Renormalization group effects in non-universal DFSZ axion models

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based on arXiv: 2205.15326 [hep-ph]

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

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Strong CP problem

- CP symmetry is violated in QCD:

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

  - physical combination: $\bar{\theta} \equiv \theta + \sum_q \theta_q$
  - neutron EDM measurements: $|\bar{\theta}| \lesssim 10^{-10}$

    => why so small?

Peccei-Quinn mechanism and axion

- Promote θ to a dynamical field (*axion*) Peccei, Quinn (77)

$$\theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} \to \frac{a}{f_a} \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

  - a shift symmetry: $a \to a + \alpha f_a$
  - CP symmetry preserved in QCD vacuum: $\langle a \rangle = 0$

- Weinberg-Wilczek axion (78)

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

  - axion = CP odd Higgs
  - $f_a \sim v_{\text{EW}} \Rightarrow \text{Br}(K^+ \to \pi^+ a) \sim \frac{f_\pi^2}{f_a^2} \times \text{Br}(K^+ \to \pi^+\pi^0) \sim 10^{-5}$ readily excluded

Benchmark (invisible) axion models

- **DFSZ model** Zhitnitsky (80), Dine, Fischler, Srednicki (81)

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

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

- **KSVZ model** Kim (79), Shifman, Vainshtein, Zakharov (80)
  - all SM fields are PQ neutral
  - new quarks and a singlet scalar are PQ charged

$$\mathscr{L}_{\rm KSVZ} \sim \bar{Q}_L Q_R S \qquad (\text{PQ symmetry: } Q \to e^{i\gamma_5 \alpha} Q, \quad S \to e^{-2i\alpha} S)$$

Axion couplings to matter and radiation

$$\frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

$$\frac{\alpha}{8\pi f_a} C_{a\gamma}\, a F\tilde{F}$$

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

- Defining interaction: $f_a = f/(2N)$
- N : PQ-QCD anomaly
- f : PQ breaking scale

- $C_{a\gamma} = \frac{E}{N} - 1.92$

(EM anomaly + π^0 mixing)

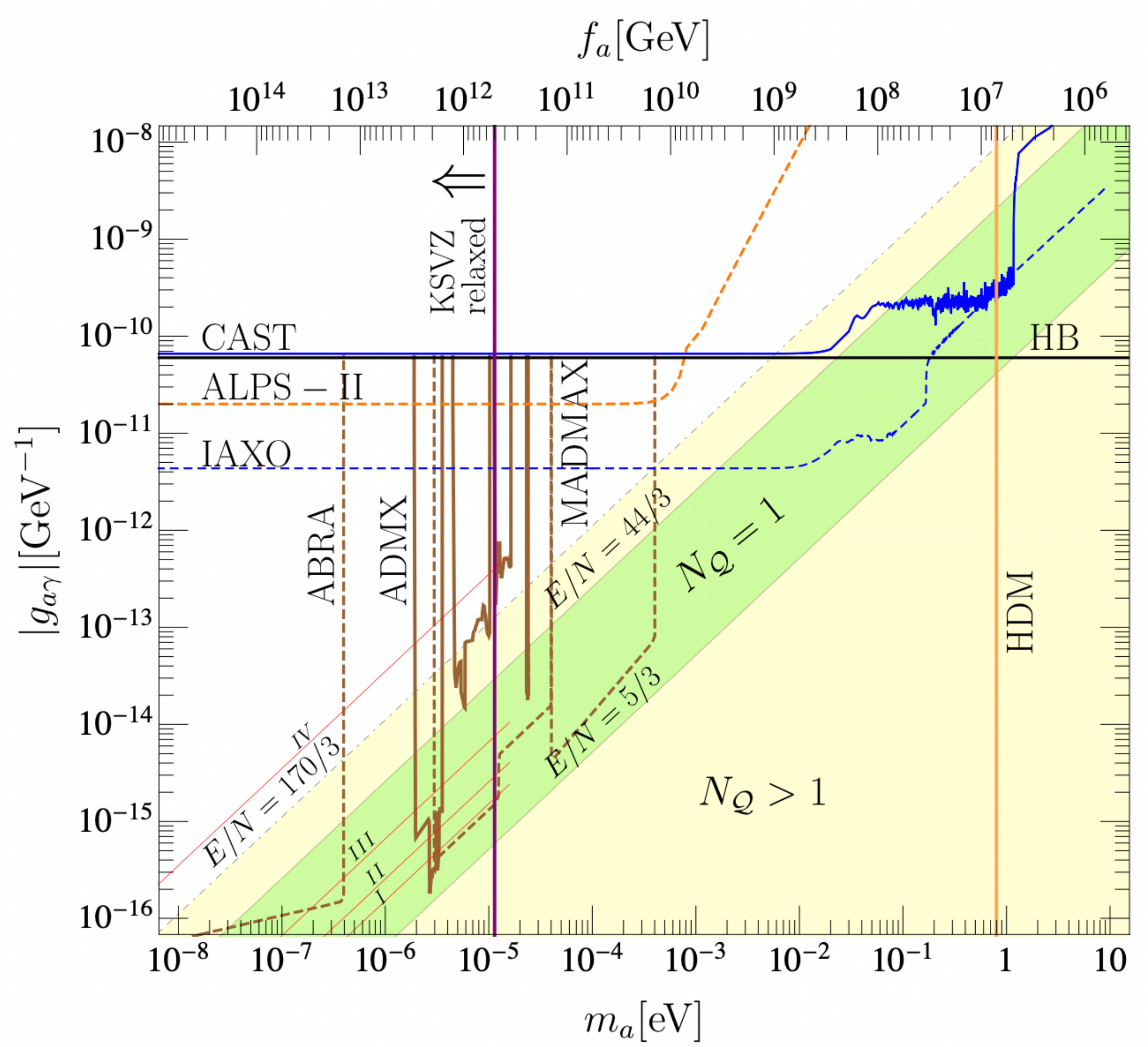
$$C_{aN} = c^0_{u,d}(X_{u,d}) + F(m_{u,d})$$

$$C_{ae} = c^0_e(X_e) + \delta_e^{\rm loop}(E/N, m_{u,d})$$

- $X_{u,d,e}$: PQ charges
- contribution from aGG

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

Cosmo/astro bounds in the canonical axion models



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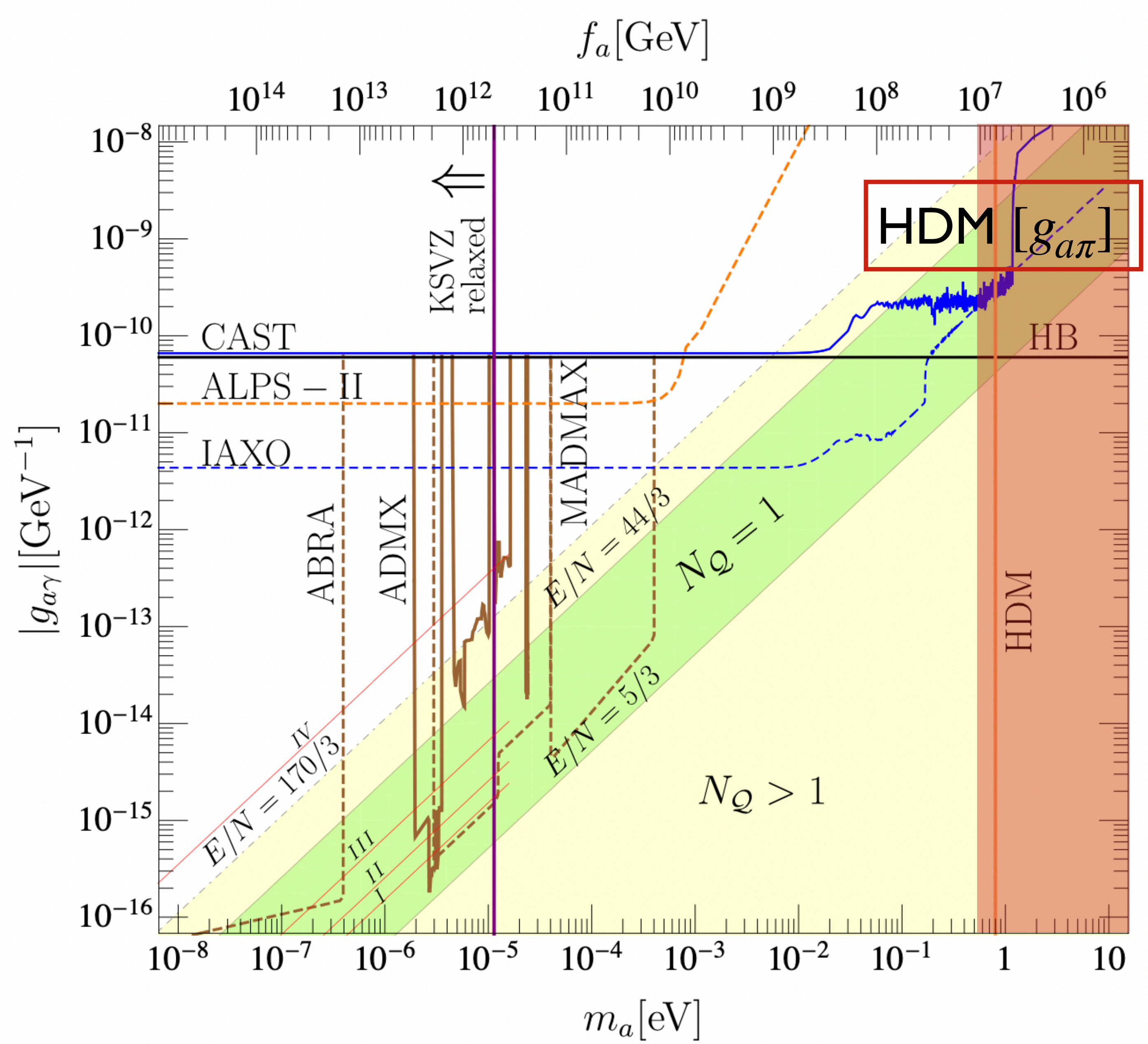

- Hot dark matter ($a\pi \leftrightarrow \pi\pi$):

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

$$g_{a\pi} \xrightarrow[\text{model}]{} f_a \xrightarrow[\substack{\text{QCD}\\\text{axion}}]{} m_a$$

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

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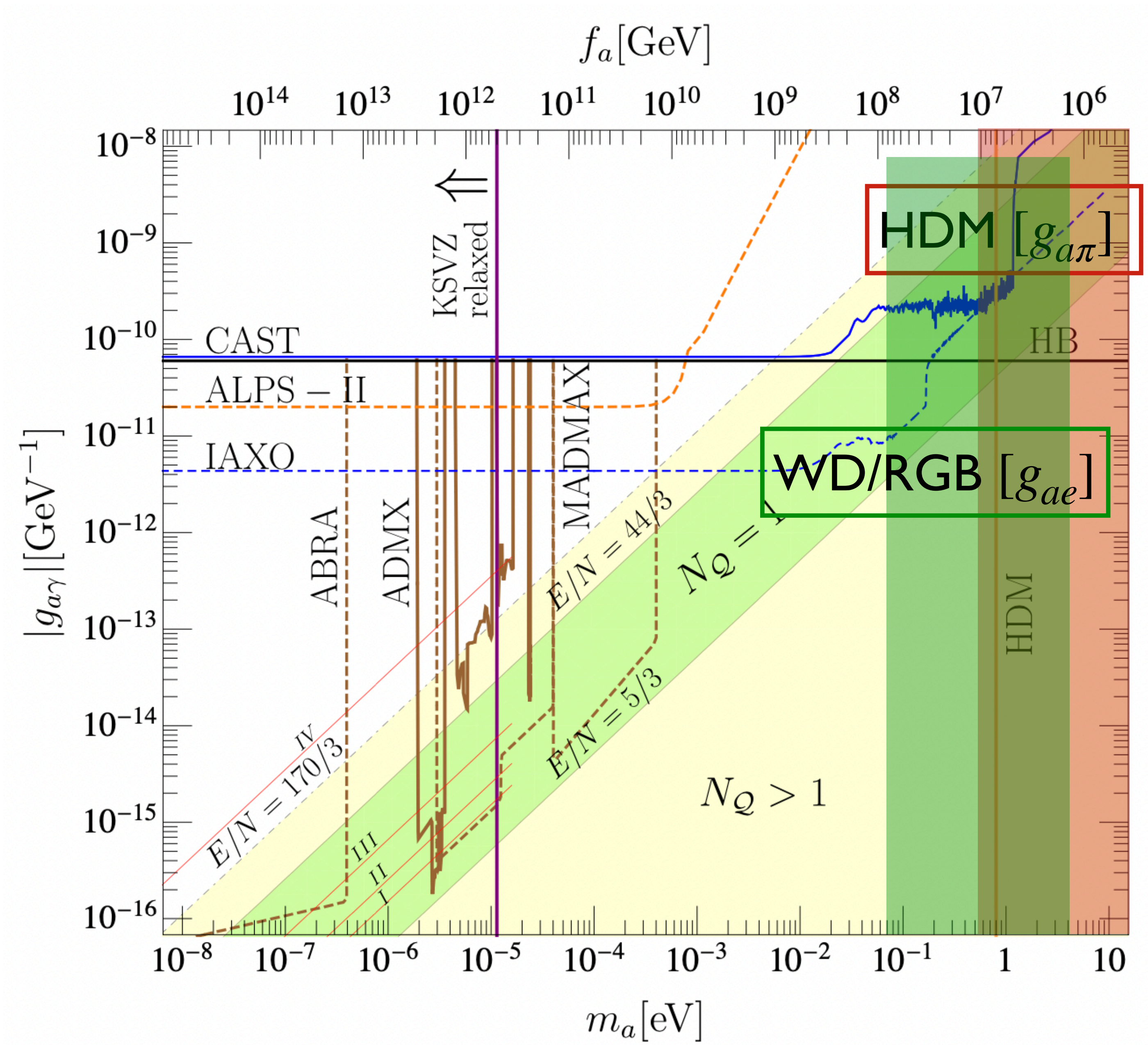

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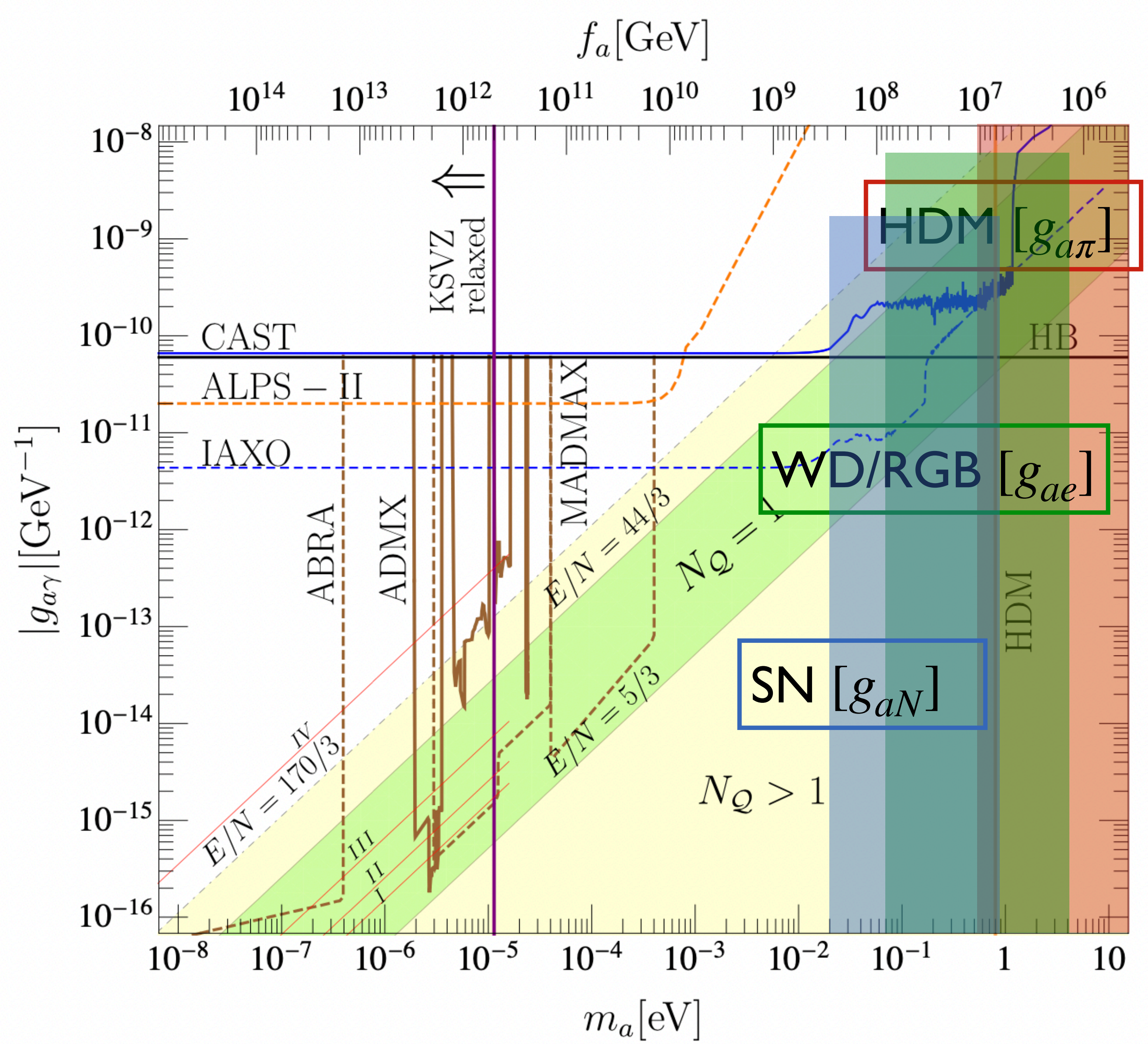

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- SN1987A bound: $g_{aN} \lesssim 0.9 \times 10^{-9}$

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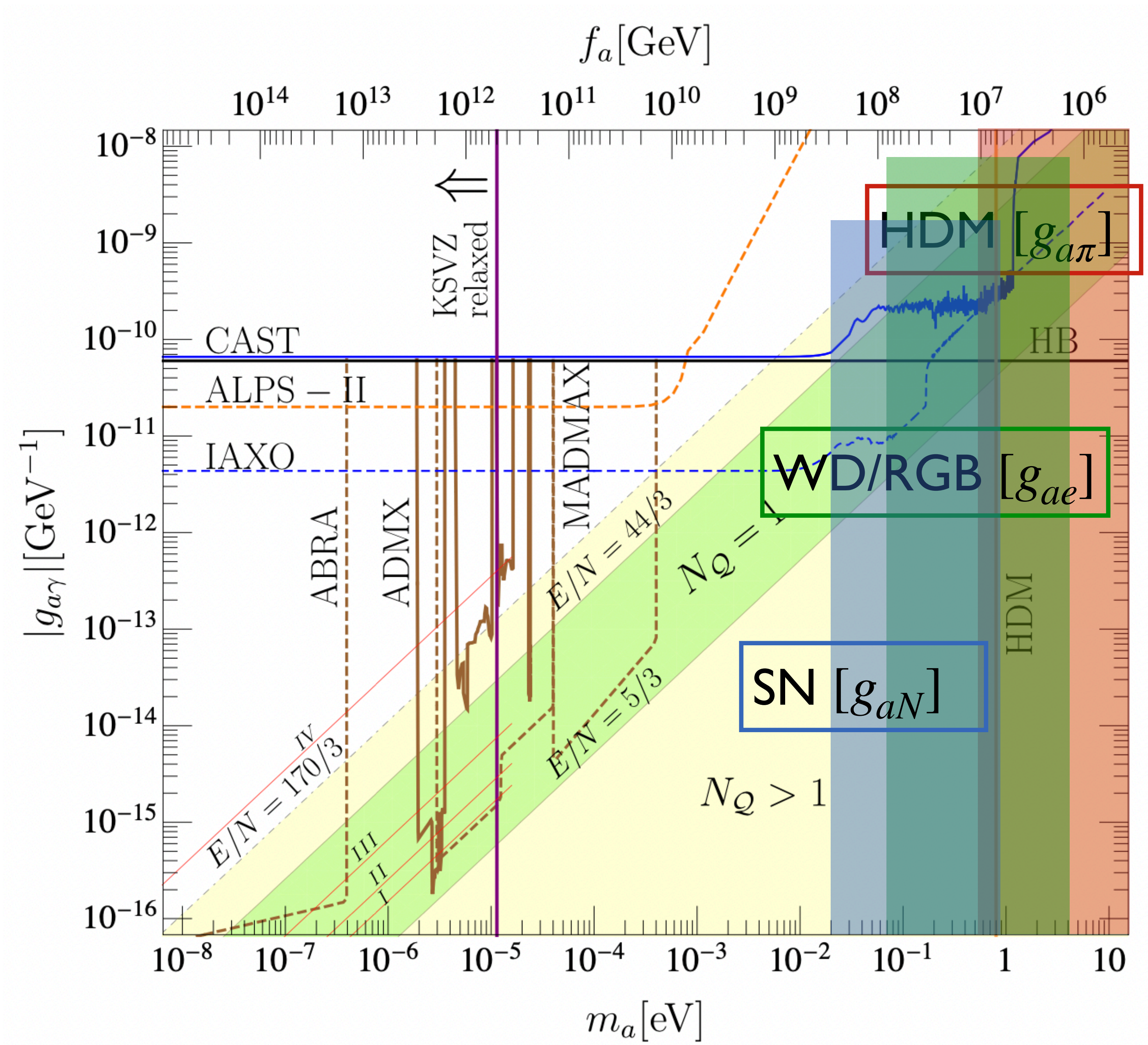

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Canonical axion models are strongly constrained by astrophysics and cosmology

Astrophobic axion

- Astrophysical bounds are significantly relaxed if $C_N \approx 0$ and $C_e \approx 0$

  $\Rightarrow$ *astrophobic axion*

- Axion astrophobia can be realized in DFSZ-like models with generation dependent PQ charge assignment for quarks and leptons

Di Luzio, Mescia, Nardi, Panci, Ziegler (2018); +Björkeroth (2019)

Nucleophobic axion $C_N \approx 0$

- axion-nucleon couplings:

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

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

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

- Hadronic matrix elements:

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

- $f_{ud} = (m_d - m_u)/(m_d + m_u)$
- $\delta_s \simeq \mathcal{O}(5\%)$ from strange quark

- nucleophobia conditions:

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

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

independent of the matrix elements and axion model construction

Axion nucleophobia indicates non-universal PQ charges

- consider a DFSZ-like model

*axion-quark couplings: $c_q = (X_{q_R} - X_{q_L})/2N$

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Only first generation quarks contribute to the QCD anomaly

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i. (2+1)-structure: $N_1 = N_2 = -N_3$ or $N = N_1, N_2 = N_3 = 0$

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

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

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Only first generation quarks contribute to the QCD anomaly

- $\mathcal{L} \supset Y_u \bar{q}_L H_1 u_R + Y_d \bar{q}_L H_2 d_R \quad \Rightarrow \quad X_{q_L} - X_{u_R} = X_1, \quad X_{q_L} - X_{d_R} = X_2$
- PQ-hypercharge orthogonality $\Rightarrow X_1 v_1^2 - X_2 v_2^2 = 0$

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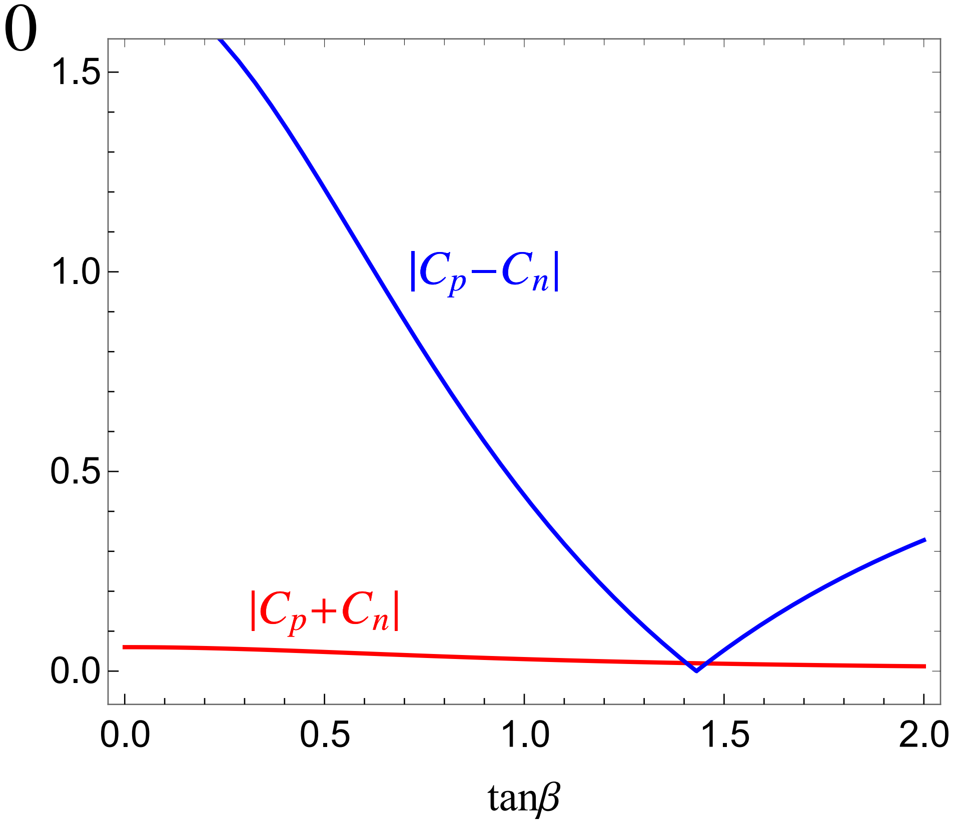
$$(2)\ c_u - c_d \approx 1/3 \Rightarrow \frac{X_1}{X_2} = \frac{v_2^2}{v_1^2} = \tan^2\beta \approx 2$$

a specific VEV ratio of two Higgs doublets $H_{1,2}$

Alves, Weiner (2017), Alves (2020)
Di Luzio, Mescia, Nardi, Panci, Ziegler (2018)



Electrophobic axion $C_e \approx 0$

- add a third Higgs doublet H_3 while unchanging up and down Yukawa:

$$\mathscr{L} \supset Y_u \bar{q}_L H_1 u_R + Y_d \bar{q}_L H_2 d_R$$
$$+ Y_e \bar{l}_L H_3 e_R$$

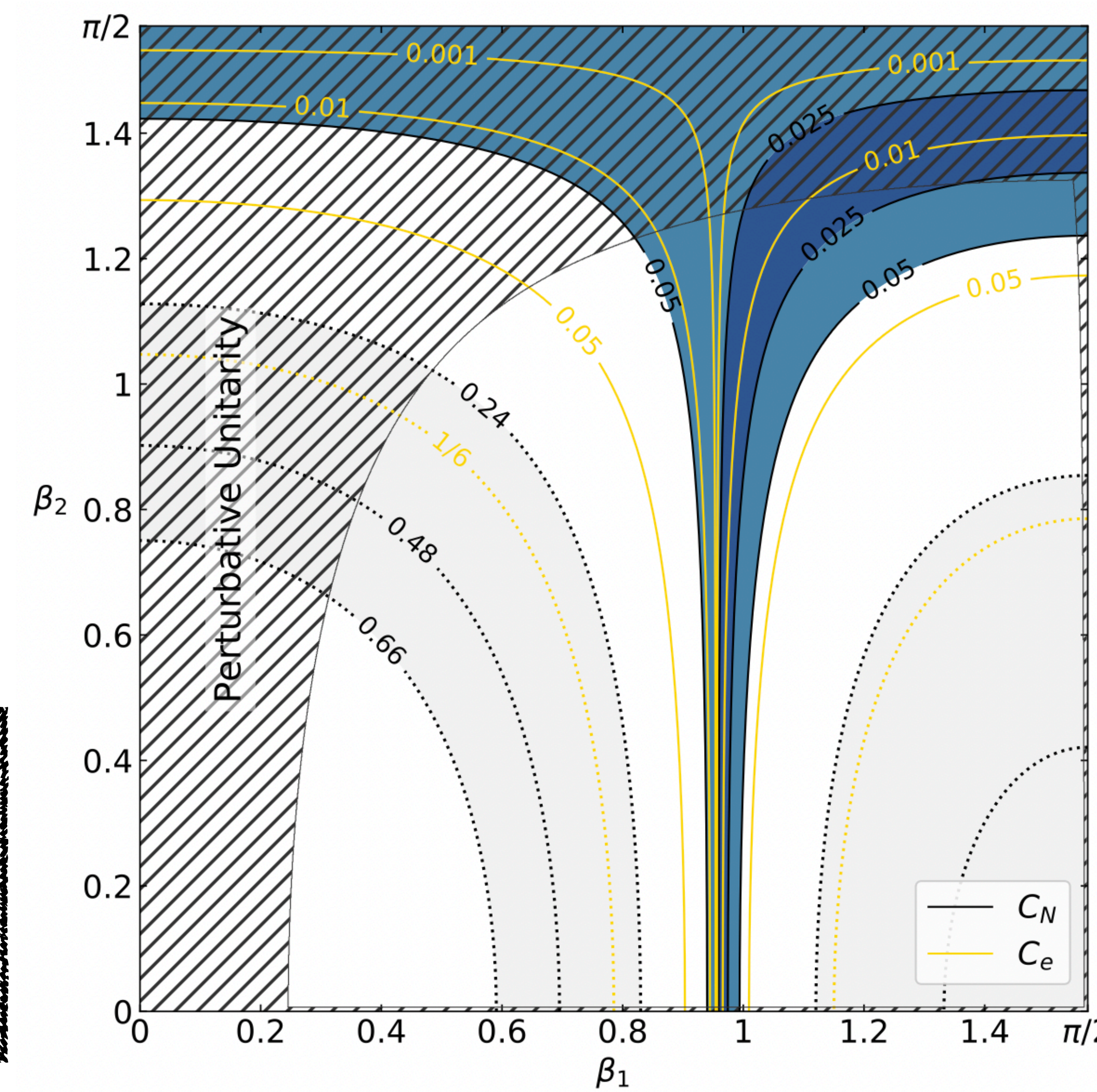
- $V \supset H_3^\dagger H_1 \Phi^2, \ H_3^\dagger H_2 \Phi^\dagger$

Electrophobia: $X_3 = 0$

Nucleophobia: $X_3 = \dfrac{1}{2}(1 - 3f_{ud}) \approx 0$

$$(^* f_{ud} = \frac{m_d - m_u}{m_d + m_u} \approx 1/3\ )$$

Björkeroth, Di Luzio, Mescia, Nardi, Panci, Ziegler (2019)



*PQ-hypercharge orthogonality:

$$\sum_i X_i v_i^2 = 0 \ \Rightarrow \ X_3 = (3\cos^2\beta_1 - 1)\cos^2\beta_2$$

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

Radiative stability of axion astrophobia?

- Axion nucleo/electrophobia is implemented by imposing

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

$$\left.\begin{array}{l}(2)\ c_u - c_d \approx 1/3 \\ (3)\ c_e \sim X_3 \approx 0\end{array}\right\} \Leftarrow \text{a specific VEV ratio and numerical accident}$$

- all conditions are imposed at tree level
- spoiled by renormalization group evolution?

Radiative stability of axion astrophobia?

- Axion nucleo/electrophobia is implemented by imposing

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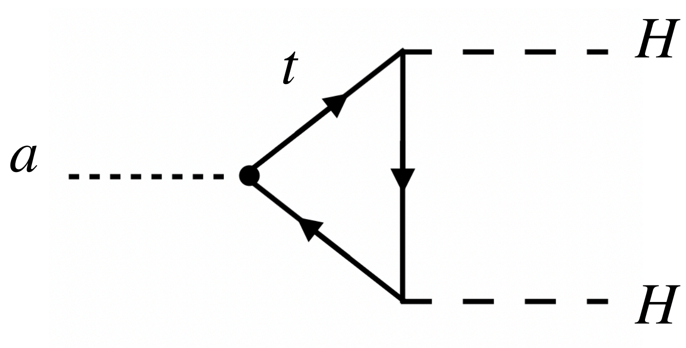
(3) $c_e \sim X_3 \approx 0$
$\Big\}$ $\Leftarrow$ a specific VEV ratio and numerical accident

- all conditions are imposed at tree level
- spoiled by renormalization group evolution?
  - No, the axion astrophobia **survives** even after taking the RG corrections into account

Di Luzio, Mescia, Nardi, SO (2022)

RG corrections to axion couplings

- leading effects from top-loop in DFSZ-type models



Choi, Im, Park, Yun (2017); Choi, Im, Kim, Seong (2021)
Bauer, Neubert, Renner, Schäuble, Thamm (2020)

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

- universal for u, d, e except for the sign difference originating from their weak isospins:

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

$$c_{d,e}(\mu) \simeq c_{d,e}^0(\Lambda) + \kappa_t(\mu, \Lambda)\, c_t^0(\Lambda)$$

$^*\kappa_t(\mu, \Lambda) \approx 30\,\%$ for $\mu = 2\,\text{GeV}$ and $\Lambda = 10^{10}\,\text{GeV}$

RG effects on axion astrophobia (1/2)

- The astrophobic conditions modified:

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

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

(3) $c_e \simeq c_e^0 + \kappa_t c_t^0 \approx 0$ (c_f^0 : axion couplings at PQ scale)

⇒

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

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

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

$\approx 0 \ (f_{ud} \approx 1/3)$

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

Axion astrophobia is stable against the RG corrections, but with a shift of parameter space

X3 = 0 -> X3 = kt/(1-kt)

RG effects on axion astrophobia (2/2)

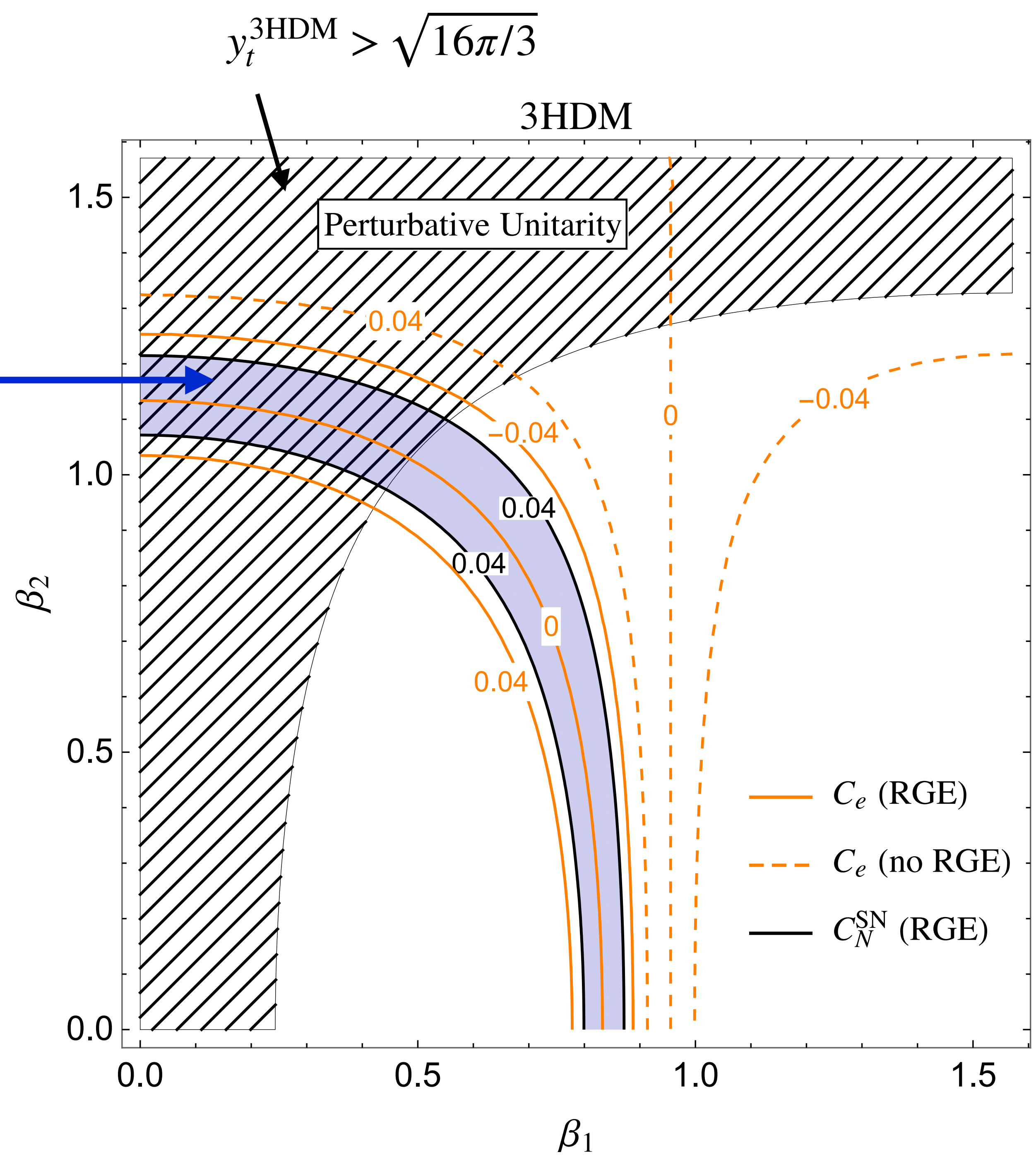
- nucleo/electrophobic parameter space in terms of two VEV ratios:

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

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

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

  - heavy scalars integrated out at 10^{10} GeV
  - Numerically solve the full set of RGEs including all sub-leading contributions and threshold corrections at the weak scale



Di Luzio, Mescia, Nardi, SO (2022)

Summary

- QCD axion can be ***astrophobic***
  - strong SN1987A and RGB bounds are relaxed if axion couplings to nucleon and electron are suppressed -> *astrophobic axion*
  - axion astrophobia is realized by generation dependent PQ charge assignment in DFSZ-like model
  - the astrophobic feature keeps holding even after taking the RG corrections into account, albeit within a different parameter space

Thank you for your attention!

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