Distinguishing axion models with running axion couplings

Kiwoon Choi, SHI, Hee Jung Kim, Hyeonseok Seong : arXiv 2106.05816, JHEP accepted

Sang Hui Im (IBS-CTPU)

Workshop on "Darkness on the table", Aug 9, 2021

Outline

- Three classes of axion models
  - KSVZ-like
  - DFSZ-like
  - String-theoretic axions
- Running axion couplings
- Distinguishing the axions by low energy precision experiments

Strong CP problem and QCD axion

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

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

Non-observation of neutron EDM

[Abel et al '20]

CPV in the QCD sector

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

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_s^2}{32\pi^2} c_G \frac{a}{f_a} G^{\mu\nu}\tilde{G}_{\mu\nu}$$
$$+ \frac{a}{f_a} \sum_{A=W,B,\ldots} \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu}\tilde{F}^A_{\mu\nu} + \frac{\partial_\mu a}{f_a}\left(\sum_{\psi=q,\ell,\ldots} c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_{\phi=H,\ldots} c_\phi \phi^\dagger i\overleftrightarrow{D}^\mu \phi\right)$$

$$U(1)_{PQ}: \quad a(x) \to a(x) + \alpha$$

broken by $c_G \neq 0$ non-perturbatively

$$m_a^2 \simeq c_G^2 \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

The axion couplings to the other SM particles $c_W, c_B, c_q, c_\ell, c_H$ are model-dependent.

Axion-Like Particles (ALPs)

- Relatives of the QCD axion, not being involved in the strong CP problem (so c_G can be 0)
- Ubiquitous in many BSM scenarios, e.g. string theory

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

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

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

: ALP can be naturally light.

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

: f_a characterizes typical size of ALP couplings.

KSVZ model

Kim ’79, Shifman, Vainshtein, Zakharov ’80

Introduces a heavy exotic fermion Q charged under the SM gauge groups

$$\boxed{y\Phi Q Q^c + \text{h.c.}}$$

$$\Phi = \frac{1}{\sqrt{2}}(\rho + f_a)e^{ia/f_a}$$

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}} f_a \qquad m_Q = \frac{y}{\sqrt{2}} f_a \sim f_a$$

$$U(1)_{PQ}: \quad \Phi \to \Phi e^{i\alpha} (\equiv \frac{a}{f_a} \to \frac{a}{f_a} + \alpha),\ Q \to Q e^{-i\alpha/2},\ Q^c \to Q^c e^{-i\alpha/2}$$

SM fields are *not* charged under $U(1)_{PQ}$.

$$\boxed{y\Phi Q Q^c + \text{h.c.}} \quad U(1)_{PQ}: \; \Phi \to \Phi e^{i\alpha} \left(\equiv \frac{a}{f_a} \to \frac{a}{f_a} + \alpha\right), \; Q \to Q e^{-i\alpha/2}, \; Q^c \to Q^c e^{-i\alpha/2}$$

$$Q \to Q e^{-ia/2f_a}, \; Q^c \to Q^c e^{-ia/2f_a}$$

: axion-dependent field redefinition proportional to the PQ charge

$$\mathcal{L}_{\text{eff}}(\mu > m_Q) = \frac{\partial_\mu a}{2 f_a} \left(Q^\dagger \bar{\sigma}^\mu Q + Q^{c\dagger} \bar{\sigma}^\mu Q^c \right) + \frac{a}{f_a} \sum_A \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu} \widetilde{F}^A_{\mu\nu}$$

$$c_A = 2\,\text{tr}(T_A^2(Q))$$

: Dynkin index

$$U(1)_{PQ}: \; \frac{a}{f_a} \to \frac{a}{f_a} + \alpha$$

Below the exotic heavy fermion mass scale

$$\mathcal{L}_{\text{eff}}(\mu < m_Q) = \frac{a}{f_a} \sum_A \frac{g_A^2}{32\pi^2} c_A F^{A\mu\nu} \widetilde{F}^A_{\mu\nu}$$

"KSVZ-like axions"

: vanishing tree-level couplings to the SM fermions

DFSZ model

Dine, Fischler, Srednicki '81, Zhitnitsky '80

The axion couples to the SM sector at tree-level through the Higgs portal.

$$y_u u_R^c Q_L H_u + y_d d_R^c Q_L H_d + y_e e_R^c L H_d + \lambda \Phi^2 H_u H_d + \mathrm{h.c.}$$

$$\Phi = \frac{1}{\sqrt{2}}(\rho + f_a) e^{ia/f_a}$$

$$U(1)_{PQ}: \;\; \Phi \to \Phi e^{i\alpha}, \;\; H_d \to H_d e^{-i2\alpha}, \;\; d_R^c \to d_R^c e^{i2\alpha}, \;\; e_R^c \to e_R^c e^{i2\alpha}$$

Some of SM fields are charged under $U(1)_{PQ}$.

$$y_u u_R^c Q_L H_u + y_d d_R^c Q_L H_d + y_e e_R^c L H_d + \lambda \Phi^2 H_u H_d + \text{h.c.}$$

$$U(1)_{PQ}: \quad \Phi \to \Phi e^{i\alpha}, \ H_d \to H_d e^{-i2\alpha}, \ d_R^c \to d_R^c e^{i2\alpha}, \ e_R^c \to e_R^c e^{i2\alpha}$$

$$H_d \to H_d e^{-i2a/f_a}, \ d_R^c \to d_R^c e^{i2a/f_a}, \ e_R^c \to e_R^c e^{i2a/f_a}$$

: axion-dependent field redefinition proportional to the PQ charge

$$\mathcal{L}_{\text{eff}}(\mu > m_{H^\pm}) = -2\frac{\partial_\mu a}{f_a}\left(d_R^{c\dagger}\bar{\sigma}^\mu d_R^c + e_R^{c\dagger}\bar{\sigma}^\mu e_R^c - H_d^\dagger i \overleftrightarrow{D}^\mu H_d\right) - \frac{g_s^2}{32\pi^2} 6 \frac{a}{f_a} G^{\mu\nu}\widetilde{G}_{\mu\nu} - \frac{g_1^2}{32\pi^2} 16 \frac{a}{f_a} B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

$$U(1)_{PQ}: \ \frac{a}{f_a} \to \frac{a}{f_a} + \alpha$$

After Z-boson integrated out,
$t_\beta \equiv \langle H_u \rangle / \langle H_d \rangle$

$$\mathcal{L}_{\text{eff}}(\mu < m_Z) = -\frac{\partial_\mu a}{f_a}\left(c_\beta^2\, u^\dagger \gamma^\mu \gamma_5 u + s_\beta^2\, d^\dagger \gamma^\mu \gamma_5 d + s_\beta^2\, e^\dagger \gamma^\mu \gamma_5 e\right) - \frac{g_s^2}{32\pi^2} 6 \frac{a}{f_a} G^{\mu\nu}\widetilde{G}_{\mu\nu} - \frac{g_1^2}{32\pi^2} 16 \frac{a}{f_a} F^{\mu\nu}\widetilde{F}_{\mu\nu}$$

"DFSZ-like axions"
: $O(1)$ tree-level couplings to the SM fermions

String-theoretic axions

$$C_{[m_1 m_2 .. m_p]}(x^\mu, y^m) = a(x^\mu)\Omega_{[m_1 m_2 .. m_p]}(y^m)$$

Ω : harmonic p-form on the compact internal space

4D axions identified as zero modes of higher-dimensional p-form gauge field

SUSY-preserving compactification

$$T = \tau + ia$$

Axion chiral superfield (τ : volume modulus of p-cycle dual to Ω)

$$U(1)_{PQ} : \quad a \to a + \text{const}$$

: remnant of a higher-dimensional gauge symmetry

$$\delta C_{[m_1 m_2 .. m_p]} = \partial_{[m_1}\Lambda_{m_2,..,m_p]}$$

4D Low energy effective action

$$K = K_0(T + T^*) + Z_I(T + T^*)\Phi_I^*\Phi_I$$

$$\mathcal{F}_A = c_A T \qquad c_A \sim \mathcal{O}(1)$$

$$Z_I \propto (T + T^*)^{\omega_I} \qquad \omega_I \sim \mathcal{O}(1)$$

scaling weight of Φ_I

$$K = K_0(T+T^*) + Z_I(T+T^*)\Phi_I^*\Phi_I$$

$$\mathcal{F}_A = c_A T \qquad Z_I \propto (T+T^*)^{\omega_I} \quad \omega_I \sim \mathcal{O}(1) \quad c_A \sim \mathcal{O}(1)$$

$$T = \tau + ia$$

$$\mathcal{L}_{\rm eff} = \frac{M_P^2}{4}\partial_\tau^2 K_0\,(\partial_\mu a)^2 + \frac{\omega_I}{2\tau}\partial_\mu a\left(\psi_I^\dagger\bar{\sigma}^\mu\psi_I + \phi_I^\dagger i\overset{\leftrightarrow}{D^\mu}\phi_I\right) - \frac{1}{4}c_A\tau F^{A\mu\nu}F^A_{\mu\nu} + \frac{c_A}{4}aF^{A\mu\nu}\widetilde{F}^A_{\mu\nu}$$

$\sim O(1)$ $\sim O(1)$

$$\tau = \frac{1}{c_A g_A^2} \sim \mathcal{O}(1)$$

String-theoretic axion couplings to matter fields and gauge fields are comparable to each other.

Canonical normalization $\quad a \to \dfrac{a}{8\pi^2 f_a} \qquad f_a = \dfrac{M_P}{8\pi^2}\sqrt{\dfrac{\partial_\tau^2 K_0}{2}}$

$$\mathcal{L}_{\rm eff} = -\frac{1}{4g_A^2}F^{A\mu\nu}F^A_{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 + \omega_I\frac{c_A g_A^2}{16\pi^2}\frac{\partial_\mu a}{f_a}\left(\psi_I^\dagger\bar{\sigma}^\mu\psi_I + \phi_I^\dagger i\overset{\leftrightarrow}{D^\mu}\phi_I\right) + \frac{c_A}{32\pi^2}\frac{a}{f_a}F^{A\mu\nu}\widetilde{F}^A_{\mu\nu}$$

$\sim O(g^2/16\pi^2)$

Comparison of tree-level axion couplings to the SM fermions

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

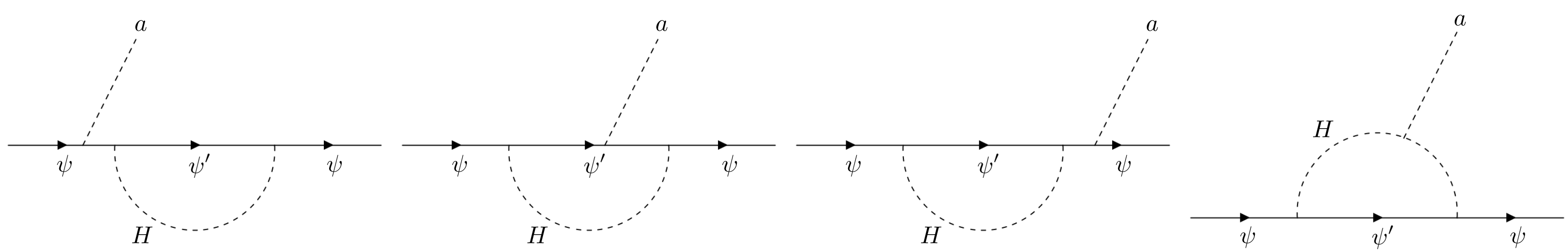
- DFSZ-like axions: $C_\Psi^0 \sim O(1)$
- KSVZ-like axions: $C_\Psi^0 = 0$
- String-theoretic axions: $C_\Psi^0 \sim O(g^2/16\pi^2)$

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.

Axion coupling running by Yukawa interactions

K Choi, SHI, CB Park, S Yun '17, Camalich, Pospelov, Vuong, Ziegler, Zupan '20
Heiles, König, Neubert '20, Chala, Guedes, Ramos, Santiago '20



$$\frac{\partial_\mu a}{f_a}\left(\sum_\psi c_\psi \psi^\dagger \bar\sigma^\mu \psi + \sum_{\alpha=1,2} c_{H_\alpha} H_\alpha^\dagger i \overleftrightarrow{D}^\mu H_\alpha\right) + \sum_A \frac{g_A^2}{32\pi^2} c_A \frac{a}{f_a} F^{A\mu\nu}\widetilde{F}^A_{\mu\nu}$$

$$y_t u_3^c Q_{L3} H_u \quad \Rightarrow$$

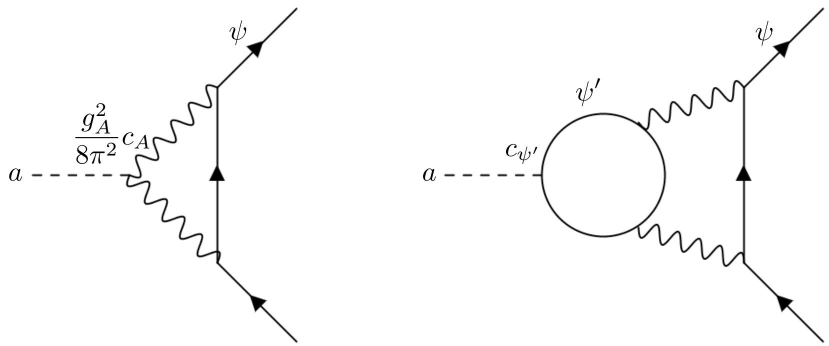
$$\frac{dc_{Q_3}}{d\ln\mu} \approx \frac{\xi_y}{16\pi^2} y_t^2 n_t$$

$$\frac{dc_{u_3^c}}{d\ln\mu} \approx \frac{\xi_y}{8\pi^2} y_t^2 n_t \qquad n_t \equiv c_{Q_3} + c_{u_3^c} + c_{H_u}$$

$$\frac{dc_{H_u}}{d\ln\mu} \approx \frac{3\xi_y}{16\pi^2} y_t^2 n_t \qquad \xi_y = \begin{cases} 1 & \text{for non-SUSY models} \\ 2 & \text{for SUSY models}\end{cases}$$

Axion coupling running by gauge interactions

Srednicki '85, S Chang and K Choi '93
K Choi, SHI, CS Shin '20,
Chala, Guedes, Ramos, Santiago '20
Bauer, Neubert, Renner, Schnubel, Thamm '20



$$\frac{\partial_\mu a}{f_a}\left(\sum_\psi c_\psi \psi^\dagger \bar\sigma^\mu \psi + \sum_{\alpha=1,2} c_{H_\alpha} H_\alpha^\dagger i \overleftrightarrow{D}^\mu H_\alpha\right) + \sum_A \frac{g_A^2}{32\pi^2} c_A \frac{a}{f_a} F^{A\mu\nu}\widetilde{F}^A_{\mu\nu}$$

$$\left.\frac{dc_\psi}{d\ln\mu}\right|_{\rm gauge} = -\xi_g \sum_A \frac{3}{2}\left(\frac{g_A^2}{8\pi^2}\right)^2 \mathbb{C}_A(\psi)\,\tilde c_A \qquad \tilde c_A \equiv c_A - \sum_{\psi'} c_{\psi'}$$

$$\left.\frac{dc_{H_\alpha}}{d\ln\mu}\right|_{\rm gauge} = -\xi_H \sum_A \frac{3}{2}\left(\frac{g_A^2}{8\pi^2}\right)^2 \mathbb{C}_A(H_\alpha)\,\tilde c_A \qquad \mathbb{C}_A(\Phi) : \text{quadratic Casimir}$$

$$\xi_g = \begin{cases} 1 & \text{for non-SUSY models} \\ 2/3 & \text{for SUSY models}\end{cases}, \quad \xi_H = \begin{cases} 0 & \text{for non-SUSY models} \\ 2/3 & \text{for SUSY models}\end{cases}$$

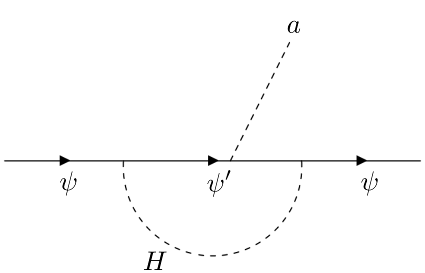
Numerical results

For $f_a = 10^{10}$ GeV, $t_\beta = 10$, and $m_{SUSY} = 10$ TeV,

$$
\begin{aligned}
C_u(2\,\mathrm{GeV}) &\simeq C_u(f_a) - 0.28\, n_t(f_a) + [17.7\,\tilde{c}_G(f_a) + 0.52\,\tilde{c}_W(f_a) + 0.036\,\tilde{c}_B(f_a)] \times 10^{-3}\,, \\
C_d(2\,\mathrm{GeV}) &\simeq C_d(f_a) + 0.31\, n_t(f_a) + [19.4\,\tilde{c}_G(f_a) + 0.23\,\tilde{c}_W(f_a) + 0.0047\,\tilde{c}_B(f_a)] \times 10^{-3}\,, \\
C_e(m_e) &\simeq C_e(f_a) + 0.29\, n_t(f_a) + [0.81\,\tilde{c}_G(f_a) + 0.28\,\tilde{c}_W(f_a) + 0.10\,\tilde{c}_B(f_a)] \times 10^{-3}\,.
\end{aligned}
$$

$$\frac{y_t^2}{8\pi^2} n_t(f_a) \ln\left(\frac{f_a}{m_t}\right) \sim \text{a few} \times 0.1\, n_t(f_a)$$

$$\left(\frac{g_A^2}{8\pi^2}\right)^2 \tilde{c}_A(f_a) \ln\left(\frac{f_a}{\mu}\right) \sim (10^{-4} - 10^{-2})\, \tilde{c}_A(f_a)$$



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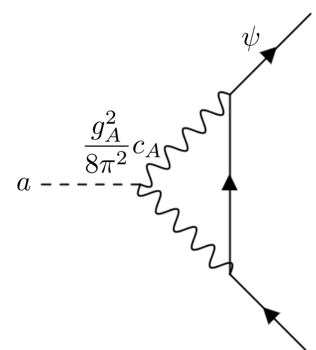
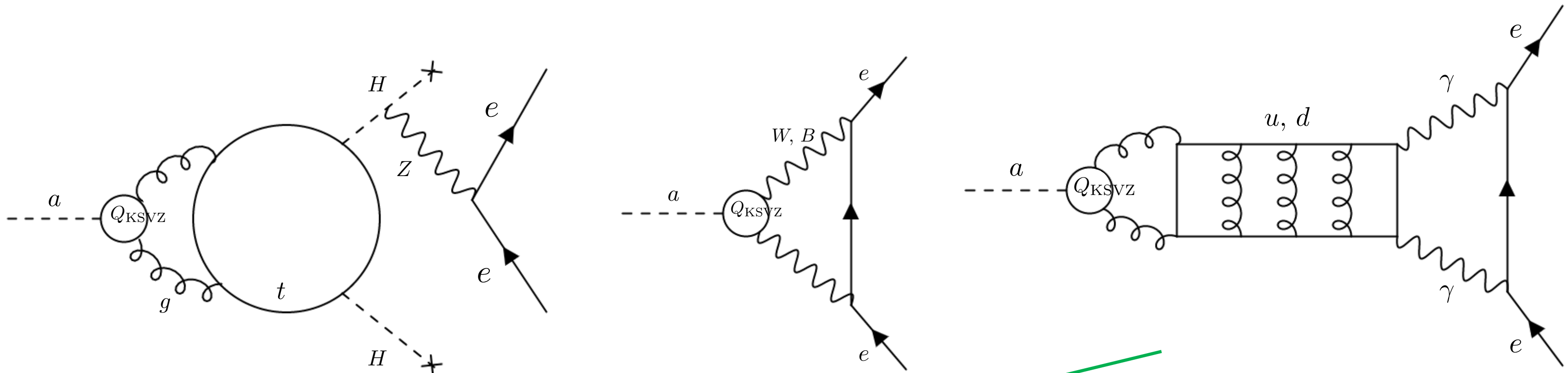


ΔC_e in KSVZ-like models

Srednicki '85
S Chang and K Choi '93
Bauer, Neubert, Renner, Schnubel, Thamm '20

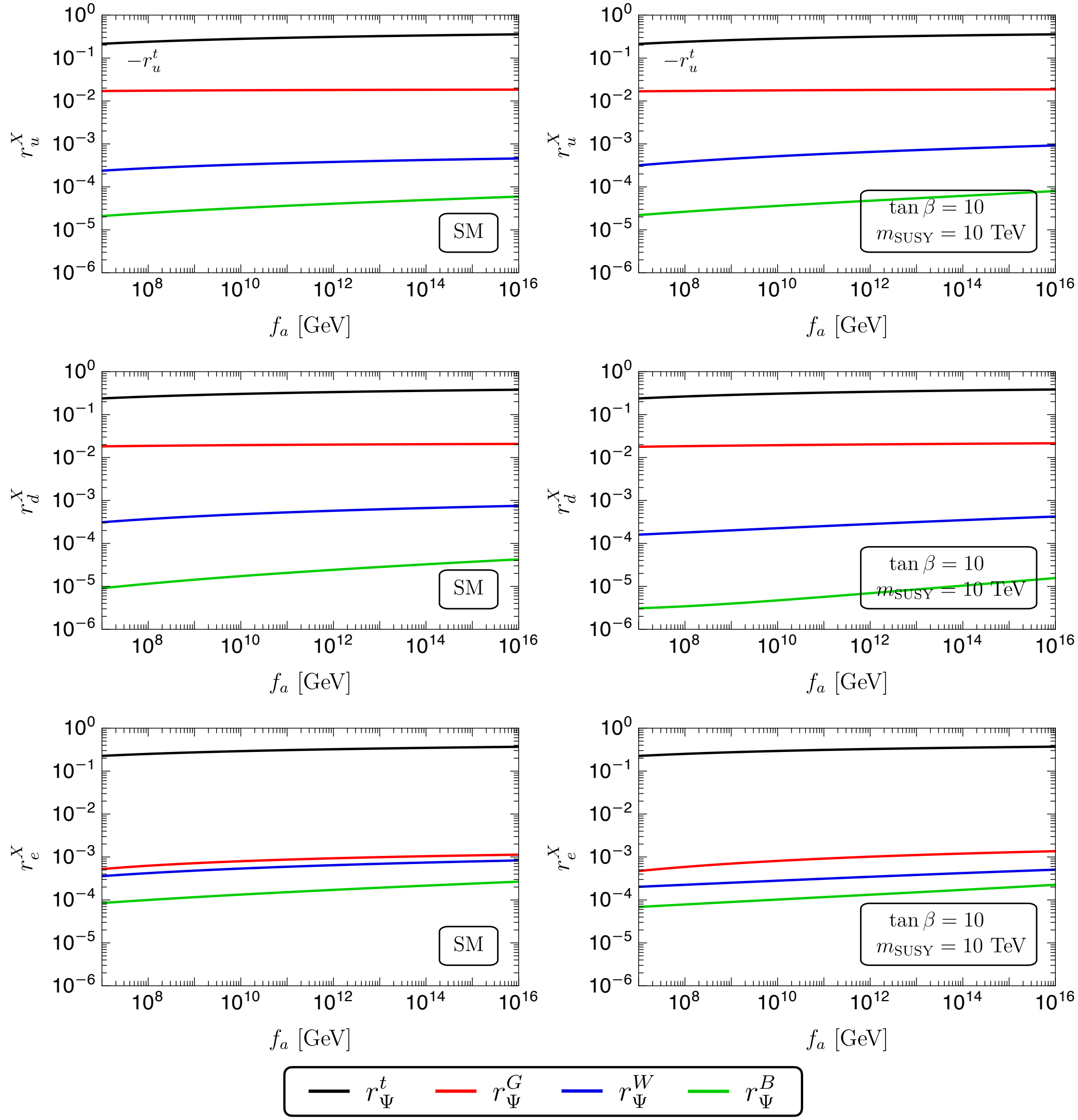


$$C_e(m_e) \simeq \left[0.84\, c_G - 0.03\, c_G + 0.28\, c_W + 0.10\, c_B\right] \times 10^{-3} \quad \text{(KSVZ with MSSM)}$$

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

Previously ignored because it is at three-loop level.

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



A few factor difference in the previous numerical values for different f_a from 10^7 GeV to 10^{16} GeV.

$$\text{SM}: \quad \Delta C_\Psi = r_\Psi^t C_t(f_a) + r_\Psi^G \tilde{c}_G(f_a) + r_\Psi^W \tilde{c}_W(f_a) + r_\Psi^B \tilde{c}_B(f_a),$$

$$\text{MSSM}: \quad \Delta C_\Psi = r_\Psi^t n_t(f_a) + r_\Psi^G \tilde{c}_G(f_a) + r_\Psi^W \tilde{c}_W(f_a) + r_\Psi^B \tilde{c}_B(f_a).$$

Consequences in low energy observables

Axion couplings to the photon, electron, neutron, and proton below GeV

$$\frac{1}{4} g_{a\gamma} a \vec{E} \cdot \vec{B} + \partial_\mu a \left[\frac{g_{ae}}{2m_e} \bar{e} \gamma^\mu \gamma_5 e + \frac{g_{an}}{2m_n} \bar{n} \gamma^\mu \gamma_5 n + \frac{g_{ap}}{2m_p} \bar{p} \gamma^\mu \gamma_5 p \right]$$

$$g_{a\gamma} \simeq \frac{\alpha_{\rm em}}{2\pi} \frac{1}{f_a} \Big(c_W + c_B - \frac{2}{3} \frac{m_u + 4m_d}{m_u + m_d} c_G \Big) \simeq \frac{\alpha_{\rm em}}{2\pi} \frac{1}{f_a} \Big(c_W + c_B - 1.92 c_G \Big),$$

$$g_{ap} \simeq \frac{m_p}{f_a} \left(C_u \Delta u + C_d \Delta d - \left(\frac{m_d}{m_u + m_d} \Delta u + \frac{m_u}{m_u + m_d} \Delta d \right) c_G \right),$$

$$\simeq \frac{m_p}{f_a} \Big(0.90\, C_u(2\,\mathrm{GeV}) - 0.38\, C_d(2\,\mathrm{GeV}) - 0.48\, c_G \Big),$$

$$g_{an} \simeq \frac{m_n}{f_a} \left(C_d \Delta u + C_u \Delta d - \left(\frac{m_u}{m_u + m_d} \Delta u + \frac{m_d}{m_u + m_d} \Delta d \right) c_G \right),$$

$$\simeq \frac{m_n}{f_a} \Big(0.90\, C_d(2\,\mathrm{GeV}) - 0.38\, C_u(2\,\mathrm{GeV}) - 0.04\, c_G \Big),$$

$$g_{ae} \simeq \frac{m_e}{f_a} C_e(m_e),$$

$$\underbrace{\langle p | \bar{u} \gamma^\mu \gamma_5 u | p \rangle}_{s^\mu \Delta u}$$

$$\underbrace{\langle p | \bar{d} \gamma^\mu \gamma_5 d | p \rangle}_{s^\mu \Delta d}$$

Cortona, Hardy, Vega, Villadoro '15

Taking into account the radiative corrections with the choice of parameters $f_a = 10^{10}$ GeV, $t_\beta = 10$, and $m_{SUSY} = 10$ TeV,

$$g_{ap} \simeq \frac{m_p}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ -0.48c_G + (0.5c_W + 0.05c_B) \times 10^{-3}, & \text{KSVZ-like} \\ -0.48c_G + 0.7\omega_I g_{\rm GUT}^2 \times 10^{-2}, & \text{String} \end{cases}$$

$$g_{an} \simeq \frac{m_n}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ -0.03c_G + (0.5c_W - 0.15c_B) \times 10^{-4}, & \text{KSVZ-like} \\ -0.03c_G + 0.63\,\omega_I g_{\rm GUT}^2 \times 10^{-2}, & \text{String} \end{cases}$$

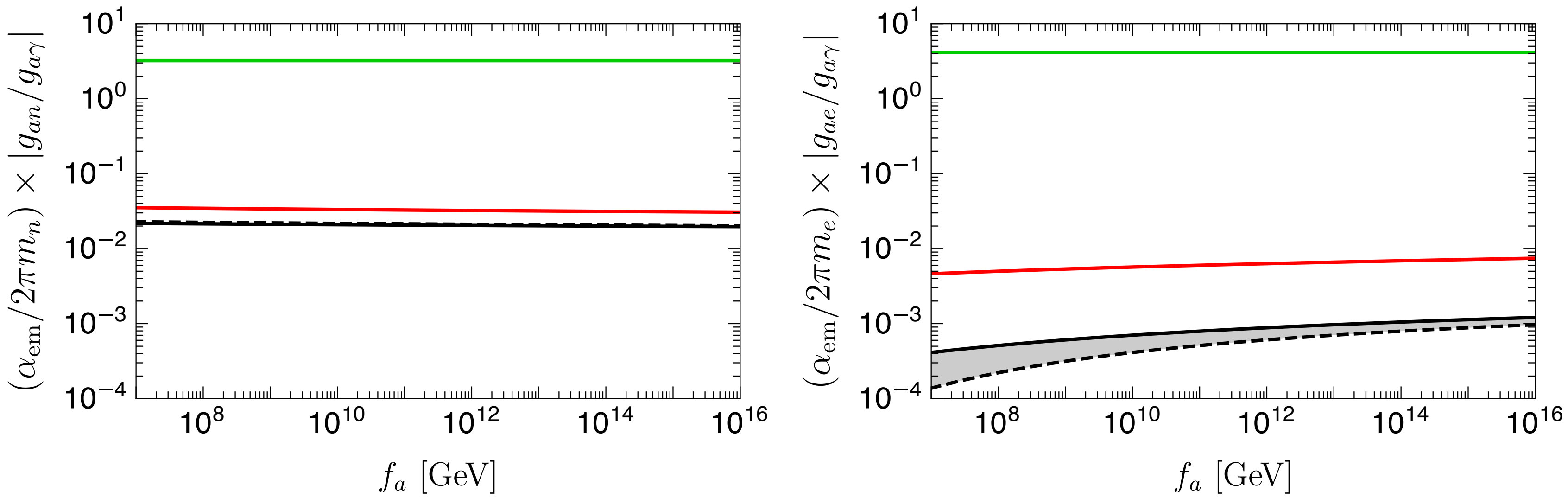
$$g_{ae} \simeq \frac{m_e}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ (c_G + 0.4c_W + 0.15c_B) \times 10^{-3}, & \text{KSVZ-like} \\ (c_G + 0.4c_W + 0.15c_B) \times 10^{-3} + \omega_I g_{\rm GUT}^2 \times 10^{-2}, & \text{String} \end{cases}$$

For string-theoretic axions, a universal scaling weight ω_I is assumed.

Ex) $\omega_I = \frac{1}{2}$, $\omega_I g_{GUT}^2 \sim 0.25$ in a type-IIB string Large Volume Scenario

Distinguishing the axions by coupling ratios

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

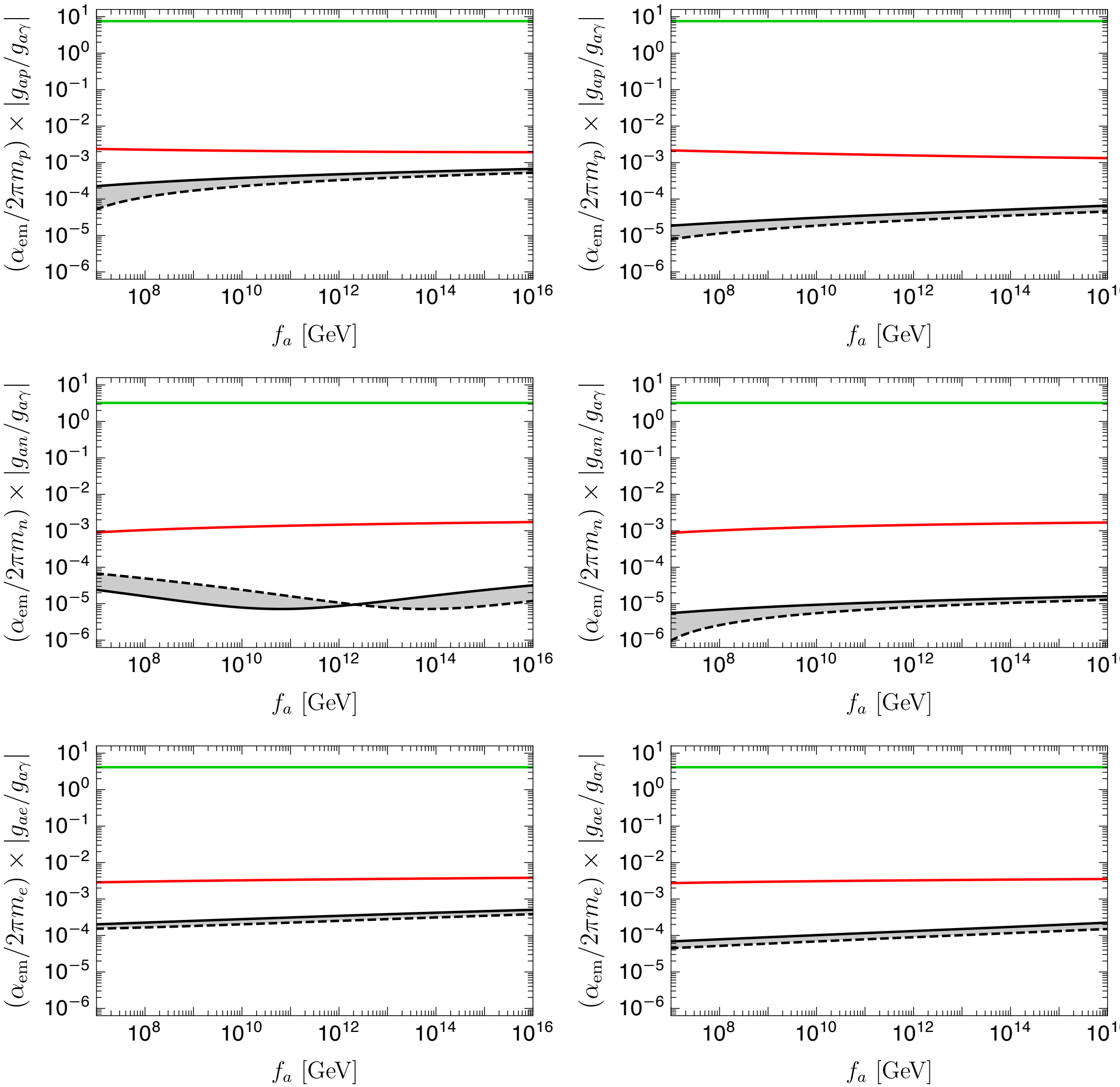


Green : DFSZ-like axion

Red : String-theoretic axion

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

For ALPs with ($c_G = 0$),



Green : DFSZ-like axion

Red : String-theoretic axion

Black : KSVZ-like axion

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

solid : $m_{KSVZ} = f_a$)

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

Conclusions

- Axions are theoretically well-motivated new particles which may be an important clue for underlying UV physics when they are discovered.
- We have three classes of axion models : KSVZ-like axions, DFSZ-like axions, String-theoretic axions. They show clearly different patterns of the couplings to the SM particles at tree-level.
- We examine how much radiative correction may affect the patterns.
- We find that as for QCD axion, it may be challenging to discriminate string-theoretic axions from KSVZ-like axions if not impossible. For this the axion-electron coupling plays an important role.
- On the other hand, for ALPs without gluon coupling, it is much more promising to distinguish among the three classes of models by various precision measurements of low energy axion couplings.

Back-up slides

Laboratory searches for axion DM -photonic probes

$$\frac{g_{a\gamma}}{4} aF\tilde{F} \Rightarrow \nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} \underbrace{- g_{a\gamma} \vec{B} \partial_t a}_{\vec{J}_{\text{eff}}}$$

$\vec{J}_{\text{eff}}$ effective current

Background axion DM field

$$a \approx a_0 \cos\left[m_a(t - \vec{v} \cdot \vec{x})\right]$$

$$\rho_a = \frac{1}{2} m_a^2 a_0^2 \qquad |\vec{v}| \sim 10^{-3} c$$

$$\Rightarrow \vec{J}_{\text{eff}} \approx g_{a\gamma} \sqrt{2\rho_a} \vec{B} \sin m_a t$$

The best experimental sensitivity on $g_{a\gamma}$ is obtained when $\rho_a = \rho_{DM}$.

Misalignment axion DM

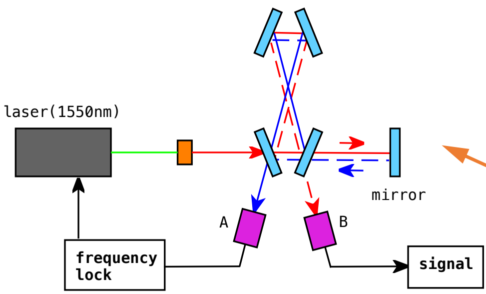
$$f_a \simeq 10^{17}\,\text{GeV} \left(\frac{10^{-22}\,\text{eV}}{m_a}\right)^{1/4} \sqrt{\frac{\rho_a}{\rho_{\text{DM}}}} \Rightarrow g_{a\gamma} = \frac{e^2}{8\pi^2} \frac{1}{f_a} c_{a\gamma}$$

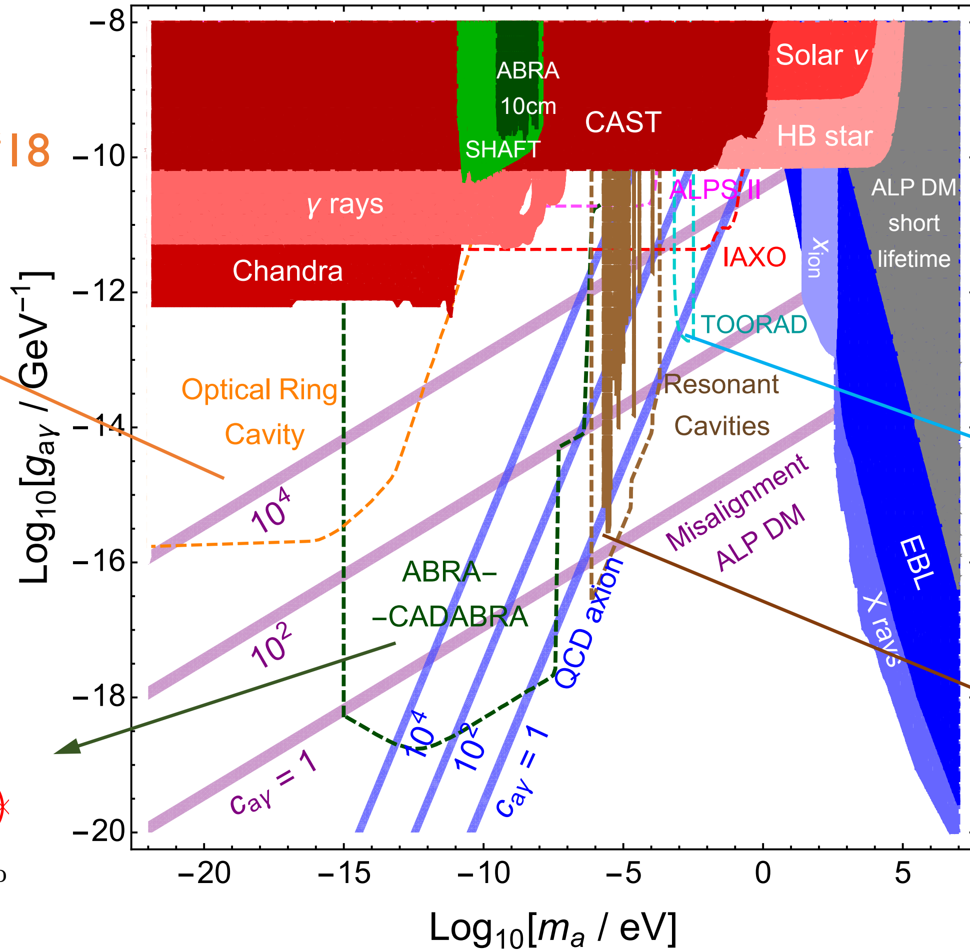
Given axion DM mass,
$g_{a\gamma}$ is determined for $c_{a\gamma} \sim O(1)$.

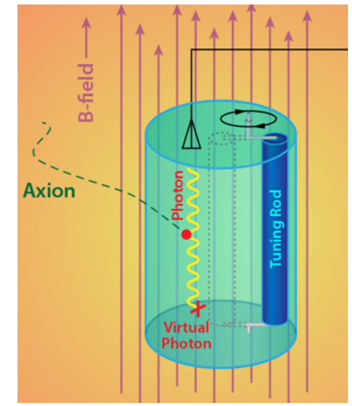
Current and future limits on $g_{a\gamma}$

Choi, SHI, Shin '20

Obata, Fujita, Michimura '18

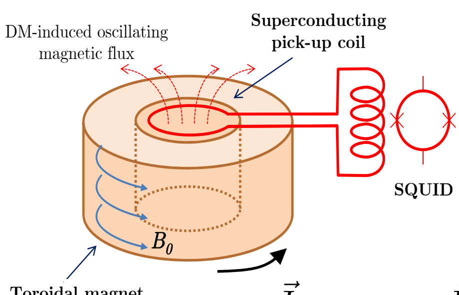






Marsh, Fong, Lentz, Smejkal, Ali '18

Kahn, Safdi, Thaler '16



$$\vec{J}_{\rm eff} = -g_{a\gamma}\vec{B}_0\partial_t a$$

ADMX, IBS-CAPP, MADMAX…

Laboratory searches for axion DM -nucleonic probes

$$g_{aN}\frac{\partial_\mu a}{2m_N}\bar{N}\gamma^\mu\gamma^5 N \quad \Rightarrow \quad \underbrace{g_{aN}\frac{\nabla a}{\gamma_N m_N}}_{\vec{B}_{\rm eff}}\cdot\gamma_N\vec{S}_N$$

γ_N : nucleon gyromagnetic ratio

Background axion DM field

$$a \approx a_0\cos\left[m_a(t-\vec{v}\cdot\vec{x})\right] \quad \Rightarrow \quad \vec{B}_{\rm eff}\approx g_{aN}\frac{\sqrt{2\rho_a}}{\gamma_N m_N}\vec{v}_a\sin m_a t$$

$$\rho_a = \frac{1}{2}m_a^2 a_0^2 \qquad |\vec{v}|\sim 10^{-3}c$$

The best experimental sensitivity on g_{aN} is obtained when $\rho_a = \rho_{DM}$.

Misalignment axion DM

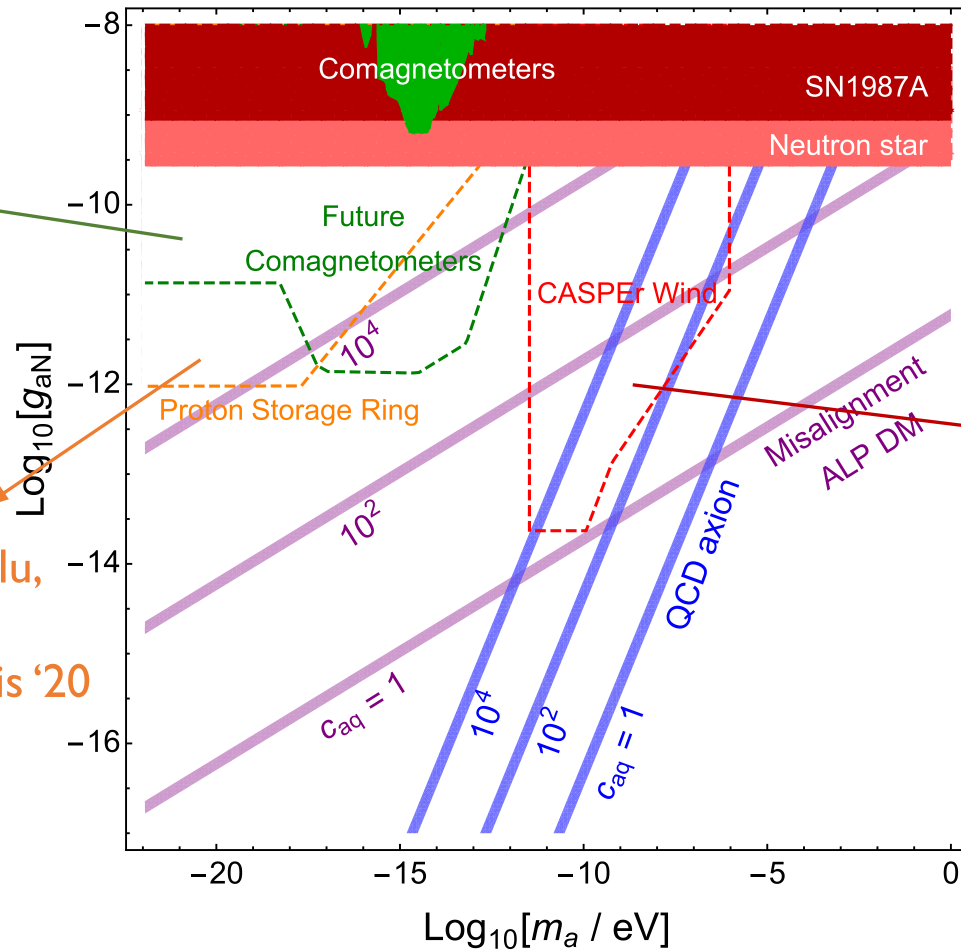
$$f_a \simeq 10^{17}\,{\rm GeV}\left(\frac{10^{-22}\,{\rm eV}}{m_a}\right)^{1/4}\sqrt{\frac{\rho_a}{\rho_{\rm DM}}} \quad \Rightarrow \quad g_{aN} = \frac{m_N}{f_a}c_{aq}\times\mathcal{O}(1)$$

Given axion DM mass,
g_{aN} is determined for $c_{aq}\sim O(1)$.

Current and future limits on g_{aN}

Bloch, Hochberg, Kuflik, Volansky '19

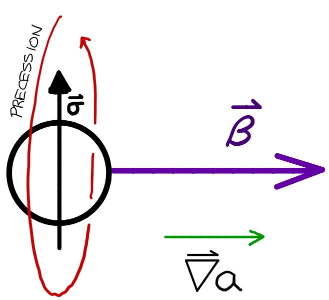
$$\frac{B^e_{\rm eff}}{B^N_{\rm eff}} \sim \frac{c_{ae} m_e}{c_{aN} m_N} \neq 1$$

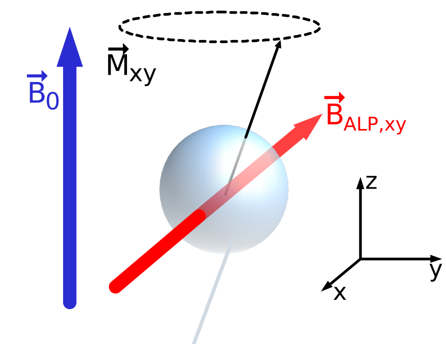


Choi, SHI, Shin '20

Kimball et al '17

Graham, Haciomeroglu, Kaplan, Omarov, Rajendran, Semertzidis '20





NMR