Variant Nelson-Barr Mechanism with MFV

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Strong CP Problem and Nelson-Barr

- Why is the neutron electric dipole moment so small??

$$\bar{\theta} = \theta + \sum_r C(r) \arg\det M_r < 10^{-10}$$

- Nelson-Barr solution:
  - CP conserved at some high scale ($\theta = 0$)
  - Then, you just need the fermion mass matrices to get the other term in $\bar{\theta}$ to vanish.
- Problem: There's CP violation in the Standard Model (CKM)
- Solution: Transmit spontaneous CP violation at a high scale to light quarks through mixing with heavy vector-like quarks (VLQ's)

$$\mathcal{M} = \begin{pmatrix} A & B \\ 0 & C \end{pmatrix}, \qquad A^\dagger = A, \qquad B^\dagger = B$$

Nelson-Barr and Quality

- Vanilla Nelson-Barr mechanism is very vulnerable to corrections from higher order operators.
- Try enforcing a *different* relation:

$$\mathcal{M} = \begin{pmatrix} r\,A & 0 \\ 0 & A^* \end{pmatrix}$$

- Might do this with parity and a mirror electroweak sector[1,2,3], or we can keep our normal electroweak sector, and see what happens if we use **flavor symmetry**

[1]R.N. MOHAPATRA AND G. SENJANOVIC, PHYS. LETT. B **79** (1978) 283-286
[2]K. S. BABU AND R. N. MOHAPATRA, PHYS. REV. D **41** (1990) 1286
[3]S.M. BARR, D. CHANG, AND G. SENJANOVIC, PHYS. REV. LETT. **67** (1991) 2765-2768

MFV Nelson-Barr

$SU(3)_{q_L} \times SU(3)_{d_R} \times SU(3)_{u_R} \times U(1)_u \times U(1)_d$

	SM	$SU(3)^3$	$U(1)_d$	$U(1)_u$
q_L	$(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$(\mathbf{3},\mathbf{1},\mathbf{1})$	0	0
d_R	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{1},\mathbf{3},\mathbf{1})$	+1	0
u_R	$(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$(\mathbf{1},\mathbf{1},\mathbf{3})$	0	+1
B_L	$(\mathbf{3},\mathbf{1})_{Q_B}$	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1})$	0	0
B_R	$(\mathbf{3},\mathbf{1})_{Q_B}$	$(\mathbf{1},\overline{\mathbf{3}},\mathbf{1})$	−1	0
T_L	$(\mathbf{3},\mathbf{1})_{Q_T}$	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1})$	0	0
T_R	$(\mathbf{3},\mathbf{1})_{Q_T}$	$(\mathbf{1},\mathbf{1},\overline{\mathbf{3}})$	0	−1

	$SU(3)^3$	$U(1)_u$	$U(1)_d$
$\Sigma_d = f_d R_d$	$(\mathbf{3},\overline{\mathbf{3}},\mathbf{1})$	−1	0
$\Sigma_u = f_u R_u$	$(\mathbf{3},\mathbf{1},\overline{\mathbf{3}})$	0	−1

- Vector-like fields conjugate under flavor group to SM chiral fields
- SM quark masses at dimension-5 ($\propto v\, R_{u,d}$), vector-like quark masses at dimension-4 ($\propto f_{u,d} R_{u,d}$).
- At tree-level, $\bar{\theta} = 0$
- No mixed anomalies with QCD

Higher-Dimensional Corrections

$$\mathcal{M}^u = \begin{pmatrix} \frac{y_u\, v}{\sqrt{2}} R_u & 0 \\ 0 & f_u R_u^* \end{pmatrix}, \qquad \mathcal{M}^d = \begin{pmatrix} \frac{y_d\, v}{\sqrt{2}} R_d & 0 \\ 0 & f_d R_d^* \end{pmatrix}$$

- MFV → Only physical phase is the CKM phase
- Leading correction to $\bar{\theta}$ appears as…

$$\Delta\bar{\theta} \sim 2\,J \left(\frac{m_s^2 m_c^2}{m_b^2 m_t^2}\right) \frac{f_d^6}{f_u^6} \sim (3.1 \times 10^{-13}) \frac{f_d^6}{f_u^6}$$

- Perturbative unitarity suggests either $f_d \ll f_u$ or $f_d \sim f_u$
- Planck-suppressed explicit symmetry breaking? Not necessarily– symmetry group is non-anomalous and might be feebly gauged!

Phenomenology– Goldstone Bosons

- What are the phenomenological consequences? Depends on what we say about the flavor symmetry
  - Gauged? Messy, only particles at heavy scales
  - Global (or feebly gauged)? Simple, and low-energy new physics
- We'll stick to the simple case: Then we have **26 light Goldstone bosons– ALPs!**
- In the simplest (massless) case, model is dictated entirely by parameters f_u, f_d.
- Two possible couplings of these fields to the SM
  - **Matter:** $\mathcal{L} \supset -\frac{\partial_\mu a}{f_u} \sum_{\psi=q,u,d} c_{ij}^{\psi} \bar{\psi}_i \gamma^\mu \psi_j$
  - **Photons (possible):** $\mathcal{L} \supset \frac{a}{f_u}\left[c_u^{\gamma}\left(Q_T^2 - \frac{4}{9}\right) + c_d^{\gamma}\left(Q_B^2 - \frac{1}{9}\right)\right] \frac{\alpha_{\rm em}}{4\,\pi}\, F^{\mu\nu}\tilde{F}_{\mu\nu}$

Phenomenology: Nucleon Coupling

- Weak matter coupling contributes to additional energy loss in SN-1987A: Need the energy loss from the ALPs to be less than the neutrino luminosity.

- Constraints are dependent only on f_u, f_d, and SM flavor parameters.
  $f_d \gtrsim 7.7 \times 10^{11}$ GeV, $\qquad f_u \gtrsim 7.1 \times 10^{13}$ GeV

- Flavor-violating constraints, esp. $K \to \pi + X$, mean there's no way to "trap" these ALPs with sufficiently small $f_{u,d}$

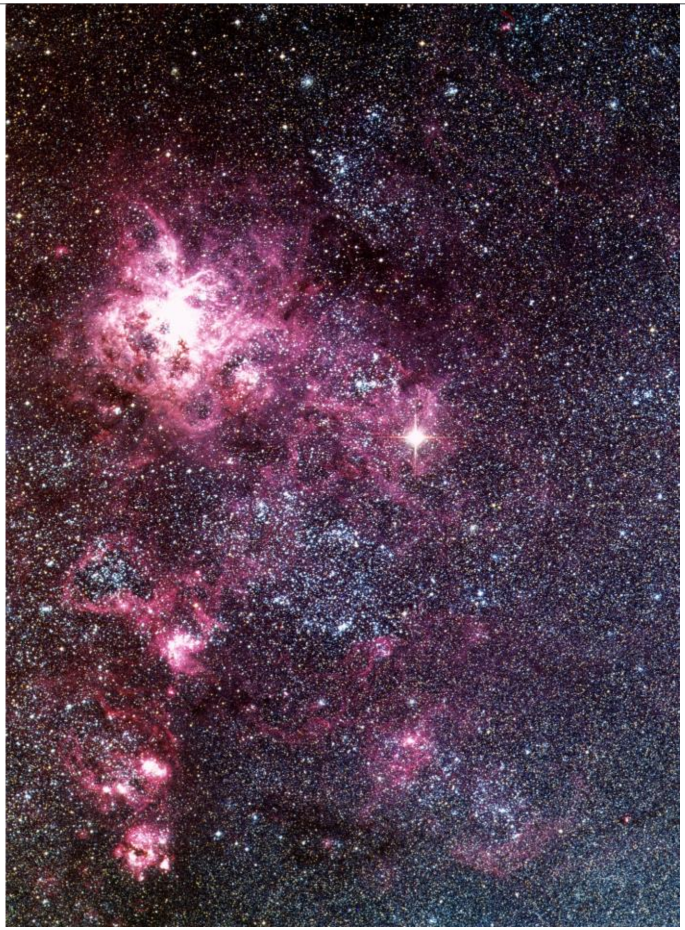


Photo: ESO

Phenomenology: Photon Coupling

- Photon coupling comes from electromagnetic anomaly, depends on vector-like quark charges Q_B and Q_T, specifically their differences with down- and up-like quark EM charges, respectively.
- Coupling vanishes if we assume global symmetry is feebly gauged, has no anomalies.
- For $O(1)$ charge splitting with SM quarks,
  $f_u \gtrsim O(10^{13})$ GeV, $f_d \gtrsim O(10^{10})$ GeV

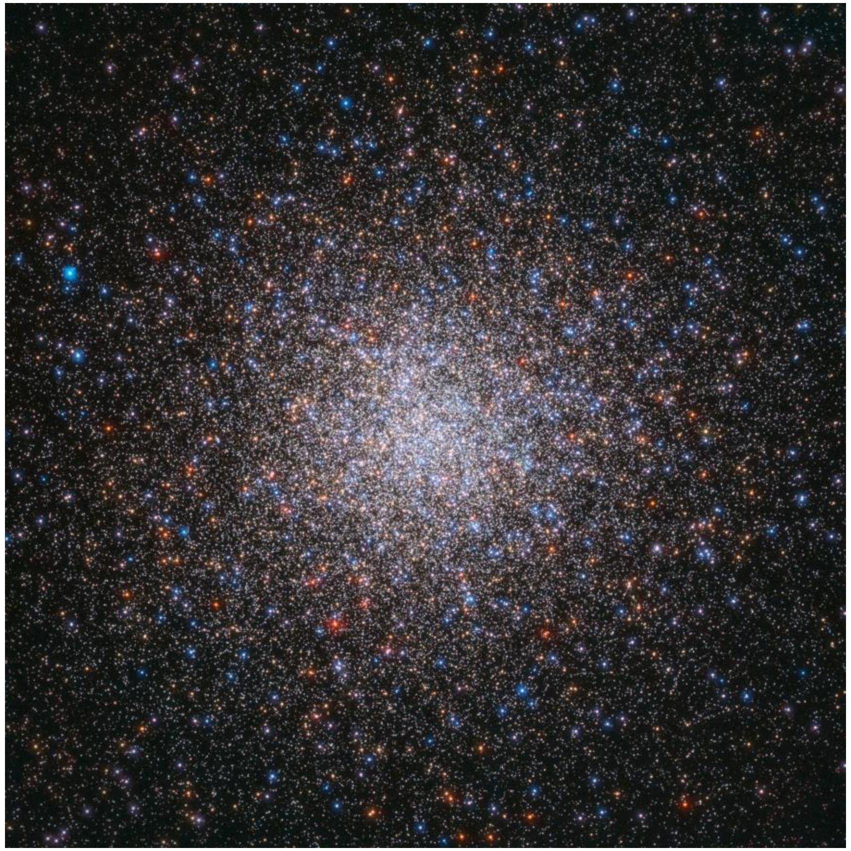
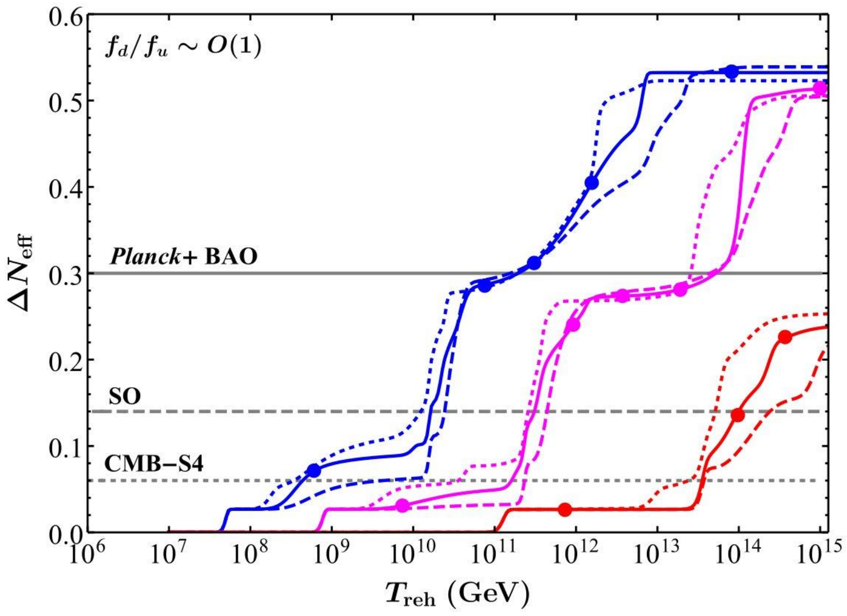


Photo: ESA/Hubble

Phenomenology: Flavor Stairway

- Strongest cosmological constraint comes from stable or long-lived vector-like quarks, but high mass means these are easy to avoid with tiny additional symmetry breaking
- 26 Goldstone bosons → potentially large contribution to effective number of neutrino species at recombination, ΔN_{eff}
- Dependent on the reheating temperature of the universe, $T_{\rm reh}$
- Note the distinctive stairway plot as a function of $T_{\rm reh}$-- comes from where thermal production of heavy vector-like fermion species turn on.
- *Unlike other ALP ΔN_{eff} models, exotic vector-like quarks dominate thermal ALP production in the early universe*



Conclusions

- We presented a mechanism for solving the strong CP problem based on a large flavor symmetry
- Vector-like quarks are unobservably heavy, but there are ample signatures for the lighter Goldstone bosons
- MFV is just the first example that comes to mind, but the pheno is distinctive and many characteristics likely carry over to other constructions:
  - Large flavor symmetry with parameters dictated mostly by SM flavor structure
  - Large number of Goldstone bosons
  - ALP cosmology dominated by vector-like quarks

Thank You!