Hearing the echoes of dark matter and new physics

Fa Peng Huang

(CTPU-IBS)

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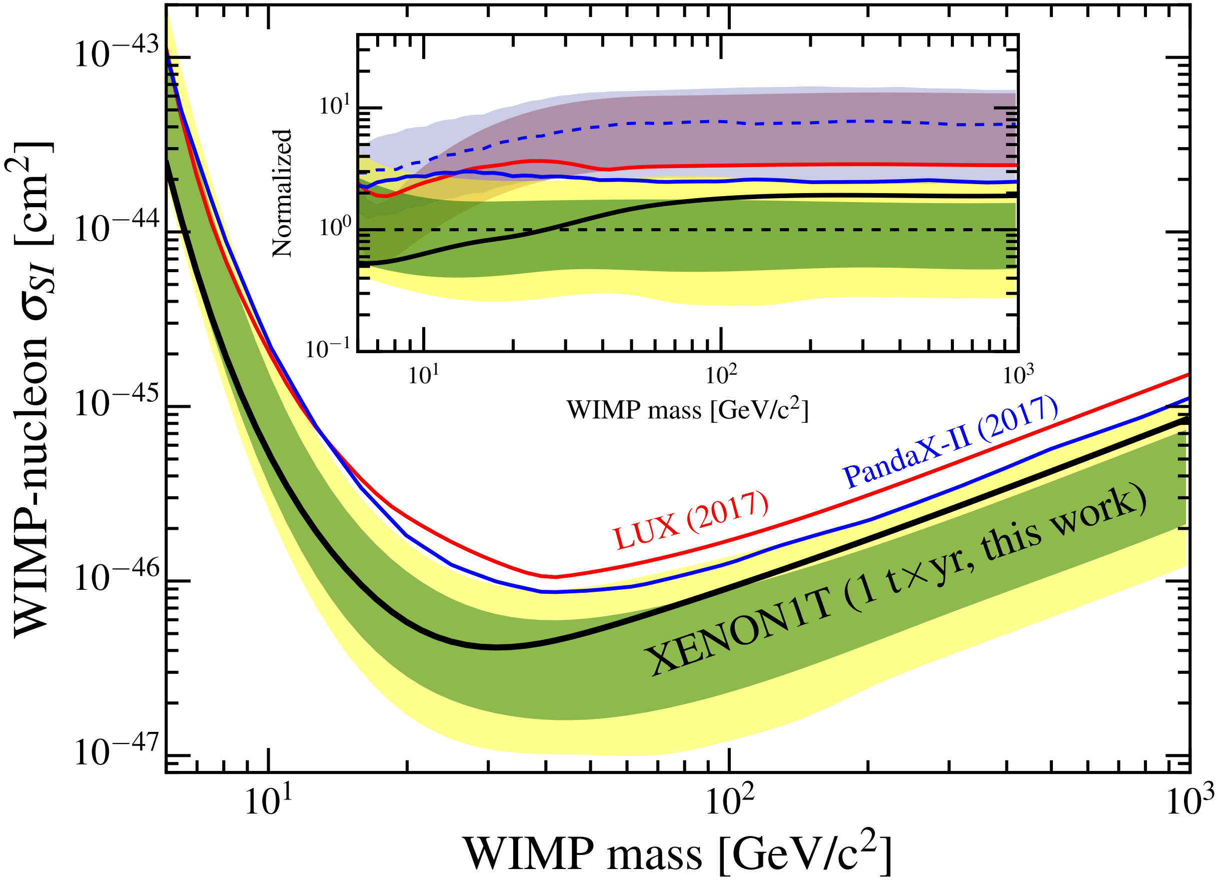
Outline

- ➢Research Motivation
- ➢Phase transition gravitational wave (GW) in a nutshell
- ➢Probing dark matter (DM) blind spots by GW&Collider
- ➢Probing baryogenesis and DM simultaneously by GW&Collider
- ➢Probing other new physics (NP) by GW
- ➢Summary and outlook

Motivation

Motivated by the absence of DM signal in DM direct detection experiments and NP signal at LHC, we study how to hear the echoes of the NP, especially the DM and baryogenesis by new approaches, such as the Laser Interferometer experiments (aLIGO, LISA 2034, Tianqin, Taiji…) and pulsar timing array experiments (SKA, FAST…).



arXiv:1805.12562

Motivation

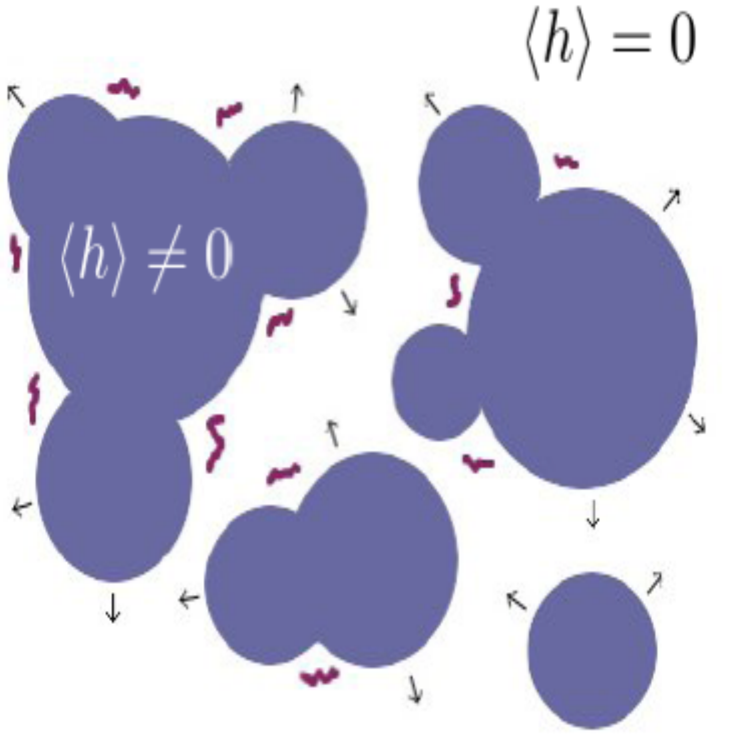
- The observation of GW by aLIGO has initiated a new era of exploring the nature of gravity, cosmology and the fundamental particle physics by GW.

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

- GW may be used to hear the echoes of DM, baryogenesis, NP models, symmetry breaking patterns of the universe.

Hearing the signal of dark sectors with gravitational wave detectors
J.Jaeckel, V. V. Khoze, M. Spannowsky, Phys.Rev. D94 (2016) no.10, 103519

phase transition GW in a nutshell



Strong First-order phase transition (FOPT) 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 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);

To discuss the phase transition GW spectra in NP models, it is necessary to begin with the one-loop finite temperature effective potential:

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

where Φ represents the order parameter of the phase transition (a real scalar field), V_{cw} is the one-loop Coleman-Weinberg potential at $T = 0$, and $V_{\text{ther}} + V_{\text{daisy}}$ 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 bubble nucleation rate, the profile of the scalar field needs to be calculated by solving the following bounce equation using the overshooting/undershooting method:

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

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.)

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

Bubble collision

$$\Omega_{\rm co}(f)h^2 \simeq 1.67\times10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\lambda_{co}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{\frac{1}{3}} \times\left(\frac{0.11v_b^3}{0.42+v_b^3}\right)\left[\frac{3.8(f/f_{\rm co})^{2.8}}{1+2.8(f/f_{\rm co})^{3.8}}\right].$$

Turbulence

$$\Omega_{\rm tu}(f)h^2 \simeq 3.35\times10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\lambda_{\rm tu}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*^t}\right)^{\frac{1}{3}} v_b \times\frac{(f/f_{\rm tu})^3}{(1+f/f_{\rm tu})^{11/3}(1+8\pi f a_0/(a_* H_*))}.$$

Sound wave

$$\Omega_{\rm sw}(f)h^2 \simeq 2.65\times10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\lambda_{sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{\frac{1}{3}} v_b \times\left[\frac{7(f/f_{\rm sw})^{6/7}}{4+3(f/f_{\rm sw})^2}\right]^{7/2},$$

I. Probing DM blind spot by GW&collider

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

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

provide natural DM candidate

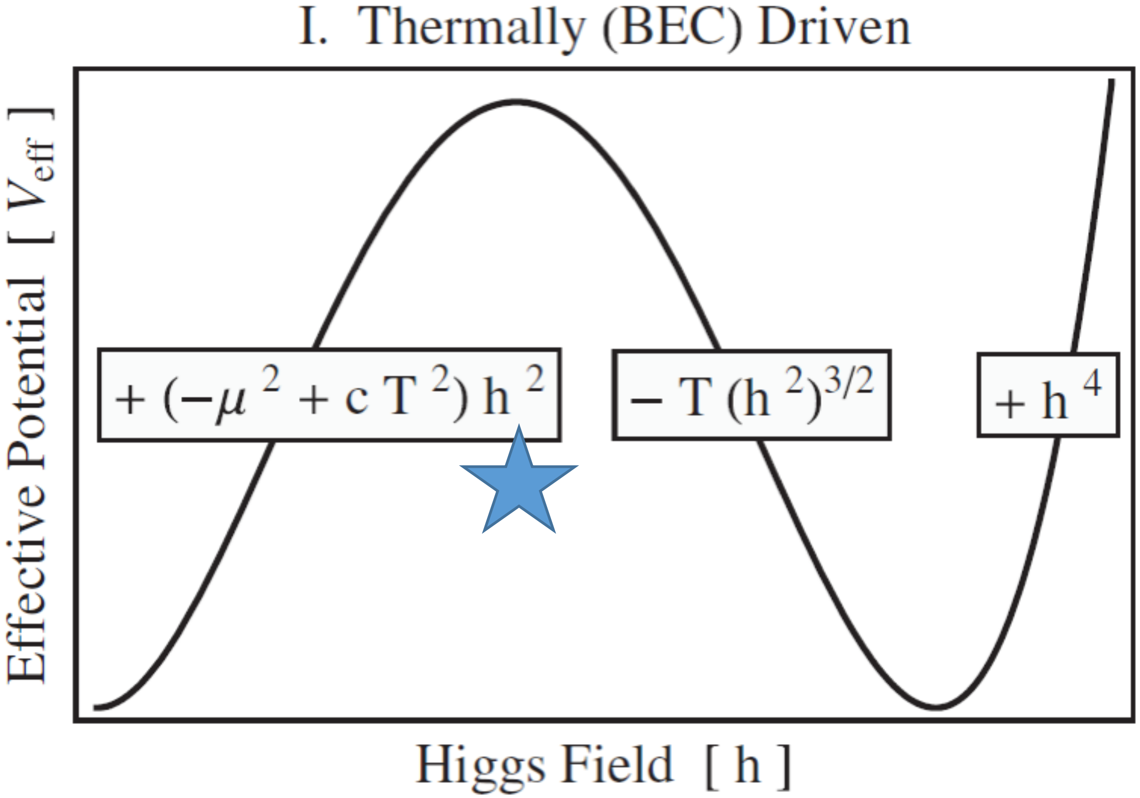
provide strong FOPT and phase transition GW

FPH, Jiang-hao Yu, arXiv: 1704.04201

One-loop finite temperature effective potential

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

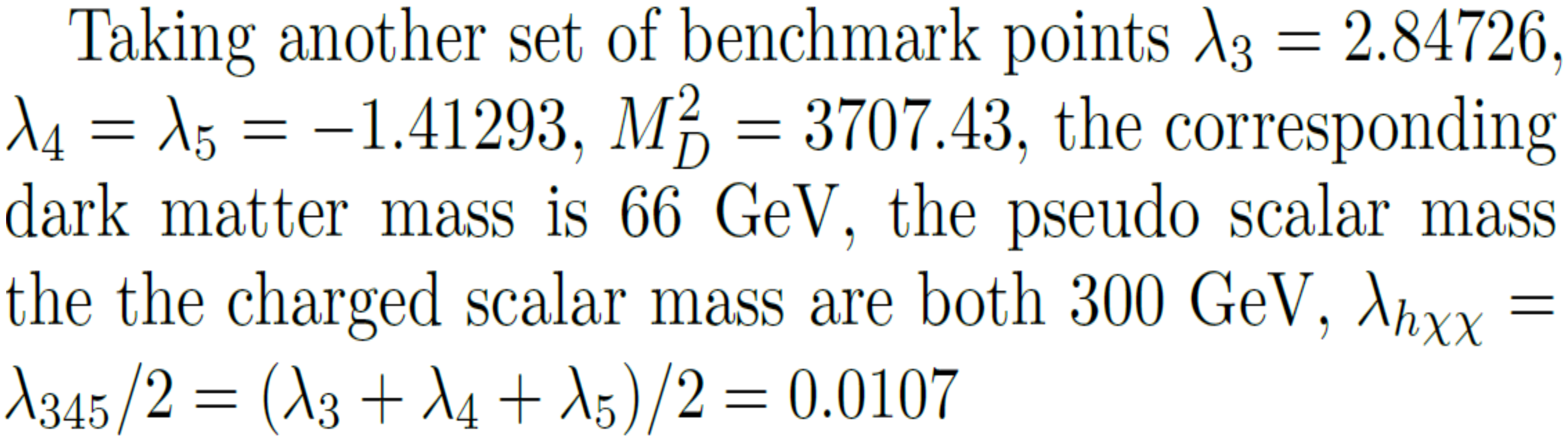
EW phase transition type in inert doublet model



DM and FOPT favor Higgs funnel region

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

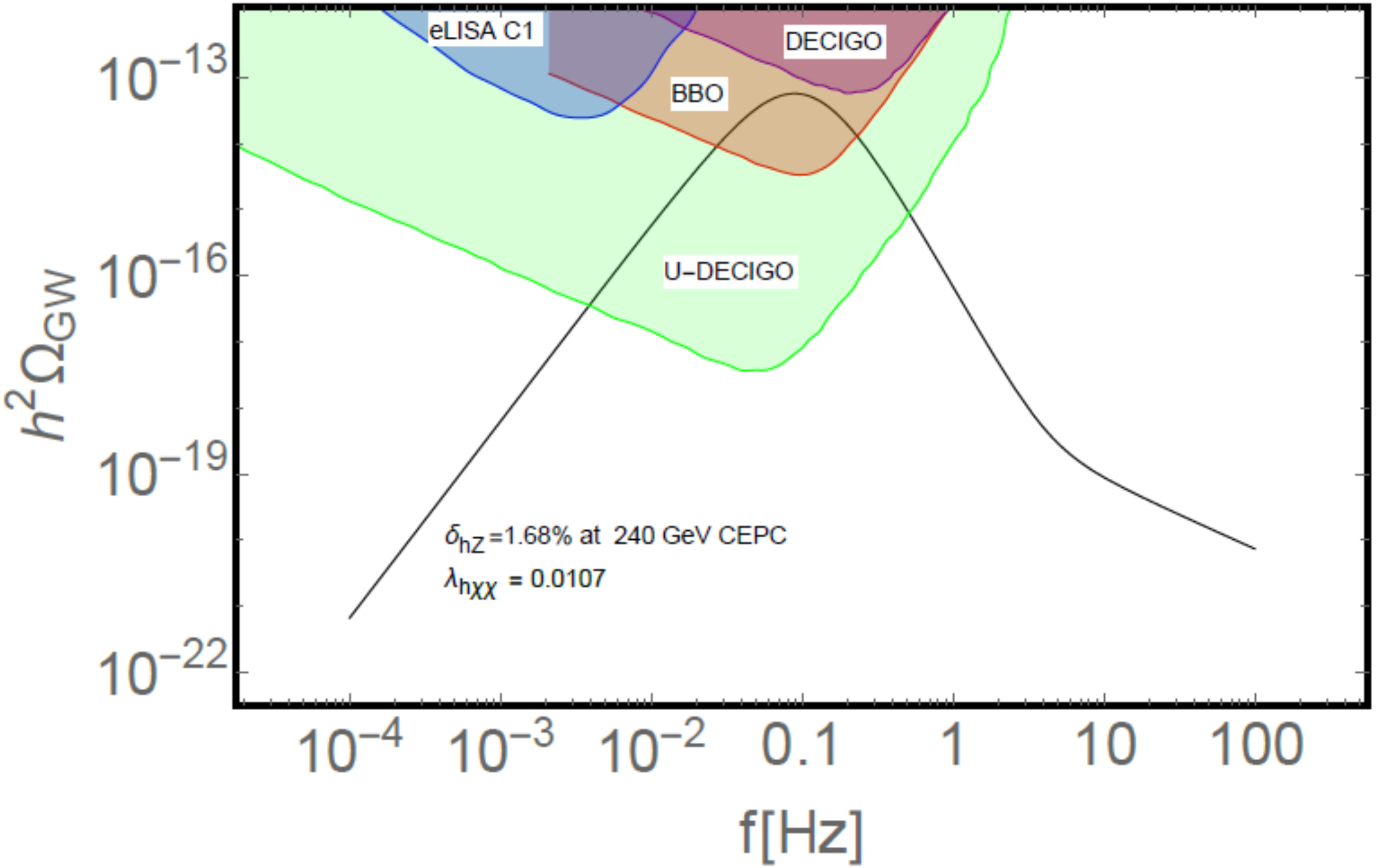
Higgs funnel region: the DM mass is about half of the Higgs mass



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, $\lambda_{h\chi\chi} = \lambda_{345}/2 = (\lambda_3 + \lambda_4 + \lambda_5)/2 = 0.0107$

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

Correlate DM, particle collider and GW signals



$$\delta_{hZ} \equiv \frac{\sigma - \sigma_{SM}}{\sigma_{SM}}$$

- **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

Work in progress with Eibun Senaha to include the baryogenesis in minimal extended inert doublet model

II. Probing DM and baryogenesis relaxed in phase transition by GW&Collider

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

FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028

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 out by inverse processes. In order to guarantee the efficiency production of BAU, we need to tune the reheating temperature carefully.

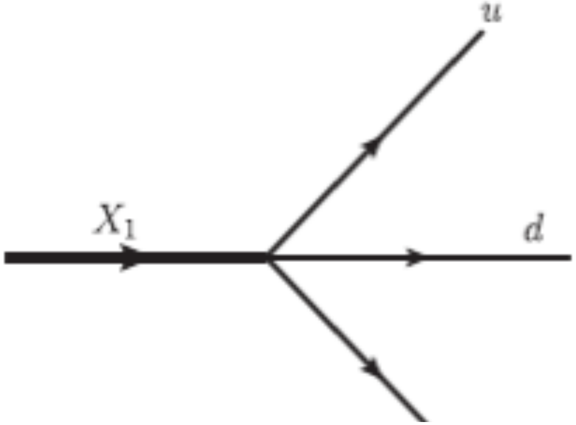
B. Shuve, C. Tamarit, JHEP 1710 (2017) 122

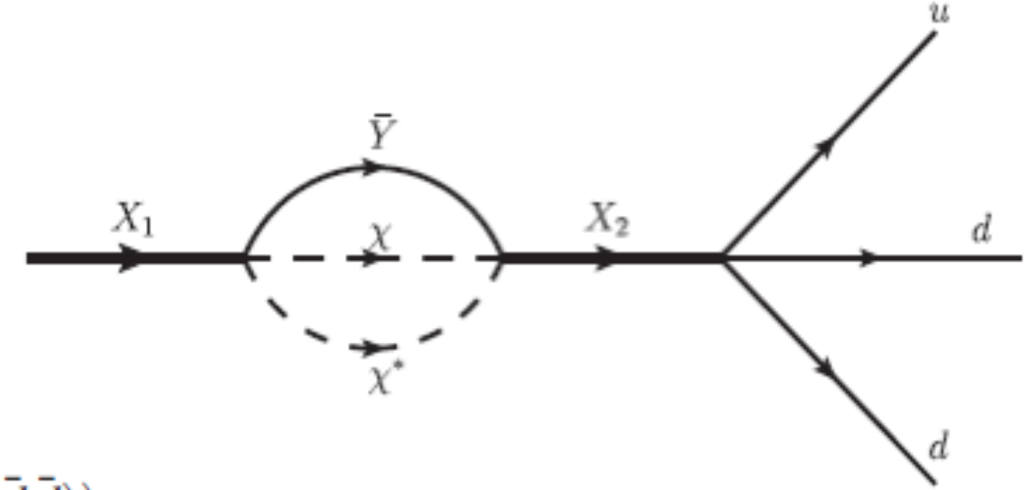
FOPT naturally correlates DM, baryogenesis, particle collider and GW signals.

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

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 can be generated by heavy particle decay from the interference effects between the tree-level diagram and two-loop diagram:





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

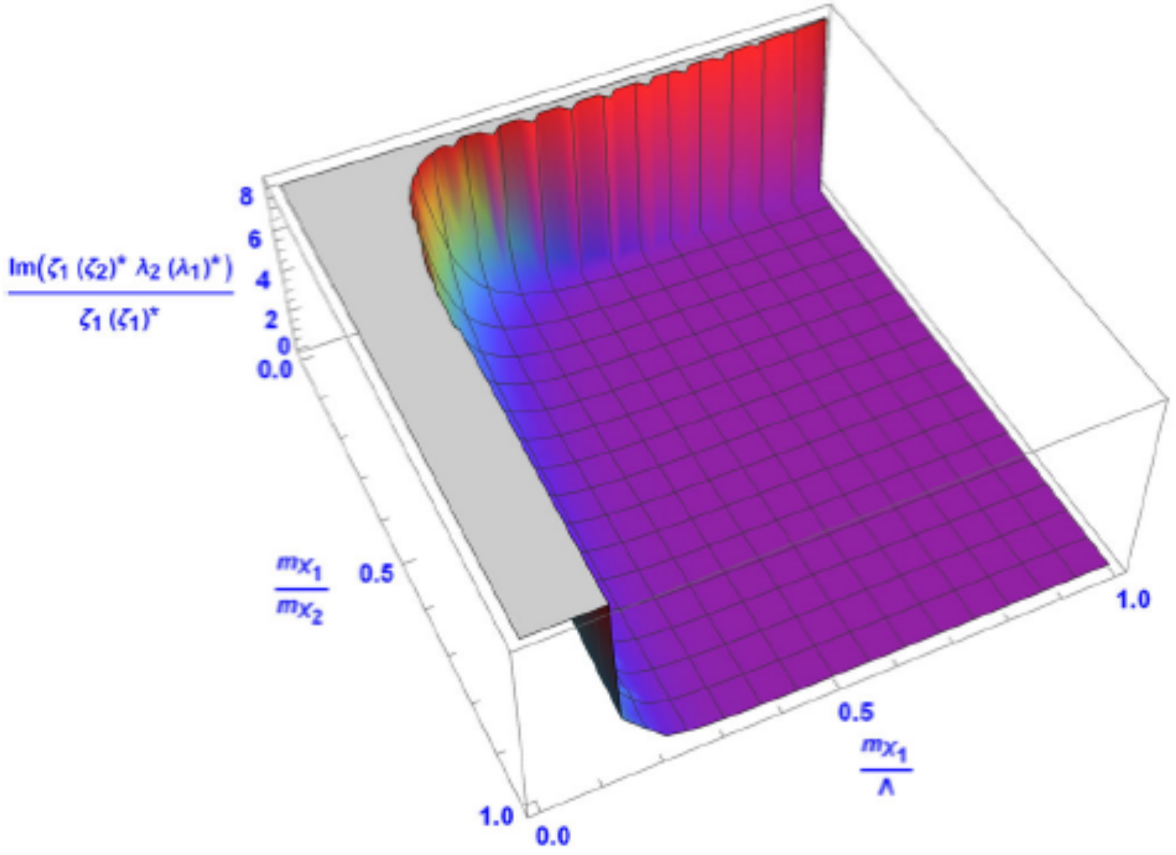
$$\sim 10^{-5} \times \frac{\mathrm{Im}[\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*]}{|\zeta_1|^2} \frac{m_{X_1}}{m_{X_2}} \left(\frac{m_{X_1}}{\Lambda}\right)^4.$$

The produced baryon asymmetry is proportional to ϵ

The allowed parameter spaces for successful baryon asymmetry of the universe

$$\text{as} \quad \eta_B \equiv n_B/s \sim \varepsilon/g_*$$

$$\eta_B \simeq 10^{-10}, \;\; \varepsilon \sim 10^{-8}$$



Step II: After the needed baryon asymmetry is produced, a strong FOPT occurs when S acquires VEV(symmetry breaking phase). Then, χ obtains huge mass.

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

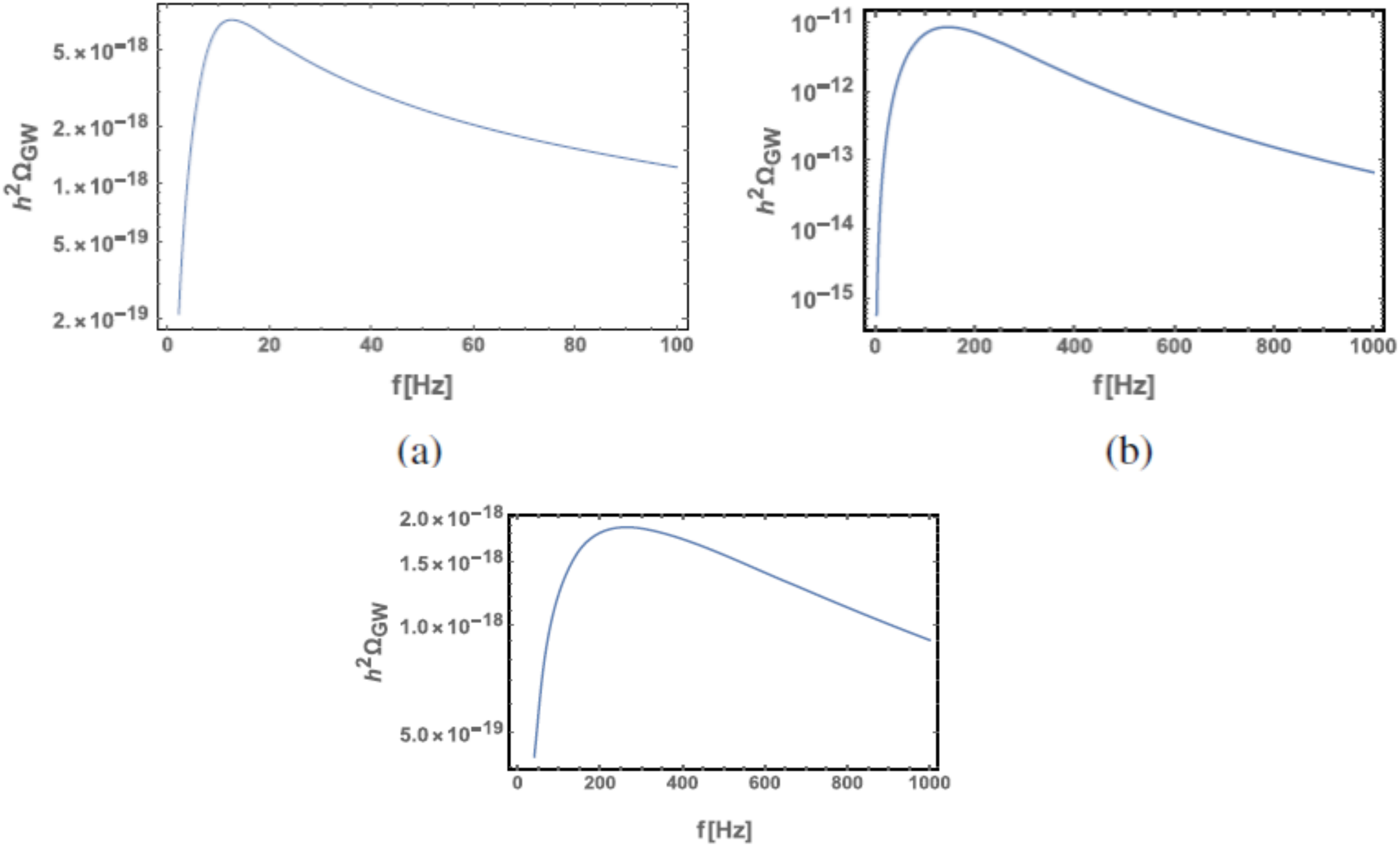
E.Krylov,A.Levin,V.Rubakov,Phys.Rev.D87(2013)no.8,083528

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 baryon asymmetry and DM density: FPH, C.S. Li, **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 points with $v_b = 0.3$. 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

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 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.

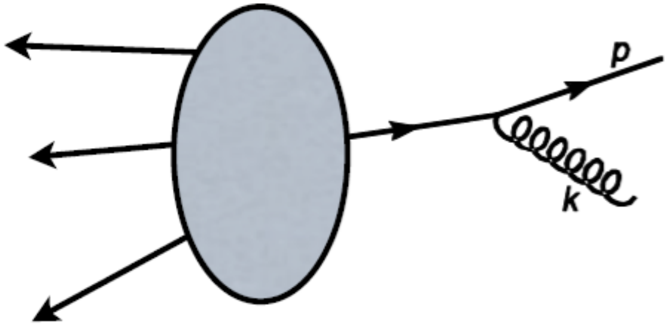
Because the LHC is a proton-proton collider with high precision, the QCD NLO predictions for these processes are necessary in order to obtain reliable results.

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.

The Key point for QCD NLO calculation is Infrared divergence

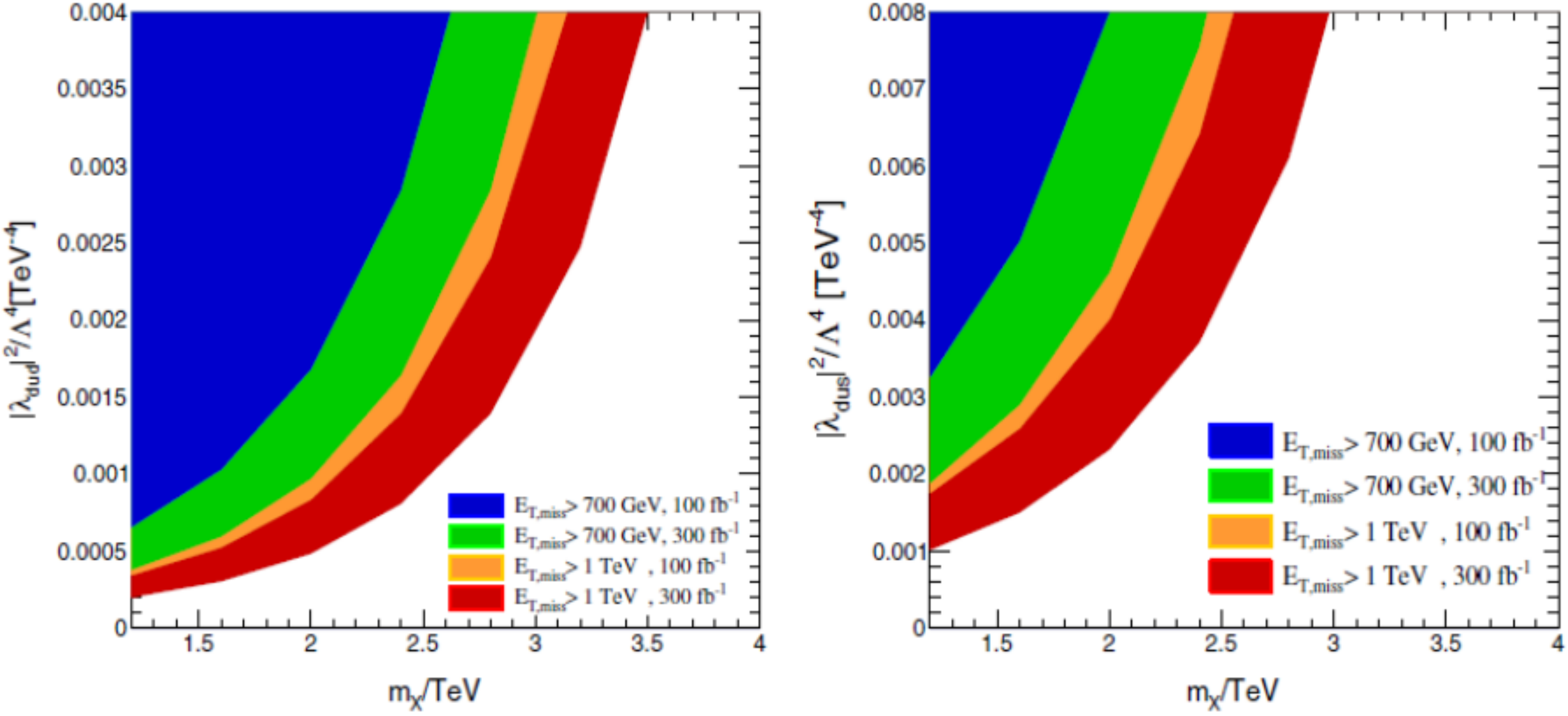
Origin of singular contributions: soft and collinear emission



$$\frac{1}{(p+k)^2}=\frac{1}{2\,p\cdot k}=\frac{1}{2E_q\underset{\substack{\uparrow\\ \text{soft}}}{E_g}(1-\underset{\substack{\uparrow\\ \text{collinear}}}{\cos\theta_{qg}})}$$

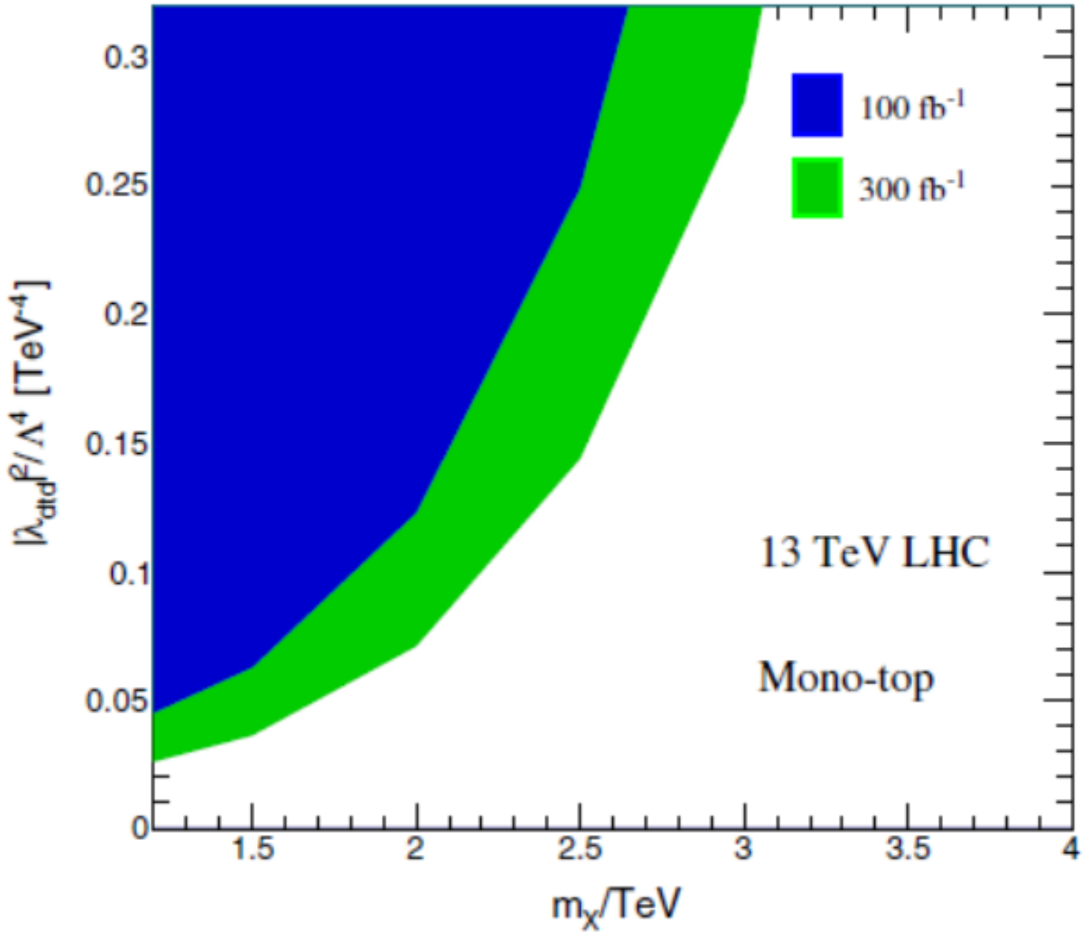
QCD NLO calculation:
Two cutoff phase space slicing method (δs,δc).

Mono-jet analysis at QCD NLO



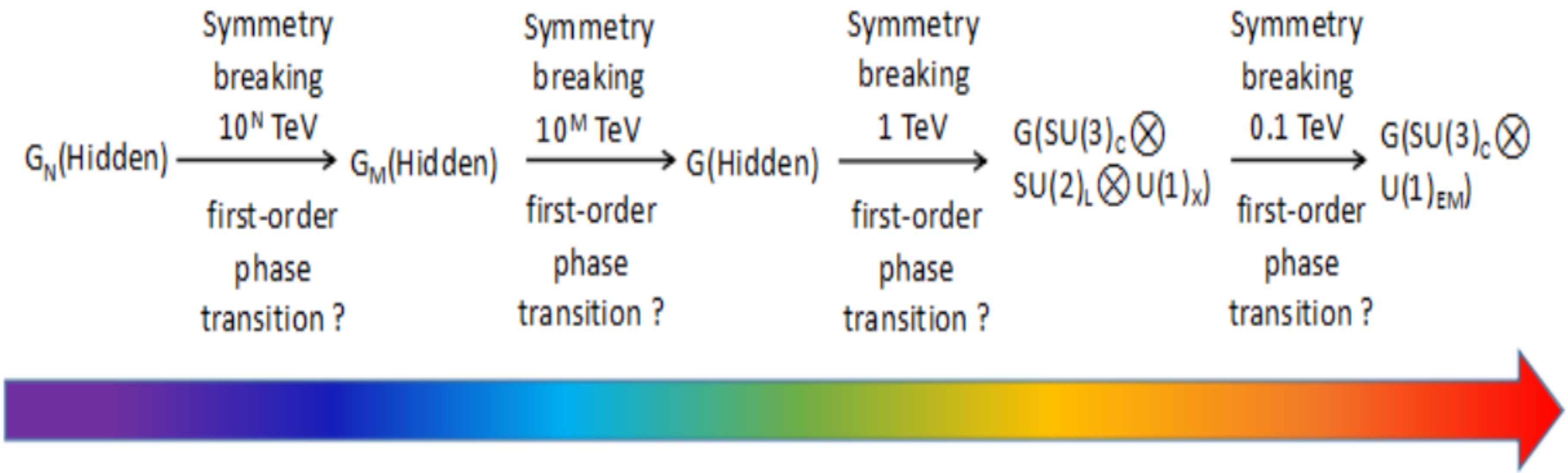
Constraints on coupling λ_{ijk} and mass m_X by monojet measurements at the 13 TeV LHC.

Mono-top analysis at QCD NLO



FPH, C.S. Li , **Phys.Rev. D96 (2017) no.9, 095028**

III. GW from other NP



$$G_N(\text{Hidden}) \xrightarrow[\text{first-order phase transition ?}]{\text{Symmetry breaking } 10^N \text{ TeV}} G_M(\text{Hidden}) \xrightarrow[\text{first-order phase transition ?}]{\text{Symmetry breaking } 10^M \text{ TeV}} G(\text{Hidden}) \xrightarrow[\text{first-order phase transition ?}]{\text{Symmetry breaking } 1 \text{ TeV}} G(SU(3)_c \otimes SU(2)_L \otimes U(1)_X) \xrightarrow[\text{first-order phase transition ?}]{\text{Symmetry breaking } 0.1 \text{ TeV}} G(SU(3)_c \otimes U(1)_{EM})$$

symmetry breaking/ phase transition pattern with the evolution of our universe

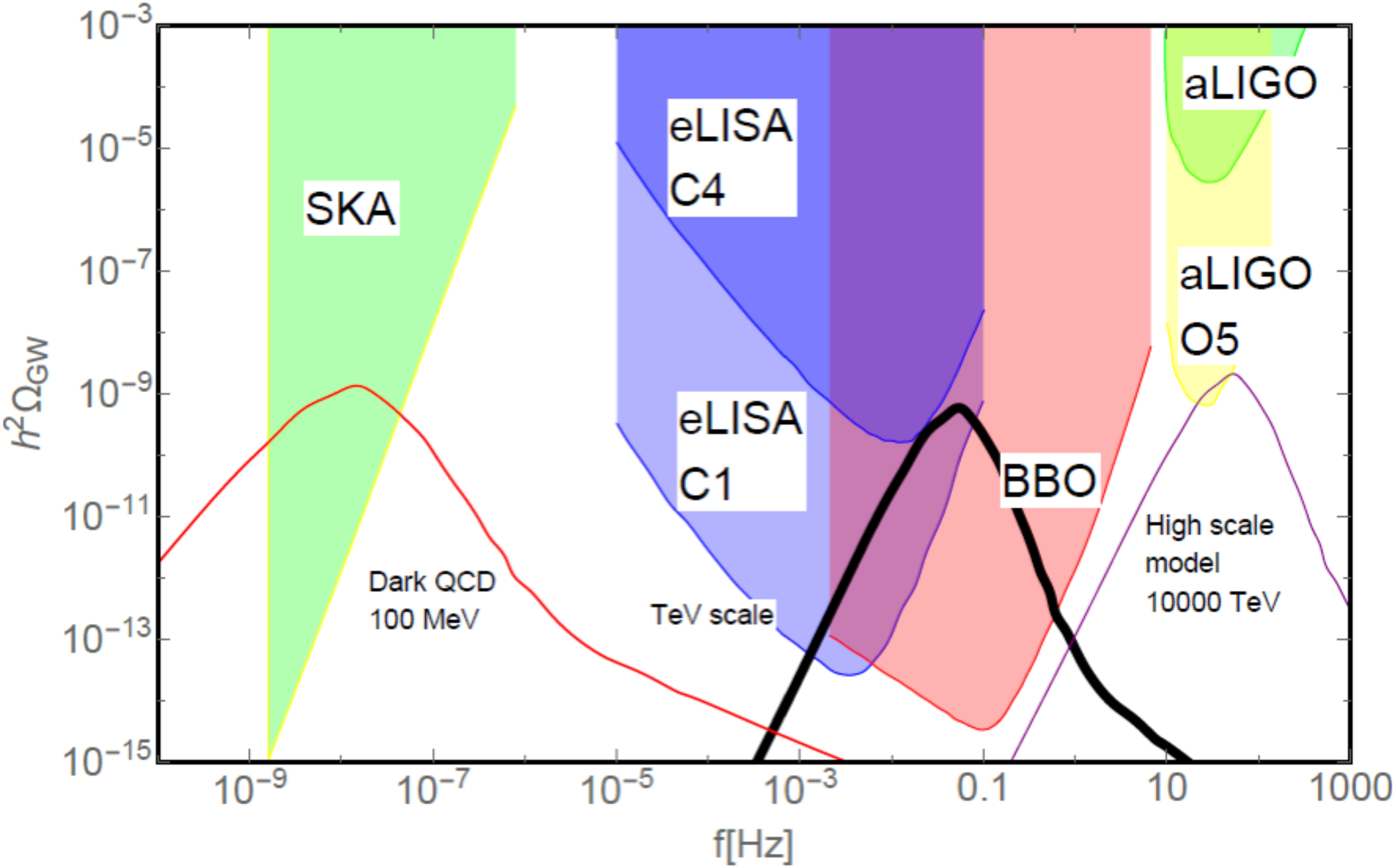
Generally, FOPT may be induced in many other NP models, which may produce detectable GW.

Examples: (1)Electroweak baryogenesis models (LISA):

Exploring dynamical CP violation induced baryogenesis by gravitational waves and colliders
FPH, Zhuoni Qian, Mengchao Zhang arXiv:1804.06813 Phys. Rev. D 98, 015014 (2018)

(2) Dark matter models with dark SU(N) sector (SKA):

Gravitational Waves from a Dark Phase Transition
P. Schwaller Phys.Rev.Lett. 115 (2015) no.18, 181101



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 and outlook

- ➢**GW provides a novel way to explore DM, baryogenesis…(More and more relevant experiments, aLIGO, LISA, SKA, FAST, Tianqin, Taiji…)**
- ➢**GW becomes a new and realistic approach to explore the particle cosmology and fundamental physics.**

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

(See K. Kadota talk)

- ➢**The correlation between GW and collider signals can make a double test on DM, baryogenesis and other NP.**

Thanks for your attention