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# Dark Energy from New Confining Force

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It is possible that a new confining force exists beyond the observed visible sector forces. If so, its connection to the visible sector is possible through gravitational interaction. One such hints is through dark energy in the universe, and here such a possibility is explored in case the condensation scale of the hidden-sector is known.

*Corfu Summer Institute 2022 "School and Workshops on Elementary Particle Physics and Gravity",*
*28 August - 1 October, 2022*
*Corfu, Greece*

*Speaker





PoS(CORFU2022)087

## 1. Introduction

Light pseudoscalar particles are most probably pseudo-Goldstone bosons of spontaneously broken global symmetry, which can be the lampposts to the road leading to physics scales much above their masses. The well-known example is the pion triplet which guided toward the chiral symmetry at the strong interaction scale [1, 2]. Another is the very light axion which hints the intermediate energy scale if the axion is responsible for dark matter in the universe [3, 4]. The scale where the symmetry manifests itself is for the pseudoscalar mass $m$ above $\Lambda$, where $\Lambda$ is the strong interaction scale. The potential of the pseudoscalar is a periodic function, and the maximum point of the potential of the pseudo-Goldstone boson is of order $\Lambda^4$: $\Lambda^4(1-\cos\frac{\Lambda}{f_\pi})$. For pions, $\Lambda$ is the strong interaction scale, and $f_\pi$ and the pion mass are around 140 MeV, with $f_\pi^2 m_\pi^2 \simeq \Lambda^4$.

If the very light axion represents dark energy (DE) of the universe *naturally* in terms of the QCD scale, the overall coefficient $\Lambda^4$ is expected to be of order the strong interaction scale. The current value of DE , $\approx (0.003\,\text{eV})^4$ [5]. If a combination of $X^2$ and $f_{\rm DE}^2$ can explain this small magnitude via the potential $X^4(1-\cos\frac{\langle a\rangle}{f_{\rm DE}})$, $X^4/f_{\rm DE}^2$ is the axion mass where $f_{\rm DE}$ is of the order the Planck scale, in which case $X$ must be very small. The situation is depicted in Fig. 1. How $X^4$ can

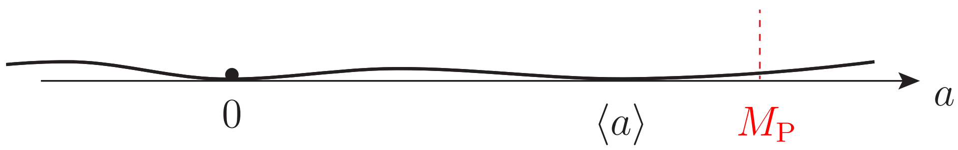


**Figure 1:** A schematic view of the periodic function, $\langle a\rangle = 2\pi n f_a, n = 0, \pm1, \pm2, \cdots$, on the limits of the axion mass and the decay constant [7]. The axion mass is given by the curvature at the minima.

be so small at the Planck or the grand unification scale is the question. Since it is difficult to explain this magnitude naturally, even an anthropic principle was invoked [6]. In Fig. 2, a schematic view on the current bounds on $m_a$ and $f_a$ are depicted. If the axion works as an inflaton, the point where the axion sits during inflation is shown as the red dashed line. Inflation ends when the axion starts to roll down the hill.

## 2. Quintessential Axions

If an axion realizes the above scenario, it is called 'quintessential axion'. Quintessential axion (QA) requires

- The decay constant $f_{\rm QA}$ is near the Planck scale, and
- The QA mass is near $10^{-32}$ eV.

Another parameter which is important in the gauge hierarchy problem is the scale around $10^{11} \sim 10^{13}$ GeV which is the confining scale of a hypothetical non-Abelian gauge group responsible

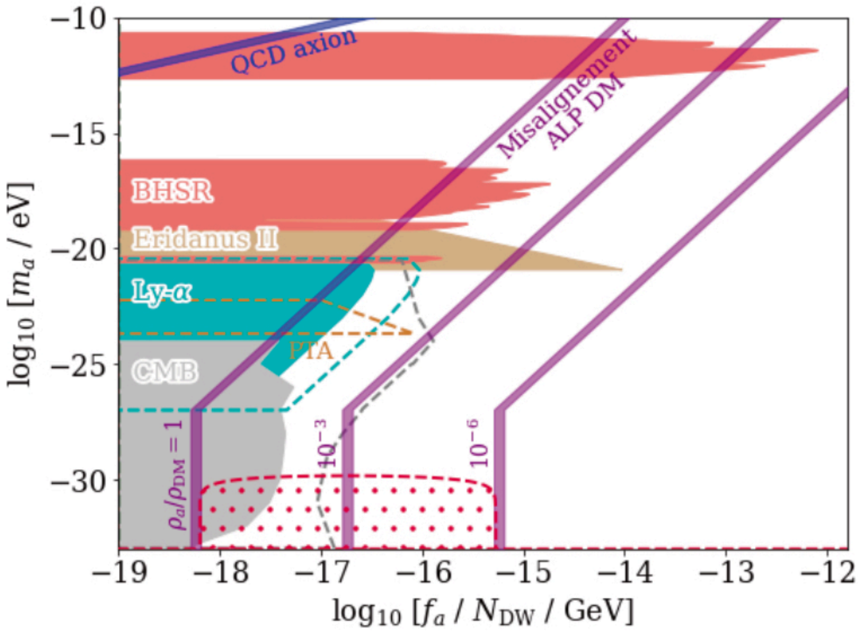


**Figure 2:** A schematic view on the limits of the axion mass versus the decay constant [7].

for supersymmetry breaking [8]. The responsible non-Abelian gauge force has two parameters, the confining scale $\Lambda$ of the hidden-sector quark $Q$ and the decay constant $f$ of the resulting pseudo-Goldstone boson multiplet $\Pi^a$,

$$\langle \overline{Q}_L (T^a)^i_j Q_L \rangle = \Lambda^3 e^{i(\Pi^a)^i_j/f} \tag{1}$$

where $f$ can be near or far away from the confining scale. Note that the octet mesons $\pi, K, \eta$ from the confining light quarks of QCD gives $f$ around 250 MeV. In supergravity, usually confining forces are introduced. For a new confining force example of Ref. [9], the gravitino mass to the confining scale is related as

$$m_{3/2} = \frac{\mu^3}{M_{\rm Pl}^2} \tag{2}$$

where $\mu$ is around the confining scale. For $m_{3/2}$ to be around the electroweak scale, $\mu$ has to be around $10^{13}$ GeV.

We attempt to use the above idea for the QA, the idea of which was introduced in [10]. However, we attempt to be more realistic by including another pseudo-Goldstone boson also, namely the QCD axion [3,4]. Then, the bound is given on the plane as shown in Fig. 4. Parametrizing the potential in terms of mass $m_Q$ of the hidden-sector quark, gravitino mass $m_{\tilde G}$ and the hidden-sector scale $\Lambda_h$, the vacuum energy

$$\lambda_h^4 \equiv m_Q^n m_{\tilde G}^N \Lambda_h^{4-n-N} \approx (0.003\,{\rm eV})^4 \tag{3}$$

is obtained for

$$\left(\frac{m_Q}{\Lambda_h}\right)^n \sim \begin{cases} 10^{-68}, & \text{for } SU(3)_h \\ 10^{-58}, & \text{for } SU(4)_h \\ 10^{-48}, & \text{for } SU(5)_h \end{cases} \tag{4}$$

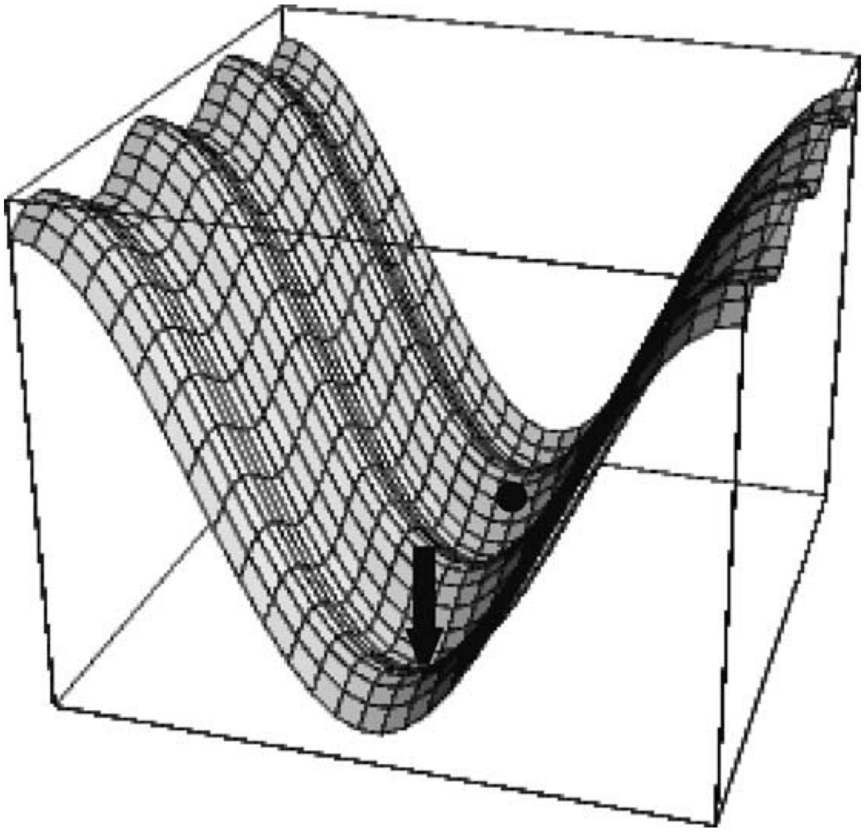

**Figure 3:** The axion potential on the plane of $m_a$($x$-axis) and $f_a$($y$-axis), which is a periodic function in $f_a$.

For $N = 4$, $m_Q \simeq 10^{-45}$ GeV, $10^{-16}$ GeV, $10^{-7}$ GeV, respectively, for $n = 1, 2$, and 3.

There have been many attempts to obtain this kind of almost flat potential, among which the closest cousin to the present talk is Ref. [11]. We try to explain not by ex-quark mass, but by the confining scale itself. Then, we have another reason for introducing a new confining force. Mesons have the adjoint representation of $SU(N)_A$ which is a subgroup of $SU(N)\times SU(N)$. Condensation is parametrized in Eq. (1). Without supersymmetry, we have Table 1, where $\sigma$ is the complex singlet housing the QA. Consistently with the discrete symmetry $\mathbf{Z}_{12}$, we have the following interaction term,

$$\frac{1}{M}\,\overline{Q}_L C^{-1} Q_L \sigma^{10}, \tag{5}$$

and a needed confining scale toward a correct order for the DE scale in a non-supersymmetric model is $\Lambda \simeq 2.9 \times 10^6$ GeV.

| | Representation under $\mathcal{G} \equiv SU(\mathcal{N})$ | SU$(N)_L$ | $\mathbf{Z}_{12}$ |
|---|---|---|---|
| $Q_L$ | $\mathcal{N}$ | $\mathbf{N}$ | +1 |
| $\overline{Q}_L$ | $\overline{\mathcal{N}}$ | $\overline{\mathbf{N}}$ | +1 |
| $\sigma$ | $\mathbf{1}$ | $\mathbf{1}$ | +7 |

**Table 1:** The $\mathbf{Z}_{12}$ quantum numbers of, the hidden-sector quarks $Q_L$ and $\overline{Q}_L$ and the complex singlet $\sigma$.

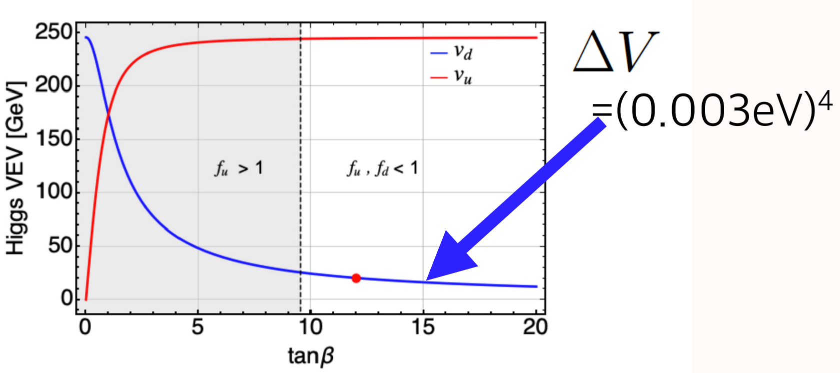


**Figure 4:** The saturated dark energy in terms of $\tan\beta$. The red curve is $v_u$ and the blue curve is $v_d$. The red bullet corresponds to $\tan\beta = 12$.

## 3. A model with supersymmetry

For supersymmetry, let us consider a superpotential which contains the quark condensation in the hidden sector and square of $(H_uH_d)$,

$$\Delta W = \frac{1}{M^{n+3}}\overline{Q}_L Q_L (H_uH_d)^2\sigma^n \tag{6}$$

where we determine $n$ by requiring that $\Delta W$ leads to the DE scale,

$$\frac{1}{M^{n+3}}\Lambda^3(v_uv_d)^2\langle\sigma\rangle^n = \frac{1}{M^{n+3}}\Lambda^3\frac{v_d^4}{\cos^4\beta}\langle\sigma\rangle^n \simeq (0.003\,\mathrm{eV})^4. \tag{7}$$

For $\langle\sigma\rangle \simeq 10^{12}$ GeV and $\Delta V = (0.003\,\mathrm{eV})^4$, $v_u$ and $v_d$ are shown for $\tan\beta$ in Fig. 4.

The model presented in Table 2 realizes the above scenario given in Eq. (7). We can write the

| | Representation under $\mathcal{G} \equiv SU(\mathcal{N})$ | $\mathrm{SU(2)}_W\times\mathrm{U(1)}_Y$ | $\mathbf{Z}_{6R}$ |
|---|---|---|---|
| $Q_L$ | $\mathcal{N}$ | $\mathbf{1}$ | $+1$ |
| $\overline{Q}_L$ | $\overline{\mathcal{N}}$ | $\mathbf{1}$ | $-1$ |
| $H_u$ | $\mathbf{1}$ | $\mathbf{2}_{+1/2}$ | $+3$ |
| $H_d$ | $\mathbf{1}$ | $\mathbf{2}_{-1/2}$ | $+2$ |
| $\sigma$ | $\mathbf{1}$ | $\mathbf{1}$ | $+4$ |
| $S$ | $\mathbf{1}$ | $\mathbf{1}$ | $+5$ |

**Table 2:** The $\mathbf{Z}_{6R}$ quantum numbers of the superfields.

superpotential terms having $\mathrm{U(1)}_R$ quantum numbers 2 modulo 6,

$$W = -\alpha\,\sigma S^2 + \frac{\varepsilon}{M}S^4 - \frac{x}{M^2}\sigma S^2 Q_L\overline{Q}_L + \cdots \tag{8}$$

Supersymmetry conditions

$$\frac{\partial W}{\partial\sigma} : Q_L\overline{Q}_L = -\frac{\alpha M^2}{x} \tag{9}$$

$$\frac{\partial W}{\partial S} : \ (x\frac{Q_L\overline{Q}_L}{M^2} + \alpha)\sigma = -\frac{2\varepsilon}{M}S^2 \tag{10}$$

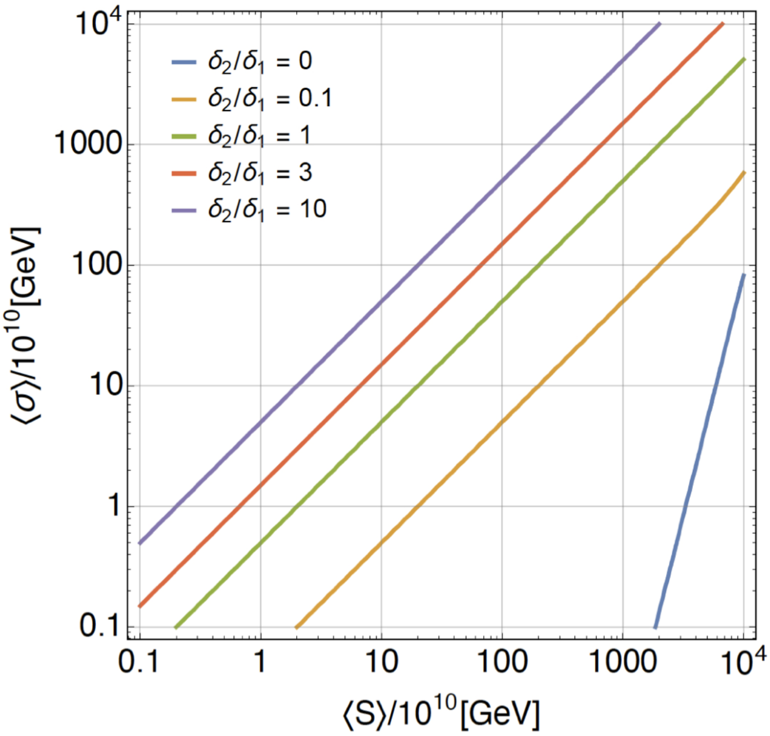


**Figure 5:** Two dark matters $\sigma$ and $S$.

do not lead to an acceptable solution. Since supersymmetry breaking is induced at the TeV scale by the source breaking supersymmetry dynamically above $10^{13}$ GeV, in Eqs. (9 ) – (11) we introduce TeV scale supersymmetry breaking parameters with coefficients $\delta_1$ and $\delta_2$,

$$-\alpha S^2 - \tfrac{x}{M^2} Q_L \overline{Q}_L + \delta_1 \Lambda^2 = 0, \tag{11}$$

$$-\alpha S\sigma - \tfrac{x}{M^2} S Q_L \overline{Q}_L \sigma + \delta_1 \Lambda^2 \tfrac{\sigma}{S} = 0, \tag{12}$$

$$2\alpha S^2 \sigma + 2\tfrac{\varepsilon}{M} S^4 + \left(\tfrac{\delta_2 S - 2\delta_1 \sigma}{2}\right) \Lambda^2 = 0. \tag{13}$$

In case two mark matters $\sigma$ and $S$ close the universe, Fig. 5 shows the allowed region of $\sigma$ and $S$.

And $f_{\rm DE}$ is not at the confining scale but near the Planck scale. Note, however, that in supersymmetric models condensation of scalar ex-quarks do not break supersymmetry. Therefore, the hidden-sector squark condensation scale, for example in Eqs. (11)–(13), can be nearer to the Planck scale without breaking supersymmetry.

Let us consider a general superpotential consistent with the symmetries of Table 2,

$$W = \Lambda X - \frac{1}{2M_{\rm P}} X^2 + \cdots \tag{14}$$

$$V = \left(\Lambda - \frac{1}{M_{\rm P}} X\right)^2 + \cdots \tag{15}$$

where $X$ is the hidden-sector squark condensation scale $Q_L \overline{Q}_L$ and dots are the higher order terms. In this case, the shape of this potential is depicted in Fig. 6. So, $f_{\rm DE}$ is expected at a median of $\Lambda$

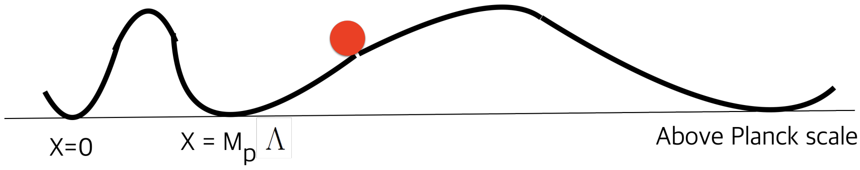


**Figure 6:** A schematic shape of the DE potential, where the hights of the maxima are the same.

and $M_{\rm P}$. For supersymmetry breaking effects to the SM superpartners, we need the $\mu$ term [12],

$$W_\mu = \frac{(10^{10}\,{\rm GeV})^2}{M_{\rm P}} H_u H_d. \tag{16}$$

Without $H_u H_d$ and $H_u H_d S$ terms, we can have a needed $\mu$ term with a leading superpotential term $W_\mu = \frac{\sigma S}{M} H_u H_d$ where $\langle\sigma\rangle$ and $\langle S\rangle$ VEVs are around $10^{10}$ GeV.

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