

QCD axions beyond the QCD axion

Prateek Agrawal



HARVARD
UNIVERSITY

GGI Workshop

Where do we go from here?

Oct 05, 2018



[1710.04213], [1712.0580] Kiel Howe

[1709.06085] Jiji Fan, Matt Reece, LianTao Wang

[1708.05008] Gustavo Marques-Tavares, Wei Xue

The strong CP problem

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

Two sources of CP violation

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

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

[neutron EDM]

Sequestered from the CKM phase

No anthropic selection

An unobserved renormalizable term in the SM

Ellis, Gaillard [1979]

Kaloper, Terning [1710.01740]

The QCD Axion

A Peccei-Quinn U(1) global symmetry

Anomalous with QCD

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

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

Spontaneously broken at some high scale F_a

Axion: the (pseudo)-Nambu Goldstone Boson

[Peccei, Quinn 1977]

[Weinberg 1978]

[Wilczek 1978]

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

QCD breaks the shift symmetry to a discrete shift symmetry

The QCD axion

QCD dynamics give axion a potential that dynamically solves the strong CP problem

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

[Vafa, Witten 1984]

Axion is naturally misaligned from its minimum in the early universe

Coherent oscillations of the axion make a classical fluid

[Abbott, Sikivie 1983]

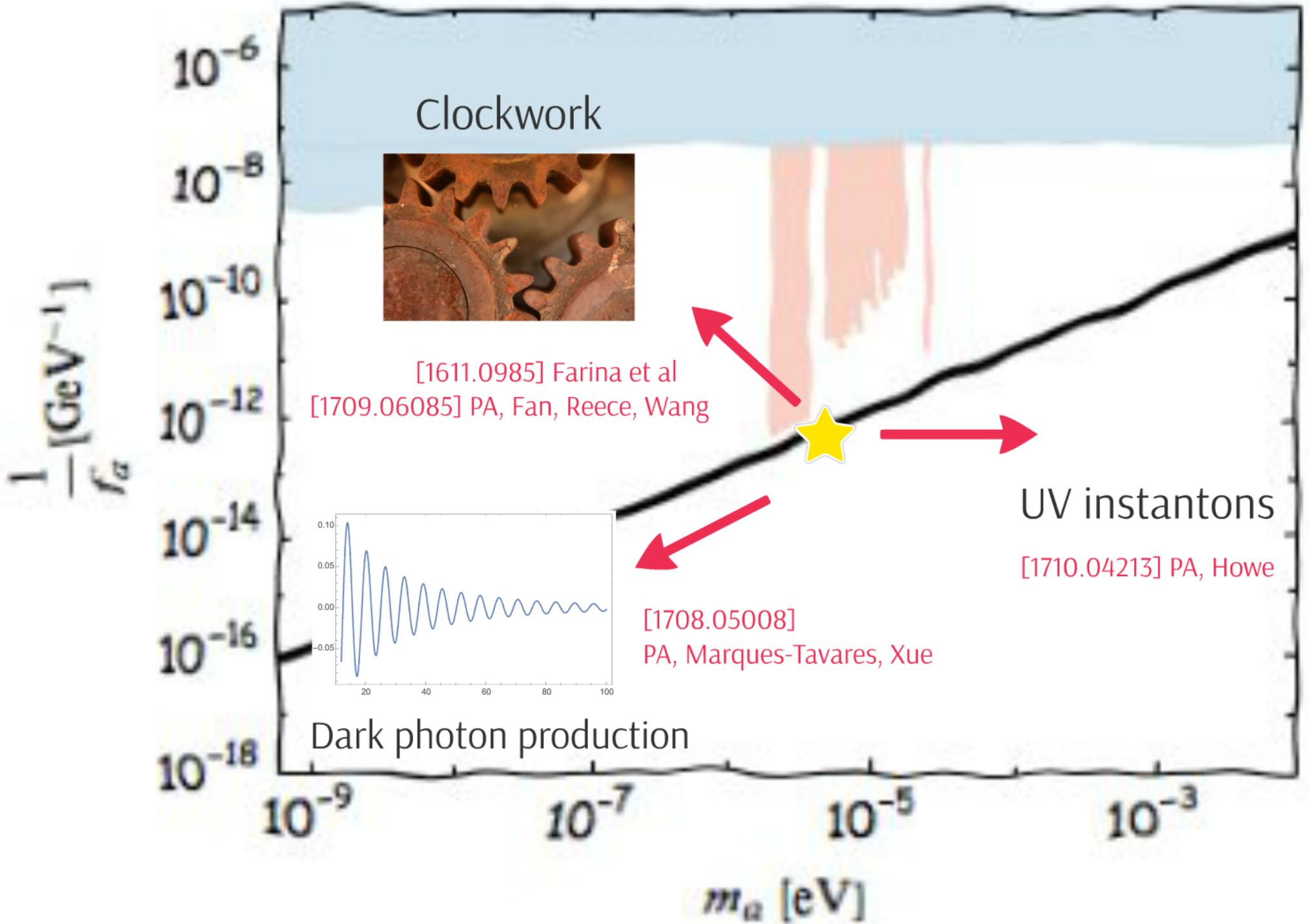
[Dine, Fischler 1983]

Ω_a set by the misalignment mechanism

[Preskill, Wise, Wilczek 1983]

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

Assume PQ symmetry is broken before inflation



Clockwork / Alignment

In "aligned" multi-axion models, the light mode can inherit parametrically different couplings to different gauge groups

Two axion model

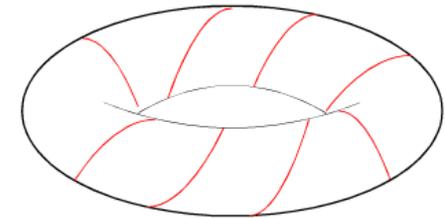
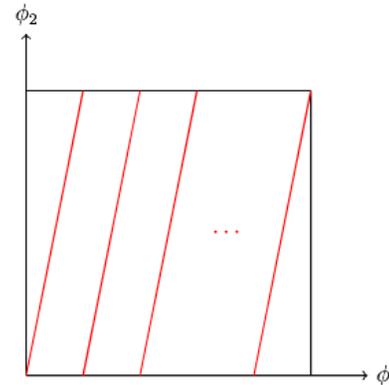
[hep-ph/0409138] Kim, Nilles, Peloso

$$\frac{a}{f_a} \frac{\alpha_a}{8\pi} F_a \tilde{F}_a + \frac{b}{f_b} \frac{\alpha_b}{8\pi} F_b \tilde{F}_b + \Lambda^4 \cos \left(\frac{a}{f_a} + \frac{Qb}{f_b} \right)$$

The massless mode $\phi = \frac{-Qf_a a + f_b b}{\sqrt{f_b^2 + Q^2 f_a^2}}$

$$\frac{Q\phi}{f_{\text{eff}}} \frac{\alpha_a}{8\pi} F_a \tilde{F}_a + \frac{\phi}{f_{\text{eff}}} \frac{\alpha_b}{8\pi} F_b \tilde{F}_b$$

$$f_{\text{eff}} = \sqrt{f_b^2 + Q^2 f_a^2}$$



[1404.6209] Choi, Kim, Yun

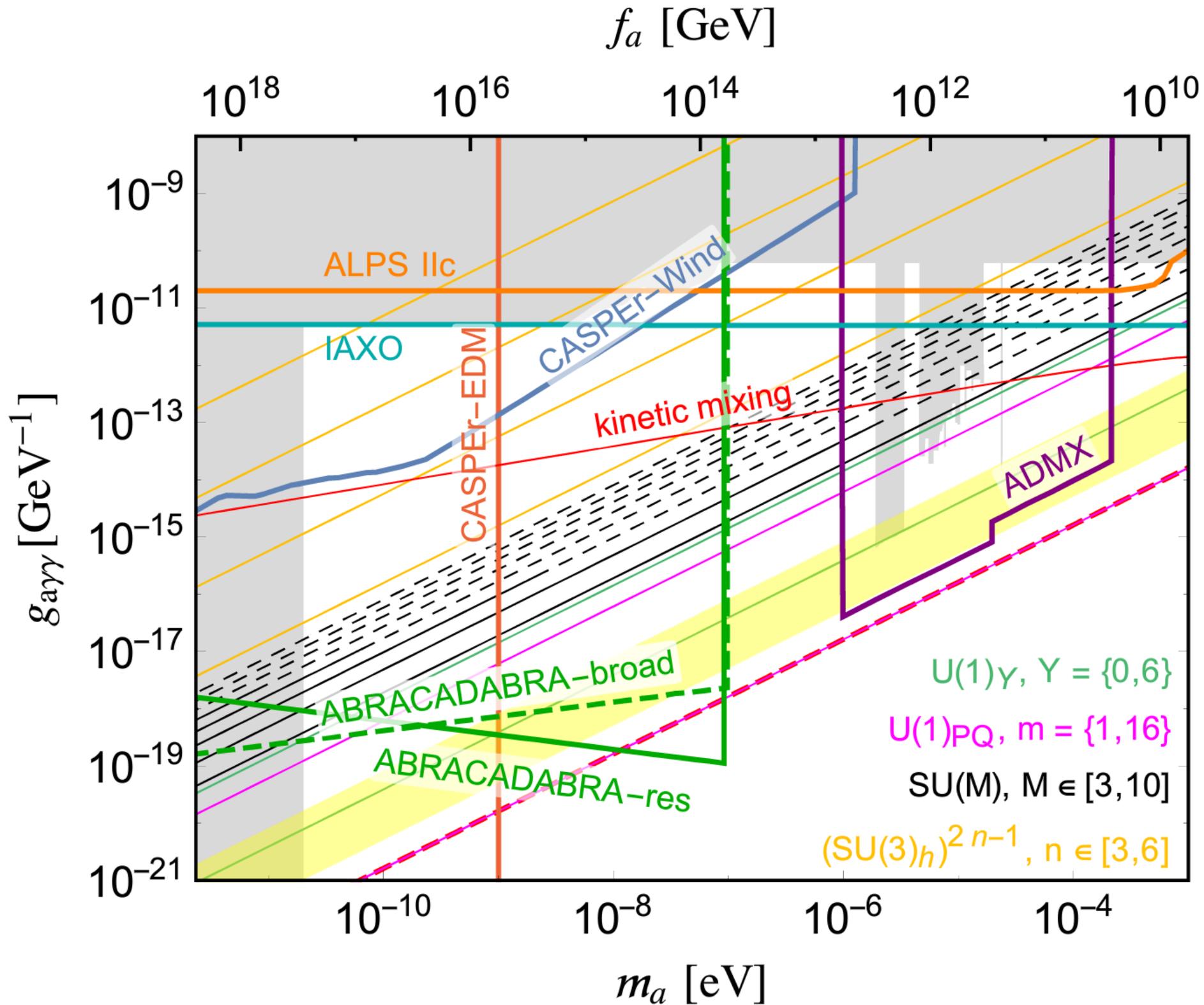
[1511.00132] Choi, Im

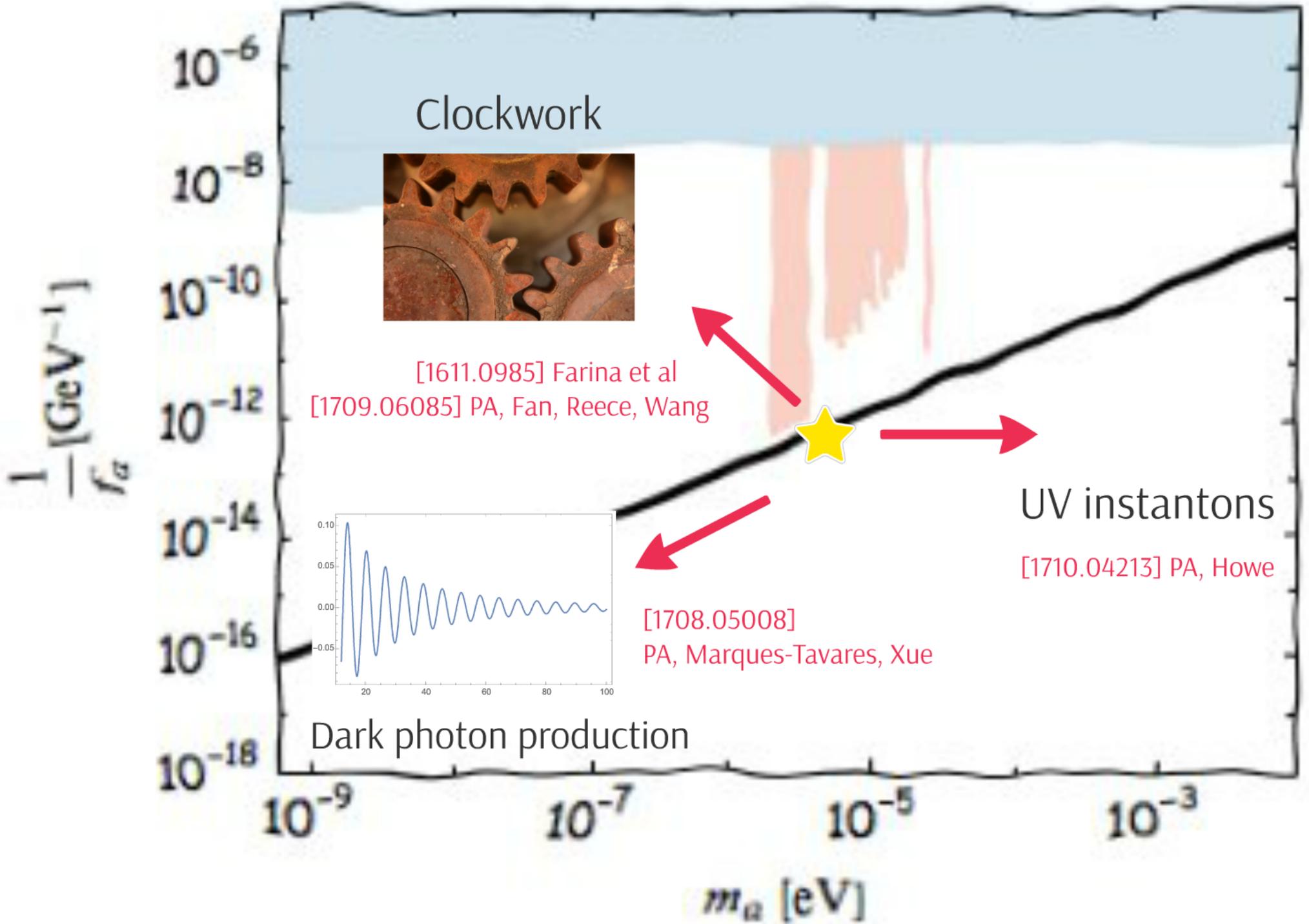
[1511.01827] Kaplan, Rattazzi

[1611.0985] Farina, Pappadopulo, Rompineve, Tesi

[1709.06085] PA, Fan, Reece, Wang

Clockwork: Rinse, repeat





Particle production

Depleting axion energy into dark radiation

$$\mathcal{L} = \frac{a}{f_a} \frac{\alpha}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{\beta a}{f_a} \frac{\alpha_D}{8\pi} (F_D)_{\mu\nu} \tilde{F}_D^{\mu\nu}$$

Equation of motion for the gauge field

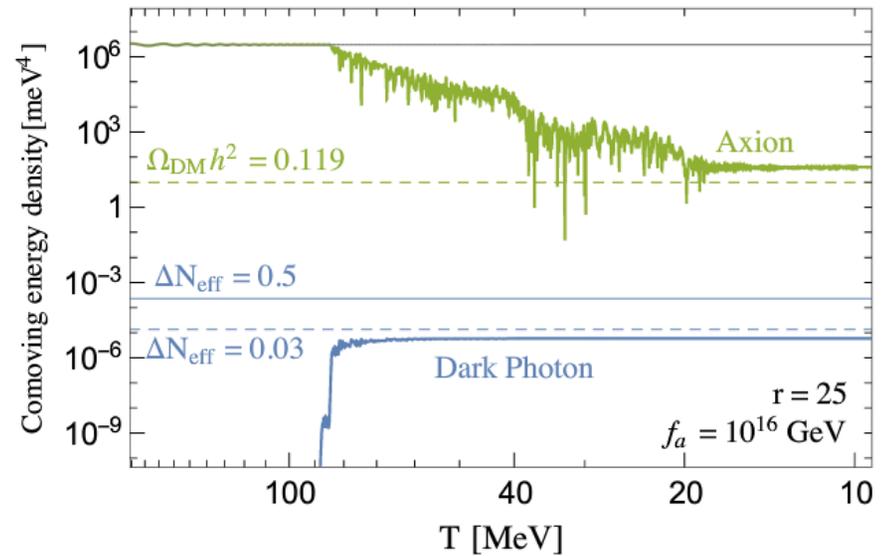
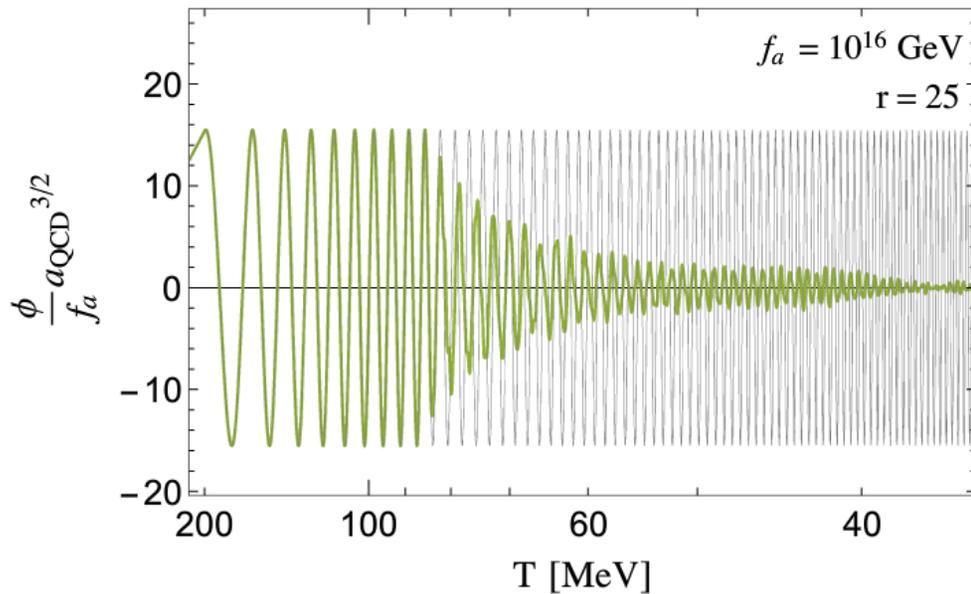
$$A''_{\pm} + \underbrace{\left(k^2 \mp \frac{\beta k \phi'}{f_a} \right)}_{\omega^2(k)} A_{\pm} = 0 \quad (\text{in conformal time})$$

Tachyonic instability

(can also be used to populate ultralight dark photon dark matter)

PA, Kitajima, Reece, Sekiguchi, Takahashi [to appear] + 3 other groups

Axion depletion



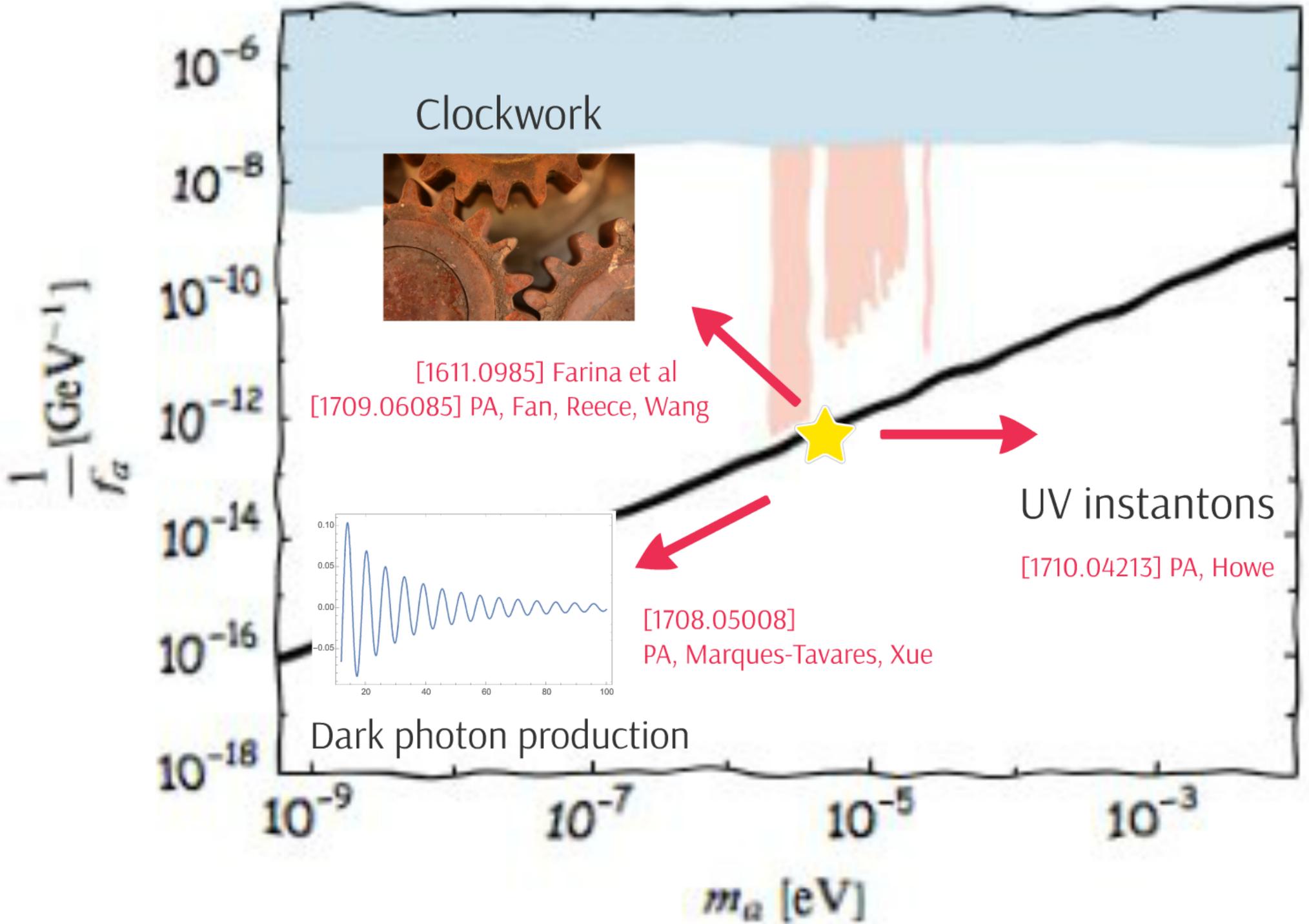
Neglecting backscattering into axion k-modes

High number of dark photons scatter back into axions

Need lattice simulation for k-modes of dark photons and axions

[1802.00444] Kitajima, Sekiguchi, Takahashi

$f_a \sim 10^{15}$ GeV viable without tuning initial conditions



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 will not be aligned with $\theta = 0$

Rubakov [hep-ph/9703409]

Hook [1411.3325]

Dimopoulos, Hook, Huang, Marques-Tavares [1606.03097]

Gherghetta, Nagata, Shifman [1604.01127]

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

Holdom, Peskin [Nucl. Phys. B208 (1982)]

Holdom [Phys. Lett. B154 (1985)]

Dine, Seiberg [Nucl. Phys. B273 (1986)]

Choi, Kim, Sze [Phys. Rev. Lett. 61 (1988)]

Flynn, Randall [Nucl. Phys. B293 (1987)]

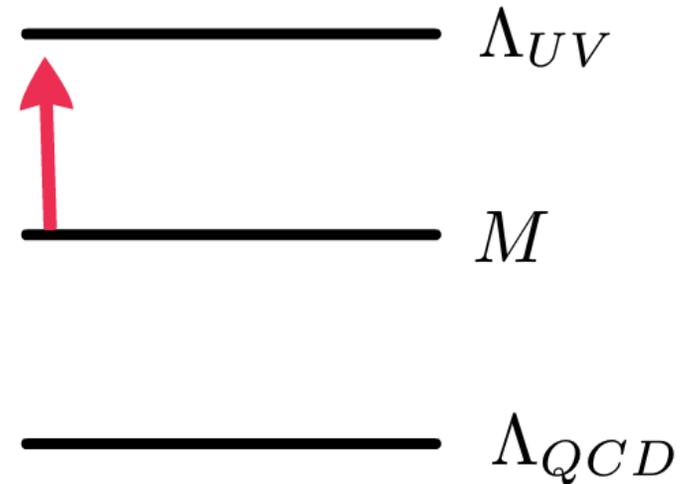
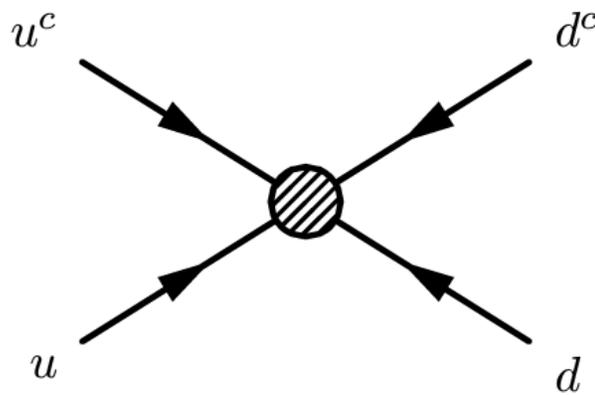
Choi, Kim [hep-ph/9809286]

UV instantons

Two-flavor example

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

Contributions above a scale M captured by 't Hooft vertex



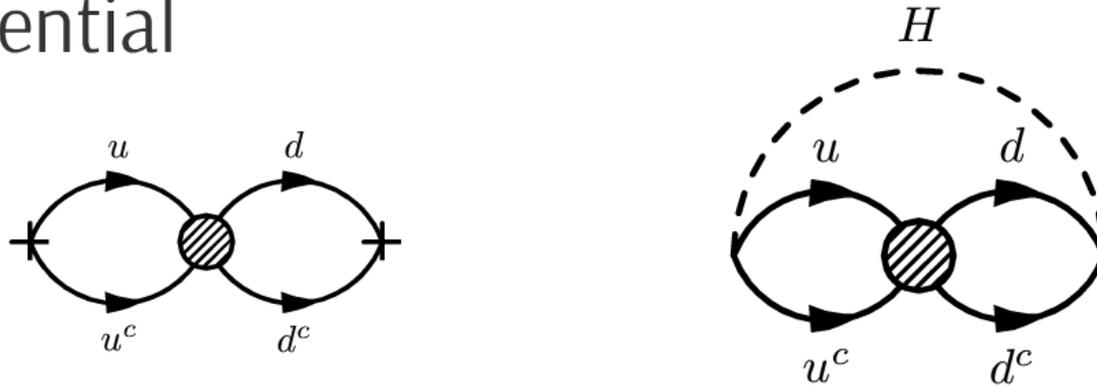
$$\mathcal{L}_{\text{eff}} = 2e^{i(\theta+a/f_a)} \int_0^{1/M} \frac{d\rho}{\rho^5} \rho^6 \langle uu^c dd^c \rangle e^{-2\pi/\alpha} \left(\frac{2\pi}{\alpha}\right)^6 + \text{h.c.}$$

Heavy QCD axion

Two-flavor example

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

Axion potential



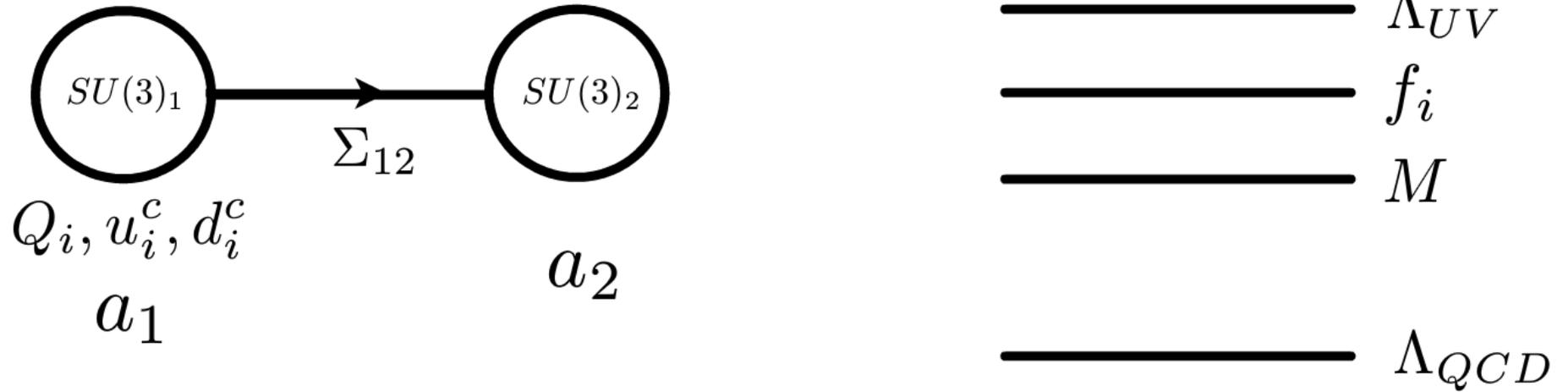
$$V(a) = \Lambda^4 \cos \left(\theta + \frac{a}{f_a} \right)$$

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

Two site model

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

M



$$\mathcal{L} = -\frac{1}{4}(G_1)_{\mu\nu}^a (G_1)^{a,\mu\nu} + \frac{g_{s1}^2}{32\pi^2} \left(\frac{a_1}{f_1} - \theta_1 \right) (\tilde{G}_1)_{\mu\nu}^a (G_1)^{a,\mu\nu}$$

$$- \frac{1}{4}(G_2)_{\mu\nu}^a (G_2)^{a,\mu\nu} + \frac{g_{s2}^2}{32\pi^2} \left(\frac{a_2}{f_2} - \theta_2 \right) (\tilde{G}_2)_{\mu\nu}^a (G_2)^{a,\mu\nu}$$

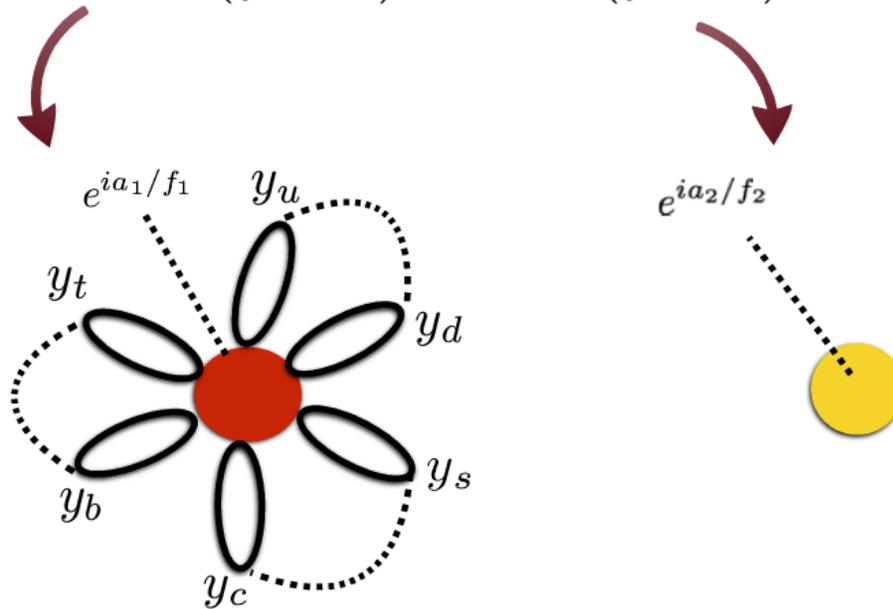
$$V_\Sigma = -m_\Sigma^2 \text{Tr}(\Sigma_{12}\Sigma_{12}^\dagger) + \frac{\lambda}{2} [\text{Tr}(\Sigma_{12}\Sigma_{12}^\dagger)]^2 + \frac{\kappa}{2} \text{Tr}(\Sigma_{12}\Sigma_{12}^\dagger \Sigma_{12}\Sigma_{12}^\dagger)$$

SU(3) X SU(3)

Lagrangian below the scale M

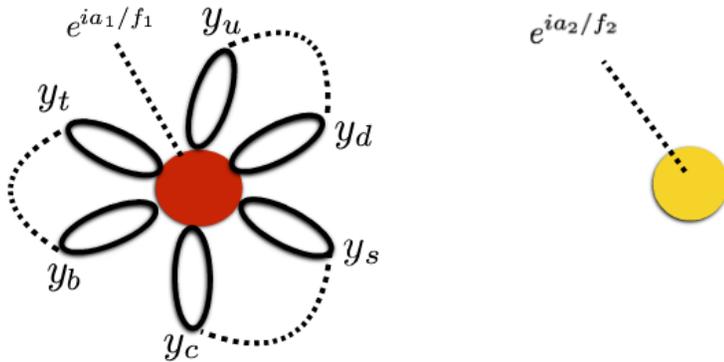
$$\mathcal{L}_a = -\frac{1}{4} G_{\mu\nu}^a G^{a,\mu\nu} + \frac{g_s^2}{32\pi^2} \left(\left(\frac{a_1}{f_1} - \bar{\theta}_1 \right) + \left(\frac{a_2}{f_2} - \bar{\theta}_2 \right) \right) G\tilde{G}$$

$$+ \Lambda_1^4 \cos \left(\frac{a_1}{f_1} - \bar{\theta}_1 \right) + \Lambda_2^4 \cos \left(\frac{a_2}{f_2} - \bar{\theta}_2 \right)$$

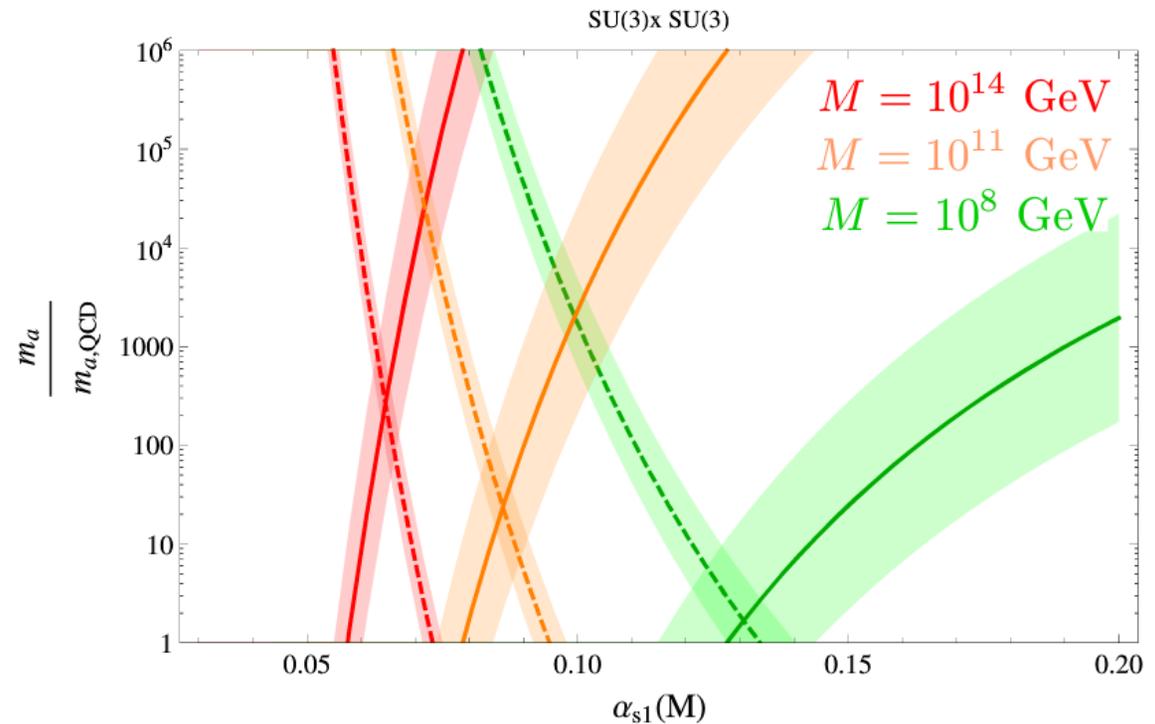


$$\bar{\theta}_{eff} = \left\langle \left(\frac{a_1}{f_1} + \bar{\theta}_1 \right) + \left(\frac{a_2}{f_2} + \bar{\theta}_2 \right) \right\rangle = 0$$

SU(3) x SU(3)



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



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

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

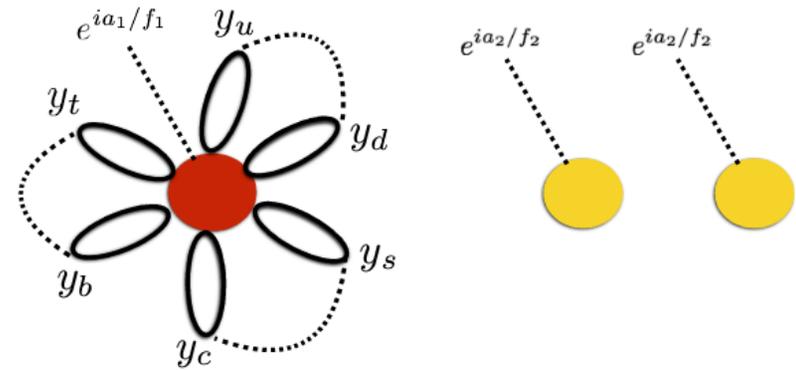
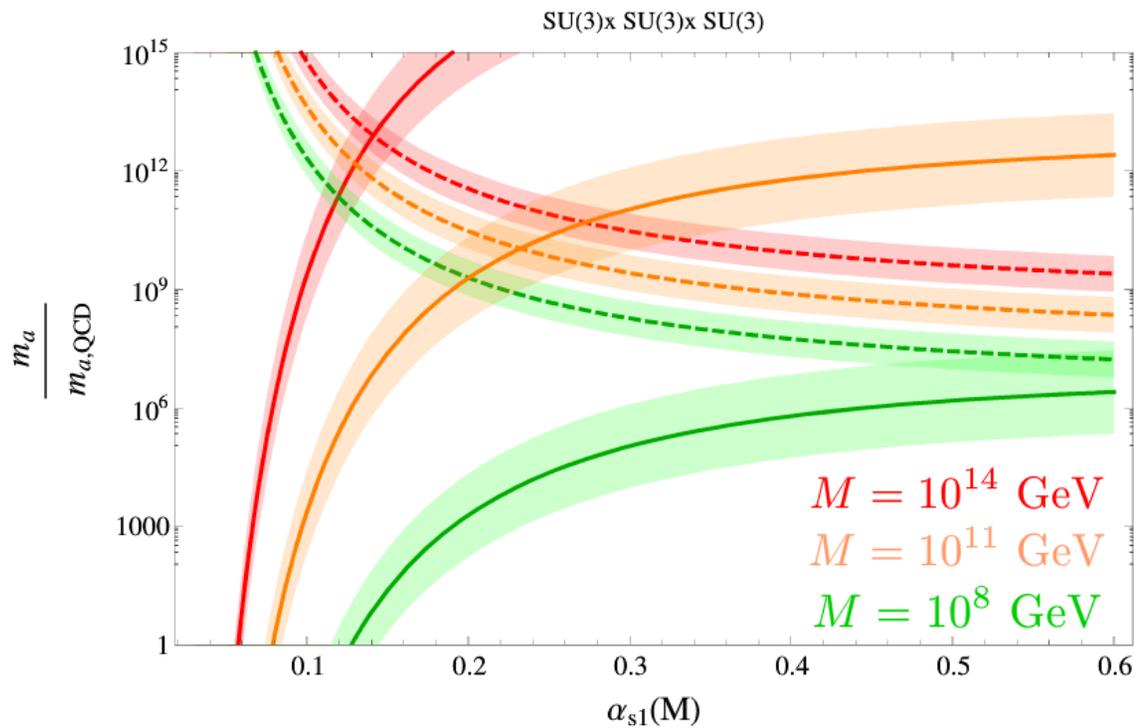
$$D[\alpha] = D_0 e^{-2\pi/\alpha} \left(\frac{2\pi}{\alpha} \right)^6$$

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

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

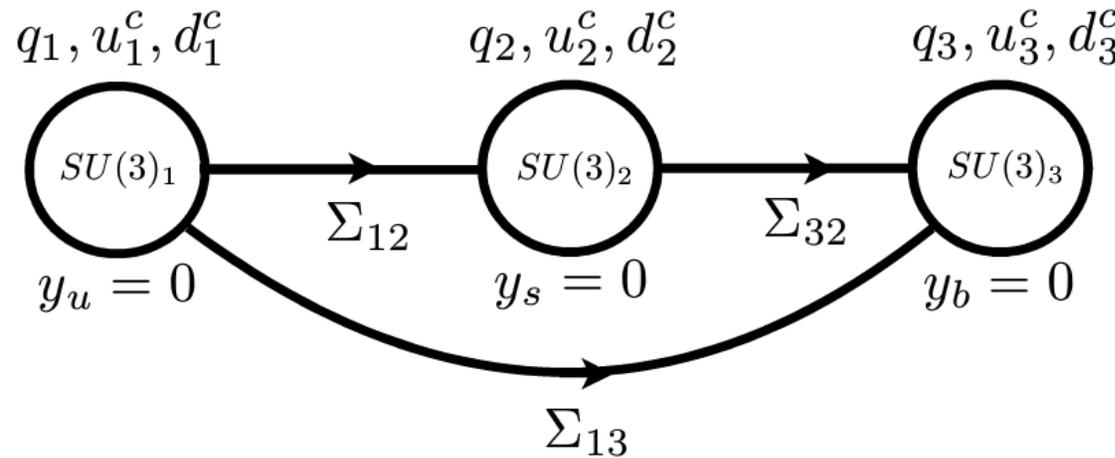
$$\frac{1}{\alpha_s(\mu)} = \frac{1}{\alpha_{s_1}(\mu)} + \frac{1}{\alpha_{s_2}(\mu)} + \frac{1}{\alpha_{s_3}(\mu)}, \quad \mu = M$$

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

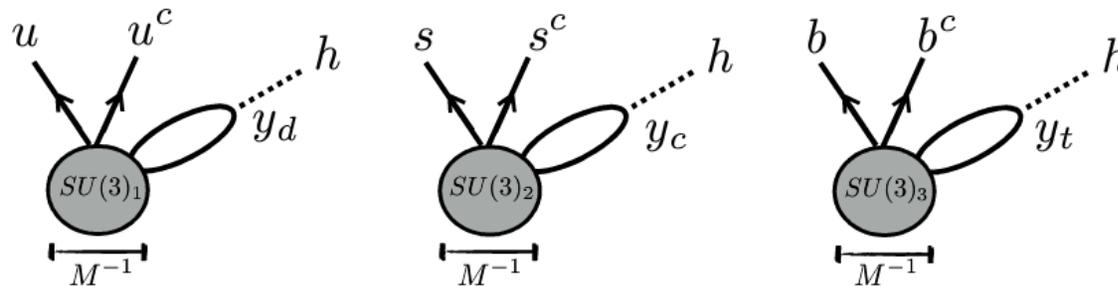


Aside: Massless up quark

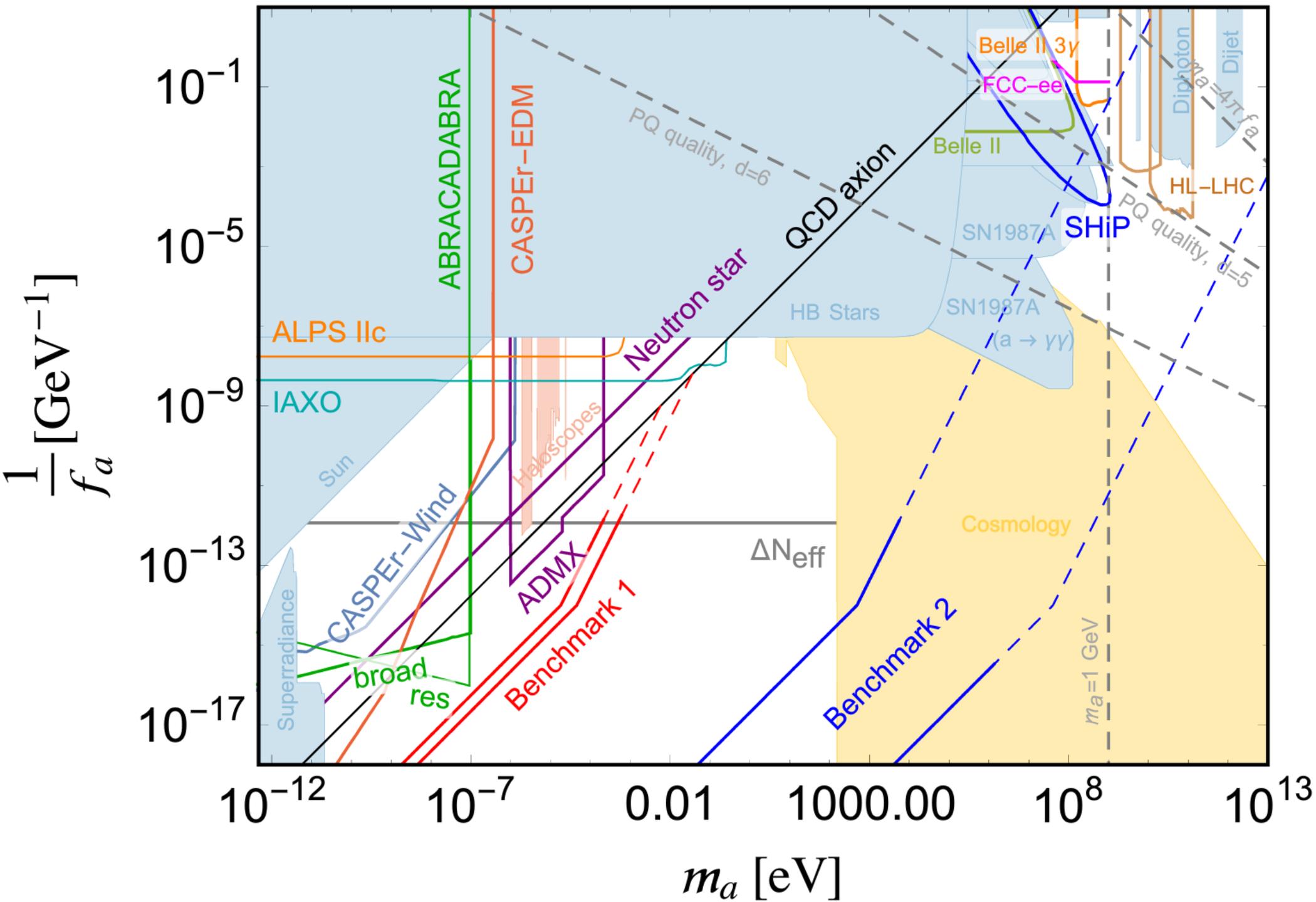
[1712.05803] PA, Howe



Generate lighter quark masses in each generation non-perturbatively



Interesting flavor model building avenues



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