

New Directions in Axions and Dark Photons

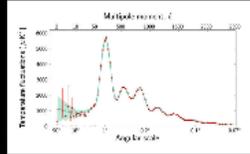
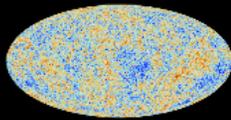
8th PIKIMO meeting
2 November 2019
University of Cincinnati

Prateek Agrawal



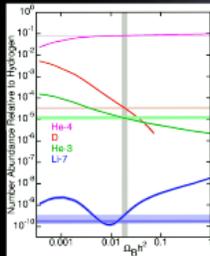
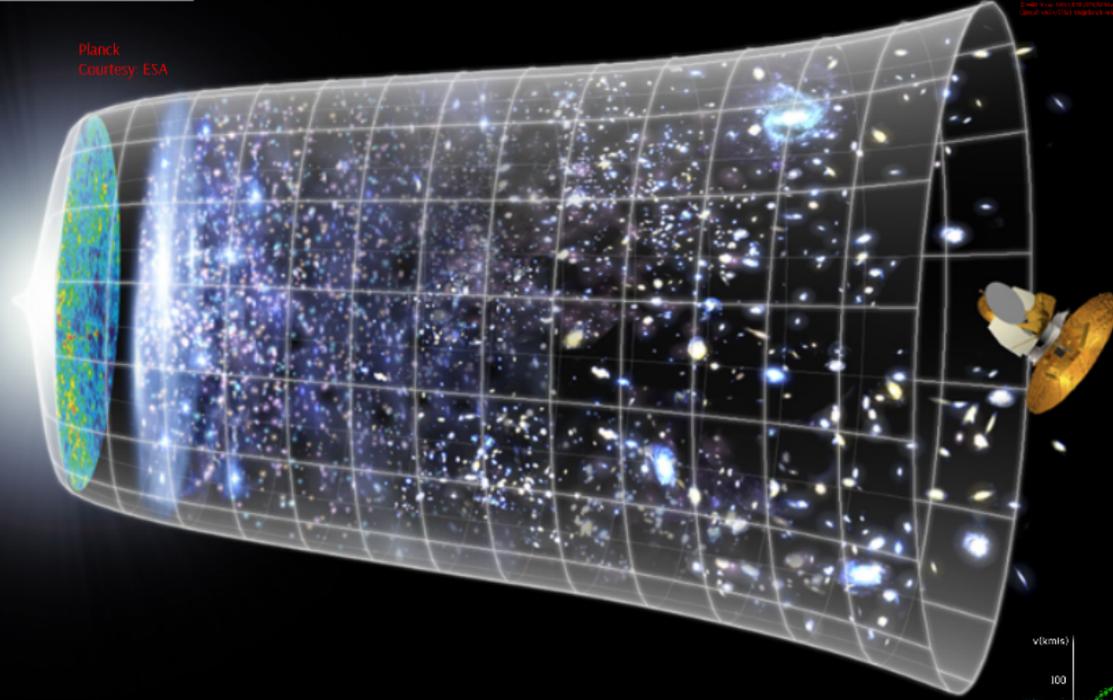
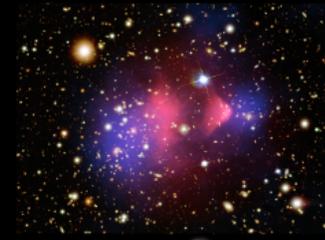
HARVARD
UNIVERSITY

Cosmic Microwave Background



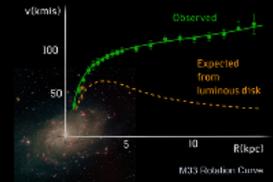
Planck
Courtesy: ESA

The Bullet Cluster



(credit: Edward L. Wright)

Big Bang Nucleosynthesis



(credit: Harvard-Smithsonian Center for Astrophysics)

Wikipedia: [Dark Matter \(BIBLIOPEDIA\)](#), [NOT an NDSM/ALBA/NOT](#), [MATHS/ALBA/NOT](#)

Galactic Rotation Curves

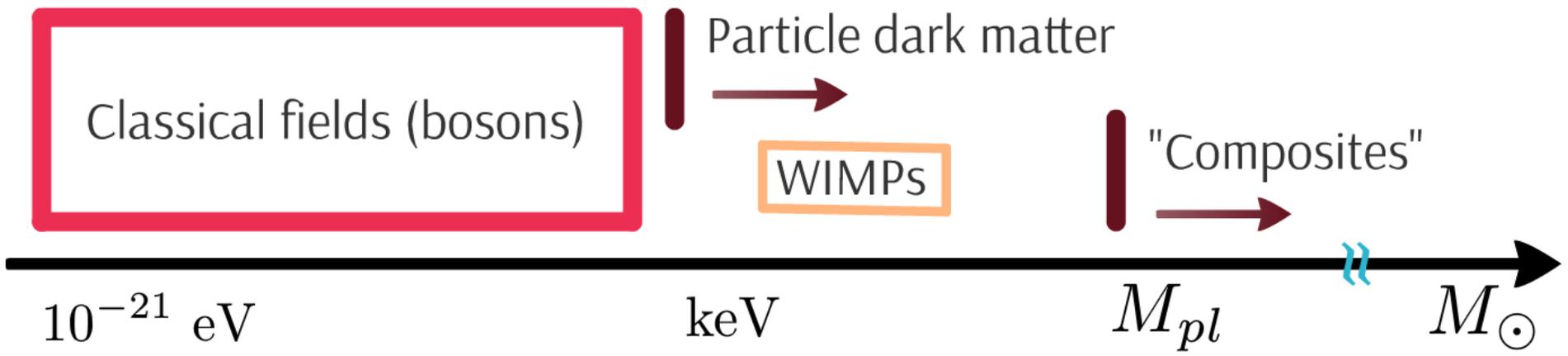
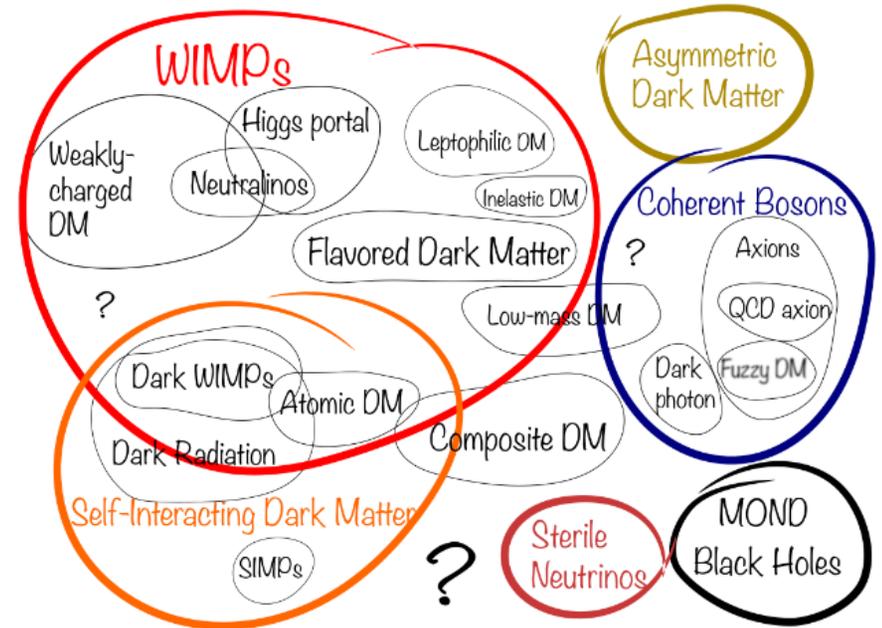
Vast Space of possibilities

A large number of particle physics ideas

The mass scale for dark matter spans many orders of magnitude

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

For masses $\gtrsim M_{pl}$:
dark matter is not a fundamental particle,
e.g. nuggets, primordial black holes



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

Motivated as a solution to the strong CP problem

The strong CP phase is constrained to be small

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

[neutron EDM]

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

Make $\bar{\theta}$ a dynamical field, the axion

Peccei, Quinn [1977]

Weinberg [1978]

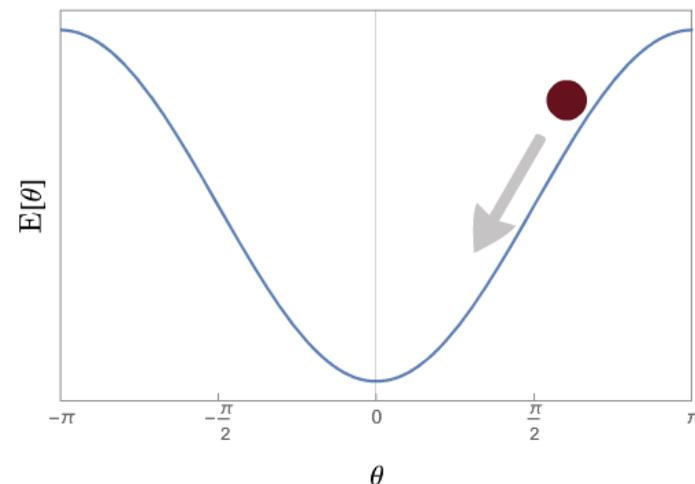
Wilczek [1978]

QCD generates a potential for the axion

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

Potential is minimized at $\bar{\theta} = 0$ Vafa, Witten [1984]

Mass and couplings of the axion are set by f_a



Axion dark matter abundance

Dark matter abundance depends on (only) a few details of cosmology

Misalignment mechanism

QCD axion: temperature dependent mass

Axion-like particles

QCD axion: Non-standard cosmology

Anthropic axion / entropy dump / particle production

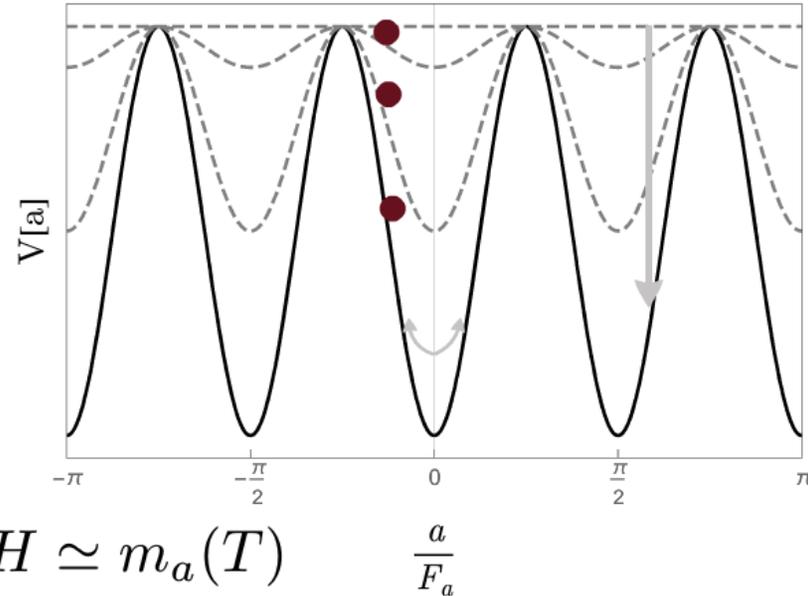
Production from topological defects

QCD Axion Dark Matter 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 $H \simeq m_a(T) \quad \frac{a}{F_a}$

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

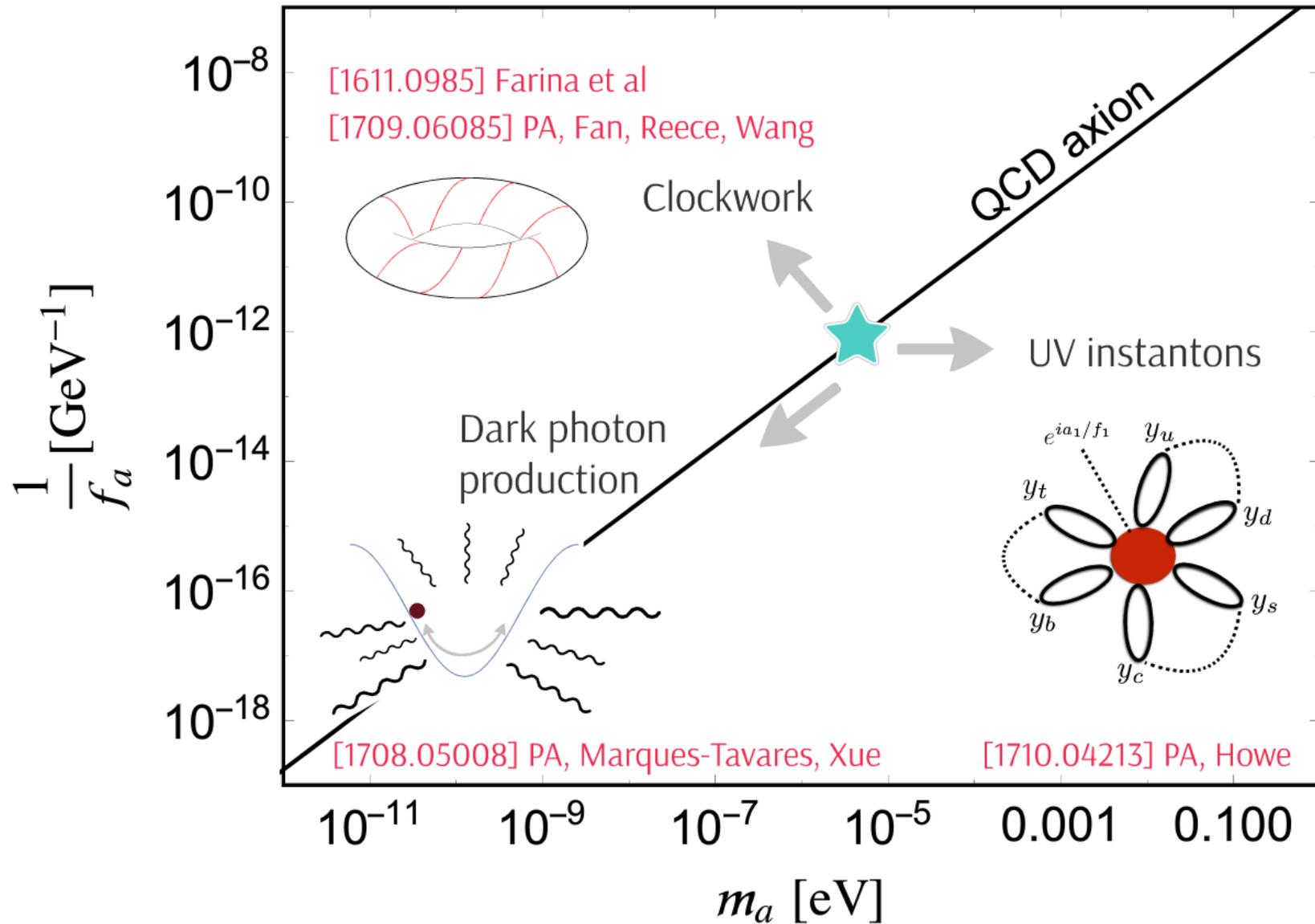
Under adiabatic evolution, comoving number density conserved

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

The dark matter abundance today is

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

Expanded Axion target space



Clockwork / Alignment

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

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

Two axion model

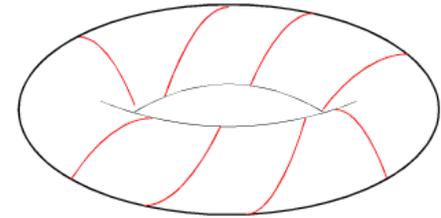
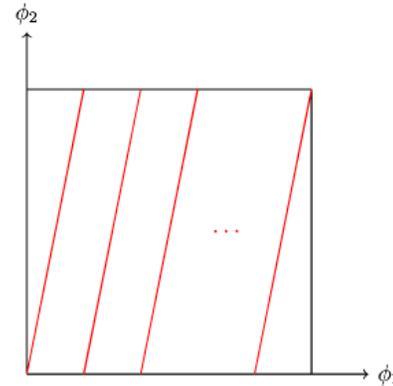
$$\frac{a}{f_a} \frac{\alpha_a}{8\pi} F_a \tilde{F}_a + \frac{b}{f_b} \frac{\alpha_b}{8\pi} F_b \tilde{F}_b + \Lambda^4 \cos \left(\frac{a}{f_a} + \frac{Qb}{f_b} \right)$$

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

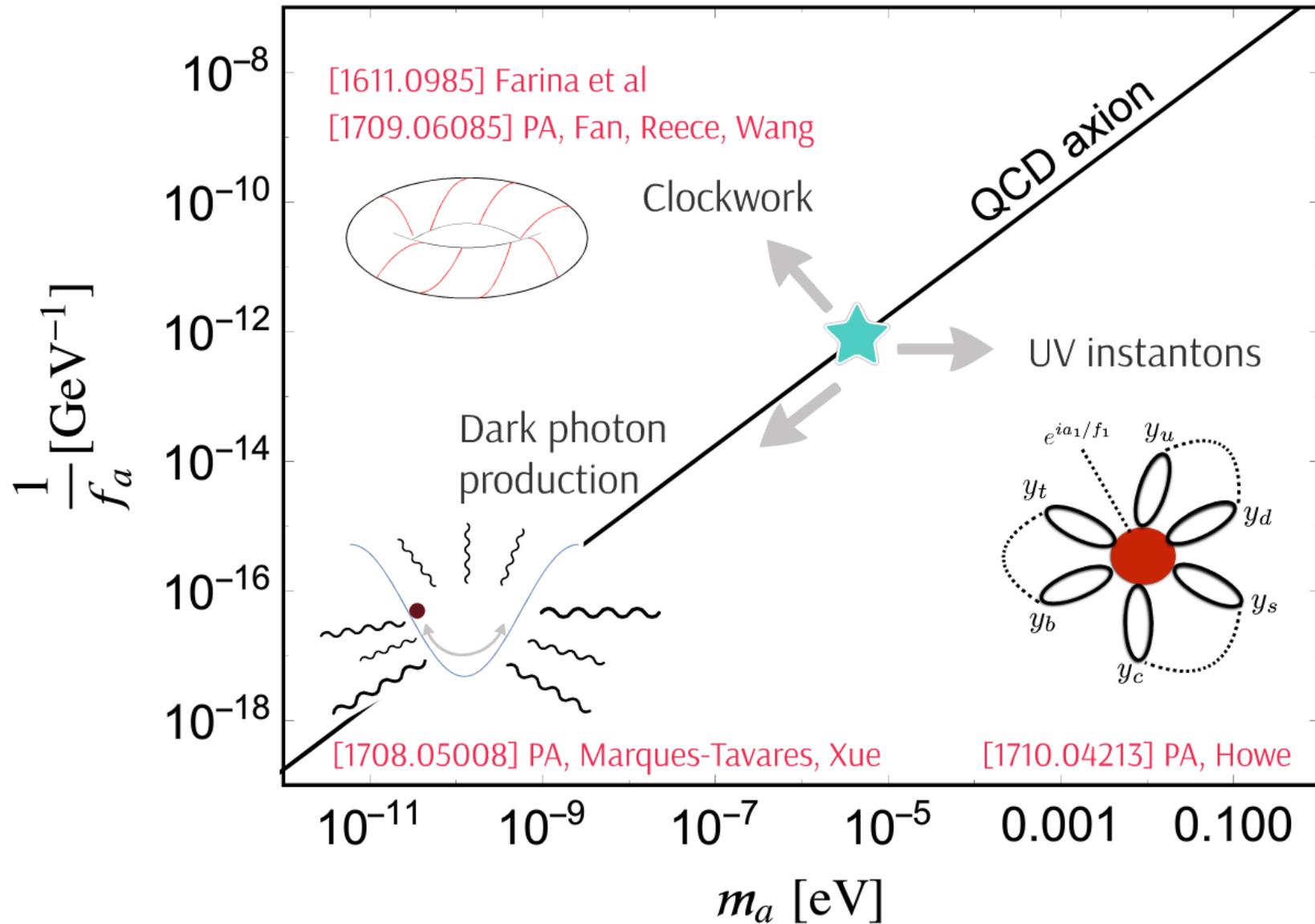
[1511.01827] Kaplan, Rattazzi

[1611.0985] Farina, Pappadopulo, Rompineve, Tesi

[1709.06085] PA, Fan, Reece, Wang

Clockwork: Rinse, repeat

Expanded Axion target space



Particle production

Couple the axion to dark photon

$$\mathcal{L} = \frac{a}{f_a} \frac{\alpha}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{\beta}{4} \frac{a}{f_a} (F_D)_{\mu\nu} \tilde{F}_D^{\mu\nu}$$

As the axion oscillates, depletes energy into dark radiation

Equation of motion for the gauge field in time-dependent axion background

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

Tachyonic instability

Conditions for efficient depletion

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

Large coupling required (requires clockworking)

$$\beta \gg 1$$

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

Growth rate of the tachyonic modes set by k

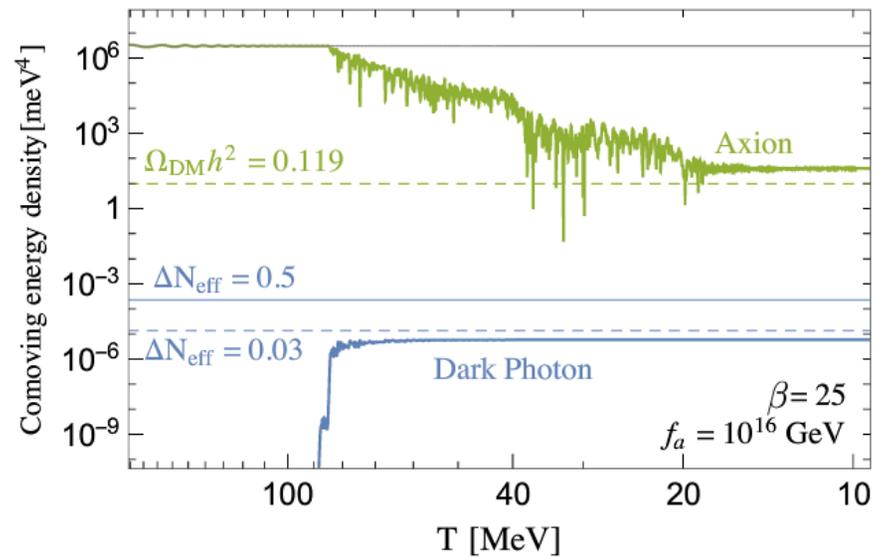
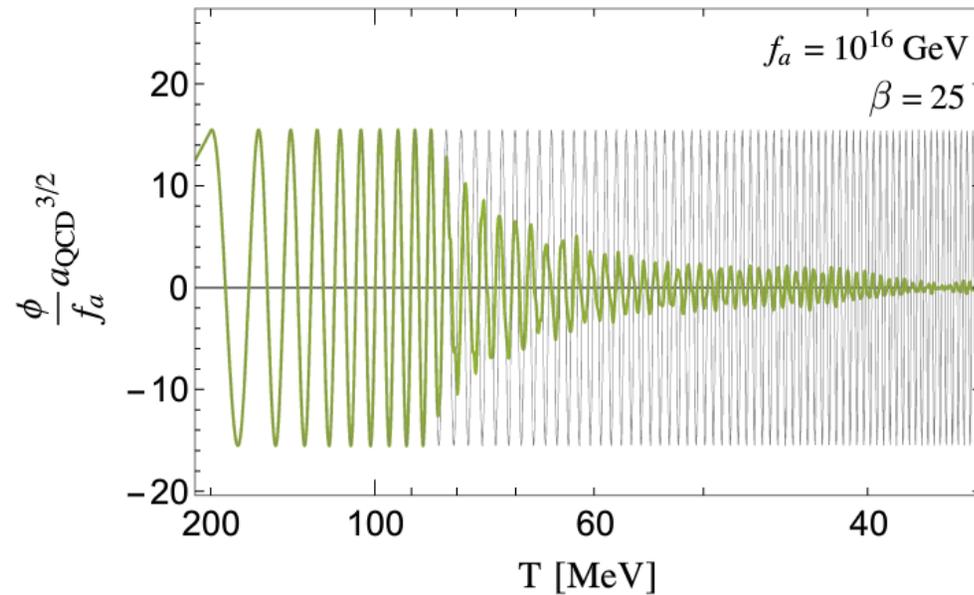
Small (no) thermal mass

Cannot use SM photon

Particles with dark charge should be absent

Results

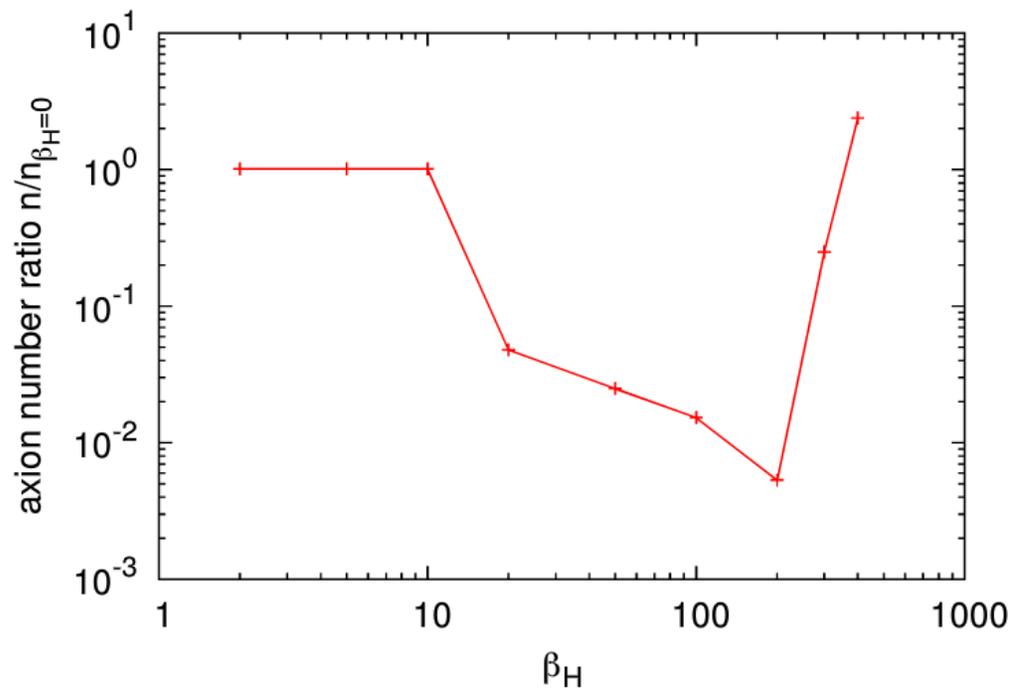
Neglecting backscattering into axion k-modes



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?

Dark Photon Dark Matter

Spin-1 fields with very small masses

Dark electric field ~ 50 V/cm

Common / Complementary probes with the axion

Challenging to populate light dark photon dark matter

(Tuned) couplings to curvature

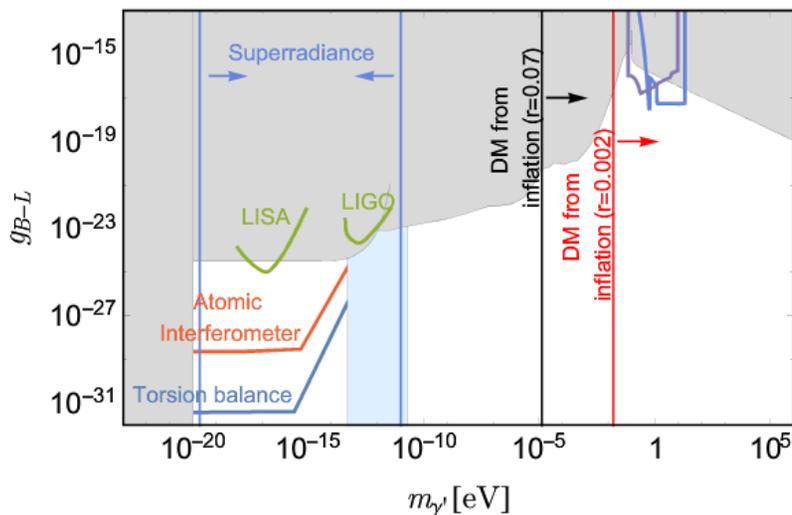
Limited inflationary production mechanism

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

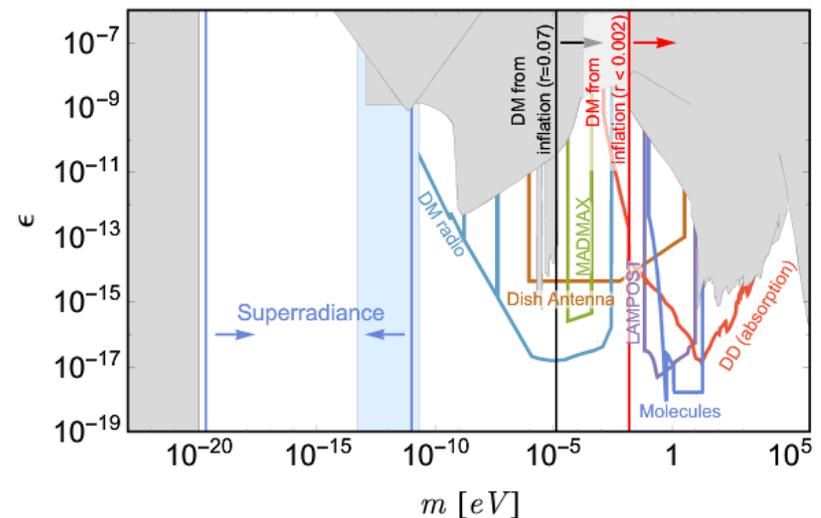
$$\Omega_{\gamma'} = \Omega_{DM} \sqrt{\frac{m_{\gamma'}}{6 \times 10^{-6} \text{ eV}}} \left(\frac{H_I}{10^{14} \text{ GeV}} \right)^2$$

Graham, Mardon, Rajendran [1504.02102]

B-L gauge boson



Kinetically mixed with photons



Massive dark photons

Couple dark photons to an axion

$$\mathcal{L} = \frac{a}{f_a} \frac{\alpha}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{\beta}{4} \frac{a}{f_a} (F_D)_{\mu\nu} \tilde{F}_D^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 A_\mu A^\mu$$

Energy density initially stored in the axion

As the axion starts to oscillate, dumps energy into dark photons

Equation of motion for the massive gauge field

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

Bastero-Gil, Santiago, Ubaldi, Vega-Morales
[1810.07208]

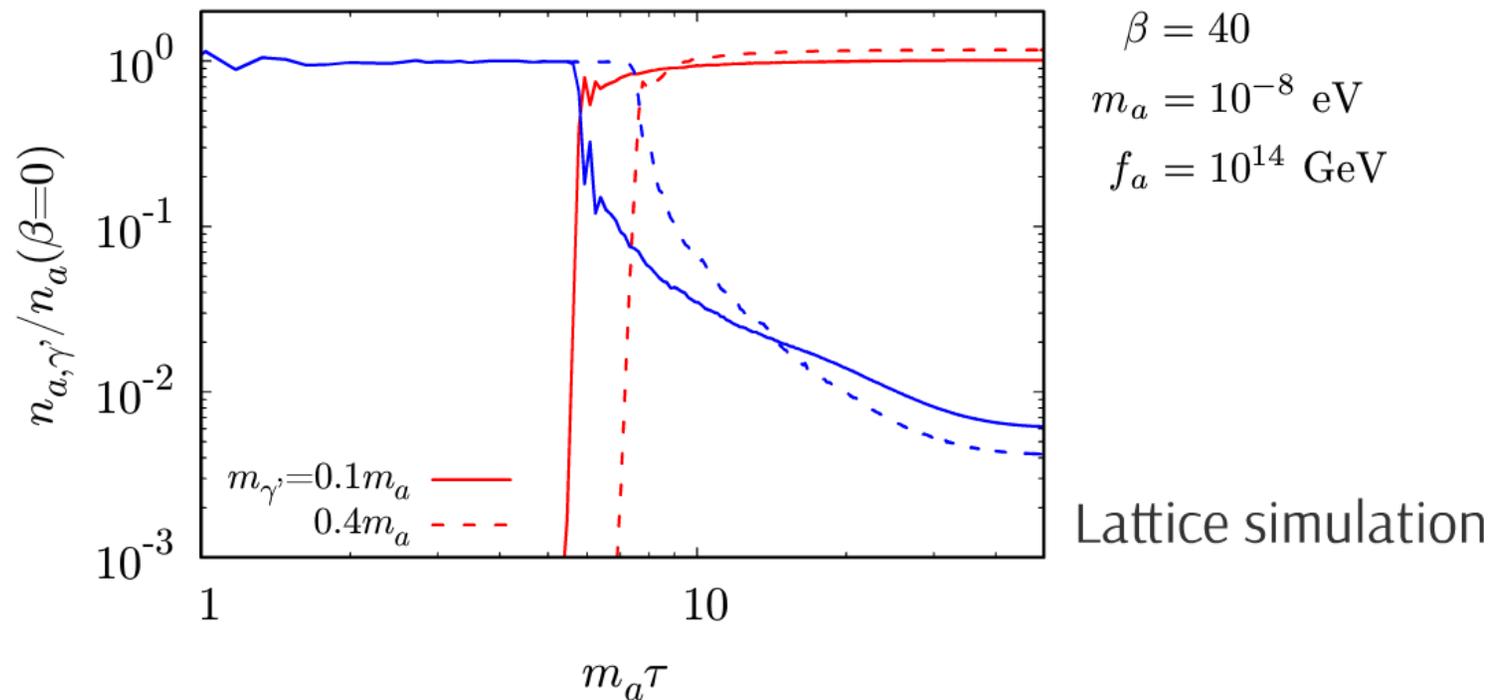
Co, Pierce, Zhang, Zhao [1810.07196]

Dror, Harigaya, Narayan [1810.07195]

PA, Kitajima, Reece, Sekiguchi, Takahashi,
[1810.07188]

Massive dark photons

Less than a 1% of initial number density remains in the axion



If $m_{\gamma'} \ll m_a$, axions still constitute most of dark matter

This simulation used axion-like particles, but also possible to use QCD axion

Dark Photon Spectrum

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

Typical k for tachyonic growth

$$\frac{k}{a} \sim \beta m_a$$

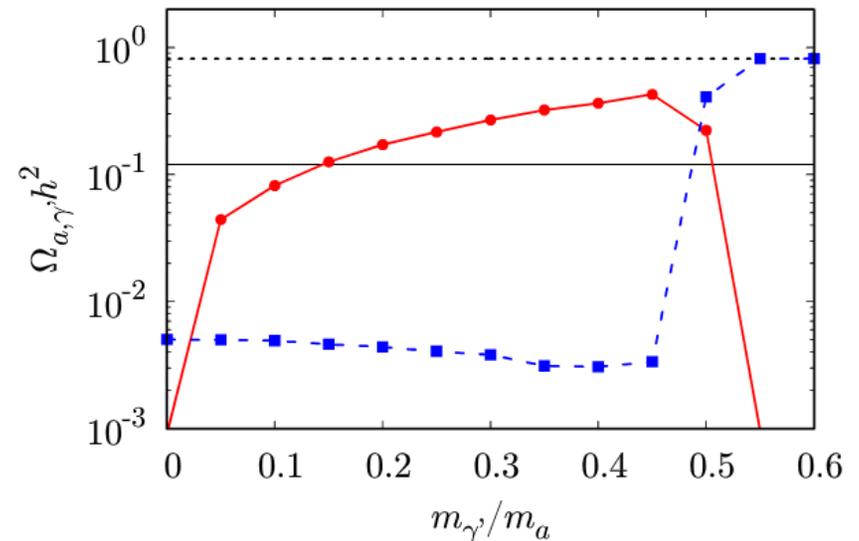
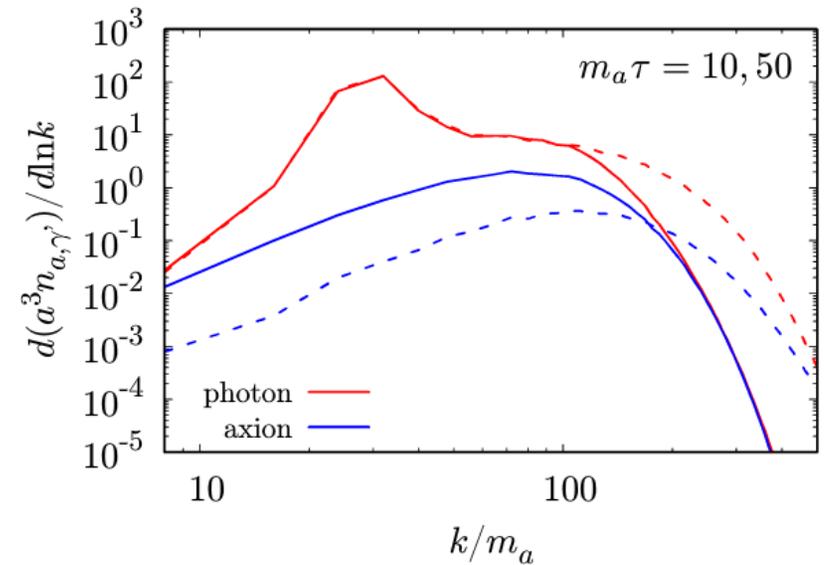
Mass of dark photon should be close to axion mass

$$m_{\gamma'} \lesssim m_a$$

$$\beta = 40$$

$$m_a = 10^{-8} \text{ eV}$$

$$f_a = 10^{14} \text{ GeV}$$



Model building requirements

Coincidence of mass scales

$$m_{\gamma'} \lesssim m_a$$

Large coupling $\beta \gg 1$

$$\beta = kj \frac{\alpha}{8\pi}$$

Large charges

Clockwork

Landau pole in the UV completion $k\alpha \lesssim 1$

→ Need clockwork for particle production

Maximum clockwork (unitarity)

$$j < \sqrt{\frac{f_a}{m_a}}$$

Origin of dark photon mass: Higgs mechanism / Stueckelberg

Quartic couplings

Dark photon quartic coupling affects phenomenology

$$\lambda_{\gamma'; \text{Higgs}} \sim \frac{g_D^4 q_h^4}{4\lambda_h}$$

$$\lambda_{\gamma'; \text{generic}} \sim \frac{m_{\gamma'}^4}{f_\theta^4}$$

Decay constant of the eaten Goldstone

Self-energy can shut off particle production

$$\lambda_{\gamma'} A_\mu^4 \lesssim m_{\gamma'}^2 A_\mu^2 \longrightarrow \lambda_{\gamma'} \lesssim \frac{m_{\gamma'}^4}{m_a^2 f_a^2}$$

Backreaction on the Higgs

$$g_D^2 q_h^2 \langle A_\mu^2 \rangle \ll \lambda_h v_h^2$$

Dark photons require very large charged objects

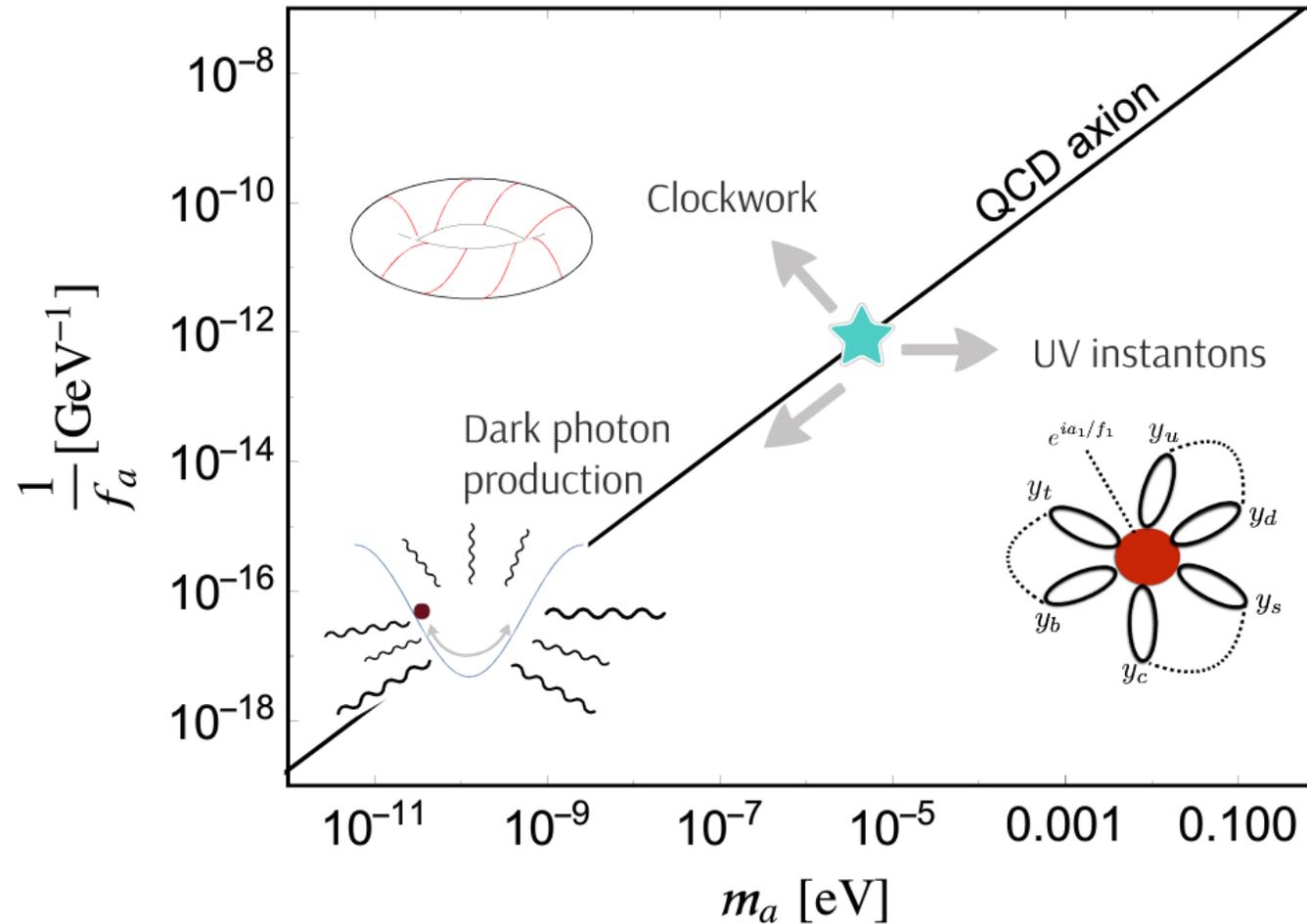
$$v_h \gtrsim 1 \text{ GeV} \left(\frac{1}{\lambda_h} \right)^{1/4} \left(\frac{m_a}{\mu\text{eV}} \right)^{1/2} \left(\frac{f_a}{10^{14} \text{ GeV}} \right)^{1/2}$$

$$g_D \lesssim 10^{-15} \left(\frac{\lambda_h}{q_h^4} \right)^{1/4} \left(\frac{m_{\gamma'}}{\mu\text{eV}} \right) \left(\frac{\mu\text{eV}}{m_a} \right)^{1/2} \left(\frac{10^{14} \text{ GeV}}{f_a} \right)^{1/2}$$

$$\beta = kj \frac{\alpha}{8\pi} \quad j < \sqrt{\frac{f_a}{m_a}}$$

$$kj \sim 10^{30}, j < 10^{15}$$

Conclusion



Theoretical mechanisms open up new parameter space for QCD axion dark matter

Make light dark photon a viable dark matter candidate