Ultra-light Dark Matter

Theory and Overview

Prateek Agrawal

HARVARD UNIVERSITY

Open Symposium - Update of the European Strategy for Particle Physics

Granada, May 14, 2019

European Strategy Update

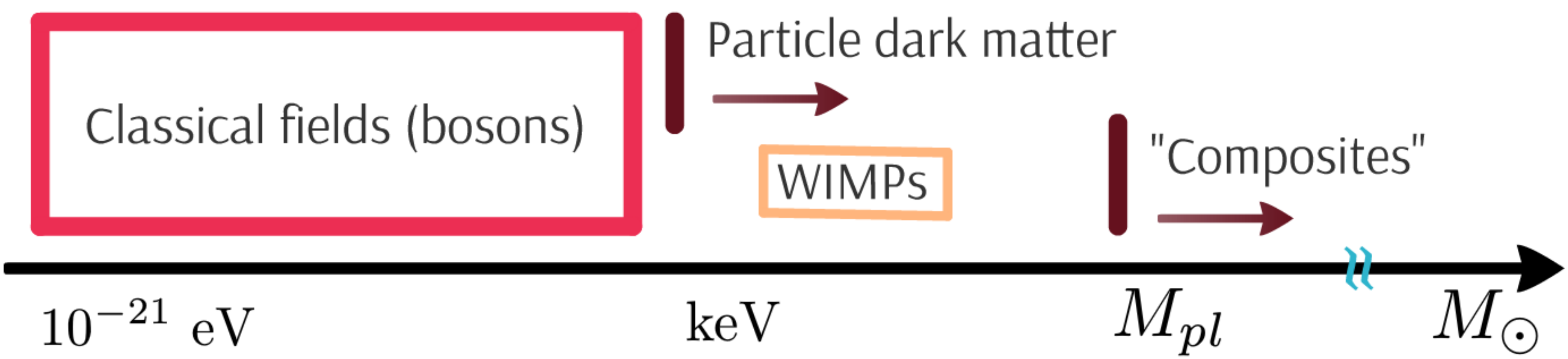
Sub-eV Dark Matter

Dark Matter is one of the most concrete clues of physics beyond the Standard Model

The mass scale for dark matter spans many orders of magnitude

For masses $\lesssim \mathrm{eV}$, the dark matter has to be bosonic, non-thermal, and is aptly described by a classical field

Large range of parameter space that requires particular search strategy



Bosonic Sub-eV Dark Matter

A number of well-motivated models fall in this category

Why are these light?

(Pseudo-)Nambu - Goldstone bosons

QCD Axion
Axion-like particles
:

Light spin-1 particles

Dark photons

Very weakly coupled scalars

Modulus / dilaton fields

Expected to be ubiquitous in theories of quantum gravity

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

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

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

[neutron EDM]
Baker et al [2006]

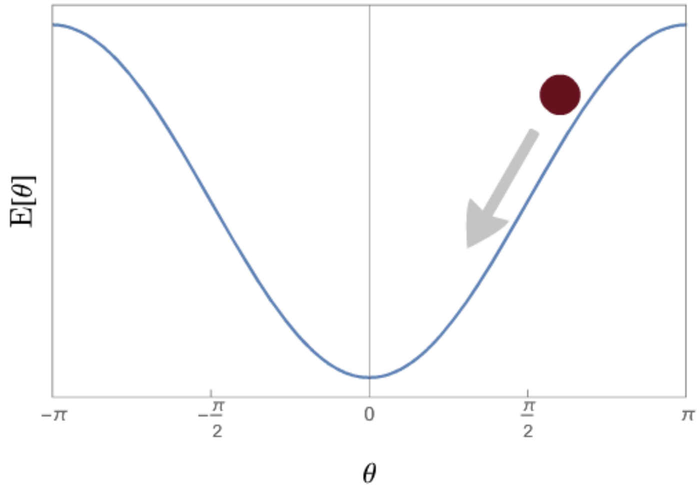
The vacuum energy of QCD is minimized at $\bar{\theta} = 0$ Vafa, Witten [1984]

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

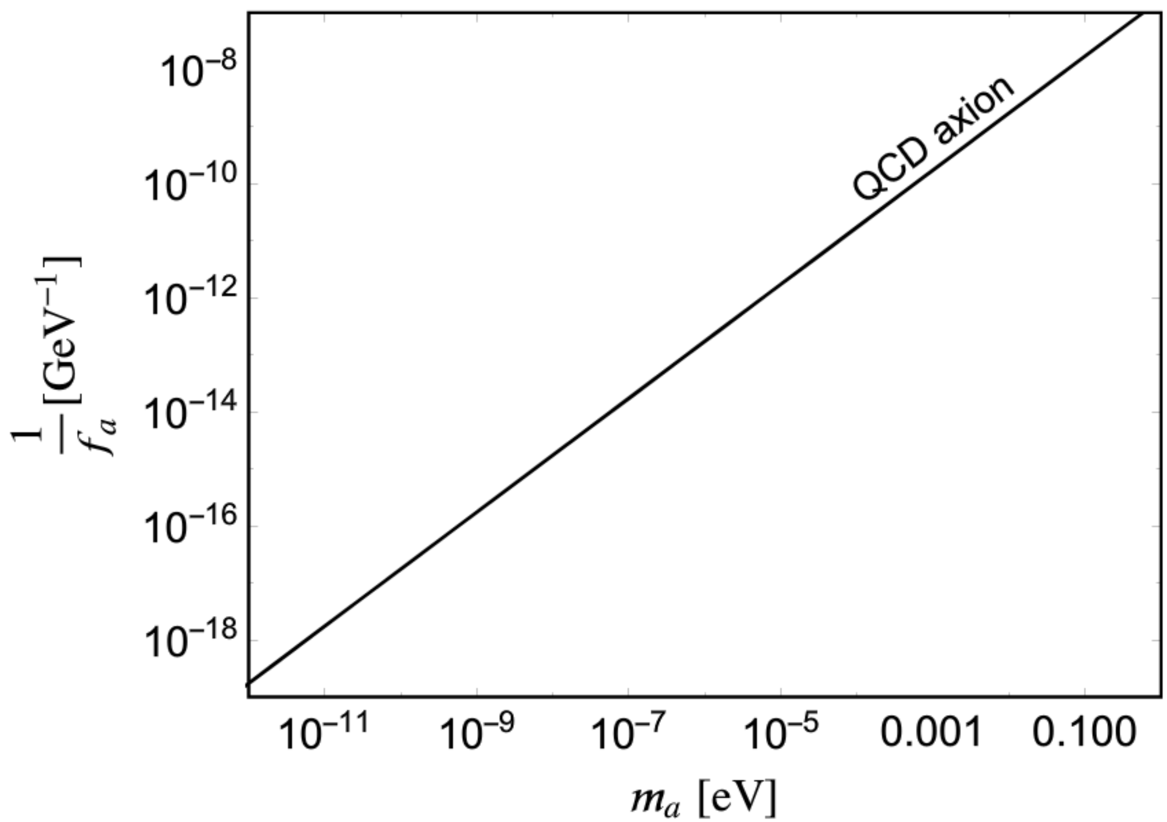
Mass and decay constant

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

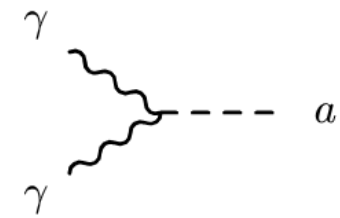
$$V(a) \simeq -f_\pi^2 m_\pi^2 \cos\left(\theta + \frac{a}{f_a}\right)$$



QCD Axion parameter space

Coupling to photons

The coupling to photons is phenomenologically important

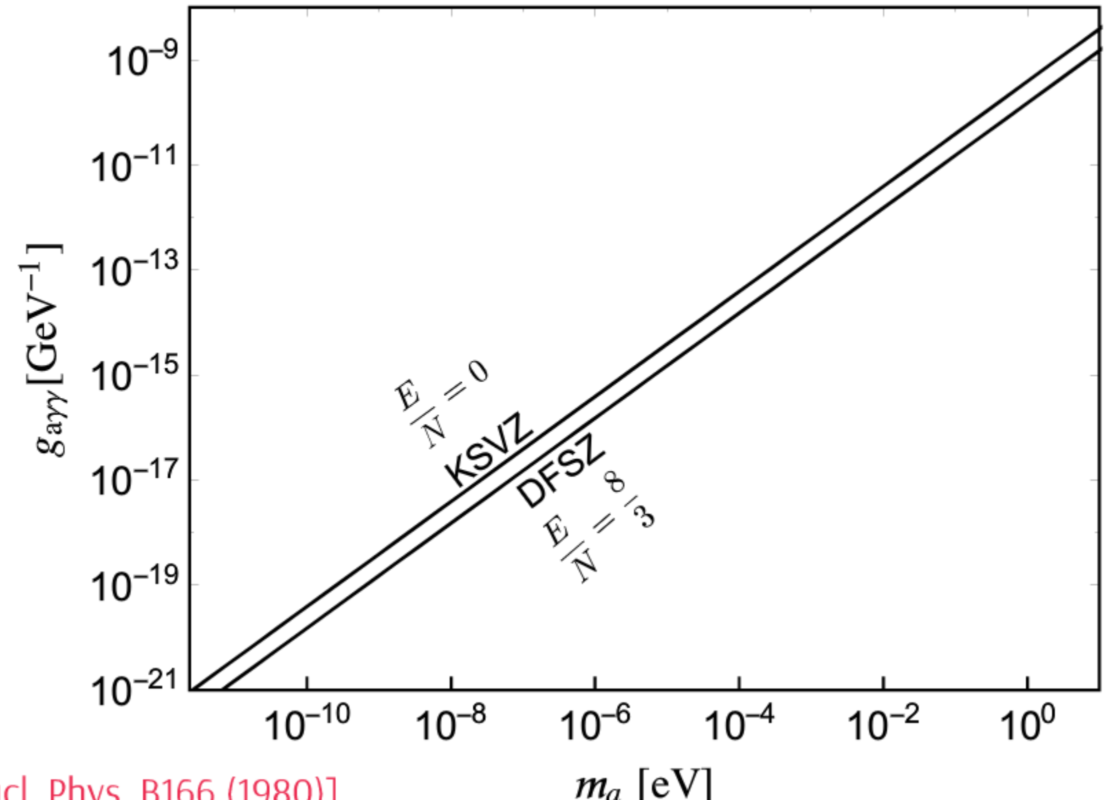


Model dependent UV contribution: charges of PQ fermions

Model independent IR contribution:
axion-meson mixing

UV → $\frac{E}{N}$, IR → -1.92

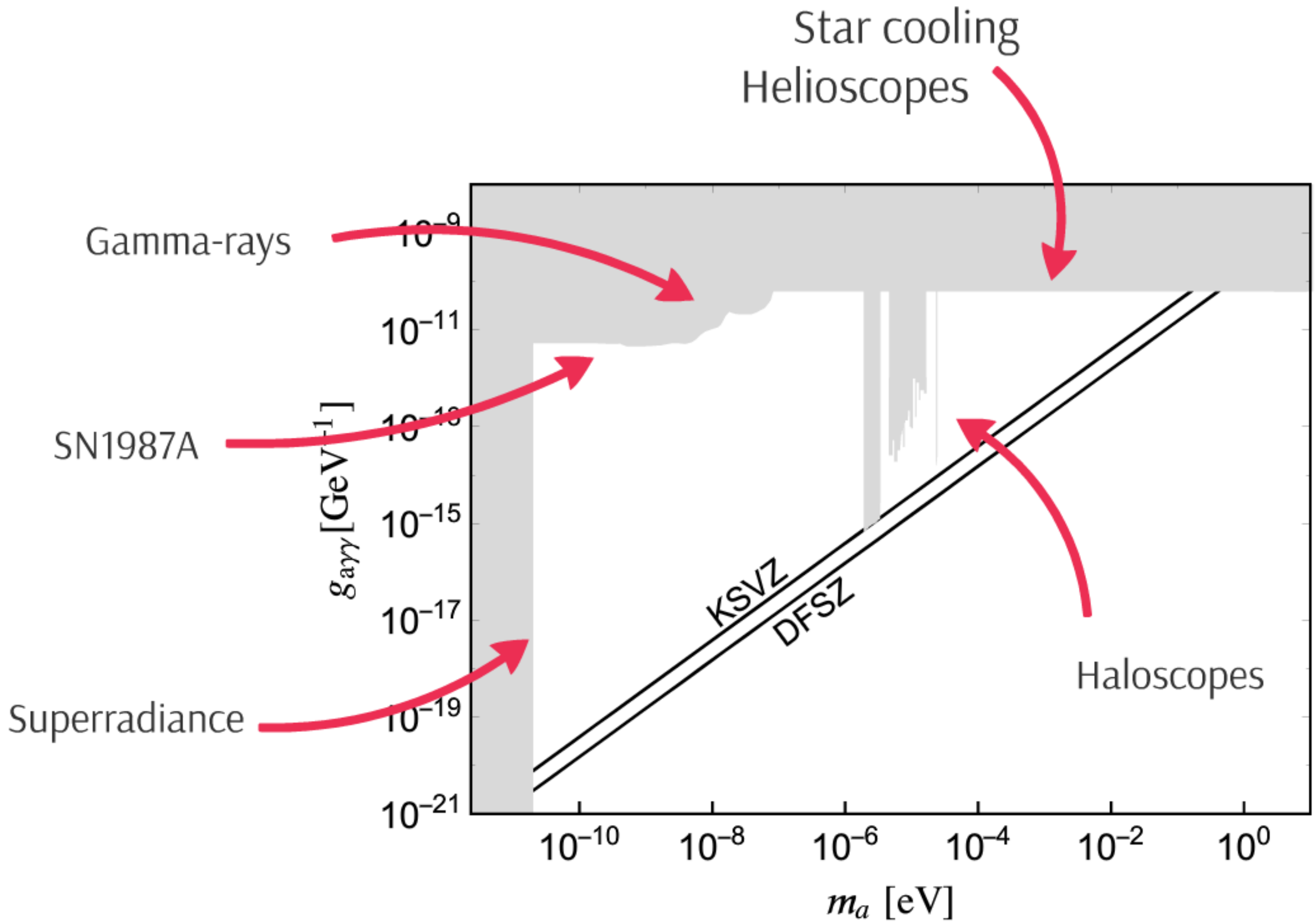
$$\frac{a}{f_a} \underbrace{\frac{\alpha}{8\pi}\left[\frac{E}{N} - 1.92\right]}_{\frac{1}{4} g_{a\gamma\gamma}} F_{\mu\nu}\widetilde{F}^{\mu\nu}$$



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)]

Constraints and Hints

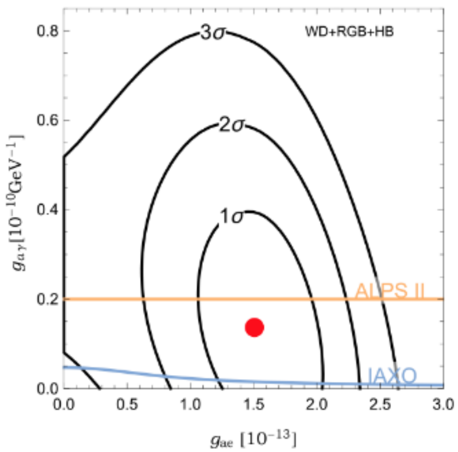
Axion-photon coupling is constrained by many observations



Constraints and Hints

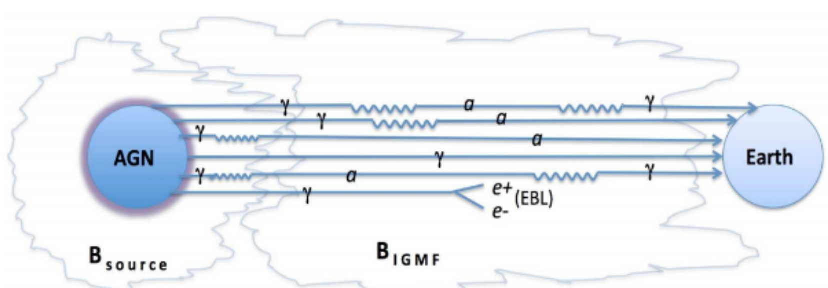
Phenomenological hints for axions

Excessive energy losses in stars

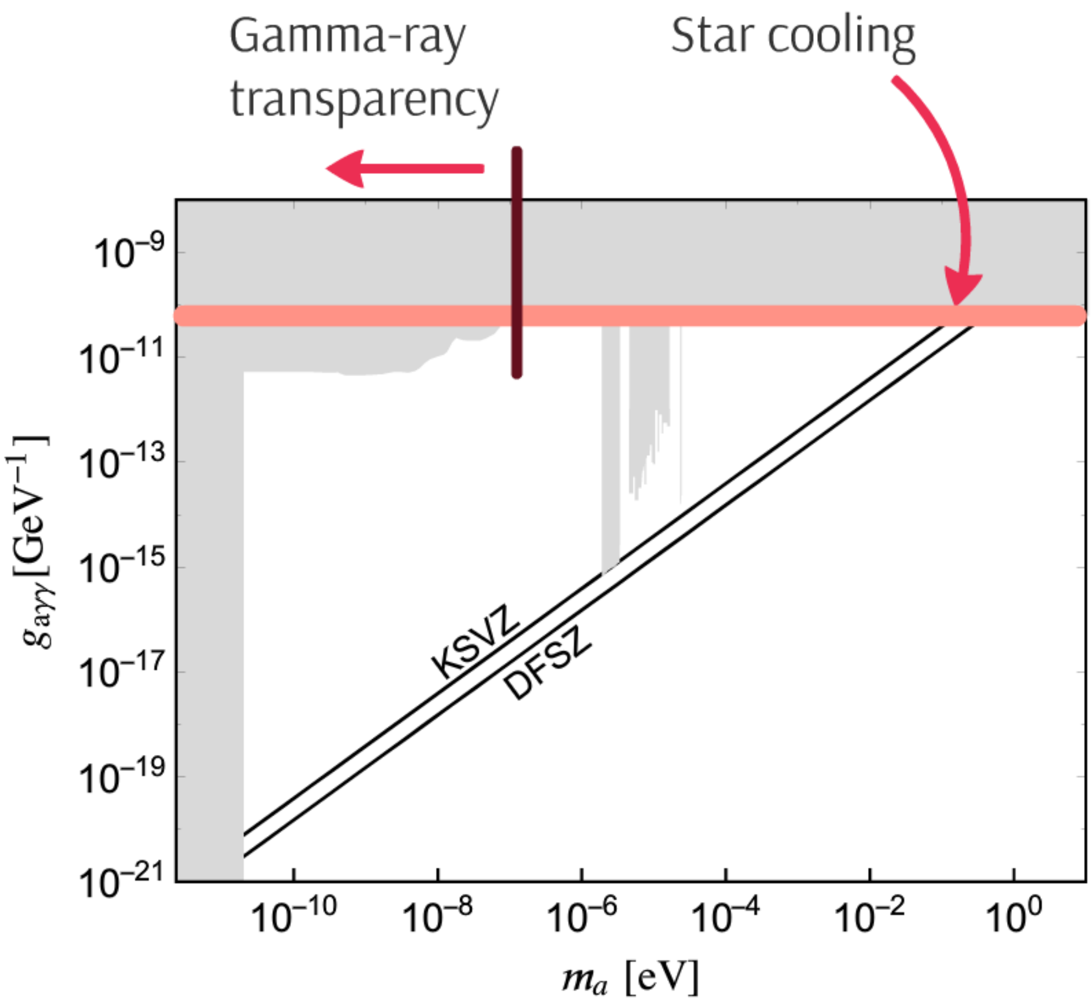


Giannotti et al [1512.08108]

Gamma-ray transparency



Sánchez-Conde et al [0905.3270]



Axion Cosmology

There are a number of mechanisms to populate axion dark matter

Misalignment (PQ breaking before inflation)

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

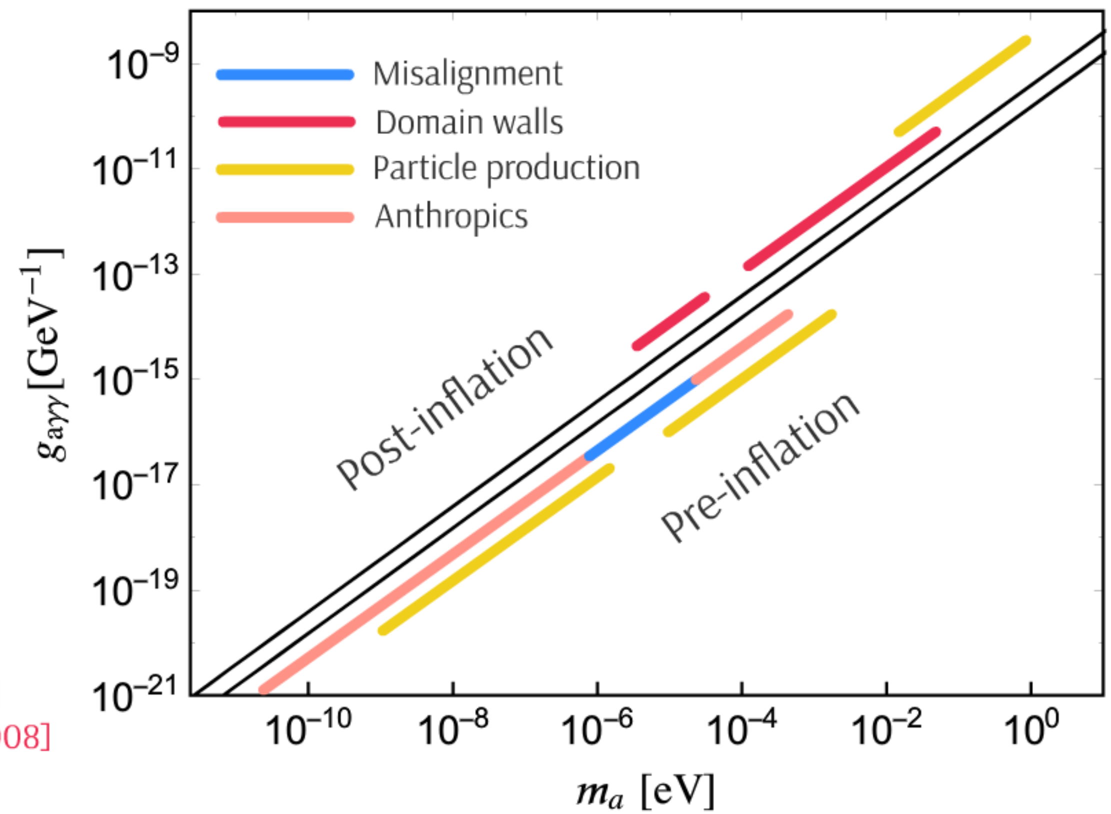
Topological defects (post-inflation)

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 [1711.1048]



Should look for QCD axions everywhere!

Axion target space

Traditional target space: variants of the KSVZ and DFSZ models

Kim [hep-ph/9802220]

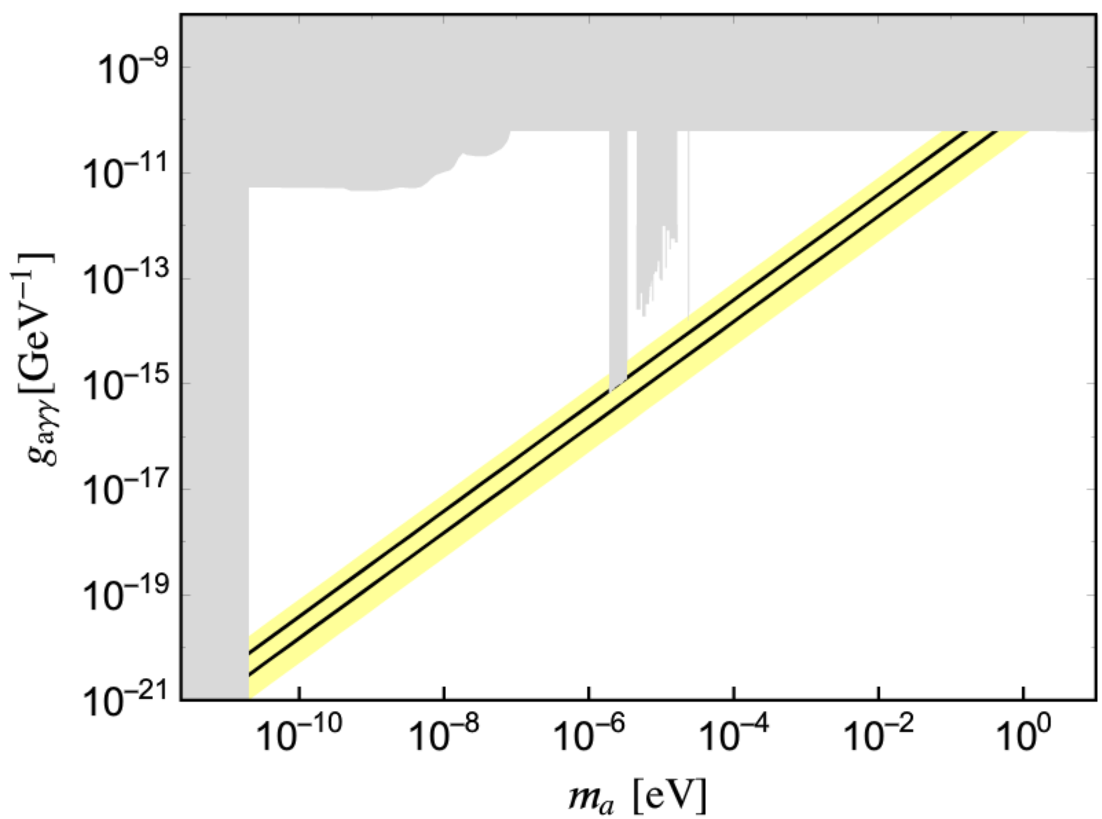
Some guiding principles

- 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



Hypercharge / PQ charge

Models where the PQ fermions have large hypercharge or Peccei-Quinn charge have moderately enhanced couplings to photons

$$\frac{1}{4} g_{a\gamma\gamma} = \frac{\alpha}{8\pi}\left[\frac{E}{N} - 1.92\right]$$

Hypercharge

Landau pole above Planck scale

$$Y \lesssim 6$$

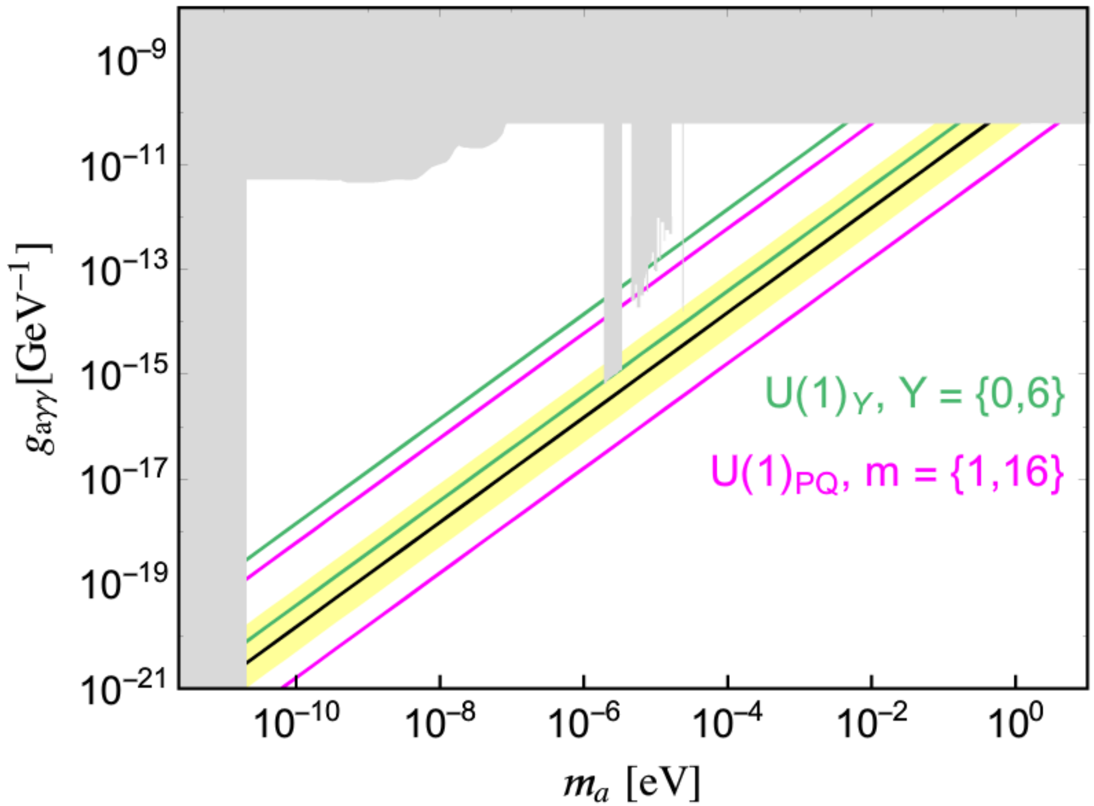
Enhancement: $2Y^2$

PQ charge

Mass of fermions suppressed

$$M_\psi \lesssim f_a \left(\frac{f_a}{\Lambda}\right)^{m-1}$$

Enhancement: $2m$



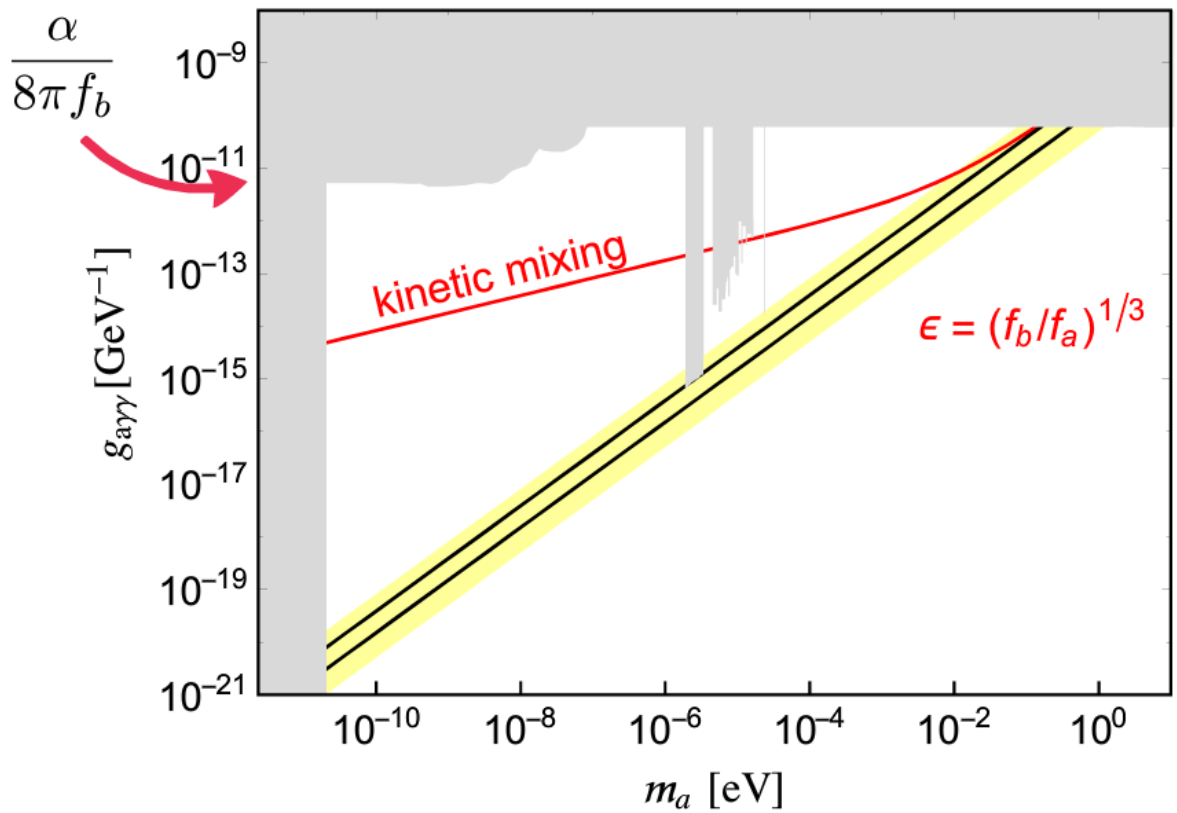
Kinetic mixing

String-inspired theories predict a large number of axions

Two axion model

$$\frac{1}{2}\partial_\mu a \partial^\mu a + m_\pi^2 f_\pi^2 \cos\frac{a}{f_a} + \epsilon \partial_\mu a \partial^\mu b + \frac{1}{2}\partial_\mu b \partial^\mu b + \frac{b}{f_b}\frac{\alpha}{8\pi} F\widetilde{F}$$

$$b \to b - \epsilon a$$



Enhanced coupling

$$\frac{\epsilon f_a}{f_b}\frac{\alpha}{8\pi} a F\widetilde{F}$$

If generated in QFT, effect of kinetic mixing is expected to be small

String compactifications can have larger kinetic mixing

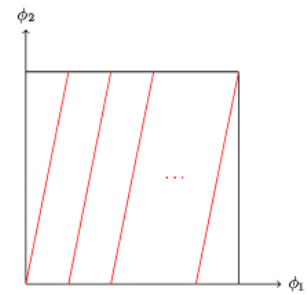
Cicoli, Goodsell, Ringwald [1206.0819]

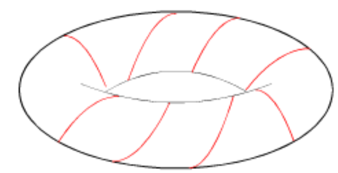
Alignment mechanism

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





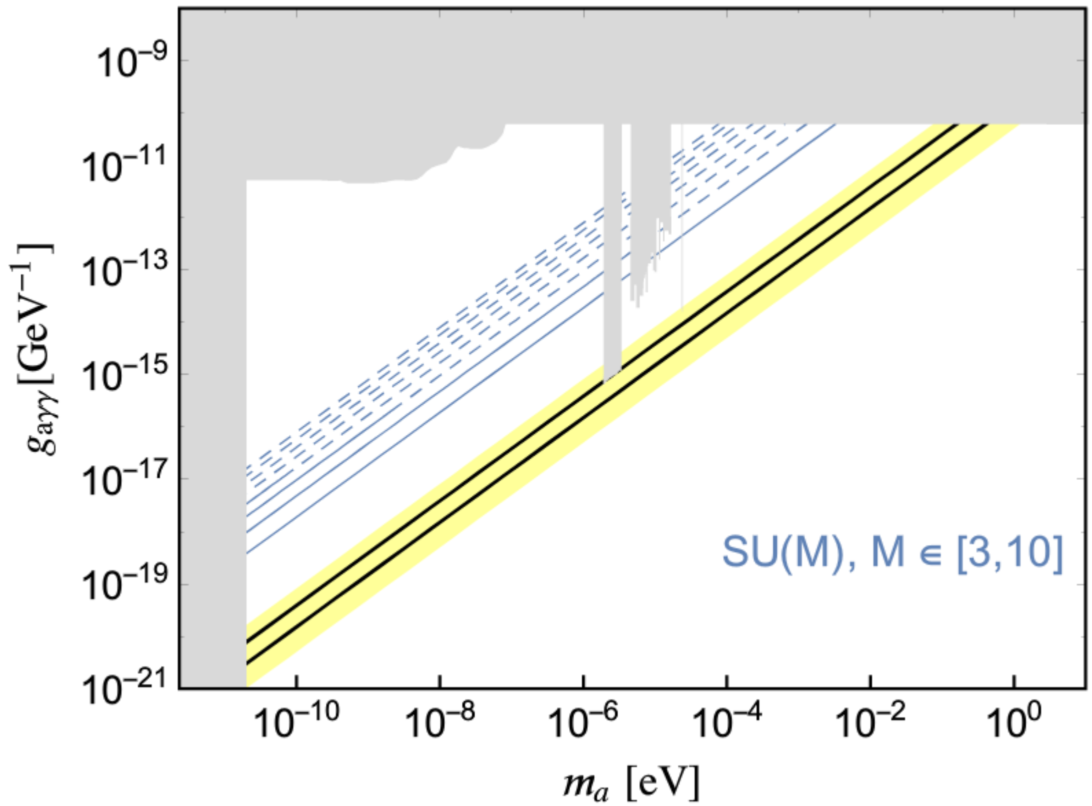
The light eigenstate

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

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

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

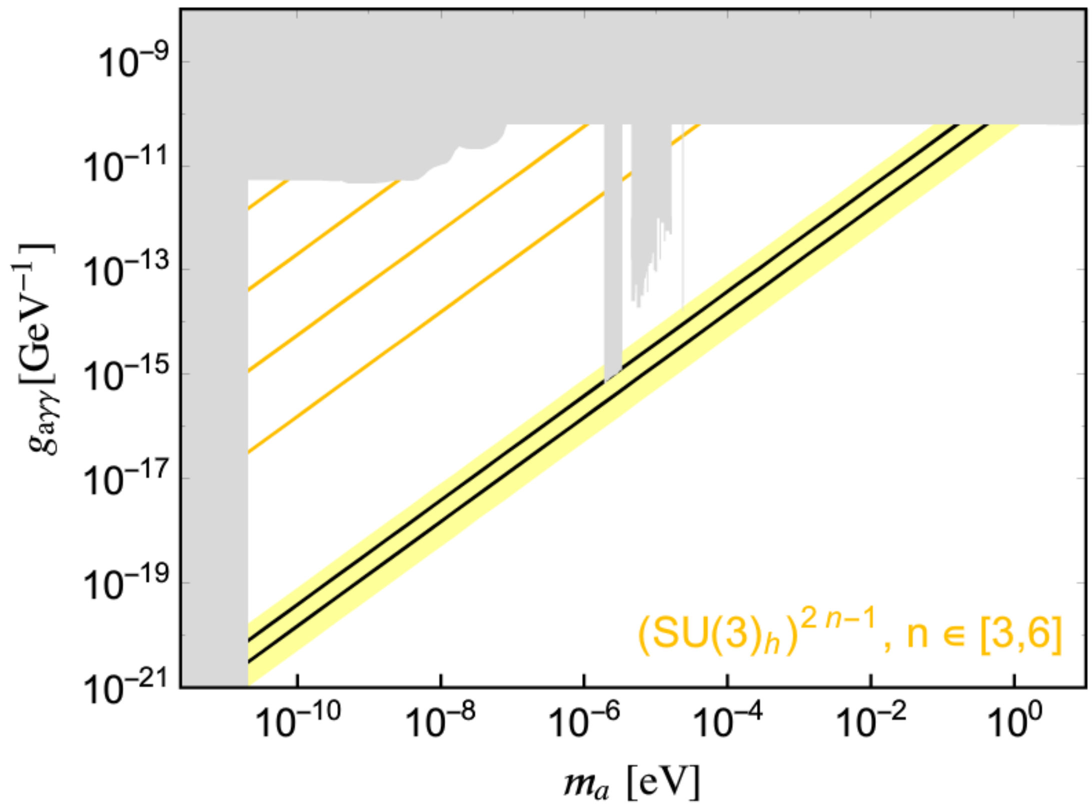
The light eigenstate

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

Exponential enhancement

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

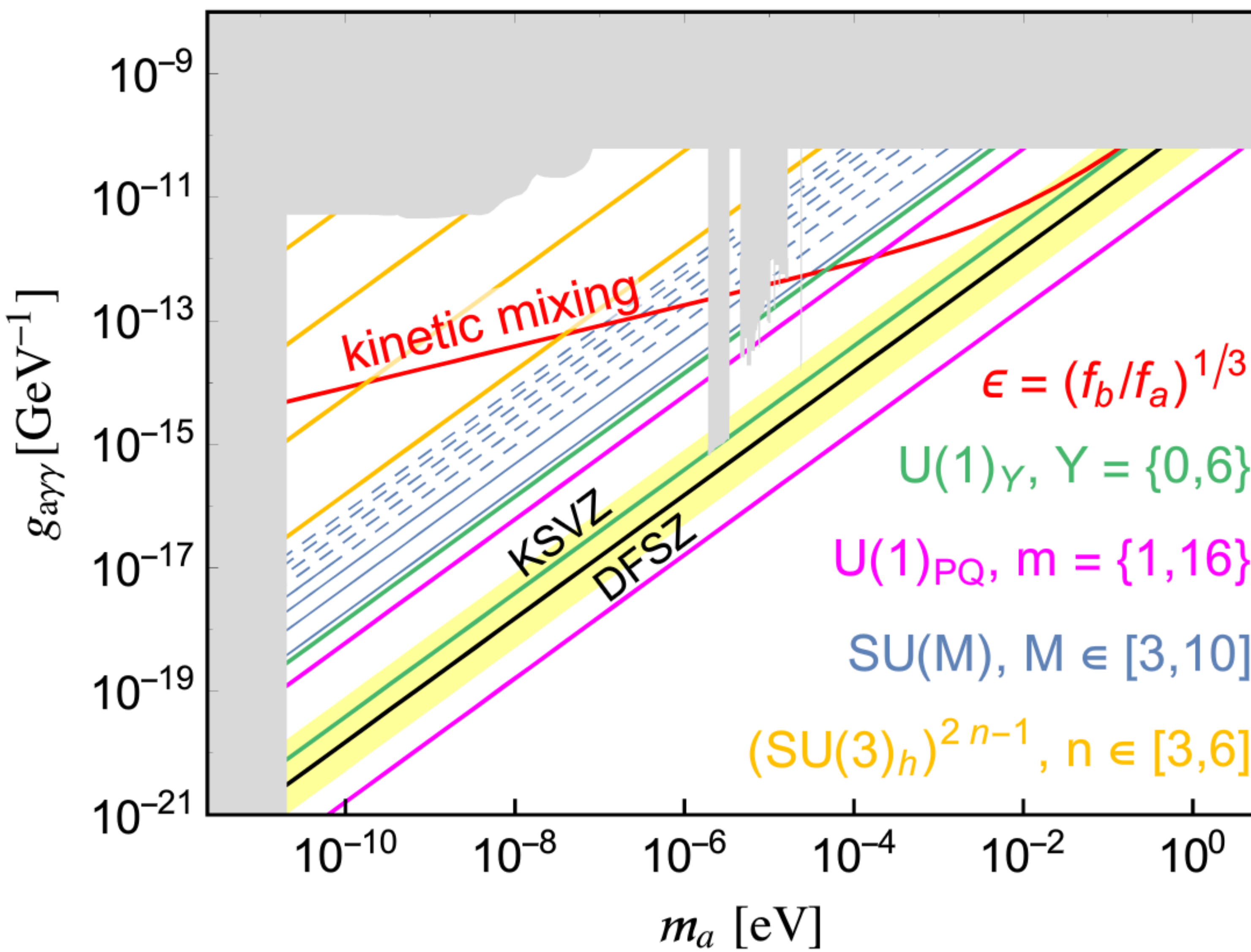
$$f_{\text{eff}} \approx fQ^{n-1}$$



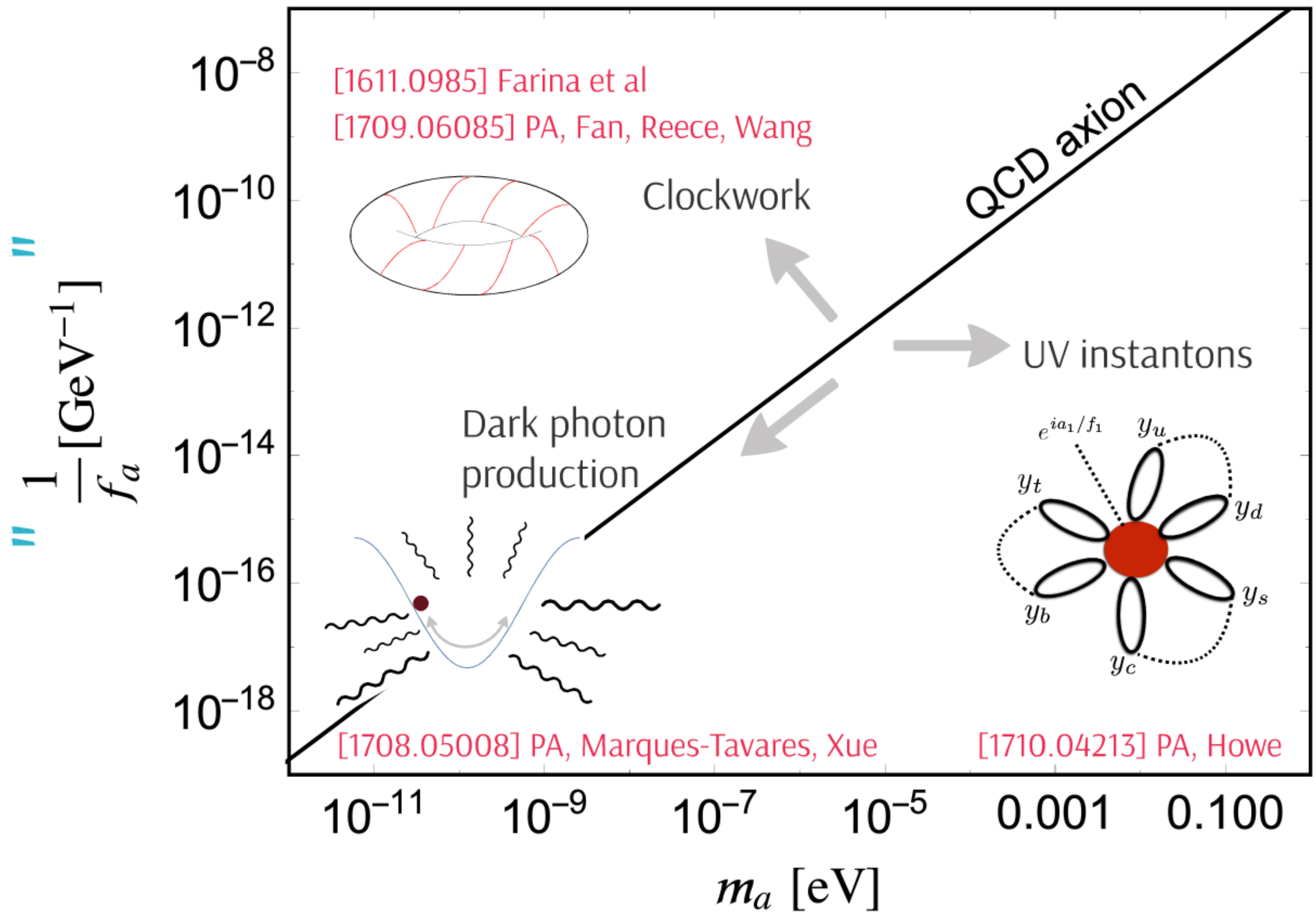
[1404.6209] Choi, Kim, Yun
[1511.00132] Choi, Im
[1511.01827] Kaplan, Rattazzi
[1611.0985] Farina, Pappadopulo, Rompineve, Tesi
[1709.06085] PA, Fan, Reece, Wang

Enhanced Photon-Axion coupling

Wider target for QCD axion searches



Extended QCD Axion target space



Dark Photon Dark Matter

Spin-1 fields with very small masses

Dark electric field ~ 50 V/cm

Challenging to populate light dark photon dark matter

- Very limited misalignment mechanism
- Couplings to curvature

Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald [1201.5902]

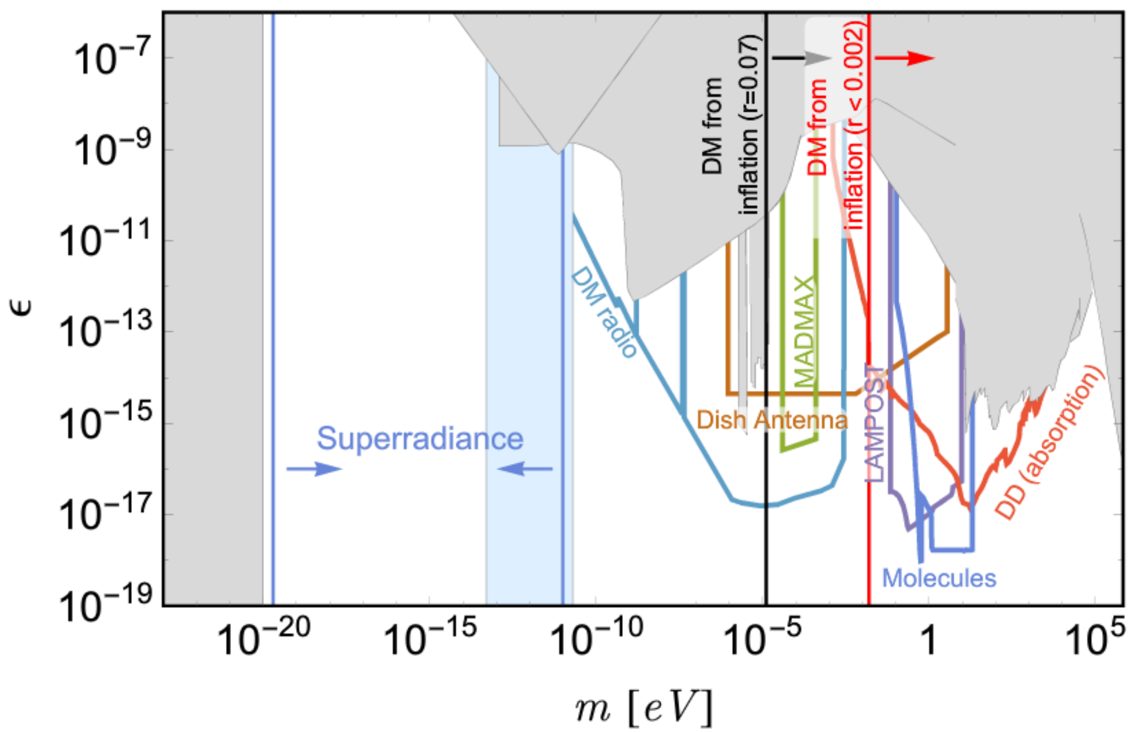
Tachyonic particle production

- Store energy in an axion, transfer to dark photons

PA, Kitajima, Reece, Sekiguchi, Takahashi, [1810.07188]
Bastero-Gil, Santiago, Ubaldi, Vega-Morales [1810.07208]
Co, Pierce, Zhang, Zhao [1810.07196]
Dror, Harigaya, Narayan [1810.07195]

Common / Complementary probes with the axion

Kinetically mixed with photons



Light scalar dark matter

[+ CP violating axion coupling]

Light scalars (moduli) appear ubiquitously in higher dimensional theories

These set the masses and coupling strengths for particles

- Constrained by fifth force / equivalence principle tests
- Dark matter → oscillating masses / couplings

Other probes

- Absorption in molecules — Arvanitaki, Dimopoulos, Van Tilburg [1709.05354]
- Gravitational wave detectors (MAGIS/AION) — Arvanitaki et al [1606.04541]
  - Modulation of atomic transition energies
- Atomic clocks — Stadnik, Flambaum [2016]
- Atomic spectroscopy — Van Tilburg et al [2015], Aharony et al [1902.02788], Antypas et al [1905.02968], Banerjee et al [1902.08212]...
- GPS — Roberts et al [Nat. Comm. 8, 1195 (2017)]

A vast effort in tabletop / GW experiments leveraging new advances in sensors technology

Conclusions

Ultralight dark matter models are compelling, and constitute a large part of theory space for possible dark matter candidates

Some of the best-motivated part of the parameter space is being probed now

Very rich experimental program is underway / being planned / being proposed

Very active field of research:

- new theoretical ideas are expanding where we might find dark matter
- new experimental ideas are increasingly covering the preferred parameter space

We stand to learn quite a bit about new physics from axion searches