Scale & Gravitational wave-genesis by Dark Matter

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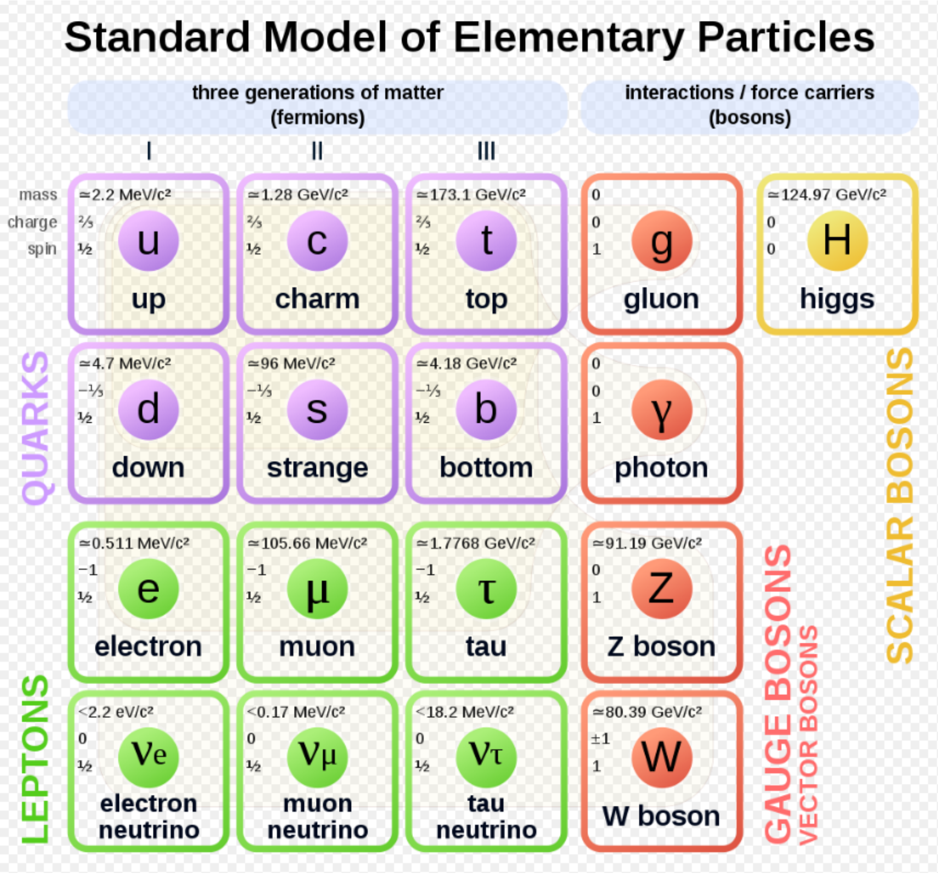
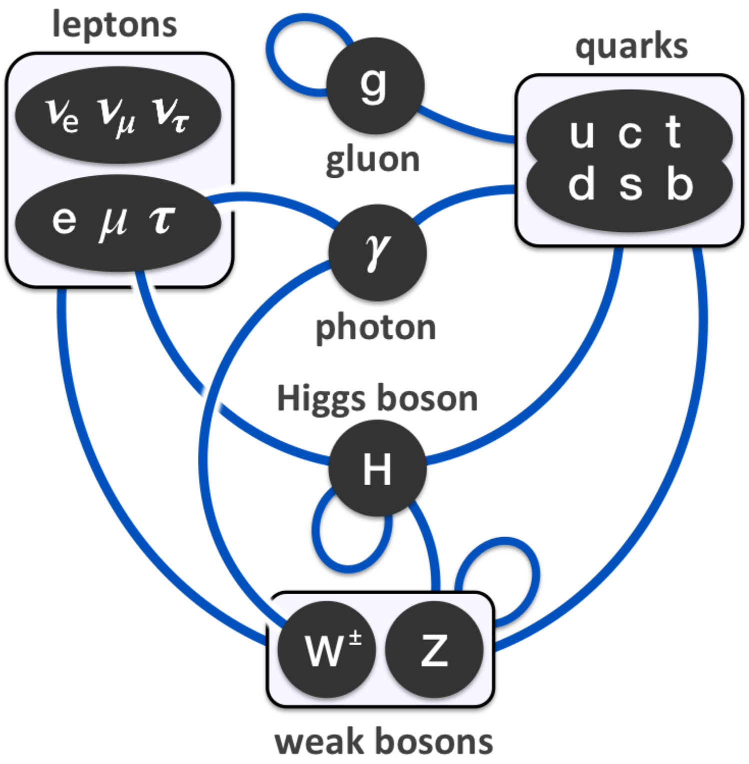
Introduction

- **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

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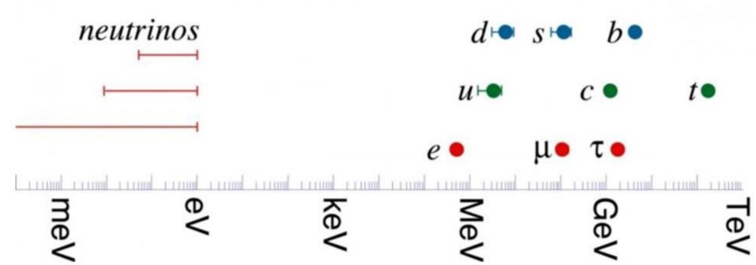
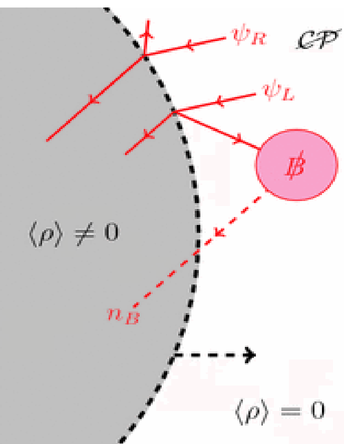
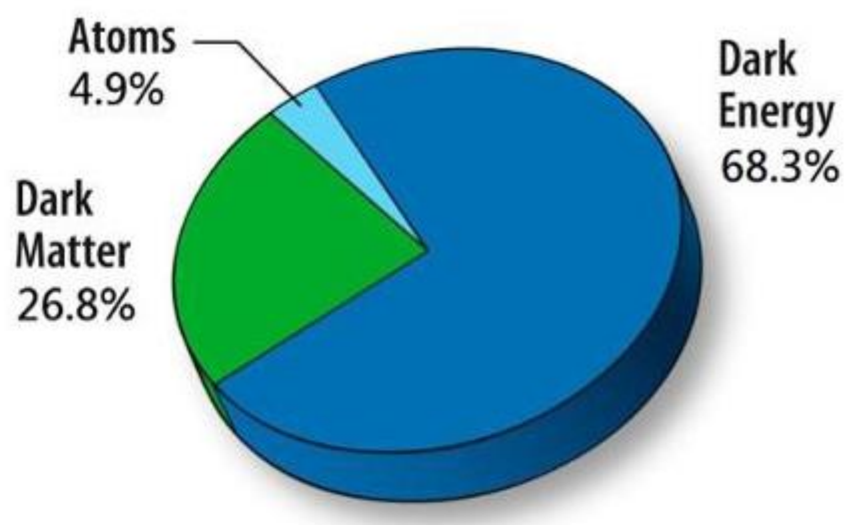






RSB triggered by Dark Matter

- **Motivation**

1. The origin of EW scale-μ?

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

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**

H,S have CSI vacuum $\xrightarrow{\text{CW mechanism / break CSI by DM}}$ H,S process VEV $\rightarrow$ The mass of DM yield by VEV, not by hand

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

- **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

- **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

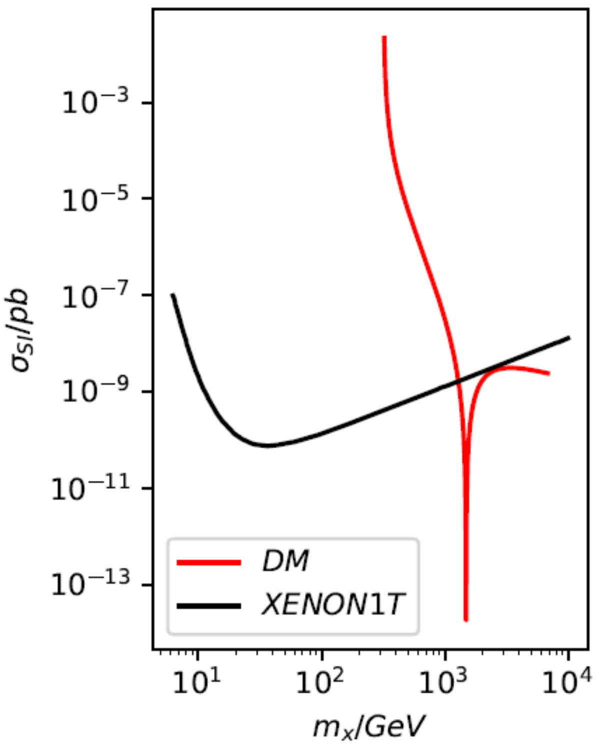
This case is a **decoupling limit situation** $\lambda_{hs} \ll 1$, which means one field should break firstly and generate a non-trivial VEV. Then, this VEV will provide EW scale μ for the SM Higgs field.

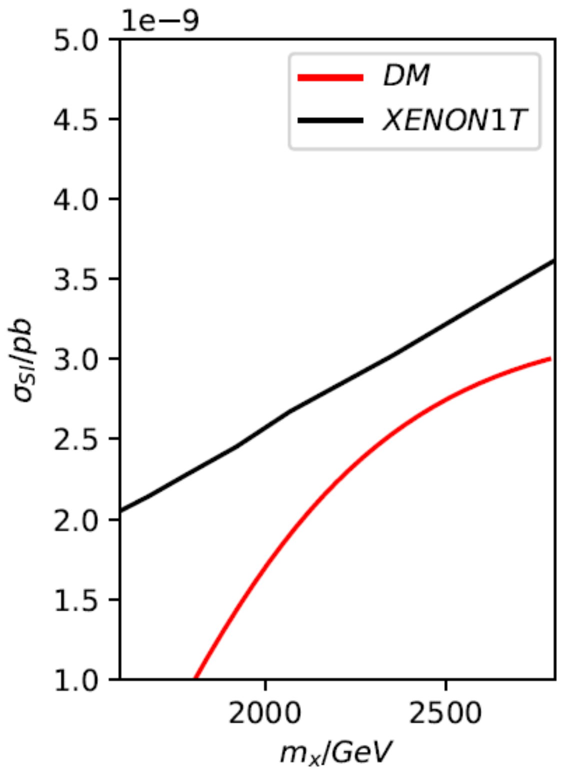
Both should be constrained by: SM particle mass, Mixing angle, and Dark matter data

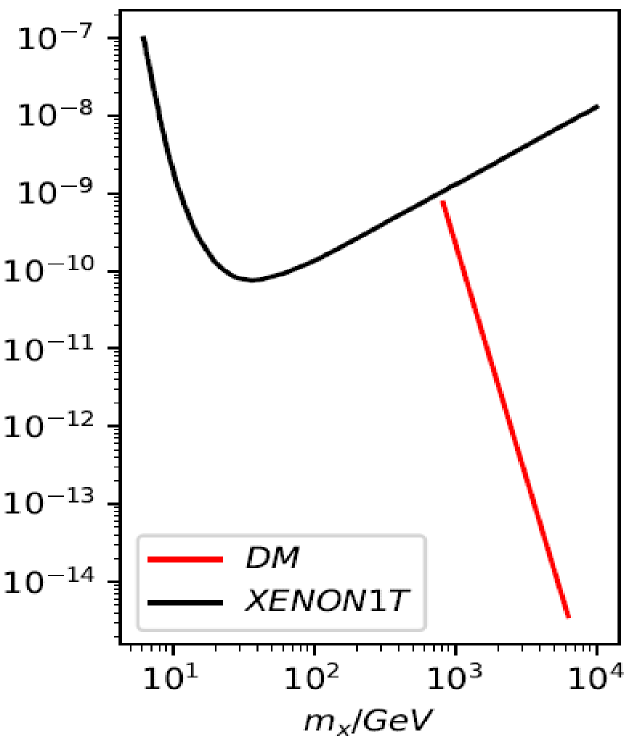
RSB triggered by Dark Matter

- **Dark matter 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}







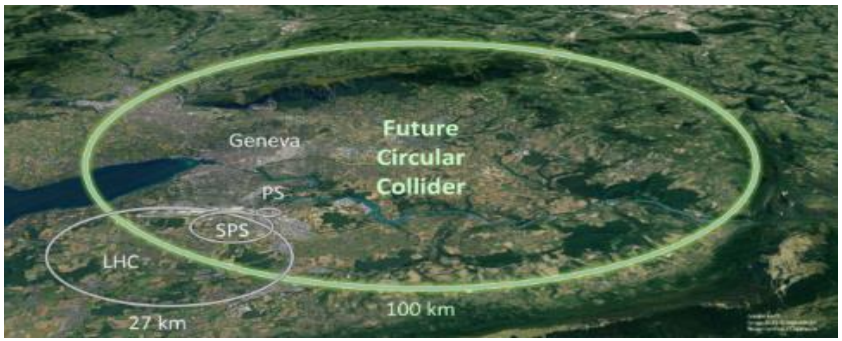
Test at Collider?

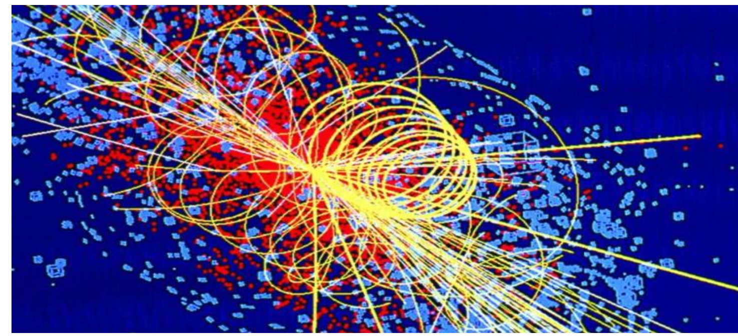
CSI Supercooling Phase Transition

- **Test of our Model：**

1) Collider：LHC, FCC, CEPC e.g.

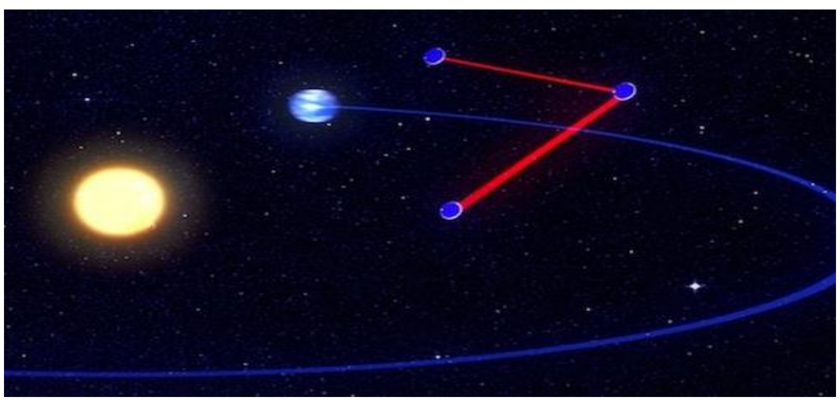
Strong interaction & light particle **Difficult**

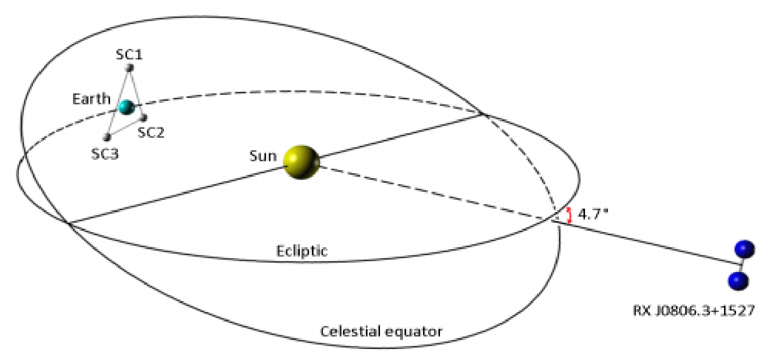




2)Gravitation：LISA，TianQin e.g.

Complement





CSI Supercooling Phase Transition

- **Phase Transition**

The behavior of universe at high temperature:

① $T > T_1$

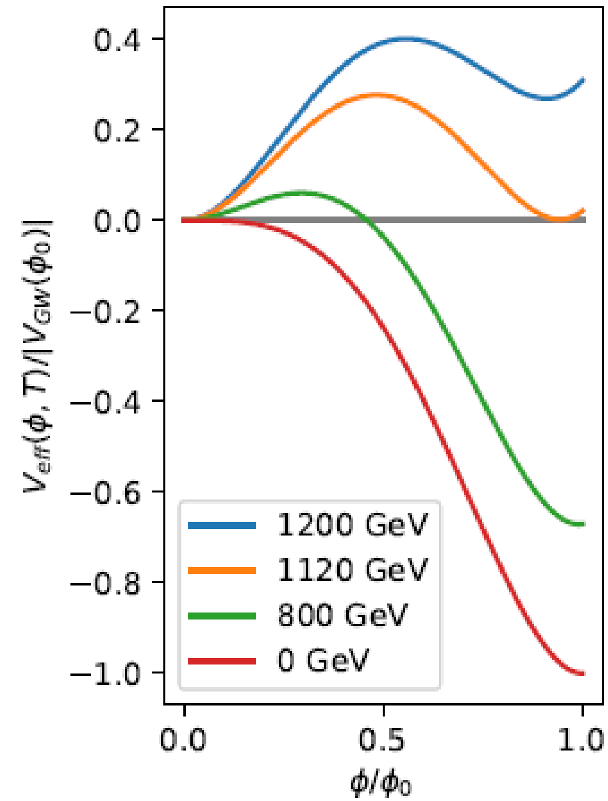
Only one minimum $\phi_0 = \phi_{min}$

② $T_1 > T > T_*$

there is a second extremum ϕ_-, but the minimum is still $\phi_0 = \phi_{min}$

③ $T_c > T$

two extremums, minimum is $\phi_- = \phi_{min}$



- **Transition Rate**

①Transition by quantum tunneling : $\Gamma = Ae^{-S_4}$

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

- **Three parameters in phase transition**

①the strength of phase transition: α

②the time scale of phase transition: β

③the temperature of phase transition: T_n

$$\alpha = \frac{\Delta\epsilon}{\rho}\Big|_{T=T_n} \qquad \frac{\beta}{H_n} = T_n \frac{d(S_3/T)}{dT}\Big|_{T=T_n}$$

CSI Supercooling Phase Transition

- **S_3 in thermal tunneling**

There are few things we need to comment:

① S_3 is obtained by numerical package CosmoTransition. This program works poorly in low temperature area which, however, is the focus in our study.

② We use linear fit in order to get S_3, dropping some points with very large S_3/T

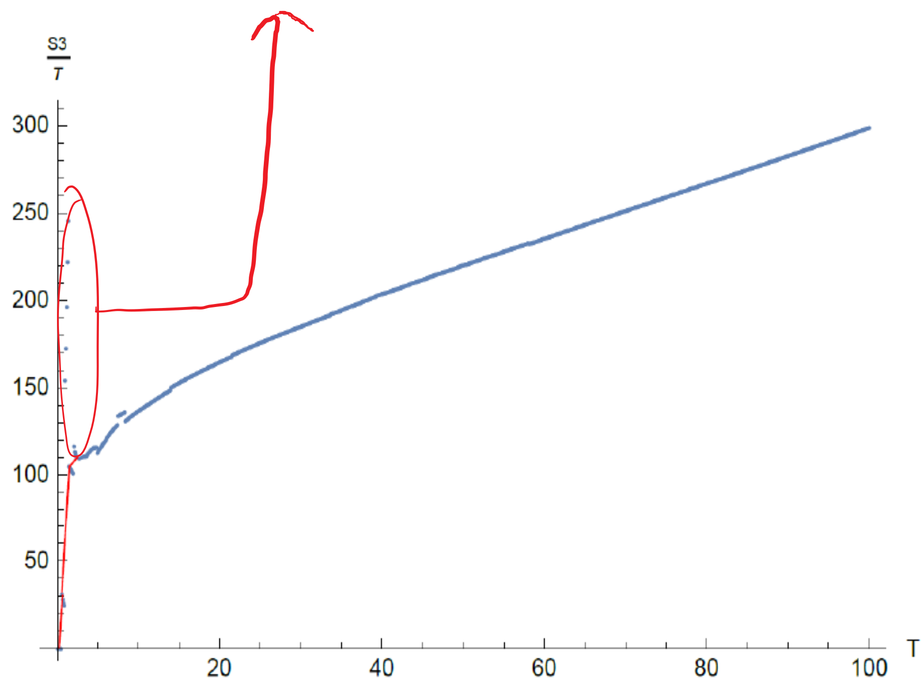
Support from Witten approximation based on the effective potential

$$V_{eff}(\phi,T) \simeq \frac{m^2_{eff}(T)}{2}\phi^2 - \frac{\lambda_{eff}(T)}{4}\phi^4$$

It gives

$$\frac{S3(T)}{T} = 18.897\frac{m_{eff}(T)}{T\lambda_{eff}(T)}$$

which Indicate when $\mathrm{T} \rightarrow 0, \frac{S_3}{T} \rightarrow 0$



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：

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

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

$$\boxed{\rho_r = \frac{\pi^2}{30} g_* T^4} \qquad \boxed{\rho_0 = V_0^{(1)}(0, T_n) - V_0^{(1)}(\langle\phi\rangle, T_n) = \frac{1}{2} B \langle\phi\rangle^4}$$

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

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

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 derived a new approximation for phase transition happened in vacuum dominated period

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

TABLE I. Possible Parameter

	v_s/GeV	λ	λ_s	λ_x	λ_{hx}	λ_{sx}	α	β/H	T_n/GeV	T_*/GeV
A	1886	0.1269	0.000037	0.2	10^{-3}	1.09	$1.4*10^8$	113.124	0.898	388
B	2076	0.1273	0.000025	0.2	10^{-3}	1.20	$8.2*10^7$	104.087	1.182	464
C	2595	0.1279	0.000010	0.2	10^{-3}	1.50	$2.5*10^7$	98.157	2.228	689
D	3460	0.1284	0.000003	0.2	10^{-3}	2.00	0.907	79.302	248	1112
E	5433	0.1288	$5.4*10^{-7}$	0.2	10^{-3}	3.14	0.025	219.136	1170	2285
F	1886	0.1269	0.000037	1.20	10^{-3}	1.09	$6.0*10^7$	93.028	1.105	423
G	2076	0.1273	0.000025	1.20	10^{-3}	1.20	$3.5*10^7$	88.382	1.461	511

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 speed wave

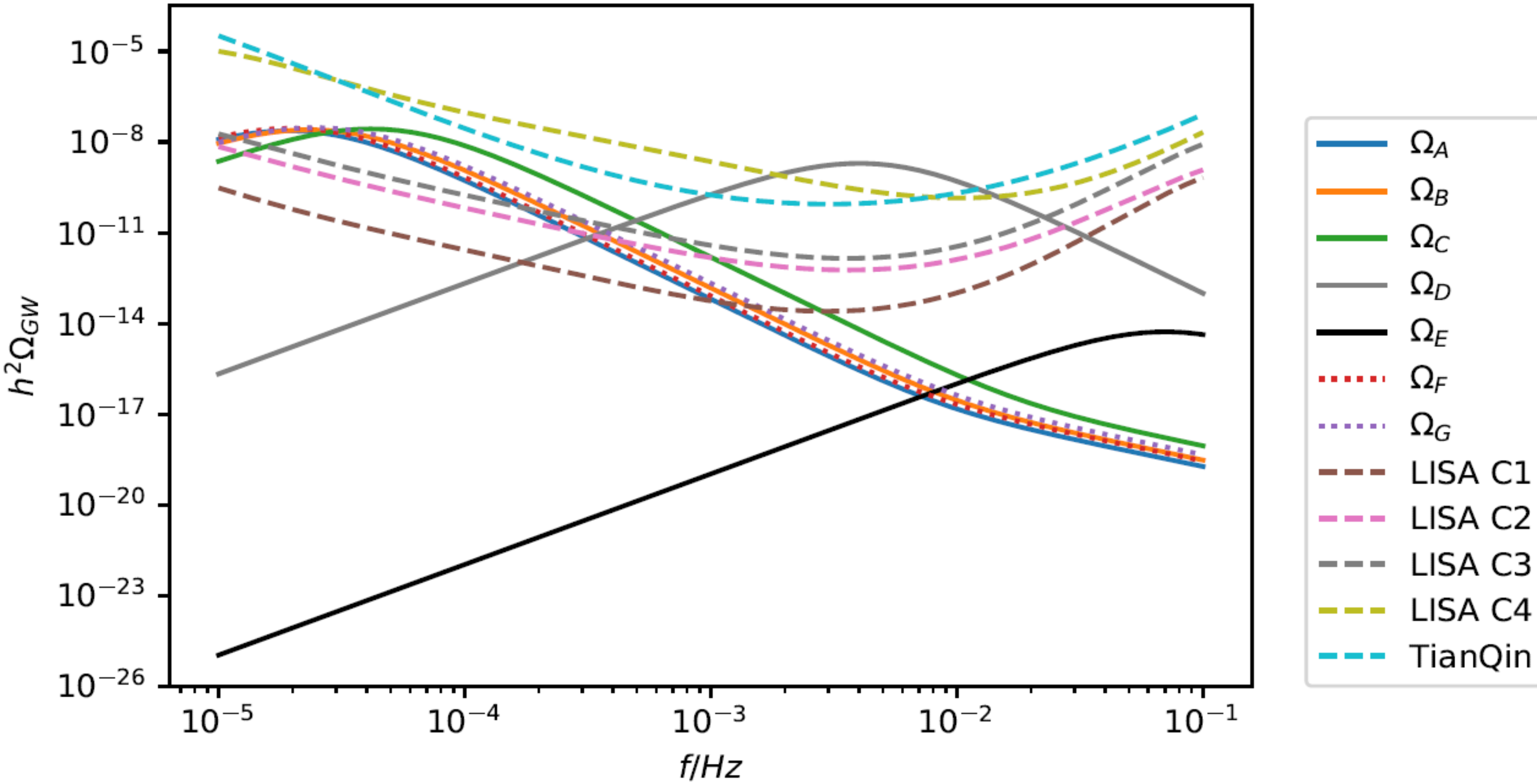
$$h^2\Omega_{\rm sw}(f) = 2.65\times 10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w\, S_{\rm sw}(f)$$

$$S_{\rm sw}(f) = (f/f_{\rm sw})^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

$$f_{\rm sw} = 1.9\times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

CSI Gravitational Wave

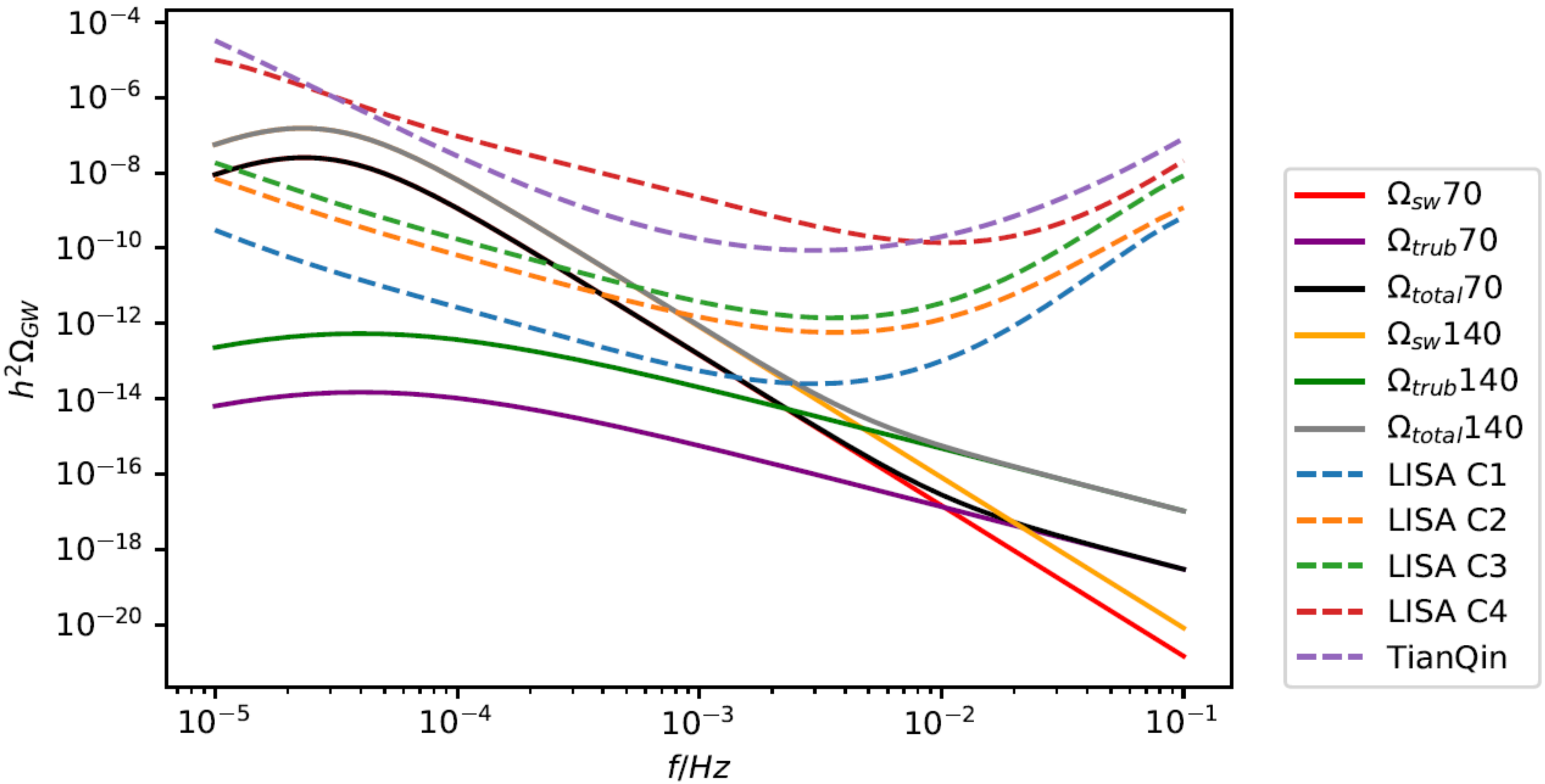
- **LISA & TianQin detectable Gravitational Wave Signal**



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.
  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.

- **Outlook**

  There are more details we need to discuss in Gildener-Weinberg approach, since the traditional analysis of this model ignores the influence given by 1-loop contribution in mixing angle which may give some corrections to feasible parameter and Gravitational spectrum