Rethinking the QCD axion

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Particle and Astroparticle Theory Seminar

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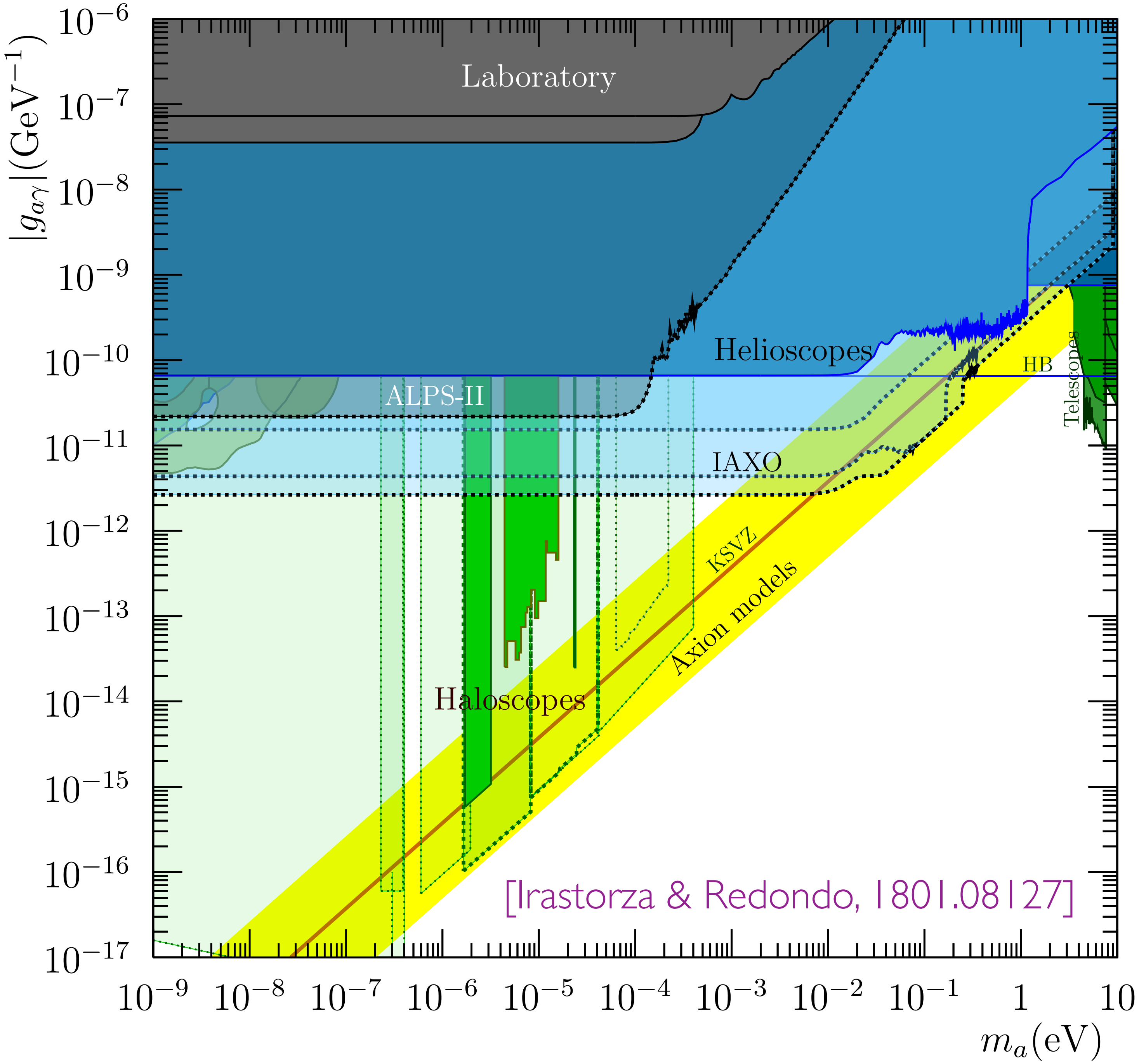
In 10 years from now ?



✤ A great opportunity to discover the QCD axion !

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

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) + work in progress

The strong CP problem

- CP violation in QCD

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

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- GGtilde is a total derivative (<u>no effects in PT</u>)

- QCD vacuum structure [Belavin, Polyakov, Schwarz, Tyupkin PLB59 (1975), 't Hooft PRL37 + PRD14 (1976), Callan, Dashen, Gross, PLB63 (1976), …]

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

- dominated by "large instantons" of size $\rho \sim 1/\Lambda_{\rm QCD}$ (semi-classical approx. breaks down)

→ need chiral Lagrangian for quantitative statements

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)]

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

$\longrightarrow$ $\overline{\theta} = \theta - \theta_q$ 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

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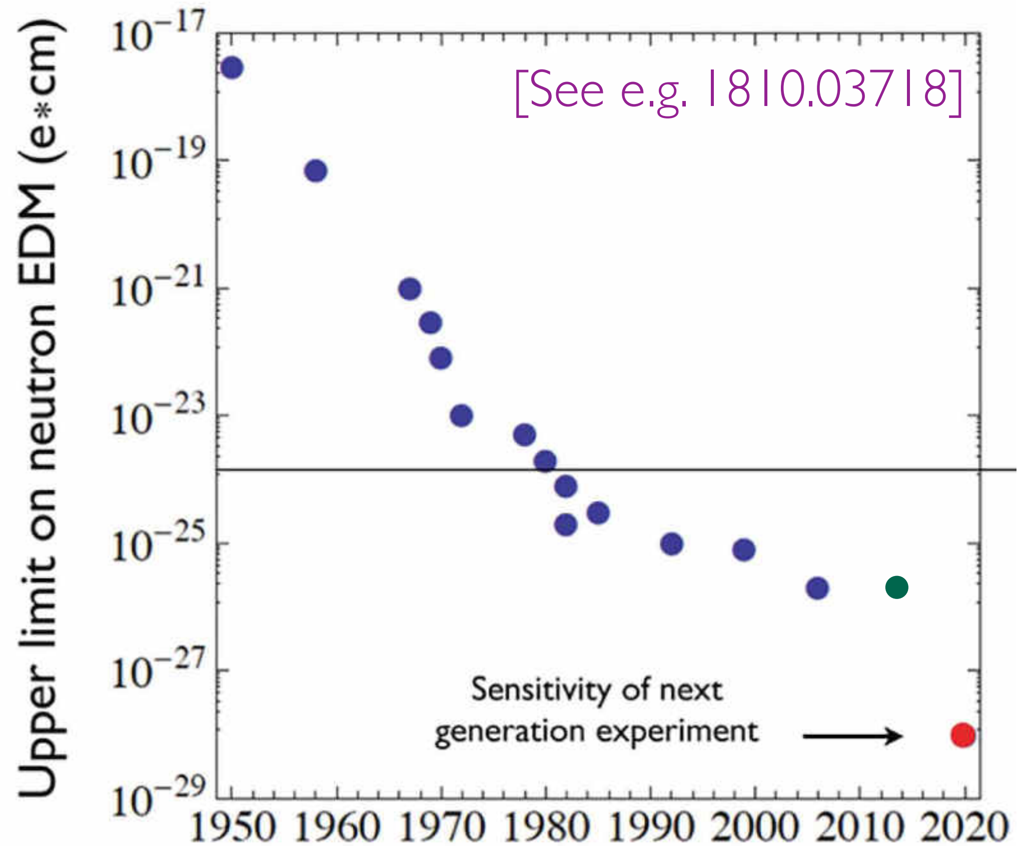
- Non-zero neutron EDM



[B. Fillipone]

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

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

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

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

“Small value” problems

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

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

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

[Ubaldi, 0811.1599]

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- More than a small value problem ?

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

$\swarrow$ QCD $\qquad$ $\searrow$ 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]

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- A massless quark would make the theta term unphysical (excluded at 20σ by Lattice)
- 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

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

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

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

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

θ-dependence of QCD vacuum

- Ground state energy in Euclidean V_4 [Vafa, Witten PRL 53 (1984)]

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

$$\longrightarrow \quad E(0) \leq E(\theta_{\rm eff})$$

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

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

- 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

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

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

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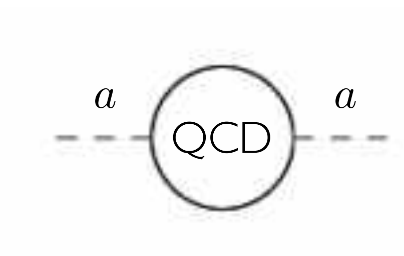
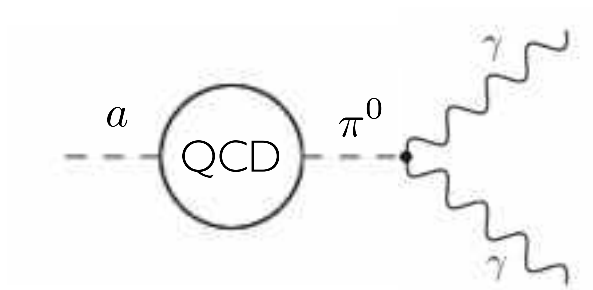
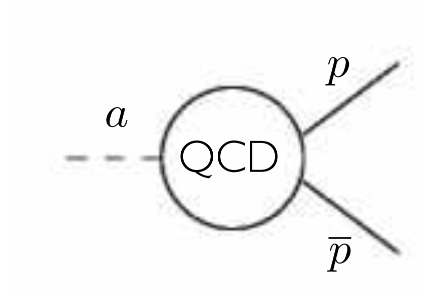
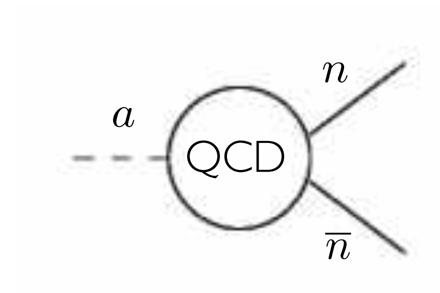


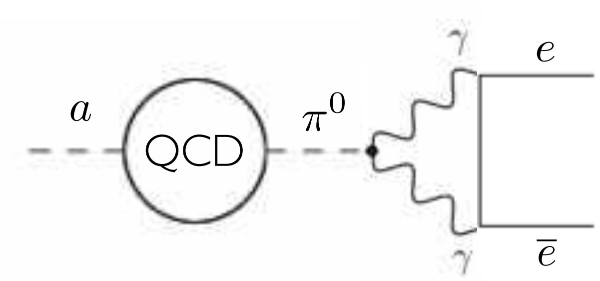
$$\sim \frac{\Lambda^4_{\text{QCD}}}{f_a^2} \qquad m_a \sim \Lambda^2_{\text{QCD}}/f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a}\right)$$

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









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

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

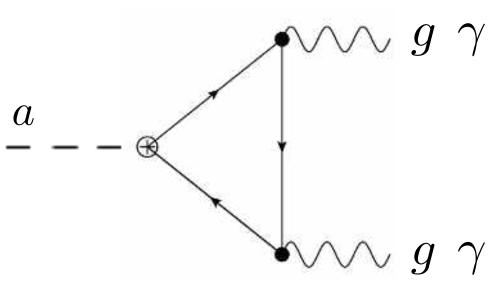
[From NLO Chiral Lagrangian,
Grilli di Cortona et al., 1511.02867]

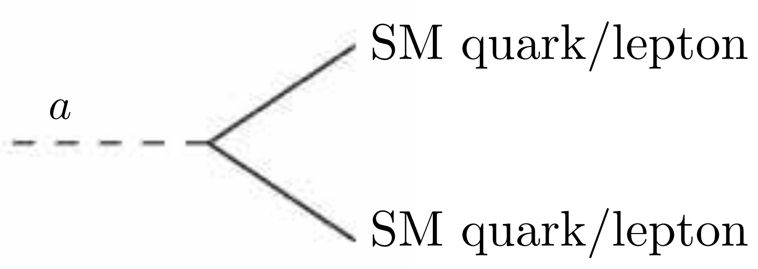
Axion properties [EFT]

- 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)

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

SM fermions → 2Higgs+Singlet

DFSZ

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

$\tan\beta = v_2/v_1$

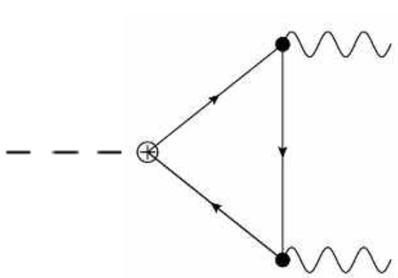
BSM fermions → Higgs+Singlet

KSVZ

$C_p \simeq -0.5$

$C_{n,e} \simeq 0$

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



Astro bounds

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

  - light: $m_a \lesssim 10\,T_\star$ (e.g. typical interior temperature of the Sun ~ 1 keV)

  - weakly coupled (otherwise we would have already seen them in labs)

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

<u>neutrino interactions</u> (d=6 op.)

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

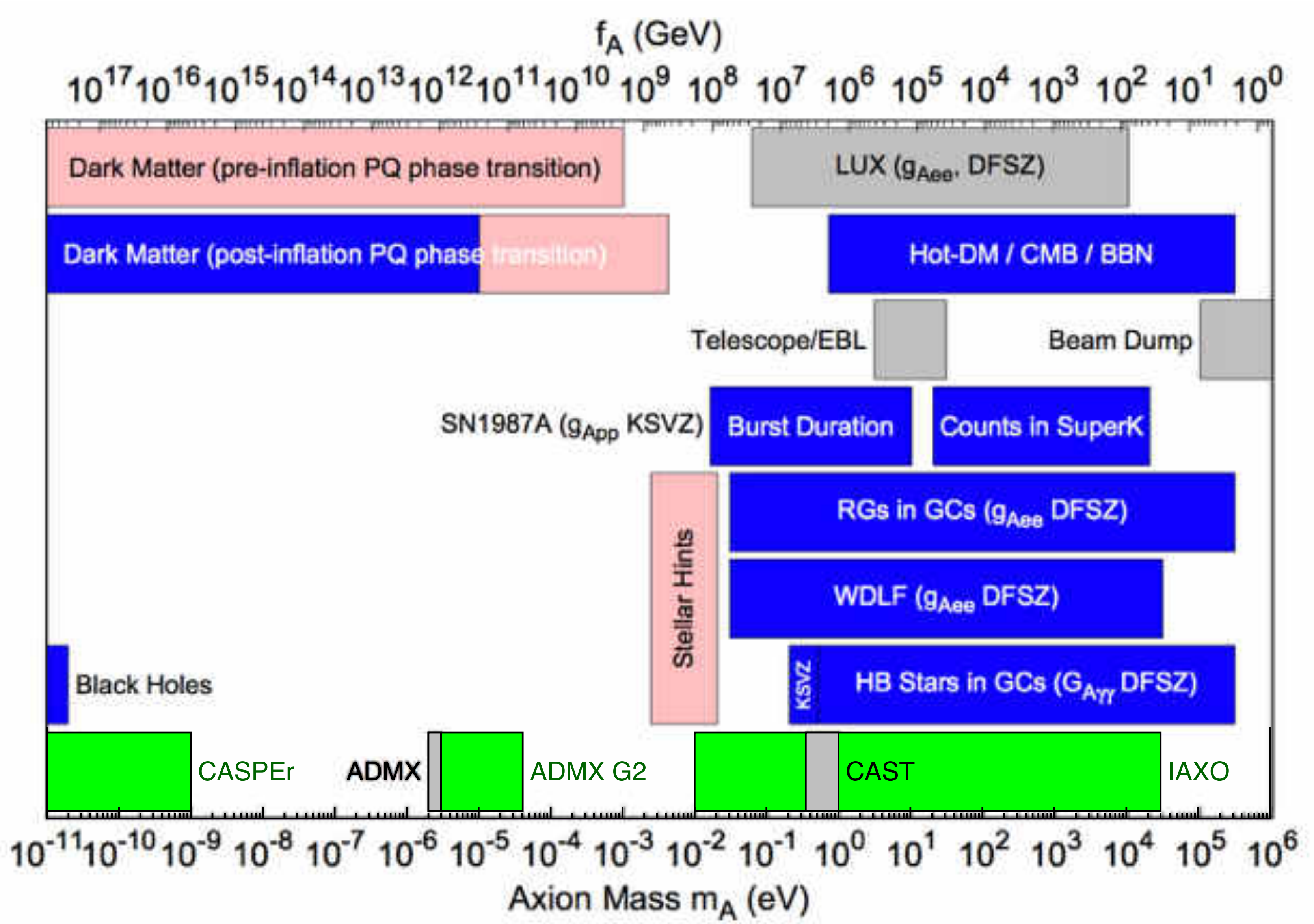
<u>axion interactions</u> (d=5 op.)

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

→ 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 (2016)]

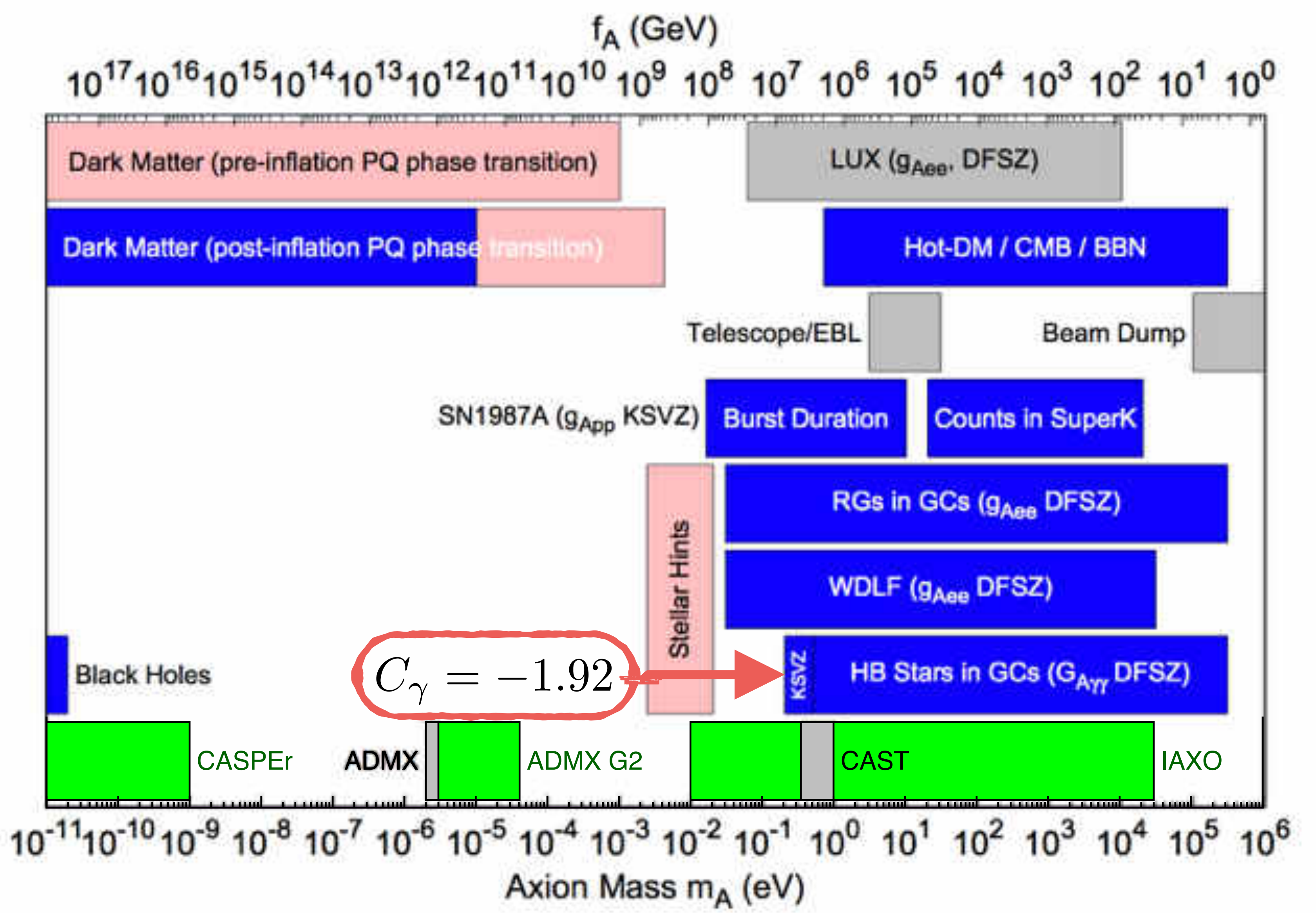
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

Axion landscape



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Lab exclusions

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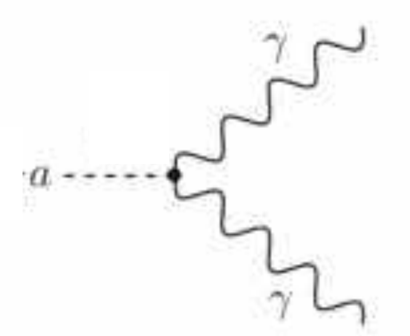
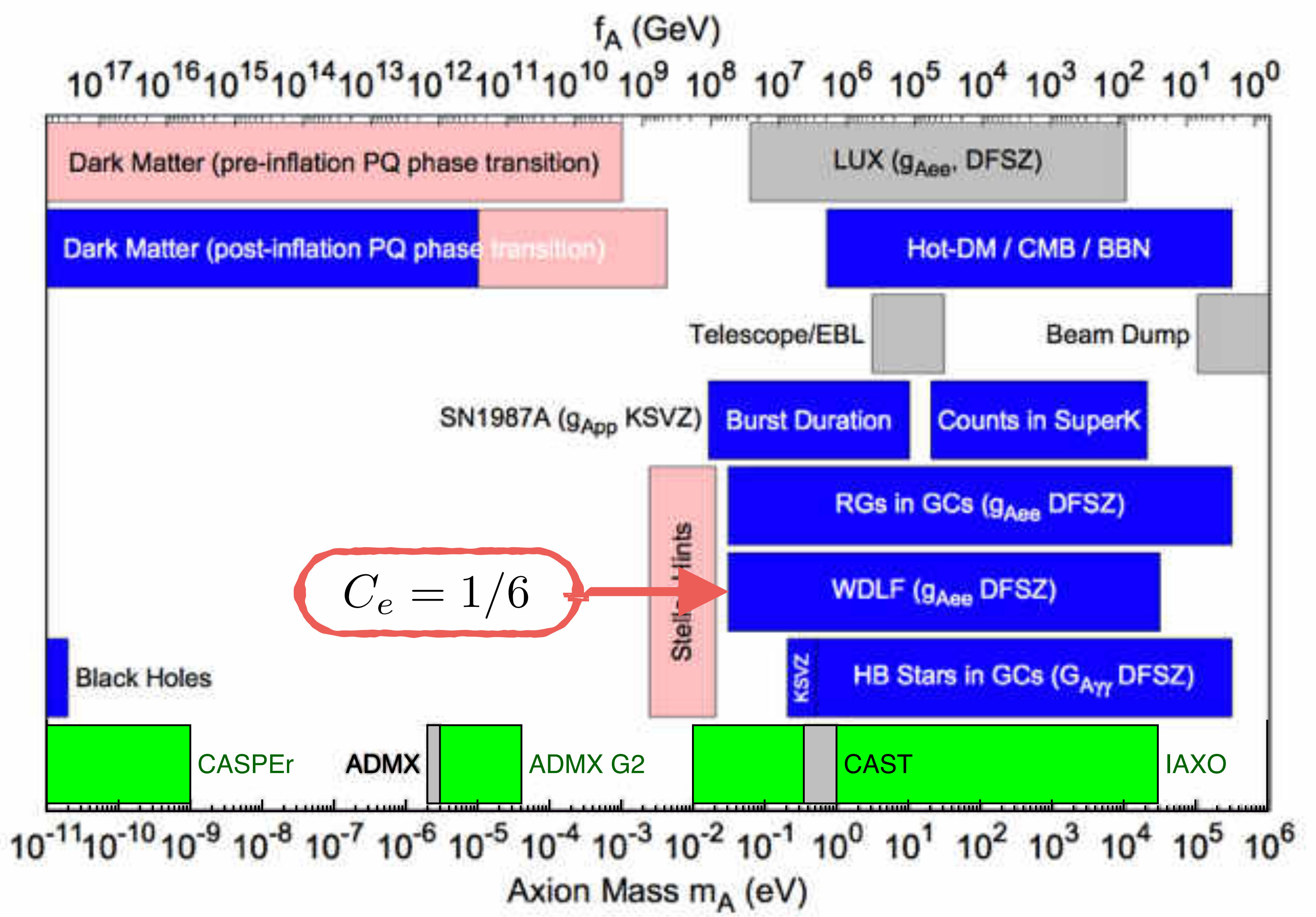
Exp. sensitivities

- Horizontal branch star evolution in globular clusters



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

Axion landscape



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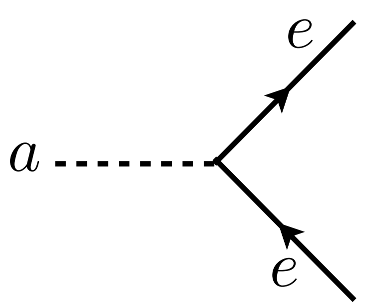
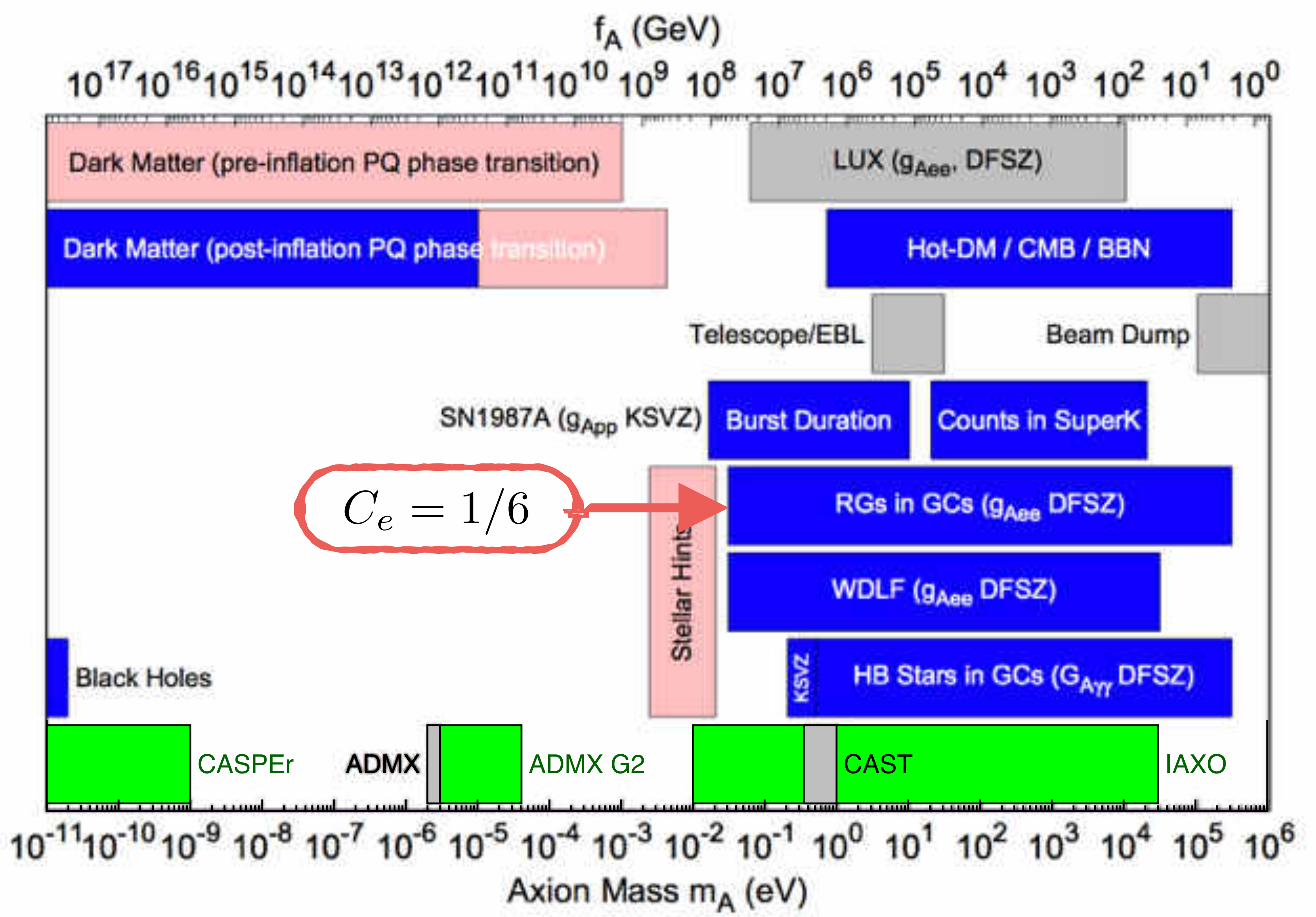
Exp. sensitivities

- 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 (2016)]

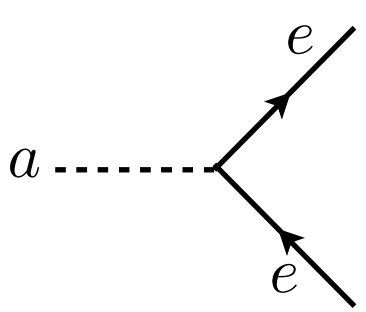
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

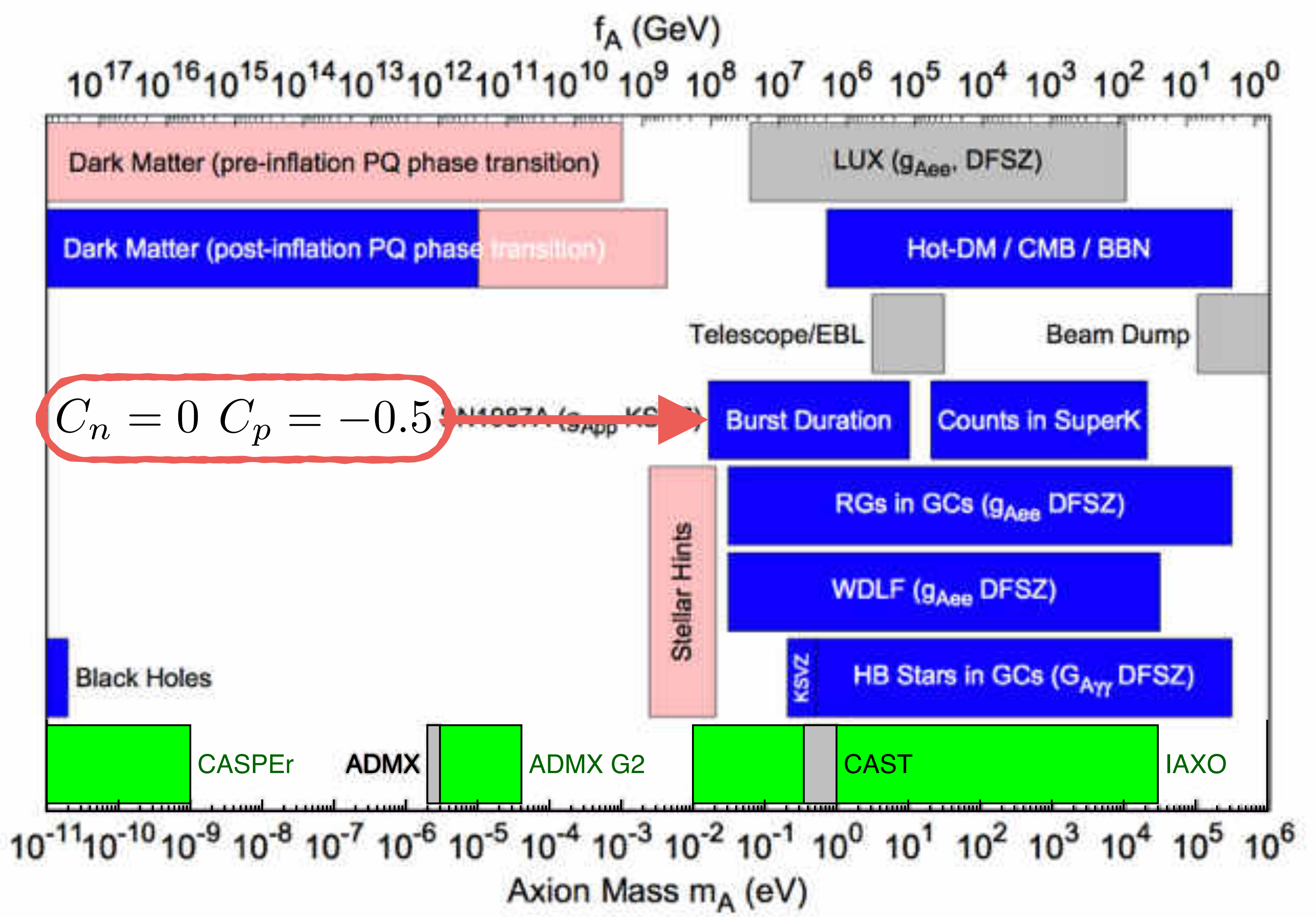
Exp. sensitivities

- Red giants evolution in globular clusters



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

Axion landscape



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

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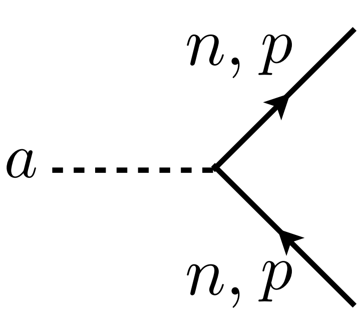
Exp. sensitivities

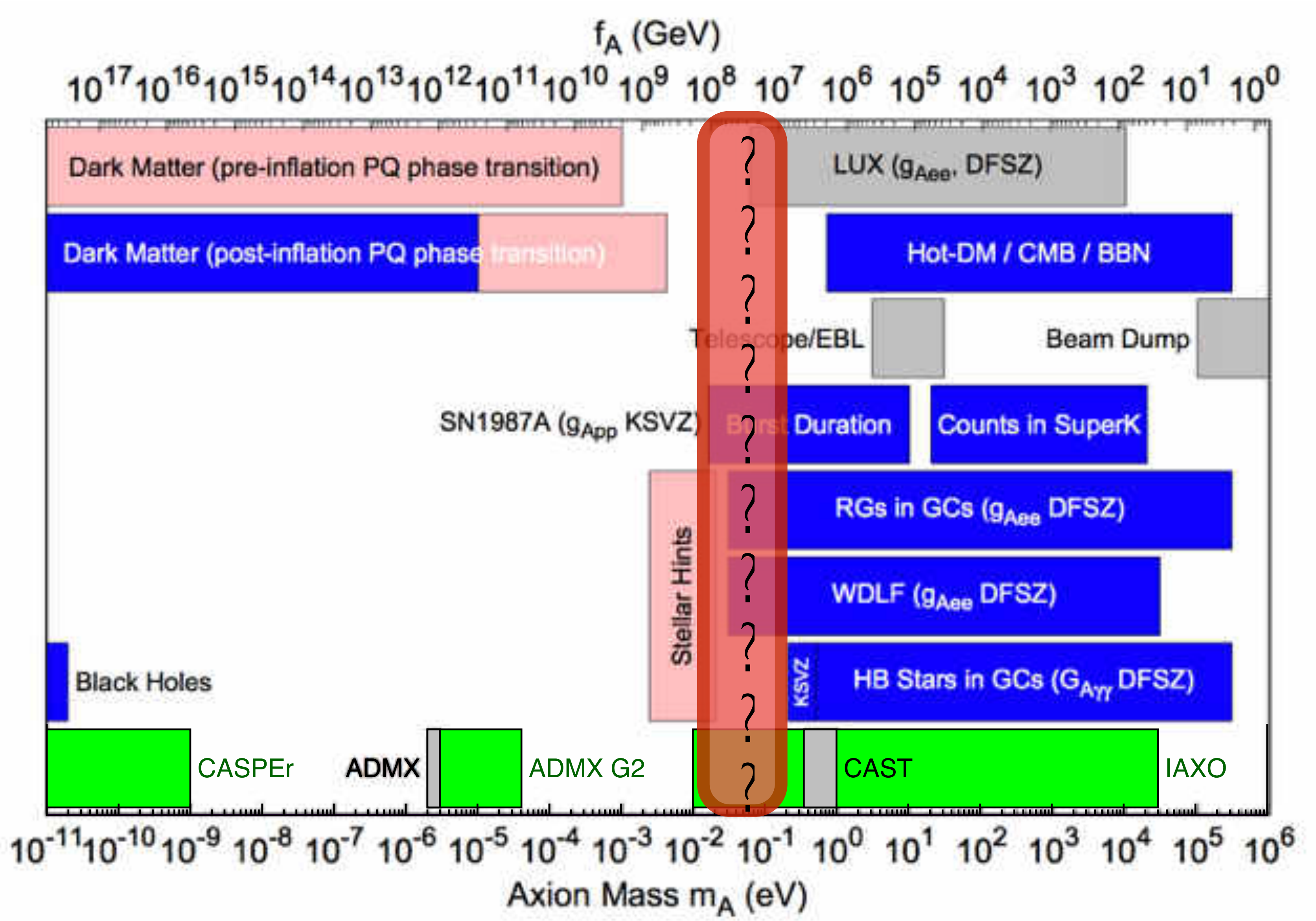
- Burst duration of SN1987A nu signal



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

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

Axion landscape



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

Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

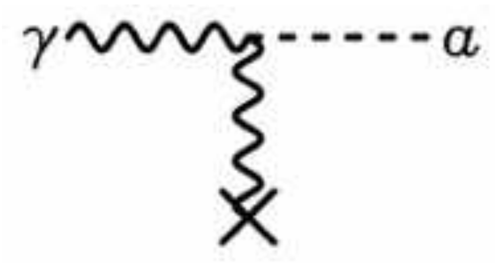
- Bound on axion mass is of <u>practical</u> convenience, but misses model dependence !

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

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



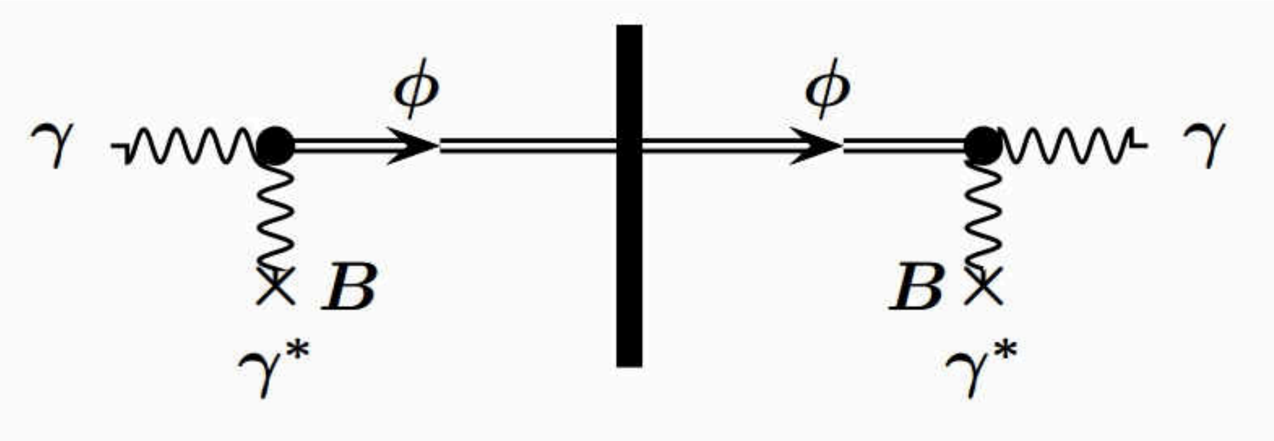
- Light Shining through Walls [See e.g. Redondo, Ringwald hep-ph/1011374I]

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

- Helioscopes (axions from the Sun)

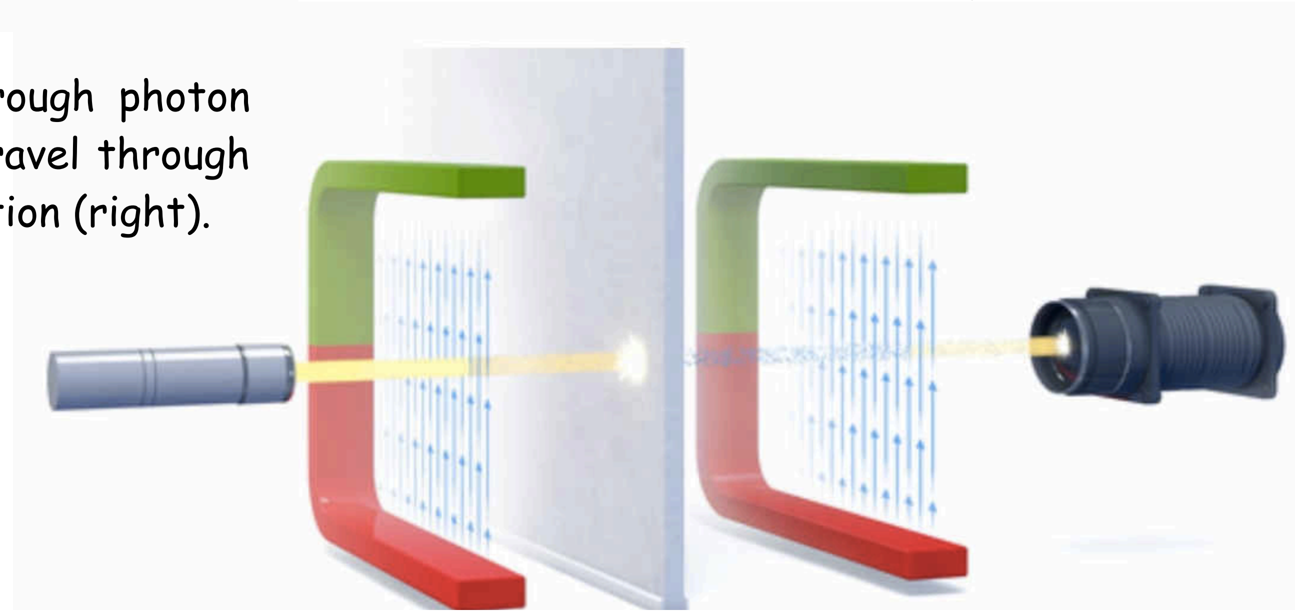
Light Shining through Walls (LSW)

- PVLAS discovery claim (2006) → boosted exp. activity
- 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



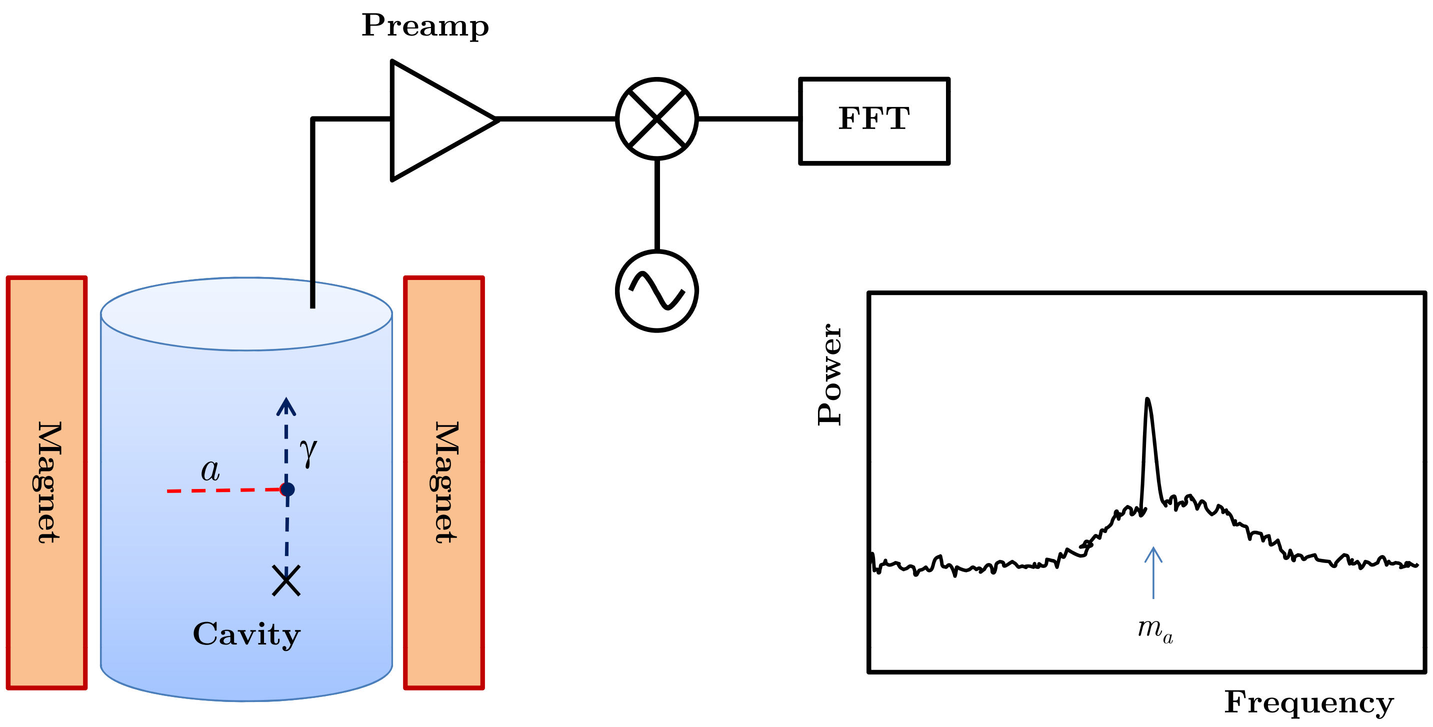
- LSW experiments pay a $g^4_{a\gamma\gamma}$ suppression

Haloscopes

- Look for DM axions with a microwave resonant cavity

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

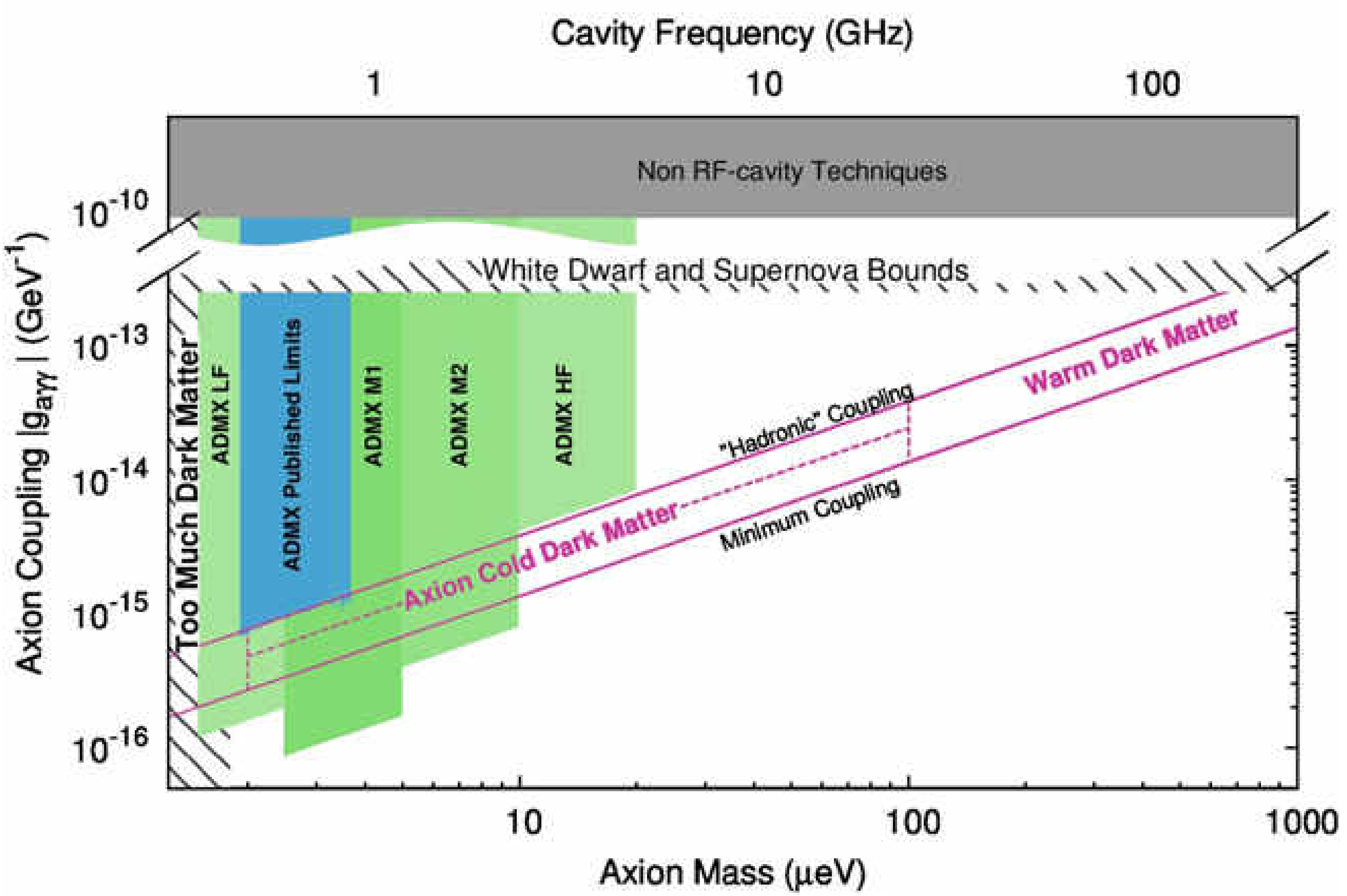
  - resonance condition: need to tune the frequency of the EM cavity on the axion mass



Haloscopes

- Look for DM axions with a microwave resonant cavity

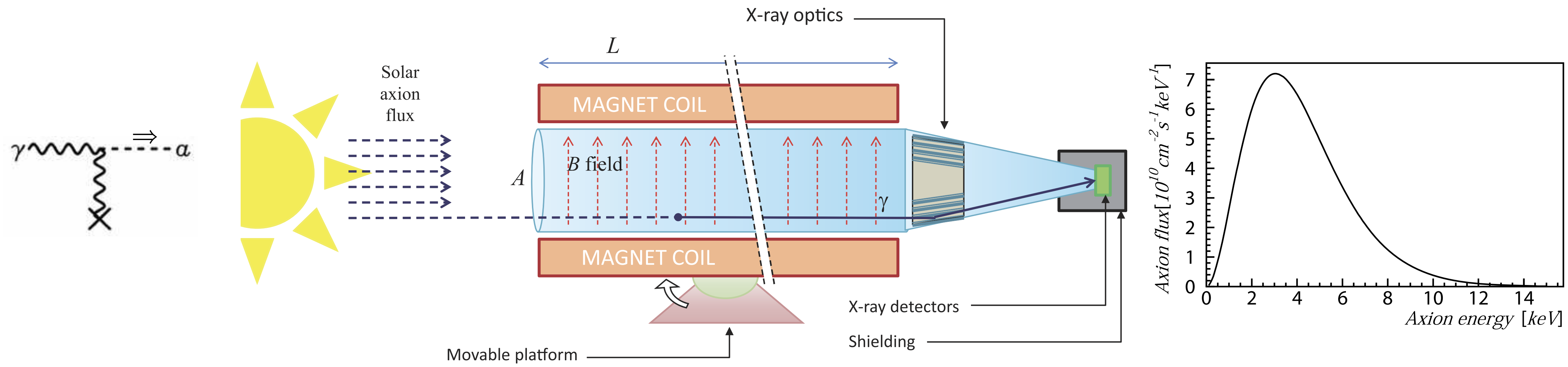
  - Axion Dark Matter eXperiment (ADMX) (U. of Washington)



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

Helioscopes

- The Sun is a potential axion source



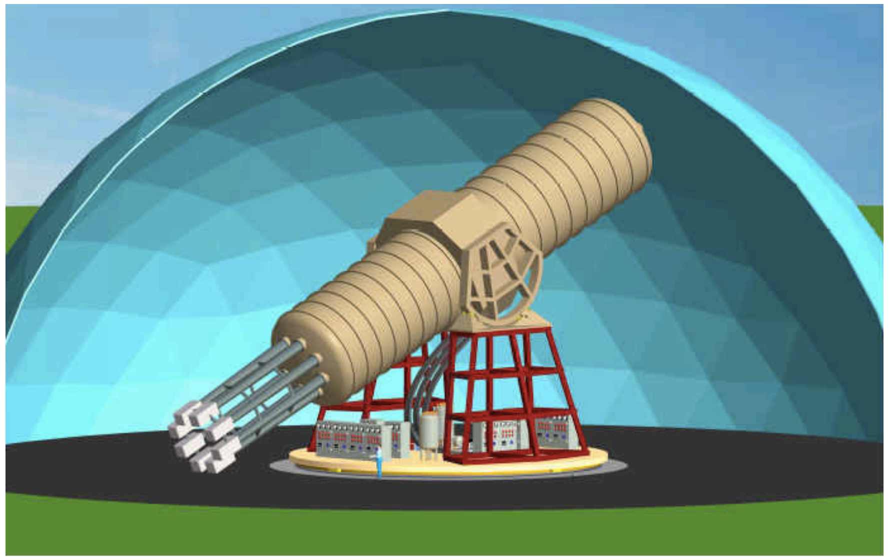
- macroscopic B-field can provide a coherent axion-photon (x-ray) conversion rate over a big volume

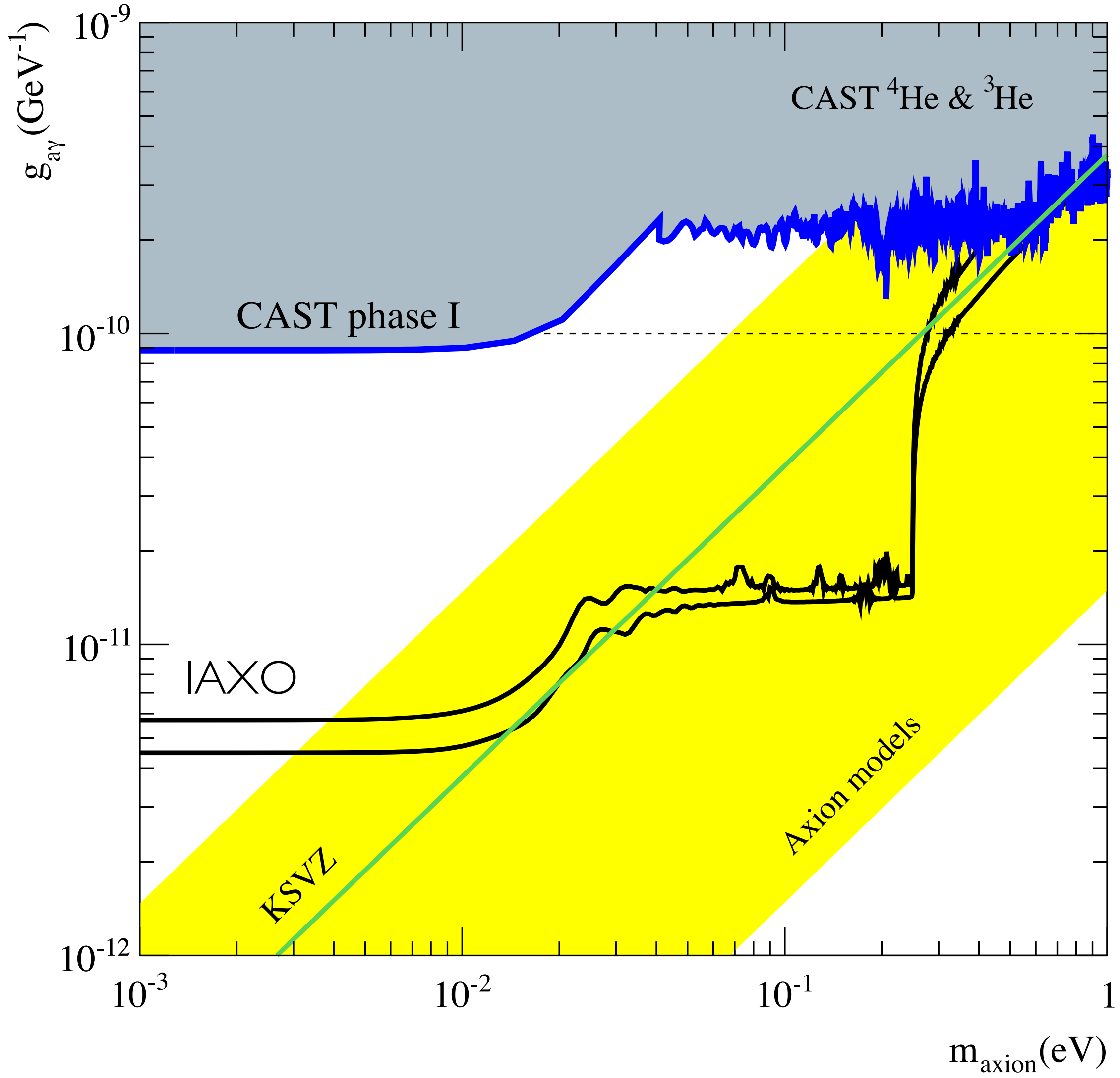
Helioscopes

- 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

Broadband and Resonant Approaches to Axion Dark Matter Detection

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

Dielectric Haloscopes: A New Way to Detect Axion Dark Matter

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Searching for galactic axions through magnetized media: The QUAX proposal

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PHYSICAL REVIEW D **91,** 084011 (2015)

Discovering the QCD axion with black holes and gravitational waves

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(Received 16 December 2014; published 7 April 2015)

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

The Axion Rush

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g_{aNN}

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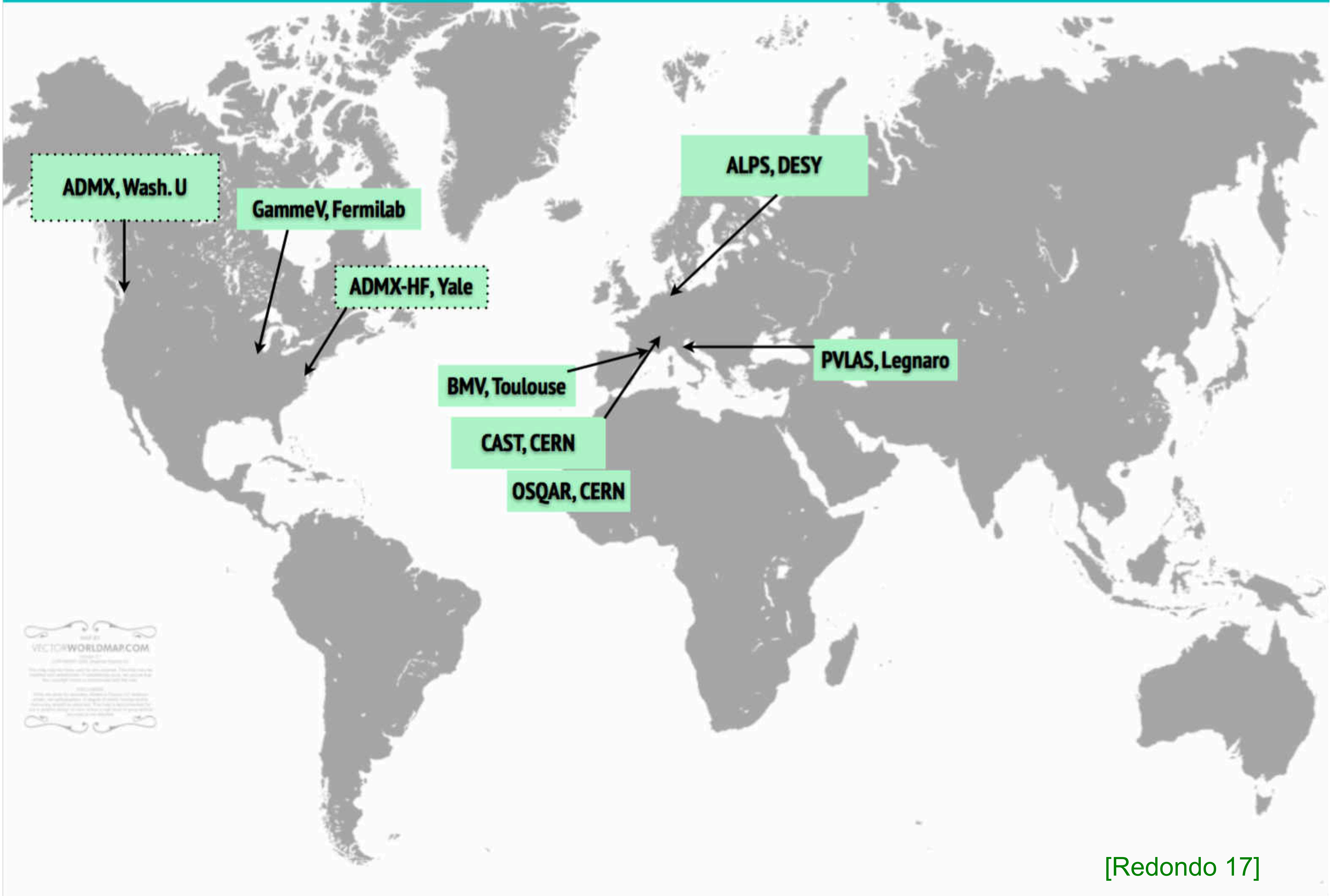
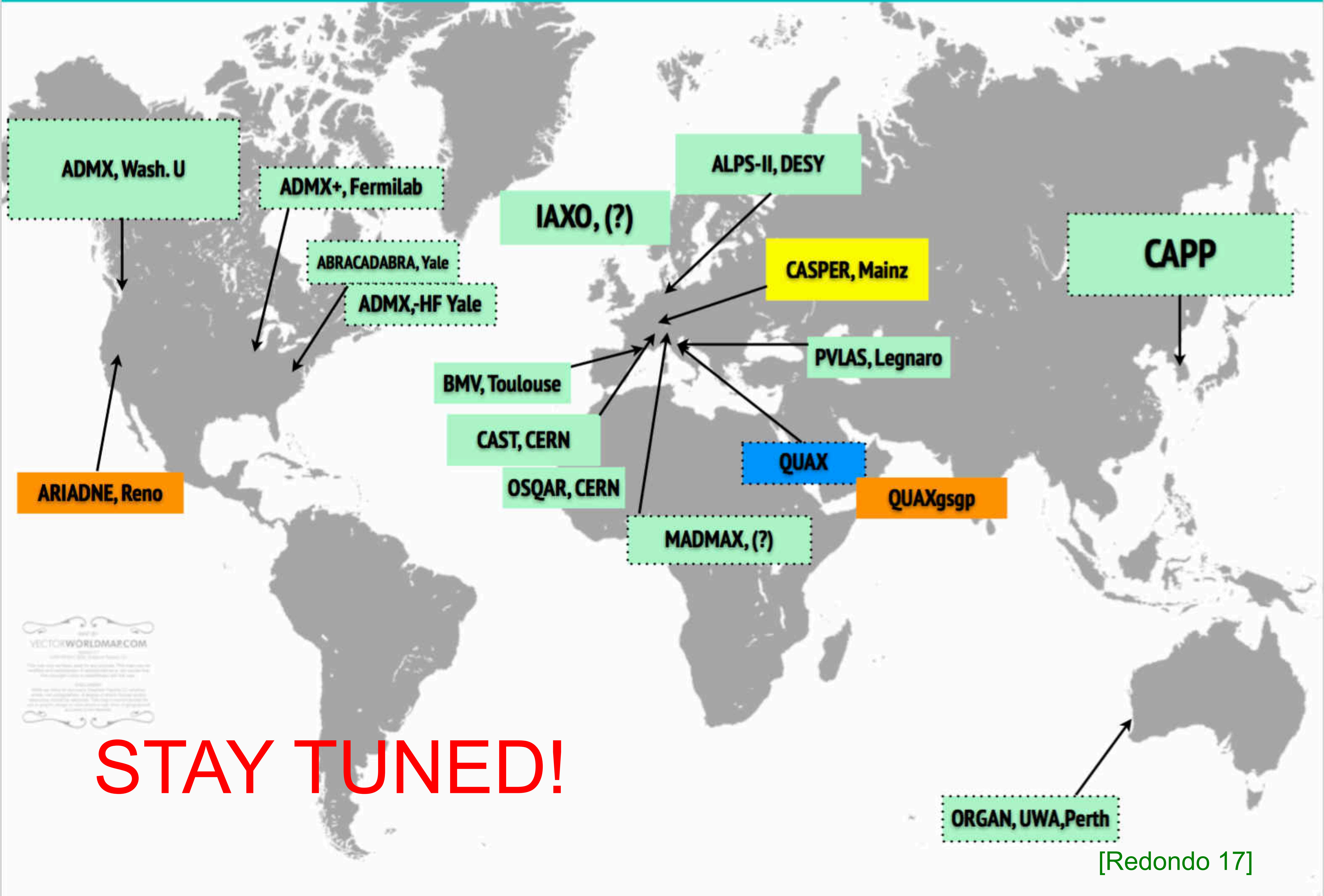
$g_{a\gamma\gamma}$

Lab experiments 2011



[Redondo 17]

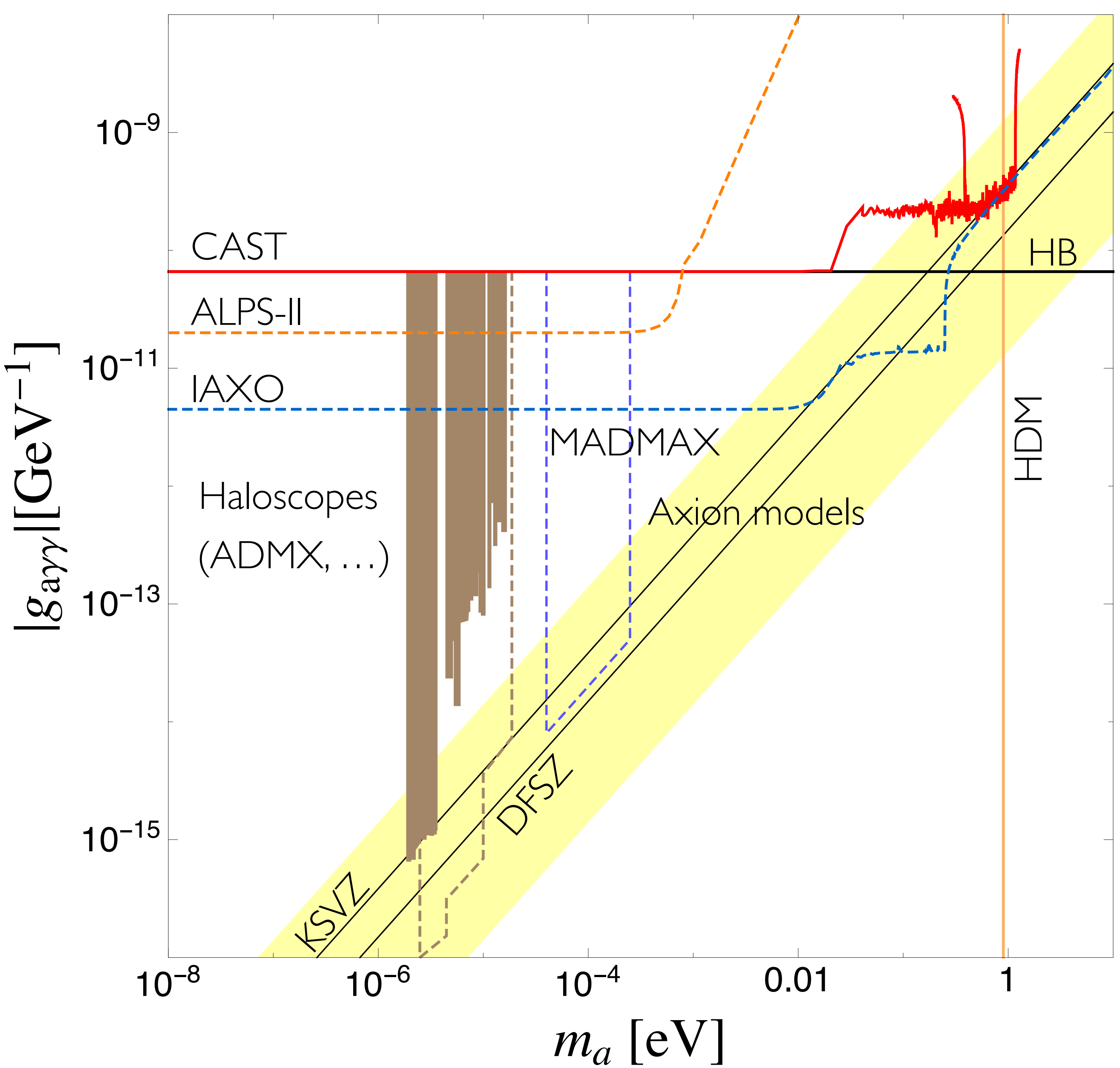
Lab experiments 2017



STAY TUNED!

[Redondo 17]

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)]

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

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

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

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Φ	0	1	1	0	1

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

- Lagrangian

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

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

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

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

- $\mathcal{L}_{Qq}$ 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>

$\Downarrow$

cosmological issue if thermally produced
in the early universe !

Q stability

- Symmetry of the kinetic term

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

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

- if $\mathcal{L}_{Qq} \neq 0$ $U(1)_{\rm Q}$ 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
$(3,1,-1/3)$	$\overline{Q}_L d_R$	$9.3 \cdot 10^{38}(g_1)$	$2/3$
$(3,1,2/3)$	$\overline{Q}_L u_R$	$5.4 \cdot 10^{34}(g_1)$	$8/3$
$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5 \cdot 10^{39}(g_1)$	$5/3$
$(3,2,-5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3 \cdot 10^{27}(g_1)$	$17/3$
$(3,2,7/6)$	$\overline{Q}_L u_R H$	$5.6 \cdot 10^{22}(g_1)$	$29/3$
$(3,3,-1/3)$	$\overline{Q}_R q_L H^\dagger$	$5.1 \cdot 10^{30}(g_2)$	$14/3$
$(3,3,2/3)$	$\overline{Q}_R q_L H$	$6.6 \cdot 10^{27}(g_2)$	$20/3$
$(3,3,-4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18}(g_1)$	$44/3$
$(\overline{6},1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$2.3 \cdot 10^{37}(g_1)$	$4/15$
$(\overline{6},1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$5.1 \cdot 10^{30}(g_1)$	$16/15$
$(\overline{6},2,1/6)$	$\overline{Q}_R \sigma_{\mu\nu} q_L G^{\mu\nu}$	$7.3 \cdot 10^{38}(g_1)$	$2/3$
$(8,1,-1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6 \cdot 10^{22}(g_1)$	$8/3$
$(8,2,-1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7 \cdot 10^{27}(g_1)$	$4/3$
$(15,1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3 \cdot 10^{21}(g_3)$	$1/6$
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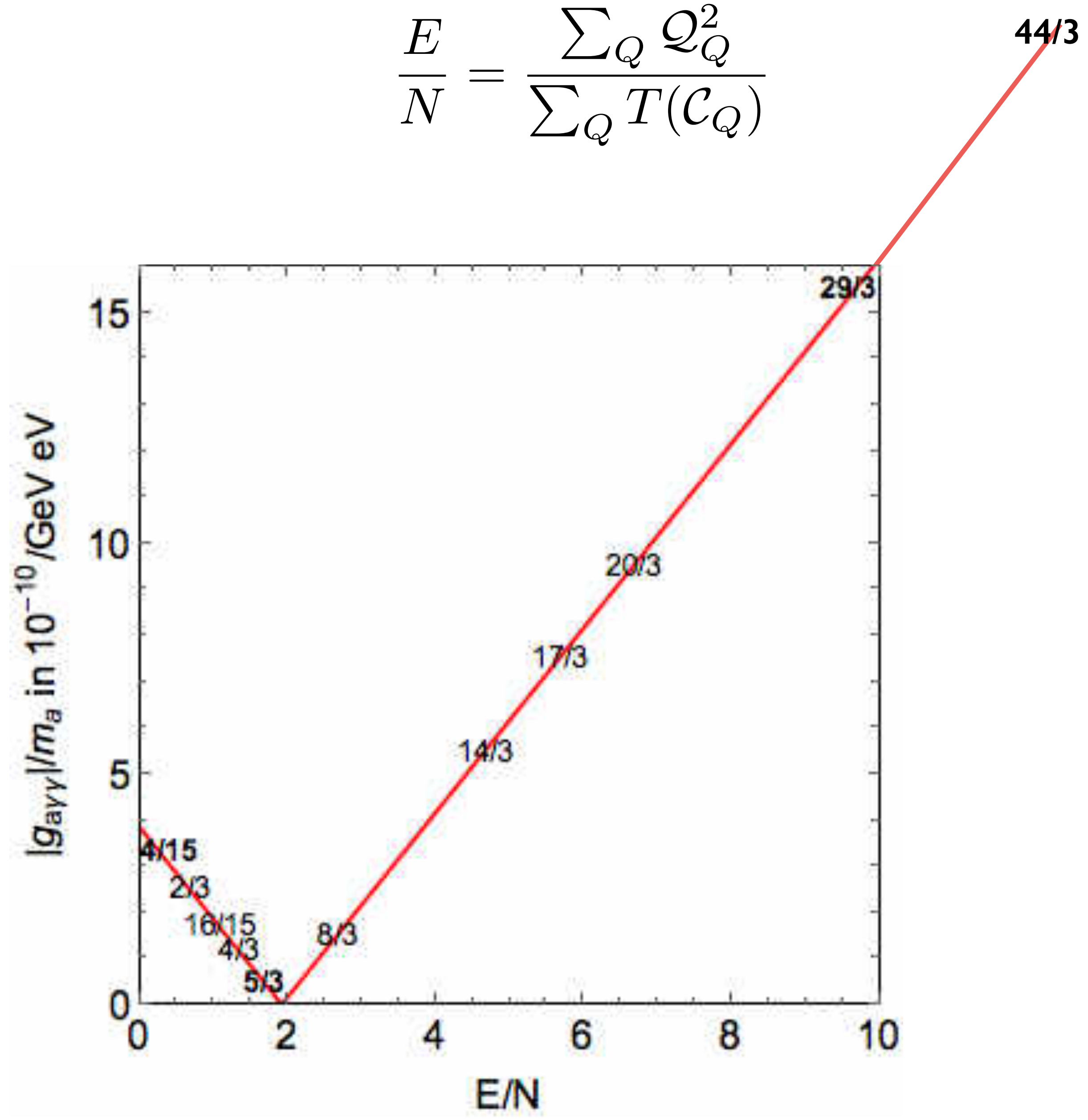

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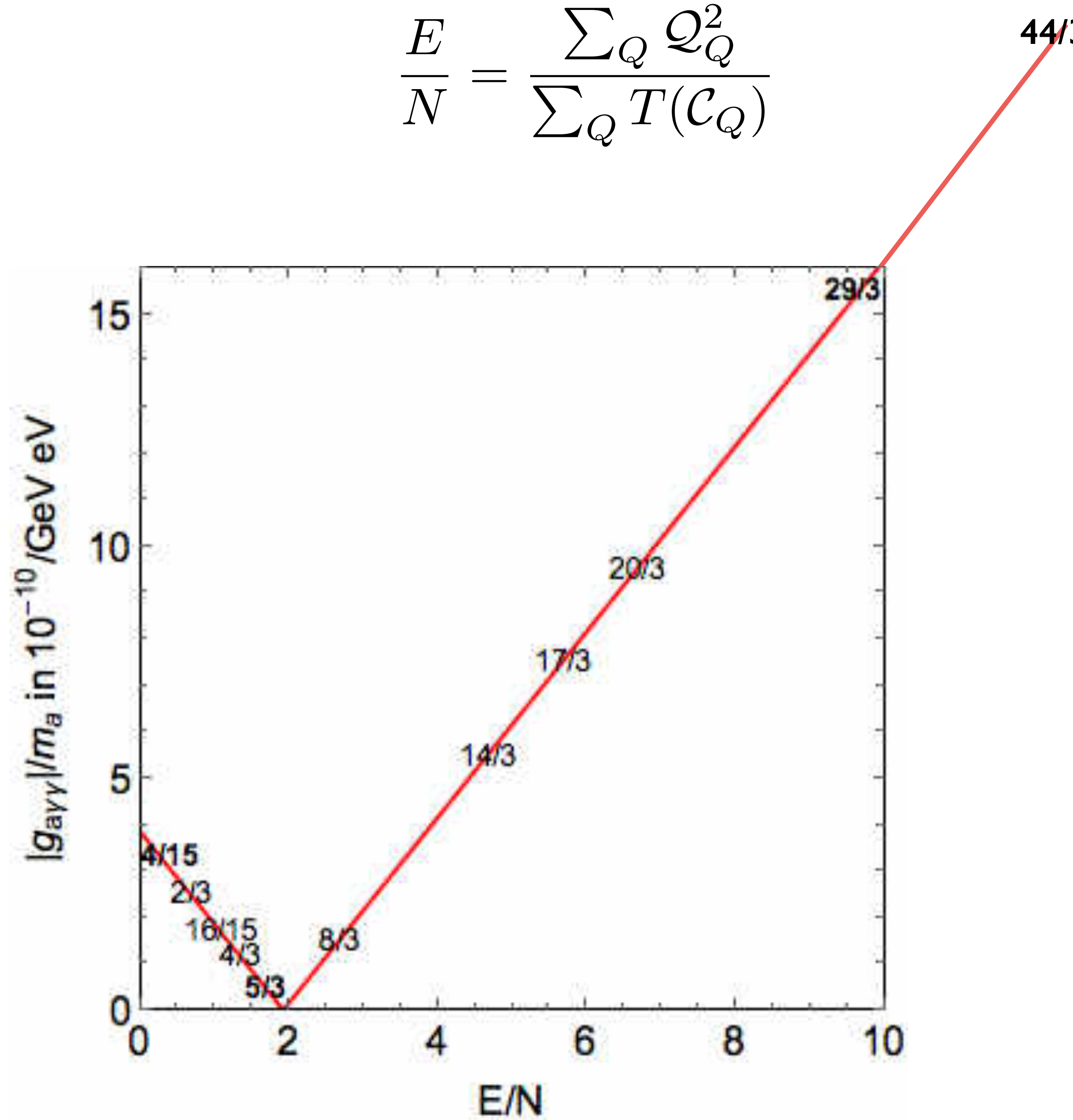
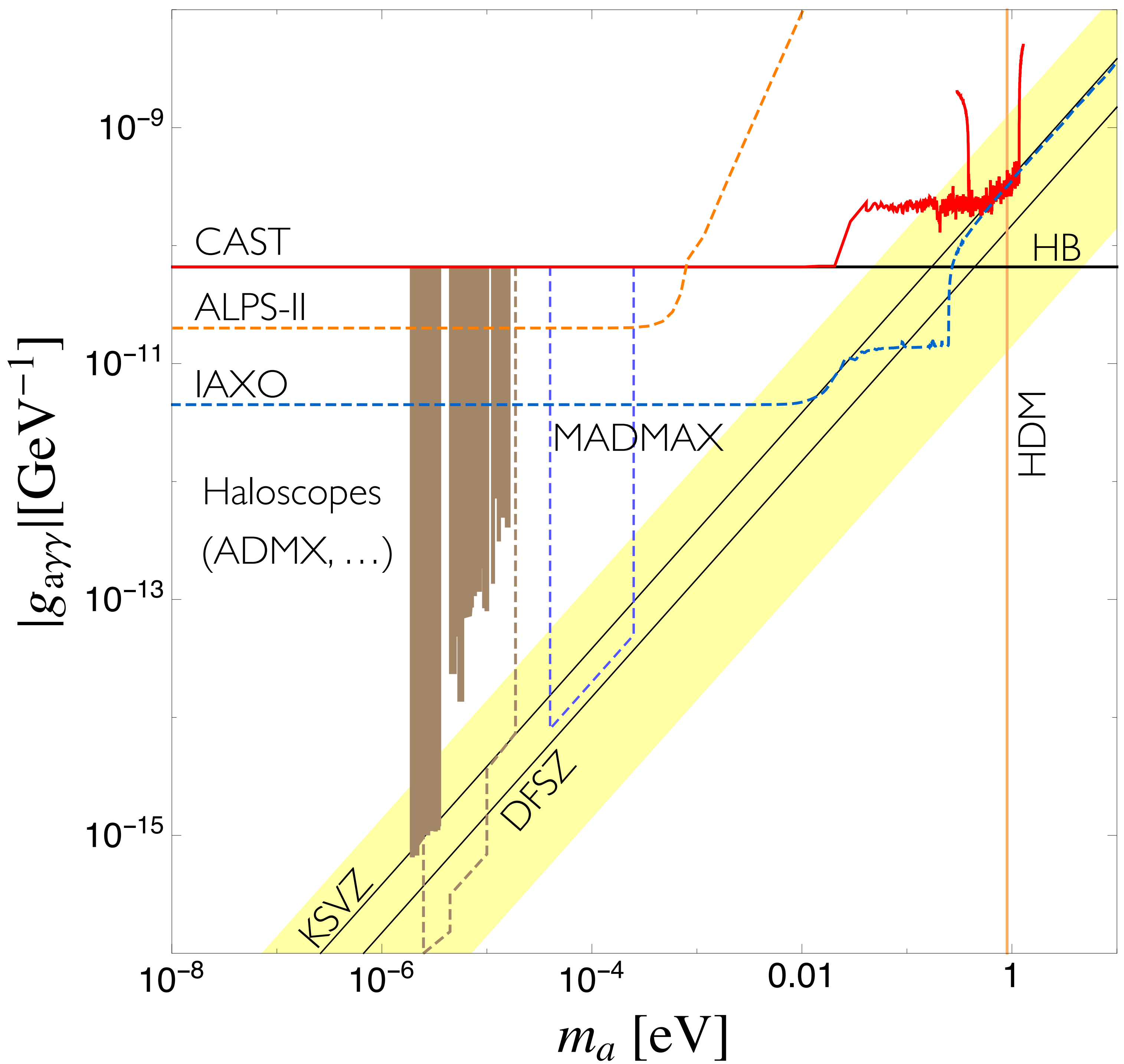


Redefining the axion window



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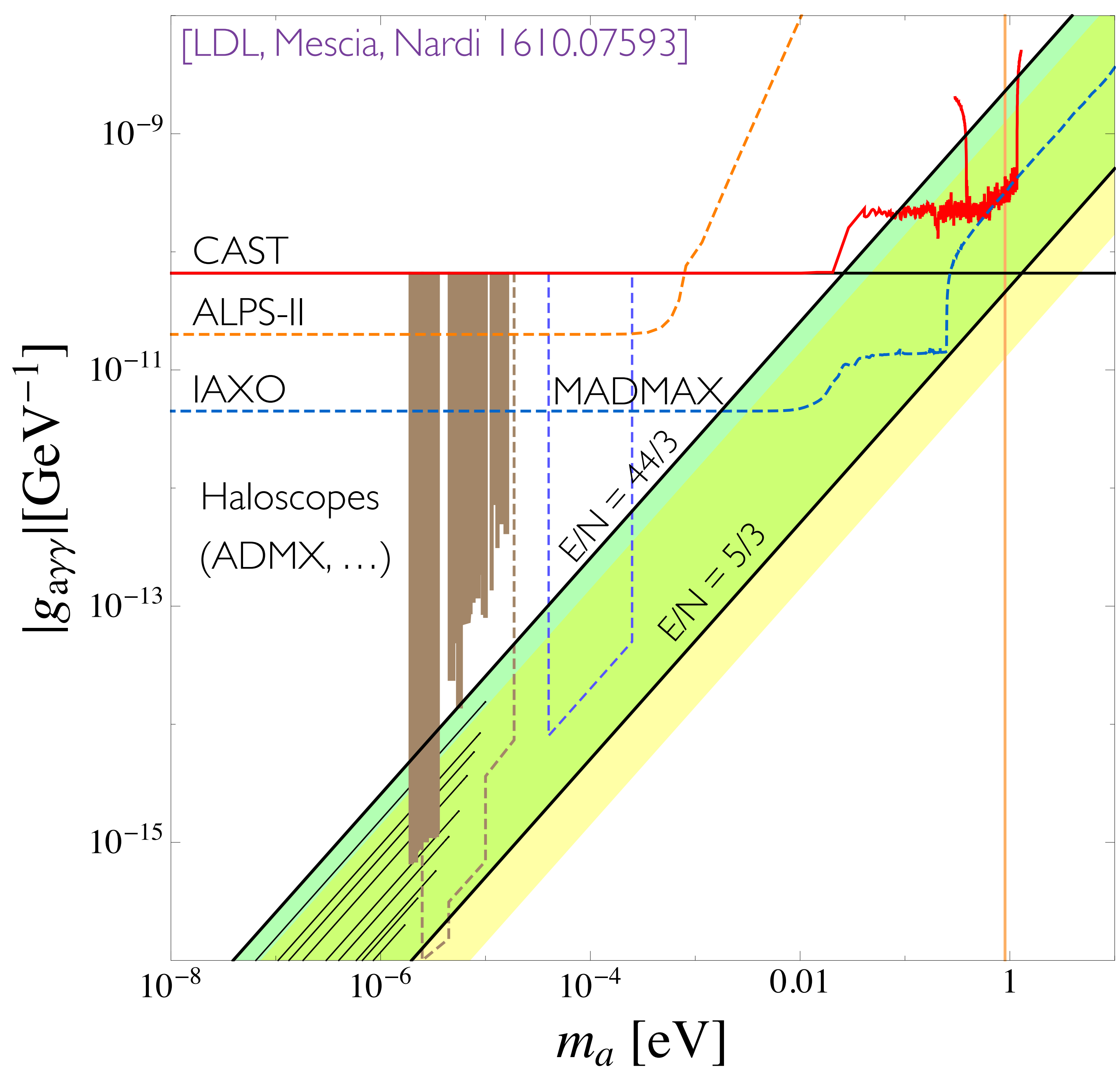


More Q's

- 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)

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

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

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

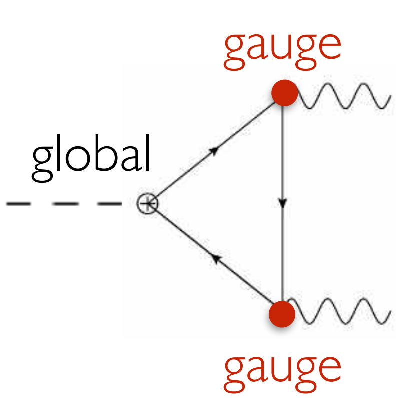
$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10}\ \text{GeV}} \left(\frac{E_c}{N_c} - 1.92(4)\right)$$

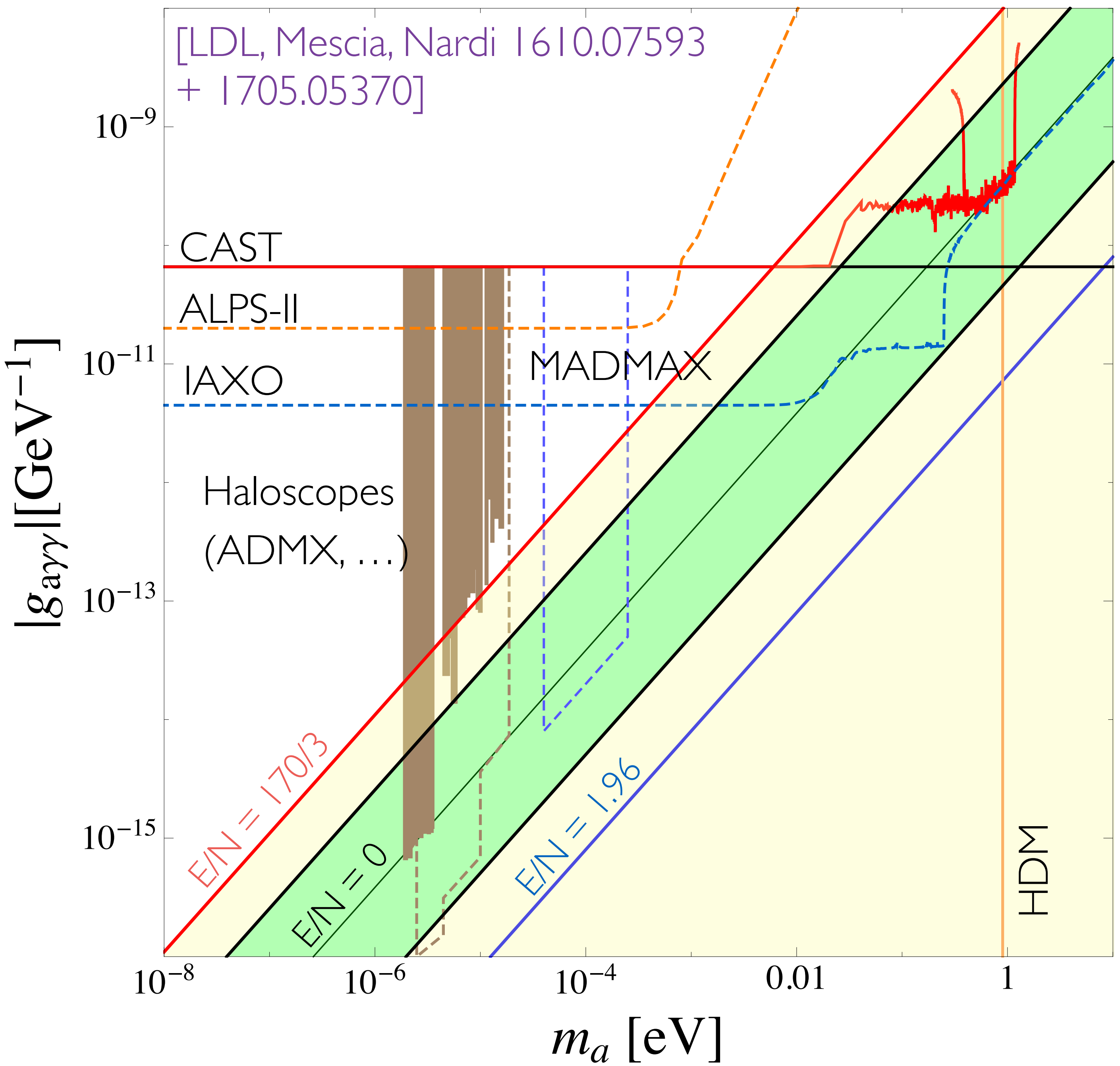
about photophobia: "such a cancellation is immoral, but not unnatural" [D. B. Kaplan, (1985)]

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

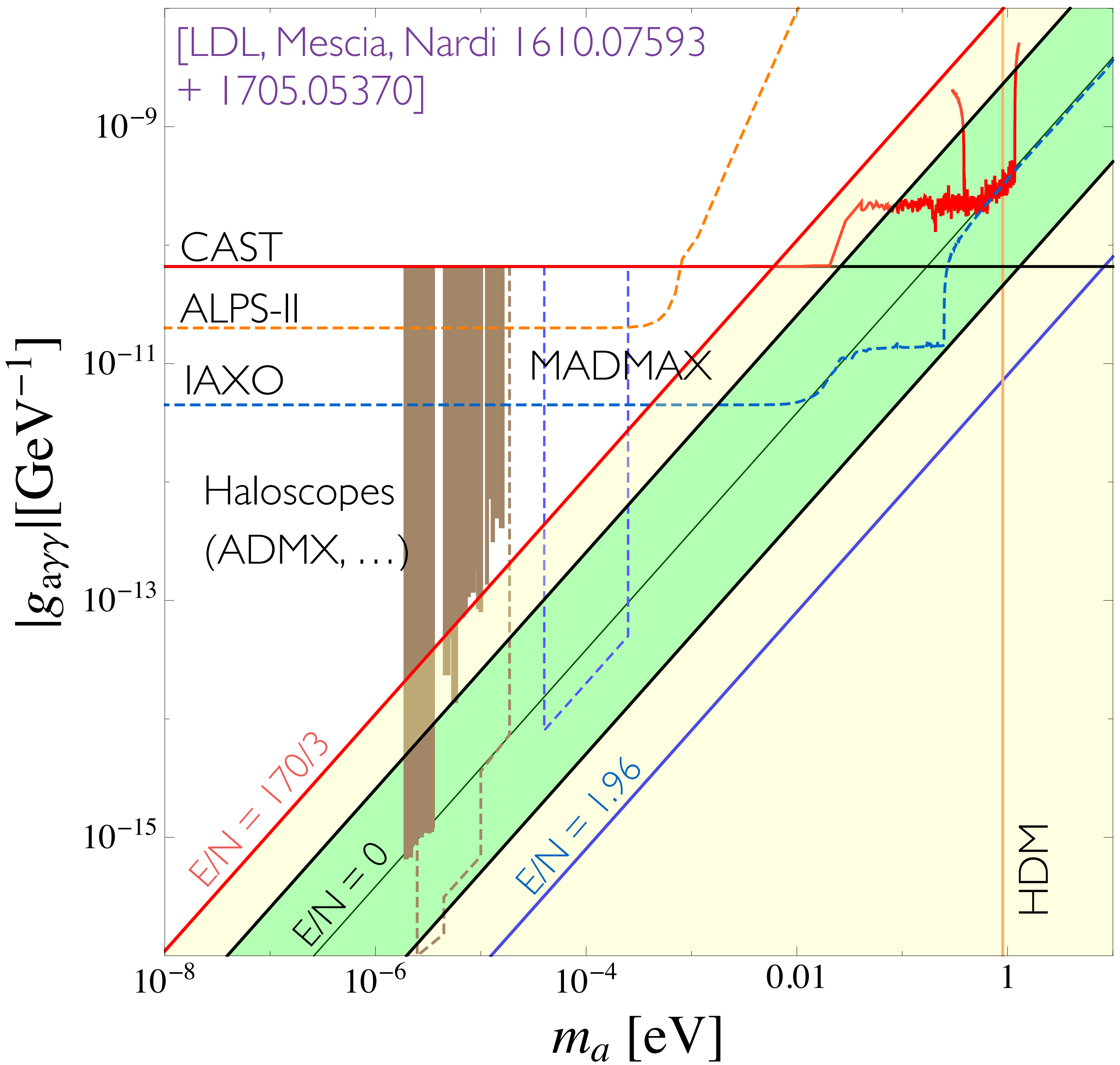
- Red line set by perturbativity [KSVZ] (going much above requires exotic constructions *[more in backup slides]*)

- 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)



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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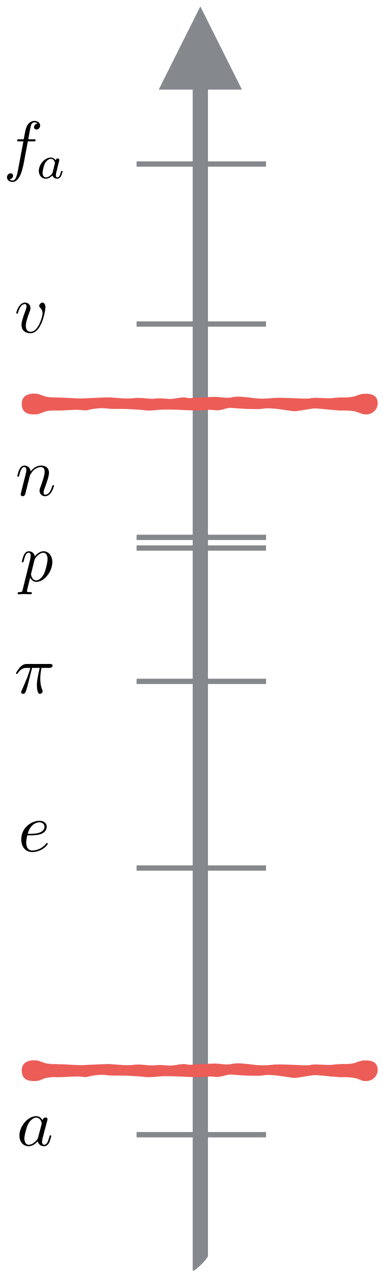
5. unexpected connection with flavour

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

Conditions for nucleophobia

- Axion-nucleon couplings

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



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

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

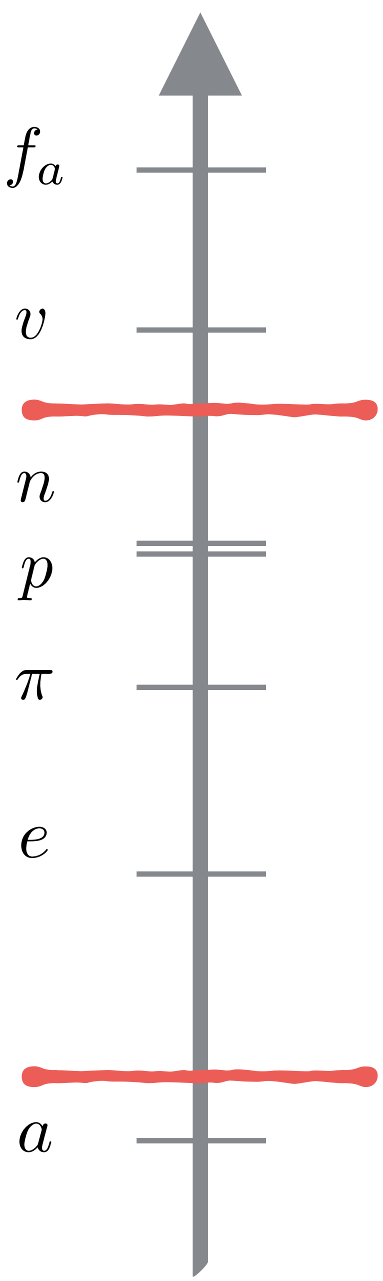
$$\mathcal{L}_N = \frac{\partial_\mu a}{2 f_a} C_N \overline{N} S^\mu N \qquad N = (p, n)$$

EFT-II: non-relativistic nucleons

Conditions for nucleophobia

- Axion-nucleon couplings

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



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

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

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

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

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

Independently of matrix elements:

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

KSVZ/DFSZ no-go

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

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

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

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

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

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

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

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

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

KSVZ/DFSZ no-go

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

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

KSVZ/DFSZ no-go

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

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

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

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

Implementing nucleophobia

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

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

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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

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

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

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

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

Flavour connection

- Nucleophobia implies flavour violating axion couplings !

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

e.g. RH down rotations become physical

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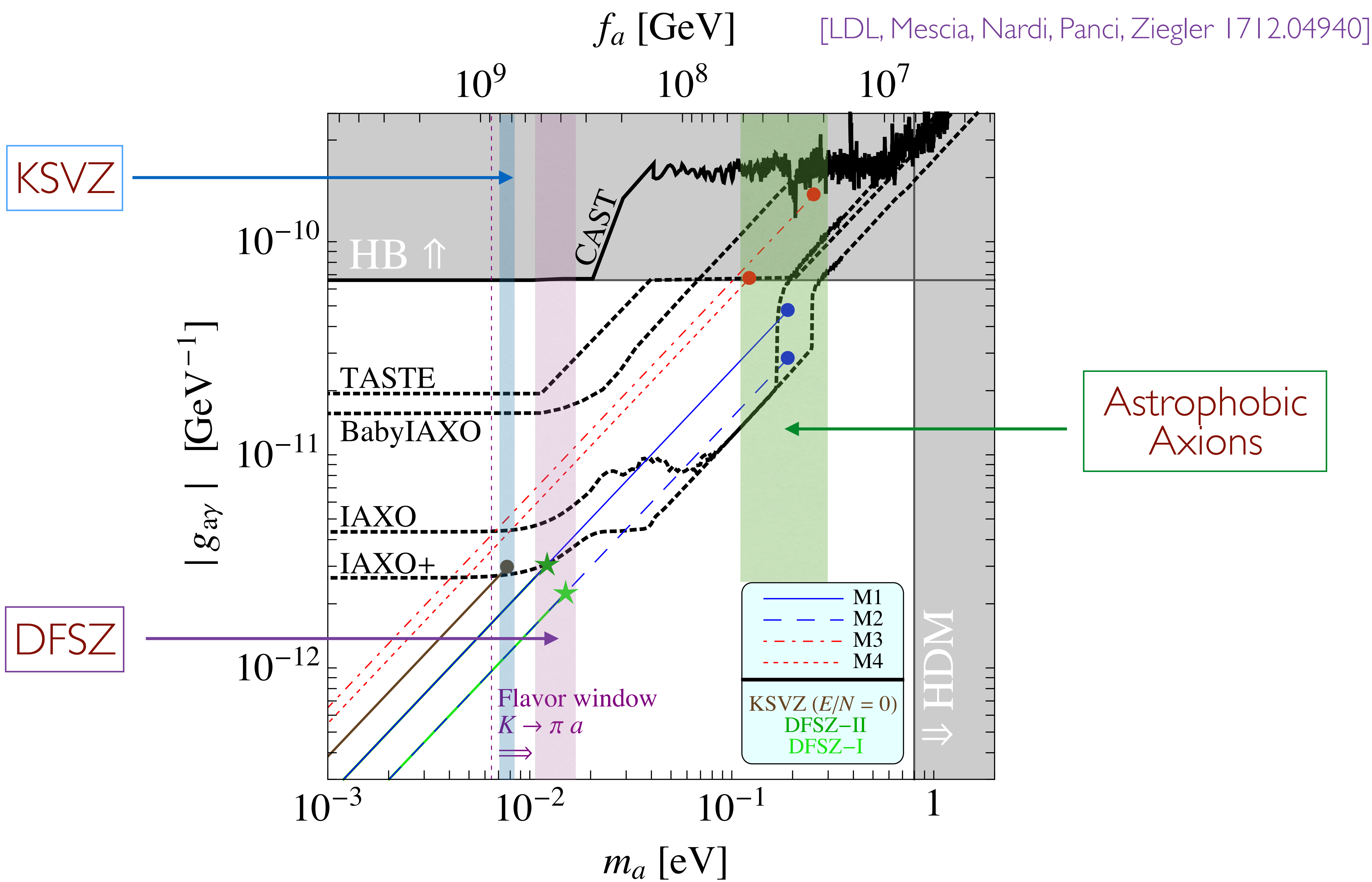
- Plethora of low-energy flavour experiments probing $\frac{\partial_\mu a}{2 f_a} \bar{f}_i \gamma^\mu (C^V_{ij} + C^A_{ij}\gamma_5) f_j$

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

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

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

  - we are entering <u>now</u> the preferred window for the QCD axion

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

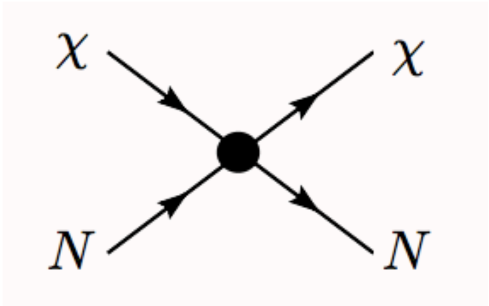
Backup slides

Axions as Dark Matter

Heavy particle vs. light scalar field

(WIMPs) (Axions)

search for single particle scattering



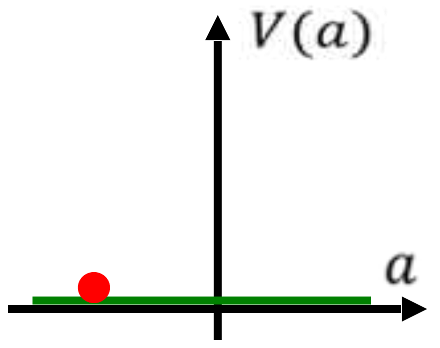
search for coherent effects of the entire field, not particle scattering

(e.o.m. in a FRW background)

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

Axions as Dark Matter

- $T \sim f_a$ (very early Universe)
  - $U(1)_{PQ}$ spontaneously broken, but axion massless
  - axion field sits at $a_0 = \theta_0 f_a$



[Raffelt]

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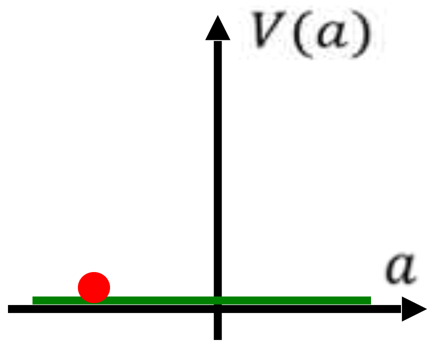
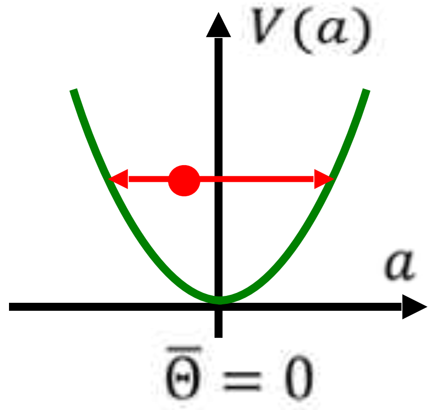
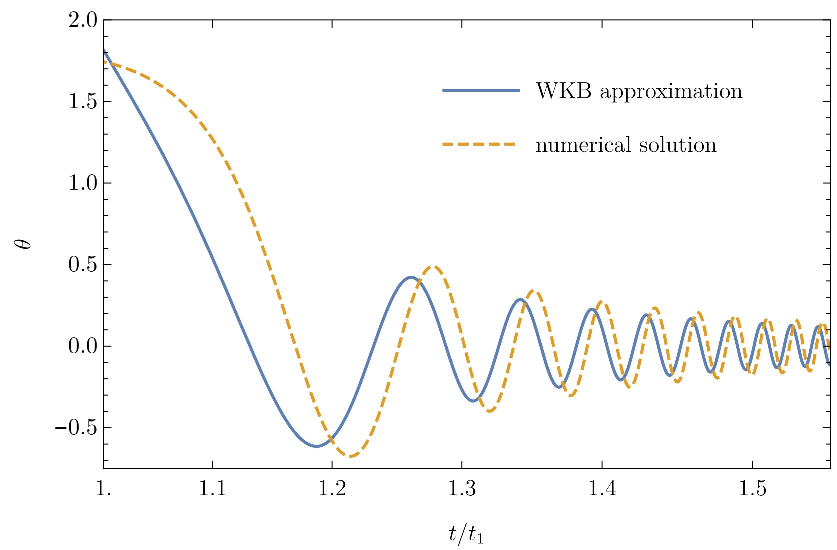


[Raffelt]

- T ~ 1 GeV ($H \sim 10^{-9}$ eV)
  - axion mass turns on due to non-perturbative QCD effects
  - field starts oscillating when $m_a \gtrsim 3H$





[J. Stadler]

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

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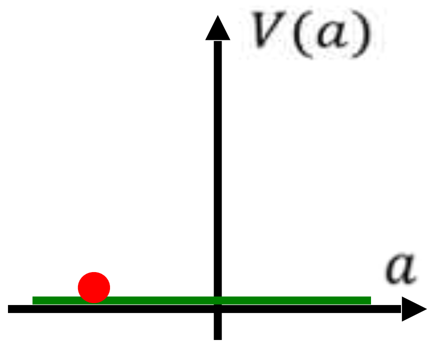

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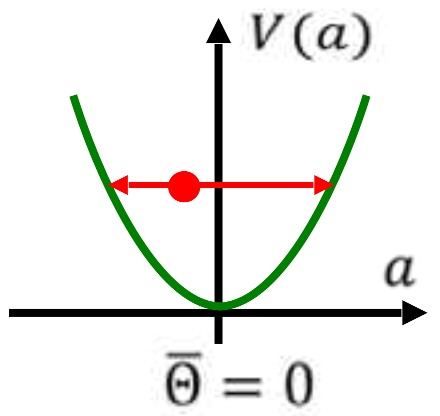


- Energy stored in axion oscillations behaves as Cold DM

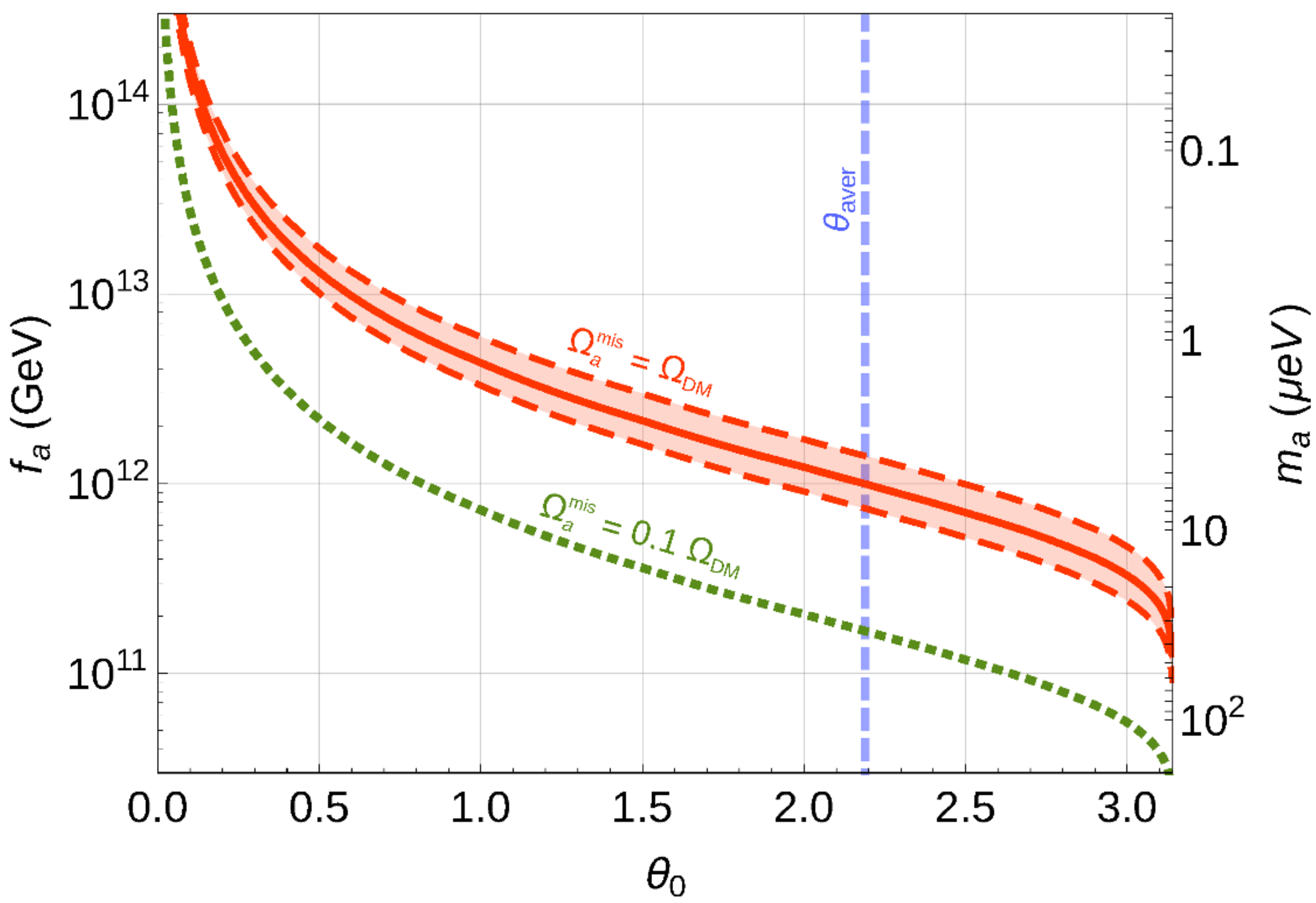
[Preskill, Wise, Wilczek PLB 120 (1983), Abott, Sikivie PLB 120 (1983), Dine, Fischler PLB 120 (1983)]

$a(t) = a_0 \cos(m_a t)$ → depends on the initial condition: misalignment mechanism

Relic abundance

- From lattice QCD simulations: $f_a \lesssim 10^{11\div12}$ GeV for $\theta_0 = \mathcal{O}(1)$

[Bonati et al. 1512.06746, Petreczky et al. 1606.03145, Borsanyi et al. 1606.07494, ...]



Relic abundance

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post-inflationary PQ breaking	*pre-inflationary PQ breaking*
$f_a < \max\{H_I, T_R\}$	$f_a > \max\{H_I, T_R\}$
θ_0 averaged over several Universe patches	θ_0 arbitrary
$\Omega_a^{\text{mis}} < \Omega_{\text{DM}} \xrightarrow{\langle\theta_0\rangle = \pi/\sqrt{3}} f_a \lesssim 5 \cdot 10^{11}$ GeV	misalignment contribution unique, but depends on initial conditions
+ contribution from topological defects	$f_a \gg 10^{12}$ GeV only for $\theta_0 \ll 1$

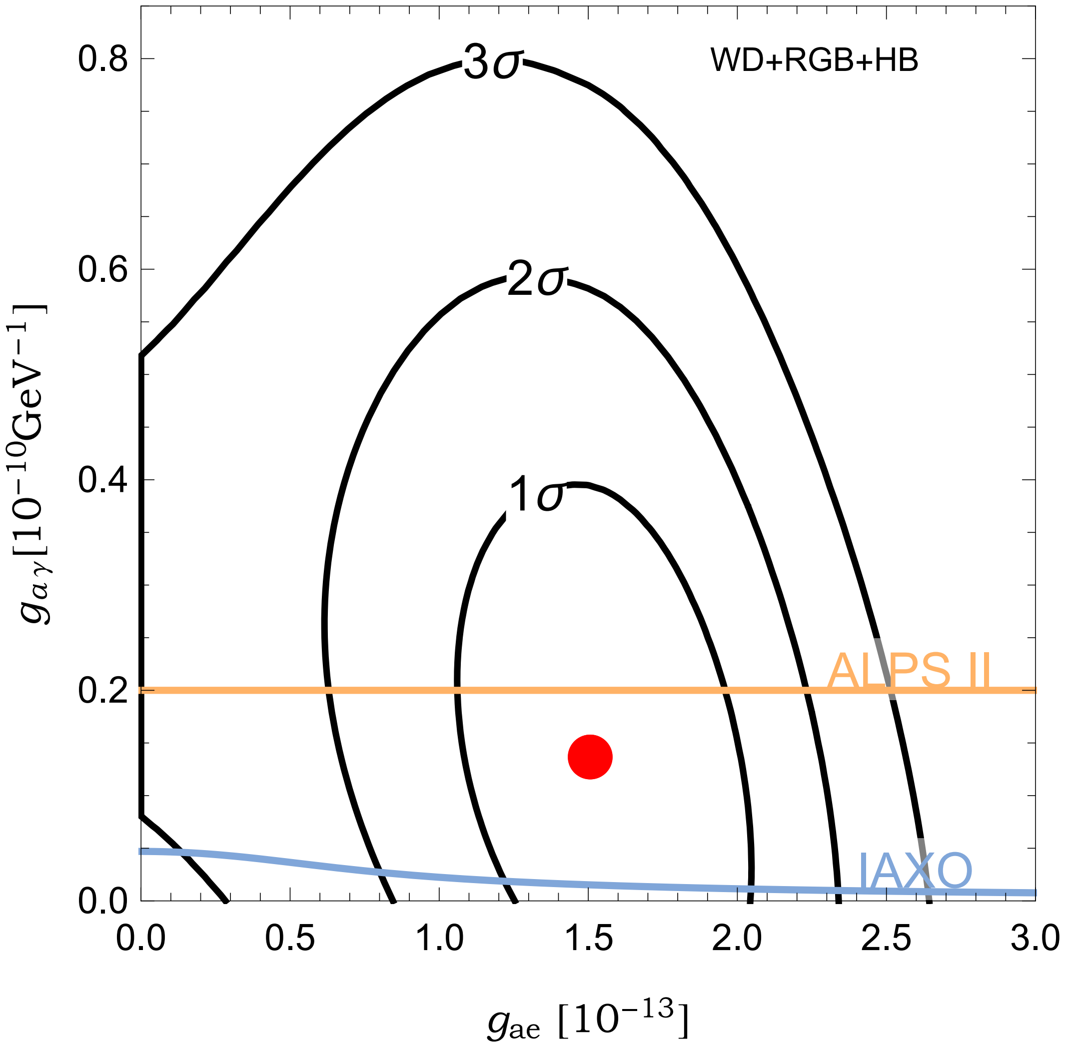
[See e.g. Ringwald, Saikawa 1512.06436
Gorghetto, Hardy, Villadoro 1806.04677]

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

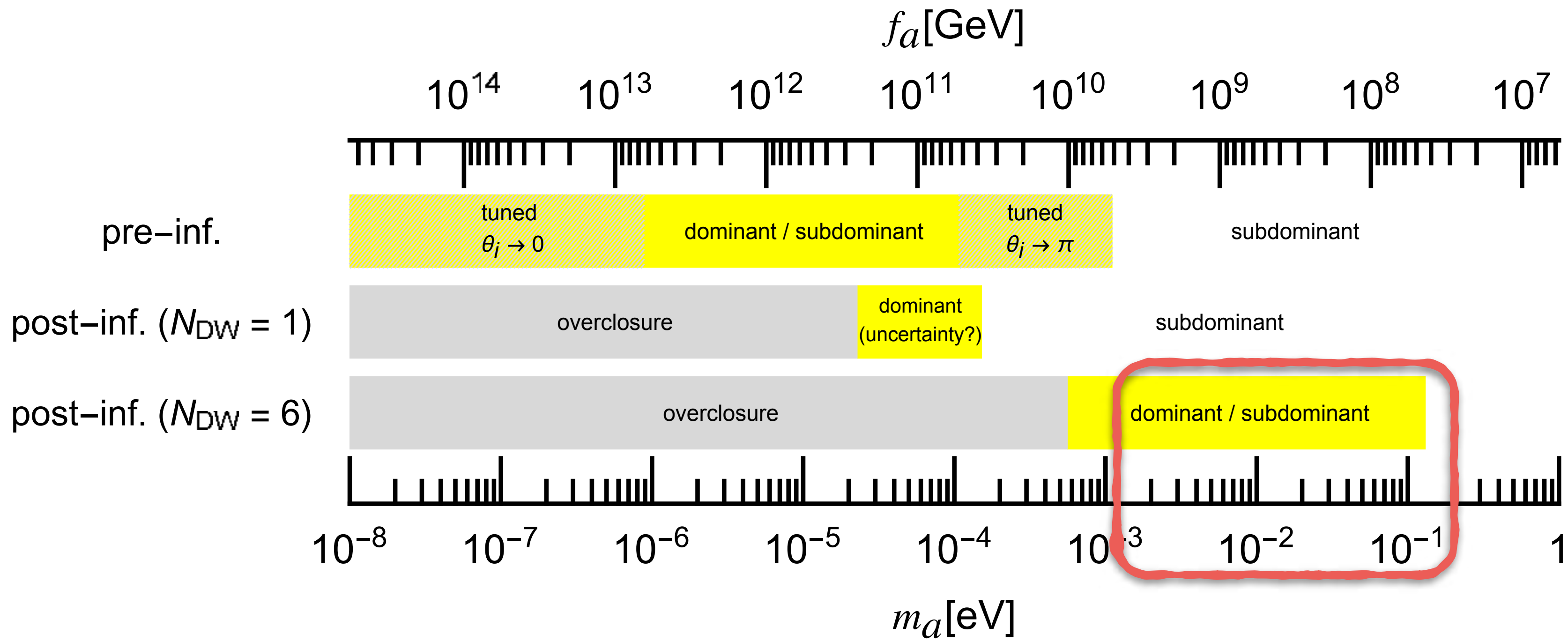
*SN bound a factor ~4 weaker than PDG one ?

[Chang, Essig, McDermott 1803.00993]

DM in the heavy axion window

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

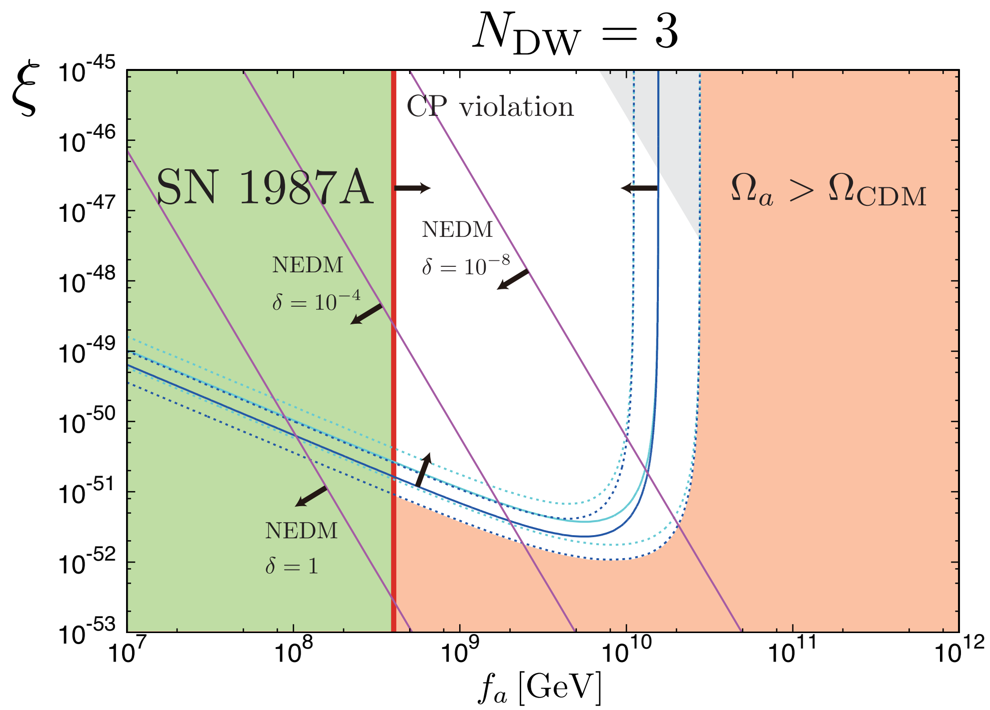
[Kawasaki, Saikawa, Sekiguchi, 1412.0789 1709.07091]



- axion production from topological defects

- requires explicit PQ breaking term

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



Boosting E/N in DFSZ

- Potentially large E/N due to electron PQ charge

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

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

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

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

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

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

Boosting E/N in DFSZ

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

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

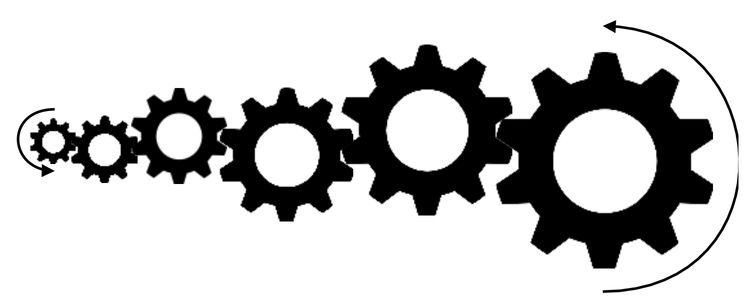
- Clockwork-like scenarios allow to boost E/N [LDL, Mescia, Nardi 1705.05370]

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

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

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

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



[Giudice, McCullough]

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

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

Axion coupling to photons

- Axion effective Lagrangian [See e.g. Grilli di Cortona et al., 1511.02867]

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

field-depended chiral transformation to eliminate aGGtilde: $q = \begin{pmatrix} u \\ d \end{pmatrix} \to e^{i\gamma_5 \frac{a}{2f_a}Q_a}\begin{pmatrix} u \\ d \end{pmatrix}$

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

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

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

$$\Downarrow$$

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

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

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

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

model independent

depends on UV completion

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

Selection criteria

- We require: [for $T_{reheating} > m_Q \sim f_a$ (post-inflat. PQ breaking)]

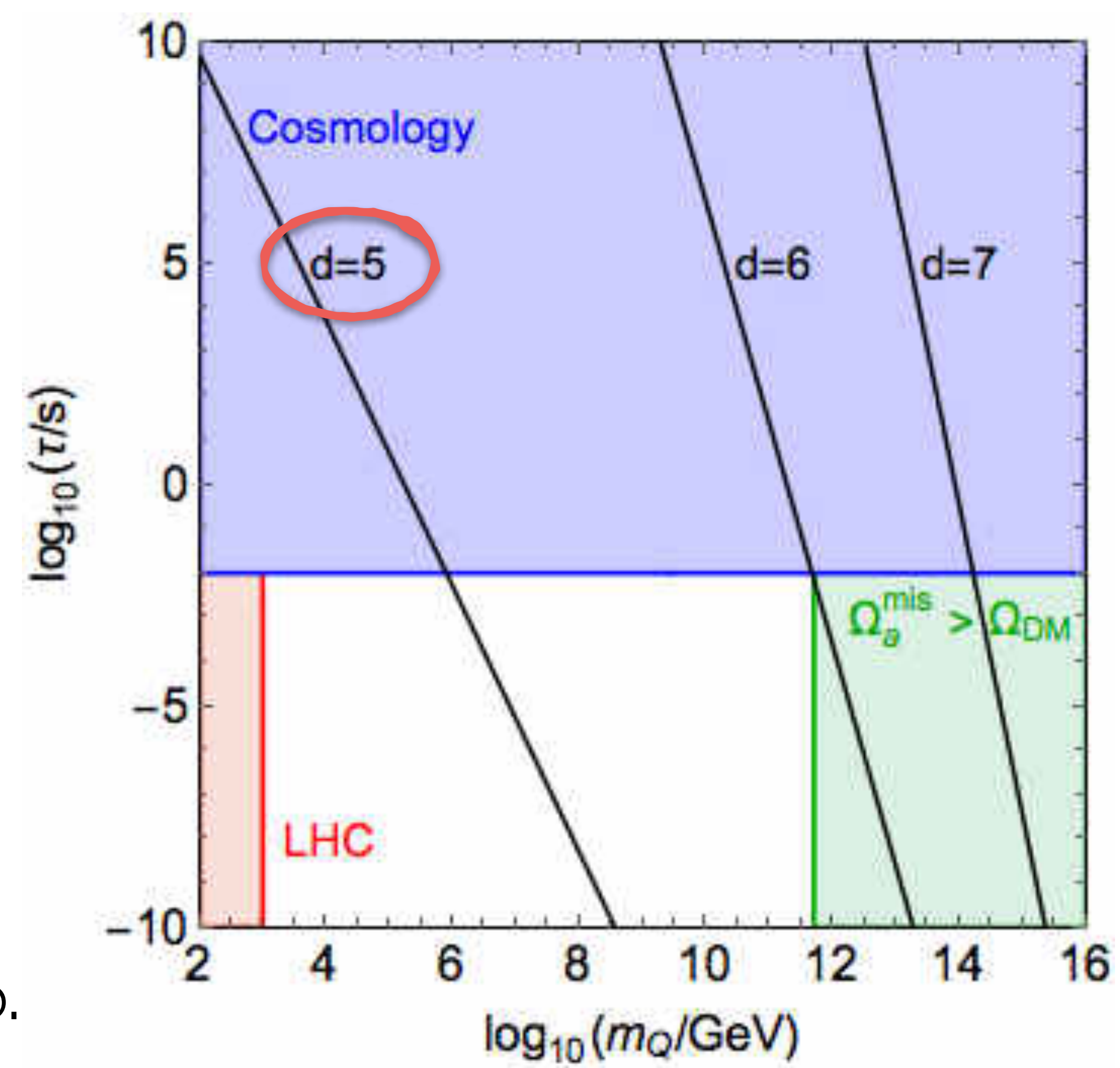
1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s

   - decays via d=4 operators are fast enough

   - decays via effective operators

$$\mathcal{L}_{Qq}^{d>4} = \frac{1}{M_{\text{Planck}}^{(d-4)}} \mathcal{O}_{Qq}^{d>4} + \text{h.c.}$$

$$\Gamma_{\text{NDA}} = \frac{1}{4(4\pi)^{2n_f-3}(n_f-1)!(n_f-2)!} \frac{m_Q^{2d-7}}{M_{\text{Planck}}^{2(d-4)}}$$



→ "safe" Q must allow for d=4 or 5 decay op.

Selection criteria

- We require: [for $T_{reheating} > m_Q \sim f_a$ (post-inflat. PQ breaking)]

1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s
2. No Landau poles below 10^{18} GeV

   - bound on Q multiplet dimensionality

$$\mu \frac{d}{d\mu} g_i = -b_i \, g_i^3 \qquad b_i = \text{gauge -matter}$$

N.B. two-loop effects crucial if 1-loop b.f. is accidentally small

[LDL, Gröber, Kamenik, Nardecchia, 1504.00359]