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INFN
Istituto Nazionale di Fisica Nucleare

The Axion Window on Low-Energy Precision Physics

4th Liverpool Workshop on Muon Precision Physics 2025

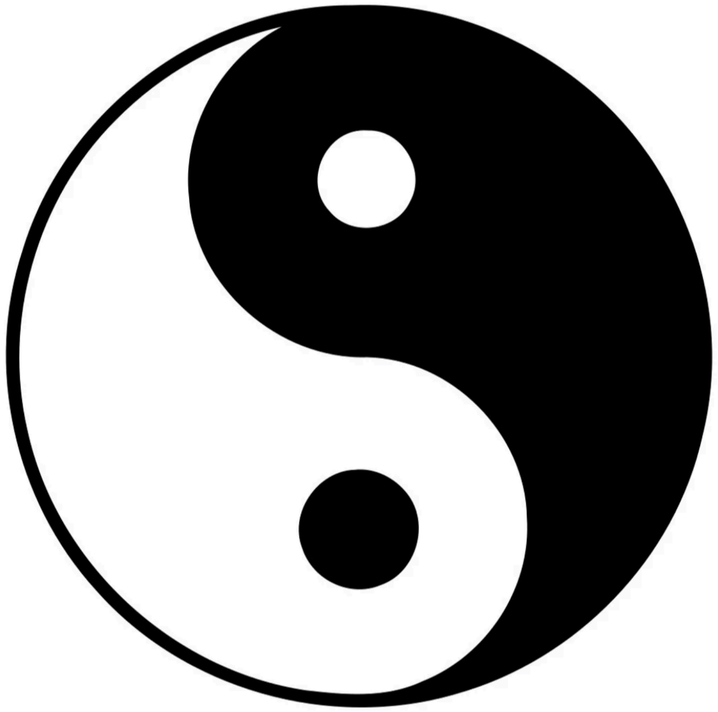
Luca Di Luzio

INFN PADOVA

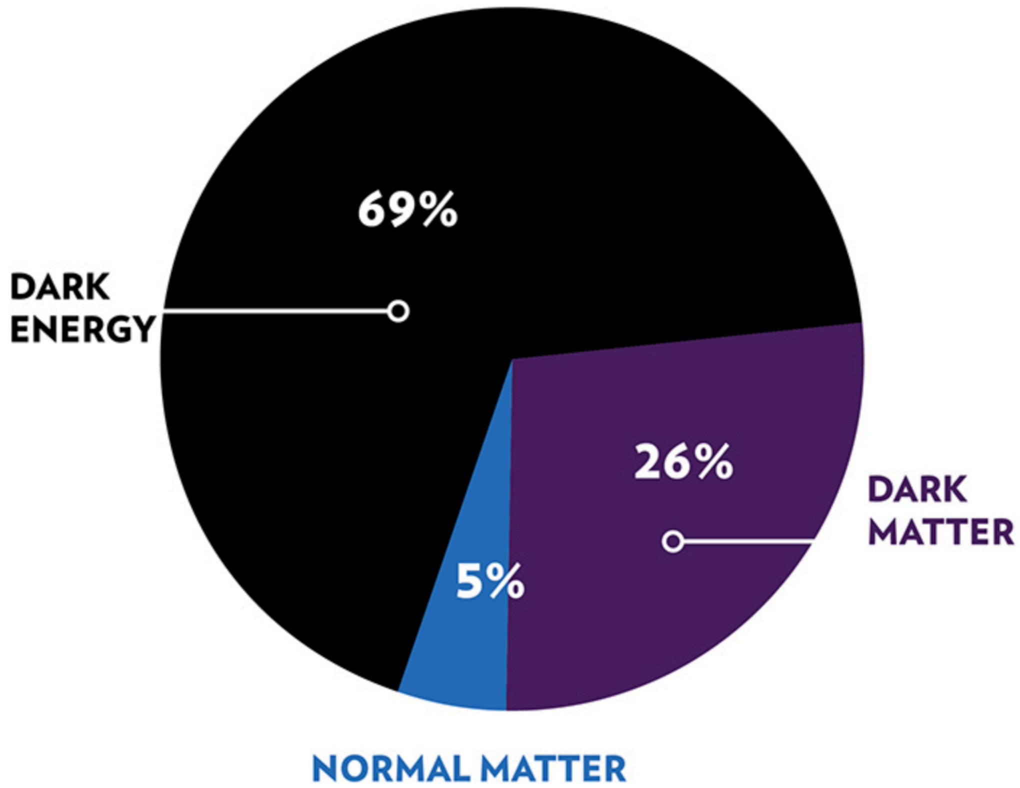
Work supported by the European Union - Next Generation EU and by the Italian Ministry of University and Research (MUR) via the PRIN 2022 project n. 2022K4B58X - AxionOrigins

The QCD axion

Strong CP problem



Dark Matter



QCD axion & strong CP

- Introduced to address the strong CP problem [Peccei, Quinn '77, Weinberg '78, Wilczek '78]

$$\delta\mathcal{L}_{\rm QCD} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G} \qquad |\theta| \lesssim 10^{-10} \qquad \text{(bound from nEDM)}$$

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- Naive Dimensional Analysis:

$$\mathcal{L} = -d_n \, \frac{i}{2} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu} \qquad \Longleftrightarrow \qquad H = -d_n \, \mathbf{E} \cdot \hat{\mathbf{S}}$$

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$$\frac{e}{m_n} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu} + \text{h.c.}$$

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$$\left(1 - c \frac{m_q}{2m_n} e^{i\theta}\right) \frac{e}{m_n} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu} + \text{h.c.} \longrightarrow d_n = c \frac{m_q}{m_n} \frac{e}{m_n} \theta$$

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$$|d_n^{\rm exp}| < 1.8 \cdot 10^{-26} \ e \ \text{cm} \ (90\% \ \text{CL})$$

[Abel et al, Phys. Rev. Lett. 124 (2020) 081803]

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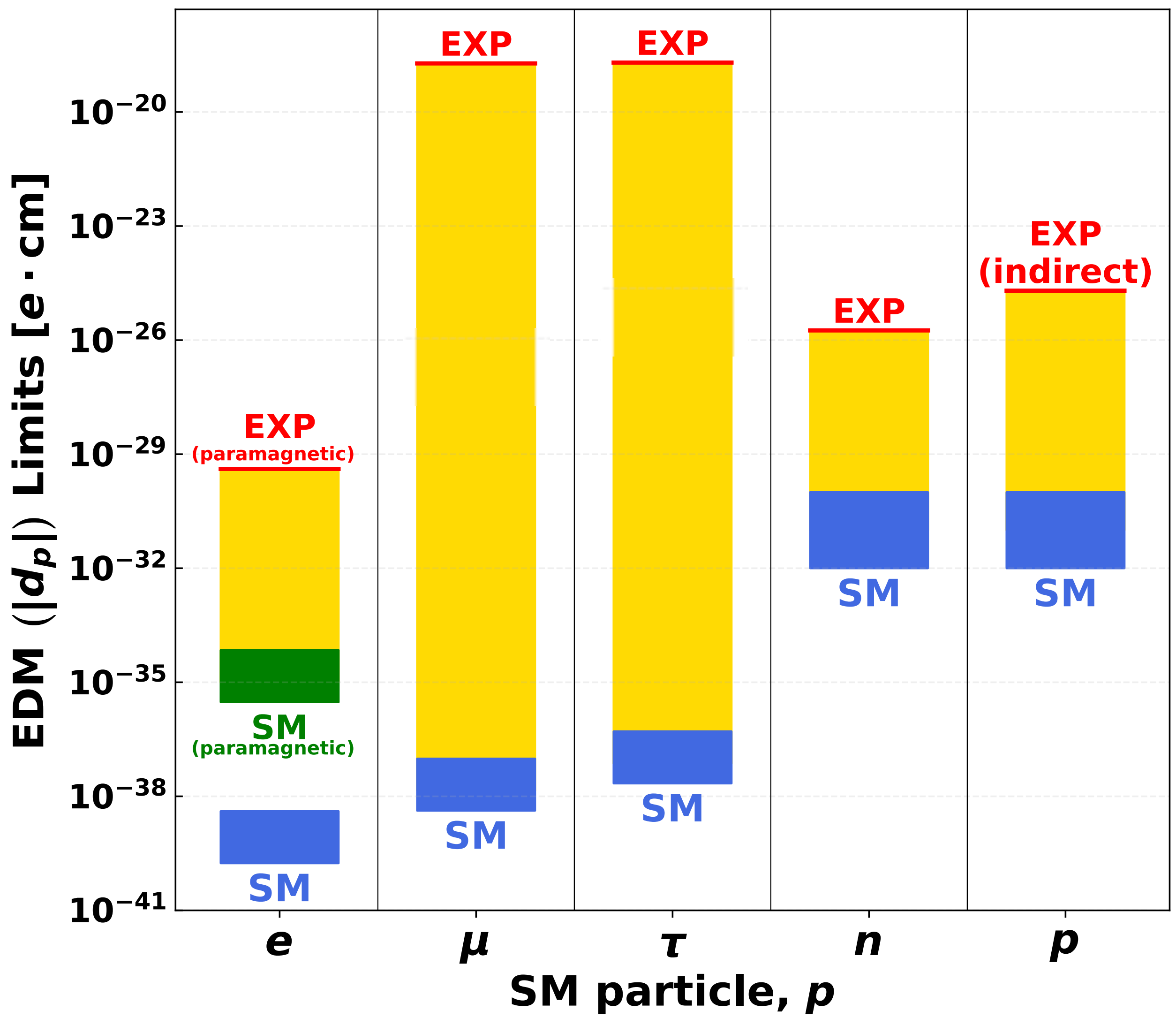
[Courtesy of A. Keshavarzi]



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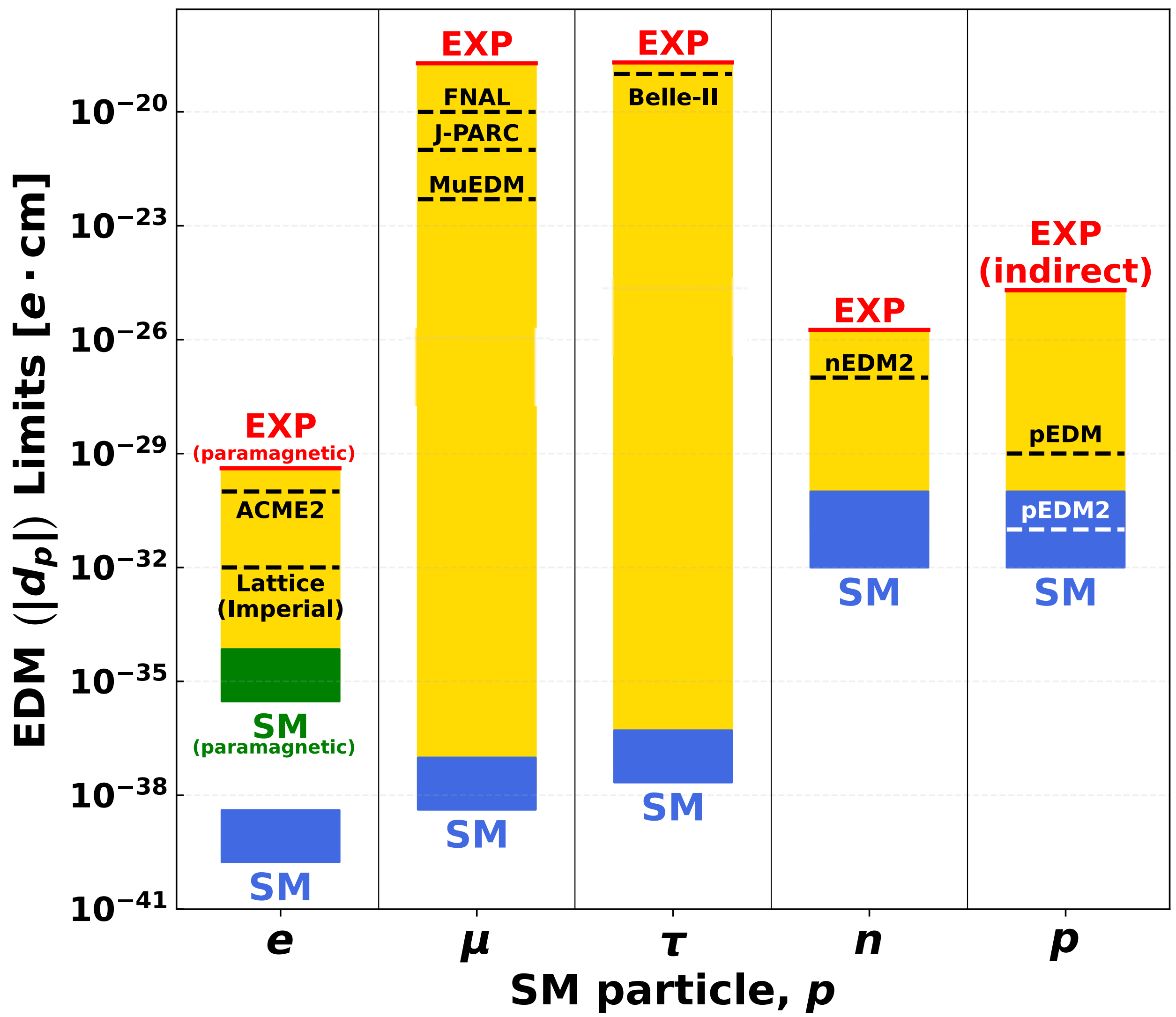

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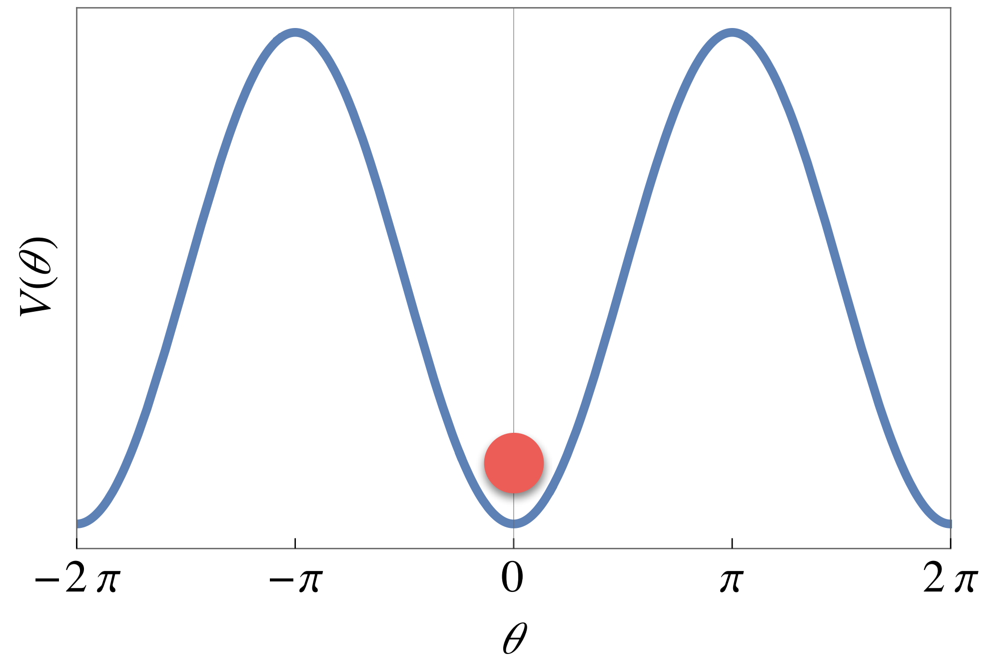
$$\delta\mathcal{L}_{\rm QCD} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$

- promote θ to a dynamical field (axion): $\theta \to \frac{a}{f_a}$

- acquires a QCD potential and relaxes dynamically to zero



QCD axion & dark matter

- Unavoidably contributes to $\Omega_{\rm DM}$

i) misalignment mechanism (axion oscillations)

[Preskill, Wise, Wilczek '83,
Abbott, Sikivie '83,
Dine, Fischler '83]

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

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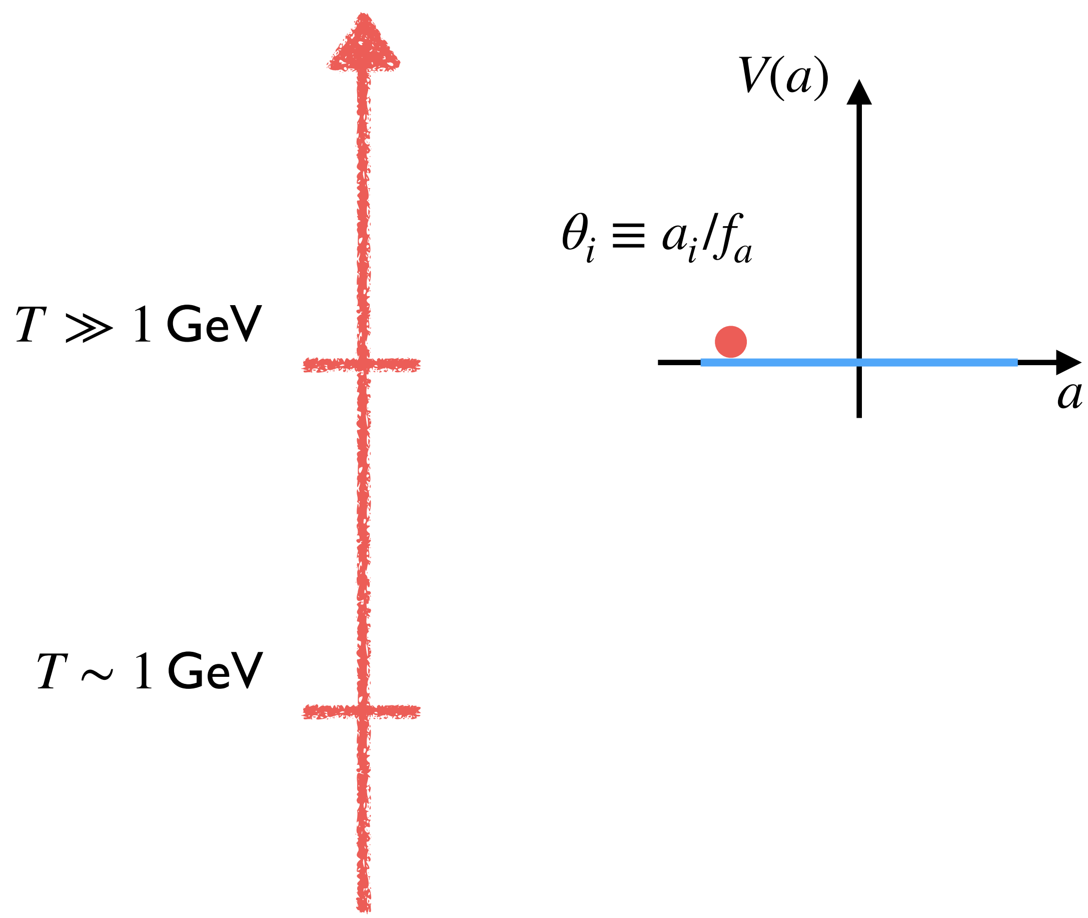

$$\ddot{a} + 3H\dot{a} + \cancel{m_a^2(T)} f_a \sin\left(\frac{a}{f_a}\right) = 0$$

$(T \gg T_c \approx 150\,\text{MeV})$

$$m_a^2(T) \approx m_a^2 \left(T/T_c\right)^{-8}$$

[Axion mass at finite T from lattice QCD inputs - see e.g. Borsanyi et al 1606.07494]

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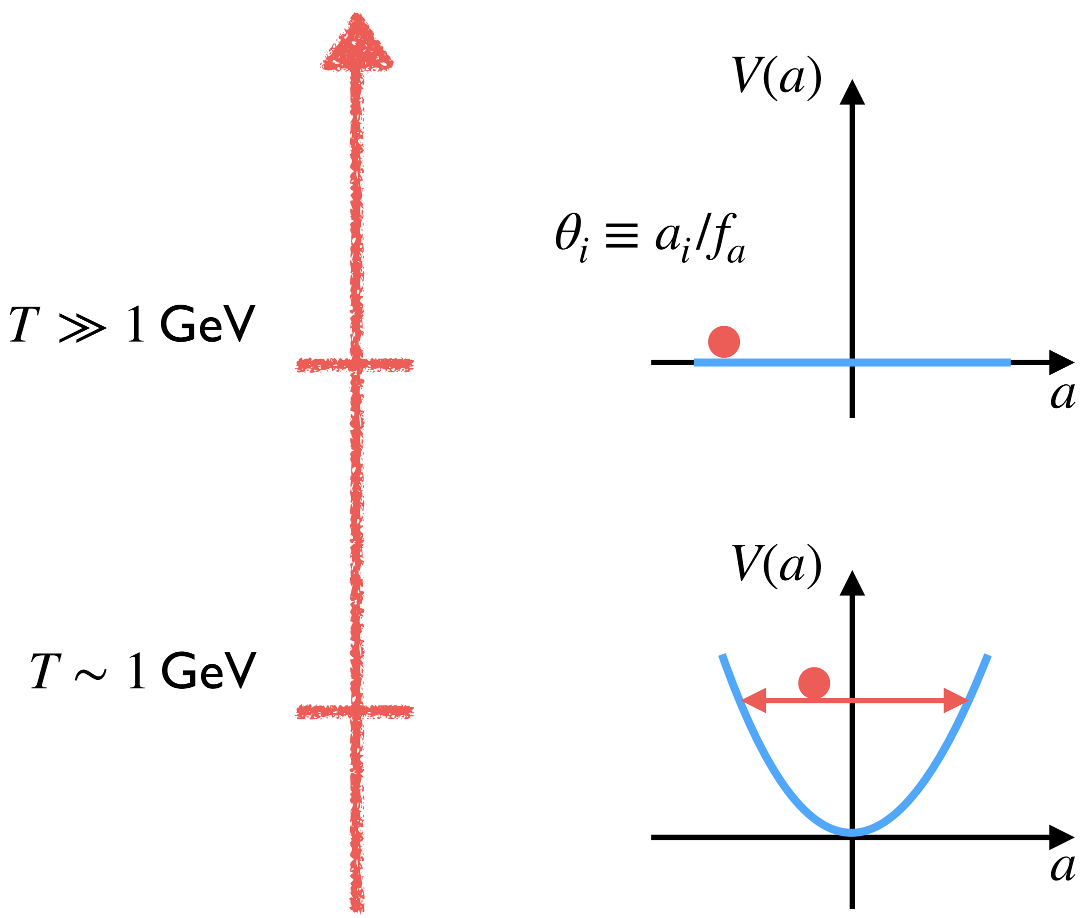

$$\ddot{a} + \cancel{3H}\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

$$\Omega_a h^2 \approx 0.12 \left(\frac{6\,\mu\text{eV}}{m_a}\right)^{1.16} \theta_i^2$$

$$\left.\frac{a(t)}{f_a}\right|_{\rm today} \sim \underbrace{\sqrt{\frac{2\rho_{\rm DM}}{m_a^2 f_a^2}}}_{10^{-18}} \cos(m_a t)$$

QCD axion & dark matter

- Unavoidably contributes to $\Omega_{\rm DM}$

i) misalignment mechanism (axion oscillations)

ii) topological defects (axion strings, …) [Davies '86, Harari Sikivie '87, …]

→ *absent if PQ symmetry is broken before inflation (Pre-inflation)*

QCD axion & dark matter

- Unavoidably contributes to $\Omega_{\rm DM}$

i) misalignment mechanism (axion oscillations)

ii) topological defects (axion strings, …)

post-inflationary PQ breaking	*pre-inflationary PQ breaking*
$f_a < \max\{H_I, T_R\}$	$f_a > \max\{H_I, T_R\}$
$\langle\theta_i\rangle = \frac{\pi}{\sqrt{3}}$	θ_i arbitrary
$\Omega_a^{\rm mis} < \Omega_{\rm DM}$ $\longrightarrow$ $m_a \gtrsim 30\ \mu{\rm eV}$	misalignment contribution unique, but depends on initial conditions
+ contribution from topological defects	$\Omega_a h^2 \approx 0.12 \left(\frac{6\,\mu{\rm eV}}{m_a}\right)^{1.16} \theta_i^2$

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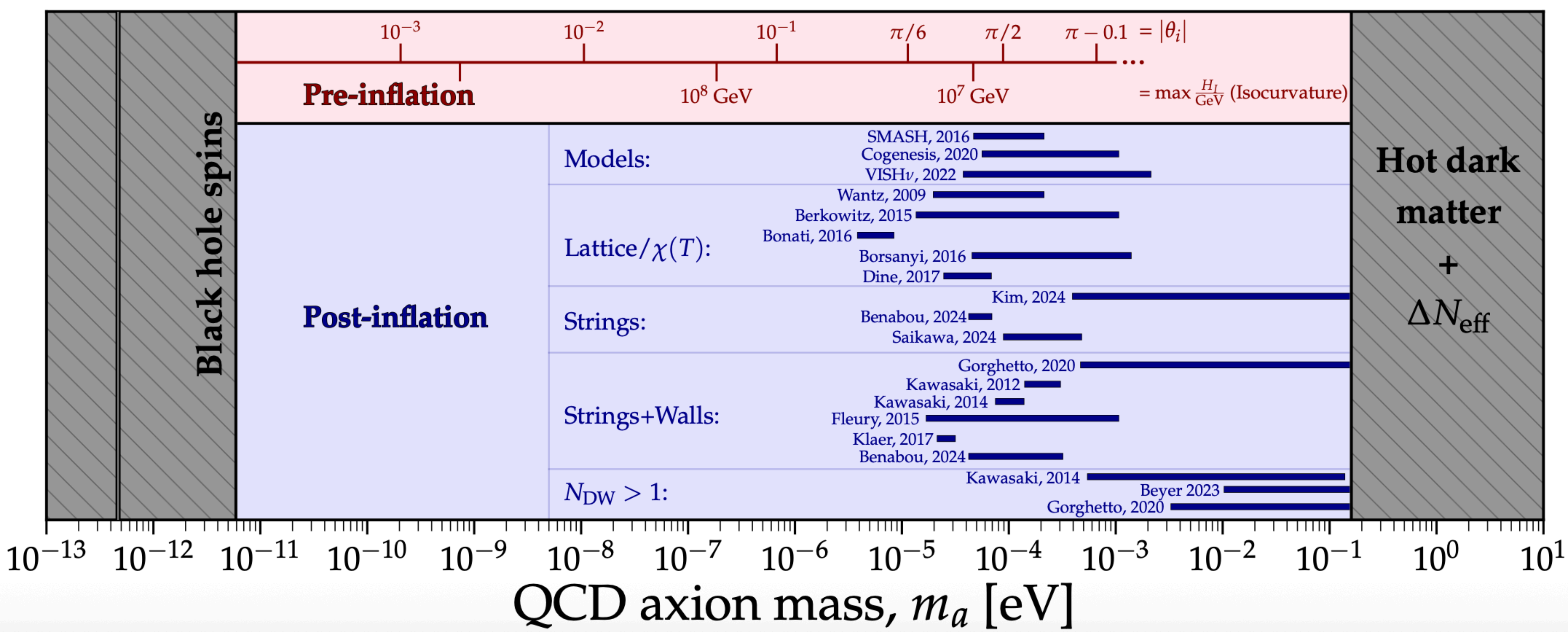
[https://cajohare.github.io/AxionLimits]



Back to PQ mechanism

- New spin-0 boson with a pseudo-shift symmetry $a \to a + \kappa f_a$

broken by $\frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G}$ $\longrightarrow$ $E(0) \leq E(\langle a \rangle)$ [Vafa, Witten PRL 53 (1984)]

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$$\theta_{\rm eff} = \frac{\langle a \rangle}{f_a}$$

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

**path-integral measure positive definite for a vector-like theory (e.g. QCD)*

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- Does the axion really relax to zero ?

→ $\theta_{\rm eff} = \frac{\langle a \rangle}{f_a} \sim G_F^2 f_\pi^4 j_{\rm CKM} \approx 10^{-18}$ [Georgi, Randall, NPB276 (1986)]

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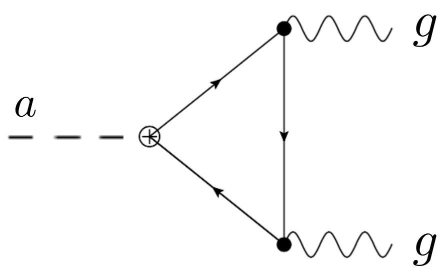
- its origin can be traced back to a <u>global</u> U(1)$_{PQ}$ [Peccei, Quinn '77, Weinberg '78, Wilczek '78]

1. spontaneously broken (the axion is the associated pNGB)
2. QCD anomalous

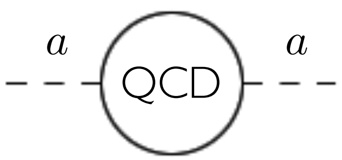


$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G}$$

Axion properties

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

Axion mass



$$\sim \frac{\Lambda_{\rm QCD}^4}{f_a^2} \qquad \longrightarrow \qquad m_a \sim \Lambda_{\rm QCD}^2/f_a$$

Axion properties

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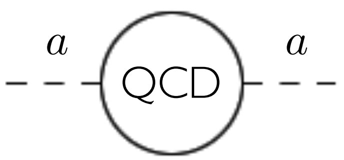
Axion mass



$\sim \frac{\Lambda_{\rm QCD}^4}{f_a^2}$ $\longrightarrow$ $m_a = 5.691(51)\,\text{meV}\left(\frac{10^9\,\text{GeV}}{f_a}\right)$

[Gorghetto, Villadoro 1812.01008 (NNLO chiPT)
Bonati et al, 1512.06746 + Borsanyi et al 1606.07494 (lattice)]

$f_a \gtrsim 10^9$ GeV from astrophysics $\longrightarrow$ very light & weakly coupled

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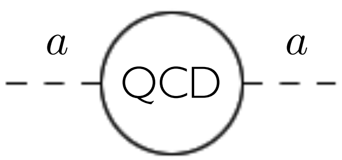

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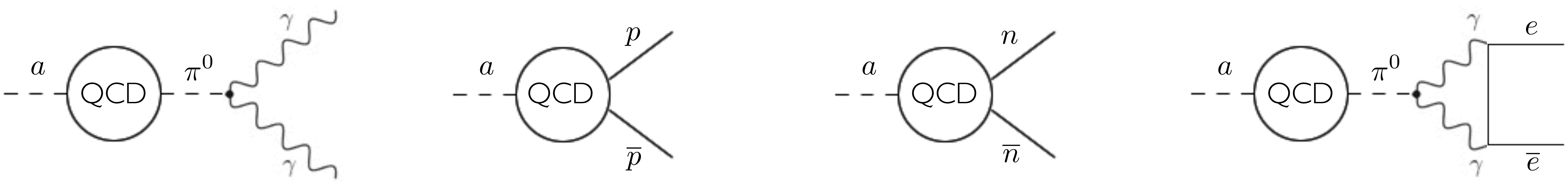
- experimentally, more useful to think about the axion as wave

$$\lambda_a = \frac{h}{m_a c} \sim 20 \text{ cm}\,\frac{\mu\text{eV}}{m_a}$$

Axion properties

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

Axion couplings to photons, nucleons, electrons, …



$$C_\gamma = -1.92(4) \qquad C_p = -0.47(3) \qquad C_n = -0.02(3) \qquad C_e = -7.8(2)\times 10^{-6}\log\left(\frac{f_a}{m_e}\right)$$

$$\mathcal{L}_a \supset \frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{C_f}{2f_a}\partial_\mu a\bar{f}\gamma^\mu\gamma_5 f \qquad (f = p, n, e)$$

[Grilli di Cortona, Hardy, Vega, Villadoro 1511.02867 (NLO chiPT)
Lu, Du, Guo, Meißner, Vonk 2003.01625 (NNLO chiPT)]

Axion properties

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

Axion couplings to photons, nucleons, electrons, …

A motivated target for experiments,
but UV completion can drastically affect low-energy axion properties

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Benchmark axion models

- global $U(1)_{PQ}$ (QCD anomalous + spontaneously broken)

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

SM fermions | BSM fermions

2Higgs

PQWW

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

2Higgs+Singlet

DFSZ

[Zhitnitsky '80,
Dine, Fischler, Srednicki '81]

Higgs+Singlet

KSVZ

[Kim '79,
Shifman, Vainshtein, Zakharov '80]

$f_a \sim v$ ruled out

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

Benchmark axion models

- global U(1)$_{\mathrm{PQ}}$ (QCD anomalous + spontaneously broken)

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

SM fermions

BSM fermions

2Higgs+Singlet

Higgs+Singlet

DFSZ

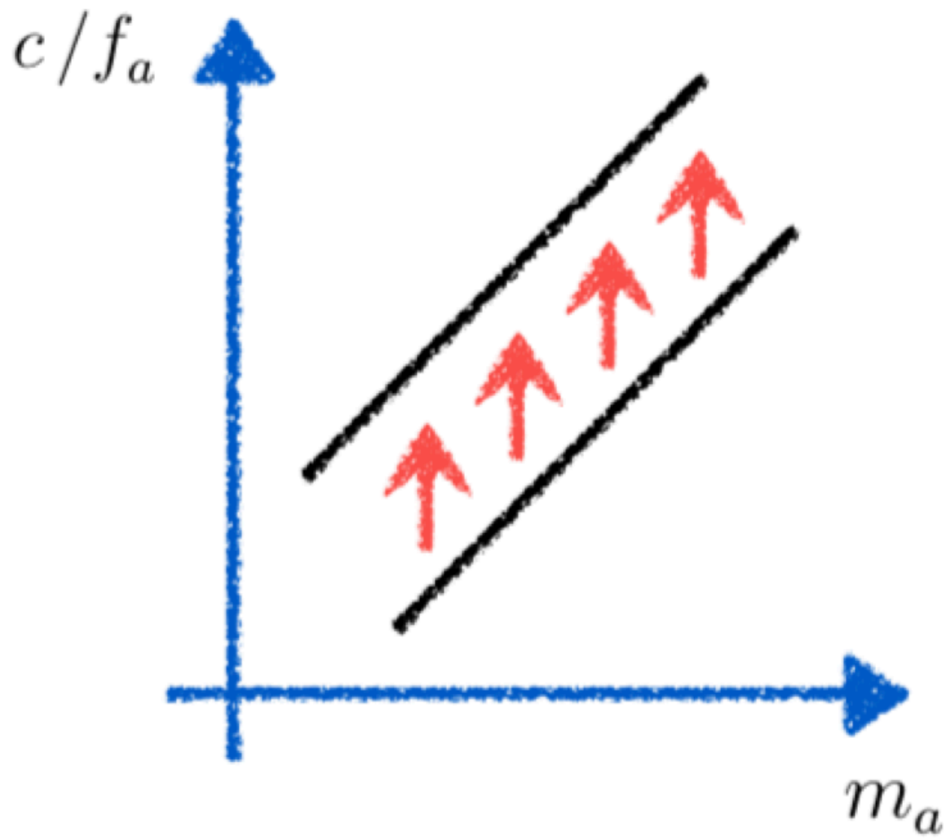
KSVZ

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

DFSZ: $E/N = 8/3$, $C_{p,n,e}(\beta) \sim \mathcal{O}(1)$

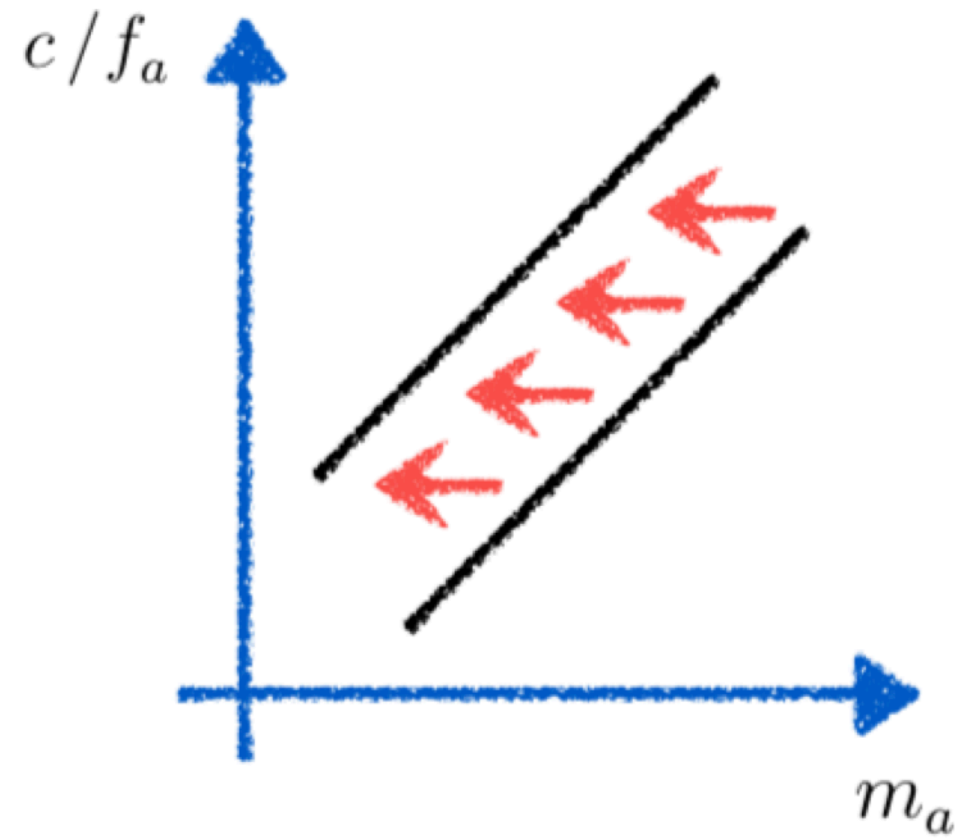
KSVZ: $E/N = 0$, $C_p \simeq -0.5$, $C_{n,e} \simeq 0$

Axions beyond benchmarks



enhance Wilson coefficient for fixed m_a

[LDL, Mescia, Nardi 1610.07593 + 1705.05370
Farina, Pappadopulo, Rompineve, Tesi 1611.09855
Agrawal, Fan, Reece, Wang 1709.06085
Darme', LDL, Giannotti, Nardi 2010.15846
Ringwald, Sokolov 2104.02574, …]

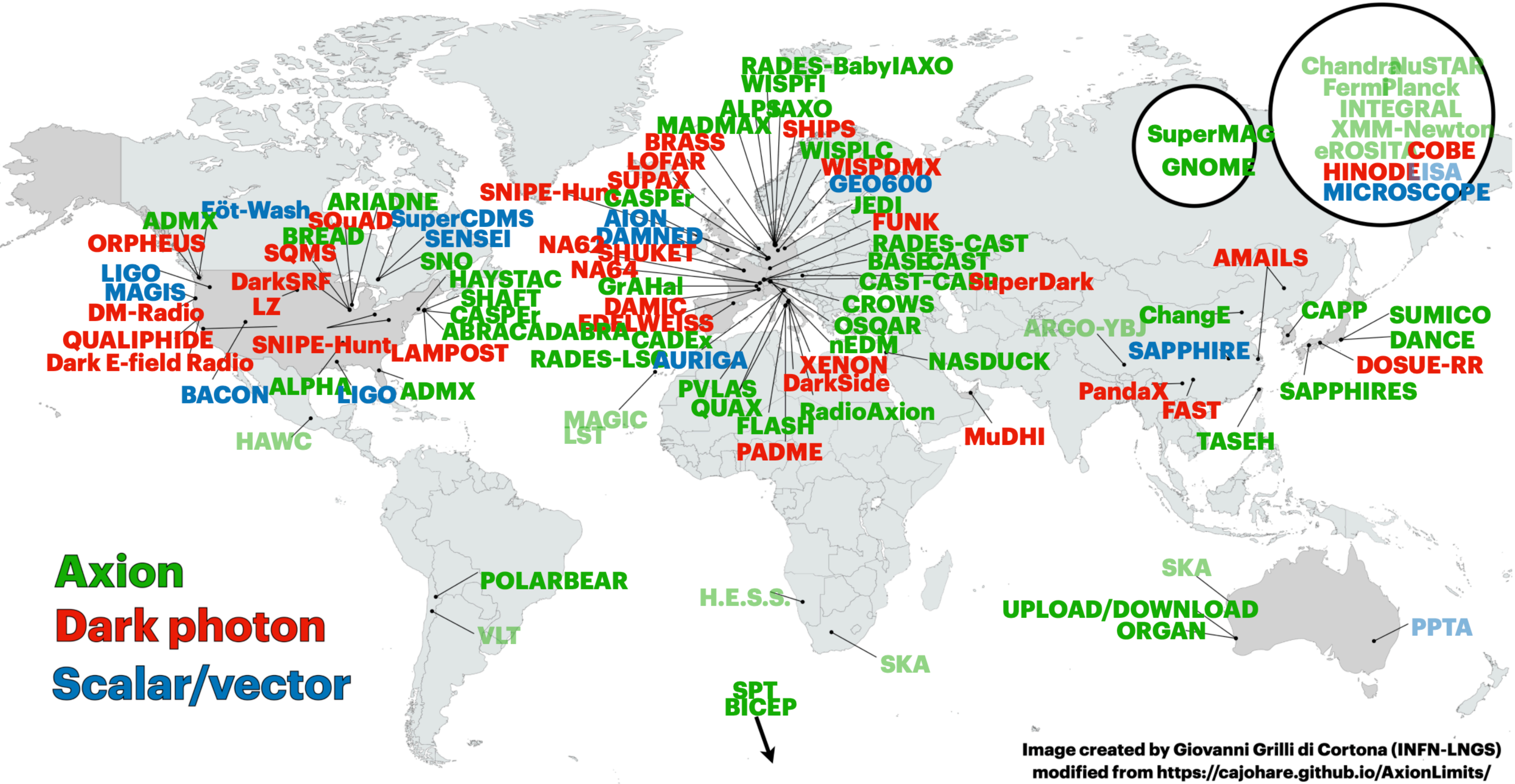


suppress axion mass for fixed f_a

[Hook 1802.10093,
LDL, Gavela, Quilez, Ringwald 2102.00012
+ 2102.01082]

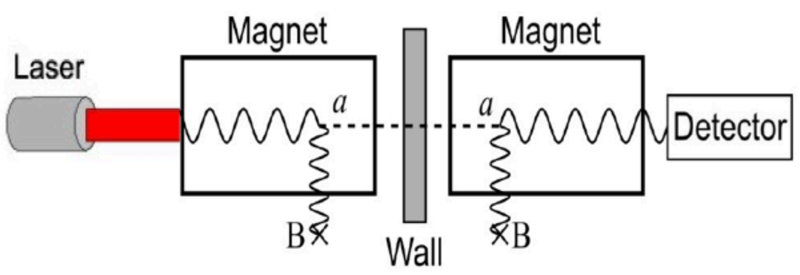
→ *QCD axion parameter space <u>much larger</u> than what traditionally thought*

Experimental landscape



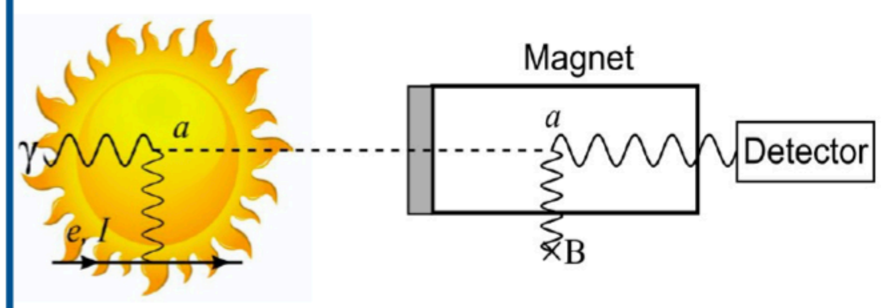
Axion detection

- Ways to look for axions



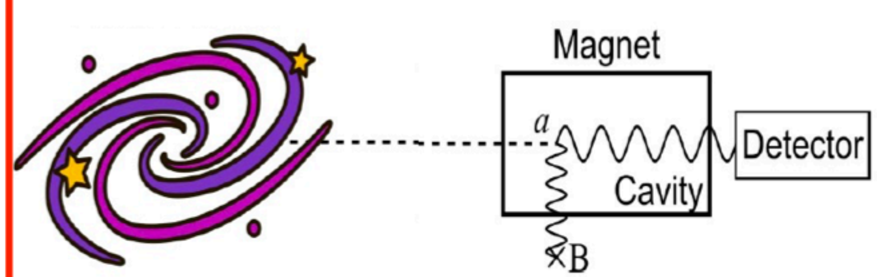
Light-Shining-Through-Wall Experiment

Laboratory-based experiments producing and detecting axions



Helioscope

Scientific instrument designed to detect axions or axion-like particles (ALPs) coming from the Sun



Haloscope

Scientific instrument designed to detect axions in the Milky Way halo

Axion detection

- Classification by couplings vs. production mechanism

	LAB	HELIO	HALO
- photons	✘	✘	✘
- electrons		✘	✘
- nucleons			✘
- EDMs			✘
- CP-violating	✘		
- flavour-violating	✘		
- …			

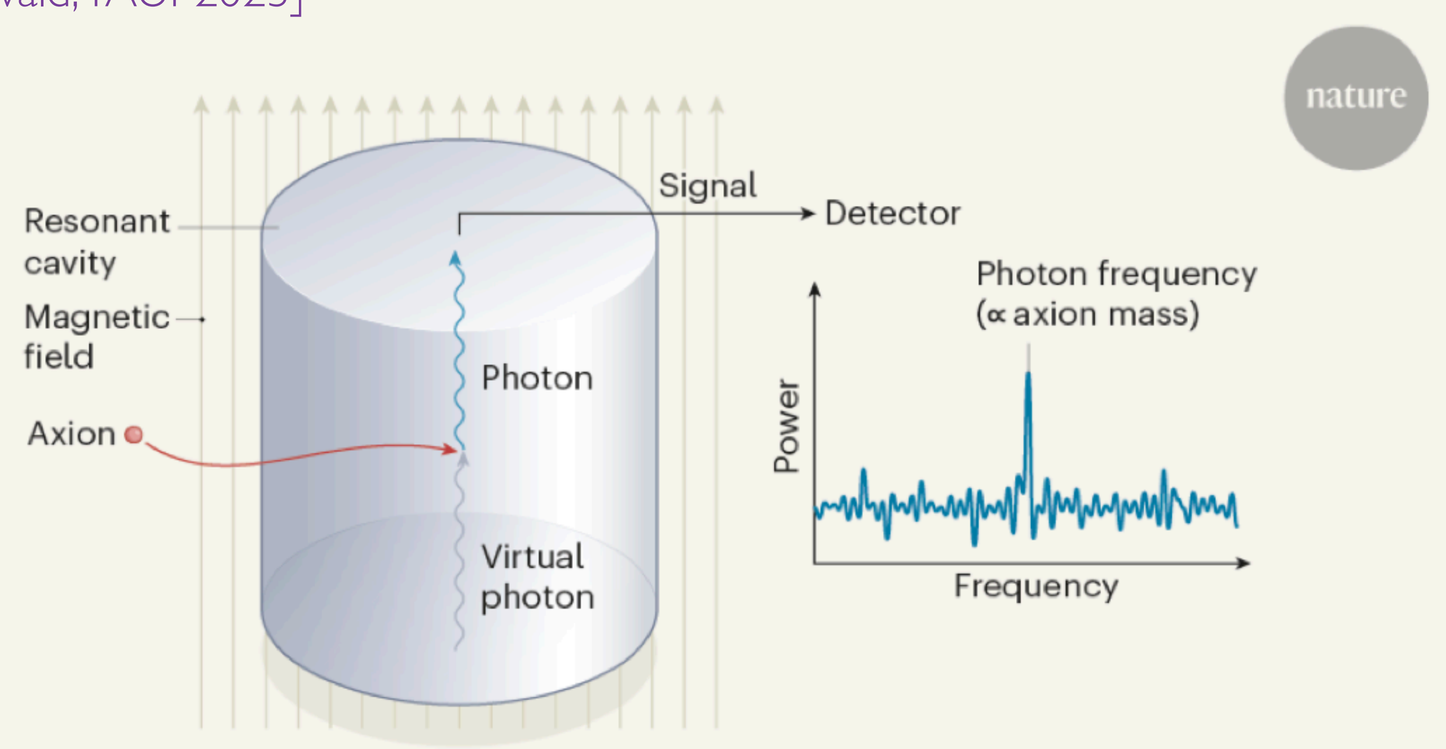
Axion-photon

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

Haloscope principle: P. Sikivie, *Phys. Rev. Lett.*, **51**, 1415 (1983)

- **Concept:** In microwave cavity placed in magnetic field, DM axion converts into photon

[A. Ringwald, TAUP2023]



[Irastorza, Nature '21]

- If axion mass matches resonance frequency of cavity,

$$m_a = 2\pi\nu_{\rm res} \sim 4\,\mu{\rm eV}\left(\frac{\nu_{\rm res}}{\rm GHz}\right)$$

power output

$$P_{\rm out} \sim g_{a\gamma}^2\,\rho_{\rm a}\,B_0^2\,V\,Q$$

enhanced by quality factor

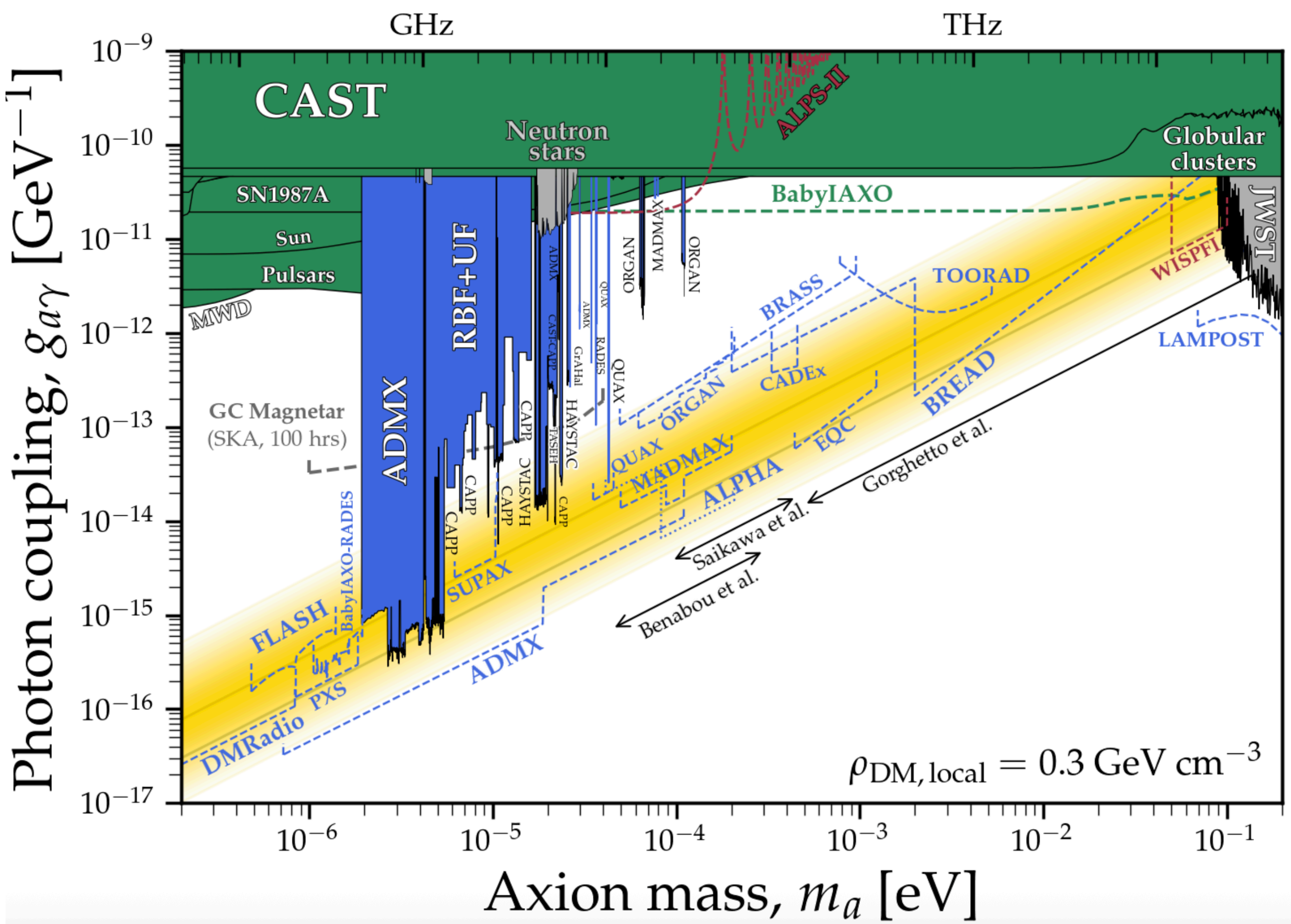
$$Q \sim 10^5$$

- Need to scan by tuning resonance frequency

Axion-photon

- $\mathscr{L} \supset \frac{1}{4} g_{a\gamma}\, a F \tilde{F}$ → *the QCD axion DM hypothesis will be largely tested in the next decades*

[https://cajohare.github.io/AxionLimits]



Axion-electron

- $\mathscr{L} \supset g_{ae} \frac{\partial_\mu a}{2m_e} \bar{e} \gamma^\mu \gamma_5 e$ $\longrightarrow$ $H \supset -\frac{g_{ae}}{2m_e} \vec{\nabla} a \cdot \vec{\sigma} - \frac{g_{ae}}{2m_e^2} \dot{a} \vec{\sigma} \cdot \vec{P}$

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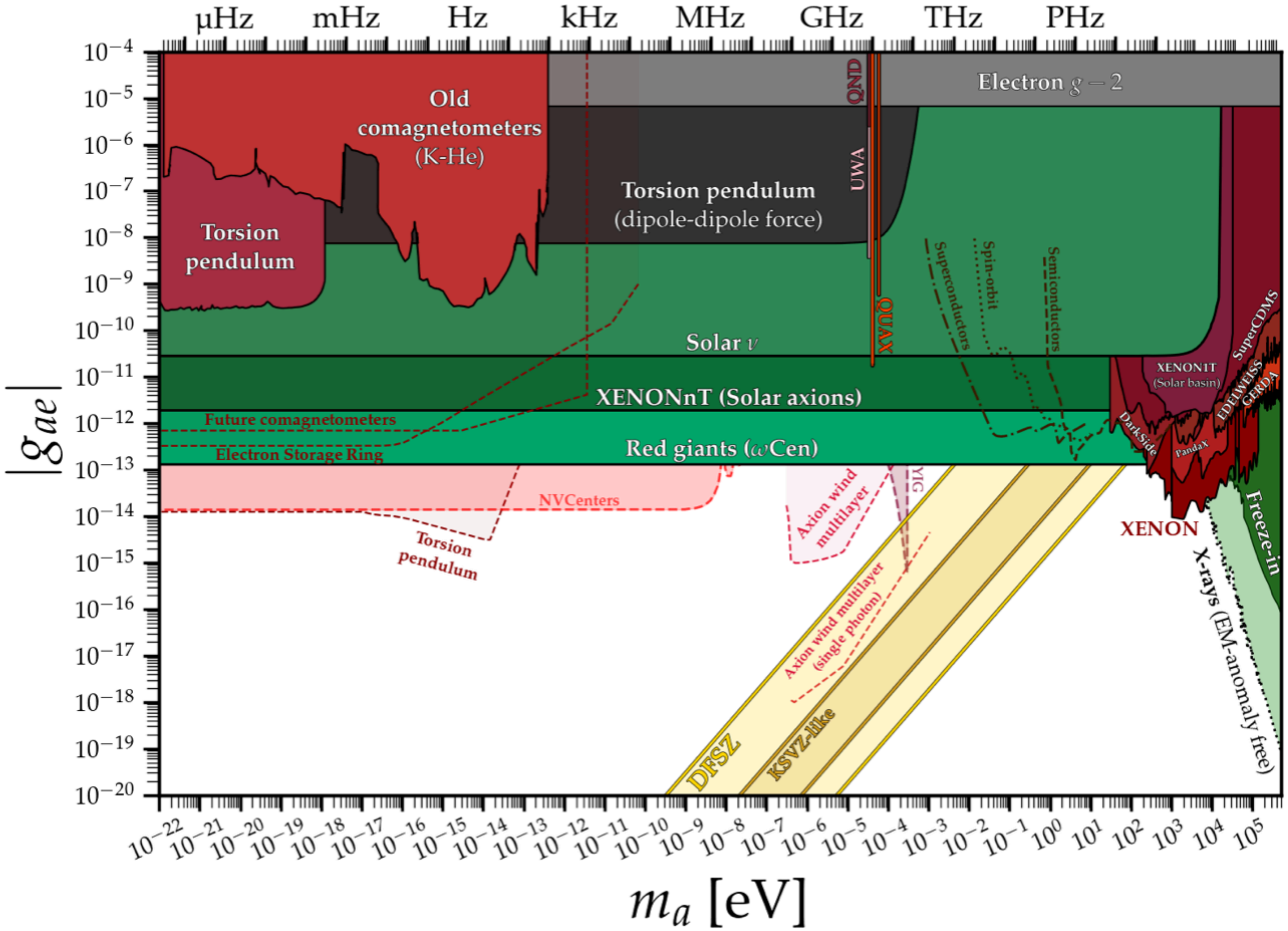
$a(t) \simeq a_0 \cos(m_a t - \vec{p} \cdot \vec{x})$

axion-wind $\qquad$ axion-electric

Axion-electron

- $\mathscr{L} \supset g_{ae} \frac{\partial_\mu a}{2 m_e} \bar{e} \gamma^\mu \gamma_5 e$ $\longrightarrow$ $H \supset -\frac{g_{ae}}{2m_e} \vec{\nabla} a \cdot \vec{\sigma} - \frac{g_{ae}}{2m_e^2} \dot{a} \vec{\sigma} \cdot \vec{P}$

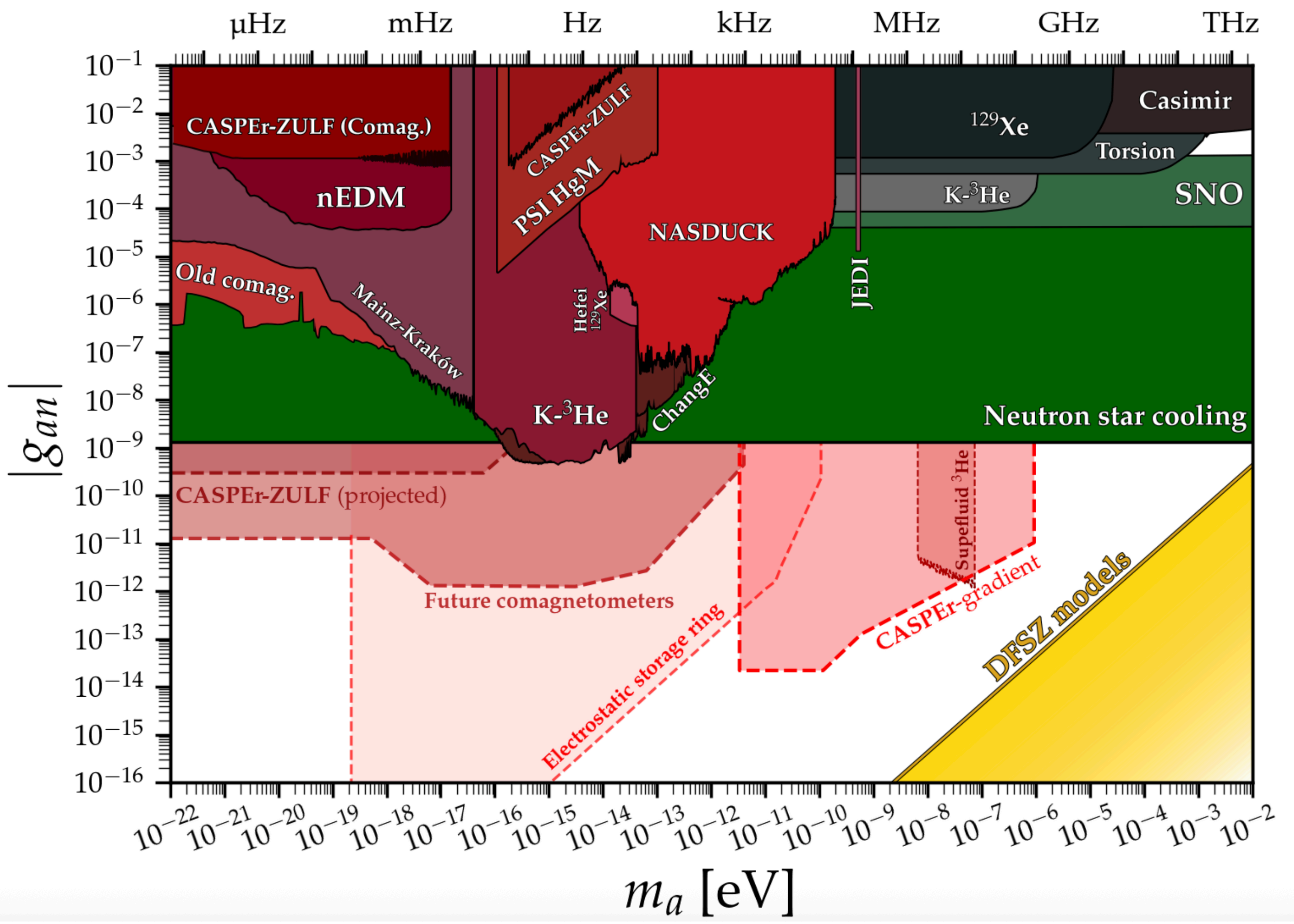
[https://cajohare.github.io/AxionLimits]



Axion-neutron

- $\mathscr{L} \supset g_{an} \dfrac{\partial_\mu a}{2m_e} \bar{n}\gamma^\mu\gamma_5 n$

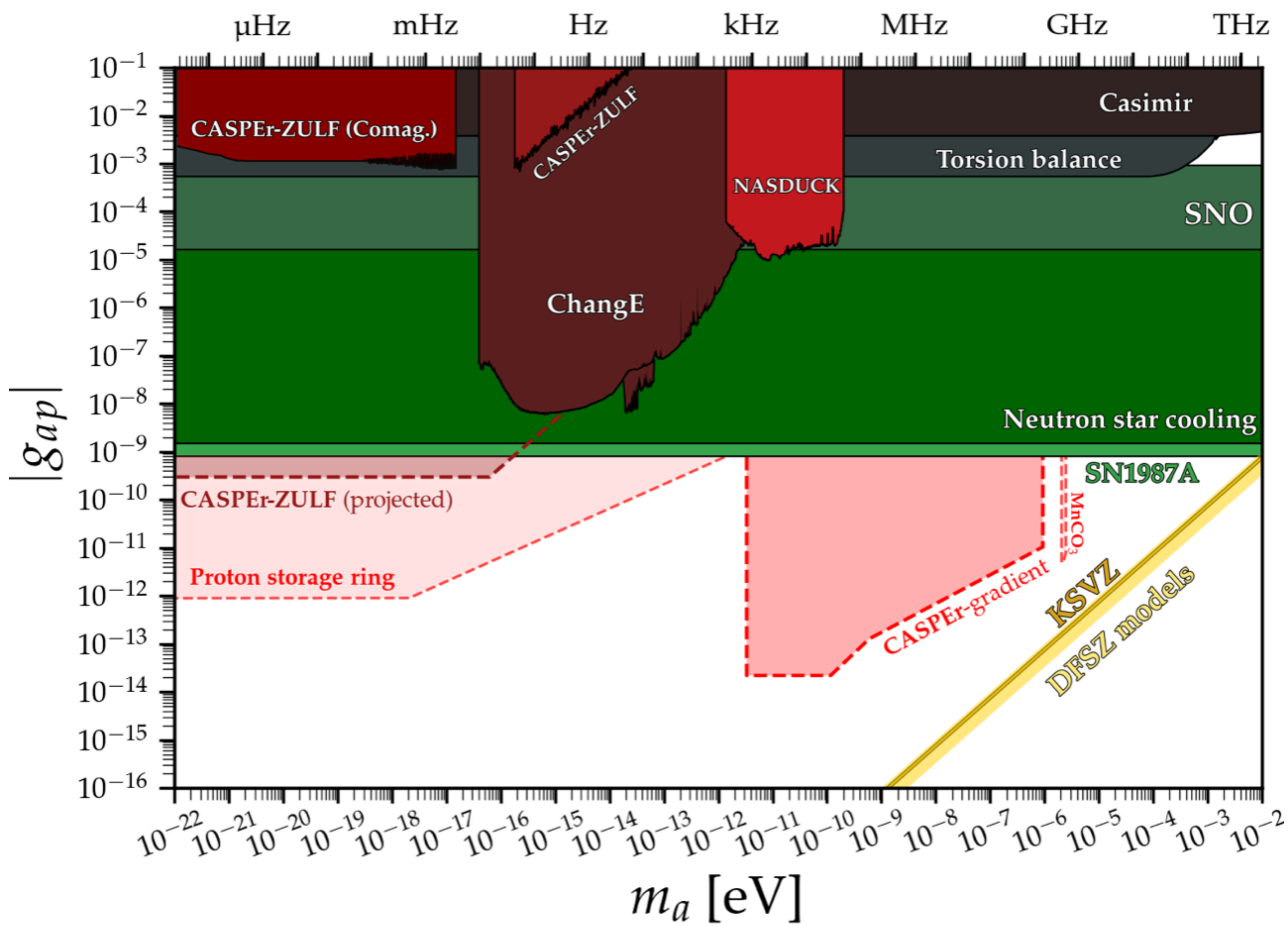
[https://cajohare.github.io/AxionLimits]



Axion-proton

- $\mathscr{L} \supset g_{ap} \frac{\partial_\mu a}{2 m_e} \overline{p} \gamma^\mu \gamma_5 p$

[https://cajohare.github.io/AxionLimits]



Axion-EDM

- CP-violating axion DM background induces an oscillating (nucleon) EDM

$$\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} \quad \longrightarrow \quad \mathcal{L} \supset -\frac{i}{2}g_{an\gamma}\, a\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

Axion-EDM

- CP-violating axion DM background induces an oscillating (nucleon) EDM

$$\mathscr{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} \longrightarrow \mathscr{L} \supset -\frac{i}{2}\underbrace{g_{an\gamma}}\, a\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

$$a(t) \simeq \sqrt{\frac{2\rho_{\rm DM}}{m_a^2}}\cos(m_a t)$$

$$d_n(t) = g_{an\gamma}\sqrt{\frac{2\rho_{\rm DM}}{m_a^2}}\cos(m_a t) \simeq 10^{-34}\, e\, cm\, \cos(m_a t)$$

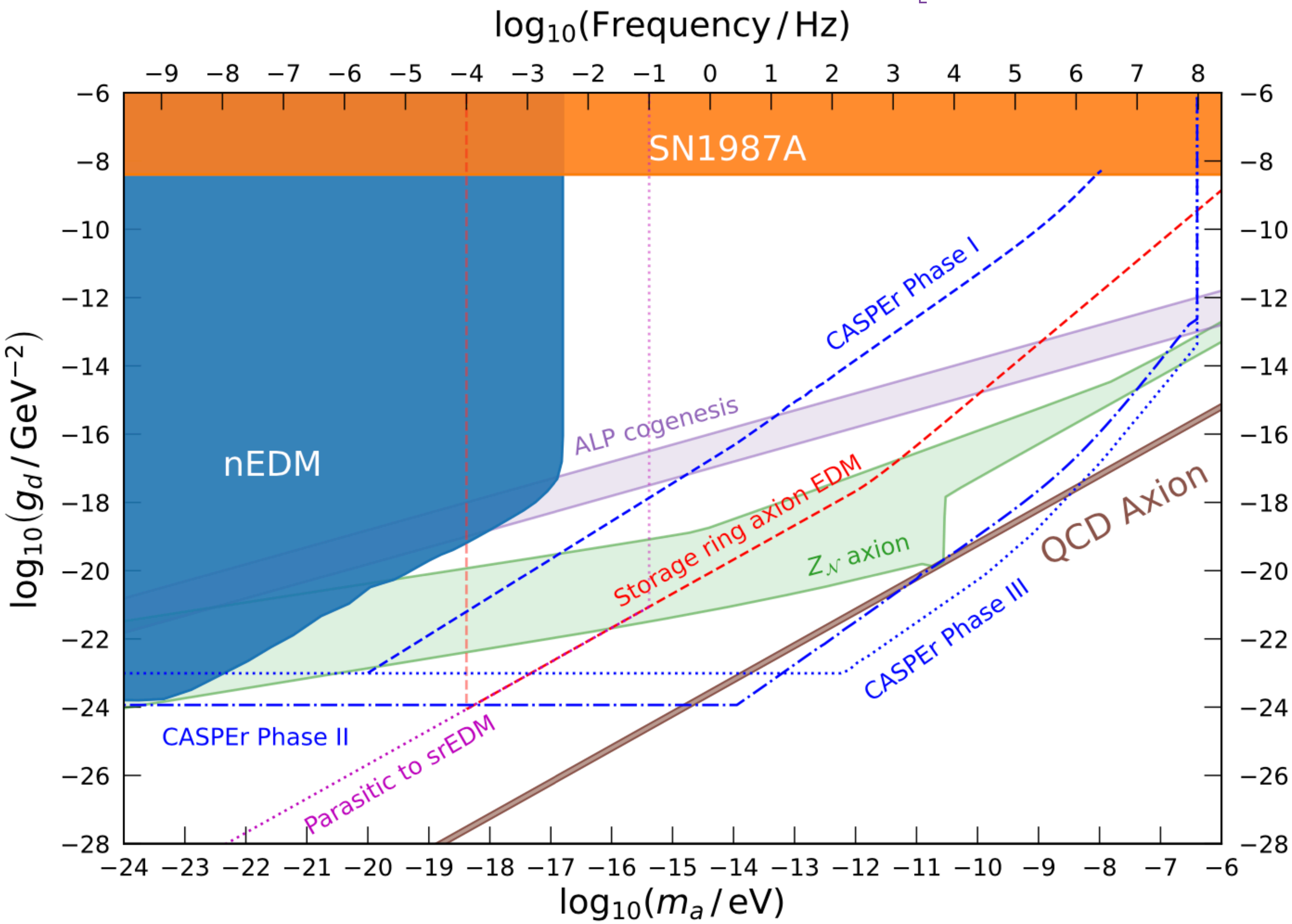
- NMR techniques (CASPEr-electric) [Graham, Rajendran Phys. Rev. D 88 (2013), Budker, Graham, Ledbetter, Rajendran, Sushkov, Phys. Rev. X 4 (2014)]

- proton storage rings [Graham et al, Phys. Rev. D 103 (2021) Kim, Semertzidis, Phys. Rev. D 104 (2021)]

Axion-EDM

- CP-violating axion DM background induces an oscillating (nucleon) EDM

[Alexander et al, 2205.00830]



RadioAxion

- Time modulation of α-radioactivity from axion DM [Broggini, Di Carlo, LDL, Toni 2404.18993]

RadioAxion

- Time modulation of α-radioactivity from axion DM [Broggini, Di Carlo, LDL, Toni 2404.18993]

$$\mathscr{L}_\theta = \frac{g_s^2\theta}{32\pi^2} G\tilde{G}$$

θ-dependence impacts nuclear physics (studied in the anthropic context)

[Ubaldi 0811.1599
Lee, Meißner, Olive, Shifman, Vonk 2006.12321]

$$\theta(t) \simeq \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a}\cos(m_a t)$$

time modulation of radioactive decays

[Tritium-decay previously considered in Zhang, Houston, Li 2303.09865]

$$I_{\rm exp}(t) \equiv (N(t) - \langle N\rangle)/\langle N\rangle$$

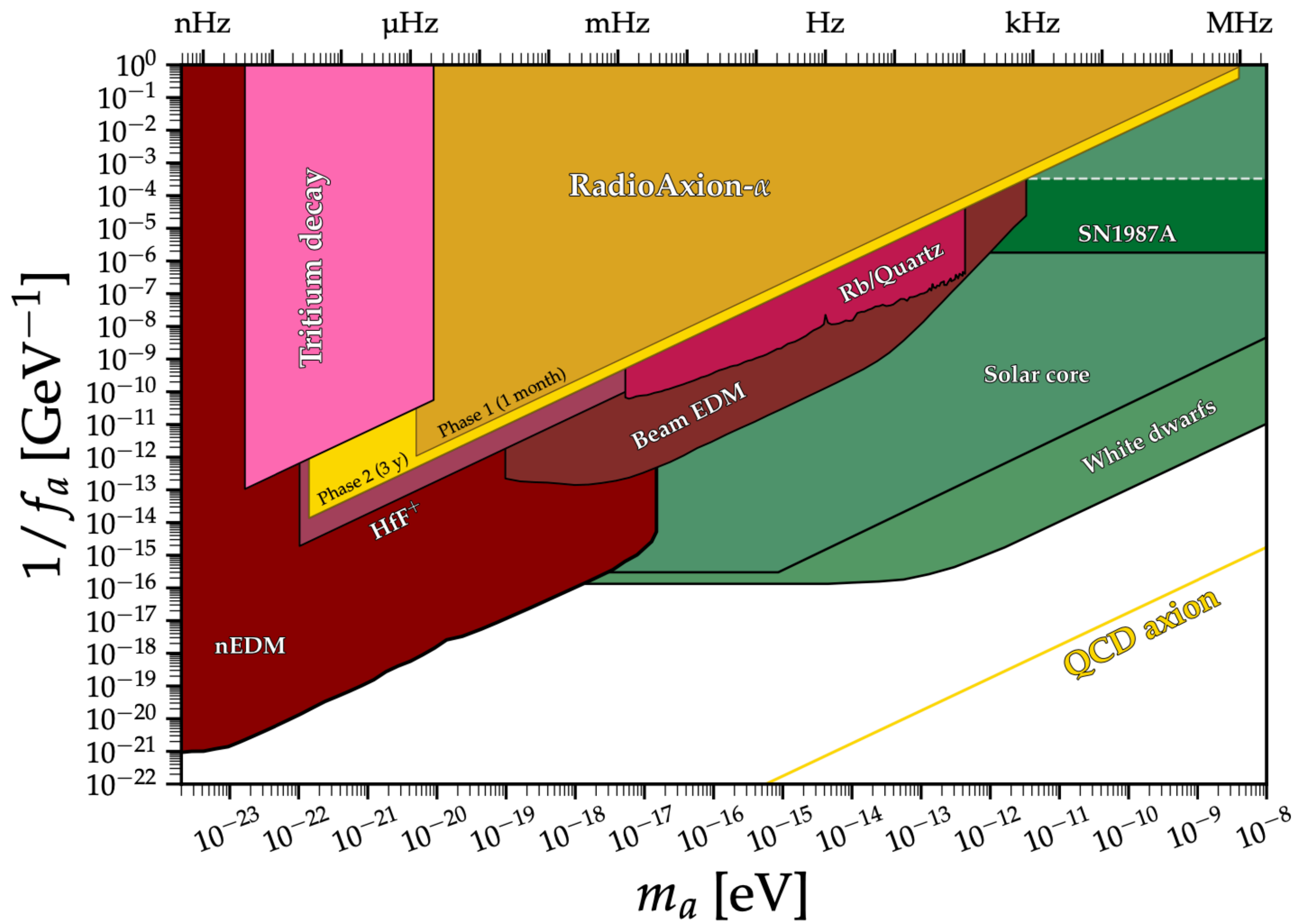
RadioAxion

- Time modulation of α-radioactivity from axion DM [Broggini, Di Carlo, LDL, Toni 2404.18993]

we computed expected time modulation for α-decay [see backup slides]

we started data taking with an ^{241}*Am source in the Gran Sasso Labs*

$$I_{\rm exp}(t) \equiv (N(t) - \langle N \rangle)/\langle N \rangle$$
$$= -4.3 \times 10^{-6} \cos(2 m_a t) \left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV/cm^3}} \right)$$
$$\times \left(\frac{10^{-16}\ {\rm eV}}{m_a} \right)^2 \left(\frac{10^8\ {\rm GeV}}{f_a} \right)^2 ,$$



[Beta decay and electron capture considered in Alda, Broggini, Di Carlo, LDL, Piatti, Rigolin, Toni 2412.20930]

CP-violating axions

- $\mathcal{L} \supset g^P_{aN} a \overline{N} i \gamma_5 N + g^S_{aN} a \overline{N} N$

$$g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\text{eff}}$$

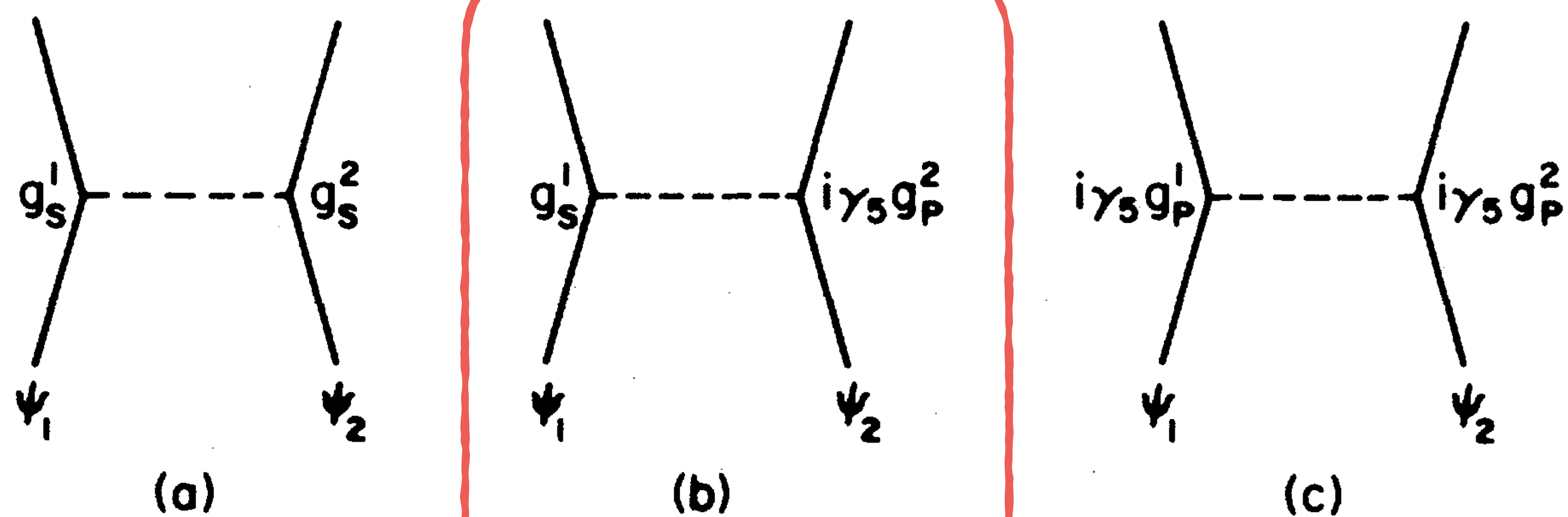
from UV sources of CP-violation or PQ breaking

[Moody, Wilczek PRD 30 (1984)
Barbieri, Romanino, Strumia hep-ph/9605368
Pospelov hep-ph/9707431
Bertolini, LDL, Nesti 2006.12508
Okawa, Pospelov, Ritz, 2111.08040
Dekens, de Vries, Shain, 2203.11230]

CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i \gamma_5 N + g^S_{aN} a \overline{N} N$ $\qquad g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\text{eff}}$ ← from UV sources of CP-violation or PQ breaking

New macroscopic forces from non-relativistic potentials [Moody, Wilczek PRD 30 (1984)]



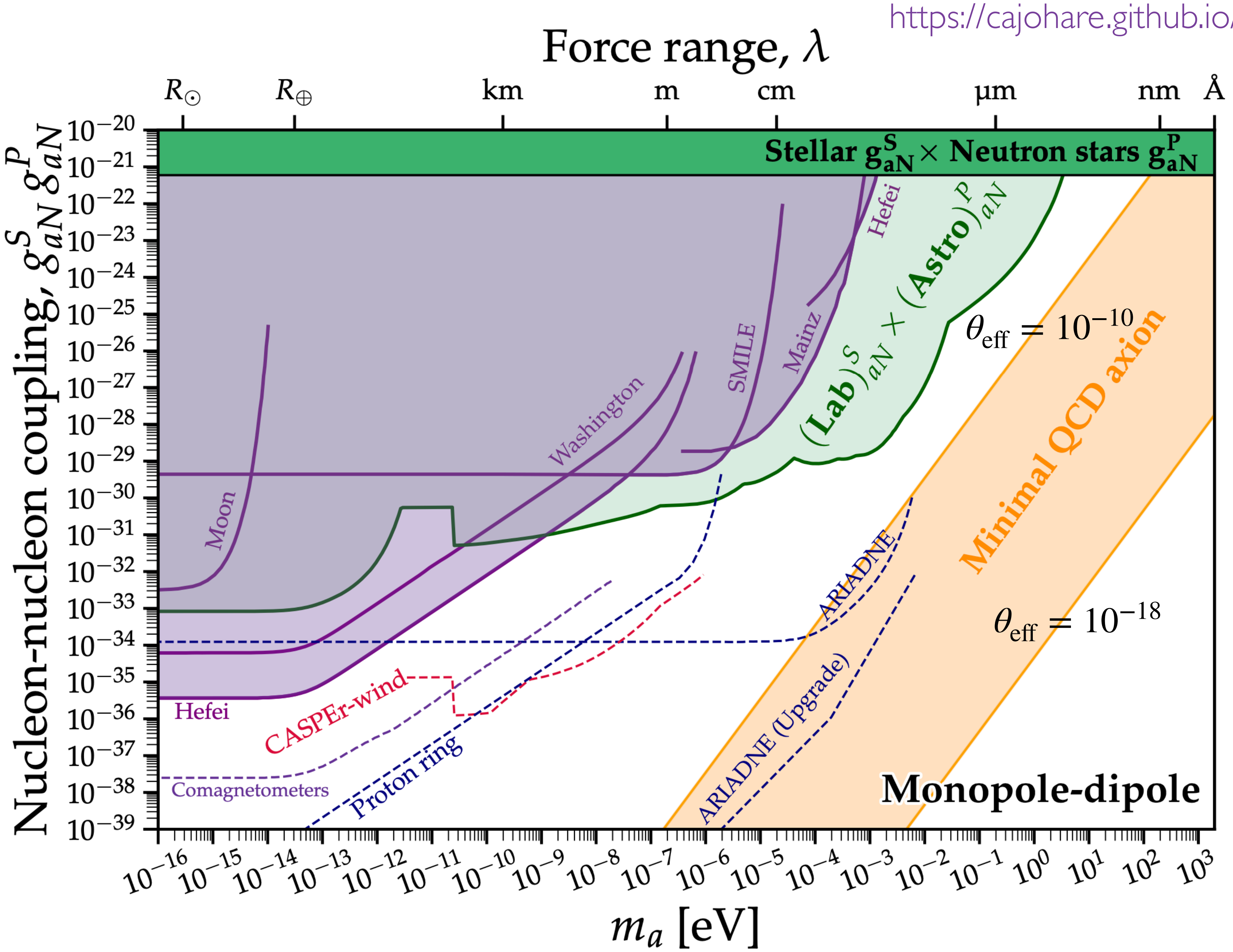
monopole-monopole | monopole-dipole | dipole-dipole

double θ_{eff} suppression | ARIADNE, QUAX-gpgs, … | *spin suppression + bkgd from ordinary magnetic forces*

CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i\gamma_5 N + g^S_{aN} a \overline{N} N$ $g^S_{aN} \sim \frac{f_\pi}{f_a}\theta_{\rm eff}$ from UV sources of CP-violation or PQ breaking

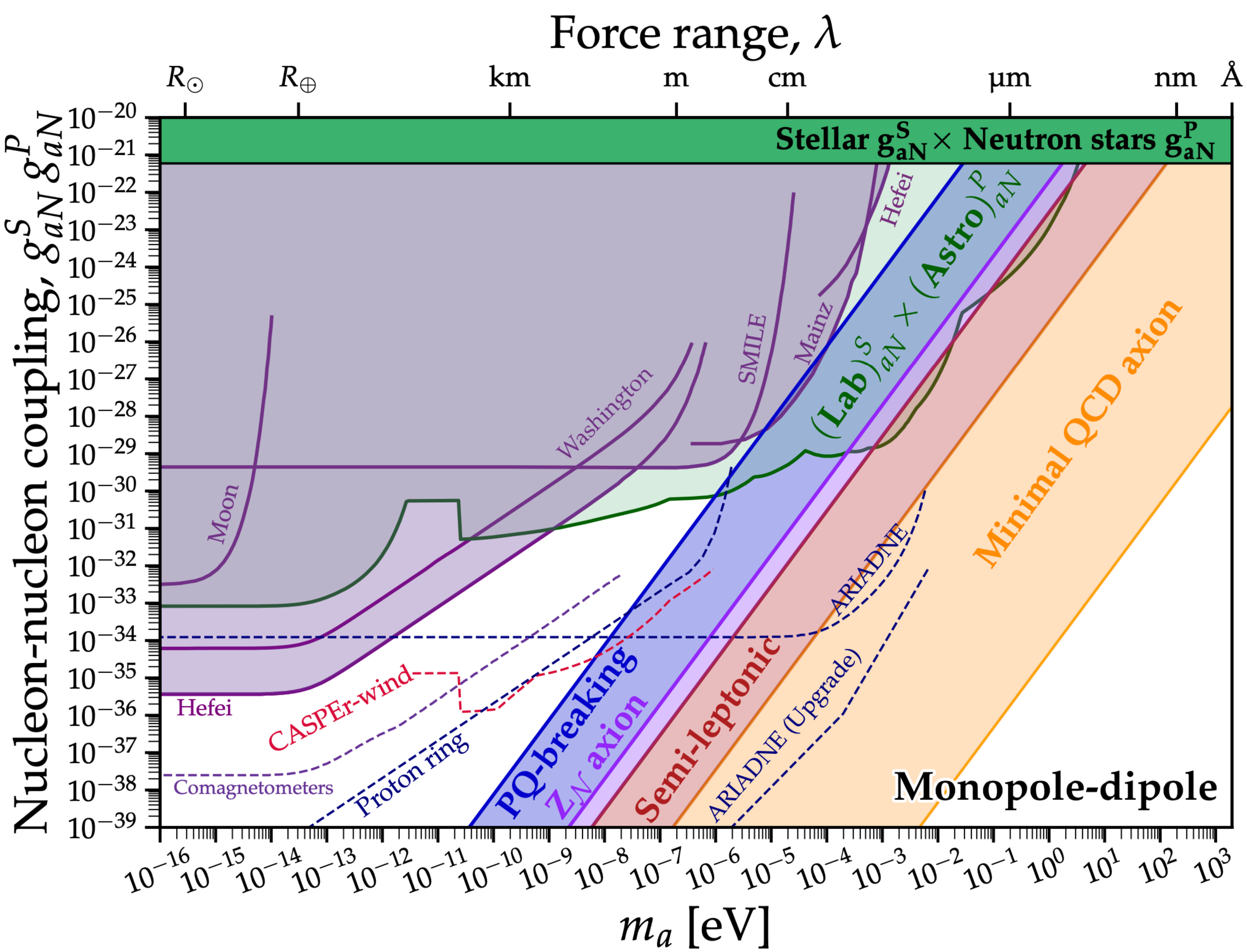
[O'Hare, Vitagliano 2010.03889 https://cajohare.github.io/AxionLimits]



CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i\gamma_5 N + g^S_{aN} a \overline{N} N$ $\qquad g^S_{aN} \sim \dfrac{f_\pi}{f_a}\theta_{\text{eff}}$ from UV sources of CP-violation or PQ breaking

[LDL, Gisbert, Nesti, Sørensen - 2407.15928]



Flavour-violating axions

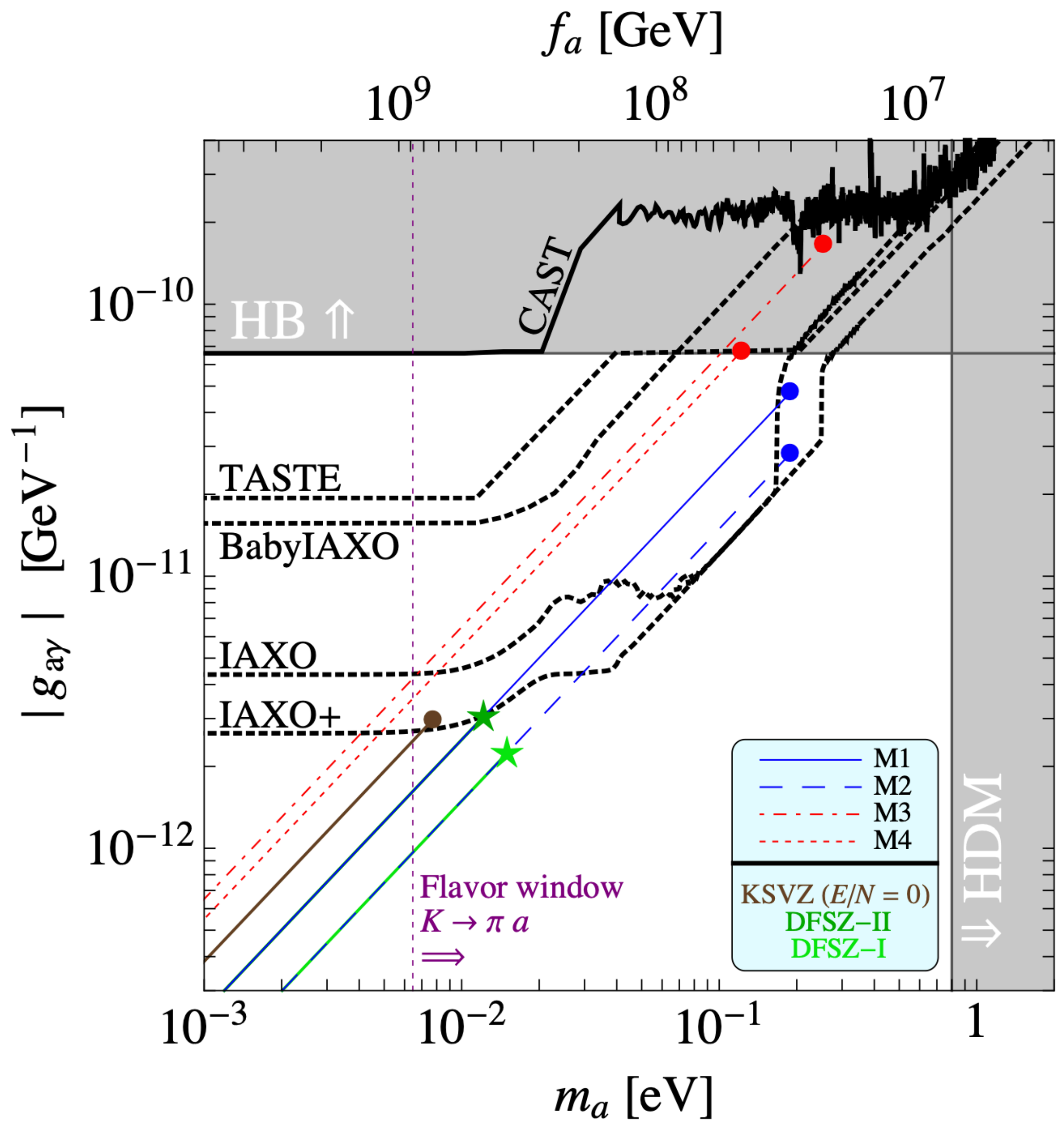
$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} \underbrace{\overline{\psi}_i \gamma^\mu (C^V_{ij} + C^A_{ij} \gamma_5) \psi_j}_{J^\mu_{\rm PQ}}$$

Flavour-violating axions

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} \underbrace{\overline{\psi}_i \gamma^\mu (C^V_{ij} + C^A_{ij}\gamma_5)\psi_j}_{J^\mu_{\rm PQ}}$$

enhance/suppress $C_{p,n,e}$

["Astrophobic Axions" with non-universal PQ allow to relax SN1987A + WD/RGB bounds by ~ 1 order of magnitude LDL, Mescia, Nardi, Panci, Ziegler, 1712.04940 + 1907.06575]



Flavour-violating axions

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2 f_a} \underbrace{\overline{\psi}_i \gamma^\mu (C^V_{ij} + C^A_{ij}\gamma_5)\psi_j}_{J^\mu_{\rm PQ}}$$

enhance/suppress $C_{p,n,e}$

$\boxed{\text{flavour-violating axion coupling}}$

$C^{V,A}_{i\neq j} \propto (V_\psi^\dagger \mathrm{PQ}_\psi V_\psi)_{i\neq j} \neq 0$ if PQ_ψ non-universal

$\rightarrow$ PQ as a flavour symmetry ?

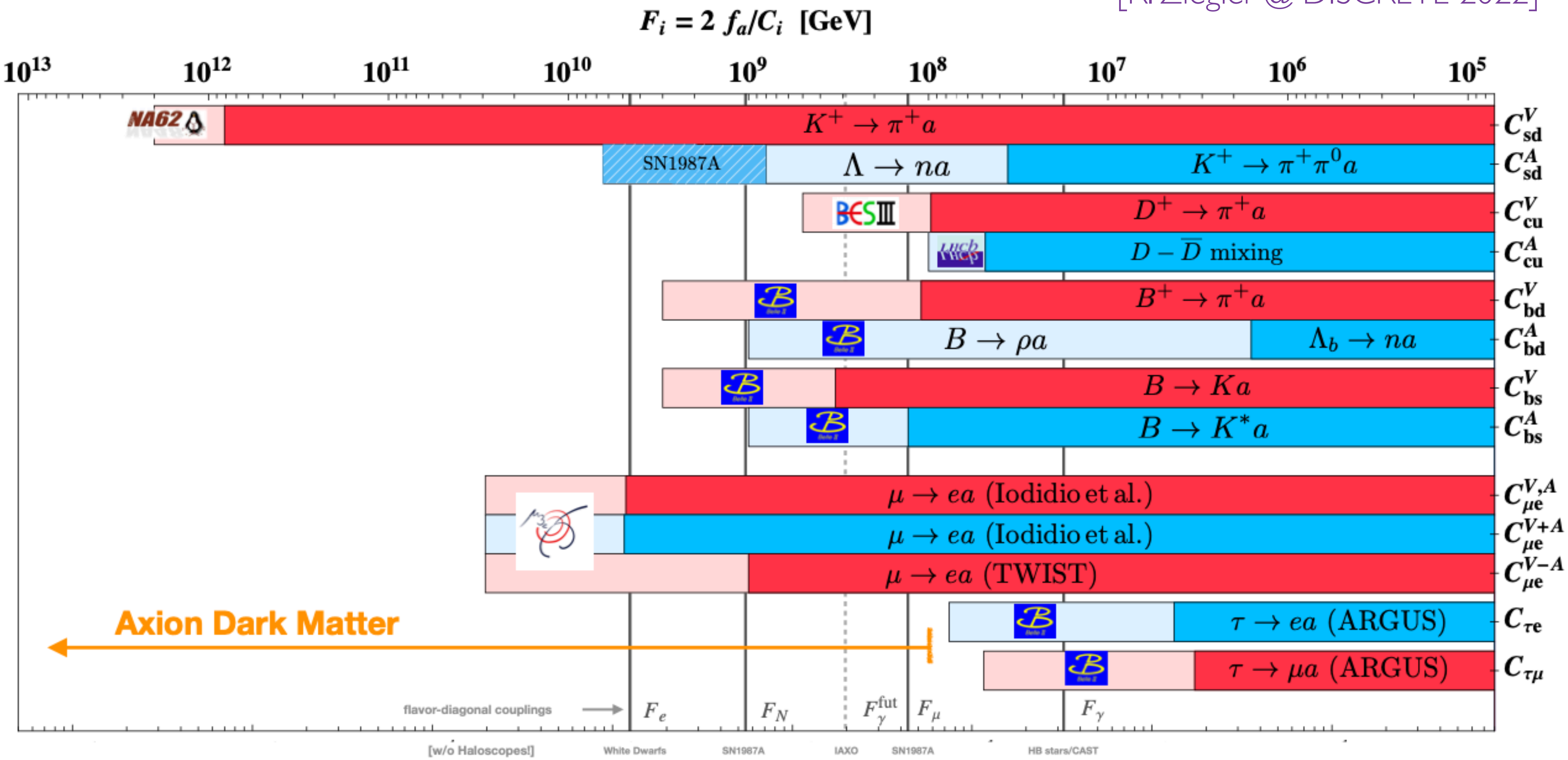
[Davidson, Wali PRL 48 (1982)
Wilczek PRL 49 (1982)
...
Ema, Hamaguchi, Moroi, Nakayama 1612.05492
Calibbi, Goertz, Redigolo, Ziegler, Zupan 1612.08040
Björkeroth, LDL, Mescia, Nardi 1811.09637]

Flavour-violating axions

$$\mathscr{L}_a \supset \frac{\partial_\mu a}{2f_a}\overline{\psi}_i\gamma^\mu(C^V_{ij} + C^A_{ij}\gamma_5)\psi_j$$

$C^{V,A}_{i\neq j} \propto (V^\dagger_\psi \mathrm{PQ}_\psi V_\psi)_{i\neq j} \neq 0$ if PQ_ψ non-universal

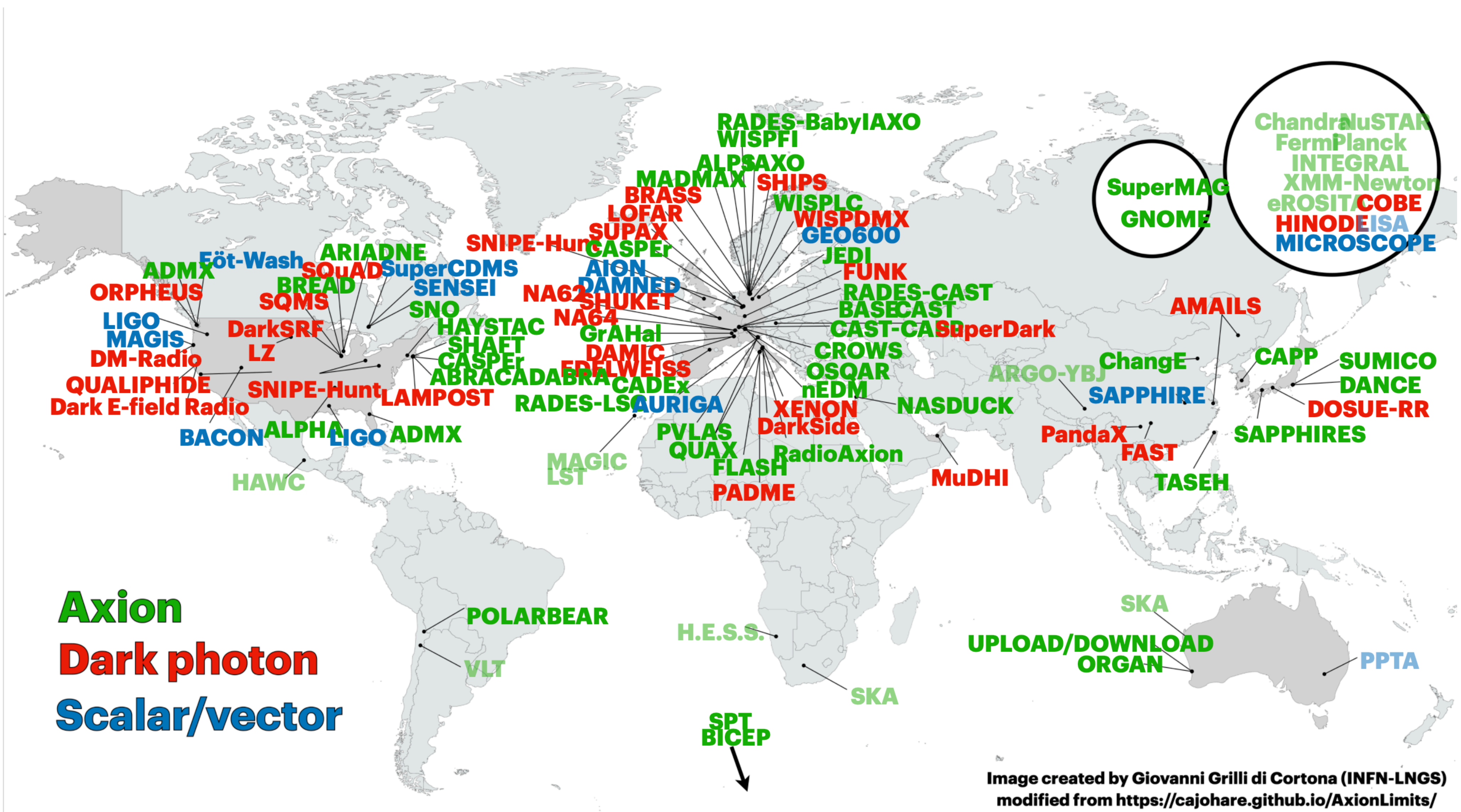
[R. Ziegler @ DISCRETE 2022]



for $C_i = \{C_\gamma, C_e, C_N, C_{sd}, C_{bs}, C_{bd}, C_{\mu e}\} = 1$ *flavour beats astrophysics !*

Conclusions

- The QCD axion provides a guide for where to search
- World-wide experimental effort, employing complementary techniques and couplings



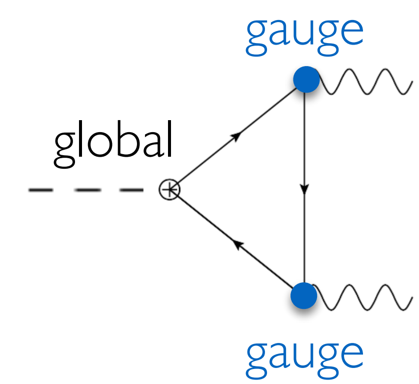
Backup slides

Enhancing $g_{a\gamma}$

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a}$$

$$\boxed{C_{a\gamma} = E/N - 1.92(4)}$$

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



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

- Pheno preferred <u>hadronic axions</u>

  1. Q-fermions short lived (no coloured relics)

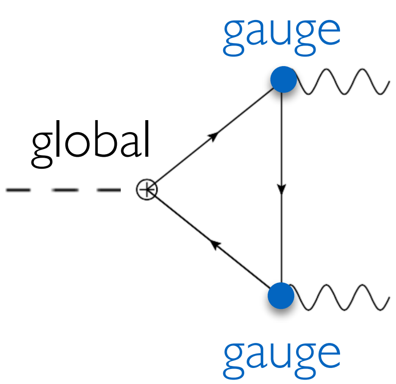
  2. No Landau poles below Planck

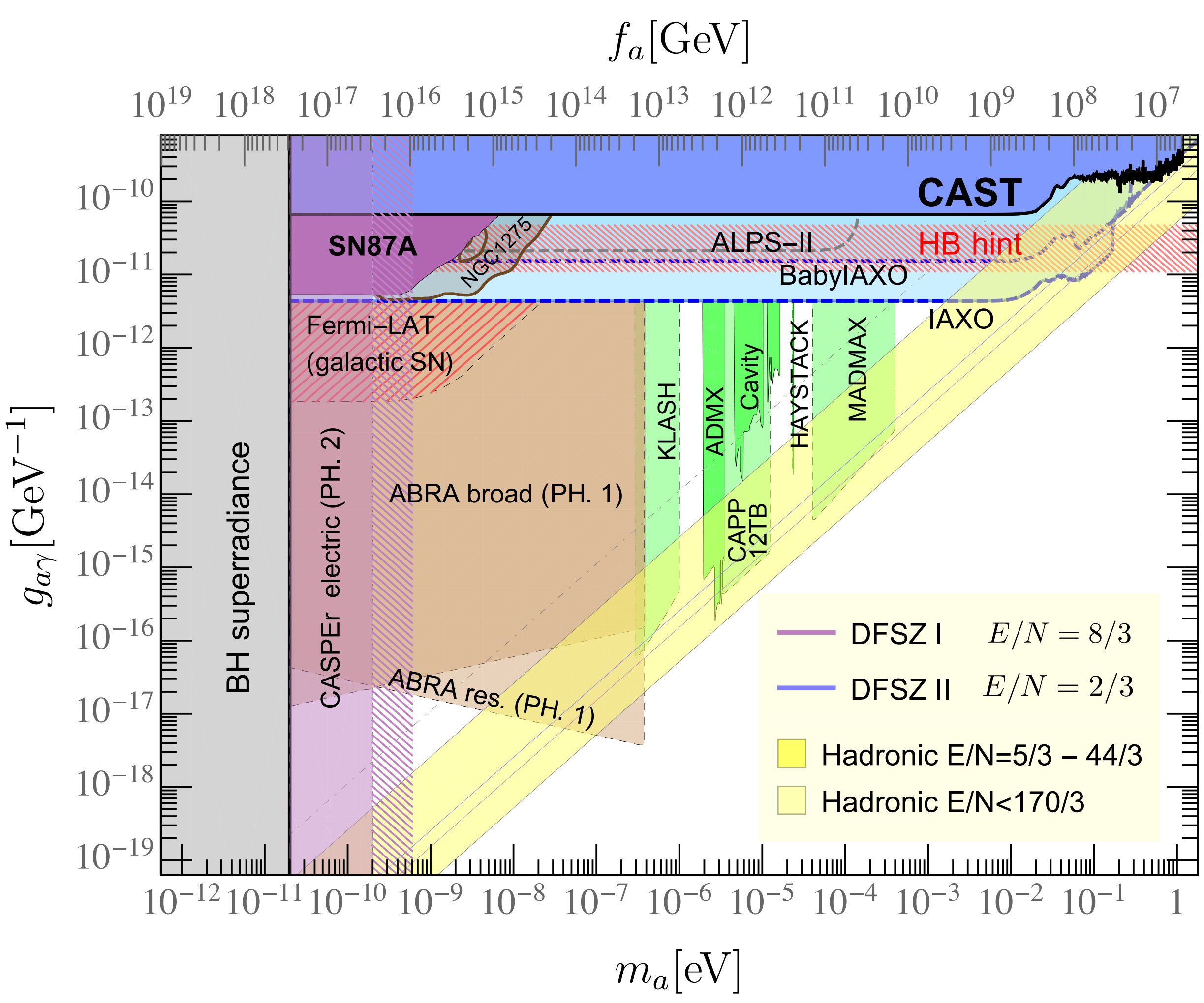
$$\longrightarrow \quad E/N \in [5/3, 44/3]$$

[LDL, Mescia, Nardi 1610.07593]

Enhancing $g_{a\gamma}$

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \qquad \boxed{C_{a\gamma} = E/N - 1.92(4)} \qquad \partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$





- Pheno preferred hadronic axions

1. Q-fermions short lived (no coloured relics)

2. No Landau poles below Planck

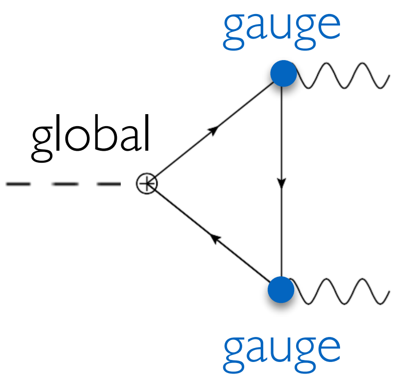
$\rightarrow$ $E/N \in [5/3, 44/3]$

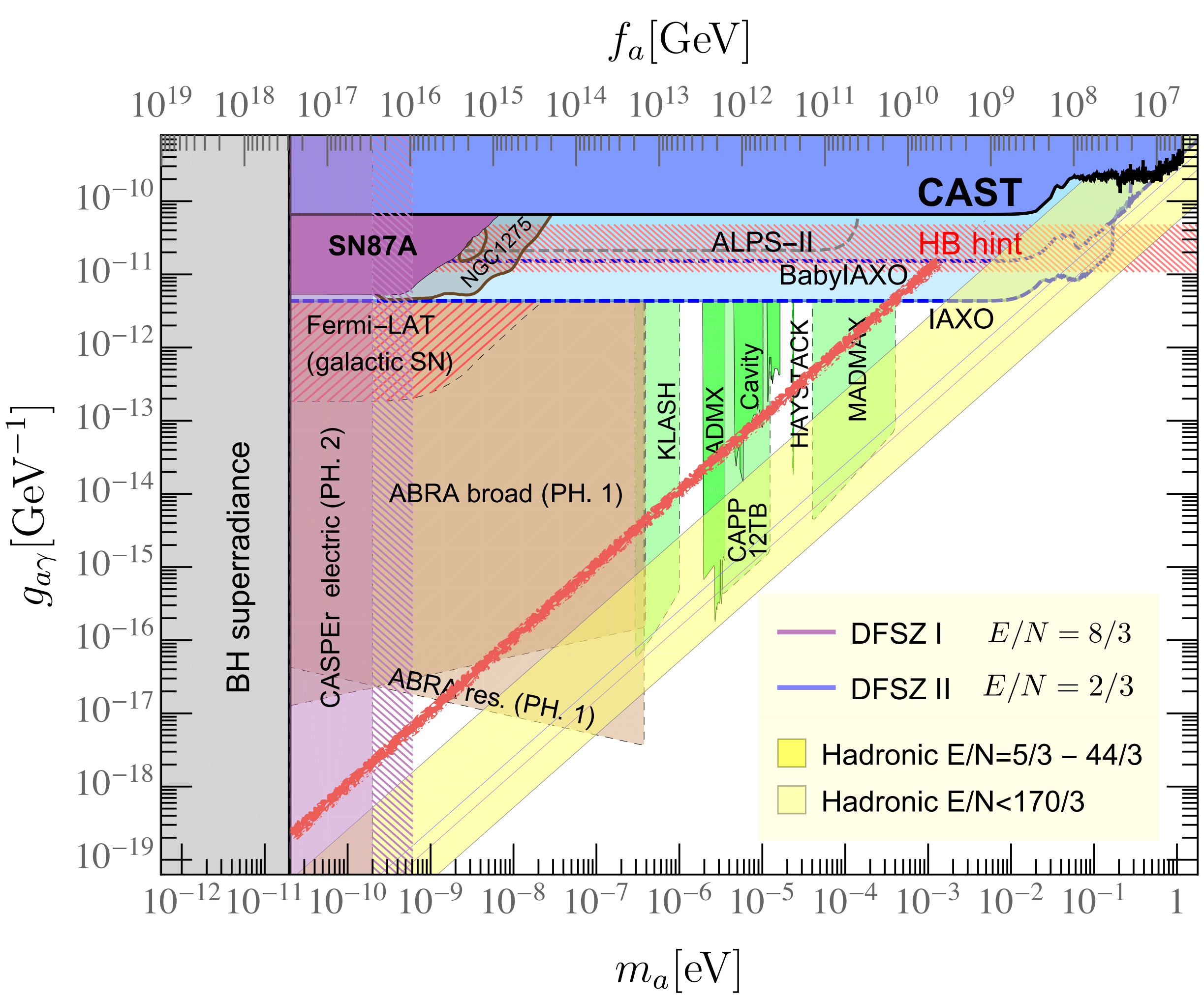
[LDL, Mescia, Nardi 1610.07593]

[LDL, Giannotti, Nardi, Visinelli 2003.01100]

Enhancing $g_{a\gamma}$

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \qquad \boxed{C_{a\gamma} = E/N - 1.92(4)} \qquad \partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$





[LDL, Giannotti, Nardi, Visinelli 2003.01100]

- Pheno preferred <u>hadronic axions</u>

  1. Q-fermions short lived (no coloured relics)

  2. No Landau poles below Planck

- More Q's ? [LDL, Mescia, Nardi 1705.05370 Plakkot, Hoof 2107.12378]

  $E/N < 170/3$ *(perturbativity)*

- Going <u>above</u> E/N = 170/3 ?

  - *boost global charge (clockwork)*

    [Farina, Pappadopulo, Rompineve, Tesi 1611.09855 Darme', LDL, Giannotti, Nardi 2010.15846]

  - *be agnostic, E/N is a free parameter*

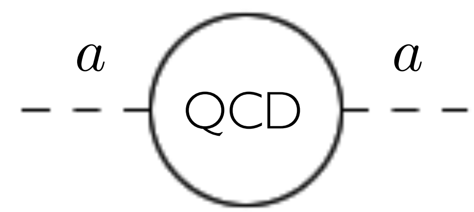
CPV beyond CKM

- Axion potential in the presence of $\mathcal{O}_{\rm CPV}$

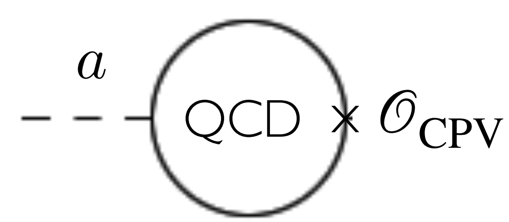
e.g. $\mathcal{O}_{\rm CPV} = \frac{1}{\Lambda^2_{\rm CPV}} (\bar{q} q)(\bar{q} i \gamma_5 q)$

$$V(a) \simeq \frac{1}{2} K \left(\frac{a}{f_a} \right)^2 + K' \left(\frac{a}{f_a} \right)$$

$$K = \langle G\tilde{G}, G\tilde{G} \rangle \sim \Lambda^4_{\rm QCD}$$



$$K' = \langle G\tilde{G}, \mathcal{O}_{\rm CPV} \rangle \sim \frac{\Lambda^6_{\rm QCD}}{\Lambda^2_{\rm CPV}}$$



$$\theta_{\rm eff} \equiv \frac{\langle a \rangle}{f_a} \simeq - \frac{K}{K'} \sim \frac{\Lambda^2_{\rm QCD}}{\Lambda^2_{\rm CPV}} = 10^{-10} \left(\frac{100 \text{ TeV}}{\Lambda_{\rm CPV}} \right)^2$$

CPV beyond CKM

- Axion potential in the presence of $\mathscr{O}_{\mathbf{CPV}}$

e.g. $\mathscr{O}_{\rm CPV} = \dfrac{1}{\Lambda^2_{\rm CPV}}(\bar{q}q)(\bar{q}i\gamma_5 q)$

Fundamental origin of CP violation / PQ breaking
Baryogenesis ?

$\Lambda_{\rm CPV}$

$\mathcal{O}_{\rm CPV}$

$\Lambda_{\rm QCD}$

$\left\langle G\tilde{G}, \mathcal{O}_{\rm CPV} \right\rangle \neq 0 \longrightarrow \theta_{\rm eff} \equiv \dfrac{\langle a \rangle}{f_a}$ nEDM

$\longrightarrow g^S_{aN}\, a\overline{N}N$ new macroscopic forces

θ-dependence of α-decay

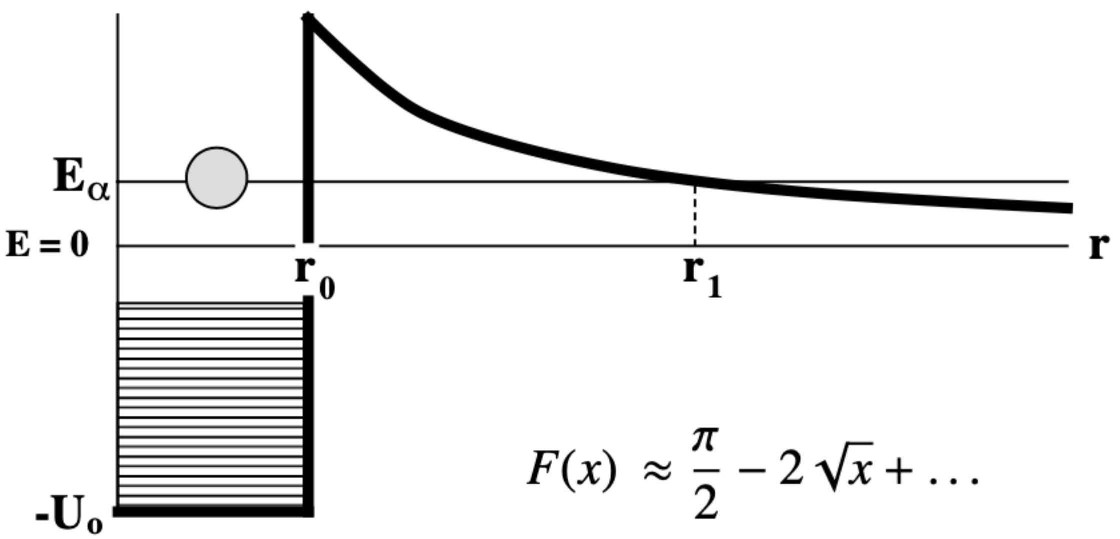
- Gamow theory of α-decay

[Broggini, Di Carlo, LDL, Toni 2404.18993]

$$T_{1/2} = \frac{\ln 2}{\nu_0}\exp(K)$$

$$K = 2\int_{r_1}^{r_2} dr\ \sqrt{2\mu[V_{\rm tot}(r) - Q_\alpha]}$$

$$= Z_\alpha Z_d \alpha_{\rm QED}\left(\frac{8\mu}{Q_\alpha}\right)^{1/2} F\left(\frac{Q_\alpha R_{\rm well}}{Z_\alpha Z_d \alpha_{\rm QED}}\right)$$



$$F(x) \approx \frac{\pi}{2} - 2\sqrt{x} + \ldots$$

- half-life is highly sensitive to Q-value $\quad Q_\alpha = \mathrm{BE}(A-4, Z-2) + \mathrm{BE}(4,2) - \mathrm{BE}(A,Z)$

- θ-term changes the size of the scalar (attractive) and vector (repulsive) nuclear interaction

$$H = G_S(\bar{N}N)(\bar{N}N) + G_V(\bar{N}\gamma_\mu N)(\bar{N}\gamma^\mu N)$$

$$\eta_S = \frac{G_S(\theta)}{G_S(\theta=0)}, \quad \eta_V = \frac{G_V(\theta)}{G_V(\theta=0)}$$

$\longrightarrow$

$$Q_\alpha(\theta) = Q_\alpha(\theta=0) - 97\ \mathrm{MeV}\ (\eta_S(\theta) - 1) \times ((A-4)^{2/3} + 4^{2/3} - A^{2/3}).$$

[Damour, Donoghue 0712.2968]

θ-dependence of α-decay

- Gamow theory of α-decay

[Broggini, Di Carlo, LDL, Toni 2404.18993]

$$T_{1/2} = \frac{\ln 2}{\nu_0}\exp(K) \qquad T_{1/2}(\theta) \approx T_{1/2}(0) + \mathring{T}_{1/2}(0)\theta^2$$

$$I(t) \equiv \frac{T^{-1}_{1/2}(\theta(t)) - \langle T^{-1}_{1/2}\rangle}{\langle T^{-1}_{1/2}\rangle} \qquad \theta(t) = \theta_0 \cos(m_a t),$$

$$\approx -\frac{1}{2}\frac{\mathring{T}_{1/2}(0)}{T_{1/2}(0)}\theta_0^2 \cos(2m_a t) \qquad \theta_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m_a f_a}$$

$$= -4.3\times 10^{-6}\cos(2m_a t)\left(\frac{\rho_{\rm DM}}{0.45\,{\rm GeV/cm^3}}\right) \times\left(\frac{10^{-16}\,{\rm eV}}{m_a}\right)^2\left(\frac{10^8\,{\rm GeV}}{f_a}\right)^2,$$

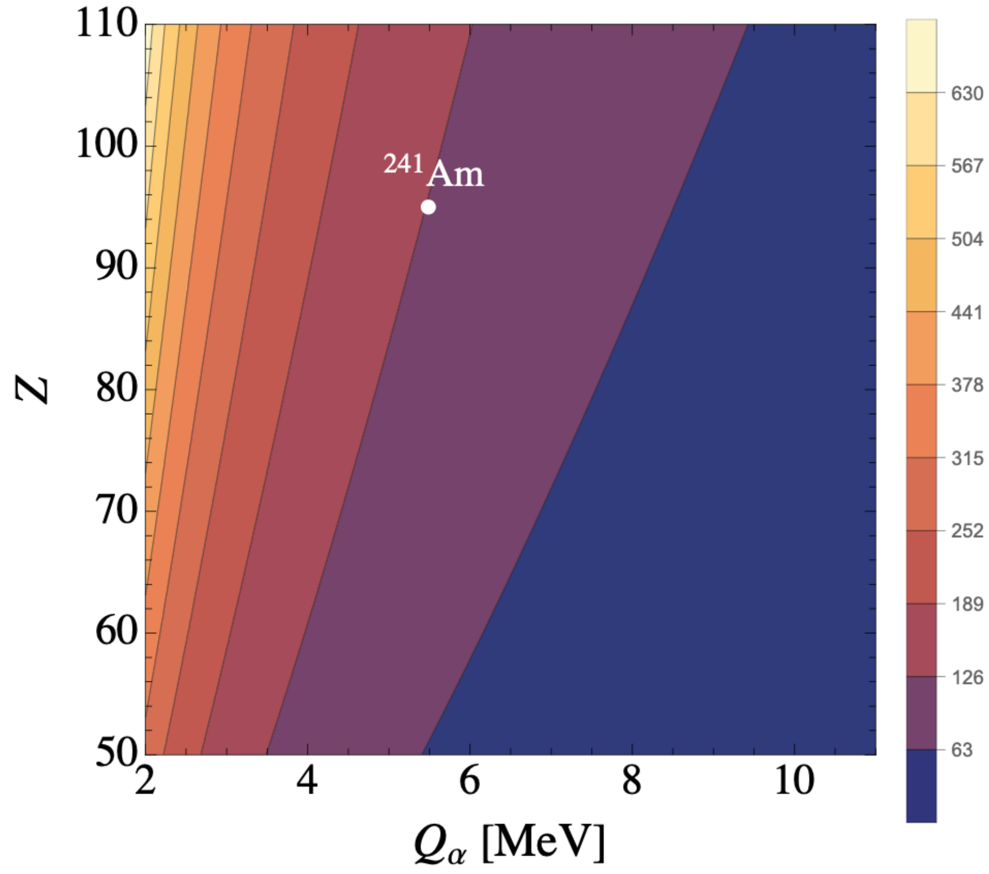


Figure A.3: Contours of $\mathring{T}_{1/2}(0)/T_{1/2}(0)$ in the (Q_α, Z) plane for $A = 241$. The case of ^{241}Am is indicated by a white dot.

$$\frac{\mathring{T}_{1/2}(0)}{T_{1/2}(0)} \approx \mathring{K} \approx \frac{\partial K}{\partial Q_\alpha}\,\mathring{Q}_\alpha \approx 8.45\,(Z-2)\left[4^{2/3} - \frac{8}{3A^{1/3}}\right]\left(\frac{\rm MeV}{Q_\alpha}\right)^{3/2}$$

≈ 125 (for Americium-241)