Probing new physics and cosmological symmetry breaking by gravitational waves

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Based on our recent works: arXiv:1709.09691 Phys.Rev. D96 (2017) no.9, 095028; Phys.Rev.D94(2016)no.4,041702 ; Phys.Rev.D93 (2016) no.10,103515; arXiv:1708.0473; arXiv: 1704.04201; JCAP 1702 (2017) no.02, 039

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Outline

- Motivation
- Phase transition gravitational waves(GW) in a nutshell
- Probing Higgs nature and EW baryogenesis by GW&Collider
- Probing dark matter(DM) blind spots by GW&Collider
- Probing baryogenesis and DM simultaneously by GW&Collider
- Probing other new physics (NP) and cosmic symmetry breaking by GW
- Summary and outlook

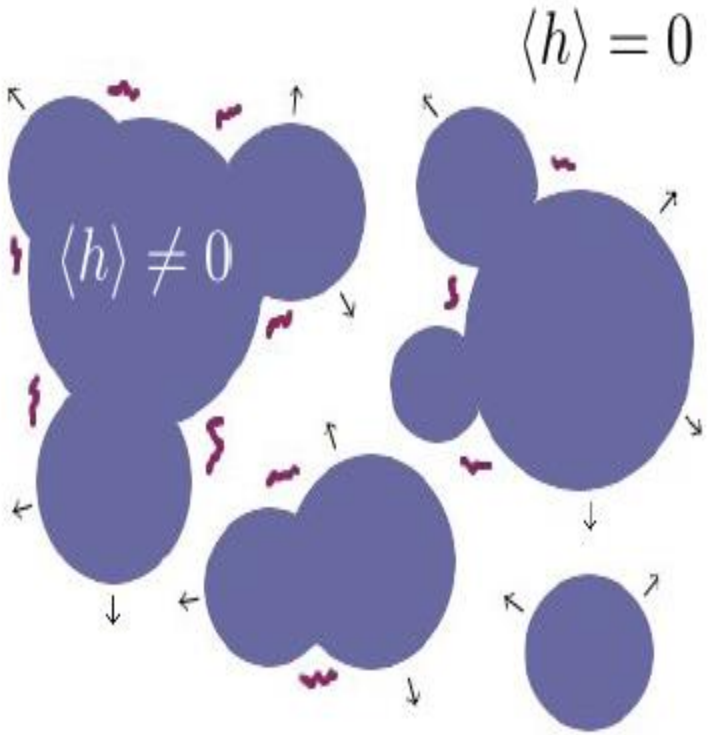
Motivation

- **The observation of gravitational wave 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 baryon asymmetry of the universe and the DM) and no evidence of NP at LHC may just point us GW approach.**

- **GW may helps to probe the nature of Higgs boson, the baryogenesis, DM, NP models, symmetry breaking patterns of the universe.**

phase transition GW in a nutshell



First order phase transition can drive the plasma of the early universe out of thermal equilibrium, and bubble nucleate during it, which will produce GWs.

Pictures from Prof. Huber and Konstandin

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 GW during phase transition

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

M.Hindmarsh, *et al.*, PRL **112**, 041301 (2014); G. Christophe *et al.* Phys.Rev. D75 (2007) Caprini, Chiara *et al.* JCAP 1604 (2016)

Detectable GW signals will be produced during the phase transition from the three mechanisms

To discuss the phase transition GW spectra, it is necessary to begin with the one-loop finite temperature effective potential using the finite temperature field theory:

$$V_{\rm eff} = V_{\rm tree}(\Phi) + V_{\rm cw}(\Phi) + V_{\rm ther}(\Phi, T) + V_{\rm daisy}(\Phi, T)$$

where Φ represents the order parameter of the phase transition (a real scalar field), $V_{\rm cw}$ is the one-loop Coleman-Weinberg potential at $T = 0$, and $V_{\rm ther} + V_{\rm daisy}$ is the thermal contribution including the daisy resummation

During a FOPT, bubbles are nucleated with the following nucleation rate:

$$\Gamma = \Gamma_0(T) e^{-S_E(T)} \text{ with } \Gamma_0(T) \propto T^4$$

$S_E(T) \simeq S_3(T)/T$ is Euclidean action

$$S_E(T) = \int d\tau d^3x \left[\frac{1}{2}\left(\frac{d\Phi}{d\tau}\right)^2 + \frac{1}{2}(\nabla\Phi)^2 + V_{\text{eff}}(\Phi, T)\right]$$

To obtain the bubbles nucleation rate, the profile of the scalar field needs to calculated by solving the following bounce equation using the overshooting/undershooting method.

$$\frac{d^2\Phi}{dr^2} + \frac{2}{r}\frac{d\Phi}{dr} - \frac{\partial V_{\text{eff}}(\Phi, T)}{\partial\Phi} = 0 \quad \frac{d\Phi}{dr}(r=0) = 0, \quad \Phi(r=\infty) = \Phi_{\text{false}}$$

The GW spectrum depends on the four parameters:α, β, bubble wall velocity v and the efficiency factor λ.

$$\alpha \equiv \frac{\epsilon(T_*)}{\rho_{\rm rad}(T_*)} \qquad \tilde{\beta} \equiv \frac{\beta}{H_*} = T_* \frac{dS}{dT}\bigg|_{T_*} = T_* \frac{d}{dT}\left(\frac{S_3}{T}\right)\bigg|_{T_*}$$

Bubble wall collision

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

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

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

I. Probing EW baryogenesis and Higgs potential by GW&Collider

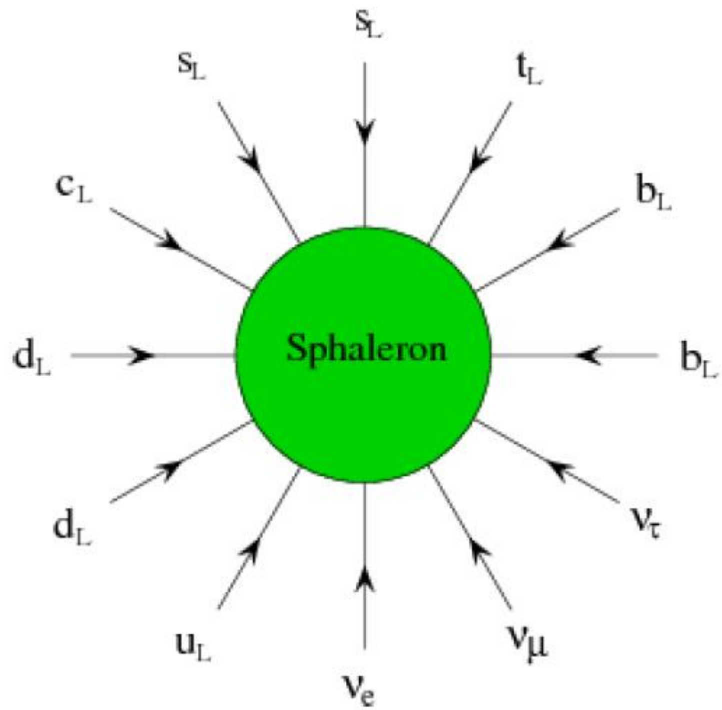
A long standing problem in particle cosmology is to unravel the origin of baryon asymmetry of the universe (BAU).

After the discovery of the 125 GeV Higgs, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

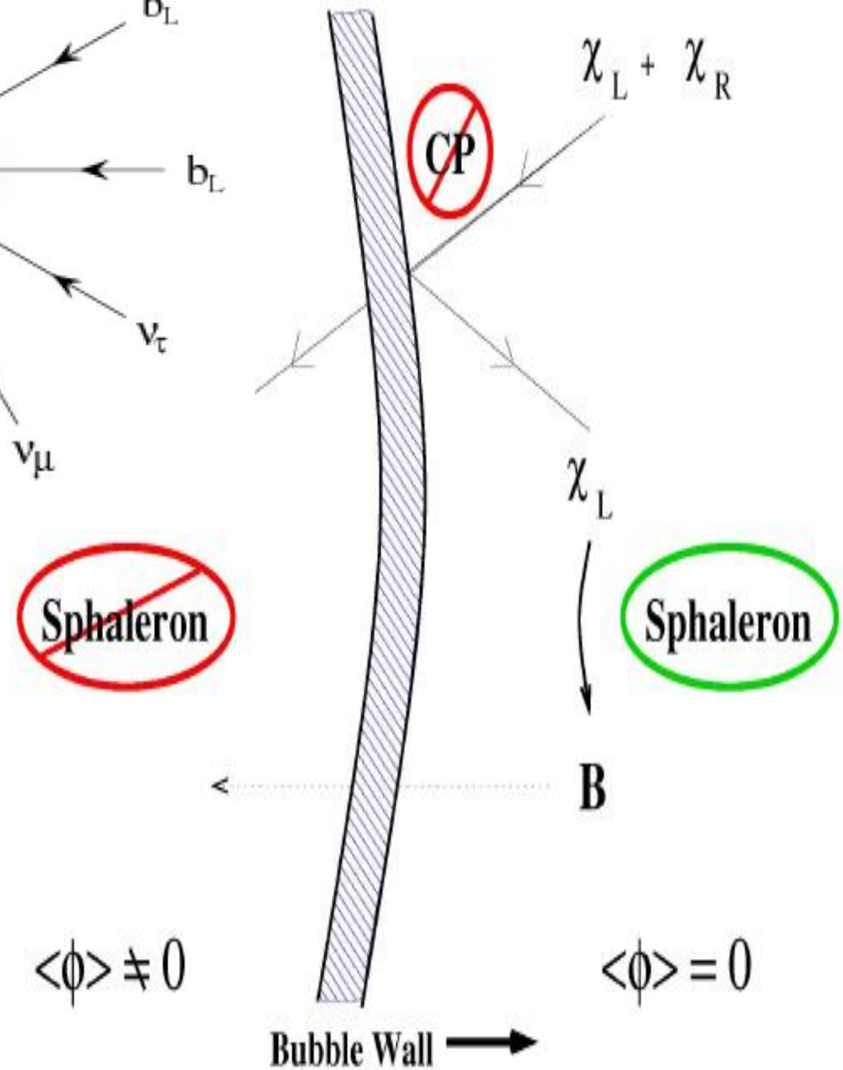
$\eta = n_B/n_\gamma = 6.05(7) \times 10^{-10}$ **(from CMB, BBN)**

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.**
- **First order phase transition with expanding Higgs Bubble wall.**



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

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

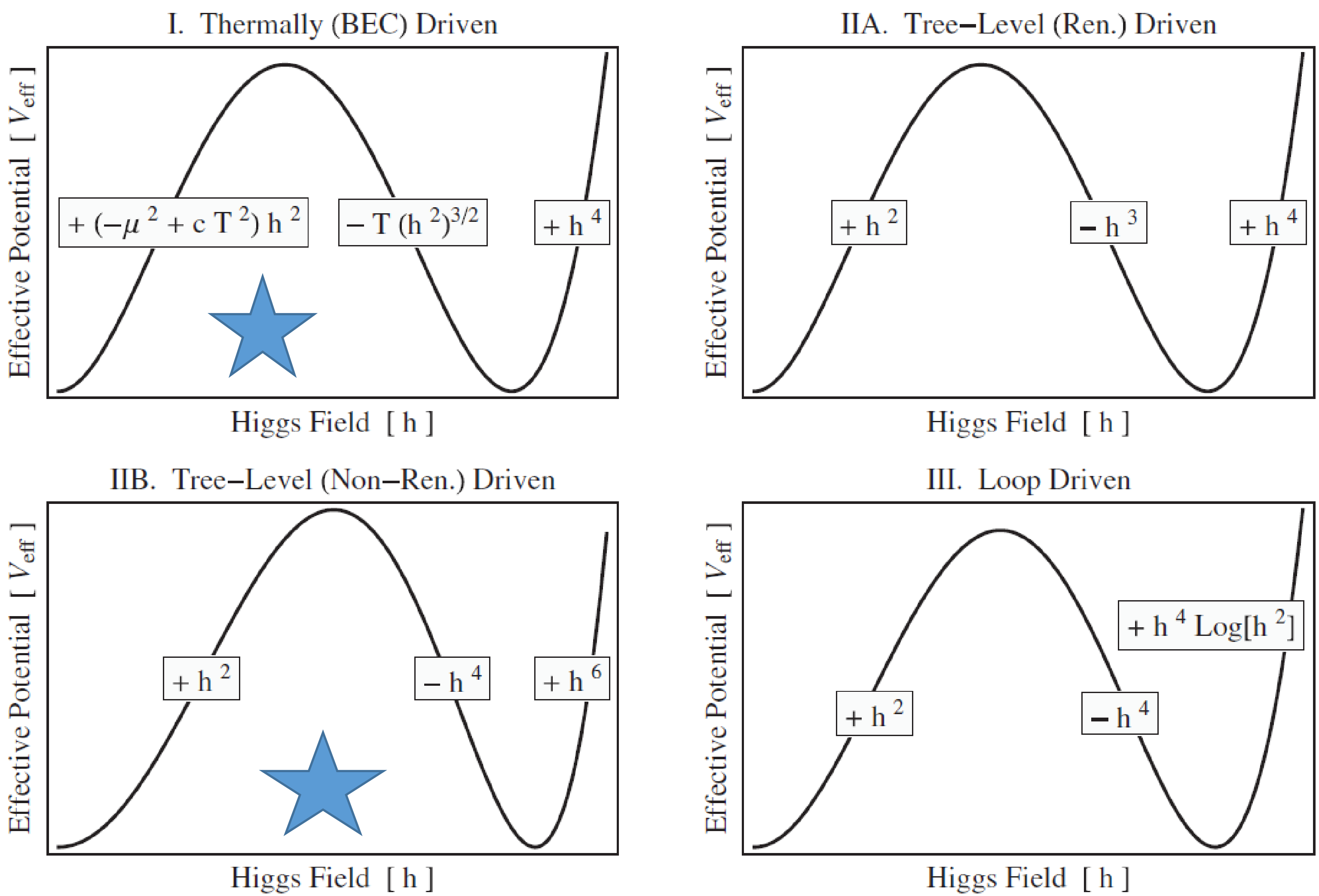
Phase transition Physics

- **The true shape of Higgs potential (Exp:CEPC,ILC)**
- Baryon **asymmetry of the universe (baryogenesis)**
- **Gravitational wave (Exp:LISA 2034)**
- **DM blind spots,**

Asymmetry DM

Study of EW phase physics at CEPC/ILC and LISA helps to explore the symmetry breaking history of the universe.

Typical types of EW phase transition



Lian-Tao Wang, et.al

PHYSICAL REVIEW D **87,** 023509 (2013)

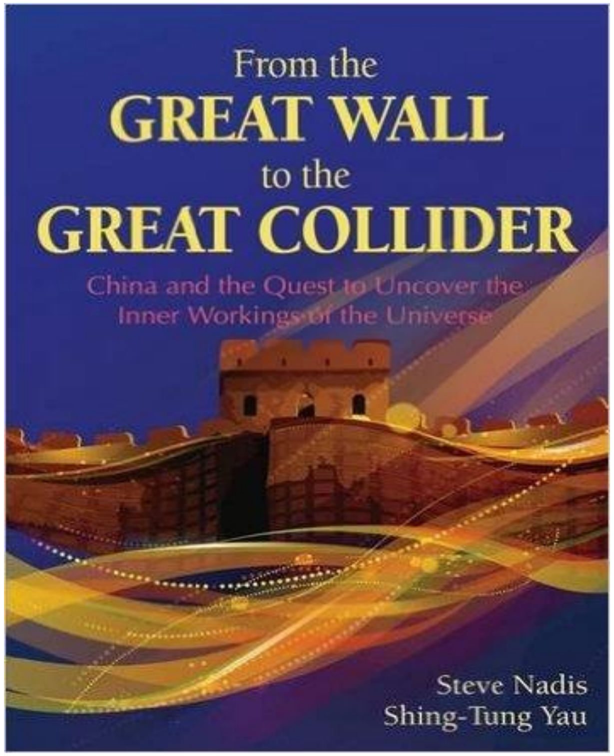
Current particle collider has no ability to unravel the true potential of the Higgs boson, we need new experiments.

Particle approach

we can build more powerful colliders, such as the planned CEPC/ILC/SppC.

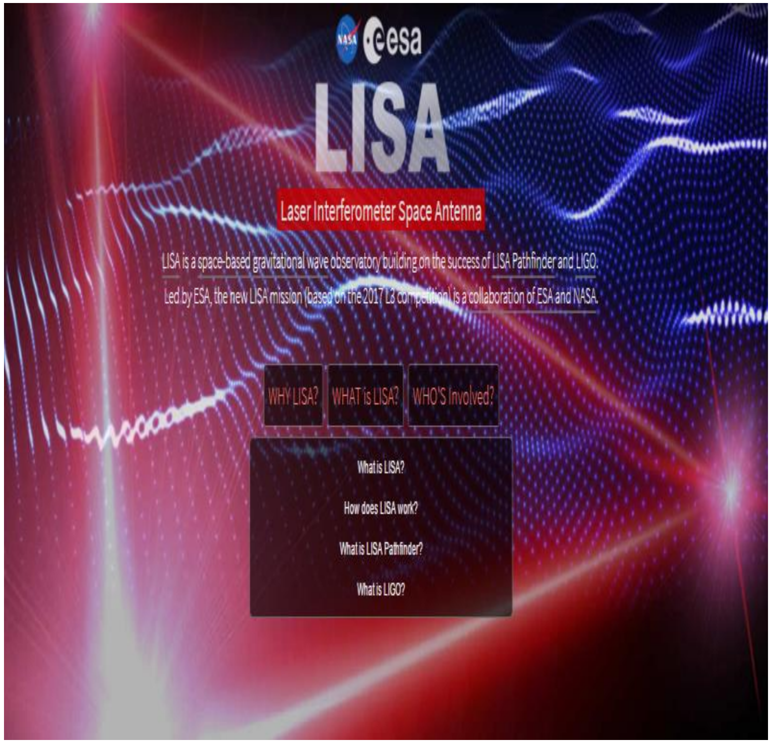
Wave approach

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



Relate by EW phase transition

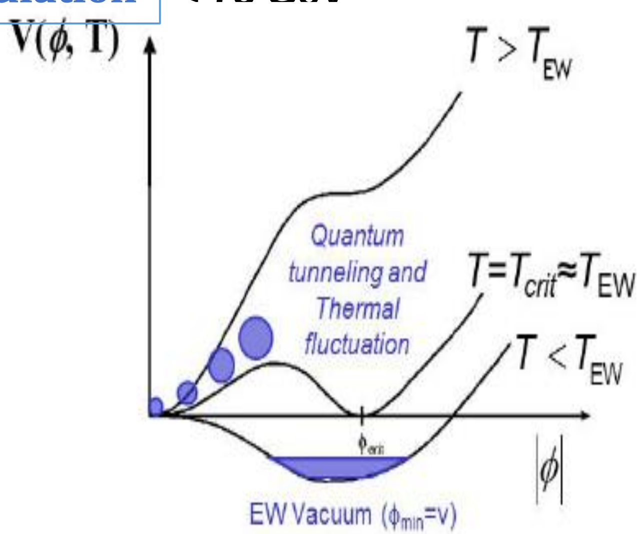
Double test on the Higgs potential



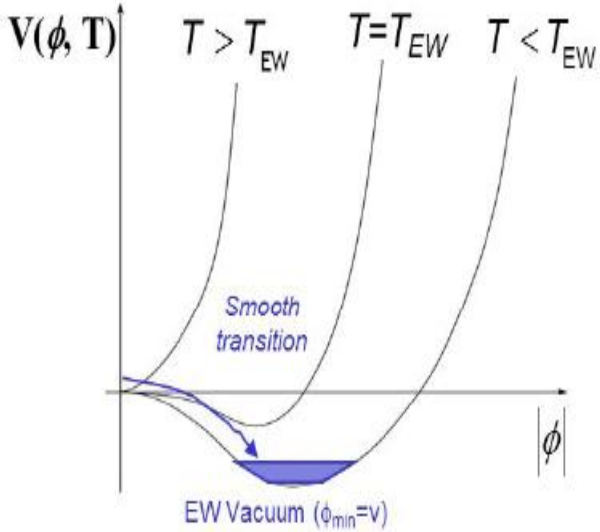
First-order phase transition (FOPT) in Higgs extended model motivated by baryogenesis, DM…

From lattice simulation

Strong First Order phase transition for m_H < 75 GeV



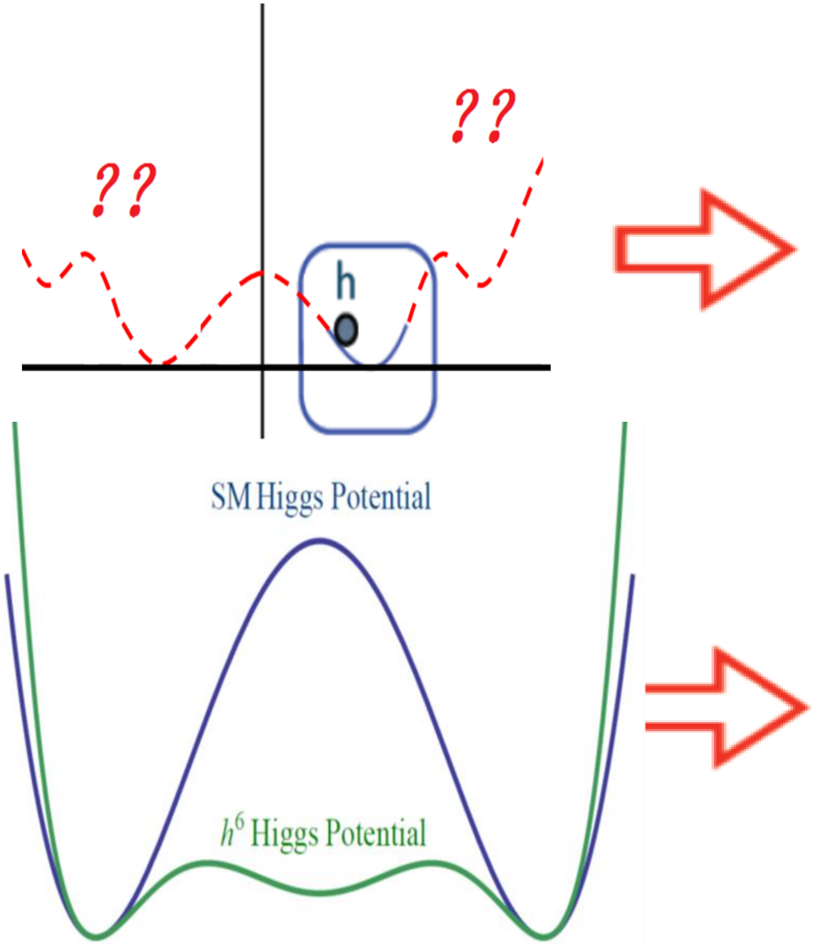
Cross over for m_H > 75 GeV



Extension of the Higgs sector is needed to produce strong first order phase transition for 125 GeV Higgs boson.

We study some well motivated extensions (baryogenesis, DM…) of the Higgs section, which can produce strong first-order phase transition.

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



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

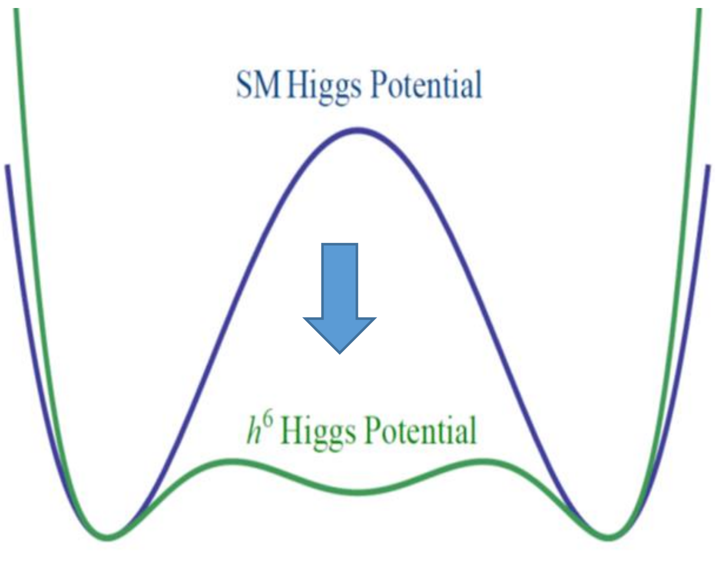
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

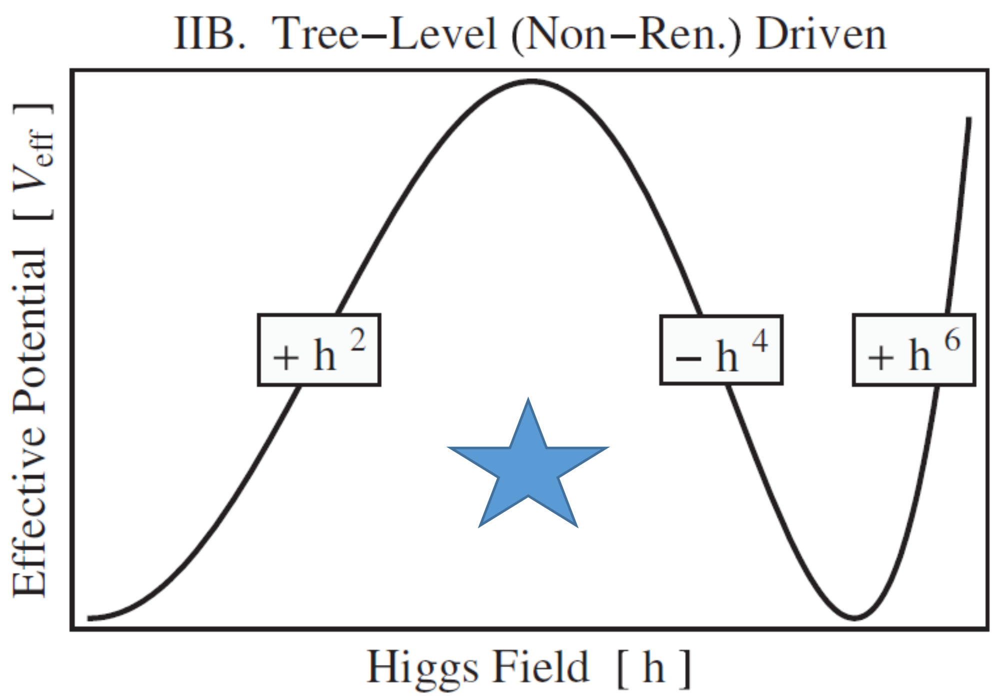
or $$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

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

- **The concerned dim-6 operators can be induced from certain renormalizable extension of the SM.**
- **We built simplified model with vector-like quark and triplet scalar.** model details see FPH, et. al Phys.Rev. D93 (2016) 103515

Here, we focus on the EW phase transition type





New Higgs potential and EW phase transition

For simplicity to investigate the signals from particle colliders to GW detector, we use the effective Lagrangian form for future discussion.

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

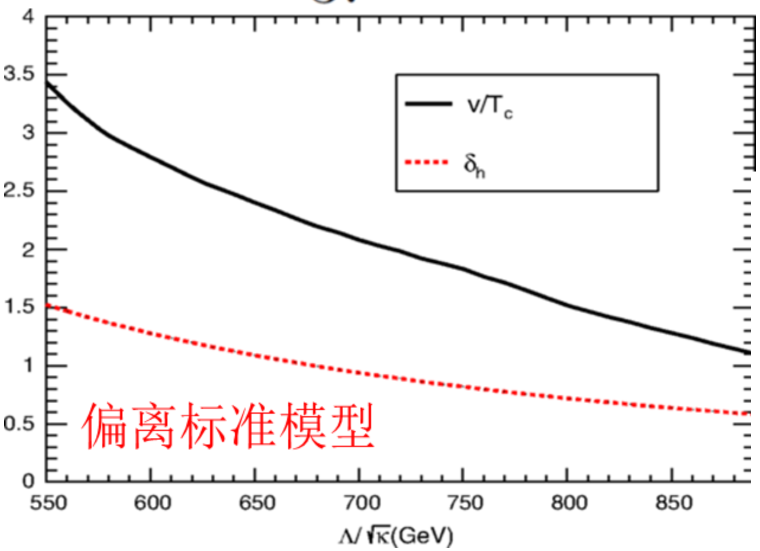
To study the EW phase transition, we need to calculate the one-loop finite temperature effective potential using the finite temperature field theory:

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

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
Lots of discussions, sorry that I can’t cover all

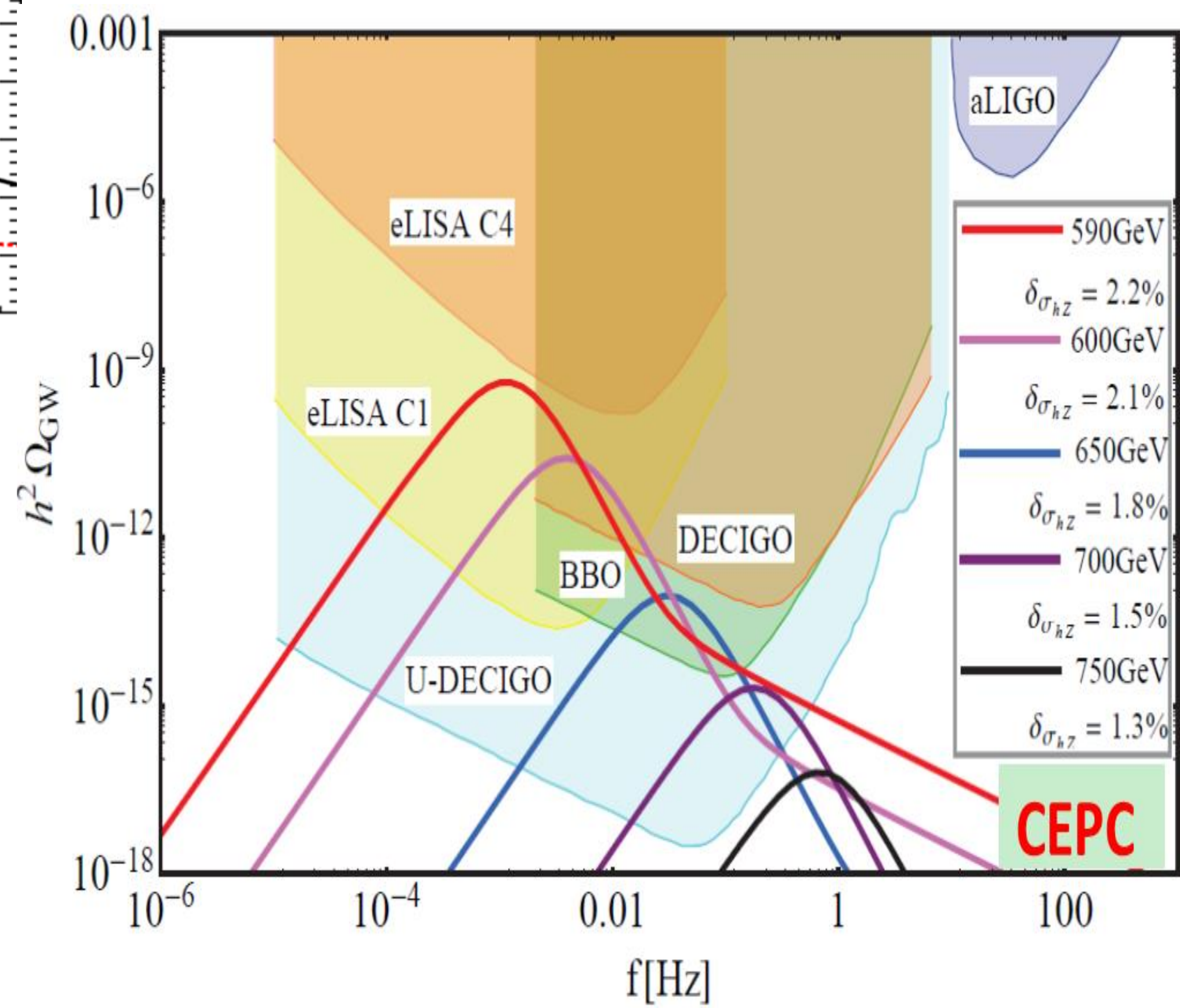
FOPT leads to obvious deviation of the tri-linear Higgs coupling

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



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

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



Correlate particle collider and GWs 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

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,
it is interesting to ask how well the type of FOPT induced by Higgs sextic operator be compatible with those EW precision tests.

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

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

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

SFOPT produce large δ_h **Then c_6 dominate the hZ cross section deviation**

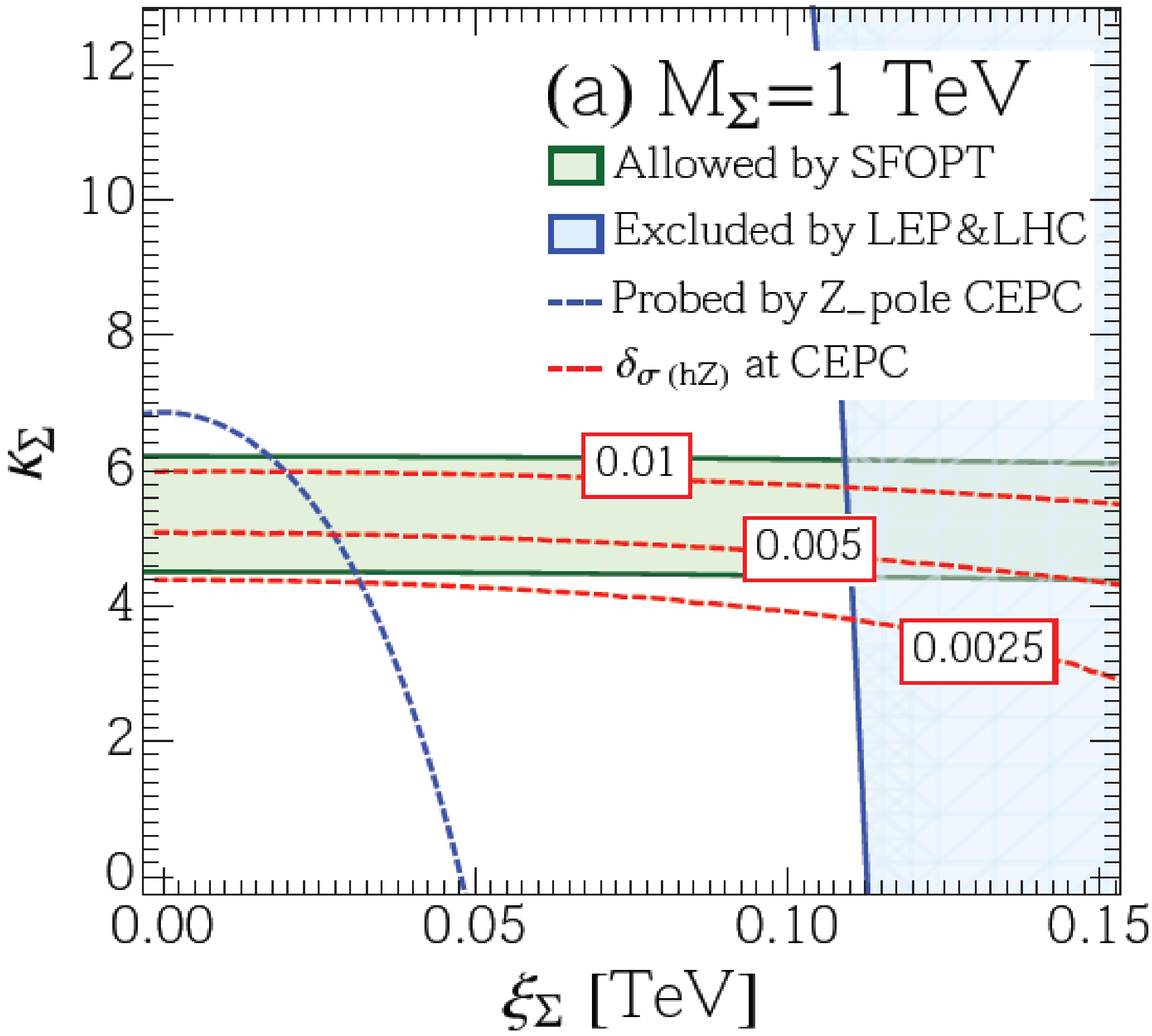
Renormalizable realization of the effective Lagrangian: triplet model

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

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

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 matched dimension-six operators and the corresponding coefficients in triplet scalar models.



The parameter space of triplet model(without hypercharge) that compatible with SFOPT and current experiments including the future CEPC's prediction.

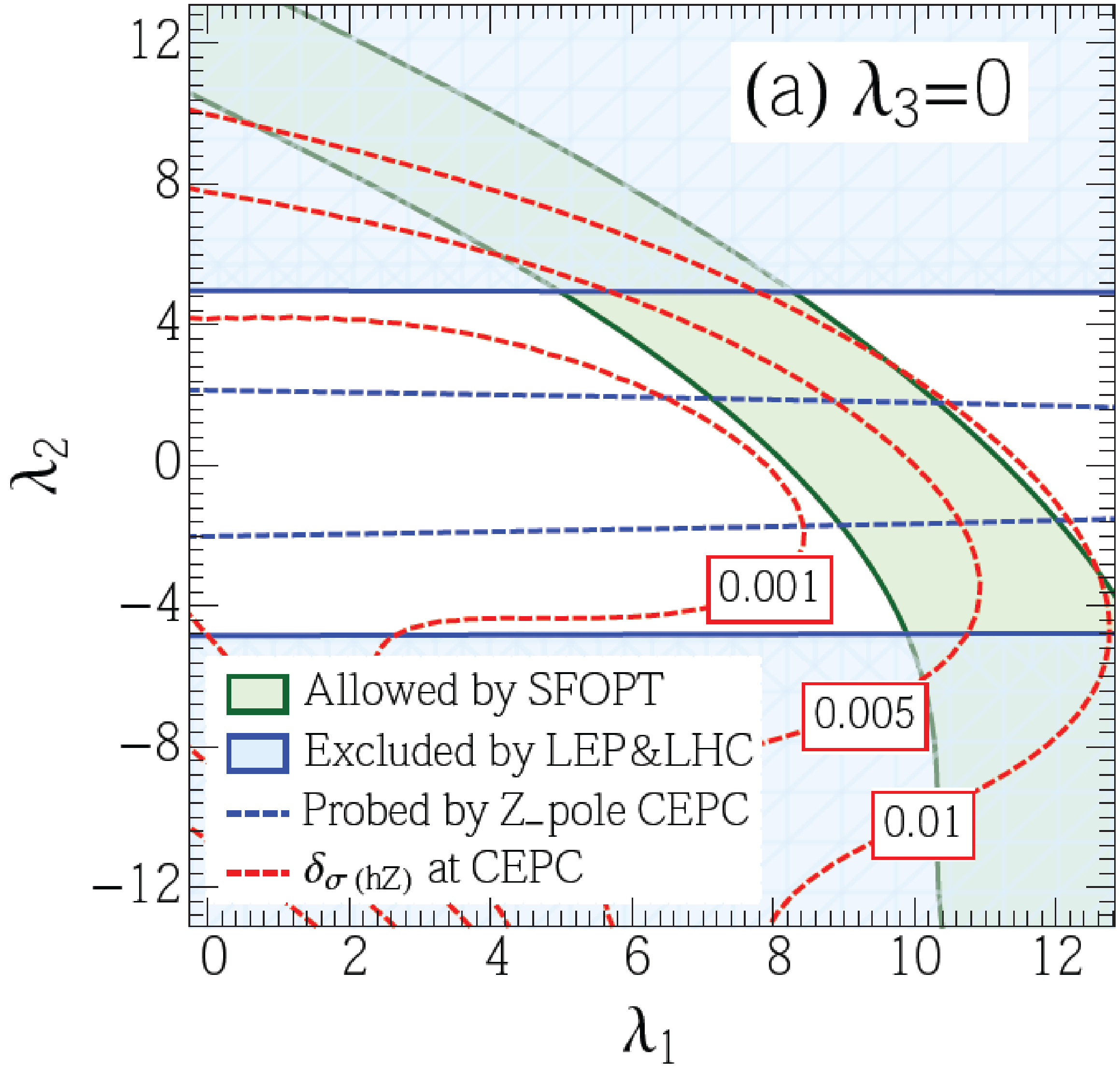
Qing-Hong Cao, FPH , Ke-Pan Xie, Xinmin Zhang arXiv:1708.0473

Renormalizable realization of the effective Lagrangian: doublet model

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

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

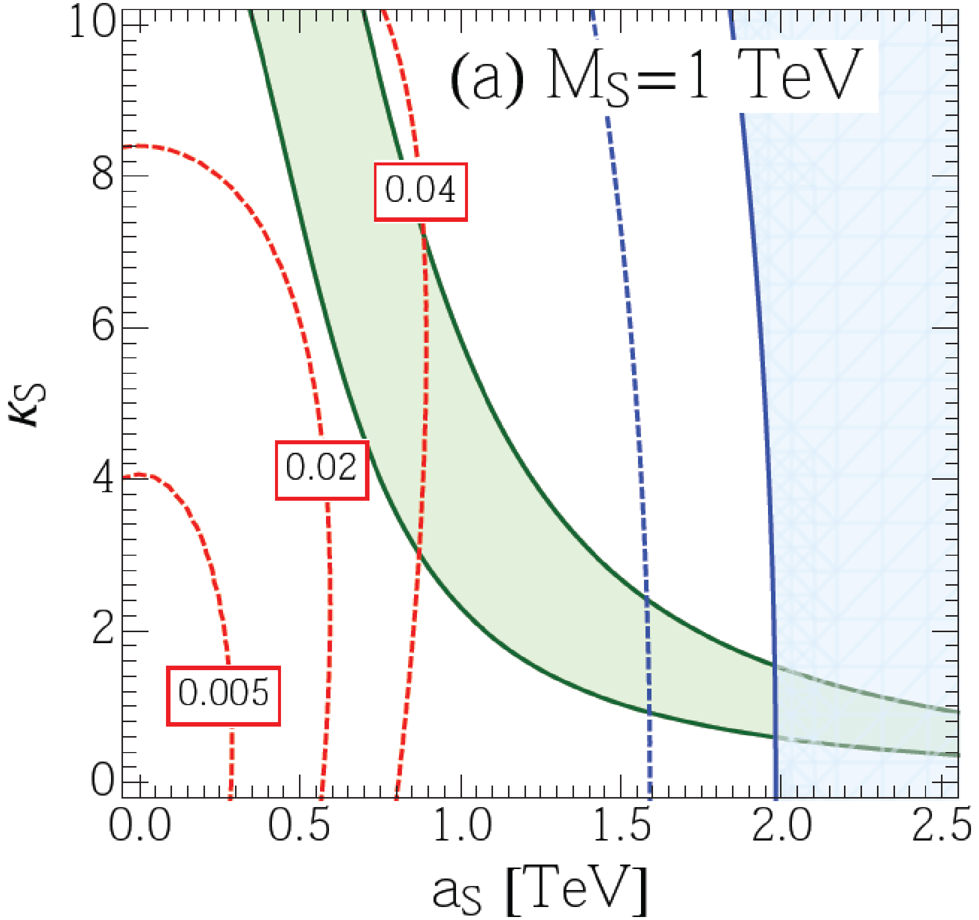
The matched dim-6 operators and the corresponding coefficients in the doublet scalar models.



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

Singlet model

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



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

II. Probing DM blind spot by GW&collider

Motivated by the absence of DM signals in DM direct detection (such as the recent LUX and PandaX-II), a generic classes of scalar DM models have been pushed to the blind spots where dark matter-Higgs coupling is approaching zero.
We use the complementary searches via phase transition GWs and the future lepton collider signatures to un-blinding 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

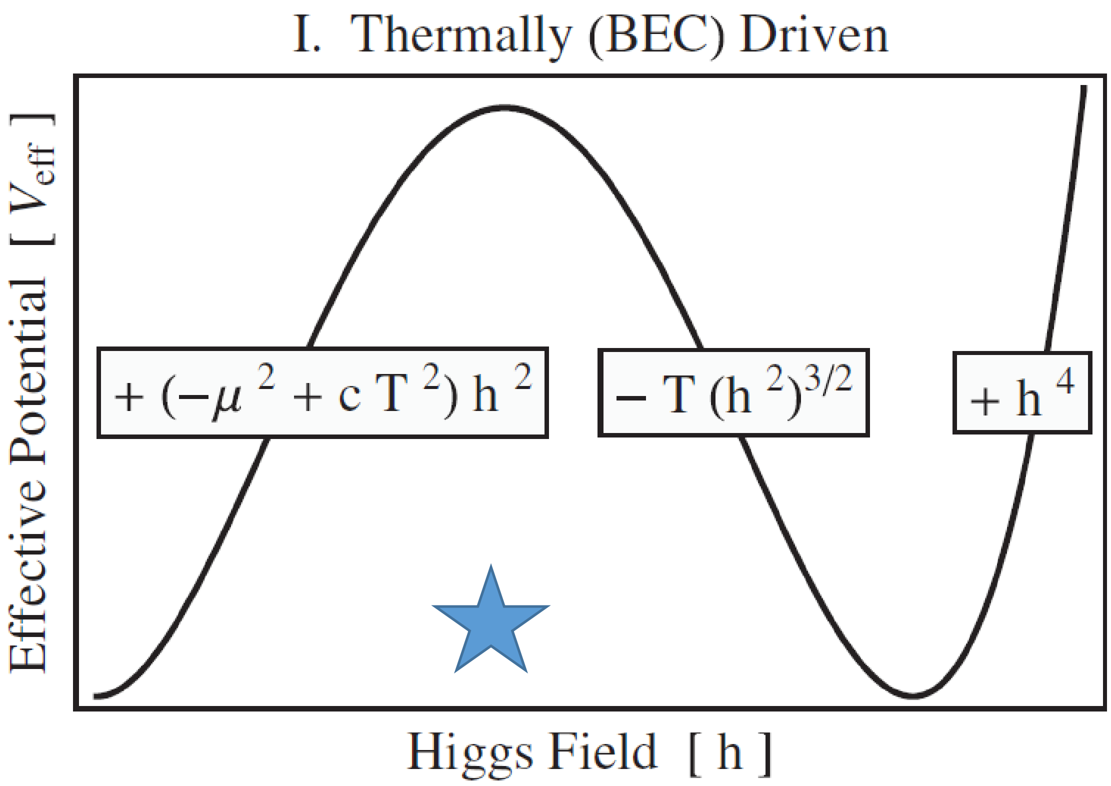
provide strong first order phase transition and phase transition GWs

FPH, Jiang-hao Yu arXiv: 1704.04201

One-loop finite temperature effective potential

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

EW phase transition type



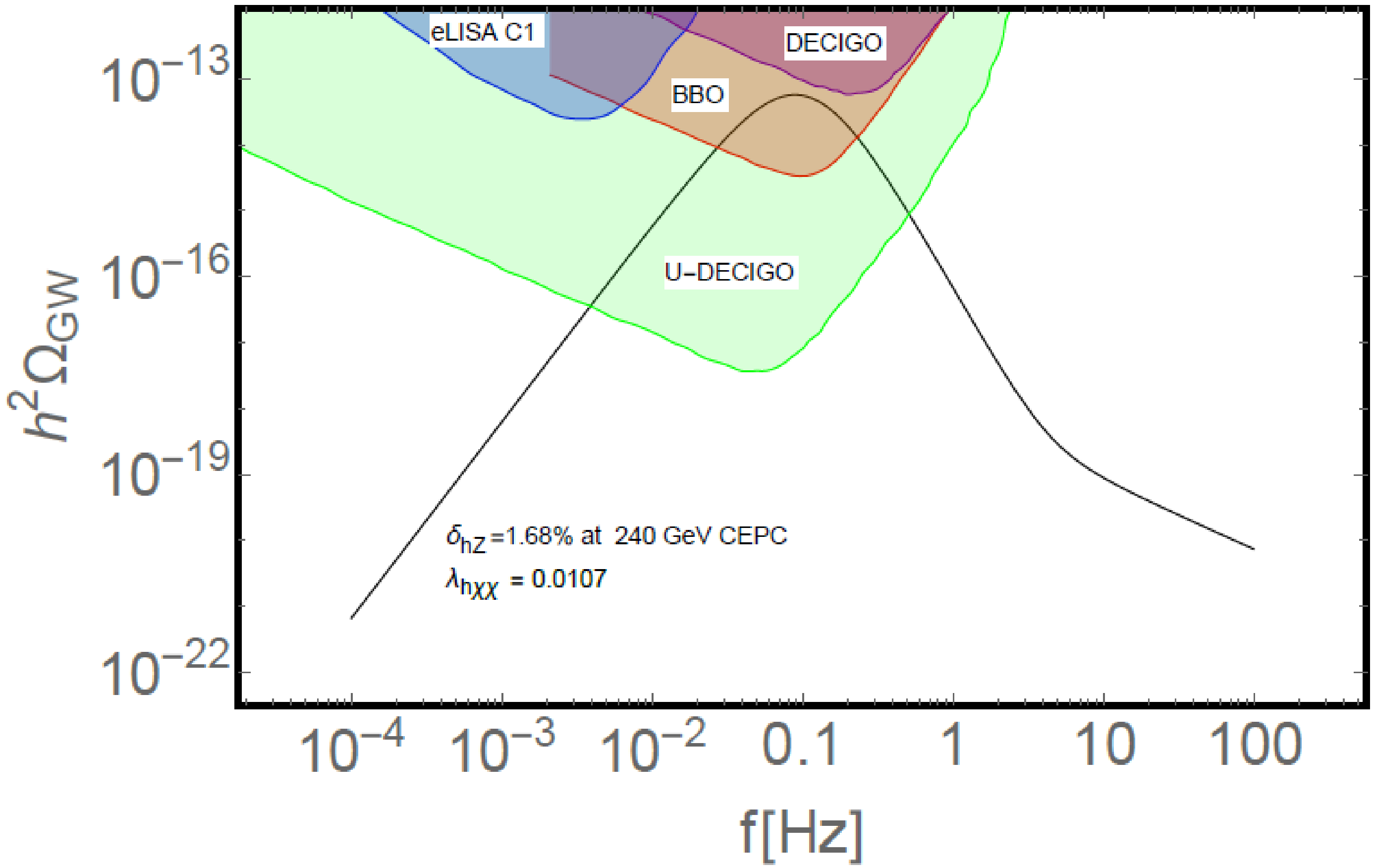
DM and first-order phase transition favors Higgs funnel region

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

Higgs funnel region: m_H around $55 \sim 75$ GeV with $\lambda_{345} < 0.04$;

Taking another set of benchmark points $\lambda_3 = 2.84726$, $\lambda_4 = \lambda_5 = -1.41293$, $M_D^2 = 3707.43$, the corresponding dark matter mass is 66 GeV, the pseudo scalar mass the the charged scalar mass are both 300 GeV, $\lambda_{h\chi\chi} = \lambda_{345}/2 = (\lambda_3 + \lambda_4 + \lambda_5)/2 = 0.0107$

Correlate dark matter, particle collider and GWs signals



- **CEPC and GW 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

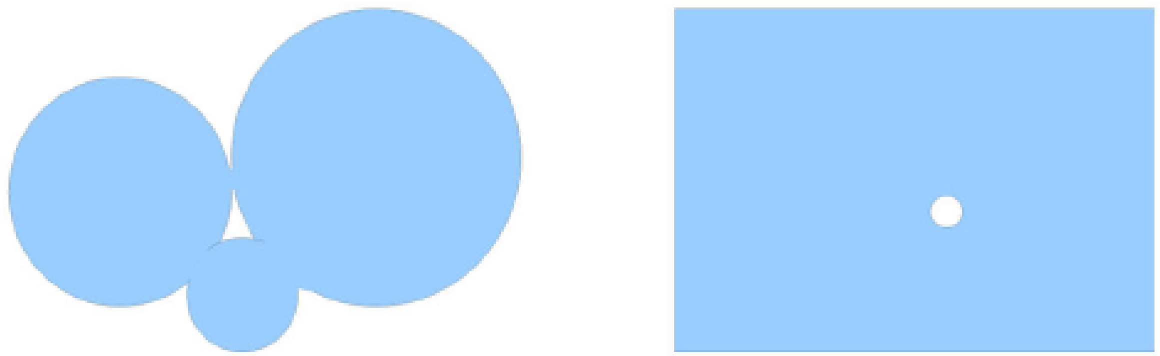
III. Probing baryogenesis and DM relaxed in phase transition by GW&colliders

The cosmic phase transition with Q-balls production mechanism can explain the baryogenesis and DM simultaneously, where constraints on DM masses and reverse dilution are significantly relaxed. We study how to probe this scenario by collider signals at QCD NLO and GW signals.

Many mechanisms to simultaneously solve the baryogenesis and DM puzzles usually have two strong constraints. One is that the DM mass is usually several GeV, and the other constraint is that in the most cases the baryon asymmetry produced by heavy particles decays should not be washed ou by inverse processes. In order to guarantee the efficiency production of BAU, we need to tune the reheating temperature carefully

FPH, Chong Sheng Li. **arXiv:1709.09691** **Phys.Rev. D96 (2017) no.9, 095028**

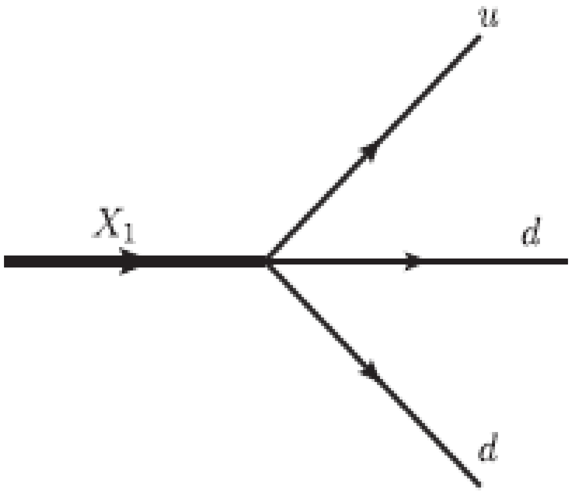
First-order phase transition naturally correlate DM, baryogenesis, particle collider and GW signals.

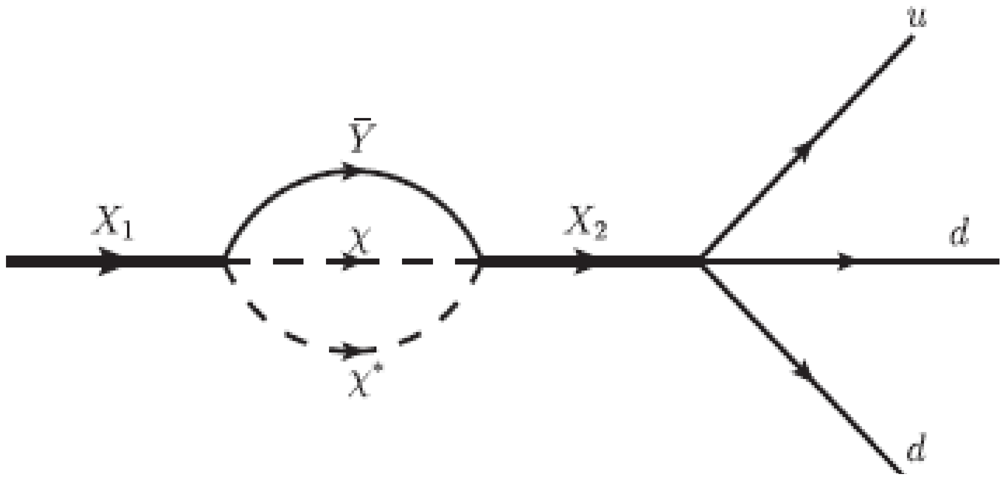


$$
\begin{aligned}
\mathcal{L} = & \frac{1}{2}(\partial_\mu S)^2 - U(S) + (\partial_\mu \chi)^*(\partial_\mu \chi) - k_1^2 S^2 \chi^* \chi \\
& - \sum_i \frac{h_i^2}{2} S^2 \phi_i^2 + \sum_i \frac{1}{2}(\partial_\mu \phi_i)^2 \\
& - \sum_{a=1,2} \frac{\lambda_a^{ijk}}{\Lambda^2} \bar{X}_a P_R D_i \bar{U}_j^C P_R D_k + \frac{\zeta_a}{\Lambda} \bar{X}_a Y^C \chi \chi^* \\
& + \mathrm{H.c.}
\end{aligned}
$$

Step I: In the early universe, the potential is symmetric and S has no vacuum expectation value (VEV). We call it symmetry phase.

Baryon asymmetry in symmetry phase by heavy particle decay from the interference effects between the tree-level diagram and two-loop diagram:



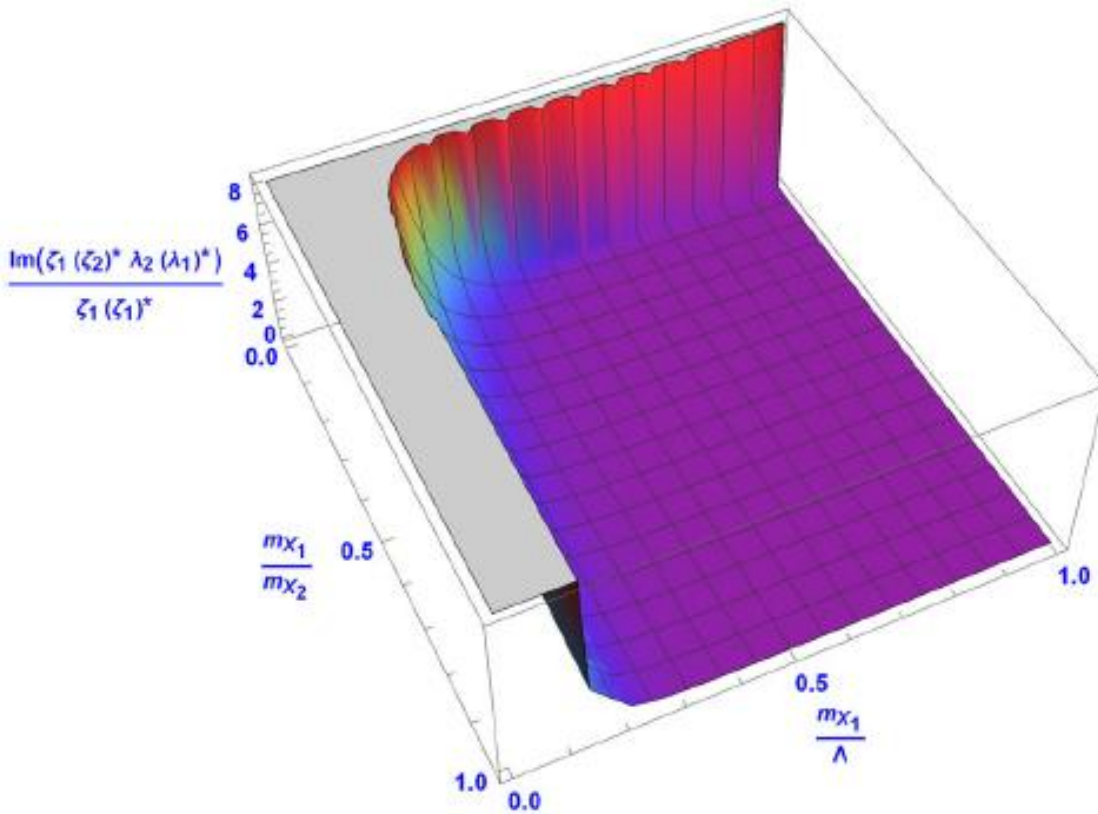


The produced baryon asymmetry is proportional to ϵ

$$\varepsilon \equiv \frac{1}{2\Gamma_{X_1}}\left(\Gamma(X_1 \to udd) - \Gamma(\bar{X}_1 \to \bar{u}\,\bar{d}\,\bar{d})\right)$$

$$\sim 10^{-5} \times \frac{\mathrm{Im}[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{|\zeta_1|^2} \frac{m_{X_1}}{m_{X_2}} \left(\frac{m_{X_1}}{\Lambda}\right)^4 .$$

$$\text{as}\quad \eta_B \equiv n_B/s \sim \varepsilon/g_*$$
$$\eta_B \simeq 10^{-10},\ \varepsilon \sim 10^{-8}$$



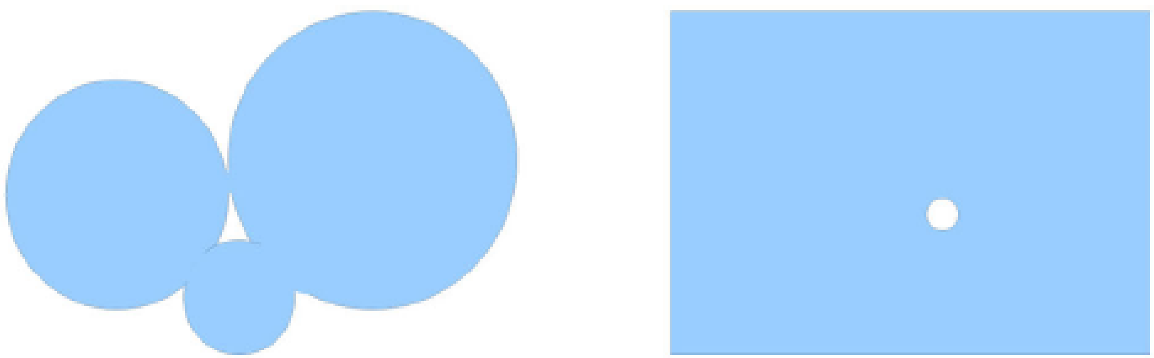
The allowed parameters spaces for successful BAU.

Step II: After the needed baryon asymmetry is produced, a strong first-order phase transition occurs when S acquires VEV(symmetry breaking phase).

The χ particles trapped in the symmetry phase and become the so called Q-ball DM.

E.Krylov,A.Levin,V.Rubakov,Phys.Rev.D87(2013)no.8,083528

Q-ball is proposed by T.D. Lee in 1976,which is a compact non-topological soliton objects in a field theory of a complex scalar field with U(1) global symmetry.

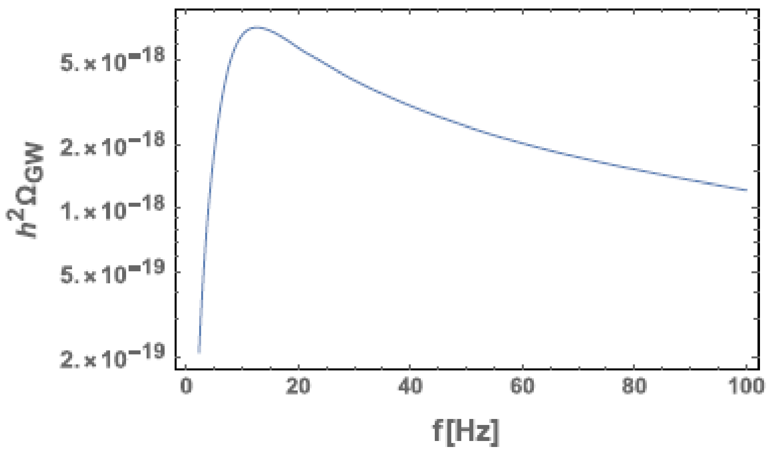


Final conditions to produce the observed BAU and DM density

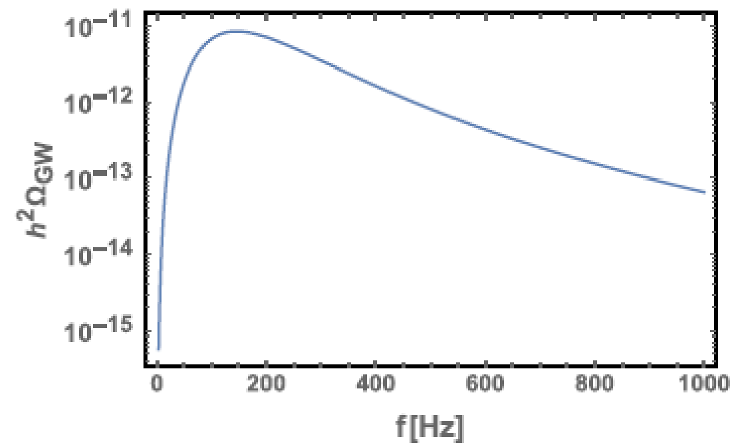
FPH, Chong Sheng Li. **arXiv:1709.09691** **Phys.Rev. D96 (2017) no.9, 095028**

$$\rho_{\rm DM}^4 v_b^{3/4} = 73.5(2\eta_B s_0)^3 \lambda_S \sigma^4 \Gamma^{3/4}$$

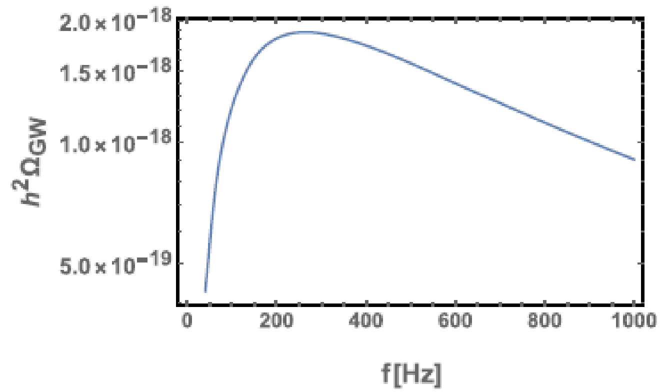
The predicted GW spectrum for benchmark I with vb = 0.3. Figure(a), (b), (c) represents the GW spectrum from bubble collision, sound waves and turbulence, respectively, which may be detected by future LIGO like experiments



(a)



(b)



(c)

Collider phenomenology

From the Lagrangian there are many types of combinations for the up-type quark and down-type quark, which result in abundant collider phenomenology at the LHC.

The dominant decay channel of behaves as the missing energy in the detector. The subdominant process of four jet (X can decay to three quarks) is not discussed in this work.

So the interactions can be explored by performing mono-jet and mono-top analysis at the LHC.

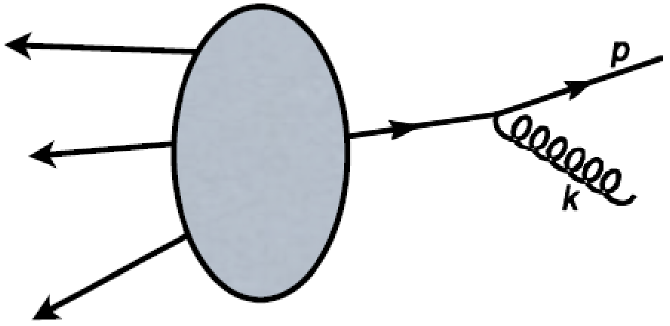
Because the LHC is a proton-proton collider with high precision, the QCD NLO predictions for these processes are necessary in order to obtain reliable results.

QCD NLO prediction at the LHC

We perform QCD the next-leading-order (NLO) correction for these two cases and discuss the discovery potential at the LHC.

QCD NLO calculation:Infrared divergence

Origin of singular contributions: soft and collinear emission



$$\frac{1}{(p+k)^2} = \frac{1}{2\,p\cdot k} = \frac{1}{2E_qE_g(1-\cos\theta_{qg})}$$

soft collinear

QCD NLO calculation:
Two cutoff phase space slicing method (δs,δc).

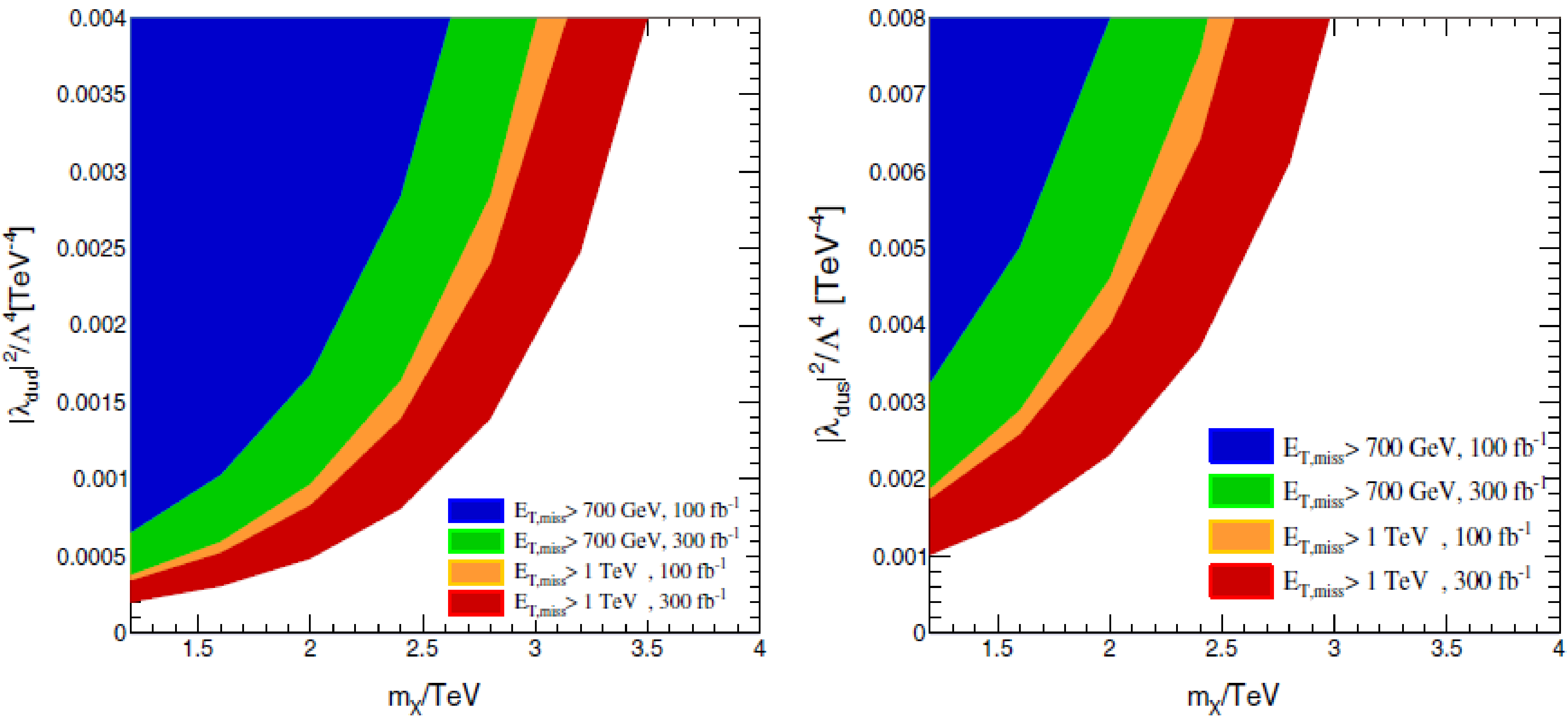


FIG. 7. Constraints on coupling λ_{ijk} and mass m_X by monojet measurements at the 13 TeV LHC.

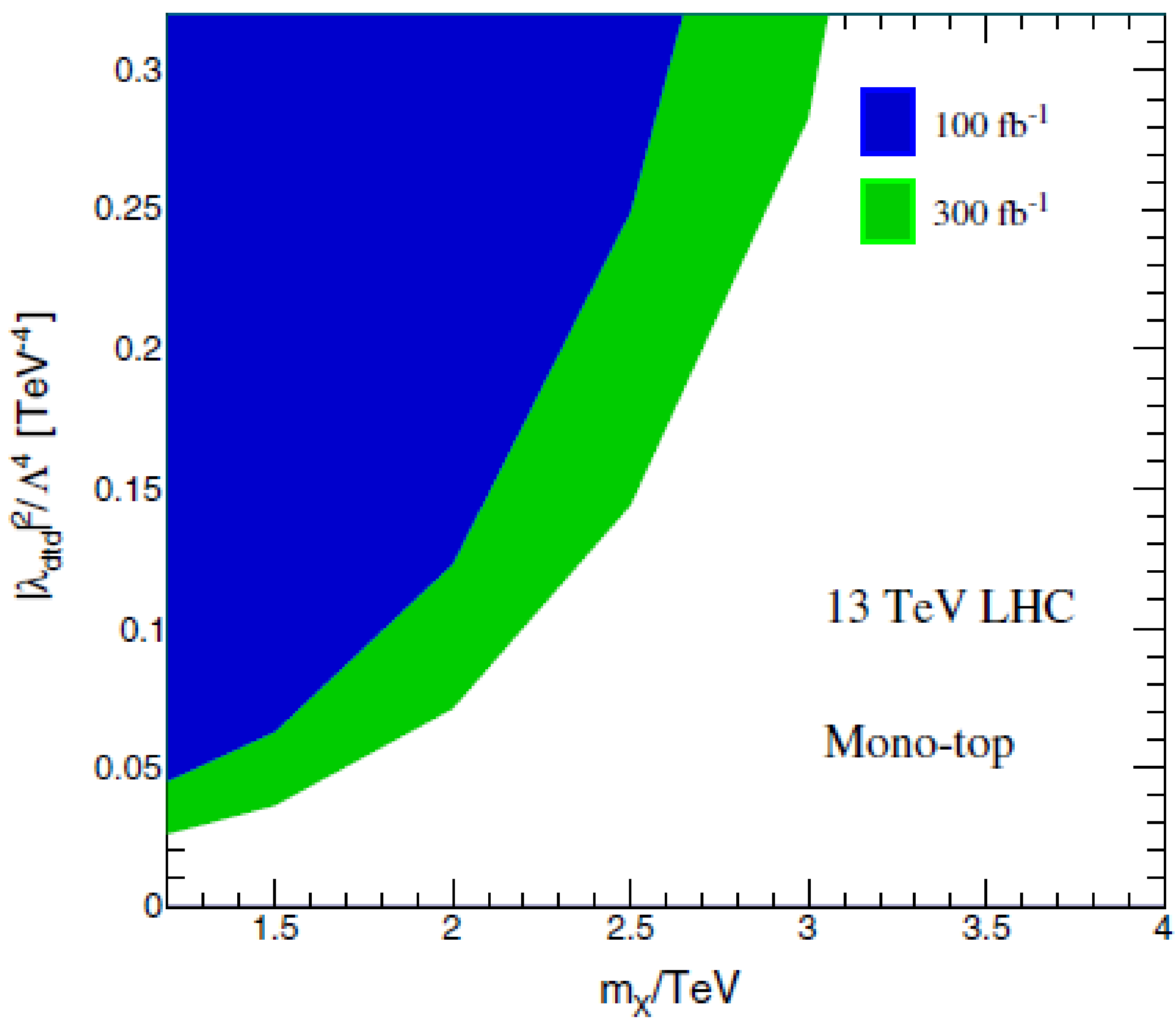
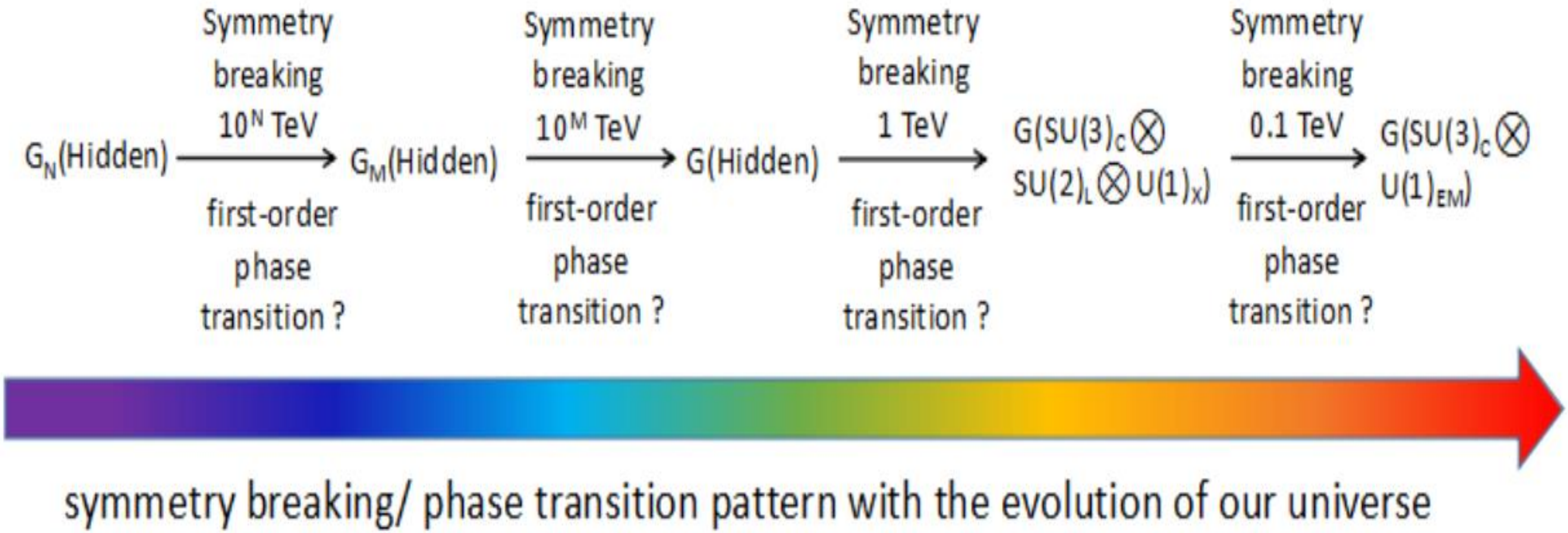
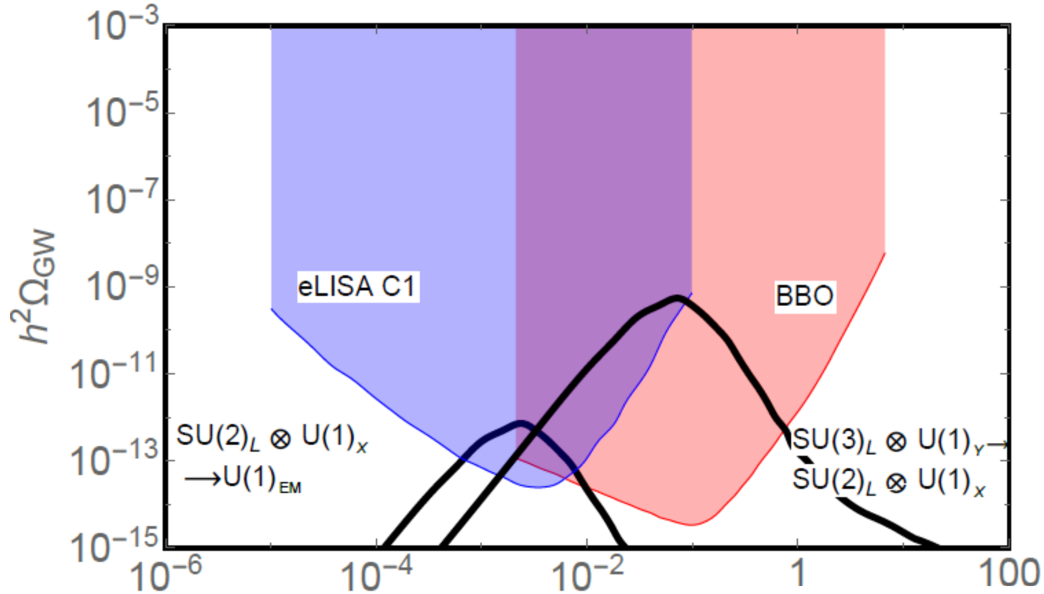


FIG. 9. Normalized spectra for signal and background in monotop searching at the 13 TeV LHC.

GWs motivated by symmetry breaking history of the universe

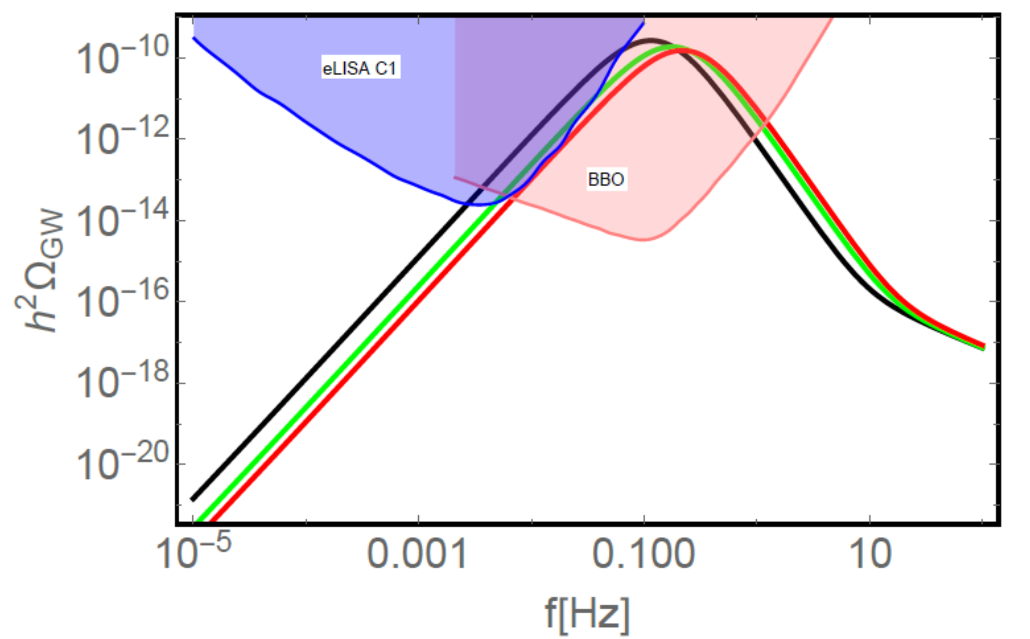


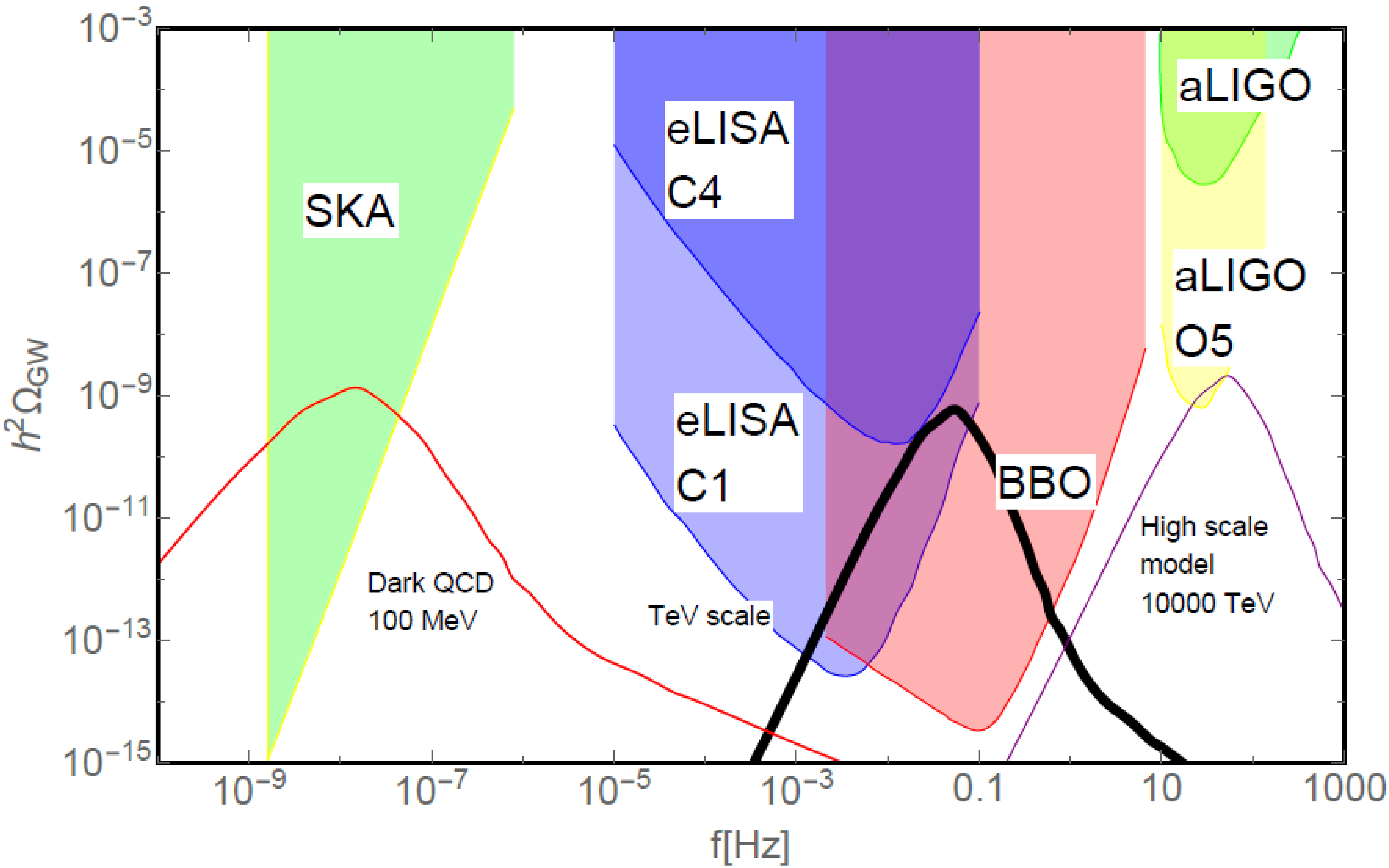
Our early universe may undergo one or several times spontaneously symmetry breaking associated with first order phase transition in a generic classes of gauge group extended SM models, which may produce detectable GW.



f[Hz]

$$SU(3)_c \otimes SU(3)_L \otimes U(1)_Y$$





Schematic phase transition GW spectra

Probing the gauge symmetry breaking of the early universe and new physics by gravitational waves

FPH, Xinmin Zhang, arXiv:1701.04338

Summary

- For cosmology, our universe may undergo one or several times phase transition. And we can hear the cosmological phase transition using GW.
- The phase transition process in the early universe may play an important role in solving the fundamental problems in particle cosmology.
- For particle physics, this phase transition GW approach can compensate for the collider experiments to explore the new physics models (especially the hidden sector) and provide a novel approach to probe the symmetry breaking or phase transition patterns.
- For particle cosmology, GW provides a novel way to unravel the dark matter, baryogenesis……

Outlook

- **New physics models in particle physics can provide abundant GW source! !**
- **GW becomes a new and realistic approach to explore the particle cosmology and fundamental physics.**

For example, Probing extra dimension through gravitational wave observations of compact binaries and their electromagnetic counterparts **using the fact that graviton can travel shortcuts in extra dimension** Hao Yu, Bao-min Gu, **FPH**, Yong-qiang wang , Xin-he meng, Yu-xiao liu. JCAP 1702 (2017) no.02, 039

Thanks for your attention