QCD axions beyond the QCD axion

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[1708.05008] Gustavo Marques-Tavares, Wei Xue

The strong CP problem

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s \theta}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu} + y_u Q H u^c + y_d Q \widetilde{H} d^c$$

Two sources of CP violation

$$\delta_{\rm CKM} = \arg\det\left[y_u y_u^\dagger, y_d y_d^\dagger\right] \simeq \mathcal{O}(1)$$

$$\bar{\theta} = \arg\det\left(e^{i\theta} y_u^\dagger y_d^\dagger\right) \lesssim 10^{-10}$$

[neutron EDM]

Sequestered from the CKM phase
No anthropic selection
An unobserved renormalizable term in the SM

[Ellis, Gaillard,1979]

The QCD Axion

A Peccei-Quinn U(1) global symmetry

Anomalous with QCD

$$\psi \to e^{i\phi}\psi$$

$$\theta \to \theta + \frac{\alpha_s}{8\pi}\phi$$

Spontaneously broken at some high scale F_a

Axion: the (pseudo)-Nambu Goldstone Boson

[Peccei, Quinn 1977]

[Weinberg 1978]

[Wilczek 1978]

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} + \frac{\theta + a/f_a}{8\pi}\alpha_s G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + y_u Q H u^c + y_d Q \widetilde{H} d^c$$

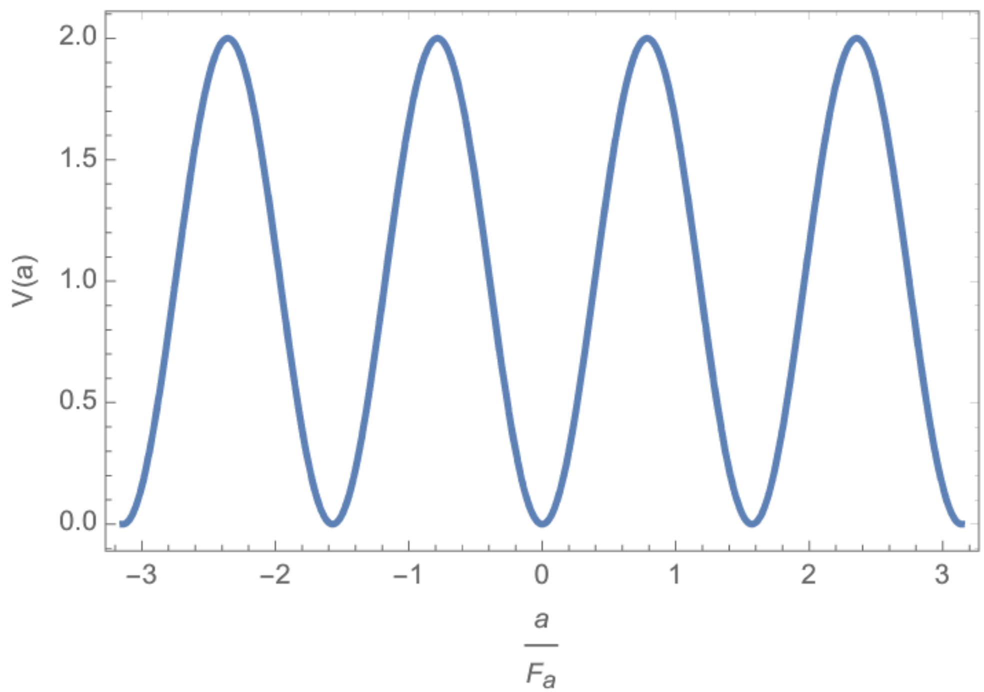
QCD breaks the shift symmetry to a discrete shift symmetry

QCD Axion solves strong-CP

QCD dynamics give axion a potential

$$V(a) \simeq -f_\pi^2 m_\pi^2 \cos\left(\theta + \frac{a}{f_a}\right)$$

[Vafa, Witten 1984]



Dynamically solves the strong CP problem

Axion Dark Matter

The axion is naturally misaligned from its minimum in the early universe

[Abbott, Sikivie 1983]
[Dine, Fischler 1983]
[Preskill, Wise, Wilczek 1983]

Coherent oscillations of the axion make a classical fluid

Equation of state

$$w = \left\langle \frac{\frac{1}{2}\dot{a}^2 - V(a)}{\frac{1}{2}\dot{a}^2 + V(a)} \right\rangle = 0$$

Inherits fluctuations from inflation

The axion is a very well-motivated dark matter candidate

Axion cosmology

Assume PQ symmetry is broken before inflation

Inflation ensures entire hubble patch has the same θ

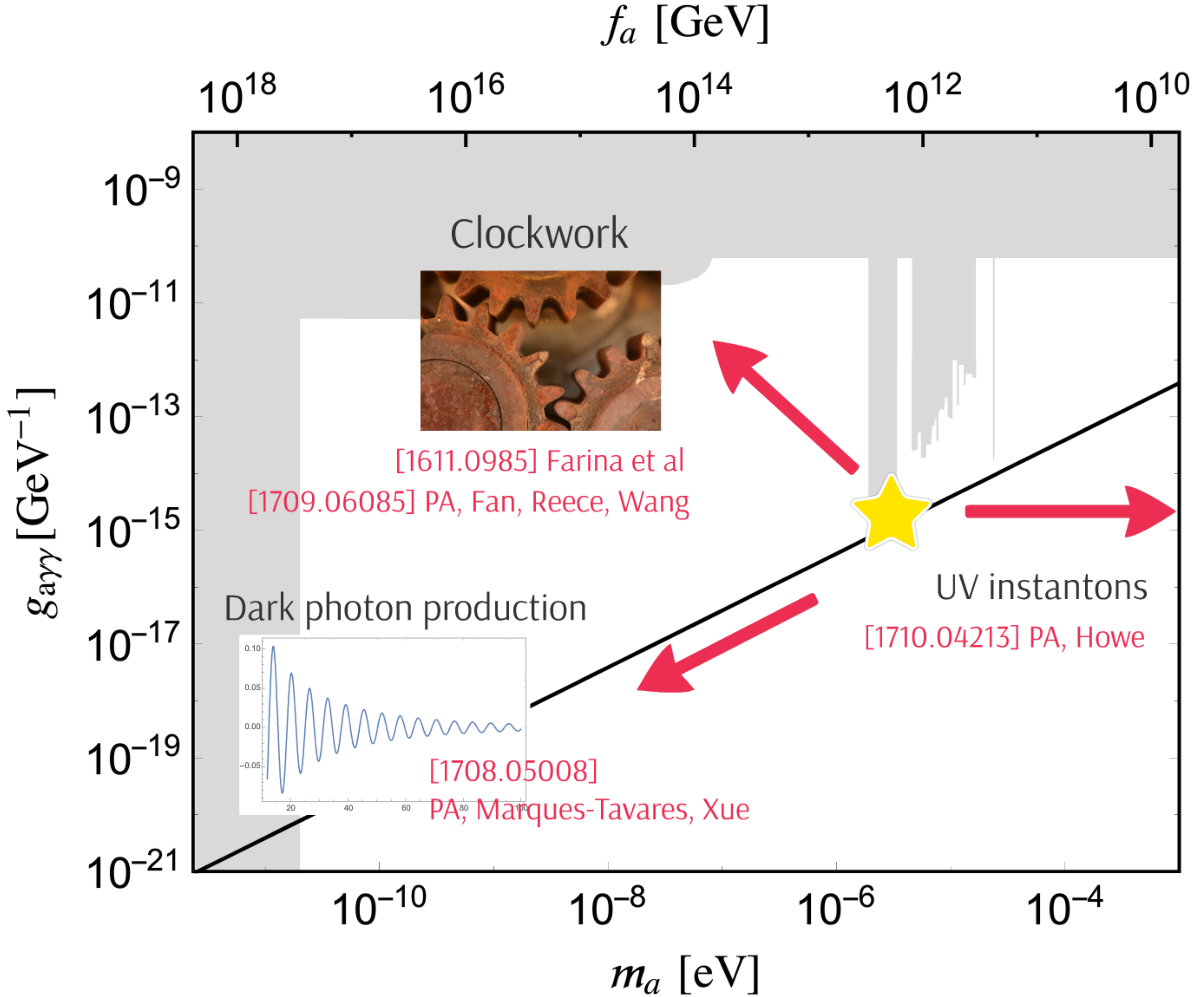
Ω_a set by the misalignment mechanism

Axion starts oscillating when $H \simeq m_a$

$$\rho_a(T_{osc}) = m_a^2 f_a^2 \theta_i^2$$

Subsequent evolution conserves axion number (adiabatic evolution)

$$\Omega_a h^2 \simeq 0.1 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^{7/6} \theta_i^2$$



f_a [GeV]
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
$g_{a\gamma\gamma}$ [GeV^{-1}]
Clockwork
[1611.0985] Farina et al
[1709.06085] PA, Fan, Reece, Wang
UV instantons
[1710.04213] PA, Howe
Dark photon production
[1708.05008]
PA, Marques-Tavares, Xue
10^{-10}
10^{-8}
10^{-6}
10^{-4}
m_a [eV]

Heavy QCD axion

Mass of the axion is a robust IR prediction

$$V(a) \simeq -f_\pi^2 m_\pi^2 \cos\left(\theta + \frac{a}{f_a}\right) + V_{new}(a)$$

New contributions to the mass in general not be aligned with $\theta = 0$

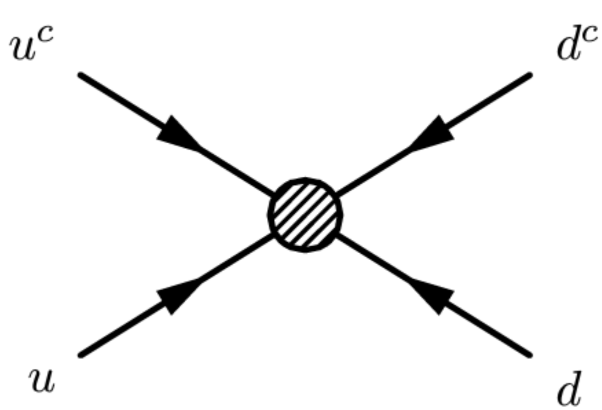
Contribution from UV instantons is naturally aligned, but too small in QCD

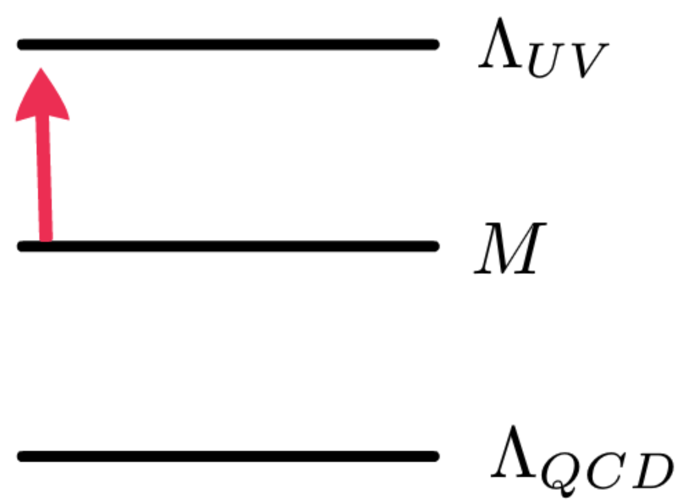
UV instantons

Two-flavor example

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} + \frac{\theta + a/f_a}{8\pi}\alpha_s G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + y_u Q H u^c + y_d Q \widetilde{H} d^c$$

Contributions above a scale M captured by 't Hooft vertex





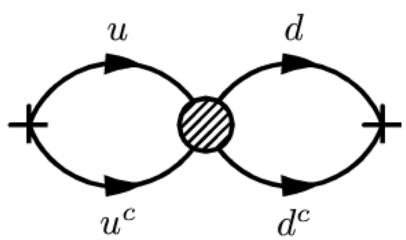
$$\mathcal{L}_{\text{eff}} = 2e^{i(\theta + a/f_a)} \int_0^{1/M} \frac{d\rho}{\rho^5}\rho^6 \langle u u^c d d^c\rangle\, e^{-2\pi/\alpha}\left(\frac{2\pi}{\alpha}\right)^6 + \text{h.c.}$$

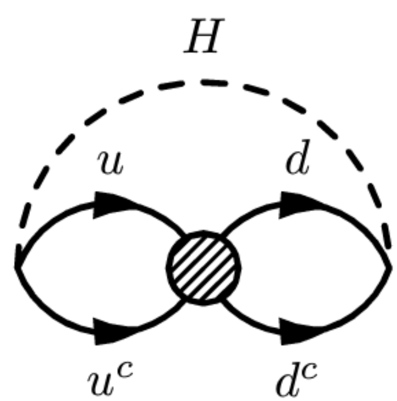
Heavy QCD axion

Two-flavor example

$$\mathcal{L}_{\rm eff} = 2e^{i(\theta+a/f_a)} \int_0^{1/M} \frac{d\rho}{\rho^5}\rho^6 \langle uu^c dd^c\rangle\, e^{-2\pi/\alpha} \left(\frac{2\pi}{\alpha}\right)^6 + \text{h.c.}$$

Axion potential





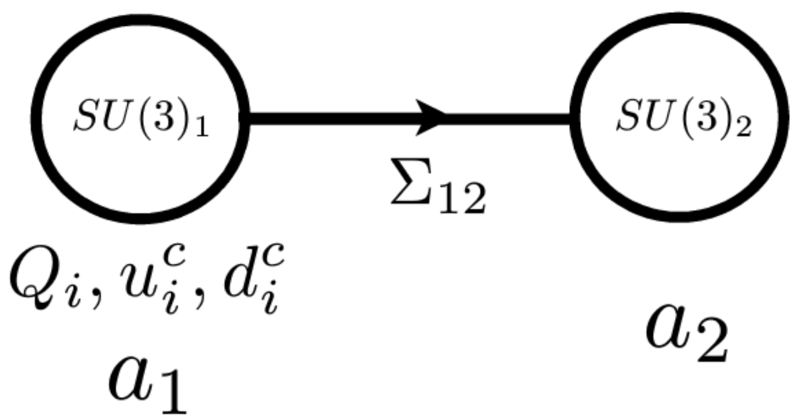
$$V(a) = \Lambda^4 \cos\left(\theta + \frac{a}{f_a}\right)$$

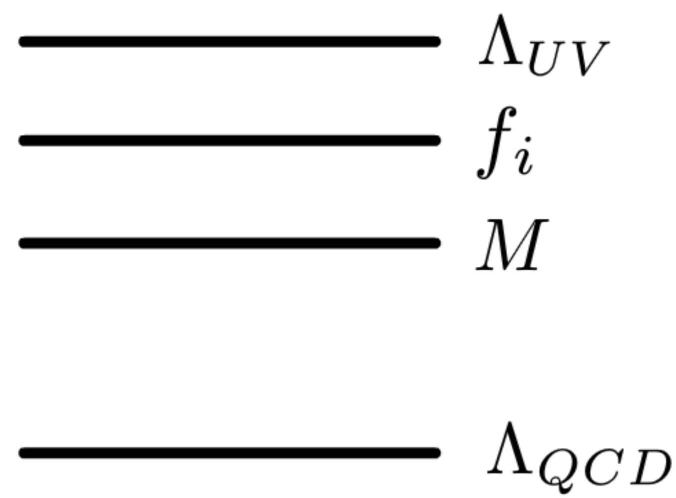
$$\Lambda^4 = M^4 D[\alpha(M)] \left(\prod \frac{m_q}{M} + \prod \frac{y_q}{4\pi}\right) \qquad D[\alpha] = D_0 e^{-2\pi/\alpha}\left(\frac{2\pi}{\alpha}\right)^6$$

Two site model

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

M





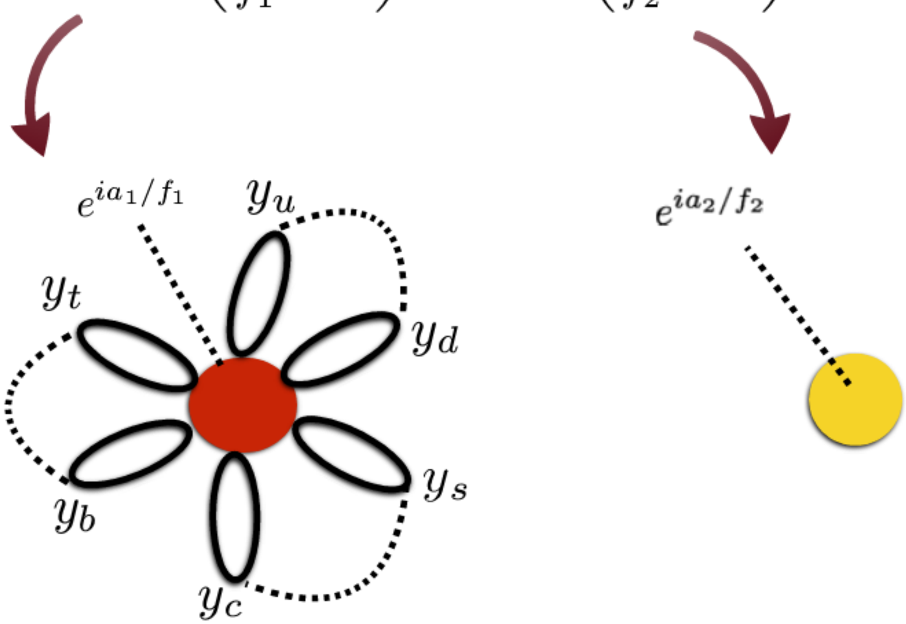
$$\mathcal{L} = -\frac{1}{4}(G_1)^a_{\mu\nu}\ (G_1)^{a,\mu\nu} + \frac{g_{s1}^2}{32\pi^2}\left(\frac{a_1}{f_1} - \theta_1\right)(\widetilde{G}_1)^a_{\mu\nu}\ (G_1)^{a,\mu\nu}$$
$$- \frac{1}{4}(G_2)^a_{\mu\nu}\ (G_2)^{a,\mu\nu} + \frac{g_{s2}^2}{32\pi^2}\left(\frac{a_2}{f_2} - \theta_2\right)(\widetilde{G}_2)^a_{\mu\nu}\ (G_2)^{a,\mu\nu}$$

$$V_\Sigma = -m_\Sigma^2 \mathrm{Tr}(\Sigma_{12}\Sigma_{12}^\dagger) + \frac{\lambda}{2}[\mathrm{Tr}(\Sigma_{12}\Sigma_{12}^\dagger)]^2 + \frac{\kappa}{2}\mathrm{Tr}(\Sigma_{12}\Sigma_{12}^\dagger\Sigma_{12}\Sigma_{12}^\dagger)$$

SU(3) X SU(3)

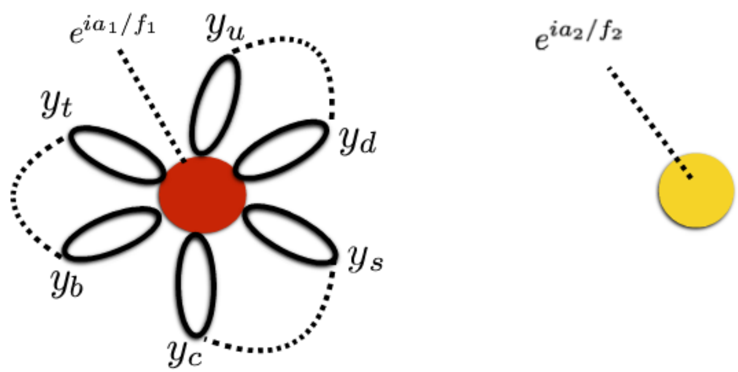
Lagrangian below the scale M

$$\mathcal{L}_a = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \frac{g_s^2}{32\pi^2} \left(\left(\frac{a_1}{f_1} - \bar{\theta}_1 \right) + \left(\frac{a_2}{f_2} - \bar{\theta}_2 \right) \right) G\tilde{G}$$
$$+ \Lambda_1^4 \cos\left(\frac{a_1}{f_1} - \bar{\theta}_1 \right) + \Lambda_2^4 \cos\left(\frac{a_2}{f_2} - \bar{\theta}_2 \right)$$

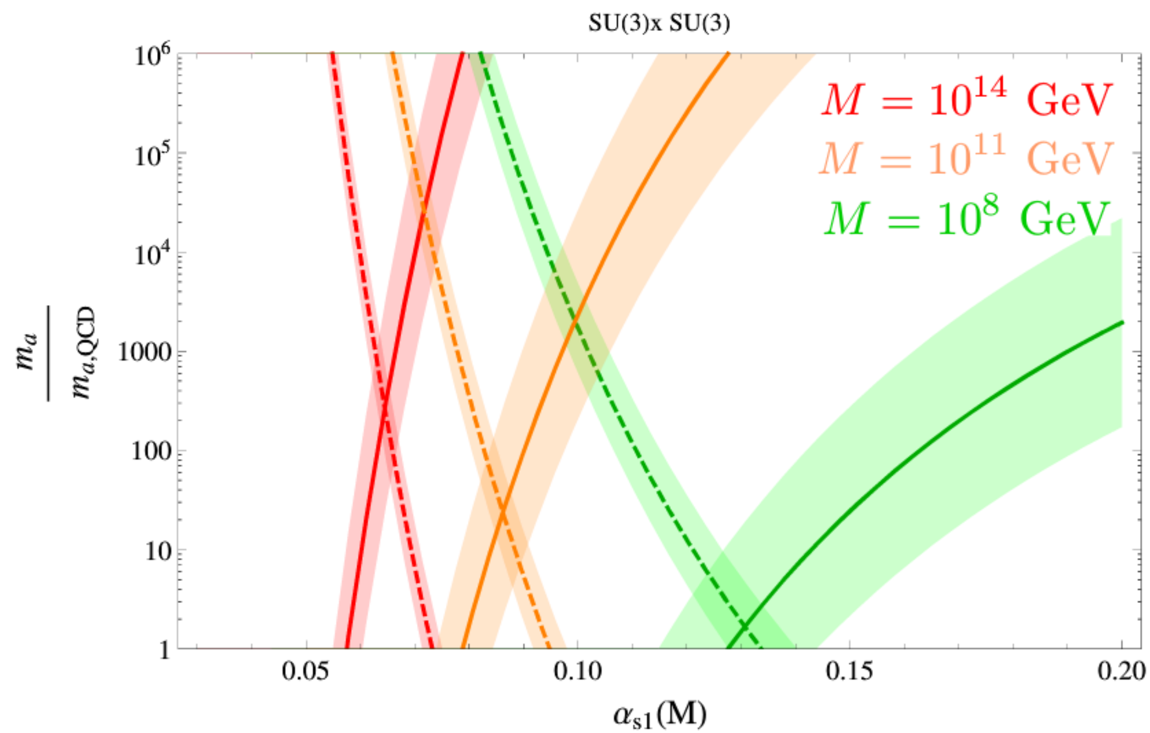


$$\bar{\theta}_{eff} = \left\langle \left(\frac{a_1}{f_1} + \bar{\theta}_1 \right) + \left(\frac{a_2}{f_2} + \bar{\theta}_2 \right) \right\rangle = 0$$

SU(3) X SU(3)



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



$$\Lambda_1^4 \simeq K \frac{4}{5} D[\alpha_{s_1}(M)] M^4$$

$$\Lambda_2^4 = \frac{4}{13} D[\alpha_{s_2}(M)] M^4$$

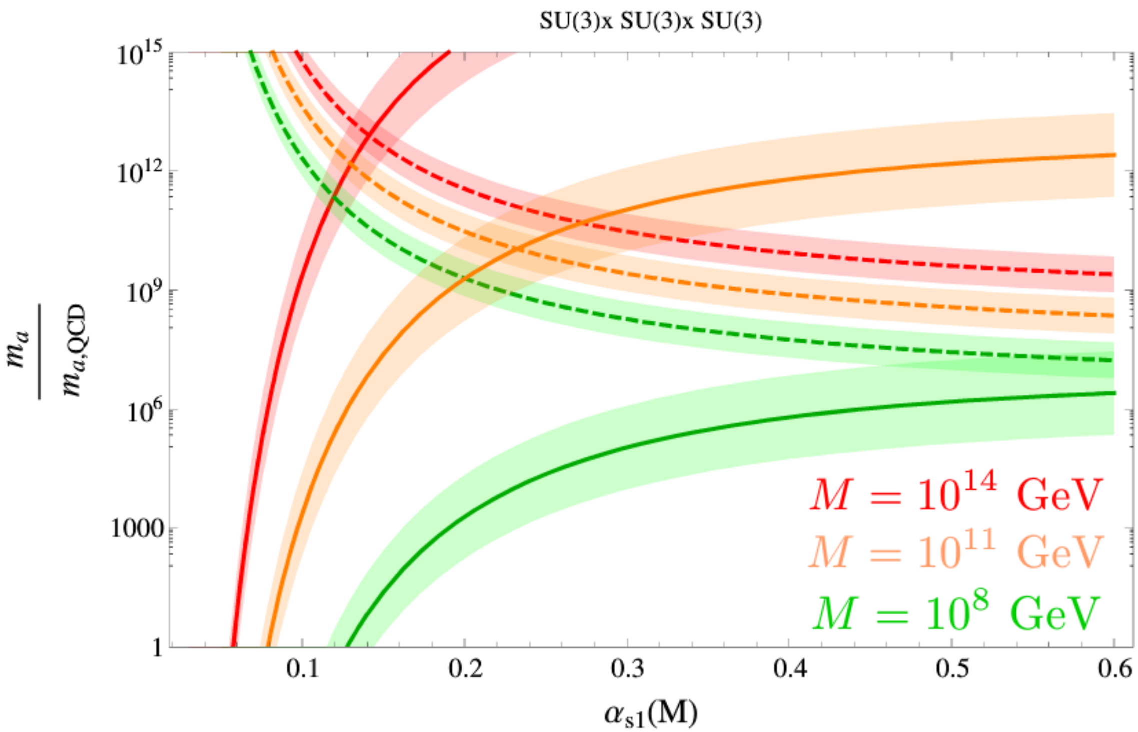
$$D[\alpha] = D_0 e^{-2\pi/\alpha} \left(\frac{2\pi}{\alpha}\right)^6$$

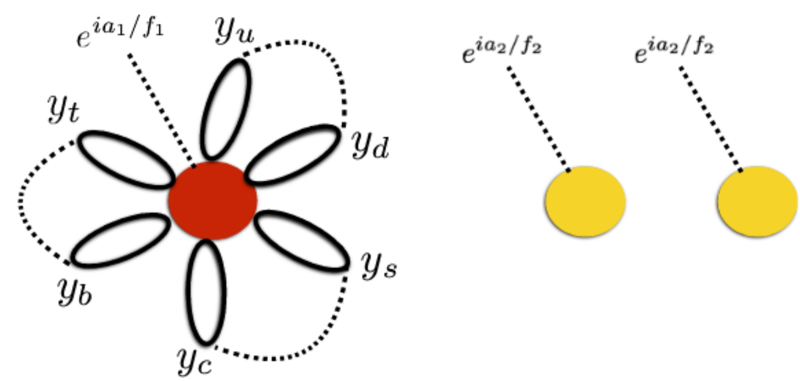
$$K = \left(\frac{y_u}{4\pi}\right)\left(\frac{y_d}{4\pi}\right)\left(\frac{y_c}{4\pi}\right)\left(\frac{y_s}{4\pi}\right)\left(\frac{y_t}{4\pi}\right)\left(\frac{y_b}{4\pi}\right) \approx 10^{-23}.$$

SU(3) X SU(3)x SU(3)

$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_{s_1}(\mu)} + \frac{1}{\alpha_{s_2}(\mu)} + \frac{1}{\alpha_{s_3}(\mu)}, \qquad \mu = M$$

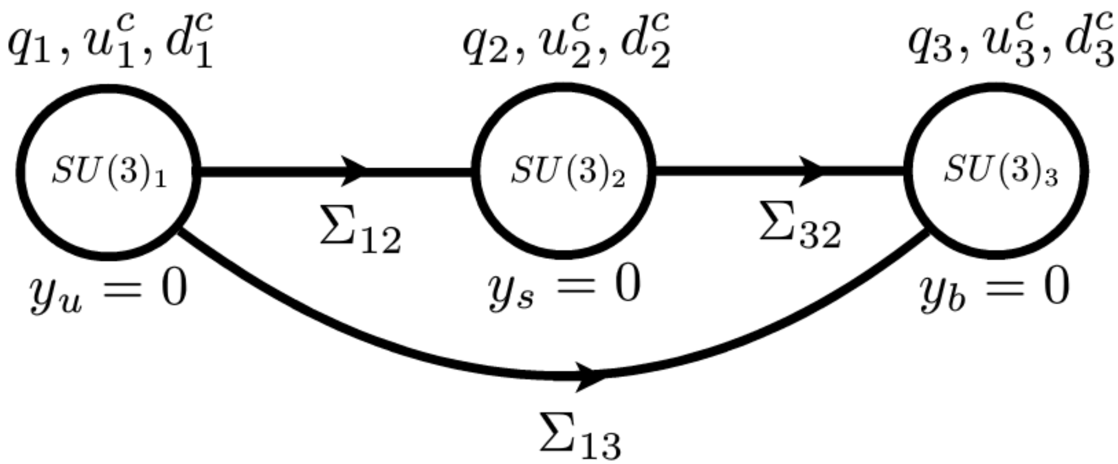
$$\alpha_{s_2} = \alpha_{s_3}$$



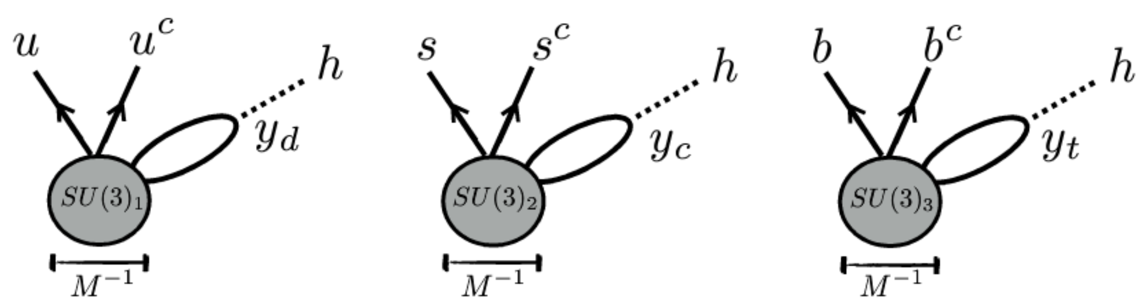


Aside: Massless up quark

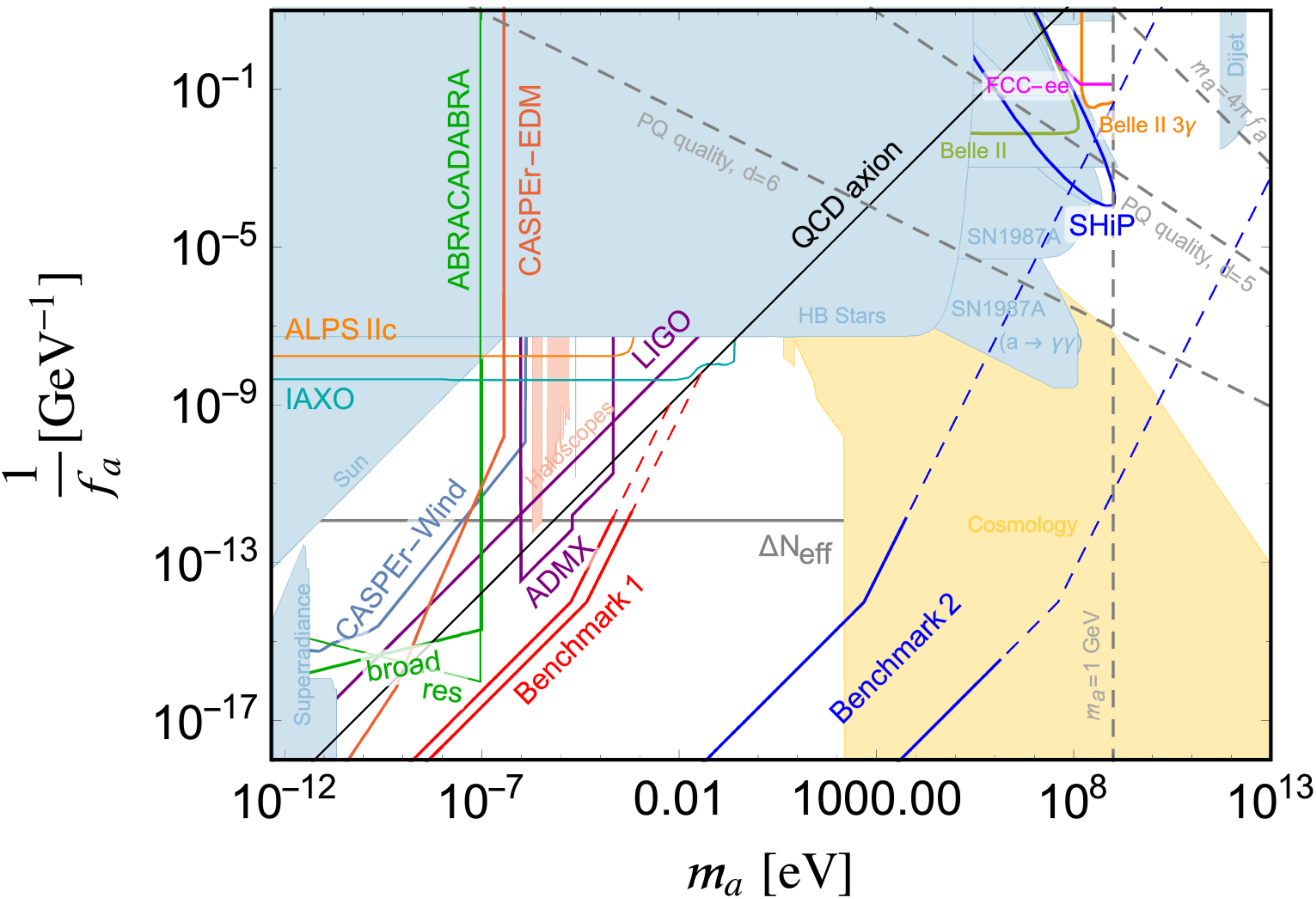
[1712.05803] PA, Howe



Generate lighter quark masses in each generation non-perturbatively



Interesting flavor model building avenues



ABRACADABRA
CASPEr−EDM
PQ quality, d=6
QCD axion
FCC−ee
Belle II 3γ
Belle II
Dijet
$m_a = 4\pi f_a$
SHiP
PQ quality, d=5
SN1987A
HB Stars
SN1987A
(a → γγ)
ALPS IIc
LIGO
IAXO
Haloscopes
Sun
CASPEr−Wind
ADMX
ΔN_eff
Cosmology
Superradiance
broad
res
Benchmark 1
Benchmark 2
m_a=1 GeV
10^{-1}
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-12}
10^{-7}
0.01
1000.00
10^{8}
10^{13}
$\frac{1}{f_a}[\mathrm{GeV}^{-1}]$
m_a [eV]

Summary

QCD axion dark matter is a prime target for new physics searches

In simplest models this target is relatively narrow

Possible to dramatically enhance the axion-photon coupling

Cosmological mechanisms allow for large-f_a axions (as favored in string theory)

Axions can be made heavy while solving strong-CP problem

New target space for dark matter, or collider visible QCD axions

Motivates casting a wide net in the hunt for axions