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The axion flavour connection

L.Darmé, E.Nardi, C.Smarra

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Speaker: Clemente Smarra

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Outline

- Strong CP problem in one slide
- Benchmark axion solutions:
  - Focus on the origin and ~~quality~~ (phew...see Giacomo's talk) issues
- The Axion-Flavour connection
  - Cook our recipe: a simple (simplistic?) realisation

Strong CP problem

- The QCD Lagrangian contains a CP-violating term

$$\mathcal{L}_{QCD} = \sum_f \bar{\psi}_f (i\not{D} - m_f)\psi_f - \frac{1}{4}(G_{\mu\nu}, G^{\mu\nu}) + \theta \frac{1}{32\pi^2}(G_{\mu\nu}, \tilde{G}^{\mu\nu})$$

- However, experimental bounds indicate that, in strong interactions, $\theta \lesssim 10^{-10}$
- How can we explain this ? Anthropic reasoning? No..
  - Mechanism that constrains or drives it to 0.

$\theta \lesssim 10^{-10}$

Benchmark Axion Models

- Different ways of implementing the PQ mechanism can be organised in three large classes:
  - The Peccei-Quinn-Weinberg-Wilczek (PQWW) model.
  - The Dine-Fishler-Srednicki-Zhitnitsky (DFSZ) model;
  - The Kim-Shifman-Vainshtein-Zakharov (KSVZ) model.

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PQWW Model

- In the PQWW model, the SM is extended by adding a new complex scalar, namely a second Higgs doublet. The Lagrangian contains:

$$\mathcal{L} \supset -y_u \bar{q}_L H_u u_R - y_d \bar{q}_L H_d d_R - V(H_u, H_d) + \text{h.c.}$$

$$V = \frac{\lambda_u}{4}\left(|H_u|^2 - \frac{v_u^2}{2}\right)^2 + \frac{\lambda_d}{4}\left(|H_d|^2 - \frac{v_d^2}{2}\right)^2 + \lambda_{ud}\left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right) + \ldots$$

- One could naively say that, since there are two Higgs fields, there are two independent symmetries, which can be redefined to obtain the hypercharge and an orthogonal accidental Peccei-Quinn symmetry. Is it true? NO!

PQWW Model

- The general two Higgs doublet model potential, in fact, can be written as

$$
\begin{aligned}
V(H_u, H_d) = {} & m_u^2 H_u^\dagger H_u + m_d^2 H_d^\dagger H_d - \left[\cancel{m_{ud}^2 H_u^\dagger H_d + \text{h.c.}}\right] + \frac{1}{2}\lambda_1 \left(H_u^\dagger H_u\right)^2 + \\
& + \frac{1}{2}\lambda_2 \left(H_d^\dagger H_d\right)^2 + \lambda_3 \left(H_u^\dagger H_u\right)\left(H_d^\dagger H_d\right) + \lambda_4 \left(H_u^\dagger H_d\right)\left(H_d^\dagger H_u\right) + \\
& + \left[\cancel{\frac{1}{2}\lambda_5 \left(H_u^\dagger H_d\right)^2} + \cancel{\lambda_6 \left(H_u^\dagger H_u\right)\left(H_u^\dagger H_d\right)} + \cancel{\lambda_7 \left(H_d^\dagger H_d\right)\left(H_u^\dagger H_d\right)} + \text{h.c.}\right],
\end{aligned}
$$

- Therefore, if we want a PQ symmetry, we must *impose* that some terms are absent. *No accidental PQ symmetry*

ACHTUNG!

In general, all the afore-mentioned axion models DO NOT feature an accidental PQ symmetry.

But why do we focus on the fact that the PQ symmetry is not accidental? For two reasons:

- Global symmetries are widely believed not to be fundamental in QFT;
- Being anomalous, $U(1)_{PQ}$ is not a symmetry of the quantum world.

Origin and quality of the PQ symmetry

Therefore, we should account for the origin of the PQ symmetry. It would be desirable that it came accidentally, as a result of imposing “sacred” principles: Lorentz and gauge invariance

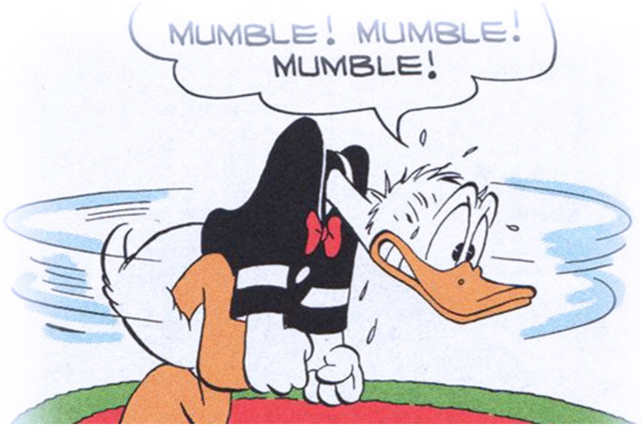
Moreover, experimental bounds constrain $\theta \lesssim 10^{-10}$, so our symmetry must be highly protected. This is commonly referred to as the PQ quality issue.

Origin and quality of the PQ symmetry

Various constructions that enforce a high quality, accidental PQ symmetry have been proposed, but they all rely on imposing the dimension of the first PQ breaking operator by hand

Not satisfying..

Thus, we need a mechanism that enforces a high quality, accidental PQ symmetry without imposing any condition by hand



The Flavour puzzle

On a completely different note, the fermion mass hierarchy problem represents one among the most puzzling features of the Standard Model. In two lines, there is a 5 order of magnitude difference between the Yukawa couplings of the top quark and of the up quark.

The Axion Flavour connection: a top-down approach

- We will assume that the SM flavour pattern is generated by a SB flavour symmetry, which will be identified requiring that
  - It must automatically enforce an *accidental* global anomalous PQ symmetry
  - It must protect $U(1)_{PQ}$ up to a sufficiently large operator dimension
- Then, we will analyse whether it reproduces, upon SSB, the observed pattern of quark mass hierarchies.

The Axion Flavour Connection: Rectangular symmetries

- Let us consider the following examples of flavour symmetries:
  - : Y in the bifundamental, *det(Y)* is PQ-violating;
  - $SU(N)_L \times SU(N)_R$:Y in the bifundamental, no *det(Y)*

    $SU(M)_L \times SU(N)_R M \neq N$
- Therefore, rectangular symmetries are more effective, as for the *quality* issue

The Axion Flavour Connection: Model Building

- *Simplicity:* simplest consistent gauge group and smallest number of fermions;
- *Phenomenology:*
  - Masses: top mass at tree level from renormalizable coupling to Higgs. Up and charm from effective operators
  - Mixings: field content sufficiently rich to generate all the masses and mixings of the quarks
- *Gauge anomalies:* gauge symmetries must be anomaly free
- *PQ origin and quality:* accidental and highly protected PQ symmetry

Cook our recipe: a simple realisation

- The "simplest" model complying with all these requirements is a 2HDM containing 6 scalars (X Y, Z, K, Hu, Hd) and a 7x7 fermion mass matrix, transforming under the G_{SM} x G_F x $U(1)_F$ gauge group, where G_F = SU(3) x SU(2)

$$q_L \sim (\mathbf{3},\mathbf{1}),\ u_R \sim (\mathbf{1},\mathbf{2}),\ t_R \sim (\mathbf{1},\mathbf{1}),\ Q_L \sim (\mathbf{1},\mathbf{1})$$
$$U_R \sim (\mathbf{3},\mathbf{1}),\ U_L \sim (\mathbf{1},\mathbf{2}),\ T_L \sim (\mathbf{1},\mathbf{1}),\ Q_R \sim (\mathbf{1},\mathbf{1})$$

- The most general G_F invariant mass matrix is

$$\begin{array}{c} \begin{matrix} u_R & u_R & t_R & U_R & U_R & U_R & Q_R \end{matrix} \\ \mathcal{M}_u = \begin{pmatrix} 0 & 0 & 0 & v & 0 & 0 & z_1 \\ 0 & 0 & 0 & 0 & v & 0 & z_2 \\ 0 & 0 & 0 & 0 & 0 & v & z_3 \\ 0 & 0 & v & 0 & 0 & 0 & M \\ \Lambda_u & 0 & x_1^* & y_1^* & 0 & 0 & 0 \\ 0 & \Lambda_u & x_2^* & 0 & y_2^* & 0 & 0 \\ x_1 & x_2 & \Lambda_t & z_1^* & z_2^* & z_3^* & v \end{pmatrix} \begin{matrix} q_L \\ q_L \\ q_L \\ Q_L \\ U_L \\ U_L \\ T_L \end{matrix} \end{array}$$

How to construct a (failing) model

- Under G_F = SU(3)xSU(2) we consider:

$$q_L \sim (\mathbf{3},\mathbf{1}), \quad u_R \sim (\mathbf{1},\mathbf{2}), \quad t_R \sim (\mathbf{1},\mathbf{1}),$$
$$U_R \sim (\mathbf{3},\mathbf{1}), \quad U_L \sim (\mathbf{1},\mathbf{2}), \quad T_L \sim (\mathbf{1},\mathbf{1}).$$

$$Y \sim (\mathbf{3},\bar{\mathbf{2}}), \quad Z \sim (\mathbf{3},\mathbf{1}), \quad X \sim (\mathbf{1},\bar{\mathbf{2}})$$

seesaw structure

3 light and 3 heavy eigenstates

non-vanishing determinant

$$\begin{array}{c} \quad u_R \;\; u_R \;\; t_R \;\; U_R \;\; U_R \;\; U_R \\ \mathcal{M} = \begin{pmatrix} 0 & 0 & 0 & v & 0 & 0 \\ 0 & 0 & 0 & 0 & v & 0 \\ 0 & 0 & 0 & 0 & 0 & v \\ \Lambda_u & 0 & x_1^* & y_1^* & 0 & 0 \\ 0 & \Lambda_u & x_2^* & 0 & y_2^* & 0 \\ x_1 & x_2 & \Lambda_t & z_1^* & z_2^* & z_3^* \end{pmatrix} \begin{matrix} q_L \\ q_L \\ q_L \\ U_L \\ U_L \\ T_L \end{matrix} \end{array}$$

$$\det(\mathcal{M}) = v^3 \Lambda_u \left[|X|^2 - \Lambda_t \Lambda_u \right]$$

How to construct a (failing) model

- From the determinant we can read off which operators must be allowed by $U(1)_F$
- We can read off th

$$\mathcal{L} \supset \bar{q}_L H_u U_R + \Lambda_u \bar{U}_L u_R + \begin{cases} \Lambda_t \bar{T}_L t_R & \text{or} \\ \bar{T}_L X u_R + \bar{U}_L X^\dagger t_R \end{cases}$$

$$q_L - U_R = H_u,\ U_L - u_R = 0,\ \begin{cases} T_L - t_R = 0 & \text{or} \\ T_L - u_R = t_R - U_L = X \end{cases}$$

- and compute the

$$\mathcal{A} = 3q_L - 2u_R - t_R + 2U_L + T_L - 3U_R$$

How to construct a (failing) model

- Substituting the charges, the anomaly yields

$$\mathcal{A} = \begin{cases} 3H_u + (T_L - t_R) = 3H_u & \text{or} \\ 3H_u + (T_L - u_R) + (U_L - t_R) = 3H_u \end{cases}$$

- If down-sector replicates the same structure, then

$$\mathcal{A} = 3(H_u + H_d)$$

- $U(1)_F$: $\mathcal{A}_F = 0 \quad F_{H_u} = -F_{H_d}$
- $U(1)_{PQ}$: $\mathcal{A}_{PQ} \neq 0 \quad \mathcal{X}_{H_u} + \mathcal{X}_{H_d} \neq 0$
- Therefore, $H_u H_d$ gauge-allowed, but PQ-violating at D=2!

Cook our recipe: a simple realization

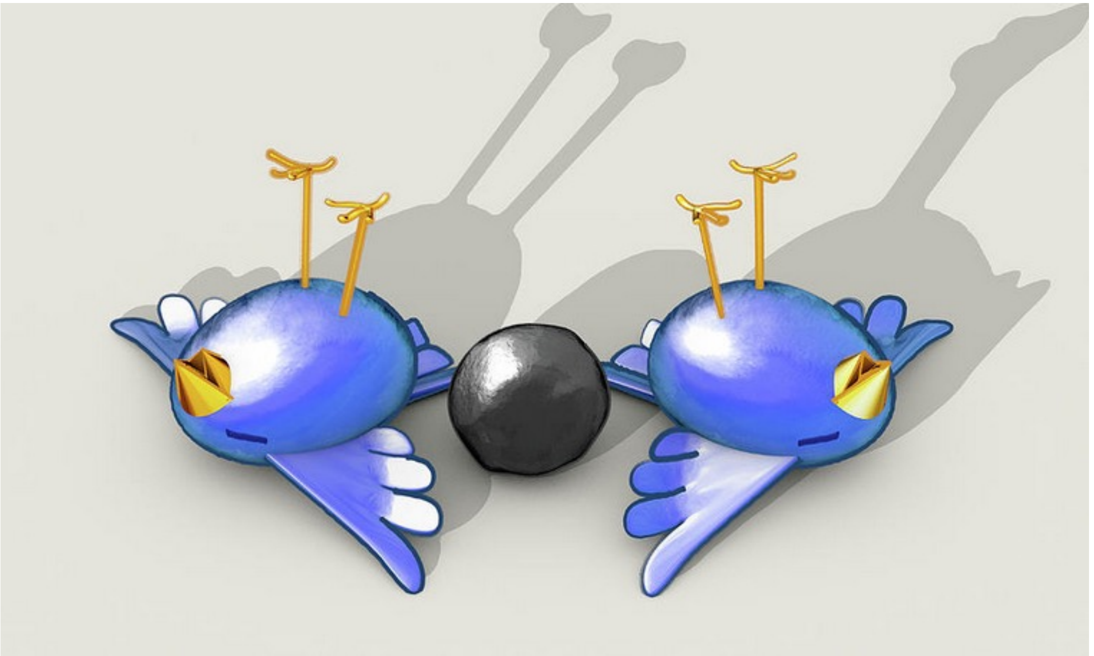
- In the models analysed, we were able to retrieve compatible quark mass hierarchies from non-hierarchical (or mildly hierarchical) input parameters without imposing any number by hand.

	model	experimental
m_b(GeV)	1.5	1.5
m_c(GeV)	0.5	0.4
m_s(MeV)	20	30
m_d(MeV)	0.5	1.5
m_u(MeV)	0.3	0.7

Numerical values of the quark masses and their experimental values evolved at the scale of 10^8 GeV. m_t = 102.5GeV

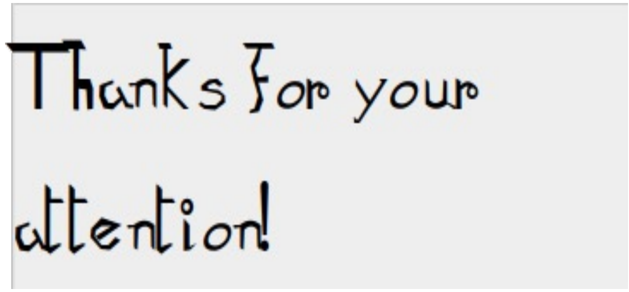
The Axion Flavour connection: conclusion and prospects

- As we have shown, the axion-flavour connection is a sensible ansatz to tackle the SM flavour puzzle and the strong CP problem in one fell swoop.



The Axion Flavour connection: conclusions and prospects

- I have a dream! Flavour + Strong CP problem + CDM
- Research strategies:
  - Implement powerful minimisation routines (any suggestion accepted!!!) and try to obtain CKM + Hierarchies simultaneously
  - Extend the gauge symmetry (trade off with simplicity though)
  - Extend to the lepton sector



BACKUP SLIDES

Hierarchical structure of the VEVs

- The minimisation of the scalar potential yields hierarchical entries in the VEVs of the scalar fields.

$$|x_1|,\ |y_{1,2}|,\ |z_3|,\ |k_2|\ \sim\ O(\Lambda),\ \ |x_2|, |z_{1,2}|\ \sim\ O(10^{-5}\Lambda),\ |k_{1,3}|\ \sim O(10^{-6}\Lambda)$$

$$\Lambda\ =\ 10^{11}\,\mathrm{GeV}$$

- This intuitively explains how we can get hierarchies starting from non-hierarchical (or mildly hierarchical) input parameters

PQ quality: the role of higher-dim operators

- In general, a PQ-breaking operator can be written as:

$$\eta \frac{\Phi^D}{M_P^{D-4}} + \text{h.c.} \approx \left(\frac{f_a}{M_P}\right)^{D-4} f_a^4 \cos\left(\frac{a}{f_a} + \xi_\eta\right)$$

- The total potential (QCD + PQ-break) would then be

$$V \supset -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{f_a}\right) + \left(\frac{f_a}{M_P}\right)^{D-4} f_a^4 \cos\left(\frac{a}{f_a} + \xi_\eta\right)$$

- To comply with $\theta \lesssim 10^{-10}$, then

$$\left(\frac{f_a}{M_P}\right)^{D-4} f_a^4 \lesssim 10^{-10} m_\pi^2 f_\pi^2 \rightarrow D \gtrsim 8\,(13) \Leftrightarrow f_a \lesssim 10^8\,(10^{13})$$

You cannot have your cake and eat it too: a no-go theorem

- The Yukawa Lagrangian can be written as

$$\mathcal{L}_Y = \sum_{i,j} \lambda_{ij}\, \bar{Q}_{m_i} Y_{m_i n_j} q_{n_j}$$

For which the mass matrix is

$$\mathcal{M} = \left(\begin{array}{c|c|c|c|c} \lambda_{m_1 n_1} Y_{m_1 n_1} & \lambda_{m_1 n_2} Y_{m_1 n_2} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \lambda_{m_2 n_3} Y_{m_2 n_3} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \lambda_{m_i n_j} Y_{m_i n_j} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{array}\right)$$

You cannot have your cake and eat it too: a no-go theorem

- In order to have massive quarks, we need to require

$$\mathrm{Det}\,(\mathcal{M}) = \varepsilon_{\alpha_1\alpha_2\ldots\alpha_N}\mathcal{M}_{1\alpha_1}\mathcal{M}_{2\alpha_2}\ldots\mathcal{M}_{N\alpha_N} \neq 0$$

- Such an operator has a charge proportional to the anomaly

$$\mathcal{A}_{PQ} \propto \sum_i m_i \mathcal{X}_{Q_{m_i}} - \sum_j n_j \mathcal{X}_{q_{n_j}} \neq 0$$

and thus breaks PQ at dimension N. Thus, if we want massive quarks and a PQ colour anomaly, we cannot help but break PQ at dimension N

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