Hidden QCD Phase Transition in a Scale Invariant Theory

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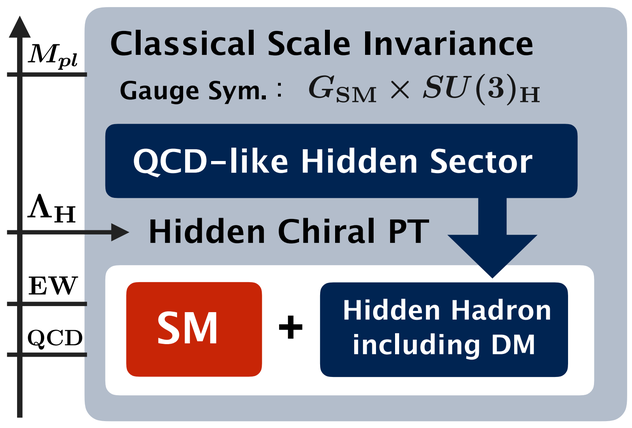
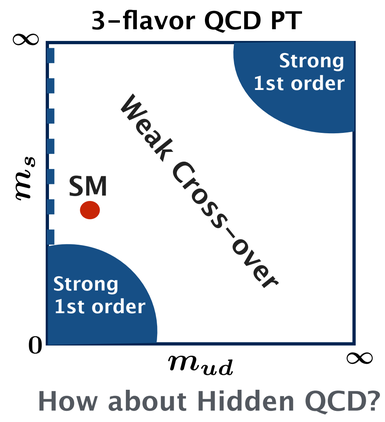
HPNP2017, Toyama

1. Introduction to Scale Invariant Hidden QCD Model

Motivation — What is the origin of mass? —

ALL mass was generated at Hidden Chiral Phase Transition (PT)





Hidden QCD PT may have produced Gravitational Waves (GW).

1-a. Model

T. Hur, D-W. Jung, P. Ko and J-Y. Lee
arXiv: 0709.1218, 1103.2571

Particle Content: SM + Real Singlet Scalar S + Hidden Quark (SM Singlet) ψ

Classical Scale Invariant SU(3) Hidden Sector Lagrangian

$$\mathcal{L}_{\rm H} = -\frac{1}{2}{\rm Tr}\, F^2 + {\rm Tr}\, \bar{\psi}\,(i\partial\!\!\!/ + g_{\rm H}G\!\!\!/ - yS)\,\psi \qquad (N_f = 3)$$

$$V_{{\rm SM}+S} = \lambda_H (H^\dagger H)^2 - \frac{1}{2}\lambda_{HS} S^2 (H^\dagger H) + \frac{1}{4}\lambda_S S^4$$

- Hidden Chiral Symmetry Breaking as a Trigger of EWPT

$$\langle\bar{\psi}\psi\rangle \neq 0 \;\rightarrow\; -y\,\langle\bar{\psi}\psi\rangle\, S \;\rightarrow\; \langle S\rangle \neq 0 \;\rightarrow\; -\frac{1}{2}\lambda_{HS}\,\langle S\rangle^2\,(H^\dagger H)^2$$

- Nambu-Goldstone Bosons = Dark Matter Candidates

$SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$ ϕ : Stable thanks to flavor symmetry

DM Annihilation Process

1-b. Nambu—Jona-Lasinio Analysis

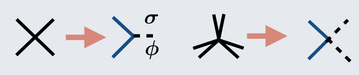
M. Holthausen, J. Kubo, K-S. Lim and M. Lindner
arXiv: 1310.4423

NJL Lagrangian as Low energy Effective Theory of $\mathcal{L}_{\rm H}$ $(N_f = 3)$

$$\mathcal{L}_{\rm NJL} = {\rm Tr}\,\bar{\psi}(i\partial\!\!\!/ - yS)\psi + 2G{\rm Tr}\,\Phi^\dagger\Phi + G_D({\rm det}\,\Phi + h.c) \qquad (\Phi)_{ij} = \bar{\psi}_i(1-\gamma_5)\psi_j$$

- **Self-Consistent Mean Field Approximation**

$$\langle\Phi\rangle = -\frac{1}{4G}\,({\rm diag.}(\sigma,\sigma,\sigma) + i(\lambda^a)^T\phi^a)$$



$$V_{\rm NJL} = \frac{3}{8G}\sigma^2 - \frac{G_D}{16G^3}\sigma^3 \quad + \quad \bigcirc \quad M = \sigma + yS - \frac{G_D}{8G^2}\sigma^2 \qquad \Lambda_{\rm H}$$

How do we know Hidden QCD Scale $\Lambda_{\rm H}$?

$$V_{\rm eff}(h,S,\sigma) \quad \text{with} \quad \Lambda_{\rm H} \;\longleftarrow\; \langle h\rangle = 246\ {\rm GeV}$$

$$= V_{{\rm SM}+S} + V_{\rm NJL} \quad \text{with} \quad \Lambda_{\rm QCD} \;\xrightarrow{\text{Compute}}\; \langle h\rangle_{\rm QCD} \;\xrightarrow{\text{Scale-up}}$$

$$@\ \Lambda_{\rm QCD} = 0.930\ {\rm GeV} \qquad G^{1/2}\Lambda = 1.82 \qquad (-G_D)^{1/5}\Lambda = 2.29$$

1-c. Hidden Phase Transitions and Dark Matter

When hidden PT become strong 1st Order? - Need small y cf. $m_c = y\,\langle S\rangle$

For small y how can we explain DM relic abundance? - Need $m_S \simeq 2m_\phi$

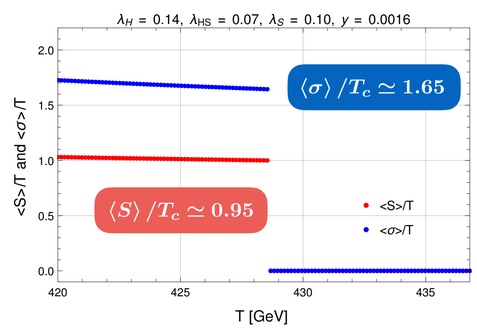
e.g. $(\lambda_H, \lambda_{HS}, \lambda_S, y)$
$= (0.14, 0.07, 0.10, 0.0016)$

$m_\phi = 133.5\ {\rm GeV}$

$m_S = 267.7\ {\rm GeV} \quad \Lambda_{\rm H} = 5.7\ {\rm TeV}$

1st order PTs happen
at $T_c \simeq 428.6\ {\rm GeV}$

— How about GW production?



2. Gravitational Waves from Hidden QCD Phase Transition

M. Aoki, HG and J. Kubo [work-in-progress]

2-a. Method

C. Grojean, G Servant
arXiv: 0607107

Quantities to characterize GW signals produced during Phase Transition

T_t Transition Temperature $\alpha \equiv \epsilon/\rho$ Ratio of latent heat and energy density β^{-1} Duration time of phase transition

$\Omega_{\rm GW}h^2(f)$ ← $(\alpha, \beta; T_{\rm t})$ ← $V(\phi, T)$ Effective Potential

Tunneling process from false vacuum to true vacuum and its latent heat

Bubble nucleation rate per unit volume per unit time

$$\Gamma = \Gamma_0 e^{\beta t} \simeq \Gamma_0 e^{-S_3(T)/T} \qquad S_3(T)$$ 3D Euclidian action of critical bubble for $V(\phi, T)$

Transition condition

$$\Gamma/H^4\big|_{T=T_t} \simeq 1$$

Latent heat

$$\epsilon = -\Delta V + T\frac{\partial \Delta V(T)}{\partial T}\bigg|_{T=T_t}$$

Duration time

$$\frac{\beta}{H} = T\frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\bigg|_{T=T_t}$$

2-b. Tunneling Process of Hidden QCD PT

3D Euclidian Action set h=0

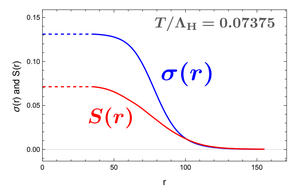
$$S_3(T) = \int d^3r \left[\frac{Z_\sigma^{-1}(\sigma,S,T)}{2}\left(\frac{d\sigma}{dr}\right)^2 + \frac{1}{2}\left(\frac{dS}{dr}\right)^2 + V_{\rm EFF}(\sigma,S,T)\right]$$ Kinetic term computed from

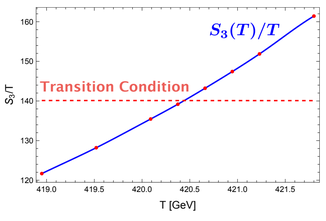
$$\frac{d^2\sigma}{dr^2} + \frac{2}{r}\frac{d\sigma}{dr} = Z_\sigma(S,\sigma,T) \times \left[\frac{\partial V_{\rm EFF}(S,\sigma,T)}{\partial\sigma} + \frac{1}{2}\frac{\partial Z_\sigma^{-1}(S,\sigma,T)}{\partial\sigma}\left(\frac{d\sigma}{dr}\right)^2\right]$$

$$\frac{d^2S}{dr^2} + \frac{2}{r}\frac{dS}{dr} = \frac{\partial V_{\rm EFF}(S,\sigma,T)}{\partial S} + \frac{1}{2}\frac{\partial Z_\sigma^{-1}(S,\sigma,T)}{\partial S}\left(\frac{d\sigma}{dr}\right)^2$$

where $\phi_i'(0) = 0 \quad \phi_i(\infty) = 0$.

$\lambda_S = 0.10,\ y = 0.0016$
$\Lambda_{\rm H} = 5.7\ {\rm TeV}$





$T_t = 420.4\ {\rm GeV}$
$\alpha = 0.1217$
$\beta/H = 5.9 \times 10^3$

2-c. GW Spectrum from Hidden QCD PT

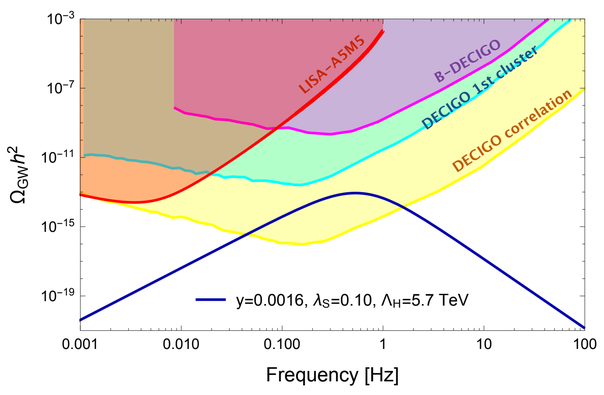
Dominant Contribution

$$\Omega_{\rm GW}h^2(f) \simeq \Omega_{\rm sw}h^2(f)$$

Sound waves after the bubble collisions

Peak Frequency and $\Omega_{\rm sw}h^2$

$$f_{\rm sw} = 0.53\ {\rm Hz}$$
$$\Omega_{\rm sw}h^2 = 8.7 \times 10^{-14}$$



Summary

1. Scale Invariant Hidden QCD Model
- can explain the origin of mass and DM.
- For small y Strong 1st order PT occurs.

2. GW from hidden QCD PT
- We calculated its spectrum using NJL model.
- its signal peak appears in the 0.1~1 Hz region.
- it can be tested at future GW experiments, DECIGO.