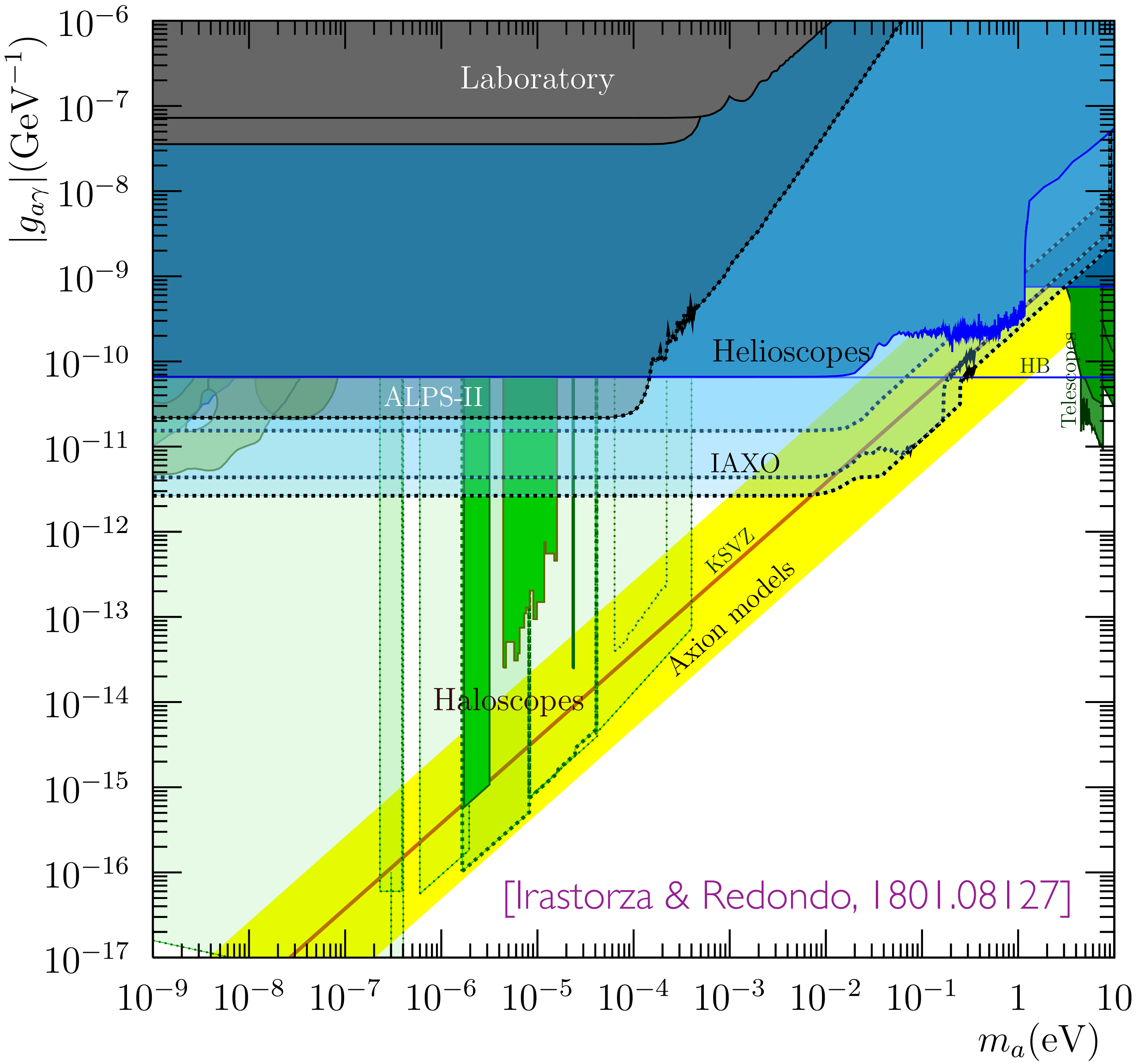
# Rethinking the QCD axion

DESY-HU Theorie-Seminar - 15.11.18

Luca Di Luzio

# In 10 years from now ?




✤ A great opportunity to discover the QCD axion !

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

# Outline

1. Strong CP problem
2. QCD axion
3. Current limits and search strategies
4. Beyond standard axion scenarios

Based on:
LDL, Mescia, Nardi 1610.07593 (PRL) + 1705.05370 (PRD)
LDL, Mescia, Nardi, Panci, Ziegler 1712.04940 (PRL) + work in progress

# The strong CP problem

- CP violation in QCD

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

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- GGtilde is a total derivative (no effects in PT)

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

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

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

→ need chiral Lagrangian for quantitative statements

# The strong CP problem

- CP violation in QCD

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

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

$$q \to e^{i\gamma_5 \alpha} q \quad \longrightarrow \quad \begin{cases} \theta_q \to \theta_q + 2\alpha \\ \theta \to \theta + 2\alpha \end{cases}$$

from non-invariance of path integral measure (chiral anomaly) [Fujikawa, PRL 42 (1979)]

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

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

$= \theta - \arg\det\left(Y_u Y_d\right)$ (generalization to an arbitrary chiral transf. in the EW theory)

# The strong CP problem

- CP violation in QCD

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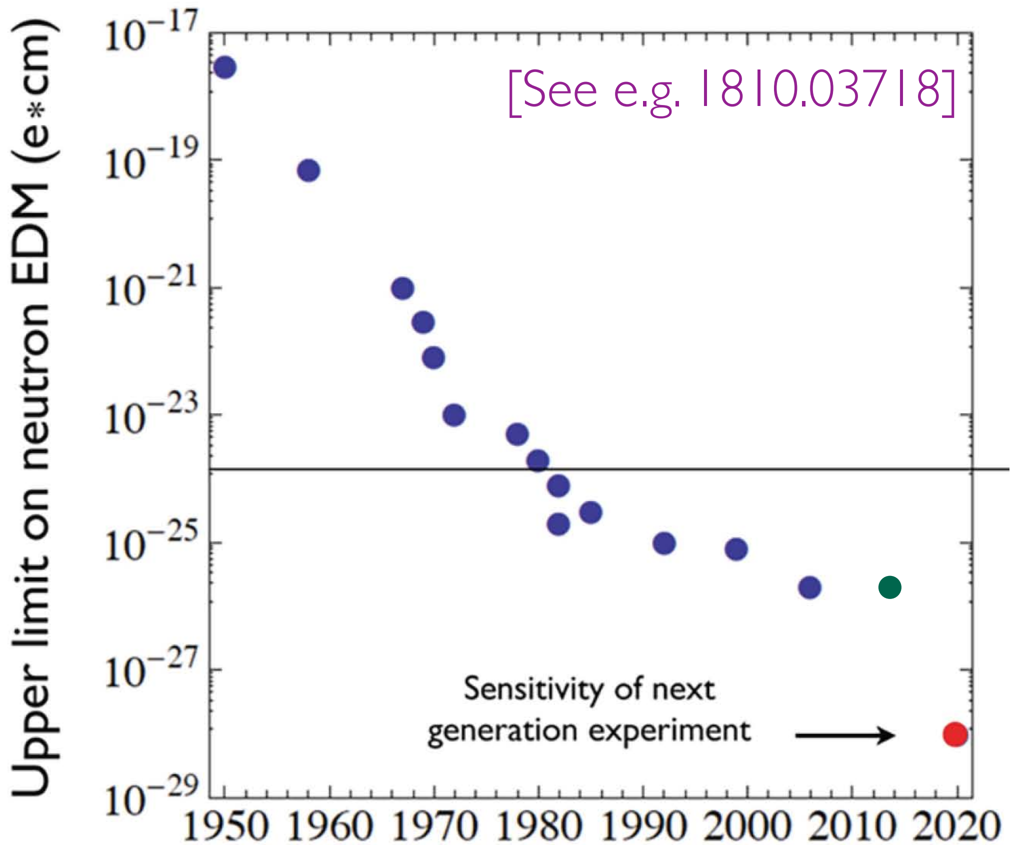
- Non-zero neutron EDM




[B. Fillipone]

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

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

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

$$\rightarrow \quad |\overline{\theta}| \lesssim 10^{-10}$$

why so small ?

# “Small value” problems

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

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

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

$$\downarrow$$

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

- expect to arise at 7-loops

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

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

   nuclear physics and BBN practically unaffected for $\overline{\theta} \lesssim 10^{-2}$ [Ubaldi, 0811.1599]

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- More than a small value problem ?

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

QCD

flavour

(imagine a theory of flavour generating Yukawas: would expect O(1) phases like CKM)

# Solutions

- Do we really understand QCD vacuum structure ?

  - e.g. confinement might screen theta term [Polyakov… ]

  - attempts in this directions often fail to solve eta' problem !

$$m_{\eta'} \approx 958\,\mathrm{MeV} \qquad\qquad m_{\eta'} < \sqrt{3} m_\pi$$ [Weinberg sum-rule for pNGB]

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- Spontaneous CP (or P) violation [Nelson PLB 136 (1983), PLB 143 (1984)] [Barr PRD 30 (1984)]

  - $\bar{\theta} = 0$ in the CP limit

  - need to generate CKM (and CP violation for BAU) without inducing a too large $\bar{\theta}$

  - non-trivial model building + no clear experimental signature

# Solutions

- Do we really understand QCD vacuum structure ?
- A massless quark would make the theta term unphysical (excluded at 20σ by Lattice)
- Spontaneous CP (or P) violation
- PQ mechanism [Peccei, Quinn PRL 38 (1977), PRD 16 (1997)]

  - assume a global U(1)$_{PQ}$ : i) QCD anomalous and ii) spontaneously broken

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

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

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

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

# θ-dependence of QCD vacuum

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

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

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

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

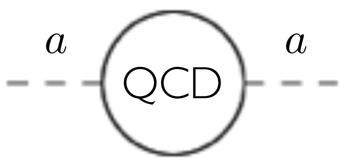
$$\left( \overline{\theta} + \frac{a}{f_a} \right) \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} \quad \xrightarrow{a \to \langle a \rangle + a} \quad \frac{a}{f_a} \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

- aGGtilde not a total derivative (effects in PT)

# Axion properties [EFT]

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

  - generates axion mass




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

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

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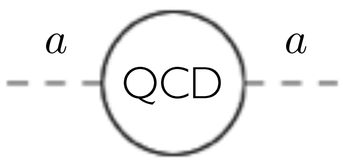
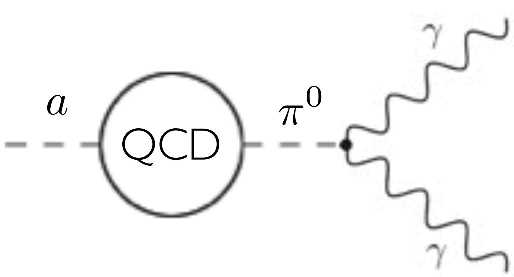
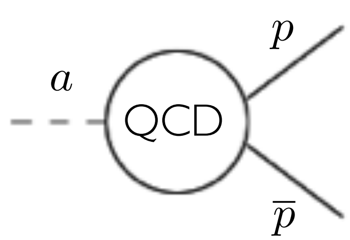



$$\sim \frac{\Lambda^4_{\rm QCD}}{f_a^2} \qquad m_a \sim \Lambda^2_{\rm QCD}/f_a \simeq 0.1 \text{ eV} \left(\frac{10^8 \text{ GeV}}{f_a}\right)$$

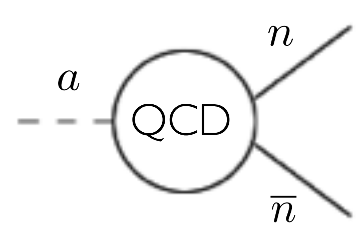
- generates "model independent" axion couplings to photons, nucleons, electrons, …



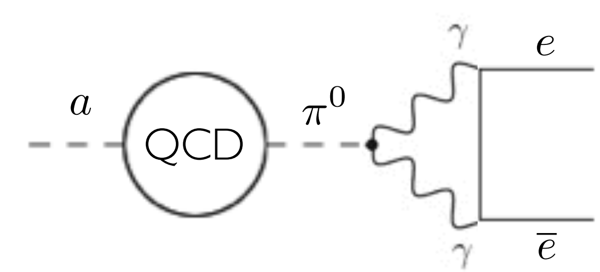

$C_\gamma = -1.92(4)$




$C_p = -0.47(3)$




$C_n = -0.02(3)$




$C_e \simeq 0$

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

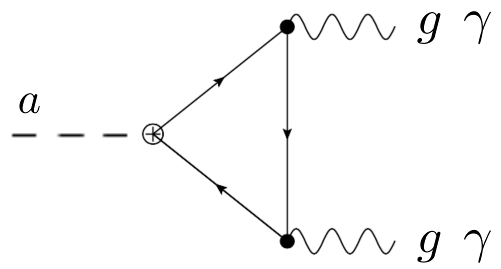
[From NLO Chiral Lagrangian,
Grilli di Cortona et al., 1511.02867]

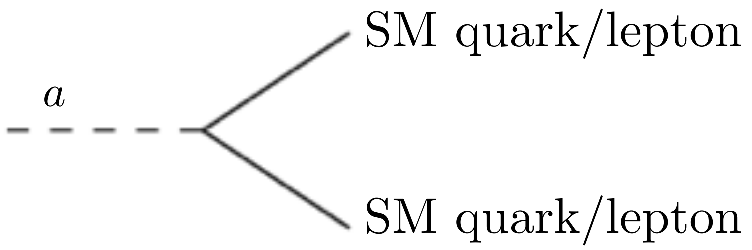
# Axion properties [EFT]

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

 - EFT breaks down at energies of order $f_a$

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



# Axion models [UV completion]

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

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

SM fermions | BSM fermions

| 2Higgs | 2Higgs+Singlet | Higgs+Singlet |
|---|---|---|
| PQWW | DFSZ | KSVZ |
| [Peccei, Quinn '77, Weinberg '78, Wilczek '78] | [Zhitnitsky '80, Dine, Fischler, Srednicki '81] | [Kim '79, Shifman, Vainshtein, Zakharov '80] |

$f_a \sim v$ ruled out

$f_a \gg v$ "Invisible" axion (phase of singlet field)

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

SM fermions

BSM fermions

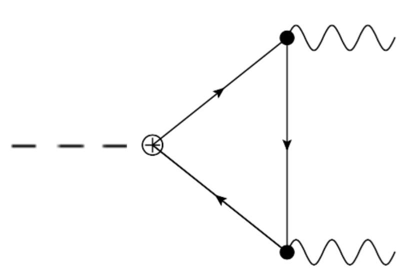
2Higgs+Singlet

Higgs+Singlet

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

DFSZ

KSVZ



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

$\tan\beta = v_2/v_1$

$C_p \simeq -0.5$

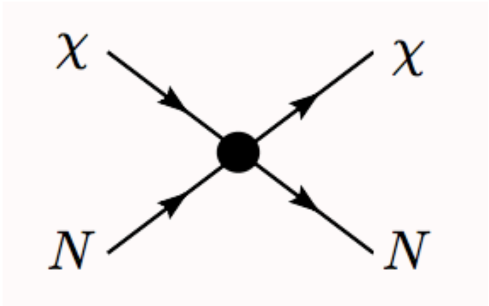
$C_{n,e} \simeq 0$

# Axions as Dark Matter

Heavy particle vs. light scalar field

(WIMPs) (Axions)

search for single particle scattering



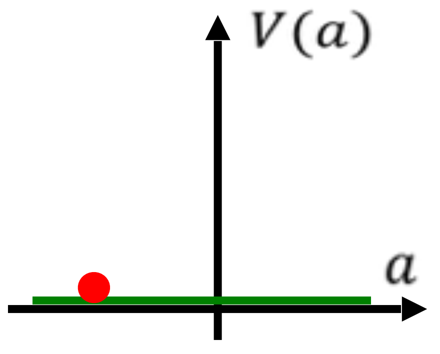

search for coherent effects of the entire field, not particle scattering

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

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

# Axions as Dark Matter

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




[Raffelt]

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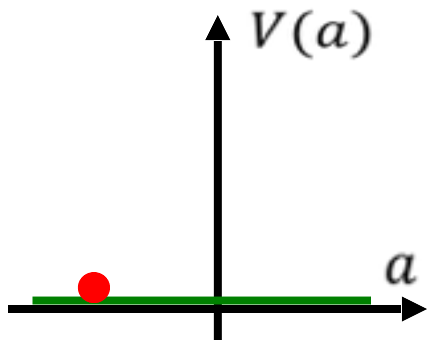
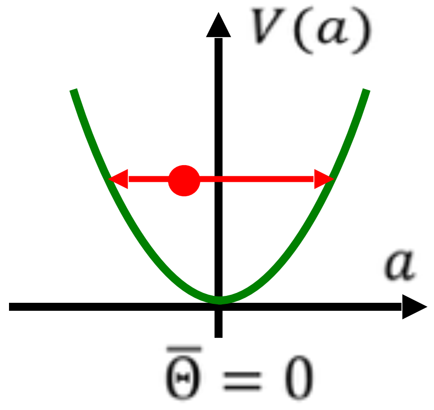
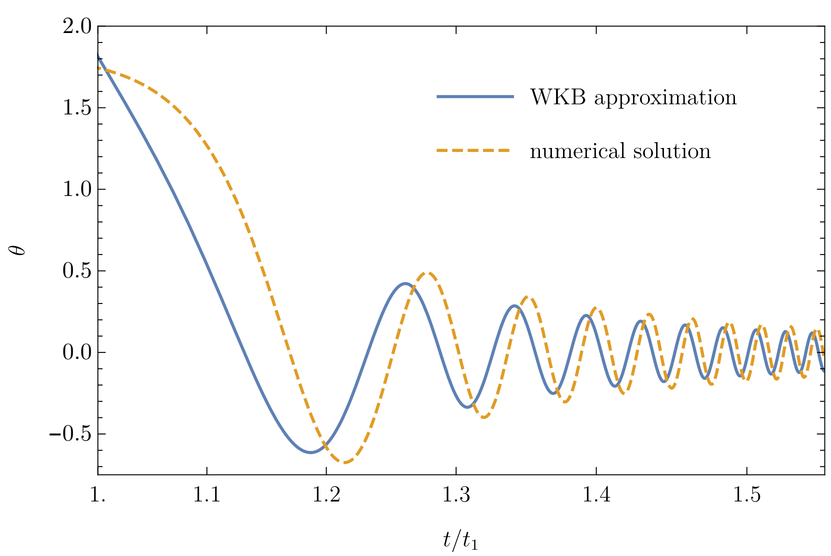



[Raffelt]

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




[J. Stadler]

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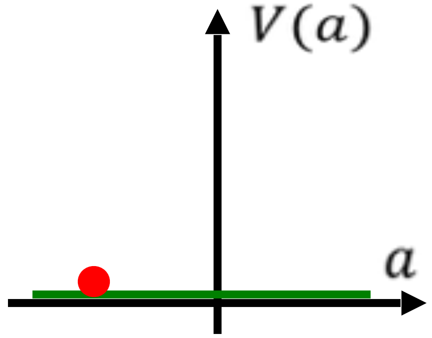


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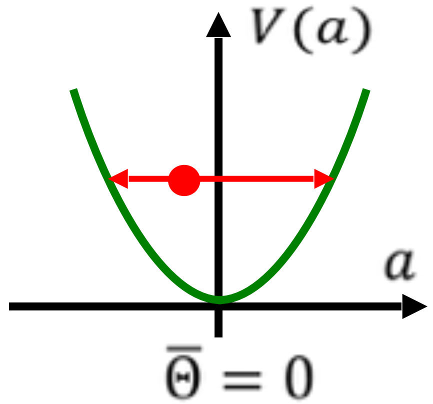



- Energy stored in axion oscillations behaves as Cold DM

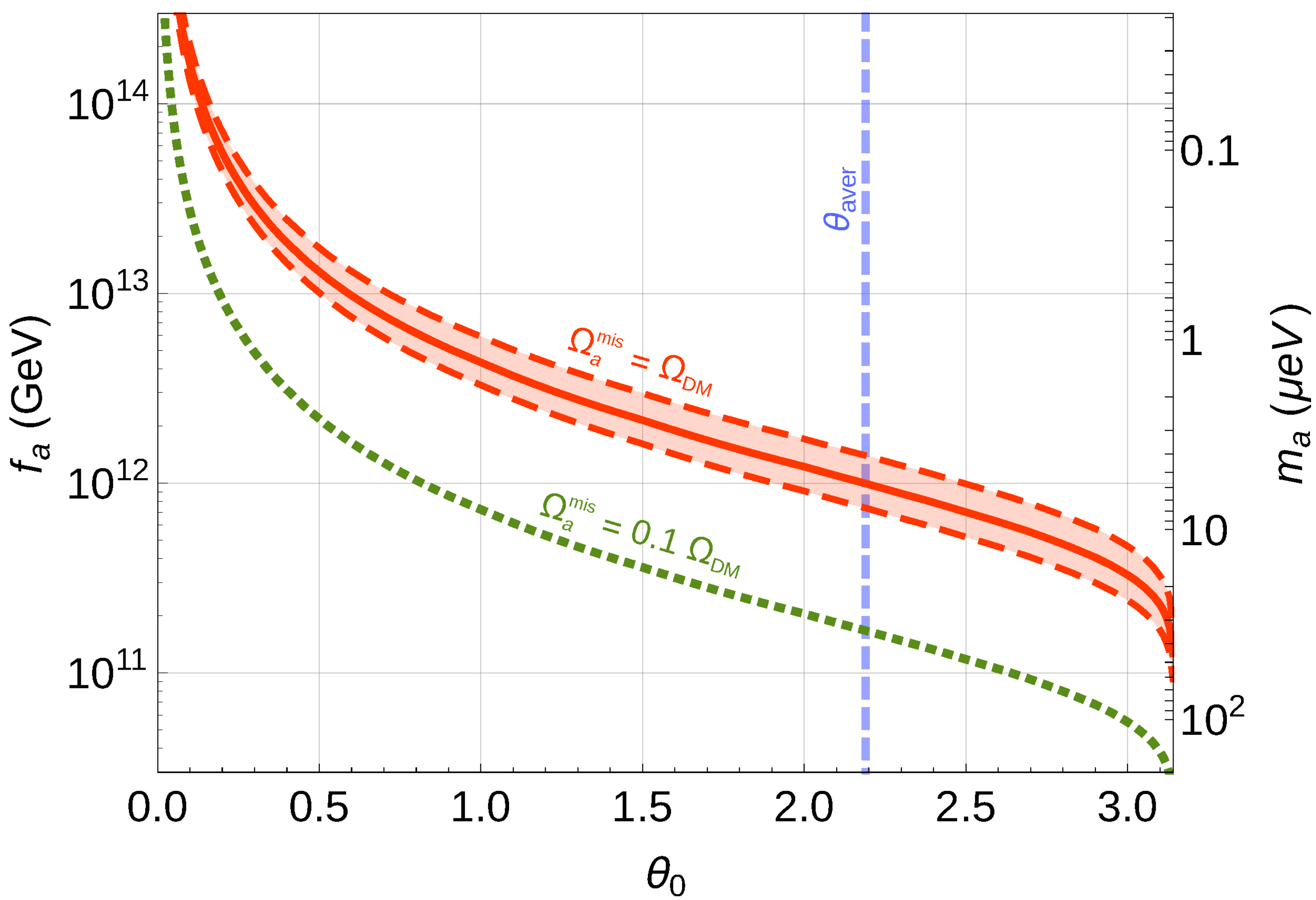
[Preskill, Wise, Wilczek PLB 120 (1983),
Abott, Sikivie PLB 120 (1983),
Dine, Fischler PLB 120 (1983)]

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

# Relic abundance

- From lattice QCD simulations: $f_a \lesssim 10^{11 \div 12}$ GeV for $\theta_0 = \mathcal{O}(1)$

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



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

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

# Astro bounds

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

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

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

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

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

neutrino interactions (d=6 op.)

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

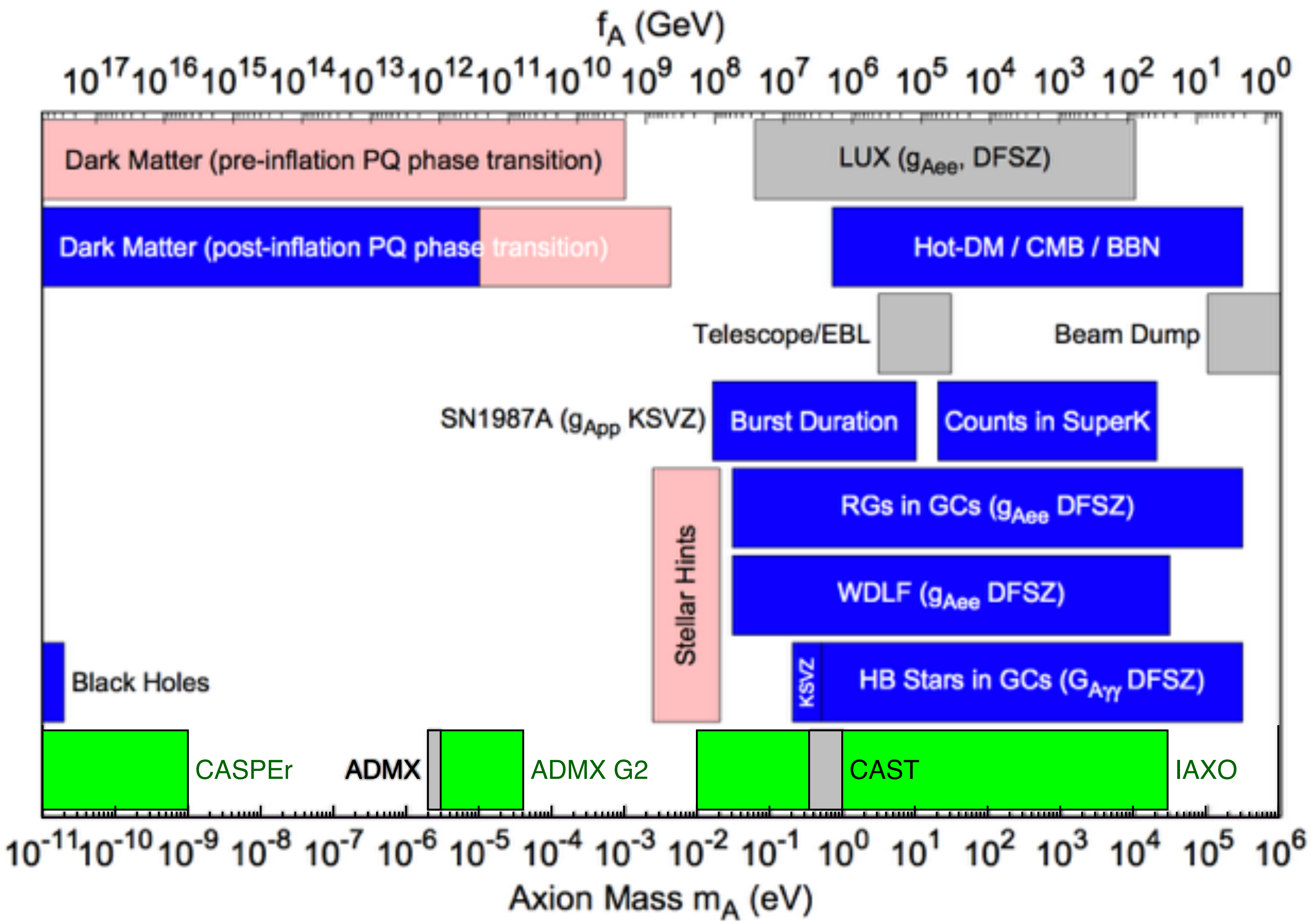
axion interactions (d=5 op.)

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

→ axions are a perfect target !

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

# Axion landscape




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

Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

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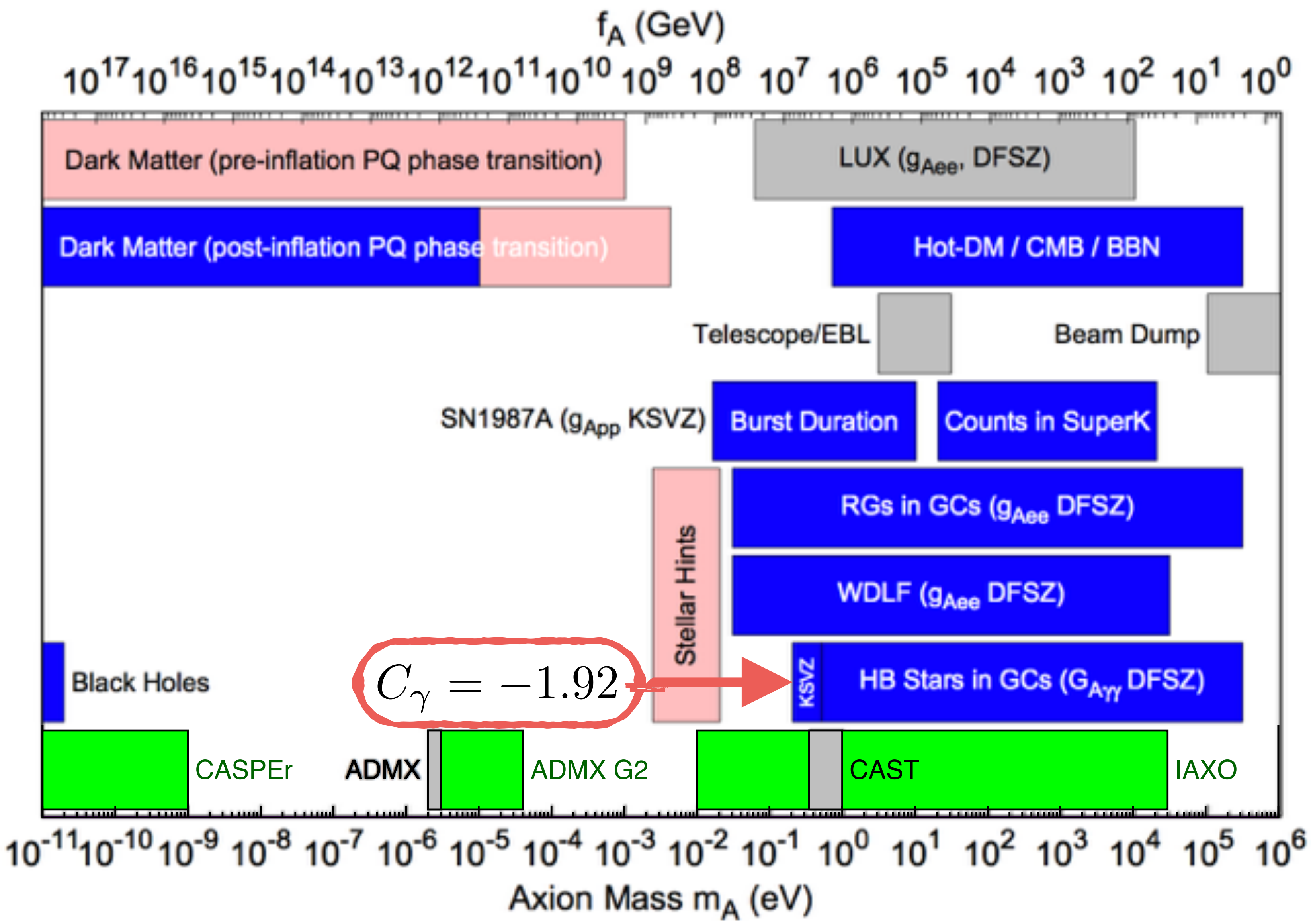


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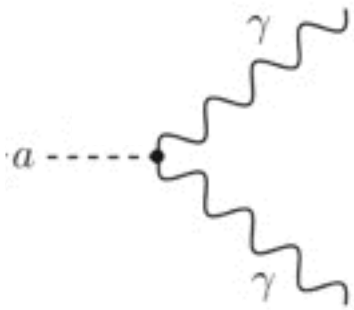
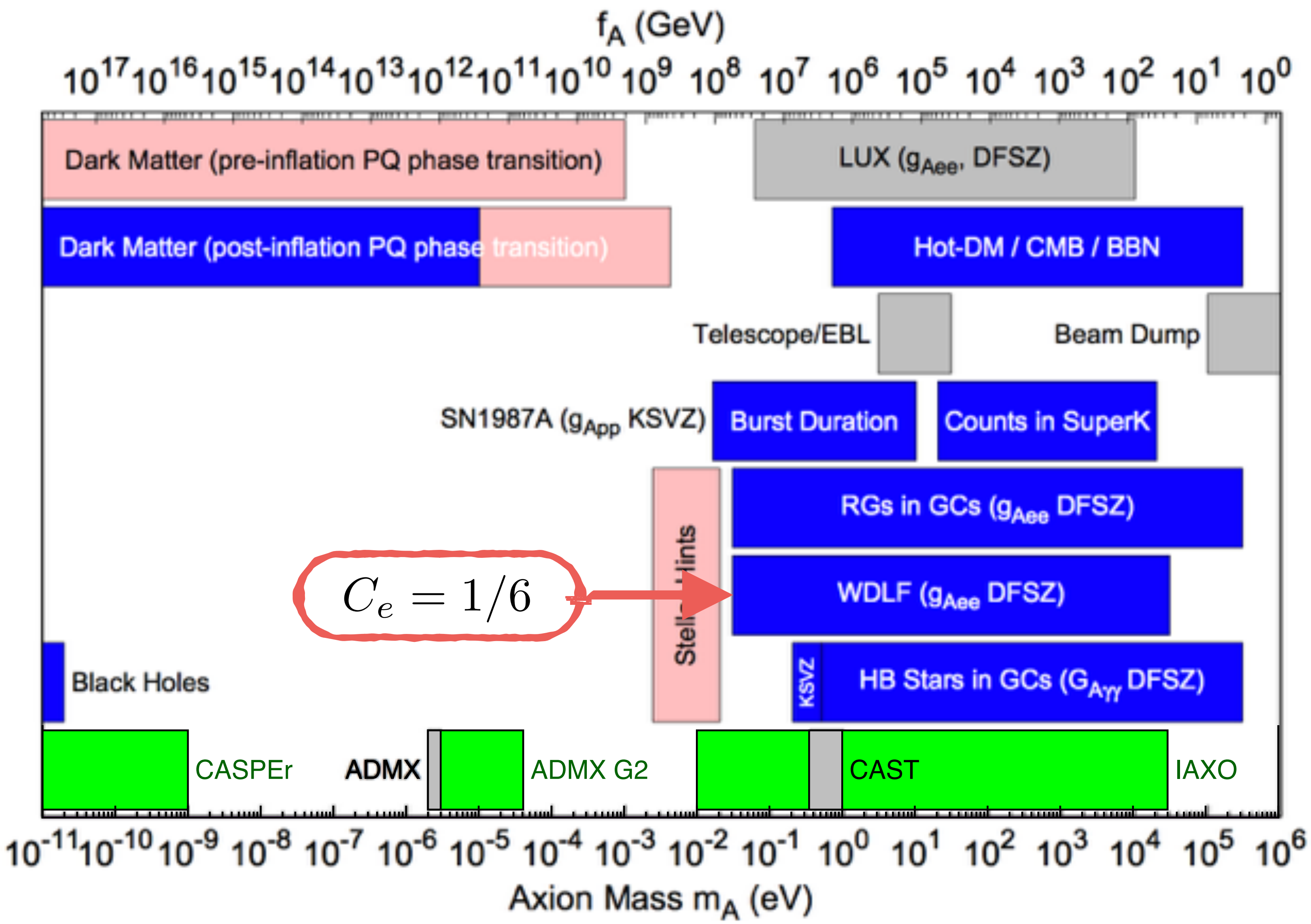
Exp. sensitivities

- Horizontal branch star evolution in globular clusters




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

# Axion landscape

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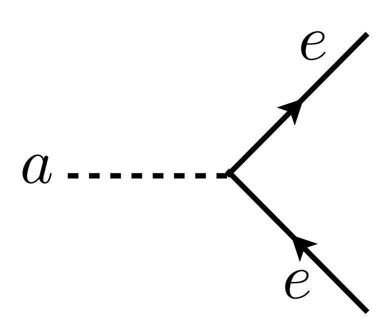
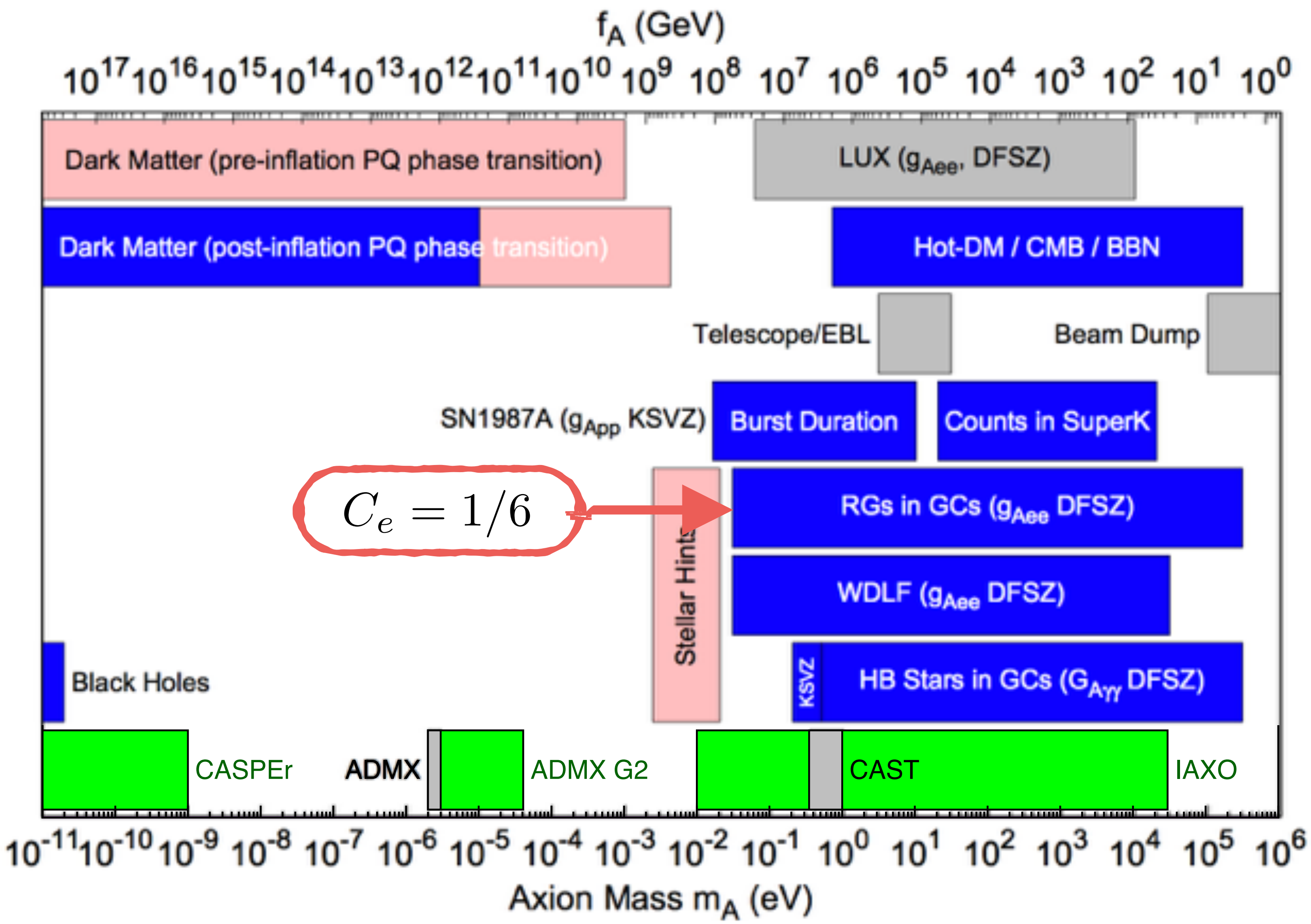
- White dwarfs luminosity function (cooling)




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

# Axion landscape




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

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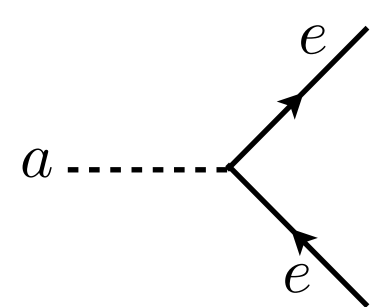


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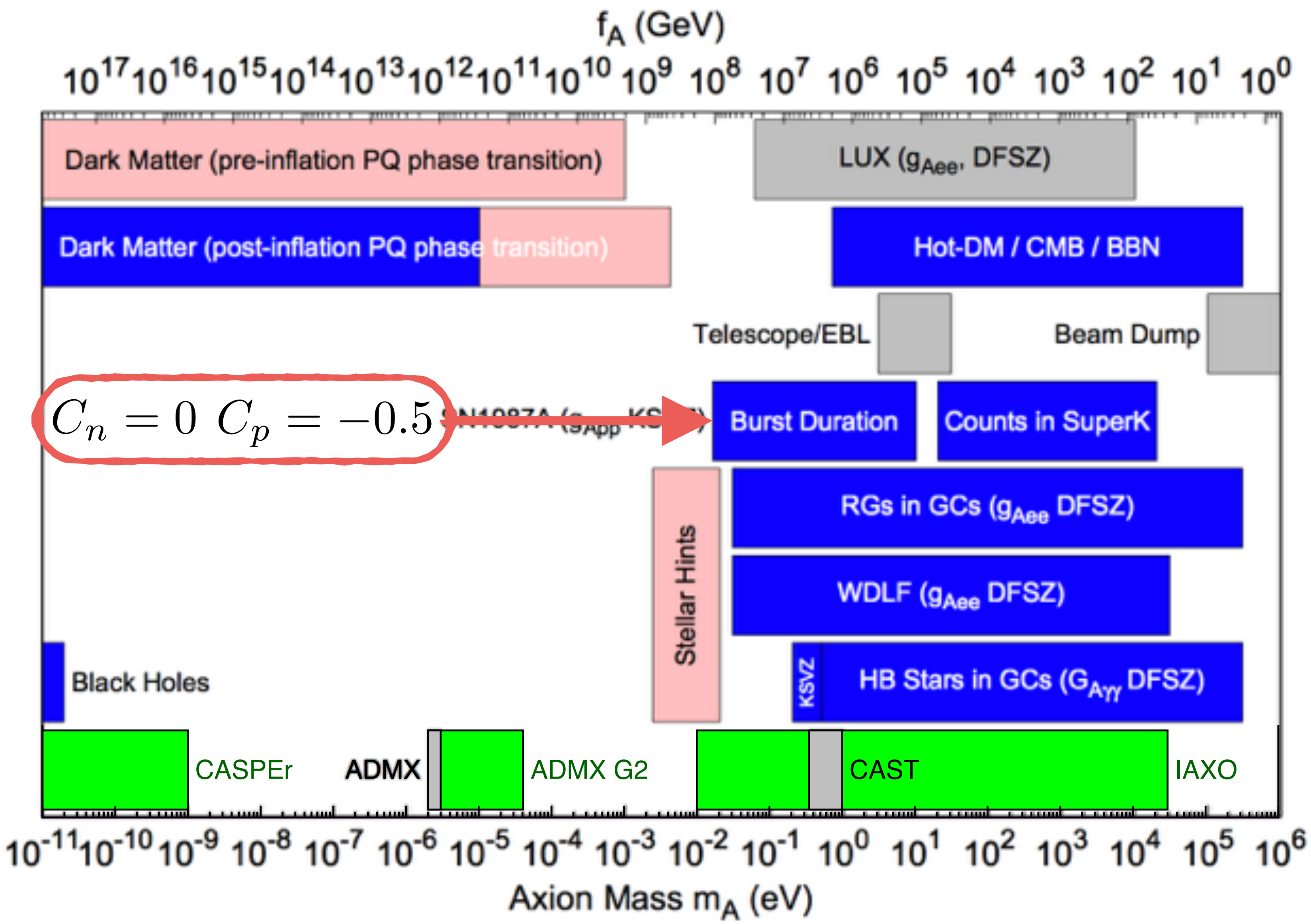
# Axion landscape




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

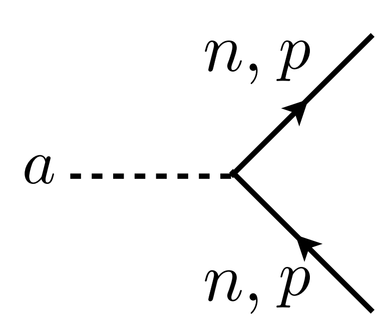
Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

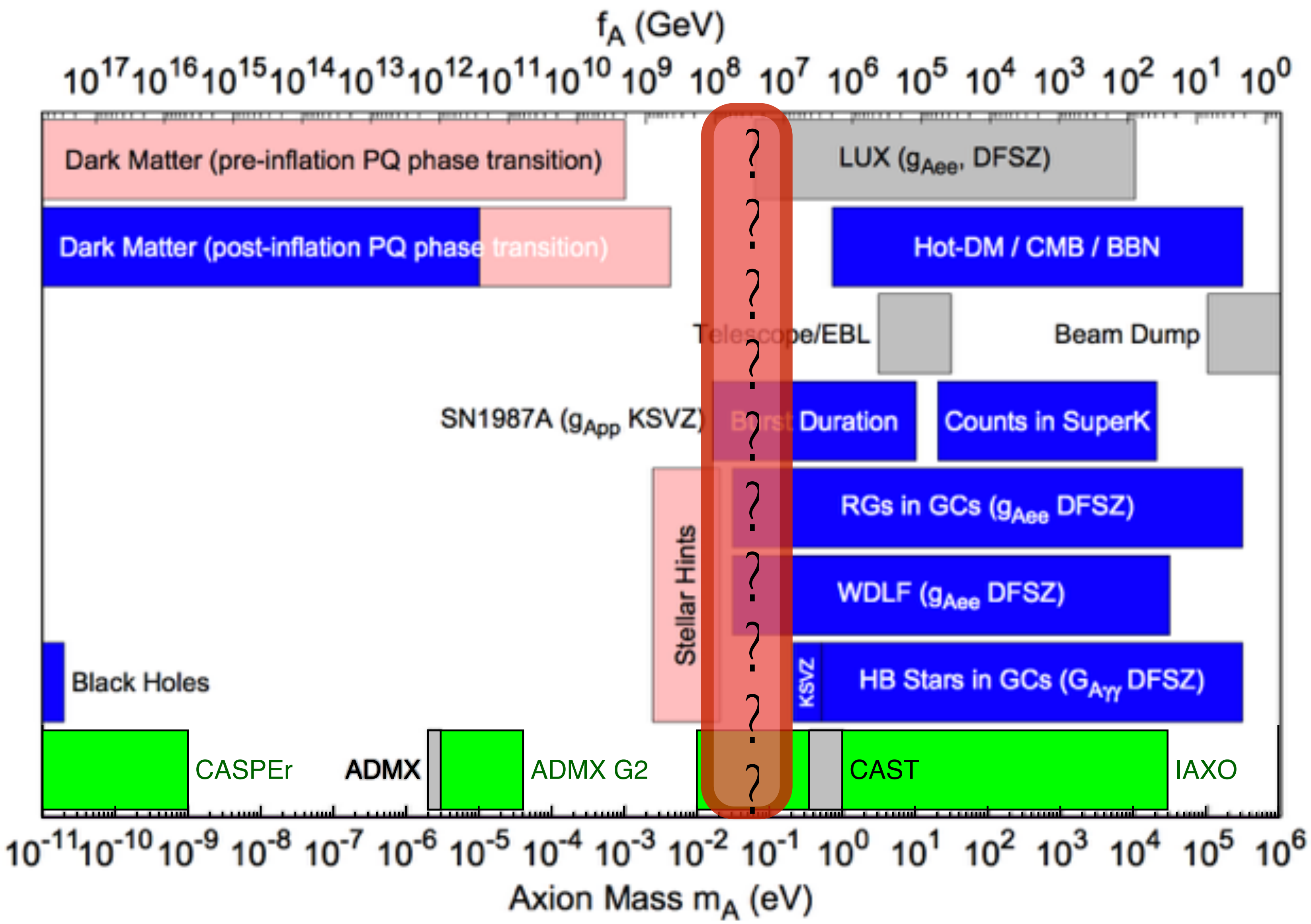
- Burst duration of SN1987A nu signal




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

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

# Axion landscape




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

Lab exclusions

Astro/cosmo exclusions

DM explained / Astro Hints

Exp. sensitivities

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

# Search strategies

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

<u>Primakoff effect</u>: axion-photon transition in external static E or B field

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

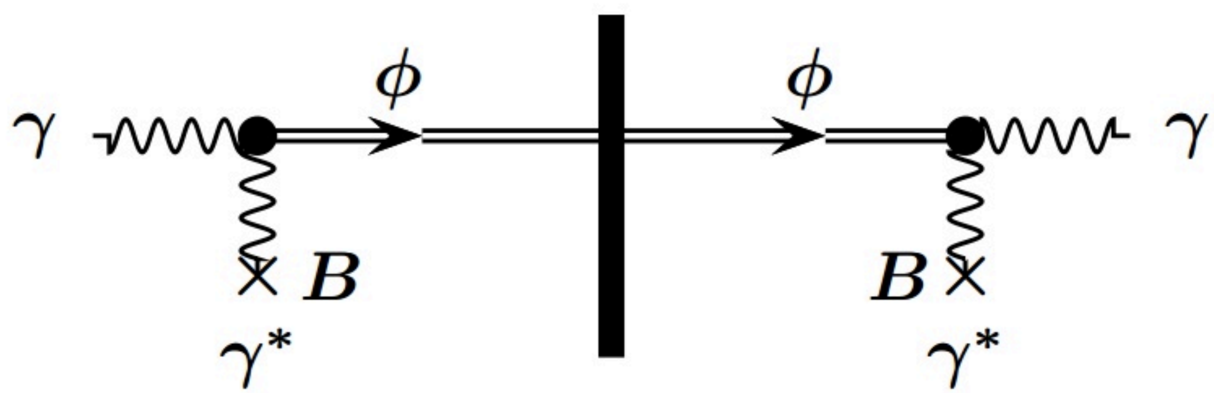

- Light Shining through Walls [See e.g. Redondo, Ringwald hep-ph/1011374l]

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

- Helioscopes (axions from the Sun)

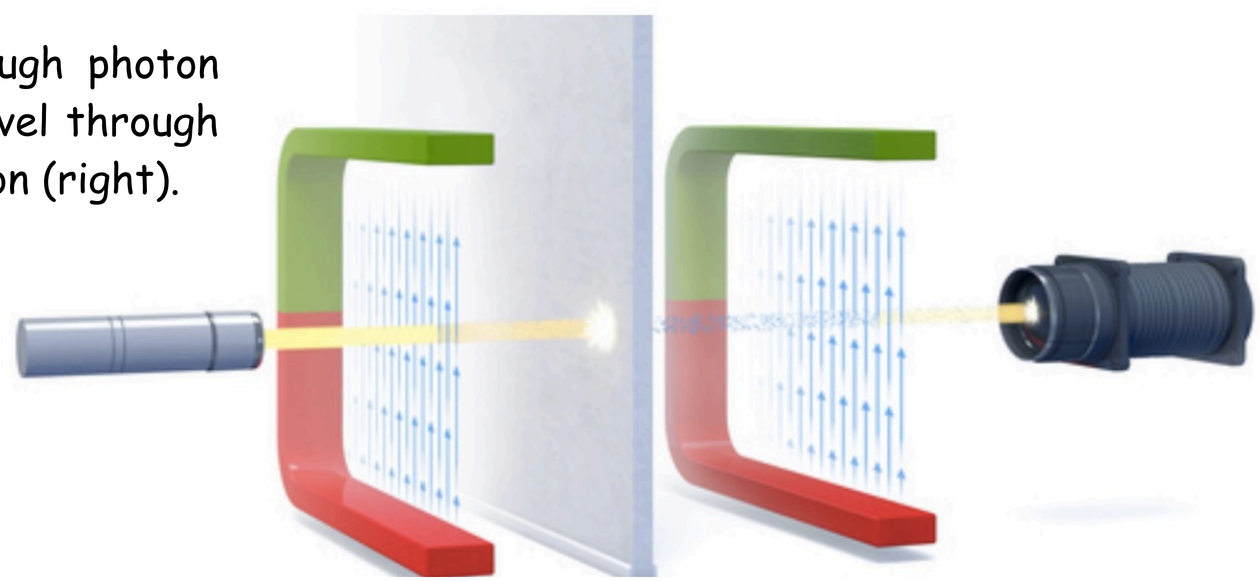
# Light Shining through Walls (LSW)

- PVLAS discovery claim (2006) → boosted exp. activity
- Any Light Particle Search (DESY): ALPS-I (2007-2010) and ALPS-II (2013-…)




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

Artist view of a light shining through a wall experiment



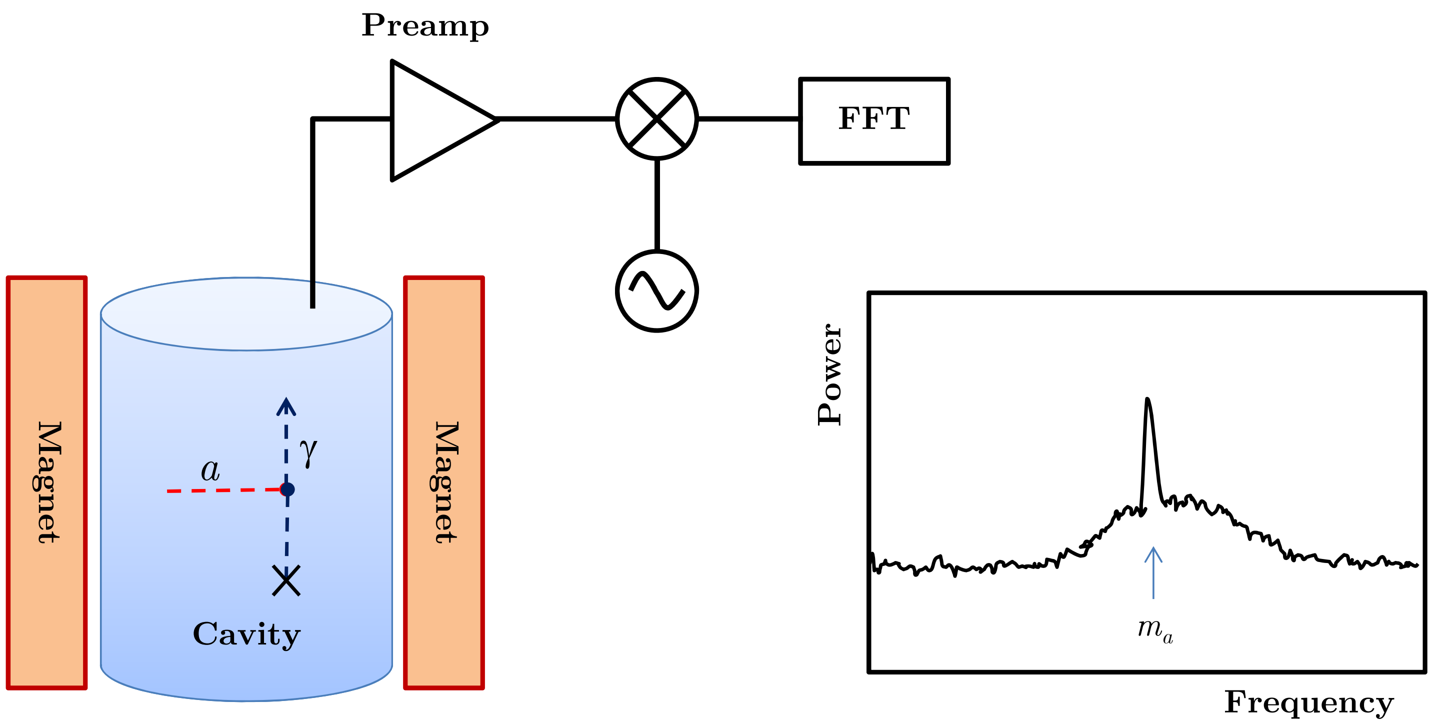
- LSW experiments pay a $g^4_{a\gamma\gamma}$ suppression

# Haloscopes

- Look for DM axions with a microwave resonant cavity

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

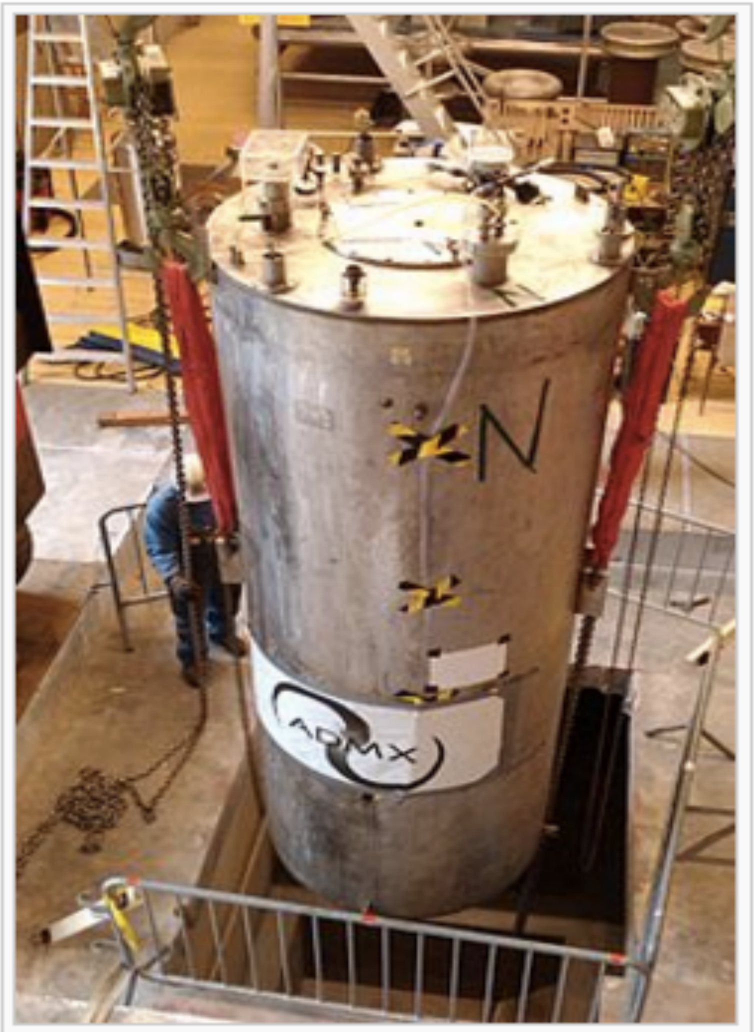
  - resonance condition: need to tune the frequency of the EM cavity on the axion mass

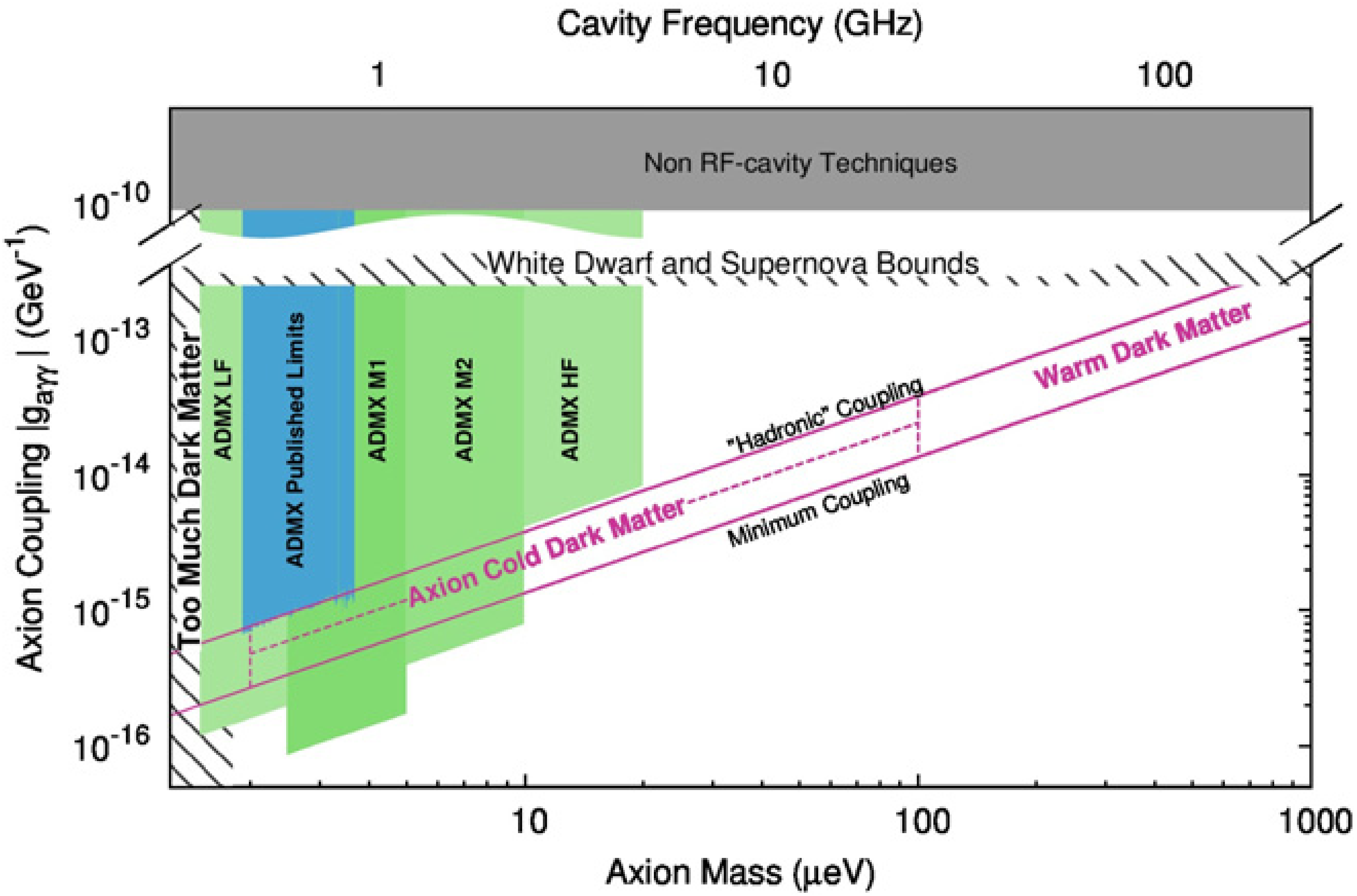


# Haloscopes

- Look for DM axions with a microwave resonant cavity

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

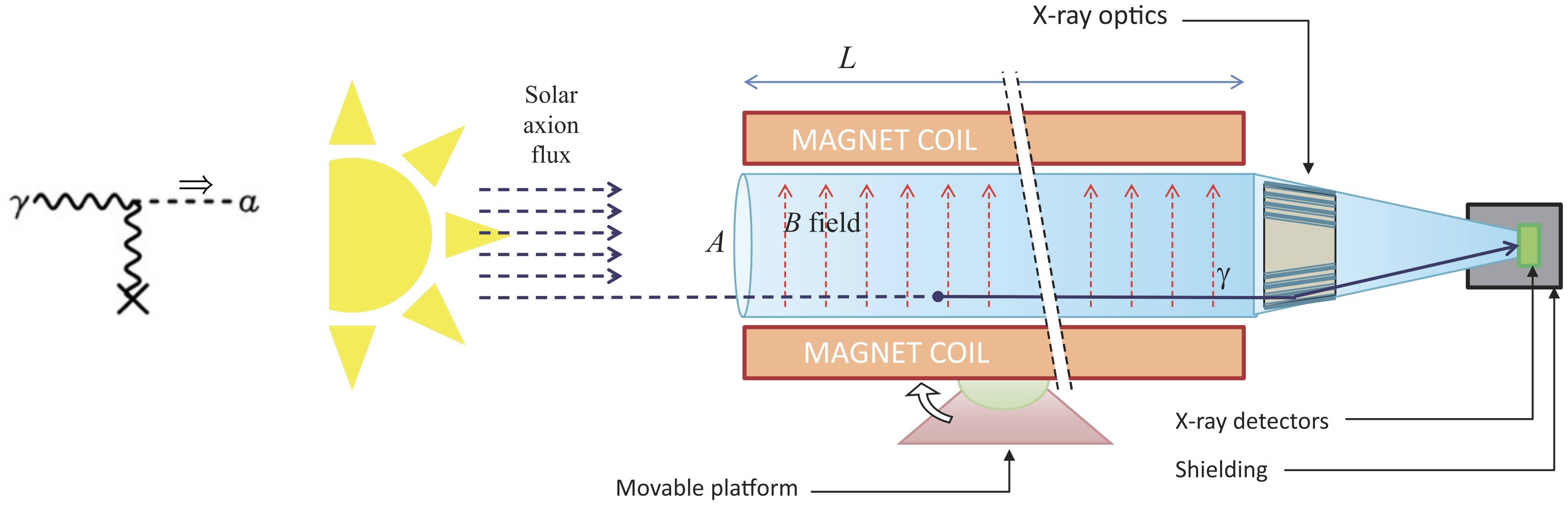


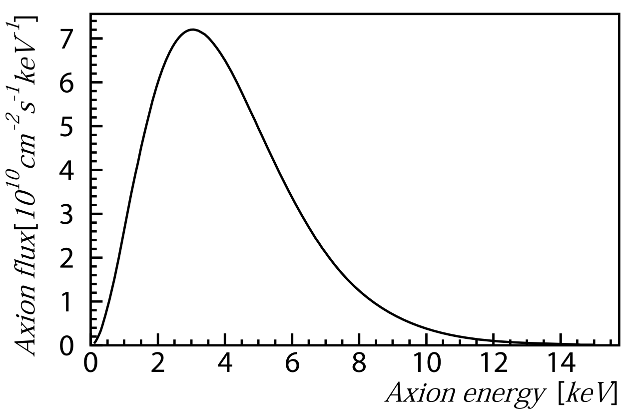




[ADMX Collaboration, Phys. Dark Univ. 4 (2014)]

# Helioscopes

- The Sun is a potential axion source



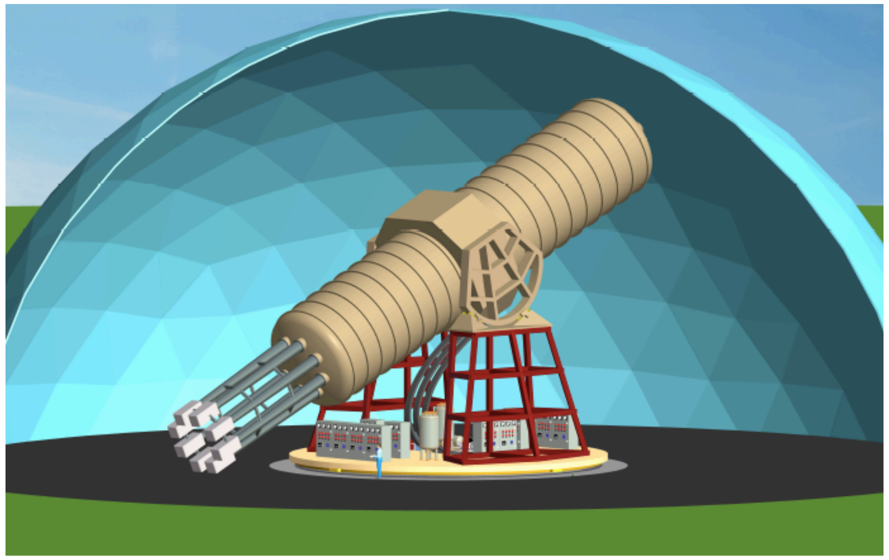

- macroscopic B-field can provide a coherent axion-photon (x-ray) conversion rate over a big volume

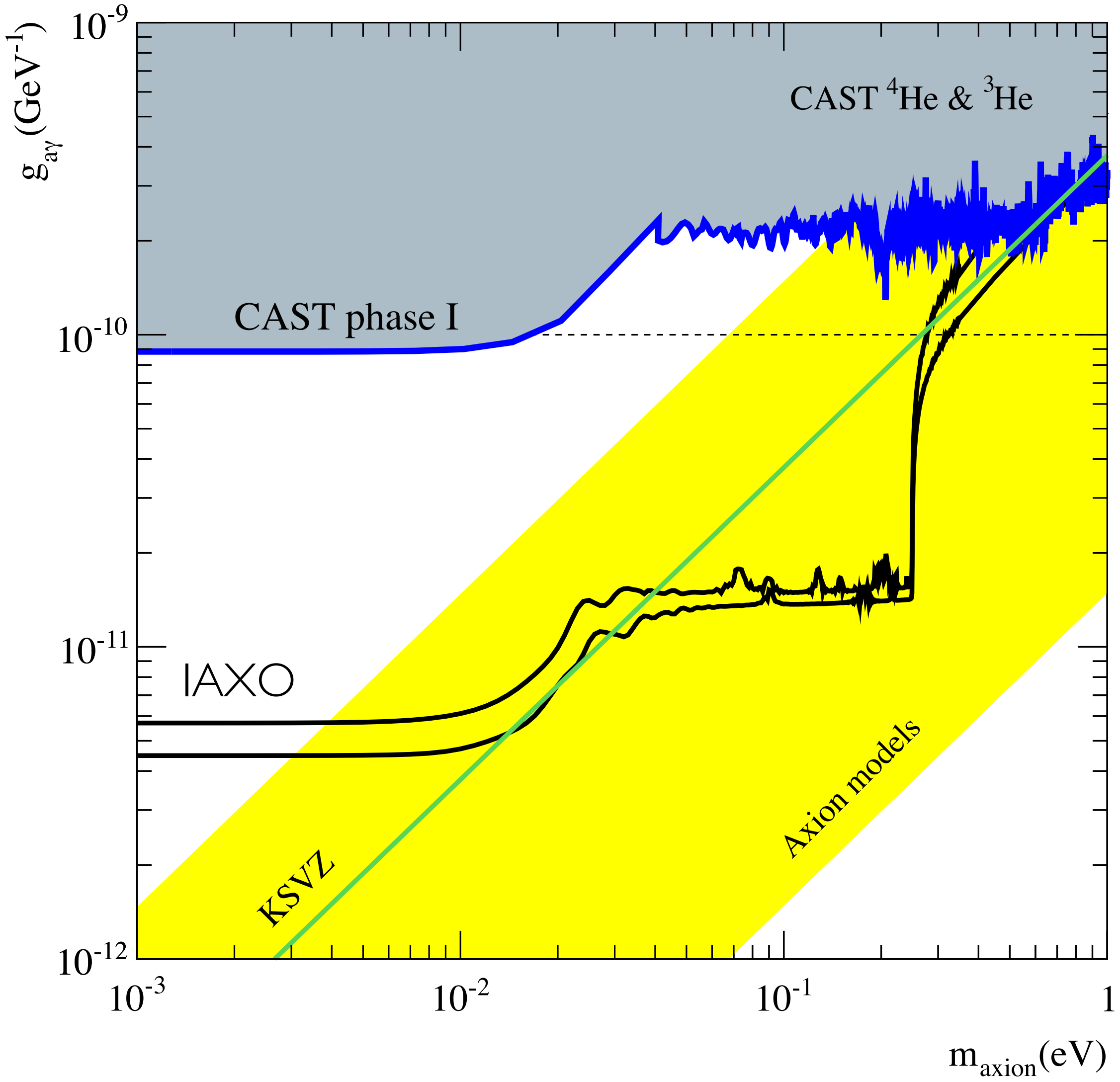
# Helioscopes

- The Sun is a potential axion source

  - CERN Axion Solar Telescope (CAST)

  - International AXion Observatory (IAXO)






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

# The Axion Rush

PHYSICAL REVIEW X 4, 021030 (2014)

**Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)**

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

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

**Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance**

Asimina Arvanitaki[1] and Andrew A. Geraci[2,*]

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Searching for galactic axions through magnetized media: The QUAX proposal

R. Barbieri [a,b], C. Braggio [c], G. Carugno [c], C.S. Gallo [c], A. Lombardi [d], A. Ortolan [d], R. Pengo [d], G. Ruoso [d,*], C.C. Speake [e]

PHYSICAL REVIEW D 91, 084011 (2015)

**Discovering the QCD axion with black holes and gravitational waves**

Asimina Arvanitaki[*]
*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

Masha Baryakhtar[†] and Xinlu Huang[‡]
*Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA*
(Received 16 December 2014; published 7 April 2015)

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Aryeh Brill
*Yale University, New Haven, Connecticut 06520, USA*
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**CULTASK, The Coldest Axion Experiment at CAPP/IBS/KAIST in Korea**

**Woohyun Chung**[*]
*Center for Axion and Precision Physics Research, Institute for Basic Science (IBS), Republic of Korea*

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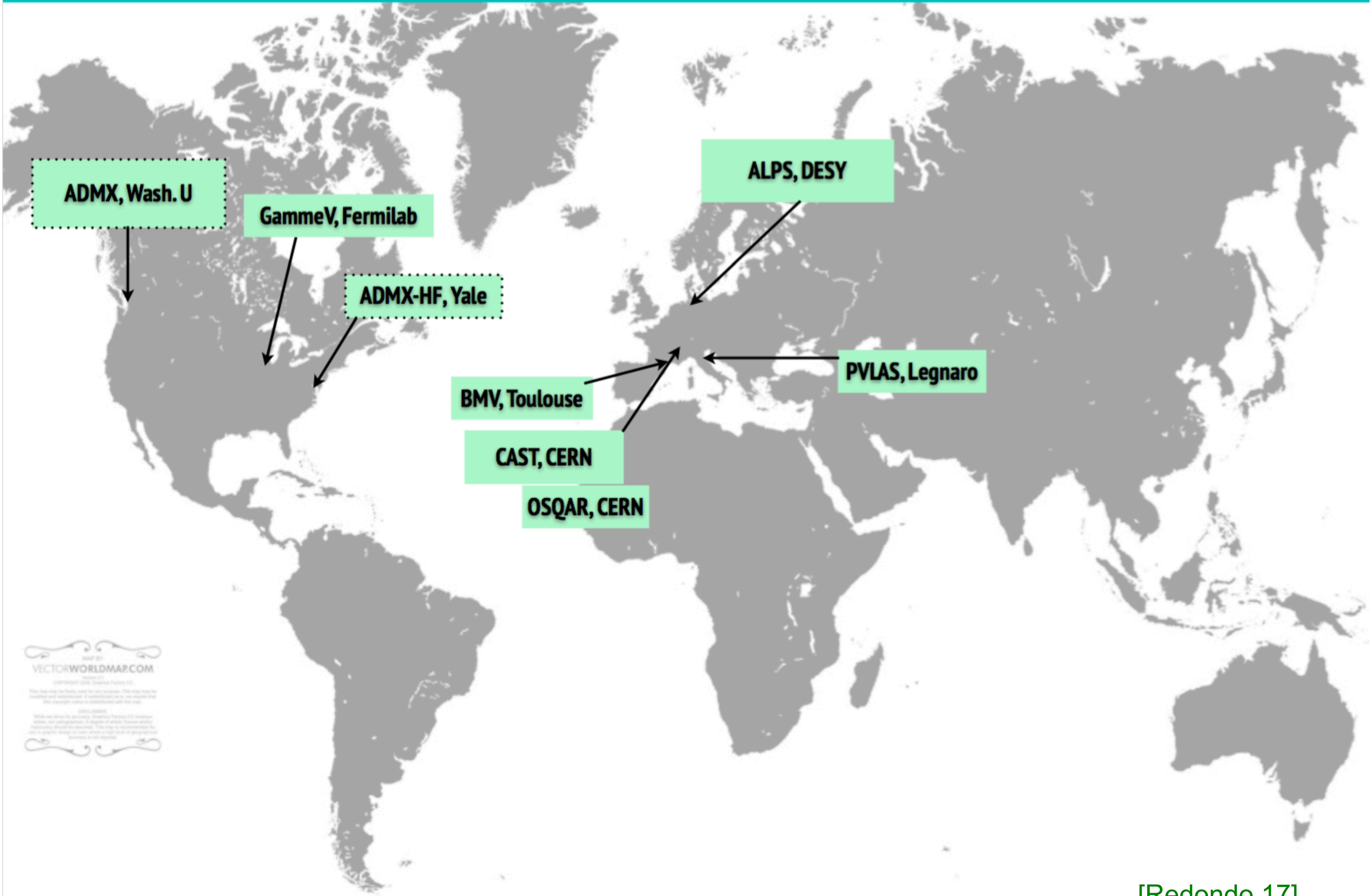
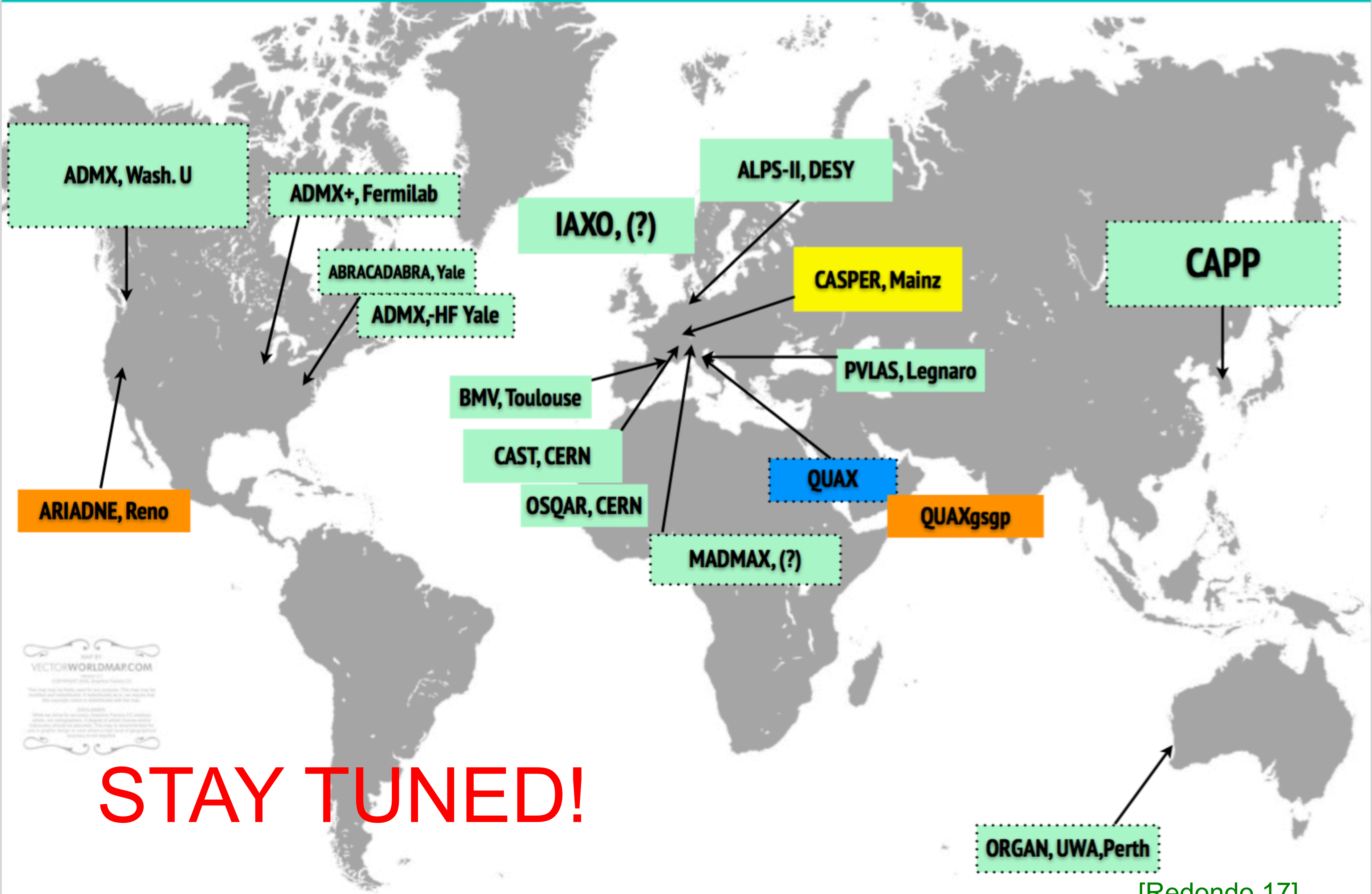
$g_{a\gamma\gamma}$

# Lab experiments 2011




[Redondo 17]

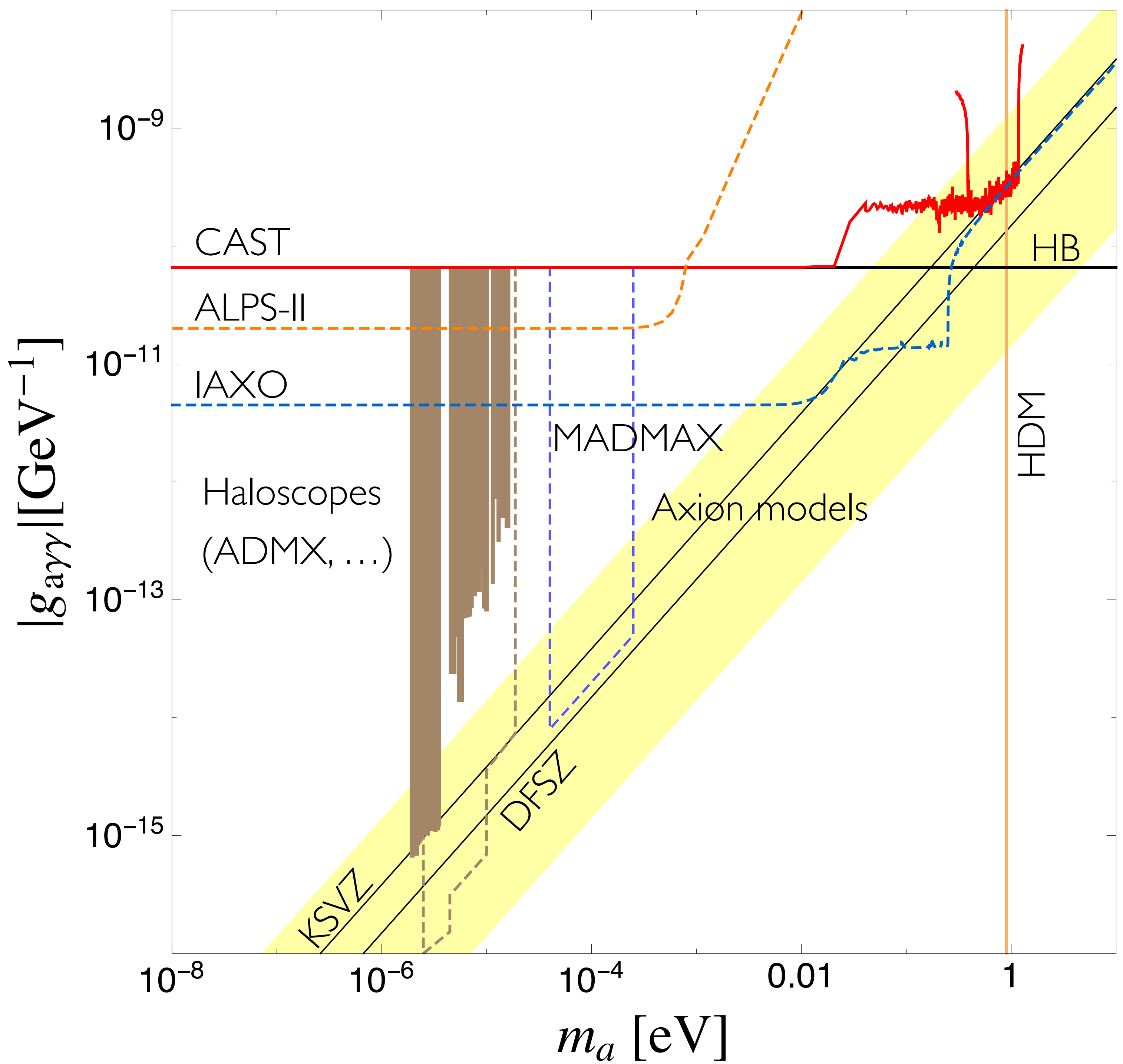
# Lab experiments 2017




STAY TUNED!

[Redondo 17]

# Need to know where to search




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

E/N anomaly coefficients, depend on UV completion

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

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

# Pheno preferred KSVZ fermions

- Q short lived + no Landau poles < Planck

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

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

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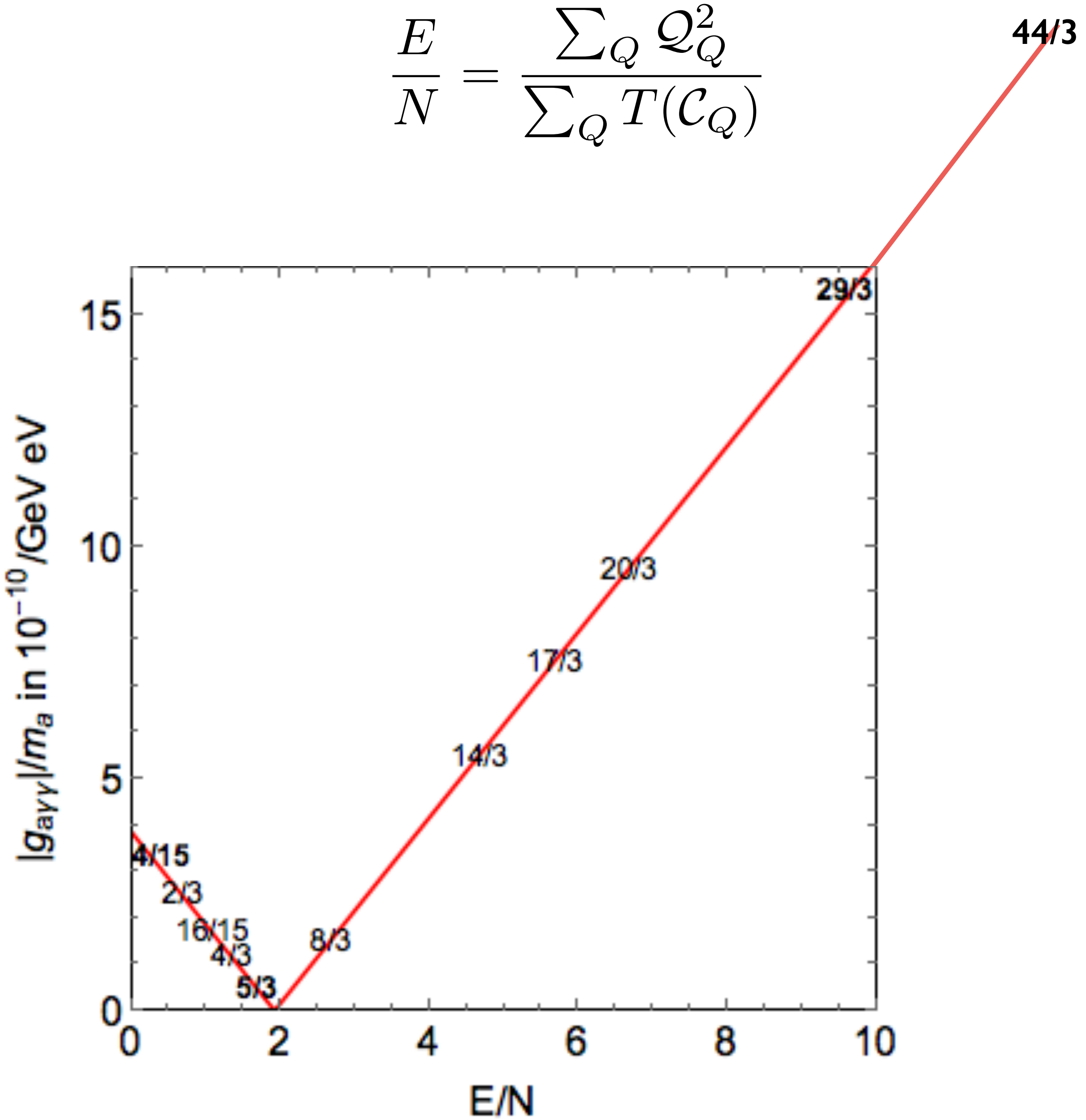

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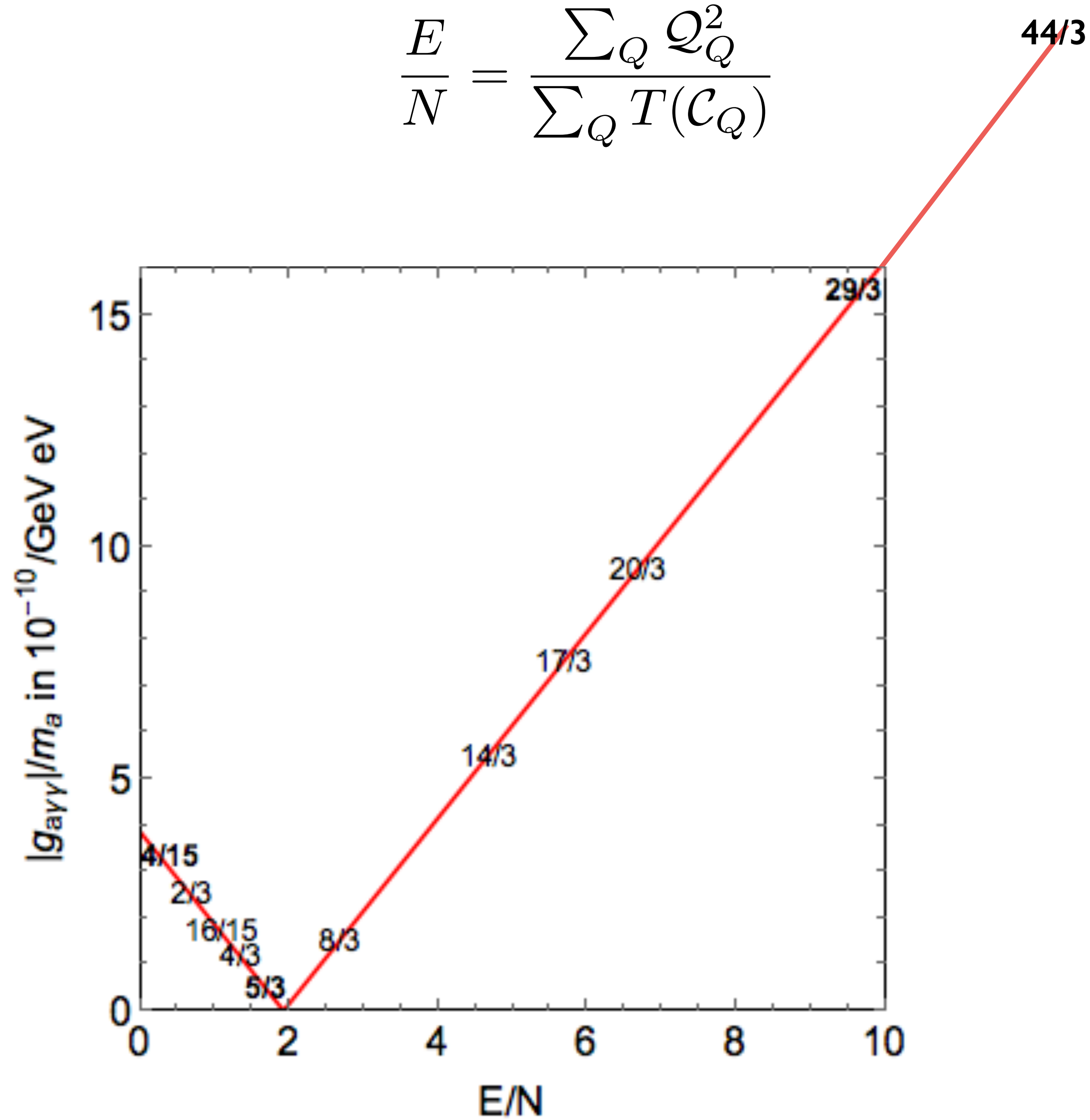
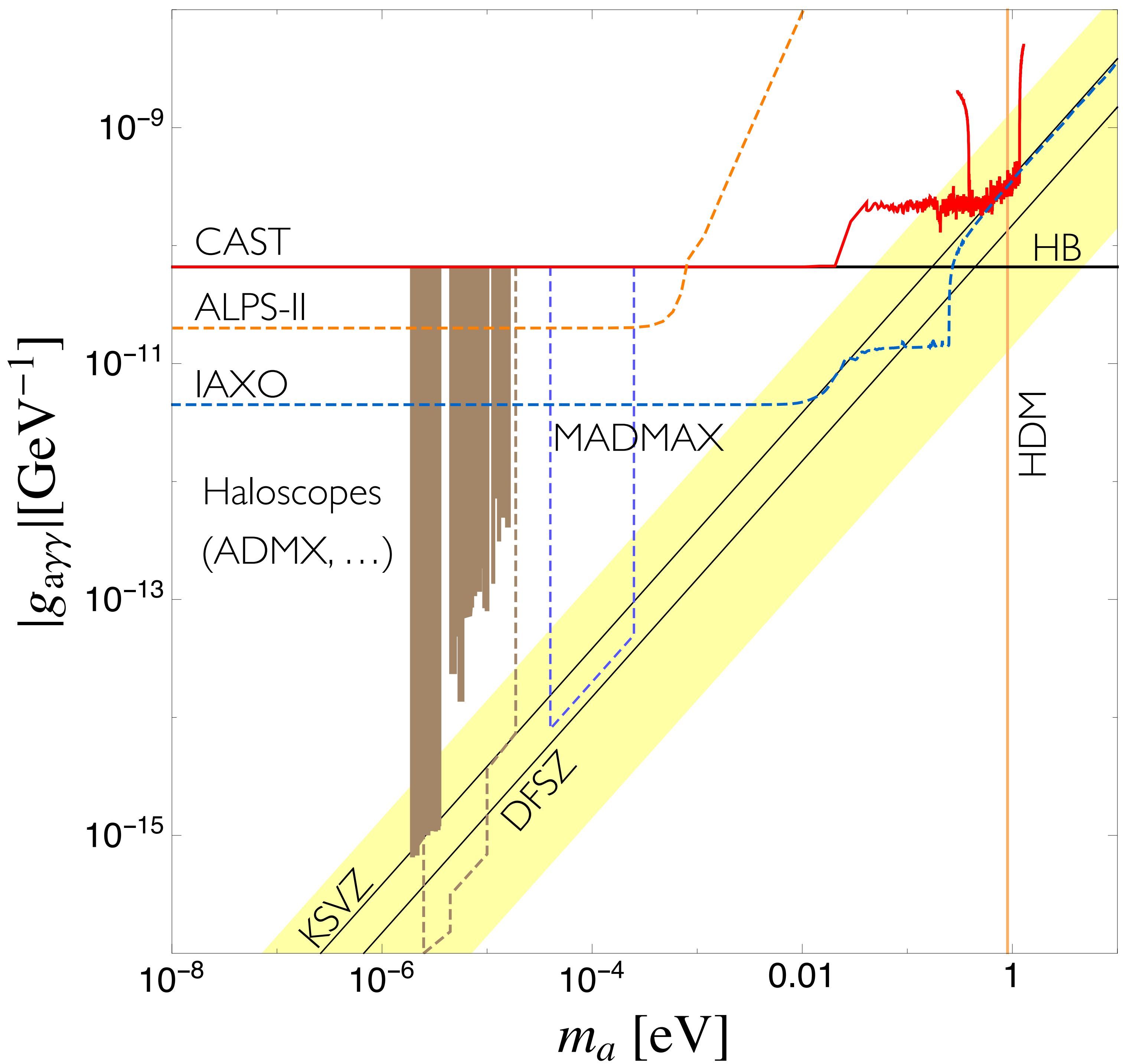


# Redefining the axion window



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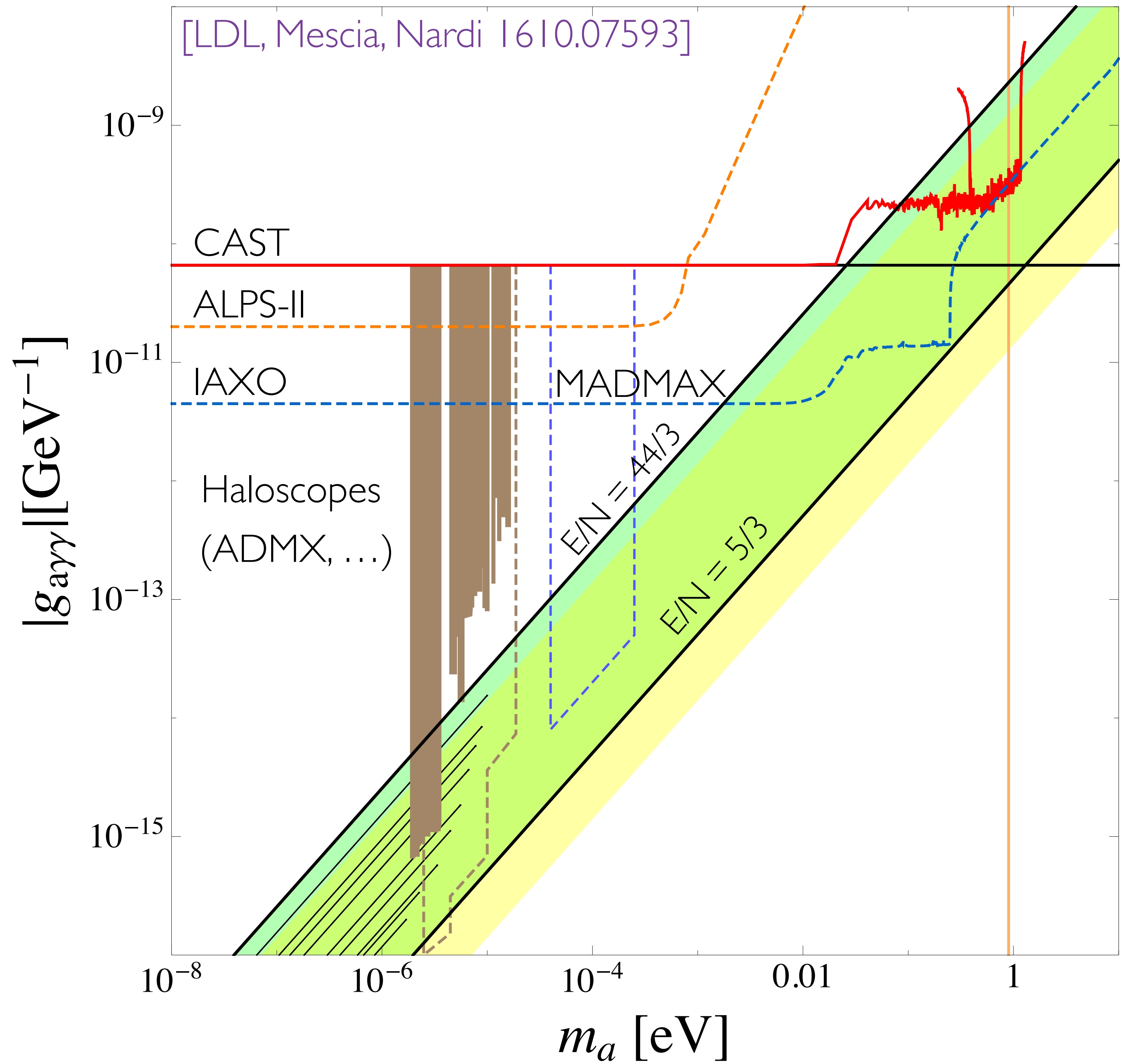


# More Q's

- Combined anomaly factor

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

- Strongest coupling (compatible with LP criterium)

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

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

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

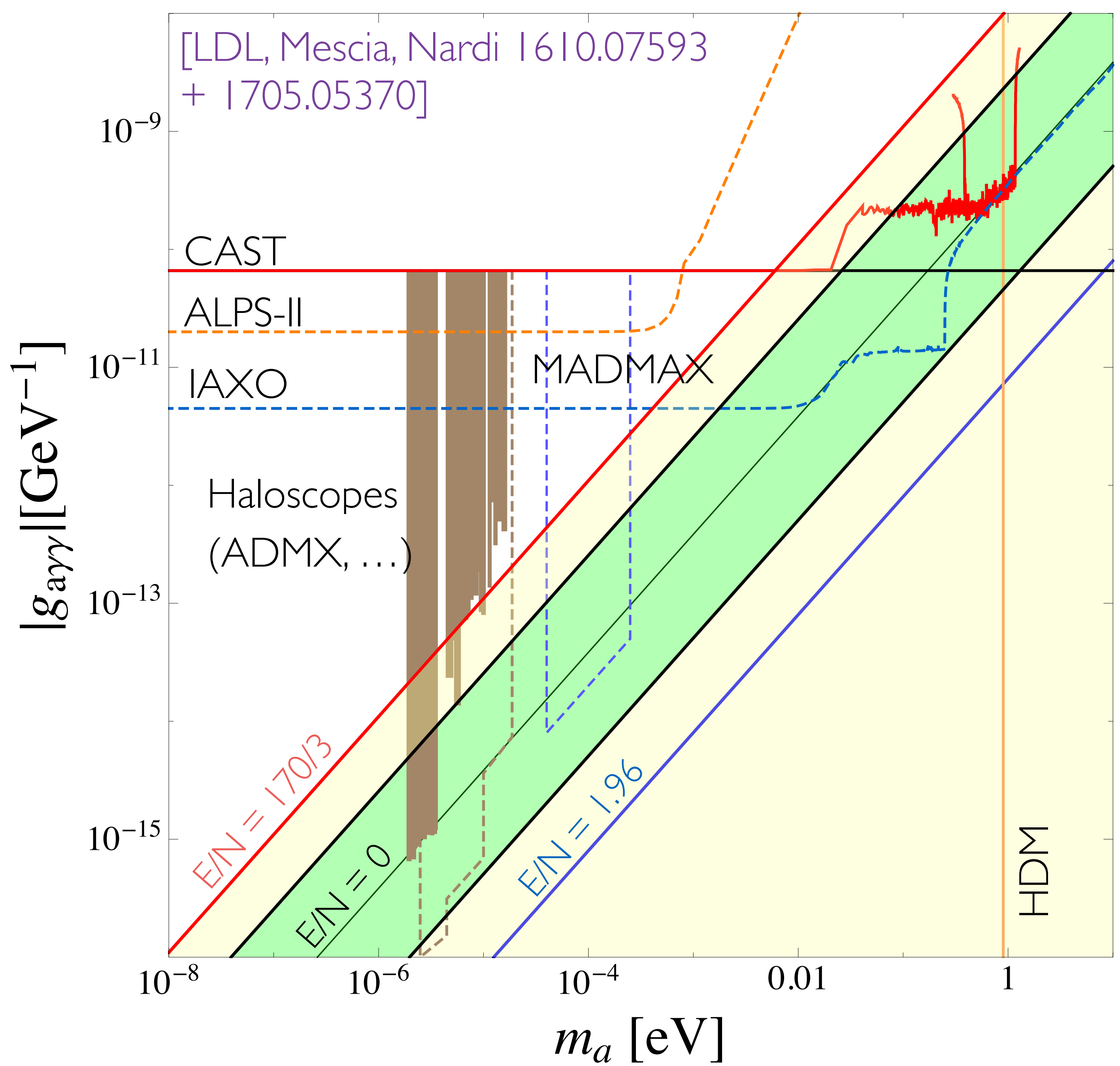
$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10}\ \text{GeV}} \left(\frac{E_c}{N_c} - 1.92(4)\right)$$

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

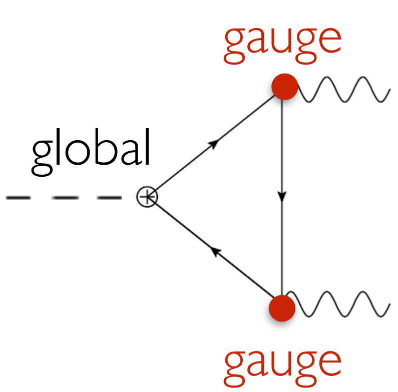
# Axion-photon summary

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

- Blue line corresponds to a 2% 'tuning in theory space'




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



# Axion-photon summary

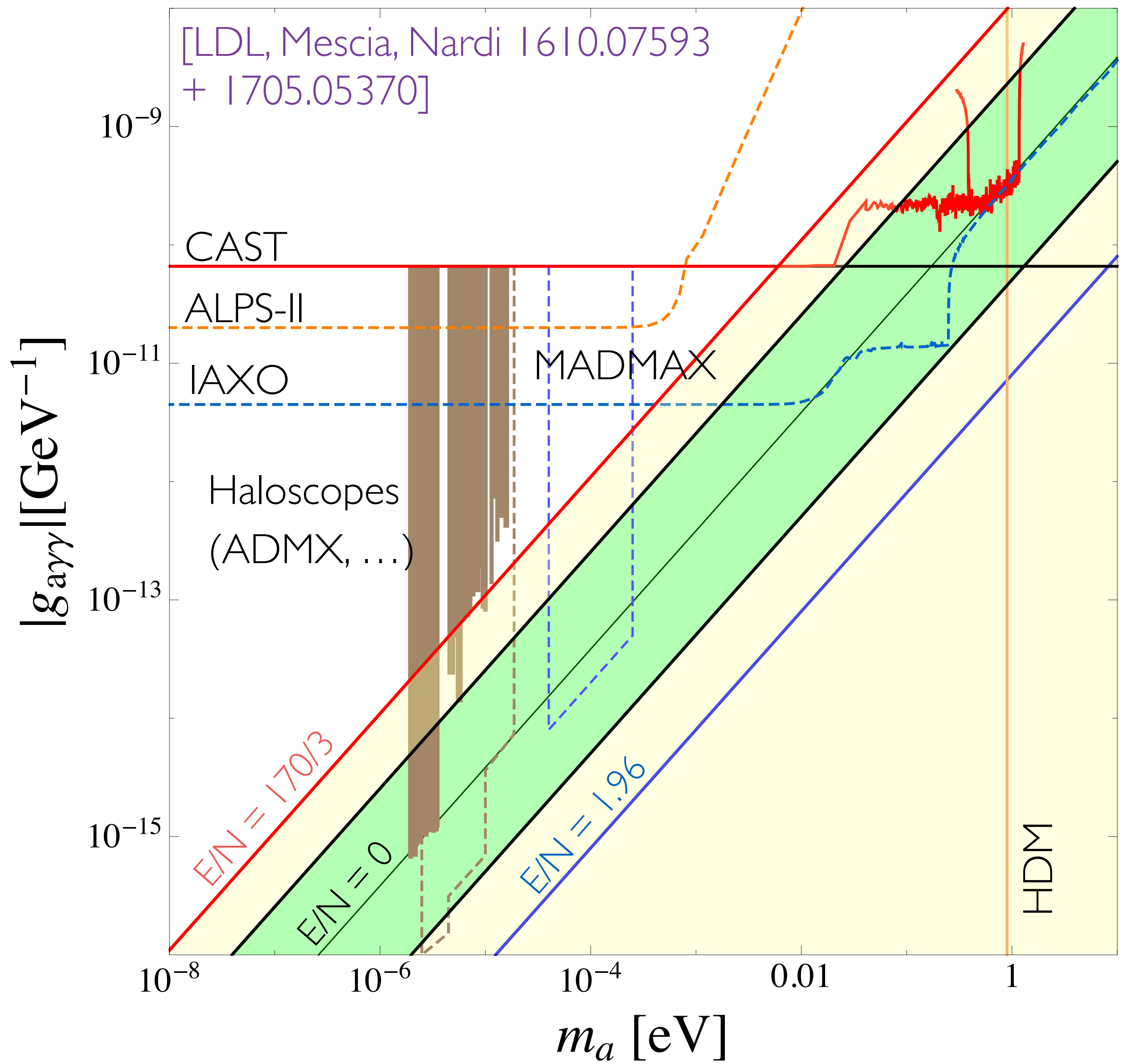
- Red line set by perturbativity [KSVZ] (going much above requires exotic constructions *[more in backup slides]*)

- Blue line corresponds to a 2% 'tuning in theory space'

- Messages for exp.'s :

1. The QCD axion might already be in the reach of your experiment !

2. Don't stop at E/N = 0 (go deeper if you can)



# Astrophobia

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

→ nucleophobia + electrophobia = astrophobia

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

1. is it possible at all ?
2. would allow to relax the upper bound on axion mass by ~ 1 order of magnitude
3. would improve visibility at IAXO (axion-photon)
4. would improve fit to stellar cooling anomalies (axion-electron) [Giannotti et al. 1708.02111]
5. unexpected connection with flavour

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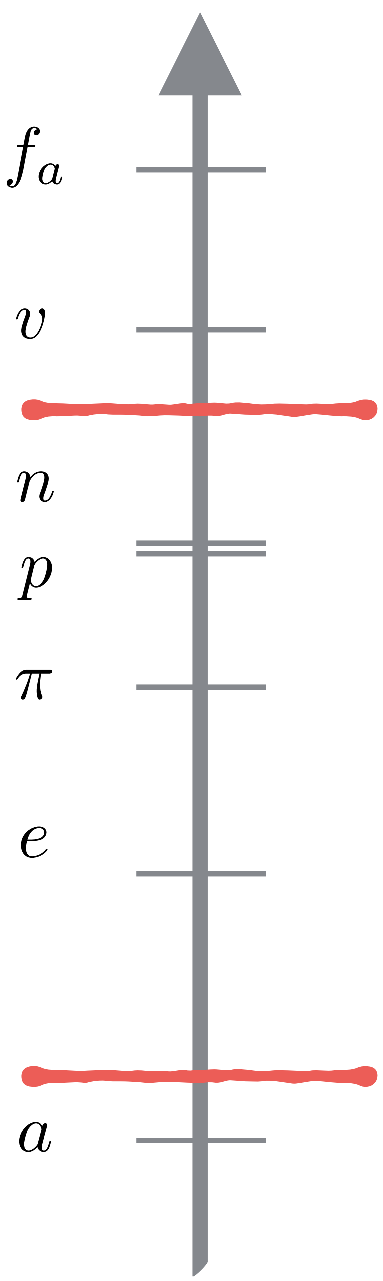
5. unexpected connection with flavour

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

# Conditions for nucleophobia

- Axion-nucleon couplings

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




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

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

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

EFT-II: non-relativistic nucleons

# Conditions for nucleophobia

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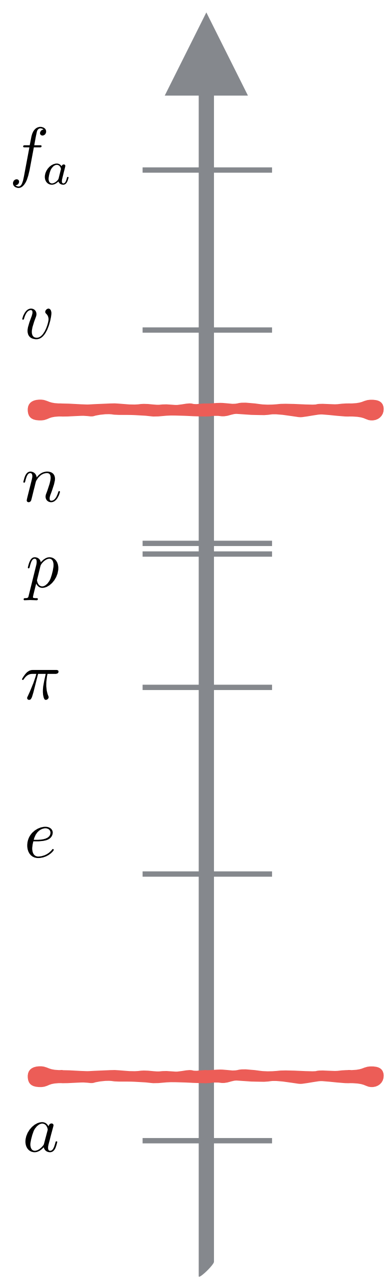
[Kaplan NPB 260 (1985), Srednicki NPB 260 (1985), Georgi, Kaplan, Randall PLB 169 (1986), …, Grilli di Cortona et al. 1511.02867]




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

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

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

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

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

Independently of matrix elements:

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

# KSVZ/DFSZ no-go

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

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

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

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

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

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

# KSVZ/DFSZ no-go

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

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

# KSVZ/DFSZ no-go

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

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

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

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

# Implementing nucleophobia

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

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

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

$$\boxed{\begin{aligned} \mathcal{L}_Y \supset\ & \bar{q}_3 u_3 H_1 + \bar{q}_3 d_3 \tilde{H}_2 + (\bar{q}_3 u_2 ... + \ldots) \\ +\ & \bar{q}_2 u_2 H_2 + \bar{q}_2 d_2 \tilde{H}_1 + (\bar{q}_2 d_3 ... + \ldots) \end{aligned}} \quad \boxed{\begin{aligned} &\Rightarrow \mathcal{N}_{3^{rd}} = 2X_{q_3} - X_{u_3} - X_{d_3} = X_1 - X_2 \\ &\Rightarrow \mathcal{N}_{2^{nd}} = 2X_{q_2} - X_{u_2} - X_{d_2} = X_2 - X_1 \end{aligned}}$$

- 1st condition automatically satisfied

# Implementing nucleophobia

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

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

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

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

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

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

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

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

# Flavour connection

- Nucleophobia implies flavour violating axion couplings !

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

e.g. RH down rotations become physical

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e.g. RH down rotations become physical

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

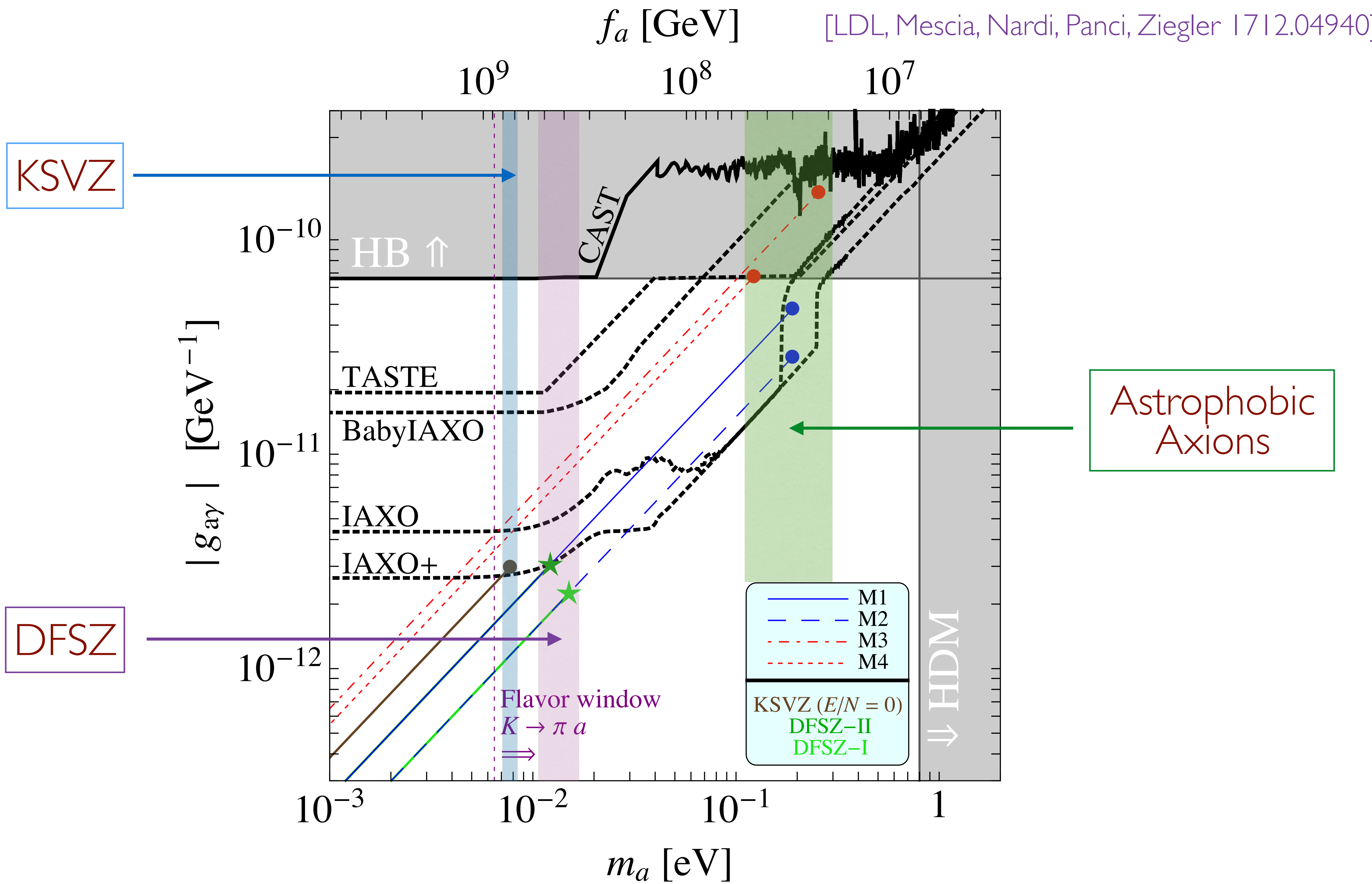
- $K \to \pi a \; : \; m_a < 1.0 \times 10^{-4} \dfrac{\mathrm{eV}}{|C^V_{sd}|}$ [E787, E949 @ BNL, 0709.1000] → NA62

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

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

# Astrophobic axion models

[LDL, Mescia, Nardi, Panci, Ziegler 1712.04940]



# Conclusions

- QCD axion: 2 birds with 1 stone

  - solves the strong CP problem

  - provides an excellent DM candidate

- Healthy phase (experimentally driven)

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

# Conclusions

- QCD axion: 2 birds with 1 stone

  - solves the strong CP problem

  - provides an excellent DM candidate

- Healthy phase (experimentally driven)

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

- KSVZ and DFSZ are well-motivated minimal benchmarks, but…

  - axion couplings are UV dependent

  - worth to think about alternatives when confronting exp. bounds and sensitivities

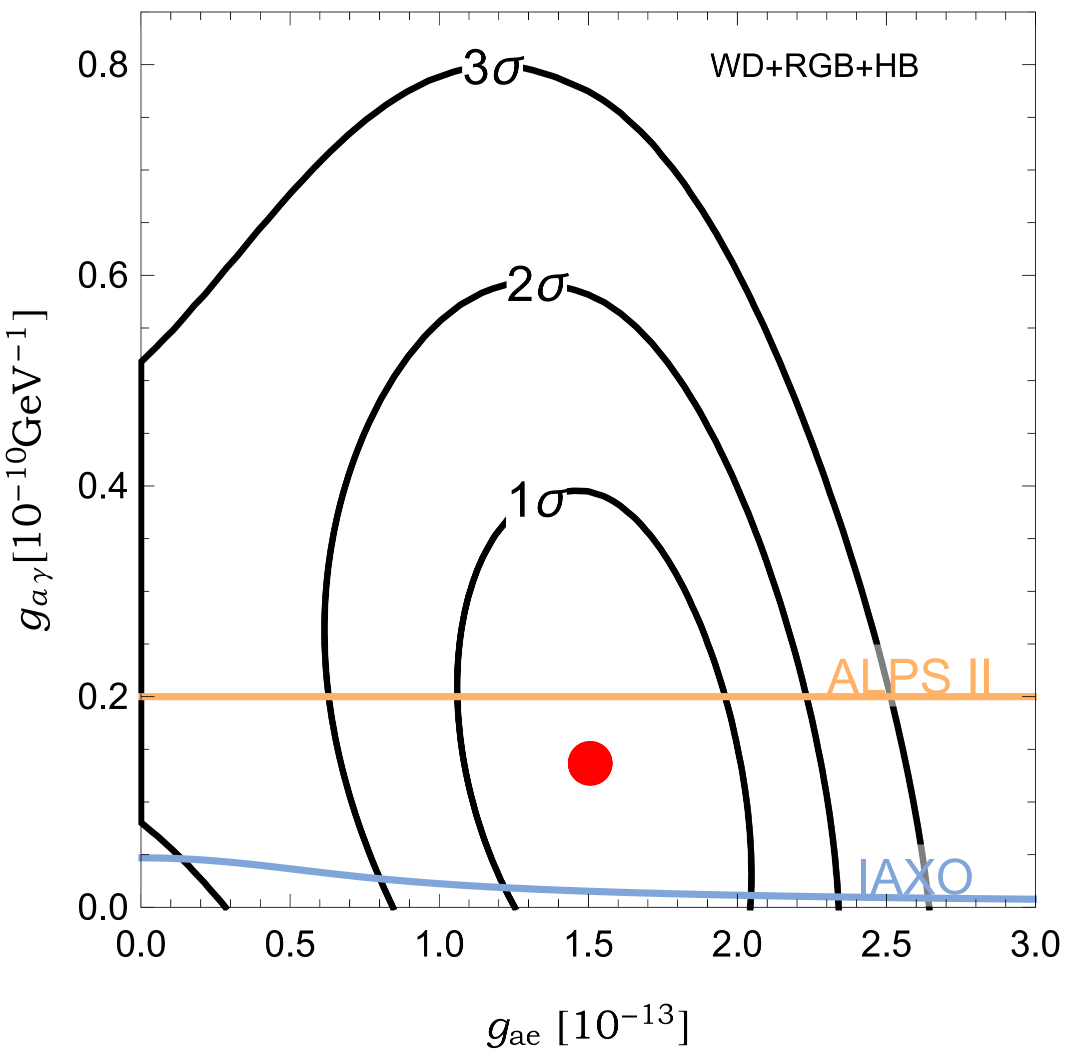
# Backup slides

# Stellar cooling anomalies

- Hints of excessive cooling in WD+RGB+HB can be explained via an axion

  - requires a sizeable axion-electron coupling in a region disfavoured by SN bound*

[Giannotti, Irastorza, Redondo, Ringwald, Saikawa 1708.02111]




| Model | Global fit includes | $f_a$ $[10^8$ GeV$]$ | $m_a$ [meV] | $\tan\beta$ | $\chi^2_{\mathrm{min}}$/d.o.f. |
|---|---|---|---|---|---|
| DFSZ I | WD,RGB,HB | 0.77 | 74 | 0.28 | 14.9/15 |
| | WD,RGB,HB,SN | 11 | 5.3 | 140 | 16.3/16 |
| | WD,RGB,HB,SN,NS | 9.9 | 5.8 | 140 | 19.2/17 |
| DFSZ II | WD,RGB,HB | 1.2 | 46 | 2.7 | 14.9/15 |
| | WD,RGB,HB,SN | 9.5 | 6.0 | 0.28 | 15.3/16 |
| | WD,RGB,HB,SN,NS | 9.1 | 6.3 | 0.28 | 21.3/17 |

★ Nucleophobic axions should improve fit, allowing for fully perturbative Yukawas

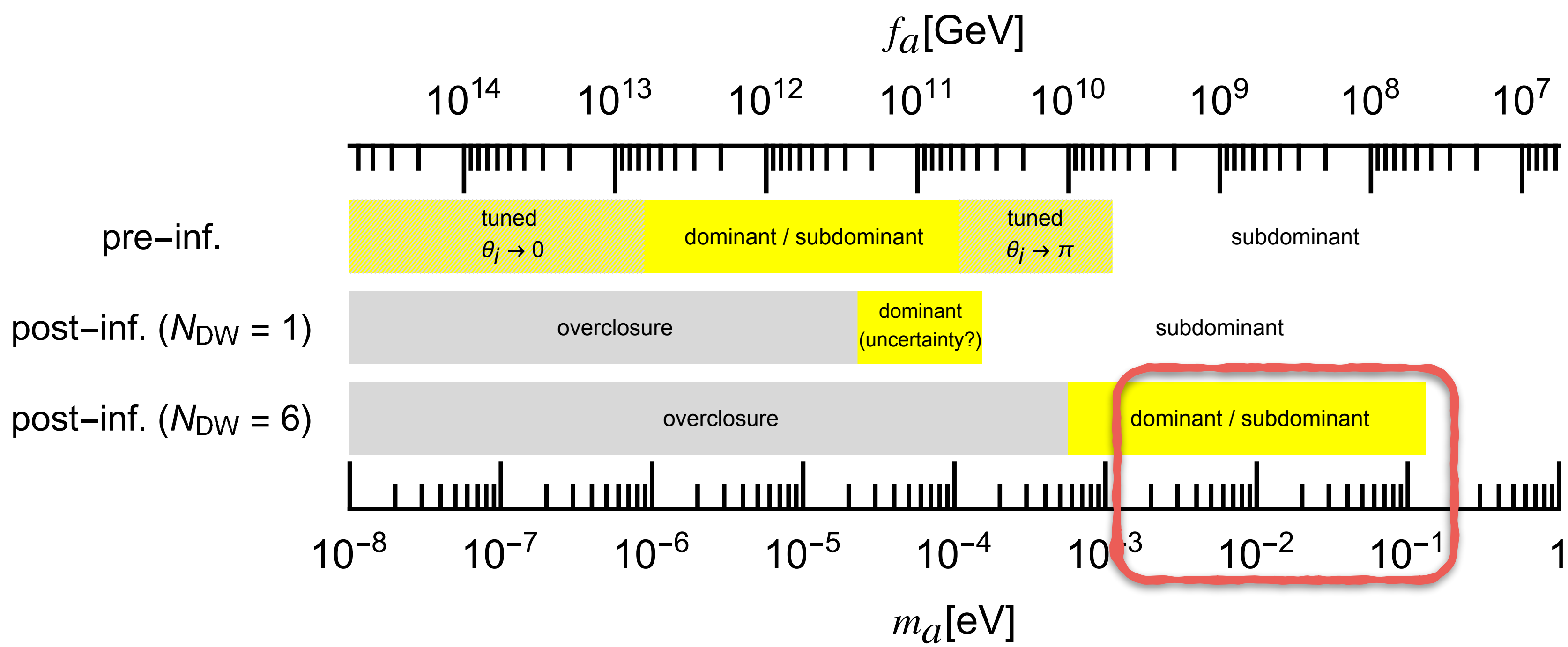
*SN bound a factor ~4 weaker than PDG one ?

[Chang, Essig, McDermott 1803.00993]

# DM in the heavy axion window

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

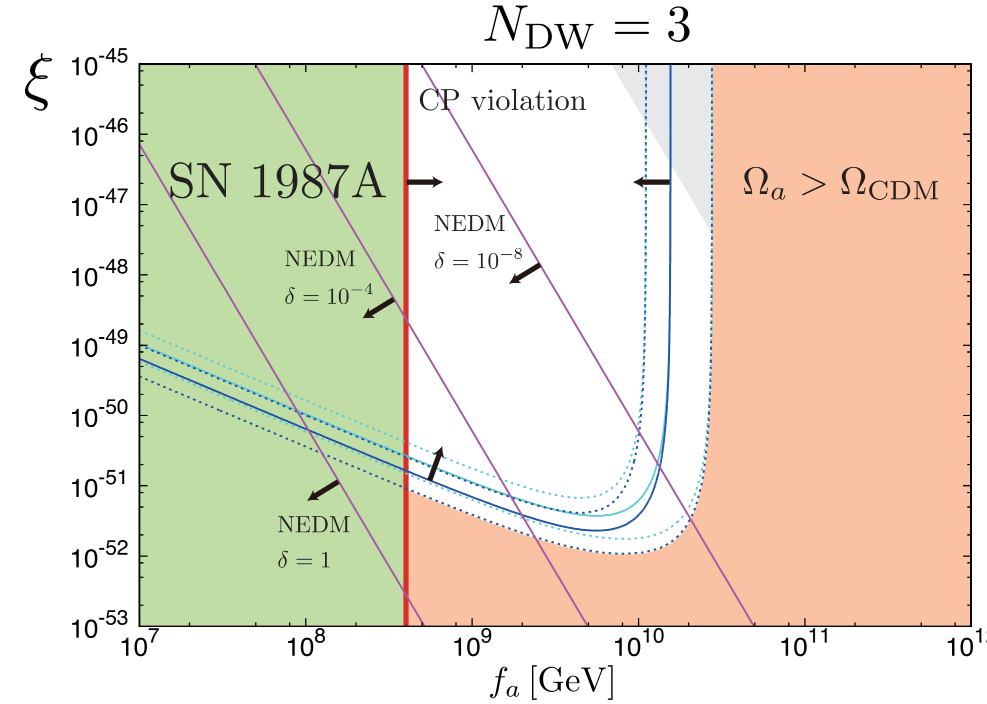
[Kawasaki, Saikawa, Sekiguchi, 1412.0789 1709.07091]




- axion production from topological defects

- requires explicit PQ breaking term

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



# Boosting E/N in DFSZ

- Potentially large E/N due to electron PQ charge

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

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

- with $n_H$ Higgs doublets and a SM singlet $\Phi$, enhanced global symmetry

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

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

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

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

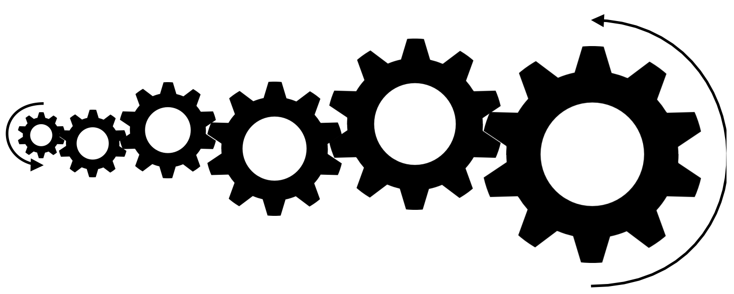
- Clockwork-like scenarios allow to boost E/N [LDL, Mescia, Nardi 1705.05370]

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

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

$$(H_k H^*_{k-1})(H^*_{k-1} H^*_d)$$

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



[Giudice, McCullough]

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

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

# Axion coupling to photons

- Axion effective Lagrangian

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

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

field-depended chiral transformation to eliminate aGGtilde:

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

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

# Axion coupling to photons

- Axion effective Lagrangian

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

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

$$\Downarrow$$

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

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

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

model independent

depends on UV completion

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

# KSVZ axions

- Field content

| Field | Spin | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_{PQ}$ |
|---|---|---|---|---|---|
| $Q_L$ | $1/2$ | $\mathcal{C}_Q$ | $\mathcal{I}_Q$ | $\mathcal{Y}_Q$ | $\mathcal{X}_L$ |
| $Q_R$ | $1/2$ | $\mathcal{C}_Q$ | $\mathcal{I}_Q$ | $\mathcal{Y}_Q$ | $\mathcal{X}_R$ |
| $\Phi$ | $0$ | $1$ | $1$ | $0$ | $1$ |

- PQ charges carried by a vector-like quark $Q = Q_L + Q_R$

- original KSVZ model assumes Q ~ (3,1,0), but in general only $\mathcal{C}_Q \neq I$ required

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

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

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

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

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| $Q_L$ | $1/2$ | $\mathcal{C}_Q$ | $\mathcal{I}_Q$ | $\mathcal{Y}_Q$ | $\mathcal{X}_L$ |
| $Q_R$ | $1/2$ | $\mathcal{C}_Q$ | $\mathcal{I}_Q$ | $\mathcal{Y}_Q$ | $\mathcal{X}_R$ |
| $\Phi$ | $0$ | $1$ | $1$ | $0$ | $1$ |

- Lagrangian

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

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

# Q stability

- Symmetry of the kinetic term

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

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

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

cosmological issue if thermally produced
in the early universe !

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

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

- if $\mathcal{L}_{Qq} \neq 0$ $U(1)_{\rm Q}$ is further broken and Q-decay is possible [Ringwald, Saikawa, 1512.06436]

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

→ stability depends on Q representations

# Selection criteria

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

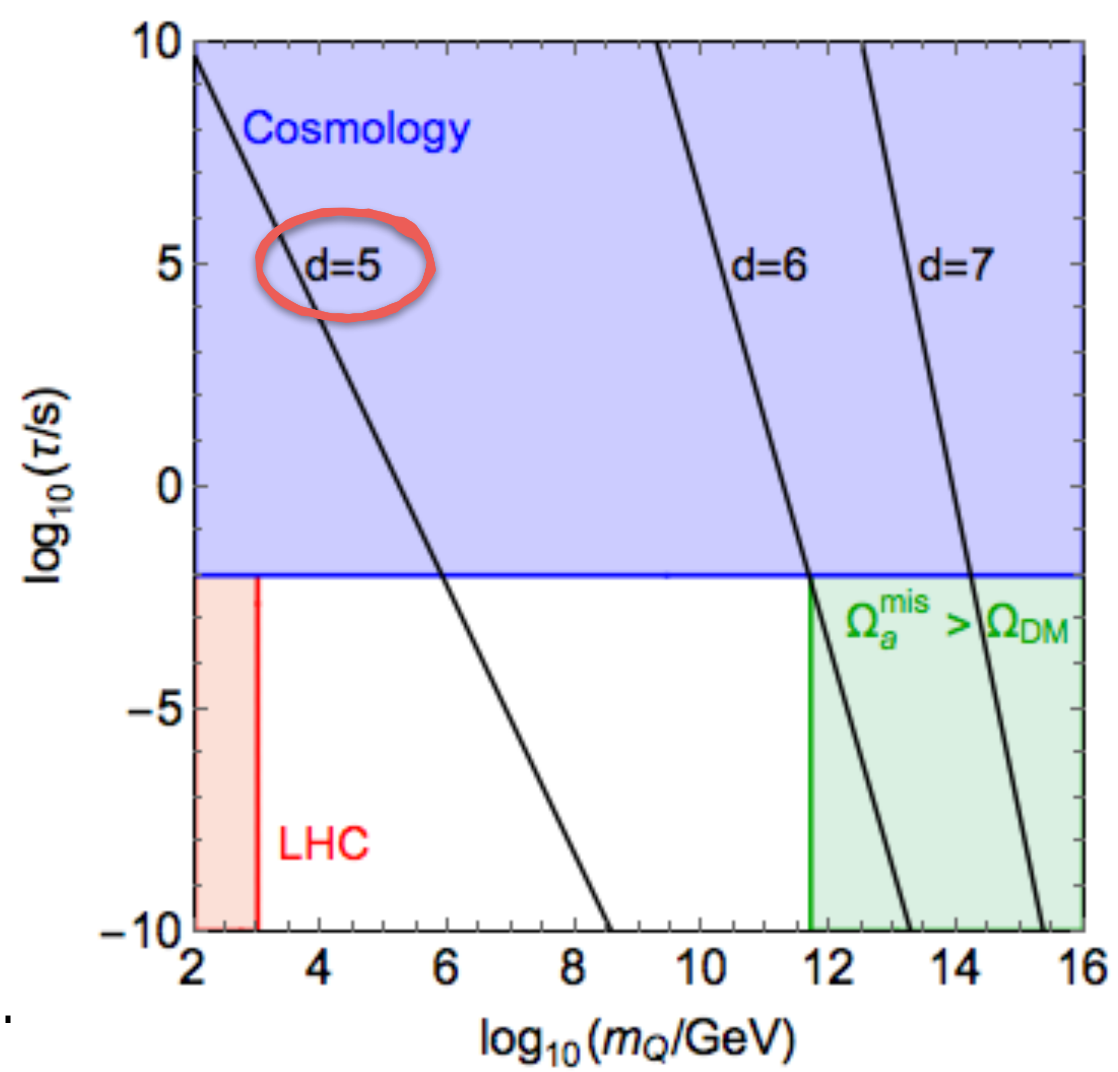
1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s

   - decays via d=4 operators are fast enough

   - decays via effective operators

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

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




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

# Selection criteria

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

   - bound on Q multiplet dimensionality

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

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

[LDL, Gröber, Kamenik, Nardecchia, 1504.00359]