Uncovering microscopic origins of axions by low energy precision physics

Sang Hui Im (IBS-CTPU)

K. Choi, SHI, H. J. Kim, H. Seong, *JHEP 08 (2021) 058, 2106.05816*

GGI axion workshop, Florence, Italy

May 12th, 2023

Outline

- Classification of possible UV physics for axions
  KSVZ-like models
  DFSZ-like models
  String-theoretic models
- RGE of axion couplings
- UV-characteristic patterns of low energy axion couplings

Strong CP problem and QCD axion

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

$$\Rightarrow \quad \bar{\theta} = \theta + \arg\det\left(y_u y_d\right) < 10^{-10}$$

Non-observation of neutron EDM

[Abel et al '20]

CPV in the QCD sector

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

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) : $\dfrac{g_s^2}{32\pi^2}\left(\theta + \dfrac{a}{f_a}\right)G\tilde{G}$

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

QCD axion lagrangian

See lectures by G.Villadoro in the last training week

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

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

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

broken by $c_G \neq 0$ non-perturbatively

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

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

Axion-Like Particles (ALPs)

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

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

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

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

: 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
up to UV-dependent dimensionless coefficients c_A, c_ψ, c_ϕ.

KSVZ model

Kim '79, Shifman, Vainshtein, Zakharov '80

(See the lecture by A. Ringwald)

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

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

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

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

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

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

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

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

: axion-dependent field redefinition proportional to the PQ charge

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

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

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

: Dynkin index

Below the exotic heavy fermion mass scale

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

"KSVZ-like models"

: vanishing tree-level couplings to the SM fermions

DFSZ model

Dine, Fischler, Srednicki '81, Zhitnitsky '80

(See the lecture by A. Ringwald)

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

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

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

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

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

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

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

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

: 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 models"
: $O(1)$ tree-level couplings to the SM fermions

String-theoretic models

Witten '84

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

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)

$$U(1)_{PQ} : \quad a \rightarrow a + \mathrm{const}$$

: 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

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

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

scaling weight of Φ_I

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

Conlon, Cremades, Quevedo '06

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

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

$$T = \tau + ia$$

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

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

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

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

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

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

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

Comparison of tree-level axion couplings to the SM fermions

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

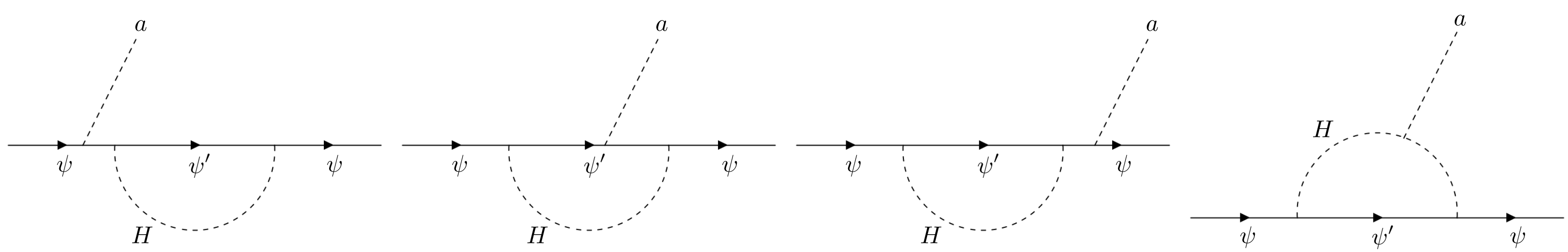
- DFSZ-like models: $C_\Psi^0 \sim O(1)$
- KSVZ-like models: $C_\Psi^0 = 0$
- String-theoretic models: $C_\Psi^0 \sim O(g^2/16\pi^2)$

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

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



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

$y_t u_3^c Q_3 H_\alpha$ ⇒

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

$$\frac{dc_{u_3^c}}{d\ln\mu} \approx \frac{\xi_y}{8\pi^2} y_t^2 n_t$$

$$\frac{dc_{H_u}}{d\ln\mu} \approx \frac{3}{8\pi^2} y_t^2 n_t$$

$n_t = c_{u_3^c} + c_{Q_3} + c_{H_\alpha}$

$= 0$ for KSVZ-like models

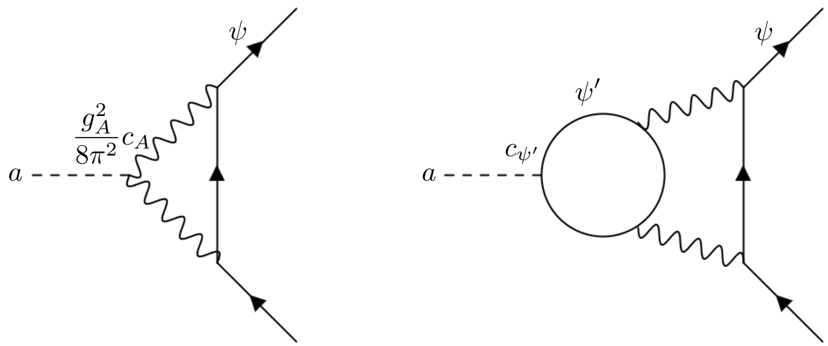
$\neq 0$ for the DFSZ model

below $\mu = m_{H^\pm}$

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

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



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

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

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

$$\tilde c_A \equiv c_A - \sum_{\psi'} c_{\psi'}$$

$\neq 0$

for field-theoretic axions below the mass scale of the heaviest ψ'

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

$\mathbb{C}_A(\Phi)$: quadratic Casimir

Numerical results

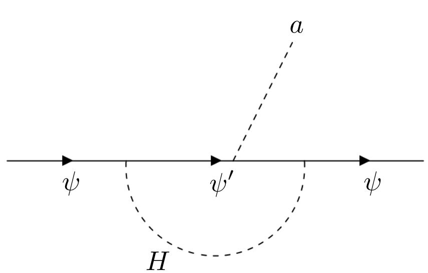
For $m_{BSM} = 10^{10}$ GeV and $\tan\beta = 10$,

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

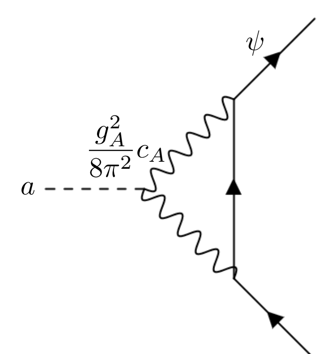
Talk by Maurizio

$$\frac{y_t^2}{8\pi^2} n_t(f_a) \ln \frac{m_{BSM}}{m_t} \sim 0.3\, \mathrm{n_t(f_a)}$$

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

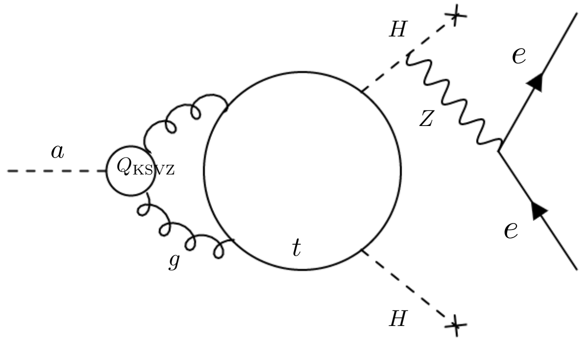


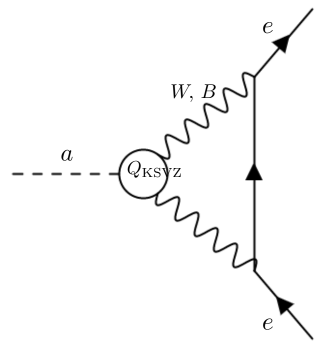
??

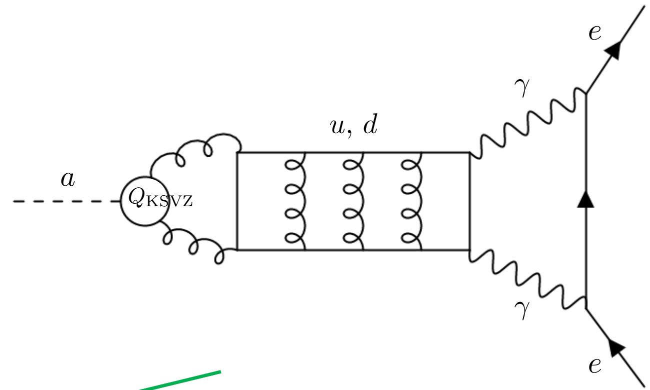


ΔC_e in KSVZ-like models

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







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

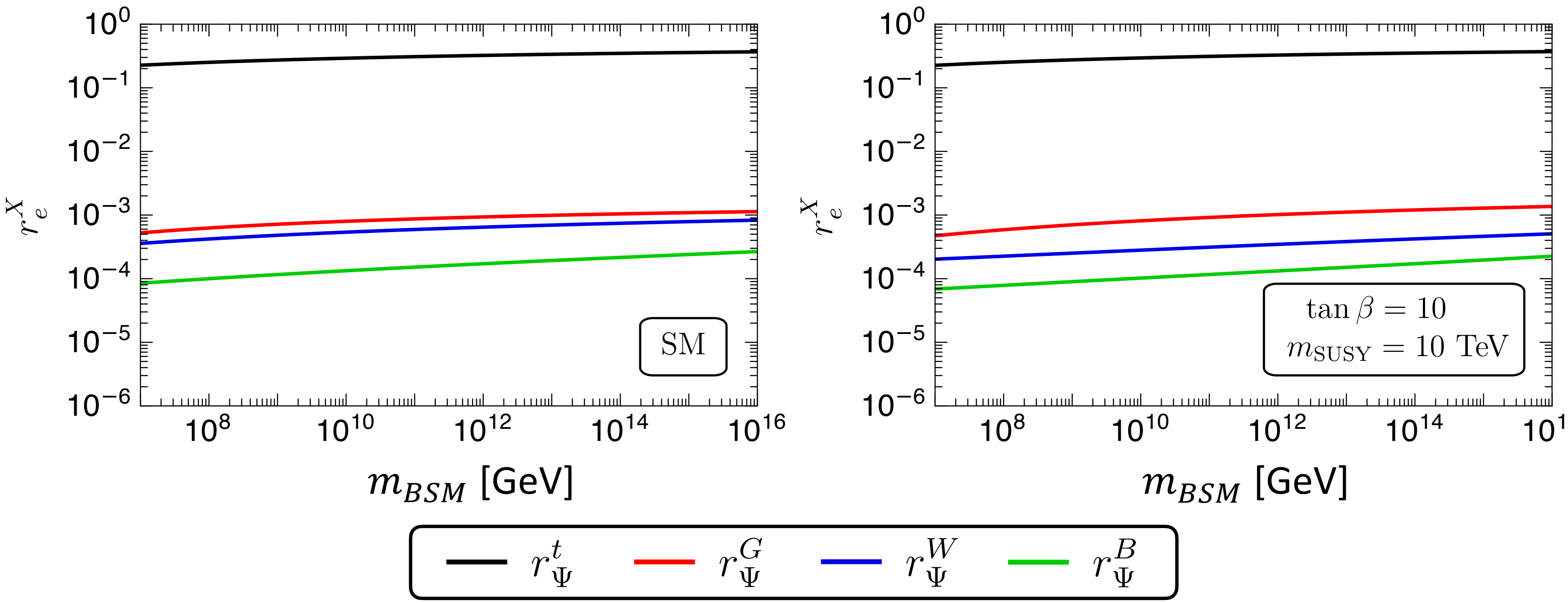
$$C_e(m_e) \simeq \left[0.83\, c_G - 0.03\, c_G + 0.54\, c_W + 0.13\, c_B\right] \times 10^{-3} \quad \text{(KSVZ with SM)},$$

Previously ignored because it is at three-loop level.

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

RG correction :

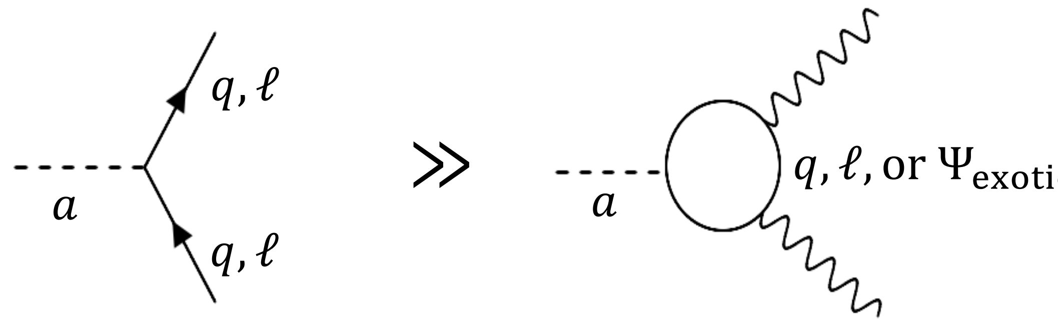
$$\Delta C_\Psi = r_\Psi^t(m_{BSM})\, n_t(f_a) + \sum_{A=G,W,B} r_\Psi^A\,(m_{BSM})\, \tilde{c}_A(f_a)$$



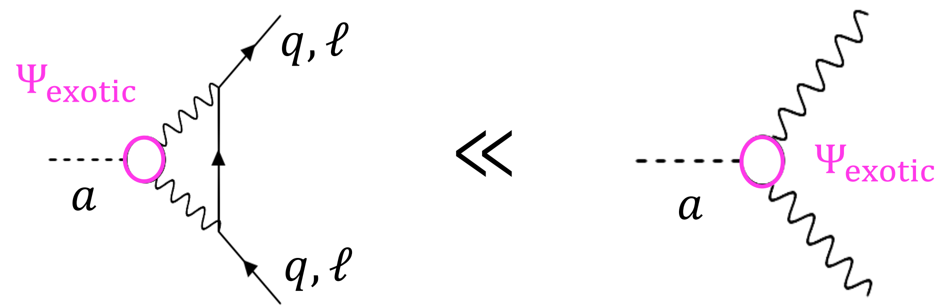
A few factor difference in the previous numerical values for different m_{BSM} from 10^7 GeV to 10^{16} GeV (can be quite much smaller for $m_{BSM}\sim 1$ TeV: Maurizio's talk).

Summary: axion couplings including loops

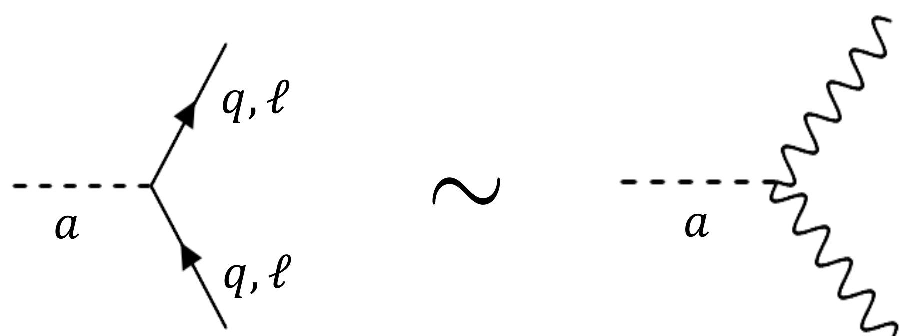
DFSZ-like models



KSVZ-like models



String-theoretic models



Consequences in low energy observables

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

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

$$
\begin{aligned}
g_{a\gamma} &\simeq \frac{\alpha_{\rm em}}{2\pi}\frac{1}{f_a}\Big(c_W + c_B - \frac{2}{3}\frac{m_u+4m_d}{m_u+m_d}c_G\Big) \simeq \frac{\alpha_{\rm em}}{2\pi}\frac{1}{f_a}\Big(c_W + c_B - 1.92 c_G\Big),\\
g_{ap} &\simeq \frac{m_p}{f_a}\left(C_u\Delta u + C_d\Delta d - \Big(\frac{m_d}{m_u+m_d}\Delta u + \frac{m_u}{m_u+m_d}\Delta d\Big)c_G\right),\\
&\simeq \frac{m_p}{f_a}\Big(0.90(3)\, C_u(2\,\mathrm{GeV}) - 0.38(2)\, C_d(2\,\mathrm{GeV}) - 0.48(3)\, c_G\Big),\\
g_{an} &\simeq \frac{m_n}{f_a}\left(C_d\Delta u + C_u\Delta d - \Big(\frac{m_u}{m_u+m_d}\Delta u + \frac{m_d}{m_u+m_d}\Delta d\Big)c_G\right),\\
&\simeq \frac{m_n}{f_a}\Big(0.90(3)\, C_d(2\,\mathrm{GeV}) - 0.38(2)\, C_u(2\,\mathrm{GeV}) - 0.04(3)\, c_G\Big),\\
g_{ae} &\simeq \frac{m_e}{f_a}C_e(m_e),
\end{aligned}
$$

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

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

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,

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

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

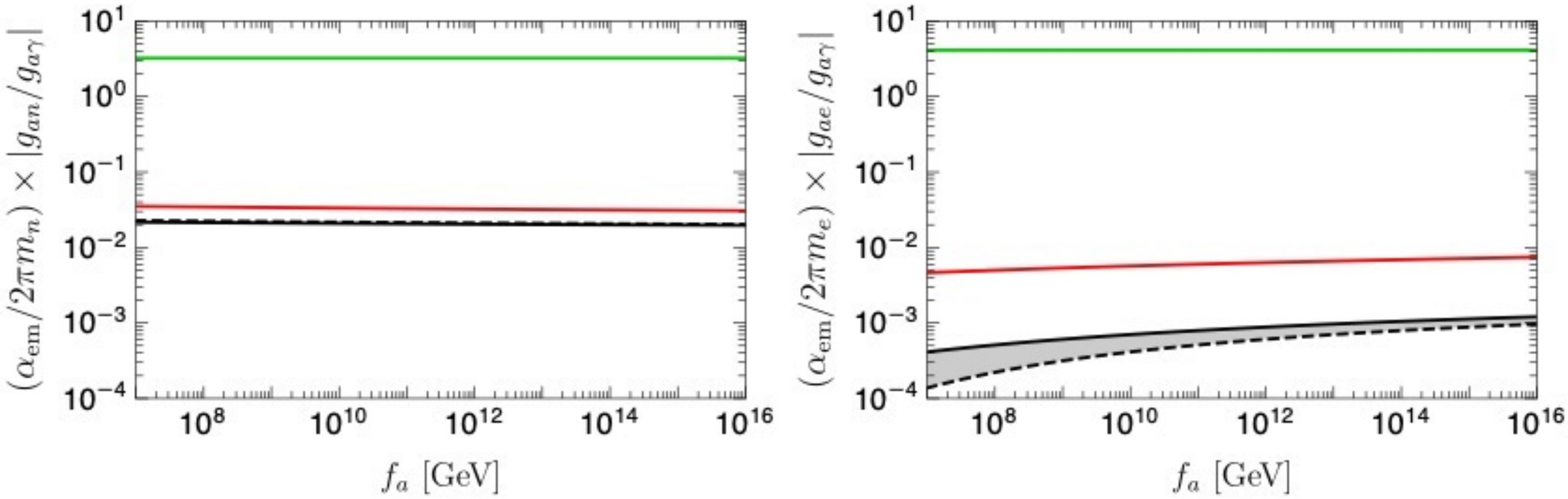
$$g_{ae} \simeq \frac{m_e}{f_a} \begin{cases} \mathcal{O}(1), & \text{DFSZ-like} \\ (c_G + 0.4 c_W + 0.15 c_B) \times 10^{-3}, & \text{KSVZ-like} \\ (c_G + 0.4 c_W + 0.15 c_B) \times 10^{-3} + \omega_I g_{\rm GUT}^2 \times 10^{-2}, & \text{String} \end{cases}$$

For the string-theoretic model, 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 models of an axion 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

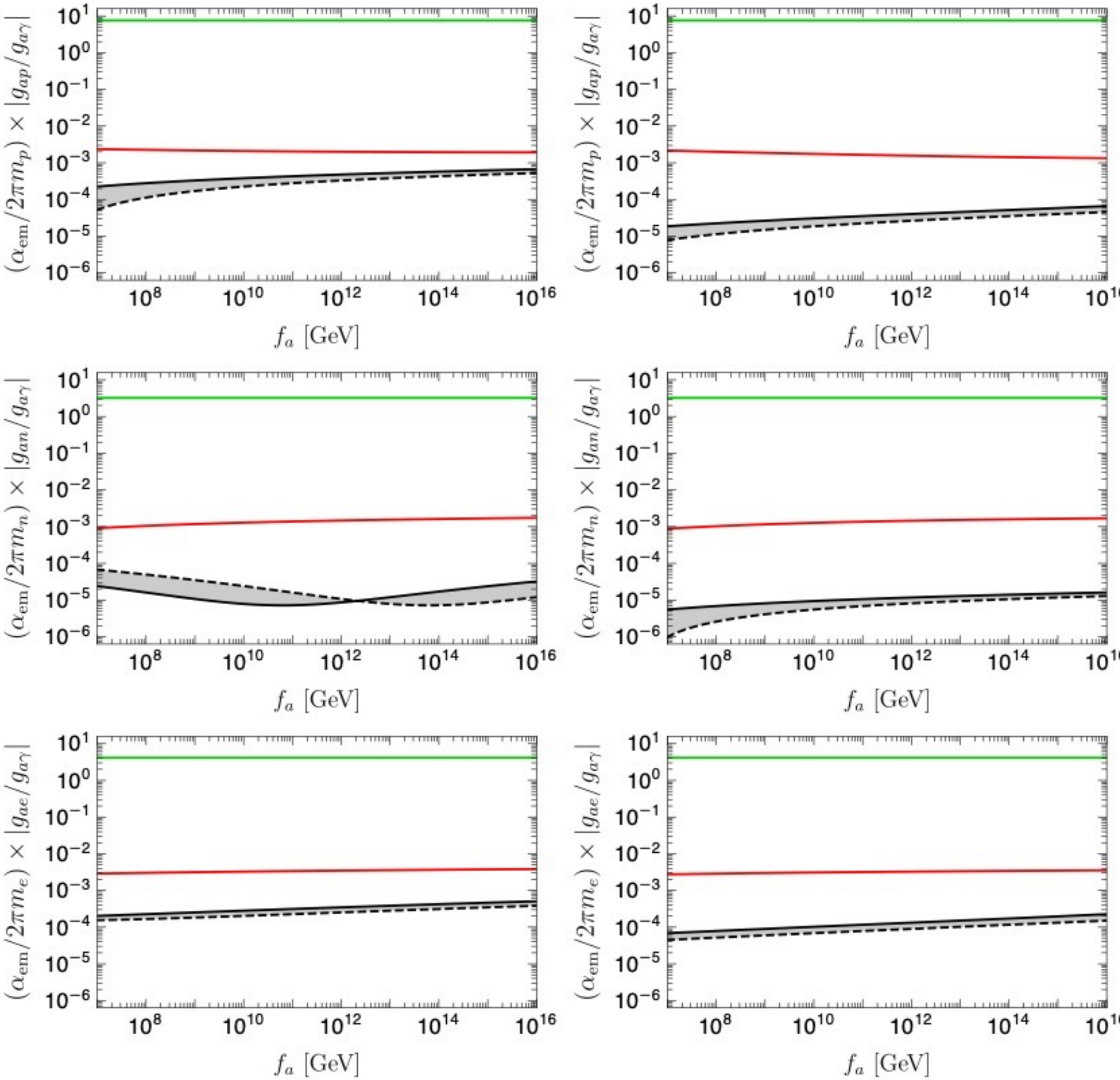


Green : DFSZ-like model (DFSZ-1 with $\tan\beta = 10$ and $m_{H^\pm} = 10$ TeV)

Red : String-theoretic model

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

For ALPs with ($c_G = 0$),



Green : DFSZ-like model

Red : String-theoretic model

Black : KSVZ-like model

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

solid : $m_Q = f_a$)

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

Summary

- 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 UV physics for axions, showing 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.
- Maurizio will continue discussion on astro/cosmological implications of running couplings of the DFSZ-QCD axions.

Part 2:

Phenomenological Implications

DFSZ axion

M. Giannotti, S. Owaka, E. Nardi, L. Di Luzio, F. Mescia, G. Piazza

GGI, May 10, 2023

Corrections to couplings

The leading contribution to the running axion couplings arises from top loop diagrams induced by the axion-top coupling C_t

$$C_\Psi(2\text{GeV}) \simeq C_\Psi(f_a) + r^t_\Psi(m_{\text{BSM}})\, C_t(f_a) \qquad (\Psi = u, d, e)$$

These can be expressed in terms of

$$\tan\beta = \frac{< H_u >}{< H_d >} = v_u/v_d \quad \Rightarrow \quad \begin{cases} C_{u,c,t} = \dfrac{1}{3}\cos^2\beta \\ C_{d,s,b} = \dfrac{1}{3}\sin^2\beta \\ C_{e,\mu,\tau} = \dfrac{1}{3}\sin^2\beta \end{cases}$$

Corrections to couplings

The leading contribution to the running axion couplings arises from top loop diagrams induced by the axion-top coupling C_t

$$C_\Psi(2\mathrm{GeV}) \simeq C_\Psi(f_a) + \underbrace{r^t_\Psi(m_{\mathrm{BSM}})\, C_t(f_a)}_{} \qquad (\Psi = u, d, e)$$

This terms measures the corrections induced from the high energy

Corrections may be significant (depend on m_{BSM} and on other parameters of the theory)

Corrections to couplings

Possible *qualitative phenomenological changes*

$$C_\Psi(2\text{GeV}) \simeq C_\Psi(f_a) + r^t_\Psi(m_{\text{BSM}})\, C_t(f_a) \qquad (\Psi = u, d, e)$$

This may be zero and yet

This may be finite

This is the case of C_e in the DFSZ axion for small $\tan\beta$

Corrections to couplings

$$C_\Psi(2\text{GeV}) \simeq C_\Psi(f_a) + \; r^t_\Psi(m_{\text{BSM}}) \; C_t(f_a) \qquad\qquad (\Psi = u, d, e)$$

$\Rightarrow$ *unavoidable additional uncertainty*

… but there are some general results

Corrections to couplings

$$C_\Psi(2\text{GeV}) \simeq C_\Psi(f_a) + r^t_\Psi(m_{\text{BSM}})\, C_t(f_a)$$

Analytical Approximations

$$\left.\begin{aligned} r^t_3(m_{\text{BSM}}) &= r^t_u - r^t_d \simeq -0.54\ln\left(\sqrt{x} - 0.52\right) \\ r^t_0(m_{\text{BSM}}) &= r^t_u + r^t_d \simeq 3.8\times 10^{-4}\ln^2\left(x - 1.25\right) \approx 0 \\ r^t_e(m_{\text{BSM}}) &\simeq -\frac{1}{2}\, r^t_3 \end{aligned}\right\} \quad \text{with } x = \log_{10}\left(\frac{m_{\text{BSM}}}{\text{GeV}}\right)$$

Corrections to couplings

$$C_\Psi(2\text{GeV}) \simeq C_\Psi(f_a) + r^t_\Psi(m_{\text{BSM}})\, C_t(f_a)$$

Analytical Approximations

$$\boxed{r^t_3(m_{\text{BSM}}) = r^t_u - r^t_d \simeq -0.54 \ln\left(\sqrt{x} - 0.52\right)}$$

Large

$$r^t_0(m_{\text{BSM}}) = r^t_u + r^t_d \simeq 3.8 \times 10^{-4} \ln^2\left(x - 1.25\right) \approx 0$$

$$r^t_e(m_{\text{BSM}}) \simeq -\frac{1}{2} r^t_3$$

with $x = \log_{10}\left(\frac{m_{\text{BSM}}}{\text{GeV}}\right)$

Corrections to couplings

$$C_\Psi(2\mathrm{GeV}) \simeq C_\Psi(f_a) + r^t_\Psi(m_{\mathrm{BSM}})\, C_t(f_a)$$

Analytical Approximations

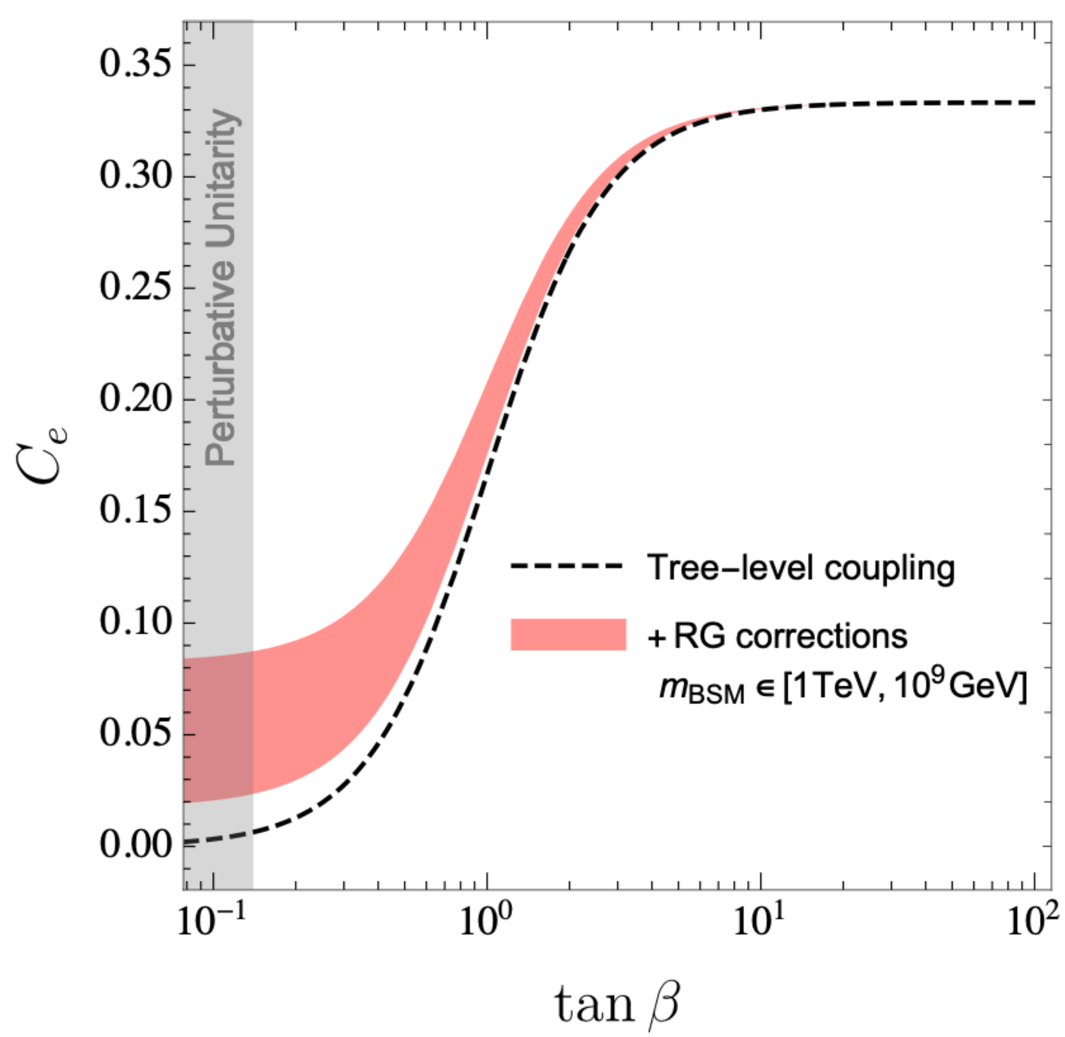
Small

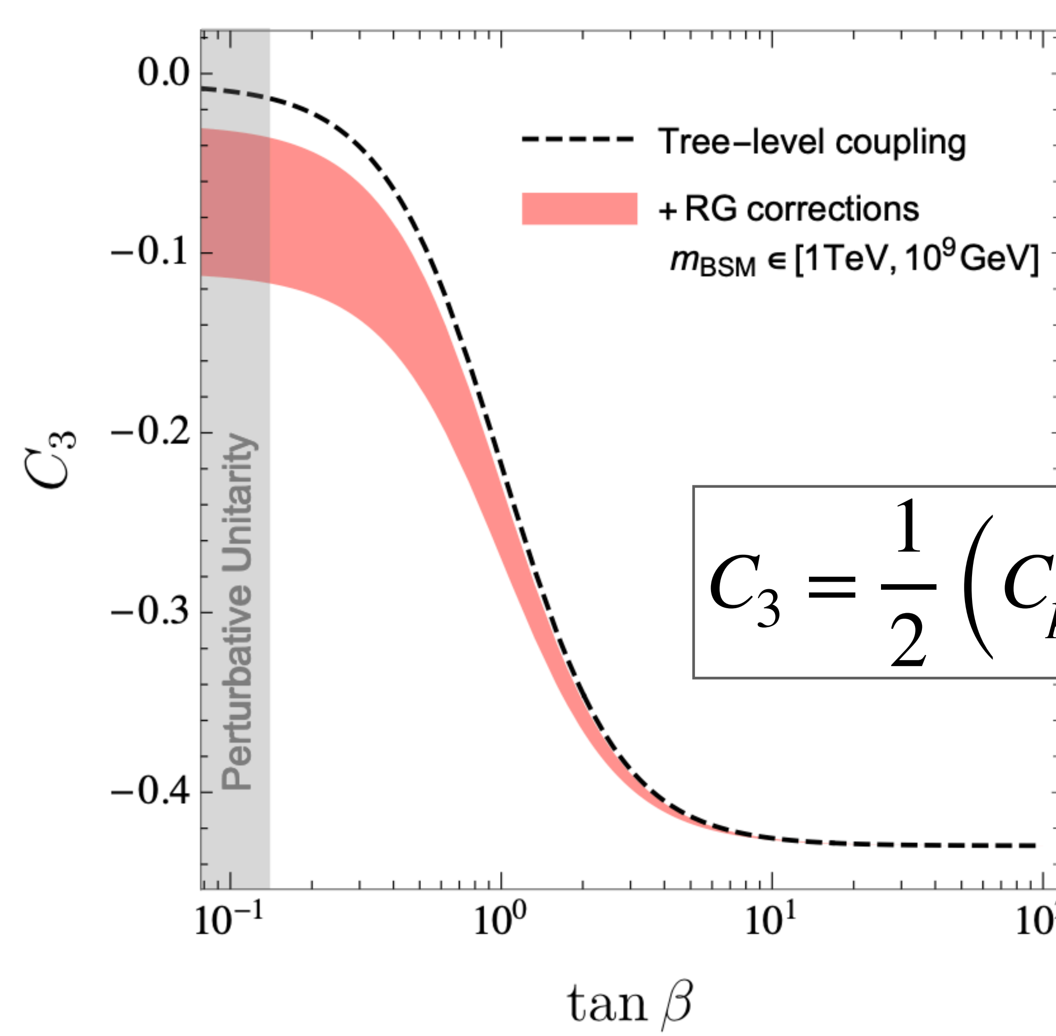
$$\left.\begin{aligned} r^t_3(m_{\mathrm{BSM}}) &= r^t_u - r^t_d \simeq -0.54 \ln\left(\sqrt{x} - 0.52\right) \\ &\boxed{r^t_0(m_{\mathrm{BSM}}) = r^t_u + r^t_d \simeq 3.8 \times 10^{-4} \ln^2\left(x - 1.25\right) \approx 0} \\ r^t_e(m_{\mathrm{BSM}}) &\simeq -\frac{1}{2} r^t_3 \end{aligned}\right\} \quad \text{with } x = \log_{10}\left(\frac{m_{\mathrm{BSM}}}{\mathrm{GeV}}\right)$$

DFSZ axions: Explicit Results

Coupling (DFSZ1)	Coupling (DFSZ2)	Approx. Correction
$C_0 \simeq -0.20$	$C_0 \simeq -0.20$	$\Delta C_0 \approx 0$
$C_3 \simeq -0.43\ \sin^2\beta$	$C_3 \simeq -0.43\ \sin^2\beta$	$\Delta C_3 \simeq -0.12\, l(x)\ \cos^2\beta$
$C_e = \frac{1}{3}\sin^2\beta$	$C_e = -\frac{1}{3}\cos^2\beta$	$\Delta C_e \simeq 0.094\, l(x)\ \cos^2\beta$
$C_\gamma = \frac{8}{3} - 1.92$	$C_\gamma = \frac{2}{3} - 1.92$	$\Delta C_\gamma = 0$

$$\boxed{l(x) = \ln\left(\sqrt{x} - 0.52\right)}$$





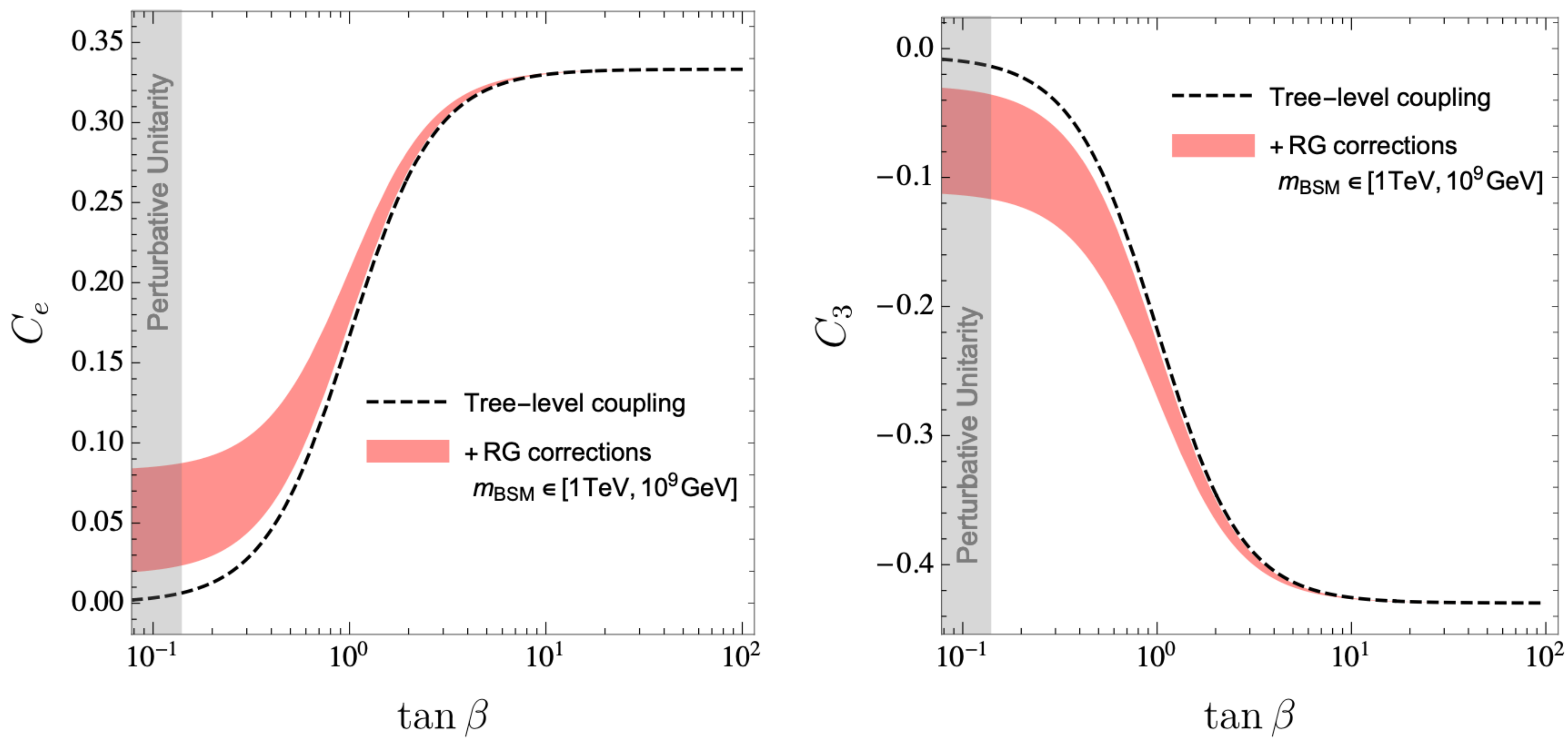
$$\boxed{C_3 = \frac{1}{2}\left(C_p - C_n\right)}$$

DFSZ axions

Coupling (DFSZ1)	Coupling (DFSZ2)	Approx. Correction
$C_0 \simeq -0.20$	$C_0 \simeq -0.20$	$\Delta C_0 \approx 0$
$C_3 \simeq -0.43\,\sin^2\beta$	$C_3 \simeq -0.43\,\sin^2\beta$	$\Delta C_3 \simeq -0.12\,l(x)\,\cos^2\beta$
$C_e = \frac{1}{3}\sin^2\beta$	$C_e = -\frac{1}{3}\cos^2\beta$	$\Delta C_e \simeq 0.094\,l(x)\,\cos^2\beta$
$C_\gamma = \frac{8}{3} - 1.92$	$C_\gamma = \frac{2}{3} - 1.92$	$\Delta C_\gamma = 0$

Corrections vanish at large $\tan\beta$

$$\boxed{l(x) = \ln\left(\sqrt{x} - 0.52\right)}$$

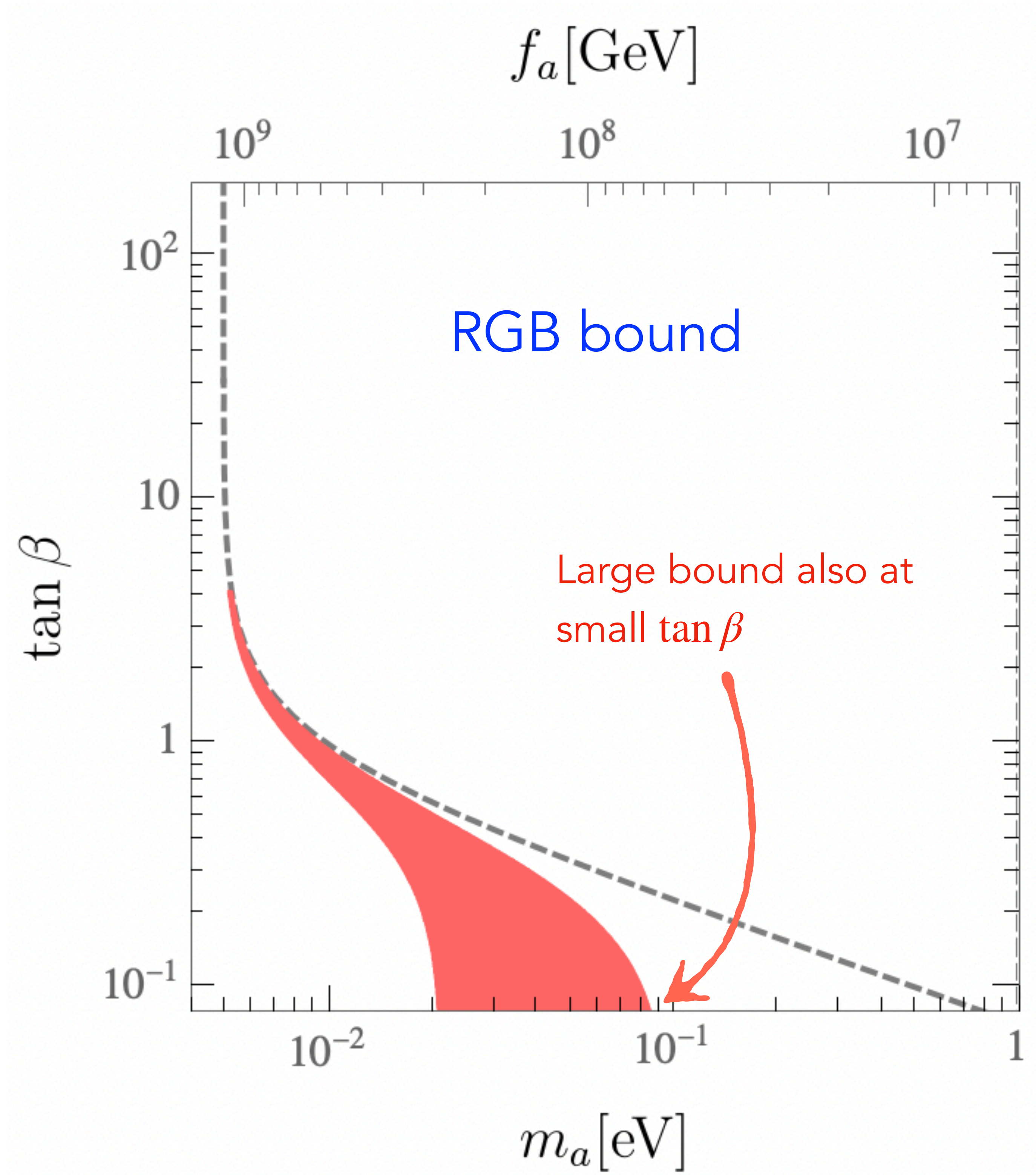


Red Giant Branch (RGB) bound

$$|C_e| \leq 1.65 \times 10^{-3} \left(\frac{m_a}{\mathrm{eV}}\right)^{-1}$$

Update to the latest published results

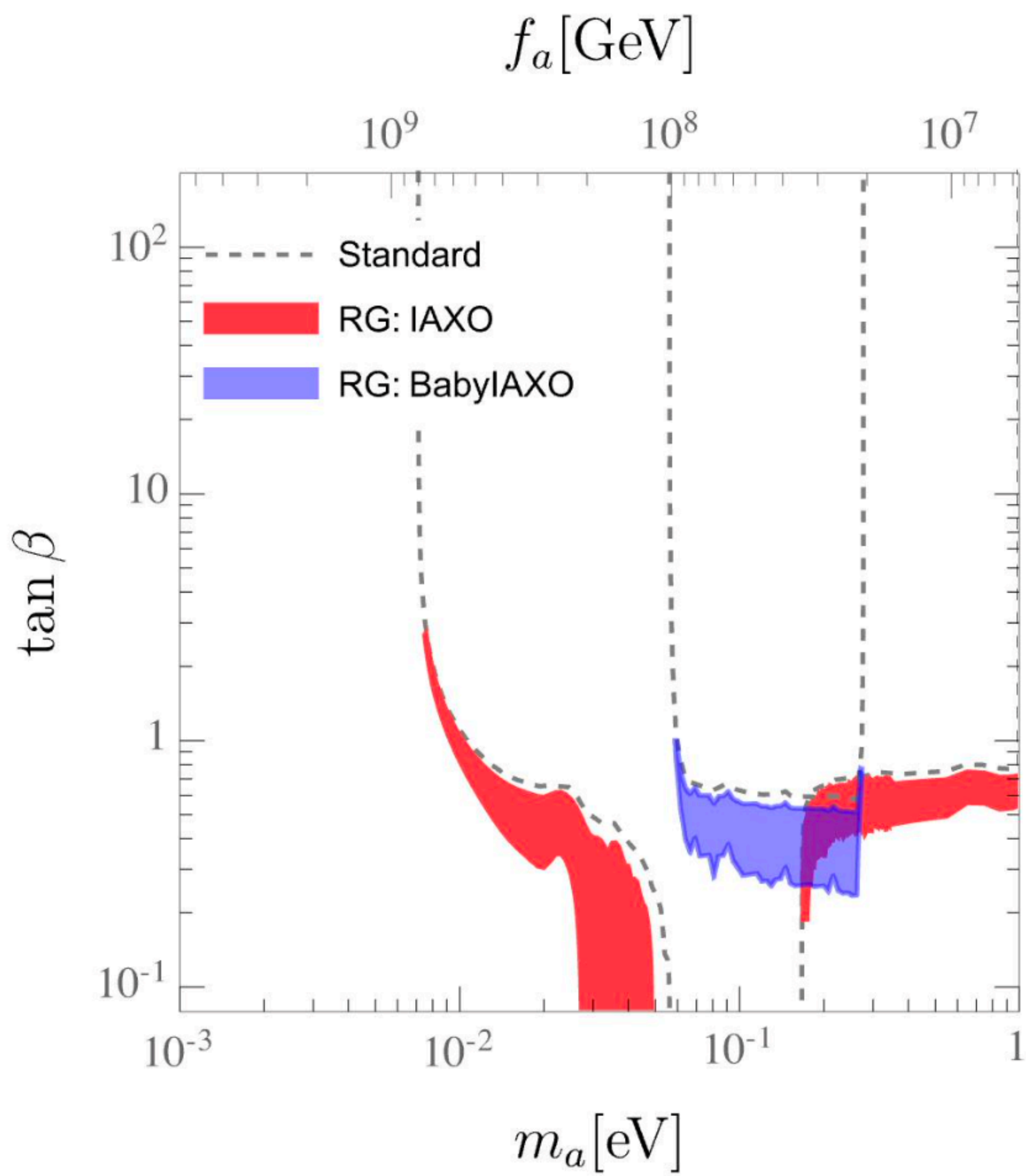
[there are, however, more stringent results.
⇒ O. Straniero Talk]



Detection of DFSZ axions

The solar flux of DFSZ axions has *always* a g_{ae} component.

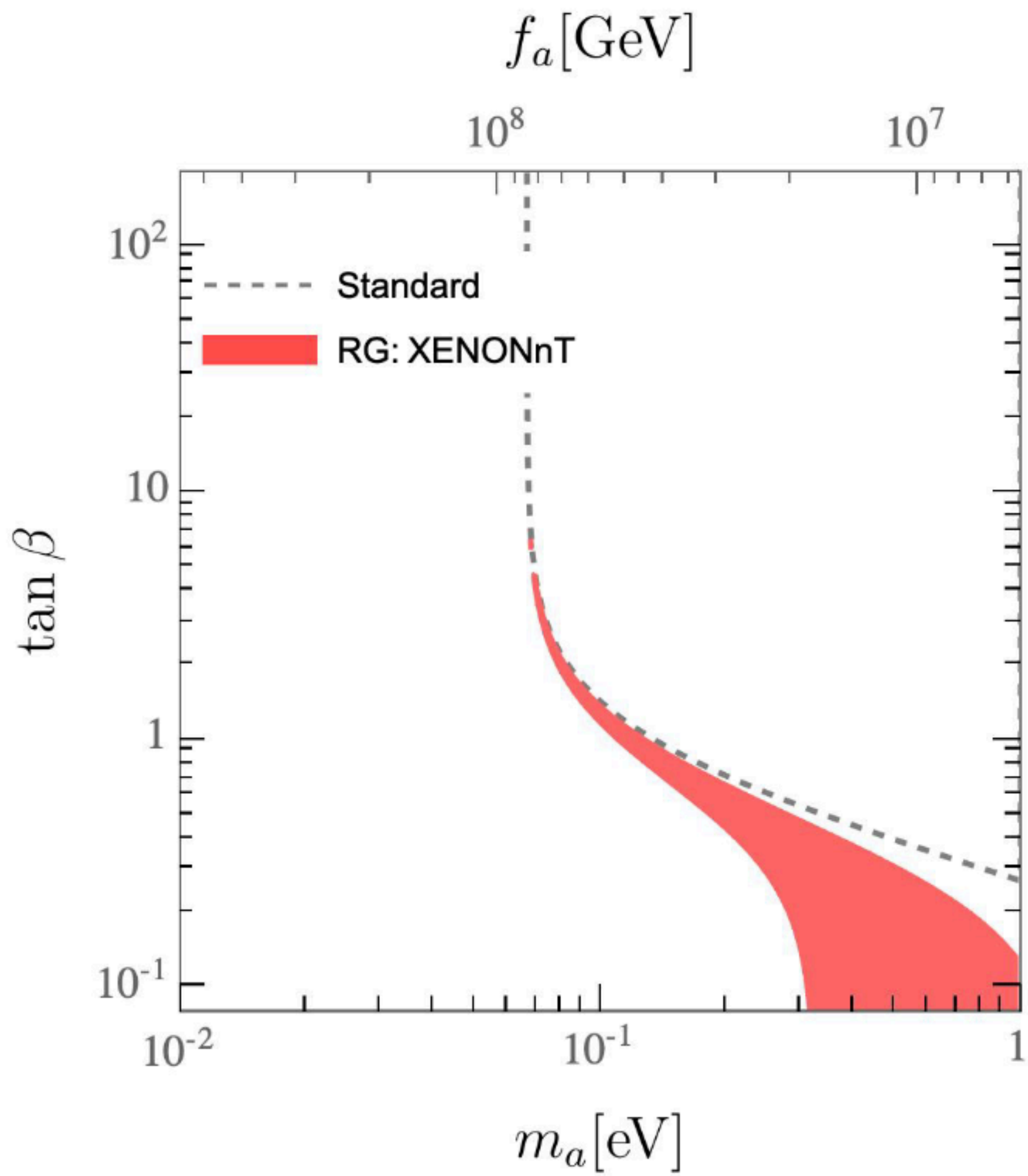
The helioscope detection potential is *necessarily* higher than expected



Detection of DFSZ axions

The solar flux of DFSZ axions has *always* a g_{ae} component.

The helioscope detection potential is *necessarily* higher than expected



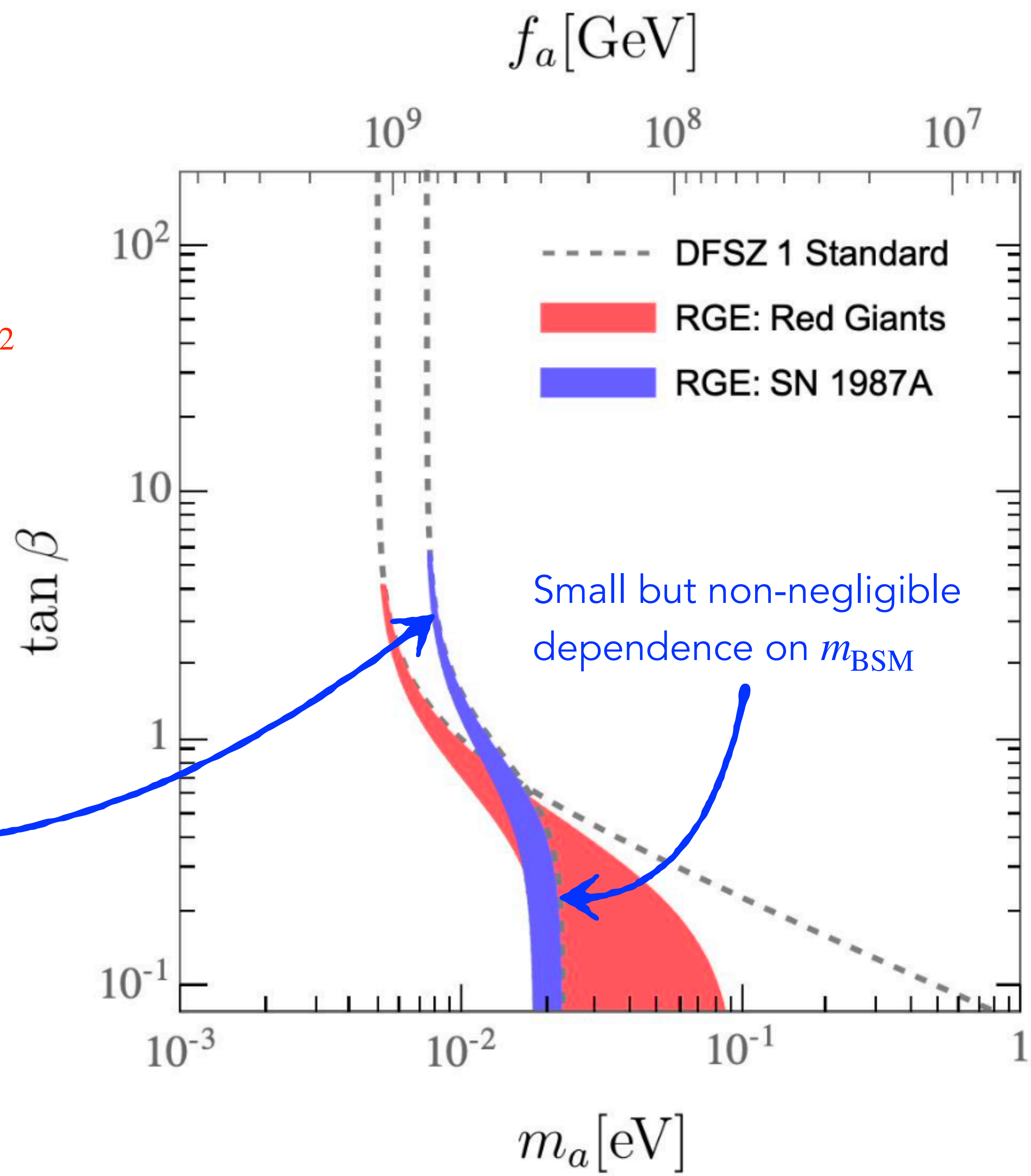
Supernova (SN) bound

⇒ G. Lucente talk,

$$C_{\rm SN} \simeq 1.4\left(C_0^2 + 0.11\, C_0 C_3 + 1.3\, C_3^2\right)^{1/2}$$

This translates in the bound

$$m_a \leq \frac{\bar{m}}{C_{\rm SN}}, \quad \text{with} \quad \bar{m} \sim 5\,\text{meV}$$

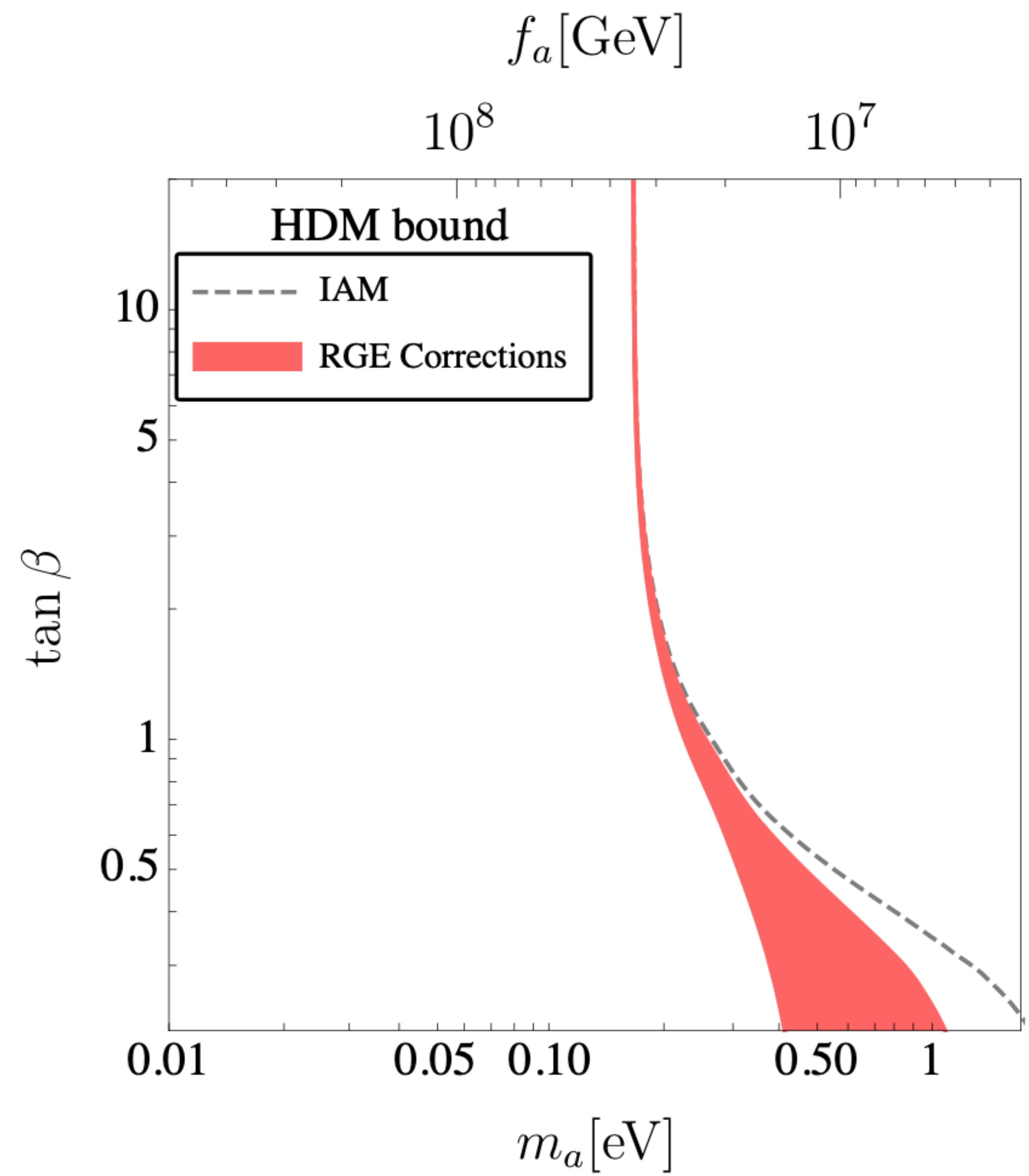


The C_3 dependence comes mostly (not exclusively) from pion interactions.

Hot DM bound

Axion-pion coupling $\propto C_3$, receives large corrections.

$\Rightarrow$ the HDM bound depends on the unknown m_{BSM} scale



Unitarized thermal rate based on the Inverse Amplitude Method

[L.DiLuzio, J.Martin Camalich, G.Martinelli, J.A. Oller, G. Piazza (2023)]

Conclusions

- Radiative corrections may modify significantly the coupling for specific models and hence their phenomenology.

- In an age where the axion detection is a realistic possibility, we should take into account such theoretical effects in assessing the instrument sensitivities and phenomenological constraints.