Renormalization group effects in non-universal DFSZ axion models

Shohei Okawa

(Universitat de Barcelona/ICCUB)

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in collaboration with Luca Di Luzio, Federico Mescia, Enrico Nardi

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Strong CP problem

- CP symmetry is violated in QCD:

$$\mathscr{L}_{\rm QCD} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \theta\,\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_q \bar{q}\, i\gamma^\mu D_\mu\, q - (\bar{q}_L M_q\, e^{i\theta_q} q_R + h.c)$$

  - Rotate away quark mass phases by chiral transformation:

$$q \to e^{-i\gamma_5\theta_q/2}\, q \quad \Rightarrow \quad \theta \to \bar{\theta} \equiv \theta + \sum_q \theta_q$$

  - From neutron EDM measurements: $|\bar{\theta}| \lesssim 10^{-10}$ Unnaturally small

Peccei-Quinn mechanism and axion

- Add a complex scalar to restore chiral symmetry of quarks:

Peccei, Quinn (1977)
Weinberg (1978), Wilczek (1978)

$$\mathscr{L}_{\rm PQ} = -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \theta\,\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_q \bar{q}i\gamma^\mu D_\mu q - (y\,\bar{q}_L\,\phi\,q_R + h.c.)$$

<u>PQ symmetry</u>

$$\begin{cases} q \to e^{i\gamma_5\theta_q/2}\,q \\ \phi \to e^{-i\theta_q}\,\phi \end{cases}$$

- θ can be rotated away by using this chiral symmetry: $\theta \to 0$
- In the quark mass basis,

$$\begin{cases} \phi \to f_a\,e^{ia(x)/f_a} \\ q \to e^{-i\gamma_5 a(x)/2f_a}\,q \end{cases} \Rightarrow \delta\mathscr{L}_{\rm PQ} = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} \Rightarrow \langle a/f_a\rangle = 0$$

θ is promoted to a dynamical field (axion)!

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■ Weinberg-Wilczek axion:

$$\mathscr{L}_{\mathrm{2HDM}} \sim -y_u\,\bar{q}_L\,H_u\,u_R - y_d\,\bar{q}_L\,H_d\,d_R - V(H_u, H_d)$$

- axion = CP odd Higgs
- $f_a \sim v_{\mathrm{EW}}$

$$\Rightarrow \mathrm{Br}(K^+ \to \pi^+ a) \sim \frac{f_\pi^2}{f_a^2} \times \mathrm{Br}(K^+ \to \pi^+\pi^0) \sim 10^{-5}$$

readily excluded

Benchmark (invisible) axion models

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- DFSZ model Zhitnitsky (1980), Dine, Fischler, Srednicki (1981)

$$\mathscr{L}_{\mathrm{DFSZ}} \sim -\, y_u\, \bar{q}_L\, H_u\, u_R - y_d\, \bar{q}_L\, H_d\, d_R - V(H_u, H_d) \,+\, H_u H_d\, (S^*)^2$$

  - SM quarks, leptons and two Higgs doublets are PQ charged
  - PQ symmetry broken mostly by a singlet scalar: $\langle S \rangle \sim f_a \gg v_{\mathrm{EW}}$

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- **KSVZ model** Kim (1979), Shifman, Vainshtein, Zakharov (1980)
  - all SM fields are PQ neutral
  - new quarks and a singlet scalar are PQ charged

$$\mathscr{L}_{\mathrm{KSVZ}} \sim \bar{Q}_L\, Q_R\, S \qquad \text{PQ symmetry:} \begin{cases} Q \to e^{i\gamma_5 \alpha}\, Q \\ S \to e^{-2i\alpha}\, S \end{cases}$$

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- Axion-gluon coupling:
  (Defining interaction)

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$f_a = f/(2N)$

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$$\frac{C_{aN}}{2f_a}\partial_\mu a\, \bar{N}\gamma_\mu\gamma_5 N \qquad (N = p, n)$$

$$C_{aN} = c^0_{u,d}(X_{u,d}) + F(m_{u,d})$$

$$\frac{C_{ae}}{2f_a}\partial_\mu a\, \bar{e}\gamma_\mu\gamma_5 e$$

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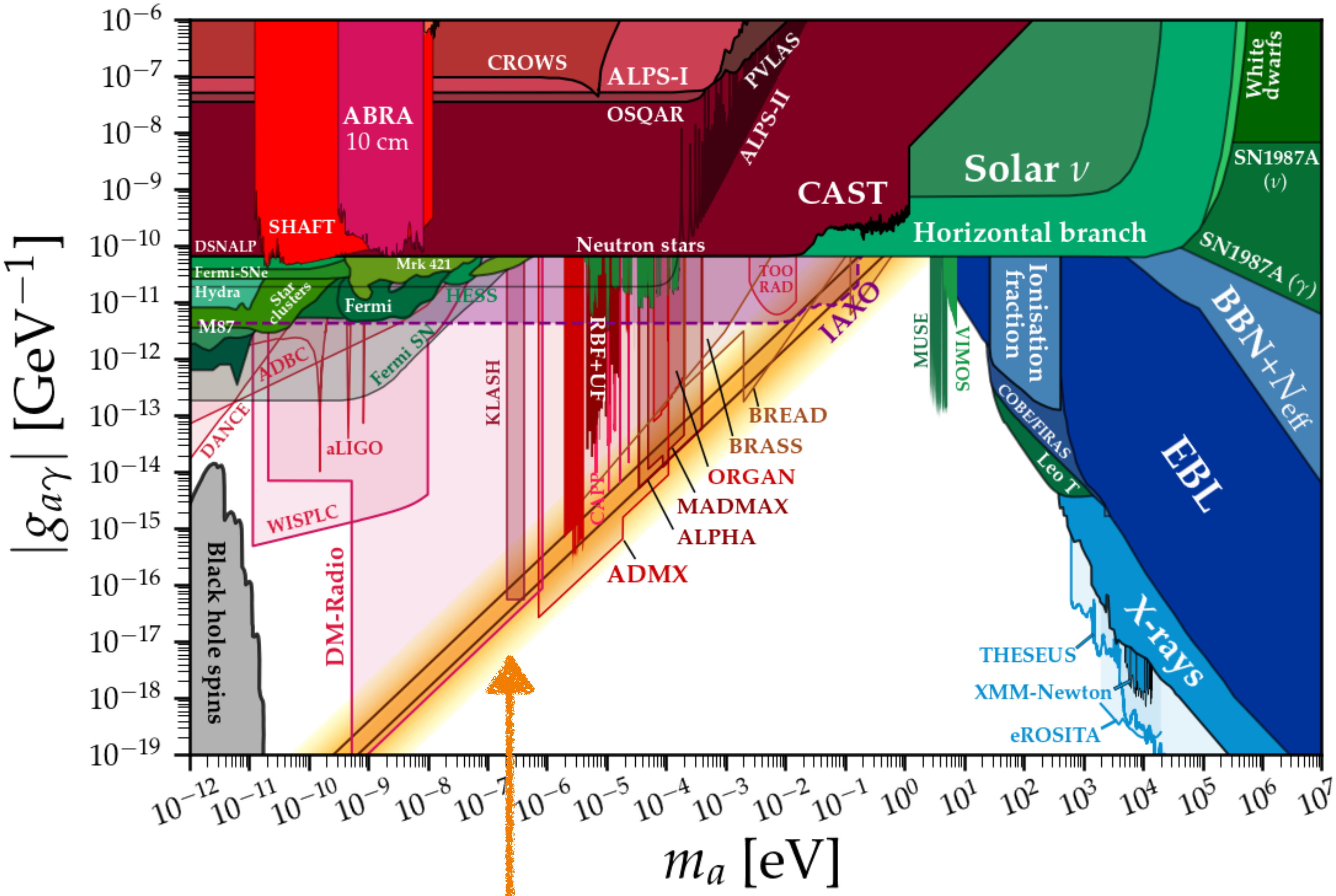
In canonical KSVZ/DFSZ models, these couplings relate each other: $C_{a\gamma} \leftrightarrow C_{aN}, C_{ae}, f_a\,(m_a)$

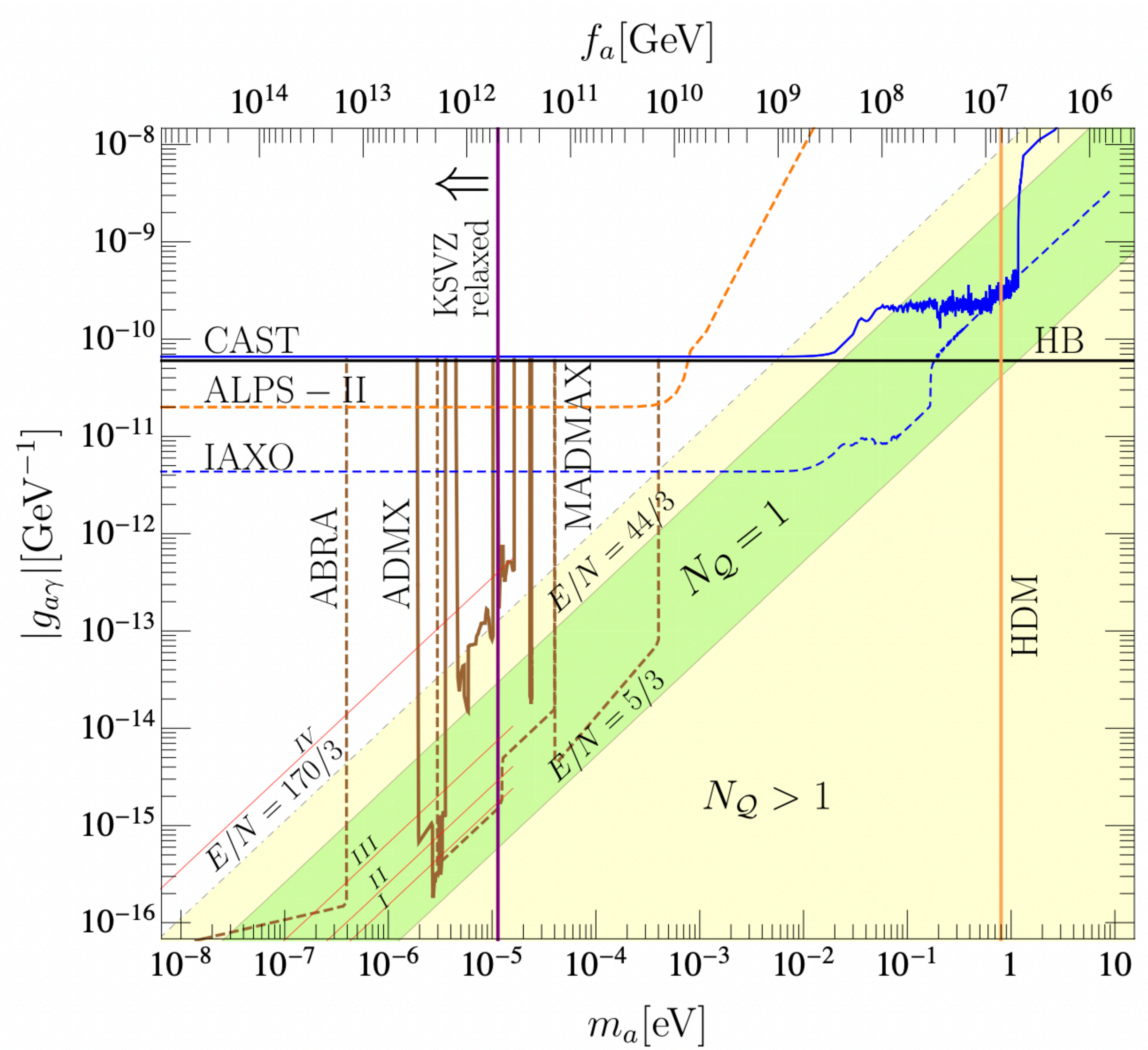
Traditional axion limits: $(m_a\,, g_{a\gamma})$ plots



'Canonical' axion window

Figure from AxionLimits
[https://cajohare.github.io/AxionLimits/]

Cosmo/astro bounds in the canonical axion window



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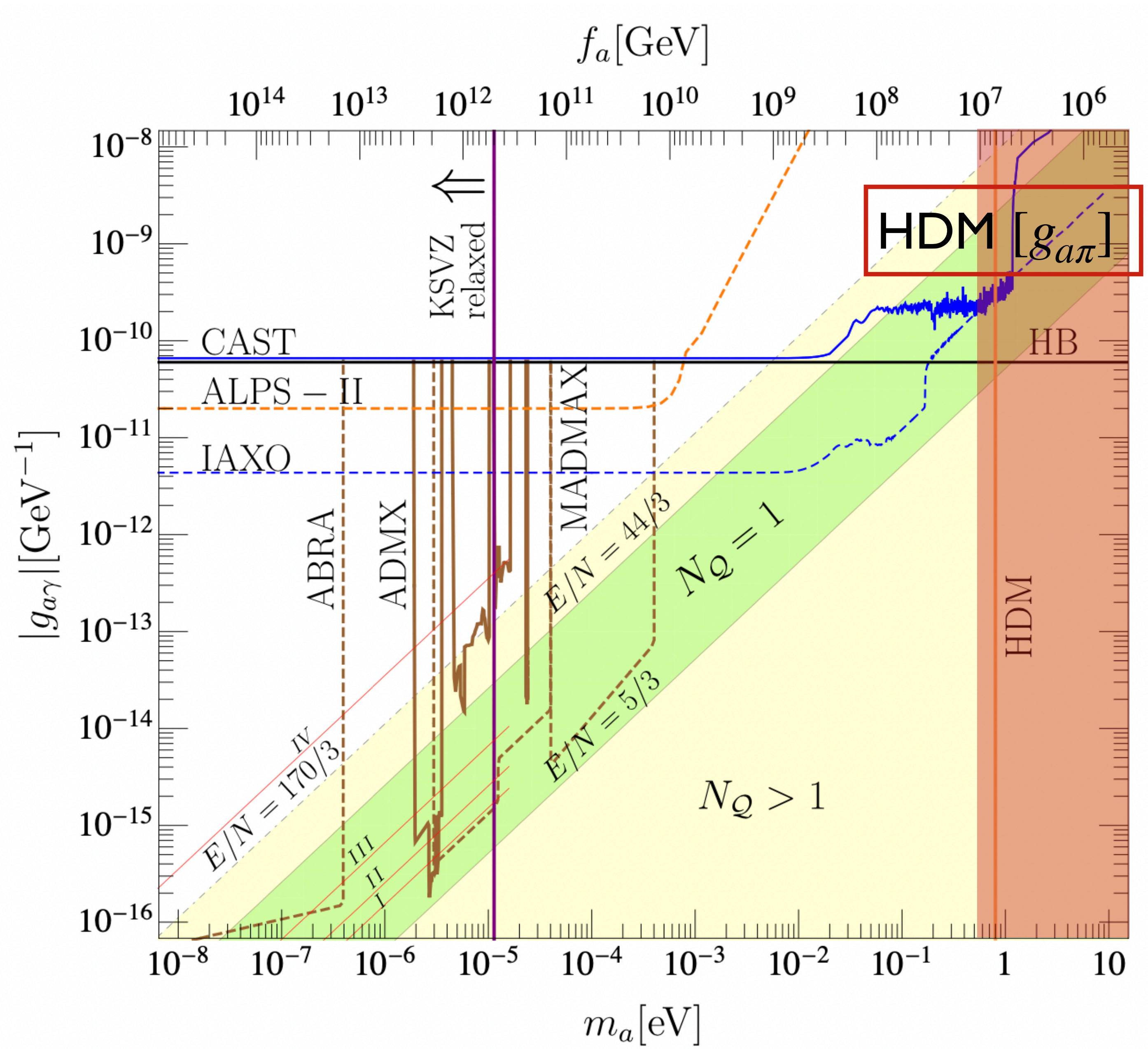

*These bounds depend on model construction in fact. The above bound holds only within a specific DFSZ model.

- **Hot dark matter ($a\pi \leftrightarrow \pi\pi$):**

$$g_{a\pi} \sim (f_\pi f_a)^{-1} \lesssim 2 \times 10^{-7}\,\text{GeV}^{-2}$$

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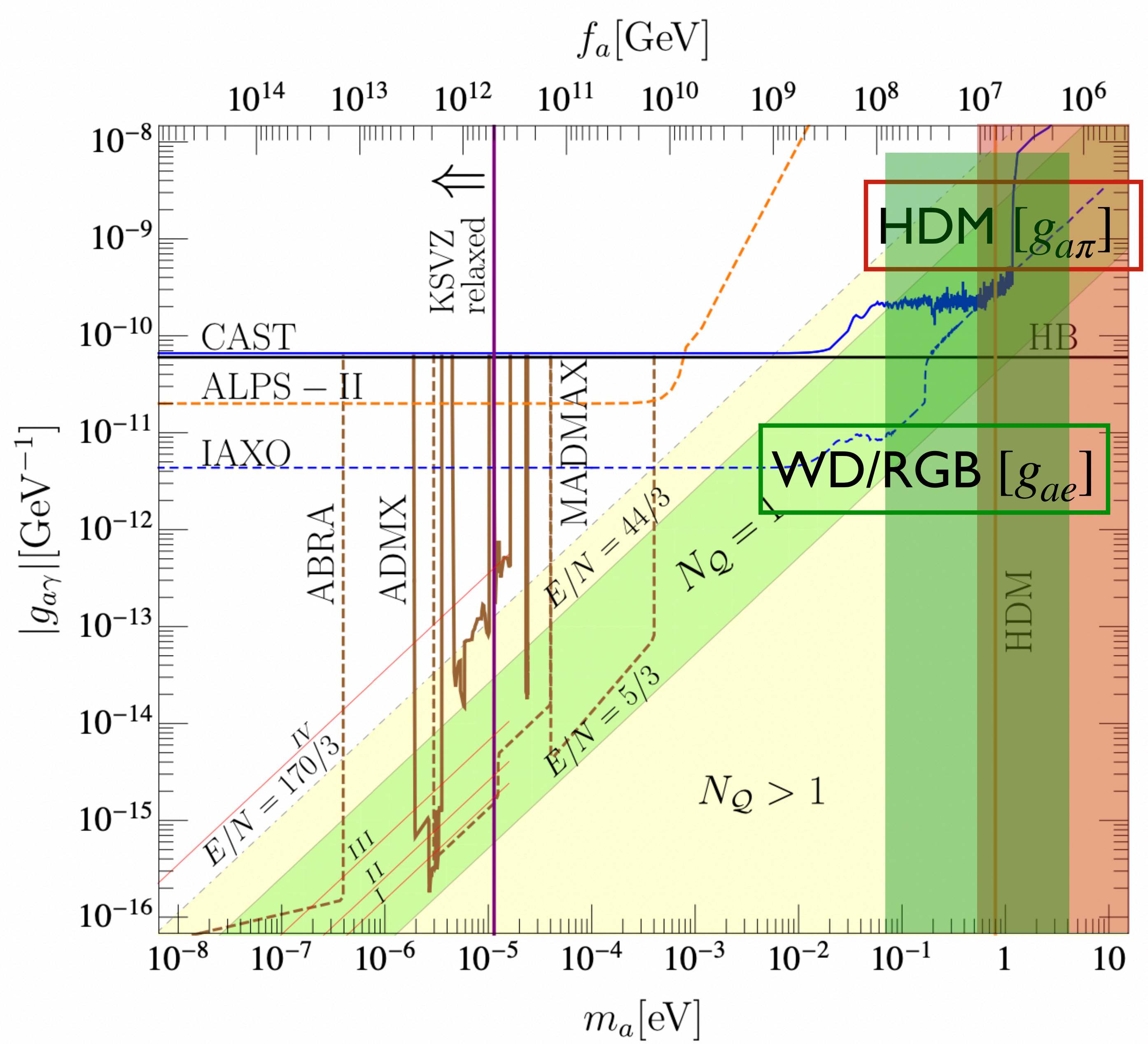

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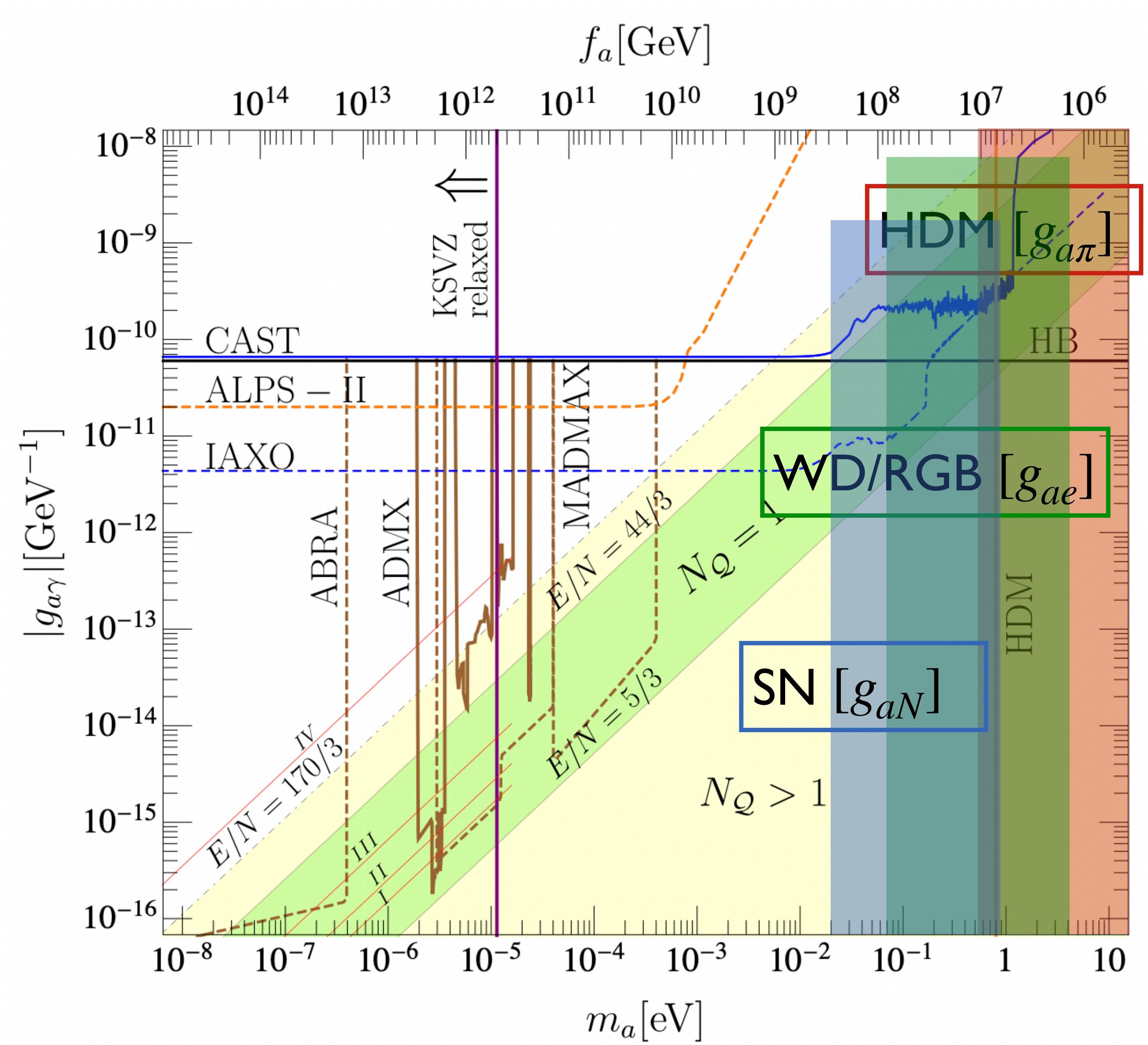

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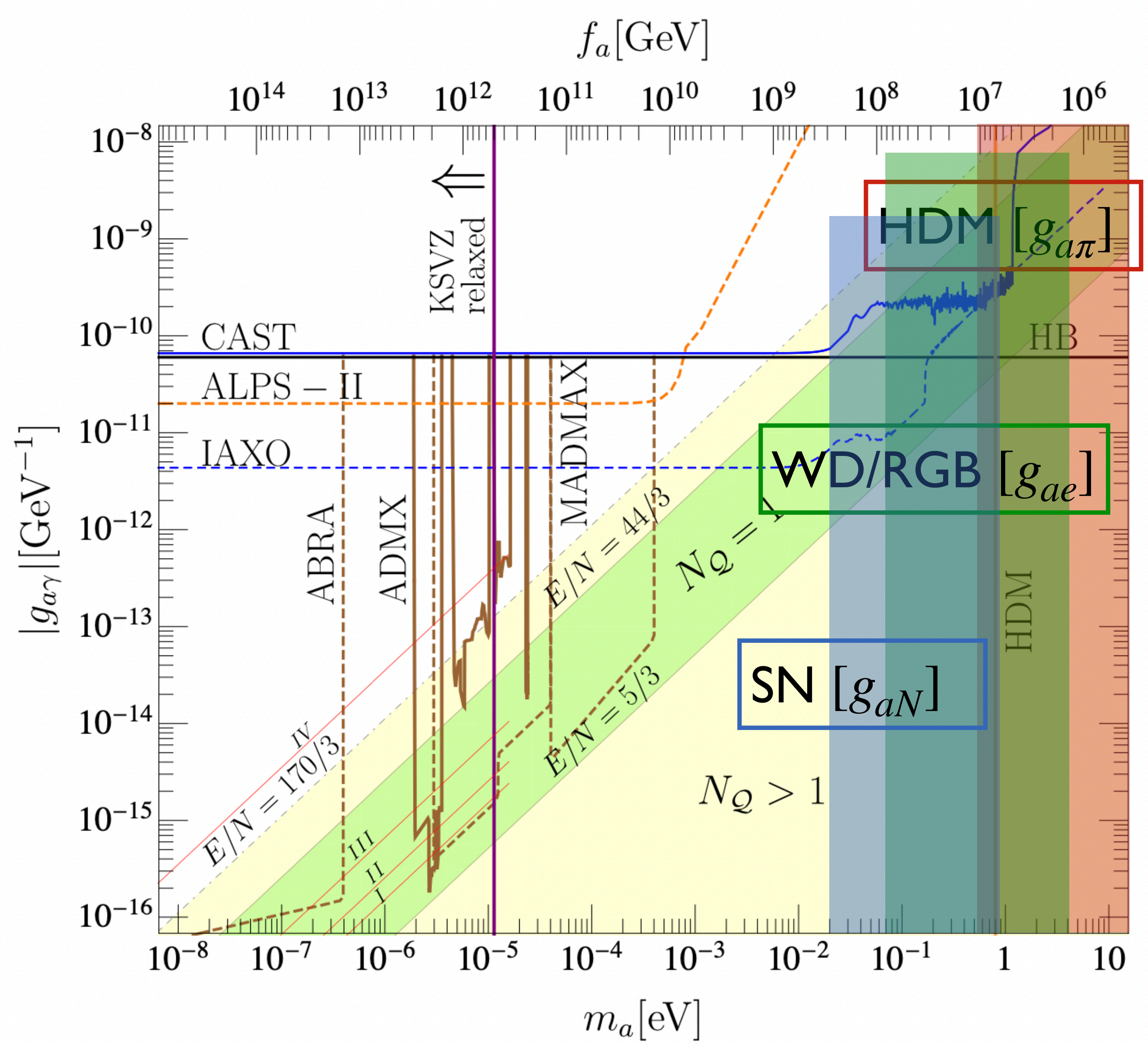

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Canonical axion models are strongly constrained by astrophysics and cosmology

Nucleo/electrophobic axions
in non-universal DFSZ models

Nucleophobic axion

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$$C_N \frac{\partial_\mu a}{2f_a} \bar{N}\gamma_\mu\gamma_5 N \longleftarrow \frac{\partial_\mu a}{2f_a} c_q \bar{q}\gamma_\mu\gamma_5 q, \quad \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G} \qquad \text{@ QCD scale}$$

$$C_p + C_n = (c_u + c_d - 1)(\Delta_u + \Delta_d) - 2\delta_s$$

$$C_p - C_n = (c_u - c_d - f_{ud})(\Delta_u - \Delta_d)$$

- Hadronic matrix elements:

  $2s^\mu \Delta_q \equiv \langle N | \bar{q}\gamma^\mu\gamma_5 q | N \rangle$

- $f_{ud} = (m_d - m_u)/(m_d + m_u)$
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Thus, independently of the matrix elements and axion model construction

Nucleophobia conditions:

(1) $C_p + C_n \approx 0 \;\Rightarrow\; c_u + c_d \approx 1$

(2) $C_p - C_n \approx 0 \;\Rightarrow\; c_u - c_d \approx f_{ud} \approx 1/3 \quad (\because m_d/m_u \approx 2)$

Closer look at the nucleophobic conditions (1/2)

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- Two structures:

$$(a)\ 2+1 : \ N_1 = N_2 = -N_3 \quad \text{or} \quad N = N_1\,,\ N_2 = N_3 = 0$$

$$(b)\ 1+1+1 : \ N_2 = -N_3\,,\ N = N_1 \neq N_{2,3}$$

Hindmarsh, Moulatsiotis (1997)
Di Luzio, Mescia, Nardi, Panci, Ziegler (2018)
Björkeroth, Di Luzio, Mescia, Nardi (2018)

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Alves, Weiner (2017), Alves (2020)
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a specific VEV ratio of two Higgs doublets $H_{1,2}$

- Yukawa structure:

$$\bar{q}_L H_i q_R \;\Rightarrow\; X_{q_R} - X_{q_L} = -X_i$$

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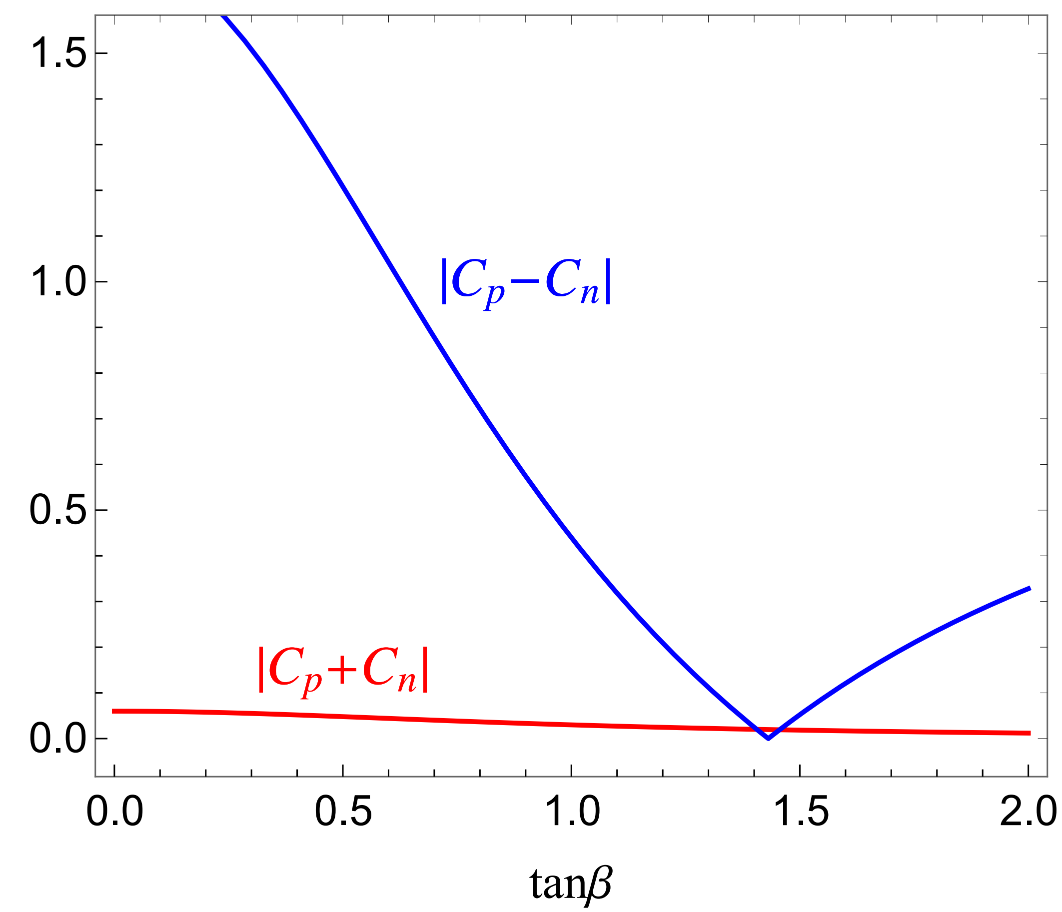

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$$\sum_i X_i v_i^2 = 0$$

$$\Rightarrow \quad X_3 = (3\cos^2\beta_1 - 1)\cos^2\beta_2$$

$$\tan\beta_1 = v_2/v_1, \ \ \tan\beta_2 = v_3/\sqrt{v_1^2 + v_2^2}$$

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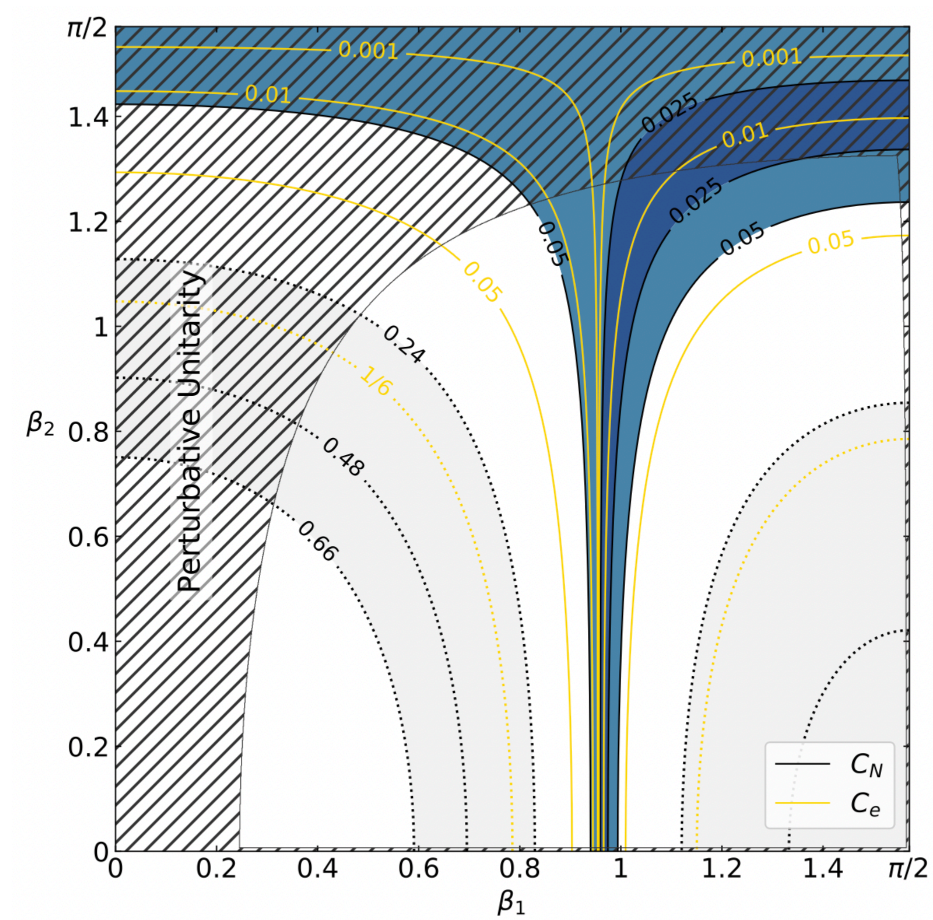

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- Nucleo/electrophobia is implemented by imposing

$$(1)\ c_u + c_d \approx 1:$$ non-universality of quark PQ charges

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  - ➡ No, the axion astrophobia survives after taking the RG corrections into account

Di Luzio, Mescia, Nardi, SO (2022)

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  - complete set of one-loop anomalous dimensions Choi, Im, Park, Yun (2017); Choi, Im, Kim, Seong (2021)
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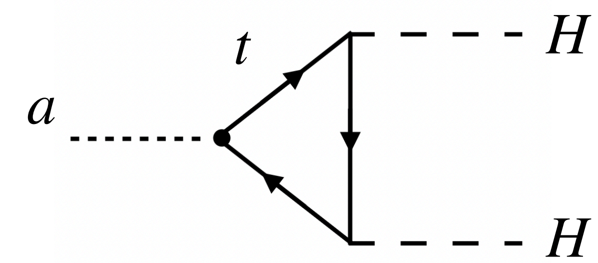
- Points:

1. Top-loop dominates the running:



$$\frac{\partial_\mu a}{f}(H^\dagger i D_\mu H) \rightarrow \frac{\partial_\mu a}{f} \sum_{\psi=q_L,u_R,\ldots} \beta_\psi \bar{\psi}\gamma_\mu \psi \qquad (\beta_\psi = Y_\psi / Y_H)$$

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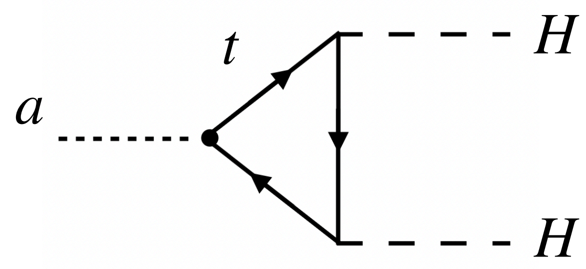
- RG evolution of axion couplings has been examined in detail
  - complete set of one-loop anomalous dimensions Choi, Im, Park, Yun (2017); Choi, Im, Kim, Seong (2021)
  - including threshold corrections at the weak scale Bauer, Neubert, Renner, Schäuble, Thamm (2020)
  - application to flavour physics of ALPs Bauer, Neubert, Renner, Schäuble, Thamm (2021)

- Points:



1. Top-loop dominates the running:

$$\frac{\partial_\mu a}{f}(H^\dagger i D_\mu H) \;\to\; \frac{\partial_\mu a}{f}\sum_{\psi=q_L,u_R,\ldots}\beta_\psi \bar\psi\gamma_\mu\psi \qquad (\beta_\psi = Y_\psi/Y_H)$$

2. The leading contribution is universal for u, d, e except for the sign difference originating from weak isospin:

$$c_u(\mu) \simeq c_u^0(\Lambda) - \kappa_t(\mu,\Lambda)\, c_t^0(\Lambda)$$

$$c_{d,e}(\mu) \simeq c_{d,e}^0(\Lambda) + \kappa_t(\mu,\Lambda)\, c_t^0(\Lambda) \qquad [\kappa_t \approx 30\,\% \ \text{for} \ \mu = 2\,\mathrm{GeV},\ \Lambda = 10^{10}\,\mathrm{GeV}]$$

RG effects on astrophobia (1/2)

- Modification to the astrophobic conditions:

$$(1)\ c_u + c_d \simeq c_u^0 + c_d^0 = 1$$ unaffected

$$(2)\ c_u - c_d \simeq c_u^0 - c_d^0 - f_{ud} - 2\kappa_t c_t^0 \approx f_{ud}$$

$$(3)\ c_e \simeq c_e^0 + \kappa_t c_t^0 \approx 0$$

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Nucleophobia: $$X_3 = \frac{\frac{1}{2}(1 - 3f_{ud}) + \kappa_t}{1 - \kappa_t}$$

Electrophobia: $$X_3 = \frac{\kappa_t}{1 - \kappa_t}$$

Given $f_{ud} \sim 1/3$, perhaps unexpectedly,
axion astrophobia is stable against the RG corrections

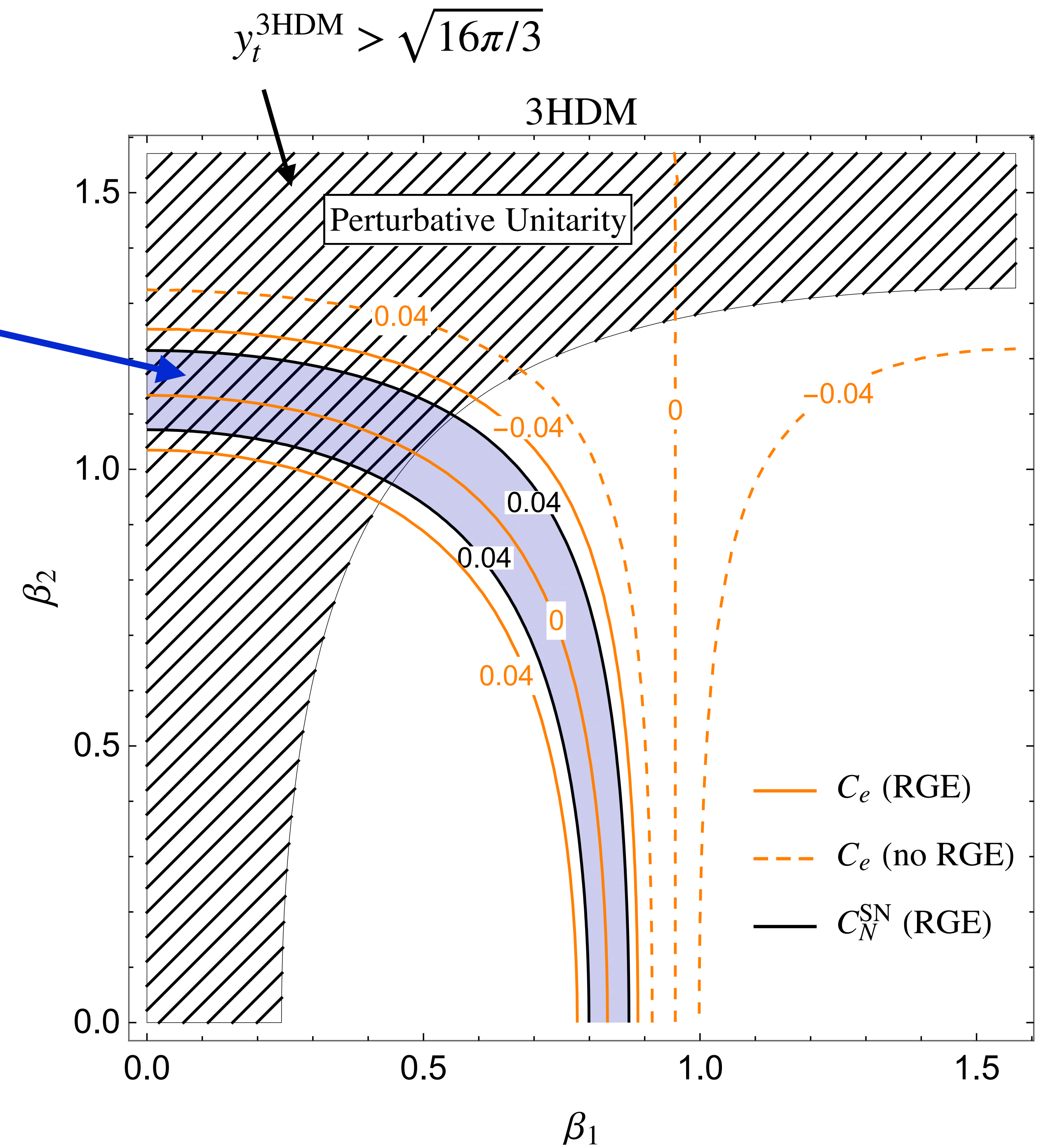
RG effects on astrophobia (2/2)

- Nucleo/electrophobic parameter space in terms of two VEV ratios:

$$\tan\beta_1 = v_2/v_1, \quad \tan\beta_2 = v_3/\sqrt{v_1^2 + v_2^2}$$

$$C_N^{\rm SN} \equiv (C_n^2 + 0.61 C_p^2 + 0.53 C_p C_n)^{1/2} < 0.04$$

Carenza, Fischer, Giannotti, Guo, Martínez-Pinedo, Mirizzi (2020)



- Numerically solve the full set of RGEs including all sub-leading contributions and threshold corrections at the weak scale
- Axion astrophobia survives in a certain parameter space
- The only modification is a shift of the astrophobic parameter space

Di Luzio, Mescia, Nardi, SO (2022)

Summary

- Unconventional axion models draw an attention
  - QCD axion window is larger than what we thought $\rightarrow$ axion "zoo"

- Astrophobic axion models
  - Axion couplings to nucleon and electron can be suppressed by generation dependent PQ charge assignment
  - Astrophobic feature keeps holding after taking the RG corrections into account
  - Further application to other variant axion models would be important