Rethinking the QCD axion

L2C Seminar - Montpellier - 21.03.19

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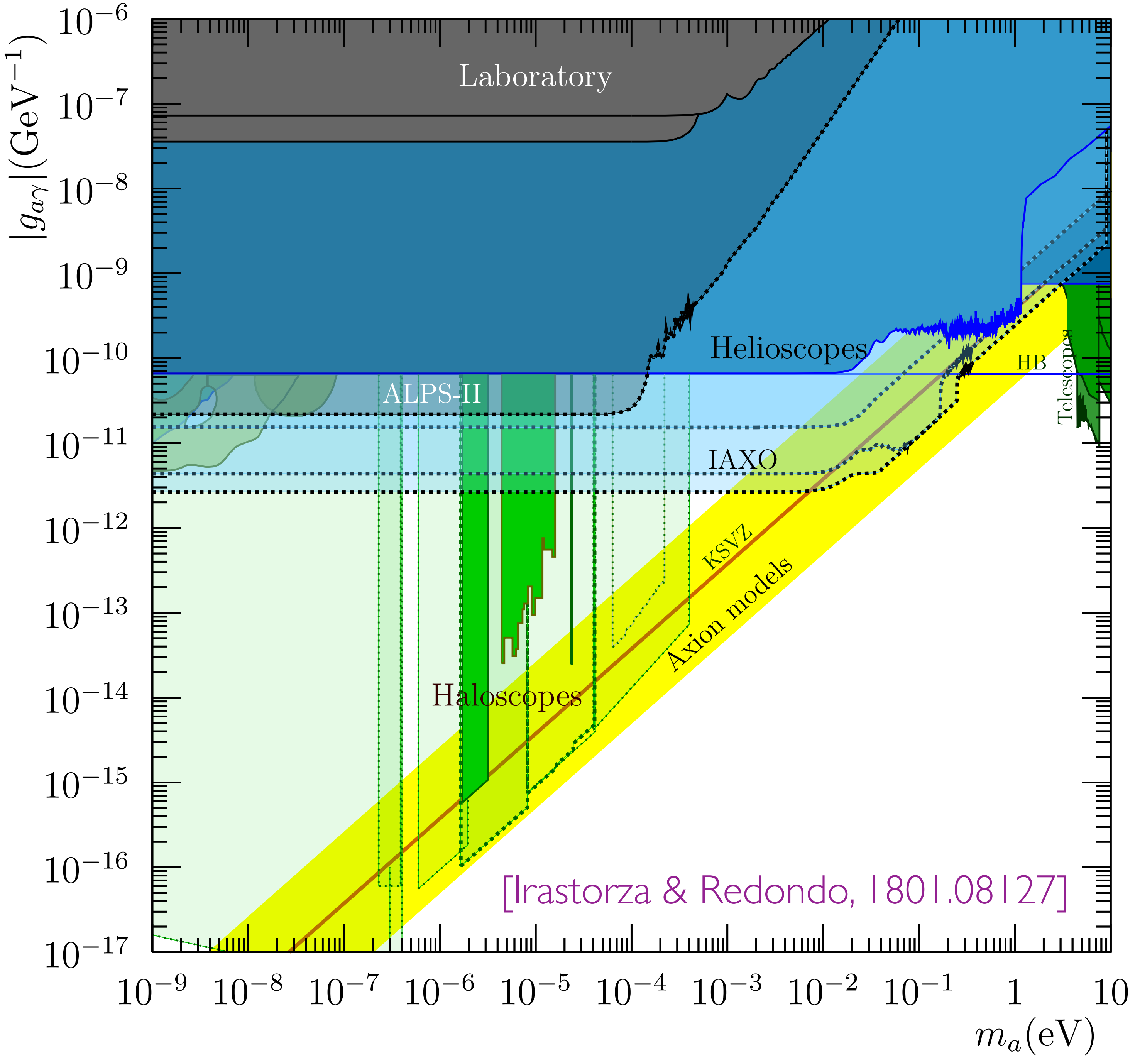
INFN

In 10 years from now ?



[Irastorza & Redondo, 1801.08127]

✤ A great opportunity to discover the QCD axion !

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

Outline

1. Strong CP problem
2. QCD axion
3. Current limits and search strategies
4. Beyond standard axion scenarios

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

The strong CP problem

- CP violation in QCD

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}\left(i\not{D} - m_q e^{i\theta_q}\right) q - \frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} \qquad \left(\tilde{G}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} G^{a,\rho\sigma}\right)$$

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- GGtilde is a total derivative (no effects in PT)

\- QCD instantons [Belavin, Polyakov, Schwarz, Tyupkin PLB59 (1975), 't Hooft PRL37 + PRD14 (1976)]

$$Z = \int \delta G \, e^{-\frac{1}{4}\int GG - i\theta \frac{\alpha_s}{8\pi}\int G\tilde{G}} \sim e^{-\frac{8\pi}{g_s^2}} e^{i\theta} \xrightarrow{\rm I + AI} e^{-\frac{8\pi}{g_s^2}} \cos\theta$$

The strong CP problem

- CP violation in QCD

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

- Non-trivial role of quark fields: under a chiral transformation

$$q \to e^{i\gamma_5 \alpha} q \quad \longrightarrow \quad \begin{cases} \theta_q \to \theta_q + 2\alpha \\ \theta \to \theta + 2\alpha \end{cases}$$

from non-invariance of path integral measure (chiral anomaly) [Fujikawa, PRL 42 (1979)]

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

→ $\overline{\theta} = \theta - \theta_q$ invariant

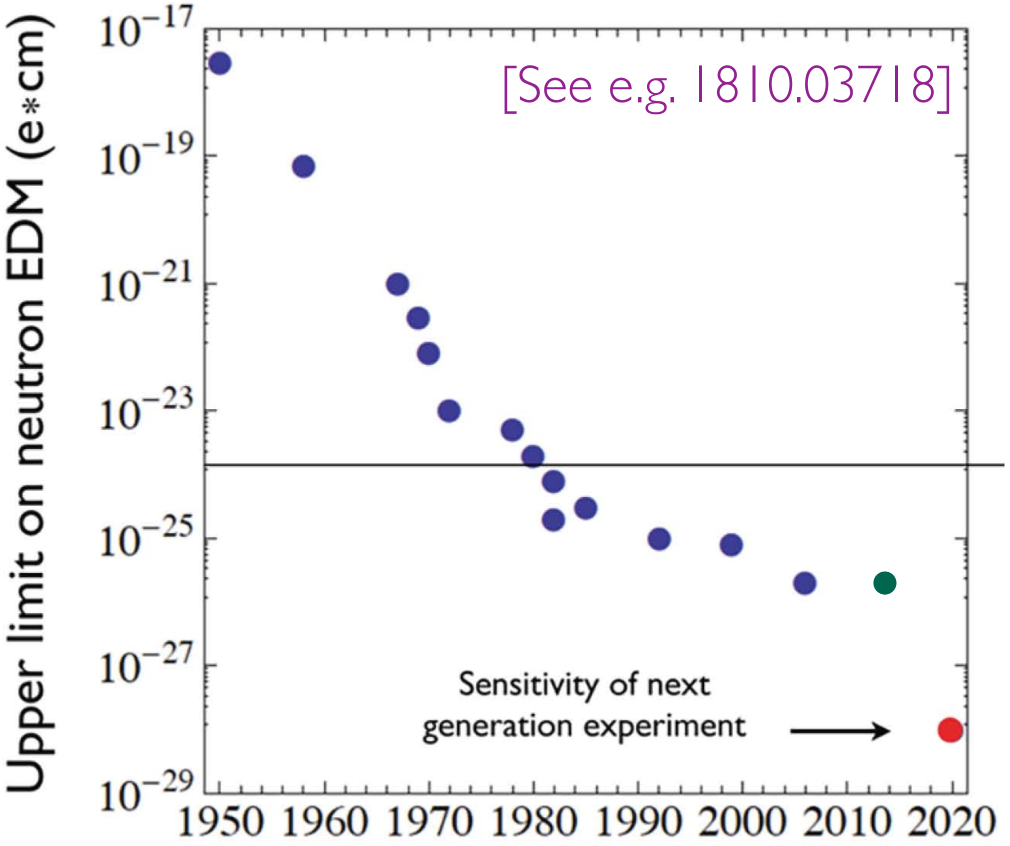
$= \theta - \arg\det\left(Y_u Y_d\right)$ (generalization to an arbitrary chiral transf. in the EW theory)

The strong CP problem

- CP violation in QCD

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

- Non-zero neutron EDM



[See e.g. 1810.03718]

[B. Fillipone]

$$\mathcal{L}_\chi \supset d_n \, \bar{n} \, \sigma^{\mu\nu} \gamma_5 \, n \, F_{\mu\nu}$$

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

[Baluni PRD 19 (1979), Crewther, Di Vecchia, Veneziano, Witten PLB 88 (1979), …]

$\rightarrow$ $\left|\bar{\theta}\right| \lesssim 10^{-10}$ why so small ?

“Small value” problems

- Strong CP: <u>qualitatively different</u> from other small value problems of the SM

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1. theta is radiatively stable (unlike $m_H^2 \ll \Lambda_{\rm UV}^2$)

[Ellis, Gaillard NPB 150 (1979),
Khriplovich, Vainshtein NPB 414 (1994)]

$$\overline{\theta} \sim \frac{1}{(4\pi)^{14}} g'^2 \left[Y^2(u_R) - Y^2(d_R)\right] J_{\rm CKM} \log \Lambda_{\rm UV}$$

↓

$$J_{\rm CKM} = {\rm Im\,Det}\left[Y_U Y_U^\dagger, Y_D Y_D^\dagger\right] \approx 10^{-29}$$

- divergence expected to arise at 7-loops

Fig. 9. Generic topology of a class of divergent *CP* violating 14th-order diagrams in the Kobayashi-Maskawa model [21,22].

“Small value” problems

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[Ellis, Gaillard NPB 150 (1979),
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2. it evades anthropic explanations (unlike $\Lambda_{\rm c.c.}$ and $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$)

nuclear physics and BBN practically unaffected for $\bar\theta \lesssim 10^{-2}$

[Ubaldi, 0811.1599]

→ Solution of strong CP likely unrelated to other small value problems in the SM ?

“Small value” problems

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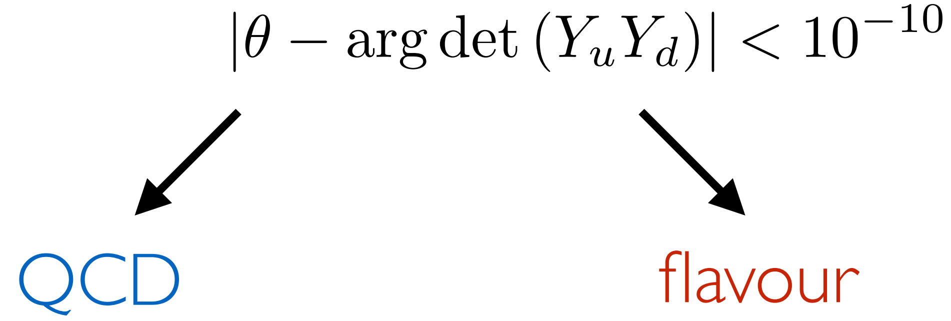
- More than a small value problem ?



$$|\theta - \arg\det\left(Y_u Y_d\right)| < 10^{-10}$$

QCD

flavour

(imagine a theory of flavour generating Yukawas: would expect O(1) phases like CKM)

Solutions

- Do we really understand QCD vacuum structure ?

  - e.g. confinement might screen theta term [Polyakov…]

  - attempts in this directions often fail to solve eta' problem !

$$m_{\eta'} \approx 958\,\mathrm{MeV} \qquad\qquad m_{\eta'} < \sqrt{3} m_\pi$$

[Weinberg sum-rule for pNGB]

$$m^2_{\eta'} = \frac{6\,\mathcal{X}}{f^2_\pi} + \mathcal{O}\left(m_q\right) + \mathcal{O}\left(\frac{1}{N^2_c}\right)$$

[Witten NPB156 (1979),
Veneziano NPB159 (1979)]

$$\mathcal{X} = -i \int d^4x \, \langle 0 | T \tfrac{1}{32\pi^2} G\tilde{G}(x) \tfrac{1}{32\pi^2} G\tilde{G}(0) | 0 \rangle$$

Solutions

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- Do we really understand QCD vacuum structure ?
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- Spontaneous CP (or P) violation

[Nelson PLB 136 (1983), PLB 143 (1984)]

[Barr PRD 30 (1984)]

- $\bar{\theta} = 0$ in the CP limit

- need to generate CKM (and CP violation for BAU) without inducing a too large $\bar{\theta}$

- non-trivial model building + no clear experimental signature

Solutions

- Do we really understand QCD vacuum structure ?
- A massless quark would make the theta term unphysical (excluded at 20σ by Lattice)
- Spontaneous CP (or P) violation
- PQ mechanism [Peccei, Quinn PRL 38 (1977), PRD 16 (1997)]

- assume a global $U(1)_{PQ}$: i) QCD anomalous and ii) spontaneously broken

- <u>axion</u>: pNGB of $U(1)_{PQ}$ breaking [Weinberg PRL 40 (1978), Wilczek PRL 40 (1978)]

$$a(x) \to a(x) + \delta\alpha\, f_a$$

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

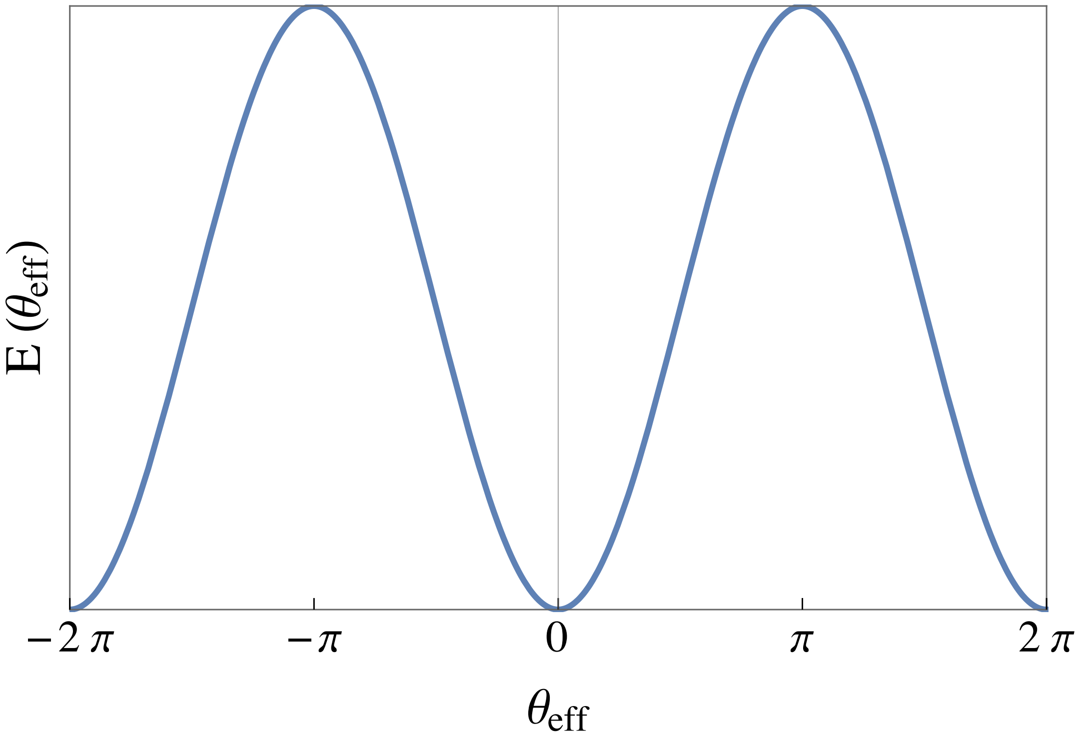
→ set to zero by QCD dynamics

θ-dependence of QCD vacuum

- Ground state energy in Euclidean V_4

[Vafa, Witten PRL 53 (1984)]

$$
\begin{aligned}
e^{-V_4 E(\theta_{\rm eff})} &= \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\rm eff}\, G\tilde{G}} \\
&= \left| \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\rm eff}\, G\tilde{G}} \right| \\
&\leq \int \mathcal{D}\varphi \, \left| e^{-S_0 + i\theta_{\rm eff}\, G\tilde{G}} \right| = e^{-V_4 E(0)}
\end{aligned}
$$



→ $E(0) \leq E(\theta_{\rm eff})$

θ-dependence of QCD vacuum

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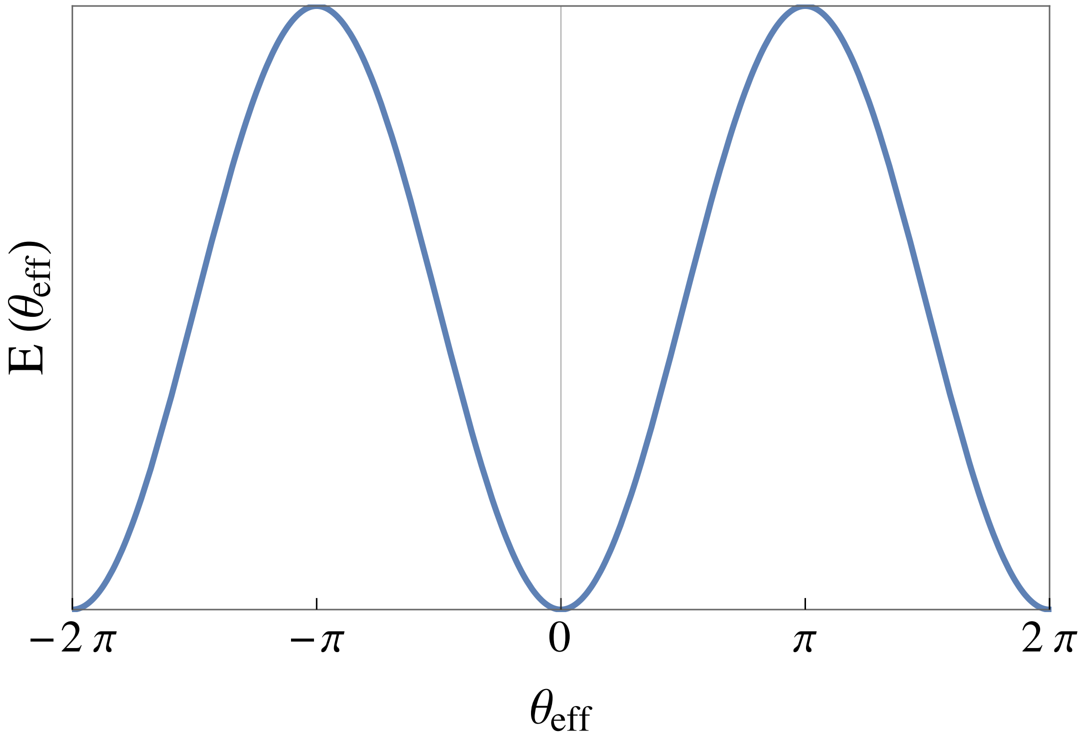


- theta term dynamically relaxed to zero on the axion ground state $\langle a(x) \rangle = -\bar{\theta} f_a$

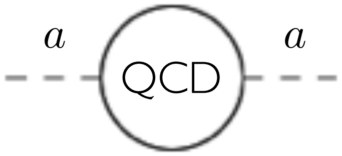
$$\left(\bar{\theta} + \frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} \xrightarrow{a \to \langle a \rangle + a} \frac{a}{f_a} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

- aGGtilde not a total derivative (effects in PT)

Axion properties [EFT]

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

  - generates axion mass



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

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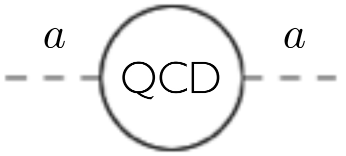

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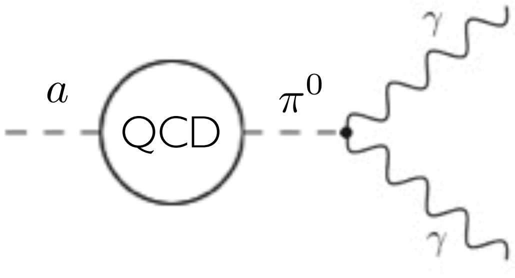
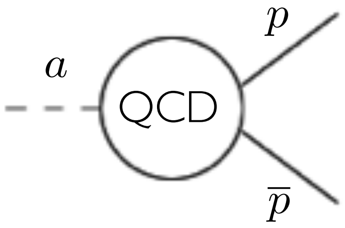
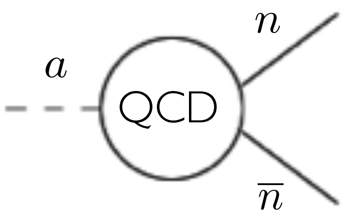
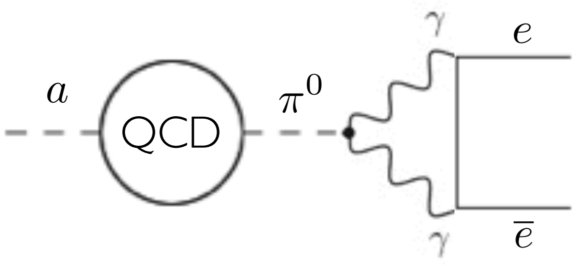
  - generates "model independent" axion couplings to photons, nucleons, electrons, …









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

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

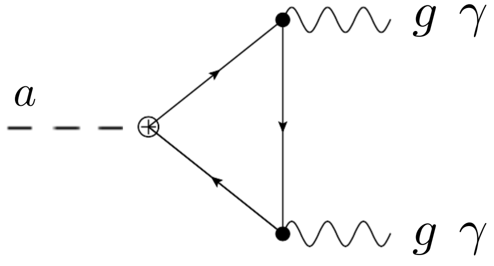
[From NLO Chiral Lagrangian,
Grilli di Cortona et al., 1511.02867]

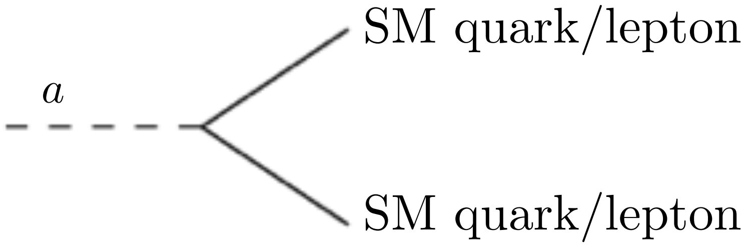
Axion properties [EFT]

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

- EFT breaks down at energies of order f_a

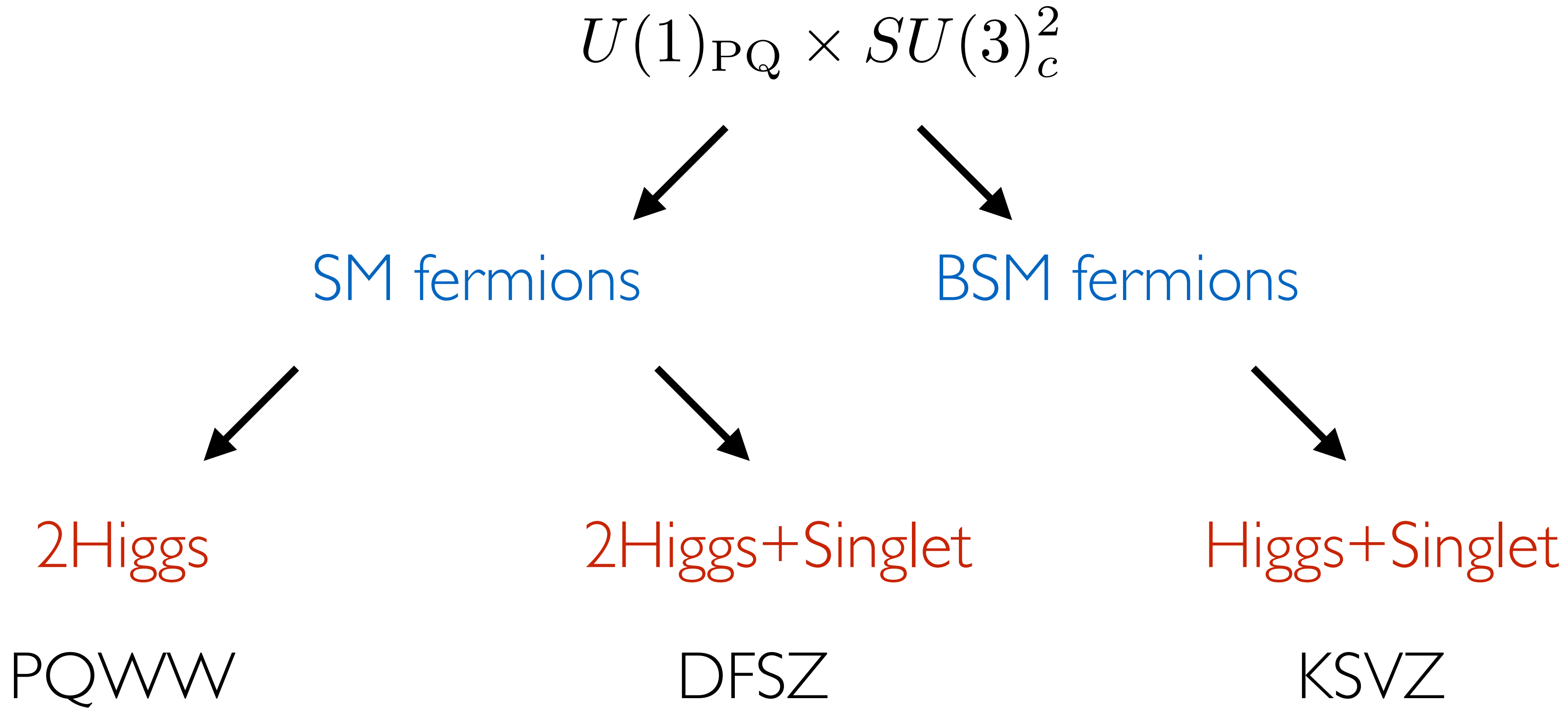
→ UV completion can still affect low-energy axion properties !





Axion models [UV completion]

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



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

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)

Axion models [UV completion]

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

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

SM fermions

BSM fermions

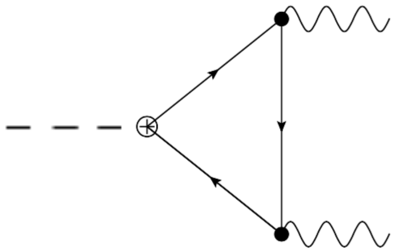
2Higgs+Singlet

Higgs+Singlet

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

DFSZ

KSVZ



$C_{p,n,e}(\beta) \sim \mathcal{O}(1)$

$\tan\beta = v_2/v_1$

$C_p \simeq -0.5$

$C_{n,e} \simeq 0$

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]*

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

neutrino interactions (d=6 op.)

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

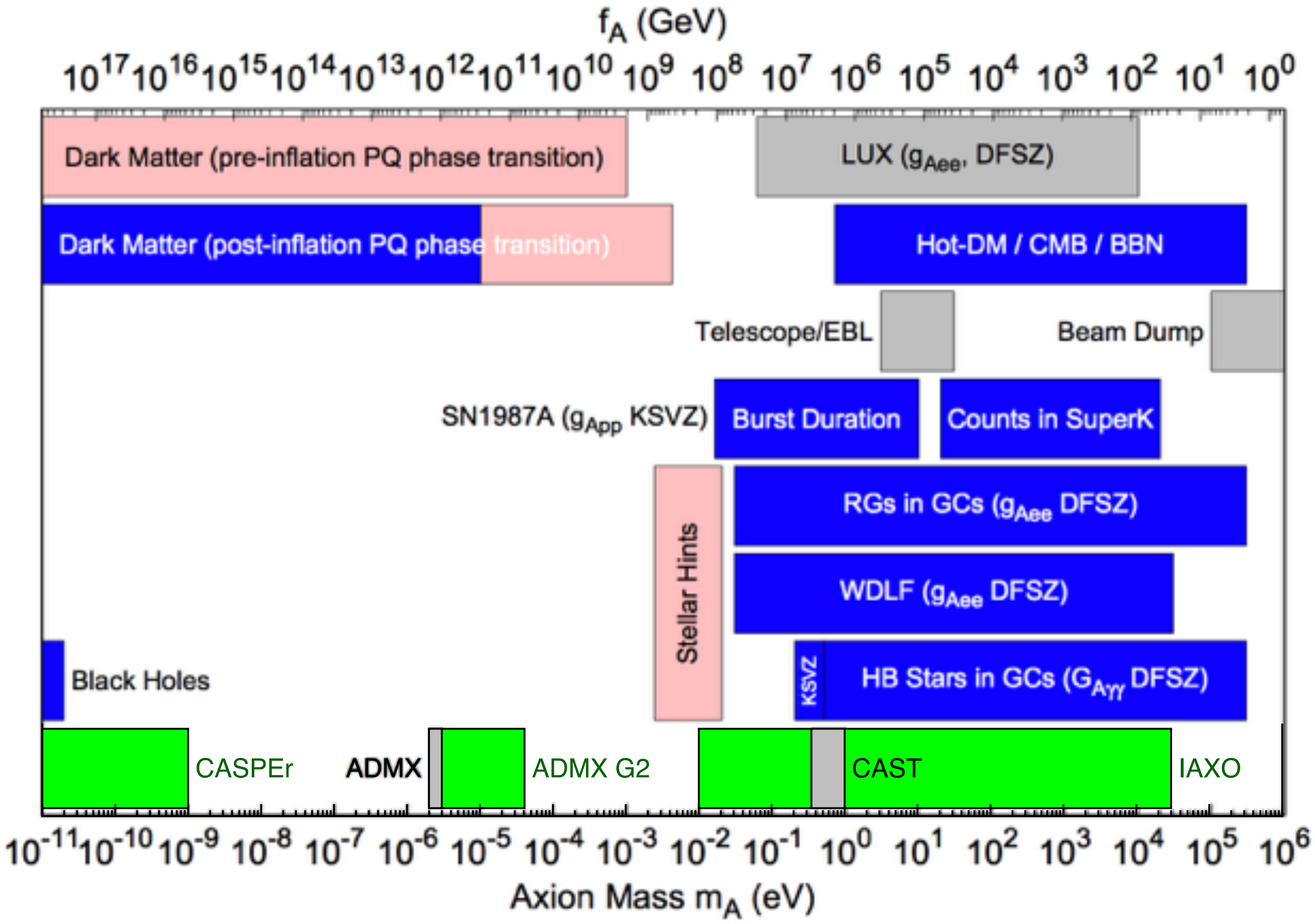
axion interactions (d=5 op.)

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

→ axions are a perfect target !

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

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

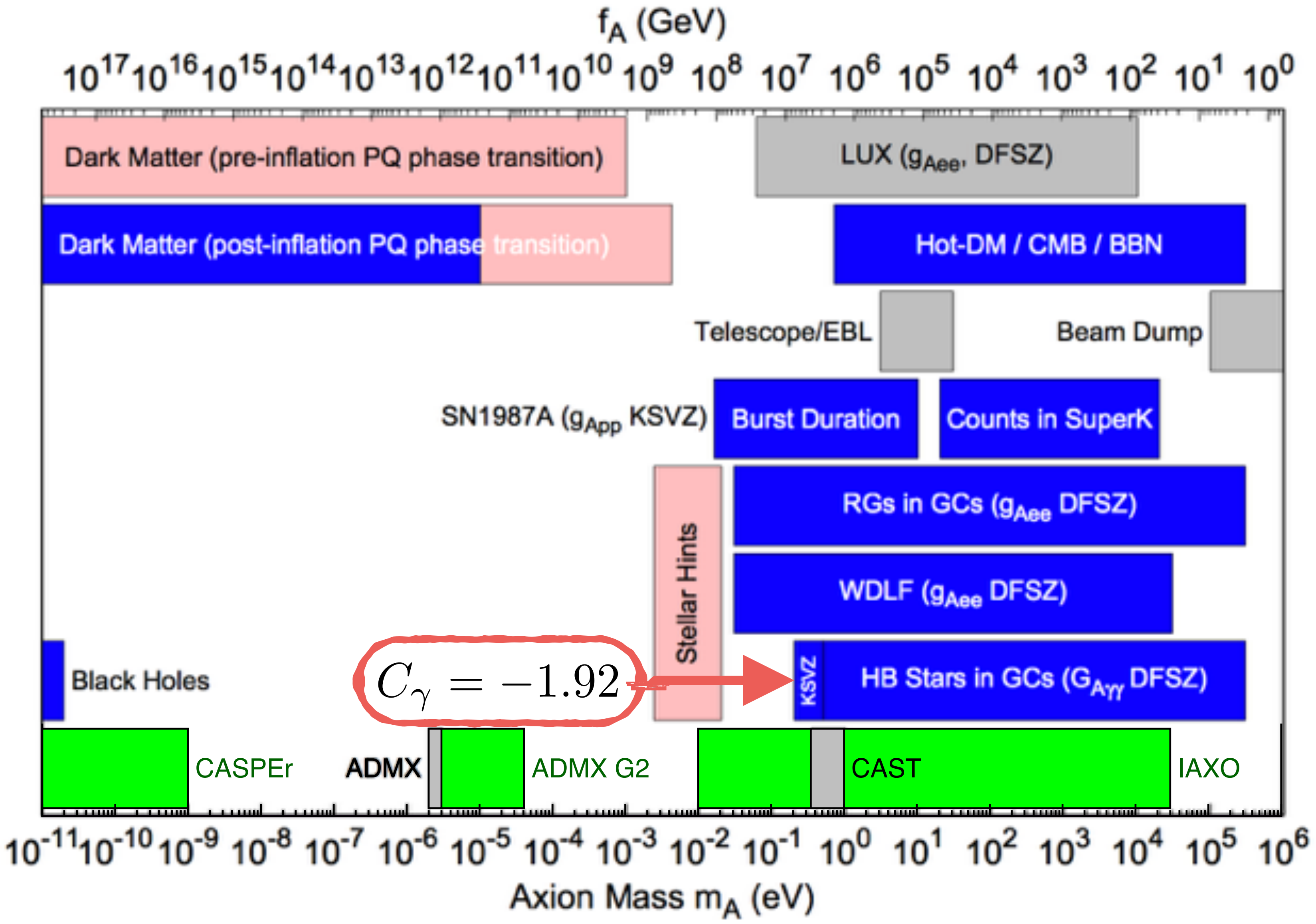
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Axion landscape



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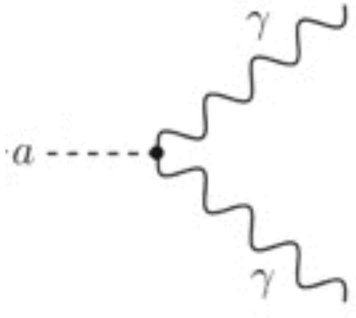
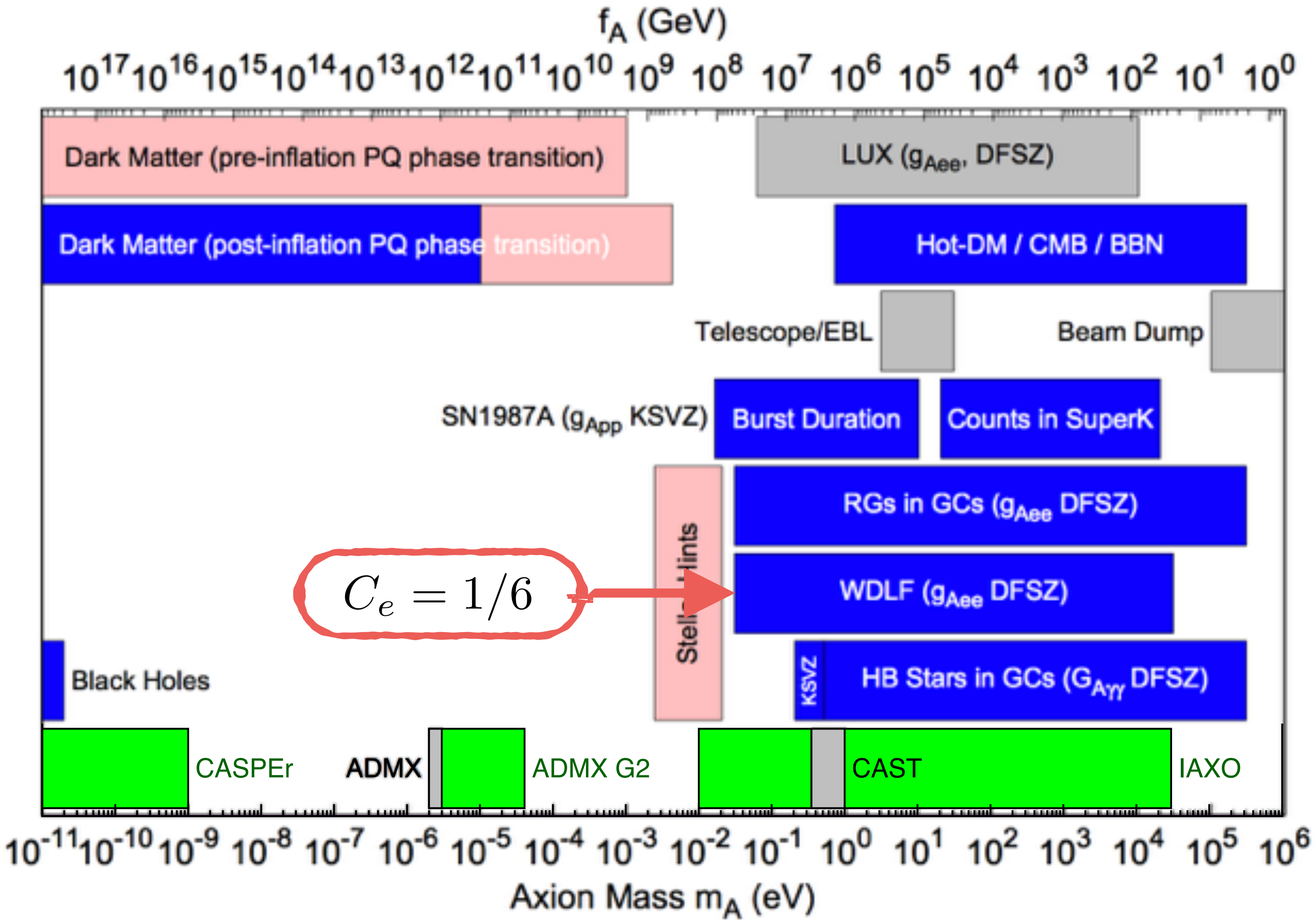
Exp. sensitivities

- 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



$C_e = 1/6$

[Ringwald, Rosenberg, Rybka, Particle Data Group]

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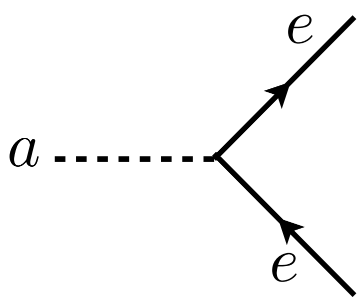
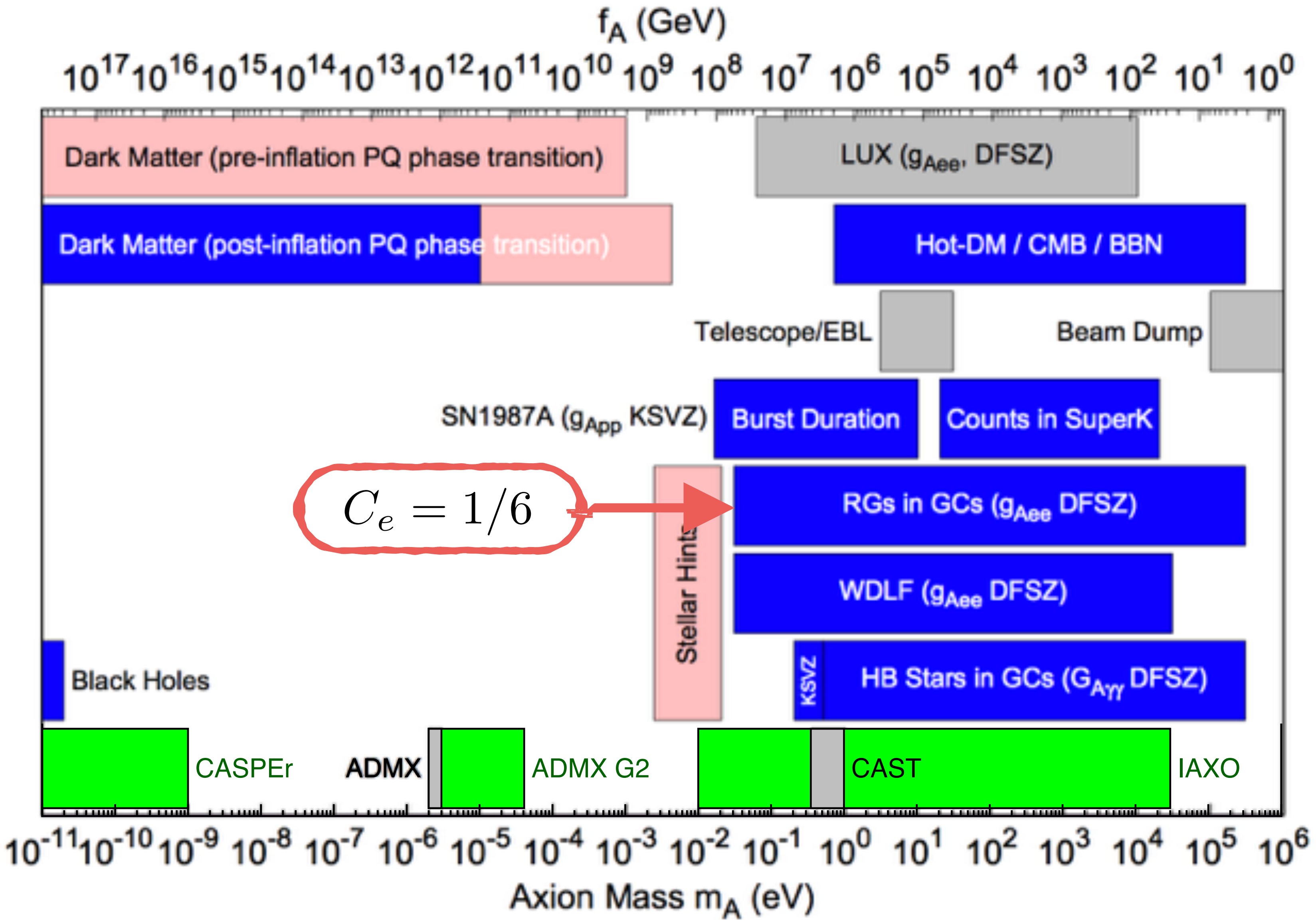
Exp. sensitivities

- White dwarfs luminosity function (cooling)



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

Axion landscape



$C_e = 1/6$

[Ringwald, Rosenberg, Rybka, Particle Data Group]

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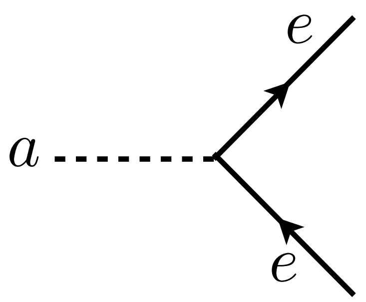
Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- Red giants evolution in globular clusters



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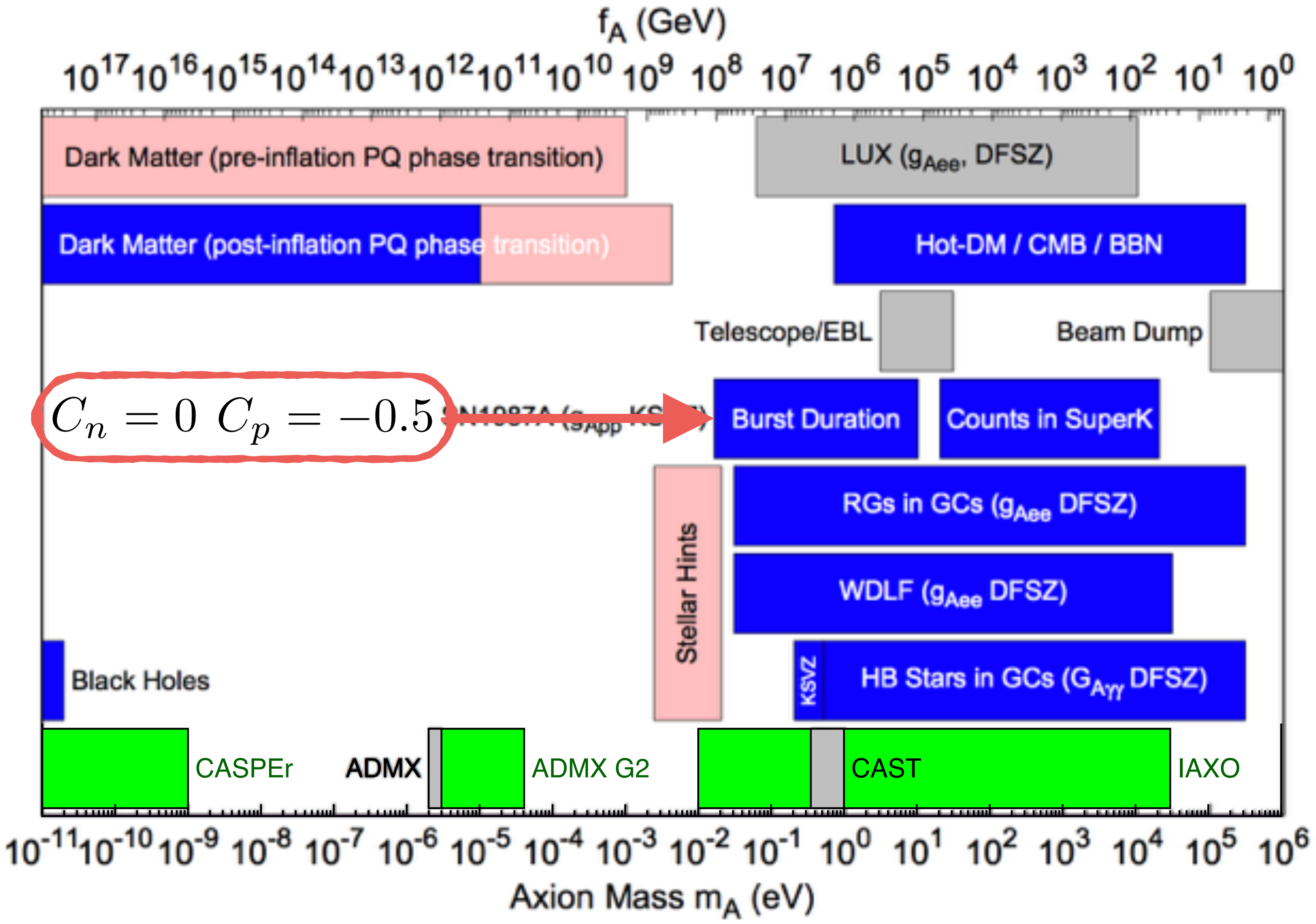
Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

Lab exclusions

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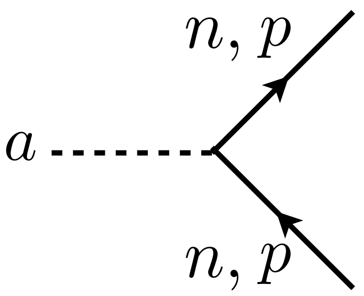
DM explained / Astro Hints

Exp. sensitivities

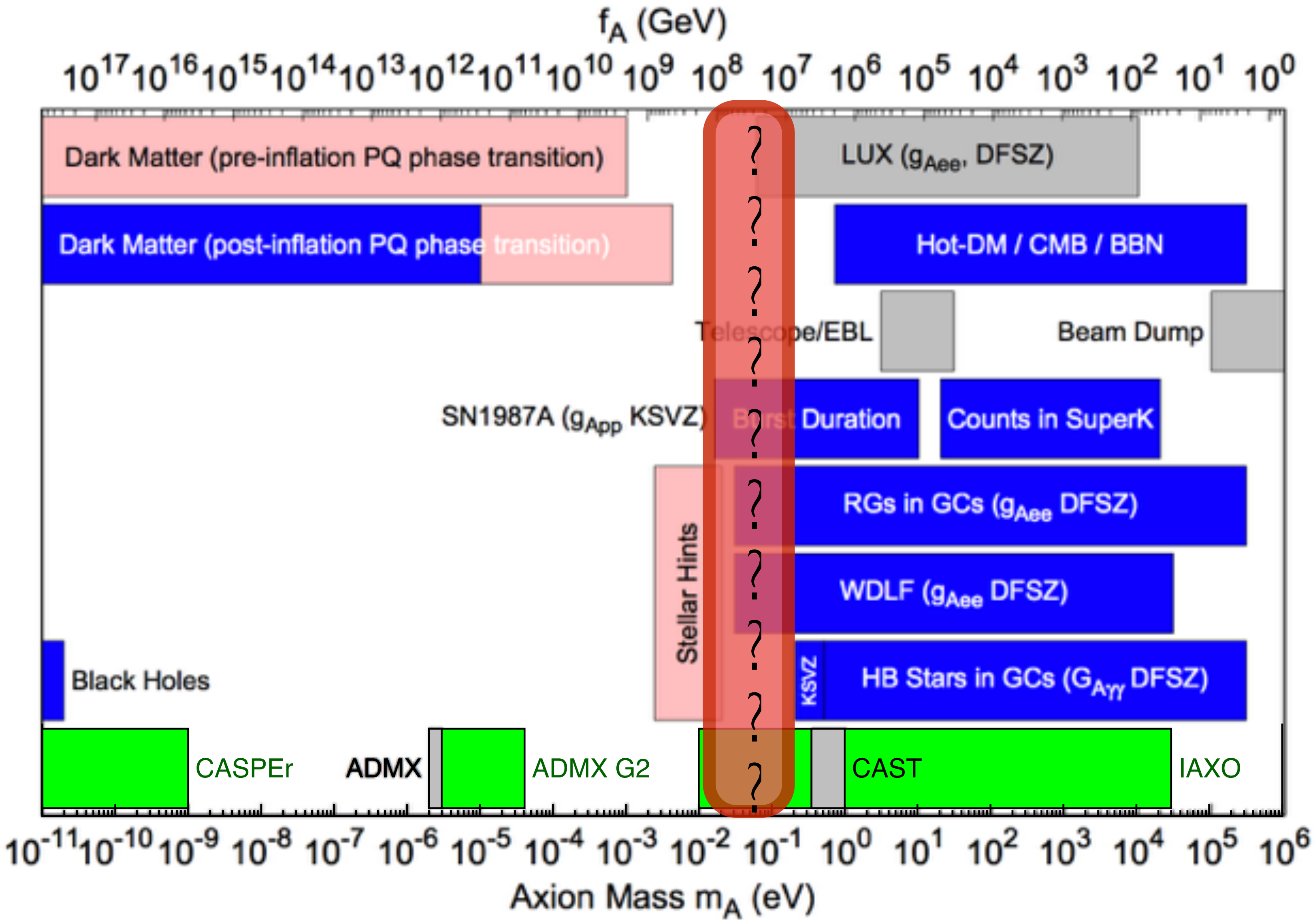
- Burst duration of SN1987A nu signal



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

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

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

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

Search strategies

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

<u>Primakoff effect</u>: axion-photon transition in external static E or B field

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F \cdot \tilde{F} = g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$

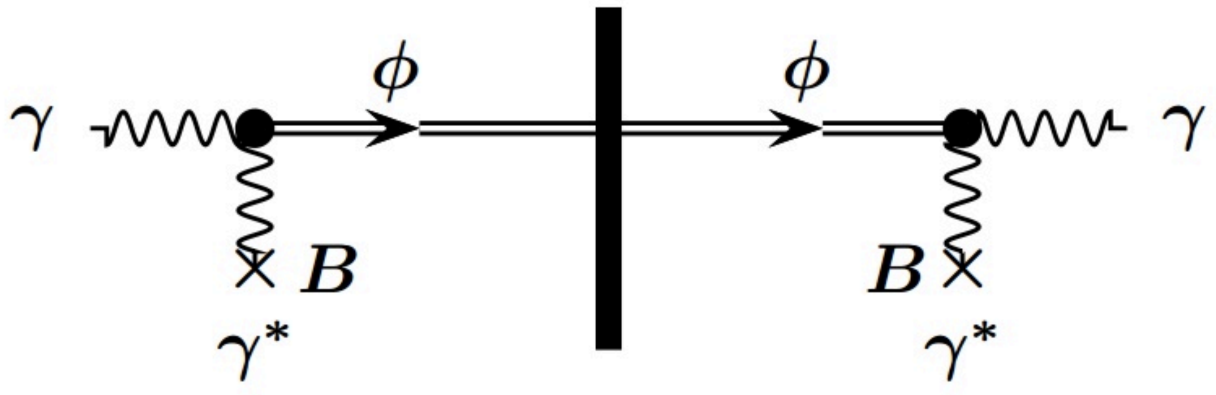
1. Light Shining through Walls (axions in the lab) [See e.g. Redondo, Ringwald hep-ph/1011374]

2. Haloscopes (axion Dark Matter) [Sikivie PRL 51 (1983)]

3. Helioscopes (axions from the Sun)

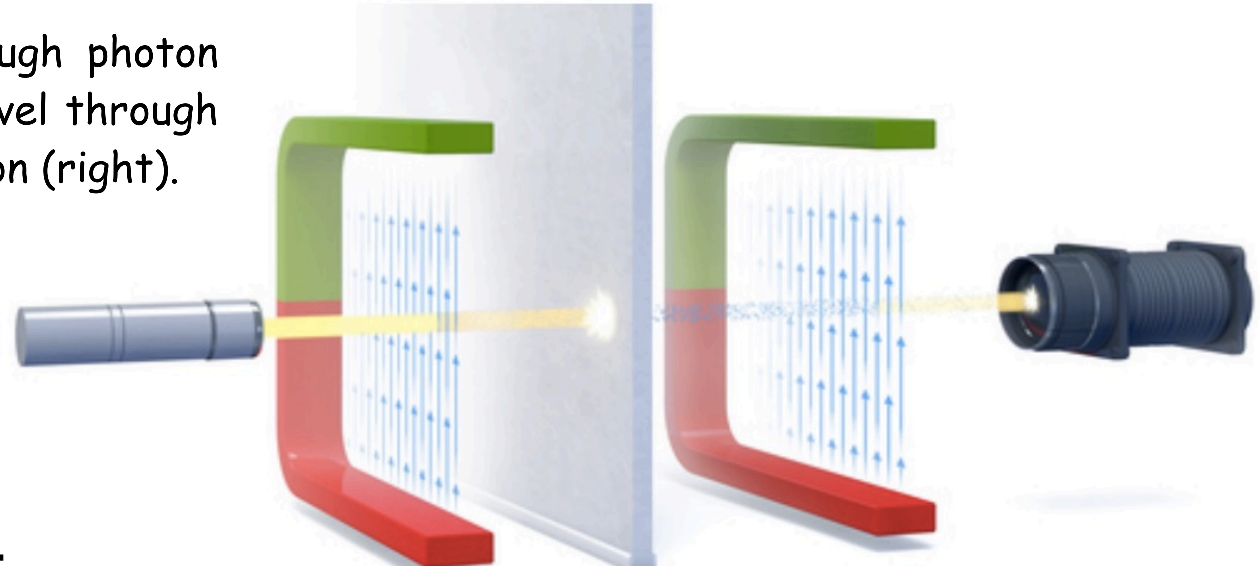
Light Shining through Walls (LSW)

- Any Light Particle Search (DESY) ALPS-I (2007*-2010) and ALPS-II (2013-…)



Schematic view of axion (or ALP) production through photon conversion in a magnetic field (left), subsequent travel through a wall, and final detection through photon regeneration (right).

Artist view of a light shining through a wall experiment



LSW experiments pay a $g_{a\gamma\gamma}^4$ suppression

Boost of exp. activity after PVLAS discovery claim in 2006

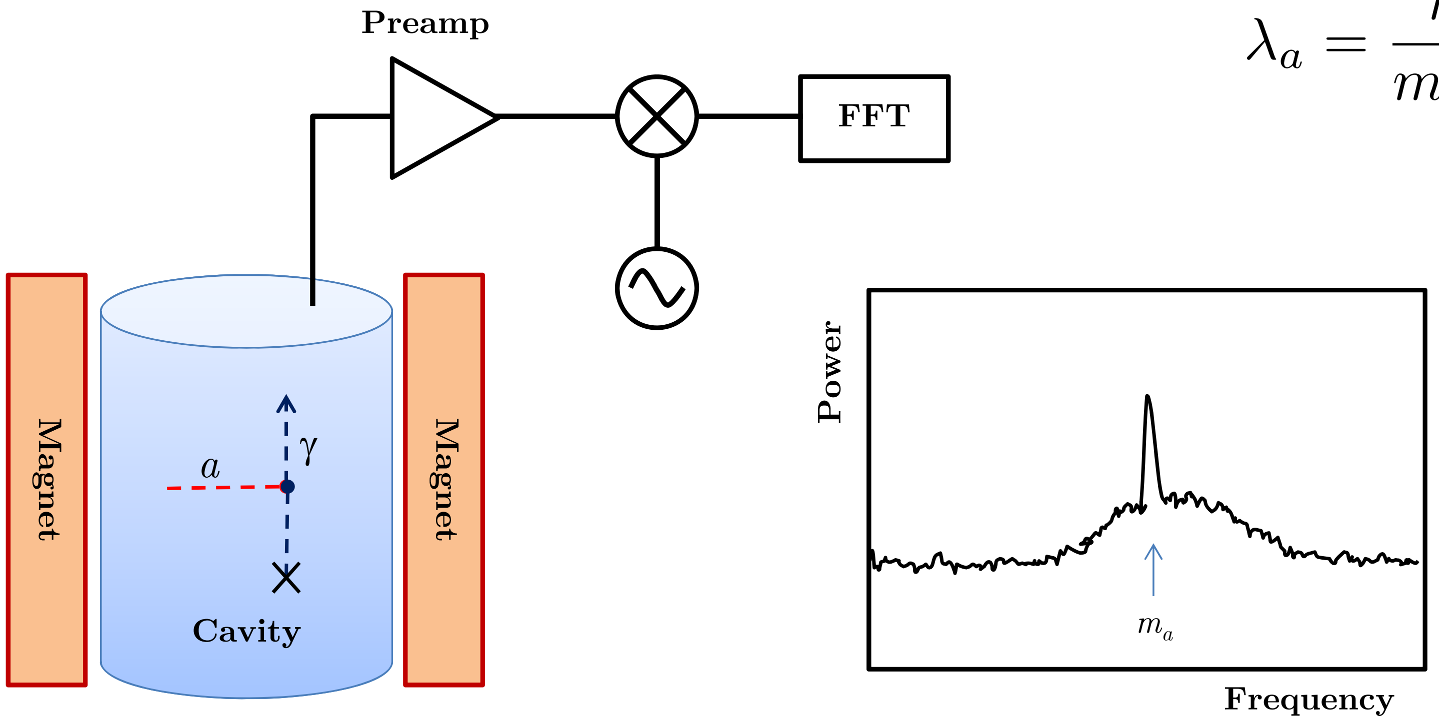
Haloscopes

- Look for DM axions with a microwave resonant cavity

  - power of axions converting into photons in an EM cavity $P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\text{eff}}$

  - <u>resonance condition</u>: need to tune the frequency of the EM cavity on the axion mass

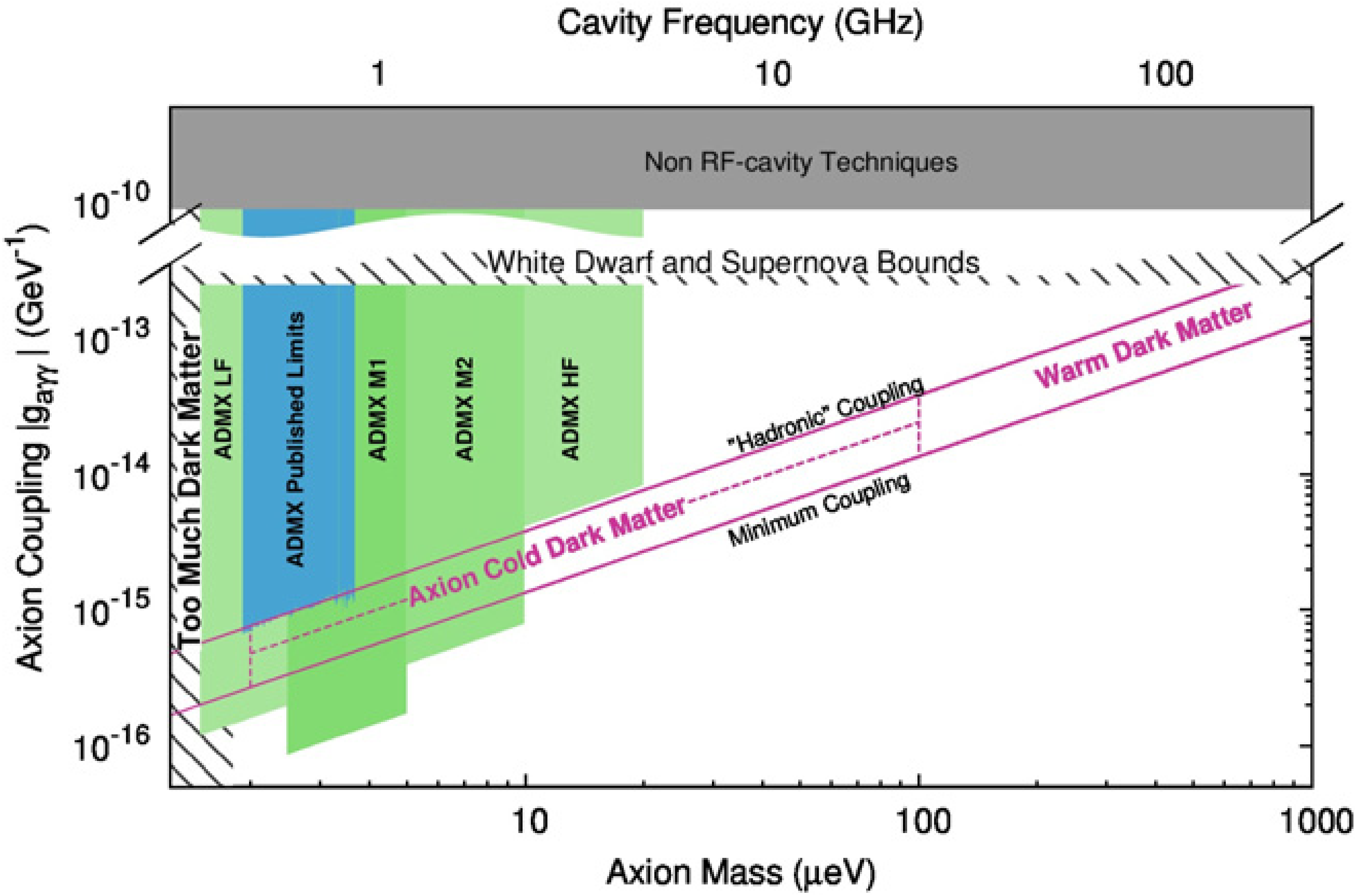
$$\lambda_a = \frac{h}{m_a c} \sim 20 \text{ cm} \frac{\mu\text{eV}}{m_a}$$



Haloscopes

- Look for DM axions with a microwave resonant cavity

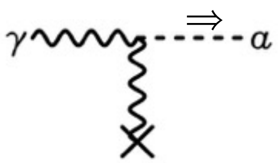
- Axion Dark Matter eXperiment (ADMX) (U. of Washington)

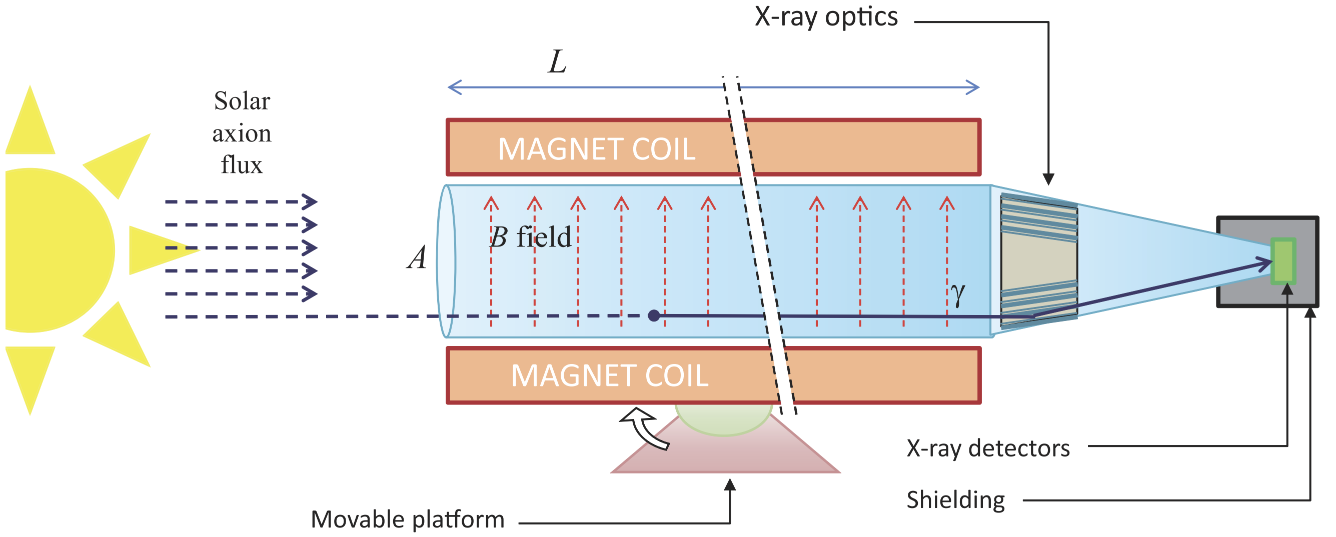


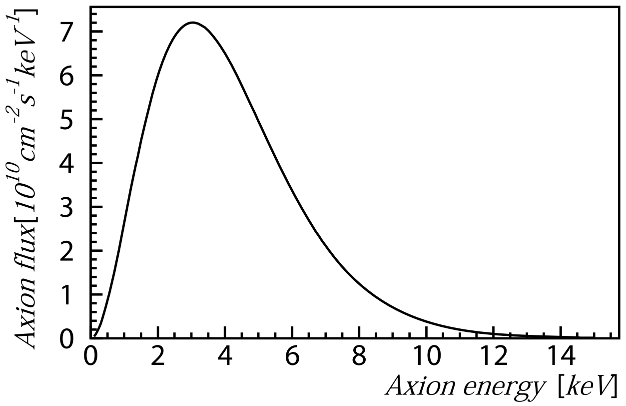
[ADMX Collaboration, Phys. Dark Univ. 4 (2014)]

Helioscopes

- The Sun is a potential axion source







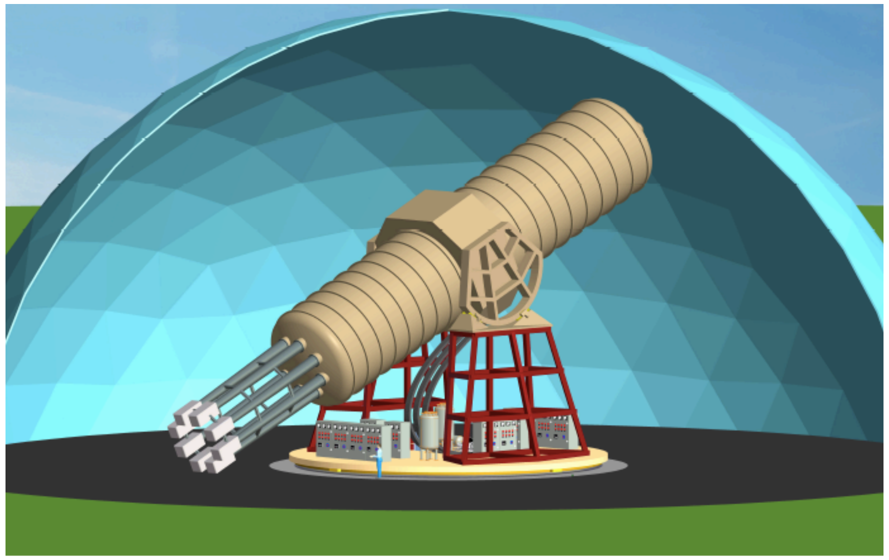
- macroscopic B-field can provide a coherent axion-photon conversion rate over a big volume

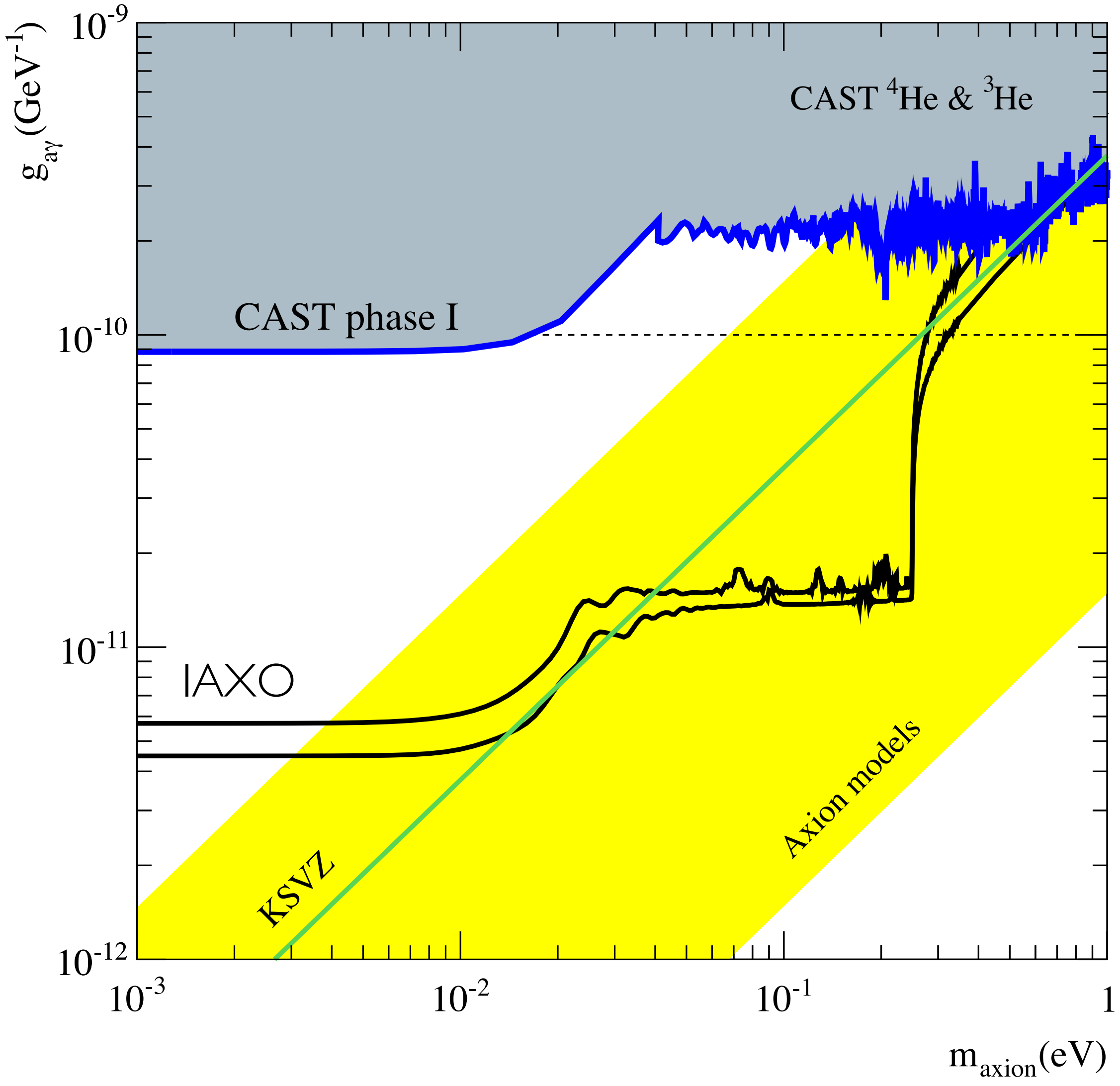
Helioscopes

- The Sun is a potential axion source

  - CERN Axion Solar Telescope (CAST)

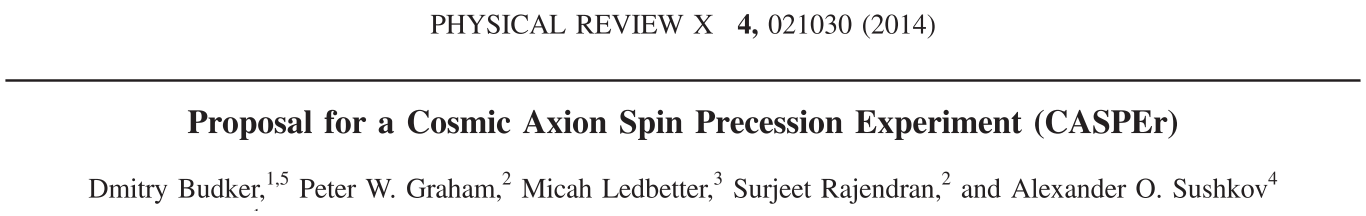
  - International AXion Observatory (IAXO)





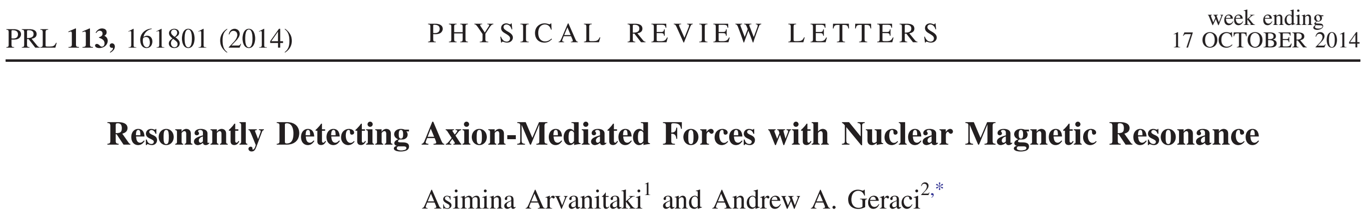
[IAXO "Letter of intent", CERN-SPSC-2013-022]

The Axion Rush


PHYSICAL REVIEW X 4, 021030 (2014)

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker,[1,5] Peter W. Graham,[2] Micah Ledbetter,[3] Surjeet Rajendran,[2] and Alexander O. Sushkov[4]


PRL 113, 161801 (2014) PHYSICAL REVIEW LETTERS week ending 17 OCTOBER 2014

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

Asimina Arvanitaki[1] and Andrew A. Geraci[2,*]


PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

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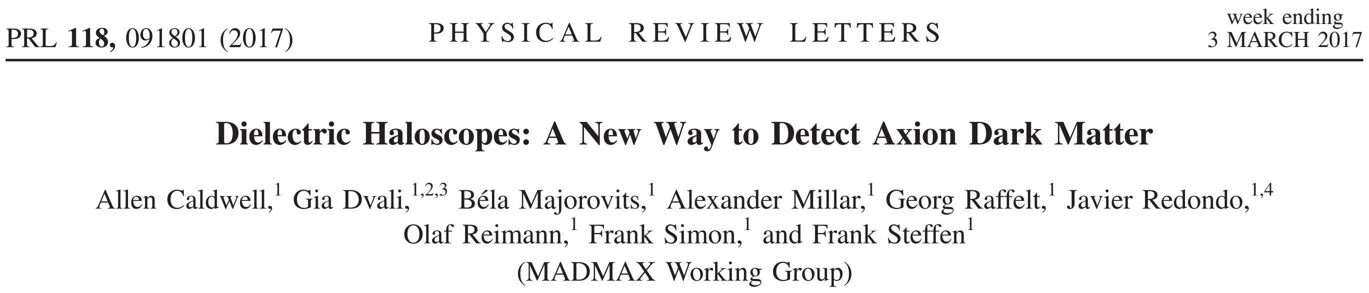
Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]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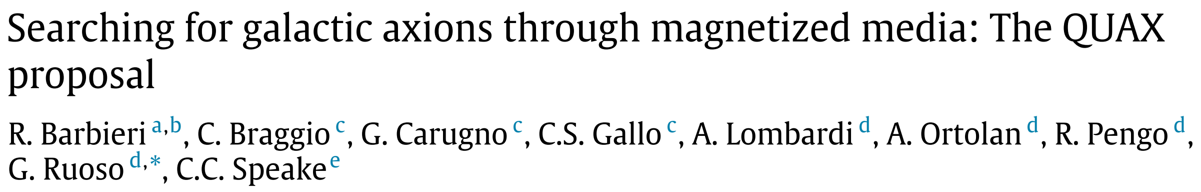

Searching for galactic axions through magnetized media: The QUAX proposal

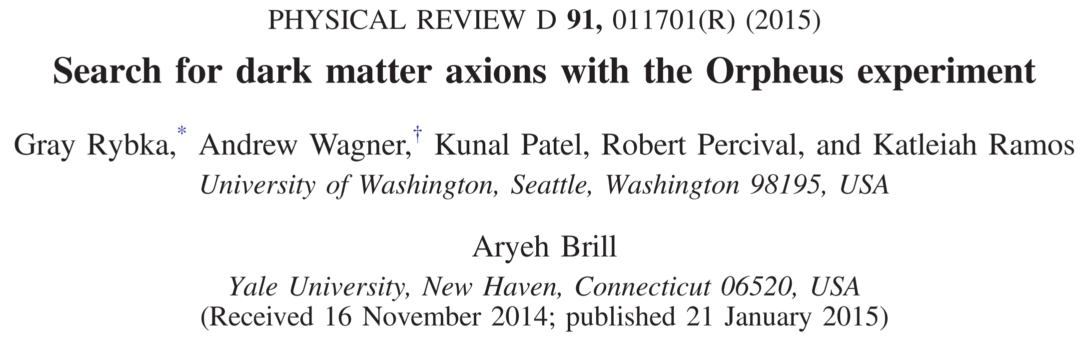
R. Barbieri[a,b], C. Braggio[c], G. Carugno[c], C.S. Gallo[c], A. Lombardi[d], A. Ortolan[d], R. Pengo[d], G. Ruoso[d,*], C.C. Speake[e]


PHYSICAL REVIEW D 91, 084011 (2015)

Discovering the QCD axion with black holes and gravitational waves

Asimina Arvanitaki[*]
Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada

Masha Baryakhtar[†] and Xinlu Huang[‡]
Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA
(Received 16 December 2014; published 7 April 2015)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Search for dark matter axions with the Orpheus experiment

Gray Rybka,[*] Andrew Wagner,[†] Kunal Patel, Robert Percival, and Katleiah Ramos
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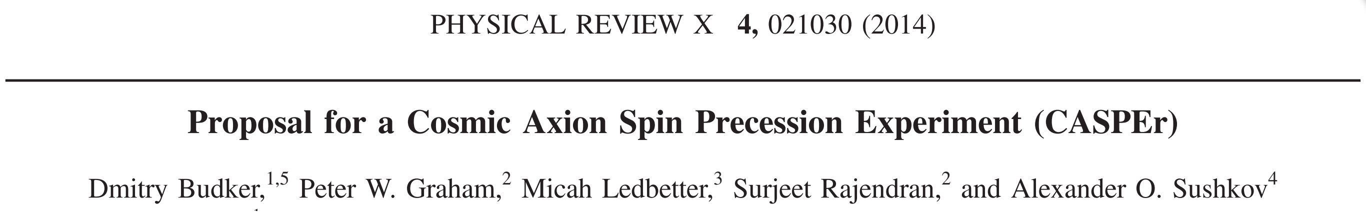
CULTASK, The Coldest Axion Experiment at CAPP/IBS/KAIST in Korea

Woohyun Chung[*]
Center for Axion and Precision Physics Research, Institute for Basic Science (IBS), Republic of Korea

The Axion Rush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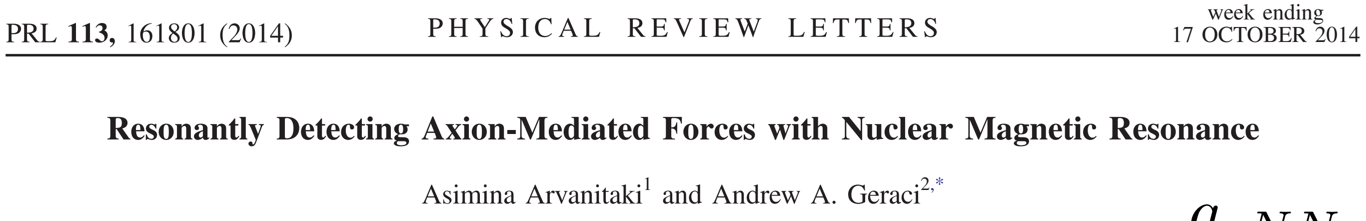
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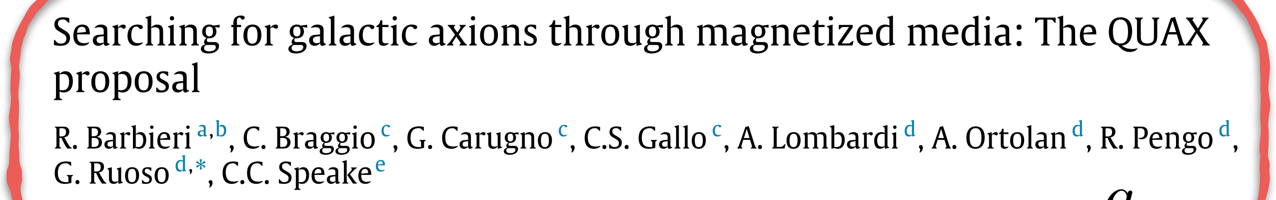
g_{aNN}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g_{aee}


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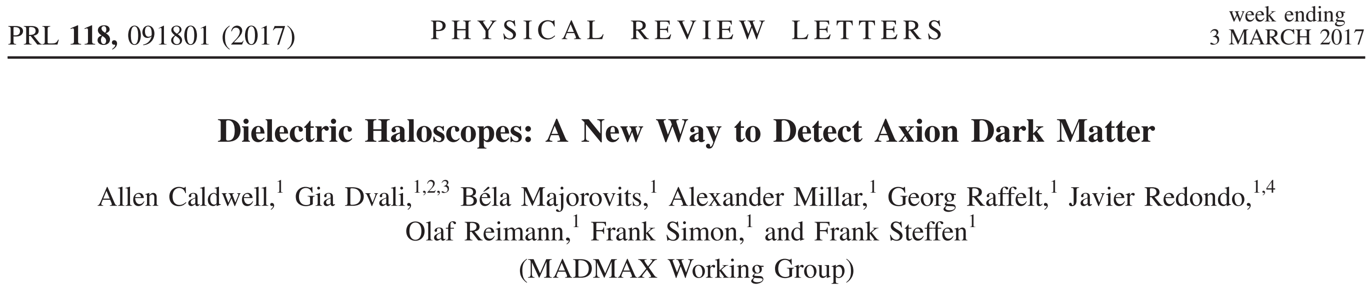
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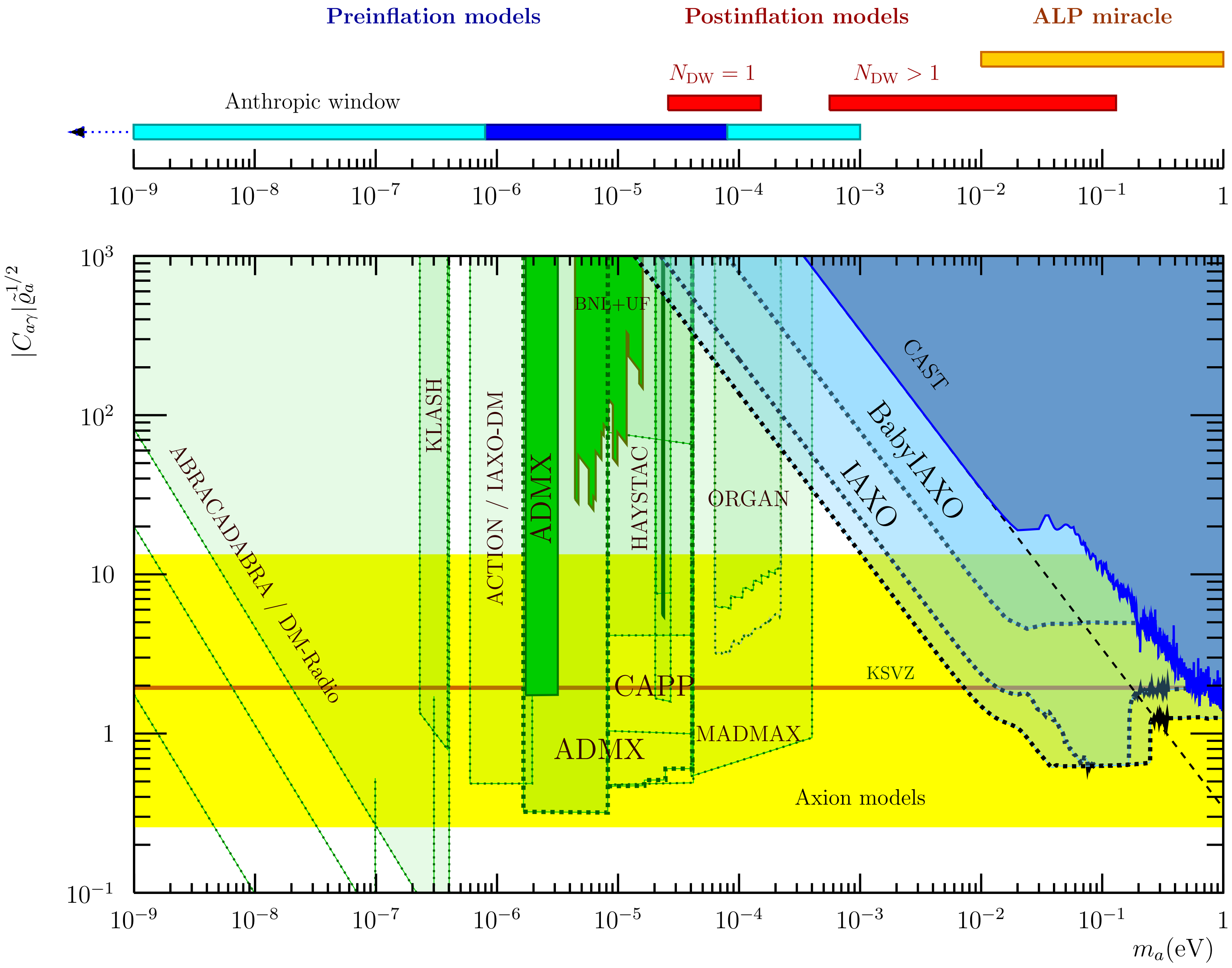
$g_{a\gamma\gamma}$

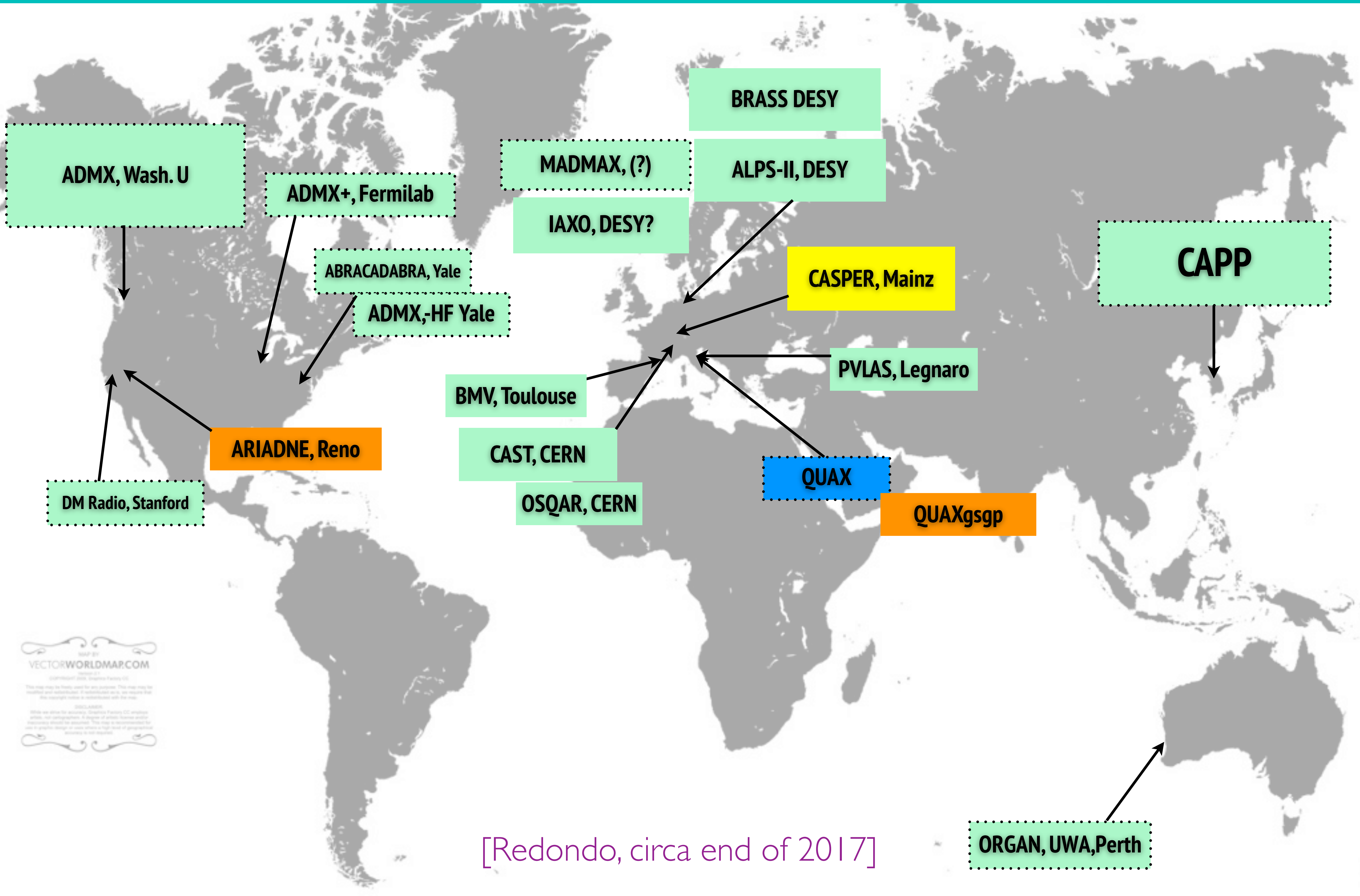
The Axion Rush

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)	proposed
CASPEr (Mainz)	proposed
…	…



[Irastorza & Redondo, 1801.08127]

In a small context



ADMX, Wash. U

ADMX+, Fermilab

ABRACADABRA, Yale

ADMX,-HF Yale

ARIADNE, Reno

DM Radio, Stanford

MADMAX, (?)

IAXO, DESY?

BRASS DESY

ALPS-II, DESY

CASPER, Mainz

BMV, Toulouse

CAST, CERN

OSQAR, CERN

PVLAS, Legnaro

QUAX

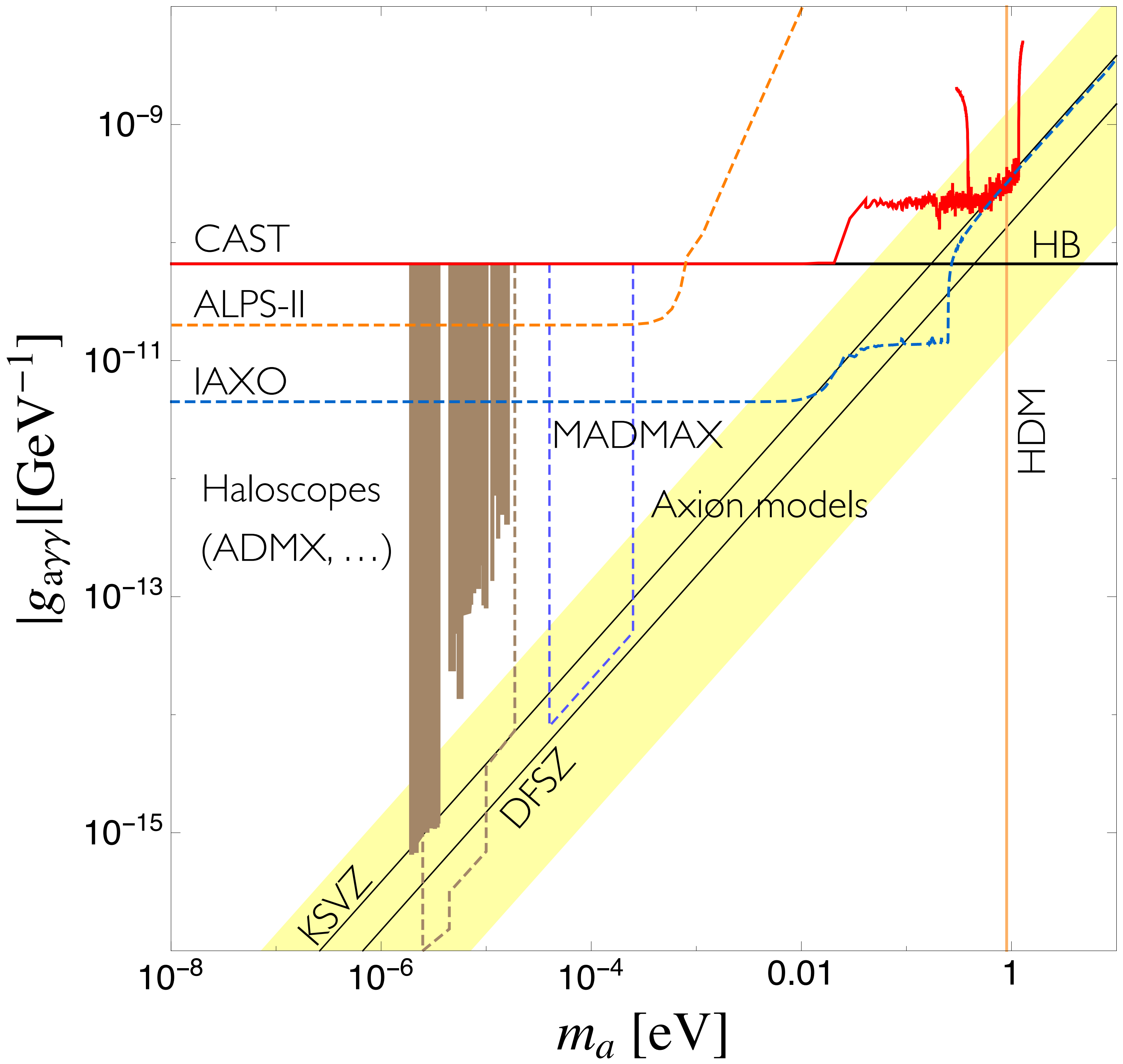
QUAXgsgp

CAPP

ORGAN, UWA,Perth

[Redondo, circa end of 2017]

Need to know where to search



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

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)]

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

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

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

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

KSVZ axions

- Field content

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
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Φ	0	1	1	0	1

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

- 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

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

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

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

cosmological issue if thermally produced
in the early universe !

Q stability

- Symmetry of the kinetic term

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

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

- if $\mathcal{L}_{Qq} \neq 0$ U(1)$_{\mathrm{Q}}$ 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

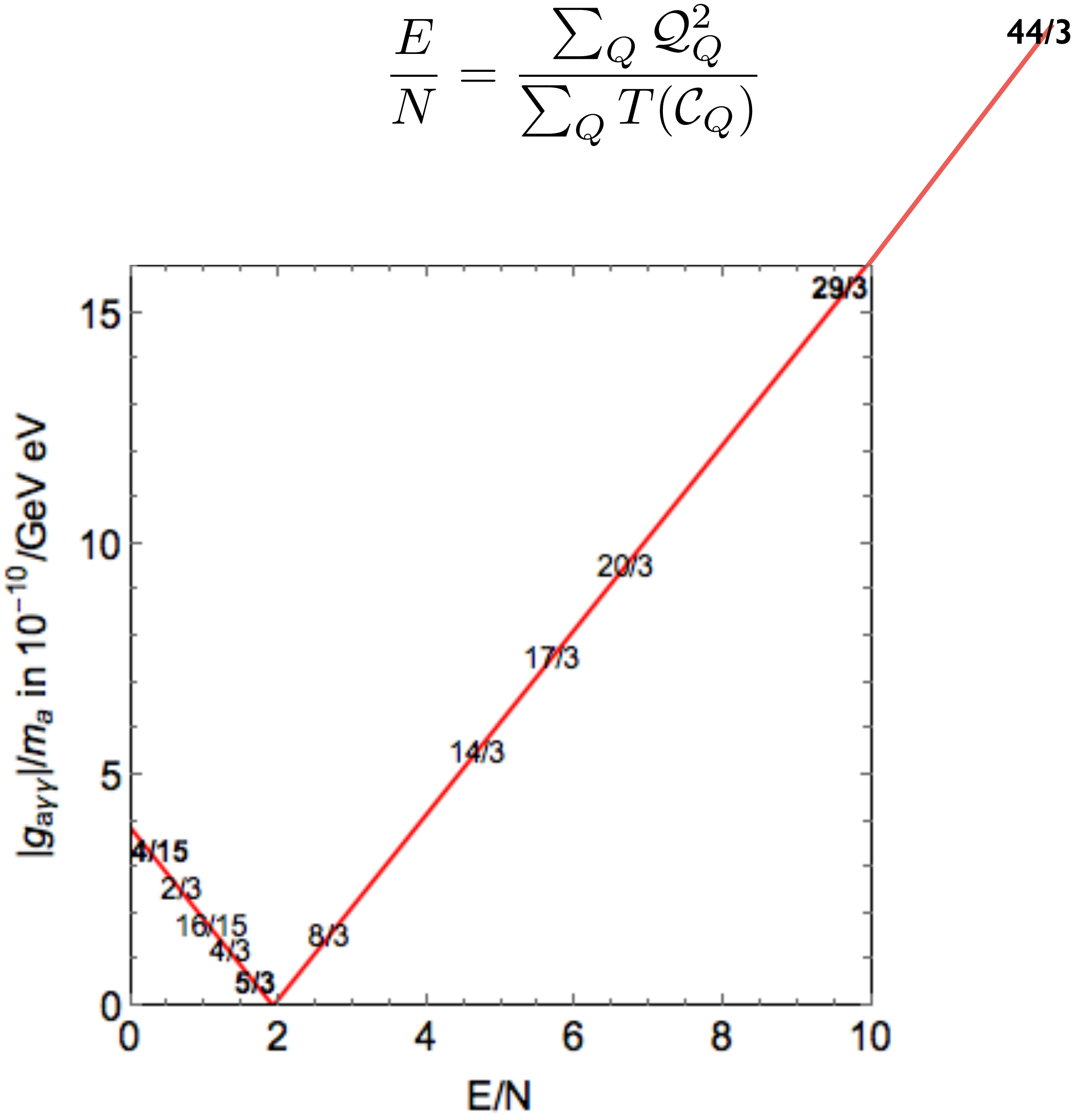
Pheno preferred KSVZ fermions

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



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R_Q^w	$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5 \cdot 10^{39} (g_1)$	$5/3$
	$(3,2,-5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3 \cdot 10^{27} (g_1)$	$17/3$
	$(3,2,7/6)$	$\overline{Q}_L u_R H$	$5.6 \cdot 10^{22} (g_1)$	$29/3$
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	$(3,3,2/3)$	$\overline{Q}_R q_L H$	$6.6 \cdot 10^{27} (g_2)$	$20/3$
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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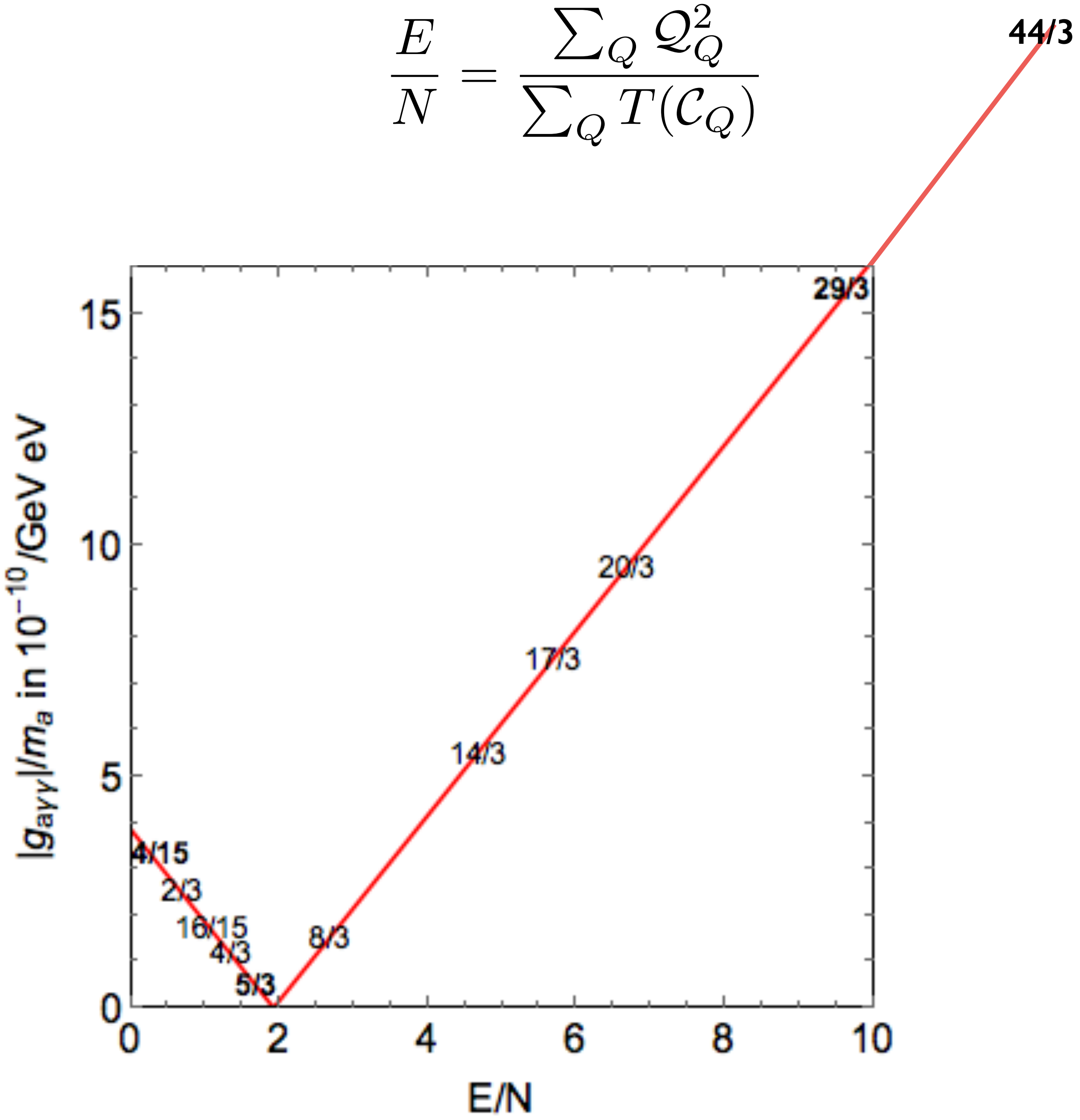
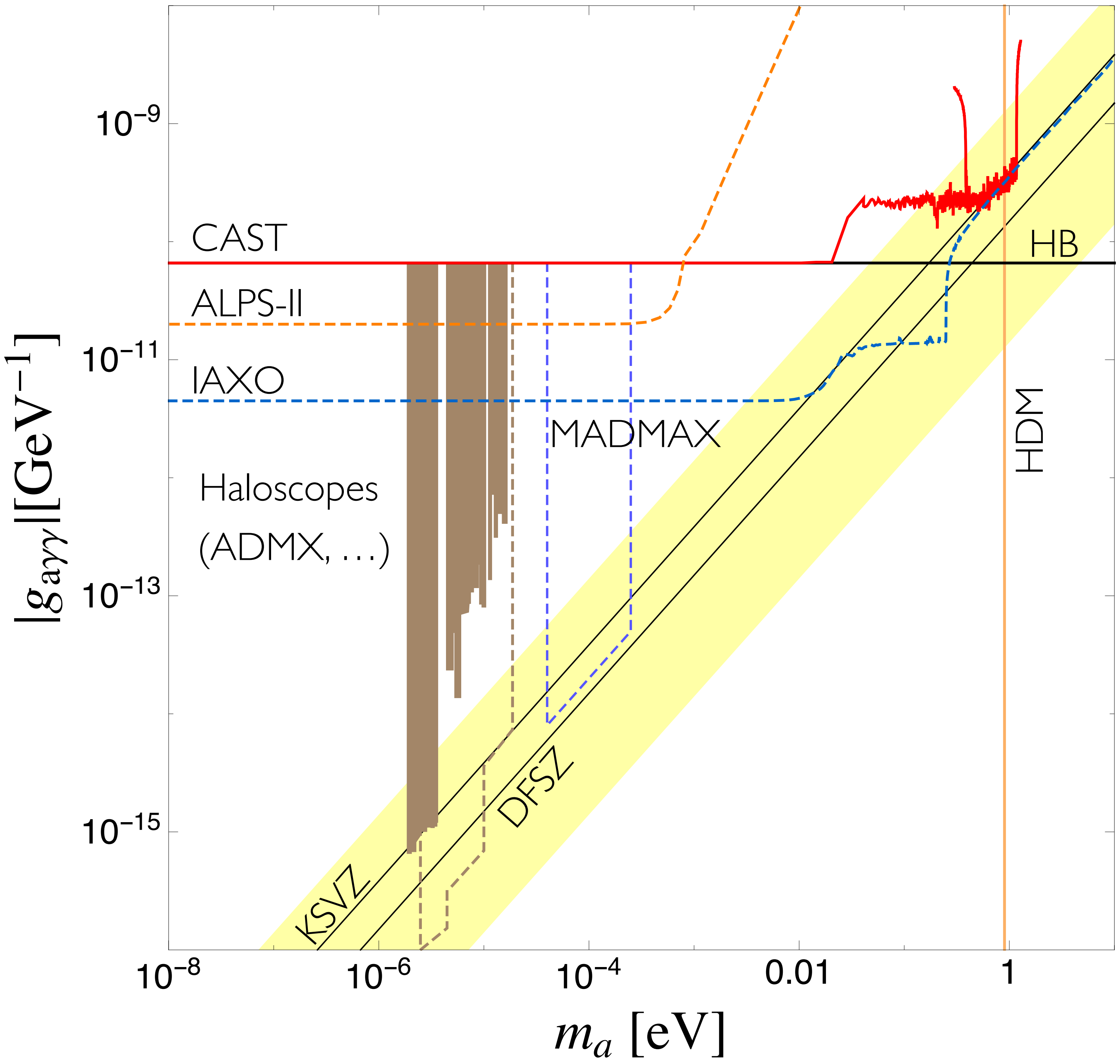
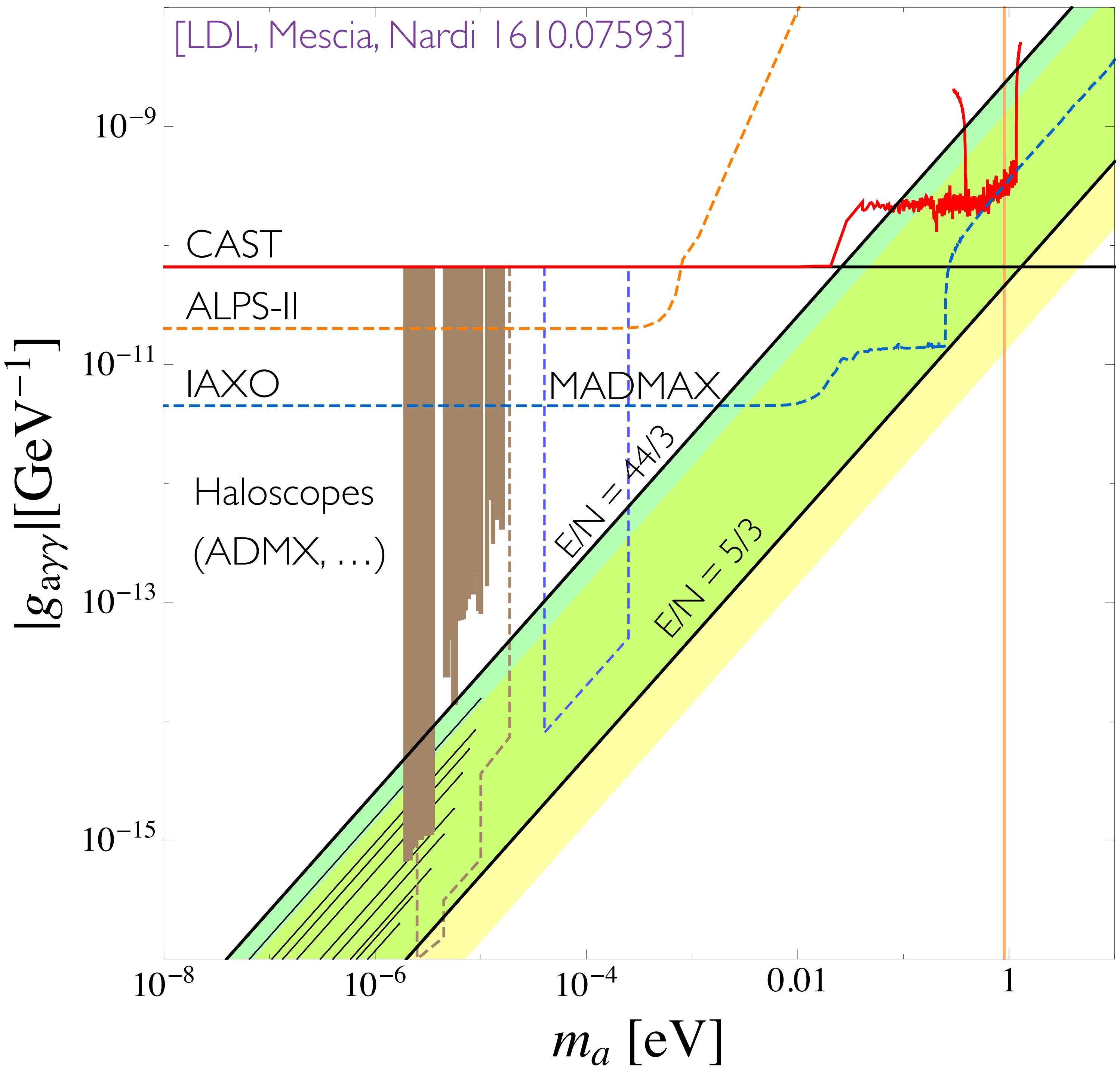
	$(8,1,-1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6 \cdot 10^{22} (g_1)$	$8/3$
	$(8,2,-1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7 \cdot 10^{27} (g_1)$	$4/3$
	$(15,1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3 \cdot 10^{21} (g_3)$	$1/6$
	$(15,1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$7.6 \cdot 10^{21} (g_3)$	$2/3$



Redefining the axion window



Redefining the axion window



More Q's

- Combined anomaly factor

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

- Strongest coupling (compatible with LP criterium)

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

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

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

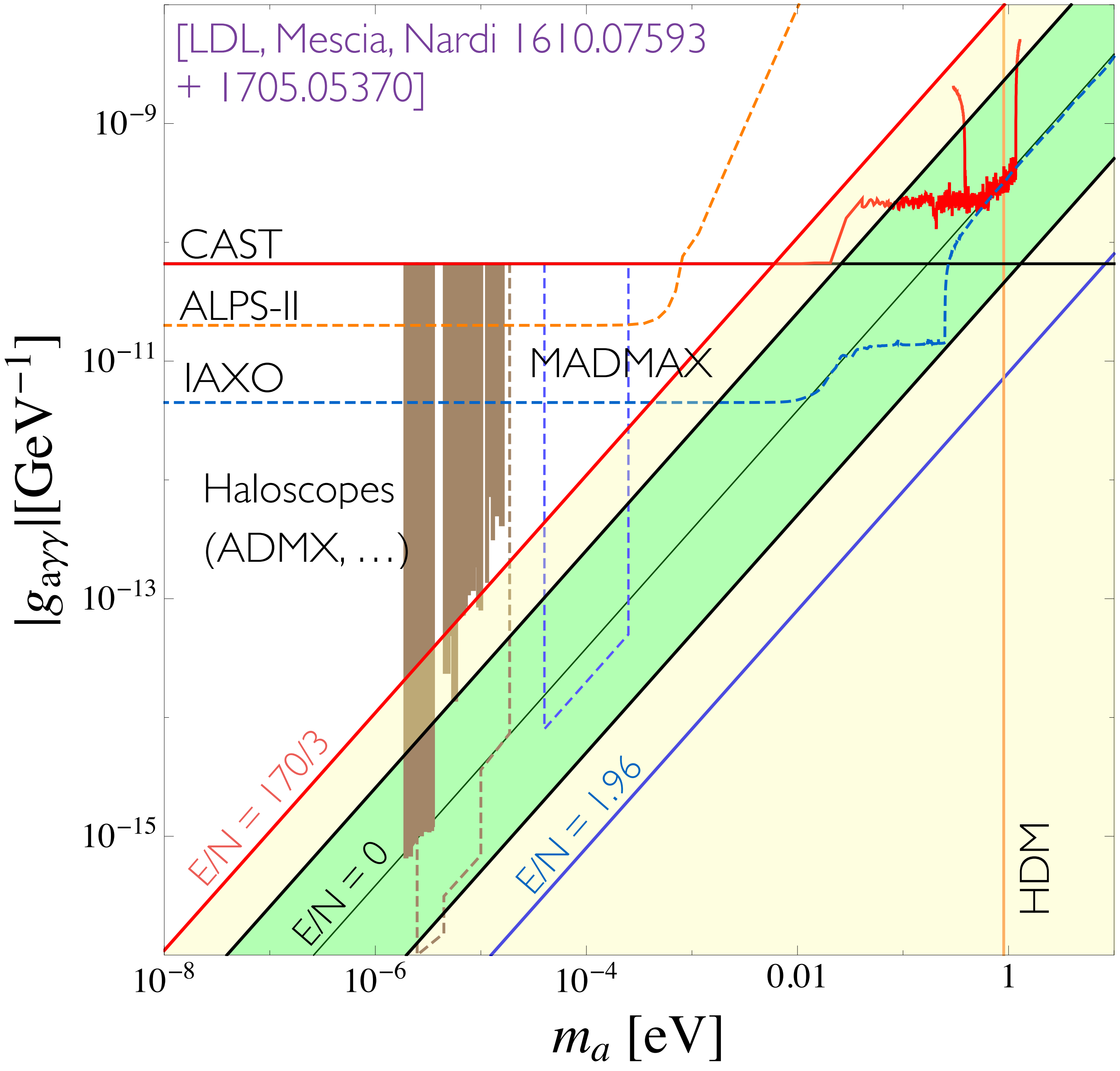
$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10}\ \text{GeV}} \left(\frac{E_c}{N_c} - 1.92(4) \right)$$

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

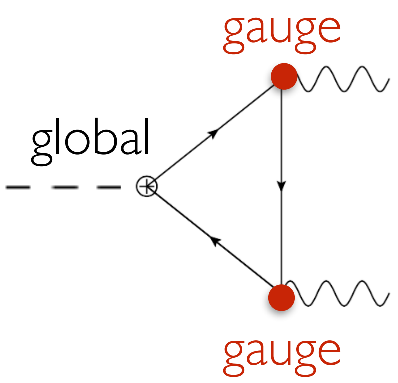
Axion-photon summary

- Red line set by perturbativity [KSVZ] (going much above requires exotic constructions *[more in backup slides]*)

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



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



Axion-photon summary

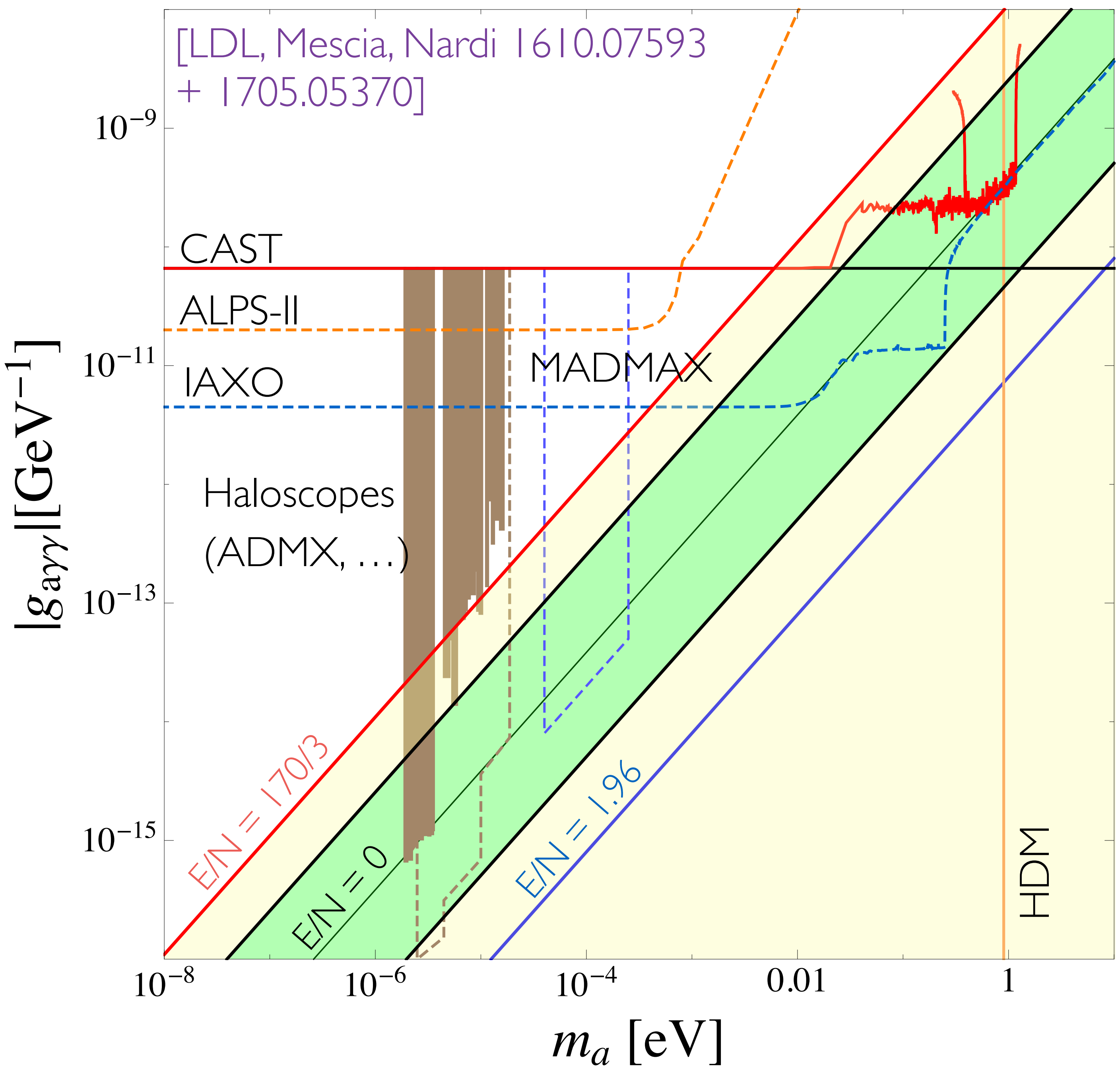
- Red line set by perturbativity [KSVZ] (going much above requires exotic constructions *[more in backup slides]*)

- 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)



[LDL, Mescia, Nardi 1610.07593 + 1705.05370]

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

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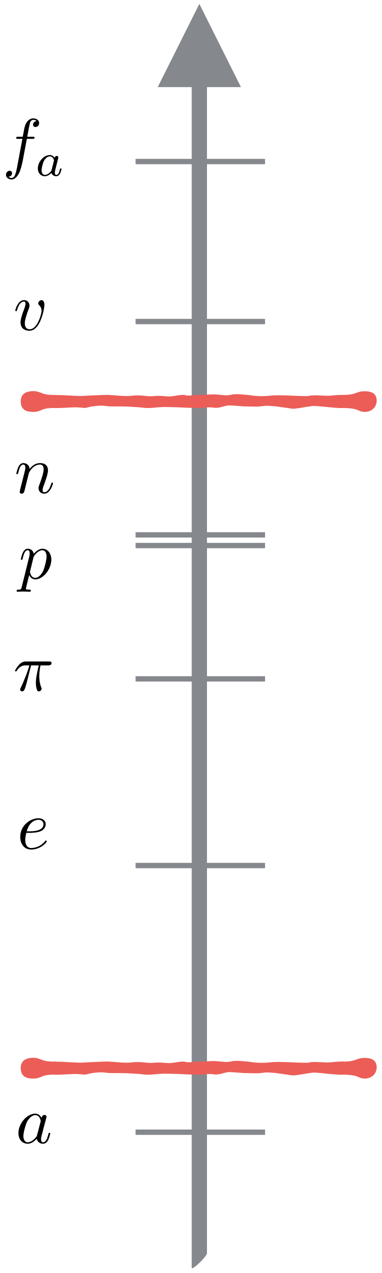
*conceptually easy (e.g. couple the electron to 3rd Higgs uncharged under PQ)

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]



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

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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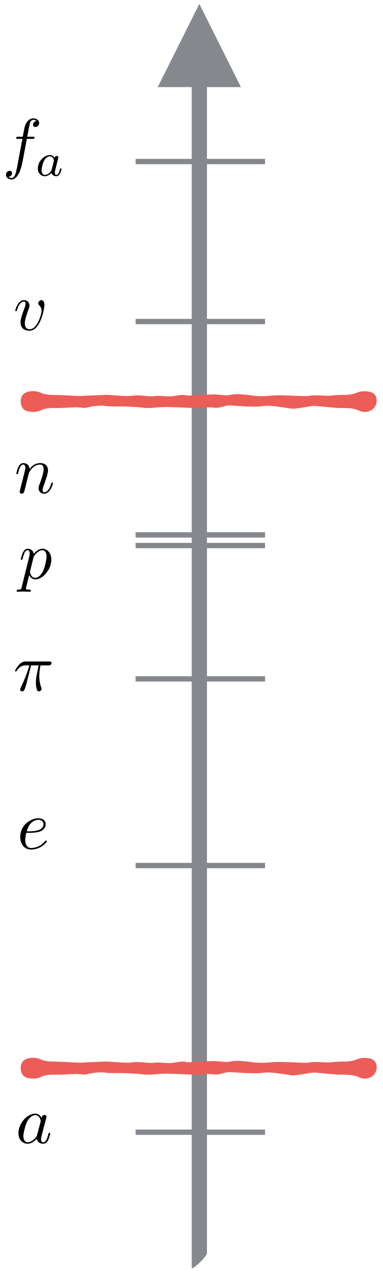

$$\mathcal{L}_q = \frac{\partial_\mu a}{2 f_a} c_q \, \bar{q} \gamma^\mu \gamma_5 q$$

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

↓

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

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

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

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

$$0 = c_u + c_d = \frac{X_u + X_d}{N} - 1 \quad \left\{ \begin{array}{ll} \xrightarrow[X_u = X_d = 0]{\text{KSVZ}} & \qquad -1 \\[2em] \xrightarrow[N = n_g(X_u + X_d)]{\text{DFSZ}} & \qquad \dfrac{1}{n_g} - 1 \end{array} \right.$$

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

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

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

- 1st condition automatically satisfied

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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 !

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

e.g. RH down rotations become physical

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e.g. RH down rotations become physical

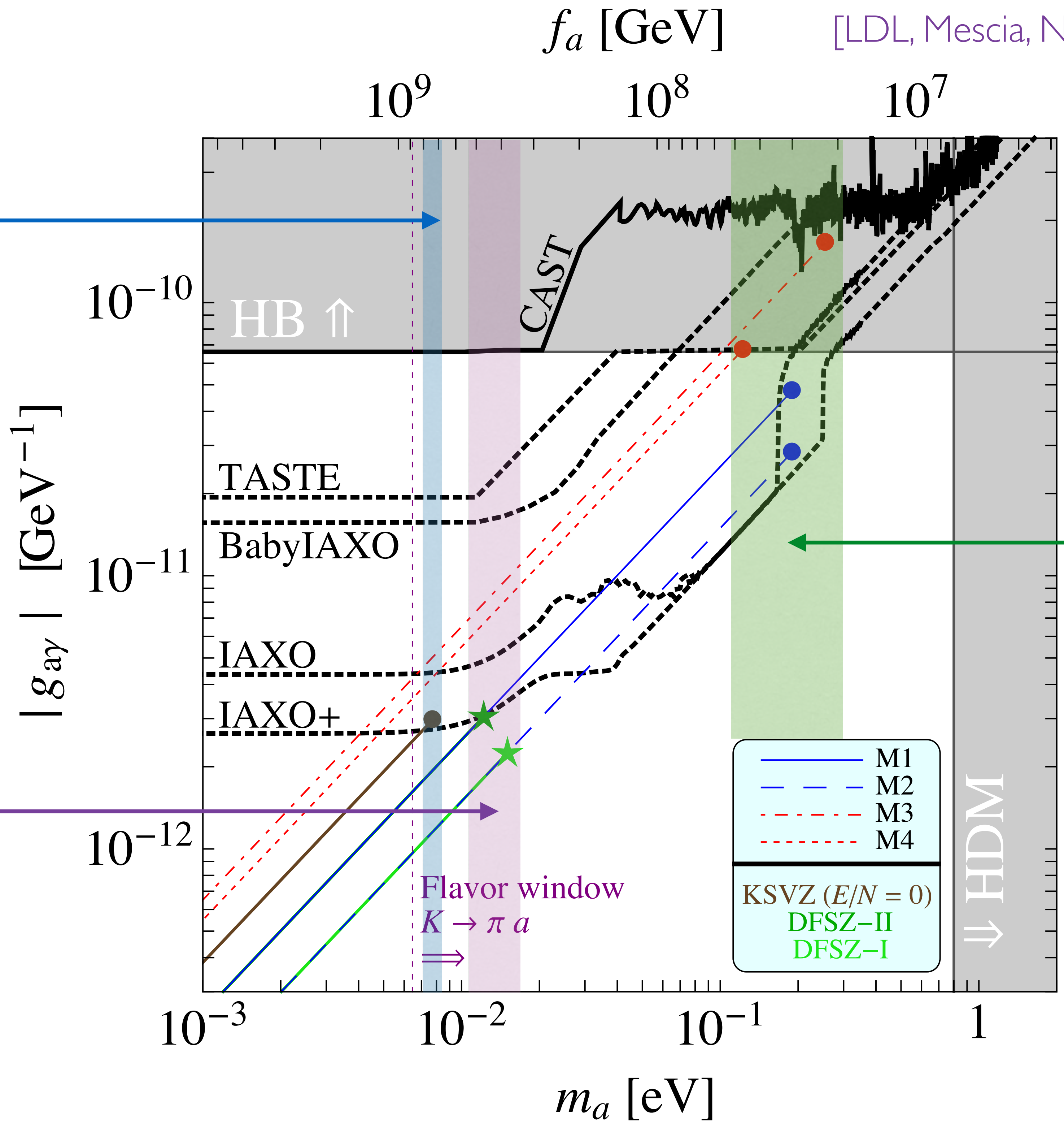
- Plethora of low-energy flavour experiments probing $\frac{\partial_\mu a}{2 f_a} \overline{f}_i \gamma^\mu (C^V_{ij} + C^A_{ij} \gamma_5) f_j$

- $K \to \pi a \; : \; m_a < 1.0 \times 10^{-4} \frac{\mathrm{eV}}{|C^V_{sd}|}$ [E787, E949 @ BNL, 0709.1000] → NA62
- $B \to K a \; : \; m_a < 3.7 \times 10^{-2} \frac{\mathrm{eV}}{|C^V_{bs}|}$ [Babar, 1303.7465] → Belle-II
- $\mu \to e a \; : \; m_a < 3.4 \times 10^{-3} \frac{\mathrm{eV}}{\sqrt{|C^V_{\mu e}|^2 + |C^A_{\mu e}|^2}}$ [Crystal Box @ Los Alamos, Bolton et al PRD38 (1988)] → MEG II

Astrophobic axion models

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

KSVZ



Astrophobic Axions

DFSZ

Conclusions

- QCD axion: 2 birds with 1 stone

  - solves the strong CP problem
  - provides an excellent DM candidate

- Healthy phase (experimentally driven)

  - we are entering now the preferred window for the QCD axion

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- 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