Exploring dynamical CP violation induced baryogenesis by gravitational waves and colliders

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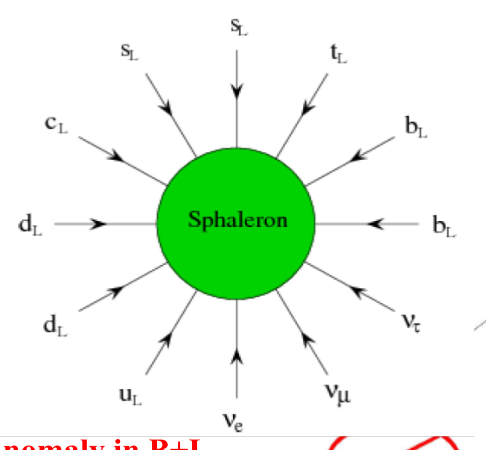
EW baryogenesis in a nutshell

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.

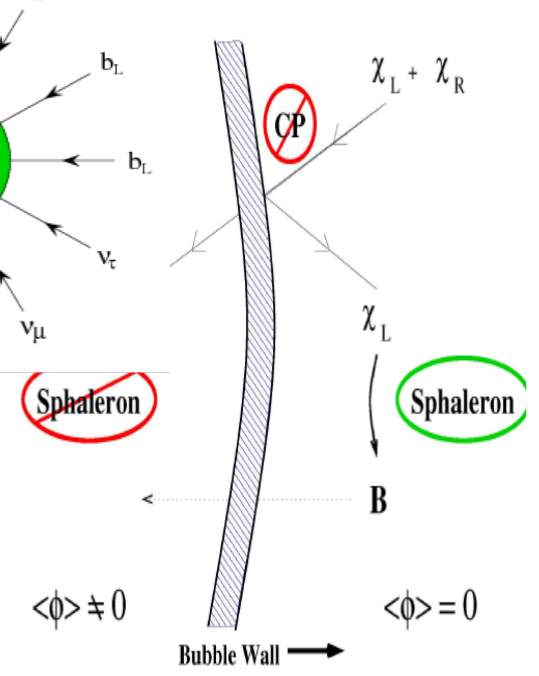
$$\eta_B = n_B/n_\gamma = 5.8 - 6.6\times 10^{-10} \quad \text{(CMB, BBN)}$$

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.

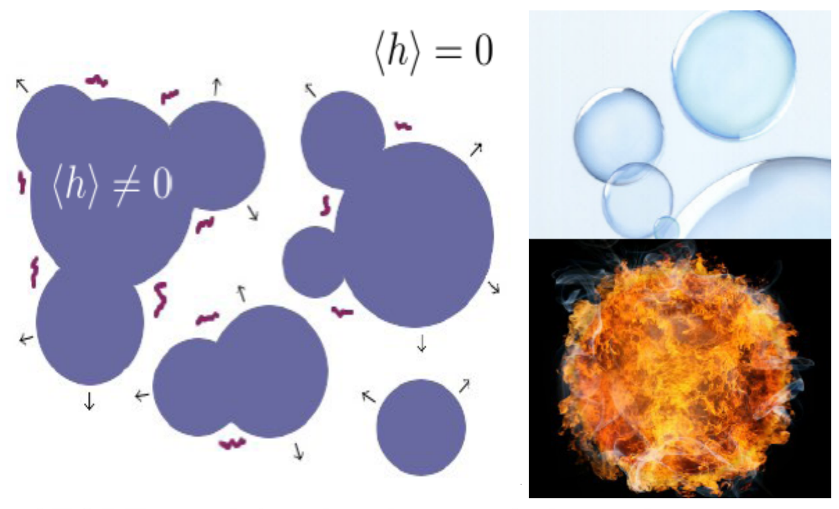


- B violation from anomaly in B+L current.
- CKM matrix, but too weak.
- strong first-order phase transition (SFOPT) with expanding Higgs Bubble wall.

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



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.

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 !

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:

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

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

$\eta = a + ib$ — 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)

Particle phenomenology induced by CP-violating top loop

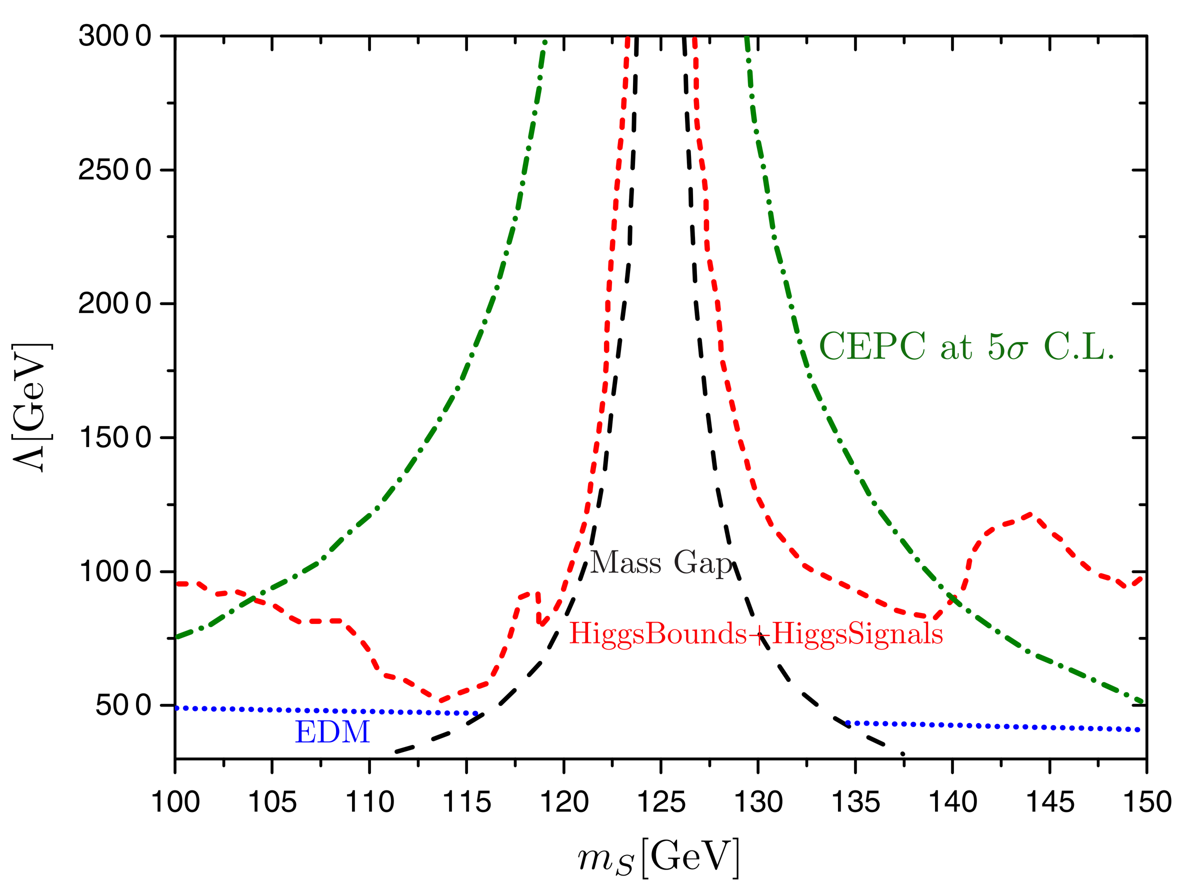
After the SM Higgs obtains a VEV v at the end of the phase transition, we have

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

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

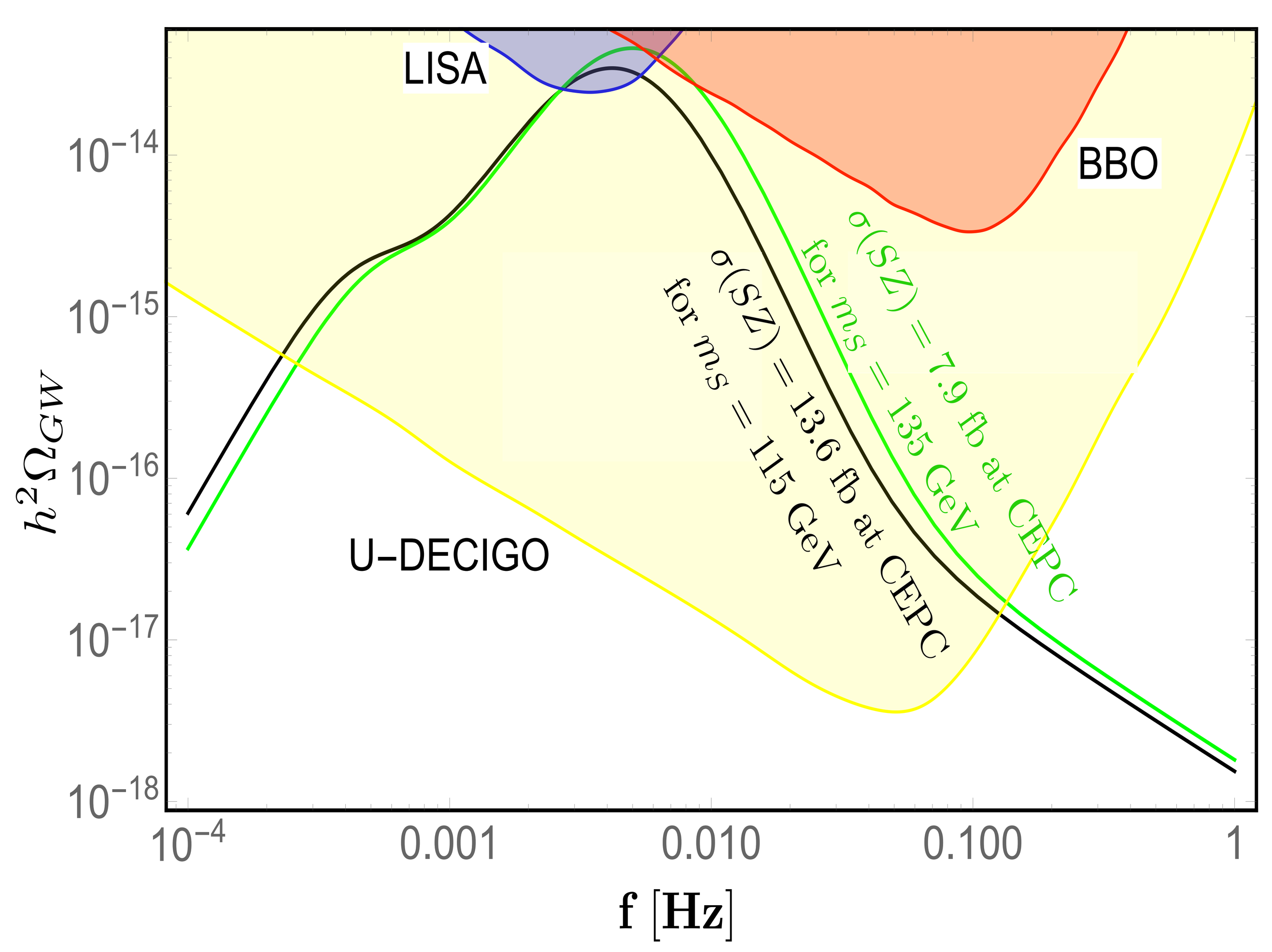
$$\mathcal{L}'_{SVV} = \frac{a\alpha_S}{12\pi\Lambda}SG^a_{\mu\nu}G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda}SG^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{2a\alpha_{EW}}{9\pi\Lambda}SF_{\mu\nu}F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda}SF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Mixing for H and S from one-loop contribution



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

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.

Secondly, we study a renormalizable model to achieve dynamical CP violation for the successful EW baryogenesis (work in progress with Eibun Senaha)

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

The new lepton Yukawa interaction is

$$-\mathcal{L}_Y \ni y_{ij}\bar{\ell}_{iL}\eta E_{jR} + m_{E_i}\bar{E}_{iL}E_{iR} + {\rm h.c.}\quad \text{vector-like lepton } (E_i)$$

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!