Signatures of Astrophobic QCD axion

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based on:
JHEP 09 (2024) 136 [arXiv:2403.05621], MB, K. Harigaya, M. Łukawski, R. Ziegler

see also:
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
JHEP 02 (2025) 014 [arXiv:2410.18186], MB, M. Laletin

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Outline

- QCD axion
- Why astrophobic axion?
- Simple astrophobic axion models
- Thermal production of astrophobic axions and the impact on CMB

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

DFSZ Models

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

Construct 2HDM Lagrangian invariant under single U(1)

$$\mathcal{L}_{\rm yuk} = y^u_{ij} \overline{Q}_i U_j \begin{cases} H_1 \\ H_2 \end{cases} \xrightarrow[\text{U(1) PQ charges}]{\text{flavor-universal}} \begin{matrix} \overline{Q}_i U_j \, H_1 \\ \overline{Q}_i D_j \, \tilde{H}_2 \\ \overline{L}_i E_j \, \tilde{H}_{1\,\text{or}\,2} \end{matrix}$$

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:

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

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

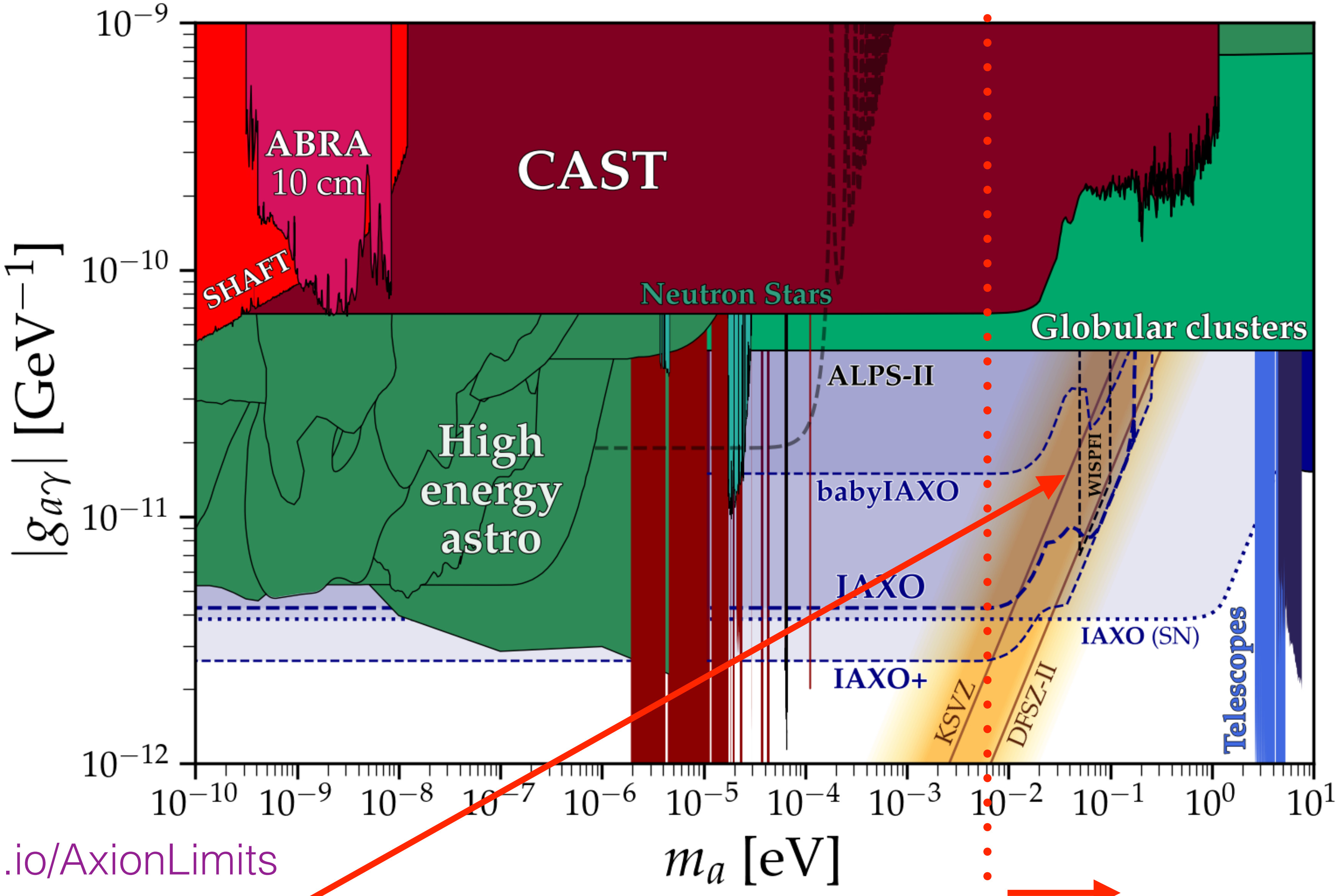
axion fermion couplings
(in general flavor-violating)

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

Astrophysical constraints on axions

- Astrophysics typically provides the strongest lower bounds on the axion decay constant
- Light axions efficiently cool neutron stars via axion bremsstrahlung off nucleons $N + N \rightarrow N + N + a$
- 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

$f_a < 10^9$ GeV

Large axion-photon couplings excluded by astrophysics in minimal models

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 $f_a \lesssim 10^9~\mathrm{GeV}$

[Giannotti, Irastorza, Redondo, Ringwald '16]
[MB,Grilli di Cortona, Tabet, Ziegler '21]

- Axiogenesis

[Co, Harigaya '19]

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

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

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

$$C_u + C_d = 1 \qquad\qquad C_u \approx 2/3 \qquad\qquad C_i \equiv C^A_{ii}$$

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

Nucleophobia ⇒ flavor-violating axion couplings!

Non-universal DFSZ 2HDM models

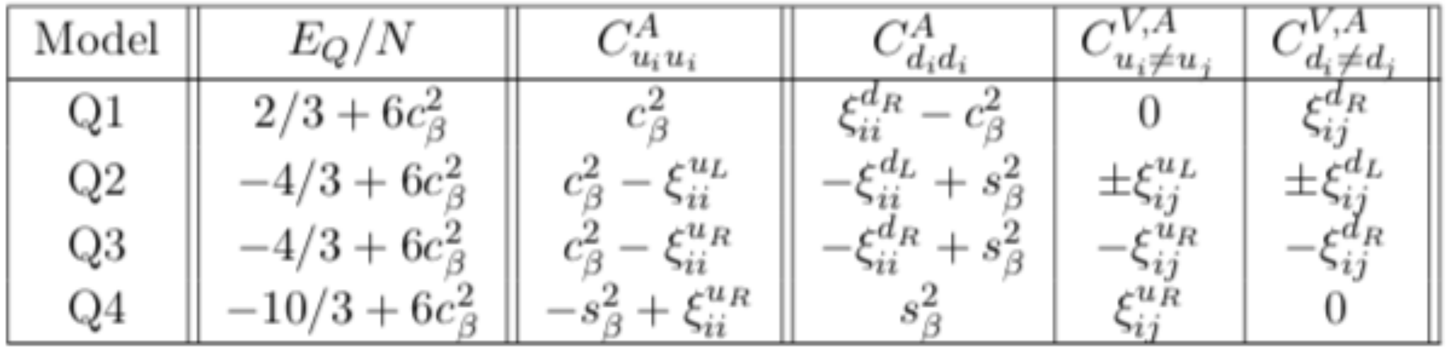
There are 4 nucleophobic charge assignments in the quark sector: non-universal in q **or** u/d sector

e.g.

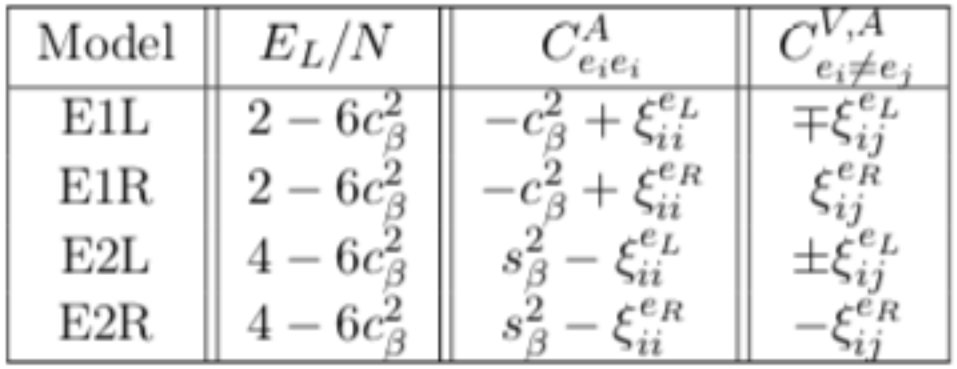
$$\mathcal{L} \sim \begin{matrix}\overline{f}_{L3} f_{R3} \\ \overline{f}_{L3} f_{Ra}\end{matrix} \begin{cases} h_1 & u \\ \tilde{h}_2 & d \end{cases} + \begin{matrix}\overline{f}_{La} f_{Rb} \\ \overline{f}_{La} f_{R3}\end{matrix} \begin{cases} h_2 & u \\ \tilde{h}_1 & d \end{cases}$$

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	$2/3 + 6c_\beta^2$	c_β^2	$\xi_{ii}^{d_R} - c_\beta^2$	0	$\xi_{ij}^{d_R}$
Q2	$-4/3 + 6c_\beta^2$	$c_\beta^2 - \xi_{ii}^{u_L}$	$-\xi_{ii}^{d_L} + s_\beta^2$	$\pm\xi_{ij}^{u_L}$	$\pm\xi_{ij}^{d_L}$
Q3	$-4/3 + 6c_\beta^2$	$c_\beta^2 - \xi_{ii}^{u_R}$	$-\xi_{ii}^{d_R} + s_\beta^2$	$-\xi_{ij}^{u_R}$	$-\xi_{ij}^{d_R}$
Q4	$-10/3 + 6c_\beta^2$	$-s_\beta^2 + \xi_{ii}^{u_R}$	s_β^2	$\xi_{ij}^{u_R}$	0



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

Thermal production of axions

Thermal axion production

- Axions have also cosmological signatures
- For small enough f_a axions can be in thermal equilibrium with the SM plasma
- Thermally produced axions contribute to

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}} \left.\frac{\rho_a}{\rho_\gamma}\right|_{T_{\rm CMB}}$$

leading to lower bounds on f_a from the CMB data

Thermal production of astrophobic axions

[MB, Harigaya, Łukawski, Ziegler '24]

[MB, Laletin '25]

Astrophobic axions are dominantly produced via:

- flavor-conserving axion-lepton scattering

$$l^{\pm}\gamma \leftrightarrow l^{\pm}a \qquad l^{+}l^{-} \leftrightarrow \gamma a \qquad\qquad (l = \mu, \tau)$$

- flavor-violating $\tau \to la$ decays $(l = e, \mu)$

Precise determination of ΔN_{eff} requires solving Boltzmann equations:

$$\frac{dn_a}{dt} + 3Hn_a = \left(\sum_i \Gamma_i\right)\left(n_a^{\mathrm{eq}} - n_a\right)$$

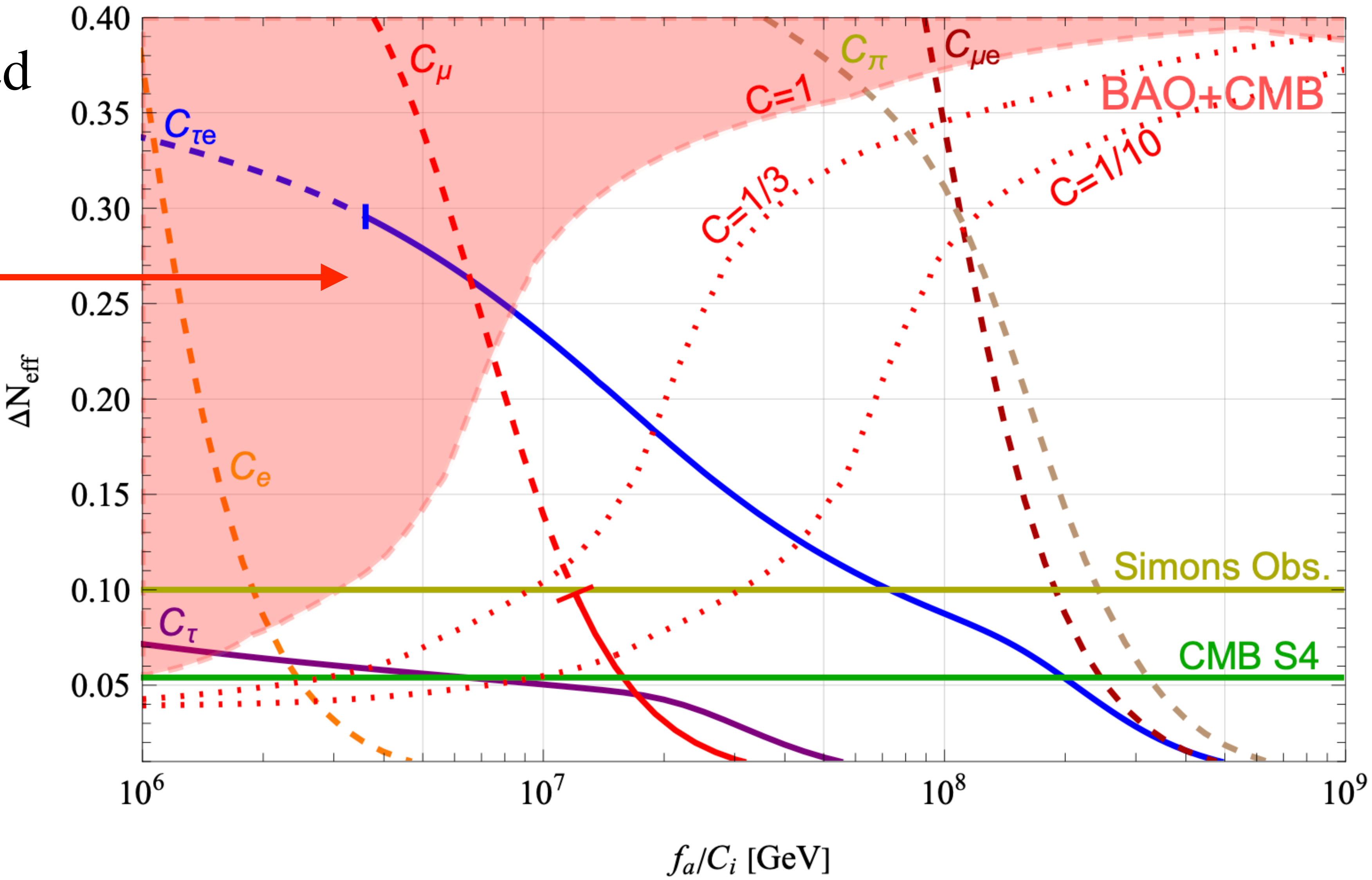
Thermally averaged axion production rates

ΔN_{eff} from dominant channels

------ excluded

Excluded by Planck →

effect of the axion mass impacts CMB constraints



For O(1) axion couplings FV $\tau \to la$ decays dominate

(bound from Planck is stronger than that from Belle II)

$\Delta N_{\rm eff}$ in astrophobic 2HDM models

DFSZ-like 2HDM models with 2+1 flavor structure of PQ charges:

Nucleophobia+Electrophobia $\Rightarrow$ LFV axion couplings

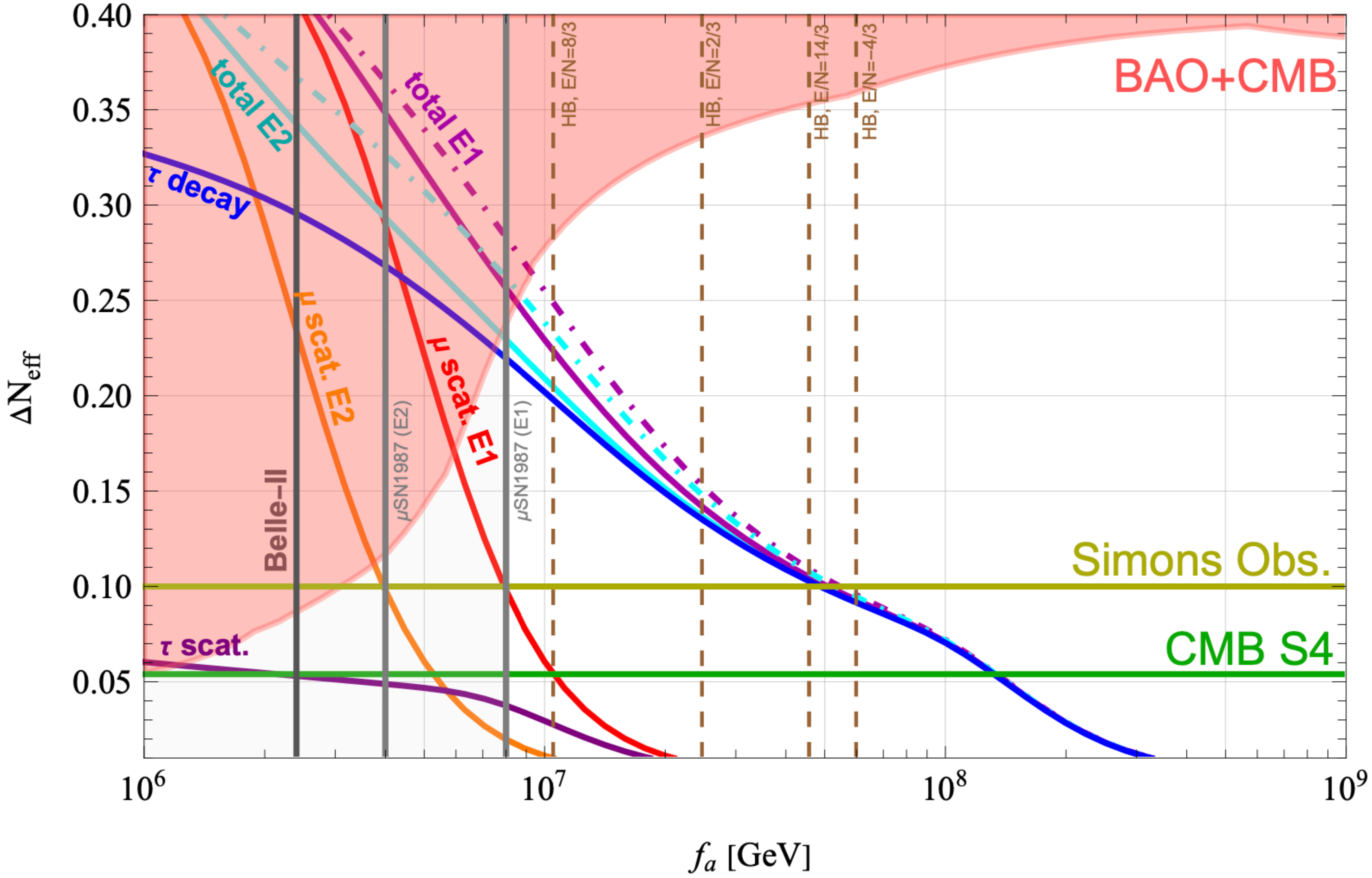
For $f_a \lesssim 10^8$ GeV all axion couplings in the lepton sector fixed once astro and exp. ($\mu \to ea$) constraints are imposed:

$$C_{\tau e} \approx \frac{2}{3} \qquad\qquad C_\tau \approx -\frac{1}{3} \qquad C_\mu \approx -\frac{2}{3}\ (\text{or } \frac{1}{3})$$

$\Delta N_{\rm eff}$ predicted as a function of f_a

Astrophobic 2HDM (with different PQ charge assignments for SM fermions) with different predictions for E/N determining the axion-photon coupling

$\Delta N_{\rm eff}$ in astrophobic 2HDM models



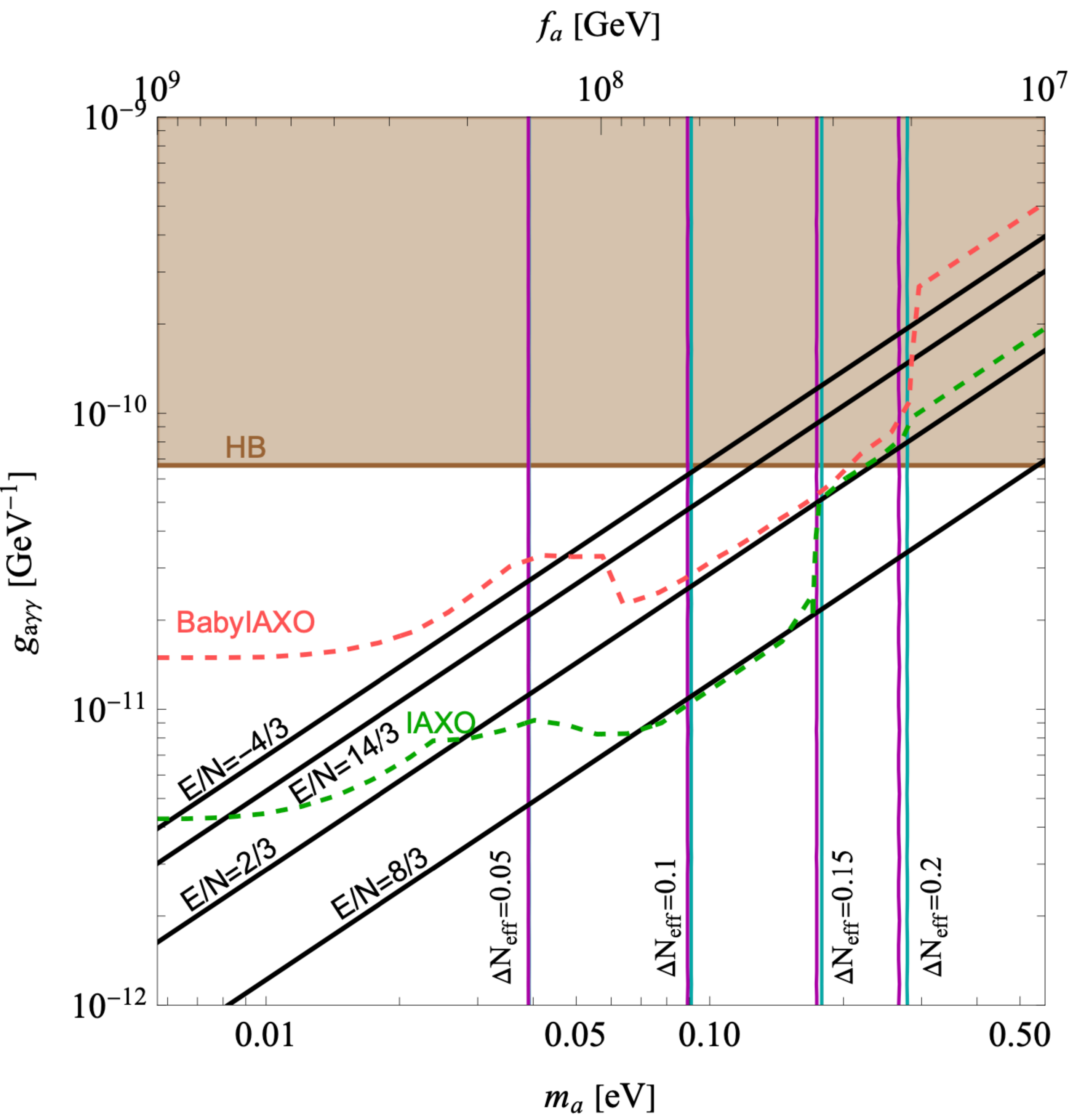
$$C_\mu \approx -\frac{2}{3}\ \text{(E1)}$$

$$C_\mu \approx \frac{1}{3}\ \text{(E2)}$$

$\Delta N_{\rm eff}$ as large as 0.25 consistent with astro constraints

Good prospects for discovery at future CMB exp. for f_a up to 10^8 GeV

Complementarity of IAXO and CMB



Strong correlations between $\Delta N_{\rm eff}$ and axion-photon coupling

If CMB-S4 measures non-zero $\Delta N_{\rm eff}$, (Baby)IAXO will confirm or rule out 2HDM astrophobic models

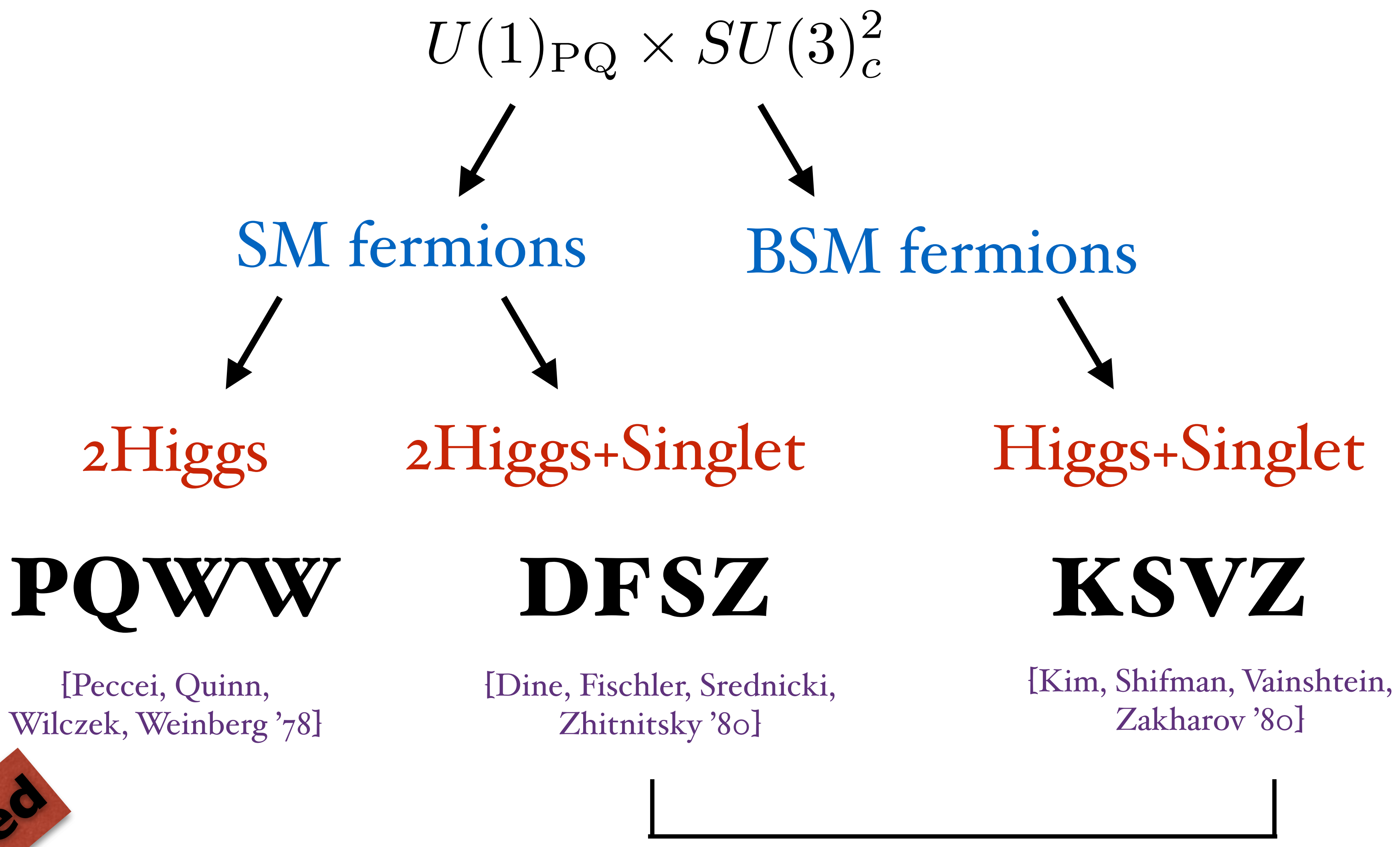
Summary

- Astrophobic QCD axions allow for much smaller f_a giving good prospects for axion discovery at IAXO, future CMB experiments and opening window for minimal axiogenesis
- The simplest models are DFSZ-like models with non-universal PQ charges featuring FV axion-fermion couplings which lead to large contributions to ΔN_{eff}

Backup

Axion Models

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



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

SM fermions

BSM fermions

2Higgs

2Higgs+Singlet

Higgs+Singlet

PQWW

[Peccei, Quinn,
Wilczek, Weinberg '78]

DFSZ

[Dine, Fischler, Srednicki,
Zhitnitsky '80]

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

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

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

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

Thermal axion production

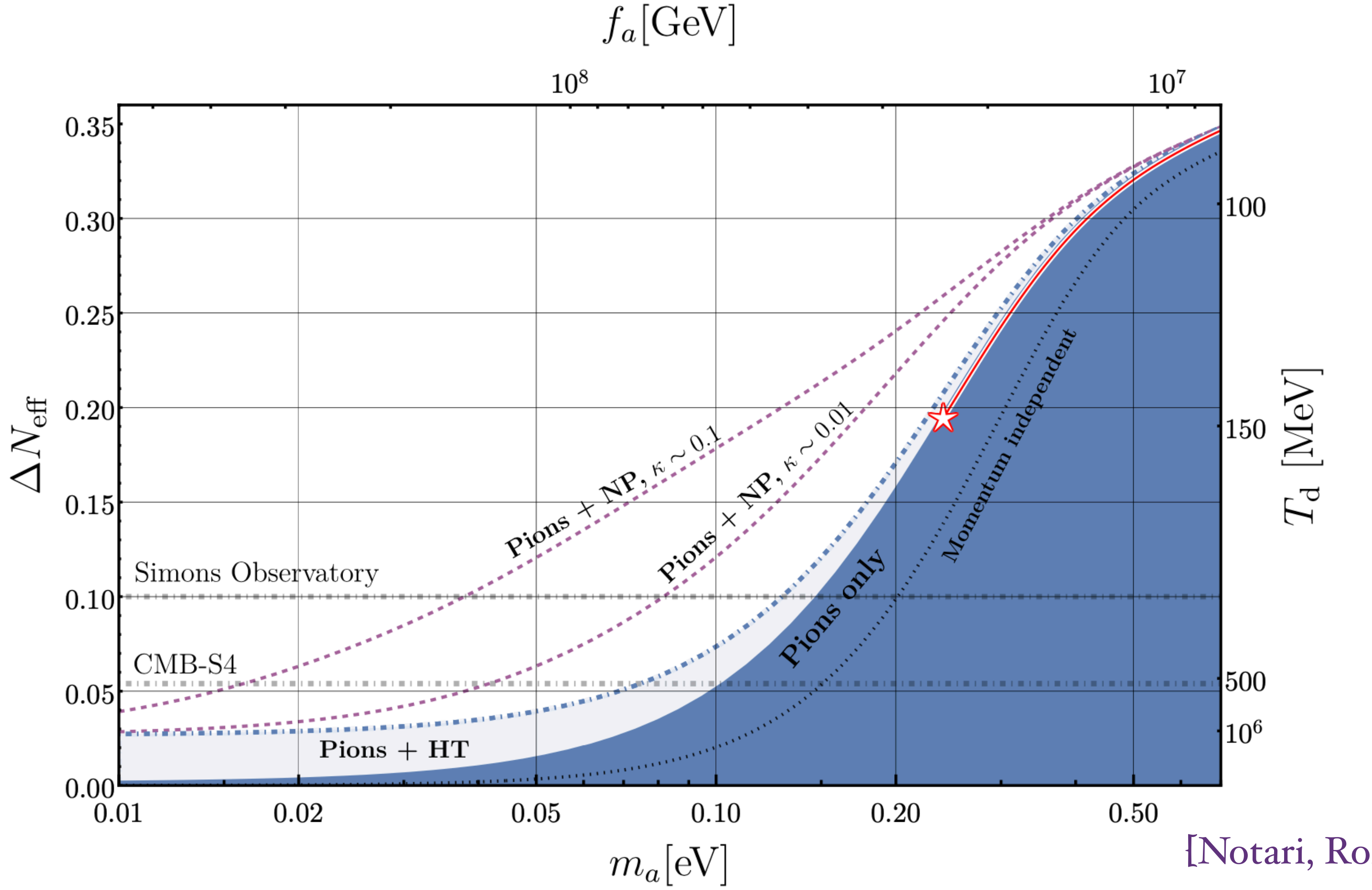
- For instantaneous axion decoupling at T_{dec} :

$$\Delta N_{\text{eff}} \approx 0.03 \left(\frac{100}{g_{*s}(T_{\text{dec}})} \right)^{4/3}$$

- Current bound from Planck: $\Delta N_{\text{eff}} \lesssim 0.3$
- Expected CMB-S4 sensitivity: $\Delta N_{\text{eff}} \lesssim 0.05$
- ΔN_{eff} sizeable if axion decouples during or after QCD phase transition

Axion-pion scattering

Typically dominant production channel is axion-pion scattering



[Notari, Rompineve, Villadoro '22]

[Chang, Choi '93]

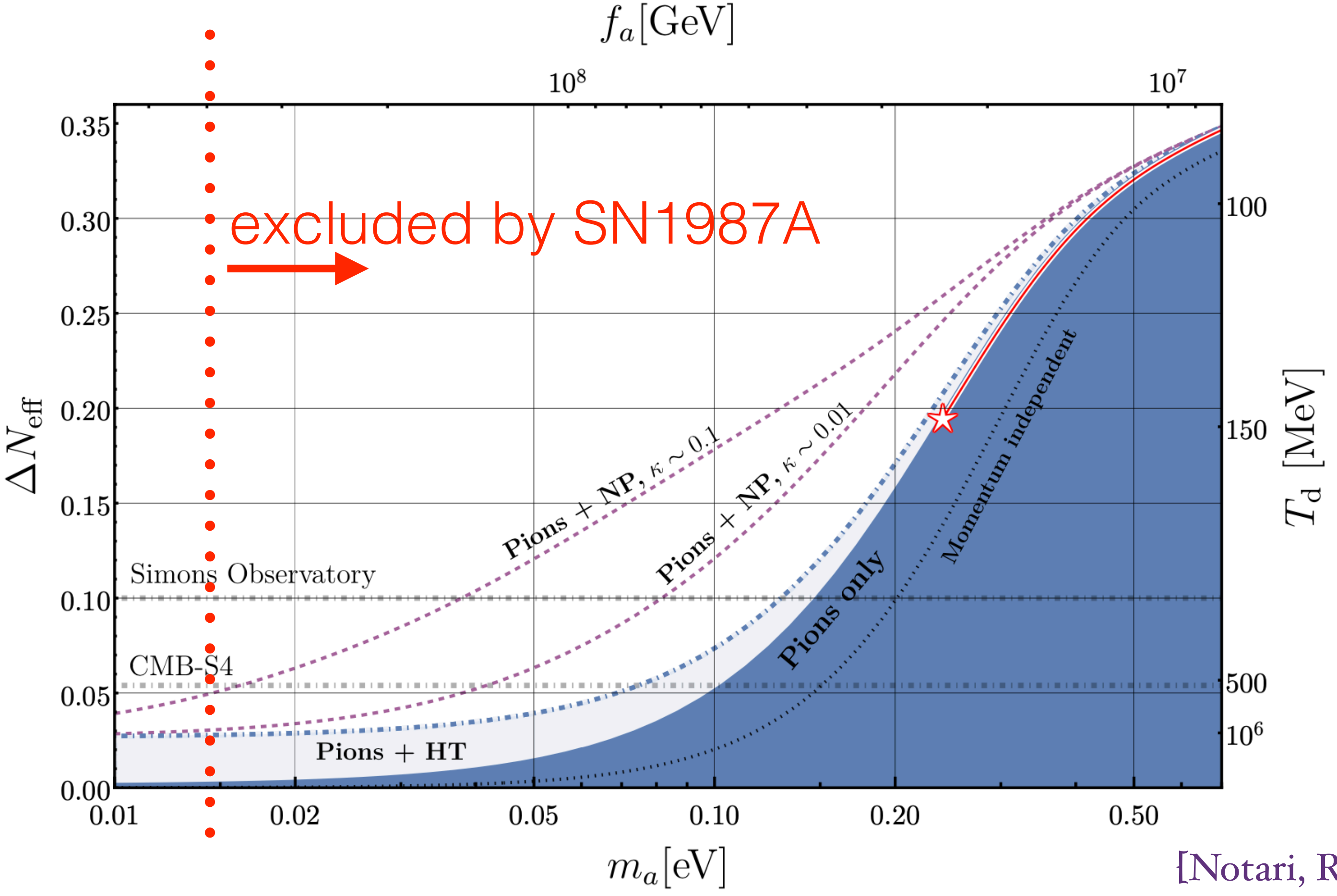
$$\pi\pi \leftrightarrow \pi a$$

Hot dark matter bound for the KSVZ (hadronic) axion:
$m_a \lesssim 0.24$ eV (or $f_a \gtrsim 2 \times 10^7$ GeV)

Note: the above bound is highly model dependent!

Axion-pion scattering

Typically dominant production channel is axion-pion scattering



[Notari, Rompineve, Villadoro '22]

[Chang, Choi '93]

$$\pi\pi \leftrightarrow \pi a$$

The astrophysical bound on f_a is much stronger than CMB one

Astro bounds on f_a in the KSVZ model imply negligible $\Delta N_{\rm eff}$ beyond the reach of future CMB experiments

Naturally Astrophobic Axion

[MB, Harigaya '23]

- 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

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

axion couplings to nucleons and photons naturally suppressed!

$$\frac{E}{N} = 2$$

$$C_\gamma = E/N - 2.07(4)$$

$$f_a \gtrsim 2 \times 10^7 \, |C_\gamma| \quad \text{(from horizontal branch stars)}$$

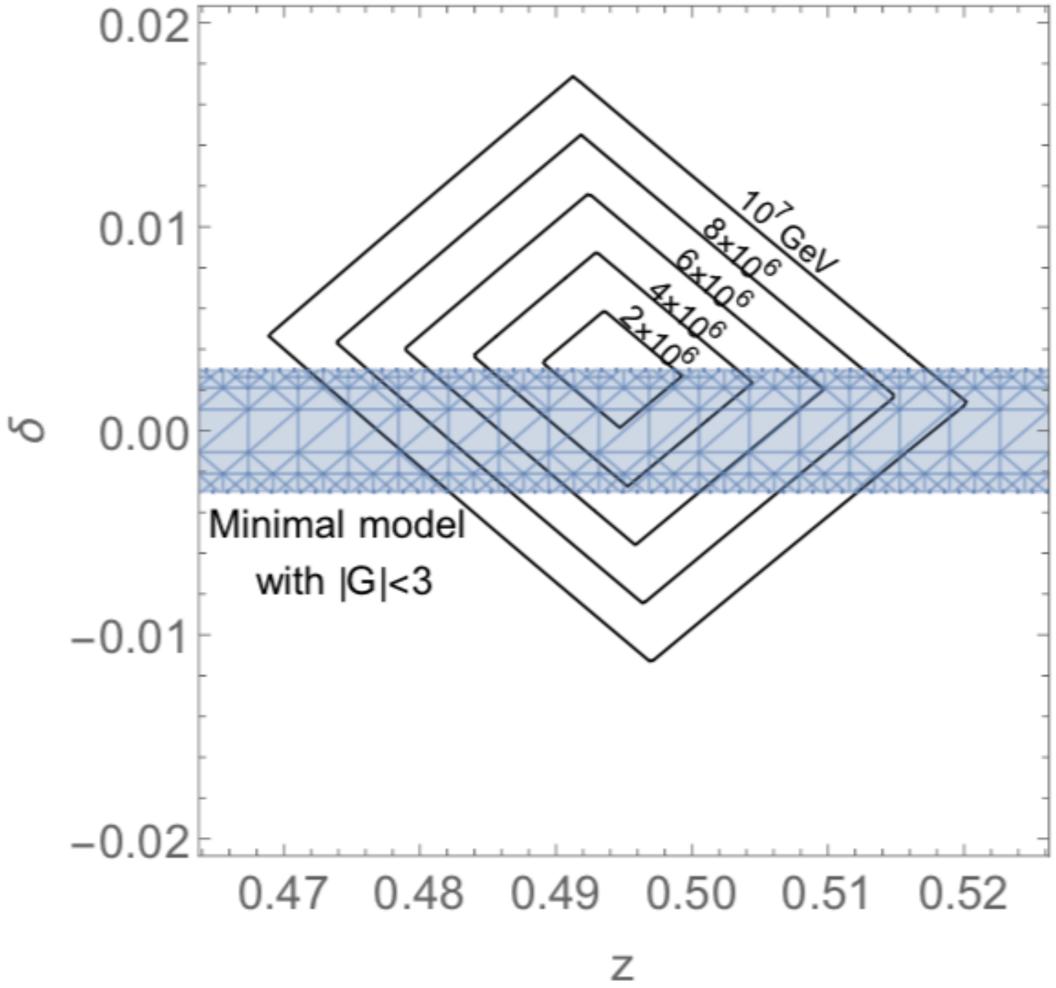
Naturally Astrophobic Axion, precisely

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

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

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

$g_A^u - g_A^d$	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 Naturally Astrophobic Axion

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

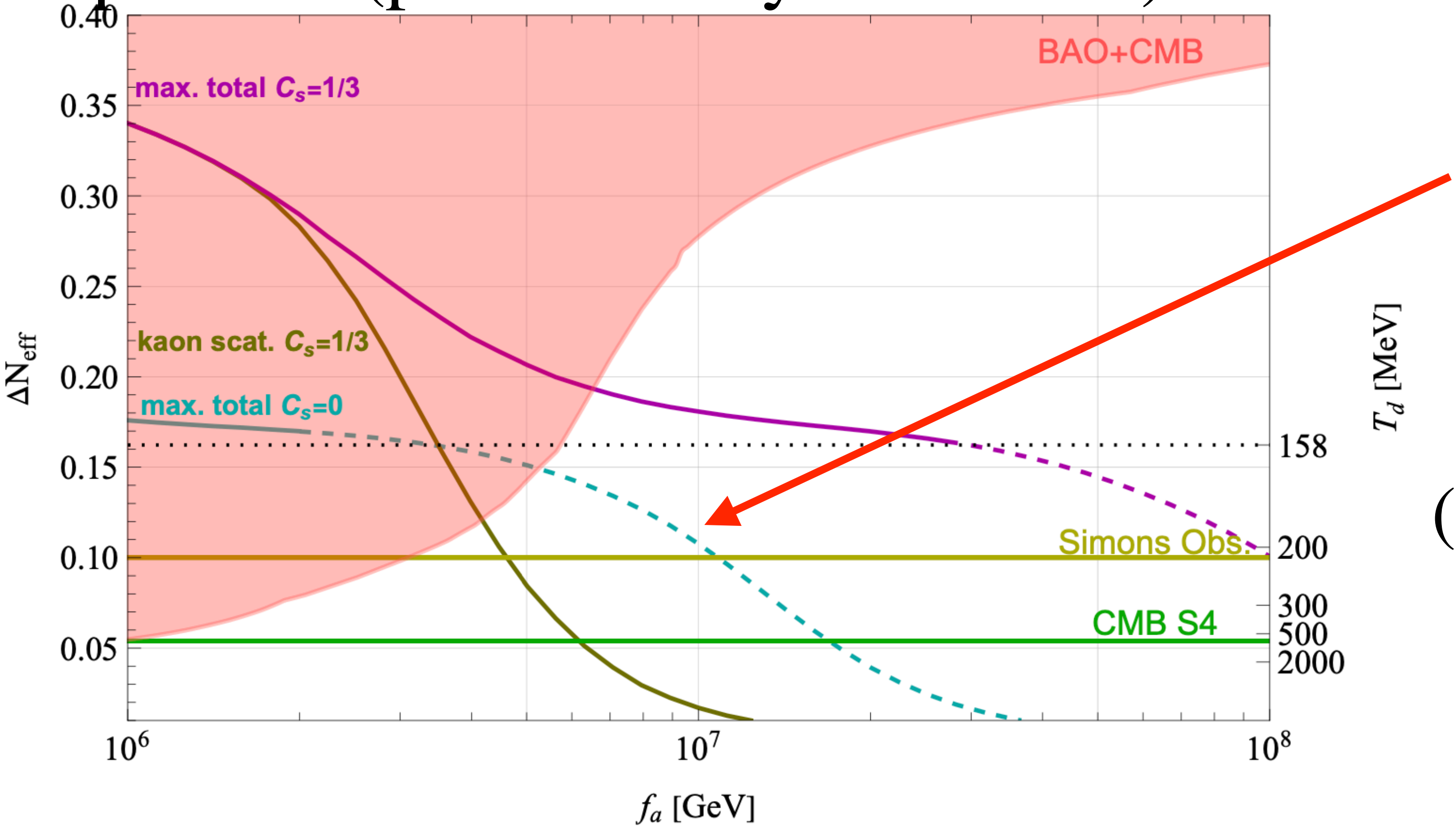
$$\mathcal{L}_{\rm yuk} \sim \; y_d \bar{Q} d \, H_1 \;\; + \;\; y_u \bar{Q} u \, H_2 \;\; + \; y_{f_i} \bar{f}_L f_R H_{SM}$$

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

All SM fermions except up and down

$\Delta N_{\rm eff}$ from Naturally Astrophobic Axion

$f_a < 10^7$ GeV possible due to suppressed axion couplings also to photons (possible only for E/N=2) and muons.



Estimate of maximal $\Delta N_{\rm eff}$
from axion-quark scattering
above QCD PT
by taking $g_s = 4\pi$
(perturbative calc. not reliable
for relevant temperatures)

Minimal model predicts negligible $\Delta N_{\rm eff}$ from processes below QCD phase transition

Even aggressive estimate of $\Delta N_{\rm eff}$ above QCD PT allows for $f_a \approx 5 \times 10^6$ GeV $(m_a \approx 1$ eV$)$