Axions beyond DFSZ/KSVZ

Flavour and Dark Matter workshop
Universität Heidelberg - 26.09.17

Luca Di Luzio

IPPP
Durham University

Based on

Redefining the Axion Window, LDL, F. Mescia, E. Nardi
Phys. Rev. Lett. 118 (2017) no.3, 031801, arXiv:1610.07593 [hep-ph]

Window for preferred axion models, LDL, F. Mescia, E. Nardi
to appear in Phys. Rev. D, arXiv:1705.05370 [hep-ph]

The Nucleophobic Axion, LDL, F. Mescia, E. Nardi, P. Panci, M. Redi, R. Ziegler
In preparation

Outline

- The QCD axion
- Experimental axion searches
- Axion couplings beyond DFZS/KSVZ benchmarks

The strong CP problem

- CP violation in QCD

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

- $\overline{\theta} = \theta - \sum_q \theta_q$ invariant under a chiral transformation ($q \to e^{i\gamma_5 \alpha} q$)

- exp. limit from neutron EDM → $|\overline{\theta}| \lesssim 10^{-10}$ why so small ?

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

- $\overline{\theta} \propto J_{\rm CKM} \log \Lambda_{\rm UV}$ radiatively stable (unlike $m^2_H \ll \Lambda^2_{\rm UV}$) [Ellis, Gaillard NPB 150 (1979)]

- it evades explanations based on environmental selection (unlike $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$)

[Ubaldi, 0811.1599]

The QCD axion

- PQ mechanism [Peccei, Quinn PRL 38 (1977), PRD 16 (1997)]
  - assume a global $U(1)_{PQ}$: i) QCD anomalous and ii) spontaneously broken
  - axion: PGB of $U(1)_{PQ}$ breaking [Weinberg PRL 40 (1978), Wilczek PRL 40 (1978)]

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

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

$\langle \theta_{\text{eff}}(x) \rangle \to 0$ (dynamically, via a QCD-induced axion potential)

Axion models (UV completions)

- PQWW axion

  - axion identified with the phase of the Higgs in a 2HDM ($f_a \sim v$, ruled out long ago)

- Needs $f_a \gg v$ → invisible axion (phase of a SM singlet)

  - DFSZ axion: [Zhitnitsky SJNP 31 (1980), Dine, Fischler, Srednicki PLB 104 (1981)]

    SM quarks charged under PQ (requires 2HDM)

  - KSVZ axion: [Kim PRL 43 (1979), Shifman, Vainshtein, Zakharov NPB 166 (1980)]

    new vector-like quarks charged under PQ

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    SM quarks charged under PQ (requires 2HDM)

  - KSVZ axion:

    new vector-like quarks charged under PQ

→ Here: focus on general DFSZ/KSVZ models

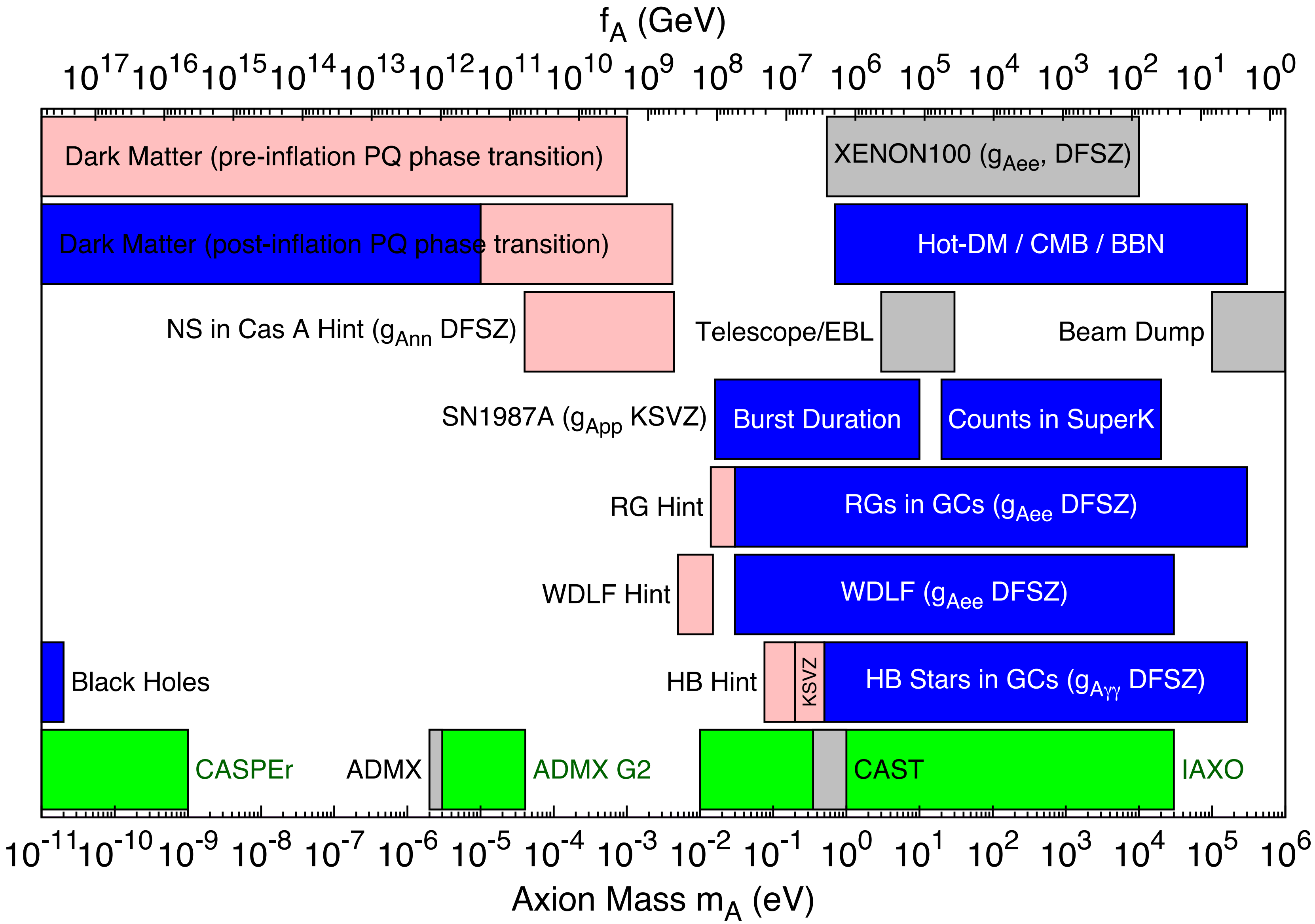
- Other variants: composite axion, heavy axion, axiflavon, etc.

[Kim PRD 31 (1985), …]
[Rubakov JETP 65 (1997), …]
[Calibbi et al. 1612.08040, …]

Axion landscape

- axion mass $m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$

- axion couplings $\sim 1/f_a$



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

Astro/cosmo exclusions

Lab exclusions

Exp. sensitivities

DM explained / Astro Hints

Outburst of exp. proposals

PHYSICAL REVIEW X 4, 021030 (2014)

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

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

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

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

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

PRL 117, 141801 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]

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

Dielectric Haloscopes: A New Way to Detect Axion Dark Matter

Allen Caldwell,[1] Gia Dvali,[1,2,3] Béla Majorovits,[1] Alexander Millar,[1] Georg Raffelt,[1] Javier Redondo,[1,4] Olaf Reimann,[1] Frank Simon,[1] and Frank Steffen[1]
(MADMAX Working Group)

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[‡]
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(Received 16 December 2014; published 7 April 2015)

PHYSICAL REVIEW D 91, 011701(R) (2015)

Search for dark matter axions with the Orpheus experiment

Gray Rybka,[*] Andrew Wagner,[†] Kunal Patel, Robert Percival, and Katleiah Ramos
University of Washington, Seattle, Washington 98195, USA

Aryeh Brill
Yale University, New Haven, Connecticut 06520, USA
(Received 16 November 2014; published 21 January 2015)

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

Outburst of exp. proposals

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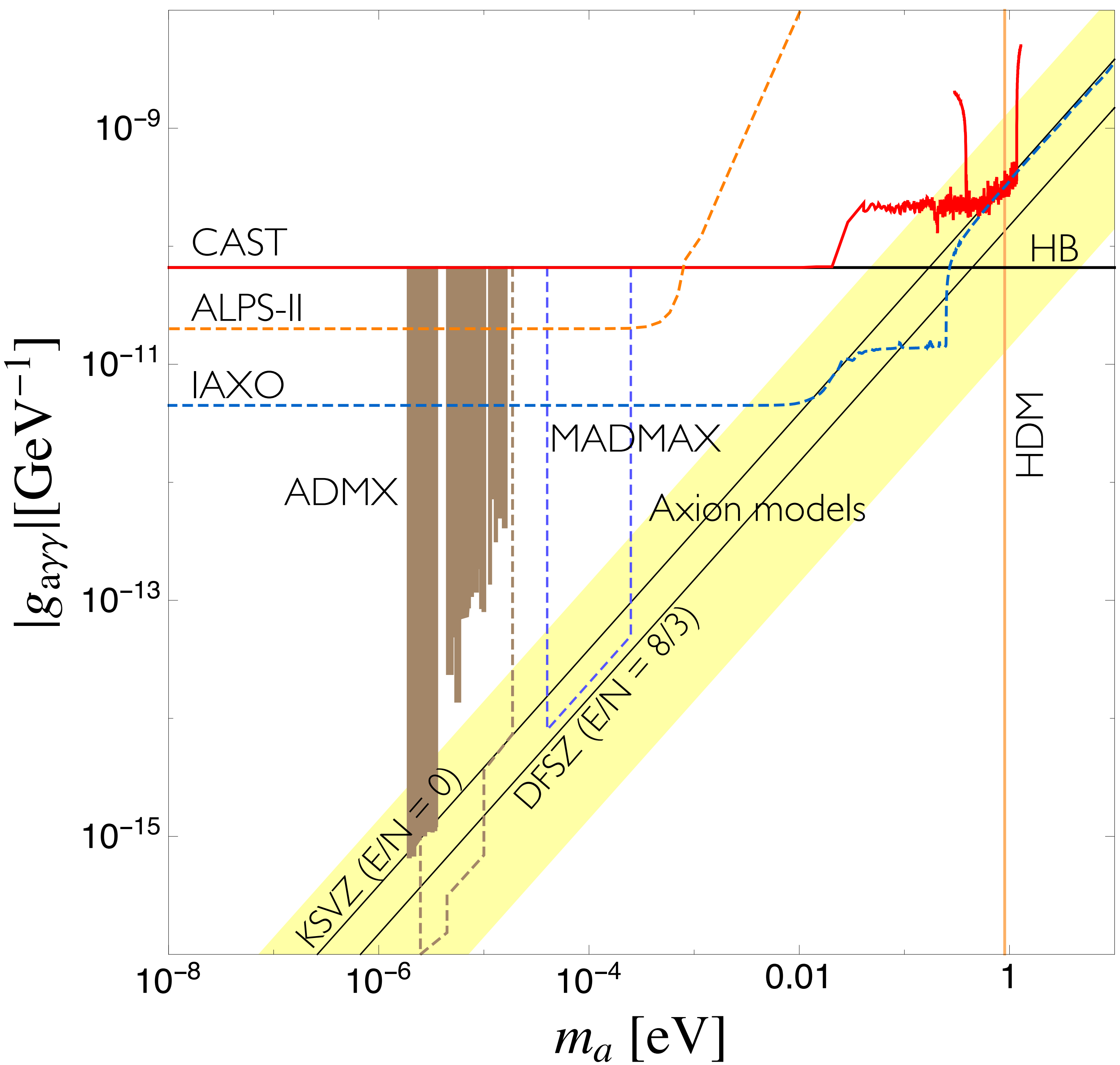
$g_{a\gamma\gamma}$

The "usual" axion window



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

E/N anomaly coefficients, depend on UV completion

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

[Axion band from PDG (since end of 90's). Includes representative KSVZ/DFSZ models e.g. from:
- Kaplan, NPB 260 (1985),
- Cheng, Geng, Ni, PRD 52 (1995),
- Kim, PRD 58 (1998)]

Hadronic axions

- Field content

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

- *PQ charges carried by a vector-like quark Q = Q$_L$ + Q$_R$*

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

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

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

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

} anomaly coeff.

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

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

Hadronic axions

- Field content

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

- Lagrangian

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

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

Q-stability issue

- Symmetry of the kinetic term

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

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

- U(1)$_\text{Q}$ is the Q-baryon number. If exact, Q would be stable

↓

issue with cosmology *[see backup slides]*

Q-stability issue

- 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)$_{\rm Q}$ is the Q-baryon number. If exact, Q would be stable

- Q-decay possible if U(1)$_{\rm Q}$ broken via:

- $\mathcal{L}_{Qq} \neq 0$

- Planck-suppressed op. $\mathcal{L}_{Qq}^{d>4}$

Selection criteria

- We require:

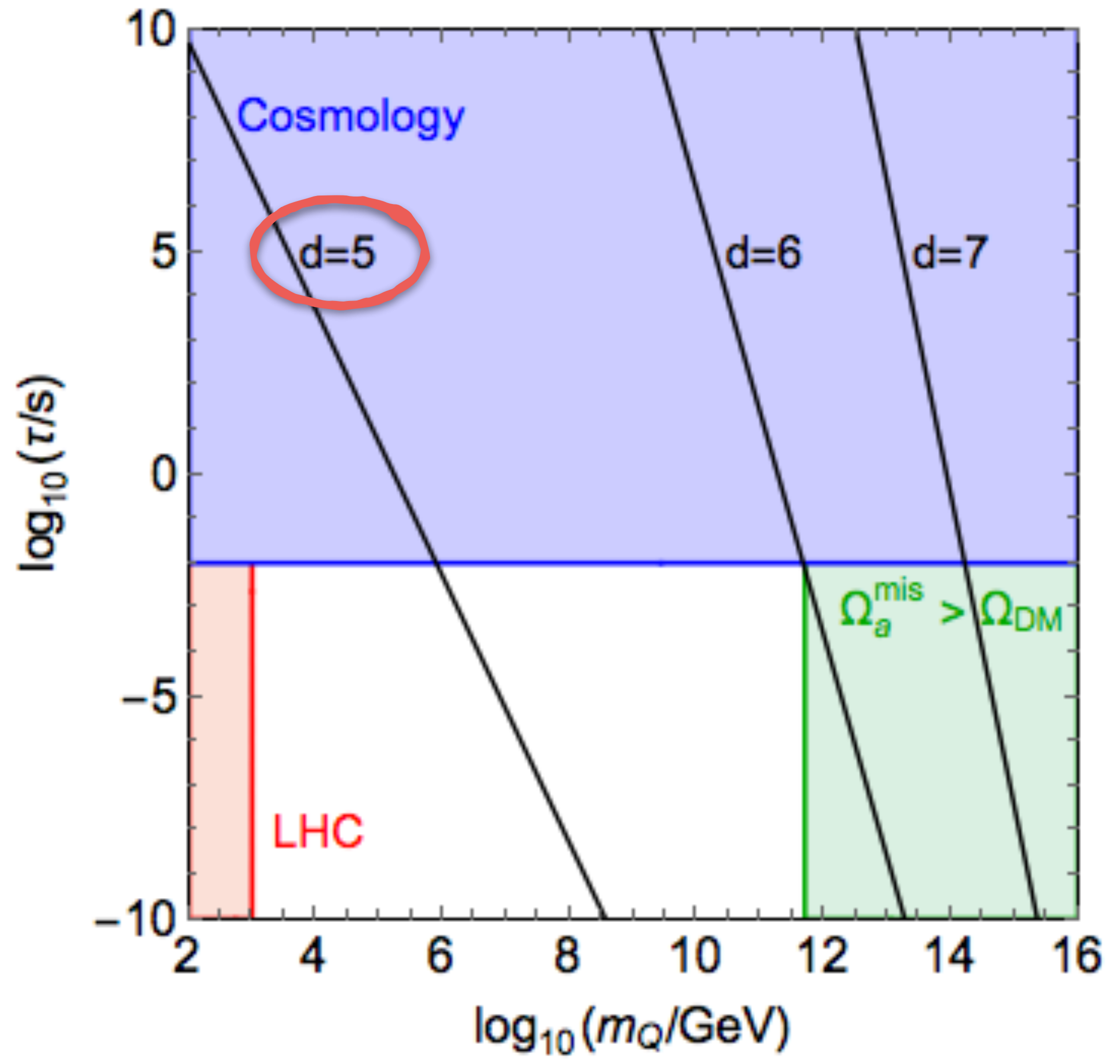
1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s *(applies only to $T_{reheating} > m_Q$)*

- decays via d=4 op. fast enough

- decays via effective op.

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

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



→ Q must allow for d=4 or 5 decay op.'s

Selection criteria

- We require:

1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s *(applies only to $T_{reheating} > m_Q$)*
2. No Landau poles below 10^{18} GeV
3. Absence of domain walls
4. Q-assisted unification

Phenomenologically preferred Q's

- Only 15 Q's survive to conditions 1. and 2.

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

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

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

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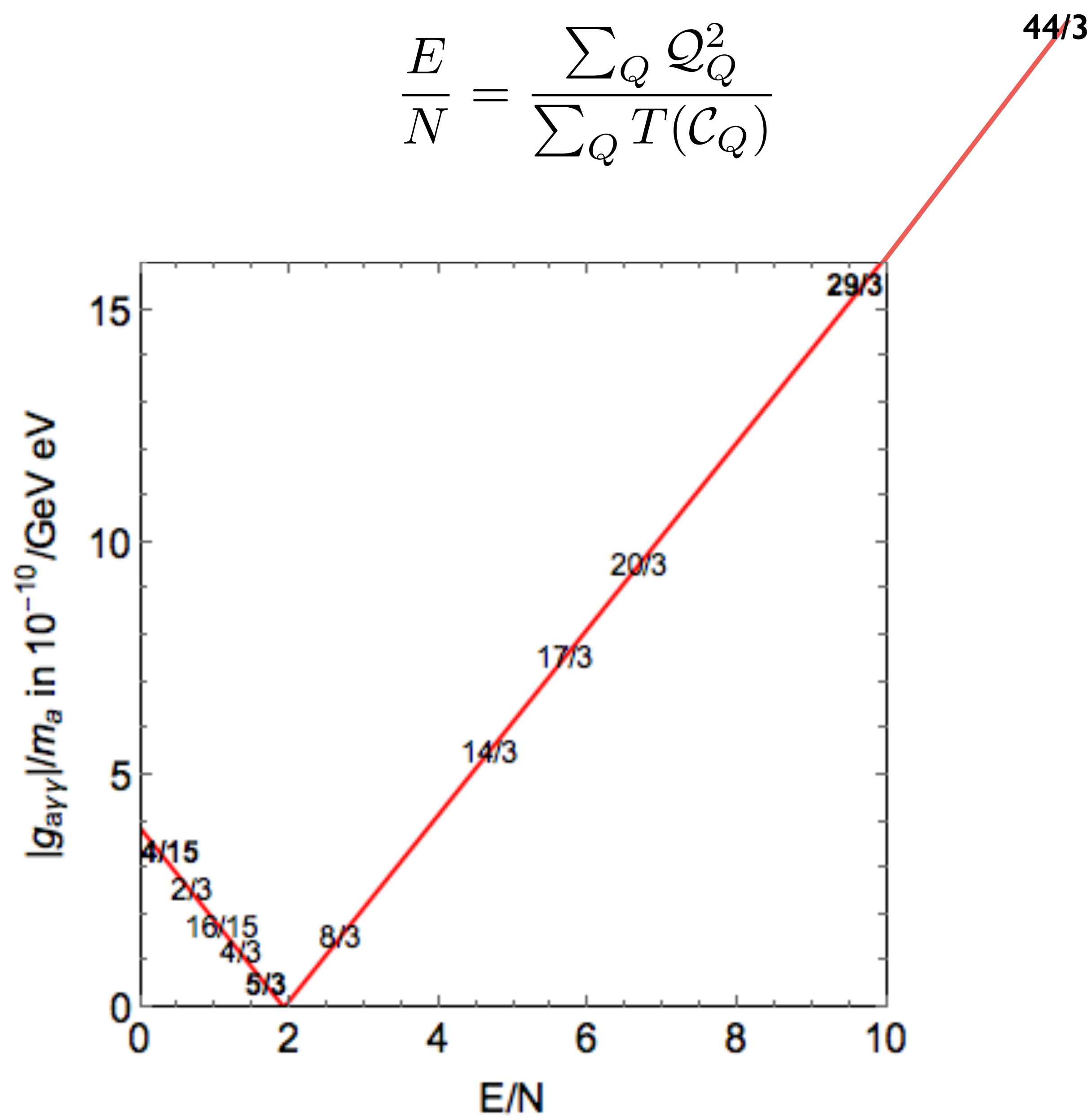
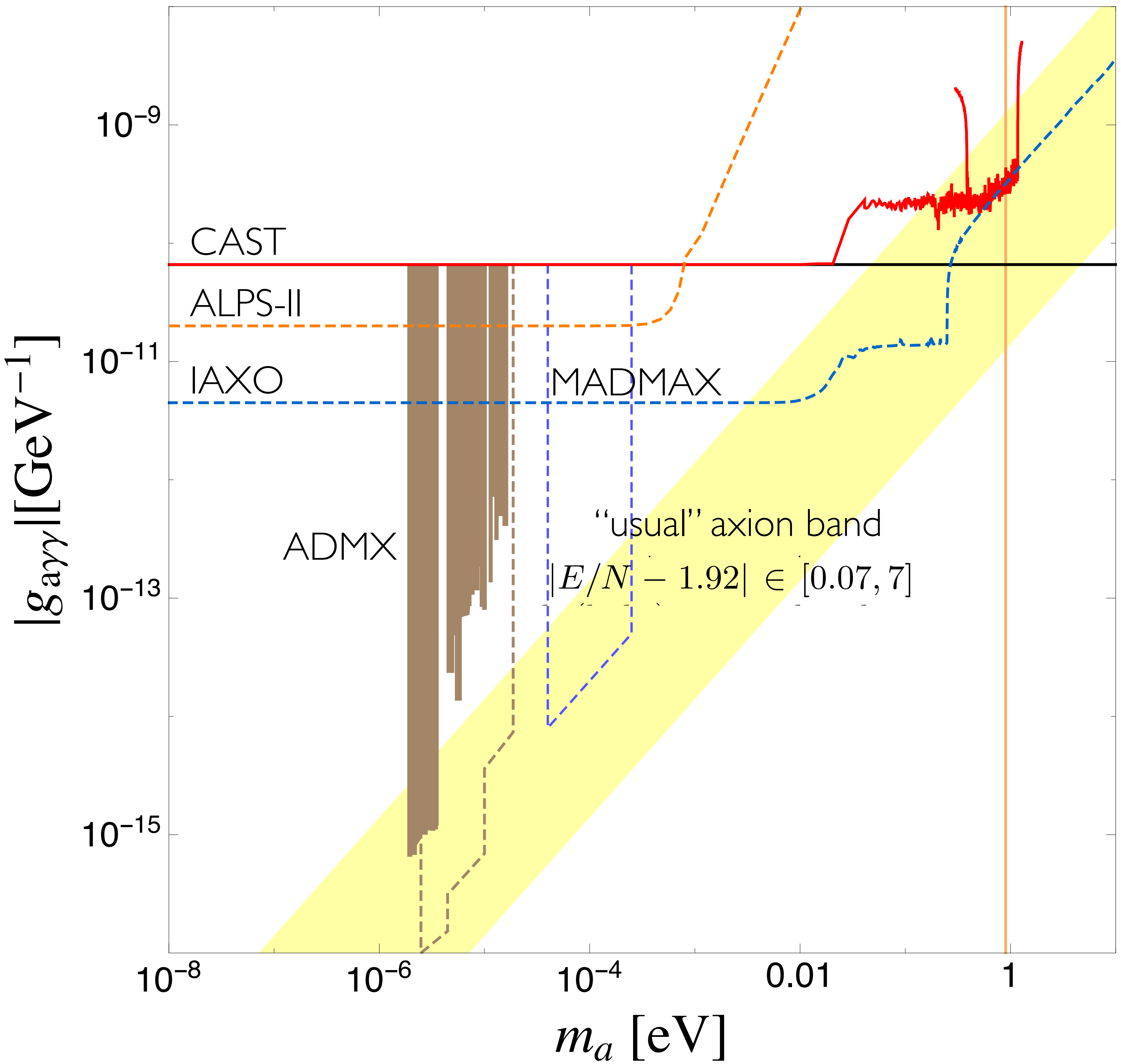
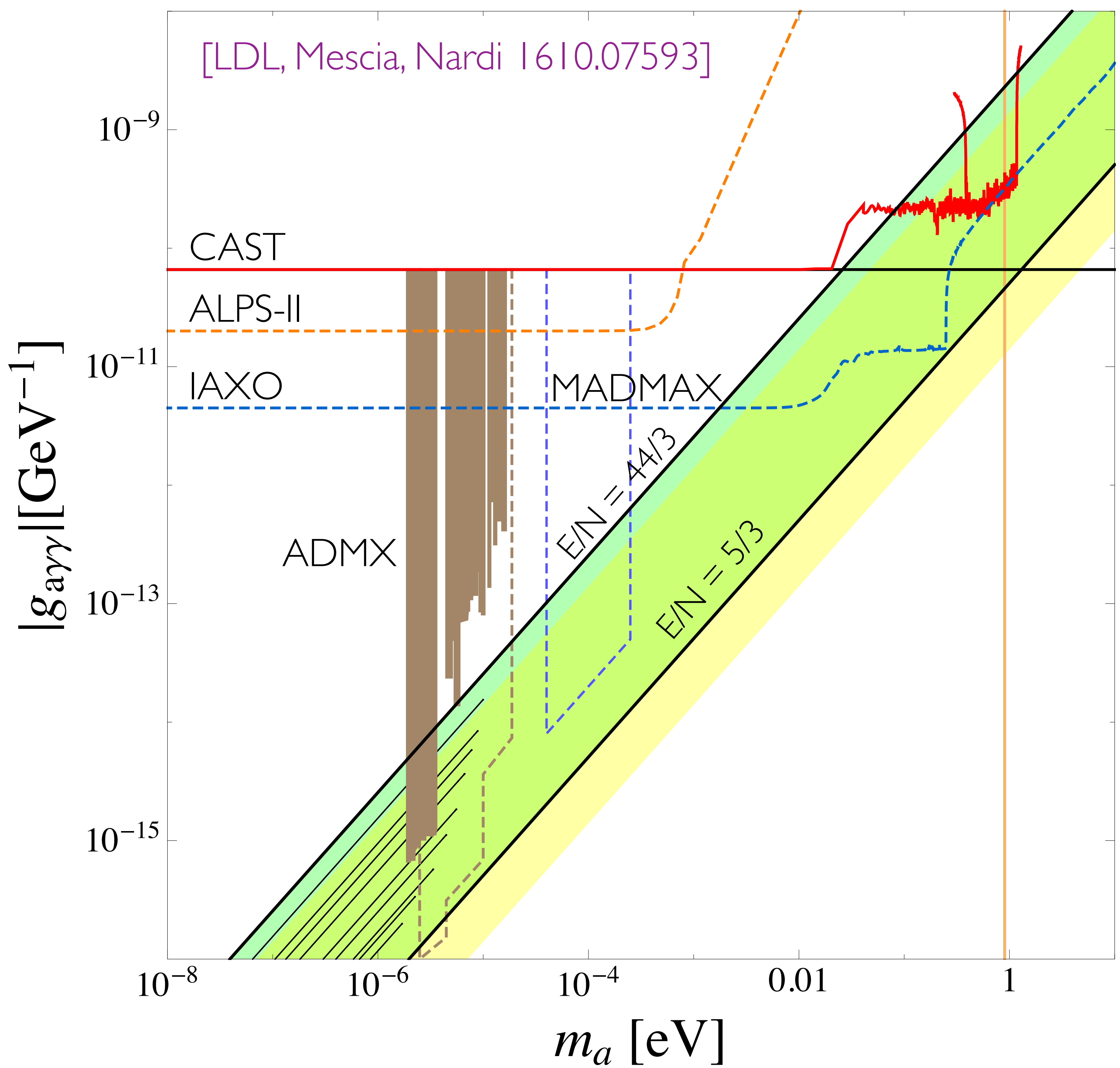


Redefining the axion window



Redefining the axion window



More Q's

- What happens for $N_Q > 1$?

  - combined anomaly factor for $R_Q^1 + R_Q^2 + \dots$: $\frac{E_c}{N_c} = \frac{E_1 + E_2 + \dots}{N_1 + N_2 + \dots}$

- Strongest coupling (compatible with LP criterium)

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

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

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

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

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

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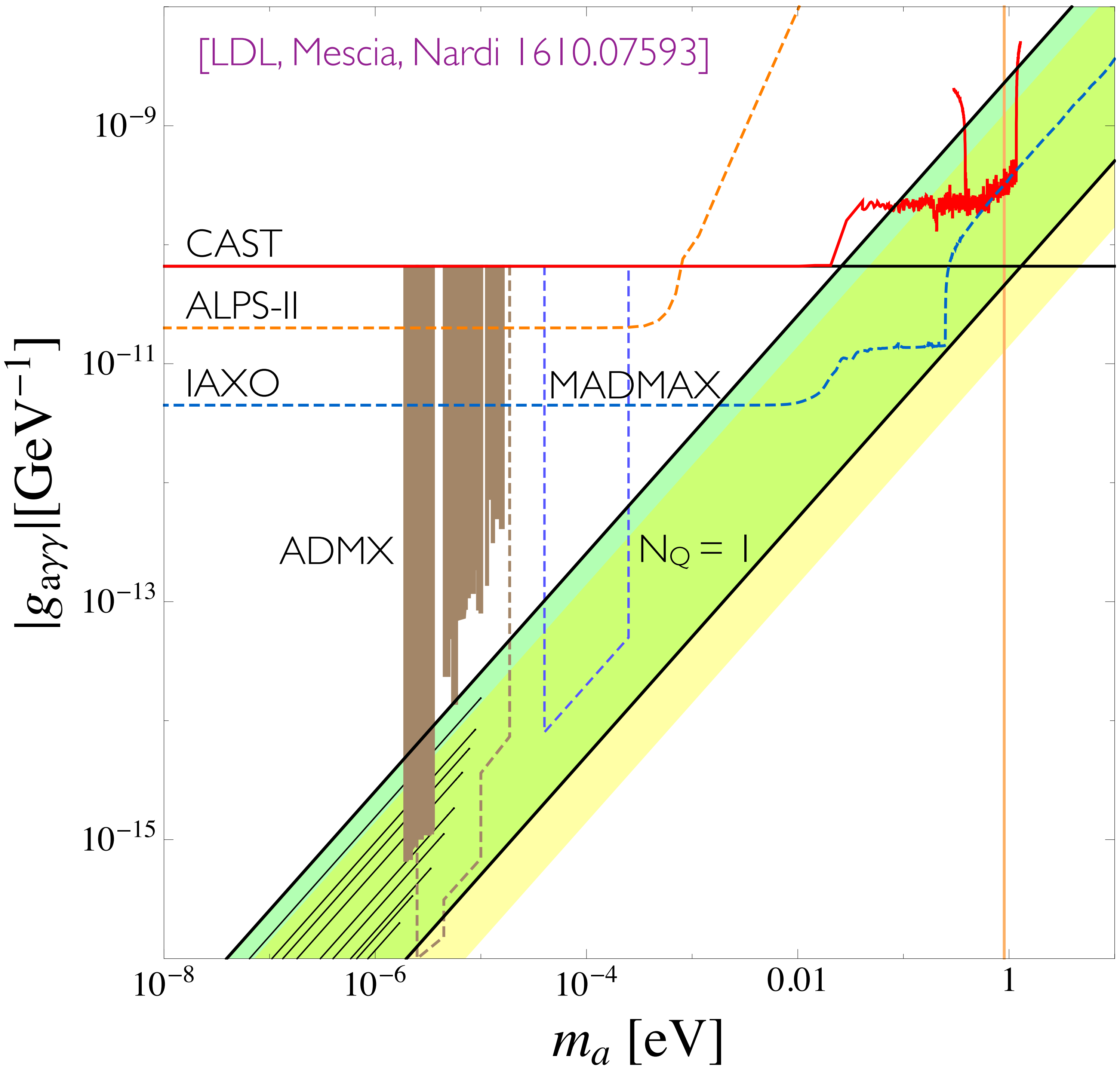
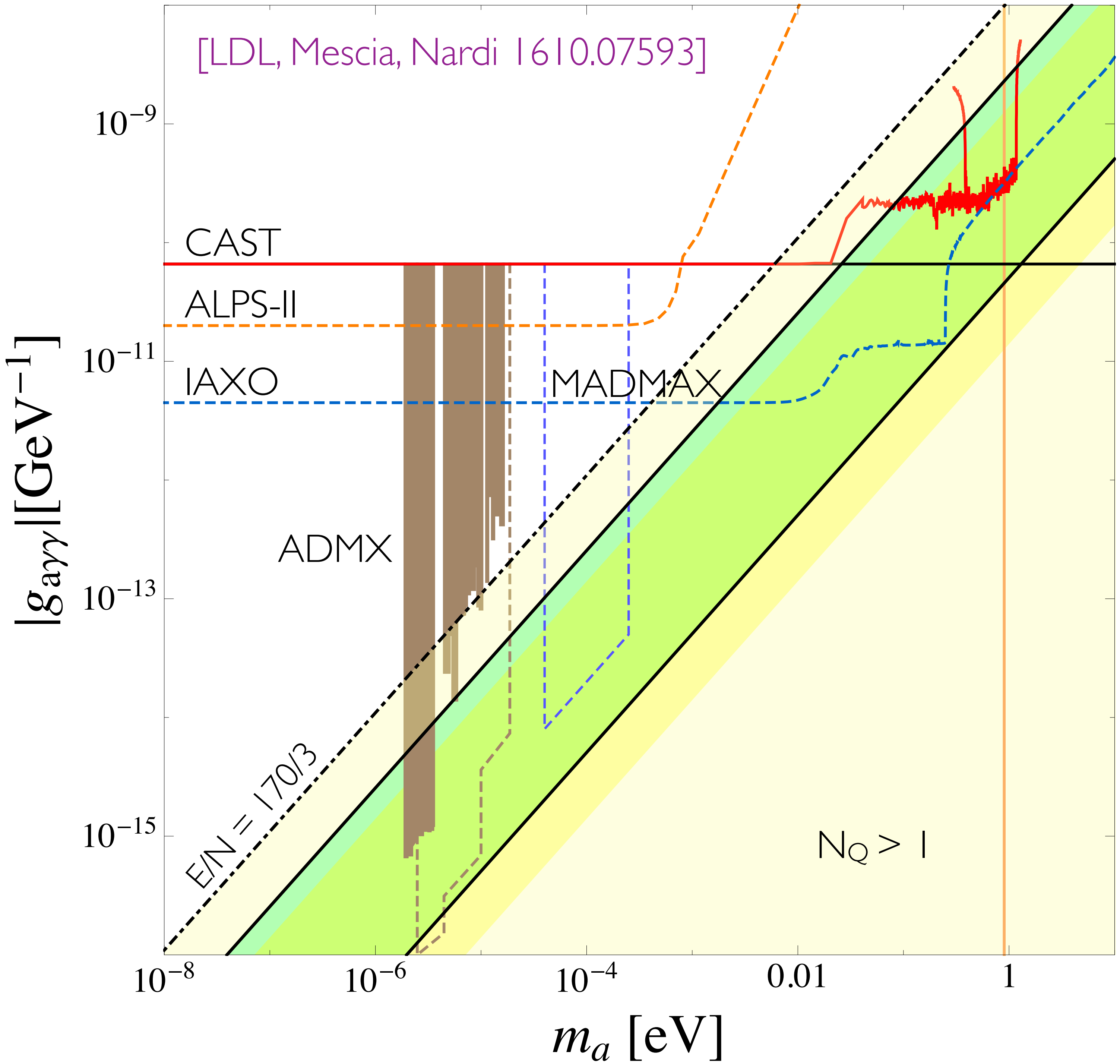
"such a cancellation is immoral, but not unnatural" [D. B. Kaplan, (1985)]

More Q's



[LDL, Mescia, Nardi 1610.07593]
CAST
ALPS-II
IAXO
MADMAX
ADMX
$N_Q = 1$
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$|g_{a\gamma\gamma}|[\mathrm{GeV}^{-1}]$
10^{-8}
10^{-6}
10^{-4}
0.01
1
m_a [eV]

More Q's



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10^{-8}
10^{-6}
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0.01
1
m_a [eV]

DFSZ-like axions

- Potentially large E/N due to electron PQ charge

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

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

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

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

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*

DFSZ-like axions

- 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 2 or 3 Higgs doublets, DFSZ remains within $N_Q = 1$ KSVZ window

- $n_H = 2$

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

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

- $n_H = 3$

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

DFSZ-like axions

- Potentially large E/N due to electron PQ charge

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

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- With 2 or 3 Higgs doublets, DFSZ remains within N_Q = 1 KSVZ window

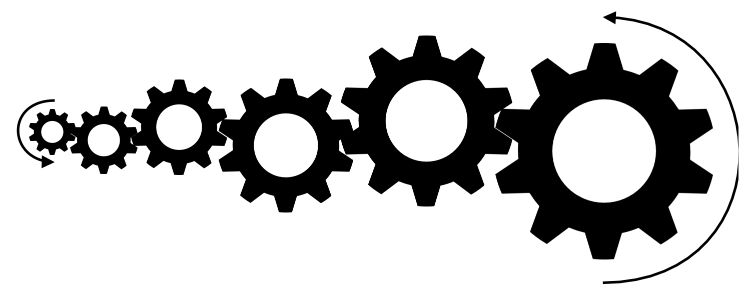
- Clockwork-like scenarios allow to boost E/N

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

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

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

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



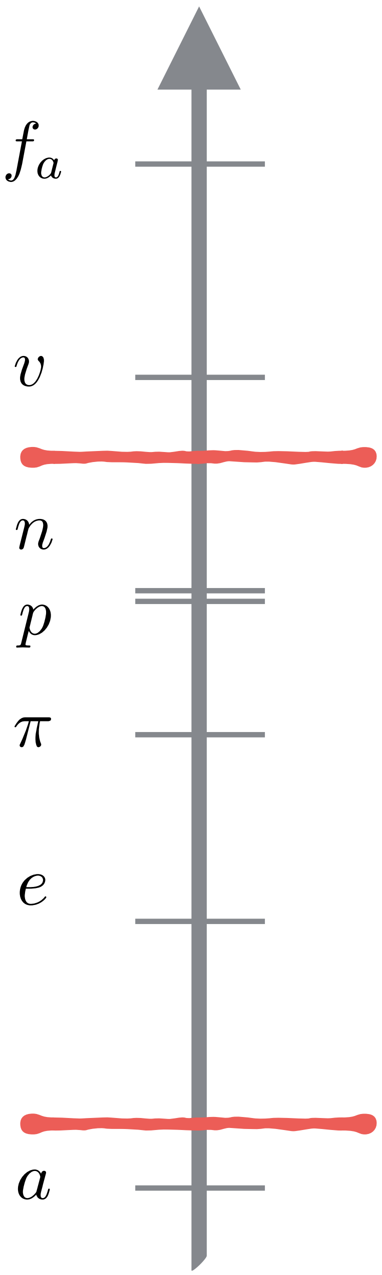
$$E/N \sim 2^n$$

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

Axion couplings to matter

- Axion-nucleons couplings

[Kaplan NPB 260 (1985), Srednicki NPB 260 (1985), … Grilli di Cortona et al. 1511.02867]



$$\mathcal{L}_a \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\partial_\mu a}{2f_s} c_q^0 \overline{q}\gamma^\mu\gamma_5 q$$

$c_q^0 = 0$ (KSVZ)

$c^0_{u,c,t} = \frac{1}{3}\sin^2\beta = \frac{1}{3} - c^0_{d,s,b}$ (DFSZ)

EFT-1: quarks and gluons

$$\mathcal{L}_N \supset \overline{N} v^\mu D_\mu N + 2 g_A A^i_\mu \overline{N} S^\mu \sigma^i N + 2 g_0^{u+d} \hat{A}^{u+d}_\mu \overline{N} S^\mu N$$

$A^3_\mu = c_{(u-d)/2}\,\frac{\partial_\mu a}{2f_a}$ (iso-vector)

$\hat{A}^{u+d}_\mu = c_{(u+d)/2}\,\frac{\partial_\mu a}{2f_a}$ (iso-scalar)

EFT-II: non-relativistic nucleons (Galilean group + isospin)

Axion couplings to matter

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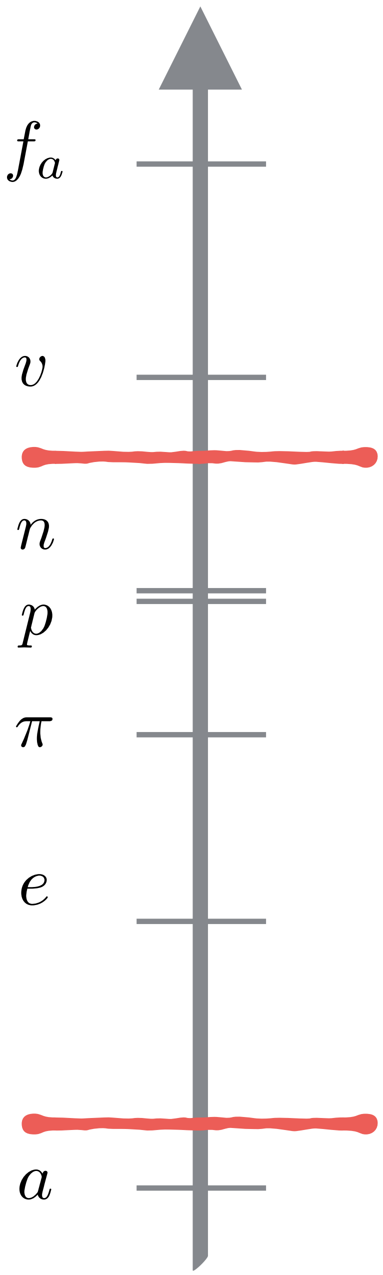

Matching over a single-nucleon state

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

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

$$g_A = \Delta u - \Delta d = 1.2723(23) \quad \text{(β-decay)}$$

$$g_0^{u+d} = \Delta u + \Delta d = 0.541(50) \quad \text{(Lattice)}$$

$$\frac{\partial_\mu a}{2 f_a} c_N \overline{N} \gamma^\mu \gamma_5 N$$

$$\begin{aligned} c_p = {} & -0.47(3) + 0.88(3)c_u^0 - 0.39(2)c_d^0 - 0.038(5)c_s^0 \\ & - 0.012(5)c_c^0 - 0.009(2)c_b^0 - 0.0035(4)c_t^0 \,, \\ c_n = {} & -0.02(3) + 0.88(3)c_d^0 - 0.39(2)c_u^0 - 0.038(5)c_s^0 \\ & - 0.012(5)c_c^0 - 0.009(2)c_b^0 - 0.0035(4)c_t^0 \,, \end{aligned}$$

model-independent

The Nucleophobic axion

- Is it possible to suppress simultaneously both c_p and c_n ?

$$\frac{\partial_\mu a}{2f_a} c_N \overline{N} \gamma^\mu \gamma_5 N$$

$$c_p + c_n = \left(c_u^0 + c_d^0 - 1\right)(\Delta u + \Delta d) \qquad \text{(2-flavours, no-running)}$$

$$c_p - c_n = (c_u^0 - c_d^0 + \underbrace{\frac{m_u - m_d}{m_u + m_d}}_{-0.35})(\Delta u - \Delta d)$$

- KSVZ: $c^0_{u,d} = 0$

- DFSZ: $c_u^0 + c_d^0 = \frac{1}{N_f}$ $\left(N_f = 3\right)$

→ <u>theorem</u>: nucleophobia requires non-universal DFSZ

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→ <u>theorem</u>: nucleophobia requires non-universal DFSZ

- Some applications: *[work in progress]*

- Relaxation of SN bound (improved sensitivity @ IAXO)

- Low $f_a \sim 10^8$ GeV can help in explaining stellar cooling anomalies [Giannotti et al. 1708.02111]

- Interplay with flavour observables (e.g. $K \to \pi a$)

Conclusions

- The QCD axion is a well-motivated BSM scenario

  - solves the strong CP problem

  - provides an excellent DM candidate

- Healthy experimental program

  - experiments are entering now the preferred window for the QCD axion

  - outburst of ideas in the recent years

→ Take home message: *axion couplings might sizeably deviate from the standard DFSZ/KSVZ benchmarks (relevant when confronting exp. sensitivities and bounds)*

Backup slides

Pre-inflationary scenarios

- What about $T_{reheating} < m_Q$?

  - condition on Q decay is relaxed, but Landau pole still applies

- $m_Q \sim y_Q f_a < 5 \cdot 10^{11}$ GeV

  - $N_Q = 1$: $(E/N)_{max(pre)} = 2.5\ (E/N)_{max(post)}$

  - $N_Q > 1$: $(E/N)_{max(pre)} = 1.2\ (E/N)_{max(post)}$

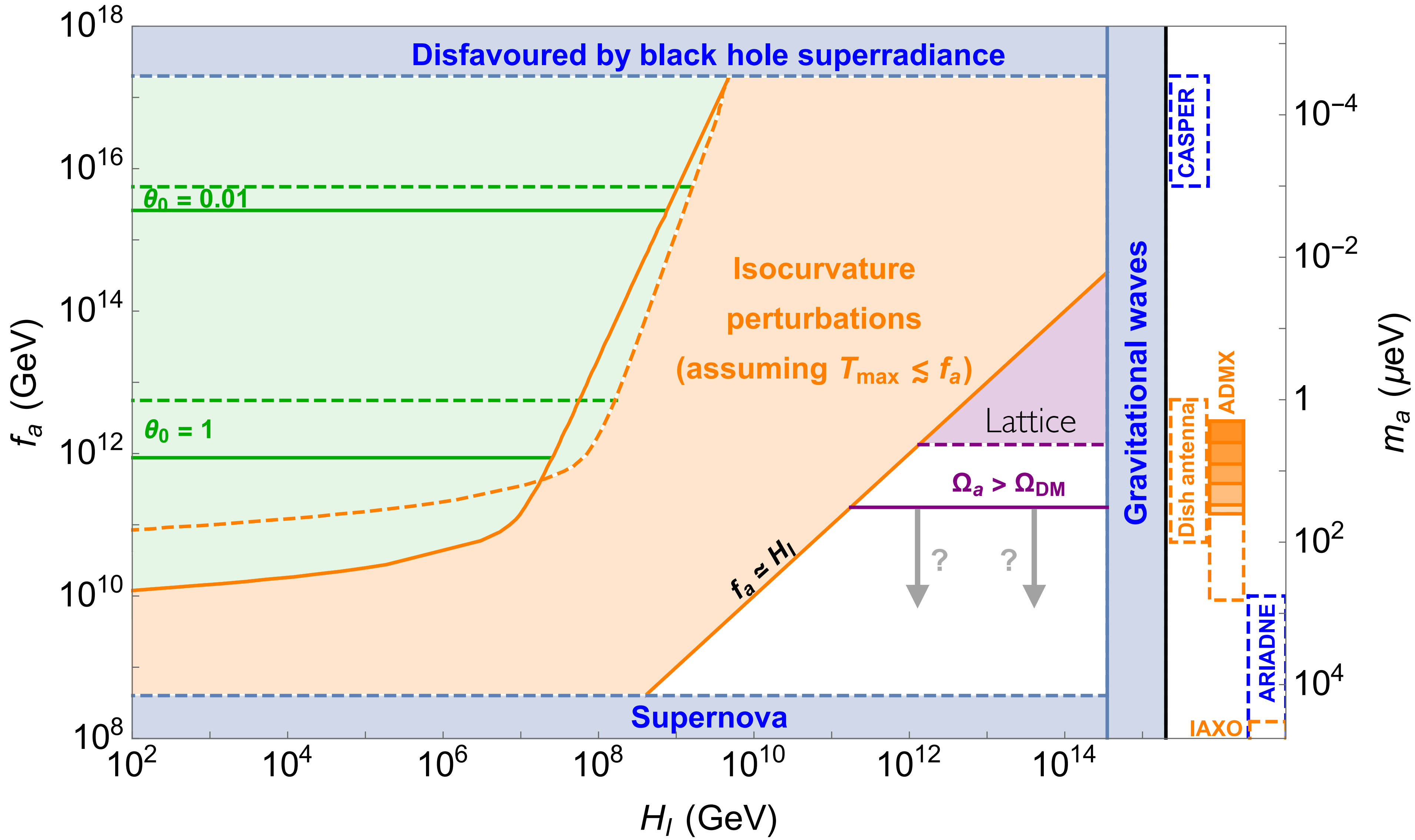
  → *axion-photon coupling well-described by post-inflationary axion window*

- $f_a \gg 5 \cdot 10^{11}$ GeV (requires $\theta_0 \ll 1$)

  → *arbitrarily large axion-photon coupling at the cost of tuning initial mis. condition*

Relic abundance from mis. mechanism

- Upper limit from recent lattice QCD calculations: $f_a \lesssim 10^{11\div12}$ GeV for $\theta_0 = \mathcal{O}(1)$

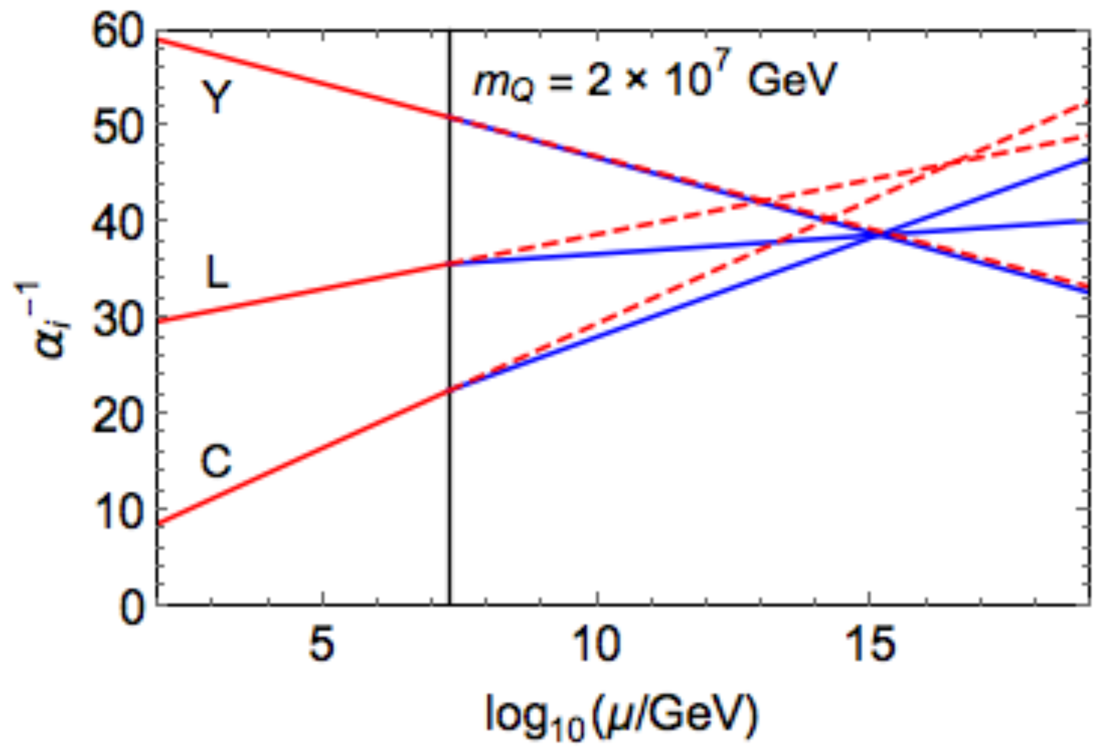


[Grilli di Cortona et al. 1511.02867]

Unificaxion

- Some Q's might improve gauge coupling unification [Giudice, Rattazzi, Strumia, 1204.5465]

  - out of all our 15 cases, just one works well: Q ~ (3, 2, 1/6)



Unificaxion

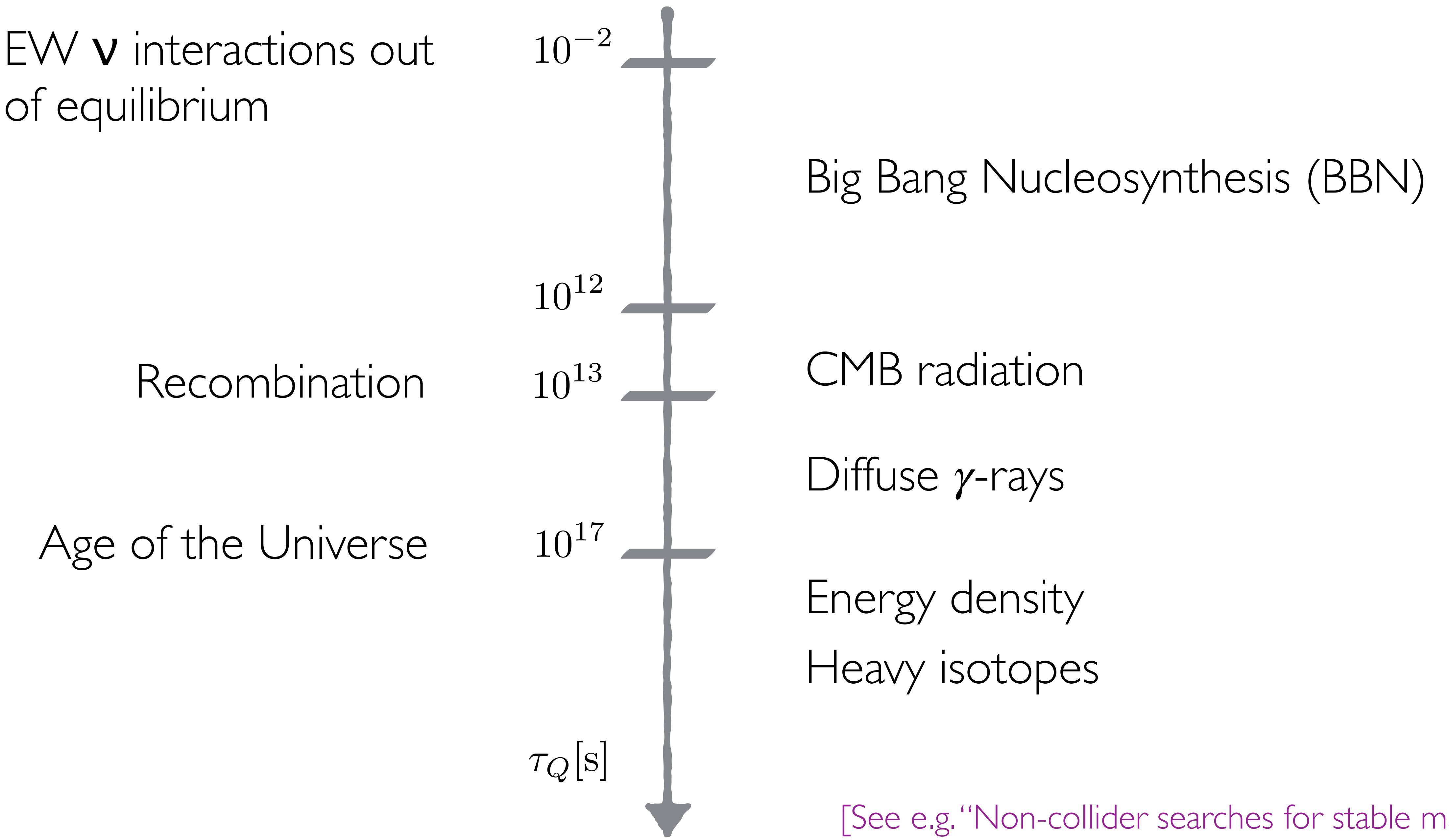
- Some Q's might improve gauge coupling unification [Giudice, Rattazzi, Strumia, 1204.5465]
  - out of all our 15 cases, just one works well: Q ~ (3, 2, 1/6)
- Conceiving a UV model remains, however, a non-trivial challenge
  - $Q \in \psi_{\text{GUT}}$
  - $m_Q \lesssim f_a \ll M_{\text{GUT}}$

$$[\text{PQ}, \text{GUT}] = 0 \quad \longrightarrow \quad m_{\psi_{\text{GUT}}} = \mathcal{O}(f_a)$$

  - a complete GUT multiplet doesn't help !

Cosmological constraints

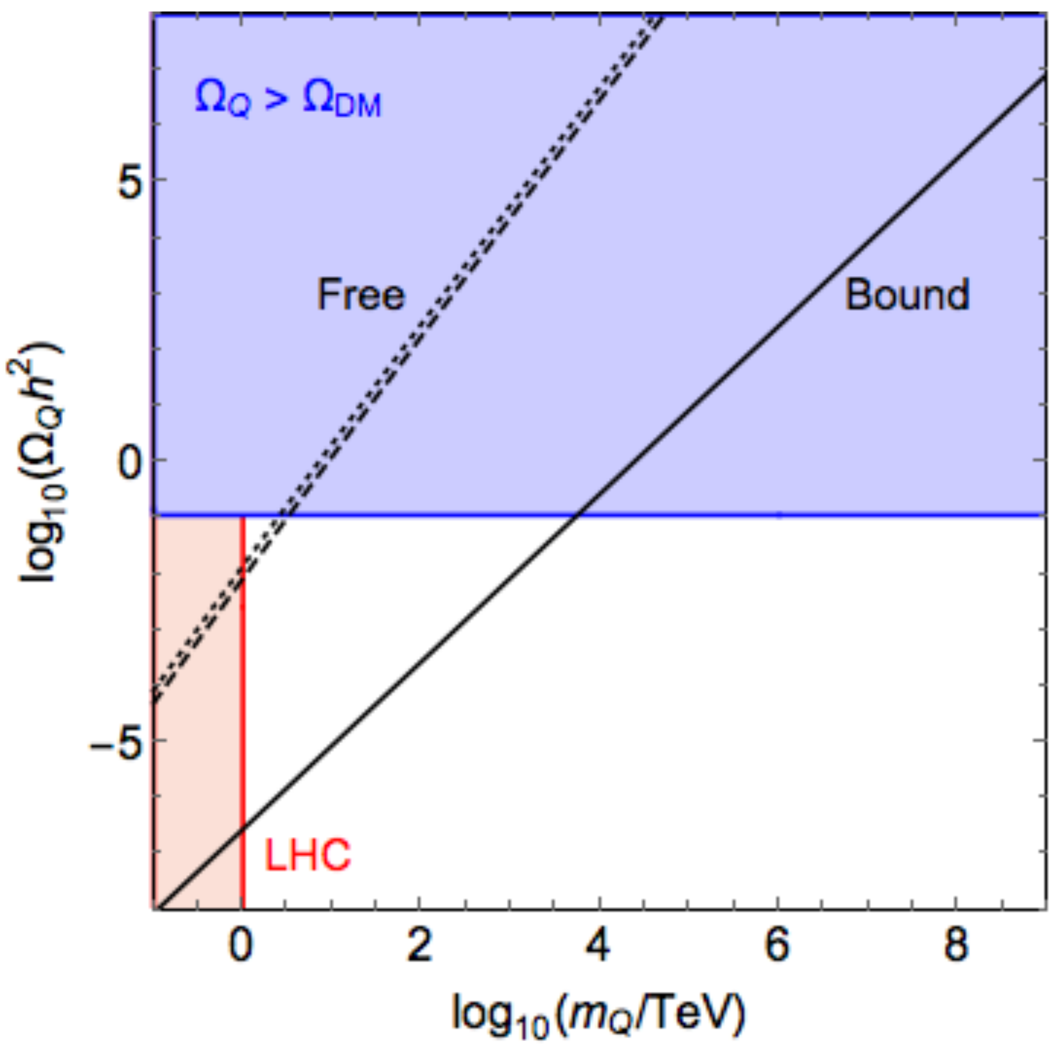
- Long-lived and strongly-interacting particles are severely bounded by cosmology



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

Heavy Q's relic density

- $T_{reheating} > m_Q$ (thermal distribution of Q's as initial condition)
- Reliable estimates on Ω_Q remain an open issue, but Q abundances too high



[Rich literature: e.g.
Dover, Gaisser, Steigman PRL 42 (1979),
Nardi, Roulet PLB 245 (1990),
Arvanitaki et al., hep-ph/0504210,
Kang, Luty, Nasri, hep-ph/0611322,
Jacob, Nussinov, 0712.2681
Kusakabe, Takesako, 1112.0860]

Axion coupling to photons

- Axion effective Lagrangian

See e.g. 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

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

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

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{1}{4}\, a\, g_{a\gamma\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} - \bar{q}_L M_a q_R + h.c.$$

$$M_a = e^{i\frac{a}{2f_a}Q_a} M_q\, e^{i\frac{a}{2f_a}Q_a}, \qquad M_q = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}, \qquad Q = \begin{pmatrix} \frac{2}{3} & 0 \\ 0 & -\frac{1}{3} \end{pmatrix}$$

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

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