EW phase transition at colliders and its cosmological connections

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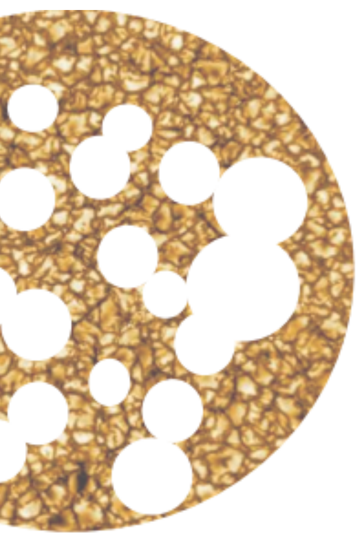
电弱相变与Higgs物理专题研讨会@IHEP
July 31th, 2020

Outline

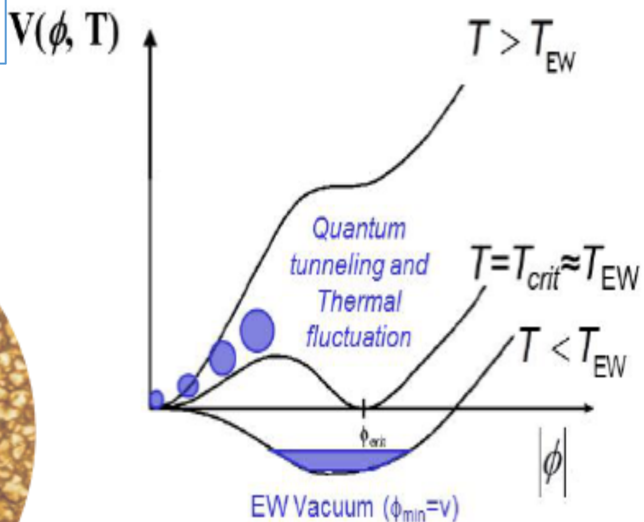
- **Electroweak (EW) phase transition dynamics and its cosmological implications**
- **Three concrete simple examples.**
- **Summary and outlook**

Strong First-order phase transition (SFOPT) in Higgs extended model motivated by baryogenesis, dark matter and new physics

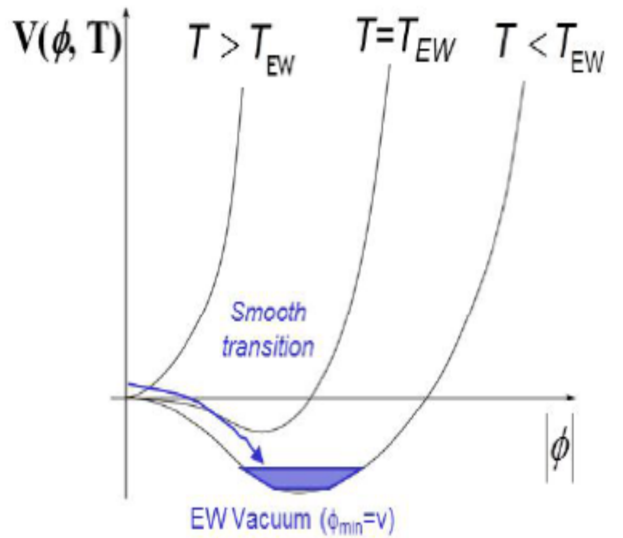
From lattice simulation



SFOPT for $m_H < 75$ GeV



Cross over for $m_H > 75$ GeV



of the Higgs sector is needed to SFOPT for 125 GeV Higgs boson.

We discuss well-motivated extensions (baryogenesis, dark matte…) of the Higgs section to realize SFOPT with abundant cosmological effects. EW phase transition and its GW signals becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.

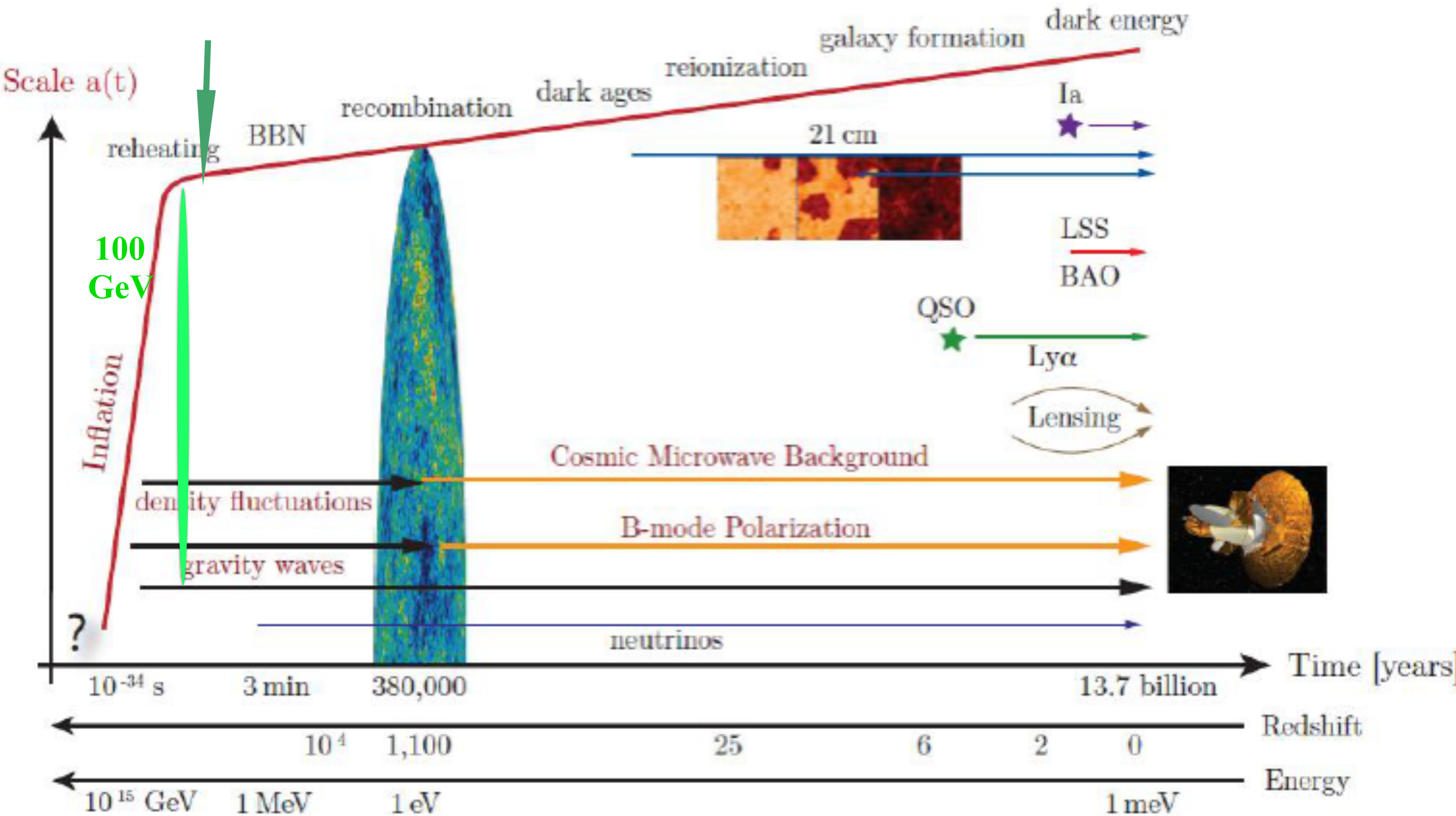
EW phase transition from particle to cosmology

- The true shape of Higgs potential and Higgs physics at colliders (Exp:CEPC/FCC-ee/LHC)
- Baryogenesis
- Gravitational wave (Exp:LISA,Tianqin/Taiji)
- new ideas of Dark Matter(DM):DM blind spots, Asymmetry DM, (Primordial black hole)PBH DM,Q-ball DM
- Primordial magnetic field
- Z-pole physics

For example, bubble in SFOPT can be the "filters" to packet your needed heavy dark matter.

1709.09691,FPH, C.S. Li
1912.04238,Dongjin Chway, Tae Hyun Jung, Chang Sub Shin
1912.0283 Michael J. Baker,Joachim Kopp,and Andrew J. Long

Study of EW phase physics at CEPC and LISA helps to explore the cosmic evolution history of the Universe at 100 GeV temperature.



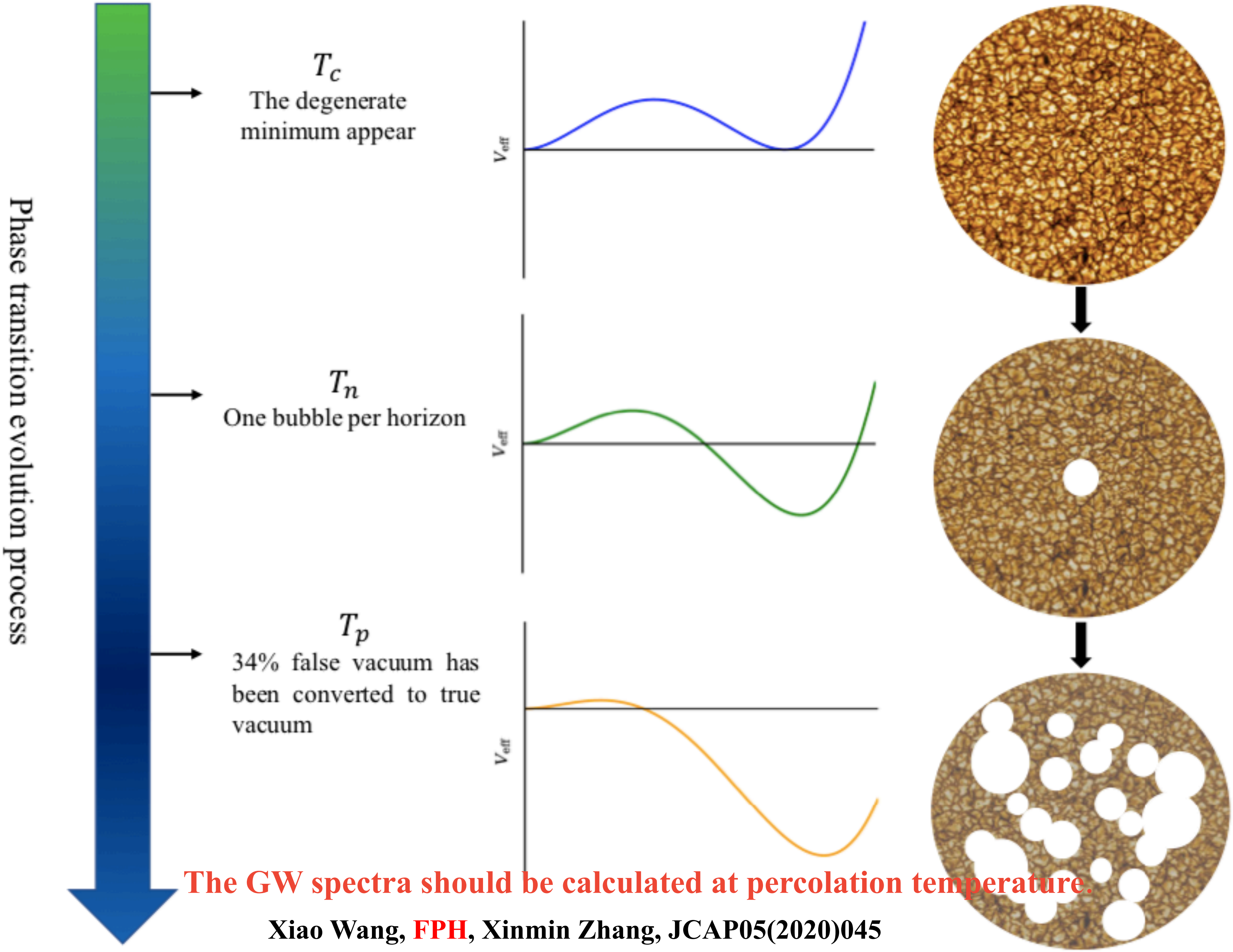
credit:D.Baumann

EW phase transition dynamics

To discuss the phase transition dynamics, we need to calculate the finite-temperature effective $V_{eff}(h,T)$ potential using the thermal field theory.

There are many difficult problems

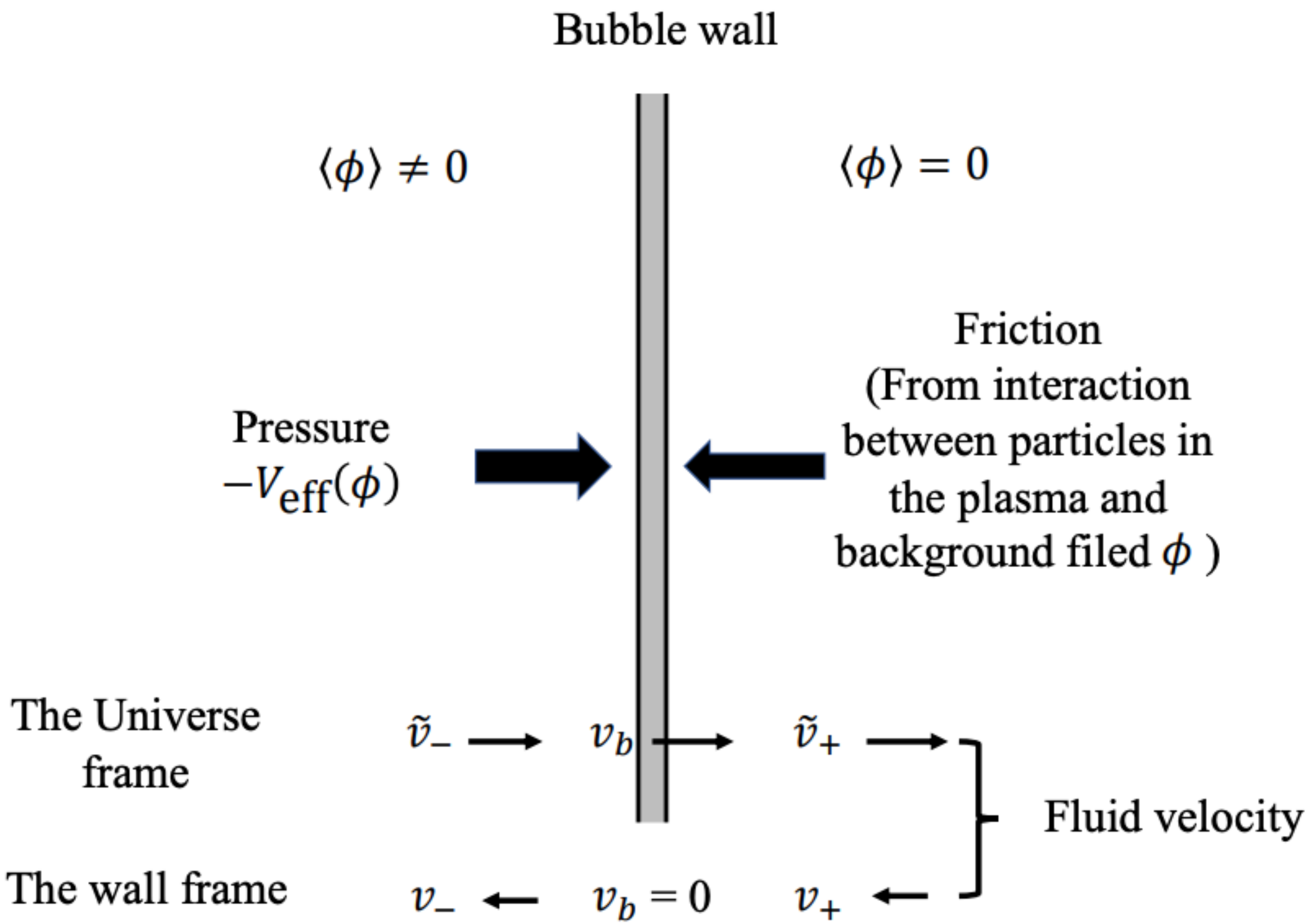
1. **Daisy resummation problem: Pawani scheme vs. Arnold scheme**
2. **Gauge dependence problem:See Michael J. Ramsey-Musolf's paper and talk**
3. **No perturbative calculations:lattice calculations and dim-reduction method recently by D. Weir,Michael J. Ramsey-Musolf et.al**
4. **Reliable calculations of bubble wall velocity:work in process with Xiao Wang and Xinmin**
5. **GW spectra prediction for ultra-supercooling**

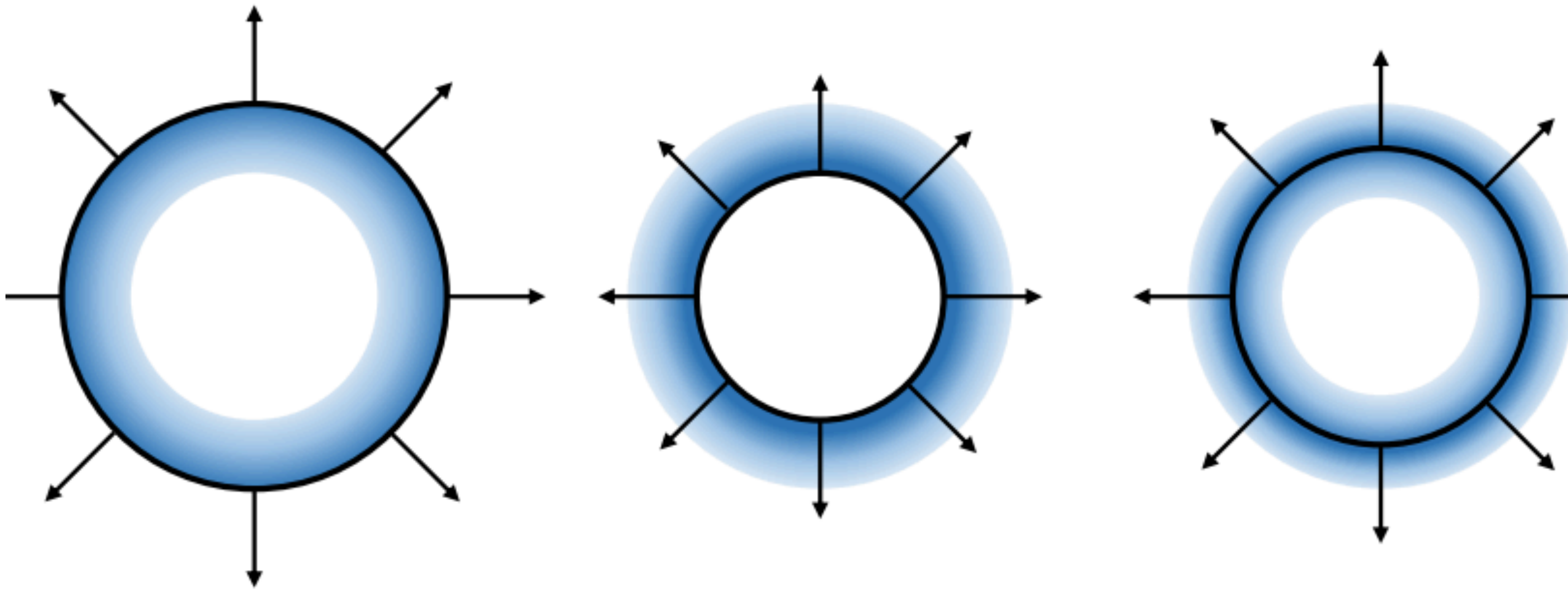


The GW spectra should be calculated at percolation temperature.

Xiao Wang, FPH, Xinmin Zhang, JCAP05(2020)045

Bubble wall velocity: stronger GW signals favor large bubble velocity, EW baryogengesis favor small bubble velocity.
New idea by James et.al. EW baryogensis with high bubble velocity





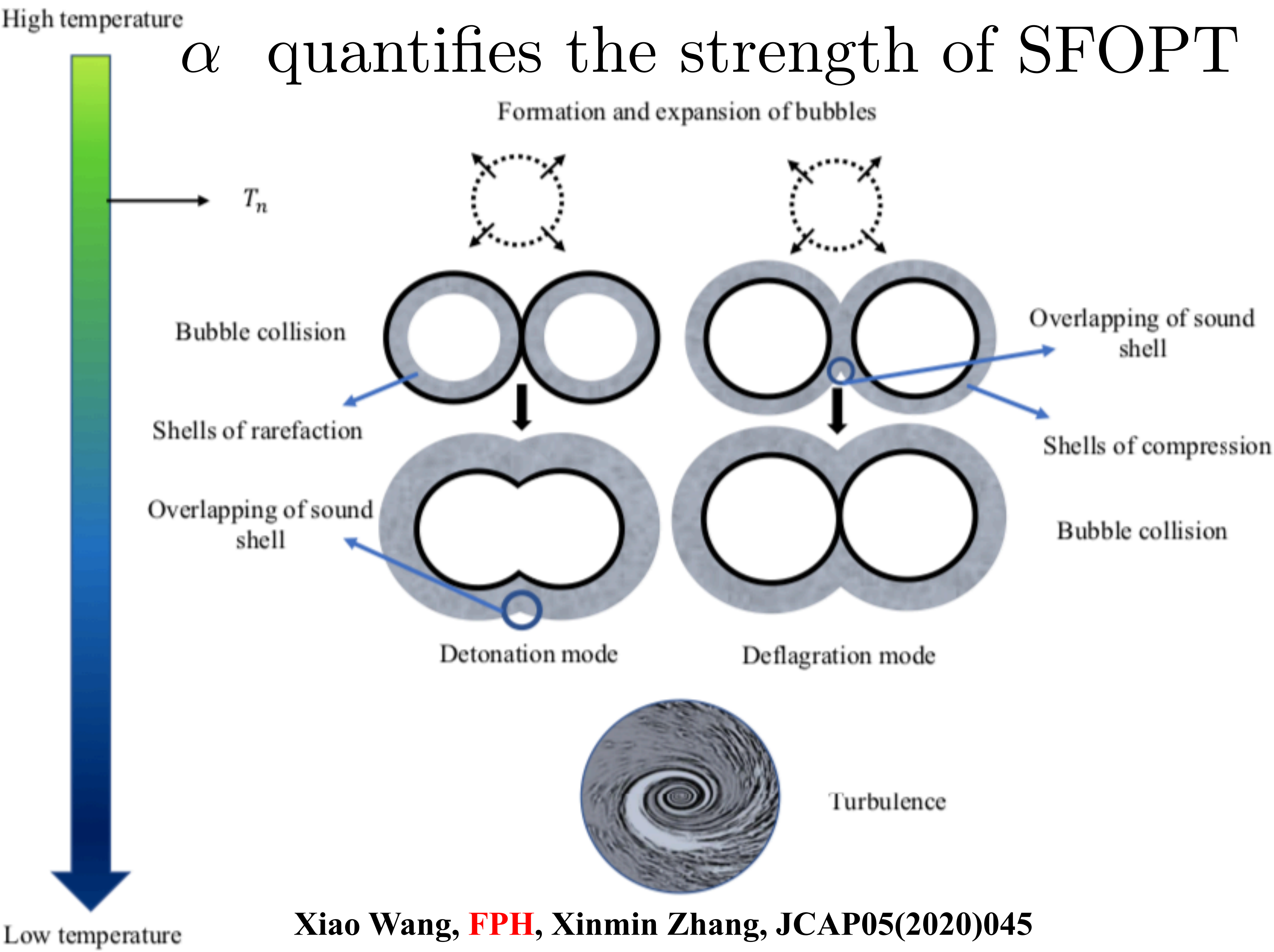
Detonation
$v_b > c_s$

Deflagration
$v_b < c_s$

Hybrid
$v_b > c_s$

Stronger GW signal favored **EW baryogengesis favored**

α quantifies the strength of SFOPT



Xiao Wang, FPH, Xinmin Zhang, JCAP05(2020)045

We have classified the SFOPT into four cases based on the properties of the phase transition strength:

1. Slight supercooling. It corresponds to $\alpha_p \leq 0.1$. In this case, α_n can be a good approximation to α_p since $\alpha_n - \alpha_p \ll 0.1$. For slight supercooling, the GW signal is too weak and difficult to be detected by LISA. The signal may be within the sensitivity of BBO and U-DECIGO.

2. Mild supercooling. It corresponds to $0.1 \leq \alpha_p \leq 0.5$. For mild supercooling, its GW signal is well within the expected sensitivity of LISA, Taiji, TianQin, DECIGO, BBO and U-DECIGO. The phase transition strength at the percolation temperature is larger than one at the nucleation temperature.

3. Strong supercooling. It corresponds to $0.5 \leq \alpha_p \leq 1.0$. For strong supercooling, the phase transition GW is more stronger than the mild supercooling, and can be detected by LISA, Taiji, TianQin, DECIGO, BBO and U-DECIGO. And, the phase transition strength at the percolation temperature is obviously larger than the values at the nucleation temperature.

4. Ultra supercooling. It corresponds to $\alpha_p \geq 1$. For ultra supercooling, its GW signal is even stronger and more easy to be detected by LISA, Taiji, TianQin, DECIGO, BBO and U-DECIGO. The hierarchy of phase transition strength derived from the nucleation and the percolation temperature becomes more significant.

Xiao Wang, FPH, Xinmin Zhang, JCAP05(2020)045

GW signals from SFOPT

Bubble collisions

$$h^2\Omega_{\rm co}(f) \simeq 1.67\times 10^{-5}(\frac{H_* R_*}{(8\pi)^{1/3}})^2\left(\frac{\kappa_\phi \alpha}{1+\alpha}\right)^2\left(\frac{100}{g_\star}\right)^{1/3}\frac{0.11 v_b}{0.42+v_b^2}\frac{3.8(f/f_{\rm co})^{2.8}}{1+2.8(f/f_{\rm co})^{3.8}}$$

Turbulence

$$h^2\Omega_{\rm turb}(f) \simeq 1.14\times 10^{-4} H_* R_*\left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*}\right)^{1/3}\frac{(f/f_{\rm turb})^3}{(1+f/f_{\rm turb})^{11/3}(1+8\pi f/H_*)}$$

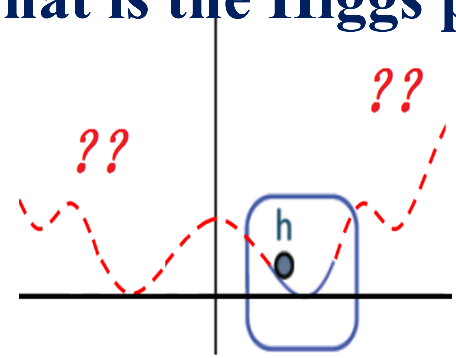
Sound wave

$$h^2\Omega_{\rm sw}(f) \simeq 1.64\times 10^{-6}(H_*\tau_{\rm sw})(H_* R_*)\left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}(f/f_{\rm sw})^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

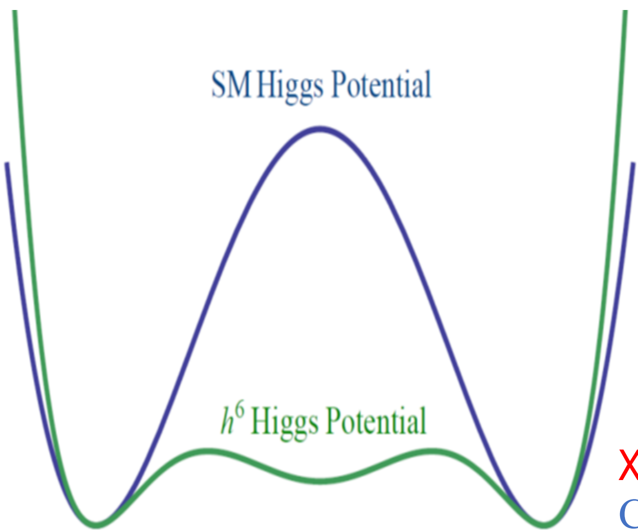
E. Witten, Phys. Rev. D 30, 272 (1984)
C. J. Hogan, Phys. Lett. B 133, 172 (1983);
M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994))Mark Hindmarsh, *et al.*, PRL 112, 041301 (2014); Lots of unlisted papers.

I. Benchmark scenario in SM EFT

What is the Higgs potential?



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

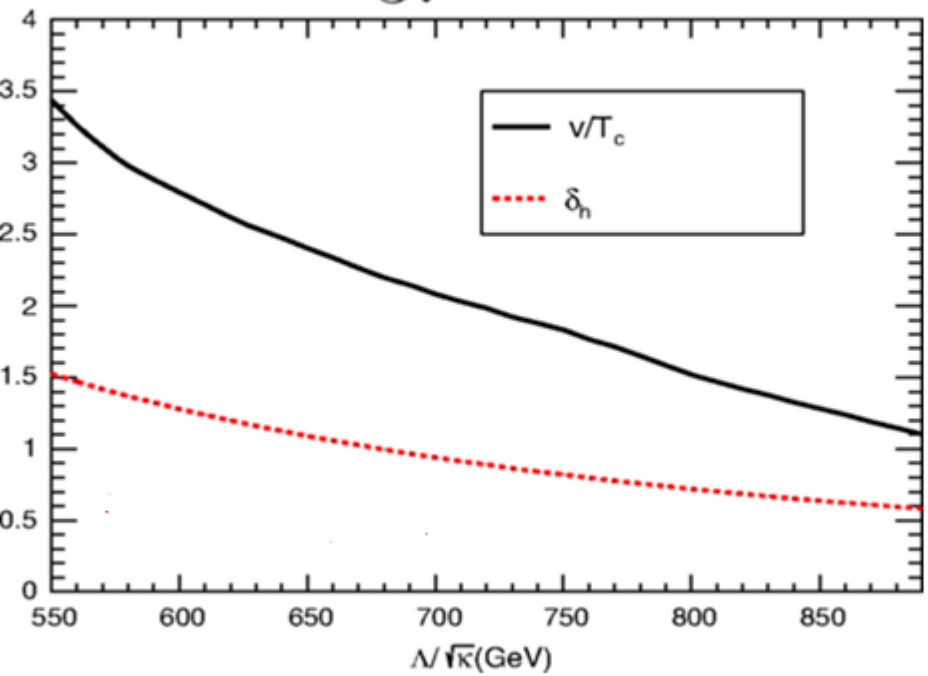
Produce a SFOPT

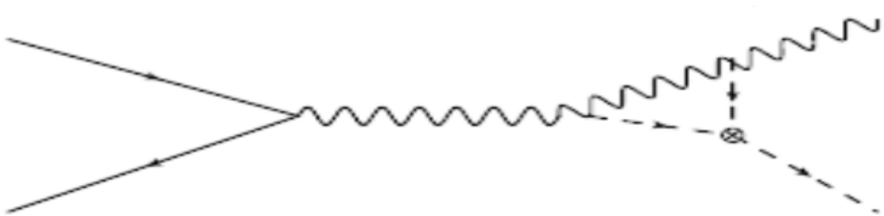
Xinmin Zhang Phys.Rev. D47 (1993) 3065-3067
C. Grojean, G. Servant, J. Well PRD71(2005)036001
D.J.H. Chung, A. J. Long, Lian-tao Wang Phys.Rev. D87(2013) 023509
FPH, et.al, Phys.Rev.D94(2016)no.4,041702 , Phys.Rev.D93 (2016) no.10,103515

arXiv:1511.06495 Nima Arkani-Hamed, Tao Han, Michelangelo Mangano, Lian-Tao Wang
PreCDR of CEPC arXiv: 1811.10545 CDR of CEPC

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

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





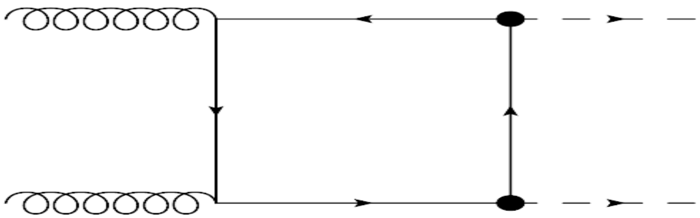
At one-loop level, deviation of the tri-linear Higgs coupling

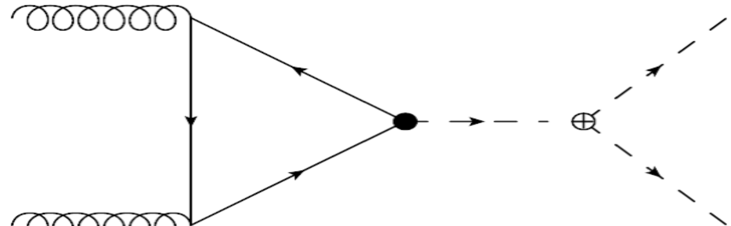
$$\boldsymbol{\delta_h \in (0.6, 1.5)}$$

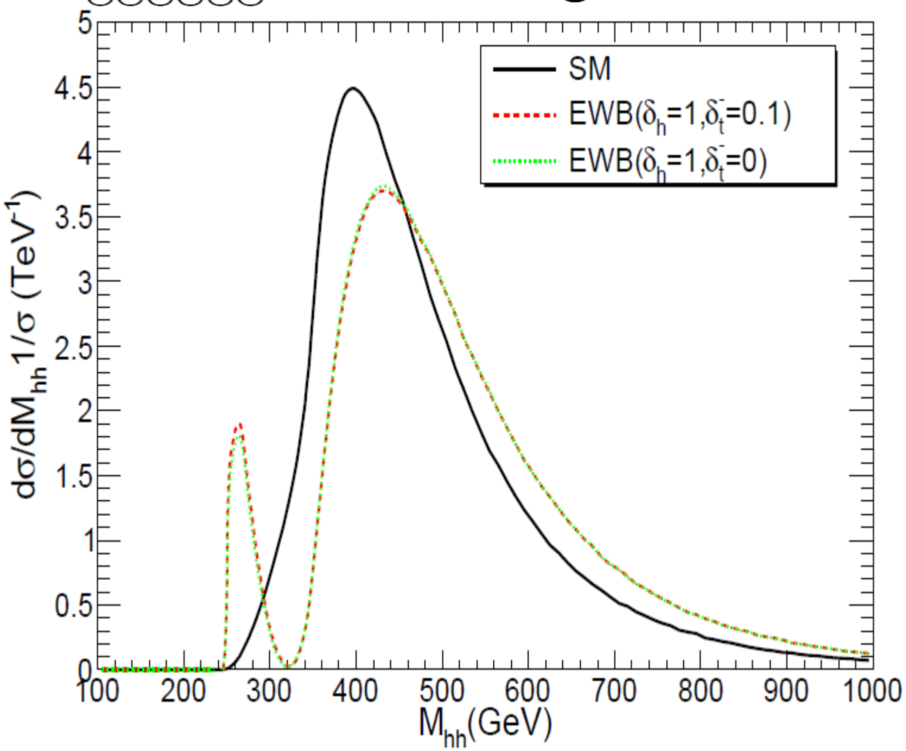
The Circular Electron Positron Collider (CEPC), ILC, FCC-ee can precisely test this scenario by precise measurements of the hZ cross section ($e^- e^+ \longrightarrow hZ$).
SM NNLO hZ cross section recently by Lilin Yang, et al 2016, Yu Jia et at 2016

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

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

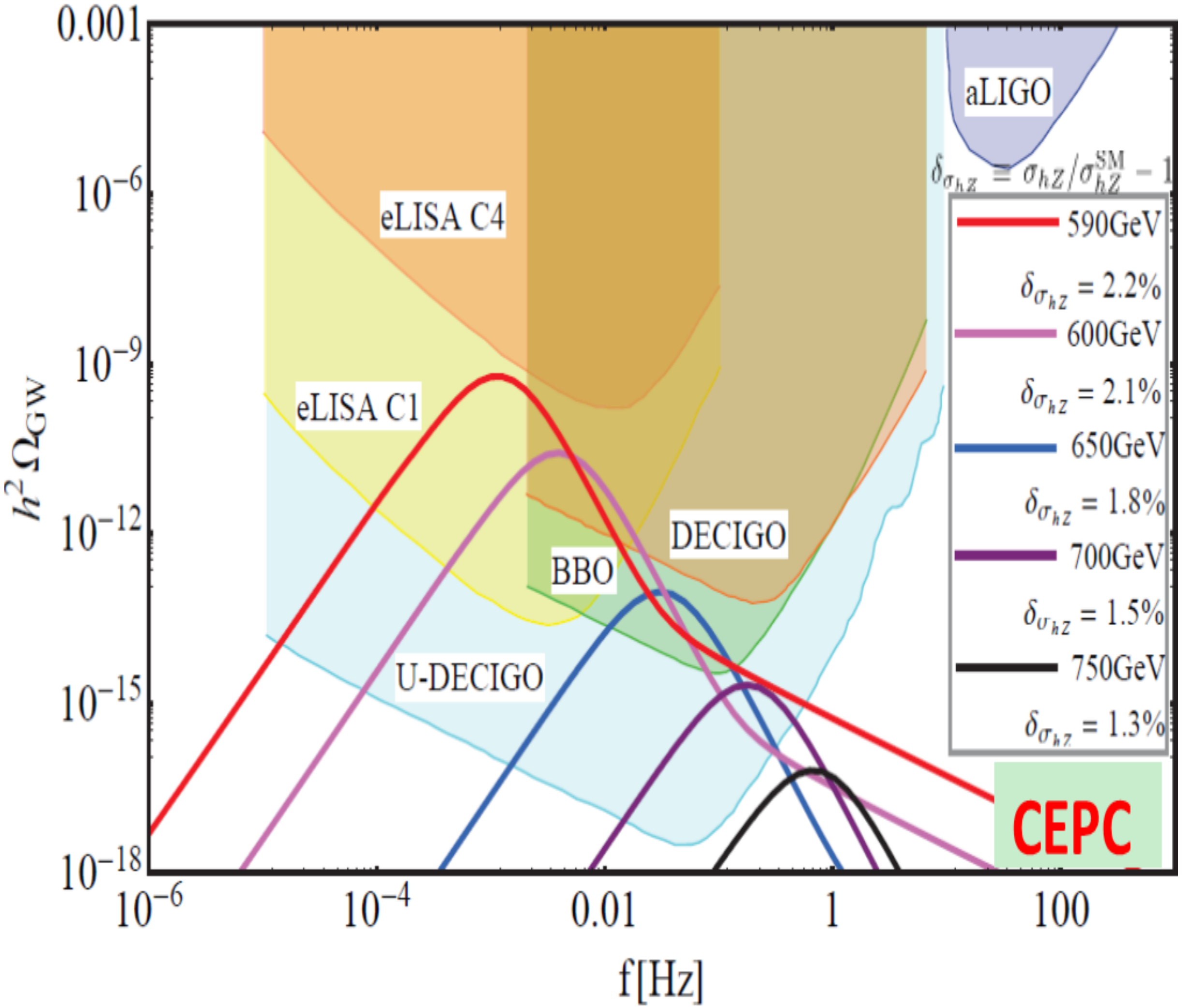






- **Two peaks for the baryogenesis scenario, one peak for the SM.**
- **Due to the difficulties to suppress backgrounds at the LHC, it will be difficult to completely pin down these anomalous coupling at 14 TeV LHC, even with 3000 ab^{-1} integrated luminosity.**
- **Exploiting boosted tricks helps to 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 .**

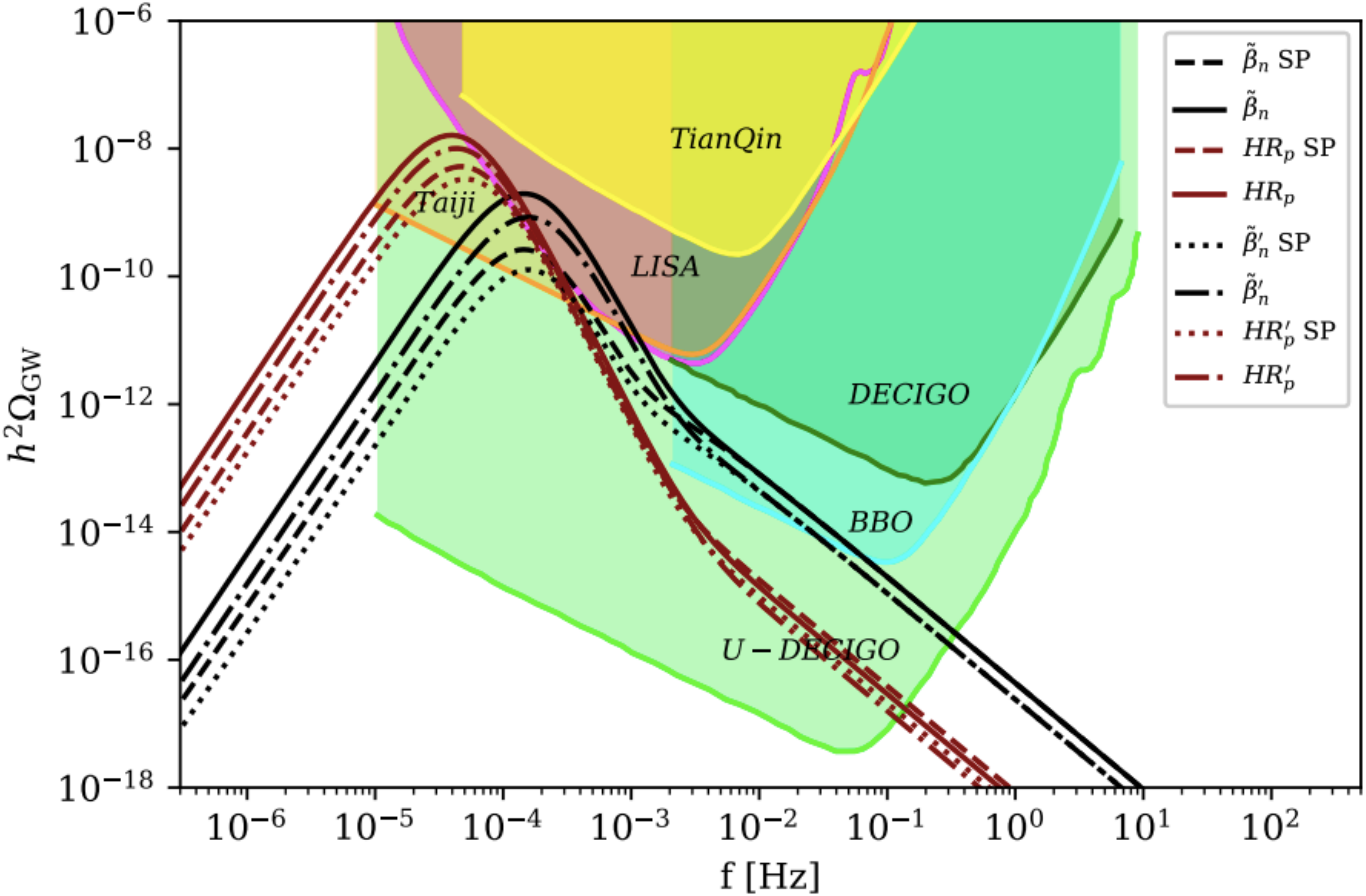
Correlate particle collider and GW signals: Double test on Higgs nature and baryogenesis from particle to wave



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

- **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**

GW spectra for ultra-supercooling case(585.254 GeV cutoff)



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

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.

$$\mathcal{L} \supset -\mu^2|H|^2 - \lambda|H|^4 + c_6|H|^6$$
$$+ c_T\mathcal{O}_T + c_{WW}\mathcal{O}_{WW} + \text{other dimension-six operators}$$

$$\delta_{\sigma(hZ)} \approx (0.26c_{WW} + 0.01c_{BB} + 0.04c_{WB} - 0.06c_H - 0.04c_T + 0.74c_L^{(3)\ell}$$
$$+0.28c_{LL}^{(3)\ell} + 1.03c_L^{\ell} - 0.76c_R^{e}) \times 1\ \text{TeV}^2 + \boxed{0.016\delta_h},$$

SFOPT produce large modification of tri-linear Higgs coupling δ_h

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

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

Renormalizable realization of Singlet model

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

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

Naive dimensional analysis (NDA) for composite Higgs

Usually, the SFOPT needs the Higgs portal coupling to be of order one, and the large Higgs portal coupling may give a hint of the composite nature of the Higgs boson. If the Higgs boson is a pseudo-Goldstone boson, from strong dynamics, the coefficients of dim-6 operators can be estimated by NDA. The coefficients of dominant CP-conserving operators, estimated from the NDA

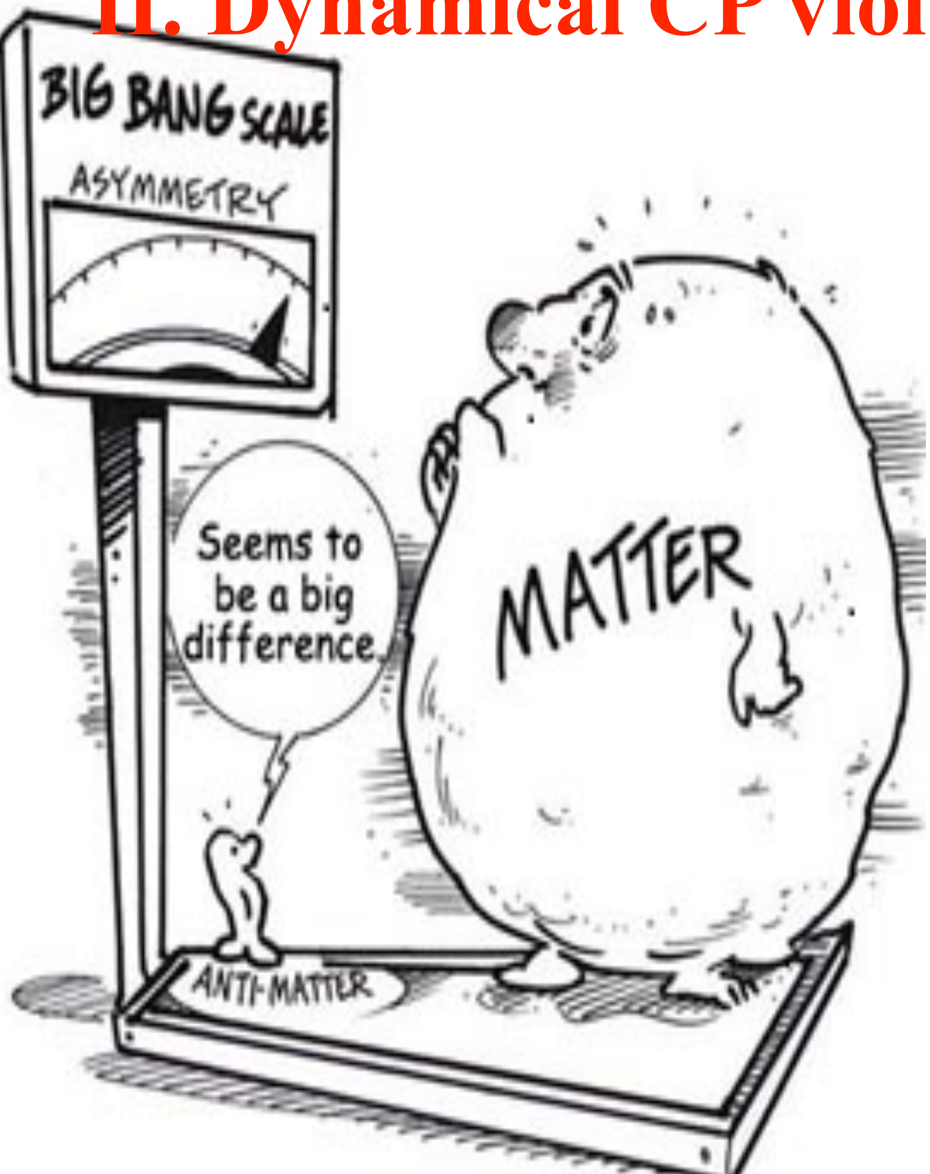
$$c_{WW} \sim c_{BB} \sim c_{WB} \sim 1/\Lambda^2 \sim 1/(4\pi f)^2$$

$$c_H \sim c_T \sim 1/f^2$$

$$c_6 \sim -\Lambda^2/f^4 = -1/(f/4\pi)^2.$$

The parameter space of all these given models are compatible with SFOPT and current experiments including the future CEPC's prediction. Qing-Hong Cao, FPH , Ke-Pan Xie, Xinmin Zhang
arXiv:1708.0473

II. Dynamical CP violation for baryogengesis



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

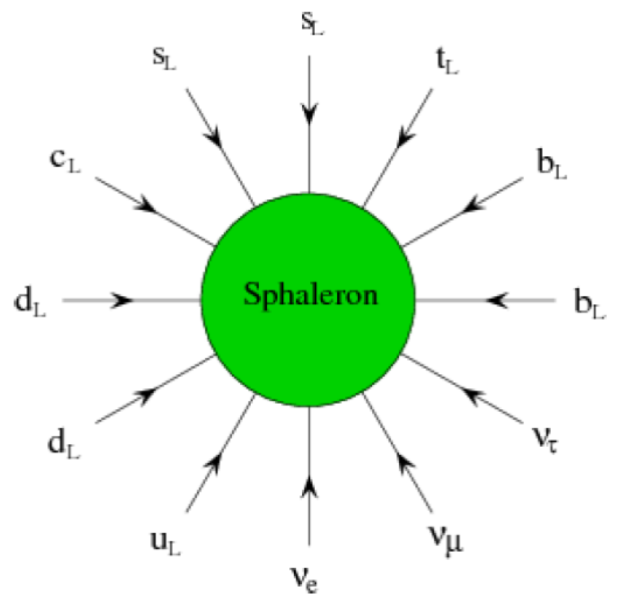
After the discovery of the Higgs boson by LHC and gravitational waves (GW) by aLIGO, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

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

II. Dynamical CP violation for baryogengesis

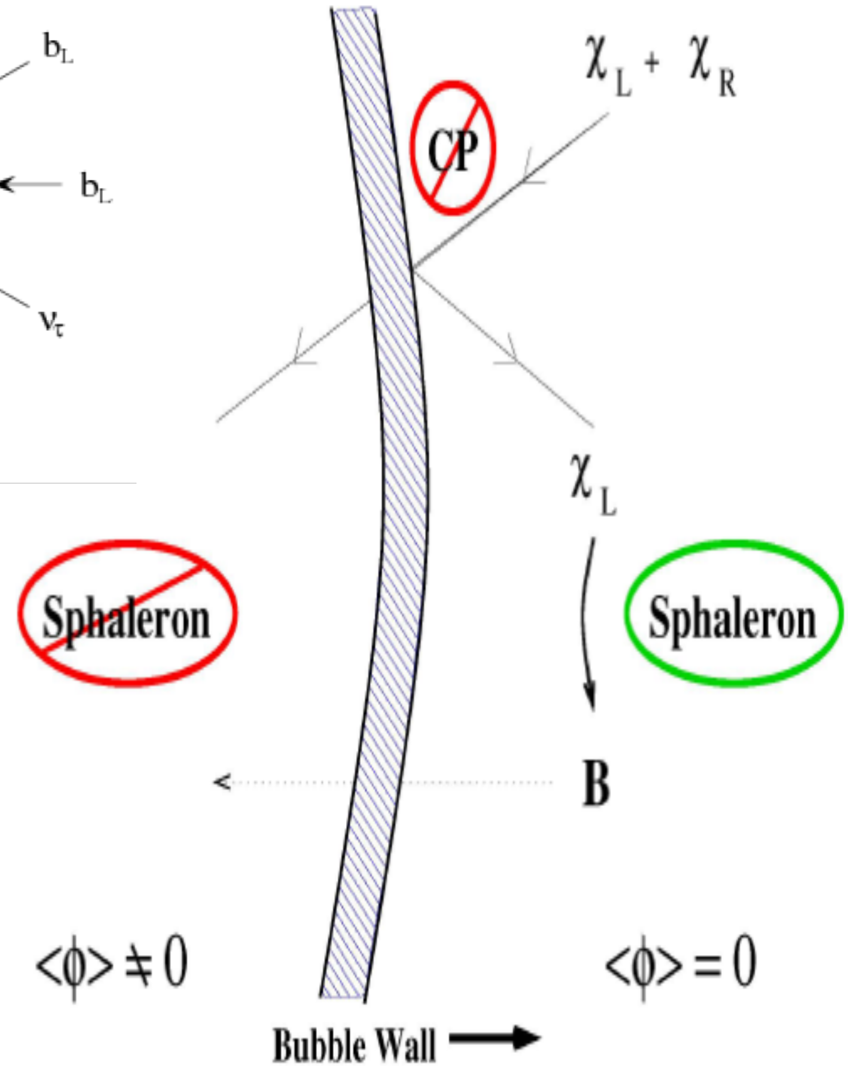
EW baryogenesis

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).



II. Dynamical CP violation for baryogengesis

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 EDM measurements ?

Answer: Dynamical CP-violating source

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

Effective field theory study: FPH, Zhuoni Qian, Mengchao Zhang, Phys.Rev. D98 (2018) no.1, 015014

FPH, Chong Sheng Li, Phys. Rev. D 92, 075014 (2015)

Renormalizble model:

Complex 2HDM: Xiao Wang, FPH, Xinmin Zhang, arXiv: 1909.02978

And work in progress with Eibun Senaha in a extended IDM model

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)

First, we study the following effective scenario as a representative example:

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

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

$\eta = a + ib$ **The singlet and the dim-5 operator can come from many types composite Higgs model, 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)

Benchmark points, which can give SFOPT and produce phase transition GW

Benchmark set	κ	m_S [GeV]	T_N [GeV]	α	$\tilde{\beta}$
I	2.00	115	106.6	0.035	107
II	2.00	135	113.6	0.04	120

After the first step of phase transition, S field obtains a VEV, and then the CP violating top quark Yukawa coupling is obtained. Thus, during the SFOPT, the top quark has a spatially varying complex mass

$$m_t(z) = \frac{y_t}{\sqrt{2}} H(z) \left(1 + (1+i)\frac{S(z)}{\Lambda}\right) \equiv |m_t(z)| e^{i\Theta(z)}$$

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 \tilde{v}_b g_* T} \int dz\, \mu_{B_L} f_{\rm sph}\, e^{-45\,\Gamma_{\rm sph}|z|/(4\tilde{v}_b)}$$

$$\tilde{v}_b(0.2) < v_b(0.5) < c_s(\sqrt{3}/3)$$

Particle phenomenology induced by CP-violating top loop

After the SM Higgs obtains a VEV v at the end of the phase transition, we have

$$\mathcal{L}_{Stt} = -\left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v}\right) S \left(a\bar{t}t + ib\bar{t}\gamma_5 t\right)$$

The one-loop effective operators can be induced by covariant derivative expansion method

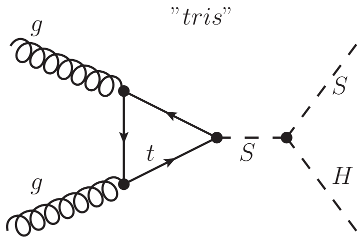
$$\begin{aligned}\mathcal{L}'_{SVV} &= \frac{a\alpha_S}{12\pi\Lambda} S G^a_{\mu\nu} G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} S G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \\ &+ \frac{2a\alpha_{EW}}{9\pi\Lambda} S F_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} S F_{\mu\nu} \tilde{F}^{\mu\nu}\end{aligned}$$

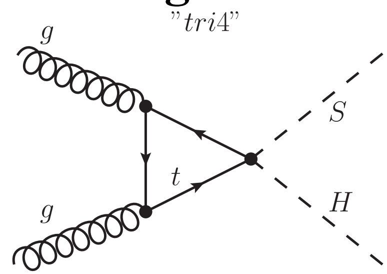
Mixing for H and S from one-loop contribution

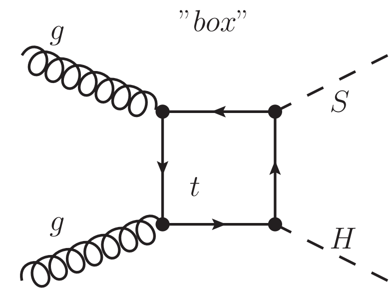
Abundant collider signals

Hadron collider:

$$pp \to HS$$



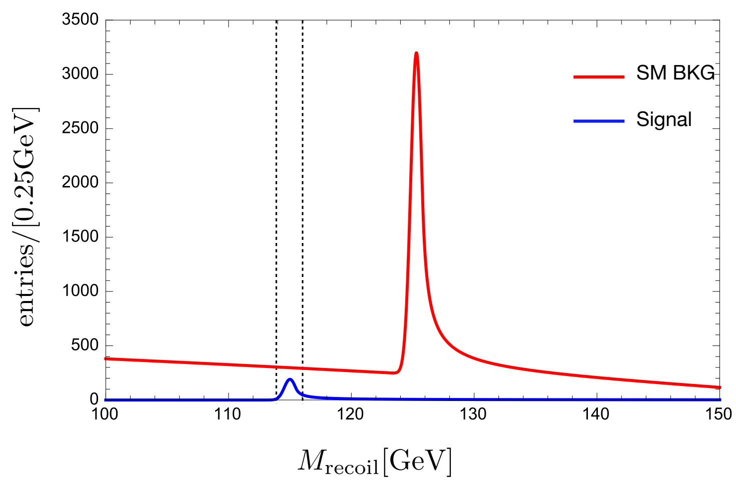


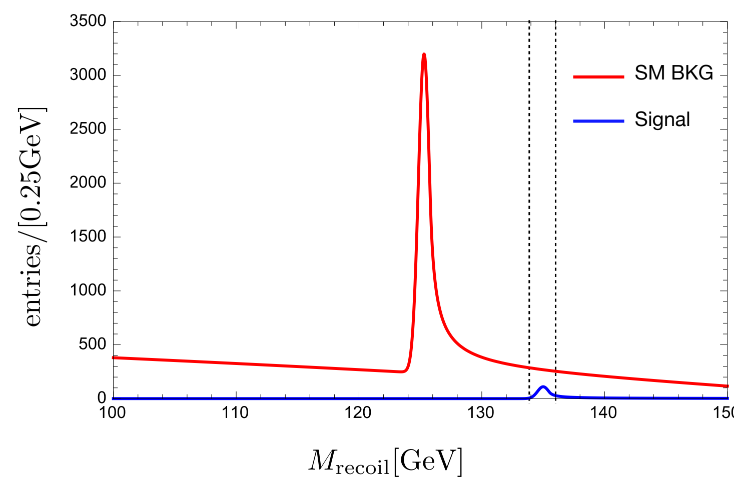


Lepton collider (CEPC for example):

1.Direct search: ZS production recoiled muon pair mass distribution:

$$\sigma(e^+e^- \to ZS) = \frac{G_F^2 m_Z^4}{96\pi s}(v_e^2 + a_e^2)|\mathcal{O}_{12}|^2 \sqrt{\tilde{\lambda}}\, \frac{\tilde{\lambda} + 12 m_Z^2/s}{(1 - m_Z^2/s)^2}$$

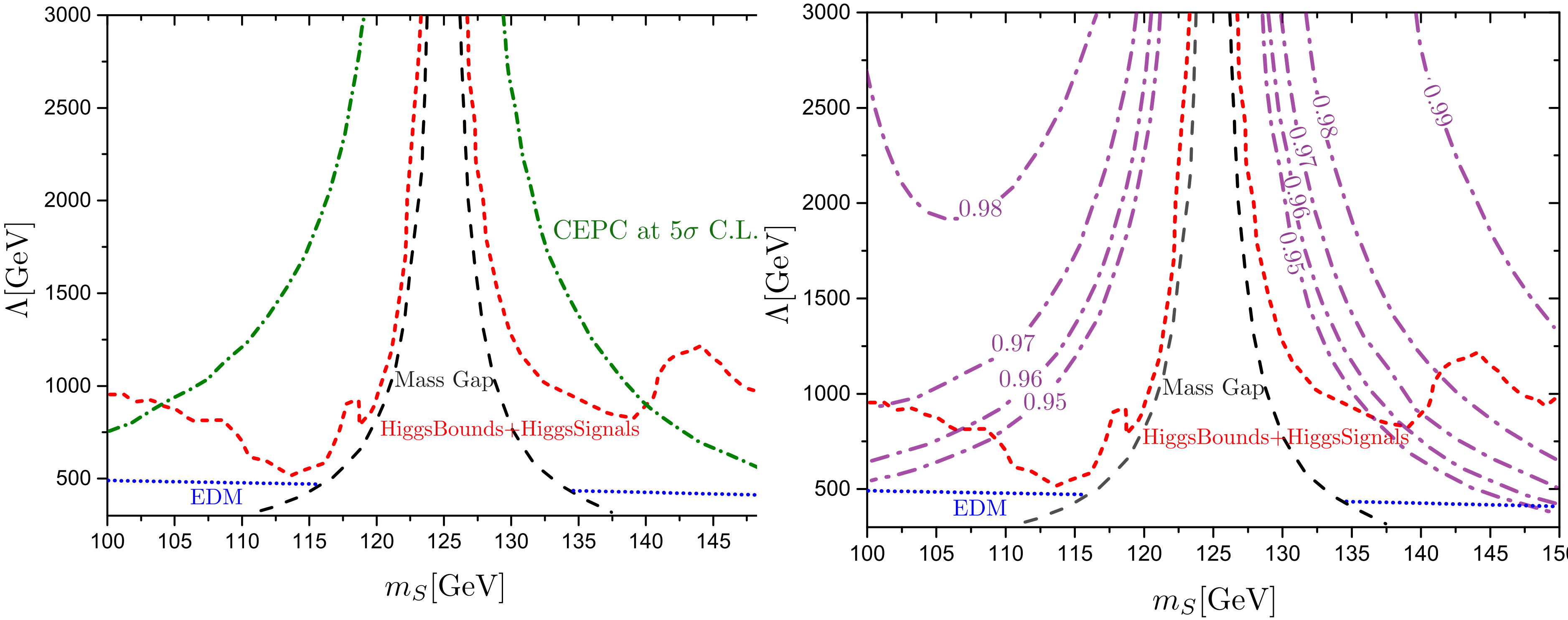




2.Indirect search: ZH cross section deviation from mixing and field strength renormalization:

$$\mathcal{Z} = 1 + \frac{\kappa^2 v^2}{32\pi^2 m_H^2}\left(1 - \frac{4m_S^2}{m_H^2}\frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}} \arctan \frac{1}{\sqrt{\frac{4m_S^2}{m_H^2} - 1}}\right)$$

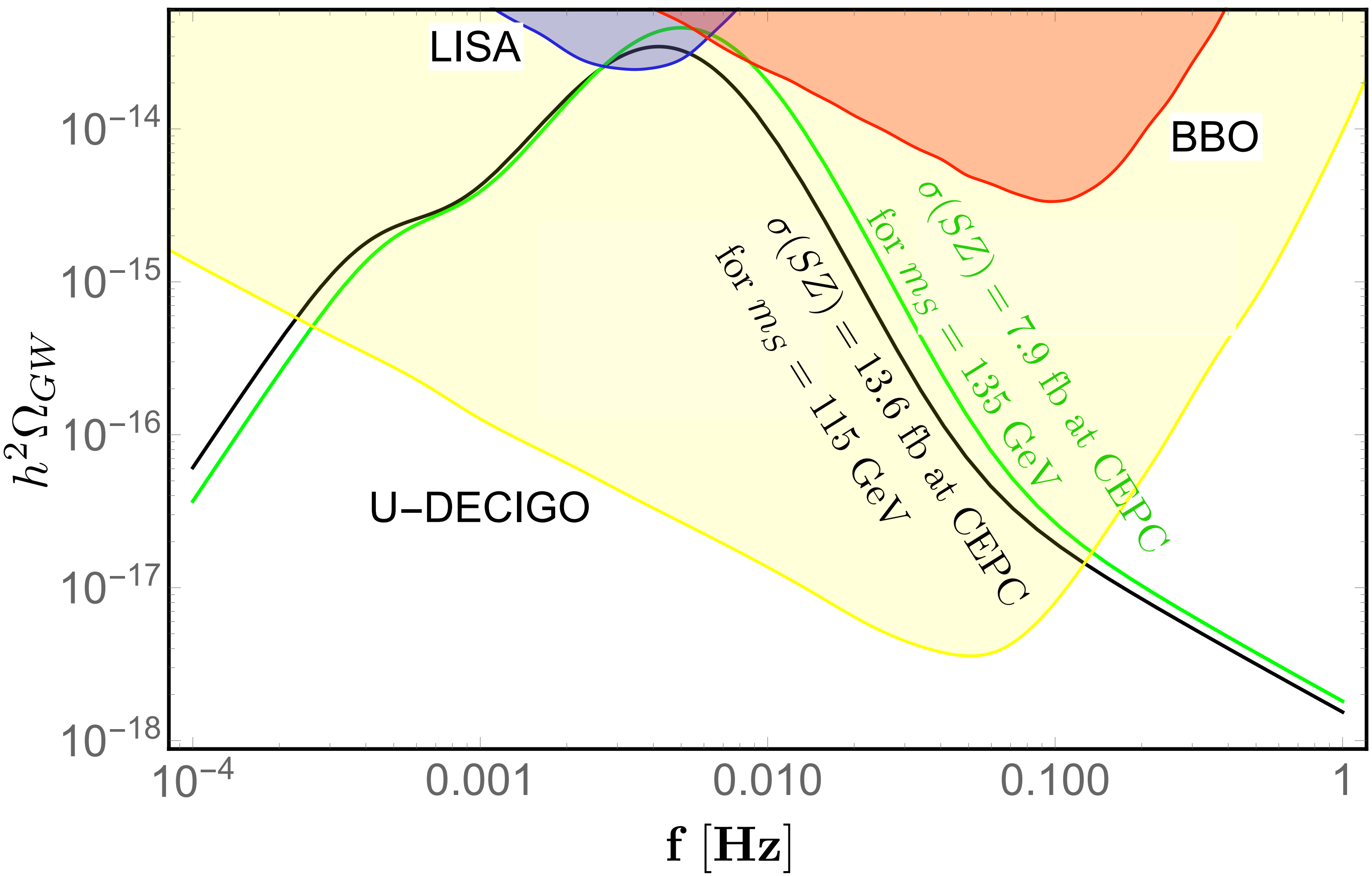
So $\sigma(e^+e^- \to HZ)$ will be rescaled by a factor $|\mathcal{O}_{22}|^2\mathcal{Z}$



Current exclusion limit and future search sensitivity projected on Λ versus ms plane.The regions below dotted blue lines have been excluded by EDM measurement; regions below dashed red lines have been excluded by collider scalar searches and Higgs data. In the left plot, regions below dash dotted olive lines can be observed from ZS production at 5 ab^{-1} CEPC with a C.L. higher than 5σ. In the right plot, we show the ratio of ZH cross section with purple dash dotted contour lines.

N.B. Limit from EDM is much weaker than Higgs data, due to the fact the contributions to EDM in this scenario come from three-loop contributions

The correlation between the future GW and collider signals



For example taking benchmark set I, the GW spectrum is represented by the black line, which can be detected by LISA and U-DECIGO. The black line also corresponds to $0.9339\sigma_{SM}$(HZ) of the HZ cross section for $e^+e^- \rightarrow$ HZ process and 115 GeV recoil mass with 13.6 fb cross section for the $e^+e^- \rightarrow$ SZ process, which has a 5σ discovery potential with 5 ab^{-1} luminosity at CEPC.

III.Successful DM and EW baryogenesis with dynamical CP-violating source

Based on arXiv:1905.10283, Phys. Rev. D**100**, 035014 (2019)FPH, Eibun Senaha,
and work in progress with Eibun Senaha

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

The new lepton Yukawa interaction is

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

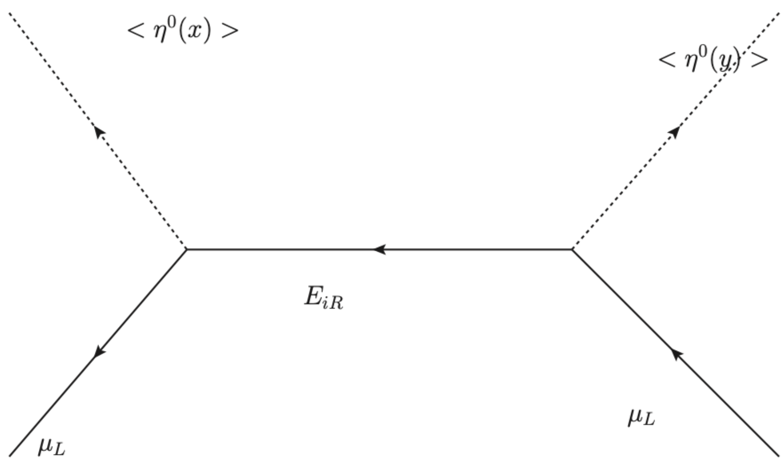
vector-like lepton (E_i)

D. Borah, S. Sadhukhan and S. Sahoo, Phys. Lett. B **771**, 624 (2017).
L. Calibbi, R. Ziegler and J. Zupan, JHEP **1807**, 046 (2018).
D. Borah, P. S. B. Dev and A. Kumar, Phys. Rev. D **99**, no. 5, 055012 (2019).

Dynamical CP violation can be produced during first-order phase transition process in the early universe induced by the complex Yukawa coupling.

For example, at temperature around 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: $\varphi_1 = v,\ \varphi_2 = \varphi_3 = 0$

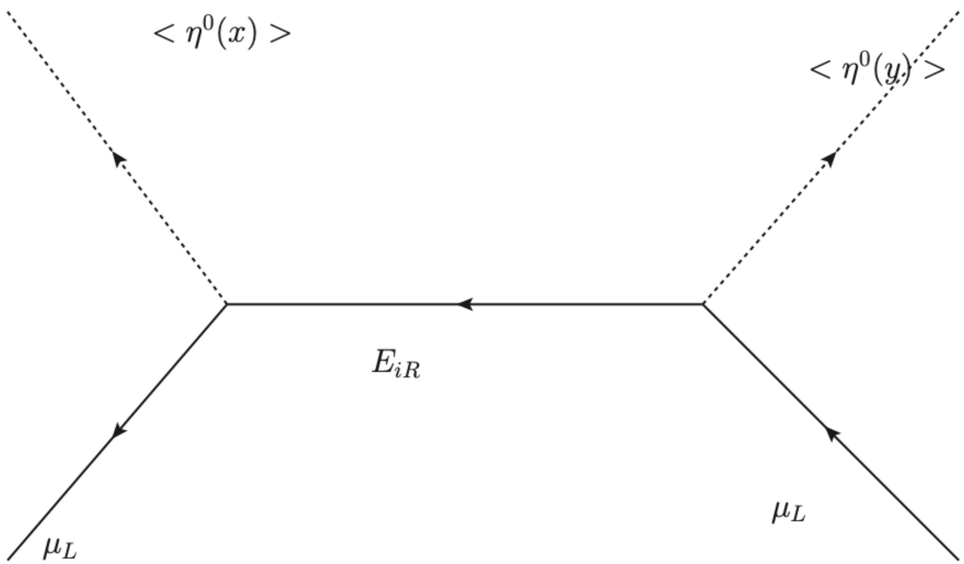
CP-violating source term

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

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

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



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

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

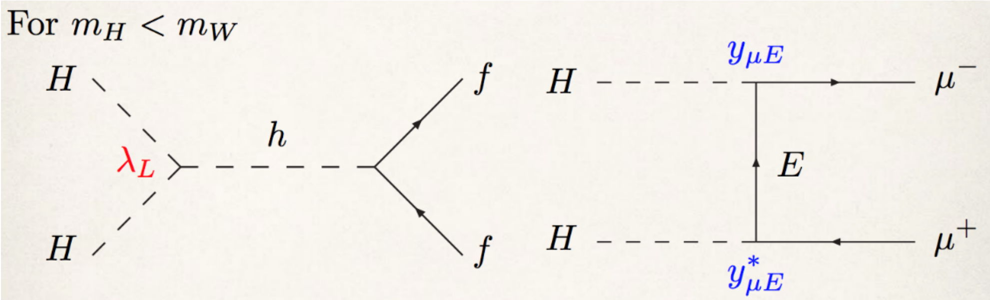
CP-conserving source term

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

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

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

Dark Matter



$$m_h^2 = \lambda_1 v^2,$$

$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2,$$

$$m_H^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5)v^2 = m_{H^\pm}^2 + \frac{1}{2}(\lambda_4 + \lambda_5)v^2,$$

$$m_A^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5)v^2 = m_{H^\pm}^2 + \frac{1}{2}(\lambda_4 - \lambda_5)v^2,$$

Without loss of generality, we can assume $\lambda_4 + \lambda_5 < 0$ and $\lambda_5 < 0$,

In this simple scenario, the CP-even particle H can be DM candidate.

Further, if $\lambda_4 = \lambda_5 < 0$,**T parameter is zero and** $m_{H^\pm} = m_A$

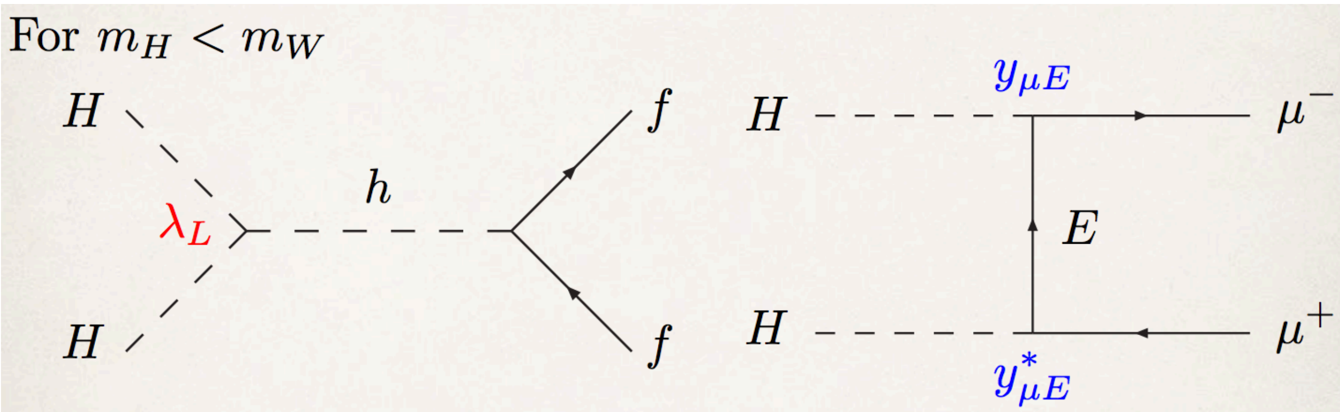
Planck 2018

$$\Omega_{\rm DM} h^2 = 0.11933 \pm 0.00091.$$

As for the DM direct detection, the recent XENON1T data put a strong constraint on the DM-nucleon spin-independent elastic scatter cross-section $\sigma_{\rm SI}$. For instance, the most excluded region at 90% confidence level reaches $\sigma_{\rm SI} = 4.1 \times 10^{-47}$ cm^2 with the DM mass of 30 GeV. Therefore, for a light DM, the direct detection data favor the so-called Higgs funnel region where the DM mass is close to half of the Higgs mass, namely, $m_H \simeq m_h/2 \simeq 63$ GeV. In this model, the cross-section $\sigma_{\rm SI}$ is approximated as

$$\sigma_{\rm SI} \simeq \frac{\lambda_L^2 f_N^2}{4\pi} \left(\frac{m_N^2}{m_H m_h^2} \right)^2 ,$$

where $\lambda_L = \lambda_3 + \lambda_4 + \lambda_5$ and $f_N \simeq 0.3$. To evade the current DM direct detection constraints in this Higgs funnel region, $\lambda_L \lesssim 0.003$ is required



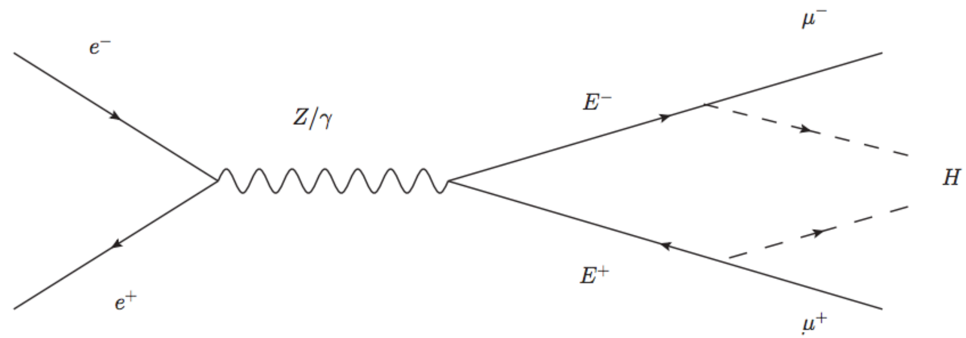
As a benchmark scenario, we consider

$$m_E = (105 - 125)\ \text{GeV}, \quad |y_{\mu E}| = 1.0, 0.5 \text{ and } 0.3.$$

Allowed by LHC data, Lorenzo Calibbi, Robert Ziegler, Jure Zupan, 1804.00009 (JHEP)

The DM relic abundance is always satisfied by judiciously choosing m_H and λ_L. For instance, for $m_E = 110$ GeV and $|y_{\mu E}| = 0.5$, the choice of $m_H = 62.55$ GeV and $\lambda_L = 0.001$ gives $\Omega_{\rm DM} h^2 = 0.12$ and $\sigma_{\rm SI} = 8.7 \times 10^{-48}$ cm^2. Here, we set $m_A = m_{H^\pm} = 300$ GeV and $\lambda_2 = 0.3$, though they are not sensitive to the results.

Direct measurements of vector-like lepton mass



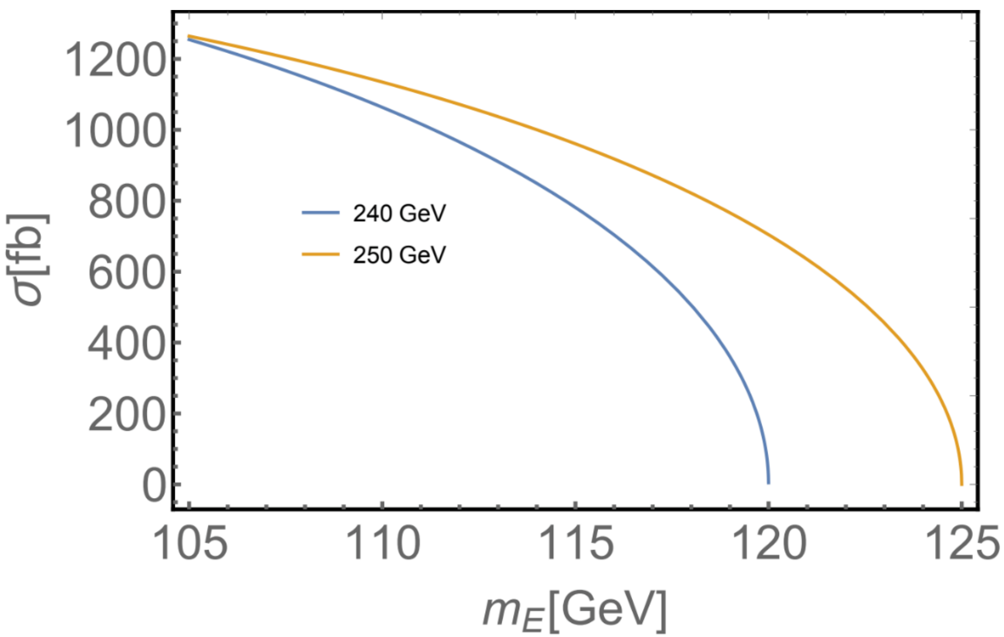
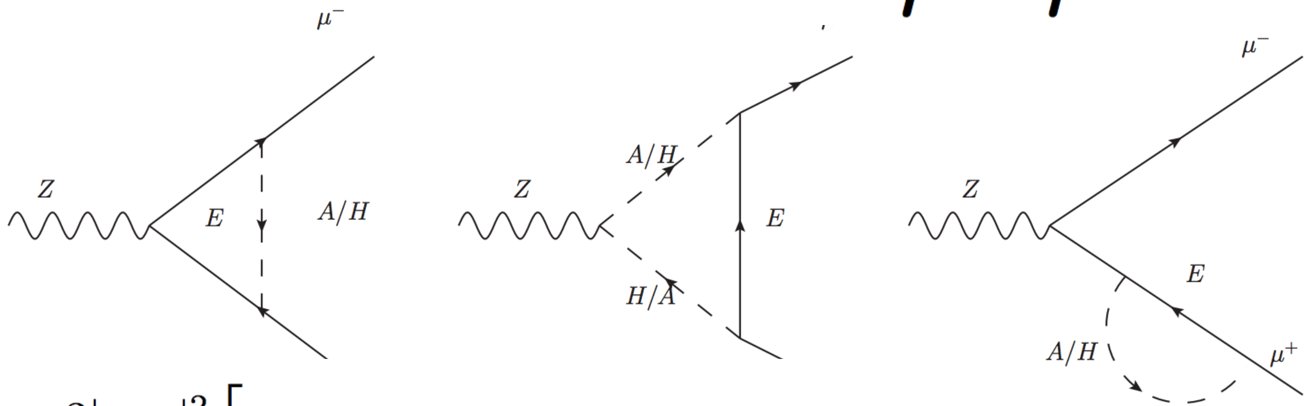


FIG. 6. The cross-section $\sigma(e^+e^- \to \gamma/Z \to E^+E^-)$ as a function of m_E. We take $\sqrt{s} = 240$ GeV (blue) and 250 GeV (orange), respectively.

Indirect search by $Z \to \mu^+\mu^-$



$$\Delta g^L_{Z\bar{\mu}\mu} = \frac{3|y_{\mu E}|^2}{32\pi^2}\Bigg[\tilde{F}_3(m_E, m_H, m_A) + \sum_{\phi=H,A}\Bigg\{\left(-\frac{1}{2}+s_W^2\right)F_2(m_E, m_\phi) + s_W^2 F_3(m_E, m_\phi)\Bigg\}$$

An important missing observable in many previous study!

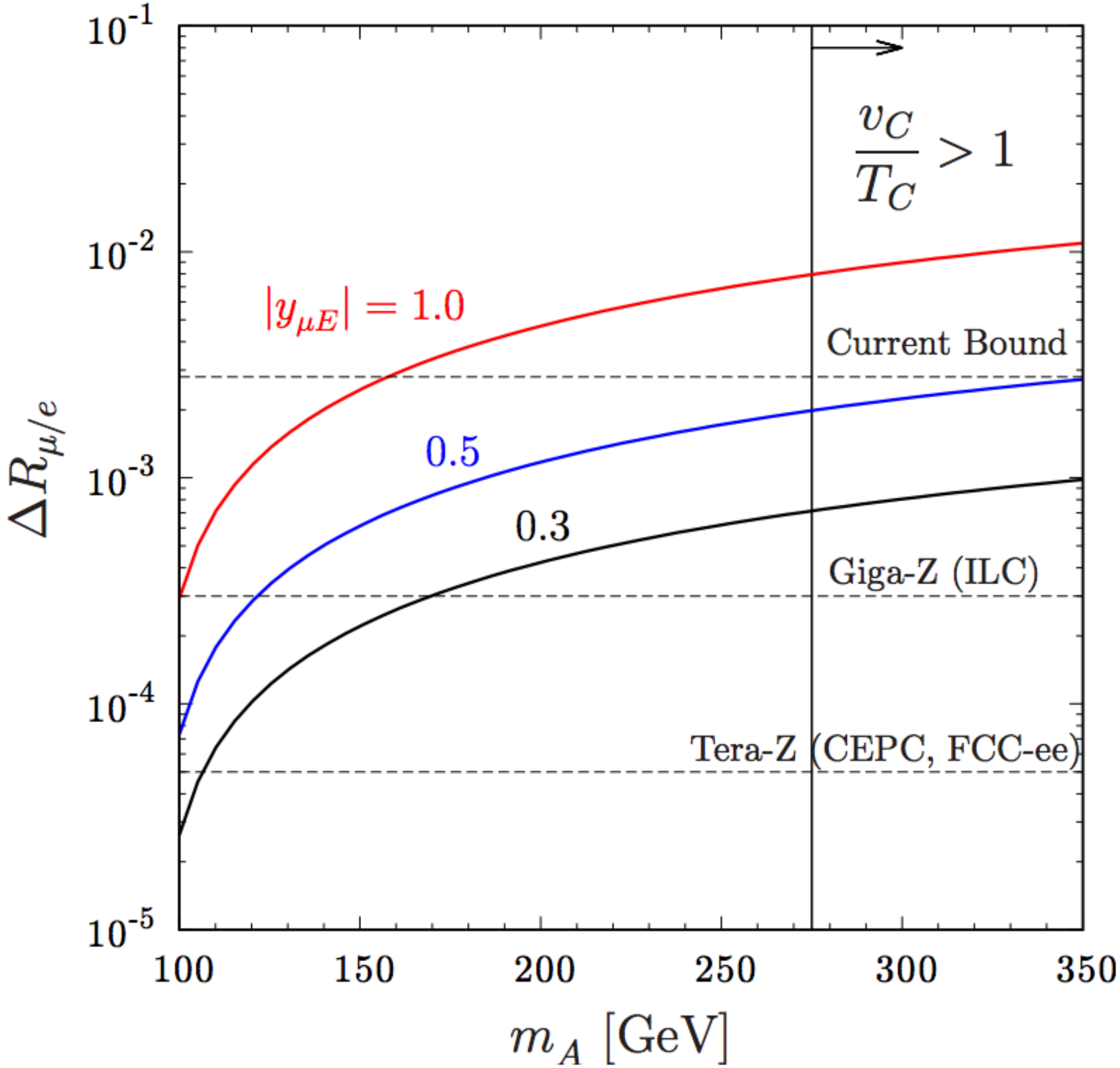
$$R_{\mu/e} = \frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma(Z \to e^+e^-)}$$

deviation of $R_{\mu/e}$ from the SM value as

$$\Delta R_{\mu/e} \equiv \frac{R_{\mu/e} - R^{\rm SM}_{\mu/e}}{R^{\rm SM}_{\mu/e}} \simeq \frac{2g^{L,\rm SM}_{Z\bar{\mu}\mu}{\rm Re}(\Delta g^L_{Z\bar{\mu}\mu}) + |\Delta g^L_{Z\bar{\mu}\mu}|^2}{|g^{L,\rm SM}_{Z\bar{\mu}\mu}|^2 + |g^{R,\rm SM}_{Z\bar{\mu}\mu}|^2},$$

Large enhancement of Z boson decay by the requirements of EW baryogenesis and DM.

Further generalisation of this enhancement effects from the aspects of symmetry breaking is working in progress.

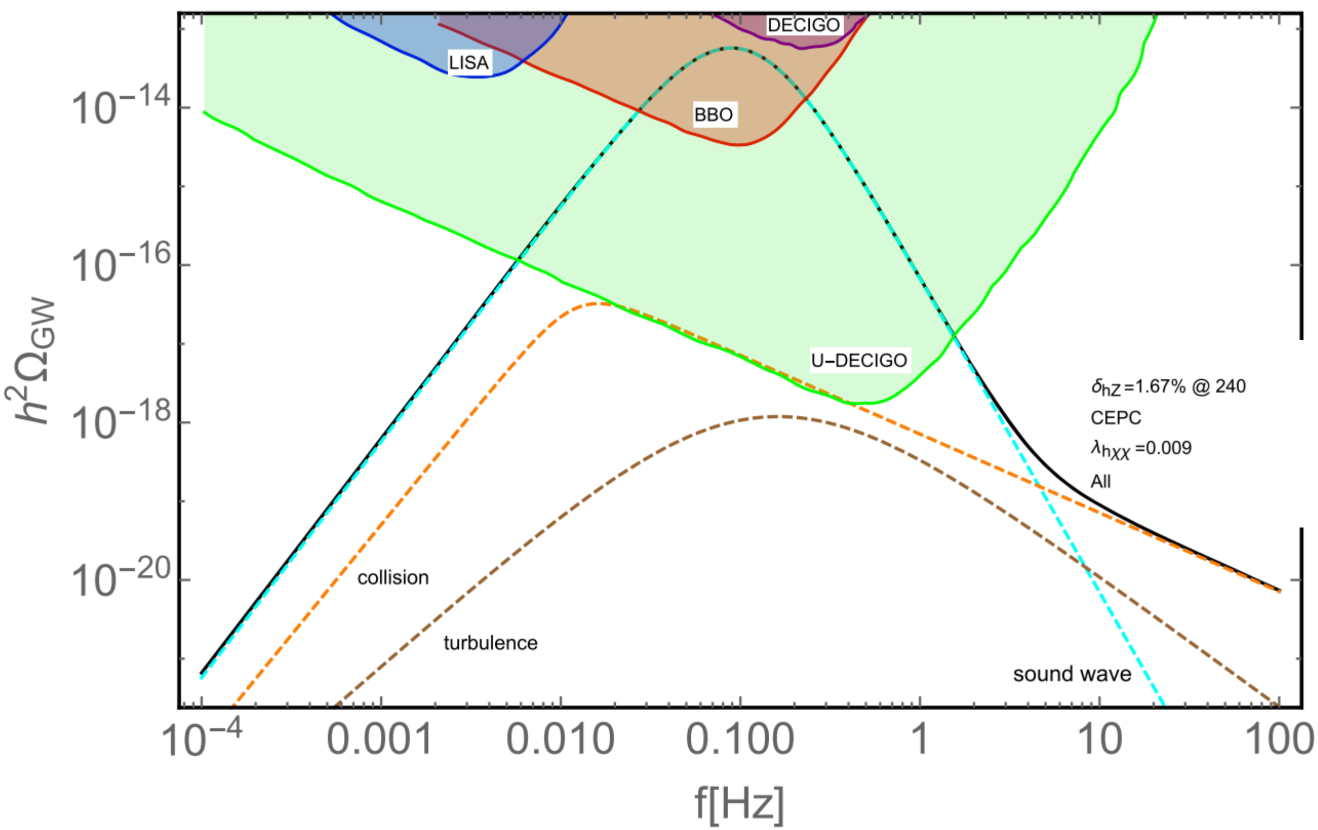


To satisfy the EW strong first-order phase transition (baryogenesis) and DM it requires the large mass splitting of the scalar mass spectrum in the same multiplet, which leads to significant enhancement of the Z boson decay.

Tera-Z can be a new indirect search to explore DM and baryogenesis.

Indirect search by GW signals

Complementary test by GW signals, precise measurements of Z boson decay, HZ cross section measurements and direct production of di-muon plus MET.



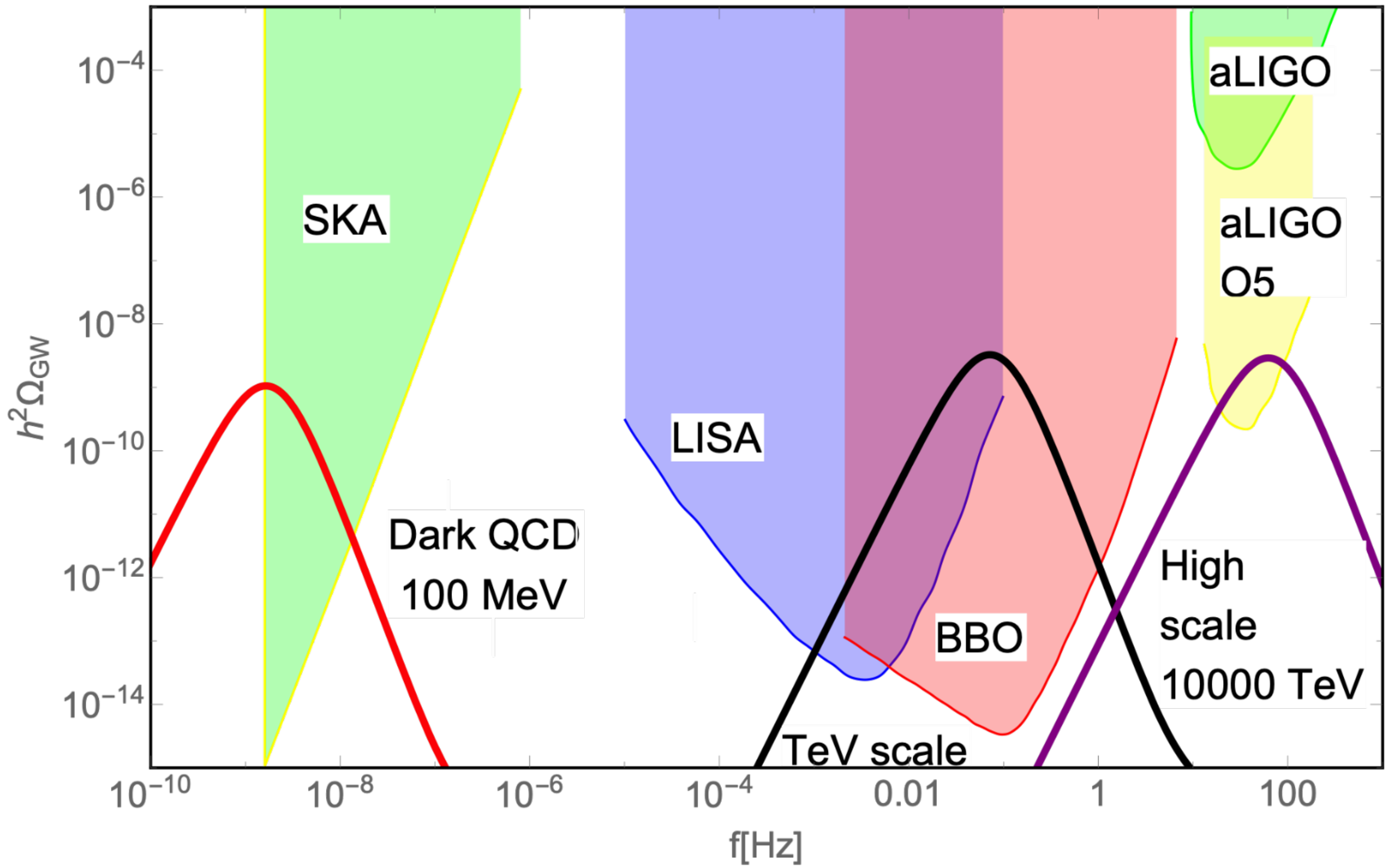
FPH, **Jiang-hao Yu,** Phys.Rev.D 98 (2018) 9, 095022

Other possible realization

Gravitational wave and collider signals in complex two-Higgs doublet model with dynamical CP-violation at finite temperature
Xiao Wang, FPH, Xinmin Zhang, *Phys.Rev.D* 101 (2020) 1, 015015

Dynamical CP-violating source for electroweak baryogenesis can appear only at finite temperature in the complex two-Higgs doublet model, which might help to alleviate the strong constraints from the electric dipole moment experiments. In this scenario, we study the detailed phase transition dynamics and the corresponding gravitational wave signals in synergy with the collider signals at future lepton colliders. For some parameter spaces, various phase transition patterns can occur, such as the multi-step phase transition and supercooling. Gravitational wave in complementary to collider signals can help to pin down the underlying phase transition dynamics or different patterns.

Extended to phase transition at different energy scale



Schematic phase transition GW spectra for SKA-like and LISA-like experiments to explore DM and baryogenesis

FPH, Xinmin Zhang, Physics Letters B 788 (2019) 288-294

Summary and outlook

- **EW first-order phase transition has abundant collider and cosmological effects in baryogenesis, dark matter, GW…**
- **The correlation between GW and collider signals at CEPC can make a double test on the Higgs nature, baryogenesis, dark matter and the cosmic evolution history at 100 GeV.**
- **More precise study are needed, such as reliable daisy resummation scheme, non-perturbative calculations, bubble dynamics, GW spectra for ultra-supercooling…**

Thanks for your attention