

Rethinking the QCD axion

Particle Physics Seminar - Genova - 12.03.19

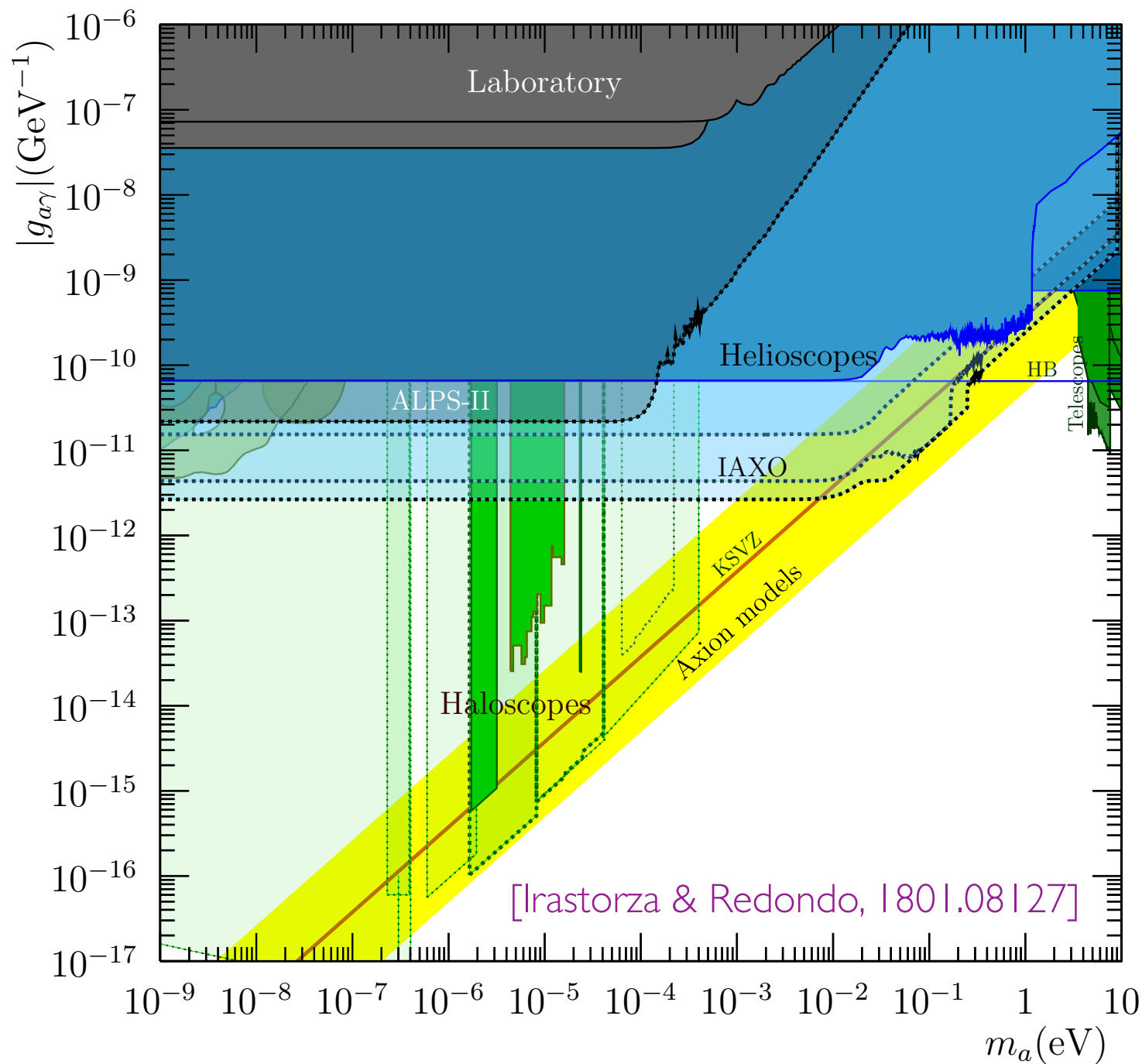
Luca Di Luzio



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In 10 years from now ?



- ✿ A great opportunity to discover the QCD axion !
- ★ Time now 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

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{q} (i\not{D} - \textcolor{red}{m}_q e^{i\textcolor{red}{\theta}_q}) q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \textcolor{red}{\theta} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a \quad \left(\tilde{G}_{\mu\nu}^a = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} G^{a,\rho\sigma} \right)$$

The strong CP problem

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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)]

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

The strong CP problem

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

$$q \rightarrow e^{i\gamma_5 \alpha} q \quad \longrightarrow \quad \left\{ \begin{array}{l} \theta_q \rightarrow \theta_q + 2\alpha \\ \theta \rightarrow \theta + 2\alpha \end{array} \right.$$

from non-invariance of path integral measure
(chiral anomaly)

[Fujikawa, PRL 42 (1979)]

$$\mathcal{D}q \mathcal{D}\bar{q} \rightarrow \exp \left(-i\alpha \int d^4x \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a \right) \mathcal{D}q \mathcal{D}\bar{q}$$

$$\longrightarrow \quad \bar{\theta} = \theta - \theta_q \quad \underline{\text{invariant}}$$

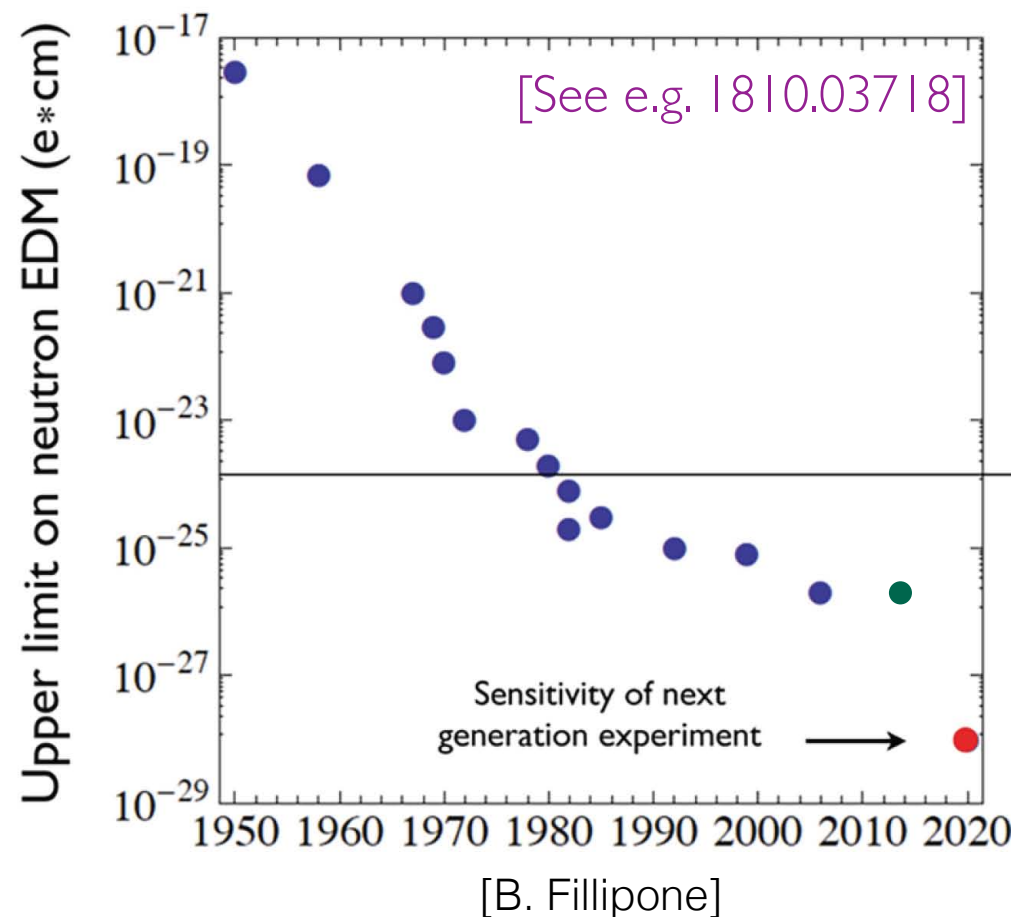
$$= \theta - \arg \det (Y_u Y_d) \quad (\text{generalization to an arbitrary chiral transf. in the EW theory})$$

The strong CP problem

- CP violation in QCD

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

- Non-zero neutron EDM



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

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

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



$$|\bar{\theta}| \lesssim 10^{-10}$$

why so small ?

“Small value” problems

- Strong CP: qualitatively different from other small value problems of the SM

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

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

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



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

- 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

- Strong CP: qualitatively different from other small value problems of the SM

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

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

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

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

[Ubbaldi, 08 I.I.599]

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

“Small value” problems

- Strong CP: qualitatively different from other small value problems of the SM

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

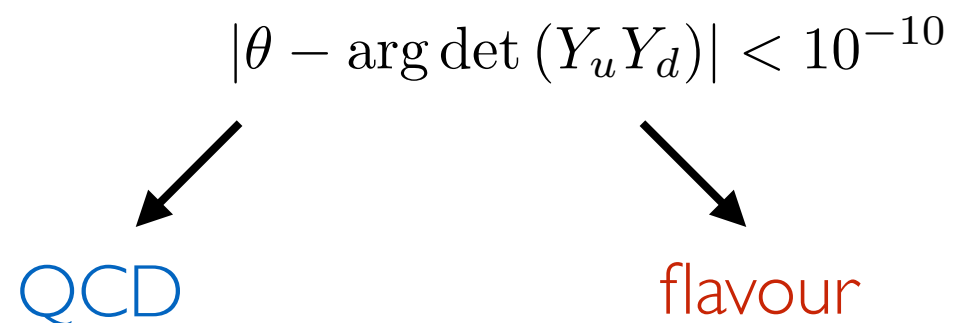
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- More than a small value problem ?



(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 !

$$m_{\eta'} \approx 958 \text{ MeV}$$

$$m_{\eta'} < \sqrt{3} m_{\pi}$$

[Weinberg sum-rule for pNGB]

$$m_{\eta'}^2 = \frac{6\mathcal{X}}{f_{\pi}^2} + \mathcal{O}(m_q) + \mathcal{O}\left(\frac{1}{N_c^2}\right)$$

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

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

Solutions

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- 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
 - $\bar{\theta} = 0$ 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

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

[Barr PRD 30 (1984)]

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

$$a(x) \rightarrow a(x) + \delta\alpha f_a$$

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

$\theta_{\text{eff}}(x)$  set to zero by QCD dynamics

θ -dependence of QCD vacuum

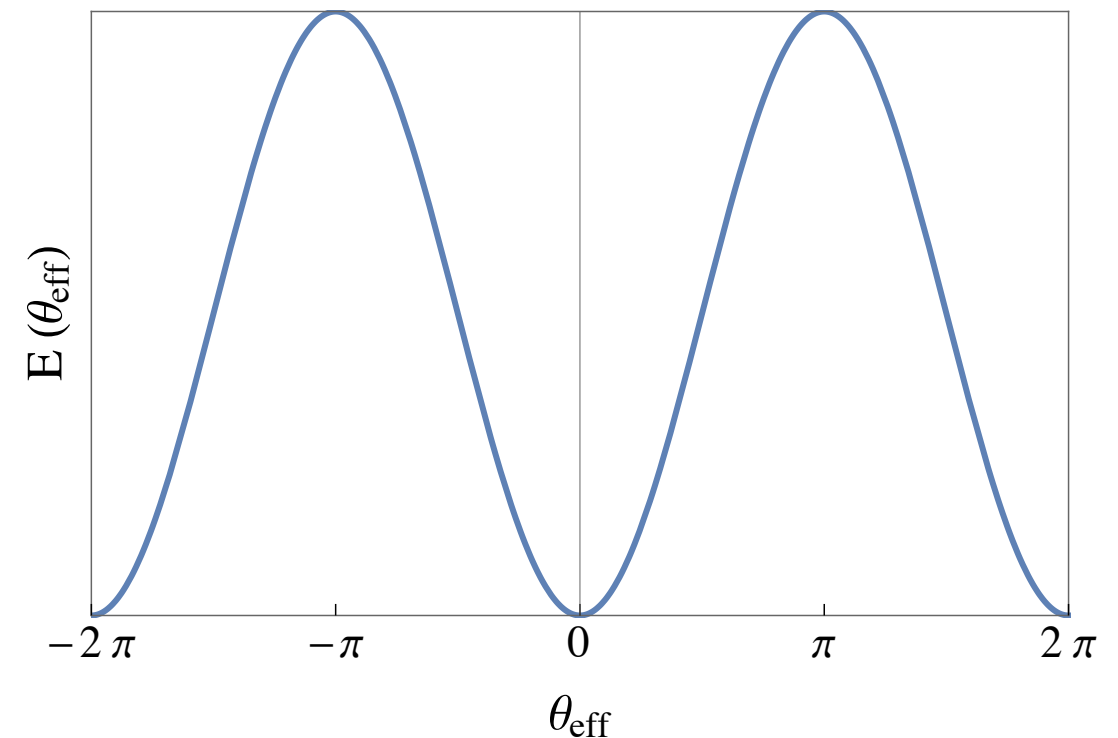
- Ground state energy in Euclidean V_4

[Vafa, Witten PRL 53 (1984)]

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



$$E(0) \leq E(\theta_{\text{eff}})$$

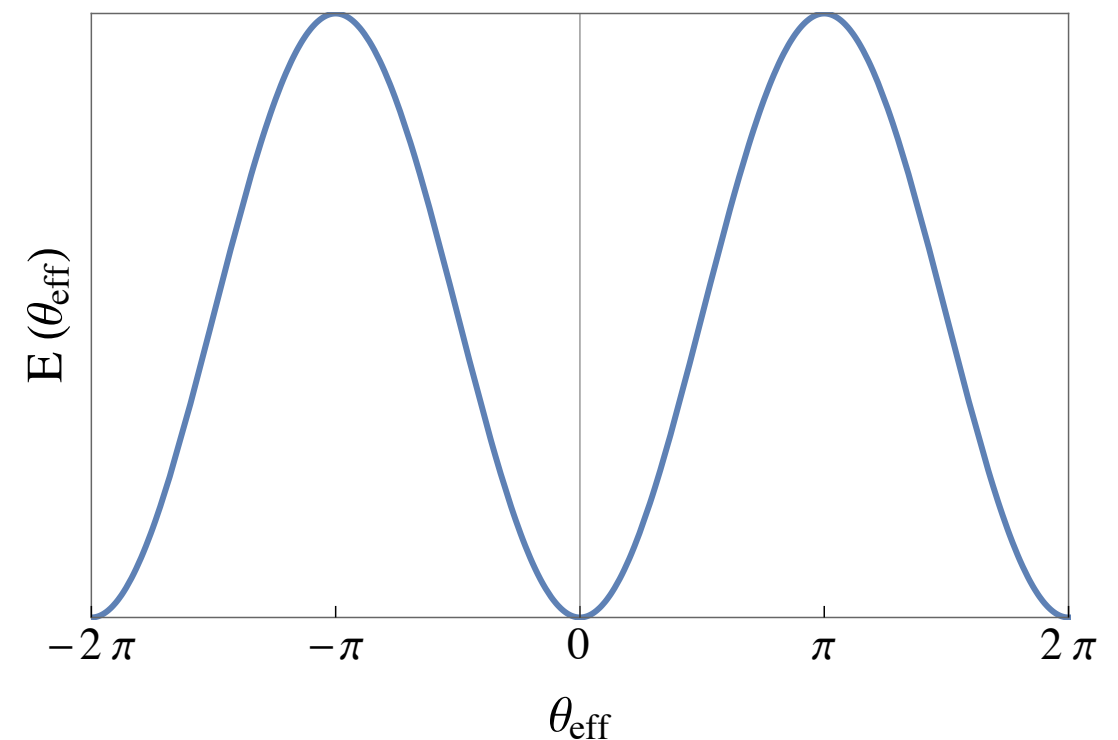


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- theta term dynamically relaxed to zero on the axion ground state $\langle a(x) \rangle = -\bar{\theta} f_a$

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

- $a G\tilde{G}$ not a total derivative (effects in PT)

Axion properties [EFT]

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

- generates axion mass

$$\text{---} \overset{a}{\text{---}} \text{---} \text{QCD} \text{---} \text{---} \overset{a}{\text{---}} \text{---} \sim \frac{\Lambda_{\text{QCD}}^4}{f_a^2} \quad \longrightarrow \quad m_a \sim \Lambda_{\text{QCD}}^2 / f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a} \right)$$

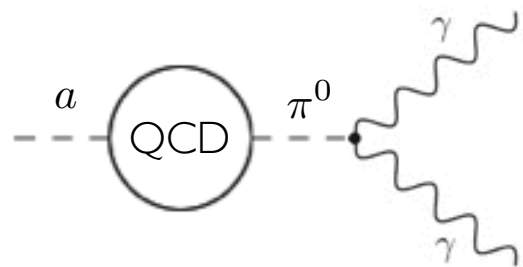
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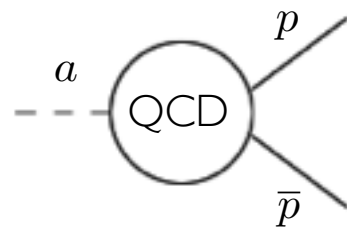
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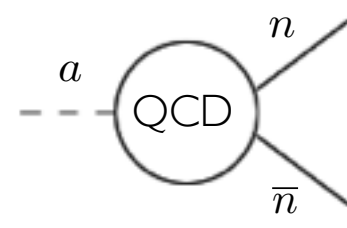
- generates “model independent” axion couplings to photons, nucleons, electrons, ...



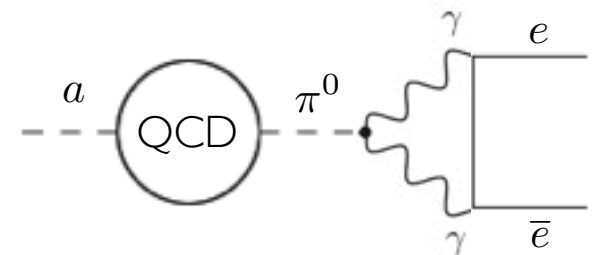
$$C_\gamma = -1.92(4)$$



$$C_p = -0.47(3)$$



$$C_n = -0.02(3)$$



$$C_e \simeq 0$$

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

$$C_\Psi m_\Psi \frac{a}{f_a} [i \bar{\Psi} \gamma_5 \Psi]$$

$$(\Psi = p, n, e)$$

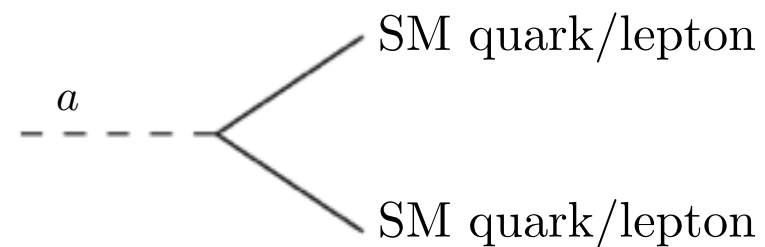
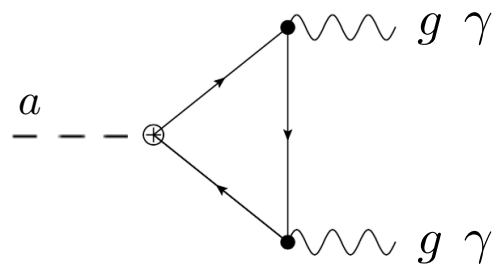
[From NLO Chiral Lagrangian,
Grilli di Cortona et al., 1511.02867]

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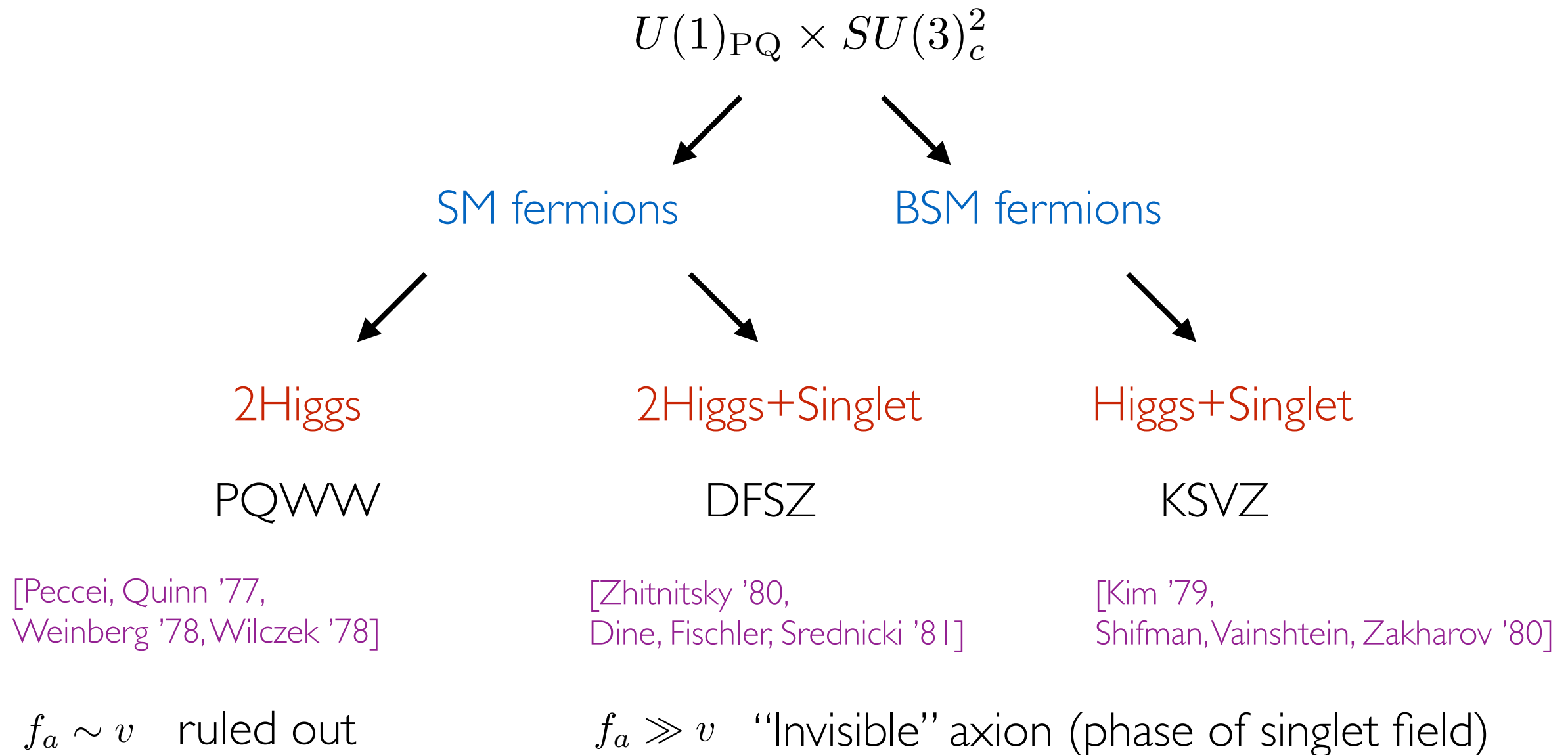
- EFT breaks down at energies of order f_a

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



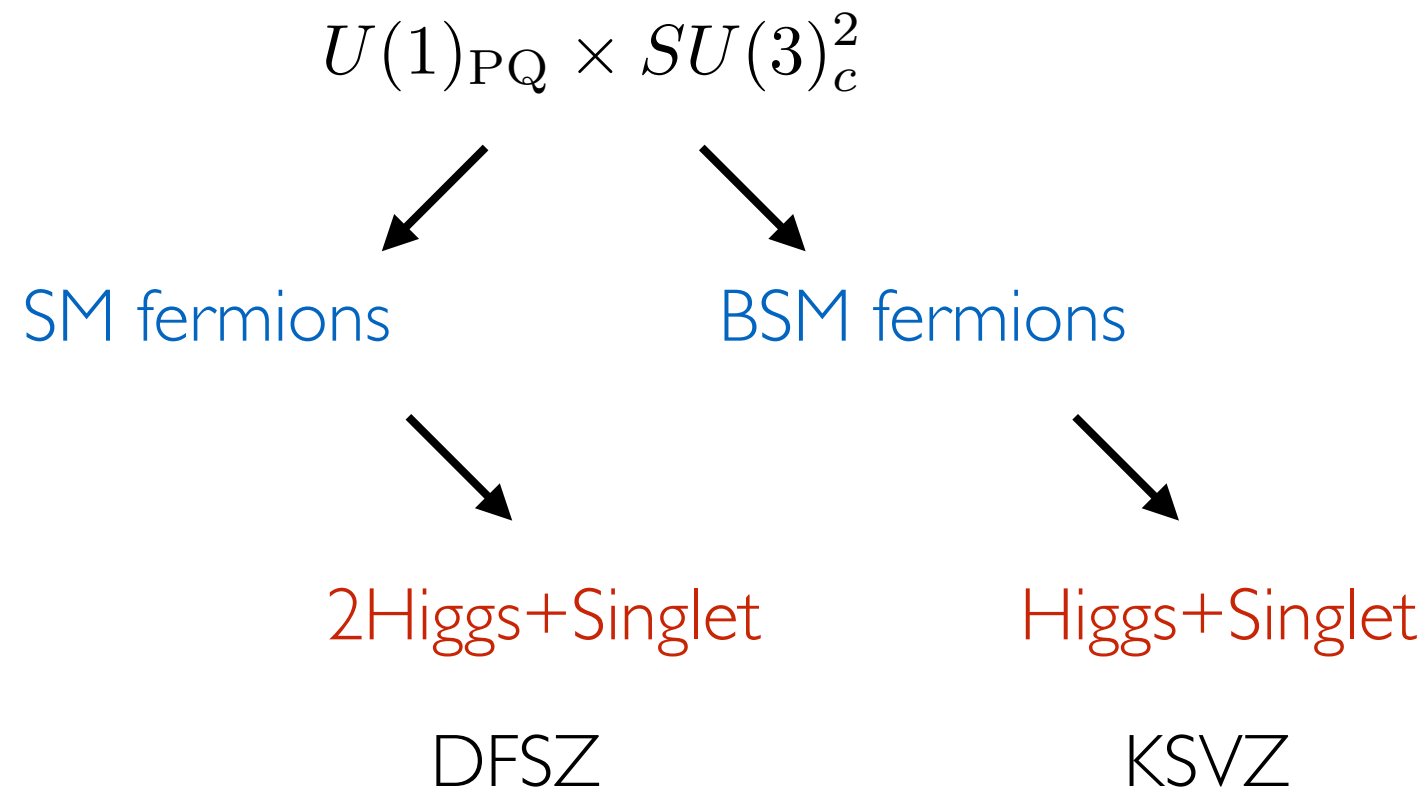
Axion models [UV completion]

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

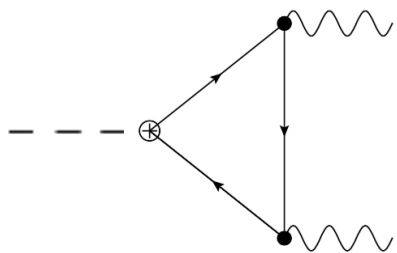


Axion models [UV completion]

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



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



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

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

$$C_p \simeq -0.5$$

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

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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 - light: $m_a \lesssim 10 T_\star$ [e.g. typical interior temperature of the Sun ~ 1 keV]
 - weakly coupled [otherwise we would have already seen them in labs]
- constraints from “energy loss”, relevant when more interacting than neutrinos

neutrino interactions (d=6 op.)

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

axion interactions (d=5 op.)

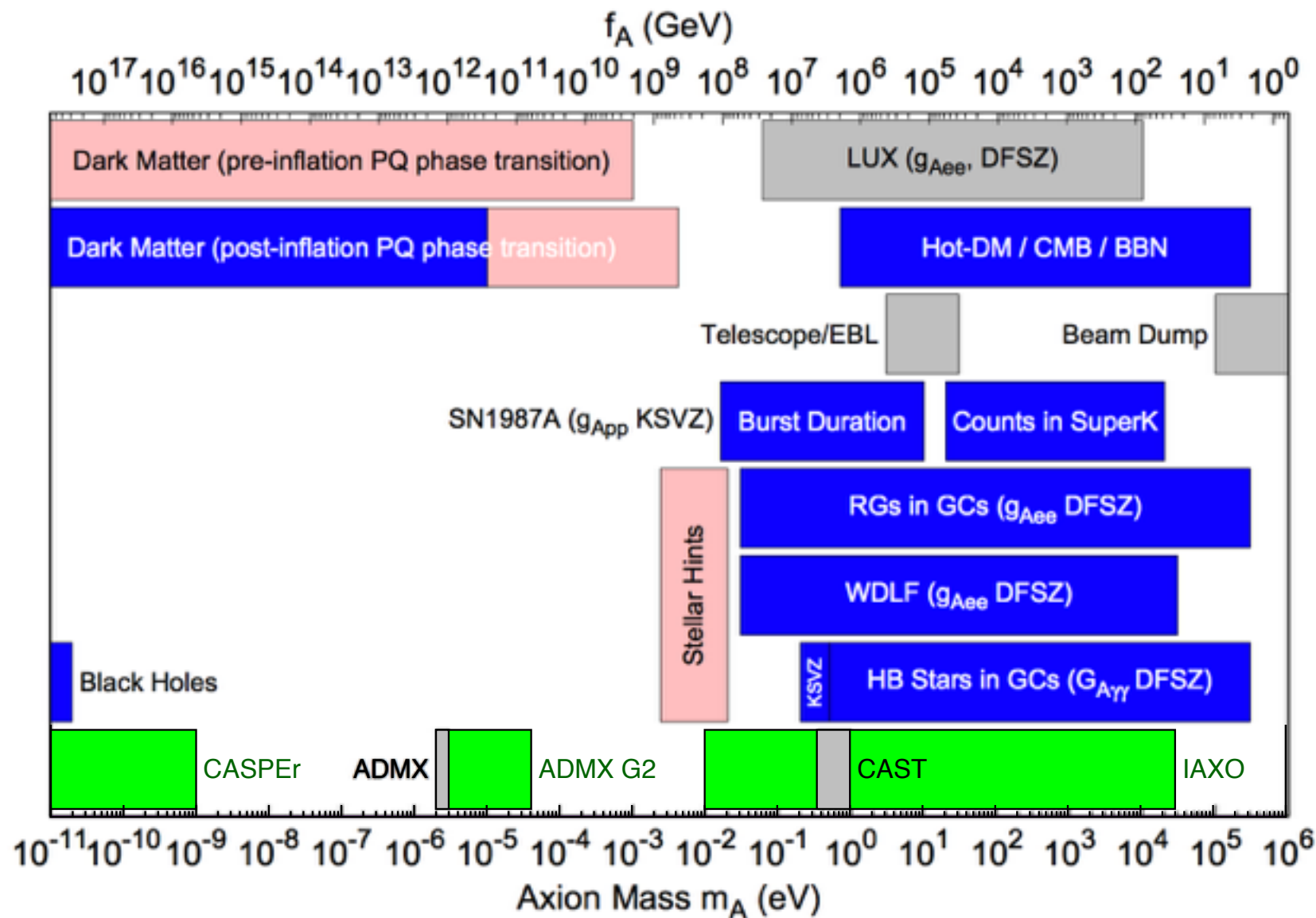
$$\frac{m_e}{f_a} \simeq 10^{-12} \left(\frac{10^8 \text{ GeV}}{f_a} \right)$$



axions are a perfect target !

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

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

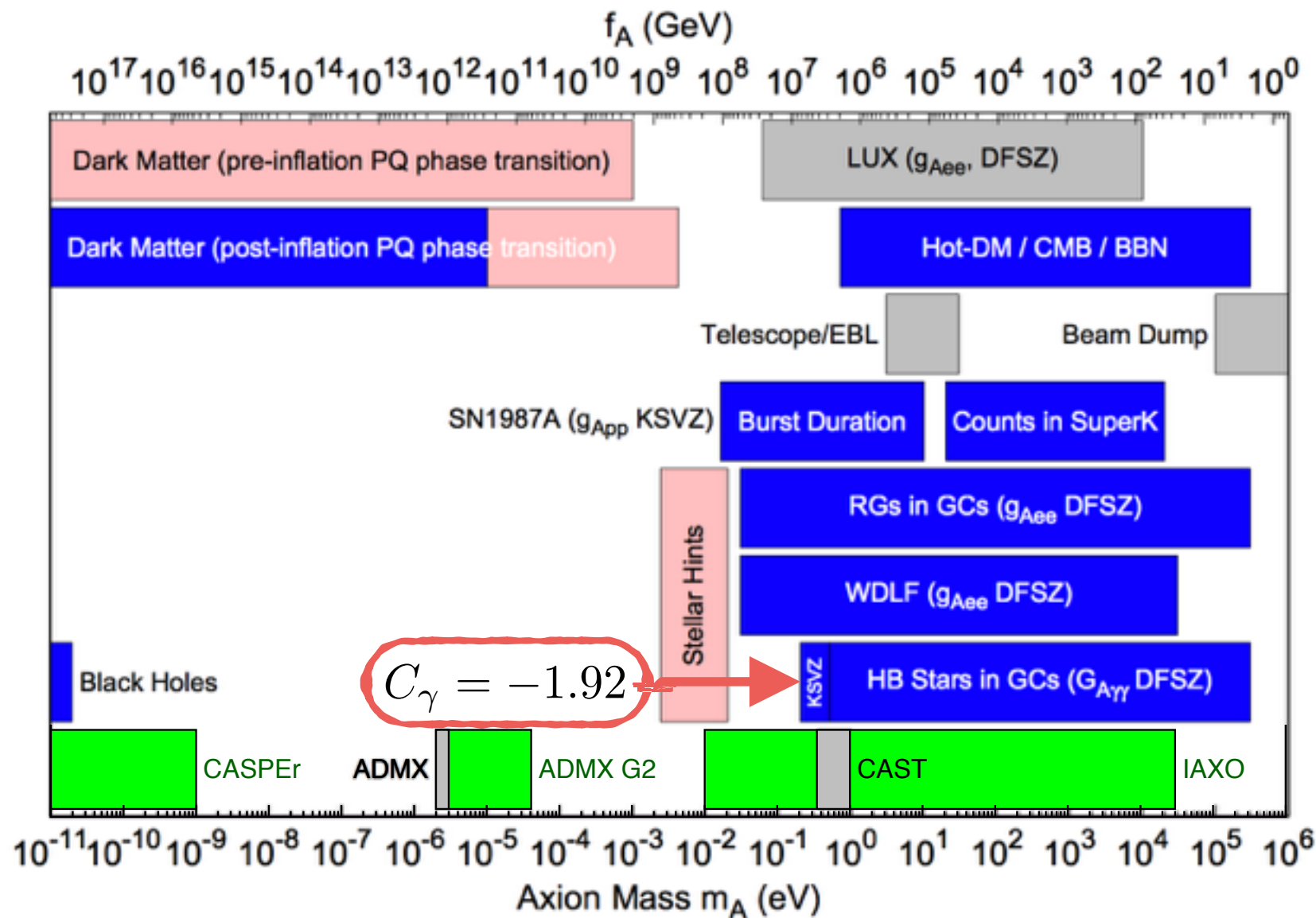
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

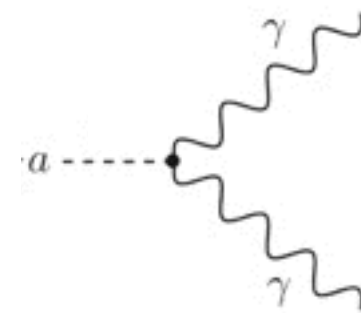
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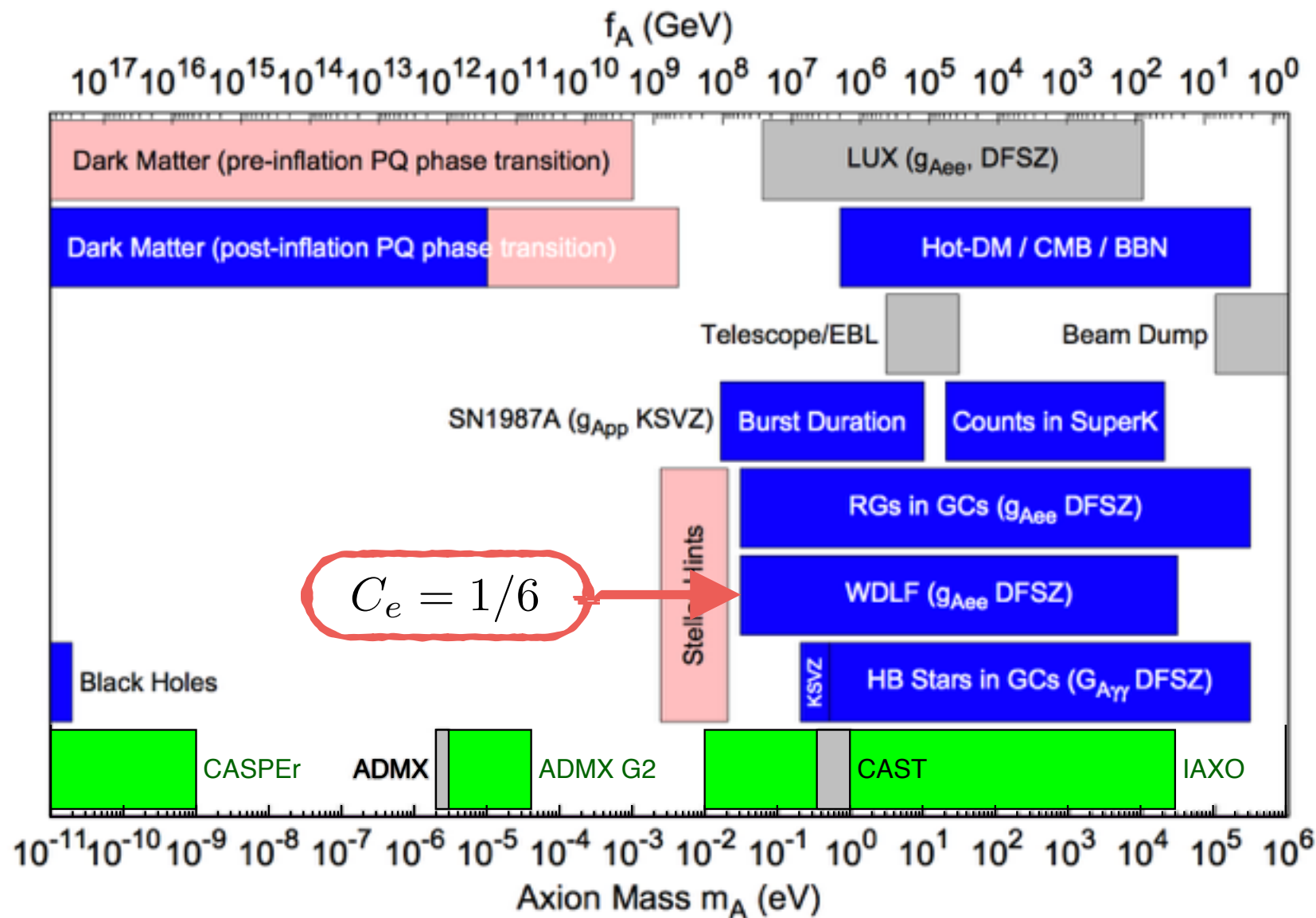
Exp. sensitivities

- 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



[Ringwald, Rosenberg, Rybka, Particle Data Group]

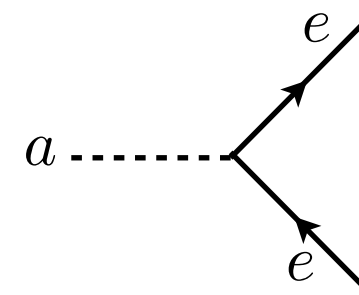
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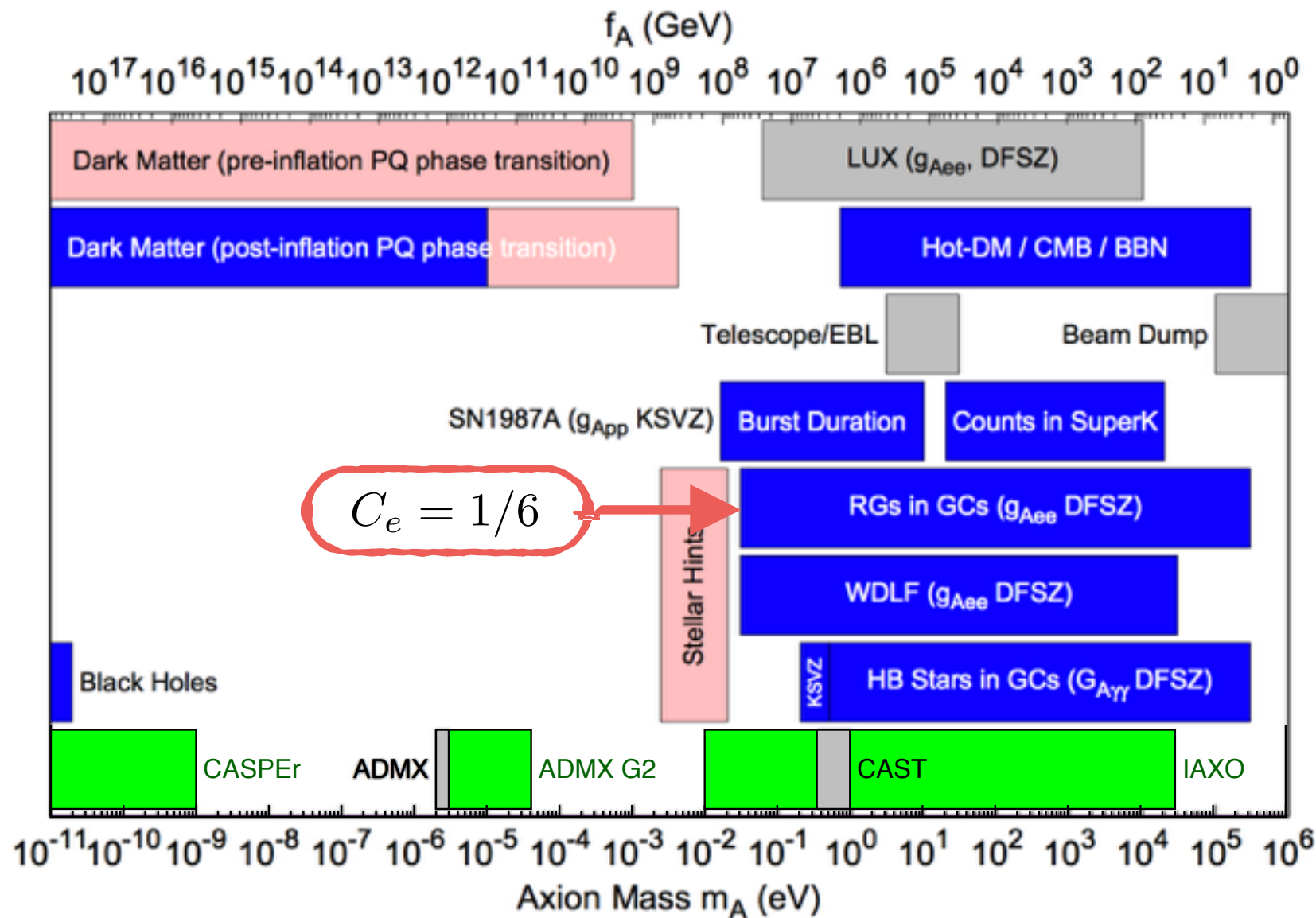
Exp. sensitivities

- White dwarfs luminosity function (cooling)



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

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

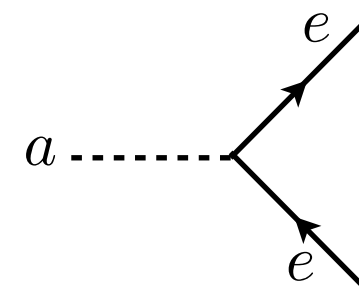
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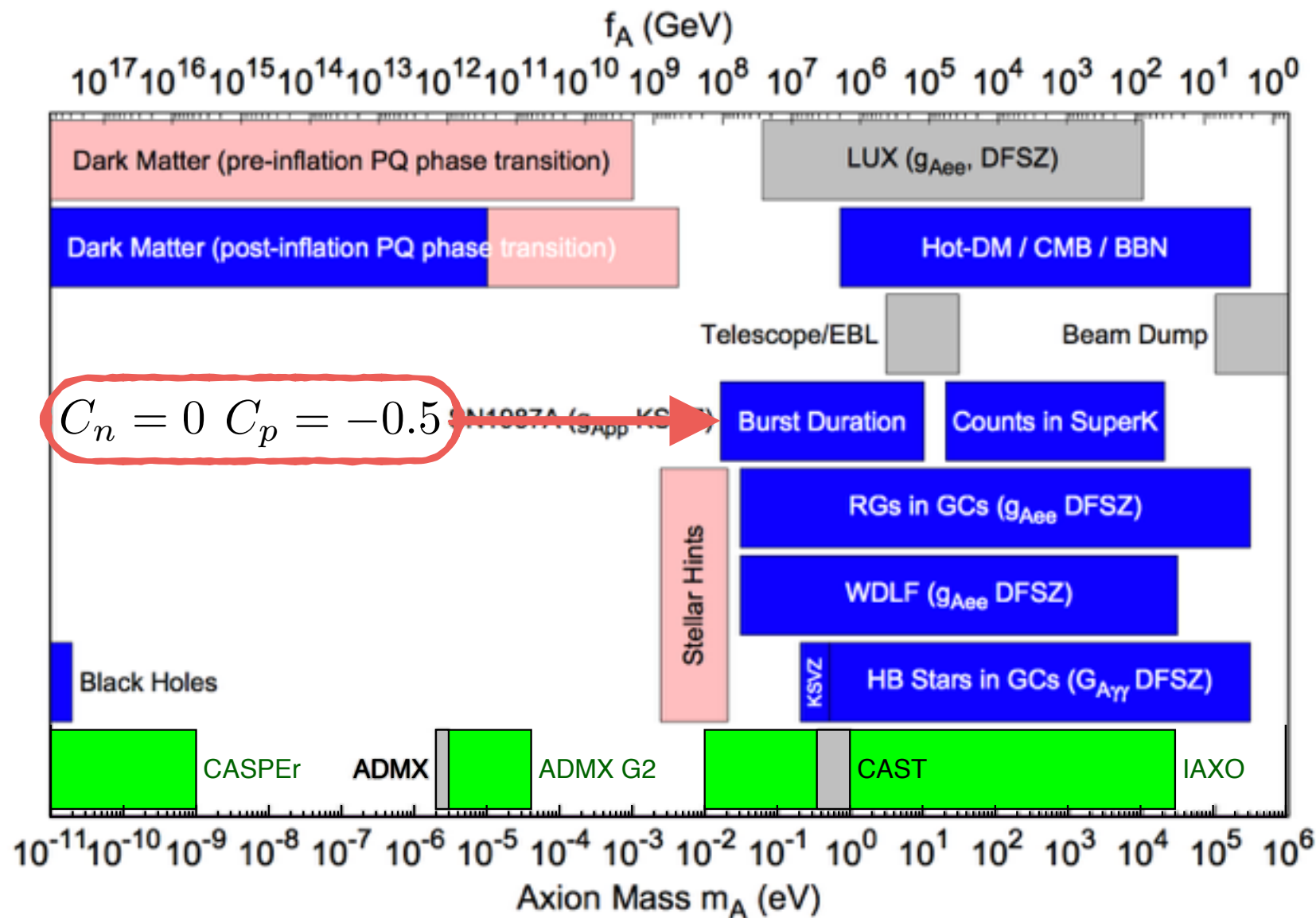
Exp. sensitivities

- Red giants evolution in globular clusters



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

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

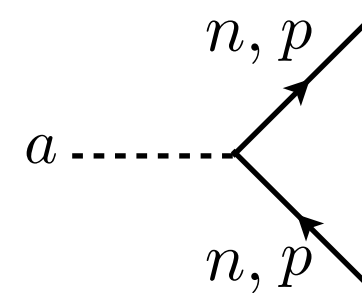
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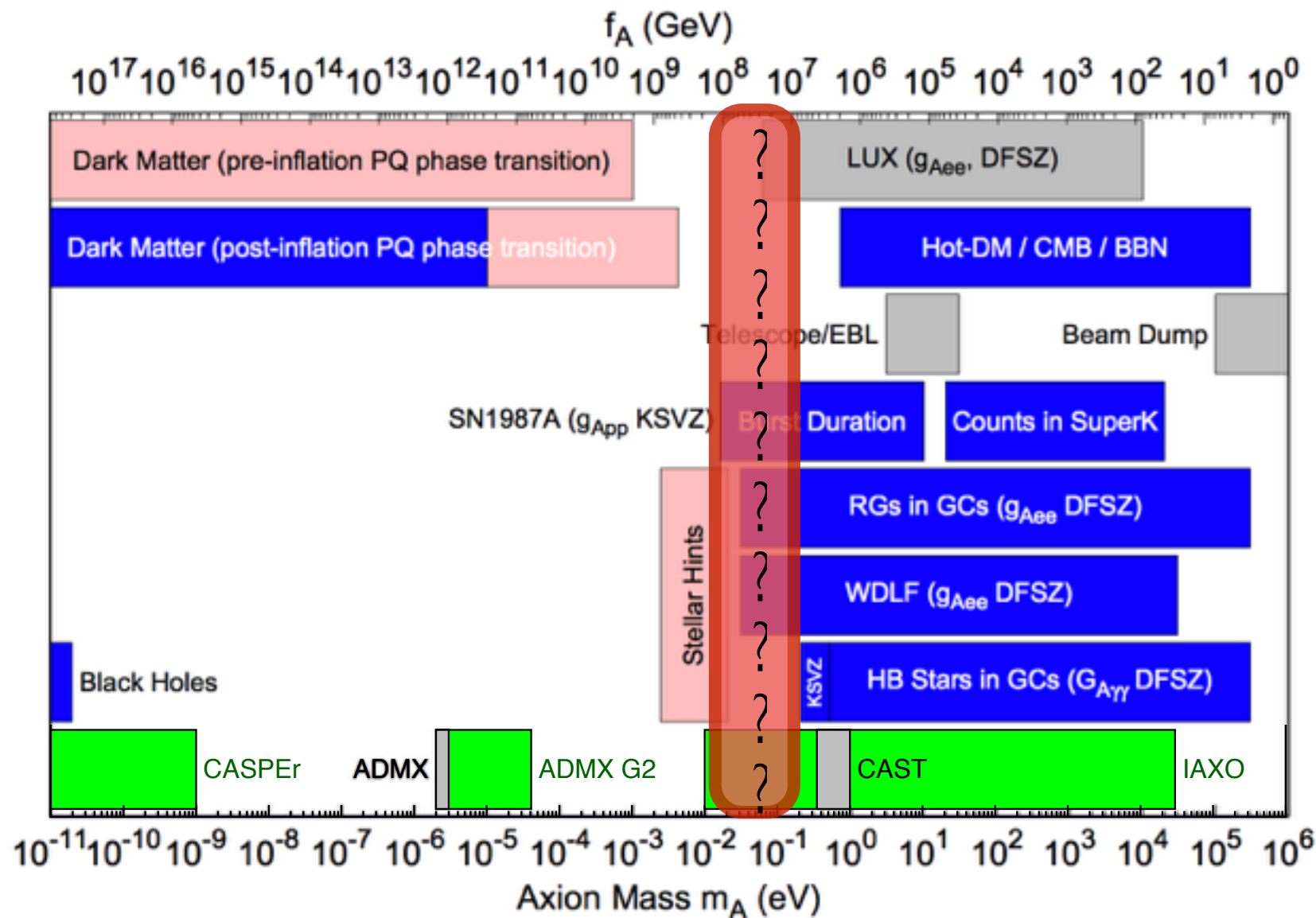
- Burst duration of SN 1987A nu signal



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

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

Axion landscape



[Ringwald, Rosenberg, Rybka, Particle Data Group]

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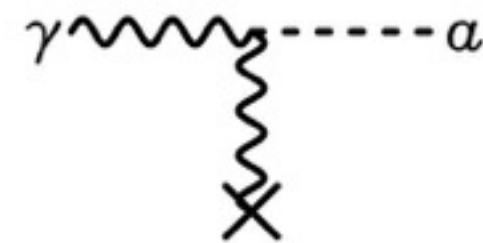
- Bound on axion mass is of practical convenience, but misses model dependence !

Search strategies

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

Primakoff effect: 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/10113741]

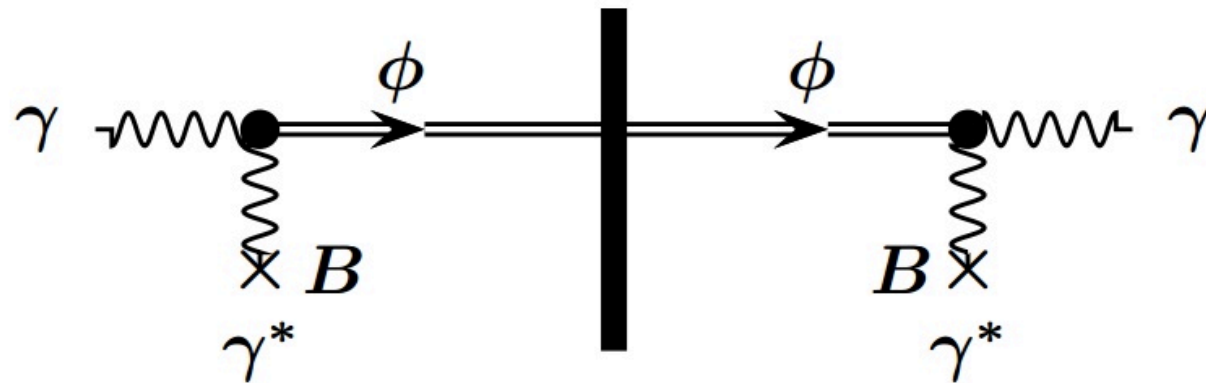
2. Haloscopes (axion Dark Matter)

[Sikivie PRL 51 (1983)]

3. Helioscopes (axions from the Sun)

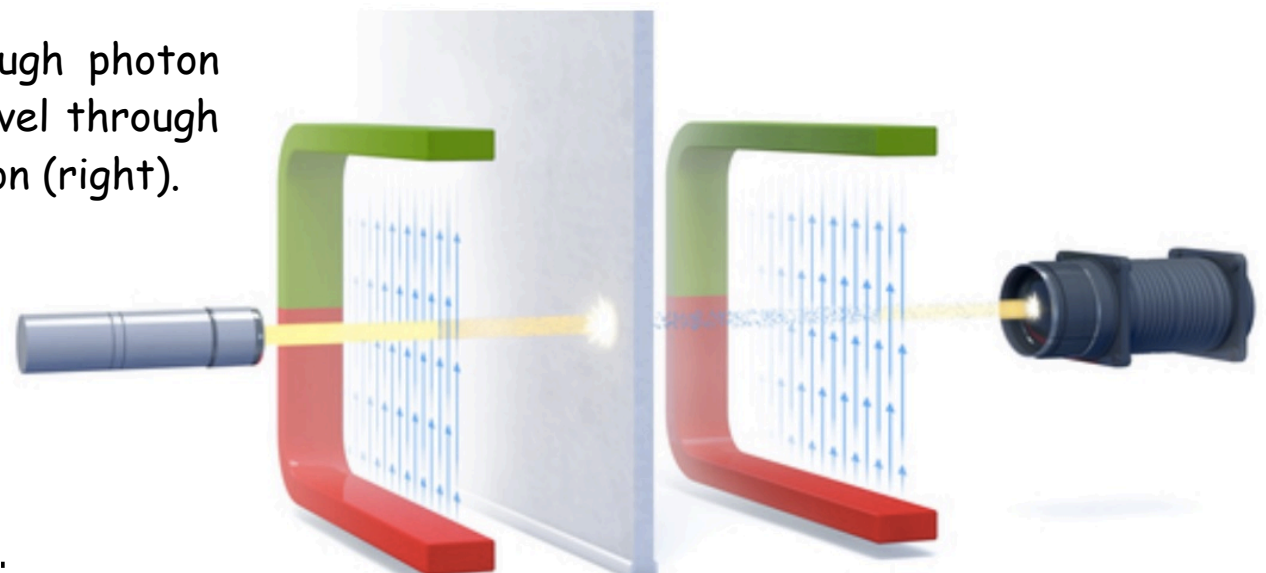
Light Shining through Walls (LSW)

- 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

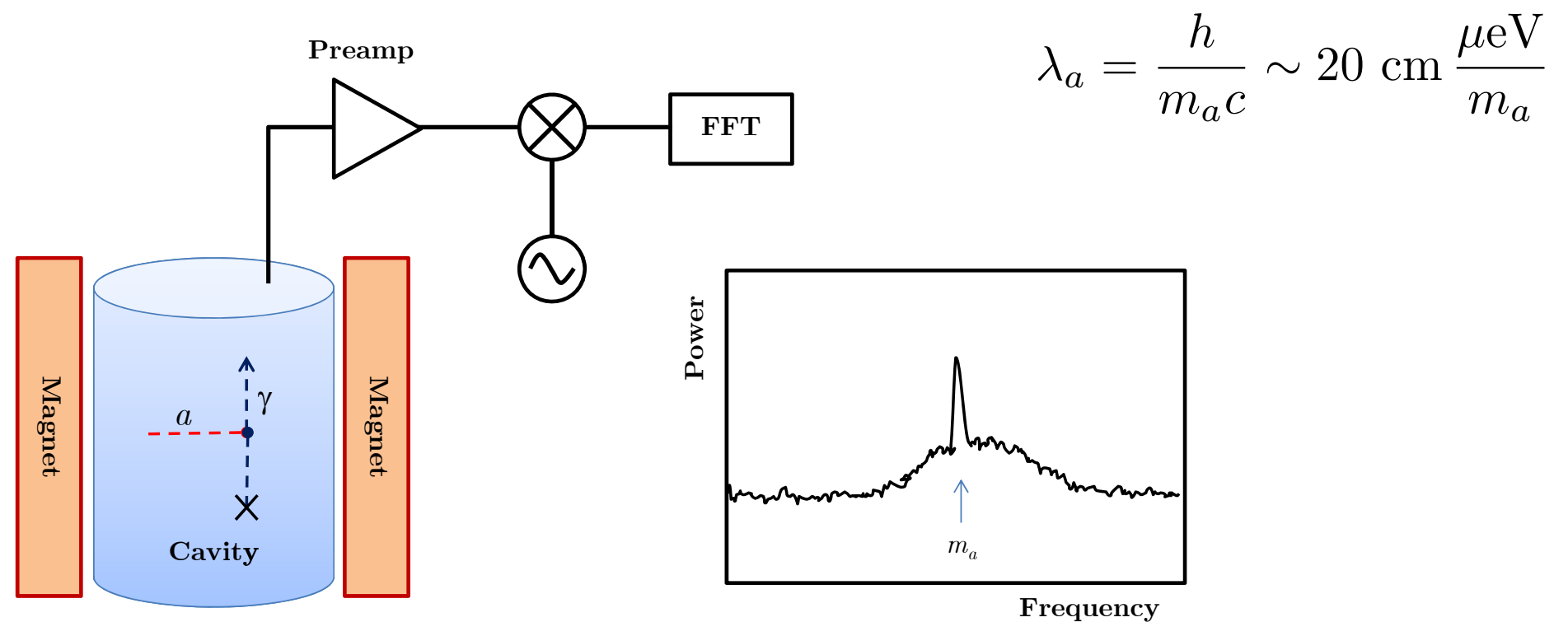


LSW experiments pay a $g_{a\gamma\gamma}^4$ suppression

**Boost of exp. activity after PVLAS discovery claim in 2006*

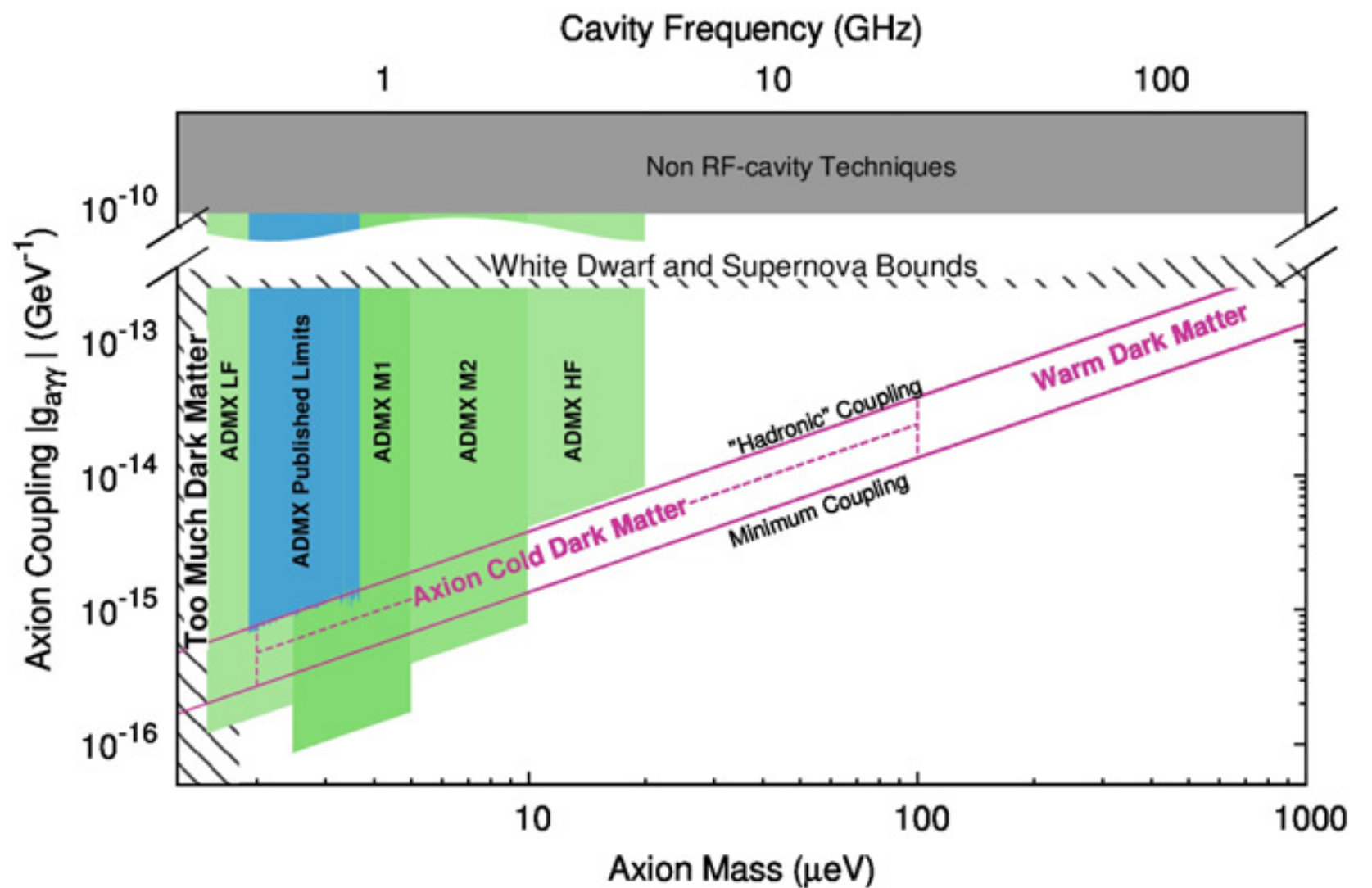
Haloscopes

- Look for DM axions with a microwave resonant cavity
 - power of axions converting into photons in an EM cavity $P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\text{eff}}$
 - resonance condition: need to tune the frequency of the EM cavity on the axion mass



Haloscopes

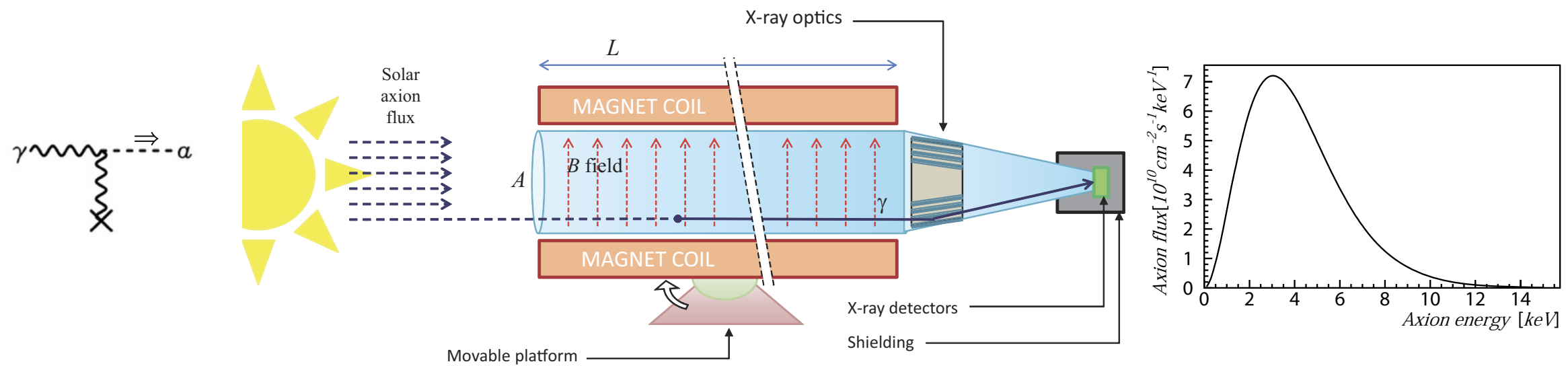
- Look for DM axions with a microwave resonant cavity
 - Axion Dark Matter eXperiment (ADMX) (U. of Washington)



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

Helioscopes

- The Sun is a potential axion source



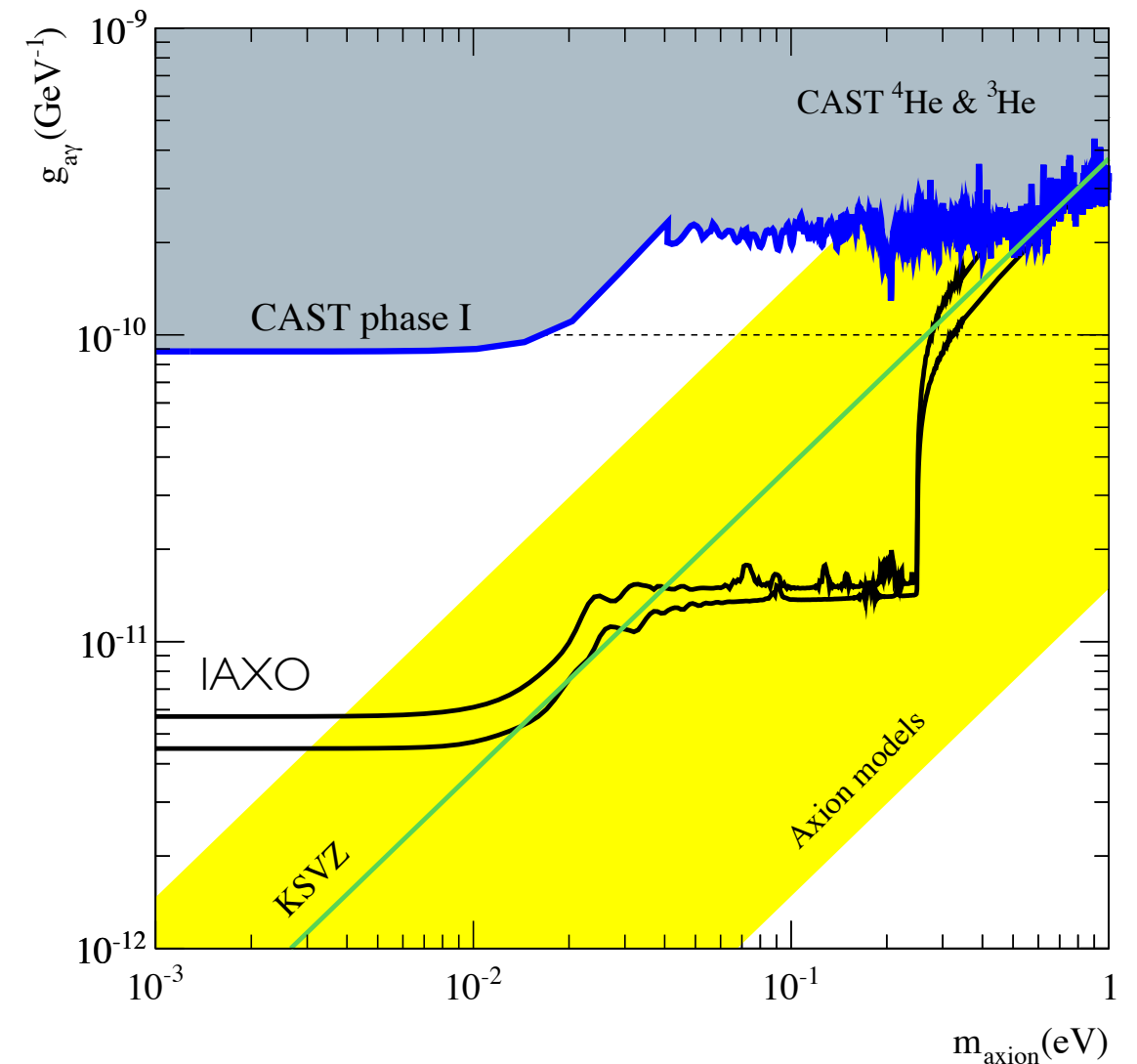
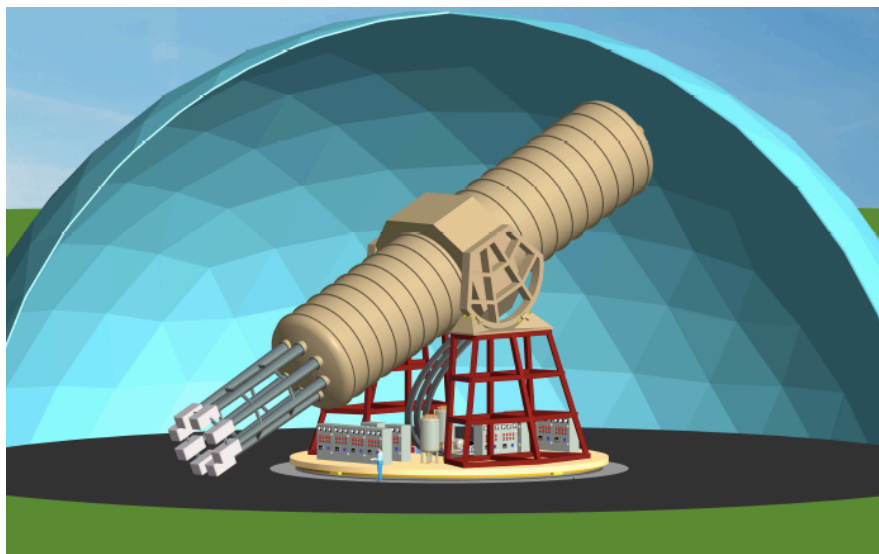
- macroscopic B-field can provide a coherent axion-photon conversion rate over a big volume

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. Sushkov⁴

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

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

Asimina Arvanitaki¹ and Andrew A. Geraci^{2,*}

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

Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,^{1,*} Benjamin R. Safdi,^{2,†} and Jesse Thaler^{2,‡}

PRL **118**, 091801 (2017) PHYSICAL REVIEW LETTERS week ending
3 MARCH 2017

Dielectric Haloscopes: A New Way to Detect Axion Dark Matter

Allen Caldwell,¹ Gia Dvali,^{1,2,3} Béla Majorovits,¹ Alexander Millar,¹ Georg Raffelt,¹ Javier Redondo,^{1,4}
Olaf Reimann,¹ Frank Simon,¹ and Frank Steffen¹
(MADMAX Working Group)

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

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PHYSICAL REVIEW D **91**, 011701(R) (2015)

Search for dark matter axions with the Orpheus experiment

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CULTASK, The Coldest Axion Experiment at CAPP/IBS/KAIST in Korea

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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. Sushkov⁴

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

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

Asimina Arvanitaki¹ and Andrew A. Geraci^{2,*}

g_{aNN}

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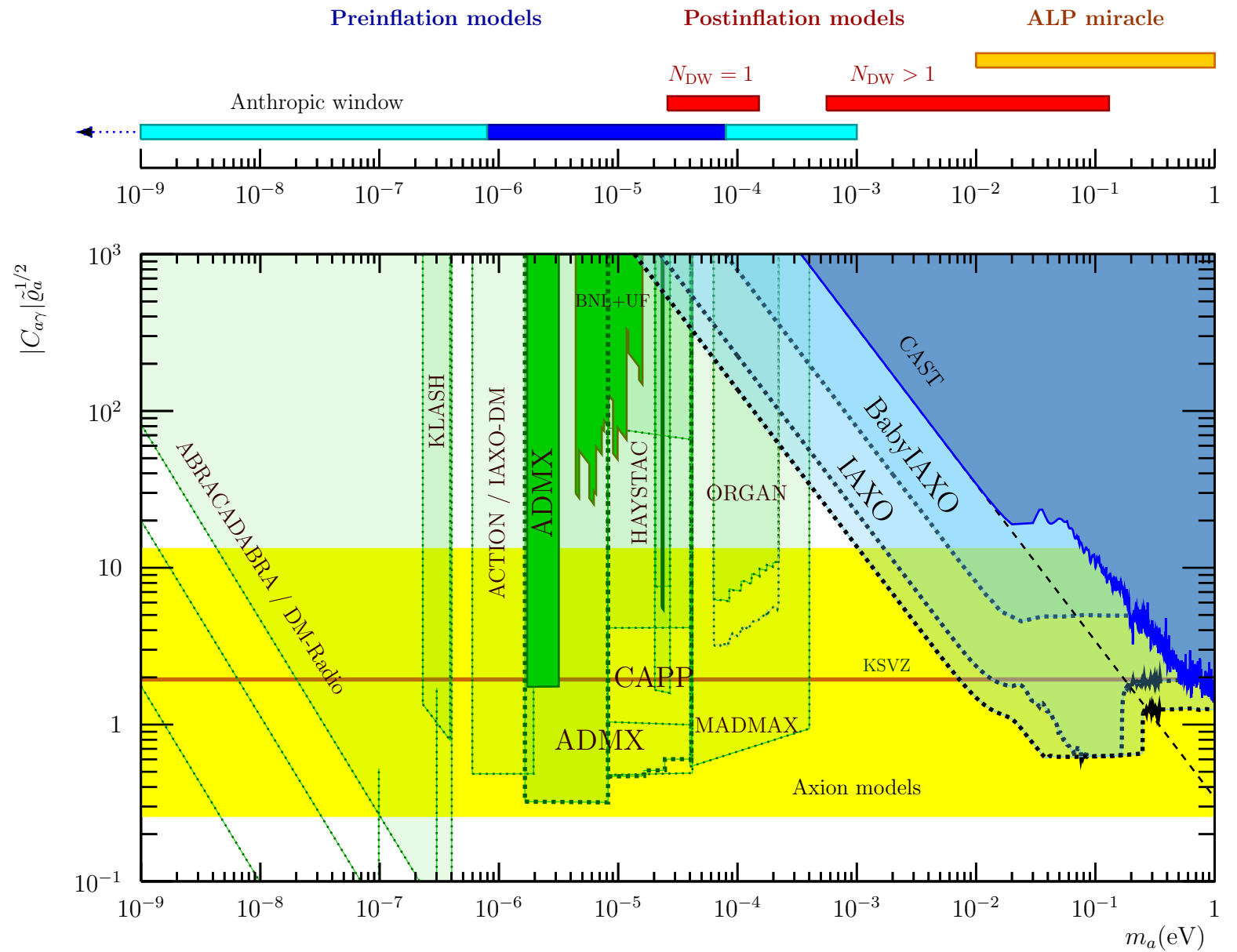
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Center for Axion and Precision Physics Research, Institute for Basic Science (IBS), Republic of Korea

$g_{a\gamma\gamma}$

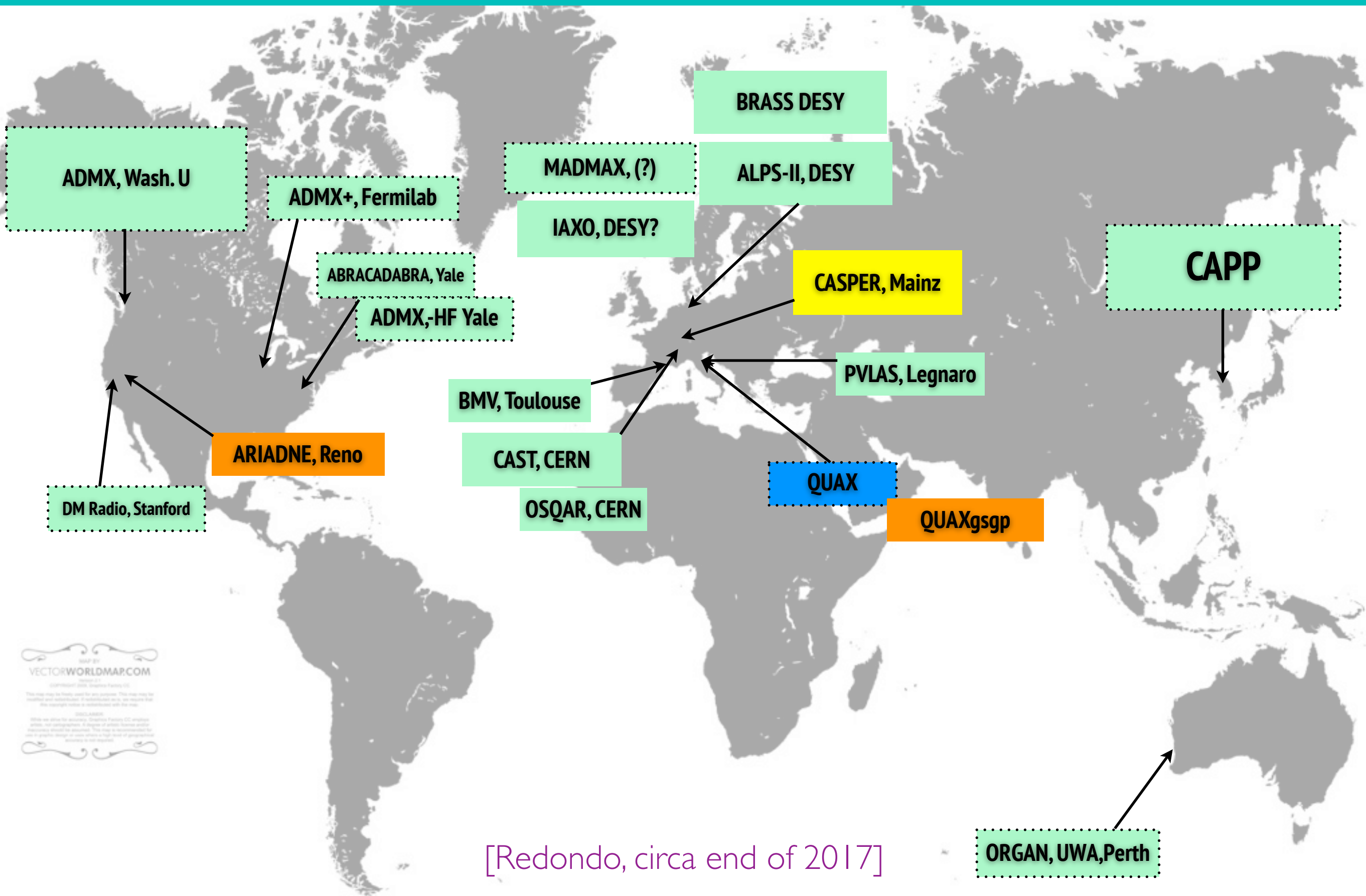
The Axion Rush

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
...	...

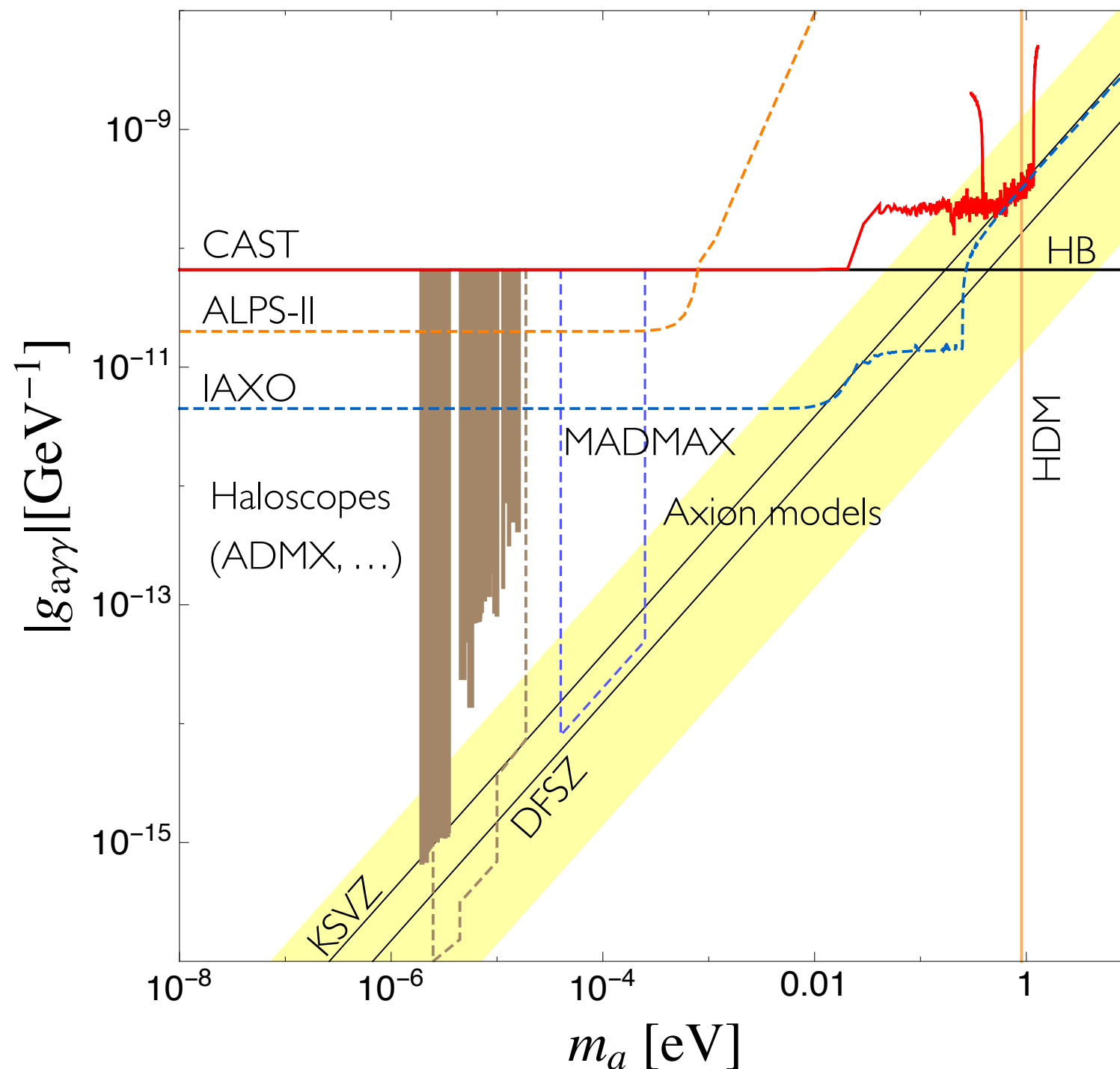


[Irastorza & Redondo, 1801.08127]

In a small context



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

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

[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 $Q \sim (3, 1, 0)$]

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

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

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

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

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]

- Lagrangian

$$\mathcal{L}_a = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{PQ}} - V_{H\Phi} + \mathcal{L}_{Qq} \quad |\mathcal{X}_L - \mathcal{X}_R| = 1$$

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

Q stability

- Symmetry of the kinetic term

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

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

- $U(1)_Q$ 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

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

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

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

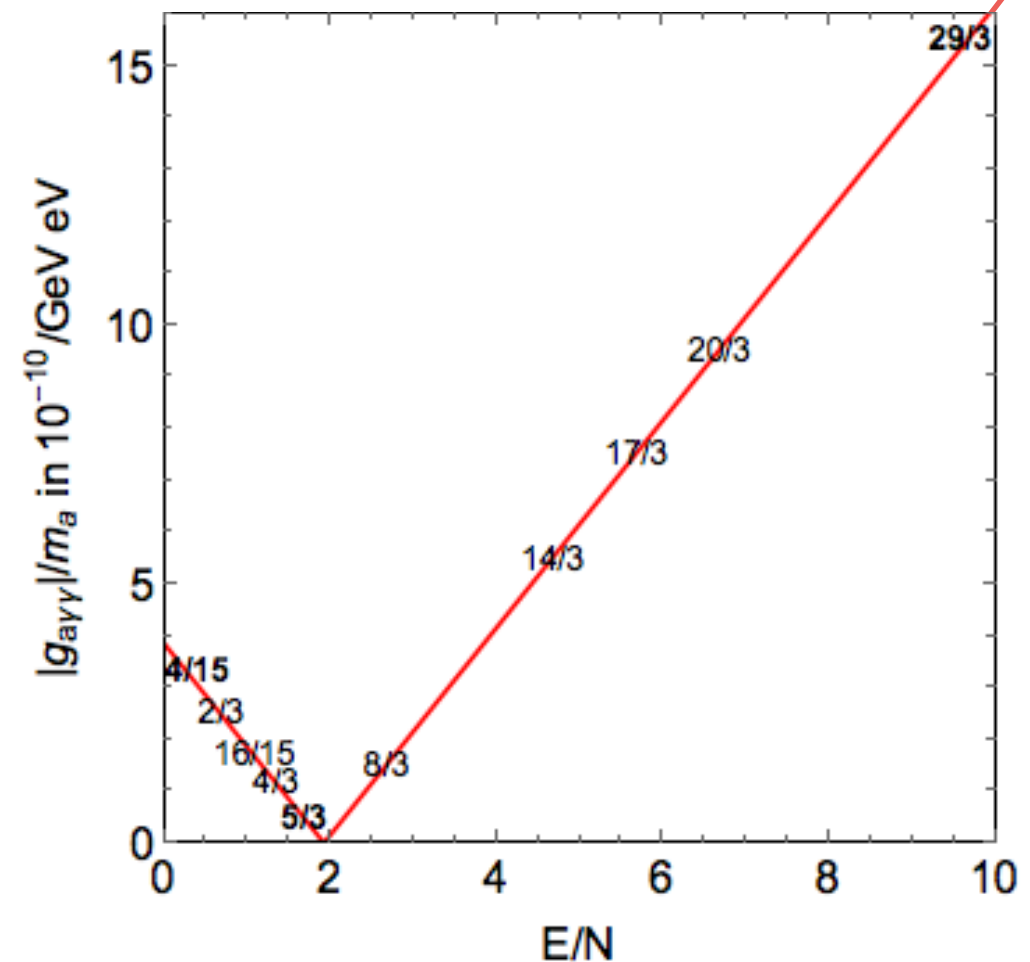
Pheno preferred KSVZ fermions

- Q short lived + no Landau poles < Planck

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

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

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



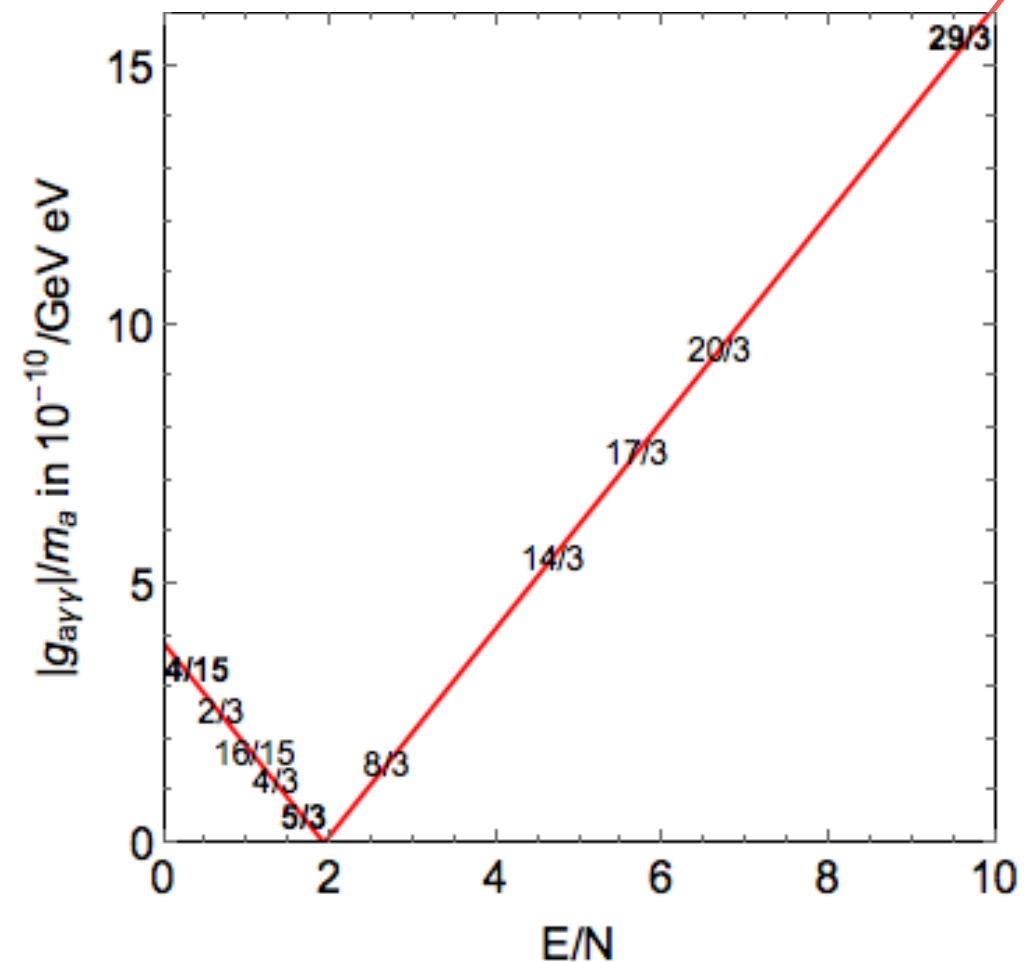
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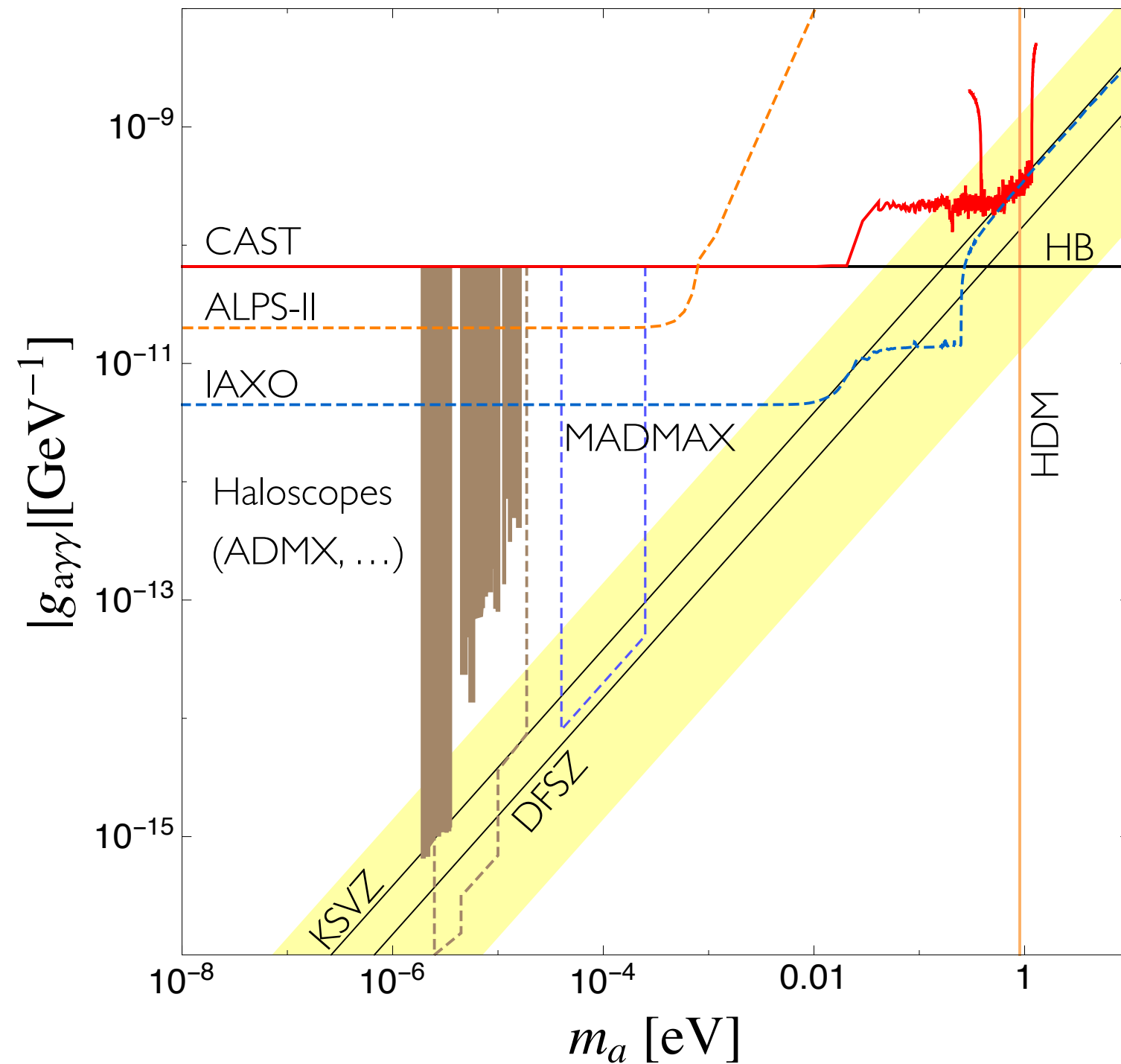
$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10} \text{ GeV}} \left(\frac{E}{N} - 1.92(4) \right)$$

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

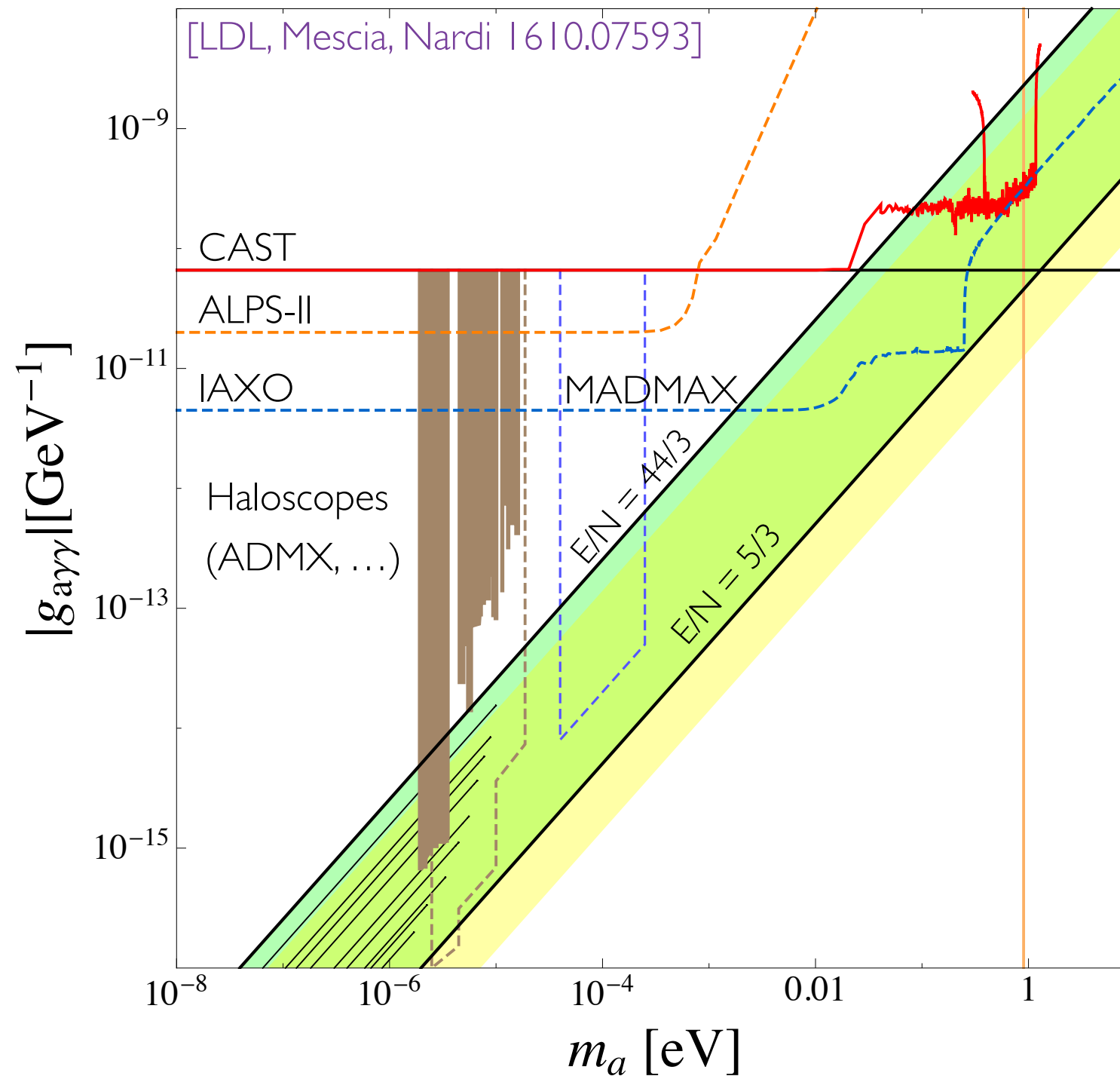
	R_Q	$\mathcal{O}_{Qq}$	$\Lambda_{\text{Landau}}^{2\text{-loop}} [\text{GeV}]$	E/N
R_Q^w	$(3, 1, -1/3)$	$\bar{Q}_L d_R$	$9.3 \cdot 10^{38} (g_1)$	$2/3$
	$(3, 1, 2/3)$	$\bar{Q}_L u_R$	$5.4 \cdot 10^{34} (g_1)$	$8/3$
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	$(3, 3, -1/3)$	$\bar{Q}_R q_L H^\dagger$	$5.1 \cdot 10^{30} (g_2)$	$14/3$
R_Q^s	$(3, 3, 2/3)$	$\bar{Q}_R q_L H$	$6.6 \cdot 10^{27} (g_2)$	$20/3$
	$(3, 3, -4/3)$	$\bar{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18} (g_1)$	$44/3$
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Redefining the axion window



Redefining the axion window



More Q's

- Combined anomaly factor

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

- Strongest coupling (compatible with LP criterium)

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

- Complete decoupling within theoretical error possible as well:

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

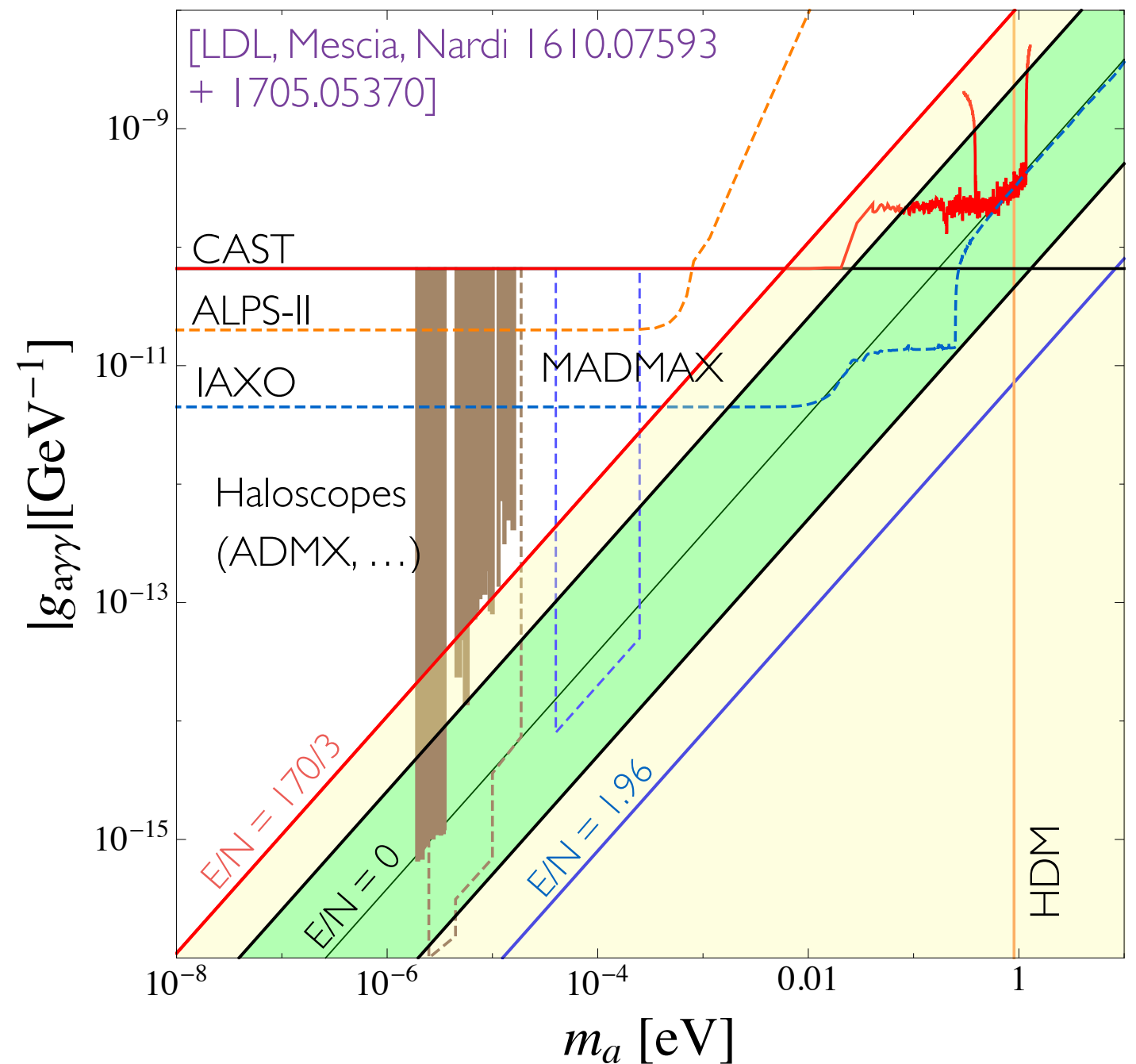
$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10} \text{ GeV}} \left(\frac{E_c}{N_c} - 1.92(4) \right)$$

about photophobia: “such a cancellation is immoral, but not unnatural”

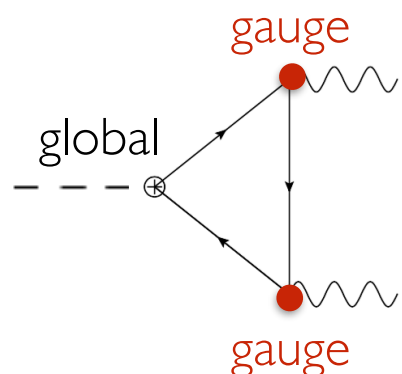
[D. B. Kaplan, (1985)]

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'

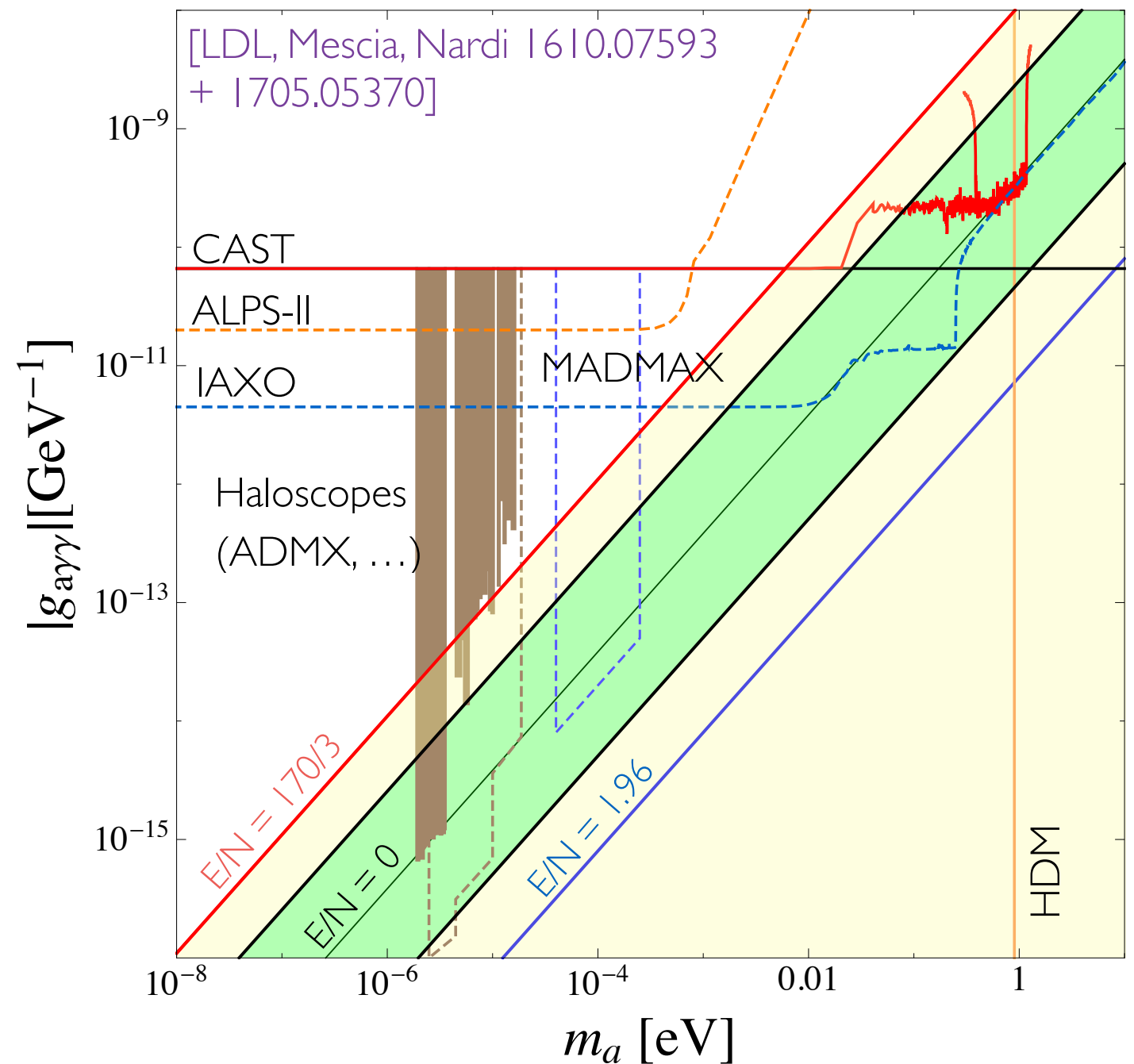


$$C_\gamma = E/N - 1.92(4)$$



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)



Astrophobia

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



nucleophobia + electrophobia = astrophobia

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

1. is it possible at all ?

2. would allow to relax the upper bound on axion mass by ~ 1 order of magnitude

3. would improve visibility at IAXO (axion-photon)

4. would improve fit to stellar cooling anomalies (axion-electron) [\[Giannotti et al. 1708.02111\]](#)

5. unexpected connection with flavour

Astrophobia

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nucleophobia + electrophobia* = astrophobia

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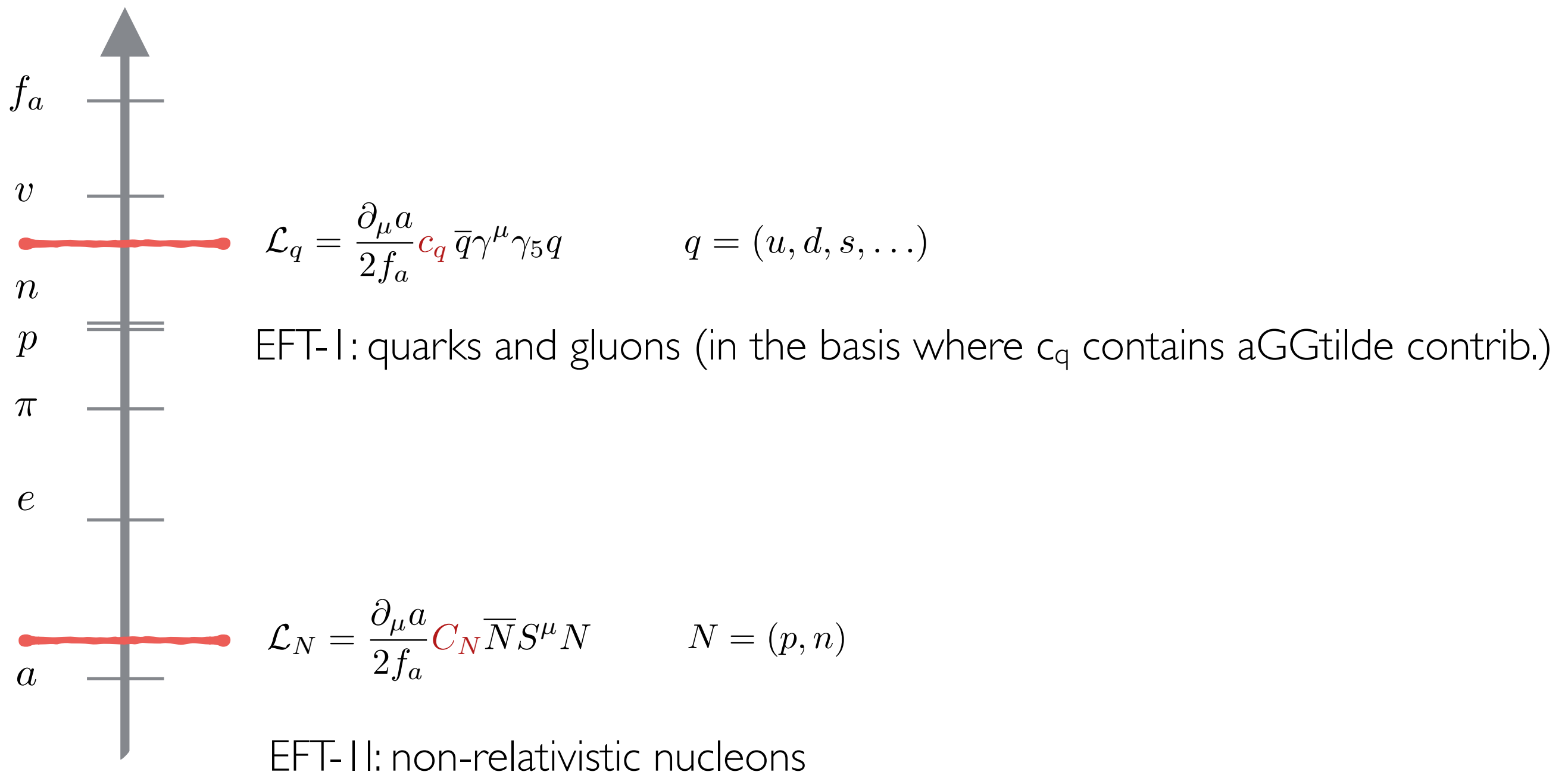
5. unexpected connection with flavour

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

Conditions for nucleophobia

- Axion-nucleon couplings

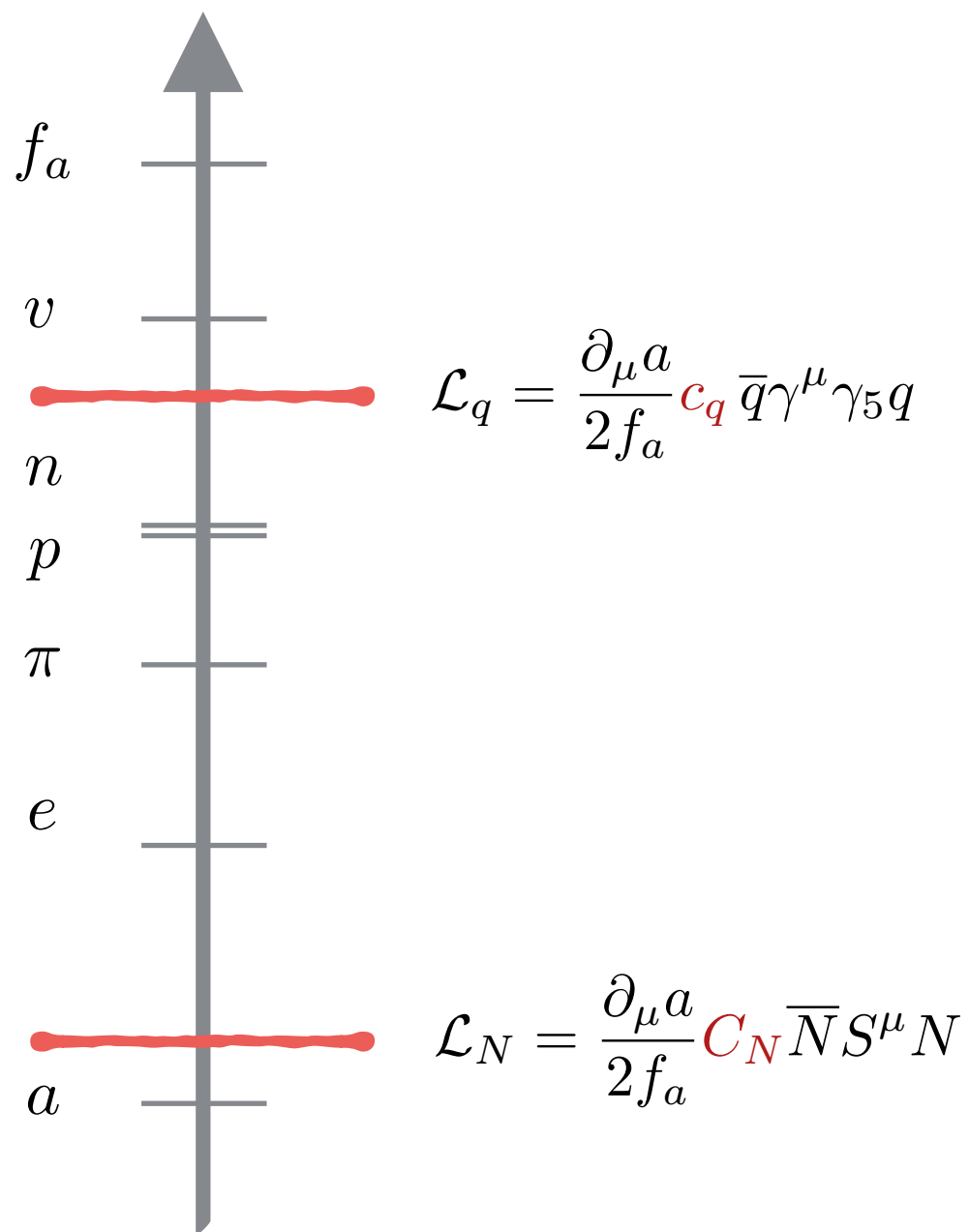
[Kaplan NPB 260 (1985), Srednicki NPB 260 (1985), Georgi, Kaplan, Randall PLB 169 (1986), ..., Grilli di Cortona et al. 1511.02867]



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]



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



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

$$C_p + C_n = (c_u + c_d) (\Delta_u + \Delta_d) - 2\delta_s \quad [\delta_s \approx 5\%]$$

$$C_p - C_n = (c_u - c_d) (\Delta_u - \Delta_d)$$

Independently of matrix elements:

$$(1): \quad C_p + C_n \approx 0 \quad \text{if} \quad c_u + c_d = 0$$

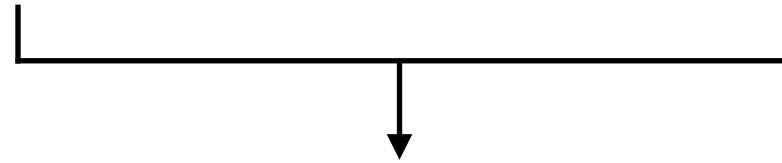
$$(2): \quad C_p - C_n = 0 \quad \text{if} \quad c_u - c_d = 0$$

KSVZ/DFSZ no-go

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

KSVZ/DFSZ no-go

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

KSVZ/DFSZ no-go

$$\mathcal{L}_a \supset \frac{a}{f_a} \frac{\alpha_s}{8\pi} \cancel{G\tilde{G}} + \frac{\partial_\mu a}{v_{PQ}} \left[X_u \bar{u} \gamma^\mu \gamma_5 u + X_d \bar{d} \gamma^\mu \gamma_5 d \right]$$
$$\frac{\partial_\mu a}{2f_a} \left[\frac{X_u}{N} \bar{u} \gamma^\mu \gamma_5 u + \frac{X_d}{N} \bar{d} \gamma^\mu \gamma_5 d \right]$$

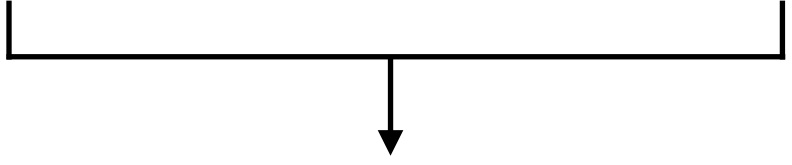


$$\frac{X_u}{N} \rightarrow c_u = \frac{X_u}{N} - \frac{m_d}{m_d + m_u}$$

$$\frac{X_d}{N} \rightarrow c_d = \frac{X_d}{N} - \frac{m_u}{m_d + m_u}$$

KSVZ/DFSZ no-go

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



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



$$\frac{X_u}{N} \rightarrow c_u = \frac{X_u}{N} - \frac{m_d}{m_d + m_u}$$

$$\frac{X_d}{N} \rightarrow c_d = \frac{X_d}{N} - \frac{m_u}{m_d + m_u}$$

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



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



KSVZ/DFSZ no-go

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

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

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

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

Implementing nucleophobia

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

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

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

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

- 1st condition automatically satisfied

Implementing nucleophobia

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$\mathcal{L}_Y \supset \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 \dots + \dots)$ $+ \bar{q}_2 u_2 H_2 + \bar{q}_2 d_2 \tilde{H}_1 + (\bar{q}_2 d_3 \dots + \dots)$	$\Rightarrow \mathcal{N}_{3rd} = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2$ $\Rightarrow \mathcal{N}_{2nd} = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1$
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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 !

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

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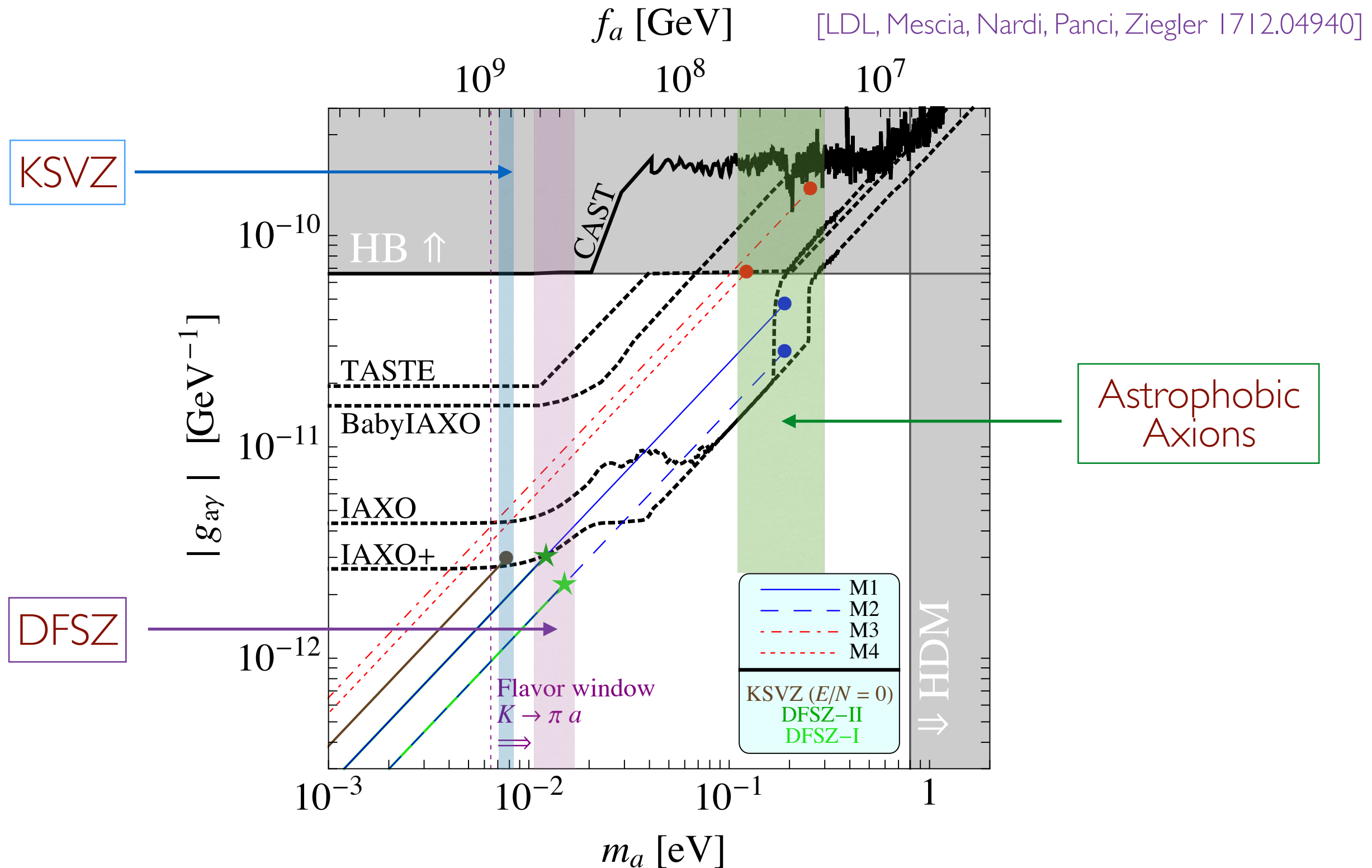
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- Plethora of low-energy flavour experiments probing $\frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C_{ij}^V + C_{ij}^A \gamma_5) f_j$

- $K \rightarrow \pi a$: $m_a < 1.0 \times 10^{-4} \frac{\text{eV}}{|C_{sd}^V|}$ [E787, E949 @ BNL, 0709.1000]  NA62
- $B \rightarrow Ka$: $m_a < 3.7 \times 10^{-2} \frac{\text{eV}}{|C_{bs}^V|}$ [Babar, 1303.7465]  Belle-II
- $\mu \rightarrow ea$: $m_a < 3.4 \times 10^{-3} \frac{\text{eV}}{\sqrt{|C_{\mu e}^V|^2 + |C_{\mu e}^A|^2}}$ [Crystal Box @ Los Alamos, Bolton et al PRD38 (1988)]  MEG II

Astrophobic axion models



Conclusions

- QCD axion: 2 birds with 1 stone
 - solves the strong CP problem
 - provides an excellent DM candidate
- Healthy phase (experimentally driven)
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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
- 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