Axions (and flavour)

Flavour changing and conserving processes
Capri Workshop - 31.08.19

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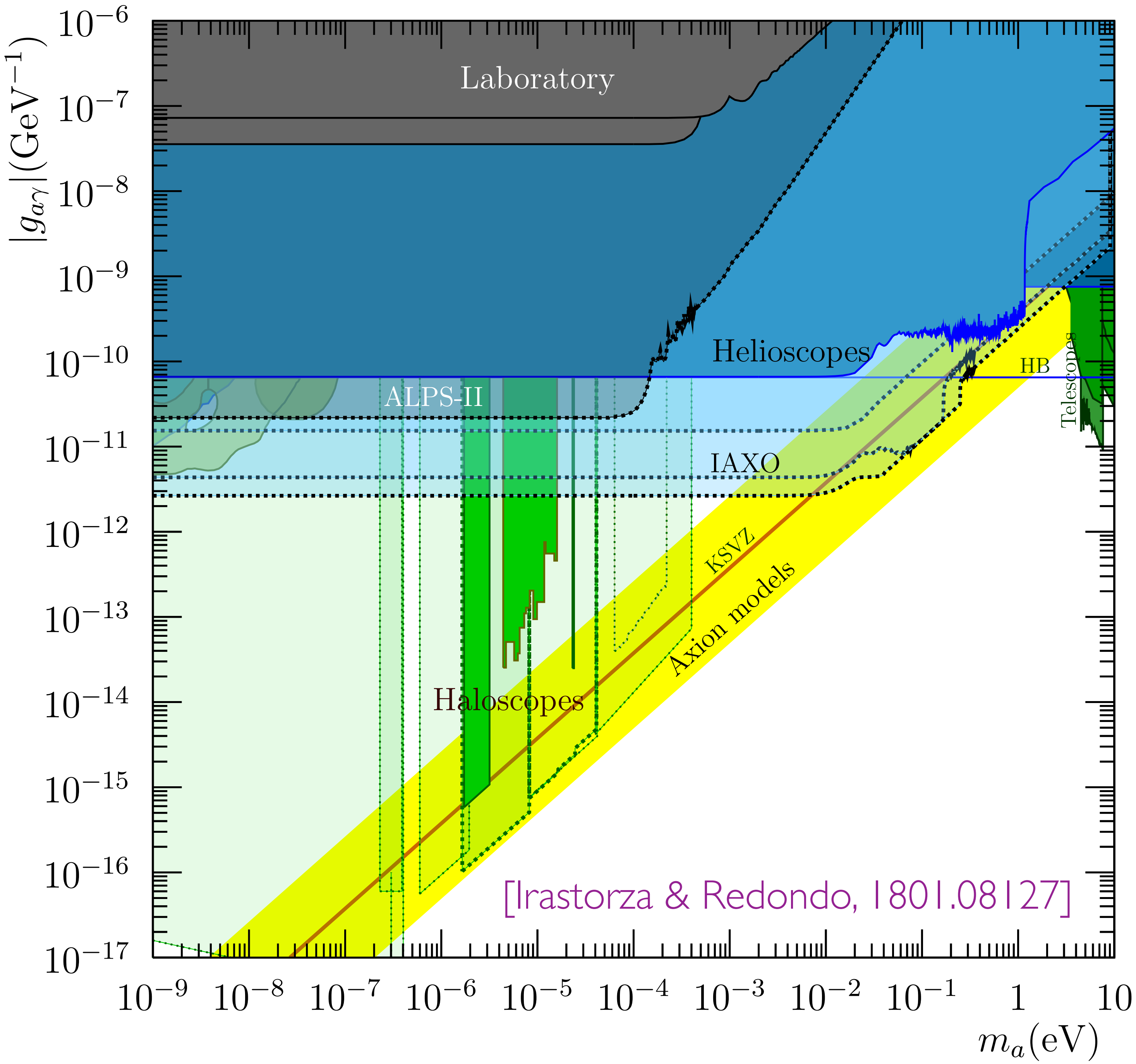
erc European Research Council

In 10 years from now ?



✤ A great exp. opportunity

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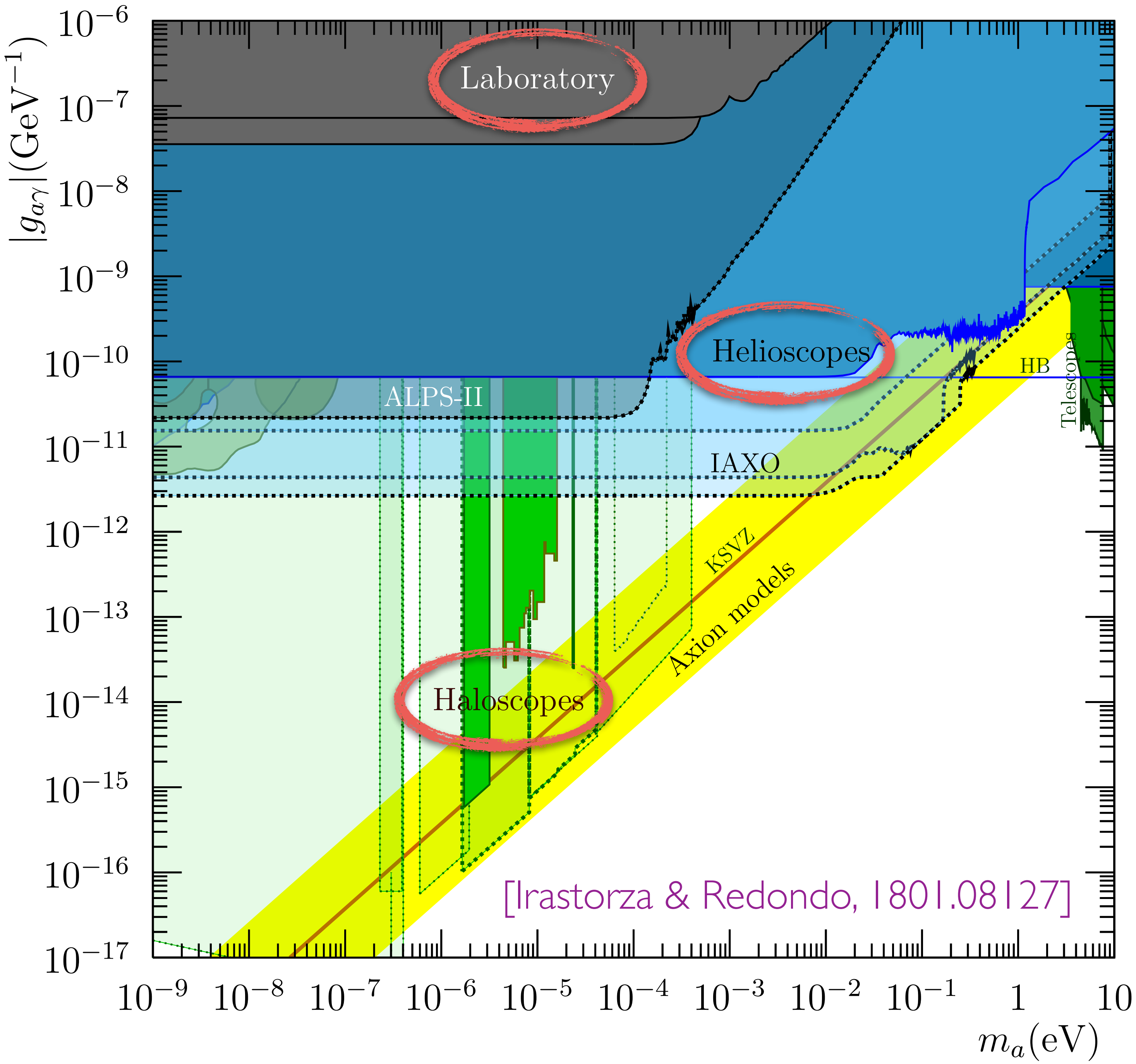

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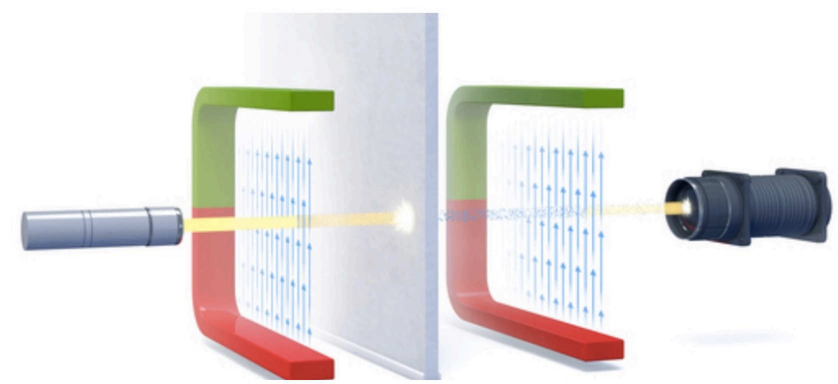

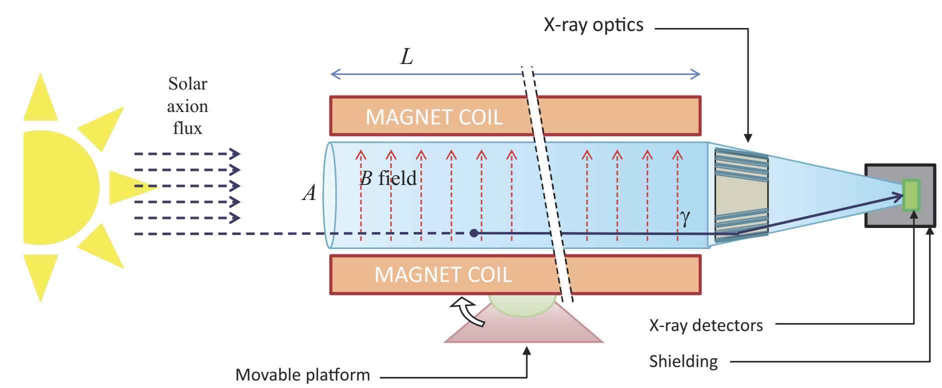

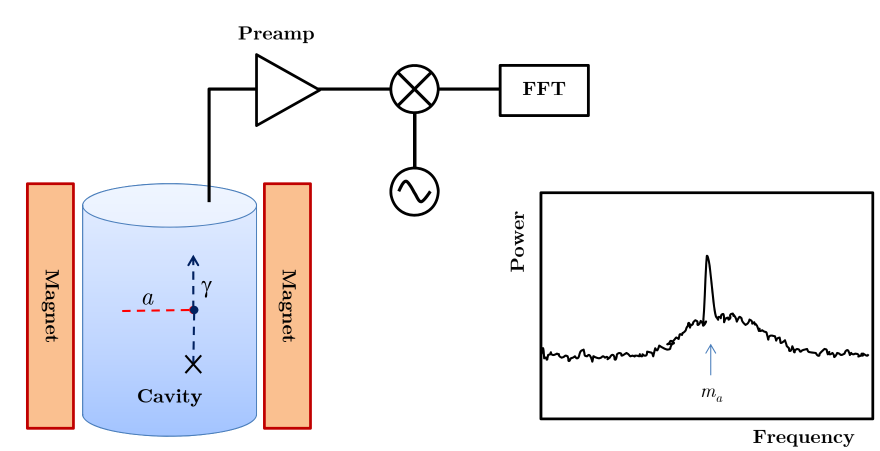

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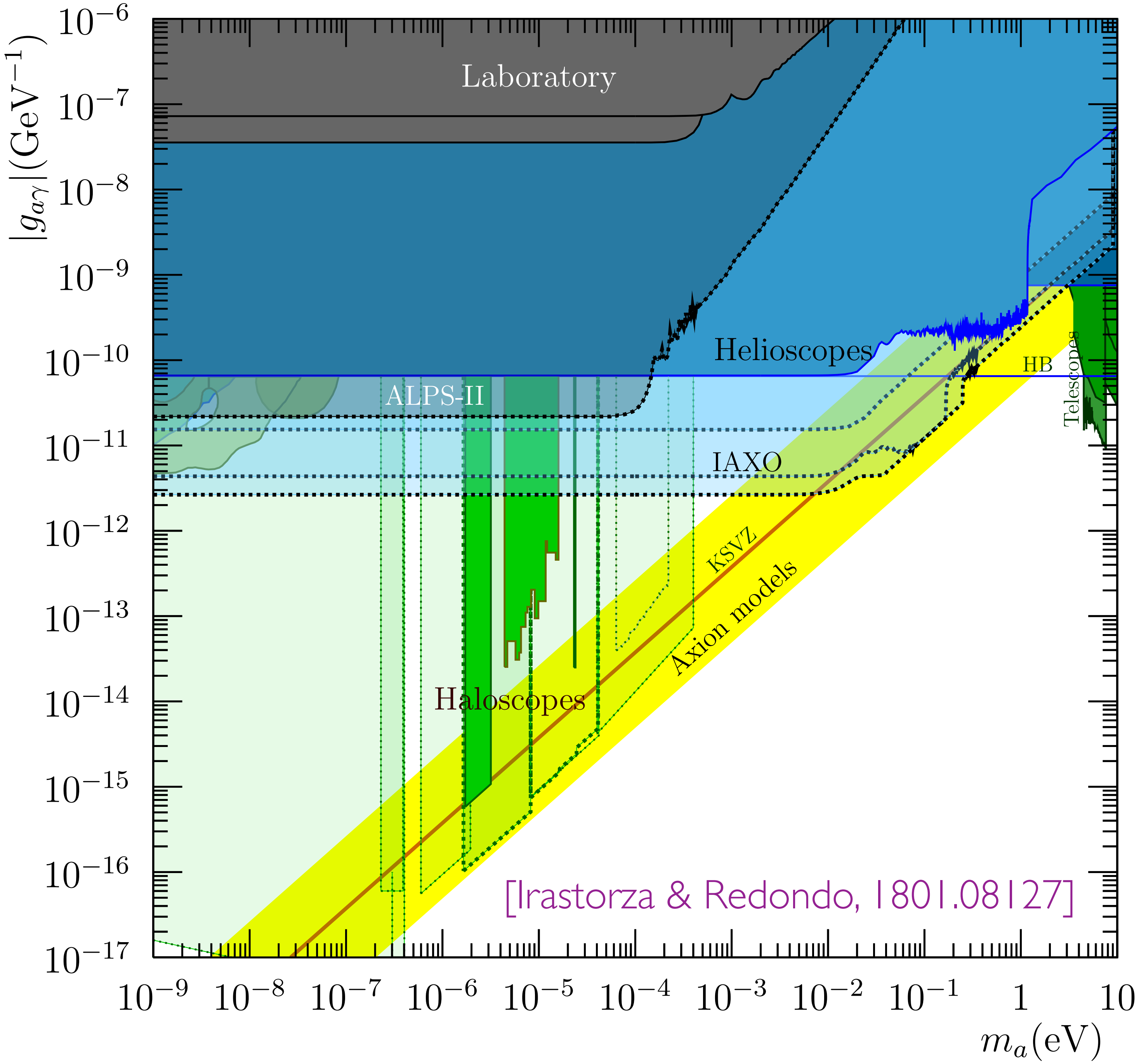


✤ A great exp. opportunity

★ Time <u>now</u> to rethink the QCD axion

1. Axion couplings

2. Astro bounds

3. Axion Window

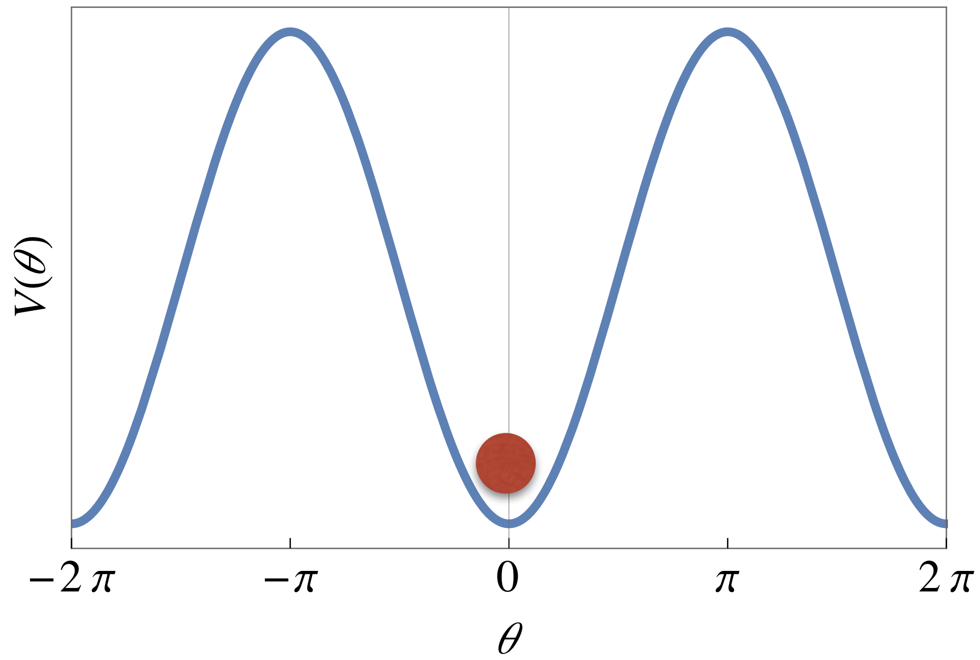
4. The flavour option

QCD axion

Strong CP problem

$$\delta\mathcal{L}_{\rm QCD} = \theta \frac{\alpha_s}{8\pi} G\tilde{G} \qquad |\theta| \lesssim 10^{-10}$$

promote θ *to a dynamical field,*
which relaxes to zero via QCD dynamics



$$\theta \to \frac{a}{f_a} \qquad \textit{with} \qquad \langle a \rangle = 0$$

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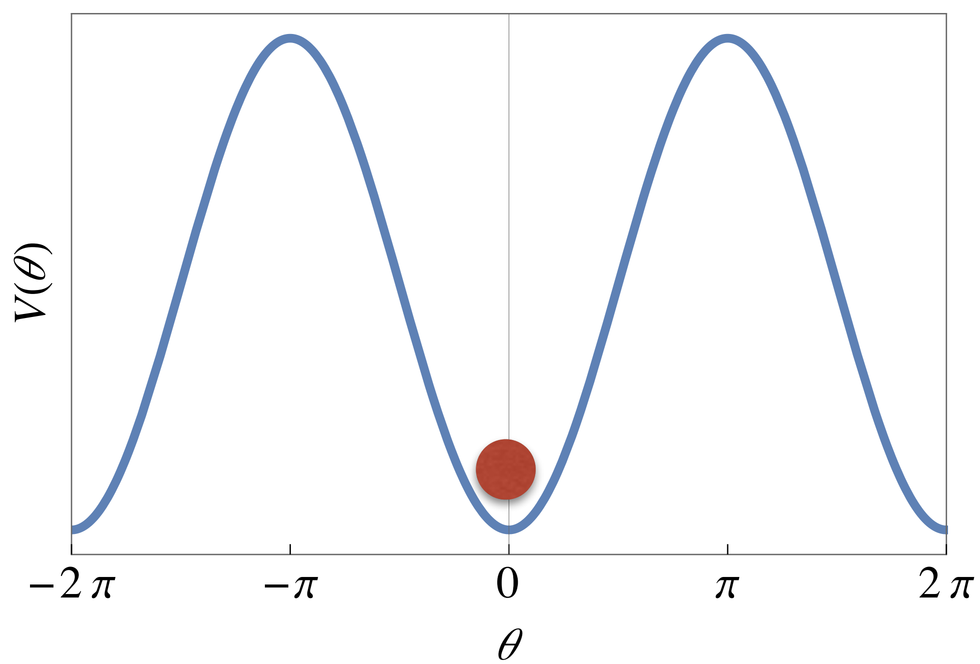
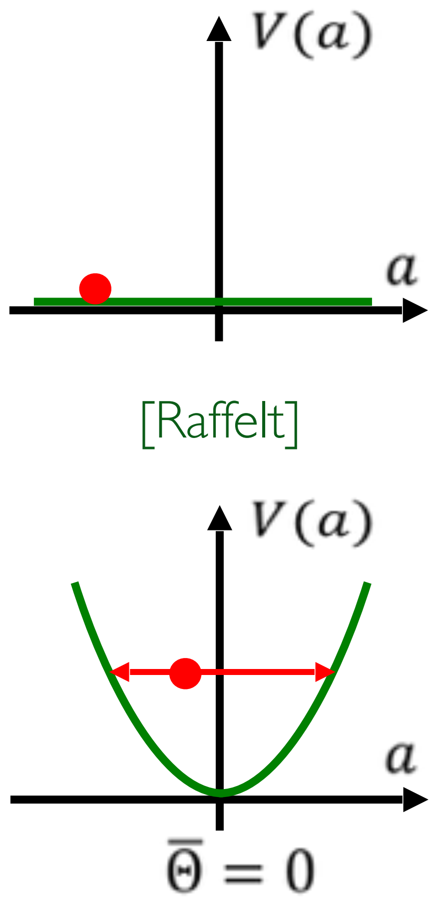


$$\theta \to \frac{a}{f_a} \qquad \textit{with} \qquad \langle a \rangle = 0$$

Dark Matter

vacuum re-alignment mechanism:



$$\ddot{a} + 3H\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

Axion properties *[model-indep.]*

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

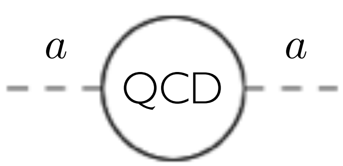
Axion properties *[model-indep.]*

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

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

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

  1. axion mass



$\sim \frac{\Lambda^4_{\rm QCD}}{f_a^2}$ $\longrightarrow$ $m_a \sim \Lambda^2_{\rm QCD} / f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a} \right)$

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

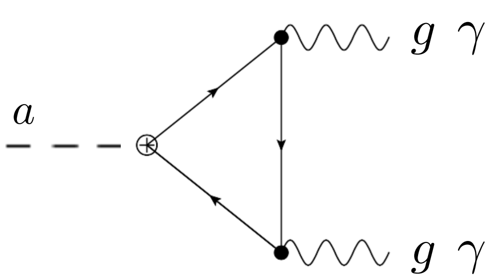
$C_\gamma = -1.92(4)$ $\quad$ $C_p = -0.47(3)$ $\quad$ $C_n = -0.02(3)$ $\quad$ $C_e \simeq 0$

$$\mathcal{L}_a \supset \frac{\alpha}{8\pi}\frac{C_\gamma}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{C_f}{2f_a}\partial_\mu a \overline{f}\gamma^\mu\gamma_5 f \qquad (f = p, n, e)$$

Axion properties *[model-dep.]*

- EFT breaks down at energies of order f_a

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



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

$$\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G} + \frac{E\alpha}{4\pi} F \cdot \tilde{F}$$

depends on UV completion

model independent

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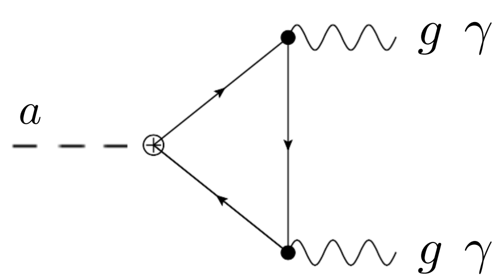

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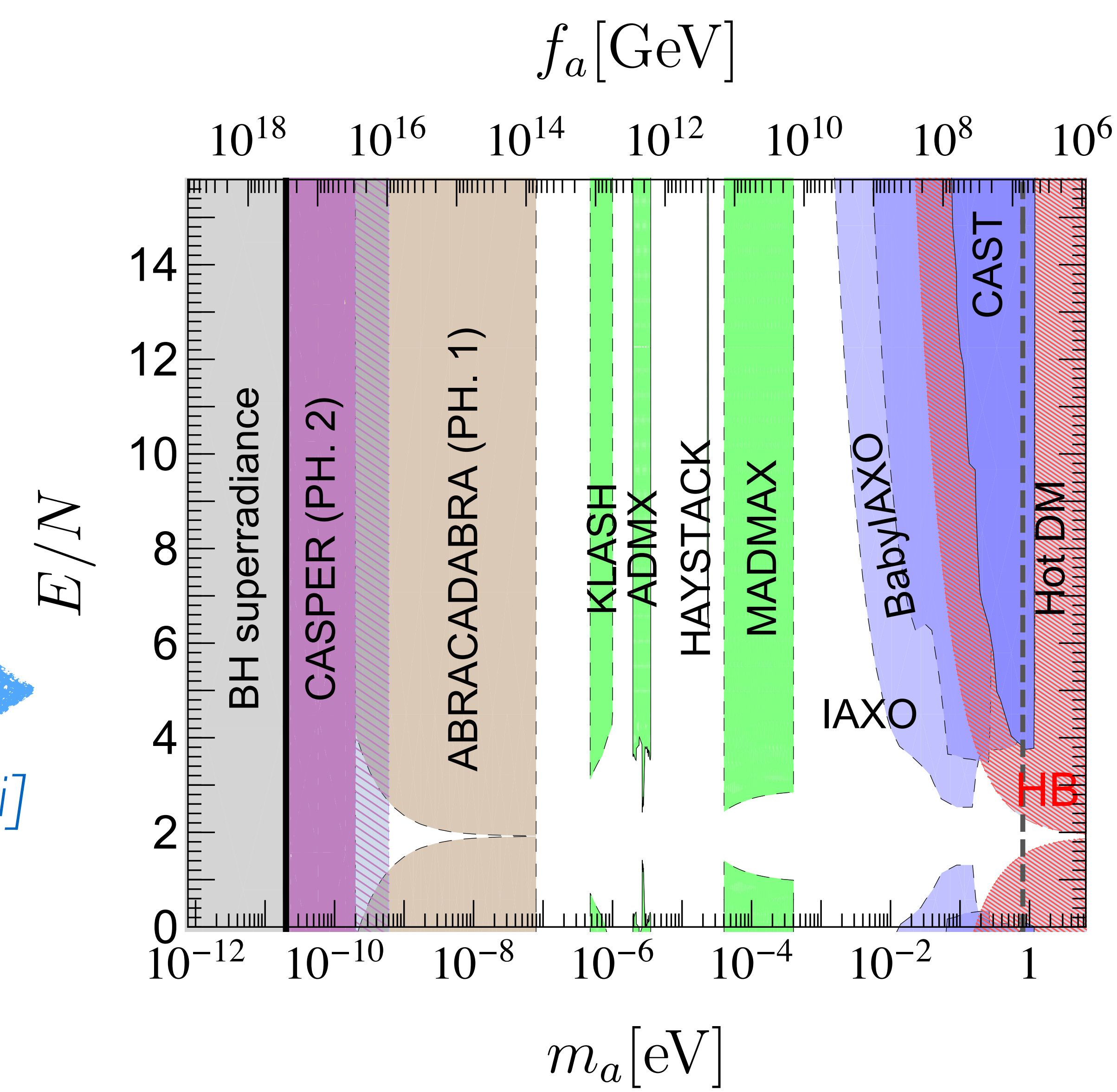
Axion exp.'s should explore the parameter space regardless of theoretical prejudice →



[Courtesy of Maurizio Giannotti]

[For theory motivated ranges of E/N see backup slides and/or LDL, Mescia, Nardi 1610.07593 + 1705.05370]

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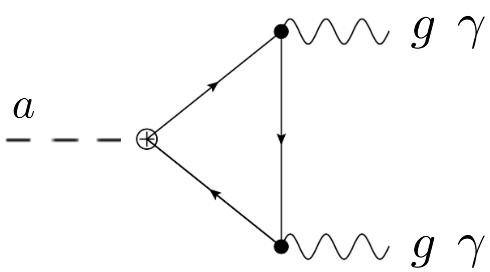

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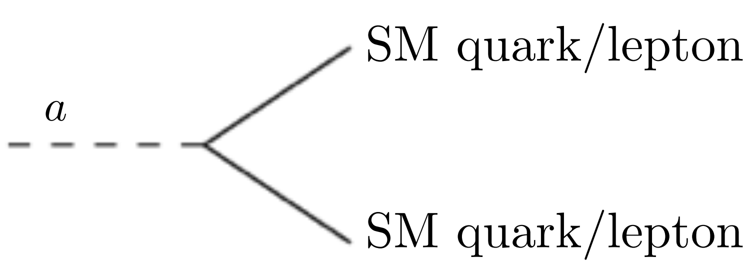

$$\frac{\partial_\mu a}{2 f_a} \overline{\psi}_i \gamma^\mu (C^V_{ij} + C^A_{ij} \gamma_5) \psi_j$$

{ enhance/suppress $C_{p,n,e}$
{ <u>flavour-violating</u> axion coupl.

Axion models [UV completion]

- global U(1)$_{PQ}$ (*QCD anomalous* + *spontaneously broken*)

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

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]

$f_a \sim v$ ruled out

$f_a \gg v$ "Invisible" axion (phase of singlet field)

A lesson from flavour…

- *is an MeV-scale standard axion really ruled out ?*

the axion just gives, experimentally, a missing energy signal (a = nothing). The most stringent bound for these axions was obtained by KEK [18] with

$$B(\mathrm{K}^+ \to \pi^+ + \text{nothing}) < 2.7 \times 10^{-8}. \quad (3.1)$$

Although, as we shall see, it is difficult to reliably compute the nonleptonic process $\mathrm{K}^+ \to \mathrm{a}\pi^+$, for the case of the standard axion one has a penguin contribution, which gives a relatively safe estimate [19]

$$B^{\text{penguin}}(\mathrm{K}^+ \to \mathrm{a}\pi^+) \approx 10^{-6} \times x^2. \quad (3.2)$$

Hence x must be small to survive (3.1). However, an $x \approx 10^{-1}$ would then lead one into contradiction with the $\Upsilon \to \mathrm{a}\gamma$ bound [6]. So a combination of the K decay bound and the Υ decay bound rules out the standard axion.

2Higgs

PQWW

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

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- *yes, if PQ is family universal*

[To rule out non-universal PQWW axion from rare π and K decays
it required almost a decade - e.g. Bardeen, Peccei, Yanagida NB279 (1987)]

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[Alves & Weiner 1710.03764 claim that an O(10) MeV axion is not ruled out, if
1) axion couples only to first generation fermions
2) axion-pion coupling is very suppressed
3) large hadronic uncertainties in rare kaon decays are invoked]

Astro bounds

- Stars are powerful sources of light and weakly coupled particles

[see e.g. G. Raffelt, 'Stars as Laboratories for Fundamental Physics' (1996)]

- 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)*

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

neutrino interactions (d=6 op.)

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

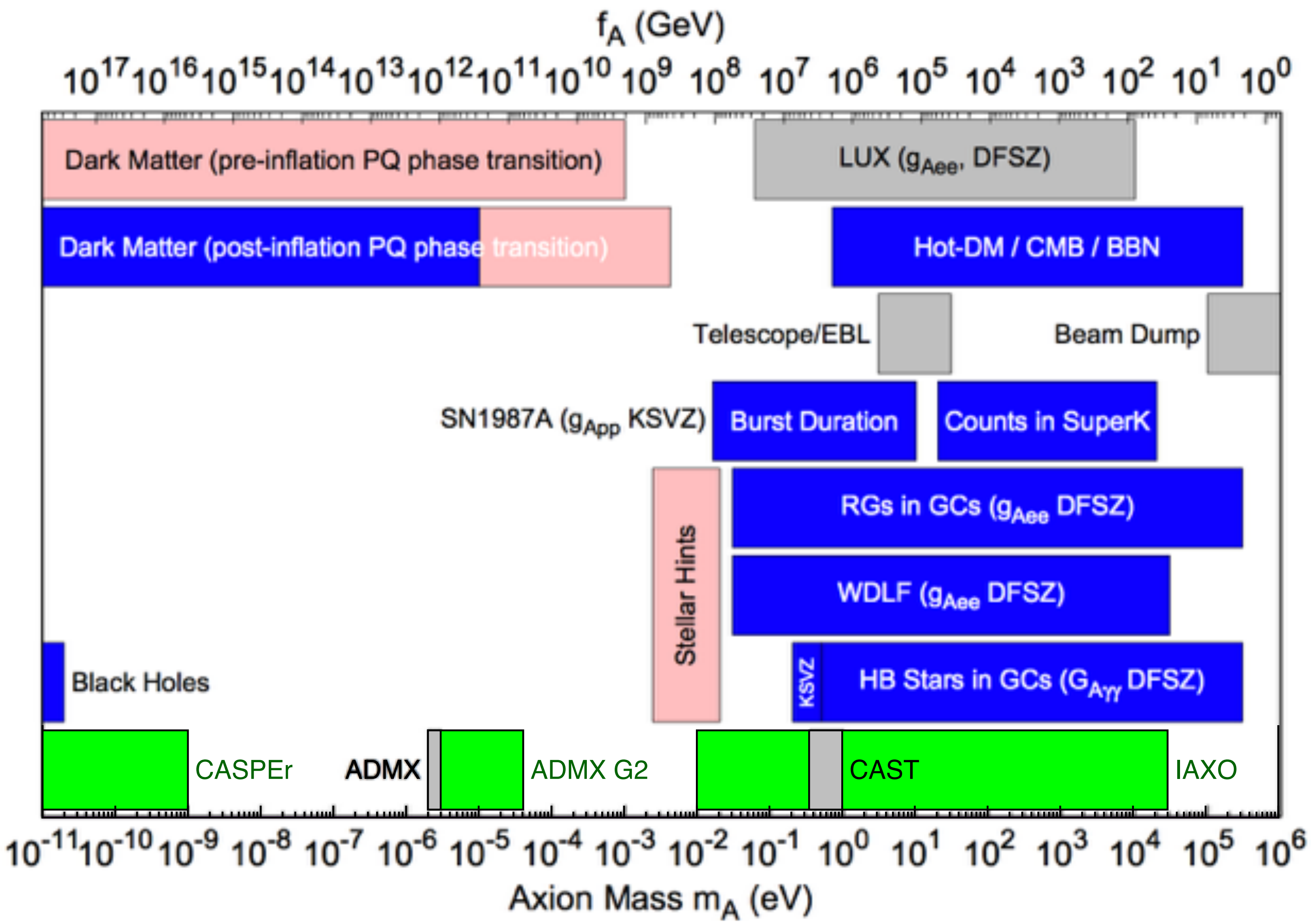
axion interactions (d=5 op.)

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

→ axions are a perfect target !

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

Astro bounds *[critical approach]*



[Ringwald, Rosenberg, Rybka, Particle Data Group]

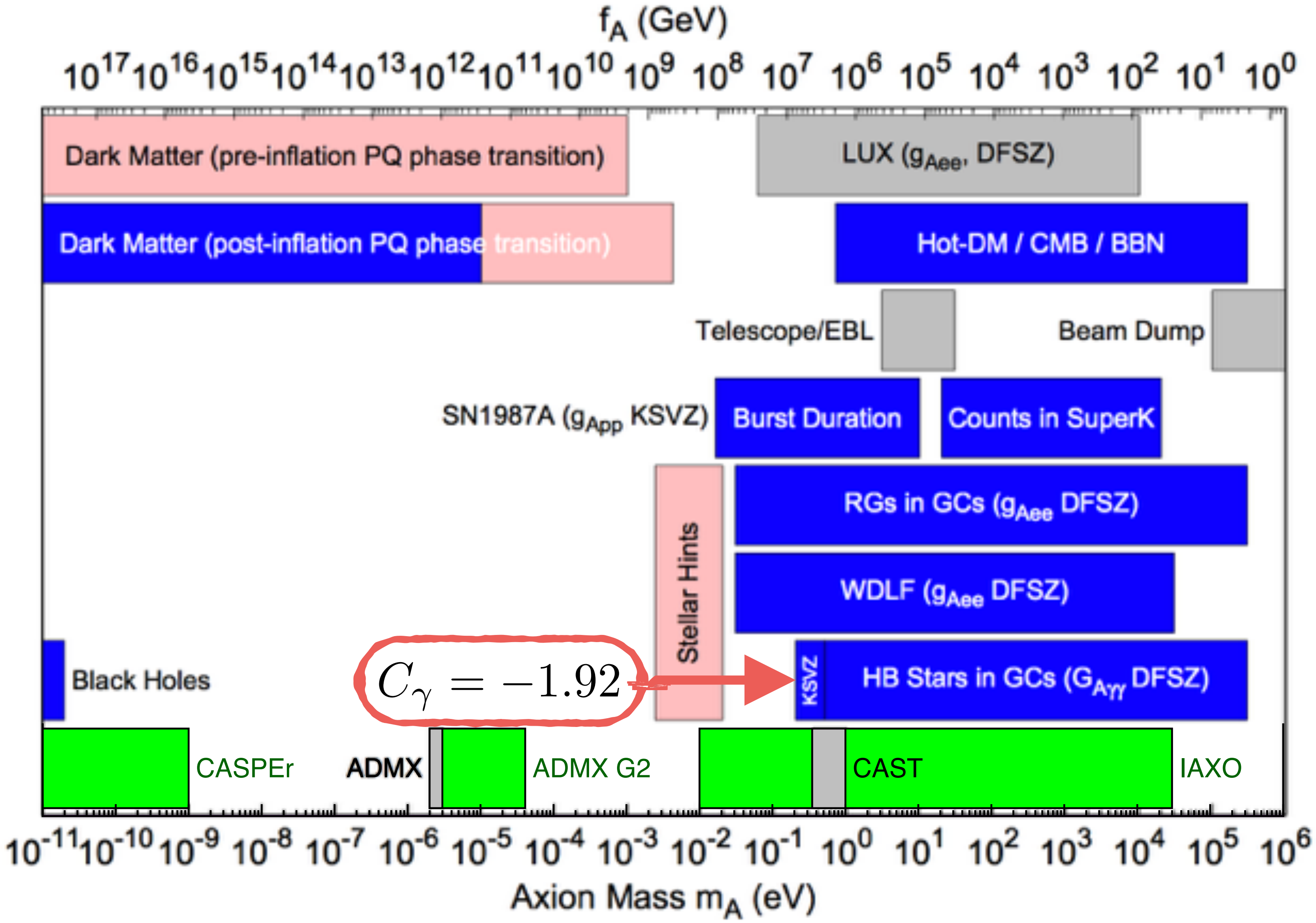
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Astro bounds *[critical approach]*



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Lab exclusions

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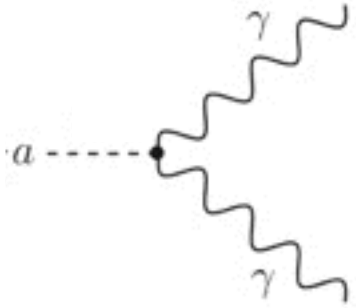
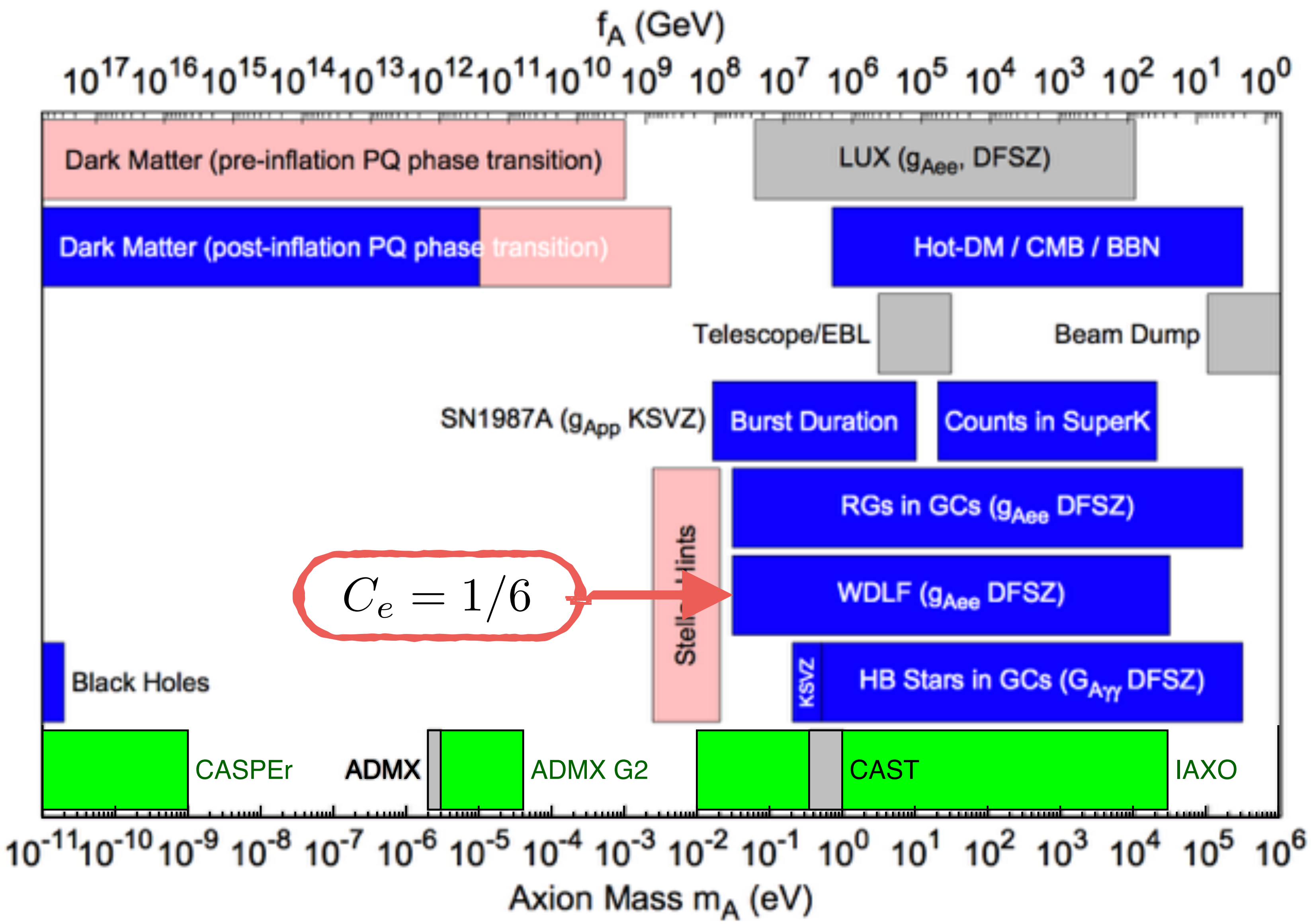
Exp. sensitivities

- Horizontal branch star evolution in globular clusters



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

Astro bounds *[critical approach]*



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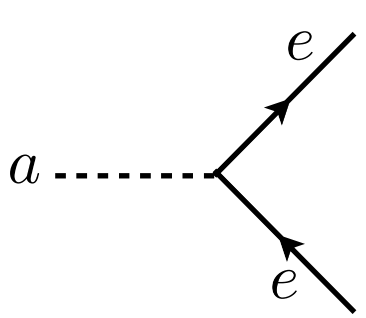
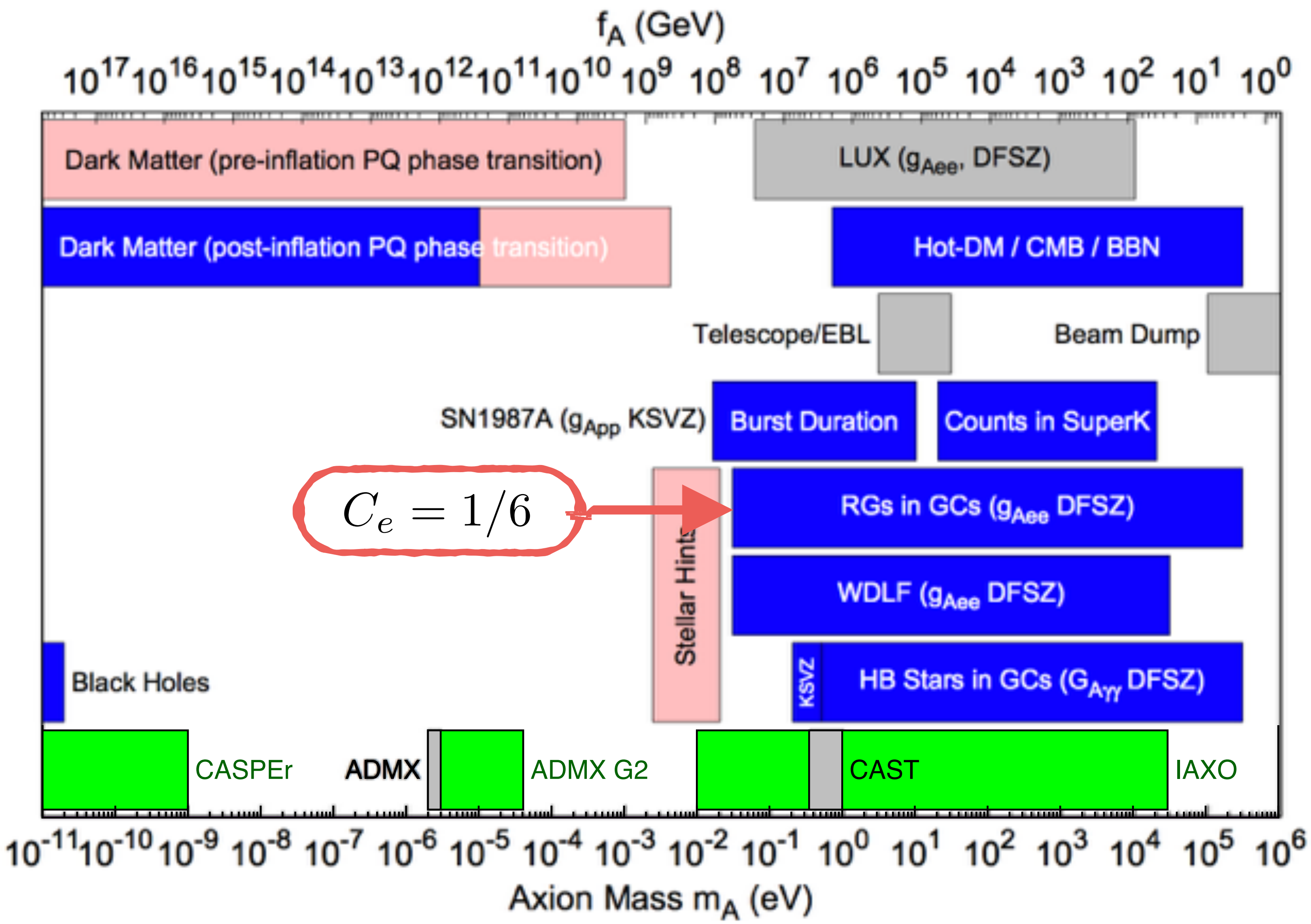
Exp. sensitivities

- White dwarfs luminosity function (cooling)



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

Astro bounds *[critical approach]*



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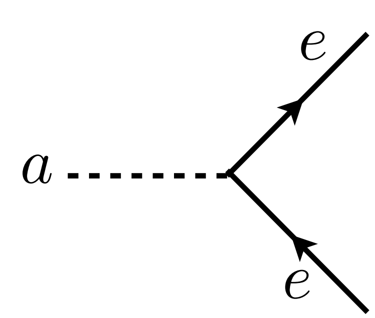
Exp. sensitivities

- Red giants evolution in globular clusters



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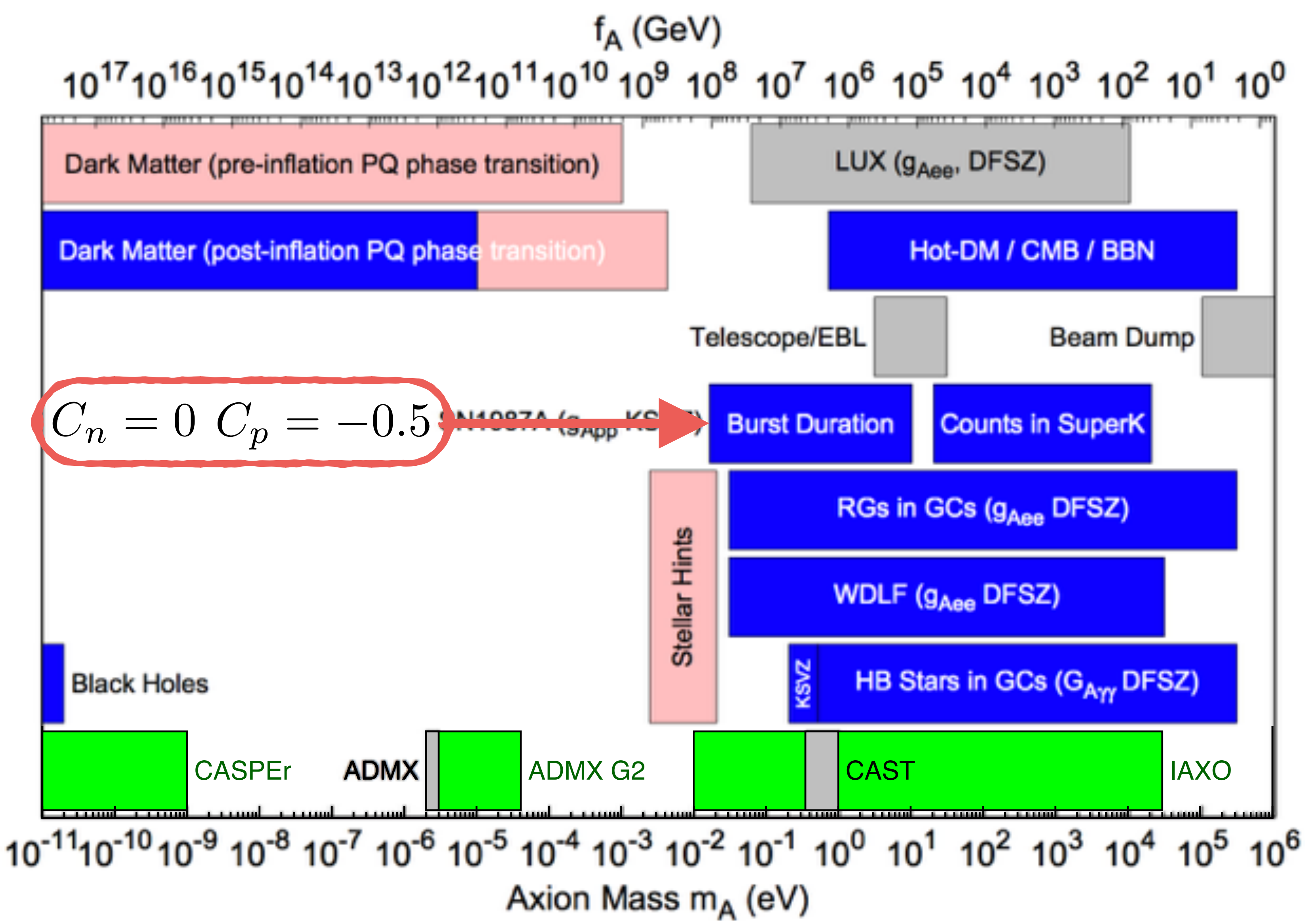

[Ringwald, Rosenberg, Rybka, Particle Data Group]

Lab exclusions

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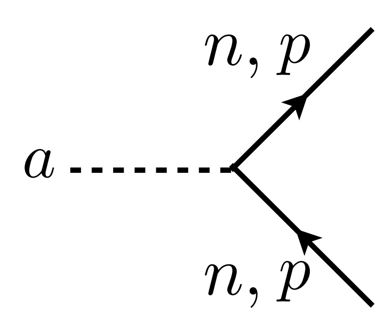
Exp. sensitivities

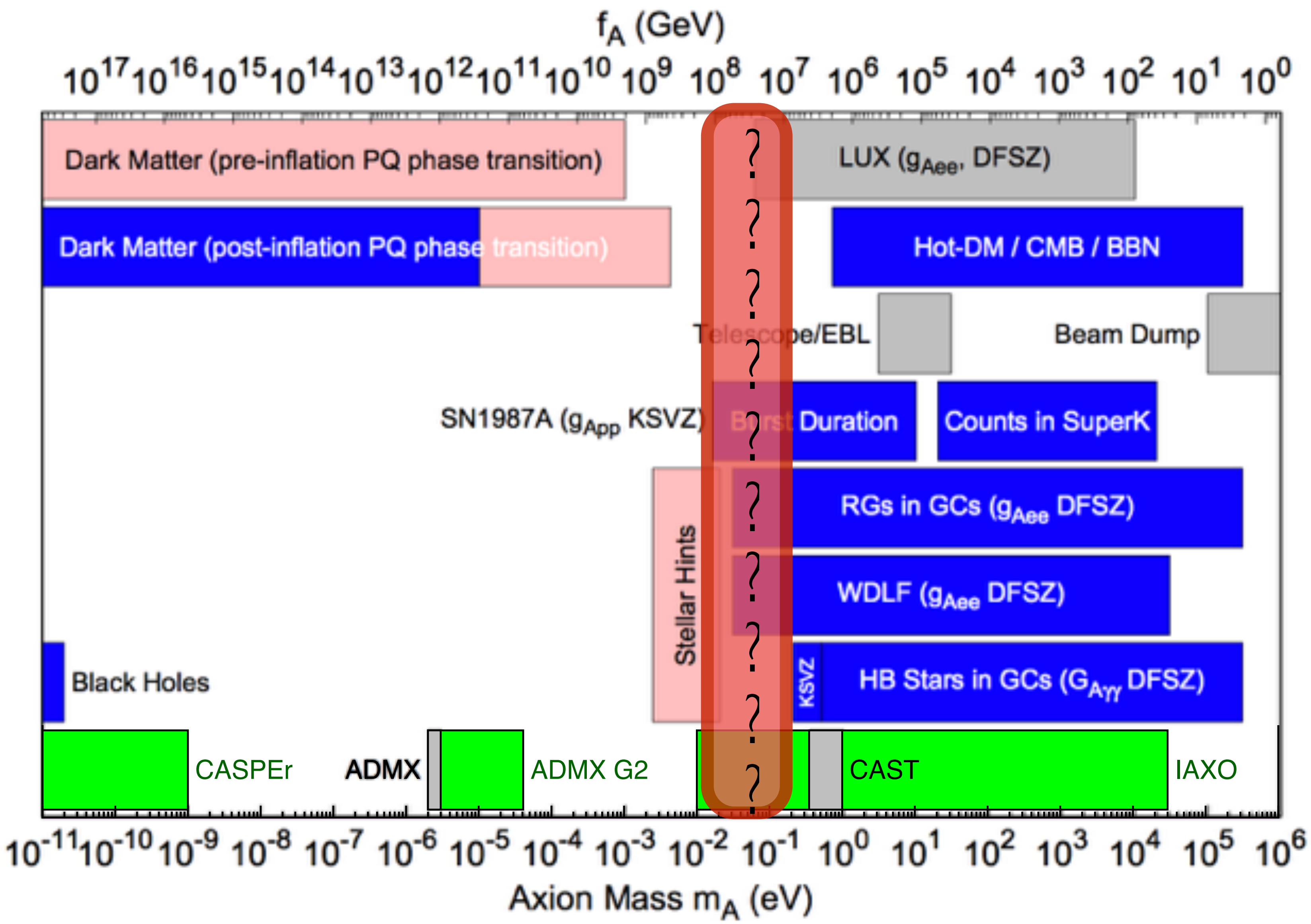
- Burst duration of SN1987A nu signal



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

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

Astro bounds *[critical approach]*



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Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- *Bound on axion mass is of <u>practical</u> convenience, but misses model dependence !*

Astrophobia

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

→ nucleophobia + electrophobia = astrophobia

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- *Why interested in such constructions ?*

[LDL, Mescia, Nardi, Panci, Ziegler 1712.04940
Bjorkeroth, LDL, Mescia, Nardi 1811.09637
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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 <u>flavour</u>

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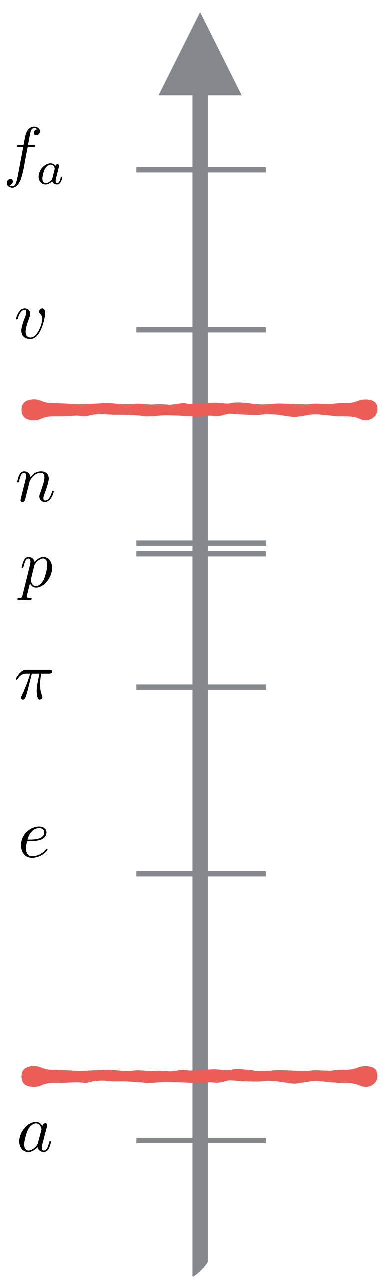
*e.g. couple the electron to 3rd Higgs uncharged under PQ

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]



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

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

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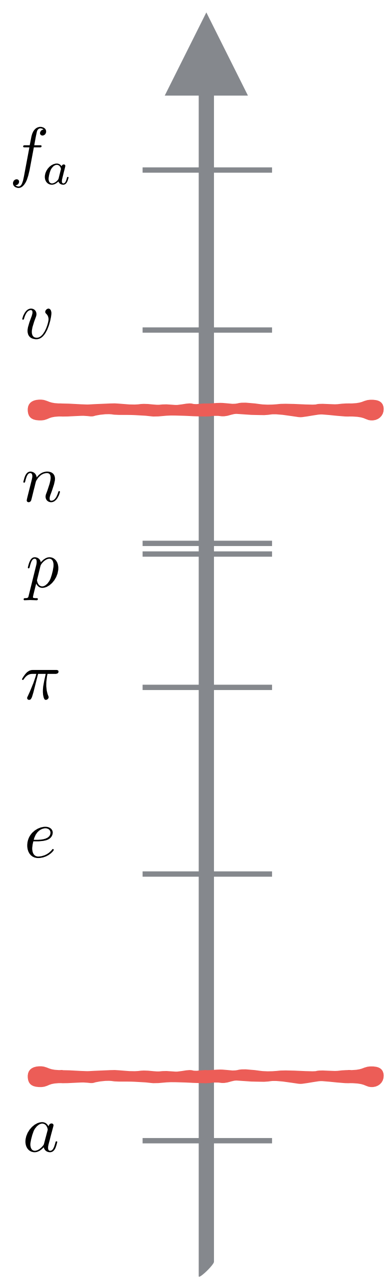

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$$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \overline{N} S^\mu N$$

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

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

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

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

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

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

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

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

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

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

$$N = N_1 \equiv X_u + X_d$$

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

- KSVZ: $X_u = X_d = 0$ → -1
- DFSZ: $N = n_g(X_u + X_d)$ → $\frac{1}{n_g} - 1$

Implementing nucleophobia

- <u>Simplification</u>: 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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$$N \equiv N_1 + N_2 + N_3 = N_1 \quad \longrightarrow \quad N_1 = N_2 = -N_3$$

- $N_2 + N_3 = 0$ easy to implement with 2HDM

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

$$\Longrightarrow \quad N_3 = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2$$

$$\Longrightarrow \quad N_2 = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1$$

- 1st condition automatically satisfied

Implementing nucleophobia

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

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- 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

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

$[\mathrm{PQ}_d, Y_d^\dagger Y_d] \neq 0$ ↓ *diagonal (non-universal) PQ charge matrix of d_R quarks*

$C_{a d_i d_j} \propto (V_d^\dagger \, \mathrm{PQ}_d V_d)_{i \neq j} \neq 0$ ↓ *right unitary rotation diagonalizing Y_d*

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- Rare decays with invisible/massless final states probing $\frac{\partial_\mu a}{2 f_a}\overline{\psi}_i\gamma^\mu(C^V_{ij} + C^A_{ij}\gamma_5)\psi_j$

$K \to \pi a$ (E787+E949, '08): $m_a < \frac{2\cdot 10^{-5}\,\mathrm{eV}}{|C^V_{sd}|}$ $\xrightarrow{\times 1/8}$ **NA62**

$\mu \to e a \gamma$ (Crystal Box, '88): $m_a < \frac{3\cdot 10^{-3}\,\mathrm{eV}}{|C_{\mu e}|}$ $\xrightarrow{?}$ **MEG, Mu3e**

$B \to K a$ (CLEO, '01): $m_a < \frac{9\cdot 10^{-2}\,\mathrm{eV}}{|C^V_{bs}|}$ $\xrightarrow{\times 1/10}$ **BELLE II**

[Robert Ziegler, La Thuile'19 +1901.01084]

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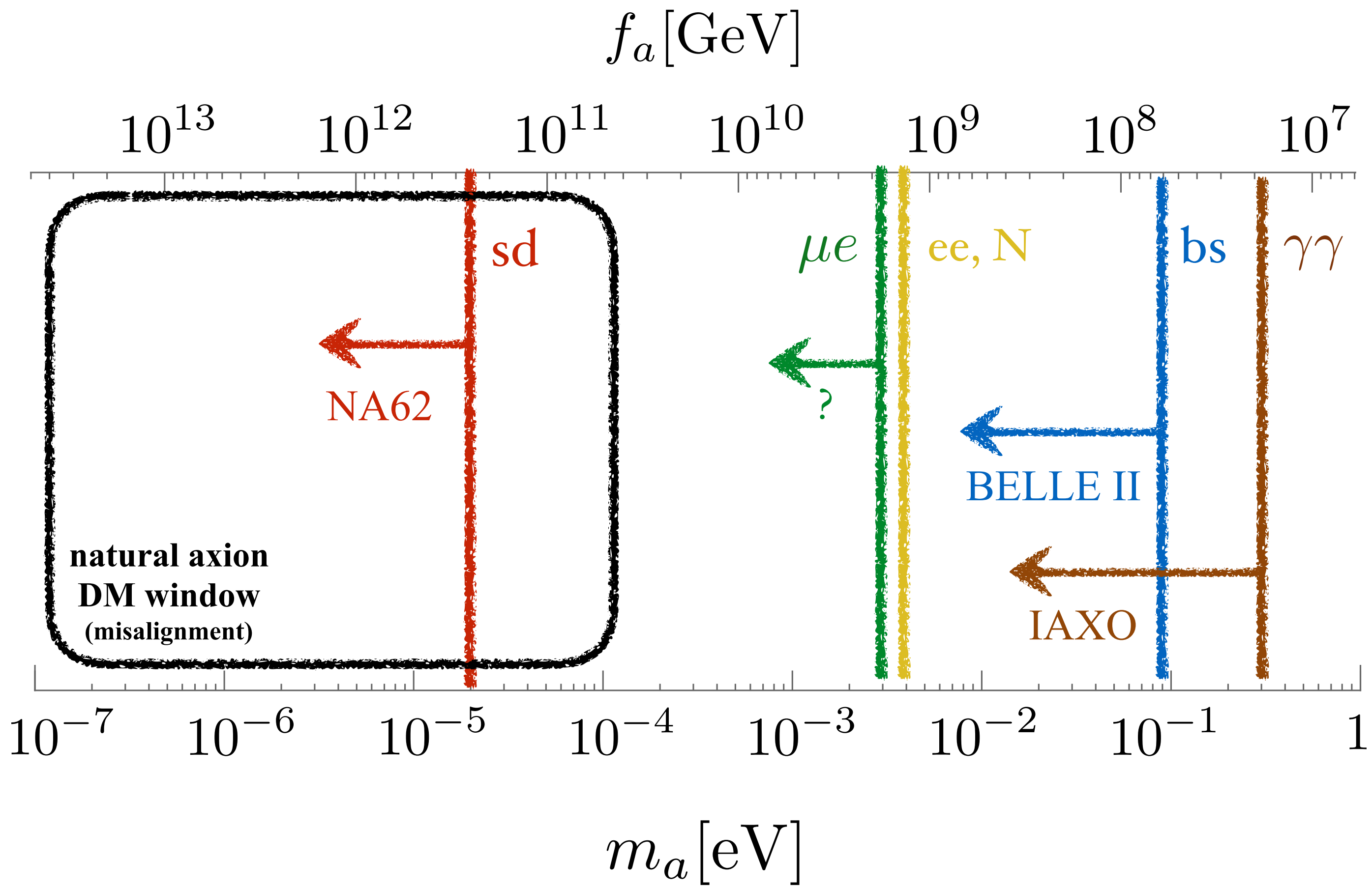

[Robert Ziegler, La Thuile'19 +1901.01084]

(for $C_i = \{C_\gamma, C_e, C_N, C^V_{sd}, C^V_{bs}\} = 1$)

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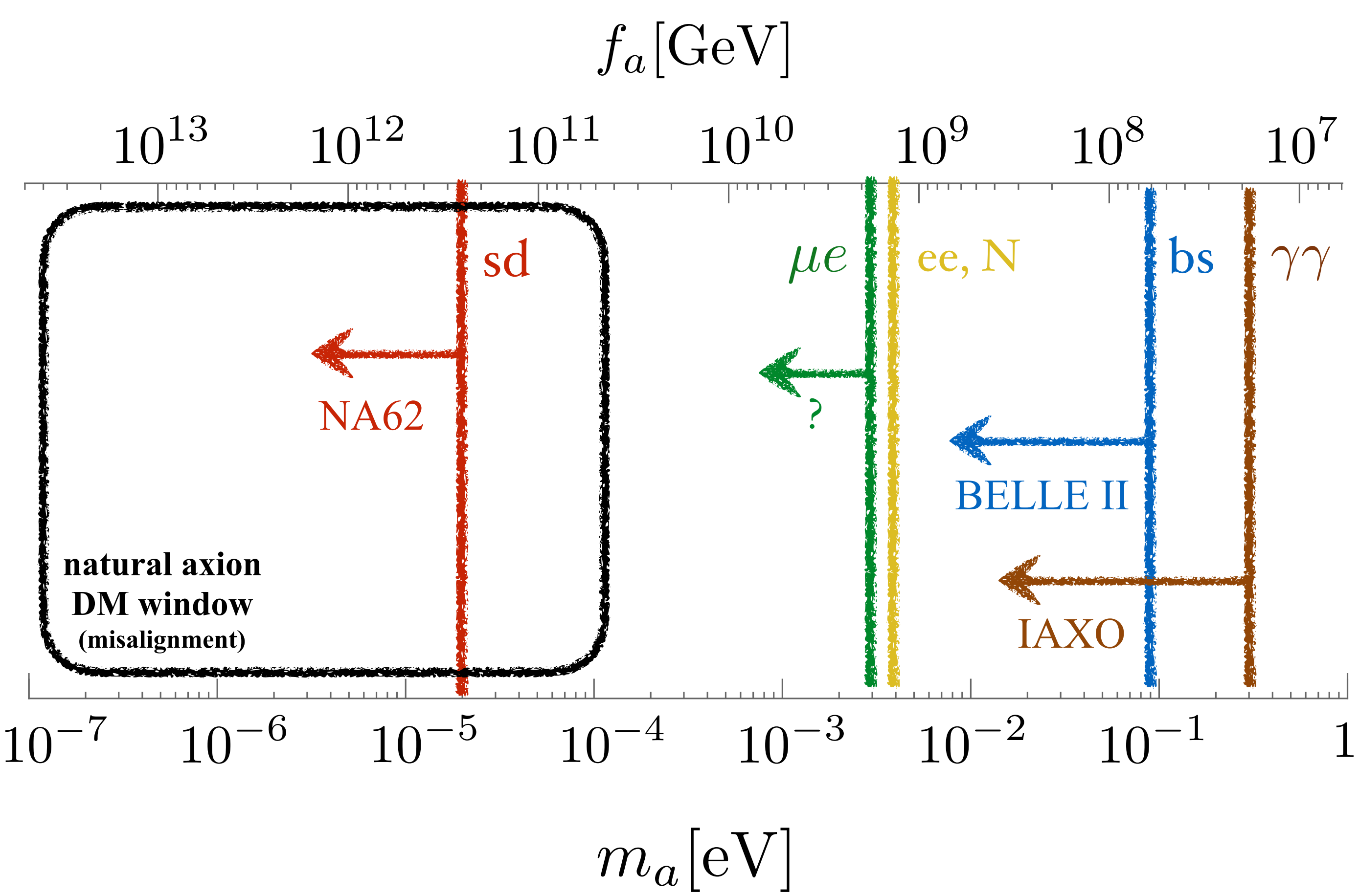

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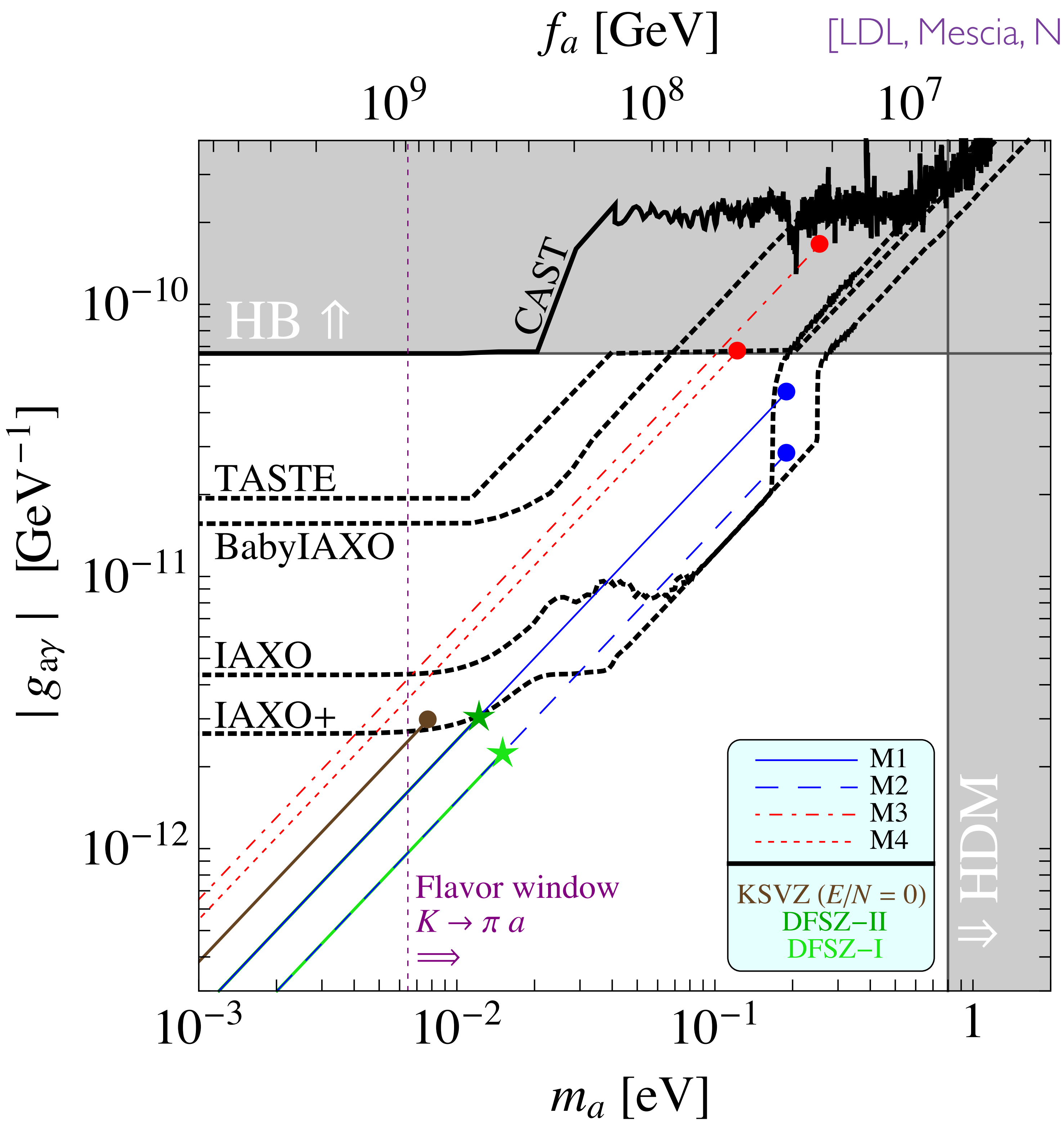
(for $C_i = \{C_\gamma, C_e, C_N, C^V_{sd}, C^V_{bs}\} = 1$)

size of flavour coefficients can be fixed in flavour models, e.g. PQ = FN

[For recent discussions see e.g.
Ema et al 1612.05492
Calibbi et al 1612.08040
Arias-Aragon, Merlo 1709.07039
Linster, Ziegler 1805.07341
Björkeroth et al 1811.09637]

Re-opening the Axion Window

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



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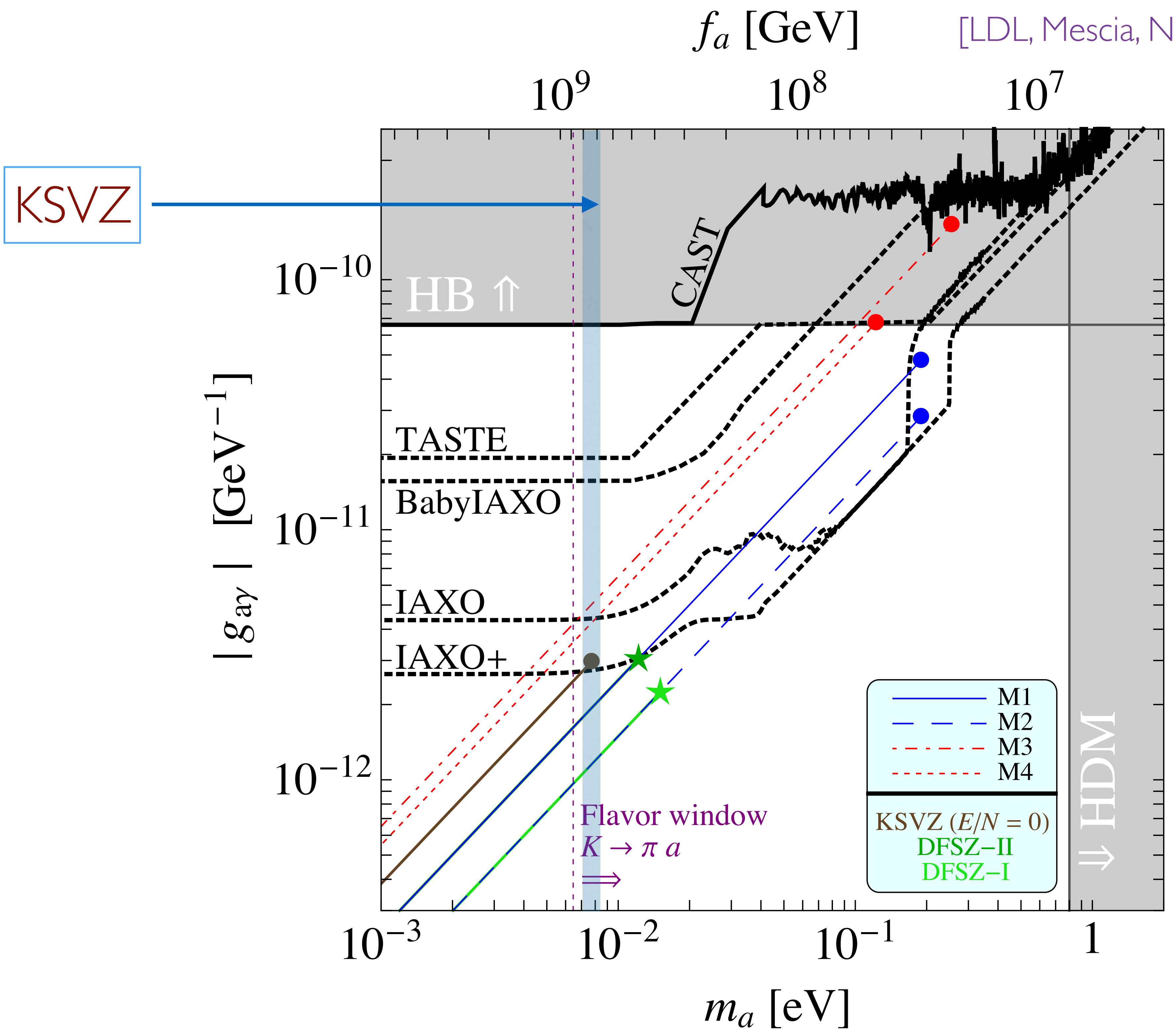
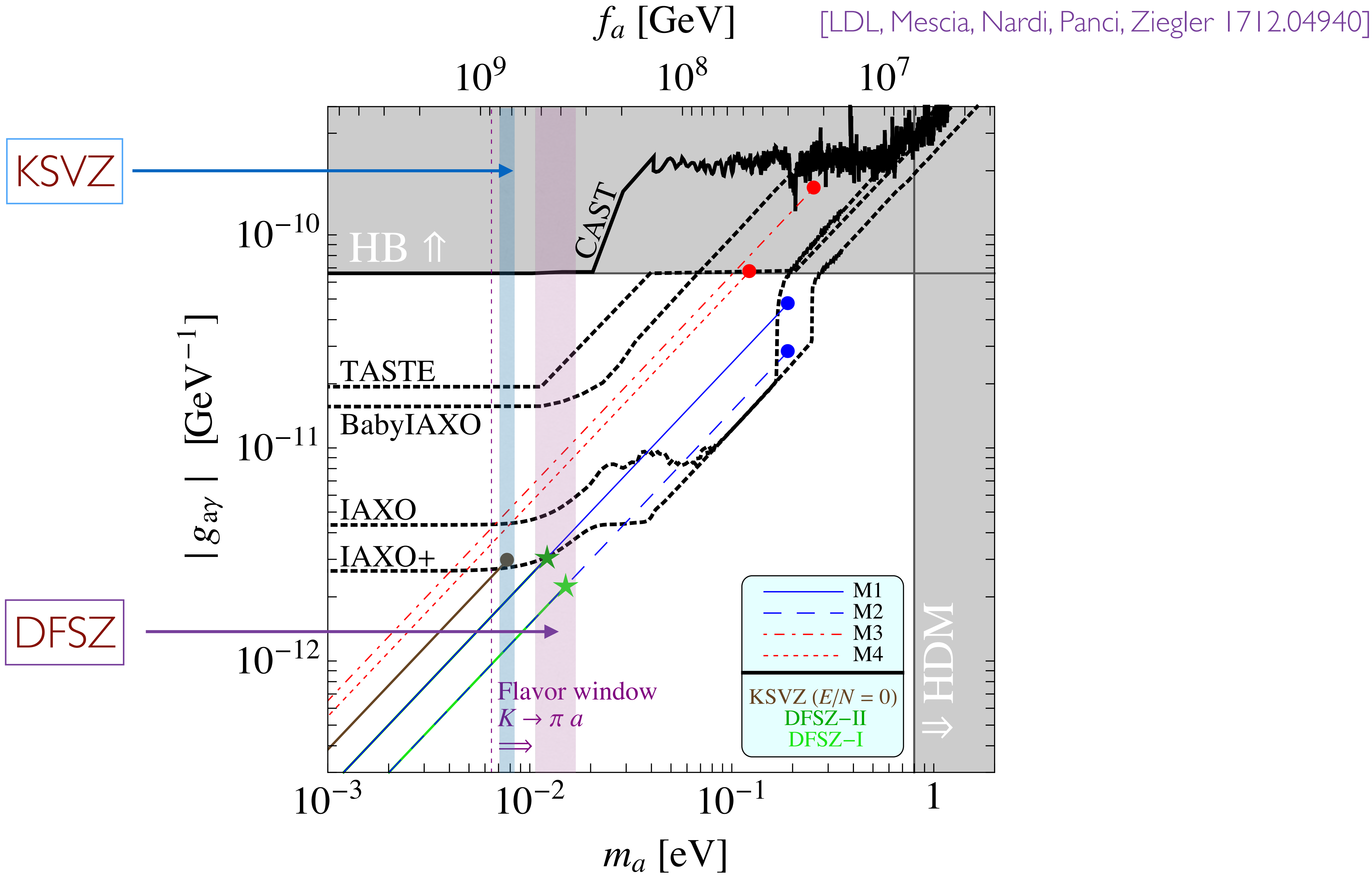


Re-opening the Axion Window



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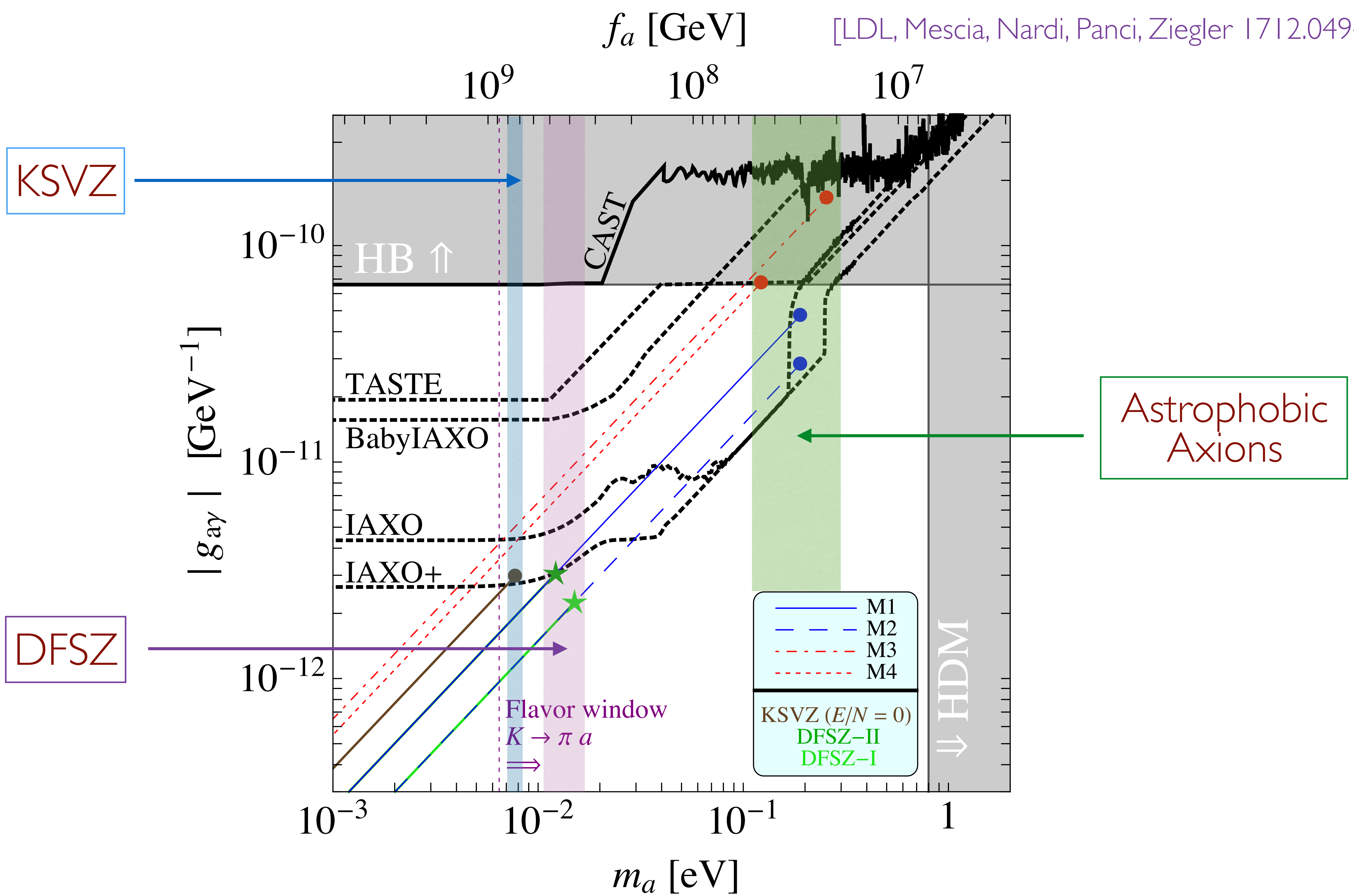

Conclusions

- Axion physics is entering an experimentally driven era

  - *axion couplings are UV dependent*

  - *worth to think about alternatives to KSVZ/DFSZ when confronting exp. bounds/sensitivities*

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(an analogy I cannot resist: DFSZ = cMSSM)

↙ *flavour opportunity (blessing)*

↘ *flavour problem (curse)*

Conclusions

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(an analogy I cannot resist: DFSZ = cMSSM)

↙ *flavour opportunity (blessing)*

↘ *flavour problem (curse)*

- Relaxing flavour universality of PQ opens new pathways:

  - *heavy axion ?*

  - *nucleophobia*

  - *flavoured axion searches*

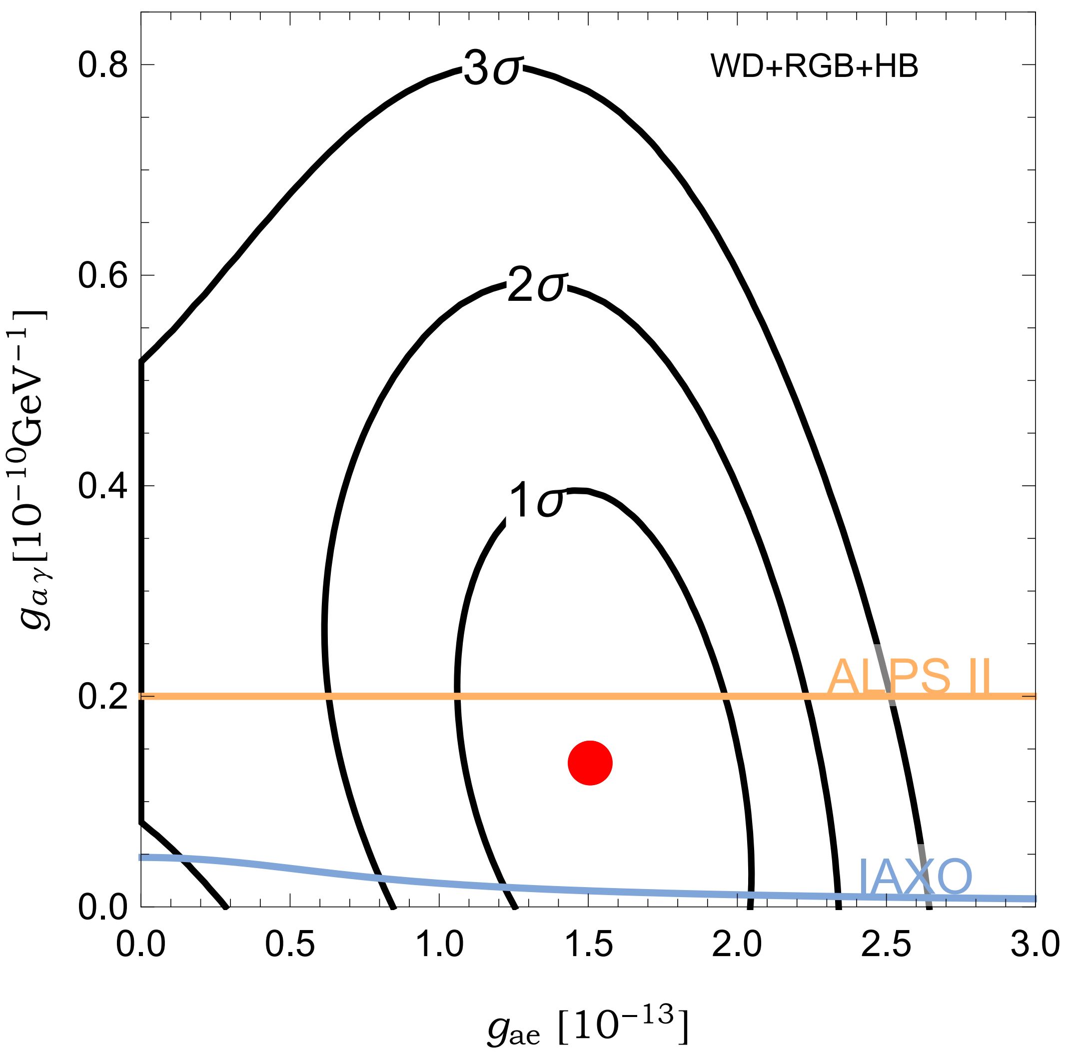
  - *connection to SM flavour pattern*

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, Irastorza, Redondo, Ringwald, Saikawa 1708.02111]



Model	Global fit includes	f_a [10^8 GeV]	m_a [meV]	$\tan\beta$	$\chi^2_{\rm min}$/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 axions should improve fit, allowing for fully perturbative Yukawas

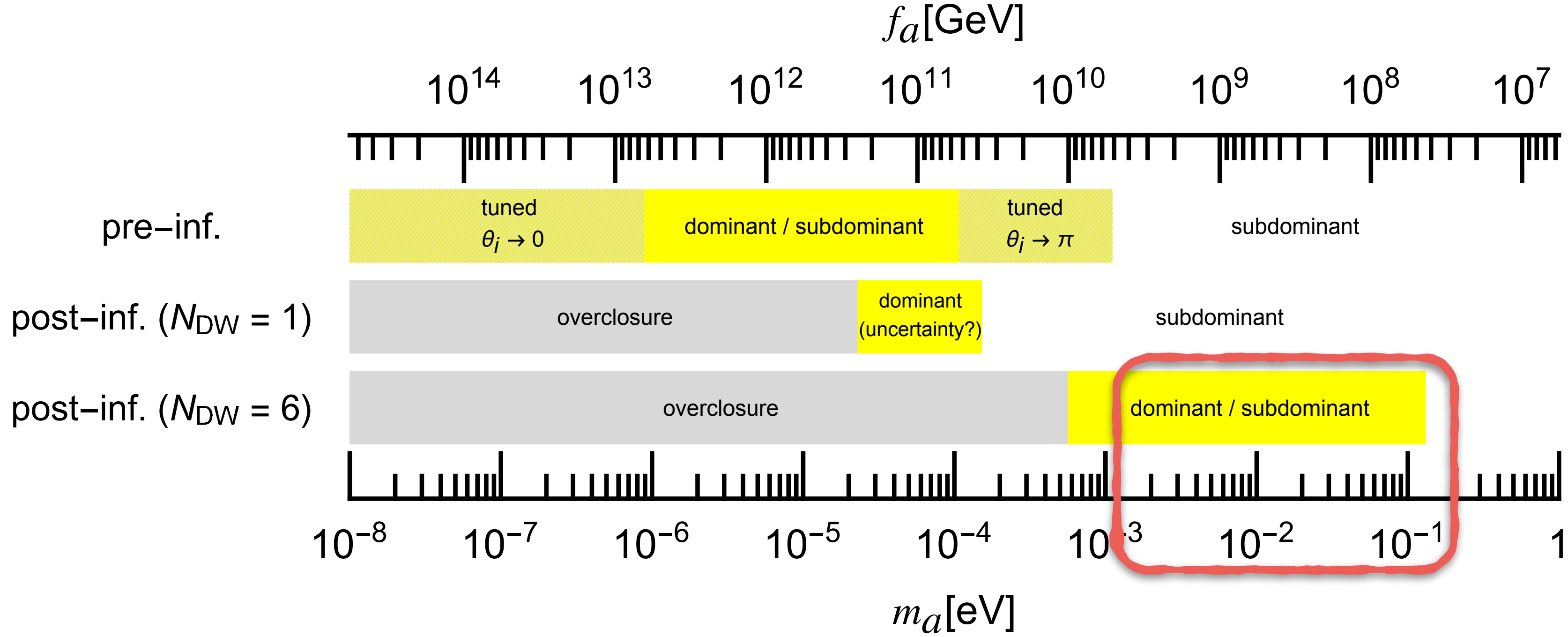
*SN bound a factor ~4 weaker than PDG one ?

[Chang, Essig, McDermott 1803.00993,
Carenza, Fischer, Giannotti, Mirizzi 1906.11844]

DM in the heavy axion window

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

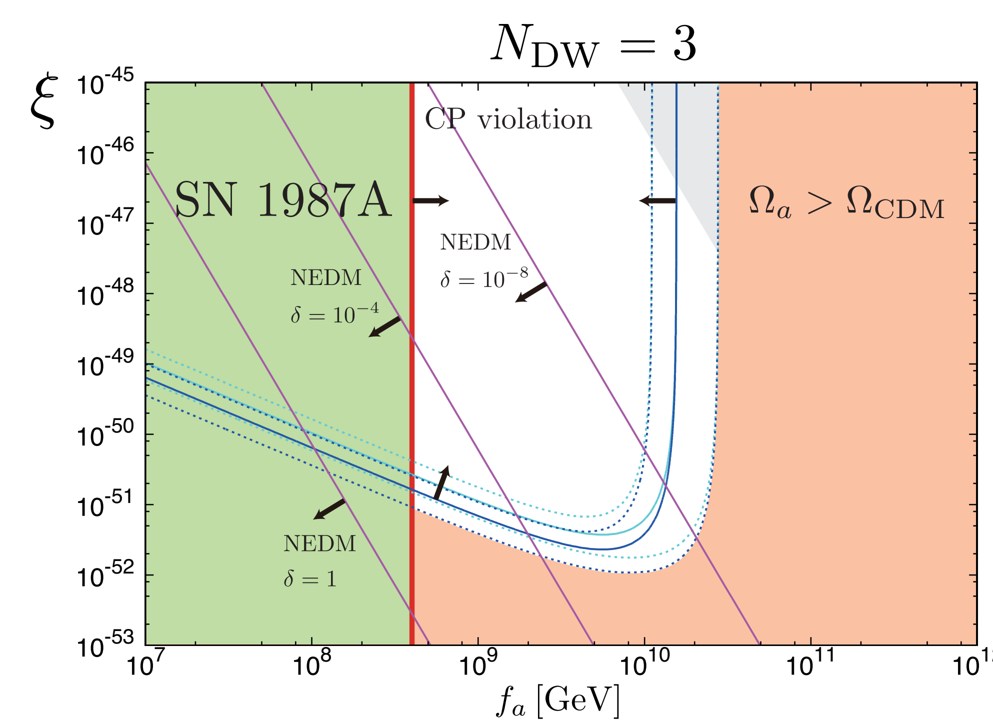
[Kawasaki, Saikawa, Sekiguchi, 1412.0789 1709.07091]



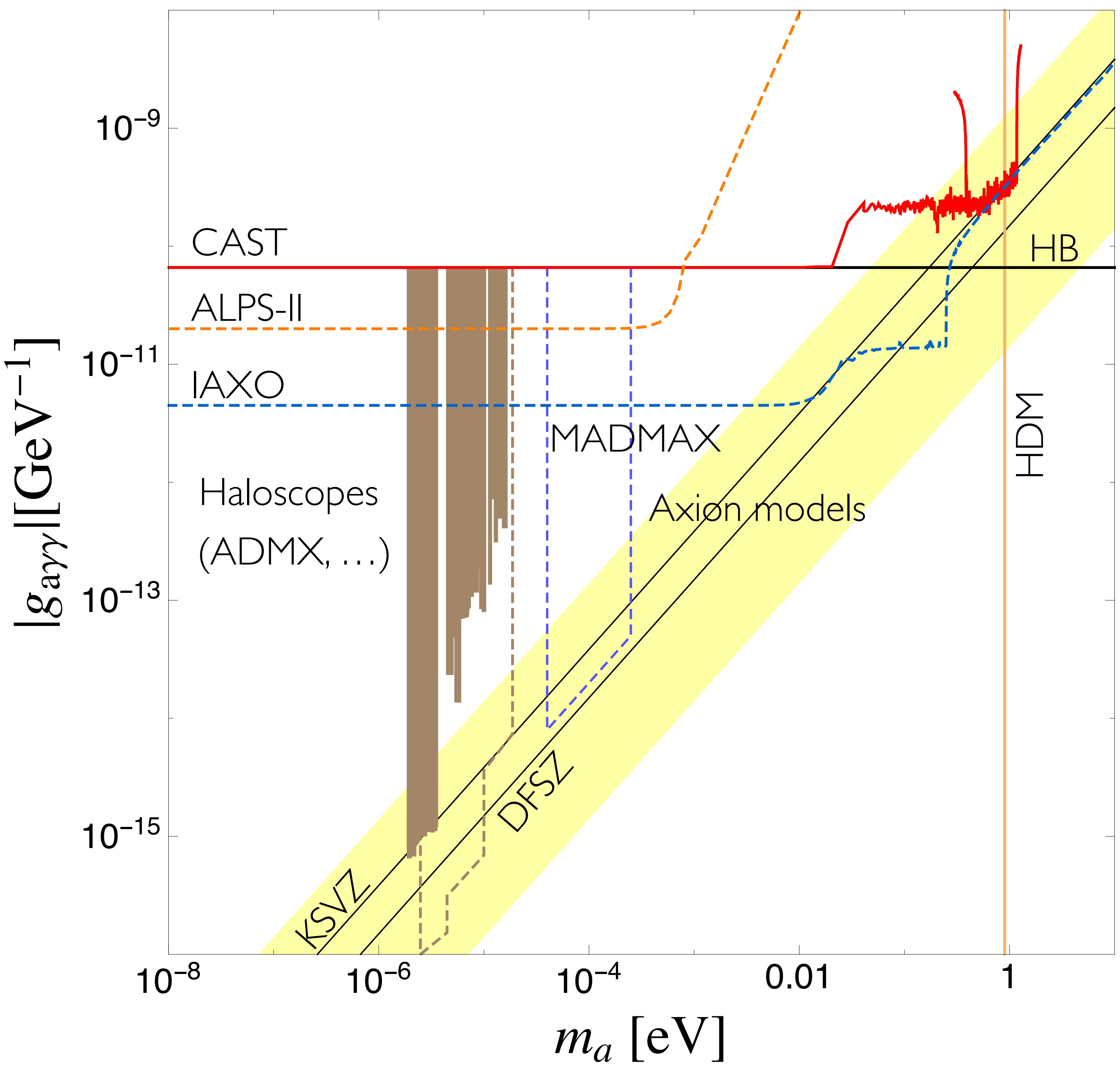
- axion production from topological defects

- requires explicit PQ breaking term

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



Need to know where to search



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

E/N anomaly coefficients, depend on UV completion

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

[Particle Data Group (since end of 90's). Chosen to include some representative KSVZ/DFSZ models e.g. from:
- Kaplan, NPB 260 (1985),
- Cheng, Geng, Ni, PRD 52 (1995),
- Kim, PRD 58 (1998)]

KSVZ axions

- Field content

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
Q_L	$1/2$	$\mathcal{C}_Q$	$\mathcal{I}_Q$	$\mathcal{Y}_Q$	$\mathcal{X}_L$
Q_R	$1/2$	$\mathcal{C}_Q$	$\mathcal{I}_Q$	$\mathcal{Y}_Q$	$\mathcal{X}_R$
Φ	0	1	1	0	1

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

PQ charges carried by a vector-like quark $Q = Q_L + Q_R$

[original KSVZ model assumes Q ~ (3,1,0)]

$$\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G} + \frac{E\alpha}{4\pi} F \cdot \tilde{F}$$

$$N = \sum_Q (\mathcal{X}_L - \mathcal{X}_R)\ T(\mathcal{C}_Q)$$

$$E = \sum_Q (\mathcal{X}_L - \mathcal{X}_R)\ \mathcal{Q}_Q^2$$

} anomaly coeff.

and a SM singlet **Φ** containing the "invisible" axion ($f_a \gg v$)

$$\Phi(x) = \frac{1}{\sqrt{2}} \left[\rho(x) + f_a\right] e^{ia(x)/f_a}$$

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Φ	0	1	1	0	1

[Kim '79,
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- Lagrangian

$$\mathcal{L}_a = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm PQ} - V_{H\Phi} + \mathcal{L}_{Qq}$$

$$|\mathcal{X}_L - \mathcal{X}_R| = 1$$

- $\mathcal{L}_{\rm PQ} = |\partial_\mu \Phi|^2 + \overline{Q} i \not{D} Q - (y_Q \, \overline{Q}_L Q_R \Phi + \text{H.c.})$ → $m_Q = y_Q f_a/\sqrt{2}$
- $V_{H\Phi} = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2$ → $m_\rho \sim f_a$
- $\mathcal{L}_{Qq}$ d ≤ 4 mixing with SM quarks (depends in Q-gauge quantum numbers)

Q stability

- Symmetry of the kinetic term

$$U(1)_{Q_L} \times U(1)_{Q_R} \times U(1)_{\Phi} \xrightarrow{y_Q \neq 0} U(1)_{\rm PQ} \times U(1)_{\rm Q}$$

$$\mathcal{L}_{\rm PQ} = |\partial_\mu \Phi|^2 + \overline{Q} i \not{D} Q - (y_Q \overline{Q}_L Q_R \Phi + \text{H.c.})$$

- $U(1)_Q$ is the Q-baryon number: <u>if exact, Q would be stable</u>

↓

cosmological issue if thermally produced
in the early universe !

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- if $\mathcal{L}_{Qq} \neq 0$ $U(1)_Q$ is further broken and Q-decay is possible [Ringwald, Saikawa, 1512.06436]

- decay also possible via d>4 operators (e.g. Planck-induced)

→ stability depends on Q representations

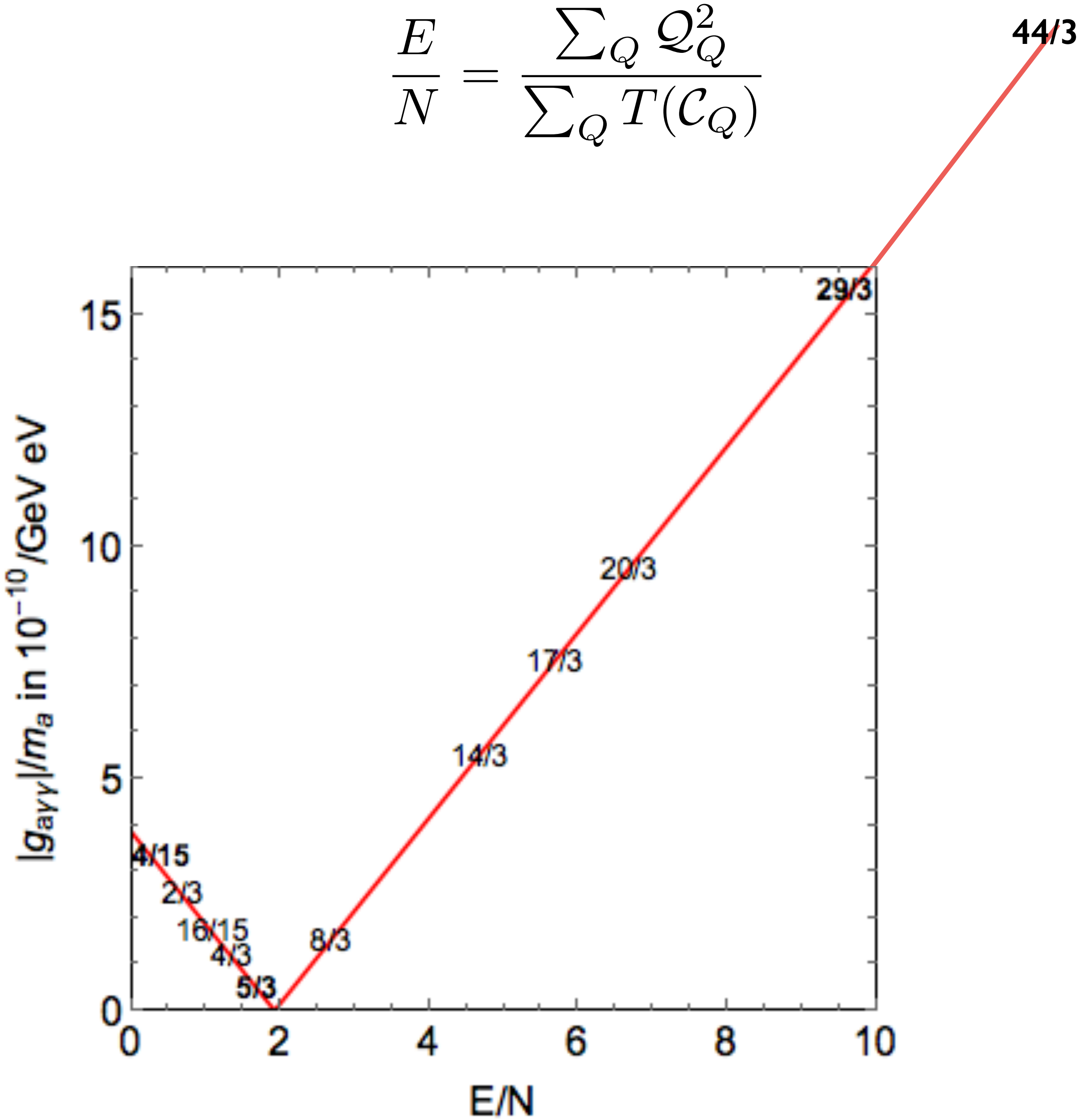
Pheno preferred KSVZ fermions

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



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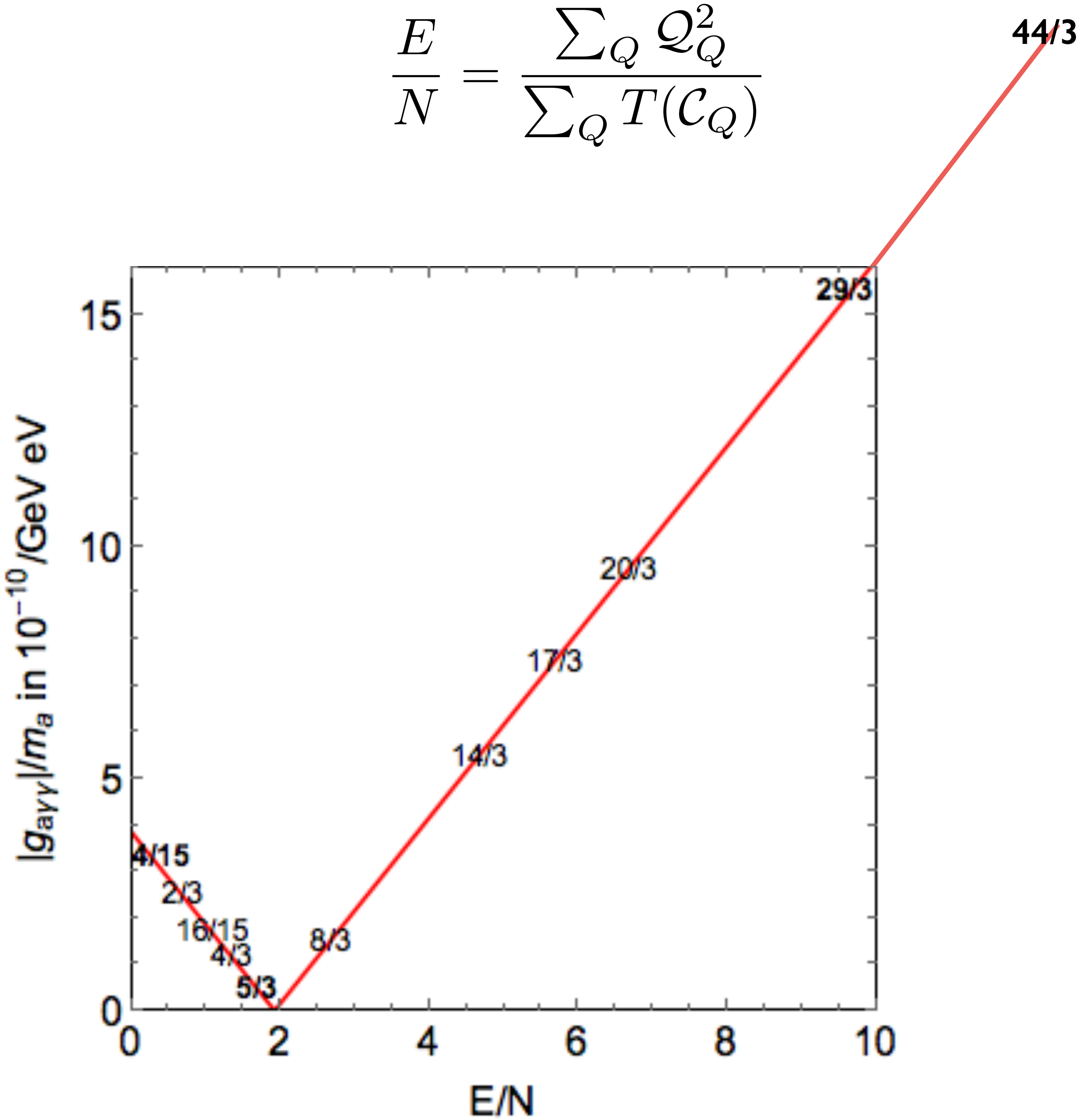
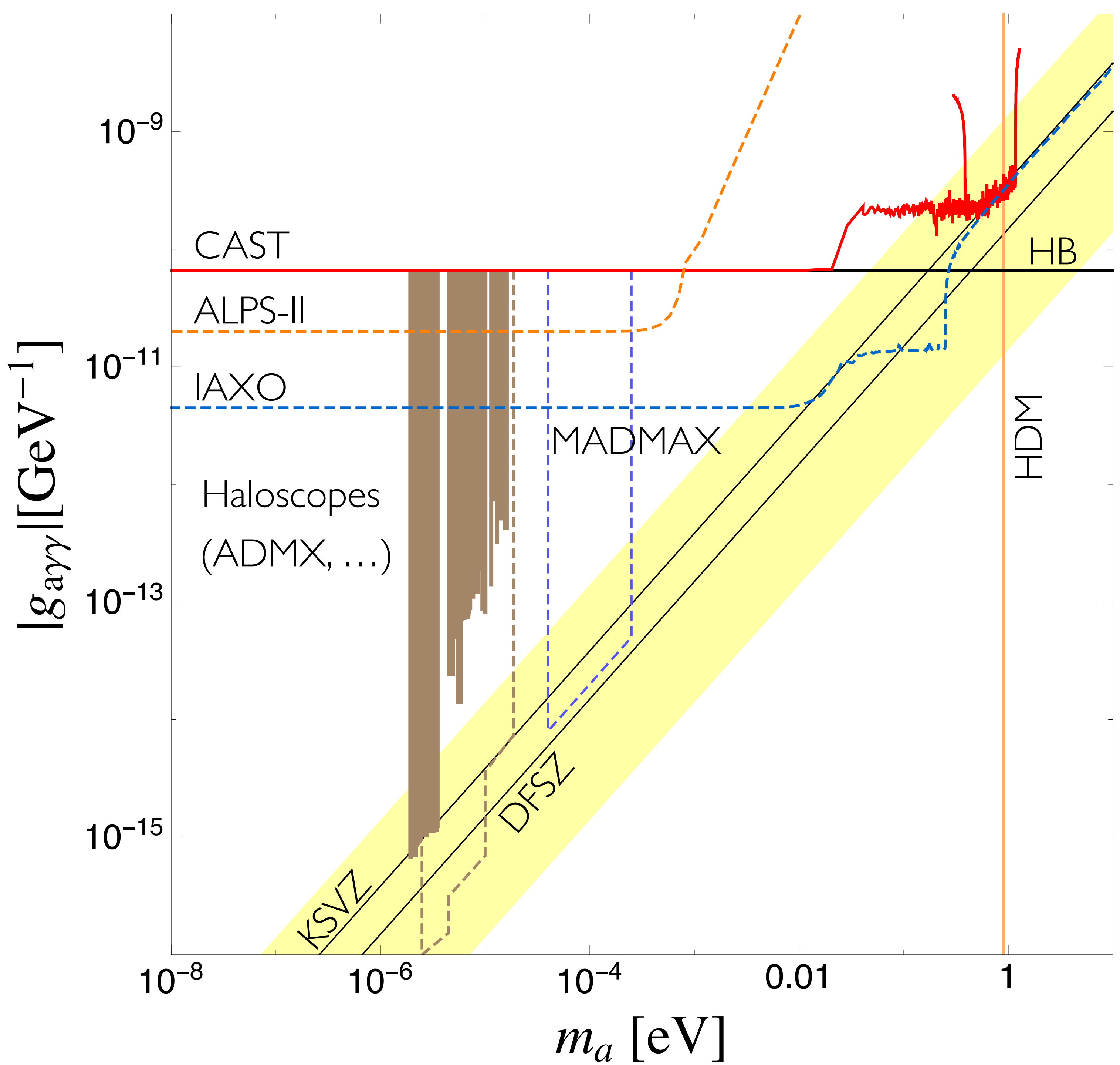
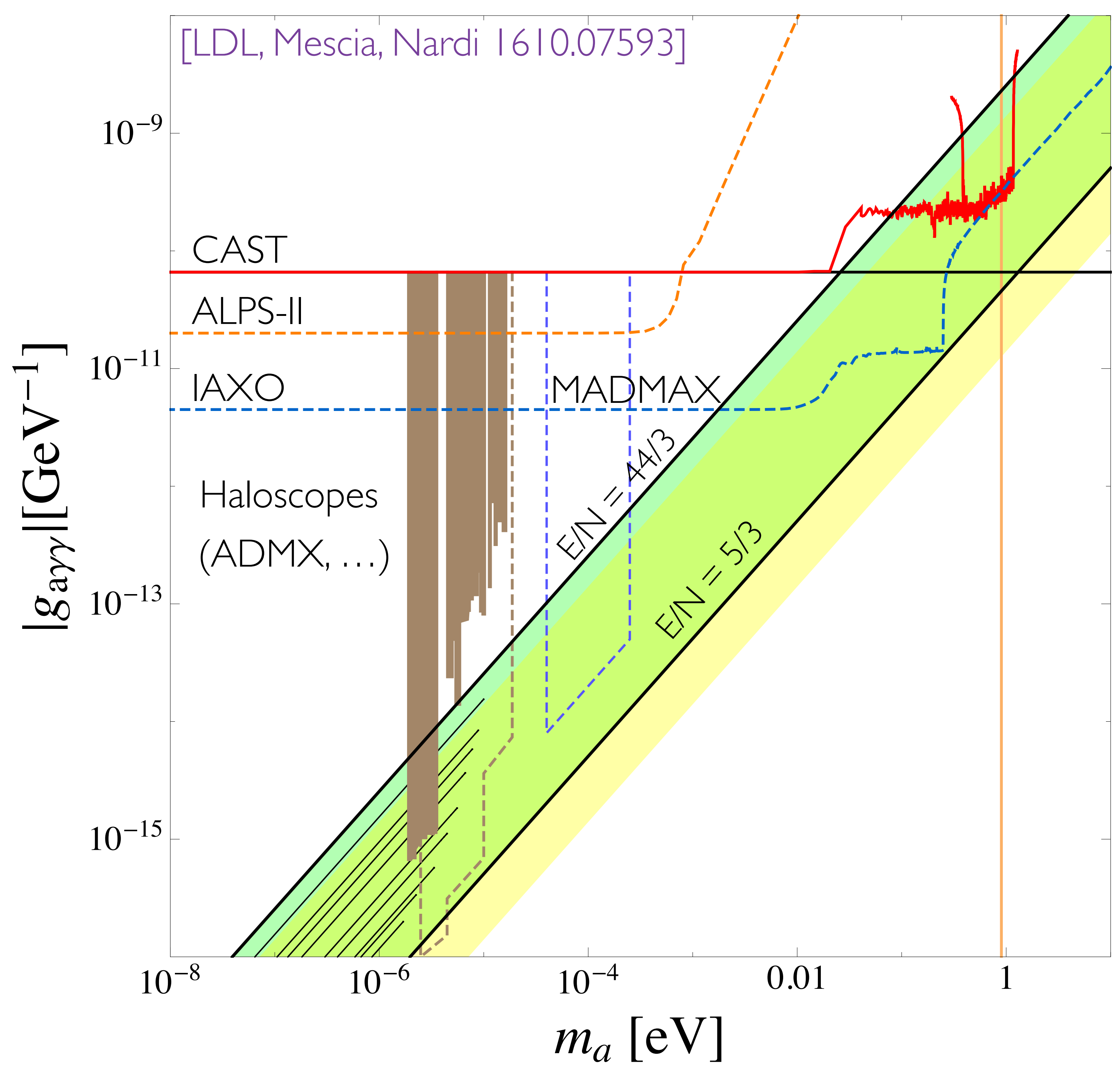


Redefining the axion window



Redefining the axion window



More Q's

- Combined anomaly factor

$$R_Q^1 + R_Q^2 + \dots \qquad \frac{E_c}{N_c} = \frac{E_1 + E_2 + \dots}{N_1 + N_2 + \dots}$$

- Strongest coupling (compatible with LP criterium)

$$(3, 3, -4/3) \oplus (3, 3, -1/3) \ominus (\overline{6}, 1, -1/3) \longrightarrow E_c/N_c = 170/3$$

- Complete decoupling within theoretical error possible as well:

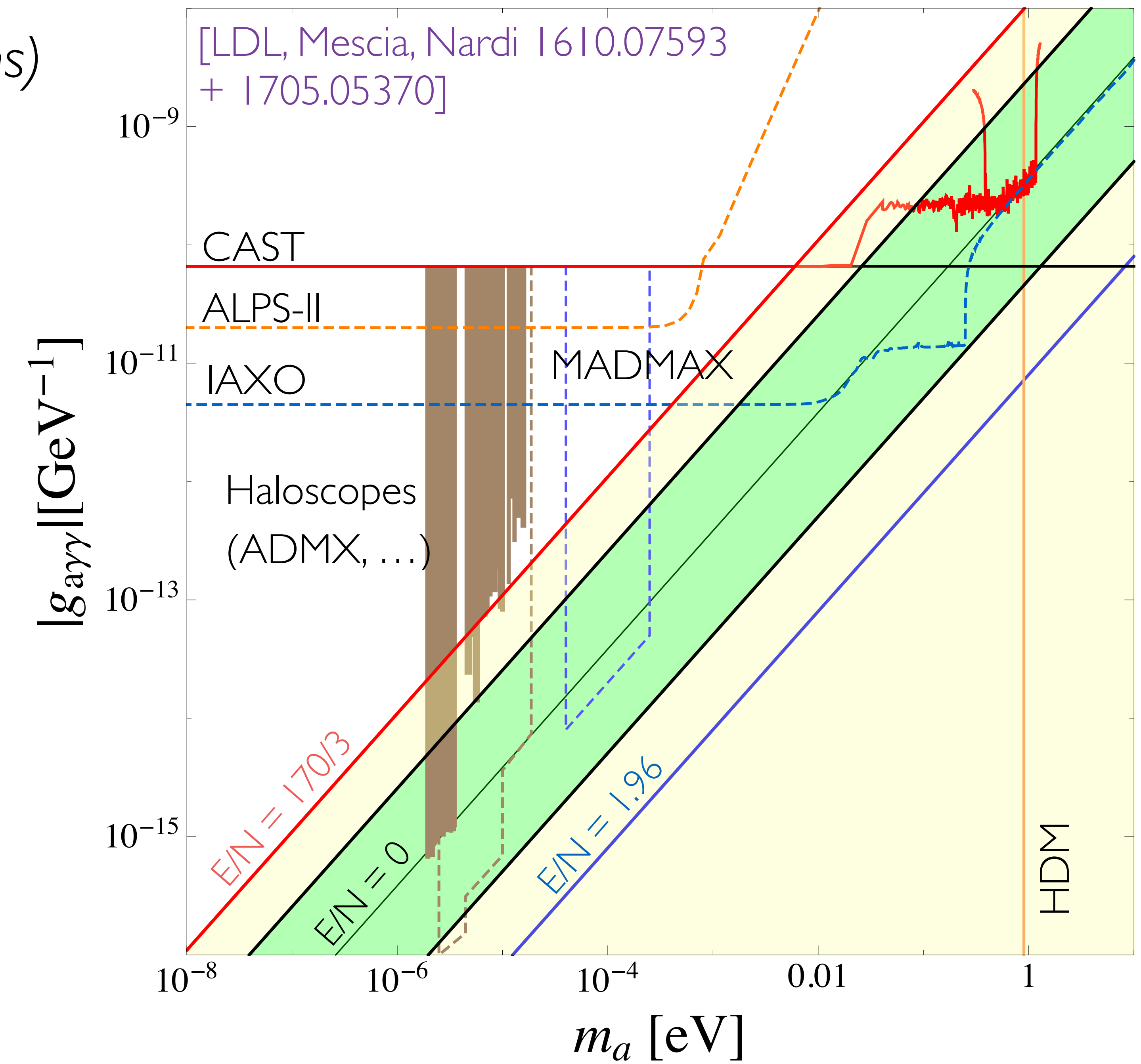
$$\left.\begin{matrix} (3, 3, -1/3) \oplus (\overline{6}, 1, -1/3) \\ (\overline{6}, 1, 2/3) \oplus (8, 1, -1) \\ (3, 2, -5/6) \oplus (8, 2, -1/2) \end{matrix}\right\} \quad E_c/N_c = (23/12, 64/33, 41/21) \approx (1.92, 1.94, 1.95)$$

$$g_{a\gamma\gamma} = \frac{m_a}{\mathrm{eV}} \, \frac{2.0}{10^{10}\ \mathrm{GeV}} \left(\frac{E_c}{N_c} - 1.92(4) \right)$$

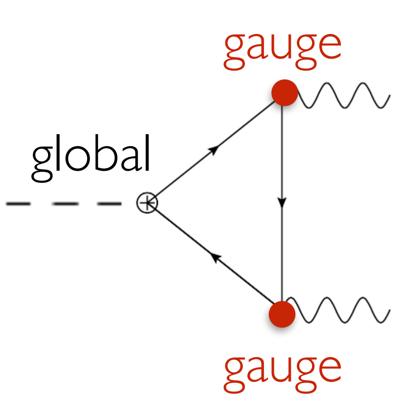
about photophobia: "such a cancellation is immoral, but not unnatural" [D. B. Kaplan, (1985)]

Axion-photon summary

- Red line set by perturbativity [KSVZ]
  (going above requires exotic constructions)
- Blue line corresponds to a 2% 'tuning in theory space'



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



Axion-photon summary

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  (going above requires exotic constructions)

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

- Messages for exp.'s :

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)