Pseudo Goldstone Dark Matter and Inflation

Based on JHEP 1810 (2018) 124

Subhaditya Bhattacharya, Abhijit Kumar Saha, Arunansu Sil, Jose Wudka

Motivation

- Inflation and Dark matter can't be explained within SM.
- The two unknown problems may be connected.
- We look for a solution by considering a different sector that can address these two.
- Inflation sector can be embedded into a hidden susy breaking sector where inflationary energy scale can be dynamically generated.
- The susy breaking sector could be a SQCD sector in the form of supersymmetric QCD.
- SQCD-embedded inflation model has existence of a UV complete theory.

- Inflationary sector represented by a strongly coupled supersymmetric SU(N) gauge group with $N_f = N_C$ flavours of quark superfields Q_i and $\bar{Q}_i$.

  Global symmetry: $SU(N_f) \times SU(N_f) \times U(1)_B \times U(1)_R$.
  Below the strong coupling regime (Λ_0) they form mesons and baryons [hep-th/0602239]

$$T_{ij} = \frac{Q_i \bar{Q}_i}{\Lambda_0}, \ B = \frac{\epsilon_{abcd} Q_1^a Q_2^b Q_3^c Q_4^d}{\Lambda_0^3}, \ \bar{B} = \frac{\epsilon_{1234} \bar{Q}_1^a \bar{Q}_2^b \bar{Q}_3^c \bar{Q}_4^d}{\Lambda_0^3} \quad (1)$$

  Superpotential: $W_{N_f=N_c} = S(\frac{\det \mathrm{T}}{\Lambda_0^2} - B\bar{B} - \Lambda_{\text{eff}}^2)$

- $N_f = N_C$ theory can be realized from $N_f = N_c + 1$ version of SQCD by making the N_fth quark heavy ($W_m = m_Q Q_{N_f+1} \bar{Q}_{N_f+1}$) below it.
- The heavy quark can be identified with the S-field and $\Lambda_{\text{eff}} = m_Q \Lambda_0$.

contd.

- Inflation can be realized with $N_f = N_c = 4$ along $B = \bar{B} = 0$ and $T_{ij} = \chi\delta_{ij}$[arXiv:0902.0972].

  So inflationary superpotential [hep-ph/9606297]

$$W_{\rm Inf} = S\left(\frac{\chi^4}{\Lambda_0^2} - \Lambda_{\rm eff^2}\right) \tag{2}$$

  At global minimum $T = \sqrt{\Lambda_0\Lambda_{\rm eff}}$, thus breaks the global symmetry
  $SU(4)_L \times SU(4)_R \times U(1)_B \times U(1)_R \to SU(4)_V \times U(1)_B \times U(1)_R$.

  Inflationary predictions: $r \simeq 10^{-7}$, $n_s = 0.967$.
  Allowed by Planck 2016???[arXiv:1502.01589]

NGB as DM

- Associated flavor symmetry breaks down after inflation, 15 NGB's will appear.

$$T_{N_f \times N_f} = \chi \exp\left(\frac{iG_S^a \lambda^a}{\langle\chi\rangle}\right), \tag{3}$$

Can those (t^a) be DM??

- Masses of NGB's can be generated through Dashen formulla by explicit breaking of broken $SU(4)$ in the superpotential $(m = \mathrm{diag}\{m_1, m_2, m_3, m_4\})$.

$$\langle\chi\rangle^2 (m^a_{G_S})^2 = \langle 0|[\tilde{\mathcal{Q}}_a, [\tilde{\mathcal{Q}}_a, H]]|0\rangle \tag{4}$$

$$= \bar{\psi}\left[\frac{\lambda_a}{2}, \left[\frac{\lambda_a}{2}, m_{\mathrm{diag}}\right]_+\right]_+ \psi \tag{5}$$

We modify the inflationary superpotential to generate the interactions of NGBs with SM

$$W_{\mathrm{Inf}} = S\left(\frac{\det T}{\Lambda_0^2} - \Lambda_{\mathrm{eff}}^2\right) + \kappa_1 S\left\{\mathrm{Tr}(T^2) - \frac{(\mathrm{Tr}\ T)^2}{N_f}\right\} + \kappa_2 S H_u H_d, \tag{6}$$

- If $m_1 = m_2 = m_3 = m_4$ we get 15 no's of degenerate DM.
- For a different choice $m_1 = m_2 = m_3 = m_\gamma$ and $m_4 \gg m_\gamma$, three different sets of NGB
  (i) $m_A = m_\gamma \frac{\Lambda^3_{\rm eff}}{\langle\chi\rangle^2}$,
  (ii) $m_B = \left(m_4 + m_\gamma\right) \frac{\Lambda^3_{\rm eff}}{\langle\chi\rangle^2}$,
  (iii) $m_C = \left(\frac{3}{2} m_4 + \frac{m_\gamma}{2}\right) \frac{\Lambda^3_{\rm eff}}{\langle\chi\rangle^2}$.

  Degeneracies 8,6 and 1.
  Interaction Lagrangian with visible sector:

$$V \supset -\left(\lambda' h^2 + \lambda'' h v_d\right) \sum_a{}' (G^a_S)^2 \,, \tag{7}$$

where

$$\lambda = \frac{\kappa_1 \kappa_2}{2}, \lambda' = \frac{1}{2}\lambda \sin\alpha\cos\alpha, \quad \lambda'' = \frac{1}{2}\lambda \cos\alpha(\tan\alpha - \tan\beta) \tag{8}$$

Important formulas

$$\tan\beta = \frac{v_u}{v_d}, v = \sqrt{v_u^2 + v_d^2} \simeq 246\mathrm{GeV} \tag{9}$$

The mixing angle α can be expressed in terms of β and the pseudoscalar A mass as

$$\tan 2\alpha = \tan 2\beta \, \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}, \tag{10}$$

(11)

In large M_A limit $tan2\alpha = \tan 2\beta$. Solutions: $\alpha = \beta$ and $\alpha = \beta + \frac{\pi}{2}$.

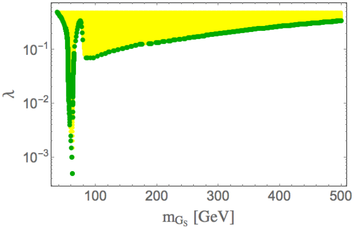
We work with $\alpha = \beta + \frac{\pi}{2}$ otherwise $\lambda^{''} \to 0$.

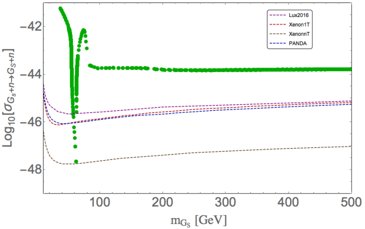
Relic density and direct search

Three parameters m_{G_s}, λ, $\tan\beta$.
Case I: Boltzman equation:

$$\dot{n}_{G_S} + 3Hn_{G_S} = -\langle\sigma v\rangle_{G_S G_S \to SM}(n_{G_S}^2 - n_{eq}^2) \qquad (12)$$

Relic density $\Omega_T = 15\Omega_{G_s}$.





Case II: Three sets of DM ($m_A < m_B < m_C$).

Assume A-type having mass $m_h/2$.

$CC \to BB, AA$ and $BB \to AA$ possible.

Hierarchy:	m_C >	m_B >	m_A
Masses:	m_C	$\sim \frac{4m_C + m_h}{6}$	$\sim \frac{m_h}{2}$
Degeneracy:	1	6	8
Relevant pNGB-pNGB interactions:	$CC \to BB$ $CC \to AA$	$BB \to AA$	$None$

Interacton term: $\frac{\kappa_1^2}{4}\sum_{a,b}(G_s^a)^2(G_s^b)^2$

A-type has negligible contribution to total relic.

$$\Omega_T = 6\Omega_B + \Omega_C \tag{13}$$

Parameters: $\{\kappa_1,\ \lambda, m_B, m_C\}$

Boltzman equations:

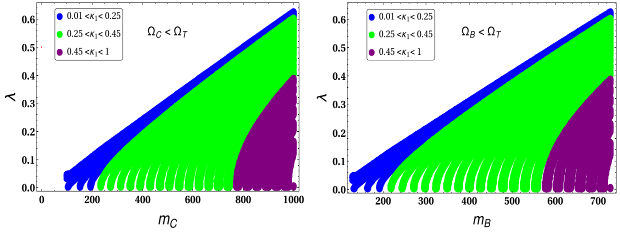
$$\frac{dn_C}{dt}+3Hn_C=-\langle\sigma v\rangle_{G_C G_C\to \mathrm{SM}}(n_C^2-n_C^{\mathrm{eq}2})-6\langle\sigma v\rangle_{G_C G_C\to G_B G_B}(n_C^2-\frac{n_C^{\mathrm{eq}2}}{n_B^{\mathrm{eq}2}}n_B^2)$$

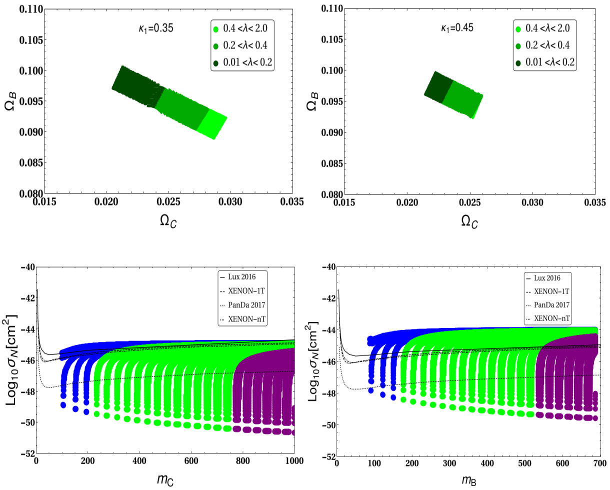
$$-8\langle\sigma v\rangle_{G_C G_C\to G_A G_A}(n_C^2-\frac{n_C^{\mathrm{eq}2}}{n_A^{\mathrm{eq}2}}n_A^2)$$

$$\frac{dn_{B_i}}{dt}+3Hn_{B_i}=-\langle\sigma v\rangle_{G_{B_i} G_{B_i}\to \mathrm{SM}}(n_{B_i}^2-n_{B_i}^{\mathrm{eq}2})+\langle\sigma v\rangle_{G_C G_C\to G_{B_i} G_{B_i}}(n_C^2-\frac{n_C^{\mathrm{eq}2}}{n_{B_i}^{\mathrm{eq}2}}n_{B_i}^2)$$

$$+8\langle\sigma v\rangle_{G_{B_i} G_{B_i}\to G_{A_i} G_{A_i}}(n_{B_i}^2-\frac{n_{B_i}^{\mathrm{eq}2}}{n_{A_i}^{\mathrm{eq}2}}n_{A_i}^2)$$

Results:





κ1=0.35
0.4 <λ< 2.0
0.2 <λ< 0.4
0.01 <λ< 0.2
ΩB
ΩC
κ1=0.45
0.4 <λ< 2.0
0.2 <λ< 0.4
0.01 <λ< 0.2
ΩB
ΩC
Lux 2016
XENON−1T
PanDa 2017
XENON−nT
Log10σN[cm2]
mC
Lux 2016
XENON−1T
PanDa 2017
XENON−nT
Log10σN[cm2]
mB

Conclusions

- Chiral symmetry broken down spontaneously at the end of inflation, NGB appears in the set-up.
- Depending on the explicit chiral symmetry breaking term, there could be different degree of degenracy among the masses of these pNGBs.
- 15 dengenerate DM is almost ruled out from direct detection limit
- However degerenrate DM scenario is still valid thanks to the interactions among them.