Astrophobic Axions

Based on: "Astrophobic Axions"
Phys.Rev.Lett. 120 (2018) no.26, 261803 [arXiv:1712.04940]
In collaboration with L. Di Luzio (IPPP, Durham), F. Mescia (Barcelona U.), P. Panci (CERN) and R. Ziegler (CERN))

Some remarks from
"U(1) flavour symmetries as PQ symmetries" [arXiv:1811.09637]
In collaboration with Fredrik Bjorkeroth (Frascati), Luca Di Luzio (IPPP, Durham) and Federico Mescia (Barcelona U.))

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The strong CP problem

- QCD is defined in terms of two dimensionless parameters which are not predicted by the theory. Measurements yield:

$\alpha_s \sim O(0.1\text{-}1)$ and $\bar{\theta} < 10^{-10}$ $[\not{P}\ \&\ \not{T}]$

$$\mathcal{L}_{\rm QCD} = \bar{q}\left(i\not{D} - m_q e^{i\theta_q}\right) q - \frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

- The difference $\bar{\theta} = \theta - \theta_q$ gives the amount CP viol. in QCD

$$q \to e^{i\gamma_5 \alpha} q \quad \longrightarrow \quad \theta_q \to \theta_q + 2\alpha \quad \text{and} \quad \theta \to \theta + 2\alpha$$

- Change in θ is given by the change of the path integral measure:

$$\mathcal{D}q\mathcal{D}\bar{q} \to \exp\left(-i\alpha \int d^4x \, \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}\right) \mathcal{D}q\mathcal{D}\bar{q}$$

[Fujikawa (1979)]

A small value problem

- $\bar{\theta} \neq 0$ implies a non-zero neutron EDM [Baluni (1979), Crewther et al. (1979)]

$$d_n \approx \frac{e\,|\bar{\theta}|\,m_\pi^2}{m_n^3} \approx 10^{-16}\,|\bar{\theta}|\,e\,\mathrm{cm}$$

- However, $d_n \lesssim 3 \cdot 10^{-26} e\,\mathrm{cm}$ implying: → $\bar{\theta} \lesssim 10^{-10}$

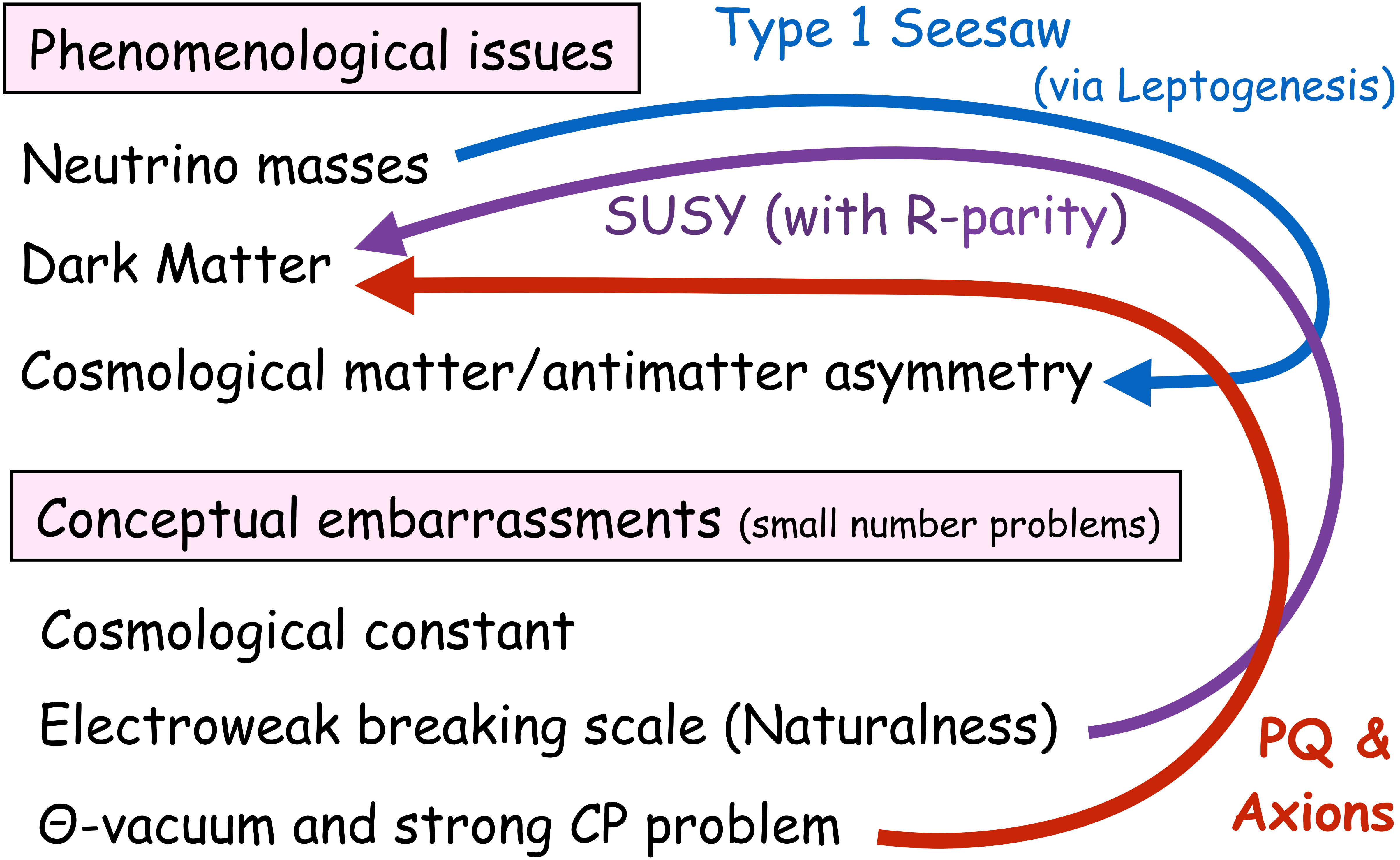
- This is qualitatively different from other small values problems:
  - In the SM $\bar{\theta}$ receives the first finite Log corrections at $O(\alpha^2)$ [Ellis, Gaillard (1979)]

    Unlike m_H^2 that is quadratically sensitive to Λ^2_{UV}

  - Unlike $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$ it evades explanations based on environmental selection

[Ubaldi, 0811.1599]
[Kaloper & Terning, 1710.01740]
[Dine, Stephenson Haskins, Ubaldi, & Di Xu 1801.03466]

Unexplained issues within the SM



Phenomenological issues

Neutrino masses

Dark Matter

Cosmological matter/antimatter asymmetry

Conceptual embarrassments (small number problems)

Cosmological constant

Electroweak breaking scale (Naturalness)

Θ-vacuum and strong CP problem

Type 1 Seesaw
(via Leptogenesis)

SUSY (with R-parity)

PQ &
Axions

Dark Energy (?)

Three types of solutions

- A massless quark. One exact chiral symmetry: $\bar{\theta} \to 0$
  - From lattice: $m_u \neq 0$ by more than 20 σ [Aoki (2013)] [Manhoar & Sachrajda, PDG(2014)]
- CP symmetry + Spontaneous CP violation [Barr (1984), Nelson (1984)]
  - Set $\bar{\theta}$ = 0 by imposing CP. Need to break spont. for CKM (+BAU)
  - High degree of fine tuning, or elaborated constructions to keep $\bar{\theta} < 10^{-10}$ at all orders. No unambiguous exp. signatures.
- Peccei-Quinn solution [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]
  - Assume a global $U(1)_{PQ}$: (i) Spontaneously broken; (ii) QCD anomalous
  - Implies a PGB of $U(1)_{PQ}$: the Axion. Shift symmetry: $a(x) \to a(x) + \delta\alpha\, f_a$

$$\mathcal{L}_{\text{eff}} = \underset{\theta_{\text{eff}}(x)}{\left(\bar{\theta} + \frac{a}{f_a}\right)} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} - \frac{1}{2} \partial^\mu a \partial_\mu a + \mathcal{L}(\partial_\mu a, \psi)$$

Axion models

- PQWW axion:

  Axion identified with the phase of the Higgs in a 2HDM ($f_a \sim V_{EW}$ was quickly ruled out long ago)

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

We need to require $f_a \gg V_{EW}$: "invisible axion"

- DSFZ Axion: SM quarks and Higgses, charged under PQ.

  Requires 2HDM + 1 scalar singlet. SM leptons are also PQ charged.

  [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

- KSVZ Axion (or hadronic axion):

  All SM fields are neutral under PQ. QCD anomaly is induced by new quarks, vectorlike under the SM, chiral under PQ.

  [Kim (1979), Shifman, Vainshtein, Zakharov (1980)]

Model independent features

- Axion mass: $\sim 1/f_a$
- All axion couplings: $\sim 1/f_a$

The lighter is the axion, the weaker are its interactions:

$$\boxed{m_a^2 = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2} .}$$

$$\boxed{m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}}$$

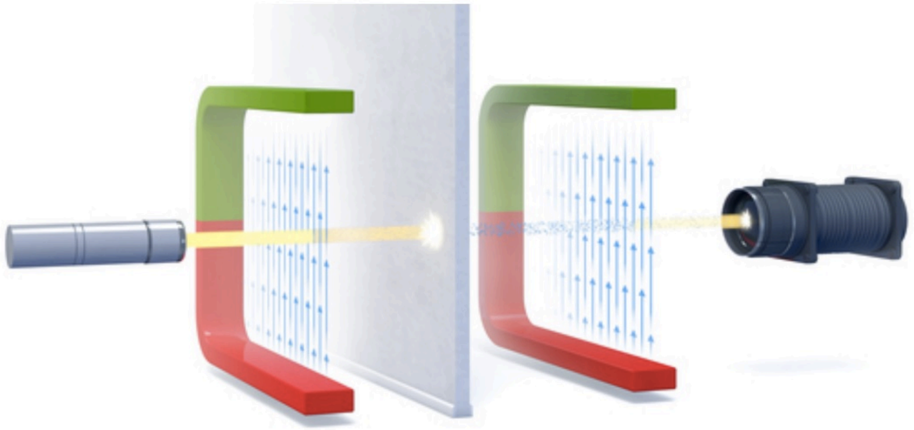
$$\boxed{g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a} \left[\frac{E}{N} - \frac{2}{3} \frac{4m_d + m_u}{m_d + m_u} \right]}$$

Search strategies and current limits

- Laboratory search techniques are sensitive to $g_{a\gamma\gamma}$

- Light Shining trough Walls [see e.g. Redondo, Ringwald hep-ph/1011.3741]

Photon conversion into Axions,
Axions reconverted back into
photons after passing a wall



ALPS 2
DESY

- Haloscopes [Sikivie 1983]

Search for Axion Halo Dark Matter with microwave resonant cavities (ADMX, U. Washington; HAYSTAC, Yale U.)

- Helioscopes

Search for Axions
produced in the Sun

CAST
CERN

ADMX
U. Washington

Astrophysical Bounds (anomalous Eng. losses)

Yukawa-like axion-fermion couplings: $g_{af} = (m_f/f_a)\, C_f$

Axion-Photon coupling [GeV^{-1}]: $g_{a\gamma} = \alpha_{em}/(2\pi f_a)\, C_\gamma$

HB stars evolution in globular clusters: $g_{a\gamma} < 6.6 \cdot 10^{-11}\ \mathrm{GeV}^{-1}$

[Ayala et al., arXiv: 1406.6053 (PRL)]

WD luminosity function (cooling): $g_{ae} < 2.7 \cdot 10^{-13}$ [Miller Bertolami et al., arXiv: 1406.7712 (JCAP)]

RG evolution in globular clusters: $g_{ae} < 4.3 \cdot 10^{-13}$ [Viaux et al., arXiv: 1311.1699 (PRL)]

Burst duration of SN1987A ν signal: $g^2_{ap} + g^2_{an} < (6 \cdot 10^{-10})^2$

[Giannotti et al., arXiv: 1708.02111 (PRD)]

Astro-limits used to constrain f_a and in turn $m_a \sim m_\pi f_\pi / f_a$

We need to know where to search

Preferred window versus constraints

Theoretical central value

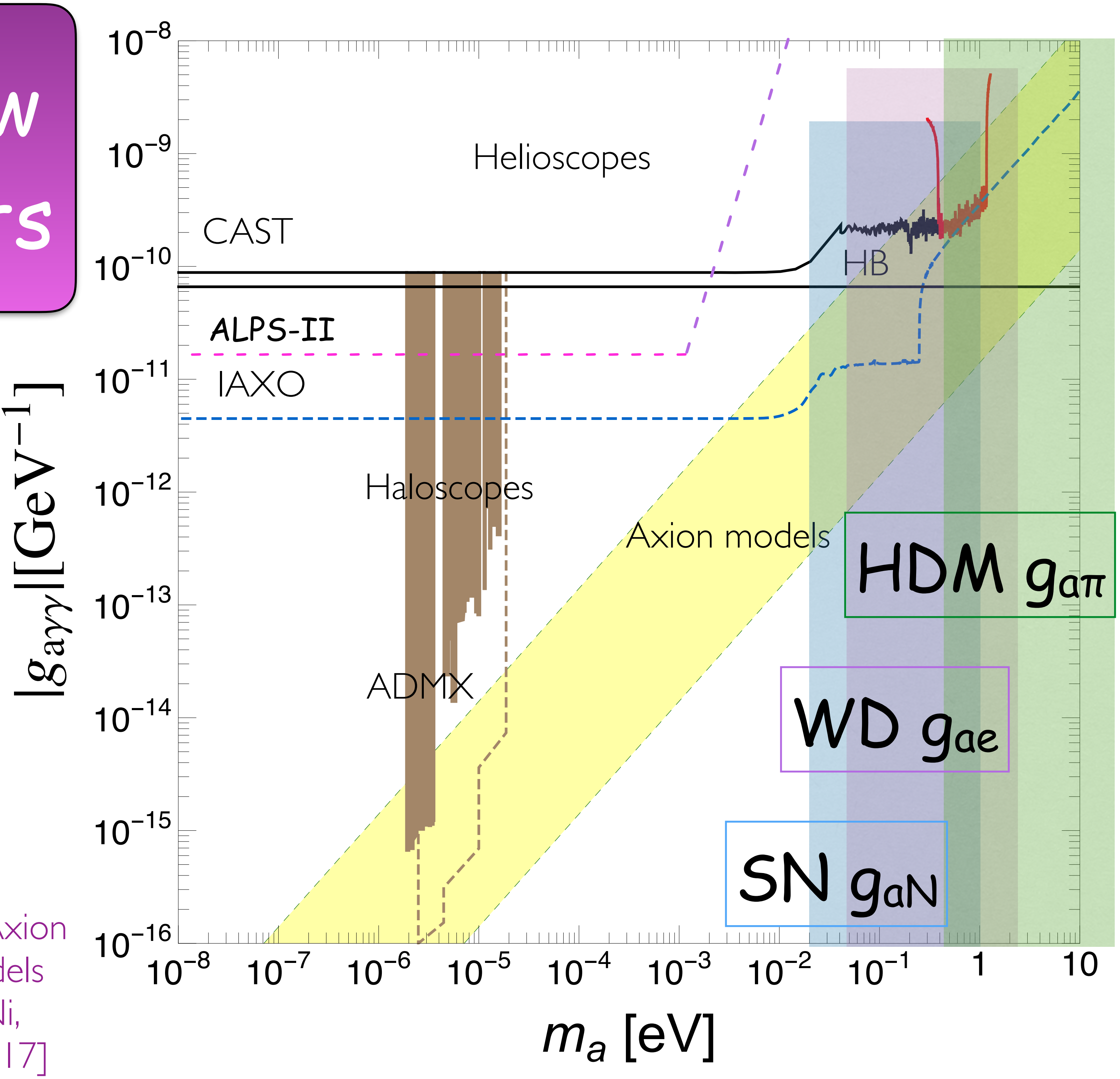
$$g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi}\frac{m_a}{f_\pi m_\pi} \sim \frac{10^{-10}}{\mathrm{GeV}}\left(\frac{m_a}{\mathrm{eV}}\right)$$

Model dependence:

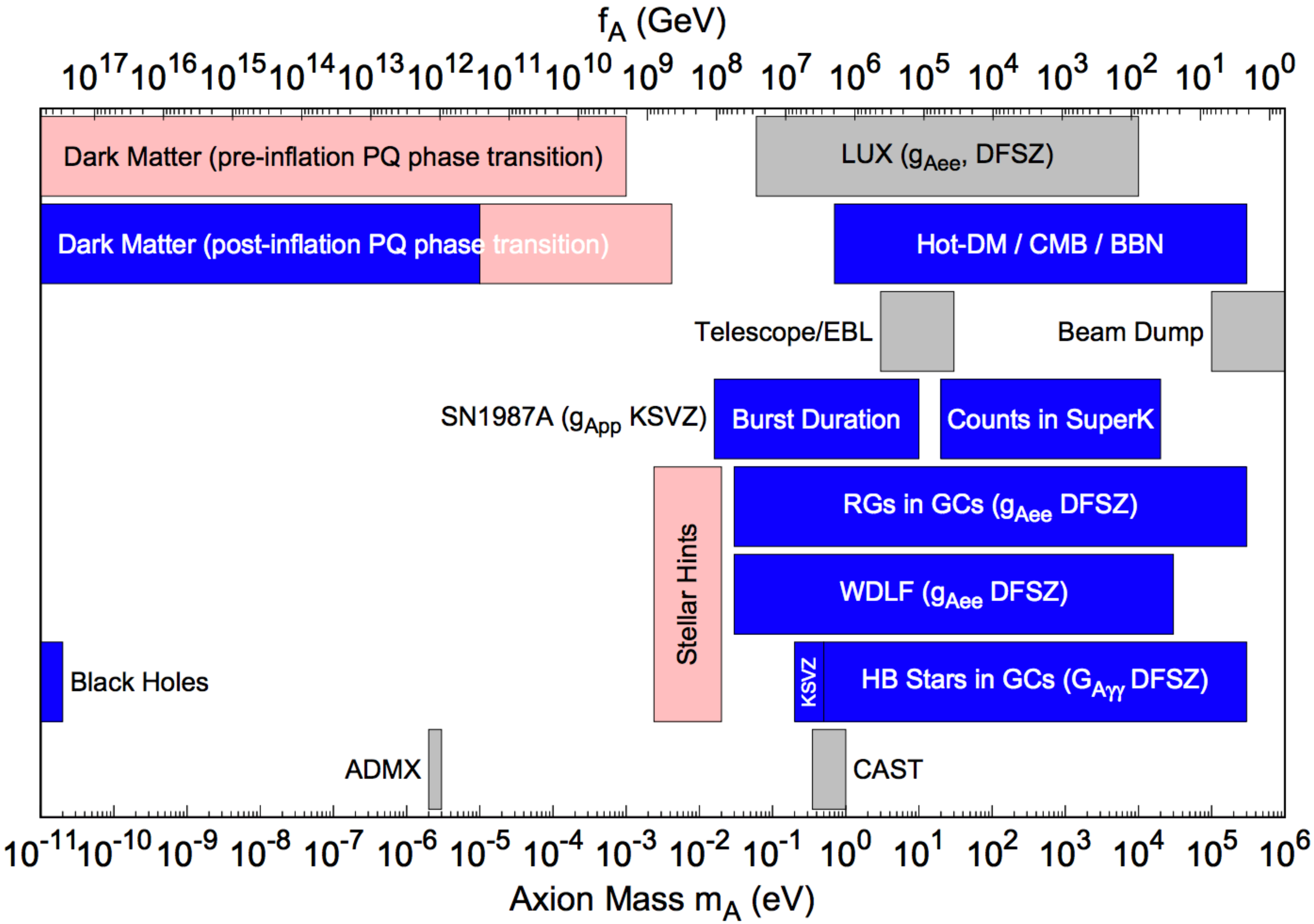
$$g_{a\gamma\gamma} = \frac{m_a}{\mathrm{eV}}\frac{2.0}{10^{10}\ \mathrm{GeV}}\left(\frac{E}{N}-1.92\right)$$

$$|E/N - 1.92| \in [0.07, 7]$$

[Particle Data Group (since the end of 90's): Axion window chosen to include representative models from: Kaplan, NPB 260 (1985); Cheng, Geng, Ni, PRD 52 (1995),; Kim, PRD 58 (1998). New 2017]



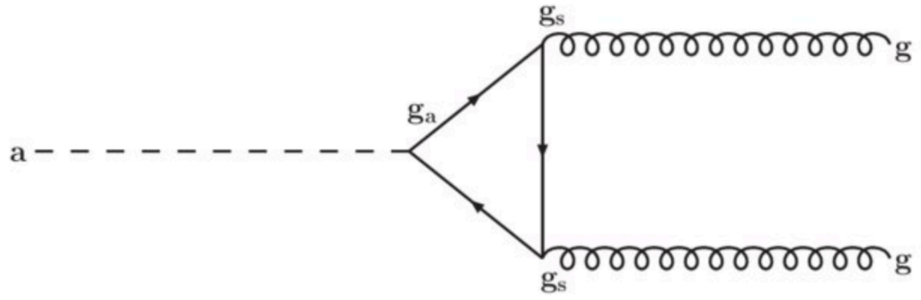
Exclusion Limits: f_a -> m_a (PDG 2017)



Can we have "Astrophobic Axions"? decoupled from Nucleons and from Electrons

Model independent contribution to g_{aN}:

g_{aN} ←



KSVZ axions are decoupled from the leptons $(g_{ae} \approx 0)$
Coupling to nucleons are model independent $(g_{aN} \neq 0)$

DFSZ axions couple to the leptons $(g_{ae} \neq 0)$
Coupling to nucleons nonzero but model dependent $(g_{aN} \neq 0)$

Generalized DFSZ axions can (approximately) decouple from nucleons $(g_{aN} \approx 0)$ and from electrons $(g_{ae} \approx 0)$

The two conditions for "Nucleophobia"

From the UV theory we have: $$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \bar{q}\gamma^\mu\gamma_5 \, q$$

We want: $$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \, \bar{N}\gamma^\mu\gamma_5 \, N$$

C_N in terms of c_q and of matrix elements $s^\mu \Delta_q = \langle N|\bar{q}\gamma^\mu\gamma_5 q|N\rangle$ by matching the matrix elements of $\mathcal{L}_q$ and $\mathcal{L}_N$. One obtains:

$$C_p + C_n = 0.50(5)(C_u^0 + C_d^0 - 1) - 2\delta_s, \qquad |\delta_s| \lesssim 0.04$$

$$C_p - C_n = 1.273(2)\left(C_u^0 - C_d^0 - \frac{1}{3}\right),$$

We want to see if it is possible to set

$$C_u + C_d - 1 \approx 0$$

$$C_u - C_d - 1/3 \approx 0$$

First Condition: $C_u + C_d - 1 = 0$

$$\mathcal{L}_a \supset \frac{a}{f_a}\cancel{\frac{\alpha_s}{8\pi}}G\tilde{G} + \frac{a}{f_a}\frac{\alpha}{8\pi}\frac{E}{N}F\tilde{F} + \frac{\partial_\mu a}{v_a}\left[X_u\,\bar{u}\gamma^\mu\gamma_5 u + X_d\,\bar{d}\gamma^\mu\gamma_5 d\right]$$

$$\left(f_a = \frac{v_a}{2N}\right)$$

$$\frac{\partial_\mu a}{2f_a}\left[\frac{X_u}{N}\,\bar{u}\gamma^\mu\gamma_5 u + \frac{X_d}{N}\,\bar{d}\gamma^\mu\gamma_5 d\right]$$

model independent contributions

$$\frac{E}{N} \to \frac{E}{N} - 1.92(4)\,;\; C_u = \frac{X_u}{N} \to \frac{X_u}{N} - \frac{m_d}{m_u + m_d}\,;\quad C_d = \frac{X_d}{N} \to \frac{X_d}{N} - \frac{m_u}{m_u + m_d}$$

Therefore: $C_p + C_n \sim \frac{X_u + X_d}{N} - 1 = \frac{N_\ell}{N} - 1$

$$\boxed{\xrightarrow[N=n_g(X_u+X_d)]{universality} \quad \frac{1}{n_g} - 1 \neq 0}$$

Nucleophobia unavoidably requires DFSZ-type of models with generation dependent PQ charges, s.t.

$$\boxed{N = N_{(1^{st}gen)}}$$

(and it is not possible for KSVZ-type of models)

Second Condition: $C_u - C_d - 1/3 \approx 0$

$C_p - C_n \sim X_u - X_d - 1/3 \simeq 0$ where: $\frac{1}{3} \simeq \frac{m_d - m_u}{m_d + m_u}$

Scalar content of DFSZ-like models: H_1, H_2, Φ_a with VEVs $v_1, v_2, (v_1^2 + v_2^2 = v^2), v_a$, the PQ charges are X_1, X_2, X_a

Goldstone of Hyperchage: $\varphi_Y = (v_2 \varphi_{H2} - v_1 \varphi_{H1})/v$

To avoid a-φ_Y mixing redefine the charges so that:

$X_1 v_1^2 + X_2 v_2^2 = 0 \longrightarrow X_1/X_2 = - v_2^2/v_1^2$

The choice: $v_2^2/v_1^2=2$ —> $X_u-X_d = X_2-X_1 \approx 1/3$

allows for axion-Nucleons decoupling

WD+RG bounds: Electrophobia $C_e \approx 0$

In DFSZ models leptons carry PQ charges and couple to a(x)

$$\mathcal{L}_a \supset \frac{\partial_\mu a}{2f_a}\left\{\bar{\ell}^0_L\, X_{\ell_L}\, \gamma^\mu\, \ell^0_L \;+\bar{\ell}^0_R\, X_{\ell_R}\, \gamma^\mu\, \ell^0_R\right\}$$

Introduce a Higgs doublet for the Leptons H_3

The axion-NGB(hypercharge) orthogonality condition becomes:

$$X_1 v_1^2 + X_2 v_2^2 + X_3 v_3^2 = 0$$

The previous choice $X_1/X_2 = -v_2^2/v_1^2$ here implies $X_3 v_3^2 = 0$:

$X_3 = 0$ ⟶ leptons decouple from the PQ symmetry: $C_e \approx 0$

Electrophobia needs H_1, H_2, H_3 but no additional conditions

Nucleophobia —> Flavour Violation

Nucleophobia $\Rightarrow$ Generation dependent PQ quark charges $\Rightarrow$ Flavour Violating Axion interactions

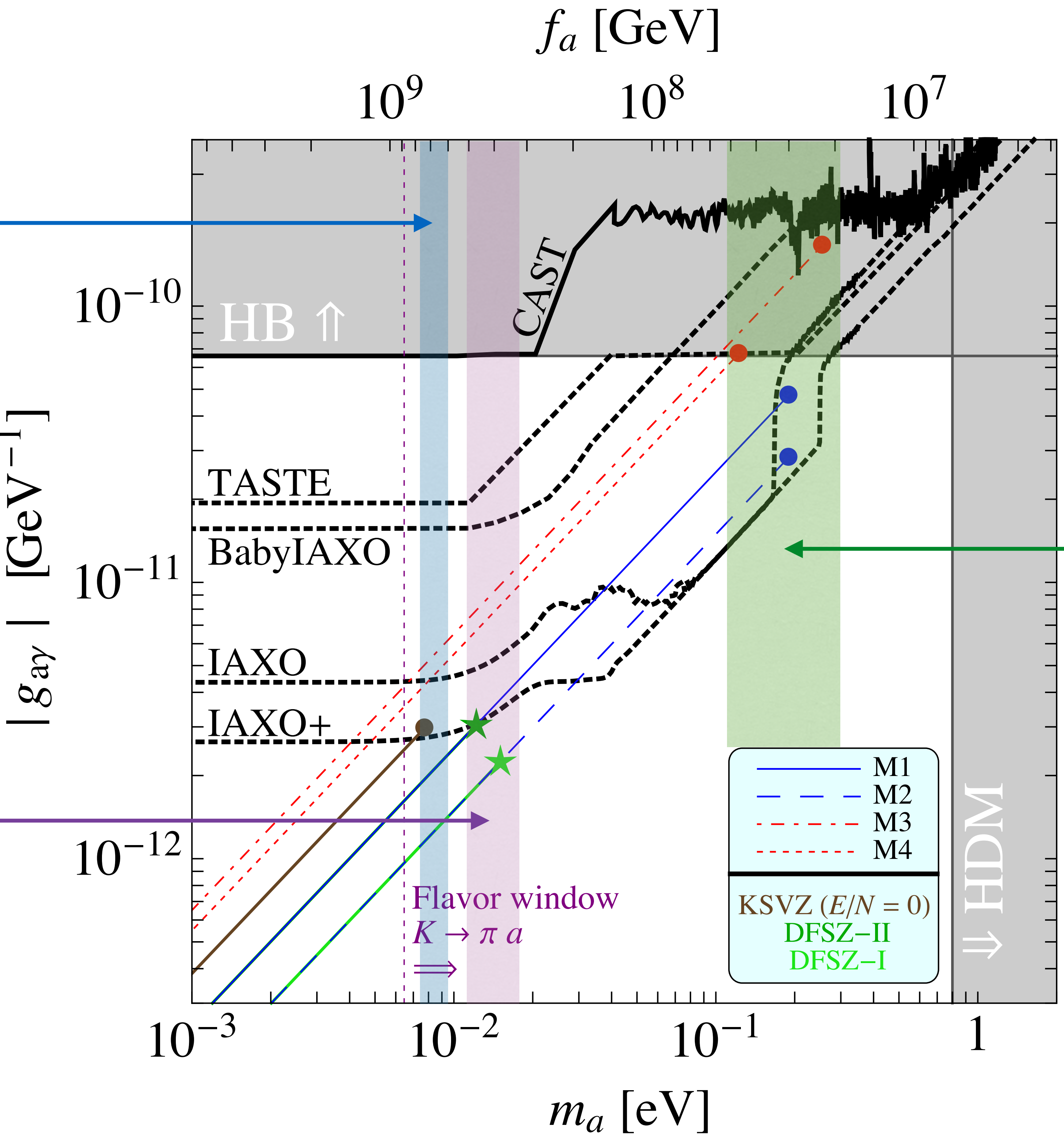
Nucleophobia predicts
$K^+ \to \pi^+ a$, $B^+ \to K^+ a$, etc.

Observable signals for: $f_a \lesssim 2 \cdot 10^9$ GeV ($m_a \gtrsim 6 \cdot 10^{-3}$ eV)

Precision flavour experiments can provide powerful and complementary probes for astrophobic axions

SUMMARY PLOT

KSVZ
SN g_{aN}



DFSZ
SN g_{aN}
WD g_{ae}

Astrophobic
Axions

Conclusions

- The axion hypothesis provides a well motivated BSM scenario

- Theoretical developments are still ongoing

- Healthy and lively experimental program

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  - solves the strong CP problem
  - provides an excellent DM candidate (2 problems at once)
  - it is unambiguously testable by detecting the axion
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- The axion hypothesis provides a well motivated BSM scenario
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  - keep controlled theoretical uncertainties due to “model building”
  - $g_{a\gamma} \approx 0$; $g_{ae} \approx 0$; $g_{aN} \approx 0$ are unexpected phenomenological possibilities
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  - solves the strong CP problem
  - provides an excellent DM candidate
  - is unambiguously testable by detecting the axion
- Theoretical developments are still ongoing
  - keep controlled theoretical uncertainties due to "model building"
  - $g_{a\gamma} \approx 0$; $g_{ae} \approx 0$; $g_{aN} \approx 0$ are indeed phenomenological possibilities
- Healthy and lively experimental program
  - experiments are entering now the preferred window for the QCD axion
  - astrophobic axions: flavour violation experiments can play a crucial role
  - complementarity of different experimental approaches is a must !

Thanks for your attention !