Theoretical perspective on axion detection

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Outline

- QCD axion, Axion-Like Particle (ALP), and Axion Dark Matter: mass and couplings
- Direct detection of axions: challenges from theoretical perspective
- Experimental discrimination of axion models

Strong CP problem and QCD axion

$$y_u H Q_L u_R^c + y_d H^* Q_L d_R^c + \frac{g_s^2}{32\pi^2}\theta G\tilde{G}$$

CPV in the QCD sector

$$\bar{\theta} = \theta + \arg\,\det\,(y_u y_d) < 10^{-10}$$

Non-observation of neutron EDM

[Abel et al '20]

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

The QCD vacuum energy is minimized at the CP-conserving point ($\bar{\theta} = 0$).

[Vafa, Witten '84]

$$V_{\rm QCD} = -\Lambda_{\rm QCD}^4 \cos\bar{\theta}$$

Promote $\bar{\theta}$ to a dynamical field (=QCD axion) : $\frac{g_s^2}{32\pi^2}\left(\theta + \frac{a}{f_a}\right)G\tilde{G}$

[Peccei, Quinn '77, Weinberg '78, Wilczek '78]

QCD axion lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_s^2}{32\pi^2} c_G \frac{a}{f_a} G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$

$$+ \frac{g_2^2}{32\pi^2} c_W \frac{a}{f_a} W^{a\mu\nu}\widetilde{W}^a_{\mu\nu} + \frac{g_1^2}{32\pi^2} c_B \frac{a}{f_a} B^{\mu\nu}\widetilde{B}_{\mu\nu} + \frac{\partial_\mu a}{f_a}\left(\sum_q c_q q^\dagger \bar{\sigma}^\mu q + \sum_\ell c_\ell \ell^\dagger \bar{\sigma}^\mu \ell\right)$$

- $c_G \neq 0$ to solve the strong CP problem.
- c_W, c_B, c_q, c_ℓ are model-dependent and can be vanishing (at tree level).

i) approximate shift symmetry $U(1)_{PQ}$ $\quad a(x) \to a(x) + c \;\; (c \in \mathbb{R})$

: broken by a non-zero c_G through QCD non-perturbative effect (instanton)

→ QCD axion potential and mass

ii) periodicity $\quad \frac{a(x)}{f_a} \equiv \frac{a(x)}{f_a} + 2\pi$ due to $\Phi = \frac{1}{\sqrt{2}}(\rho + f_a)e^{ia/f_a}$ $\quad \langle\Phi\rangle = \frac{1}{\sqrt{2}} f_a$

: the coefficients $c_G, c_W, c_B, c_q, c_\ell$ are integer or rational numbers.

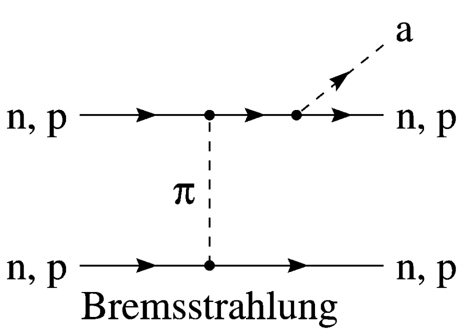
→ A typical size of QCD axion couplings is characterized by f_a (axion decay constant).

QCD axion mass and coupling

- Mass and coupling relation

$$\frac{g_s^2}{32\pi^2} c_G \frac{a}{f_a} G^{a\mu\nu} \widetilde{G}^a_{\mu\nu} \Rightarrow m_a \simeq c_G \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi f_\pi}{f_a} \simeq 5.7\,\mu\mathrm{eV} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a/c_G} \right)$$

- Constraint for the axion-gluon coupling



$$f_a/c_G \gtrsim 10^9\,\mathrm{GeV} \Rightarrow m_a \lesssim \mathcal{O}(1)\,\mathrm{meV}$$

To be compatible with observed cooling rates of the supernova (SN1987A) and neutron star (HESS J1731).

QCD axion couplings are too small to be detectable in typical collider experiments (thus called invisible axion).

Axion-Like Particles (ALPs)

- Cousins of the QCD axion, not being involved in the strong CP problem (so c_G can be 0)
- Ubiquitous in many new physics scenarios, particularly in string theory

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, Marsh-Russell, '09]

$$\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{a}{f_a}\sum_A \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu}\widetilde{F}^A_{\mu\nu} + \frac{\partial_\mu a}{f_a}\sum_\psi c_\psi \psi^\dagger \bar{\sigma}^\mu \psi$$

i) approximate shift symmetry $U(1)_{PQ}$ $\quad a(x) \to a(x) + c \ \ (c \in \mathbb{R})$

: ALP can be naturally light.

ii) periodicity $\quad \frac{a(x)}{f_a} \equiv \frac{a(x)}{f_a} + 2\pi$

: the coupling coefficients c_A, c_ψ are integer-valued.

→ f_a characterizes a typical size of ALP couplings.

ALP mass and coupling

- *No* mass and coupling relation

  Ex) axions in string theory

$$V(a) = -\Lambda^4 e^{-S_{\rm ins}} \cos\frac{a}{f_a}, \quad m_a^2 = \frac{\Lambda^4}{f_a^2} e^{-S_{\rm ins}}$$

$S_{\rm ins} \sim O(100)$: instanton action of various stringy objects

  - ALP mass and coupling are independent free parameters.
  - In particular, possible mass range is vast due to the exponential factor.

- Typical coupling size for string-theoretic axions

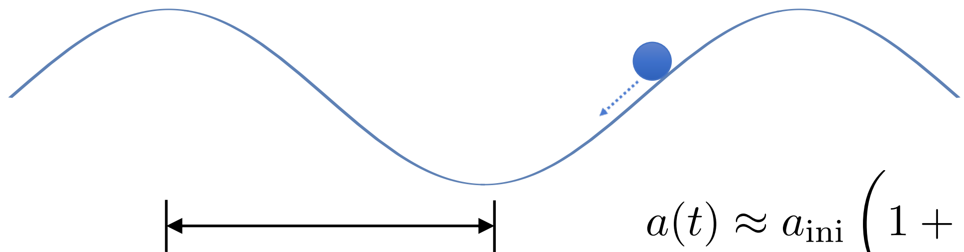
$$f_a \sim \frac{M_P}{S_{\rm ins}}, \quad S_{\rm ins} \sim 8\pi^2 \mathcal{V}_{\rm extra}$$

$\mathcal{V}_{\rm extra}$: volume of the extra dimensional (sub)space in the unit of the string length

So without a large extra dimensional space, $f_a \sim 10^{16}\,\mathrm{GeV}$ very tiny coupling

Cosmological evolution of an axion field

$m_a \ll H(t)$

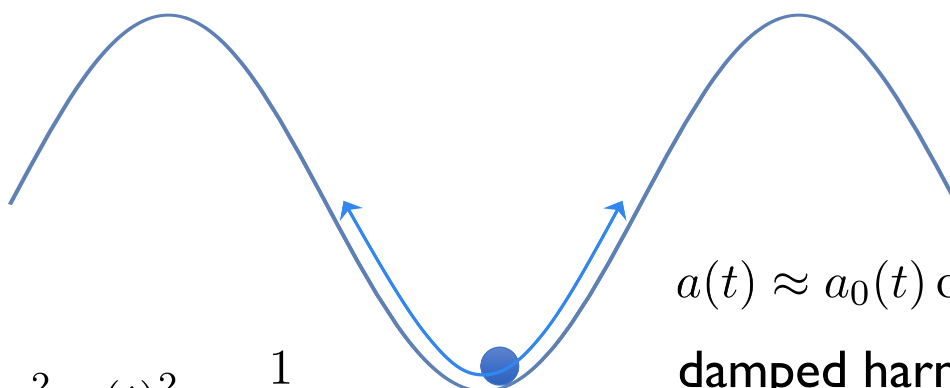


$\sim f_a$

$$a(t) \approx a_{\rm ini} \left(1 + \frac{1}{20}\left[\frac{m_a^2}{H_{\rm ini}^2} - \frac{m_a^2}{H(t)^2}\right]\right)$$

slow-roll : dark energy

$m_a \gg H(t)$

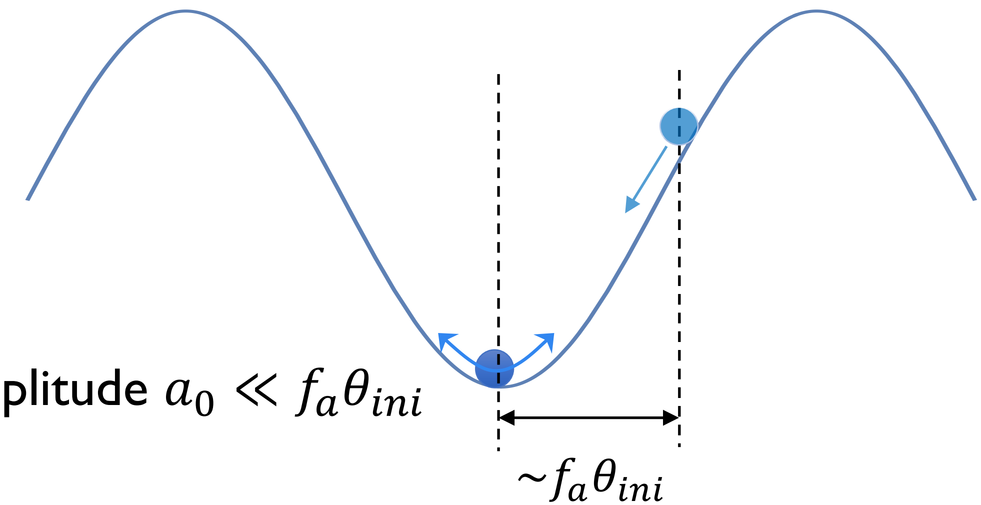


$$a(t) \approx a_0(t) \cos(m_a t)$$

damped harmonic oscillator : cold dark matter

$$\rho_a \approx \frac{1}{2} m_a^2 a_0(t)^2 \propto \frac{1}{R^3}$$

Misalignment production of axion dark matter



Present oscillation amplitude $a_0 \ll f_a \theta_{ini}$

$$a(t, \vec{x}) \approx a_0 \cos m_a (t - \vec{v} \cdot \vec{x})$$

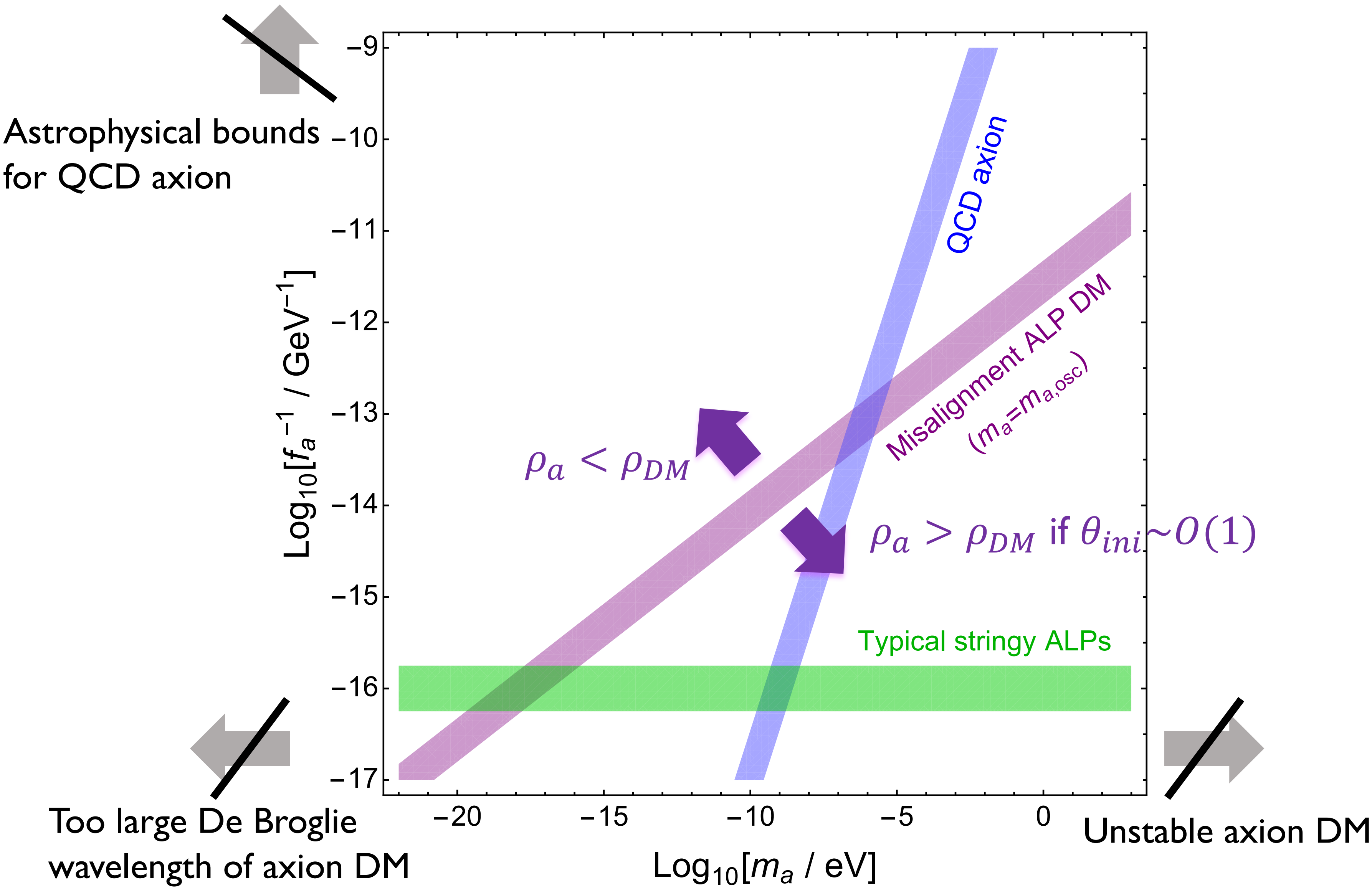
$|\vec{v}| \sim 10^{-3}$: virial velocity of the DM

$$\rho_a \approx \frac{1}{2} m_a^2 a_0^2 \quad \Rightarrow \quad \frac{\rho_a}{\rho_{\rm DM}} \simeq \sqrt{\frac{m_a}{1\,\mu{\rm eV}}} \left(\frac{f_a \theta_{\rm ini}}{10^{13}\,{\rm GeV}} \right)^2 \times \underbrace{\sqrt{\frac{m_a}{m_{a,{\rm osc}}}}}_{O(100)}$$

$O(100)$ for QCD axion

The present amplitude a_0 is determined from the initial amplitude $\sim f_a \theta_{ini}$ and the axion mass m_a (present mass) & $m_{a,osc}$ (mass at the oscillation starting time) .

Theoretically motivated main parameter space for axions



Axion effective interactions to the SM

$$\frac{a}{f_a}\sum_{A=G,W,B}\frac{g_A^2}{32\pi^2}c_A F^{A\mu\nu}\widetilde{F}^A_{\mu\nu}+\frac{\partial_\mu a}{f_a}\sum_{\psi=q,\ell}c_\psi\psi^\dagger\bar{\sigma}^\mu\psi$$

⬇ At low energies below GeV

$$\frac{e^2}{32\pi^2}c_\gamma\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}-\kappa_N\frac{a}{f_a}\frac{i}{2}F_{\mu\nu}(\bar{N}\sigma^{\mu\nu}\gamma^5 N)+\frac{\partial_\mu a}{f_a}\left(c_N\bar{N}\gamma^\mu\gamma^5 N+c_e\bar{e}\gamma^\mu\gamma^5 e\right)$$

Photon coupling

$$c_\gamma \simeq c_W + c_B - 1.92\, c_G$$

Nucleon EDM coupling

$$\kappa_n \simeq 2.4\cdot 10^{-16}\, c_G \text{ e cm}$$

Nucleon and Electron couplings

$$c_p \simeq -0.24\, c_G + 0.88\, c_u - 0.39\, c_d$$

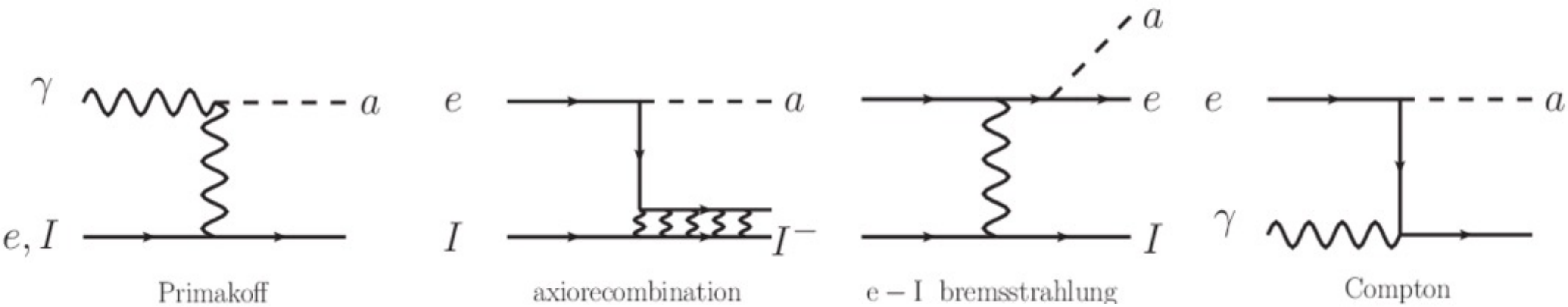
$$c_n \simeq -0.01\, c_G - 0.39\, c_u + 0.88\, c_d$$

$$c_e \simeq c_e^0 + (0.81 c_G + 0.28 c_W + 0.10 c_B)\times 10^{-3}$$

K Choi, SHI, HJ Kim, H Seong '21

Major axion sources for direct detection

- Axions from the sun (Solar axions)



Primakoff process (from c_γ)

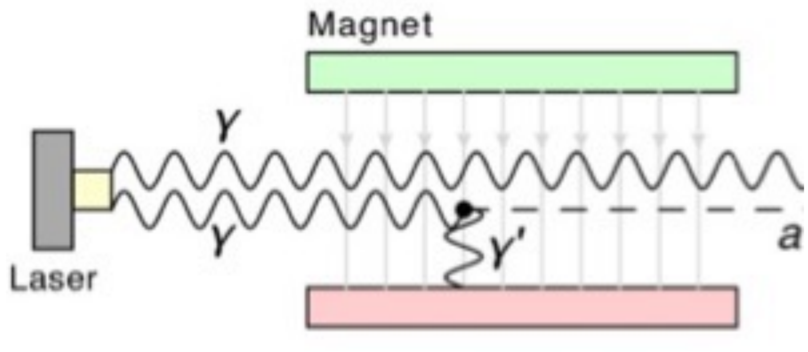
ABC process (from c_e)

- Produced axion spectrum peaked around $\omega_a \sim \mathrm{keV}$
- Net axion flux at the earth position $\sim (1/\mathrm{cm}^3) \times \left(c_\gamma^2 + (10^3 c_e)^2\right) \left(\frac{10^7\,\mathrm{GeV}}{f_a}\right)^2$

Star cooling constraints : $\frac{c_\gamma}{f_a} \lesssim 10^{-7}\,\mathrm{GeV}^{-1}$ (HB stars) $\frac{c_e}{f_a} \lesssim 10^{-10}\,\mathrm{GeV}^{-1}$ (White Dwarf)

Major axion sources for direct detection

- Axions from an intense laser beam (Lab axions)



  - Produced axion spectrum peaked around $\omega_a \sim \mathrm{eV}$
  - Axion flux $\sim (0.1/\mathrm{cm}^3) \times c_\gamma^2 \left(\frac{10^7\,\mathrm{GeV}}{f_a}\right)^2 \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 \left(\frac{L}{100\mathrm{m}}\right)^2 \left(\frac{P_{\mathrm{in}}}{1\,\mathrm{MW}}\right)$

Similar intensity to the solar axions with the current technology

Major axion sources for direct detection

- Axions as dark matter (DM axions)

$$a(t,\vec{x}) \approx a_0 \cos m_a(t - \vec{v}\cdot\vec{x}) \quad \rho_a \approx \frac{1}{2} m_a^2 a_0^2$$: non-relativistic particles

$|\vec{v}| \sim 10^{-3}$: virial velocity of the DM

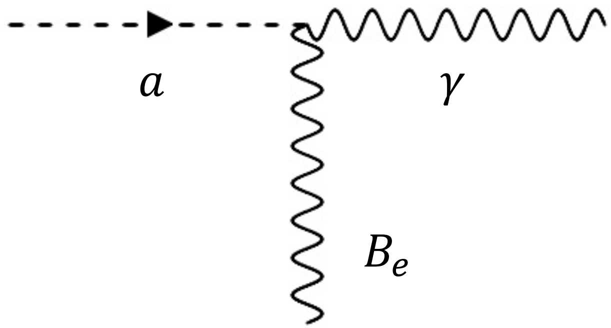
Number density $$n_a = \frac{\rho_a}{m_a} \sim (10^{14}/\mathrm{cm}^3) \times \left(\frac{\mu\mathrm{eV}}{m_a}\right)\left(\frac{\rho_a}{\rho_{\mathrm{DM}}}\right)$$

with the local DM density $\rho_{\mathrm{DM}} \simeq 0.4\,\mathrm{GeV/cm}^3$

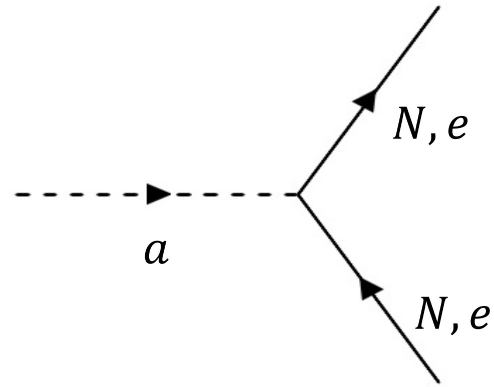
: enormous intensity compared to the other sources if the axion constitutes a major component of the whole dark matter density.

Yet axion DM-induced signals will have a small frequency ($= m_a$), which may give rise to another challenge to detect those signals for ultra-light axions. 1 Hz ~ 10^{-14} eV

Direct detection of axions

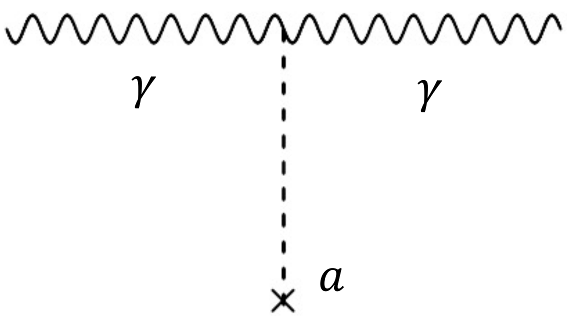


Axion-photon conversion

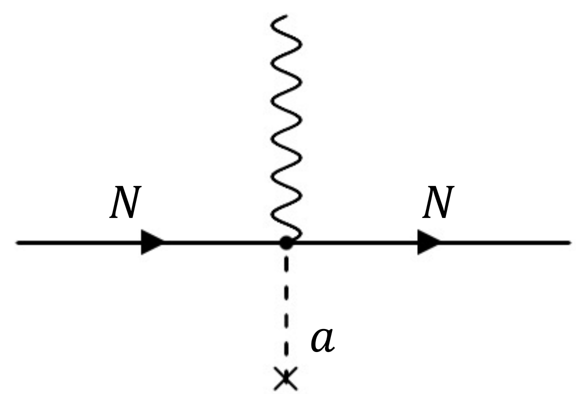


Nucleon or electron scattering off axions

(Non-relativistic axion : $\nabla a \sim B_{\text{eff}}$ interacting with fermion spins)



P-violating axion background



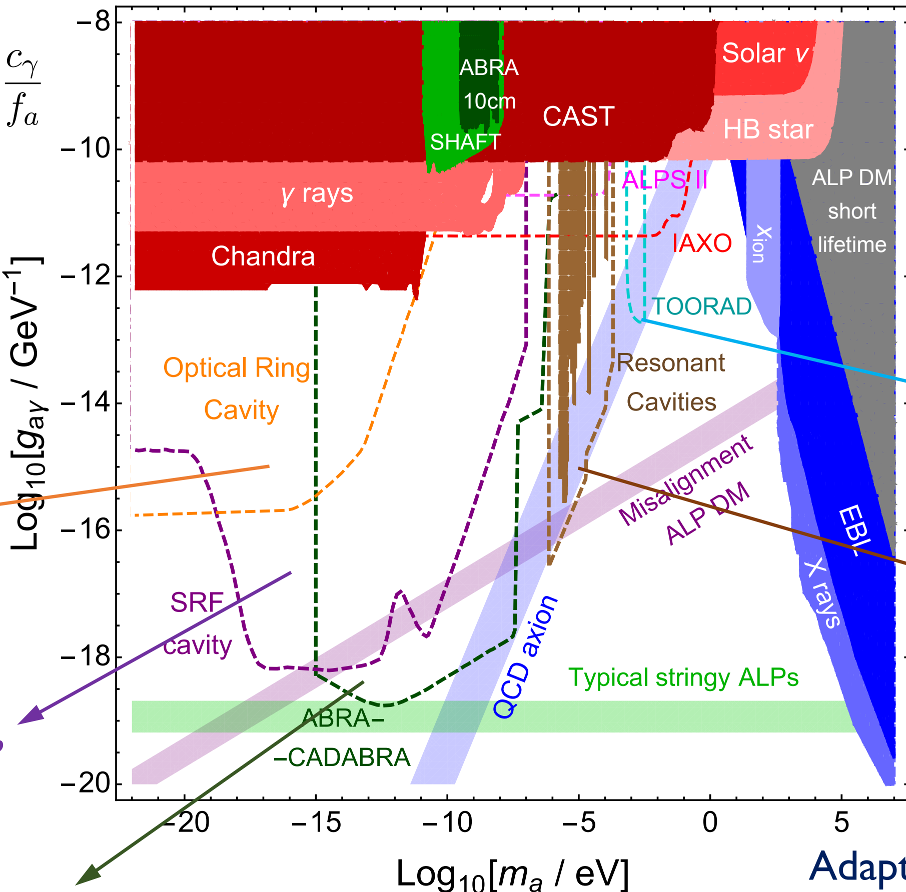
Nucleon EDM interaction

Exclusions and projected sensitivities for the axion-photon coupling

Shaded: excluded

Dashed: future sensitivity

$$g_{a\gamma} \equiv \frac{\alpha}{2\pi}\frac{c_\gamma}{f_a} \sim 10^{-3}\frac{c_\gamma}{f_a}$$



-ALPS II: Lab axions

-IAXO: Solar axions

-The other dashed: DM axions

Marsh, Fong, Lentz, Smejkal, Ali '18

Obata, Fujita, Michimura '18

IBS-CAPP, ADMX, MADMAX…

Berlin, D'Agnolo, Ellis, Zhou '20

Kahn, Safdi, Thaler '16

Adapted from K Choi, SHI, CS Shin '20

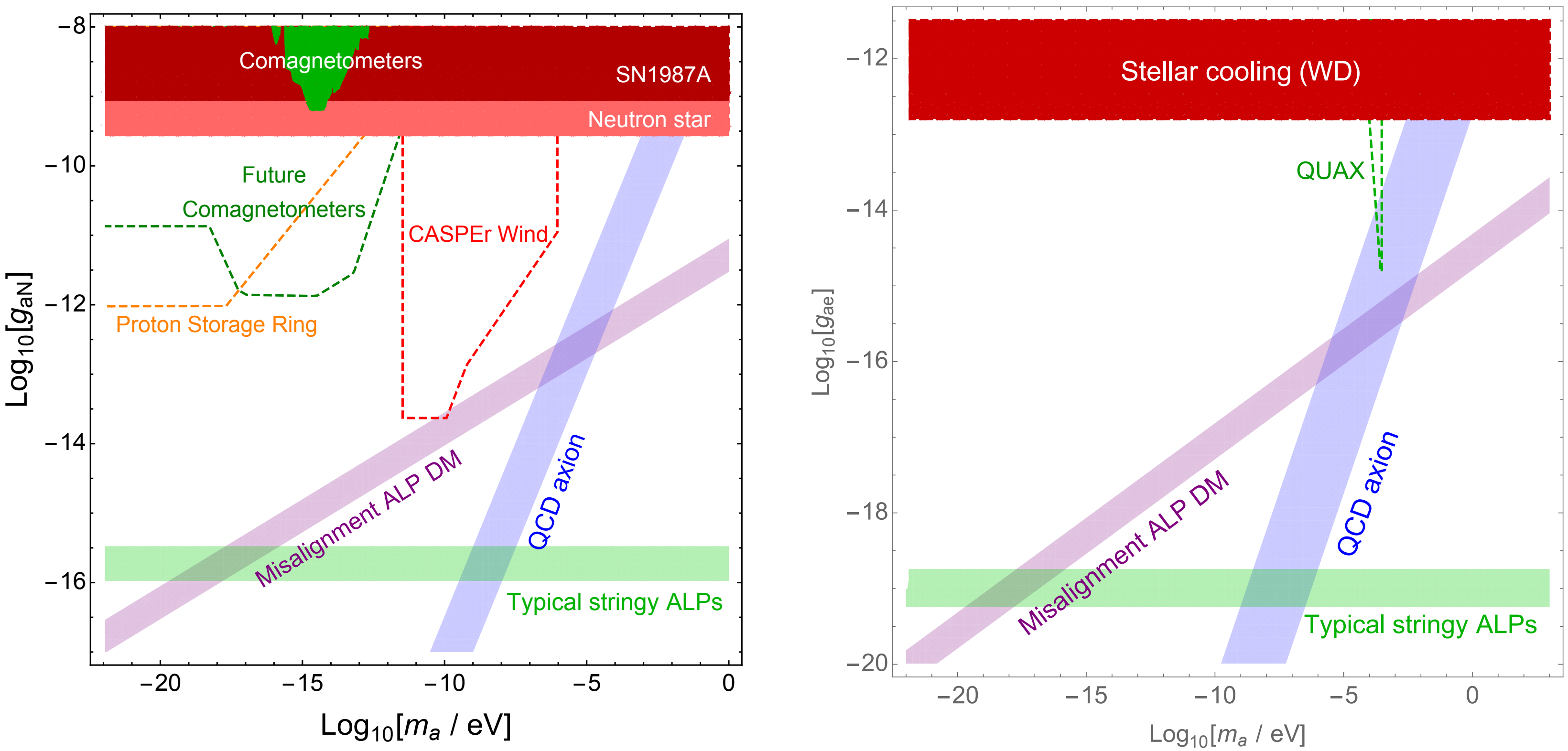
Recently remarkable progress which may cover the theoretically motivated parameter spaces in the future

Exclusions and projected sensitivities for the axion-fermion couplings

$$g_{aN} \equiv c_N \frac{m_N}{f_a}, \;\; g_{ae} \equiv c_e \frac{m_e}{f_a}$$

Shaded: excluded

Dashed: future sensitivity (for DM axions)

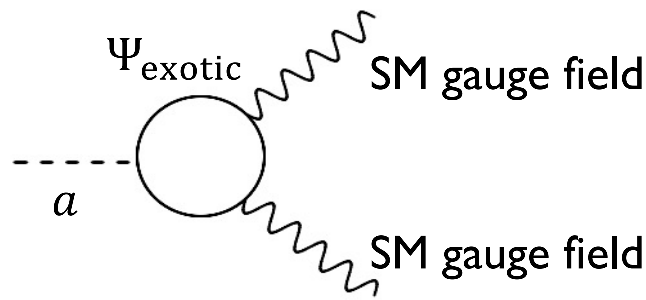


- Much more challenging compared to the axion-photon coupling
- Good sensitivity only for DM axions currently
- Important for discrimination of axion models (now to be discussed)

Three possible classes of axion models

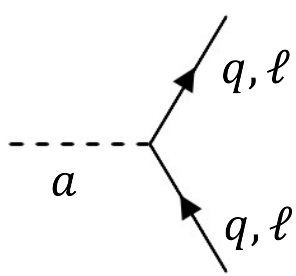
- KSVZ-like

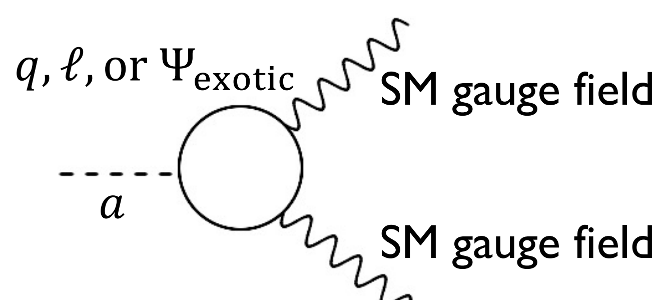
Axion has *no direct couplings to the SM fermions*, and it couples to the SM gauge fields through a heavy exotic fermion loop.



- DFSZ-like

Axion has *direct couplings to the SM fermions*.

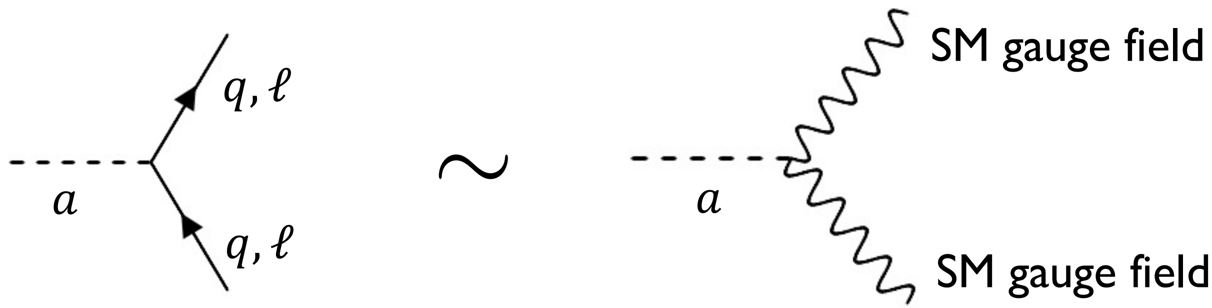




Three possible classes of axion models

- String-theoretic axions

Axion has *direct couplings to the SM fermions, which are comparable with its couplings to the SM gauge fields.*



This is due to the fundamentally different origin of a string-theoretic axion identified as a higher-dimensional gauge field rather than the phase of a complex scalar field.

Comparison of tree-level axion couplings to the SM fermions

$$\frac{\partial_\mu a}{2f_a} \sum_{\Psi=u,d,e} C_\Psi \Psi^\dagger \gamma^\mu \gamma_5 \Psi + \frac{e^2}{32\pi^2} \frac{a}{f_a} c_\gamma F^{\mu\nu} \widetilde{F}_{\mu\nu} \qquad c_\gamma \sim \mathcal{O}(1)$$

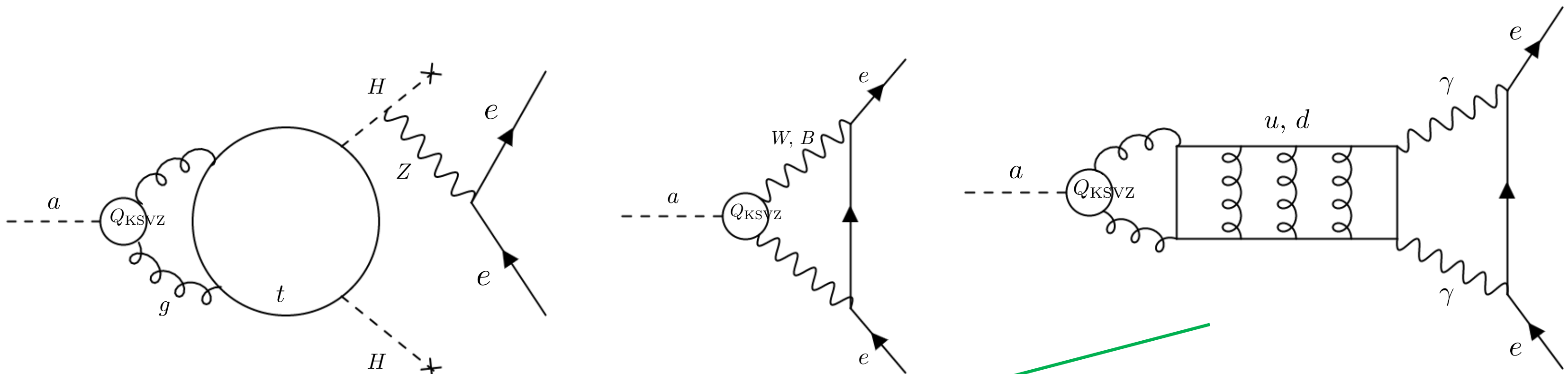
- DFSZ-like axions: $C_\Psi^0 \sim O(1)$
- KSVZ-like axions: $C_\Psi^0 = 0$
- String-theoretic axions: $C_\Psi^0 \sim O(g^2/16\pi^2)$

At tree-level, the three classes of axions show clearly different patterns that they may be distinguished by precision experiments.

Yet radiative correction has to be carefully taken into account to see whether it is indeed possible, especially for discriminating string-theoretic axions from KSVZ-like axions by low energy experiments.

Radiatively generated axion-electron coupling

Srednicki '85
S Chang and K Choi '93
Bauer, Neubert, Renner, Schnubel, Thamm '20
K Choi, SHI, HJ Kim, H Seong '21



$$C_e(m_e) \simeq \left[0.84\,c_G - 0.03\,c_G + 0.28\,c_W + 0.10\,c_B\right] \times 10^{-3} \quad \text{(KSVZ with MSSM)}$$

$$C_e(m_e) \simeq \left[0.83\,c_G - 0.03\,c_G + 0.54\,c_W + 0.13\,c_B\right] \times 10^{-3} \quad \text{(KSVZ with SM)},$$

$$\left(\frac{\alpha_s}{2\pi}\right)^3 y_t^2 c_G \ln\left(\frac{f_a}{m_t}\right) \sim 10^{-3} c_G$$

Previously ignored because it is at three-loop level.
But actually most important for KSVZ-like axions.

Distinguishing the axions by coupling ratios

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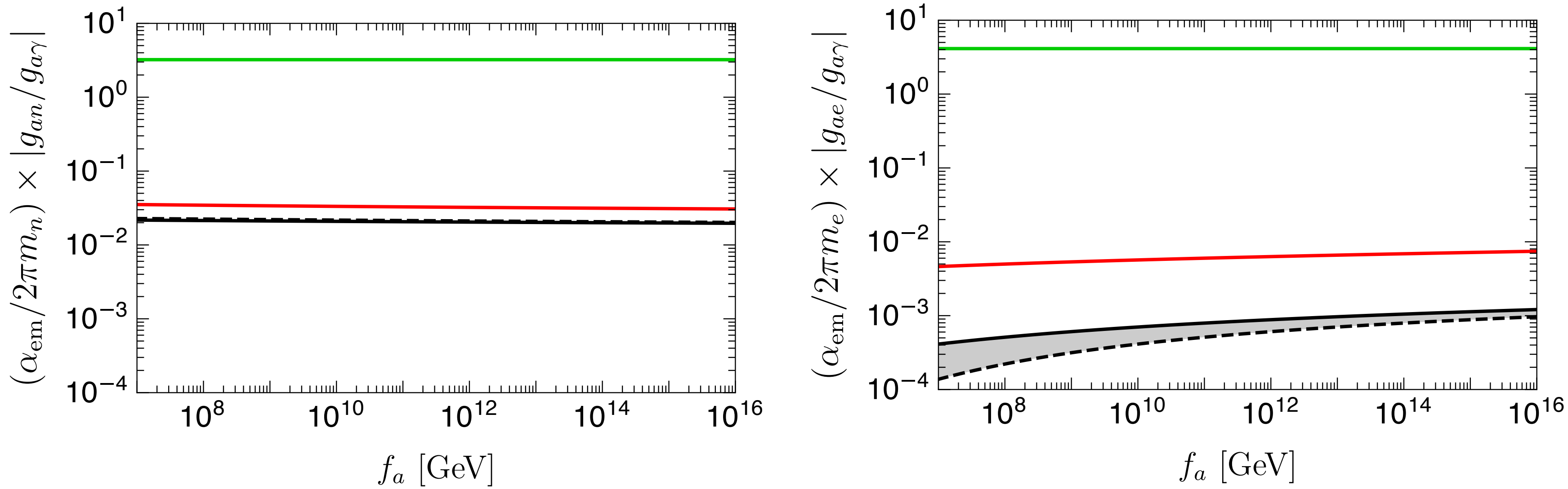
For QCD axion ($c_G \neq 0$), $g_{ap} \sim \frac{\mathrm{m_p}}{\mathrm{f_a}}$ regardless of the classes of models

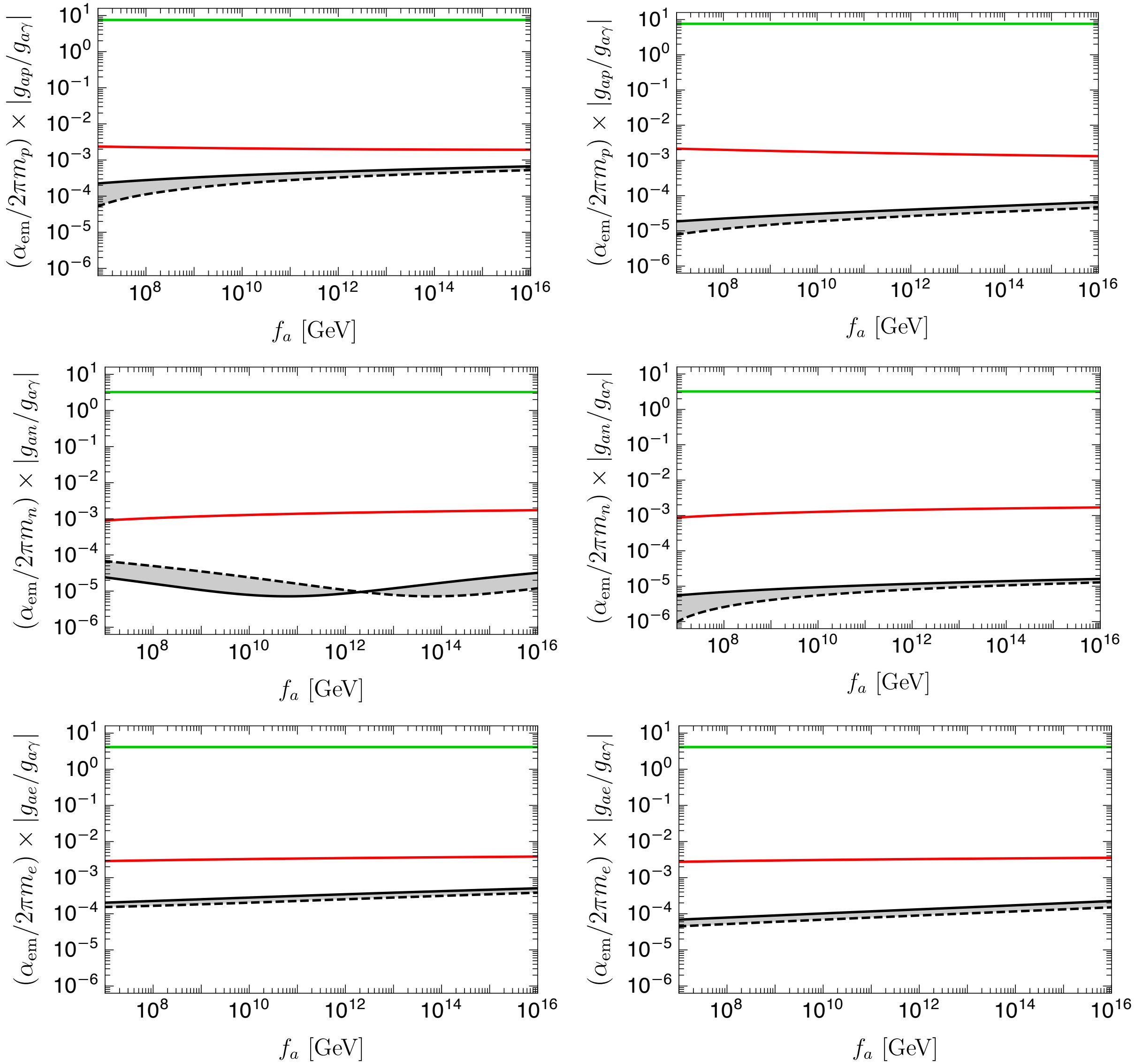


Green : DFSZ-like axion

Red : String-theoretic axion

Black : KSVZ-like axion (dashed : $m_Q = 10^{-3} f_a$, solid : $m_Q = f_a$)

For ALPs with ($c_G = 0$),



$c_W = 1$ ($c_G = c_B = 0$)

$c_B = 1$ ($c_G = c_W = 0$)

Green : DFSZ-like axion

Red : String-theoretic axion

Black : KSVZ-like axion

(dashed : $m_{KSVZ} = 10^{-3} f_a$,

solid : $m_{KSVZ} = f_a$)

Summary

- QCD axion, axion-like particles, and axion dark matter have their own strong theoretical motivations and predict relevant ranges for axion mass and couplings.
- Those parameter spaces, however, predict quite small couplings that are difficult to be probed using available axion sources (e.g. sun, lab, and DM).
- Recently significant progress has been made for the axion-photon coupling detection based on the axion DM hypothesis, which can cover a major part of ultra-light axion DM parameter space.
- Currently projected sensitivities for axion-fermion couplings mostly cannot touch the theoretically motivated axion parameter spaces.
- A development for precise measurements of axion-fermion couplings will provide important clues for an underlying UV model of the axion.