Axions, Versatile Friends to Probe Beyond the Standard Model

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Outline

Strong CP Puzzle

Excess of the meson η’ mass

↓

Non-trivial Quantum Chromodynamic vacuum structure

CP violating electroweak processes

↓

Yukawa phases of Quarks-Higgs couplings

$$\delta\mathcal{L}_{CP} = (\theta_{QCD} - \text{Arg}\, Y_u - \text{Arg}\, Y_d)\frac{\alpha_S}{8\,\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

↑

Neutron Electric Dipole Moment experiment: $\bar{\theta} \coloneqq \theta_{QCD} - \text{Arg}\, Y_u - \text{Arg}\, Y_d < 10^{-10}$

How Yukawa phases speaks to Gluons:

$$\psi_L \to e^{+\frac{i\alpha}{2}}\psi_L$$
$$\psi_R \to e^{-\frac{i\alpha}{2}}\psi_R$$

$\Rightarrow$

$$\overline{\psi}_L\psi_R \to e^{i\alpha}\overline{\psi}_L\psi_R$$
$$+\delta\mathcal{L}_{Ano} \propto \alpha\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Chiral anomaly of fermions.

What about $SU(2) \times U(1)_Y$?

Strong CP Puzzle

Similar contributions for $SU(2) \times U(1)_Y$:

$$\delta\mathcal{L}_{CP} = \theta_{SU(2)} \frac{g^2}{16\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu} + \theta_{U(1)} \frac{g'^2}{16\pi^2} B_{\mu\nu}\tilde{B}^{\mu\nu} + \bar{\theta} \frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$U(1)_{\mathcal{L}+\mathcal{B}}$ is anomalous ⇒ rotate away

$U(1)_Y$ is trivial ⇒ Integrate by parts

How Yukawa phases speaks to Gluons:

$$\psi_L \to e^{+\frac{i\alpha}{2}}\psi_L \qquad \psi_R \to e^{-\frac{i\alpha}{2}}\psi_R$$

⇒

$$\overline{\psi}_L\psi_R \to e^{i\alpha}\overline{\psi}_L\psi_R \quad +\delta\mathcal{L}_{Ano} \propto \alpha\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Chiral anomaly of fermions.

$U(1)_{\mathcal{L}-\mathcal{B}}$ is not anomalous.
QCD operator cannot be removed.

How to Cook Axions (KSVZ type)

1. Consider ϕ with global $U(1)_{PQ}$ coupled to colored fermions:

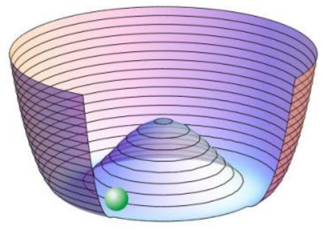
$$\mathcal{L}_{KSVZ} = \bar{\psi}_{L/R} i D \psi_{L/R} + y\phi\bar{\psi}_L\psi_R - \frac{G_{\mu\nu}G^{\mu\nu}}{4} - \bar{\theta}\,\frac{\alpha_S}{8\,\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + V(\phi^\dagger\phi)$$

2. $U(1)_{PQ}$ is chiral, hence anomalous:

$$\begin{aligned} \phi &\to e^{i\theta}\phi \\ \psi_L &\to e^{+i\theta}\psi_L \\ \psi_R &\to e^{-i\theta}\psi_R \end{aligned} \quad \Rightarrow \quad \begin{aligned} J^\mu &= \bar{\psi}\gamma^\mu\gamma^5\psi \\ \partial_\mu J^\mu &\propto G_{\mu\nu}\tilde{G}^{\mu\nu} \end{aligned}$$

3. Potential induces a spontaneous breaking:

$$\begin{aligned} \phi &= (\sigma + v)e^{ia/v} \\ \langle 0|J^\mu|a(p)\rangle &= i v p^\mu \end{aligned}$$



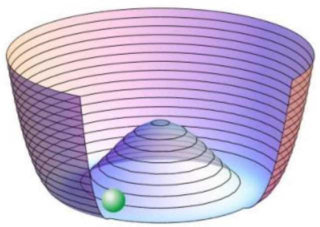
Axions have a shift invariance, up to the anomalous coupling.

$$\mathcal{L}_{KSVZ} = -\frac{G_{\mu\nu}G^{\mu\nu}}{4} + \frac{1}{v}\partial_\mu a\, J^\mu - \left(\bar{\theta} + \frac{a}{v}\right)\frac{\alpha_S}{8\,\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{1}{4} g^0_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$

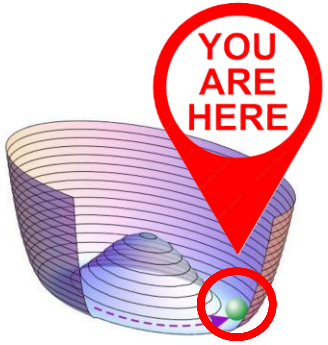
[Peccei,Quinn(1977), Weinberg(1978),Wilczek(1978)]

Axions Solves Strong CP

Below $\Lambda_{QCD} \Rightarrow$ contribution to axion's potential



$\Rightarrow$



$\langle a \rangle = 0$

$\langle a \rangle = -v\bar{\theta}$

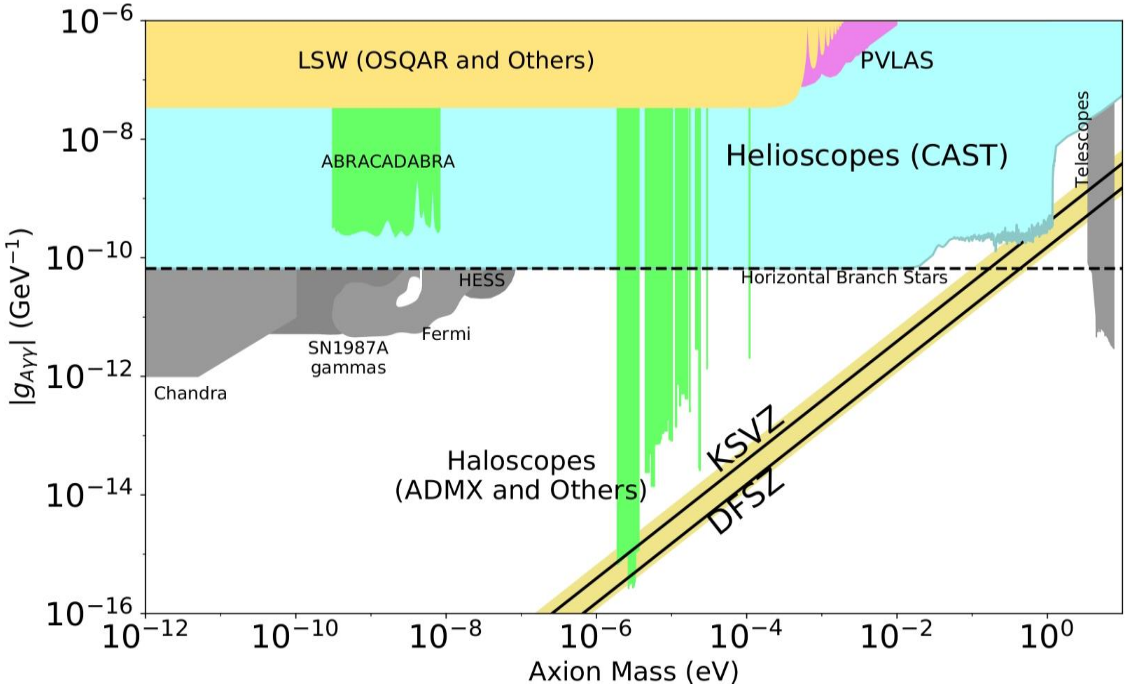
$$-\left(\bar{\theta} + \frac{a}{v}\right)\frac{\alpha_S}{8\,\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

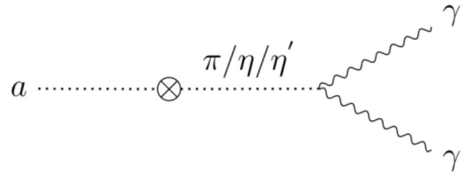
$$V_{eff}\left(\bar{\theta} + \frac{a}{v}, \pi, \eta, \ldots\right)$$

Mass computed from Chiral theory:

$$\frac{v^2 m_a^2}{f_\pi^2 m_\pi^2} = \frac{m_u m_d}{m_u + m_d}$$

[PDG 2019 (simplified)]





$$-\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} \propto aE\cdot B$$

$$g_{a\gamma\gamma} = g_{a\gamma\gamma}^{0} + g_{a\gamma\gamma}^{\pi,\eta,\eta'} \approx m_a 10^{-10\pm1}$$

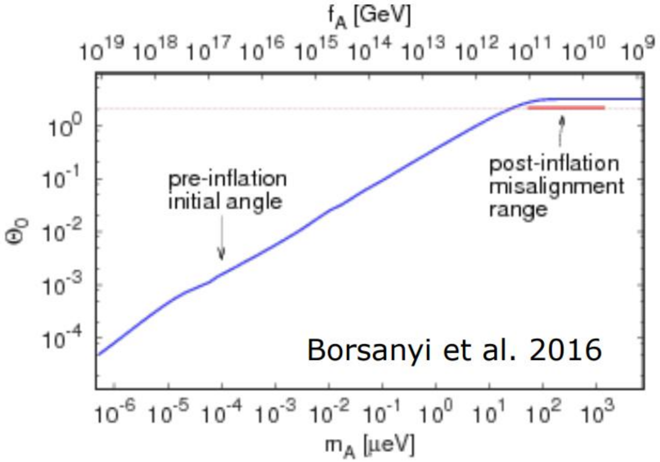
Axions as Cold Dark Matter

Axions production : misalignement mechanism.

Non-thermal production
⇒ Axions are cold.

Density of state depends on unknown θ_i:

$$n(T) \approx v m_a(T)\theta_i^2$$



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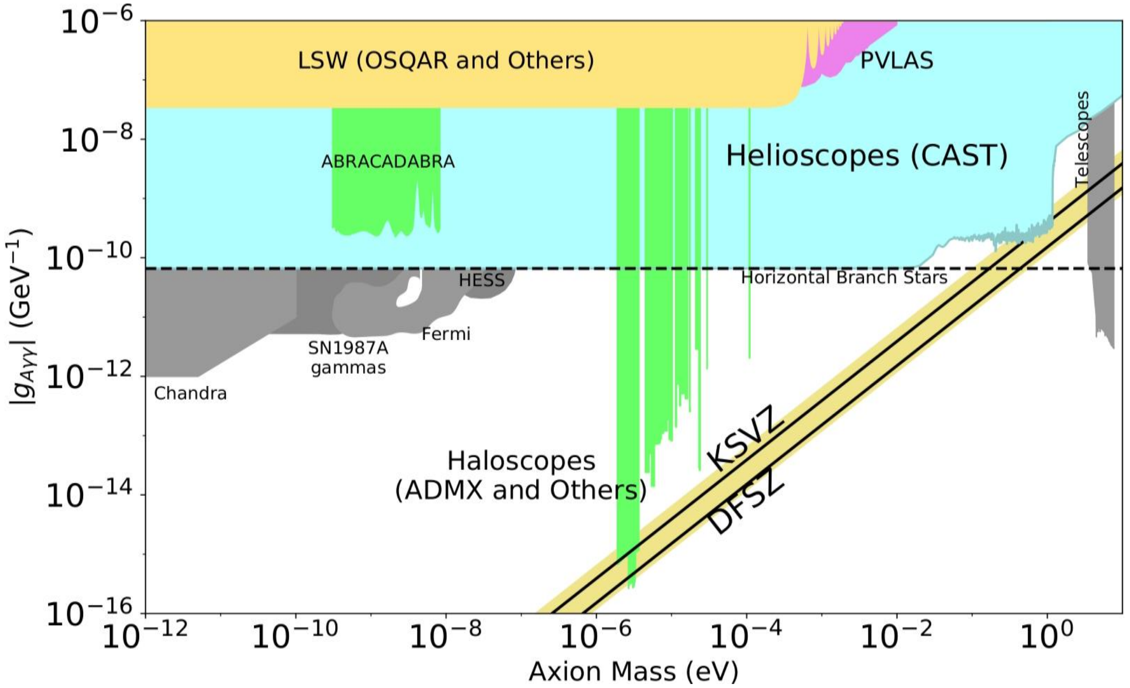
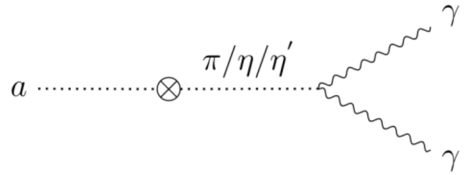




$$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \propto aE \cdot B$$

$$g_{a\gamma\gamma} = g^0_{a\gamma\gamma} + g^{\pi,\eta,\eta'}_{a\gamma\gamma} \approx m_a 10^{-10\pm 1}$$

Models of Invisible Axions

$$\phi = (\sigma + v)e^{ia/v}$$

One new scalar field, two path to reach SM:

KSVZ: $\phi\bar{\psi}_L\psi_R$

[Kim (1979), Shifman,Vainhstein,Zakharov (1980)]

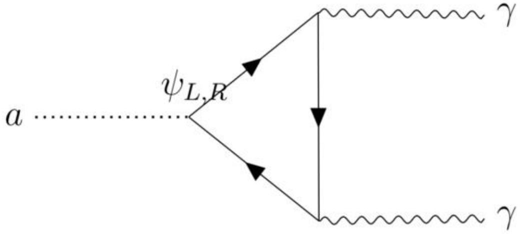
DFSZ: $\phi H_u^\dagger H_d$ $\quad v \gg v_{EW}$

[Dine,Fischer,Srednicky(1981), Zhitnitsky(1980)]

Small mixing of pseudo-scalar modes.

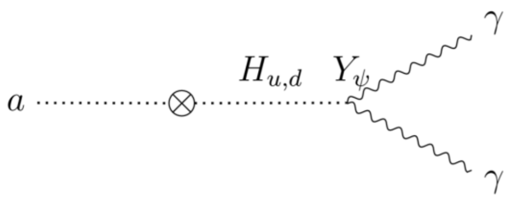
Coupling to SM by gauge bosons:

$$\frac{a}{16\pi^2 v}\sum_{X\in SM} g_X^2 N_X X_{\mu\nu}\tilde{X}^{\mu\nu}$$



Coupling to SM by left fermions:

$$\frac{a}{v}\sum_{\psi_L\in SM}\chi_\psi\bar{\psi}_L\gamma^5\psi_L$$



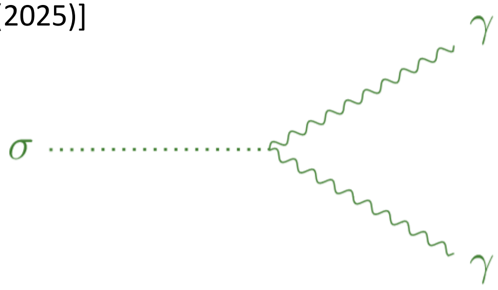
Extensions Beyond DFSZ/KSVZ

Beyond, many alternatives of models:

- QCD axions off the band:
  heavy (mirror QCD) or ultra light (Z_n-symmetry) axions, enlarging the band (many fields), …
  [Di Luzio, Mescia, Nardi (2016)] [Di Luzio, Gavela, Quilez, Ringwald (2021)] [Gaillard, Gavela, Houtz, Quilez, del Rey (2018)]
- DM axion off misalignment mass range:
  Only a fraction of DM, kinetic misalignement, topological defects, curvature-induced production,…
  [Co, Hall, Harigaya (2019)] [Marsch (review,2015)] [Eröncel, Gouttenoire, Sato, Servant, Simakachorn (2025)]
- Axion-like particles (no correlation of m_a and $g_{a\gamma\gamma}$):
  Do not solve Strong CP, but natural DM candidate and arise in string theory.
  [Ringwald (review, 2014)]

Space-Time Entanglement

Some models predicts axions and dilatons together (e.g. Einstein-Cartan gravity):
[Karananas, Shaposhnikov, Zell (2025)]



The dilaton phenomenology close to axions:

Scalar field weakly interacting,
May play a role in cosmological scenarios,[Banerjee, Csáki, Geller, Heller-Algazi, Ismail (2025)]
Goldstone with anomalous coupling to the gauge bosons. [Adler, Collins, Duncan (1977)]

$$J^\mu = x_\nu T^{\mu\nu}$$

$$\partial_\mu J^\mu = 2M_H^2(1+\gamma)|H|^2 + \sum_{X\in SM} \beta_X X_{\mu\nu}X^{\mu\nu}$$

[Coleman Callan Jackiw (1970)]

But space-time symmetries are much more involved:

Inverse Higgs constraint : 5 broken generators → 1 Goldstone, [Low, Manohar (2001)]
Current of the symmetry with explicit coordinates dependance,
⇒ Deriving effective theories consistently is tedious.

Mixing with $\mathcal{L}, \mathcal{B}$

Peccei-Quinn is a flavor symmetry which can naturally mix with $\mathcal{L}, \mathcal{B}$.

Breaking spontaneously $\mathcal{L}$ or $\mathcal{B}$ could explain matter asymetry.

Closeness of seesaw scale and v:
$\Rightarrow$ attemps to unite them with $\phi N_R N_R$.

[Dias,Machado, Nishi, Ringwald, Vaudrevange (2014)]

Cosmological role as DM candidate:
$\Rightarrow$ axions inducing baryogenesis ?

DM and baryonic relic densities are close $\Rightarrow$ motivates such models.

Baryon Violation

Baryogenesis requires B, L violating processes.
A naturally preferred mode ⇒ $\Delta B = 2$ models.

$$\mathcal{L} = \bar{n}(i\gamma^\mu \partial_\mu - m)n - \varepsilon(\bar{n}n^C + \bar{n}^C n) - \mu_n F^{\mu\nu}(\bar{n}\sigma_{\mu\nu}n)$$

[Mohapatra (1980)]

$$i\frac{d}{dt}\begin{pmatrix} n \\ n^C \end{pmatrix} = \begin{pmatrix} E & \varepsilon \\ \varepsilon & E^C \end{pmatrix}\begin{pmatrix} n \\ n^C \end{pmatrix}$$

Non-Relativistic description: 2 by 2 system with $\Delta E = 2\mu_n B$.

$$P_{n\to n^C}(t) = e^{-\Gamma t}\frac{\varepsilon^2}{\left(\frac{\Delta E}{2}\right)^2 + \varepsilon^2}\sin\left(t\sqrt{\left(\frac{\Delta E}{2}\right)^2 + \varepsilon^2}\right)^2.$$

- In quasi-free regime $t\Delta E \ll 1$: $P_{n\to n^C}(t) \approx e^{-\Gamma t}(\varepsilon t)^2$,
- Energy splitting is hard to minimize,
- Current bound: $\varepsilon \leq 0.8 \times 10^{-23} eV$.

[ILL,Grenoble (1994)]

Dark Matter Enhanced Oscillations

Baryonic Dark Matter: $\lambda\phi\bar{n}^C n \Rightarrow$ dynamical parameter.

$$\varepsilon \to \varepsilon(t) = \varepsilon_0 \sin m_\phi t$$

$$i\frac{d}{dt}\begin{pmatrix} n \\ n^C \end{pmatrix} = \begin{pmatrix} E & \varepsilon(t) \\ \varepsilon(t) & E^C \end{pmatrix}\begin{pmatrix} n \\ n^C \end{pmatrix} \quad \Rightarrow \quad P_{n\to n^C}(t) = e^{-\Gamma t}\frac{\varepsilon_0^2}{\left(\frac{\Delta E - m_\phi}{2}\right)^2 + \varepsilon_0^2}\sin\left(t\sqrt{\left(\frac{\Delta E - m_\phi}{2}\right)^2 + \varepsilon_0^2}\right)^2.$$

Rabi Resonance at $\Delta E = m_\phi$:

[Rabi (1937)]

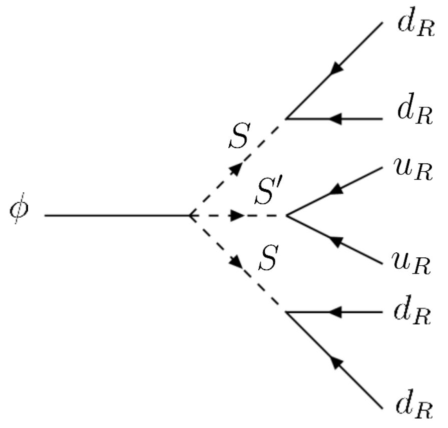
$$P_{n\to n^C}(t) = e^{-\Gamma t}\sin(t\varepsilon_0)^2.$$

[Smith,TB (2024)]

- Convert 50% of the neutrons ?!
- From $\mu_n = 6.02 \times 10^{-8} eV.T^{-1}$, $m_\phi \sim 1\mu eV \Rightarrow B \approx 16T$,
- Tuning at the precision of ε_0 …
- The ILL measurements give a bound : $P_{n\to n^C}(t) \approx e^{-\Gamma t}\left(\frac{\varepsilon_0}{m_\phi}t\right)^2$, $\varepsilon_0 \leq 10^{-15} eV$
- Well choosen magnetic field may improve the constraint.

Axionic Couplings to Baryonicity

Two $(\Delta B, \Delta L) = (2{,}0)$ couplings in SM:



[Arias-Aragón,Smith(2022)]

Identify Baryonic and Peccei-Quinn using Diquarks.

$U(1)_{PQ} = U(1)_B$: $\mathcal{L}_{eff} \supset -\varepsilon_S \phi \bar{n} n^C - \varepsilon_P \phi \bar{n} \gamma^5 n^C$

SSB of Baryonic number, axion = « baryonon »:

$$\mathcal{L}_{eff} \supset -e^{ia/v}(m_S \bar{n} n^C + m_P \bar{n} \gamma^5 n^C)$$

Dominant contribution is constant: $ve^{ia/v} = (v + ia + \cdots)$

$$\mathcal{L}_{linear} \supset -i\frac{a}{v}(m_S \bar{n} n^C + m_P \bar{n} \gamma^5 n^C)$$

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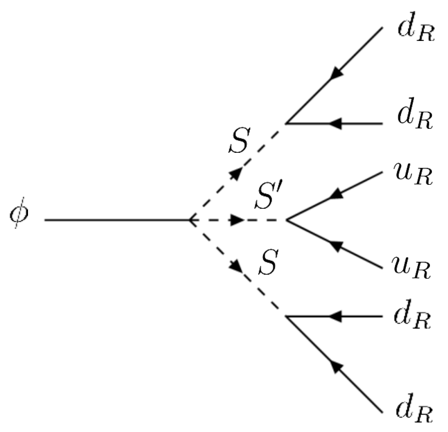

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$$\mathcal{L}_{linear} \supset -i\frac{a}{v}(m_S \bar{n} n^C + m_P \bar{n} \gamma^5 n^C)$$

Parity odd (γ^5) couplings are technically challenging for Non-Relativistic reduction.

Derivative Coupling in Oscillations

$$\mathcal{L} \supset -e^{ia/v}(m_S \bar{n} n^C + m_P \bar{n}\gamma^5 n^C)$$

Field redefinition

Baryonic current is ΔB=0 !

$$\mathcal{L} \supset -(m_S \bar{n} n^C + m_P \bar{n}\gamma^5 n^C) + \frac{1}{v}\partial_\mu a(\bar{n}\gamma^\mu n) + (\delta\mathcal{L}_{Ano})$$

$U(2)$ diagonalization with Weyl rotations

$O(3)$ mixing with ΔB=2 currents

$$\mathcal{L} \supset -\varepsilon(\bar{n} n^C + \bar{n}^C n) + \frac{1}{v}\partial_\mu a(\bar{n}\gamma^\mu n + \varepsilon_+ \bar{n}^C \gamma^\mu \gamma^5 n + \varepsilon_- \bar{n}\gamma^\mu\gamma^5 n^C) + (\delta\mathcal{L}_{Ano})$$

Can be turned off!

Coupling to axion wind, in oscillations description:

$$\varepsilon(t) = \frac{\varepsilon_\pm}{v}\vec{\nabla} a = \frac{m_a \varepsilon_\pm v_{DM}}{v}\sin(m_a t)$$

Extra derivative in the coupling:
Signal for QCD axions way too small.

What about other probes : Solar axions, Binary systems, …

[Smith,TB (2024)]

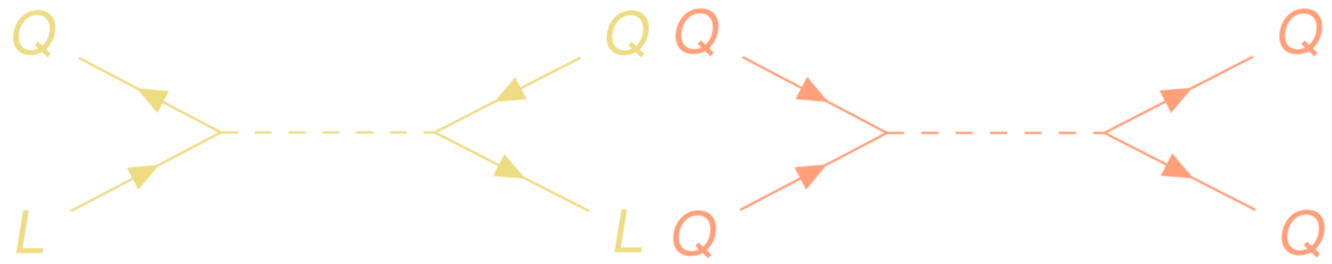
Conclusion

- Resonances from DM is relevant for future neutron experiments,
- Baryonic QCD axion requires another probe, what source would be best ?
- The formalism fits to Leptogenesis by identifying axion to majoron,
- Hints of Baryonic/Leptonic Dark Matter would motivate the investigations.

Thank you for your attention!

Leptoquark and Diquarks : mediators of B-violation

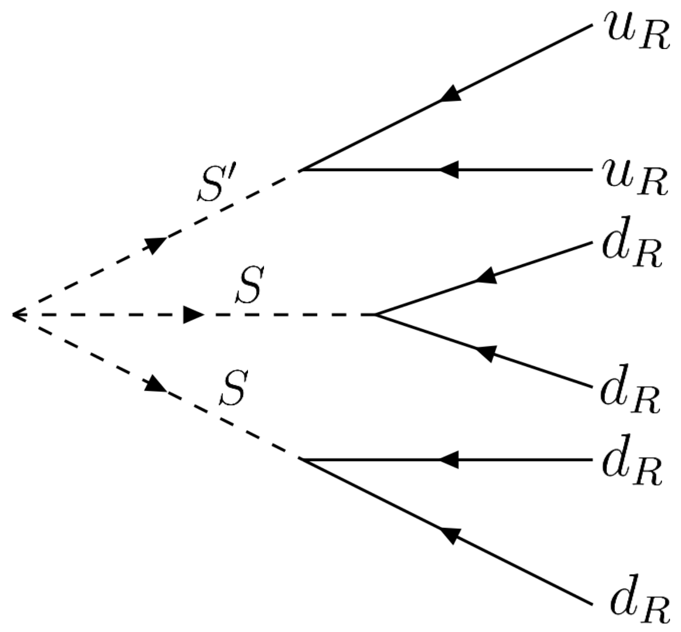
Leptoquark and Diquark are mediating Fermi interactions to colored pairs of Quark/Lepton. They arise naturally in some theories (SUSY).



They are classified according to their SM charges and carry Leptonic/Baryonic Number.

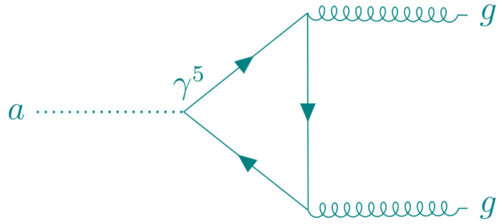
They can be used to construct (ΔB,ΔL) = (2,0) couplings.

On the right : scalar coupling, requiring 2 di-quarks.



Reparametrization Invariance

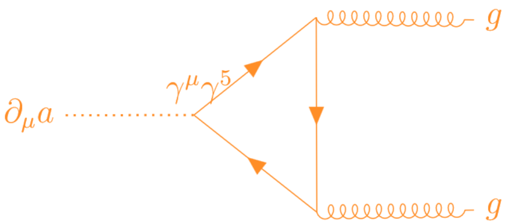
In the UV, CPV gauge coupling is not always explicit:

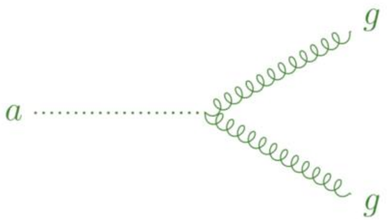


$$\mathcal{L}_{Polar} = -\frac{G_{\mu\nu}G^{\mu\nu}}{4} - \bar{\theta}\,\frac{\alpha_S}{8\,\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \bar{\psi} i D \psi + m\bar{\psi} e^{i\gamma^5 a/v}\psi$$

Change variables to make the fermions PQ invariant $\psi \to e^{i\gamma^5 a/2v}\psi$:

$$\partial_\mu \bar{\psi}\gamma^\mu\gamma^5\psi = im\bar{\psi}\gamma^5\psi + \frac{\alpha_S}{8\,\pi} G_{\mu\nu}\,\tilde{G}^{\mu\nu}$$





$$\mathcal{L}_{Der} = -\frac{G_{\mu\nu}G^{\mu\nu}}{4} - \left(\bar{\theta} - \frac{a}{v}\right)\frac{\alpha_S}{8\,\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \bar{\psi} i D \psi + m\bar{\psi}\psi + \frac{1}{2v}\partial_\mu a\, J^\mu$$

[Quevillon Smith (2019)]