The window for preferred axion models

Based on Phys.Rev.Lett. 118 (2017) no.3, 031801 [arXiv:1610.07593]
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Outline

- The strong CP problem (a short review)
- Experimental searches (a short summary)
- Types of axion models; KSVZ (QCD) and DFSZ) axions
- Dark Matter from axion misalignment
- The window for preferred hadronic axion models
- Preferred region for Dine-Fischler-Srednicki-Zhitnitsky type of axions

The strong CP problem

- QCD is defined in terms of two dimensionless parameters which are not predicted by the theory. Measurements yield:

$$\alpha_s \sim O(0.1\text{-}1) \qquad \text{and} \qquad \bar{\theta} < 10^{-10}$$

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

- The difference $\overline{\theta} = \theta - \theta_q$ gives the amount CP viol. in QCD

$$q \to e^{i\gamma_5 \alpha} q \quad \longrightarrow \quad \theta_q \to \theta_q + 2\alpha \quad \text{and} \quad \theta \to \theta + 2\alpha$$

- Change in θ is given by the change of the path integral measure:

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

[Fujikawa (1979)]

A small value problem

- $\overline{\theta} \neq 0$ implies a non-zero neutron EDM [Baluni (1979), Crewther et al. (1979)]

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

- However, $d_n \lesssim 3\cdot 10^{-26} e\,\mathrm{cm}$ implying: $\longrightarrow$ $\overline{\theta} \lesssim 10^{-10}$

- This is qualitatively different from other small values problems:
  - In the SM $\overline{\theta}$ is only log-divergent (at 7 loops !). Finite corrections O(α^2)

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

Unlike $m_H^2 \ll \Lambda^2_{UV}$ [Ellis, Gaillard (1979)]

  - Unlike $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$ it evades explanations based on environmental selection [Ubaldi, 0811.1599]

Three types of solutions

- **A massless quark. One exact chiral symmetry:** $\overline{\theta} \to 0$
  - From lattice: $m_u \neq 0$ by more than 20 σ [Aoki (2013)] [Manhoar & Sachrajda, PDG(2014)]
- **Spontaneous CP violation** [Barr (1984), Nelson (1984)]
  - Set $\overline{\theta}$ = 0 by imposing CP. Need to break spont. for CKM (+BAU)
  - High degree of fine tuning, or elaborated constructions to keep $\overline{\theta} < 10^{-10}$ at all orders. No unambiguous exp. signatures.
- **Peccei-Quinn solution** [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]
  - Assume a global U(1)$_{PQ}$: (i) spontaneously broken; (ii) QCD anomalous
  - Implies a PGB of U(1)$_{PQ}$: the Axion. Shift symmetry: $a(x) \to a(x) + \delta\alpha\, f_a$

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

Axion models

- PQWW axion:

  Axion identified with the phase of the Higgs in a 2HDM

  ($f_a \sim V_{EW}$ was quickly ruled out long ago) [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

The need to require $f_a \gg V_{EW}$: "invisible axion"

- DSFZ Axion: SM quarks and Higgs charged under PQ.

  Requires 2HDM + 1 scalar singlet. SM leptons can also be charged.

  [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

- KSVZ Axion (or QCD axion, or hadronic axion):

  All SM fields are neutral under PQ. QCD anomaly is induced by new quarks, vectorlike under the SM, chiral under PQ.

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

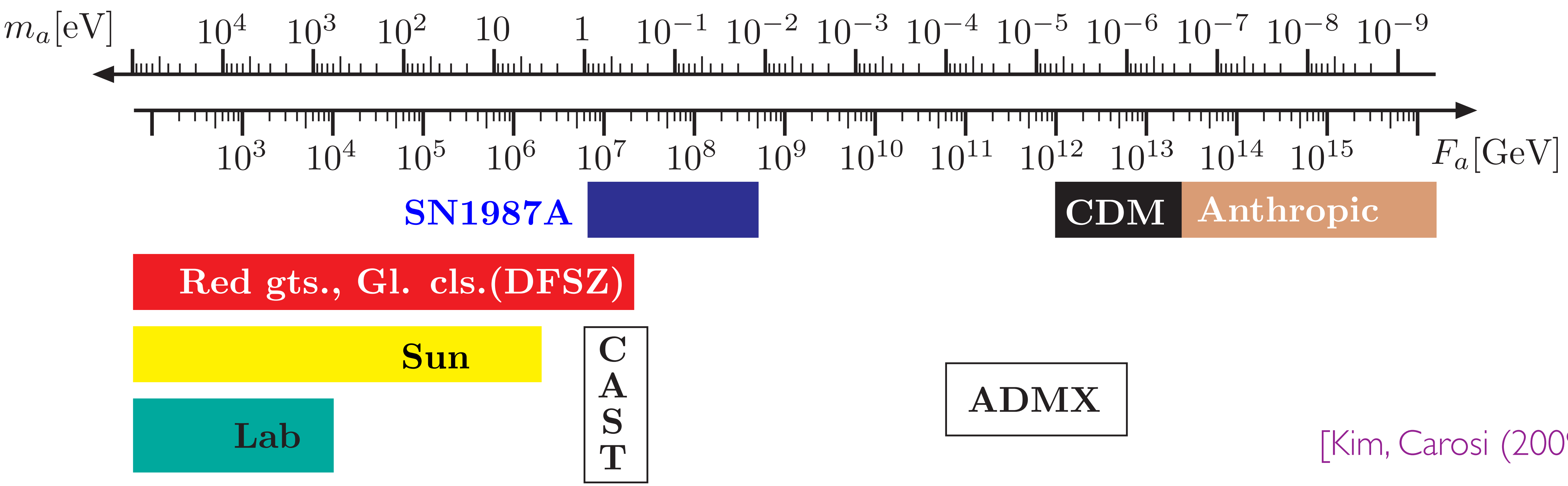
Model independent features

- Axion mass: $\sim 1/f_a$ $\quad m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$

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

The lighter is the axion, the weaker are its interactions

Axion Landscape:



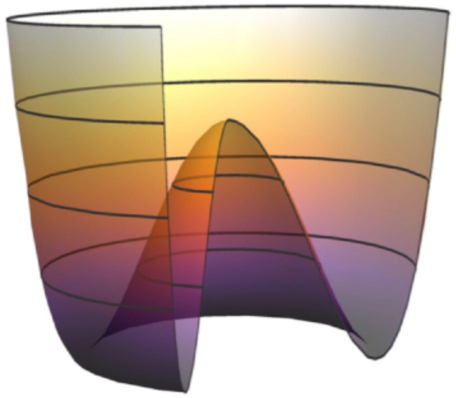
[Kim, Carosi (2009)]

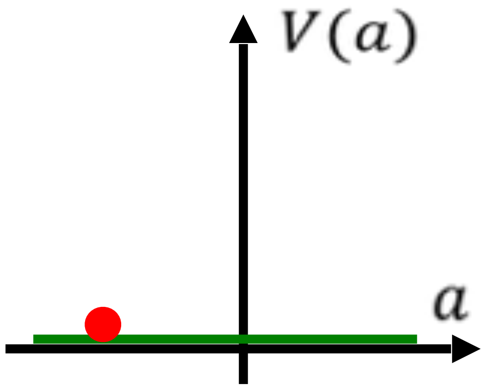
Axion CDM from misalignment

- **As long as $\Lambda_{QCD} < T < f_a$:**

  $U(1)_{PQ}$ broken only spontaneously,

  $m_a = 0$, $\langle a_0 \rangle = \theta_0 f_a \sim f_a$





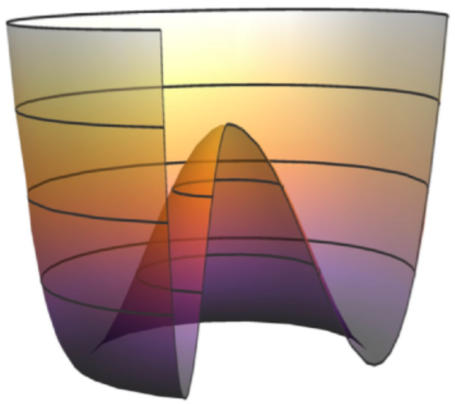
- **As soon as $T \sim \Lambda_{QCD}$:**

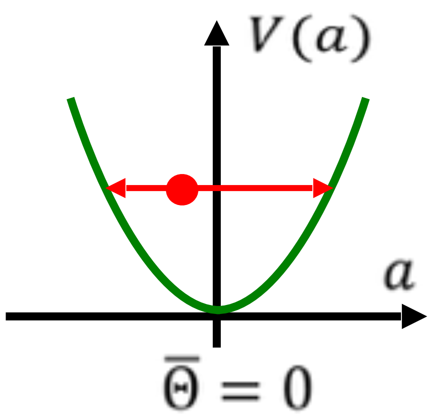
  $U(1)_{PQ}$ explicit breaking (instanton effects)

  $m_a(T)$ turns on. When $m_a(T) > H \sim 10^{-9}$ eV,

  $\langle a_0 \rangle \longrightarrow 0$ and starts oscillating undamped

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





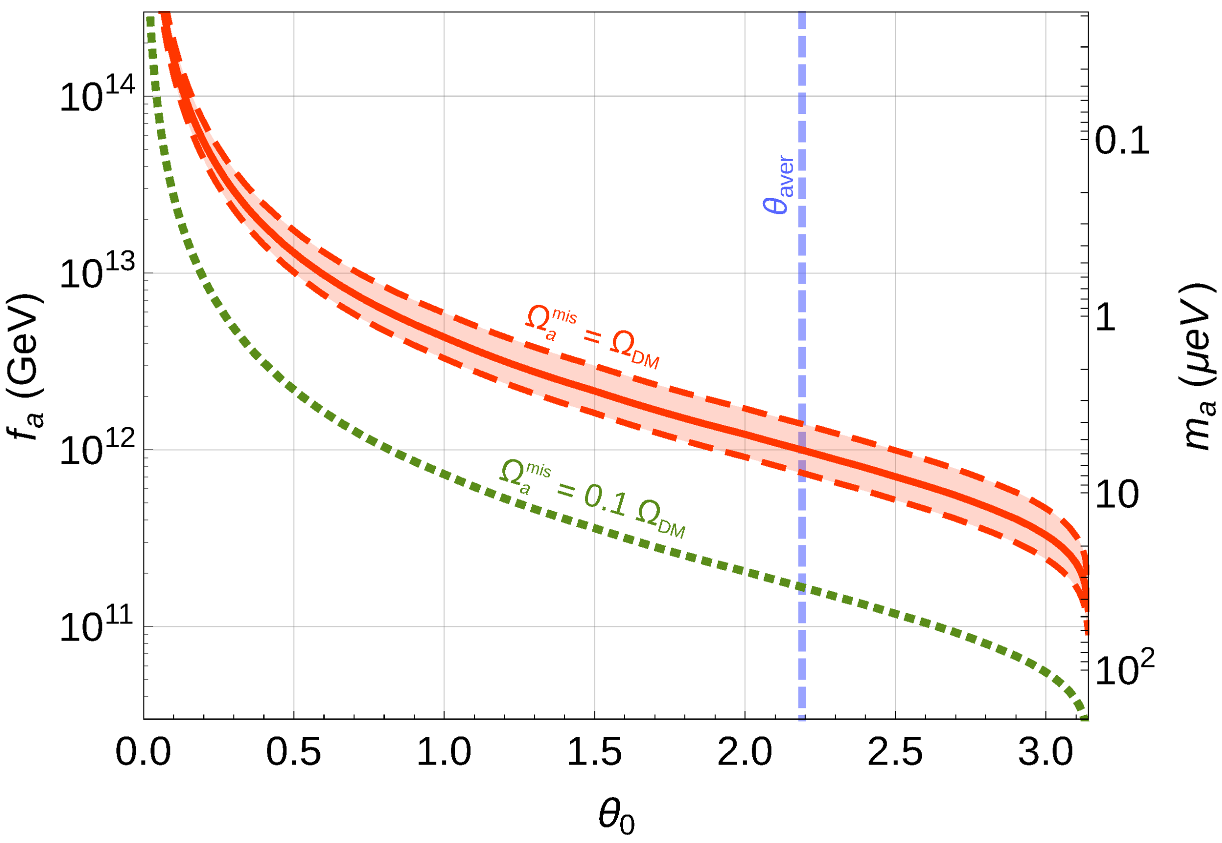
- **Energy stored in oscillations behaves as CDM**

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

Energy density & initial conditions

- From recent lattice QCD calculations, [Bonati et al. 1512.06746, Petreczky et al. 1606.03145, Borsanyi et al. 1606.07494]

  for $\theta_0 = \mathcal{O}(1)$ upper limit $f_a \lesssim 10^{11\div12}$ GeV



- Value of θ_0 depends on the scale of inflation versus the PQ breaking scale f_a

  — $U(1)_{PQ}$ broken after inflation: average over several Universe patches : $\langle\theta_0\rangle = \pi/\sqrt{3}$

  — $U(1)_{PQ}$ broken before inflation: in the whole observable Universe the same random value of θ_0

  — "Antropic Axion": $f_a \gg 10^{12}$ GeV is allowed only if $\theta_0 \ll 1$

Search strategies and current limits

- **Astrophysical bounds** [For a collection see e.g. Raffelt, hep-ph/0611350]
  - 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 $g_{aNN} \lesssim 3 \times 10^{-7}\,\mathrm{GeV}^{-1} \longrightarrow f_a \gtrsim 2 \times 10^{8}\,\mathrm{GeV}$

- **Most laboratory search techniques are sensitive to $g_{a\gamma\gamma}$**
  - Light Shining trough Walls [see e.g. Redondo, Ringwald hep-ph/1011.3741]

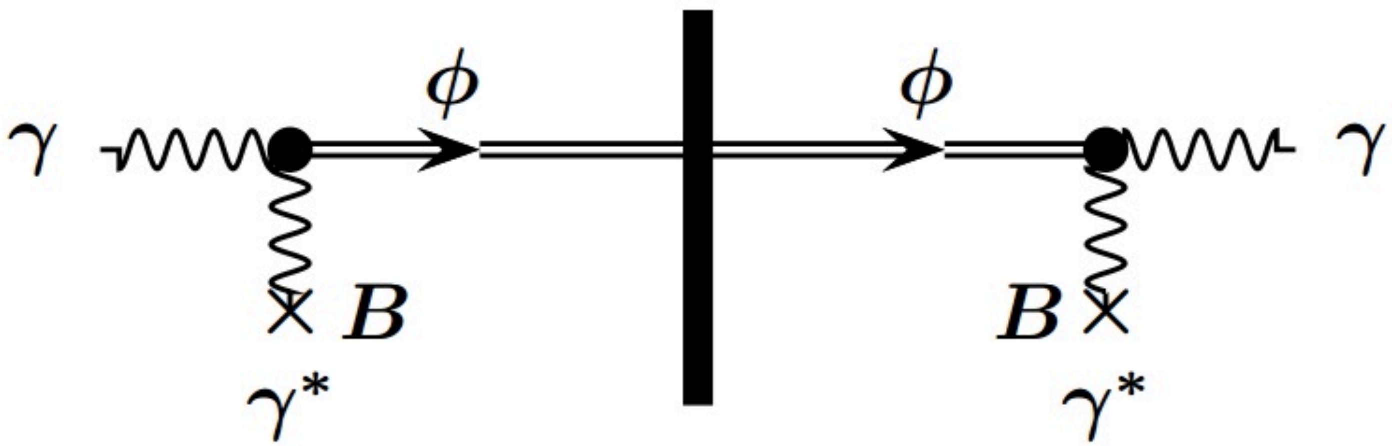
    Photon conversion into Axions, reconverted back into photons after passing a wall
  - Haloscopes [Sikivie 1983]

    Search for Axion Dark Matter
  - Helioscopes

    Search for Axions produced in the Sun

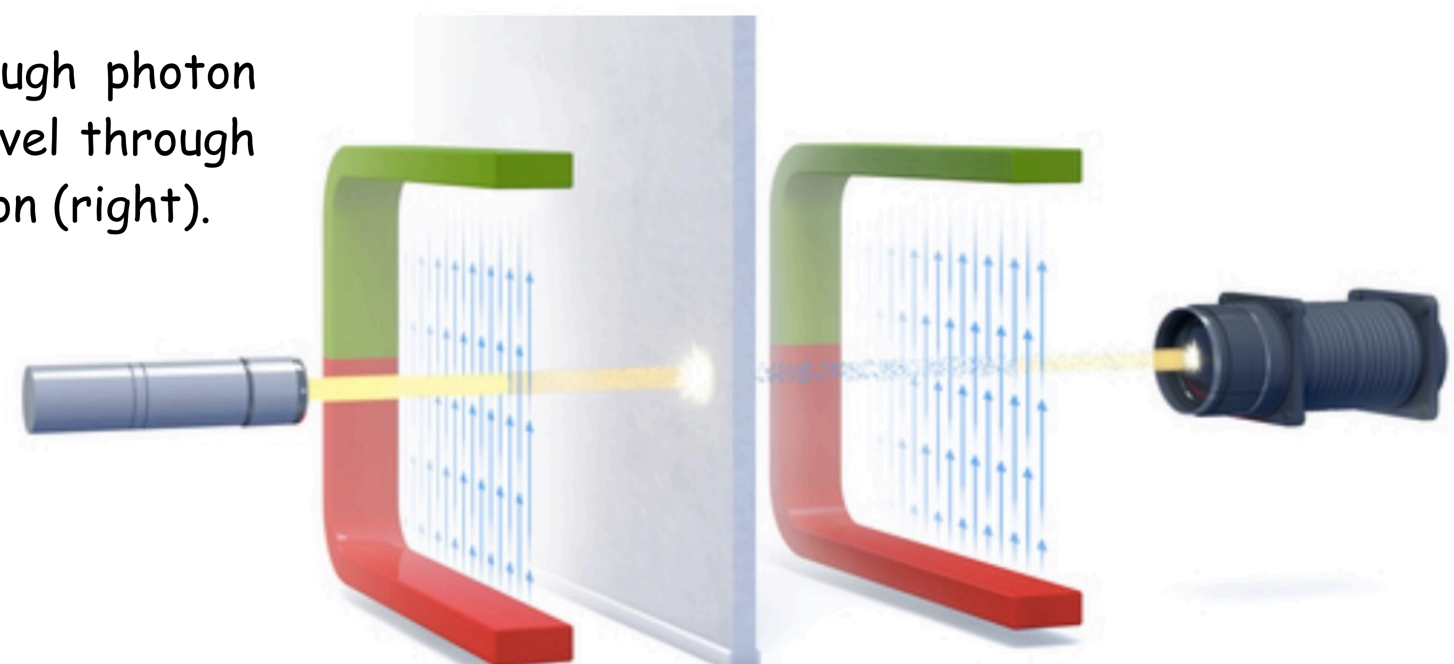
Light Shining trough Walls (LSW)

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

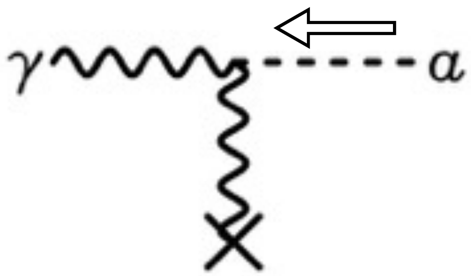


$\longrightarrow$ LSW experiments pay a $(g_{a\gamma\gamma})^4$ suppression

Haloscopes

- 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

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



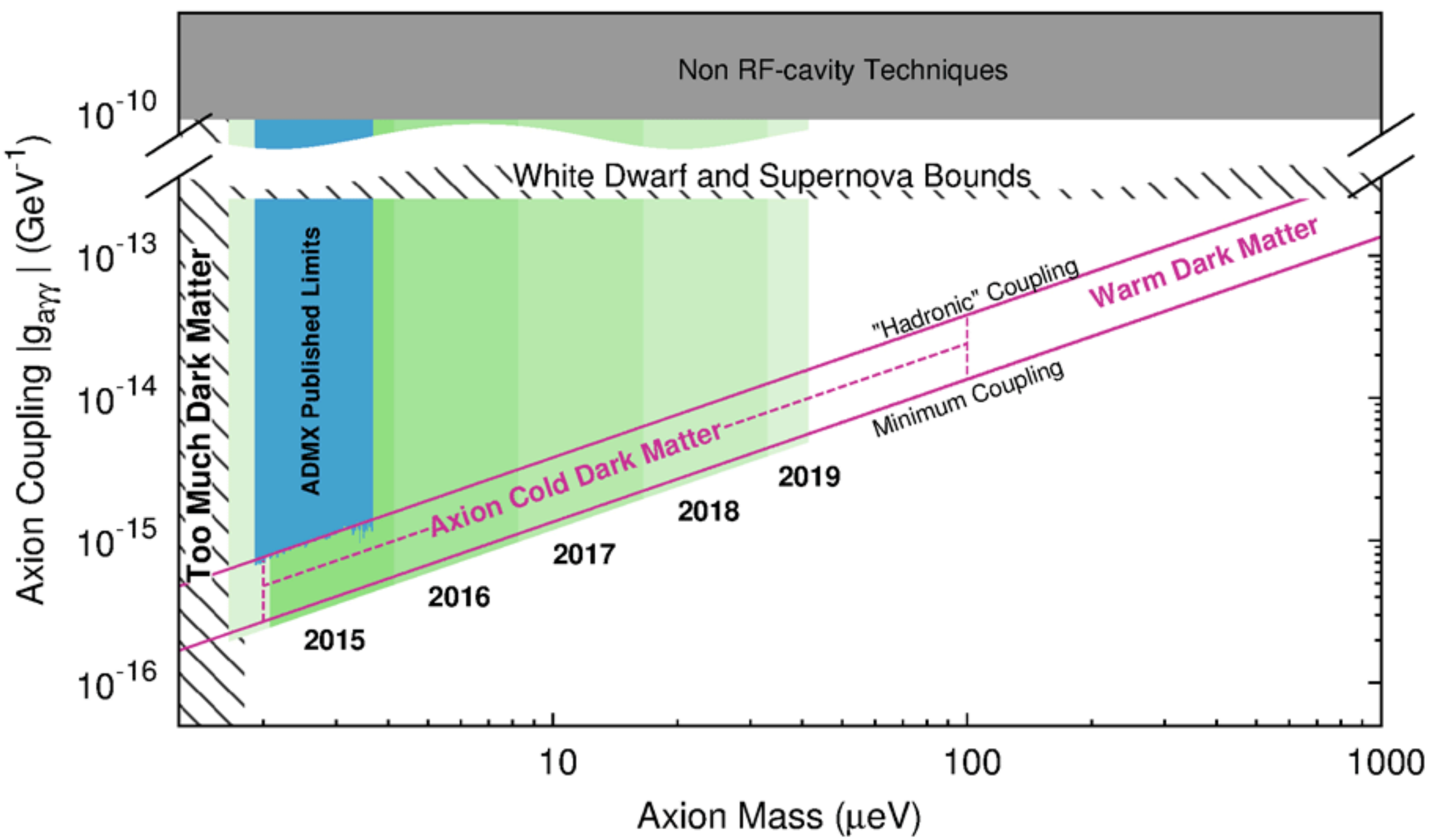
  - power of axions converting into photons in an EM cavity

$$P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\rm eff}$$

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

Haloscopes

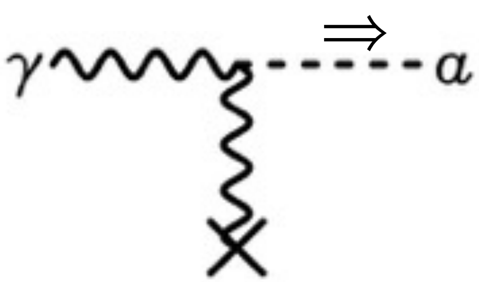
- Look for DM axions with a microwave resonant cavity
  - Axion Dark Matter eXperiment (ADMX) (U. of Washington)

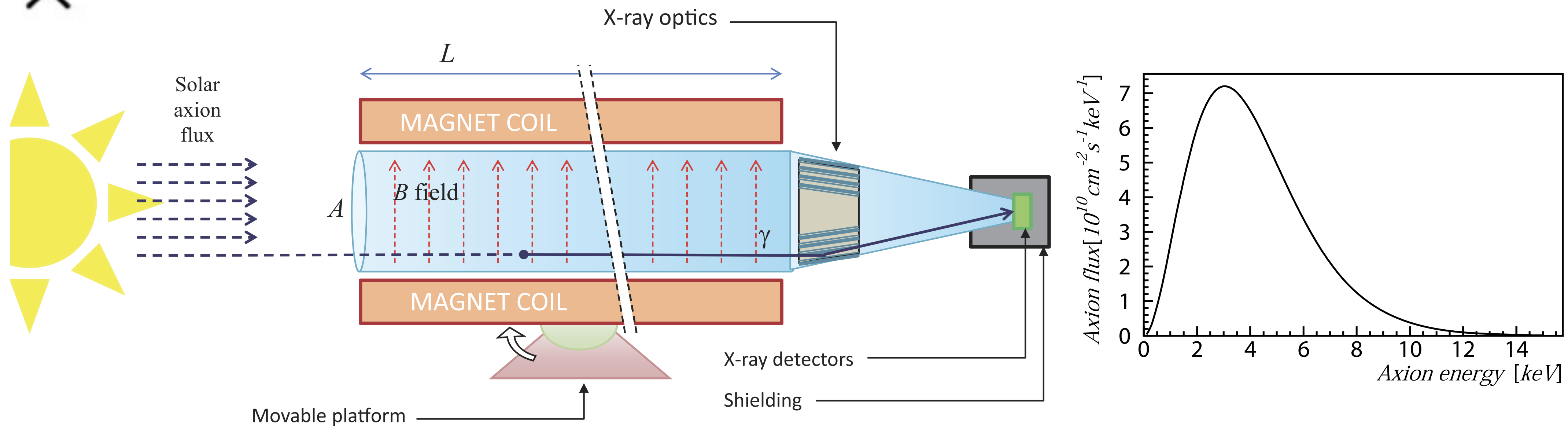


[ADMX Collaboration, 0910.5914]

Helioscopes

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





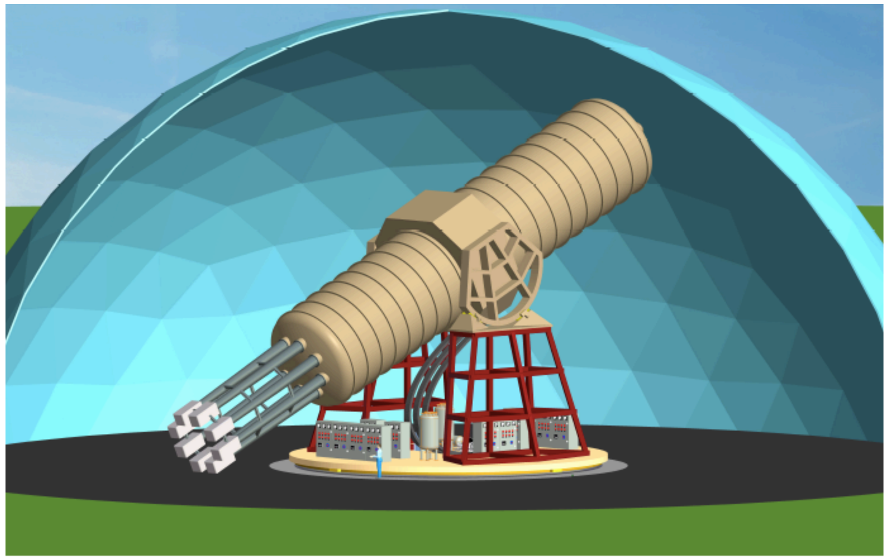
- macroscopic transverse B-field over a large volume triggers axion to photon (x-ray) conversion

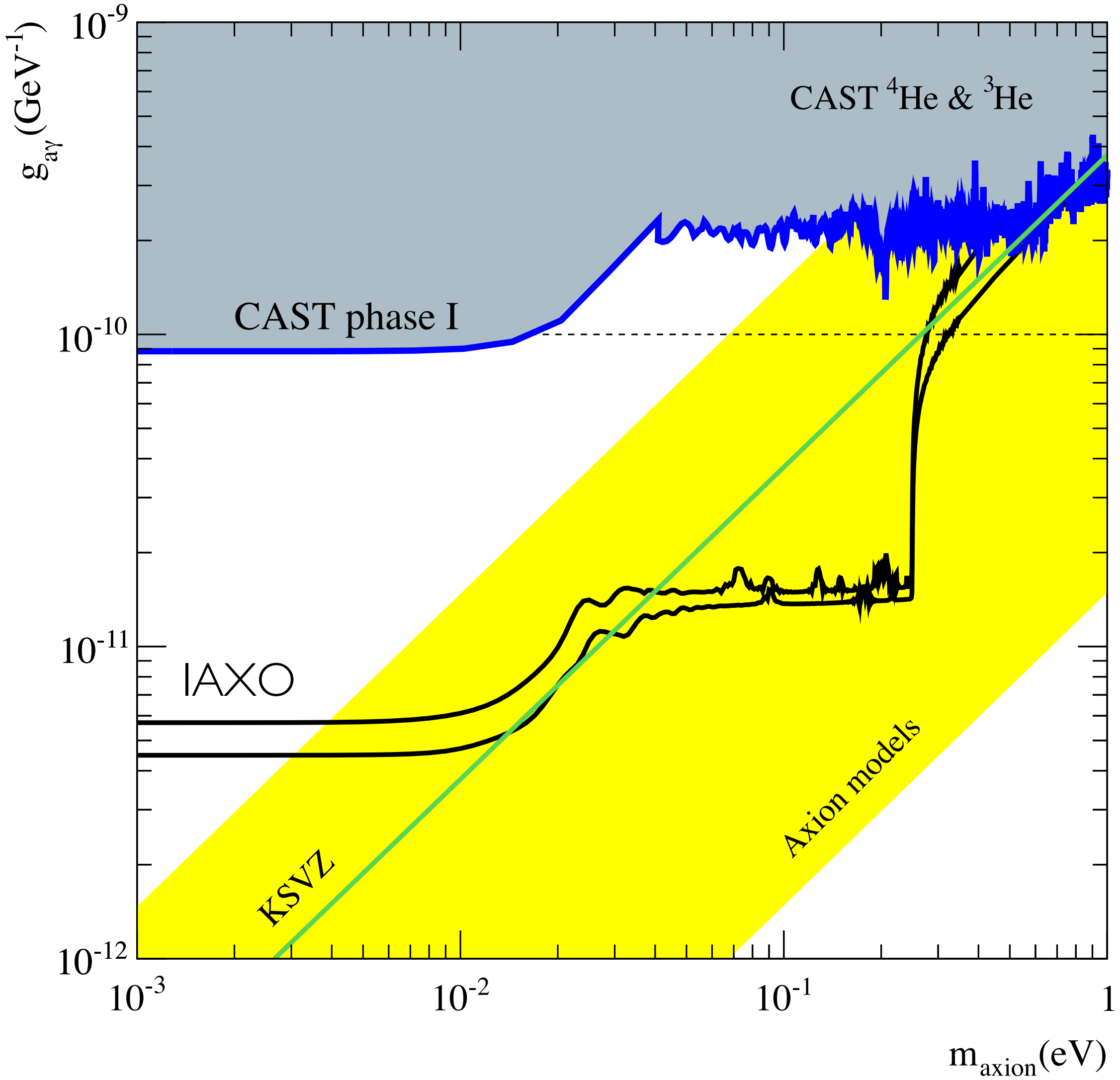
Helioscopes

- 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]

New proposals & search strategies

Broadb

ABRACADABRA

The QUAX proposal: a search of galactic axion with magnetic materials

G Ruoso[1], A Lombardi[1], A Ortolan[1], R Pengo[1], C Braggio[2], G Carugno[2], C S Gallo[2], C C Speake[3]

High and low mass

Ben T. McAllister, Stephen R. Parker, Eugene N. Ivanov, and Michael E. Tobar

The CryOgenic Resonant Group Axion CoNverter (ORGAN)

Dark Matter Detection

Jesse Thaler[2, ‡]

Detection with an Am

B-field Ring Ap

at CAPP/IBS/KAIST in Korea

xion Search in Korea (CULTASK)

ew Dark Matter Axion Search

loscope

the MADMAX Working Group

B. Majorovits[1], A. Millar[1], G. Raffelt[1],

Axion Dark Matter Detection using an LC Circuit

P. Sikivie, N. Sullivan and D.B. Tanner

The Cold

Woohyun Chung

CA

usin

Béla Majorovits[1]

G. Dvali

Cosmic Axion Spin Precession Experiment (CASPEr)

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

But we need to know where to search

The "usual" axion window

Central value:

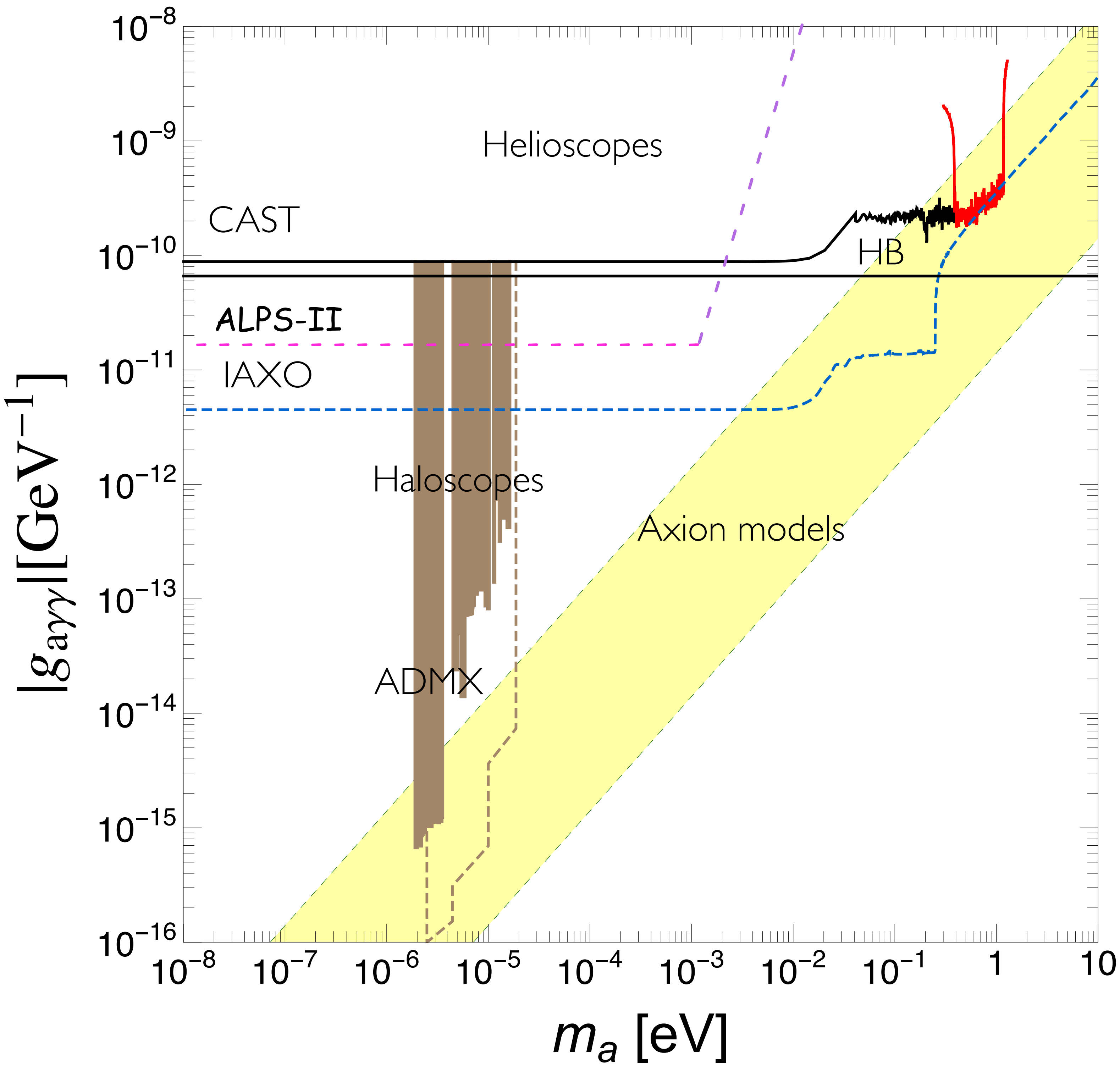
$$g_{a\gamma\gamma} \sim \frac{\alpha}{2\pi}\frac{m_a}{f_\pi m_\pi} \sim \frac{10^{-10}}{\text{GeV}}\left(\frac{m_a}{\text{eV}}\right)$$

Model dependence:

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

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

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



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) [only $\mathcal{C}_Q \neq I$ is in fact required].

  However in general:

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

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

- and 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, Sakharov (1980)]

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

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

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

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

Accidental symmetries

- Symmetries of the gauge invariant new kinetic term

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

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

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

- if $\mathcal{L}_{Qq} \neq 0$ $U(1)_Q \times U(1)_B$ is broken to `extended' $U(1)_{B'}$. Q's can decay

- All global symmetries broken at least by Planck-scale effects

  - Effective operators explicitly breaking $U(1)_Q$ and $U(1)_{PQ}$:

$\mathcal{L}^{d>4}_{Qq}$ → Can allow Q decays even if $\mathcal{L}_{Qq} = 0$

$V^{d>4}_\Phi \ni \dfrac{\Phi^N}{M^{N-4}_{\mathrm{Planck}}}$ → If N < 10 would spoil the PQ solution

[Kamionkowski, March-Russell (1992), Holman et al. (1992), Barr, Seckel (1992)]

Enforcing accidental symmetries

- Assume a suitable discrete (gauge) symmetry $\mathbb{Z}_\mathbb{N}$ ensuring

1. U(1)$_{PQ}$ arises accidentally and is of the required **high quality**
2. U(1)$_{Q}$ is either broken at the ren. level, or is of sufficient **bad quality**

These two requirements can be simultaneously and consistently satified

- An example with R(Q) ~ R(d$_R$), such that gauge symm. allows $\mathcal{L}_{Qq} \neq 0$

$$Q_L \to Q_L \,, \quad Q_R \to \omega^{\mathbb{N}-1} Q_R \,, \quad \Phi \to \omega\, \Phi \,, \qquad \text{where} \qquad \omega \equiv e^{i2\pi/\mathbb{N}}$$

Ensures that the min. dimension of the U(1)$_{PQ}$ breaking operators in $V_\Phi^{d>4}$ is $\mathbb{N}$. The dim of the U(1)$_Q$ breaking opts. depends on $\mathbb{Z}_\mathbb{N}(q)$

$\mathbb{Z}_\mathbb{N}(q)$	$d \leq 4$	$d = 5$	$(\mathcal{X}_L, \mathcal{X}_R)$
1	$\overline{Q}_L d_R$	$\overline{Q}_L \gamma_\mu q_L \, (D^\mu H)^\dagger$	$(0,-1)$
ω	$\overline{Q}_L d_R \Phi^\dagger$		$(-1,-2)$
$\omega^{\mathbb{N}-2}$	$-$	$\overline{Q}_L d_R \Phi^2, \; \overline{Q}_R q_L H^\dagger \Phi$	$(2,1)$
$\omega^{\mathbb{N}-1}$	$\overline{q}_L Q_R H, \; \overline{Q}_L d_R \Phi$	$-$	$(1,0)$

Cosmological constraints on τ_Q

- Strongly interacting long-lived particles are an issue in cosmology

EW ν interactions out of equilibrium

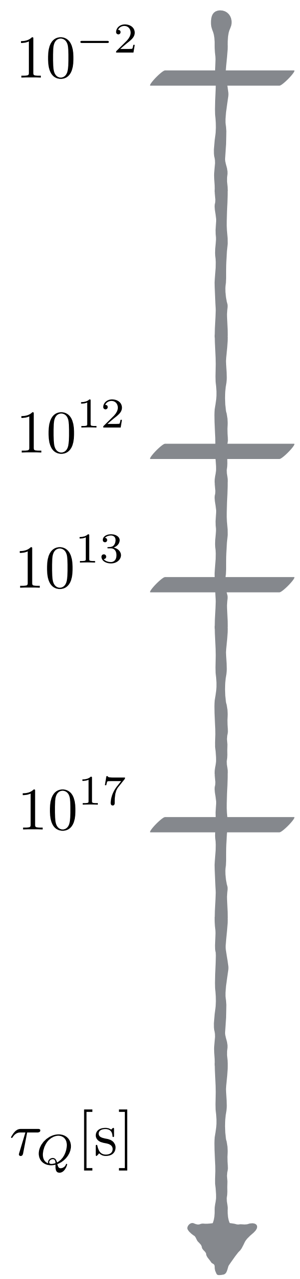
Big Bang Nucleosynthesis (BBN)

Recombination

CMB radiation

Diffuse γ-rays

Age of the Universe



- Excess Universe energy density
- Anomalously heavy isotopes

[See e.g. "Non-collider searches for stable massive particles", Burdin et al. Physics Reports 582 (2015) 1–52]

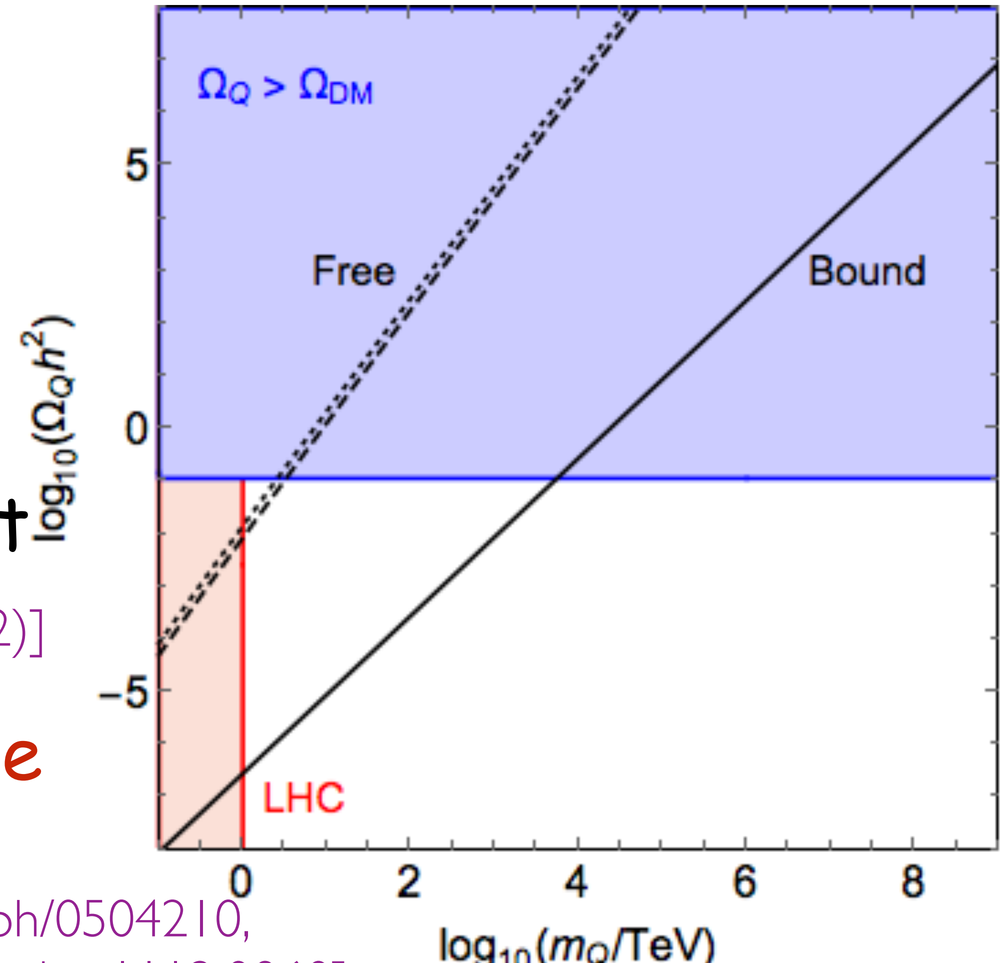
Constraints on stable Q ($\tau_Q > 10^{17}$s.)

- Assume $m_Q \ll T_{reheating}$ (thermal distribution of Q's as initial condition)

  Free quark annihilation: excess $\Omega_Q > \Omega_{DM}$ would allow to exclude $\tau_Q > \tau_{Univ}$

- At $T < \Lambda_{QCD}$ bound state formation can catalyse annihilations.

  E.g. for color triplets: Q*q + Qqq -> [Q*Q] + qqq [Arvanitaki (2005), Kang (2008), Jacoby (2007)]



- However QQ...; QQQ bound states (so far not taken into account) would hinder it. [Kusakabe (2012)]
- Reliable estimates of Ω_Q remain an open issue

[Dover, Gaisser, Steigman (1979), Nardi, Roulet (1990), Arvanitaki et al., hep-ph/0504210, Kang, Luty, Nasri, hep-ph/0611322, Jacob, Nussinov, 0712.2681, Kusakabe, Takesako, 1112.0860]

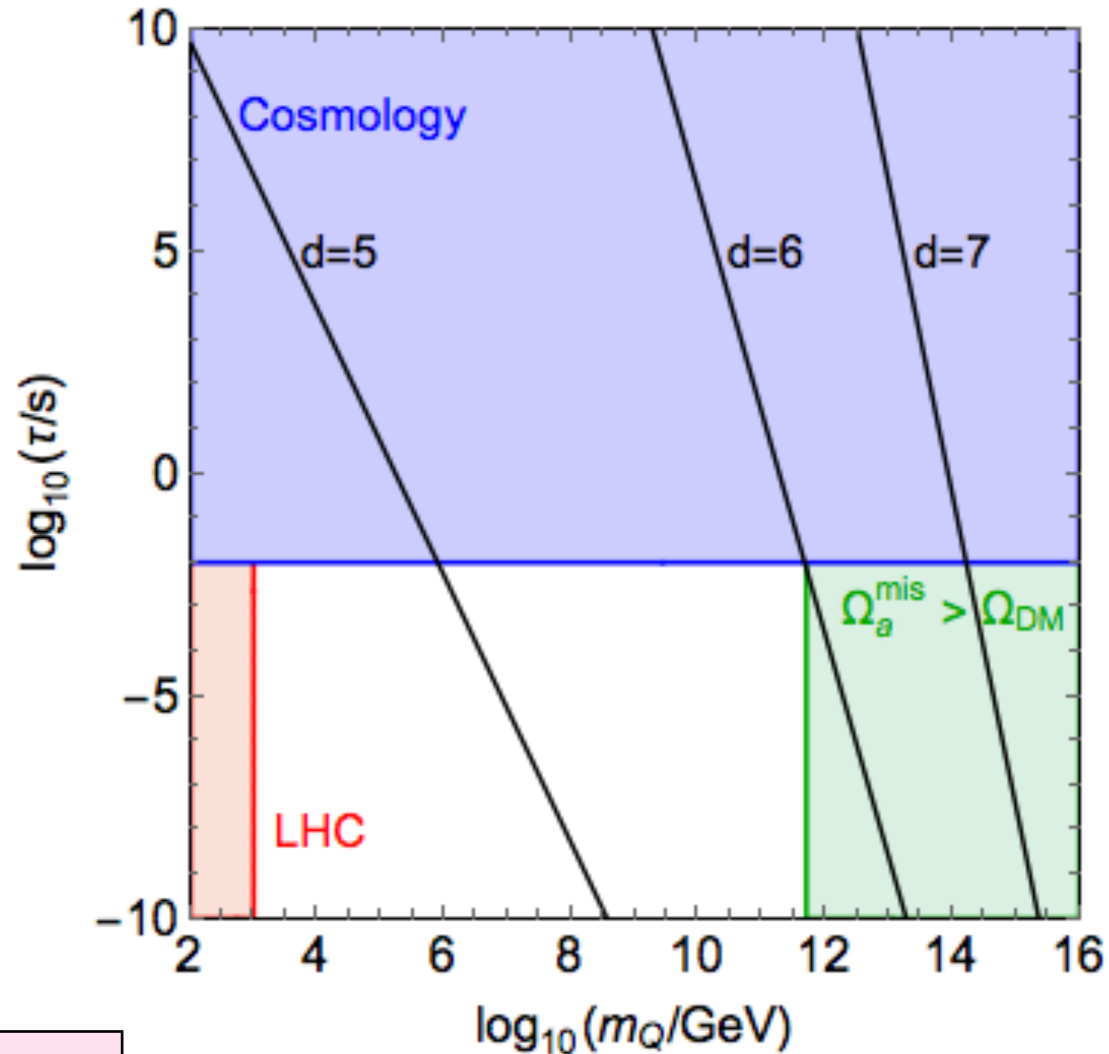
First selection criterium

- Require that the Q are sufficiently short lived: $\tau_Q \lesssim 10^{-2}$ s.

  - Decays via d=4 operators are always sufficiently fast.

  - Decays via higher order operators are fast enough only for d=5 and $m_Q \gtrsim 800$ TeV.

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



Therefore, "safe" R(Q) must allow for gauge invariant d=4 or d=5 operators

Second selection criterium

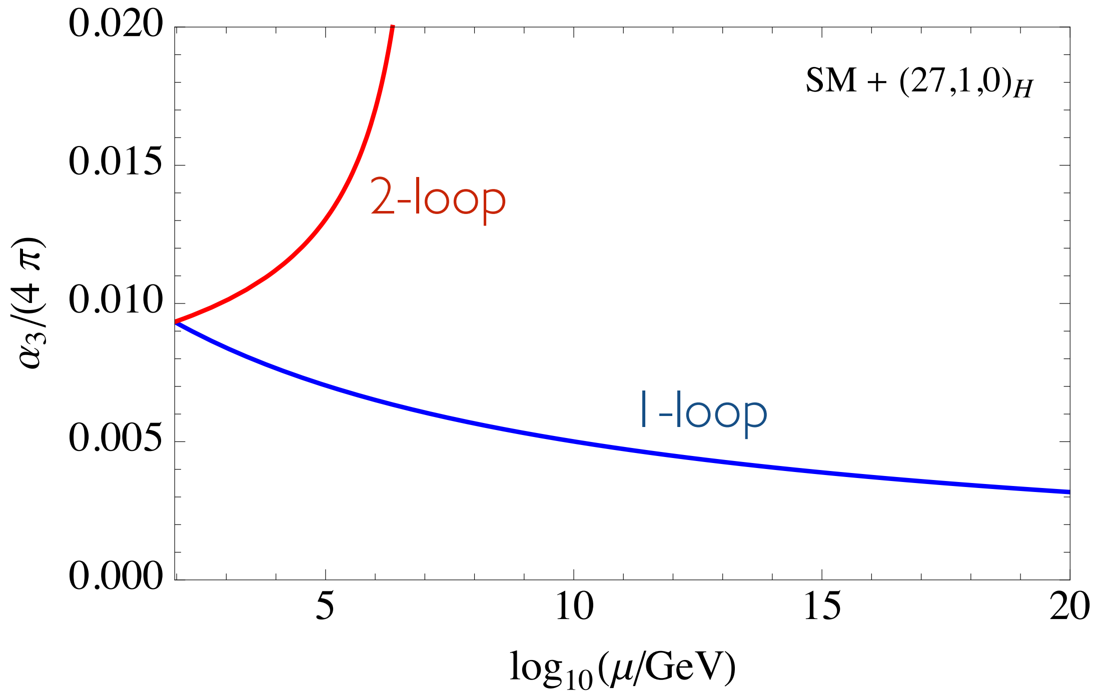
- The new R(Q) should not induce Landau poles below 10^{18} GeV

  - Large Q multiplets can drive the gauge couplings towards a non-perturbative regime, at uncomfortably low scales

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

Two-loop β functions help to avoid spurious results from accidental cancellations in 1-loop β functions…

[Di Luzio, Gröber, Kamenik, Nardecchia, 1504.00359]



Phenomenologically preferred Q's

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

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

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

Phenomenologically preferred Q's

- Only 15 Q's survive:

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

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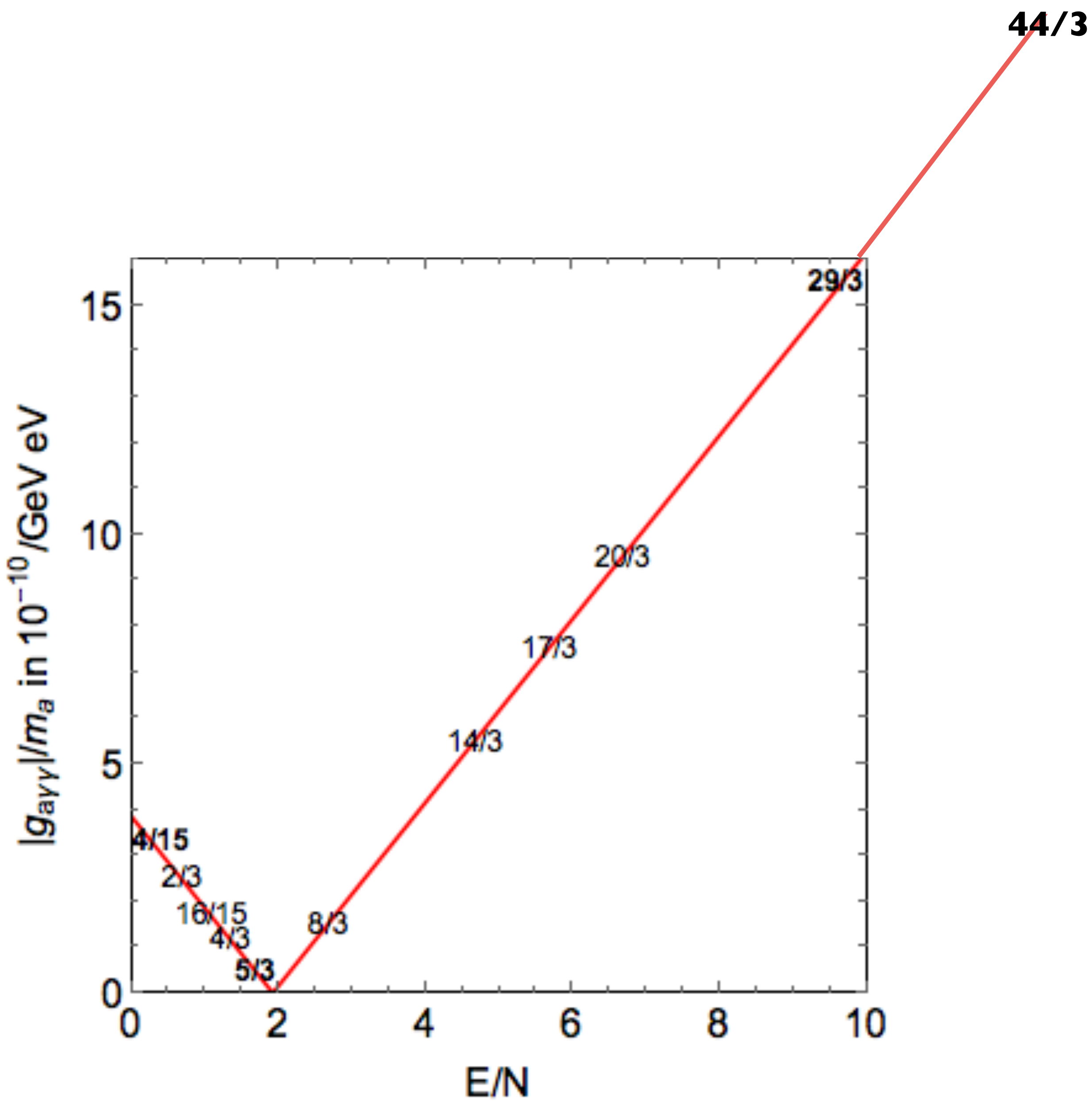
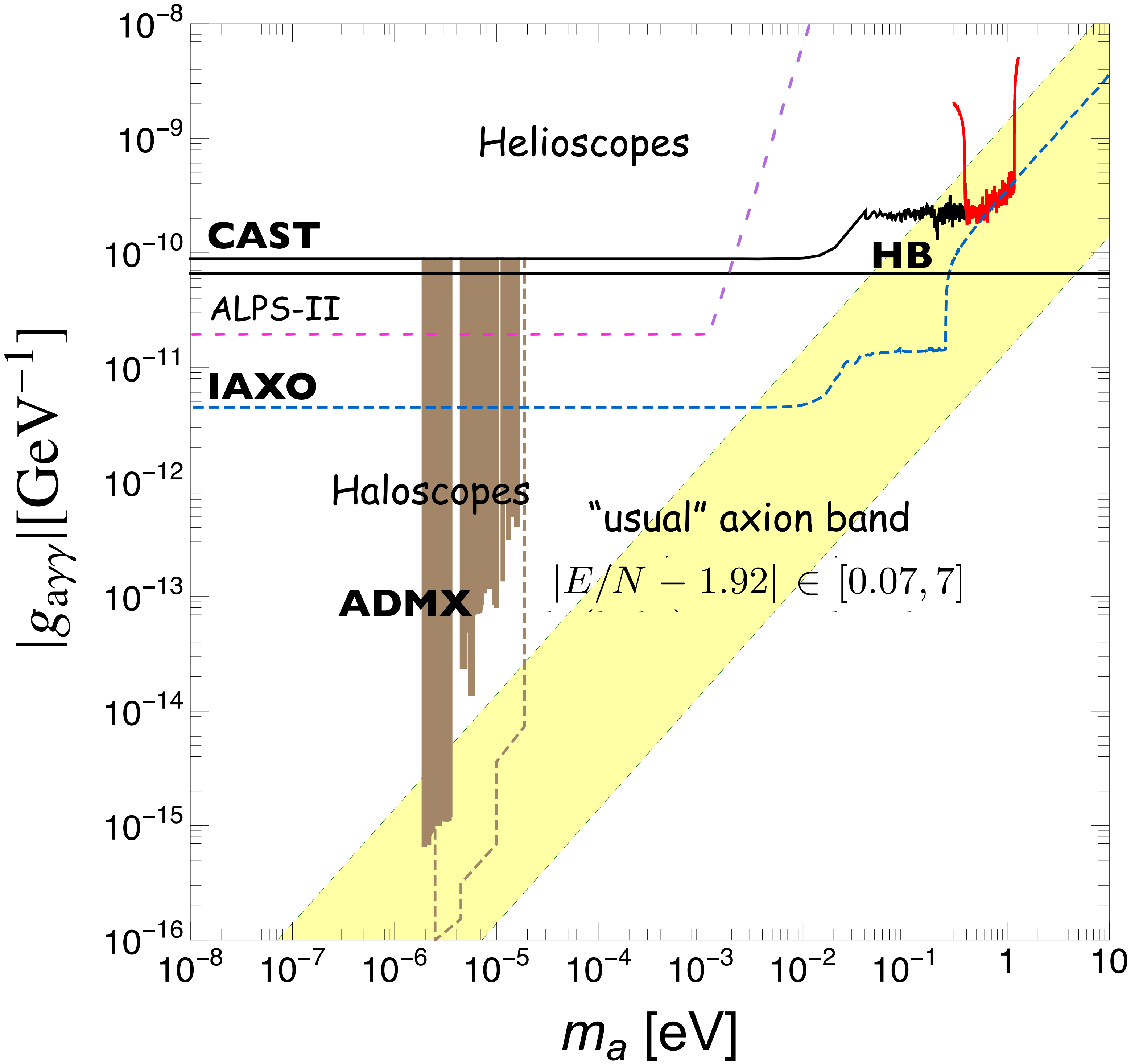


Redefining the axion window



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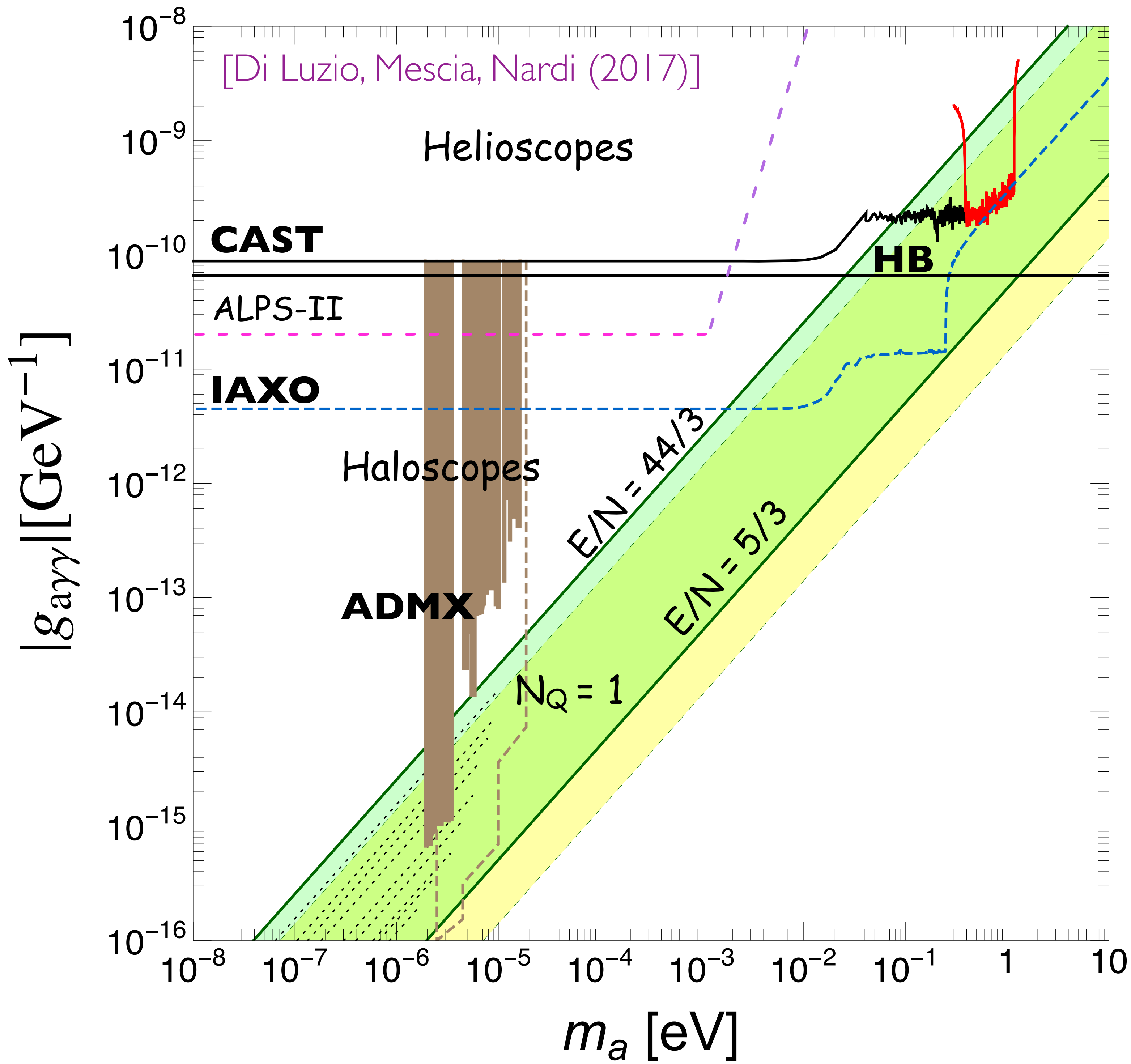

More Q representations

- What happens with $N_Q \geq 2$?
  - Combined anomaly factor for $R_Q^1 + R_Q^2$: $\frac{E_c}{N_c} = \frac{E_1 + E_2}{N_1 + E_2}$

- E.g. with 2 R_Q (compatible with LP criterium) the largest coupling is with

$$R^s_Q \oplus R^w_Q = (3,2,1/6) \oplus (3,3,-4/3) \quad \to \quad E_c/N_c = 122/3$$

- The strongest coupling allowed by LP condition is E_c/N_c=170/3 (with 3 R_Q)

- Complete axion-photon decoupling (within theoretical errors) can also occur

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

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

[Theoretical error from NLO χPT Grilli di Cortona et al., 1511.02867]

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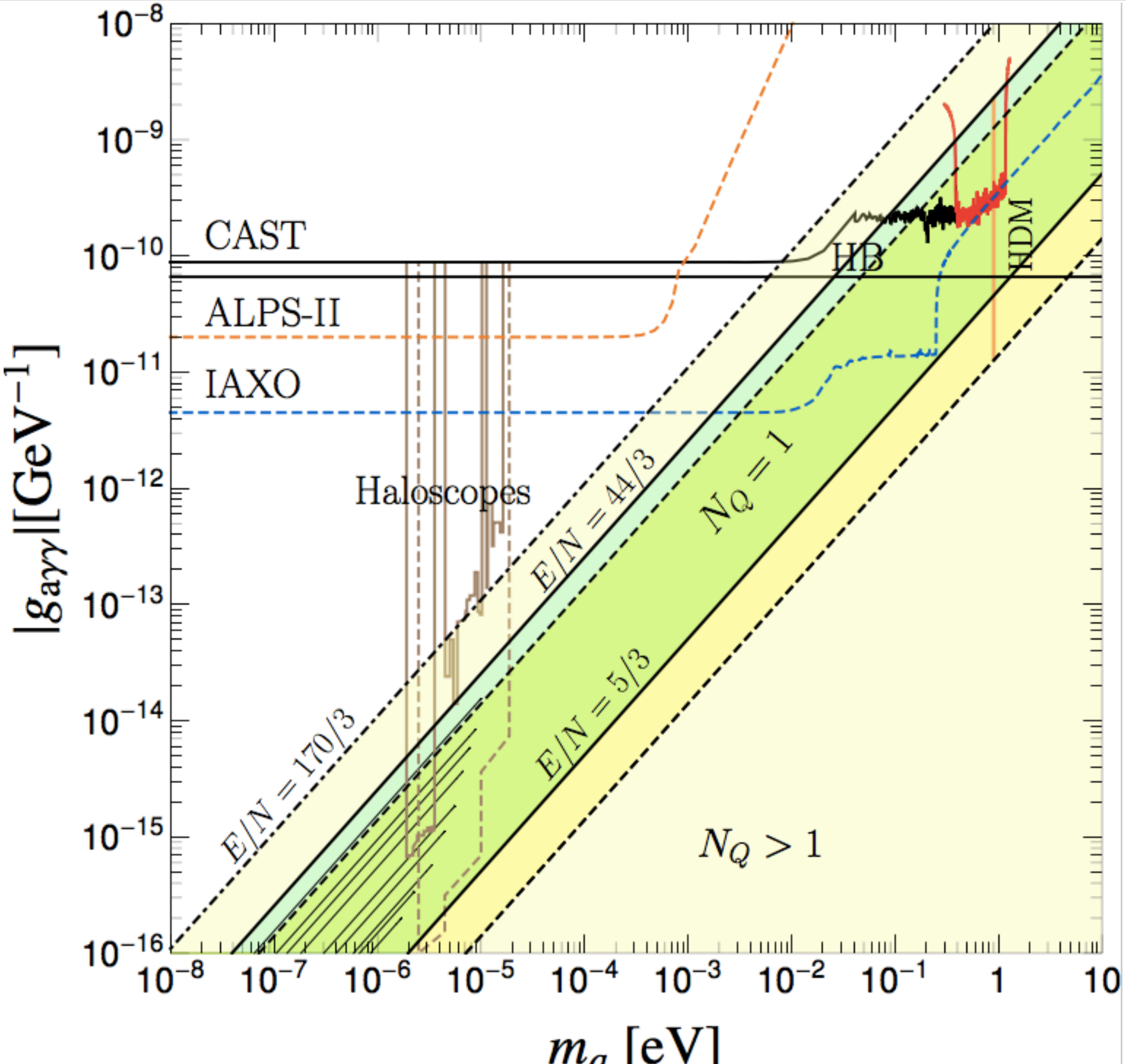

[Di Luzio, Mescia, Nardi (2017)]

What about DFSZ axions ?

- In general each R-handed SM fermion can have a specific PQ charge $\mathcal{X}_{f_j}$

$$u_R^j \to \exp\left(i X_{uj}\right) u_R^j \,, \quad d_R^j \to \exp\left(i X_{dj}\right) d_R^j \,, \quad e_R^j \to \exp\left(i X_{ej}\right) e_R^j \,.$$

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

- For generation independent charges DFSZ remains within KSVZ window:

$$\text{DFSZ-I}: \quad X_e = X_d \,, \quad E/N = 8/3$$

$$\text{DFSZ-II}: \quad X_e = -X_u \,, \quad E/N = 2/3$$

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}): $E/N_{(max)} = 524/3 = 3 \cdot E/N_{(max)}$(KSVZ)

An immoral DFSZ construction

1. Consider $(H_u H_d \Phi^2)$ and normalize $\mathcal{X}_\Phi \equiv q$; $\Longrightarrow$ $\mathcal{X}_u = -2q$; $\mathcal{X}_d = 0$

2. Define $H_1 = H_u$. Add m up-type doublets: $(H_k H^*_{k-1})(H^*_{k-1} H^*_d)$,

$$\mathcal{X}_k = -2^k q$$

3. Finally couple also the lepton Higgs H_e: $(H_e H_m)(H_m H_d)$

$$\mathcal{X}_e = 2^{m+1} q$$

One can obtain in this way: $$\boxed{\frac{E}{N} = \frac{2}{3} + 2\frac{\mathcal{X}_u + \mathcal{X}_e}{\mathcal{X}_u + \mathcal{X}_d} \sim 2^{m+1}}$$

Up to m ~ 50 scalar doublets are allowed by the LP condition !

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- Here: Axion window defined via precise phenom. requirements.