Exploring dynamical CP violation induced baryogenesis by gravitational waves and colliders

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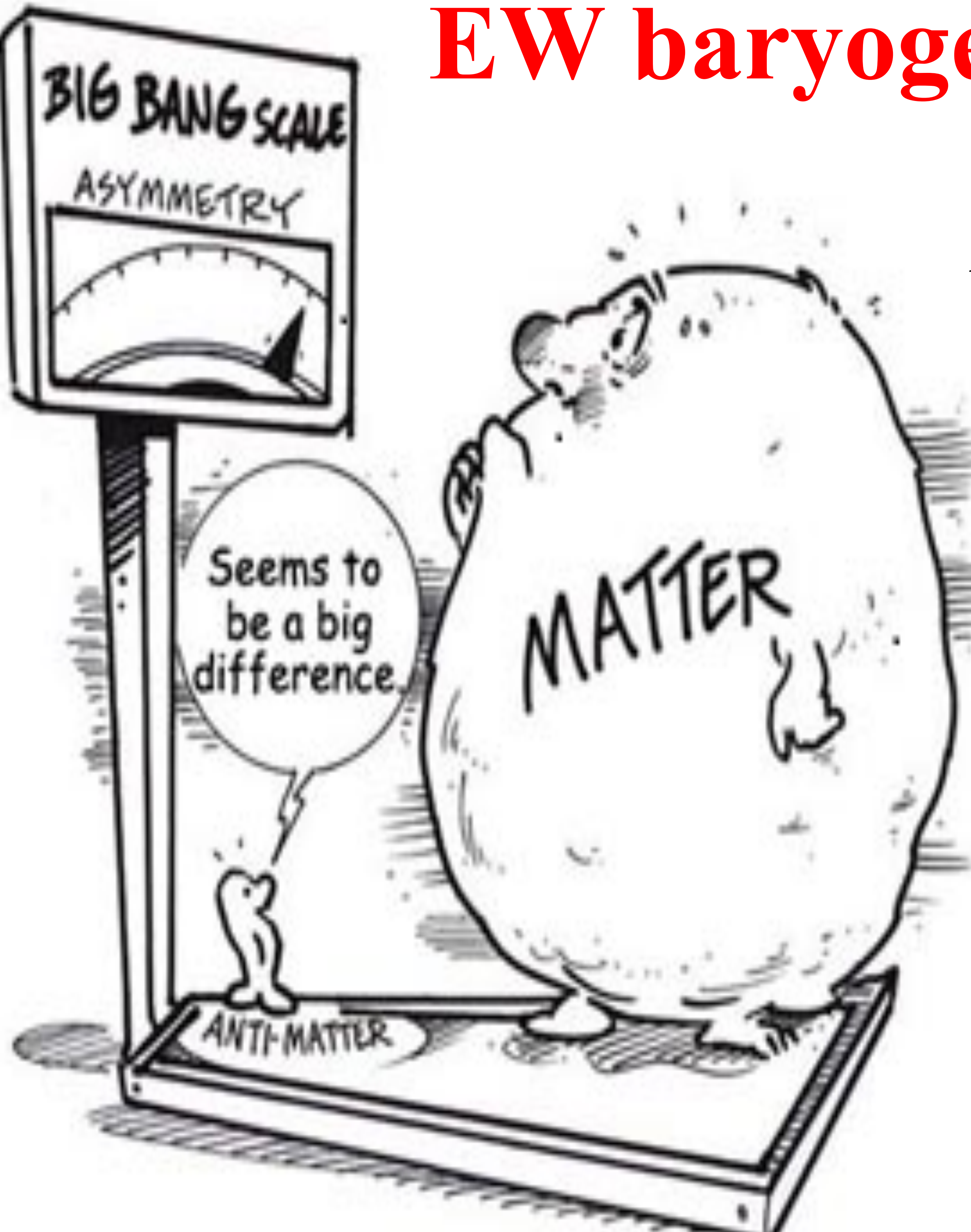
mainly based on our recent work: arXiv:1804.06813, Phys.Rev. D98 (2018) no.1, 015014
(FPH, Zhuoni Qian, Mengchao Zhang)

EW baryogenesis in a nutshell



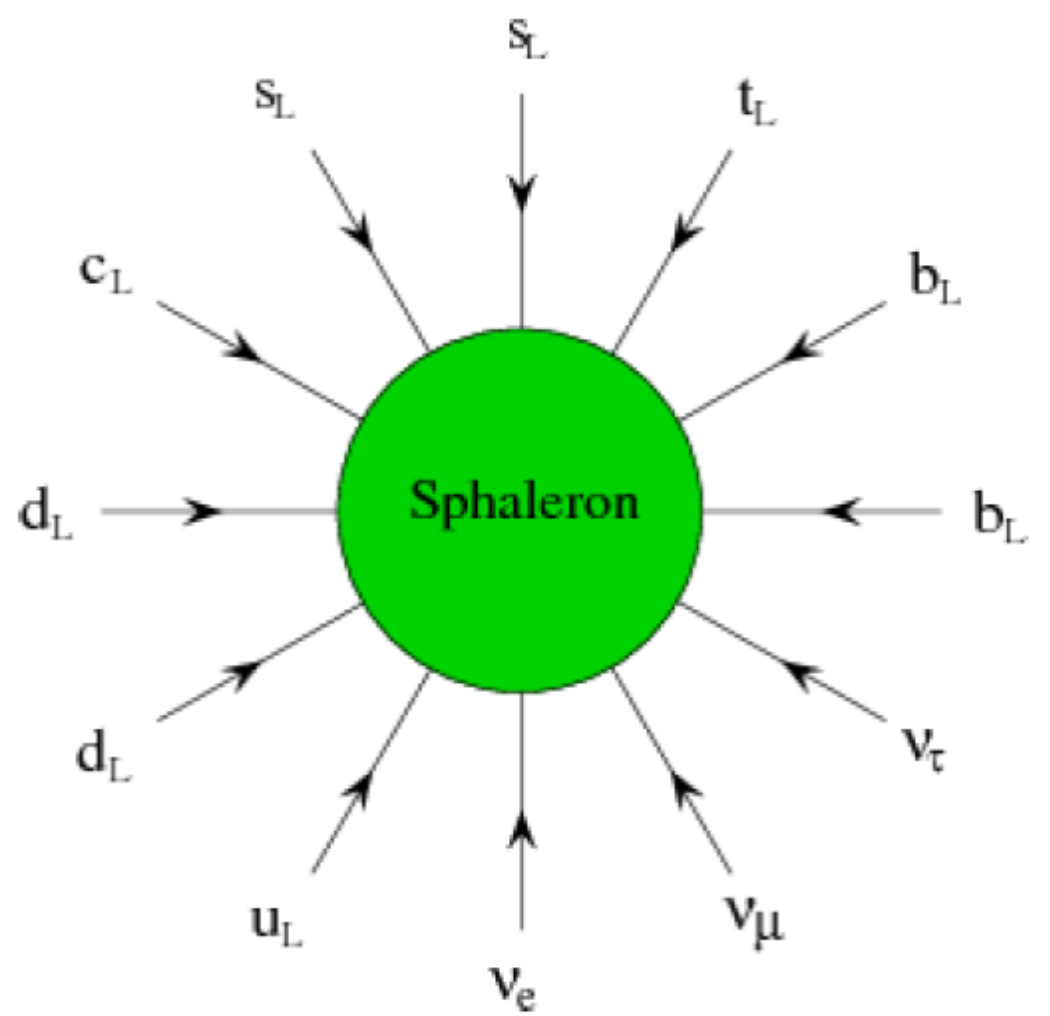
A long standing problem in particle cosmology is the origin of baryon asymmetry of the universe (BAU).

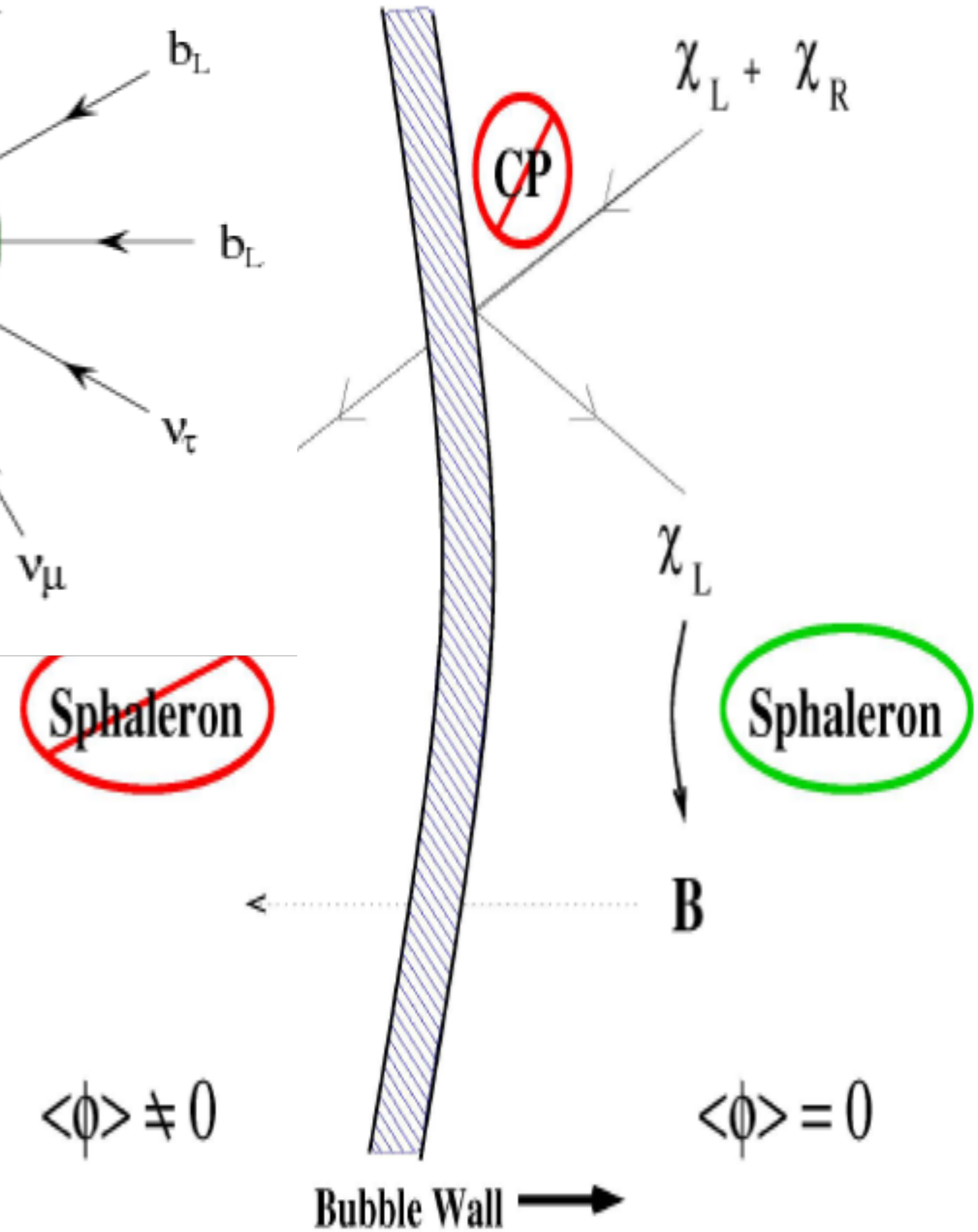
After the discovery of the Higgs boson by LHC and gravitational waves (GW) by aLIGO, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

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

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.**

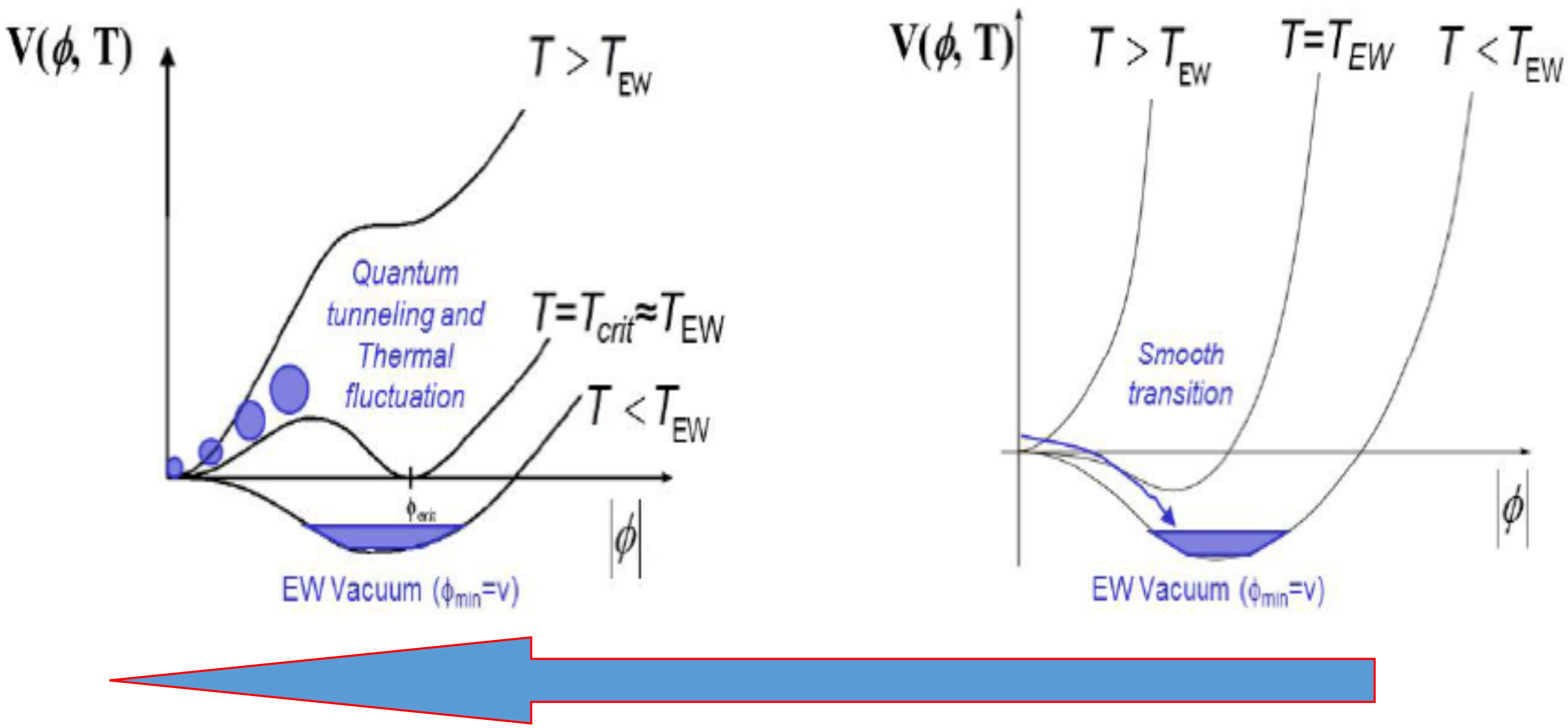
D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. 14, 125003 (2012).

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.

Sufficient CP-violation for baryogenesis v.s. electric dipole moment (EDM) measurement

Current electric dipole moment (EDM) experiments put severe constraints on many baryogenesis models. For example, the ACME Collaboration's new result, i.e. $|d_e| < 8.7 \times 10^{-29}$ cm · e at 90% C.L. , 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 .

For example, the CP-violating Yukawa can evolves from a sufficiently large value in the early universe to a loop-suppressed small value at current time, by assuming it depends on a dynamical scalar field, i.e. the two step phase transition process can make the CP violating Yukawa coupling transit from a large value to zero at tree level.

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

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

Dynamical/cosmological evolve, See Prof. Servant's talk tomorrow

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 take the following case as a representative example:

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

$\eta = a + ib$ **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 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)

Phase transition history in the early universe

To study the phase transition dynamics, we write the effective potential as a function of spatially homogeneous background scalar fields

$$V_{\text{eff}}(H,\sigma,T) = V_{\text{tree}}(H,\sigma) + \Delta V_1^{T\neq 0}(H,\sigma,T) + V_1^{T=0}(H,\sigma)$$

$$\Gamma/\mathcal{H}^4|_{T=T_N} \simeq 1 \qquad \frac{S_3(T_N)}{T_N} = 4\ln(T_N/100\text{GeV}) + 137$$

$$S_3 = \int d^3 r \left\{ \frac{1}{2}\left(\frac{dH}{dr}\right)^2 + \frac{1}{2}\left(\frac{d\sigma}{dr}\right)^2 + V_{\text{eff}}(H,\sigma,T) \right\}$$

$$\vec{\varphi}(t) = (H(t),\sigma(t)) \qquad \frac{d^2\varphi_b}{dr^2} + \frac{2}{r}\frac{d\varphi_b}{dr} = \frac{\partial V_{\text{eff}}}{\partial \varphi_b}, \qquad \lim_{r\to\infty}\varphi_b = 0, \quad \left.\frac{d\varphi_b}{dr}\right|_{r=0} = 0.$$

$$\tilde{\beta} = T_N \frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Bigg|_{T=T_N} \qquad \alpha = \frac{\varepsilon(T_N)}{\rho_{\text{rad}}(T_N)}$$

$$\varepsilon(T) = -V_{\text{eff}}(\varphi_B(T),T) + T\frac{\partial V_{\text{eff}}(\varphi_B(T),T)}{\partial T} \qquad \rho_{\text{rad}}(T) = (\pi^2/30)g_*(T)T^4$$

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

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

We choose reasonably small relative velocity $\tilde{v}_b \sim$ 0.2, which is favored by the EW baryogenesis to guarantee a sufficient diffusion process in front of the bubble wall, and large enough bubble wall velocity $v_b \sim 0.5$ to produce stronger phase transition GW (Roughly speaking, for deflagration case, a larger bubble wall velocity v_b gives stronger GW)

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

- J. M. No, Phys. Rev. D 84, 124025 (2011)

From the roughly numerical estimation, we see that the observed BAU can be obtained as long as $\Delta\sigma/\Lambda \sim 0.1 - 0.3$, where $\Delta\sigma$ is the change of σ during the phase transition

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

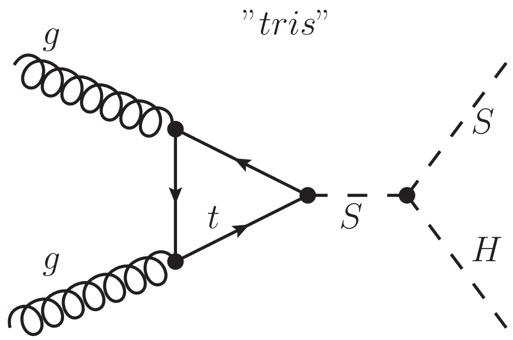
$$\begin{aligned}\mathcal{L}'_{SVV} &= \frac{a\alpha_S}{12\pi\Lambda} S G^a_{\mu\nu} G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} S G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \\ &+ \frac{2a\alpha_{EW}}{9\pi\Lambda} S F_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} S F_{\mu\nu} \tilde{F}^{\mu\nu}\end{aligned}$$

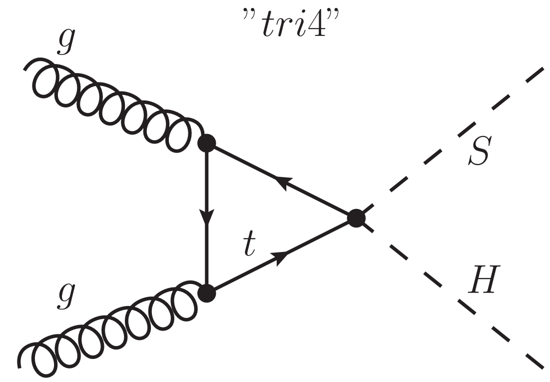
Mixing for H and S from one-loop contribution

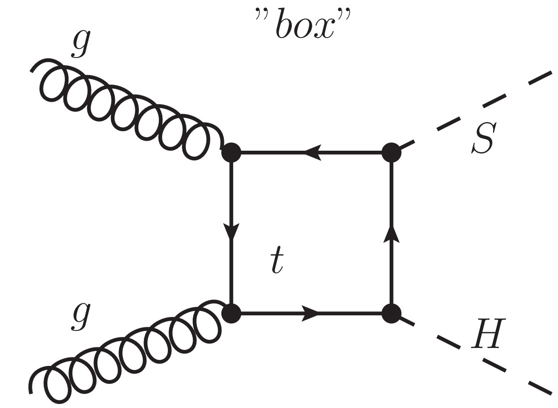
Abundant collider signals

Hadron collider:

$$pp \to HS$$



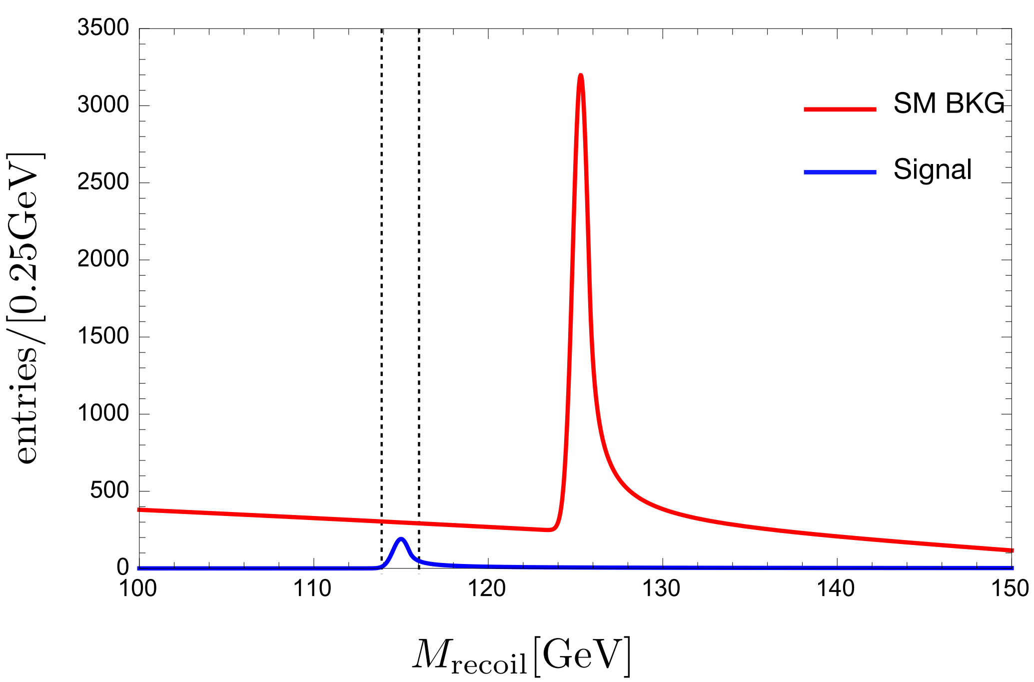


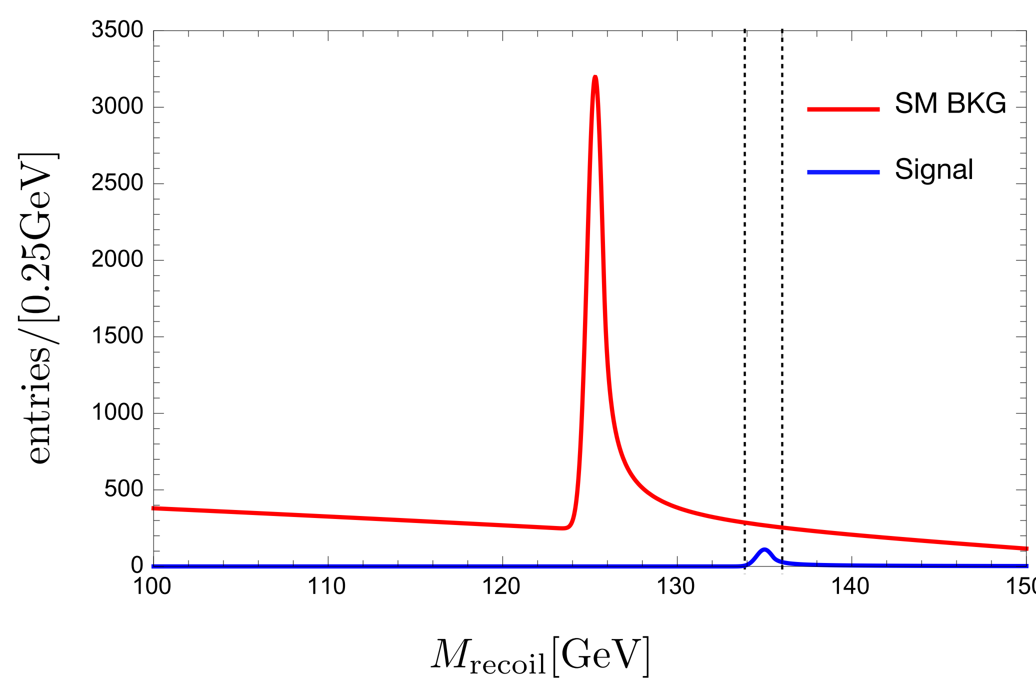


Lepton collider (CEPC for example):

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

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

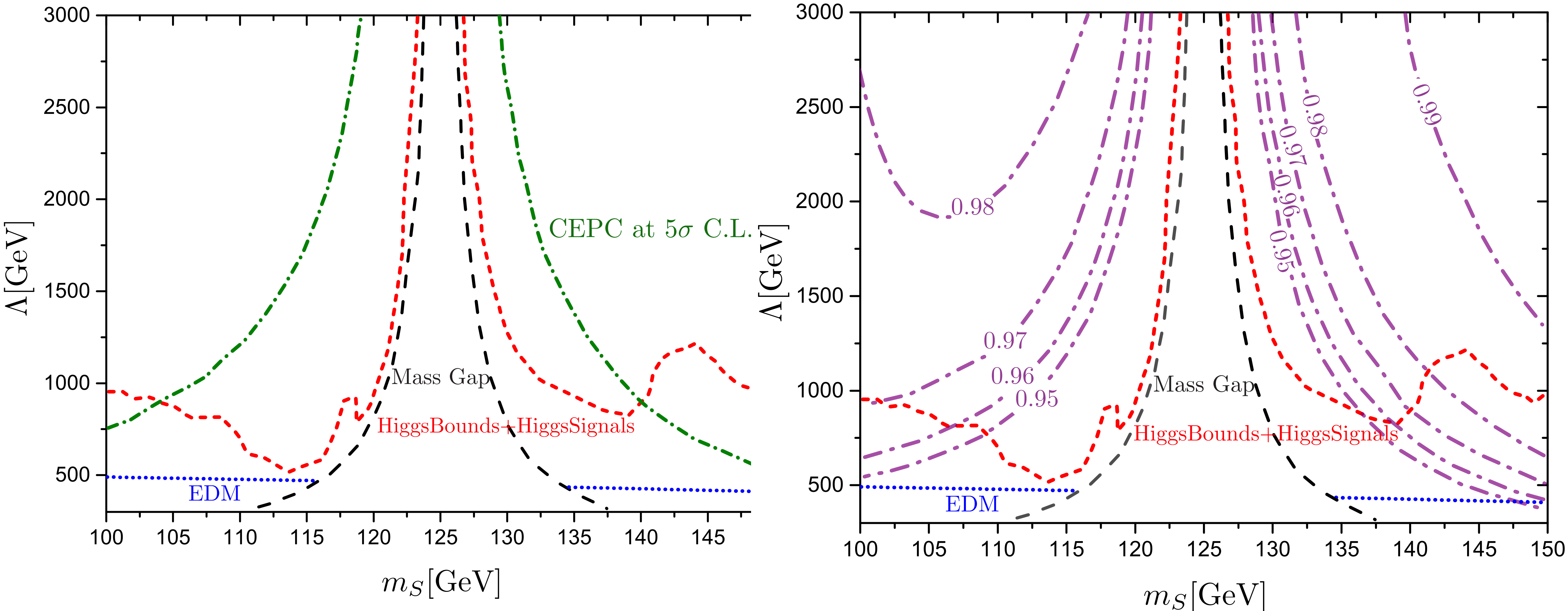




2.Indirect search: ZH cross section deviation from mixing and field strength renormalization:

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

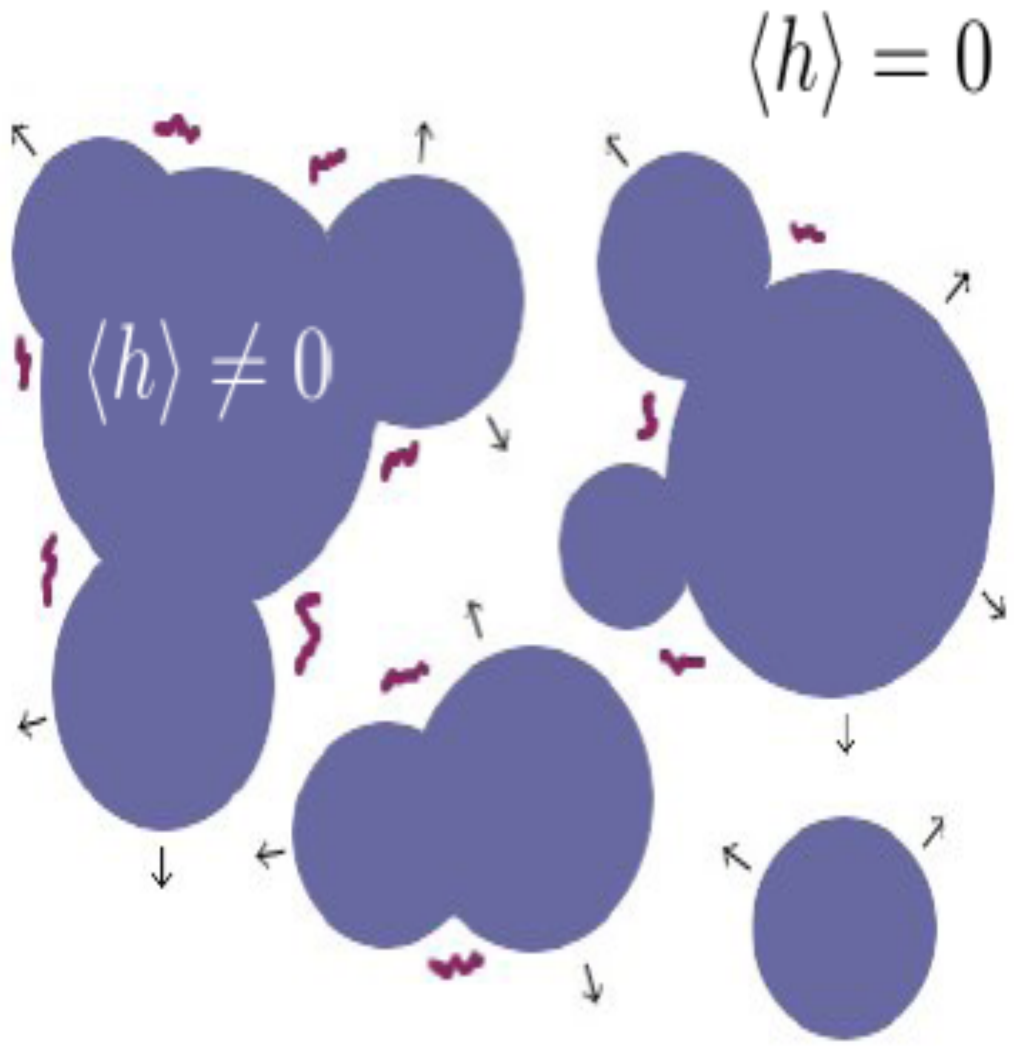
So $\sigma(e^+e^- \to HZ)$ will be rescaled by a factor $|\mathcal{O}_{22}|^2\mathcal{Z}$



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

phase transition GW signals



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.

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

Mechanisms of GW during phase transition

- **Bubble collision:** **well-known source from 1983**

- **Turbulence in the plasma fluid:** **a fraction of the bubble wall energy converted into turbulence.**

- **Sound wave in the plasma fluid: after the collision a fraction of bubble wall energy converted into motion of the fluid (and is only later dissipated).**
  New mechanism of GW : sound wave
  Mark Hindmarsh, *et al.*, PRL 112, 041301 (2014);

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 collision

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

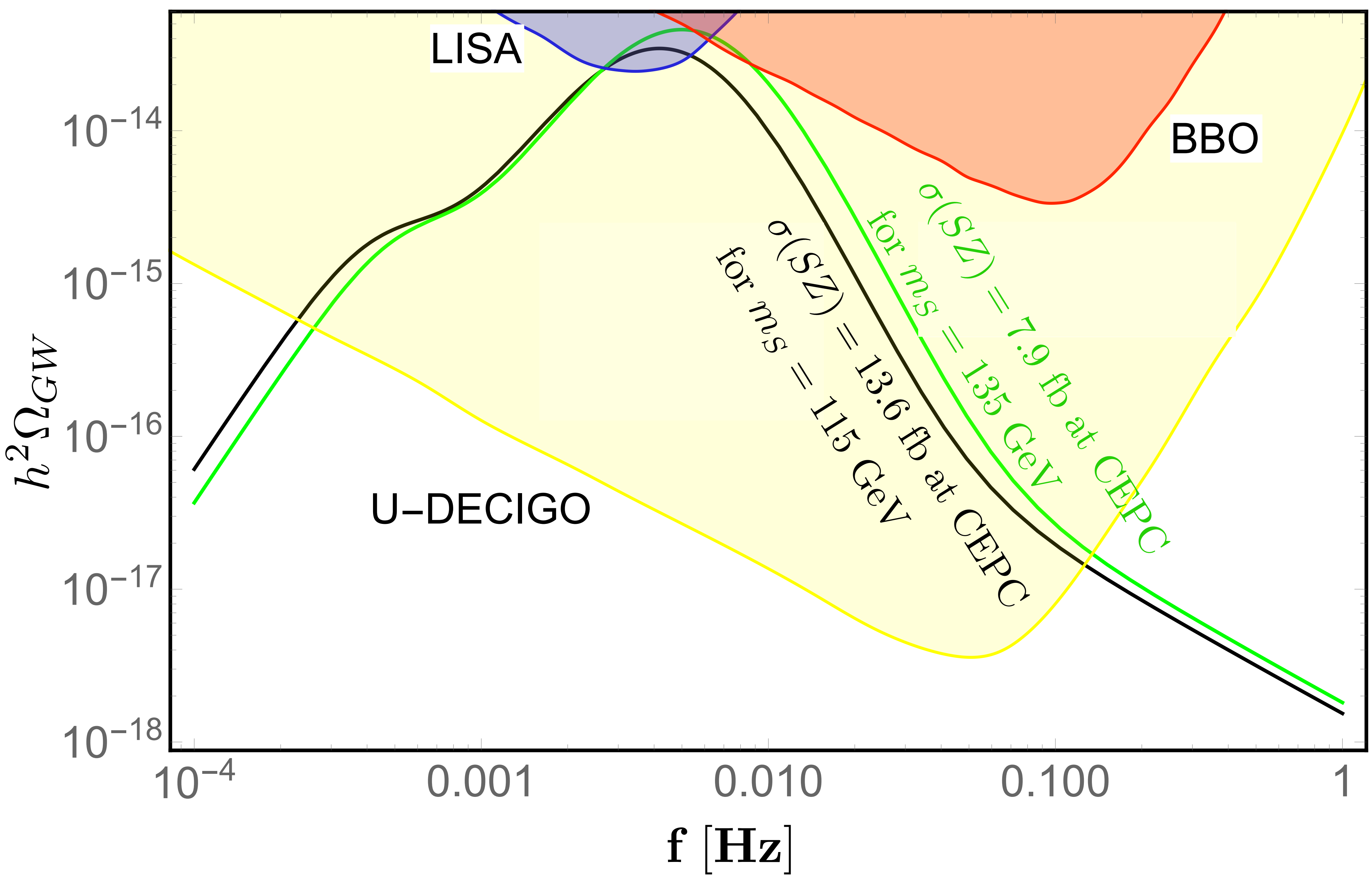
Turbulence

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

Sound wave

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

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 $e^+e^- \to HZ$ process and 115 GeV recoil mass with 13.6 fb cross section for the $e^+e^- \to SZ$ process, which has a 5σ discovery potential with 5 ab^{-1} luminosity at CEPC.

Summary and outlook

By assuming a dynamical source of CP violation, the tension between sufficient CP violation for successful electroweak baryogenesis and strong constraints from current EDM measurements could be alleviated.

We have studied how to explore such scenarios through gravitational wave in synergy with collider signals for a representative example. The correlation between GW and collider signals can make a double test.

The dynamical CP-violation for baryogenesis from cosmological evolutions deserves further study:

1. A renormalizable model to achieve the EW baryogenesis with dynamical CP-violation is working in process with Eibun Senaha by extending the Two Higgs doublet model.

2. Dynamical CP-violation from inflation is also under study.

Thanks for your attention!