# Gravitational waves from first order phase transition

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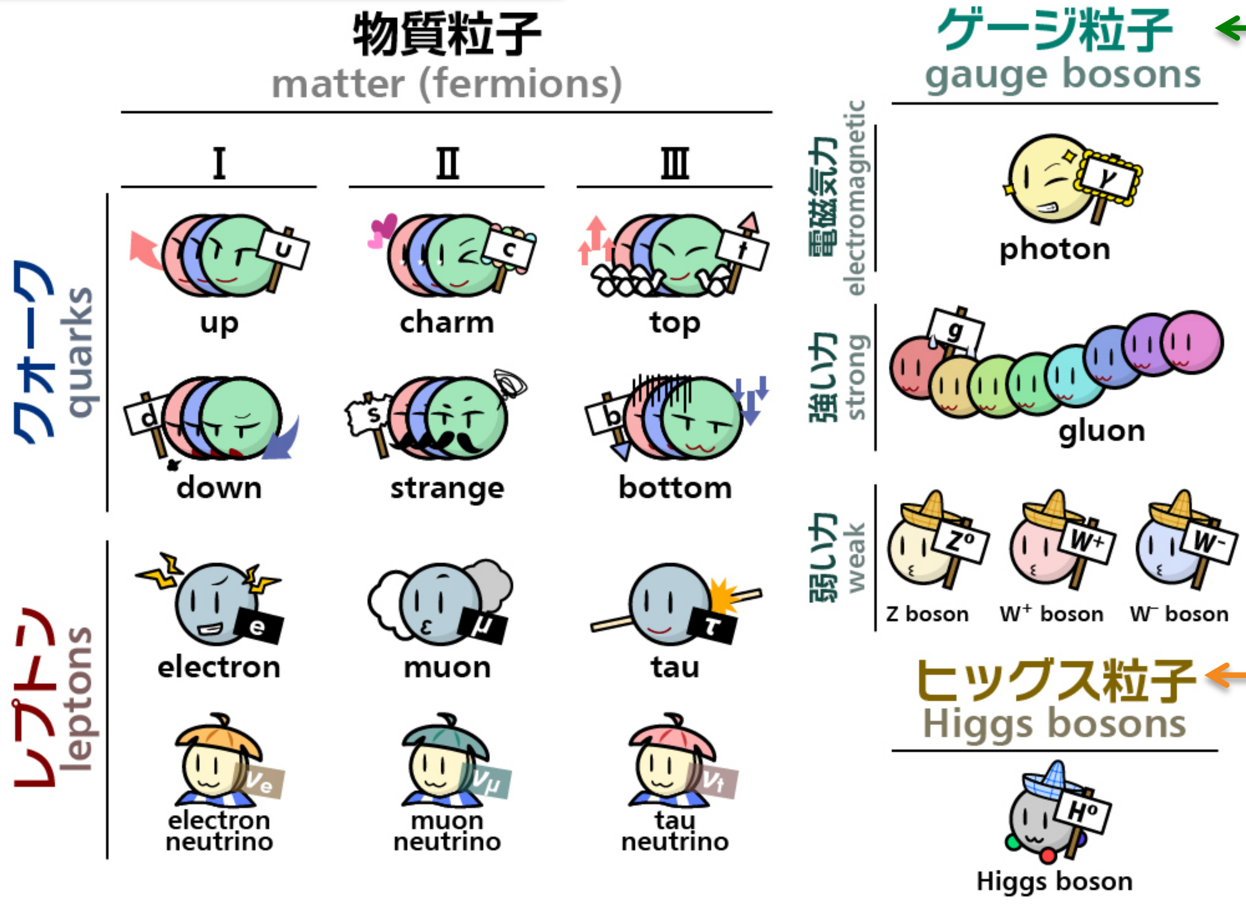
- References:
  - Hashino, Jinno, MK, Kanemura, Takahashi and Takimoto, arXiv:1809.04994
    Accepted by Physical Review D

# Contents

# Standard Model of Particle Physics

Standard Model (SM)



Force mediator

Origin of elementary particle mass
（discovered in 2012）

- Established theory describing elementary particles
- But, some phenomena demand new physics beyond the SM

# New Physics Beyond the Standard Model

## Beyond the Standard Model → Aoki

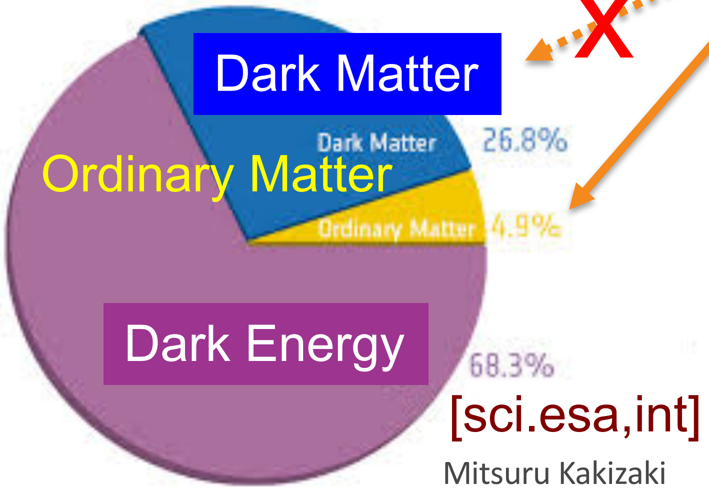
Experimental problems:

- Neutrino oscillations → Sugiyama, Okui
- Existence of dark matter → Ishiwata
- Existence of dark energy → Shima
- Baryon asymmetry → Asaka
- Cosmic inflation → Kubo
- Other anomalies

Theoretical puzzles:

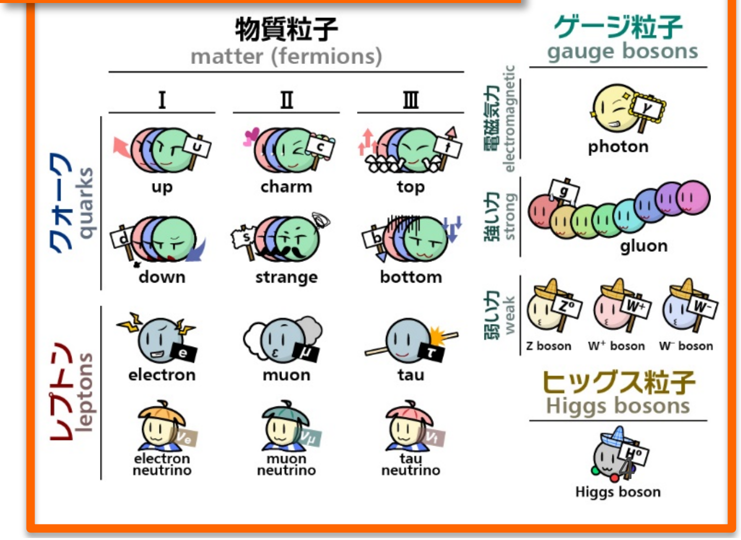
- Structure of the Higgs sector, Hierarchy problem, etc.

## What is the Universe made of?



[sci.esa,int]

## Standard Model



# History of the Universe

Big bang nucleosynthesis

Recombination (Cosmic microwave bg.)

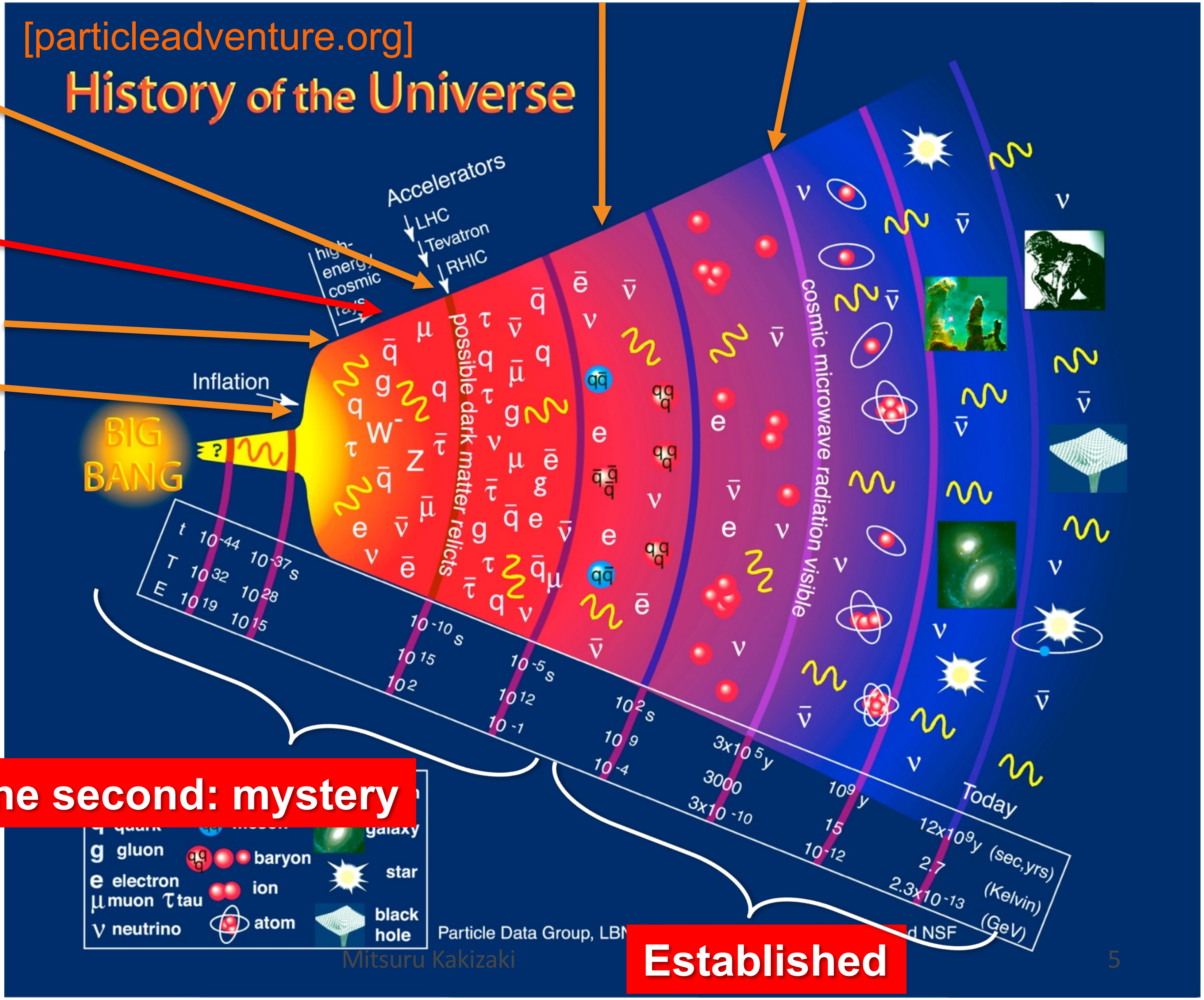
Generation of dark matter?

Electroweak phase transition?

Baryogenesis?

Cosmic Inflation

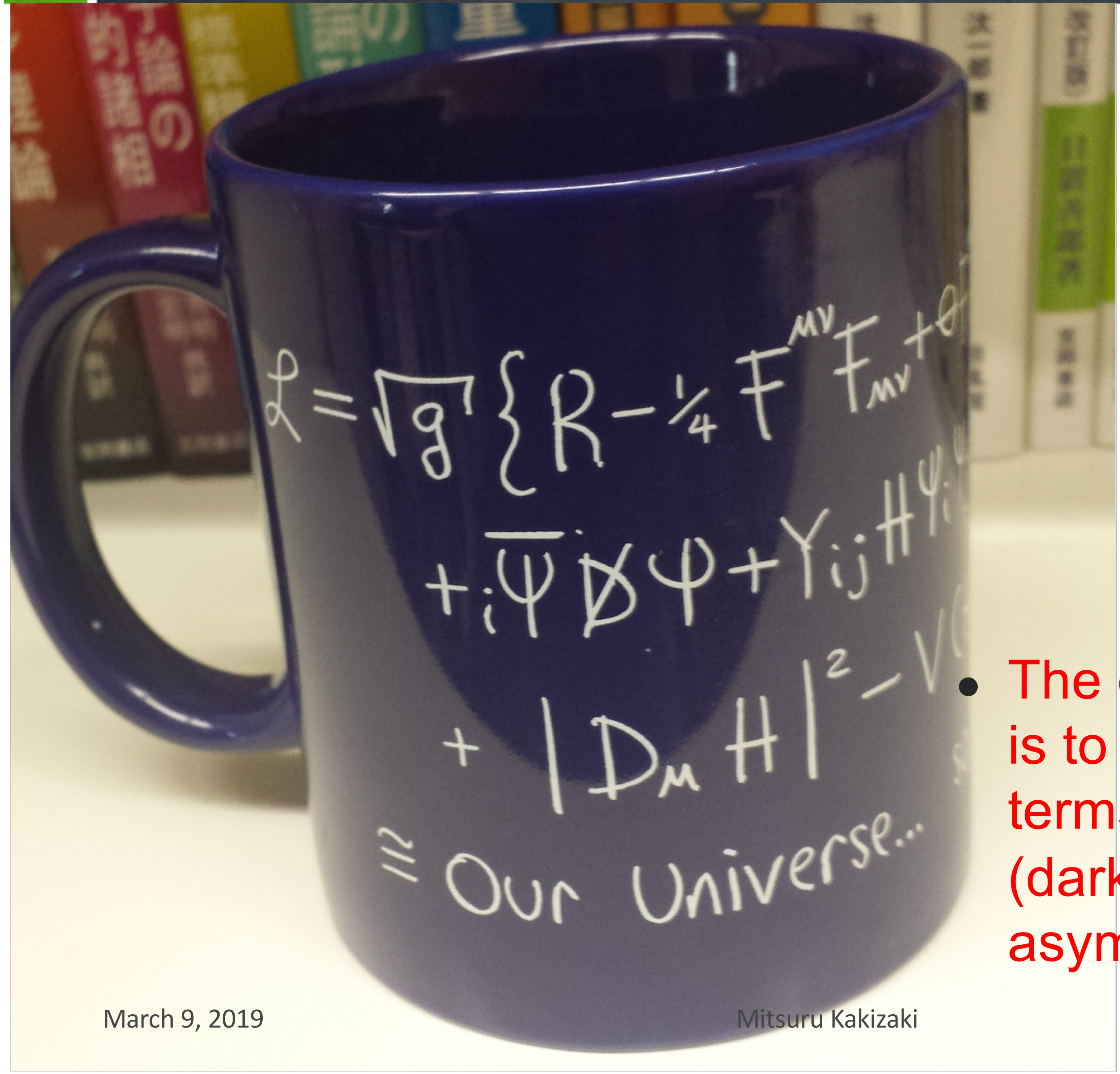
[particleadventure.org]



**The first one second: mystery**

**Established**

# Our Universe (in mathematical language) = Standard Model x General Relativity + New Physics



- The goal of this research is to reveal unknown terms for new physics (dark matter, baryon asymmetry, etc.)

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1. Introduction for non-particle physicists
2. Introduction for non-gravitational wave physicists
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4. Gravitational waves from first order phase transition
5. Expected constraints on model parameters
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# Gravitational Waves

## Gravitational waves (GWs)

- Non-uniform motion of a massive object

→ Ripples of spacetime propagating at the speed of light

c.f. Non-uniform motion of a charged object

→ Electromagnetic waves

## Properties of gravitational waves

- Transverse to the direction of propagation
- Spin 2
- 2 polarization modes: Plus mode h+ & Cross mode hx

## Sources of gravitational waves

Astrophysical origin

- Binaries (NS, BH, ...)
- Supernovae
- etc.

Cosmological origin

- 1st order phase transition
- Cosmic inflation
- Topological defects

# Gravitational Waves as a Probe for the Early Universe

## Weak field approximation

- Metric close to flat $g_{\mu\nu}(x) = \eta_{\mu\nu} + \underline{h_{\mu\nu}(x),} \quad |h_{\mu\nu}| \ll 1$

➡ Linearlized Einstein equation in vacuum

$$\Box h_{\mu\nu} = 0 \quad \longleftarrow \quad \text{Wave equation!}$$

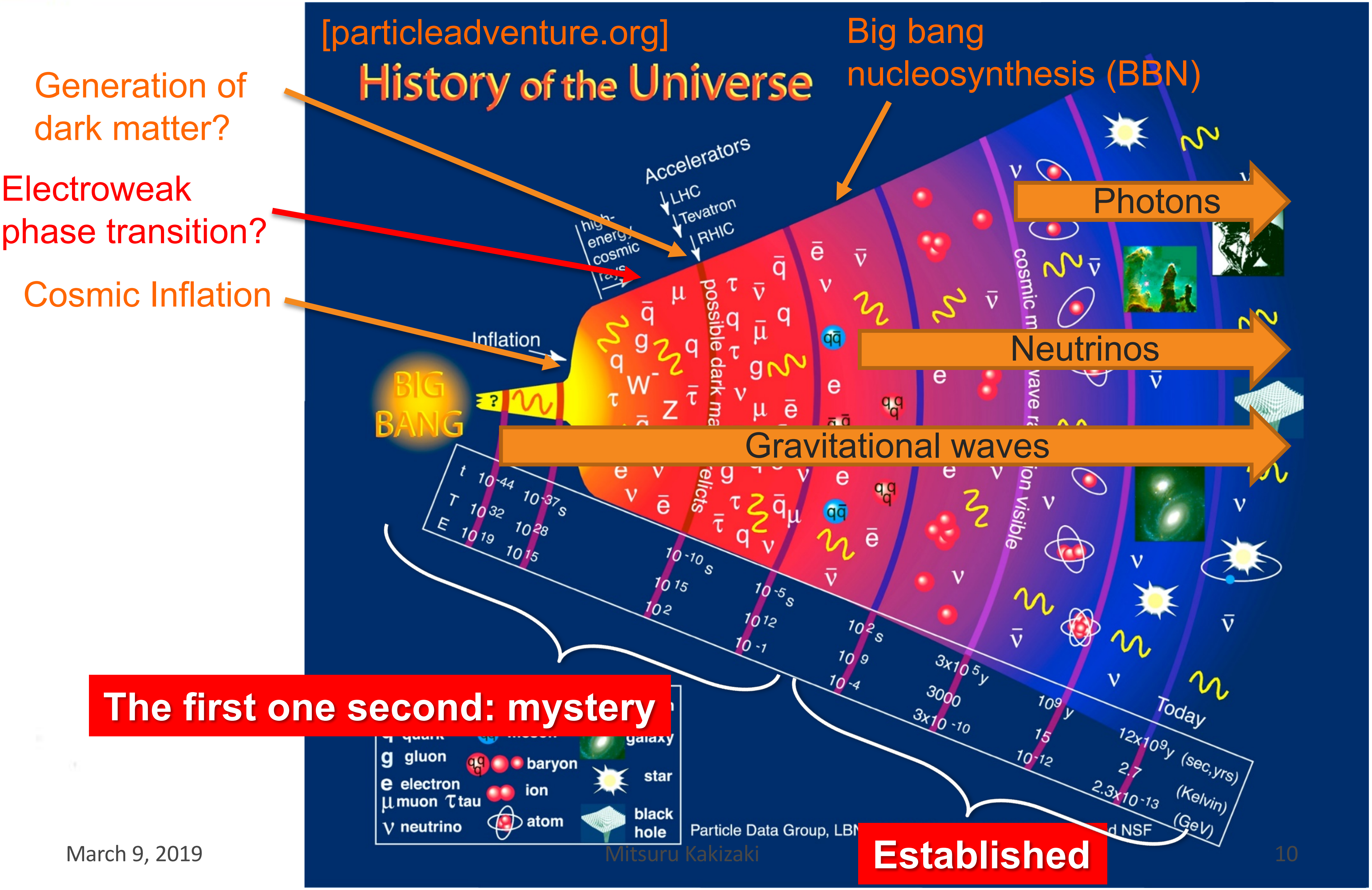
## Interaction rate of gravitational waves

- Interaction rate: $\Gamma = \underset{T^3}{n}\,\underset{G_N^2 T^2 = \frac{T^2}{M_{\rm Pl}^4}}{\sigma}\,\underset{1}{v}$
- Expansion rate of the Universe: $H \sim \dfrac{T^2}{M_{\rm Pl}}$

➡ $\dfrac{\Gamma}{H} \sim \dfrac{T^3}{M_{\rm Pl}^3}$

GWs decouple at temperatures below the Planck scale

# Universe earlier than big bang nucleosynthesis can be probed by using GWs



[particleadventure.org]

Big bang nucleosynthesis (BBN)

Generation of dark matter?

Electroweak phase transition?

Cosmic Inflation

Photons

Neutrinos

Gravitational waves

**The first one second: mystery**

**Established**

# Relic gravitational waves

Characteristics of relic gravitational waves

- Homogeneous • Isotropic • Static • Unpolarized

➡ Relic GWs are characterized only by frequency $f$

Energy density of relic gravitational waves

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

- Normalized Energy density per unit logarithmic interval of frequency

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

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

# Typical frequency of relic gravitational waves

Gravitational waves produced with frequency $f_t$, abundance $\Omega^t_{\rm GW}$ are red-shifted due to the expansion of the Universe

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

$a$ : scale factor

→ Red-shifted GW relic abundance observed today:

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

Red-shifted typical frequency observed today:

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

For typical electroweak phase transition:

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

Range for future space-based interferometers

# Contents

# Motivation

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

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

This is not the end of the story

## Puzzles in the Higgs sector

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

## Phenomena beyond the SM (BSM)

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

## Idea: Higgs sector = Window to New Physics

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

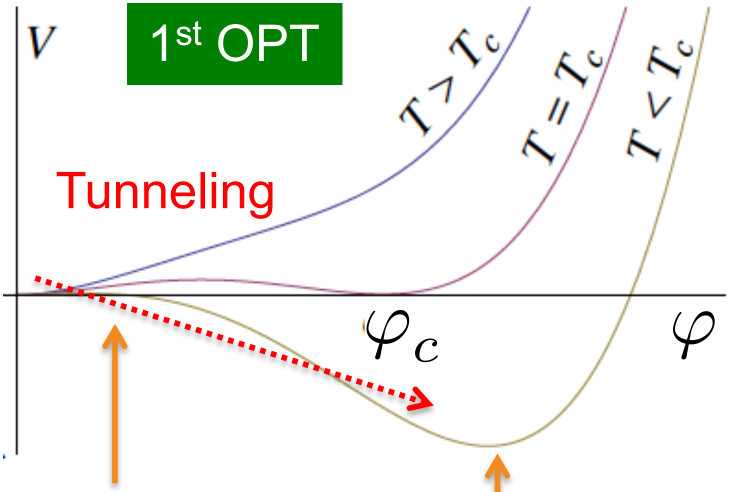
Information on new physics can be obtained by investigating the properties of the Higgs sector

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

## Sakharov's conditions for BAU

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

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



Potential barrier

True vacuum

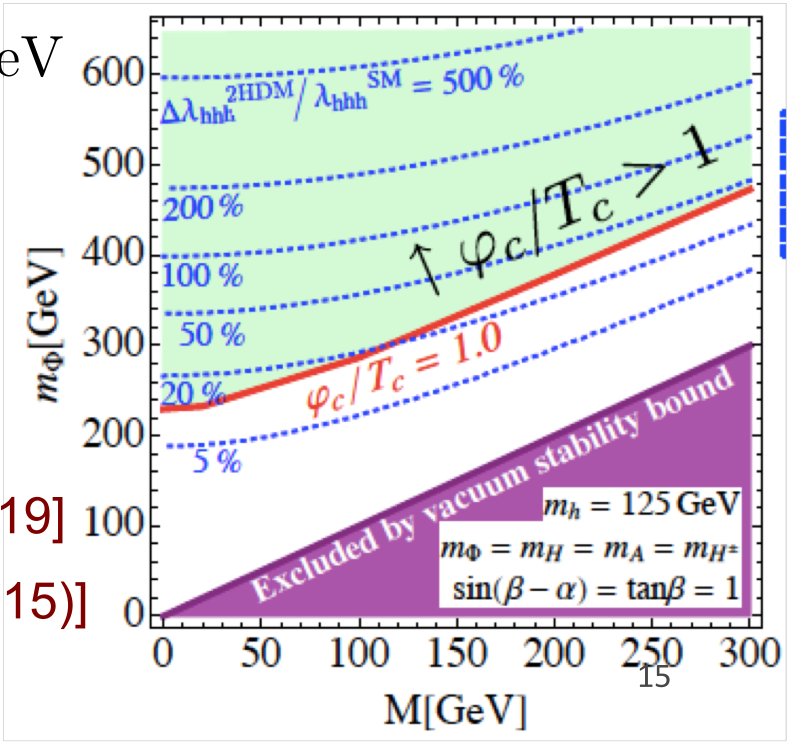
## SM Higgs potential w/ one doublet:

- PT is NOT of 1st order for $m_h = 125\ \text{GeV}$

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

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

[Kanemura, Okada, Senaha (2005)]



## Future accuracy:

- High-Luminosity LHC:

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

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

# Gravitational waves (GWs) as a probe of EWPT

Ground-based interferometers:

advanced LIGO, advanced Virgo, KAGRA, ...

- Main targets: GWs from binary systems, supernovae, ...
- aLIGO made the first direct observation of GWs

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

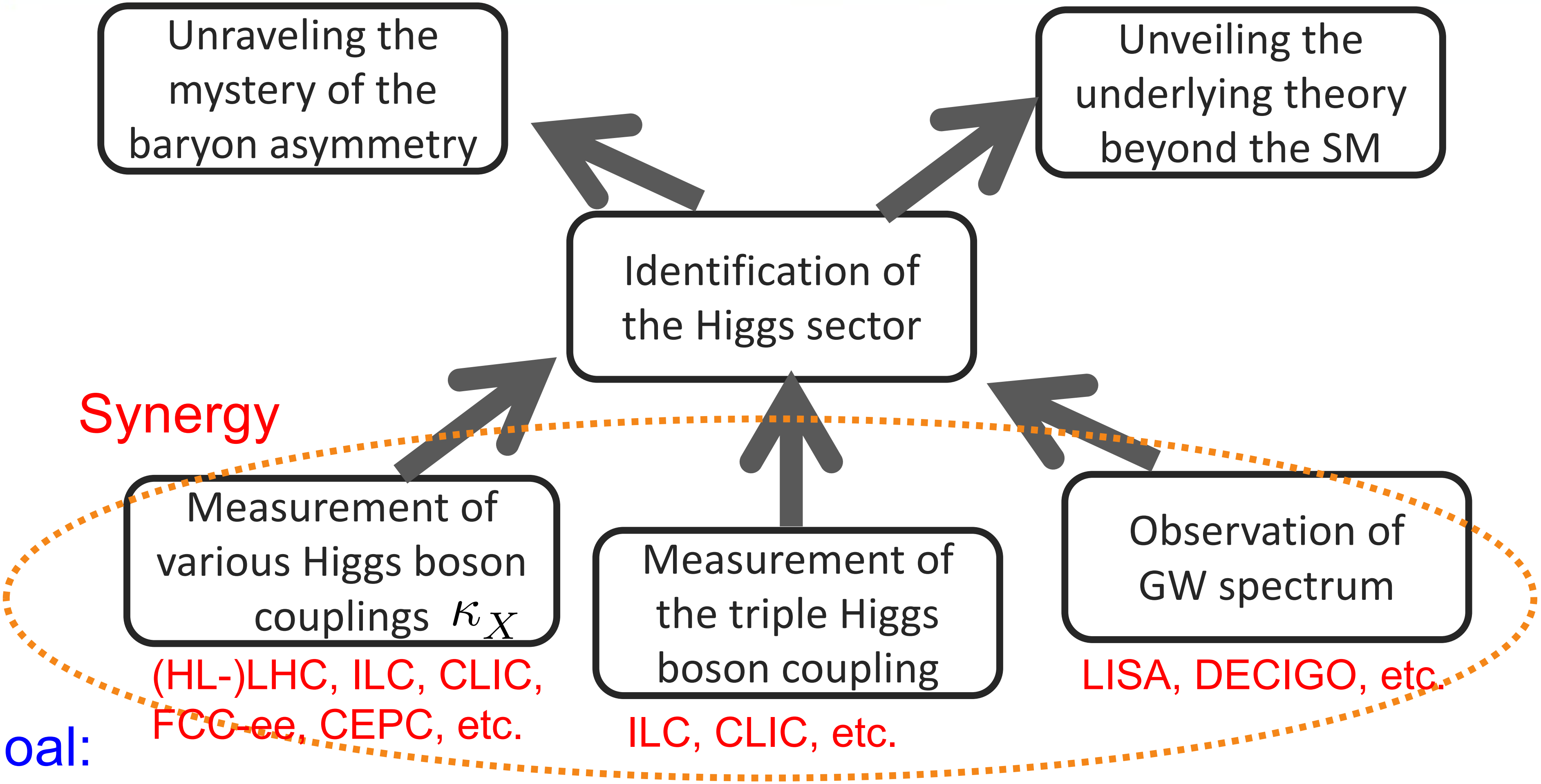
Future space-based interferometers:

LISA (2034-), DECIGO, ...

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

→ New era for fundamental physics

# Synopsis



Unraveling the mystery of the baryon asymmetry

Unveiling the underlying theory beyond the SM

Identification of the Higgs sector

Synergy

Measurement of various Higgs boson couplings $\kappa_X$

(HL-)LHC, ILC, CLIC, FCC-ee, CEPC, etc.

Measurement of the triple Higgs boson coupling

ILC, CLIC, etc.

Observation of GW spectrum

LISA, DECIGO, etc.

Goal:

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

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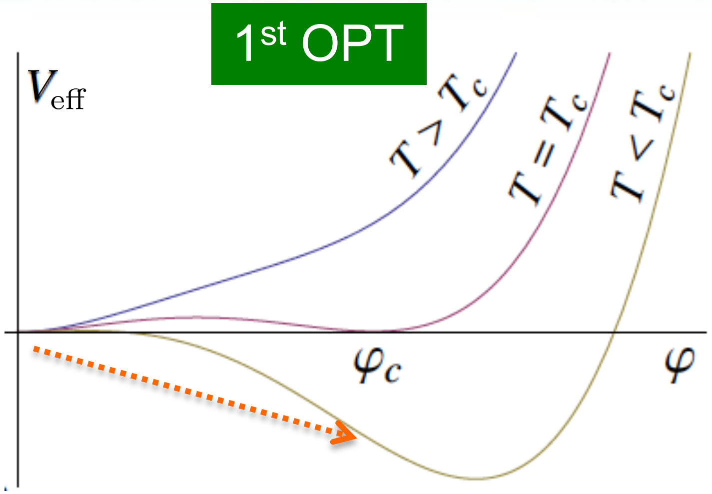
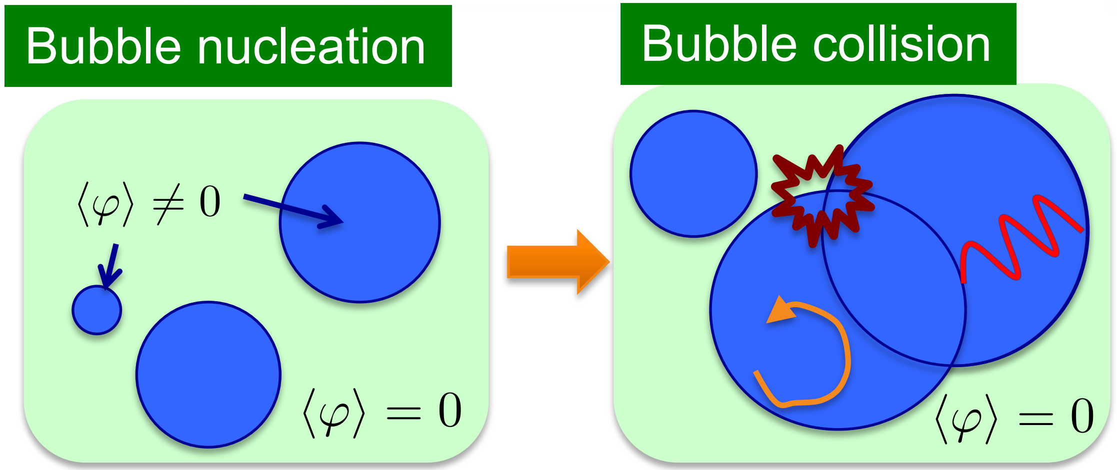
# GWs from 1st OPT


1st OPT


Bubble nucleation

Bubble collision

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

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

Sources of GWs

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

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

# Important quantities for GW spectrum

Bubble nucleation rate per unit volume per unit time:

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

Transition temperature $\boxed{T_*}$

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

Released false vacuum energy (Latent heat)

$$\epsilon(T) = -V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial V_{\rm eff}(\varphi_B(T), T)}{\partial T}$$

Normalized parameter: $\boxed{\alpha = \frac{\epsilon(T_*)}{\rho_{\rm rad}(T_*)}}$

Inverse of the duration of phase transition

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

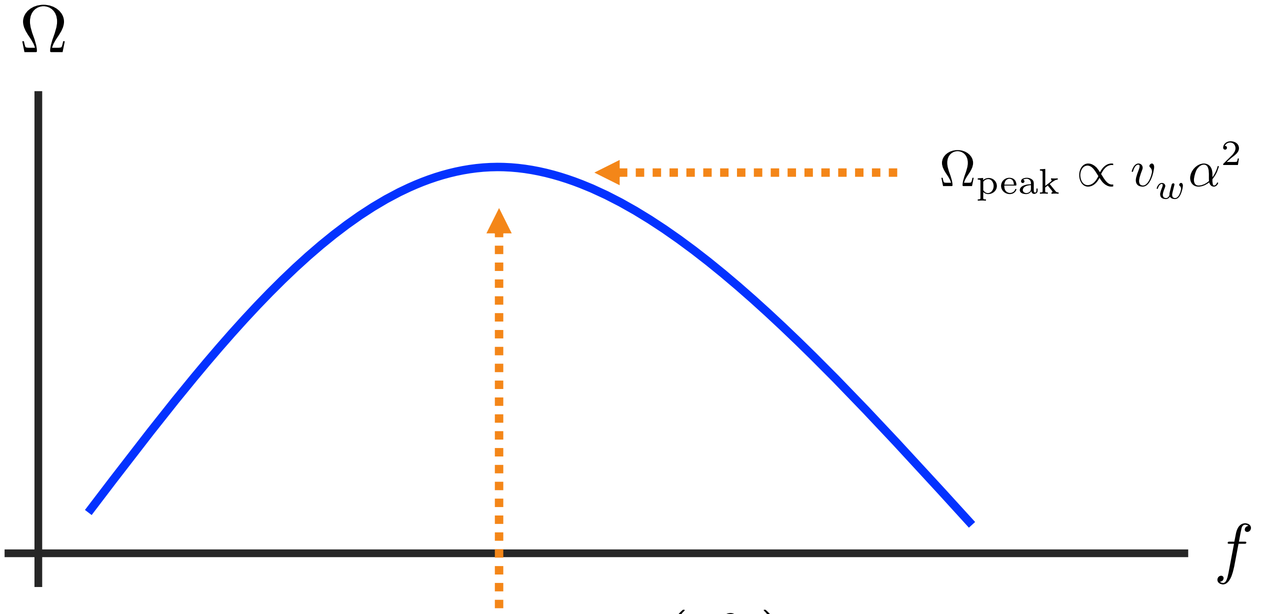
Normalized parameter: $\boxed{\frac{\beta}{H_*}\left(= \tilde{\beta}\right)}$

Wall velocity $\boxed{v_w}$

# GW spectrum

Rough spectrum from the dominant sound wave contribution

$$\Omega(f) \equiv \frac{1}{\rho_c} \frac{d\rho}{d \ln f}$$



$$\Omega_{\text{peak}} \propto v_w \alpha^2 \left( \frac{\beta}{H_*} \right)^{-1}$$

$$f_{\text{peak}} \propto v_w^{-1} T_* \left( \frac{\beta}{H_*} \right)$$

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

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# Fisher Analysis

## Likelihood function

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 w.r.t. $\{p\} = \{\hat{p}\}$

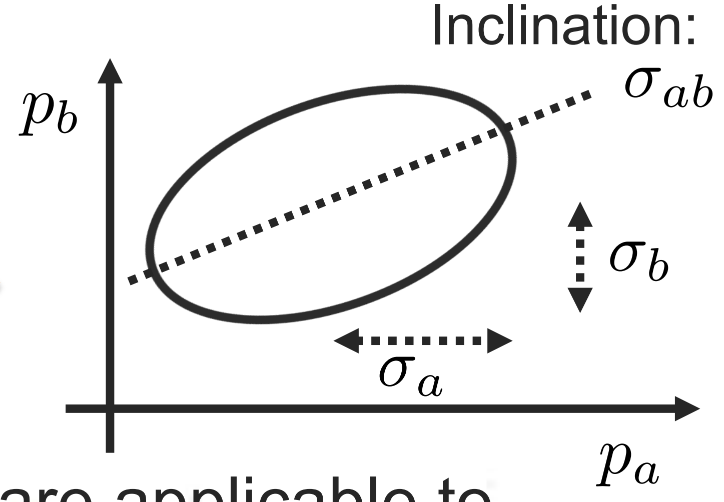
$$\delta\chi^2(\{p\}\,,\{\hat{p}\}) \simeq \mathcal{F}_{ab}(p_a - \hat{p}_a)(p_b - \hat{p}_b)$$

## Fisher information matrix

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

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

**Confidence ellipse**

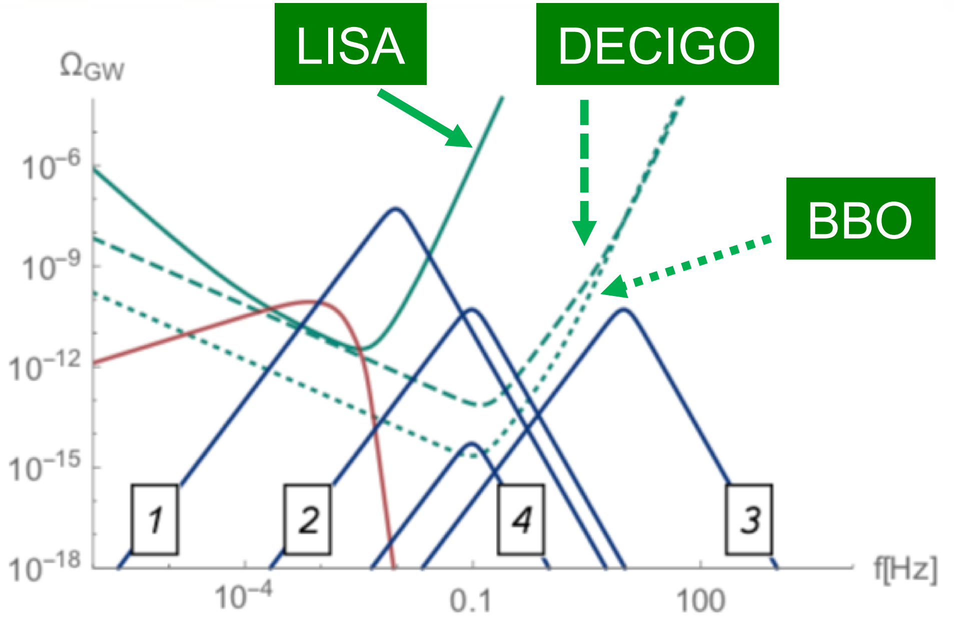


n.b.: we assume that these expressions are applicable to a single-detector like LISA

# Constraints on the shape of GW spectrum

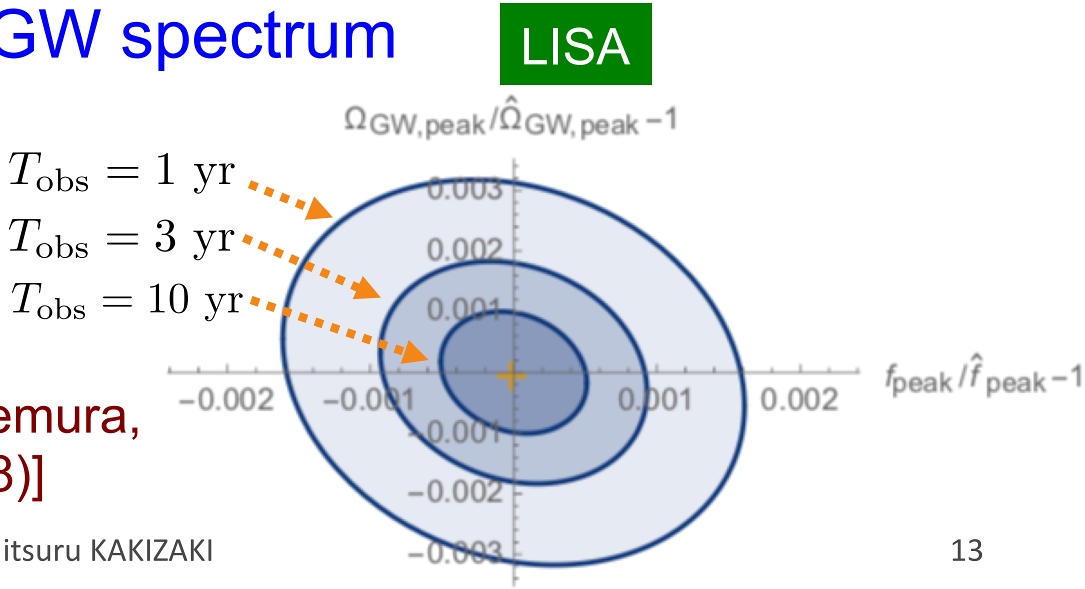
## GW spectrum

- 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

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



$T_{\rm obs} = 1$ yr
$T_{\rm obs} = 3$ yr
$T_{\rm obs} = 10$ yr

[Hashino, Jinno, MK, Kanemura, Takahashi, Takimoto (2018)]

# Constraints on transition parameters

## Constraining parameters

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

➡ Our Fisher analysis generically constrain 2 combinations of underlying parameters

## Quantities describing transition dynamics

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

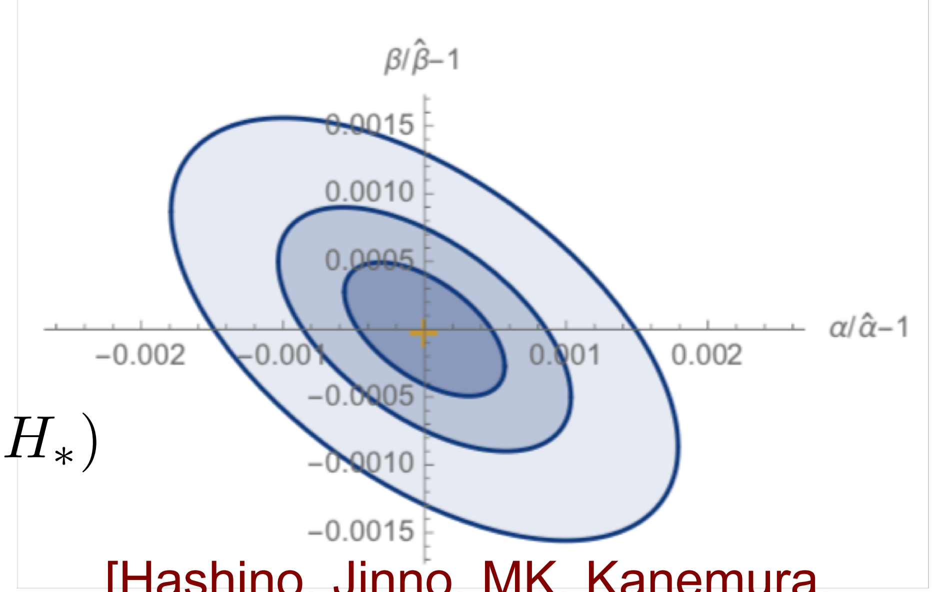
## Expected constraints on the transition parameters

- Fiducial values

  $(\alpha, \beta/H_*, v_w, T_*) = (1, 100, 1, 100\ \mathrm{GeV})$

- $1\ \sigma$ confidence ellipse in $(\alpha, \beta/H_*)$ for fixed $T_*$ and $v_w$

LISA



[Hashino, Jinno, MK, Kanemura, Takahashi, Takimoto (2018)]

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

## Typical examples for 1st OPT from thermal loop effects

- Models with CSI
  - Tree-level Higgs potential

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

$\Phi$ :Higgs doublet

$\vec{S} = (S_1, \ldots, S_N)$

  - Fiducial parameters

$$(N, \lambda_S) = (2, 0.1)$$

➡ $(\alpha, \beta/H_*, T_*\ [\mathrm{GeV}]) \simeq (0.080, 1000, 82)$

- Models without CSI
  - Tree-level Higgs potential

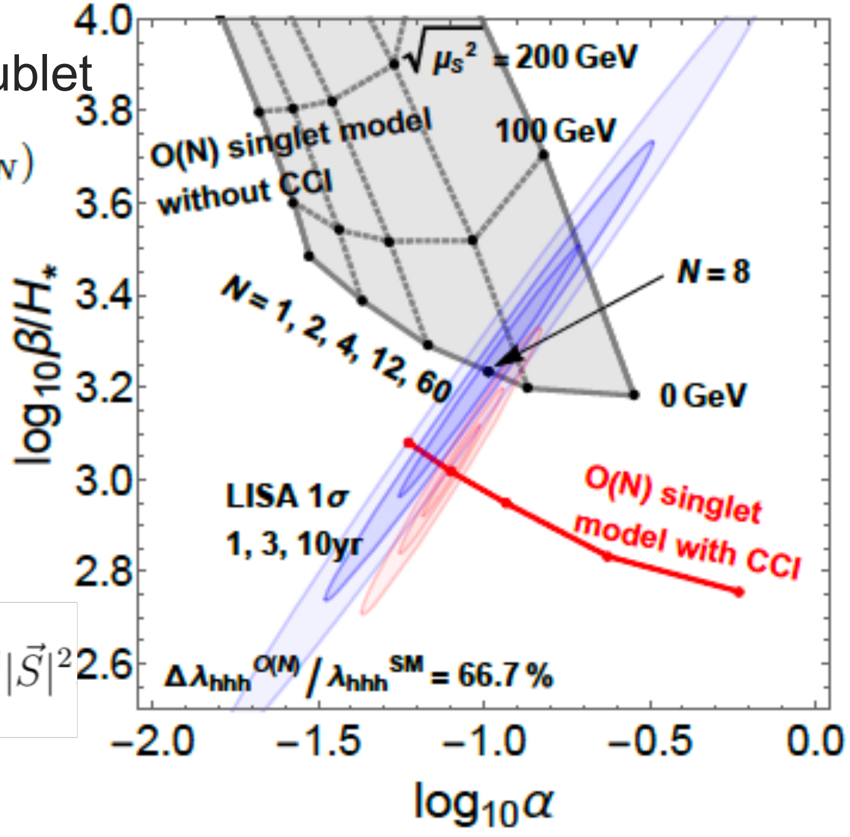
$$V_0 = -\mu^2|\Phi|^2 + \mu_S^2|\vec{S}|^2 + \lambda_\Phi |\Phi|^4 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2$$

  - Fiducial parameters

$$(N, \lambda_S, m_S\ [\mathrm{GeV}], \mu_S^2\ [\mathrm{GeV}^2]) = (8, 0.1, 385, 0)$$

➡ $(\alpha, \beta/H_*, T_*\ [\mathrm{GeV}]) \simeq (0.10, 1700, 83)$

LISA



[Hashino, Jinno, MK, Kanemura, Takahashi, Takimoto (2018)]

# Higgs singlet model

Typical example for 1st OPT from tree-level mixing

- Tree-level Higgs potential

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

→ Additional Higgs boson mass: $m_H$

Scaling factor: $\kappa$ ( $\kappa = 1$ in the SM)

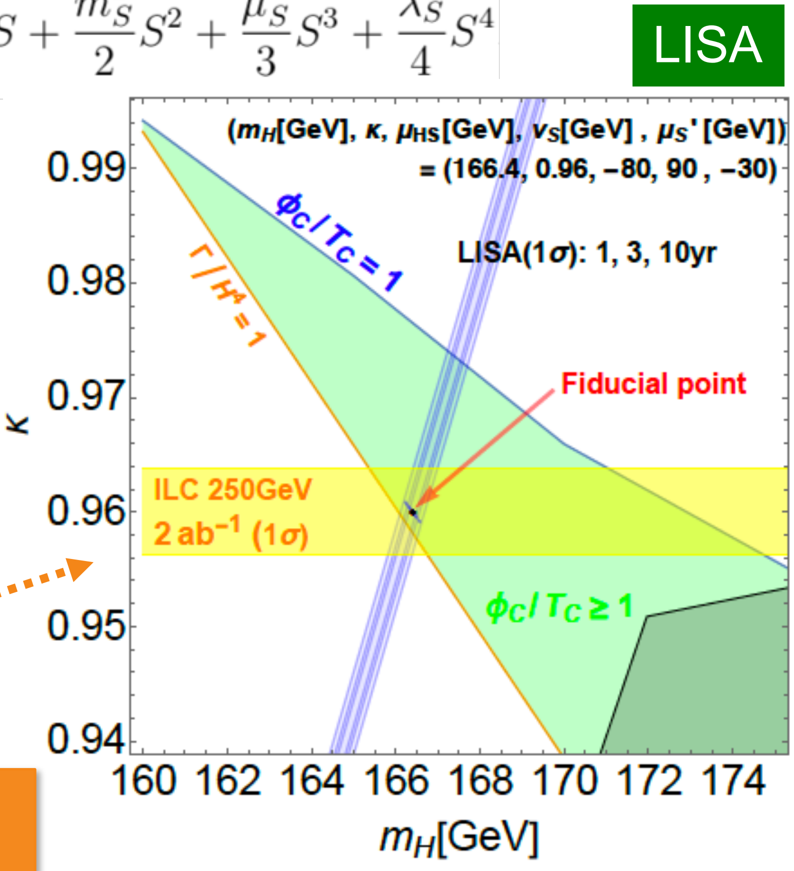
- Fiducial parameters

$$(m_H\ [\mathrm{GeV}], \kappa, \mu_{\Phi S}\ [\mathrm{GeV}], v_S\ [\mathrm{GeV}], \mu_S'\ [\mathrm{GeV}])$$
$$= (166, 0.96, -80, 90, -30)$$

→ $(\alpha, \beta/H_*, T_*\ [\mathrm{GeV}]) \simeq (0.085, 420, 93)$

Future colliders

- ILC [Fujii et al. (2017)]

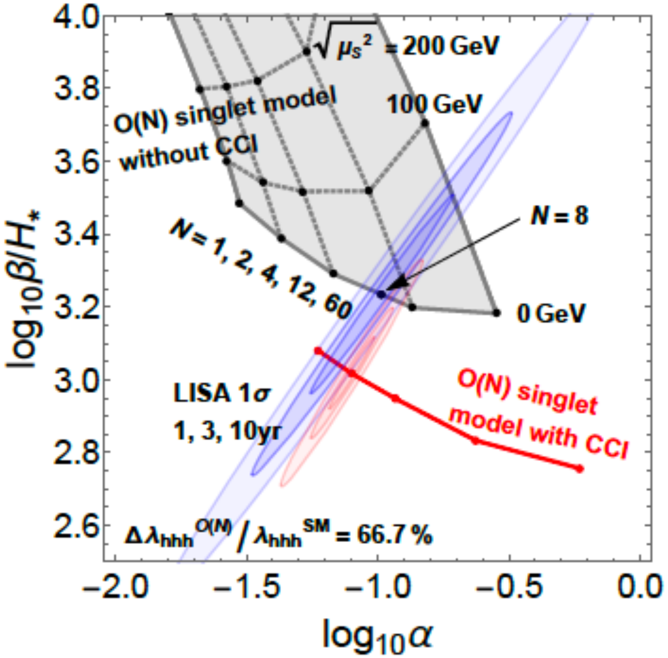


**The synergy between colliders and GW observations can narrow down the allowed parameter space**

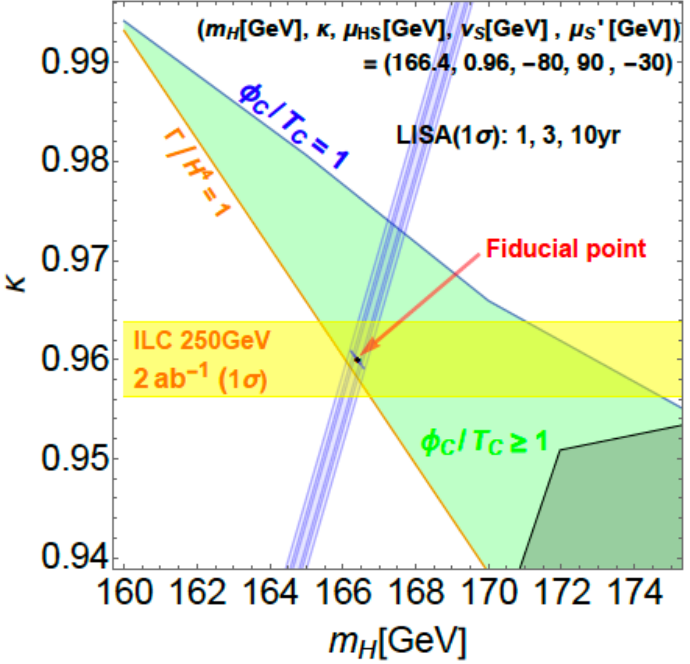
[Hashino, Jinno, MK, Kanemura, Takahashi, Takimoto (2018)]

# 6. Summary

- Models with additional singlet scalars



- Higgs singlet model



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