Astrophobic Axions

DMUK Meeting, Durham - 13.07.18

Luca Di Luzio

Based on 1712.04940 (PRL):
with F. Mescia (Barcelona U.), E. Nardi (LNF Frascati), P. Panci (CERN), R. Ziegler (CERN)

Outline

1. Astrophysical axion bounds [critical approach]
2. Axion couplings [in standard axion models]
3. Re-opening the axion window [astrophobia = nucleophobia + electrophobia]
4. Flavour complementarity

Astro axion bounds

- Stars as powerful sources of light and weakly coupled particles

  - light: $m_a \lesssim 10\, T_\star$ (e.g. typical interior temperature of the Sun ~ 1 keV)

  - weakly coupled: otherwise we would have already seen them in labs !

Astro axion bounds

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  - weakly coupled: otherwise we would have already seen them in labs !

- constraints from "energy loss", relevant when more interacting than neutrinos

neutrino interactions (d=6 op.)

$$G_F\, m_e^2 \simeq 10^{-12}$$

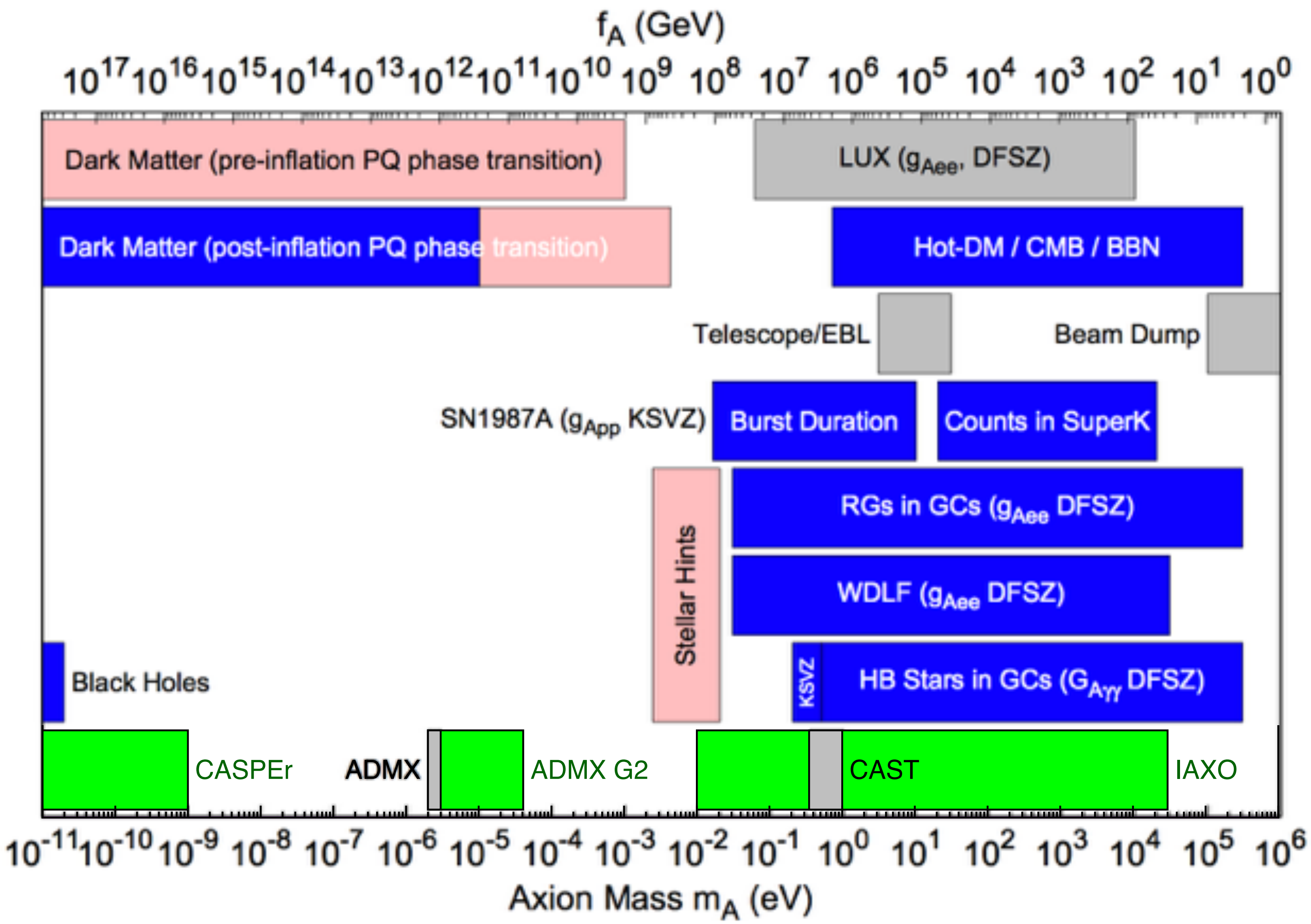
axion interactions (d=5 op.)

$$\frac{m_e}{f_a} \simeq 10^{-12} \left(\frac{10^8 \text{ GeV}}{f_a} \right)$$

→ axions are a perfect example !

$$m_a \sim \Lambda^2_{\text{QCD}} / f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a} \right)$$

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group (2016)]

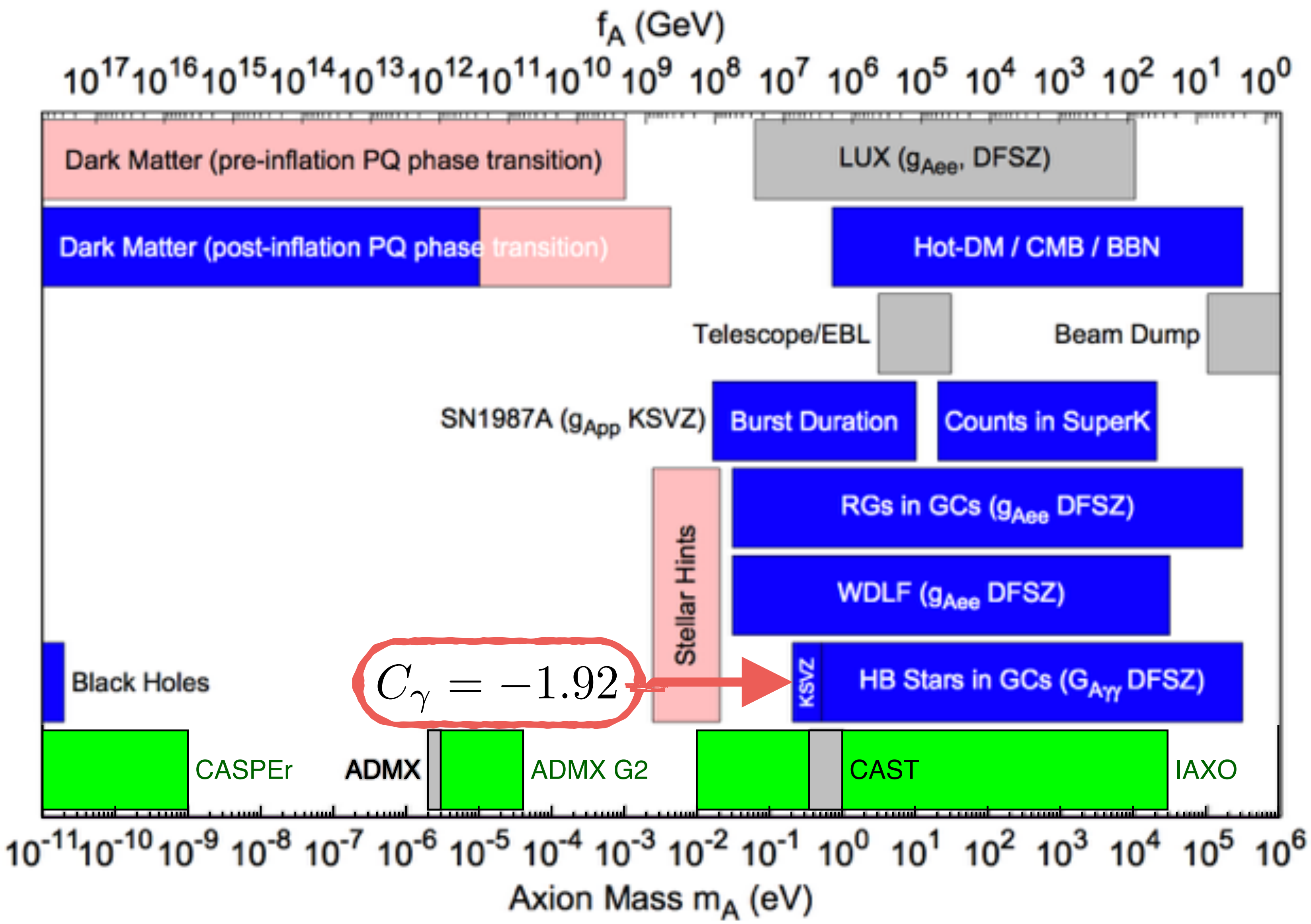
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Axion landscape



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Lab exclusions

Astro/cosmo exclusions

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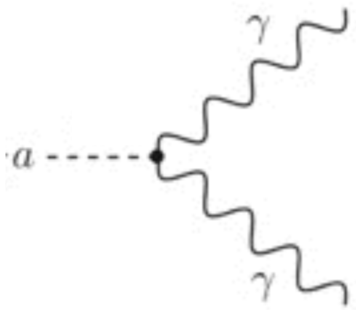
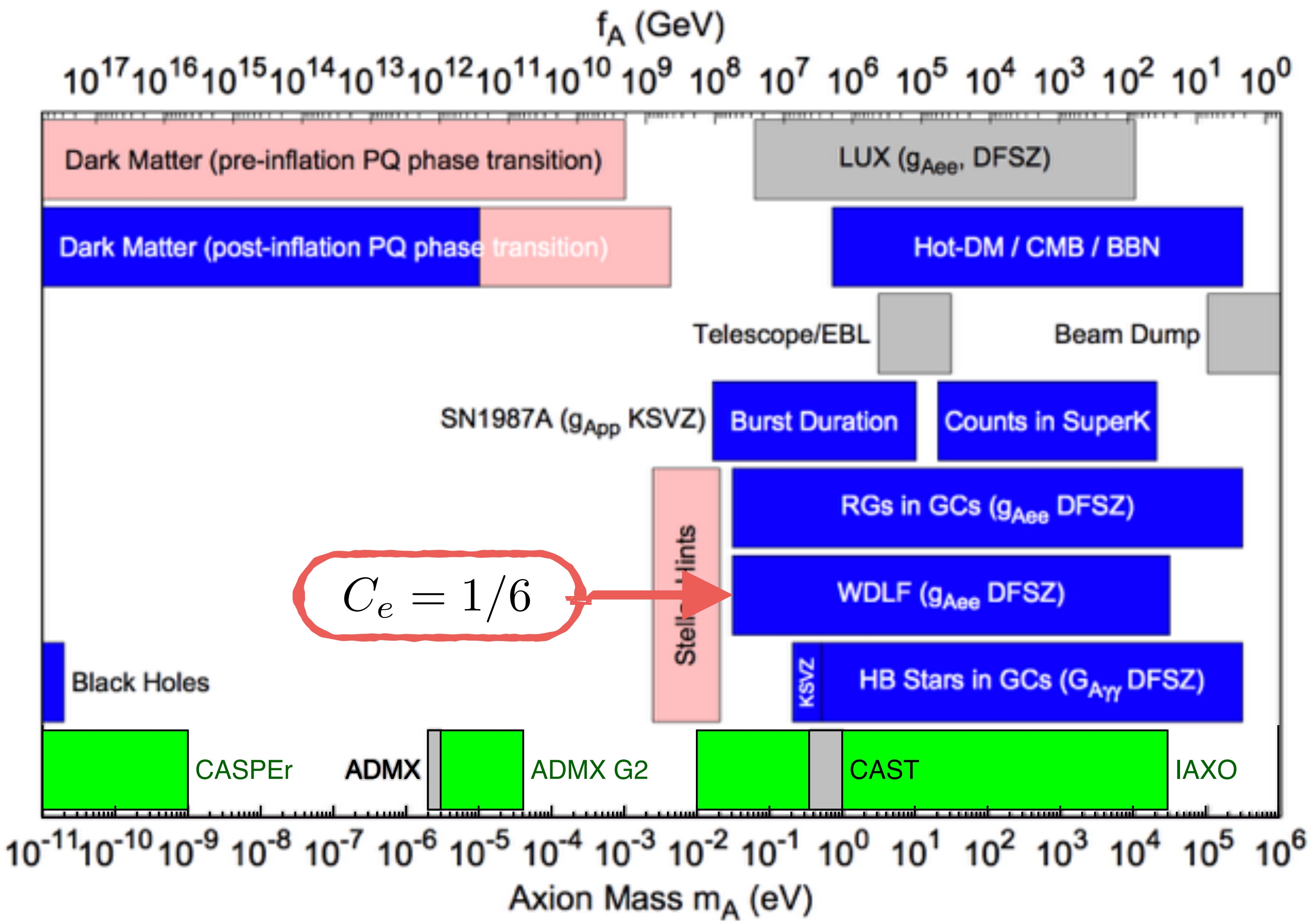
Exp. sensitivities

- Horizontal branch star evolution in globular clusters



$$\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Axion landscape



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Lab exclusions

Astro/cosmo exclusions

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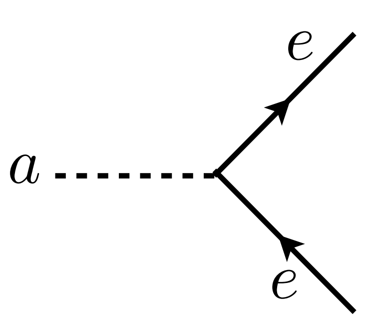
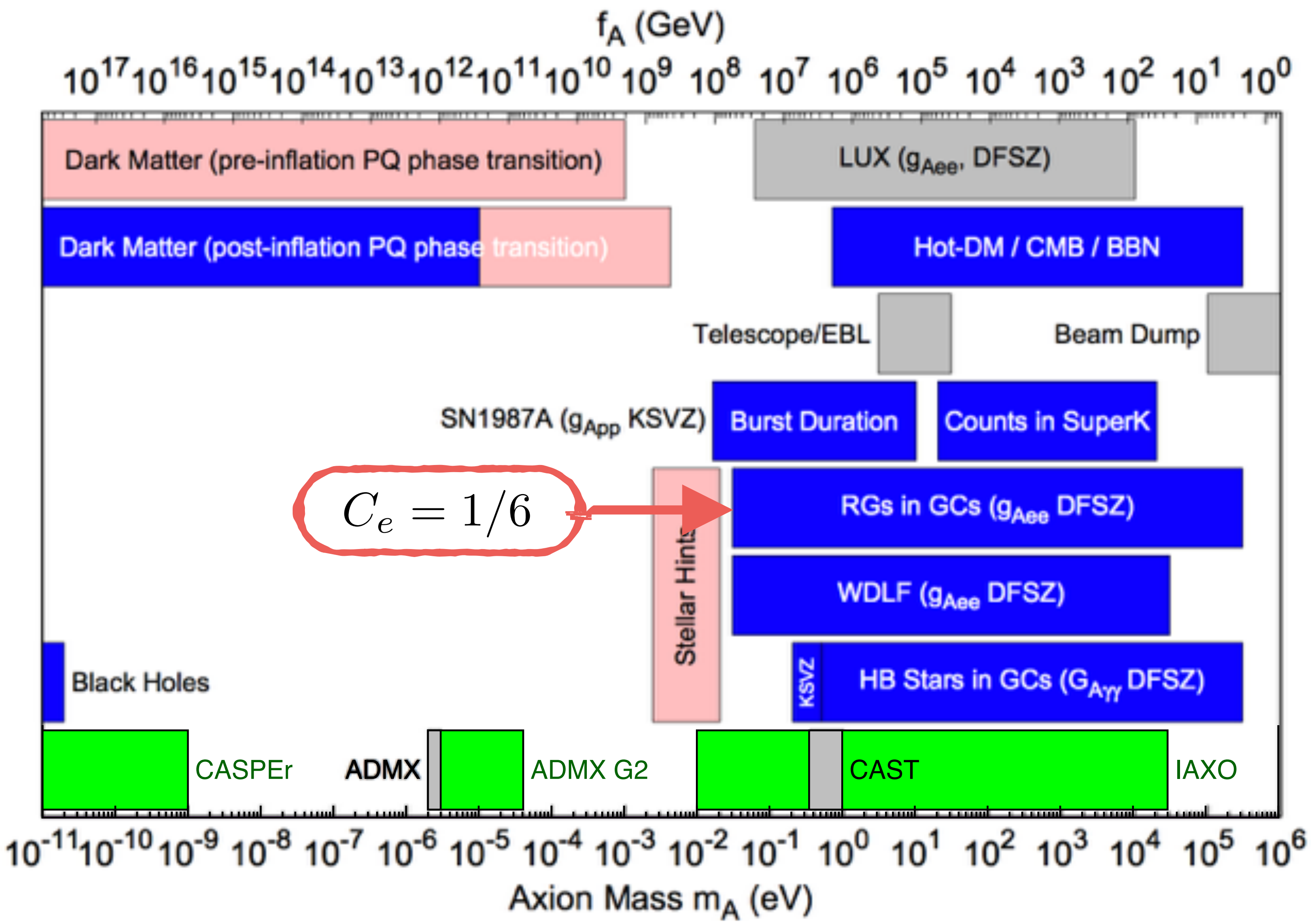
Exp. sensitivities

- White dwarfs luminosity function (cooling)



$$C_e m_e \frac{a}{f_a} [i \bar{e} \gamma_5 e]$$

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group (2016)]

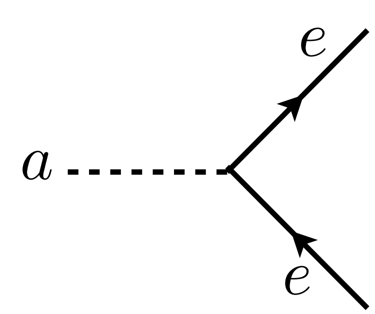
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- Red giants evolution in globular clusters



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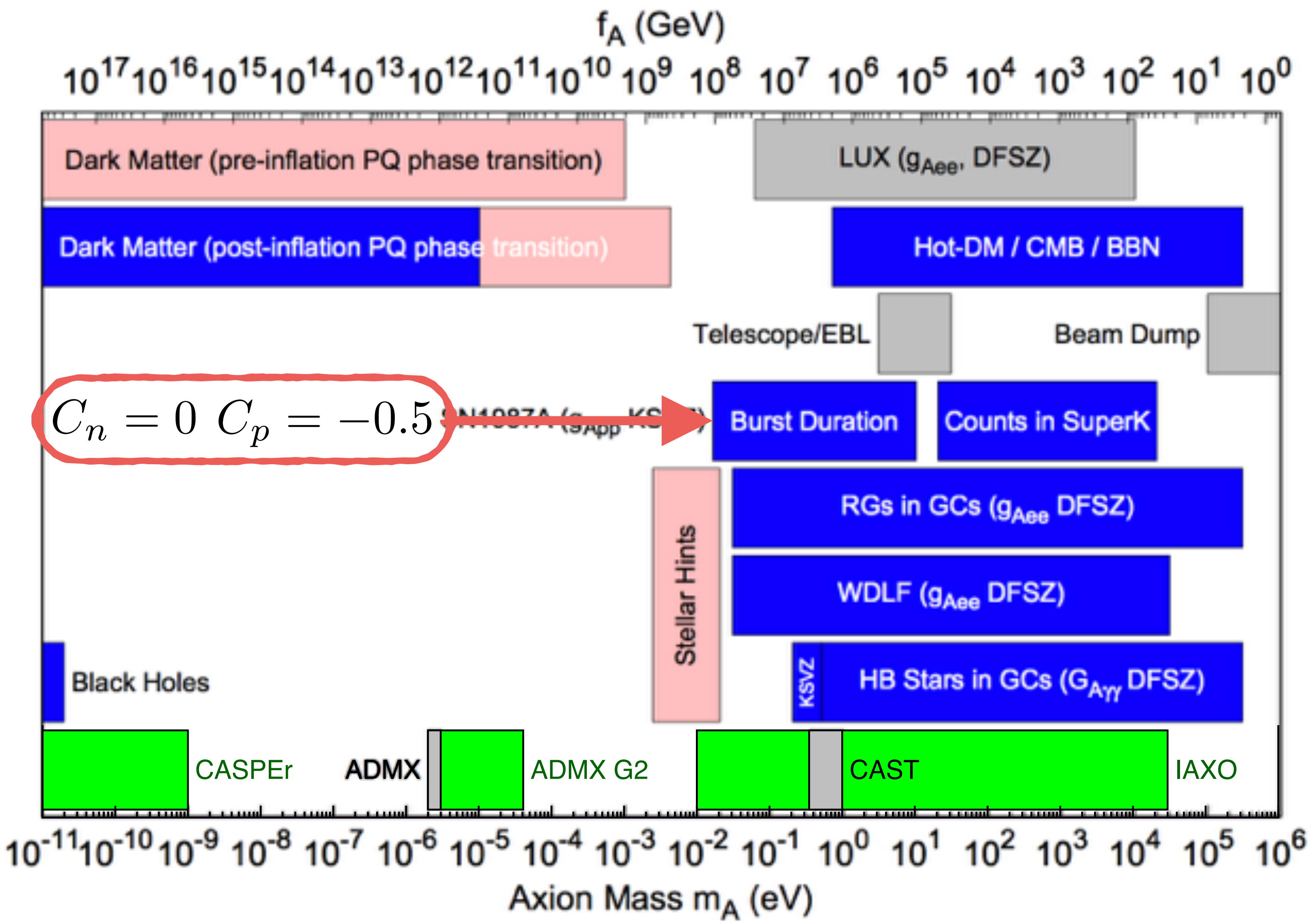
Axion landscape



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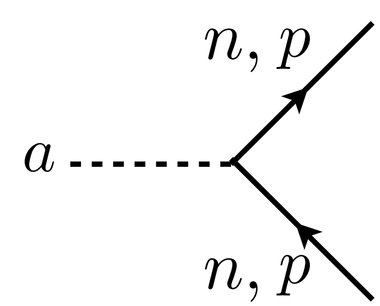
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

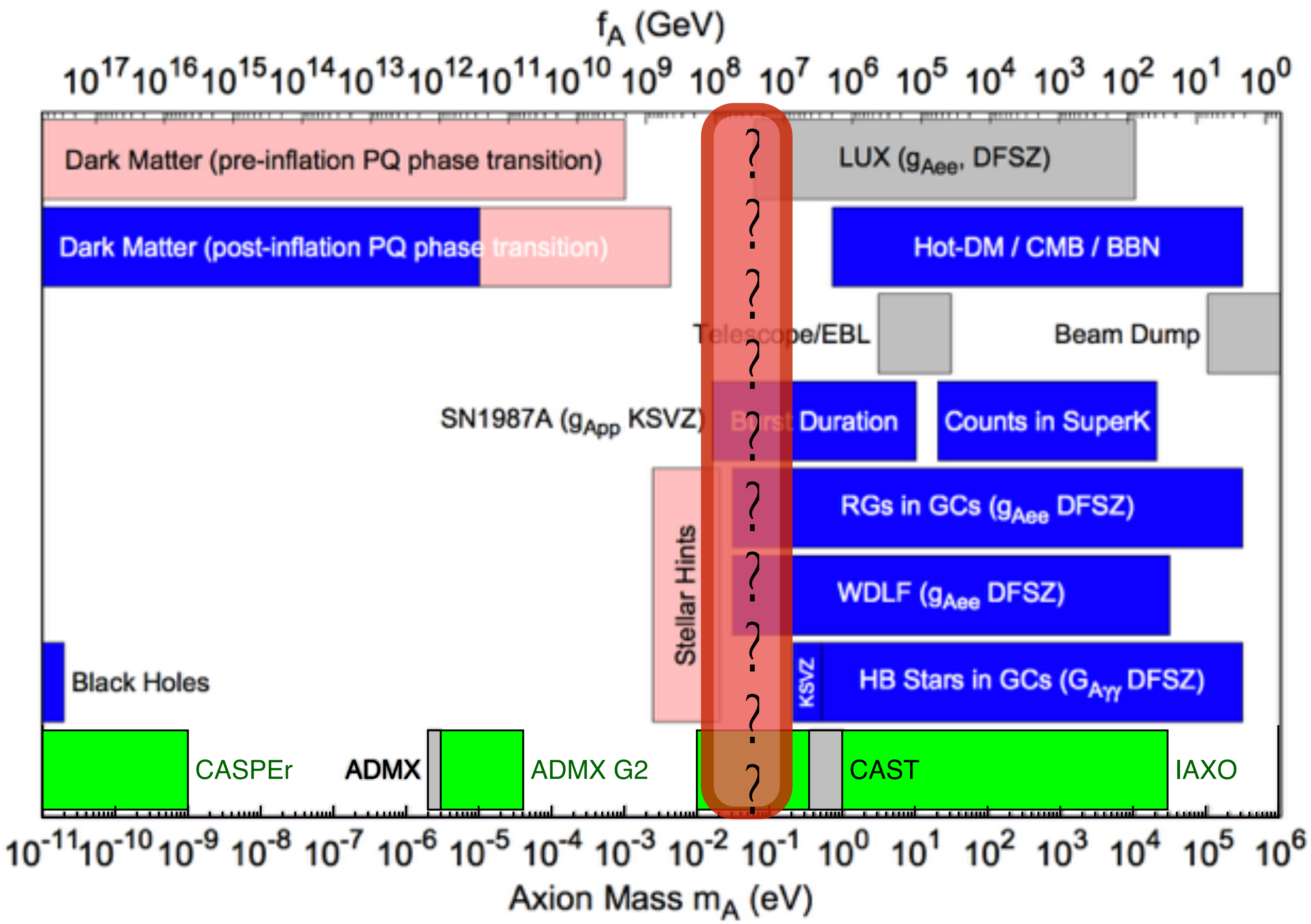
- Burst duration of SN1987A nu signal



$$C_n m_n \frac{a}{f_a} [i\bar{n}\gamma_5 n]$$

$$C_p m_p \frac{a}{f_a} [i\bar{p}\gamma_5 p]$$

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group (2016)]

Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- Bound on axion mass is of practical convenience, but misses model dependence !

Axion models [EFT]

- Only ingredient to wash out strong CP problem is

$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

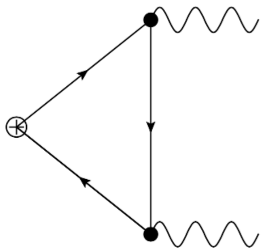
- generates "model independent" axion couplings to photons, nucleons, electrons, …

$$C_\gamma = -1.92(4) \qquad C_p = -0.47(3) \qquad C_n = -0.02(3) \qquad C_e \simeq 0$$

[Theoretical errors from Grilli di Cortona et al., 1511.02867]

- EFT breaks down at energies of order f_a

→ UV completion can still affect low-energy axion properties !



Axion models [UV completion]

- Axion as a PGB of QCD-anomalous global $U(1)_{PQ}$:

anomalous PQ breaking (fermion sector) + spontaneous PQ breaking (scalar sector)

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

SM fermions — BSM fermions

2Higgs	2Higgs+Singlet	Higgs+Singlet
PQWW	DFSZ	KSVZ
[Peccei, Quinn '77, Weinberg '78, Wilczek '78]	[Zhitnitsky '80, Dine, Fischler, Srednicki '81]	[Kim '79, Shifman, Vainshtein, Zakharov '80]

EXCLUDED

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

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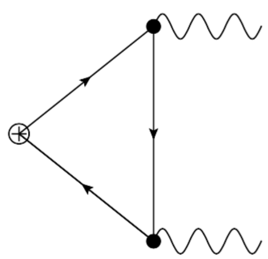
$$U(1)_{\rm PQ} \times SU(3)_c^2$$

SM fermions | BSM fermions

2Higgs+Singlet | Higgs+Singlet

$C_\gamma = E/N - 1.92(4)$

DFSZ | KSVZ



$C_{p,n,e} \neq 0$

$C_p \simeq -0.5$

$C_{n,e} \simeq 0$

Astrophobia

- Is it possible to decouple the axion both from nucleons and electrons ?

→ nucleophobia + electrophobia = astrophobia

- Why interested in such constructions ? [LDL, Mescia, Nardi, Panci, Ziegler 1712.04940]

1. is it possible at all ?
2. would allow to relax the upper bound on axion mass by ~ 1 order of magnitude
3. would improve visibility at IAXO (axion-photon)
4. would improve fit to stellar cooling anomalies (axion-electron) [Giannotti et al. 1708.02111]
5. unexpected connection with flavour

Astrophobia

- Is it possible to decouple the axion both from nucleons and electrons ?

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- Electrophobia

  - conceptually easy (e.g. couple the electron to 3rd Higgs uncharged under PQ)

Astrophobia

- Is it possible to decouple the axion both from nucleons and electrons ?

→ nucleophobia + electrophobia = astrophobia

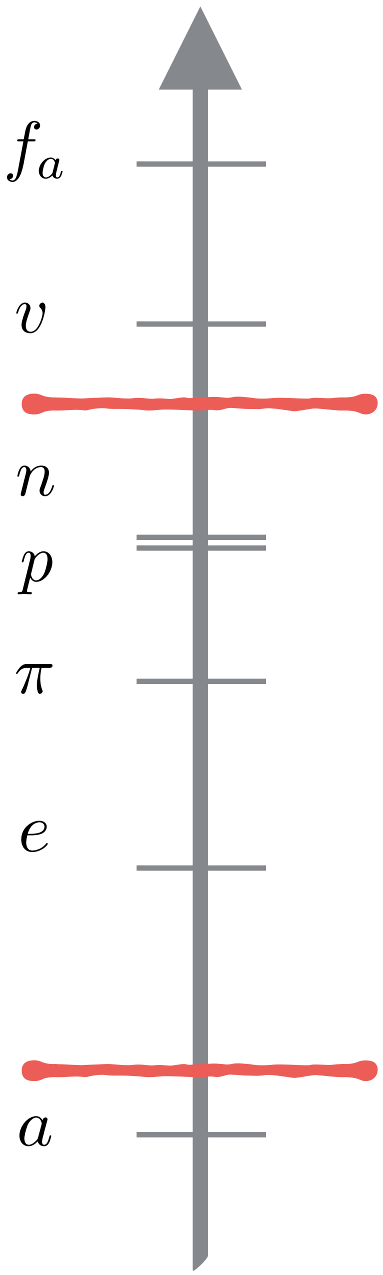
- Nucleophobia

  - is the real bottleneck !

Conditions for nucleophobia

- Axion-nucleons couplings

[Kaplan NPB 260 (1985), Srednicki NPB 260 (1985), Georgi, Kaplan, Randall PLB 169 (1986), …, Grilli di Cortona et al. 1511.02867]



$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \overline{q} \gamma^\mu \gamma_5 q \qquad q = (u, d, s, \ldots)$$

EFT-I: quarks and gluons (in the basis where c_q contains aGGtilde contrib.)

$$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \overline{N} S^\mu N \qquad N = (p, n)$$

EFT-II: non-relativistic nucleons

Conditions for nucleophobia

- Axion-nucleons couplings

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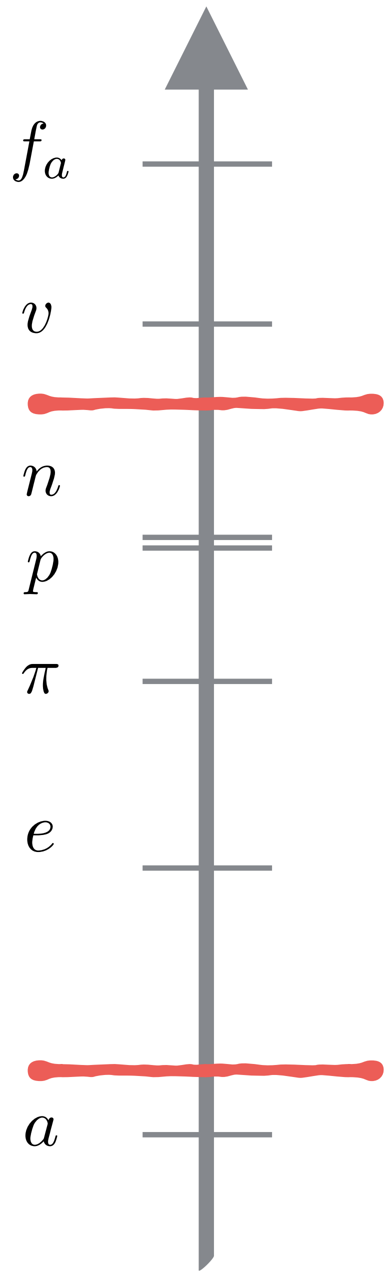

$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \overline{q} \gamma^\mu \gamma_5 q$$

$$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \overline{N} S^\mu N$$

$$\langle p | \mathcal{L}_q | p \rangle = \langle p | \mathcal{L}_N | p \rangle$$

$$\Big\downarrow \quad s^\mu \Delta q \equiv \langle p | \overline{q} \gamma_\mu \gamma_5 q | p \rangle$$

$$\begin{aligned} C_p + C_n &= (c_u + c_d)(\Delta_u + \Delta_d) - 2\delta_s \qquad [\delta_s \approx 5\%] \\ C_p - C_n &= (c_u - c_d)(\Delta_u - \Delta_d) \end{aligned}$$

Independently of matrix elements:

$$\begin{aligned} (1): \quad C_p + C_n &\approx 0 \quad \text{if} \quad c_u + c_d = 0 \\ (2): \quad C_p - C_n &= 0 \quad \text{if} \quad c_u - c_d = 0 \end{aligned}$$

A no-go in KSVZ & DFSZ

$$\mathcal{L}_a \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} + \frac{\partial_\mu a}{v_{PQ}}\left[X_u\,\overline{u}\gamma^\mu\gamma_5 u + X_d\,\overline{d}\gamma^\mu\gamma_5 d\right]$$

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$$\left(f_a = \frac{v_{PQ}}{2N} \right) \qquad \frac{\partial_\mu a}{2 f_a} \left[\frac{X_u}{N} \, \overline{u}\gamma^\mu \gamma_5 u + \frac{X_d}{N} \, \overline{d}\gamma^\mu \gamma_5 d \right]$$

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$$\downarrow$$

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

$$\longrightarrow \quad \frac{X_u}{N} \to c_u = \frac{X_u}{N} - \frac{m_d}{m_d + m_u} \qquad \frac{X_d}{N} \to c_d = \frac{X_d}{N} - \frac{m_u}{m_d + m_u}$$

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

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1st condition $\quad 0 = c_u + c_d = \dfrac{X_u + X_d}{N} - 1 \quad$ ✗

2nd condition $\quad 0 = c_u - c_d = \dfrac{X_u - X_d}{N} - \underbrace{\dfrac{m_d - m_u}{m_d + m_u}}_{\simeq 1/3} \quad$ ✔

A no-go in KSVZ & DFSZ

1st condition $0 = c_u + c_d = \frac{X_u + X_d}{N} - 1$

$$\left\{ \begin{array}{l} \xrightarrow[X_u = X_d = 0]{\text{KSVZ}} \qquad -1 \\ \\ \xrightarrow[N = n_g (X_u + X_d)]{\text{DFSZ}} \qquad \frac{1}{n_g} - 1 \end{array} \right.$$

A no-go in KSVZ & DFSZ

Nucleophobia <u>requires</u> DFSZ models with non-universal (i.e. generation dependent) PQ charges, such that

$$\boxed{N = N_1 \equiv X_u + X_d}$$

1st condition $\quad 0 = c_u + c_d = \dfrac{X_u + X_d}{N} - 1 \quad \begin{cases} \xrightarrow[X_u = X_d = 0]{\text{KSVZ}} & -1 \\ \\ \xrightarrow[N = n_g (X_u + X_d)]{\text{DFSZ}} & \dfrac{1}{n_g} - 1 \end{cases}$

Implementing nucleophobia

- Simplification: assume 2+1 structure $X_{q_1} = X_{q_2} \neq X_{q_3}$

$$N \equiv N_1 + N_2 + N_3 = N_1 \quad \longrightarrow \quad N_1 = N_2 = -N_3$$

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- $N_1 + N_3 = 0$ easy to implement with 2HDM (H_1, H_2, $Y(H_{1,2}) = -1/2$)

$$\mathcal{L}_Y \supset \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 ... + \ldots) + \bar{q}_2 u_2 H_2 + \bar{q}_2 d_2 \tilde{H}_1 + (\bar{q}_2 d_3 ... + \ldots)$$

$$\Rightarrow \mathcal{N}_{3rd} = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2$$
$$\Rightarrow \mathcal{N}_{2nd} = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1$$

- 1st condition automatically satisfied

Implementing nucleophobia

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$$\boxed{\begin{aligned} \mathcal{L}_Y \supset \; & \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 ... + \ldots) \\ + \; & \bar{q}_2 u_2 H_2 + \bar{q}_2 d_2 \tilde{H}_1 + (\bar{q}_2 d_3 ... + \ldots) \end{aligned}} \quad \boxed{\begin{aligned} &\Rightarrow \; \mathcal{N}_{3rd} = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2 \\ &\Rightarrow \; \mathcal{N}_{2nd} = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1 \end{aligned}}$$

- 2nd condition can be implemented via a 10% tuning

$$\tan\beta = v_2/v_1$$

$$X_1/X_2 = -\tan^2\beta$$

$$c_u - c_d = \underbrace{\frac{X_u - X_d}{N}}_{c_\beta^2 - s_\beta^2} - \underbrace{\frac{m_d - m_u}{m_u + m_d}}_{\simeq \frac{1}{3}} = 0 \quad \longrightarrow \quad c_\beta^2 \simeq 2/3$$

Flavour connection

- Nucleophobia implies flavour violating axion couplings !

$$[\mathrm{PQ}_d, Y_d^\dagger Y_d] \neq 0 \quad \longrightarrow \quad C_{ad_id_j} \propto (V_d^\dagger\, \mathrm{PQ}_d V_d)_{i\neq j} \neq 0$$

e.g. RH down rotations become physical

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e.g. RH down rotations become physical

- Plethora of low-energy flavour experiments probing $\frac{\partial_\mu a}{2f_a} \overline{f}_i \gamma^\mu (C_{ij}^V + C_{ij}^A \gamma_5) f_j$

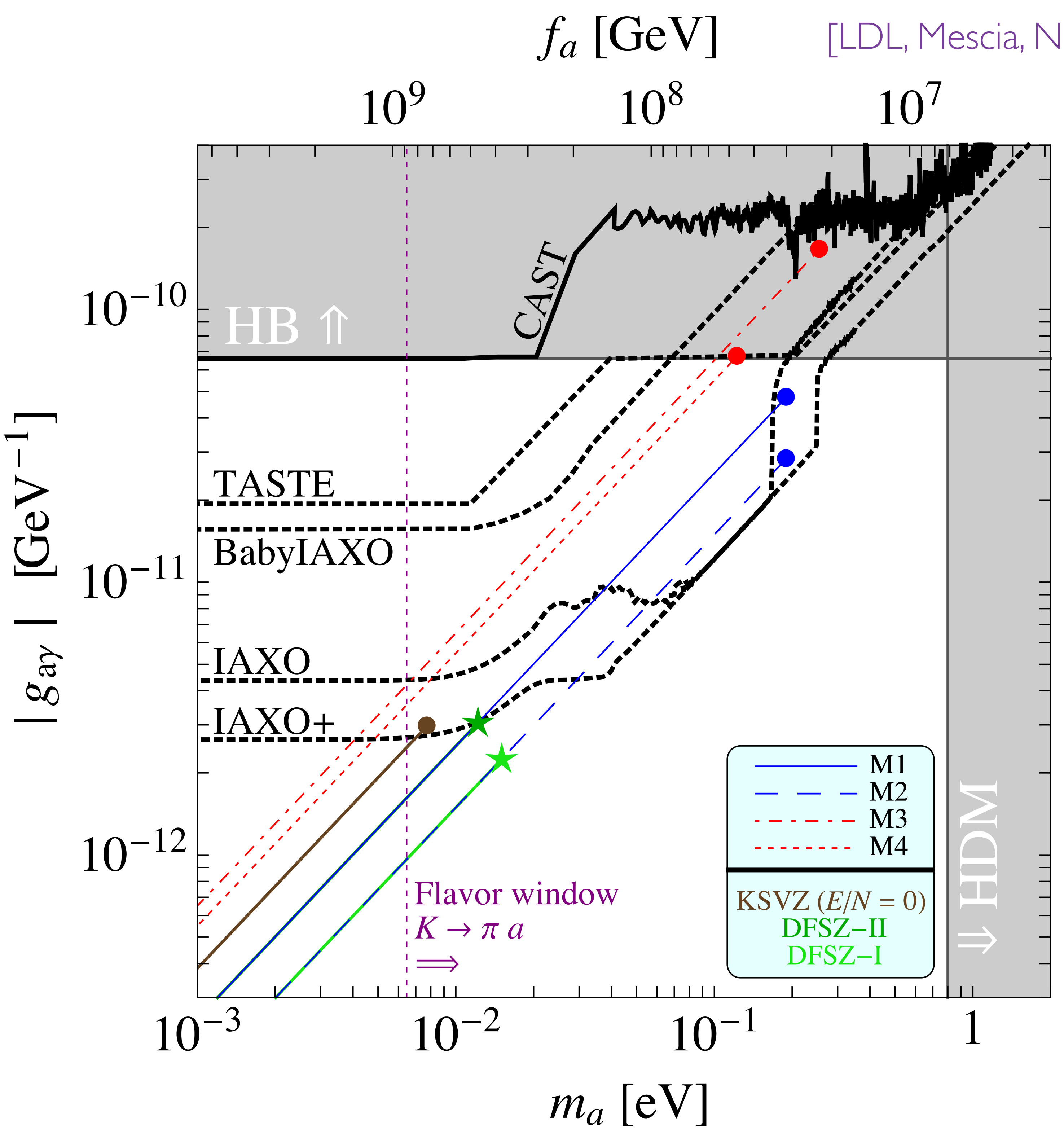
- $K \to \pi a \;:\; m_a < 1.0 \times 10^{-4} \frac{\mathrm{eV}}{|C_{sd}^V|}$ [E787, E949 @ BNL, 0709.1000] $\longrightarrow$ NA62

- $B \to K a \;:\; m_a < 3.7 \times 10^{-2} \frac{\mathrm{eV}}{|C_{bs}^V|}$ [Babar, 1303.7465] $\longrightarrow$ Belle-II

- $\mu \to e a \;:\; m_a < 3.4 \times 10^{-3} \frac{\mathrm{eV}}{\sqrt{|C_{bd}^V|^2 + |C_{bd}^V|^2}}$ [Crystal Box @ Los Alamos, Bolton et al PRD38 (1988)]

Astrophobic axion models

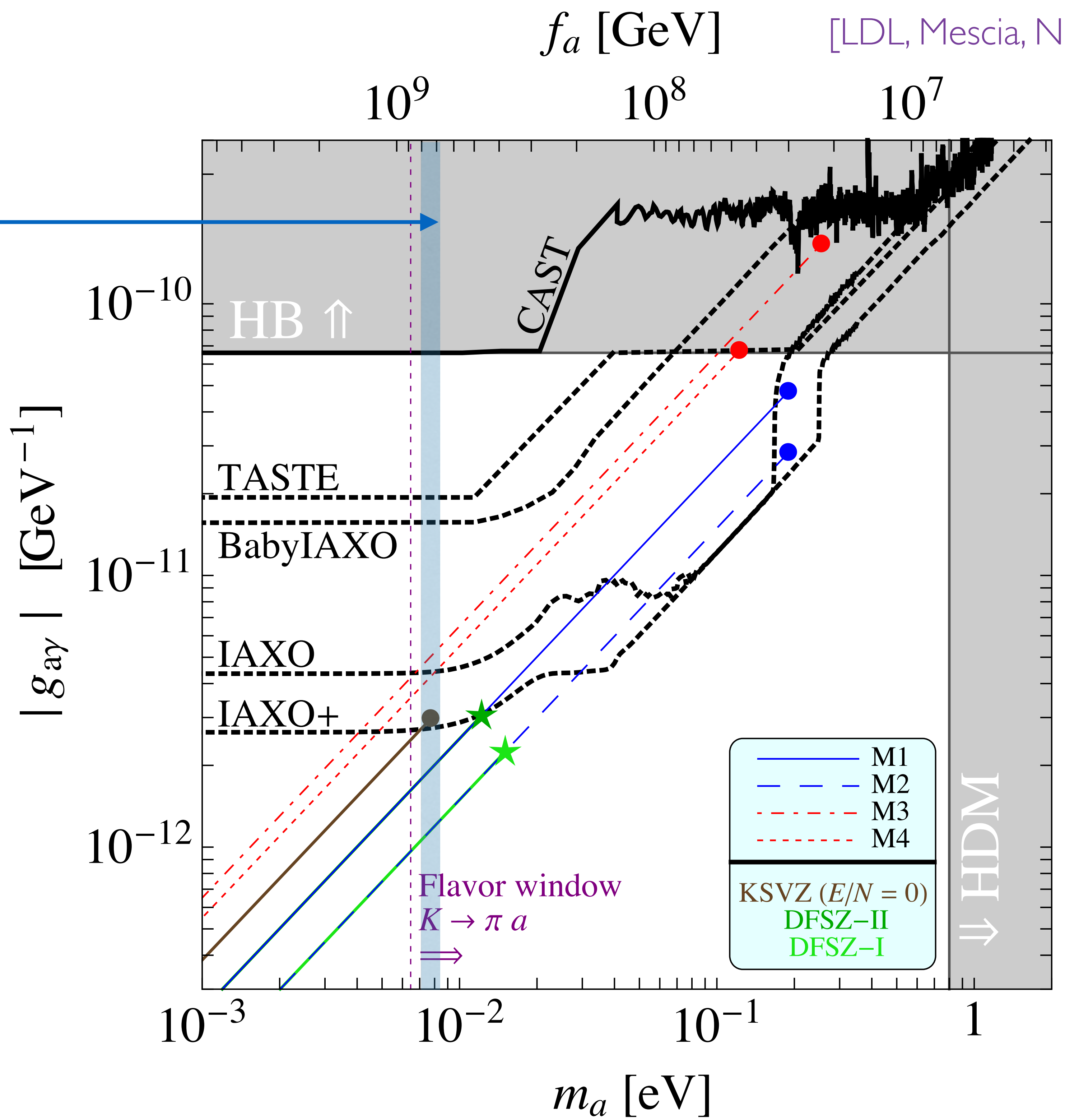
[LDL, Mescia, Nardi, Panci, Ziegler 1712.04940]



Astrophobic axion models

[LDL, Mescia, Nardi, Panci, Ziegler 1712.04940]

KSVZ



Astrophobic axion models

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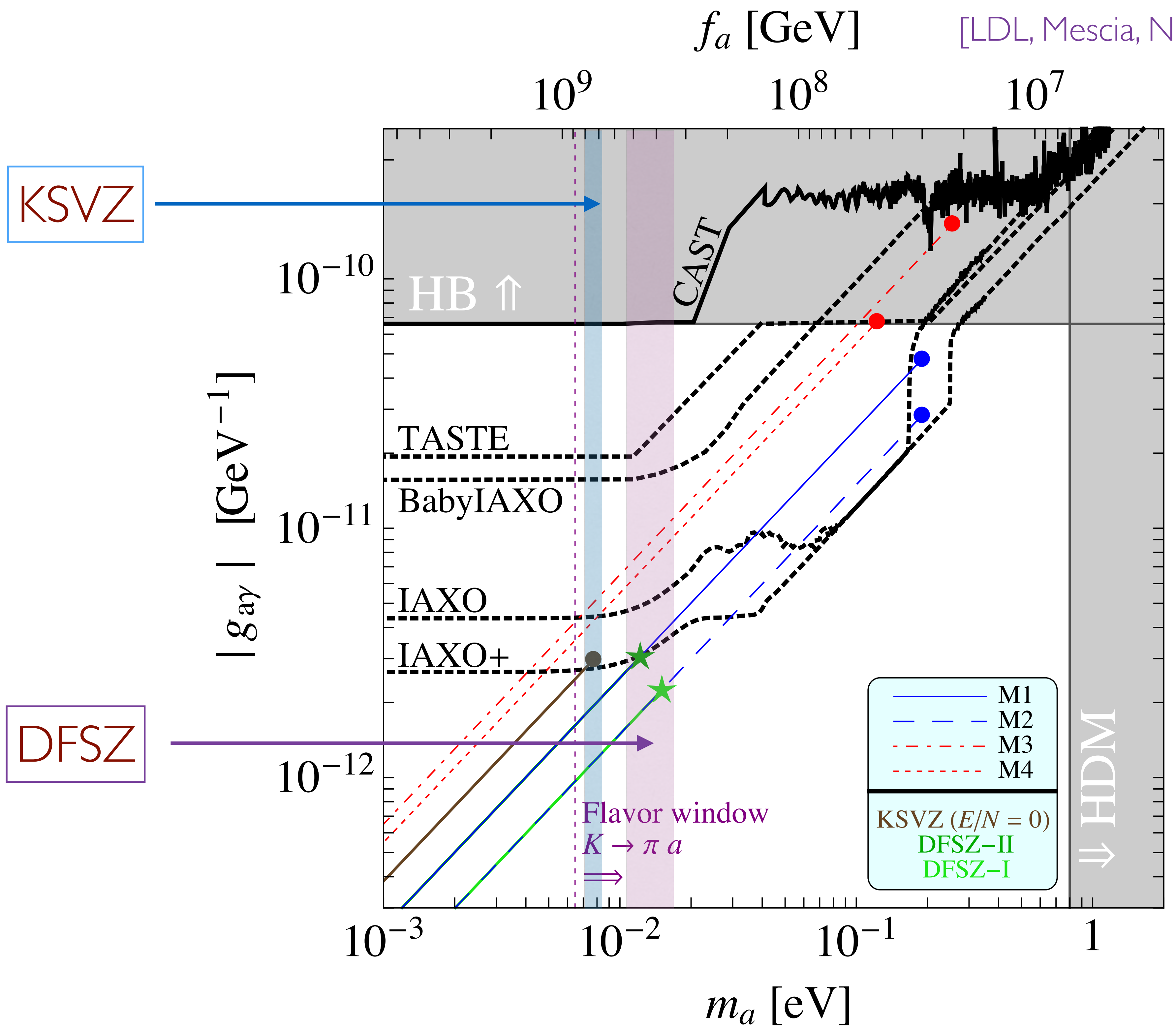

Astrophobic axion models

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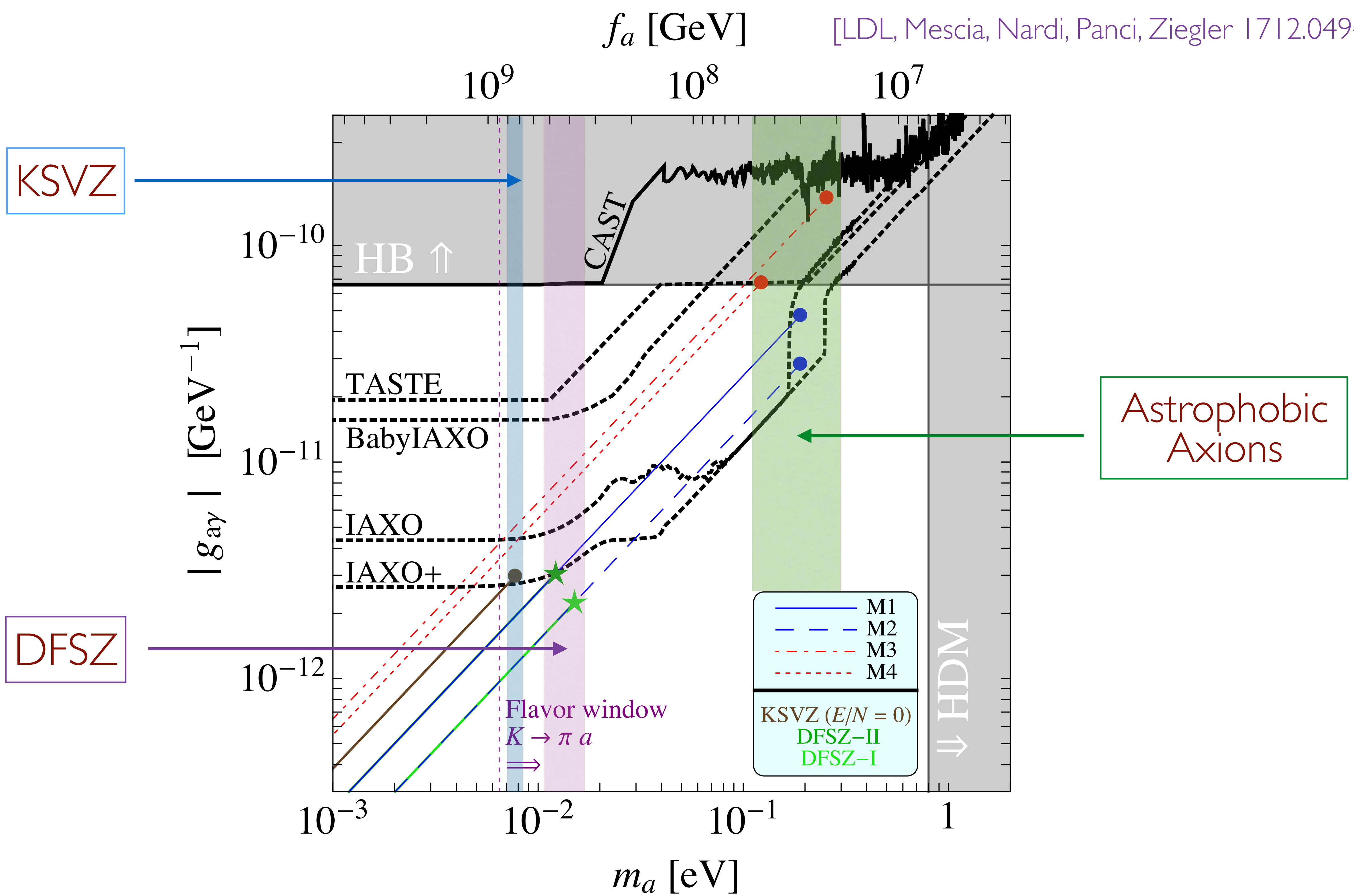


Conclusions

- KSVZ and DFSZ are well-motivated minimal benchmarks, but…

  - axion couplings are essentially UV dependent

  - worth to think about alternatives when confronting exp. bounds and sensitivities

- Astrophobic Axions (suppressed couplings to nucleons and electrons)

  1. relax astro bounds on axion mass by ~ 1 order of magnitude

  2. improve visibility at IAXO

  3. improve fit to stellar cooling anomalies

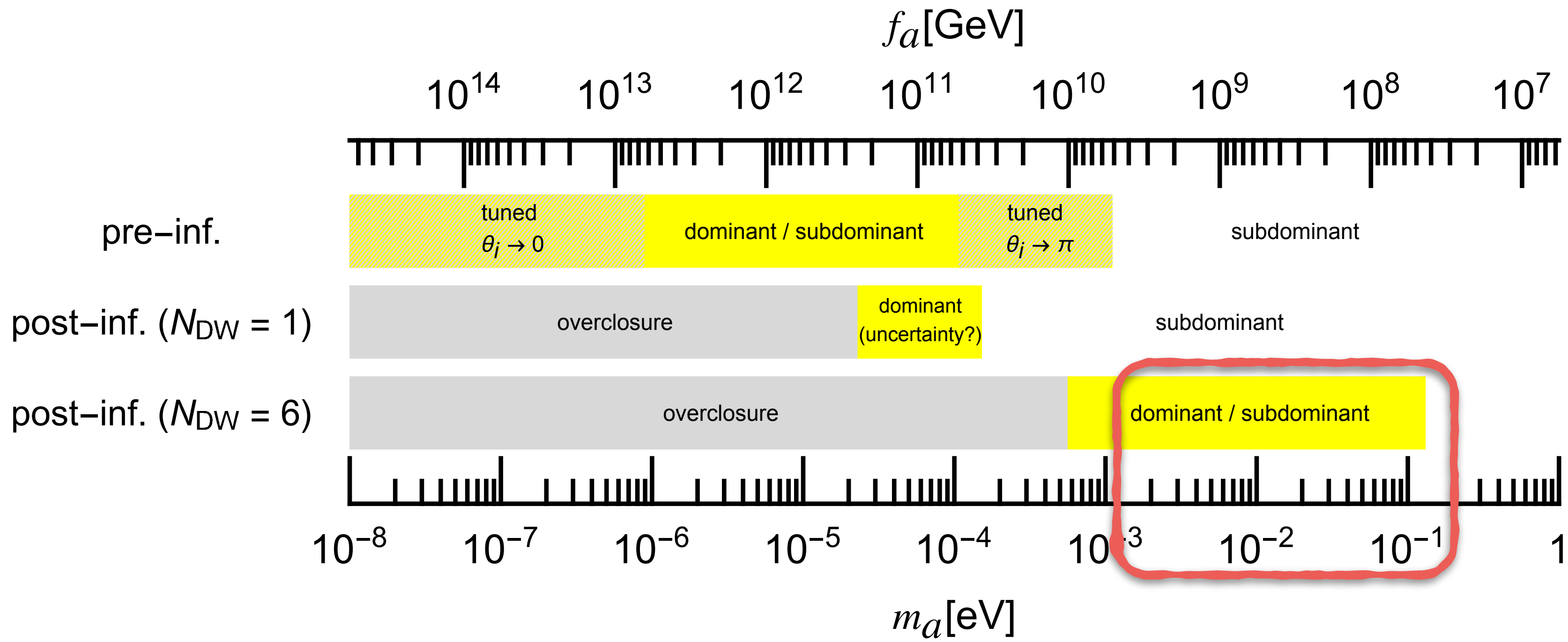
  4. can be complementarily tested in axion flavour exp.

Backup slides

DM in the heavy axion window

- Post-inflationary PQ breaking with $N_{DW} \neq 1$

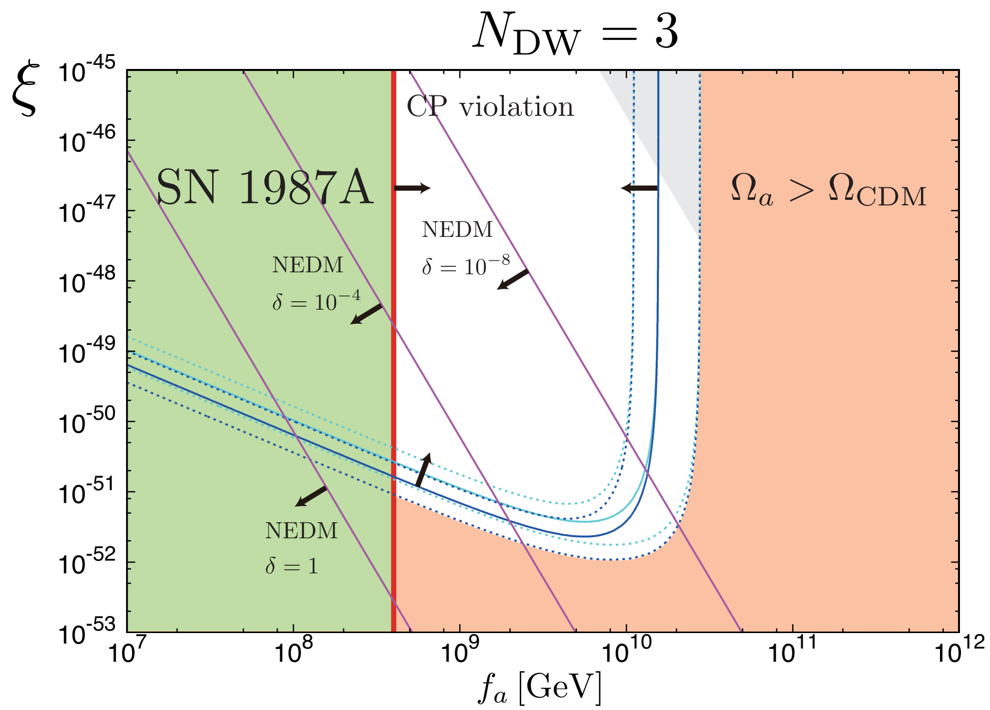
[Kawasaki, Saikawa, Sekiguchi, 1412.0789 1709.07091]



- axion production from topological defects

- requires explicit PQ breaking term

$$\Delta V \sim -\xi f_a^3 \Phi e^{-i\delta} + \text{h.c.}$$

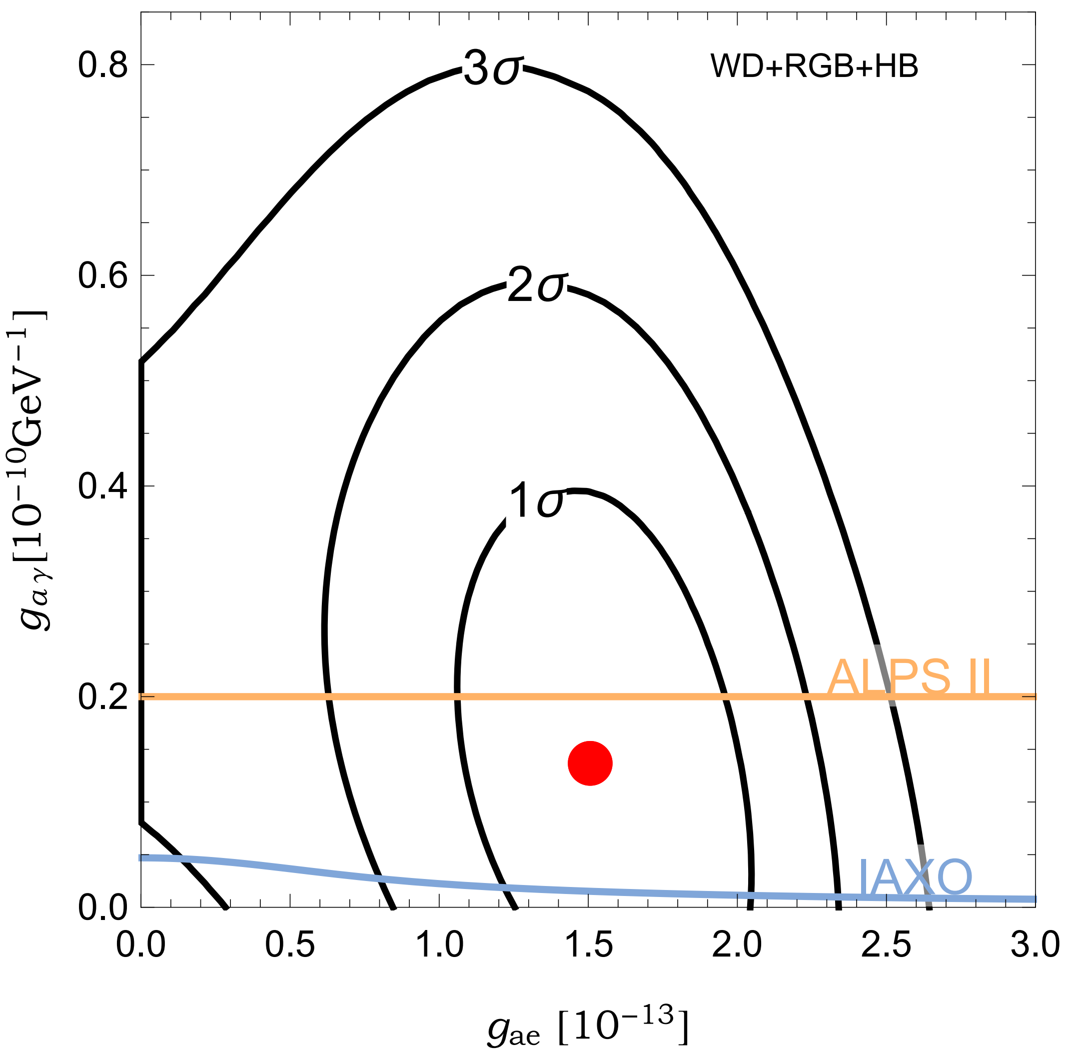


Stellar cooling anomalies

- Hints of excessive cooling in WD+RGB+HB can be explained via an axion

  - requires a sizeable axion-electron coupling in a region disfavoured by SN bound*

[Giannotti et al. 1708.02111]



Model	Global fit includes	f_a $[10^8$ GeV$]$	m_a [meV]	$\tan\beta$	$\chi^2_{\min}$/d.o.f.
DFSZ I	WD,RGB,HB	0.77	74	0.28	14.9/15
	WD,RGB,HB,SN	11	5.3	140	16.3/16
	WD,RGB,HB,SN,NS	9.9	5.8	140	19.2/17
DFSZ II	WD,RGB,HB	1.2	46	2.7	14.9/15
	WD,RGB,HB,SN	9.5	6.0	0.28	15.3/16
	WD,RGB,HB,SN,NS	9.1	6.3	0.28	21.3/17

Nucleophobic axion improves fit…

*SN bound a factor ~4 weaker than PDG one ?

[Chang, Essig, McDermott 1803.00993]

Summary axion-photon

Region of 'realistic' KSVZ/DFSZ axion models

Going above red line requires either:

i) very exotic constructions

ii) tuning $\theta_0 \ll 1$ (KSVZ pre-inflat.)

Going below blue line requires a 'tuning in theory space' < 2%