1st order phase transition in Complex singlet extension of the Standard Model

Chikako Idegawa

Introduction

Sakharov Conditions

1. Baryon number violation
2. C and CP symmetry violation
3. Interaction out of thermal equilibrium

Baryon generating interaction must satisfy **Sakharov conditions**.

In **electroweak Baryogenesis** , in order to satisfy Sakharov conditions, a **strong 1st order phase transition** is needed.

CxSM(Complex singlet extension of the SM)

Scalar potential for SM higgs field H and complex scalar field S

$$V=\frac{m^2}{2}|H|^2+\frac{\lambda}{4}|H|^4+\frac{\delta_2}{2}|H|^2|S|^2+\frac{b_2}{2}|S|^2+\frac{d_2}{4}|S|^4+\left(a_1 S+\frac{b_1}{4}S^2+\text{c.c.}\right)$$

$$H=\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h\end{pmatrix},\quad S=(v_S+s+i\chi)/\sqrt{2}$$

χ ⋯⋯ dark matter

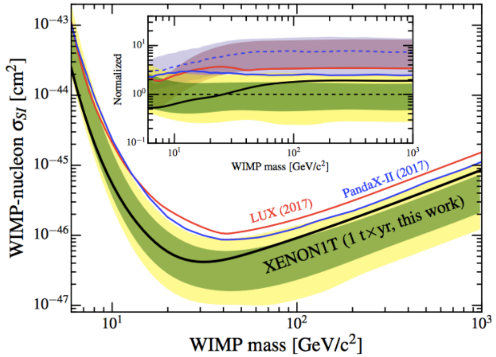
h_1, h_2 ⋯⋯ eigenstates of h, s (two higgs bosons)

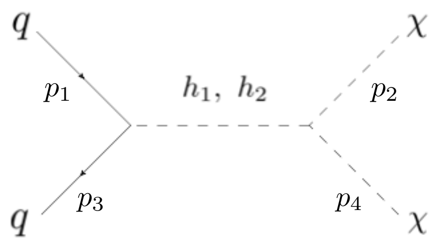
Amplitudes suppression condition

$$m_{h1}\approx m_{h2}$$

$m_{h1}=125\ \text{GeV}, m_{h2}=124\ \text{GeV}$

XENON Collaboration [arXiv:1805.12562]

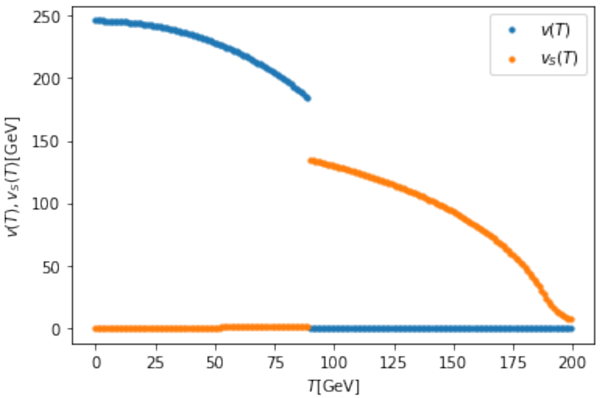




1st order phase transition in CxSM

The order of the phase transition is determined using **the effective potential**.

① HT effective potential $V^{\text{HT}}=V^{\text{tree}}+\Sigma_H(T)+\Sigma_S(T)$

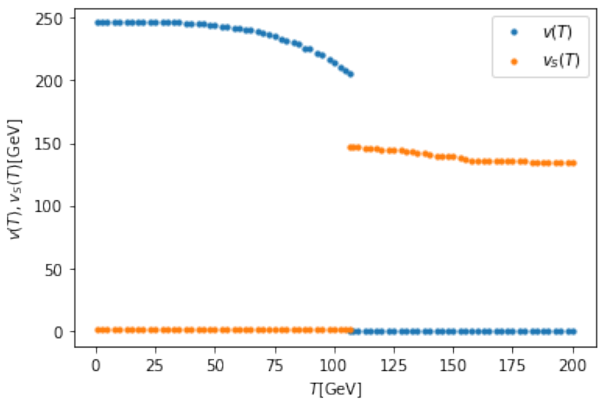


$\Sigma_H(T), \Sigma_S(T)$ ⋯⋯2 point self-energy

$T_c=89.8\ \text{GeV}$

$v(T_c)=183.1\ \text{GeV}$

② Full effective potential $V^{\text{Full}}=V^{\text{tree}}+V^{\text{CW}}+V^{\text{FT}}(T)+V^{\text{ring}}(T)$



$T_c=106.8\text{GeV}$

$v(T_c)=205.8\text{GeV}$

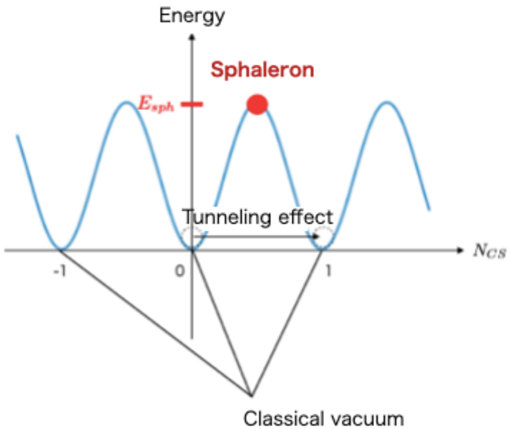
Strong first order phase transition

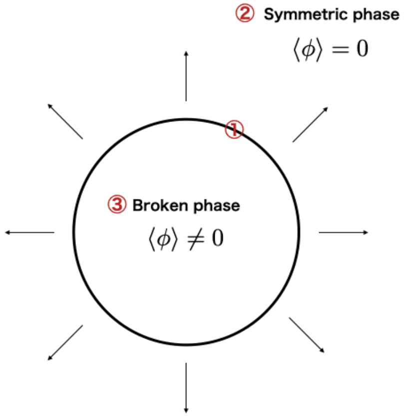
$\frac{v_c}{T_c}\gtrsim 1$ **Clear!**

Electroweak Baryogenesis

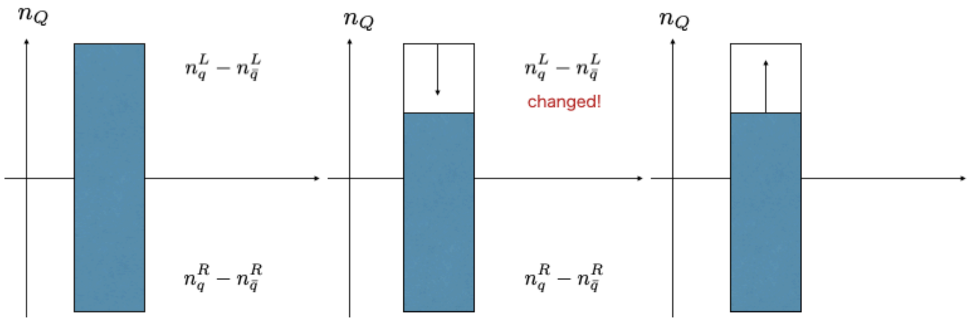
Sakharov Conditions in EWBG

1. Baryon number violation → Sphaleron process
2. C and CP symmetry violation → CKM phase etc.
3. Interaction out of thermal equilibrium → Strong 1st order phase transition





① On the wall ② Symmetric phase ③ Broken phase



$n_Q \equiv n_q^L - n_{\bar{q}}^L + n_q^R - n_{\bar{q}}^R = 0$

$n_Q \equiv n_q^L - n_{\bar{q}}^L + n_q^R - n_{\bar{q}}^R \neq 0$

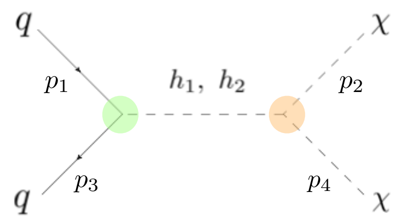
$\Gamma_B^{(b)} < H$

$$\Gamma_B^{(b)}(T) \simeq (\text{ pre }) \frac{\Gamma_{\text{sph}}^{(b)}}{T^3} \simeq (\text{ pre }) e^{-E_{\text{sph}}/T}$$

$$E_{\text{sph}} \propto v(T)$$

→ $$\frac{v_c}{T_c} \gtrsim 1$$

DM-nucleon scattering suppression process



$$\mathcal{L}_S = g_{h_1\chi\chi} h_1 \chi^2 + g_{h_2\chi\chi} h_2 \chi^2$$

$$g_{h_1\chi\chi} \equiv \frac{m_{h_1}^2 + \frac{a_S}{2v_S}}{2v_S} \sin\theta$$

$$g_{h_2\chi\chi} \equiv -\frac{m_{h_2}^2 + \frac{a_S}{2v_S}}{2v_S} \cos\theta$$

$$\mathcal{L}_Y = \frac{m_f}{v} \bar{f} f (h_1 \cos\theta + h_2 \sin\theta)$$

$F(m_{h_1}) \cos^2\alpha + F(m_{h_2}) \sin^2\alpha \simeq F(m_{h_{SM}})$ for $m_{h_1} \simeq m_{h_2} \simeq m_{h_{SM}}$

propagator = h_1: $i\mathcal{M}_{h_1} = -i \frac{m_f}{v v_S} \frac{m_{h_1}^2 + \frac{a_S}{2v_S}}{t - m_{h_1}^2} \sin\theta \cos\theta \bar{u}(p_3) u(p_1)$

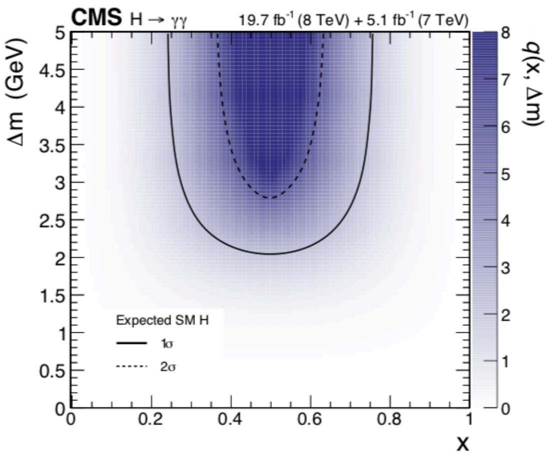
+) propagator = h_2: $i\mathcal{M}_{h_2} = +i \frac{m_f}{v v_S} \frac{m_{h_2}^2 + \frac{a_S}{2v_S}}{t - m_{h_2}^2} \sin\theta \cos\theta \bar{u}(p_3) u(p_1)$

total amplitude : $i(\mathcal{M}_{h_1} + \mathcal{M}_{h_2}) = i \frac{m_f}{v v_S} \left(-\frac{m_{h_1}^2 + \frac{a_S}{2v_S}}{t - m_{h_1}^2} + \frac{m_{h_2}^2 + \frac{a_S}{2v_S}}{t - m_{h_2}^2} \right) \sin\theta \cos\theta \bar{u}(p_3) u(p_1)$

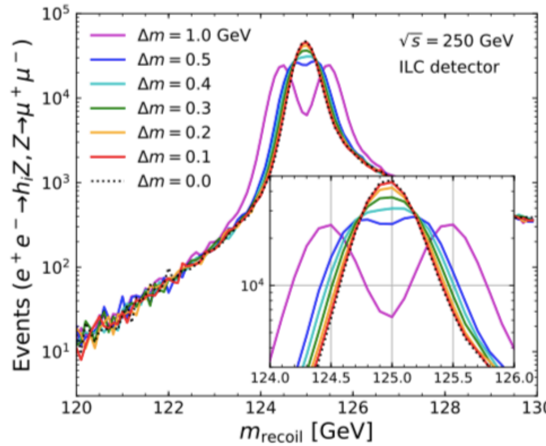
$$\propto \frac{a_S}{v_S} \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right) \quad (t \to 0)$$

Amplitudes suppression condition

~~$a_S \to 0$~~ or $m_{h_1} \simeq m_{h_2}$



CMS collaboration,



Gi-Chol Cho et al., arXiv:2101.04887

Phase transition in SM

Effective potential $V_{\rm SM}^{\rm eff} = V^{\rm tree} + V^{\rm CW} + V^{\rm FT}(T)$ ϕ_c : real back ground field

- Tree level potential $V^{\rm tree} = -\frac{m^2}{2}\phi_c^2 + \frac{\lambda}{4}\phi_c^4$
- 1-loop zero temperature potential

$$V^{\rm CW} = \frac{1}{64\pi^2}\sum_i \left\{ m_i^4(\phi_c)\left(\log\frac{m_i^2(\phi_c)}{m_i^2(v)} - \frac{3}{2}\right) + 2m_i^2(v)m_i^2(\phi_c)\right\}$$

- 1-loop finite temperature potential

$$V^{\rm FT}(T) = \frac{T^4}{2\pi^2}\left[\sum_{i=W,Z} n_i J_B\left[m_i^2(\phi_c)/T^2\right] + n_t J_F\left[m_t^2(\phi_c)/T^2\right]\right]$$

$$H = \begin{pmatrix} \chi_1 + i\chi_2 \\ \frac{\phi_c + h + i\chi_3}{\sqrt{2}} \end{pmatrix}$$

$$D = \frac{2m_W^2 + m_Z^2 + 2m_t^2}{8v^2}$$

$$E = \frac{2m_W^3 + m_Z^3}{4\pi v^3}$$

$$T_o^2 = \frac{m_h^2 - 8Bv^2}{4D}$$

$$B = \frac{3}{64\pi^2 v^4}\left(2m_W^4 + m_Z^4 - 4m_t^4\right)$$

$$\lambda(T) = \lambda - \frac{3}{16\pi^2 v^4}\left(2m_W^4 \log\frac{m_W^2}{A_B T^2} + m_Z^4\log\frac{m_Z^2}{A_B T^2} - 4m_t^4 \log\frac{m_t^2}{A_F T^2}\right)$$

$$\Rightarrow \quad V_{\rm SM}^{\rm eff} = D\left(T^2 - T_o^2\right)\phi_c^2 - ET\phi_c^3 + \frac{\lambda(T)}{4}\phi_c^4$$

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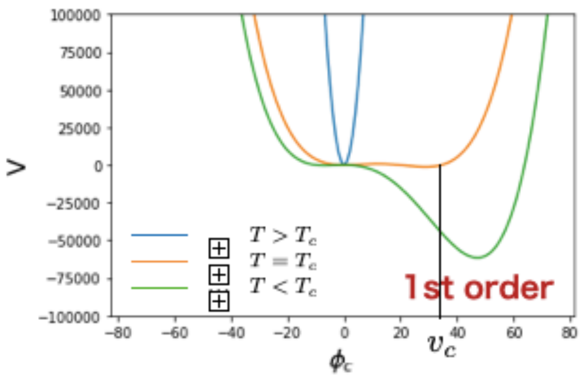

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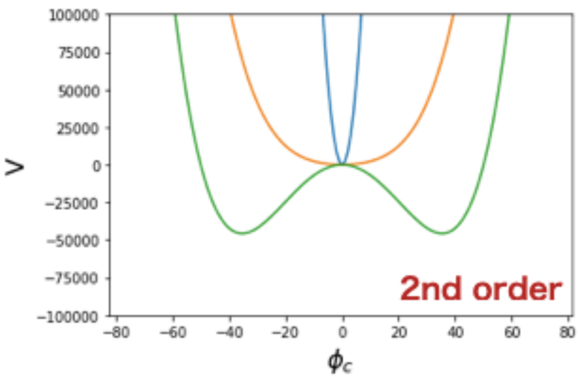
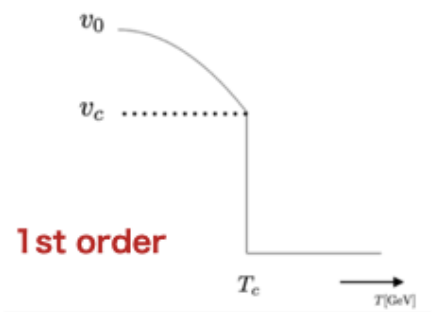
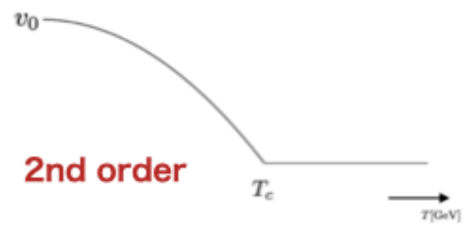






ϕ_c^3 term is important for the 1st order phase transition .

$$\frac{v_c}{T_c} \gtrsim 1$$

$$\Downarrow$$

$$m_h \lesssim 64 \text{ GeV}$$

Phase transition in CxSM

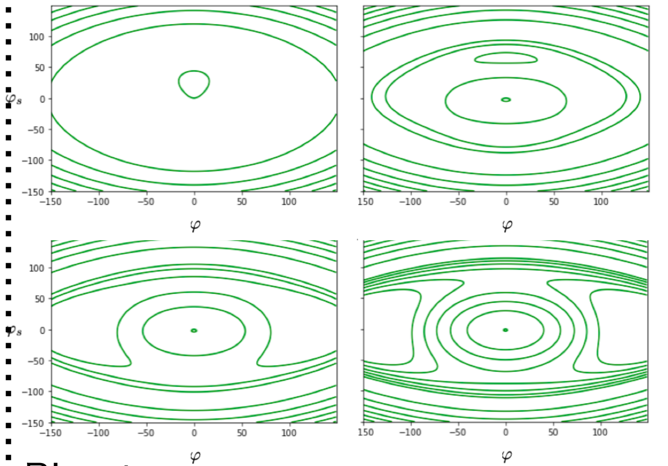
① HT effective potential

- ○ Gauge independent
- ○ Not include 1-loop contribution

② Full effective potential

- ○ Include 1-loop contribution
- ○ Gauge dependent
- ○ There are parameter regions where the potential is complex

Internal lines: h, s, DM, W, Z, t



Ring term

$$V^{\rm ring}(T) = \sum_{\substack{i=h_{1,2},\\ W_L, Z_L, \gamma_L}} -n_j \frac{T}{12\pi} \times \left[\left(M_i^2(T)\right)^{3/2} - \left(m_i^2\right)^{3/2}\right]$$

$M_i^2(T)$: thermal corrected field dependent mass