# 相变引力波

中山大学物理与天文学院天琴中心 黄发朋

中国高能物理非加速器战略研讨会

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# 报告提纲

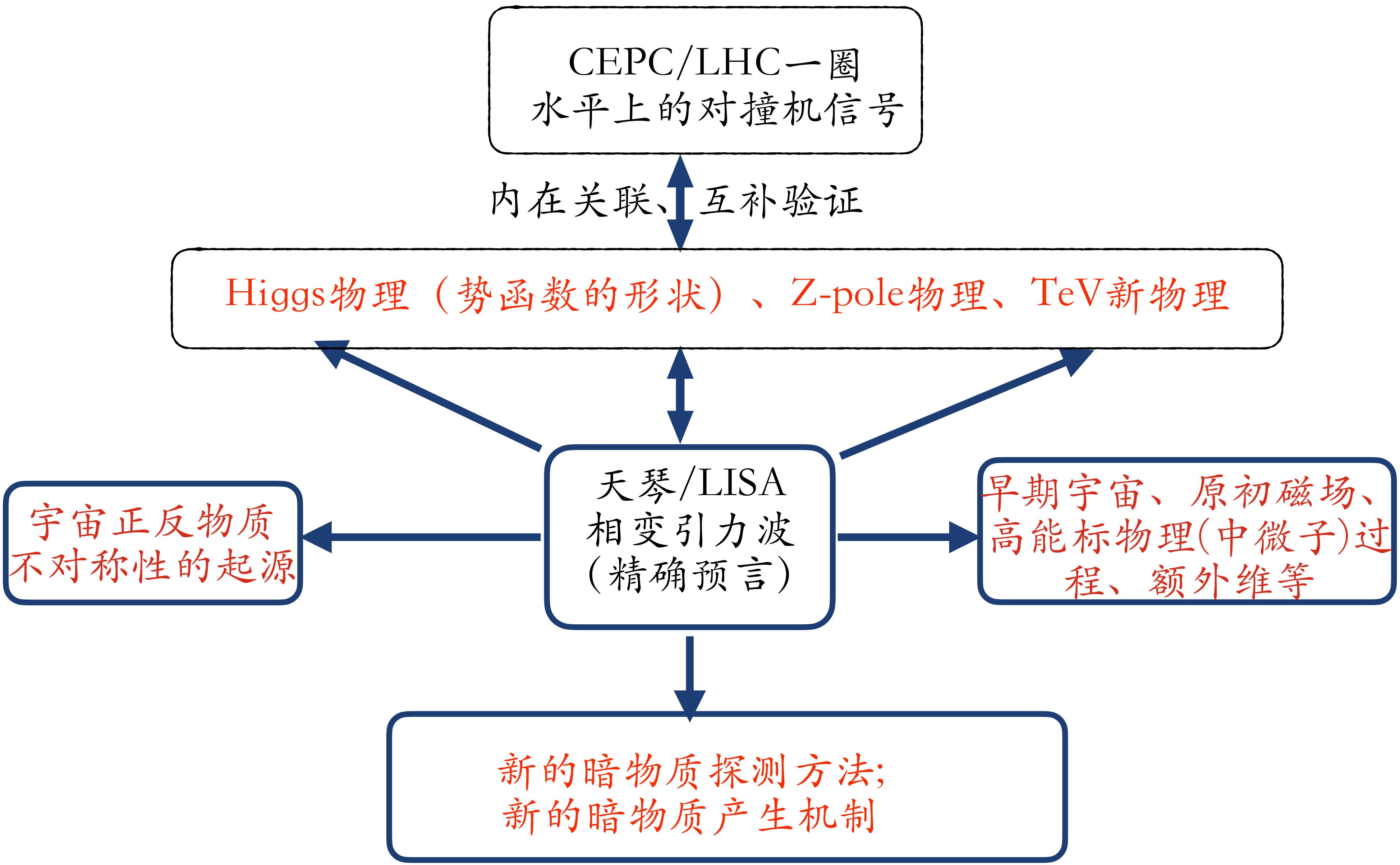
一、研究动机

二、相变引力波简介

三、四个重要的方向

四、总结和展望

# 理论动机

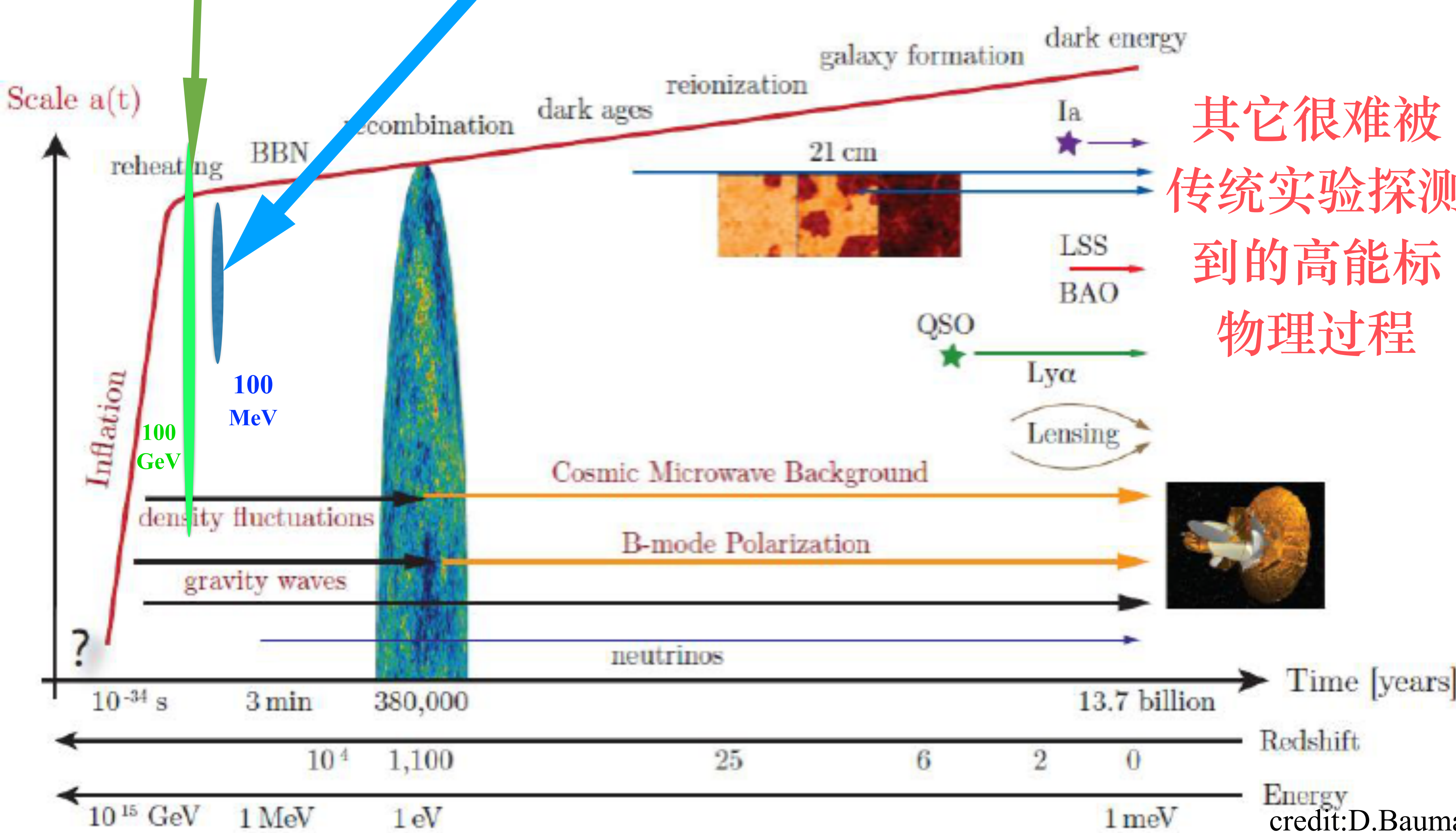


CEPC/LHC一圈
水平上的对撞机信号
内在关联、互补验证
Higgs物理（势函数的形状）、Z-pole物理、TeV新物理
宇宙正反物质
不对称性的起源
天琴/LISA
相变引力波
(精确预言)
早期宇宙、原初磁场、
高能标物理(中微子)过
程、额外维等
新的暗物质探测方法;
新的暗物质产生机制

# 实验动机

电弱相变、TeV相变
(宇宙正反物质不对称性的起源、暗物质)：
天琴/太极/LISA

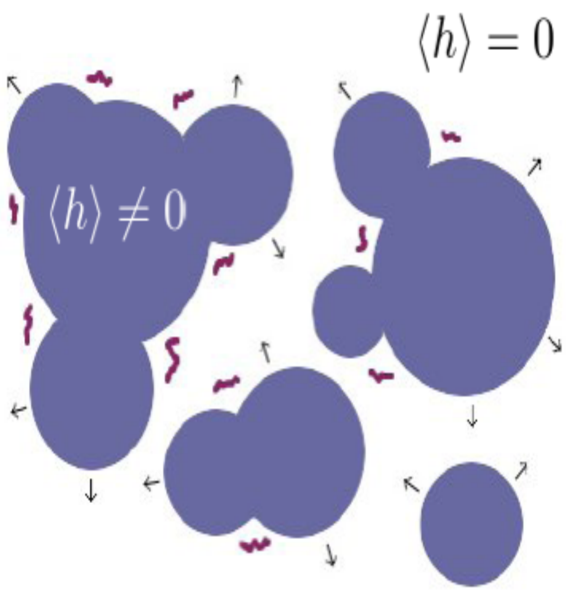
QCD 相变(暗物质)：SKA/FAST

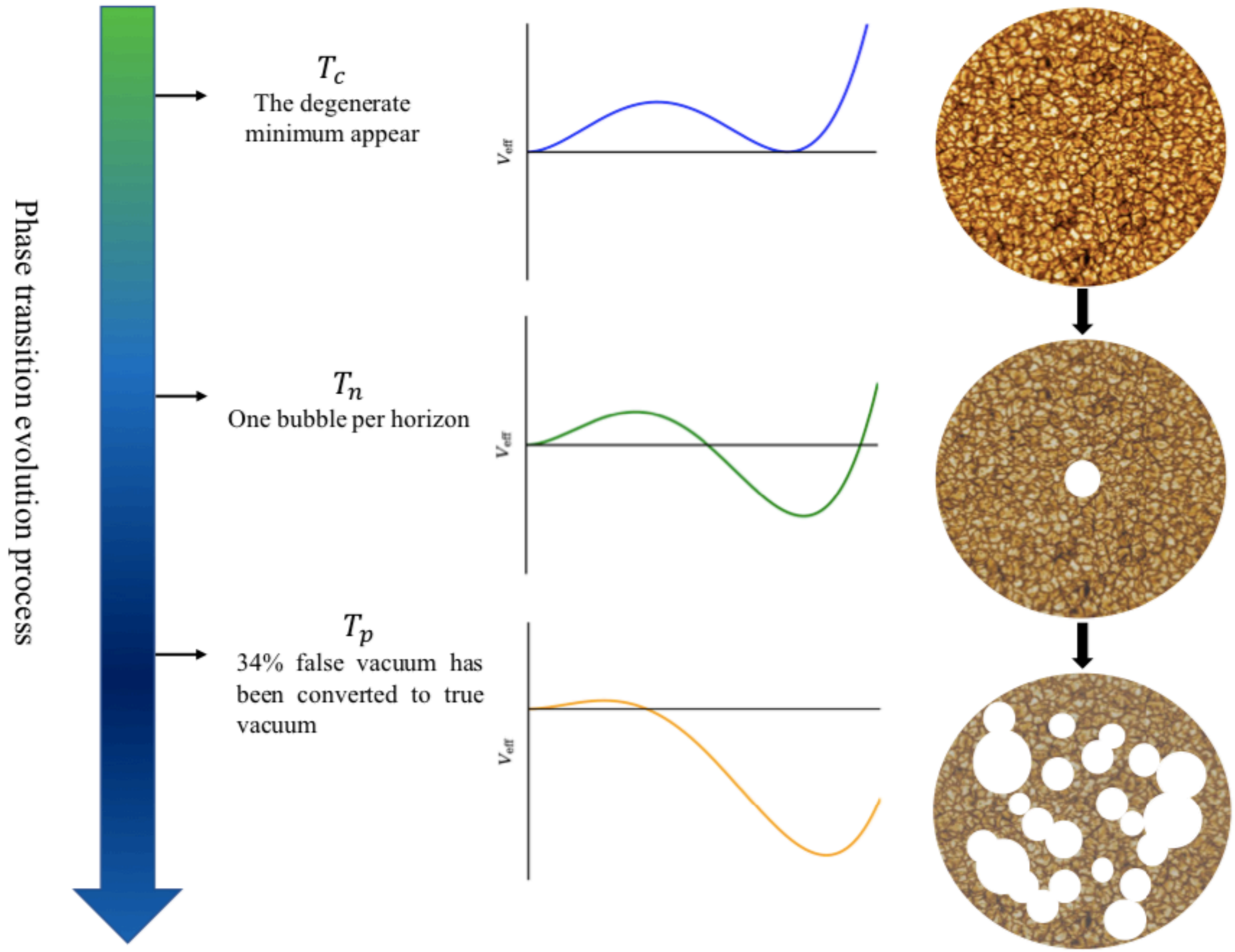



其它很难被传统实验探测到的高能标物理过程

credit:D.Baumann

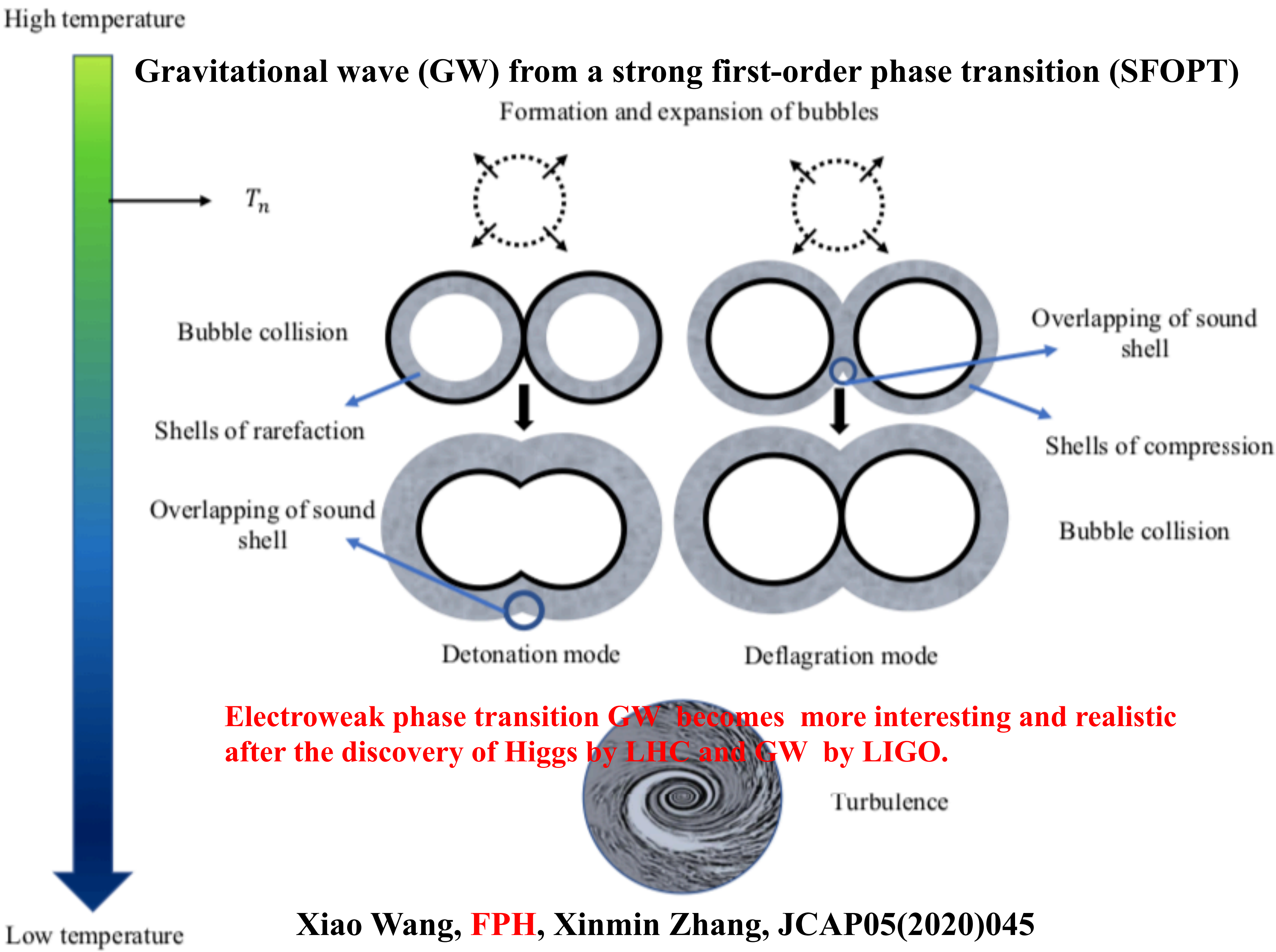
# 相变引力波简介




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

# Gravitational wave (GW) from a strong first-order phase transition (SFOPT)




**Electroweak phase transition GW becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.**

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

# GW signals from SFOPT

## Bubble collisions

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

## 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.

# 相变动力学、相变引力波精确预言

**There are many difficult but interesting directions**

**1.Daisy resummation problem: Pawani scheme vs. Arnold scheme**
**2.Gauge dependence problem: see Michael J. Ramsey-Musolf's works**
**3.No perturbative calculations:lattice calculations and dim-reduction method： by D. Weir, Michael J. Ramsey-Musolf et.al**
**4.Reliable calculations of bubble wall velocity**

Xiao Wang, **FPH**, Xinmin Zhang,arXiv:2011.12903,
S. H¨oche, J. Kozaczuk, A. J. Long, J. Turner and Y. Wang，arXiv:2007.10343，
Avi Friedlander, Ian Banta, James M. Cline, David Tucker-Smith，arXiv:2009.14295v2

**5.GW spectra prediction for ultra-supercooling**
**6.energy budget during phase transition**

**Xiao Wang,FPH** and Xinmin Zhang, ***arXiv:2010.13770***
F. Giese, T. Konstandin, K. Schmitz and J. van de Vis,arXiv:2010.09744

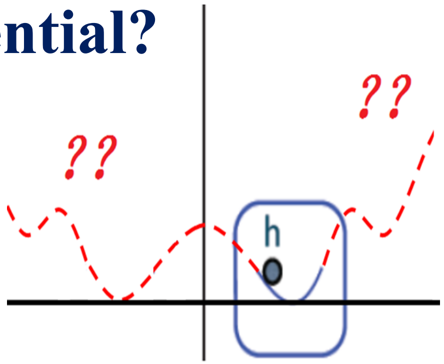
# 相变引力波的实验迹象

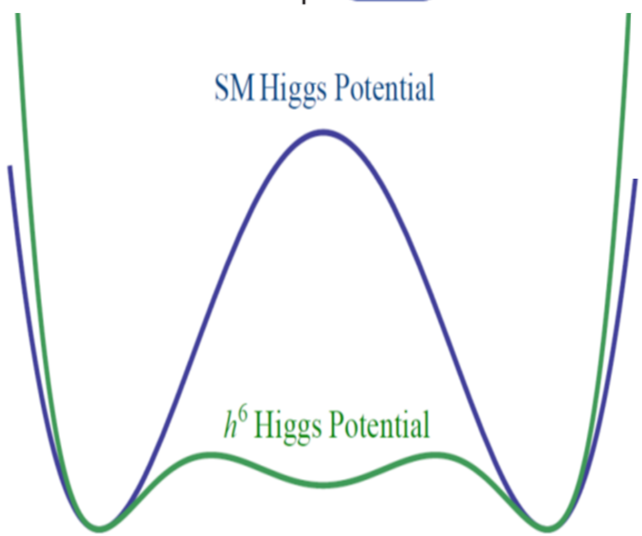
**Searching For Gravitational Waves From Cosmological Phase Transitions With The NANOGrav 12.5-year dataset (The NANOGrav Collaboration) arXiv:2104.13930 .**

**“We find that the data can be explained in terms of a strong first order phase transition taking place at temperatures below the electroweak scale.”**

# 相变引力波与希格斯物理

**What is the shape of Higgs potential?**




**From current data, we know nothing but the quadratic oscillation around the VEV 246 GeV with 125 GeV mass.**

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

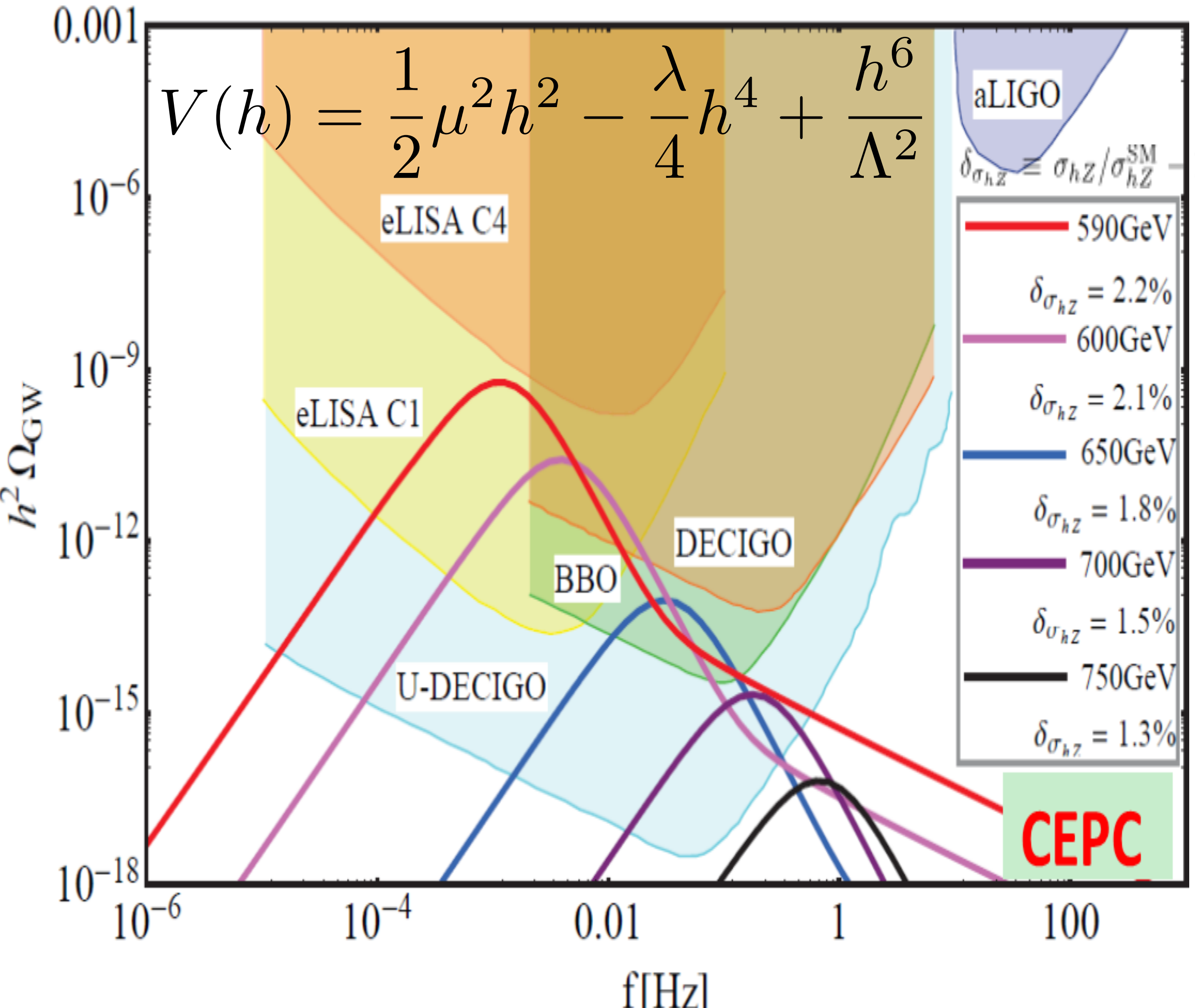
or $$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

**Produce a SFOPT, large deviation of Higgs trilinear coupling and GW**

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 ,**
**FPH, et.al, Phys.Rev.D93 (2016) no.10,103515**

arXiv:1511.06495 Nima Arkani-Hamed et. al.;
PreCDR of CEPC; arXiv: 1811.10545 CDR of CEPC

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




- For CEPC with 10 $ab^{-1}$ at $\sqrt{s} = 240$ GeV, precision of $\sigma_{zh}$ 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


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

# Consistent check in standard model effective field theory from EW observables to future lepton collider

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

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

**SFOPT produces large modification of trilinear Higgs coupling** $\delta_h$

$c_6$ **dominates the hZ cross section deviation**

**Taking a general study of the scalar extended models and the composite Higgs model as examples, we can see that the Higgs sextic scenario still works well after considering all the dim-6 operators and the precise measurements.**

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

# 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 Covariant Derivative Expansion method, the matched dim-6 operators and their coefficients in the doublet scalar models are obtained:**

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

# 相变引力波与宇宙正反物质不对称性的起源

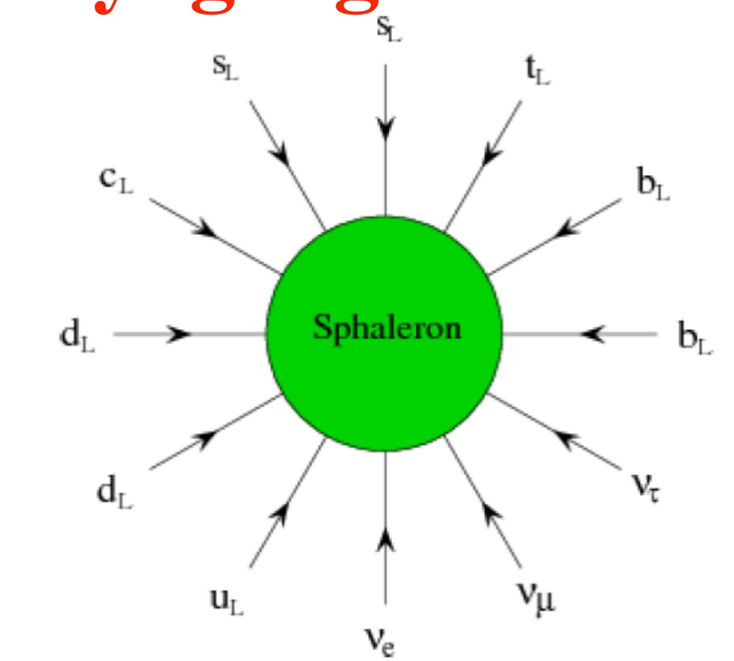

**A long standing problem in particle cosmology is the origin of baryon asymmetry of the universe (BAU).**

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

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

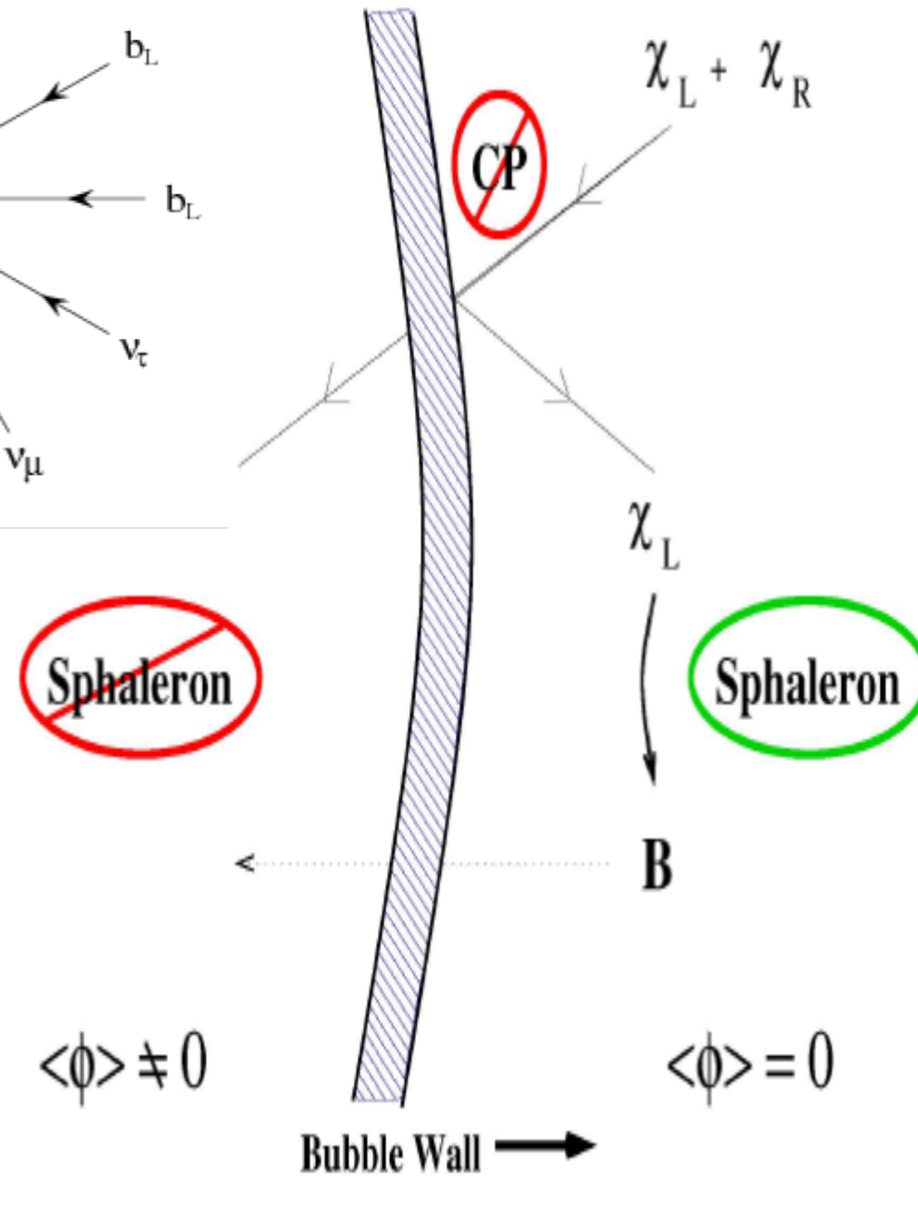
# Electroweak baryogengesis

**SM technically has all the three elements for baryogenesis , (B aryon violation, C and CP violation, D eparture from thermal equilibrium or CPT violation) but not enough.**




- **B violation from anomaly in B+L current.**
- **CKM matrix, but too weak.**
- **SFOPT with expanding Higgs bubble wall**

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



# 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 $\cdot$ 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 for successful baryogenesis?

## 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 an 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)

# Taking the effective scenario as a representative example:

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

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

$\eta = a + ib$ **The singlet and the dim-5 operator can come from many types composite Higgs model, arXiv:0902.1483 , arXiv:1703.10624 ,arXiv:1704.08911,**

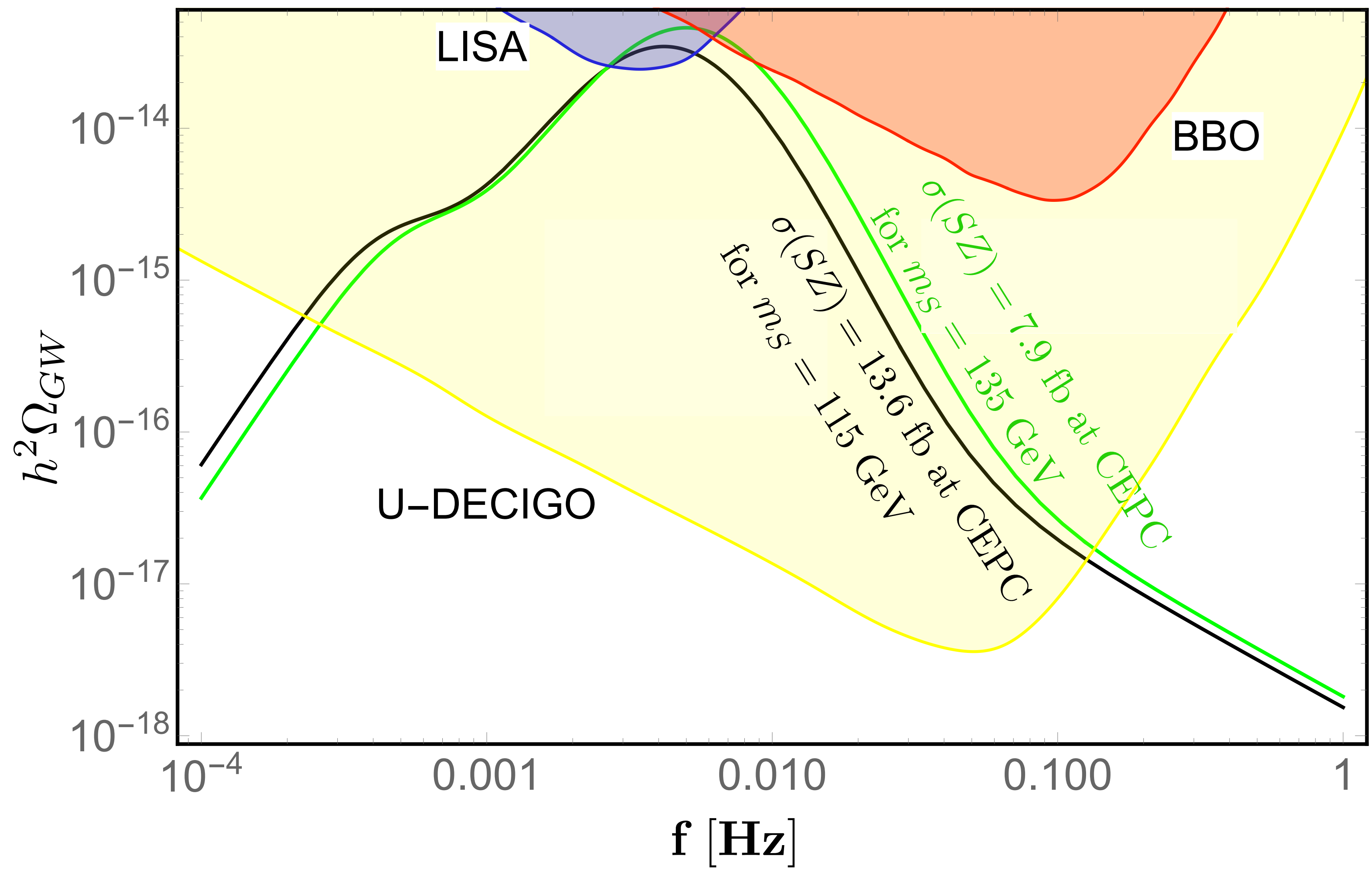
**Firstly, a second-order phase transition happens, the scalar field S acquire a vacuum exception value (VEV) and the dim-5 operator generates a sizable CP-violating Yukawa coupling for successful baryogenesis.**

**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**

J. R. Espinosa, B. Gripaios, T. Konstandin and F. Riva, JCAP **1201**, 012 (2012)

J. M. Cline and K. Kainulainen, JCAP **1301**, 012 (2013)

# 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.**

➢**New dark matter (DM) production scenario filtered by the bubbles of the SFOPT in the early universe**

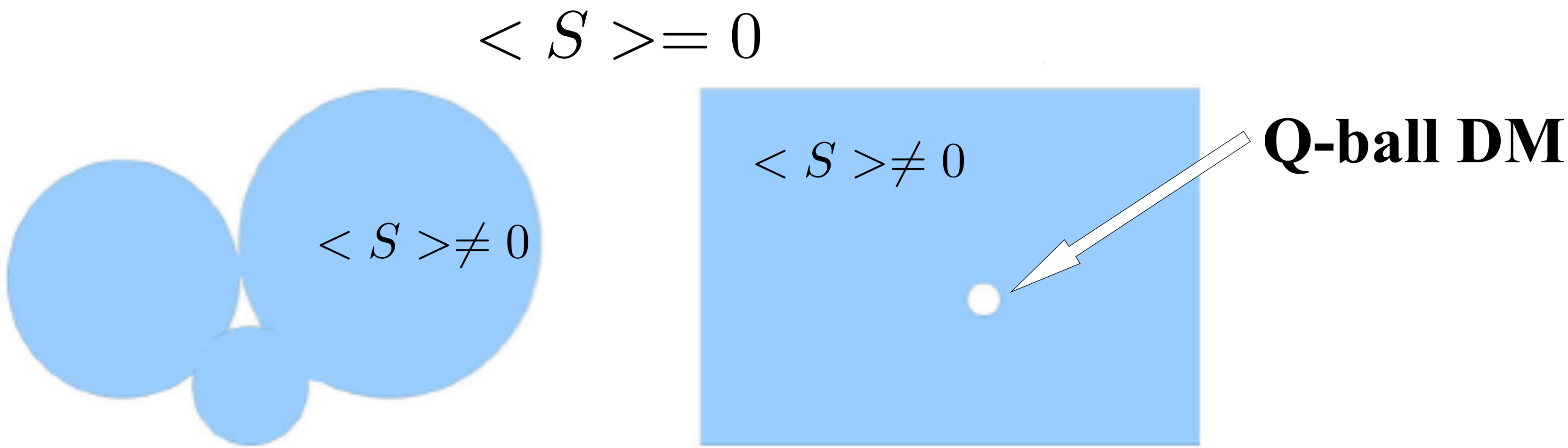
**The cosmic phase transition with Q-balls production can explain baryogenesis and DM simultaneously, where constraints on DM mass and reverse dilution are significantly relaxed. We study how to probe this scenario by GW signals and collider signals at QCD NLO.**

**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.**

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

## SFOPT naturally correlates DM, baryogenesis, particle collider and GW signals.




**And with the bubble expansion, the symmetric phase eventually shrinks to very small size objects and become the so-called Q-balls as DM candidates.**

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

**Final conditions to produce the observed baryon asymmetry and DM density: FPH, C.S. Li, Phys.Rev. D96 (2017) no.9, 09502**

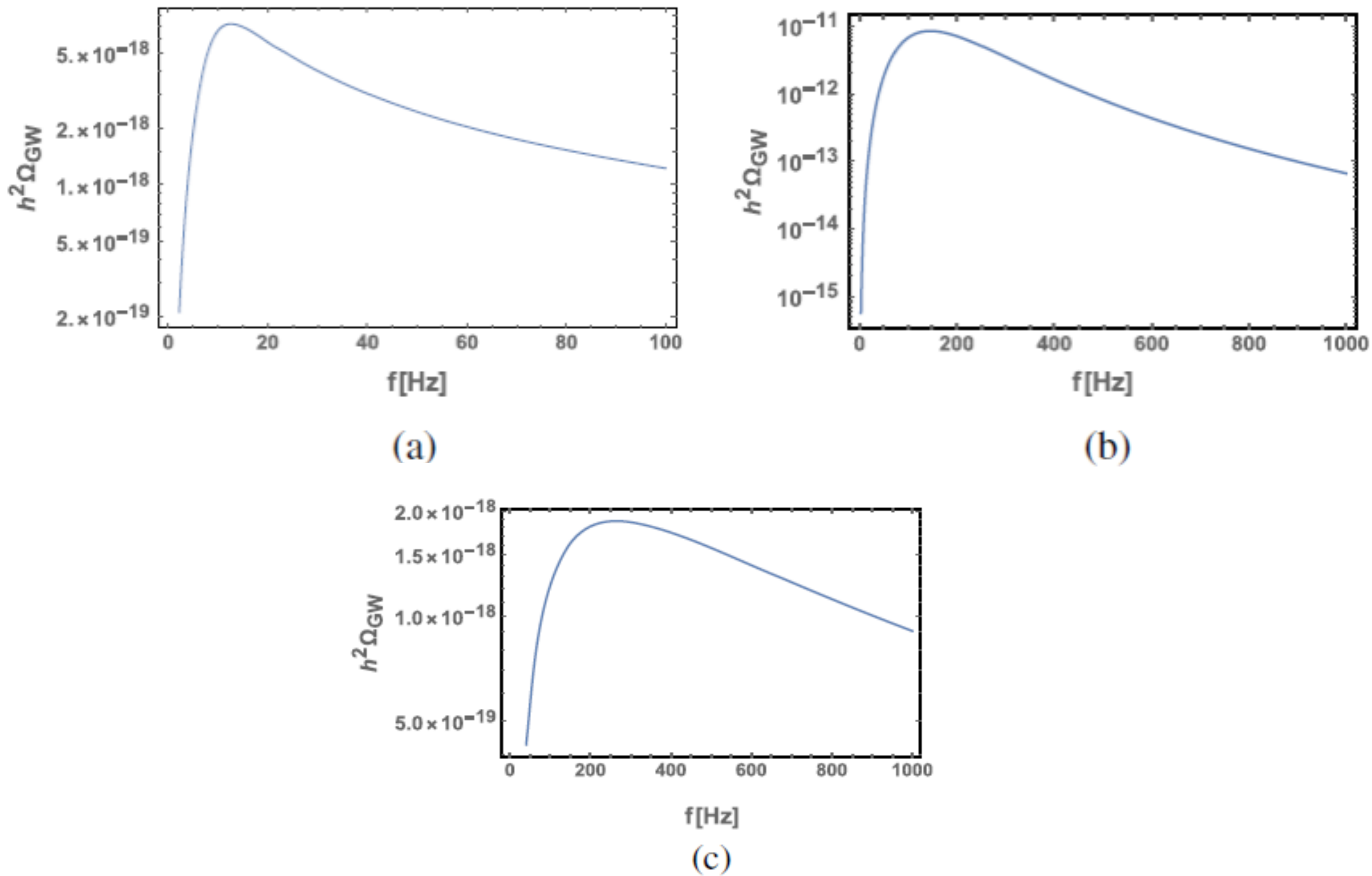
$$\rho_{\mathrm{DM}}^4 v_b^{3/4} = 73.5(2\eta_B s_0)^3 \lambda_S \sigma^4 \Gamma^{3/4}$$

TABLE I. The benchmark sets after considering the combined constraints for producing the observed DM density and BAU with $v_b = 0.3$.

| Benchmark sets | $\lambda_S$ | $e$ | $c$ | $T_c$ [TeV] | $\frac{\sigma}{T_C}$ |
|---|---|---|---|---|---|
| I | 0.008 | 0.754 | 1 | 15.9 | 5 |
| II | 0.0016 | 0.151 | 1 | 6.6 | 5 |

**Extension work for the gauged Q-balls is working in progress with Prof. P. Ko**

**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, Einstein telescope or cosmic explorer.**



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

**In the recent two years, this dynamical DM formed by phase transition has became a new idea and attracted more and more attentions.**
**Namely, bubbles in SFOPT can be the "filters" to packet your needed heavy DM.**

**arXiv:1912.04238, Dongjin Chway, Tae Hyun Jung, Chang Sub Shin**
**arXiv:1912.02830, Michael J. Baker, Joachim Kopp,and Andrew J. Long**
**arXiv:2012.15113, Wei Chao, Xiu-Fei Li, Lei Wang**
**arXiv:2101.05721, Aleksandr Azatov, Miguel Vanvlasselaer, Wen Yin**
**arXiv:2103.09827, Pouya Asadi , Eric David Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, Juri Smirnov**
**arXiv:2103.09822, Pouya Asadi , Eric David Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, Juri Smirnov**
**arXiv:2008.04430 Jeong-Pyong Hong， Sunghoon Jung, Ke-pan Xie**

➢The observation of GW by LIGO has initiated a new era of exploring DM by GW.

➢ DM can trigger a SFOPT in the early universe, which can leads to detectable GW signals.

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

Yan Wang, Chong Sheng Li, and **FPH**, arXiv:2012.03920
**FPH**, Eibun Senaha Phys.Rev. D100 (2019) no.3, 03501
**FPH** PoS ICHEP2018 (2019) 397
**FPH**, Chong Sheng Li Phys.Rev. D96 (2017) no.9, 095028
**FPH**, Jiang-Hao Yu Phys.Rev. D98 (2018) no.9, 095022
**FPH**, Xinmin Zhang, Phys.Lett. B788 (2019) 288-29

## Inert Doublet Models

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

**mixed singlet-doublet model**

$$V_0 = \frac{1}{2} M_S^2 S^2 + M_D^2 H_2^\dagger H_2 + \frac{1}{2}\lambda_S S^2 |\Phi|^2 + \lambda_3 \Phi^\dagger \Phi H_2^\dagger H_2 + \lambda_4 |\Phi^\dagger H_2|^2 + \frac{\lambda_5}{2}[(\Phi^\dagger H_2)^2 + \text{H.c.}] + A[S\Phi H_2^\dagger + \text{H.c.}].$$

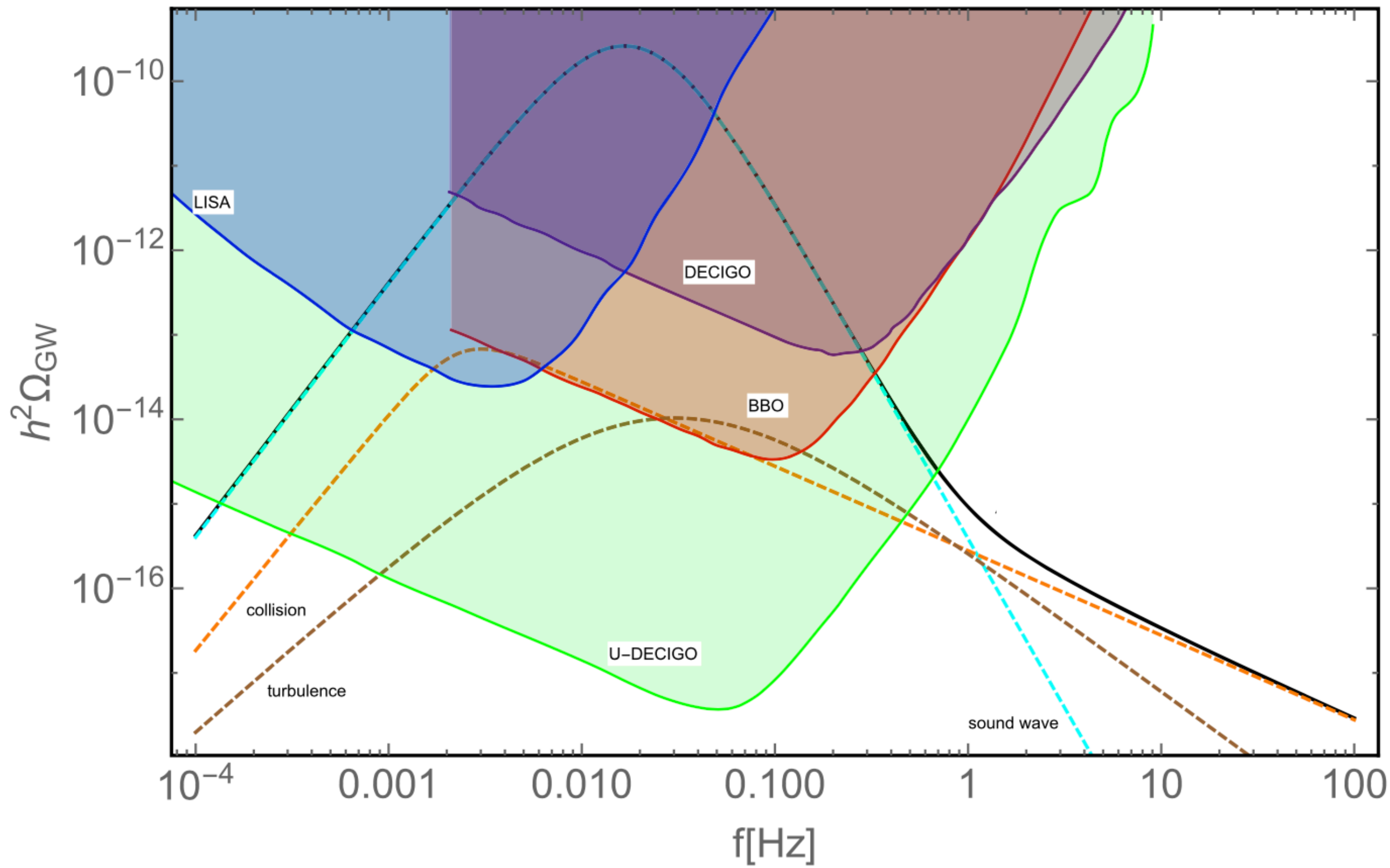
**mixed singlet-triplet model**

$$V_0 = \frac{1}{2} M_S^2 S^2 + M_\Sigma^2 \text{Tr}(H_3^2) + \kappa_\Sigma \Phi^\dagger \Phi \text{Tr}(H_3^2) + \frac{\kappa}{2}|\Phi|^2 S^2 + \xi S \Phi^\dagger H_3 \Phi.$$

**provide natural DM candidate**

**produce SFOPT and phase transition GW**

FPH, Jiang-hao Yu, Phy. Rev. D 98, 095022 (2018)
Yan Wang, Chong Sheng Li, FPH, arXiv: 2012.03920




**GW in the mixed singlet-doublet model**

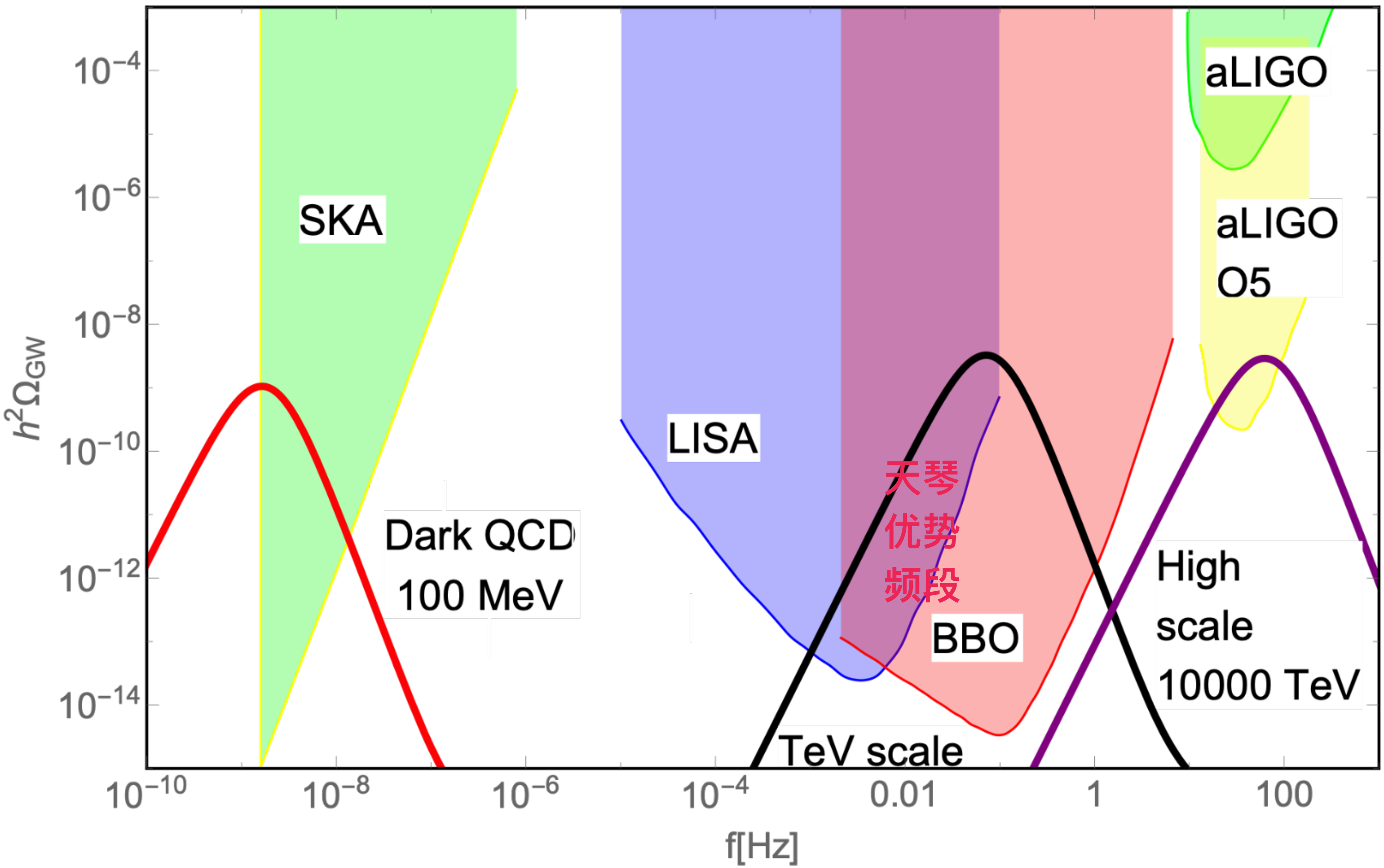
**FPH, Jiang-hao Yu, Phy. Rev. D 98, 095022 (2018)**

- Phase transition GW can provide a unique way to probe many important physics processes: inflation, PQ-symmetry breaking, neutrino physics, axion physics, extra dimension, primordial magnetic field, cosmic defects…


Wei-Chih Huang, et. al, arXiv: 2012.11614
Mark Hindmarsh, et. al. arXiv: 2011.12878
Bhupal Dev, et. al. arXiv: 1905.00891
Yiyang Zhang, et. al. arXiv:1902.02751
Yang Bai, et. al. arXiv:1810.04360
Andrew Long, et. al. arXiv:1703.04902
Graciela Gelmini, et. al. arXiv:2009.01903
Stephen King, et.al. arXiv:2005.13549
Bhupal Dev, et.al. arXiv:1602.04203
Astrid Eichhorn et.al. arXiv:2010.00017
,

Yuefeng Di, et. al., arXiv: 2012.15625
Haipeng An,et.al. arXiv:2009.12381
FPH, Xinmin Zhang, Phys.Lett. B788 (2019) 288-29,
Jia Liu, et.al. arXiv:2104.06421
Zhao Zhang, et. al. arXiv:2102.01588
Wei Liu， et.al. arXiv:2101.10469
Cheng-wei Chiang, et.al. arXiv:2012.14071
Ke-Pan Xie, arXiv:2011.04821
Ligong Bian， arxiv:1907.13589

# More general cases

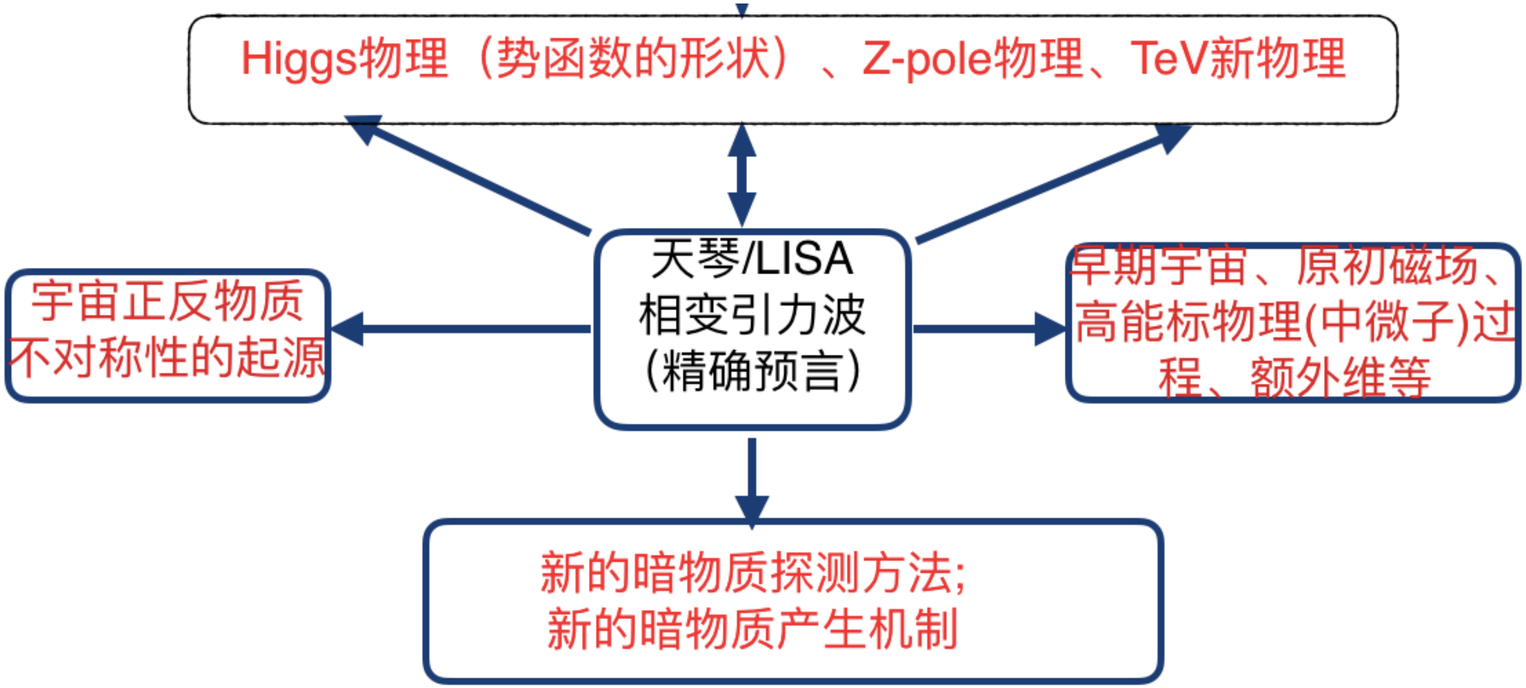



**Schematic phase transition GW spectra for SKA-like and LISA-like experiments to explore DM and baryogenesis**

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

# 总结与展望

- 从理论角度相变引力波能给提供探索**Higgs**、**TeV**新物理、暗物质、宇宙正反物质不对称性的起源等新的方法.
- 从实验角度国际国内空间引力波实验的快速推进，使这些研究有实验验证.




感谢您的参加!

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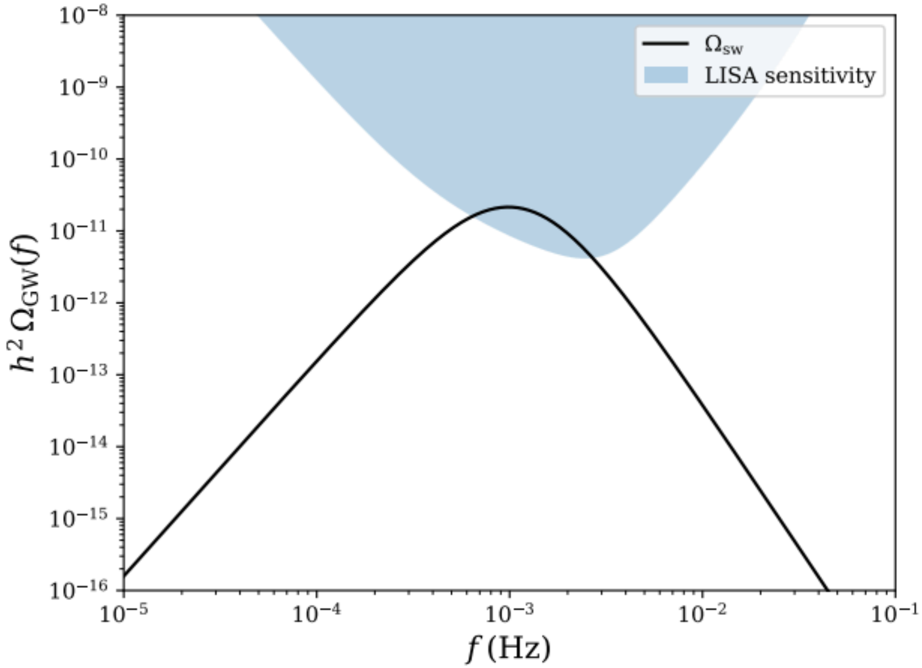



**2034**

LISA
CosWG-19-04

DESY 19-159
IPPP/19/27
HIP-2019-14/TH
MITP/19-066
IFT-UAM/CSIC-19-139



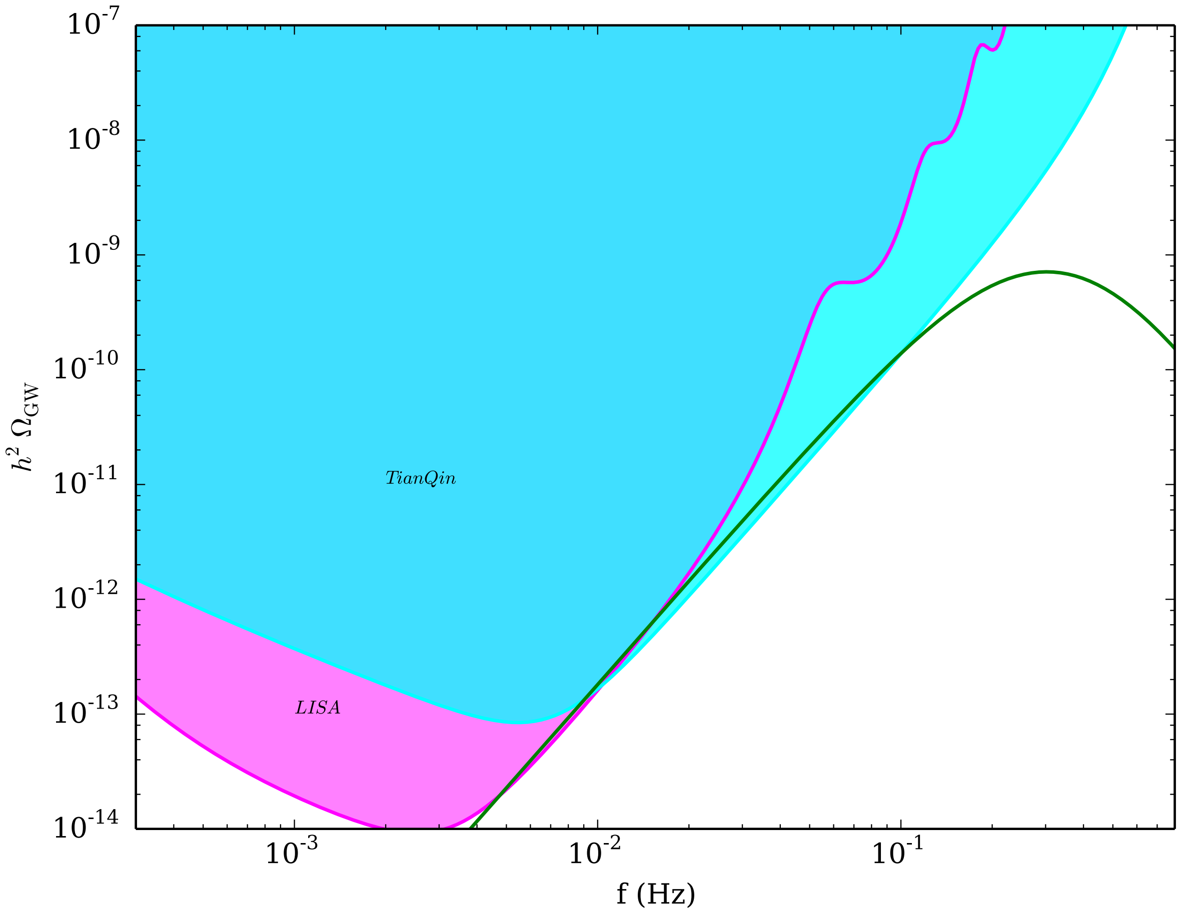
# Detecting gravitational waves from cosmological phase transitions with LISA: an update

**"Our results emphasize LISA's importance for exploring the early Universe and BSM physics, as well as the Mission's complementarity with other experimental efforts."**

For the LISA Cosmology Working Group

**JCAP03(2020)024**

# 天琴探测相变引力波的优势频段




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