QCD Axion
Beyond the Axion Band

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Feebly Interacting Particles 2020

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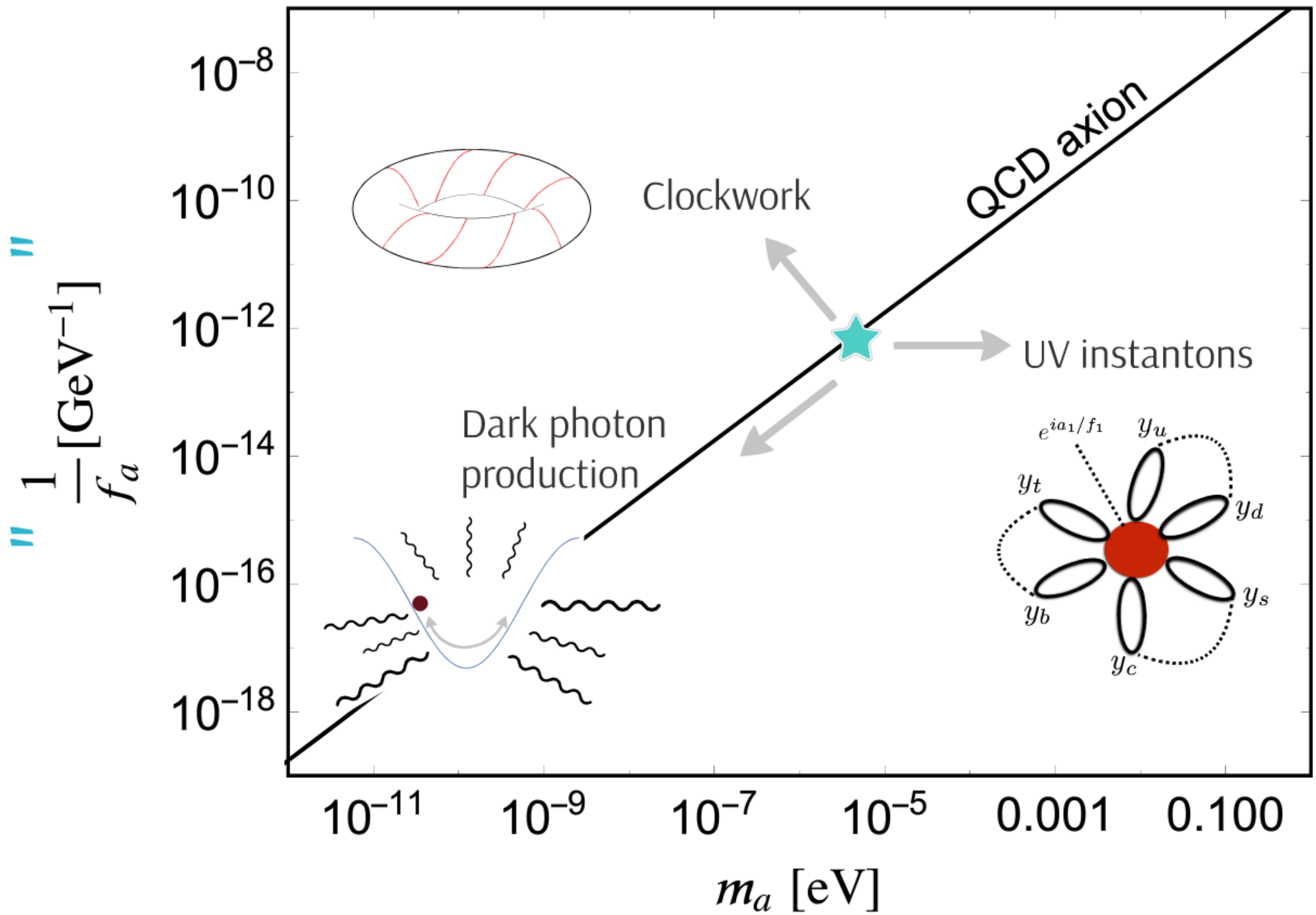
Take Away



QCD axion
Clockwork
UV instantons
Dark photon production
e^{ia_1/f_1}
y_u
y_t
y_d
y_b
y_s
y_c
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
0.001
0.100
" $\frac{1}{f_a}[\mathrm{GeV}^{-1}]$ "
m_a [eV]

The QCD axion

A solution to the strong CP problem

The QCD Lagrangian

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

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]
Baker et al [2006]

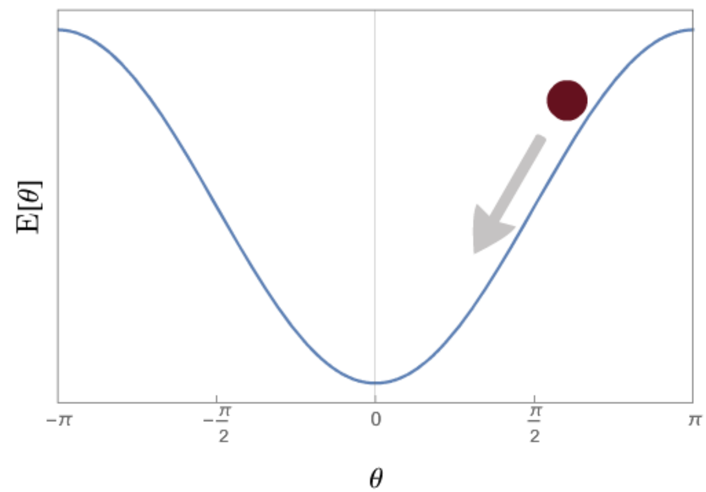
The vacuum energy of QCD is minimized at $\bar{\theta} = 0$ — Vafa, Witten [1984]

Make $\bar{\theta}$ a dynamical field

Peccei - Quinn symmetry: (anomalous) chiral rotations of colored fermions — Peccei, Quinn [1977]

PQ symmetry spontaneously broken at scale F_a

(Pseudo) Nambu - Goldstone boson of spontaneous breaking of PQ symmetry: Axion — Weinberg [1978], Wilczek [1978]



QCD Axion parameter space

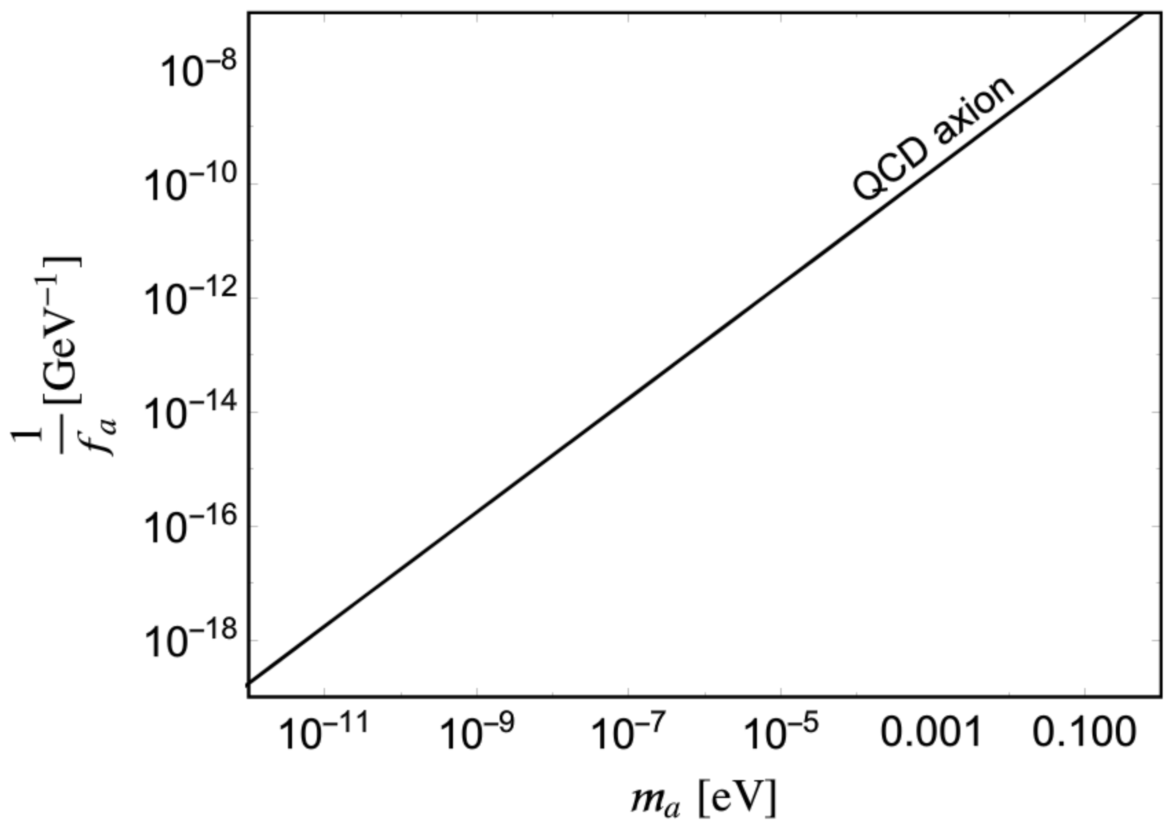
Mass and decay constant

The number f_a characterizes axion couplings

$$\left(\theta + \frac{a}{f_a}\frac{\alpha_s}{8\pi}\right) G^a_{\mu\nu}\widetilde{G}^{\mu\nu,a} + \frac{a}{f_a}\frac{\alpha E}{8\pi N}F_{\mu\nu}\widetilde{F}^{\mu\nu} + c'\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$$

QCD generated potential

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

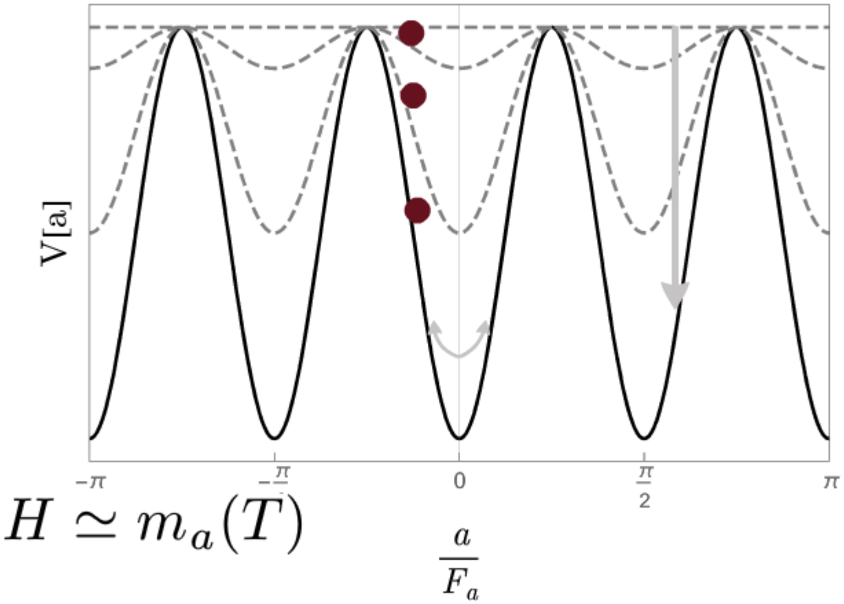


QCD Axion Abundance : misalignment

Abundance set by initial misalignment and f_a

In the early universe the axion is misaligned from its minimum

Axion potential depends on temperature, turns on at QCD phase transition



The axion starts oscillating around its minimum when $H \simeq m_a(T)$

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

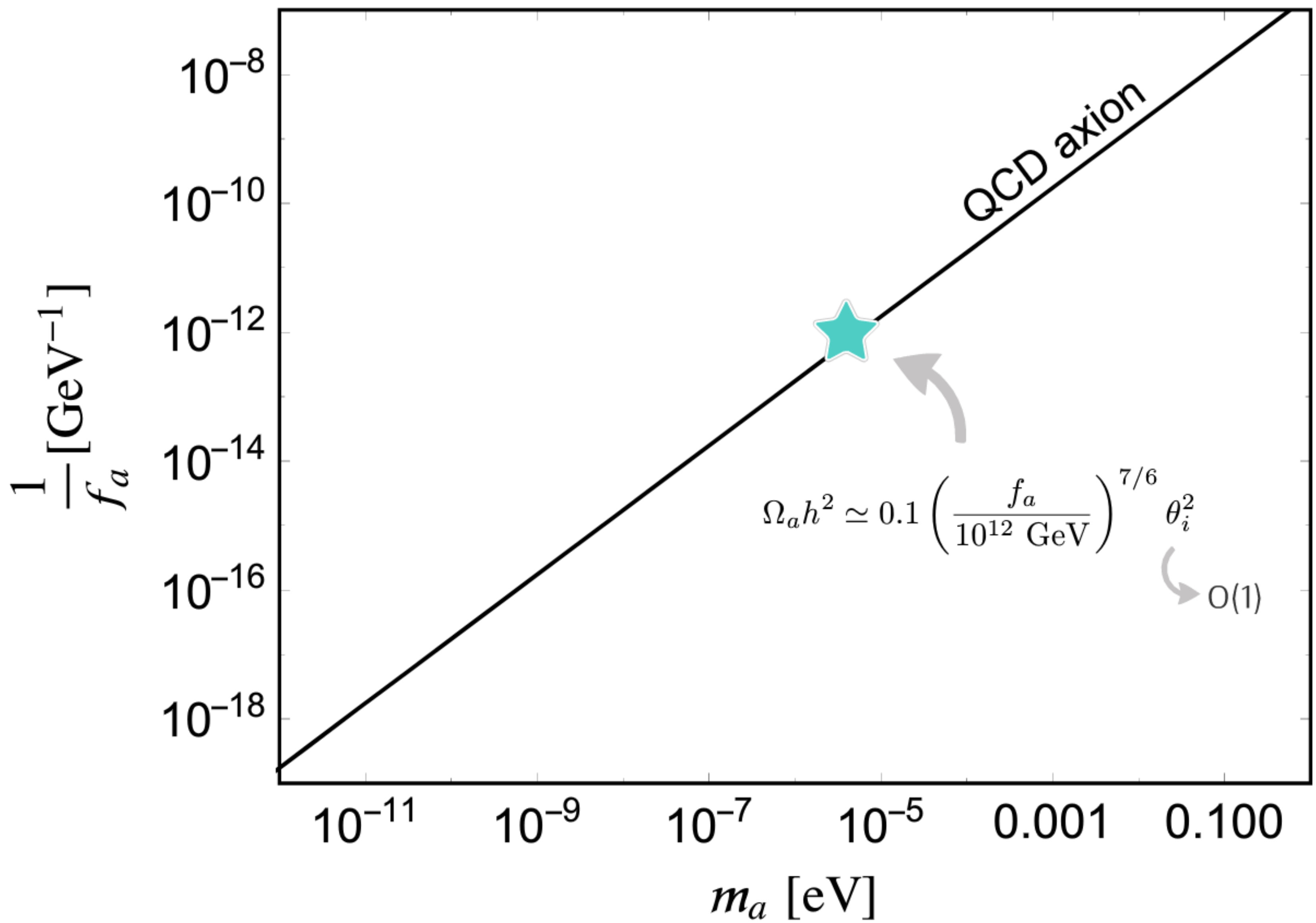
Under adiabatic evolution, comoving number density conserved

$$\frac{\rho_a(T_0)}{m_a(T_0)s(T_0)} \simeq \frac{\rho_a(T_{\rm osc})}{m_a(T_{\rm osc})s(T_{\rm osc})}$$

The dark matter abundance today is

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

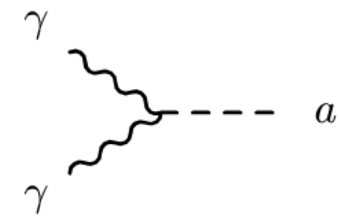
Axion target space



QCD Axion Coupling to Photons

Coupling to photons

The coupling to photons is phenomenologically important

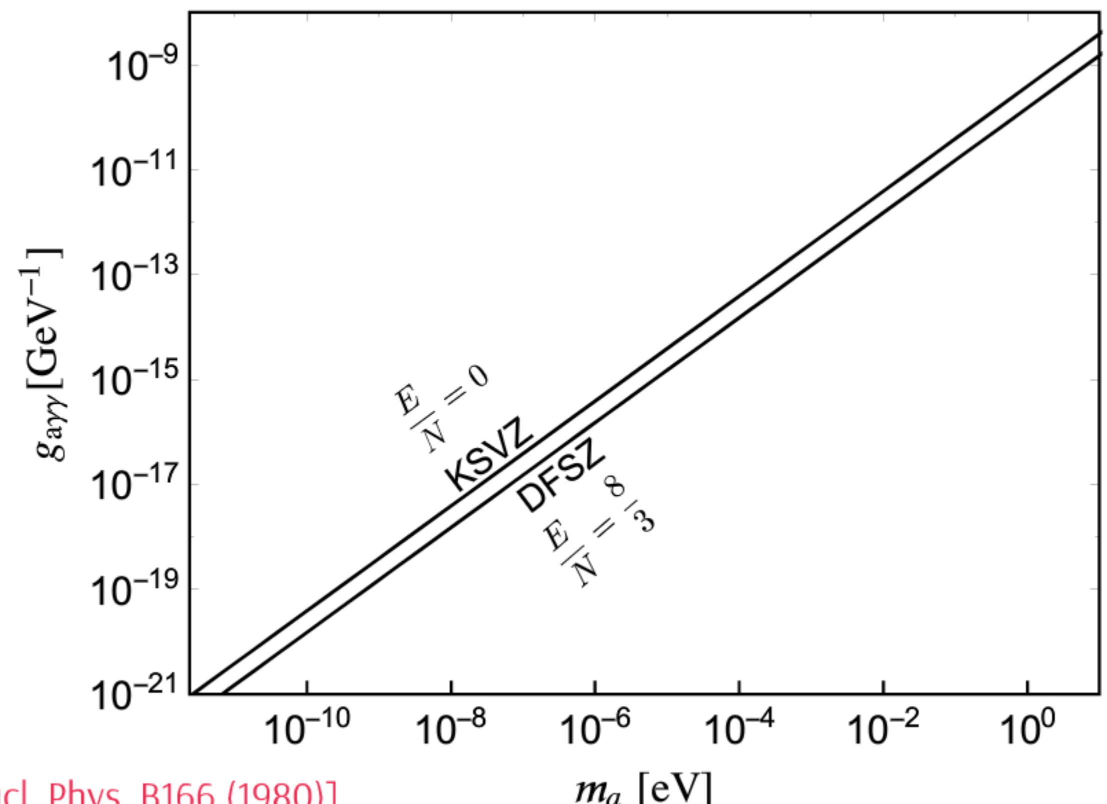


Model dependent UV contribution: charges of PQ fermions

Model independent IR contribution:
axion-meson mixing

UV → IR

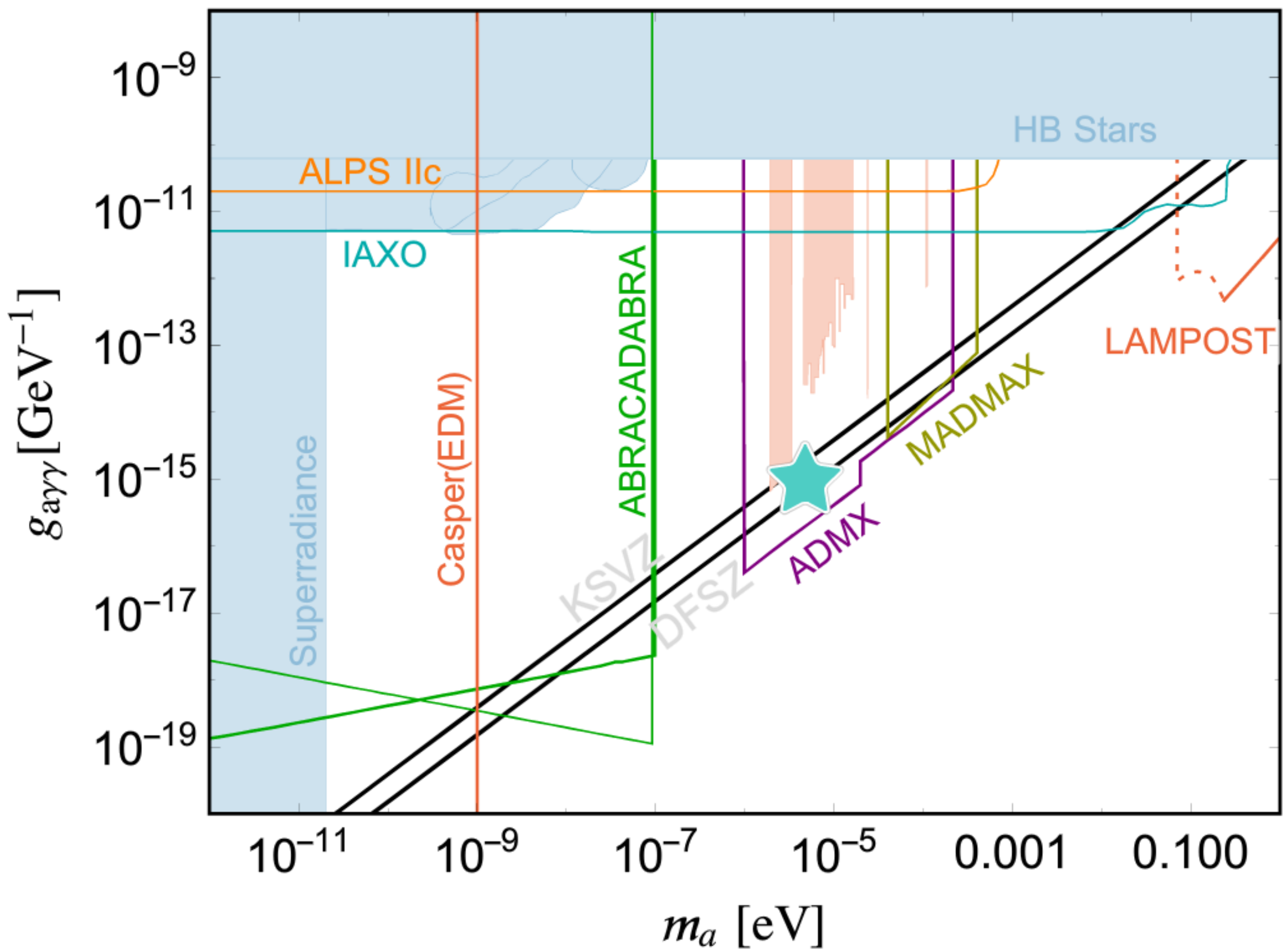
$$\frac{a}{f_a} \underbrace{\frac{\alpha}{8\pi}\left[\frac{E}{N} - 1.92\right]}_{\frac{1}{4} g_{a\gamma\gamma}} F_{\mu\nu}\widetilde{F}^{\mu\nu}$$



Kim [Phys. Rev. Lett. 43 (1979)]
Shifman, **V**ainshtein, **Z**akharov [Nucl. Phys. B166 (1980)]
Dine, **F**ischler, **S**rednicki [Phys. Lett. 104B (1981)]
Zhitnitsky [Sov. J. Nucl. Phys. 31 (1980)]

Axion target space

Constraints and future sensitivity



Axion target space

Traditional target space: variants of the KSVZ and DFSZ models

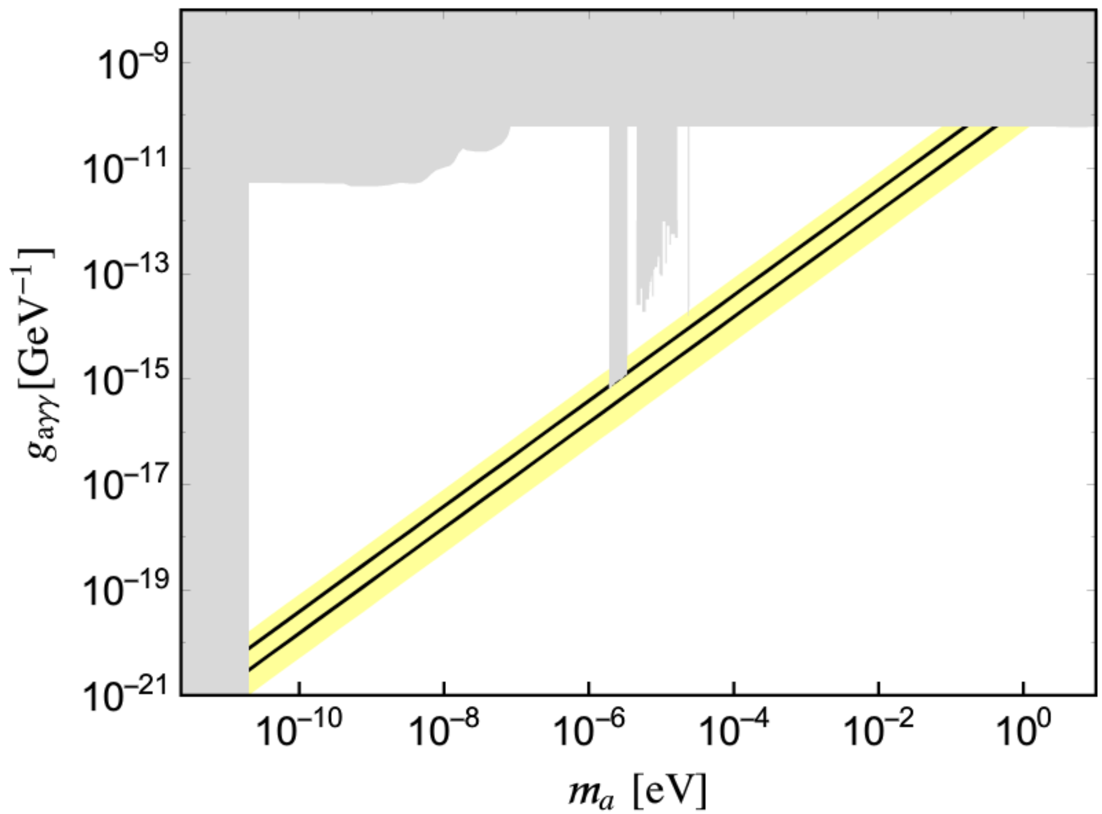
Kim [hep-ph/9802220]

Some guiding principles

- Small representations
- Unification
- No Landau poles

Giudice, Rattazzi, Strumia [1204.5465]

Luzio, Mescia, Nardi [1610.07593], [1705.05370]



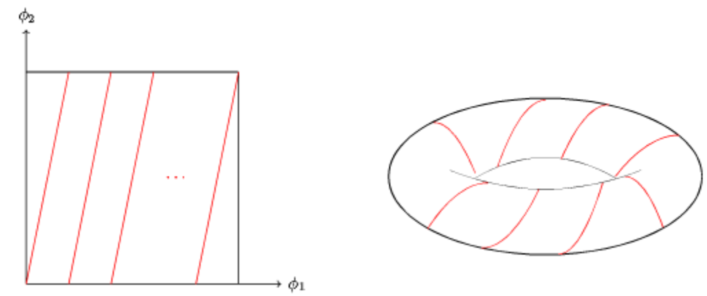
In general, a much wider target space is possible in extended models

Alignment mechanism

Aligned two axion model

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

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



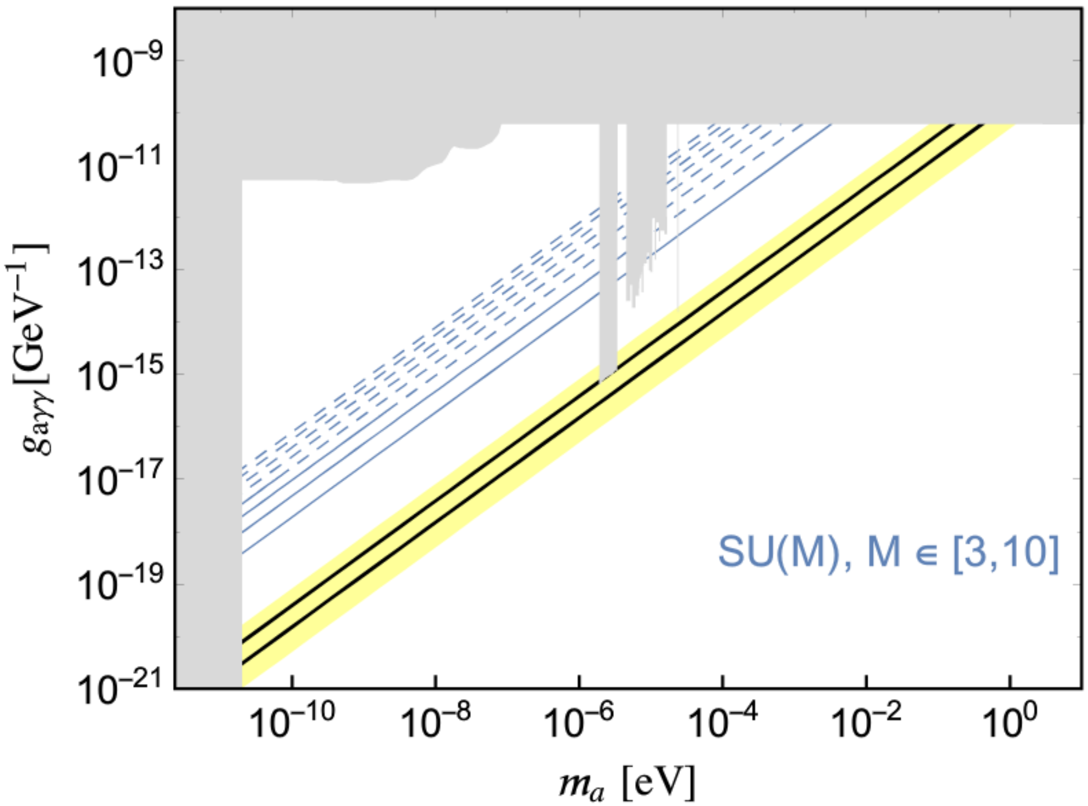
The light eigenstate

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

Enhanced couplings to photons

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

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



Clockwork

N-site alignment model

Aligned multi-axion model

$$\frac{a_1}{f}\frac{\alpha_1}{8\pi}F_a\widetilde{F}_a + \Lambda^4\cos\left(\frac{a_1}{f}+\frac{Qa_2}{f}\right) + \ldots + \Lambda^4\cos\left(\frac{a_{n-1}}{f}+\frac{Qa_n}{f}\right) + \frac{a_n}{f}\frac{\alpha_n}{8\pi}F_b\widetilde{F}_b$$

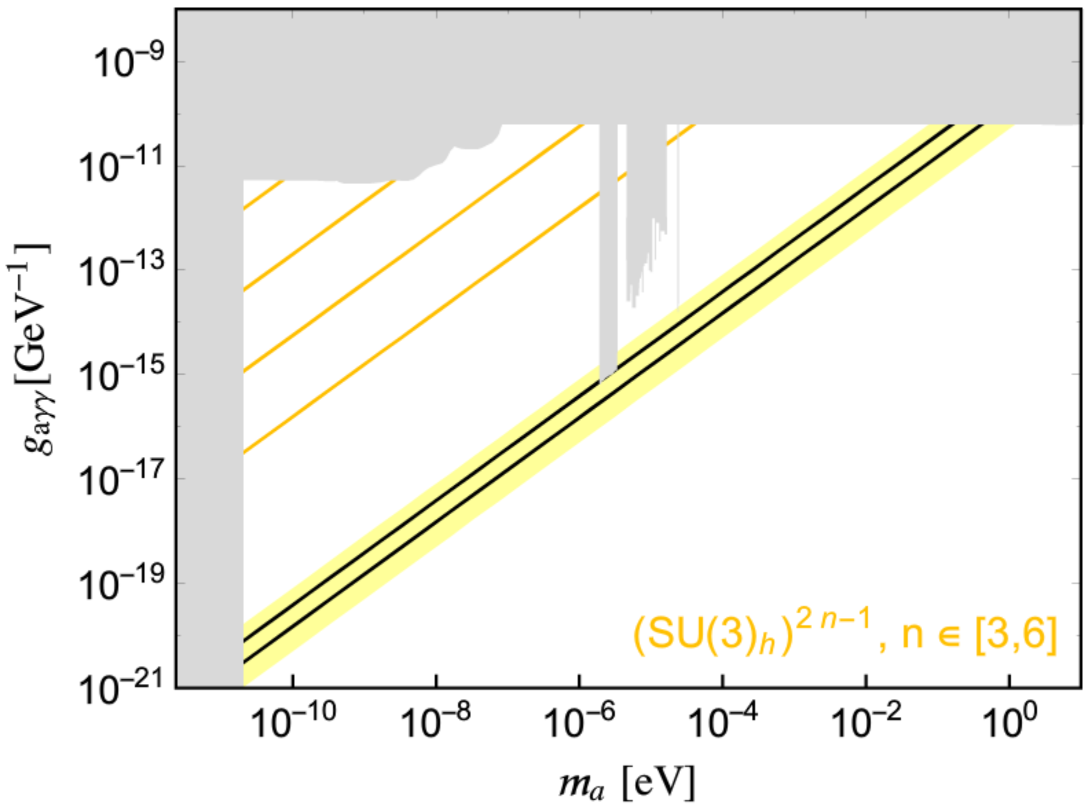
The light eigenstate

$$\phi \approx a_1 + \frac{a_2}{Q} + \ldots + \frac{a_n}{Q^{n-1}}$$

Exponential enhancement

$$\frac{Q^{n-1}\phi}{f_{\text{eff}}}\frac{\alpha_1}{8\pi}F_a\widetilde{F}_a + \frac{\phi}{f_{\text{eff}}}\frac{\alpha_n}{8\pi}F_b\widetilde{F}_b$$

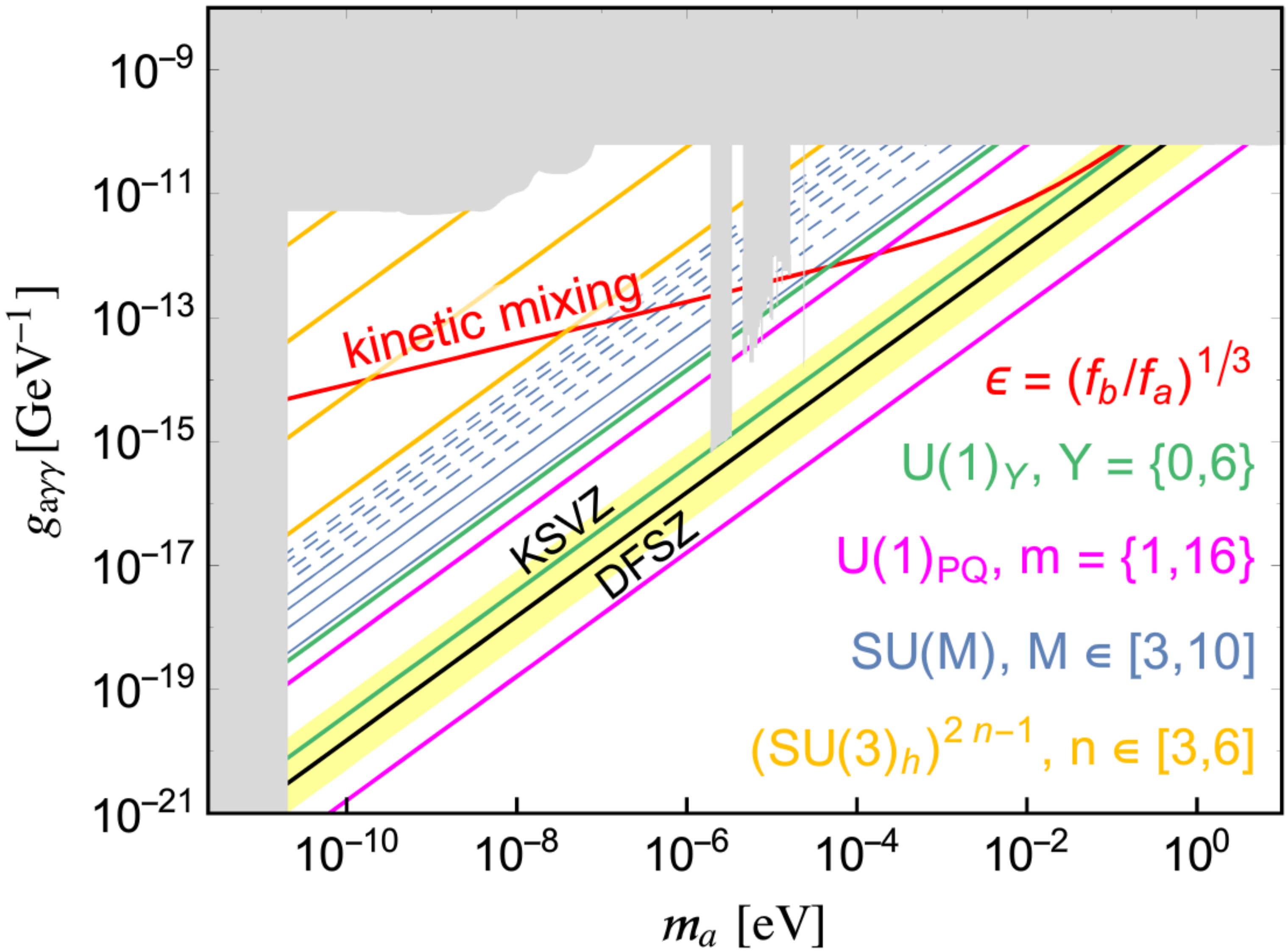
$$f_{\text{eff}} \approx fQ^{n-1}$$



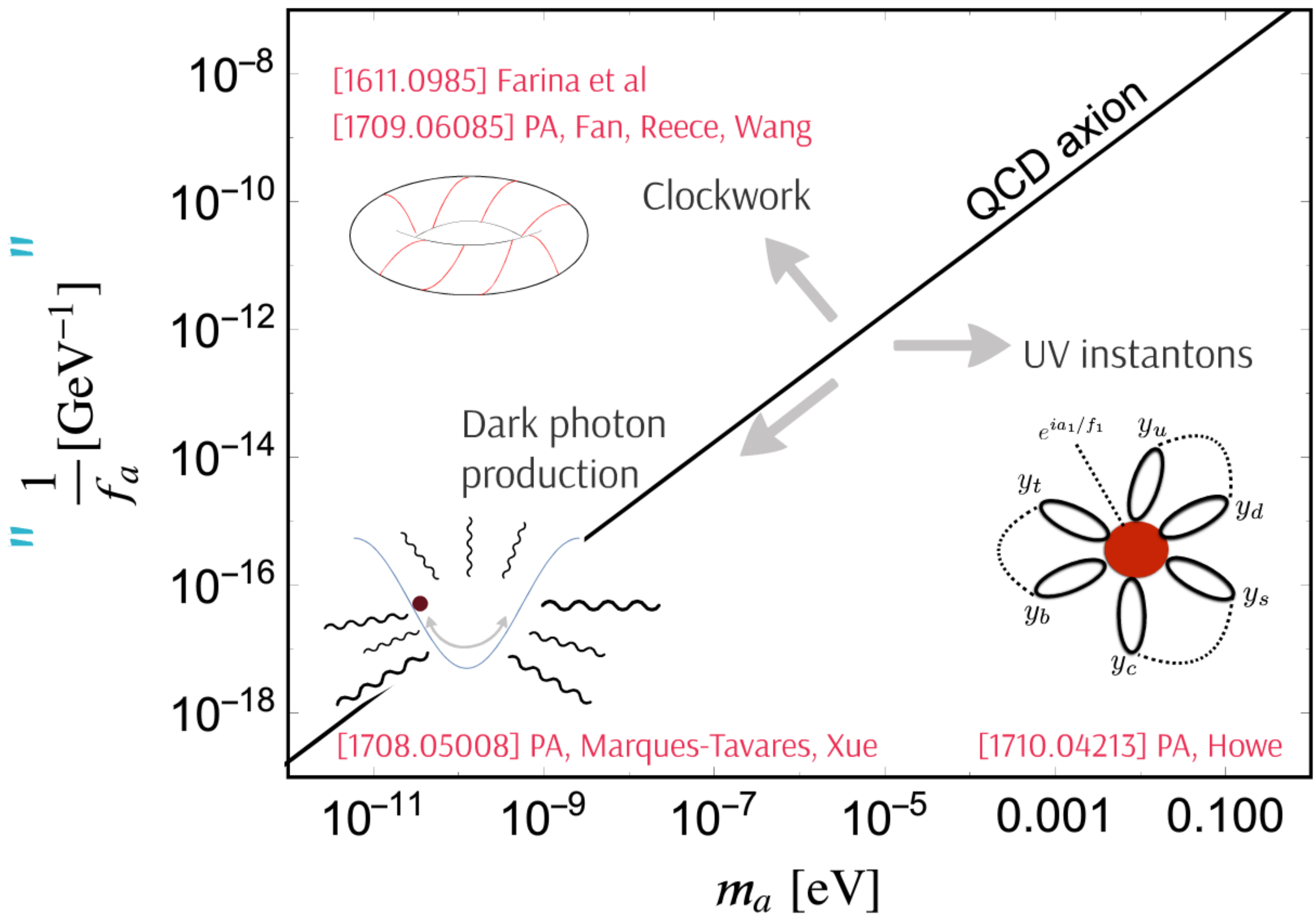
[1404.6209] Choi, Kim, Yun
[1511.00132] Choi, Im
[1511.01827] Kaplan, Rattazzi
[1611.0985] Farina, Pappadopulo, Rompineve, Tesi
[1709.06085] PA, Fan, Reece, Wang

Enhanced Photon-Axion coupling

Wider target for QCD axion searches



Extended QCD Axion target space



Particle production

Depleting axion energy into dark radiation

(set to 1)

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

Equation of motion for the gauge field

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

(in conformal time)

Tachyonic instability

Conditions for efficient depletion

$$A''_{\pm} + \left(k^2 \mp \frac{\beta k \phi'}{f_a}\right) A_{\pm} = 0$$

Large coupling required (alignment mechanism)

$$\beta \gg 1$$

$$k \sim \frac{\beta \phi'}{f_a} \sim \theta_i \beta m_a$$

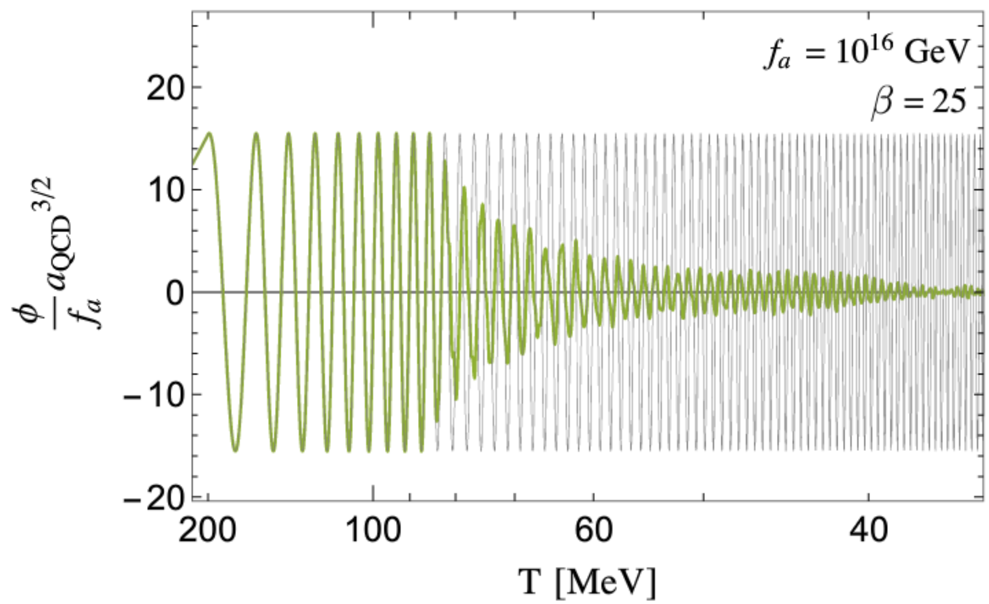
Growth rate of the tachyonic modes set by k

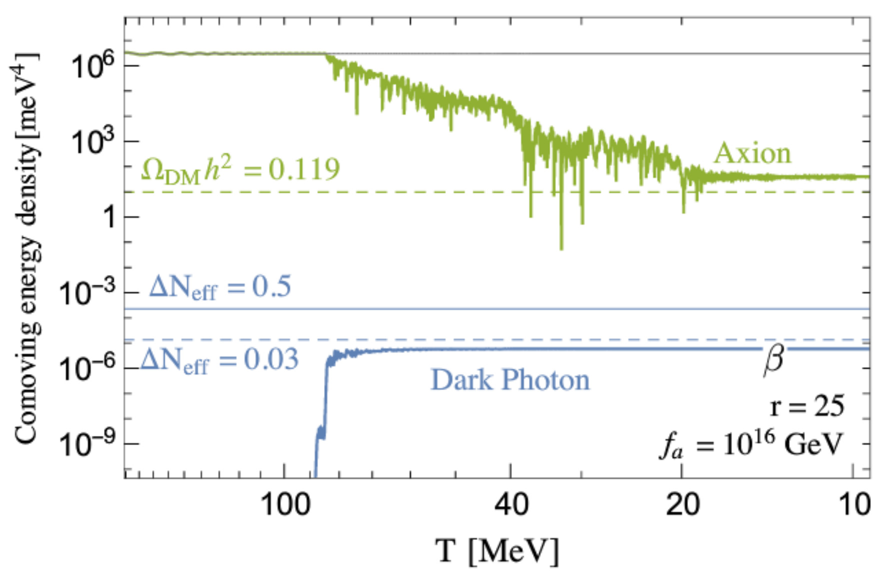
Small (no) thermal mass

Cannot use SM photon
Particles with dark charge should be absent

Results

Neglecting backscattering into axion k-modes

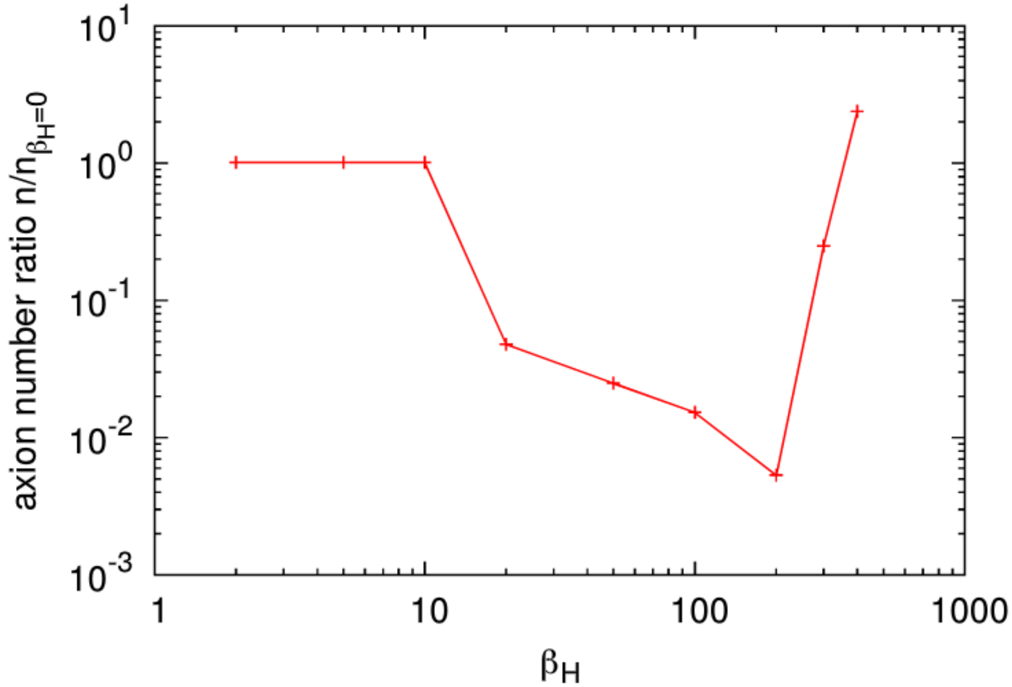




Impact of backscattering

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

may be viable

Effect on matter power spectrum?

Axion Cosmology

There are a number of mechanisms to populate axion dark matter

Misalignment (PQ breaking before inflation)

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

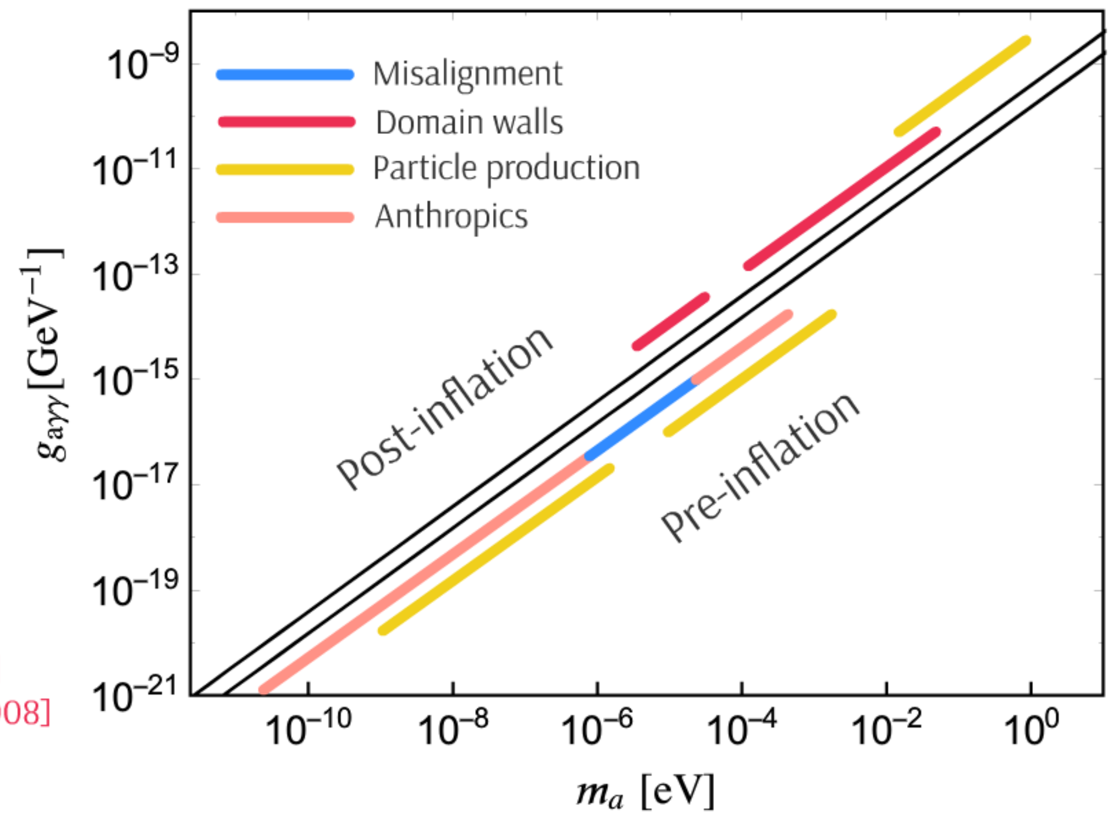
Topological defects (post-inflation)

Significant uncertainty in predictions currently

Extended cosmological mechanisms

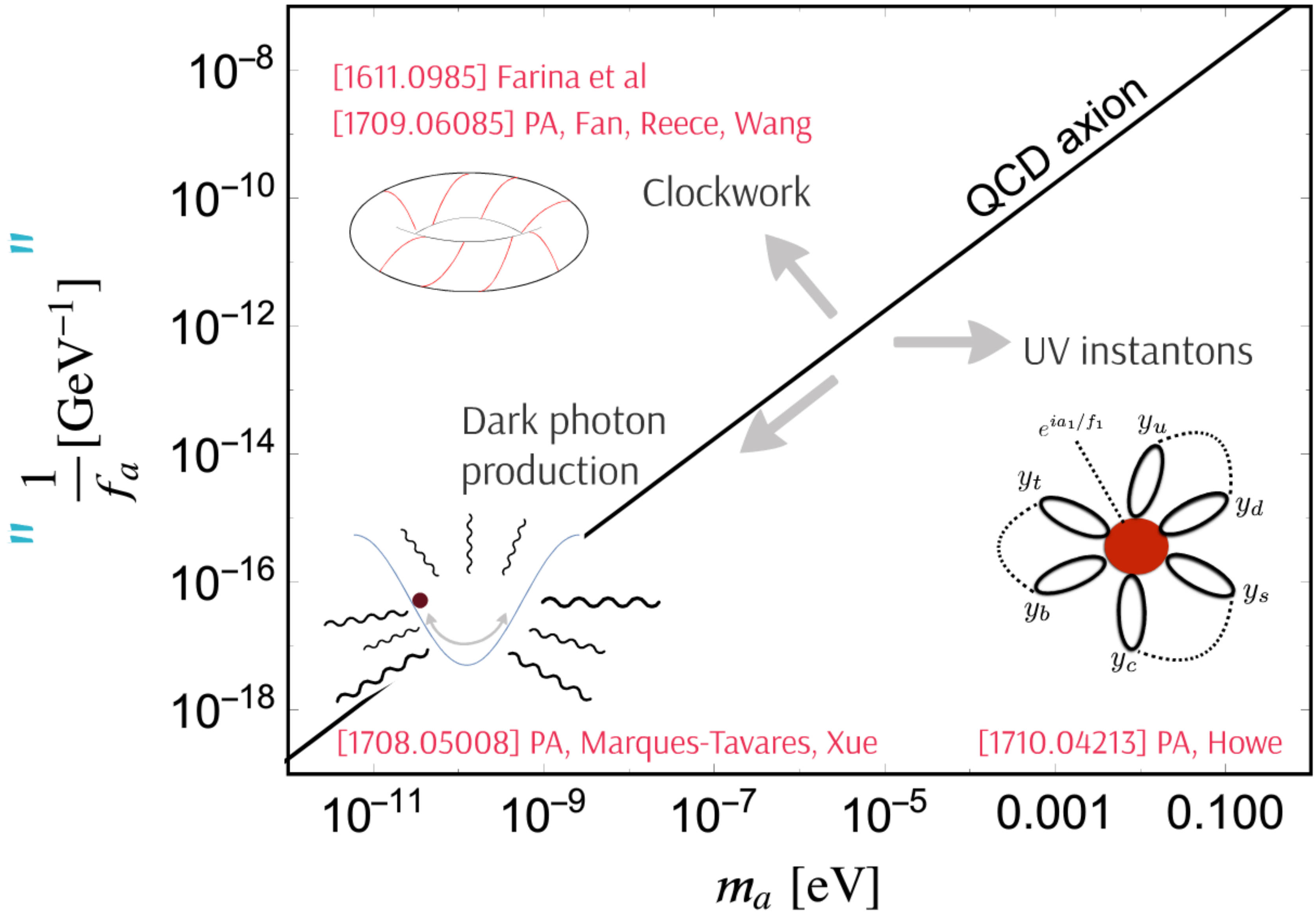
Entropy dump
Particle production

Daido, Takahashi, Wen [1702.03284]
PA, Marques-Tavares, Xue [1708.05008]
Co, Hall, Harigaya [1711.10486]
Ben-Abad, Fan [1911.05737]



Should look for QCD axions everywhere!

Extended QCD Axion target space



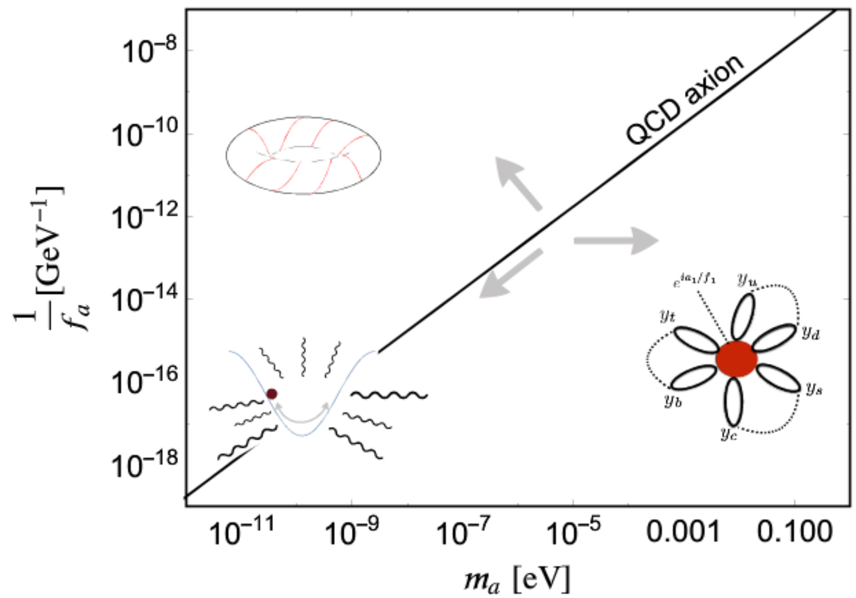
Summary

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

In simplest models this target is relatively narrow

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

- 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 the strong-CP problem



Motivates casting a wide net in the hunt for QCD axions