中山大學天琴中心
TIANQIN CENTER FOR GRAVITATIONAL PHYSICS, SYSU

Phase transition and gravitational wave
——Higgs potential from 10^{-11}s of early universe to 2022

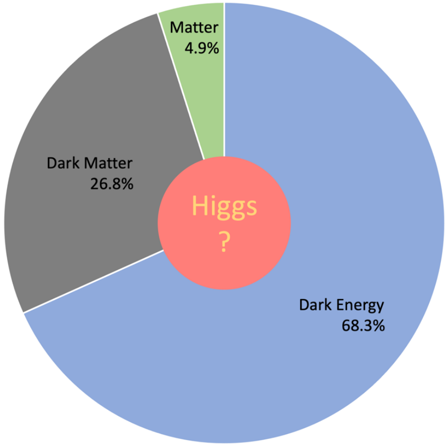
Fa Peng Huang (黄发朋)

Higgs potential 2022@Peking University, July 26, 2022
(Online talk)

Outline

1. Motivation
2. Electroweak Phase transition and phase transition gravitational wave in a nutshell
3. Six important directions on Electroweak Phase transition
4. Summary and outlook

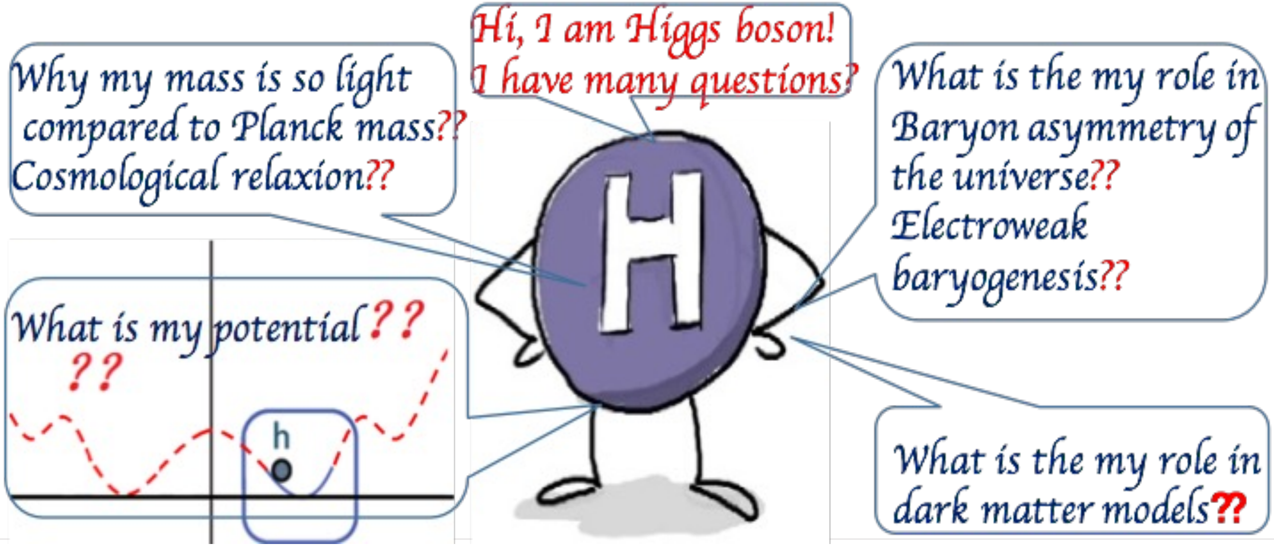
Motivation



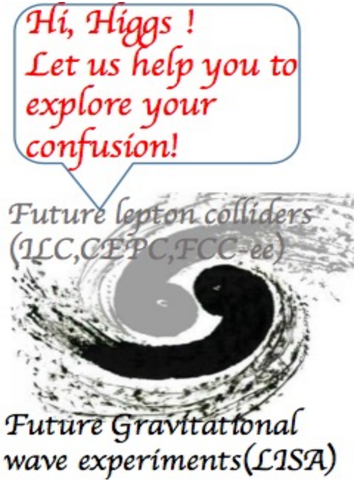
Higgs@10:Higgs particle cosmology

After the discovery of 125 GeV scalar, it becomes a realistic portal to study the fundamental physics and its deep connections to cosmology

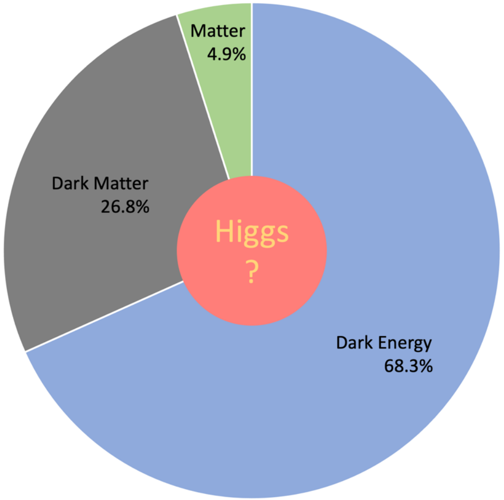
What is the role of Higgs in the early universe?



How to test?



Motivation



Higgs@10:Higgs particle cosmology

Higgs' deep connections to cosmology, such as Higgs (portal) inflation, Neutrino mass (leptogenesis), cosmological relaxion, EW phase transition/baryogenesis, dark matter(DM)…

$$+\mathcal{O}_{hidden}H^{\dagger}H$$

Relaxion $\mathcal{O} = M^2 - g\phi$

FPH,et.al.arXiv:1605.03120

$\mathcal{O} = ll$ **neutrino mass and leptogenesis**

$\mathcal{O} = R$

Higgs (bouncing) inflation,

FPH,et.al.arXiv:1307.7458, arXiv:1509.08772

$\mathcal{O} = \phi\phi$

Higgs portal dark matter

FPH,et.al.arXiv:1704.04201

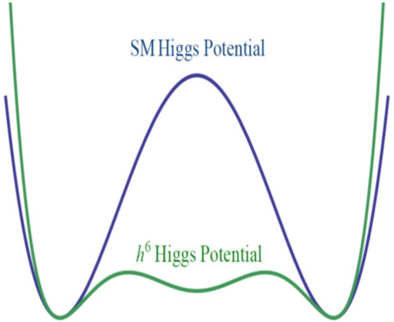
$\mathcal{O} = \phi S, \phi\phi$

EW phase transition/ baryogenesis

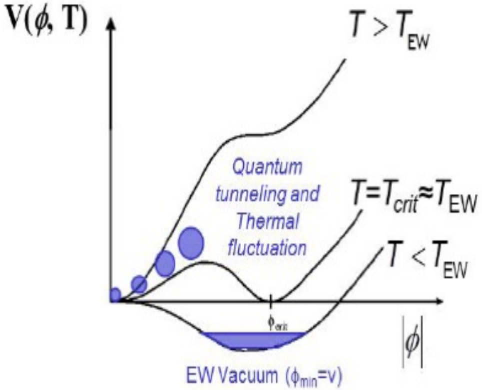
FPH,et.al.arXiv:1507.08168, arXiv:1511.03969; arXiv:1601.01640,arXiv:1704.04201,arXiv:1709.09691 arXiv:1804.06813, arXiv:1905.10283, arXiv:1909.02978

Motivation

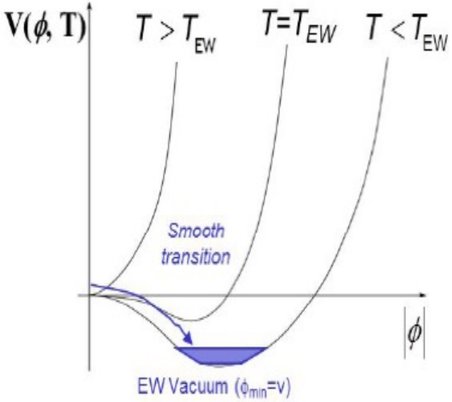
From lattice simulation



SFOPT for m_H < 75 GeV



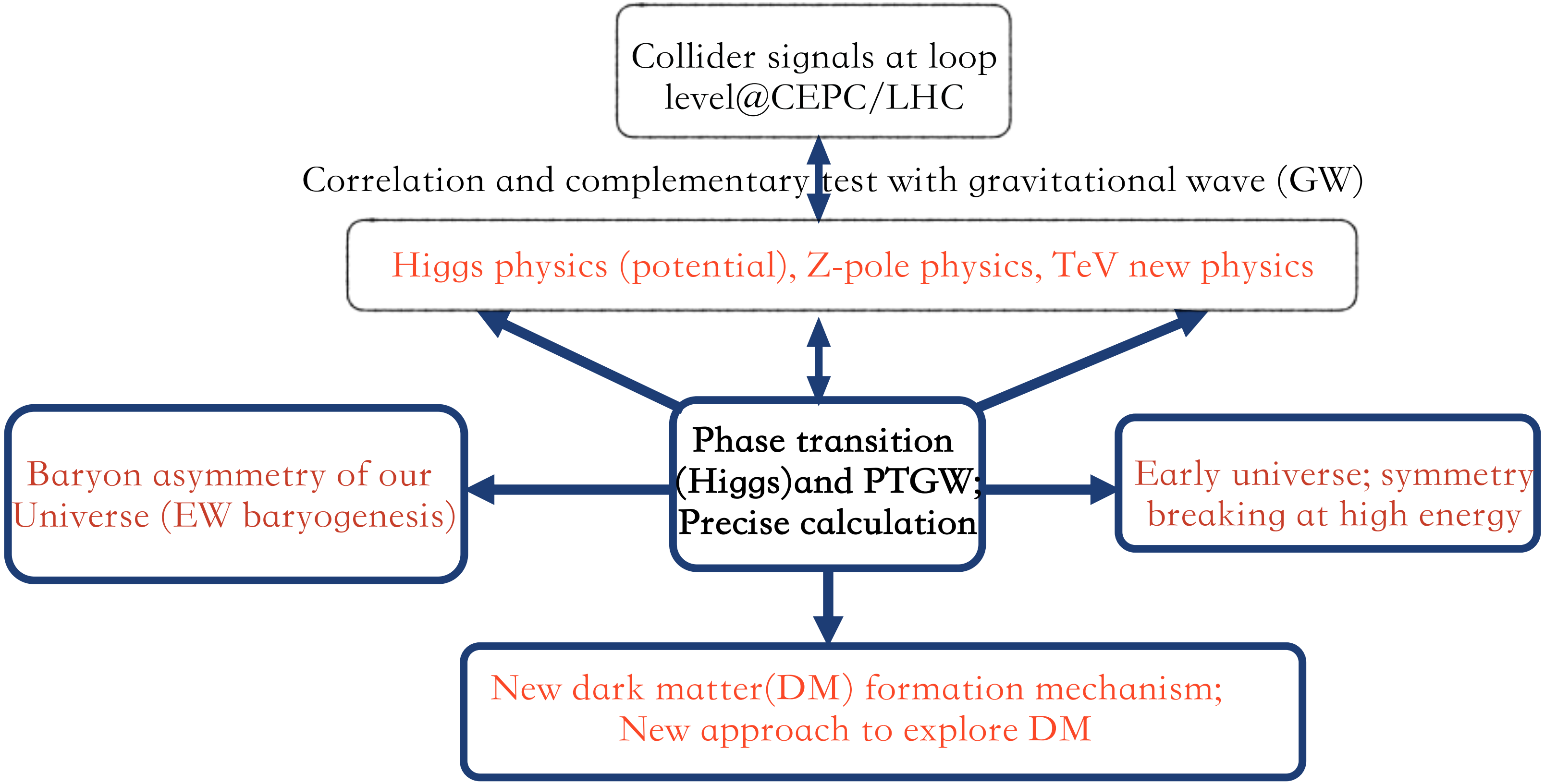
Cross over for m_H > 75 GeV



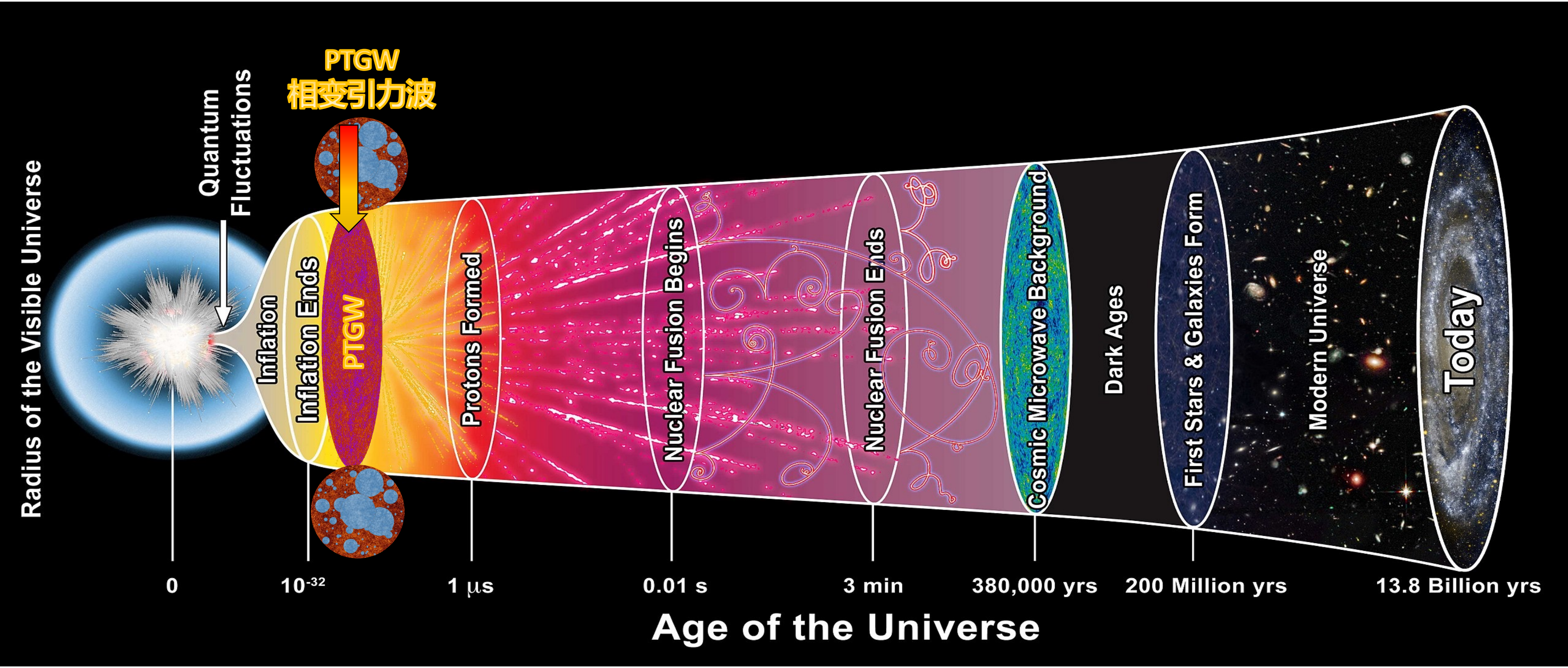
Extension of the Higgs sector is needed to SFOPT for 125 GeV Higgs boson.

We discuss well-motivated extensions (baryogenesis, DM…) of Higgs section to realize strong first-order phase transition (SFOPT) with abundant cosmological effects.
EW phase transition and its GW signals becomes realistic after the discovery of Higgs by LHC and GW by LIGO.

Motivation


Collider signals at loop level@CEPC/LHC
Correlation and complementary test with gravitational wave (GW)
Higgs physics (potential), Z-pole physics, TeV new physics
Baryon asymmetry of our Universe (EW baryogenesis)
Phase transition (Higgs)and PTGW; Precise calculation
Early universe; symmetry breaking at high energy
New dark matter(DM) formation mechanism; New approach to explore DM

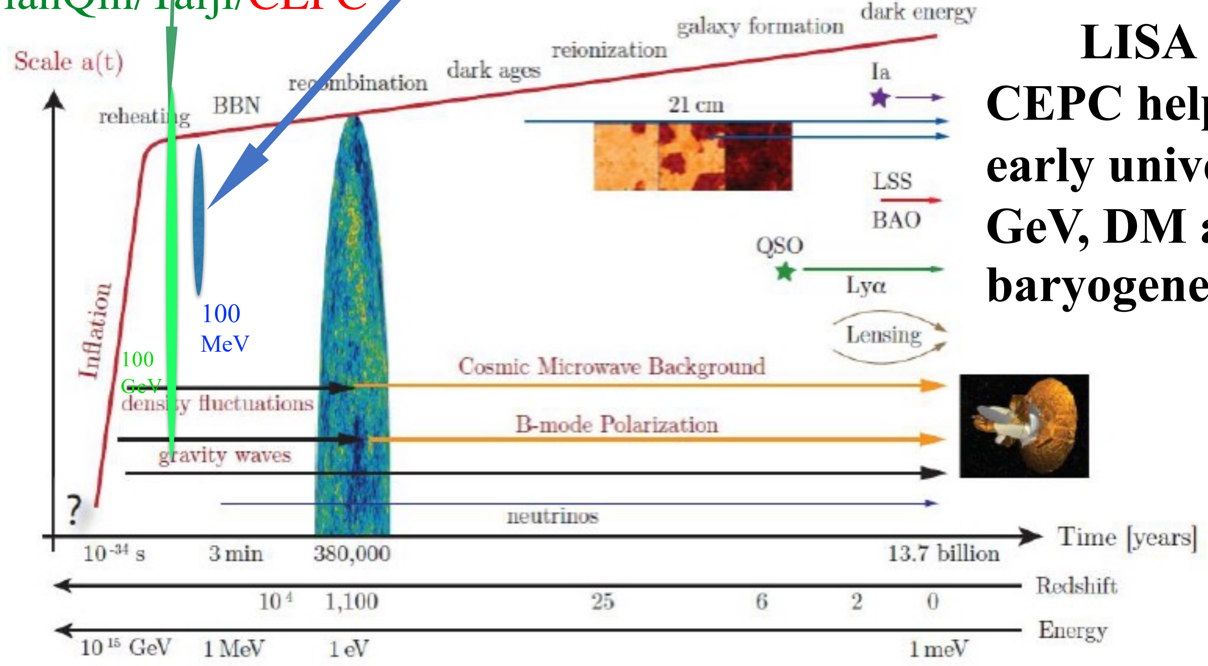
Motivation


PTGW
相变引力波
Quantum Fluctuations
Radius of the Visible Universe
Inflation
Inflation Ends
PTGW
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10^{-32}
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe

Motivation

EW phase transition/ baryogenesis: LISA/TianQin/Taiji/CEPC

QCD phase transition and axion cold DM: SKA, FAST, GBT



LISA in synergy with CEPC helps to explore the early universe around 100 GeV, DM and baryogenesis.

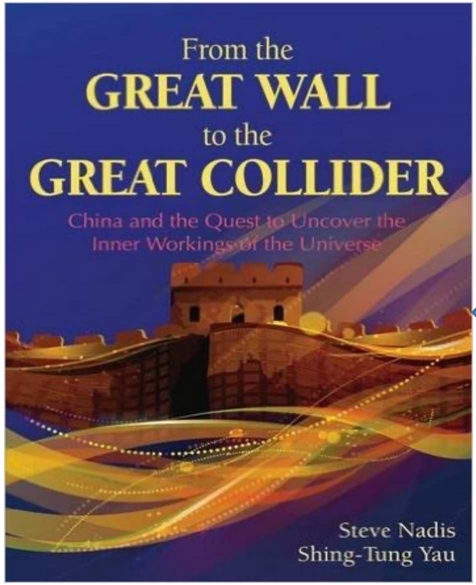
credit:D.Baumann

Motivation

Complementary

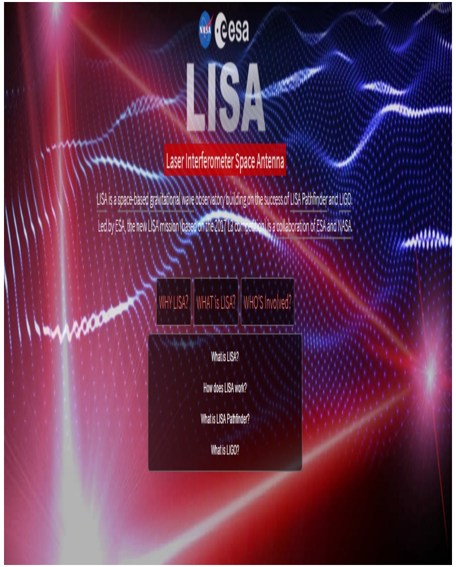
Particle approach
CEPC/SppC, FCC etc.

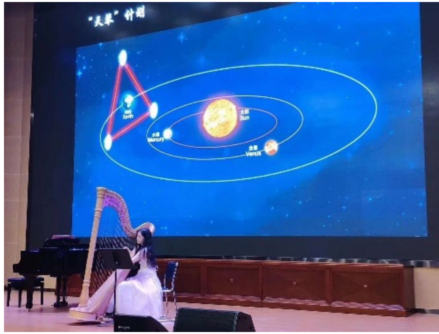
Wave approach
LISA/TianQin/Taiji ~2034



Relate by Higgs physics:EW phase transition/baryogenesis

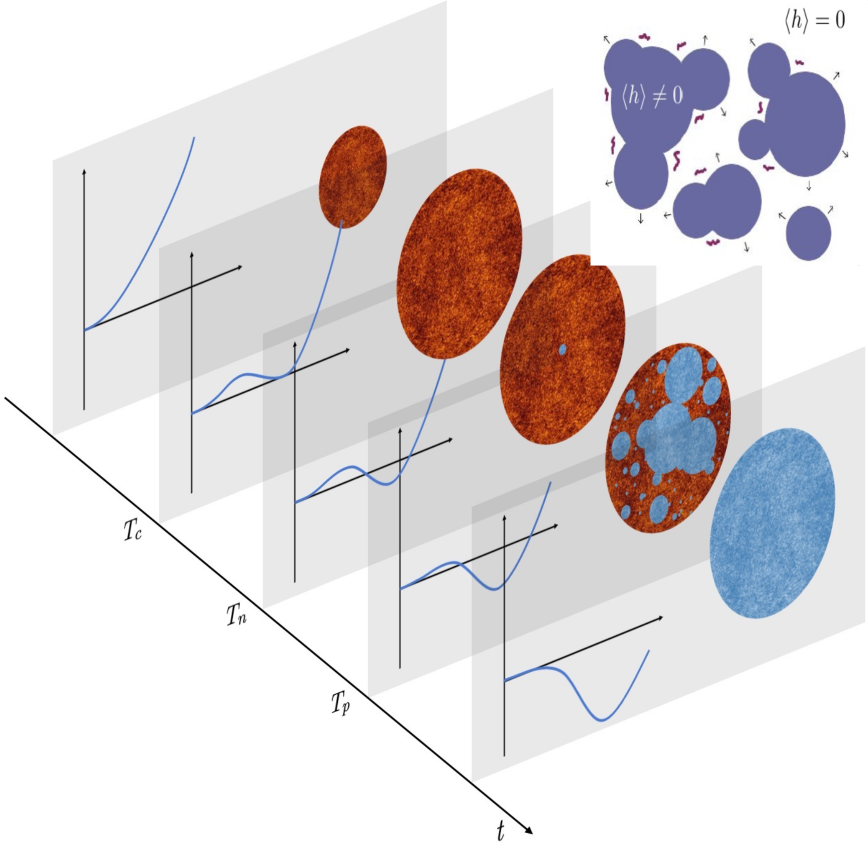
Double test on the Higgs potential and baryogenesis, DM





“天琴”
“Harpe in space”

Phase transition GW in a nutshell



calculate the finite-temperature effective potential using the thermal field theory: free energy density.

$$V_{\text{eff}}^{(1)}(\bar{\phi}) = \sum_i n_i \Big[\int \frac{\mathrm{d}^D p}{(2\pi)^D} \ln\big(p^2 + m_i^2(\bar{\phi})\big) + J_{\mathrm{B,F}}\Big(\frac{m_i^2(\bar{\phi})}{T^2}\Big) \Big]$$

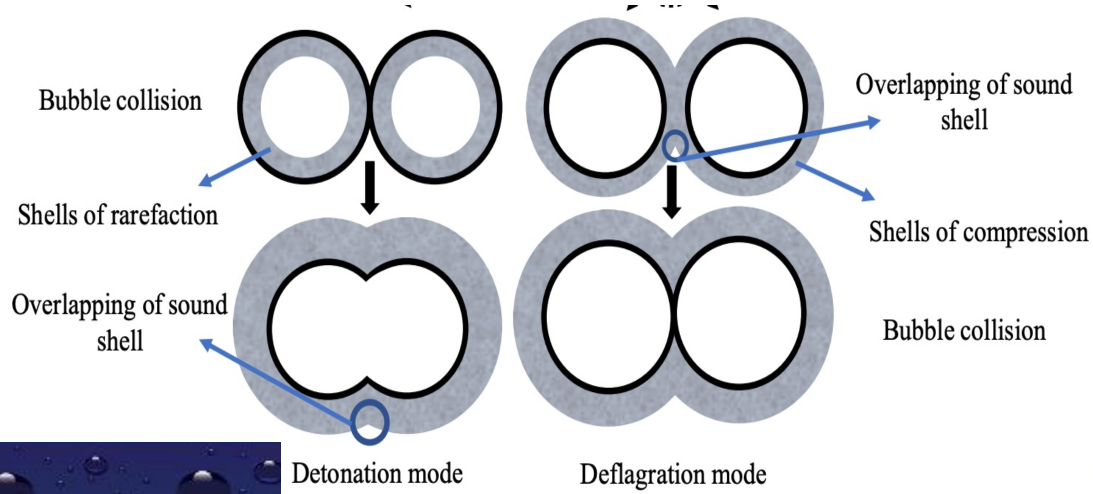
$$S(T) = \int d^4x \left[\frac{1}{2} \left(\frac{\partial \phi}{\partial x} \right)^2 + V_{\text{eff}}\,(\phi, T) \right]$$

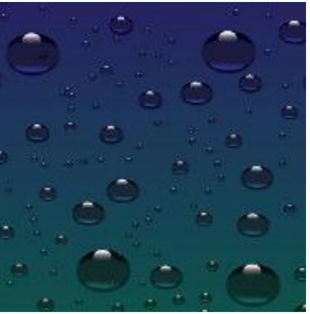
$$\Gamma = \Gamma_0 e^{-S(T)}$$

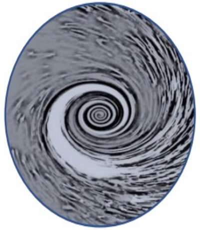
这世上的热闹，源自遂穿

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

Phase transition GW in a nutshell

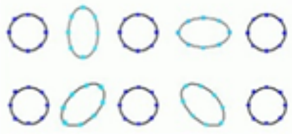






$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$h_{ij} \simeq \frac{2G}{c^4 r} \ddot{Q}_{ij}^{TT}(t - r/c)$$



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.

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

Phase transition GW in a nutshell

$$\ddot{h}_{ij}(\mathbf{x},t) + 3\,H\,\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2} h_{ij}(\mathbf{x},t) = 16\pi G\,\Pi_{ij}(\mathbf{x},t)$$

Possible sources of tensor anisotropic stress in the early universe

- Scalar field gradients $\Pi_{ij} \sim [\partial_i\phi\partial_j\phi]^{TT}$ eg. Collisions of bubble walls
- Bulk fluid motion $\Pi_{ij} \sim [\gamma^2(\rho+p)v_iv_j]^{TT}$ eg. Sound waves and turbulence in the fluid
- Gauge fields $\Pi_{ij} \sim [-E_iE_j - B_iB_j]^{TT}$ eg. Primordial magnetic fields (MHD turbulence
- Second order scalar perturbations, Π_{ij} from a combination of $\partial_i\Psi, \partial_i\Phi$
- ... arXiv:1801.04268

Phase transition GW in a nutshell

Bubble collisions

$$h^2\Omega_{\rm co}(f) \simeq 1.67\times10^{-5}(\frac{H_* R_*}{(8\pi)^{1/3}})^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_\star}\right)^{1/3}\frac{0.11v_b}{0.42+v_b^2}\frac{3.8(f/f_{\rm co})^{2.8}}{1+2.8(f/f_{\rm co})^{3.8}}$$

Turbulence

$$h^2\Omega_{\rm turb}(f) \simeq 1.14\times10^{-4}H_* R_*\left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*}\right)^{1/3}\frac{(f/f_{\rm turb})^3}{(1+f/f_{\rm turb})^{11/3}(1+8\pi f/H_*)}$$

Sound wave

$$h^2\Omega_{\rm sw}(f) \simeq 1.64\times10^{-6}(H_*\tau_{\rm sw})(H_* R_*)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}(f/f_{\rm sw})^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

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.

See Huai-ke and Ligong's works for current constraints from GW data

Phase transition Dynamics

Precise predictions on the phase transition dynamics and its GW signals

1.Precisely calculate the finite-temperature effective potential $V_{eff}(\phi, T)$

(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, (see Michael J. Ramsey-Musolf's works, also Ligong's recent work)

and dim-reduction method: by D. Weir, Michael J. Ramsey-Musolf et.al

α T_p $R_* H_*$

2. Reliable calculations of bubble wall velocity v_b

S. Hoche, 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
Xiao Wang, **FPH**, Xinmin Zhang,arXiv:2011.12903

3. Energy budget during phase transition κ

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

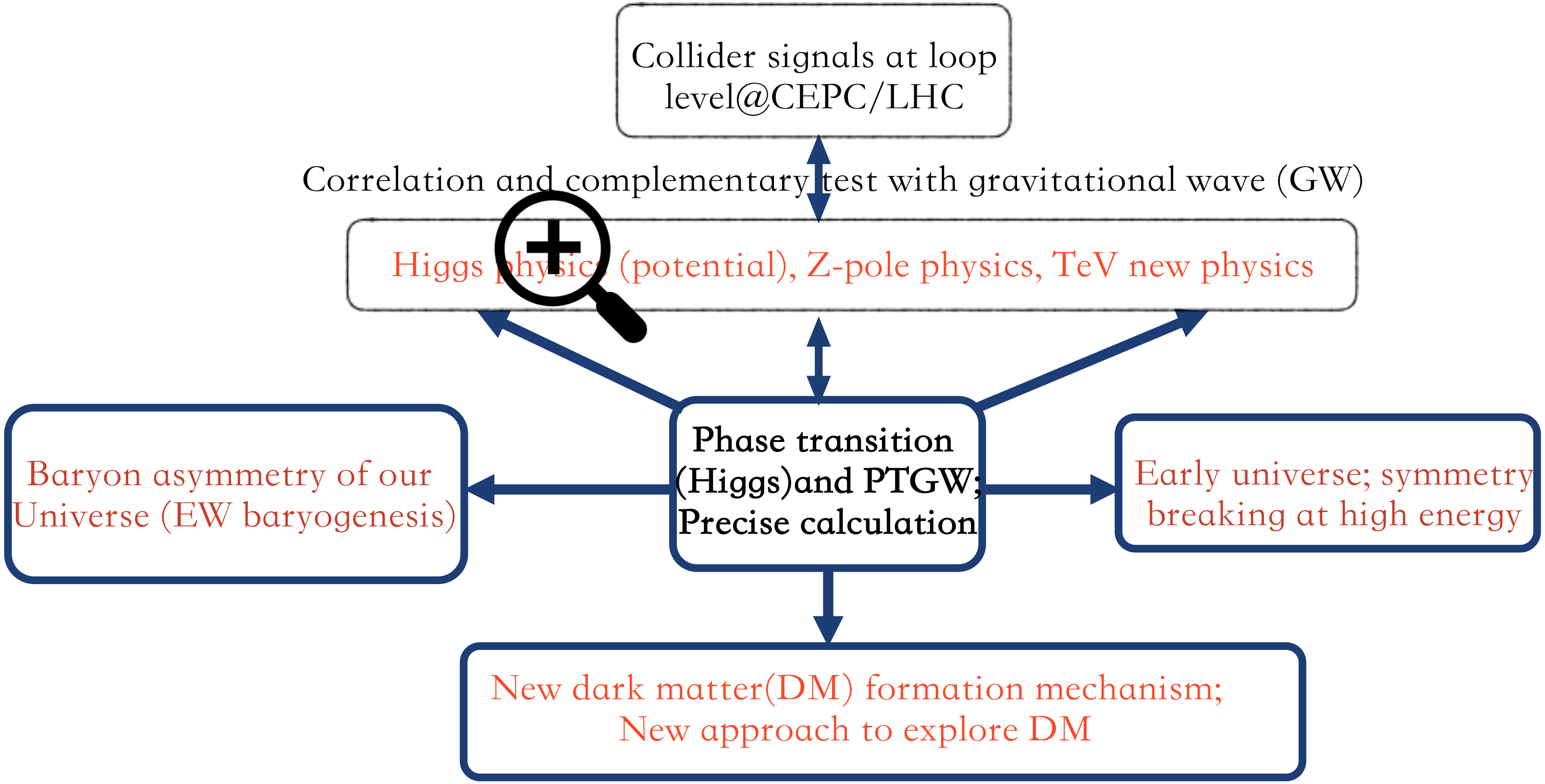
Phase transition Dynamics

Classify the SFOPT into four cases:

- **Slight supercooling**: $\alpha_p < 0.1$ the GW is too weak to be detected by LISA, might be within the sensitivity of BBO and ultimate-DECIGO.
- **Mild supercooling:** $0.1 < \alpha_p < 0.5$ the GW could be detected by LISA, TianQin, Taiji, BBO, DECIGO.
- **Strong supercooling:** $0.5 < \alpha_p < 1$
- **Ultra supercooling:** $\alpha_p > 1$

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

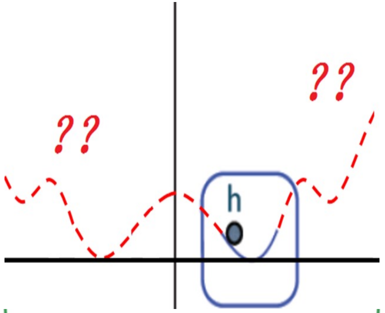
Motivation

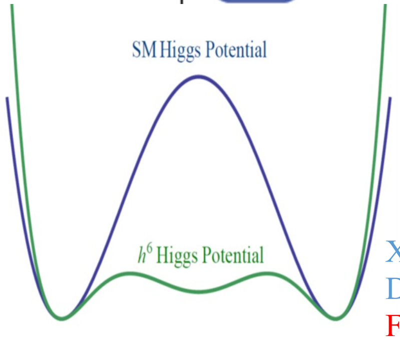


Collider signals at loop level@CEPC/LHC
Correlation and complementary test with gravitational wave (GW)
Higgs physics (potential), Z-pole physics, TeV new physics
Baryon asymmetry of our Universe (EW baryogenesis)
Phase transition (Higgs)and PTGW; Precise calculation
Early universe; symmetry breaking at high energy
New dark matter(DM) formation mechanism; New approach to explore DM

SFOPT and Higgs potential

What is the shape of Higgs potential?





Current data tells us 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

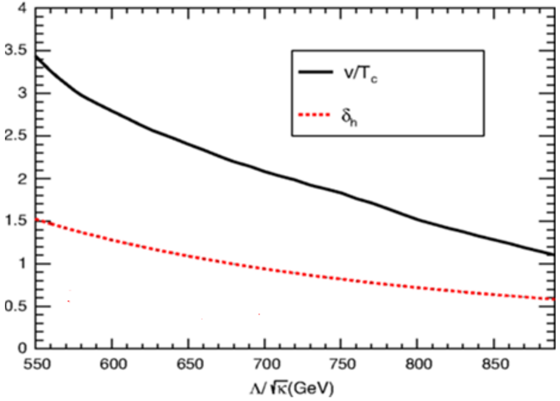
Xinmin Zhang Phys.Rev. D47 (1993) 3065-3067;C. Grojean, G. Servant, J. Well PRD71(2005)036001
D.J.H. Chung, A. J. Long, Lian-tao Wang Phys.Rev. D87(2013) 023509
FPH, et.al, Phys.Rev.D94(2016)no.4,041702 ; FPH, et.al, Phys.Rev.D93 (2016) no.10,103515
arXiv:1511.06495, Nima Arkani-Hamed et. al.; PreCDR of CEPC; arXiv: 1811.10545,CDR of CEPC

SFOPT and Higgs potential

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

See Prof. Lilin Yang's talk

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

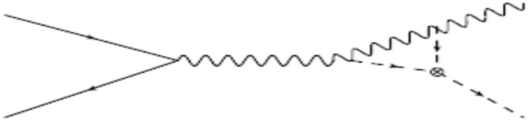


At one-loop level, deviation of the tri-linear Higgs coupling

$$\boldsymbol{\delta_h \in (0.6, 1.5)}$$

The Circular Electron Positron Collider (CEPC), ILC, FCC-ee can precisely test this scenario by precise measurements of the hZ cross section ($e^- e^+ \longrightarrow hZ$).

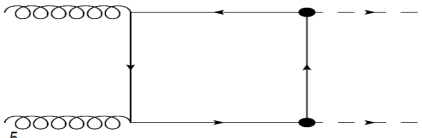
SM NNLO hZ cross section recently by Lilin Yang, et al 2016, Yu Jia et at 2016

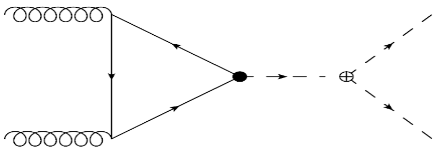


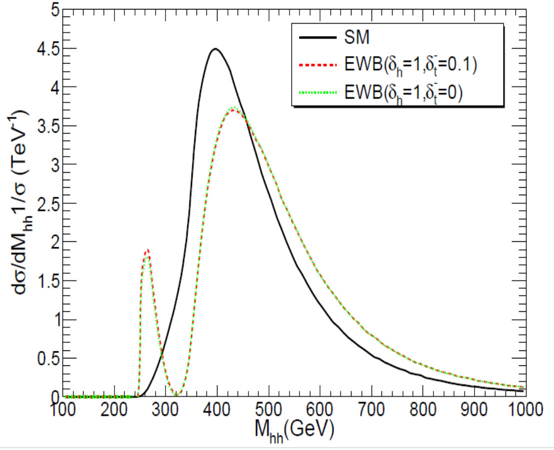
$$\delta_\sigma = \frac{\sigma_{hz,\delta_h \neq 0}}{\sigma_{hz,SM}} - 1$$

SFOPT and Higgs potential

Hints at hadron collider: Modify the invariant mass distribution of Higgs pair due to interference effects:





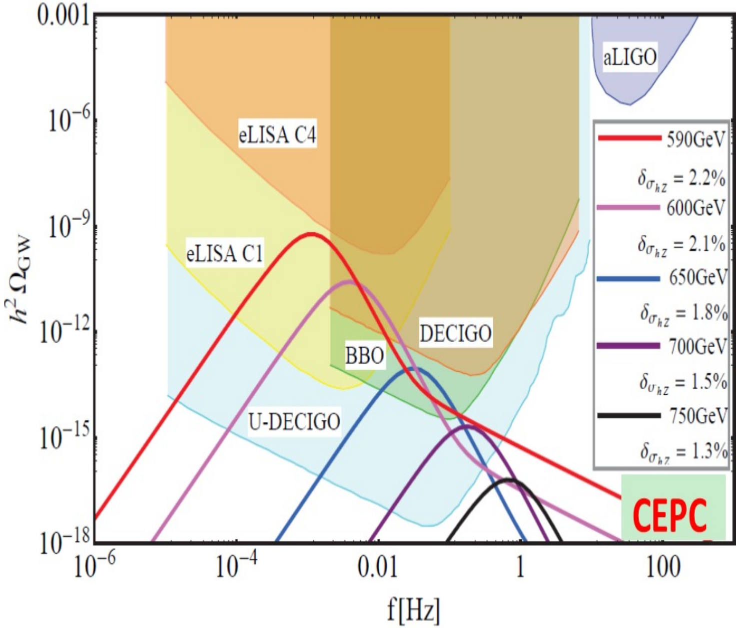


- **Two peaks for the baryogenesis scenario, one peak for the SM.**
- **Due to the difficulties to suppress backgrounds at the LHC, it will be difficult to completely pin down these anomalous coupling at 14 TeV LHC, even with 3000 ab^{-1} integrated luminosity.**
- **Exploiting boosted tricks helps to increase ability to extract the anomalous couplings.**
- **More precise information may come from future100 TeV hadron collider, such as SppC, or future lepton collider, such as CEPC .**

See Prof. Shufang Su, Lilin Yang, Yaquan FANG, Zhen Liu's talk

SFOPT and Higgs potential

Correlate particle collider and GW signals: double test on Higgs potential from particle to wave



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

SFOPT and Higgs potential

SM EFT

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

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

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

SFOPT produces large modification of trilinear Higgs coupling δ_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 find 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,
See Jianghao Yu's papers for more systematical study from SM EFT

SFOPT and Higgs potential

One examples

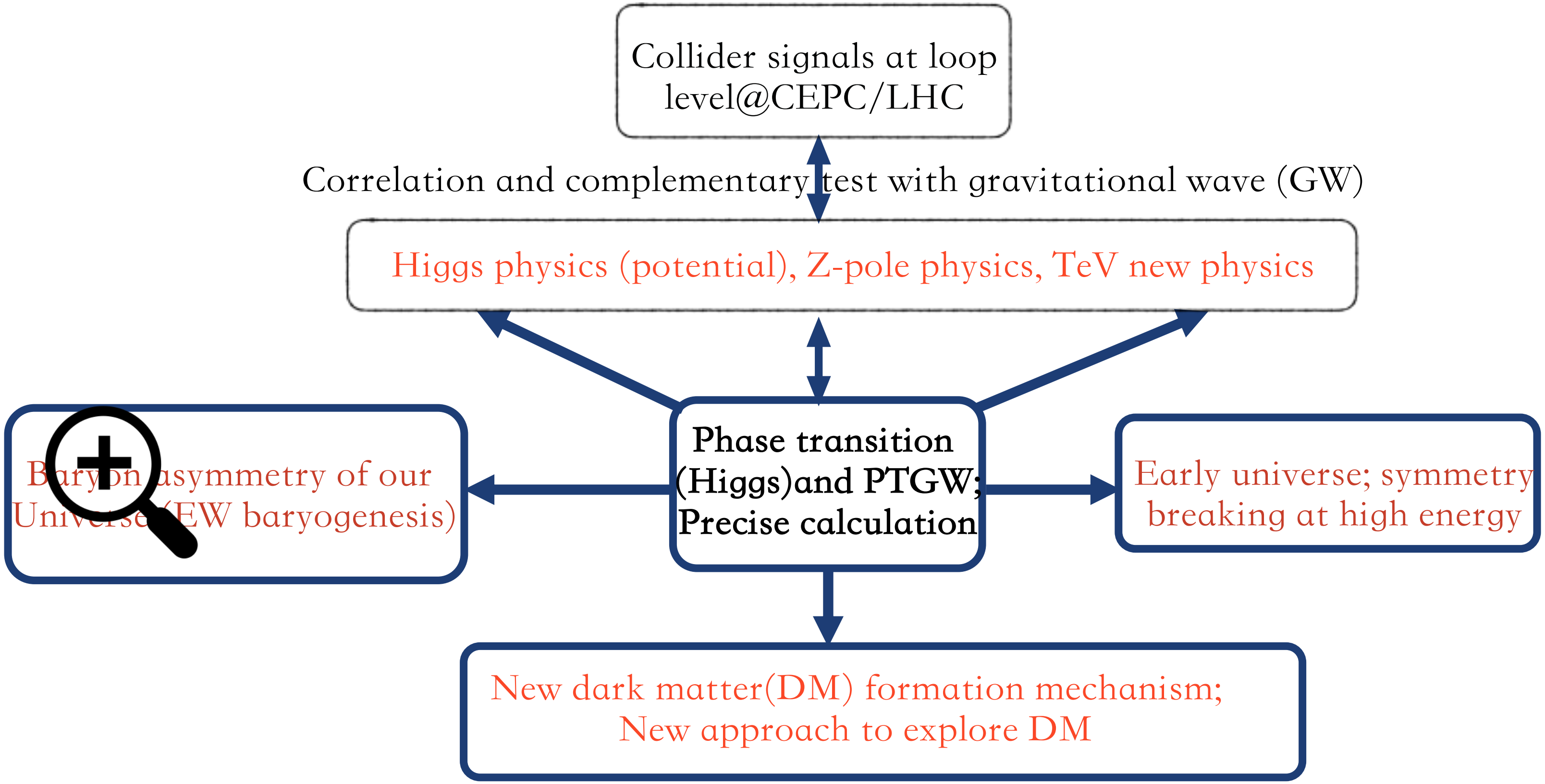
Qing-Hong Cao, FPH, Ke-Pan Xie, Xinmin Zhang, arXiv:1708.0473,
See Jianghao Yu's papers for more systematical study from SM EFT

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

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

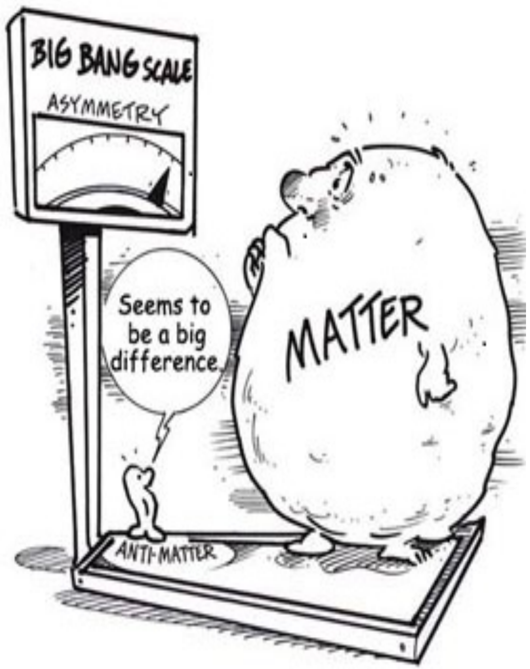
Dimension-six operator	Wilson coefficient
$\mathcal{O}_{WW} = g^2\|H\|^2 W^a_{\mu\nu}W^{a,\mu\nu}$	$c_{WW} = \frac{1}{(4\pi)^2}\frac{1}{48}(2\lambda_1+\lambda_2)\frac{1}{M_\Phi^2}$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	$c_{2W} = \frac{1}{(4\pi)^2}\frac{g^2}{60}\frac{1}{M_\Phi^2}$
$\mathcal{O}_{3W}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

Motivation



Collider signals at loop level@CEPC/LHC
Correlation and complementary test with gravitational wave (GW)
Higgs physics (potential), Z-pole physics, TeV new physics
Phase transition (Higgs)and PTGW; Precise calculation
Baryon asymmetry of our Universe (EW baryogenesis)
Early universe; symmetry breaking at high energy
New dark matter(DM) formation mechanism; New approach to explore DM

SFOPT and EW baryogenesis



$\eta_B = n_B/n_\gamma = 5.8 - 6.6 \times 10^{-10}$

(CMB, BBN)

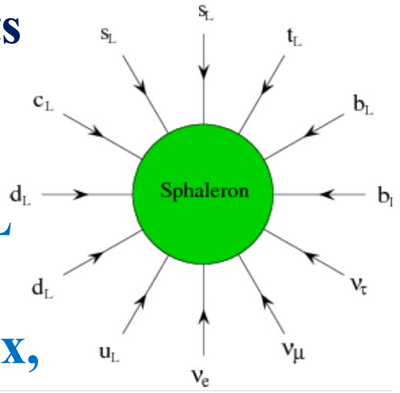
A long standing problem in particle cosmology is the origin of baryon asymmetry of the universe (BAU).

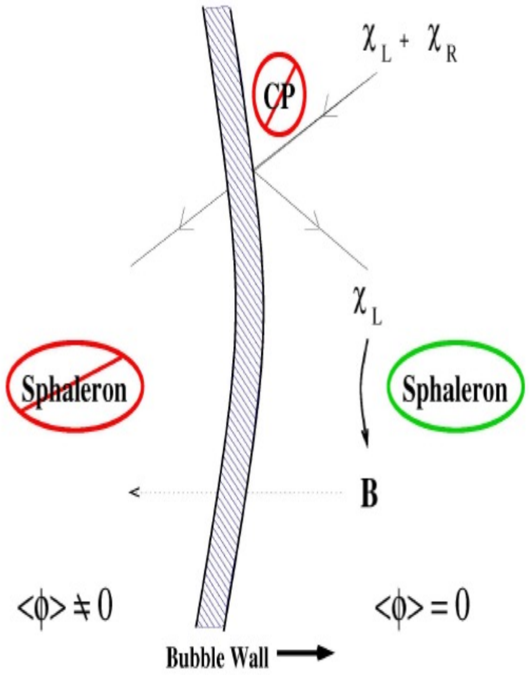
After the discovery of the Higgs boson by LHC and GW by aLIGO, electroweak (EW) baryogenesis becomes a timely and testable scenario for explaining the BAU.

SFOPT and EW baryogenesis

SM technically has all the 3 elements for baryogenesis (Sakharov conditions)

- **B violation from anomaly in B+L current;**
- **C and CP-violation: CKM matrix, but too weak, need new CP-violating sources;**
- **Departure from thermal equilibrium: SFOPT with expanding Higgs bubble wall**





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

SFOPT and EW baryogenesis

Dynamical CP violation for baryogengesis

Large enough CP-violating source for successful EW baryogenesis

Strong tension in most cases

pretty small CP-violation to avoid strong EDM constraints

EDM, ACME Collaboration, i.e. $|d_e| < 1.1\times 10^{-29}$ cm · e at 90% C.L. (Nature vol.562,357,2018)

How to alleviate this tension for successful baryogenesis?

SFOPT and EW baryogenesis

Question: How to alleviate the tension for successful baryogenesis ?

Answer: Dynamical CP-violating source

Large enough CP-violating source 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**: **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, work in progress with Eibun Senaha, Xiao Wang in an extended IDM model

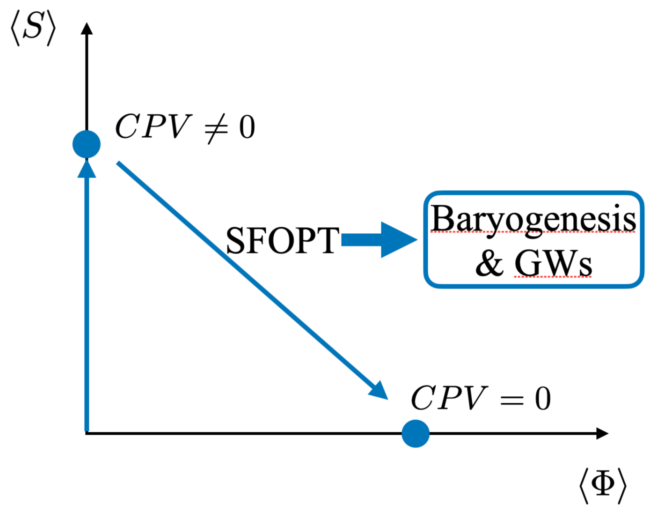
Baldes, T. Konstandin and G. Servant, arXiv:1604.04526;I. Baldes, T. Konstandin and G. Servant, JHEP 1612, 073 (2016);S. Bruggisser,T.Konstandin and G. Servant, JCAP 1711, no. 11, 034 (2017)

SFOPT and EW baryogenesis

Taking the effective scenario as a representative example:

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

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



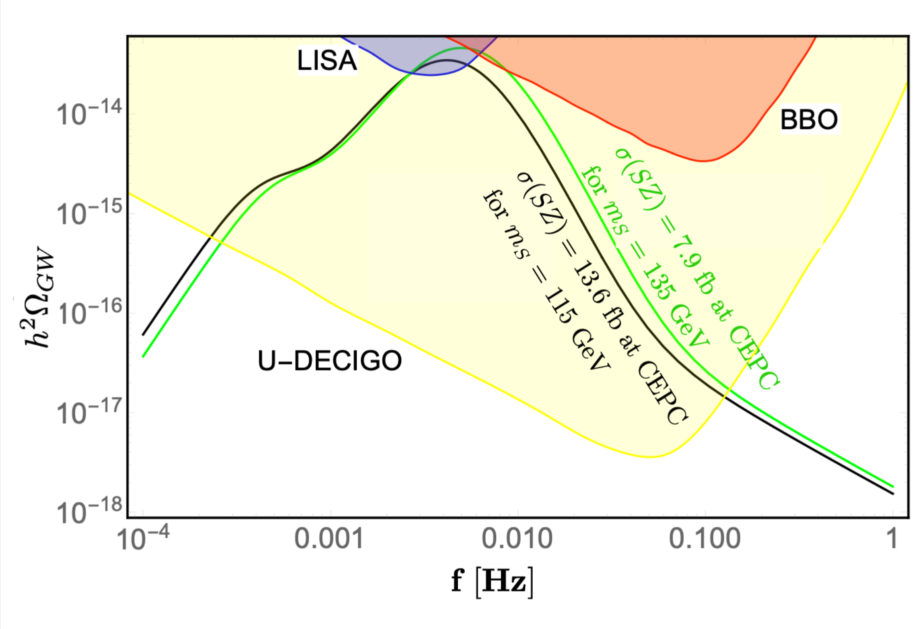
The singlet and the dim-5 operator can come From many types composite Higgs model, arXiv:0902.1483 , arXiv:1703.10624 ,arXiv:1704.08911,

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

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

SFOPT and EW baryogenesis

The correlation between the future GW and collider signals



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

SFOPT and EW baryogenesis

We study a simple model for the successful DM and EW baryogenesis with dynamical CP-violating source.

arXiv:1905.10283, FPH, Eibun Senaha and work in progress with Eibun Senaha

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

The new lepton Yukawa interaction is

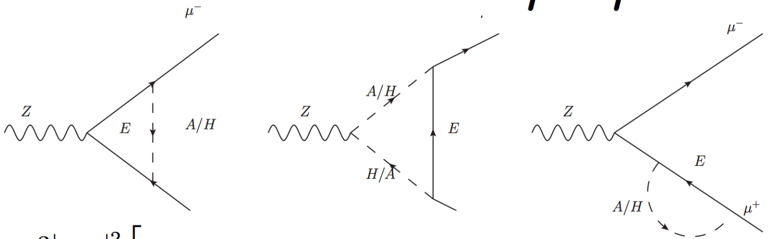
$$-\mathcal{L}_Y \ni y_{ij}\bar{\ell}_{iL}\eta E_{jR} + m_{E_i}\bar{E}_{iL}E_{iR} + \text{h.c.}$$

vector-like lepton (E_i)

D. Borah, S. Sadhukhan and S. Sahoo, Phys. Lett. B **771**, 624 (2017).
L. Calibbi, R. Ziegler and J. Zupan, JHEP **1807**, 046 (2018).
D. Borah, P. S. B. Dev and A. Kumar, Phys. Rev. D **99**, no. 5, 055012 (2019).

SFOPT and EW baryogenesis

Indirect search by $Z \to \mu^+\mu^-$



$$\Delta g^L_{Z\bar{\mu}\mu} = \frac{3|y_{\mu E}|^2}{32\pi^2}\Bigg[\tilde{F}_3(m_E, m_H, m_A) + \sum_{\phi=H,A}\left\{\left(-\frac{1}{2}+s_W^2\right)F_2(m_E, m_\phi) + s_W^2 F_3(m_E, m_\phi)\right\}$$

An important missing observable in many previous study!

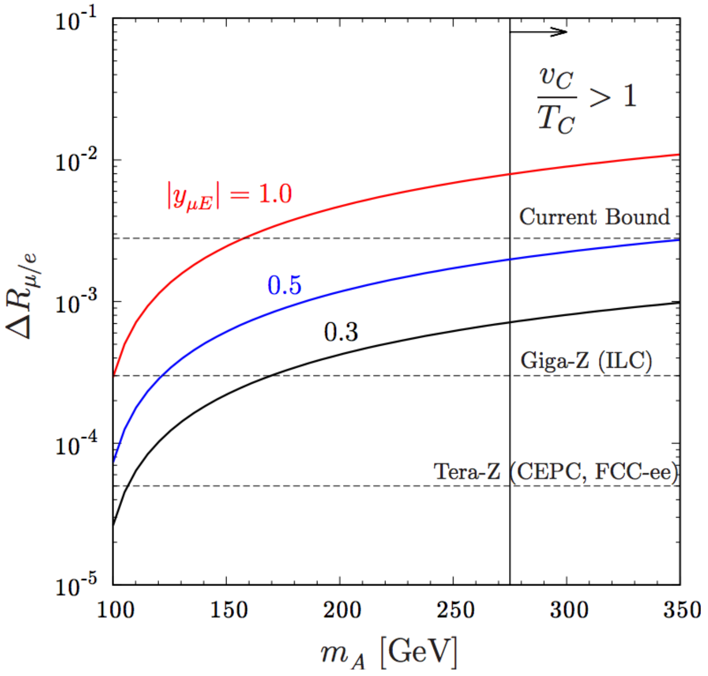
$$R_{\mu/e} = \frac{\Gamma(Z\to\mu^+\mu^-)}{\Gamma(Z\to e^+e^-)}$$

deviation of $R_{\mu/e}$ from the SM value as

$$\Delta R_{\mu/e} \equiv \frac{R_{\mu/e} - R^{\rm SM}_{\mu/e}}{R^{\rm SM}_{\mu/e}} \simeq \frac{2g^{L,\rm SM}_{Z\bar{\mu}\mu}{\rm Re}(\Delta g^L_{Z\bar{\mu}\mu}) + |\Delta g^L_{Z\bar{\mu}\mu}|^2}{|g^{L,\rm SM}_{Z\bar{\mu}\mu}|^2 + |g^{R,\rm SM}_{Z\bar{\mu}\mu}|^2},$$

Large enhancement of Z boson decay by the requirements of EW baryogenesis and DM.
Further generalisation of this enhancement effects from the aspects of symmetry breaking is working in progress.

SFOPT and EW baryogenesis



To satisfy the EW strong first-order phase transition (baryogenesis) and DM it requires the large mass splitting of the scalar mass spectrum in the same multiplet, which leads to significant enhancement of the Z boson decay.

Tera-Z can be a new indirect search to explore DM and baryogenesis.

Motivation

Collider signals at loop level@CEPC/LHC

Correlation and complementary test with gravitational wave (GW)

Higgs physics (potential), Z-pole physics, TeV new physics

Baryon asymmetry of our Universe (EW baryogenesis)

Phase transition (Higgs)and PTGW; Precise calculation

Early universe; symmetry breaking at high energy

New dark matter(DM) formation mechanism;
New approach to explore DM

SFOPT and new DM mechanism/signal

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

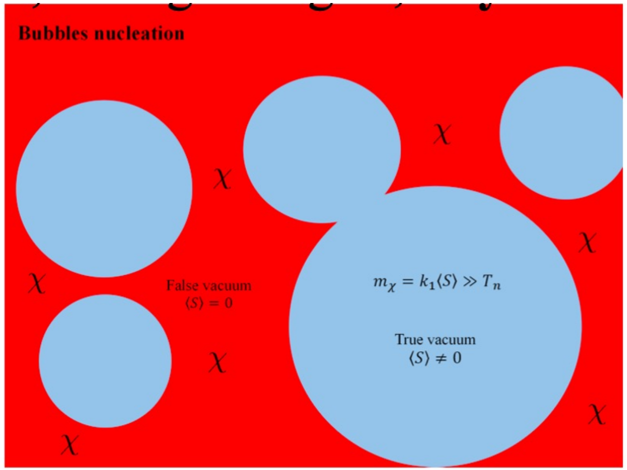
The cosmic phase transition with Q-balls production can explain baryogenesis and DM simultaneously, where constraints on DM mass and reverse dilution are significantly relaxed. We study how to probe this scenario by GW signals and collider signals at QCD NLO.

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

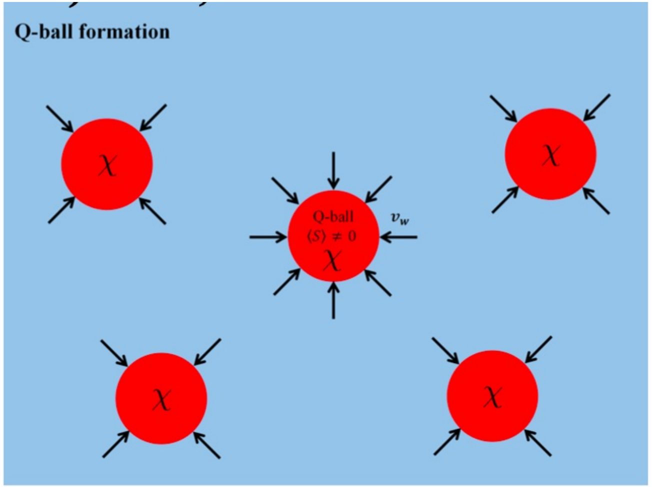
$$\rho_{\mathrm{DM}}^4 v_b^{3/4} = 73.5(2\eta_B s_0)^3 \lambda_S \sigma^4 \Gamma^{3/4}$$

SFOPT and new DM mechanism/signal

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



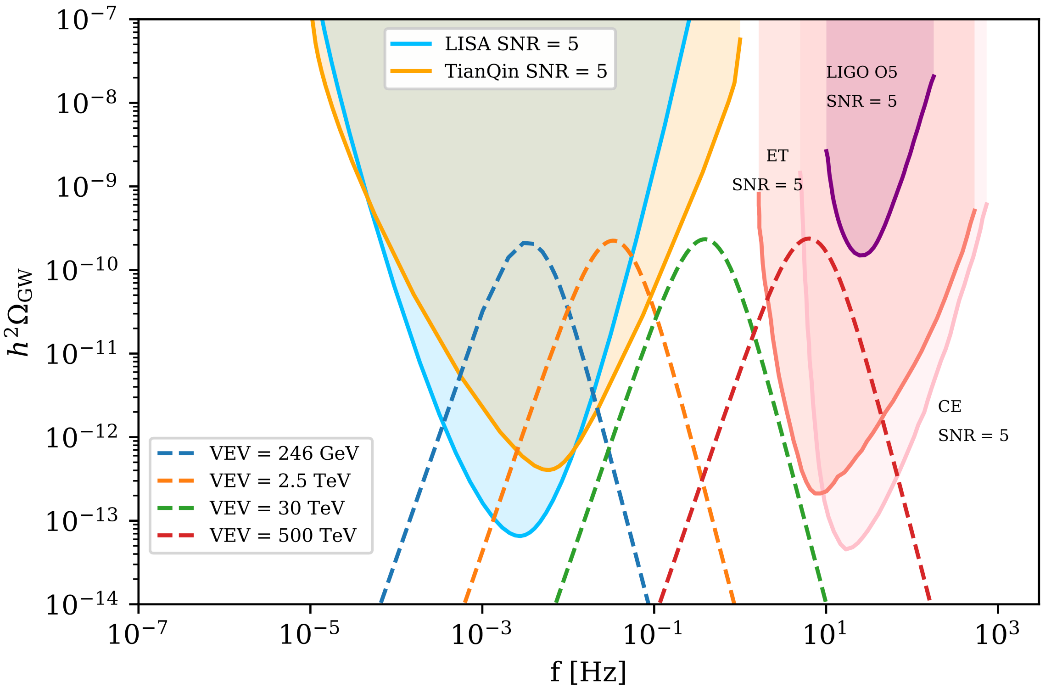
(a) Bubble nucleation: χ particles trapped in the false vacuum due to Boltzmann suppression



(b) Q-ball formation: After the formation of Q-balls, they should be squeezed by the true vacuum

FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028; **FPH**, Xiao Wang, this work:arXiv:2208:xxxxx

SFOPT and new DM mechanism/signal



FPH, Xiao Wang, this work:arXiv:2208:xxxxx

SFOPT and new DM mechanism/signal

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.

FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028
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 D. Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, J. Smirnov
arXiv:2103.09822, Pouya Asadi , Eric D. Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, J. Smirnov
arXiv:2008.04430 Jeong-Pyong Hong， Sunghoon Jung, Ke-pan Xie
See Ke-Pan's talk for the primordial black hole DM formed by EWPT

SFOPT and new DM mechanism/signal

- New 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
Zhaofeng Kang,et.al. arXiv:2101.03795
Zhaofeng Kang, et. al. arXiv:2003.02465
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

SFOPT and new DM mechanism/signal

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

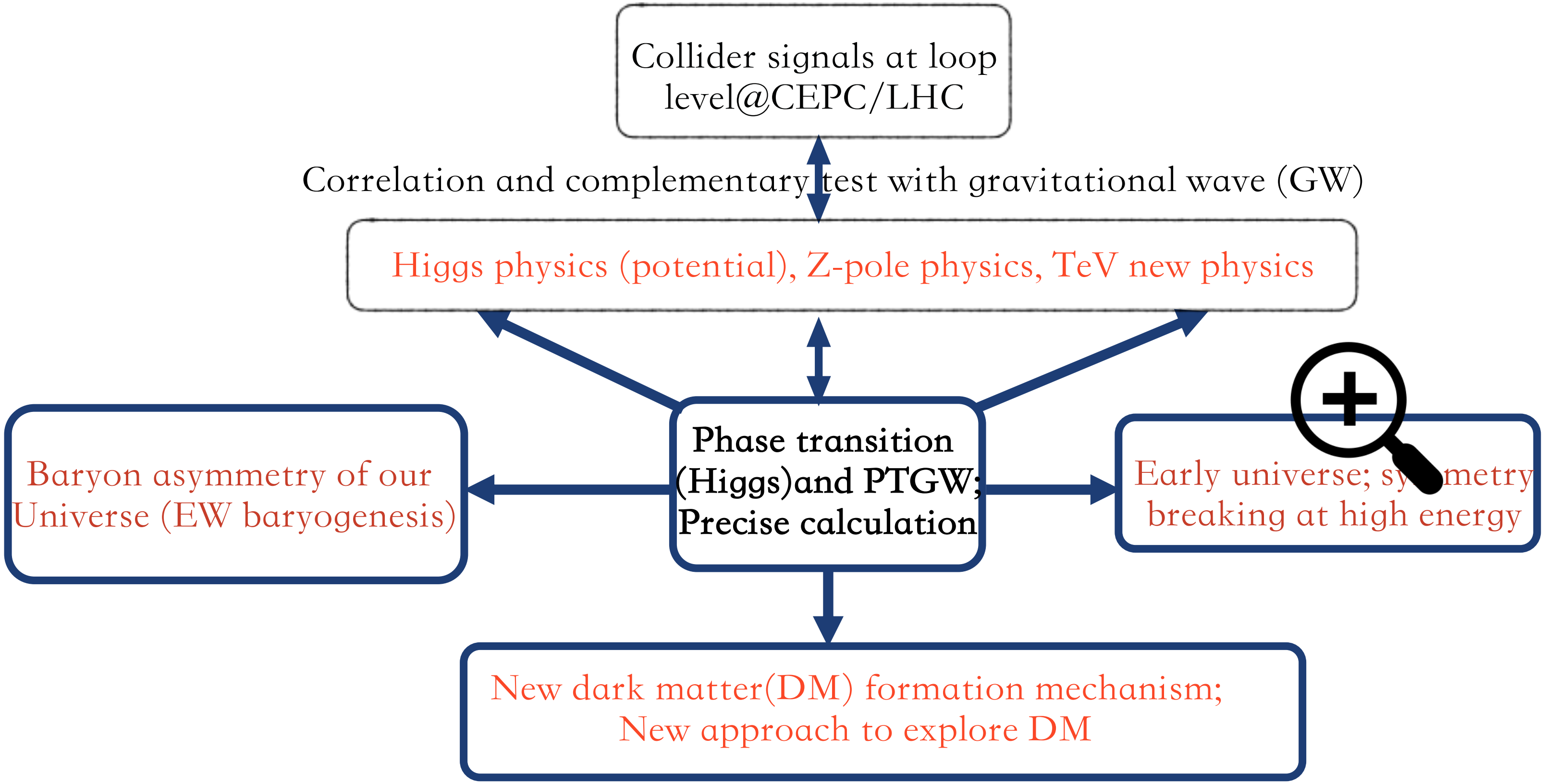
Yan Wang, Chong Sheng Li, and **FPH**, arXiv:2012.03920; **FPH**, Jiang-Hao Yu, Phys.Rev. D98 (2018) no.9, 095022

SFOPT and new DM mechanism/signal

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, et.al. arXiv:2011.04821
Ligong Bian，et.al. arxiv:1907.13589
Zhaofeng Kang,et.al. arXiv:2101.03795
Zhaofeng Kang, et. al. arXiv:2003.02465
a lot of new and nice works unmentioned here

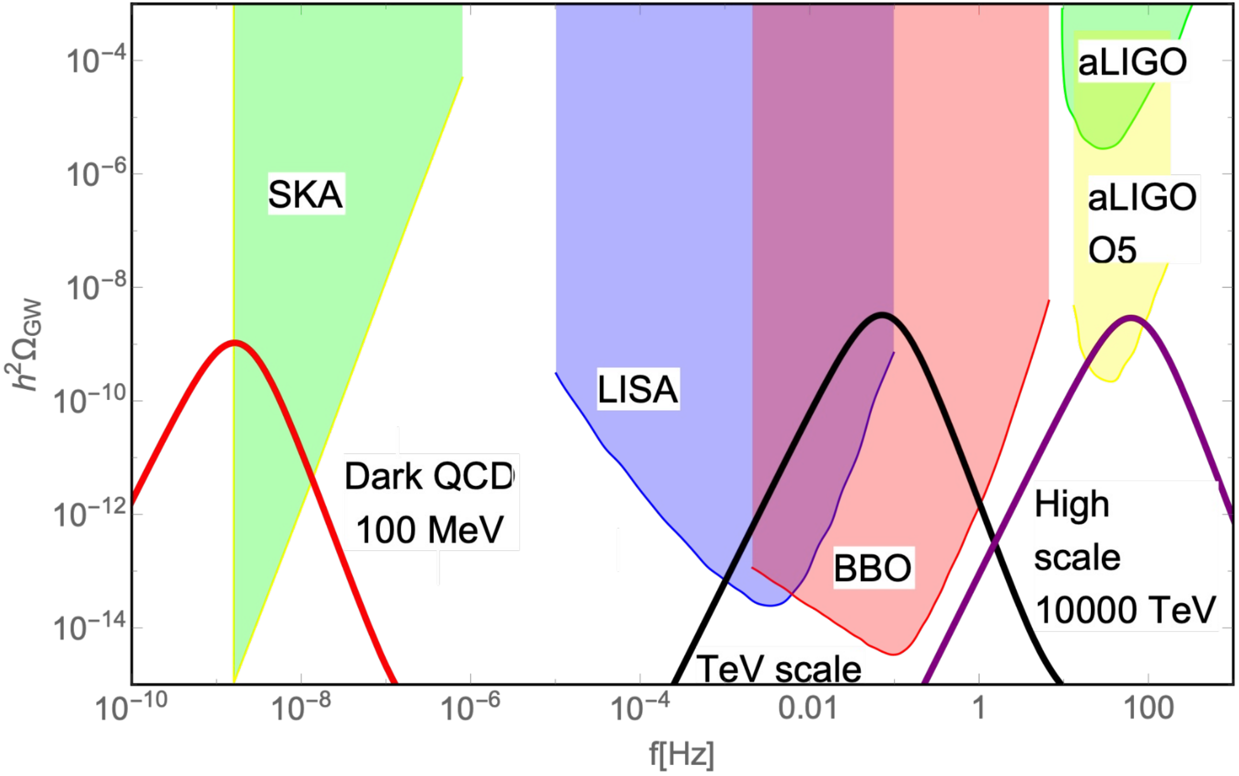
Motivation



Collider signals at loop level@CEPC/LHC
Correlation and complementary test with gravitational wave (GW)
Higgs physics (potential), Z-pole physics, TeV new physics
Baryon asymmetry of our Universe (EW baryogenesis)
Phase transition (Higgs)and PTGW; Precise calculation
Early universe; sy metry breaking at high energy
New dark matter(DM) formation mechanism; New approach to explore DM

SFOPT and new physics/early universe

Generally

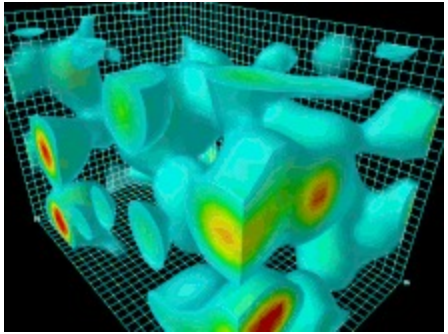


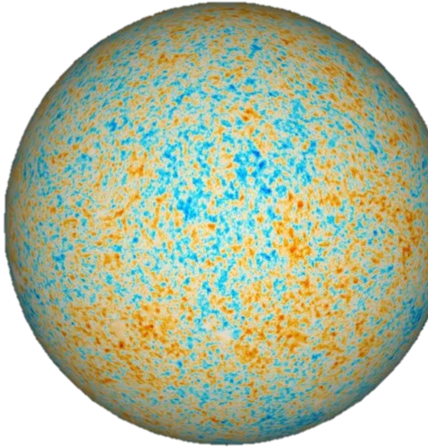
FPH, Xinmin Zhang, Phys.Lett. B788 (2019) 288-29,

PTGW anisotropy and its implication for primordial seeds of our universe

Primordial power spectra

$$P_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2}\left\langle |\mathcal{R}_k|^2 \right\rangle\Big|_{aH=k} = \frac{H^2}{\pi \varepsilon_{\rm sr} m_{\rm pl}^2}\Big|_{aH=k} = A_s\left(\frac{k}{k_*}\right)^{n_s-1}$$



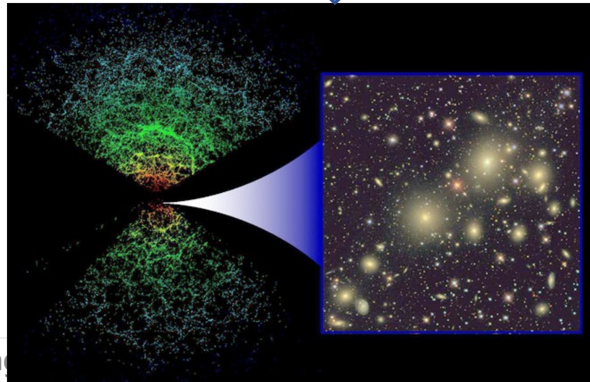


angular power spectra

$$C_l = \frac{2}{\pi}\int_0^\infty dk k^2 P_{\mathcal{R}}(k)\,|\mathcal{T}_l(k)|^2$$

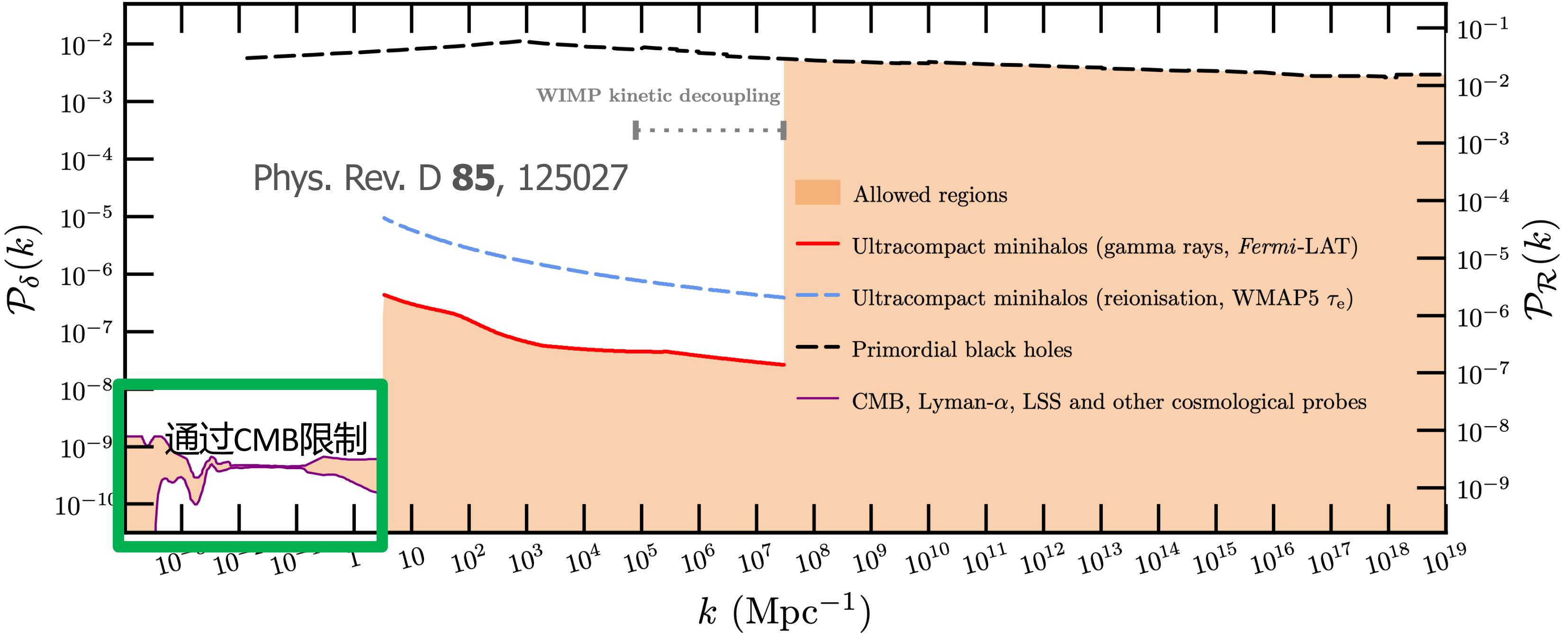
$$C_\ell^{\rm obs} = \frac{1}{2\ell+1}\sum_{\ell m} a_{\ell m} a_{\ell m}^*$$

The Primordial density Perturbation (quantum fluctuation) from inflation or alternative as the origin of structure



PTGW anisotropy and its implication for primordial seeds of our universe

The quest for small-scale power spectrum——The road less traveled



- ✓ A complete model of inflation requires a solid understanding of the small-scale primordial power spectrum;
- ✓ however, it is hard!

PTGW anisotropy and its implication for primordial seeds of our universe

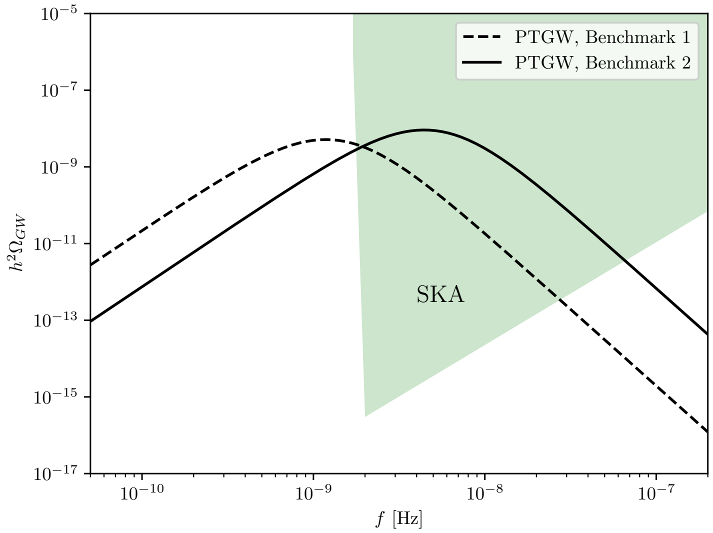
$$\boxed{H_*^2 = \rho/3M_{\rm pl}^2}$$

$$h^2\Omega_{\rm GW}(f) \simeq 1.64\times10^{-6}\left(\frac{4}{3}\right)^{\frac{1}{2}}\boxed{(H_*R_*)^2}\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^{\frac{3}{2}}\times\left(\frac{100}{g_*}\right)^{\frac{1}{3}}(f/f_{\rm sw})^3\left(\frac{7}{4+3\,(f/f_{\rm sw})^2}\right)^{\frac{7}{2}}$$

$$f_{\rm sw}\simeq 2.6\times10^{-5}\ {\rm Hz}\frac{1}{H_*R_*}\left(\frac{T_*}{100{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$ Peak frequency

QCD-like DM model

	Benchmark 1	Benchmark 2
phase transition strength	$\alpha = 0.5$	
D.O.F	$g_* = 10$	
efficiency factor	$\kappa_v \approx 0.44$	
bubble wall velociy	$v_b = 0.95$	
characteristic temperature	$T_* = 1$ MeV	$T_* = 5$ MeV
mean bubble separation	$H_*R_* = 0.15$	$H_*R_* = 0.2$



PTGW anisotropy and its implication for primordial seeds of our universe

Phys. Lett. B, 2017, 771: 9-12 ; Phys. Rev. D, 2019, 100(12): 121501 ; Phys. Rev. D, 2021, 103 (2): 023522 ; Phys. Rev. Lett., 2021, 127(27): 271301

distribution function $$f(\eta,\boldsymbol{x},\boldsymbol{p})=\bar{f}(\eta,p)-p\frac{\partial\bar{f}(\eta,p)}{\partial p}\mathcal{G}(\eta,\boldsymbol{x},\hat{\boldsymbol{p}})$$

$\mathcal{G}(\eta,\boldsymbol{x},\hat{\boldsymbol{p}})$

quantify the imhomogeneity of graviton

$$ds^2=-(1+2\Psi)dt^2+a^2(1-2\Phi)\delta_{ij}dx^idx^j$$

Boltzmann equation $$\frac{df}{dt}=C[f]\Rightarrow\mathcal{G}'+ik\mu\mathcal{G}=\Phi'-ik\mu\Psi$$

$$\begin{aligned}\mathcal{G}(\eta_0,k,\mu)=&\mathcal{G}(\eta_{\rm pt},k,\mu)e^{ik\mu(\eta_{\rm pt}-\eta_0)}+\int_{\eta_{\rm pt}}^{\eta_0}d\eta\left[\Phi'(\eta,k)-ik\mu\Psi(\eta,k)\right]e^{ik\mu(\eta-\eta_0)}\\=&\mathcal{G}(\eta_{\rm pt},k,\mu)e^{ik\mu(\eta_{\rm pt}-\eta_0)}+\int_{\eta_{\rm pt}}^{\eta_0}d\eta\left[\Phi'(\eta,k)e^{ik\mu(\eta-\eta_0)}-\frac{d}{d\eta}\left(\Psi(\eta,k)e^{ik\mu(\eta-\eta_0)}\right)+\Psi'(\eta,k)e^{ik\mu(\eta-\eta_0)}\right]\\=&\underbrace{\left[\mathcal{G}(\eta_{\rm pt},k)+\Psi(\eta_{\rm pt},k)\right]e^{ik\mu(\eta_{\rm pt}-\eta_0)}}_{\rm SW}+\underbrace{\int_{\eta_{\rm pt}}^{\eta_0}d\eta\left[\Phi'(\eta,k)+\Psi'(\eta,k)\right]e^{ik\mu(\eta-\eta_0)}}_{\rm ISW}\end{aligned}$$

PTGW anisotropy and its implication for primordial seeds of our universe

$$(\mathcal{G}+\Psi)\left(\eta_{\mathrm{pt}}, k\right)=-\frac{1}{3} \mathcal{R}(k)$$ radiation dominate

$$\mathcal{G}_{\ell}^{\mathrm{SW}}\left(\eta_0, k\right)=(\mathcal{G}+\Psi)\left(\eta_{\mathrm{pt}}, k\right) j_{\ell}\left[k\left(\eta_{\mathrm{pt}}-\eta_0\right)\right]$$

$$C_{\ell}^{\mathcal{G}, \mathrm{SW}}=\frac{4 \pi}{9} \int_0^{\infty} \frac{d k}{k} P_{\mathcal{R}}(k) j_{\ell}^2\left[k\left(\eta_0-\eta_{\mathrm{pt}}\right)\right]$$

$$\int_{\eta_{\mathrm{pt}}}^{\eta_0} d \eta\left[\Phi^{\prime}(\eta, k)+\Psi^{\prime}(\eta, k)\right] e^{i k \mu\left(\eta-\eta_0\right)}$$

$$\mathcal{G}_{\ell}^{\mathrm{ISW}}\left(\eta_0, k\right)=\int_{\eta_{pt}}^{\eta_0} d \eta\left(\Phi^{\prime}+\Psi^{\prime}\right)(\eta, k) j_{\ell}\left[k\left(\eta-\eta_0\right)\right]$$

$$\left(\Phi^{\prime}+\Psi^{\prime}\right)(\eta, k) \approx-(\Phi+\Psi)\left(\eta_{\mathrm{pt}}, k\right) \delta\left(\eta-\eta_k\right)$$

$$(\Phi+\Psi)\left(\eta_{\mathrm{pt}}, k\right)=-\frac{4}{3} \mathcal{R}(k)$$

small scale

$$C_{\ell}^{\mathcal{G}, \mathrm{ISW}}=\frac{64 \pi}{9} \int_0^{\infty} \frac{d k}{k} P_{\mathcal{R}}(k) j_{\ell}^2\left[k\left(\eta_0-\eta_{\mathrm{pt}}\right)\right]$$

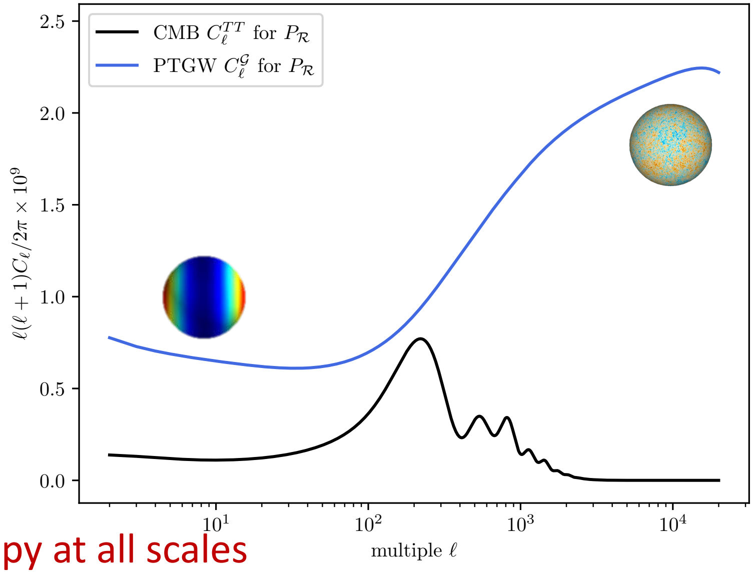
PTGW anisotropy and its implication for primordial seeds of our universe

$$C_\ell^{\mathcal{G}} \approx C_\ell^{\mathcal{G},\mathrm{SW}} = \frac{4\pi}{9}\int_0^\infty \frac{dk}{k} P_{\mathcal{R}}(k) j_\ell^2\left[k\left(\eta_0-\eta_{\mathrm{pt}}\right)\right]$$

$$\begin{aligned}\mathcal{G}_\ell\left(\eta_0,k\right) &= \left(\mathcal{G}_\ell^{\mathrm{SW}}+\mathcal{G}_\ell^{\mathrm{ISW}}\right)\left(\eta_0,k\right)\\ &\approx \left[(\mathcal{G}+\Psi)-(\Phi+\Psi)\right]\left(\eta_{pt},k\right) j_\ell\left[k\left(\eta_{\mathrm{pt}}-\eta_0\right)\right]\end{aligned}$$

$$C_\ell^{\mathcal{G}} = 4\pi\int_0^\infty \frac{dk}{k} P_{\mathcal{R}}(k) j_\ell^2\left[k\left(\eta_0-\eta_{\mathrm{pt}}\right)\right]$$

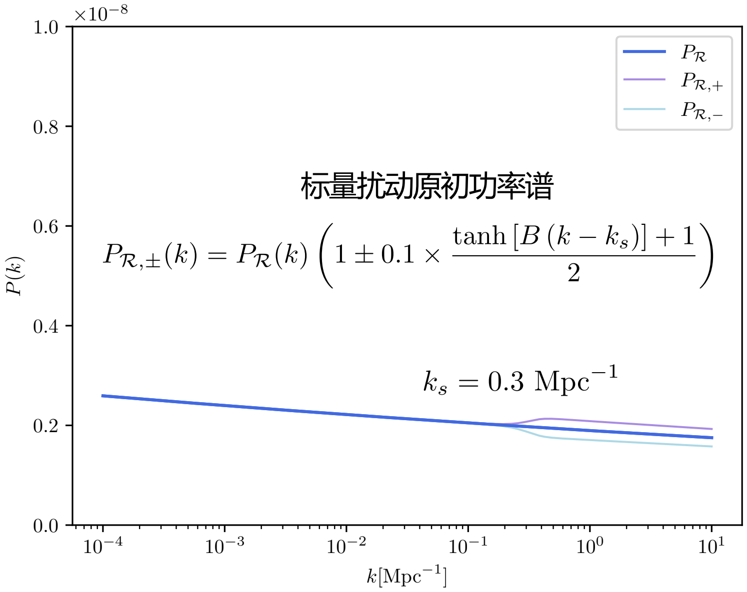
Planck: $\ln(10^{10}A_s) = 3.040 \pm 0.016 \quad n_s = 0.9626 \pm 0.0057$

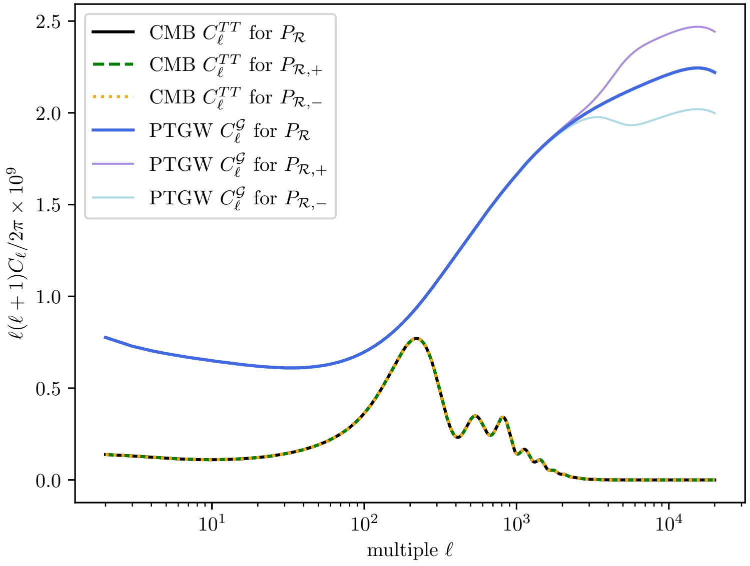


Angular power spectra

- ✓ The anisotropy of PTGW is stronger than CMB anisotropy at all scales
- ✓ The anisotropy of PTGW goes up at small scale

PTGW anisotropy and its implication for primordial seeds of our universe





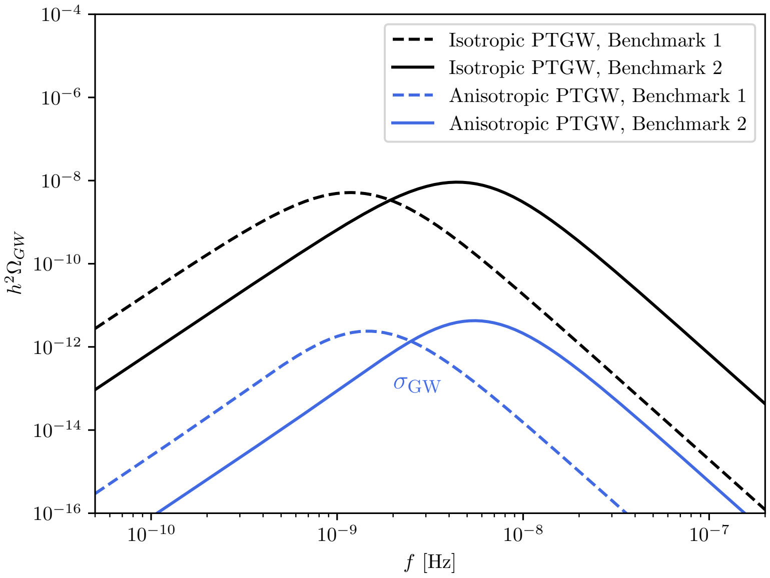
✓ The anisotropy of PTGW keeps more small-scale information.

PTGW anisotropy and its implication for primordial seeds of our universe

$$\mathrm{Var}^{\mathcal{G}} = \frac{1}{4\pi}\sum_{\ell}(2\ell+1)C_{\ell}^{\mathcal{G}}$$

$$\sigma_{\rm GW}(p) \equiv h^2\Omega_{\rm GW}(p)\sqrt{\mathrm{Var}^{\delta_{\rm GW}}(p)}$$

CMB TT anisotropy	4×10^{-5}
PTGW anisotropy	1×10^{-4}
PTGW energy spectra anisotropy	8×10^{-4} $(> f_{\rm sw})$



PTGW anisotropy and its implication for primordial seeds of our universe

$$\rho_{\rm GW}(\eta,\boldsymbol{x}) = \int d^3\boldsymbol{p}\, p f(\eta,\boldsymbol{x},\boldsymbol{p}) = \int dp d\hat{\boldsymbol{p}} p^3 f(\eta,\boldsymbol{x},p,\hat{\boldsymbol{p}})$$

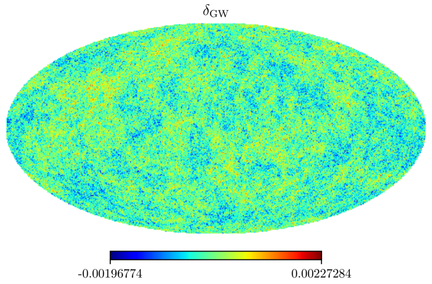
$$\Omega_{\rm GW}(\eta,\boldsymbol{x},p) = \int \frac{d\hat{\boldsymbol{p}}}{4\pi}\bar{\Omega}_{\rm GW}(\eta,p)\left[1+\delta_{\rm GW}(\eta,\boldsymbol{x},p,\hat{\boldsymbol{p}})\right]$$

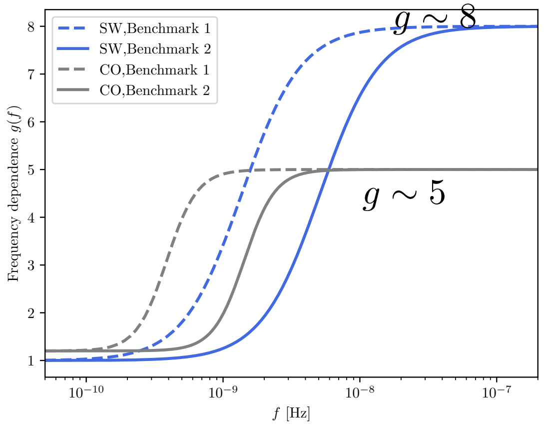
$$= \int d\hat{\boldsymbol{p}}\frac{p^4}{\rho_c}\left[\bar{f}(\eta,p) - p\frac{\partial \bar{f}(\eta,p)}{\partial p}\mathcal{G}(\eta,\boldsymbol{x},\hat{\boldsymbol{p}})\right]$$

anisotropy of GW energy spectra $\delta_{\rm GW} = \frac{\delta\Omega_{\rm GW}(\eta,\boldsymbol{x},p,\hat{p})}{\bar{\Omega}_{\rm GW}(\eta,p)}$

$$\delta_{\rm GW}(\eta,\boldsymbol{x},p,\hat{p}) = \left[4 - \frac{\partial \ln\bar{\Omega}_{\rm GW}(\eta,p)}{\partial \ln p}\right]\mathcal{G}(\eta,\boldsymbol{x},\hat{p})$$

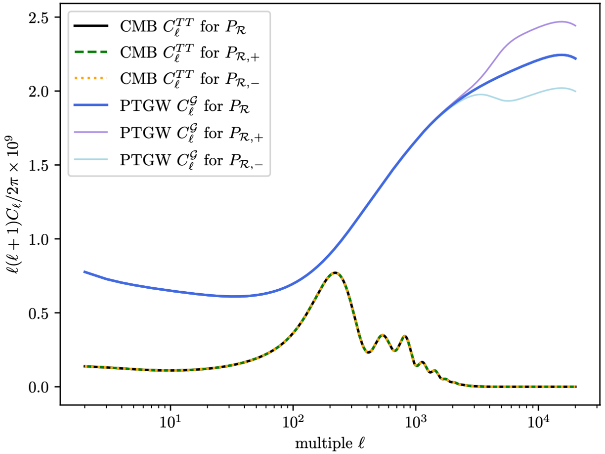
$$C_l^{\delta_{\rm GW}}(p) = g^2(p) C_l^{\mathcal{G}}$$

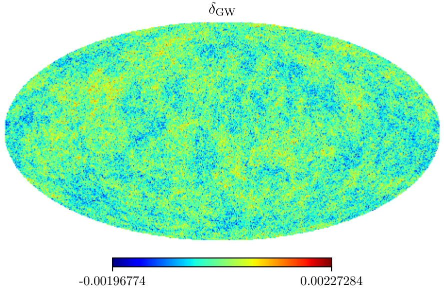


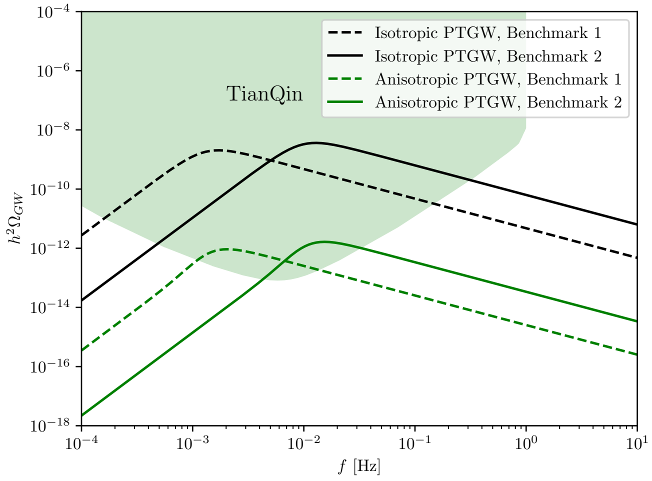


PTGW anisotropy and its implication for primordial seeds of our universe

Application to EWPT

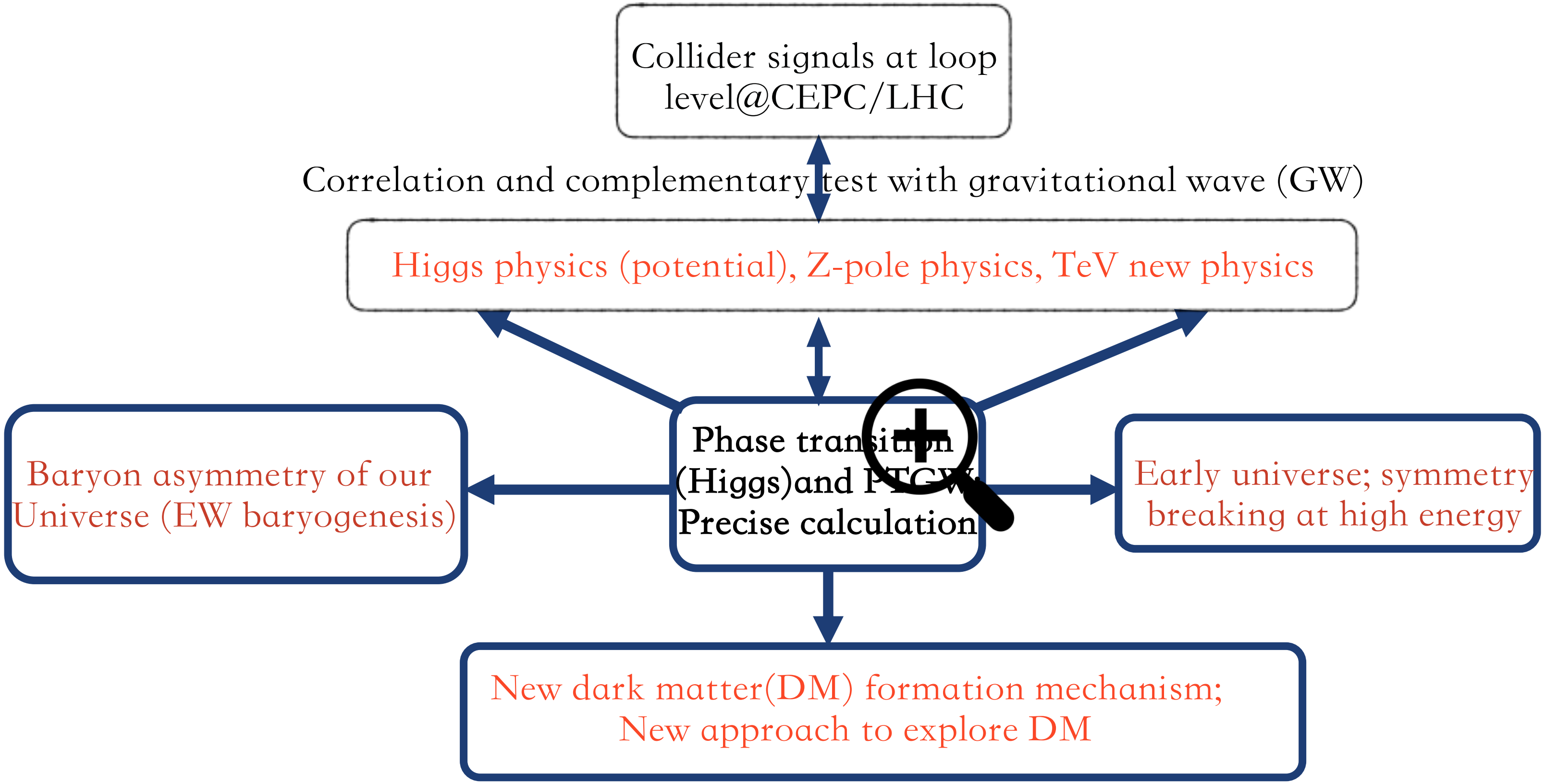






Yongping Li, **FPH**, Xiao Wang, Xinmin Zhang, Phys.Rev.D 105 (2022) 083527
Yongping Li, **FPH**, Xiao Wang, work in progress

Motivation


Collider signals at loop level@CEPC/LHC
Correlation and complementary test with gravitational wave (GW)
Higgs physics (potential), Z-pole physics, TeV new physics
Baryon asymmetry of our Universe (EW baryogenesis)
Phase transition (Higgs)and PTGW; Precise calculation
Early universe; symmetry breaking at high energy
New dark matter(DM) formation mechanism; New approach to explore DM

Phase transition Dynamics

Precise predictions on the phase transition dynamics and its GW signals

1.precisely calculate the finite-temperature effective potential $V_{eff}(\phi, T)$

(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

α T_p $R_* H_*$

2. Reliable calculations of bubble wall velocity v_b

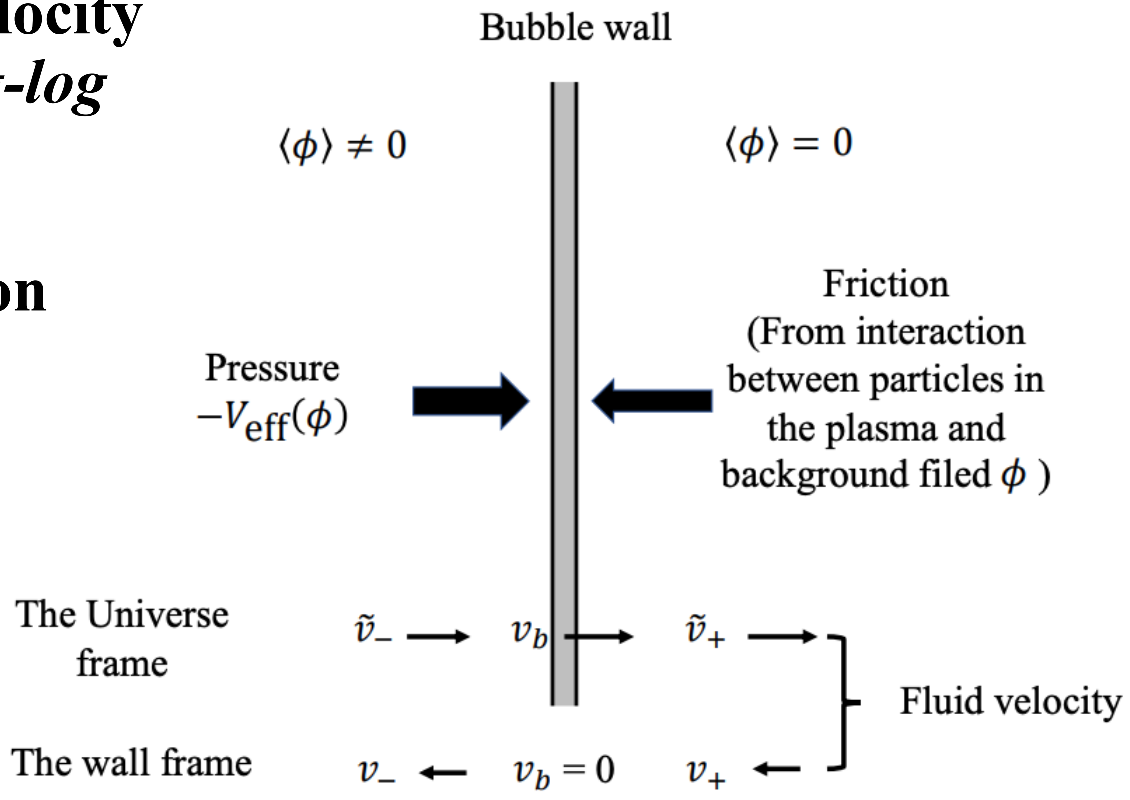
S. Hoche, J. Kozaczuk, A. J. Long, J. Turner and Y. Wang, arXiv:2007.10343 ,
Avi Friedlander, Ian Banta, James M. Cline, David Tucker-Smith, arXiv:2009.14295v2
Xiao Wang, **FPH**, Xinmin Zhang,arXiv:2011.12903

3. energy budget during phase transition κ

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

Phase transition Dynamics

Bubble wall velocity beyond *leading-log* approximation in electroweak phase transition



Phase transition Dynamics

Bubble wall velocity beyond *leading-log* approximation in electroweak phase transition

The EOM of Higgs filed (order parameter field)

- Energy momentum conservation of scaler-plasma system in WKB approximation

$$\Box\phi + \frac{\partial V_0(\phi)}{\partial\phi} + \sum \frac{dm^2}{d\phi}\int\frac{d^3p}{(2\pi)^3 2E}f(p,x) = 0\ ,$$

Zero-temperature part of effective potential

$$f \equiv f_0 + \delta f\ .$$

$$\Box\phi + \frac{\partial V_{\rm eff}(\phi,T)}{\partial\phi} + \sum \frac{dm^2}{d\phi}\int\frac{d^3p}{(2\pi)^3 2E}\delta f(p,x) = 0\ ,$$

Full thermal effective potential

Friction term

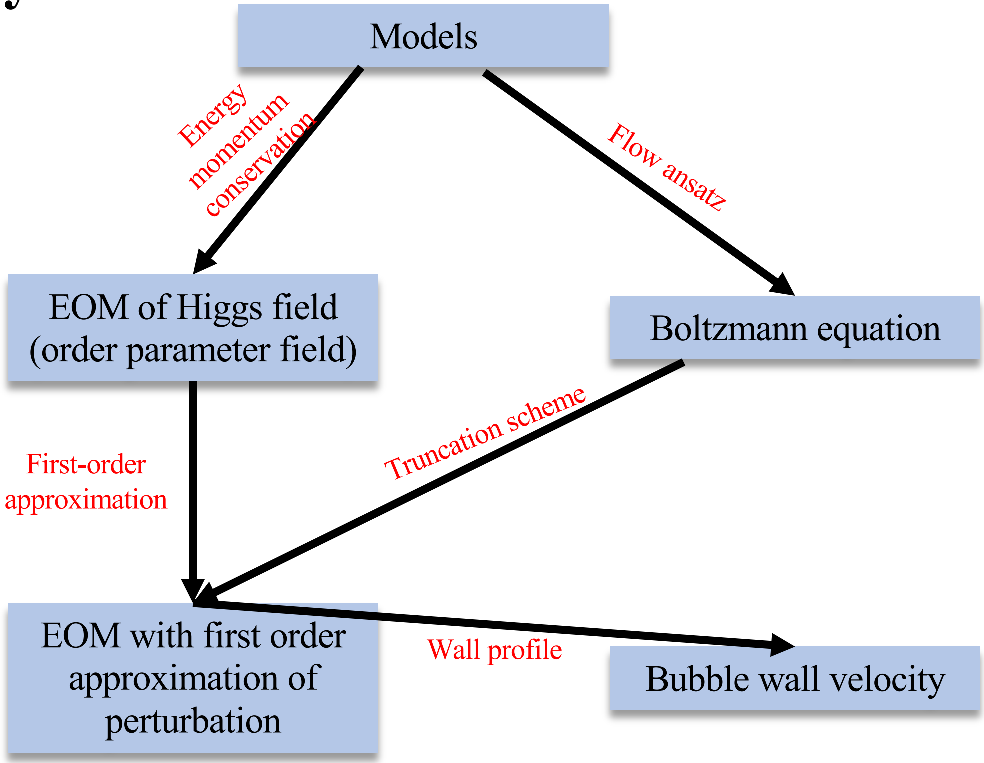
Deviation from equilibrium

Field dependent mass

Phase transition Dynamics

Bubble wall velocity beyond *leading-log* approximation in electroweak phase transition

arXiv:2011.12903, Xiao wang, FPH, Xinmin Zhang



Phase transition Dynamics

The deviation distribution part for each massive particle is crucial

With WKB approximation $p \gg 1/L_w$, we can describe it with Boltzmann equation

$$\frac{d}{dt} f = \left(\frac{\partial}{\partial t} + \dot{z} \frac{\partial}{\partial z} + \dot{p}_z \frac{\partial}{\partial p_z} \right) f = -C[f] \; ,$$

- For thermal equilibrium situation, the collision term is zero, hence the non-equilibrium part can be derived from this equation

To solve the Boltzmann equation

- *Appropriate form for the distribution function (flow ansatz)*
- *Specific truncation scheme*
- *Proper treatment of collision term*

Phase transition Dynamics

Key point:calculate the particle scattering amplitude in thermal plasma

The collision term in Boltzmann equation

$$C[f] = \sum_i \frac{1}{2E_p} \int \frac{d^3k d^3p' d^3k'}{(2\pi)^9 2E_k 2E_{p'} 2E_{k'}} \bar{\Sigma}|M|^2 (2\pi)^4 \delta^4(p+k-p'-k')\mathcal{P}[f_i] \ ,$$

$$\mathcal{P}[f_i] = f_1 f_2 (1 \pm f_3)(1 \pm f_4) - f_3 f_4 (1 \pm f_1)(1 \pm f_2) \ .$$

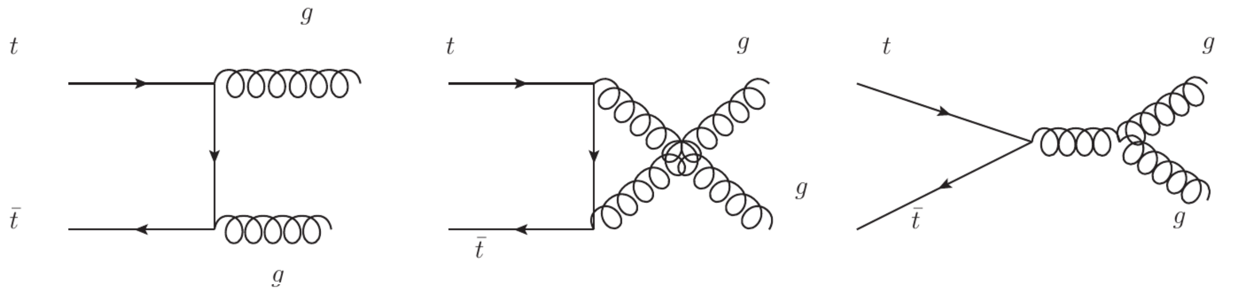
To the first-order a

$$\mathcal{P}[f_i] \approx \frac{\delta_1 + \delta_2 - \delta_3 - \delta_4}{T} f_1 f_2 (1 \pm f_3)(1 \pm f_4) \ .$$

Phase transition Dynamics

Top quark: $t\bar{t} \to gg$

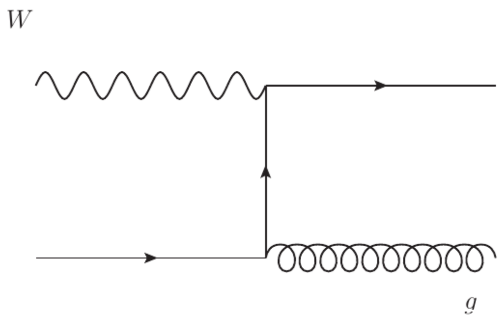
- Interactions of $O(g_s^4)$

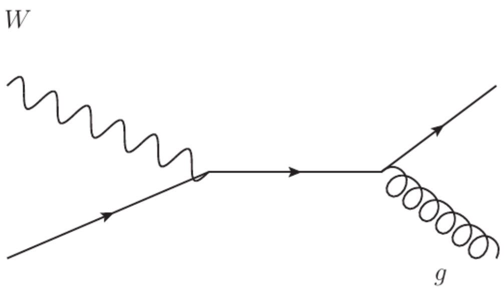


Phase transition Dynamics

W/Z boson: $Wu \to dg$

- Interactions of $O(g_s^2 g_w^2)$

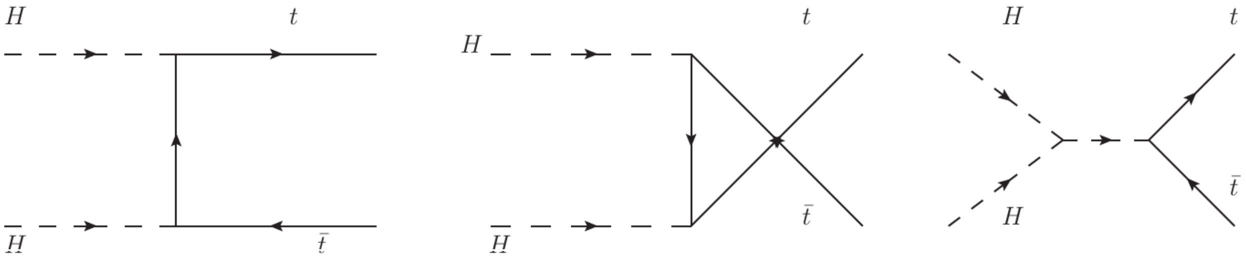




Phase transition Dynamics

Higgs boson: $HH \to t\bar{t}$

- Interactions of $O(y_t^4)$



Phase transition Dynamics

To the first order of perturbations, we can derive the following EOM of the Higgs field.

$$-(1-v_w^2)\phi'' + \frac{\partial V_{\text{eff}}(\phi,T)}{\partial\phi} + \delta T_{\text{bg}}\frac{\partial^2 V_{\text{eff}}(\phi,T)}{\partial T\partial\phi}$$
$$+\frac{N_t T}{2}\frac{dm_t^2}{d\phi}\left(c_1^f\mu_t + c_2^f(\delta T_t + \delta T_{bg})\right)$$
$$+\frac{N_W T}{2}\frac{dm_W^2}{d\phi}\left(c_1^b\mu_W + c_2^b(\delta T_W + \delta T_{bg})\right)$$
$$+\frac{N_H T}{2}\frac{dm_H^2}{d\phi}\left(c_1^b\mu_H + c_2^b(\delta T_H + \delta T_{bg})\right) = 0$$

$$T = T_+ + \delta T_{bg}(z) \longrightarrow T_n = T_+ = T$$

Here we take an approximation

Phase transition Dynamics

Bubble wall velocity beyond *leading-log* approximation in electroweak phase transition

- For a specific benchmark point, the results of beyond leading-log approximation with the contribution of Higgs boson

	$\Lambda/\sqrt{\kappa}$ [GeV]	v_w	$L_w T$	v_c/T_c	T_n [GeV]
Two-particle	780	0.3382	20.1863	1.1044	100.977
Three-particle	780	0.2499	18.1759	1.1044	100.977

arXiv:2011.12903, Xiao wang, FPH, Xinmin Zhang

Phase transition Dynamics

Precise predictions on the phase transition dynamics and its GW signals

1.precisely calculate the finite-temperature effective potential $V_{eff}(\phi, T)$

(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

α T_p $R_* H_*$

2. Reliable calculations of bubble wall velocity v_b

S. Hoche, 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
Xiao Wang, **FPH**, Xinmin Zhang,arXiv:2011.12903

3. energy budget during phase transition κ

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

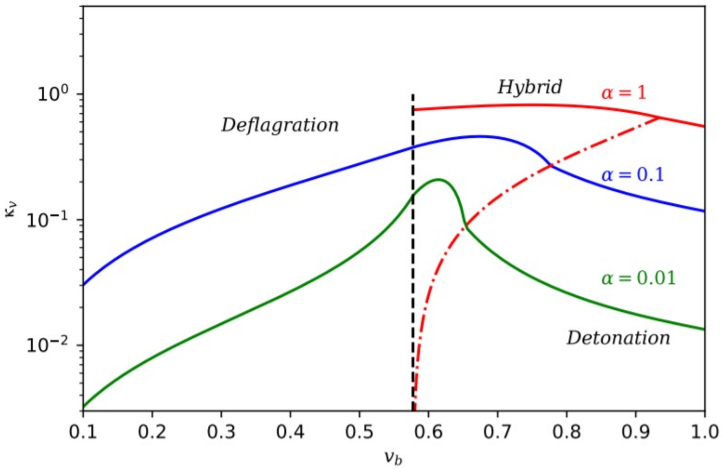
Phase transition Dynamics

Energy budget for phase transition GW

Energy budget **(to measure the efficiency of the energy released by a SFOPT converting to the kinetic energy of sounding plasma)**

$$h^2\Omega_{\rm sw}(f) \simeq 1.64\times 10^{-6}(H_*\tau_{\rm sw})(H_*R_*)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3}(f/f_{\rm sw})^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

LISA Cosmology working group *JCAP* 03 (2020) 024



The efficiency parameter (based on the bag model), the energy budget/efficiency parameter beyond the bag model are study in our recent work:

Xiao Wang, FPH and Xinmin Zhang, PRD 103 (2021) 10, 103520

Xiao Wang, **FPH** and Xinmin Zhang, JCAP 05, 045 (2020)

J. R. Espinosa, T. Konstandin, J. M. No, and G. Servant, JCAP 06 (2010) 028.

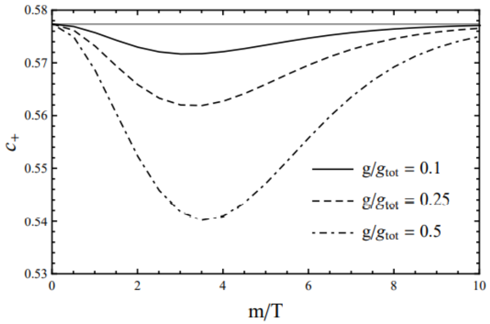
Phase transition Dynamics

Energy budget for phase transition GW

- GW signals generated during a SFOPT are directly related to efficiency parameter: $h\Omega_{GW} \propto \kappa^2$ or $\kappa^{\frac{3}{2}}$;
- Most of current studies of the efficiency parameter are based on bag EoS, which assume the sound velocity is $1/\sqrt{3}$ in both phases. But for a realistic SFOPT, particle can obtain the mass, hence, the sound velocity can deviate from pure radiation phase.

$$K \equiv \frac{\rho_{\text{fl}}}{e_+} = \frac{3}{e v_w^3} \int w(\xi)\, v^2 \gamma^2 \xi^2 d\xi \,, \quad \rho_{\text{fl}} = \frac{3}{v_w^3} \int \xi^2 v^2 \gamma^2 w d\xi$$

$$\Omega_{GW} \propto \left(\frac{\rho_{\text{fl}}}{e_+}\right)^2 , \qquad \kappa_{\bar\theta} = \frac{4\rho_{\text{fl}}}{\Delta\bar\theta} \quad K = \left(\frac{\Delta\bar\theta}{4e_+}\kappa_{\bar\theta}\right)$$



L. Leitao and A. Megevand, Nucl. Phys. B **891**, 159-199 (2015)

Phase transition Dynamics

Energy budget for phase transition GW

Bag EoS

$$p_+ = \frac{1}{3}a_+T_+^4 - \epsilon_+, \quad e_+ = a_+T_+^4 + \epsilon_+ \,,$$

$$p_- = \frac{1}{3}a_-T_-^4 - \epsilon_-, \quad e_- = a_-T_-^4 + \epsilon_- \,.$$

$$\alpha_\theta = \frac{4}{3}\frac{\Delta\epsilon}{w_+}, \quad \epsilon_\pm = \frac{1}{4}(e_\pm - 3p_\pm)$$

Strength parameter

$$\partial p/\partial e = c_s^2 = \text{constant}$$

EoS with different sound velocity (DSVM)

$$p_+ = c_+^2 a_+T_+^4 - \epsilon_+, \quad e_+ = a_+T_+^4 + \epsilon_+ \,,$$

$$p_- = c_-^2 a_-T_-^4 - \epsilon_-, \quad e_- = a_-T_-^4 + \epsilon_- \,,$$

$$\alpha_{\bar\theta} = \frac{\Delta\bar\theta}{3w_+}, \quad \bar\theta = e - p/c_-^2$$

Strength parameter

F. Giese, T. Konstandin, and J. van de Vis, JCAP. 07 (2020) 057.

Phase transition Dynamics

Energy budget for phase transition GW

- Matching condition

$$w_- v_-^2 \gamma_-^2 + p_- = w_+ v_+^2 \gamma_+^2 + p_+,$$
$$w_- v_- \gamma_-^2 = w_+ v_+ \gamma_+^2.$$

$$\longrightarrow \quad v_+ v_- = \frac{p_+ - p_-}{e_+ - e_-}, \quad \frac{v_+}{v_-} = \frac{e_- + p_+}{e_+ + p_-}.$$

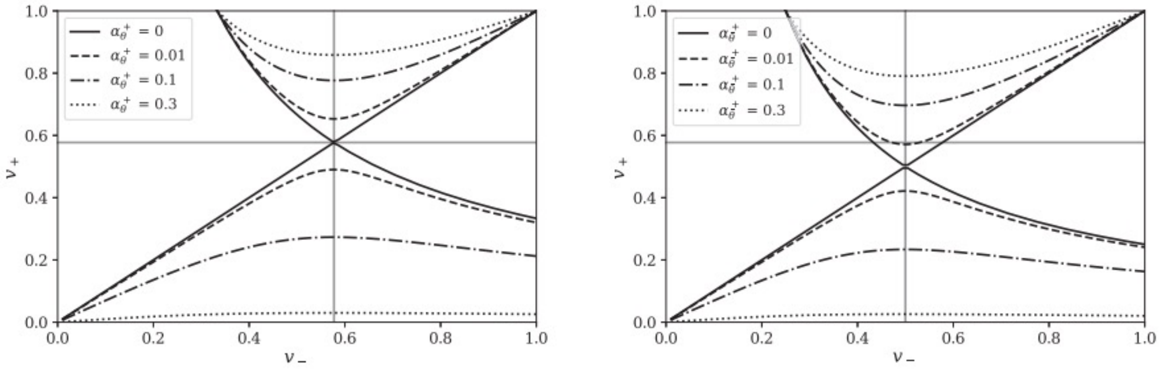


FIG. 1. The fluid velocities v_+ and v_- in the reference frame of bubble wall for different definitions and values of phase transition strength parameter. The horizontal and vertical gray lines indicate the sound velocities of symmetric and broken phase. Left panel: the bag model. Right panel: the DSVM with $c_+^2 = 1/3$ and $c_-^2 = 0.25$.

X. Wang, F. P. Huang and X. Zhang, PRD 103 (2021) 10, 103520

Phase transition Dynamics

Energy budget for phase transition GW

- Energy momentum conservation derive fluid equation:

$$(\xi - v)\frac{\partial_\xi e}{w} = 2\frac{v}{\xi} + \gamma^2(1 - v\xi)\partial_\xi v \ ,$$

$$(1 - v\xi)\frac{\partial_\xi p}{w} = \gamma^2(\xi - v)\partial_\xi v \ .$$

$$2\frac{v}{\xi} = \gamma^2(1 - v\xi)\left[\frac{\mu^2}{c_s^2} - 1\right]\partial_\xi v$$

Velocity profile

$$\frac{\partial_\xi w}{w} = \left(1 + \frac{1}{c_s^2}\right)\mu\gamma^2\partial_\xi v$$

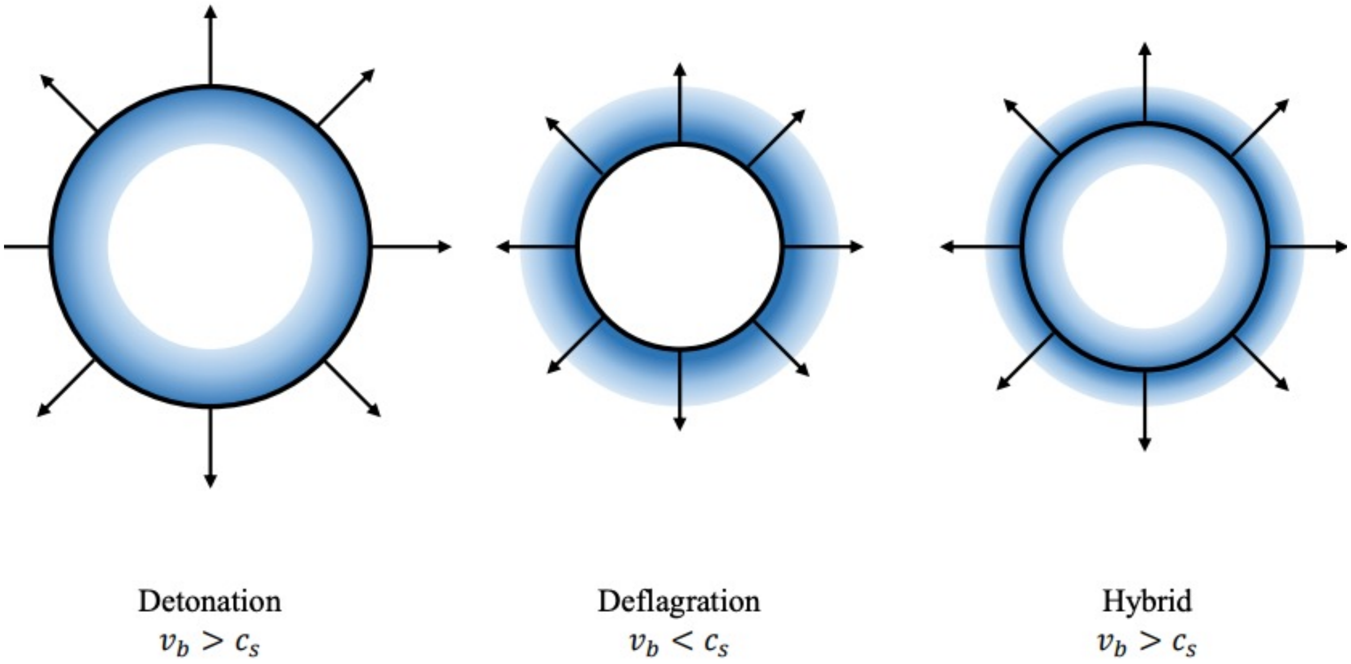
Enthalpy profile

$$\frac{\partial_\xi T}{T} = \gamma^2\mu\partial_\xi v$$

Temperature profile

Different boundary conditions give different hydrodynamical modes.

Phase transition Dynamics

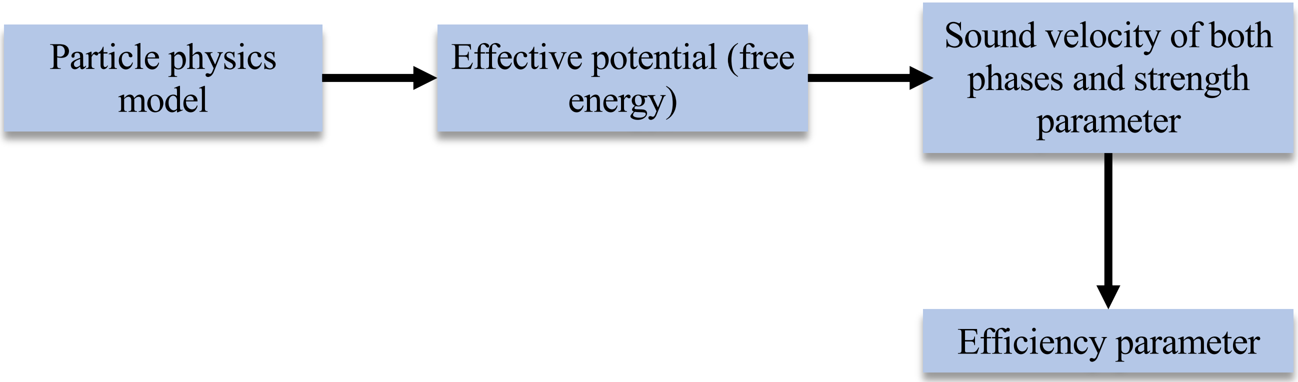


Stronger GW signal favored **EW baryogengesis favored**

Phase transition Dynamics

Energy budget for phase transition GW

- The method to map a particle physics model on the DSVM to get efficiency parameter

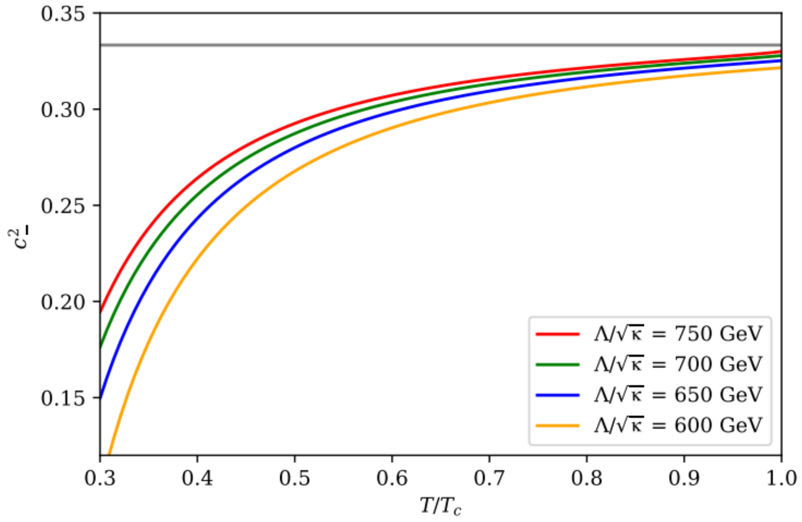


Phase transition Dynamics

Energy budget for phase transition GW

The evolution of sound velocity of broken phase and symmetric phase in Dim-6 effective model:

$$\mathcal{F}(\phi,T) \approx -\frac{a_\pm}{3}T^4 + \frac{\mu^2 + cT^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{\kappa}{8\Lambda^2}\phi^6$$



X. Wang, F. P. Huang and X. Zhang, PRD 103 (2021) 10, 103520

Phase transition Dynamics

Energy budget for phase transition GW

GW spectrum and SNR for different EoS with different parameter combination:

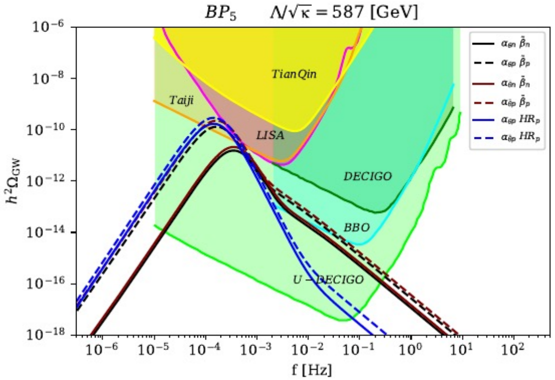


TABLE II. The SNR of BP_5 for different experiment configurations with different combinations of phase transition parameters and models of EOS.

	$\alpha_{\theta n}\,\tilde{\beta}_n$	$\alpha_{\theta p}\,\tilde{\beta}_p$	$\alpha_{\bar{\theta} n}\,\tilde{\beta}_n$	$\alpha_{\bar{\theta} p}\,\tilde{\beta}_p$	$\alpha_{\theta p}\,HR_p$	$\alpha_{\bar{\theta} p}\,HR_p$
$SNR_{(LISA)}$	7.949	16.930	10.913	28.836	16.009	27.468
$SNR_{(Taiji)}$	14.760	58.607	20.271	100.343	66.216	113.609
$SNR_{(TianQin)}$	0.452	1.506	0.620	2.576	1.629	2.794

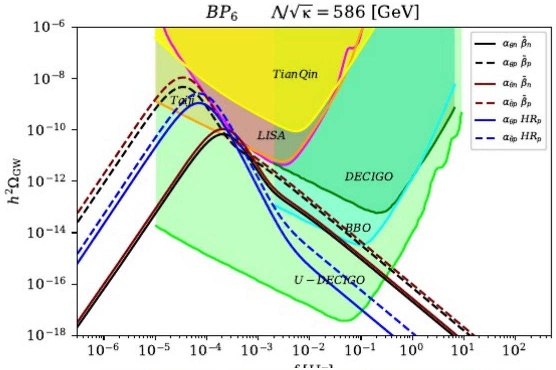


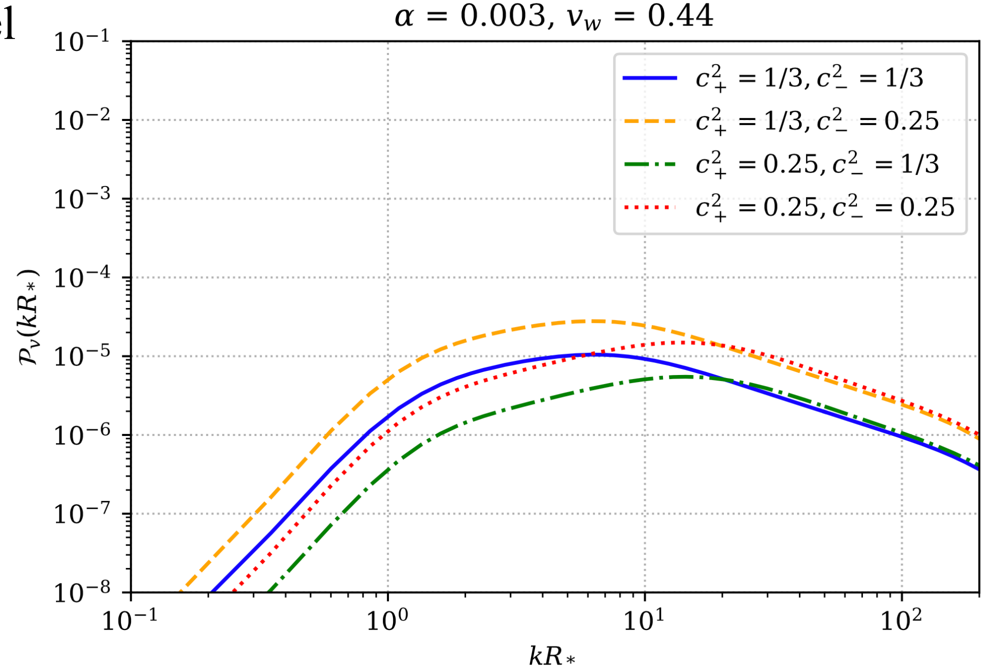
TABLE III. The SNR of BP_6 for different experiment configurations with different combinations of phase transition parameters and models of EOS.

	$\alpha_{\theta n}\,\tilde{\beta}_n$	$\alpha_{\theta p}\,\tilde{\beta}_p$	$\alpha_{\bar{\theta} n}\,\tilde{\beta}_n$	$\alpha_{\bar{\theta} p}\,\tilde{\beta}_p$	$\alpha_{\theta p}\,HR_p$	$\alpha_{\bar{\theta} p}\,HR_p$
$SNR_{(LISA)}$	14.230	15.368	22.470	26.382	17.367	40.816
$SNR_{(Taiji)}$	38.666	427.813	61.208	1000.501	213.123	500.668
$SNR_{(TianQin)}$	1.060	5.569	1.678	12.934	3.973	9.333

X. Wang, F. P. Huang and X. Zhang, PRD 103 (2021) 10, 103520

Phase transition Dynamics

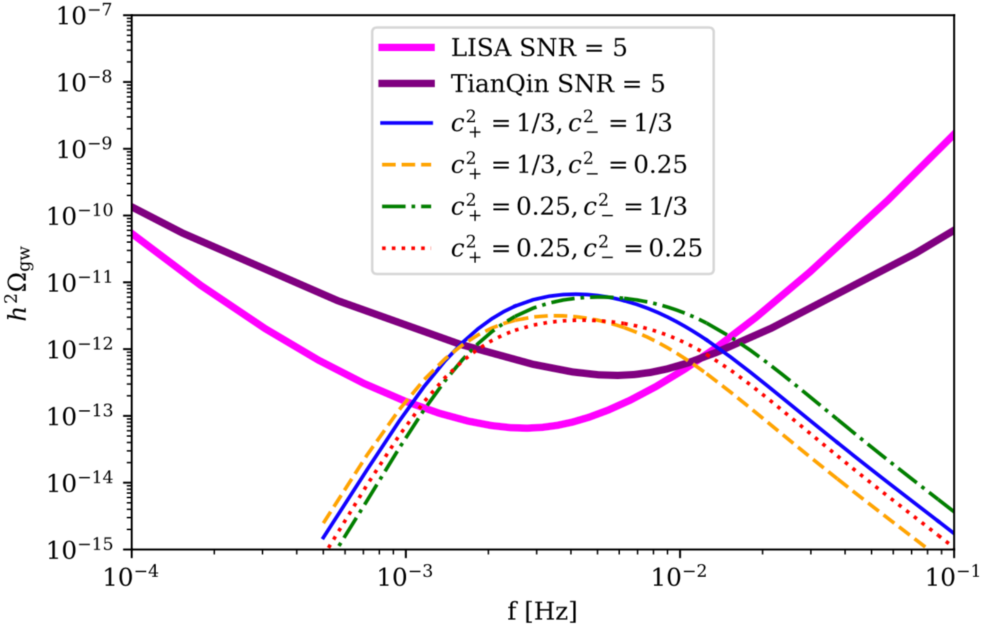
Sound velocity effects on the phase transition gravitational wave spectrum in the Sound Shell Model



Xiao Wang, **FPH**, Yongping Li, Sound velocity effects on the phase transition gravitational wave spectrum in the Sound Shell Model, arXiv:2112.14650

Xiao Wang, **FPH,** Xinmin Zhang, Energy budget and the gravitational wave spectra beyond the bag model ,Phys.Rev.D 103 (2021) 10, 103520

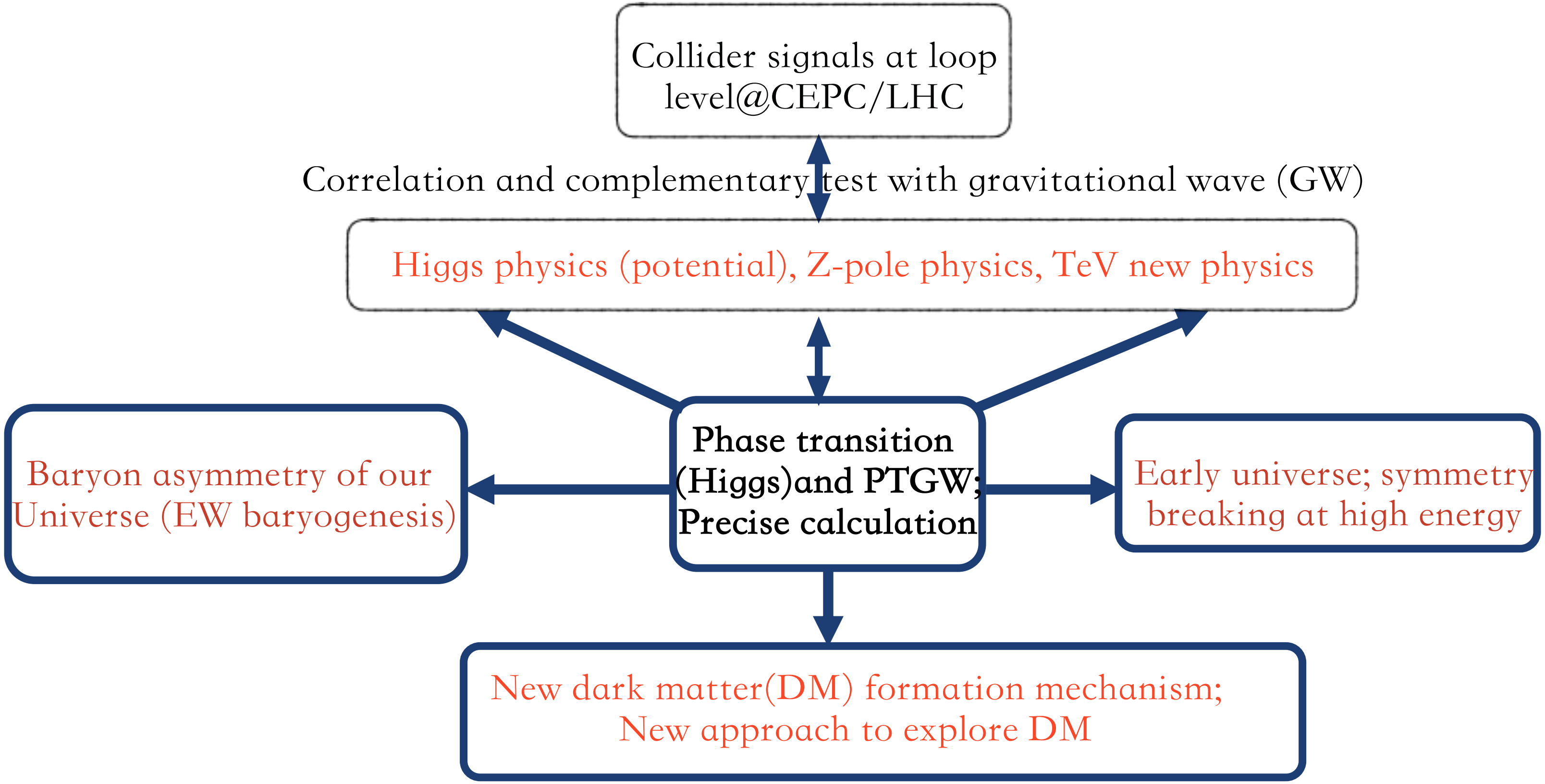
Phase transition Dynamics



Xiao Wang, **FPH**, Yongping Li, Sound velocity effects on the phase transition gravitational wave spectrum in the Sound Shell Model, arXiv:2112.14650

Xiao Wang, **FPH,** Xinmin Zhang, Energy budget and the gravitational wave spectra beyond the bag model ,Phys.Rev.D 103 (2021) 10, 103520

Summary


Collider signals at loop level@CEPC/LHC
Correlation and complementary test with gravitational wave (GW)
Higgs physics (potential), Z-pole physics, TeV new physics
Baryon asymmetry of our Universe (EW baryogenesis)
Phase transition (Higgs)and PTGW; Precise calculation
Early universe; symmetry breaking at high energy
New dark matter(DM) formation mechanism; New approach to explore DM

Summary and Outlook

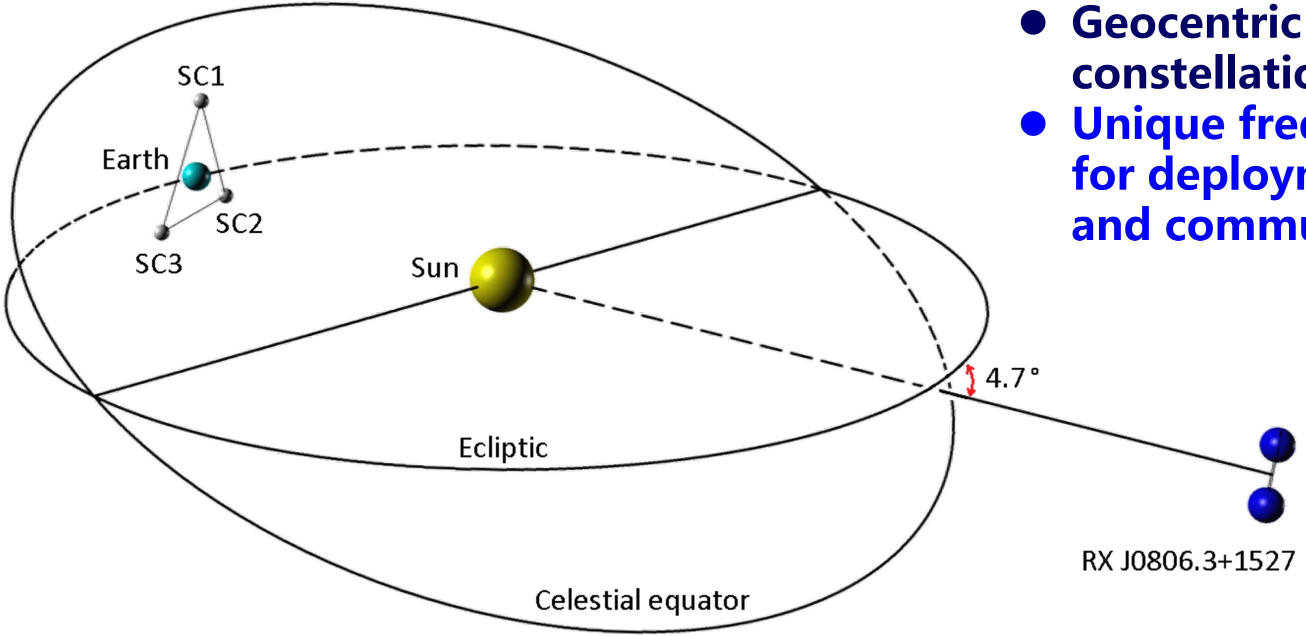
- EW first-order phase transition has abundant collider and cosmological effects in baryogenesis, dark matter, GW…
- The correlation between GW and collider signals at CEPC can make complementary test on the Higgs nature, baryogenesis, dark matter and the cosmic evolution history at 100 GeV.
- More precise study are needed: reliable resummation， non-perturbative calculations, bubble dynamics (wall velocity, energy budget).

Thanks! Comments and collaborations are welcome!

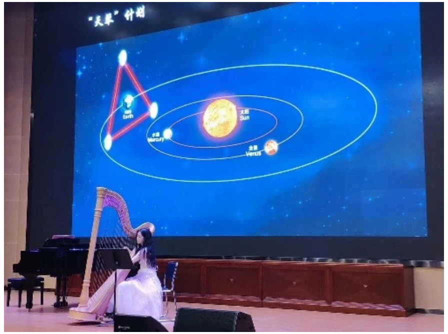
Email:huangfp8@sysu.edu.cn

TianQin

- **Expected in 2035**
- **Geocentric orbit, normal triangle constellation, radius ~10^5km**
- **Unique frequency band, easier for deployment, tracking, control, and communication**



J. Luo et al. TianQin: a space-borne gravitational wave detector, Class. Quant. Grav. 33 (2016) no.3, 035010.



“天琴”

“Harpe in space”