Astrophobic QCD axion

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based on:
JHEP 10 (2021) 181 [arXiv:2107.09708], MB, G. Grilli di Cortona, M. Tabet, R. Ziegler
JHEP 06 (2023) 014 [arXiv:2301.09647], MB, K. Harigaya

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Outline

- QCD axion
- Why astrophobic axion?
- DFSZ-like models with generation-dependent PQ charges
- Flavor-violating Higgs decays
- Natural astrophobic QCD axion

QCD axion

QCD axion - one of the best candidates for New Physics

- predicted by Peccei-Quinn (PQ) mechanism solving the strong CP problem
- constitutes a good dark matter candidate
- axion is PNGB of U(1) PQ symmetry broken by non-perturbative QCD effects

Axion Models

Need anomalous breaking of PQ (fermion sector)
and spontaneous PQ breaking (scalar sector)

$$U(1)_{\rm PQ} \times SU(3)_c^2$$

SM fermions → 2Higgs: **PQWW** [Peccei, Quinn, Wilczek, Weinberg '78]

SM fermions → 2Higgs+Singlet: **DFSZ** [Dine, Fischler, Srednicki, Zhitnitsky '80]

BSM fermions → Higgs+Singlet: **KSVZ** [Kim, Shifman, Vainshtein, Zakharov '80]

excluded $J/\psi \to \gamma a$

$\langle \text{Singlet} \rangle \gg v$: "Invisible" axion models

slide borrowed from R. Ziegler

DFSZ Models

SM fermions + 2Higgs + Singlet $\begin{cases} \langle H_1 \rangle = c_\beta v \qquad \langle H_2 \rangle = s_\beta v \\ \langle \Phi \rangle = v_{\rm PQ} \gg v \end{cases}$

Construct 2HDM Lagrangian invariant under single U(1)

$$\mathcal{L}_{\rm yuk} = y^u_{ij} \overline{Q}_i U_j \begin{cases} H_1 \\ H_2 \end{cases}$$

flavor-universal U(1) charges →

$$\overline{Q}_i U_j \; H_1$$
$$\overline{Q}_i D_j \; \tilde{H}_2$$
$$\overline{L}_i E_j \; \tilde{H}_{1 \text{ or } 2}$$

Break residual U(1) by H-Singlet couplings $\mathcal{L} \sim H_1^\dagger H_2 \Phi$

Axion fermion couplings fixed by $\tan\beta$

Axion effective Lagrangian

- UV models can be described by effective Lagrangian well below the PQ scale

$$\mathcal{L} = \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + \frac{E}{N}\frac{a}{f_a}\frac{\alpha_{\rm em}}{8\pi}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\bar{f}_i\gamma^\mu\left(C^V_{ij} + C^A_{ij}\gamma_5\right)f_j$$

solves strong CP problem and generates axion mass:

$$m_a \approx 6\ \mathrm{meV}\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)$$

axion photon couplings allowing to search for axions in helioscopes e.g. IAXO

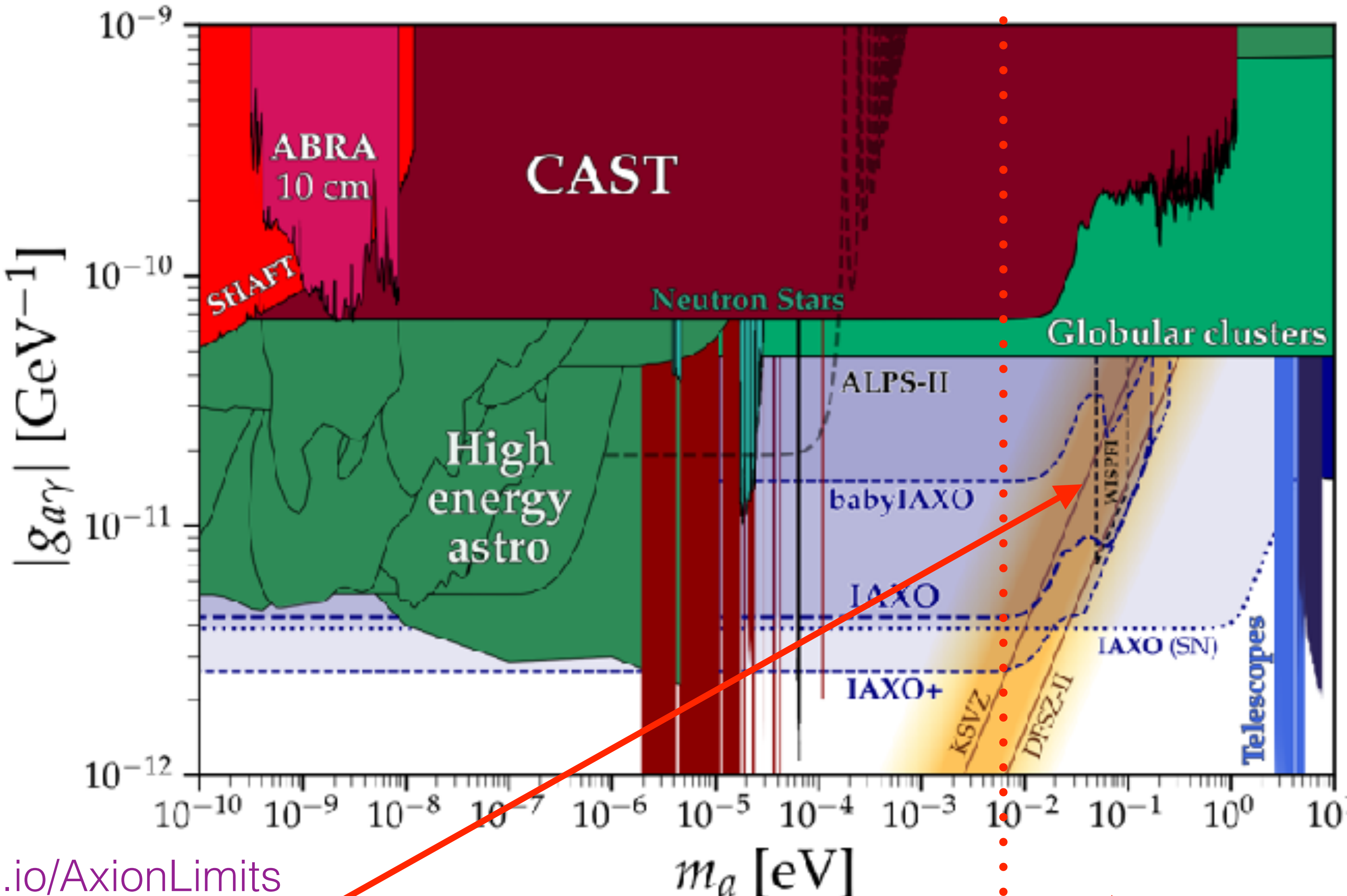
axion fermion couplings (in general flavor-violating)

Axion decay constant controls the size of axion couplings to SM particles

Astrophysical constraints on axions

- Astrophysics provides the strongest lower bounds on the axion decay constant
- Light axions efficiently cool neutron stars via axion bremstrasslung off nucleons $N + N \to N + N + a$
- Neutron star cooling and constraints from SN1987A set lower bound on $f_a \gtrsim \mathcal{O}(10^9)$ GeV in minimal axion models
- Cooling rate of White Dwarfs constrains axion-electron coupling $f_a/C_e \gtrsim 3 \times 10^9$ GeV

Detecting axions in helioscopes



cajohare.github.io/AxionLimits

Large axion-photon couplings excluded by astrophysics in minimal models

$f_a < 10^9$ GeV

No signal expected at IAXO unless axion is astrophobic

Other motivations for astrophobic axions

- Stellar cooling hints

Excessive energy losses have been observed in several stellar environments e.g. anomalous cooling of White Dwarfs -> axion explanation typically prefers $f_a \lesssim 10^9$ GeV

[Giannotti, Irastorza, Redondo, Ringwald '16]

- Axiogenesis

[Co, Harigaya '19]

Baryon asymmetry and dark matter abundance can be explained by axion rotation. Minimal models predict

$$f_a \in (10^6, 10^7)\ \text{GeV}$$

Nucleophobic axion models

[Di Luzio, Mescia, Nardi, Panci, Ziegler '17]

- SN1987A and NS bounds can be relaxed if axion nucleon coupling is suppressed which happens for

$$C_u + C_d = 1 \qquad\qquad C_u \approx 2/3$$

- Nucleophobia realised in DFSZ-like models with non-universal PQ charges

Nucleophobia ⇒ flavor-violating axion couplings!

Nucleophobic Non-universal DFSZ models

Generalized DFSZ-type models:
PQ charges universal only for two generations

Have non-trivial transition to mass basis

$$X_f = \mathrm{diag}(X_1, X_1, X_3) \to V_f^\dagger X_f V_f = X_1 \delta_{ij} + (X_3 - X_1)\xi_{ij}^f$$

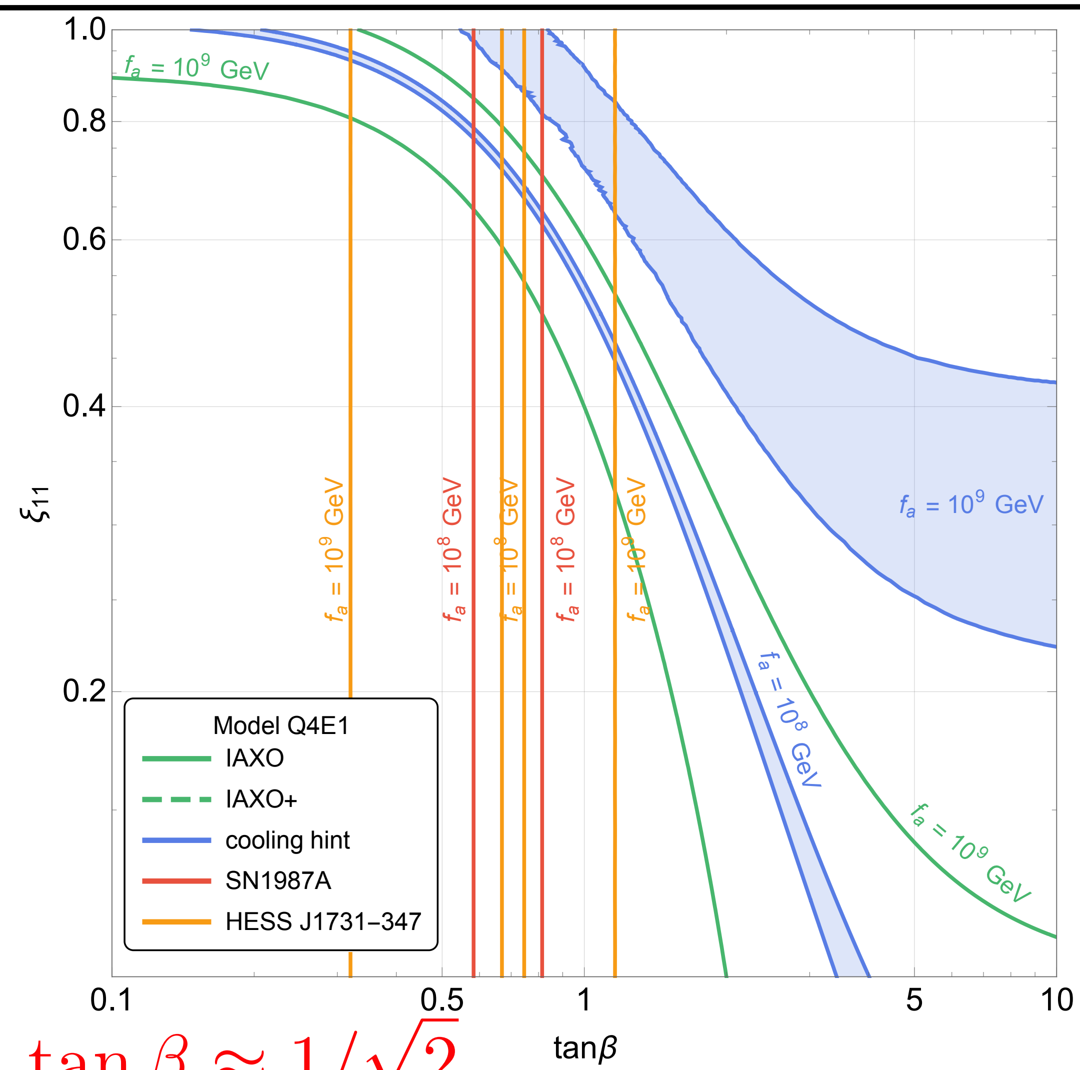
$$\xi_{ij}^f \equiv (V_f)_{i3}^* (V_f)_{j3} \qquad f = u_L, u_R, d_L, d_R, e_L, e_R$$

Generically flavor-violating axion couplings
depend on 2 misalignment parameters in each sector

$$0 \leq \xi_{ii}^f \leq 1 \qquad \sum_i \xi_{ii}^f = 1 \qquad |\xi_{ij}^f| = \sqrt{\xi_{ii}^f \xi_{jj}^f}$$

$$C_{ii}^f = X_1 + (X_3 - X_1)\xi_{ii}^f \qquad |C_{i\neq j}^f| = |X_3 - X_1| |\xi_{ij}^f|$$

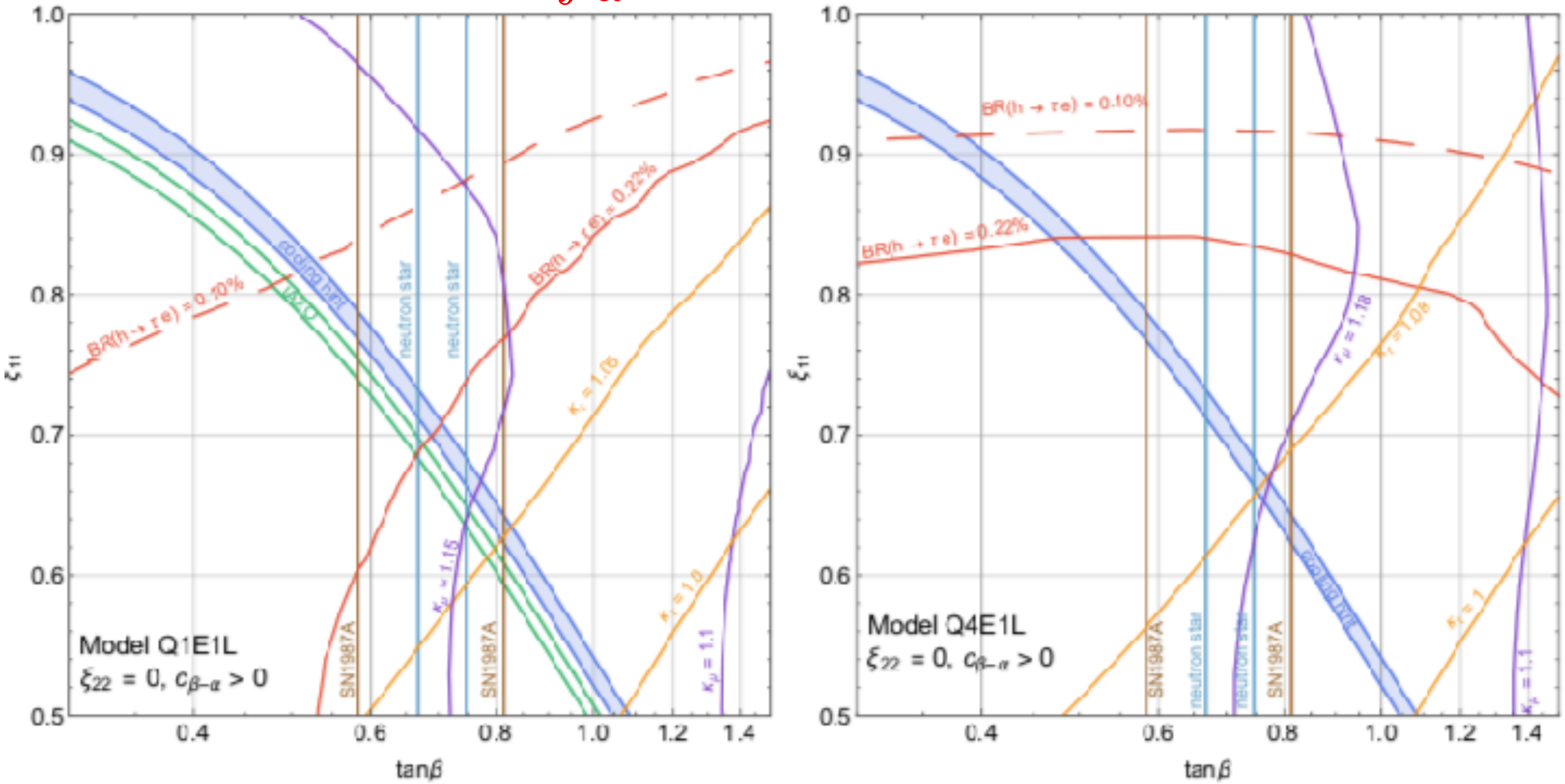
Axion phenomenology



- Nucleophobia realised for $\tan\beta \approx 1/\sqrt{2}$
- For $f_a = 10^8$ GeV bounds from SN1987A and WD cooling enforce flavor violation $(\xi_{11} \neq 0)$
- IAXO will probe the entire region explaining cooling anomalies even up to $f_a = 10^9$ GeV

Higgs-axion interplay

$f_a = 10^8\ \text{GeV}$



- If the second Higgs mass ~1 TeV flavor-violating decays of the SM-like Higgs possible: $\text{BR}(h \to \tau e) \sim \mathcal{O}(0.1)\%$
- Higgs muon coupling κ_μ larger than in the SM by up to 20%

Natural Astrophobic Axion

- Non-universal DFSZ-like models with 2 Higgs doublets (2HDM) require tuning of parameters to suppress axion couplings to nucleons and electrons
- Astrophobia can be realised without tuning for a specific PQ charge assignment for the SM fermions:

	$\bar{u}$	$\bar{d}$
Q_f	2	1

$\longrightarrow$ $C_u = 2/3 \quad C_d = 1/3$

axion-nucleon couplings naturally suppressed!

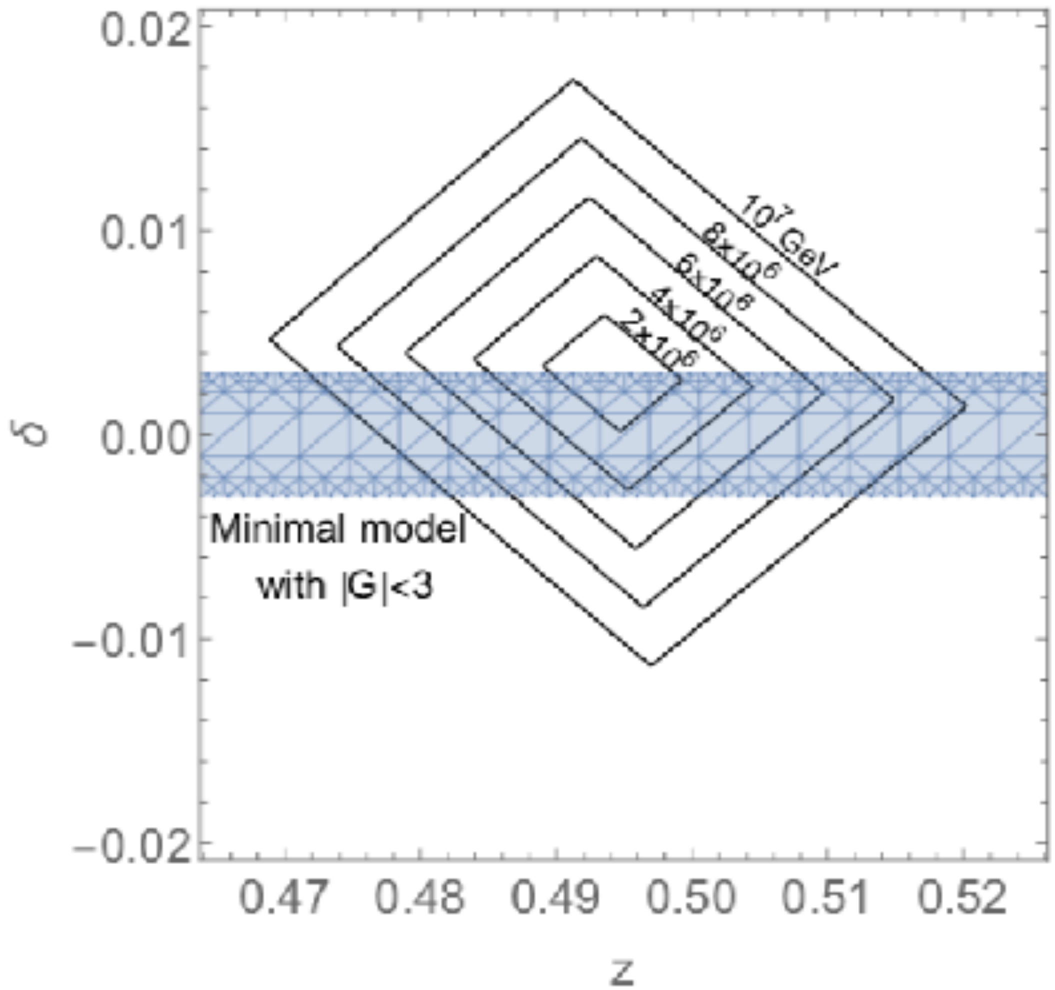
Natural Astrophobic Axion, precisely

$$C_p - C_n = \left(g_A^u - g_A^d\right)\left(C_u - C_d - \frac{1-z}{1+z+w}\right),$$

$$C_p + C_n = \left(g_A^u + g_A^d\right)\left(0.95\,(C_u + C_d) + 0.05 - \frac{1+z}{1+z+w}\right) - 2\delta,$$

$$\delta = \sum_{i=s,c,b} \delta_i C_i + \frac{m_\pi^2}{m_{\eta'}^2}\frac{f_\pi}{m_N}\frac{\sqrt{6}z}{(1+z)^2} \times G.$$

$g_A^u - g_A^d$	1.2723(23)	
	$N_f = 2+1+1$	$N_f = 2+1$
$g_A^u + g_A^d$	0.34(5)	0.44(4)
δ_s	0.059(8)	0.044(9)
δ_c	0.0065(39)	0.0092(39)
δ_b	0.0045(12)	0.0063(15)
$z = m_u/m_d$	0.465(24)	0.485(19)
$w = m_u/m_s$	0.023(1)	0.024(1)



$f_a \sim \mathcal{O}(10^7)$ GeV is consistent with the NS cooling bound

$(f_a \sim \mathcal{O}(10^6)$ GeV if $m_u/m_d \approx 0.49)$

UV complete Natural Astrophobic Axion

Natural astrophobic axion is obtained e.g. in DFSZ-like models with 3 Higgs doublets:

$$\mathcal{L}_{\rm yuk} \sim \; y_d \bar{Q} d \, H_1 \quad + \quad y_u \bar{Q} u H_2 \quad + \; y_{f_i} \bar{f}_L f_R H_{SM}$$

All SM fermions except up and down

$$\langle H_1 \rangle \, , \langle H_2 \rangle \ll \langle H_{\rm SM} \rangle$$

Summary

- Astrophobic axions allow for much smaller f_a giving good prospects for axion discovery at IAXO and opening window for axiogenesis

- The simplest models are DFSZ-like models with non-universal PQ charges featuring flavor-violating axion-fermion couplings

- Non-universal 2HDM DFSZ models can explain stellar cooling anomalies and may lead to the enhancement of $\mathrm{BR}(h \to \mu\mu)$ and $\mathrm{BR}(h \to \tau e)$ that can be tested at the LHC

- For appropriate choice of the SM fermion PQ charges the axion is naturally astrophobic which can be realised in 3HDM DFSZ-like models

Backup

Non-universal DFSZ models

There are 4 nucleophobic charge assignments in the quark sector: non-universal in q **or** u/d sector

<u>e.g.</u> $\mathcal{L} \sim \begin{matrix} \overline{f}_{L3} f_{R3} \\ \overline{f}_{L3} f_{Ra} \end{matrix} \begin{cases} h_1 & u \\ \tilde{h}_2 & d \end{cases} + \begin{matrix} \overline{f}_{La} f_{Rb} \\ \overline{f}_{La} f_{R3} \end{matrix} \begin{cases} h_2 & u \\ \tilde{h}_1 & d \end{cases}$

Each model in the quark sector can be combined with 4 models in the charged lepton sector

16 nucleophobic models in total

Model	E_Q/N	$C^A_{u_i u_i}$	$C^A_{d_i d_i}$	$C^{V,A}_{u_i \neq u_j}$	$C^{V,A}_{d_i \neq d_j}$
Q1	$2/3 + 6c^2_\beta$	c^2_β	$\xi^{d_R}_{ii} - c^2_\beta$	0	$\xi^{d_R}_{ij}$
Q2	$-4/3 + 6c^2_\beta$	$c^2_\beta - \xi^{u_L}_{ii}$	$-\xi^{d_L}_{ii} + s^2_\beta$	$\pm\xi^{u_L}_{ij}$	$\pm\xi^{d_L}_{ij}$
Q3	$-4/3 + 6c^2_\beta$	$c^2_\beta - \xi^{u_R}_{ii}$	$-\xi^{d_R}_{ii} + s^2_\beta$	$-\xi^{u_R}_{ij}$	$-\xi^{d_R}_{ij}$
Q4	$-10/3 + 6c^2_\beta$	$-s^2_\beta + \xi^{u_R}_{ii}$	s^2_β	$\xi^{u_R}_{ij}$	0

Model	E_L/N	$C^A_{e_i e_i}$	$C^{V,A}_{e_i \neq e_j}$
E1L	$2 - 6c^2_\beta$	$-c^2_\beta + \xi^{e_L}_{ii}$	$\mp\xi^{e_L}_{ij}$
E1R	$2 - 6c^2_\beta$	$-c^2_\beta + \xi^{e_R}_{ii}$	$\xi^{e_R}_{ij}$
E2L	$4 - 6c^2_\beta$	$s^2_\beta - \xi^{e_L}_{ii}$	$\pm\xi^{e_L}_{ij}$
E2R	$4 - 6c^2_\beta$	$s^2_\beta - \xi^{e_R}_{ii}$	$-\xi^{e_R}_{ij}$