Can the QCD axion feed the dark energy of the Universe?

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The axion solution to the strong CP problem

- The SM Lagrangian contains a CP-violating term

$$\mathcal{L} \supset \theta \tilde{G}^{\mu\nu} G_{\mu\nu}, \text{ with } \tilde{G}^{\mu\nu} = \epsilon^{\rho\sigma\mu\nu} G_{\rho\sigma} \tag{1}$$

- Introduce a pNGB field a, with the Lagrangian

$$\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 + \mathcal{L}(\partial_\mu a, \phi) + \frac{g_s^2}{32\pi^2} \frac{a}{f} G \tilde{G}. \tag{2}$$

- Under shift symmetry $a \to \kappa f$ the action is invariant up to

$$\delta S = \frac{\kappa}{32\pi^2} \int d^4 x G \tilde{G} \tag{3}$$

- This can be used to remove the θ-term.

The topological susceptibility

- The $a\tilde{G}G$ coupling generates a temperature dependent mass term

$$F^2 m_a^2 = i \int d^4x \left\langle \frac{\alpha_s}{8\pi} G(x)\tilde{G}(x) \frac{\alpha_s}{8\pi} G\tilde{G}(0) \right\rangle = \chi \tag{4}$$

- At $T >> T_c$, the color charges are screened so that $\chi = 0$.
- At $T \simeq T_c$ the free charges are confined so that $\chi \simeq (160 \text{ MeV})^4$

$$\chi = \chi(T) = F^2 m_a^2(T) \propto T^{-n}. \tag{5}$$

- The dilute instaton gas approximation (DIGA) gives

$$n = \beta_0 - n_f - 4 \text{ with } n = 8 \text{ (QCD)} \tag{6}$$

where $\beta_0 = \frac{11}{3}N - \frac{1}{3}n_s T_s - \frac{4}{3}n_f T_f$ for $SU(N)$ with n_f fermions and n_s scalars.

Comparison of non-perturbative methods close to confinement

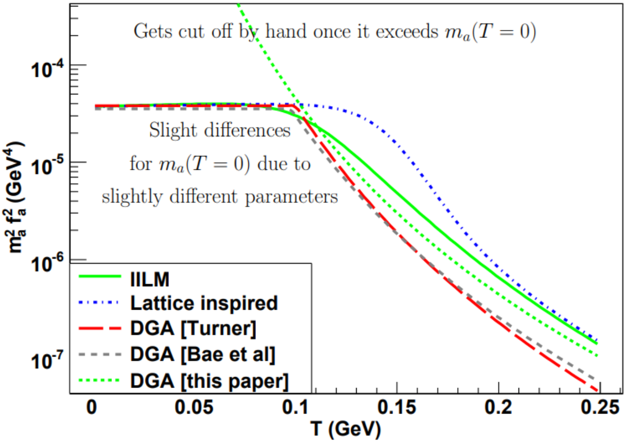

Figure 1: O. Wantz, E.P.S.Shellard, Phys. Rev. D 82, 123508, (2010)

Axion dark energy

In the following we work in matter domination era: $t \sim T^{-2/3}$

- Using $m_a^2 \sim T^{-n}$ and the continuity equation $d(\rho_a a^3) = -p_a da^3$

$$p_a = w\rho_a \implies w = -\frac{n}{6}. \tag{7}$$

- Accelerating Universe ($w > -1/3$) for $n > 2$!
- Quintessence for $n < 6$, cosmological constant for n=6, phantom dark energy for $n > 6$.
- Can we use a dark QCD confining at $T < T_0$ to explain dark energy?
- Simple considerations suggest NO:

$$\rho_b \lesssim \Lambda_b^4 < T_0^4 \sim \rho_{\rm rad} << \rho_{DE} \tag{8}$$

- So more energy needs to be extracted. For that we add another ALP.

Constructing KSZV type two axion models

1. Take two Yang-Mills groups $G_a \times G_b$
2. Introduce two new fermions and two scalars with

$$\mathcal{L}_Y \subset y_1 \bar{\psi}_L \phi_1 \psi_R + y_2 \bar{\chi}_L \phi_2 \chi_R \tag{9}$$

3. After chiral rotation the mixed anomalies generate the couplings of the axions to the gluons.
4. The potential resulting from the strong dynamics is given by

$$V = \Lambda_a^4 \left[1 - \cos\left(\frac{\varphi_a}{F}\right)\right] + \Lambda_b^4 \left[1 - \cos\left(\frac{\varphi_a}{F'} + \frac{\varphi_b}{f}\right)\right] \tag{10}$$

5. For $SU(3) \times SU(2)$ with $\psi \sim (\mathbf{1,2})$, $\chi \sim (\mathbf{3}, \mathbf{2})$ and $w \simeq -0.61$.
6. For $SU(3) \times SU(3)$ with $\psi \sim (\mathbf{1,3})$, $\chi \sim (\mathbf{3}, \mathbf{3})$ and $w \simeq -1.2$.

Dark energy with the 2 axion system

- SOLUTION: Use a two-axion system (coupled forced damped oscillators)

$$\ddot{A} + 3H\dot{A} + M^2 A = 0 \tag{11}$$

where

$$A = \begin{pmatrix} \phi_a \\ \phi_b \end{pmatrix} \quad M^2 = m_a^2 \begin{pmatrix} 1 & \epsilon r(T) \\ \epsilon r(T) & r(T) \end{pmatrix}$$
$$m_a = \frac{\Lambda_a^2}{F} \quad r(T) = \frac{m_b^2(T)}{m_a^2} \quad \epsilon \simeq \frac{f}{F} \tag{12}$$

- $\Lambda_a = 160 \mathrm{MeV}$ (QCD scale), $\Lambda_b = 10^{-4} eV$, $m_b = \Lambda_b^2/f$.
- At $T = 0, m_b > m_a$. This implies $f << F$.
- Then some part of ϕ_a is converted into ϕ_b at $m_a = m_b(t_{LC})$. $\Gamma_{LC} \simeq \epsilon t_{LC}$ is the duration of this process.

Conversion between dark matter and dark energy

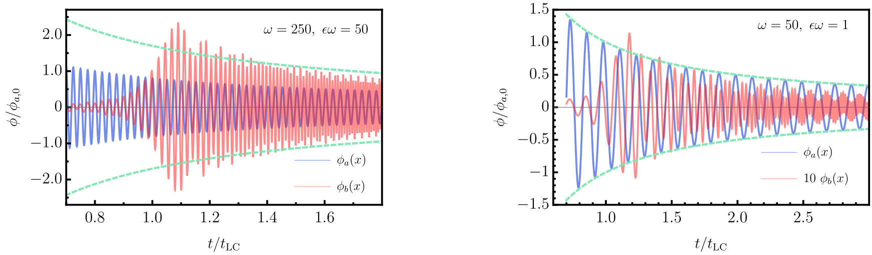

Figure 2: Difference between adiabatic ($m_a(\epsilon t_{LC}) >> 1$) and non-adiabatic $m_a(\epsilon t_{LC}) < 1$) level crossing.

The evolutionary history of the 2 axion system

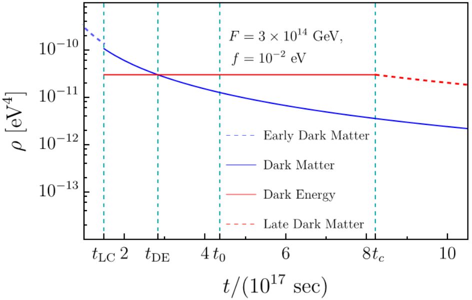

Figure 3: The cosmological evolution of dark energy and dark matter in the level crossing scenario.

The QCD axion scenario

There are several constraints in the QCD axion case:

1. Level crossing has to occur before matter-dark energy equality.

$$\epsilon \simeq \frac{f}{F} = \frac{\Lambda_b^2}{\Lambda_a^2}\frac{T_b^3}{T_{LC}^3} \lesssim 10^{-25}\left(\frac{\Lambda_b}{10^{-4}\mathrm{eV}}\frac{160\mathrm{MeV}}{\Lambda_a}\right)^2 \tag{13}$$

2. The PQ symmetries for both axions have to be broken at $T > T_{LC}$ implying $f \gtrsim 10^{-2}$ eV and $F \gtrsim 10^{14}$ GeV.
3. Pre-inflationary scenario with $m_a \lesssim 6 \times 10^{-8}$ eV and $\theta_a \lesssim 6\%$.
4. To reproduce DE at matter-DE equality only $1 - 2\%$ needs to be converted $\implies$ non-adiabatic regime.

A note on N_{eff}

- In minimal models G_a and G_b are not thermalized.
- The $g_a g_a \longleftrightarrow g_b g_b$ scattering suppressed by $m_\chi \simeq 10^{14}$ GeV.
- $\implies$ cold dark sector to alleviate constraints from N_{eff}.
- New DOF. :

$$\tilde{g} = 2N_g + \frac{7}{8}4N_c + 1. \tag{14}$$

- We have

$$\Delta N_{eff} = \frac{4}{7}\left(\frac{43}{427}\right)^{4/3} \tilde{g} \approx 0.38 \text{ (SU(2))}, \quad 0.74 \text{ (SU(3))} \tag{15}$$

- Entropy injection is needed.

Summary and implications for cosmology

- The two axion system can generate DE from DM and accommodate both.
- For the QCD axion a small conversion is needed. For axion-like particles this is not generally true.
- In this case dark energy may be dynamical: $w \neq \text{const.}$.
- It implies interaction between DE and DM and possibly clustering of DE.
- In some cases, it can imply early matter domination.

THANK YOUR FOR LISTENING!