

# Uncovering microscopic origins of axions by low energy precision physics

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Kiwoon Choi, SHI, Hee Jung Kim, Hyeonseok Seong : JHEP 08 (2021) 058,  
arXiv 2106.05816

PADUA axion workshop, Padua, Italy, Sep 12<sup>th</sup>, 2022

# Outline

- Three classes of high energy physics for an axion
  - KSVZ-like models
  - DFSZ-like models
  - String-theoretic models
- RG running of axion couplings
- Possibility to distinguish the microscopic origins by low energy precision measurements

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

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

[Vafa, Witten '84]

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

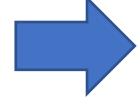
Promote  $\bar{\theta}$  to a dynamical field (=QCD axion) :  $\frac{g_s^2}{32\pi^2} \left( \theta + \frac{a}{f_a} \right) G \tilde{G}$   
[Peccei, Quinn '77, Weinberg '78, Wilczek '78]

# QCD axion lagrangian

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

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

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)

- Cousins of the QCD axion, while not being necessarily involved in the strong CP problem (so  $c_G$  can be 0)
- Ubiquitous in many BSM scenarios, in particular, string theory

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

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

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

: ALP can be naturally light.

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

:  $f_a$  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

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

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

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

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

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

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

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



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

: axion-dependent field redefinition  
proportional to the PQ charge

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

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

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

: Dynkin index



Below the exotic heavy fermion mass scale

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

**“KSVZ-like models”**  
: 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.

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

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

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

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

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

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

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



: axion-dependent field redefinition  
proportional to the PQ charge

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

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



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

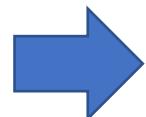
$$\begin{aligned} \mathcal{L}_{\text{eff}}(\mu < m_Z) = & - \frac{\partial_\mu a}{f_a} \left( c_\beta^2 u^\dagger \gamma^\mu \gamma_5 u + s_\beta^2 d^\dagger \gamma^\mu \gamma_5 d + s_\beta^2 e^\dagger \gamma^\mu \gamma_5 e \right) \\ & - \frac{g_s^2}{32\pi^2} 6 \frac{a}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}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

“DFSZ-like models”  
:  $O(1)$  tree-level couplings  
to the SM fermions

# String-theoretic models

$$C_{[m_1 m_2 \dots m_p]}(x^\mu, y^m) = \textcolor{blue}{a(x^\mu)} \Omega_{[m_1 m_2 \dots m_p]}(y^m) \quad \Omega : \text{harmonic } p\text{-form on the compact internal space}$$

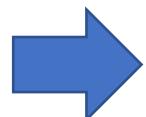
4D axions identified as zero modes of higher-dimensional  $p$ -form gauge field



SUSY-preserving compactification

$$\left\{ \begin{array}{ll} T = \tau + ia & \text{Axion chiral superfield } (\tau : \text{volume modulus of } p\text{-cycle dual to } \Omega) \\ U(1)_{PQ} : & a \rightarrow a + \text{const} \\ & : \text{remnant of a higher-dimensional gauge symmetry} \end{array} \right.$$

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



4D Low energy effective action

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

$$\mathcal{F}_A = c_A T$$

$$c_A \sim \mathcal{O}(1)$$

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

Conlon, Cremades, Quevedo '06

scaling weight of  $\Phi_I$

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

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

  $T = \tau + ia$

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

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

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

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

 **Canonical normalization**  $a \rightarrow \frac{a}{8\pi^2 f_a}$   $f_a = \frac{M_P}{8\pi^2} \sqrt{\frac{\partial_\tau^2 K_0}{2}}$

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

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

# Comparison of tree-level axion couplings to the SM fermions

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

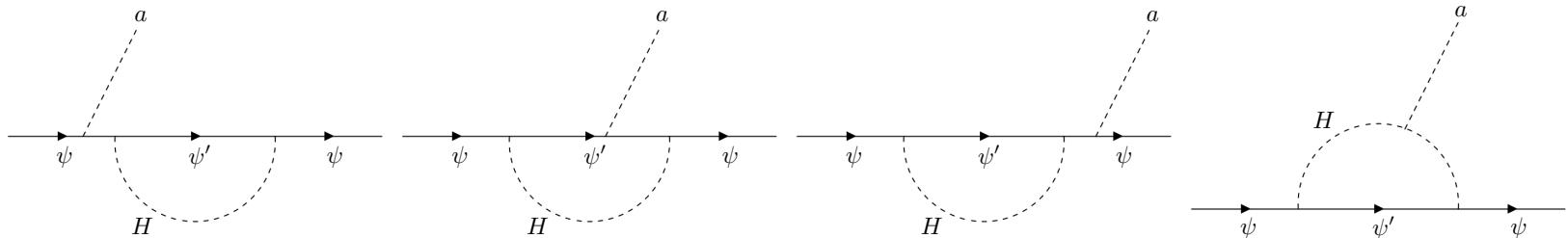
- DFSZ-like models:  $C_\Psi^0 \sim \mathcal{O}(1)$
- KSVZ-like models:  $C_\Psi^0 = 0$
- String-theoretic models:  $C_\Psi^0 \sim \mathcal{O}(g^2/16\pi^2)$

At tree-level, those three classes of high energy physics show clearly different patterns that they may be distinguished by precision experiments.

Yet radiative corrections have to be carefully taken into account in order to see whether it is indeed possible, especially for discriminating string-theoretic models from KSVZ-like models.

# Running of axion couplings 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

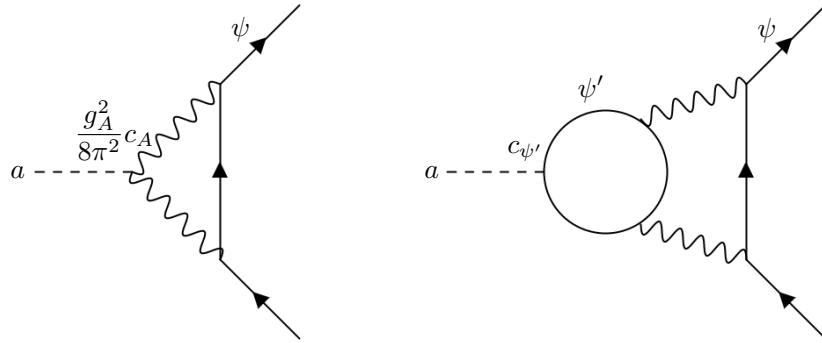


$$\frac{\partial_\mu a}{f_a} \left( \sum_\psi c_\psi \psi^\dagger \bar{\sigma}^\mu \psi + \sum_{\alpha=1,2} c_{H_\alpha} H_\alpha^\dagger i \overset{\leftrightarrow}{D}{}^\mu H_\alpha \right) + \sum_A \frac{g_A^2}{32\pi^2} c_A \frac{a}{f_a} F^{A\mu\nu} \tilde{F}_{\mu\nu}^A$$

$$y_t u_3^c Q_{L3} H_u \quad \rightarrow \quad \begin{aligned} \frac{dc_{Q_3}}{d \ln \mu} &\approx \frac{\xi_y}{16\pi^2} y_t^2 n_t \\ \frac{dc_{u_3^c}}{d \ln \mu} &\approx \frac{\xi_y}{8\pi^2} y_t^2 n_t \quad n_t \equiv c_{Q_3} + c_{u_3^c} + c_{H_u} \\ \frac{dc_{H_u}}{d \ln \mu} &\approx \frac{3}{8\pi^2} y_t^2 n_t \end{aligned}$$

$\xi_y = \begin{cases} 1 & \text{for non-SUSY models} \\ 2 & \text{for SUSY models} \end{cases}$

# Running of axion couplings 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

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

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

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

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

# Numerical results

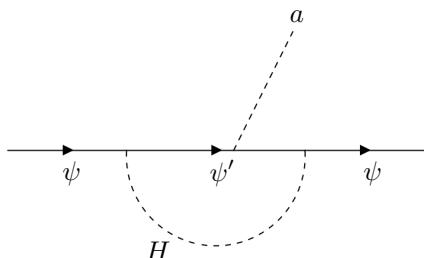
For  $f_a = 10^{10}$  GeV,  $t_\beta = 10$ , and  $m_{SUSY} = 10$  TeV,

$$C_u(2 \text{ GeV}) \simeq C_u(f_a) - 0.28 n_t(f_a) + [17.7 \tilde{c}_G(f_a) + 0.52 \tilde{c}_W(f_a) + 0.036 \tilde{c}_B(f_a)] \times 10^{-3},$$

$$C_d(2 \text{ GeV}) \simeq C_d(f_a) + 0.31 n_t(f_a) + [19.4 \tilde{c}_G(f_a) + 0.23 \tilde{c}_W(f_a) + 0.0047 \tilde{c}_B(f_a)] \times 10^{-3}$$

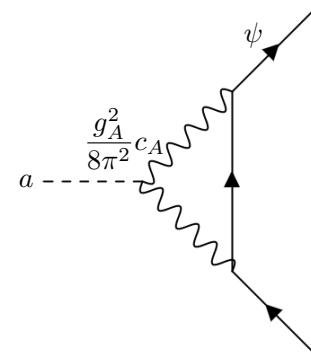
$$C_e(m_e) \simeq C_e(f_a) + 0.29 n_t(f_a) + [0.81 \tilde{c}_G(f_a) + 0.28 \tilde{c}_W(f_a) + 0.10 \tilde{c}_B(f_a)] \times 10^{-3}.$$

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



??

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

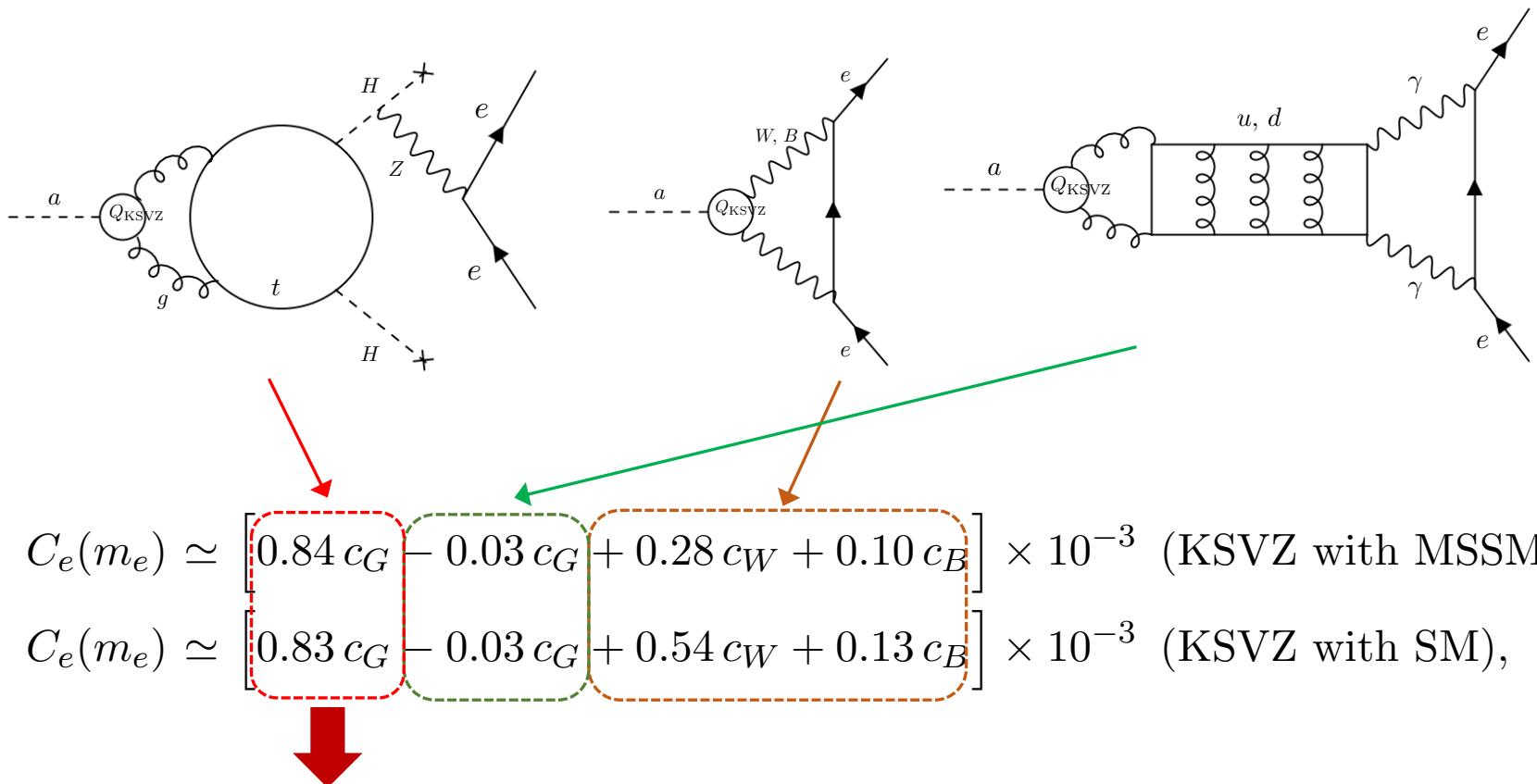


# $\Delta C_e$ in KSVZ-like models

Srednicki '85

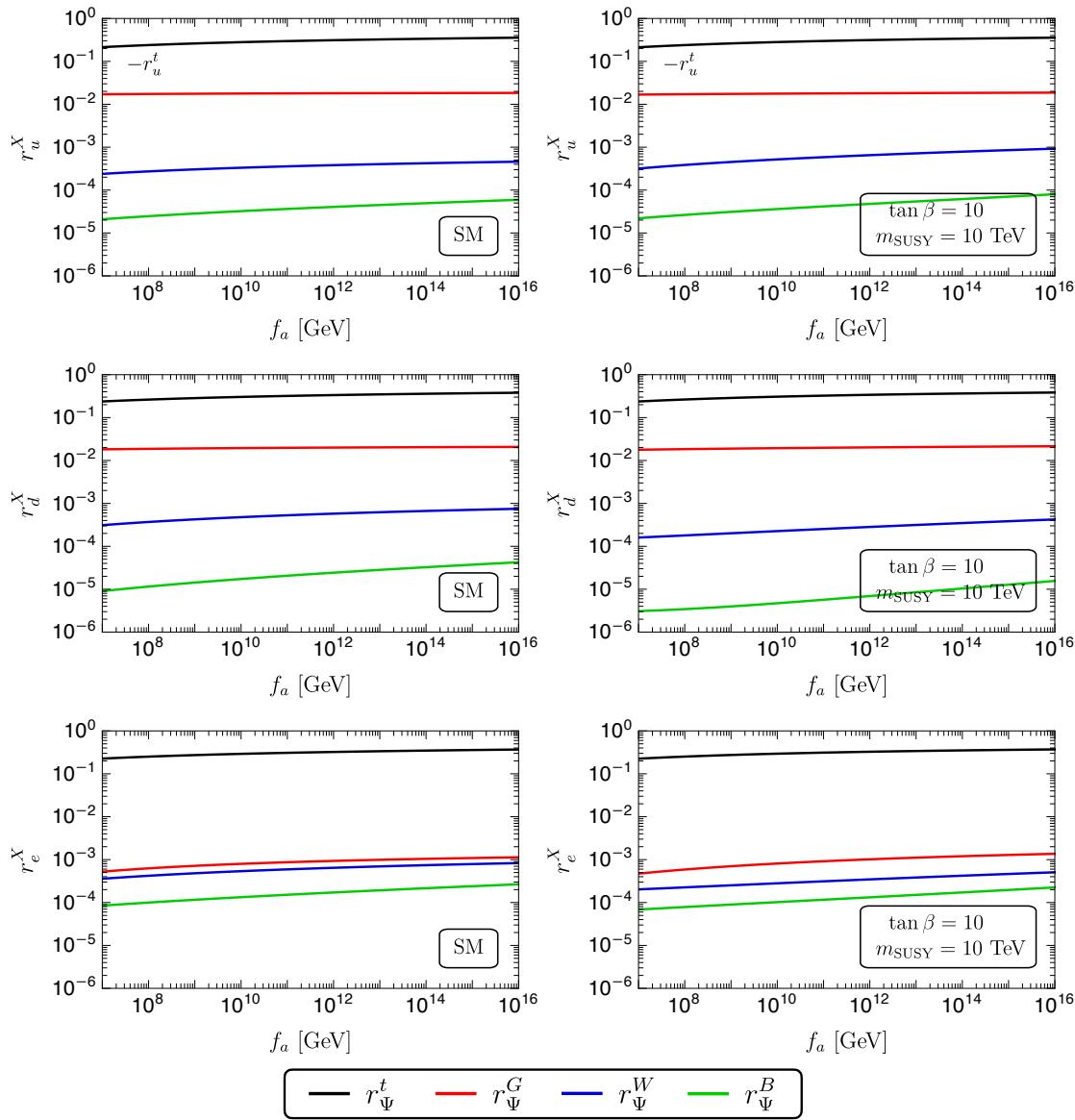
S Chang and K Choi '93

Bauer, Neubert, Renner, Schnubel, Thamm '20



Previously ignored because  
it is at three-loop level.

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

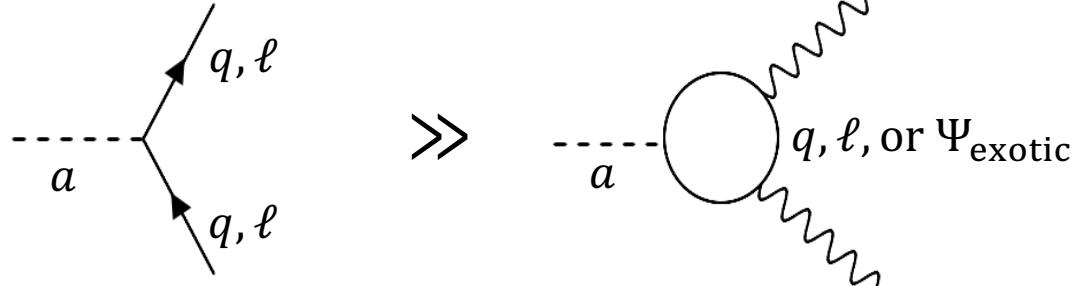


A few factor difference in the previous numerical values for different  $f_a$  from  $10^7$  GeV to  $10^{16}$  GeV.

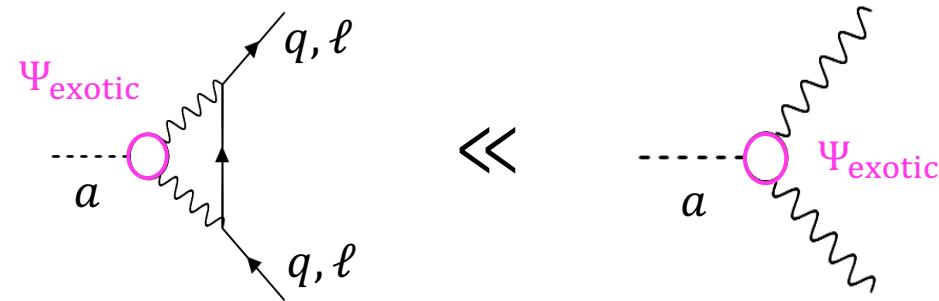
$$\begin{aligned} \text{SM : } \Delta C_\Psi &= r_\Psi^t C_t(f_a) + r_\Psi^G \tilde{c}_G(f_a) + r_\Psi^W \tilde{c}_W(f_a) + r_\Psi^B \tilde{c}_B(f_a), \\ \text{MSSM : } \Delta C_\Psi &= r_\Psi^t n_t(f_a) + r_\Psi^G \tilde{c}_G(f_a) + r_\Psi^W \tilde{c}_W(f_a) + r_\Psi^B \tilde{c}_B(f_a). \end{aligned}$$

# Summary: axion couplings including loops

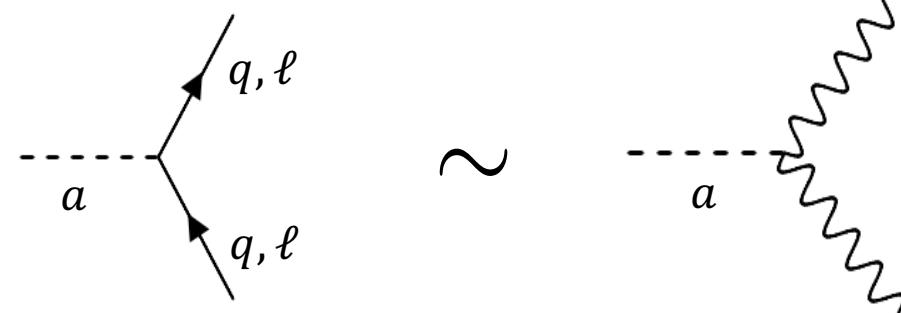
**DFSZ-like models**



**KSVZ-like models**



**String-theoretic models**



# Consequences in low energy observables

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

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

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

$$\begin{aligned} g_{ap} &\simeq \frac{m_p}{f_a} \left( C_u \Delta u + C_d \Delta d - \left( \frac{m_d}{m_u + m_d} \Delta u + \frac{m_u}{m_u + m_d} \Delta d \right) c_G \right), \\ &\simeq \frac{m_p}{f_a} \left( 0.90(3) C_u(2 \text{ GeV}) - 0.38(2) C_d(2 \text{ GeV}) - \textcolor{blue}{0.48(3) c_G} \right), \end{aligned}$$

$$\begin{aligned} g_{an} &\simeq \frac{m_n}{f_a} \left( C_d \Delta u + C_u \Delta d - \left( \frac{m_u}{m_u + m_d} \Delta u + \frac{m_d}{m_u + m_d} \Delta d \right) c_G \right), \\ &\simeq \frac{m_n}{f_a} \left( 0.90(3) C_d(2 \text{ GeV}) - 0.38(2) C_u(2 \text{ GeV}) - \textcolor{blue}{0.04(3) c_G} \right), \end{aligned}$$

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

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,

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

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

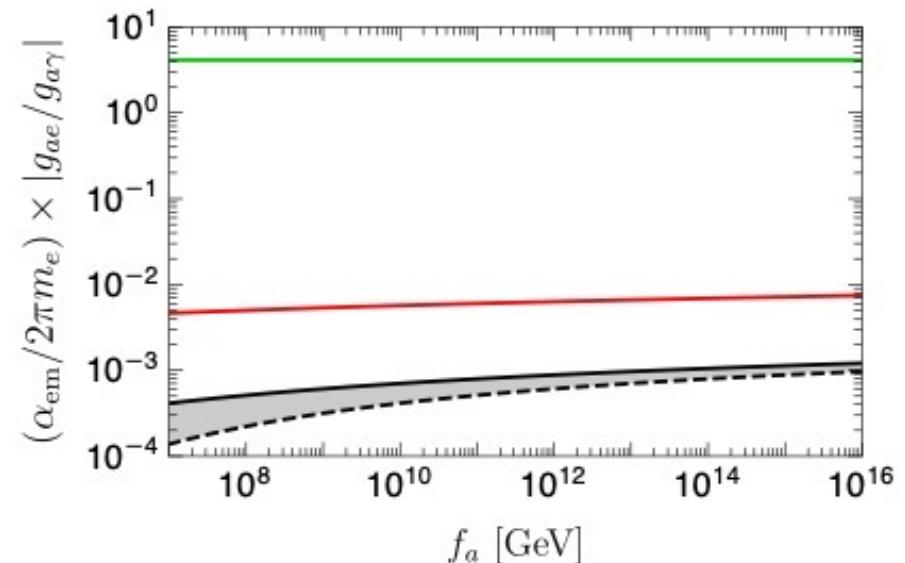
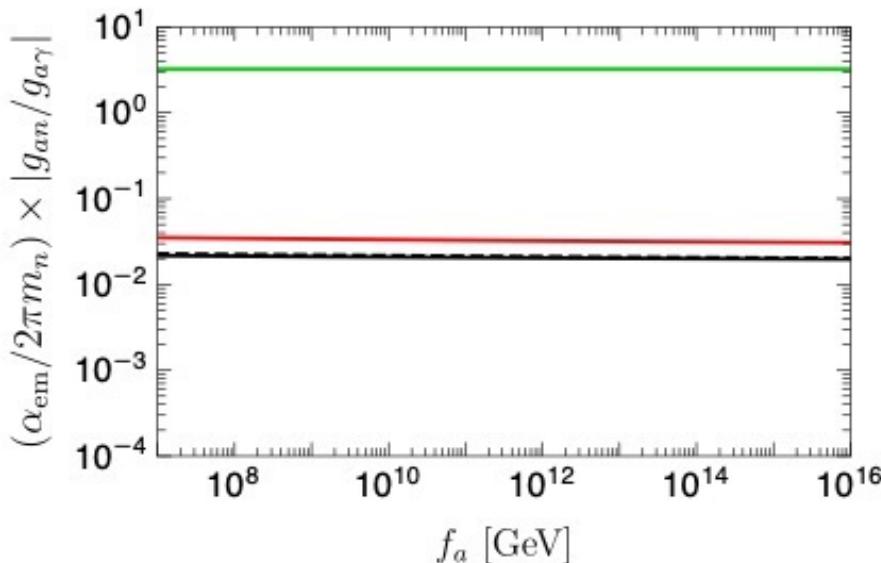
$$g_{ae} \simeq \frac{m_e}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ (c_G + 0.4c_W + 0.15c_B) \times 10^{-3}, & \text{KSVZ-like} \\ (c_G + 0.4c_W + 0.15c_B) \times 10^{-3} + \omega_I g_{\text{GUT}}^2 \times 10^{-2}, & \text{String} \end{cases}$$

For the string-theoretic model, a universal scaling weight  $\omega_I$  is assumed.

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

# Distinguishing the models of an axion by coupling ratios

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

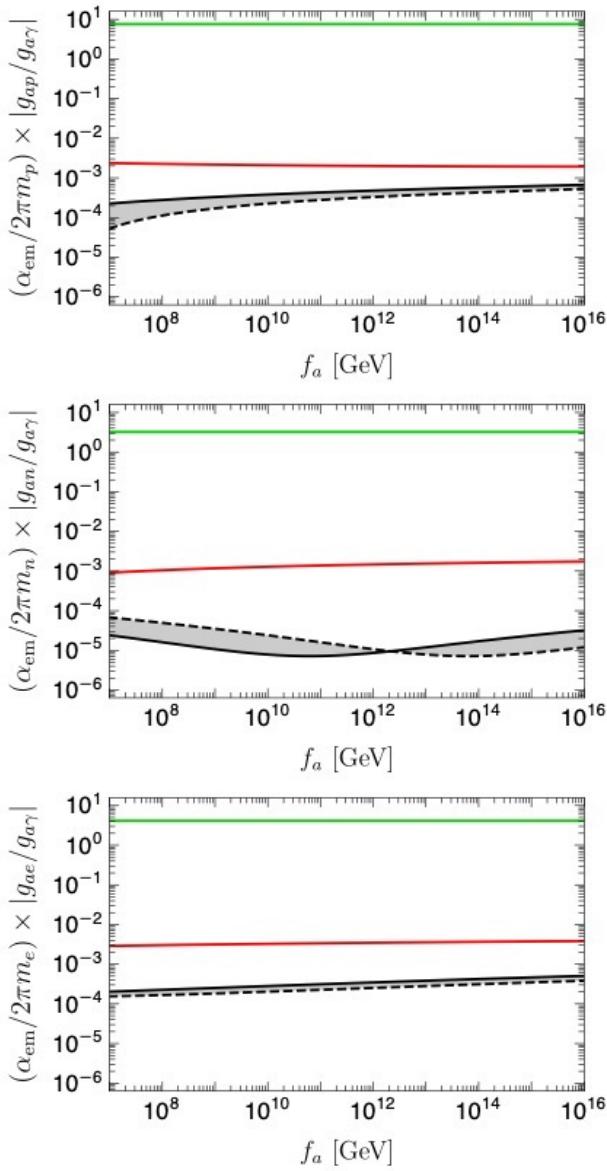


Green : DFSZ-like model

Red : String-theoretic model

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

For ALPs with ( $c_G = 0$ ),



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

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

Green : DFSZ-like model  
 Red : String-theoretic model  
 Black : KSVZ-like model  
 (dashed :  $m_{\text{KSVZ}} = 10^{-3}f_a$ ,  
 solid :  $m_{\text{KSVZ}} = f_a$ )

# Conclusion

- Axions are theoretically well-motivated new particles which may be an important clue for underlying UV physics when they are discovered.
- In principle, we have three possible classes of axion models : KSVZ-like models, DFSZ-like models, and string-theoretic models. They show clearly different patterns of axion couplings to SM particles at tree-level.
- We have carefully examined the leading loop effect on those patterns.
- We find that as for QCD axion, it may be challenging to discriminate string-theoretic models from KSVZ-like models 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

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

Background axion DM field

$$a \approx a_0 \cos [m_a(t - \vec{v} \cdot \vec{x})] \quad \rightarrow \quad \vec{J}_{\text{eff}} \approx g_{a\gamma} \sqrt{2\rho_a} \vec{B} \sin m_a t$$

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

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

## Misalignment axion DM

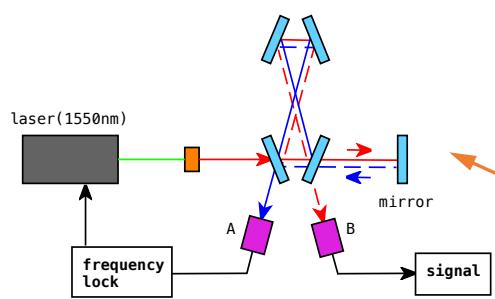
$$f_a \simeq 10^{17} \text{ GeV} \left( \frac{10^{-22} \text{ eV}}{m_a} \right)^{1/4} \sqrt{\frac{\rho_a}{\rho_{DM}}} \quad \rightarrow \quad g_{a\gamma} = \frac{e^2}{8\pi^2} \frac{1}{f_a} c_{a\gamma}$$

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

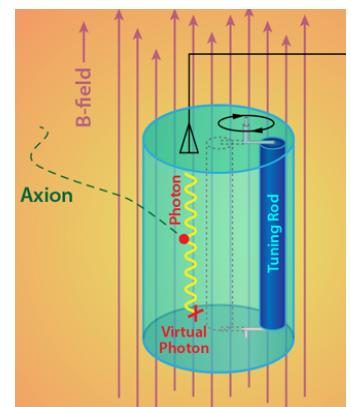
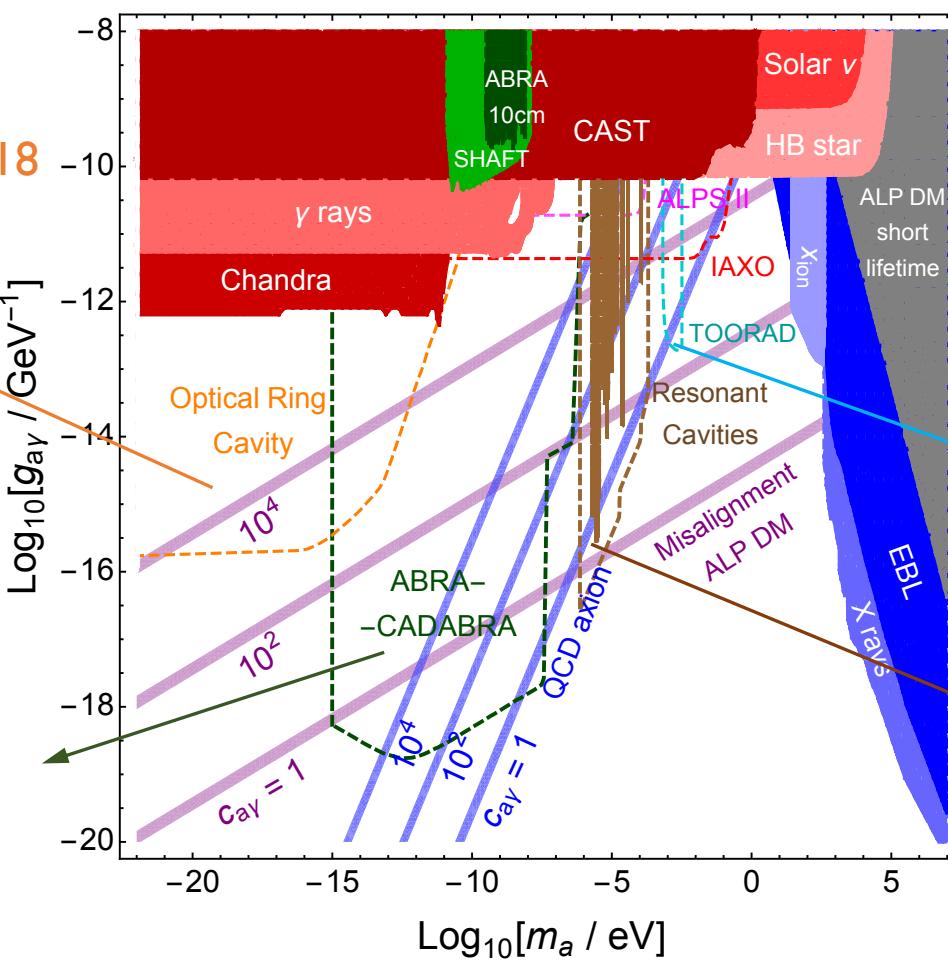
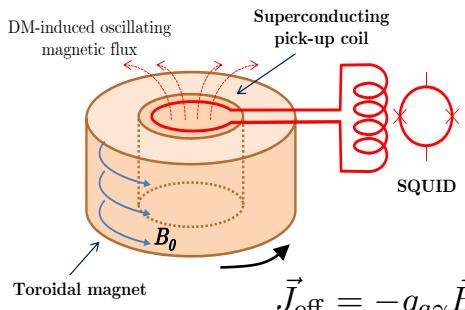
# Current and future limits on $g_{a\gamma}$

Choi, SHI, Shin '20

Obata, Fujita, Michimura '18



Kahn, Safdi, Thaler '16

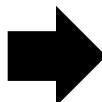


Marsh, Fong, Lentz, Smejkal, Ali '18

ADMX,  
IBS-CAPP,  
MADMAX...

# Laboratory searches for axion DM -nucleonic probes

$$g_{aN} \frac{\partial_\mu a}{2m_N} \bar{N} \gamma^\mu \gamma^5 N$$

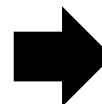


$$\underbrace{g_{aN} \frac{\nabla a}{\gamma_N m_N}}_{\vec{B}_{\text{eff}}} \cdot \gamma_N \vec{S}_N$$

$\gamma_N$  : nucleon  
gyromagnetic  
ratio

Background axion DM field

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



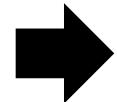
$$\vec{B}_{\text{eff}} \approx g_{aN} \frac{\sqrt{2\rho_a}}{\gamma_N m_N} \vec{v}_a \sin m_a t$$

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

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

Misalignment axion DM

$$f_a \simeq 10^{17} \text{ GeV} \left( \frac{10^{-22} \text{ eV}}{m_a} \right)^{1/4} \sqrt{\frac{\rho_a}{\rho_{DM}}}$$



$$g_{aN} = \frac{m_N}{f_a} c_{aq} \times \mathcal{O}(1)$$

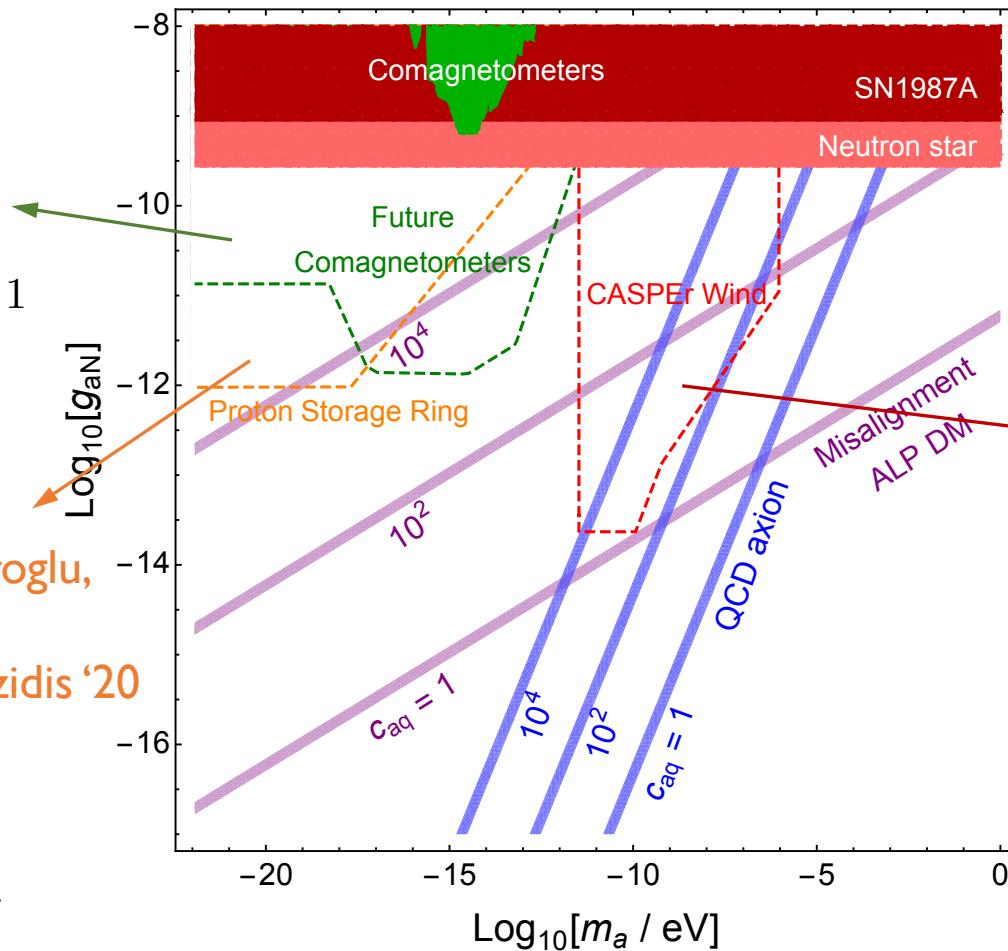
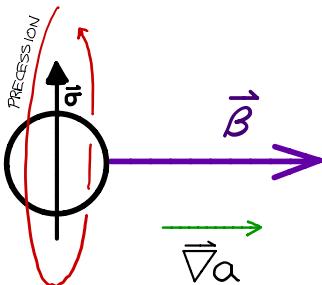
Given axion DM mass,  
 $g_{aN}$  is determined for  $c_{aq} \sim \mathcal{O}(1)$ .

# Current and future limits on $g_{aN}$

Bloch, Hochberg,  
Kuflik, Volansky '19

$$\frac{B_{\text{eff}}^e}{B_{\text{eff}}^N} \sim \frac{c_{ae} m_e}{c_{aN} m_N} \neq 1$$

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



Choi, SHI, Shin '20

