The Higgs sector and gravitational waves

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- Reference:
  - K. Hashino, R. Jinno, MK, S. Kanemura, T. Takahashi and M. Takimoto, Physical Review D99, no. 7, 075011 (2019), arXiv:1809.04994

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2. Gravitational waves
3. Gravitational waves from first order phase transition
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5. Summary

D'où venons-nous? Que sommes-nous? Où allons-nous?

[Paul Gauguin]

i.e., at the most fundamental level

- How did the Universe begin?
- What is the Universe made of?
- What is the fate of the Universe?

The goal of this research is to answer these questions

How did the Universe begin?

Recombination (Cosmic microwave bg.)

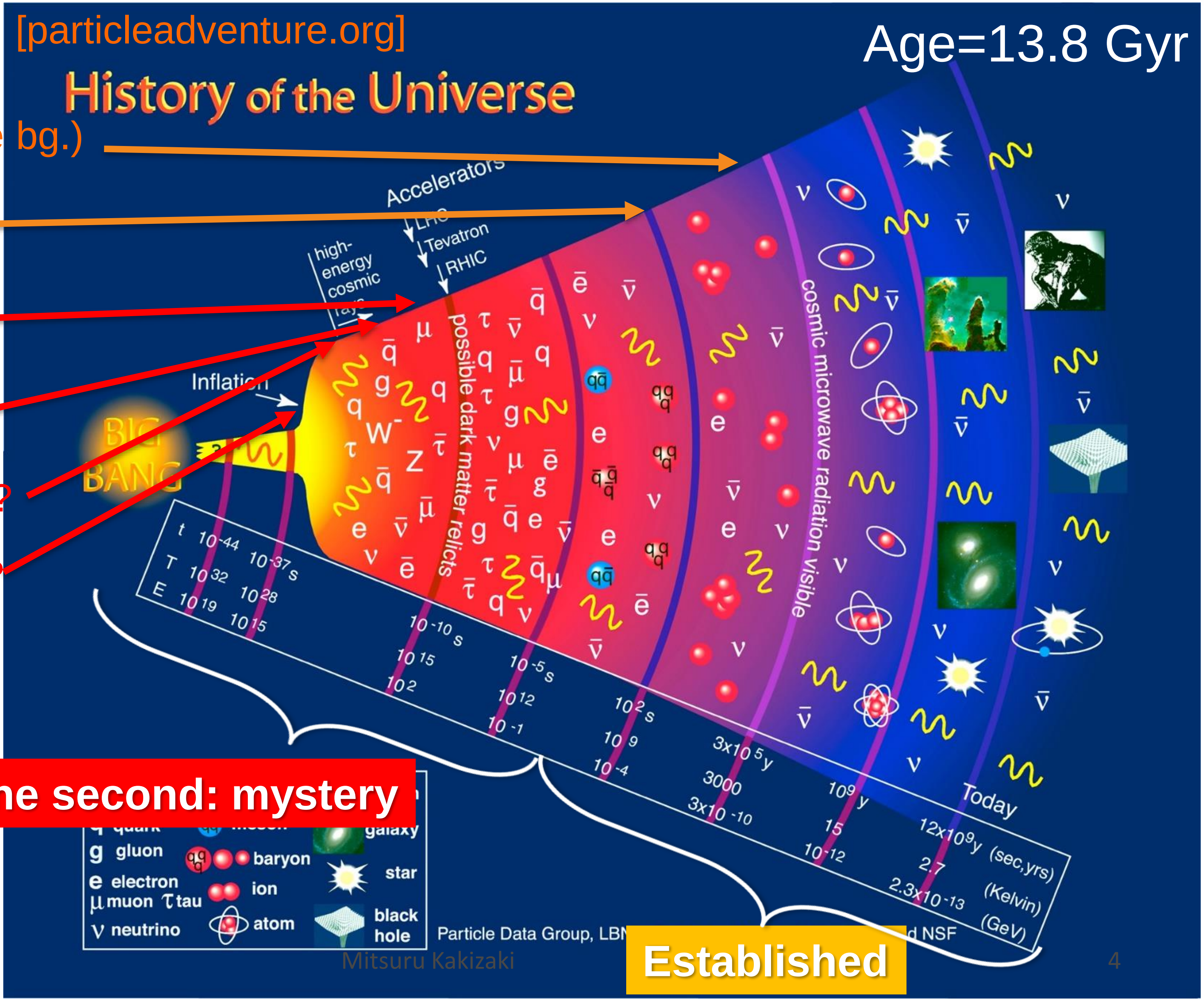
Big bang nucleosynthesis

Electroweak (EW) phase transition?

Dark matter?

Baryon asymmetry?

Cosmic inflation?



[particleadventure.org]

Age=13.8 Gyr

The first one second: mystery

Established

New Physics beyond the Standard Model

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

- Spontaneous electroweak symmetry breaking established
- Information on the Higgs sector imperfect

Phenomena beyond the Standard Model

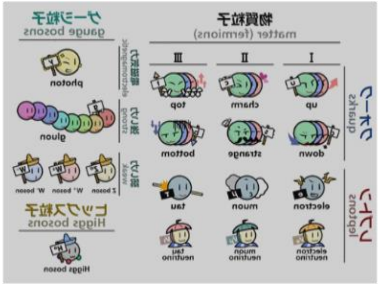
- Baryon asymmetry of the Universe
- Existence of dark matter
- Neutrino oscillations
- Cosmic inflation

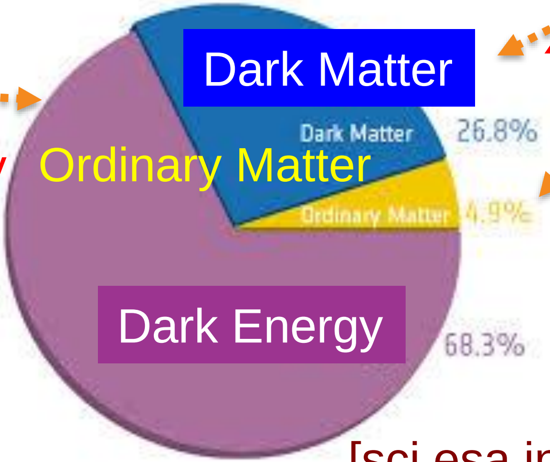
What is the Universe made of?

Anti-matter

X

Baryon asymmetry





Dark Matter

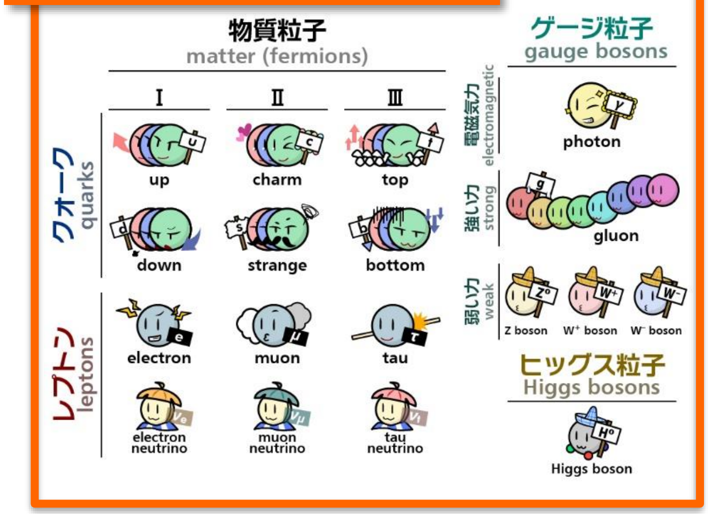
Ordinary Matter

Dark Energy

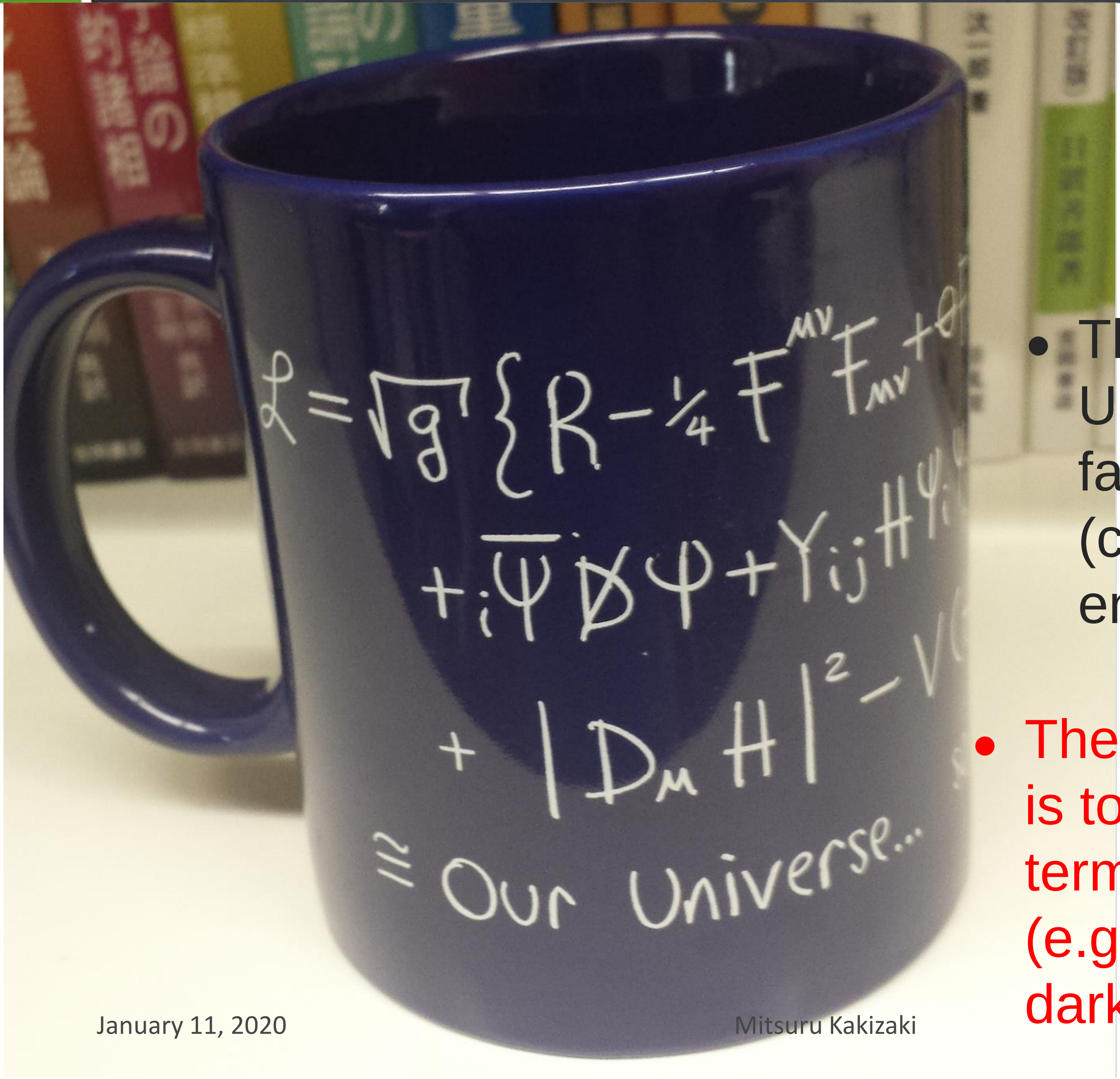
X

[sci.esa,int]

Standard Model



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



- The Lagrangian of the Universe encodes the fate of the Universe (c.f. protein structure encoded by DNA)

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

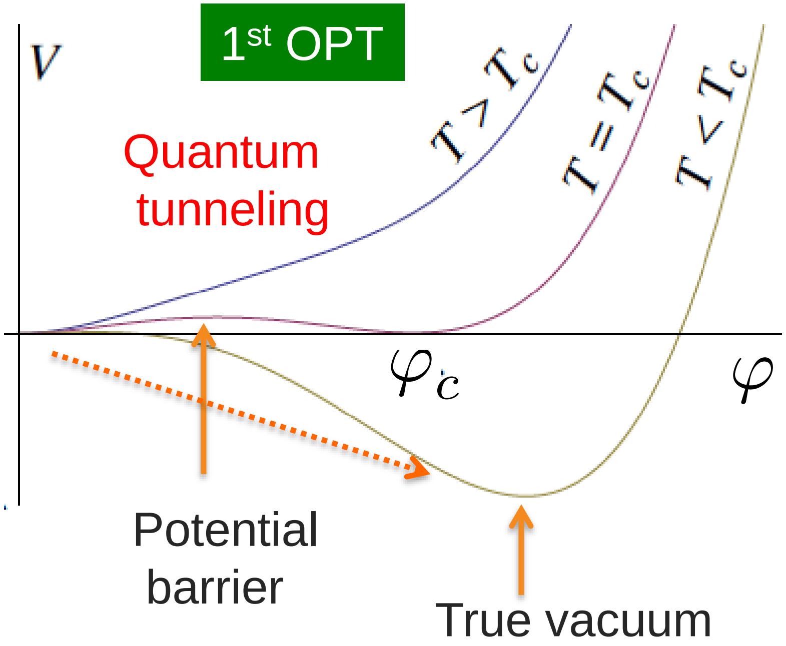
Baryon asymmetry and electroweak baryogenesis (EWBG)

Baryon-to-photon ratio

$(n_b - n_{\bar{b}})/n_\gamma \sim 10^{-9}$ ⟷ Should be zero after the cosmic inflation

Sakharov's conditions for BAU

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



1st OPT

Quantum tunneling

Potential barrier

True vacuum

SM Higgs sector w/ one doublet:

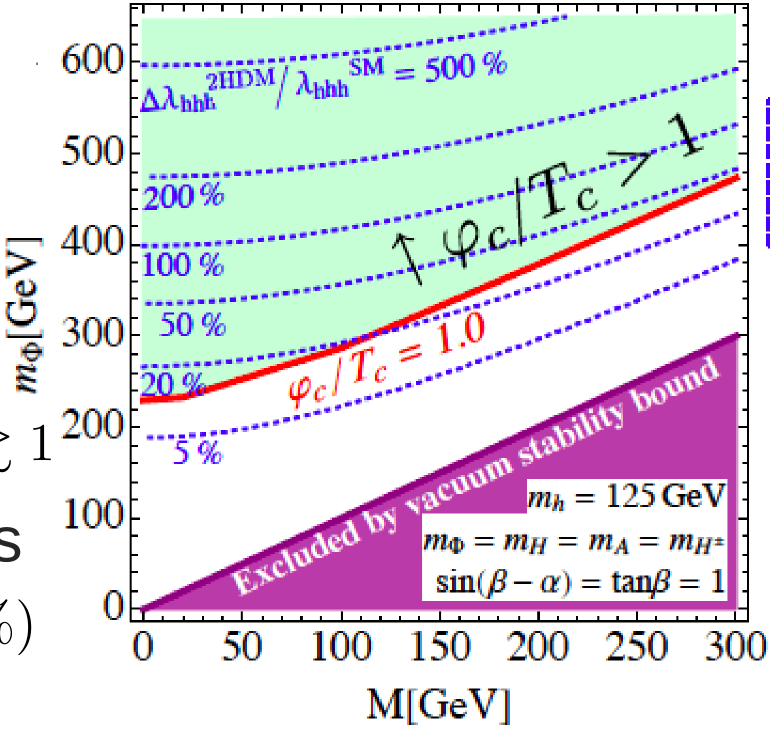
- Electroweak phase transition (EWPT) is NOT of 1st order for $m_h = 125\ \mathrm{GeV}$

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

Strongly 1st OPT and Higgs boson couplings

Models with extended Higgs sector

- 1st OPT can be easily realized
- Signatures are testable at colliders



[Kanemura, Okada, Senaha (2005)]

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

- Condition for strongly 1st OPT: $\varphi_c/T_c \gtrsim 1$

→ Large deviation in the triple Higgs boson coupling $(\Delta\lambda_{hhh}/\lambda_{hhh}^{\rm SM} \gtrsim 10\%)$

EWPT can be tested at future colliders

- High-Luminosity LHC:

  $-0.8 < \lambda_{hhh}/\lambda_{hhh}^{\rm SM} < 7.7$ (95% CL) [ATL-PHYS-PUB-2017-001]

- International Linear Collider (ILC) ($\sqrt{s} = 1$ TeV $L = 4$ ab^{-1})

  $\Delta\lambda_{hhh}$: 10% [Fujii et al., arXiv: 1908.11299]

CP phases can generate observable electric dipole moments

Gravitational waves (GWs) as a probe of EWPT

Ground-based interferometers:

- Advanced LIGO, Advanced Virgo, KAGRA, ...

- Main targets: GWs from binary systems, supernovae, ...

→ New era of GW astronomy

- GW150914 from a binary black hole:
First direct observation of GWs [LIGO and Virgo (2016)]

- GW170817 from a neutron star merger:
Breakthrough for multi-messenger astronomy (GW + EM)

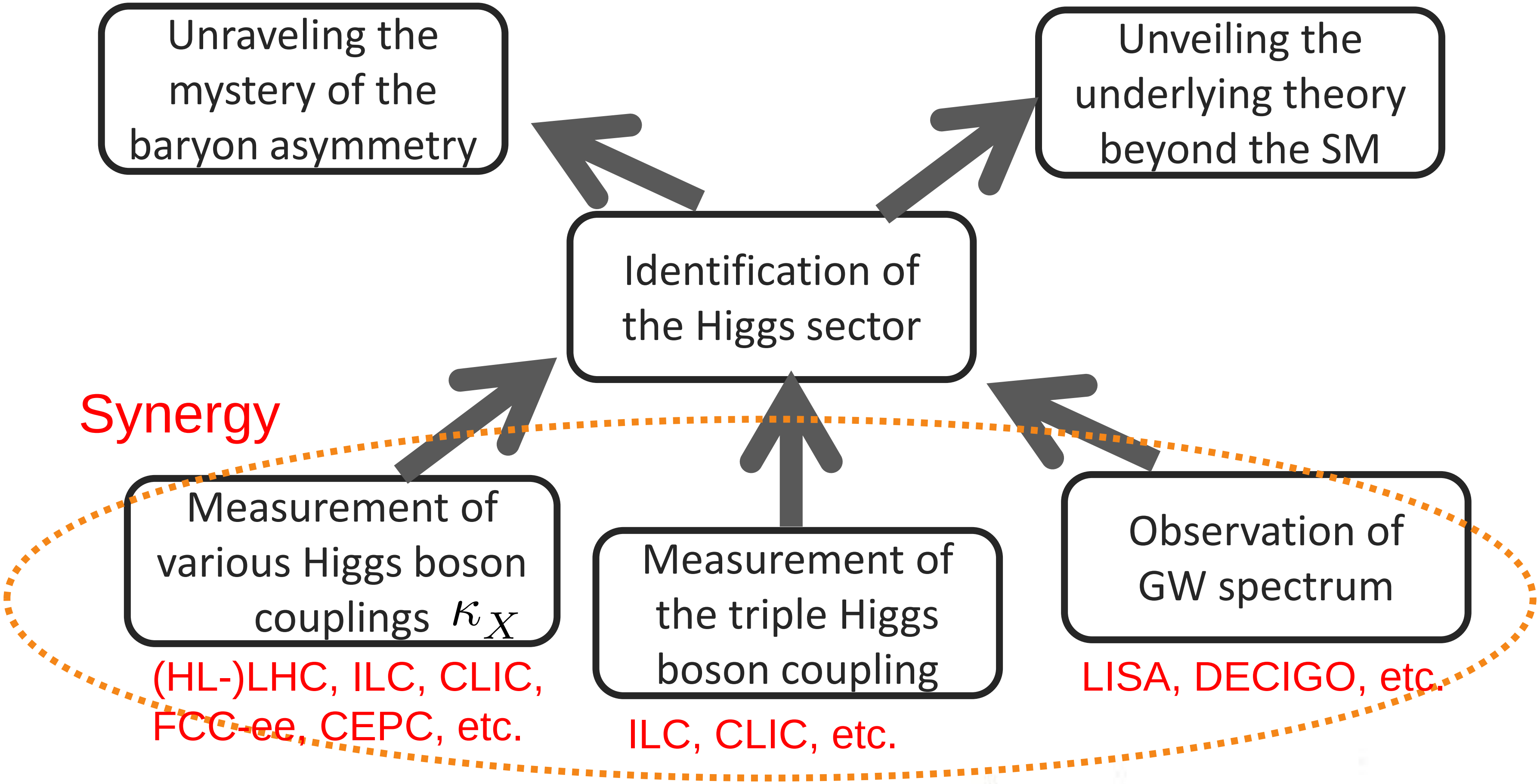
Future space-based interferometers:

- 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 κ_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.

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Gravitational waves as a probe of 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

$$\Box h_{\mu\nu} = 0 \quad \longleftarrow$$ Wave equation with $v = c$

Interaction rate of gravitational waves

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

➡ $\Gamma/H \sim T^3/M_{\rm Pl}^3 < 1$

GWs decouple at temperatures below the Planck scale

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

Recombination
(Cosmic microwave bg.)

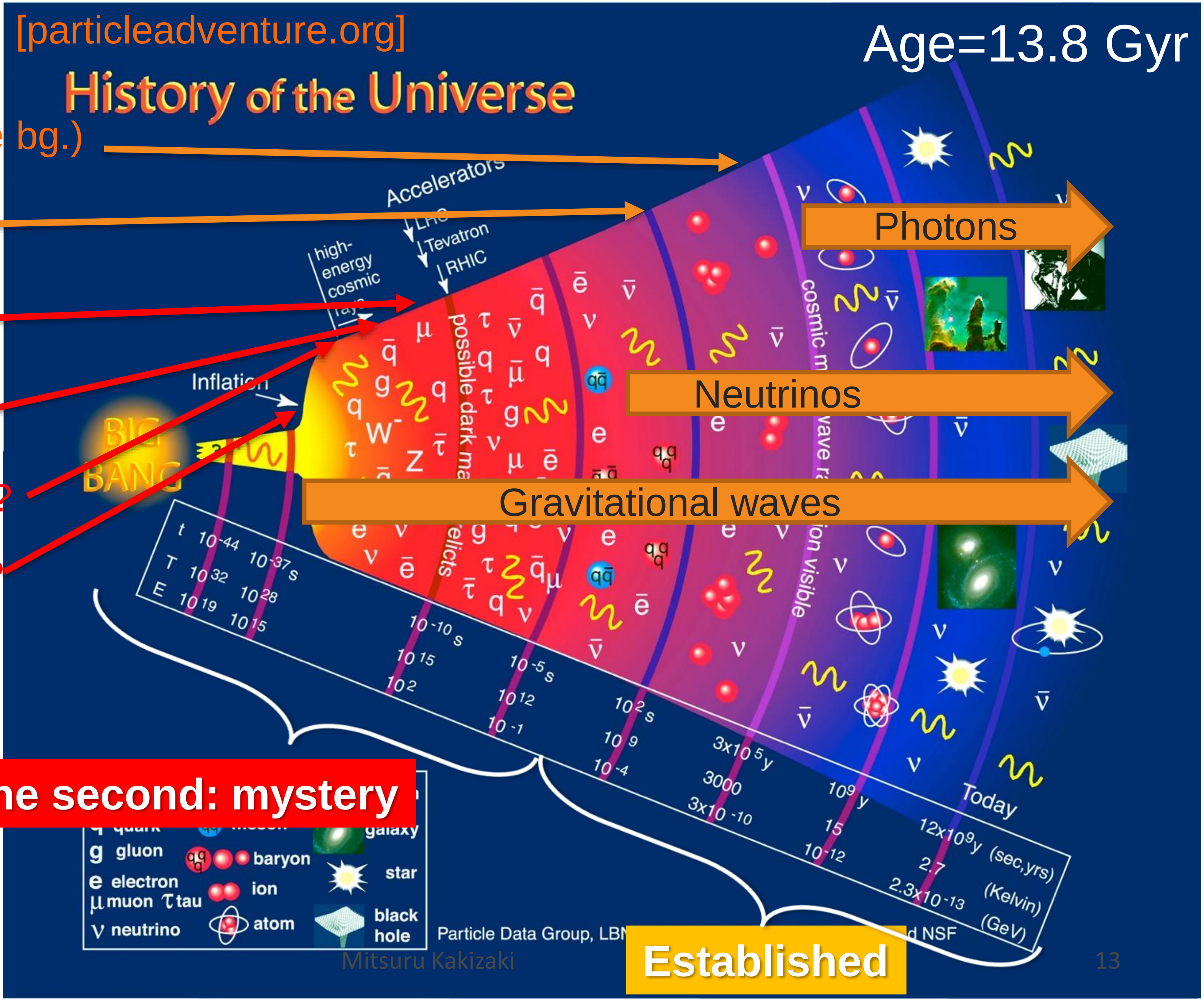
Big bang
nucleosynthesis

Electroweak (EW)
phase transition?

Dark matter?

Baryon asymmetry?

Cosmic inflation?



[particleadventure.org]

Age=13.8 Gyr

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

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

- Normalized Energy density per unit logarithmic interval of frequency

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

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

Relic gravitational waves observed today

GWs produced at temperature T_t
with abundance $\Omega_{\rm GW}^t$, frequency f_t

Adiabatic expansion of the Universe

a : scale factor $\quad\quad sa^3 = \text{const.}$

→ Energy density and frequency red-shifted:

$$\rho_{\rm GW} \propto 1/a^4 \qquad f \propto 1/a$$

GWs observed today

- Relic abundance: $\Omega_{\rm GW}h^2 \simeq 1.7\times 10^{-5}\left(\frac{100}{g_*^t}\right)^{1/3}\Omega_{\rm GW}^t$
- Frequency: $f_0 \simeq 1.7\times 10^{-5}\left(\frac{g_*^t}{100}\right)^{1/6}\left(\frac{T_t}{100\ \text{GeV}}\right)\frac{f_t}{H_t}\ \text{Hz}$

e.g., for typical electroweak phase transition

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

Range for future space-based interferometers

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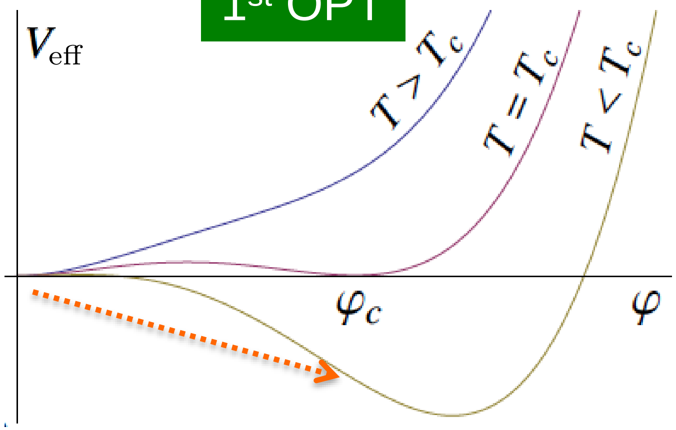
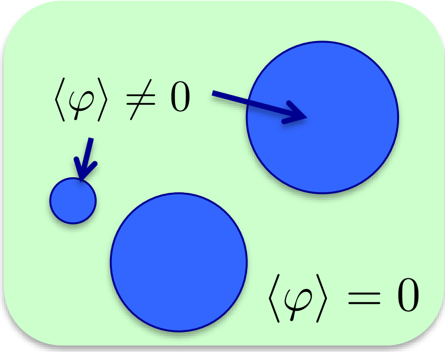
GWs from 1st OPT

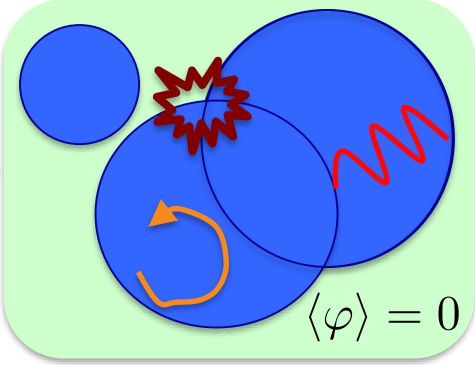
1st OPT



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

c.f. Boiling water

- 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:

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

Transition temperature $\boxed{T_*}$

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

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

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

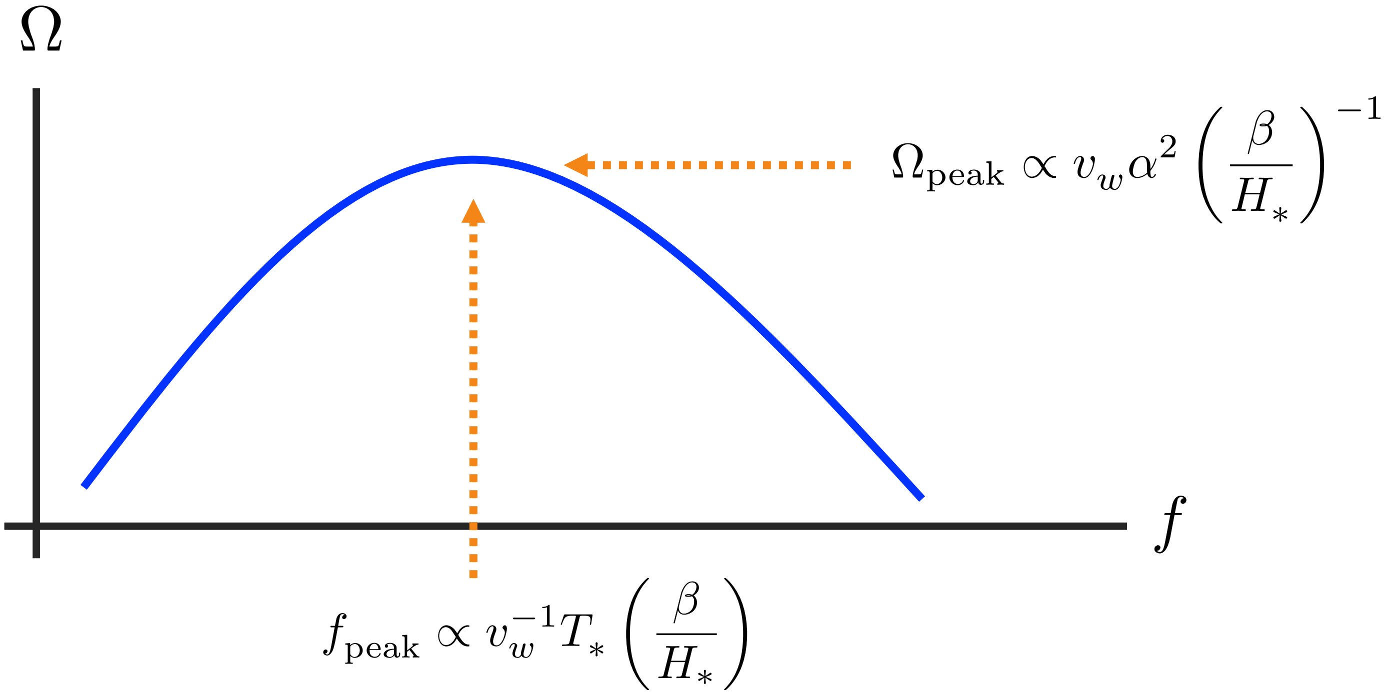
Normalized parameter: $\boxed{\frac{\beta}{H_*}\left(=\tilde{\beta}\right)}$

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. $\{p\} = \{\hat{p}\}$

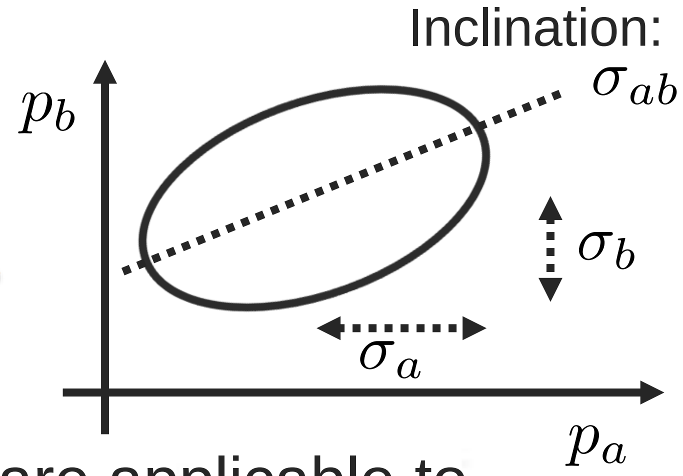
$$\delta\chi^2(\{p\}\,,\{\hat{p}\}) \simeq \mathcal{F}_{ab}(p_a - \hat{p}_a)(p_b - \hat{p}_b)$$

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

Confidence ellipse

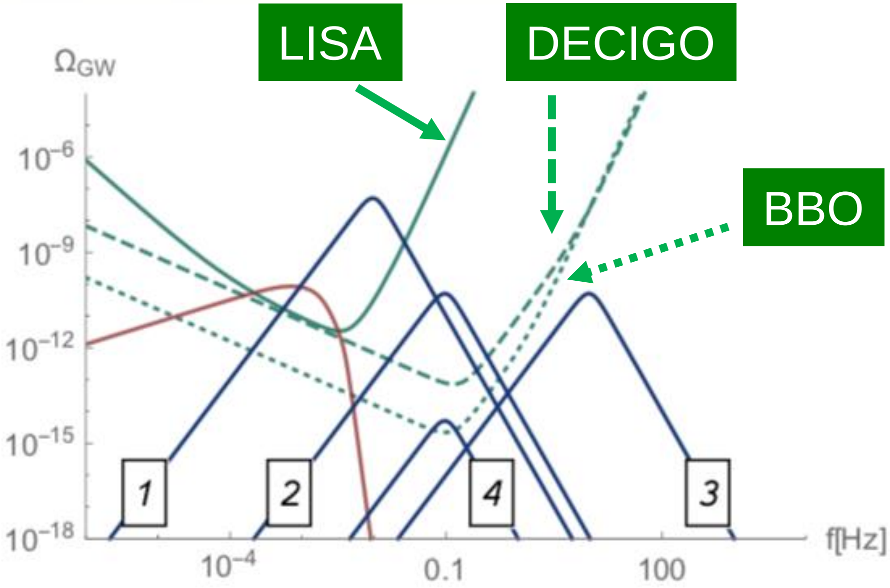


n.b.: we assume that these expressions are applicable to a single-detector like LISA

Constraints on the shape of GW spectrum

GW spectrum

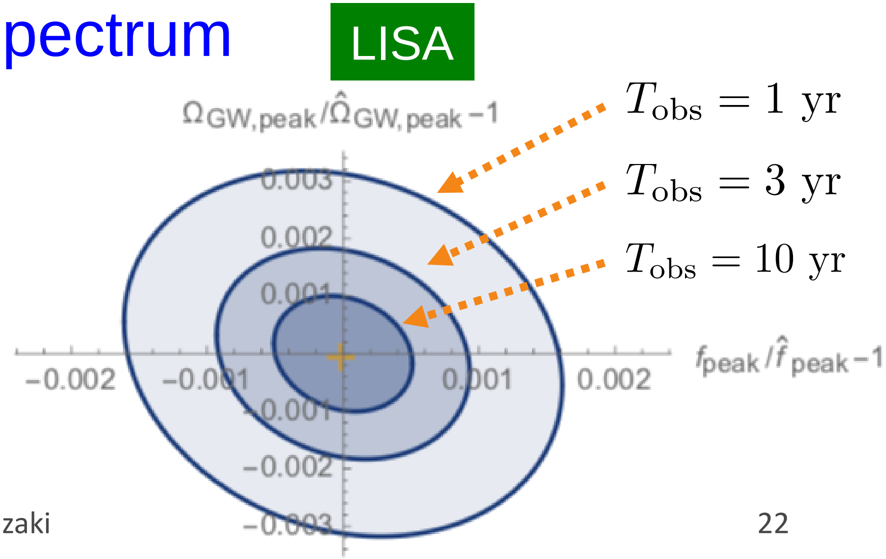
- Fiducial values
  - Point 1: $(f_{\rm peak}, \Omega_{\rm peak}) = (10^{-2}\ {\rm Hz}, 10^{-7})$,
  - Point 2: $(f_{\rm peak}, \Omega_{\rm peak}) = (10^{-1}\ {\rm Hz}, 10^{-10})$,
  - Point 3: $(f_{\rm peak}, \Omega_{\rm peak}) = (10\ {\rm Hz}, 10^{-10})$,
  - Point 4: $(f_{\rm peak}, \Omega_{\rm peak})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



Expected constraints on the GW spectrum

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

[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 constrains 2 combinations of underlying parameters

Quantities describing transition dynamics

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

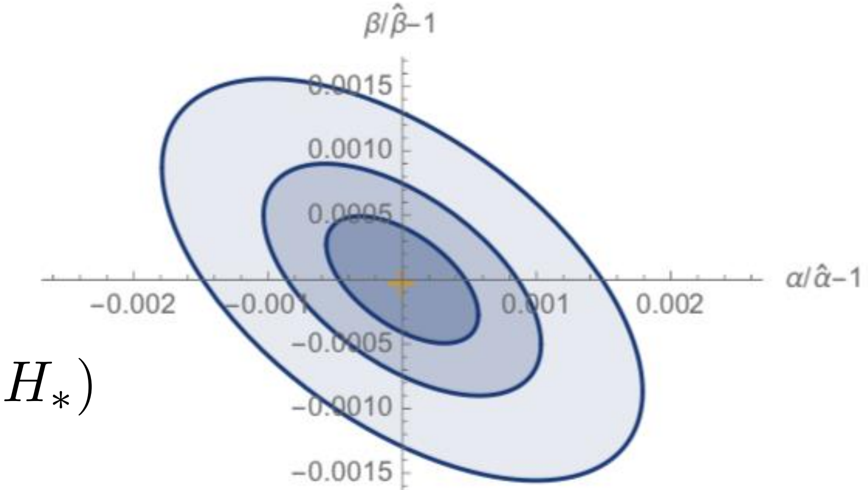
Expected constraints on the transition parameters

- 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 Classical Scale Invariance (CSI)

Typical examples for 1st OPT from thermal loop effects

LISA

Models with CSI

- Tree-level Higgs potential

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

Φ :Higgs doublet

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

- Fiducial parameters

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

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

Models without CSI

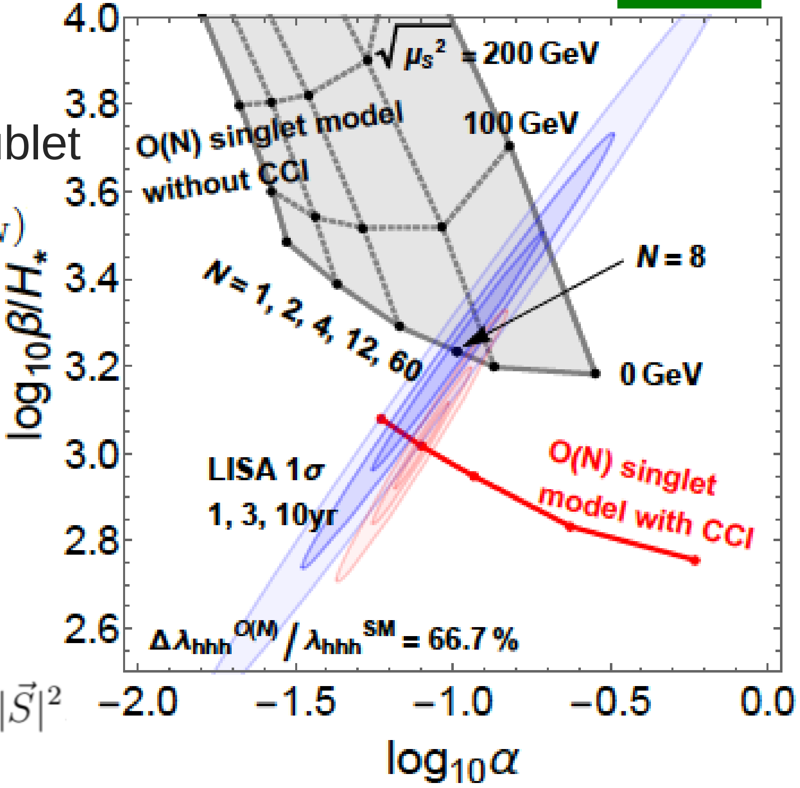
- Tree-level Higgs potential

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

- Fiducial parameters

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

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



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

Models can be distinguished, parameters can be narrowed down

Higgs singlet model

Typical example for 1$^{\rm st}$ 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: κ ($\kappa = 1$ in the SM)

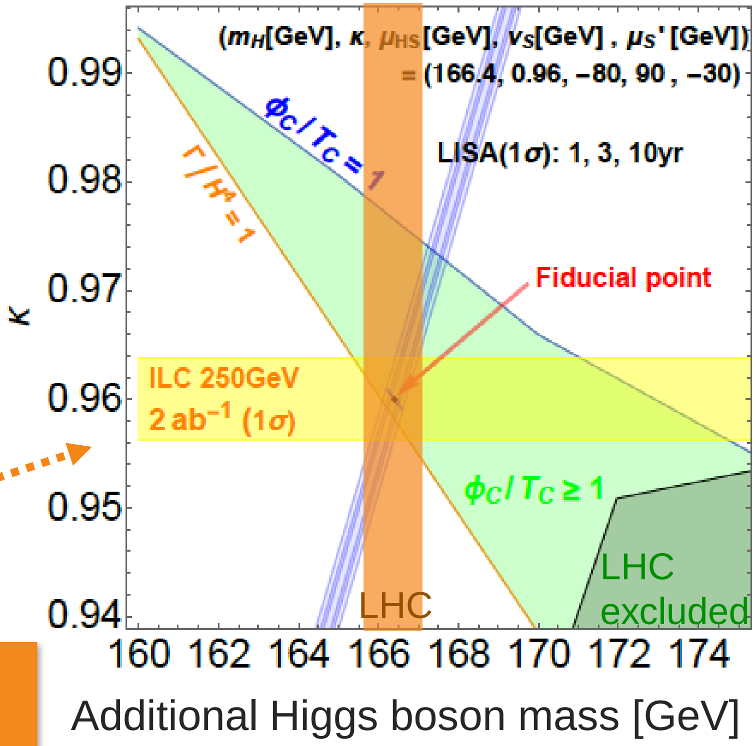
- Fiducial parameters

$$(m_H\ [\mathrm{GeV}], \kappa, \mu_{\Phi S}\ [\mathrm{GeV}], v_S\ [\mathrm{GeV}], \mu'_S\ [\mathrm{GeV}])$$

$$= (166, 0.96, -80, 90, -30)$$

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

LISA



Future colliders

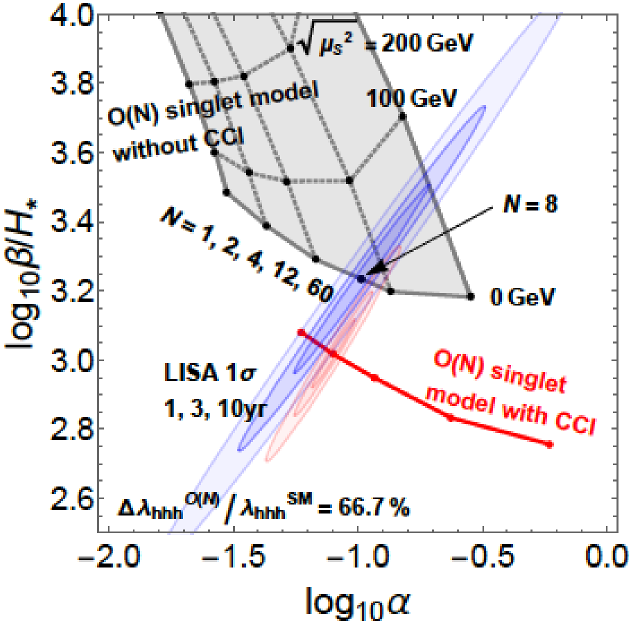
- ILC [Fujii et al. (2017)]

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

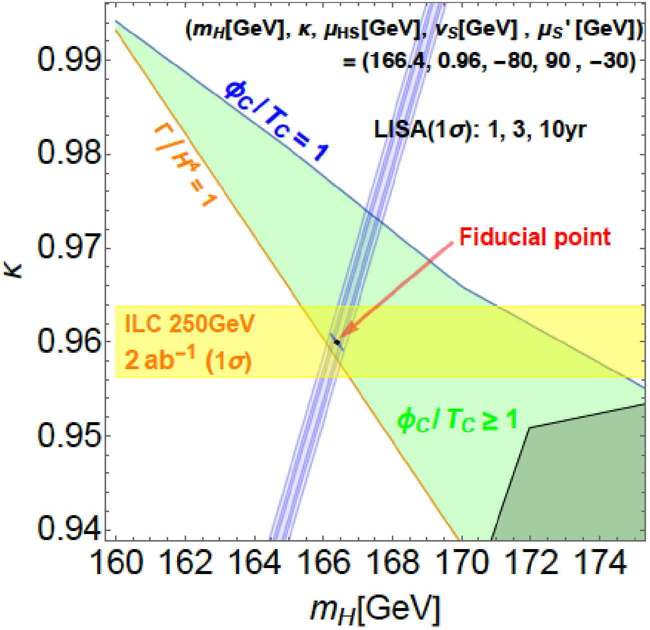
[Hashino, Jinno, MK, Kanemura, Takahashi, Takimoto (2018)]

5. 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

Backup slides

Synergy

Classification of models of 1st OPT based on experimental data

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

Non-decoupling loop effects from hypothetical particles

- One Higgs doublet
  - I : Additional scalar singlets
  - II : Inert doublet model
- Multiple Higgs doublets
  - III : 2HDM
  - IV : MSSM

Non-thermal effects (tree level)

- V : Higgs singlet model (HSM)
- VI : Next-to-MSSM

Deviation	κ_X	$h\gamma\gamma$	λ_{hhh}	GWs
I			○	○
II		○	○	○
III	○	○	○	○
IV	[Light stops excluded at LHC]			
V	○		○	○
IV	○	○	○	○

Thermal-loop induced first order phase transition

Effective potential at one-loop level:

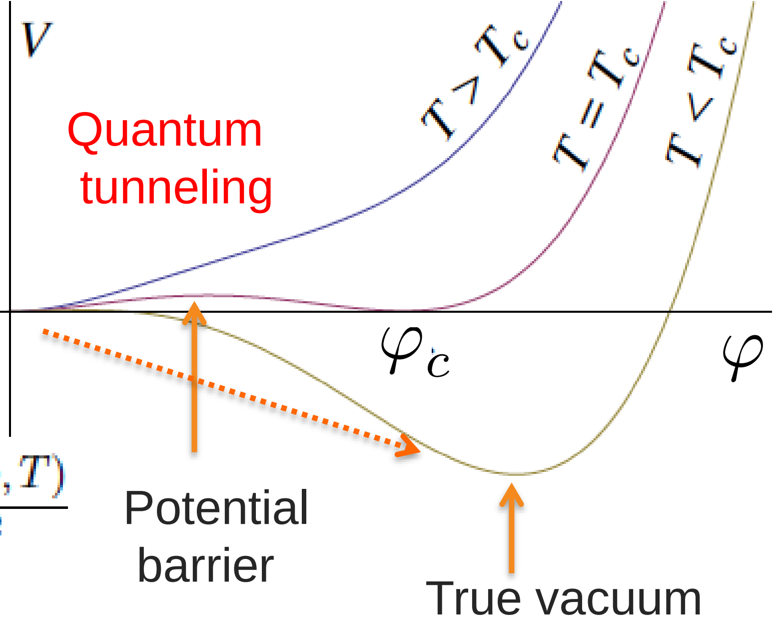
$$V_{\text{eff}}(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4 + \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi)\left(\ln\frac{M_i^2(\varphi)}{Q^2} - \frac{3}{2}\right)$$

Contribution at finite-temperatures:

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

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

1st OPT



High-temperature expansion:

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

$$\varphi_c/T_c \propto E$$

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

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

Bosonic loop contribute to the cubic term

Strongly 1st OPT $(\varphi_c/T_c \gtrsim 1)$ can be achieved by adding bosons

Necessary for successful electroweak baryogenesis

Models with additional singlet scalars (without CSI)

Idea: [MK, Kanemura, Matsui (2015)]

- To generally handle strongly 1st OPT via thermal loop, N isosinglet scalars $S_i\ (i = 1, \cdots, N)$ are introduced
- For simplicity, $O(N)$ symmetry is imposed

Tree-level scalar potential: $V_0(\Phi, \vec{S}) = V_{\rm SM}(\Phi) + \frac{\mu_S^2}{2}|\vec{S}|^2 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2$

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

Triple Higgs boson coupling:

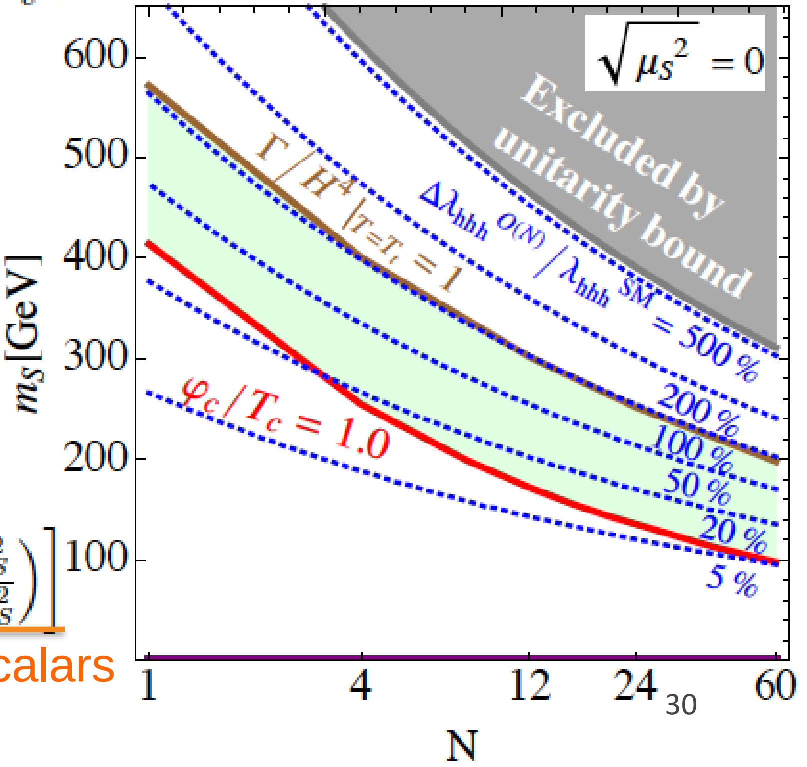
$$\lambda_{hhh}^{O(N)} = \frac{3m_h^2}{v}\left\{1 - \frac{1}{\pi^2}\frac{m_t^4}{v^2 m_h^2} + \underline{\frac{N}{12\pi^2}\frac{m_S^4}{v^2 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3}\right\}$$

Finite temperature effective potential (high temperature expansion):

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

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

Non decoupling loop effect from additional scalars



CSI models with additional singlet scalars

Idea [Hashino, Kanemura, Orikasa (2015)]

- Mass parameters are absent in the original Lagrangian due to Classical Scale Invariance (CSI) [Bardeen (1995)]
- EWSB is directly caused by thermal loop effects

Tree-level scalar potential

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

Effective potential along the flat direction

$$V_1(\varphi) = \sum_i \frac{n_i}{64\pi^2} M_i^4(\varphi)\left(\ln\frac{M_i^2(\varphi)}{Q^2} - c_i\right) \quad c_i = 3/2$$

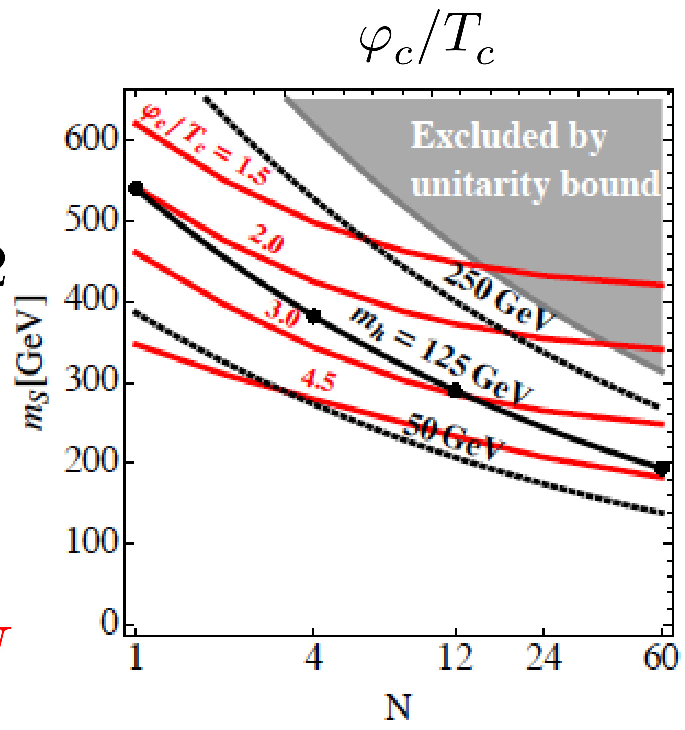
Singlet scalar boson mass

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

Triple Higgs boson coupling

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM(tree)}}} = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM(tree)}}} - 1 = \frac{2}{3}$$ independent of N

[Hashino, Kanemura, Orikasa (2015)]



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

Higgs singlet model

Idea

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

- To investigate strongly 1st OPT and Higgs couplings induced through Higgs field mixing (at least 2 classical fields needed)
- For simplicity, we introduce a singlet Higgs field S

Tree-level Higgs potential

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

$\langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\varphi_\Phi \end{pmatrix}$: SM Higgs doublet

$\langle S\rangle = \varphi_S$: Higgs singlet

Effective potential:

$$V_{\mathrm{eff},T=0}(\varphi_\Phi,\varphi_S) = V_0(\varphi_\Phi,\varphi_S) + \sum_i n_i \frac{M_i^4(\varphi_\Phi,\varphi_S)}{64\pi^2}\left(\ln\frac{M_i^2(\varphi_\Phi,\varphi_S)}{Q^2} - c_i\right)$$

$c_F = c_S = 5/6$

$c_V = 5/6$

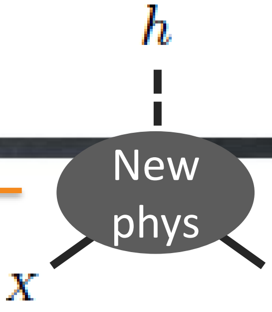
Higgs boson masses and mixing

$m_h (= 125\ \mathrm{GeV})$: Mass of the discovered Higgs boson

m_H : Mass of the additional Higgs boson

θ : Higgs mixing angle

Higgs singlet model (contd.)



X : SM particle

Higgs boson couplings to SM particles $\kappa_X = \dfrac{g_{hXX}}{g_{hXX}|_{\rm SM}}$

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

Triple Higgs boson couplings (effective potential approach)

$$\Delta\lambda_{hhh} = \frac{\lambda_{hhh}^{\rm HSM} - \lambda_{hhh}^{\rm SM}}{\lambda_{hhh}^{\rm SM}} \qquad \lambda_{hhh}^{\rm SM} = \frac{3m_h^2}{v_\Phi}\left[1 + \frac{9m_h^2}{32\pi^2 v_\Phi^2} + \sum_{i=W^\pm,Z,t,b} n_i \frac{m_i^4}{12\pi^2 m_h^2 v_\Phi^2}\right]$$

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

Finite temperature effective potential in one direction (high temperature expansion)

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

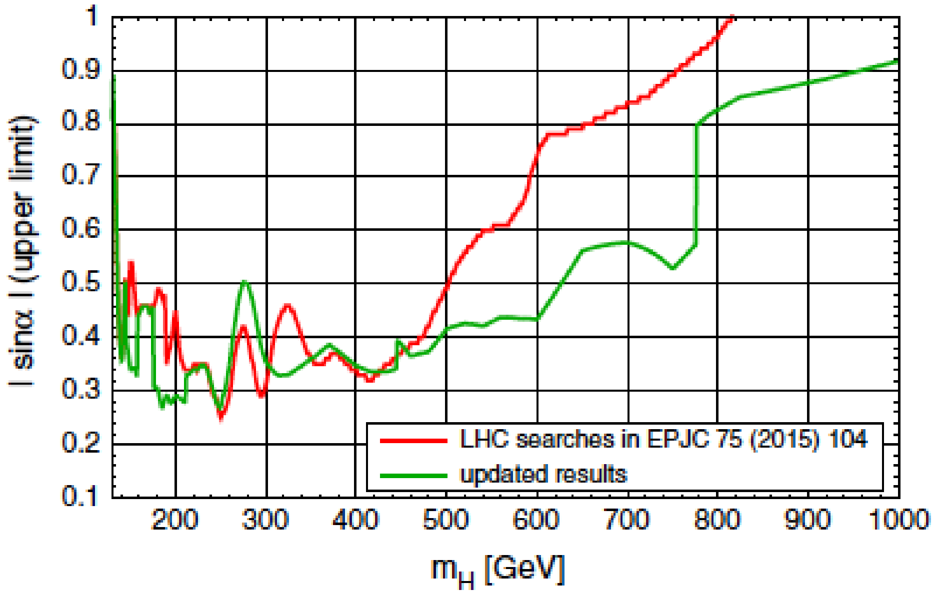
$$\Rightarrow \boxed{\frac{\varphi_c}{T_c} = \frac{2E}{\lambda}(1 \underline{- \frac{e\lambda}{ET}})}$$

Effects from the Higgs boson mixing

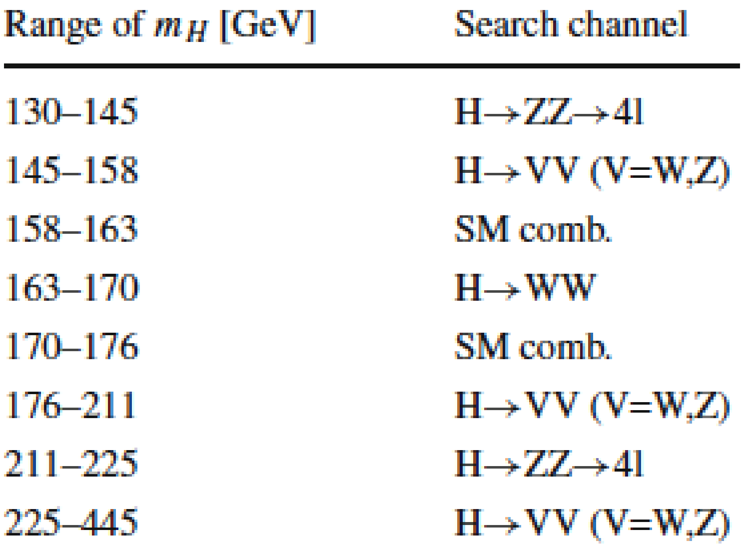
The Higgs boson mixing gives considerable contributions to deviation in the Higgs boson couplings and to phase transition

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

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

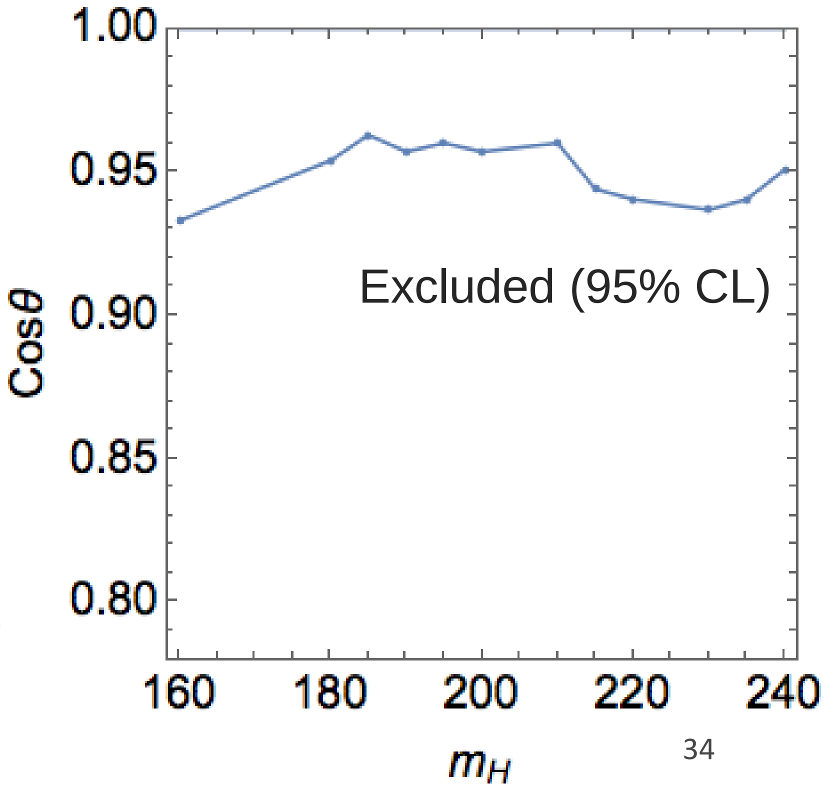


[Robens, Stefaniak (2016)]



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 $\kappa(=\cos\theta)$



Predicted values of α and $\tilde{\beta}$

- Condition for strongly 1st OPT

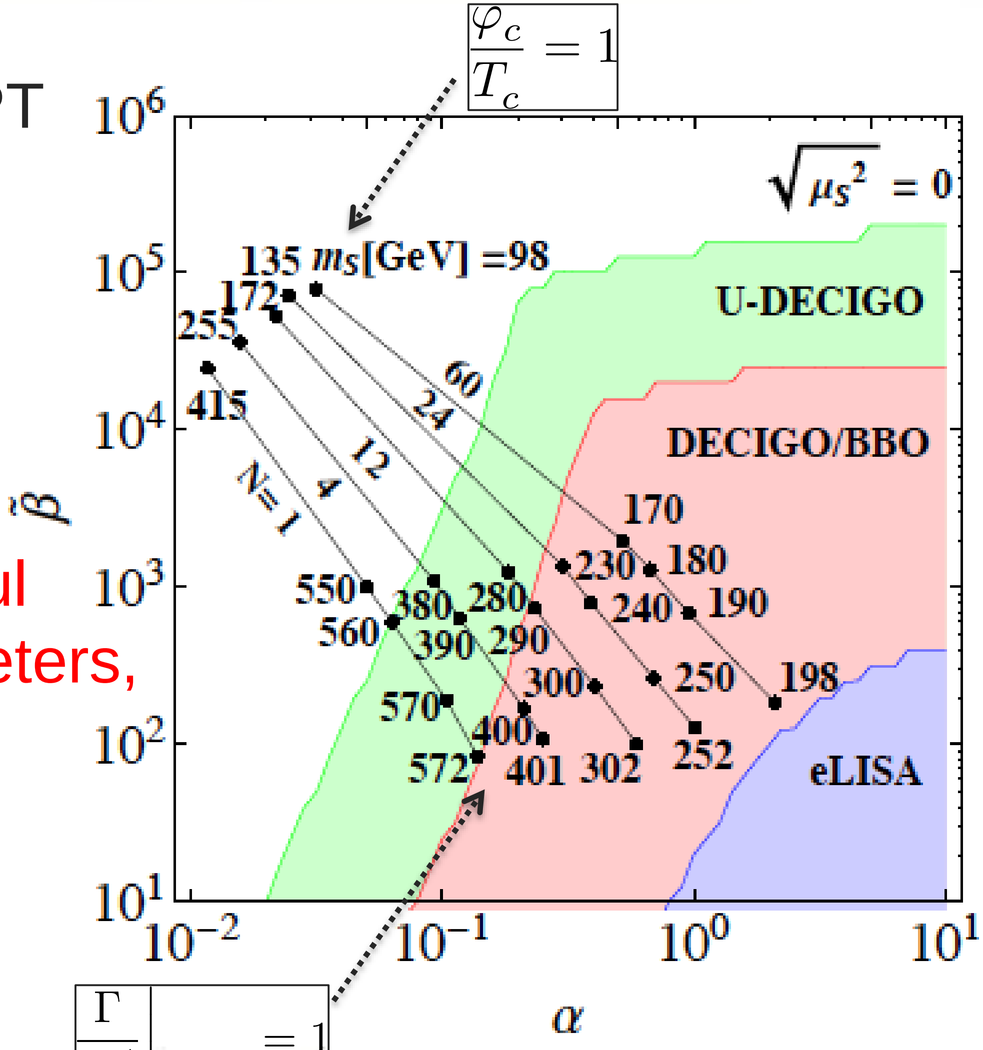
  ➡ Constraints on α and $\tilde{\beta}$ for each model

  [MK, Kanemura, Matsui (2015)]

- α and $\tilde{\beta}$ to be determined by GW observation are useful in determining model parameters, such as N and m_S

n.b.: The experimental prospects are estimated based on the traditional GW spectrum

[See e.g. Grojean, Servant (2007)]



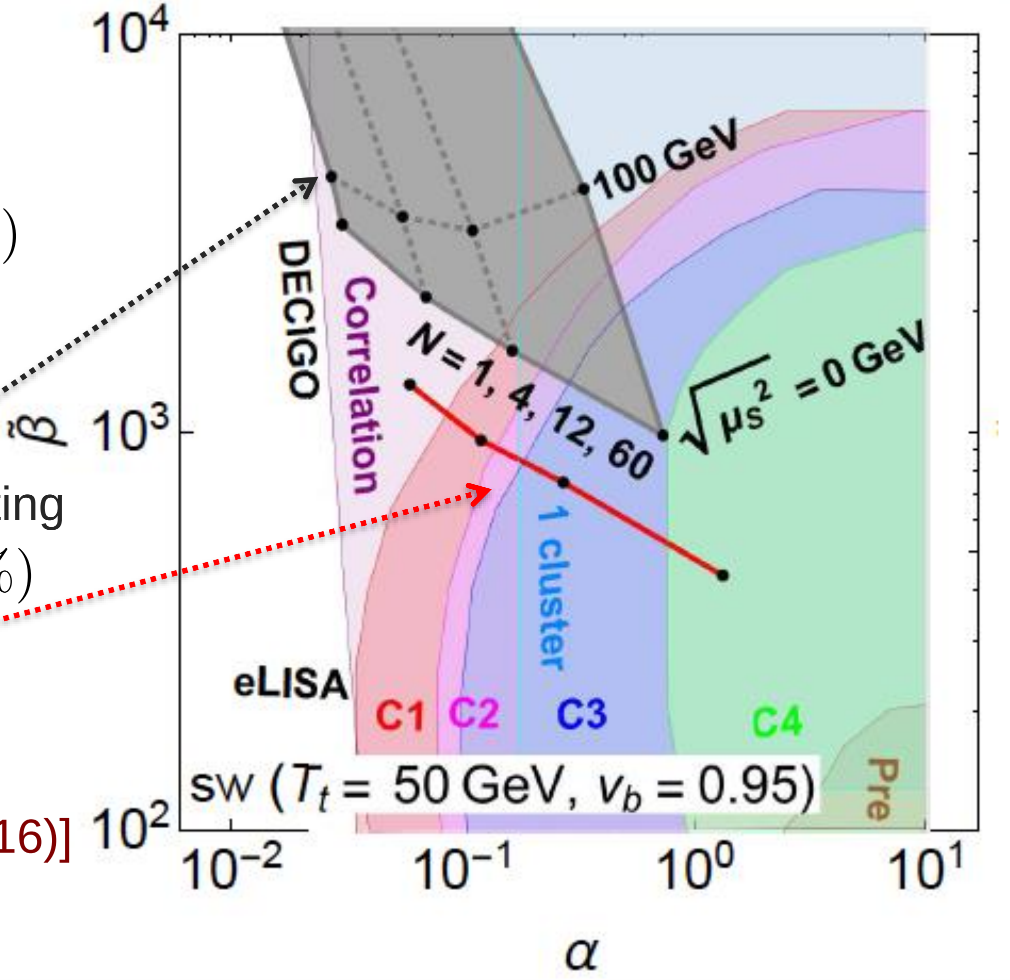
$\left.\frac{\Gamma}{H^4}\right|_{T=T_t} = 1$

[MK, Kanemura, Matsui (2015)]

Testability of models with additional singlet scalars with and without CSI

- What if the hhh coupling is found to be around
$$\Delta\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} = 2/3(\simeq 70\%)$$
at future colliders?
  - $O(N)$models without CSI predicting
$$\Delta\lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}} = 2/3(\simeq 70\%)$$
  - CSI $O(N)$ models

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



Models with and without CSI can be distinguished at future GW interferometers even if they share common hhh coupling

Synergy of measurements of various Higgs boson couplings and GWs in the HSM

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

Collider experiments

- LHC Run I results

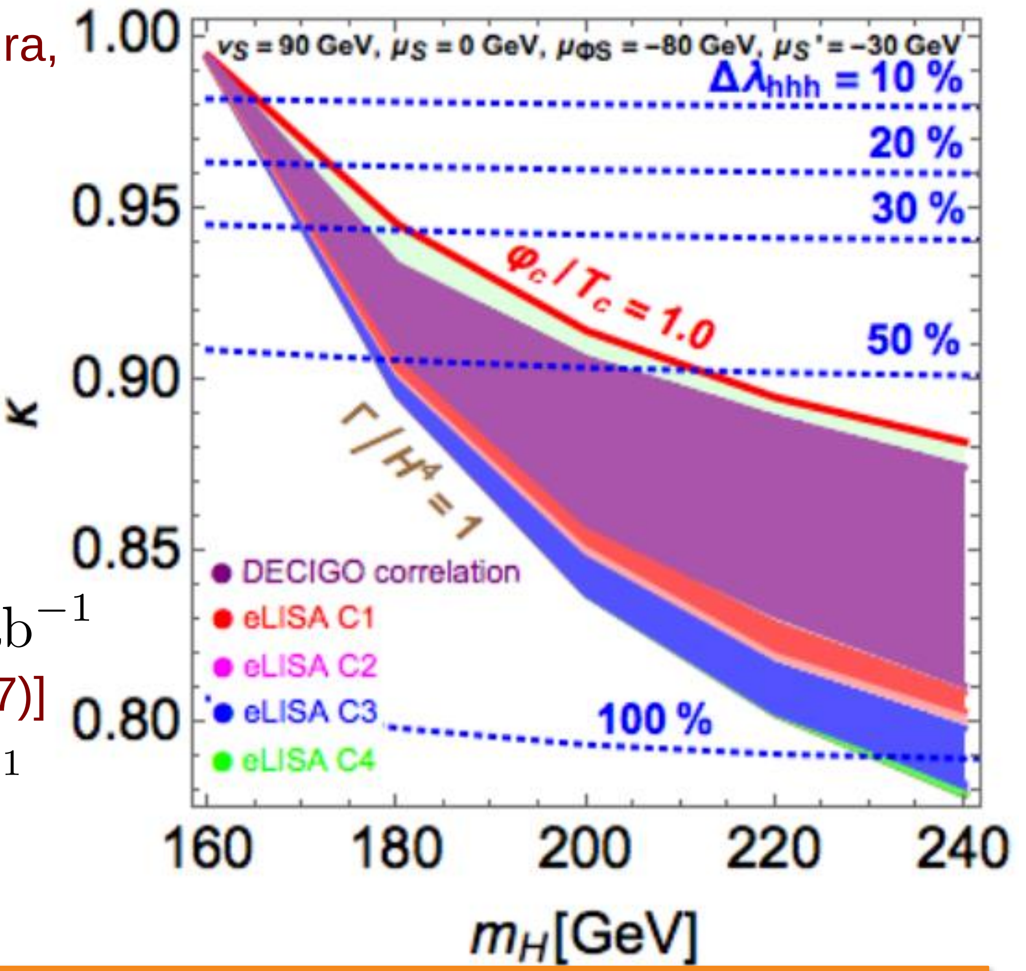
  $\kappa_Z = 1.03^{+0.11}_{-0.11}, \kappa_W = 0.91^{+0.10}_{-0.10}$

  [ATLAS, CMS (2016)]
- HL-LHC

  $\Delta\kappa_V : 2\%$ [ATLAS, CMS (2013)]
- ILC w/ $\sqrt{s} = 250\ \mathrm{GeV}\ \ L = 2\ \mathrm{ab}^{-1}$

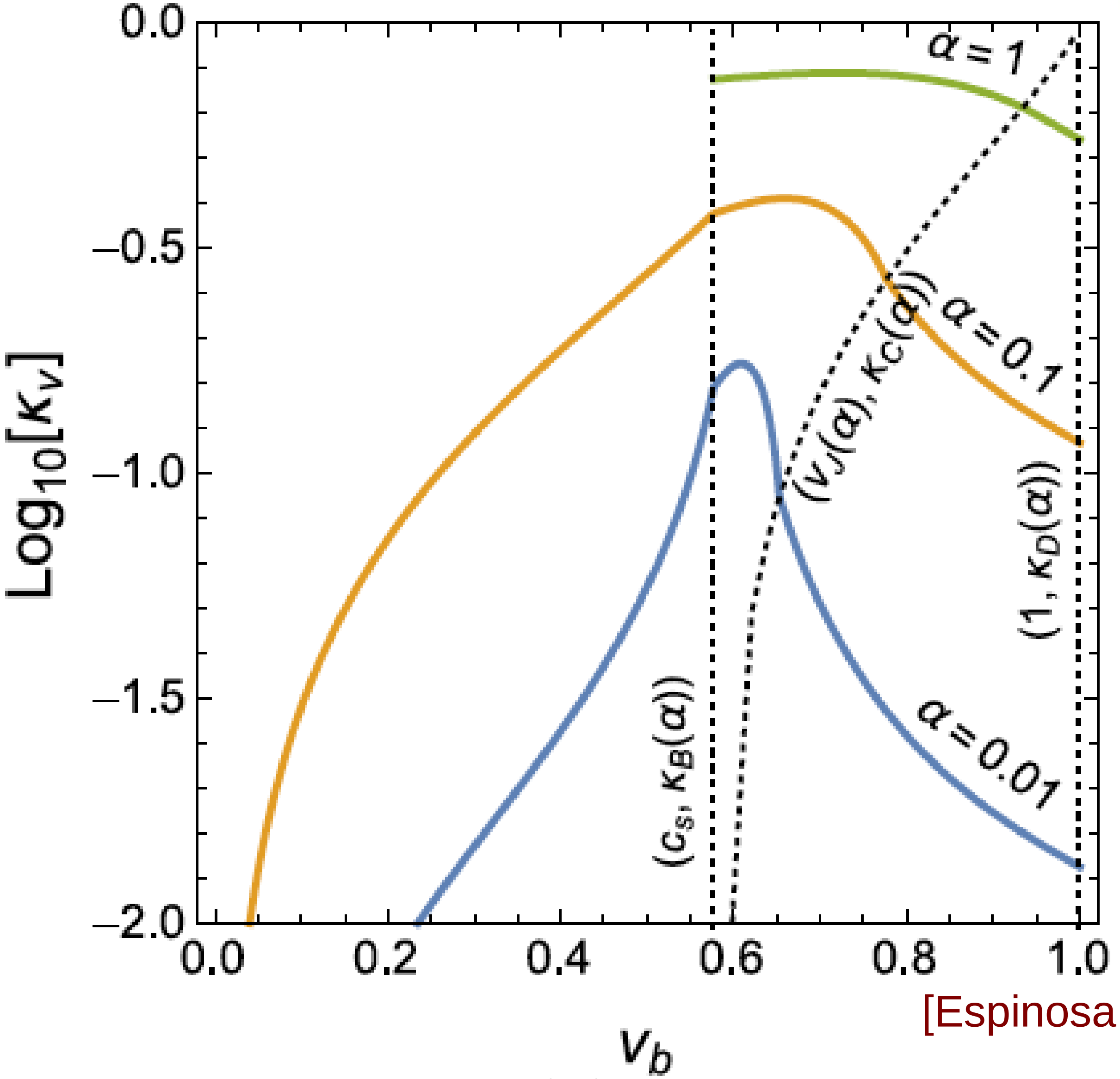
  $\Delta\kappa_V : 0.6\%$ [Durieux et al. (2017)]
- ILC w/ $\sqrt{s} = 1\ \mathrm{TeV}\ \ L = 5\ \mathrm{ab}^{-1}$

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



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

Efficiency factor

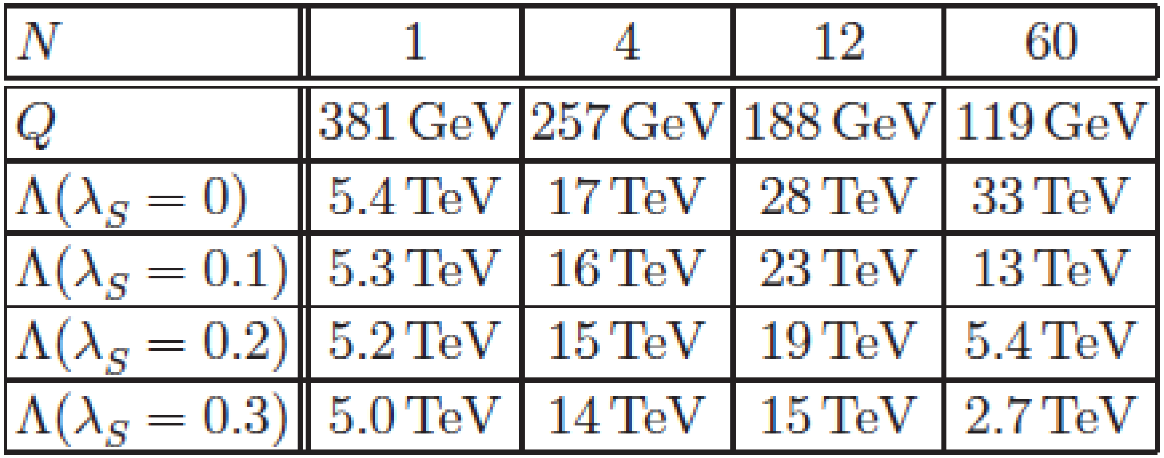


[Espinosa et al. (2010)]

Landau pole in CSI model

- Large scalar couplings at the EW scale

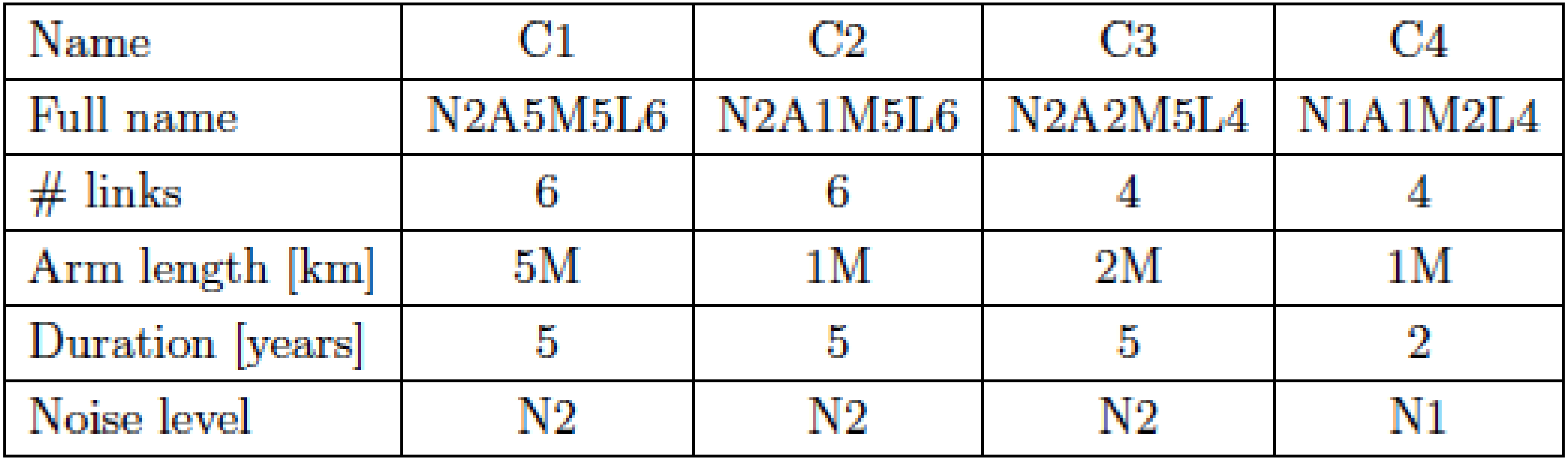
→ Landau pole near the EW scale



N	1	4	12	60
Q	381 GeV	257 GeV	188 GeV	119 GeV
$\Lambda(\lambda_S = 0)$	5.4 TeV	17 TeV	28 TeV	33 TeV
$\Lambda(\lambda_S = 0.1)$	5.3 TeV	16 TeV	23 TeV	13 TeV
$\Lambda(\lambda_S = 0.2)$	5.2 TeV	15 TeV	19 TeV	5.4 TeV
$\Lambda(\lambda_S = 0.3)$	5.0 TeV	14 TeV	15 TeV	2.7 TeV

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

LISA design



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

[Caprini et al (2015)]

Planed configuration

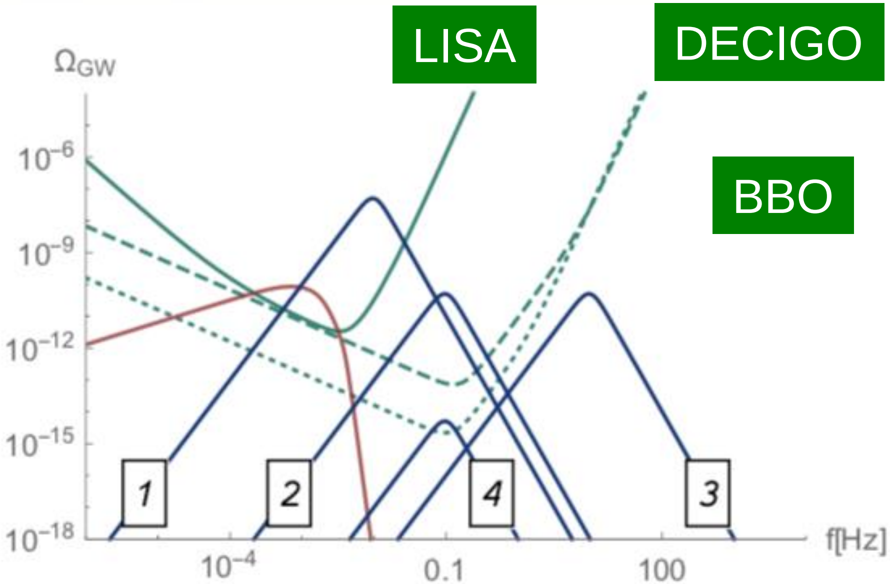
- 6 links
- 2.5M km length arms
- 4 years (possible extension to 10 years)

[Caprini et al (2019)]

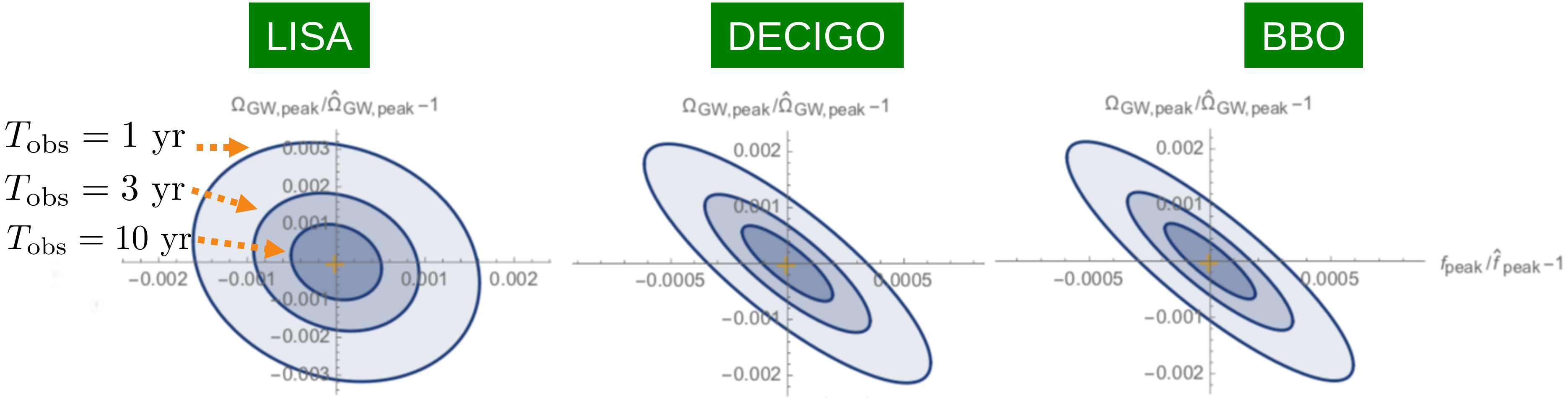
Constraints on the shape of GW spectrum

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 for Point1



LISA

DECIGO

BBO

$T_{\rm obs} = 1$ yr

$T_{\rm obs} = 3$ yr

$T_{\rm obs} = 10$ yr

Studies on the GWs from 1st order EWPT

Model independent analysis:

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

Higgs potential with higher order operators:

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

Non-decoupling loop effects from hypothetical particles:

- Light stop loop effects in the MSSM:
  [Apreda, Maggiore, Nicolis, Riotto (2002), ...]

n.b. Light stops are excluded by LHC

- Additional scalar loop effects: ← Today's topic
  [MK, Kanemura, Matsui (2015), Hashino, MK, Kanemura, Matsui (2016), ...]

Non-thermal effects at the tree level:

- Next-to-MSSM: [Apreda, Maggiore, Nicolis, Riotto (2002), Huber, Konstandin, Nardini, Rues (2015), ...]
- Real singlet extension: [Ashoorioon, Konstandin (2008)....]

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

Finding bubble configuration

- Spatial $O(3)$ symmetric bubble action

$$S_3(T) = \int 4\pi r^2 \mathrm{d}r \left[\frac{1}{2}\left(\frac{\mathrm{d}\phi}{\mathrm{d}r}\right)^2 + V(\phi, T)\right]$$

- Bounce solution that extremizes $S_3(T)$ is obtained by solving

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} - \frac{\mathrm{d}V}{\mathrm{d}\phi} = 0 \text{ with boundary conditions } \left.\frac{\mathrm{d}\phi}{\mathrm{d}r}\right|_{r=0} = 0\,, \quad \phi|_{r\to\infty} \to 0$$

Thin wall approximation (applicable for small energy difference)

$$S_3 = \underbrace{-\frac{4\pi}{3}R^3\Delta V_{\mathrm{eff}}}_{\text{Volume energy}} + \underbrace{4\pi R^2 S_1}_{\text{Surface tension}} \qquad S_1 = \int_{\phi_F}^{\phi_T} \mathrm{d}\phi\ (2V)^{1/2}$$

R :Bubble size

→ $R = \dfrac{2S_1}{\Delta V_{\mathrm{eff}}}$ $\qquad S_3 = \dfrac{16\pi S_1^3}{3(\Delta V_{\mathrm{eff}})^2}$

In general

Numerical computation is necessary for finding the solution (e.g. Overshooting-undershooting method)

GW spectrum

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

Collision of walls (Envelope approximation):

$$\widetilde{\Omega}_{\rm env} h^2 \simeq 1.67 \times 10^{-5} \times \left(\frac{0.11 v_b^3}{0.42 + v_b^2}\right) \tilde{\beta}^{-2} \left(\frac{\kappa_\phi \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*^t}\right)^{1/3}$$

$$\tilde{f}_{\rm env} \simeq 1.65 \times 10^{-5}\ {\rm Hz} \times \left(\frac{0.62}{1.8 - 0.1 v_b + v_b^2}\right) \tilde{\beta} \left(\frac{T_t}{100\ {\rm GeV}}\right)$$

Sound waves (Compression waves of thermal plasma):

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

Magnetohydrodynamic (MHD) turbulence:

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

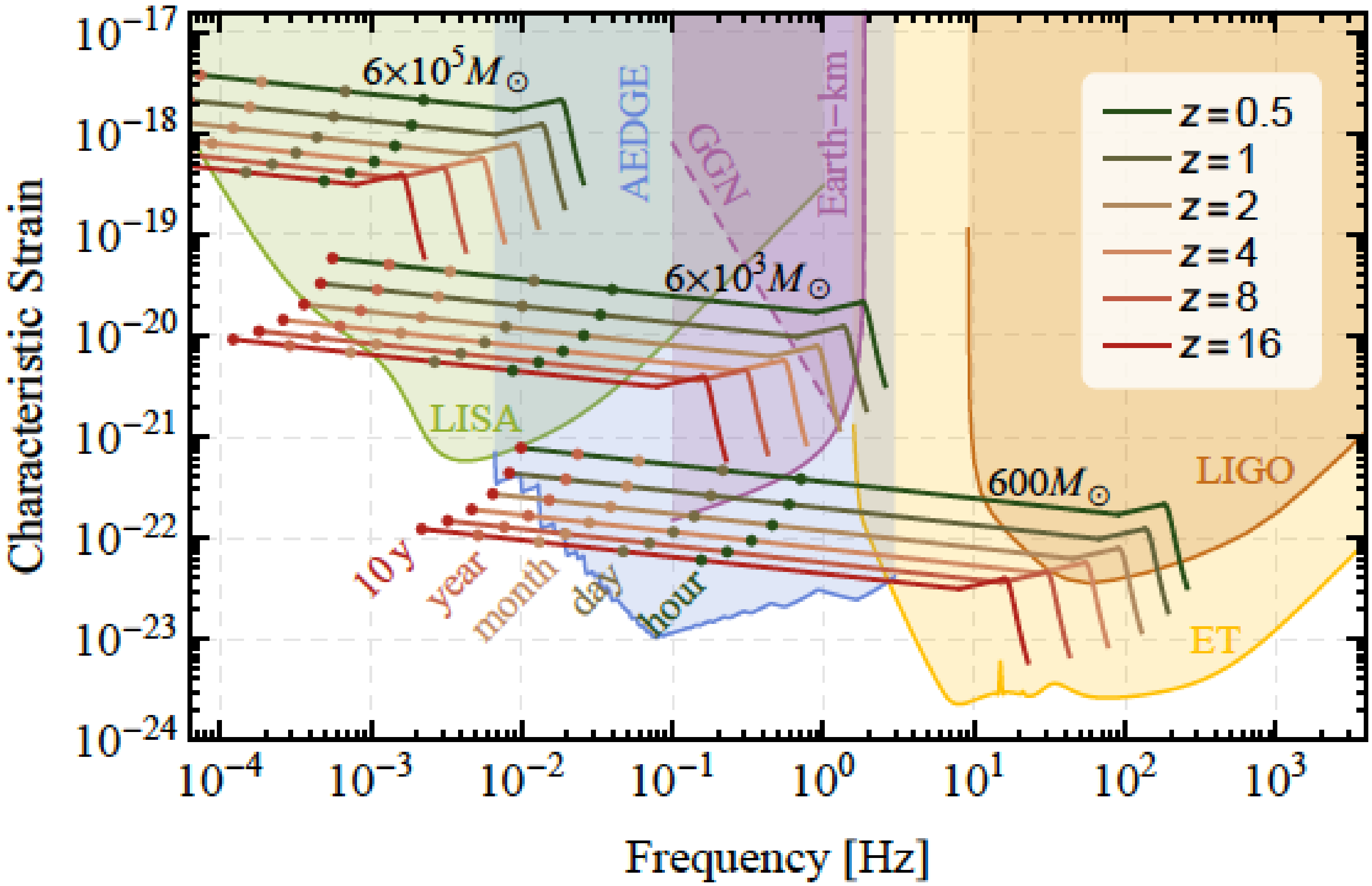
- v_b : wall velocity
- κ_ϕ , κ_v and $\epsilon = 0.05$: efficiency factors

Backup slides – GW experiments

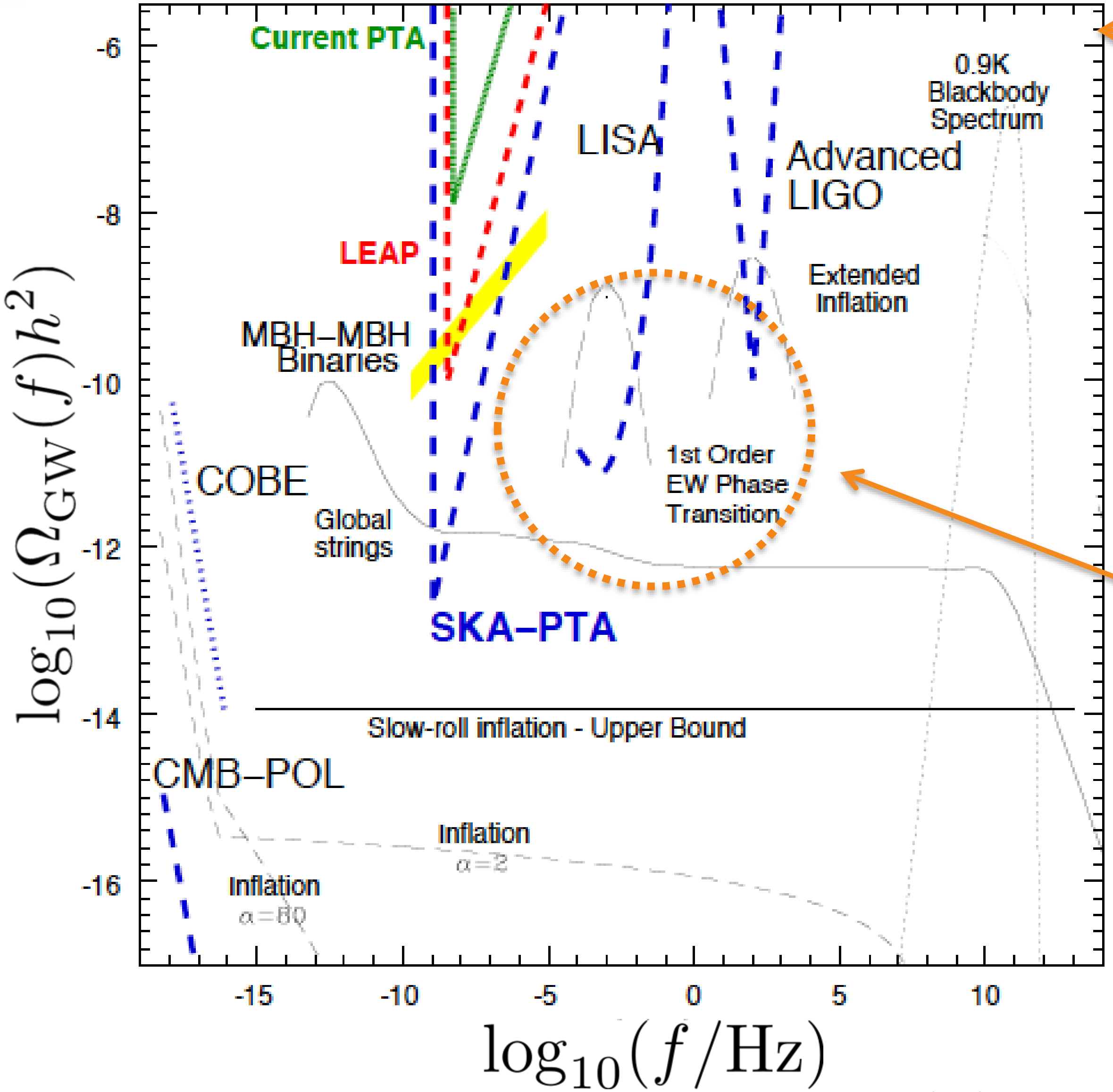
AEDGE

- Atomic Experiments for Dark matter and Gravity Exploration

[Bertoldi et al., arXiv:1908.00802]



Landscape of relic GWs



[Kramer, Stappers (2010)]

Current cosmological constraints from CMB and BBN:

- Constraints on extra radiation:

$$\Delta N_\nu \lesssim 1$$

$$\Omega_{\rm extra}h^2 = 5.6\times10^{-6}\Delta N_\nu$$

Future GW observation at space-based interferometers:

2025/26: Pre-DECIGO
Afterwards: DECIGO
2034: LISA

[Ando (2016 JPS Annual Meeting)]

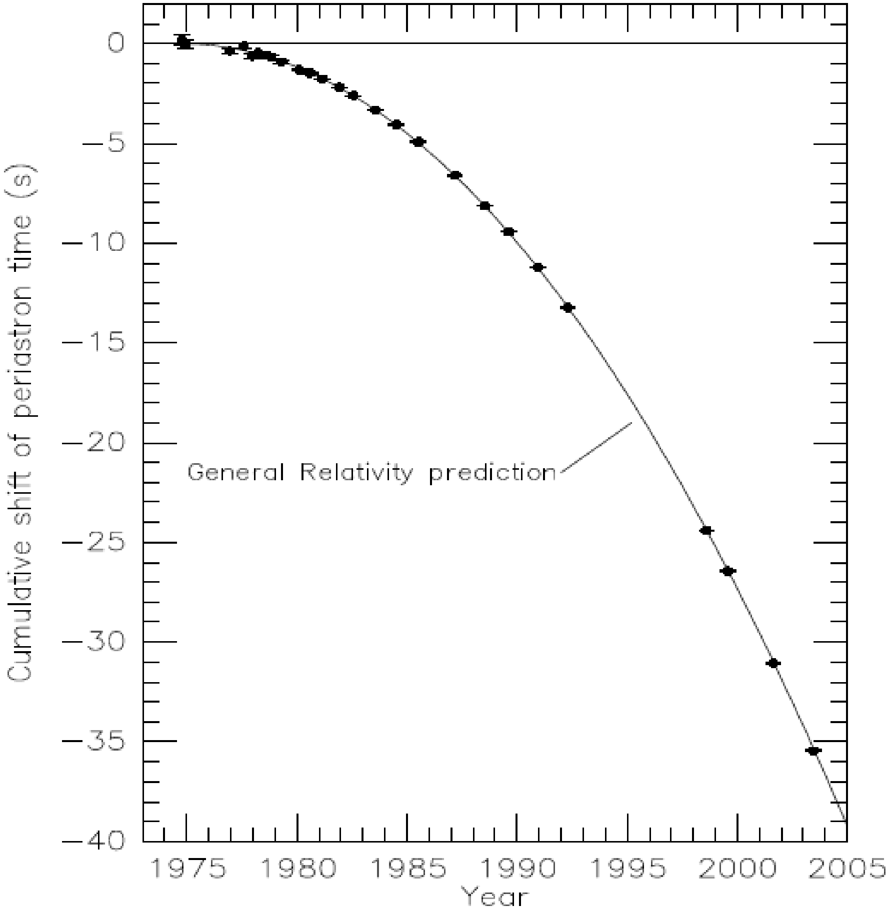
Indirect detection of gravitational waves

- Effects of gravitational waves have been observed

- In 1976, Hulse and Taylor discovered the binary pulsar (neutron star) PSR 1913+16

- The orbit is contracting due to the emission of gravitations waves

➡ 1993 Nobel prize



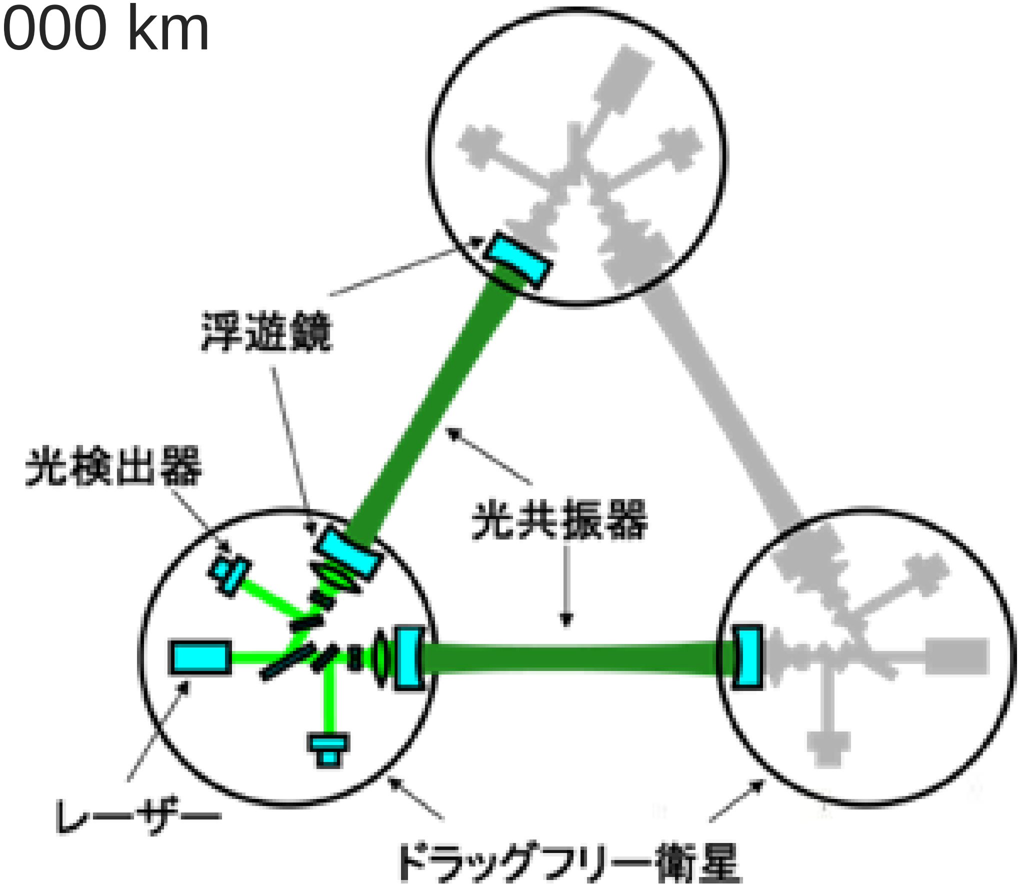
[Taylor,Weisberg(2004)]

DECIGO

Dec-hertz Interferometer Gravitational Wave Observatory

[tamago.mtk.nao.ac.jp/decigo]

- Space-based
- Arm: 1,000 km



Observation of pulsars

Pulsar as a GW detector

- Very stable pulse period: Excellent clock

  e.g. Period of PSR B1937+21

$$1.557\,806\,468\,819\,794\,5 \pm 0.000\,000\,000\,000\,000\,4 \text{ ms}$$

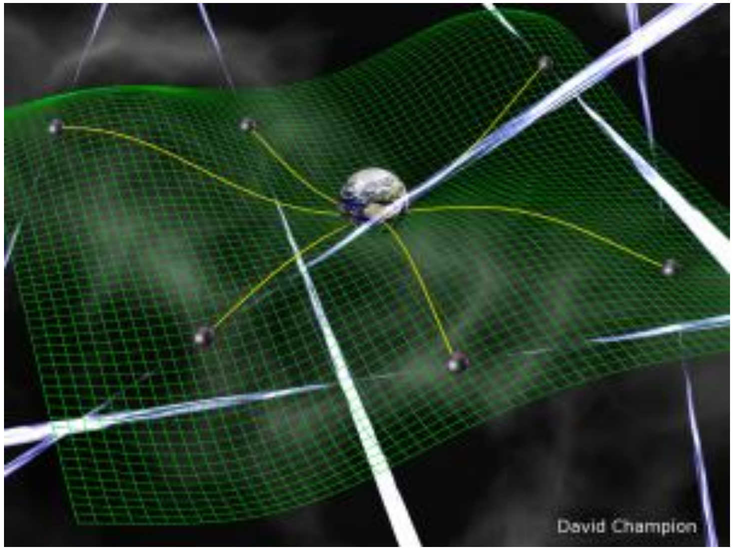
- GWs between pulsar and Earth → Fluctuation in arrival time

→ Constraints in frequency range $f \; {}^{3} \; 1/T$ (Observation duration)

Square Kilometer Array (SKA)

[www.skatelescope.org]

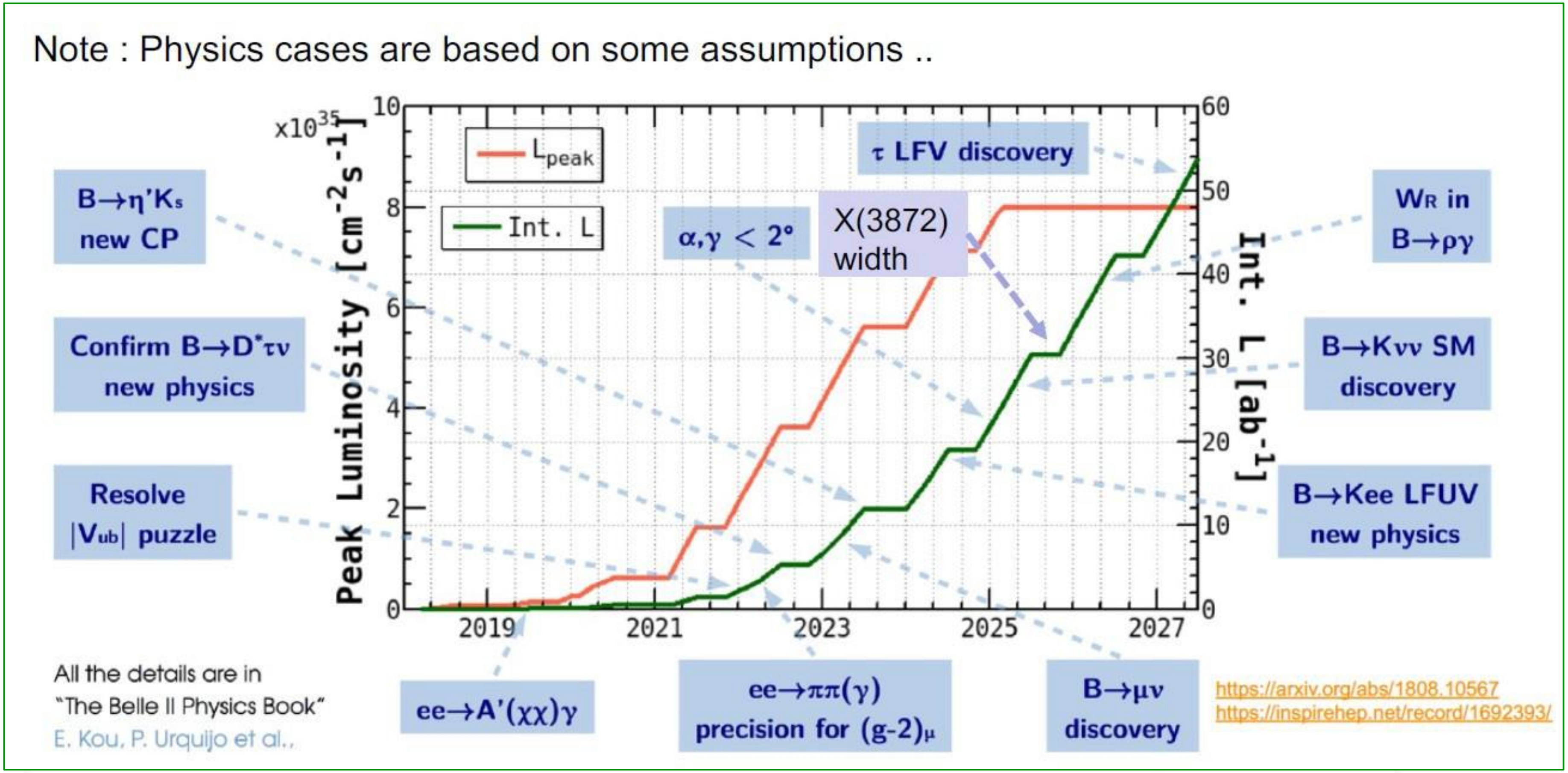
- Radio telescope
- Site candidates: Africa, Australia
- 2016: Construction Approved
  2018-23: SKA1 Construction
  2020+: Early Science



Backup slides – High energy experiments

Belle II

Run perspectives



Note : Physics cases are based on some assumptions ..

$B\to\eta' K_s$ new CP

Confirm $B\to D^*\tau\nu$ new physics

Resolve $|V_{ub}|$ puzzle

τ LFV discovery

$\alpha,\gamma < 2°$

X(3872) width

W_R in $B\to\rho\gamma$

$B\to K\nu\nu$ SM discovery

$B\to Kee$ LFUV new physics

$ee\to A'(\chi\chi)\gamma$

$ee\to\pi\pi(\gamma)$ precision for $(g\text{-}2)_\mu$

$B\to\mu\nu$ discovery

All the details are in
"The Belle II Physics Book"
E. Kou, P. Urquijo et al.,

https://arxiv.org/abs/1808.10567
https://inspirehep.net/record/1692393/

[Talk by E. Prencipe at Universal physics in Many-Body Quantum Systems (2019)]

Backup slides – Introduction

Connections between elementary particles and the Universe

Greatest puzzles in nature

- What is the Universe made of? ← Particle physics
- How did the Universe begin? ← Cosmology

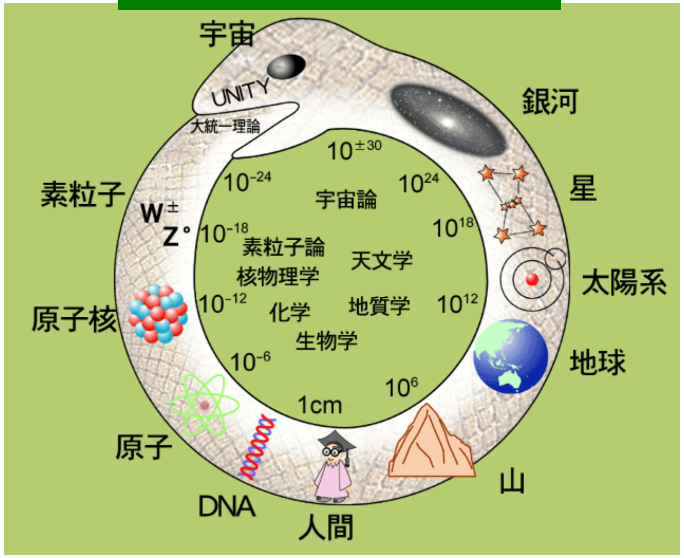
Particle physics (High energy physics)

- Studies the properties of elementary particles and their interactions

Cosmology

- Studies the origin, evolution and structure of the Universe

Cosmic Ouroboros



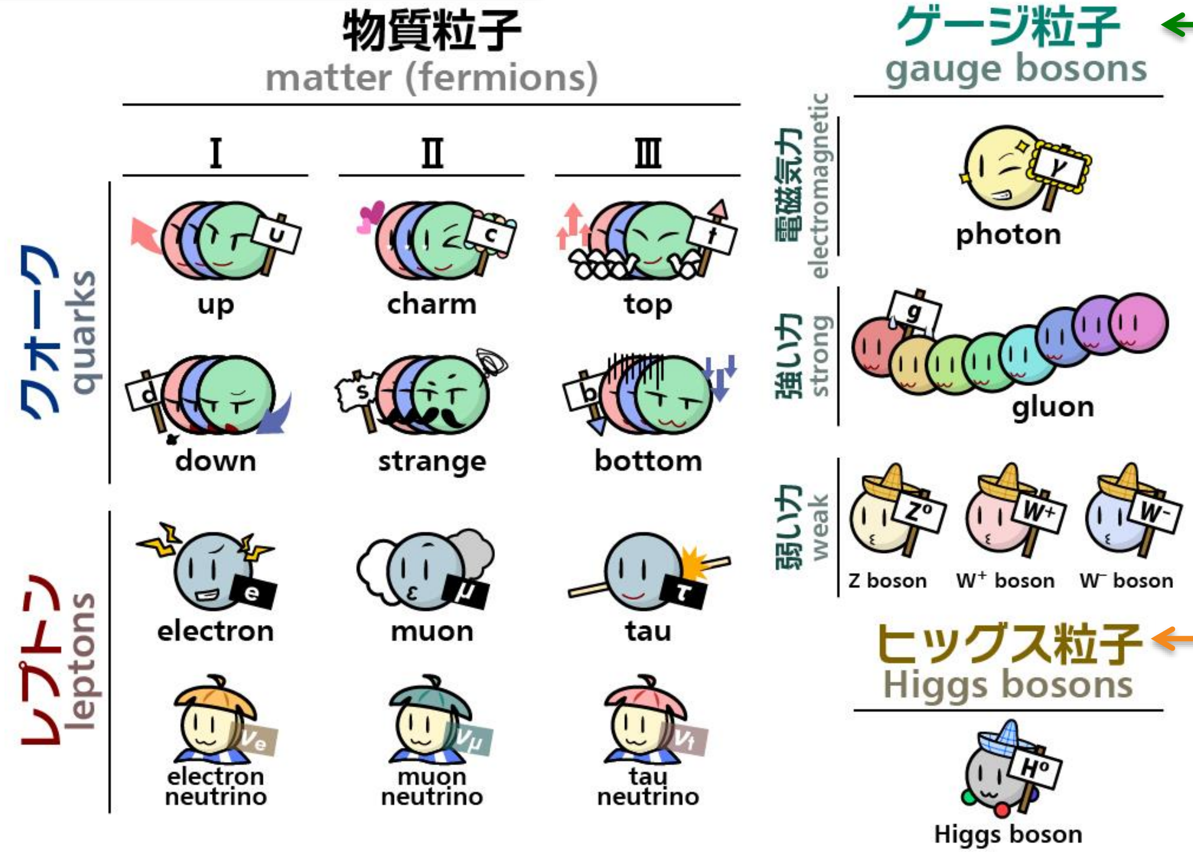
[www2.kek.jp]

Big bang cosmology connects elementary particles and the early Universe

[Sheldon Glashow]

Standard Model of particle physics

Standard Model (SM)

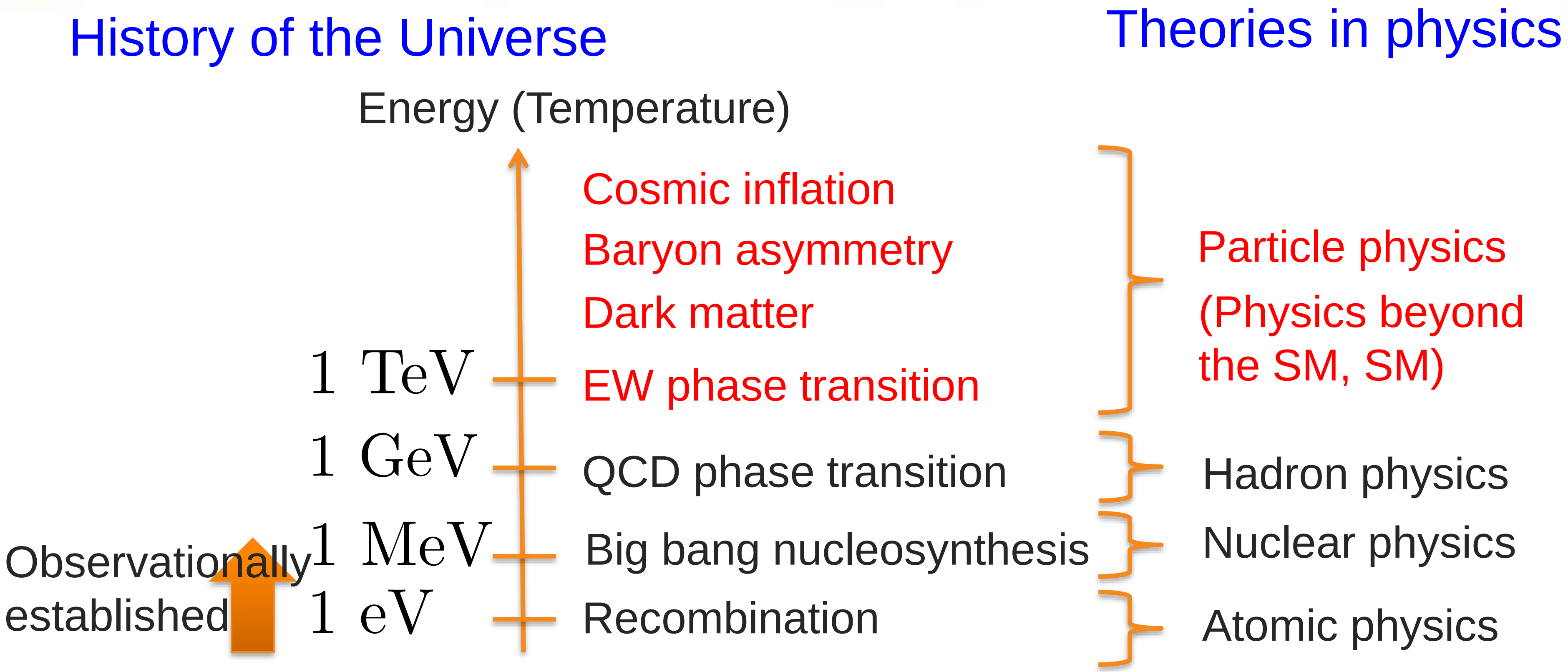


Force mediator

Origin of elementary particle mass
（discovered in 2012）

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

The role of high energy colliders



Energy (Temperature)	History of the Universe	Theories in physics
	Cosmic inflation Baryon asymmetry Dark matter	Particle physics (Physics beyond the SM, SM)
$1\ \mathrm{TeV}$	EW phase transition	
$1\ \mathrm{GeV}$	QCD phase transition	Hadron physics
$1\ \mathrm{MeV}$	Big bang nucleosynthesis	Nuclear physics
$1\ \mathrm{eV}$	Recombination	Atomic physics

Observationally established

- Mysteries in the early Universe demand developments in particle physics

High energy colliders approach the beginning of the Universe

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

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 $h_\times$

Sources of gravitational waves

Astrophysical origin

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

Cosmic origin

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