Recent developments in axion dark matter

高宇 （Yu Gao）
高能物理研究所（IHEP）

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Outline

- The axion story
- UV: Quality, Flavor connection
- Dark matter: Misalignment & defects
- Misalignment variants: good news?
- Astrophysics – mcs/birfrg/radio/soliton granularities
- HE experiment – Direct detection updates
- Axion laboratory news-haloscope updates
- Novel laboratory proposals (Intl & domestic) -- a quantum relation?

The axion story

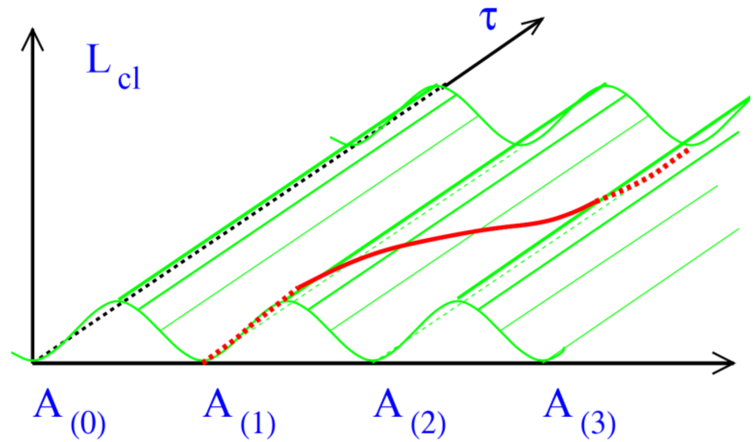
Lee & Yang, 56'; Wu, 57'

- Weak int. violates both *P* and *CP*.

Cronin, Fitch, 64'

- *CP* symmetry in strong interaction?

$$\mathcal{L} \supset -\frac{1}{4}G^2 + \frac{\theta g_s^2}{32\pi^2}G\tilde{G}$$



Classical (PG) vacua connected by instantons, hep-ph/0009136
Vacuum min. energy @ $\theta = 0$, with Dirac spectrum assumptions (Vafa, Witten 84')

In the SM, CP is broken by QCD (θ_{QCD}), as super-selection rule of QCD's instanton connected vacua

$$|\,\theta\rangle = N \sum e^{i\theta n}\,|\,n\rangle$$

And also *explicitly broken* after $U(1)_A$ breaking in the SM.
Chiral transformation shifts θ as $e^{i\alpha Q_5}|\theta>=|\theta+\alpha>$
With complex quark masses, a chiral transformation on quarks add $Arg\ det(M_q)$

$$\bar{\theta} = \theta_{QCD} + Arg\ Det\ M_q$$

Is the total angle, which breaks *P* and *T* (thus *CP* breaking), and naturally $\bar{\theta}$ ~ O(1).

$\bar{\theta}$ is an independent parameter of the theory (SM).
It is invariant under the anomalous symmetry:

$$U \to e^{i\alpha} U, \qquad \theta \to \theta - 2\alpha, \qquad M \to e^{-i\alpha} M$$

$\bar{\theta}$ in-principle only determined via measurement.
`Naturally' the combined $\bar{\theta}$ should take O(1) values.

For a conceptual review, see *"Reflections on the Strong CP Problem"*, R. Peccei, hep-ph/9807514

In the effective strong interaction potential

breaks U(1)$_A$

$$\mathcal{L} = f_\pi^2 \,\mathrm{Tr}\, \partial_\mu U \partial^\mu U^\dagger + \underline{a f_\pi^3 \,\mathrm{Tr}\, MU + b f_\pi^4 \det U} + h.c.$$

Yields the minimum at

$$\boxed{V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{\overline{\theta}}{2}}}$$

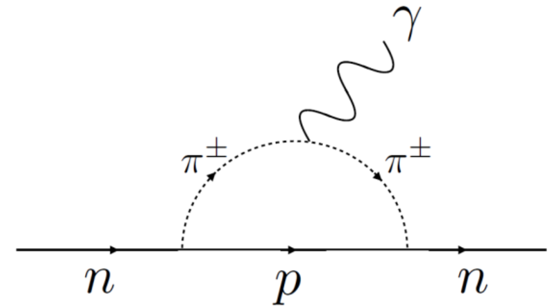
$$\overline{\theta} = \theta + \theta_u + \theta_d$$

$$b = |b| e^{i\theta}$$

$$U = e^{i \frac{\Pi^a}{\sqrt{2} f_\pi} \sigma^a}$$

$$M = \begin{pmatrix} m_u e^{i\theta_u} & 0 \\ 0 & m_d e^{i\theta_d} \end{pmatrix}$$

The strong CP problem



Feynman diagram for neutron EDM

$\bar{\theta}$ causes CP-violation and appears in baryon EDM:

$$\mathcal{L} = -\bar{\theta}\frac{c_+\mu}{f_\pi}\pi^a N\tau^a N^c - i\frac{g_A m_N}{f_\pi}\pi^a N\tau^a N^c, \qquad \mu = \frac{m_u m_d}{m_u + m_d}$$

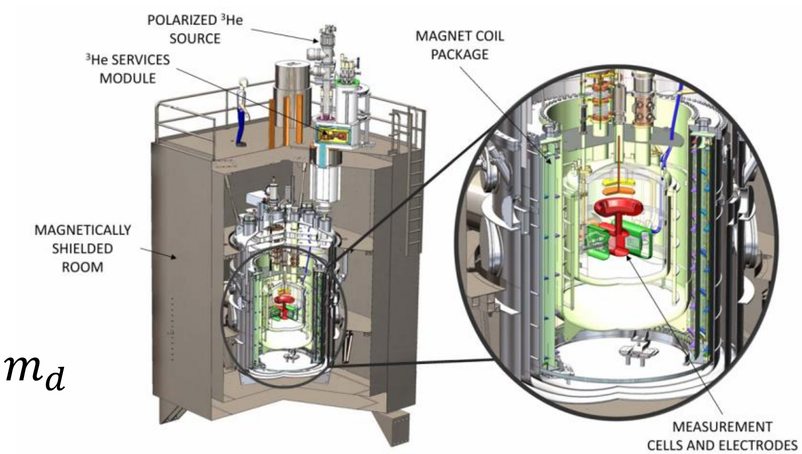
$$\boxed{d_n = \frac{e\bar{\theta} g_A c_+ \mu}{8\pi^2 f_\pi^2}\log\frac{\Lambda^2}{m_\pi^2} \sim 3\times 10^{16}\,\bar{\theta}\,\mathrm{e\ cm}}$$

$$g_A \approx 1.27$$
$$c_+ \approx 1.7$$

1509.04411

Experimental value: $\boxed{\bar{\theta} \lesssim 10^{-10}}$

10 orders of fine-tuning.



Some easy ways out:

- massless u-quark (G 't Hooft, 76'): $m_u < 10^{-10} m_d$
- P-parity models (Babu, Mahapatra, 90')
- Spontaneous CPV models (Nelson,84' & Barr, 84')

nEDM @ Oak Ridge
see recent worldwide updates: 1810.03718
& Snowmass 2203.08103

Peccei & Quinn's global U(1) symmetry

Peccei, Quinn, 77'

- After spontaneous breaking, leaves a goldstone
- Anomalous, contributes to a $U(1)_A$ rotation
- Acquires a mass (pseudo-goldstone) at low energy.

Assume a global $U(1)_{PQ}$ as good UV symmetry

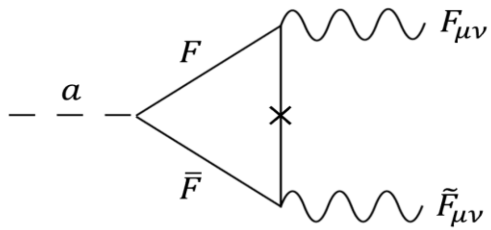
$$Q_i/U_i^c/D_i^c/L_i/E_i^c \longrightarrow e^{i\alpha} Q_i/U_i^c/D_i^c/L_i/E_i^c \ ,$$
$$H_d/H_u \longrightarrow e^{-i2\alpha} H_d/H_u \ .$$

(as in original PQWW)

$U(1)_{PQ}$ breaks after `some' scalar (has PQ charge) gets a vev ~ $O(f_a)$, leaving out a goldstone field a. The goldstone can acquire an (ABJ) anomalous coupling term :

$\frac{a}{f_a} G\tilde{G}$ that effective `extends' $\bar{\theta}$ into a dynamic field $\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}.$

$$\bar{\theta} \rightarrow \bar{\theta} = \theta + \theta_u + \theta_d + \frac{a}{f_a}$$



KSVZ model (Kim-Shifman -Vainstein-Zakharov):

heavy vector-like quarks, with coupling $\lambda_Q Q^c Q S$

Axion as the Im part of an extra scalar.

The PQ U(1): $Q^c/Q \to e^{i\alpha} Q^c/Q$, $S \to e^{-i2\alpha}\, S$

See Kim's review: *Rev.Mod.Phys.* 91 (2019) 4, 049902 (erratum)

DSFZ model (Dine-Fischler-Srednicki-Zhitnitskii):

$$\Delta L \supset \lambda H_u H_d S^2$$

$$a = \frac{1}{\sqrt{v_u^2 + v_d^2 + v_S^2}} (v_u \mathrm{Im} H_d + v_u \mathrm{Im} H_d + v_s\, \mathrm{Im} S)$$

$\{H_u, H_d, S\}$ charged as

$\{-1, -1, +1\}$ under $U(1)_{PQ}$

$$f_a = \sqrt{v_u^2 + v_d^2 + v_S^2}$$

raised by large S vev.

+ **Many other variants**, with a central goal to increase f_a to avoid astro/flavor limits.

See review: The landscape of QCD axion models, *Phys.Rept.* 870 (2020) 1-117

Example: an effective UV construction into a Fraggett-Nielson $\left(\frac{S}{\Lambda}\right)^{n\geq 1} \bar{f}_i H f_j$ like :

A DSFZ type in case of f->SM fermions, e.g. can derive from GUT/higher scale physics, & realize some flavor features.

$$\Delta L \supset -y_{ij}^u Q_i U_j^c H_u - y_{ij}^d \frac{S}{M_*} Q_i D_j^c \tilde{H}_u - y_{ij}^e \frac{S}{M_*} L_i E_j^c \tilde{H}_u$$

$$Q_i, L_i, U_i^c, D_i^c, E_i^c : 1$$
$$H_u : -2$$
$$S : -4$$

Mod.Phys.Lett.A 37 (2022) 09, 2250055

+ other PQ assignments

PQ quality problem

Global symmetries broken by non-renom. operators.

Coupled UV CPV sector gives a remnant

Georgi and Randall,86'

$$V_{\text{PQ-break}} = \frac{1}{2^{n/2-1}} \frac{f_a^n}{\Lambda_{\text{UV}}^{n-4}} \cos(n\theta + \delta_\theta)$$

Shifts the rebalanced (with V_{QCD}) θ to

$$\theta_{\text{eff}} \simeq -\frac{n\Lambda_{\text{UV}}^{4-n} f_a^n \sin\delta_\theta}{2^{\frac{n}{2}-1} f_a^2 m_a^2}$$

Q.Gravity: n > 14 not to spoil strong CP.

$$V \sim \frac{f_a^n}{M_p^{n-4}} \cos\left(\frac{a}{f_a} + \phi_n\right)$$

See: Barr, Seckel, 92' Holman,et.al.92'
Kamionkowski, March-Russell 92'
Ghigna et.al. 92'

Popular solutions:

$U(1)_{PQ}$ as a accidental sym. from a large Z_N J.Kim,81' Georgi,Hall, Wise,81'

String origin, Witten,84' Extra-dimension Cheng and D. E. Kaplan,01'

Relaxed by supersymmetry Carpenter, Dine, Festuccia, 09' Gauge symmetry Randall, 92', Dobrescu,97'

Why U(1)? A connection to flavor

$U(1)_{PQ}$ as a flavor symmetry   Davidson, Wali, 82'; Wilczek 82'   Froggatt, Nielsen, 79'

Unified PQ symmetry and the FN symmetry: "flaxion","axiflavon" etc

Ema, Hamaguchi, Moroi, Nakayama, 16'; Calibbi,Goertz, Redigolo, et.al. 16'

With a flavon field σ, its vev v_σ generates flavor hierarchies.

$$m_{ij} = y_{ij} v(\langle\sigma\rangle/\Lambda)^n$$

$$\begin{aligned}-\mathcal{L} = & \, y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj} \\ & + y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}} \overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha} \\ & + \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}\,,\end{aligned}$$

1612.05492

Flavon interactions

$$\phi = v_\phi + \frac{1}{\sqrt{2}}(s + ia), \qquad H = \begin{pmatrix} 0 \\ v_{\rm EW} + \frac{h}{\sqrt{2}} \end{pmatrix}$$

$$-\mathcal{L} = \sum_{f=u,d,l} \left[m^f_{ij}\left(1 + \frac{h}{\sqrt{2} v_{\rm EW}}\right) + \frac{m^f_{ij} n^f_{ij} (s + ia)}{\sqrt{2} v_\phi} \right] \overline{f_{Li}} f_{Rj} + \text{h.c}$$

DFSZ-type axion

Flavor non-diag. couplings have serious constraints from rare decays. See 2111.12108

Effective ops from UV:

Renorm. Lagrangian, with vector-like fields (ξ_i, ξ_i^c) with high scale masses

$$\mathcal{L}_\xi = -y'^{d}_{ij} Q_i \xi_j^c \tilde{H}_u - y'_{lk} S D_l^c \xi_k + M^\xi_{jk} \xi_j^c \xi_k$$

Integrating out ξ ξ^c fields leads to effective terms

axion: dominated by Im*S.*

$$\mathcal{L}_{\rm eff} = \frac{y'^{d}_{ij} y'_{kl}}{M^\xi_{jk}} Q_i D_l^c \tilde{H}_u S$$

Flavor diagonal axion couplings (via H): $\propto 1/v_s$, suppressed by PQ scale.
Flavor non-diagonal: only at high scale M^{-1}. (No Higgs mediated FV, by GIM)

$$g_{aqq'} = \sum_{i=1,2,3} \frac{\langle H_u^0 \rangle}{M_*} \mathcal{V}^\dagger_{qi} y^{q,\,\text{dim-5}}_{i1} \mathcal{U}_{1q'}$$

Baryon # violation operators: suppressed by v_s/M

$$\frac{\epsilon^{\eta\rho}\epsilon^{\delta\sigma} Q_\eta Q_\rho Q_\delta L_\sigma S}{M_*^3} \sim \frac{\langle S \rangle}{M_*} \cdot \frac{\epsilon^{\eta\rho}\epsilon^{\delta\sigma}}{M_*^2} Q_\eta Q_\rho Q_\delta L_\sigma \qquad \frac{U^c U^c D^c E^c S^*}{M_*^3} \sim \frac{\langle S \rangle}{M_*} \cdot \frac{1}{M_*^2} U^c U^c D^c E^c$$

An handy ALP: a Majoron?

Promote L# into PQ

Mohapatra and G. Senjanovic, 83'; Shafi and Stecker, 84’, etc

$$2X_\sigma = X_{\Phi_1} - X_{\Phi_2}$$

$$V(\Phi_1, \Phi_2, \sigma) \ni \lambda_{\Phi\sigma} \Phi_1^\dagger \Phi_2 \sigma^2 + h.c.$$

1510.01015:
DSFZ-axion + Type III seesaw

$$-\mathcal{L}_{\rm Yuk}^{\rm DFSZ_s-III_\pm} = \overline{Q}_L Y_u \tilde{\Phi}_2 u_R + \overline{Q}_L Y_d \Phi_1 d_R + \overline{L} Y_\ell \Phi_s \ell_R + \overline{L} Y_D \Sigma \tilde{\Phi}_2 + \begin{cases} \frac{1}{2}{\rm Tr}[\overline{\Sigma^c} h_\Sigma \sigma \Sigma] \\ \frac{1}{2}{\rm Tr}[\overline{\Sigma^c} h_\Sigma \sigma^* \Sigma] \end{cases} + {\rm h.c.}$$

v_σ also gives a large N mass

“SMASH” model

$$V(H,\sigma) = \lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2 + \lambda_\sigma \left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 + 2\lambda_{H\sigma} \left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)$$

Ballesteros, Redondo, Ringwald, Tamarit,16’ + several papers since.

$$\mathcal{L} \supset -\left[F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + y\, \tilde{Q} \sigma Q + y_{Q_d\,i} \sigma Q d_i + h.c.\right]$$

q	u	d	L	N	E	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

connect to seesaw scale

Q: Heavy VL quarks
KSVZ-type axion

Axion as cold dark matter

A fast oscillating field at the bottom of a $V(\phi) \sim (\phi - \phi_0)^2$ potential behaves as matter-like: $\rho(z) \sim (1+z)^3$

M. Turner, 83'

See axion cosmology review 1510.07633 & the more recent 2403.17697

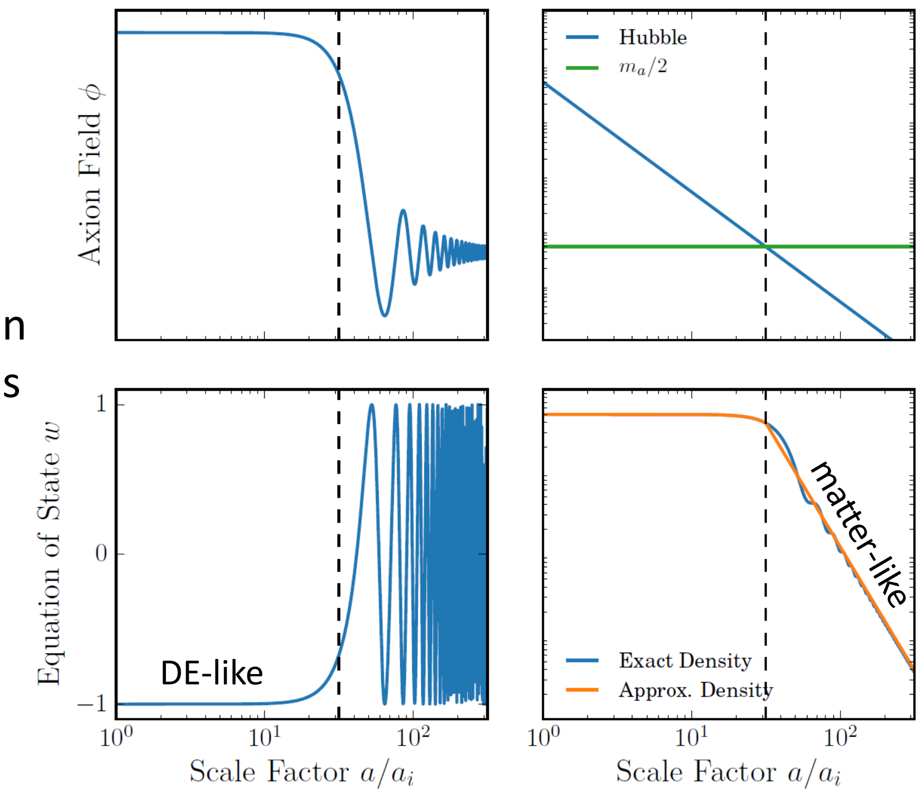
axion starts to oscillate by V_{inst}.
after strong QCD phase transition

$$a(t) = a_0 \left(\frac{R_{m\sim H}}{R(t)}\right)^{2/3} \cos(m_a t)$$

Misalignment Mechanism:
axion potential overcomes Hubble friction and start oscillation from a homogeneous initial value a_0 (via inflation). Initial value gives the DM abundance:

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)^{7/6} \langle \theta_{a,i}^2 \rangle$$

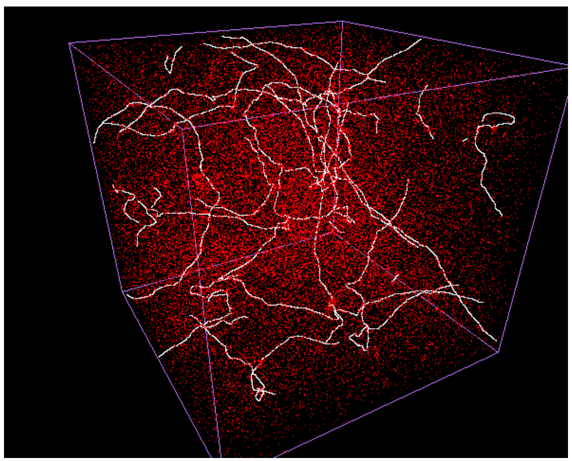
(topological defects contribute if f_a is lower than inflation scale)



Defects in post-inflation scenario

Cosmic strings form when U(1) breaks after end of inflation.

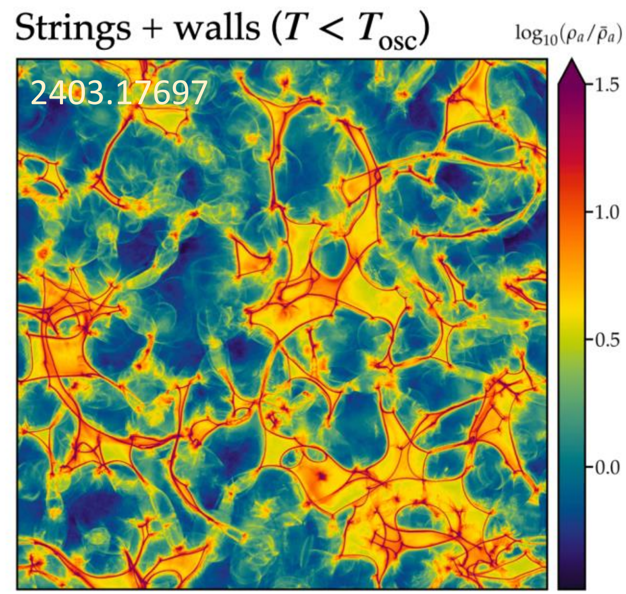
$$\phi(x) = (f_a + r(x))\, e^{i\theta(x)}$$



Contribute to the axion energy density:

$$\rho_a = \frac{1}{2} f_a^2 \dot{\theta}^2 + \frac{f_a^2}{2a(t)^2} (\nabla\theta)^2 + \chi(T)\,(1 - \cos\theta)$$

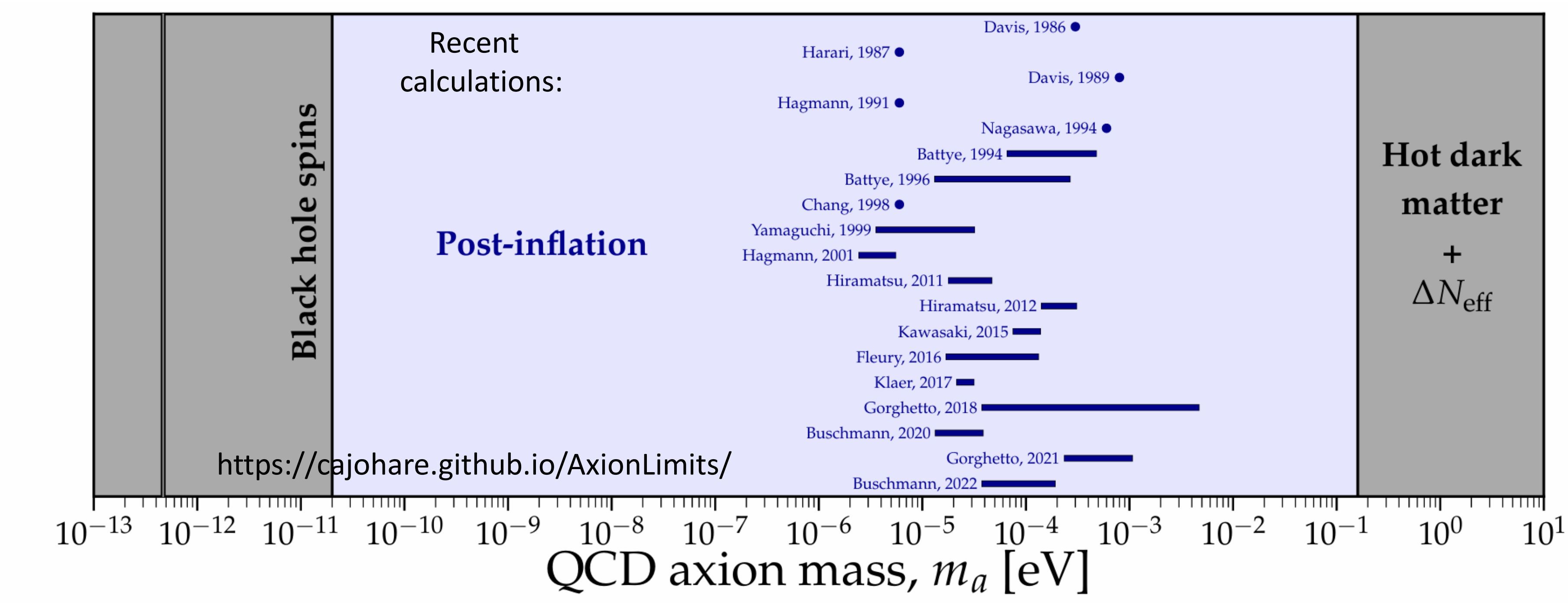
Domain walls form when V_{QCD} develops a `true' vacuum (vacua)



(DWs can unwind if N_{DW}=1)

Huge amount of numerical simulation devoted to study string networks, yet large uncertainties remain, see recent review by Saikawa, Redondo, et.al. 2401.17253

QCD axion dark matter requires $f_a \sim 10^{11}$GeV, $m_a \approx$ 10-100 μeV



$$m_a = 5.70(7)\mu eV \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right).$$

G. Grilli di Cortona, E. Hardy, J. Pardo Vega and G. Villadoro, JHEP 1601, 034 (2016)

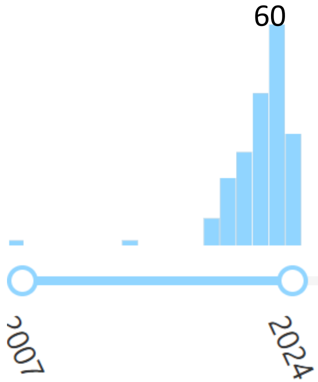
m_a = 60−150 μeV

T. Hiramatsu, et.al., PRD 85, 105020 (2012)
M. Kawasaki, et.al. PRD 91, no. 6, 065014(2015)

m_a = 26.5±3.4 μeV

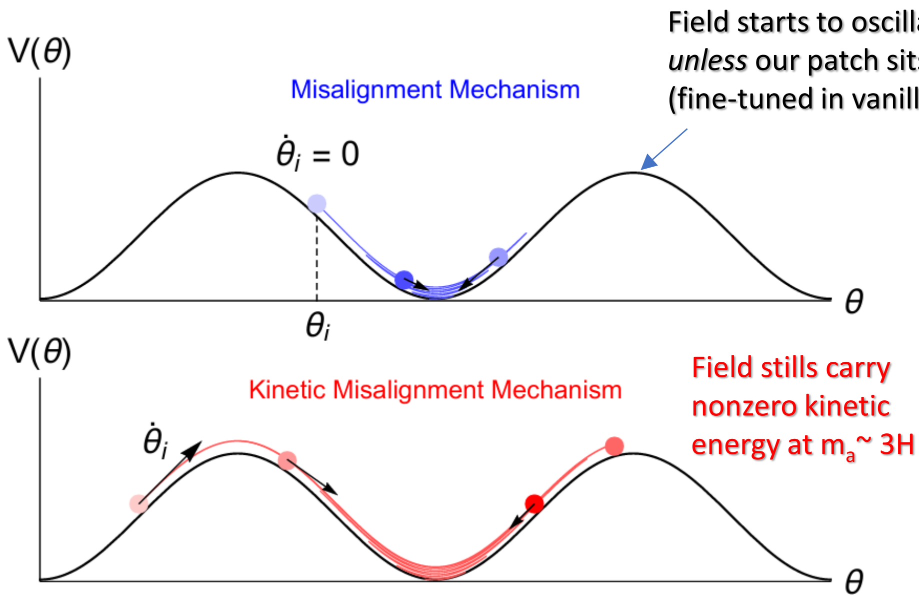
V.B.Klaer, G.D.Moore, JCAP 1711, no.11, 049 (2017)

Date of paper



Kinetic misalignment

“Some” effective PQ-breaking effect lets the phase to rotate at $\dot{\theta} \neq 0$ before V_{QCD} emerges at T^*.



R. T. Co, L. J. Hall, K. Harigaya, 19'

If the axion kinetic energy

$$K = \dot{\theta}^2 f_\phi^2 / 2$$

Keeps running over the barrier until some later time $T_{osc} < T^*$, when V > K and axion will start to oscillate like a DM.

Axion number density conserved if **adiabatic**: abundance indep. from m_a evolution

$$\frac{\rho_\phi}{s} = m_\phi(0)\frac{n_\phi(T')}{s(T')} = C m_\phi(0) Y_\theta$$

$\dot{\theta} f_\phi^2 \propto R^{-3}$ is a Noether charge with a $\theta \to \theta + \alpha f_\phi$ shift sym.

$Y_\theta = \dot{\theta} f_\phi^2 / s$ ~ const

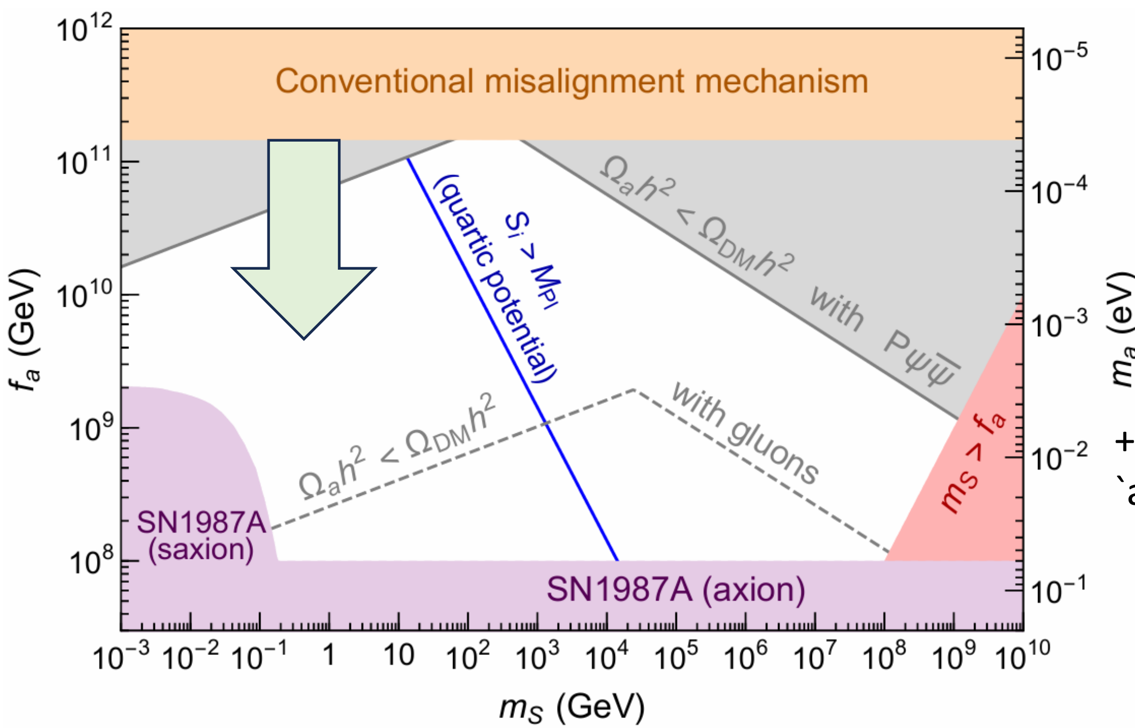
Co, Hall & Harigaya proposed the PQV field has some large initial value (thus higher-D terms might be important) and gets kicked to rotate.

$$V = \lambda^2 \left(|P|^2 - \frac{f_\phi^2}{2} \right)^2, \qquad \lambda^2 = \frac{1}{2} \frac{m_S^2}{f_\phi^2}$$

$$Y_\theta \equiv \frac{n_\theta}{s} \simeq 40\, \epsilon \left(\frac{S_i}{10^{17}\ \mathrm{GeV}} \right)^{\frac{3}{2}} \left(\frac{10^{-10}}{\lambda} \right)^{\frac{1}{2}}$$

“Free up param space otherwise discarded”

See 2305.15465 for other axion possibilities via mixing



UV completions: 1910.02080, 2006.05687, 2006.04809 +many others

+Feedback during rolling: \`axion fragmentation’ 2206.14259 See 2408.08355 for extensive model studies

Baryon asymmetry in kinetic misalignment

$$n_{PQ} = \dot{\theta} S^2$$

$$n_B = O(0.1) * \dot{\theta}(T) T^2$$

PQ charge by initial rotation $\xrightarrow[\text{sphalerons}]{\text{strong}}$ Quark chiral asymmetry $\xrightarrow[\text{sphalerons}]{\text{weak}}$ Baryon # asymmetry

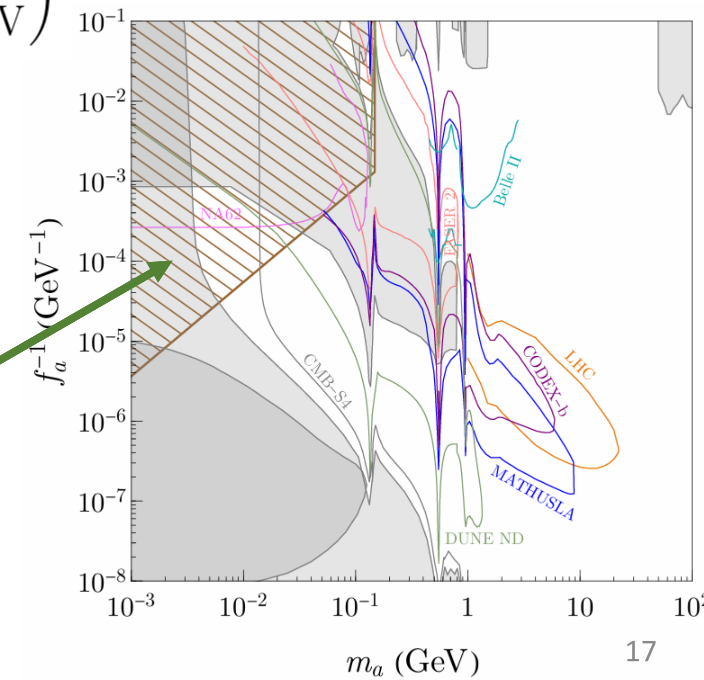
See: Co, Harigaya, 1910.02080
Co, Gherghetta, Harigaya, 2206.00678 and refs therein.

$$\frac{n_B}{s} = 8.7 \times 10^{-11} \left(\frac{Y_{\rm PQ}}{510}\right) \left(\frac{c_B}{0.1}\right) \left(\frac{10^8 \text{ GeV}}{f_a}\right)^2 \left(\frac{T_{\rm ws}}{130 \text{ GeV}}\right)^2$$

$$\frac{\rho_a}{\rho_{\rm DM}} \simeq 70 \left(\frac{f_a}{10^8 \text{ GeV}}\right) \left(\frac{130 \text{ GeV}}{T_{\rm ws}}\right)^2 \left(\frac{0.1}{c_B}\right)$$

(weak sphalerons inefficient below $T_{\rm WS}$)

Simple (traditional) scenario seems to overproduce DM. Co & company proposed a `heavy axion' to rescue



Other alternatives

"Stronger QCD" in early Universe

Jeong, Takahashi, 1304.8131

"Hidden $U(1)_H$ monopoles" gives a larger ma and earlier oscillation

Kawasaki, Takahashi, Yamada, 1511.05030

"Dynamic PQ scale"

Allali1, Hertzberg, Lyu, 2203.15817

$$\mathcal{L} = \sqrt{-g}\Big[\frac{1}{2}|\partial\Phi|^2 - \frac{\lambda}{4}(|\Phi|^2 - f(\chi)^2)^2 - V(\theta, T) + \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}m_\chi^2\chi^2\Big]$$

"Trapped misalignment"

Luzio, Gavela, Quilez, Ringwald, 2102.01082

"A Z_N symmetry on axion potential with N copies of mirror Worlds" and highly nontrivial V(θ,T) evolution.

"Axion fragmentation"

Enhanced energy dissipation by feedback from potential wiggles

$$\ddot{u}_k + \left(k^2 - \frac{\Lambda_b^4}{f^2}\cos\frac{\dot{\phi}}{f}t\right)u_k = 0$$

Fonseca, Morgante, Sato, Servant,1911.08472

Mathieu equ has growth solution at parametric resonance, releasing kinetic E into axion excitations

See recent review: Di Luzio, et.al. 2312.17310

$$\mathcal{L} = \sum_{k=0}^{\mathcal{N}-1}\left[\mathcal{L}_{\mathrm{SM}_k} + \frac{\alpha_s}{8\pi}\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right)G_k\widetilde{G}_k\right]$$

$$V_{\mathcal{N}}(\theta_a) \simeq -\frac{m_a^2 f_a^2}{\mathcal{N}^2}\cos(\mathcal{N}\theta_a)$$

2102.00012

$$m_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{f_a^2}\frac{1}{\sqrt{\pi}}\sqrt{\frac{1-z}{1+z}}\,\mathcal{N}^{3/2}\,z^{\mathcal{N}}$$

Axion miniclusters & stars

Miniclusters:

Post-inflationary scenario causes inhomogeneities.
A naïve estimate on the clump masses:

$$M \approx \frac{4\pi}{3}(1+\delta)\bar{\rho}H(T_{osc})^{-3}$$

Or solve the density fluctuation's equation

$$\ddot{\delta} + 2H\dot{\delta} + \left(\frac{c_s^2 k^2}{a^2} - 4\pi G_N \bar{\rho}_a\right)\delta = 0$$

$$c_s^2 \approx \frac{k^2}{4m_a^2 a^2}$$

1207.3124

See: 1404.1938 1810.11468 1911.07853 2006.08637

Or use N-body simulation.

1911.09417 2101.04177 2207.11276 2402.18221

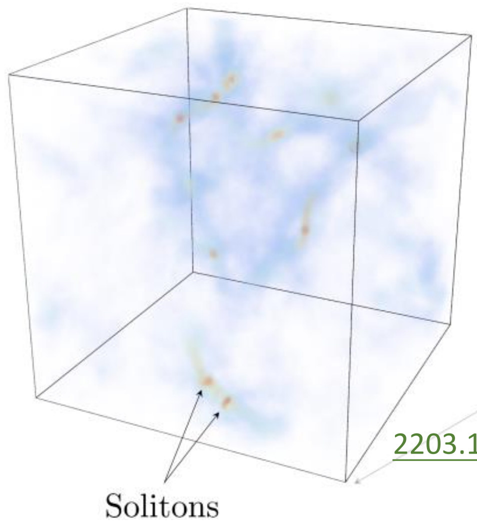
Axion stars:

See review: Braaten & Zhang, 19'

Localized (soliton) solutions under self-interaction / gravity

Oscillons ($\dot{m}_a > 0$): astro-ph/9311037
Boson star (w gravity) 1406.6586

$$i\dot{\psi} = -\frac{\nabla^2\psi}{2m} - Gm^2\,\psi\int d^3x'\frac{\psi^*(\mathbf{x}')\psi(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|} + \frac{\partial}{\partial\psi^*}V_{nr}(\psi,\psi^*)$$



2203.10100

Axion DM granularity: dynamic heating

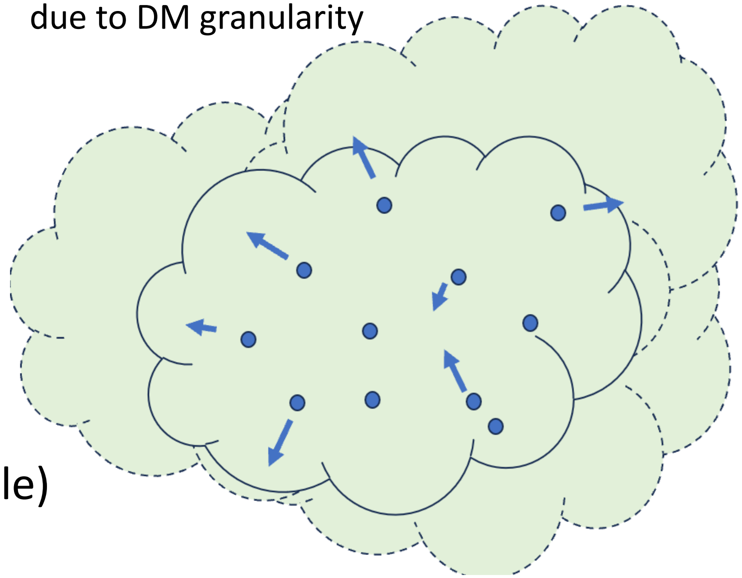
All evidences of DM are gravitational: should gravity effects tell us more?

Galaxy scale dynamics:
Disk thickening, stellar streams
Church, J. P. Ostriker, and P. Mocz, 18'
Amorisco and A. Loeb, 18'
excludes $m < 10^{-22}$ eV

Granularity above the de Broglie wavelength ~ $2\pi/mv$ L.Hui, 16'
exclusion limit $m \rightarrow 10^{-21}$eV

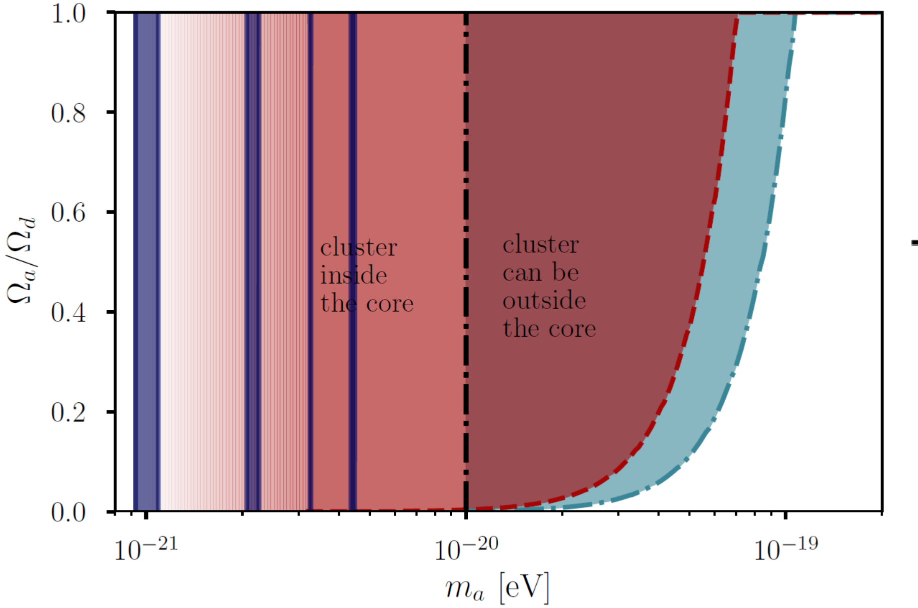
Relaxation of old cluster (dwarf galaxy scale)
exclusion limit $m \rightarrow 10^{-20} \sim 10^{-19}$eV
Bar-Or, Fouvry, and Tremaine, 19'
Marsh and Niemeye, 19'
Wasserman, 19' etc.

Stellar orbits disrupted due to DM granularity



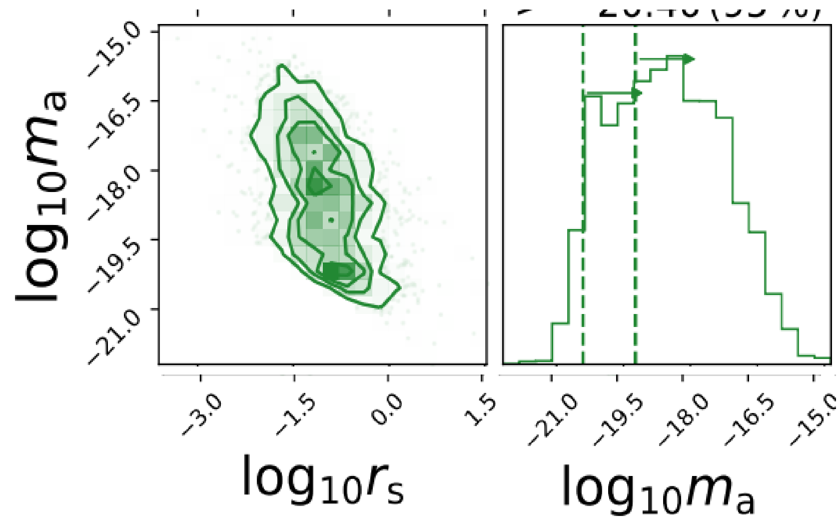
ALPs are dark, and can be tidal above their coherence scales

Relaxation on star clusters



Axion DM granularity contributes to Cluster Relaxation

Relaxation for Eridanus II, see Marsh and Niemeyer, 19’
See `revised constraints’, Chiang et.al: 2104.13359

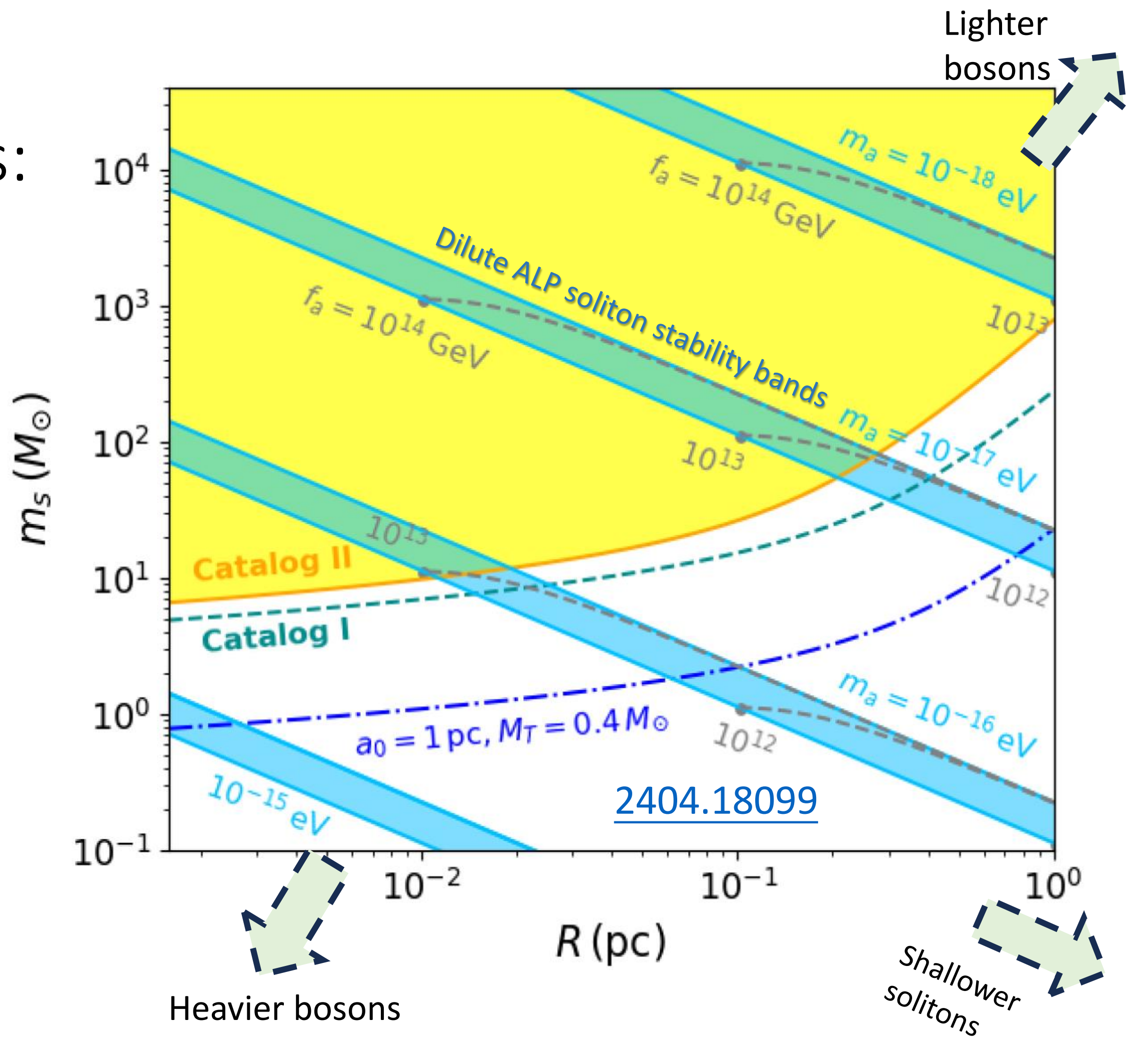


The MUSE-Faint survey (2101.00253)
Quote: “Substantial evidence (Bayes factor $\sim10^{-0.6}$) for cold dark matter (a cuspy halo) over self-interacting dark matter (a cored halo) and weak evidence (Bayes factor $\sim10^{-0.4}$) for fuzzy dark matter over cold dark matter…. These limits are equivalent to a fuzzy-dark-matter particle mass **$m_a > 4*10^{-20}$ eVc^{-2}**.”

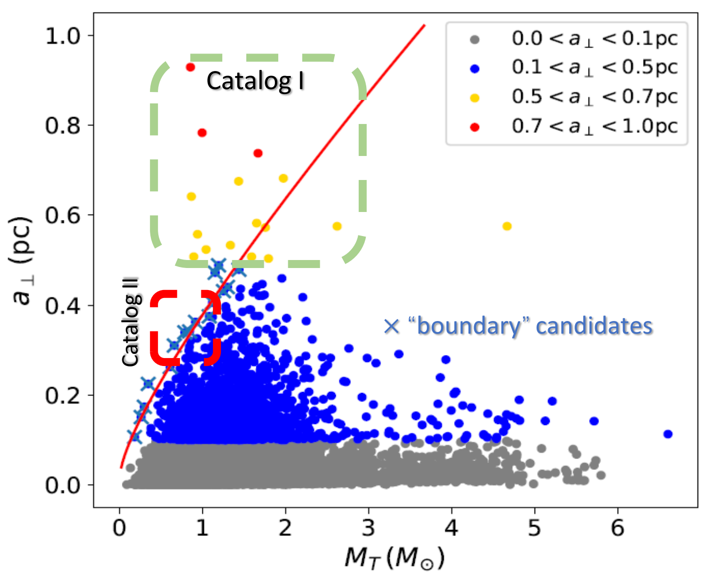
Binary star disruptions:

ALP boson stars, milliclusters may disrupt orbits near/larger than their granularity size.

Galaxy halo -> 10^{-22} eV   (100kpc)
Dwarfs -> 10^{-19} eV (kpc)
Binaries -> 10^{-16} eV (< pc)



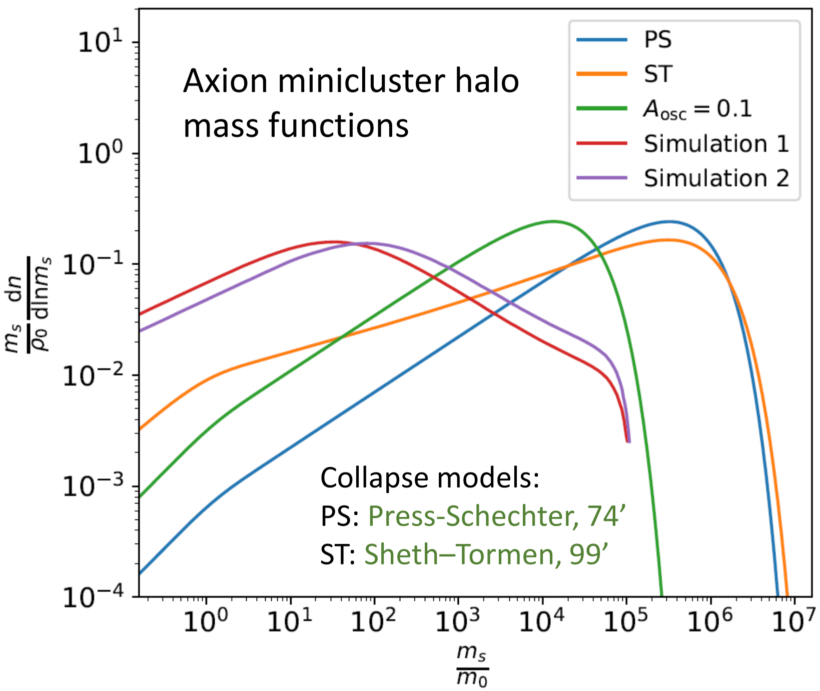
GAIA's halo-like binaries



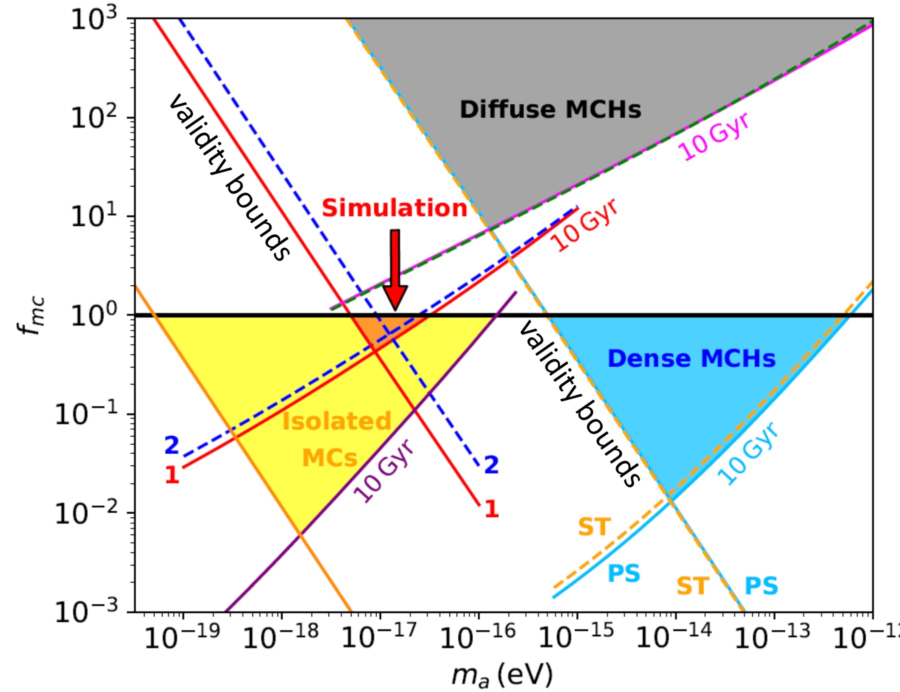
Small-scale fluctuation's binary heating rate:

$$\frac{\langle \Delta E \rangle}{T} = \sqrt{\frac{2}{\pi}}\frac{\mu \rho_0 G^2}{m_s \sigma}\int \frac{d^3k}{k^3}\rho^2(\vec{k})e^{-\frac{(\vec{k}\cdot\vec{v}_c)^2}{2k^2\sigma^2}}2\left(1-\cos\left[\vec{k}\cdot(\vec{r}_1-\vec{r}_2)\right]\right)$$

Binary disruption bounds for ALP minicluster halos



$$m_0 = 281 M_\odot \left(\frac{m_a}{10^{-16}\,\mathrm{eV}}\right)^{-\frac{3}{2}} \frac{g_{*S}(T_{\rm osc})}{g_{*S}(T_0)} g_*^{-\frac{3}{4}}(T_{\rm osc})$$

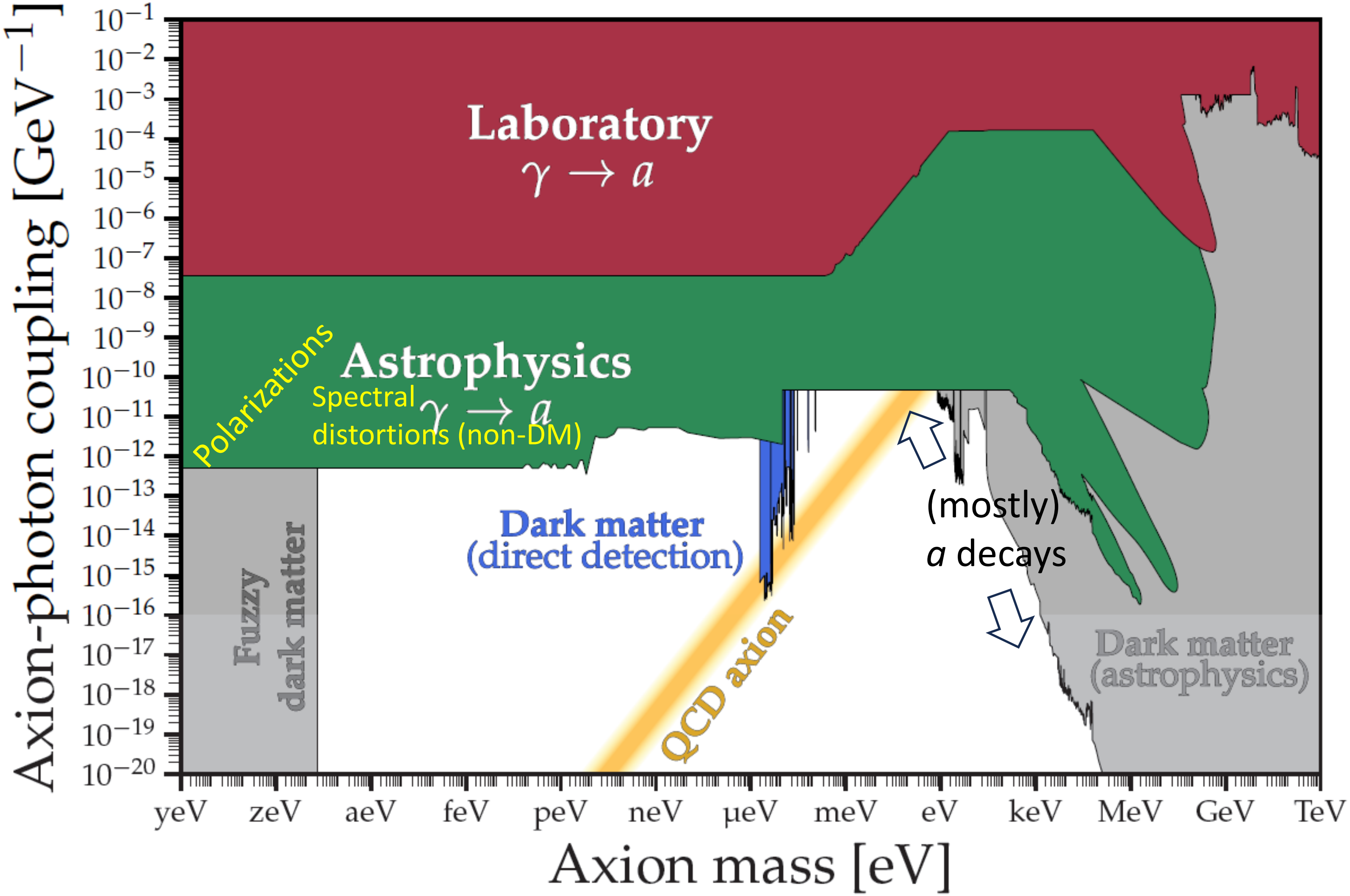


Denser models of MCH seem to indicate a disruption effect.

Z. Wang, Y. Gao, 2409.02468

Astrophysics: $a - \gamma$ conversion, a emissions, etc.

2403.17697



Birefringence (DM as a medium)

Axion field is a parity-violating medium.
It rotates the linear polarization of light.

$$\Delta\theta = \frac{1}{2} g_{a\gamma} \Delta a$$

only determined by a field difference between initial & final positions (for freq. $\omega >> m_a$) Raffelt, L. Stodolsky, 87' Carroll, Field & Jackiw, 90'

Harari, Sikivie, 92':

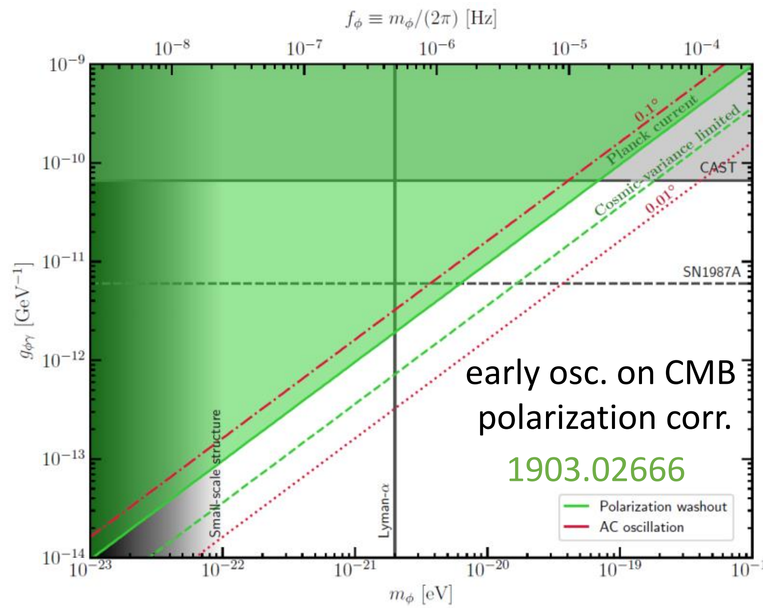
$$\boldsymbol{H} = \boldsymbol{B} - \frac{ga}{2}\boldsymbol{E} \ \& \ \boldsymbol{D} = \boldsymbol{E} + \frac{ga}{2}\boldsymbol{B}$$

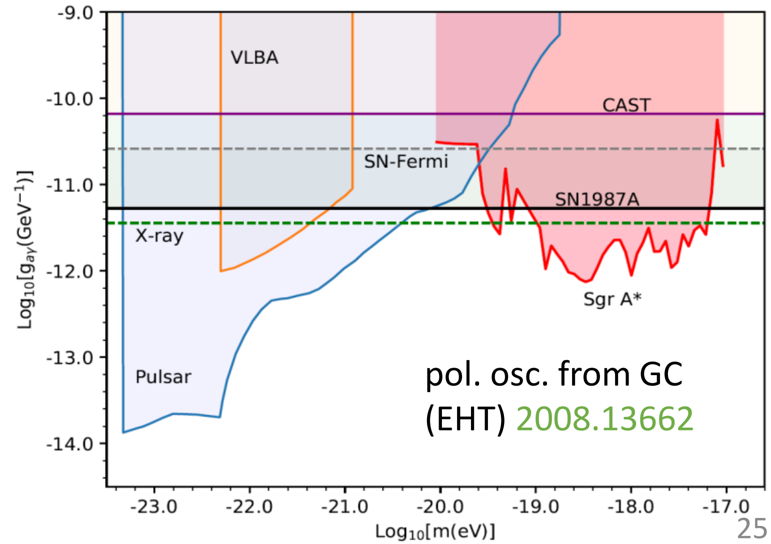
satisfy free wave equations

Comparison: Faraday effect

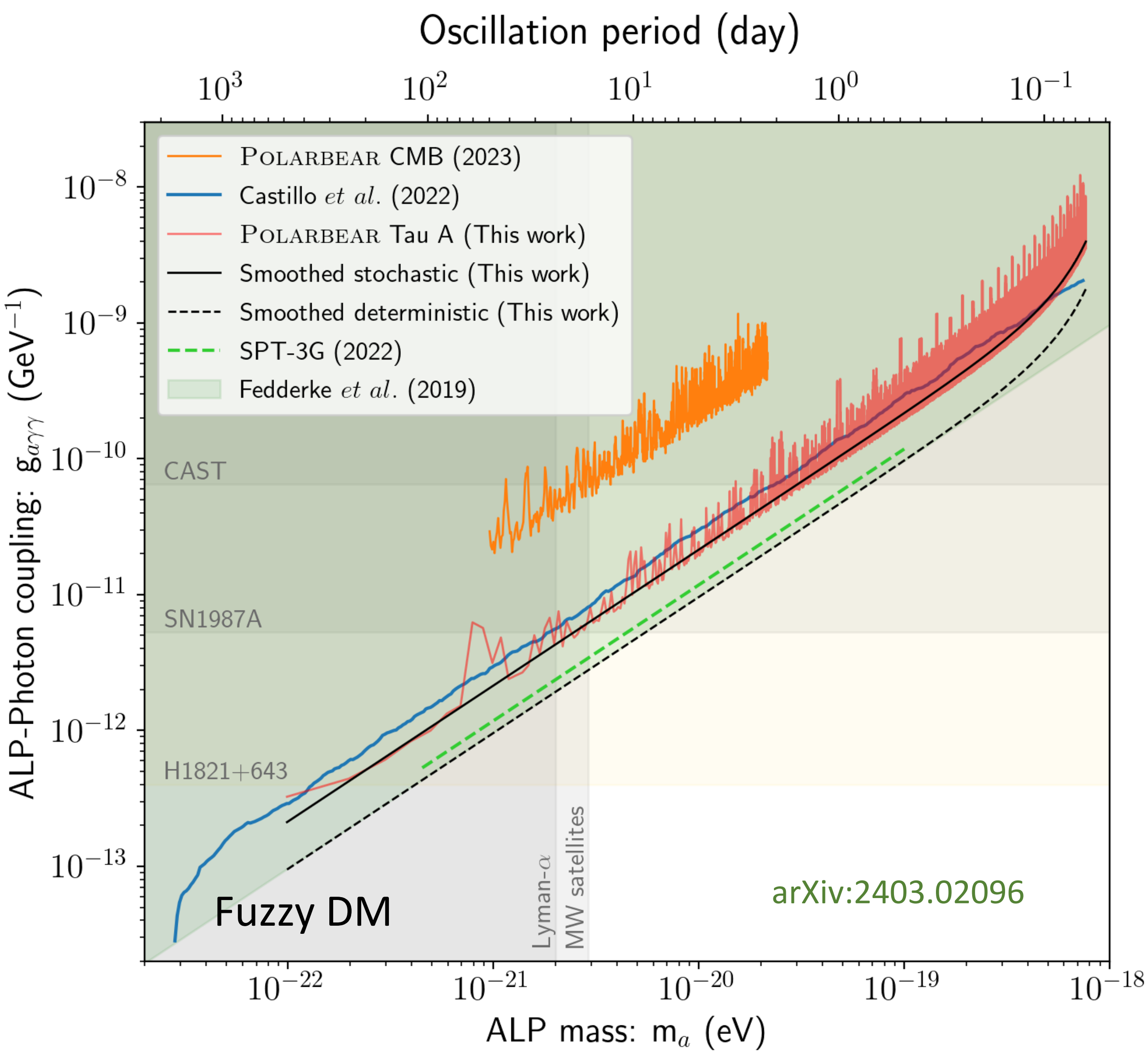
$$\theta_{\mathrm{Faraday}} = \frac{2\pi e^3}{m_e^2 k^2} \int \mathrm{d}\boldsymbol{x} \cdot \boldsymbol{B}(x)\, n_e(x)$$

+ lab searches on birefringence & dichroism under B-field





Observation Updates



Polarization angle shifts by

$$\psi = \frac{g_{a\gamma\gamma}}{2}\left(\phi_{\rm detected} - \phi_{\rm emitted}\right)$$

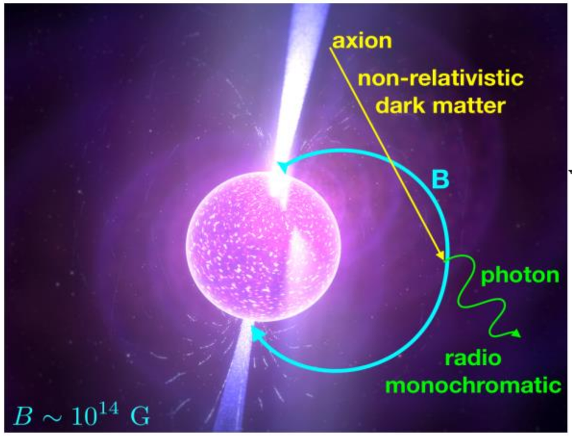
Available sources: radio galaxies, jets in active galaxies, protoplanetary disks, pulsars, and CMB

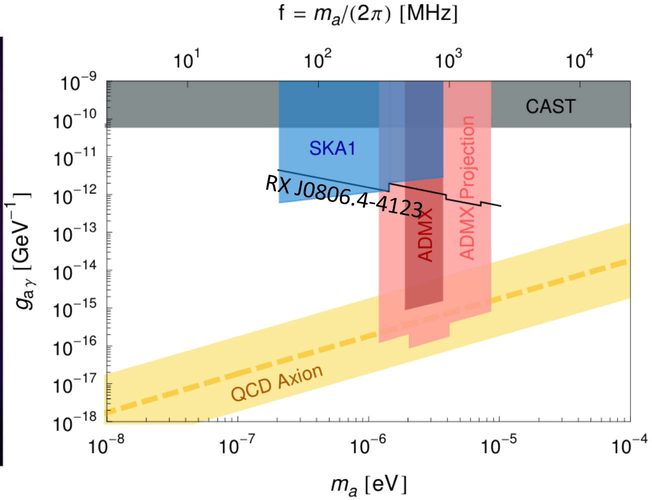
$m_a f_a \sim$ const. Smaller m_a leads to more sophisticated pattern but also a less constrained f_a

Axion DM -> light @ magnetars

Resonant axion DM > photon conversion when axion mass matches photon's (eff.) mass

$$m_a \simeq \omega_p \simeq (4\pi\alpha n_e/m_e)^{1/2}$$





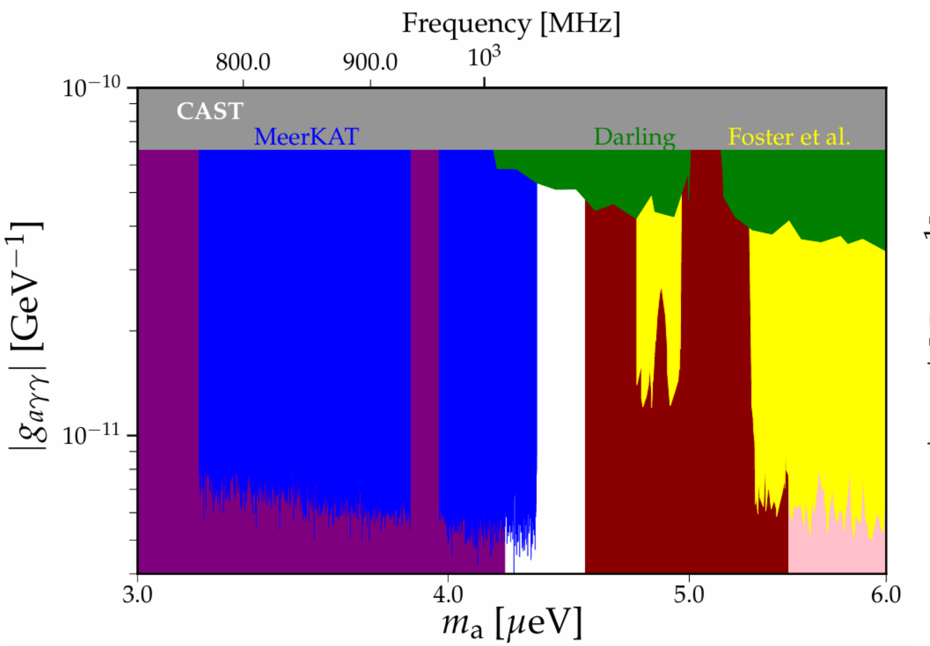
Resonance radius (NS),

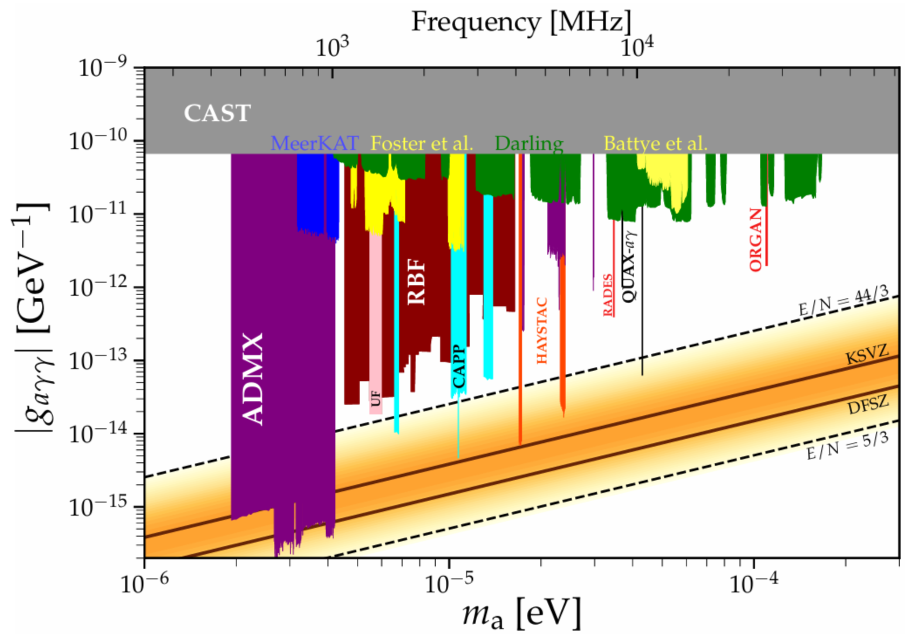
$$r_c^{\rm NS} = 168.62 \times \left|3\cos^2\theta - 1\right|^{1/3} \times \left(\frac{R_{\rm NS}}{10~{\rm km}}\right) \times \left[\frac{B_0}{10^{14}~{\rm G}}\,\frac{1~{\rm sec}}{P}\left(\frac{1~\mu{\rm eV}}{m_a}\right)^2\right]^{1/3}~{\rm km}\,,$$

$$S_{a\gamma}^{\rm NS} \simeq 71.97~\mu{\rm Jy}\left(\frac{\rho_{\rm DM}^{\infty}}{0.3~{\rm GeV/cm^3}}\right)\left(\frac{M_{\rm NS}}{M_\odot}\right)^{1/2}\left(\frac{v_0}{200~{\rm km/s}}\right)^{-1}\left(\frac{R_{\rm NS}}{10~{\rm km}}\right)^{5/2}\left(\frac{P}{1~{\rm sec}}\right)^{7/6}$$
$$\times\left(\frac{g_{a\gamma}}{10^{-12}~{\rm GeV^{-1}}}\right)^2\left(\frac{B_0}{10^{14}~{\rm G}}\right)^{5/6}\left(\frac{m_a}{1~\mu{\rm eV}}\right)^{4/3}\left(\frac{d}{100~{\rm pc}}\right)^{-2}\left(\frac{\mathcal{B}}{1~{\rm kHz}}\right)^{-1}$$

J.-W. Wang, X.-J. Bi , R.-M. Yao , P-F. Yin, Phys.Rev.D 103 (2021) 11, 2101.02585

Radio limits (MeerKAT)





Axion conversion power in NS magnetosphere:

$$\frac{d\mathcal{P}}{d\Omega} \simeq 5.7 \times 10^9\ \mathrm{W} \left(\frac{g_{a\gamma\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)^2 \left(\frac{r_{\mathrm{NS}}}{10\,\mathrm{km}}\right)^{5/2} \left(\frac{m_a}{\mathrm{GHz}}\right)^{4/3}$$
$$\times \left(\frac{B_0}{10^{14}\,\mathrm{G}}\right)^{5/6} \left(\frac{P}{\mathrm{sec}}\right)^{7/6} \left(\frac{\rho_{\mathrm{DM}}^{\infty}}{0.45\,\mathrm{GeV\,cm^{-3}}}\right) \left(\frac{M_{\mathrm{NS}}}{\mathrm{M}_\odot}\right)^{1/2}$$
$$\times \left(\frac{200\,\mathrm{km\,s^{-1}}}{v_0}\right) \frac{3\,(\hat{\mathbf{m}}\cdot\hat{\mathbf{r}})^2 + 1}{\left|3\cos\theta\,\hat{\mathbf{m}}\cdot\hat{\mathbf{r}} - \cos\theta_m\right|^{7/6}},$$

(10 hr) observation on NS J0806.4−4123

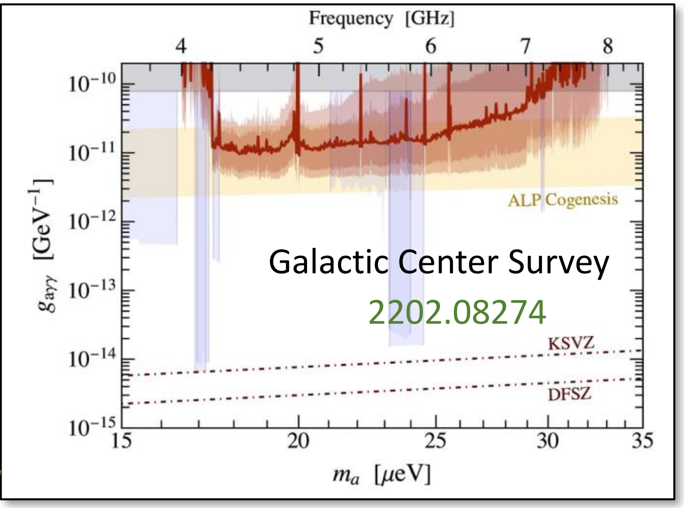
Axion conversion signal is narrow-frequency. Need good frequency resolution

Y.-F. Zhou, N. Houston, G.I.G. Jozsa, et al., *Phys.Rev.D* 106 (2022) 8, 083006, (2209.09695)

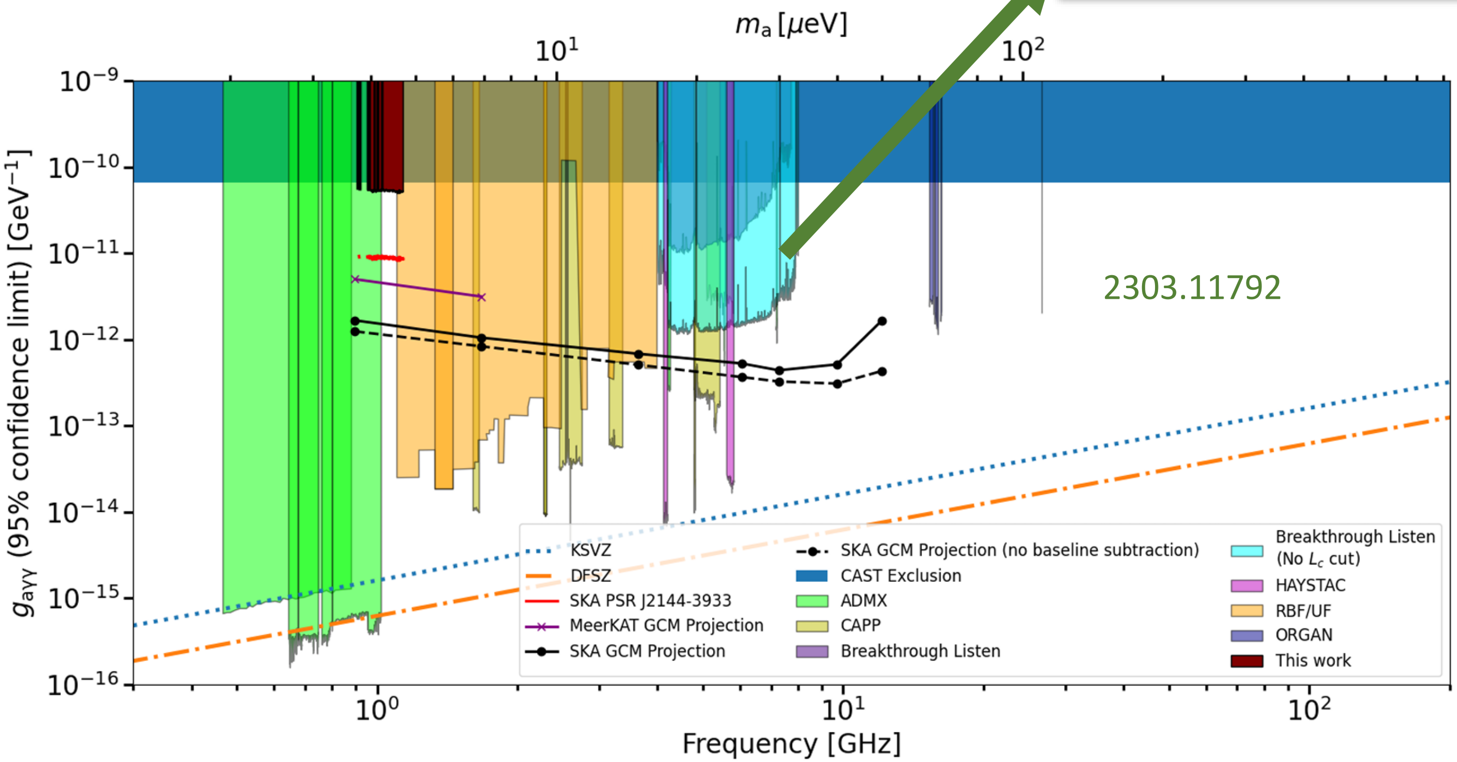
More radio limits

R. A. Battye, M. J. Keith, J. I. McDonald, et al., 2303.11792 (MeerTime)
J. W. Foster, S. J. Witte, M. Lawson, et al., 2202.08274 (Breakthrough Listen)

Recent review on astro non-DM axion bounds, see Andrea Caputo, Georg Raffelt, 2401.13728



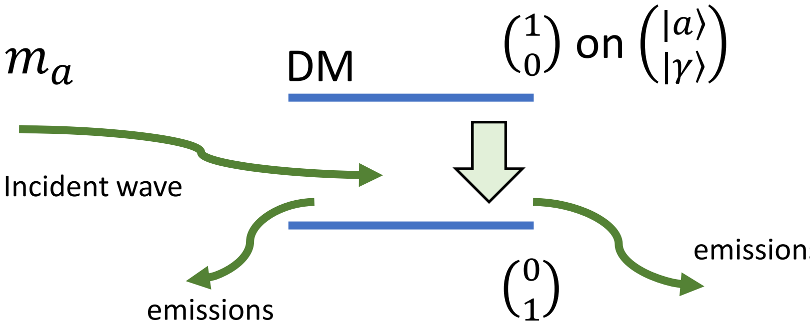
Galactic Center Survey
2202.08274



2303.11792

Radio `echo' from axion DM

- *Intriguing* (resonant) solutions to the axion-Maxwell Equations. Under the perturbation of a traveling EM wave
- Stimulated emission of photons if $\omega_\gamma = m_a$
- DM can respond with a backward emission as an `echo'

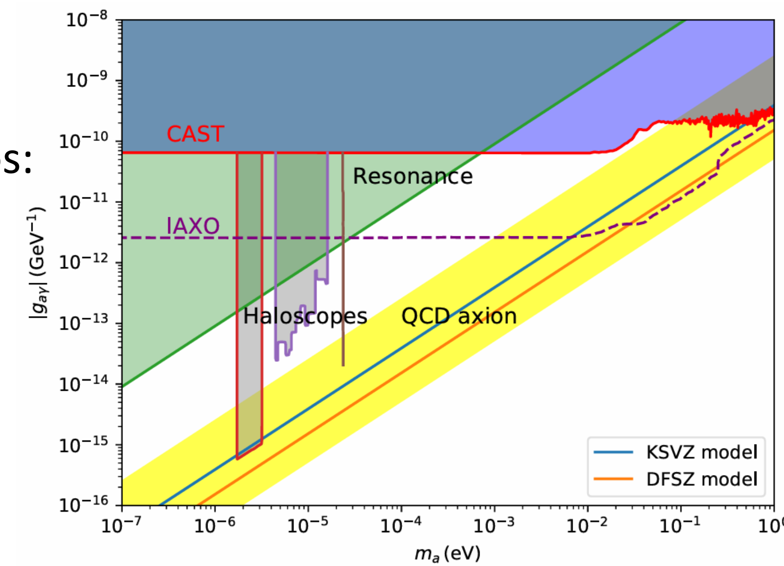


A. Arza, P. Sikivie,
Phys.Rev.Lett. 123 (2019) 13, 131804
A. Arza, E. Todarello,
Phys.Rev.D 105 (2022) 2, 023023, 2108.00195

Similar resonance solutions in other scenarios:

May stimulate the decay of axion clumps

Z. Wang, L. Shao, L.-X. Li,
JCAP 07 (2020) 038, 2002.09144



Direct detection on ALP DM

CDEX Collaboration, Phys.Rev.D 101 (2020) 5, 052003

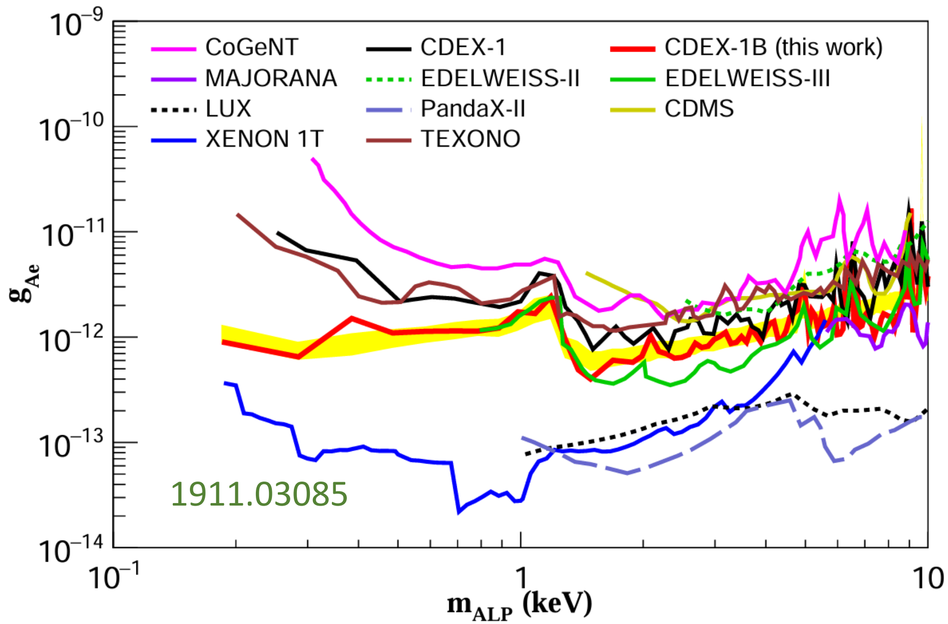


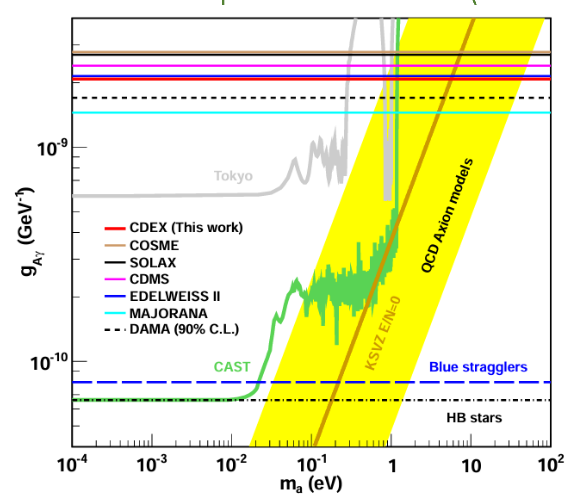
FIG. 10. The CDEX-1B 90% C.L. upper limit on coupling of ALPs as a function of m_{ALP}, together with the constraints set by CDEX-1A [18] and other experiments [9, 10, 12, 14–16, 20–

Axio-electric absorption of ALPs

$$\sigma_{Ae}(m_A) = \sigma_{pe}(m_A)\frac{g_{Ae}^2}{\beta}\frac{3{m_A}^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{\frac{2}{3}}}{3}\right)$$

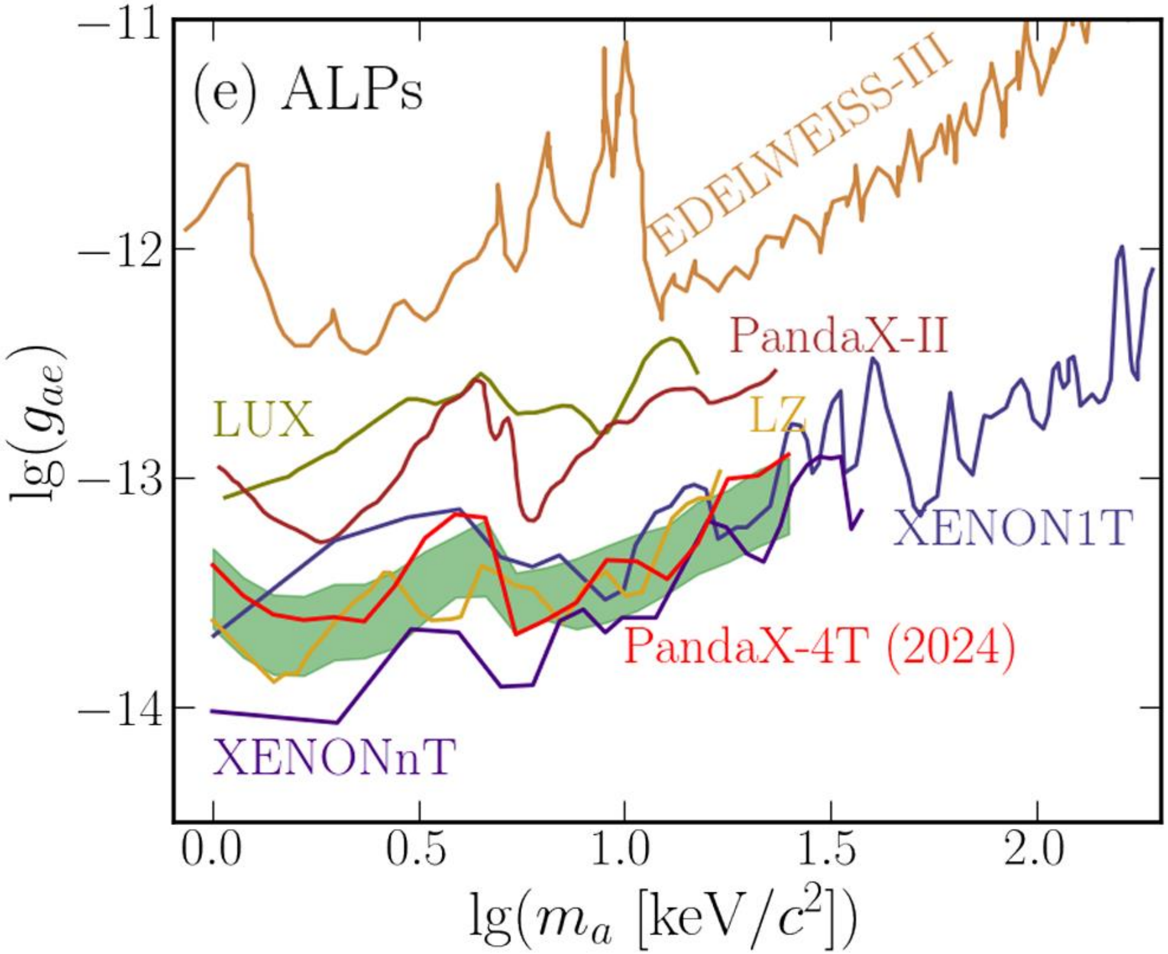
Sensitive to ALP coupling
to electrons (for ionization)
ALP mass range 0.16 - 11.66 keV

2405.07303 update on solar ALP (non-DM)

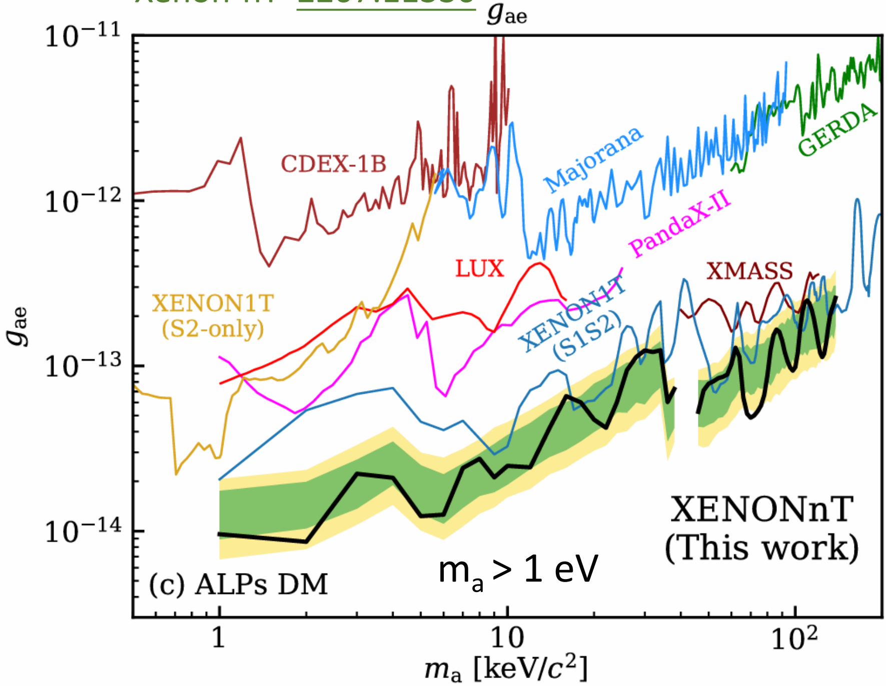


Fresh from PandaX-4T (August)

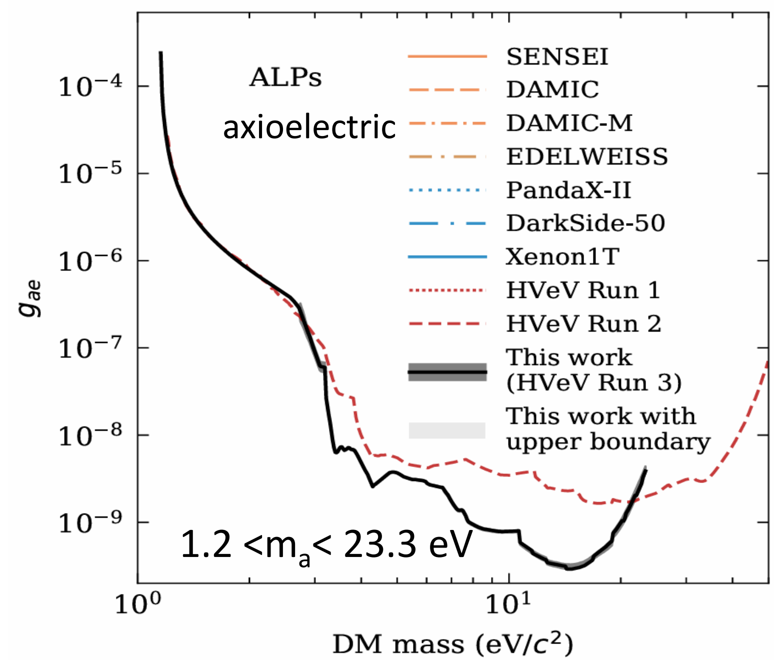
m_a from 1 to 25 keV   2408.07641



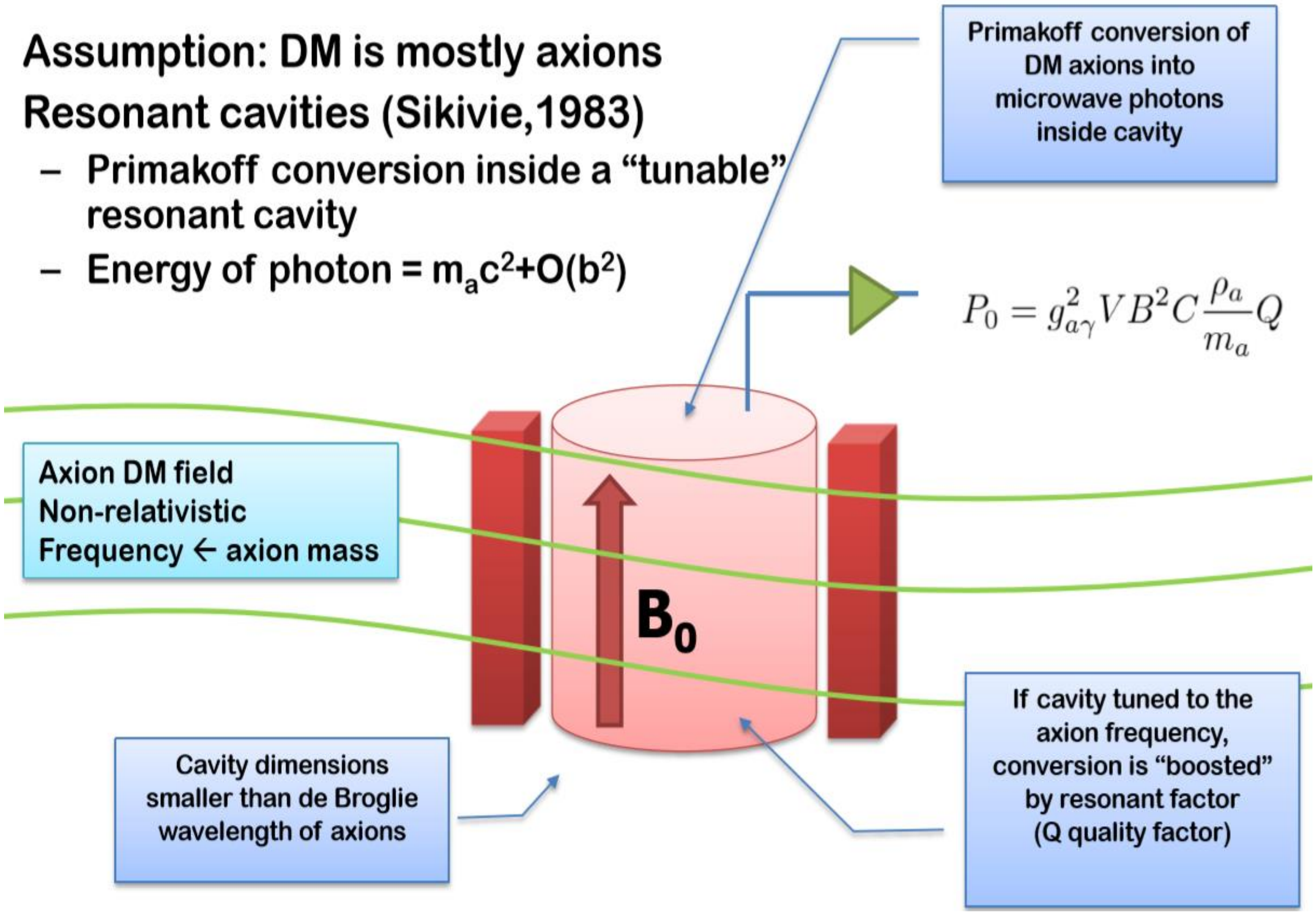
Xenon-nT 2207.11330



SuperCDMS HVeV 2407.08085,



Axion Haloscope & recent novelties



`aQED': electromagnetic tests

- Axion DM acts as a source in Maxwell equations, cavity as a pickup.

$$\vec{\nabla}\cdot\vec{E} = \rho_e + \underline{g\vec{B}\cdot\nabla a}$$

Effective charge: (any ideas?)

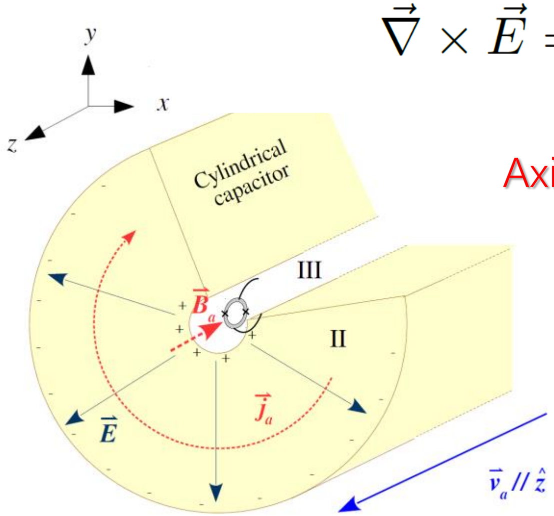
$$\vec{\nabla}\times\vec{B} - \frac{\partial\vec{E}}{\partial t} = \underline{g\vec{E}\times\vec{\nabla}a} - \underline{g\vec{B}\frac{\partial a}{\partial t}} + \vec{j}_e$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t},$$

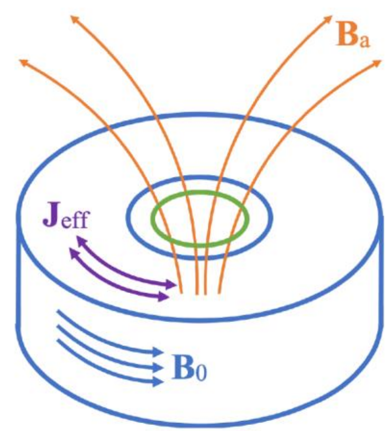
Axio-magnetic current:
Abracadabra, ADMX-SLIC, etc

Axio-electric current



DM axion *flow* Induces a magnetic signal inside E field: $\vec{j}_a = g\vec{E}\times\vec{\nabla}a$

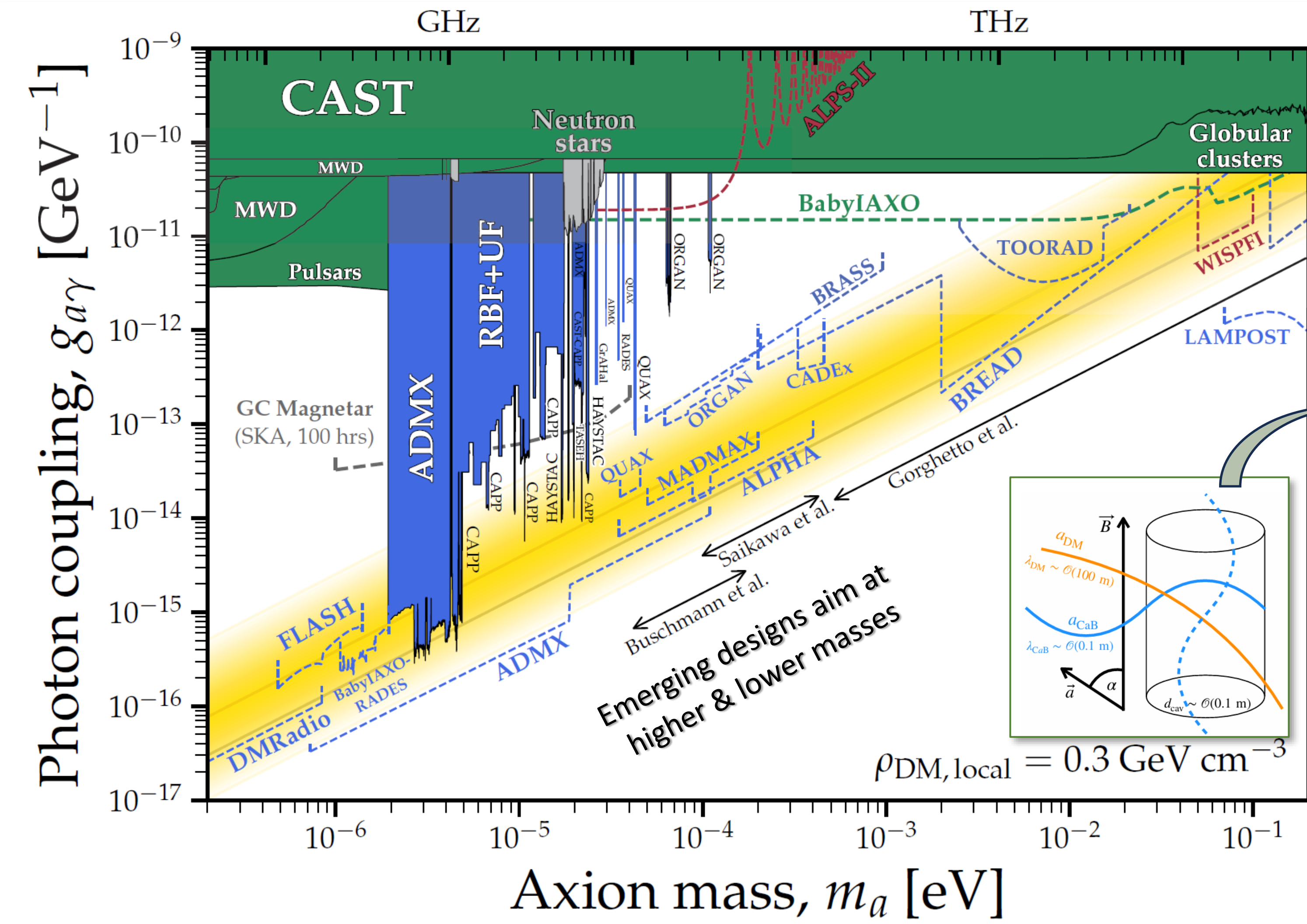
2012.13946 (broad-band) &
2204.14033 (narrow-band)



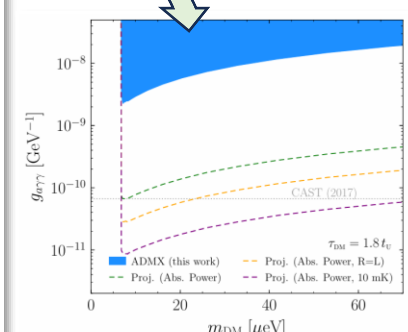
j_a under B field: (anti)parallel with B field direction

$$\vec{B}\cdot\partial_t a$$

24' updates... (from Ciaran O'Hare, 2403.17697)



Cosmic axion bkg (from DM decay) 2303.06282



A resonance enhancement

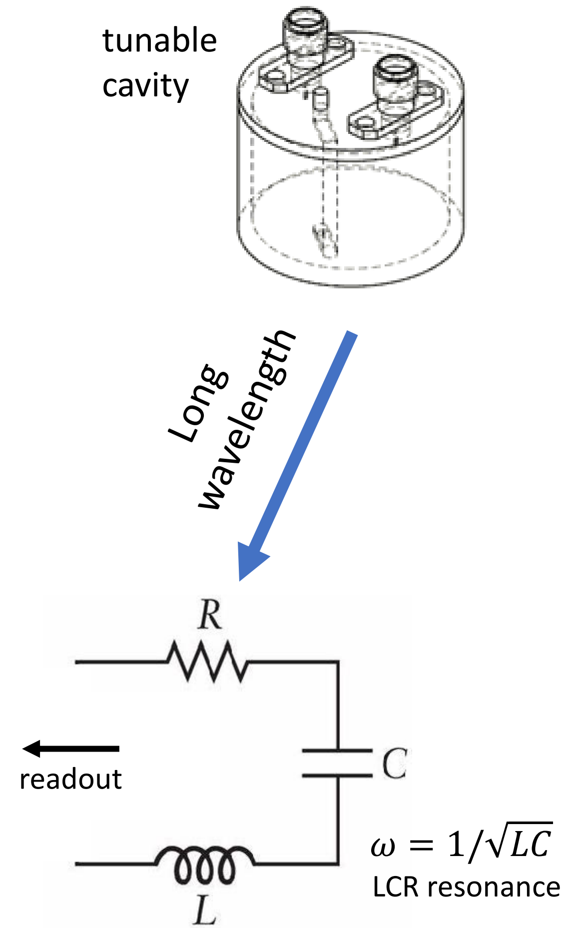
High $Q \sim 10^6$ quality factor key to good sensitivity
(to reach QCD axion parameter space)

A cavity's Q-factor enhances axion DM conversion rate at both classical & quantum (2201.08291) levels

$$R = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B_0^2 C_k V \cdot Q$$

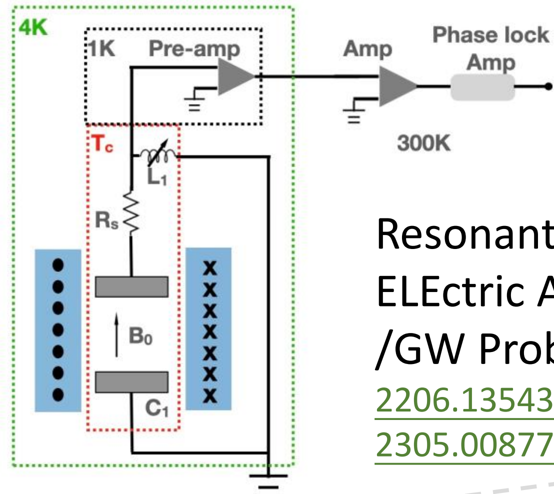
Non-cavity: use electronic (LC) circuit (P.Sikivie,13') resonance tuned to axion frequency (ADMX-SLIC,ABRACADABRA, BASE, etc.)

Inter-disciplinary
Low noise amplification/detection technique input from Quantum Optics (JPA,TWPA), HBT interferometry(2201.08291) etc.

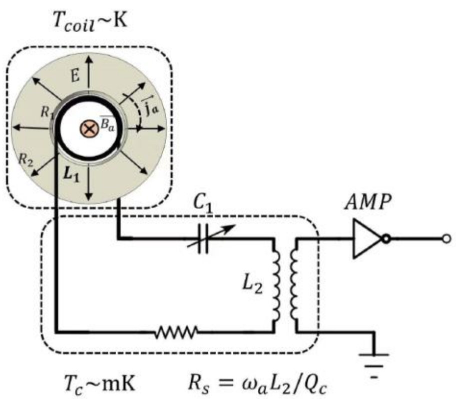


Open cavity designs: $m_a \ll \mu eV$

Cavity with magnetic field

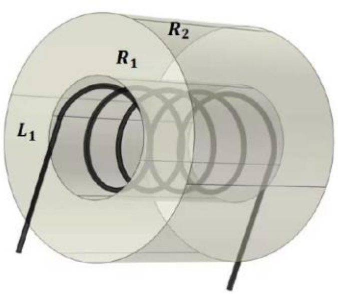


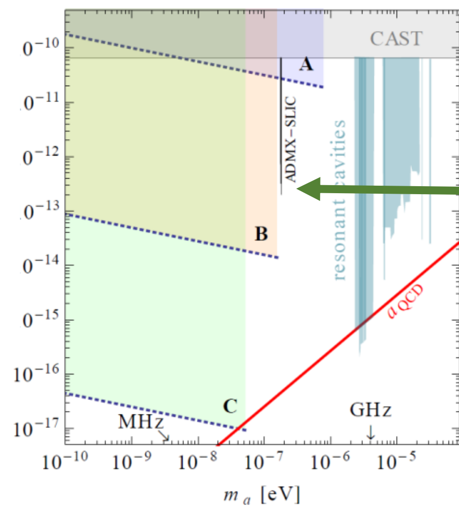
Resonant ELEctric Axion /GW Probe
2206.13543
2305.00877



Cavity with electric field

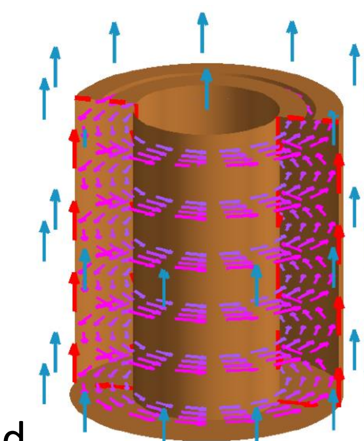
Multi-meter scale to reach QCD axion f_a





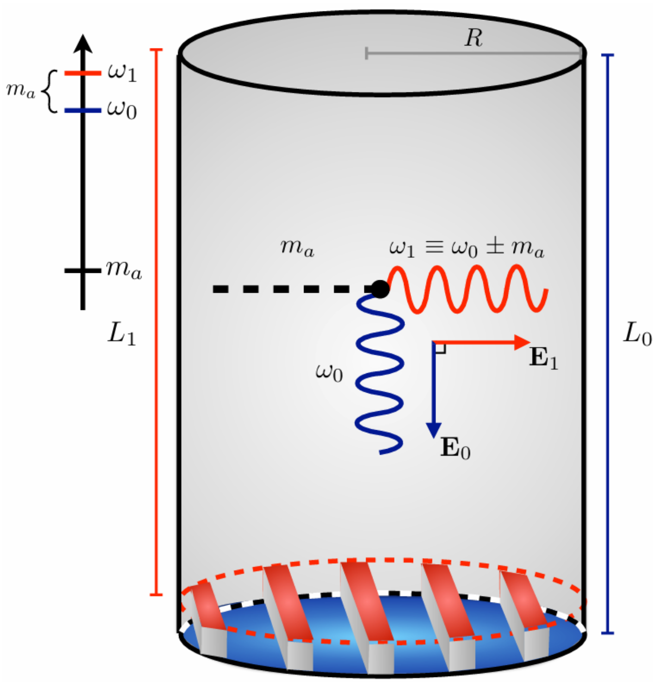
ADMX SLIC
1st result:
1911.05772

Magnetic signal from DM axion wind through a strong E field 2204.14033



DM-Radio
Magnetic signal from DM axion in a strong B field
2203.11246

Also at lower m_a: energy differences



(a) Cartoon of cavity setup.

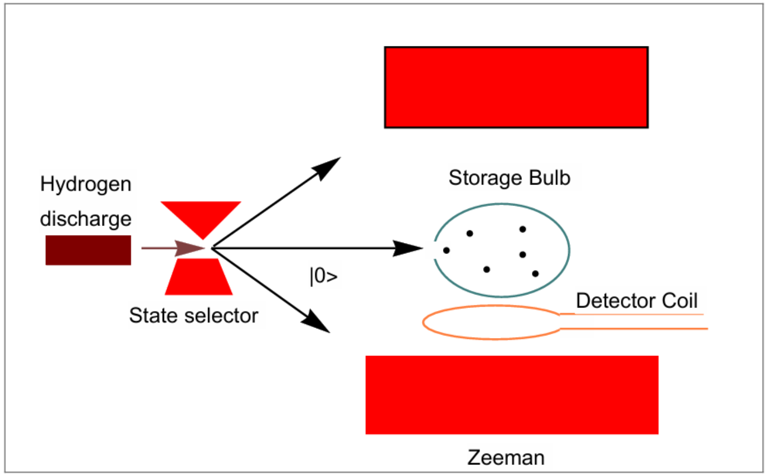
1912.11048

Also see: 2309.12387

Instead of preparing right on $\omega_{cav} = \omega_{DM}$, prepare $\omega'_{cav} = \omega^0_{cav} \pm \omega_{DM}$

** cavity mode transitions to capture DM (similarly in MNR, CASPEr systems)

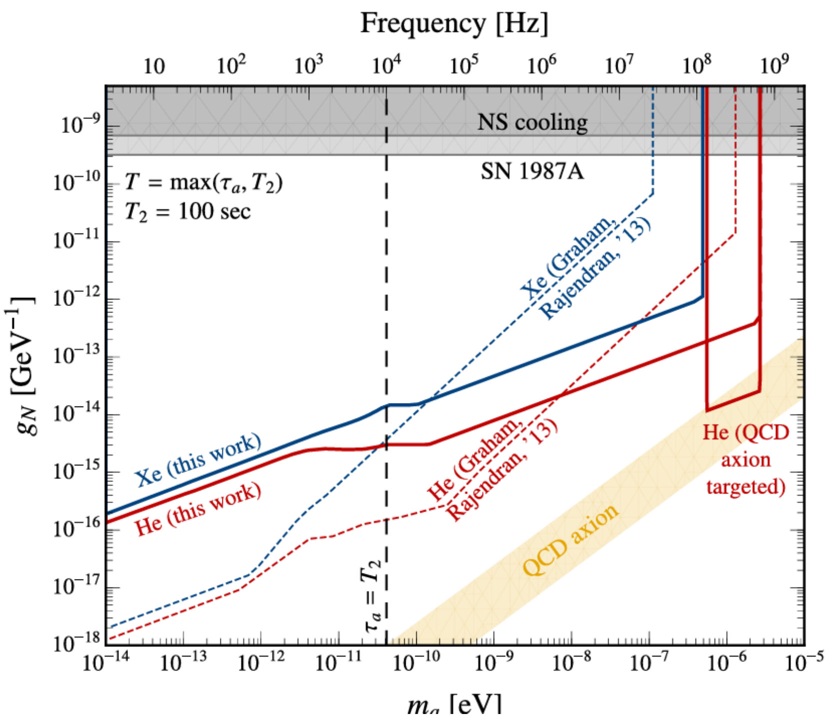
Axion DM acts as external field flip atomic hyperfine states: 1912.11472



Magnetometers

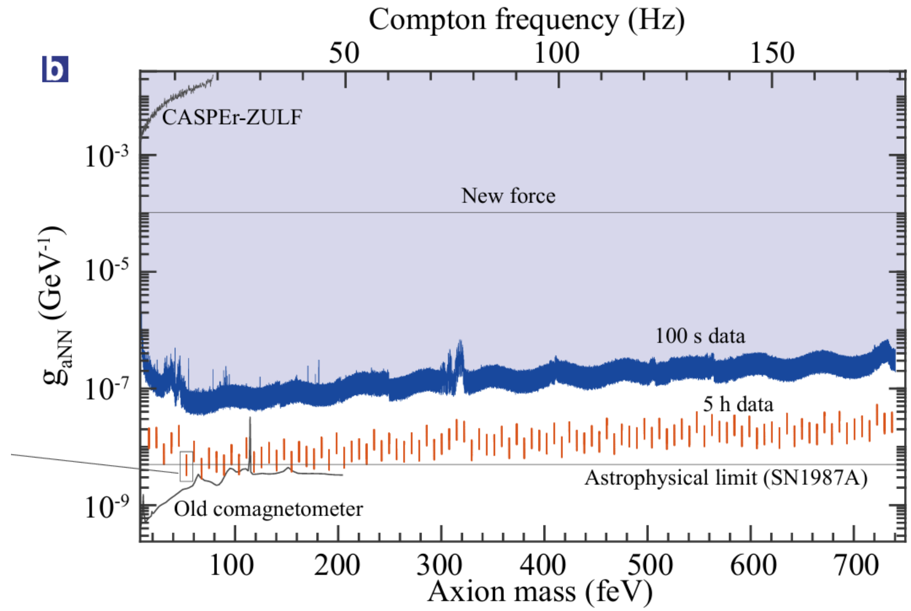
DM axion's interaction to fermions with a magnetic moment acts as external B field.

$$H = -2(g_{af}\vec{\nabla}a \cdot \vec{S}_f + g_d a\vec{E}^* \cdot \vec{S}_f)$$



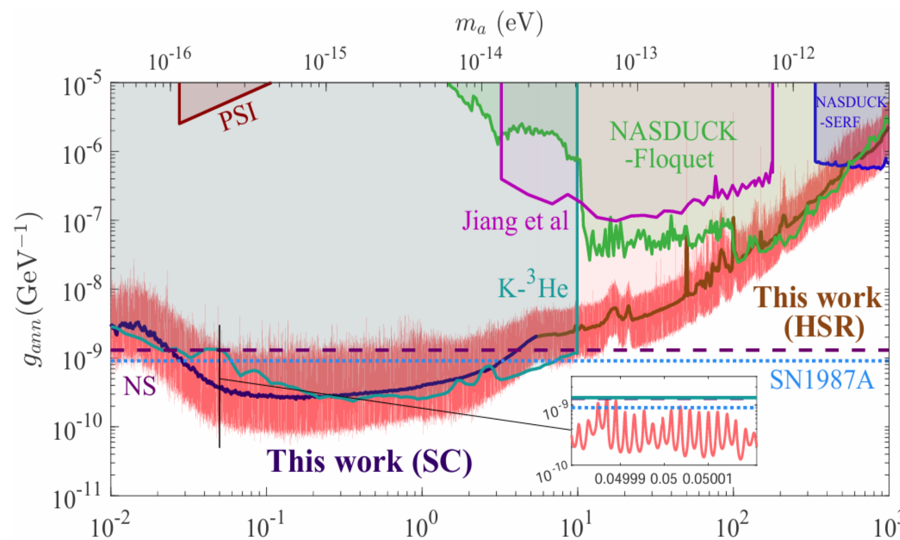
Reanalysis on `overlooked' enhancement for axion coherence time < spin relaxation time

Dror, Gori, Leedom, Rodd, *Phys.Rev.Lett.* 130 (2023) 18, 181801, (2210.06481)



M.Jiang, et al. Nature Phys. 17 (2021) 12, 1402-1407

Also see: Nature Commun. 15 (2024) 1, 3331



Kai Wei, 2306.08039

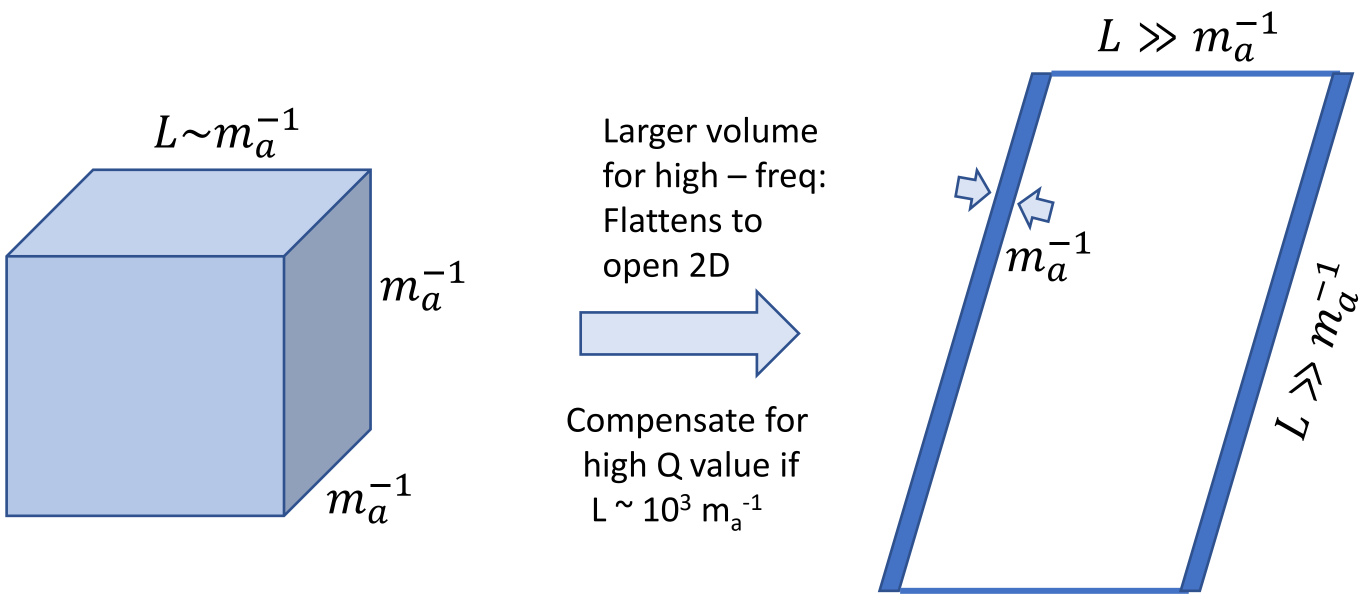
Volume issue at high frequency

`half-wavelength cutoff’:
signal coherence loss if antenna/pick is larger than photon wavelength

A dilemma btw high ω_a and a coherent volume

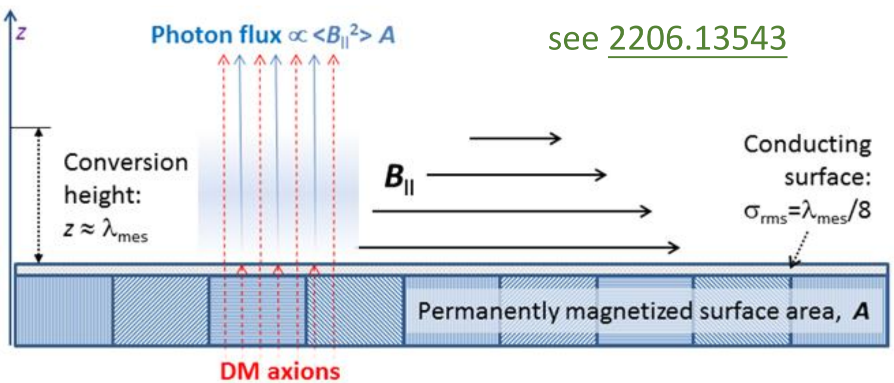
$$R \approx \frac{\pi}{2} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B_0^2 C_{\omega_a} V Q$$

Conversion Power $P = m_a R \propto m_a^{-2}$, high frequency is limited by coherent volume



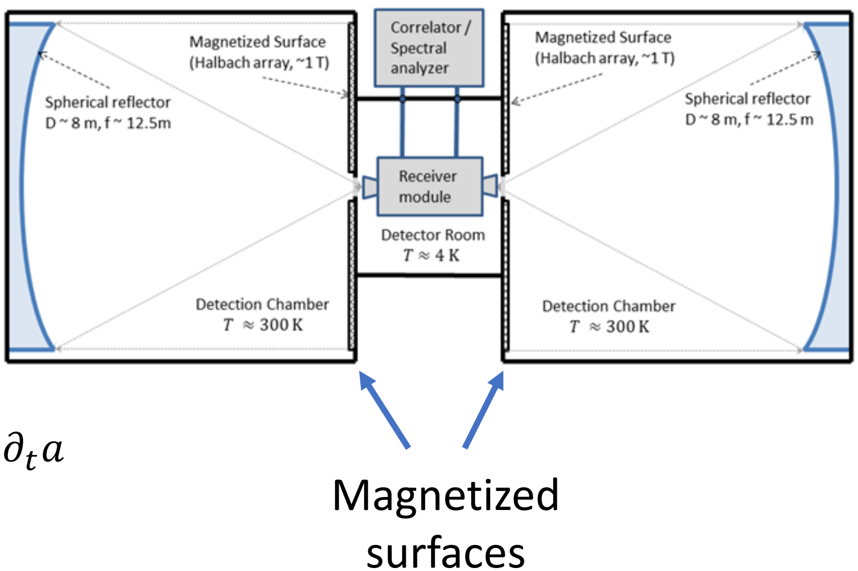
Magnetized surface: a 2D coherently radiating source

BRASS (Dish Antenna@ DESY)
http://wwwiexp.desy.de/groups/astroparticle/brass/brassweb.htm



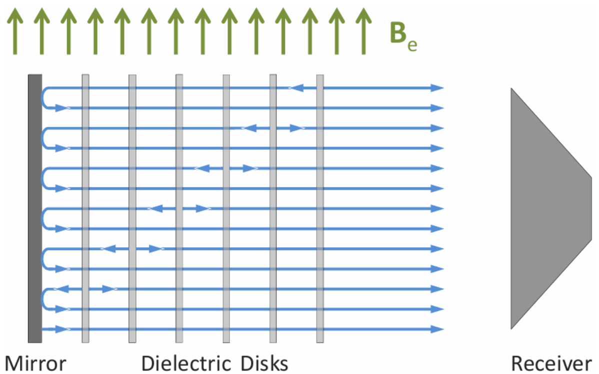
see 2206.13543

From BRASS website.



Alternative coherent effective current density $j_a = B\partial_t a$ along the surface.
Open region: total conversion power similar to a Q~1 cavity.
Radiation (coherent wave-front) maximizes in the perpendicular direction: can be focused to a detector.

MADMAX (tunable dielectric layers)



Dielectric haloscope proposal: 1611.05865

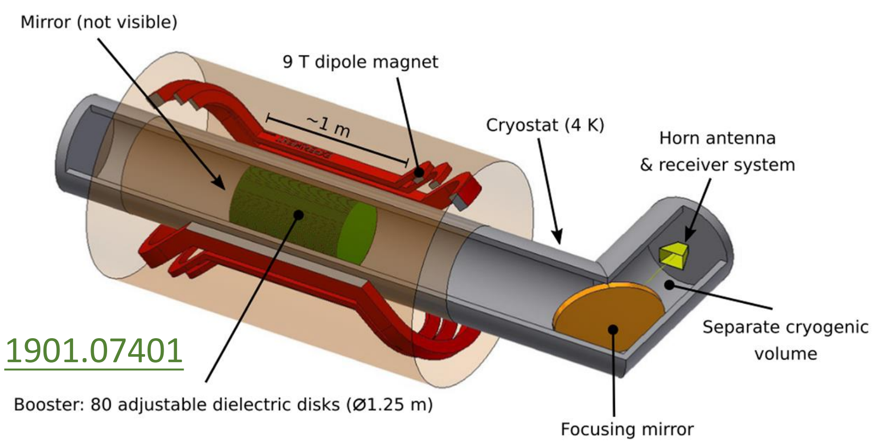
1612.07057

Dielectric boost factor $\beta \simeq \frac{m_a}{2B_e E_0}\left|\int dx E_{\mathrm{dh}} B_e\right|$

$E_0 \equiv \alpha/(2\pi)\,|C_{a\gamma}\mathbf{B}_e\,\theta_0|$

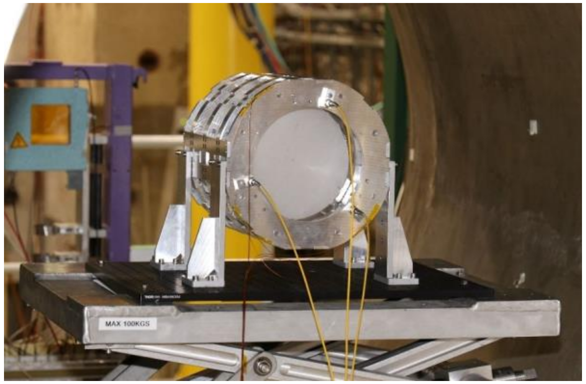
"Waves emitted by each dielectric disk are reflected by and transmitted through the other disks before exiting. With suitable disk placement, these waves add coherently to the emitted power considerably with respect to a single mirror."

$$P = P_0 \cdot \beta^2(\nu) = 1.1 \times 10^{-22}\ \mathrm{W}\left(\frac{\beta^2(\nu)}{5\times 10^4}\right)\left(\frac{A}{1\ \mathrm{m}^2}\right)\left(\frac{B_e}{10\ \mathrm{T}}\right)^2\left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm}^3}\right)C_{a\gamma}^2$$



1901.07401

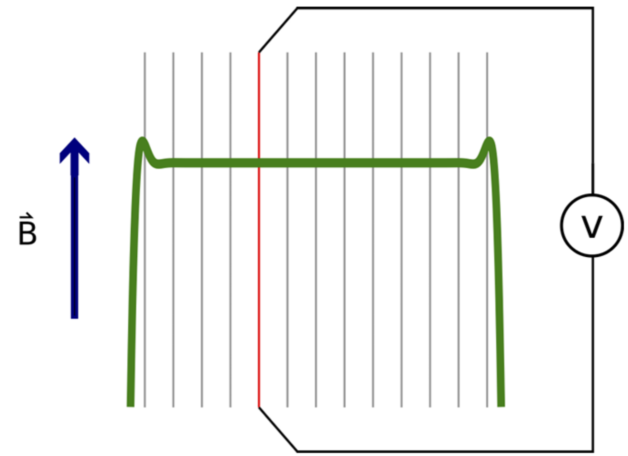
2407.10716



Plasmon-axion mixing

Tune the plasmon mass to match m_a

Metamaterial: provide a tunable plasma mass at cryogenic conditions.



$$n_e = n\frac{\pi d^2}{s^2} \quad ; \quad m_{eff} = \frac{e^2 \pi d^2 n}{2\pi} \log\frac{s}{d} \,,$$

J.B.Pendry, et.al. *Journal of Physics: Condensed Matter* 10 (1998) 47854809.

$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{s^2 \log(s/d)}$$

•ALPHA Collaboration 2210.00017 [hep-ph]

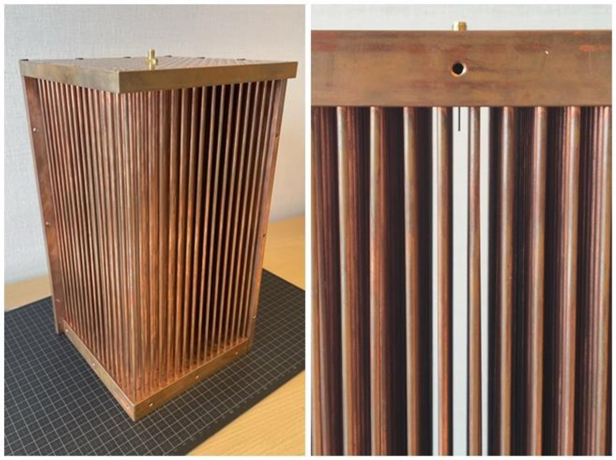
Signal power:

$$P = \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B_{\mathrm{e}}^2$$

$$\mathcal{G} = \frac{\epsilon_z^2}{a_0^2 g_{a\gamma}^2 B_{\mathrm{e}}^2 V} \frac{1}{2} \int \left(\frac{\partial(\epsilon_z \omega)}{\partial \omega} |\mathbf{E}|^2 + |\mathbf{B}|^2 \right) dV$$

"The array of wires acts as an effective medium with plasma frequency set by the wire spacing. The axion excites a bulk plasmon in the wire metamaterial."

1904.11872



Quantum clocks

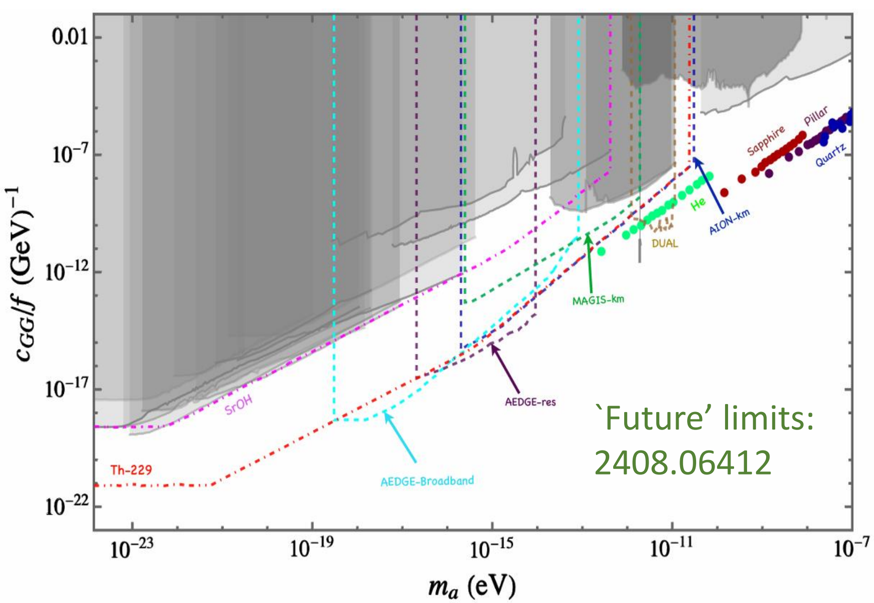
"Frequency ratio btw atomic clocks A and B is parametrised in terms of the fine-structure constant (α), electron to-proton mass ratio (m_e/m_p) and the ratio between quark mass (m_q) and QCD energy scale (Λ_{QCD}) "

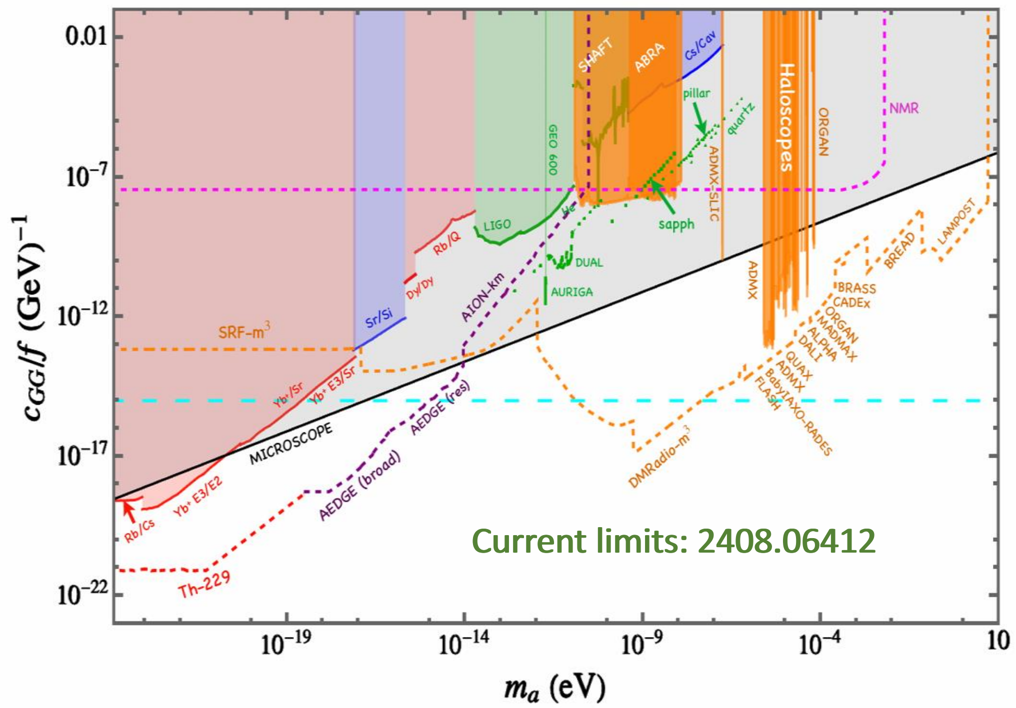
$$\frac{\delta\nu_{A/B}}{\nu_{A/B}} = k_\alpha\,\delta_\alpha(a) + k_e\,\delta_e(a) - (k_e + k_q)\,\delta_p(a) + k_q\,\delta_\pi(a)$$

See laborious studies: 1604.08514, nucl-th/0601050, 2302.04565, 2402.09643

Express $\delta(\nu_A/\nu_B)/(\nu_A/\nu_B)$ in terms of the low-energy Lagrangian parameters and the ratio a^2/f^2.

Compare microwave, atomic and nuclear clocks.

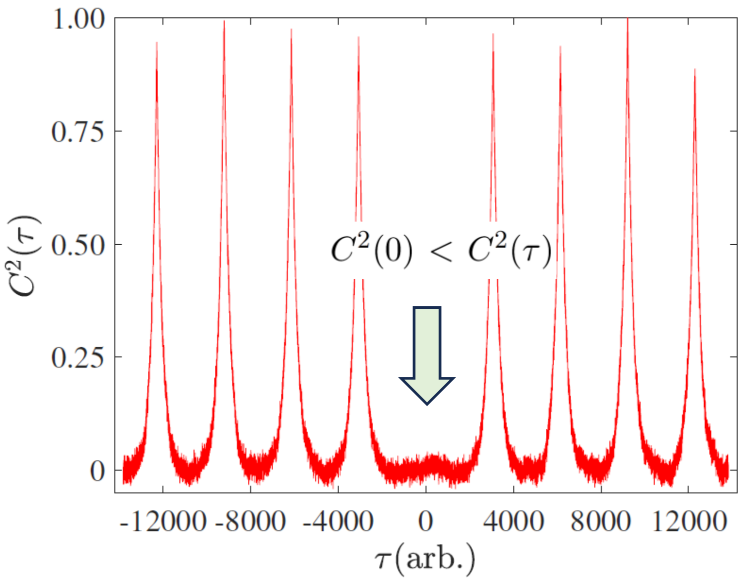


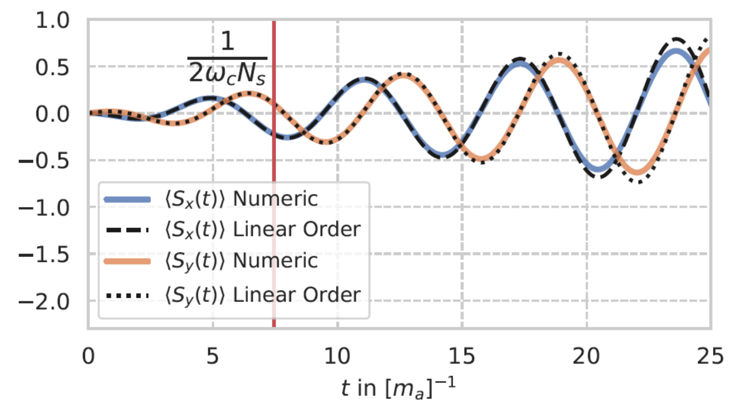


Wave-like axion DM: QM characteristics?

Sikivie & Yang, 09'

- Axion DM is in a **condensate**, and only ***occasionally*** picked up by quantized sensors
- Does `quantum-ness' leads to any observable effect?





Axion-detector interaction might cause further splitting & oscillation Jaeckel, Montoya, Quint, *Annalen Phys. 536 (2024) 1,* 2300151, 2304.02523

Low occupation # -> mostly single photon excitation state with dual-path corr. function C^2: A possibility with antibunching, as a post-discovery *test of the signal's QM state.*
Yang, Gao, Peng, Commun.Phys. 7 (2024) 1, 277, 2201.08291

Should DM live in a Coherent state (-> classical field) or a Fock state (free-streaming particles), or other?

also see discussion in: Cheong, Rodd, Wang, 2408.04696

More is coming!