

The Axion Rush

Università di Napoli - 15.06.18

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Outline

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

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{q} (iD - \cancel{m}_q e^{i\theta_q}) q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a \quad (\tilde{G}_{\mu\nu}^a = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} G^{a,\rho\sigma})$$

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- \tilde{G} is a total derivative (no effects in PT)
 - its physical relevance related to non-trivial QCD vacuum structure (**BPST instantons**)

[Belavin, Polyakov, Schwarz, Tyupkin PLB59 (1975)]

$$Z = \int \delta G \delta q \delta \bar{q} e^{-S_{\theta=0} - i\theta \frac{\alpha_s}{8\pi} \int G \tilde{G}} \sim e^{-\frac{8\pi}{g_s^2}} e^{i\theta} \rightarrow e^{-\frac{8\pi}{g_s^2}} \cos \theta$$

- dominated by “large instantons” of size $\rho \sim 1/\Lambda_{\text{QCD}}$ (semi-classical approx. breaks down)
- chiral Lagrangian for quantitative statements

The strong CP problem

- CP violation in QCD

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{q} (iD - \cancel{m}_q e^{i\theta_q}) q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

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

$$q \rightarrow e^{i\gamma_5 \alpha} q \quad \xrightarrow{\hspace{2cm}} \quad \left\{ \begin{array}{l} \theta_q \rightarrow \theta_q + 2\alpha \\ \theta \rightarrow \theta + 2\alpha \end{array} \right. \quad \xrightarrow{\hspace{2cm}} \quad \bar{\theta} = \theta - \theta_q \quad \text{invariant}$$

latter transformation e.g. from non-invariance of path integral measure (chiral anomaly)

$$\mathcal{D}q \mathcal{D}\bar{q} \rightarrow \exp \left(-i\alpha \int d^4x \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a \right) \mathcal{D}q \mathcal{D}\bar{q}$$

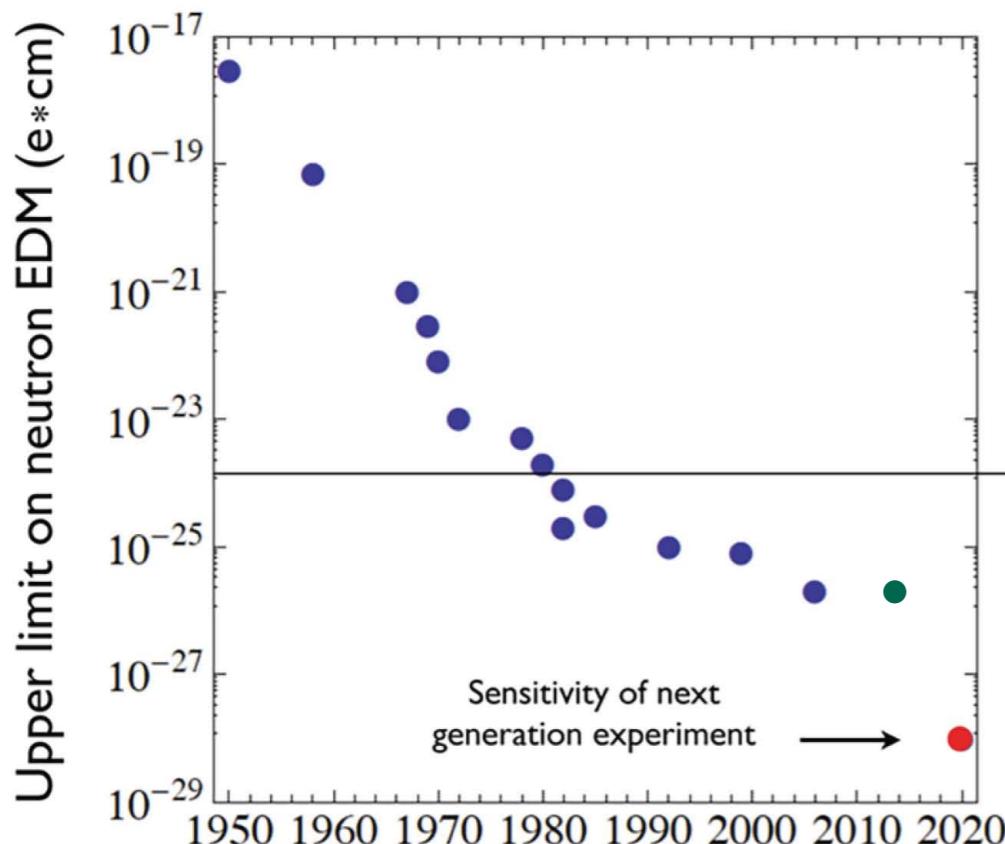
[Fujikawa, PRL 42 (1979)]

The strong CP problem

- CP violation in QCD

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{q} (iD - m_q e^{i\theta_q}) q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

- Non-zero neutron EDM



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

[Baluni PRD 19 (1979),
Crewther et al. PLB 88 (1979)]



$$|\bar{\theta}| \lesssim 10^{-10}$$

why so small ?

“Small value” problems

- Strong CP: qualitatively different from other small value problems of the SM
 - $\bar{\theta} \propto J_{\text{CKM}} \log \Lambda_{\text{UV}}$ radiatively stable (unlike $m_H^2 \ll \Lambda_{\text{UV}}^2$) [Ellis, Gaillard NPB 150 (1979)]
[Khriplovich, Vainshtein NPB 414 (1994)]
 - it evades explanations based on environmental selection (unlike $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$) nuclear physics and BBN practically unaffected for $\bar{\theta} \lesssim 10^{-2}$ [Ubaldi, 0811.1599]

 - theoretically motivated to look for an explanation of strong CP *independently* of other small value problems

Solutions

- Do we really understand QCD vacuum structure ?

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

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

$$m_{\eta'} \approx 958 \text{ MeV}$$

$$m_{\eta'} < \sqrt{3} m_\pi$$

[Weinberg sum-rule for GB]

- topological susceptibility $\neq 0$ for eta' mass not to vanish in the chiral limit

$$m_{\eta'}^2 = \frac{6 \mathcal{X}}{f_\pi^2} + \mathcal{O}(m_q) + \mathcal{O}\left(\frac{1}{N_c^2}\right)$$

[Witten NPB156 (1979),
Veneziano NPB159 (1979)]

$$\mathcal{X} = -i \int d^4x \langle 0 | T Q(x) Q(0) | 0 \rangle \quad Q \equiv \frac{1}{32\pi^2} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a$$

Solutions

- Do we really understand QCD vacuum structure ?
- A massless quark would make the theta term unphysical (excluded at 20σ by Lattice)

$$m_u^{\text{UV}} \neq m_u^{\chi\text{PT}}$$

[Kaplan-Manohar ambiguity]

Solutions

- Do we really understand QCD vacuum structure ?
- A massless quark would make the theta term unphysical (excluded at 20σ by Lattice)
- Spontaneous CP violation
 - $\bar{\theta} = 0$ 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

[Nelson PLB 136 (1983), PLB 143 (1984)]

[Barr PRD 30 (1984)]

Solutions

- Do we really understand QCD vacuum structure ?
- A massless quark would make the theta term unphysical (excluded at 20σ by Lattice)
- Spontaneous CP violation
- PQ mechanism [Peccei, Quinn PRL 38 (1977), PRD 16 (1997)]
 - assume a global $U(1)_{\text{PQ}}$: i) QCD anomalous and ii) spontaneously broken
 - axion: PGB of $U(1)_{\text{PQ}}$ breaking [Weinberg PRL 40 (1978), Wilczek PRL 40 (1978)]

$$a(x) \rightarrow a(x) + \delta\alpha f_a$$

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

$\theta_{\text{eff}}(x)$  affects QCD vacuum energy

θ -dependence of QCD vacuum

- Ground state energy in Euclidean V_4

[Vafa, Witten PRL 53 (1984)]

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



$$E(0) \leq E(\theta_{\text{eff}})$$

- theta term dynamically relaxed to zero on the axion ground state

$$\langle a(x) \rangle = -\bar{\theta} f_a$$

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

- aGGtilde not a total derivative (effects in PT)

- dim=5 op. requires a UV completion

Axion models (UV completions)

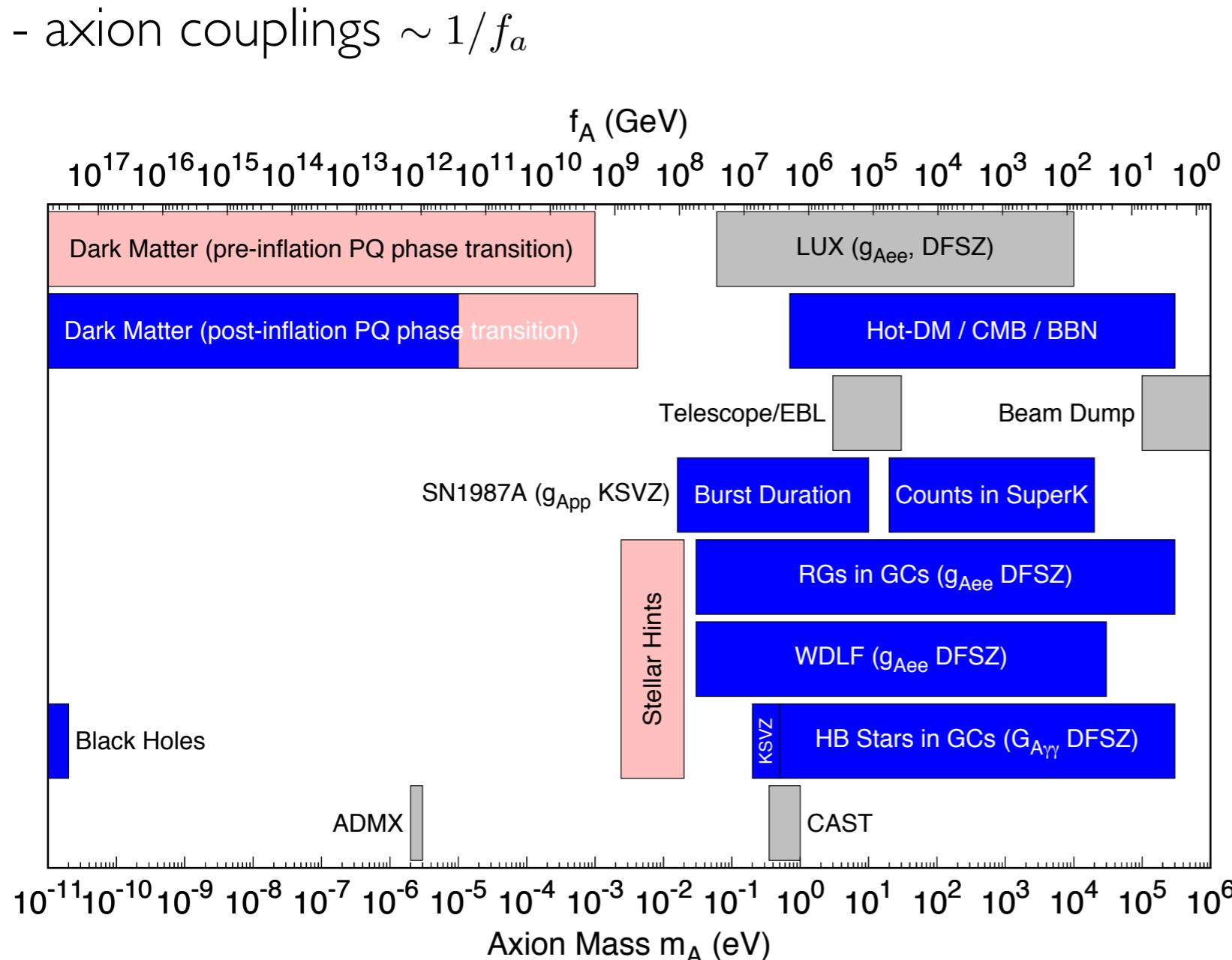
- PQWW axion
 - axion identified with the phase of the Higgs in a 2HDM ($f_a \sim v$, ruled out long ago)
- Needs $f_a \gg v$  invisible axion (phase of a SM singlet)
 - DFSZ axion: [Zhitnitsky SJNP 31 (1980), Dine, Fischler, Srednicki PLB 104 (1981)]
SM quarks charged under PQ (requires 2HDM)
 - KSVZ axion: [Kim PRL 43 (1979), Shifman, Vainshtein, Zakharov NPB 166 (1980)]
new vector-like quarks charged under PQ



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

Axion landscape

- axion mass $m_a \sim \Lambda_{\text{QCD}}^2/f_a \simeq 6 \text{ meV} \left(\frac{10^9 \text{ GeV}}{f_a} \right)$



[Ringwald, Rosenberg, Rybka,
Particle Data Group (2017)]

Lab exclusions

Astro/cosmo exclusions

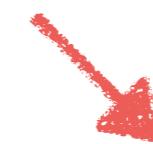
DM explained / Astro Hints

Axions as Dark Matter

Heavy particle vs. light scalar field

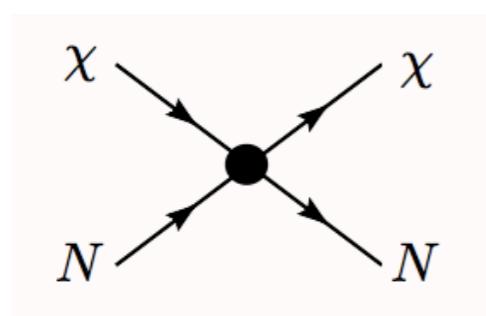
(WIMPs)

(Axions)



search for single particle scattering

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

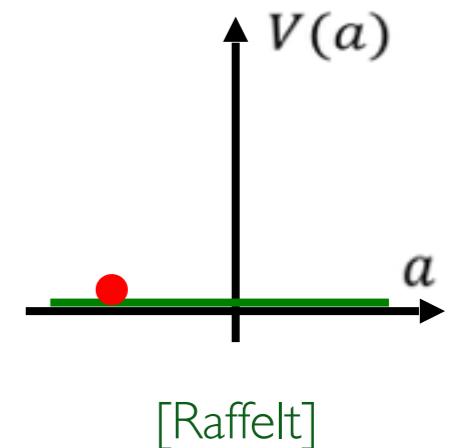


(e.o.m. in a FRW background)

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

Axions as Dark Matter

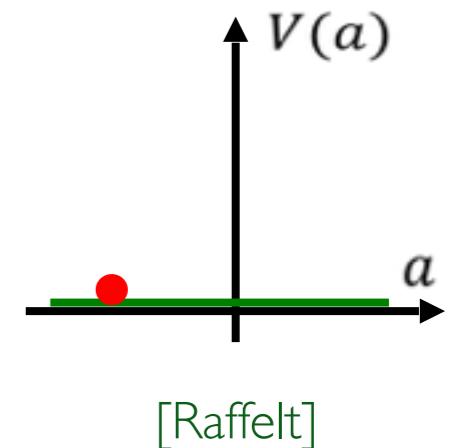
- $T \sim f_a$ (very early Universe)
 - $U(1)_{\text{PQ}}$ spontaneously broken, but axion massless
 - axion field sits at $a_0 = \theta_0 f_a$



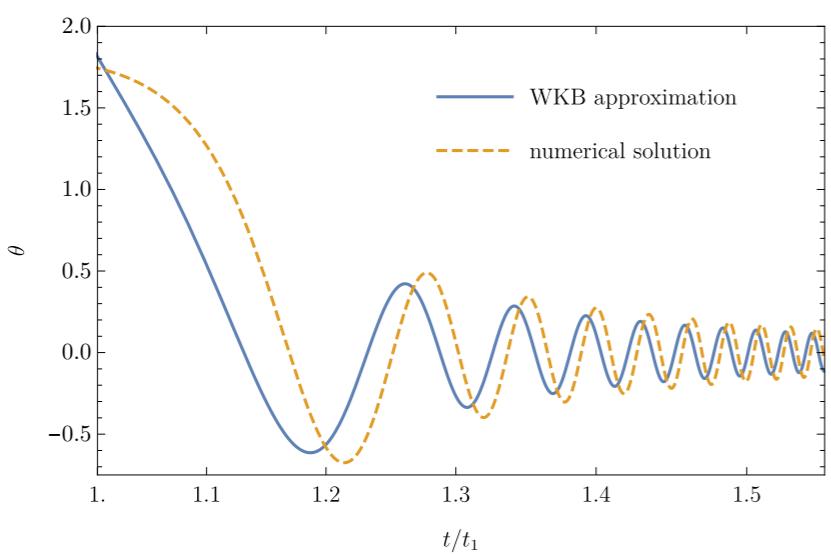
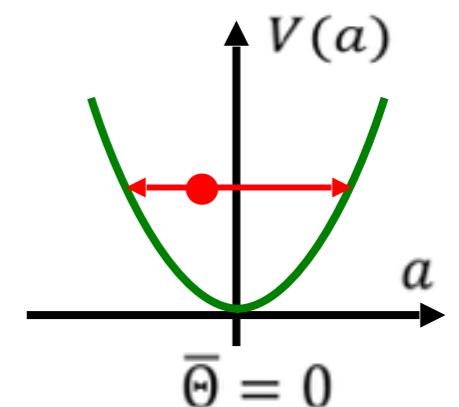
$$\ddot{a} + 3H\dot{a} + m_a^2(T) \cancel{f_a} \sin\left(\frac{a}{f_a}\right) = 0$$

Axions as Dark Matter

- $T \sim f_a$ (very early Universe)
 - $U(1)_{\text{PQ}}$ spontaneously broken, but axion massless
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- $T \sim 1 \text{ GeV}$ ($H \sim 10^{-9} \text{ eV}$)
 - axion mass turns on due to non-perturbative QCD effects
 - field starts oscillating when $m_a \gtrsim 3H$

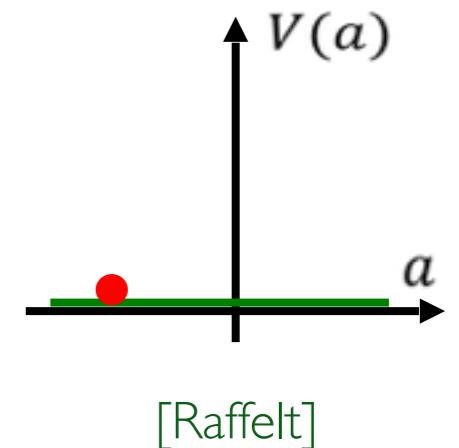


[J. Stadler]

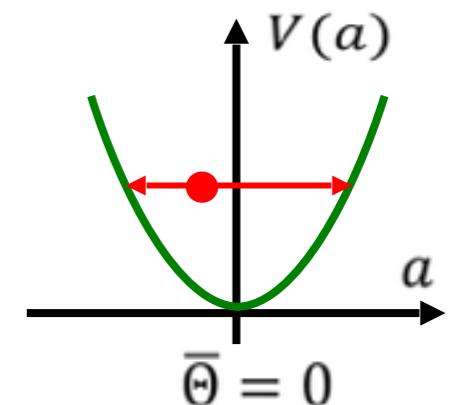
~~$$\ddot{a} + 3H\dot{a} + m_a^2(T)f_a \sin\left(\frac{a}{f_a}\right) = 0$$~~

Axions as Dark Matter

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- Energy stored in axion oscillations behaves as Cold DM

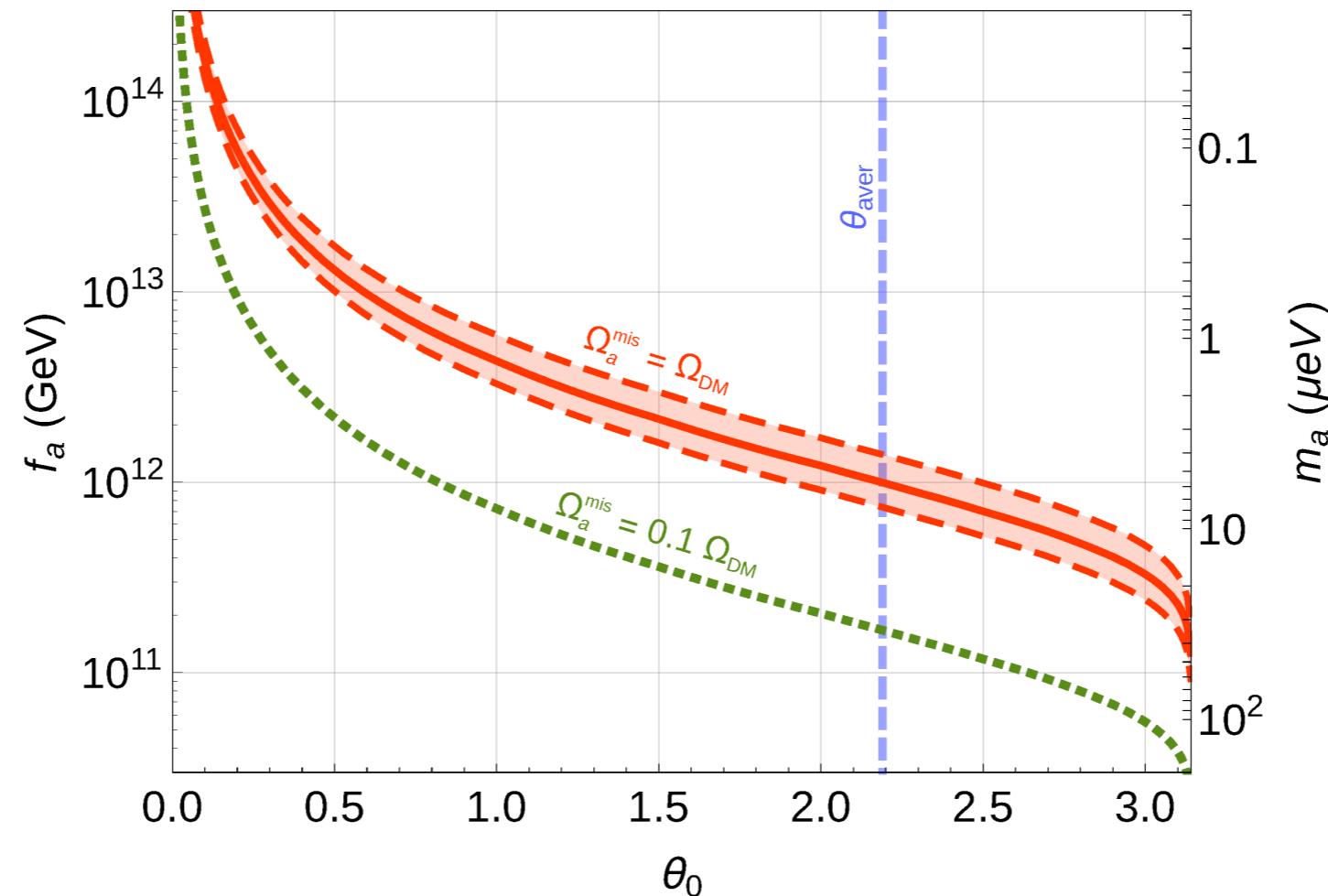
[Preskill, Wise, Wilczek PLB 120 (1983),
Abott, Sikivie PLB 120 (1983),
Dine, Fischler PLB 120 (1983)]

$$a(t) = a_0 \cos(m_a t) \quad \longrightarrow \quad \text{depends on the initial condition: } \underline{\text{misalignment mechanism}}$$

Relic abundance

- Upper limit from lattice QCD calculations: $f_a \lesssim 10^{11 \div 12} \text{ GeV}$ for $\theta_0 = \mathcal{O}(1)$

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



Relic abundance

- Upper limit from lattice QCD calculations: $f_a \lesssim 10^{11 \div 12} \text{ GeV}$ for $\theta_0 = \mathcal{O}(1)$

<i>post-inflationary PQ breaking</i>	<i>pre-inflationary PQ breaking</i>
$f_a < \max\{H_I, T_R\}$	$f_a > \max\{H_I, T_R\}$
θ_0 averaged over several Universe patches $\langle \theta_0 \rangle = \pi/\sqrt{3}$ $\Omega_a^{\text{mis}} < \Omega_{\text{DM}}$  $f_a \lesssim 5 \cdot 10^{11} \text{ GeV}$ + contribution from topological defects	θ_0 constant misalignment contribution unique, but depends on initial conditions $f_a \gg 10^{12} \text{ GeV}$ only for $\theta_0 \ll 1$
[See e.g. Ringwald, Saikawa 1512.06436 Gorghetto, Hardy, Villadoro 1806.04677]	

Current limits and search strategies

- Astrophysical bounds [For a collection see e.g. Raffelt, hep-ph/0611350]

- Star evolution

$$g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11} \text{ GeV}^{-1}$$

- White dwarf cooling

$$g_{aee} \lesssim 1.3 \times 10^{-13} \text{ GeV}^{-1}$$

- Supernova SN1987A

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



$$f_a \gtrsim 4 \times 10^8 \text{ GeV}$$

- The translation of the bound on f_a requires the specification of a UV completion
 - e.g. axion-nucleon coupling can be sizeably suppressed in the presence of a generation dependent PQ symmetry (**astrophobic axion**)

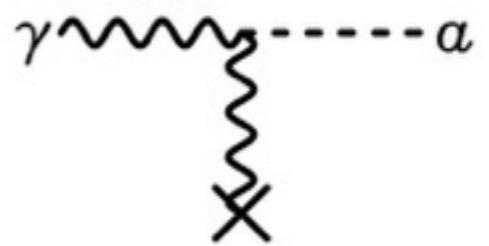
[LDL, Mescia, Nardi, Panci, Ziegler, 1712.04940]

Current limits and search strategies

- Astrophysical bounds [For a collection see e.g. Raffelt, hep-ph/0611350]
- Most laboratory search techniques are sensitive to $g_{a\gamma\gamma}$

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

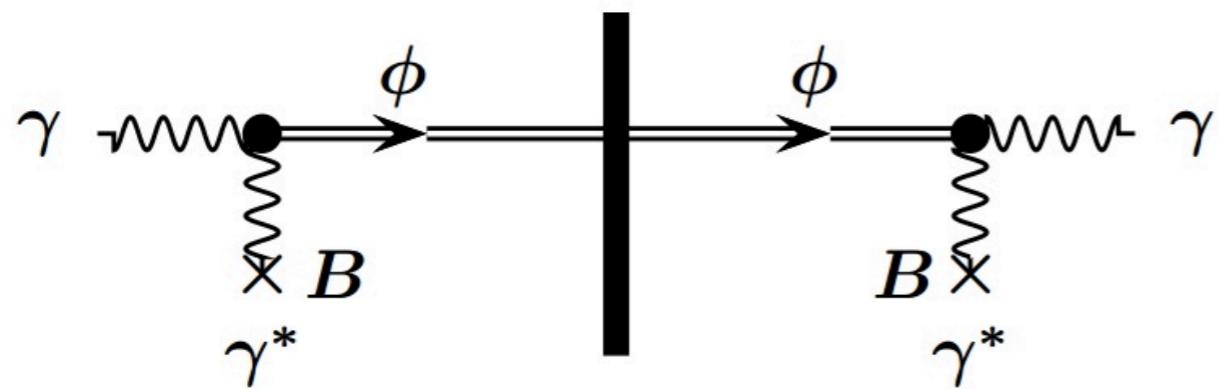
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma\gamma} a \mathbf{F} \cdot \tilde{\mathbf{F}} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



- Light Shining through Walls [See e.g. Redondo, Ringwald hep-ph/10113741]
- Haloscopes (axion Dark Matter) [Sikivie PRL 51 (1983)]
- Helioscopes (axions from the Sun)

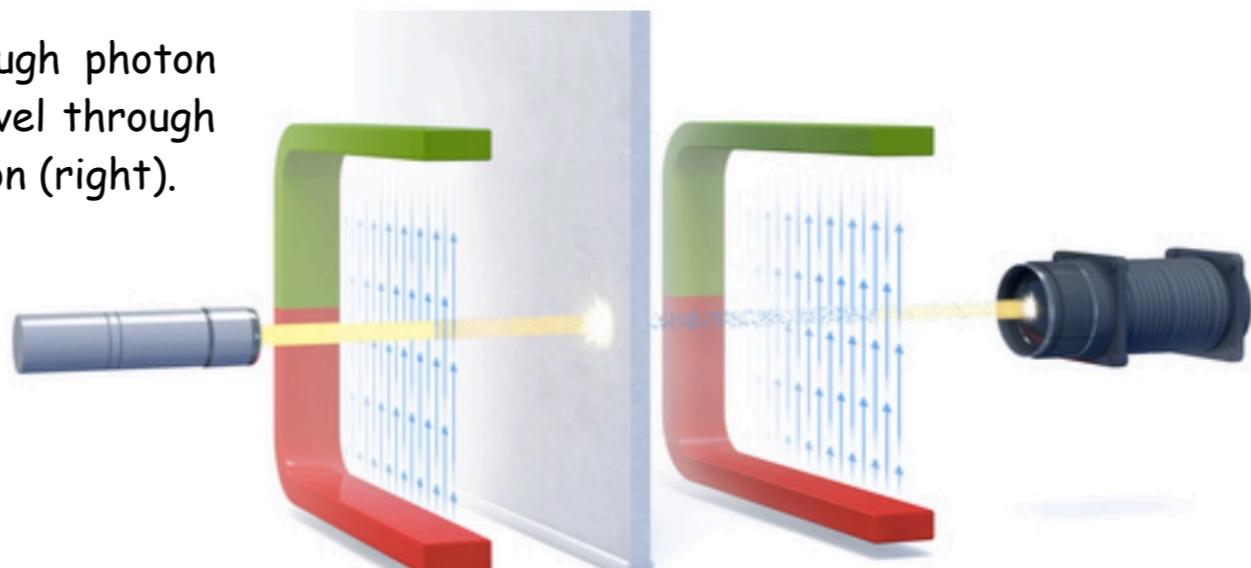
Light Shining through Walls (LSW)

- PVLAS discovery claim (2006)  exp. boost since then !
- Any Light Particle Search (DESY): **ALPS-I** (2007-2010) and **ALPS-II** (2013-...)



Artist view of a light shining through a wall experiment

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



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

Haloscopes

- Look for DM axions with a microwave resonant cavity
 - power of axions converting into photons in an EM cavity

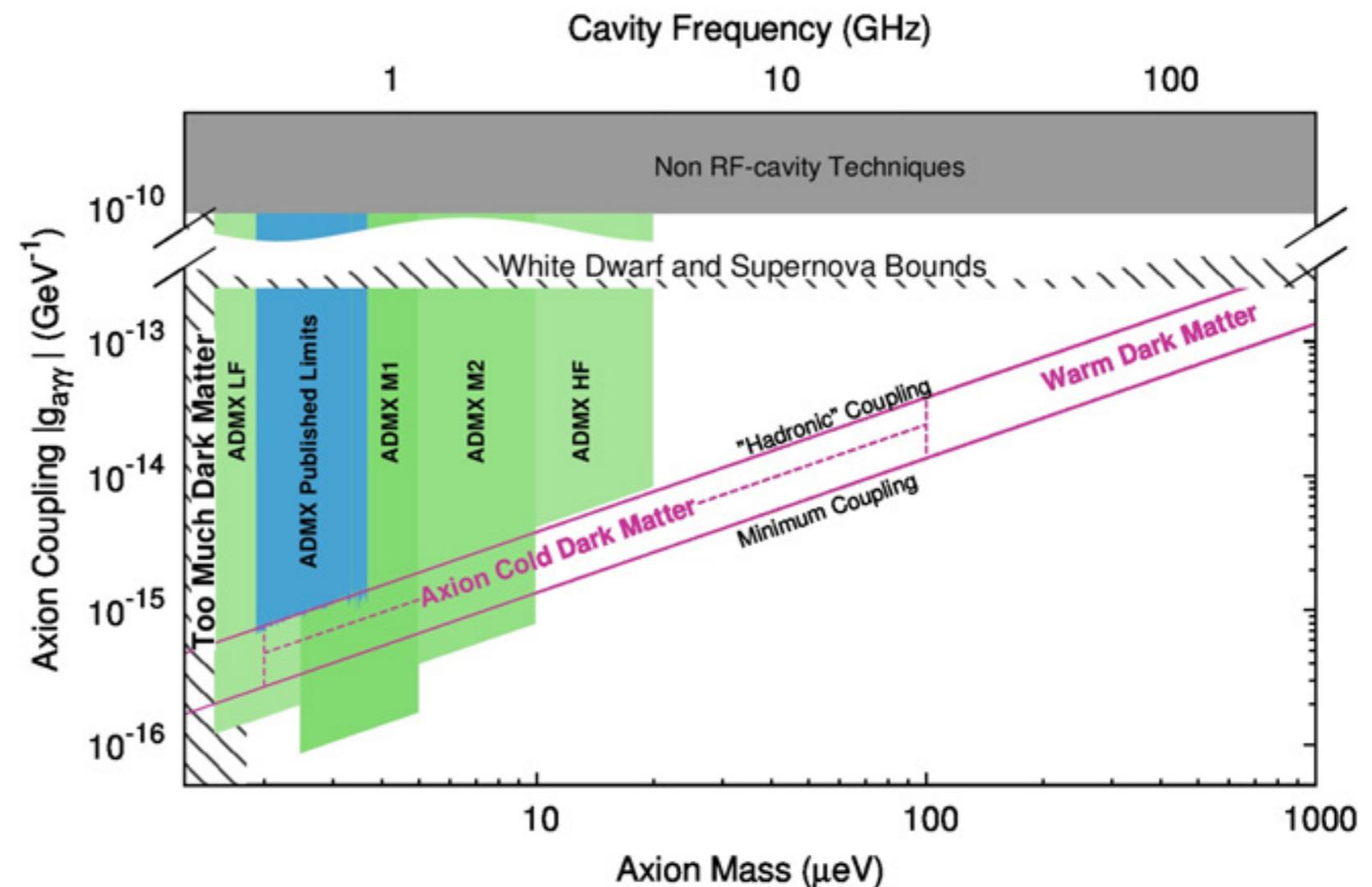
$$P_a = C g_{a\gamma\gamma}^2 V B_0^2 \frac{\rho_a}{m_a} Q_{\text{eff}}$$

- 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

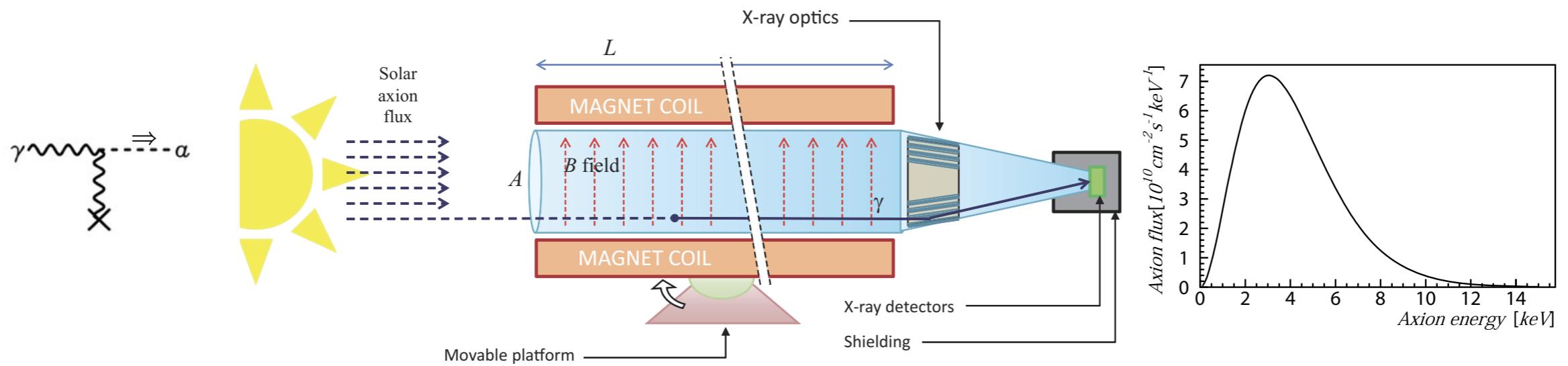
- Axion Dark Matter eXperiment (ADMX) (U. of Washington)



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

Helioscopes

- The Sun is a potential axion source



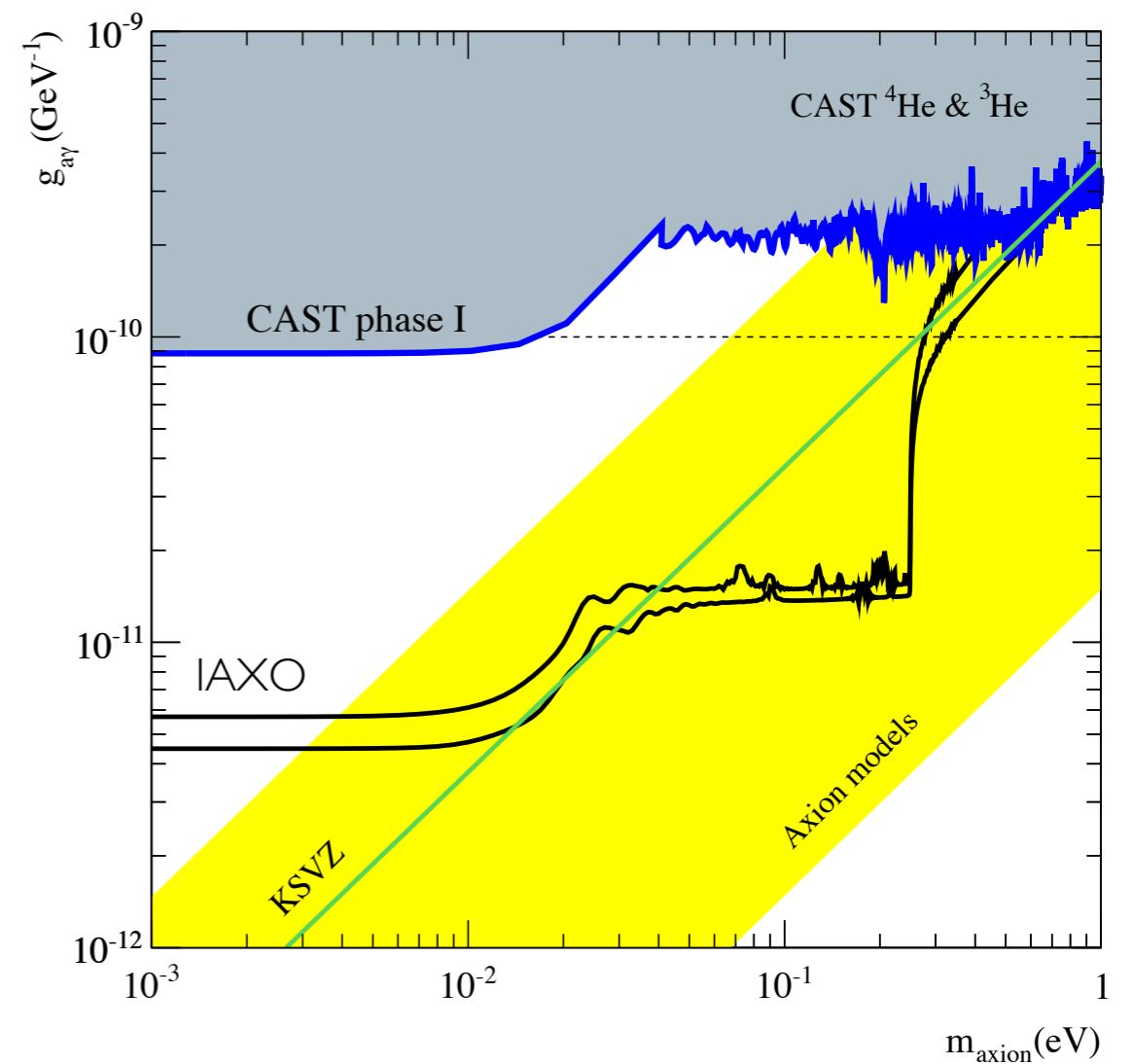
- macroscopic B-field can provide a coherent axion-photon (x-ray) conversion rate over a big volume

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. Sushkov⁴

PRL 113, 161801 (2014)

PHYSICAL REVIEW LETTERS

week ending
17 OCTOBER 2014

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

Asimina Arvanitaki¹ 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 Steffen¹
(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

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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 Katileah Ramos
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(Received 16 November 2014; published 21 January 2015)

CULTASK, The Coldest Axion Experiment at CAPP/IBS/KAIST in Korea

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g_{aee}

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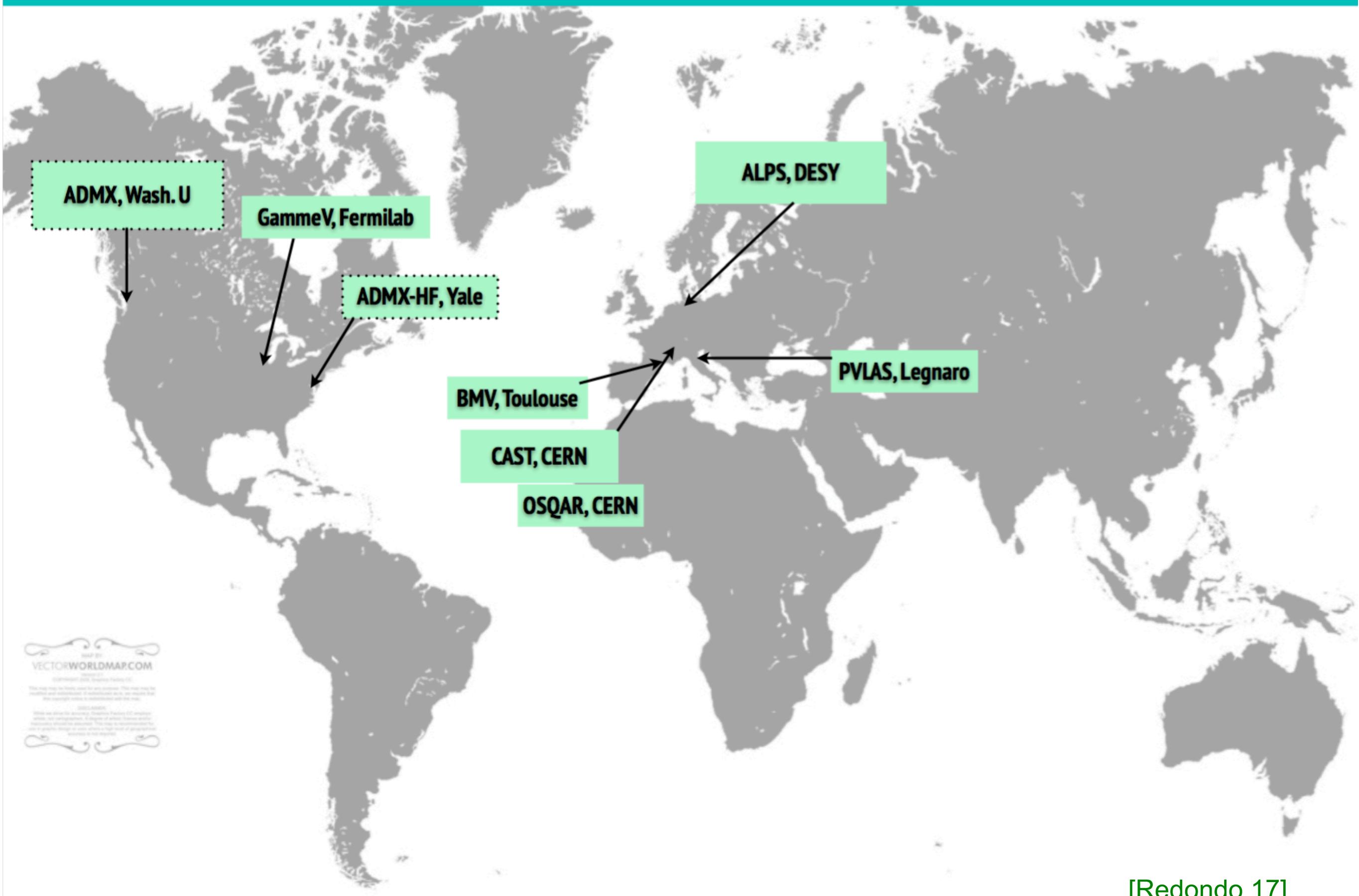
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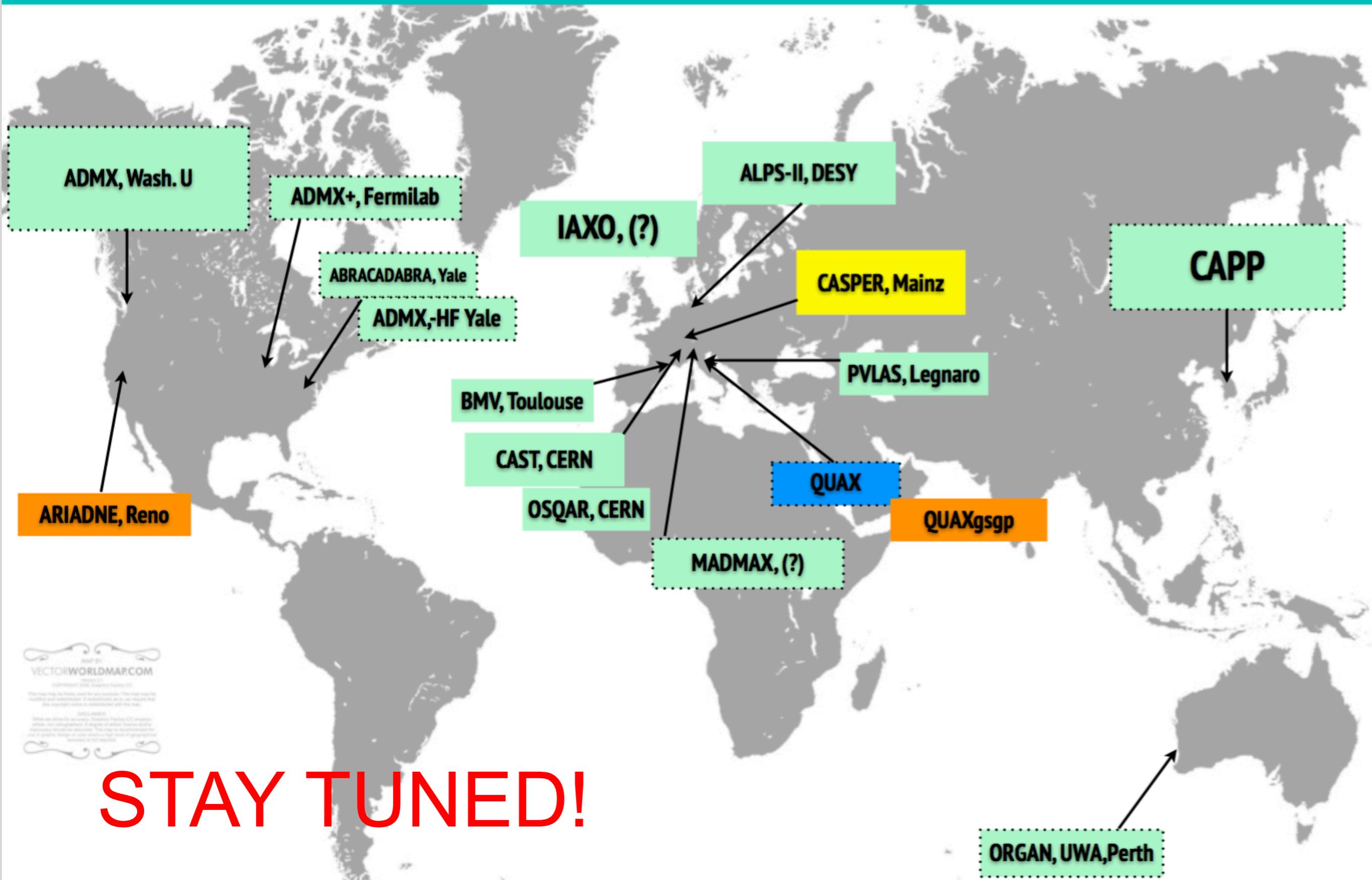
Center for Axion and Precision Physics Research, Institute for Basic Science (IBS), Republic of Korea

$g_{a\gamma\gamma}$

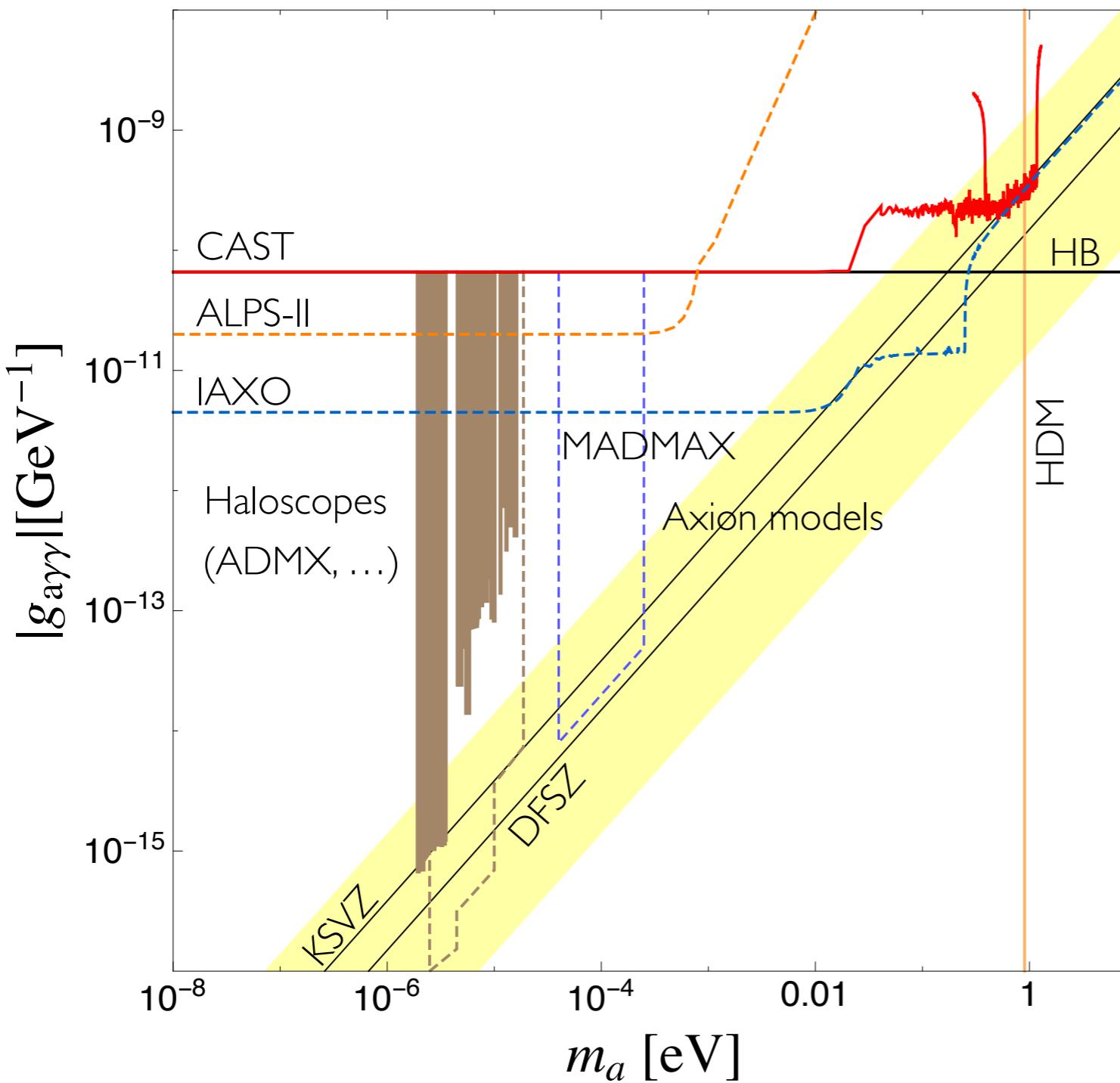
Lab experiments 2011



Lab experiments 2017



Need to know where to search



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

E/N anomaly coefficients,
depend on UV completion

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

[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)]

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
Φ	0	1	1	0	1

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

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

$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G} + \frac{E\alpha}{4\pi} F \cdot \tilde{F} \quad \left. \begin{aligned} N &= \sum_Q (\mathcal{X}_L - \mathcal{X}_R) T(\mathcal{C}_Q) \\ E &= \sum_Q (\mathcal{X}_L - \mathcal{X}_R) Q_Q^2 \end{aligned} \right\} \text{anomaly coeff.}$$

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

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

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
Φ	0	1	1	0	1

- Lagrangian

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

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

- $V_{H\Phi} = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2 \quad \rightarrow \quad m_\rho \sim f_a$

- \mathcal{L}_{Qq} d ≤ 4 mixing with SM quarks (depends in Q-gauge quantum numbers)

Q stability

- Symmetry of the kinetic term

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

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

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



cosmological issue if thermally produced
in the early universe !

Q stability

- Symmetry of the kinetic term

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

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

- $U(1)_Q$ is the Q-baryon number: if exact, Q would be stable
 - if $\mathcal{L}_{Qq} \neq 0$ $U(1)_Q$ 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 $T_{\text{reheating}} > m_Q \sim f_a$ (post-inflat. PQ breaking)]

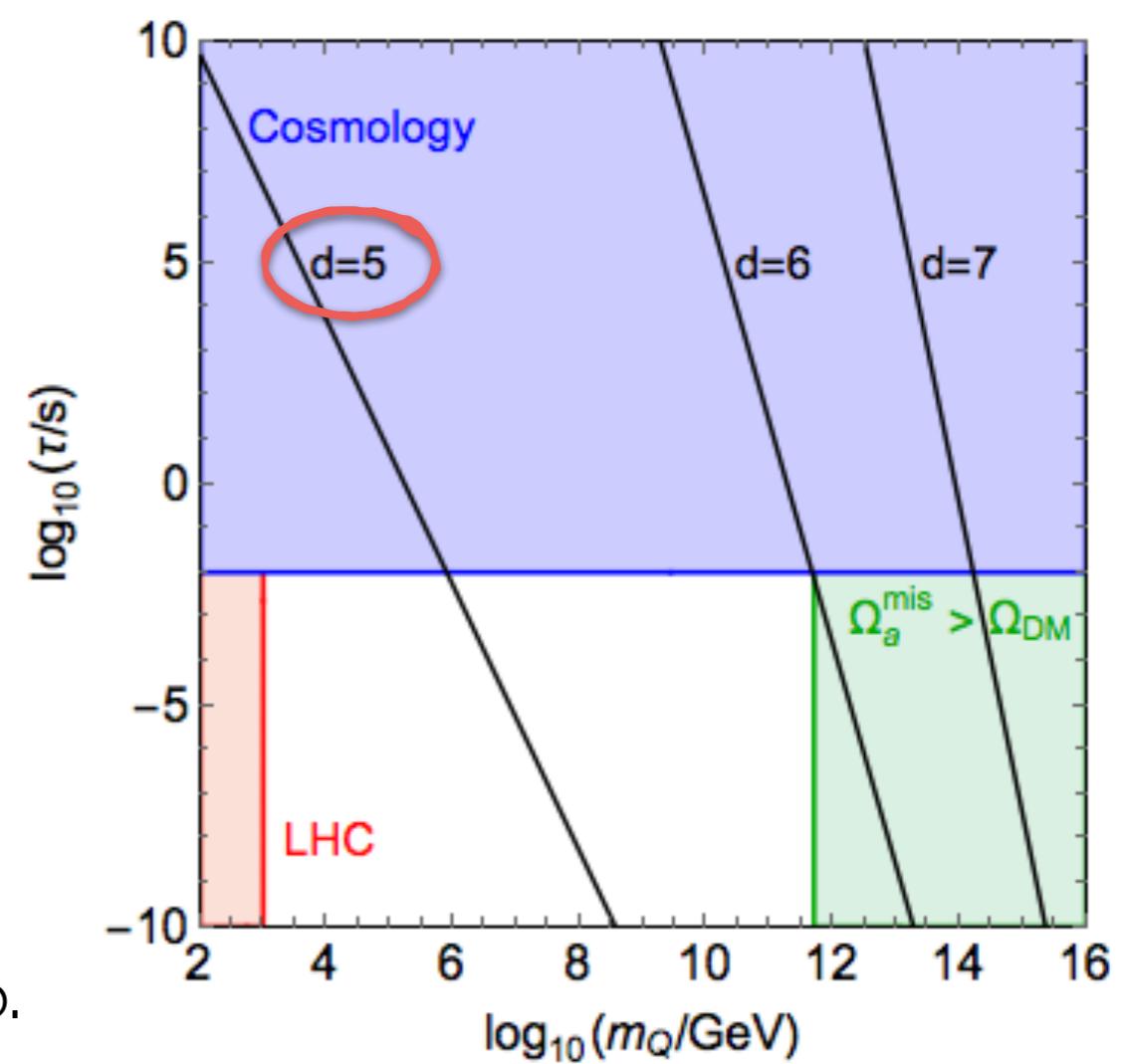
I. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s

- decays via $d=4$ operators are fast enough
- decays via effective operators

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

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

 “safe” Q must allow for $d=4$ or 5 decay op.



Selection criteria

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

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

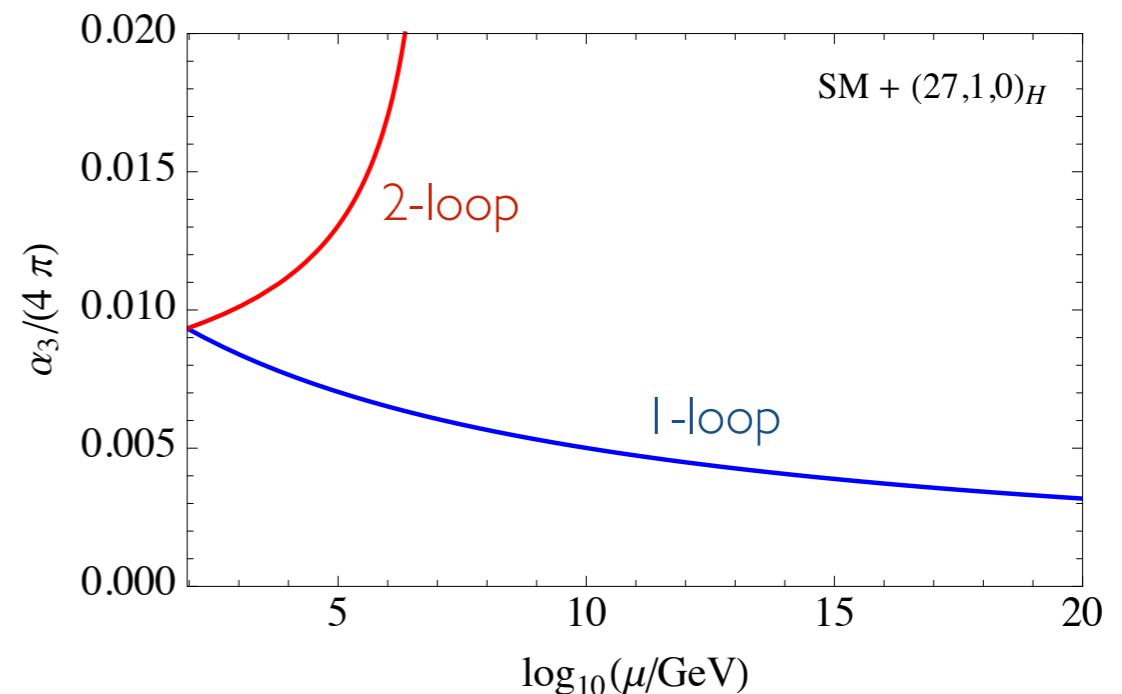
2. No Landau poles below 10^{18} GeV

- bound on Q multiplet dimensionality

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

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

[LDL, Gröber, Kamenik, Nardecchia, 1504.00359]



Selection criteria

- We require: [for $T_{\text{reheating}} > m_Q \sim f_a$ (post-inflat. PQ breaking)]
 1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s
 2. No Landau poles below 10^{18} GeV
 3. Absence of domain walls [see *backup slides*]
 4. Q-assisted unification [see *backup slides*]

Phenomenologically preferred Q's

- Only 15 Q's survive

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

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

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

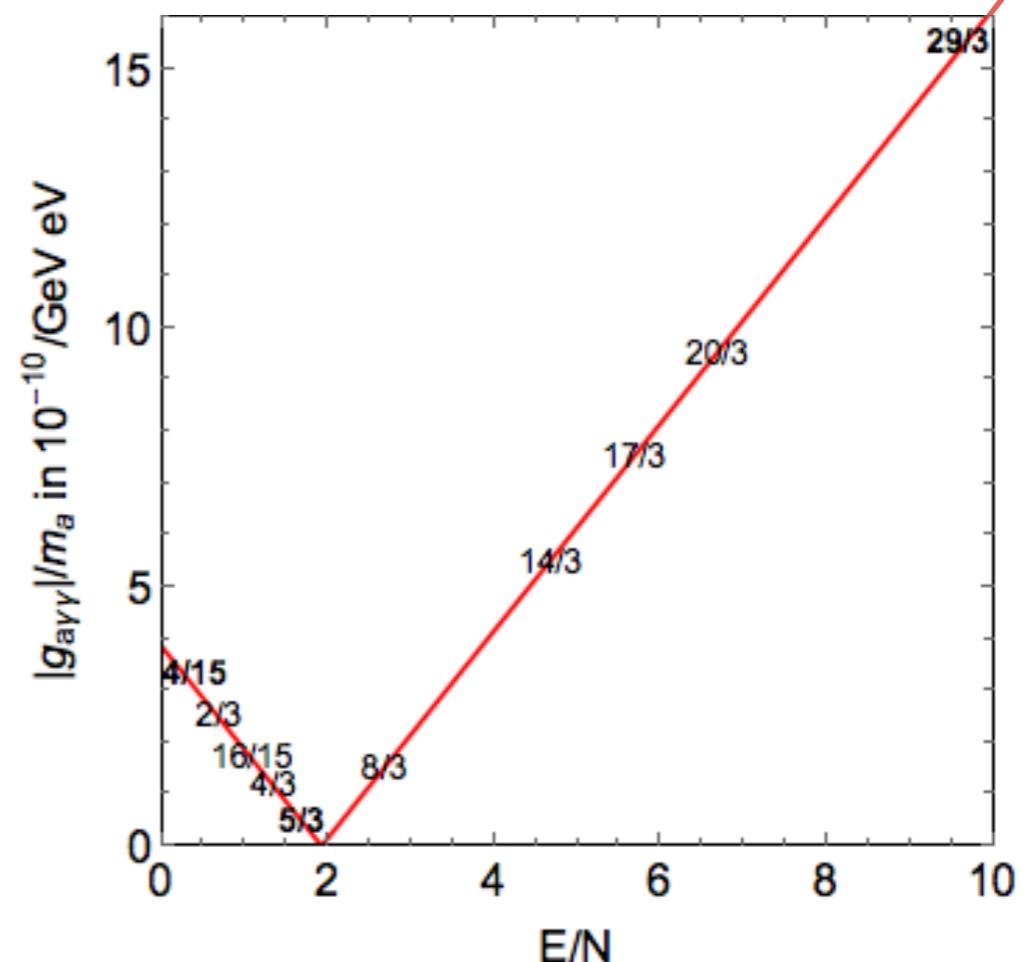
Phenomenologically preferred Q's

- Only 15 Q's survive

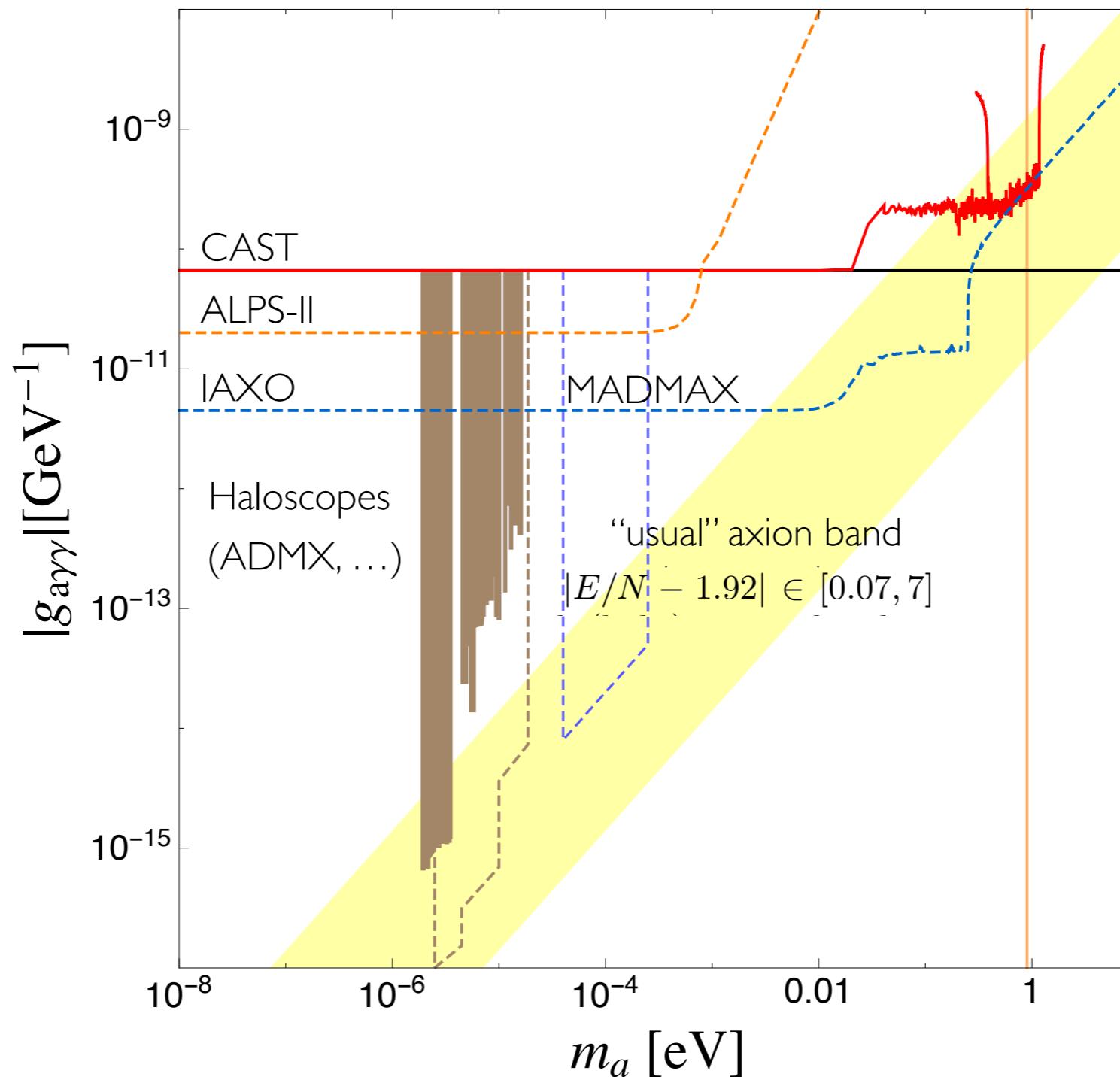
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(3, 1, 2/3)	$\bar{Q}_L u_R$	$5.4 \cdot 10^{34}(g_1)$	8/3
R_Q^w	(3, 2, 1/6)	$\bar{Q}_R q_L$	$6.5 \cdot 10^{39}(g_1)$
	(3, 2, -5/6)	$\bar{Q}_L d_R H^\dagger$	$4.3 \cdot 10^{27}(g_1)$
	(3, 2, 7/6)	$\bar{Q}_L u_R H$	$5.6 \cdot 10^{22}(g_1)$
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	(3, 3, 2/3)	$\bar{Q}_R q_L H$	$6.6 \cdot 10^{27}(g_2)$
	(3, 3, -4/3)	$\bar{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18}(g_1)$
	(6, 1, -1/3)	$\bar{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$2.3 \cdot 10^{37}(g_1)$
R_Q^s	(6, 1, 2/3)	$\bar{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$5.1 \cdot 10^{30}(g_1)$
	(6, 2, 1/6)	$\bar{Q}_R \sigma_{\mu\nu} q_L G^{\mu\nu}$	$7.3 \cdot 10^{38}(g_1)$
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$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10} \text{ GeV}} \left(\frac{E}{N} - 1.92(4) \right)$$

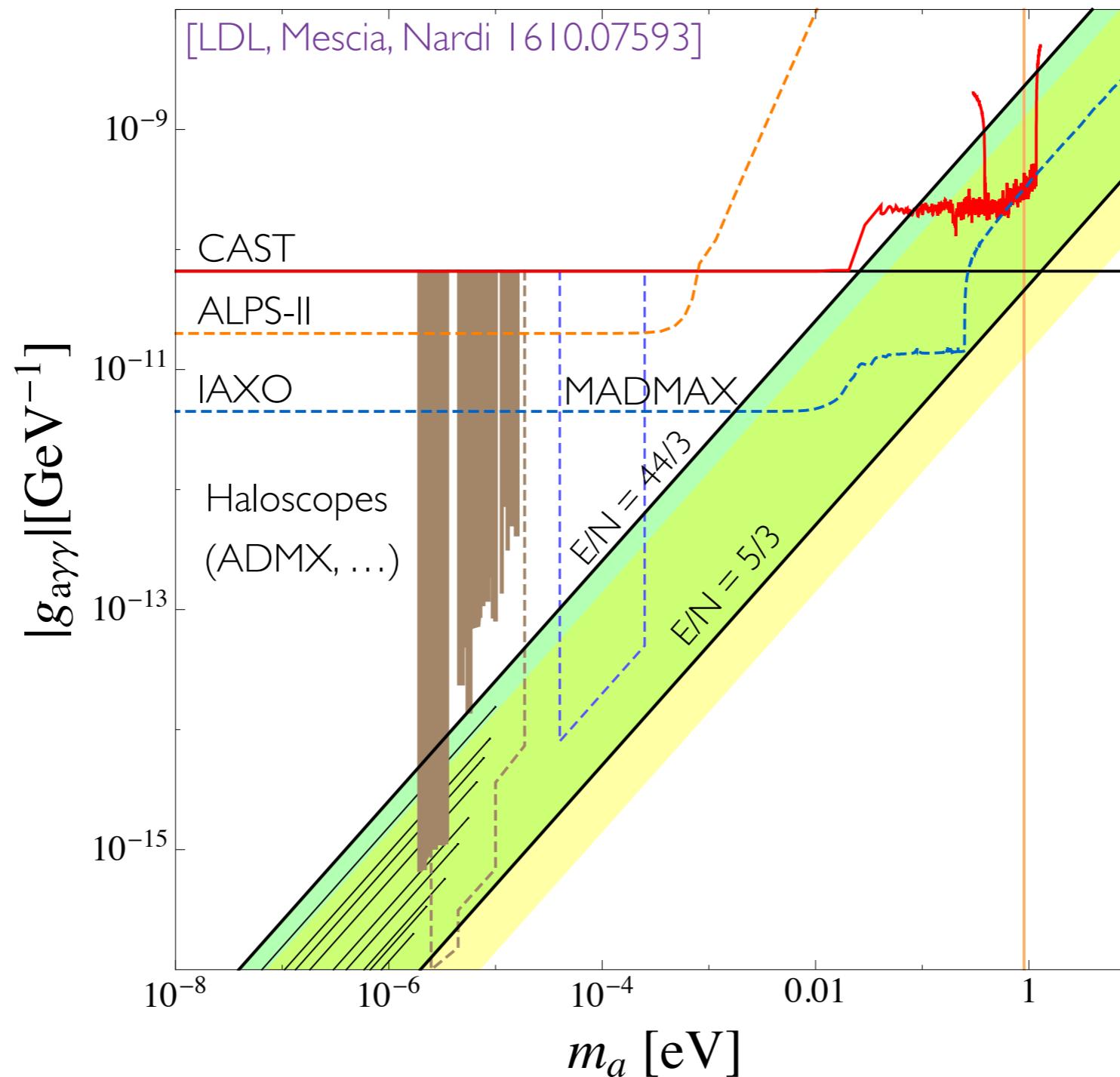
$$\frac{E}{N} = \frac{\sum_Q Q_Q^2}{\sum_Q T(\mathcal{C}_Q)}$$



Redefining the axion window



Redefining the axion window



More Q's

- What about $N_Q > 1$?

- 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) is given by

$$(3, 3, -4/3) \oplus (3, 3, -1/3) \ominus (\bar{6}, 1, -1/3) \quad \xrightarrow{\text{red arrow}} \quad E_c/N_c = 170/3$$

- Complete decoupling within theoretical error is possible as well:

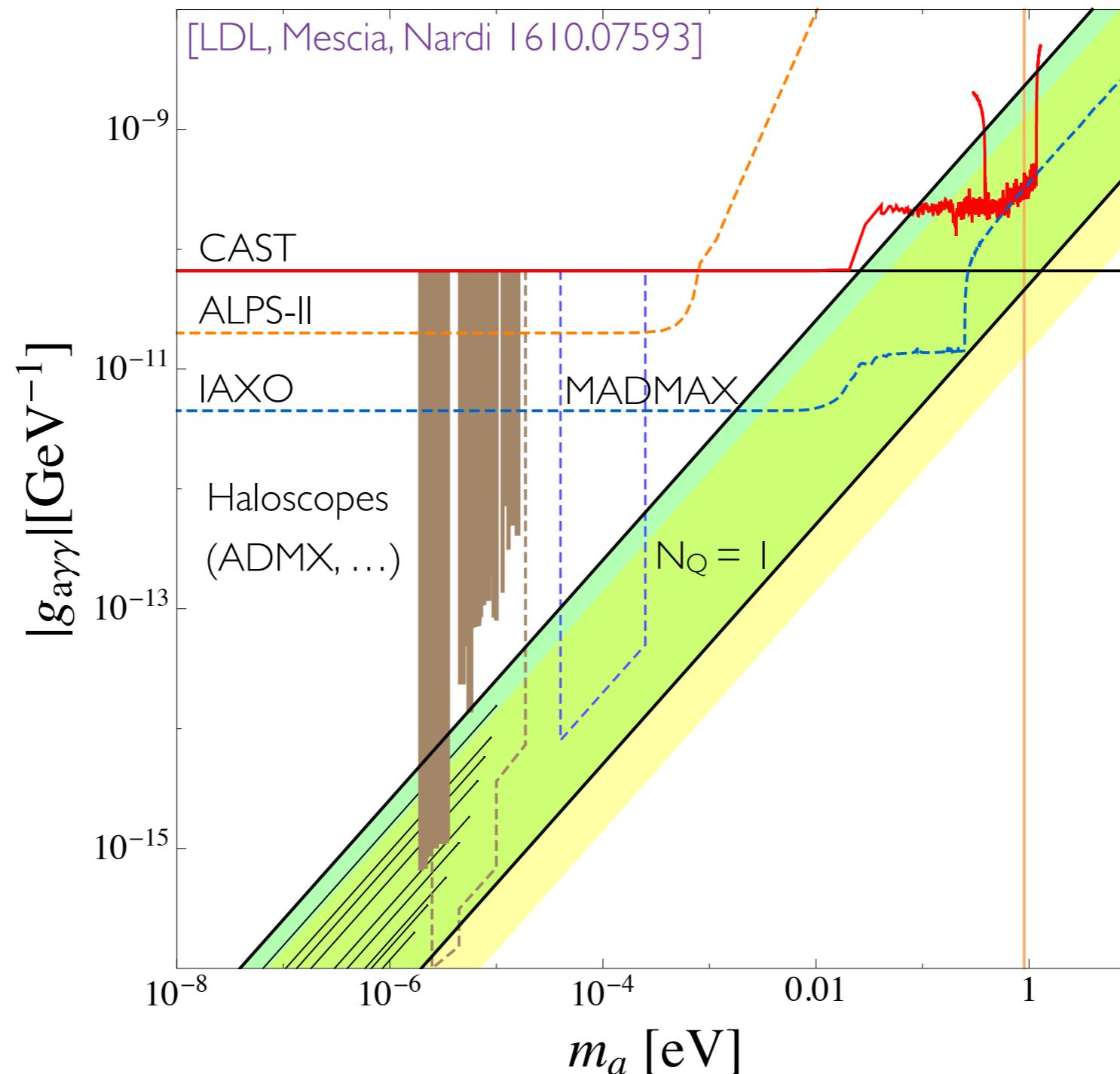
$$\left. \begin{array}{l} (3, 3, -1/3) \oplus (\bar{6}, 1, -1/3) \\ (\bar{6}, 1, 2/3) \oplus (8, 1, -1) \\ (3, 2, -5/6) \oplus (8, 2, -1/2) \end{array} \right\} \quad E_c/N_c = (23/12, 64/33, 41/21) \approx (1.92, 1.94, 1.95)$$

$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \frac{2.0}{10^{10} \text{ GeV}} \left(\frac{E_c}{N_c} - 1.92(4) \right) \quad \begin{array}{l} \text{[Theoretical error from NLO } \chi\text{PT} \\ \text{Grilli di Cortona et al., 1511.02867]}\end{array}$$

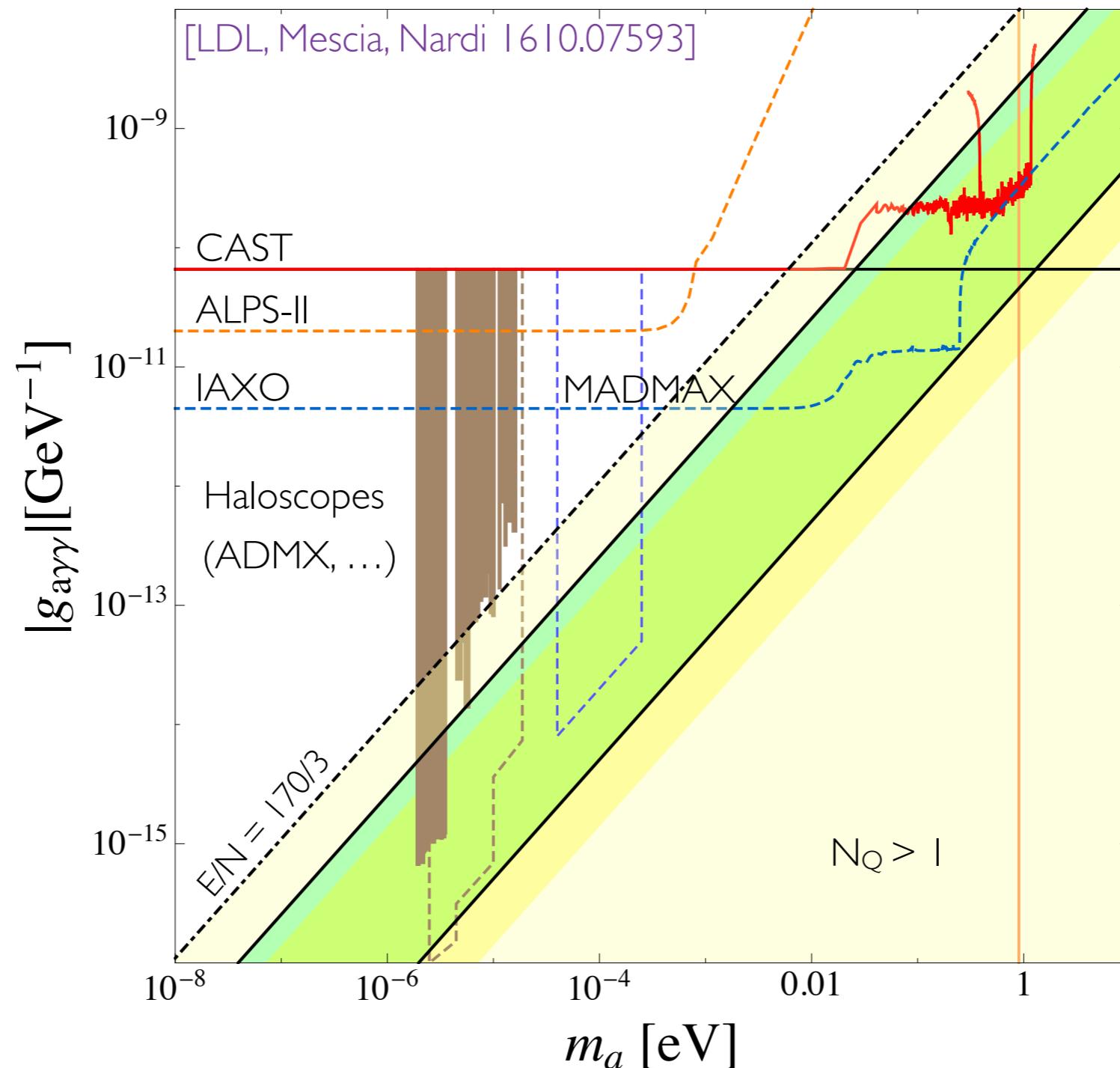
“such a cancellation is immoral, but not unnatural”

[D. B. Kaplan, (1985)]

More Q's



More Q's



KSVZ in pre-inflationary scenarios

- What about $T_{\text{reheating}} < m_Q$? [LDL, Mescia, Nardi | 705.05370]
 - condition on Q decay is relaxed, but Landau pole still applies
- $m_Q \sim y_Q f_a < 5 \cdot 10^{11} \text{ GeV}$
 - $N_Q = 1 : (E/N)_{\text{max(pre)}} = 2.5 (E/N)_{\text{max(post)}}$
 - $N_Q > 1 : (E/N)_{\text{max(pre)}} = 1.2 (E/N)_{\text{max(post)}}$
 - *axion-photon coupling well-described by post-inflationary axion window*
- $f_a \gg 5 \cdot 10^{11} \text{ GeV}$ (requires $\theta_0 \ll 1$) softens Landau pole condition
 - *arbitrarily large axion-photon coupling at the cost of tuning initial mis. condition*

DFSZ-like axions

- Potentially large E/N due to electron PQ charge

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

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

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

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

DFSZ-like axions

- Potentially large E/N due to electron PQ charge

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

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

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

- $n_H = 2$

DFSZ-I : $X_e = X_d$ $E/N = 8/3$

DFSZ-II : $X_e = -X_u$ $E/N = 2/3$

- $n_H = 3$

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

DFSZ-like axions

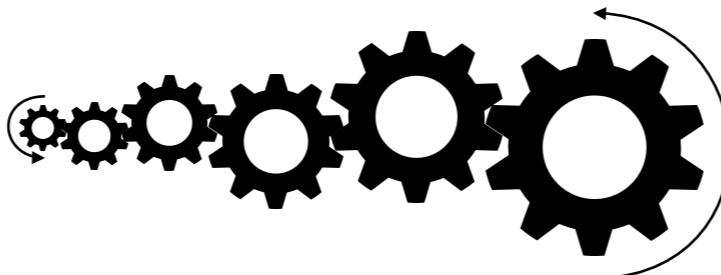
- Potentially large E/N due to electron PQ charge

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

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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 [LDL, Mescia, Nardi | 705.05370]
 - n up-type doublets which do not couple to SM fermions ($n \lesssim 50$ from LP condition)

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


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

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

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

[Giudice, McCullough]

[See also Farina et al. | 611.09855,
for KSVZ clockwork]

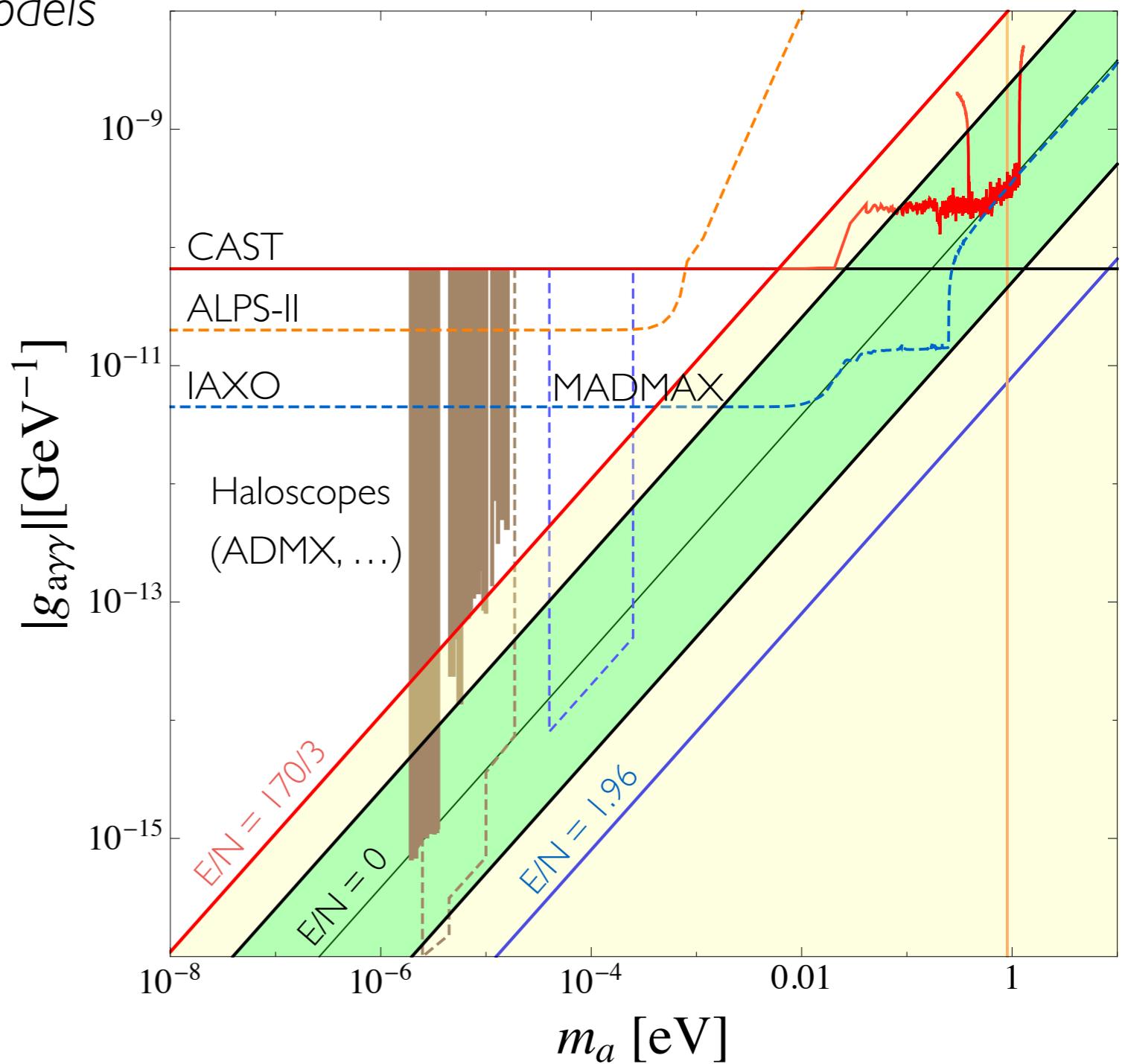
Summary axion-photon

Region of ‘realistic’ KSVZ/DFSZ axion models

Going **above red** line requires either:

- i) very exotic constructions
- ii) tuning $\theta_0 \ll 1$ (KSVZ pre-inflat.)

Going **below blue** line requires a
‘tuning in theory space’ < 2%



Conclusions

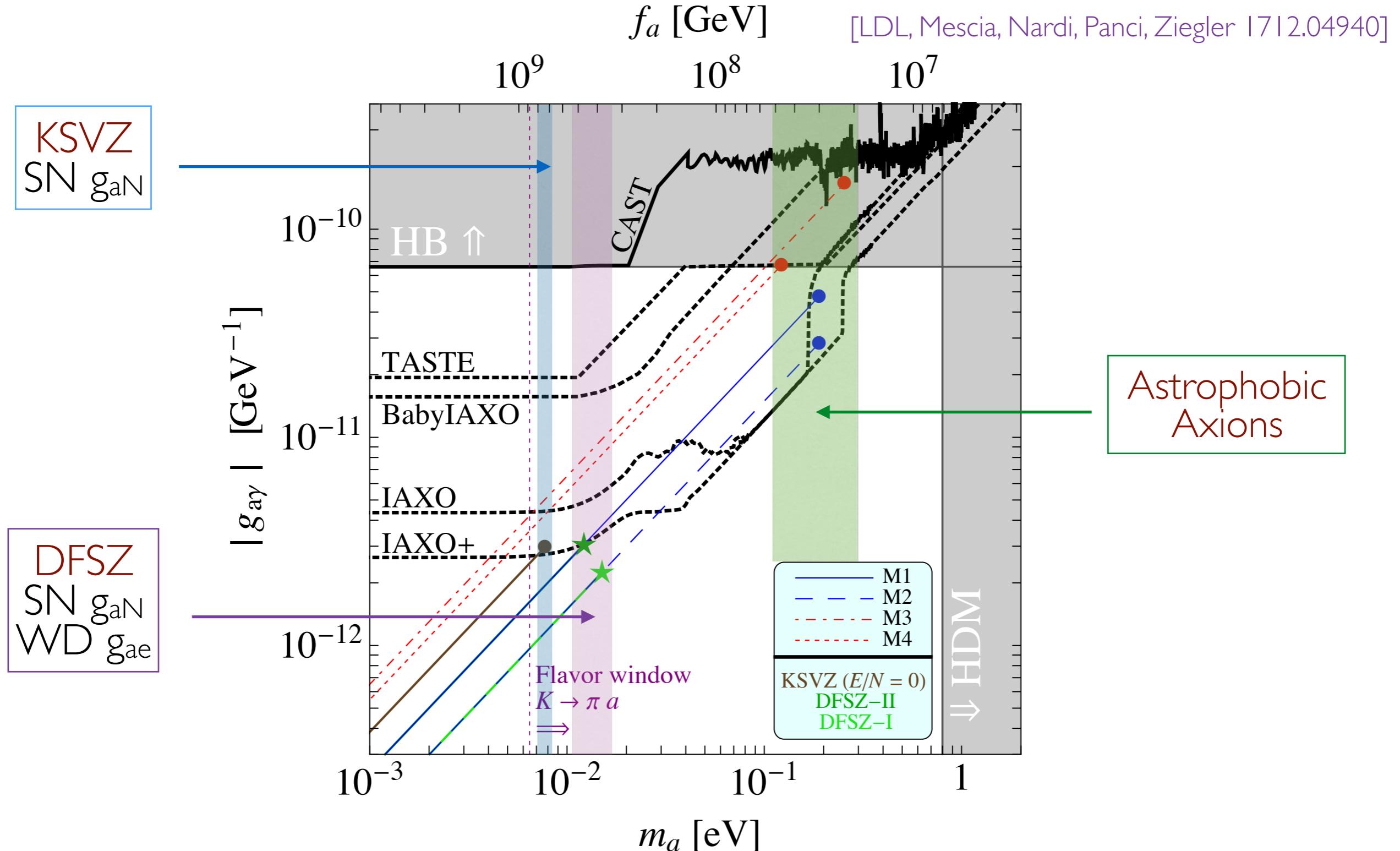
- QCD axion: 2 birds with 1 stone
 - solves the strong CP problem
 - provides an excellent DM candidate
- The Axion Rush has just started
 - experiments are entering now the preferred window for the QCD axion
 - non-negligible chance to witness a discovery within the next decade !



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

Backup slides

Astrophobic



Axion coupling to photons

- Axion effective Lagrangian

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

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

field-dependent chiral transformation to eliminate aGGtilde:

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

$$\text{tr } Q_a = 1$$

Axion coupling to photons

- Axion effective Lagrangian

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

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a} \frac{\alpha_s}{8\pi} \cancel{G}_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{1}{4} a g_{a\gamma\gamma}^0 F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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



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

$$\text{tr } Q_a = 1$$

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

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

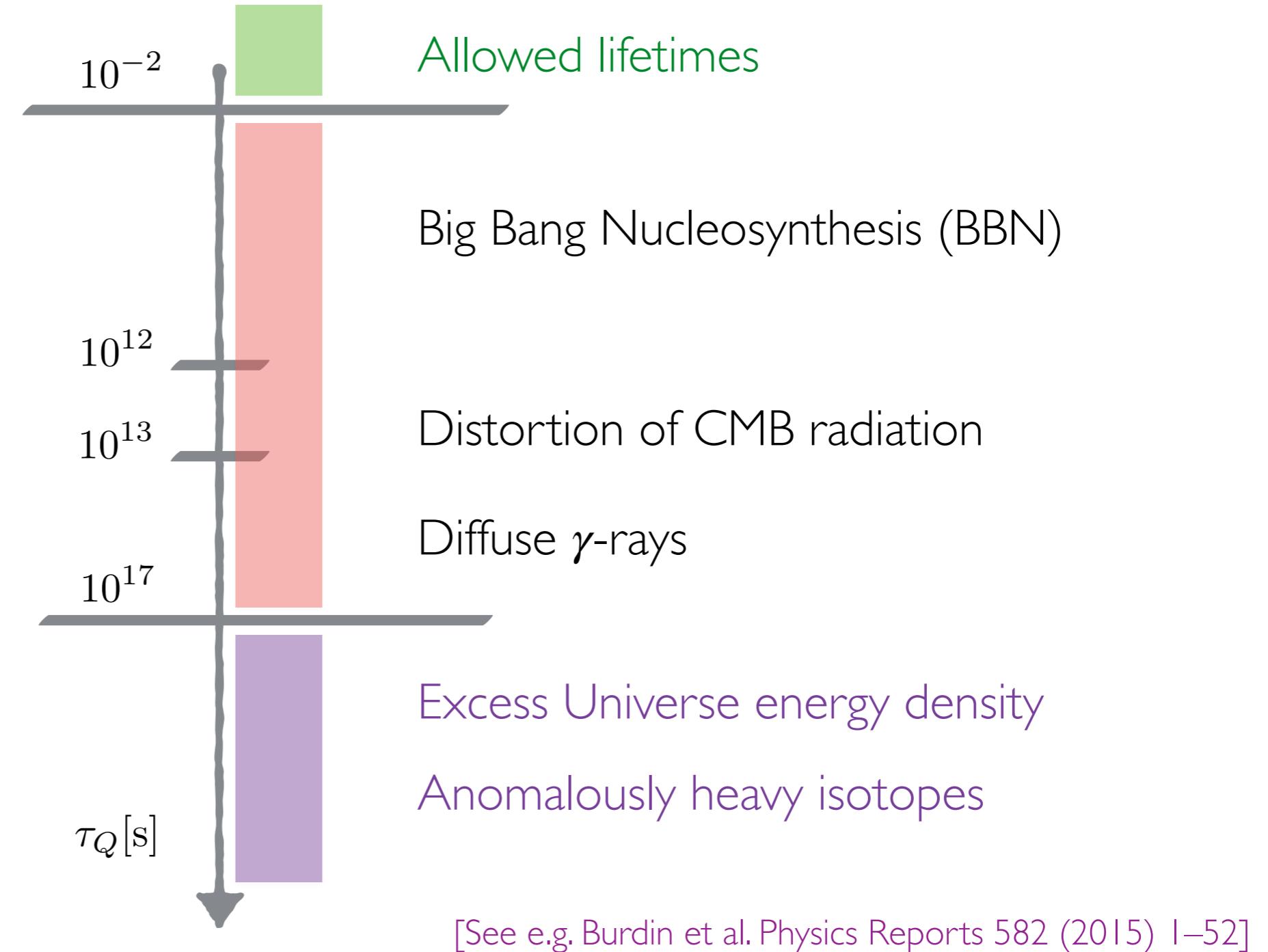
model independent
depends on UV completion

Cosmological constraints on τ_Q

EW ν interactions out of equilibrium

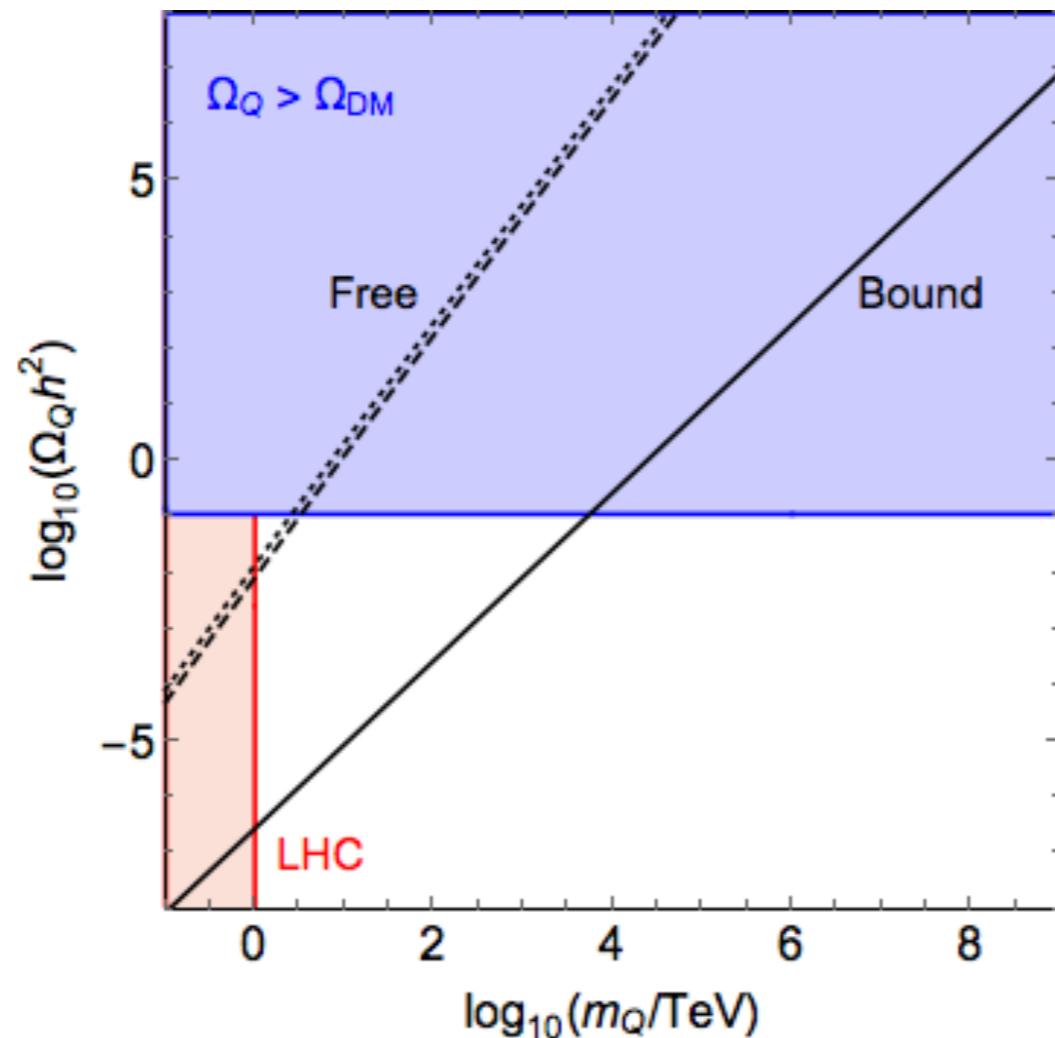
Recombination

Age of the Universe



Heavy Q's relic density (I)

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



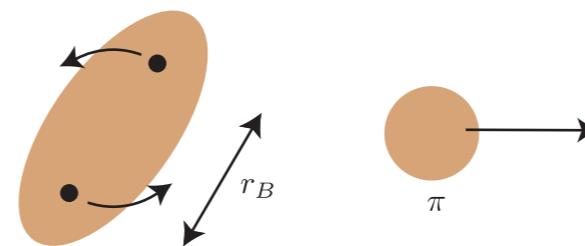
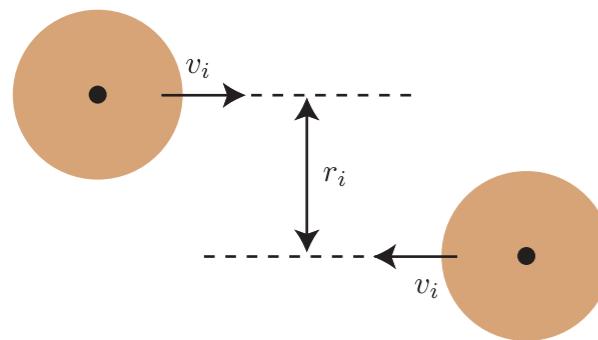
[Rich literature: e.g.
Dover, Gaisser, Steigman PRL 42 (1979),
Nardi, Roulet PLB 245 (1990),
Arvanitaki et al., hep-ph/0504210,
Kang, Luty, Nasri, hep-ph/0611322,
Jacob, Nussinov, 0712.2681
Kusakabe, Takesako, 1112.0860]

Heavy Q's relic density (2)

- above $T_C \sim 180$ MeV: perturbative annihilation

$$(\Omega_Q h^2)^{\text{Free}} = 2.0 \left(\frac{x_{fo}}{25} \right) \left(\frac{g_*}{106.75} \right)^{-1/2} \left(\frac{\langle \sigma v \rangle_{Q\bar{Q}}}{10^{-10} \text{ GeV}^{-2}} \right)^{-1} \approx 8 \cdot 10^{-3} \left(\frac{m_Q}{\text{TeV}} \right)^2$$

- below $T_C \sim 180$ MeV: heavy Q's get confined in color singlets and annihilation may restart via the formation of intermediate bound states (e.g. $\bar{Q}q + Qqq \rightarrow \bar{Q}Q + qqq$)



[Kang, Luty, Nasri, hep-ph/0611322]

$$(\Omega_Q h^2)^{\text{Bound}} = 8.7 \cdot 10^{-12} \left(\frac{R_{\text{had}}}{\text{GeV}^{-1}} \right)^{-2} \left(\frac{T_C}{180 \text{ MeV}} \right)^{-3/2} \left(\frac{m_Q}{\text{GeV}} \right)^{3/2}$$

- however QQ , QQQ , ... bound states (so far not taken into account) would hinder it

[Kusakabe, Takesako, 1112.0860]