Cosmological connections at future lepton colliders

Fa Peng Huang

(CTPU-IBS)

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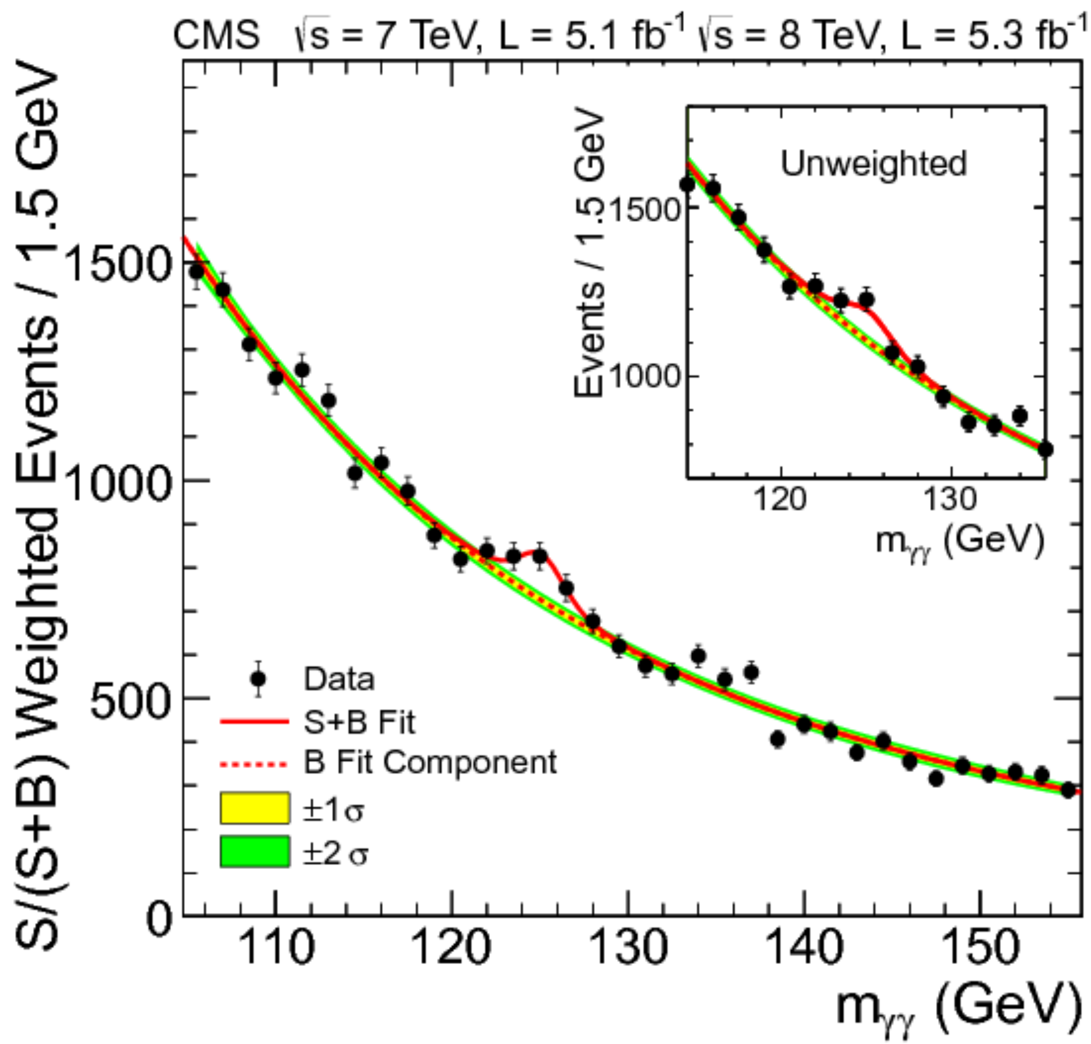
Outline

- ➢Research Motivation
- ➢ Electroweak (EW) baryogenesis and Phase transition gravitational wave (GW) in a nutshell
- ➢Cosmological connection to EW phase transition history by CEPC &LISA
- ➢Cosmological connection to EW baryogensis with dynamical CP-violation by CEPC&LISA
- ➢Cosmological connection to dark matter (DM) by GW&CEPC
- ➢Summary and outlook

Motivation from particle

Higgs Independence Day:4 July 2012@LHC **deliberate ！**



Post-Higgs Era

After the discovery of 125 GeV scalar at the LHC, Higgs becomes a new and realistic portal to study the fundamental physics and its deep connections to cosmology, such as neutrino mass (leptogenesis), Higgs (portal) inflation, cosmological relaxion, EW phase transition/baryogenesis, Higgs portal dark matter…

$$+\mathcal{O}_{hidden} H^\dagger H$$

Relaxion $\mathcal{O} = M^2 - g\phi$

FPH,et.al.arXiv:1605.03120

$\mathcal{O} = ll$

neutrino mass and leptogenesis

$\mathcal{O} = R$

Higgs (bouncing) inflation,

FPH,et.al.arXiv:1307.7458, arXiv:1509.08772

$\mathcal{O} = \phi\phi$

Higgs portal dark matter

FPH,et.al.arXiv:1704.04201

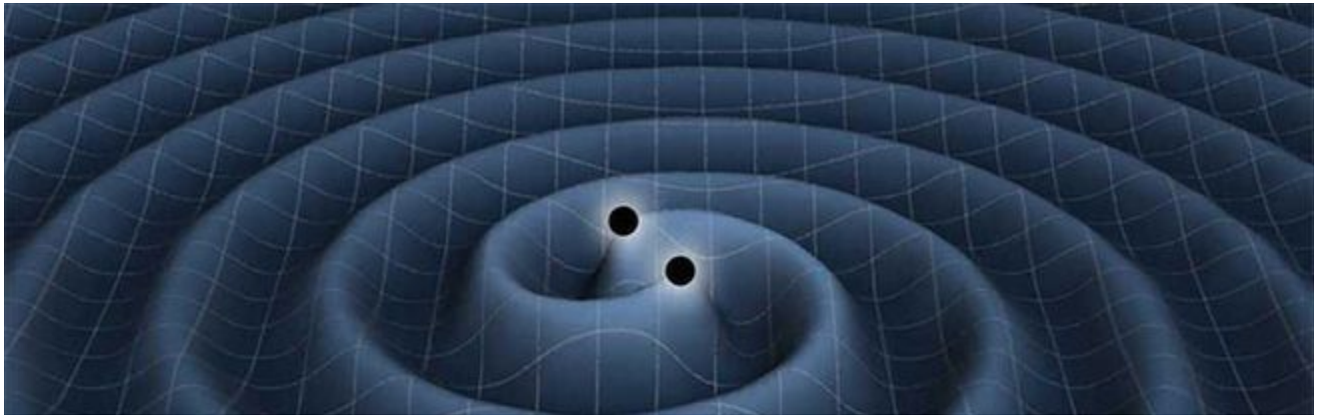
$\mathcal{O} = \phi S, \phi\phi$

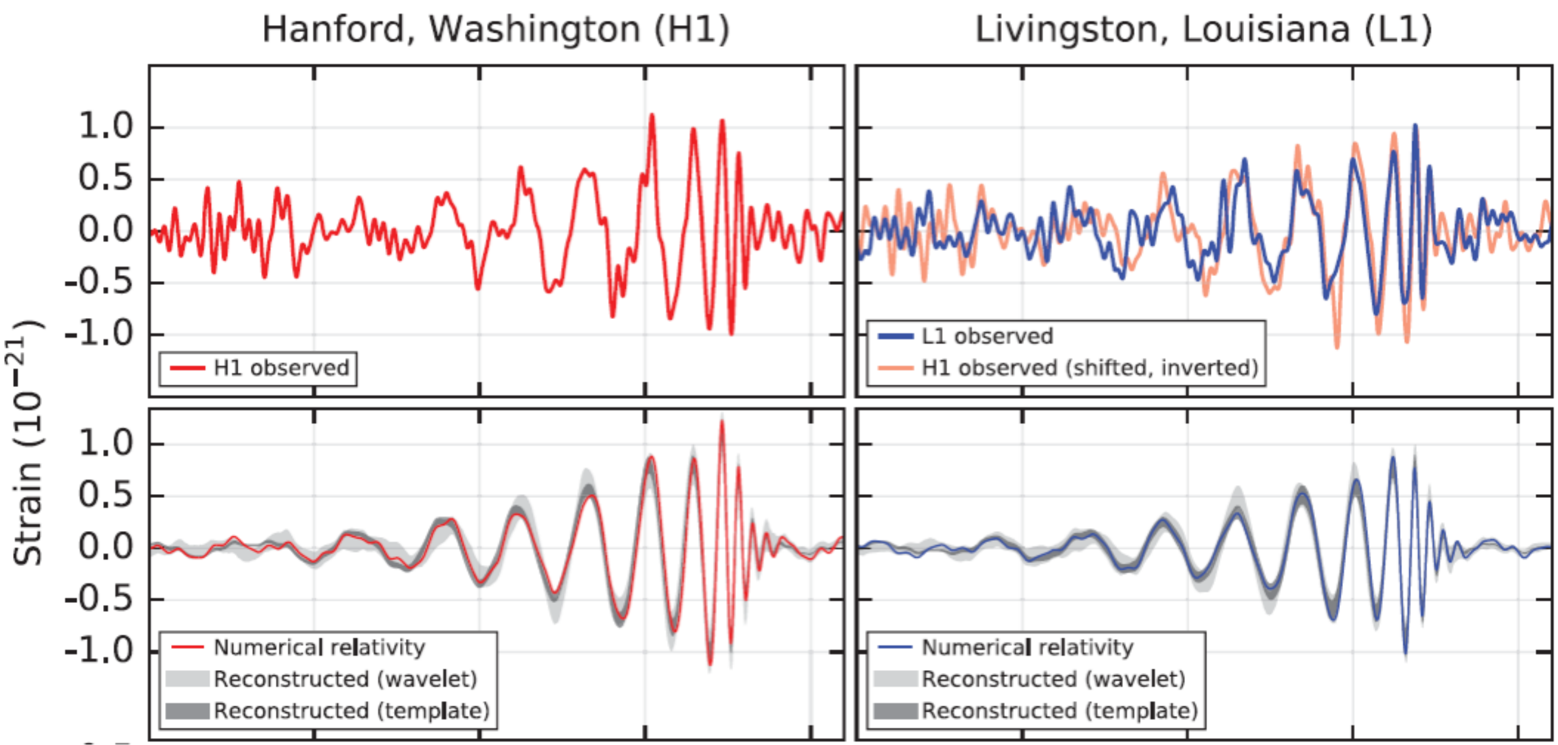
EW phase transition/ baryogenesis

FPH,et.al.arXiv:1507.08168,arXiv:1511.03969, arXiv:1601.01640,arXiv:1704.04201,arXiv:1709.09691 arXiv:1804.06813

See Andrew Long and Jonathan Kozaczuk's talk

Motivation from wave





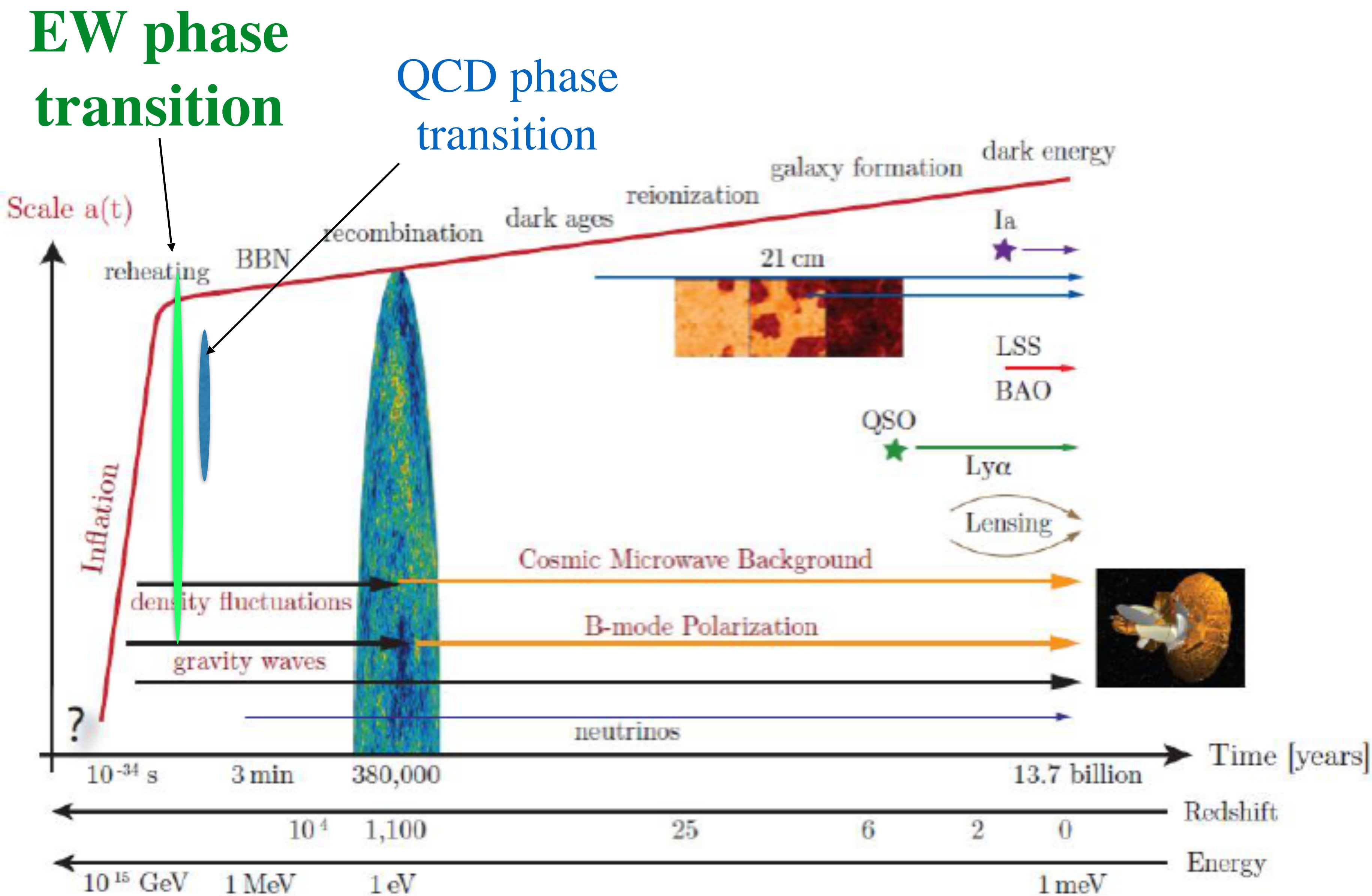
Post-GW Era

- The observation of GW by aLIGO has initiated a new era of exploring the nature of gravity, cosmology and the fundamental particle physics by GW.

- Obvious shortcomings in our understanding of particle cosmology (such as the DM and the baryon asymmetry of the universe), and no evidence of new physics at LHC may just point us GW approach.

- GW may be used to hear the echoes of EW symmetry breaking patters, DM, baryogenesis…

Motivation from cosmology



The nature of Higgs potential and the type of EW phase transition

EW phase transition Physics

- **The true shape of Higgs potential (Exp:CEPC)**
- Baryon **asymmetry of the universe (baryogenesis)**
- **Gravitational wave (Exp:LISA 2034)**
- **Dark Matter blind spots, Asymmetry dark matter**

Study of EW phase physics at CEPC and LISA helps to explore the evolution history of the universe at hundred GeV temperature.

The physics of QCD phase transition

As for （dark ） QCD phase transition physics

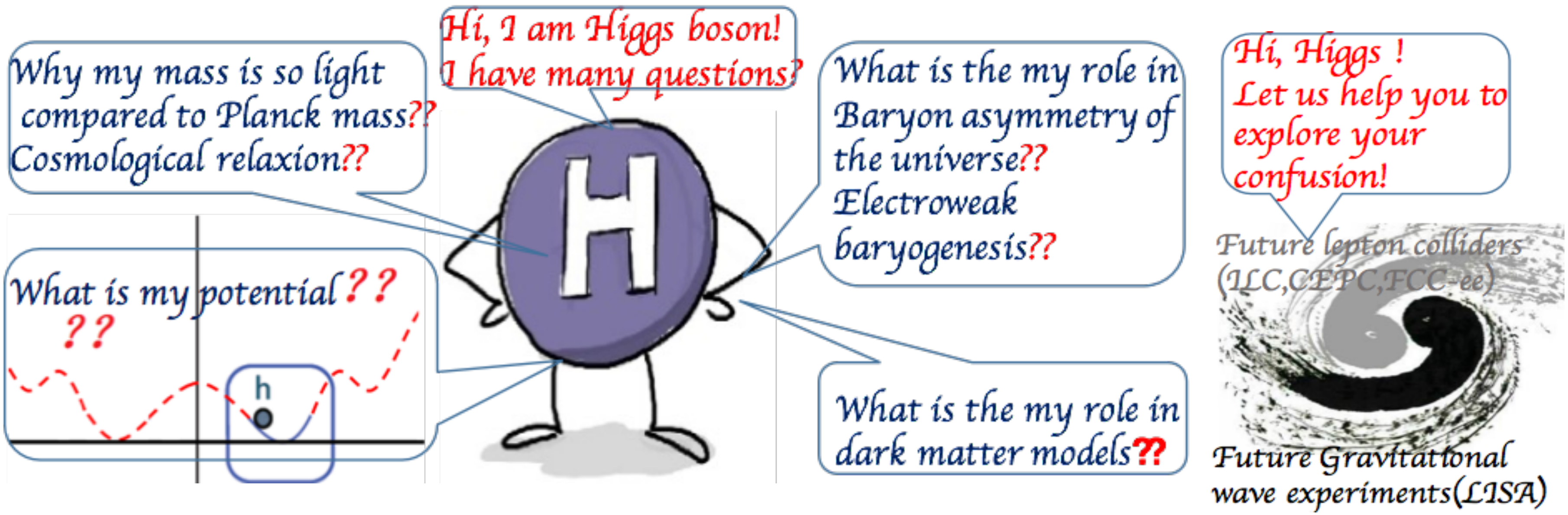
- **Axion physics**
- **Axion dark matter conversion to photon (SKA 2020)**

FPH, Kenji Kadota, Toyokazu Sekiguchi, Hiroyuki Tashiro
arXiv:1803.08230, Phys.Rev. D97 (2018) no.12, 123001

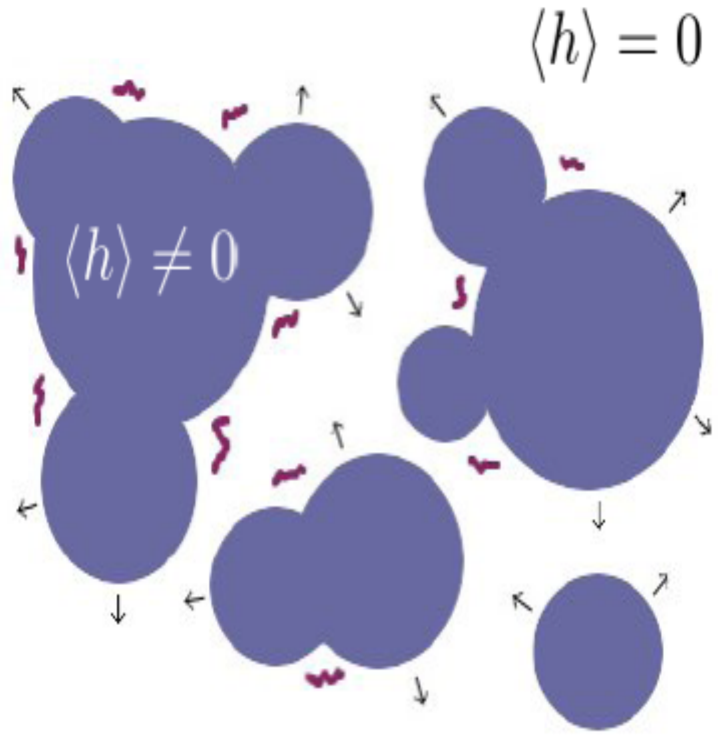
- **Gravitational wave (SKA) work in progress**

Study of QCD phase physics at SKA helps to explore the evolution history of the universe at about hundred MeV temperature and dark matter.

short summary



phase transition GW signals



SFOPT can drive the plasma of the early universe out of thermal equilibrium, and bubbles nucleate during it, which will produce GW.

E. Witten, Phys. Rev. D 30, 272 (1984)
C. J. Hogan, Phys. Lett. B 133, 172 (1983);
M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994))

EW phase transition GW becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.

Mechanisms of phase transition GW

For simplified cases, the GW spectrum depends on four parameters: α , β, bubble wall velocity v_b and the efficiency factor λ. (Explicitly, they depends on numerical simulations.)

Bubble collisions:

$$\Omega_{\rm co}(f)h^2 \simeq 1.67\times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\lambda_{co}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{\frac{1}{3}} \times\left(\frac{0.11 v_b^3}{0.42+v_b^3}\right)\left[\frac{3.8(f/f_{\rm co})^{2.8}}{1+2.8(f/f_{\rm co})^{3.8}}\right].$$

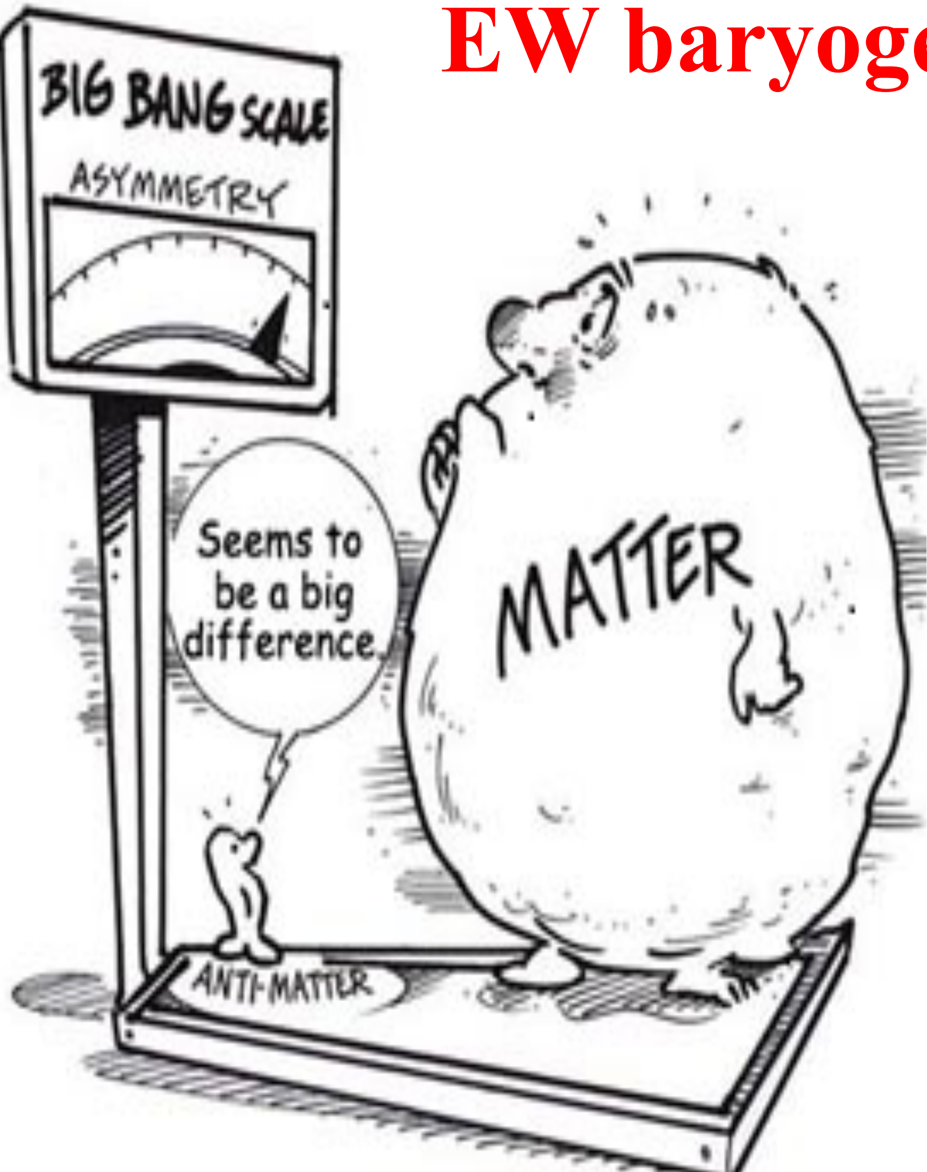
Turbulence:

$$\Omega_{\rm tu}(f)h^2 \simeq 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\lambda_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*^t}\right)^{\frac{1}{3}} v_b \times\frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f a_0/(a_* H_*))}.$$

Sound wave:

$$\Omega_{\rm sw}(f)h^2 \simeq 2.65\times 10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\lambda_{sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{\frac{1}{3}} v_b \times\left[\frac{7(f/f_{\rm sw})^{6/7}}{4+3(f/f_{\rm sw})^2}\right]^{7/2},$$

EW baryogenesis in a nutshell



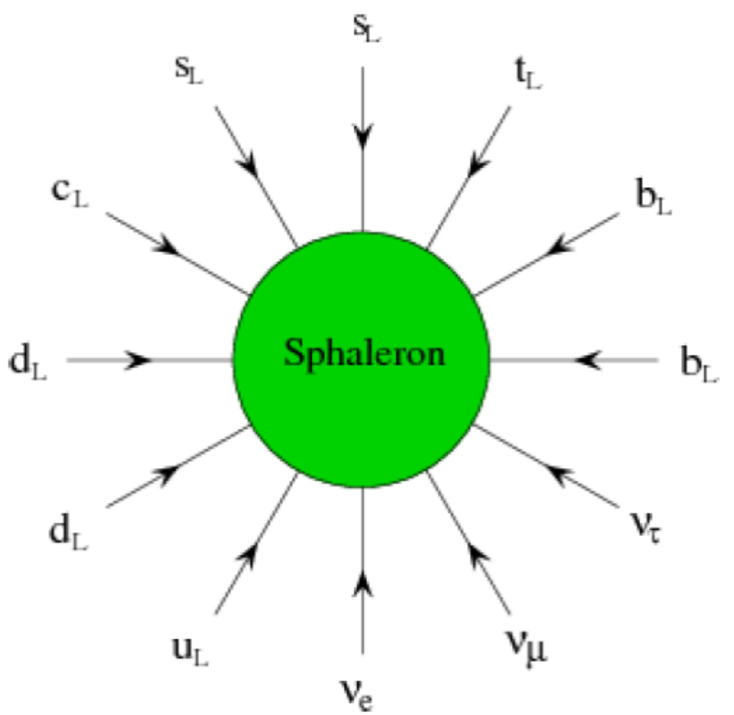
A long standing problem in particle cosmology is the origin of baryon asymmetry of the universe (BAU).

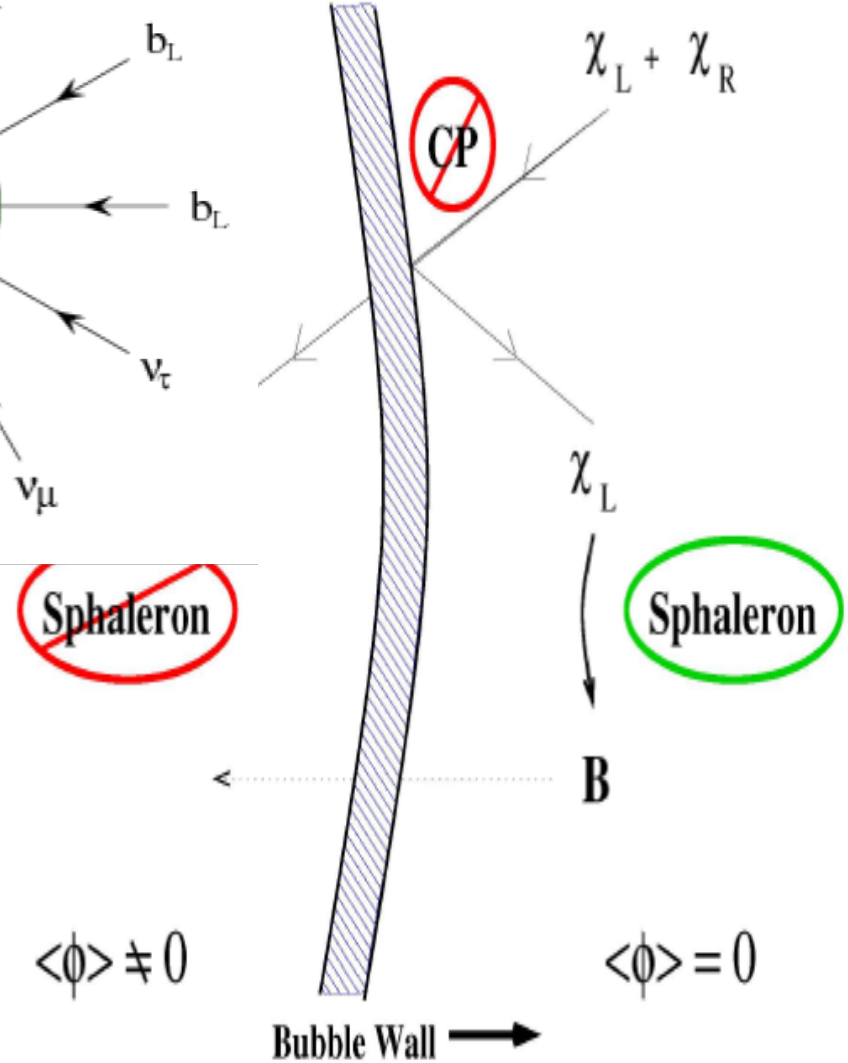
After the discovery of the Higgs boson by LHC and gravitational waves (GW) by aLIGO, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

$$\eta_B = n_B / n_\gamma = 5.8 - 6.6 \times 10^{-10} \quad \text{(CMB, BBN)}$$

EW baryogenesis:

SM technically has all the three elements for baryogenesis , (Baryon violation, C and CP violation, Departure from thermal equilibrium or CPT violation) but not enough.





- **B violation from anomaly in B+L current.**
- **CKM matrix, but too weak.**
- **strong first-order phase transition (SFOPT) with expanding Higgs Bubble wall.**

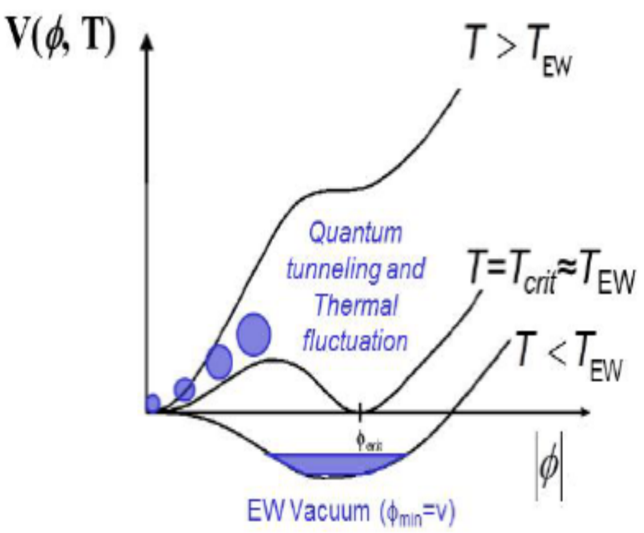
D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. 14, 125003 (2012).

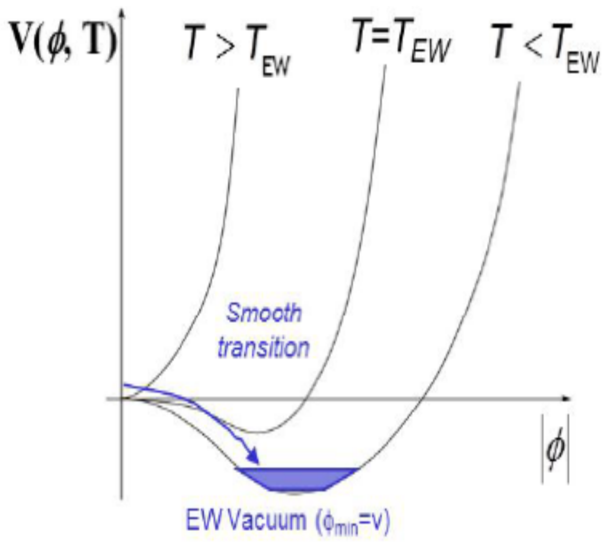
SFOPT in extended Higgs sector motivated by baryogenesis or other new physics

From lattice simulation

SFOPT for $m_H < 75$ GeV

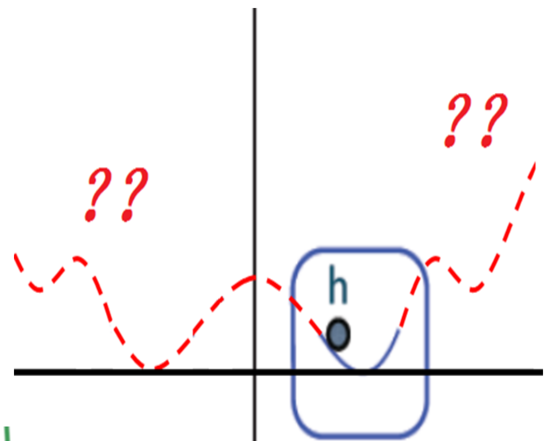
Cross over for $m_H > 75$ GeV



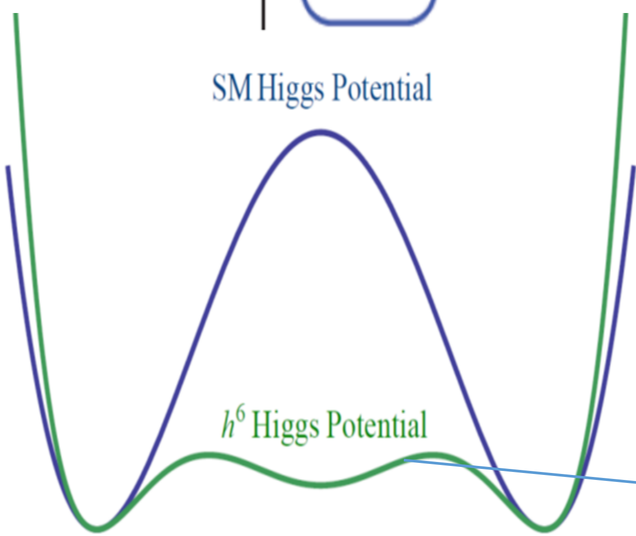


Extension of the Higgs sector can easily produce SFOPT even for 125 GeV Higgs boson.

I.Cosmological connection to EW phase transition history by CEPC and LISA



From the current data, for the Higgs potential, we know nothing but the quadratic oscillation around the vev 246 GeV with the mass 125 GeV.



$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

or $$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

Leads to SFOPT

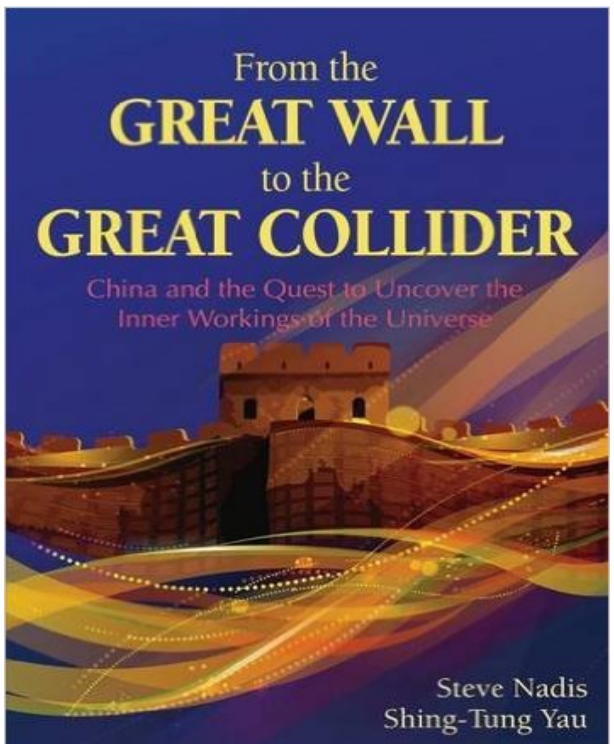
arXiv:1511.06495 Nima Arkani-Hamed, Tao Han, Michelangelo Mangano, Lian-Tao Wang

PreCDR of CEPC

Current particle collider has no ability to unravel the true potential of the Higgs boson, we need new experiments.

Particle approach

we can build more powerful colliders, such as planned

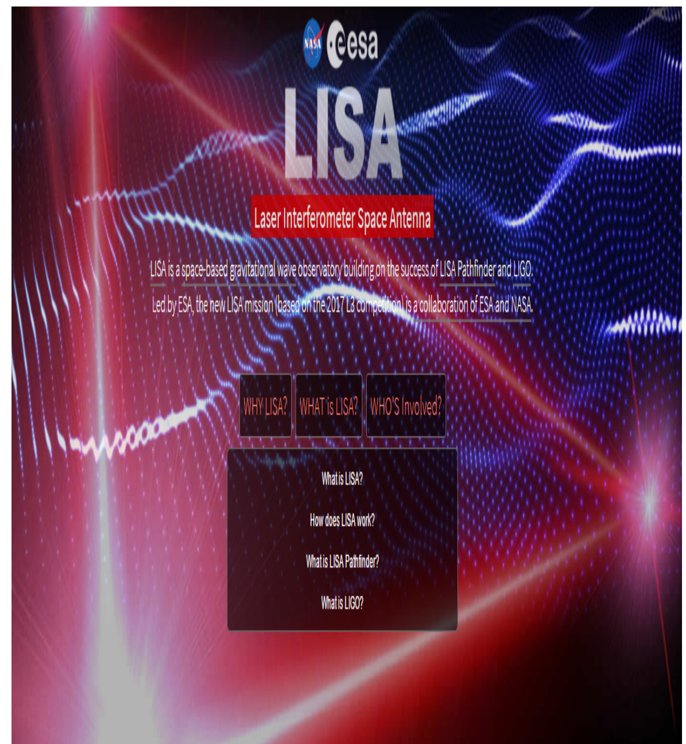


Relate by EW phase transition

Double test on the Higgs potential

Wave approach

GW detectors can test Higgs potential as complementary approach. (LISA launch 2034)



Benchmark scenario for EW phase transition

New Higgs potential and EW phase transition

For simplicity to investigate the signals from particle colliders to GW detector, we firstly use the effective Lagrangian (discuss renormalizable models later)

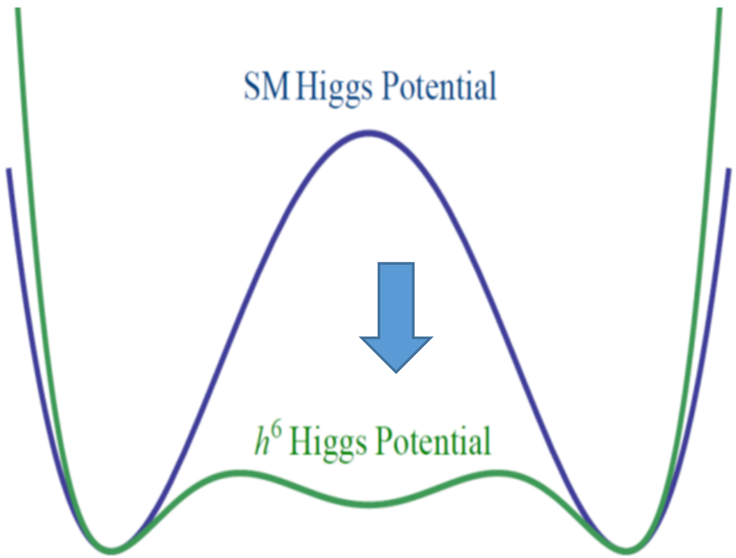
$$V_{\rm tree}(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

To study the EW phase transition, we need to calculate the one-loop finite temperature effective potential using the finite temperature field theory:

$$V_{\rm eff}(h,T) = V_{\rm tree}(h) + V_1^{T=0}(h) + \Delta V_1^{T\neq 0}(h,T) + V_{daisy}$$

Xinmin Zhang Phys.Rev. D47 (1993) 3065-3067
C. Grojean, G. Servant, J. Well PRD71(2005)036001
A.Noble, M. Perelstein Phys.Rev. D78 (2008) 063518
D. Bodeker, L. Fromme,S.J. Huber, M. Seniuch,JHEP 0502 (2005) 026
D.J.H. Chung, Andrew J. Long, Lian-tao Wang Phys.Rev. D87 (2013) , 023509
FPH, et.al, Phys.Rev.D94(2016)no.4,041702 ,Phys.Rev.D93 (2016) no.10,103515
Lots of discussions, sorry that I can’t cover all

➢Here, we focus on the EW phase transition type

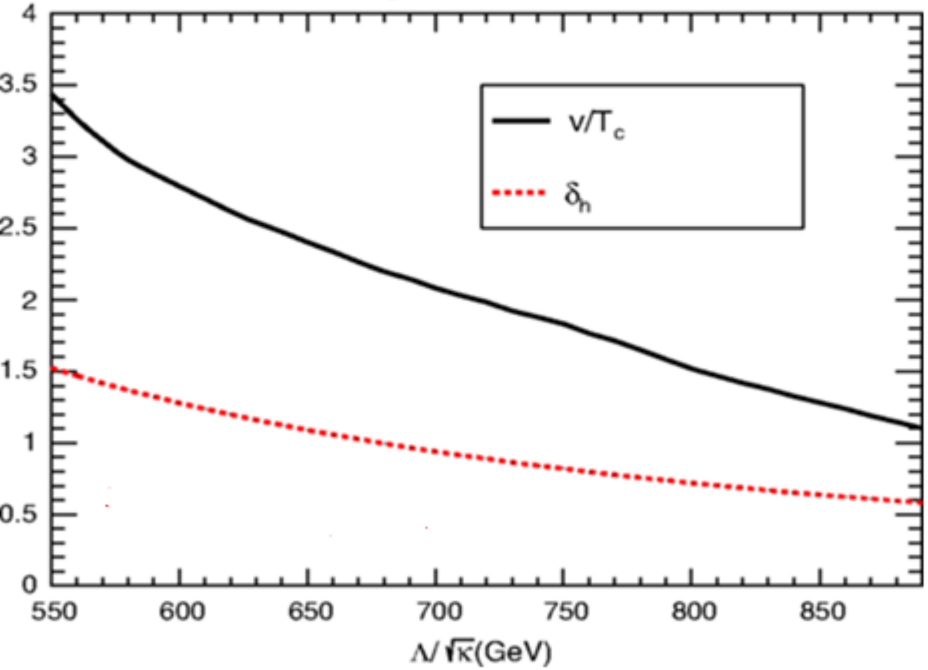


Leads to SFOPT

➢The concerned dim-6 operators can be induced from many renormalizable extension of the SM.
model details see FPH, et. al Phys.Rev. D93 (2016) 103515 and arXiv:1708.0473

SFOPT leads to obvious deviation of the tri-linear Higgs coupling

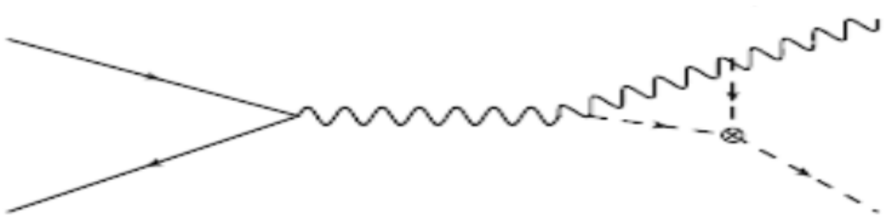
$$\mathcal{L}_{hhh} = -\frac{1}{3!}(1+\delta_h)A_h h^3$$



At one-loop level, deviation of the tri-linear Higgs coupling

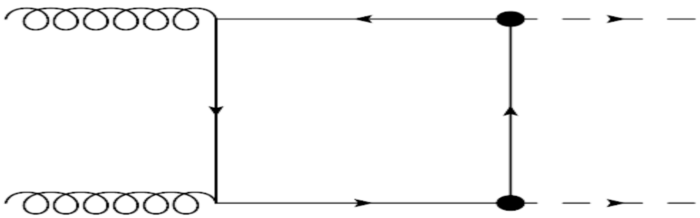
$$\delta_h \in (0.6, 1.5)$$

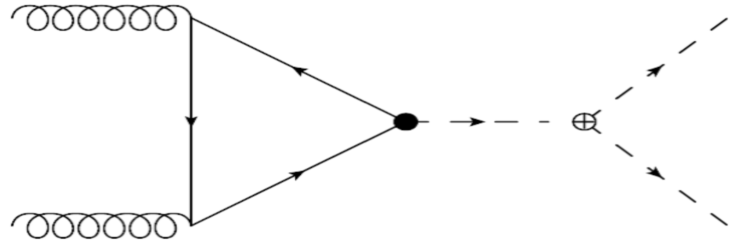
The Circular Electron Positron Collider (CEPC), ILC, FCC-ee can precisely test this scenario by precise measurements of the hZ cross section ($e^- e^+ \rightarrow hZ$).
SM NNLO hZ cross section recently by Lilin Yang, et al 2016，Yu Jia et at 2016

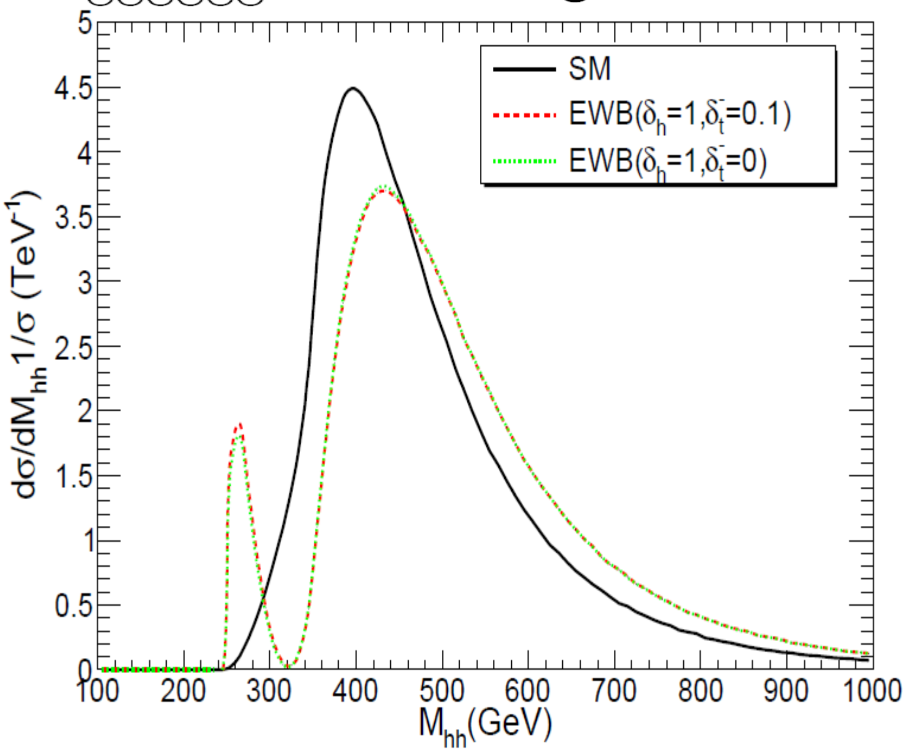


$$\delta_\sigma = \frac{\sigma_{hz,\delta_h \neq 0}}{\sigma_{hz,SM}} - 1$$

Hints at hadron collider: Modify the invariant mass distribution of Higgs pair due to interference effects:



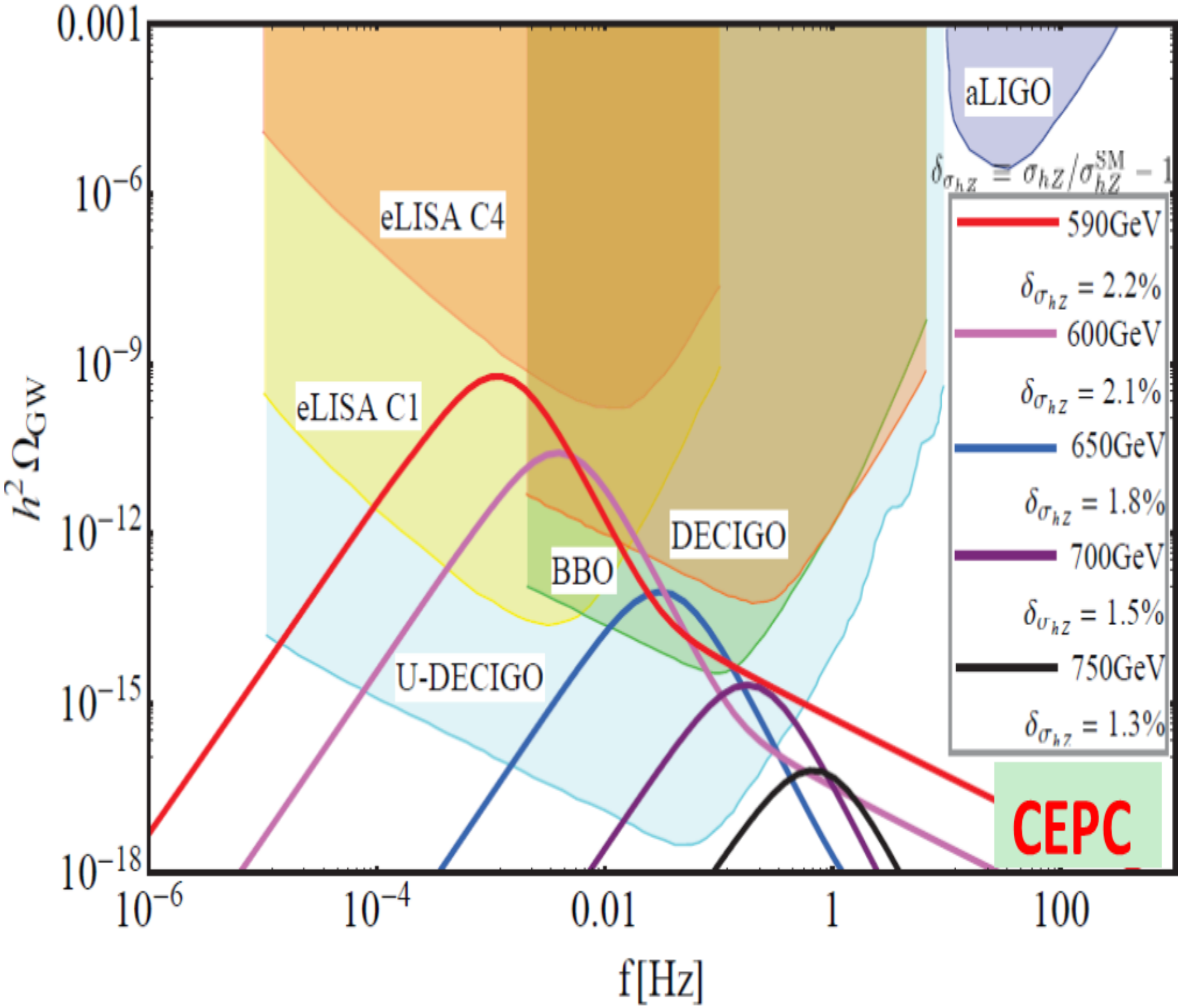




- **Two peaks for the baryogenesis scenario, one peak for the SM.**
- **Due to the difficulties to suppress backgrounds at the LHC, it will be difficult to completely pin down these anomalous coupling at 14 TeV LHC, even with 3000 ab^{-1} integrated luminosity.**
- **Exploiting boosted tricks helps to increase ability to extract the anomalous couplings.**
- **More precise information may come from future100 TeV hadron collider, such as SppC, or future lepton collider, such as CEPC .**

See Zhen Liu's talk

Correlate particle collider and GW signals: Double test on Higgs nature and baryogenesis from particle to wave



- **For CEPC with 10 ab^{-1} at $\sqrt{s} = 240$ GeV, precision of σ_{zh} may be about 0.4% and can test the scenario.**
- **LISA, BBO,U-DECIGO are capable of detection**
- **The study on EW phase transition naturally bridges the particle physics at collider with GW survey and baryogenesis**

FPH, et.al, Phys.Rev.D94(2016)no.4,041702
Phys.Rev.D93 (2016) no.10,103515

Systematic study on this type of EW phase transition in general dimension-six effective operators from EW observables to future lepton collider

Testing electroweak phase transition in the scalar extension models at lepton colliders
Qing-Hong Cao, FPH , Ke-Pan Xie, Xinmin Zhang arXiv:1708.0473

In general, many other dim-6 operators would occurs simultaneously which will make contributions to the EW precise observables. Through the following discussions, we can see that the Higgs sextic scenario still works well after considering all the dim-6 operators.

$$\mathcal{L} \supset -\mu^2|H|^2 - \lambda|H|^4 + c_6|H|^6$$

$$+ c_T\mathcal{O}_T + c_{WW}\mathcal{O}_{WW} + \text{other dimension-six operators}$$

$$\delta_{\sigma(hZ)} \approx (0.26c_{WW} + 0.01c_{BB} + 0.04c_{WB} - 0.06c_H - 0.04c_T + 0.74c_L^{(3)\ell}$$

$$+0.28c_{LL}^{(3)\ell} + 1.03c_L^{\ell} - 0.76c_R^{e}) \times 1\ \text{TeV}^2 + 0.016\delta_h,$$

SFOPT produce large modification of tri-linear Higgs coupling δ_h

Thus, $\mathbf{c_6}$ **dominate the hZ cross section deviation.**

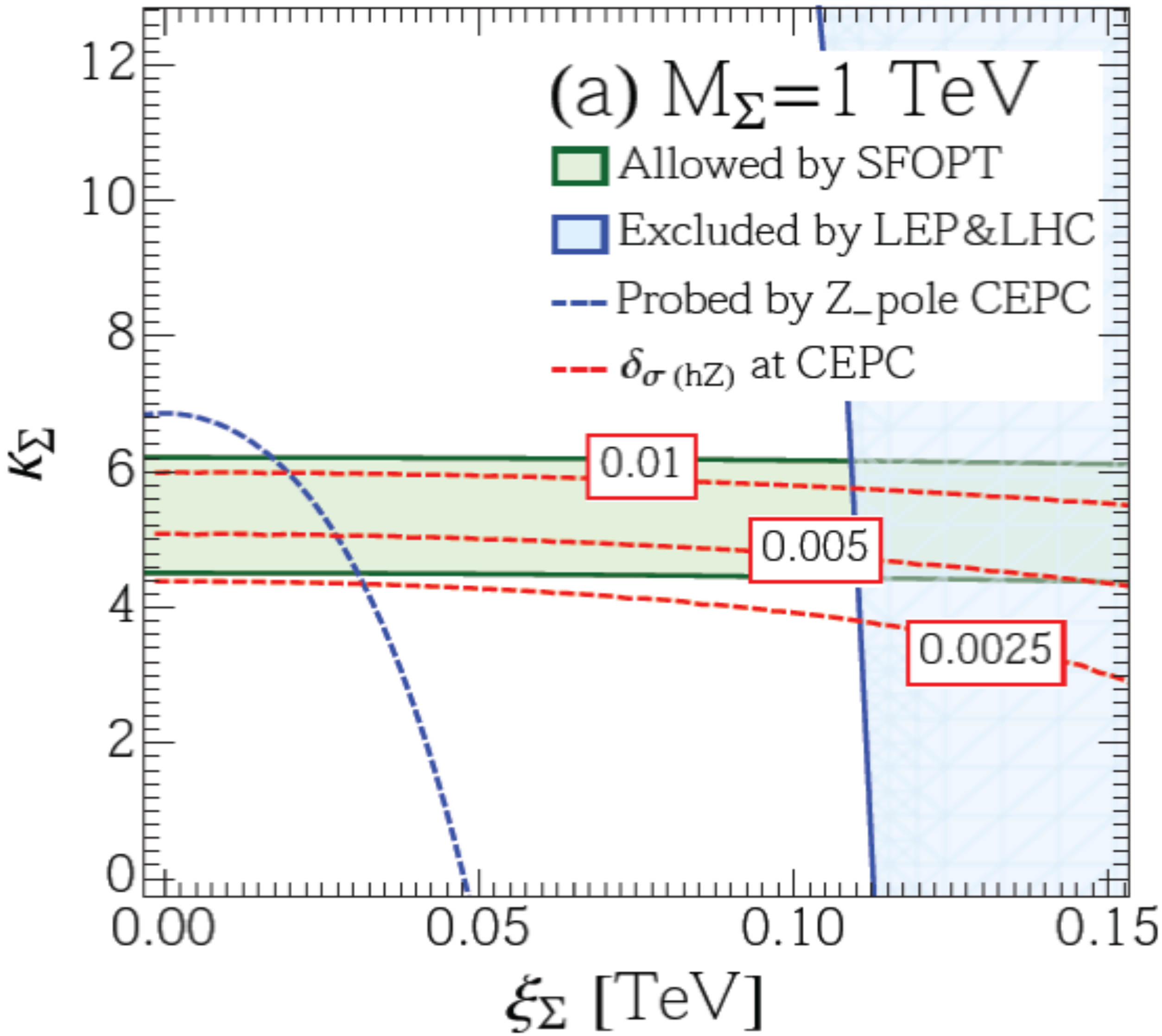
Renormalizable realization from triplet model

The model with an $SU(2)_L$ triplet scalar without hypercharge $\Sigma(1,3,0)$

$$\delta\mathcal{L} = \mathrm{Tr}[(D^\mu\Sigma)^\dagger D_\mu\Sigma] - M_\Sigma^2\mathrm{Tr}(\Sigma^2) - \zeta_\Sigma[\mathrm{Tr}(\Sigma^2)]^2 + 2\xi_\Sigma H^\dagger\Sigma H - 2\kappa_\Sigma|H|^2\mathrm{Tr}(\Sigma^2)$$

Using the covariant derivative expansion (CDE) method, the matched dim-6 operators and their coefficients at one-loop level in triplet scalar models can be systematically obtained:

Dimension-six operator	Wilson coefficient
$\mathcal{O}_{WW} = g^2\|H\|^2 W^a_{\mu\nu}W^{a,\mu\nu}$	$c_{WW} = \frac{1}{(4\pi)^2}\frac{\kappa_\Sigma}{6M_\Sigma^2}$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	$c_{2W} = \frac{1}{(4\pi)^2}\frac{g^2}{30M_\Sigma^2}$
$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon^{abc}W^{a\mu}_{\rho}W^{b\nu}_{\mu}W^{c\rho}_{\nu}$	$c_{3W} = \frac{1}{(4\pi)^2}\frac{g^2}{30M_\Sigma^2}$
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu\|H\|^2)^2$	$c_H = \frac{1}{(4\pi)^2}\frac{\kappa_\Sigma^2}{M_\Sigma^2}$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger\overleftrightarrow{D}_\mu H)^2$	$c_T = \frac{\xi_\Sigma^2}{M_\Sigma^4} + \frac{1}{(4\pi)^2}\frac{10\zeta_\Sigma\xi_\Sigma^2}{M_\Sigma^4}$
$\mathcal{O}_r = \|H\|^2\|D_\mu H\|^2$	$c_r = \frac{2\xi_\Sigma^2}{M_\Sigma^4} + \frac{1}{(4\pi)^2}\frac{20\zeta_\Sigma\xi_\Sigma^2}{M_\Sigma^4}$
$\mathcal{O}_6 = \|H\|^6$	$c_6 = -\frac{\kappa_\Sigma\xi_\Sigma^2}{M_\Sigma^4} - \frac{1}{(4\pi)^2}\frac{2\kappa_\Sigma^3}{M_\Sigma^2} - \frac{1}{(4\pi)^2}\frac{10\zeta_\Sigma\kappa_\Sigma\xi_\Sigma^2}{M_\Sigma^4}$



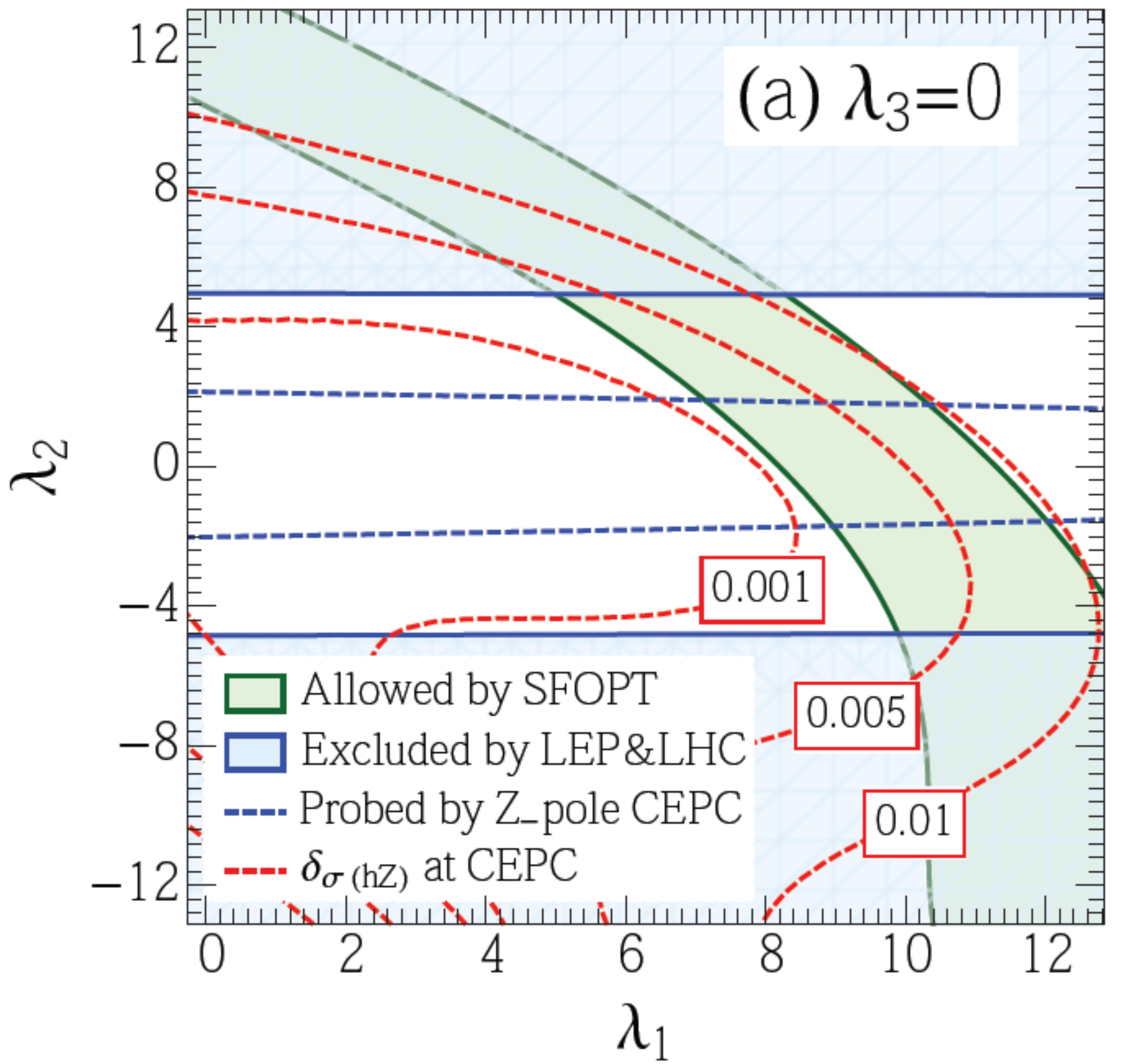
The parameter space of triplet model (without hypercharge) that compatible with strong FOPT and current experiments including the future CEPC's prediction.
Qing-Hong Cao, FPH , Ke-Pan Xie, Xinmin Zhang arXiv:1708.0473

Renormalizable realization of the from doublet model

$$\delta\mathcal{L} = D_\mu\Phi^\dagger D^\mu\Phi - M_\Phi^2\Phi^\dagger\Phi - \frac{\lambda_\Phi}{4}(\Phi^\dagger\Phi)^2 - \lambda_1\Phi^\dagger\Phi H^\dagger H - \lambda_2|\Phi\cdot H|^2$$
$$- \lambda_3[(\Phi\cdot H)^2 + h.c.] + (\eta_H|H|^2 + \eta_\Phi|\Phi|^2)(\Phi\cdot H + h.c.)\,,$$

Using CDE, the matched dim-6 operators and their coefficients in the doublet scalar models are obtained:

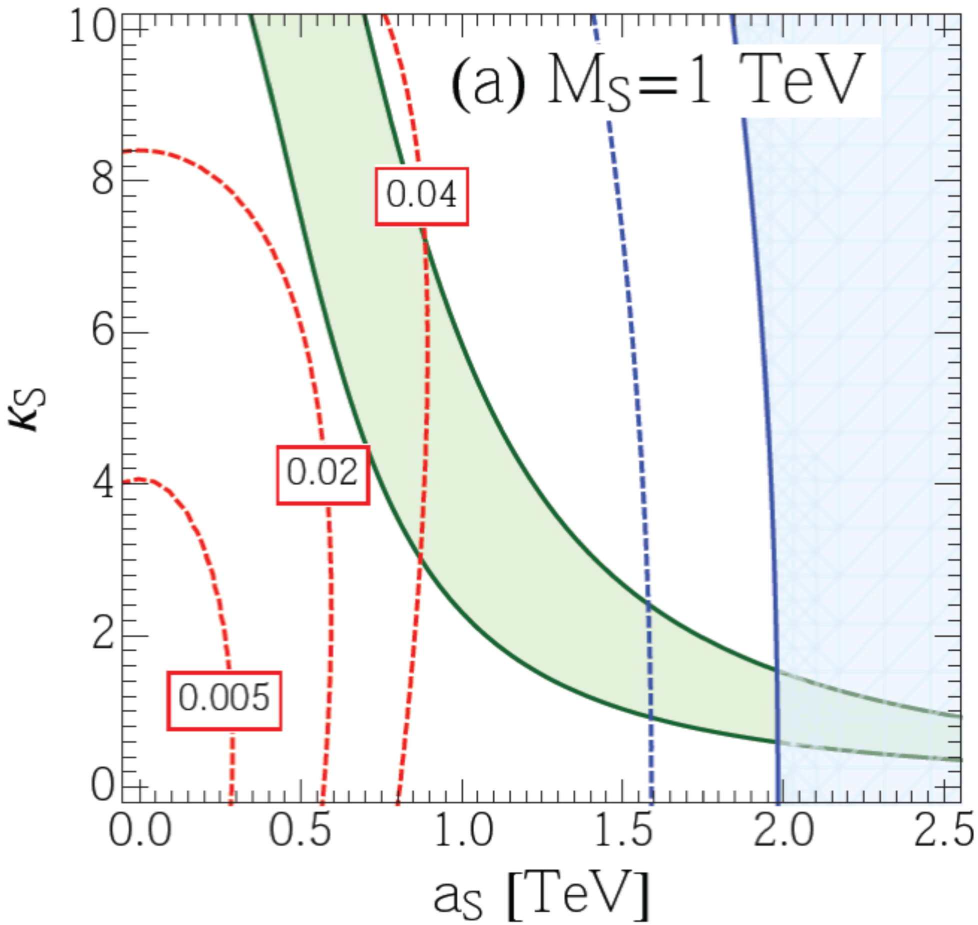
Dimension-six operator	Wilson coefficient
$\mathcal{O}_{WW} = g^2\|H\|^2 W^a_{\mu\nu}W^{a,\mu\nu}$	$c_{WW} = \frac{1}{(4\pi)^2}\frac{1}{48}(2\lambda_1+\lambda_2)\frac{1}{M_\Phi^2}$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	$c_{2W} = \frac{1}{(4\pi)^2}\frac{g^2}{60}\frac{1}{M_\Phi^2}$
$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon^{abc}W^{a\mu}_\rho W^{b\nu}_\mu W^{c\rho}_\nu$	$c_{3W} = \frac{1}{(4\pi)^2}\frac{g^2}{60}\frac{1}{M_\Phi^2}$
$\mathcal{O}_{BB} = g'^2\|H\|^2 B_{\mu\nu}B^{\mu\nu}$	$c_{BB} = \frac{1}{(4\pi)^2}\frac{1}{48}(2\lambda_1+\lambda_2)\frac{1}{M_\Phi^2}$
$\mathcal{O}_{WB} = gg' H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$	$c_{WB} = \frac{1}{(4\pi)^2}\frac{\lambda_2}{24}\frac{1}{M_\Phi^2}$
$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B^{\mu\nu})^2$	$c_{2B} = \frac{1}{(4\pi)^2}\frac{g'^2}{60}\frac{1}{M_\Phi^2}$
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu\|H\|^2)^2$	$c_H = \frac{1}{(4\pi)^2}[6\eta_\Phi\eta_H + \frac{1}{12}(4\lambda_1^2+4\lambda_1\lambda_2+\lambda_2^2+4\lambda_3^2)]\frac{1}{M_\Phi^2}$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger\overleftrightarrow{D}_\mu H)^2$	$c_T = \frac{1}{(4\pi)^2}\frac{1}{12}(\lambda_2^2-4\lambda_3^2)\frac{1}{M_\Phi^2}$
$\mathcal{O}_r = \|H\|^2\|D_\mu H\|^2$	$c_r = \frac{1}{(4\pi)^2}(6\eta_\Phi\eta_H + \frac{1}{6}(\lambda_2^2+4\lambda_3^2))\frac{1}{M_\Phi^2}$
$\mathcal{O}_6 = \|H\|^6$	$c_6 = \eta_H^2 + \frac{1}{(4\pi)^2}[\frac{3}{2}\lambda_\Phi\eta_H^2 + 6\eta_\Phi(\lambda_1+\lambda_2) - \frac{1}{6}(2\lambda_1^3+3\lambda_1^2\lambda_2+3\lambda_1\lambda_2^2+\lambda_2^3) - 2(\lambda_1+\lambda_2)\lambda_3^2]\frac{1}{M_\Phi^2}$



The parameter space of doublet model that compatible with FOPT and current experiments including the future CEPC's prediction with fixed $M_\Phi = 1\ \text{TeV}$

Singlet model

$$\delta\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{M_S^2}{2}S^2 - \frac{\mu_S}{3!}S^3 - \frac{\lambda_S}{4!}S^4 - \frac{\kappa_S}{2}S^2|H|^2 - a_S S|H|^2$$



$$\mathcal{L}_{\text{eff}} \supset \Big(-\frac{\kappa_S a_S^2}{2M_S^4} - \frac{1}{(4\pi)^2}\frac{\kappa_S^3}{12M_S^2} + \frac{\mu_S a_S^3}{3!M_S^6}\Big)\mathcal{O}_6 + \Big(\frac{a_S^2}{M_S^4} + \frac{1}{(4\pi)^2}\frac{\kappa_S^2}{12M_S^2}\Big)\mathcal{O}_H$$

II. Cosmological connection to EW baryogenesis with dynamical CP violation by CEPC and LISA

Current electric dipole moment (EDM) experiments put severe constraints on many baryogenesis models. For example, the ACME Collaboration's new result, i.e. $|d_e| < 1.1\times 10^{-29}$ cm · e at 90% C.L. (Nature vol.562,357,18th Oct.2018) , has ruled out a large portion of the CP violation parameter space for many baryogenesis models.

Large enough CP-violating source for successful EW baryogenesis

Strong tension in most cases

pretty small CP-violation to avoid strong EDM constraints

How to alleviate this tension for successful baryogenesis?

Question: How to *alleviate* the tension between sufficient CP violation for successful electroweak baryogenesis and strong constraints from current electric dipole moment measurements ?

Answer: Assume the CP violating coupling evolves with the universe. In the early universe, CP violation is large enough for successful baryogenesis. When the universe evolves to today, the CP violation becomes negligible !

Large enough CP-violating source in the early universe for successful EW baryogenesis

***alleviate* by assuming the CP-violating source is time dependent**

Dynamical/cosmological evolve

Negligible CP-violating source at current time to avoid strong EDM constraints

- I. Baldes, T. Konstandin and G. Servant, arXiv:1604.04526,
- I. Baldes, T. Konstandin and G. Servant, JHEP 1612, 073 (2016)
- S. Bruggisser, T. Konstandin and G. Servant, JCAP 1711, no. 11, 034 (2017)
- S. Bruggisser, B. Von Harling, O. Matsedonskyi and G. Servant, arXiv:1803.08546

First, we study the following case as a representative example:see Zhuoni Qian's talk for more details at CEPC.

arXiv:1804.06813, Phys.Rev. D98 (2018) no.1, 015014
(**FPH**, Zhuoni Qian, Mengchao Zhang)

$$\mathcal{L}_{\rm SM} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + {\rm H.c} + \frac{1}{2}\partial_\mu {\rm S} \partial^\mu {\rm S} + \frac{1}{2}\mu^2 {\rm S}^2 - \frac{1}{4}\lambda {\rm S}^4 - \frac{1}{2}\kappa {\rm S}^2 (\Phi^\dagger \Phi)$$

$\eta = a + ib$

The singlet and the dim-5 operator can come from many types composite Higgs models arXiv:0902.1483 , arXiv:1703.10624 ,arXiv:1704.08911,

Firstly, a second-order phase transition happens, the scalar field S acquire a vacuum exception value (VEV) and the dim-5 operator generates a sizable CP-violating Yukawa coupling for successful baryogenesis.

Secondly, SFOPT occurs when vacuum transits from (0,<S>) to (<Φ>,0).

1. During the SFOPT, detectable GW can be produced.

2. After the SFOPT, the VEV of S vanishes at tree-level which avoids the strong EDM constraints, and produces abundant collider phenomenology at the LHC and future lepton colliders, such as CEPC, ILC, FCC-ee.

J. R. Espinosa, B. Gripaios, T. Konstandin and F. Riva, JCAP **1201**, 012 (2012)

J. M. Cline and K. Kainulainen, JCAP **1301**, 012 (2013)

Second, we study a renormalizable model to achieve dynamical CP violation for the successful EW baryogenesis and g-2 discrepancy originating from the same coupling.

work in progress with Eibun Senaha

A model of BAU and $(g-2)_\mu$: two 10^{-10} problems

$$V_0(\Phi,\eta) = \mu_1^2\Phi^\dagger\Phi + \mu_2^2\eta^\dagger\eta + \frac{\lambda_1}{2}(\Phi^\dagger\Phi)^2 + \frac{\lambda_2}{2}(\eta^\dagger\eta)^2 + \lambda_3(\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4(\Phi^\dagger\eta)(\eta^\dagger\Phi) + \left[\frac{\lambda_5}{2}(\Phi^\dagger\eta)^2 + \text{h.c}\right],$$

The new lepton Yukawa interaction is

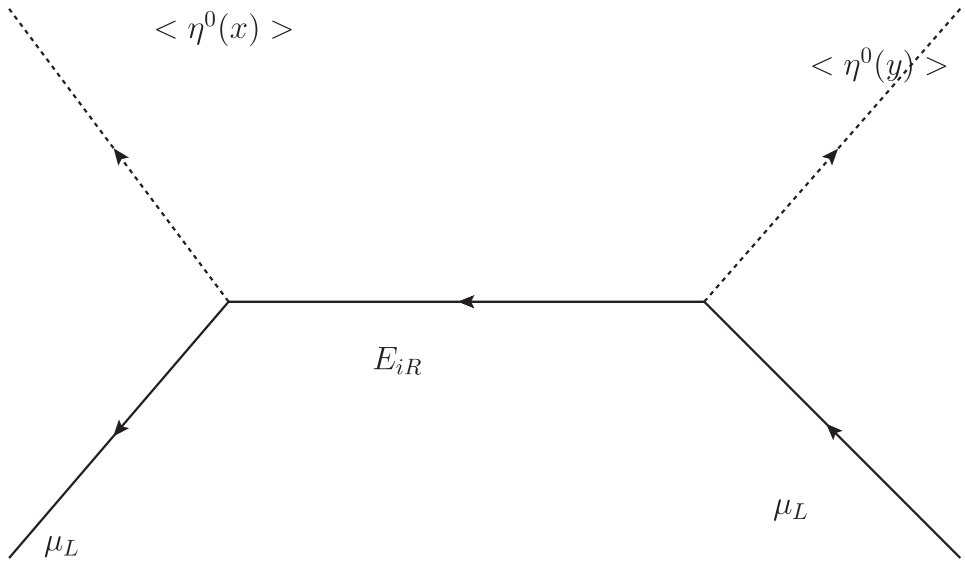
$$-\mathcal{L}_Y \ni y_{ij}\bar{\ell}_{iL}\eta E_{jR} + m_{E_i}\bar{E}_{iL}E_{iR} + \text{h.c.}$$

vector-like lepton (E_i)

Dynamical CP violation can be induced by phase transition process in the early universe.

In the early universe, for example, T=100 GeV, the new doublet scalar could have a complex VEV during the strong first-order phase transition in some parameter spaces, and then CP violating VEV is transferred to the baryon asymmetry production process through the new lepton Yukawa interaction with the following diagram.

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\varphi \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\varphi_1 \end{pmatrix}, \quad \langle\eta\rangle = e^{i\theta}\begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}\varphi_\eta \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(\varphi_2 + i\varphi_3) \end{pmatrix}$$



At late time, T=0, the CP violation disappears: $\varphi_1 = v,\ \varphi_2 = \varphi_3 = 0.$

Strong First-order EW phase transition

The daisy-improved 1-loop effective potential is

$$V_{\text{eff}}(\boldsymbol{\varphi}) = V_0(\boldsymbol{\varphi}) + V_1(\boldsymbol{\varphi};T) + V_{\text{daisy}}(\boldsymbol{\varphi};T), \tag{4.2}$$

where $\boldsymbol{\varphi} = \{\varphi_1, \varphi_2, \varphi_3\}$ and

$$\begin{aligned} V_0(\boldsymbol{\varphi}) &= \frac{1}{2}\mu_1^2\varphi_1^2 + \frac{1}{2}\mu_2^2(\varphi_2^2+\varphi_3^2) + \frac{\lambda_1}{8}\varphi_1^4 + \frac{\lambda_2}{8}(\varphi_2^2+\varphi_3^2)^2 + \frac{1}{4}(\lambda_3+\lambda_4)\varphi_1^2(\varphi_2^2+\varphi_3^2) \\ &\quad + \frac{1}{4}\Big[R_5\varphi_1^2(\varphi_2^2-\varphi_3^2) - 2I_5\varphi_1^2\varphi_2\varphi_3\Big] \\ V_1(\boldsymbol{\varphi};T) &= \sum_i n_i\left[V_{\text{CW}}(\bar{m}_i^2) + \frac{T^4}{2\pi^2}I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right)\right], \qquad (4.3) \\ V_{\text{daisy}}(\boldsymbol{\varphi};T) &= -\sum_{\substack{j=h,H,A,H^\pm,G^0,G^\pm,\\ W_L,Z_L,\gamma_L}} n_j\frac{T}{12\pi}\Big[(\bar{M}_j^2)^{3/2} - (\bar{m}_j^2)^{3/2}\Big], \qquad (4.4) \end{aligned}$$

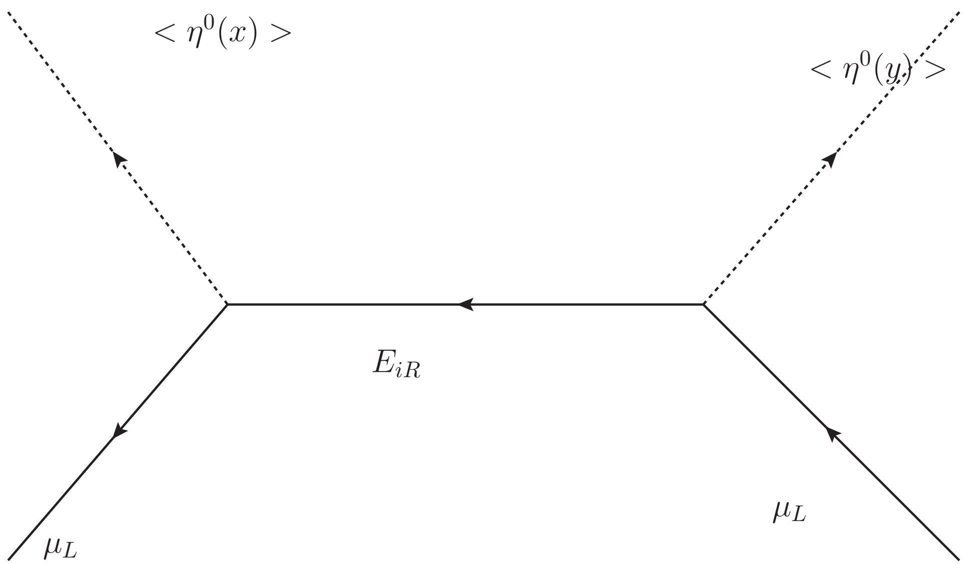
with $i = h, H, A, H^\pm, G^0, G^\pm, W, Z, t$ and $R_5 = \text{Re}(\lambda_5)$ and $I_5 = \text{Im}(\lambda_5)$. V_{CW} and $I_{B,F}(a^2)$ are defined by

CP-violating source term

Using the Closed-Time-Path (CTP) formalism, the CP-violating source of the SM lepton i induced by the vector-like lepton j may be cast into the form

$$S_{\ell_i}(X) = \frac{\left|y_{\ell_i E_j}\right|^2}{2} v_\eta^2(X)\dot{\theta}(X) H(m_i, \Gamma_i, m_j, \Gamma_j)$$

$$H(m_i, \Gamma_i, m_j, \Gamma_j) = \int_0^\infty \frac{dk\ k^2}{\pi^2} \frac{1}{\omega_i \omega_j} \mathrm{Im}\left[(-1 + n_i + n_j)\frac{\mathcal{E}_i \mathcal{E}_j + k^2}{(\mathcal{E}_i + \mathcal{E}_j)^2} + (-n_i^* + n_j)\frac{\mathcal{E}_i^* \mathcal{E}_j - k^2}{(\mathcal{E}_i^* - \mathcal{E}_j)^2}\right]$$



Diffusion equations

The relevant particle number densities are

$$Q_3 = n_{t_L} + n_{b_L}, \quad T = n_{t_R}, \quad B = n_{b_R},$$
$$L_2 = n_{\nu_{\mu_L}} + n_{\mu_L}, \quad E_R = n_{E_R},$$
$$H = n_{\Phi^+} + n_{\Phi^0} + n_{\eta^+} + n_{\eta^0}.$$

The set of Boltzmann equations is given by

$$\begin{aligned}
\partial_\mu j^\mu_{Q_3} &= -\Gamma_{Y_t}(\xi_{Q_3} + \xi_H - \xi_T) + \Gamma_{M_t}(\xi_T - \xi_{Q_3}) - 2\Gamma_{ss} N_5, \\
\partial_\mu j^\mu_T &= \Gamma_{Y_t}(\xi_{Q_3} + \xi_H - \xi_T) - \Gamma_{M_t}(\xi_T - \xi_{Q_3}) + \Gamma_{ss} N_5, \\
\partial_\mu j^\mu_{L_2} &= -\Gamma_{Y_{\mu E}}(\xi_{L_2} - \xi_H - \xi_R) + \Gamma^+_{M_{\mu E}}(\xi_{R_2} + \xi_{L_2}) + \Gamma^-_{M_{\mu E}}(\xi_{R_2} - \xi_{L_2}) + S_{\mu_L}, \\
\partial_\mu j^\mu_{E_R} &= \Gamma_{Y_{\mu E}}(\xi_{L_2} - \xi_H - \xi_R) - \Gamma^+_{M_{\mu E}}(\xi_{R_2} + \xi_{L_2}) - \Gamma^-_{M_{\mu E}}(\xi_{R_2} - \xi_{L_2}) - S_{\mu_L}, \\
\partial_\mu j^\mu_H &= \Gamma_{Y_t}(\xi_{Q_3} + \xi_H - \xi_T) + \Gamma_{Y_{\mu E}}(\xi_{L_2} - \xi_H - \xi_R) - \Gamma_H \xi_H,
\end{aligned}$$

CP-conserving source term

$$\Gamma_{\ell_i}(X) = \Gamma^+_{\ell_i}(X)(\mu_{E_j} + \mu_{\ell_i}) + \Gamma^-_{\ell_i}(X)(\mu_{E_j} - \mu_{\ell_i})$$

$$\Gamma^\pm_{\ell_i}(X) = \frac{|y_{\ell_i E_j}|^2}{2T} v_\eta^2(X) \int_0^\infty \frac{dk\ k^2}{2\pi^2} \frac{1}{\omega_i \omega_j} \mathrm{Im}\left[(\tilde{n}_j \mp \tilde{n}_i) \frac{\mathcal{E}_j \mathcal{E}_i + k^2}{\mathcal{E}_j + \mathcal{E}_i} + (\tilde{n}_j \mp \tilde{n}_i^*) \frac{\mathcal{E}_j \mathcal{E}_i^* - k^2}{\mathcal{E}_j - \mathcal{E}_i^*} \right]$$

g-2 and dark matter phenomenology

$$\delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}.$$

$$a_\mu^{(1)} \simeq \frac{1}{32\pi^2}\frac{m_\mu^2}{2M^2}|y_{\mu E_i}|^2 = (1.77 \times 10^{-9}) \left(\frac{100\ \rm GeV}{M}\right)^2 \left|\frac{y_{\mu E_i}}{1.0}\right|^2$$

If the mass of DM ($X = H/A$) is less than m_W, the main annihilation cross sections are

$$(\sigma v_{\rm rel})_{XX\to h\to f\bar{f}} = N_C^f \frac{m_f^2}{16\pi v^2}\lambda_{hXX}^2 \frac{\beta_f^3}{(s-m_h^2)^2 + m_h^2\Gamma_h^2} + \mathcal{O}(v_{\rm rel}^2),$$

$$(\sigma v_{\rm rel})_{XX\to E_k\to \ell_i\bar{\ell}_j} = \frac{|y_{\ell_i E_k} y^*_{\ell_j E_k}|^2}{60\pi m_X^2}\frac{v_{\rm rel}^4}{(1+r_{E_k})^4} + \mathcal{O}(v_{\rm rel}^6),$$

Baryon number density

$$D_Q n_B''(\bar{z}) - v_w n_B'(\bar{z}) - \theta(-\bar{z})\mathcal{R} n_B(\bar{z}) = \theta(-\bar{z})\frac{N_g}{2}\Gamma_B^{(\mathrm{sym})} n_L(\bar{z})$$

	μ-EWBG	τ-EWBG	$\mu\tau$-EWBG
Y_B	$\circ$	$\circ$	$\circ$
$(g-2)_\mu$	$\delta a_\mu \simeq 10^{-9}$	$\times$	$\delta a_\mu \simeq 10^{-9}$
$Z \to \ell\ell$	$\mathcal{B}(Z \to \mu^+\mu^-) \simeq 10^{-6}$	$\mathcal{B}(Z \to \tau^+\tau^-) \simeq 10^{-6}$	$\mathcal{B}(Z \to \mu^+\mu^-, \tau^+\tau^-, \mu^\pm\tau^\mp) \simeq 10^{-6}$
$\tau \to \mu\gamma$	$\times$	$\times$	$\mathcal{B}(\tau \to \mu\gamma) \simeq$
$\mu_{\gamma\gamma}$	0.9	0.9	0.9
$\kappa_{3h} = \lambda_{3h}/\lambda_{3h}^{\mathrm{SM}}$	$\gtrsim 1.2$	$\gtrsim 1.2$	$\gtrsim 1.2$
$\Omega_{\mathrm{DM}} h^2$	$\circ$	$\circ$	$\circ$

The CEPC can help to test this scenario by precisely measure the Higgs self coupling, Z decay mode and LISA can measure the phase transition gravitational waves.

Dynamical CP-violation from inflation is also under study.

III.Cosmological connection to DM by GW&CEPC

Motivated by the absence of DM signal in DM direct detection (such as the LUX, PandaX-II, XENON1T), a generic classes of scalar DM models have been pushed to the blind spots where dark matter-Higgs coupling is very small.

We use the complementary searches via phase transition GW and the future lepton collider signatures to un-blind the blind DM spots.

Inert Doublet Models

$$V_0 = M_D^2 D^\dagger D + \lambda_D (D^\dagger D)^2 + \lambda_3 \Phi^\dagger \Phi D^\dagger D \\ + \lambda_4 |\Phi^\dagger D|^2 + (\lambda_5/2)[(\Phi^\dagger D)^2 + h.c.],$$

provide natural DM candidate

provide SFOPT and phase transition GW

arXiv:1510.08069,N. Blinov, J. Kozaczuk, D. E. Morrissey, A. de la Puente

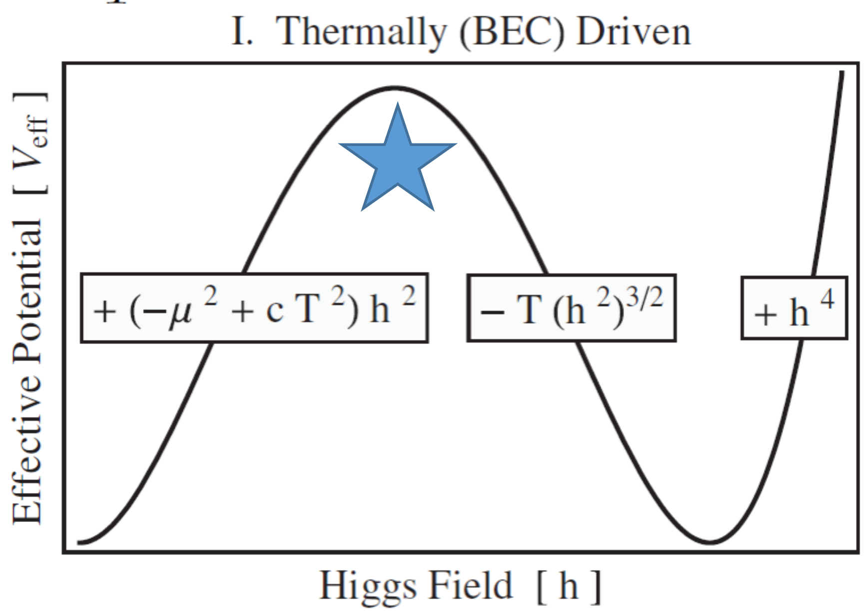
FPH, Jiang-hao Yu, arXiv: 1704.04201

One-loop finite temperature effective potential

$$V_{\rm eff}(h,T) \approx \frac{1}{2}\left(-\mu^2 + cT^2\right)h^2 + \frac{\lambda}{4}h^4 - \frac{T}{12\pi}\Sigma n_b (m_b^2(h,T))^{3/2} - \Sigma n_b \frac{m_b^4(h,T)}{64\pi^2}[log\frac{m_b^2(h,T)}{T^2} - 5.408] - n_t\frac{m_f^4(h)}{64\pi^2}[log\frac{m_f^2(h)}{T^2} - 2.635]$$

$$\begin{aligned} m_h^2(h,T) &= m_\pi^2 \approx 3\lambda h^2 - \mu^2 + c_1 T^2, \\ m_H^2(h,T) &\approx \frac{1}{2}(\lambda_3+\lambda_4+\lambda_5)h^2 + M_D^2 + c_2T^2, \\ m_A^2(h,T) &\approx \frac{1}{2}(\lambda_3+\lambda_4-\lambda_5)h^2 + M_D^2 + c_2T^2, \\ m_{H^\pm}^2(h,T) &\approx \frac{1}{2}\lambda_3 h^2 + M_D^2 + c_2T^2, \end{aligned}$$

EW phase transition type in inert doublet model



The two-loop finite temperature effective potential slightly weaken the strength of the phase transition. **arXiv:1702.07479, arXiv:1811.00336,**

DM and FOPT favor Higgs funnel region

$$\sigma_{\rm SI} \simeq f_N^2 \frac{\lambda_{h\chi\chi}^2}{\pi} \left(\frac{m_N^2}{m_\chi m_h^2} \right)^2$$

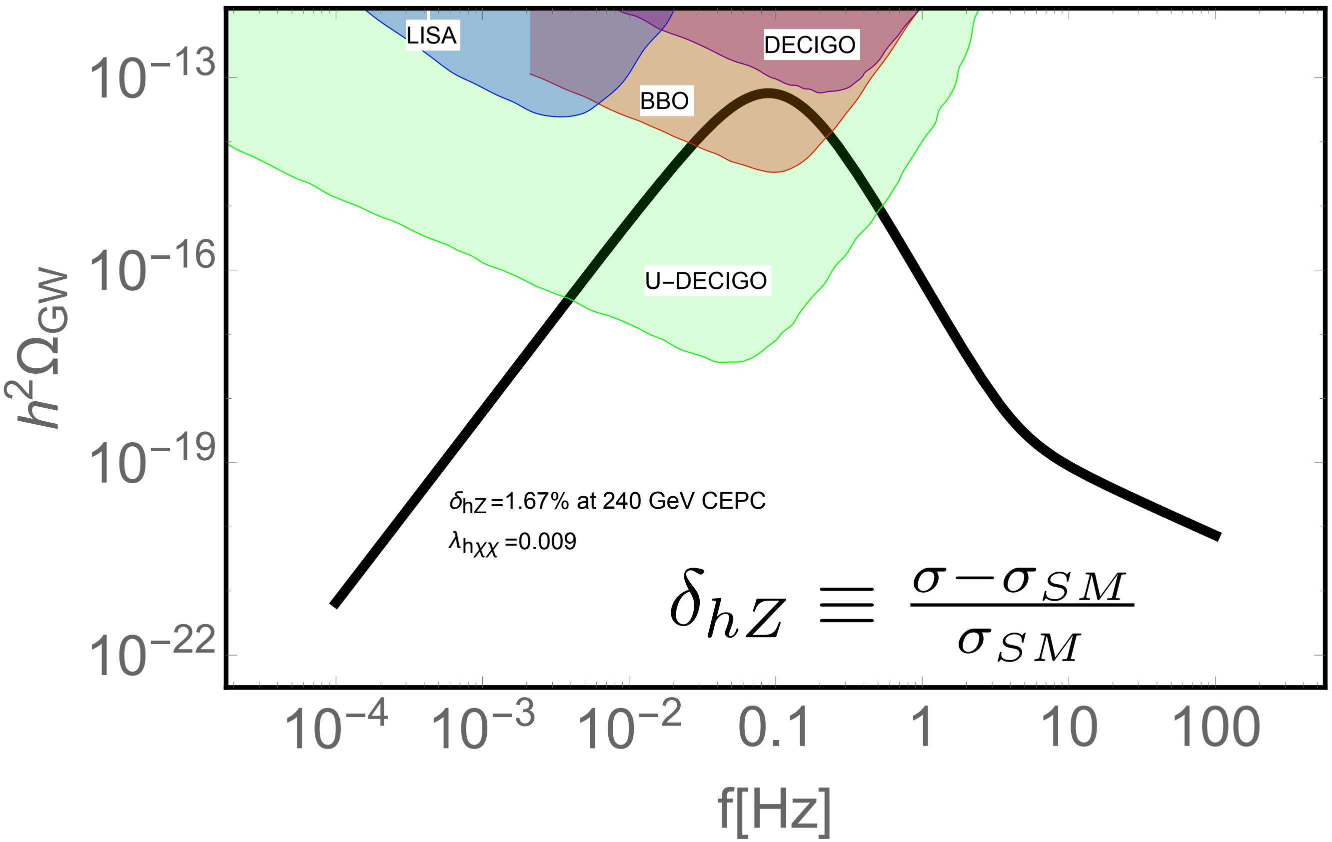
Higgs funnel region: the DM mass is about half of the Higgs mass

Considering the above discussion, we take one set of benchmark points $\lambda_3 = 2.84726$, $\lambda_4 = \lambda_5 = -1.41463$ and $M_D = 59.6$ GeV. Then, the corresponding DM mass is 64 GeV, the pseudo scalar mass and the charged scalar mass are both 299.6 GeV, $\lambda_{h\chi\chi} = \lambda_{345}/2 = 0.009$.

$$\lambda_{h\chi\chi} = (\lambda_3 + \lambda_4 + \lambda_5)/2 = \lambda_{345}/2$$

N.B.: Even though the Higgs-DM coupling are pretty small constrained from DM direct detection, the SFOPT can still be induced.

Correlate DM, particle collider and GW signals



- ➢ **GW and CEPC detectors can explore the blind spots of DM**
- ➢ **The study naturally bridges the particle physics at collider with GW and DM.**

We also study the mixed inert singlet-doublet and mixed inert singlet-triplet model in arXiv: 1704.04201 FPH, Jiang-hao Yu

Summary

- The correlation between GW and collider signals at CEPC can make a double test on the Higgs nature, DM, and baryogenesis.
- GW provides a novel way to explore cosmology, such as DM, baryogenesis…(More and more relevant experiments, LISA, SKA, FAST, Tianqin, Taiji…)

Two examples:

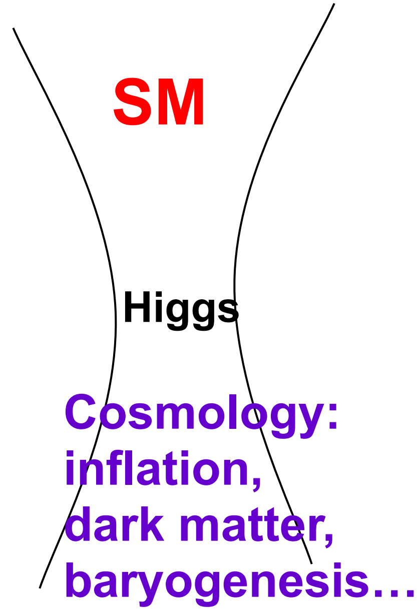
(1) Using aLIGO to probe extra dimension,

H. Yu, B. Gu, FPH, Y. Wang, X. Meng, Y. Liu. JCAP 1702 (2017) no.02, 039

(2) Using SKA to detect axion cold dark matter,

FPH, K. Kadota, T. Sekiguchi, H.Tashiro, Phys.Rev. D97 (2018) no.12, 123001

Outlook



Theoretical study?

Higgs as a portal to search for the new physics beyond the SM and the cosmology

$$+\mathcal{O}_{hidden} H^\dagger H$$

Experimental test! Crosscheck by

Higgs factory like CEPC

+ Gravitational Wave Detectors like LISA

(new experimental approach)

Thanks for your attention!