Title: Flavorful UV Instantons and the Strong CP Problem

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Abstract: We describe a new solution to the strong CP problem inspired by the massless up quark solution. At high energies, QCD is embedded in a SU(3)xSU(3)xSU(3) model, with each matter generation charged under a different site. Instanton effects are unsuppressed at the scale of Higgsing to the SM diagonal QCD, and a set of anomalous U(1)_PQ symmetries removes the low-energy strong CP phase. A non-zero theta parameter is generated at loop level near current bounds. Similar models can also lead to a heavy axion solution to the strong CP problem.

Flavorful Instantons and the Strong CP Problem

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Based on work in progress w/Prateek Agrawal

Strong CP Problem

$$\mathcal{L} = \theta G\tilde{G} + y_u HQu^c + y_d HQd^c$$

Two SM CP violating Phases:

Strong CP (non-perturbative) $\quad \bar{\theta} = \theta - \mathrm{Argdet} y_u - \mathrm{Argdet} y_d$

CKM $\quad V_{CKM} \supset e^{i\delta_{\mathrm{CKM}}}$

Puzzle: CKM Phase O(1) but $\bar{\theta} \lesssim 10^{-10}$ (neutron EDM)

Sequestering?

SM is special $\quad \Delta\bar{\theta} \ll \delta_{\mathrm{CKM}}$

Massless Up Quark Solution

Two-Flavor (single generation) QCD:

$$\mathcal{L} = \theta \tilde{G}_{\mu\nu} G^{\mu\nu} + m_u u u^c + m_d d d^c + \text{h.c.}$$

[chiral rotation: $u u^c \to e^{i\alpha} u' u^{c\prime}$, $d d^c \to e^{i\beta} d' d^{c\prime}$; Axial anomaly: $\theta \to \theta + \alpha + \beta$ } Invariant CP Phase $\bar{\theta} = \theta - \text{Arg} m_u - \text{Arg} m_d$]

$m_u = 0 \longrightarrow U(1)_{PQ} \longrightarrow$ No Strong CP violation

Anomalous → Non-perturbative QCD generates up mass $m_u \neq 0$?

Dine et. al. 1410.8505,
Choi et. al. 1988, Georgi et. al. 1981

Leading chiral Lagrangian: $m_u \approx 0.5\, m_d$

Massless Up Quark Solution

Dilute Instanton Gas Approximation

instanton "density" $D(\rho)$

$$\Delta m_u = \int_{\rho_0}^{\rho_1} \frac{d\rho}{\rho} \times C_0 \times \left(\frac{8\pi^2}{g(\rho)^2}\right)^6 e^{-\frac{8\pi^2}{g(\rho)^2}} \times m_d^* e^{i\theta}$$

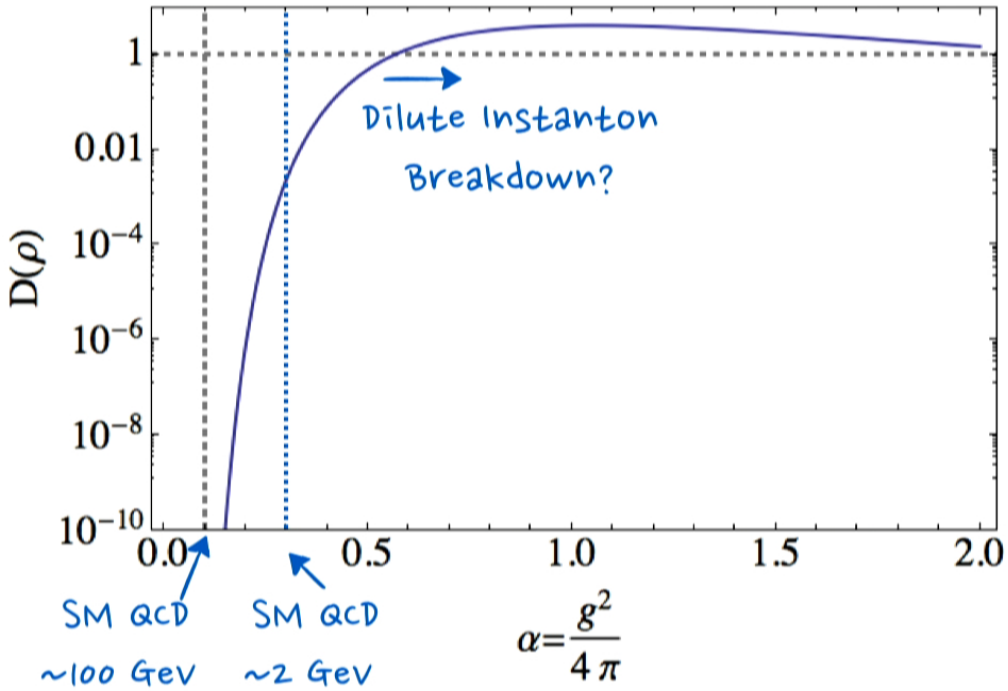
instanton sizes

invariant phase

$$\arg(\Delta m_u) + \arg(m_d) - \theta = 0$$

Massless Up Quark Solution

instanton "density" $D(\rho) = C_0 \times \left(\frac{8\pi^2}{g(\rho)^2}\right)^6 e^{-\frac{8\pi^2}{g(\rho)^2}}$



Protection from UV?

running CP phase of mass?

$$\Delta m_u = \int_{\rho_0}^{\rho_1} \frac{d\rho}{\rho} \times D(\rho) \times m_d(\rho)^* e^{-i\theta}$$

$\Lambda_{\rm UV}$

unsequestered CP violation

$$m_d' = e^{i\delta} m_d$$

$$\Delta m_u' \sim D(\Lambda_{\rm UV}^{-1}) m_d^* e^{-i\delta}$$

$$m_u = \Delta m_u + \Delta m_u'$$

—> phase mismatch

$$\Delta\bar{\theta} \sim D(\Lambda_{\rm UV}^{-1}) \frac{|m_d|}{|m_u|} \times \delta$$

$\Lambda_{\rm QCD}$

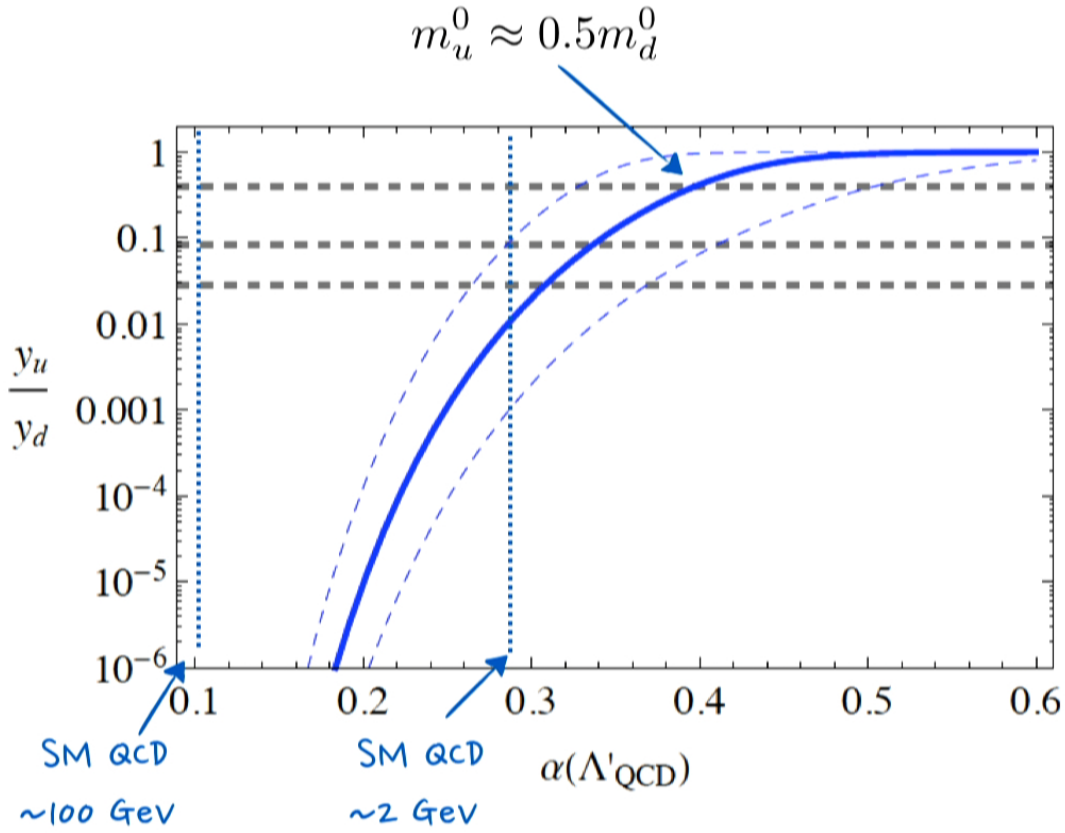
$$m_d$$

$$\Delta m_u \sim D(\Lambda_{\rm QCD}^{-1}) m_d^*$$

Suppression of extra PQ Breaking?

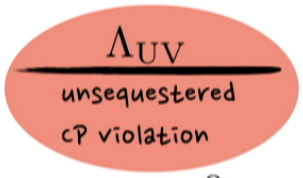
$$m_u = \Delta m_u + \Delta m_u' + m_u^0 \qquad \Delta\bar{\theta} \sim |m_u^0|/|m_u|$$

Massless Up Quark Solution

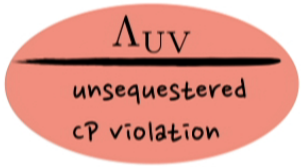


3-flavor lattice —> massless up quark solution fails

UV Instantons and PQ?



$m_u \approx 0$



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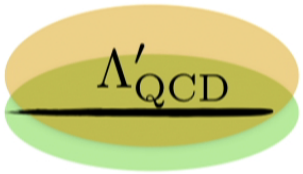
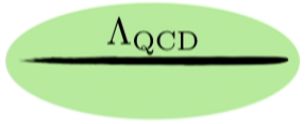


CP-violation remains sequestered

Non-perturbative effects important again

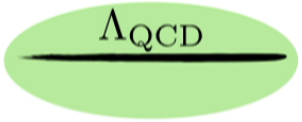
$\Delta m_u \sim m_d^* e^{i\delta}$

SM, m_u nonvanishing



Normal

($m_u = 0$ not viable)



UV Instanton solutions

One 'wrong' way

$\Lambda_{\rm UV}$

SU(3 + N)

$\Lambda'_{\rm QCD}$

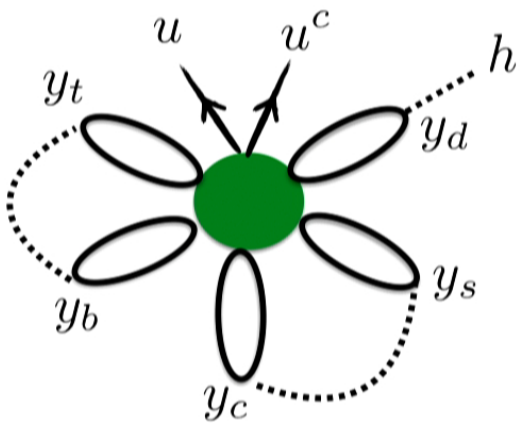
Higgsing

(+ any extra chiral symmetries strongly broken)

SM + Extra Matter

$\Lambda_{\rm QCD}$

6-flavor instanton:



$$\frac{\Delta y_u}{y_d} \sim D(\Lambda'_{\rm QCD}) \frac{y_t y_b y_s y_c}{(16\pi^2)^2}$$

too small

(extra breaking of SM chiral symmetries typically introduces phases, extra matter leads to further suppressions)

Axions: Holdom '81, Holdom & Peskin '85, Dine & Seiberg '86, Randall & Flynn '87

Flavorful Instantons

$\Lambda_{\rm UV}$

SU(3) × SU(3) × SU(3) (×···)

coincidence of scales?

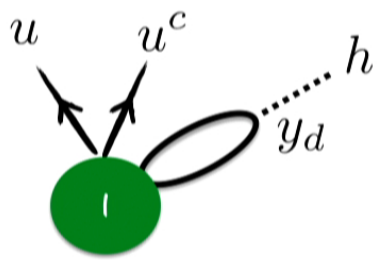
$\Lambda'_{\rm QCD}$

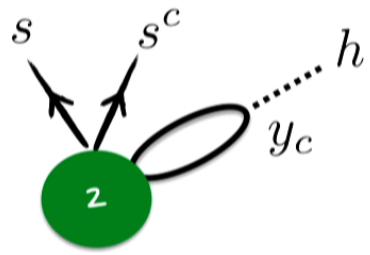
Higgsing

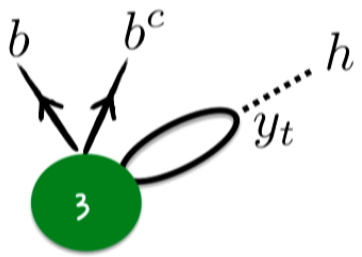
(+ any extra chiral symmetries strongly broken)

SM

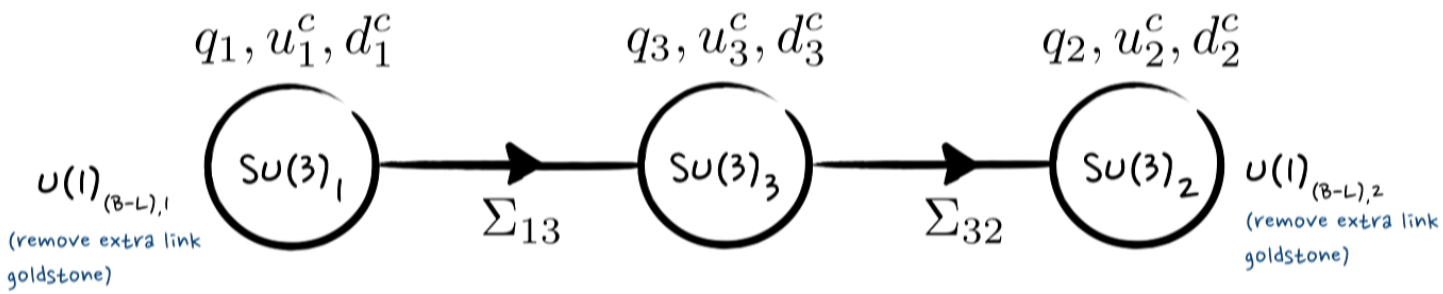
$\Lambda_{\rm QCD}$







3x(2-flavor) models



PQ x 3 [$y_u = 0$ $y_b = 0$ $y_s = 0$

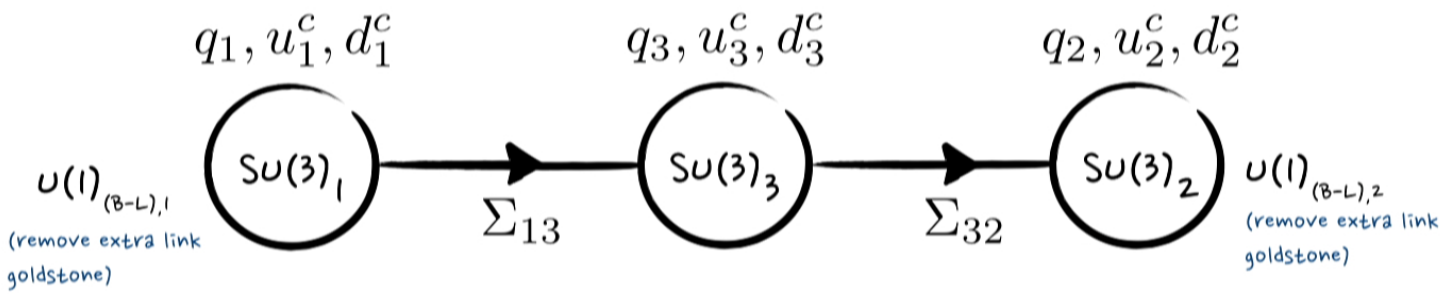
Higgsing [$V(\Sigma_{13}) = (|\Sigma_{13}|^2 - v_{13}^2)^2$ $V(\Sigma_{32}) = (|\Sigma_{32}|^2 - v_{32}^2)^2$

$SU(3)_1 \times SU(3)_2 \times SU(3)_3 \to SU(3)_{\rm QCD}$

Strongly coupled ⟶ weakly coupled

$\Lambda'_{\rm QCD} \sim g v_{13}, g v_{32}$

3x(2-flavor) models



PQ x 3 [$y_u = 0$ $y_b = 0$ $y_s = 0$

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$SU(3)_1 \times SU(3)_2 \times SU(3)_3 \to SU(3)_{\rm QCD}$

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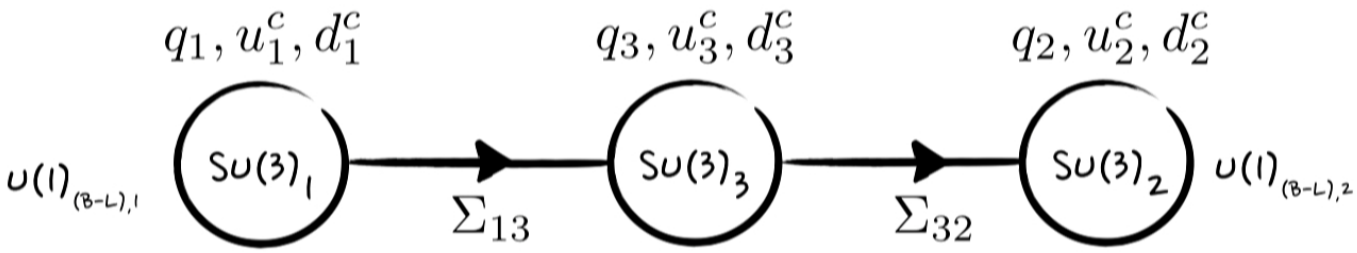
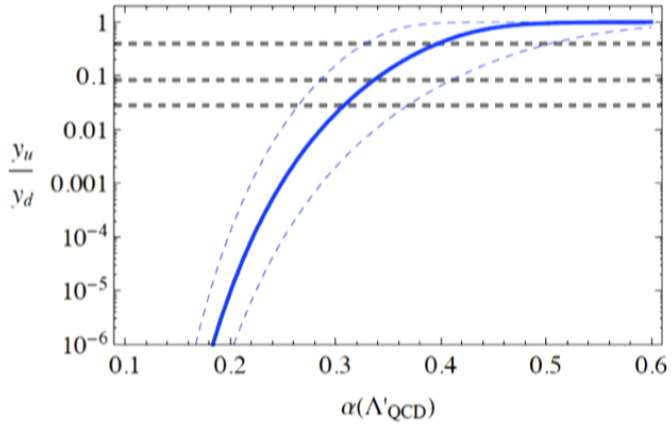


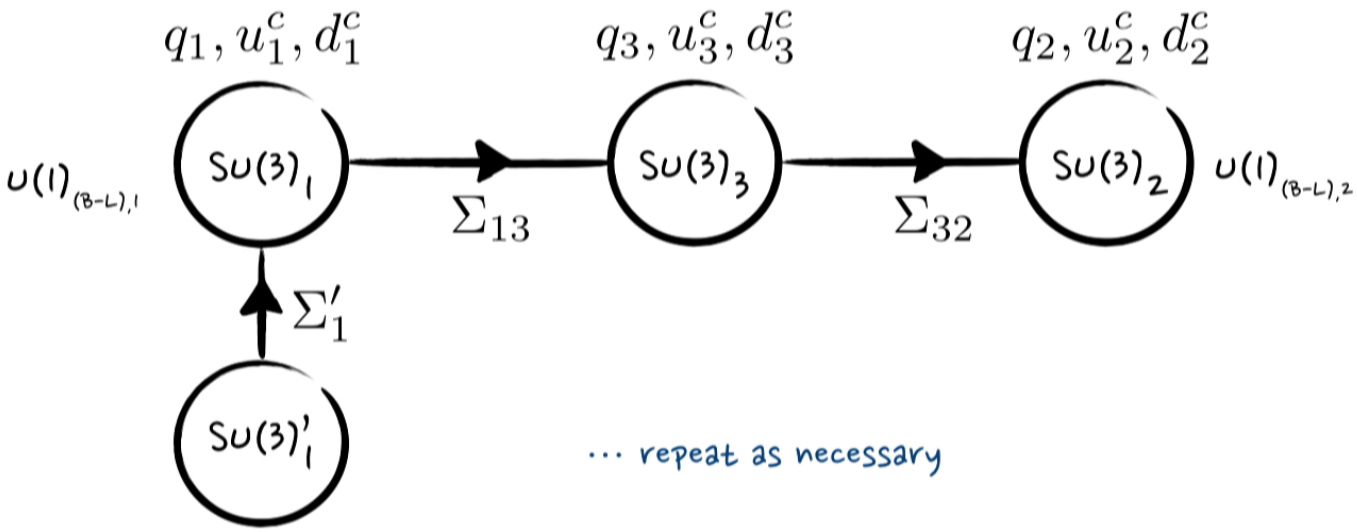
$\Delta y_u/y_d \approx 1/2 \qquad \Delta y_b/y_t \approx 1/35 \qquad \Delta y_s/y_c \approx 1/10$



$$\frac{1}{\alpha_s} = \frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{1}{\alpha_3}$$

$$\rightarrow \quad \alpha_s \sim 0.1 - 0.2$$

weak coupling

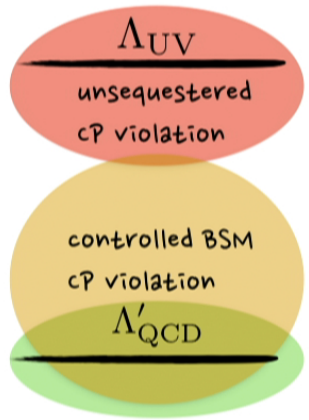


e.g. vector-like matter w/PQ

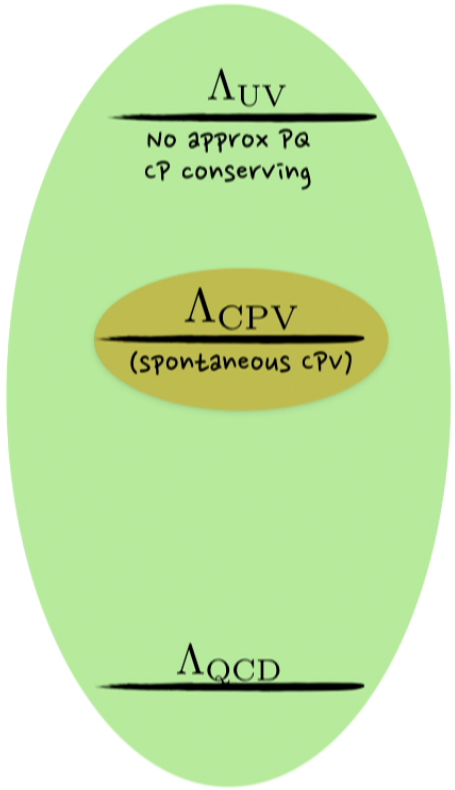
$\psi_1', \overline{\psi}_1' \qquad m_\psi = 0$

$\Delta m_\psi = D(gv_1') \times (gv_1) \sim 10^{-6} \Lambda_{\mathrm{QCD}'}$

Radiative Phases & Nelson Barr



UV Instanton Solutions



Nelson-Barr

CKM

Above instanton scale:

(background fields)

Higher dim $\sim \frac{\langle\Sigma_{13}\rangle\langle\Sigma_{32}\rangle}{\Lambda^2}$

only 1 phase (depends on 4 elements)

Anomalous U(1)'s remove theta

$(Q_i y_u^{ij} u_j^c) H \qquad (Q_i y_d^{ij} d_j^c) H^\dagger$

		$U(1)_{u_1}$	-1	-1	-1	$U(1)_{d_2}$	-1
$U(1)_{q12}$	+1	$\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$	$\begin{matrix} y_c s_{\theta_{12}} \\ y_c c_{\theta_{12}} \\ 0 \end{matrix}$	$\begin{matrix} 0 \\ 0 \\ y_t \end{matrix}$	$\begin{matrix} y_d \\ \tilde{y}_d \sim 0 \\ 0 \end{matrix}$	$\begin{matrix} 0 \\ 0 \\ 0 \end{matrix}$	$\begin{matrix} V_{31} y_b e^{i\delta_0} \\ V_{32} y_b \\ 0 \end{matrix}$
	+1						
$U(1)_{q3}$	+1						

Spurion/radiative:

$$\tilde{y}_d \sim y_d \times \frac{1}{16\pi^2}(\sim y_b^2 V_{31} V_{32} + \sim y_c^2 s_{\theta_{12}} c_{\theta_{12}})$$

Why this structure?

Need at least 3 orthogonal anomalous U(1) to remove phases

CKM

Below instanton scale:

$$(Q_i y_u^{ij} u_j^c) H \qquad (Q_i y_d^{ij} d_j^c) H^\dagger$$

$$\begin{pmatrix} \frac{y_u}{c_{\theta_{12}}} & y_c s_{\theta_{12}} & 0 \\ 0 & y_c c_{\theta_{12}} & 0 \\ 0 & 0 & y_t \end{pmatrix} \qquad \begin{pmatrix} y_d & 0 & V_{31} y_b e^{i\delta_0} \\ \tilde{y}_d \sim 0 & y_s & V_{32} y_b \\ 0 & 0 & y_b \end{pmatrix}$$

~1/100 ~$\pi/8$ ~1/25

Why this structure?

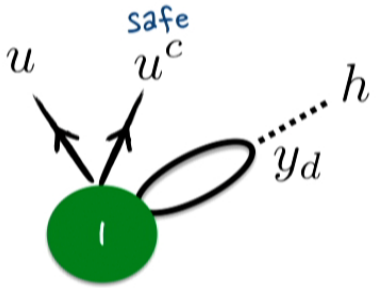
Need at least 3 orthogonal anomalous U(1) to remove phases

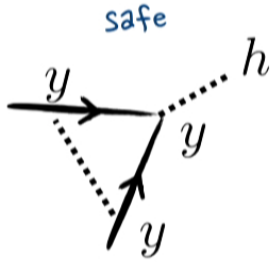
Radiative Sequestering of CPV?

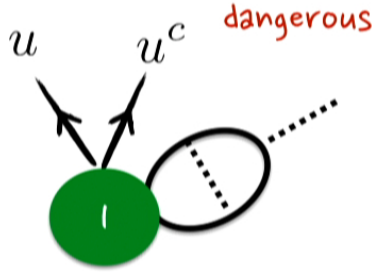
Looks a lot like the SM…
BUT SU(3)×SU(3)×SU(3) breaks many of the flavor symmetries.

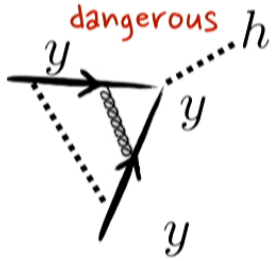
running CP phase of mass?

$$\Delta m_u = \int_{\rho_0}^{\rho_1} \frac{d\rho}{\rho} \times D(\rho) \times m_d(\rho)^* e^{-i\theta}$$



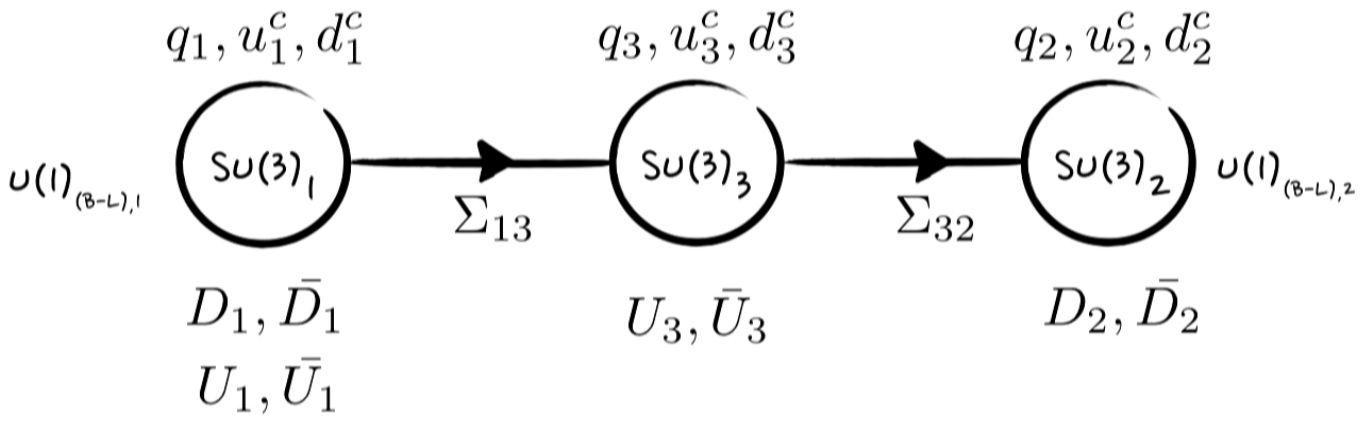


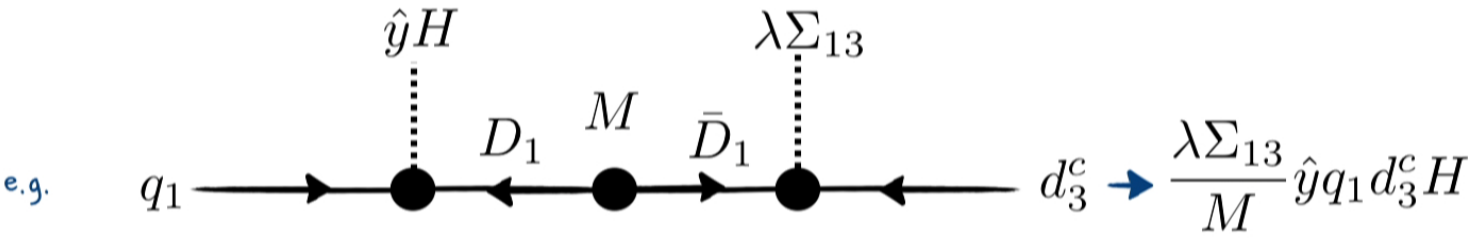




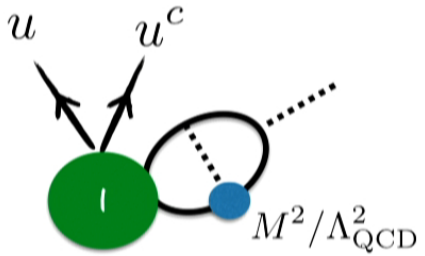
$$\Delta\bar{\theta} \approx \frac{6}{64\pi^2} \sin\delta_0 \tan\theta_{12} V_{31} V_{32} y_b^2$$
$$\approx 2 \times 10^{-10}$$

Flavor Completion

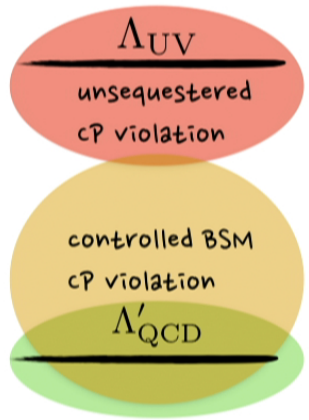




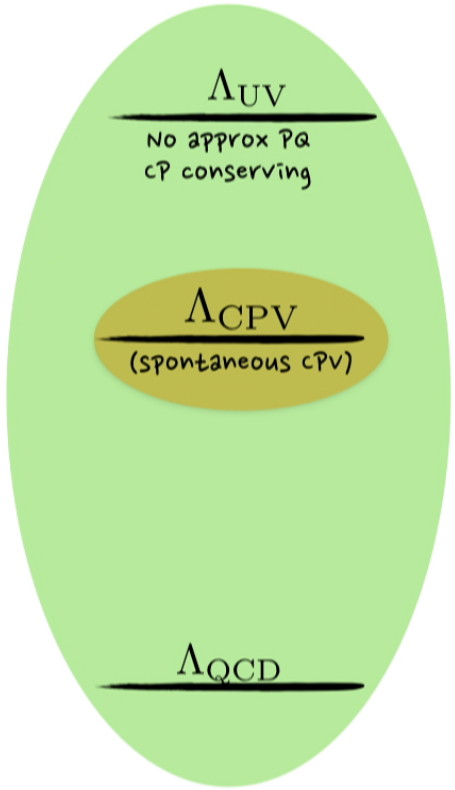
soft flavor? $M \lesssim \Lambda_{\rm QCD'}$ → soft CP violation



Radiative Phases & Nelson Barr

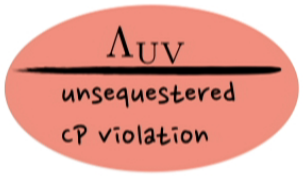


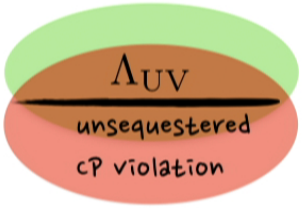
UV Instanton Solutions

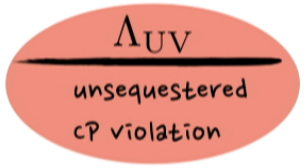


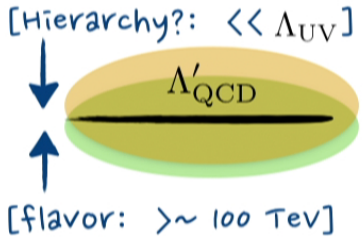
Nelson-Barr

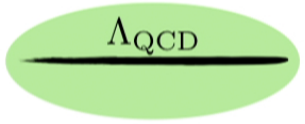
Summary



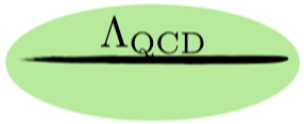




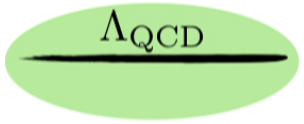




Normal
(m_u = 0 not viable)

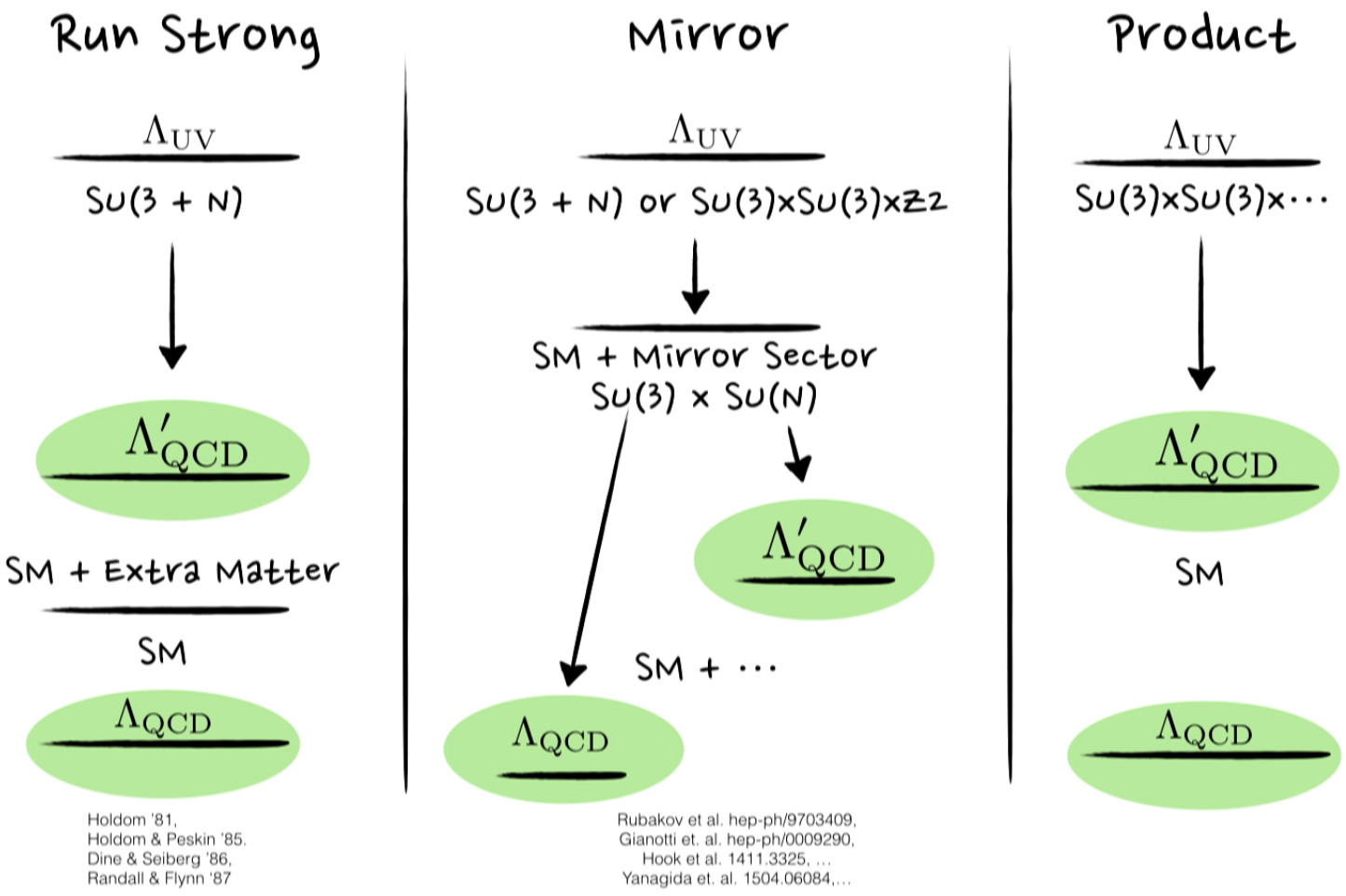


Dangerous
$\bar{\theta} \sim 1$



UV Instanton
Solutions
$\bar{\theta} \sim 10^{-10}$

Conclusions - Paths to Strong Coupling



Conclusions

- Mechanism for high-scale aligned PQ breaking effects
  - massless quark OR axion
  - PQ-symmetry quality
  - Decoupling — no light states
  - Different from Z2 or extra IR running
  - Not spontaneous CP violation
  - Experimentally observable?
    nEDM @ ORNL, proton storage ring
- Flavor Model
  - Instantons explain some hierarchies
  - Similarities to Nelson-Barr
  - Preserves sequestering of SM
  - Observable size for strong CP?

- Further directions…
  - connection to weak scale? (SUSY)
  - flavor observables
  - accidental scales?
  - axions, axions + fermions, etc.

$$\begin{pmatrix} \frac{y_u}{c_{\theta_{12}}} & y_c s_{\theta_{12}} & 0 \\ 0 & y_c c_{\theta_{12}} & 0 \\ 0 & 0 & y_t \end{pmatrix} \quad \begin{pmatrix} y_d & 0 & V_{31} y_b e^{i\delta_0} \\ \tilde{y}_d \sim 0 & y_s & V_{32} y_b \\ 0 & 0 & y_b \end{pmatrix}$$