The QCD Axion: The Good, the Bad, and the Experimental

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The QCD Axion: The Good, the Bad, and the Experimental

- **QCD puzzles:** the $U(1)_A$ (η') and the strong CP problem
  - *special gauge configurations in* QCD (instantons)

- Solutions to the strong CP problem

- The axion solution → the Peccei-Quinn mechanism: $U(1)_{PQ}$
  - *axion features: mass, couplings & dark matter cand.*
  - Recent experimental and theoretical developments
  - *dirty side of the axion solution*: *global* $U(1)_{PQ}$?

Introduction: QCD puzzles

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

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

$$\partial^\mu J^5_\mu = \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

→ The QCD topology is not trivial

$$\langle 0|\partial^\mu J^5_\mu|H\rangle = f_H m_H^2$$

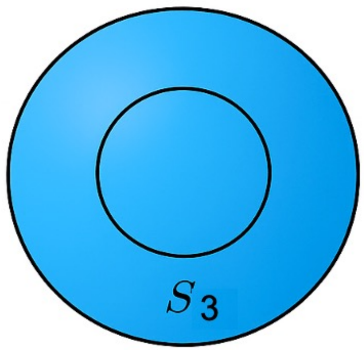
→ *add a new term to the usual QCD Lagrangian*

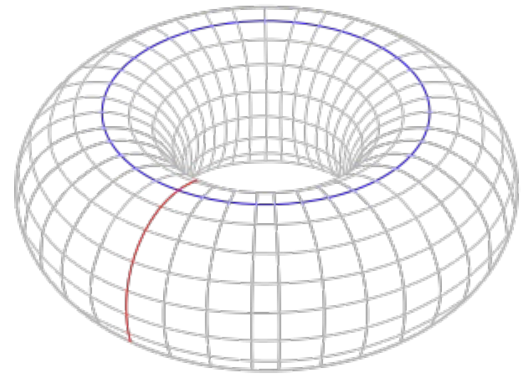
$$\mathcal{L}^{QCD}_{eff} = \mathcal{L}^{QCD} + \theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

QCD: the non-trivial topology

Introduction: the non-trivial QCD topology

$U(1)$	$SU(3)$
$\pi_3\,(U\,(1) = 0$ – No instantons	$\pi_3\,(SU\,(3) = Z$ Instantons exist





Instantons require nontrivial $\pi_3(G)$. Abelian U(1) lacks this, non-Abelian SU(N) has it.

$$Q_{QCD} = \int_{V_4} d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} = \int_{S_3} d^3x\, n_\mu K^\mu_{SU(3)} = 0?$$

$$G^a_{\mu\nu}\tilde{G}^{a\mu\nu} = \partial_\mu K^\mu$$

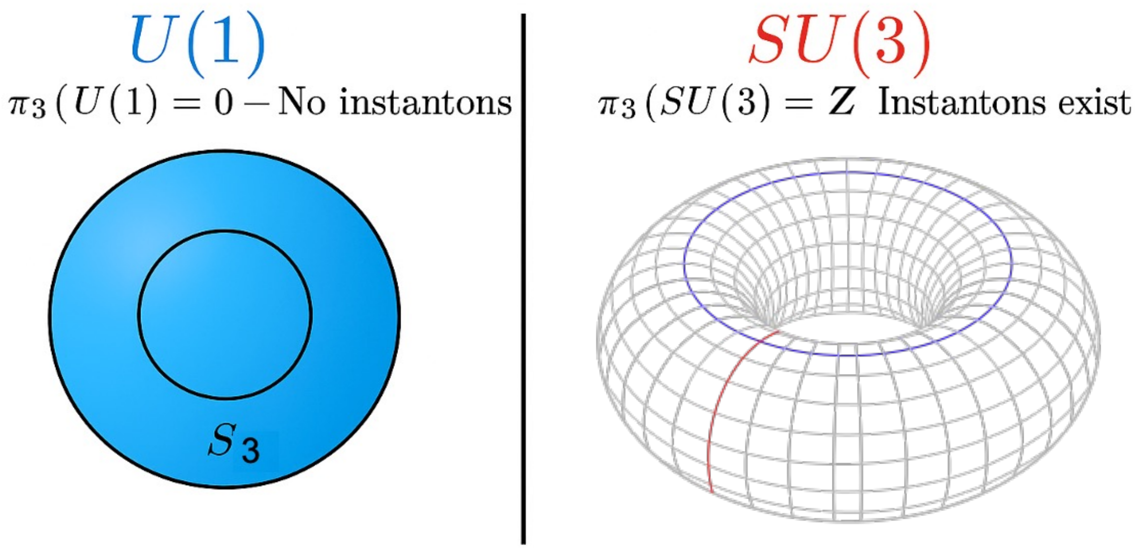
total derivative

$$K^\mu = \varepsilon^{\mu\alpha\beta\gamma} A_{a\alpha}\left[G_{a\beta\gamma} - \frac{g_s}{3} f_{abc} A_{b\beta} A_{c\gamma}\right]$$

Does it cancel at infinity?

No! for SU(2) & SU(3)!

Introduction: the non-trivial QCD topology



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$$Q_{QCD} = \int_{V_4} d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} = \int_{S_3} d^3x\, n_\mu K^\mu_{SU(3)} \neq 0$$

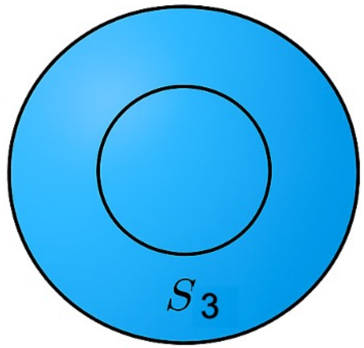
$$Q_{QED} = \int_{V_4} d^4x\, F_{\mu\nu}\tilde{F}^{\mu\nu} = \int_{S_3} d^3x\, n_\mu K^\mu_{U(1)} = 0$$

QCD: the non-trivial vacuum in SU(3)

Introduction: the non-trivial QCD topology

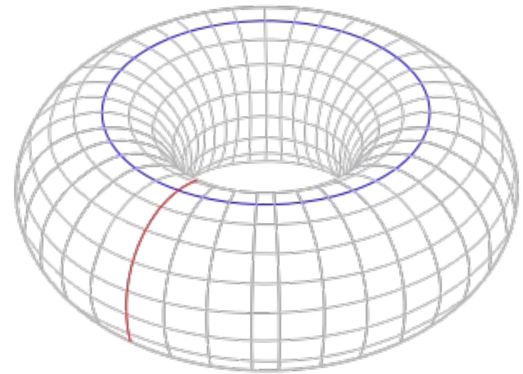
$U(1)$

$\pi_3(U(1) = 0$ – No instantons



$SU(3)$

$\pi_3(SU(3) = Z$ Instantons exist



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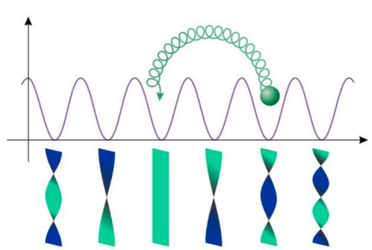
instantons

$$Q_{QCD} = \int_{V_4} d^4x \, G^a_{\mu\nu} \tilde{G}^{a\mu\nu} = \int_{S_3} d^3x \, n_\mu K^\mu_{SU(3)} \neq 0$$

Also explains η' mass ←



Fields cancel at infinity → E=0! but the θ-term no in SU(N)!

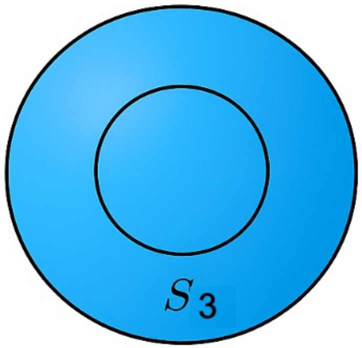
→ in SU(3) there are infinite pure gauge states, E=0, topologically inequivalent to the trivial case A_μ=0:

$$A^{(n)}_\mu(x) = \frac{i}{g} U^{-1}_{(n)}(x) \partial_\mu U_{(n)}(x), \quad U_{(n)} \in SU(3)$$

Introduction: the non-trivial QCD topology

$U(1)$

$\pi_3\,(U(1) = 0 - \text{No instantons}$



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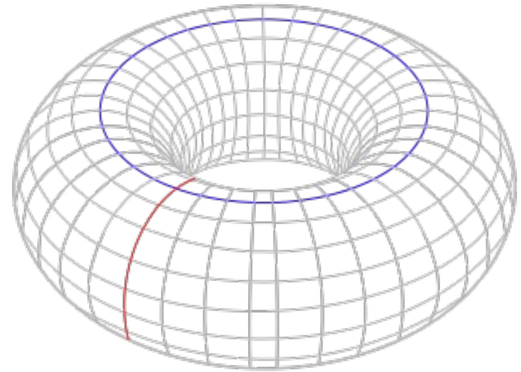


Instantons require nontrivial $\pi_3(G)$. Abelian U(1) lacks this, non-Abelian SU(N) has it.

instantons

$$Q_{QCD} = \int_{V_4} d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} = \int_{S_3} d^3x\, n_\mu K^\mu_{SU(3)} = \frac{8\pi^2}{g^2}$$

the θ-term does not cancel in SU(N)!

No! for SU(2) & SU(3)!

$$A_\mu^{Q=1}(x) = \frac{r^2}{r^2+\rho^2}\,U^{-1}(x)\partial_\mu U(x)$$

Q=1 Instanton

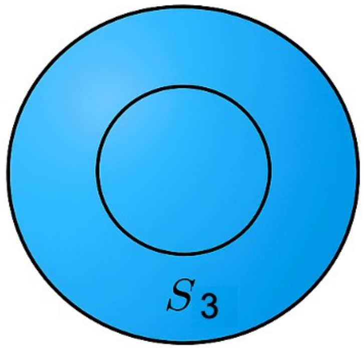
$$U(x) = \begin{pmatrix} \frac{r_\mu\sigma^\mu}{r} & 0 \\ 0 & 1 \end{pmatrix} \in SU(3)$$

$$\sigma^\mu = (\vec{\sigma}, i)$$

Introduction: the non-trivial QCD topology

$U(1)$

$\pi_3\,(U(1) = 0 - \text{No instantons}$



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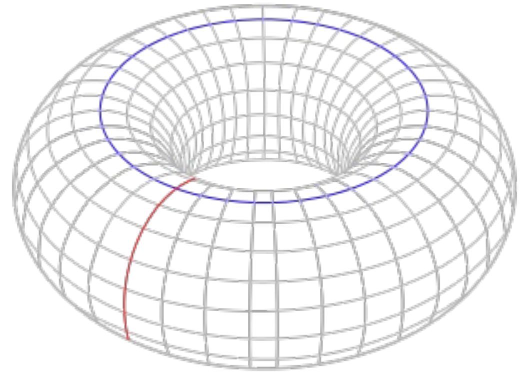

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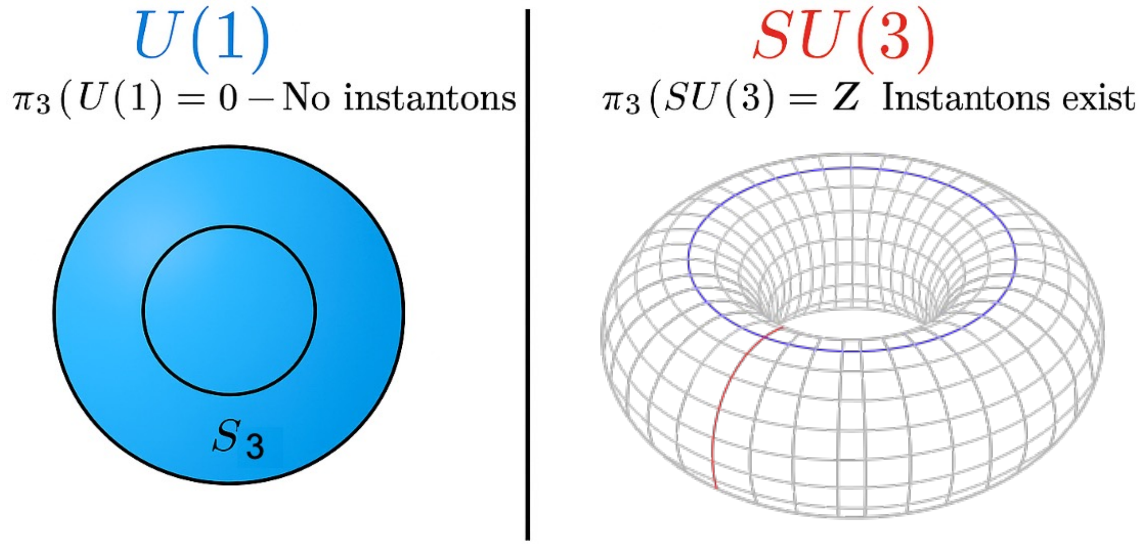
$$A^{Q=1}_\mu(x) = \frac{r^2}{r^2+\rho^2}\,U^{-1}(x)\partial_\mu U(x)$$

$$U(x) = \begin{pmatrix} \frac{r_\mu \sigma^\mu}{r} & 0 \\ 0 & 1 \end{pmatrix} \in SU(3)$$

Q=1 Instanton → non-perturbative solutions

$$\sigma^\mu = (\vec{\sigma}, i)$$

Introduction: the non-trivial QCD topology



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instantons

$$Q_{QCD} = \int_{V_4} d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} = \int_{S_3} d^3x\, n_\mu K^\mu_{SU(3)} \neq 0$$

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QCD: the non-trivial vacuum in SU(3)

Introduction: What about other SM sector?

Three CPV terms are present in the SM gauge Lagrangian:

$$\mathcal{L}_{\cancel{CP}} = \theta_C \frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \theta_L \frac{g^2}{16\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu} + \theta_Y \frac{g'^2}{16\pi^2} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

$Q_{QCD} \neq 0$

Cannot be removed
QCD puzzle

$Q_{EW} \neq 0$

Removed thanks to $U(1)_{\mathcal{B}+\mathcal{L}}$

$Q_{U(1)} = 0$

Removed by partial integration.

Remember chiral rotations:

$$\left.\begin{array}{l} \psi_R \to \exp(i\alpha)\psi_R \\ \psi_L \to \exp(i\beta)\psi_L \end{array}\right\} \Rightarrow \left\{\begin{array}{l} m\bar{\psi}_R\psi_L \to m e^{i(\alpha-\beta)}\bar{\psi}_R\psi_L \\ \delta\mathcal{L}_{anomaly} \sim (\alpha-\beta)F_{\mu\nu}\tilde{F}^{\mu\nu} \end{array}\right.$$

QCD: the non-trivial vacuum in SU(3)

The strong CP problem

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

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

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

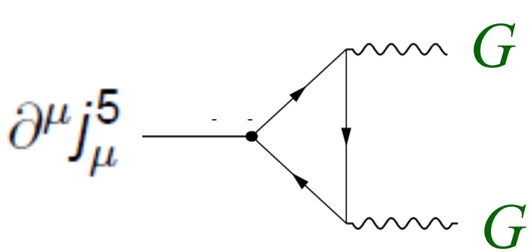
2 $\bar{\theta} = \theta - \sum_q \theta_q$

has physical meaning

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

$\theta \to \theta + 2\alpha$

because of chiral anomaly



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Now, QCD violates T and P, namely CP!

Natural expectation $\bar{\theta} \sim \mathcal{O}(1)$

Gauge-invariant + renormalizable

non-perturbative QCD (instantons)

The strong CP problem

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Natural expectation $\bar{\theta} \sim \mathcal{O}(1)$

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

Neutron EDM

$$d_{exp} \leq 10^{-26} e\, cm \qquad d_{th} \simeq e\bar{\theta} m_q / m_N^2 = 10^{-16} e\, cm$$

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

The strong CP problem

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

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

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
  - $\bar{\theta}$ is radiatively stable (unlike $m_H^2 \ll \Lambda_{\rm UV}^2$) [Ellis, Gaillard (1979)]
  - it evades explanations based on environmental selection

[Ubaldi, 0811.1599]

The strong CP problem

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

What can we do? possible solutions?

The strong CP problem: Solution 1 → m_u=0

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

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

If m=0,
θ → θ - 2α

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

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

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!

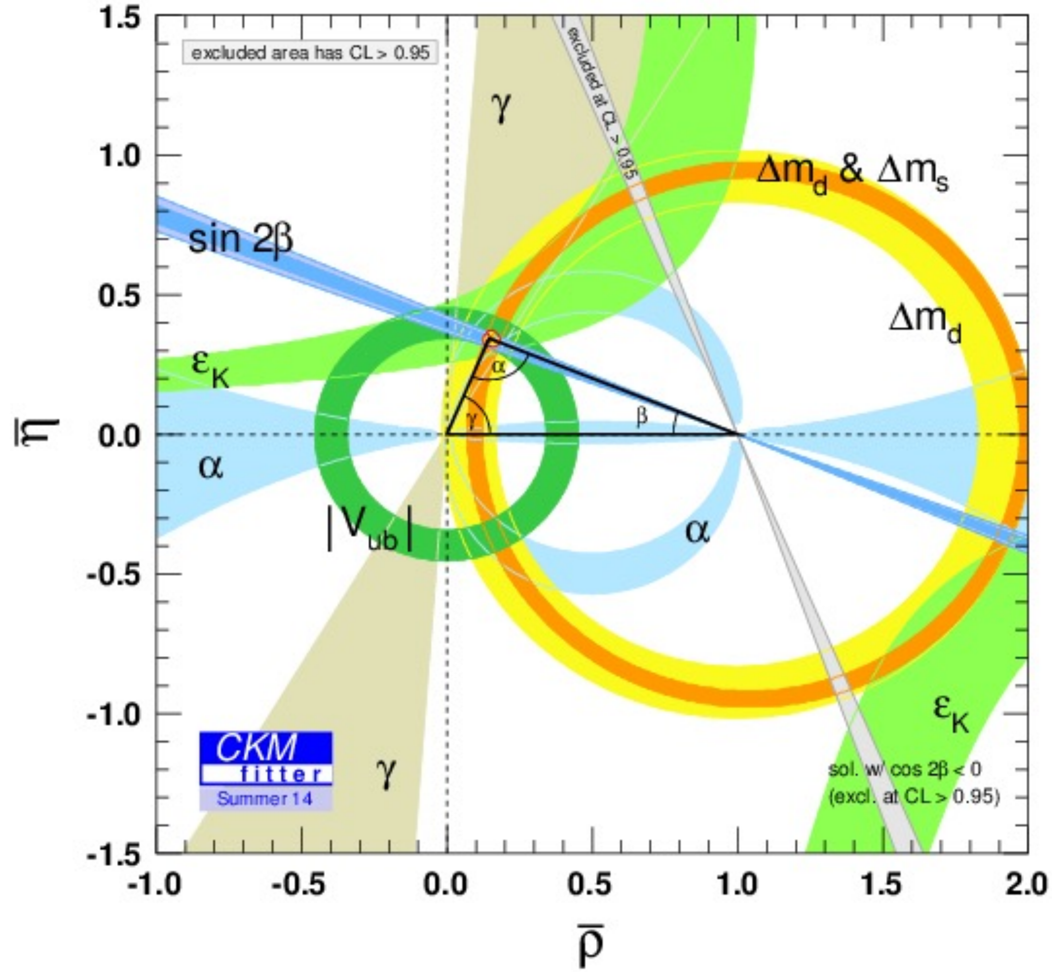
The strong CP problem: Solution 2 → CP spontaneously broken

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

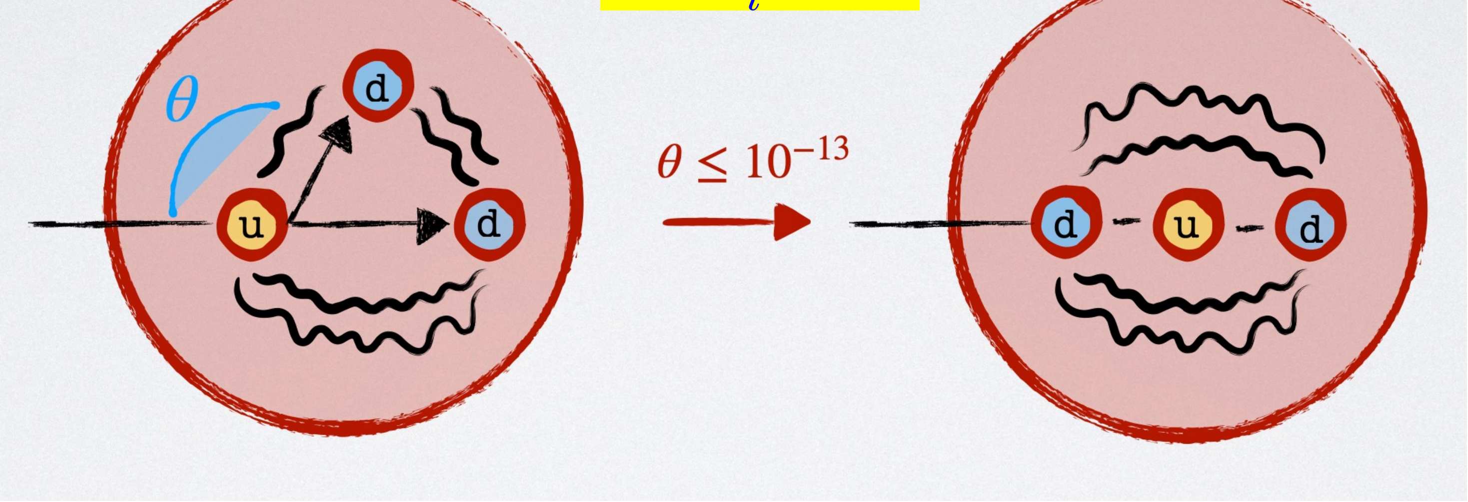


In the CKM model, CP violated by an explicit weak phase η in the off-diagonal phases of Yukawa

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

At its heart, the Strong CP problem is a question of why is the electric Dipole Moment of the neutron is so small.

$$\vec{d} = \sum_i e_{q_i} \vec{r}_i$$



Is there a dynamical explanation for that?
namely, “the neutron configuration with **(d u d)** aligned less energetic”

Yes, the axion solution, introducing the Peccei-Quinn symmetry

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

The third Solution: *an additional symmetry*

Peccei & Quinn '77
Weinberg; Wilczek '78

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

promote θ to a dynamical field

Shift Symmetry!

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

$\alpha = \bar{\theta}$
θ rotated away!
There is no strong CP problem.

***a*(*x*) is GB**

$$\Downarrow$$

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

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

$$\boxed{a(x) \to a(x) - \alpha f_a}$$

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

pseudo-Shift Symmetry!

$\Downarrow$ $\Downarrow$

Vafa, Witten '84

❖ non-linearly realized U(1) symmetry: a = phase of scalar field

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

→ $U(1)_{PQ}$: *spontaneously broken*

❖ **but, Is the ground state a=0?**

→ $E(0) < E(a) \Rightarrow a=0$ vacuum stable

❖ U(1) broken by QCD anomaly (charged under quarks)!

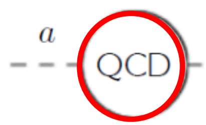
❖ **No strong CP problem!**

Axion: a new spin-0 boson → *pNGB of a spontaneously broken global* $U(1)_{PQ}$ *with QCD anomaly*

Axion Effective Theory: Model Independent Feature

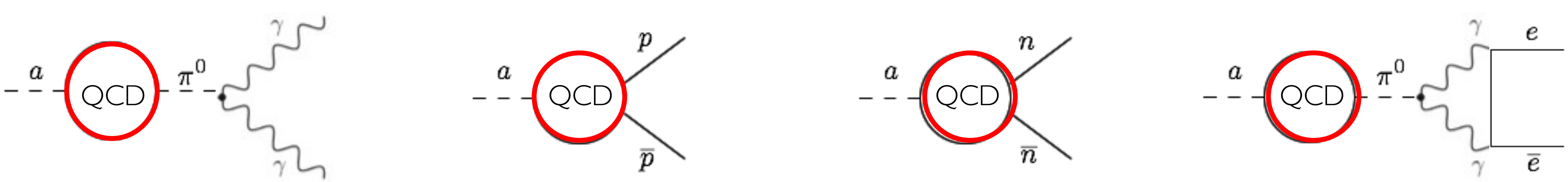
- **Consequences of** $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$ $\sim 1/f_a$

- generate axion mass $\sim 1/f_a$



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

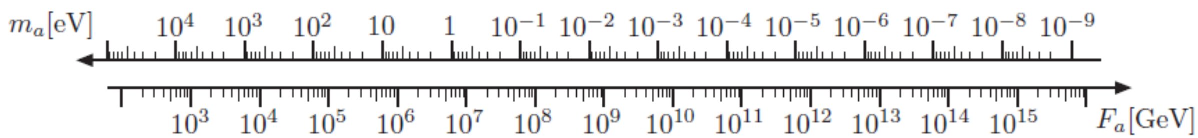
- generates axion couplings to photons, nucleons, electrons. $\sim 1/f_a$



The Axion Solution: the good

- **Axion**: ***a new spin-0*** → ***pNGB of a QCD anomalous global*** **$U(1)_{PQ}$**

1. **axion mass** $m_a \approx 1\ \mathrm{eV}\,\dfrac{10^7\,\mathrm{GeV}}{f_a}$



2. **axion couplings to photons, nucleons, electrons**

$$\rightarrow \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{a}{f_a}\frac{\alpha}{8\pi}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\partial_\mu a}{f_a}\bar{f}\gamma^\mu\gamma_5 f$$

$$(f = p, n, e)$$

The lighter the axion, the weaker are its interactions!

(not yet detected)

Invisible (feebly) **long-lived light particle →** **<u>DM candidate</u>** ☺

Search Strategies and current limits

- Astrophysical bounds

Ringwald, Rosenberg, Rybka, PDG (2025)

  - 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 $g_{aNN} \lesssim 3 \times 10^{-7}\ \mathrm{GeV}^{-1}$

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

strongest bound! ?

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

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

- Helioscopes

Search for Axions produced in the Sun

- Haloscopes

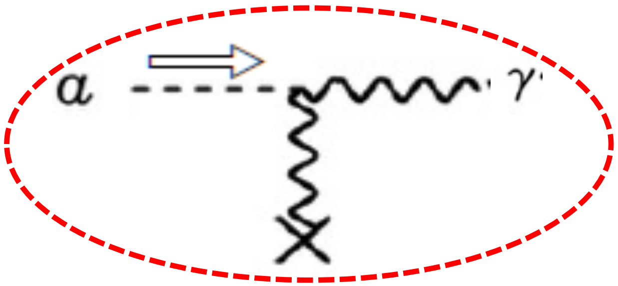
Search for Axion from the halo (Dark Matter)

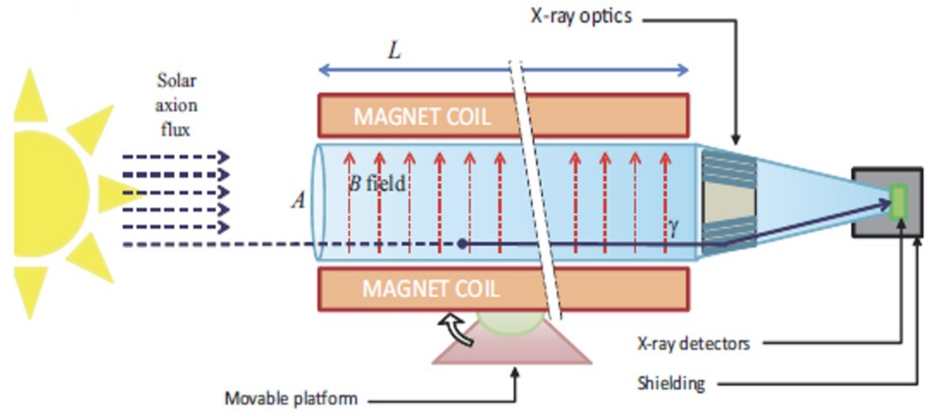
- Light Shining trough Walls

Photon conversion into Axions, reconverted back into photons after passing a wall

Helioscopes: CAST (CERN), **IAXO (DESY, 2026)**

The Sun is a potential source of an axion flux, thanks to solar nuclear reactions



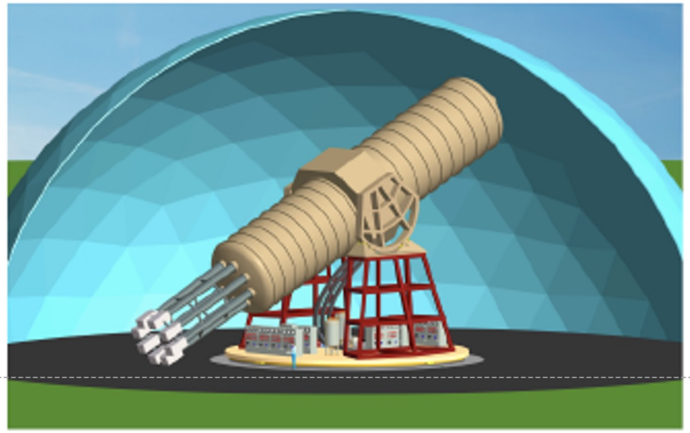


Magnetic telescopes oriented toward the Sun to convert solar axions into X-ray photons

Powers of axions converting into photons in a magnetic telescope

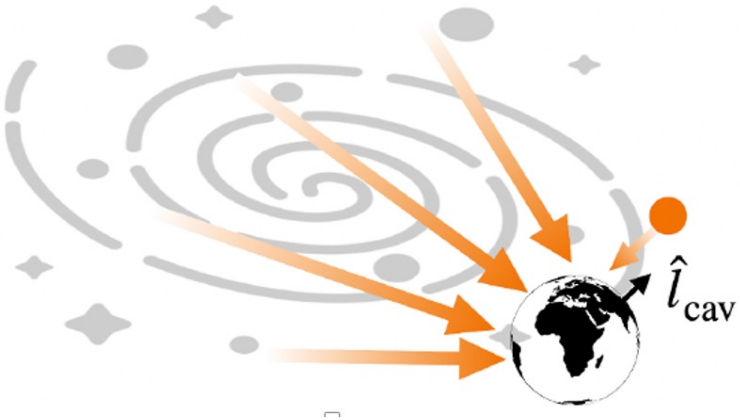
$$P_{a\to\gamma} \approx \left(\frac{g_{a\gamma} B L}{2}\right)^2$$

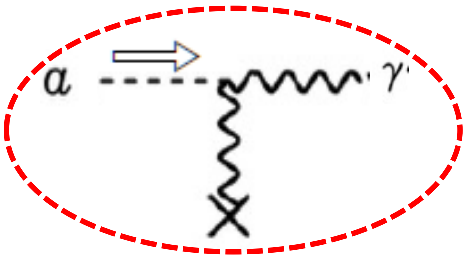
International Axion Observatory (IAXO)



Haloscopes: ADMX (Washington), FLASH (LNF, 2026)

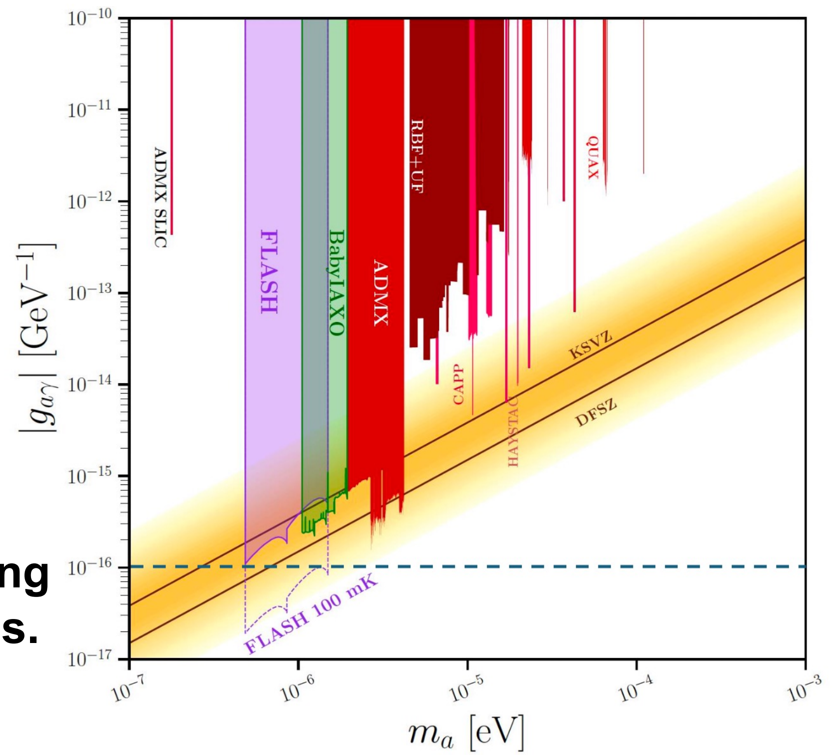
- Look for halo DM axions with a microwave resonant cavity [Sikivie (1983)]
  - exploits inverse Primakoff effect: axion-photon transition in external E or B field





The cavity is tuned to resonate at specific frequencies corresponding to possible axion masses.

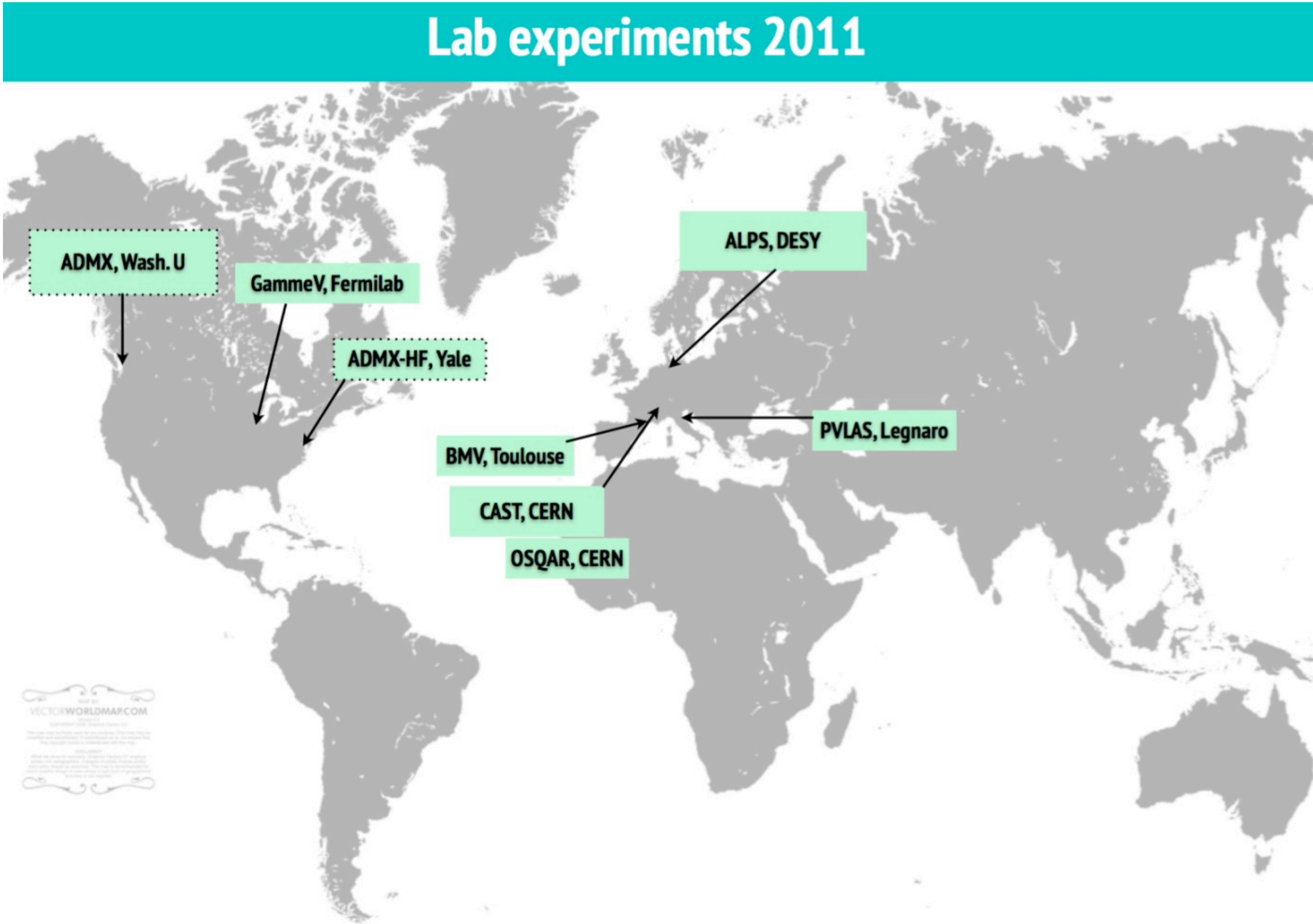
FINUDA magnet for Light Axion SearcH (FLASH)



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

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

New Proposals & search strategies



Hunting for axions: haloscopes

+ Axion Longitudinal Plasma HAloscope (ALPHA), Oak Ridge National Laboratory

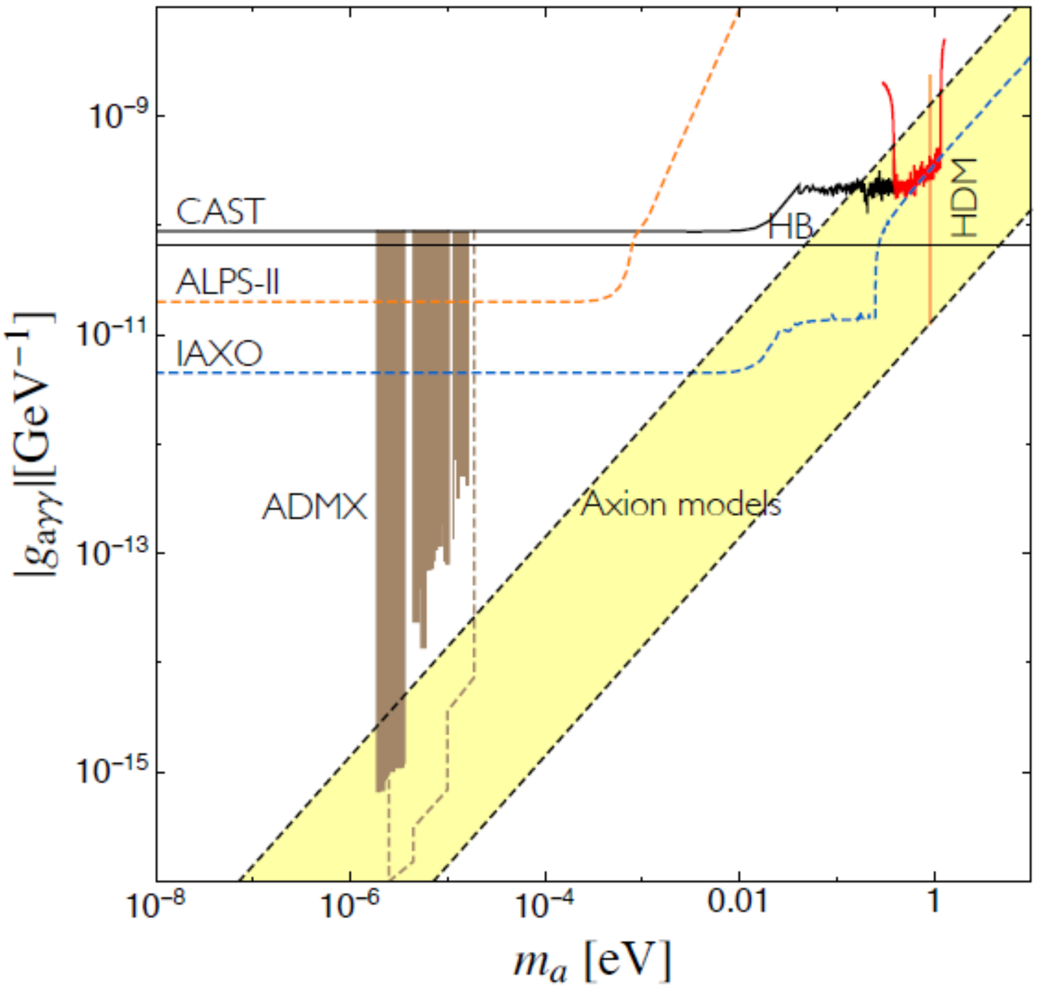
+ Taiwan Axion Search Experiment with Haloscope (TASEH)

+ Cosmic Axion Spin Precession Experiment (CASPEr), Boston and Mainz

Courtesy of Caterina Braggio

BUT WE NEED TO KNOW where to search

BUT WE NEED TO KNOW where to search



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

E/N anomaly coefficients, depend on UV completion

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

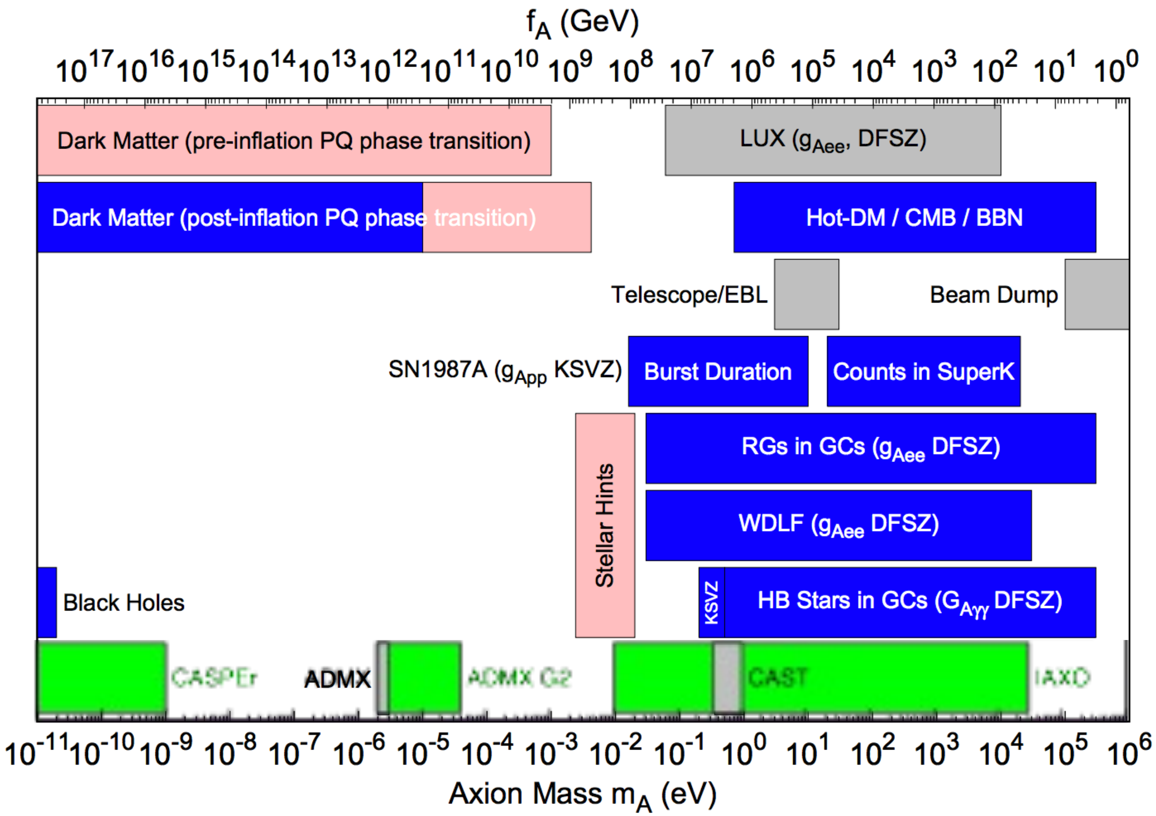
[Particle Data Group (since end of 90's). Chosen to include some representative KSVZ/DFSZ models from:
- Kaplan, NPB 260 (1985),
- Cheng, Geng, Ni, PRD 52 (1995),
- Kim, PRD 58 (1998)]

Ringwald, Rosenberg, Rybka, PDG (2020)

- PDG window is ad hoc and missed model dependence
- **Since 2018 we start to critically revise this bound !**

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2020)



Lab exclusions

Astro/cosmo exclusions

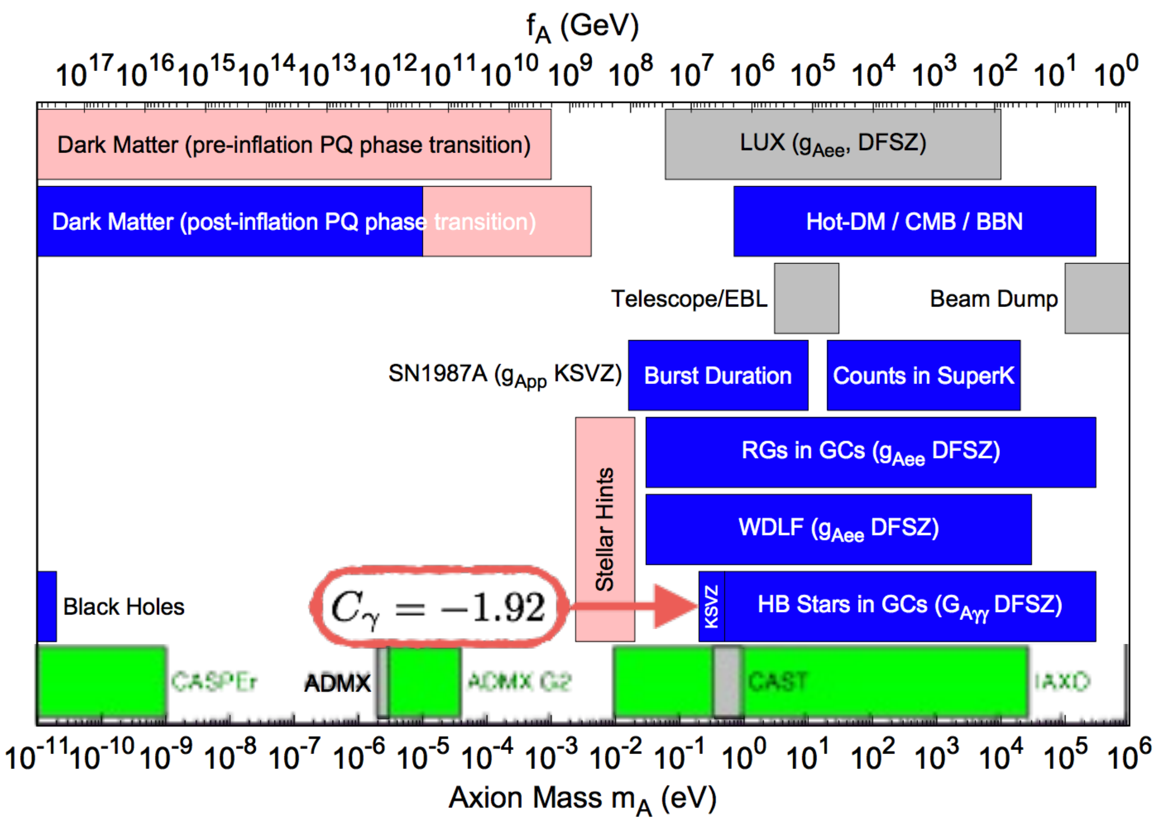
DM explained / Astro Hints

Exp. sensitivities

- Exclusion bound on axion mass from PDG

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2020)



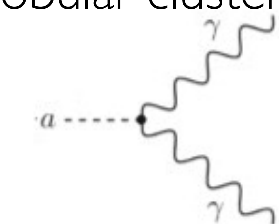
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

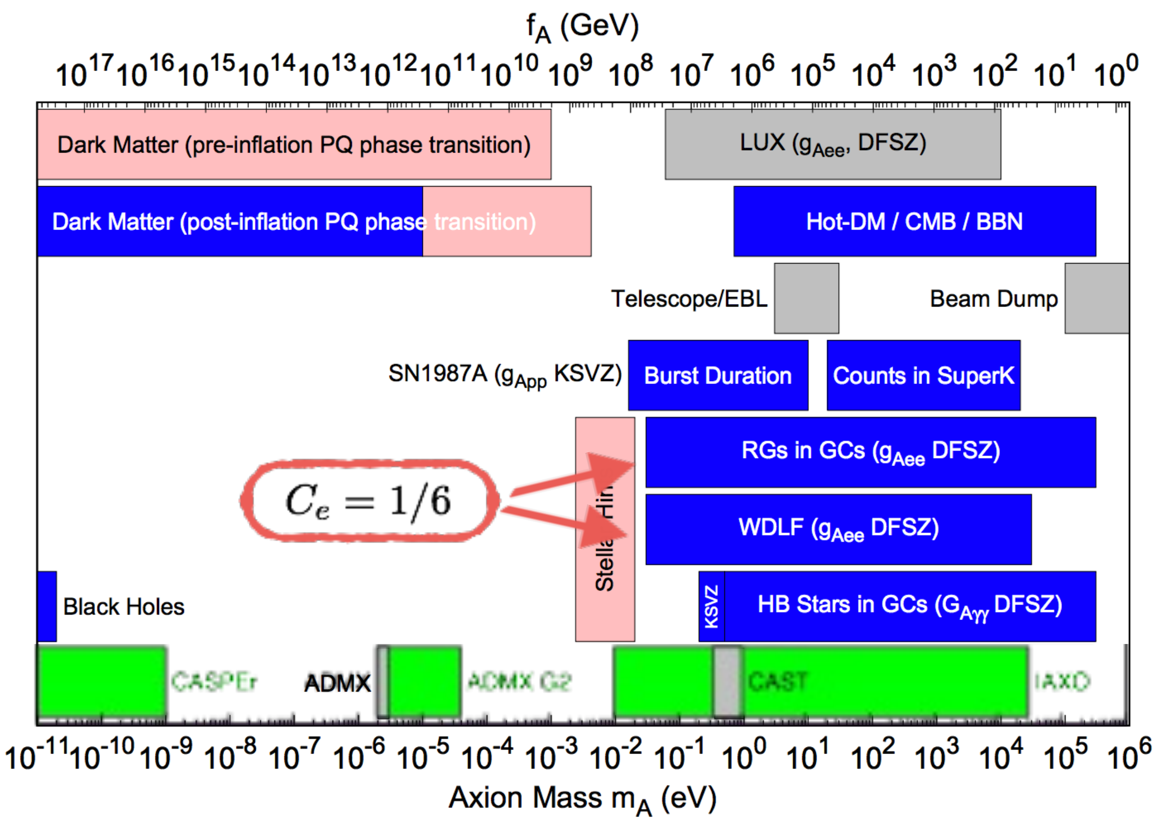
- Exclusion from Horizontal branch star evolution in globular clusters



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

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2020)



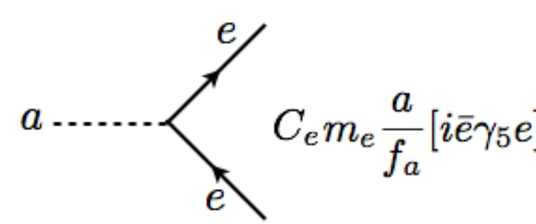
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

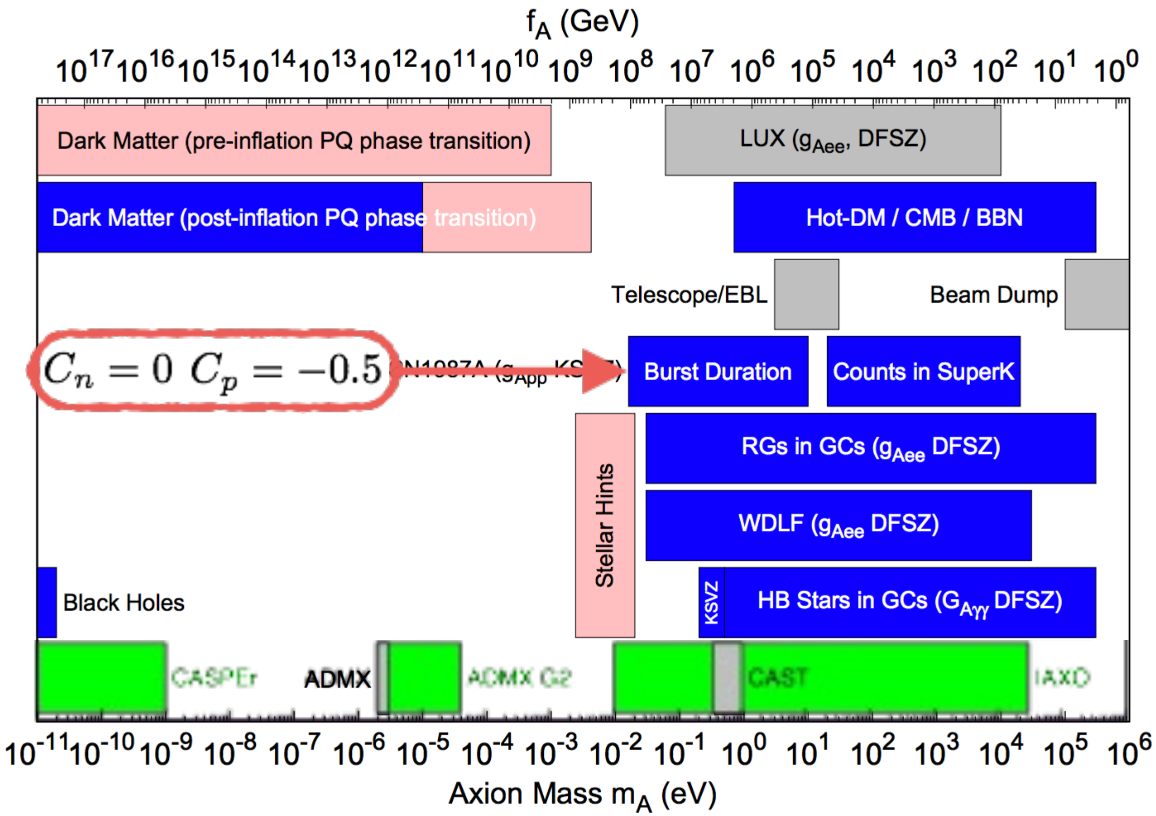
Exp. sensitivities

- Exclusion from Red Giants evolution in globular clusters
- Exclusion from White Dwarfs luminosity function (cooling)



Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2020)



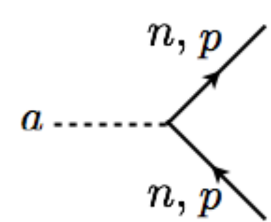
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- Exclusion from Burst duration of SN1987A nu signal

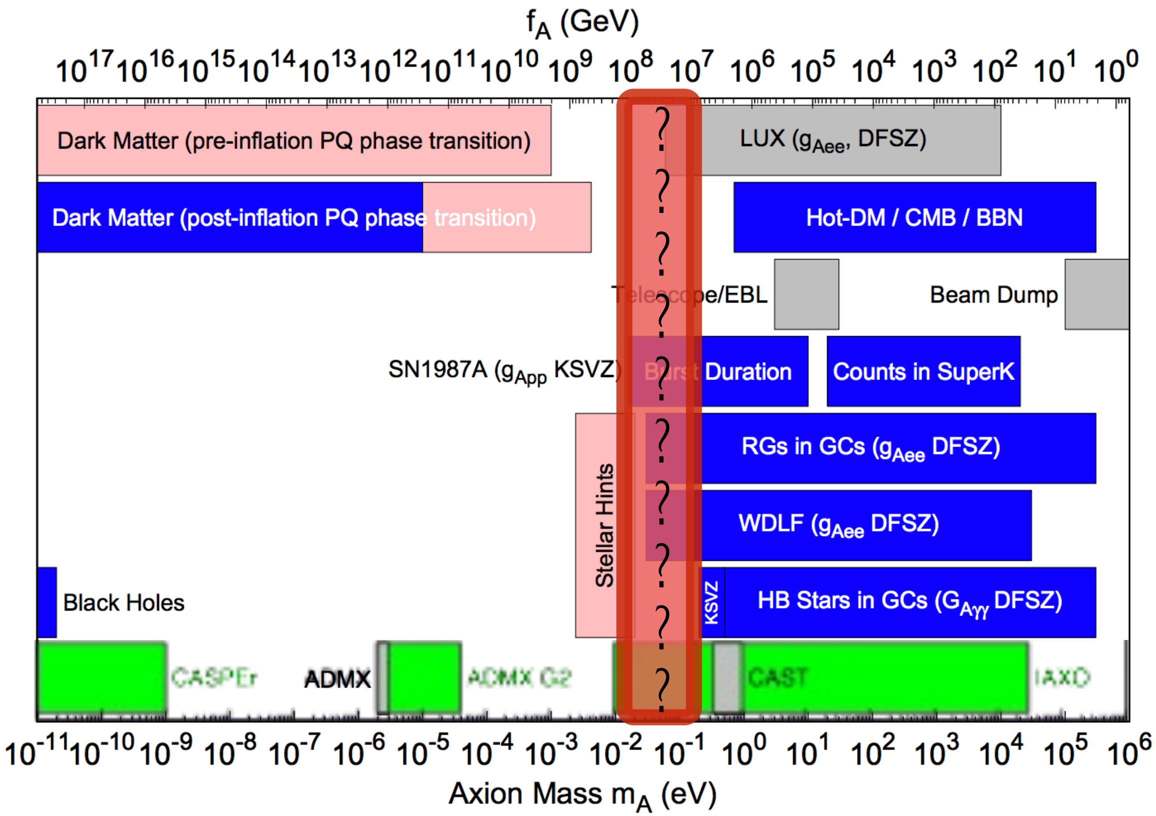


$$C_n m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n]$$

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

Axion landscape

Ringwald, Rosenberg, Rybka, PDG (2020)



Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

- PDG Bounds on axion mass are of practical convenience but misses model dependence! highly misleading
- since 2018 we have started to critically revise this bound !

Axion EFT

- **To solve the strong CP problem, all you need is**

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

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

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

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

Axion EFT

❑ **To solve the strong CP problem, all you need is**

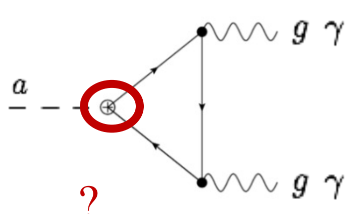
a new spin-0 boson with pseudo-shift symmetry

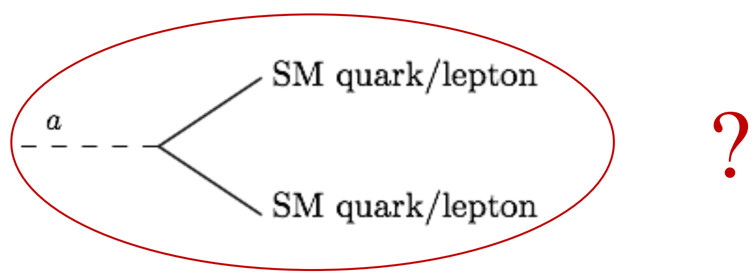
<u>broken by</u> $$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$$

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

- However, at energies of order f_a axion EFT breaks down ⇒ needs UV completion

UV completion will affect low-energy axion couplings!





Model building and Pheno

1

- ***Axion couplings to photons***

The model-dependent
part beyond EFT

Axion UV Models

- Axion: 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

Higgs

SM

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

⇒ no chiral rotation left in the SM

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

⇒ **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

Possible to have in 2HDM an anomalous

$\mathbf{U(1)_{PQ} \perp U(1)_{Y}}$

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)

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

$\swarrow$

SM quark

$\swarrow$

2 Higgs

PQWW

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

Ruled out

"Visible" axions

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

- <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

PQWW

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

Ruled out

“Visible” axions

2 Higgs + Singlet

DFSZ

Zhitnitsky ’80,
Dine, Fischler, Srednicki ’81

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

“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	2 Higgs + Singlet
PQWW	**DFSZ**
Peccei, Quinn ’77, Weinberg ’78, Wilczek ’78	Zhitnitsky ’80, Dine, Fischler, Srednicki ’81
Ruled out	$\langle \mathrm{Singlet} \rangle \gg v$
“Visible” axions	“Invisible” axion models: $f_a \gg v$

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

$$f_a \gg v$$

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

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

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

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	BSM quark
2 Higgs + Singlet	1 Higgs + Singlet
DFSZ	**KSVZ**
Zhitnitsky ’80, Dine, Fischler, Srednicki ’81	Kim ’79, Shifman, Vainshtein, Zakharov ’80

$$\boxed{\langle \mathrm{Singlet} \rangle \gg v}$$

“Invisible” axion models: $f_a \gg v$

Axion UV Models

- Axion: pNGB 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 + Singlet

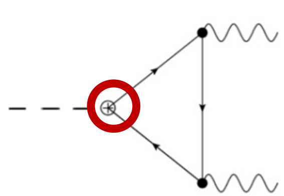
DFSZ

BSM quark

1 Higgs + Singlet

KSVZ

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



Model dependence from UV completions

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 ~ (3,1,0)

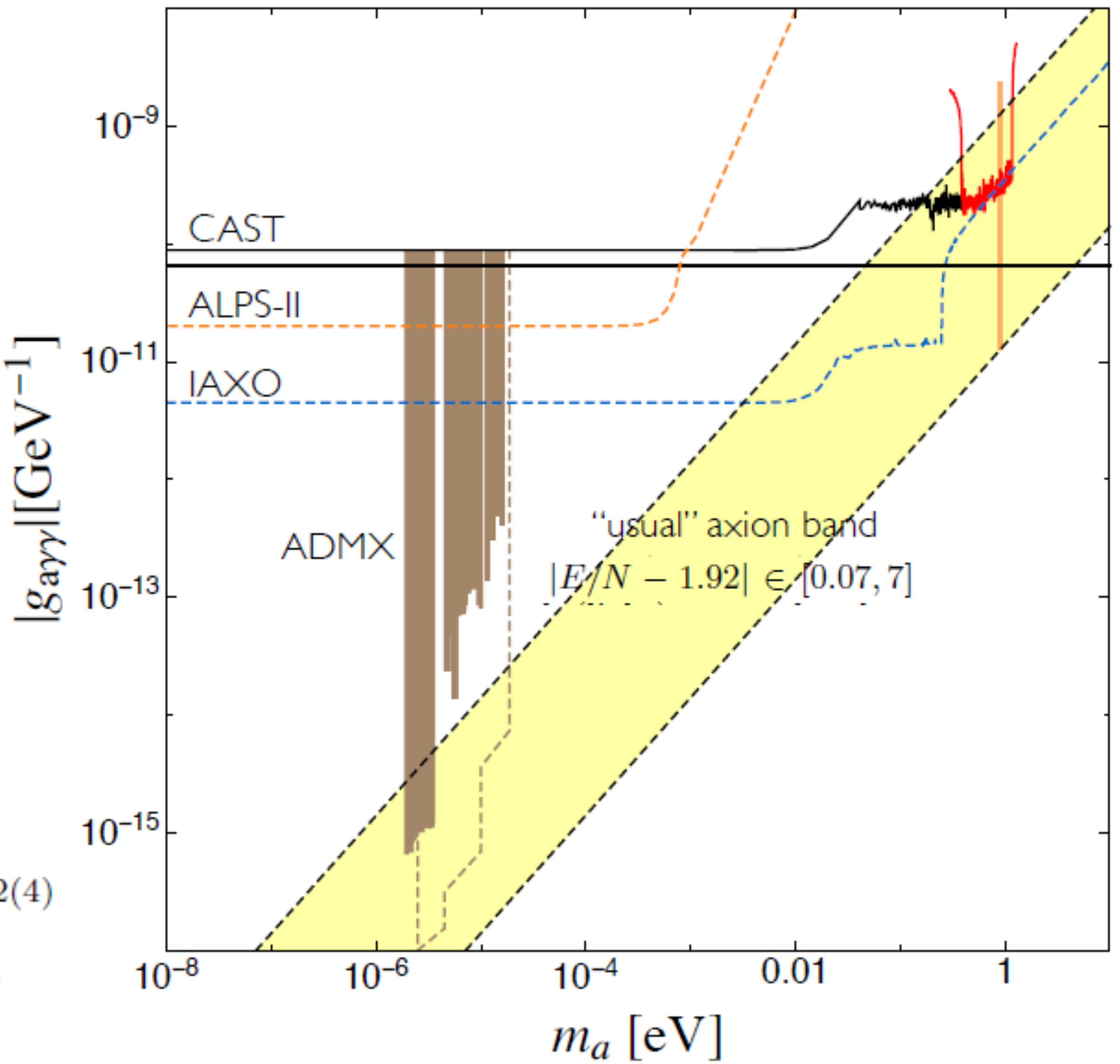
$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$

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

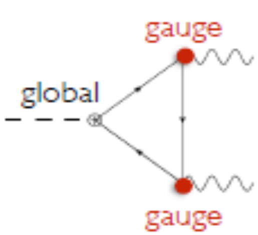
- and by a SM singlet Φ containing the "invisible" axion ($V_a \gg v_{\rm EW}$)

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

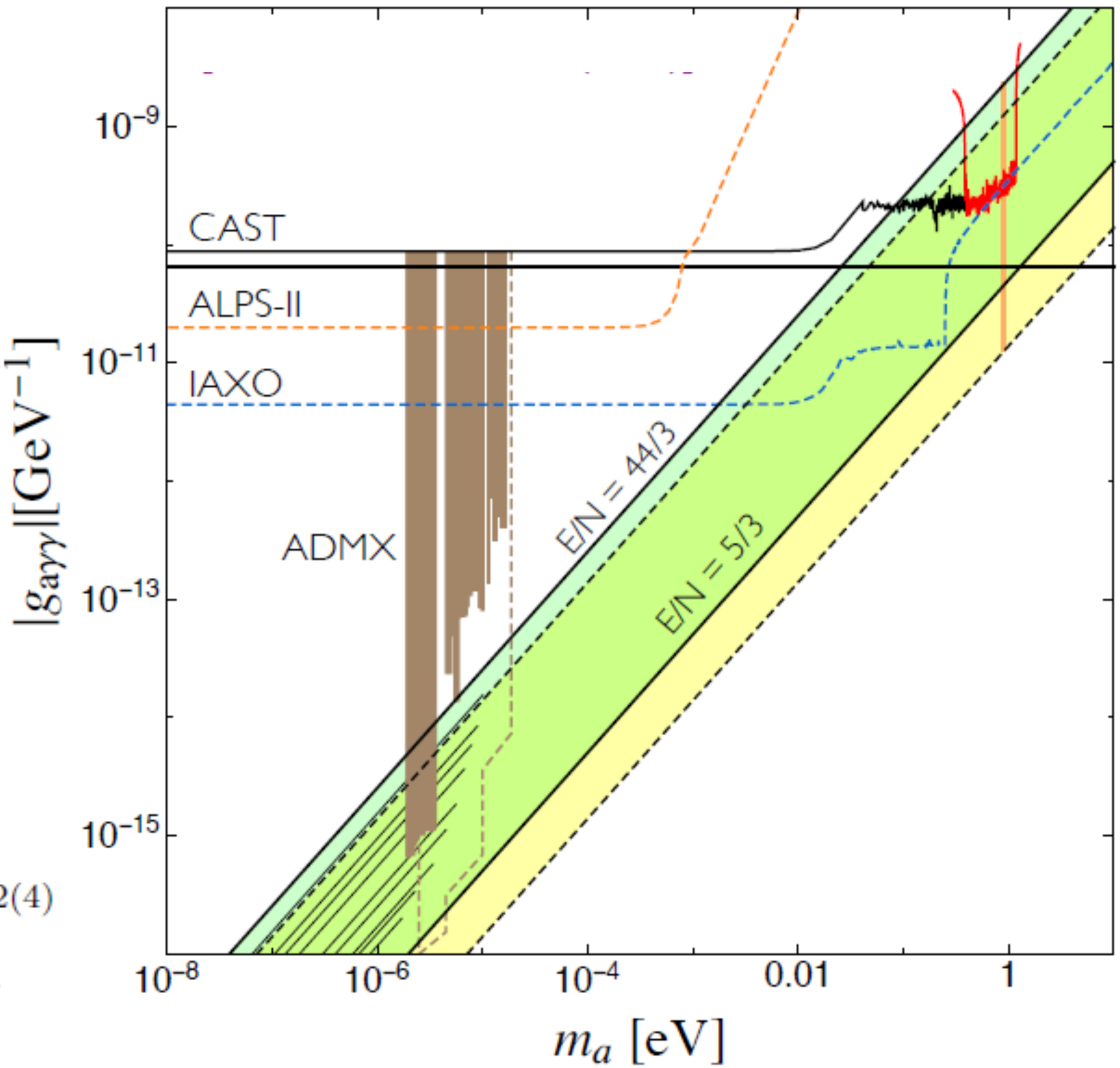
Redefining Axion Windows for a → $\gamma\gamma$: KSVZ



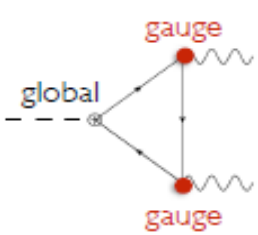
$$C_\gamma = E/N - 1.92(4)$$



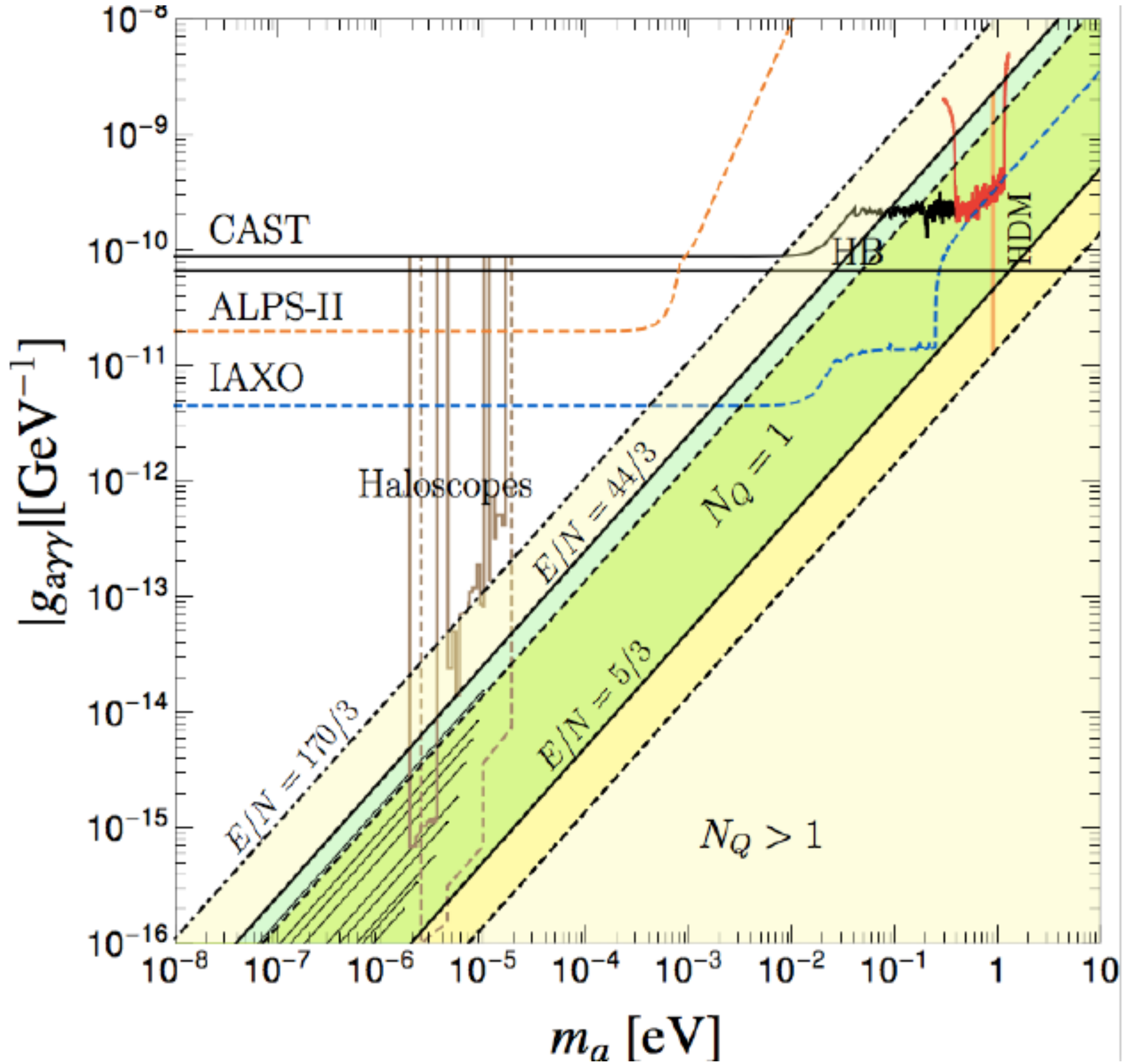
Redefining Axion Windows for a $\to \gamma\gamma$: KSVZ (N_Q=1)



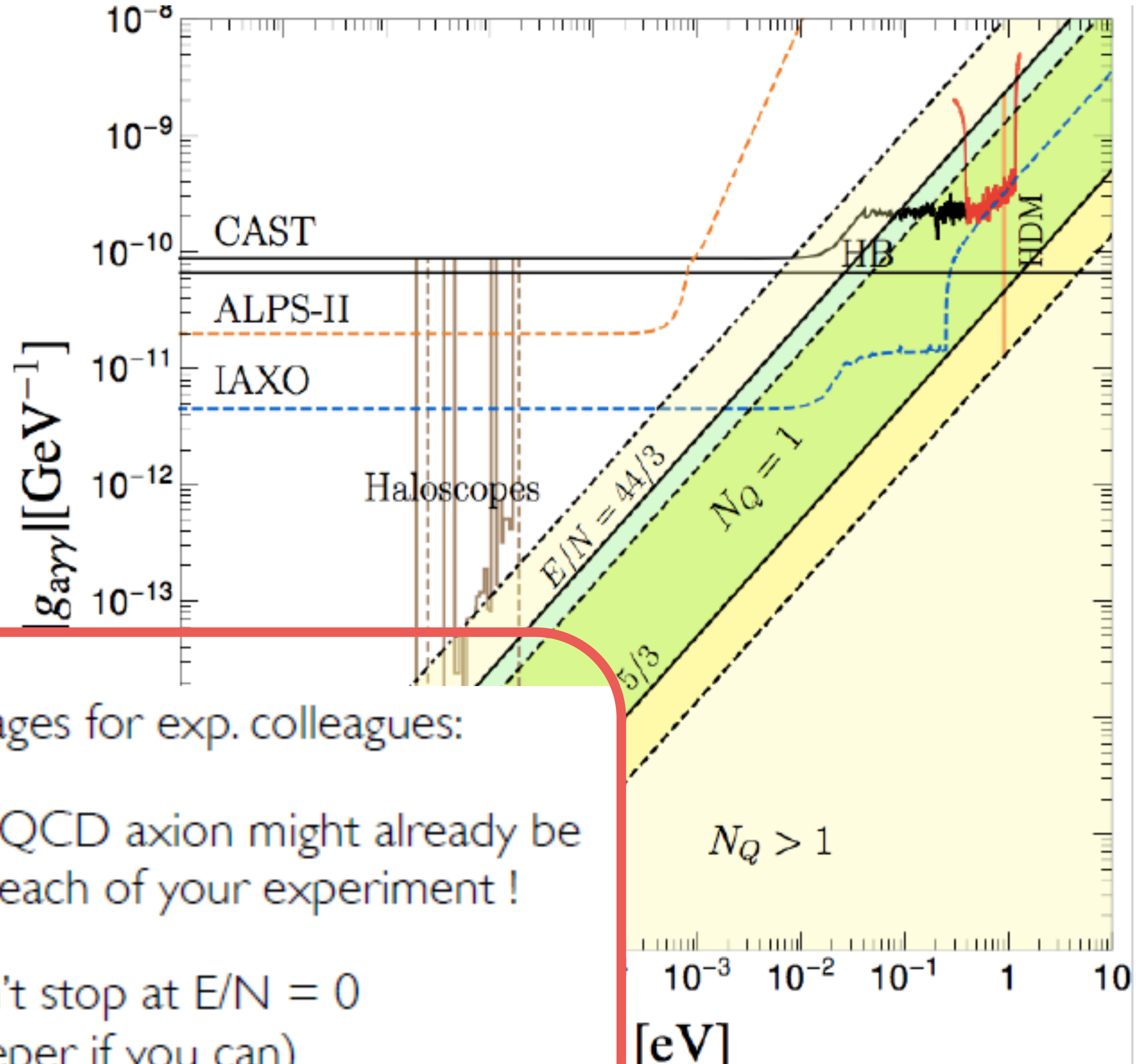
$C_\gamma = E/N - 1.92(4)$



Redefining Axion Windows for a → $\gamma\gamma$: KSVZ (N_Q>1) + DFSZ



Redefining Axion Windows for a → γγ: KSVZ (N_Q>1)



- 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)

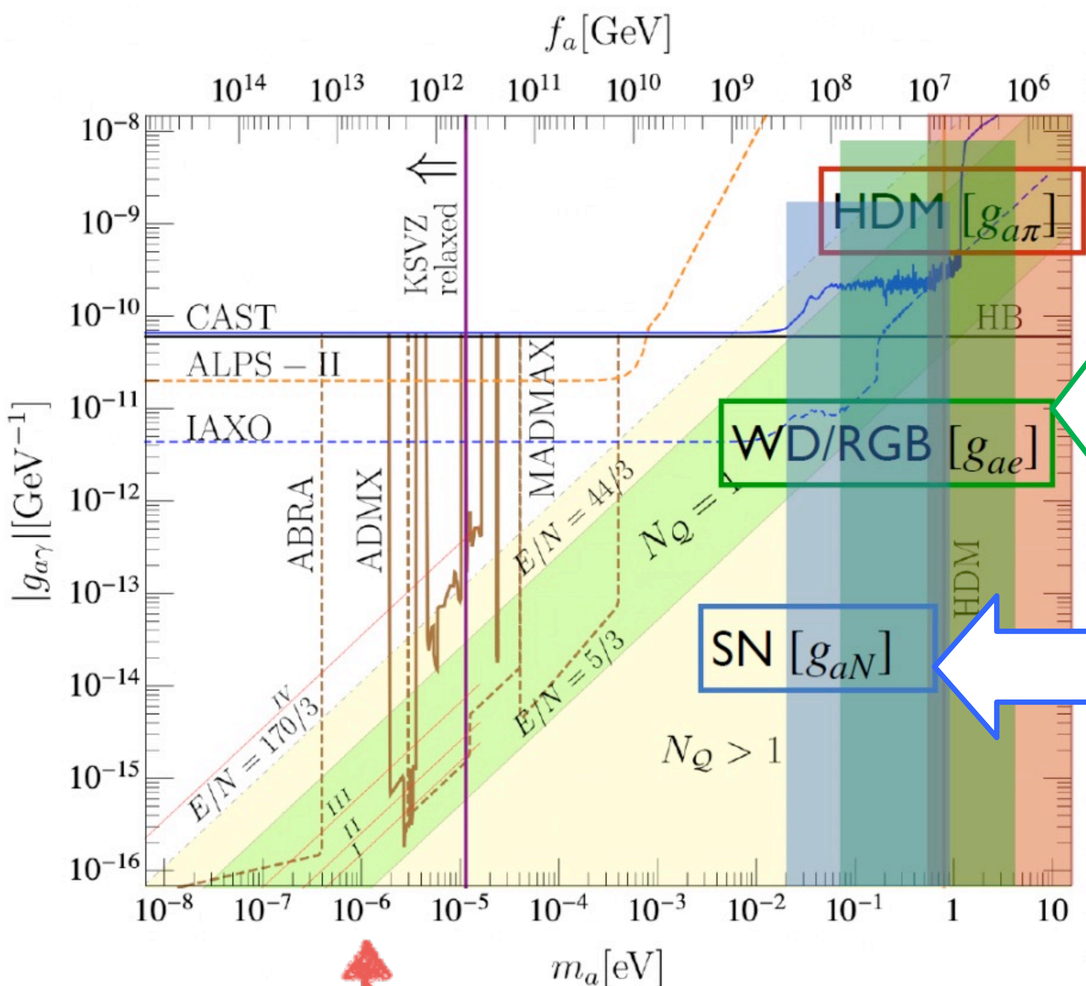
Model building and Phenomelogy

2

- ❑ ***Axion couplings to fermions***

Based on
Di Luzio, Fiorentino, Giannotti, F. M, ‘25
Di Luzio, FM, Okawa, Nardi, ‘22
Di Luzio, F.M. Nardi, Panci, Ziegler, ‘17
Björkeroth, Di Luzio, F.M. Nardi, ‘18

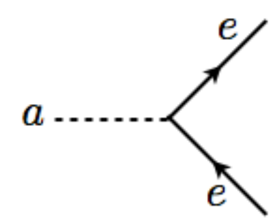
Bounds in DFSZ/KSVZ benchmark models



DFSZ & KSVZ benchmark models

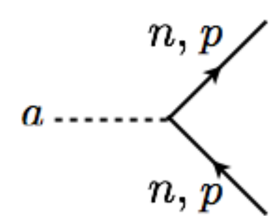
- **The strongest bounds are from astro/cosmo**

WD/RGB



$$\frac{\partial_\mu a}{2 f_a} c_e \bar{e} \gamma^\mu \gamma_5 e$$

SN1987A



$$\frac{\partial_\mu a}{2 f_a} C_N \bar{N} \gamma^\mu \gamma_5 N$$

Mind: *bounds are largely model-dependent!*

Astrophobic axion: $C_N \sim 0 + c_e \sim 0$

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

→ nucleophobia + electrophobia = astrophobia

- No: **in KSVZ-like models!**
- Yes: **in DFSZ-like models with generation dependent PQ charges!**

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

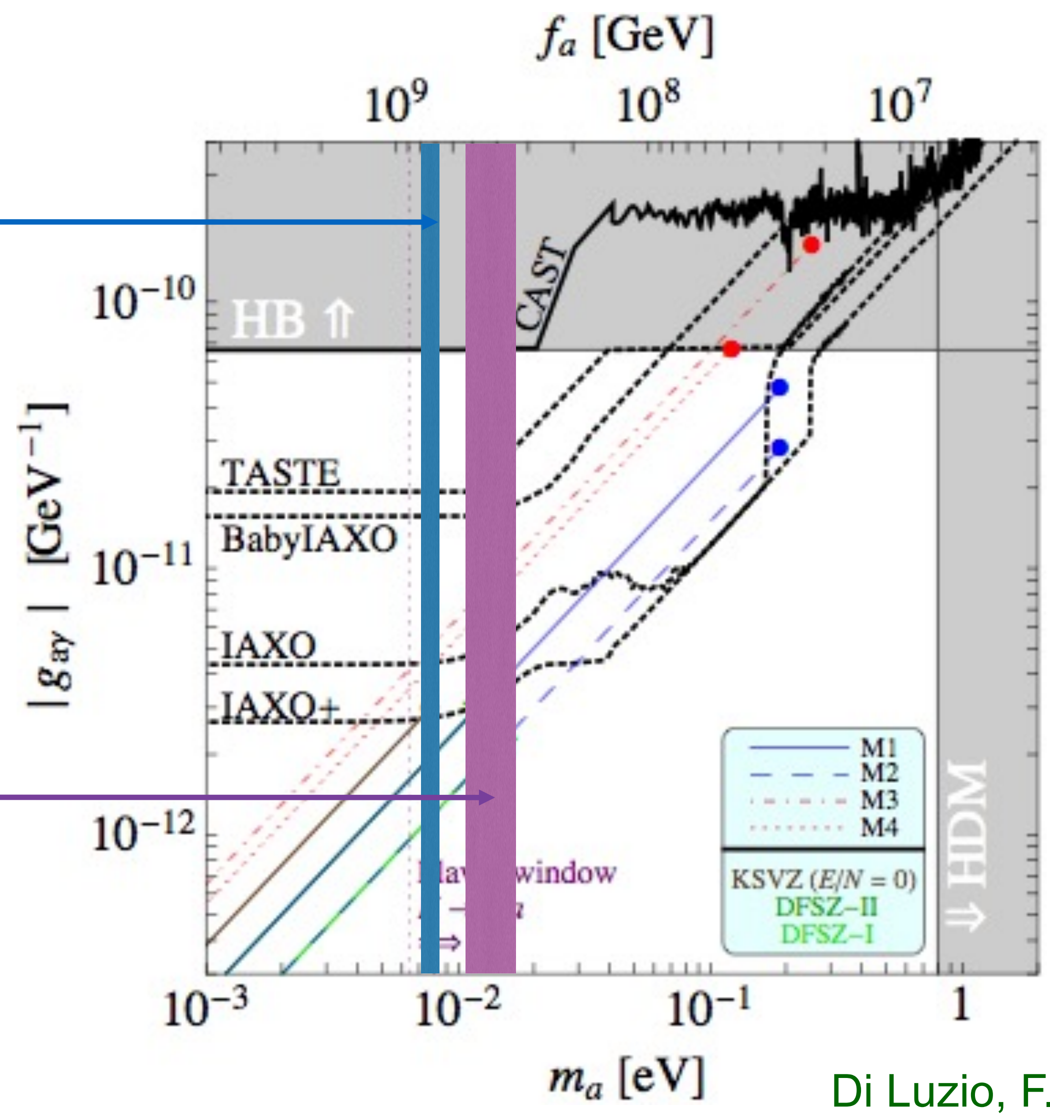
2. It will improve visibility at IAXO (axion-photon)

3. unexpected connection to flavour physics

Di Luzio, F.M. Nardi, Okawa, (2022)
Björkeroth, Di Luzio, F.M. Nardi, (2018)
Di Luzio, F.M. Nardi, Panci, Ziegler, (2017)

Axion benchmark models

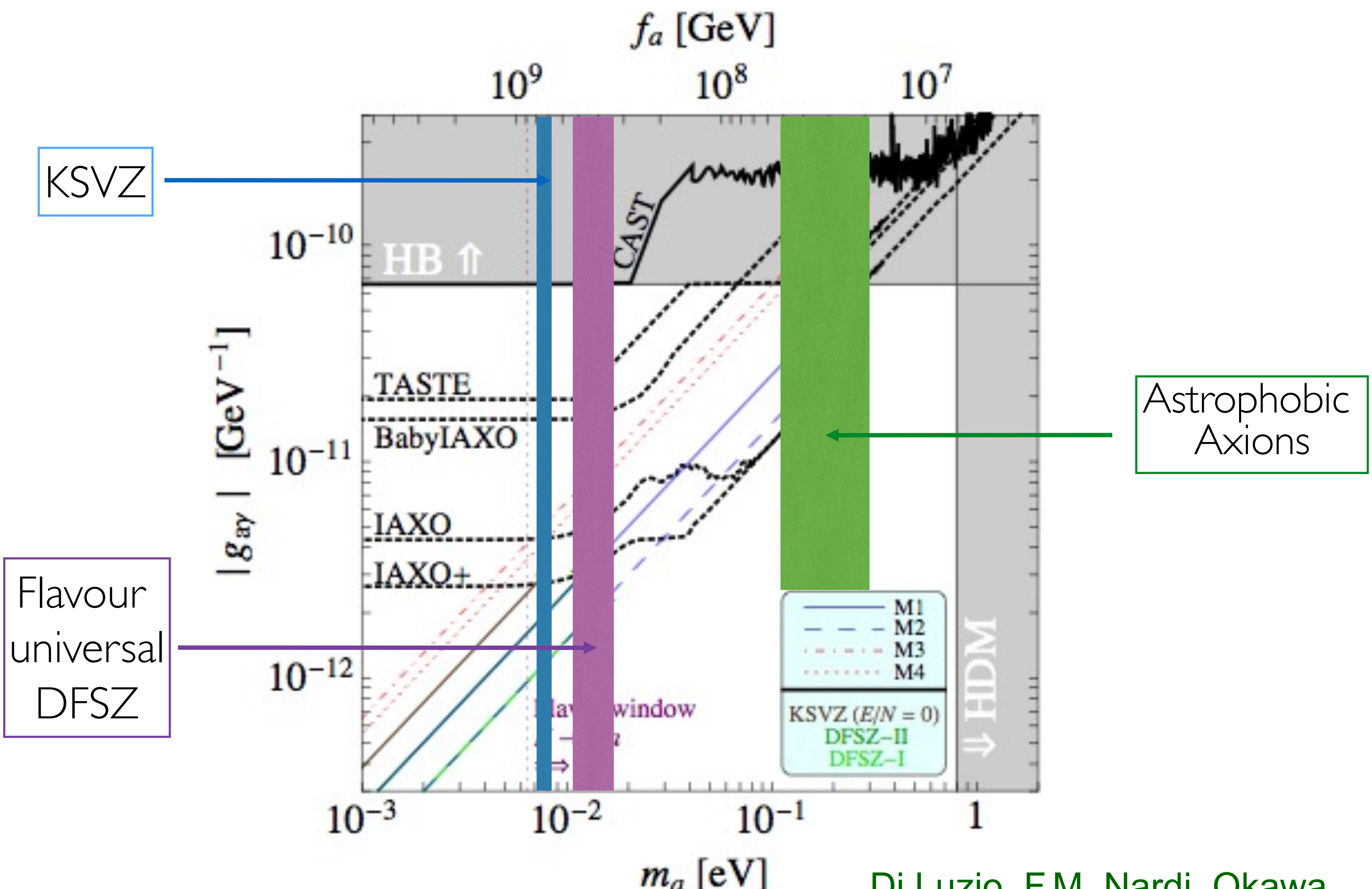
KSVZ



Flavour universal DFSZ

Di Luzio, F.M. Nardi, Okawa, (2022)

Astrophobic axion models



Di Luzio, F.M. Nardi, Okawa, (2022)

The Axion Solution: the bad

3

Do global symmetries exist in nature?

The Axion Solution: the bad

- **Origin of $U(1)_{PQ}$: *Do global symmetries exist in nature*?**

  ✓ **Global symmetries** act uniformly across spacetime (e.g., rotating all fields by the same phase)

  → *Broadly, this is at odds with the local nature of spacetime deformations in Quantum Gravity.*

  → Opposite to gauge symmetries, which are inherently local

***Global symmetries* are not believed to be fundamental,**
presumably an accident at low-energy!?!

Gauge Protection to PQ symmetries

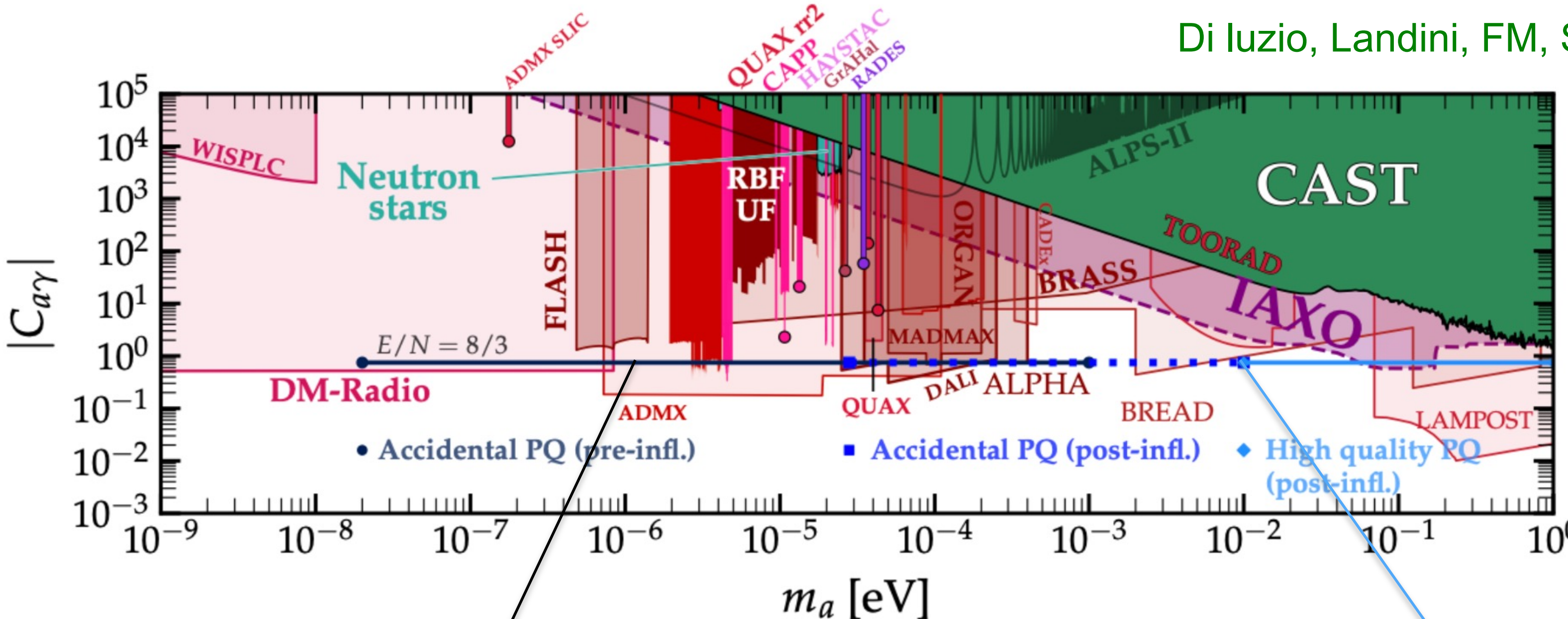
- Discrete gauge symmetries (vertical): $\mathbb{Z}_n$
  :
- Abelian gauge U(1) (vertical): U_1
- Non-Abelian gauge group (vertical): $SU(N) \otimes SU(N)$ $SU(9)_{\mathrm{GUT}}$ $SU(N) \to SO(N)$

- Recently, we have studied *models where PQ arises by GUT and flavor symmetries giving with low-energy signatures! explaining additional SM puzzles (like SM flavor structure, Dark Matter)*?

Pati-Salam – axion flavour model

Axion mass range: **high-quality** PQ vs **accidental** PQ scenario

Di Iuzio, Landini, FM, Susic '25



E/N=8/3 DFSZ-like

high-quality PQ

$m_a \gtrsim 0.01$ eV

$$\mathcal{L}_{a\gamma} = \frac{\alpha_{\rm em} C_{a\gamma}}{8\pi f_a} a\, F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad C_{a\gamma} = E/N - 1.92(4)\,,$$

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
- **FLASH@LNF is testing axion dark matter region**

❖ Theoretical developments are still ongoing

- revise theoretical uncertainties due to "model dependence"

  ➡
  - flavoured axion searches
  - connection to SM flavour puzzle: textures a la FN?

- the Peccei-Quinn symmetry must be protected by UV sources (Quality problem)

  ➡ GUT + flavor gauge symmetries provide the desired protection

Conclusion

Thanks