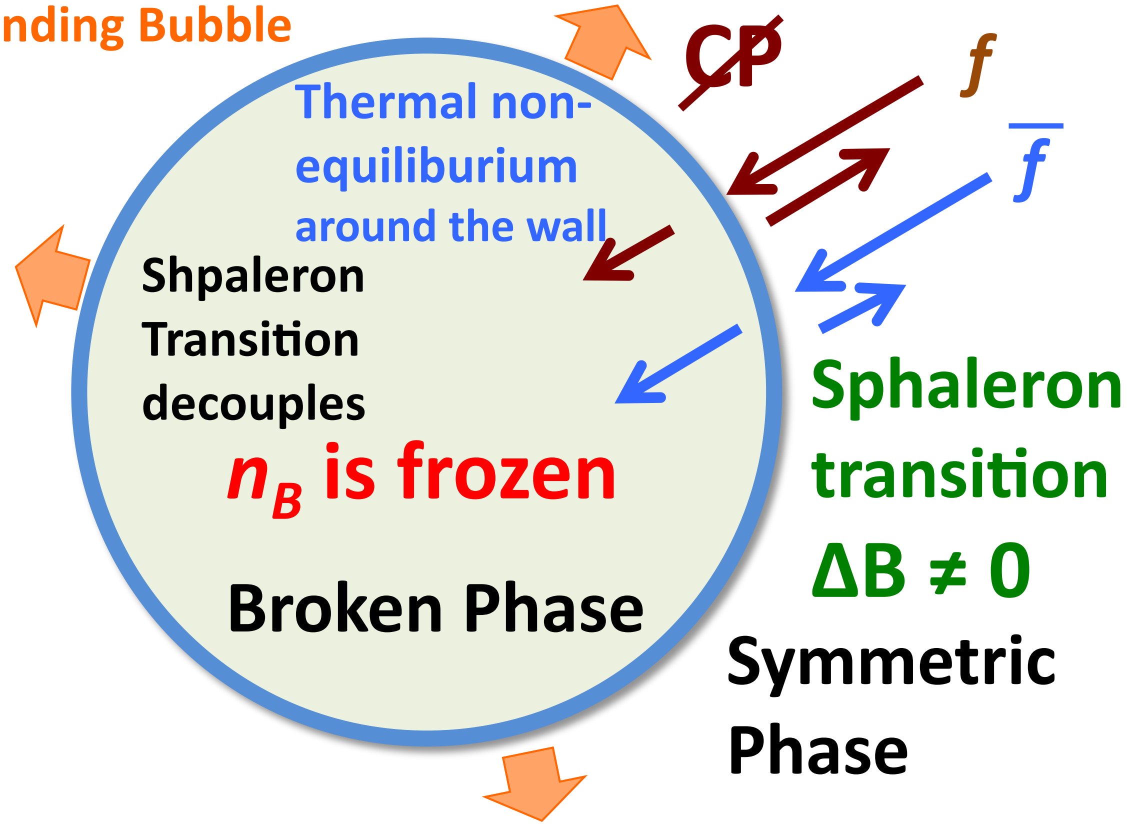
- **Electroweak Phase Transition**
  - Aspect of Transition, 1st order or not?
  - Relation to EW baryogenesis
  - Mechanism of Phase Transition



Electroweak Baryogenesis



Expanding Bubble



$\cancel{CP}$

f

$\bar{f}$

Thermal non-equiliburium around the wall

Shpaleron Transition decouples

n_B is frozen

Broken Phase

Sphaleron transition

$\Delta B \neq 0$

Symmetric Phase

Sakharov 3rd condition

Departure from Thermal equilibrium

Sphaleron Decoupling
(Strong 1st OPT)

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

Physics of the Higgs potential

1st Order Phase Transition

Effective potential at one-loop

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

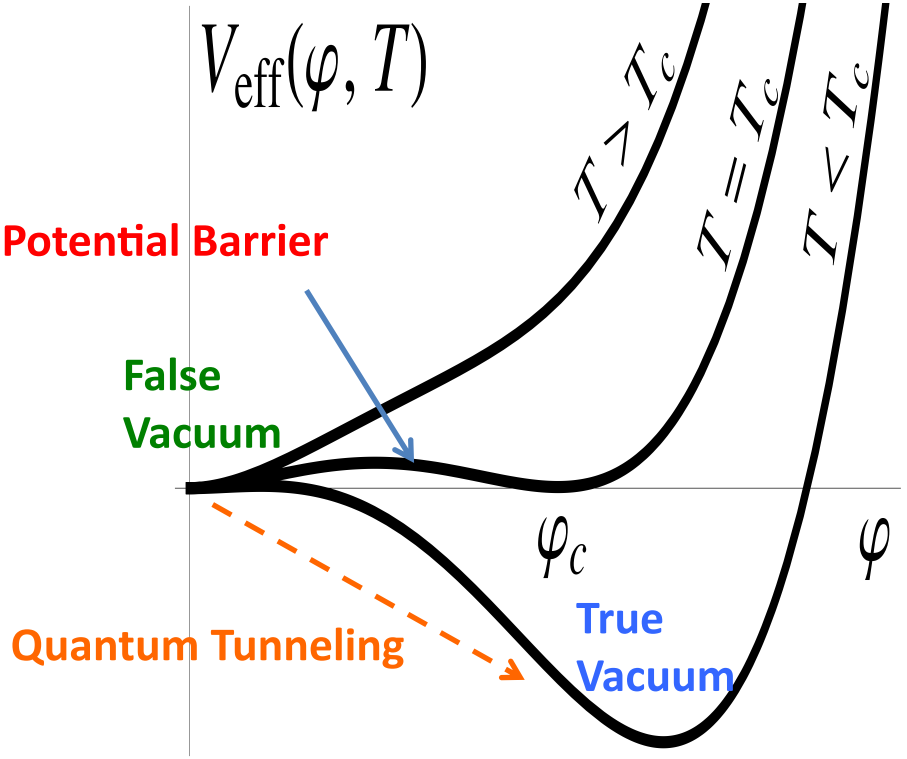
Finite temperature parts

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

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

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 → 1st OPT stronger

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

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

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

$$\begin{aligned}\log\alpha_B &= 2\log 4\pi - 2\gamma_E\\ \log\alpha_F &= 2\log\pi - 2\gamma_E\\ \gamma_E &= 0.5772\cdots\end{aligned}$$

Strongly 1st OPT

Potential at finite T (high temp. approx.)

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

$$\boxed{\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1}$$

E: **Thermal Loop Effects**

λ_{T_C} : Self couplings ~ m_h^2

SM no strong 1st OPT

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

Strongly 1st OPT

Potential at finite T
(high temp. approx.)

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***E*: Thermal Loop Effects**

λ_{Tc} : Self couplings ~ m_h^2

SM **no strong 1st OPT**

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

Extended Higgs (2HDM): 1st OPT possible

Quantum non-decoupling effect of Φ (= $H, A, H^+, \ldots$)

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

Strongly 1st OPT

Potential at finite T
(high temp. approx.)

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Prediction! **Large deviation in the *hhh* couping as well**

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

1st OPT and the *hhh* coupling

Strong 1^{st} OPT
⇔ Deviation in the *hhh* coupling

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

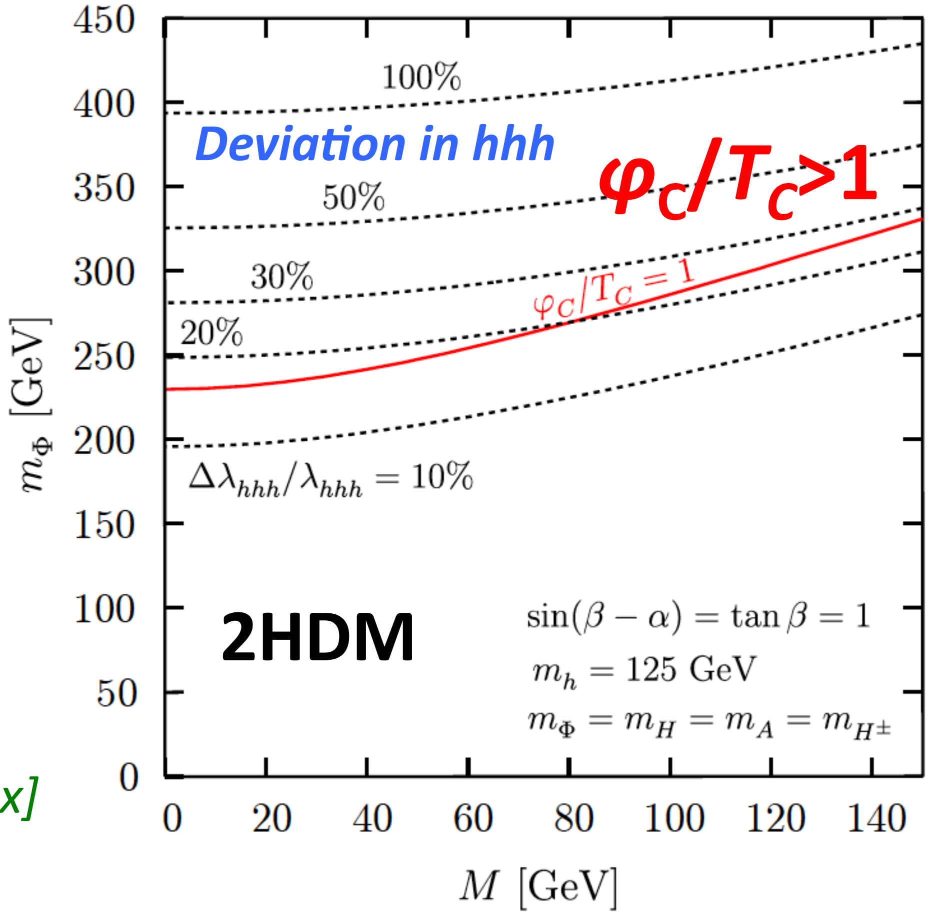
Which collider?

LHC cannot do it

Only ILC (1 TeV) can measure it by O(10) %

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

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



Deviation in hhh

$\varphi_C/T_C>1$

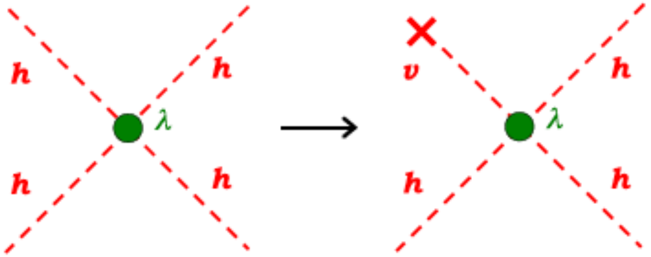
2HDM

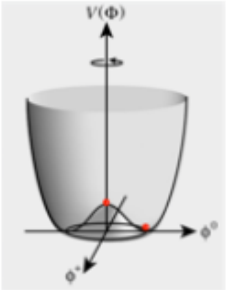
Connection between Cosmological problem and Collider

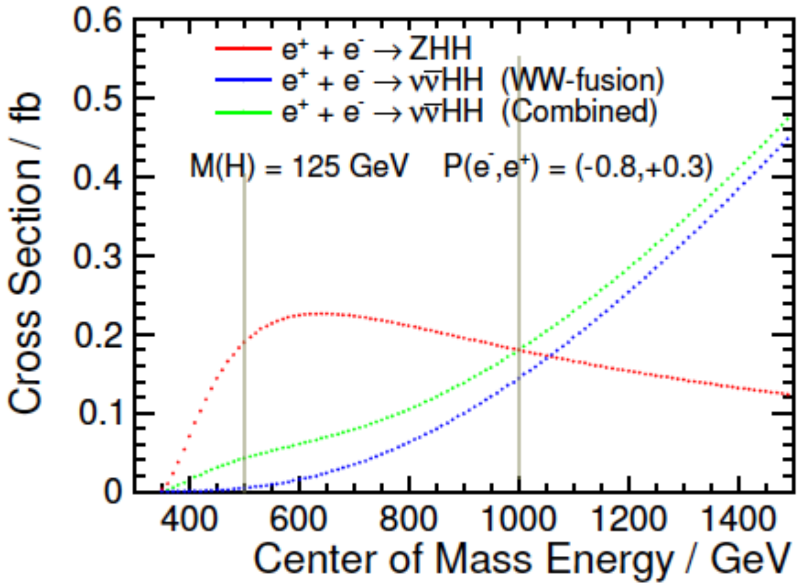
Higgs Self-Coupling

Slide by Keisuke Fujii

hhh coupling =
consequence of vacuum condensation

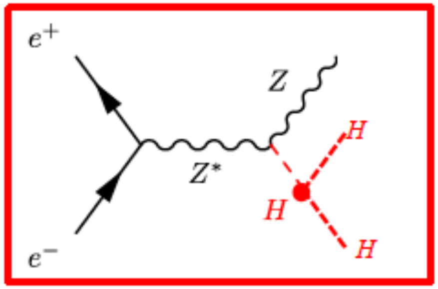




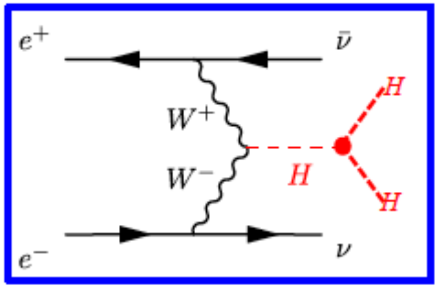


Challenging measurement because of:

- 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

3-4 Gravitational Waves: New tool to access Higgs potential

Higgs potential via GWs

In 2016, aLIGO 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…

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GW Physics?

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

Relic GWs are characterized only by frequency

Transition temperature gives typical frequencies

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

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

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

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

Radiation dominant Universe

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

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

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

Higgs potential via GWs

In 2016, aLIGO 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

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

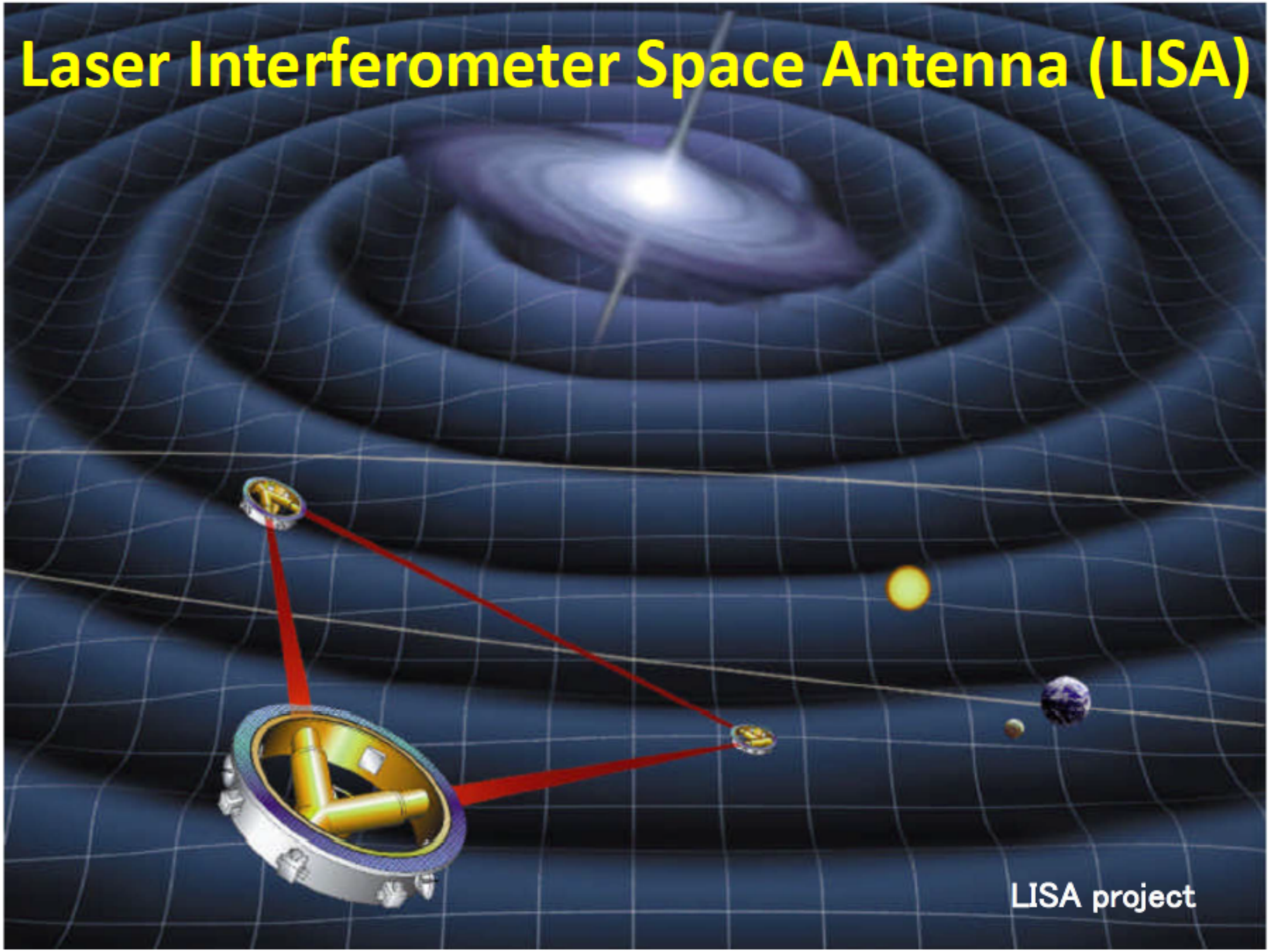
Out of sensitivity at LIGO/KAGRA (10-10^{3}Hz)

Future space based GW experiments

LISA（USA/Europe） Sensitivity around mili Hz (2034–)

DECIGO（Japan） Sensitivity around deci Hz

We can explore GWs from the early Universe!



Laser Interferometer Space Antenna (LISA)

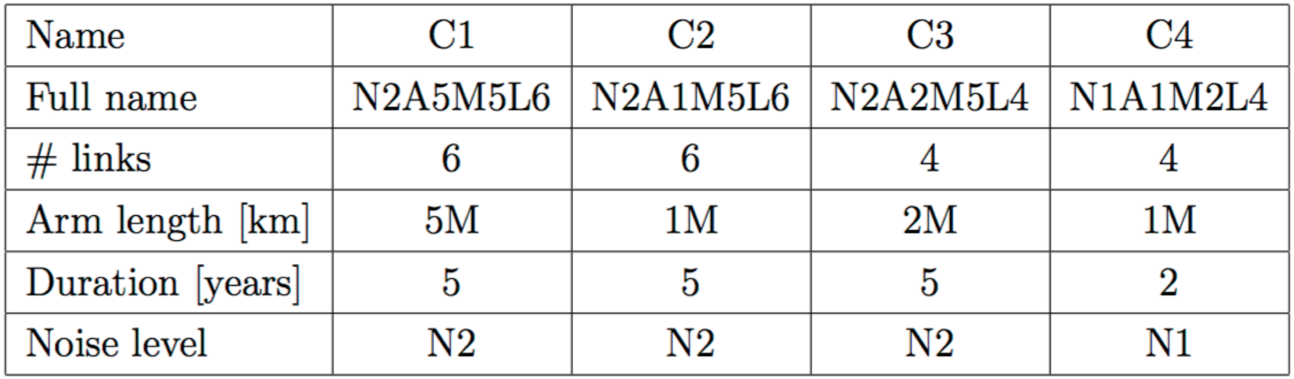
LISA project

川村静児氏のスライド

Laser interferometer space anttena

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

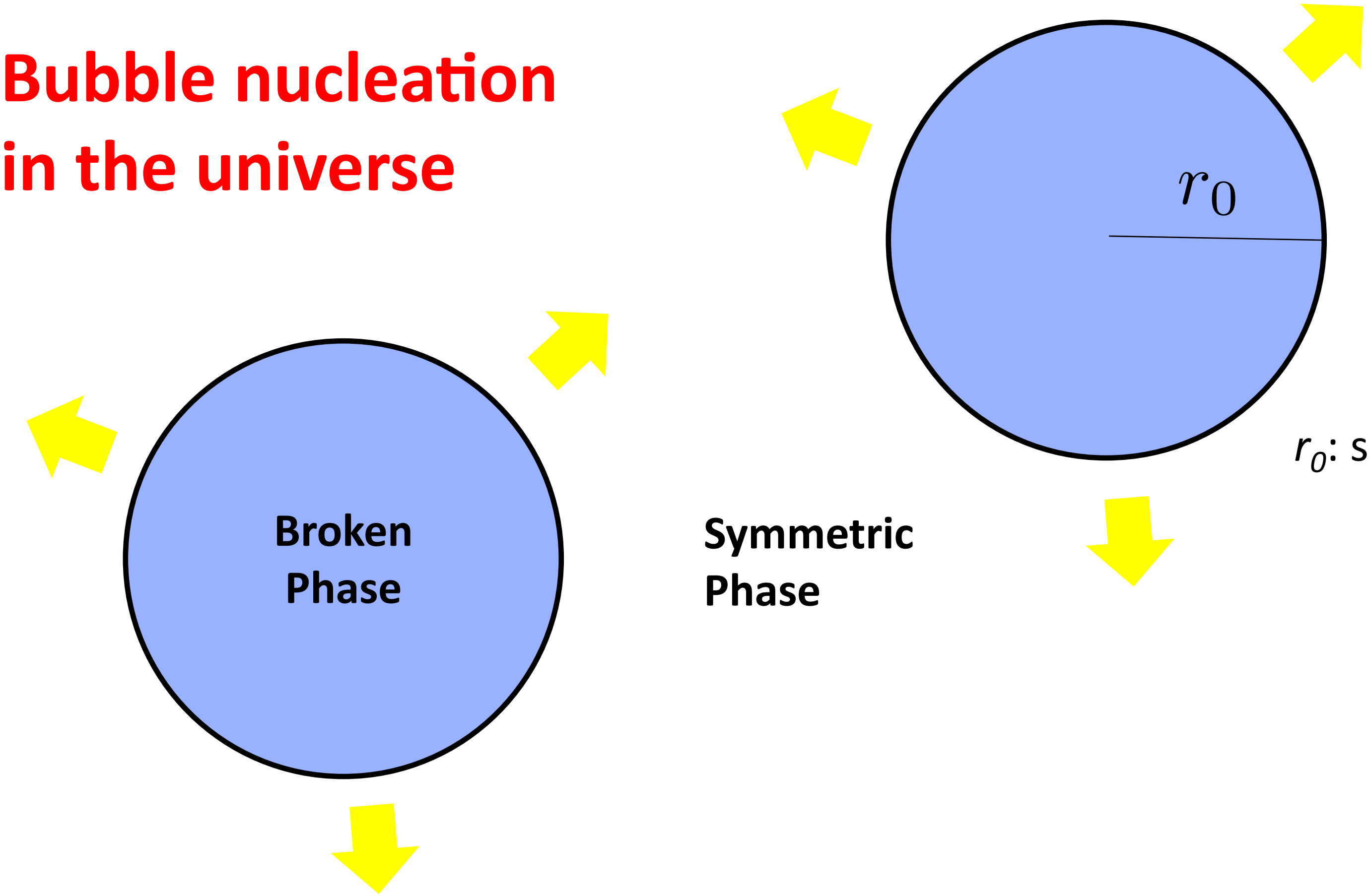
1 cluster (arm length 1000km)

Correlation between 2 cluster

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

Origin of GWs from 1st OPT

Bubble nucleation
in the universe

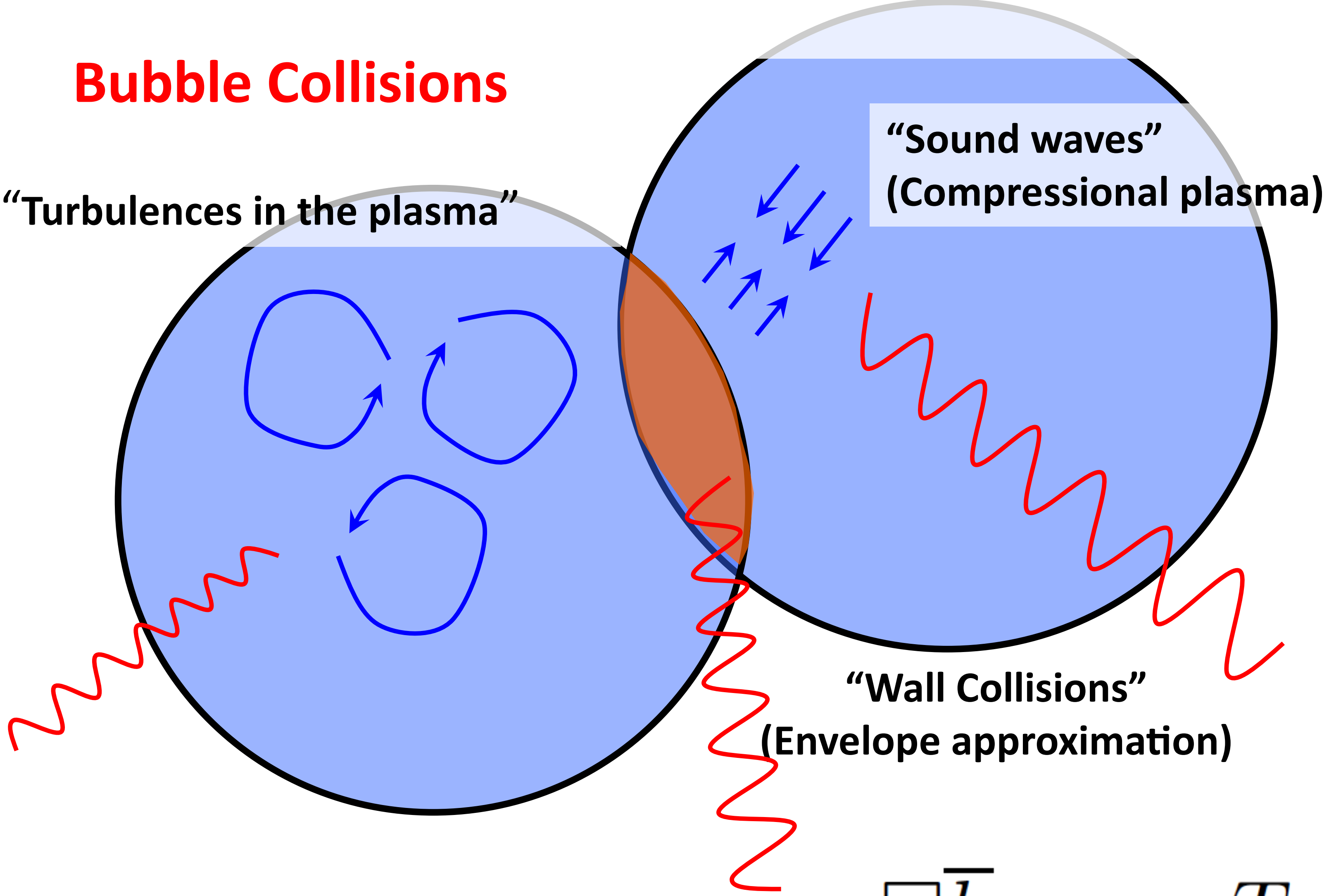


r_0: size of critical bubble

Expanding
babbles of the broken phase

Bubble is spherical
→ No GW occurs

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

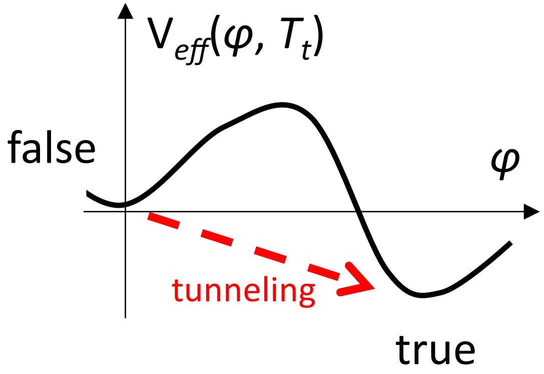
$$\Box \bar{h}_{\mu\nu} = \kappa \underline{T_{\mu\nu}}$$

Source of GW

From bubble dynamics to GW spectrum

Bubble nucleation rate per unit volume and time

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



T_t **Transition temperature**

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

α **Latent heat (released energy of false vacuum)** **Depth of the potential**

$$\alpha = \frac{\epsilon(T_t)}{\rho_{\rm rad}(T_t)} \qquad \epsilon(T) = -V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial V_{\rm eff}(\varphi_B(T), T)}{\partial T}$$

β **Inverse of duration of phase transition** **Speed of transition**

$$\beta = -\left.\frac{dS_E}{dt}\right|_{t=t_t} \simeq \left.\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right|_{t=t_t} \qquad \tilde{\beta} = \frac{\beta}{H_t}$$

GW spectrum is given as a function of T_t, α, β (and v_b) **v_b: wall velocity**

Ex) Strength and peak frequency of GW (Fitting function)

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

C.Caprini et al., arXiv:1512.06239

Characteristic GW Abundance from the strong EW 1st OPT

Normalized energy density

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

$$\left\{ \begin{array}{l} \rho_{\rm GW} = \dfrac{1}{32\pi G} \langle \dot{h}_{ij} \dot{h}_{ij} \rangle \\[2em] \rho_c = \dfrac{3H_0^2}{8\pi G} \end{array} \right.$$

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

Transverse-Traceless gauge

Red shifted abundance

Scaling

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

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

Characteristic GW Abundance from the strong EW 1st OPT

At the phase transition, we have

$$\rho^t_{\mathrm{GW}} \sim \frac{\dot{h}^2_{ij}}{G} \qquad \rho^t_c \sim \frac{H_t^2}{G}$$

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

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

$$\Omega^t_{\mathrm{GW}} \sim \frac{H_t^2}{\beta^2} \frac{\kappa^2 \alpha^2}{(1+\alpha)^2}$$

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

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

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).

Spectra of GWs from Bubble collision

Complicated numerical simulations are necessary

Approximate fitting formulae given by C.Caprini et al., arXiv:1512.06239

1. Sound waves (Compressional waves of thermal plasma)

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

2. Collision of the bubbles (envelop approximation)

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

3. Magnethydrodynamic (MHD) plasma turbulence in the bubbles

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

v_b : wall velocity κ_ϕ κ_v : efficiency factors $\epsilon = 0.05$

The spectrum are evaluated by inputting the latent heat α, variation of the bubble nuclearation rate β and transition temperature *T_t*

Higgs model with *N* singlet fields

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

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

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

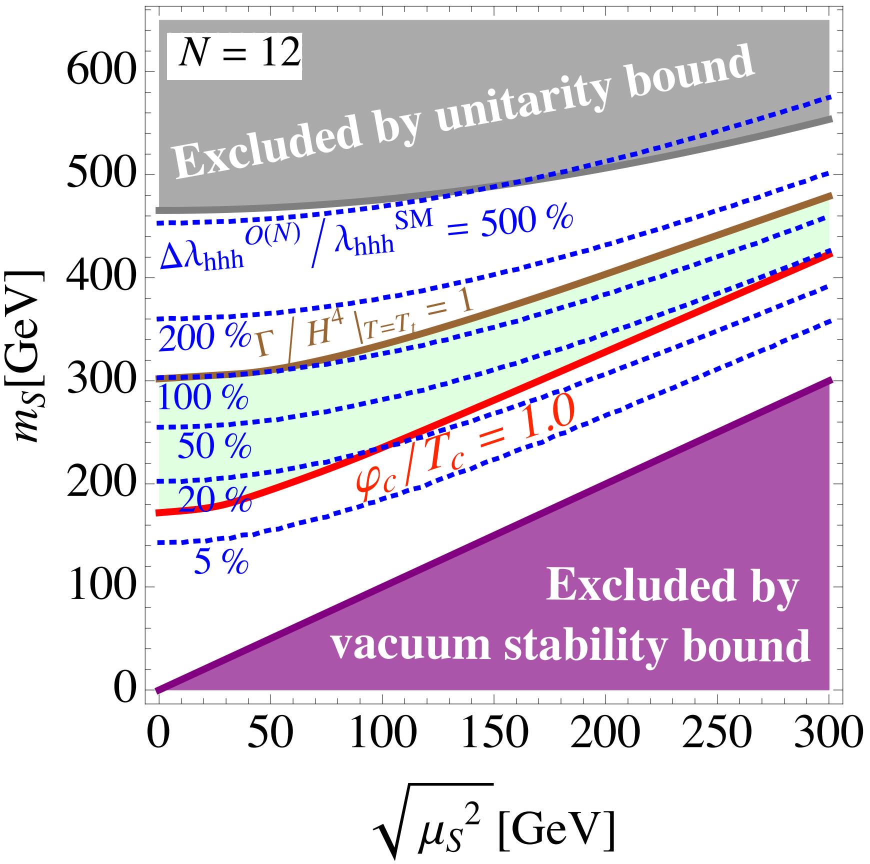
Mass of scalar fields: $\boxed{m_S^2 = \mu_S^2 + \frac{c}{2}v^2}$

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

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

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

Predictions on the *hhh* coupling

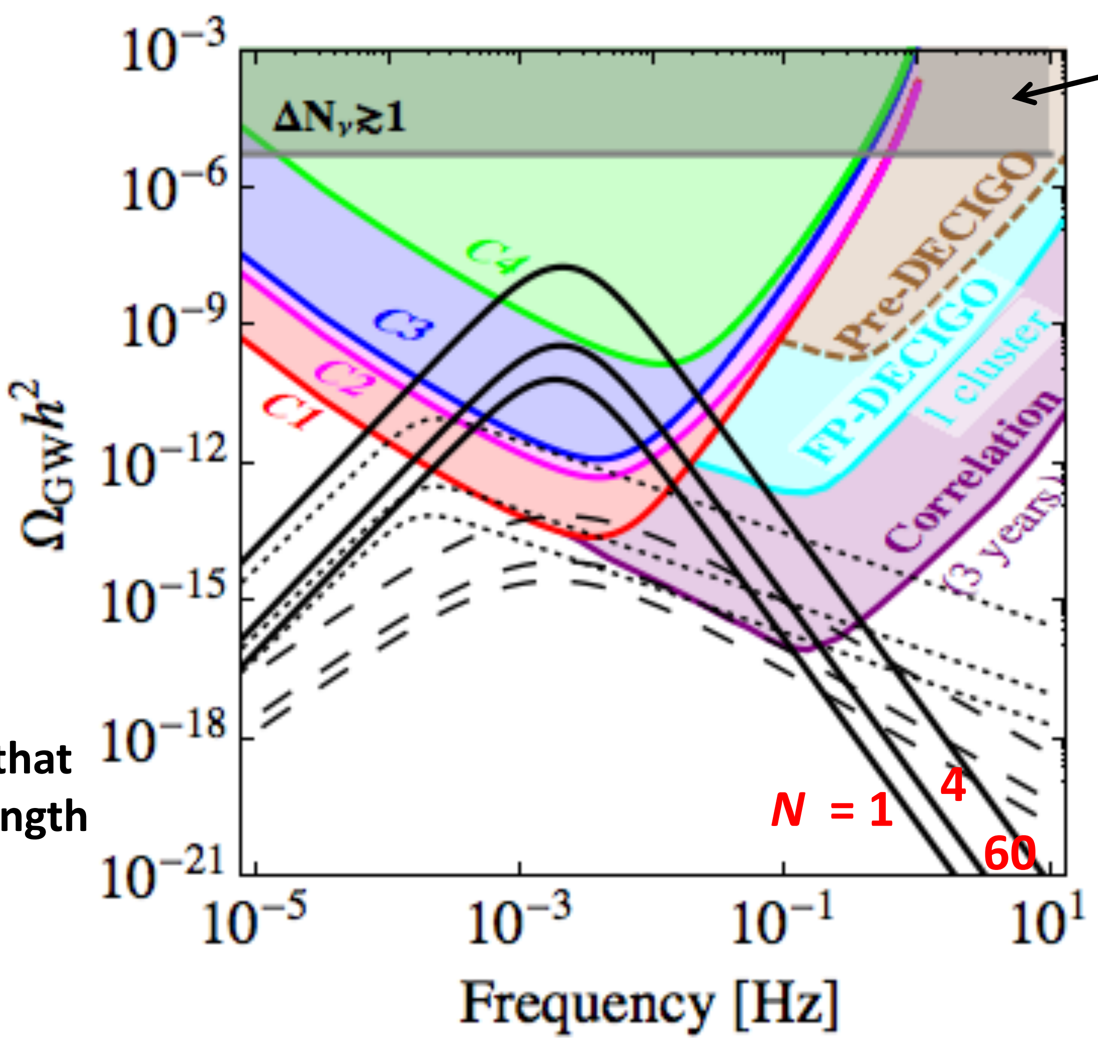


Large deviations in *hhh* coupling

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

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)

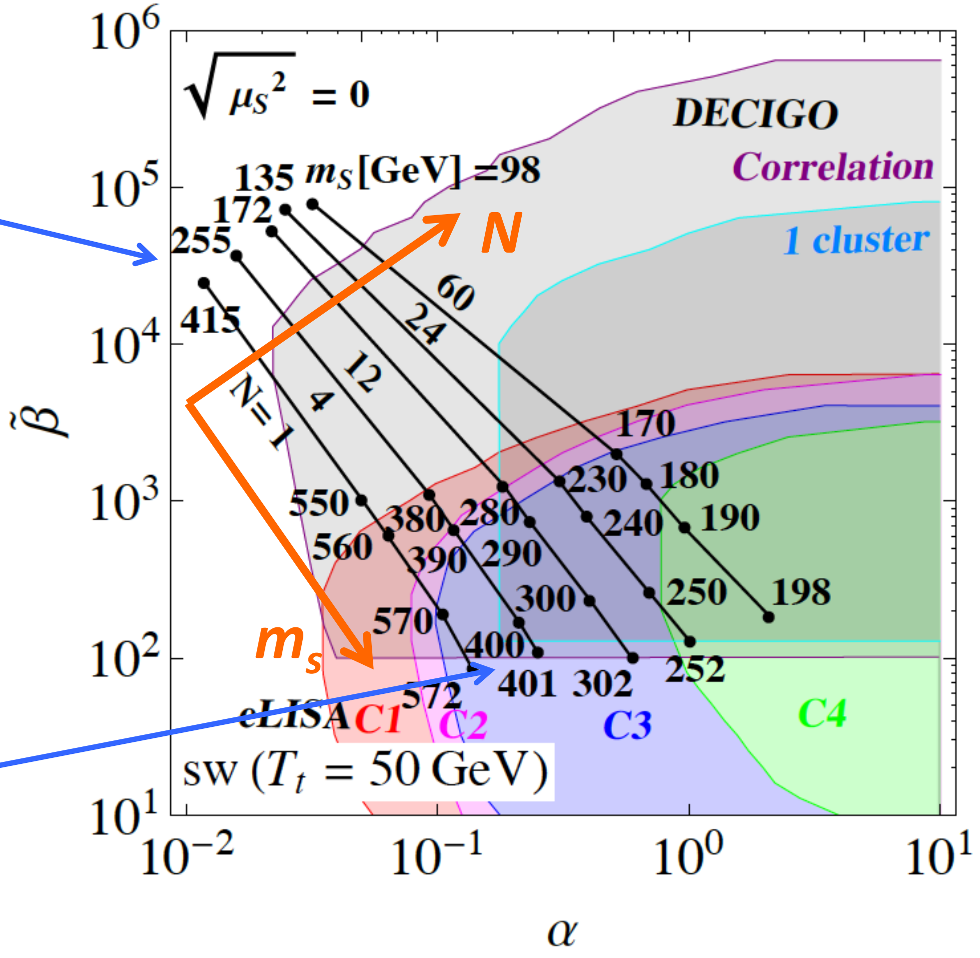
Mass m_s is chosen such that the peak strength is maximal

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



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

Sensitivities

eLISA
arXiv:1512.06239

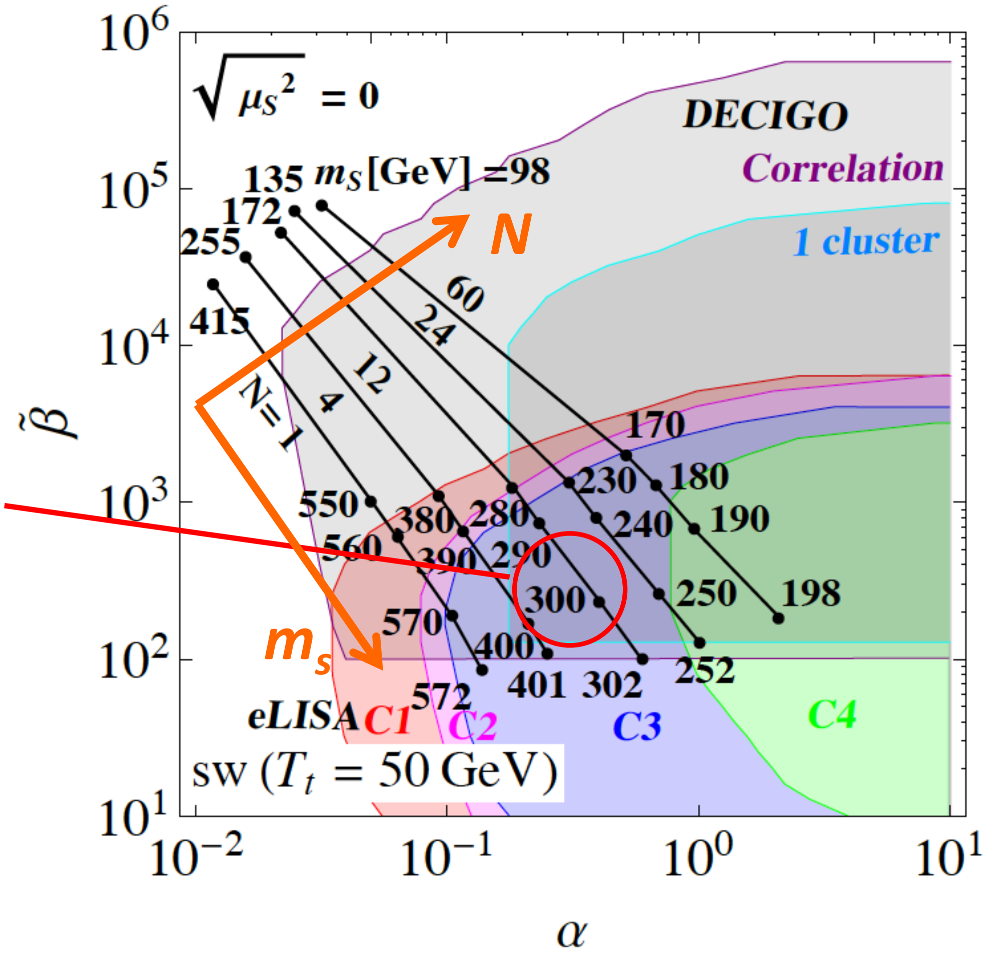
DECIGO,
Class. Quant. Grav.
28, 094011 (2011)

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 ↓

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

Non-thermal effect ↑

Higgs singlet model **K. Fuyuto and E. Senaha, 2014**

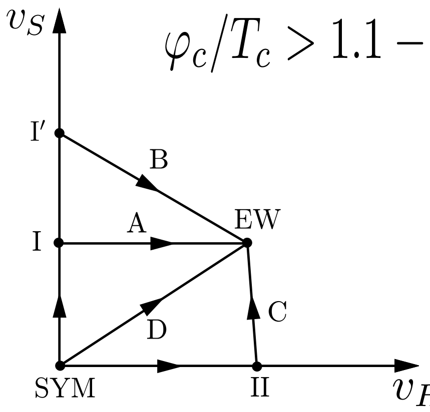
$$V_0 = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu_S'}{3}S^3 + \frac{\lambda_S}{4}S^4$$

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

Multi-field analysis of EWPT is necessary

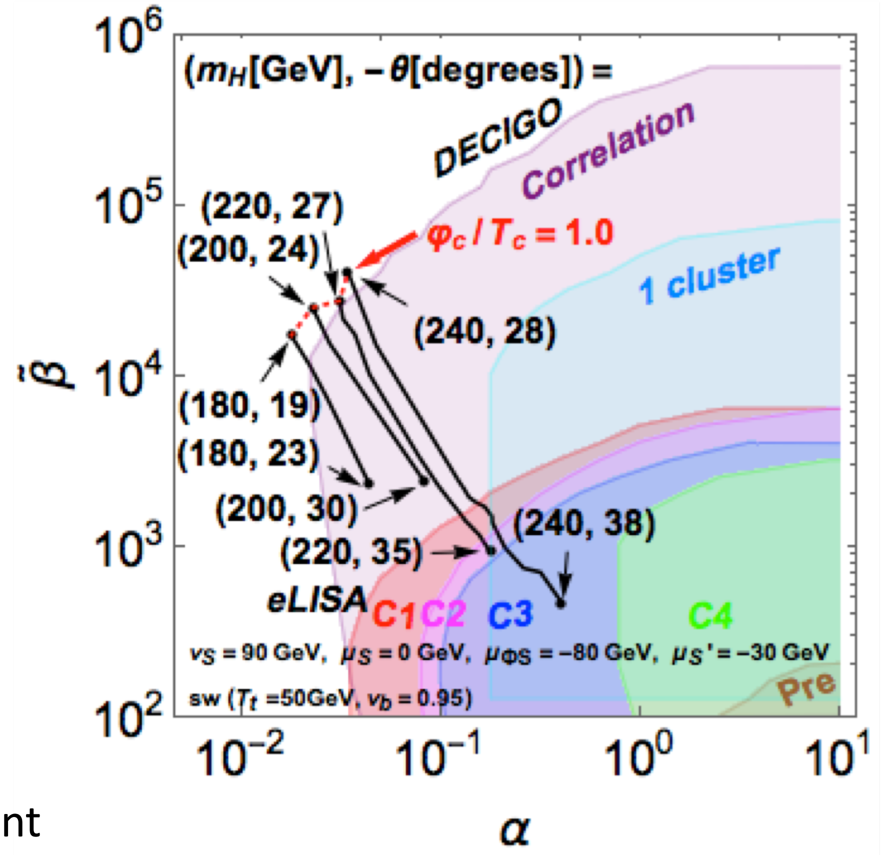
$$(v_\Phi, v_S)$$

$$\varphi_c/T_c > 1.1 - 1.2$$



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

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

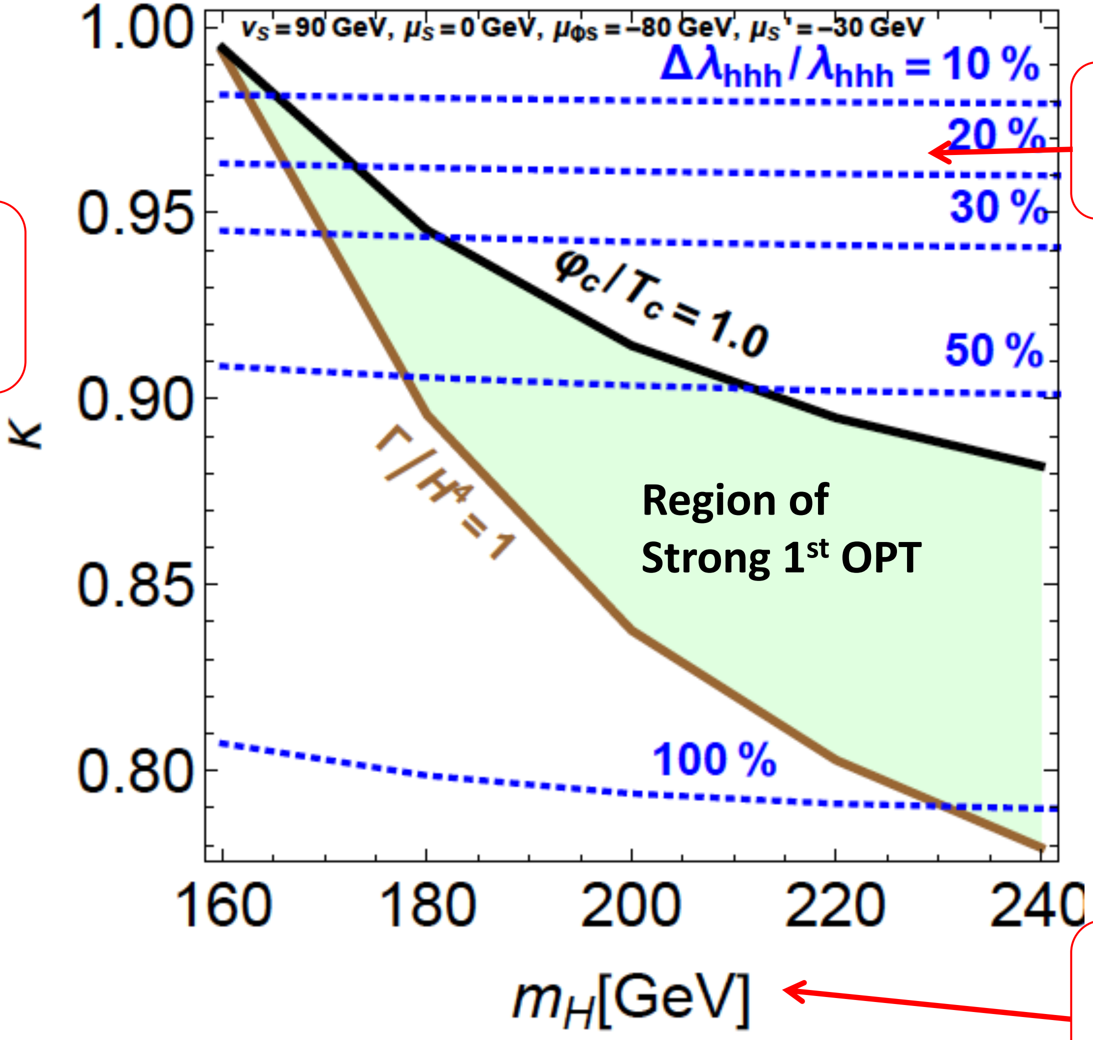
v_Φ [GeV]	v_S [GeV]	m_h [GeV]	$\mu_{\Phi S}$ [GeV]	μ'_S [GeV]	μ_S [GeV]	m_H [GeV]	θ [degrees]
246.2	90	125.5	−80	−30	0	[160, 240]	[−45, 0]

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

$\kappa = \kappa_V = \kappa_f$

$= \cos\theta$

Precision measurement at ILC/LHC



Self-coupling *hhh* measurement at ILC

Direct searches of the second Higgs at LHC

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

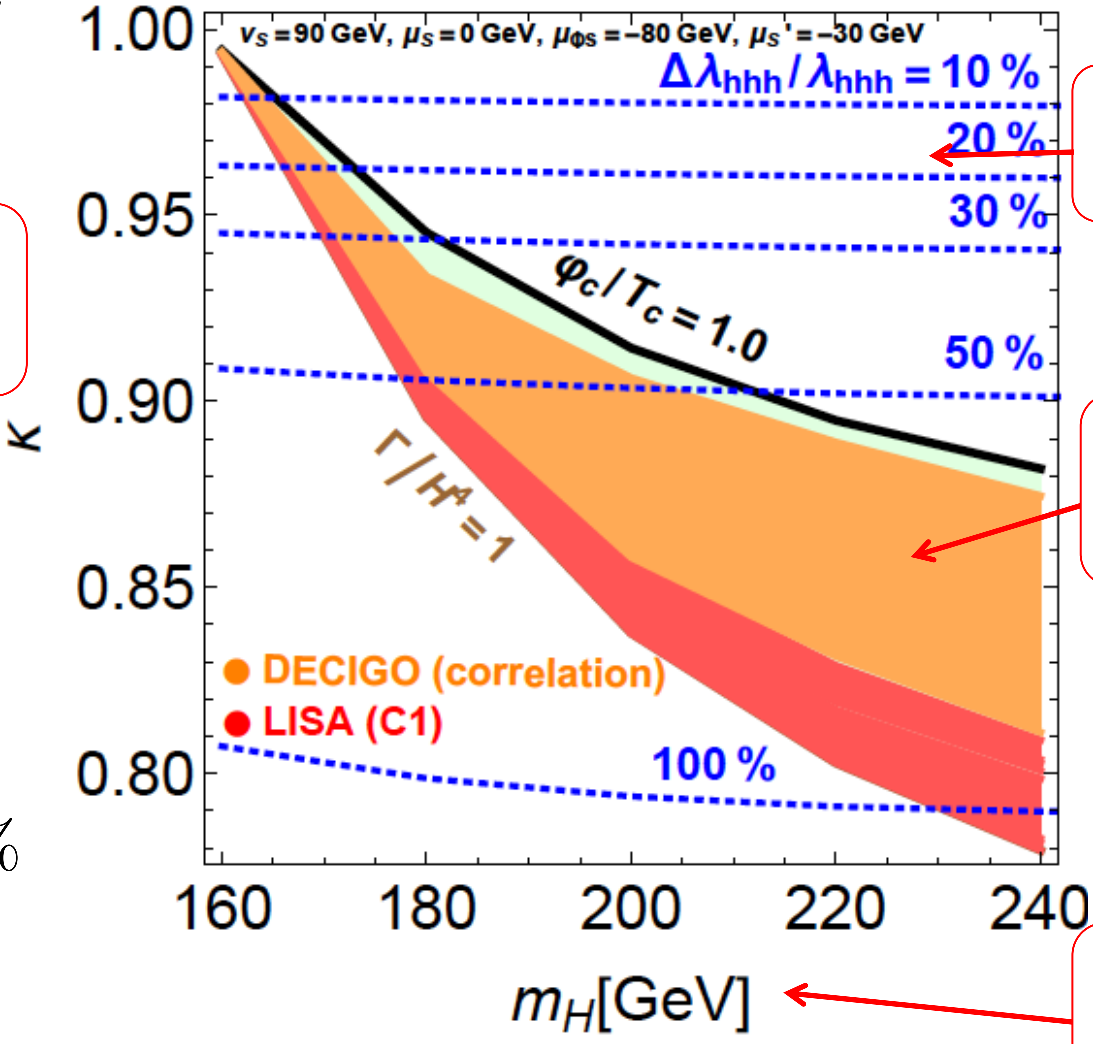
HL-LHC

$\kappa_V : 2\%$

ILC

$\kappa_Z : 0.37\%$

$\kappa_W : 0.51\%$



Self-coupling *hhh* measurement at ILC

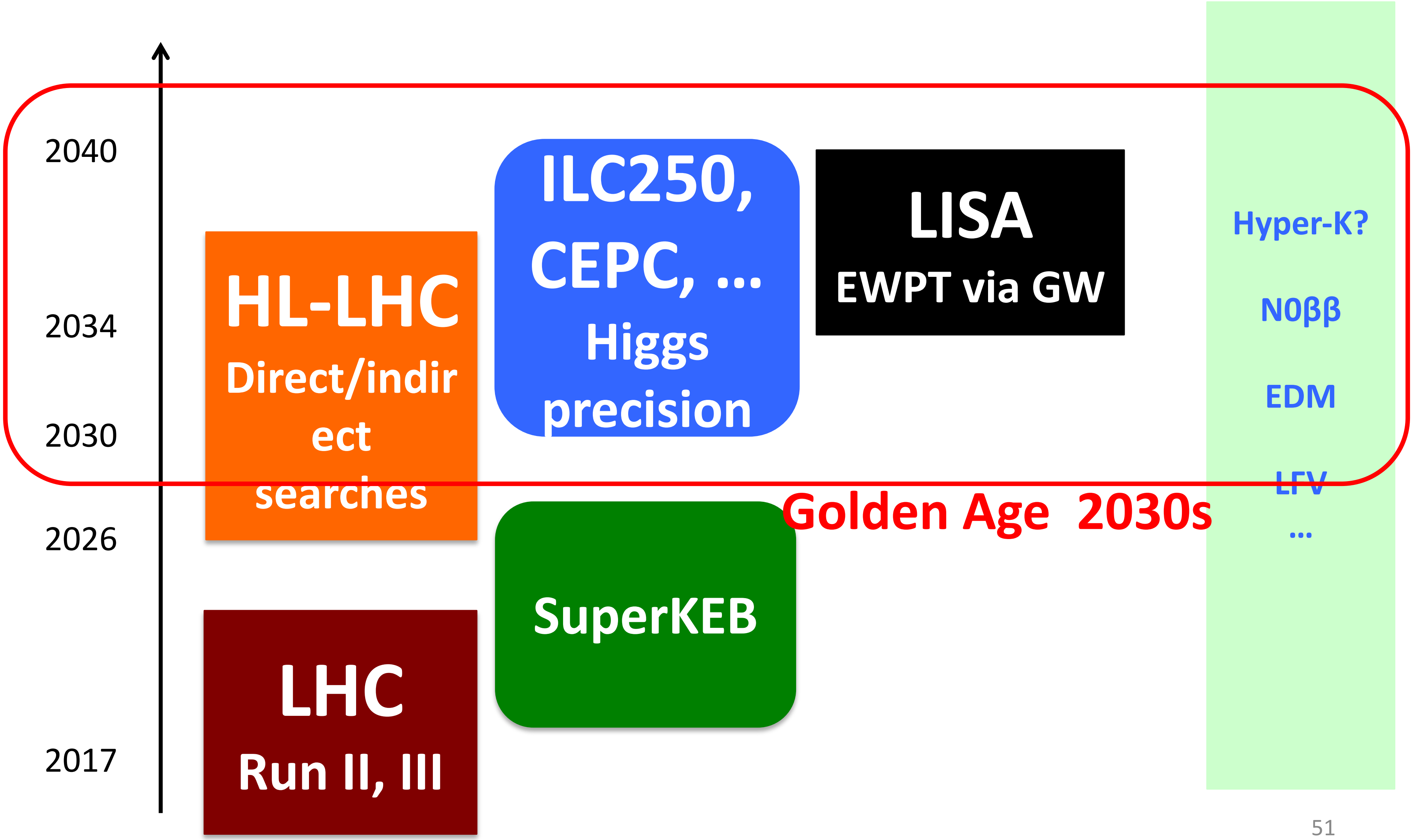
$\Delta\lambda_{hhh} : 10\%$

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)

Future experiments



2040

2034

2030

2026

2017

HL-LHC

Direct/indirect searches

ILC250, CEPC, …

Higgs precision

LISA

EWPT via GW

LHC

Run II, III

SuperKEB

Golden Age 2030s

Hyper-K?

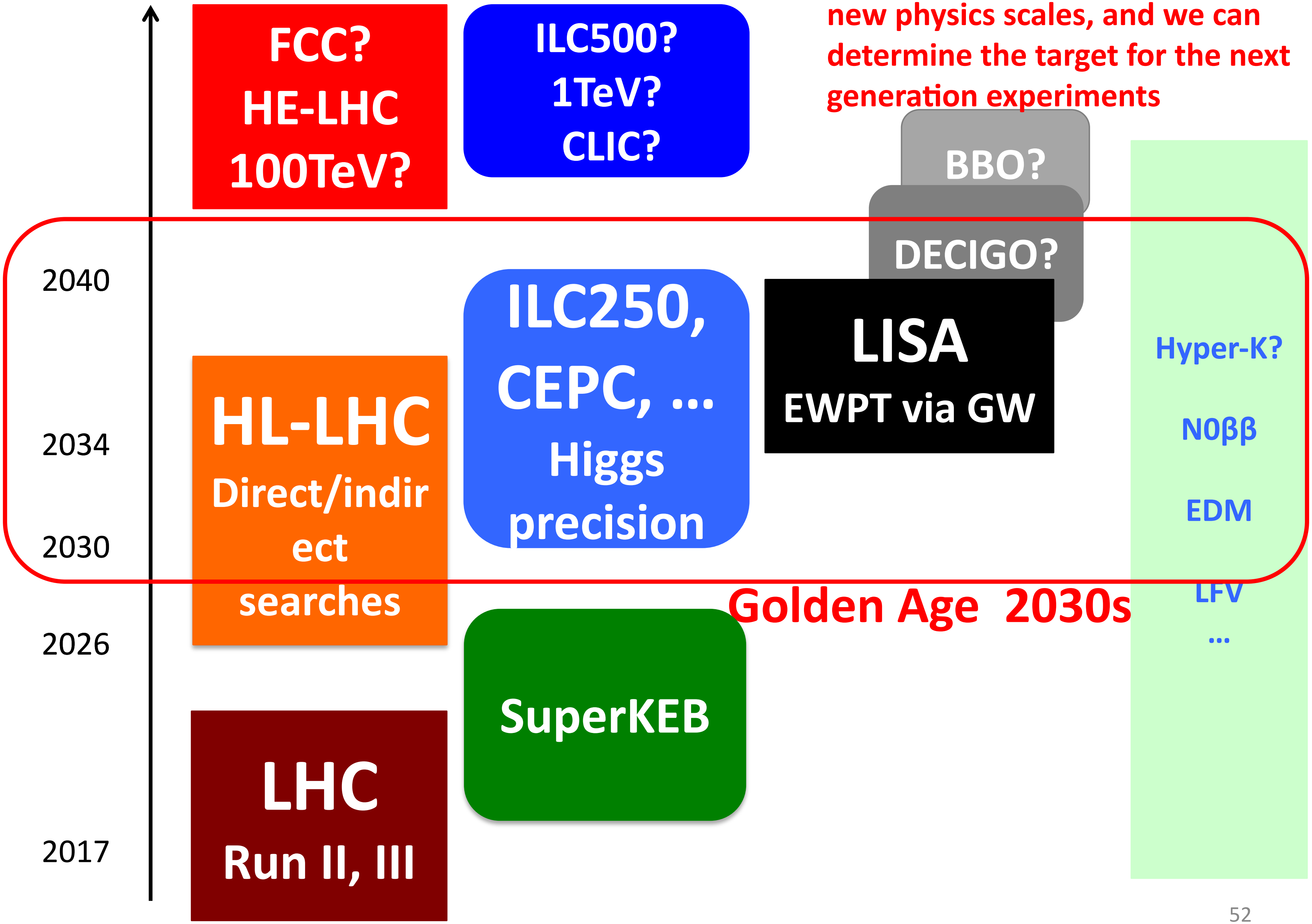
N0ββ

EDM

LFV

…

In 2030-40s, we obtain hints of the new physics scales, and we can determine the target for the next generation experiments



2040

2034

2030

2026

2017

FCC?
HE-LHC
100TeV?

ILC500?
1TeV?
CLIC?

BBO?

DECIGO?

LISA
EWPT via GW

ILC250,
CEPC, …
Higgs precision

HL-LHC
Direct/indirect searches

Hyper-K?
N0ββ
EDM
LFV
…

Golden Age 2030s

SuperKEB

LHC
Run II, III

Part III Summary

- Higgs is a probe of new physics beyond SM
  - Neutrino Mass
  - Dark Matter
  - Baryogenesis
- Higgs potential can be probed at future colliders and GW interferometers
- Synergy among LHC, LC and LISA/Decigo is important to probe new physics scenarios