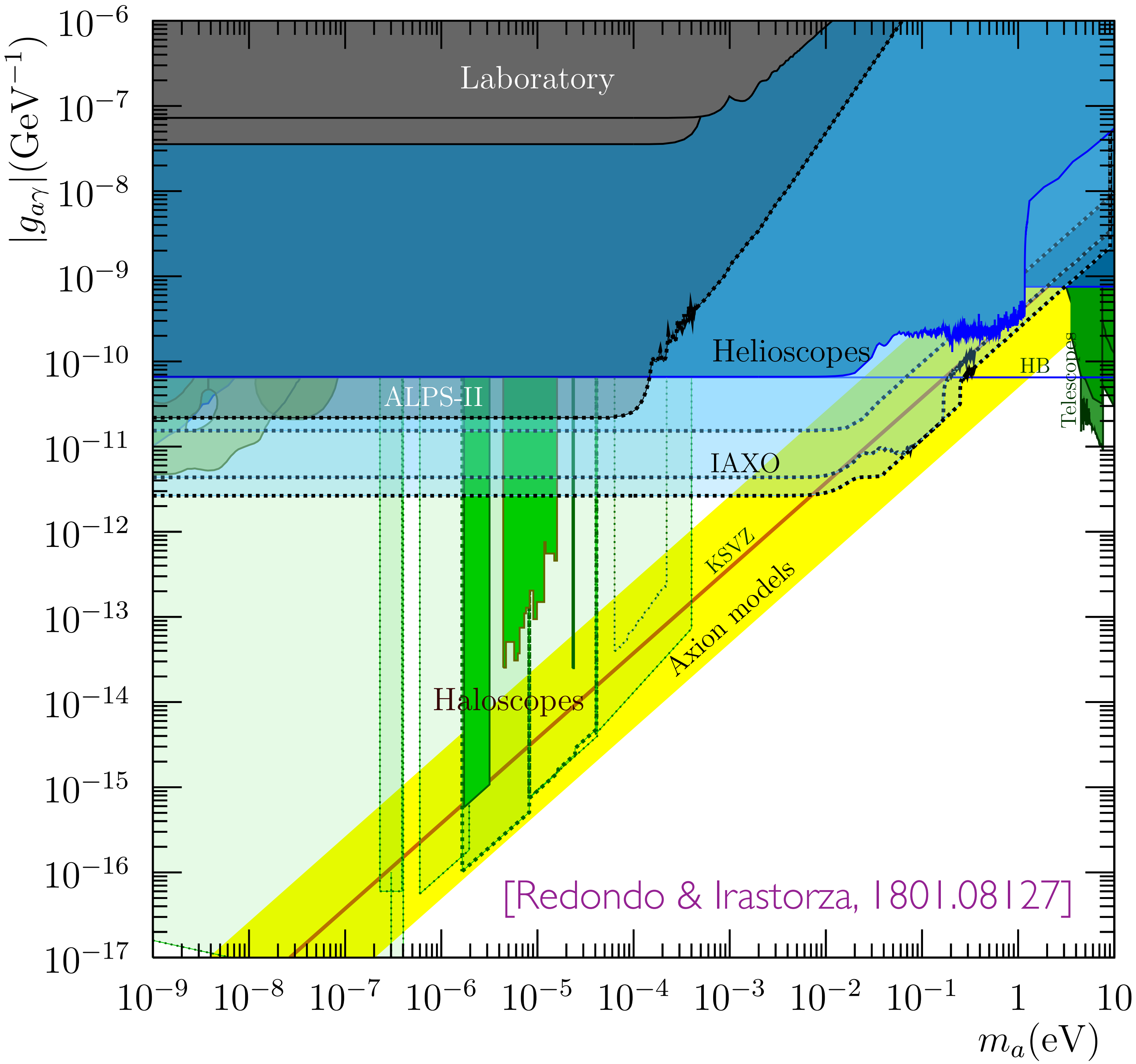
Axions couplings in non-standard axion models (about axions and their many phobias)

Invisibles18 Workshop, Karlsruhe - 05.09.18

Luca Di Luzio

In 10 years from now ?



- ✤ A great opportunity to discover the QCD axion !
- ★ Time <u>now</u> to get prepared and rethink the QCD axion

  [See also talks by Prateek Agrawal and Rachel Houtz yesterday]

Outline

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

Based on:
LDL, Mescia, Nardi 1610.07593 (PRL) + 1705.05370 (PRD)
LDL, Mescia, Nardi, Panci, Ziegler 1712.04940 (PRL)

Astro bounds

- Stars as powerful sources of light and weakly coupled particles [see e.g. Raffelt, hep-ph/0611350]

  - 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 bounds

- Stars as powerful sources of <u>light</u> and <u>weakly coupled</u> particles [see e.g. Raffelt, hep-ph/0611350]

  - 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)

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

neutrino interactions (d=6 op.)

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

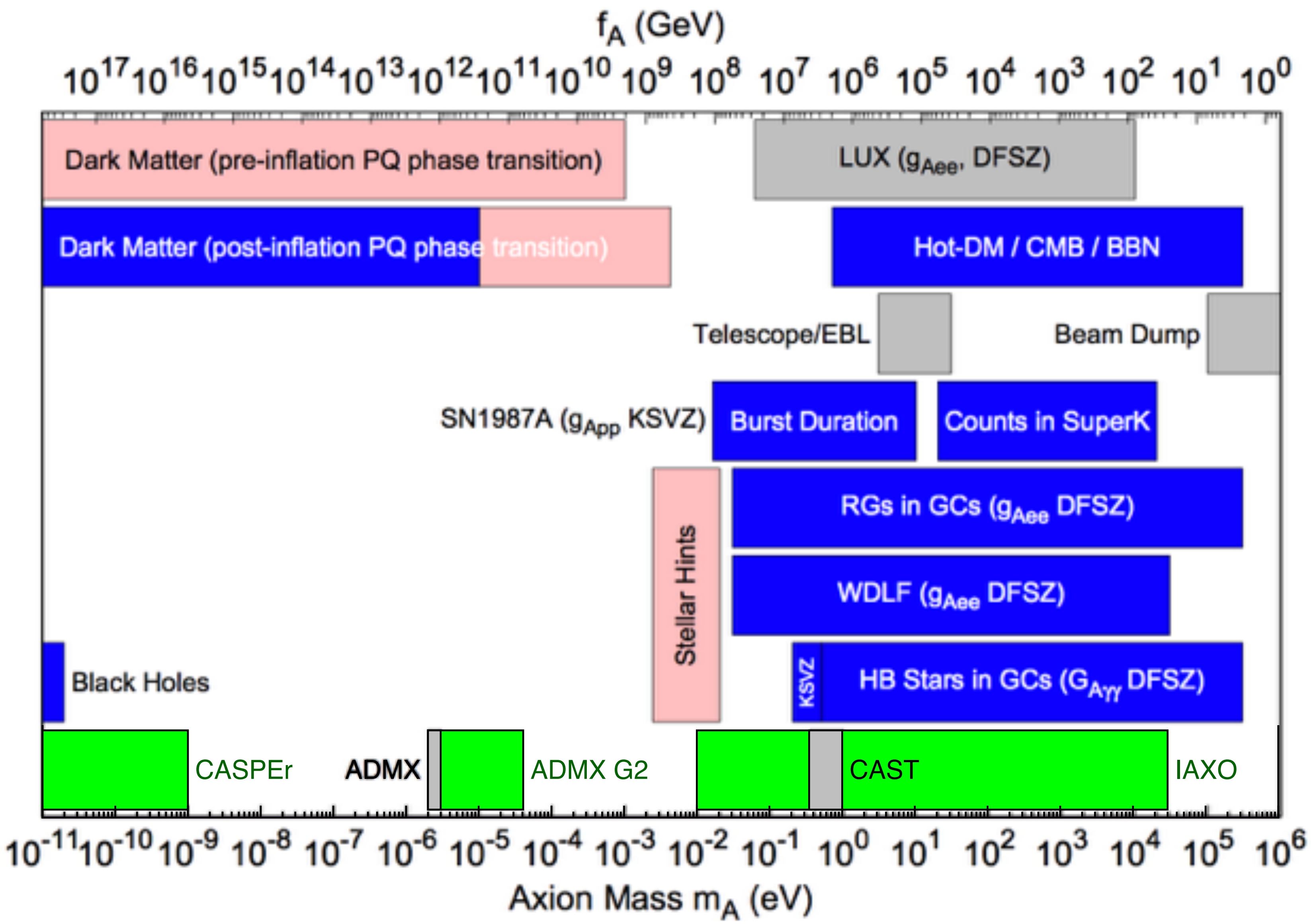
axion interactions (d=5 op.)

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

→ axions are a perfect target !

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

Axion landscape



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

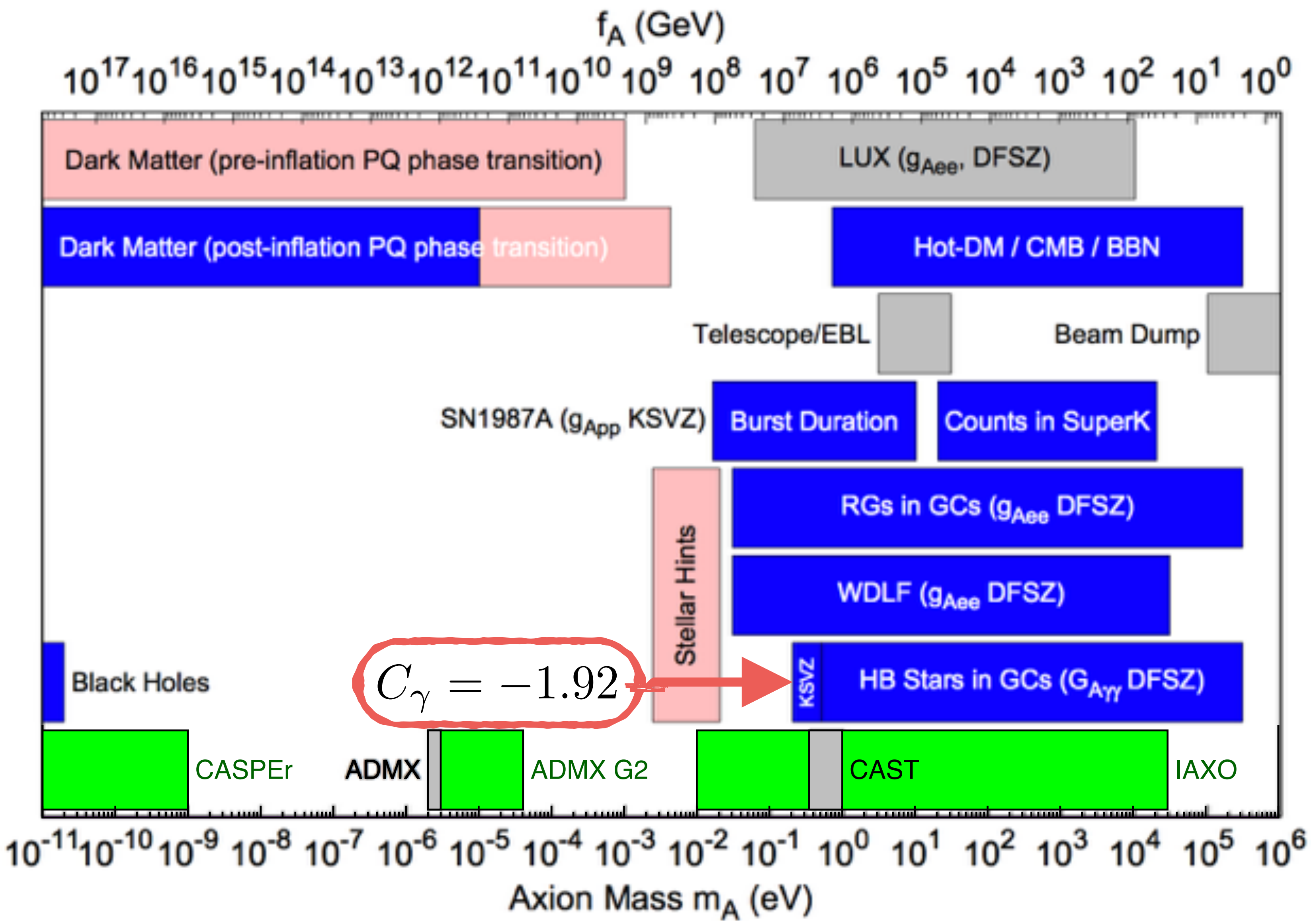
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Axion landscape



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

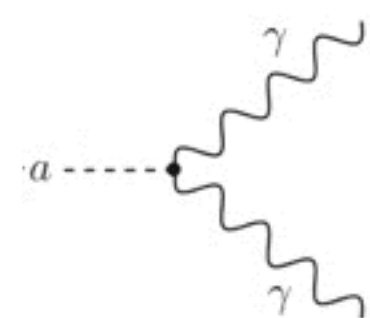
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

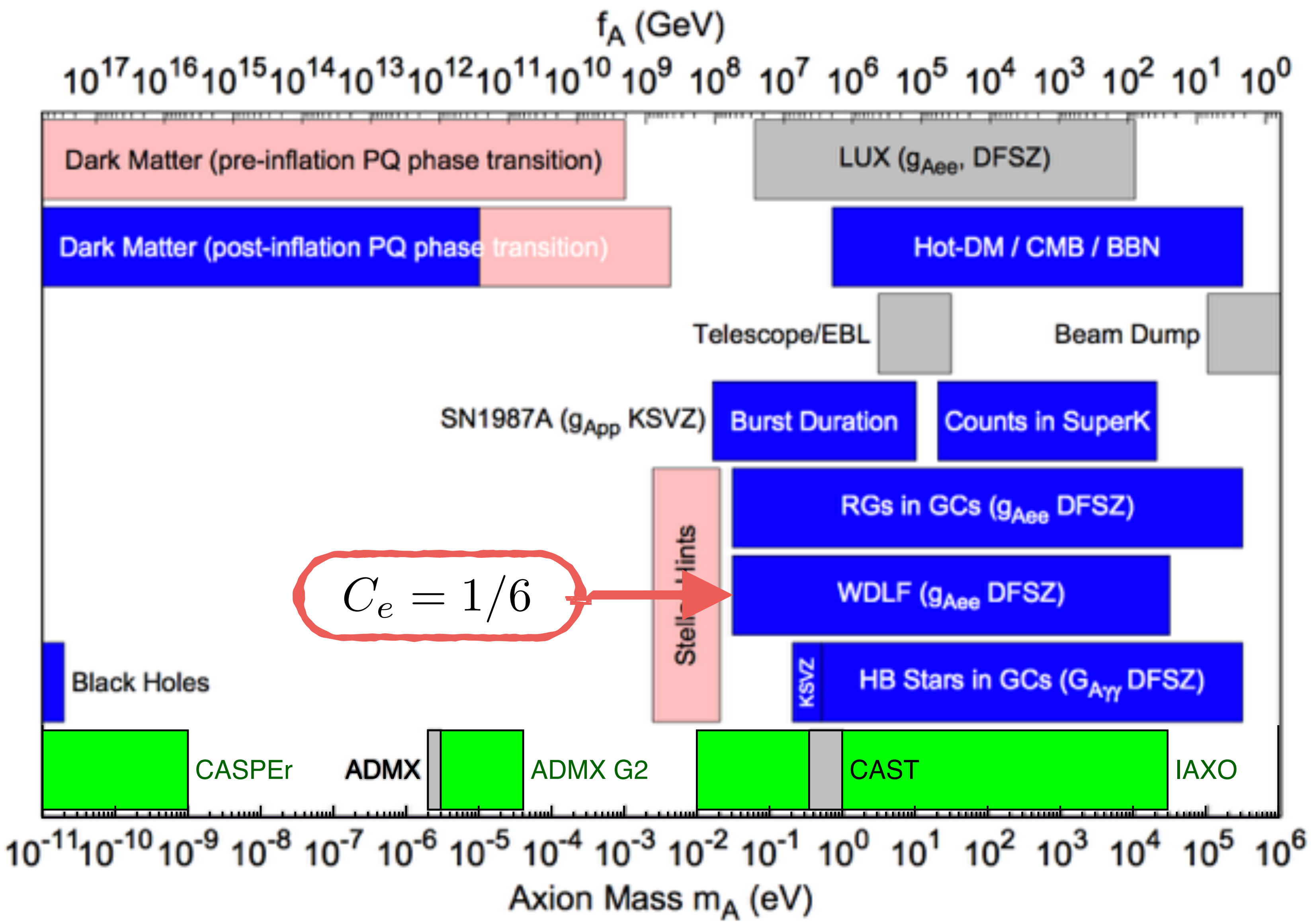
Exp. sensitivities

- 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



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

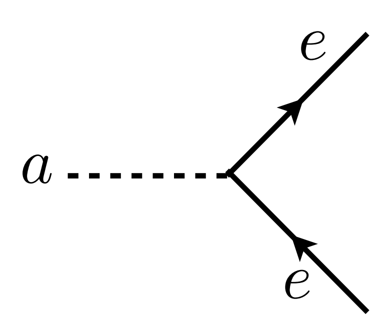
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

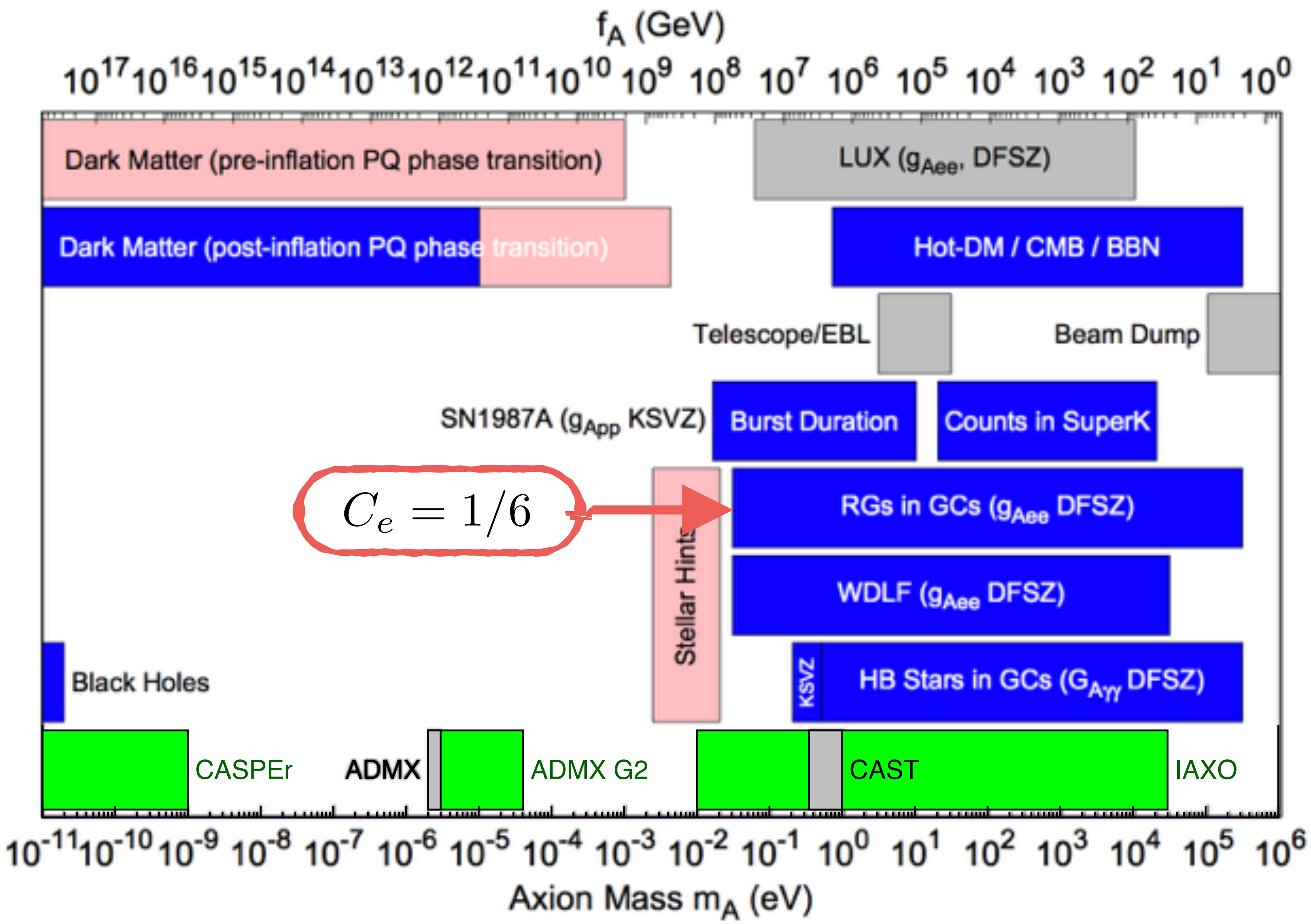
Exp. sensitivities

- 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)]

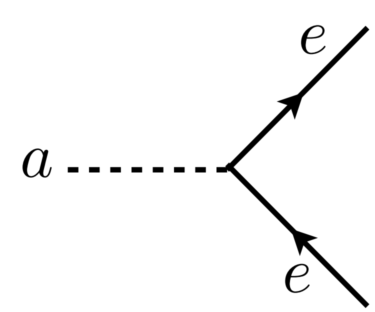
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

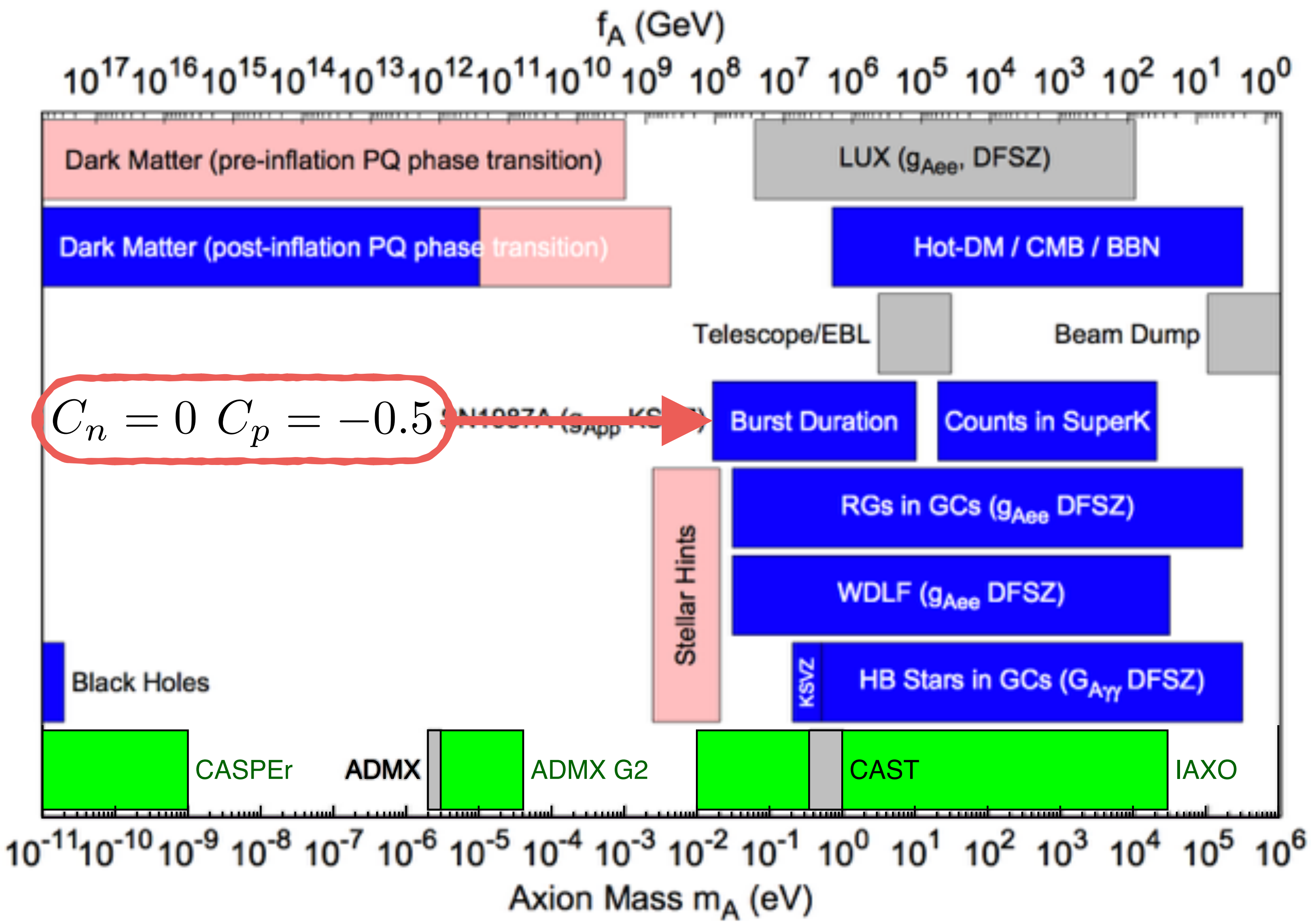
Exp. sensitivities

- Red giants evolution in globular clusters



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

Axion landscape



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

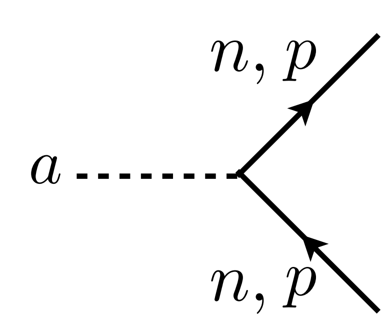
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

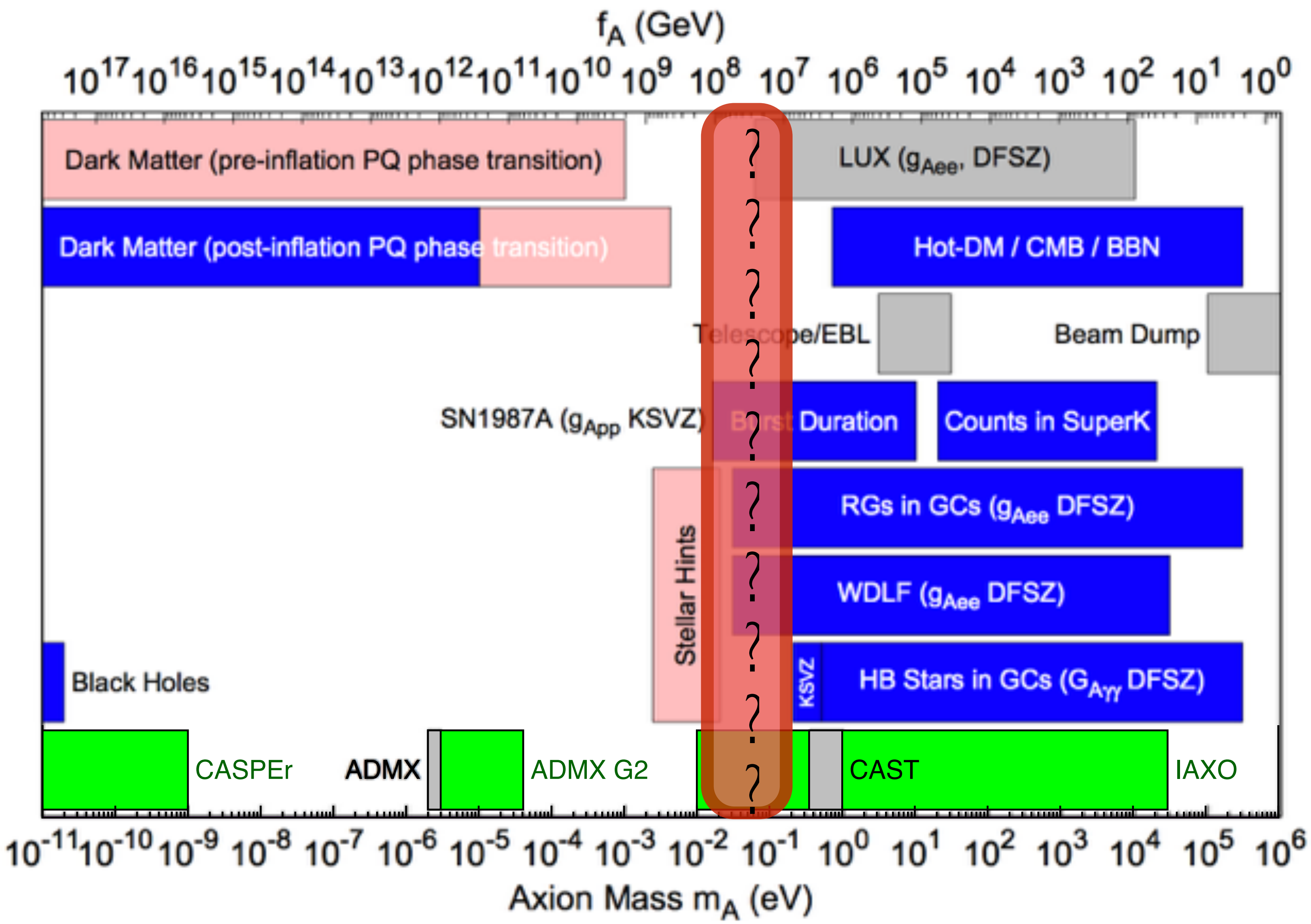
- Burst duration of SN1987A nu signal



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

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

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 [EFT]

- All you need is (to solve the strong CP problem)

  a new spin-0 boson with pseudo-shift symmetry $a \to a + \alpha\, f_a$

  broken by $\frac{a}{f_a}\frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$ $\longrightarrow$ $E(0) \leq E(a)$ [Vafa-Witten theorem, PRL 53 (1984)]

Axion [EFT]

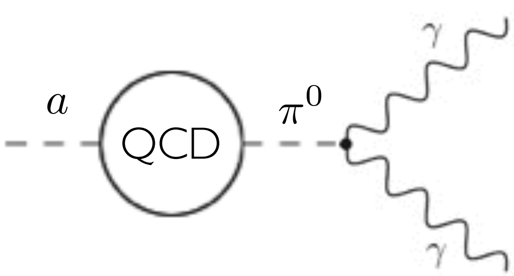
- All you need is (to solve the strong CP problem)

a new spin-0 boson with pseudo-shift symmetry $a \to a + \alpha\, f_a$

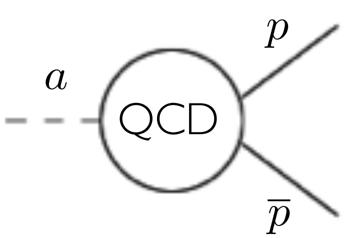
<u>broken by</u> $$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

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

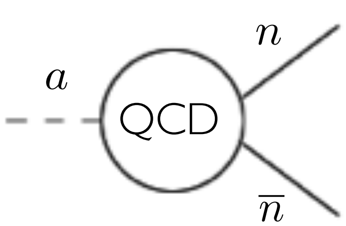
$C_\gamma = -1.92(4)$



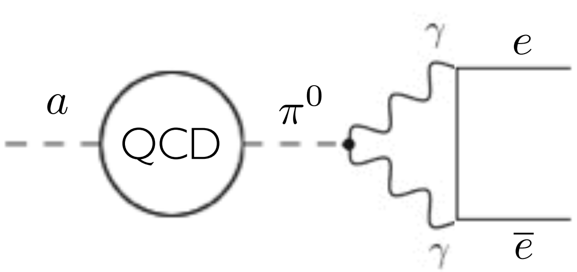
$C_p = -0.47(3)$



$C_n = -0.02(3)$



$C_e \simeq 0$



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

Axion [EFT]

- All you need is (to solve the strong CP problem)

a new spin-0 boson with pseudo-shift symmetry $a \to a + \alpha\, f_a$

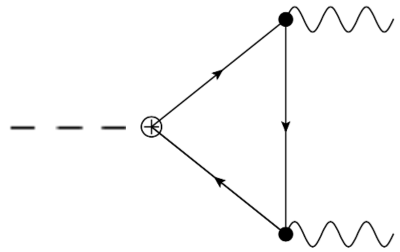
broken by $\frac{a}{f_a} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$

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

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

- EFT breaks down at energies of order f_a

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



Axion models [UV completion]

- Axion: 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

PQWW

[Peccei, Quinn '77,
Weinberg '78, Wilczek '78]

2Higgs+Singlet

DFSZ

[Zhitnitsky '80,
Dine, Fischler, Srednicki '81]

Higgs+Singlet

KSVZ

[Kim '79,
Shifman, Vainshtein, Zakharov '80]

Excluded

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

Axion models [UV completion]

- Axion: PGB of QCD-anomalous global U(1)$_{PQ}$;
anomalous PQ breaking (fermion sector) + spontaneous PQ breaking (scalar sector)

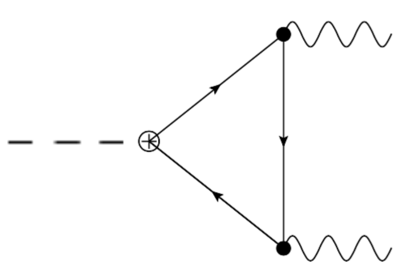
$$U(1)_{\text{PQ}} \times SU(3)_c^2$$

SM fermions | BSM fermions

2Higgs+Singlet | Higgs+Singlet

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

DFSZ | KSVZ



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

$$C_p \simeq -0.5$$

$$C_{n,e} \simeq 0$$

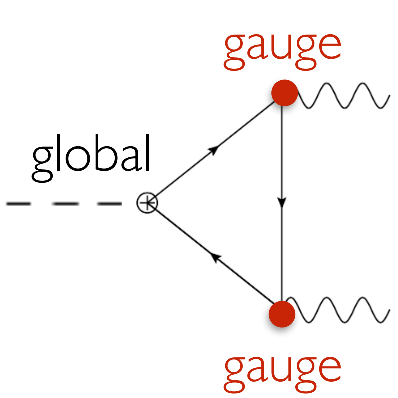
Axion-photon coupling

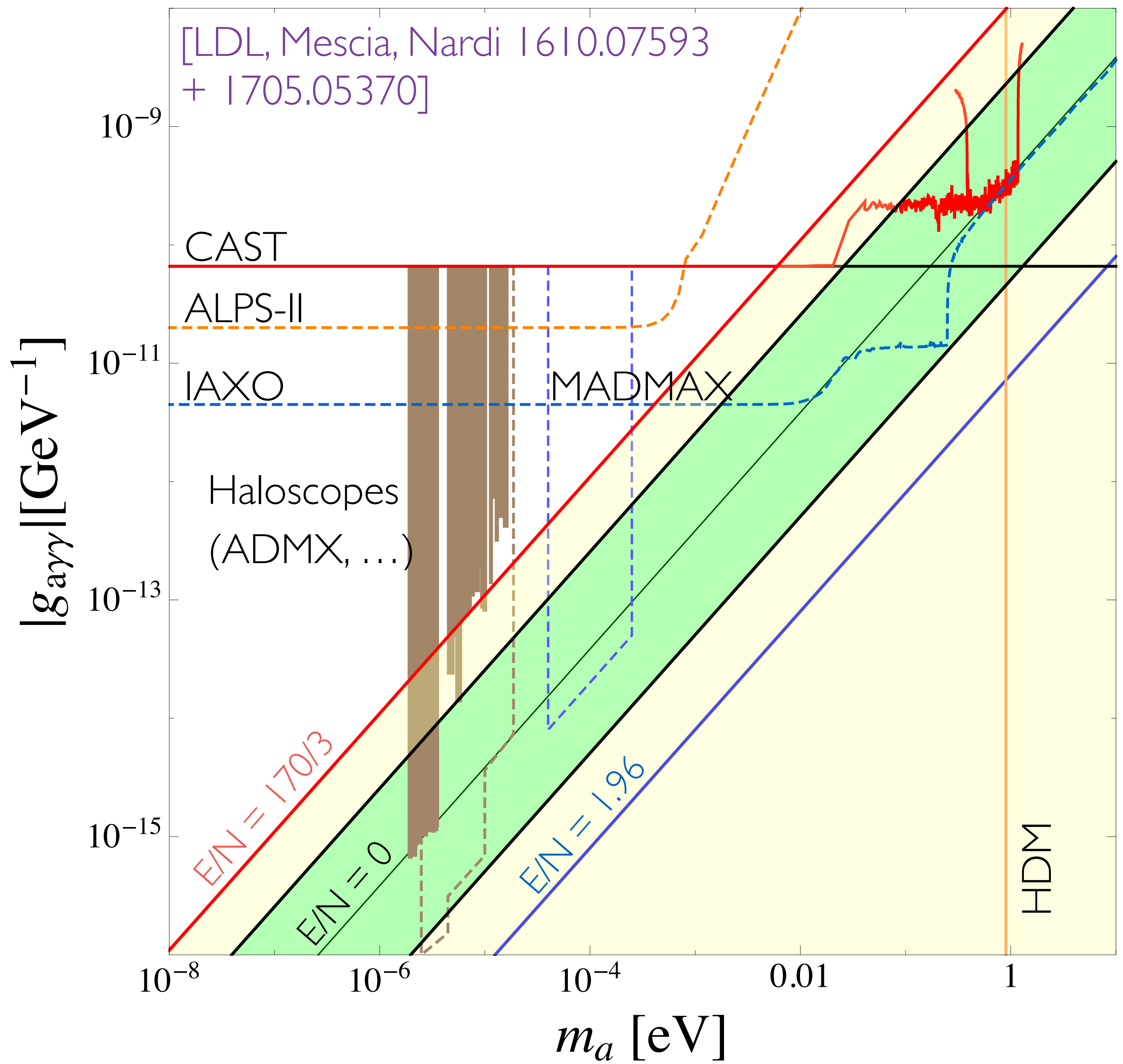
- Red line set by perturbativity [KSVZ] (going above requires more exotic constructions)

- Blue line corresponds to a 2% 'tuning in theory space'

about photophobia:
"… such a cancellation is immoral, but not unnatural" [D. B. Kaplan, (1985)]

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



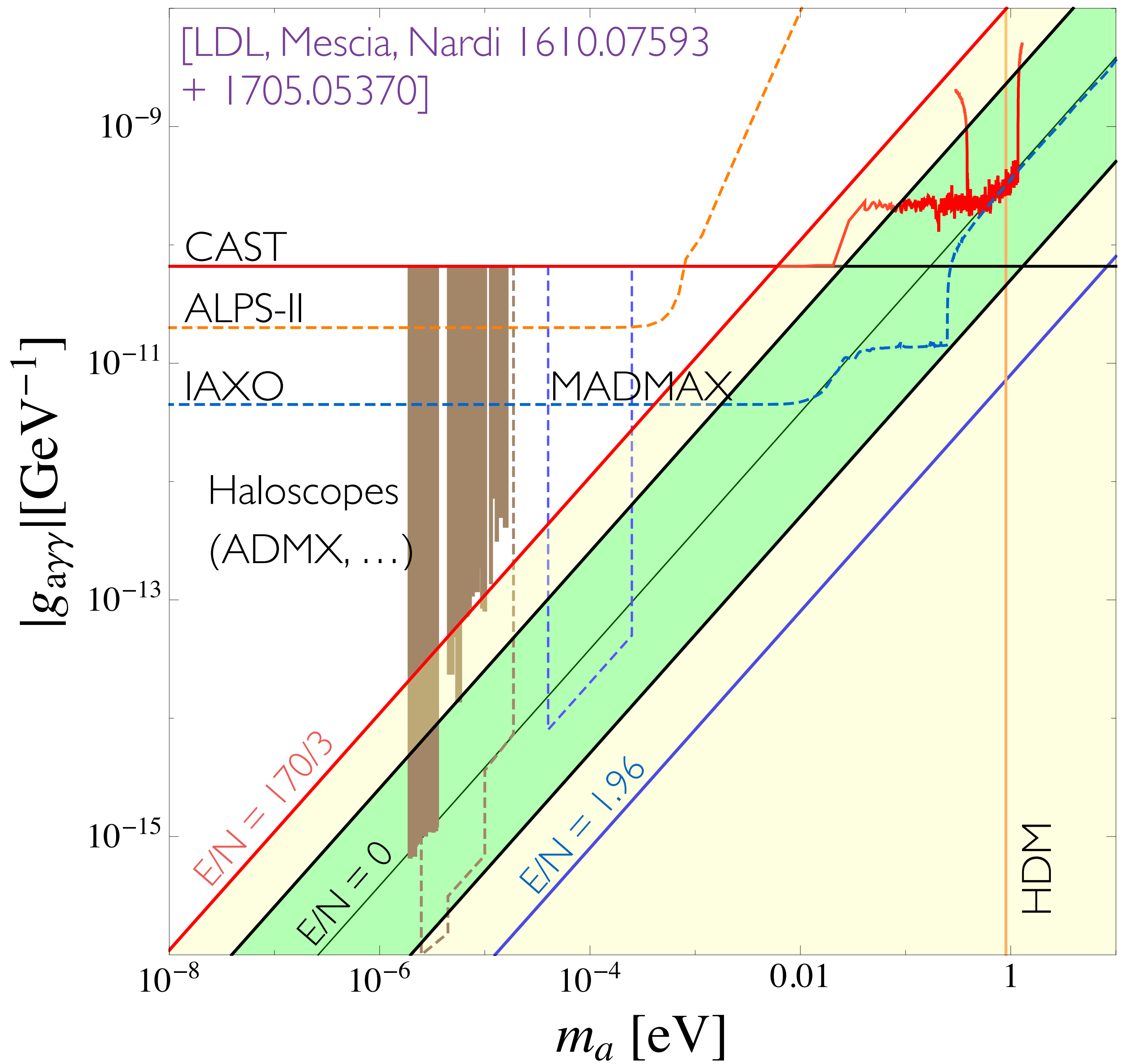


Axion-photon coupling

- Message for experimentalists:

1. The QCD axion might already be in the reach of your experiment !

2. Don't stop at E/N = 0 (go deeper if you can)



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 ?

→ nucleophobia + electrophobia* = astrophobia

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

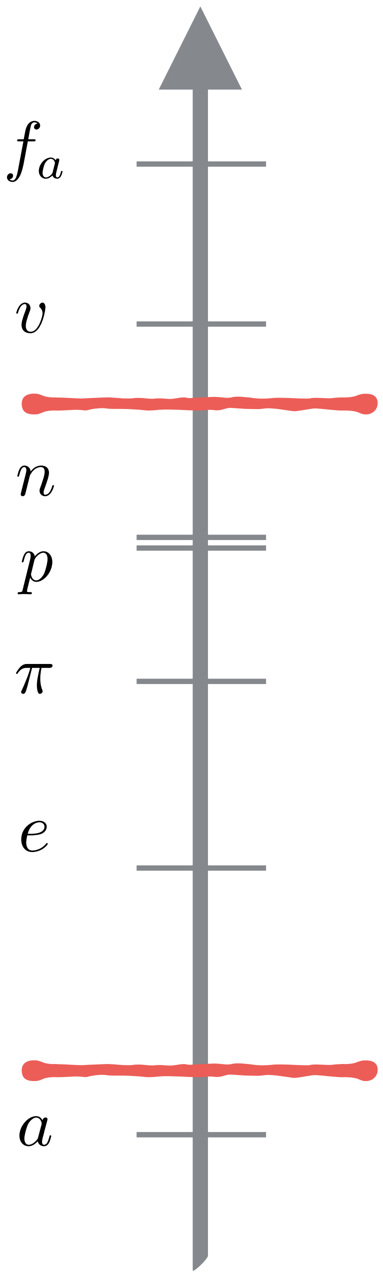
1. is it possible at all ?
2. would allow to relax the upper bound on axion mass by ~ 1 order of magnitude
3. would improve visibility at IAXO (axion-photon)
4. would improve fit to stellar cooling anomalies (axion-electron) [Giannotti et al. 1708.02111]
5. unexpected connection with flavour

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

Conditions for nucleophobia

- Axion-nucleon couplings

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



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

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

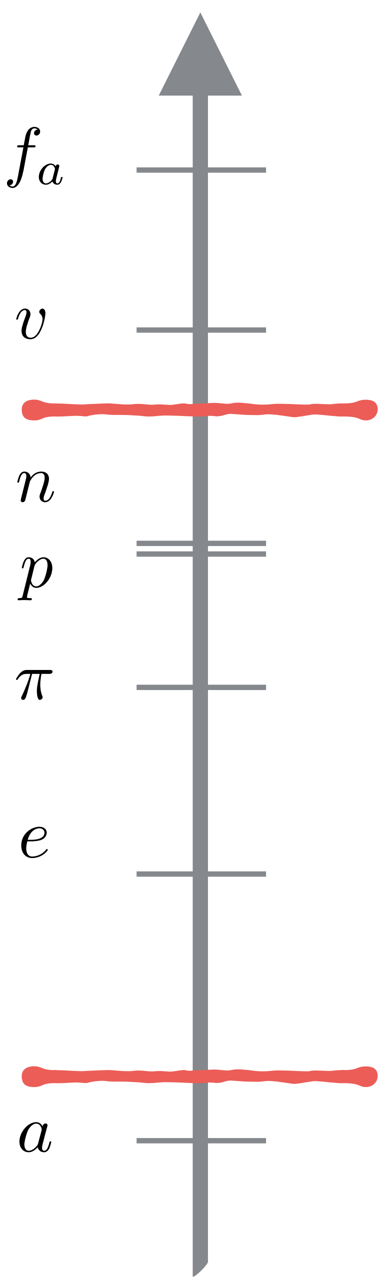
$$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \overline{N} S^\mu N \qquad N = (p, n)$$

EFT-II: non-relativistic nucleons

Conditions for nucleophobia

- Axion-nucleon couplings

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



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

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

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

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

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

Independently of matrix elements:

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

KSVZ/DFSZ no-go

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

KSVZ/DFSZ no-go

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

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

KSVZ/DFSZ no-go

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

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

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

KSVZ/DFSZ no-go

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

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

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

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

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

KSVZ/DFSZ no-go

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

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

KSVZ/DFSZ no-go

- Nucleophobia can be obtained in DFSZ models with non-universal (i.e. generation dependent) PQ charges, such that

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

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

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

Implementing nucleophobia

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

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

Implementing nucleophobia

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

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

- $N_2 + N_3 = 0$ easy to implement with 2HDM (H_1, H_2, $Y(H_{1,2}) = -1/2$)

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

- 1st condition automatically satisfied

Implementing nucleophobia

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

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

- $N_2 + N_3 = 0$ easy to implement with 2HDM (H_1, H_2, $Y(H_{1,2}) = -1/2$)

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

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

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

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

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

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

Flavour connection

- Nucleophobia implies flavour violating axion couplings !

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

e.g. RH down rotations become physical

Flavour connection

- Nucleophobia implies flavour violating axion couplings !

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

e.g. RH down rotations become physical

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

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

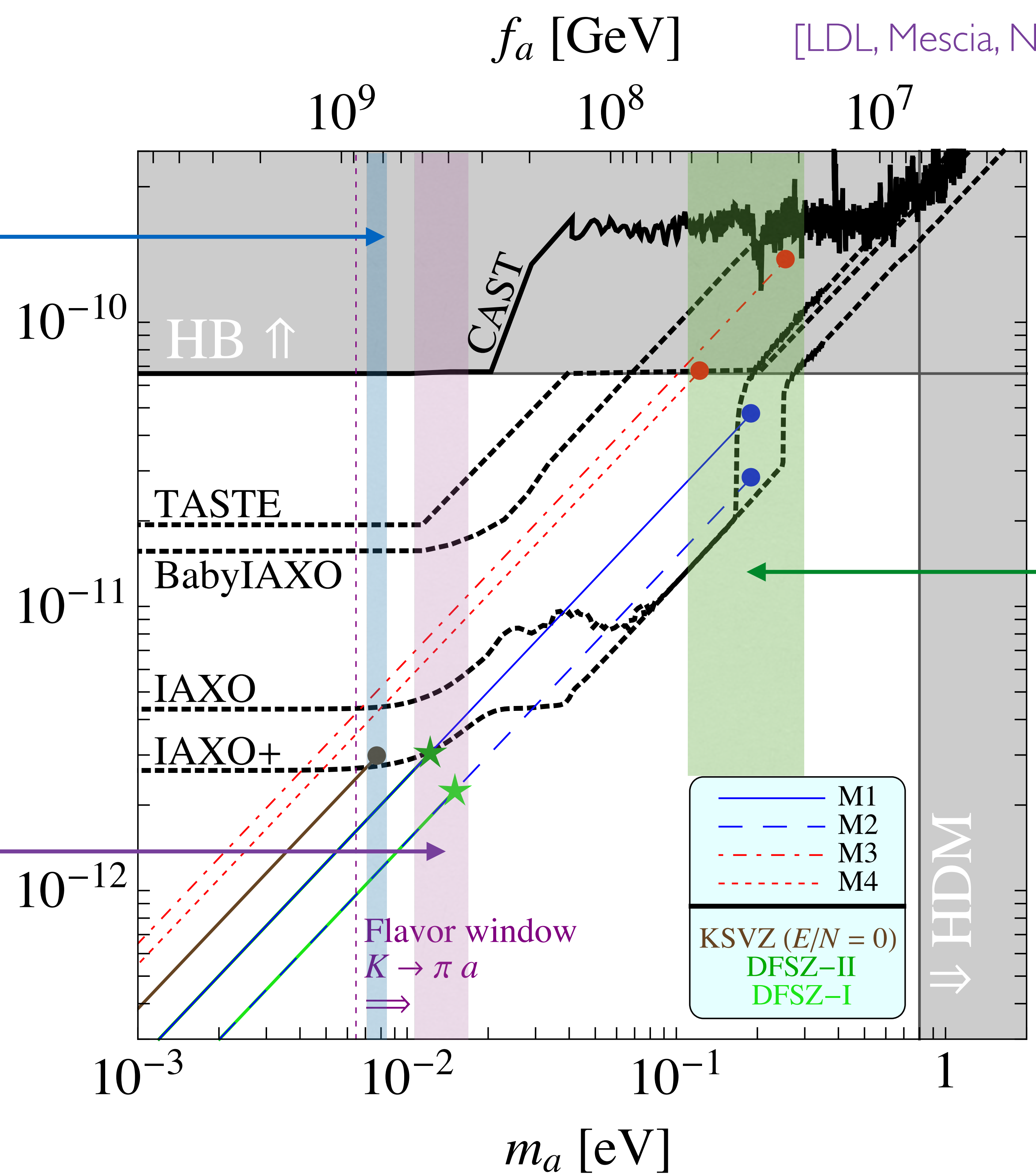
- $B \to K a \ : \ m_a < 3.7 \times 10^{-2} \frac{\mathrm{eV}}{|C^V_{bs}|}$ [Babar, 1303.7465] $\longrightarrow$ Belle-II

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

Astrophobic axion models

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

KSVZ



Astrophobic Axions

DFSZ

Conclusions

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

  - axion couplings are UV dependent

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

Conclusions

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

  - axion couplings are 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

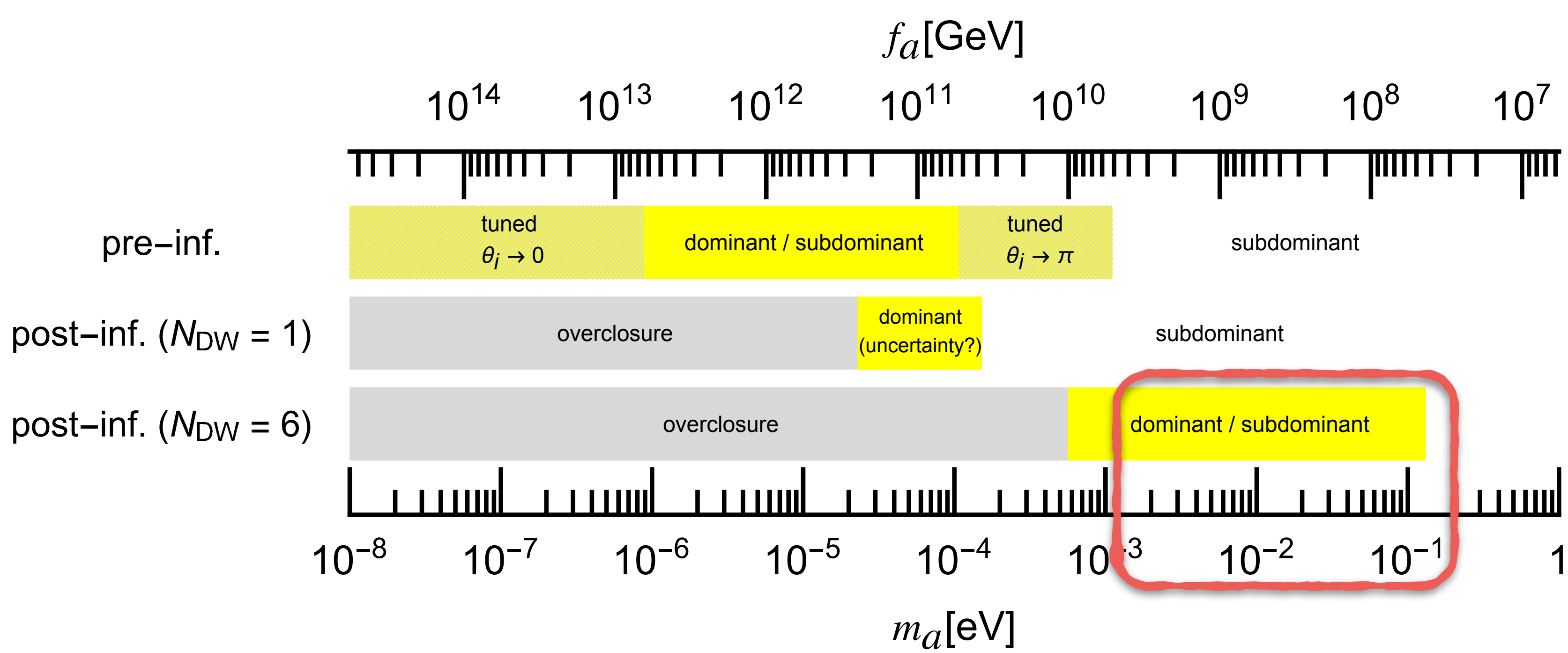
  4. can be complementarily tested in axion flavour exp.

Backup slides

DM in the heavy axion window

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

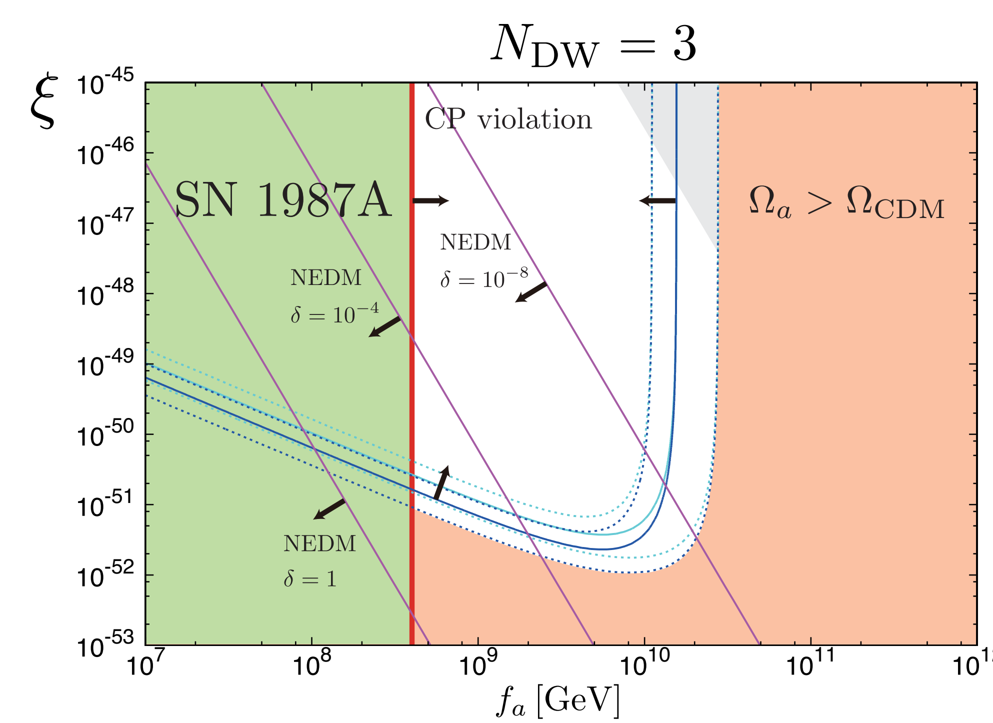
[Kawasaki, Saikawa, Sekiguchi, 1412.0789 1709.07091]



- axion production from topological defects

- requires explicit PQ breaking term

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

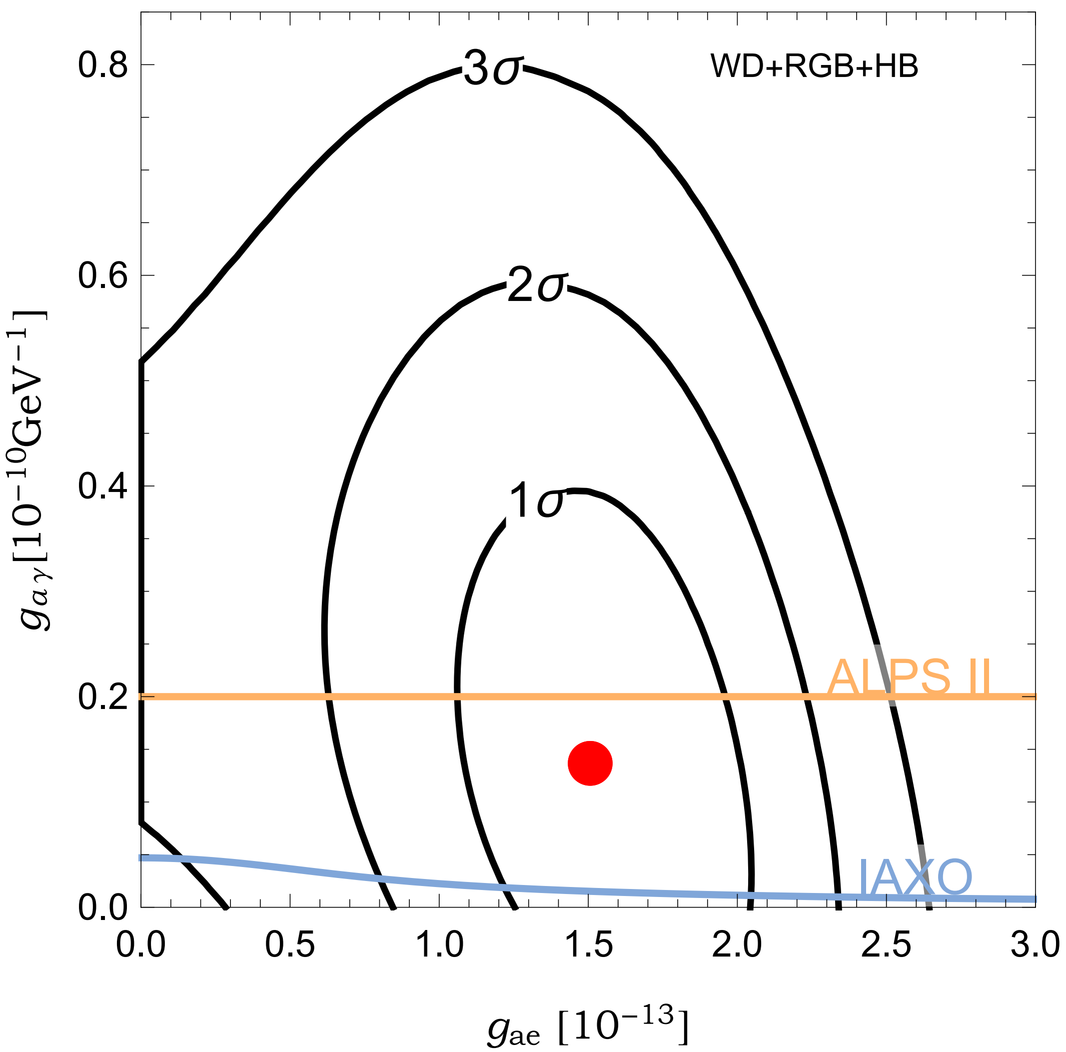


Stellar cooling anomalies

- 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	$f_a\ [10^8\ \mathrm{GeV}]$	m_a [meV]	$\tan\beta$	χ^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]

Axion coupling to photons

- Axion effective Lagrangian

[See e.g. Grilli di Cortona et al., 1511.02867]

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{1}{4}\, a\, g^0_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g^0_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\frac{E}{N}$$

field-depended chiral transformation to eliminate aGGtilde:

$$q = \begin{pmatrix} u \\ d \end{pmatrix} \to e^{i\gamma_5 \frac{a}{2f_a}Q_a}\begin{pmatrix} u \\ d \end{pmatrix}$$

$$\mathrm{tr}\, Q_a = 1$$

Axion coupling to photons

- Axion effective Lagrangian

[See e.g. Grilli di Cortona et al., 1511.02867]

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\cancel{\frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}} + \frac{1}{4}\, a\, g^0_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g^0_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\frac{E}{N}$$

$$q = \begin{pmatrix} u \\ d \end{pmatrix} \to e^{i\gamma_5 \frac{a}{2f_a} Q_a} \begin{pmatrix} u \\ d \end{pmatrix}$$

$$\mathrm{tr}\, Q_a = 1$$

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{1}{4}\, a\, g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_a}\left[\frac{E}{N} - 6\,\mathrm{tr}\left(Q_a Q^2\right)\right] = \frac{\alpha_{em}}{2\pi f_a}\left[\frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}\right] = \frac{m_a}{\mathrm{eV}}\,\frac{2.0}{10^{10}\ \mathrm{GeV}}\left(\frac{E}{N} - 1.92(4)\right)$$

model independent

depends on UV completion

$$Q_a = \frac{M_q^{-1}}{\langle M_q^{-1}\rangle}$$ (no axion-pion mixing)

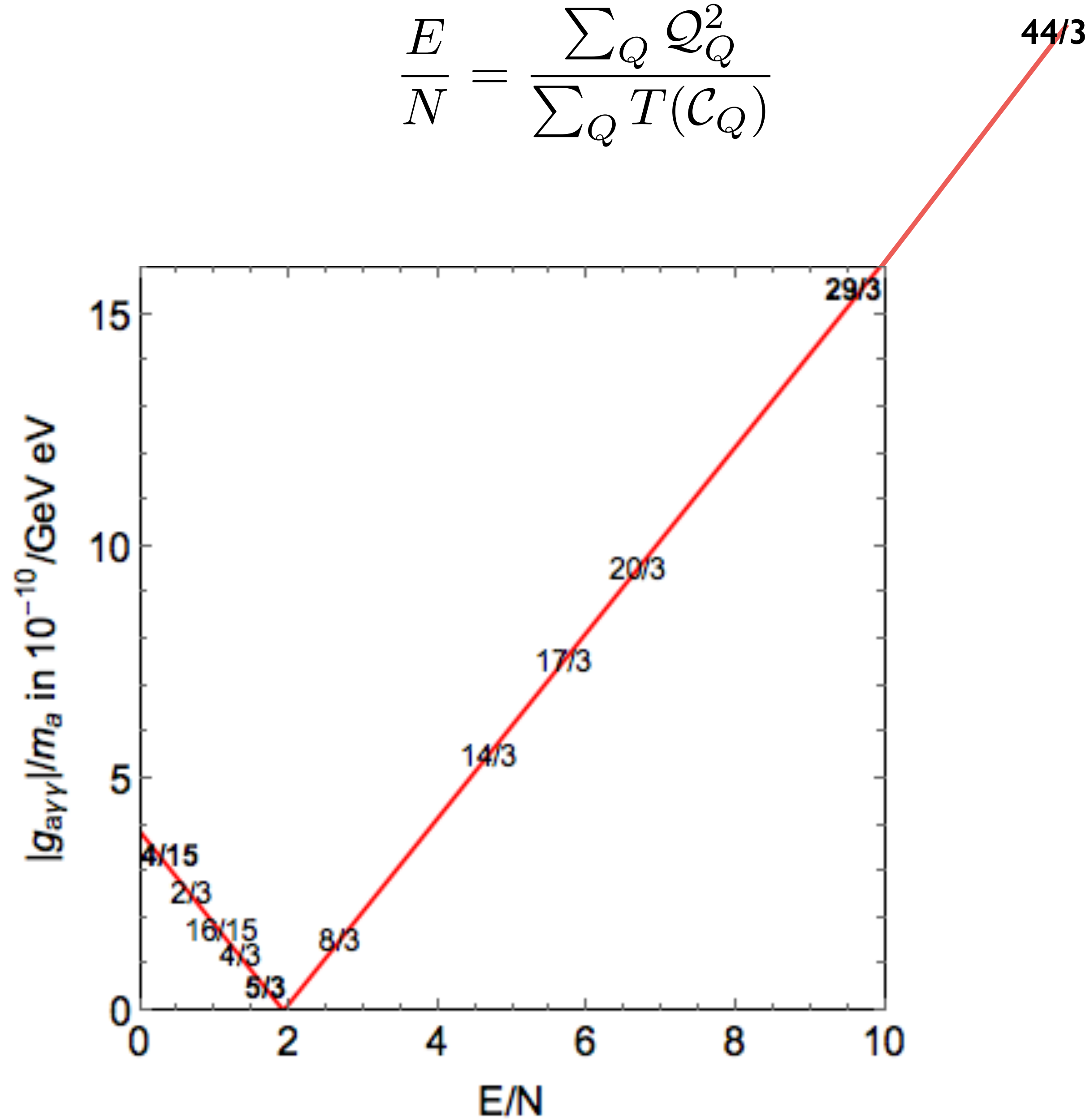
Pheno preferred Q's in KSVZ

- Q's short lived + no Landau poles < Planck

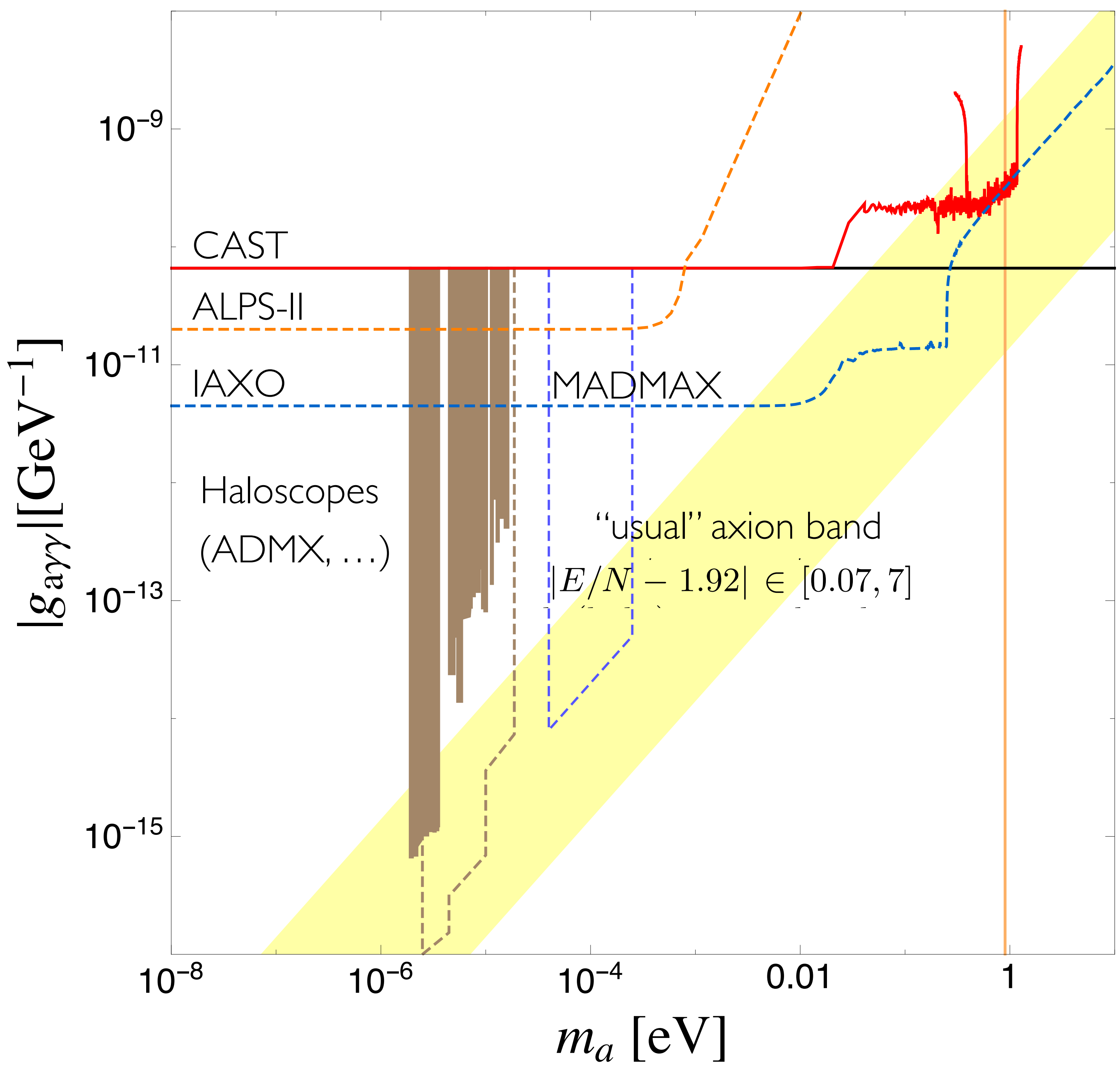
$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \, \frac{2.0}{10^{10}\ \text{GeV}} \left(\frac{E}{N} - 1.92(4) \right)$$

$$\frac{E}{N} = \frac{\sum_Q Q_Q^2}{\sum_Q T(\mathcal{C}_Q)}$$

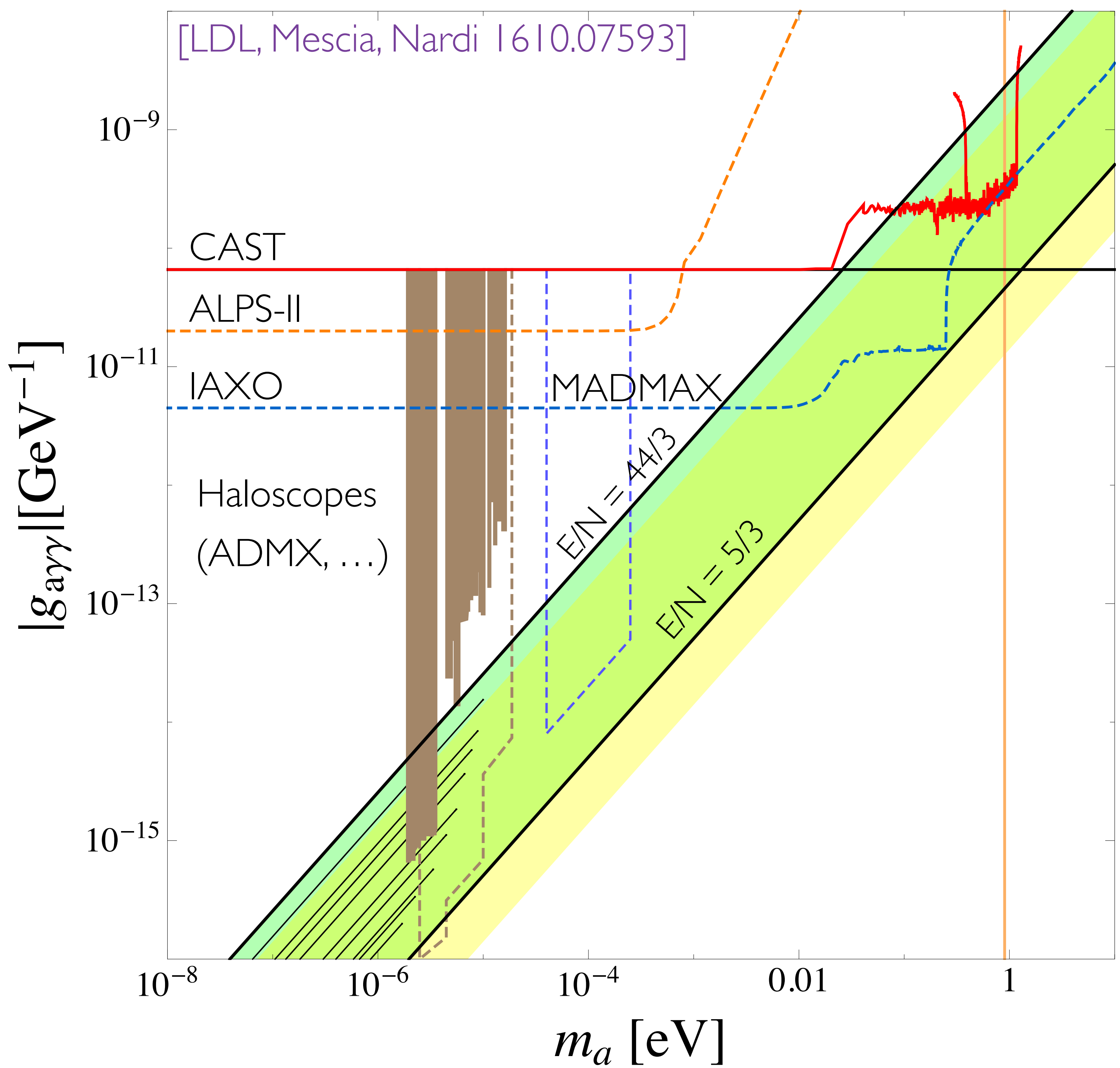
	R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{2-\text{loop}}_{\text{Landau}}[\text{GeV}]$	E/N
	$(3,1,-1/3)$	$\overline{Q}_L d_R$	$9.3 \cdot 10^{38}(g_1)$	$2/3$
	$(3,1,2/3)$	$\overline{Q}_L u_R$	$5.4 \cdot 10^{34}(g_1)$	$8/3$
R_Q^w	$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5 \cdot 10^{39}(g_1)$	$5/3$
	$(3,2,-5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3 \cdot 10^{27}(g_1)$	$17/3$
	$(3,2,7/6)$	$\overline{Q}_L u_R H$	$5.6 \cdot 10^{22}(g_1)$	$29/3$
	$(3,3,-1/3)$	$\overline{Q}_R q_L H^\dagger$	$5.1 \cdot 10^{30}(g_2)$	$14/3$
	$(3,3,2/3)$	$\overline{Q}_R q_L H$	$6.6 \cdot 10^{27}(g_2)$	$20/3$
R_Q^s	$(3,3,-4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18}(g_1)$	$44/3$
	$(\overline{6},1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$2.3 \cdot 10^{37}(g_1)$	$4/15$
	$(\overline{6},1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$5.1 \cdot 10^{30}(g_1)$	$16/15$
	$(\overline{6},2,1/6)$	$\overline{Q}_R \sigma_{\mu\nu} q_L G^{\mu\nu}$	$7.3 \cdot 10^{38}(g_1)$	$2/3$
	$(8,1,-1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6 \cdot 10^{22}(g_1)$	$8/3$
	$(8,2,-1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7 \cdot 10^{27}(g_1)$	$4/3$
	$(15,1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3 \cdot 10^{21}(g_3)$	$1/6$
	$(15,1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$7.6 \cdot 10^{21}(g_3)$	$2/3$



Redefining the axion window



Redefining the axion window



Boosting E/N in DFSZ

- Potentially large E/N due to electron PQ charge

$$\frac{E}{N} = \frac{\sum_j \left(\frac{4}{3}X_u^j + \frac{1}{3}X_d^j + X_e^j\right)}{\sum_j \left(\frac{1}{2}X_u^j + \frac{1}{2}X_d^j\right)}$$

$$\mathcal{L}_Y = Y_u \overline{Q}_L u_R H_u + Y_d \overline{Q}_L d_R H_d + Y_e \overline{L}_L e_R H_e + \text{h.c.}$$

- with n_H Higgs doublets and a SM singlet **ϕ**, enhanced global symmetry

$$U(1)^{n_H+1} \to U(1)_{\text{PQ}} \times U(1)_Y$$

must be explicitly broken in the scalar potential via non-trivial invariants (e.g. $H_u H_d \Phi^2$)

→ *non-trivial constraints on PQ charges of SM fermions*

Boosting E/N in DFSZ

- Potentially large E/N due to electron PQ charge

$$\frac{E}{N} = \frac{\sum_j \left(\frac{4}{3}X_u^j + \frac{1}{3}X_d^j + X_e^j\right)}{\sum_j \left(\frac{1}{2}X_u^j + \frac{1}{2}X_d^j\right)}$$

$$\mathcal{L}_Y = Y_u\,\overline{Q}_L u_R H_u + Y_d\,\overline{Q}_L d_R H_d + Y_e\,\overline{L}_L e_R H_e + \text{h.c.}$$

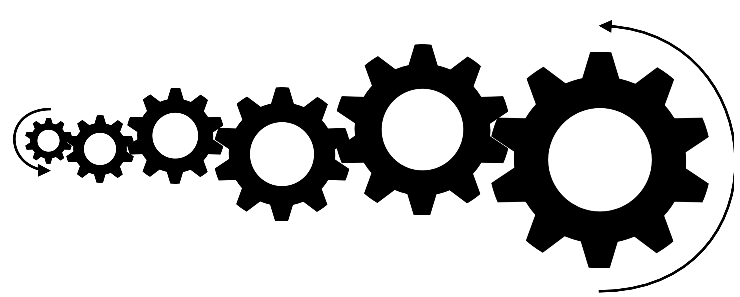
- Clockwork-like scenarios allow to boost E/N [LDL, Mescia, Nardi 1705.05370]

  - n up-type doublets which *do not couple* to SM fermions (n ≲ 50 from LP condition)

$$(H_u H_d \Phi^2)$$

$$(H_k H_{k-1}^*)(H_{k-1}^* H_d^*)$$

$$(H_e H_n)(H_n H_d)$$



[Giudice, McCullough]

$$E/N \sim 2^n$$

[See also Farina et al. 1611.09855, for KSVZ clockwork]