Axions across boundaries between Particle Physics, Astrophysics, Cosmology and forefront Detection Technologies

Axions: a short historical review. Recent results on quintessential axions from a new confining force as source of Dark Energy

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Dark Energy in the Universe

$$c.c = (3 \times 10^{-3}\ \mathrm{eV})^4$$

Why is c.c. this value?

Even anthropic principle is added!!

In 1987, S. Weinberg stated

"Our knowledge of the present expansion rate of the Universe indicates that the effective value of the cosmological constant is vastly less than what would be produced by quantum fluctuations' in any known realistic theory of elementary particles in view of the continued failure to find a microscopic explanation of the smallness of
the cosmological constant, it seems worthwhile to look for a solution in other, "anthropic",
directions. Perhaps Lambda must be small enough to allow the Universe to evolve to its present nearly empty and flat state because otherwise there would be no scientists to worry about it."

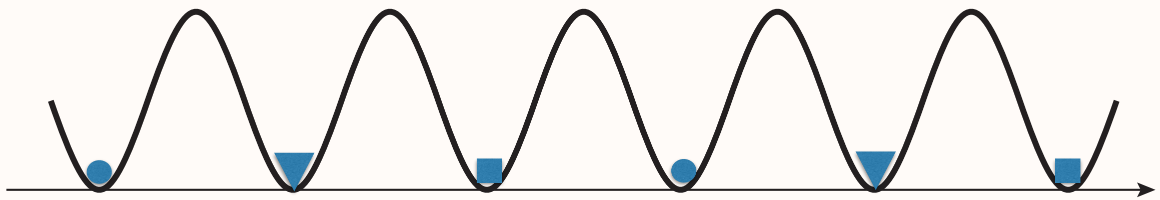
Weinberg suggested that energy of our universe be
less than 550 times the closing density,
for our Universe old enough as it is now.
But this is not in the phase of a complex field, which
makes it difficult to find a rationale.
If it is in the phase,
it may be easier to understand it.

C. N. Yang stated that
quantum mechanics is
“Phase symmetry”

QM operation is via unitary
operators exp{~ i times ***}, so
“Phase symmetry”

So, let us try to introduce it in terms of the simplest
"Phase symmetry": U(1)

Phase symmetry gives a periodicity.

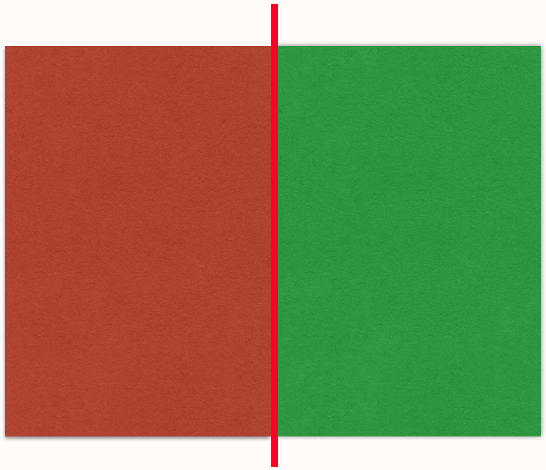


Periodicity is "domain wall number", N. In this case, three different vacua, N=3.

Out of discrete symmetric vacua, some vacuum is chosen in the evolution of the universe.

If a discrete symmetry is spontaneously broken as in this case, domain walls form in the evolving universe: Zeldovich, Kobrazev, Okun, Sov.Phys. JETP 40 (1974) 1

"Discrete symmetry is spontaneously broken—->Domain walls form"



It is disastrous in cosmology.

Only N=1 is allowed: Sikivie.

Another development is the discovery of instant solutions in non-Abelian gauge theories:

Belavin, Polyakov, Schwartz, Tyupkin, PLB 59 (1975) 85

This instant solution has led to

“SU(N) gauge theory—->has anomalous coupling to axion”

$$(a/2f)\,\varepsilon_{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$$

f is the decay constant. Usually, it comes from the VEV of some Higgs fields.

Roberto Daniele Peccei (1942 -2021) and Helen Quinn proposed a global symmetry in 1977 (the Peccei-Quinn symmetry). I heard the Peccei-Quinn symmetry for the first time from Helen Quinn at a Wednesday theory seminar at Fermilab in the middle of May (May 11 or 18, 1977), before their paper was published.

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

$Y=+1/2$

4 real components. 3 will be longitudinal modes of three gauge bosons, W, W, Z. The remaining one is Higgs boson h.

$Y=-1/2$

With one more doublet, one complex scalar doublet exists. With the PQ global symmetry, one light pseudoscalar exists: PQWW axion.

Its mass is

$$f_\pi^2 m_\pi^2 = (m_u + m_d)\langle \bar{u}u \rangle \,,$$

$$f_A^2 m_A^2 = [Z/(1+Z)^2]\, N^2 m_\pi^2 f_\pi^2 \,.$$

Or,

~ (QCD scale)/f_a

In fact, this expression is valid for the invisible axion also.
With f_a ~250 GeV, its mass is around O(1-10 keV). This could be easily found with its two photon decay mode. But, it was not.

So, $f_a > 10^{5\text{-}6}$ GeV with a singlet scalar was suggested for the invisible axion [Kim, 1979].

To have the anomalous coupling, we introduce one heavy quark Q, with N=1 [Kim, 1979].

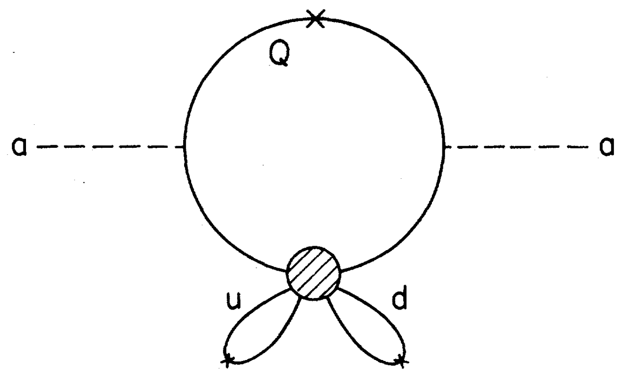


FIG. 2. Possible 't Hooft instanton interaction with a heavy quark.

The axion is the phase of the complex singlet.

In other words, a complex multiplet can have a SU(2)xU(1) invariant phase.
Two Higgs doublets can have two phases, outside the gauge symmetry. One phase turns out to be the quark number.
The other phase is toward axion [Peccei-Quinn(1977); Weinberg-Wilczek(1978)].

But, the resulting axion coupling is required to be, as we noted above, million times smaller. It requires that the VEV of the singlet is greater than 1000x1000 GeV. And from the red giants bound, the range of the singlet VEV is between

10^{9} GeV < singlet VEV < 10^{12} GeV.

So, the currently preferred value is about 5×10^{10} GeV, which is the geometric mean of the Planck mass and the EW scale.

This is the history toward the invisible axion:

(i) It is the heavy quark axion: KSVZ axion.

(ii) 6 quarks of the SM: DFSZ axion. So, N=6.
Resolution of this problem was studied by many.

$$H_u H_d S S$$

In any case, the axion is the phase of the PQ charge carrying singlet field S. To relate to the QCD anomaly, the KSVZ uses a heavy quark, and the DFSZ uses the SM quarks through the connecting coupling of S to two Higgs doublets, as given above.

It is attractive if an axion is present from the beginning.

Yes, historically, E8xE8' string model provided an example by the MI-axion.

The so-called 't Hooft mechanism is applied to the MI axion.

't Hooft mechanism:

If a gauge symmetry and a global symmetry are broken by one complex scalar by the BEHGHK mechanism, then the gauge symmetry is broken and a global symmetry remains unbroken.

Q_{gauge}	Q_{global}
1	1

Unbroken $X = Q_{global} - Q_{gauge}$

$$\phi \to e^{i\alpha(x)Q_{\rm gauge}} e^{i\beta Q_{\rm global}} \phi$$

the α direction becomes the longitudinal mode of heavy gauge boson. The above transformation can be rewritten as

$$\phi \to e^{i(\alpha(x)+\beta)Q_{\rm gauge}} e^{i\beta(Q_{\rm global}-Q_{\rm gauge})} \phi$$

Redefining the local direction as $\alpha'(x) = \alpha(x) + \beta$, we obtain the transformation

$$\phi \to e^{i\alpha'(x)Q_{\rm gauge}} e^{i\beta(Q_{\rm global}-Q_{\rm gauge})} \phi.$$

$$|D_\mu \phi|^2 = |(\partial_\mu - igQ_a A_\mu)\phi|^2_{\rho=0} = \frac{1}{2}(\partial_\mu a_\phi)^2 - gQ_a A_\mu \partial^\mu a_\phi + \frac{g^2}{2} Q_a^2 v^2 A_\mu^2$$
$$= \frac{g^2}{2} Q_a^2 v^2 (A_\mu - \frac{1}{gQ_a v}\partial^\mu a_\phi)^2$$

So, the gauge boson becomes heavy and there remains the x-independent transformation parameter beta. The corresponding charge is a combination:

$X = Q_{\rm global} - Q_{\rm gauge}$

The MI axion is 3-index tensor

$$H_{\mu\nu\rho} = M_{MI}\epsilon_{\mu\nu\rho\sigma}\,\partial^\sigma a_{MI}.$$

$$\frac{1}{2}\partial^\mu a_{MI}\partial_\mu a_{MI} + M_{MI}A_\mu\partial^\mu a_{MI}$$

This is the Higgs mechanism, i.e. a_{MI} becomes the longitudinal mode of the gauge boson. [JEK, Kyae, Nam, 1703.05345]

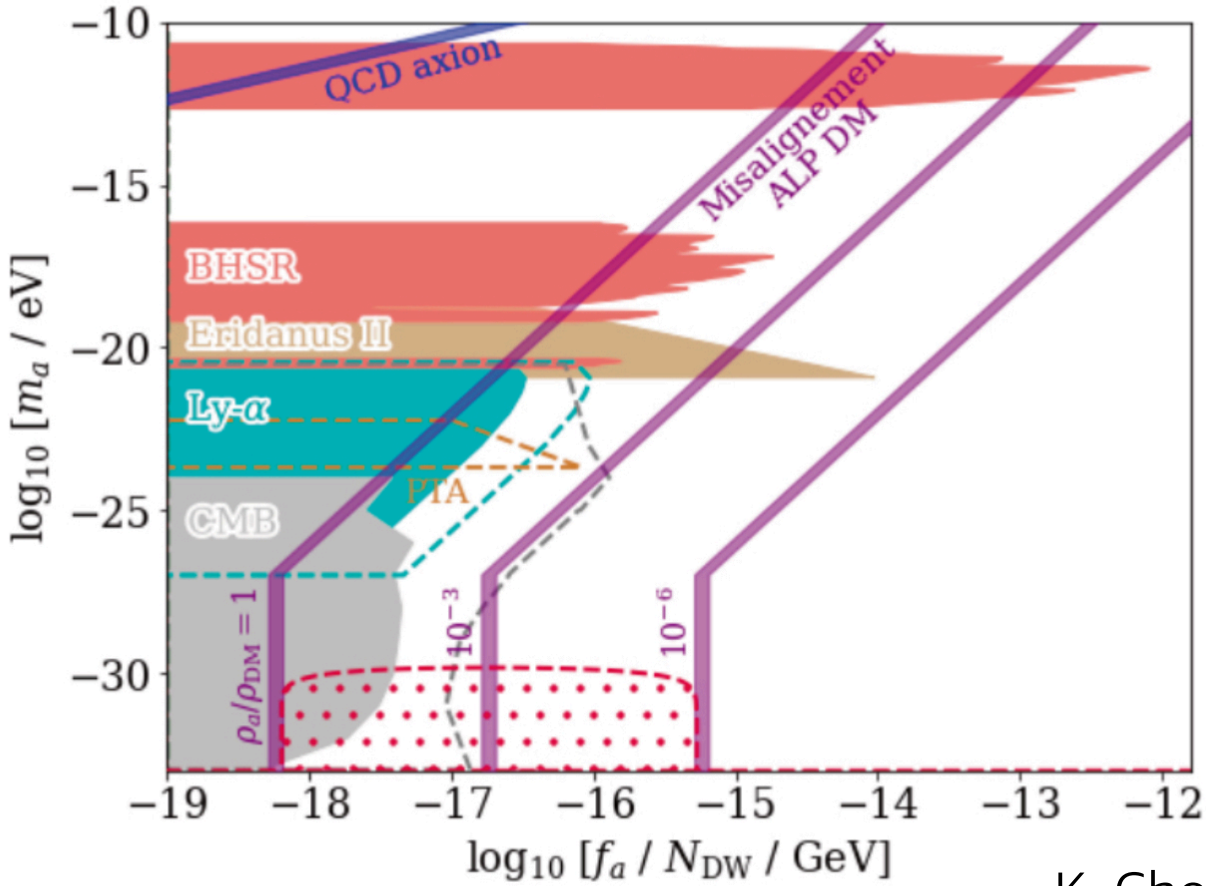
$$\frac{1}{2}(\partial_\mu a_{MI})^2 + M_{MI}A_\mu\partial^\mu a_{MI} + \frac{1}{2\cdot 3!}A_\mu A^\mu \to \frac{1}{2}M_{MI}^2(A_\mu + \frac{1}{M_{MI}}\partial_\mu a_{MI})^2.$$

It is the ’t Hooft mechanism working in the string theory. So, the continuous direction a_{MI} –> a_{MI} + (constant) survives as a global symmetry at low energy: “Invisible” axion!! appearing at $10^{10\text{-}11}$ GeV scale when the original global symmetry (of string) is broken by the VEV of some complex scalar.

This is the story on the QCD axion from string.

With this in mind, quintessential axions is required to satisfy [Sean Carroll]

- The decay constant is near the Planck scale
- QA mass is near 10^{-32} eV



K. Choi et al

FIG. 5: A summary of the axion scale $f_a/N_{\rm DW}$ versus axion mass from gravitational probes [18]. The shaded regions are excluded by the existing constraints, while the dashed lines show the sensitivities of future experiments. $f_a/N_{\rm DW}$ is identified as the field VEV $\langle a \rangle$ for ALP DM or DE.

Quark condensates from confining force

$$\langle \overline{Q}_L T^{a\,i}_j Q_L \rangle = \Lambda^3 e^{i\Pi^{a\,i}_j/f}$$

confining scale

Goldstone boson

confining scale

Mesons from light quarks in QCD

pi/K mesons and eta'

Octet
+singlet

f=250 MeV

Another parameter to mention is the confining force for SUSY breaking around

$$\Lambda = 10^{13}\ \text{GeV}$$

New Confining Force Example (fermion)

H. P. Nilles, Phys. Lett. B115, 193 (1982):
Dynamically Broken Supergravity and the Hierarchy Problem

S. Ferrara, L. Girardello, H. P. Nilles, Phys. Lett. B125, 457 (1982):
Breakdown of Local Supersymmetry Through Gauge Fermion Condensates

$$m_{3/2} = mu^3 / M^2 = \mathrm{TeV}$$

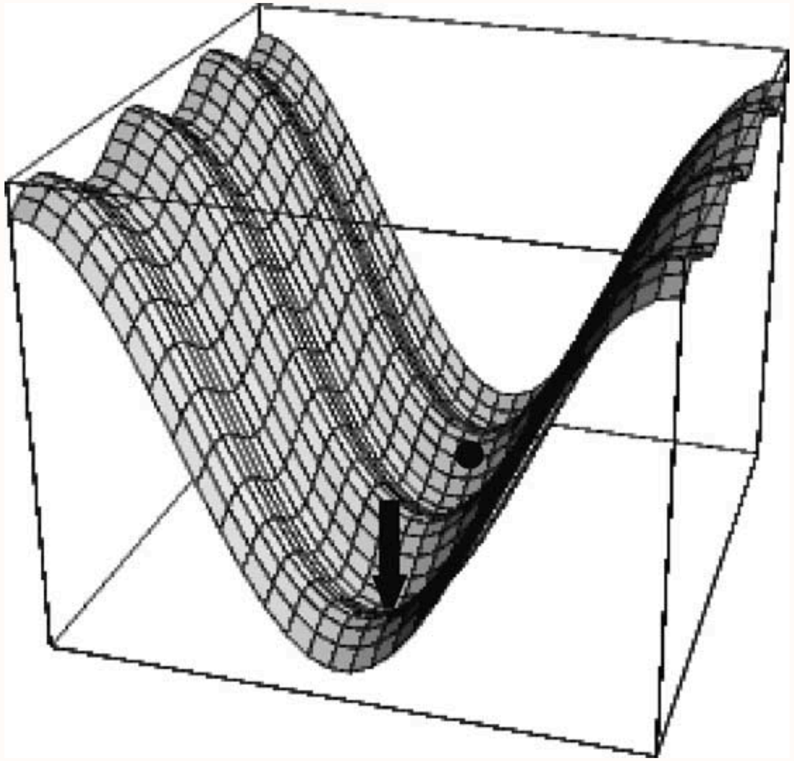
$$\Lambda = 10^{13}\ \mathrm{GeV}$$

Quintessential axion as a pseudoscalar

First introduced in,

JEK+Nilles, PLB 553, 1 (2003):

A quintessential axion



$$\lambda_h^4 \equiv m_Q^n m_{\tilde{G}}^N \Lambda_h^{4-n-N}, \tag{4}$$

where $\Lambda_h \simeq 10^{13}$ GeV is the hidden sector scale and $m_{\tilde{G}}$ is the hidden sector gaugino mass.

Let us now discuss some illustrative examples for the conditions between m_Q, n and N needed to account for the $(0.003\ \mathrm{eV})^4$ dark energy, assuming $m_{\tilde{G}} \simeq 1$ TeV,

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

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

M. Bronstein, Phys. Z. Sowjetunion 3 (1933) 73;
M. Özer, M.O. Taha, Nucl. Phys. B 287 (1987) 797;
B. Ratra, P.J.E. Peebles, Phys. Rev. D 37 (1988) 3406;
C. Wetterich, Nucl. Phys. B 302 (1988) 645;
H. Gies, C. Wetterich, hep-ph/0205226;
J.A. Frieman, C.T. Hill, R. Watkins, Phys. Rev. D 46 (1992) 1226;
R. Caldwell, R. Dave, P.J. Steinhardt, Phys. Rev. Lett. 80 (1998) 1582;
P. Binetruy, Phys. Rev. D 60 (1999) 063502;
C. Kolda, D.H. Lyth, Phys. Lett. B 458 (1999) 197;
T. Chiba, Phys. Rev. D 60 (1999) 083508;
P. Brax, J. Martin, Phys. Lett. B 468 (1999) 40;
A. Masiero, M. Pietroni, F. Rosati, Phys. Rev. D 61 (2000) 023504;
M.C. Bento, O. Bertolami, Gen. Relativ. Gravit. 31 (1999) 1461;
F. Perrotta, C. Baccigalupi, S. Matarrase, Phys. Rev. D 61 (2000) 023507;
A. Arbey, J. Lesgourgues, P. Salati, Phys. Rev. D 65 (2002) 083514.

Not by ex-quark mass, but by the scale itself. Then, we have another reason for introducing a new confining source. Mesons have the adjoint representation of $\mathrm{SU(N)}_{\mathrm{A}}$

$$\mathrm{SU}(N)_A \subset \mathrm{SU}(N)\times\mathrm{SU}(N)$$

Condensate is parametrized by and f,

$$\langle\overline{Q}_L T_j^{a\,i} Q_L\rangle = \Lambda^3 e^{i\Pi_j^{a\,i}/f}$$

Mesons from the new force provide DE.

A very small overall coefficient is needed.

Discrete symmetries may provide a rationale:

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

$$\frac{1}{M^9}\overline{Q}_L \mathcal{C}^{-1} Q_L \sigma^{10},$$

$$\Lambda \simeq 2.9 \times 10^6\,\mathrm{GeV}$$

may provide the small coefficient.

With SUSY

$$\Delta W = \frac{1}{M^{n+3}} \overline{Q}_L Q_L \left(H_u H_d\right)^2 \sigma^n .$$

Then, condensation of the hidden sector quark Q leads to the following VEVs from Eq. (7),

$$\frac{1}{M^{n+3}} \Lambda^3 (v_u v_d)^2 V^n = \frac{1}{M^{n+3}} \Lambda^3 \frac{v_d^4}{\cos\beta^4} V^n \simeq (0.003\,\mathrm{eV})^4$$

Of course, the reason HuHd is not added is from a discrete symmetry.

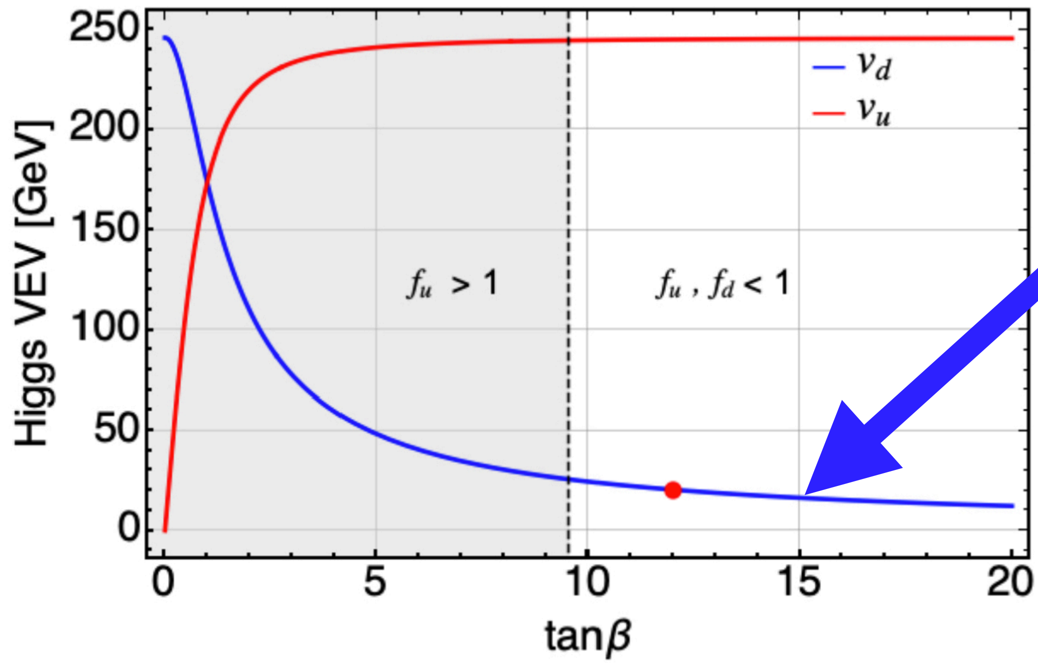


FIG. 1: Potential generated by Yukawa terms breaking $U(1)_{\mathrm{DE}}$. At the intersection of the blue curve and the $f_u = 1$ line, v_d is 25.6 GeV.

ΔV
$=(0.003\mathrm{eV})^4$

Model

	Representation under $\mathcal{G} \equiv$SU($\mathcal{N}$)	SU$(2)_W \times$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	$\mathbf{1}$	$\mathbf{2}_{-1/2}$	$+2$
σ	$\mathbf{1}$	$\mathbf{1}$	$+4$
S	$\mathbf{1}$	$\mathbf{1}$	$+5$

TABLE II: $\mathbf{Z}_{6R}$ quantum numbers of relevant chiral superfileds appearing

Here, we write W terms having $U(1)_R$ quantum number 2 modulo 6. SUSY conditions are

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

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

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

No acceptable solution.

So we add SUSY breaking effects parametrized by deltas. Then minima occur at

$$
\begin{aligned}
-\alpha S^2 - \frac{x}{M^2} S^2 Q_L \overline{Q}_L + \delta_1 \Lambda^2 &= 0, \\
-\alpha S\sigma - \frac{x}{M^2} S Q_L \overline{Q}_L \sigma + \delta_1 \Lambda^2 \sigma / S &= 0, \\
2\alpha\sigma S^2 + 2\frac{\varepsilon}{M} S^4 + \left(\frac{\delta_2 S - 2\delta_1 \sigma}{2}\right)\Lambda^2 &= 0.
\end{aligned}
$$

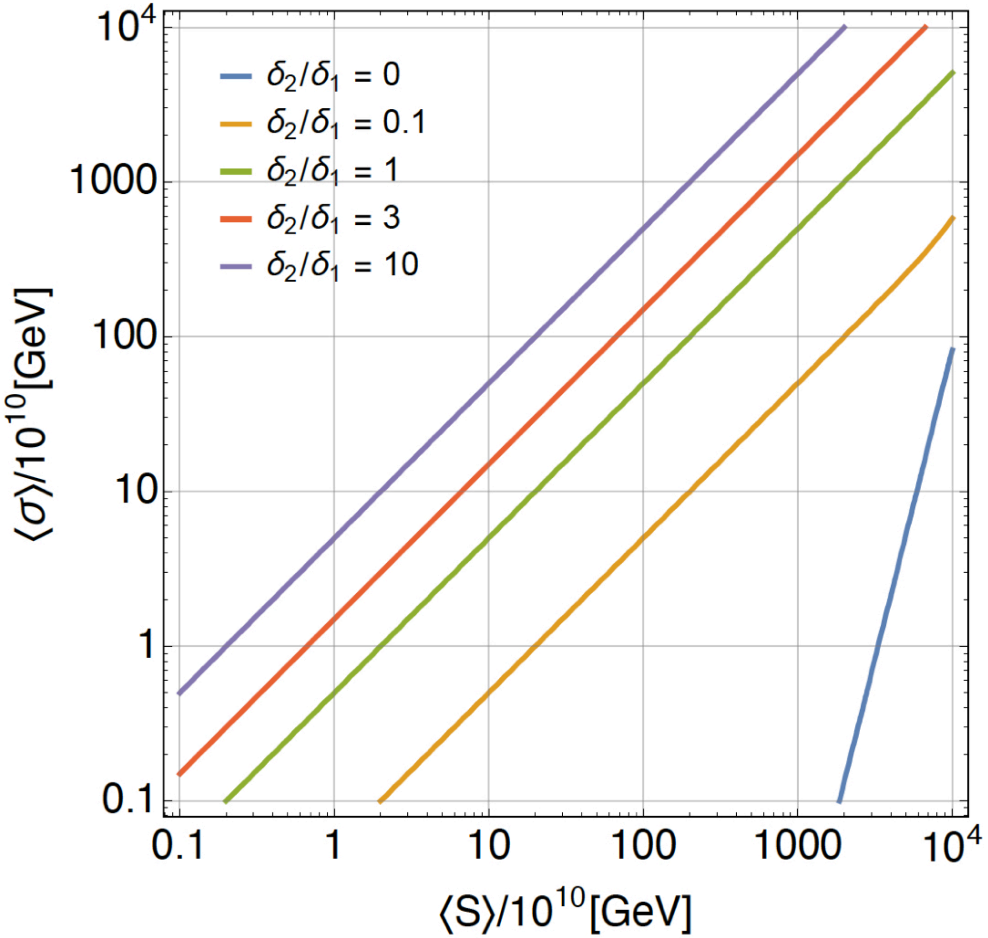


FIG. 2: Solutions of σ and S satisfying Eq. (2).

But f is near the Planck scale. Not at the confining scale.

In SUSY, condensation of scalar ex-quarks do not break SUSY. This scale can be nearer to the Planck scale.

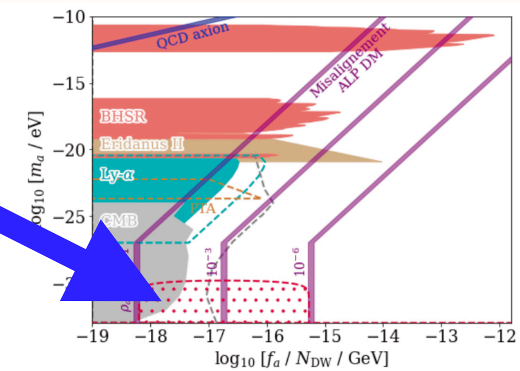


FIG. 5: A summary of the axion scale f_a/N_{DW} versus axion mass from gravitational probes [18]. The shaded regions are excluded by the existing constraints, while the dashed lines show the sensitivities of future experiments. f_a/N_{DW} is identified as the field VEV $\langle a \rangle$ for ALP DM or DE.

For SUSY breaking effects to the SM superpartners, we need the mu term

$$W_\mu = \frac{(10^{10}\ \mathrm{GeV})^2}{M}\, H_u H_d$$

J. E. Kim and H. P. Nilles, The problem and the strong CP problem, Phys. Lett.B 138 (1984) 150 [doi:10.1016/0370-2693(84)91890-2].

But, there should be no HuHd and HuHdS terms.

$$W_\mu = \frac{\sigma\, S}{M} H_u H_d$$

With <sigma> and <S> VEVs around 10^{10} GeV, we have a needed mu term.

Conclusion

I reviewed quintessential axion and introduced a new confining force for DE source.

Thanks for attention