HEAVY AXION/'MASSLESS' UP FROM PARTIAL COMPOSITENESS

HiDDeN ITN webinar

Rick Sandeepan Gupta
IPPP Durham, UK

Based on: RSG, Khoze & Spannowsky (2020)

THE STRONG CP PROBLEM

$$\boxed{m^u_{ij}\bar{u}_i u_j + m^d_{ij}\bar{u}_i u_j - \frac{g_s^2\hat{\theta}_{QCD}}{32\pi^2}G\tilde{G}}$$

- Neutron EDM bounds:

$$\boxed{\theta_{QCD} = \hat{\theta}_{QCD} + \mathrm{Arg}(\det(m_u m_d)) < 10^{-10}}$$

Pendelbury *et al* (2015)

- Why is the strong CP phase so close to 0?

BUT SM NOT CP INVARIANT

$$\boxed{m^u_{ij}\bar{u}_i u_j + m^d_{ij}\bar{u}_i u_j} - \frac{g_s^2\hat{\theta}_{QCD}}{32\pi^2} G\tilde{G}$$

- Same SM fermion mass matrix has another physical phase, the CKM phase which is non-zero:

$$\boxed{\theta_{CKM} = \mathrm{Arg}(\det(m_u m_d - m_d m_u)) \approx 1.2 \text{ radians}}$$

NEW U(1): AXION & MASSLESS UP SOLUTIONS

- Introduce new abelian symmetry. This freedom allows us to rotate away this phase
- If the up is massless chiral transformation can rotate away strong CP phase
- A new U(1), the Peccei-Quinn symmetry, is introduced. This is spontaneously broken in the UV. We have the new term involving the goldstone boson, the axion,

$$\boxed{\frac{g_s^2 \phi}{32\pi^2 f} G\tilde{G}}$$

- At high scales this allows us to rotate away the strong CP phase by the shift symmetry from the (non-linearly realised) U(1)

$$\boxed{\frac{\phi}{f} \to \frac{\phi}{f} + \theta_{QCD}}$$

AXION POTENTIAL

- QCD non perturbative effects break the shift symmetry and give the axion a potential:

$$\boxed{V(\phi) = -m_u f_\pi^3 \cos\left(\frac{\phi}{f} - \theta_{QCD}\right)}$$

- Axion stabilises such that:

$$\boxed{\frac{\phi}{f} - \theta_{QCD} = 0}$$

thus solving strong CP problem

Vafa-Witten (1984)

NELSON-BARR MECHANISM

- In a third class of solutions CP (or P) is assumed to be a symmetry of nature and CKM phase is generated at some high scale via spontaneous breaking of CP

- The RG flow of θ_{QCD} due θ_{CKM} to is negligible keeping θ_{QCD} within experimental bounds at low scales.

Nelson (1984)
Barr (1984)
Babu & Mohapatra (1990)

STRONG CP PROBLEM SOLUTIONS

- Axion
- Massless up
- Nelson-Barr type solutions

Clear low-energy signature

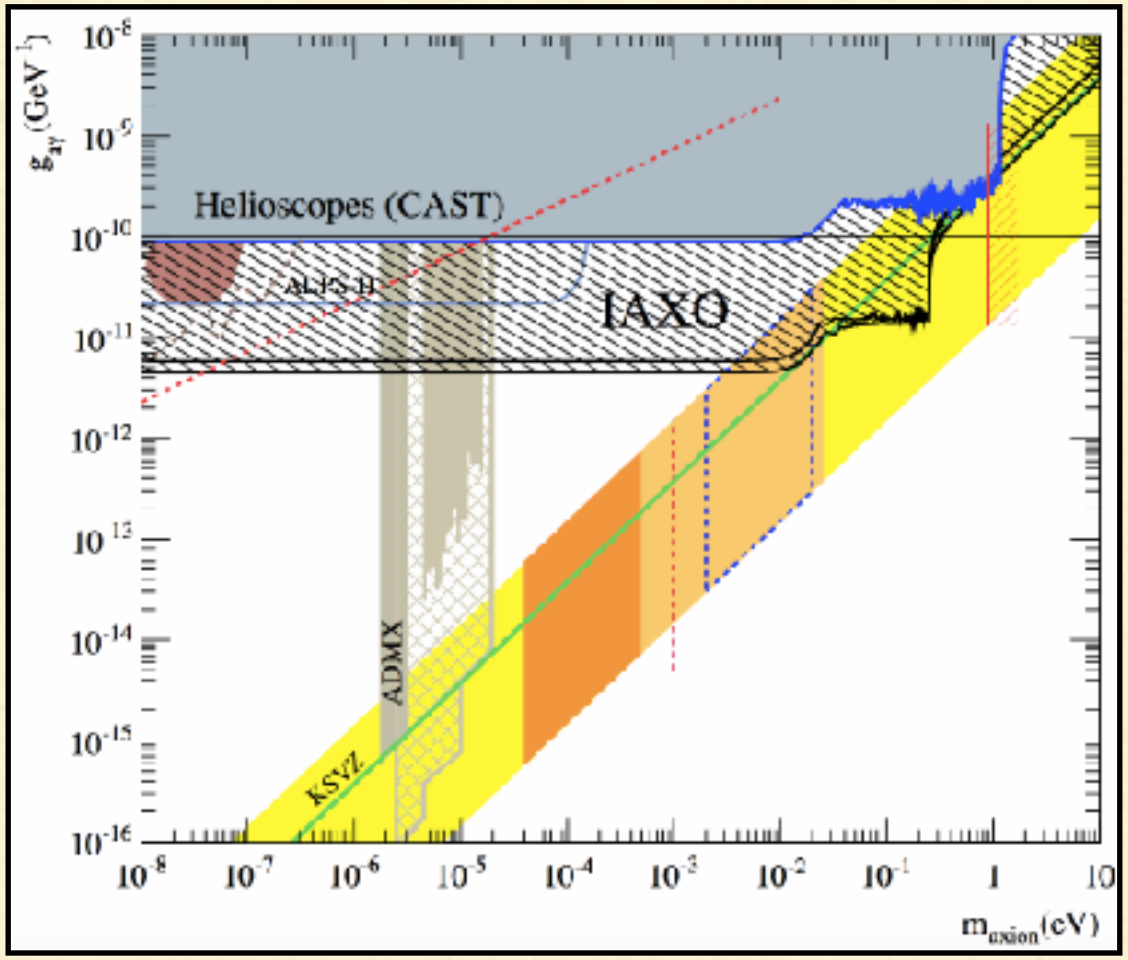
LOW ENERGY PREDICTIONS

Unlike the NB solution, the axion and massless up have unambiguous low energy predictions

1. An axion with a mass and coupling related in a precise way giving the QCD axion band

2. A massless up quark.

   seemingly ruled out by lattice data



Alexandrou *et al* (2020)

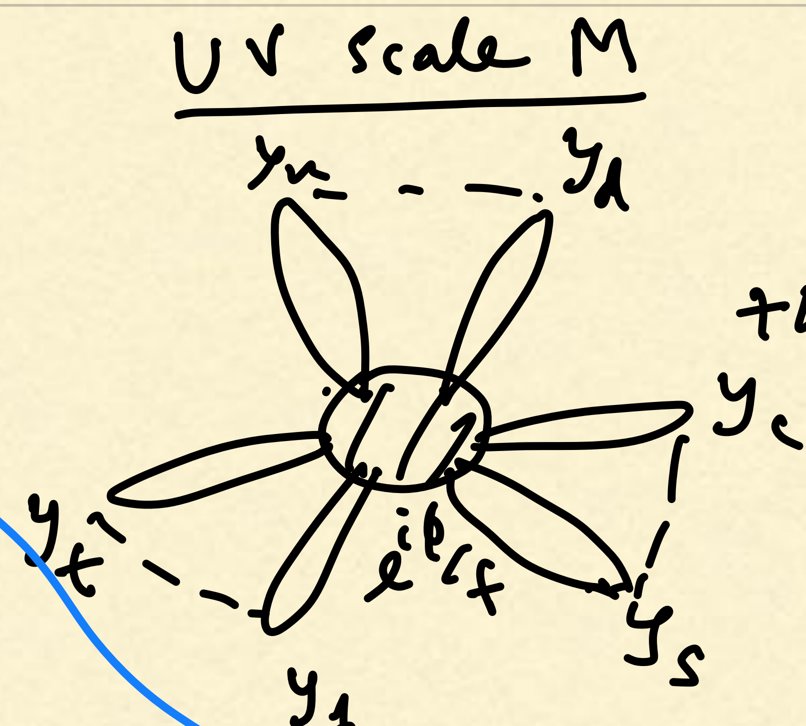
ASSUMPTION BEHIND LOW ENERGY PREDICTIONS

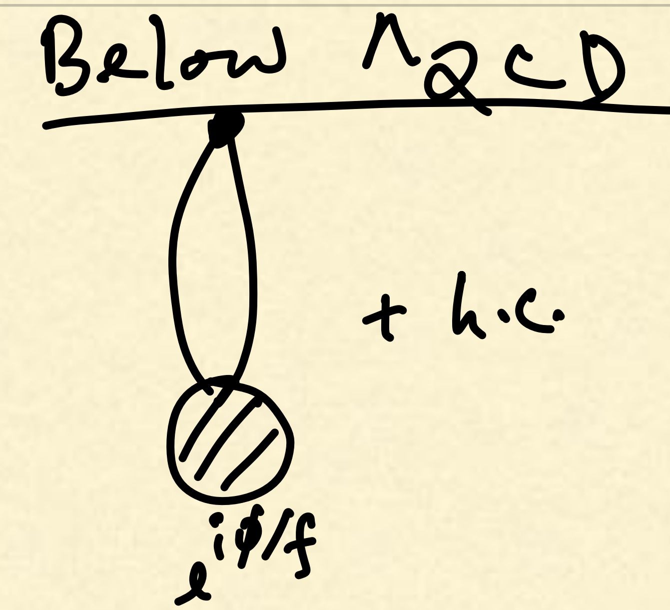
This relies on the assumption that QCD non-perturbative effects turn on only in the IR.

How robust is this assumption ?

Can we modify QCD in the UV and change these predictions ?

SMALL INSTANTONS CAN ENHANCE AXION MASS





$\kappa_f = 10^{-23}$
[Yukawa suppression]

$\kappa_s \simeq 10^{-34} - 1$
(for $g_s \simeq 1 - 4\pi$)

$$e^{-2\pi/\alpha_s(M)} \frac{y_u y_d y_c y_s y_b y_t}{(4\pi)^6} M^4 \cos\frac{\phi}{f}$$

SMALL INSTANTON

$$= m_u f_\pi^3 \cos\frac{\phi}{f}$$

LARGE INSTANTON

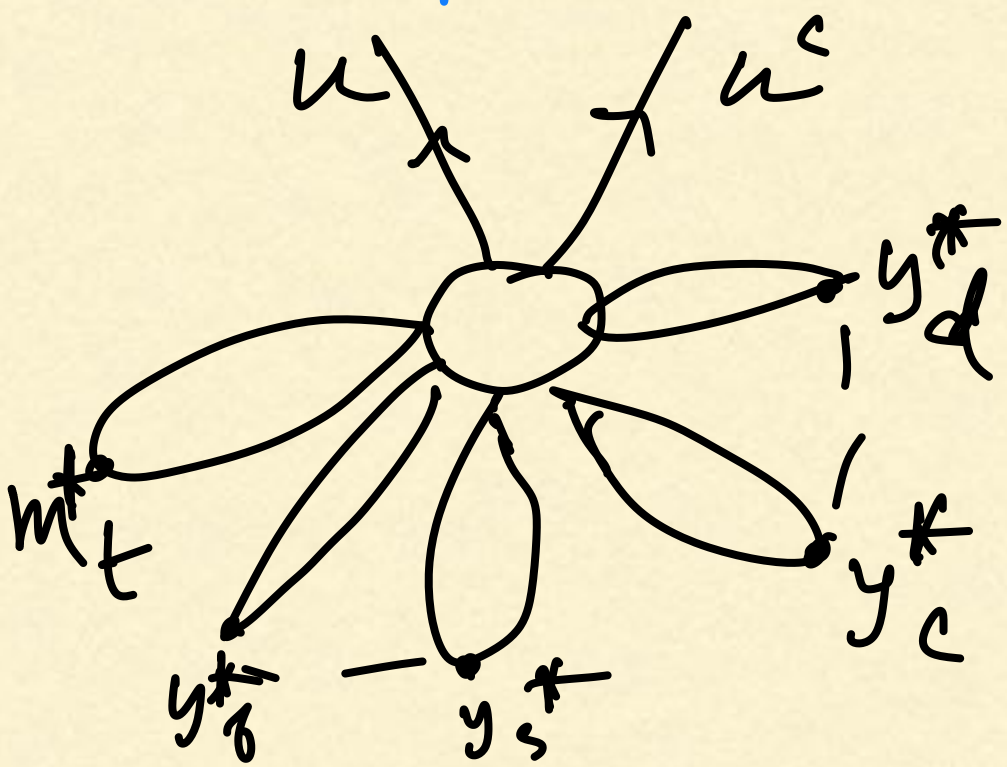
Axion potential arises from closing all the lines.

SMALL INSTANTONS CAN REVIVE MASSLESS UP SOLUTION

- Up mass can be 0 in the deep UV.
- Up mass is then generated additively entirely from instanton effects.
- In the deep UV one can use chiral rotation to remove θ_{QCD}.

SMALL INSTANTONS CAN REVIVE MASSLESS UP SOLUTION

Up mass from QCD instanton



$$y_u \sim \frac{y_b^* y_s^* y_c^* y_d^* y_t^*}{(4\pi)^4} \kappa_5$$

[Assume θ_{QCD} rotated to mass terms]

- Up mass has the right phase such that final value of θ_{QCD}=0. Possible also with IR QCD instantons but disfavoured.

Kaplan & Manohar (1986)
Choi, Kim & Sze(1988)
Banks, Nir & Seiberg (1994)
Agrawal & Howe (2017)

SMALL INSTANTONS CAN REVIVE MASSLESS UP SOLUTION

Up mass from QCD instanton

$$\bar{\theta}_{QCD} = \text{Arg Det}\left[Y_u Y_d \right] \qquad y_u \sim \frac{y_d^* y_s^* y_c^* y_d^* y_t^*}{(4\pi)^4} K_3$$

$$= \text{Arg}\left[y_d y_d^* \, y_s y_s^* \, y_c y_c^* \, y_b y_b^* \, y_t y_t^* \right] = 0$$

- Up mass has the right phase such that final value of θ_{QCD}=0. Possible also with IR QCD instantons but disfavoured.

Kaplan & Manohar (1986)
Choi, Kim & Sze(1988)
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Agrawal & Howe (2017)

MASSLESS UP IS MORE CHALLENGING

- Axion mass enhancement depends on ratio of scales

$$\frac{m_\phi^{UV}}{m_\phi^{IR}} = \kappa_5 \kappa_f \left(\frac{M}{150\ \mathrm{MeV}} \right)^4 \rightsquigarrow \text{Enhancement}$$

- Up Yukawa, dimensionless and independent of UV scale

$$y_u \sim \kappa_5 \kappa_f \rightsquigarrow \text{No enhancement}$$

OVERCOMING SMALL INSTANTON SUPPRESSION FACTORS

- The small instanton contribution in SM is suppressed because of :

1. Smallness of strong coupling (κ_s)

2. Smallness of SM Yukawa (κ_f)

OVERCOMING STRONG COUPLING SUPPRESSION

- New coloured states to alter running of α_s

Holdom & Peskin (1982)
Flynn & Randall (1987)

- QCD subgroup of enlarged color group. Eg.

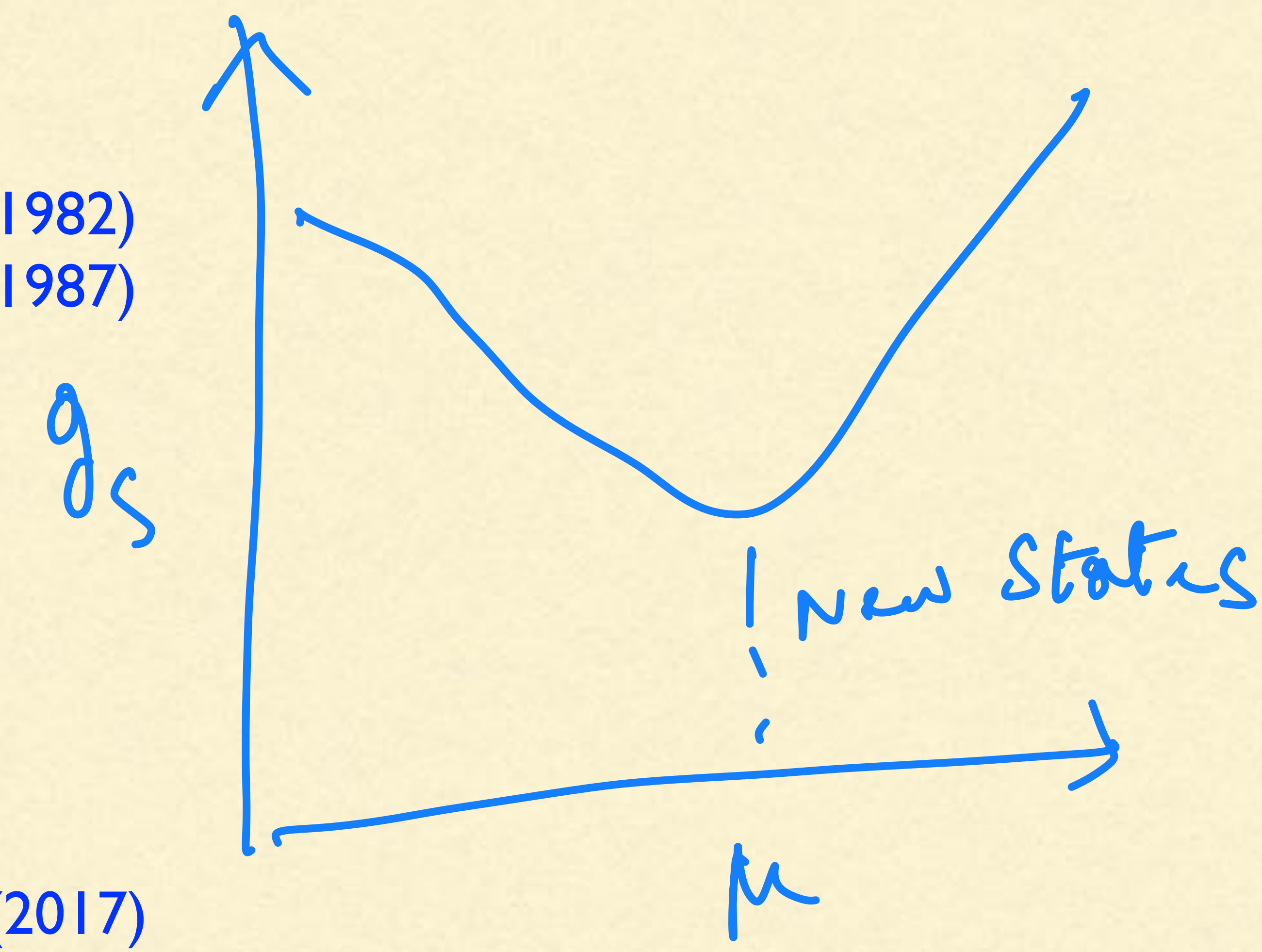
$$SU(3)_1 \times SU(3)_2 \to SU(3)_c$$

$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_{s_1}(\mu)} + \frac{1}{\alpha_{s_2}(\mu)}$$

Agrawal & Howe (2017)
Gaillard, Gavela, Houtz, Quinze, Del Ray (2018)

- Extra dimensions

Ghergetta, Khoze, Pomarol & Shirman(2020)

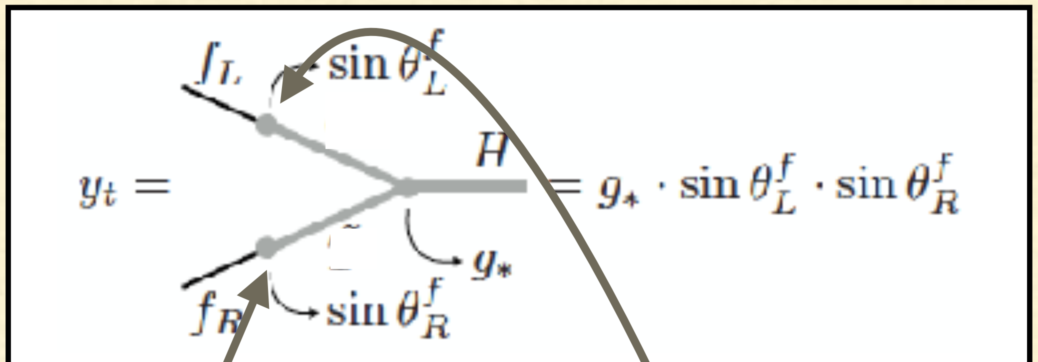


RELATION TO SM FLAVOUR PUZZLE

- In theories that address SM flavour puzzle there may be no small parameters in the UV
- Eg: Froggatt-Nielsen model, Partial Compositeness have only O(1) parameters in the UV.

We will now show that *almost* all Ingredients for ‘massless’ up solution already present in partial compositeness models. Same ingredients raise axion mass if it is present. These effects can be *almost* automatic

FLAVOUR FROM PARTIAL COMPOSITENESS



$$\mathcal{L}_{mix} = \frac{\lambda^{ij}_{u_R}}{4\pi}\frac{1}{\Lambda^{d_{U_R}-5/2}} u_R^{c,i} U_R^j + \frac{\lambda^{ij}_{u_L}}{4\pi}\frac{1}{\Lambda^{d_{U_L}-5/2}} q_L^i U_L^{c,j}$$

- Each fermion has a composite partner. The Higgs is a composite state
- These composite states map to operators in a strongly coupled theory in the UV
- Can be motivated by extra-dimensional constructions

Kaplan (1991)
Contino & Pomarol (2004)

FLAVOUR FROM PARTIAL COMPOSITENESS

$$\boxed{\lambda_{uL}^{ij}} = \boxed{\mathrm{diag}\left[y_{uL}, y_{cL}, y_{tL}\right]}$$

$$\boxed{\mu \frac{dy_f}{d\mu} = (d_F - 5/2) y_f}$$

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

- Large anomalous dimensions of the operators lead to running and exponential suppression.

- Anarchic O(1) UV structure can give rise to SM mass and mixing hierarchies

UV COMPLETION OF PARTICLE COMPOSITENESS

- We want a UV completion for the strong sector
- We follow the well-known construction of Ferretti (2014).
- We add some new states so that we have partners for all SM fermions and not just the top as in Ferretti (2014).
- No new ingredients apart from what is required to realise partial compositeness.

Ferretti (2014)

PARTICLE CONTENT AND SYMMETRY BREAKING

	$SU(4)_{HC}$	$\boxed{SU(5)}$	$SU(3)$	$SU(3)'$	$SU(3)^4_F$	$U(1)_X$	$U(1)_B$	$U(1)_{A1}$	$U(1)_{A2}$
$\boxed{\psi}$	$\mathbf{6}$	$\boxed{\mathbf{5}}$	$\mathbf{1}$	$\mathbf{1}$	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	0	$-18/5$	0
χ^i_u	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/3$	$-1/6$	1	1
$\tilde{\chi}^i_u$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$(\mathbf{1},\bar{\mathbf{3}},\mathbf{1},\mathbf{1})$	$1/3$	$1/6$	1	1
χ^j_d	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$(\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{1})$	$1/6$	$-1/6$	1	-1
$\tilde{\chi}^j_d$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$(\mathbf{1},\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$	$-1/6$	$1/6$	1	-1

$$\mathcal{L}_k = -i(\bar{\chi}^i_u \not{D}\chi^i_u + \bar{\chi}^j_d \not{D}\chi^j_d + \bar{\tilde{\chi}}^i_u \not{D}\tilde{\chi}^i_u + \bar{\tilde{\chi}}^j_d \not{D}\tilde{\chi}^j_d + \bar{\psi}\not{D}\psi)$$

Contains EW group

Ferretti (2014)
Gupta, Khoze and Spannowsky (2020)

PARTICLE CONTENT AND SYMMETRY BREAKING

New flavour symmetry (will be crucial)

	$SU(4)_{HC}$	$SU(5)$	$SU(3)$	$SU(3)'$	$\boxed{SU(3)_F^4}$	$U(1)_X$	$U(1)_B$	$U(1)_{A1}$	$U(1)_{A2}$
ψ	$\mathbf{6}$	$\mathbf{5}$	$\mathbf{1}$	$\mathbf{1}$	$(1,1,1,1)$	0	0	$-18/5$	0
χ_u^i	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$(\mathbf{3},1,1,1)$	$-1/3$	$-1/6$	1	1
$\tilde{\chi}_u^i$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$(1,\bar{\mathbf{3}},1,1)$	$1/3$	$1/6$	1	1
$\boxed{\chi_d^j}$	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$(1,1,\mathbf{3},1)$	$1/6$	$-1/6$	1	-1
$\boxed{\tilde{\chi}_d^j}$	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$(1,1,1,\bar{\mathbf{3}})$	$-1/6$	$1/6$	1	-1

$$\mathcal{L}_k = -i(\bar{\chi}_u^i \not{D} \chi_u^i + \bar{\chi}_d^j \not{D} \chi_d^j + \bar{\tilde{\chi}}_u^i \not{D} \tilde{\chi}_u^i + \bar{\tilde{\chi}}_d^j \not{D} \tilde{\chi}_d^j + \bar{\psi} \not{D} \psi)$$

New states $\boxed{\text{+ 3 copies}}$
so that all SM fermions
have partners

Ferretti (2014)
Gupta, Khoze and Spannowsky (2020)

PARTICLE CONTENT AND SYMMETRY BREAKING

Condensate:

$$\langle \psi^p \psi^q \rangle \sim \delta^{pq} \boxed{f_\psi,}\ \langle \chi_u^{p,i} \tilde{\chi}_u^{p,j} \rangle \sim \delta^{ij} \boxed{f_{\chi_u}}$$
$$\langle \chi_d^{p,i} \tilde{\chi}_d^{p,j} \rangle \sim \delta^{ij} \boxed{f_{\chi_d}}$$

TeV Scale

$$\frac{SU(5) \times SU(3) \times SU(3)' \times SU(3)_F^4 \times U(1)^4}{SO(5) \times SU(3)_c \times SU(3)_F^2 \times U(1)_X \times U(1)_B}$$

- All potential Goldstone Bosons all of which get a mass upon introduction of explicit breaking terms as we will see.

Gupta, Khoze and Spannowsky (2020)

FERMIONIC PARTNERS

$$\mathcal{O}^{c,i}_{uL} = (\chi_u \psi \chi_u)^i \quad \mathcal{O}^{i}_{uR} = (\bar{\chi}_u \bar{\psi} \tilde{\chi}_u)^i$$
$$\mathcal{O}^{c,i}_{dL} = (\chi_d \psi \chi_d)^i \quad \mathcal{O}^{i}_{dR} = (\bar{\chi}_d \bar{\psi} \tilde{\chi}_d)^i,$$

Up sector partners:

$$\begin{gathered}(\mathbf{5},\mathbf{3})_{2/3}\\ \downarrow\\ (\mathbf{3},\mathbf{2},\mathbf{2})_{2/3} + (\mathbf{3},\mathbf{1},\mathbf{1})_{2/3}\\ \downarrow\\ (\mathbf{3},\mathbf{2})_{7/6} + (\mathbf{3},\mathbf{2})_{1/6} + (\mathbf{3},\mathbf{1})_{2/3}\\ \downarrow\\ \mathbf{3}_{5/3} + 3\times\mathbf{3}_{2/3} + \mathbf{3}_{-1/3}\end{gathered}$$

Gupta, Khoze and Spannowsky (2020)

LAGRANGIAN

$$\boxed{\mathcal{L}_k = -i(\bar{\chi}_u^i \not{D} \chi_u^i + \bar{\chi}_d^j \not{D} \chi_d^j + \bar{\tilde{\chi}}_u^i \not{D} \tilde{\chi}_u^i + \bar{\tilde{\chi}}_d^j \not{D} \tilde{\chi}_d^j + \bar{\psi} \not{D} \psi)}$$

Kinetic terms

$$\boxed{\begin{aligned}\mathcal{L}_{mix} &= \frac{\lambda_{u_R}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{U_R}-5/2}}u_R^{c,i}U_R^j + \frac{\lambda_{u_L}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{U_L}-5/2}}q_L^i U_L^{c,j} \\ &+ \frac{\lambda_{d_R}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{D_R}-5/2}}d_R^{c,i}D_R^j + \frac{\lambda_{d_L}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{D_L}-5/2}}q_L^i D_L^{c,j}\end{aligned}}$$

Partial Compositeness

$$\boxed{\mathcal{L}_{new} = m_0 e^{i\theta_m}\psi_0\psi_0 + \frac{g_{4\psi}e^{i\theta_g}}{\Lambda^2}(\bar{\psi}_{-+}\bar{\sigma}_\mu\psi_0)(\bar{\psi}_{+-}\bar{\sigma}^\mu\psi_0)}$$

Gupta, Khoze and Spannowsky (2020)

LAGRANGIAN

$$\mathcal{L}_k = -i(\bar{\chi}_u^i \not{D} \chi_u^i + \bar{\chi}_d^j \not{D} \chi_d^j + \bar{\tilde{\chi}}_u^i \not{D} \tilde{\chi}_u^i + \bar{\tilde{\chi}}_d^j \not{D} \tilde{\chi}_d^j + \bar{\psi} \not{D} \psi)$$

Kinetic terms

$$\begin{aligned}\mathcal{L}_{mix} &= \frac{\lambda_{u_R}^{ij}}{4\pi} \frac{1}{\Lambda^{d_{U_R}-5/2}} u_R^{c,i} U_R^j + \frac{\lambda_{u_L}^{ij}}{4\pi} \frac{1}{\Lambda^{d_{U_L}-5/2}} q_L^i U_L^{c,j} \\ &+ \frac{\lambda_{d_R}^{ij}}{4\pi} \frac{1}{\Lambda^{d_{D_R}-5/2}} d_R^{c,i} D_R^j + \frac{\lambda_{d_L}^{ij}}{4\pi} \frac{1}{\Lambda^{d_{D_L}-5/2}} q_L^i D_L^{c,j}\end{aligned}$$

Partial Compositeness

Give masses to all goldstones

$$\mathcal{L}_{new} = m_0 e^{i\theta_m} \psi_0 \psi_0 + \frac{g_{4\psi} e^{i\theta_g}}{\Lambda^2} (\bar{\psi}_{-+} \bar{\sigma}_\mu \psi_0)(\bar{\psi}_{+-} \bar{\sigma}^\mu \psi_0)$$

Important for small instanton contributions

Only new ingredient

Gupta, Khoze and Spannowsky (2020)

RUNNING OF STRONG COUPLING

$$\boxed{\frac{dg_s}{d\log\mu} = -(11 - 2n_f/3)\frac{g_s^3}{16\pi^2}}$$

- QCD becomes strongly coupled at the M=2000 TeV scale again
- QCD instantons unsuppressed at this scale, i.e.: $\boxed{\kappa_s \sim 1}$

Gupta, Khoze and Spannowsky (2020)

RUNNING OF THE MIXING TERMS

$$\mu \frac{dy_f}{d\mu} = (d_F - 5/2) y_f + b \frac{N_{HC}\, y_f^3}{16\pi^2}$$

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

'Yukawas' O(1) at UV scale M.

SM mass/mixing suppressions from running

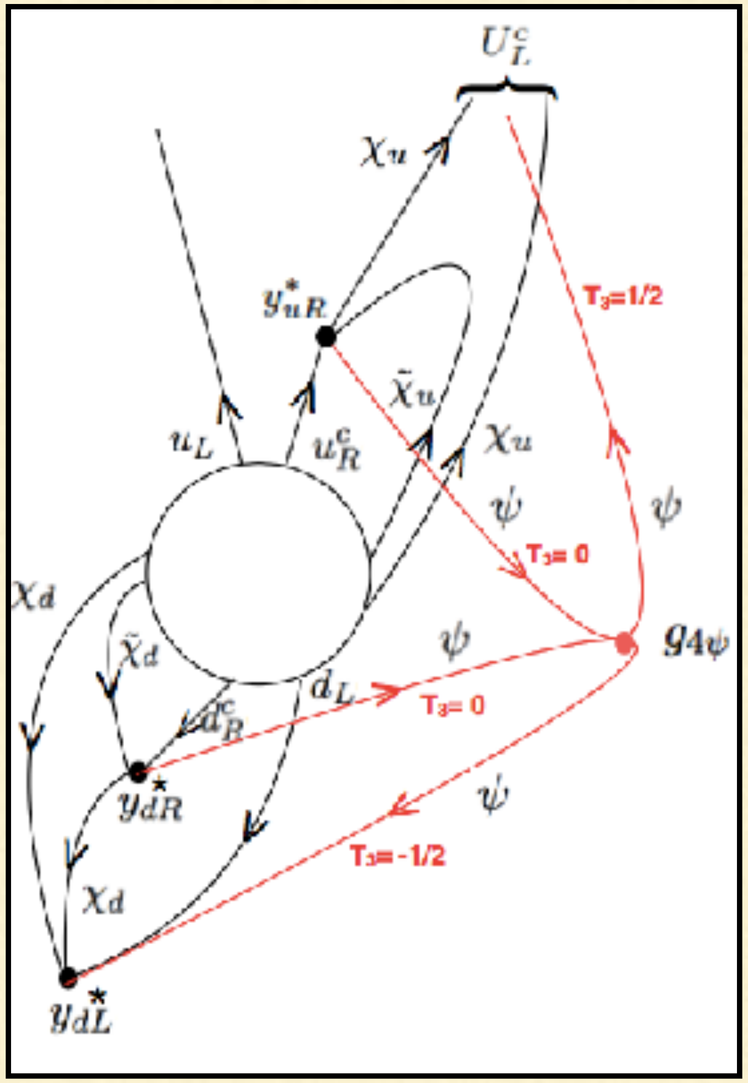
Gupta, Khoze and Spannowsky (2020)

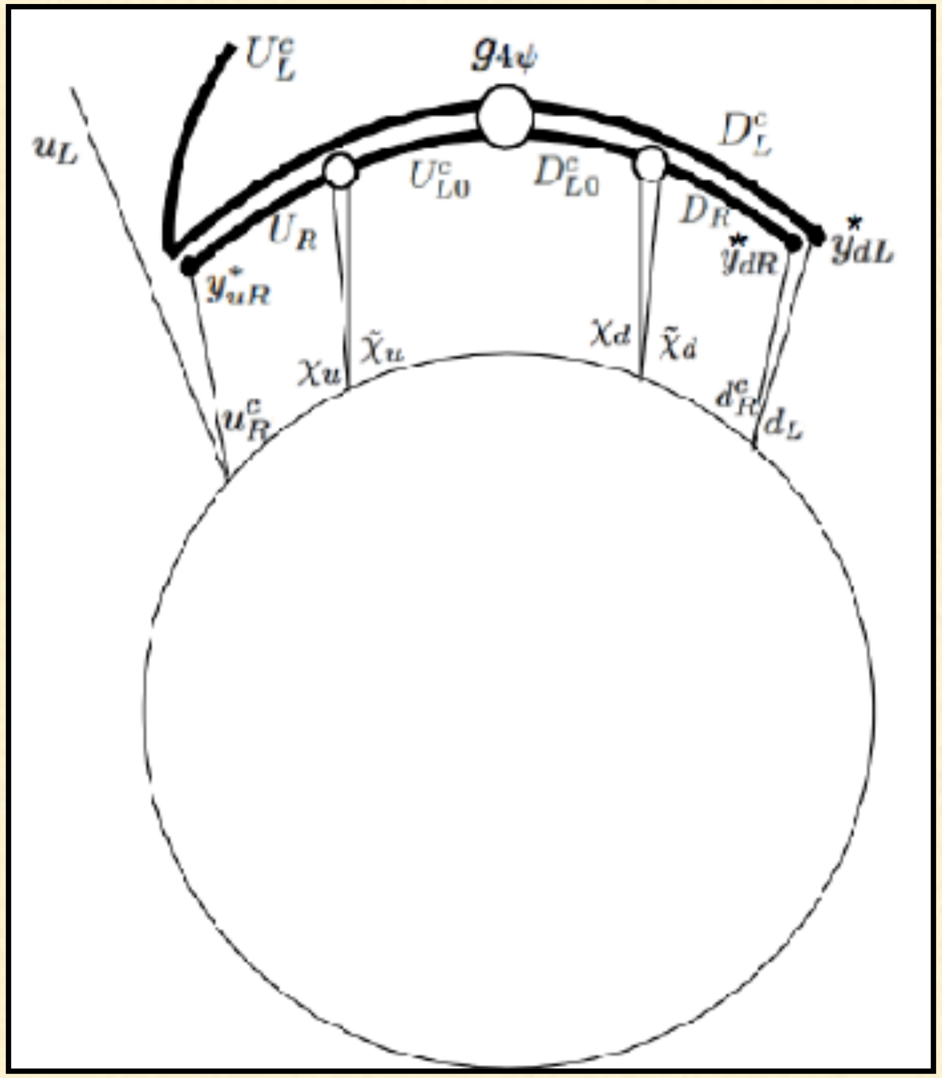
TWO SCENARIOS

- SCENARIO I: y_{uL}=0 in the deep UV and generated only additively by QCD instanton. Massless up quark solution revived
- SCENARIO II: y_{uL} non-zero but axion present. Axion becomes heavy due to instanton effects

Gupta, Khoze and Spannowsky (2020)

SCENARIO I:UP MASS FROM INSTANTON

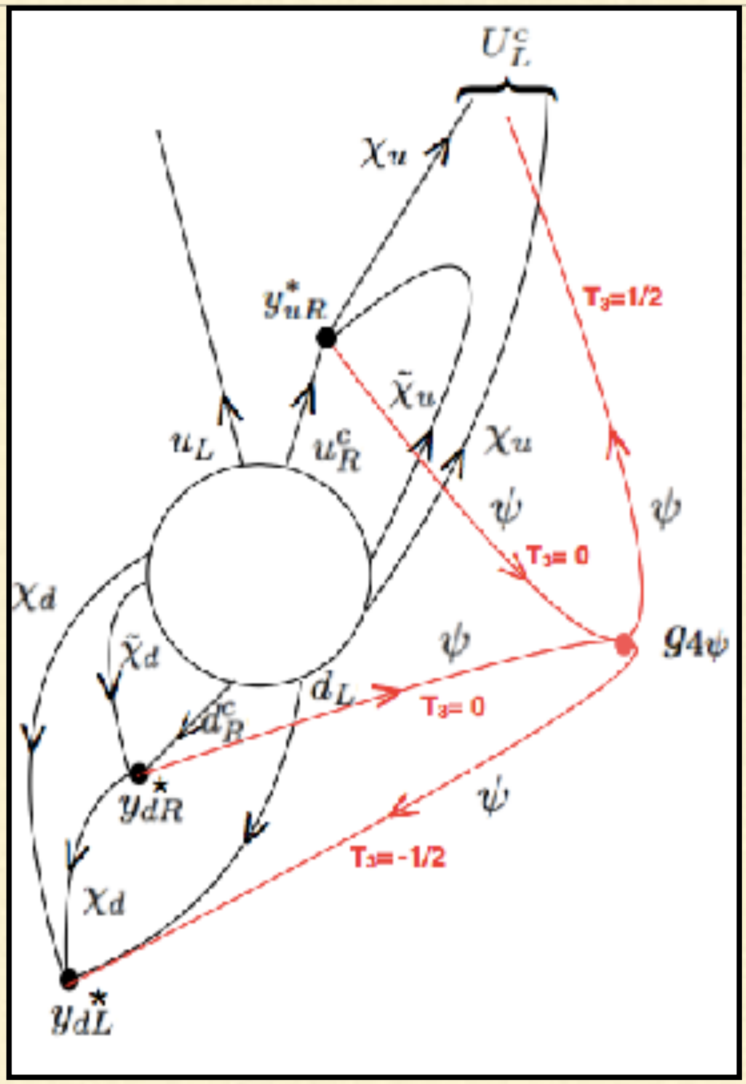


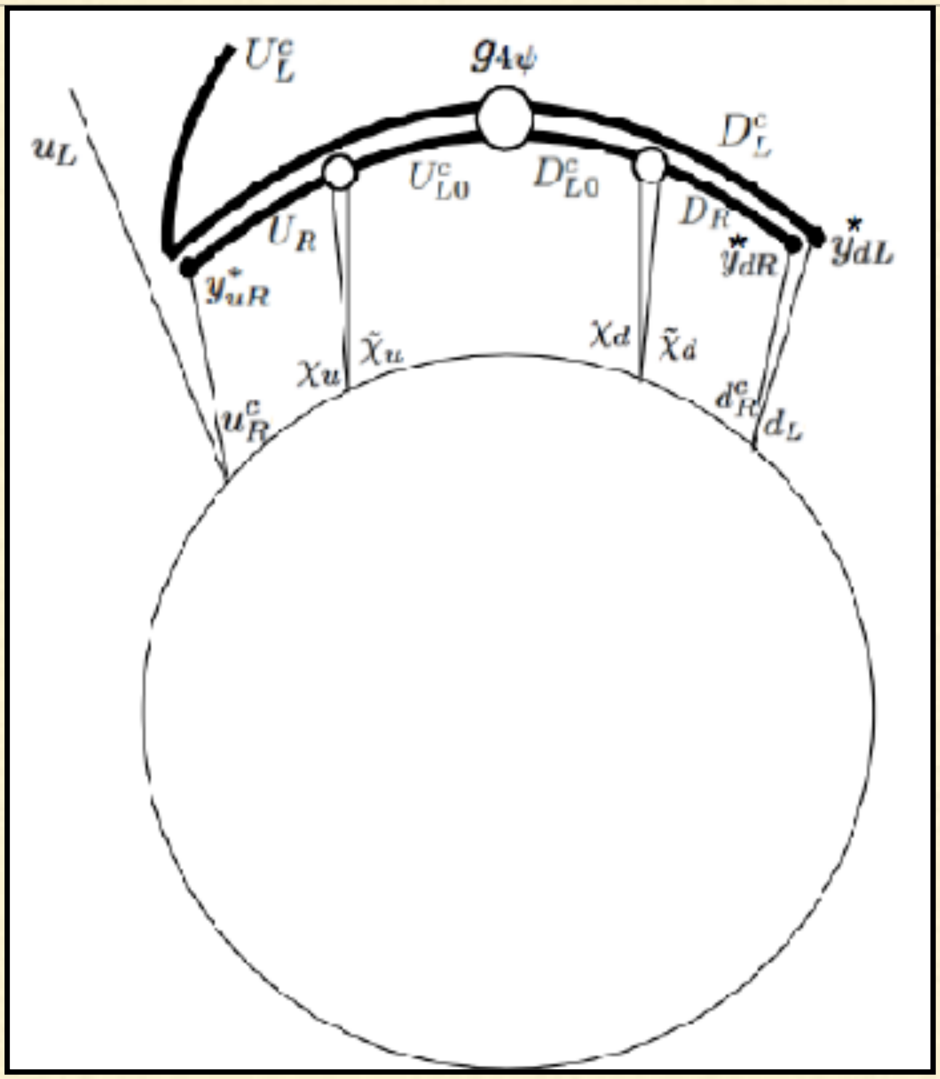


Generation of y_{uL} by QCD instanton

Gupta, Khoze and Spannowsky (2020)

SCENARIO I:UP MASS FROM INSTANTON





$$\frac{y_{uL}}{4\pi} \sim \kappa_s \left(\frac{g_{4\psi}}{16\pi^2}\right)^3 \frac{y^*_{uR}}{4\pi} \prod_{f=d,s,c,b,t} \frac{y^*_{fL}}{4\pi}\frac{y^*_{fR}}{4\pi},$$

Gupta, Khoze and Spannowsky (2020)

SCENARIO I:UP MASS FROM INSTANTON

$$\boxed{Y_u(m_\star) \sim \frac{y_{uL}(m_\star)y_{uR}(m_\star)}{4\pi} \sim 1.5 \times 10^{-5}\kappa_s \left(\frac{g_{4\psi}}{16\pi^2}\right)^3}$$

- This value was obtained by using IR values of SM Yukawa as boundary conditions
- Up Yukawa may be reproduced in the non-perturbative limit for all couplings.

Gupta, Khoze and Spannowsky (2020)

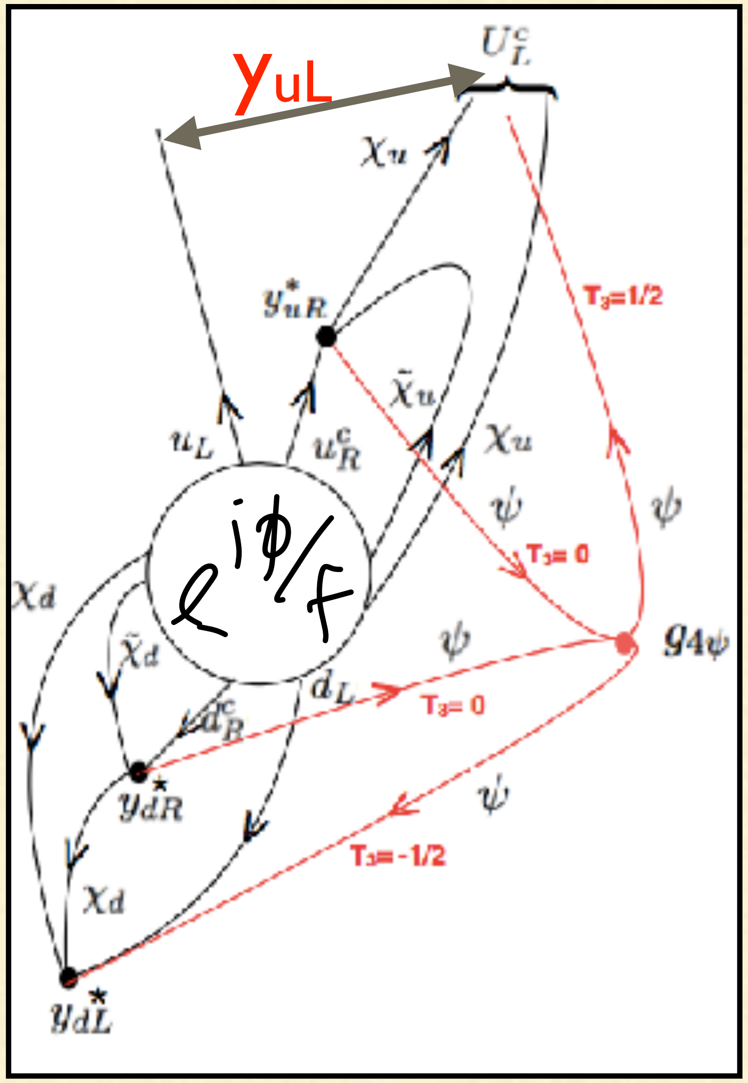
STRONG CP SOLUTION

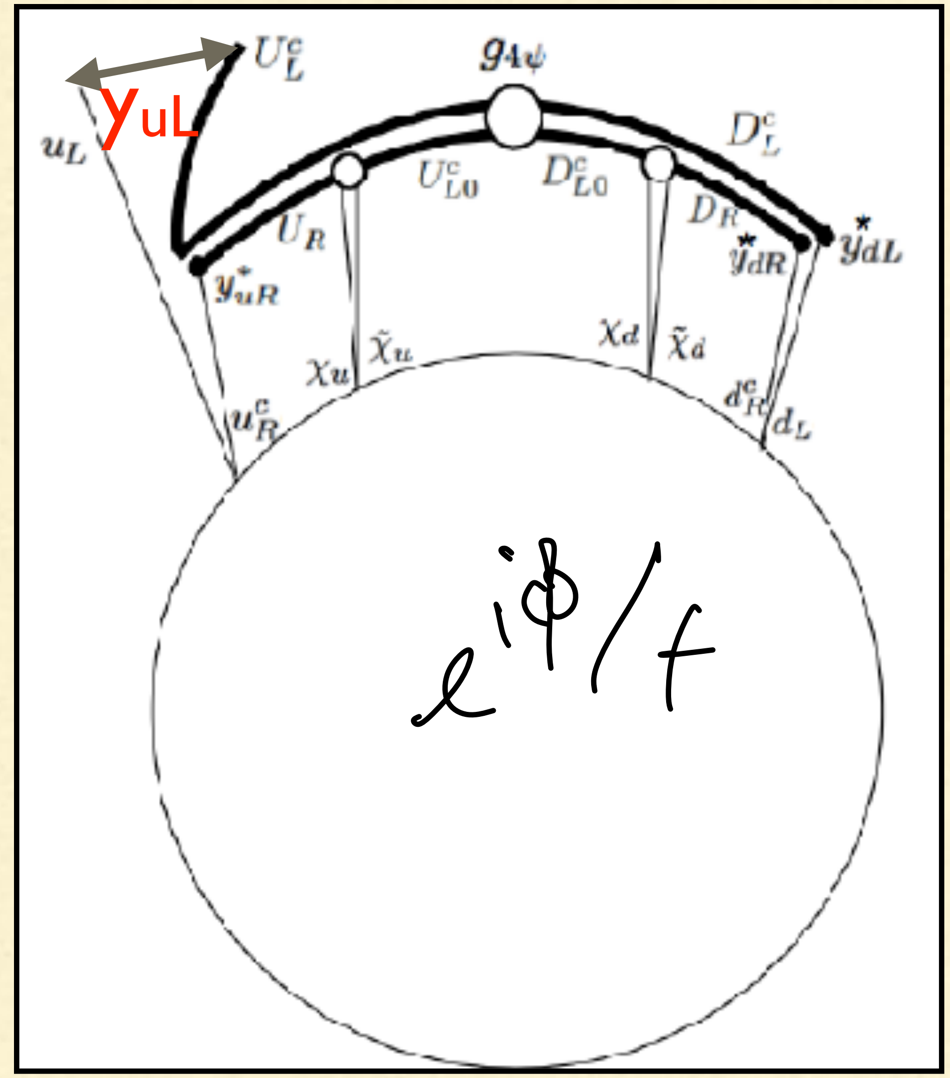
- DEEP UV: Chiral rotation of u_L can remove θ_{QCD}
- BELOW SMALL INSTANTON SCALES: y_{uL} has just the right phase to give $\theta_{QCD}=0$

$$\begin{aligned}\theta_{QCD}(M) &= \mathrm{Arg}(y^*_{uL} y^*_{uR} \prod_{f=d,s,c,b,t} y^*_{fL} y^*_{fR}) \\ &= \mathrm{Arg}(\prod_{f=u,d,s,c,b,t} |y_{fL}|^2 |y_{fR}|^2) = 0.\end{aligned}$$

Gupta, Khoze and Spannowsky (2020)

SCENARIO II: HEAVY AXION FROM INSTANTONS

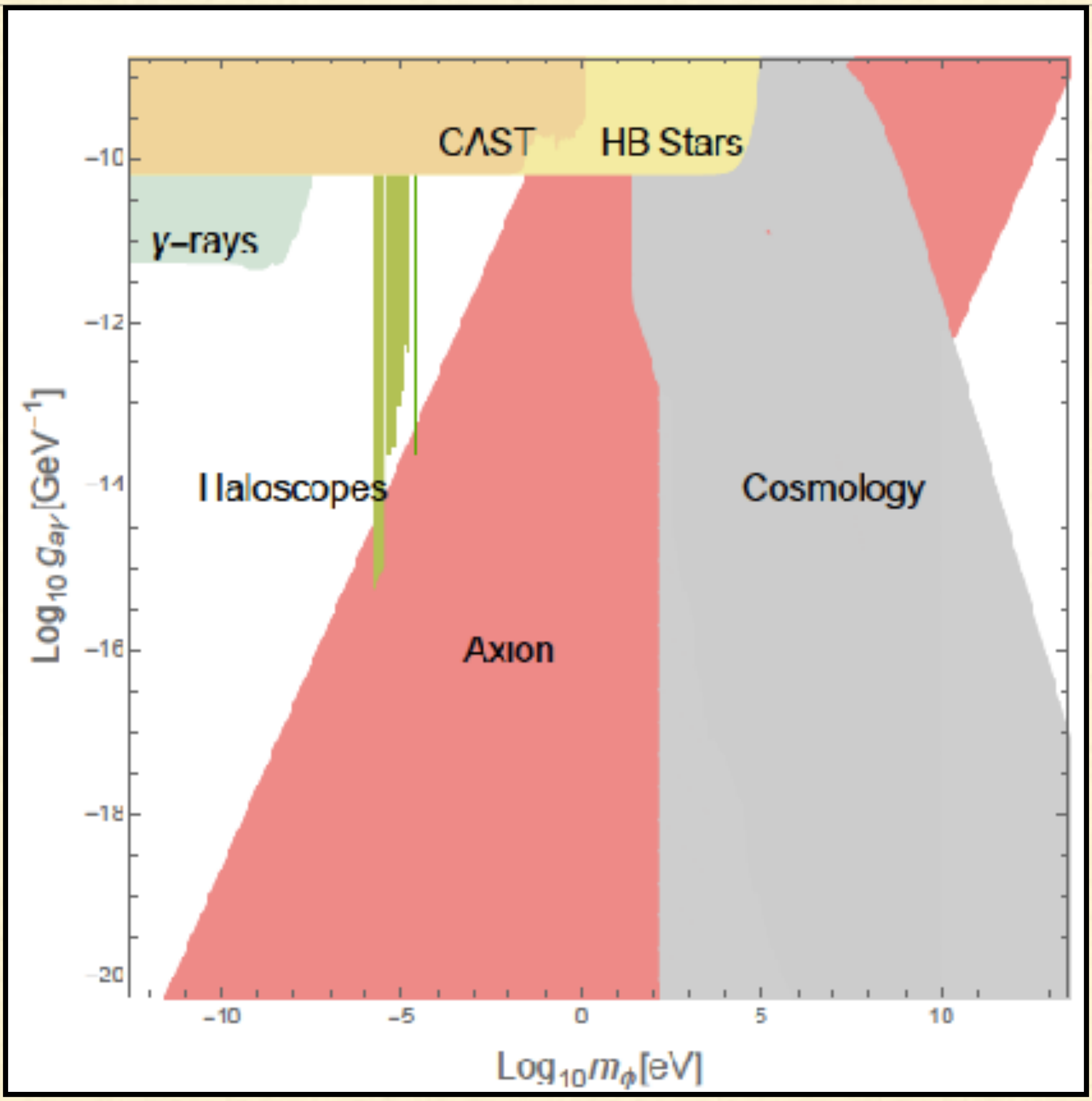




We must close all lines to obtain axion potential.

Gupta, Khoze and Spannowsky (2020)

SCENARIO II: HEAVY AXION FROM INSTANTONS



We must have f>M

$$V(\phi) = \kappa M^4 \cos\left(\frac{\phi}{f} + \bar{\theta}_{QCD}\right) + m_\pi^2 f_\pi^2 \cos\left(\frac{\phi}{f} + \bar{\theta}_{QCD}\right)$$

Gupta, Khoze and Spannowsky (2020)

OTHER PHASES/CONTRIBUTIONS ?

- Extended set ups lead to new phases usually
- Are there other phases or other ways of closing 't Hooft vertex?
- If yes this will lead to new contributions to up Yukawa/axion potential misaligned in phase. Will give a non-zero θ_{QCD}

Gupta, Khoze and Spannowsky (2020)

OTHER PHASES ?

$$\mathcal{L}_k = -i(\bar{\chi}^i_u \not{D} \chi^i_u + \bar{\chi}^j_d \not{D} \chi^j_d + \bar{\tilde{\chi}}^i_u \not{D} \tilde{\chi}^i_u + \bar{\tilde{\chi}}^j_d \not{D} \tilde{\chi}^j_d + \bar{\psi} \not{D} \psi)$$

$$\begin{aligned}\mathcal{L}_{mix} &= \frac{\lambda^{ij}_{u_R}}{4\pi} \frac{1}{\Lambda^{d_{U_R}-5/2}} u^{c,i}_R U^j_R + \frac{\lambda^{ij}_{u_L}}{4\pi} \frac{1}{\Lambda^{d_{U_L}-5/2}} q^i_L U^{c,j}_L \\ &+ \frac{\lambda^{ij}_{d_R}}{4\pi} \frac{1}{\Lambda^{d_{D_R}-5/2}} d^{c,i}_R D^j_R + \frac{\lambda^{ij}_{d_L}}{4\pi} \frac{1}{\Lambda^{d_{D_L}-5/2}} q^i_L D^{c,j}_L\end{aligned}$$

$$\mathcal{L}_{new} = m_0 e^{i\theta_m} \psi_0 \psi_0 + \frac{g_{4\psi} e^{i\theta_g}}{\Lambda^2} (\bar{\psi}_{-+} \bar{\sigma}_\mu \psi_0)(\bar{\psi}_{+-} \bar{\sigma}^\mu \psi_0)$$

1. First, the phase θ_m can be rotated away by $\psi_0 \to \psi_0 e^{-i\theta_m/2}$ which redefines θ_g, θ_R and θ'.
2. Next, the phase θ_g associated to $g_{4\psi}$ can be rotated to λ^{ij}_{uL} and λ^{ij}_{dL} by making the transformation $\psi_{-+} \to \psi_{-+} e^{i\theta_g}$. This also redefines θ'.
3. Then θ' can be eliminated by an equal rotation of all χ_i and $\tilde{\chi}_i$, which also redefines θ_{QCD}.
4. Finally θ_R can be eliminated by an equal but opposite rotation of the χ_i relative to the $\tilde{\chi}_i$.

All CP phases can be rotated to mixing terms

Gupta, Khoze and Spannowsky (2020)

MFV REALISATION

$$\mathcal{L}_{mix} = \frac{\lambda_{u_R}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{U_R}-5/2}} u_R^{c,i} U_R^j + \frac{\lambda_{u_L}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{U_L}-5/2}} q_L^i U_L^{c,j} + \frac{\lambda_{d_R}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{D_R}-5/2}} d_R^{c,i} D_R^j + \frac{\lambda_{d_L}^{ij}}{4\pi}\frac{1}{\Lambda^{d_{D_L}-5/2}} q_L^i D_L^{c,j}$$

$$\lambda_{uR,dR}^{ij} \sim y_{uR,dR}\, e^{i\theta_R}\delta^{ij}$$

$$Y_u^{ij} \sim \frac{\lambda_{uL}^{ik}\lambda_{uR}^{kj}}{4\pi} \sim \lambda_{uL}^{ij} y_{uR}$$

$$Y_d^{ij} \sim \frac{\lambda_{dL}^{ik}\lambda_{dR}^{kj}}{4\pi} \sim \lambda_{dL}^{ij} y_{dR}$$

Only two phases as in SM: $\bar{\theta}_{QCD} = \theta_{QCD} + \mathrm{ArgDet}\left[\lambda_u \lambda_d\right]$

$\theta_{CKM} = \mathrm{ArgDet}\left[\lambda_u\lambda_d - \lambda_d\lambda_u\right]$

Redi & Wulzer (2014)

Gupta, Khoze and Spannowsky (2020)

CKM PHASE ONLY OTHER PHASE

- What about contribution of CKM phase to running of θ_{QCD} in SM
- In SM this is 7 loop suppressed.
- In this model it is even more suppressed !
- Our model is secretly an NB model!

Gupta, Khoze and Spannowsky (2020)

CONCLUSIONS

- Strong CP problem solutions such as massless up solution and axion solution have clear low energy predictions
- These predictions assume QCD instantons are important only in the IR
- Small instantons can become important in some scenarios
- This happens automatically in partial compositeness yielding heavy axion/ 'massless' up solution