Nuove frontiere nella caccia all' assione

IFAE2019 - Napoli - 09.04.19

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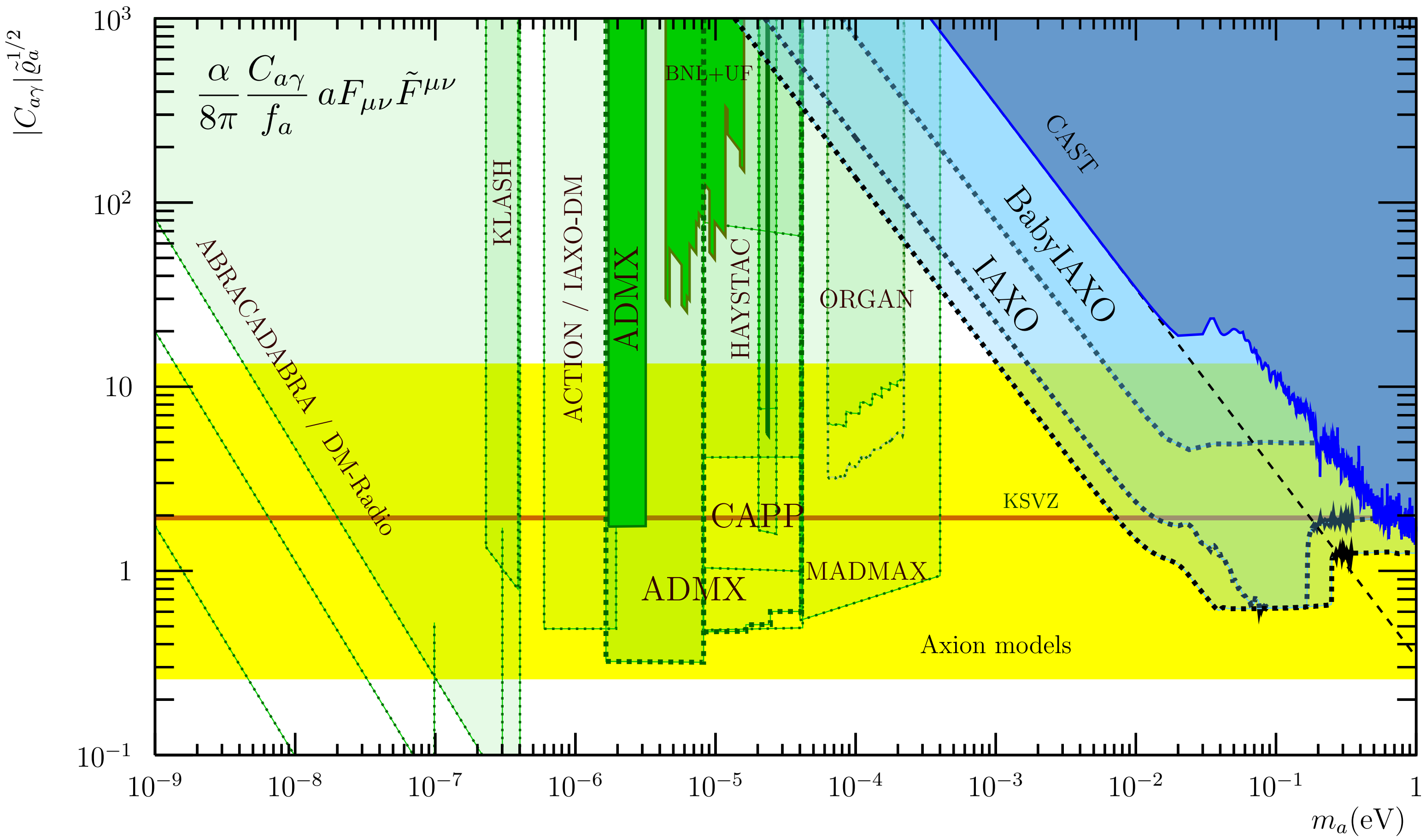
INFN

The Axion Rush

✤ A great exp. opportunity *(next 10 years ?)*

[Irastorza & Redondo, 1801.08127]



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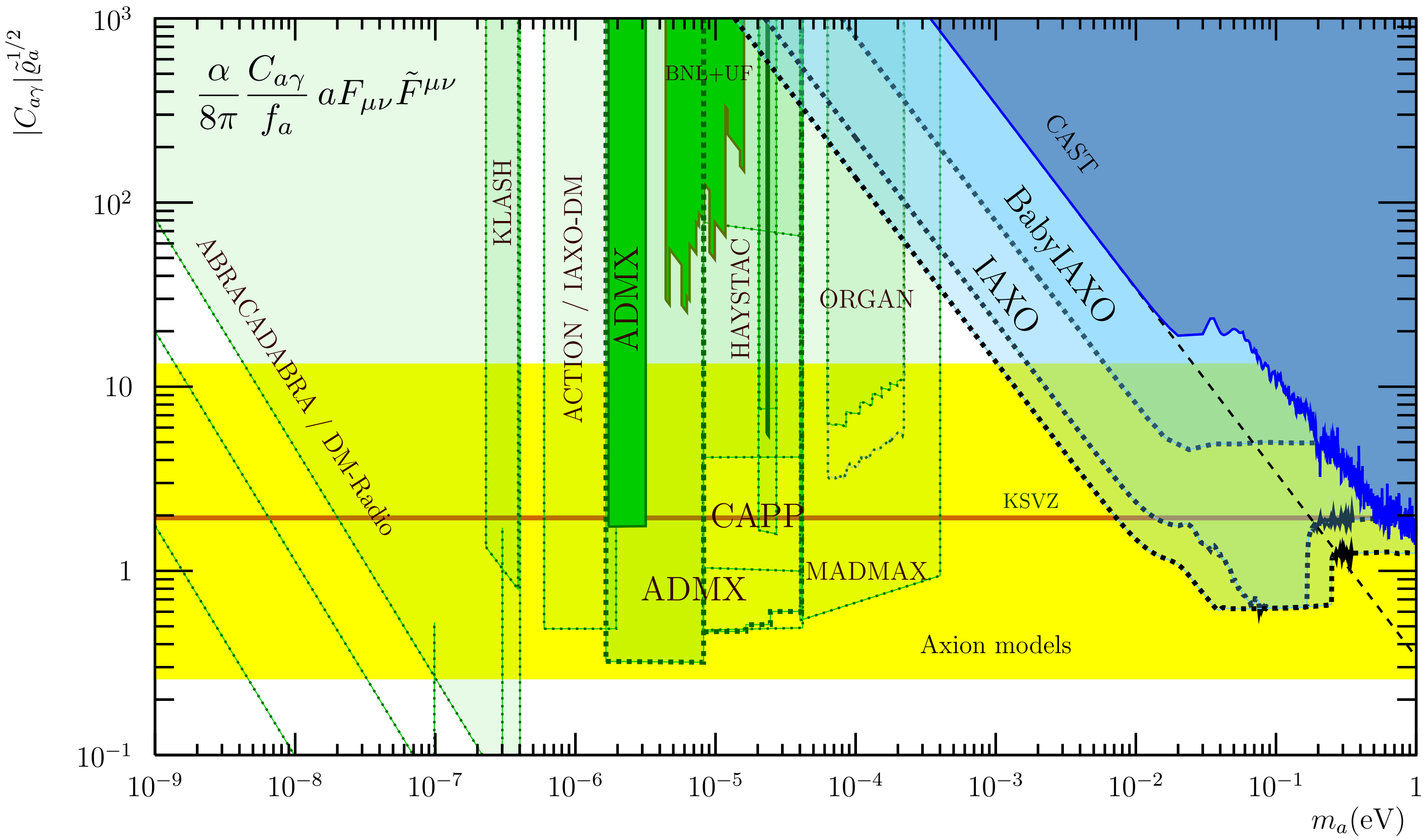

Poster by Alessio Rettaroli yesterday

EXP	STATUS
CAST (CERN)	finished
ADMX (Seattle)	running
HAYSTAC (New Haven)	running
ALPs-II (DESY)	construction
CAPP (South Korea)	construction
ORGAN (Perth)	prototype
ABRACADABRA (MIT)	prototype
(Baby)IAXO (DESY)	preparation
MADMAX (DESY)	preparation
ACTION (South Korea)	proposed
KLASH (Frascati)	proposed
QUAX (Legnaro)	prototype
CASPEr (Mainz)	proposed
…	…

The Axion Rush

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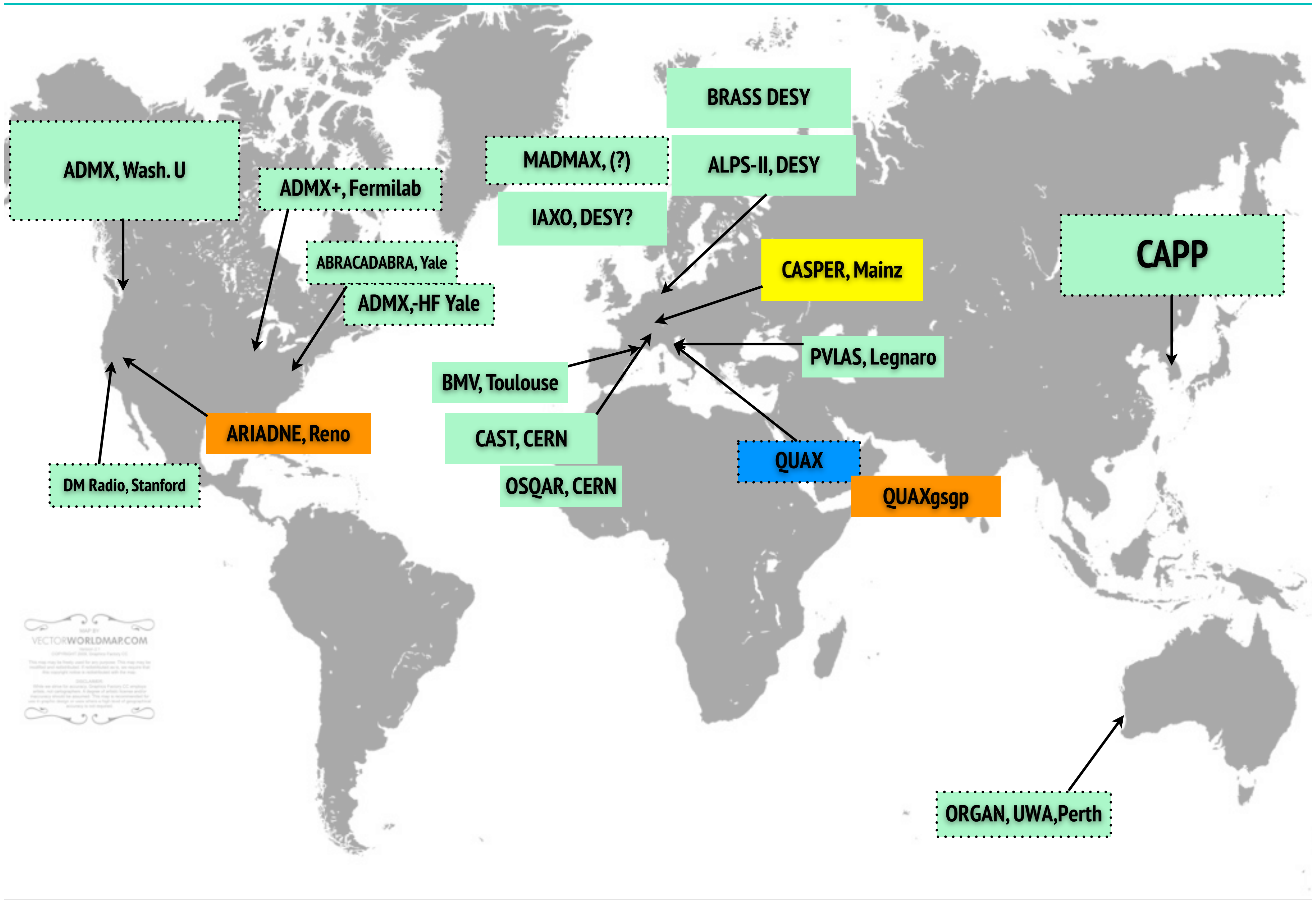
[Redondo, circa end of 2017]



The Axion Rush

✤ A great exp. opportunity *(next 10 years ?)*

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

1. Axion couplings *[model independent vs. model dependent]*

2. Astro bounds on axion mass *[critical approach]*

3. Re-opening the axion window *[astrophobia = nucleophobia + electrophobia]*

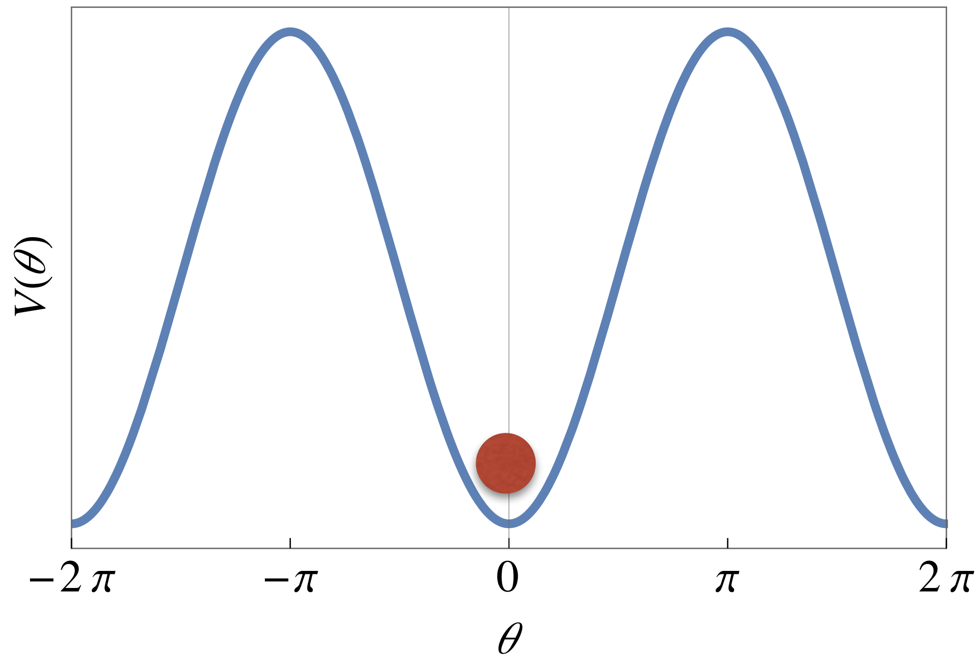
4. Flavour complementarity

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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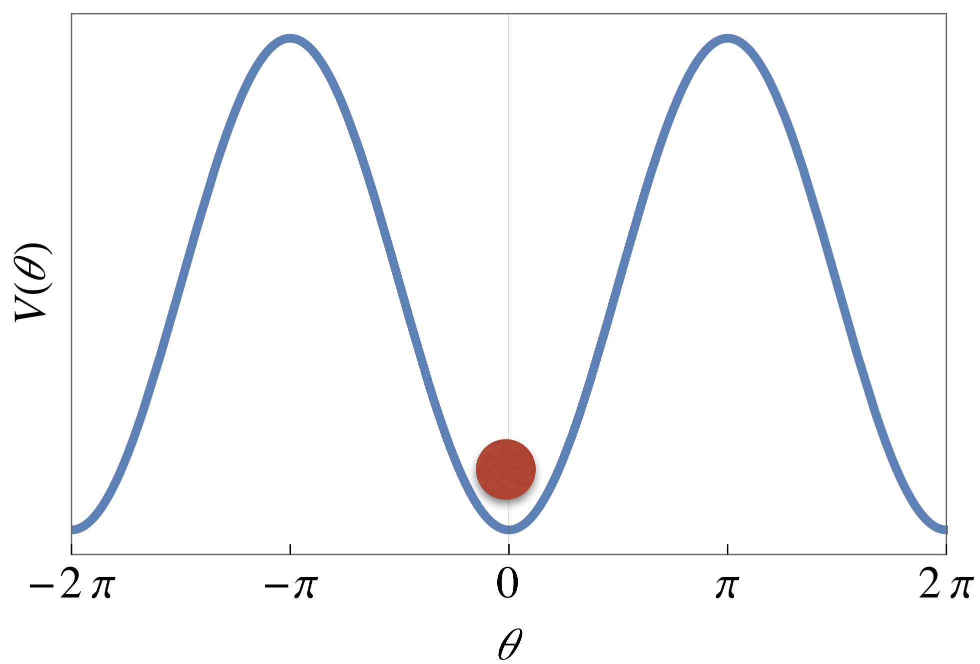
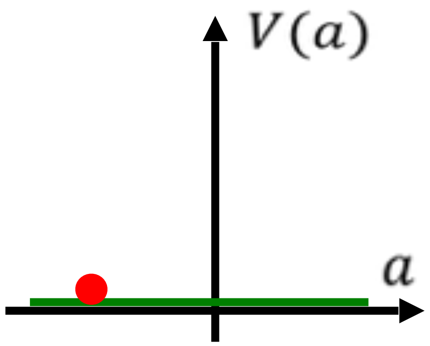


$$\theta \to \frac{a}{f_a} \qquad \textit{with} \qquad \langle a \rangle = 0$$

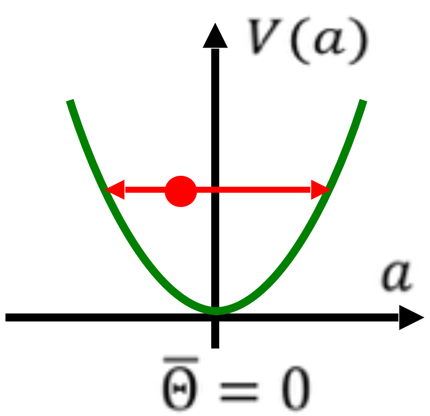
Dark Matter

vacuum re-alignment mechanism:



$T \gg 1$ GeV

[Raffelt]



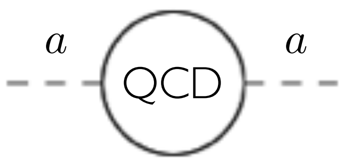
$T \sim 1$ GeV

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

Axion properties [EFT]

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

axion mass



$\sim \frac{\Lambda^4_{\rm QCD}}{f_a^2}$

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

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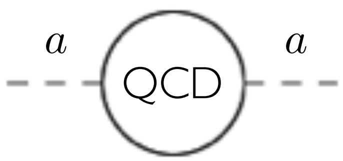
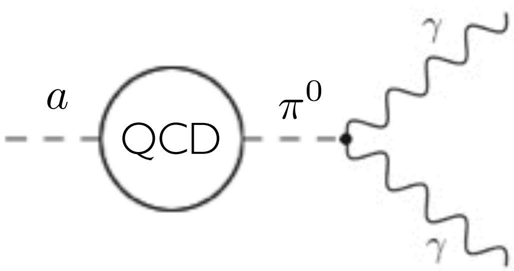
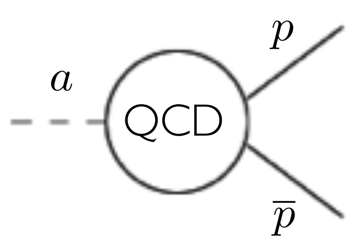
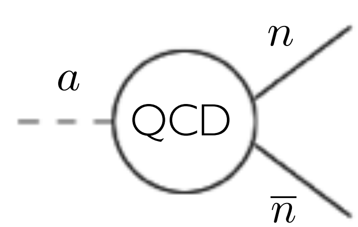


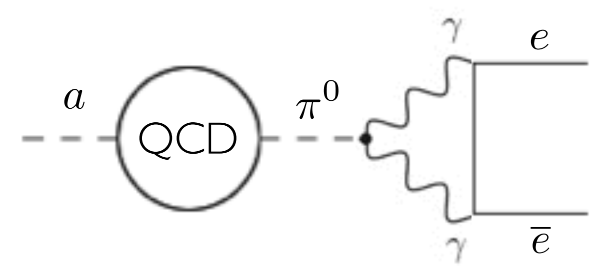
$\sim \frac{\Lambda^4_{\mathrm{QCD}}}{f_a^2}$ $\quad\longrightarrow\quad$ $m_a \sim \Lambda^2_{\mathrm{QCD}}/f_a \simeq 0.1\ \mathrm{eV}\left(\frac{10^8\ \mathrm{GeV}}{f_a}\right)$

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









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

$\frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu}$ $\qquad$ $C_\Psi m_\Psi \frac{a}{f_a}[i\overline{\Psi}\gamma_5\Psi]$ $\qquad$ $(\Psi = p, n, e)$

[From NLO Chiral Lagrangian,
Grilli di Cortona et al., 1511.02867]

Axion properties [EFT]

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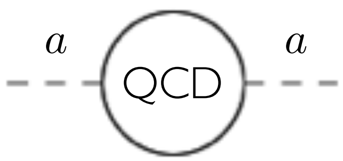
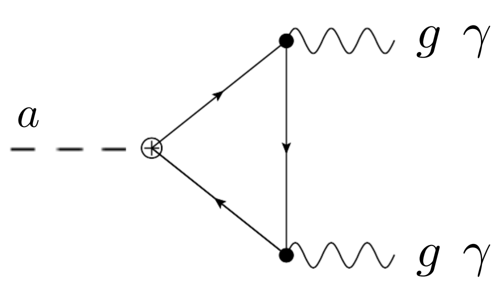


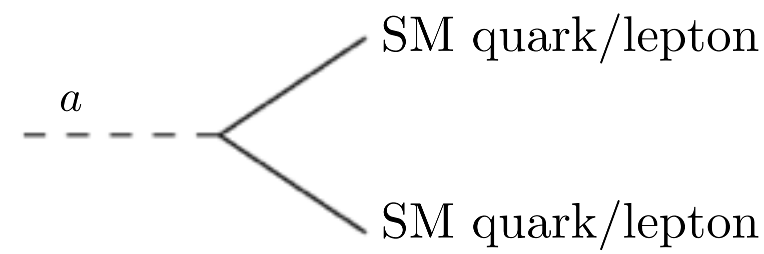
$\sim \frac{\Lambda^4_{\rm QCD}}{f_a^2}$ → $m_a \sim \Lambda^2_{\rm QCD}/f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a}\right)$

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

<u>EFT breaks down at energies of order f_a</u>

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





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

Axion models [UV completion]

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

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

SM fermions | BSM fermions

2Higgs | 2Higgs+Singlet | Higgs+Singlet

PQWW | DFSZ | KSVZ

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

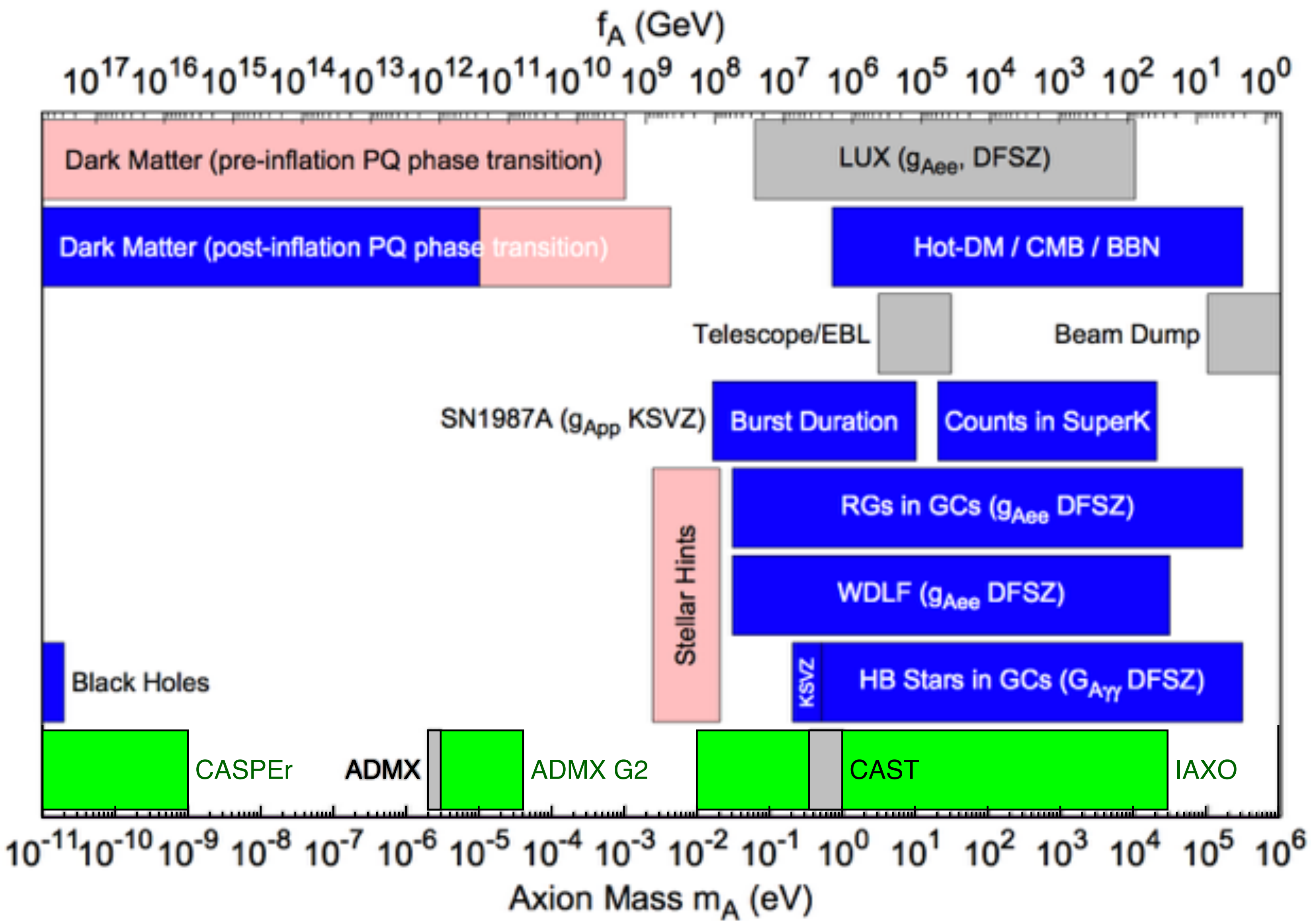
[Zhitnitsky '80, Dine, Fischler, Srednicki '81]

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

$f_a \sim v$ ruled out

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

Astro bounds



[Ringwald, Rosenberg, Rybka, Particle Data Group]

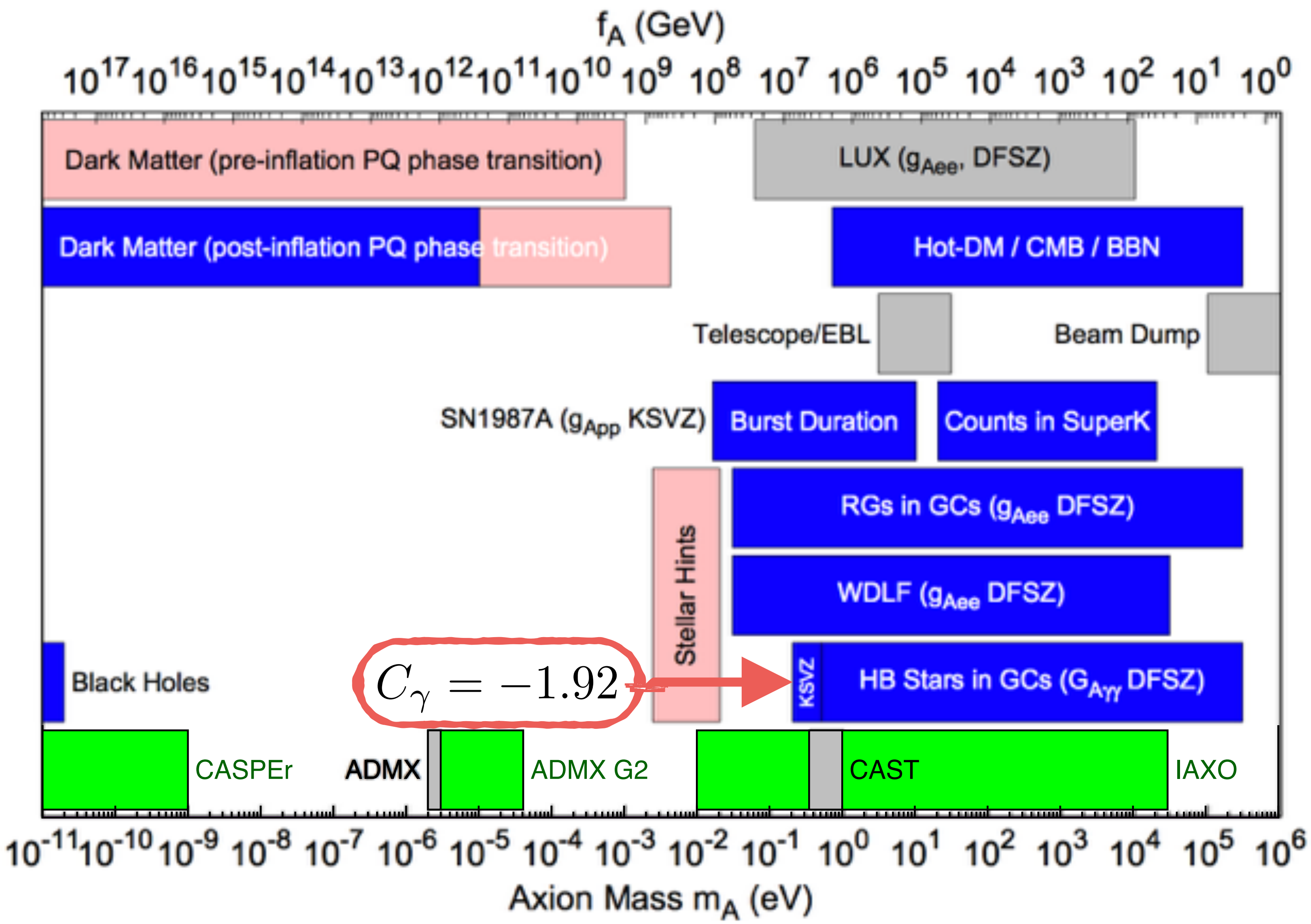
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Astro bounds



[Ringwald, Rosenberg, Rybka, Particle Data Group]

Lab exclusions

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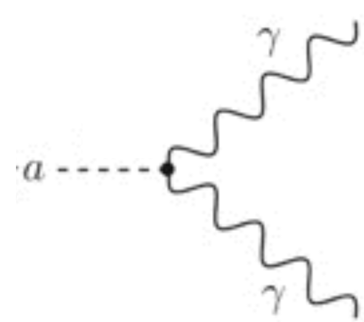
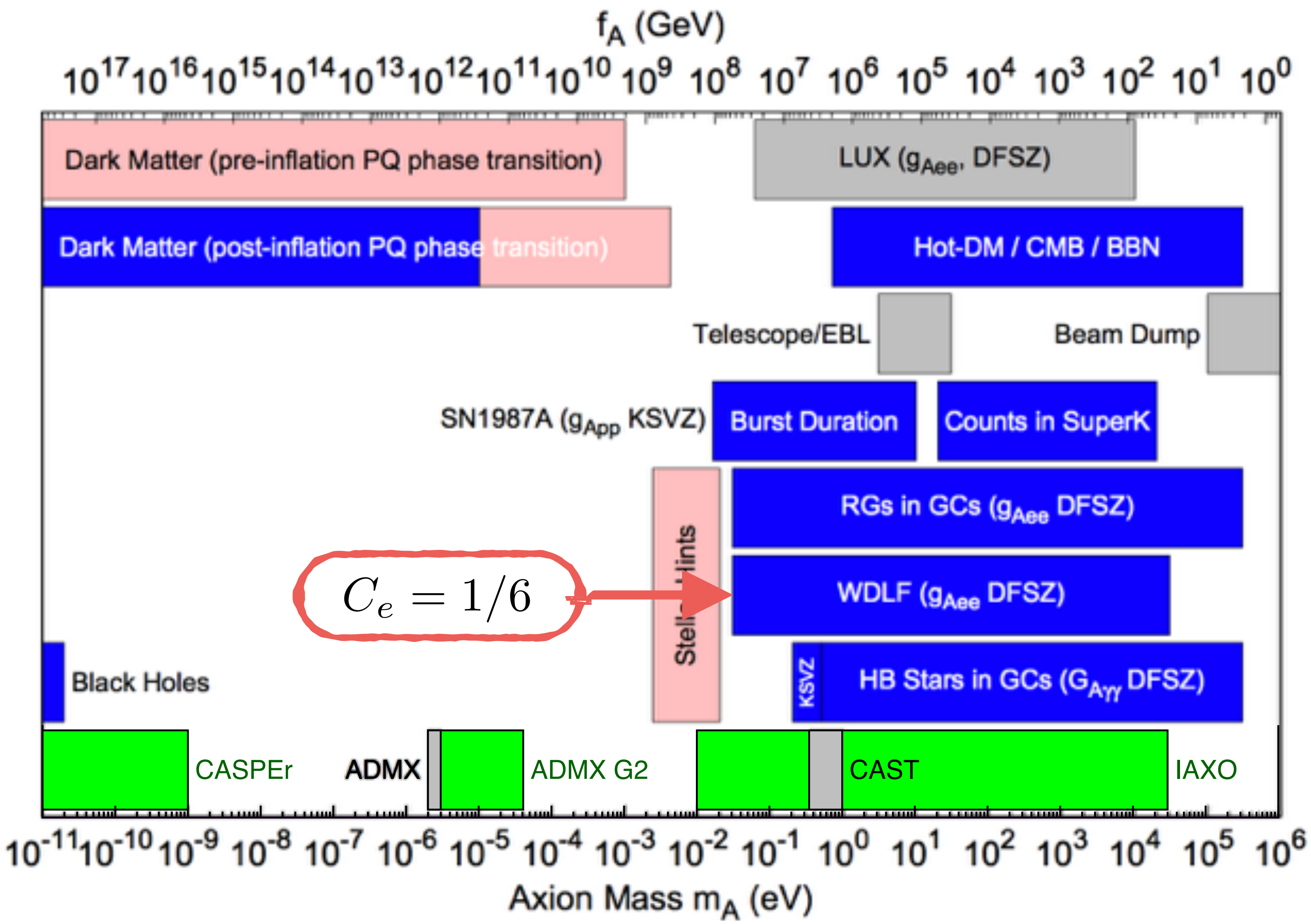
Exp. sensitivities

- 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



[Ringwald, Rosenberg, Rybka, Particle Data Group]

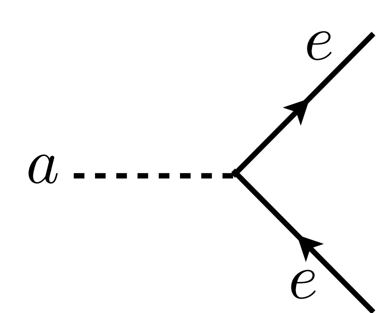
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

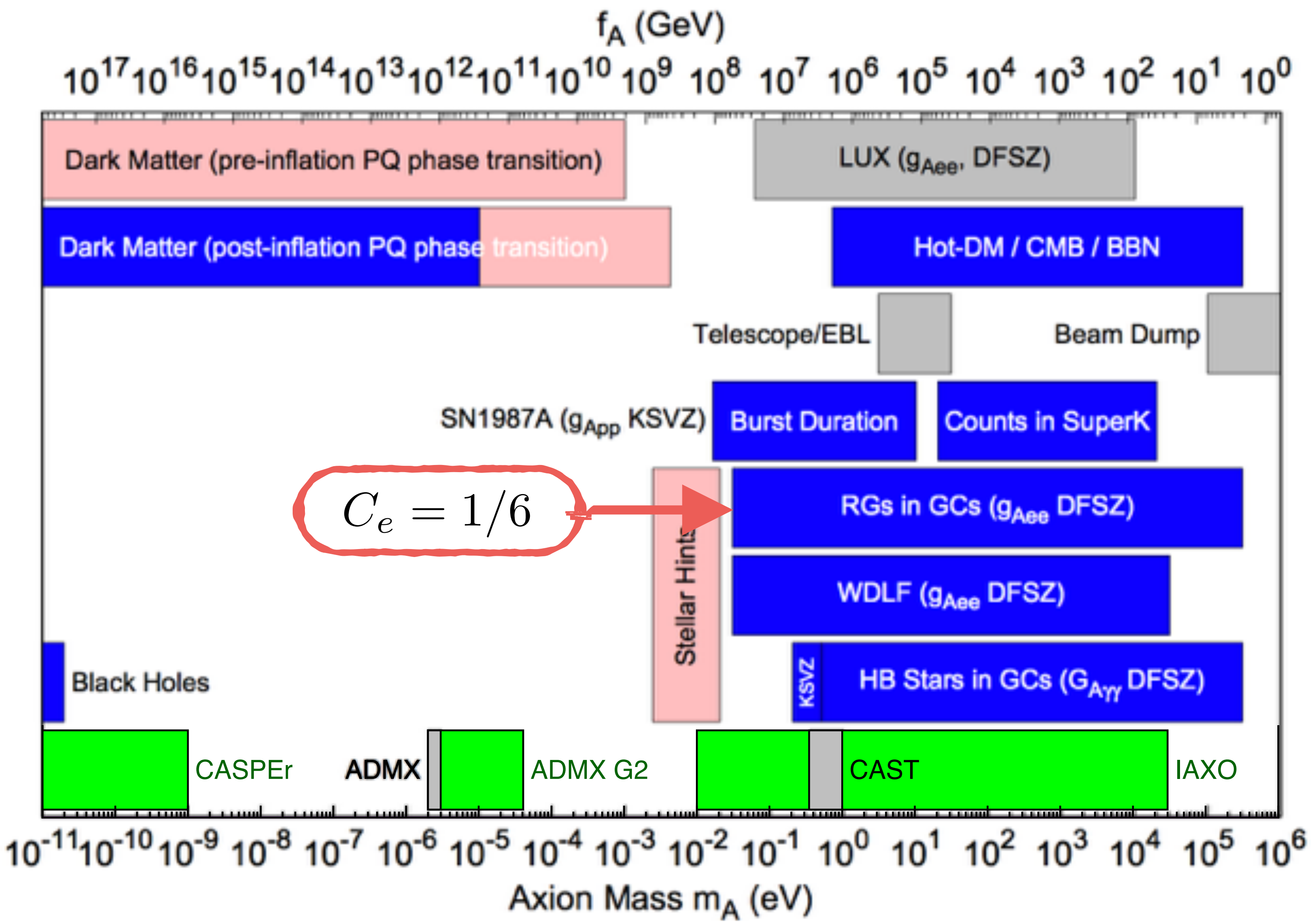
Exp. sensitivities

- White dwarfs luminosity function (cooling)



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

Astro bounds



[Ringwald, Rosenberg, Rybka, Particle Data Group]

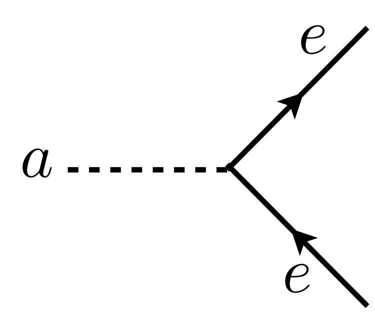
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- Red giants evolution in globular clusters



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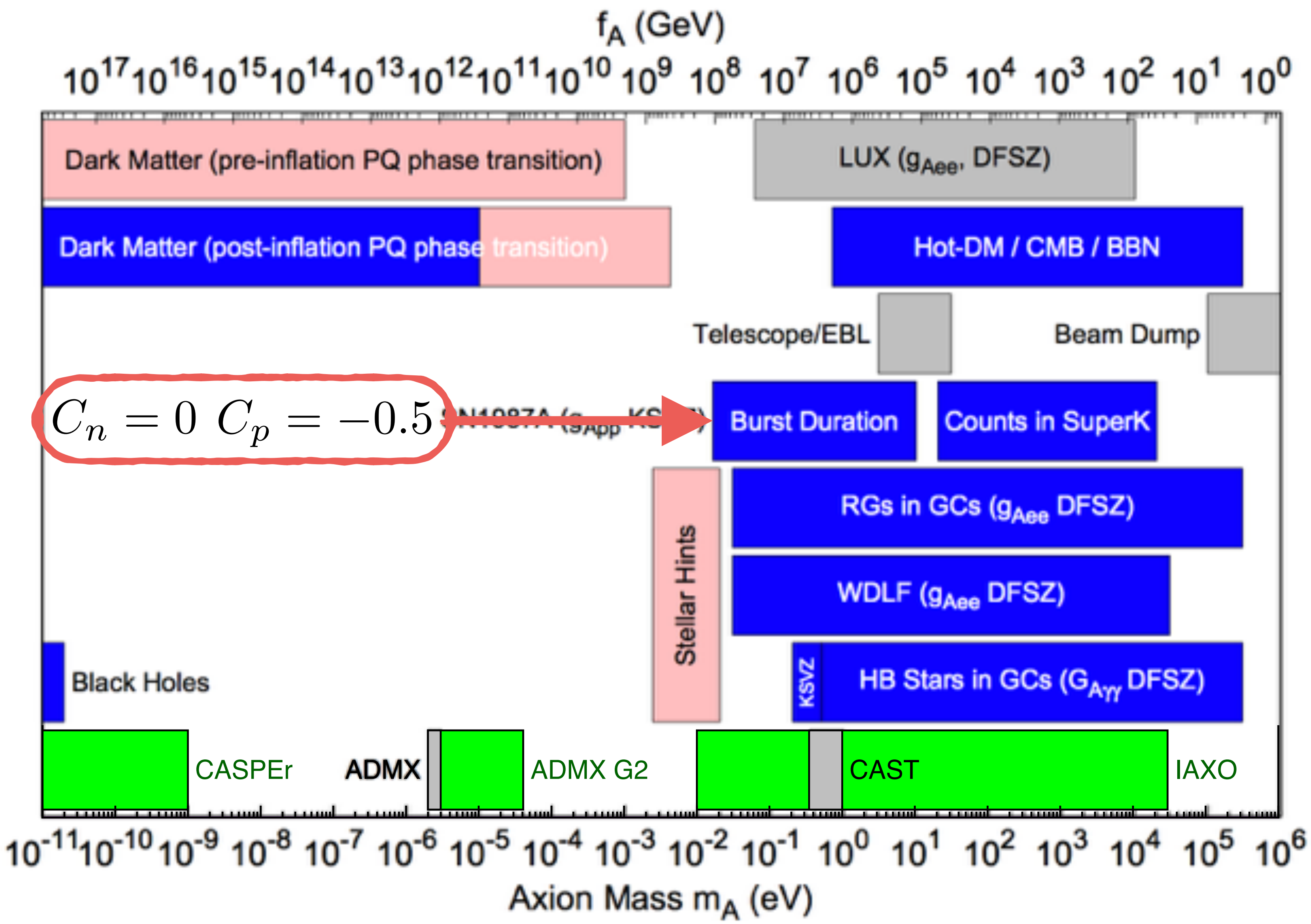
Astro bounds



[Ringwald, Rosenberg, Rybka, Particle Data Group]

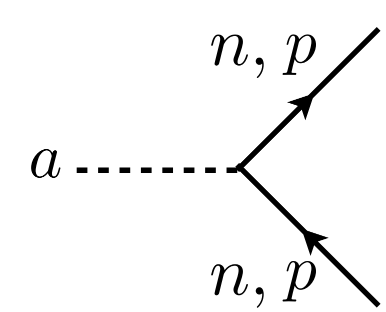
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

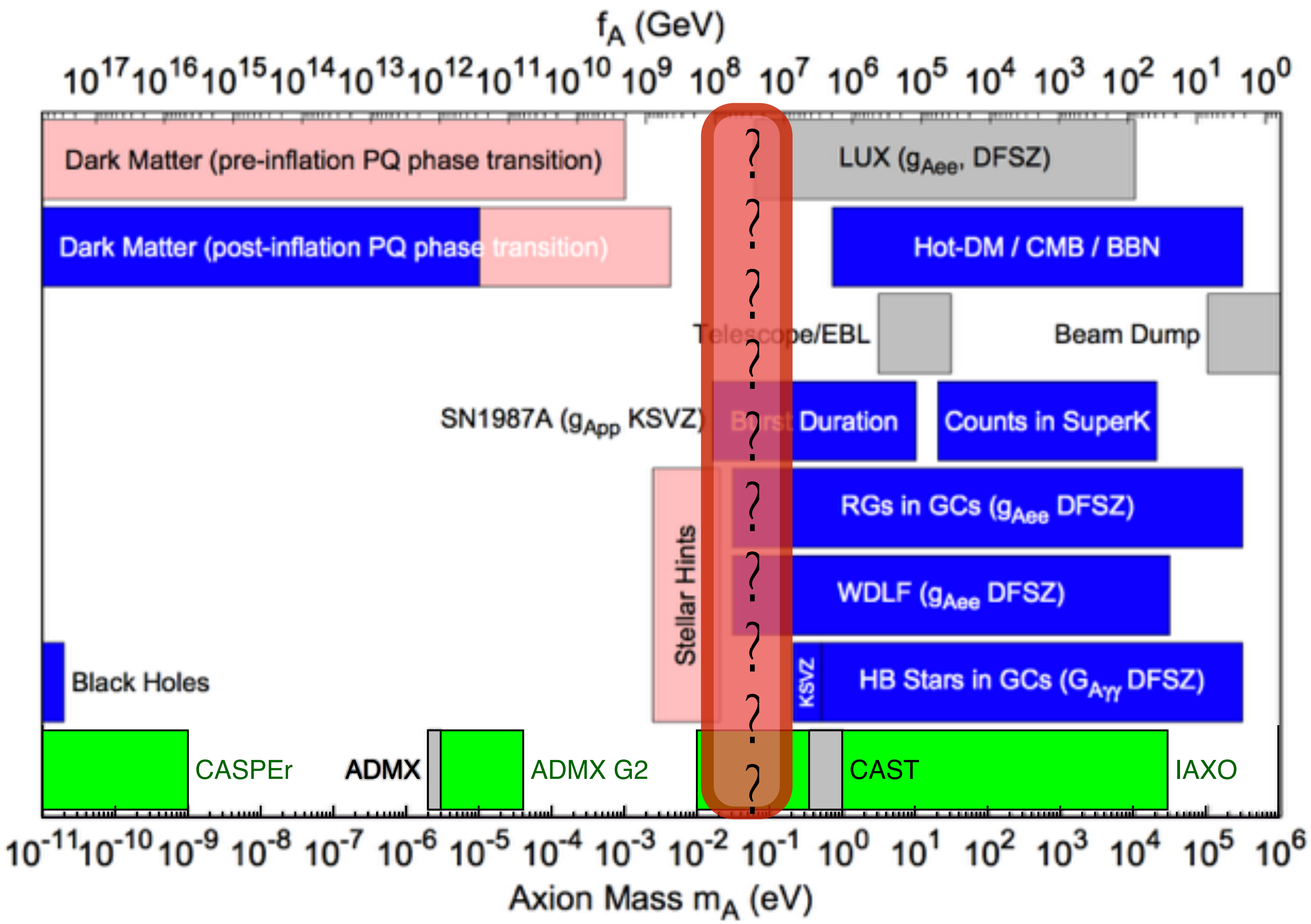
- Burst duration of SN1987A nu signal



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

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

Astro bounds



[Ringwald, Rosenberg, Rybka, Particle Data Group]

Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

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

Astrophobia

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

→ nucleophobia + electrophobia = astrophobia

Astrophobia

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→ 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

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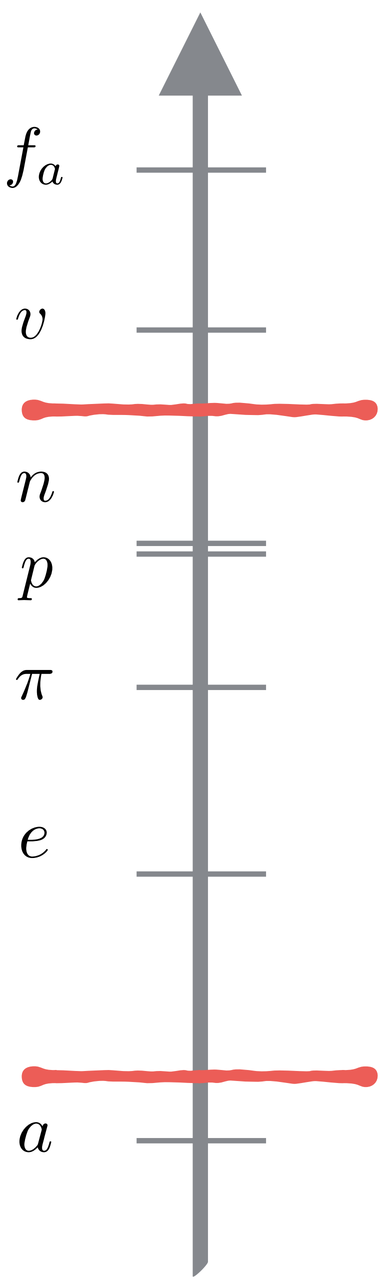
5. unexpected connection with flavour

*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]



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

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

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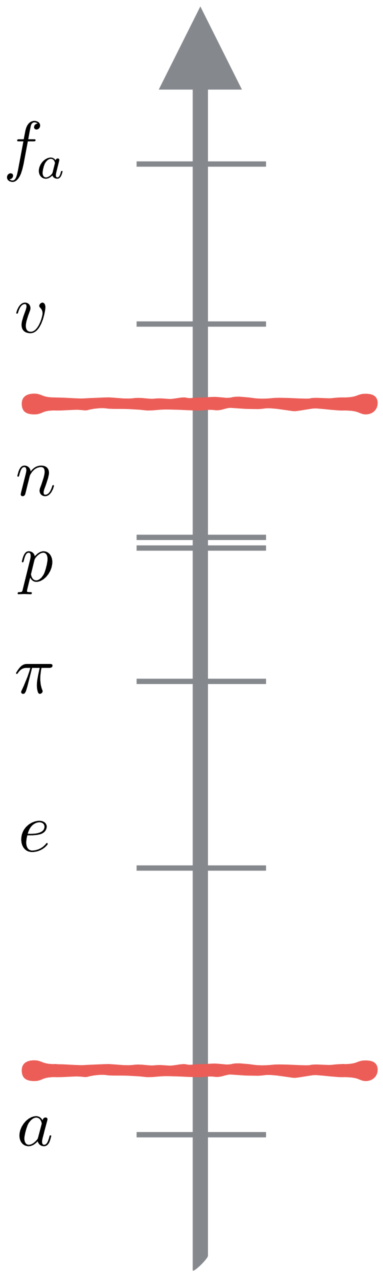

$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \overline{q} \gamma^\mu \gamma_5 q$$

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

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

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

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

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

KSVZ/DFSZ no-go

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$$\downarrow$$

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

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

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

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

KSVZ/DFSZ no-go

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

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

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

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

Implementing nucleophobia

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

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

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

$$\boxed{\begin{aligned} \mathcal{L}_Y \supset\ & \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 ... + \ldots) \\ + \ & \bar{q}_2 u_2 H_2 + \bar{q}_2 d_2 \tilde{H}_1 + (\bar{q}_2 d_3 ... + \ldots) \end{aligned}} \quad \begin{aligned} &\Longrightarrow \quad N_3 = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2 \\ &\Longrightarrow \quad N_2 = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1 \end{aligned}$$

- 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 !

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

e.g. RH down rotations become physical

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e.g. RH down rotations become physical

- Low-energy flavour experiments

$$\frac{\partial_\mu a}{2f_a}\,\overline{f}_i \gamma^\mu (C_{ij}^V + C_{ij}^A \gamma_5) f_j$$

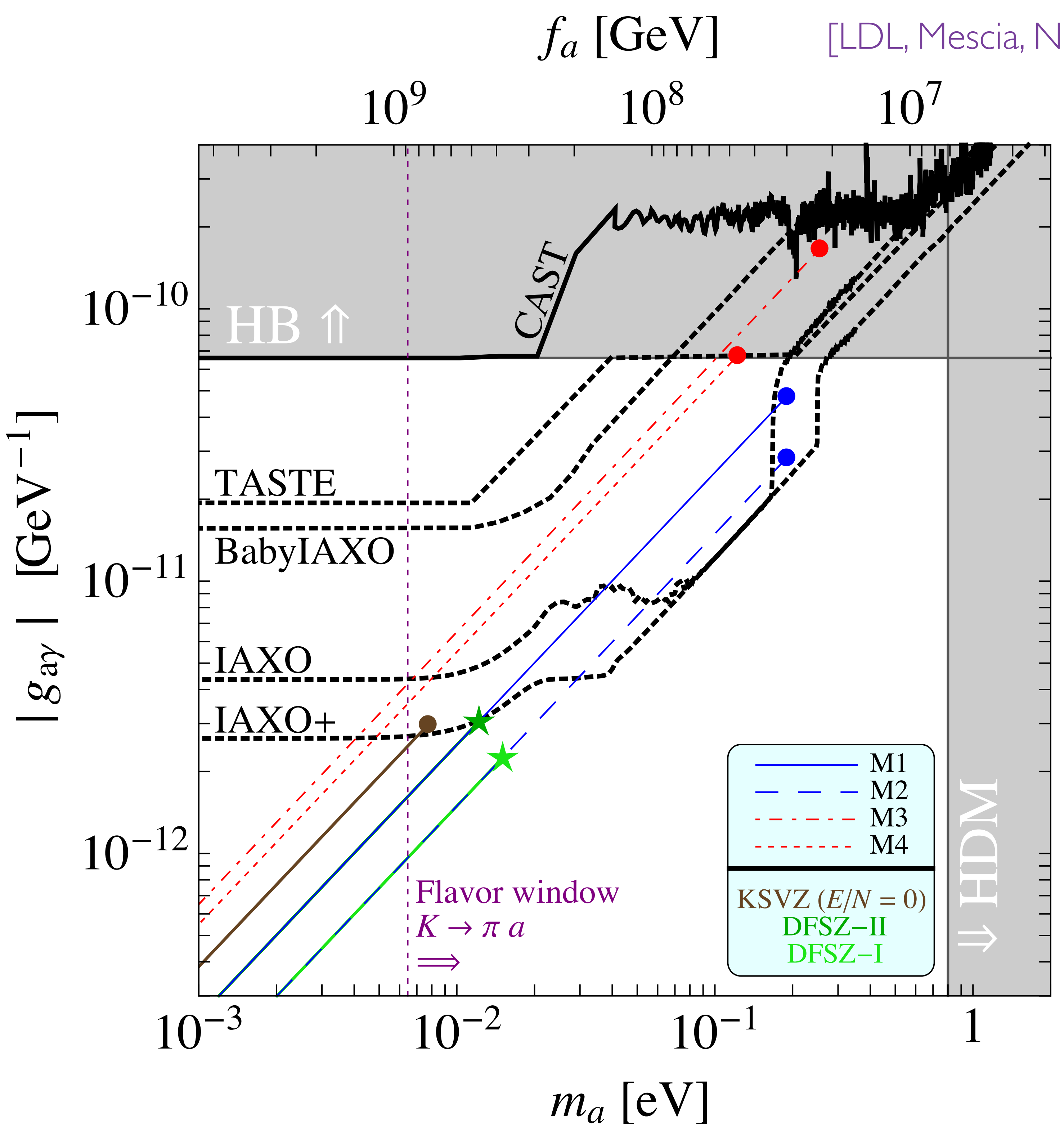
$K \to \pi a$ $\quad m_a < 1.0 \times 10^{-4} \dfrac{\mathrm{eV}}{|C_{sd}^V|}$ [E787, E949 @ BNL, 0709.1000] → NA62

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

$\mu \to e a$ $\quad m_a < 3.4 \times 10^{-3} \dfrac{\mathrm{eV}}{\sqrt{|C_{\mu e}^V|^2 + |C_{\mu e}^A|^2}}$ [Crystal Box @ Los Alamos, Bolton et al PRD38 (1988)] → MEG II

Astrophobic axion models

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



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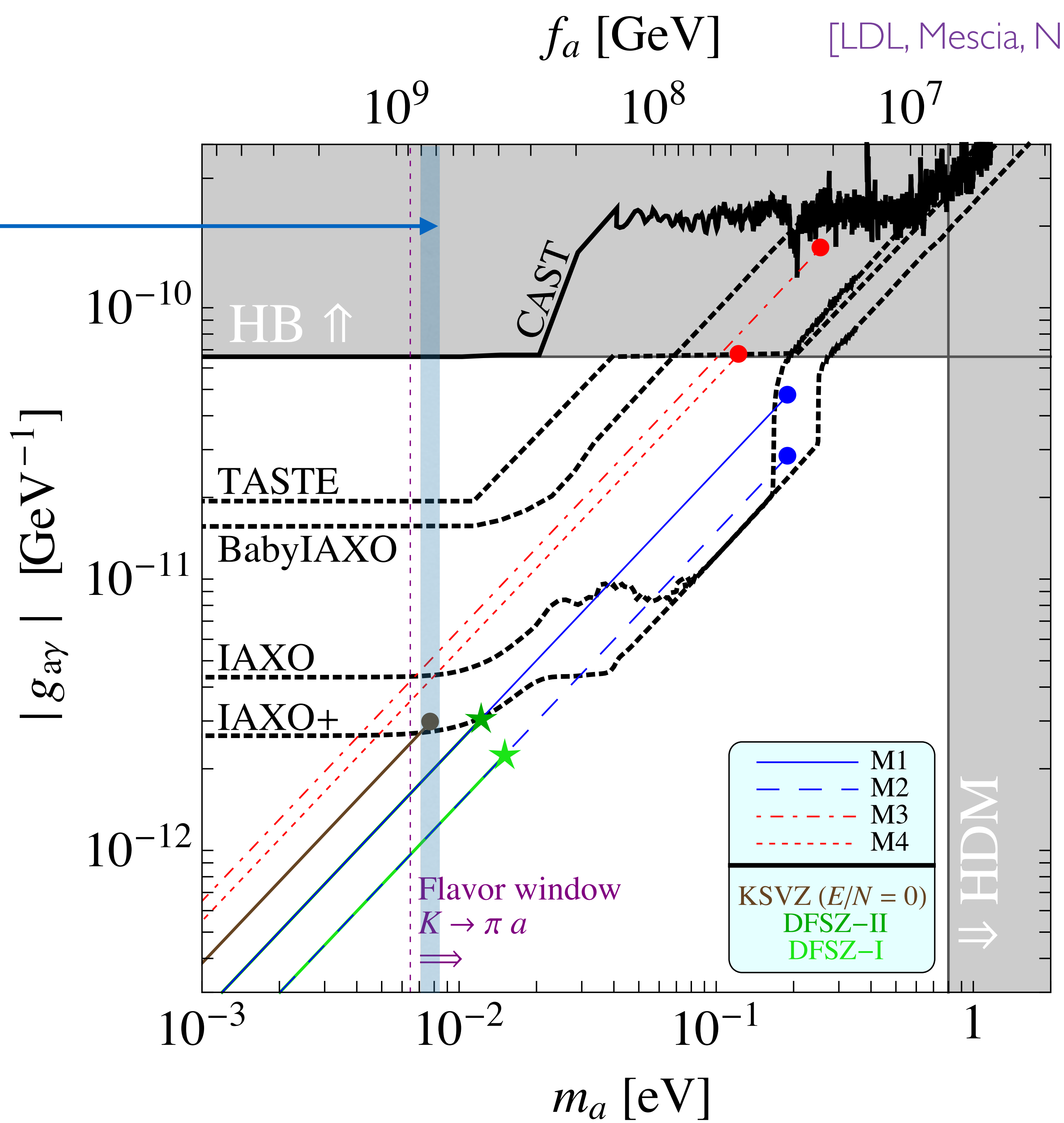
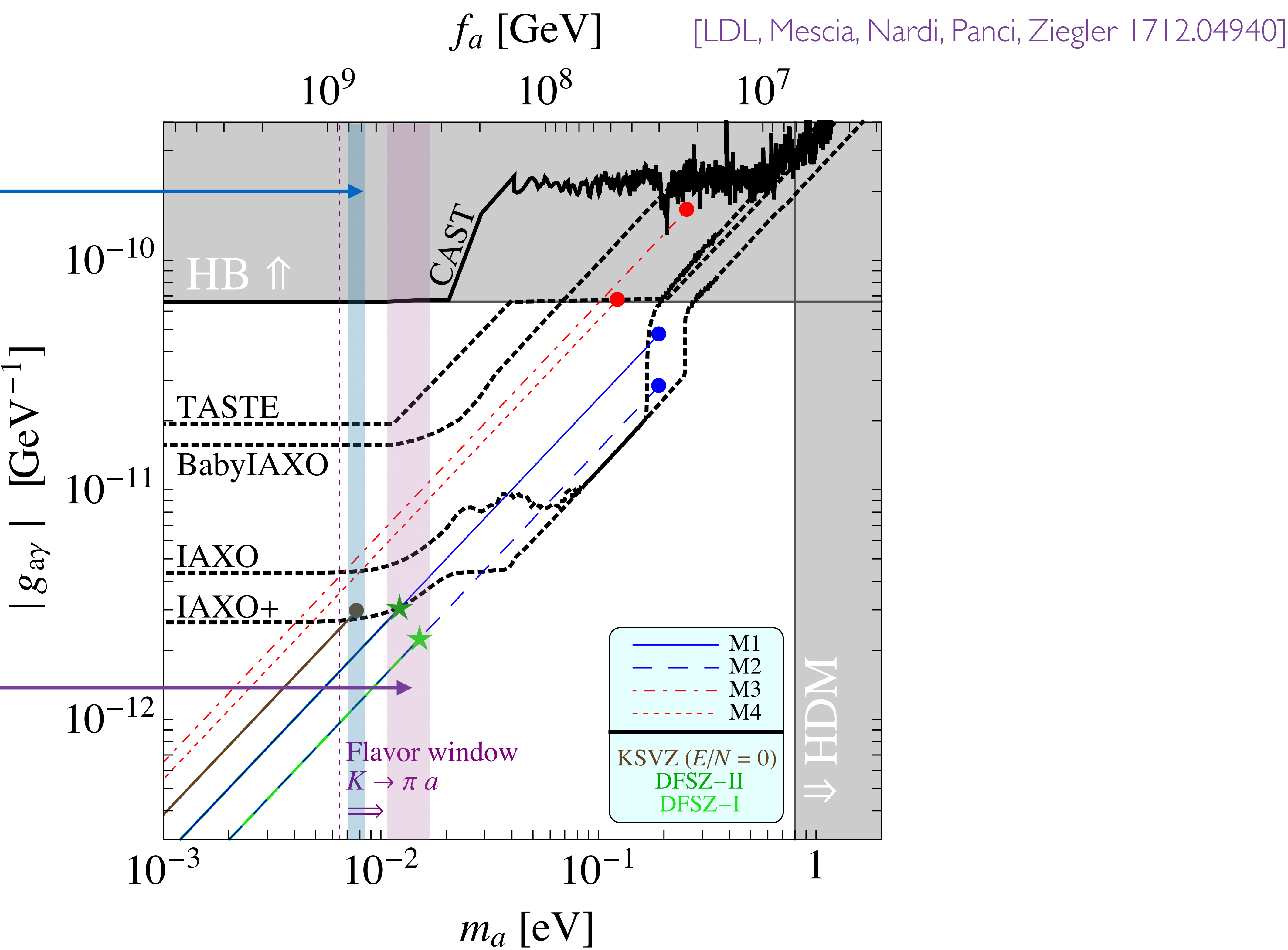
KSVZ



Astrophobic axion models

KSVZ

DFSZ



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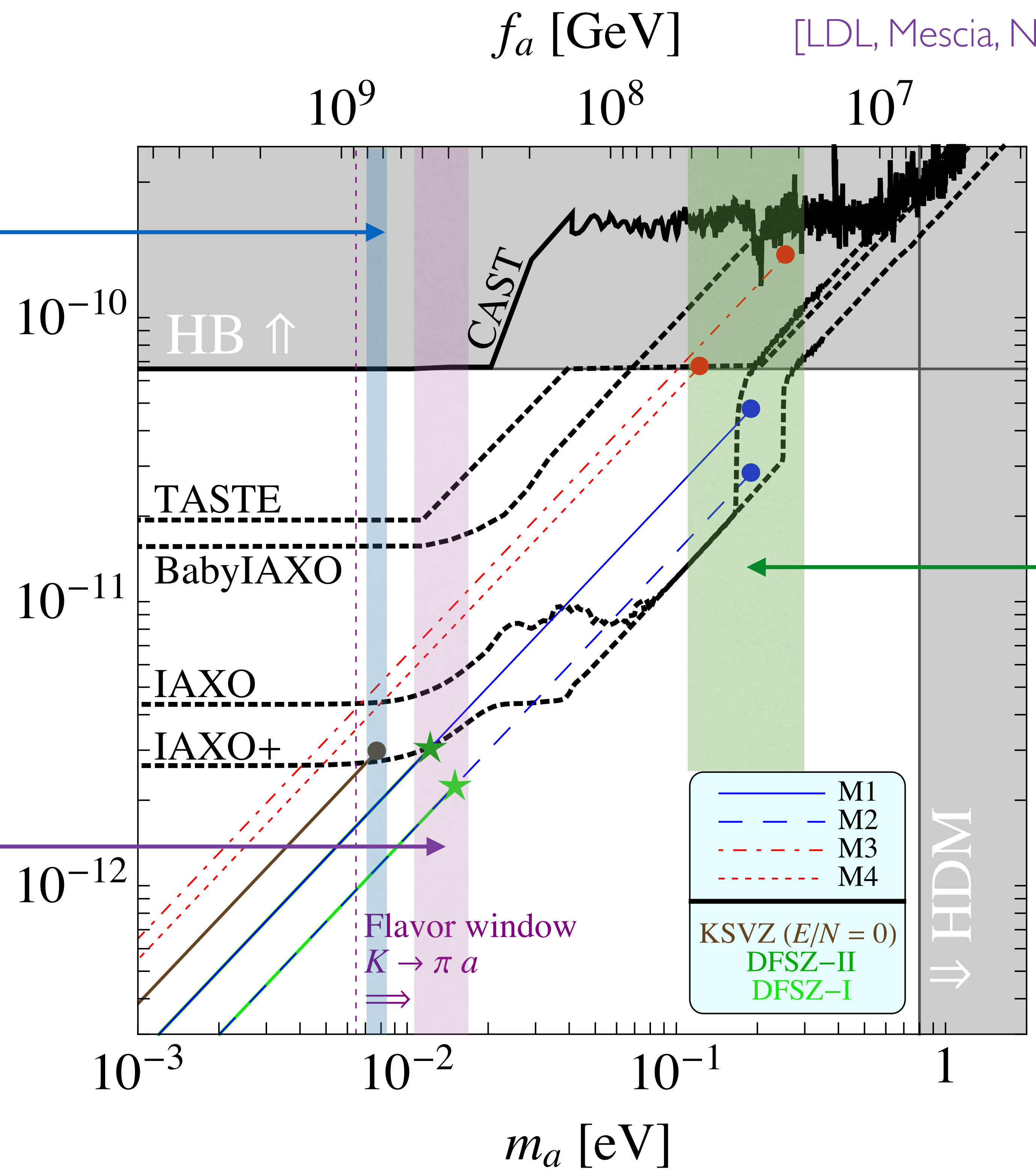
KSVZ

DFSZ



Astrophobic Axions

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*

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  - *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.*

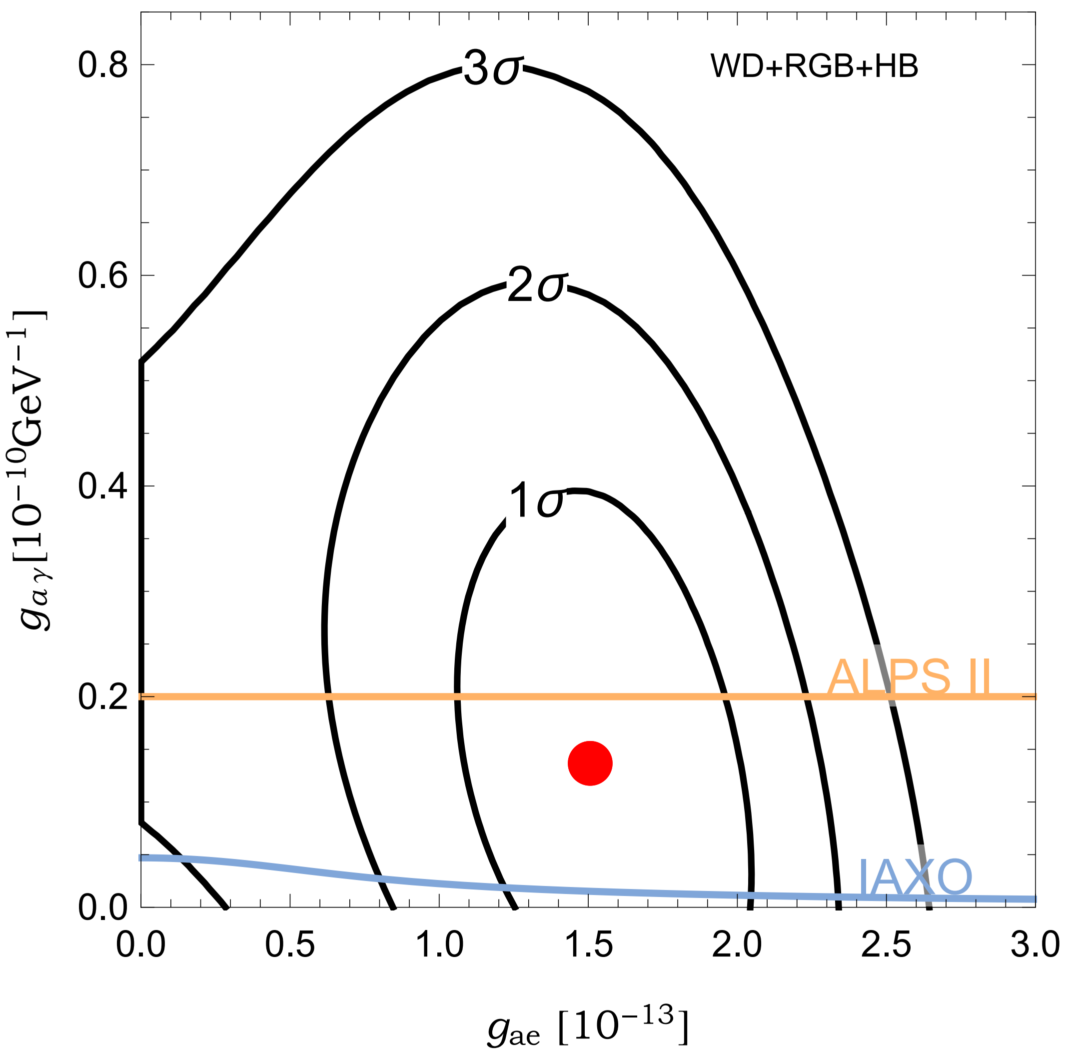
Backup slides

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	$f_a\ [10^8\ \mathrm{GeV}]$	m_a [meV]	$\tan\beta$	$\chi^2_{\min}/\mathrm{d.o.f.}$
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

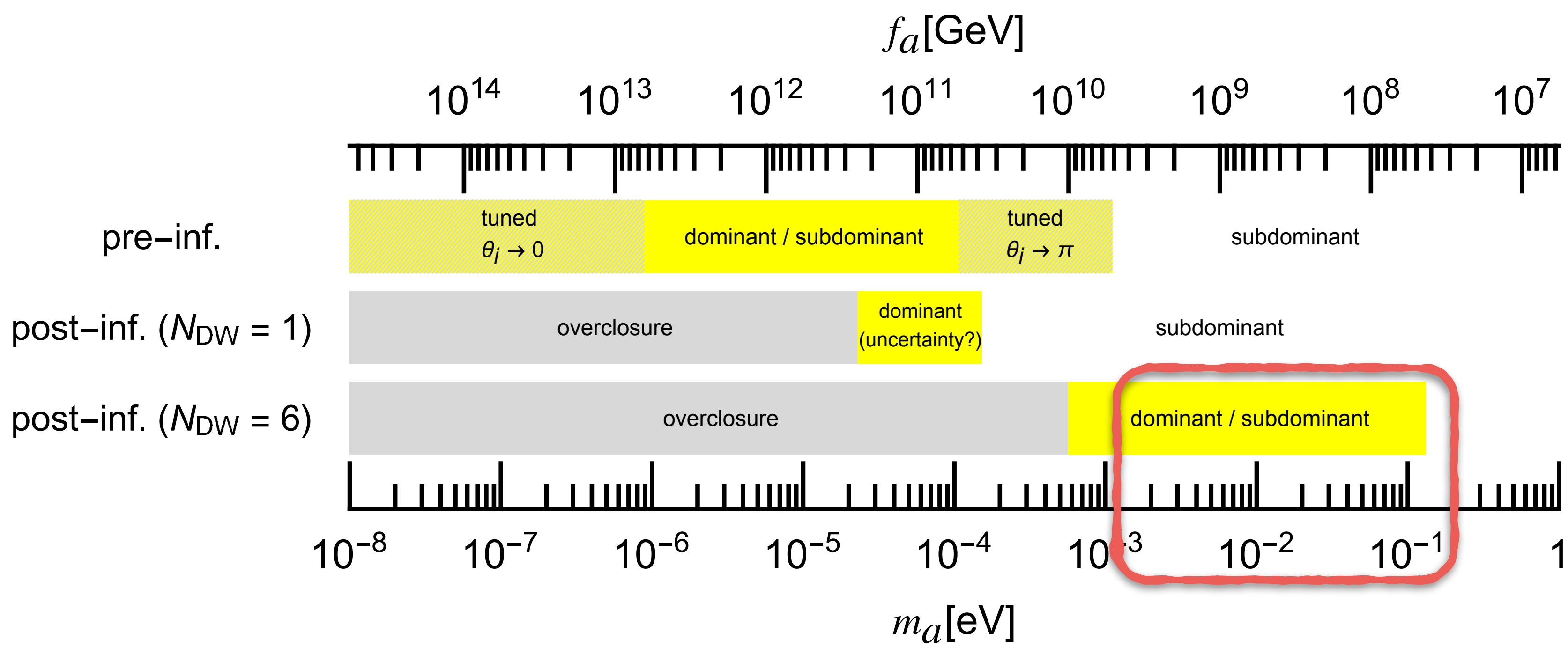
*SN bound a factor ~4 weaker than PDG one ?

[Chang, Essig, McDermott 1803.00993]

DM in the heavy axion window

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

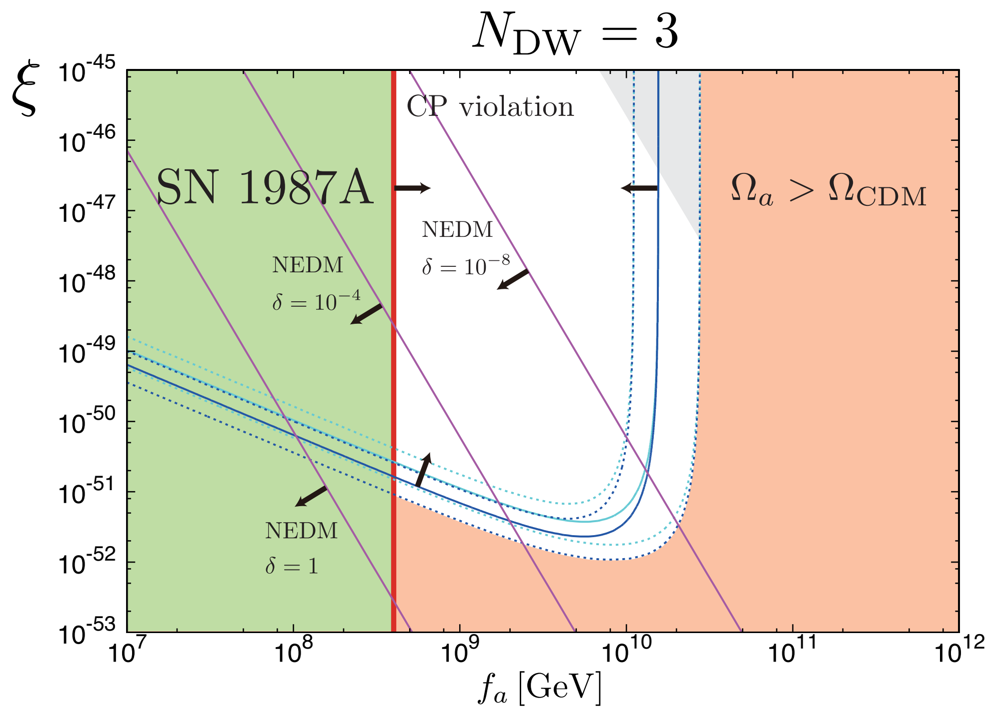
[Kawasaki, Saikawa, Sekiguchi, 1412.0789 1709.07091]



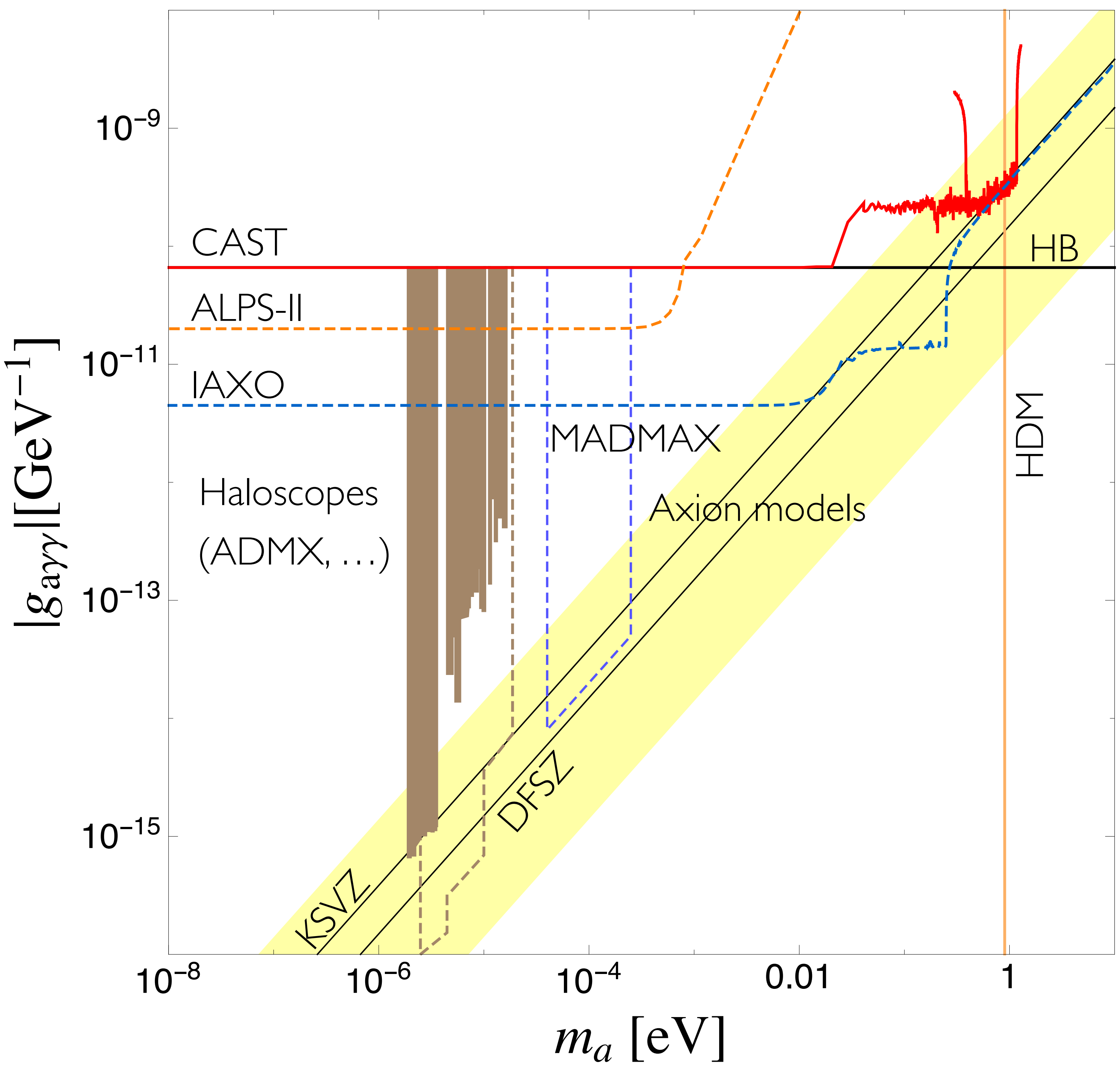
- axion production from topological defects

- 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

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

[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)]

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

$$\left.\begin{aligned} N &= \sum_Q \left(\mathcal{X}_L - \mathcal{X}_R\right) T(\mathcal{C}_Q) \\ E &= \sum_Q \left(\mathcal{X}_L - \mathcal{X}_R\right) \mathcal{Q}_Q^2 \end{aligned}\right\} \text{anomaly coeff.}$$

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

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

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

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

- $V_{H\Phi} = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2$ $\longrightarrow$ $m_\rho \sim f_a$

- $\mathcal{L}_{Qq}$ d $\leq$ 4 mixing with SM quarks (depends in Q-gauge quantum numbers)

Q stability

- Symmetry of the kinetic term

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

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

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

- 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

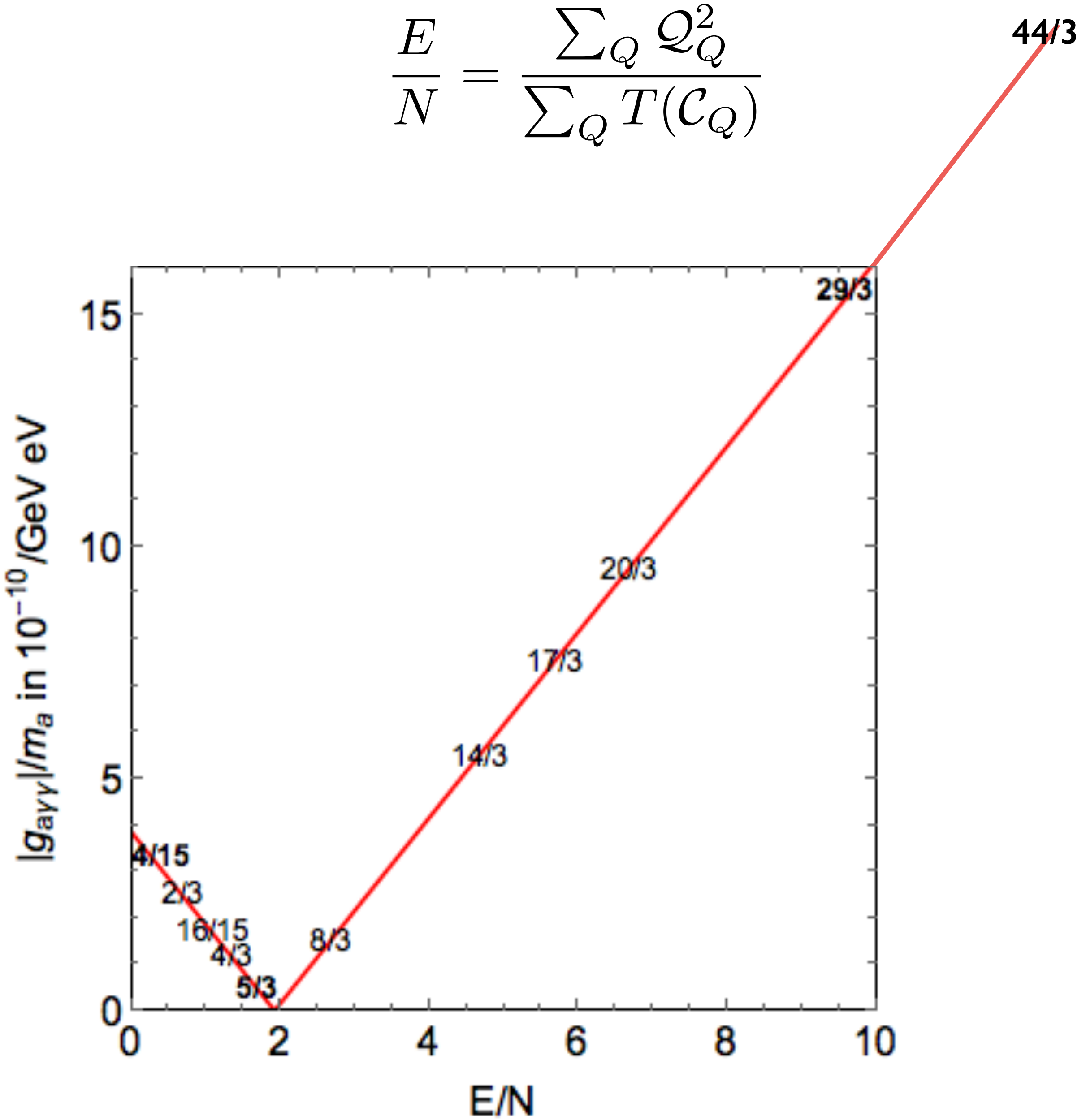
Pheno preferred KSVZ fermions

- 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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	$(3, 2, 7/6)$	$\overline{Q}_L u_R H$	$5.6 \cdot 10^{22}(g_1)$	$29/3$
	$(3, 3, -1/3)$	$\overline{Q}_R q_L H^\dagger$	$5.1 \cdot 10^{30}(g_2)$	$14/3$
	$(3, 3, 2/3)$	$\overline{Q}_R q_L H$	$6.6 \cdot 10^{27}(g_2)$	$20/3$
R_Q^s	$(3, 3, -4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18}(g_1)$	$44/3$
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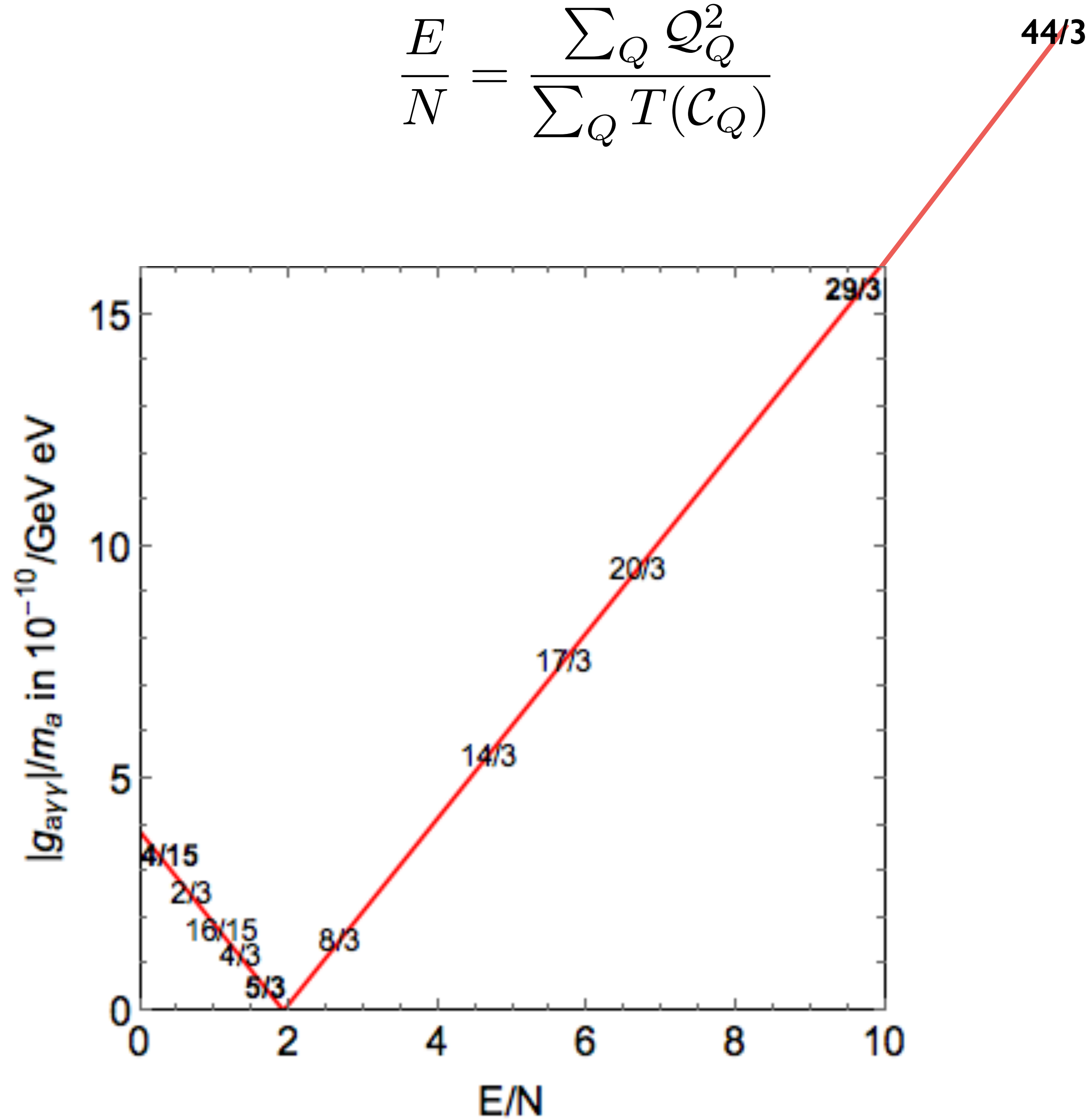
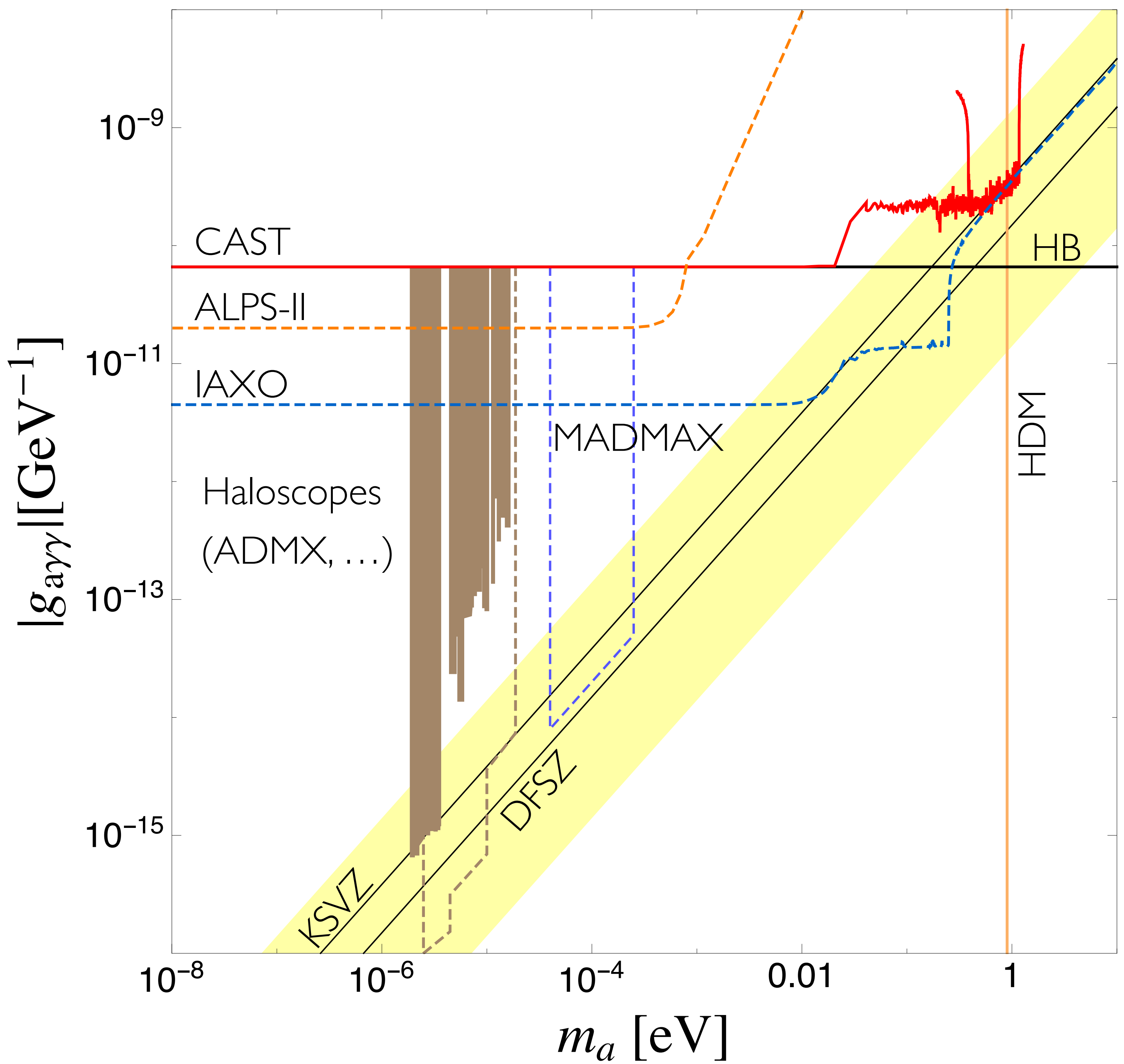


Redefining the axion window



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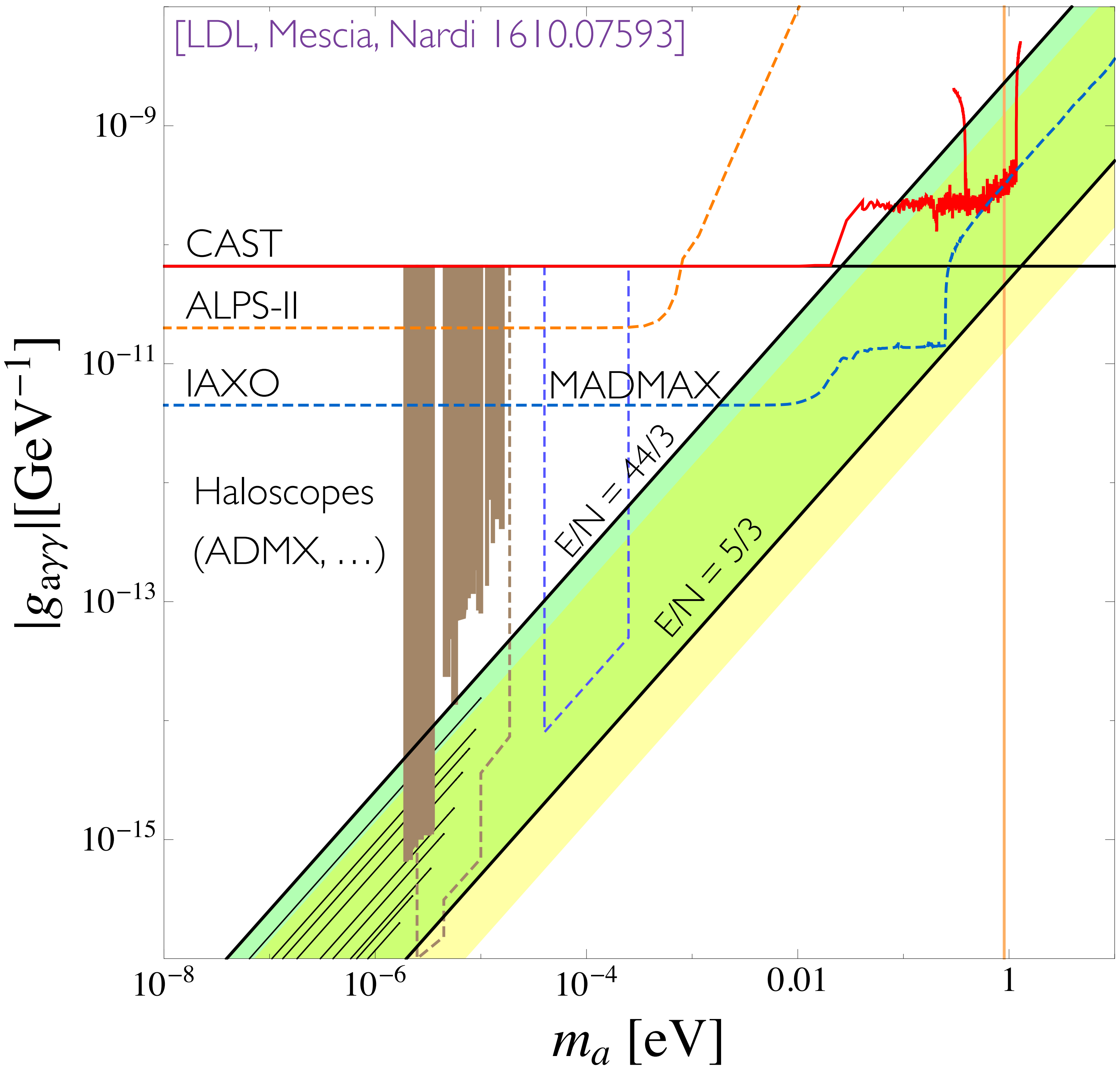


More Q's

- 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)

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

- <u>Complete decoupling</u> within theoretical error possible as well:

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

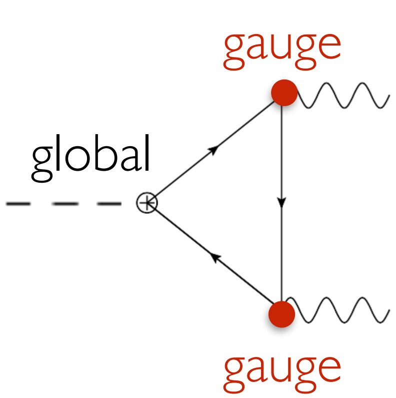
$$g_{a\gamma\gamma} = \frac{m_a}{\mathrm{eV}} \, \frac{2.0}{10^{10}\ \mathrm{GeV}} \left(\frac{E_c}{N_c} - 1.92(4) \right)$$

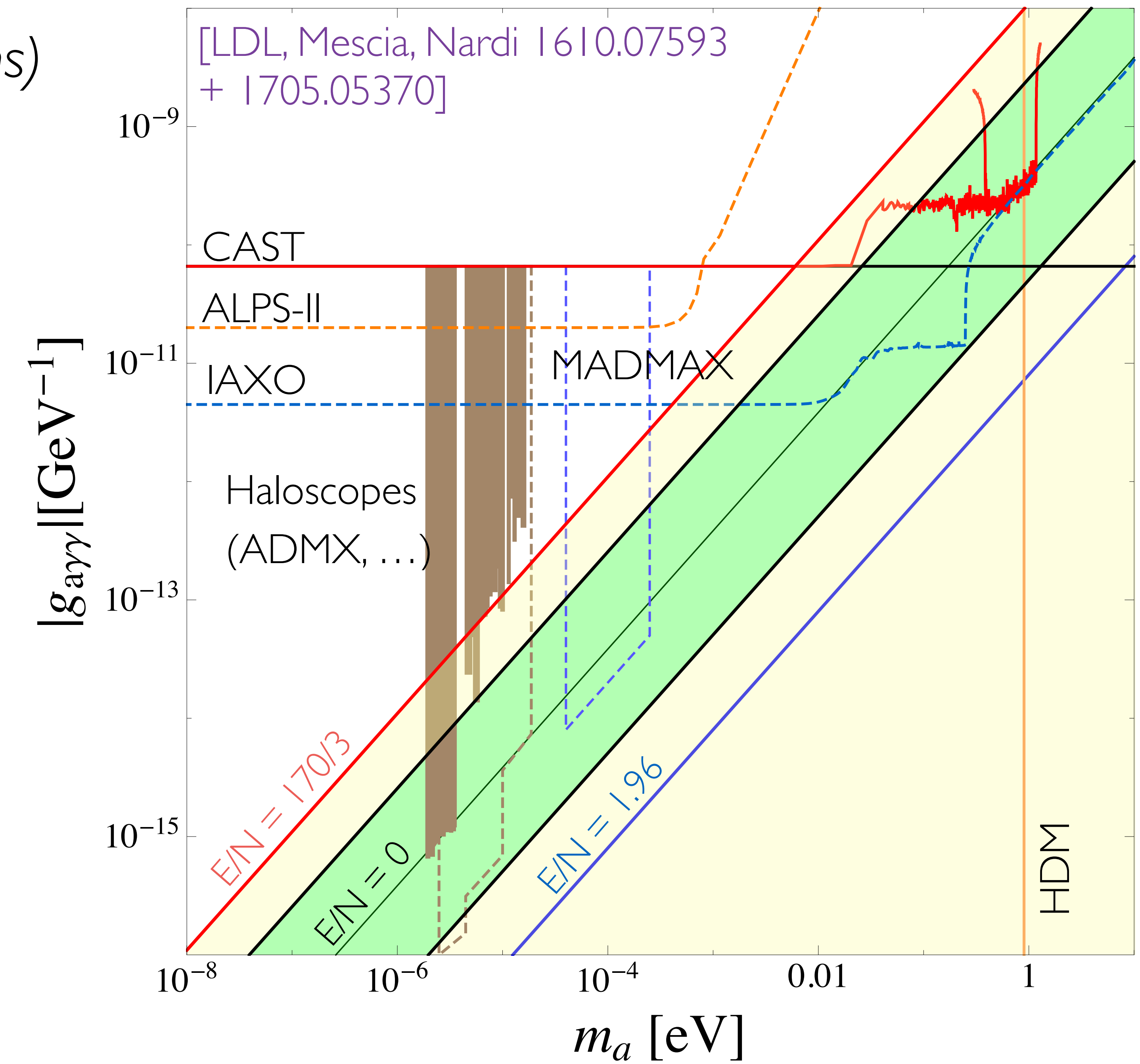
about photophobia: "such a cancellation is immoral, but not unnatural" [D. B. Kaplan, (1985)]

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

- Red line set by perturbativity [KSVZ] *(going above requires exotic constructions)*
- Blue line corresponds to a 2% 'tuning in theory space'
- <u>Messages for exp.'s</u> :

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)*