Scale & Gravitational wave-genesis by Dark Matter

Jiang Zhu

Based on arxiv: 2003.02465 Zhaofeng Kang & Jiang Zhu

Symposium on electrically weak phase transition and Higgs physics

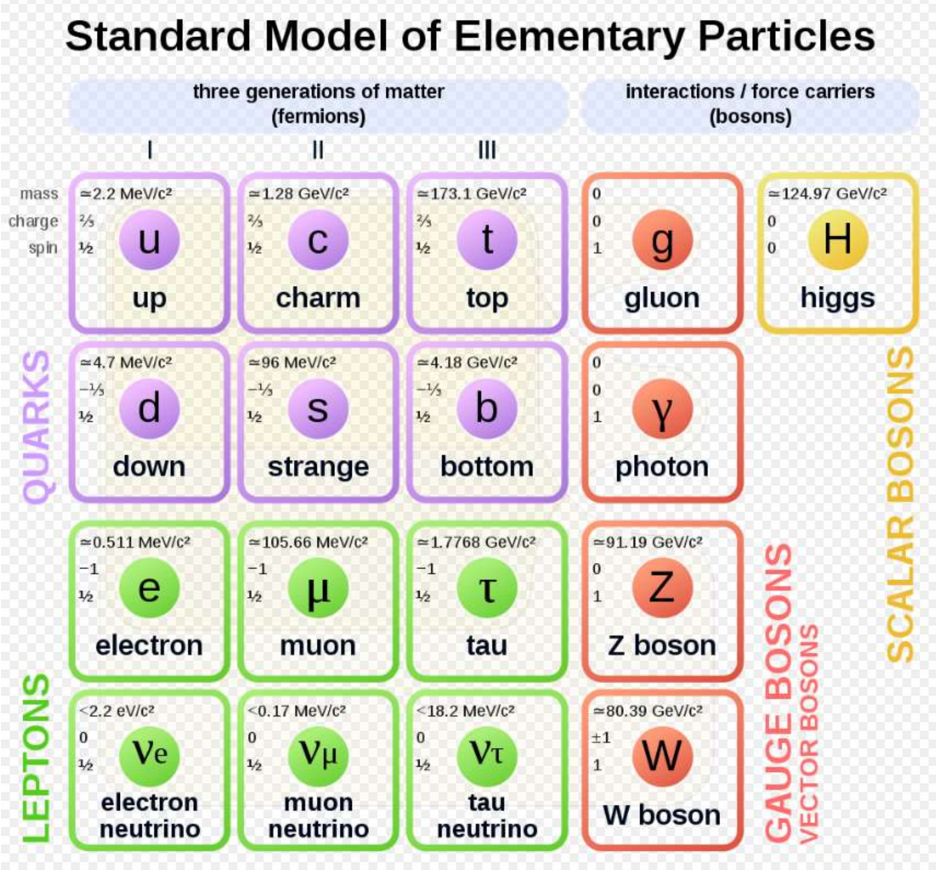
Index

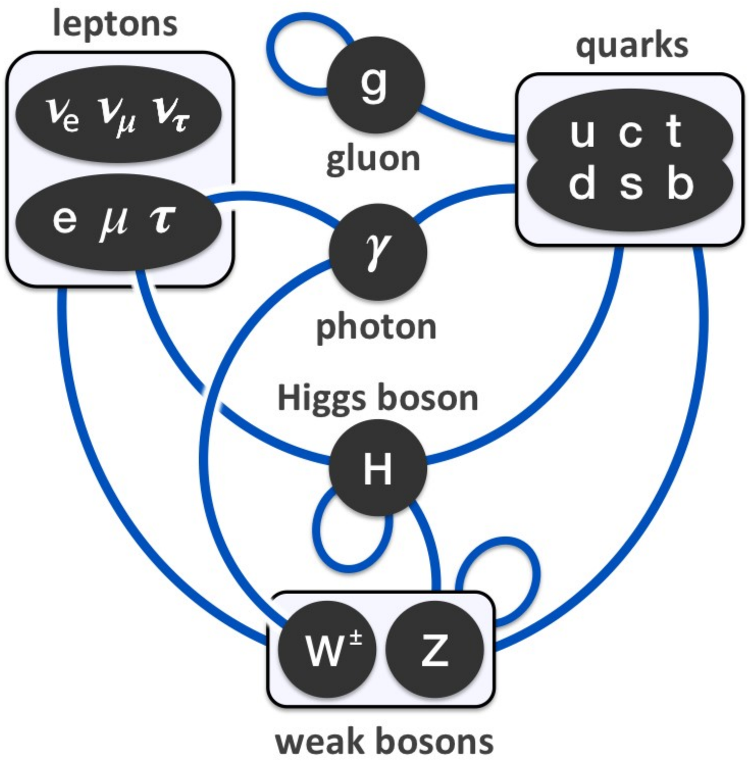
1. Introduction
2. RSB triggered by Dark matter
3. CSI Supercooling Phase Transition
4. CSI Gravitational Wave
5. Conclusion & Outlook

Introduction

- **Standard Model**

  SM gain great success in past decades!



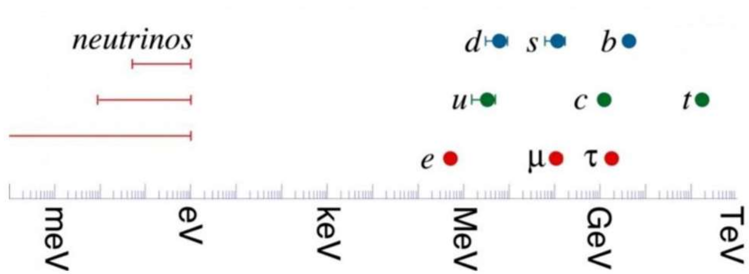


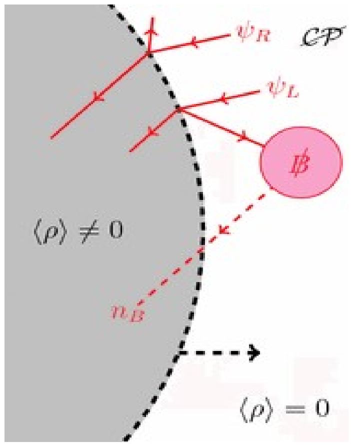
Introduction

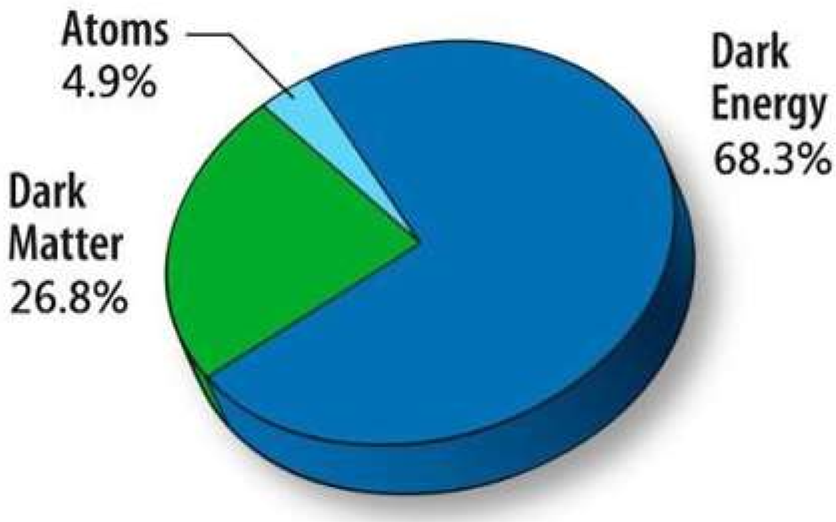
- **BUT, there are still questions left**

  1. **Hierarchy Problem**
  2. **Dark Matter** and Dark energy
  3. Baryogenesis
  4. Mass of Neutrino

  ……







RSB triggered by Dark Matter

- **Motivation**

1. The origin of EW scale-μ?

$$\mathcal{L} = \left|D_\mu \phi\right|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2.$$

2. Hierarchy Problem

Scale of EW~100GeV <<Cut off Scale, i.e Mp~10^{18}GeV?

- **Possible Solution——Classical Scale Invariance(CSI)!**

Just like chiral symmetry for the electron

It may be the **Scale invariance symmetry that protects the weak scale free of notorious fine-tuning**, provided that there is no heavy particle significantly coupling to the SM Higgs field and thus no large quadratic term is radiatively generated. And, this symmetry is broken by quantum anomaly. Quantum anomaly breaks this symmetry and generates a scale for SM

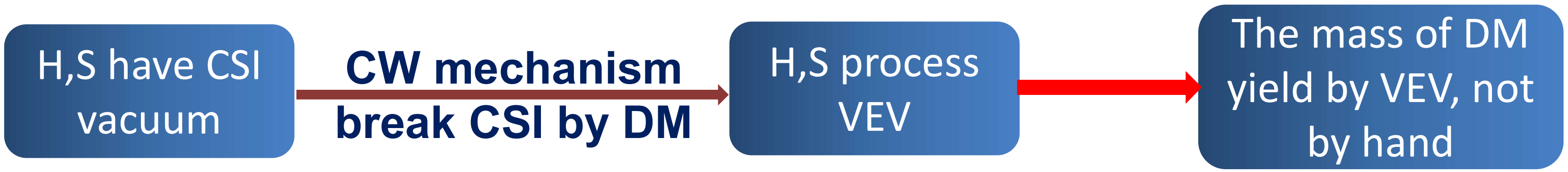
RSB triggered by Dark Matter

- **Dark Matter Plays an Important Role**

However, SM is not consistent with this symmetry, since top quark is heavier than Higgs field. **We need heavier boson!** Dark matter can be a candidate to trigger the CSISB. Therefore In such a framework DM plays a vital role, and it might explain why DM is there.

- **Radiative CSI Breaking by Dark Matter**

Our model: **WIMP dark matter X+H and S(with Z_2), X triggers RSB**



Lagrangian: $\mathcal{L} = \mathcal{L}_{SM}|_{\lambda=0,\mu=0} + K_{scalar} - V_{scalar}$

$$V_{scalar} = \lambda_1 (H^\dagger H)^2 + \frac{1}{4}\lambda_2 S^4 + \frac{1}{4}\lambda_3 X^4 + \frac{1}{2}\lambda_{12} S^2 H^\dagger H + \frac{1}{2}\lambda_{13} X^2 H^\dagger H + \frac{1}{4}\lambda_{23} S^2 X^2$$

$$H = \begin{pmatrix} \phi_1 + i\phi_2 \\ \frac{H_0 + i\phi_3}{\sqrt{2}} \end{pmatrix} \qquad H_0 = (v + h) \text{ and } S = (v_s + s)$$

To limit our discussion in perturbation area, all parameters should be smaller than π

RSB triggered by Dark Matter

- **Two Ways of RSB**

1. United symmetry breaking: Gildener-Weinberg approach

If there is a direction---’**flat direction**’ in this direction field H and S have non-trivial VEV at the same time. In other words, non-trivial VEV are function of field ϕ

$$\begin{pmatrix} h \\ s \end{pmatrix} = \phi \vec{N} = \phi \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix} = \frac{\phi}{\sqrt{\lambda^{\frac{1}{2}} + \lambda_s^{\frac{1}{2}}}} \begin{pmatrix} \lambda_s^{\frac{1}{4}} \\ \lambda^{\frac{1}{4}} \end{pmatrix}.$$

2. Separate symmetry breaking: Higgs Portal approach

This case is a **decoupling limit situation** $\lambda_{hs} \ll 1$, which means one field should break firstly and generate a non-trivial VEV. Then, this VEV will provide EW scale μ for the SM Higgs field.

Both should be constrained by: SM particle mass, Mixing angle, and Dark matter data

RSB triggered by Dark Matter

- **Dark Matter**

It is a well-known fact that the SM-Higgs and scalon mixing term is strongly constrained, rendering $\lambda_{hx} \ll 1$. And when it is small, it is nearly irrelevant with the result. So we can fix $\lambda_{hx} = 10^{-3}$

Mass of the dark matter: $m_X^2 = \frac{\lambda_{hx}}{2} h^2 + \frac{\lambda_{sx}}{2} s^2$

Other dark matter constraints:

① Dark matter freeze out relic

② Dark matter direct detection

The Dark matter relic will be put as a requirement:

λ_{hx} only influence mass of DM, however DM only sensitive to λ_{hs} since large v_s

$$\langle \sigma_{XX} v \rangle \simeq \frac{\lambda_{sx}^2}{64\pi} \frac{1}{m_X^2} = 0.89\text{pb} \times \left(\frac{\lambda_{sx}}{1.0}\right) \left(\frac{3\text{TeV}}{v_s}\right)^2$$

We will also compare the DM-nucleon scattering cross section with direct detection restriction from XENON1T

$$\sigma_{SI} = \frac{4}{\pi} \mu_p^2 f_p^2, \quad f_p = \frac{m_p}{2m_X} \sum_q \frac{a_q}{m_q} f_{T_q}^{(p)} \approx \lambda_{sx} \frac{m_p}{8m_X} \frac{v_s}{v_h} \sin 2\theta \left(\frac{1}{m_{h_{SM}}^2} - \frac{1}{m_S^2}\right) \Delta^p$$

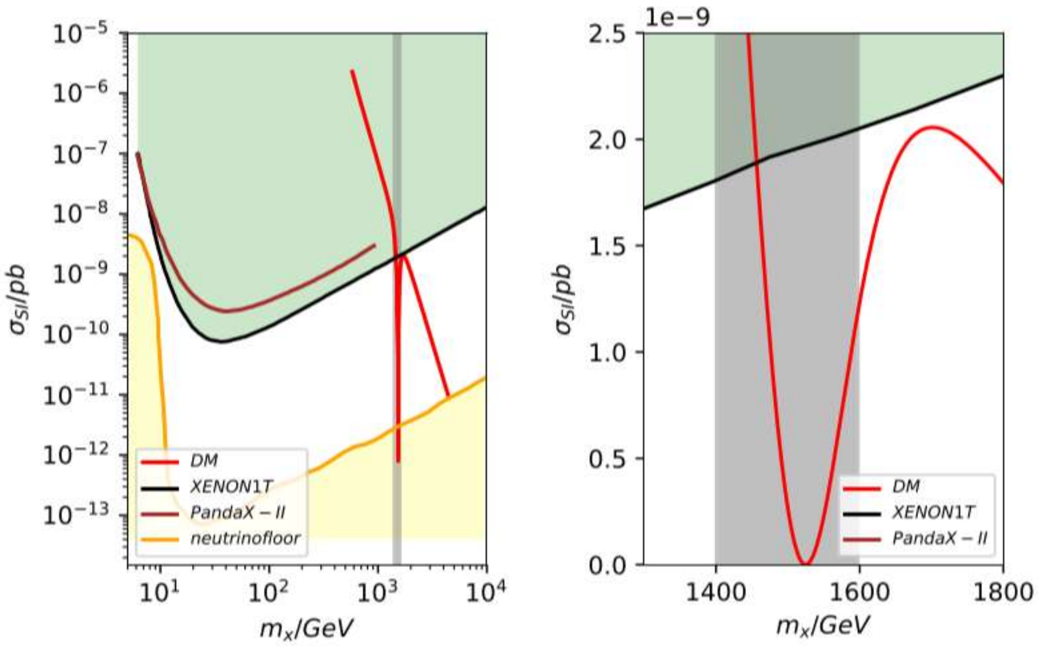
This two restriction will help us to get feasible parameter space

RSB triggered by Dark Matter

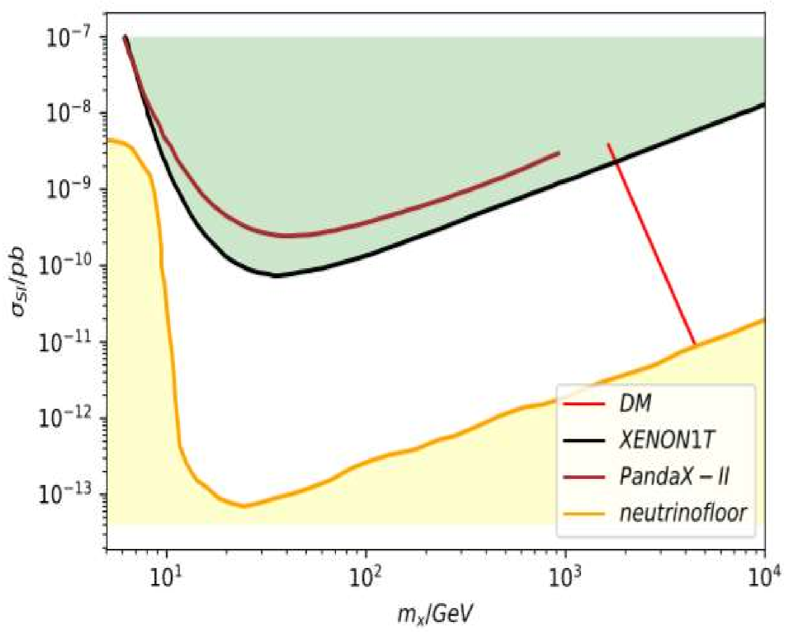
- **Dark matter restriction from XENON1T**

However, there are three equations which must be satisfied, so there is only one free parameter in λ_h, λ_s, λ_{hs}, and λ_{sx}

GW method



Higgs Portal

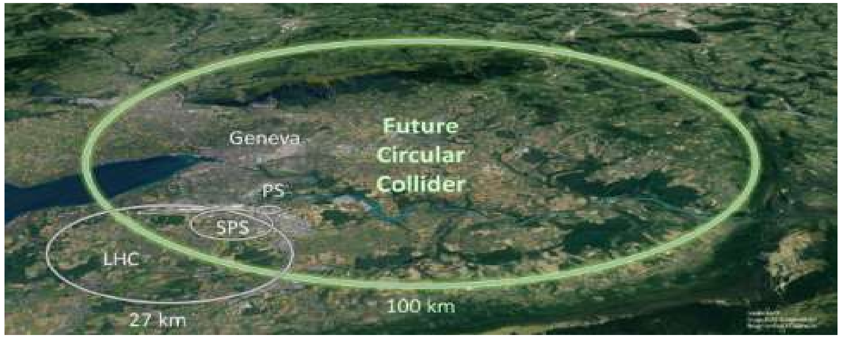


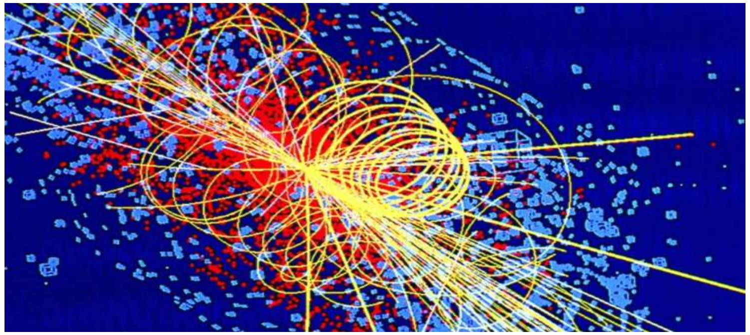
Test at Collider?

CSI Supercooling Phase Transition

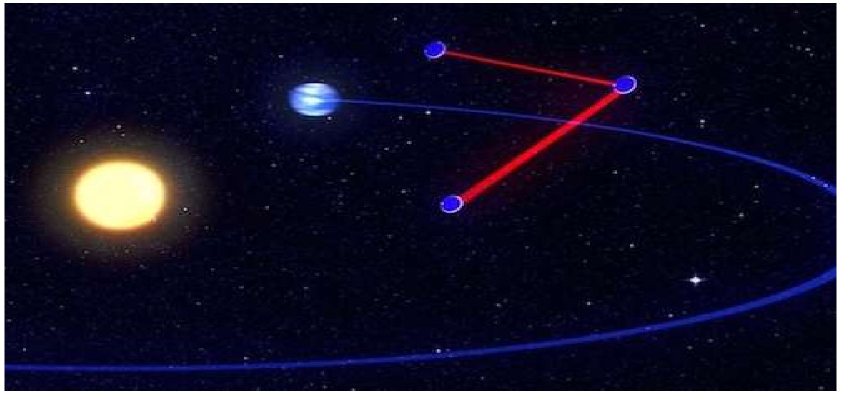
- **Test of our Model：**

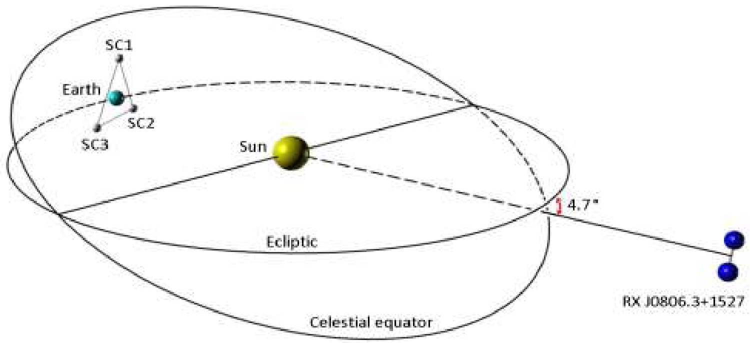
1) Collider： LHC, FCC, CEPC e.g. Strong interaction & light particle **Difficult**





2)Gravitation： LISA， TianQin e.g. **Complement**





CSI Supercooling Phase Transition

- **Finite temperature effective Potential**

The 1-loop finite temperature correction of the effective potential in our model is

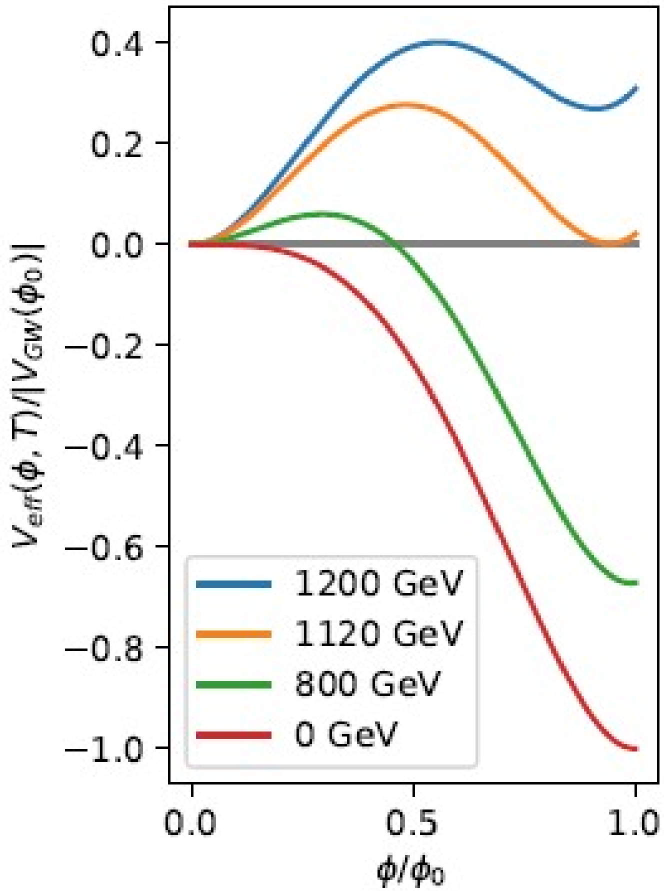
$$V_T^{(1)}(\phi,T)=\frac{T^4}{2\pi^2}\left(\sum_{a\in boson} n_a J_B(x_a)+\sum_{a\in fermion} n_a J_F(x_a)\right)$$

In addition, we also need to add the next leading order correction - The Daisy terms:

$$V_D(\phi,T)=-\frac{T}{12\pi}\sum_a n_a[M_a^3(\phi,T)-m_a^3(\phi,T)]$$

The complete potential is

$$\mathrm{V_{eff}}=V_0+V_1+V_T+V_D$$



CSI Supercooling Phase Transition

- **Nucleation rate**

Two way to tunneling

1. Transition by thermal tunneling : $\Gamma = Ae^{-S_3/T}$
2. Transition by Quantum tunneling : $\Gamma = Ae^{-S_4}$

Nucleation rate in our model is dominate by thermal tunneling is the rate depend on:

$$S_3(T) = 4\pi \int_0^\infty dR\, R^2 \left[\frac{1}{2}\left(\frac{d\phi}{dR}\right)^2 + V_{eff}(\phi, T)\right], \qquad \frac{d^2\phi}{dR^2} + \frac{2}{R}\frac{d\phi}{dR} = \frac{dV_{eff}}{d\phi}$$

- **Three parameters in phase transition**

①the strength of phase transition: α $$\alpha = \frac{\Delta\epsilon}{\rho}|_{T=T_n}$$

②the time scale of phase transition: β $$\frac{\beta}{H_n} = T_n \frac{d(S_3/T)}{dT}|_{T=T_n}$$

③the temperature of phase transition: T_n

CSI Supercooling Phase Transition

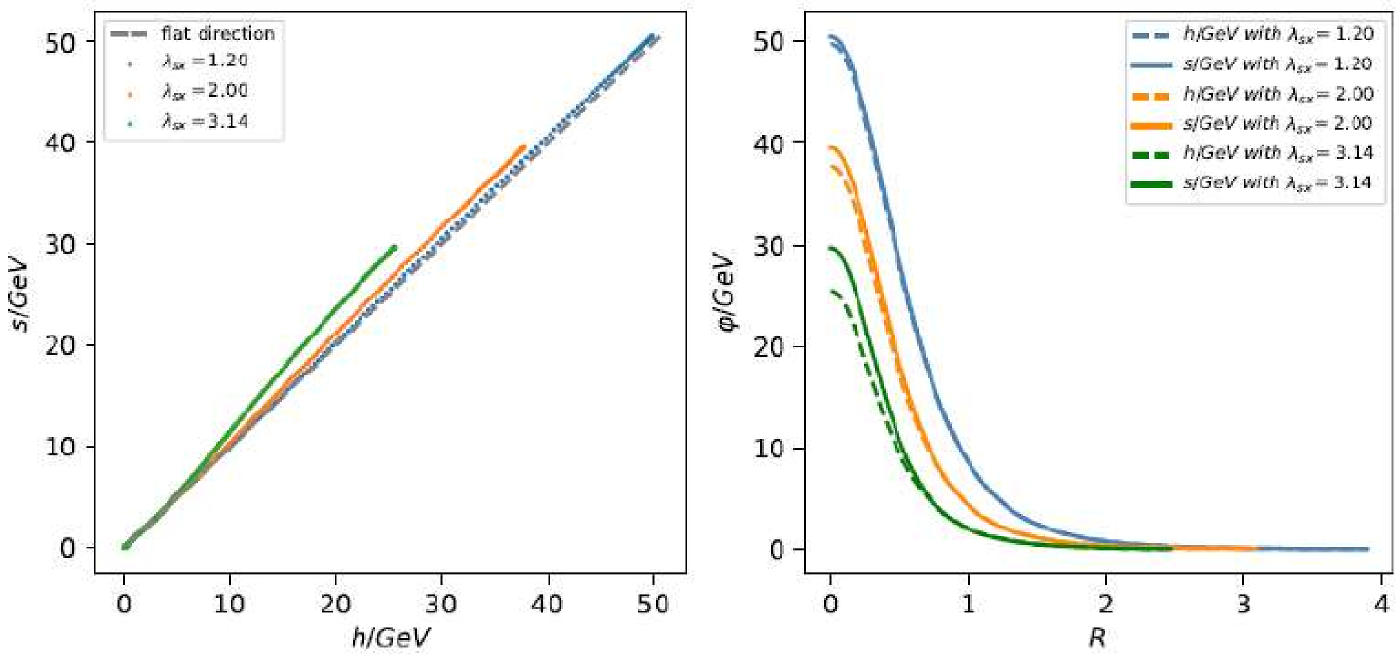
- **Multi-field Phase transition**

Motivation 1. Large QM correction $change?$ Flat direction

2. Flat direction $=?$ Tunneling Path

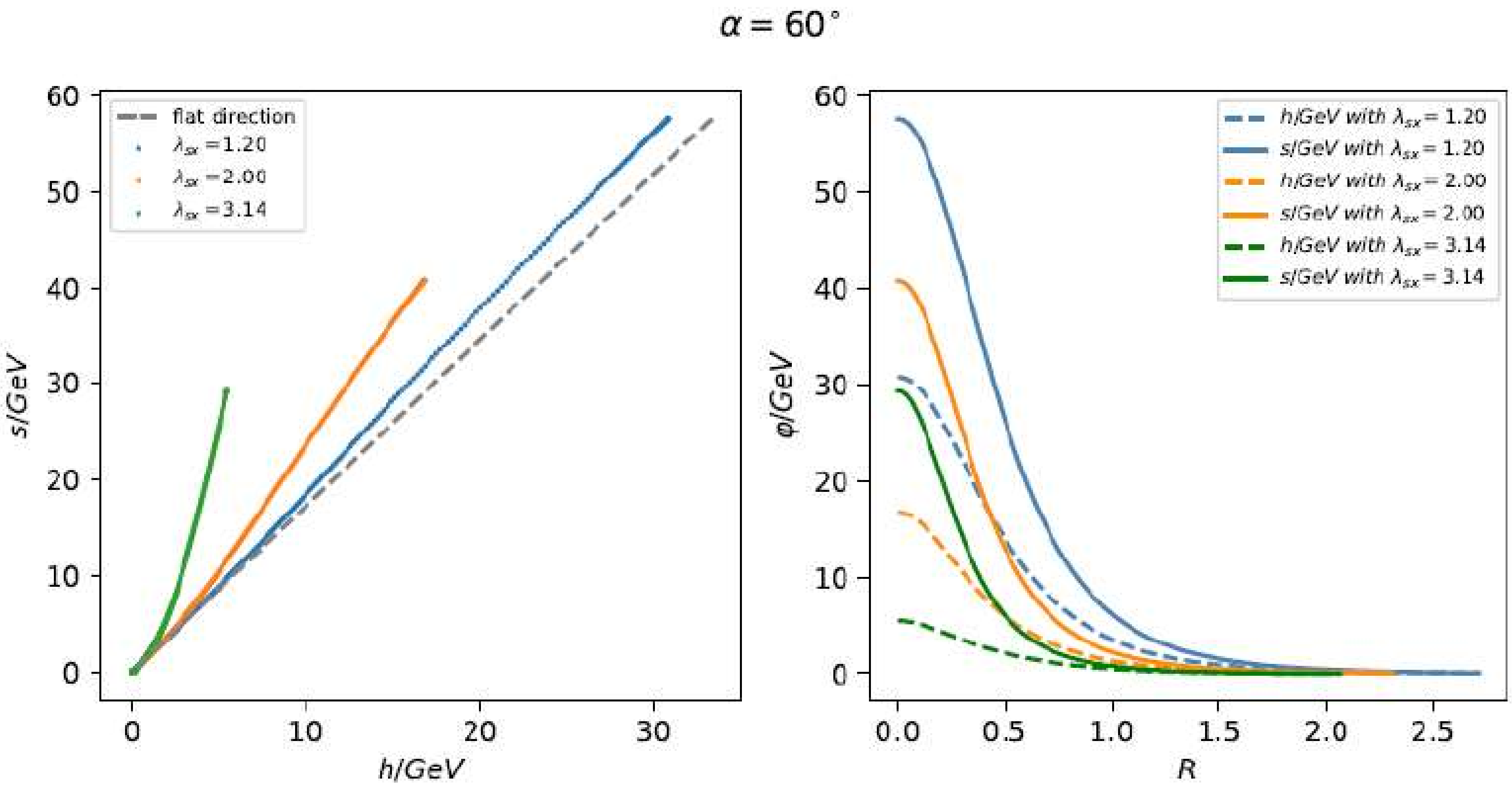
Multi-field PT：Flat direction vs Full Tunneling Path

$\alpha = 45^\circ$



CSI Supercooling Phase Transition

- **Multi-field Phase transition**



Generally speaking, if there is no large quantum correction, the flat direction is indeed a tunneling path. However, when there is a large quantum correction, the tunneling will not proceed along the flat direction. At this time, we must think about whether this approximate conclusion is still valid!

CSI Supercooling Phase Transition

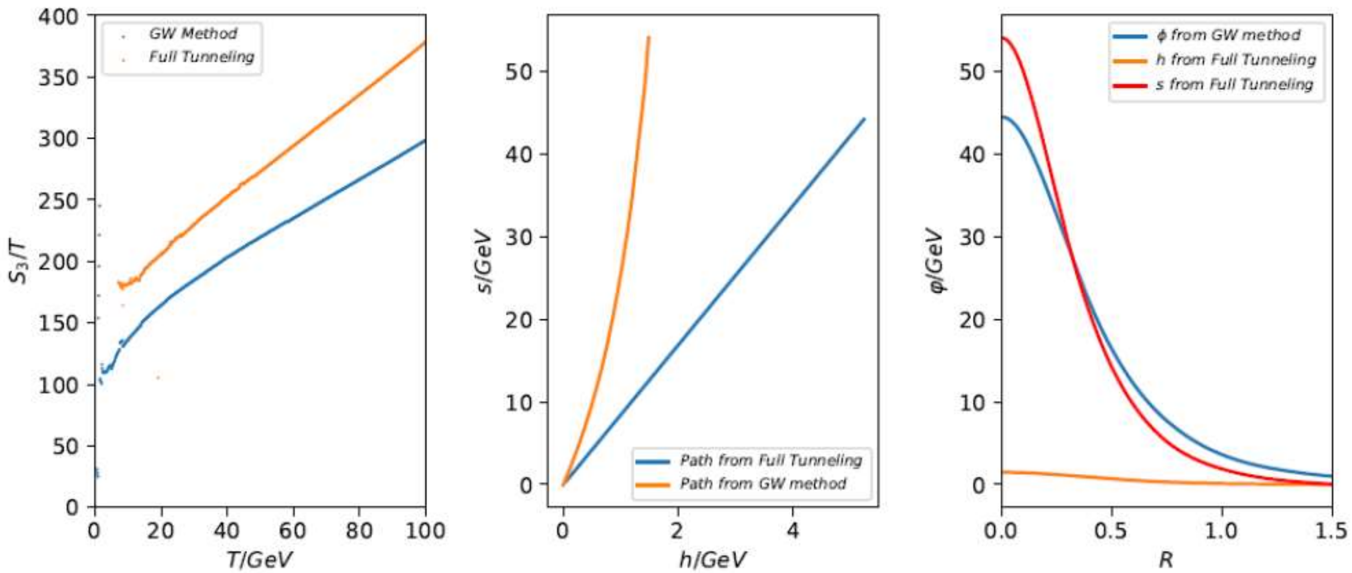
- ## Multi-field Phase transition

For this reason, we use the complete tunneling method and the approximate method to calculate S_3 in the case when $\alpha = 60^\circ$ which corresponding to large quantum correction. The result is:

$$S_3(T = 10GeV) = 387(335), 139(138), 50(62).$$

The approximation is still valid! This is because when $v_s \gg v_h$ the tunneling problem reduce to a single field tunneling problem

Our model can be a concrete example to verified this conclusion



CSI Supercooling Phase Transition

- **Radiative Dominance or Vacuum Dominance Era?**

In standard cosmology, at the period which we are considering, universe is dominated by radiation energy. So, usually the phase transition complete condition is derived in radiative dominated period：

$$N_n = \int_{t_c}^{t_n} dt \frac{\Gamma(t)}{H(t)^3} = A \int_{T_n}^{T_c} \frac{dT}{T^5} (3M_{Pl}^2)^2 \left(\frac{30}{\pi^2 g_*}\right) e^{-S(T)} \sim 1 \,,$$

$$\frac{S_3(T)}{T} \sim 140$$

However, with the temperature decreasing into low temperature regime, radiative energy density decrease with T^4, vacuum energy density nearly unchanged

$$\rho_r = \frac{\pi^2}{30} g_* T^4$$

$$\rho_0 = V_0^{(1)}(0, T_n) - V_0^{(1)}(\langle\phi\rangle, T_n) = \frac{1}{2} B \langle\phi\rangle^4$$

Therefore, if any model predicts a strong first order phase transition with:

$$T_n < \left(\frac{15B}{\pi^2 g_*}\right)^{\frac{1}{4}} v_\phi$$

Universe may go through a vacuum dominated period.

So, it is necessary to reconsider the phase transition complete condition.

CSI Supercooling Phase Transition

- **CSPT at Short Vacuum Dominance Era**

Usually, CSPT will generate a well strong First-order phase transition! Supercooling phase transition with parameter $\alpha \gg 1$, which means universe is dominated by vacuum.

In this case, we use the percolation condition $P(t) < 70\%$ derived a new approximation for phase transition happened in vacuum dominated period

$$\frac{S_3(T)}{T} \sim 70$$

TABLE I. Benchmark points in the GW scenario

	v_s/GeV	λ	λ_s	λ_x	λ_{hx}	λ_{sx}	α	$\widetilde{\beta}$	T_n/GeV	T_*/GeV
A	2400	0.1277	0.000014	0.2	10^{-3}	1.44	$3.9*10^8$	11.3	1.01	616
B	2449	0.1278	0.000013	0.2	10^{-3}	1.50	$6.6*10^7$	9.84	1.65	646
C	2683	0.1280	0.000009	0.2	10^{-3}	1.80	59805	14.36	11.40	796
D	2828	0.1281	0.000007	0.2	10^{-3}	2.00	2301	17.16	28.60	896
E	2966	0.1282	0.000006	0.2	10^{-3}	2.20	0.37	94.73	278.63	996
F	3535	0.1285	0.000003	0.2	10^{-3}	3.14	0.004	198.07	750.85	1475
G	2449	0.1278	0.000013	1.2	10^{-3}	1.50	370801	10.00	6.02	720

Many parameter sets Indicate Strong Supercooling!

CSI Gravitational Wave

- **Sources of Gravitational Wave**

Physics back ground of gravitational wave generating is CSI phase transition and releasing vacuum energy.

The total Gravitational Wave: $h^2\Omega_{\rm GW} \simeq h^2\Omega_\phi + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}$

Three sources of energy

① Bubble collision
② Turbulence in plasma
③ Sound Speed wave in plasma

The main effect in this situation is sound wave

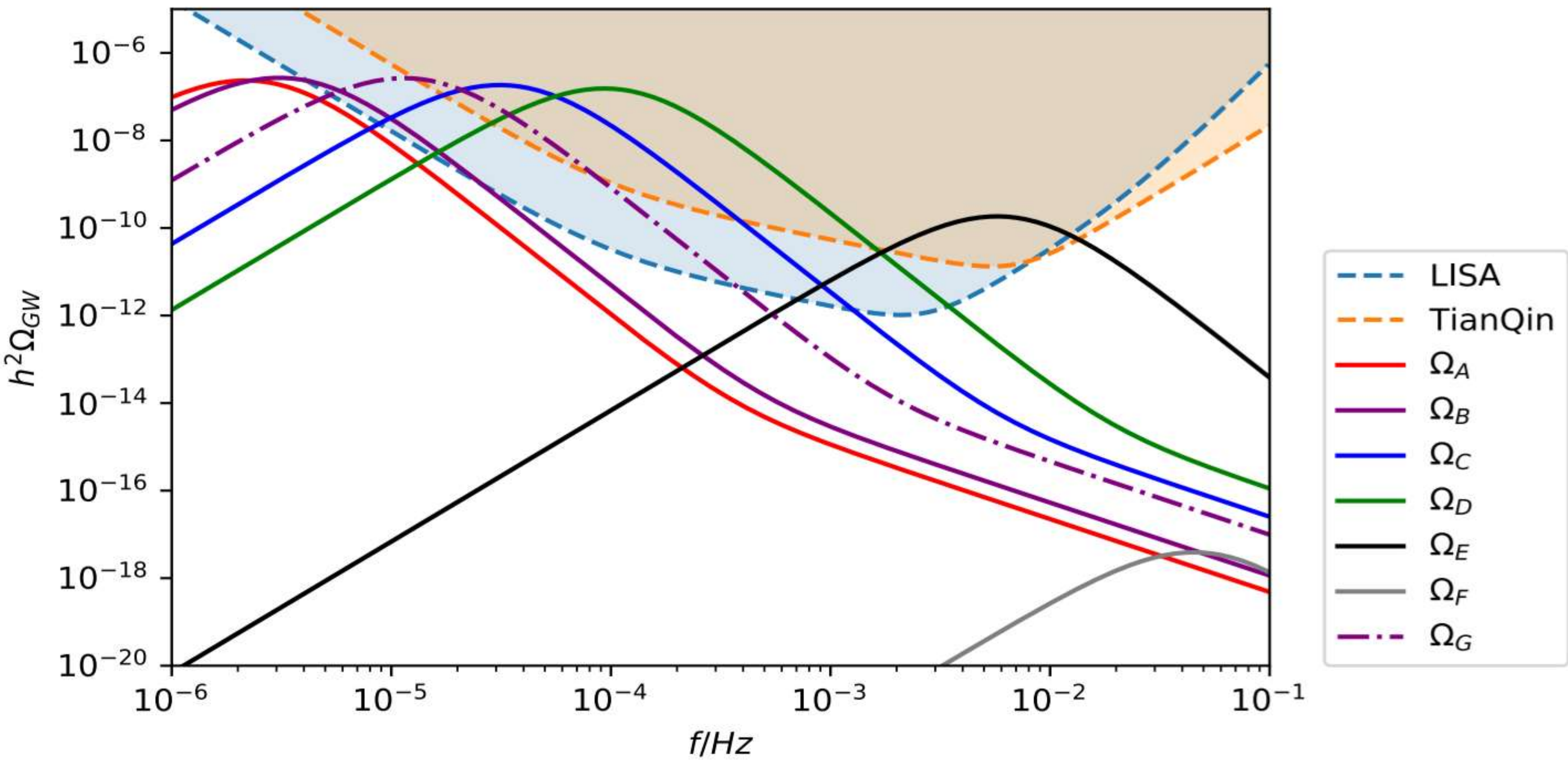
$$h^2\Omega_{\rm sw}(f) = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w\, S_{\rm sw}(f)$$

$$S_{\rm sw}(f) = (f/f_{\rm sw})^3 \left(\frac{7}{4+3\,(f/f_{\rm sw})^2}\right)^{7/2} \quad f_{\rm sw} = 1.9 \times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

However, we do not consider the effect of reduction of the sound wave in large Supercooling, and the enhancement of the turbulence effect due to RSW. This effect will affect GW signal significantly ! ! (talk about later)

CSI Gravitational Wave

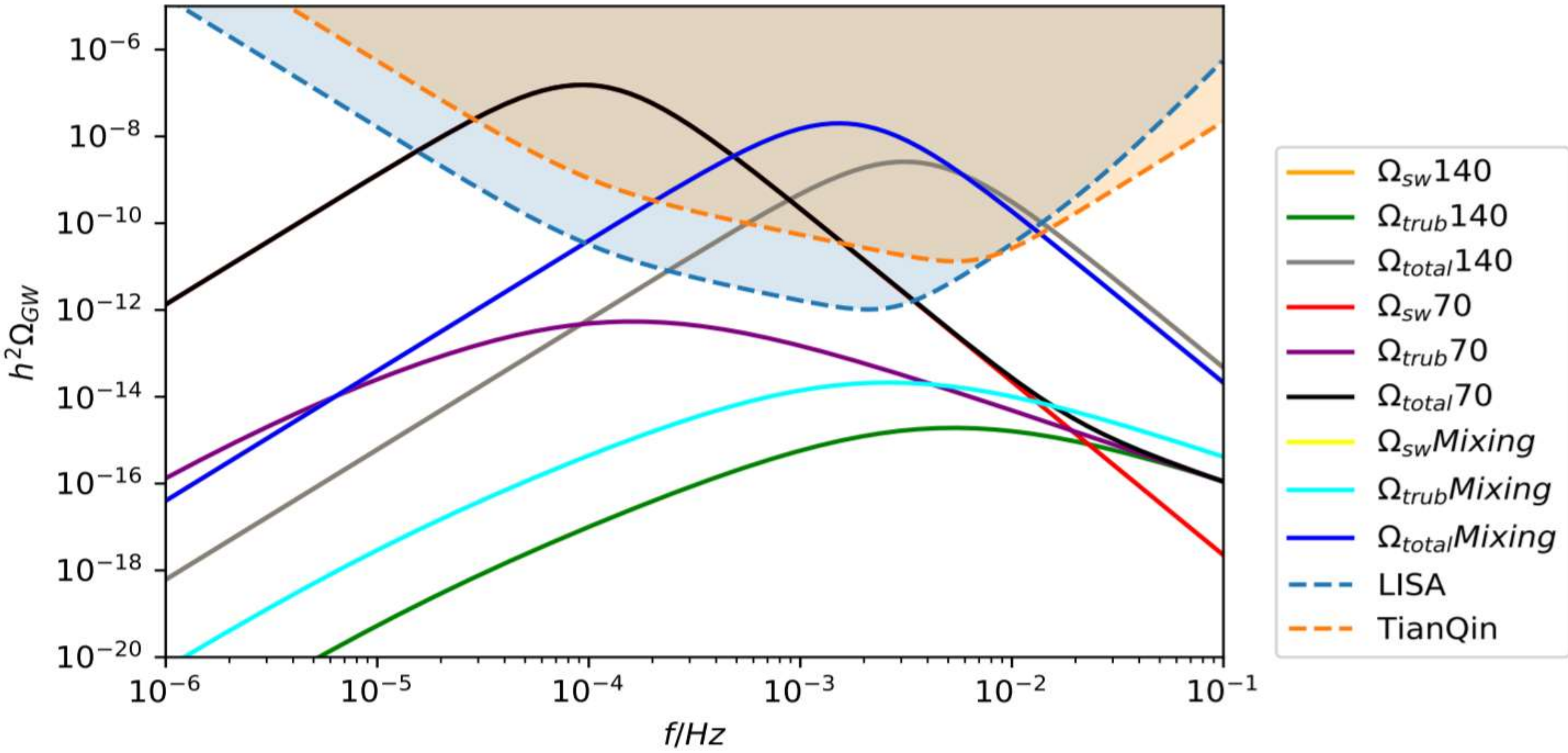
- **LISA & TianQin detectable Gravitational Wave Signal**



CSI Gravitational Wave

- **LISA & TianQin detectable Gravitational Wave Signal**

The gravitational wave difference between Vacuum dominate period and radiative dominate period



Conclusion & Outlook

- **Conclusion**

1. We analyze the zero temperature RSB triggered by DM in CSISB model and the dark matter model.

2. We re-calculated the phase transition complete condition in Vacuum dominated period and give a new condition to calculate PT.

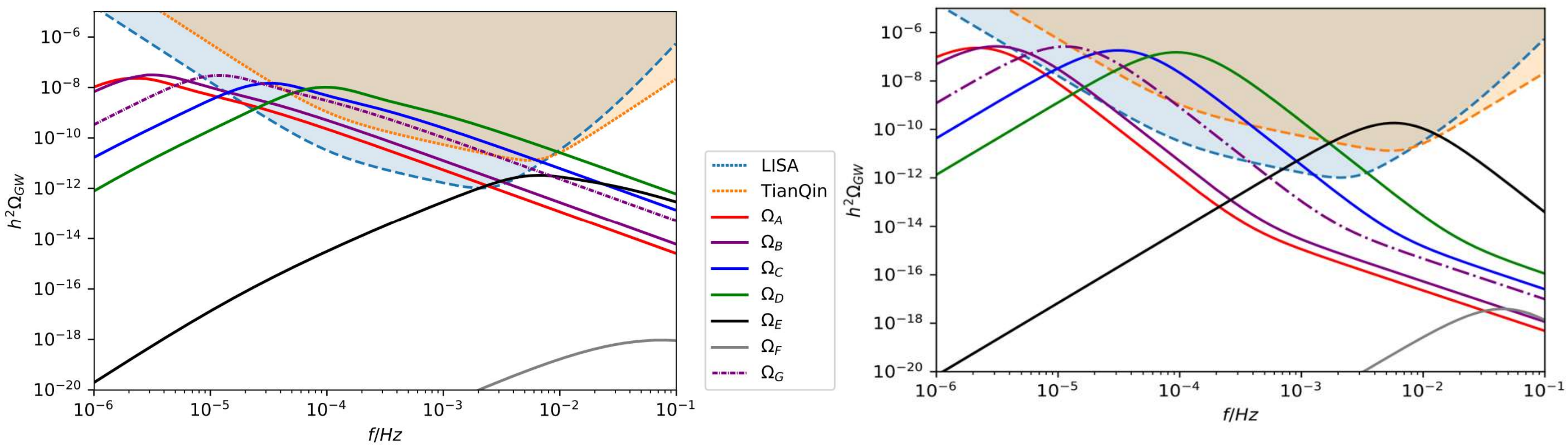
3. This model would generate a strong first order phase transition and we get the gravitational spectrum which could be tested at LISA or TianQin.

Conclusion & Outlook

- **Outlook**

There is one important thing we don’t take in to consideration: The reduction of the sound wave and the enhancement of the turbulence due to the reduction of the sound wave.

We have to mention that the accurately GW signal from turbulence is still a open question. In this work we only give a upper bound of this GW signal



Appendix

Consider the percolation condition

$$3-\frac{8\pi e^{-S(T_e)}T_e}{\beta_e^3 H_V^4}=0\Rightarrow S(T_e)=2\log\frac{3M_{\rm Pl}^2}{T_e^2}+2\log\frac{T_e^4}{\rho_0}+\log\frac{8\pi}{3x^3}.$$

Whether PT can finish?

$$T_e\beta_e=\widetilde{\beta}>3.$$

Satisfied this condition can finish

Reduce of the sound wave effect

$$h^2\Omega_{sw}(f)=2.65\,(H_*R_*)\,(H_*\tau_{sw})\left(\frac{\kappa_{sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g}\right)^{\frac{1}{3}}v_w S_{sw}(f),\quad H_*\tau_{sw}=\min[1,H_*R_*/U_f]$$

Enhancement of the turbulence

$$\Omega_{{\rm turb},*}=6.8(H_*R_*)\,(1-H_*\tau_{\rm sw})\left(\frac{\kappa_{\rm sw}\,\alpha}{1+\alpha}\right)^{3/2}\frac{\left(\frac{f_*}{f_{\rm turb}}\right)^3\left[1+\left(\frac{f_*}{f_{\rm turb}}\right)\right]^{-\frac{11}{3}}}{1+8\pi f_*/H_*},$$