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Solving the Stong CP Problem with Heavy Axions With Composite Higgs

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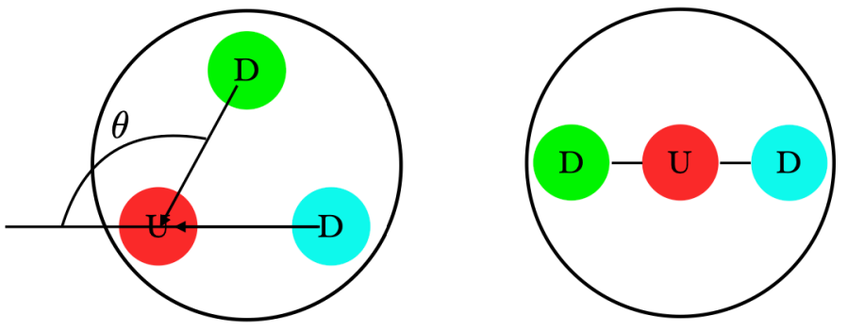
Based on: 2606.xxxx, with D. Lin, T. Ma, V. Risi (ICTP-AP), and G.Cacciapaglia (LPTHE)

Strong CP & Axion

- Strong CP problem

$$\mathscr{L} \supset \frac{\bar{\theta}}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$



→ neutron eDM

→ $\bar{\theta} \lesssim 10^{-10}$

[Anson Hook, 1812.02669]

Why such tiny?

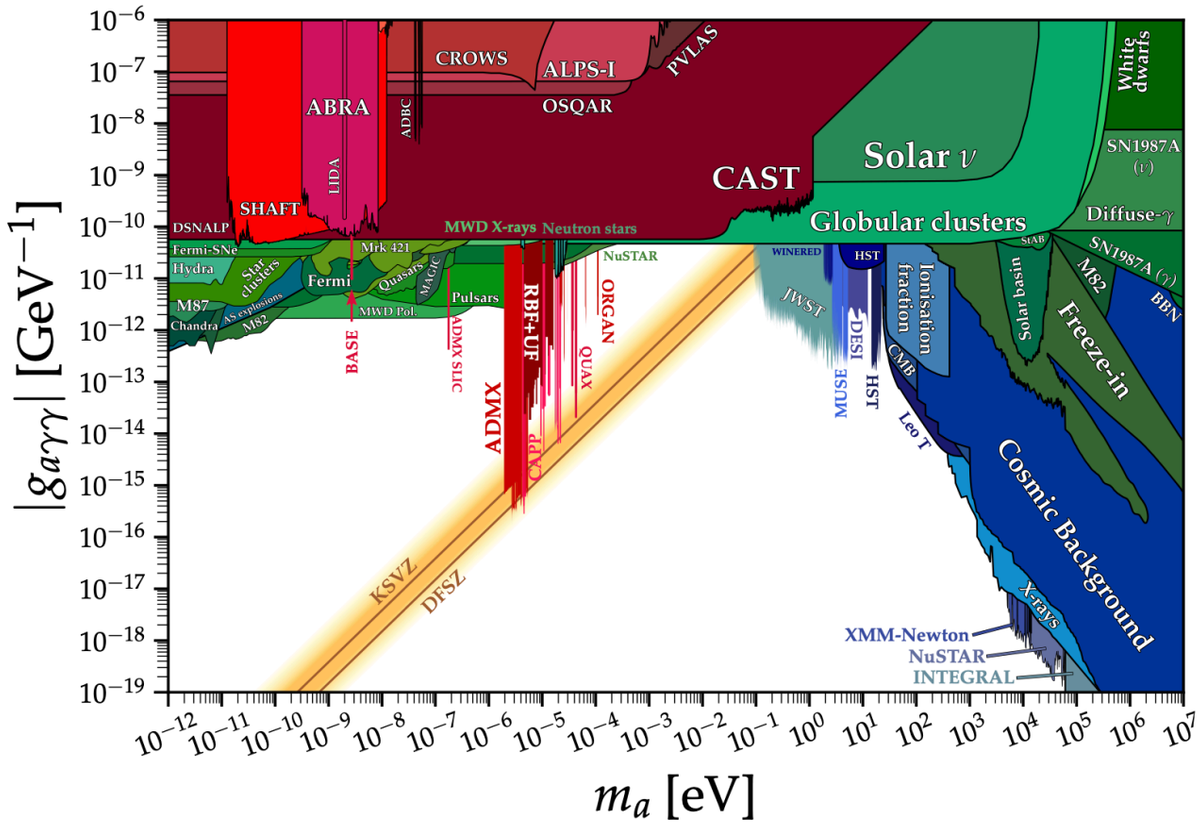
- Axion $\mathscr{L} \sim (\theta + \frac{a}{f_a}) F\tilde{F}$
  - Dynamically relaxing

$$\langle a \rangle = -f_a \bar{\theta}$$

  - QCD axion

Very light

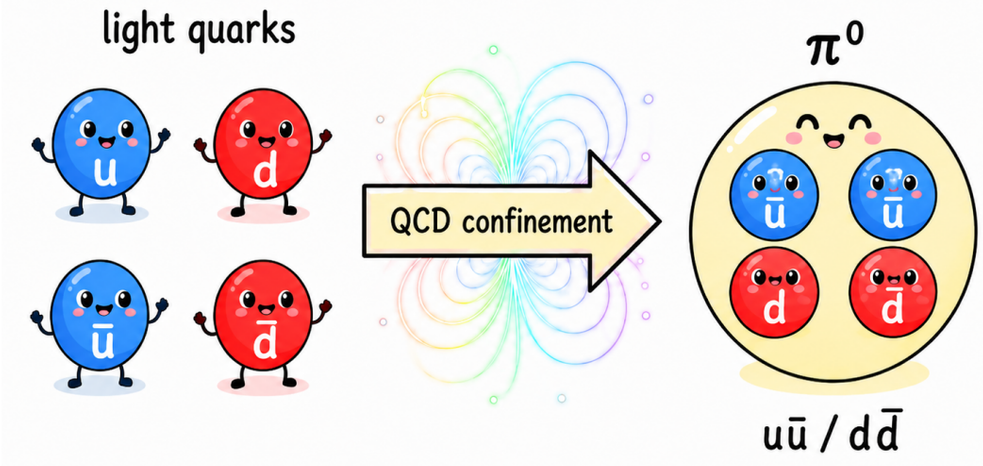
[PDG, 2025]



Motivations

- What if heavier axions
  - Feasibility @ exp facilities
  - to be high quality

- QCD revisited



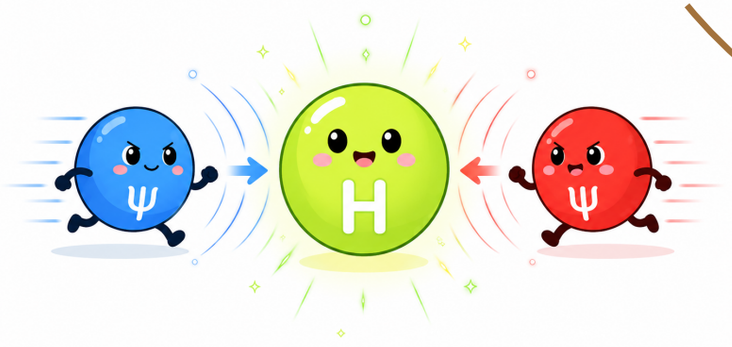
$$m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

Confinement!

- A TC sector?

Composite Higgs

$$\{m_q, f_\pi\} \rightarrow \{m_{TC}, f_H\}$$



To be heavy

Analogy to QCD

Model

- Gauge: $SU(7) \times Sp(4)' \times U(1)'_Y \times SU(2)_L$

Diagonally

$$SU(3)_c \times Sp(4)_{TC} \times U(1)_Y$$

$$\mathscr{L} \supset (\theta_7 + \frac{a_7}{f_a}) F_7 \tilde{F}_7 + (\theta_4 + \frac{a_4}{f_a}) F_4 \tilde{F}_4$$

2 axions!

- Particles
  - SM quarks in Ψ
  - TC fermions as ψ
  - Bifundamental scalars

Field	$SU(7)$	$Sp(4)'_{TC}$	$SU(2)_L$	$U(1)'_Y$
Ψ_1	$\bar{7}$	1	1	$-\frac{4}{7}$
Ψ_2	$\bar{7}$	1	1	$\frac{3}{7}$
Ψ_3	7	1	2	$\frac{1}{14}$
L	1	1	2	$-\frac{1}{2}$
e^c_R	1	1	1	1
ψ_{12}	1	4	2	0
ψ_3	1	4	1	$\frac{1}{2}$
ψ_4	1	4	1	$-\frac{1}{2}$
Σ_{TC}	7	4	1	$\frac{1}{14}$
Σ	7	4	1	$\frac{1}{14}$
$(X_i\ ,\ Y_i)$	$(7\ ,\ \bar{7})$	1	1	$(\frac{1}{14}\ ,\ -\frac{1}{14})$

Interactions

$$\mathscr{L} \supset y\Psi\Sigma\psi + M_{ij}\psi_i\psi_j$$

- TC fermions to confine
  - TC direction in Ψ: mixing with ψ $\quad M_\psi \sim \begin{pmatrix} 0 & y\langle\Sigma\rangle \\ y\langle\Sigma\rangle & M \end{pmatrix}$
  - Seesaw

$$m_H \sim M \quad \text{to decouple}$$

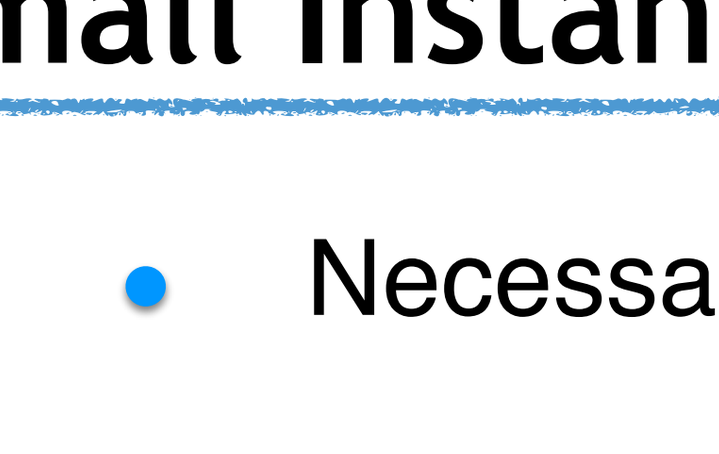
$$m_L \sim \frac{y^2\langle\Sigma\rangle^2}{M} \quad \text{to confine}$$

- SM Yukawa
  - By integrating out Σ $\quad (y_u,\, y_d) \sim \left(\frac{y_1 y_3}{\Lambda^2}\theta_{12}\theta_3,\, \frac{y_2 y_3}{\Lambda^2}\theta_{12}\theta_3\right)$
  - Partial compositeness of $(\Sigma\psi)$-system

Small Instanton

- Necessary to have 2 heavy sources

- $Sp(4)$-small instanton, up to breaking size



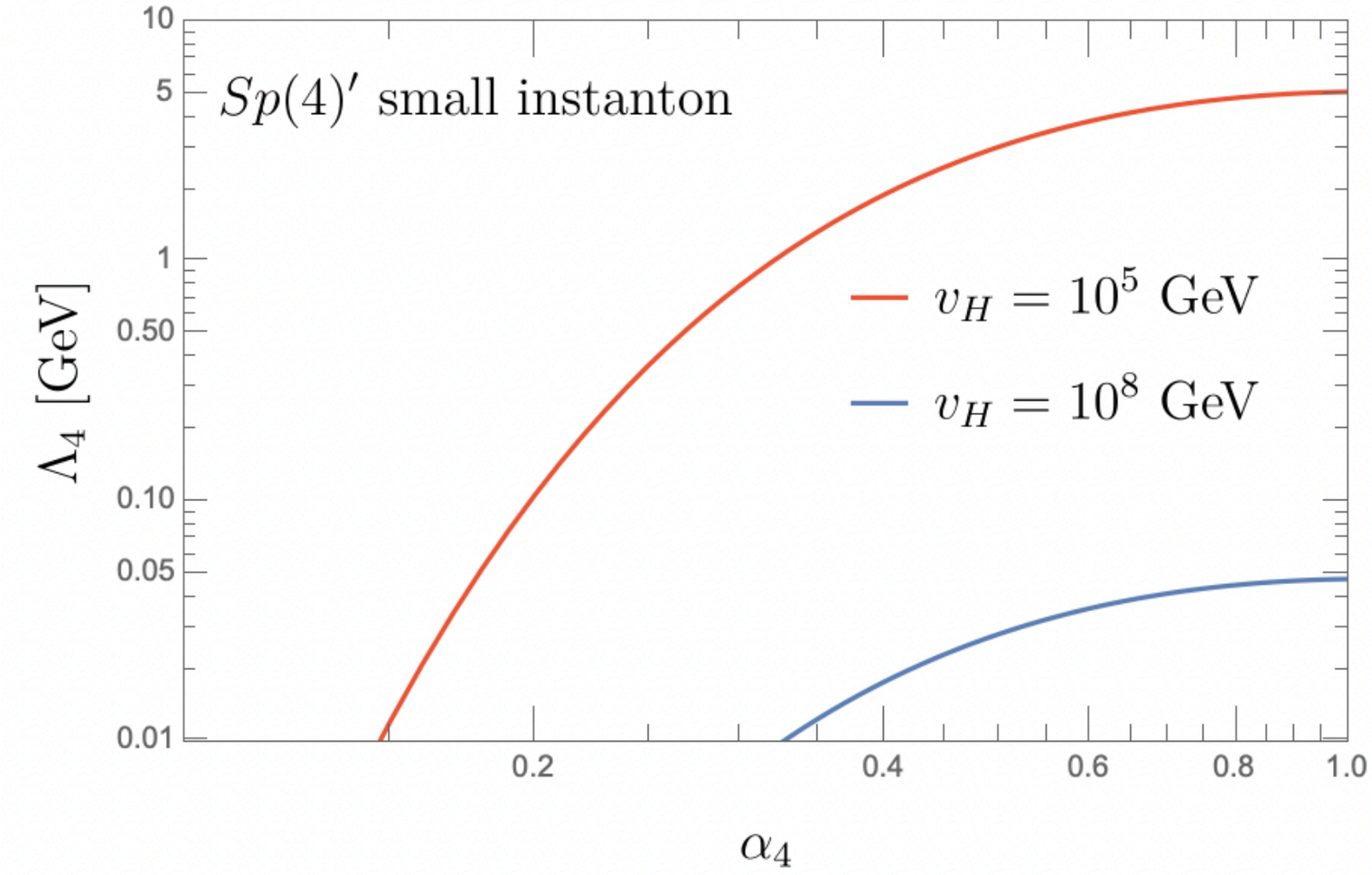
[Csaki et. al., 2311.09285]

$$V_a \supset \Lambda_4^4 \cos(\bar{\theta}_4 + \frac{a}{f_a})$$

$$\Lambda_4^4 \sim \kappa_{sp4} \int_0^{v_H^{-1}} \frac{2d\rho}{\rho^5} (v_H \rho)^{b_4} (\frac{2\pi}{\alpha_4})^6 e^{-\frac{2\pi}{\alpha_4}} \prod_i (m_i \rho)$$

Fermion zero-mode suppression

Small Instanton



- $\Lambda_4 \sim \mathcal{O}(1)$ GeV

$$\delta m_a \sim \frac{\Lambda_4^2}{f_a} \sim \frac{\Lambda_4^2}{10^{12}\ \text{GeV}} \sim 10^{-3}\ \text{eV}$$

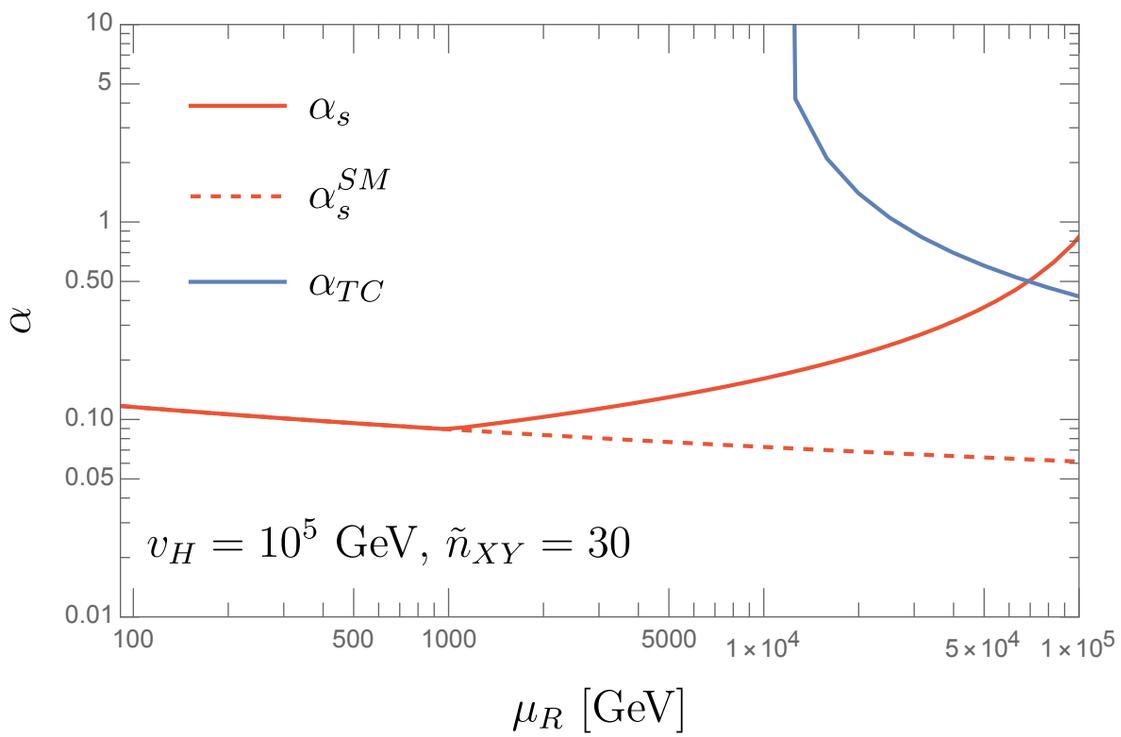
- $\Lambda_4 \sim v_H \cdot (\frac{m}{v_H})^k$

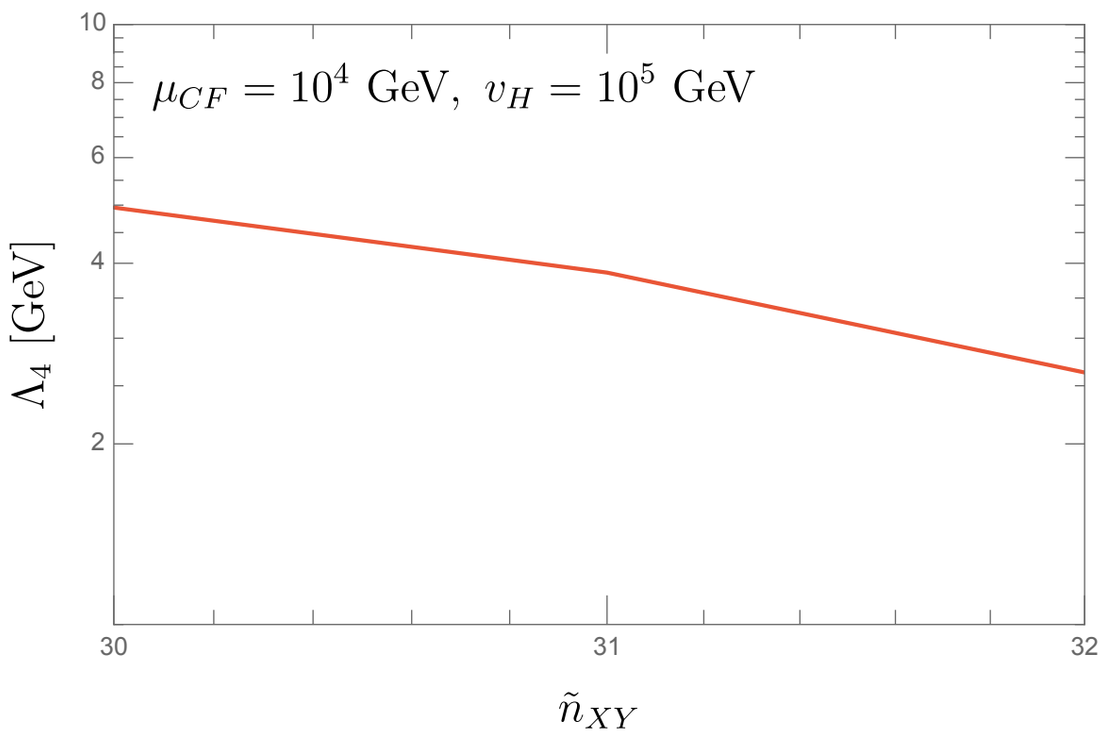
vev enhancement

vs. fermion mass suppression

RG Running

- Some conditions
  - matching $$\frac{1}{\alpha_s(v_H)} + \frac{1}{\alpha_4(v_H)} = \frac{1}{\alpha_{TC}(v_H)}$$
  - TC confinement α_{TC} to confine at 10 TeV
  - α_s away from the SM, due to (X, Y) pairs





Mass Spectrum

- Composite Higgs

$$V_{\text{mass}} = -\frac{1}{2} C_m f^3 \text{Tr}\left[M_{TC}\Sigma + \Sigma^\dagger M_{TC}^\dagger\right]$$

- Axion system

$$(a_4\ ,\ a_7\ ,\ \eta') \begin{pmatrix} \frac{f^3\mu}{4f_a^2} + \frac{\Lambda_2^4}{f_a^2} & \frac{f^3\mu}{4f_a^2} & \frac{f^2\mu}{f_a} \\ & \frac{f^3\mu}{4f_a^2} & \frac{f^2\mu}{f_a} \\ & & 16a_{TC} + 4f\mu \end{pmatrix} \begin{pmatrix} a_4 \\ a_7 \\ \eta' \end{pmatrix}$$

  - η': super heavy to be around TeV

  - $\Lambda_4 = 5$ GeV: two mass eigenstates

$$m_{aL} \sim \frac{\Lambda_4^2}{\sqrt{2} f_a} \sim 0.018 \text{ eV} \qquad m_{aH} \sim \frac{\sqrt{\mu f^3}}{\sqrt{2} f_a} \sim 20 \text{ eV}$$

$$a_L = a_4 - a_7 \qquad a_H = a_4 + a_7$$

10^4 (10^7) times heavier than QCD axion

Summary

- Compatibility: axion & composite higgs
- Heavy mass: TC confinement & small instanton
- An enhanced small instanton?
- Pheno with more details…