Rethinking the QCD Axion

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- *Outline*

- ✓ **Introduction:** *The strong CP problem*
- ✓ **Experimental Searches:**
  Axion Landscape couplings: model independent vs. model dependent
- ✓ **Model Building:** *Re-opening the axion window*

LAPth, January 11th 2019, Annecy

Introduction: Strong CP problem

❖ **Experimentally:** η' mass much larger than the π one

→ $U(1)_A$ *is an anomalous symmetry of QCD*

→ The QCD vacuum is not trivial

→ *add a θ-term to the usual QCD Lagrangian*

$$\mathcal{L}_{eff}^{QCD} = \mathcal{L}^{QCD} + \theta \frac{\alpha_s}{16\pi} G_a^{\mu\nu} G_{a,\mu\nu}$$

Now, QCD violates T and P, namely CP!

Strong CP Problem: the non-trivial QCD Vacuum

The strong CP problem

❑ **QCD is defined in terms of two dimensionless parameters, which are not predicted by the theory.**

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

1 $\alpha_s \sim O(0.1\text{-}1)$

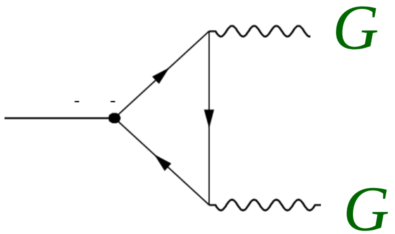
2 $\bar{\theta}$

$$\bar{\theta} = \theta - \sum_q \theta_q$$ has physical meaning

because of chiral anomaly

$$q \to e^{i\gamma_5\alpha}q$$ → $$\theta_q \to \theta_q + 2\alpha$$ $$\theta \to \theta + 2\alpha$$

$\partial^\mu j^5_\mu$



The strong CP problem

❑ **QCD is defined in terms of two dimensionless parameters, which are not predicted by the theory.**

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

1 $\alpha_s \sim O(0.1\text{-}1)$

2 $\bar{\theta}$

➢ **Experimentally:** no CP violation in the strong sector found!

Neutron EDM small

$$d \leq 6 10^{-26} \mathrm{e\ cm} \qquad d \approx e\theta m_q / M_N^2$$

⇒ $\bar{\theta} < 10^{-10}$ Why so small?

The strong CP problem

❑ **QCD is defined in terms of two dimensionless parameters, which are not predicted by the theory.**

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

Why so small?

2

$\bar{\theta} < 10^{-10}$ from the exp. bound of the neutron EDM.

- Qualitatively different from other "small value" problems of the SM

  - $\overline{\theta}$ is radiatively stable (unlike $m_H^2 \ll \Lambda_{\rm UV}^2$) [Ellis, Gaillard (1979)]

  - it evades explanations based on environmental selection

    (unlike $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$) [Ubaldi, 0811.1599]

The strong CP problem: Solution 1 → m_u=0

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}\,(i\not{D} - m_q)\,q - \frac{1}{4} G^{\mu\nu}_a G^a_{\mu\nu} - \bar{\theta}\frac{\alpha_s}{8\pi} G^{\mu\nu}_a \tilde{G}^a_{\mu\nu}$$

- **Again if we chiral transform a quark:**

If m=0,
$\theta \to \theta - 2\alpha$

$$q \to e^{i\gamma_5\alpha} q: \quad \int\left(-m\bar{q}q + \frac{\theta}{32\pi^2} G\tilde{G}\right)$$

$$\to \int\left(-m\bar{q}\,e^{2i\gamma_5\alpha} q + \frac{\theta - 2\alpha}{32\pi^2} G\tilde{G}\right)$$

Thus, setting α= θ/2, θ_{total} = θ-2α = 0.

$\bar{\theta}$ could be rotated away! There is no strong CP problem.

- In the SM, no massless quarks → m_u/m_d=0.5 at 20 σ by Lattice QCD
- BSM, new family of quarks with m=0 would imply new hadrons!

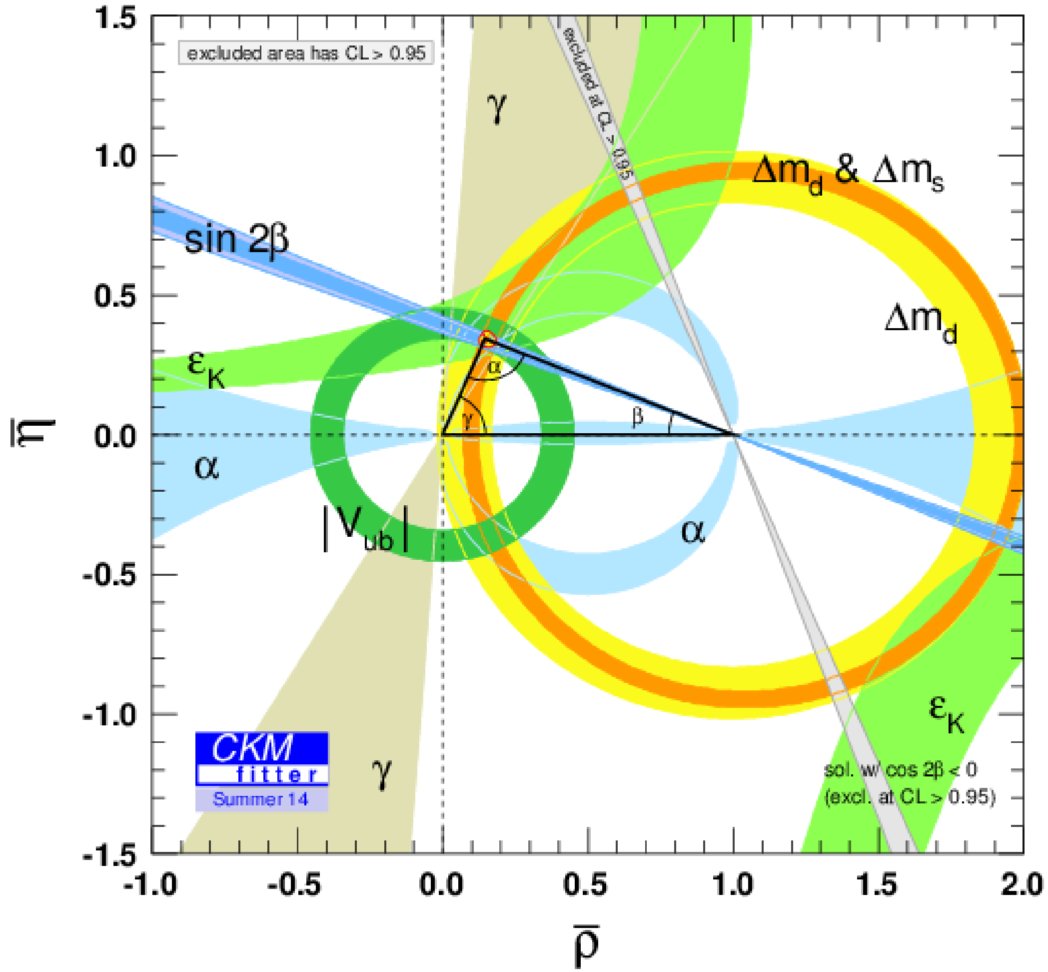
The strong CP problem: Solution 2 → CP spontaneously broken

If CP is a symmetry of nature (but spontaneously broken) then we can set $\bar{\theta}=0$ at the Lagrangian level

However ....

The strong CP problem: Solution 2 → CP spontaneously broken

Experimental data are in excellent agreement with the CKM Model – a model where CP is explicitly broken



In the CKM model, CP violated by an explicit weak phase η in the off diagonal phases of Y

The strong CP problem: Solution 3 → $\mathbf{U(1)_{PQ}}$ and Axion

The third Solution: *an additional symmetry*

Peccei & Quinn '77
Weinberg; Wilczek '78

$$\mathcal{L}_\theta = \bar{\theta}\,\frac{\alpha_s}{8\pi} G_a^{\mu\nu} G_{a,\mu\nu} \quad \Longrightarrow \quad \mathcal{L}_a^{eff} = \left(\bar{\theta} + \frac{a}{f_a}\right)\frac{\alpha_s}{8\pi} G_a^{\mu\nu} G_{a,\mu\nu} + \frac{(\partial_\mu a)^2}{2} + \mathcal{L}(\partial_\mu a, q)$$

Shift Symmetry!

$$a(x) \to a(x) - \alpha f_a$$

$a(x)$ is GB

$\alpha = \bar{\theta}$

θ rotated away!
There is no strong CP problem.

$$\mathcal{L}_a^{eff} = \frac{(\partial_\mu a)^2}{2} + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G_a^{\mu\nu} G_{a,\mu\nu} + \mathcal{L}(\partial_\mu a, q)$$

New particle, Axion, to solve the Strong CP Problem

The strong CP problem: Solution 3 → $U(1)_{PQ}$ and Axion!

Peccei & Quinn '77; Weinberg; Wilczek '78

$$a(x) \to a(x) - \alpha f_a$$

$$\mathcal{L}_a^{eff} = \frac{(\partial_\mu a)^2}{2} + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G_a^{\mu\nu} G_{a,\mu\nu} + \mathcal{L}(\partial_\mu a, q)$$

⇓ ⇓

- a non-linearly realized U(1) symmetry:

→ U(1): *spontaneously broken!*

$$\varphi = f_a e^{ia/f_a} \Rightarrow \varphi' = e^{-i\alpha}\varphi$$

- No strong CP problem
- U(1) broken by QCD anomaly (chiral rotation for fermions)!
- $H(0) < H(a) \Rightarrow a=0$ *min*. stable

$a(x)$ is PGB

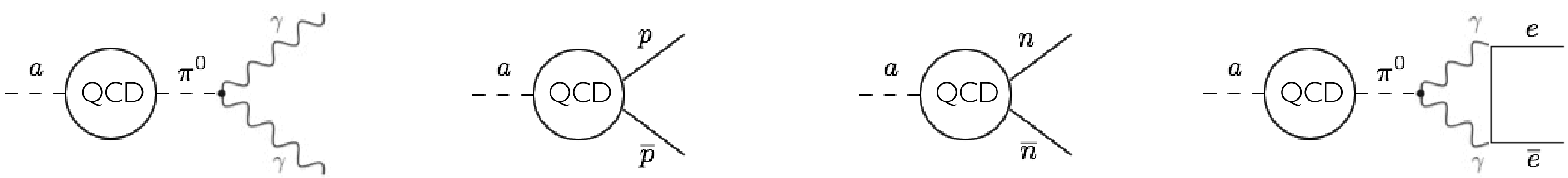
Axion EFT: Model Independent Feature

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

  - generate axion mass

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

  - generates axion couplings to photons, nucleons, electrons.



✓ **All axion couplings**: $\sim 1/f_a$

Axion EFT: Model Independent Feature

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

  - ✓ **Axion mass**: $m_a \approx 0.1\,\text{eV}\,\frac{10^8\,\text{GeV}}{f_a}$

  - ✓ **All axion couplings**: $\sim 1/f_a$

The lighter is the axion, the weaker are its interactions!

Invisible *(light)* particle *(not yet measured)*

Search Strategies and current limits

- **Astrophysical bounds**

Ringwald, Rosenberg, Rybka, PDG (2016)

  - Star evolution, RG lifetime $g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11}\ \mathrm{GeV}^{-1}$
  - White dwarf cooling $g_{aee} \lesssim 1.3 \times 10^{-13}\,\mathrm{GeV}^{-1}$
  - Supernova SN1987A $g_{aNN} \lesssim 3 \times 10^{-7}\ \mathrm{GeV}^{-1}$

→ weak couplings

$$f_a \gtrsim 2 \times 10^8\ \mathrm{GeV}$$

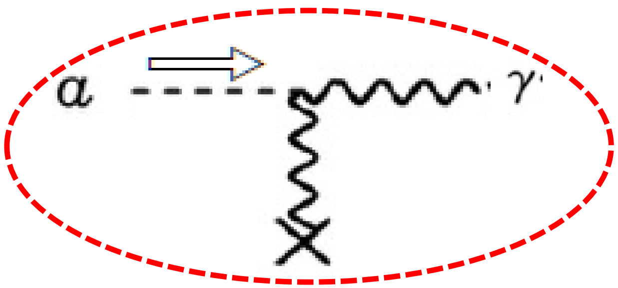
- **Most laboratory search techniques are sensitive to $g_{a\gamma\gamma}$**

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

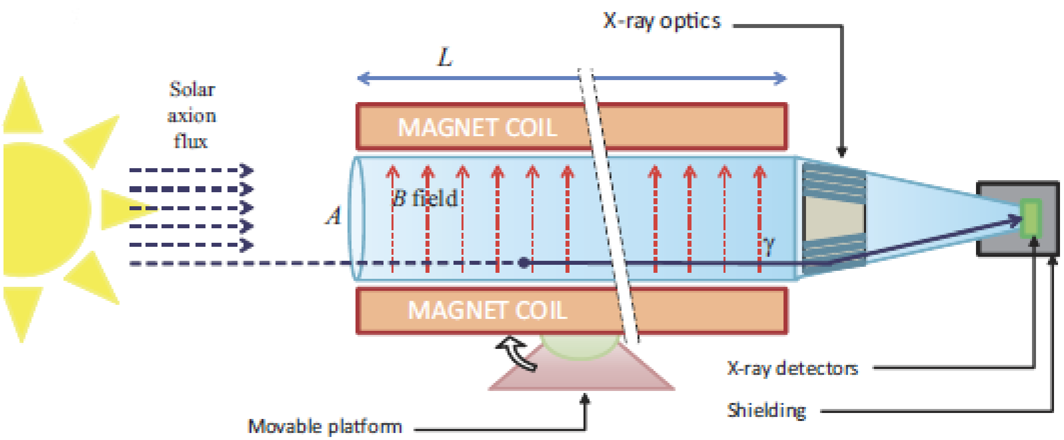
  - Light Shining trough Walls
    Photon conversion into Axions, reconverted back into photons after passing a wall
  - Haloscopes
    Search for Axion Dark Matter
  - Helioscopes
    Search for Axions produced in the Sun

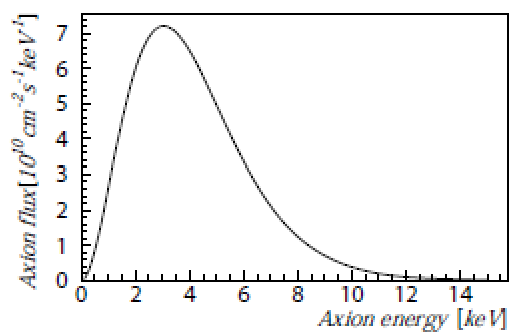
Helioscopes: CAST (CERN), **IAXO (DESY)**

- The Sun is a potential source of a copious axion flux



Primakoff efect: axion-photon transition in external static E or B field

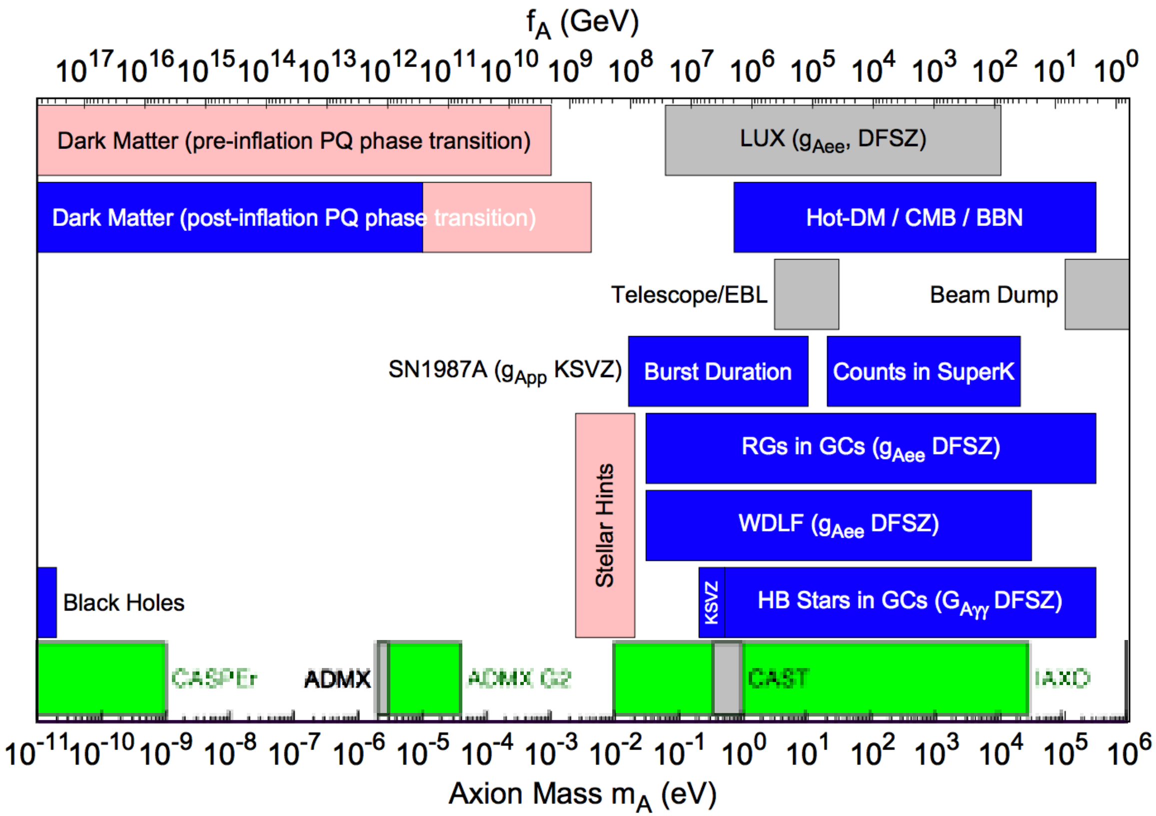




- macroscopic transverse B-field over a large volume triggers axion to photon (x-ray) conversion

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2016)



Lab exclusions

Astro/cosmo exclusions

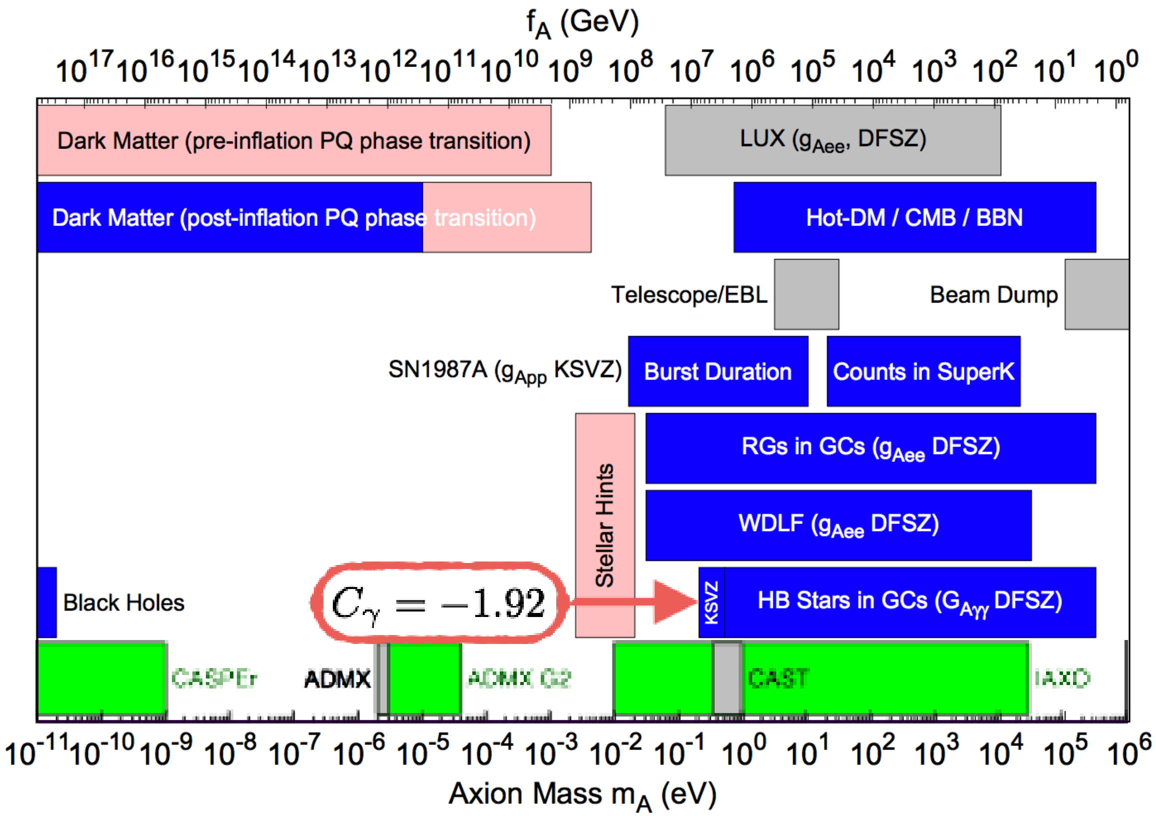
DM explained / Astro Hints

Exp. sensitivities

- Bound on axion mass is of practical convenience, but ………..!

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2016)



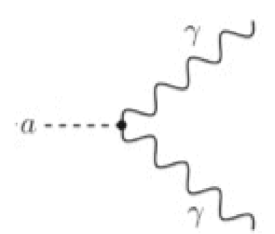
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

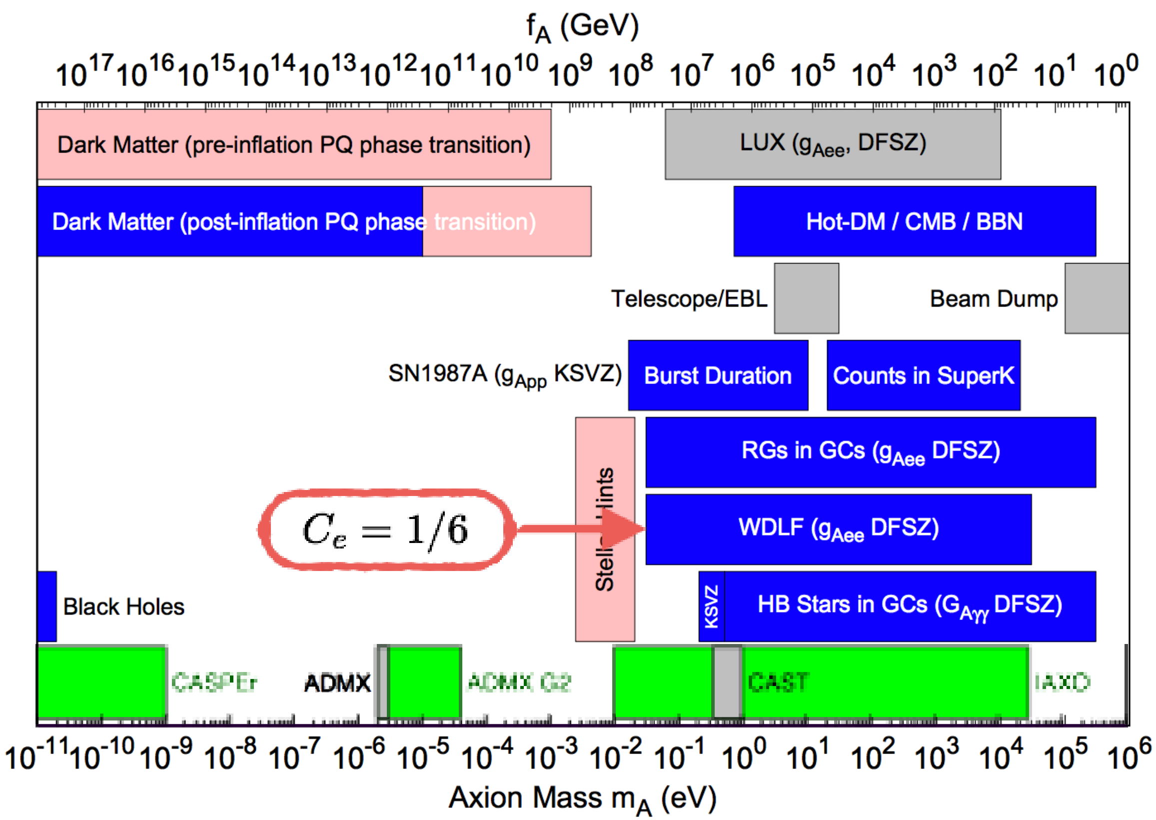
- Horizontal branch star evolution in globular clusters



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

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2016)



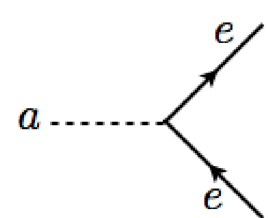
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

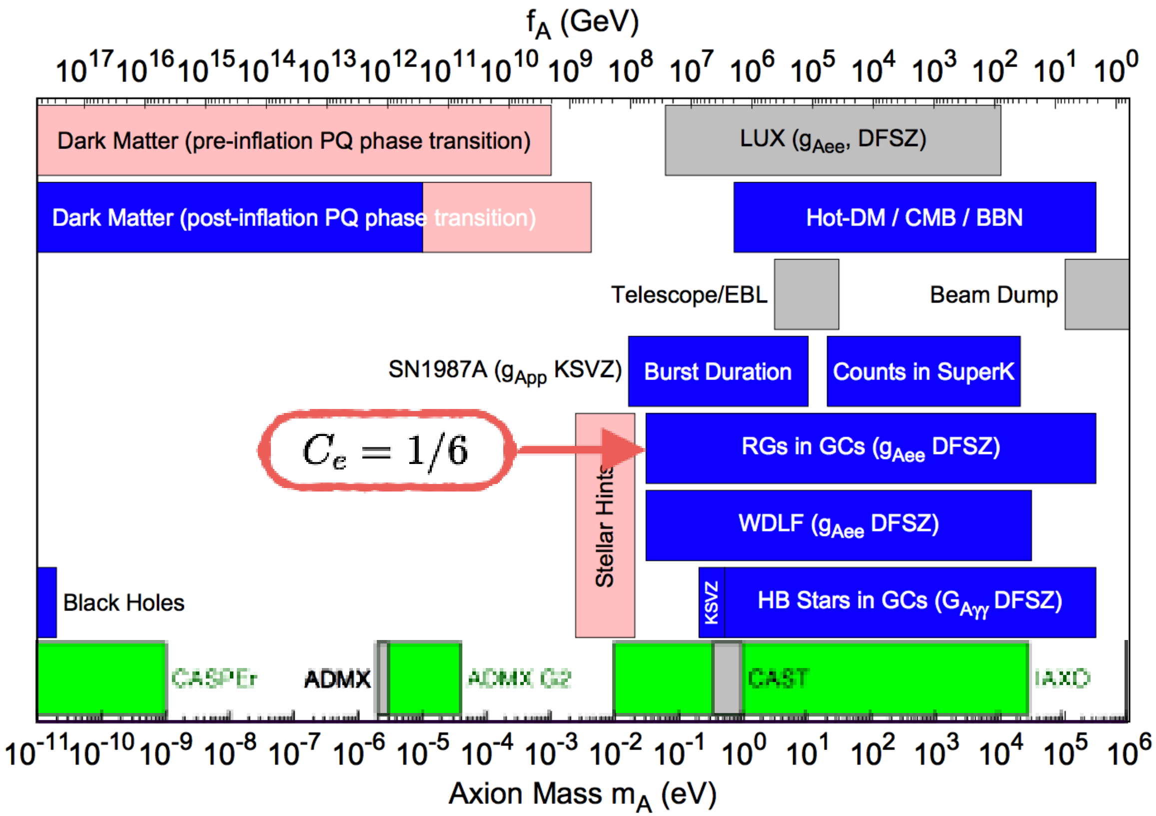
- White Dwarfs luminosity function (cooling)



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

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2016)



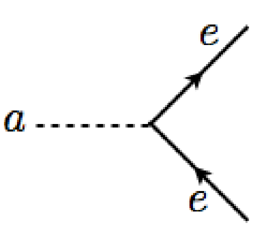
Lab exclusions

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

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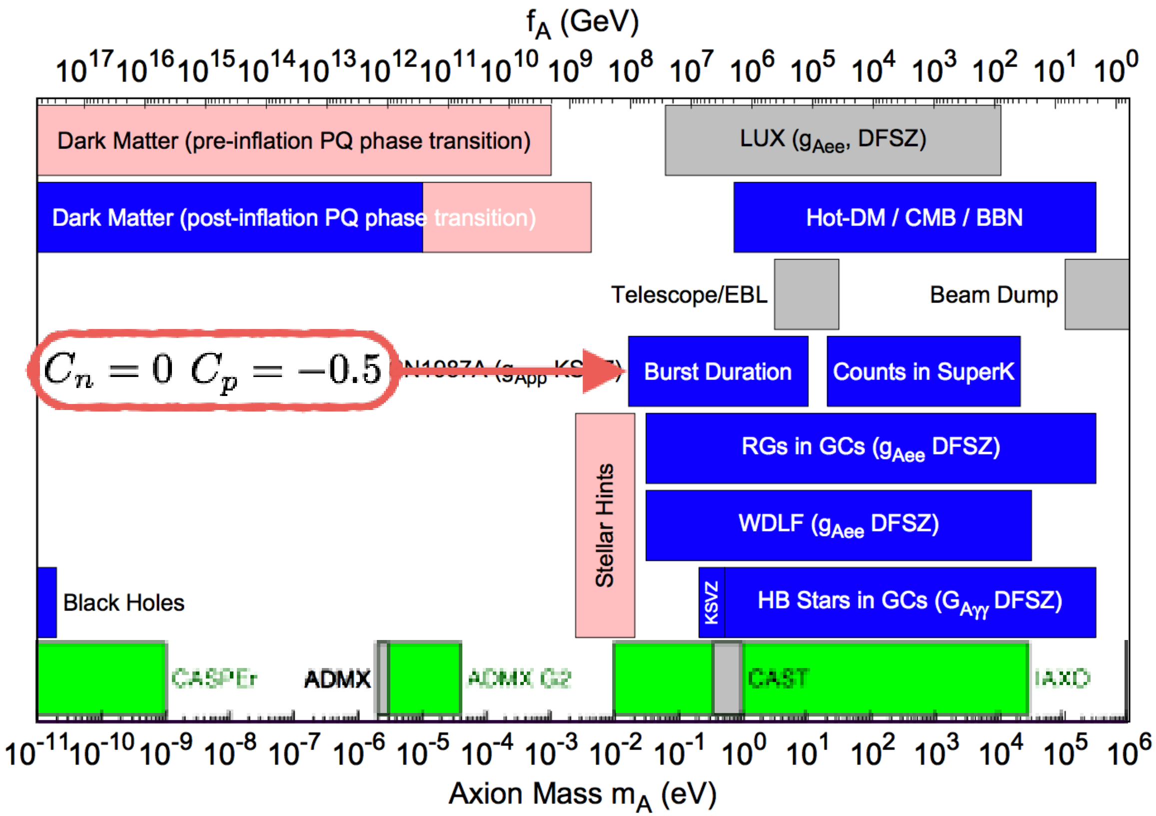


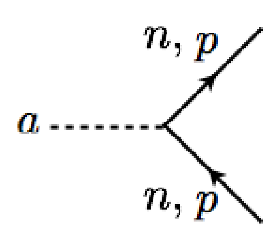
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- Burst duration of SN1987A nu signal

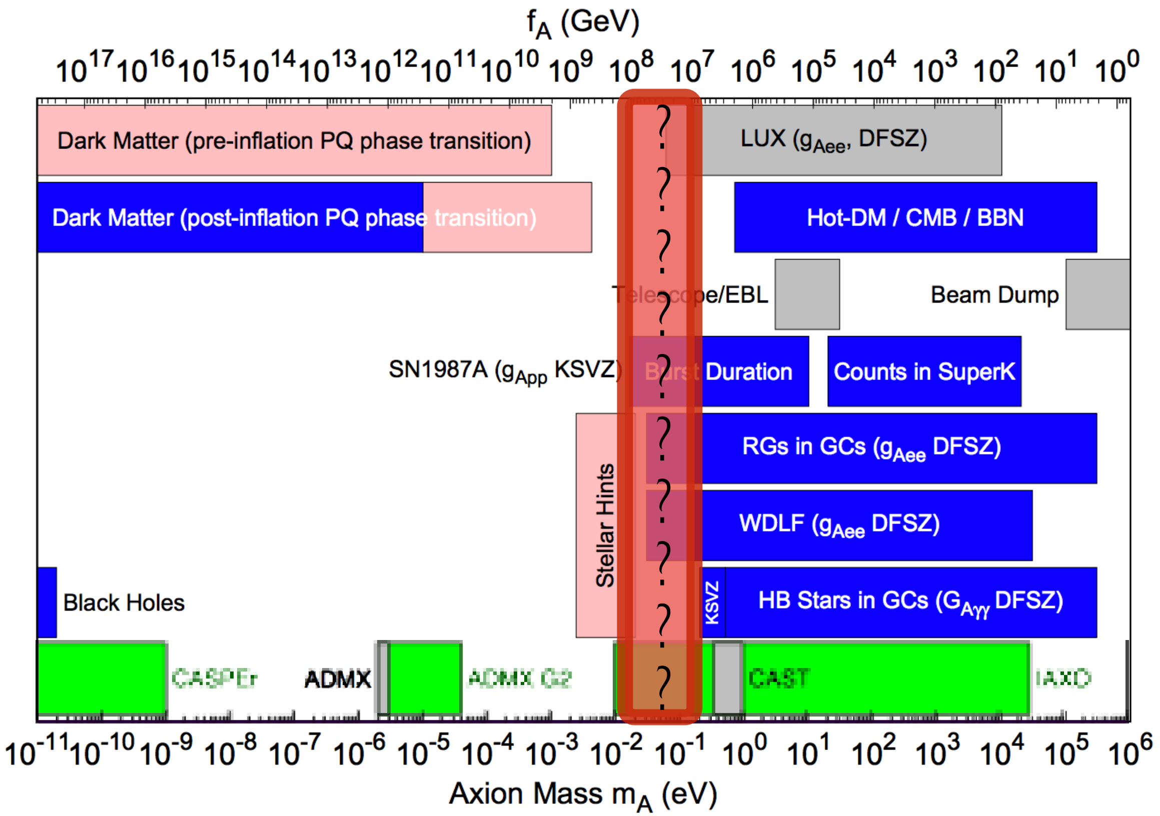


$$C_n m_n \frac{a}{f_a} [i\bar{n}\gamma_5 n]$$

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

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2016)



Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- Bound on axion mass is of practical convenience, but misses model dependence !
- since 2016 we start to critically revise this bound !

Axion EFT

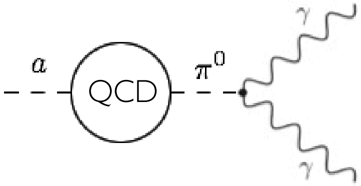
- All you need is (to solve the strong CP problem)

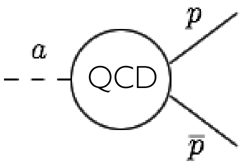
  a new spin-0 boson with pseudo-shift symmetry $a \to a + \alpha\, f_a$

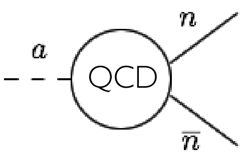
  broken by $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}_a \tilde{G}^a_{\mu\nu}$

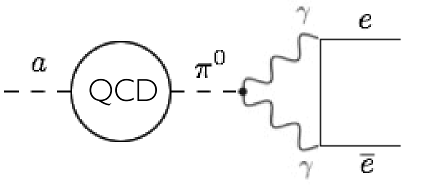
- **generates "model independent" axion couplings to photons, nucleons, electrons.**

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









Theoretical errors from NLO Chiral Lagrangian,
Grilli di Cortona et al., 1511.02867

Axion EFT

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

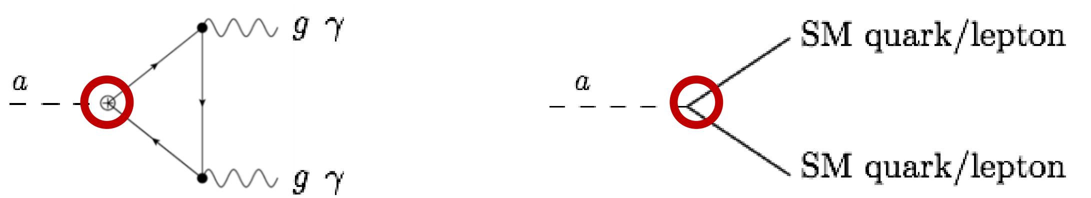
  a new spin-0 boson with pseudo-shift symmetry $a \to a + \alpha f_a$

  broken by $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

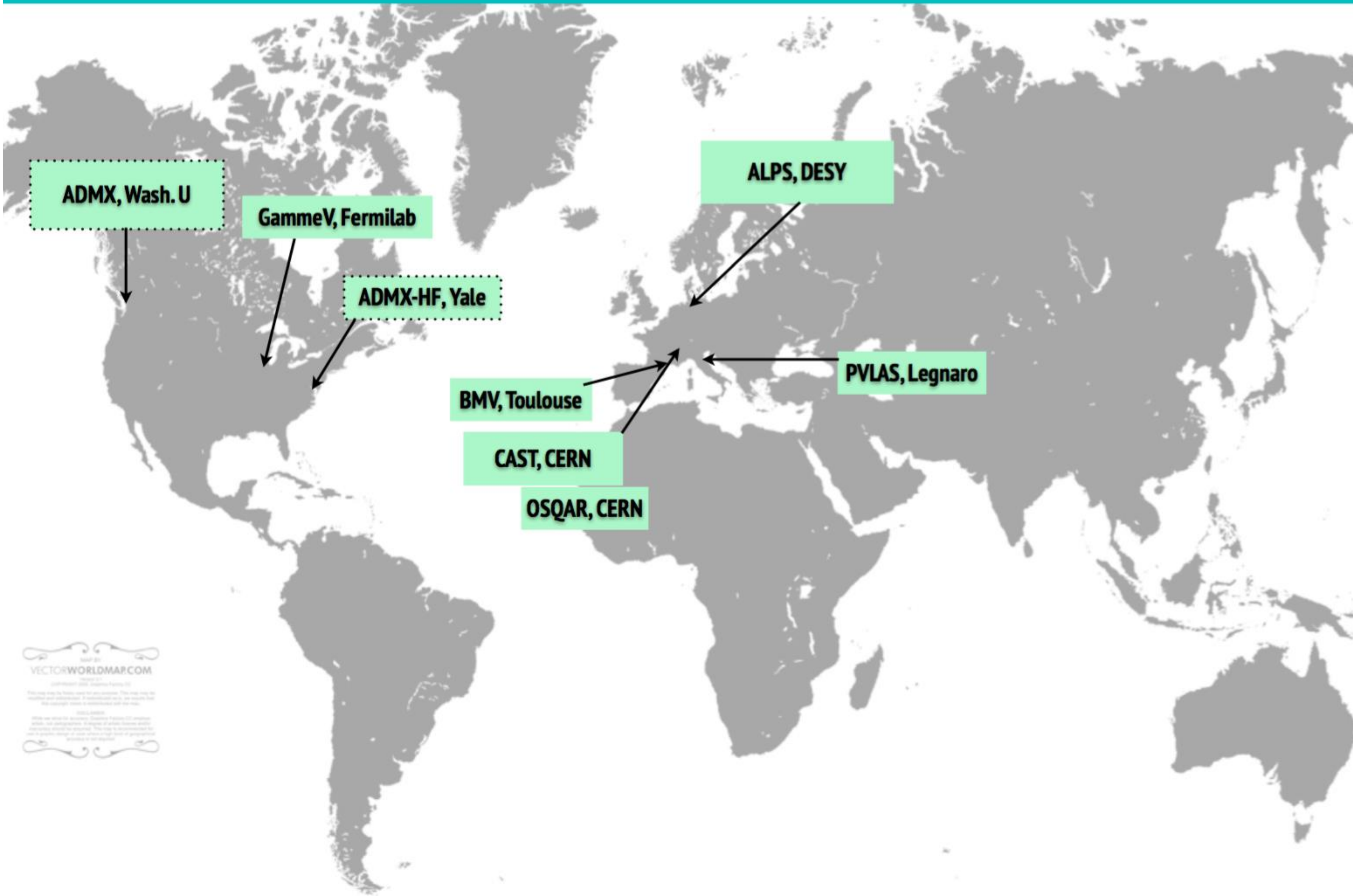
- **generates "model independent" axion couplings to photons, nucleons, electrons.**

- EFT breaks down at energies of order f_a

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

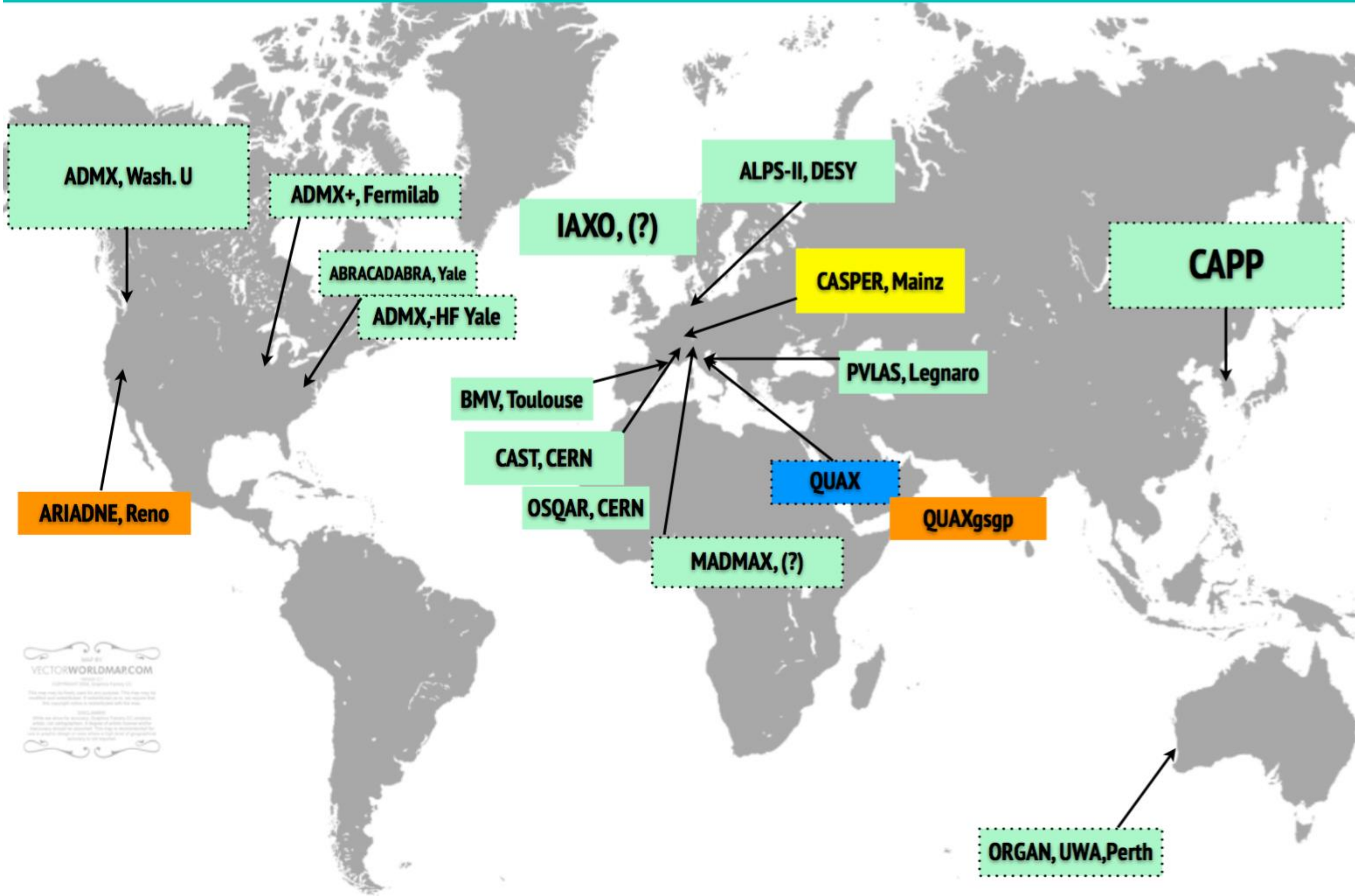


Lab experiments 2011



Redondo 17

Lab experiments 2017



Redondo 17

Axion UV Models

- Axion: PGB of QCD-anomalous global $U(1)_{PQ}$

Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

Axion UV Models

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Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

SM quark

Higgs

SM

Impossible to endow directly the SM with the $U(1)_{PQ}$:

⇒ no anomalous $\mathbf{U(1)_{PQ} \in SU(2)_L x U(1)_Y}$

Minimal Setup: SM with only axion excluded!

⇒ Axion phase belongs to BSM fields!

Axion UV Models

- Axion: PGB of QCD-anomalous global $U(1)_{PQ}$

Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

↙

SM quark

↙

2 Higgs

PQWW

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

Axion UV Models

- Axion: PGB of QCD-anomalous global $U(1)_{PQ}$

Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

↙

SM quark

↙

2 Higgs

PQWW

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

Ruled out

Possible to have in 2HDM an anomalous
$U(1)_{PQ} \perp U(1)_Y$

PQWW ruled out by experiment since $f_a = v$!

$$Br(K^+ \to \pi^+ + a) \sim 10^{-5} \left(\frac{v}{f_a} \right)^2$$

$$Br(K^+ \to \pi^+ + inv.) < 10^{-7}$$

Axion UV Models

- Axion: PGB of QCD-anomalous global $U(1)_{PQ}$

Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

↙

SM quark

↙ ↘

2 Higgs | 2 Higgs + Singlet

PQWW | **DFSZ**

Peccei, Quinn ’77,
Weinberg ’78, Wilczek ’78

Zhitnitsky ’80,
Dine, Fischler, Srednicki ’81

Ruled out

$$\langle \text{Singlet} \rangle \gg v$$

“Visible” axions

Axion UV Models

- Axion: PGB of QCD-anomalous global $U(1)_{PQ}$

Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

SM quark

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Peccei, Quinn '77,
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Ruled out

"Visible" axions

2 Higgs + Singlet

DFSZ

Zhitnitsky '80,
Dine, Fischler, Srednicki '81

$$\langle \text{Singlet} \rangle \gg v$$

$$Br(K^+ \to \pi^+ + a) \sim 10^{-5} \left(\frac{v}{f_a} \right)^2$$

$$f_a \gg v$$

$$\phi \sim f_a e^{ia/f_a}$$

$$H_1 \sim e^{iat_\beta/f_a} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$$

$$H_2 = e^{ia/t_\beta f_a} \begin{pmatrix} v_2 \\ 0 \end{pmatrix}$$

"Invisible" axion models: $f_a \gg v$

Axion UV Models

- Axion: PGB of QCD-anomalous global $U(1)_{PQ}$

Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

SM quark | BSM quark

SM quark		BSM quark
2 Higgs	2 Higgs + Singlet	1 Higgs + Singlet
PQWW	**DFSZ**	**KSVZ**
Peccei, Quinn '77, Weinberg '78, Wilczek '78	Zhitnitsky '80, Dine, Fischler, Srednicki '81	Kim '79, Shifman, Vainshtein, Zakharov '80

Ruled out

"Visible" axions

$$\langle \text{Singlet} \rangle \gg v$$

"Invisible" axion models: $f_a \gg v$

Axion UV Models

- <u>Axion</u>: PGB of QCD-anomalous global $U(1)_{PQ}$

Anomalous breaking (quark) + Spontaneously breaking (scalar)

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

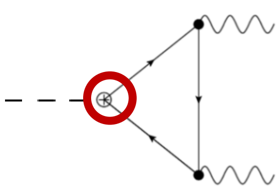
SM quark → 2 Higgs + Singlet

DFSZ

BSM quark → 1 Higgs + Singlet

KSVZ

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



Model dependence from UV completions

Di Luzio, F. M, Nardi 1610.07593 (PRL)+1705.05370 (PRD)

Hadronic Axions: KSVZ

- Field content KSVZ

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 (1979), Shifman, Vainshtein, Zakharov (1980)]

- PQ charges carried by SM-vectorlike quarks $Q = Q_L + Q_R$

  - Original model assumes $Q \sim (3,1,0)$

    However in general:

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

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

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

} anomaly coeff.

- and by a SM singlet Φ containing the "invisible" axion ($V_a \gg v_{\rm EW}$)

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

Hadronic Axions: KSVZ

- **Field content KSVZ**

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 (1979), Shifman, Vainshtein, Zakharov (1980)]

- **Generic QCD axion Lagrangian:** $\mathcal{L}_a = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm PQ} - V_{H\Phi} + \mathcal{L}_{Qq}$ $\quad |\mathcal{X}_L - \mathcal{X}_R| = 1$

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

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

$\mathcal{L}_{Qq}$: d ≤ 4 couplings to SM quarks, depend on Q-gauge quantum numbers,

Accidental Symmetries in KSVZ: Q stability issue!

- **Symmetry of the BSM Quark kinetic term -> Accidental Symmetries**

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

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

- $U(1)_Q$ is Q-baryon number. Exact $U(1)_Q \Rightarrow$ Q stability. [E.g. Q ~ (3,1,0)]

Original KSVZ model, '79, '80

Colored stable/meta-stable particles are severely bounded by cosmology

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- $U(1)_Q$ is Q-baryon number. Exact $U(1)_Q \Rightarrow$ Q stability.

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

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

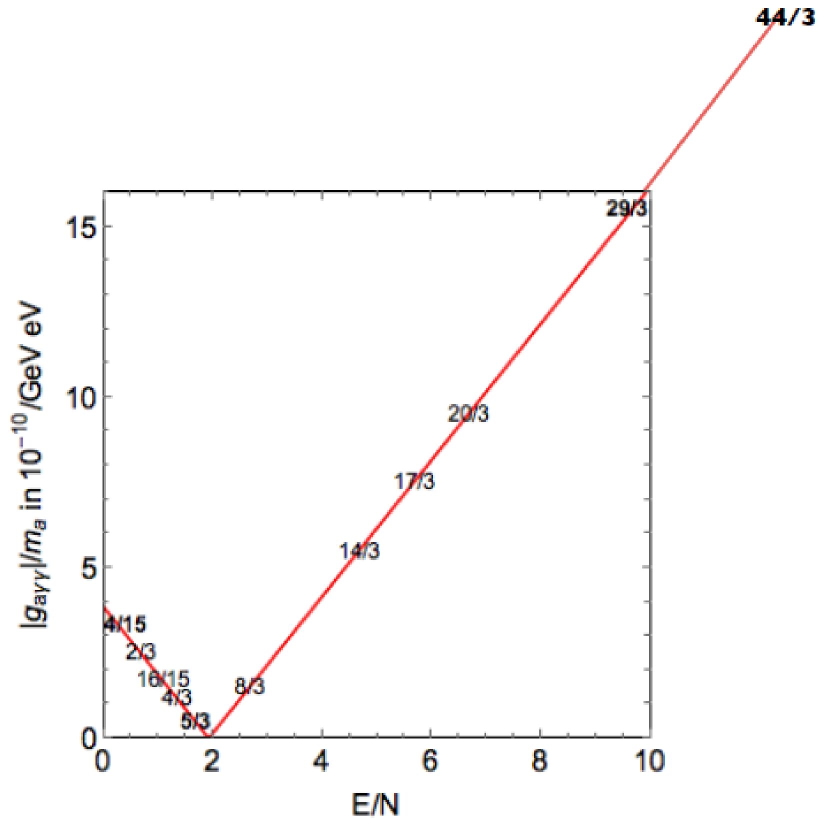
→ stability depends on Q representations

Phenomenologically preferred Q's

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

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

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



- Q short lived + no Landau poles < Planck

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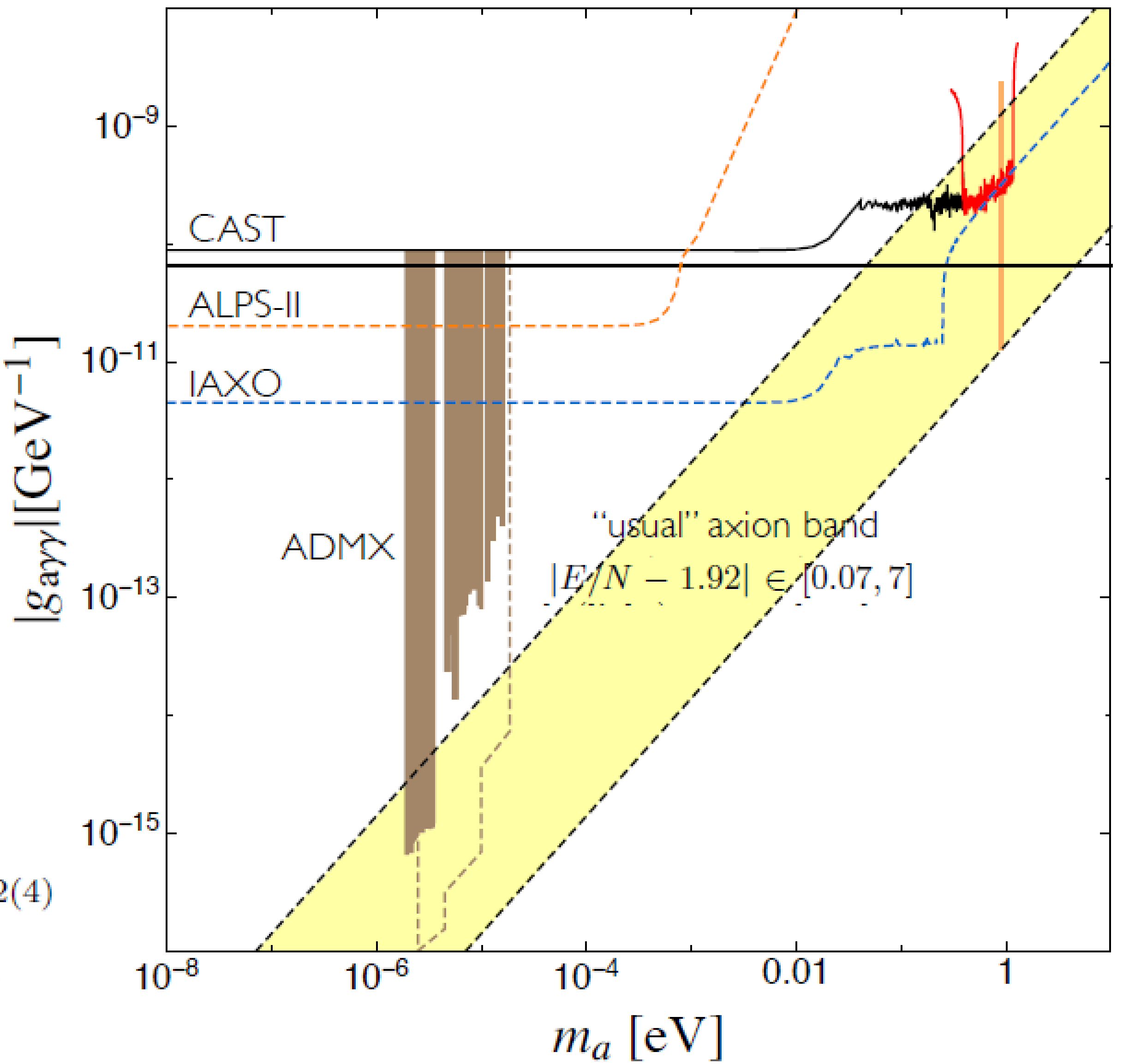
- The *weakest* coupling is obtained for $R_Q^w = (3,2,1/6)$ for which $E_w/N_w - 1.92 \sim -0.25$ is about 3.5 times larger than the usual lower value of 0.07.

- The *strongest* coupling is obtained for $R_Q^s = (3,3,-4/3)$ that gives $E_s/N_s - 1.92 \sim 12.75$, almost twice the usually adopted value of 7.0

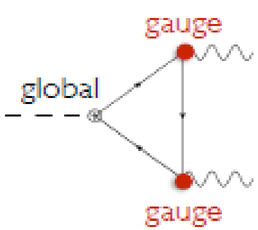
$$\frac{E}{N} = \frac{\sum_Q Q_Q^2}{\sum_Q T(\mathcal{C}_Q)}$$

- Q short lived + no Landau poles < Planck

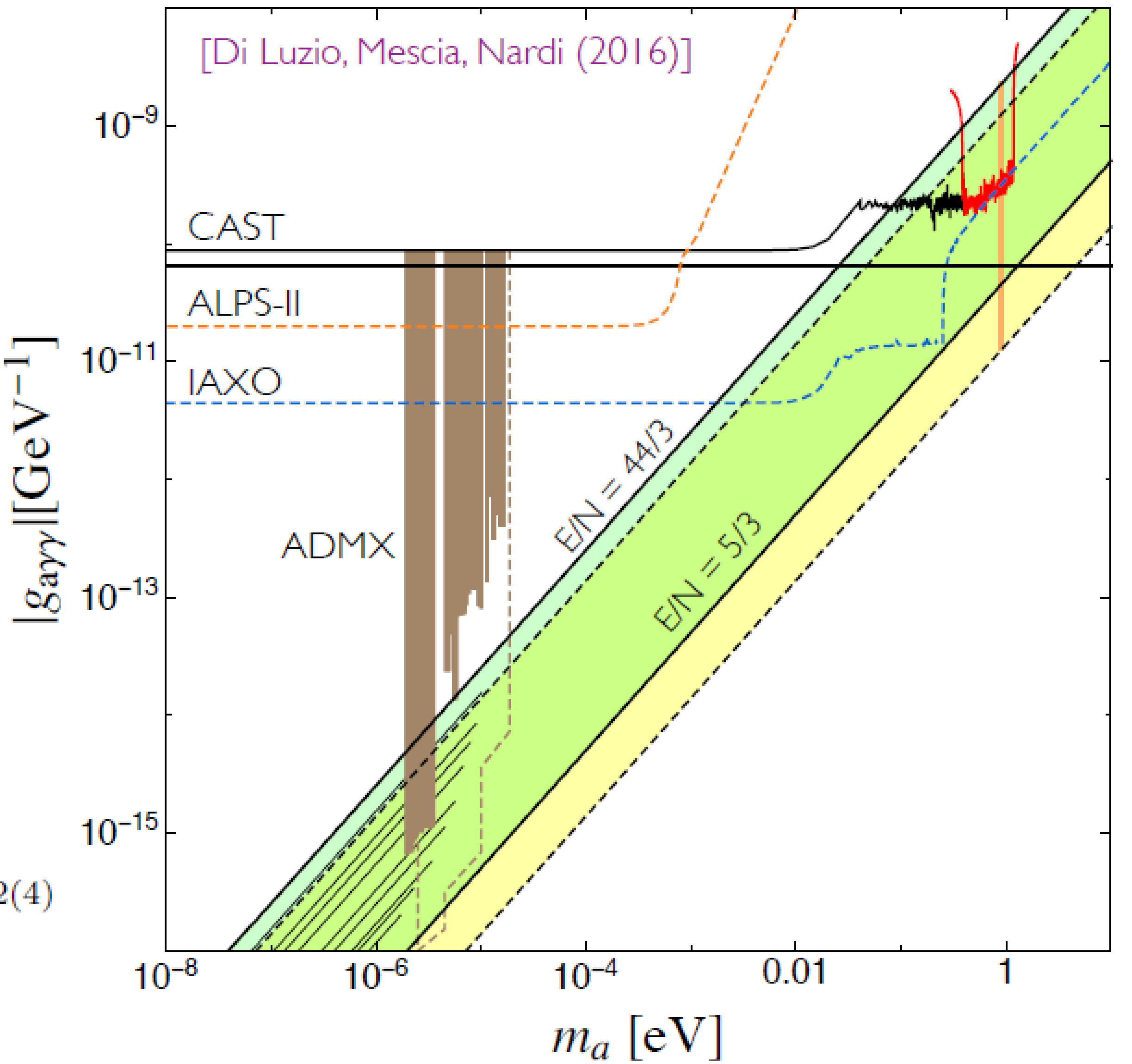
Redefining Axion Windows for a->γγ: KSVZ



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



Redefining Axion Windows: KSVZ (N_Q=1)



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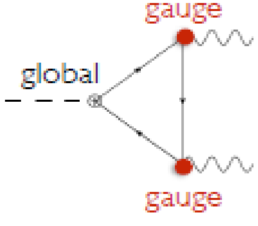
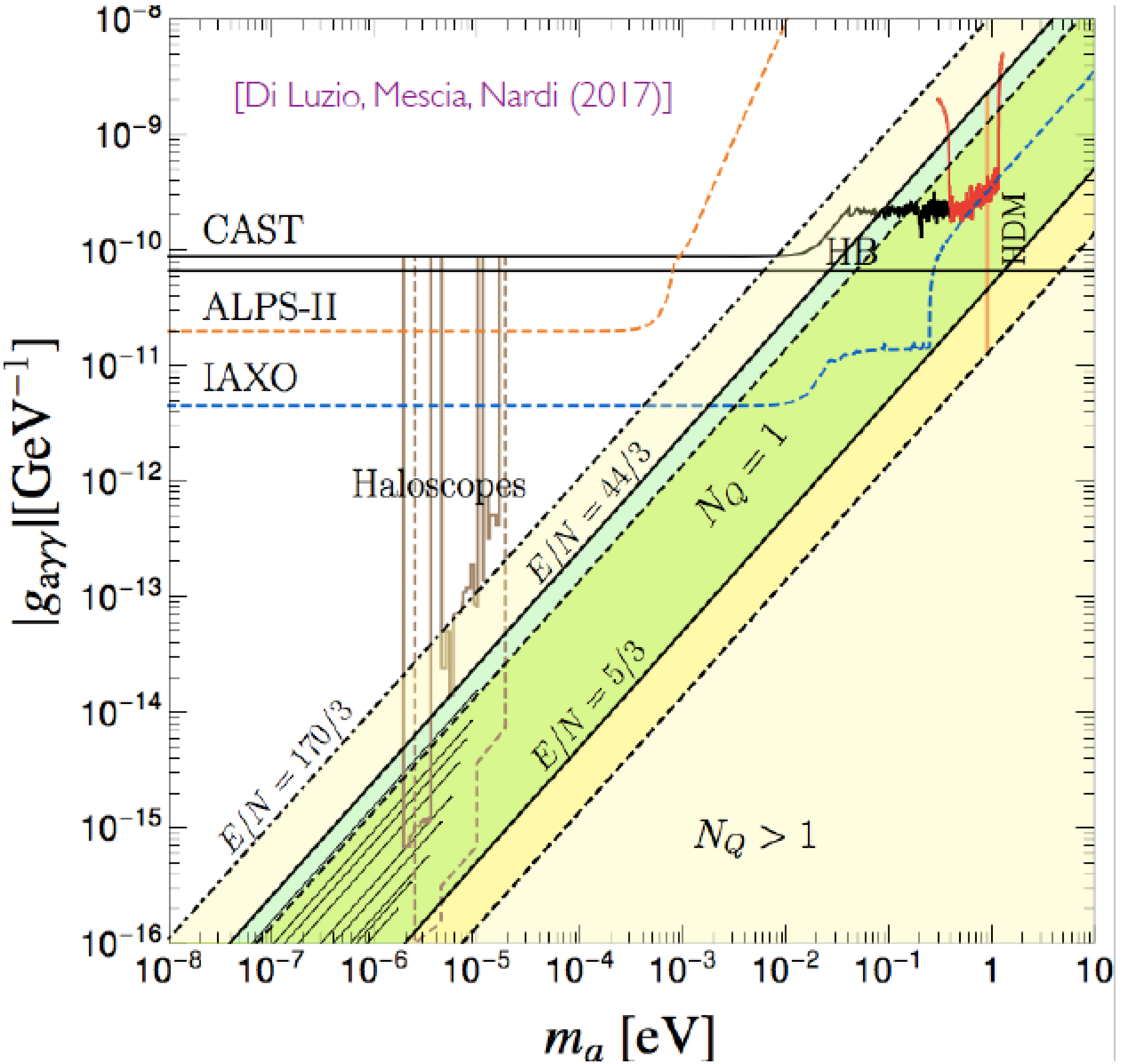
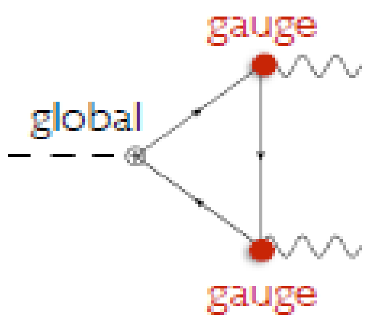


Additional Q representations: KSVZ + N_Q>1



Axion-Photon Summary (Revised)

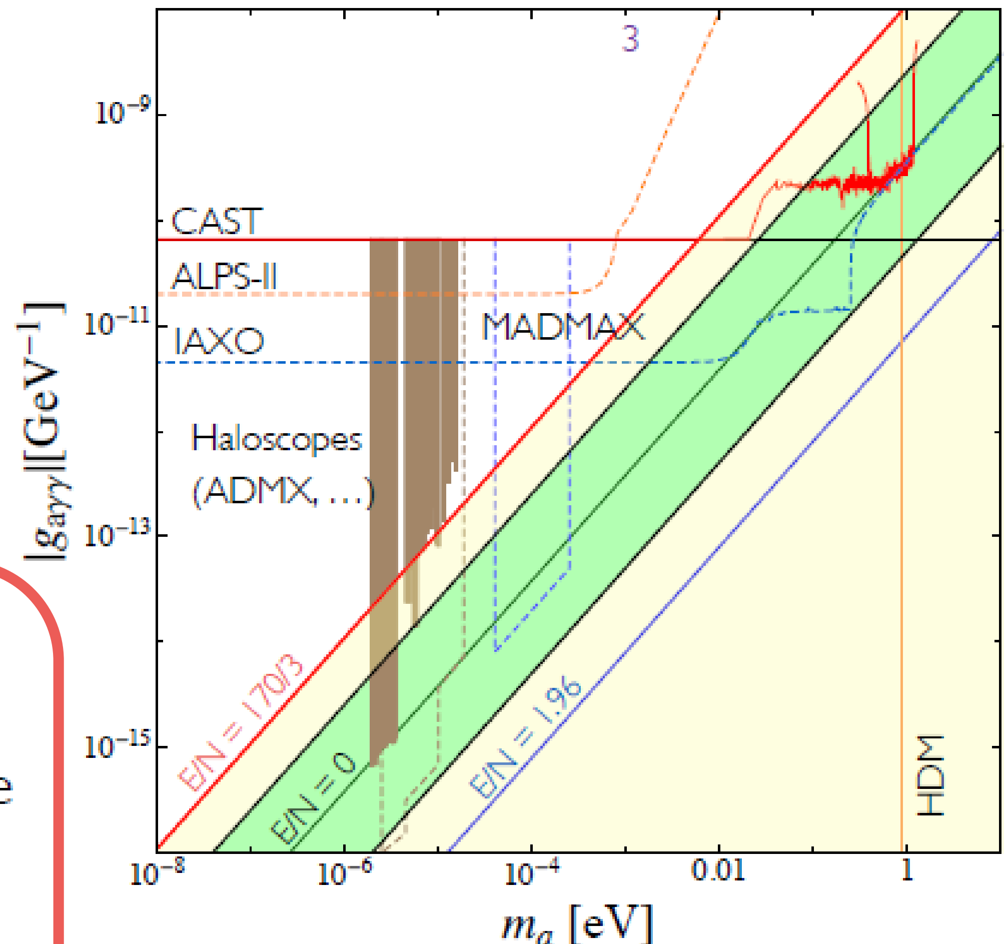
$$C_\gamma = E/N - 1.92(4)$$



- Messages for exp. colleagues:

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)



Di Luzio, F.M, Nardi 1610.07593 (PRL), 1705.05370

Model building and Pheno

2

- ❑ ***Axion couplings to fermions***

Based on
Di Luzio, F.M. Nardi, Panci, Ziegler, 1712.04940 (PRL)
Björkeroth, Di Luzio, F.M. Nardi, 1811.09637 (JHEP).

Axion Couplings to fermions

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

  → nucleophobia + electrophobia = astrophobia

- Why interested in such constructions ?

  1. is it possible at all ?

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

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

  4. unexpected connection with flavour

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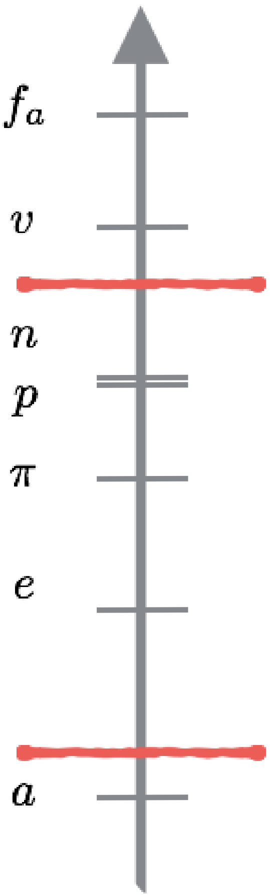
*conceptually easy (e.g. couple the electron to 3rd Higgs uncharged under PQ)

Axion-nucleon couplings



UV-theory PQ invariant

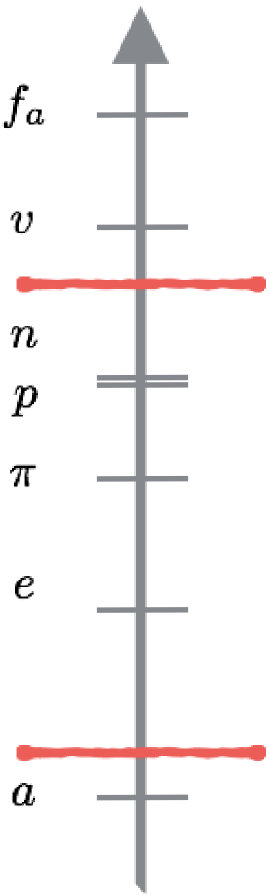
$$\mathcal{L}_q = \frac{\partial_\mu a}{2f_a} c_q \, \bar{q}\gamma^\mu\gamma_5 q \qquad q = (u, d, s, \ldots)$$

EFT-I: quarks and gluons

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

EFT-II: non-relativistic nucleons

Axion-nucleon couplings



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

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

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

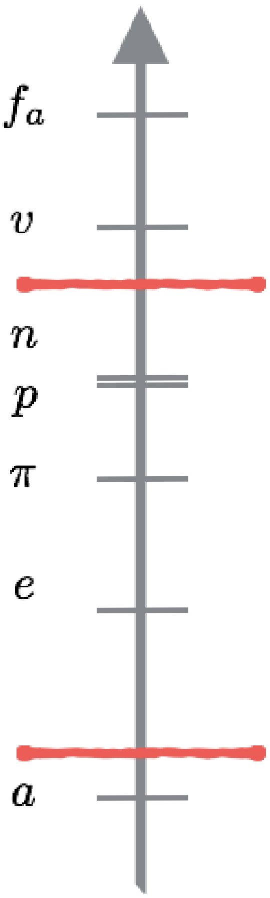
$$C_p - C_n = (c_u - c_d)(\Delta_u - \Delta_d)$$

independently of matrix elements:

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

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

Axion-nucleon couplings: KSVZ/DFSZ no-go



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

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

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

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

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

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

X

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

Axion-nucleon couplings: KSVZ/DFSZ no-go

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

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1st condition

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

KSVZ: $X_u = X_d = 0$ → -1

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

Implementing Nucleophobia

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

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

1st condition

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

$\xrightarrow{\quad\quad}$ $X_u = X_d = 0$: -1

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

Implementing Nucleophobia

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

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

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

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

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

- 1st condition automatically satisfied

Implementing Nucleophobia

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

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$$\Rightarrow \mathcal{N}_{2nd} = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1$$

- 2nd condition can be implemented via a 10% tuning

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

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

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

Flavour Connection

- Nucleophobia implies flavour violating axion couplings !

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

e.g. RH down rotations become physical

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

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

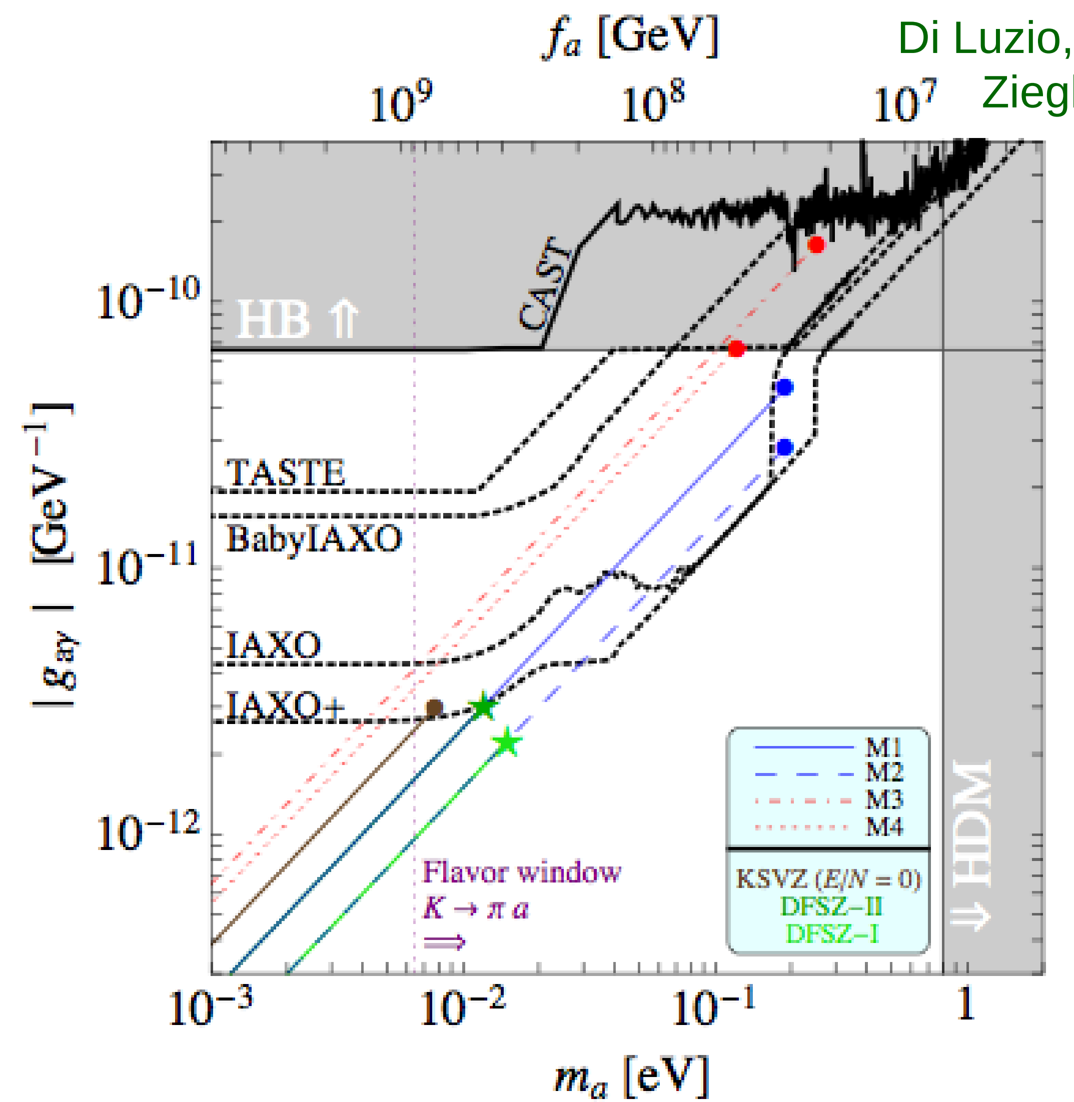
$B \to K a$ $\quad m_a < 3.7 \times 10^{-2} \dfrac{\mathrm{eV}}{|C^V_{bs}|}$ - [Babar, 1303.7465] → Belle-II

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

→ MEG II

Axion models

Di Luzio, F. M, Nardi, Panci, Ziegler 1712.04940



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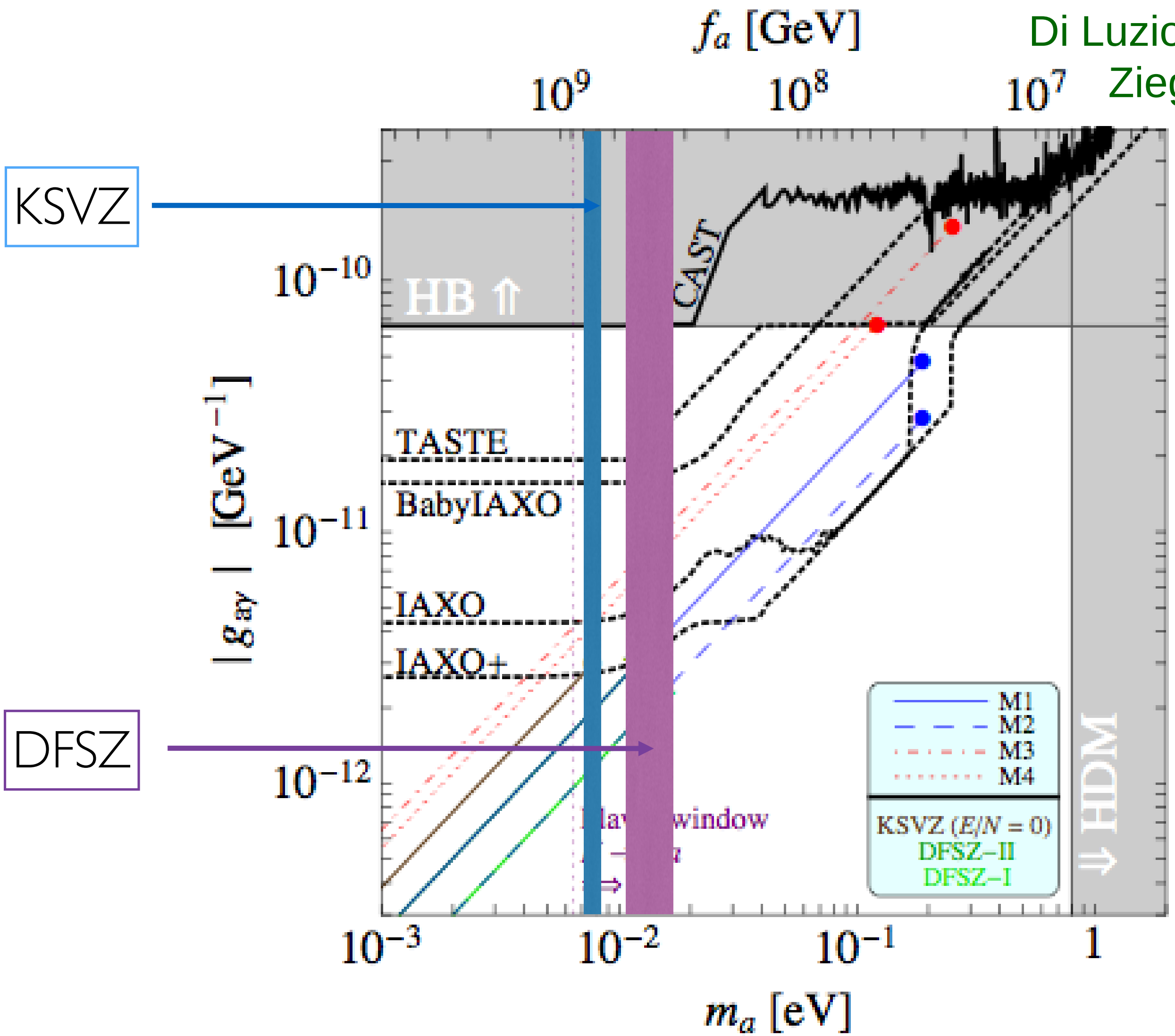
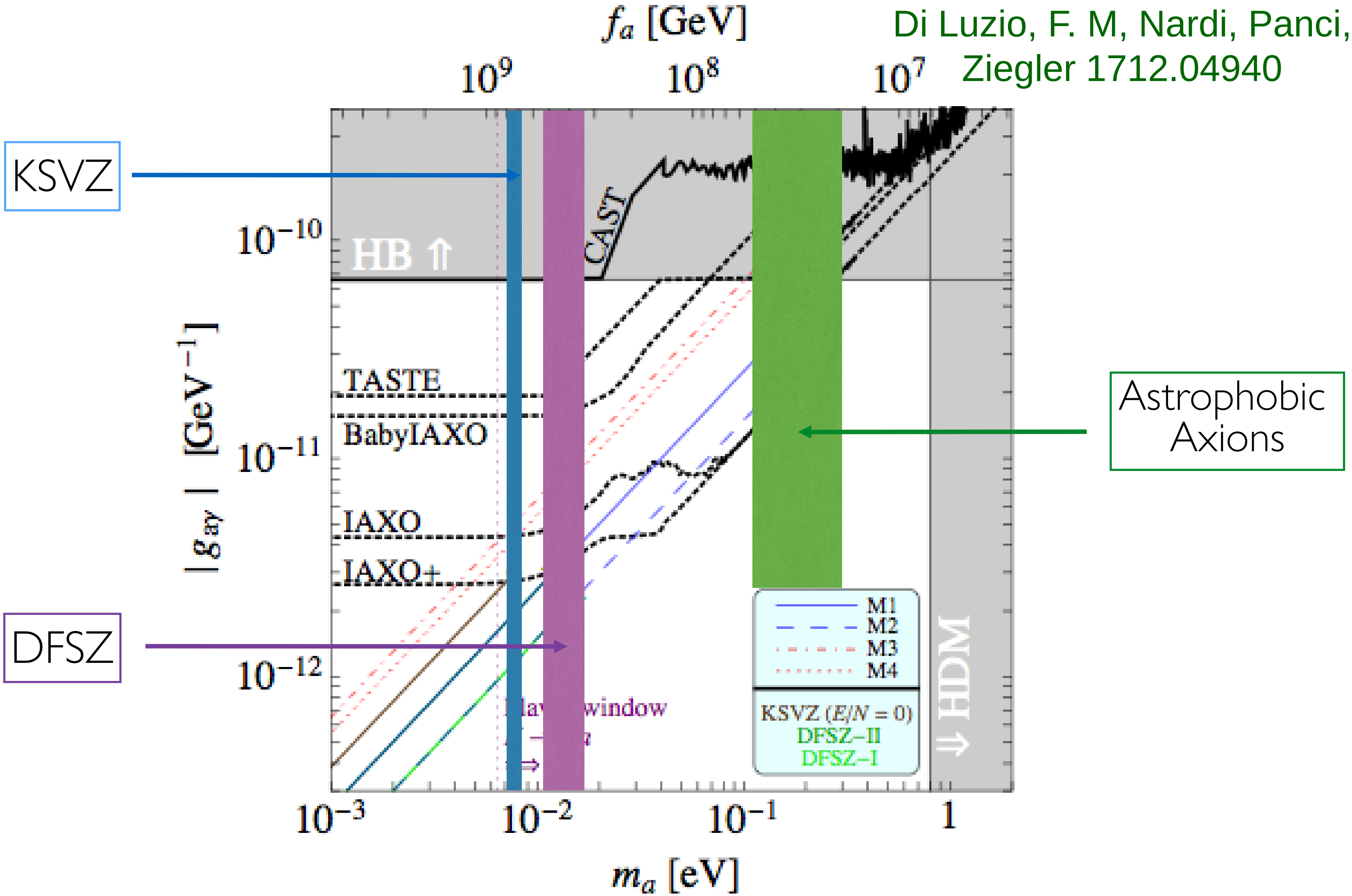
Di Luzio, F. M, Nardi, Panci, Ziegler 1712.04940



Astrophobic axion models

Di Luzio, F. M, Nardi, Panci, Ziegler 1712.04940



Conclusion

- The axion hypothesis provides a well motivated BSM scenario
  - solves the strong CP problem
  - provides a DM candidate
  - **is unambiguously testable by detecting the axion**
- Healthy and lively experimental program
  - IAXO is entering now the preferred window for the QCD axion
- Theoretical developments are still ongoing
  - reduce non-perturbative QCD uncertainties, especially on $g_{a\gamma\gamma}$ and f_a
  - **define theoretical uncertainties due to "model dependence"**

Here: Axion window defined in terms of precise pheno requirements

Thanks

What about Axion Windows: in DFSZ?

- In general each R-handed SM fermion can have a specific PQ charge X_{f_j}

$$u_R^j \to \exp(iX_{uj})\, u_R^j\,,$$
$$d_R^j \to \exp(iX_{dj})\, d_R^j\,,$$
$$e_R^j \to \exp(iX_{ej})\, e_R^j\,.$$

$$\frac{E}{N} = \frac{2}{3} + 2\frac{\sum_j (X_{uj} + X_{ej})}{\sum_j (X_{uj} + X_{dj})}$$

- For generation independent charges DFSZ remains within KSVZ window:

$$\text{DFSZ-I}: \qquad X_e = X_d\,, \qquad E/N = 8/3$$
$$\text{DFSZ-II}: \qquad X_e = -X_u\,, \qquad E/N = 2/3$$

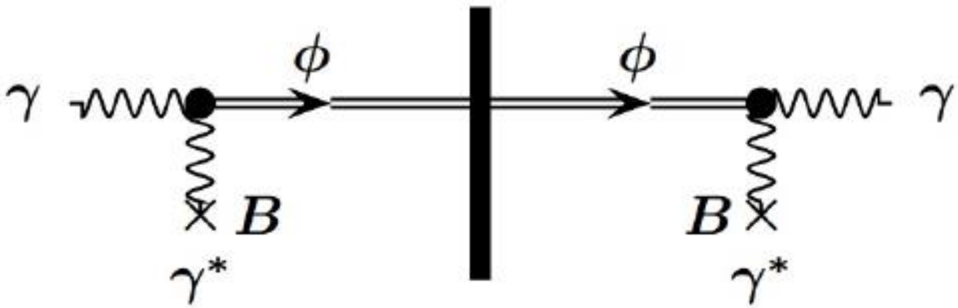
DFSZ-III: $X_e \neq X_{u,d,}$ $E/N_{(max)} = -4/3$

- For generation dependent charges with a max. of 9 Higgs doublets H_{f_j}:

DFSZ(X_{ej} $X_{dj,}$ X_{uj}): $E/N_{(max)} = 524/3 = 3 \cdot E/N_{(max)}(\text{KSVZ})$

Light Shining trough Walls: ALP1-2 (Desy)

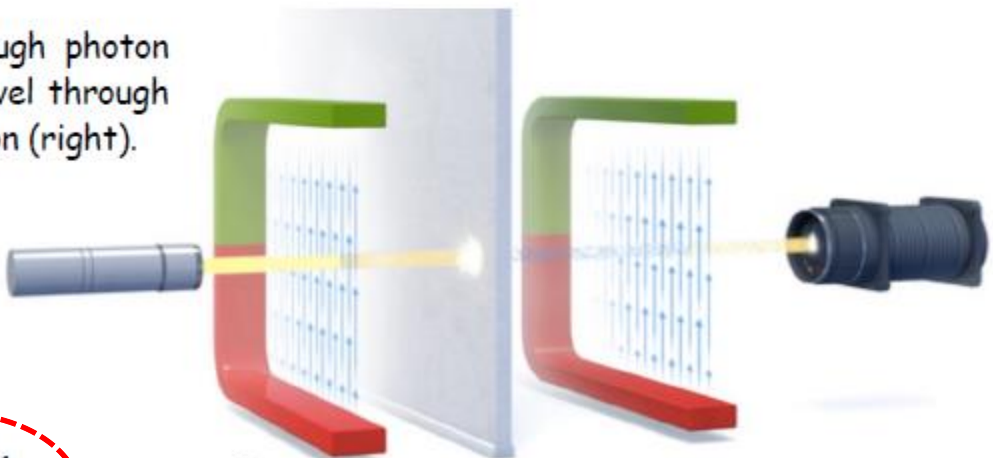
- Any Light Particle Search (DESY) Alps 1 (2007-2010) Alps 2 (2013-)



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

Artist view of a light shining through a wall experiment

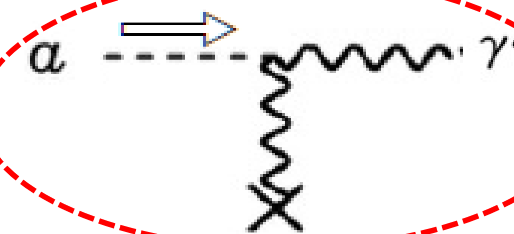
Schematic view of axion (or ALP) production through photon conversion in a magnetic field (left), subsequent travel through a wall, and final detection through photon regeneration (right).



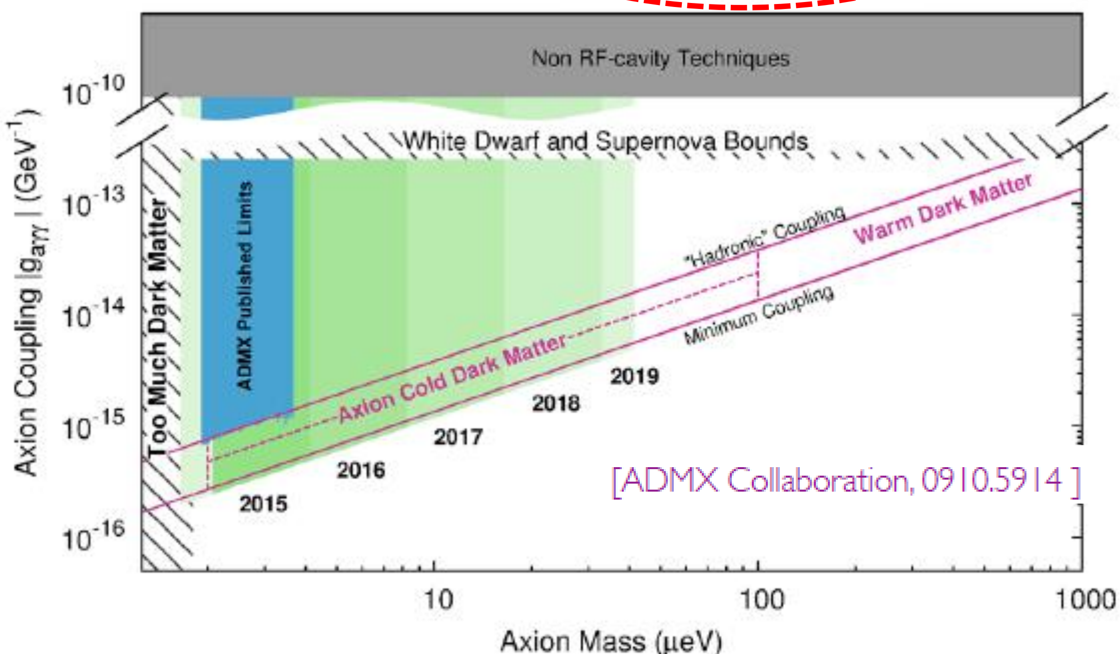
→ LSW experiments pay a $(g_{a\gamma\gamma})^4$ suppression

Haloscopes: ADMX (Washington)

- Look for halo DM axions with a microwave resonant cavity [Sikivie (1983)]
  - exploits inverse Primakoff effect: axion-photon transition in external E or B field



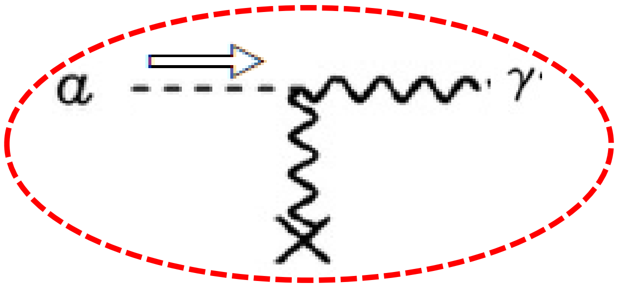
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma}\, a\, F \cdot \tilde{F} = g_{a\gamma\gamma}\, a\, \mathbf{E} \cdot \mathbf{B}$$

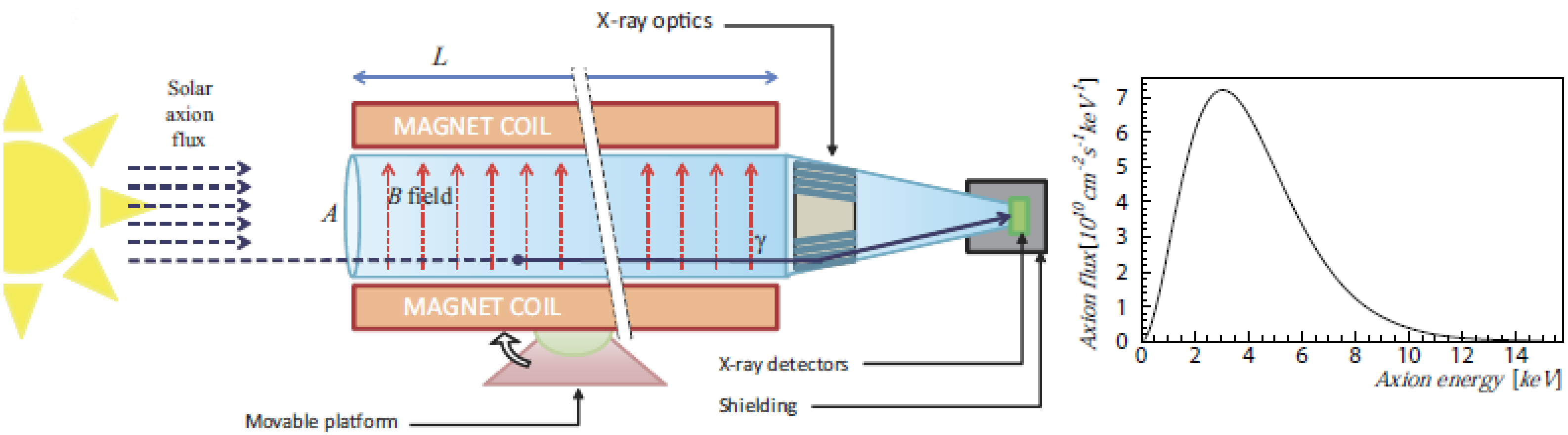


  - power of axions converting into photons in an EM cavity $P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\rm eff}$

Helioscopes: CAST (CERN), IAXO (DESY)

- The Sun is a potential source of a copious axion flux





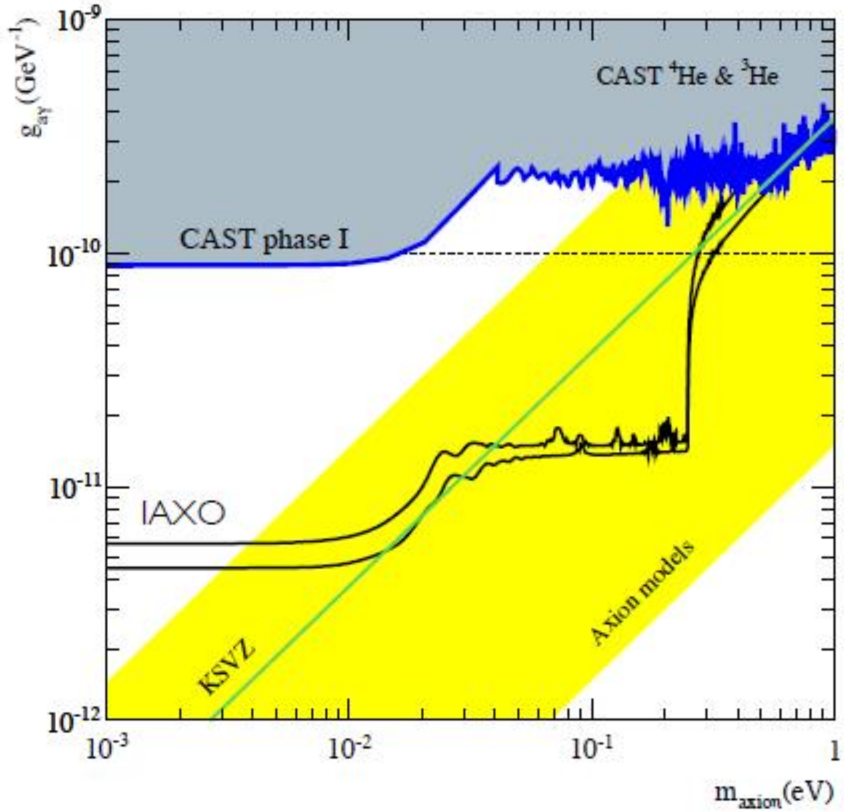
- macroscopic transverse B-field over a large volume triggers axion to photon (x-ray) conversion

Helioscopes: CAST (CERN), IAXO (DESY)

- The Sun is a potential axion source (3rd and 4th generation axion-Sun telescopes)

- CERN Axion Solar Telescope (CAST)

- International AXion Observatory (IAXO)



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