New massless up-quark solution to strong CP

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[2408.11246]

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Strong CP problem

$$\mathcal{L}_{QCD} \supset \theta G\tilde{G}$$

CP-odd term

Basis independent: $\bar{\theta} = \theta + \arg(\det \mathcal{M}_q)$

Observable effect

Neutron electric dipole moment: $d_N \simeq (5 \times 10^{-16} e \cdot \mathrm{cm})\bar{\theta}$ [Crewther, DiVecchia, Veneziano, Witten,1979]

$$|d_N| \lesssim 3 \times 10^{-26} e \cdot \mathrm{cm} \Rightarrow \boxed{\bar{\theta} \lesssim 10^{-10}}$$

Why is $\bar{\theta}$ so small?

$\bar{\theta}$ does not appear to be "anthropic"

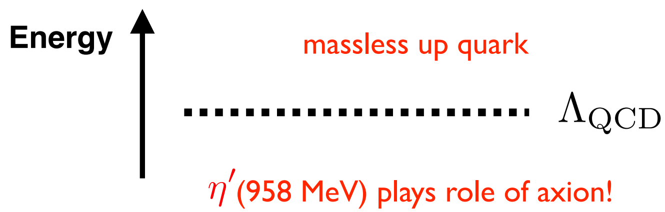
Our Universe possible for $0 \lesssim \bar{\theta} \lesssim 0.1$ [Lee,Meissner,Olive,Shifman,Vonk: 2006.12321]

Simplest solution: *massless up quark* [Georgi, McArthur 1981; Choi, Kim, Sze 1988]

$$\text{CP violation} \propto \text{Im}[e^{-i\theta}\det(M_q)]$$

$m_u = 0 \quad (u \to e^{i\alpha} u)$ ← $U(1)_A$ symmetry of u quark

⇨ $\det(M_q) = 0$ (anomalous) $U(1)_A$ removes $\bar{\theta}$ i.e. no CP violation!



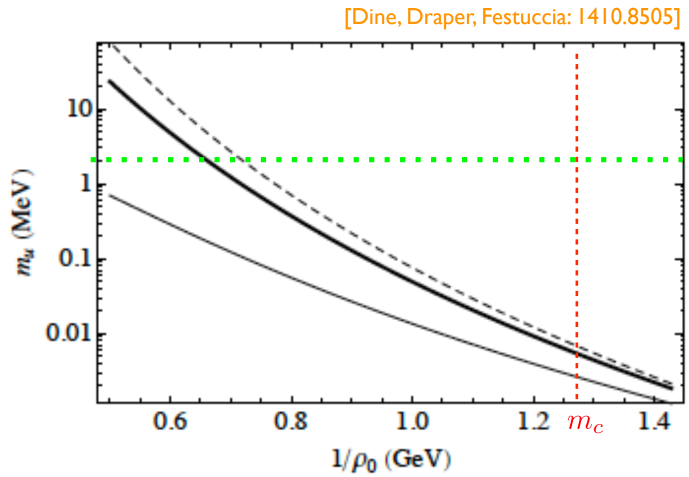
Up quark mass *is* generated by QCD:

perturbative correction = 0

$$\frac{d\,m_u}{d\ln\mu} = \gamma \cancel{m_u} + \boxed{D[\alpha(\mu)]m_d^* m_s^*}$$

nonperturbative correction

Instanton calculation with hard cutoff $1/\rho_0$



Suggests nonperturbative m_u NOT sufficiently large!

Lattice QCD: $m_u(2\ \mathrm{GeV}) = 2.16^{+0.49}_{-0.26}\ \mathrm{MeV}$ [Alexandrou et al 2002.07802]

Rules out massless up quark solution!

⇨ Require new UV contribution to m_u!

Possible ways

1. Nonzero up quark Yukawa: $y_u \neq 0$

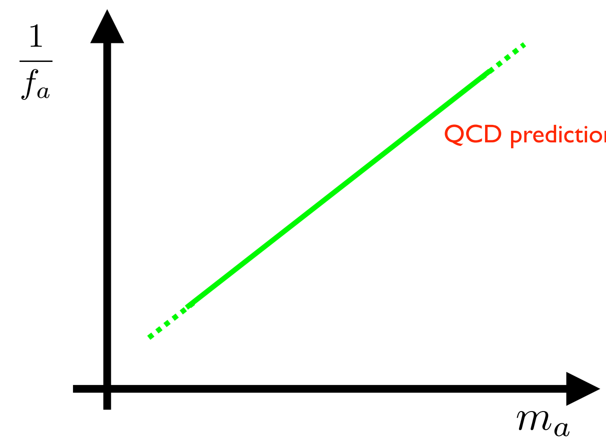
$\bar{\theta}$ cannot be removed $\longrightarrow$ introduce a new (anomalous) $U(1)$ Peccei-Quinn symmetry [Peccei, Quinn 1977] [Weinberg 1978; Wilczek 1978]

Axion potential: $$V_{\rm QCD}(a) \simeq -m_a^2 f_a^2 \cos\left(\frac{a}{f_a}+\bar{\theta}\right) + \ldots$$

➡ *minimum:* $\theta_{\rm eff} \equiv \frac{a}{f_a} + \bar{\theta} = 0\ !$ solves strong CP problem!

Axion mass: $m_a^2 = \frac{\mathcal{T}}{f_a^2}$ $\quad \mathcal{T} \equiv -i \int d^4x\, \langle 0|\mathrm{T}\left[\frac{1}{32\pi^2} G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}(x),\ \frac{1}{32\pi^2} G^b_{\rho\sigma}\widetilde{G}^{b\rho\sigma}(0)\right]|0\rangle$ topological susceptibility

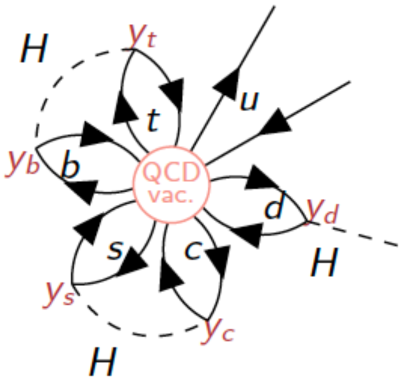
➡ $m_a^2 f_a^2 \sim m_q \Lambda^3_{\rm QCD} = \text{constant}$



Obtain (light) QCD axion $\boxed{10^{-6}\ {\rm eV} \lesssim m_a \lesssim 10^{-2}\ {\rm eV}}$

$(10^9\ {\rm GeV} \lesssim f_a \lesssim 10^{12}\ {\rm GeV})$

2. Enhance effect of small instantons



$$y_u \sim \Pi_f \underbrace{\frac{y_f}{4\pi}}_{\sim 10^{-18}} \left(\frac{8\pi^2}{g^2}\right)^6 e^{-\frac{8\pi^2}{g^2}}$$

Yukawa suppression ⟵ depends on all quark Yukawa couplings!

How to enhance QCD coupling or reduce Yukawa suppression?

EXAMPLES

(a) Partial compositeness in composite Higgs model [Gupta, Khoze, Spannowsky 2012.00017]

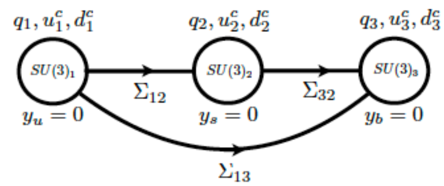
⟶ $y_f \sim 4\pi$ in the UV and "power-law" running

$$y_f(m_*) = y_f(M)\left(\frac{m_*}{M}\right)^{d_F-5/2}$$

⟶ new colored fermions in the UV $g_s \sim 4\pi$

η' pions at compositeness scale ~ TeV

(b) Product group $SU(3)^3 \to SU(3)$ [Agrawal, Howe: 1712.05803]



→ (anomalous) U(1) $u^c \to e^{i\alpha} u^c$ at each site

→ large gauge couplings at each site

$$\frac{1}{\alpha_s} = \frac{1}{\alpha_{s1}} + \frac{1}{\alpha_{s2}} + \frac{1}{\alpha_{s3}}$$

But only $y_b \propto y_t$ is viable! [Csaki, Ruhdorfer, Shirman: 1912.02197]

(c) Gauge flavor symmetry [Cordova, Hong, Koren: 2402.12453]

→ Use small instantons to generate down-type quark mass

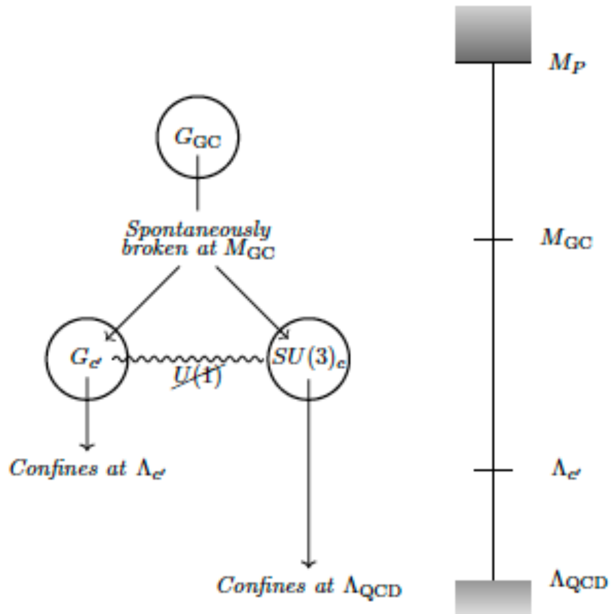
3. Alternative to generate up Yukawa coupling?

Use spontaneous breaking of chiral symmetry!  ← This talk

Toy model

Generate up-quark mass via spontaneous symmetry breaking

[Bedi, TG, Harigaya, 2408.11246]



Embed QCD into grand-color group

$$e.g. \quad G_{\rm GC} = SU(N+3) \stackrel{M_{\rm GC}}{\rightarrow} SU(N) \times SU(3)$$

(massless) $\Psi_U(\Box) \rightarrow \psi_U(\Box, 1), U(1, \Box)$

"grand-color quark partners" "quarks"

Ψ_U has a chiral symmetry $\longrightarrow$ removes θ term

[Chiral symmetry assumed to accidentally arise from exact discrete symmetry]

Below $M_{\rm GC}$ symmetry breaking scale: $\mathcal{L} \supset \dfrac{g_{\rm GC}^2}{M_{\rm GC}^2} \psi_U^\dagger \psi_{\bar{U}}^\dagger U \bar{U} + h.c.$ [e.g. technicolor: Dimopoulos, Susskind 1979]

SU(N) confinement: $\langle \psi_U \psi_{\bar{U}} \rangle \sim -\Lambda_{c'}^3$ $\Rightarrow$ $m_U \sim \dfrac{\Lambda_{c'}^3}{M_{\rm GC}^2}$

Does not depend on other quark masses!

Standard Model embedding

Embed SM quarks into $SU(2N+3)\times U(1)_{Y'}$ [TG, Nagata, Shifman 1604.01127]

$$SU(2N{+}3)\times U(1)_{Y'} \xrightarrow{M_{\rm GC}} SU(2N)\times SU(3)_c\times U(1)\times U(1)_{Y'} \xrightarrow{M_{\rm Sp}} Sp(2N)\times SU(3)_c\times U(1)_Y$$

Two-step breaking required to stabilise the vacuum

massless RH up quark removes $\bar\theta$

	$SU(2N+3)$	$U(1)_{Y'}$	$Sp(2N)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$\Psi_q \equiv \begin{pmatrix} q \\ \psi_q \end{pmatrix}$	$\square$	$\frac{1}{4N+6}$	$\mathbf{1}$ $\square$	$\square$ $\mathbf{1}$	$\square$	$1/6$ 0
$\Psi_{\bar u} \equiv \begin{pmatrix} \bar u \\ \psi_{\bar u} \end{pmatrix}$	$\bar\square$	$-\frac{1}{2}-\frac{1}{4N+6}$	$\mathbf{1}$ $\square$	$\bar\square$ $\mathbf{1}$	$\mathbf{1}$	$-2/3$ $-1/2$
$\Psi_{\bar d} \equiv \begin{pmatrix} \bar d \\ \psi_{\bar d} \end{pmatrix}$	$\bar\square$	$\frac{1}{2}-\frac{1}{4N+6}$	$\mathbf{1}$ $\square$	$\bar\square$ $\mathbf{1}$	$\mathbf{1}$	$1/3$ $1/2$

[Valenti,Vecchi, Xu, 2206.04077]

Effective Lagrangian: $$\mathcal{L} \supset \frac{g_{\rm GC}^2}{M_{GC}^2} q\bar u \psi_q^\dagger \psi_{\bar u}^\dagger - y_d \psi_q \psi_{\bar d} \widetilde H + \text{h.c.}$$

Sp(2N) confinement: $\langle \psi_{q_u}\psi_{q_d}\rangle, \langle \psi_{\bar d}\psi_{\bar u}\rangle \neq 0$ Electroweak symmetric

⇨ Spontaneously breaks $\psi_{\bar u}$ chiral symmetry, generates y_u Yukawa coupling!

How to induce nonzero $\langle \psi_q\psi_{\bar u}\rangle, \langle \psi_q\psi_{\bar d}\rangle$?

Global flavor symmetry: $SU(4)$ $\psi = (\psi_{q_u}, \psi_{q_d}, \psi_{\bar u}, \psi_{\bar d})^T$

SU(2) Higgs-like doublet Π^H ← Obtain: $m^2_{\Pi_H} \simeq \frac{g_2^2}{16\pi^2}\Lambda^2_{\rm Sp}$

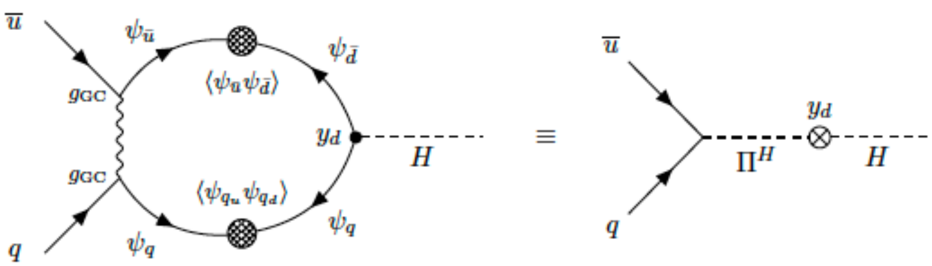
Sp(2N) confinement: $SU(4) \to Sp(4)$ ⇨ 5 = 1+$\boxed{4}$ Nambu-Goldstone bosons

Quark bilinears : $\psi_{q_d}\psi_{\bar d} = \psi_{q_u}\psi_{\bar u} \simeq \frac{\widehat\Lambda^3_{\rm Sp}}{2\sqrt{2}f}\Pi^h$ where $\frac{1}{\sqrt{2}}\Pi^h \equiv {\rm Re}\,\Pi^H_0$ $\hat\Lambda^3_{\rm Sp} \equiv \frac{N}{16\pi^2}\Lambda^3_{\rm Sp}$

Effective Lagrangian: $\mathcal{L} \supset \frac{g^2_{\rm GC}}{M^2_{GC}} q\bar u \psi^\dagger_q \psi^\dagger_{\bar u} - y_d \psi_q \psi_{\bar d} \widetilde H + {\rm h.c.}$ ⟶ $\frac{g^2_{\rm GC}\widehat\Lambda^3_{\rm Sp}}{2\sqrt{2}fM^2_{GC}} q_u \bar u\, \Pi^h - y_d \frac{\widehat\Lambda^3_{\rm Sp}}{\sqrt{2}f} \underbrace{\boxed{\Pi^h h}}_{\text{linear mixing}} - \frac{1}{2} m^2_{\Pi^H}\left(\Pi^h\right)^2$

$\langle h \rangle = v$ induces nonzero VEV $\langle \Pi^h \rangle \simeq -y_d v \frac{N\Lambda_{\rm Sp}}{\sqrt{2}g_2^2 f}$ ← generates effective up-quark Yukawa coupling

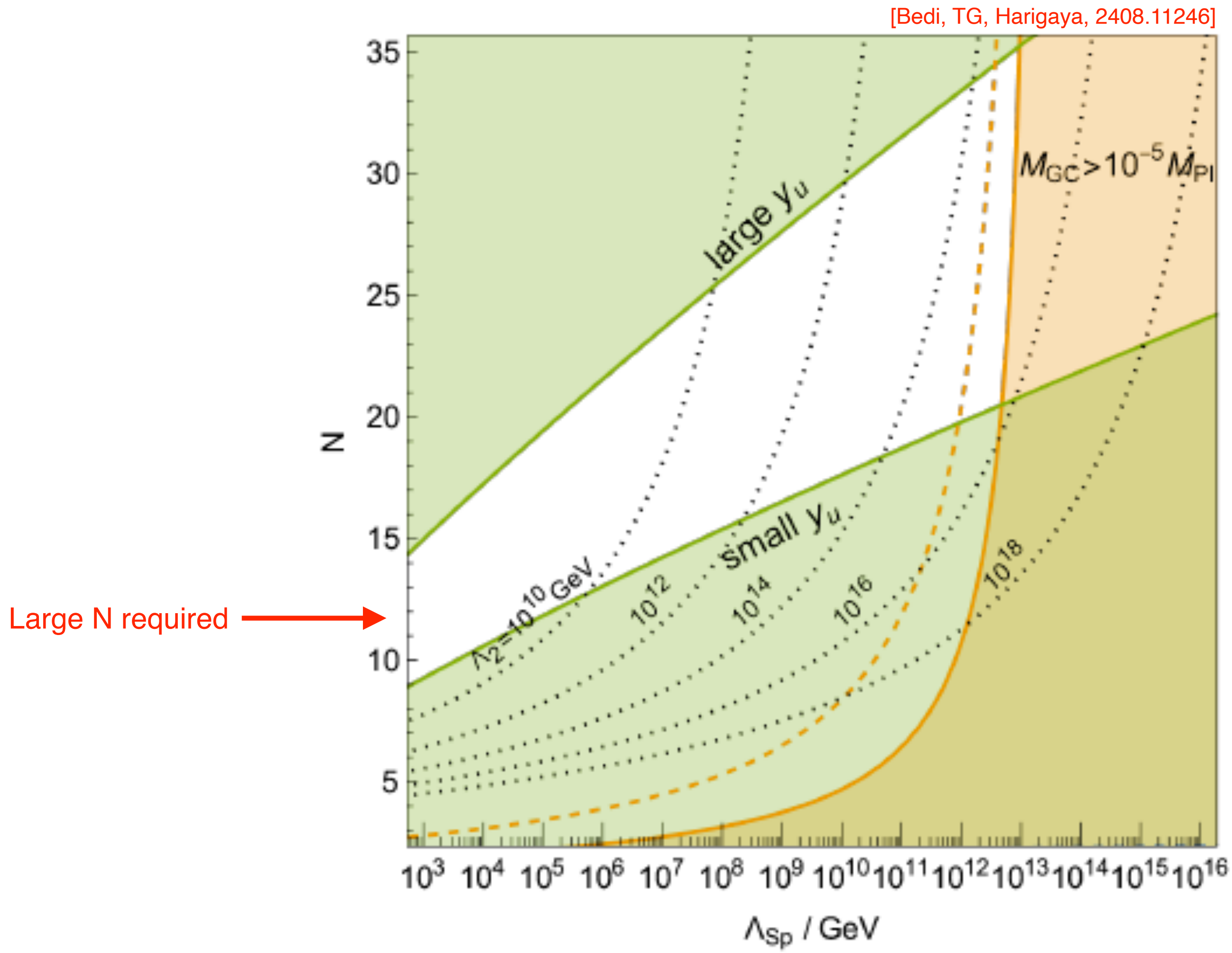
Obtain:



⇨ $$\boxed{y_u \simeq \frac{N}{4}\frac{g^2_{\rm GC}}{g_2^2}\frac{\Lambda^2_{\rm Sp}}{M^2_{\rm GC}} y_d}$$

[Bedi, TG, Harigaya, 2408.11246]

Generation of up-quark Yukawa coupling: (SM — one generation)



To reduce N, add vector-like quarks: $\Psi_U(\Box), \Psi_{\bar{U}}(\bar{\Box})$

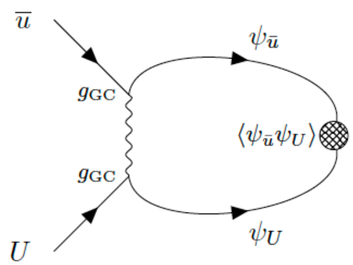
$$\mathcal{L} \supset -m_U \Psi_U \Psi_{\bar{U}} - \lambda_U \Psi_q \Psi_{\bar{U}} H + \text{h.c.}$$

$\Psi_{\bar{u}}$ has chiral symmetry

Sp(2N) confinement:

$$\langle \psi_{q_u} \psi_{q_d} \rangle = \frac{\langle \psi_{\bar{d}} \psi_{\bar{U}} \rangle}{\cos\phi} = \frac{\langle \psi_U \psi_{\bar{u}} \rangle}{\cos\phi} = \frac{\langle \psi_{\bar{d}} \psi_{\bar{u}} \rangle}{\sin\phi} = -\frac{\langle \psi_U \psi_{\bar{U}} \rangle}{\sin\phi} = \widehat{\Lambda}^3_{\rm Sp}$$

$$\phi \simeq \arctan\left(\frac{16\pi^2 m_U}{\lambda_U y_d \Lambda_{\rm Sp}}\right)$$



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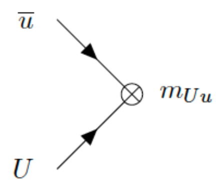
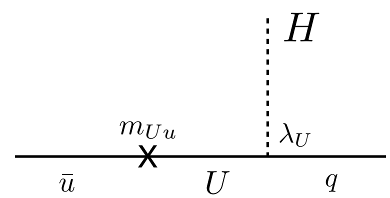
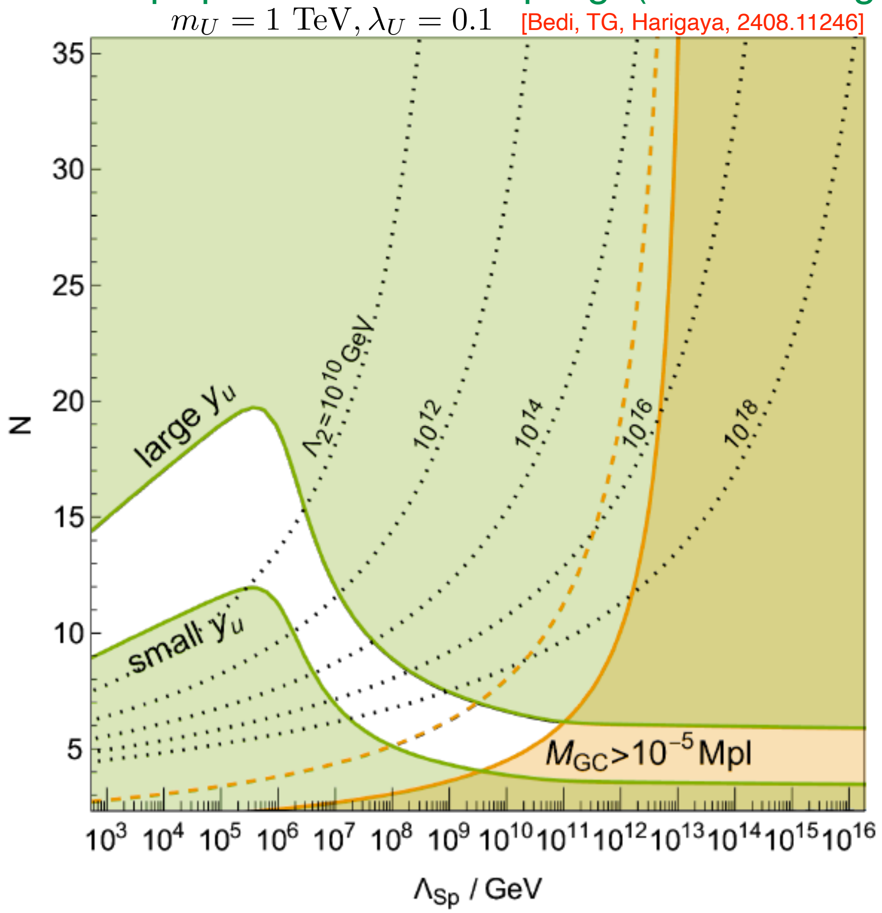




$m_U > |m_{Uu}|$

$$\boxed{y_u = \frac{N g^2_{\rm GC}}{16\pi^2} \frac{\Lambda^3_{\rm Sp}}{m_U M^2_{\rm GC}} \lambda_U \cos\phi + \frac{N}{4} \frac{g^2_{\rm GC}}{g_2^2} \frac{\Lambda^2_{\rm Sp}}{M^2_{\rm GC}} y_d \sin\phi}$$

Generation of up-quark Yukawa coupling: (SM — one generation)



Generalization to two and three generations

Minimal two-generation model *not* phenomenologically viable $\longrightarrow$ add vector like quarks

$$\mathcal{L} = -\widetilde{Y}^u_{i2}\Psi_{q_i}\Psi_{\bar{u}_2}H - \widetilde{Y}^d_{ia}\Psi_{q_i}\Psi_{\bar{d}_a}\widetilde{H} - \lambda_{Ui}\Psi_{q_i}\Psi_{\bar{U}}H - m_U\Psi_U\Psi_{\bar{U}} + \text{h.c.},$$

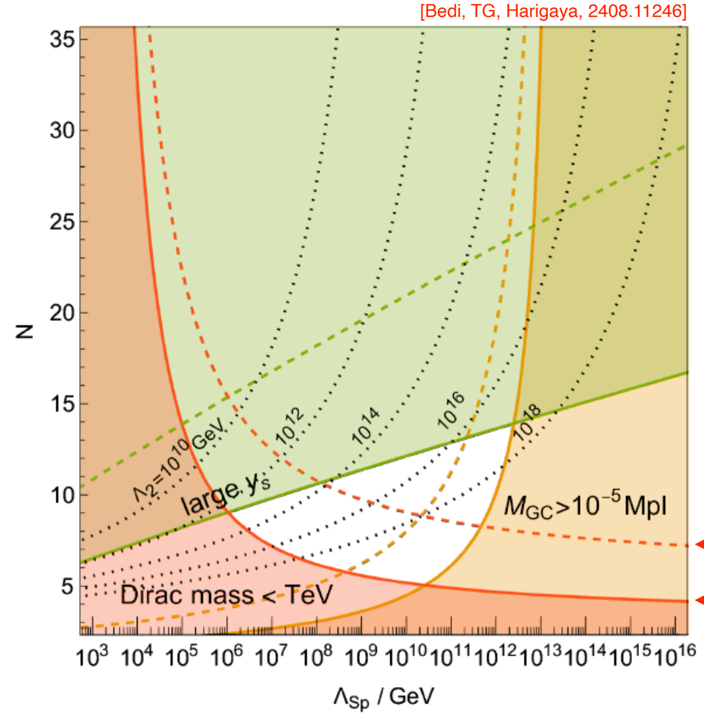
$\Psi_{\bar{u}_1}$ has chiral symmetry

$\Psi_{\bar{u}_2}, \Psi_{\bar{d}_{1,2}}$ have nonzero Yukawa couplings

$$\widetilde{Y}^u = \begin{pmatrix} 0 & y'_1 \\ 0 & y'_2 \end{pmatrix}, \quad \widetilde{Y}^d = \begin{pmatrix} y_d & 0 \\ 0 & y_s \end{pmatrix}$$

Generation of up-quark Yukawa coupling: (SM — two generations)

[Bedi, TG, Harigaya, 2408.11246]



$M_{\rm Sp} = M_{\rm GC}$

$M_{\rm Sp} = \Lambda_{\rm Sp}$

What about three generations?

Large top quark Yukawa coupling generates large Higgs-pion mixing:

SU(2) doublet pion

$$\mathcal{L} \supset -y_3 \Psi_{q_3} \Psi_{\bar{u}_3} H + \text{h.c.} \quad \Rightarrow \quad y_3 \kappa \frac{\sqrt{N}}{4\pi} \Lambda_{\text{Sp}}^2 \boxed{\Pi^H} H^\dagger + \text{h.c.},$$

Mass-squared matrix $\mathcal{M}^2$:

$$V \supset \begin{pmatrix} H^\dagger & \Pi^{H\dagger} \end{pmatrix} \begin{pmatrix} m_H^2 & y_3 \kappa \frac{\sqrt{N}}{4\pi} \Lambda_{\text{Sp}}^2 \\ y_3 \kappa \frac{\sqrt{N}}{4\pi} \Lambda_{\text{Sp}}^2 & \frac{\kappa' y_3^2}{16\pi^2} \Lambda_{\text{Sp}}^2 \end{pmatrix} \begin{pmatrix} H \\ \Pi^H \end{pmatrix}$$

$$\det \mathcal{M}^2 = 0 \quad \Rightarrow \quad m_H^2 \sim \kappa^2 N \Lambda_{\text{Sp}}^2 / \kappa'$$

SM Higgs is dominantly Π^H

$\Rightarrow$ top Yukawa: $y_t \sim y_3^2 \kappa' / (4\pi \kappa \sqrt{N})$ ⟵ requires non-perturbative y_3

Can be avoided by treating 3rd generation quarks as SU(2N+3) singlets

Extra SU(3)

Consider: $SU(2N+3) \times SU(3)_T \longrightarrow Sp(2N) \times \underbrace{SU(3) \times SU(3)_T}$

"1st, 2nd generation quarks" "3rd generation quarks"

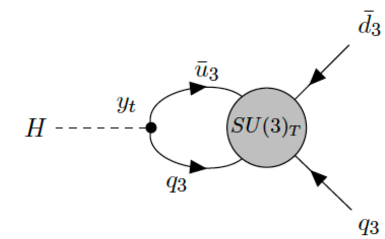
$\big\downarrow \langle \Phi_3 \rangle = v_T$

$SU(3)_c$

3rd generation quark Lagrangian:

$\mathcal{L} = -y_t q_3 \bar{u}_3 H + \mathrm{h.c.}$ ⟵ $\bar{d}_3$ has chiral symmetry ⇨ remove θ_T parameter!

Bottom quark Yukawa coupling generated by $SU(3)_T$ instanton:



⇨ $$y_b \simeq 3 \times 10^{-4} \left(\frac{\Lambda_T}{v_T}\right)^{19/2} \left(\ln \frac{\mu}{\Lambda_T}\right)^6$$

CKM mixing: add vector-like quarks $B, \bar{B}$

$\mathcal{L} = y_a^B B \bar{d}_a \Phi_3 + \mathrm{h.c.}$ $(a = 1, 2)$ ⇨ $\mathcal{L} = -\lambda_B y_a^B \dfrac{v_T}{m_B} q_3 \bar{d}_a \widetilde{H} + \mathrm{h.c.}$ ⟵ explains CKM mixing for $m_B \sim \mathrm{TeV}$, $v_T \sim 10^{13}$ GeV and $\lambda_B y_a^B \sim 10^{-12}$

Other types of models

1. Extend SU(2) electroweak group

$$SU(2)_{FS} \times SU(2)_T \to SU(2)_L$$

"1st, 2nd generation quarks" "3rd generation quarks"

(2,2) entry of mass-squared matrix receives large positive mass-squared $\sim g_{2,T}^2 \Lambda_{\rm Sp}^2/(16\pi^2)$

2. Introduce a mass term for grand-color breaking

Decouples Π^H but preserves $Sp(2N) \times SU(3) \times U(1)_Y$ symmetry

3. Supersymmetry

Can suppress off-diagonal entry of mass-squared matrix by supersymmetry

Corrections to the strong CP phase

Contribution of Yukawa phases to strong CP phase can be estimated using flavor invariants

$$\mathcal{L} = -\widetilde{Y}^u_{aj}\psi_{q_a}\psi_{\bar{u}_j}H - \widetilde{Y}^d_{ai}\psi_{q_a}\psi_{\bar{d}_i}\widetilde{H} - \widetilde{M}_{ij}\psi_{\bar{d}_i}\psi_{\bar{u}_j}$$

where

$$\psi_q = \left(\psi_{q_1},\, \dots,\, \psi_{q_{F_q}}\right)^T ,$$
$$\psi_{\bar{u}} = \left(\psi_{\bar{u}_1},\, \dots,\, \psi_{\bar{u}_{F_{\bar{u}}}},\, \psi_{\bar{U}}\right)^T$$
$$\psi_{\bar{d}} = \left(\psi_{\bar{d}_1},\, \dots,\, \psi_{\bar{d}_{F_{\bar{d}}}},\, \psi_U\right)^T$$

$\boxed{SU(2N+3)\times SU(3)_T \text{ model}}$

Flavor symmetry: $SU(2)_q \times SU(3)_{\bar{u}} \times SU(3)_{\bar{d}}$ $\quad SU(2)_B$

$(\psi_{\bar{q}_1}, \psi_{\bar{q}_2})$ $\quad (\psi_{\bar{u}_1}, \psi_{\bar{u}_2}, \psi_{\bar{U}})$ $\quad (\psi_{\bar{d}_1}, \psi_{\bar{d}_2}, \psi_U)$ $\quad (\bar{d}_3, \bar{B})$

Leading order flavor invariants:

$$\mathrm{Tr}((\widetilde{Y}^d)^T\Sigma_q\widetilde{Y}^u\Sigma_{ud}) \ ,$$
$$\mathrm{Tr}(X_B\,\widetilde{M}\,\Sigma_{ud}) \ ,$$
$$\mathrm{Tr}((\widetilde{Y}^d)^T\Sigma_q\widetilde{Y}^u\widetilde{M}^\dagger) \ ,$$
$$\mathrm{Tr}(\widetilde{Y}^u\Sigma_{ud}\widetilde{M}\widetilde{Y}^{u\,\dagger}) \ ,$$
$$\mathrm{Tr}(X_B(\widetilde{Y}^d)^T\Sigma_q\widetilde{Y}^u\Sigma_{ud}) \ ,$$
$$\mathrm{Tr}(X_B\,\widetilde{M}\,\Sigma_{ud}\widetilde{M}\,\Sigma_{ud}) \ .$$

$$X^B_{ab} \equiv y^B_a y^{B\,*}_b$$

$$\Sigma_q = \begin{array}{c} \\ \psi_{q_d} \\ \psi_{q_s} \end{array} \begin{array}{c} \begin{array}{cc} \psi_{q_u} & \psi_{q_c} \end{array} \\ \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \end{array} ,$$

$$\Sigma_{ud} = \begin{array}{c} \\ \psi_{\bar{u}} \\ \psi_{\bar{c}} \\ \psi_U \end{array} \begin{array}{c} \begin{array}{ccc} \psi_{\bar{d}} & \psi_{\bar{s}} & \psi_U \end{array} \\ \begin{pmatrix} -\sin^2\frac{\alpha}{2}\sin 2\phi & \sin\alpha\sin\phi & \cos^2\frac{\alpha}{2} + \cos 2\phi\sin^2\frac{\alpha}{2} \\ \cos^2\frac{\alpha}{2} - \cos 2\phi\sin^2\frac{\alpha}{2} & \sin\alpha\cos\phi & -\sin^2\frac{\alpha}{2}\sin 2\phi \\ -\sin\alpha\cos\phi & \cos\alpha & -\sin\alpha\sin\phi \end{pmatrix} \end{array}$$

⇨ All flavor invariants have imaginary contributions which are sufficiently suppressed

Phenomenology

1. Vector-like quarks

Required to obtain two-generation model $m_U \gtrsim \mathrm{TeV}$ ⟵ can be discovered at LHC!

2. Pion spectrum

Lightest pion = spontaneous breaking of Sp fermion number ⟵ dark matter candidate!

Next-to-lightest pions—Two cases:

$(i)\ m_U = 0$

$$m_{\Pi_{\rm NL}} \sim \frac{\sqrt{y_u y_d}}{4\pi}\Lambda_{\rm Sp} \sim 10^{-6}\Lambda_{\rm Sp}$$ ⟵ couple to photons and gluons

$\Lambda_{\rm Sp} \sim 10^{6-7}$ GeV ⇒ $m_{\Pi_{\rm NL}} \sim 1 - 10$ GeV with coupling $f \sim \frac{\sqrt{N}}{4\pi}\Lambda_{\rm Sp} \sim 10^{6-7}$ GeV

Can be discovered by axion-like particle searches at DUNE!

$\Pi_{\rm NL}$ behaves like a "heavy QCD axion"— Sp(2N) anomaly-free but obtains mass from Yukawa interactions

$(ii)\ m_U \neq 0 \qquad m_{\Pi_{\rm NL}} \sim \mathcal{O}(m_U \Lambda_{\rm Sp})$

$\Lambda_{\rm Sp} \sim 10^6$ GeV, $\quad m_U \sim 1$ TeV ⇒ $m_{\Pi_{\rm NL}} \sim 30$ TeV

As $m_U \gtrsim \Lambda_{\rm Sp}$ the next-to-lightest pion becomes the Sp(2N) η'

3. Dark matter

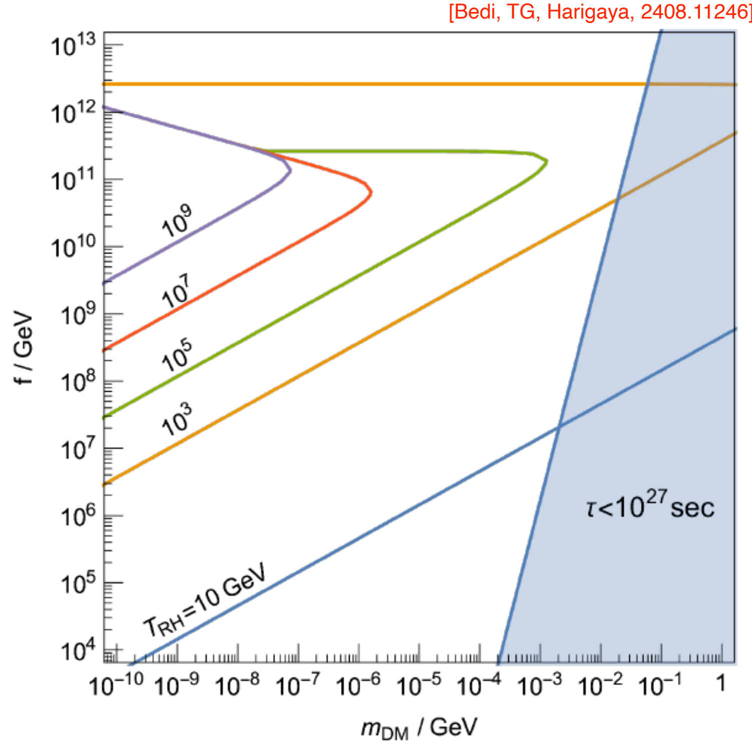
Lightest pion is massless → Generate mass by introducing explicit, small breaking of Sp fermion number

Thermal production: $$\frac{\rho_{\rm DM}}{s} \simeq 0.4\ {\rm eV} \left(\frac{10^{10}\ {\rm GeV}}{f}\right)^2 \left(\frac{m_{\rm DM}}{1\ {\rm MeV}}\right) \left(\frac{T_{\rm RH}}{10^3\ {\rm GeV}}\right) \min\left(1, \left(\frac{T_{\rm RH}}{m_Z}\right)^4\right)$$

Misalignment mechanism: $$\frac{\rho_{\rm DM}}{s} \simeq 0.4\ {\rm eV} \left(\frac{f}{10^{12}\ {\rm GeV}}\right)^2 \left(\frac{T_{\rm RH}}{10^4\ {\rm GeV}}\right) \theta_i^2 \min\left(1, \frac{\sqrt{m_{\rm DM} M_{\rm Pl}}}{T_{\rm RH}}\right)$$

Relic abundance contours for given reheat temperature

[Bedi, TG, Harigaya, 2408.11246]



horizontal or negatively sloped = misalignment dominates

positively sloped = thermal production dominates

Summary

$$SU(2N+3) \times SU(3)_T$$

$(u, \psi_u, d, \psi_d, s, \psi_s, c, \psi_c, U, \bar{U})$

chiral symmetry prevents Yukawa coupling

$(b, t, B, \bar{B})$

chiral symmetry prevents Yukawa coupling

$$Sp(2N) \times SU(3) \times SU(3)_T$$

Sp(2N) confinement spontaneously
breaks chiral symmetry

SU(3)_T instantons
generate b quark mass

$$SU(3)_{QCD}$$

(u, d, s, c, b, t)

Questions/Future Work

- Study Sp(2N) phase transition
  - — 1st order phase transition for gravitational wave signal
  - — other possible confining dynamics?
- Explore dark matter parameter space
  - — ways to explicitly break Sp fermion number
- Use spin 0 or 1/2 to mediate chiral symmetry breaking
  - — e.g. extra Higgses charged under chiral symmetry
- Implications for grand unification?
  - — embedding into string theory
- Supersymmetric extension?
  - — explain small mass scales e.g. electroweak, grand-color, Higgs-pion mixing
- ……..

Conclusion

- Strong-CP problem can be solved with massless up-quark type solution with new strong dynamics

  — *SU(3) embedded into grand-color group SU(2N+3)*

- Massless up-quark generated via ***spontaneous*** breaking of chiral symmetry

  — *Avoids product Yukawa coupling suppression, as typical for instanton effects*

- No light QCD axion, but vector-like quarks at TeV scale and axion-like particles at ~10 GeV

  — *lightest pion can be dark matter*

  — *possible gravitational wave signal from confining phase transition*