Axion Physics and Detection

Andreas Ringwald
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

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COSMIC WISPERS CA21106

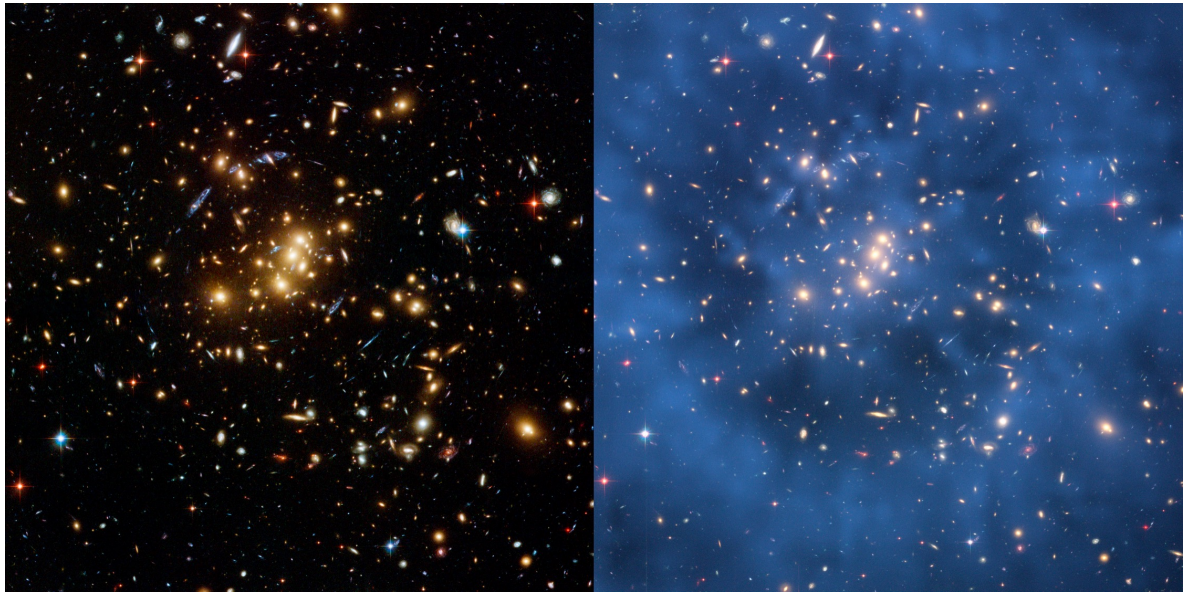
DESY.

The Axion

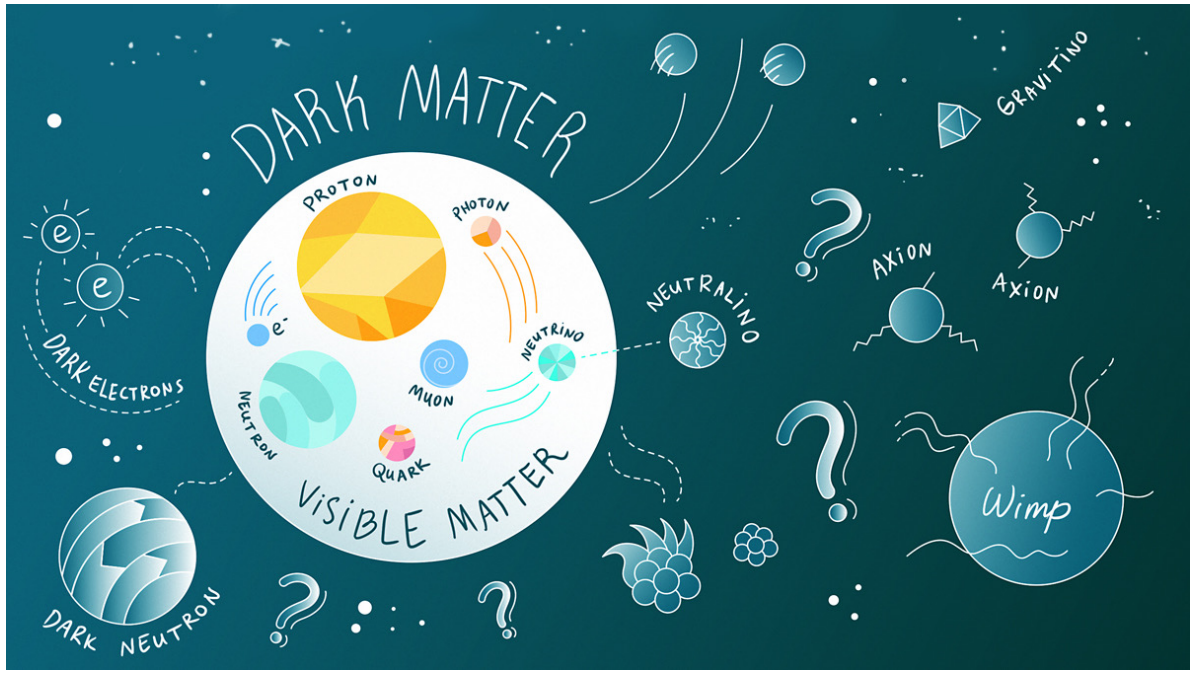
Solving two puzzles in one go

- Extensions of the Standard Model (SM) featuring the axion answer two fundamental questions in one go:

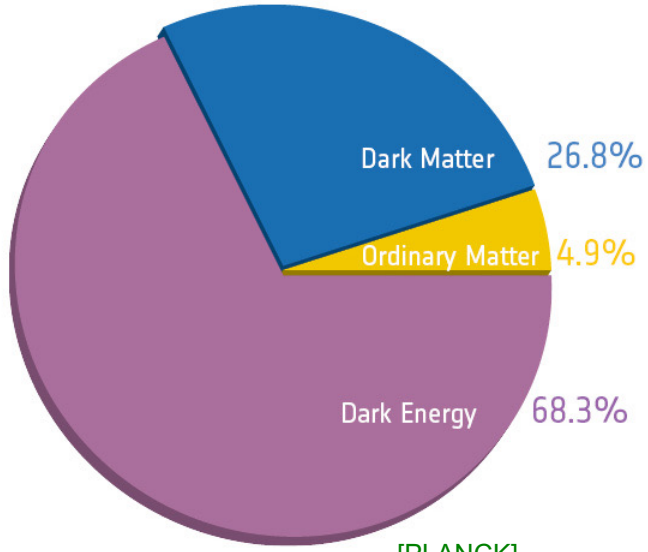
1. **What is the nature of dark matter (DM)?**
   [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83]



https://www.nasa.gov/content/discoveries-highlights-shining-a-light-on-dark-matter



[Symmetry Magazine]



[PLANCK]

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- Extensions of the Standard Model (SM) featuring the axion answer two fundamental questions in one go:

  1. **What is the nature of dark matter (DM)?**
  2. **Why do strong interactions conserve CP so accurately?**

  [Peccei,Quinn `77; Weinberg `78; Wilczek `78]

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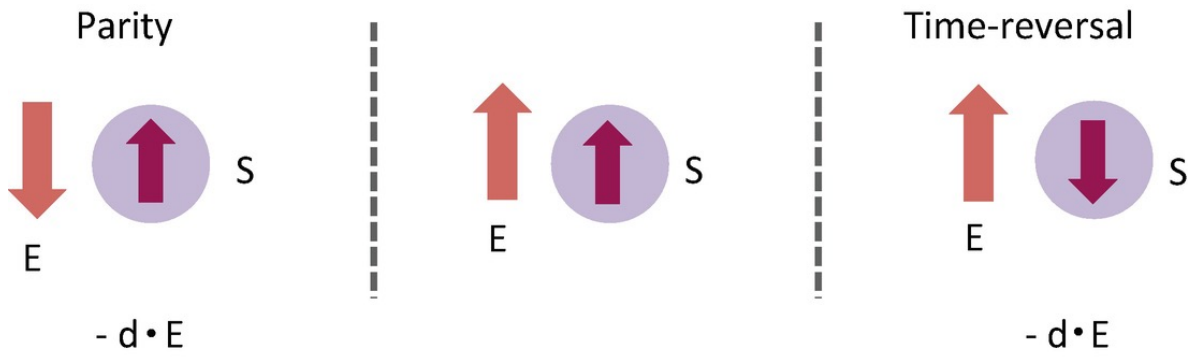
     - Why is the electric dipole moment of the neutron so tiny?
       - Experiment: $|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm}$ [Abel et al. 20]

Talk by Katia Michielsen on Thu 26/06 at 10:10 in Particles: Beyond the Standard Model & Flavour Physics parallel session



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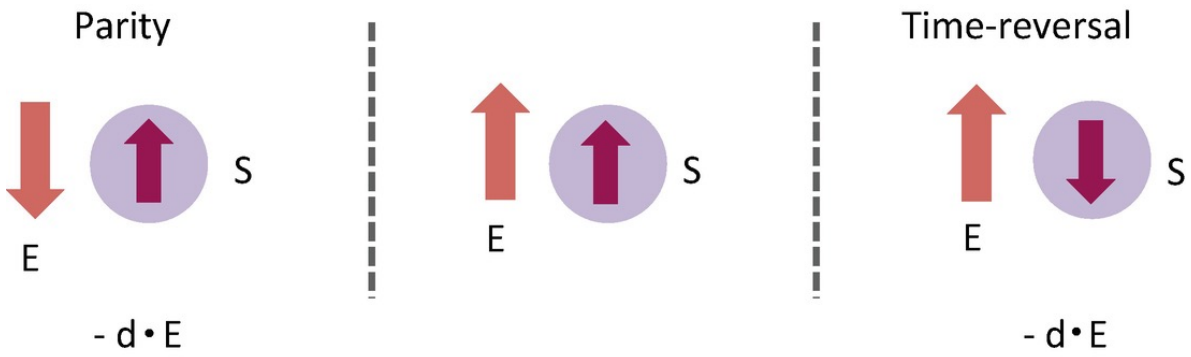

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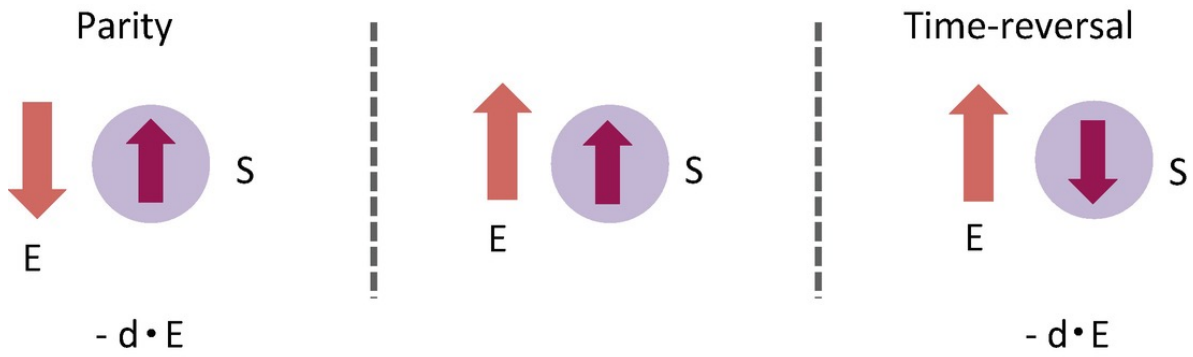

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QCD Lagrangian contains a term which violates P and T:

[Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

$$\mathcal{L}_{\mathrm{QCD}} \supset -\theta \frac{\alpha_s}{8\pi} G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} \equiv -\theta \frac{\alpha_s}{2\pi} \mathbf{E}^b \cdot \mathbf{B}^b$$

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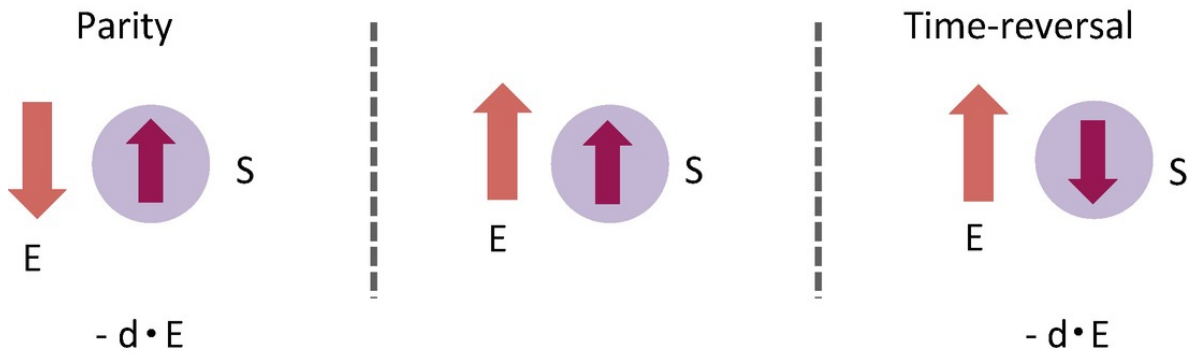

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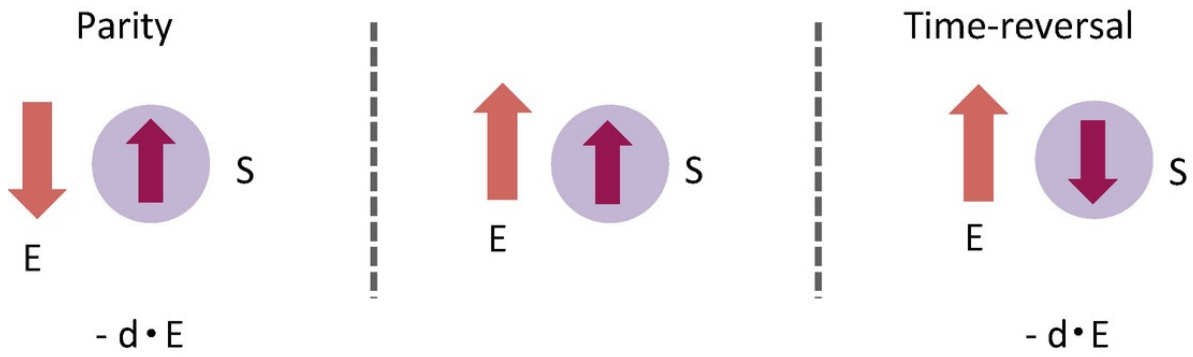

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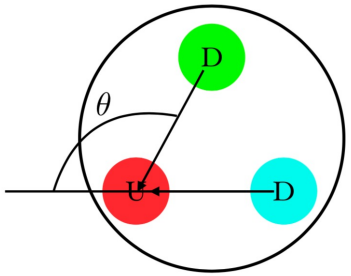
- predicts neutron electric dipole moment (nEDM):

[Crewther,Di Vecchia,Veneziano,Witten 79;...; Pospelov,Ritz 00]

$$d_n \sim \bar{\theta}\, e\, \frac{m_u}{m_n^2} \sim 10^{-16}\, \bar{\theta}\ e\,\mathrm{cm}$$



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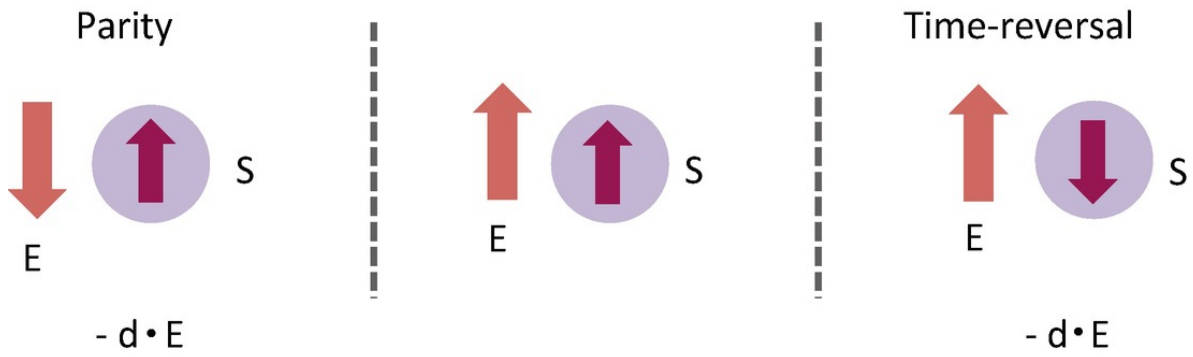

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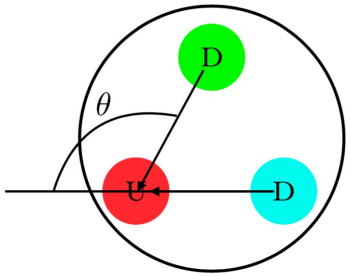
- Comparison with experiment: $\Rightarrow |\bar{\theta}| \lesssim 10^{-10}$



Strong CP Puzzle

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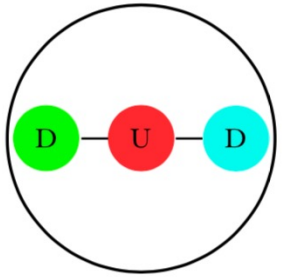

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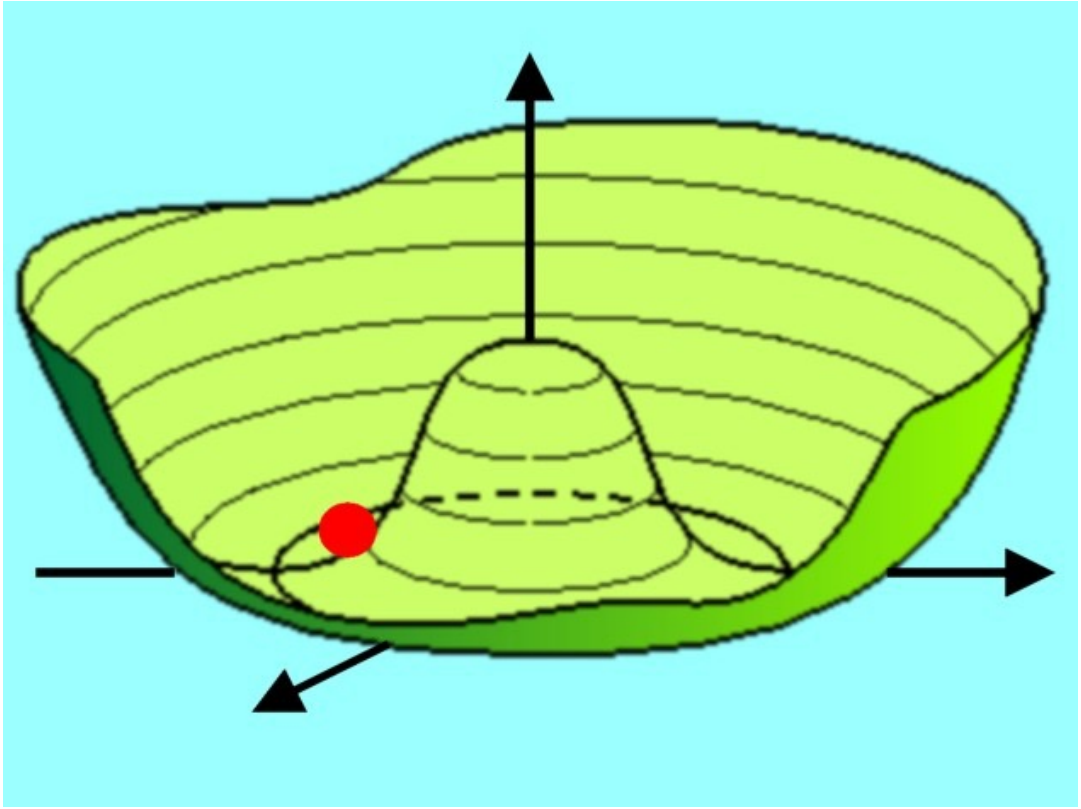
Minimal SM extension solving strong CP puzzle

[Kim 79;Shifman,Vainshtein,Zakharov 80]

- Add to SM a singlet complex scalar field σ, featuring a spontaneously broken global axial $U(1)_{\rm PQ}$ symmetry, and an exotic quark $\mathcal{Q}$ charged under it:

$$\mathcal{L} \supset -\lambda_\sigma \left(|\sigma|^2 - \frac{v_{\rm PQ}^2}{2} \right)^2 + y\,\sigma\,\bar{\mathcal{Q}}_L \mathcal{Q}_R$$



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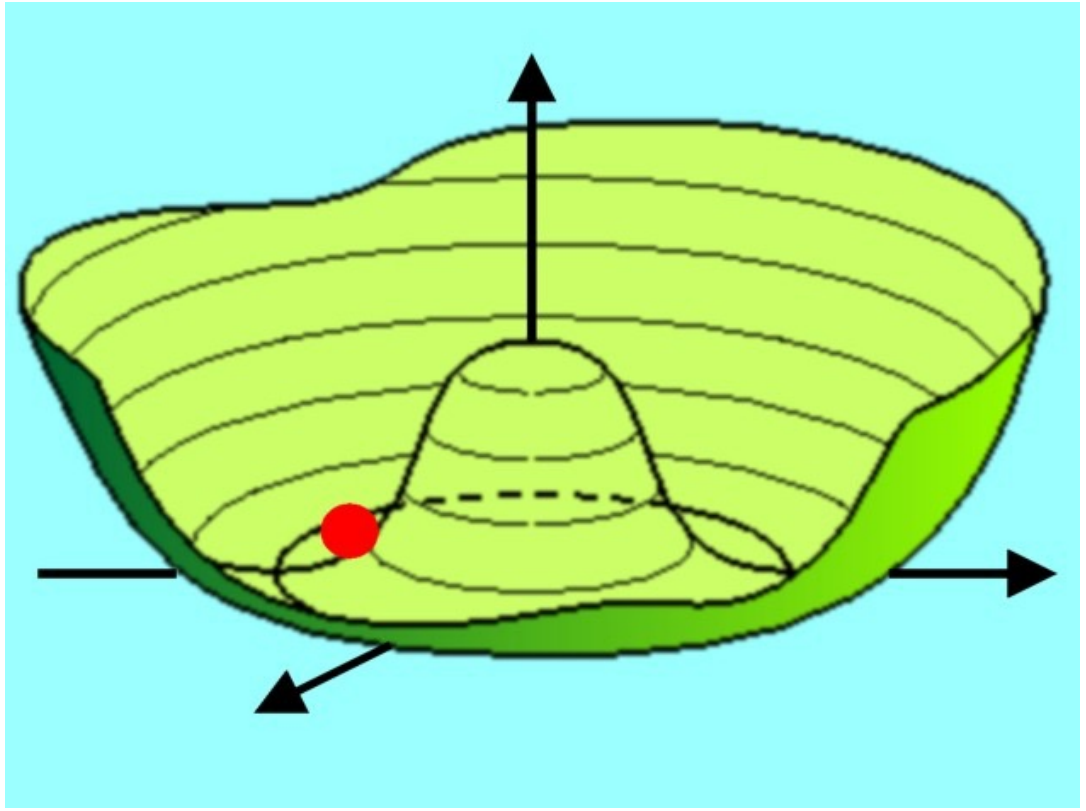
  - Features three particles beyond SM:
    1. Excitation of angular field a : axion (NG-boson)
    2. Excitation of modulus field ρ: $m_\rho = \sqrt{2\lambda_\sigma} v_{\rm PQ}$
    3. Exotic quark: $m_{\mathcal{Q}} = \frac{y}{\sqrt{2}} v_{\rm PQ}$

$$\boxed{\sigma(x) = \frac{1}{\sqrt{2}} \left(v_{\rm PQ} + \rho(x) \right) \mathrm{e}^{ia(x)/v_{\rm PQ}}}$$



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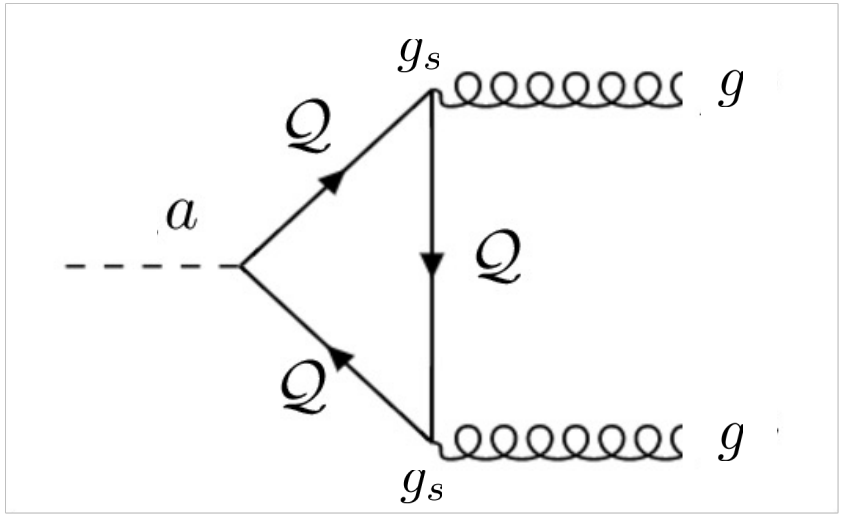

[Chadha-Day, Ellis, Marsh, Science Advances 22]

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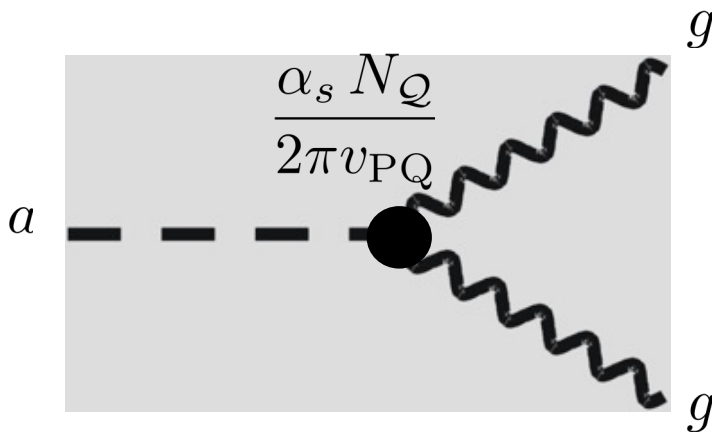
$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}\partial^\mu a\,\partial_\mu a + \frac{\alpha_s}{8\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} \quad \text{with} \quad f_a = v_{\rm PQ}/N_{\mathcal{Q}}$$



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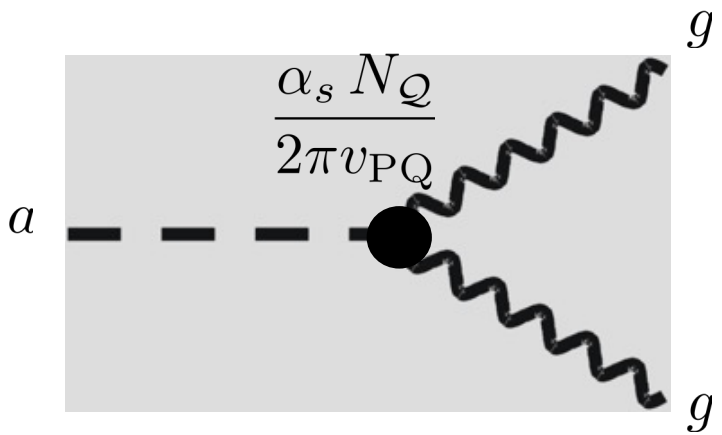

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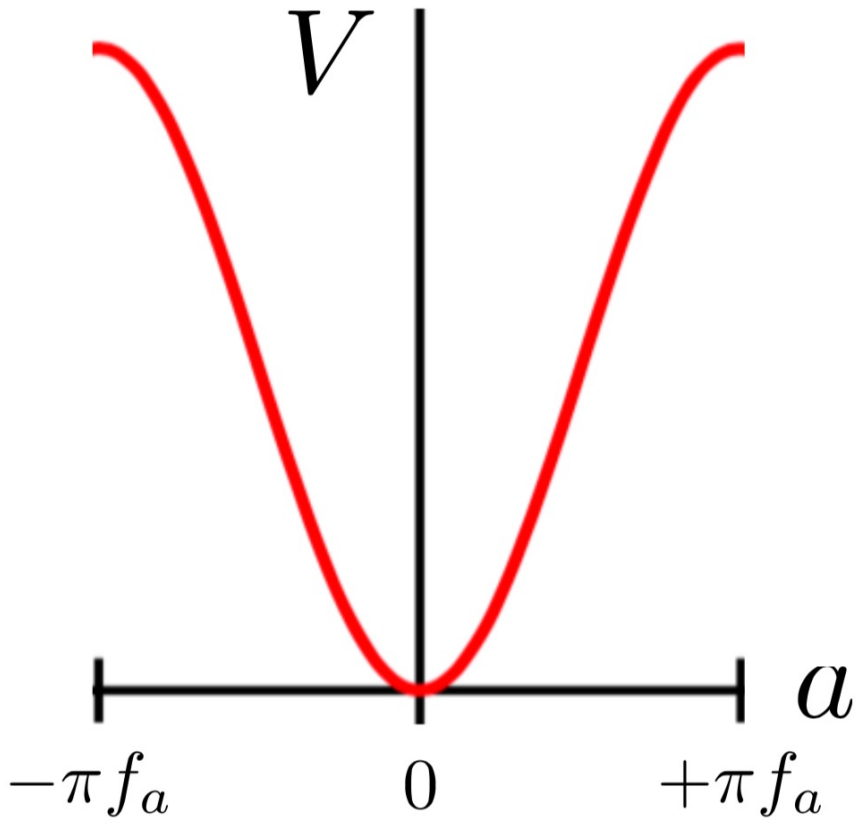
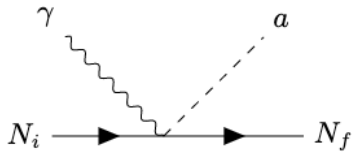
- Shifted field (the axion) acquires mass from mixing with neutral pion, $m_a \sim m_\pi\, f_\pi / f_a$: $\langle a \rangle = 0$, CP conserved

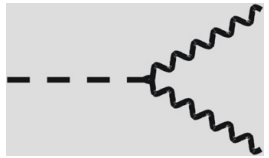


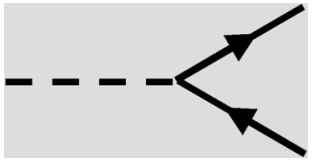
The Axion

Effective field theory below QCD scale

$$\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{i}{2} \frac{e\, C_{\mathrm{NEDM}}}{f_a}\, a\, \overline{\psi}_N \sigma_{\mu\nu} \gamma_5 \psi_N F^{\mu\nu} + C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} C_{af} \frac{\partial_\mu a}{f_a} \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$







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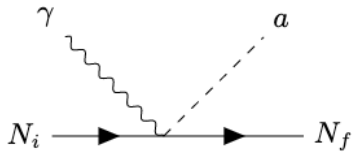
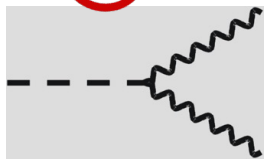
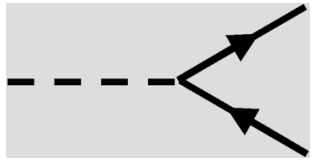
$$m_a \simeq \frac{\sqrt{z}}{1+z} \frac{m_\pi f_\pi}{f_a} \approx 6\ \text{meV} \left(\frac{10^9\ \text{GeV}}{f_a} \right)$$

$$z = m_u / m_d \simeq 1/2$$







- Suppression by inverse power of symmetry breaking scale f_a leads to tiny mass and feeble couplings to SM

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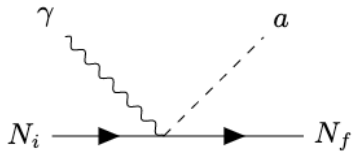
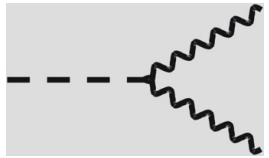
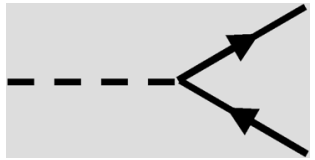






- Suppression by inverse power of symmetry breaking scale f_a leads to tiny mass and feeble couplings to SM
- Size of coefficients in vanilla axion models:
  - EDM coupling: $C_{\rm NEDM} = 2.4(1.0) \times 10^{-16}\,\text{cm}$ [Pospelov,Ritz `00]
  - Photon coupling: $C_{a\gamma} = \frac{E}{N} - \frac{2}{3}\frac{4+z}{1+z}$ [Kaplan 85;Srednicki `85; Grilli di Cortona et al. `16]
  - Nucleon couplings: $C_{aN} = \mathcal{O}(1)$ [Grilli di Cortona et al. `16]

The Axion

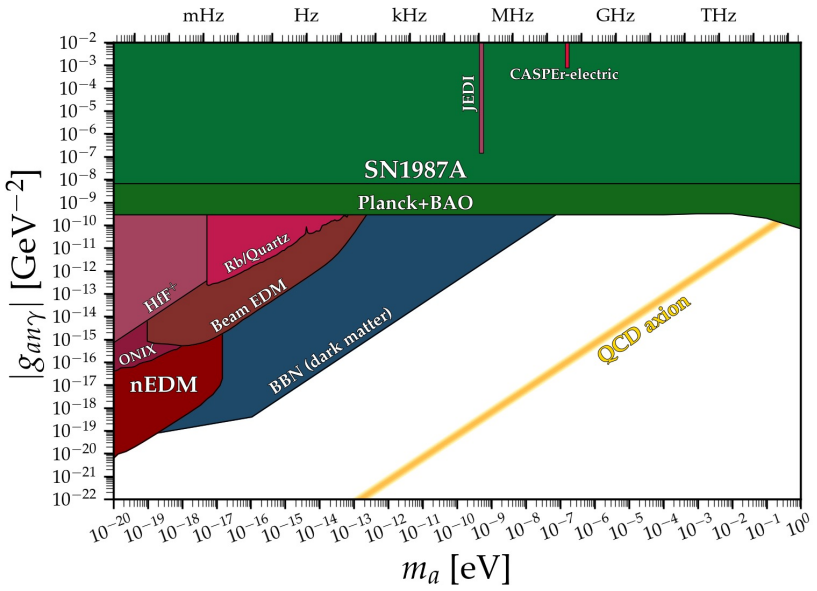
Expectations for axion couplings to SM particles

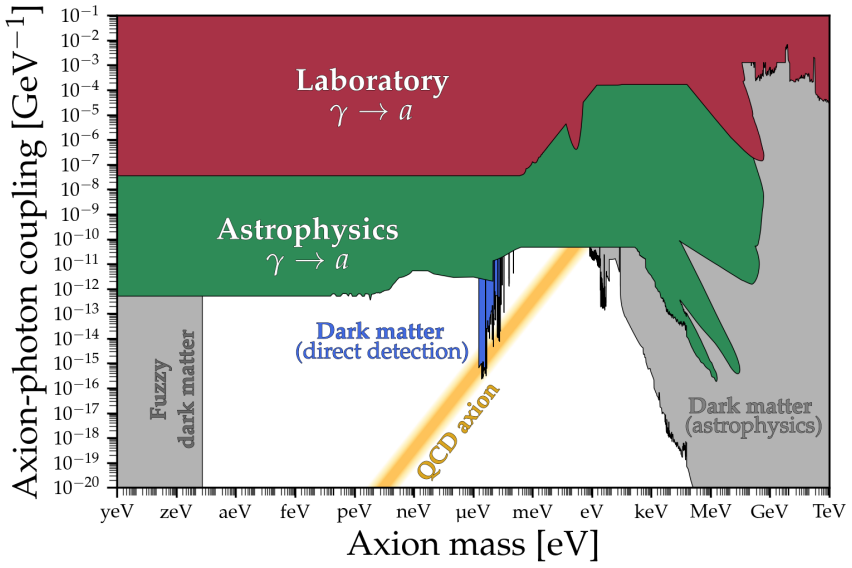
“Yellow bands” of vanilla axion couplings:

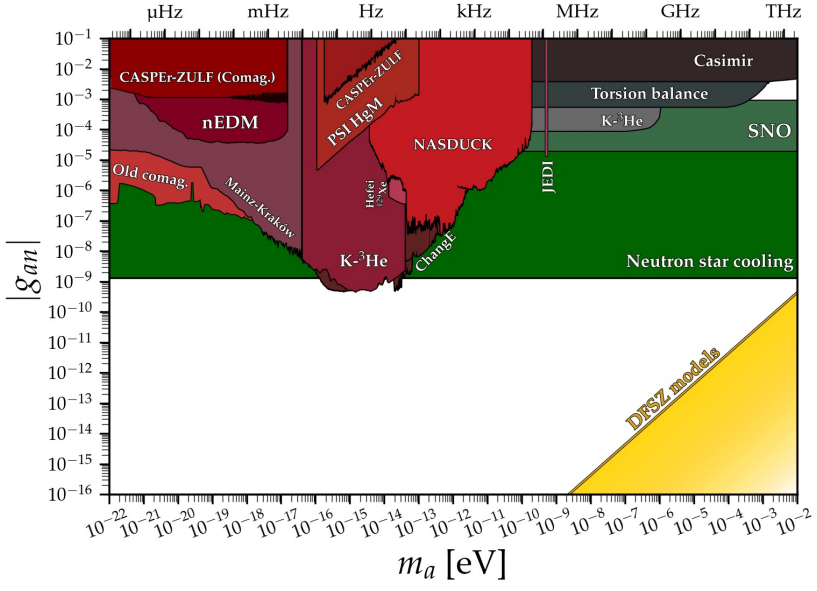
$$g_{an\gamma} = e\,\frac{C_{\mathrm{NEDM}}}{f_a}$$

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

$$g_{an} = \frac{C_{an} m_n}{f_a}$$







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

The Axion

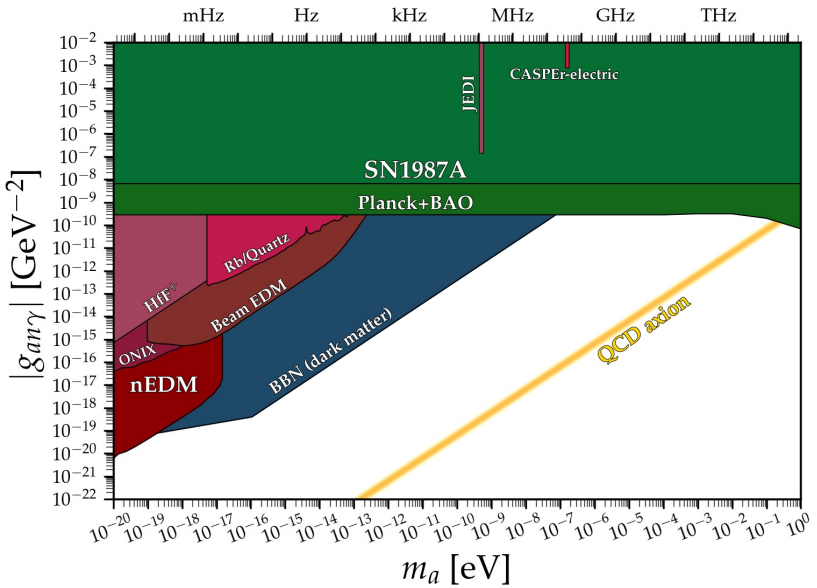
Expectations for axion couplings to SM particles

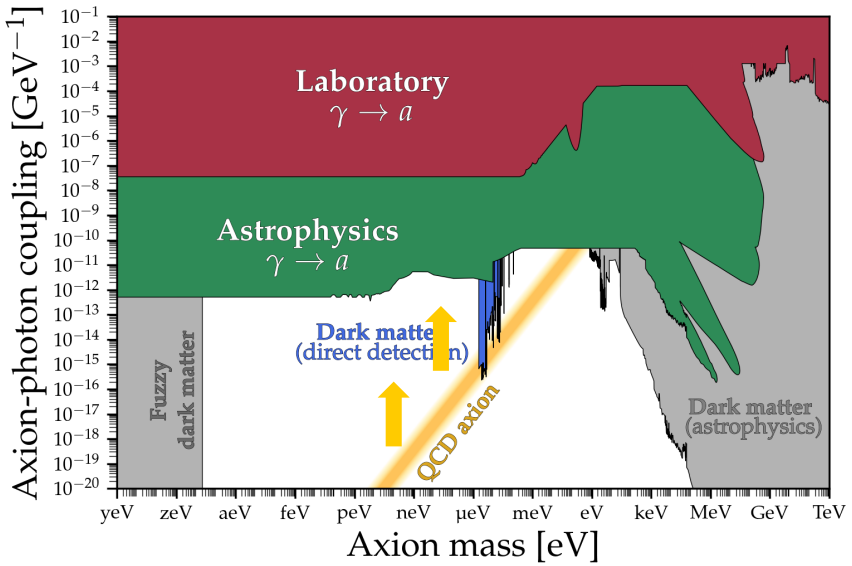
There are axion models with enhanced $C_{a\gamma}$ and/or C_{aN}:

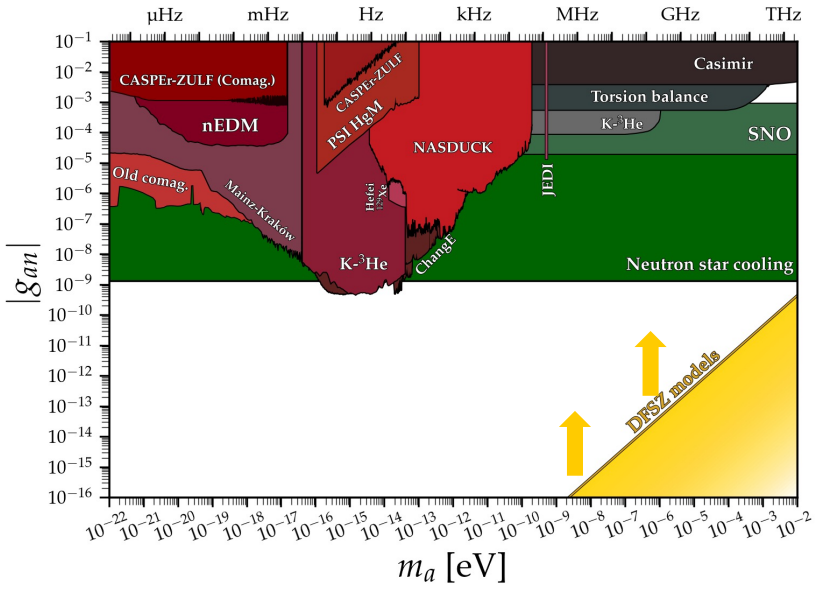
$$g_{an\gamma} = e\,\frac{C_{\mathrm{NEDM}}}{f_a}$$

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

$$g_{an} = \frac{C_{an} m_n}{f_a}$$







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

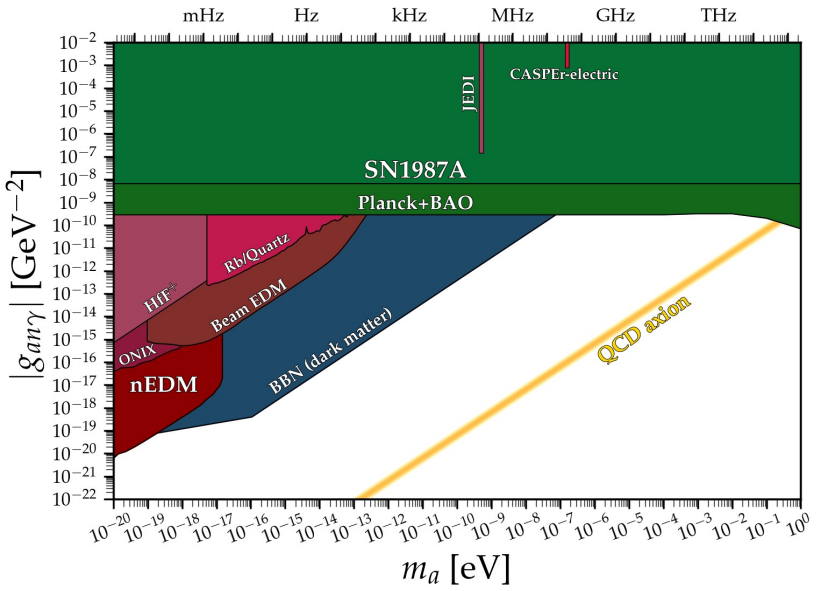
The Axion

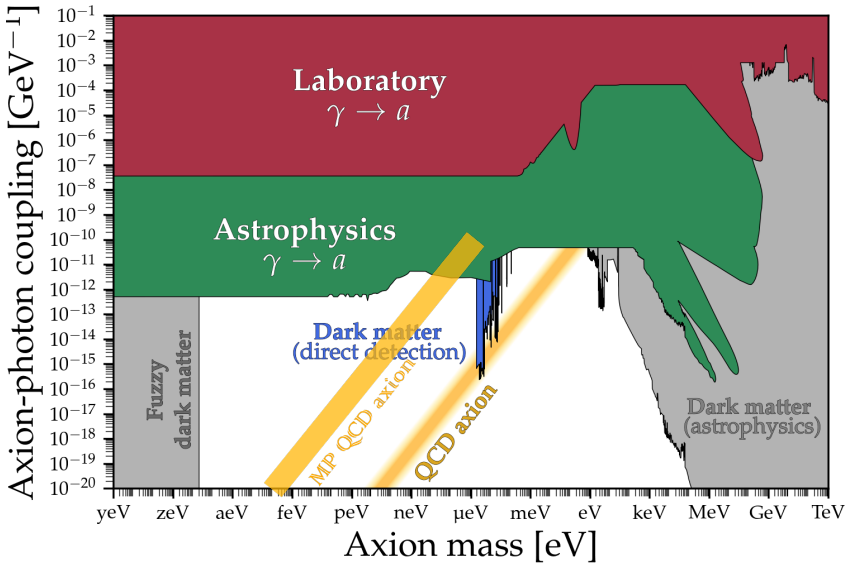
Expectations for axion couplings to SM particles

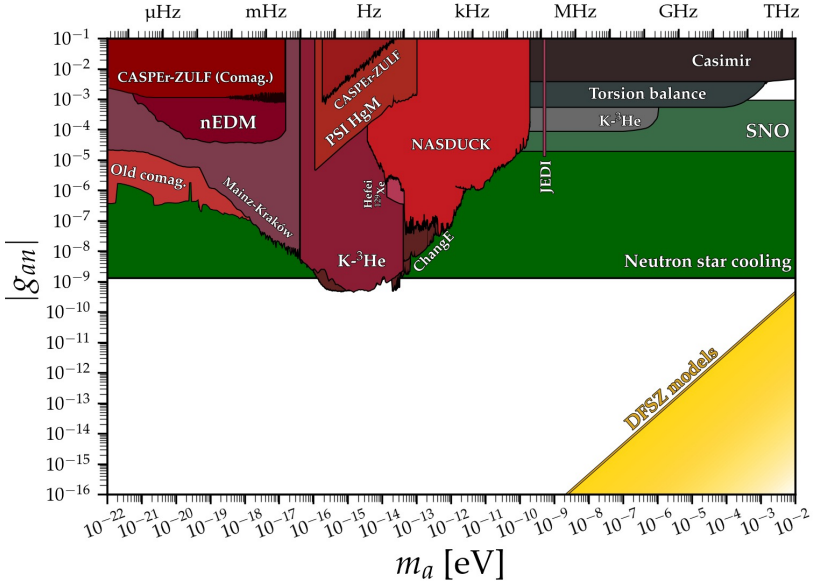
There are axion models with enhanced $C_{a\gamma}$ and/or C_{aN}, e.g. Monopole Philic (MP) axion

[Sokolov,AR, 2104.02574; 2109.08503; 2205.02605; 2303.10170]

$$g_{an\gamma} = e\,\frac{C_{\rm NEDM}}{f_a} \qquad g_{a\gamma} = \frac{\alpha}{2\pi f_a}\,C_{a\gamma} \qquad g_{an} = \frac{C_{an} m_n}{f_a}$$







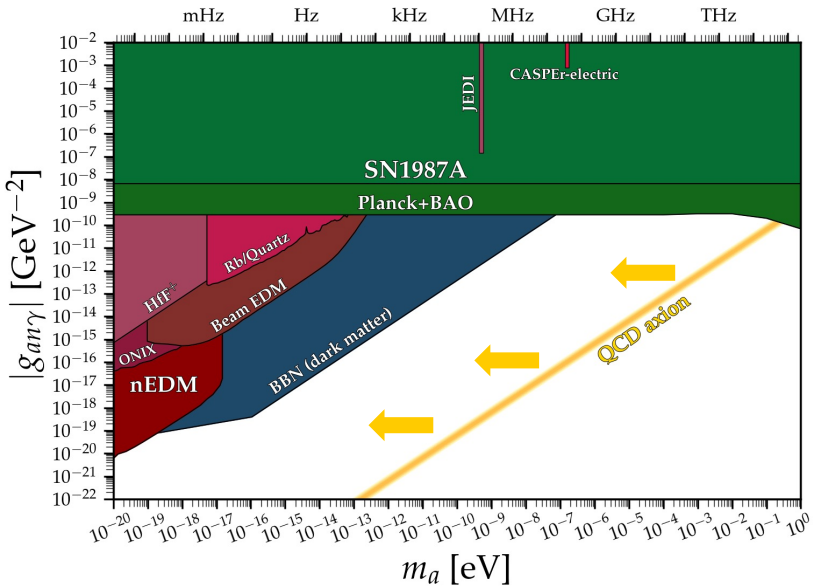
[https://github.com/cajohare/AxionLimits]

The Axion

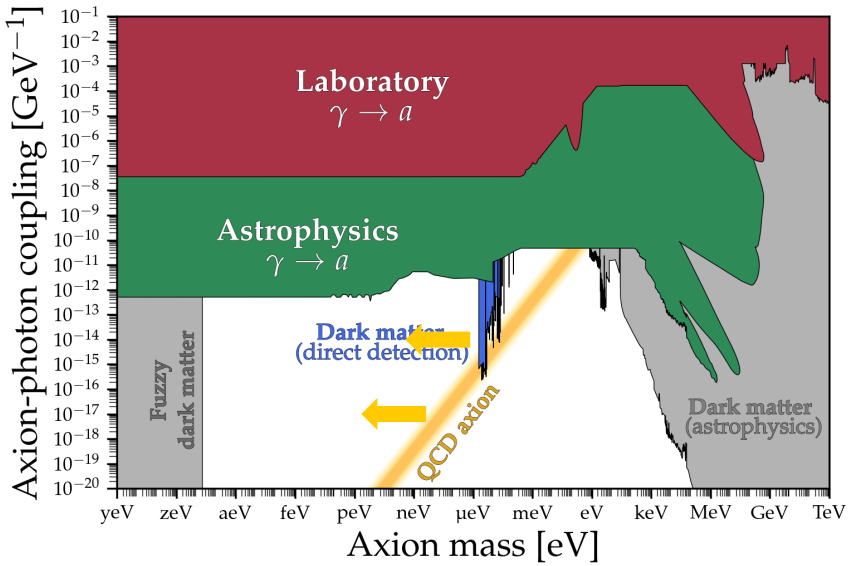
Expectations for axion couplings to SM particles

There are axion models with reduced $(m_a f_a)/(m_\pi f_\pi)$

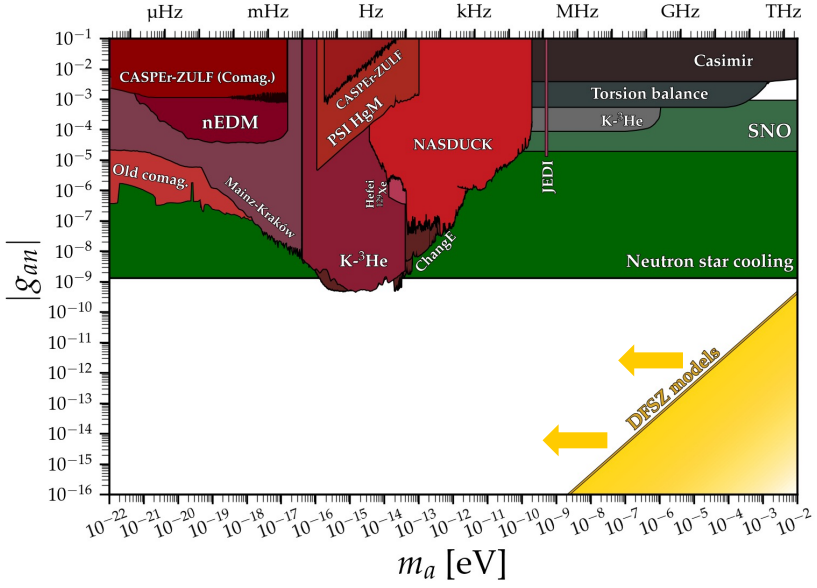
$$g_{an\gamma} = e\,\frac{C_{\mathrm{NEDM}}}{f_a}$$



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



$$g_{an} = \frac{C_{an} m_n}{f_a}$$



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

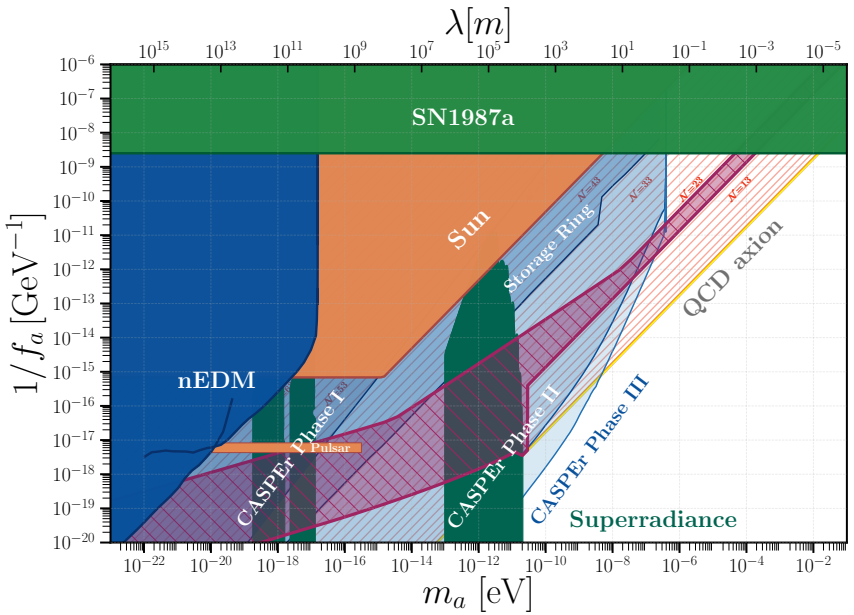
The Axion

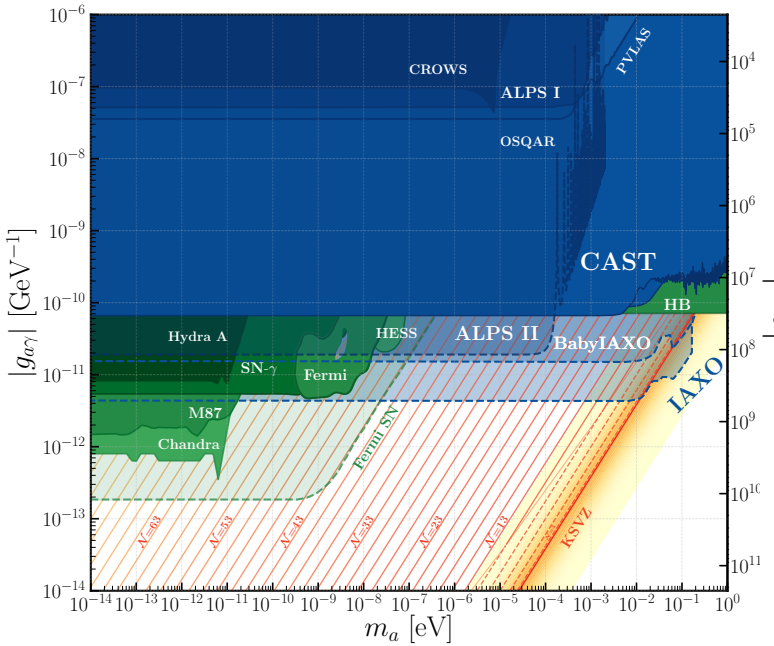
Expectations for axion couplings to SM particles

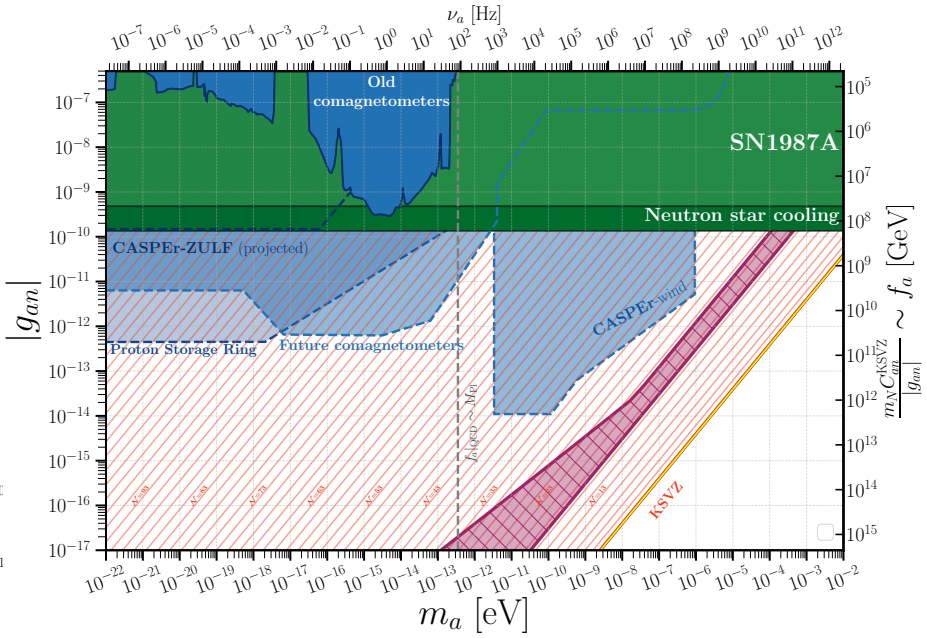
There are axion models with reduced $(m_a f_a)/(m_\pi f_\pi)$, e.g. the $Z_\mathcal{N}$ model, where $(m_a f_a)/(m_\pi f_\pi) \sim (m_u/m_d)^\mathcal{N}$

[Hook, 1802.10093; Di Luzio,Gavela,Quilez,AR, 2102.00012; 2102.01082]

$$g_{an\gamma} = e\,\frac{C_{\rm NEDM}}{f_a} \qquad g_{a\gamma} = \frac{\alpha}{2\pi f_a}\,C_{a\gamma} \qquad g_{an} = \frac{C_{an} m_n}{f_a}$$







Axion Experiments Not Relying on Axion Dark Matter

Axion Experiments Not Relying on Axion Dark Matter

Searching for solar or home-made axions

Axion Experiments Not Relying on Axion Dark Matter

Searching for solar or home-made axions

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \equiv g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}$$

Axion Experiments Not Relying on Axion Dark Matter

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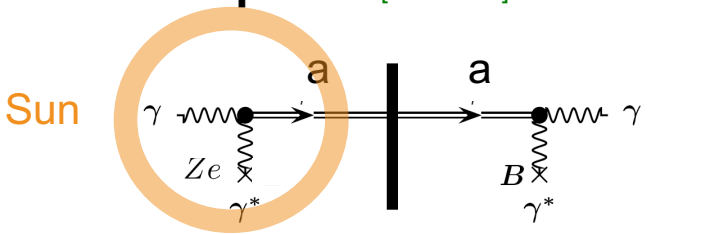
- **Helioscopes:** [Sikivie 83]



$\Phi_a \propto g_{a\gamma\gamma}^2 V_\odot$ $P(a\to\gamma) \simeq \frac{1}{4}(g_{a\gamma\gamma}BL_B)^2$

Axion Experiments Not Relying on Axion Dark Matter

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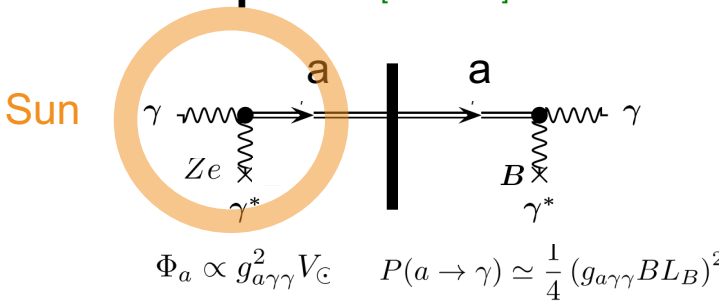

$$\Phi_a \propto g_{a\gamma\gamma}^2 V_\odot \qquad P(a\to\gamma) \simeq \frac{1}{4}\left(g_{a\gamma\gamma}BL_B\right)^2$$

- **CAST** @ CERN (2003 - 2015)

- LHC test dipole magnet (B ~ 9 T, L ~ 10 m)

Axion Experiments Not Relying on Axion Dark Matter

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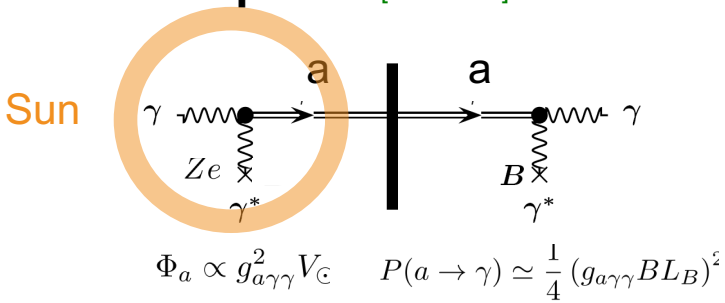
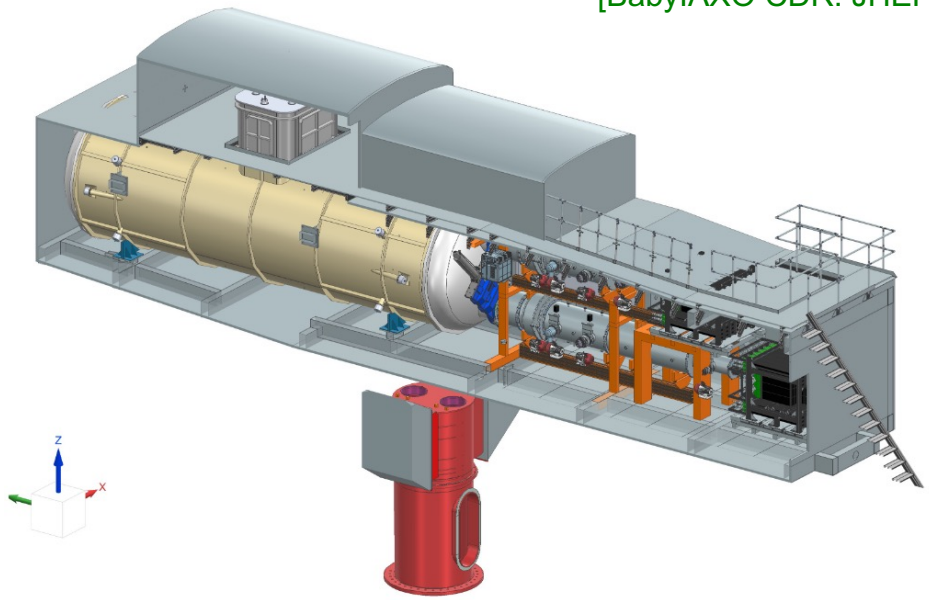


$$\Phi_a \propto g_{a\gamma\gamma}^2 V_\odot \qquad P(a\to\gamma) \simeq \frac{1}{4}\left(g_{a\gamma\gamma}BL_B\right)^2$$

- **BabyIAXO** in construction @ DESY: (1st data 2031?)

[BabyIAXO CDR: JHEP 05 (2021) 137]



- Superconducting magnet featuring two flat racetrack coils made from Niobium-Titanium wire

  B ~ 2 T, L ~10 m, 2 bores with 70 cm diameter
- 2 X-ray telescopes + 2 detection systems
- Movable platform with service

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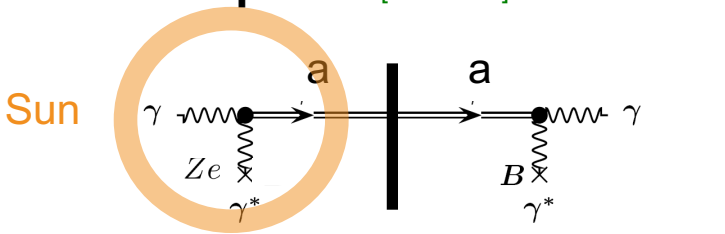
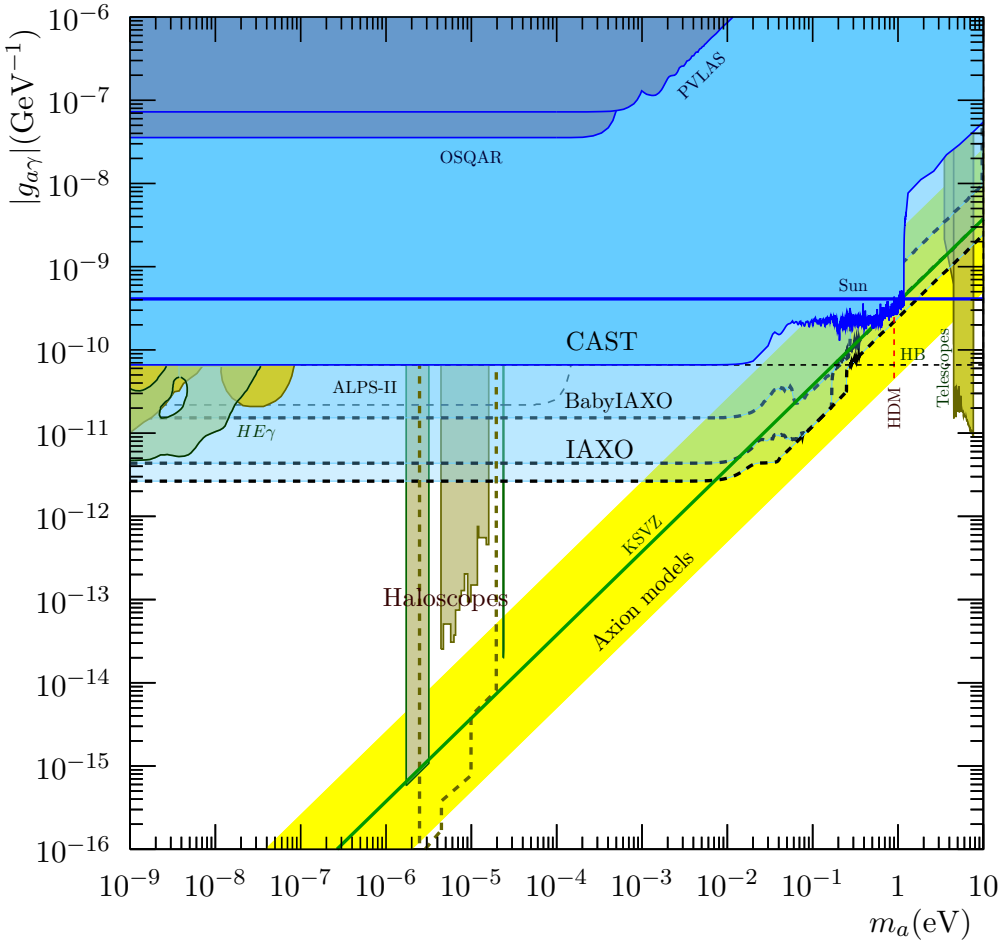


$$\Phi_a \propto g_{a\gamma\gamma}^2 V_\odot \qquad P(a\to\gamma) \simeq \frac{1}{4}\,(g_{a\gamma\gamma}BL_B)^2$$

- **BabyIAXO** sensitivity forecast:



[IAXO Collaboration, JCAP 06 (2019) 047]

Axion Experiments Not Relying on Axion Dark Matter

Searching for solar or home-made axions

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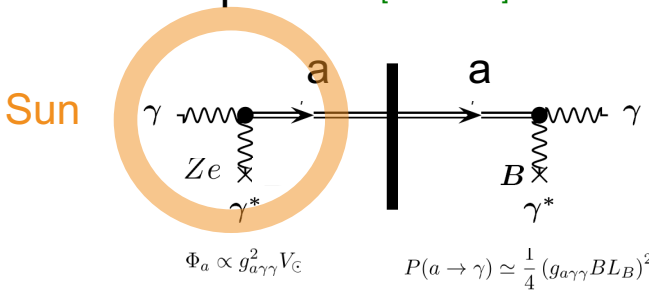
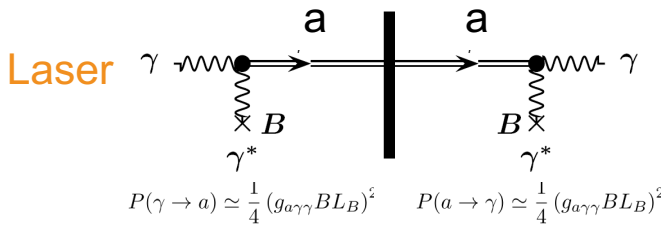


- **Light-shining through walls:** [Anselm 85; van Bibber 87]



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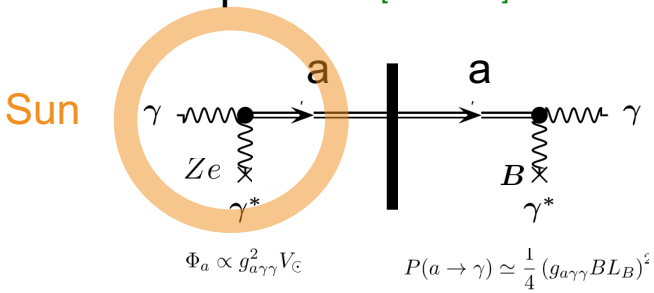

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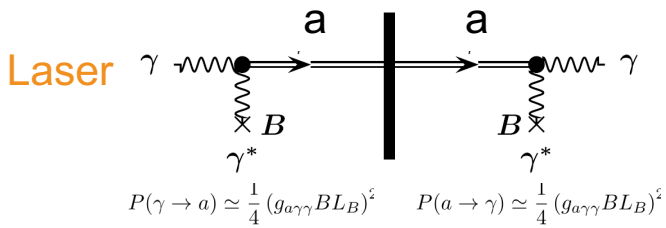

- **ALPS** @ DESY (2007 - 2009)

- HERA dipole magnet (B ~ 5 T, L ~ 9 m)

Axion Experiments Not Relying on Axion Dark Matter

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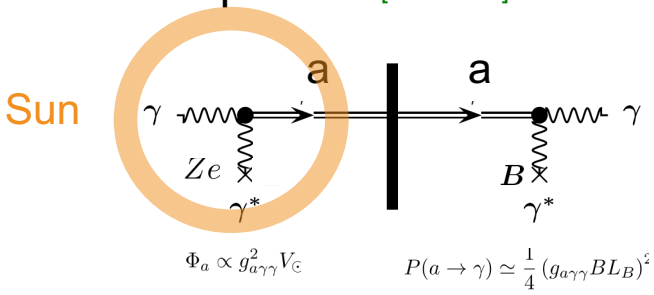

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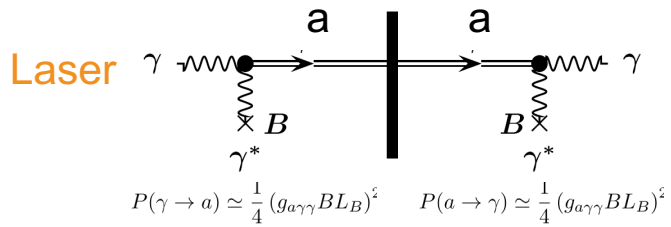
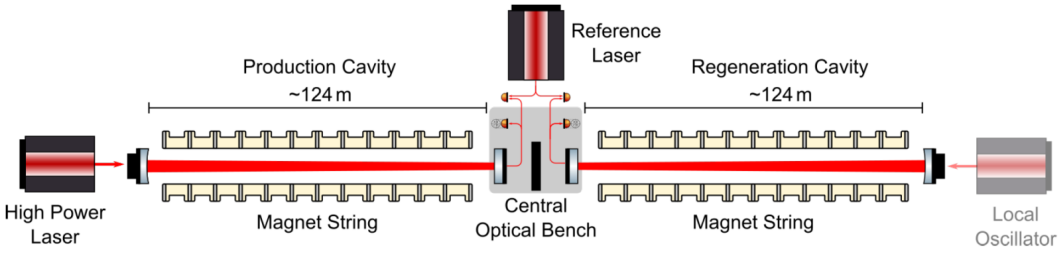


- **ALPS II** @ DESY [Bähre et al (ALPS II TDR) 13]

12 + 12 straightened HERA magnets

[AR, Phys. Lett. B 569 (2003) 51]



Optical cavities both at production and regeneration sites

[Hogeveen,Ziegenhagen 91;Sikivie,Tanner,van Bibber 07]

Two detection techniques:

- Heterodyne
- Transition Edge Sensor (TES)

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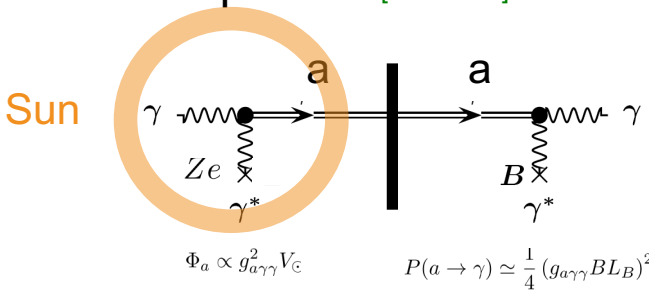

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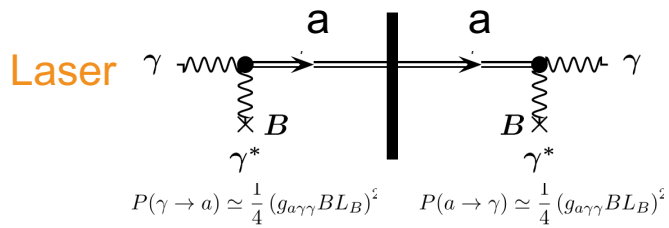
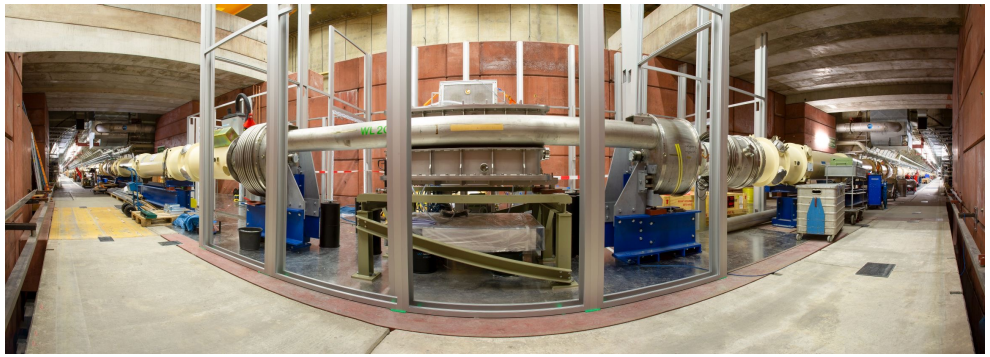


- **ALPS II** @ DESY [Bähre et al (ALPS II TDR) 13]

Installation in HERA tunnel 2019-2022



First runs in 2023-2024 with cavity only at regeneration side

First science paper 2025

[ALPS II Collaboration, 2512.14110 [hep-ex]]

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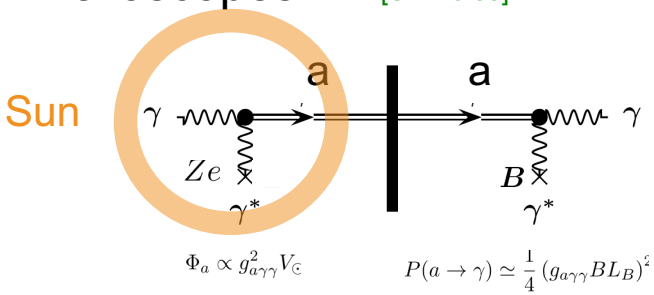

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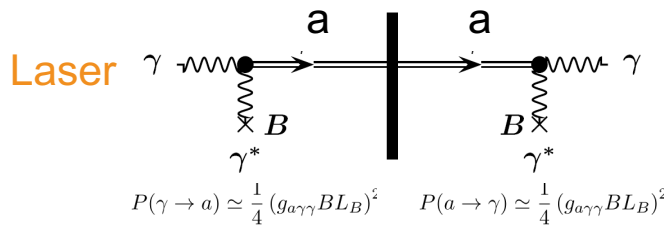
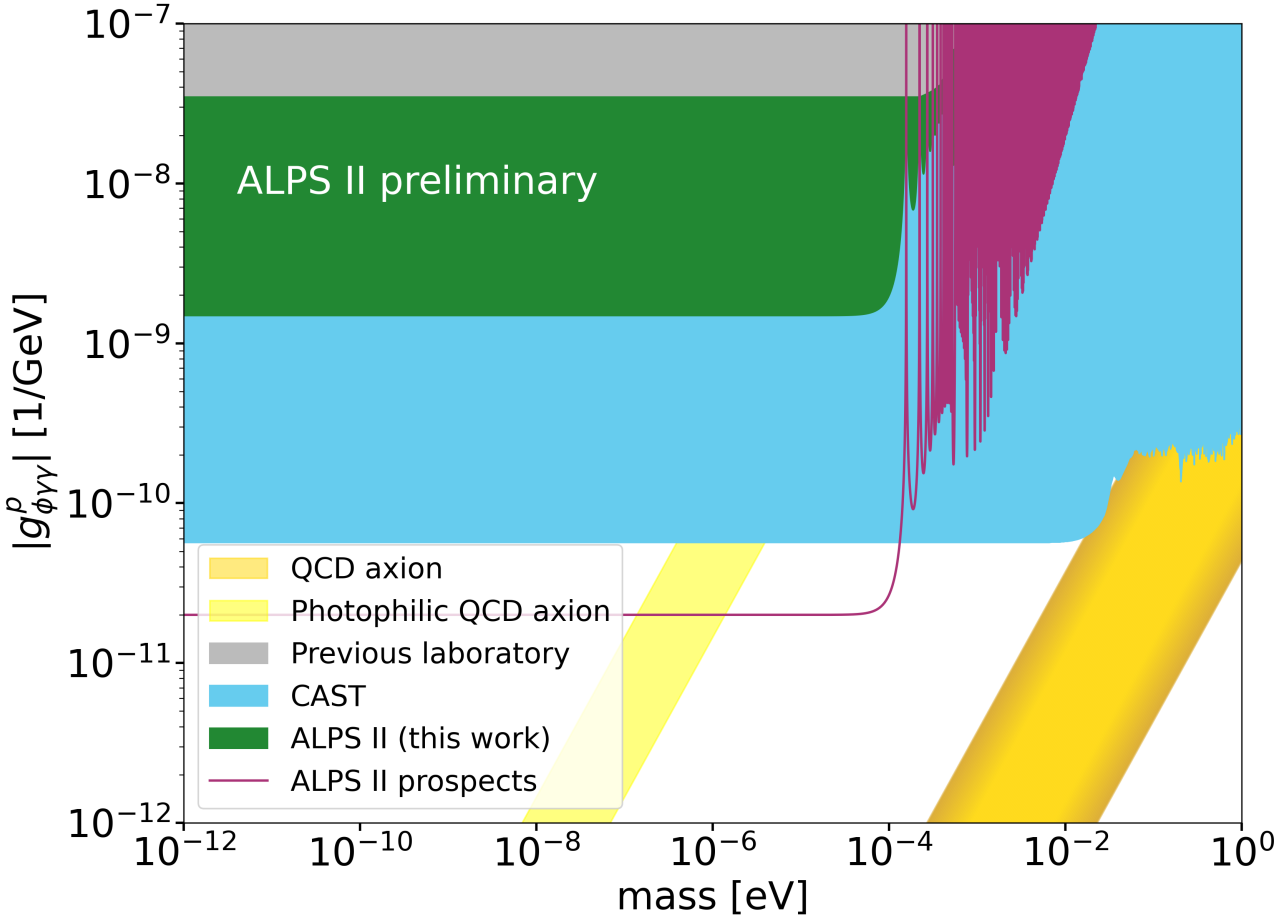


- **ALPS II** current bound:



[ALPS II Collaboration, 2512.14110 [hep-ex]]

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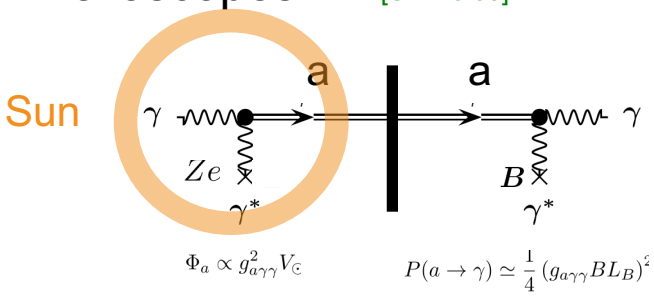

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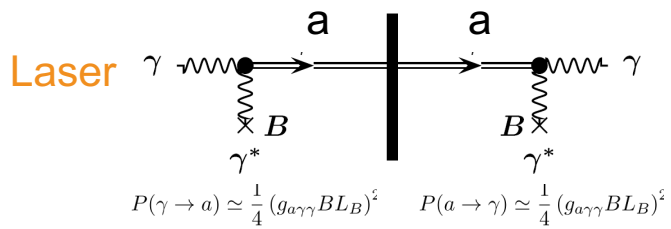

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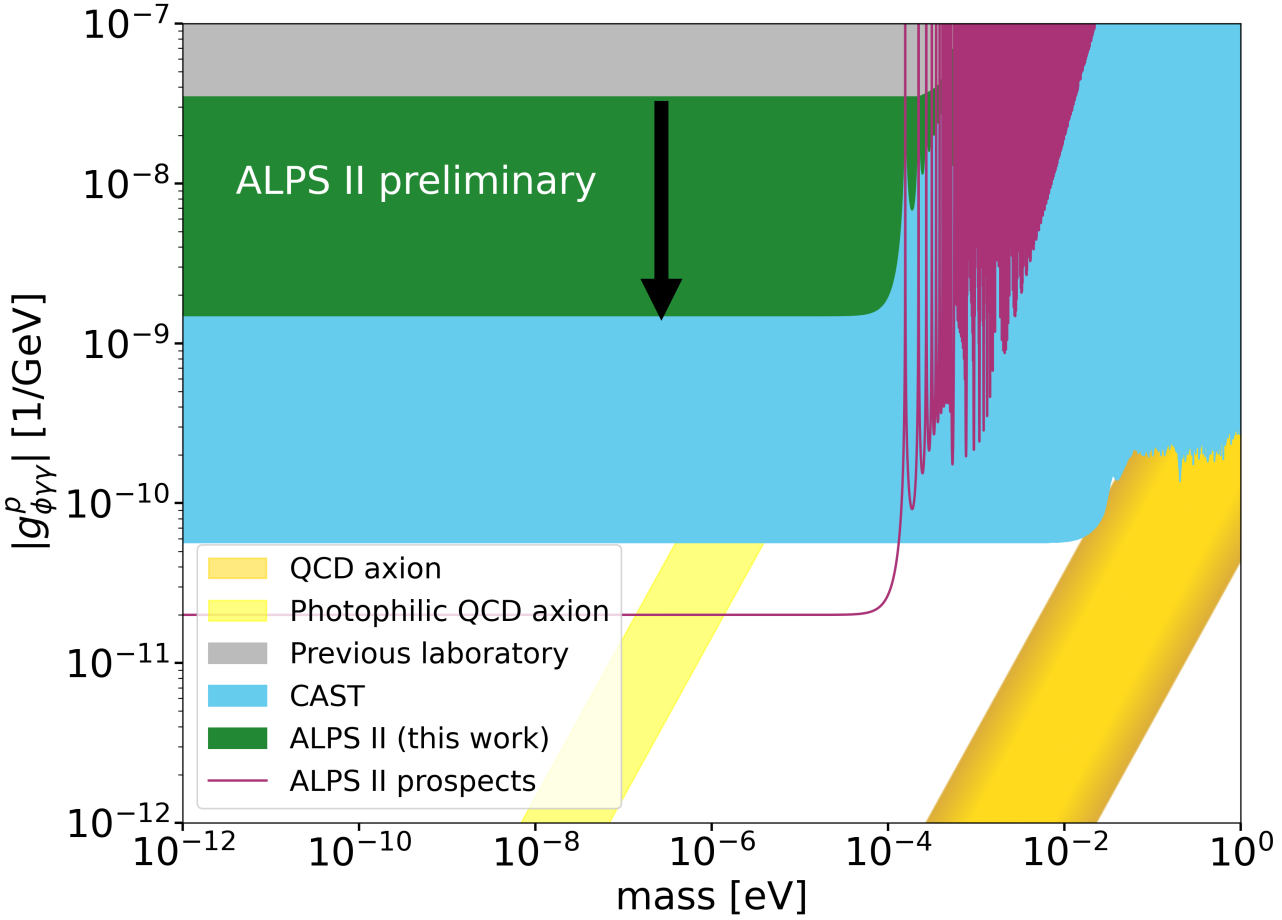

[ALPS II Collaboration, 2512.14110 [hep-ex]]

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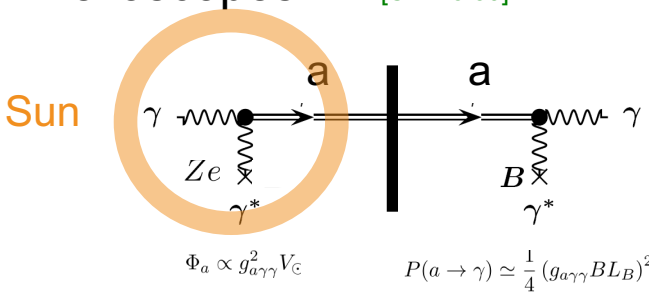

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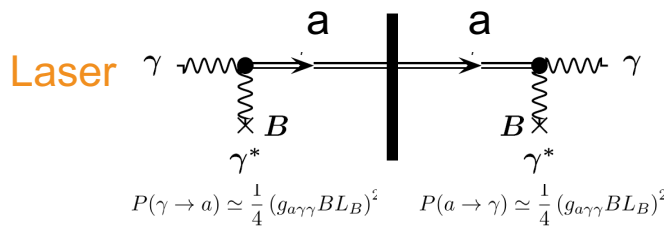
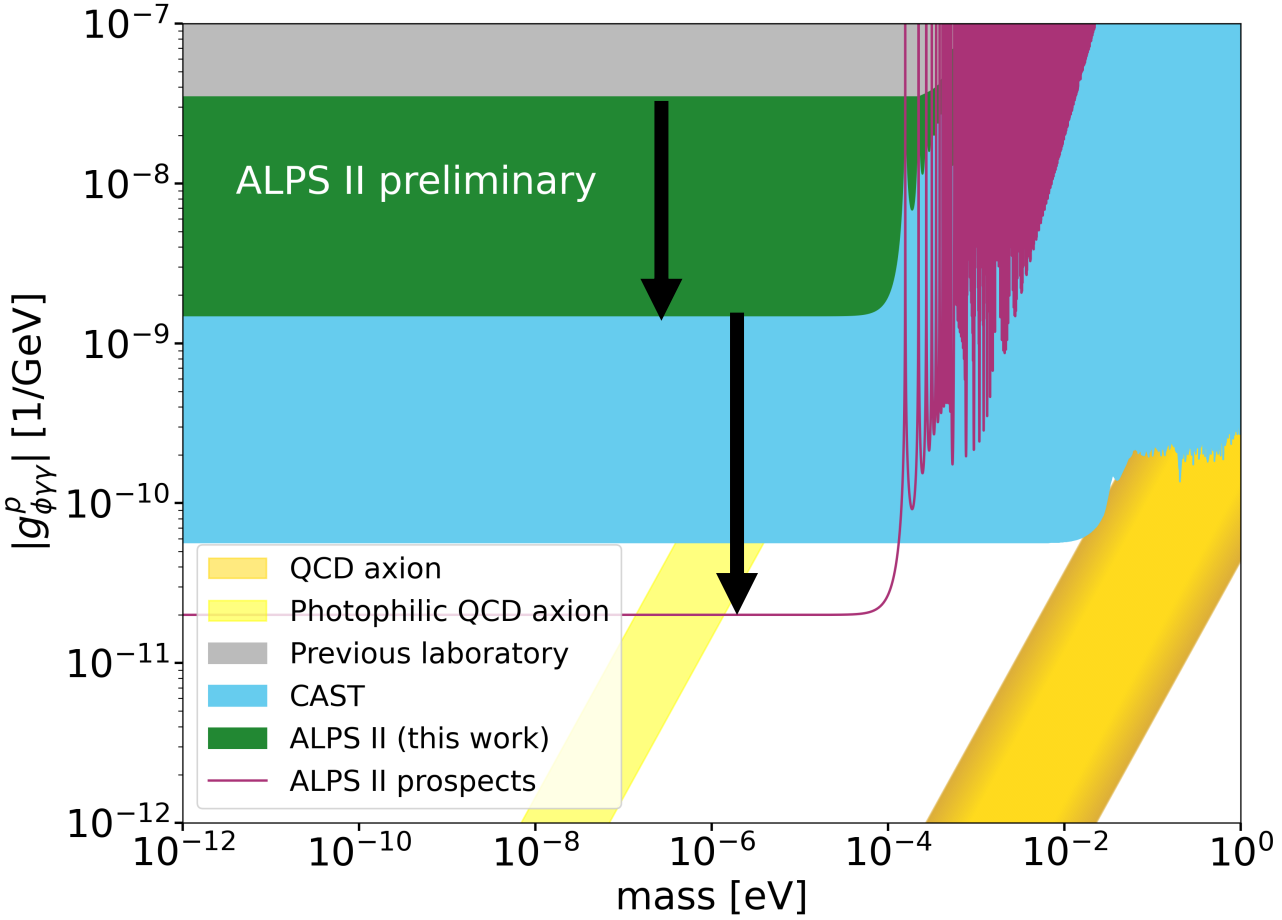


- **ALPS II** current bound and 2028(?) sensitivity:



[ALPS II Collaboration, 2512.14110 [hep-ex]]

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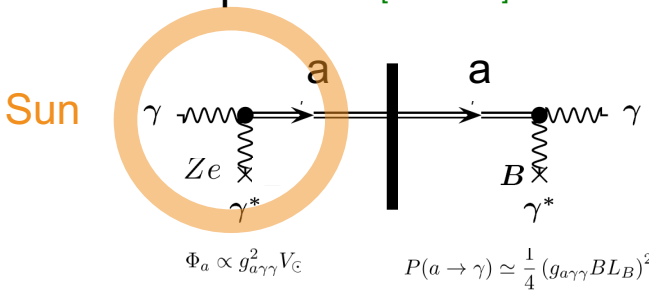

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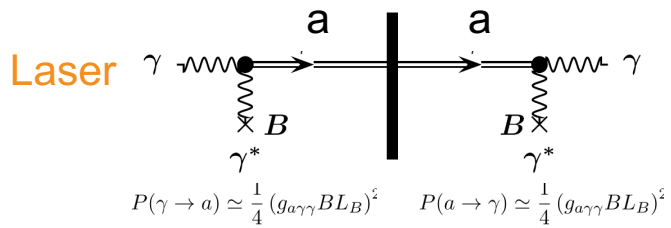

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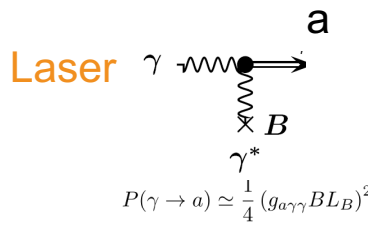

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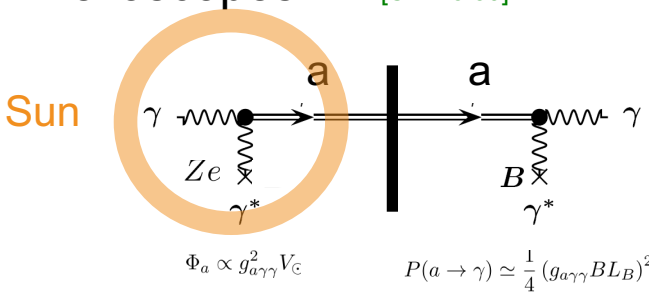

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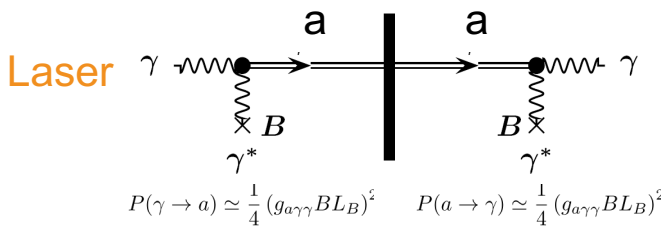

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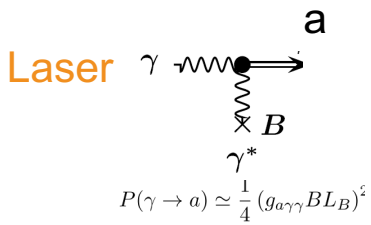

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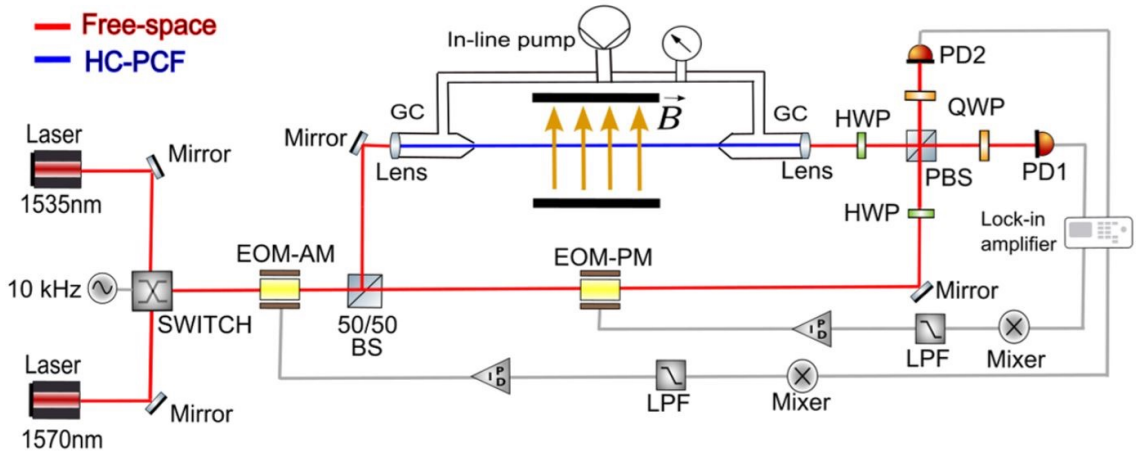

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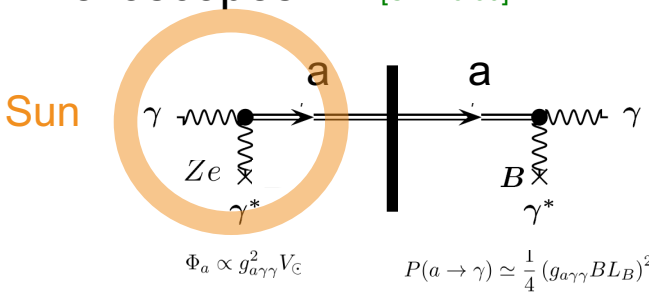

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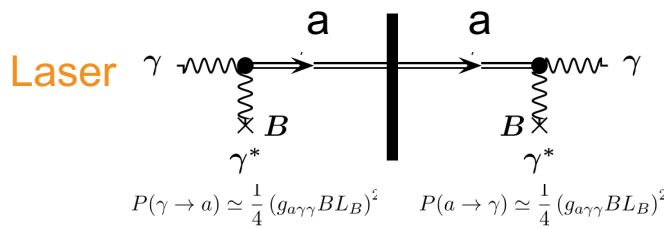

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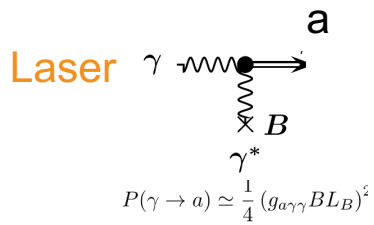

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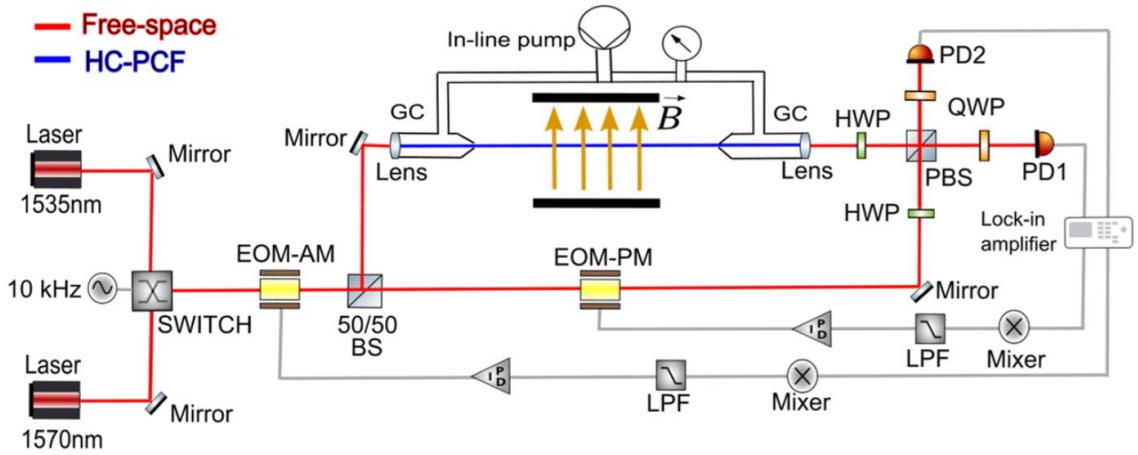

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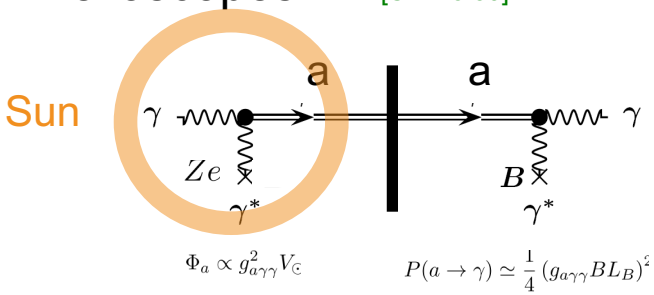

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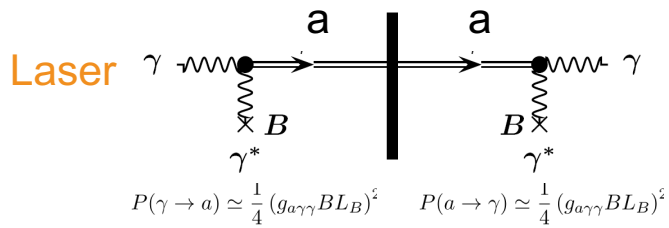

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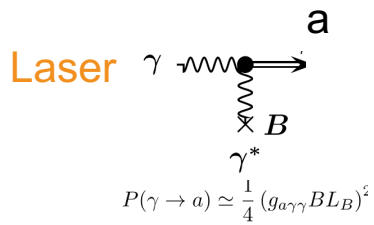

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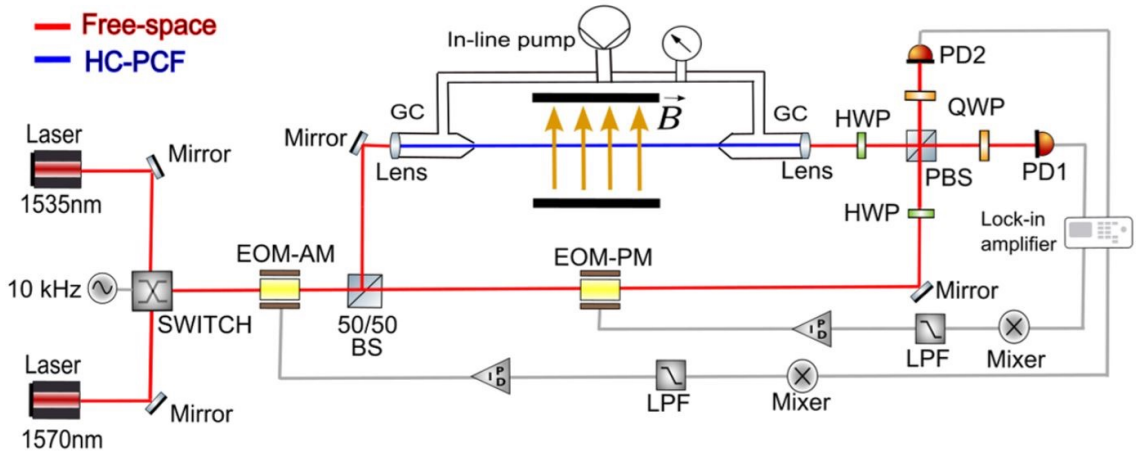

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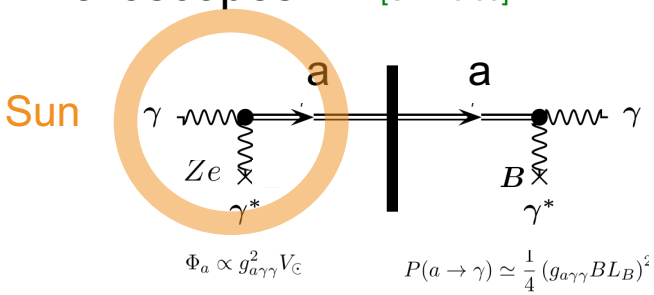

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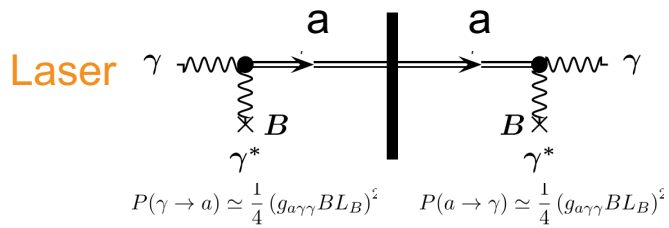

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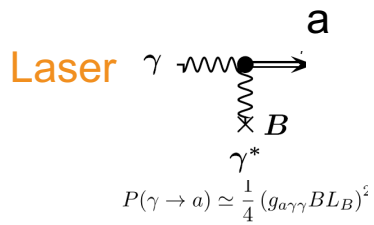

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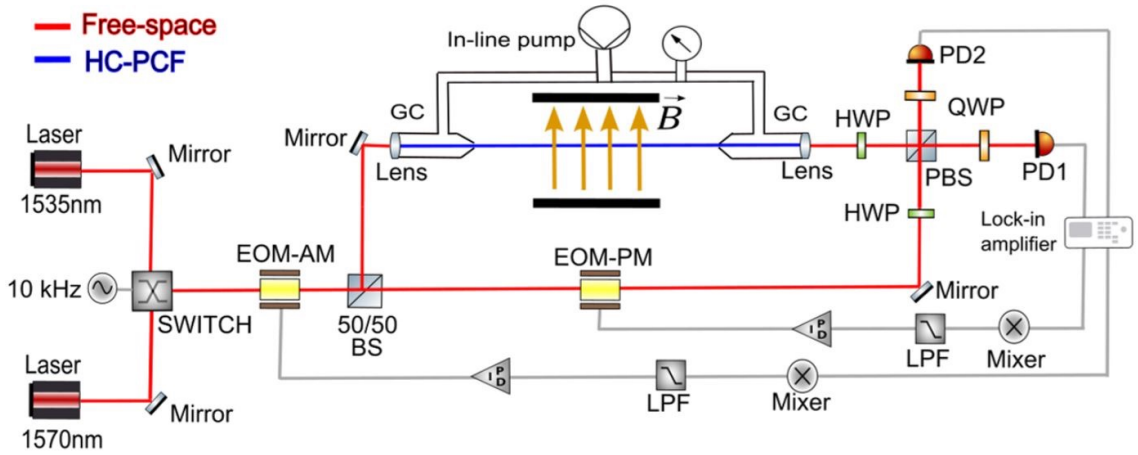

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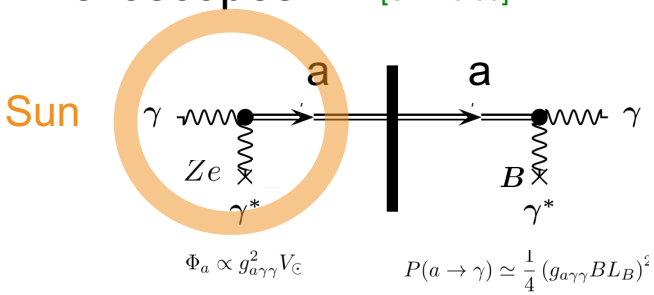

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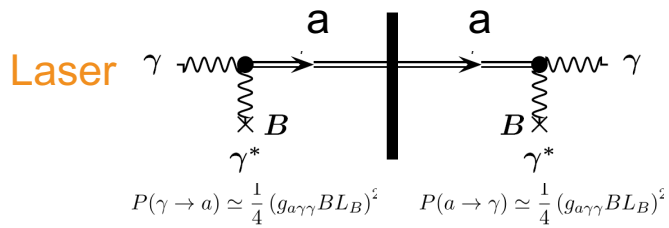

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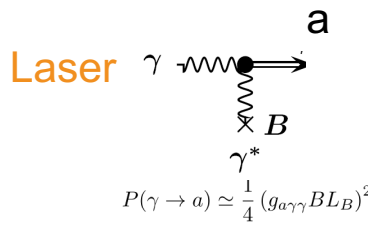

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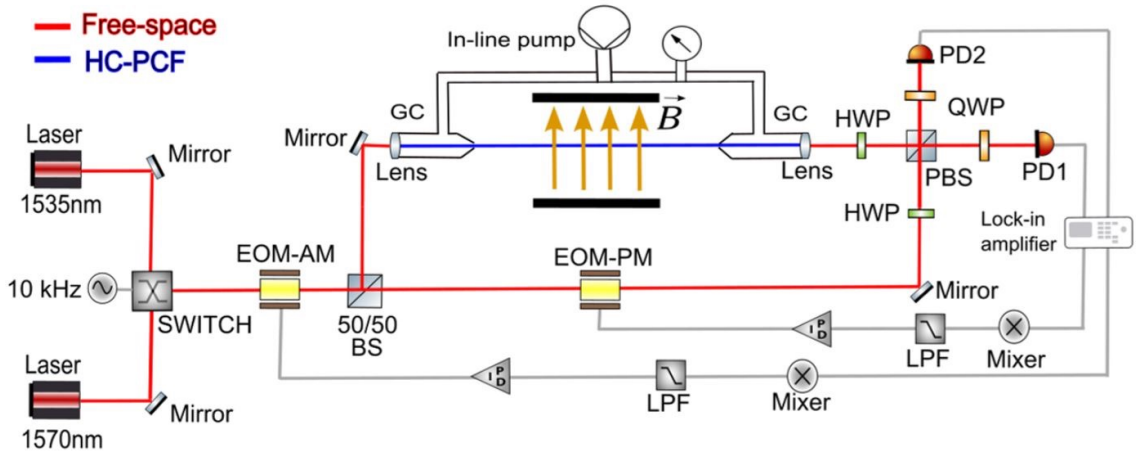

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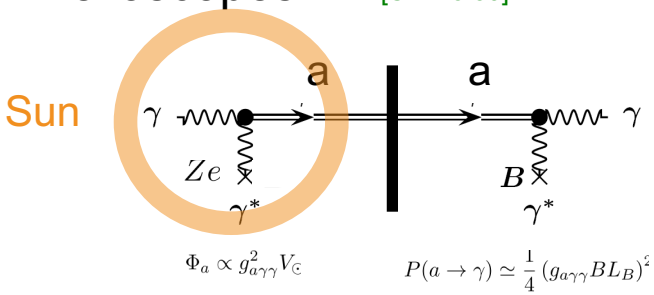

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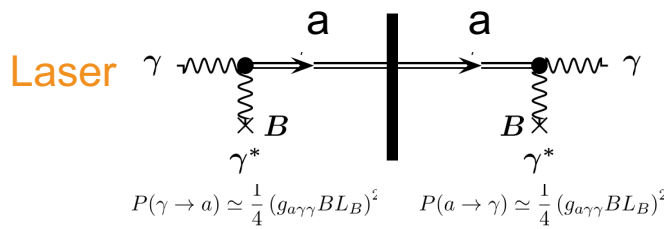

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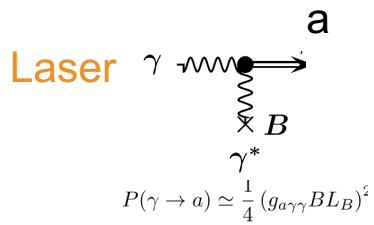

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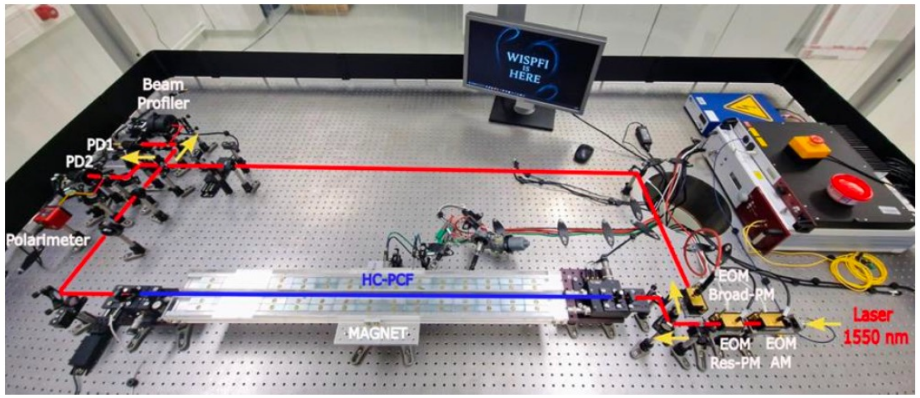
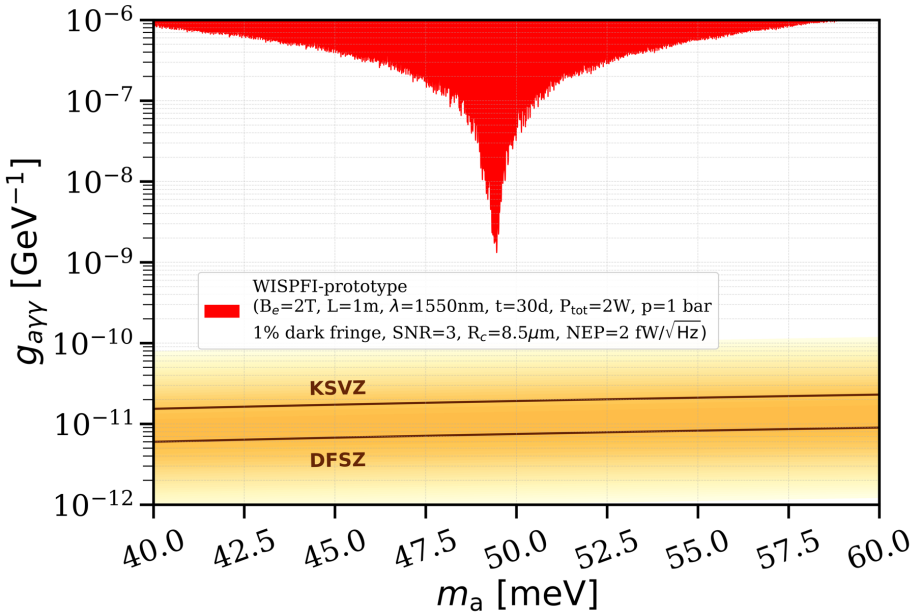
- **WISPFI** prototype sensitivity forecast: [Batllori et al., 2510.01221]





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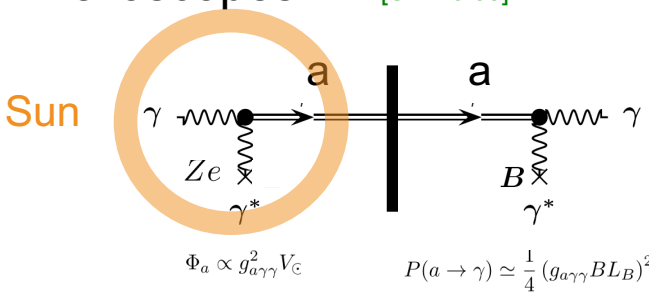

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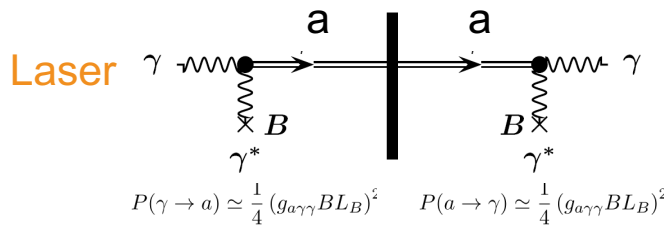

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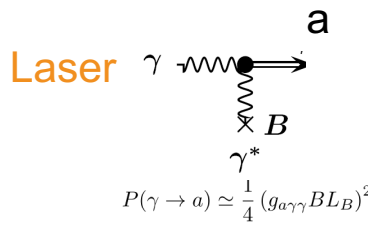

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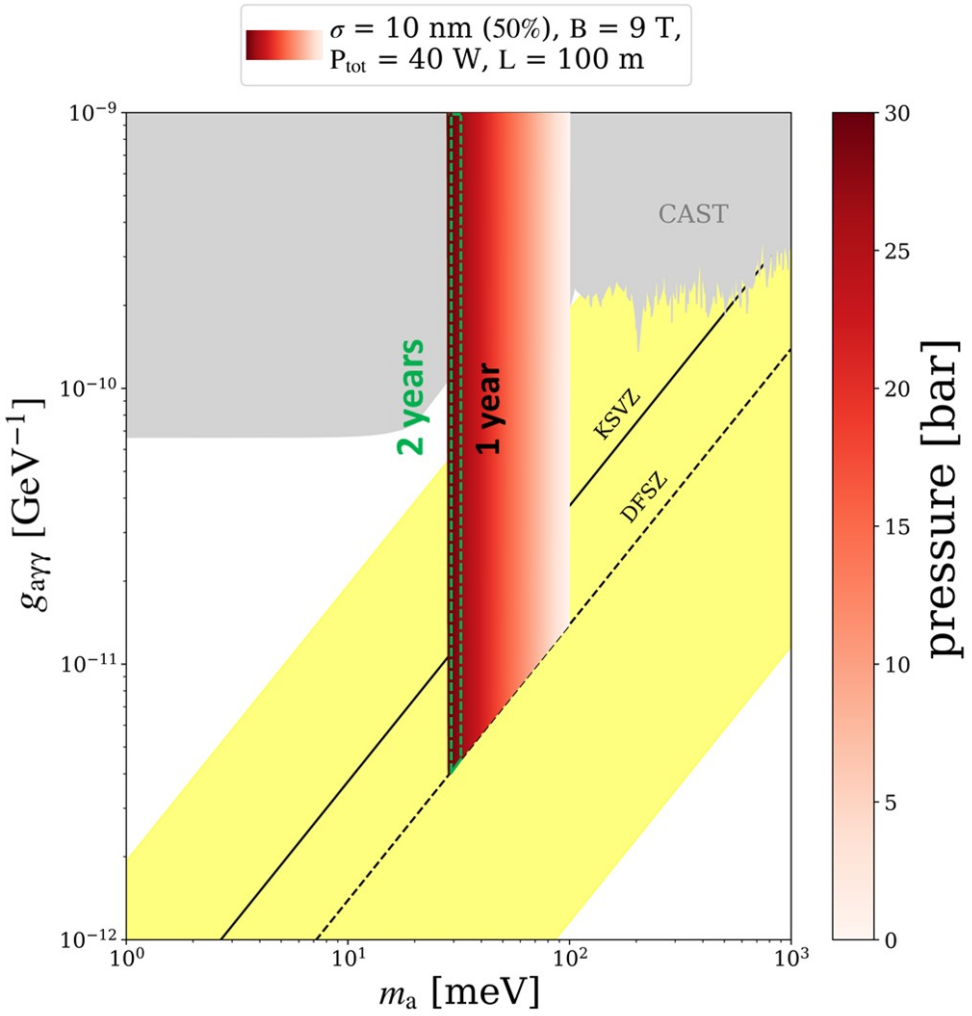

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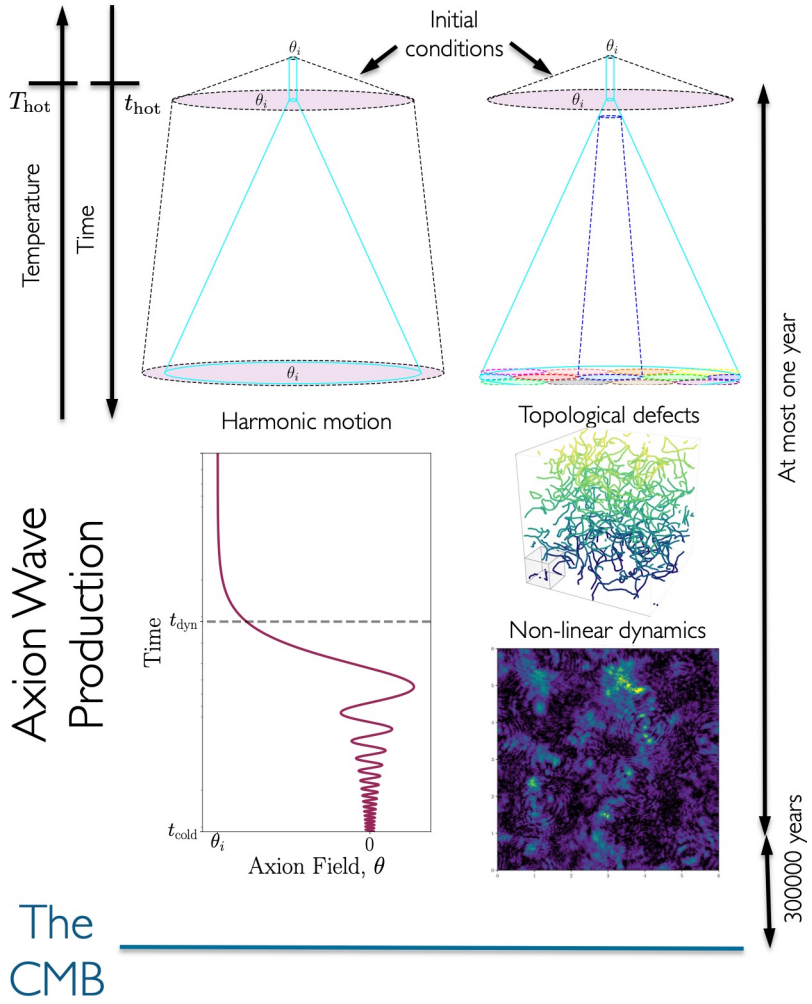

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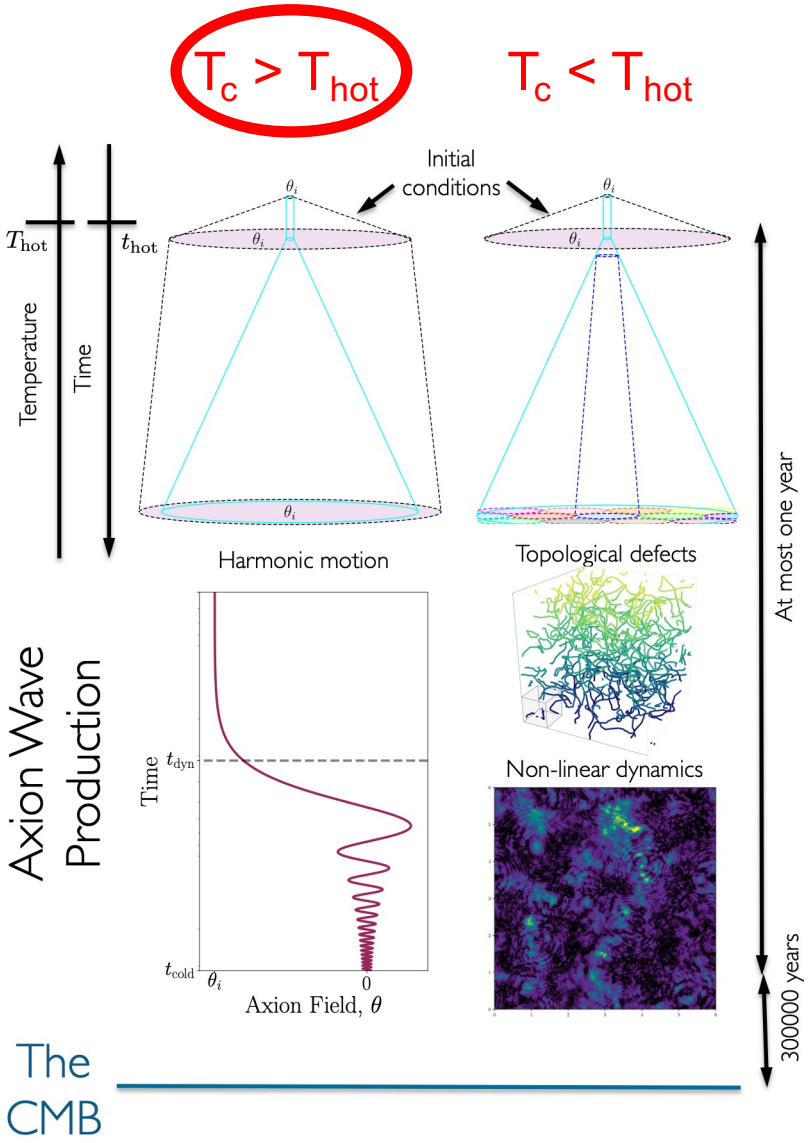

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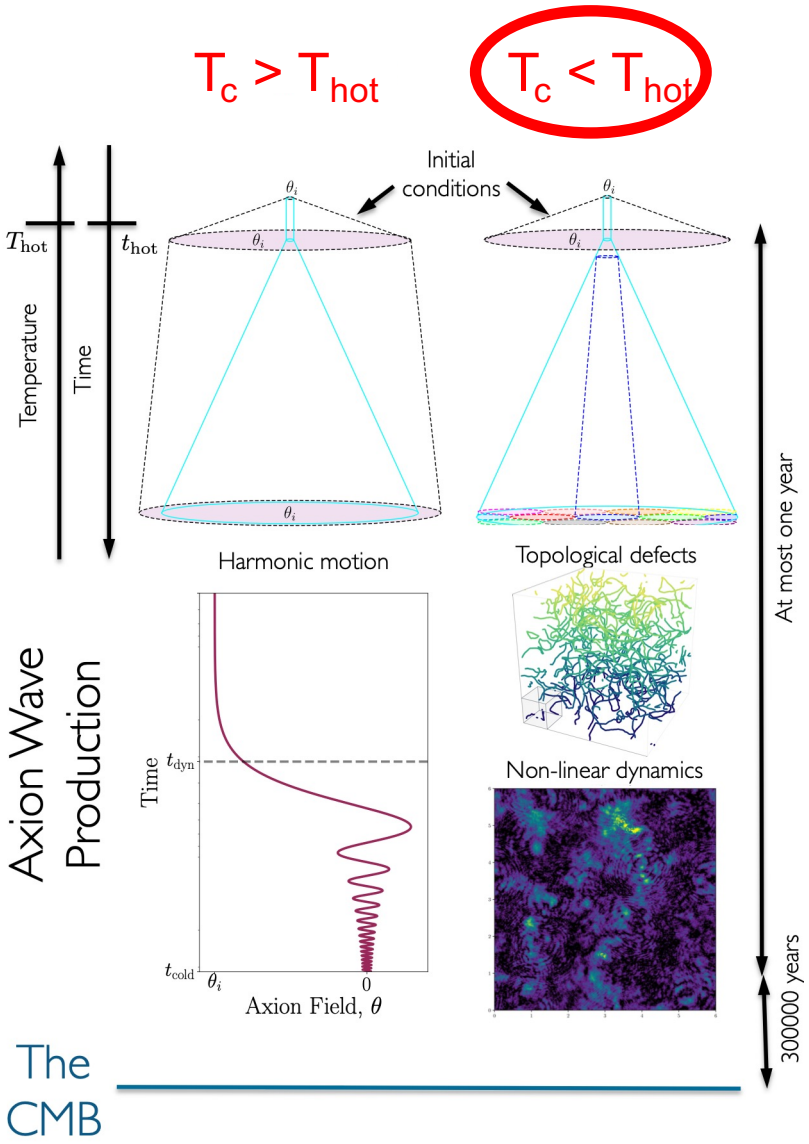

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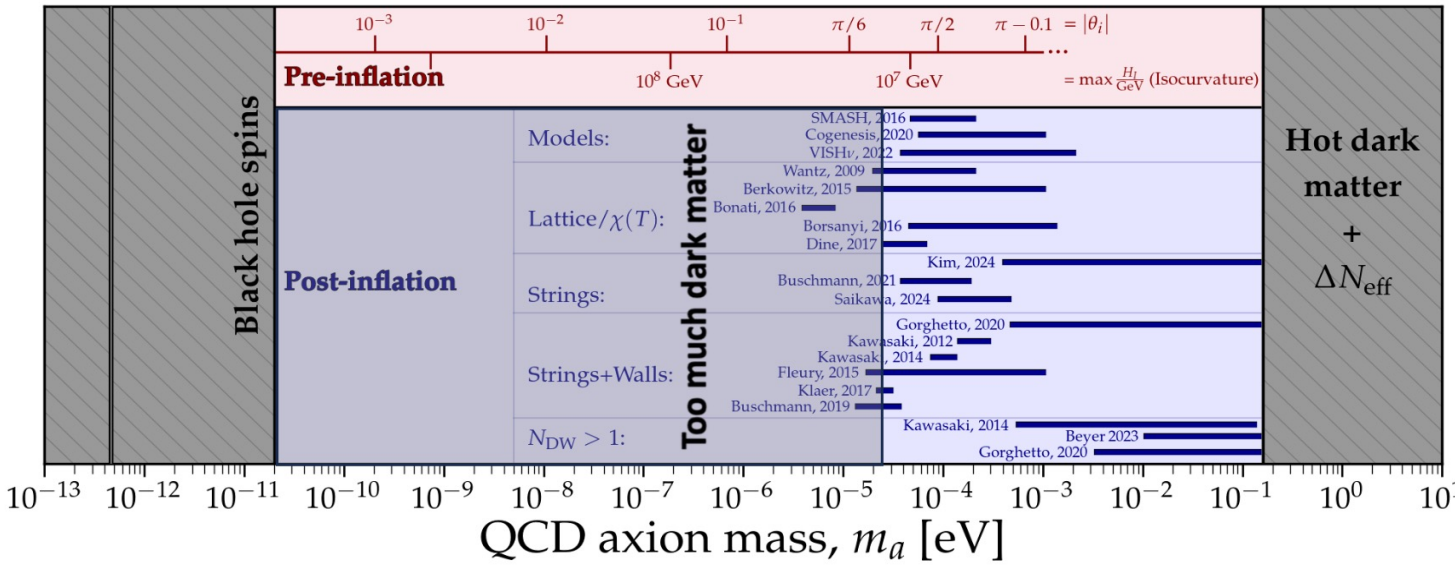
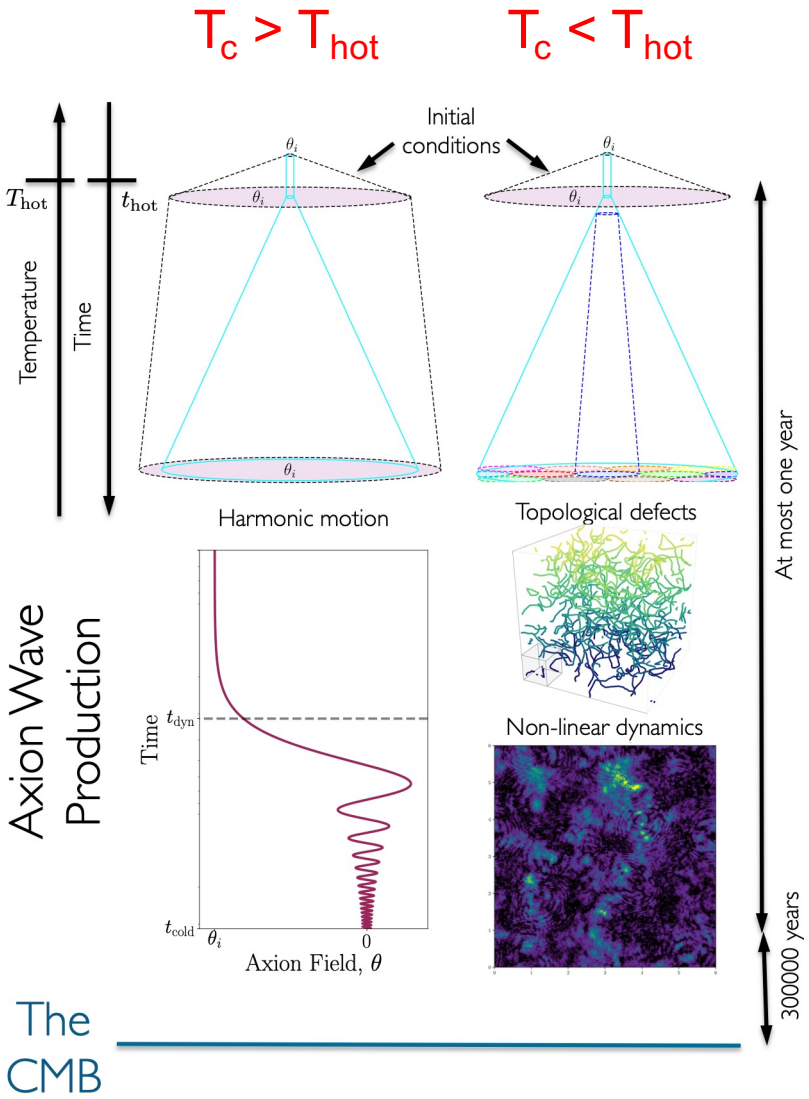


[adapted from https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionMass.png



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- The velocity dispersion of halo dark-matter axions is given by the galactic virial velocity, implying a macroscopic de Broglie wave length, $\lambda_{\rm dB} = 2\pi/(m_a v_a) \sim {\rm km}\,(\mu{\rm eV}/m_a)(10^{-3}\,c/v_a)$, and a huge occupation number per de Broglie volume,

$$N_a\,|_{\rm dB} = n_a\,\lambda_{\rm dB}^3 \sim 10^{30}\left(\frac{\rho_a}{0.3\,{\rm GeV/cm^3}}\right)\left(\frac{\mu{\rm eV}}{m_a}\right)^4$$

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$$\rho_a = \rho_{\rm DM}^{\rm halo} \approx 0.3\,{\rm GeV\,cm^{-3}}$$

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- The velocity dispersion of halo dark-matter axions is given by the galactic virial velocity, implying a macroscopic de Broglie wave length, $\lambda_{\rm dB} = 2\pi/(m_a v_a) \sim {\rm km}\,(\mu{\rm eV}/m_a)(10^{-3}\,c/v_a)$, and a huge occupation number per de Broglie volume,

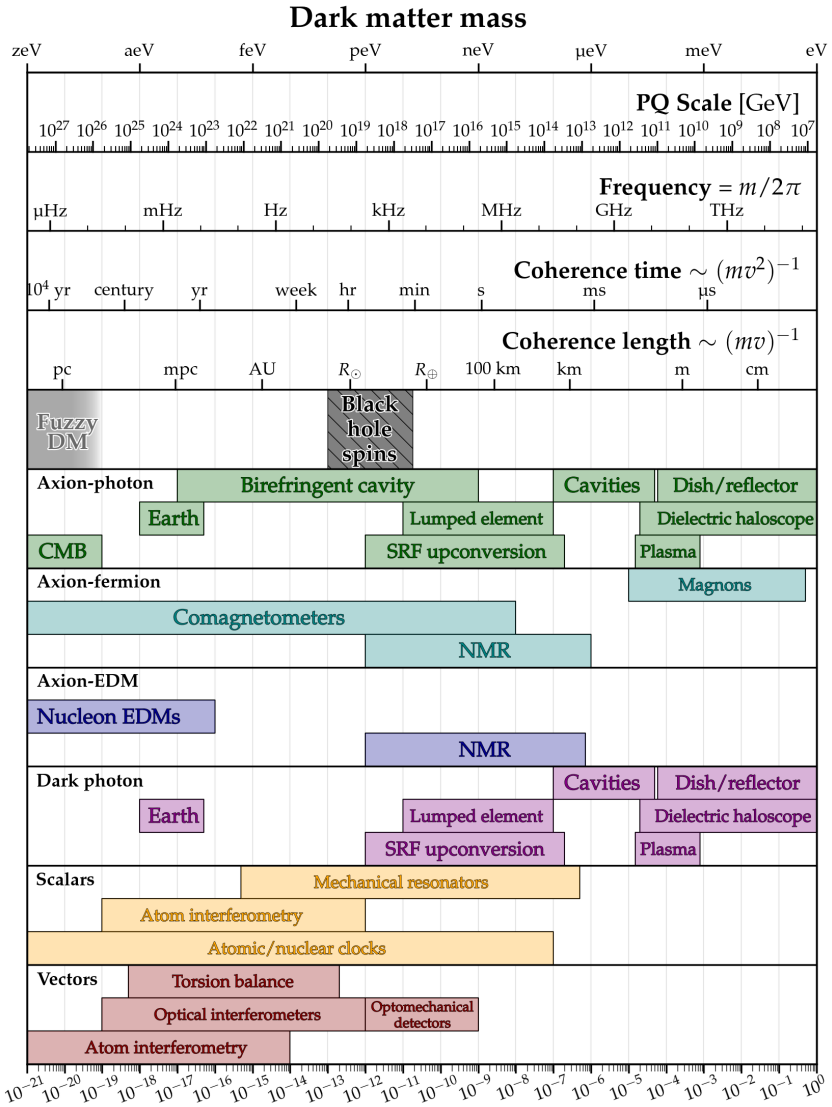
$$N_a\,|_{\rm dB} = n_a\,\lambda_{\rm dB}^3 \sim 10^{30}\left(\frac{\rho_a}{0.3\,{\rm GeV/cm^3}}\right)\left(\frac{\mu{\rm eV}}{m_a}\right)^4$$

- Correspondingly, halo dark-matter axions behave as an approximately spatially homogeneous and monochromatic classical oscillating field,

$$a(t) \simeq \sqrt{2\rho_a}\cos(m_a t)/m_a$$

Axion Dark Matter Experiments

Variety of experimental techniques



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

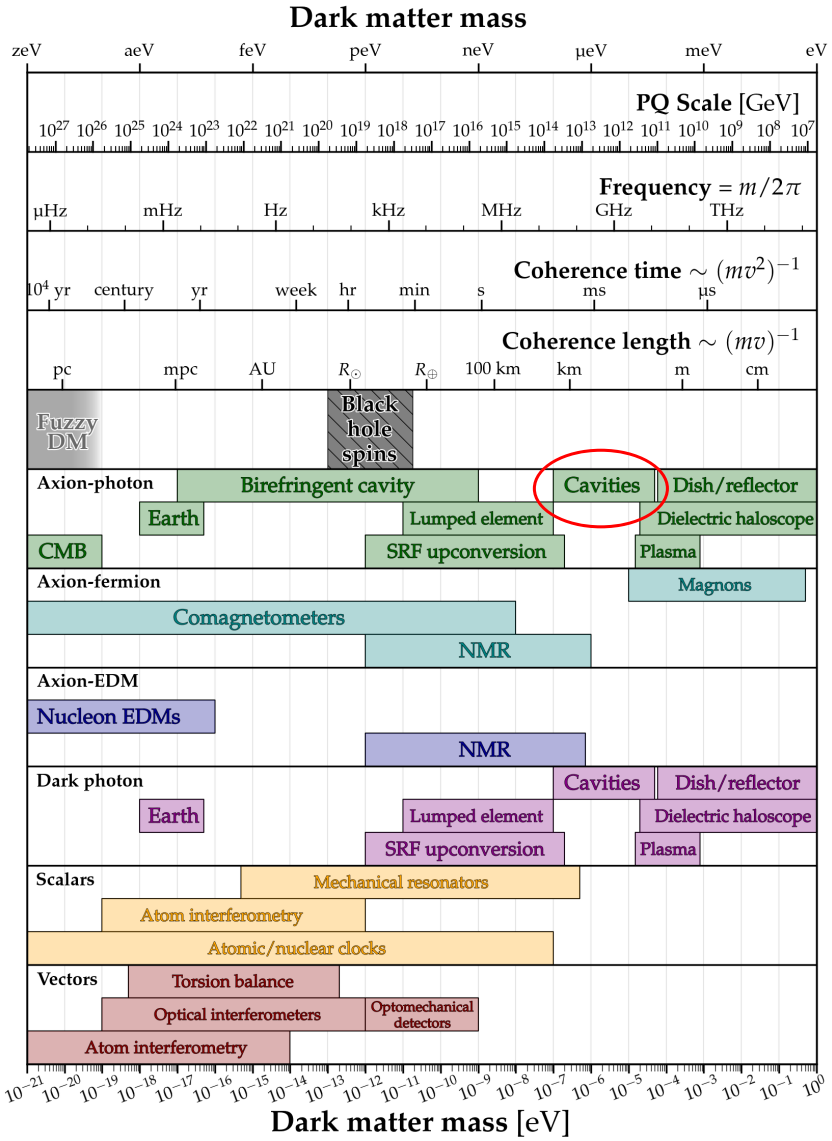
$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L} \supset \frac{1}{2}\frac{g_{aN}}{m_N}\partial_\mu a\, \overline{\psi}_N \gamma^\mu \gamma_5 \psi_N$$

$$\mathcal{L} \supset -\frac{i}{2} g_{aN\gamma}\, a\, \overline{\psi}_N \sigma_{\mu\nu}\gamma_5 \psi_N F^{\mu\nu}$$

Axion Dark Matter Experiments

Variety of experimental techniques



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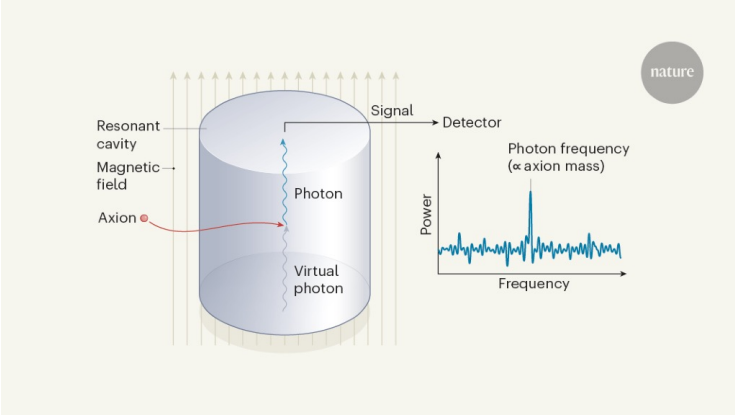
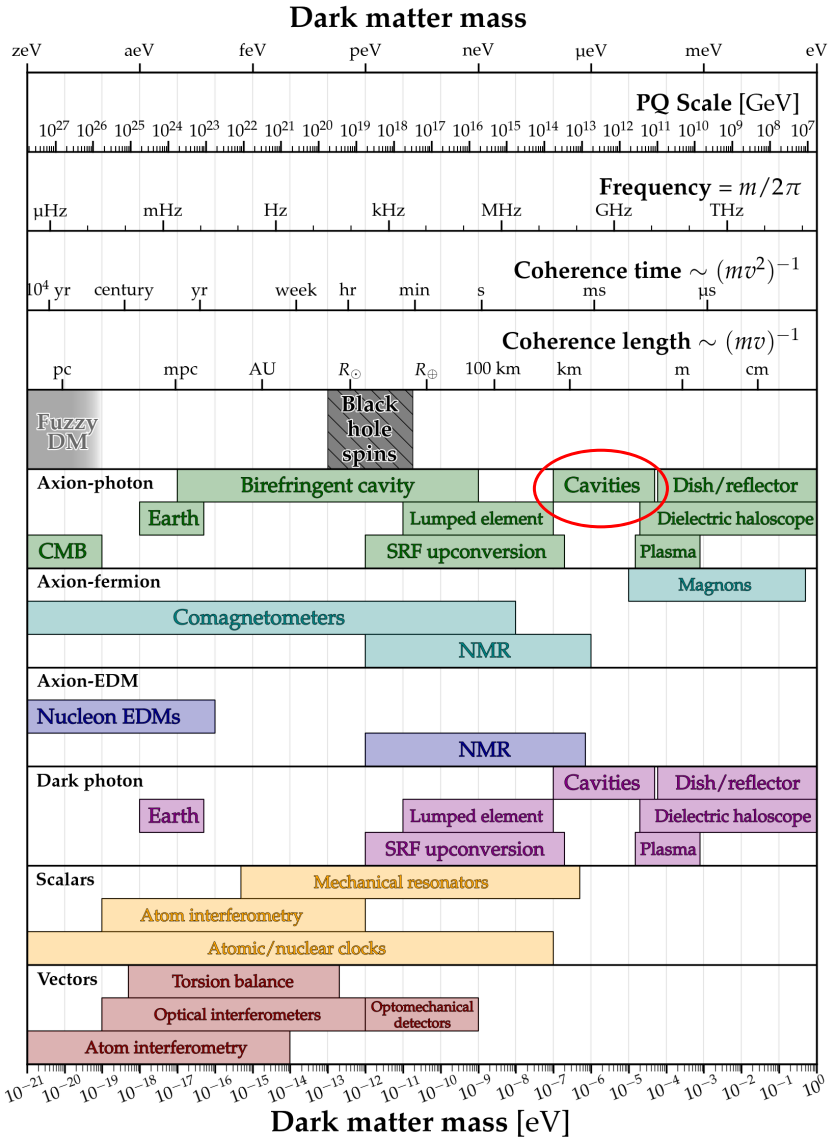


Axion Dark Matter Experiments

Variety of experimental techniques



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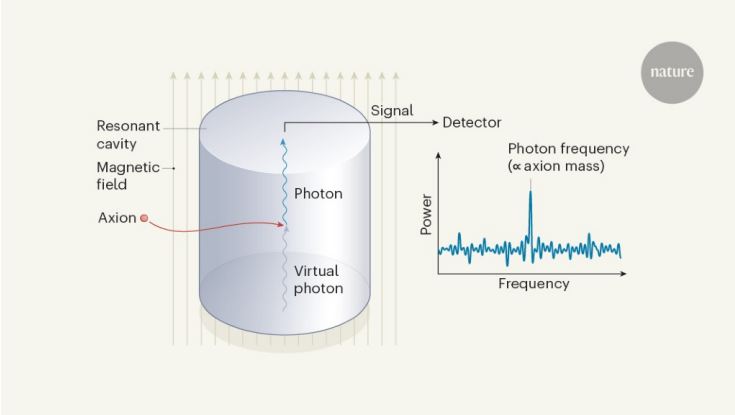


- If axion mass matches resonance frequency of cavity,

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

power output

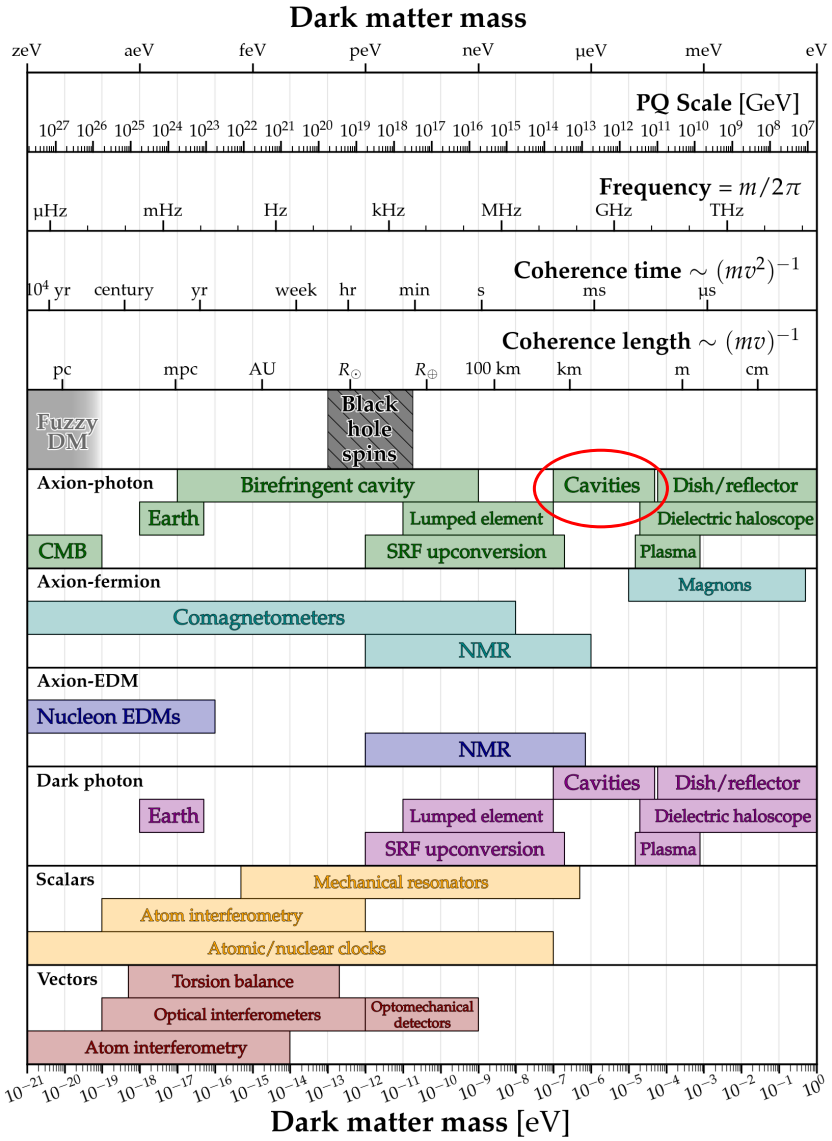
$$P_{\rm out} \sim g_{a\gamma}^2\,\rho_{\rm a}\,B_0^2\,V\,Q$$

enhanced by quality factor

$$Q \sim 10^5$$

Axion Dark Matter Experiments

Variety of experimental techniques



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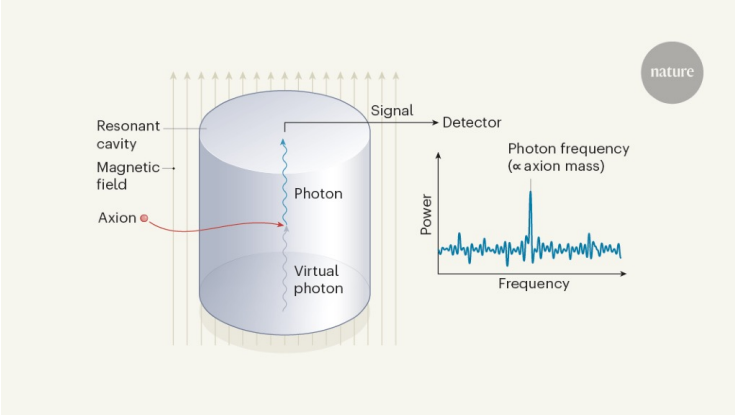

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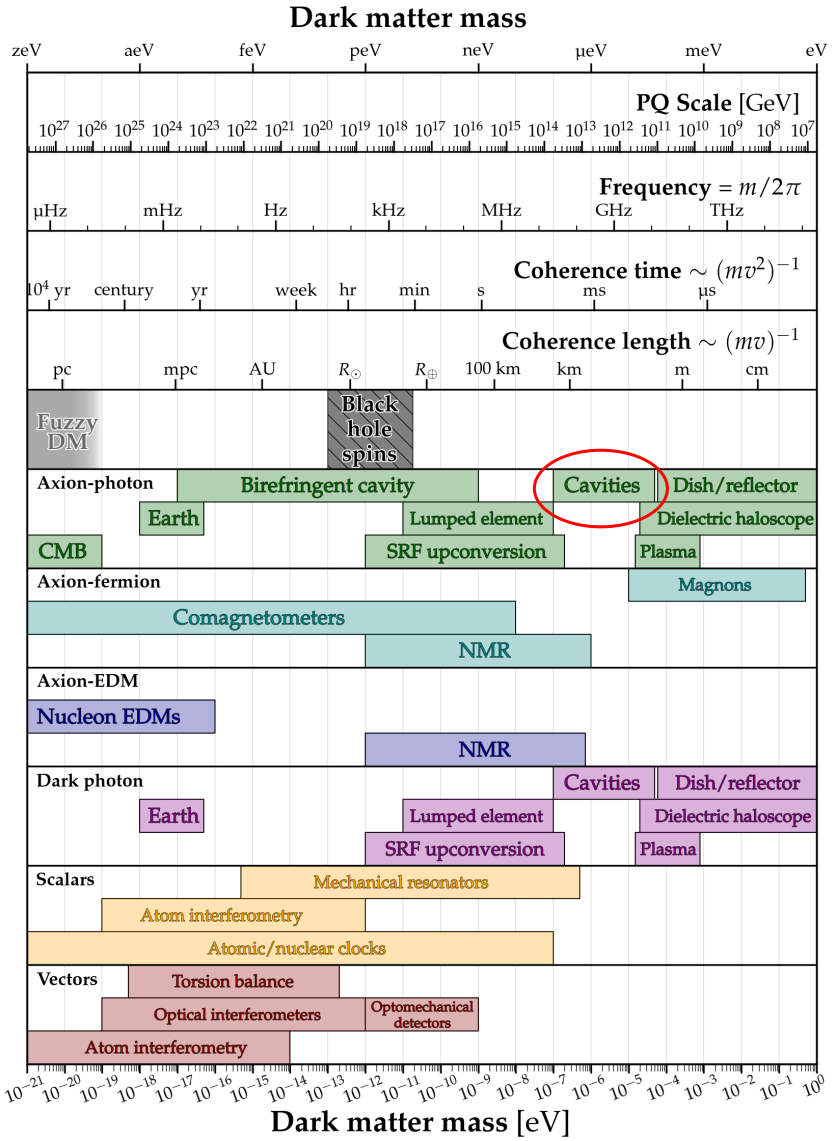
enhanced by quality factor

$$Q \sim 10^5$$

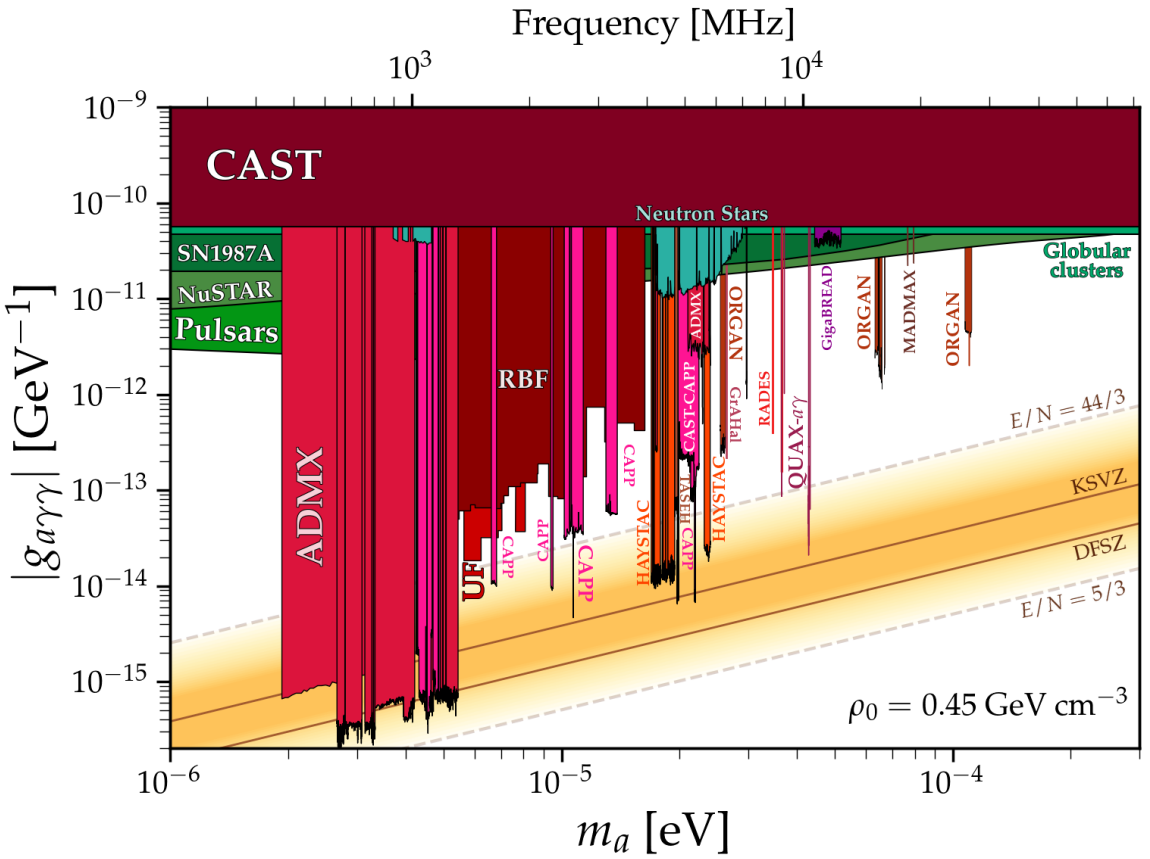
- Need to scan by tuning resonance frequency

Axion Dark Matter Experiments

Variety of experimental techniques



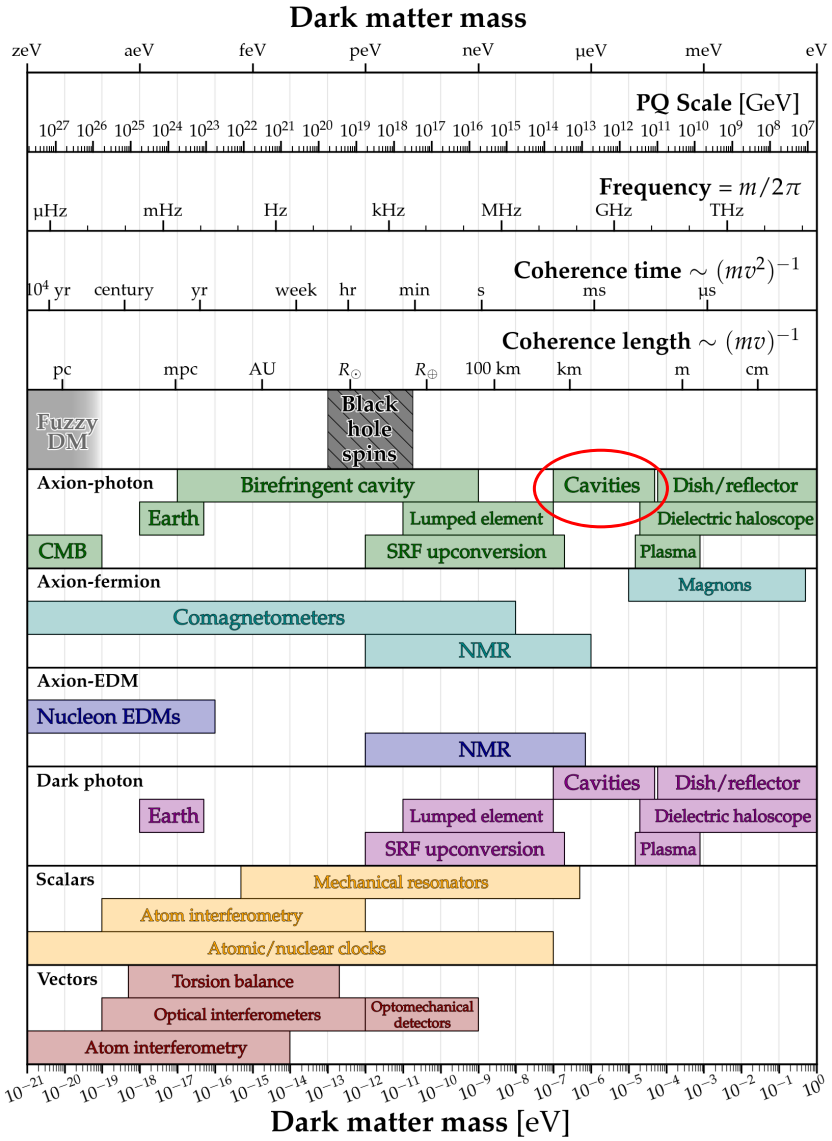
Axion DM cavity experiments have dipped already deep in axion band:



https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_RadioFreqCloseup.png

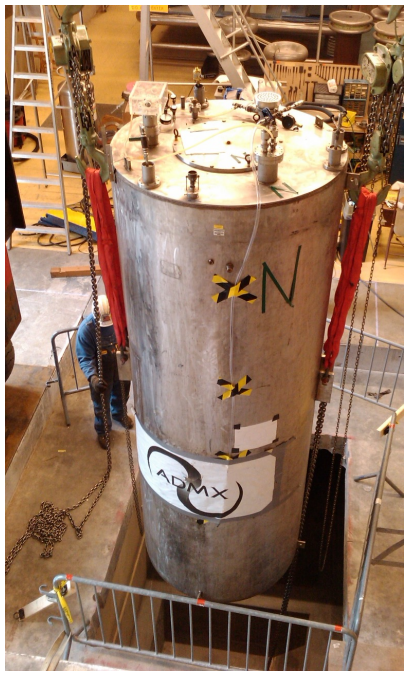
Axion Dark Matter Experiments

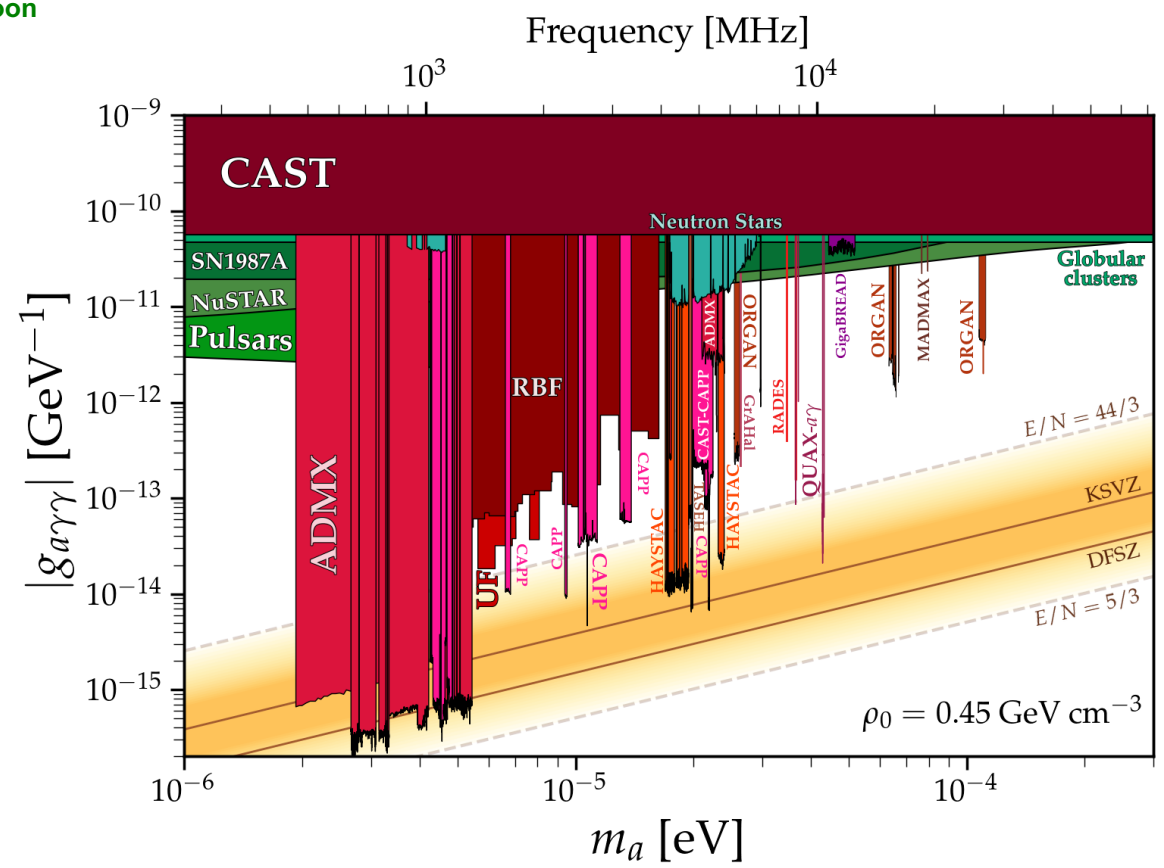
Variety of experimental techniques



Axion DM cavity experiments have dipped already deep in axion band:

Small-group visits of Quantum Sensors for the Hidden Sector (QSHS) laboratory on Wed 24/06 afternoon (sign up at registration desk)





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Axion Dark Matter Experiments

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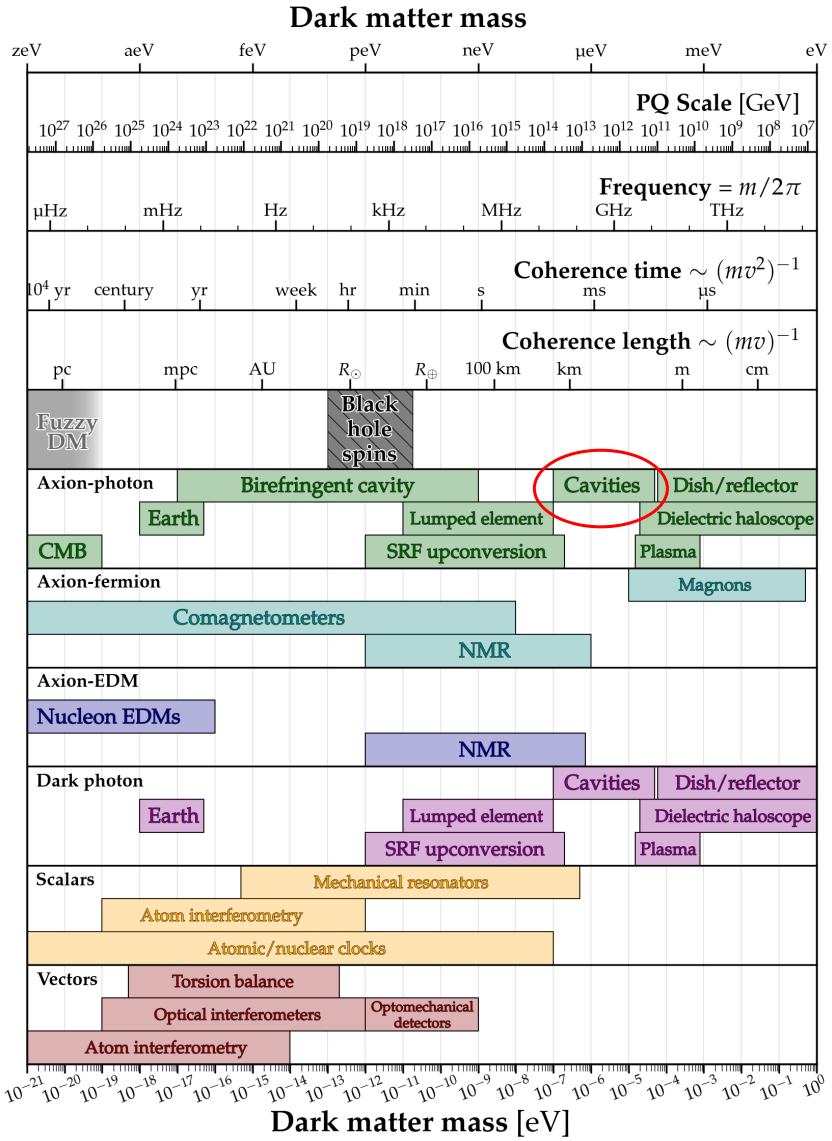
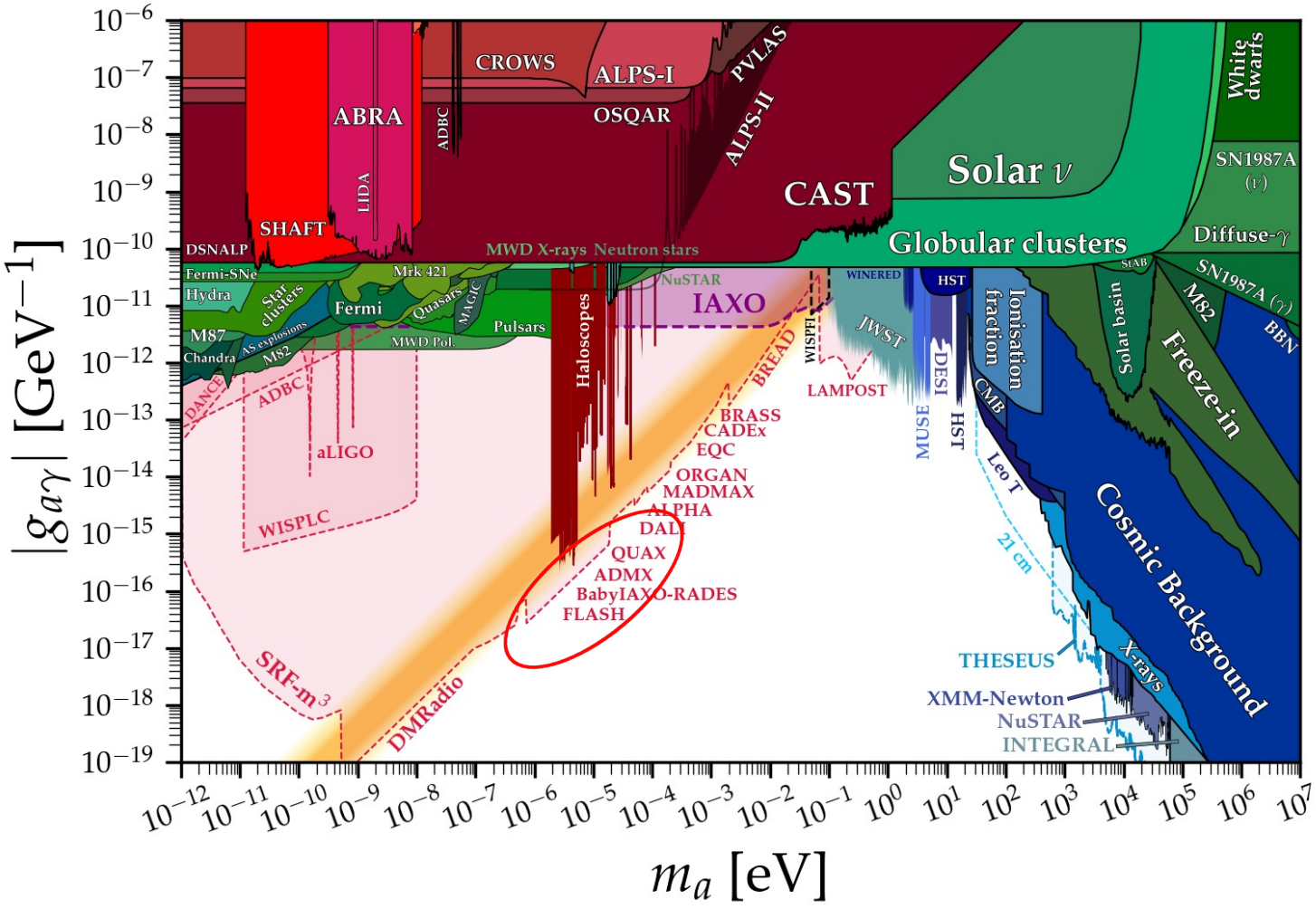


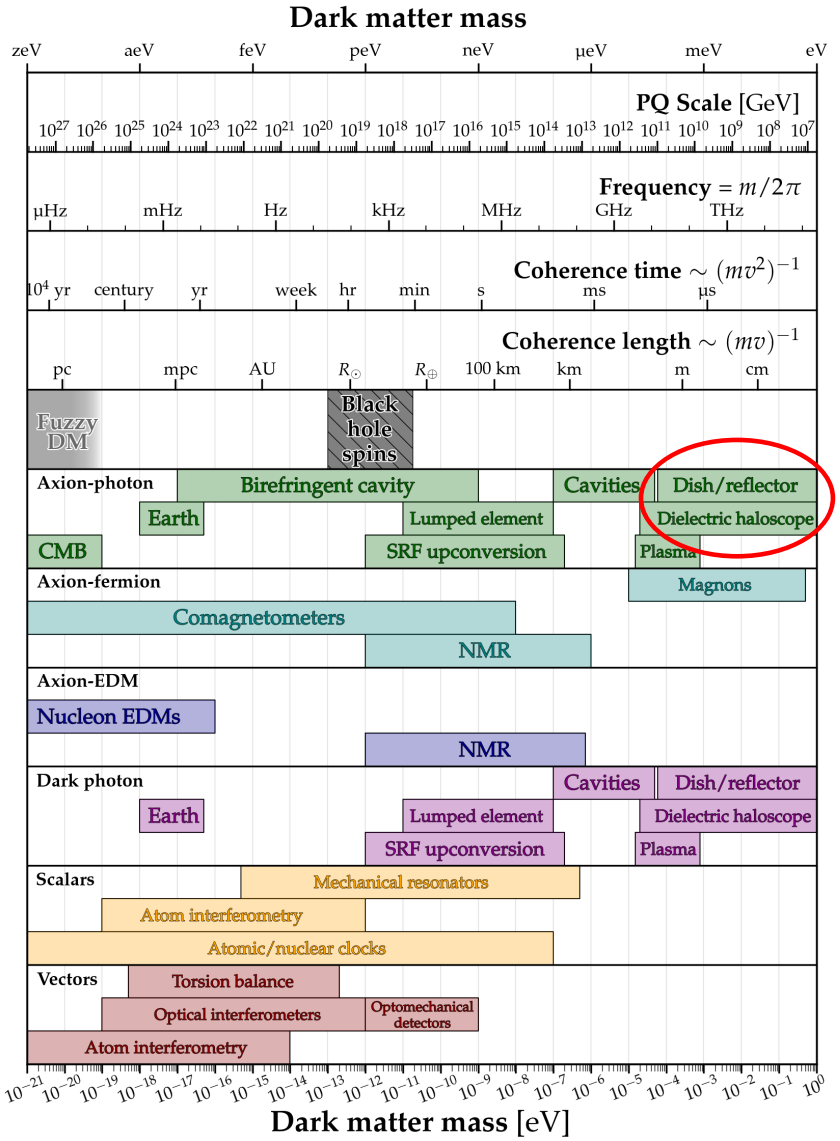
Axion DM cavity experiments have good prospects to probe entire band in mass range $\mu\text{eV} \lesssim m_a \lesssim 100\,\mu\text{eV}$:



[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Axion Dark Matter Experiments

Variety of experimental techniques



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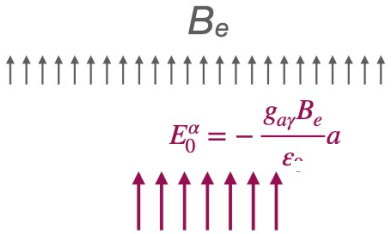
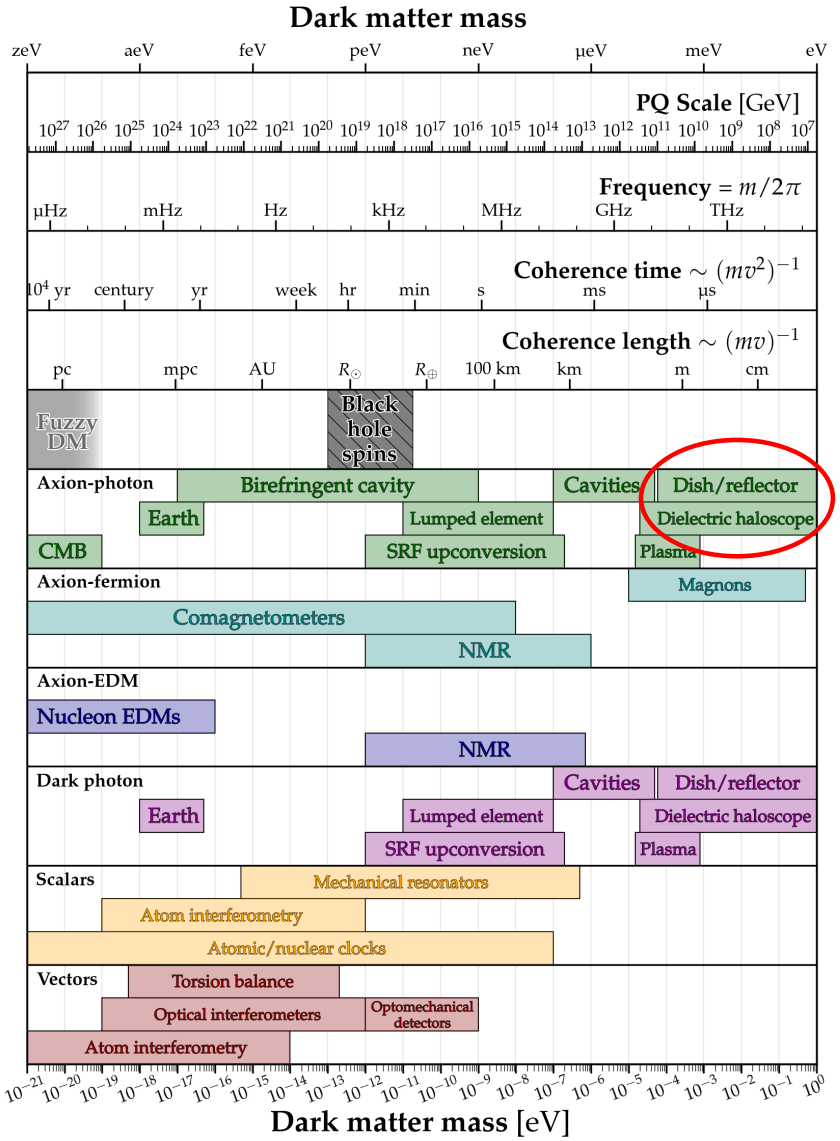


Axion Dark Matter Experiments

Variety of experimental techniques



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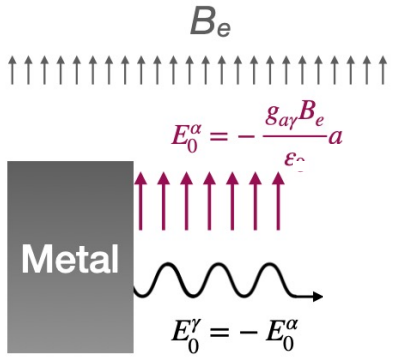
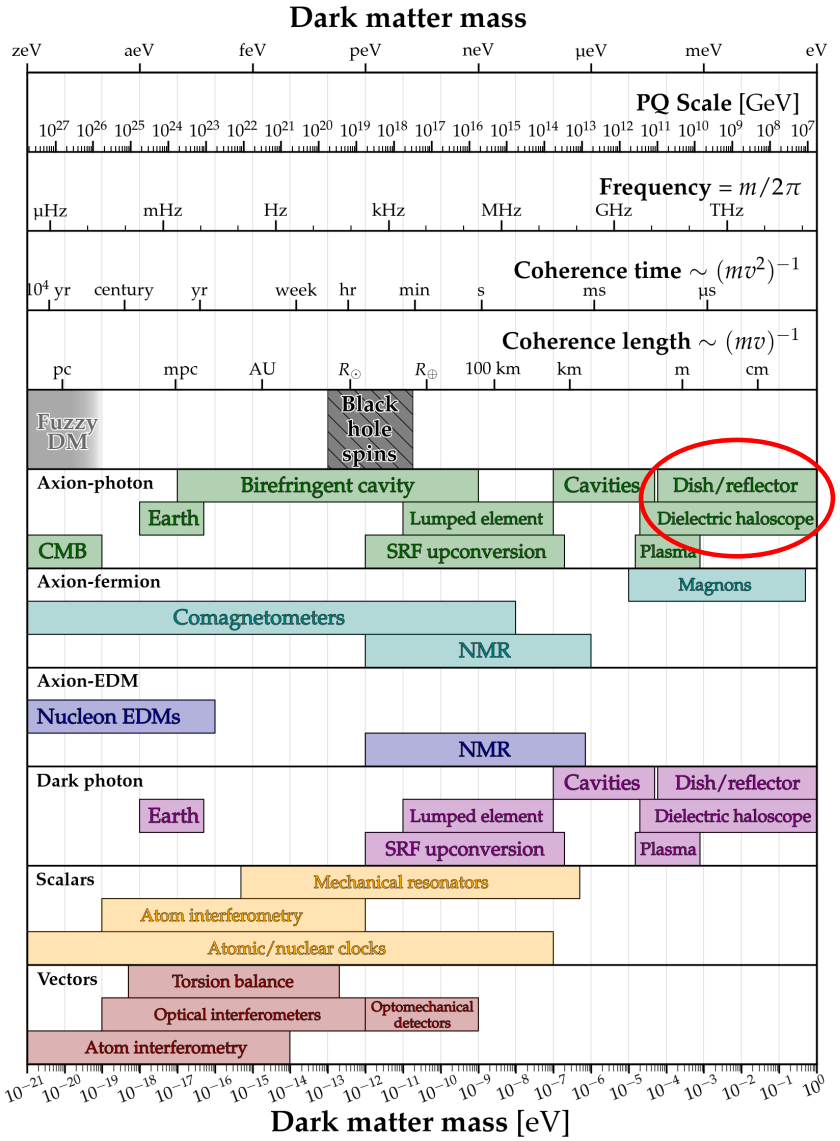


Axion Dark Matter Experiments

Variety of experimental techniques



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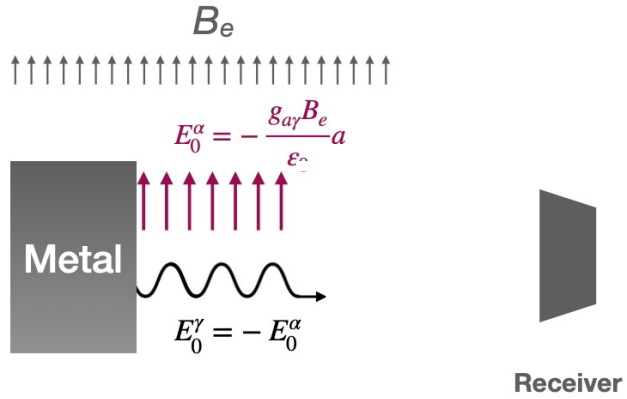

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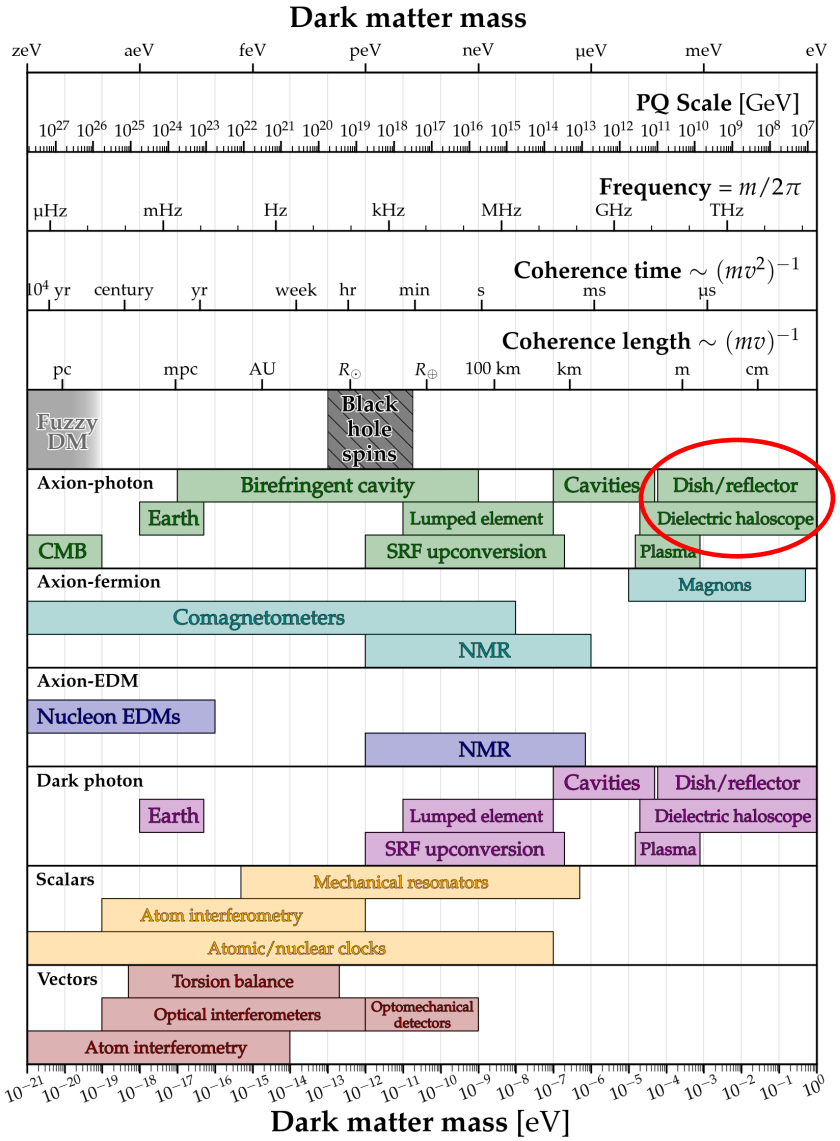

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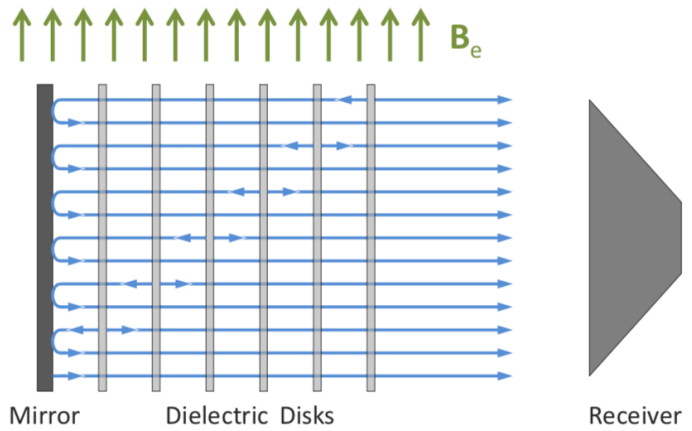

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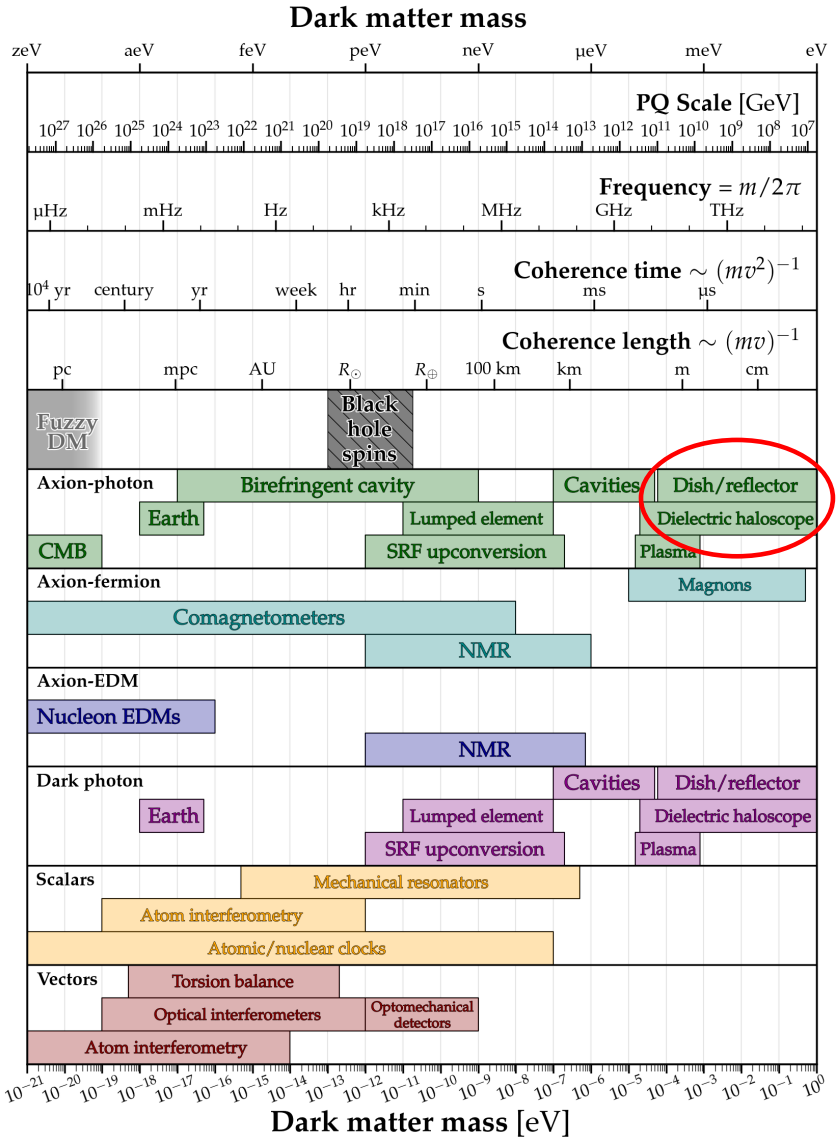

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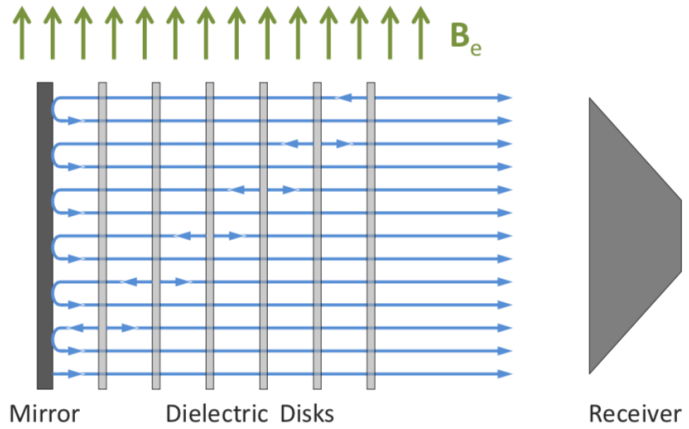
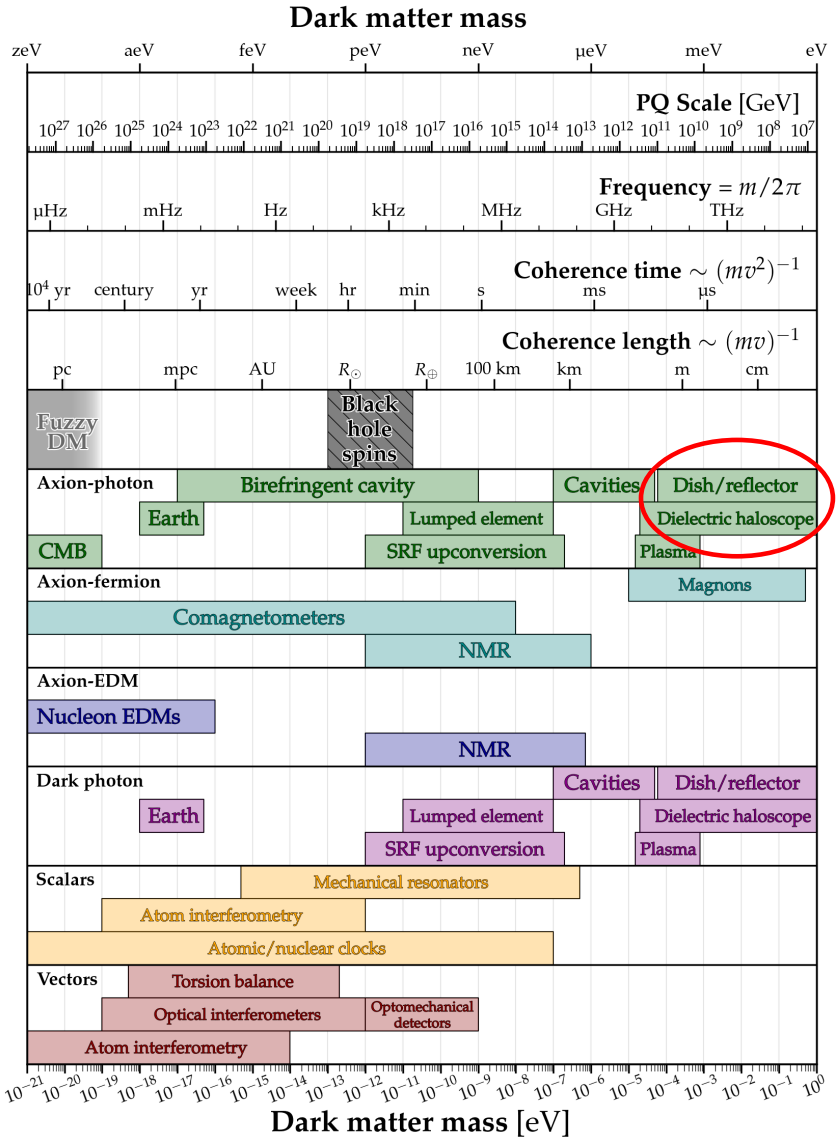


Axion Dark Matter Experiments

Variety of experimental techniques



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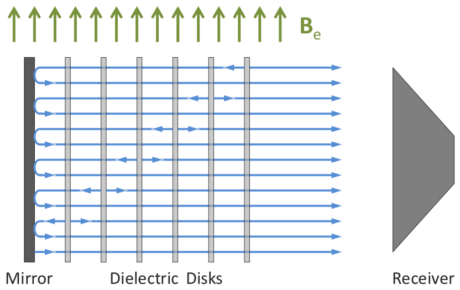

Axion Dark Matter Experiments

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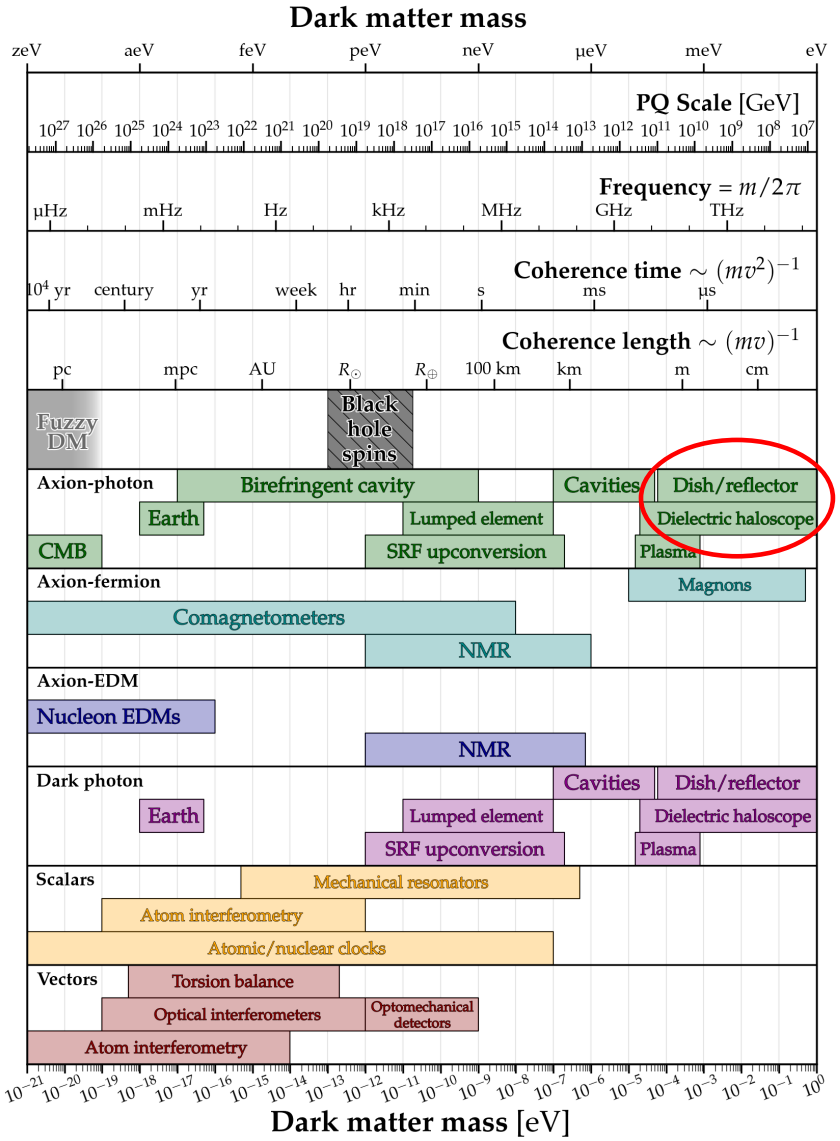

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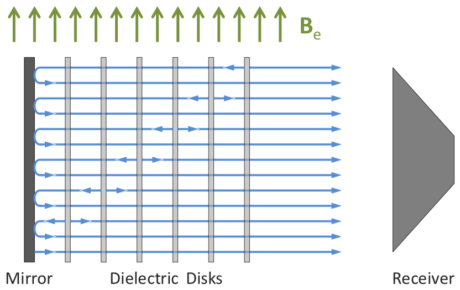
  - Moving the disks shifts the boosted band and scans the axion mass



Axion Dark Matter Experiments

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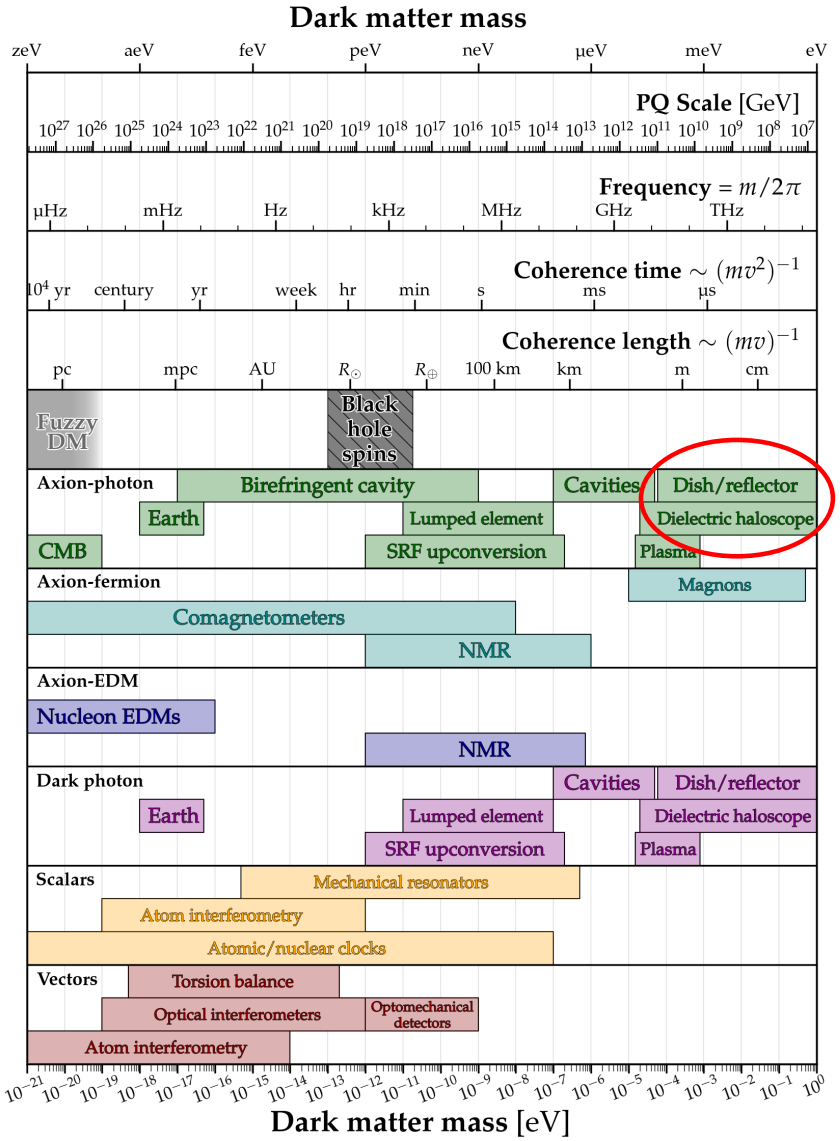
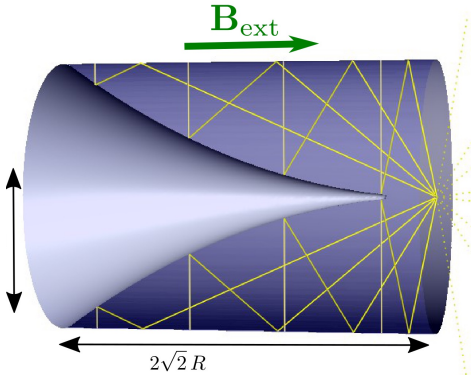


Dish/reflector example:

BREAD proposal [Liu et al., 22]

- Coaxial dish antenna allows use of solenoidal magnetic field



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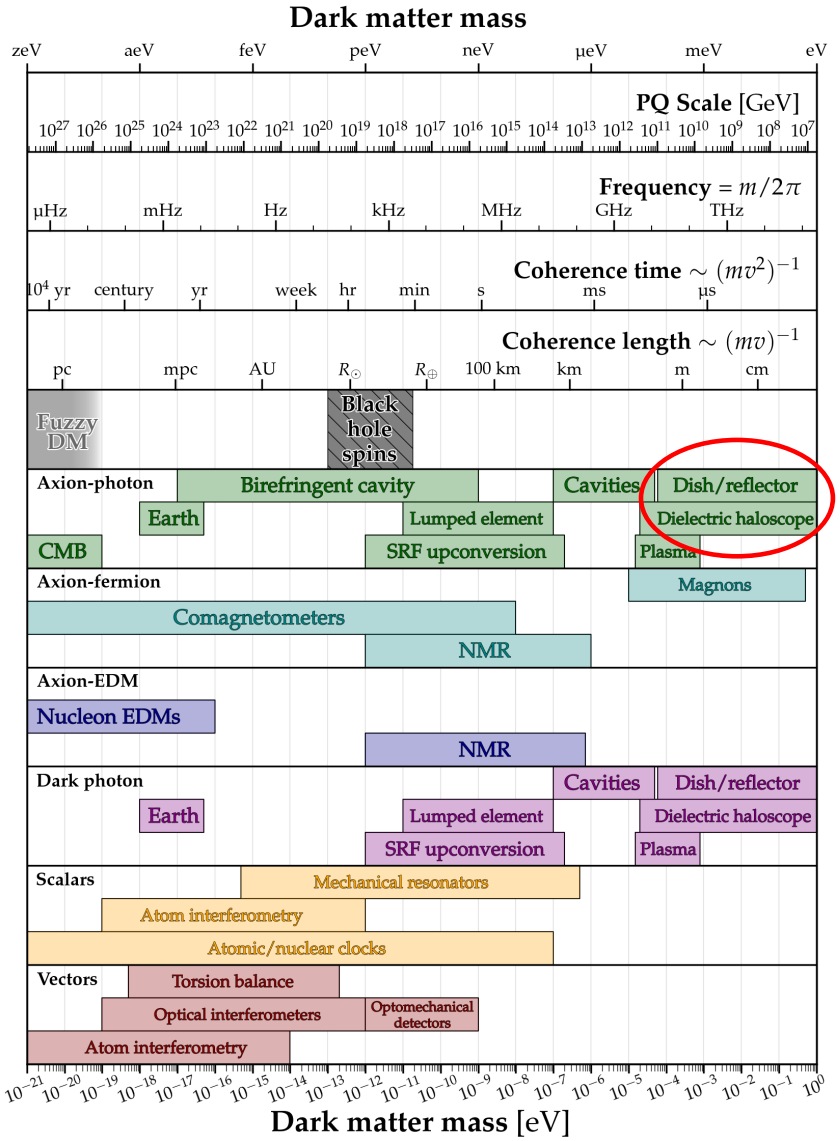

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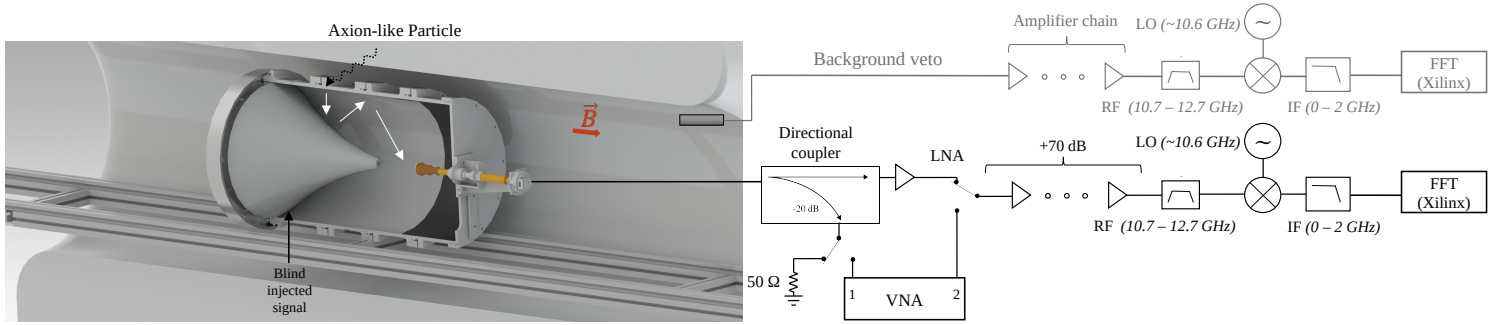

Axion Dark Matter Experiments

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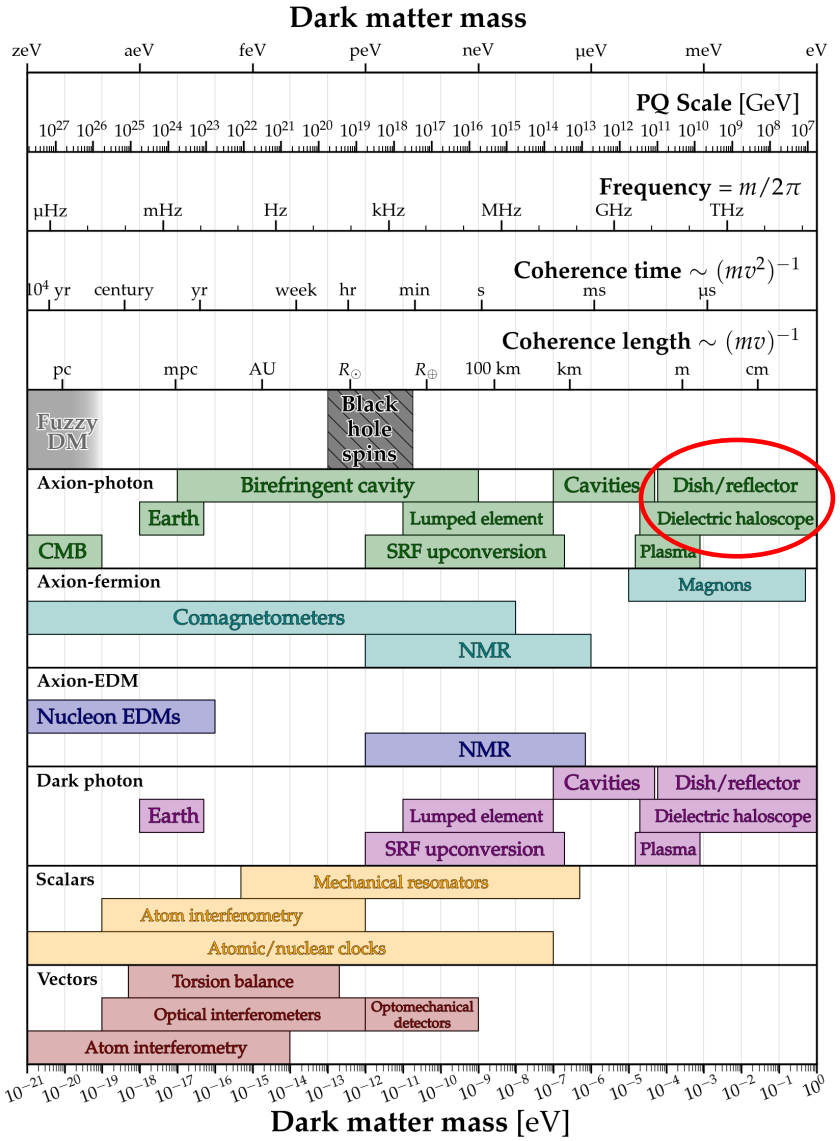

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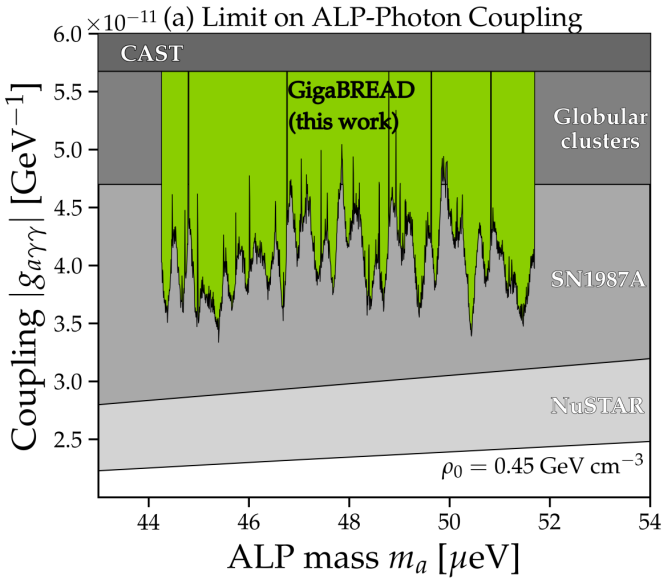

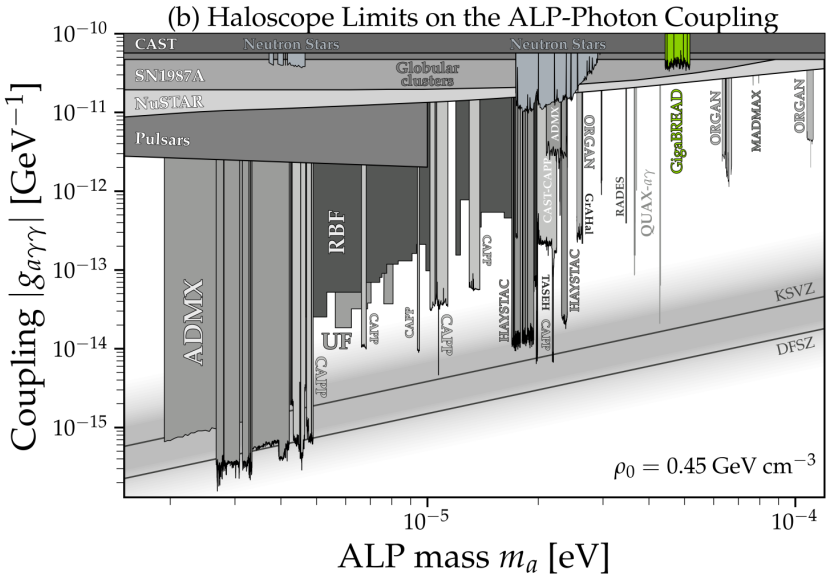

Axion Dark Matter Experiments

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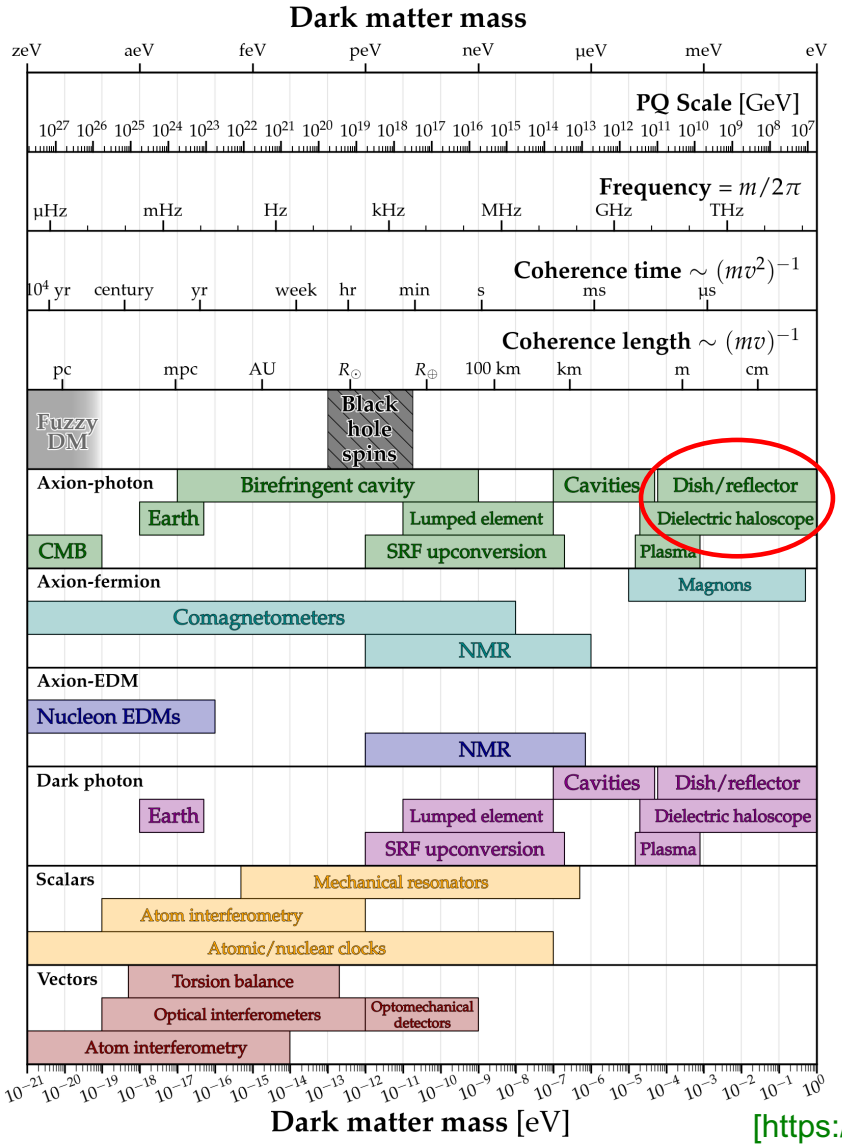
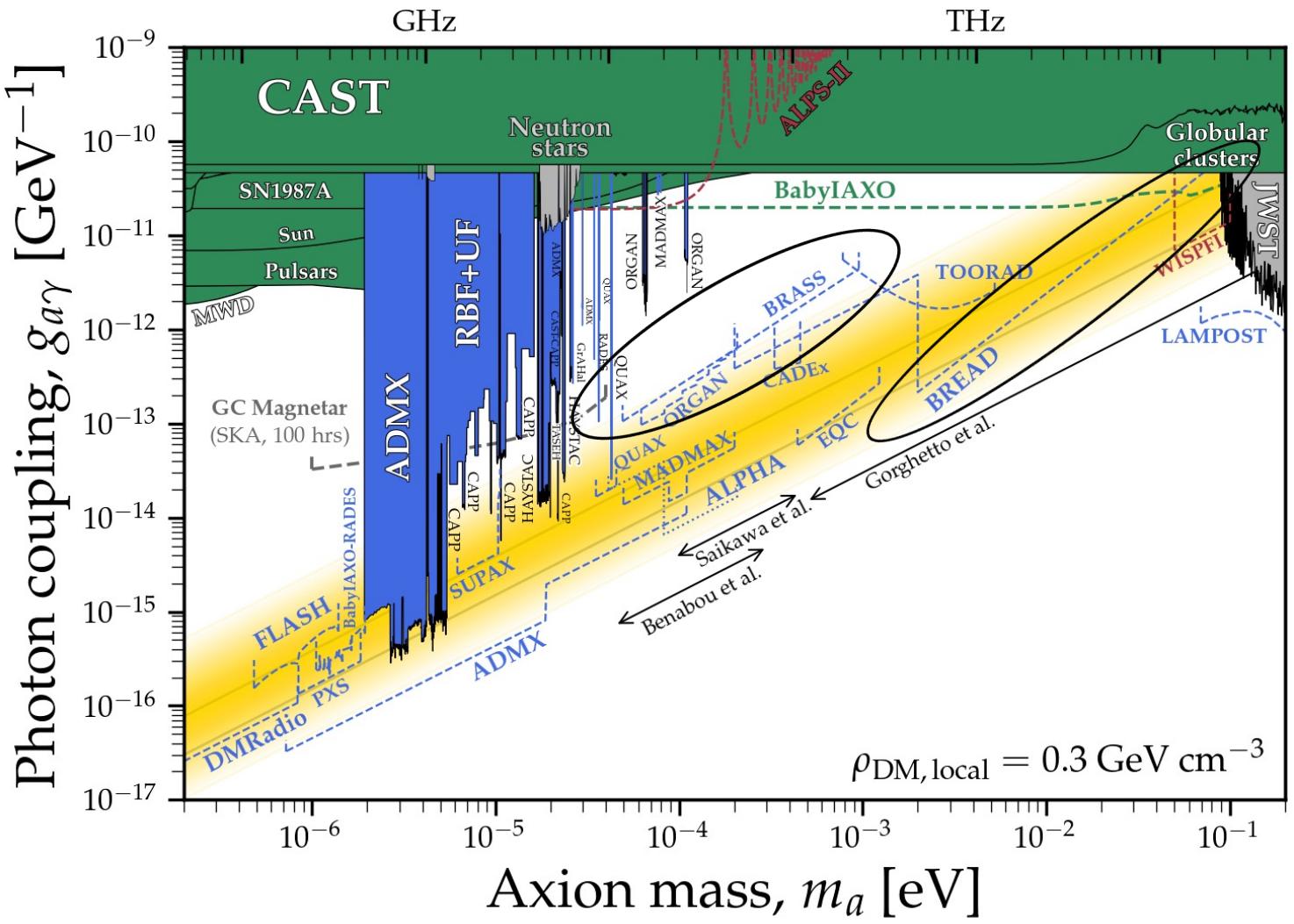


Dish/reflector prospects:



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Axion Dark Matter Experiments

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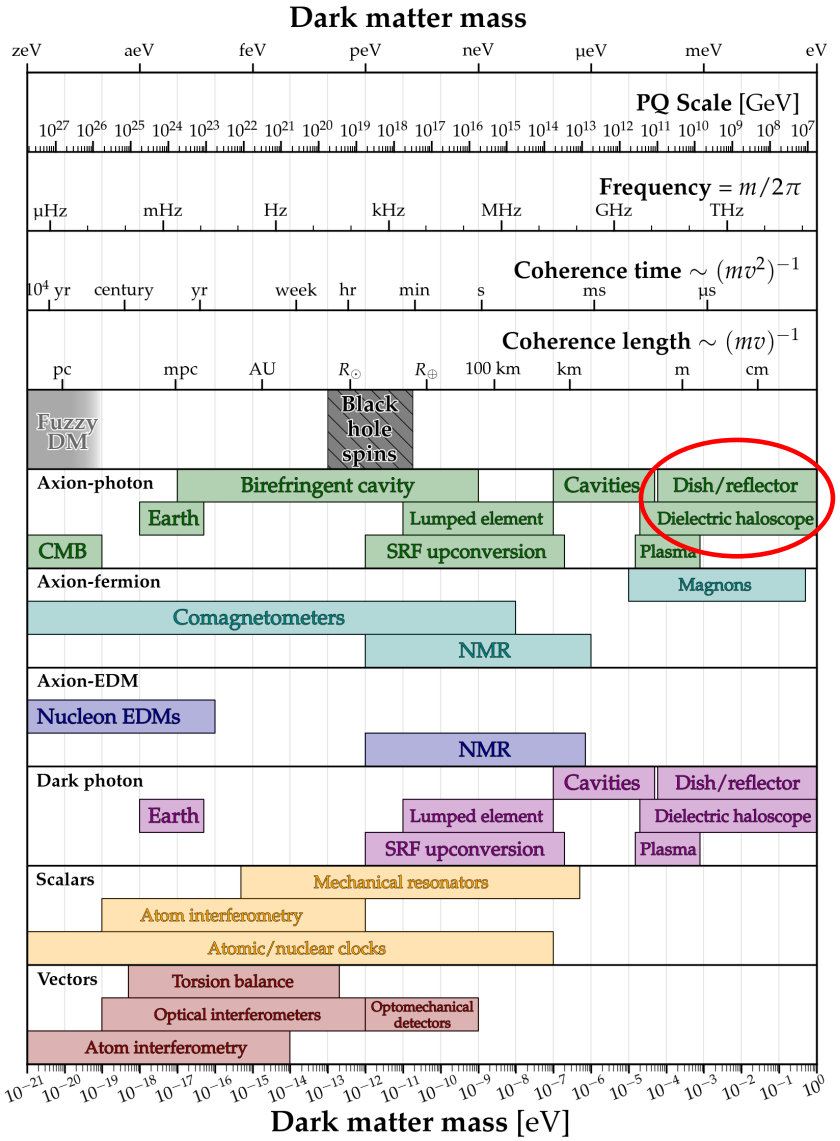
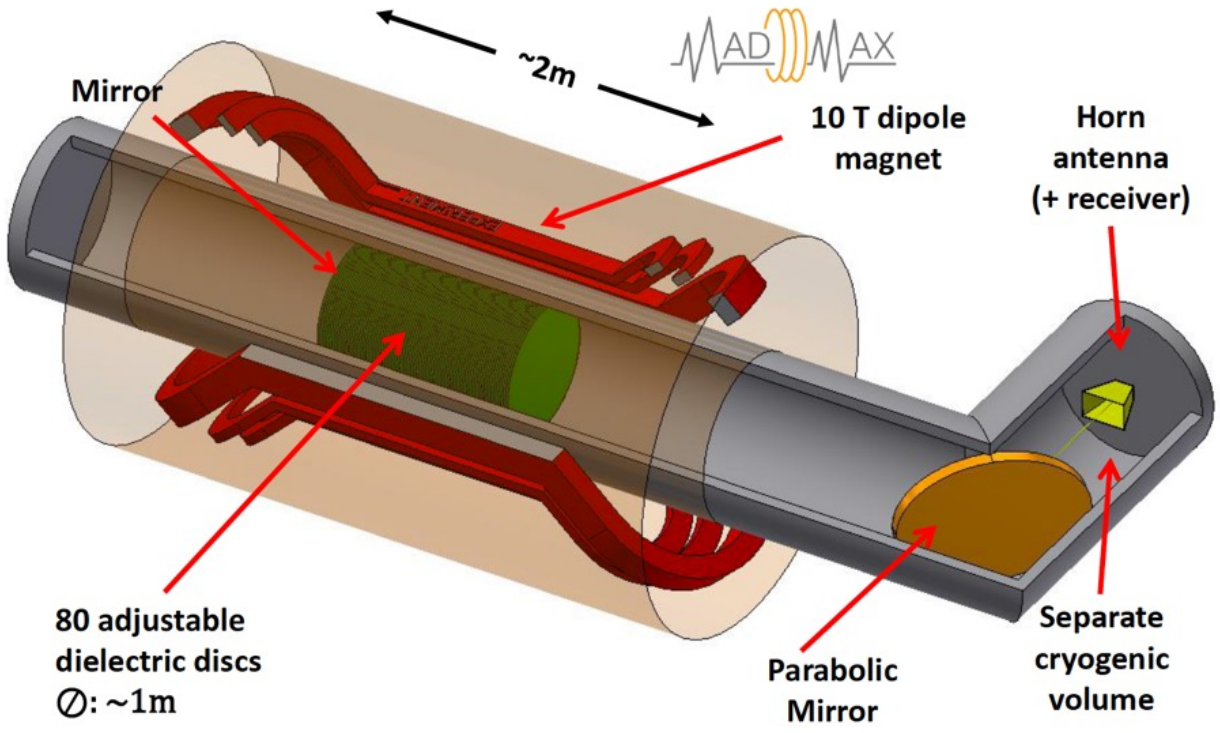


Dielectric haloscope example:

MADMAX

[MADMAX Coll., Eur.Phys.J.C 79 (2019) 3, 186]

- 10 T magnet
- Large number of adjustable dielectric disks



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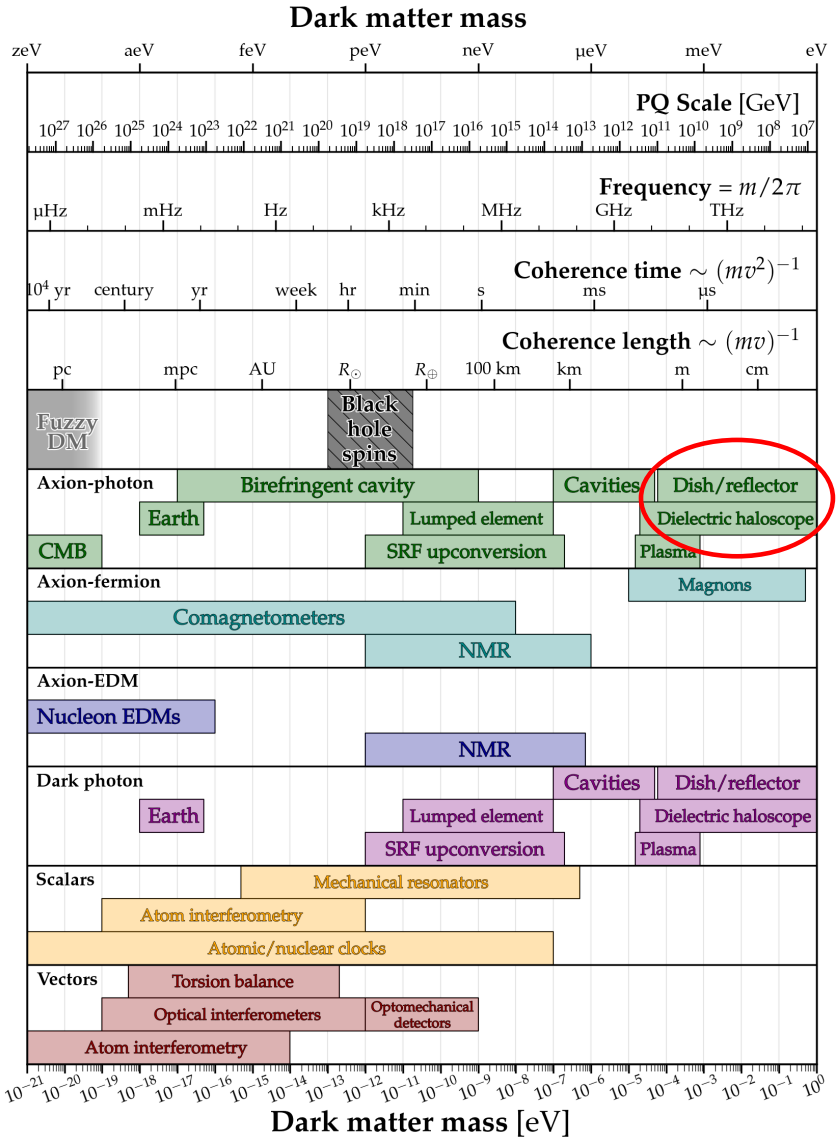

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Prototype tests and science runs with MORPURGO magnet @ CERN

~1.5 T

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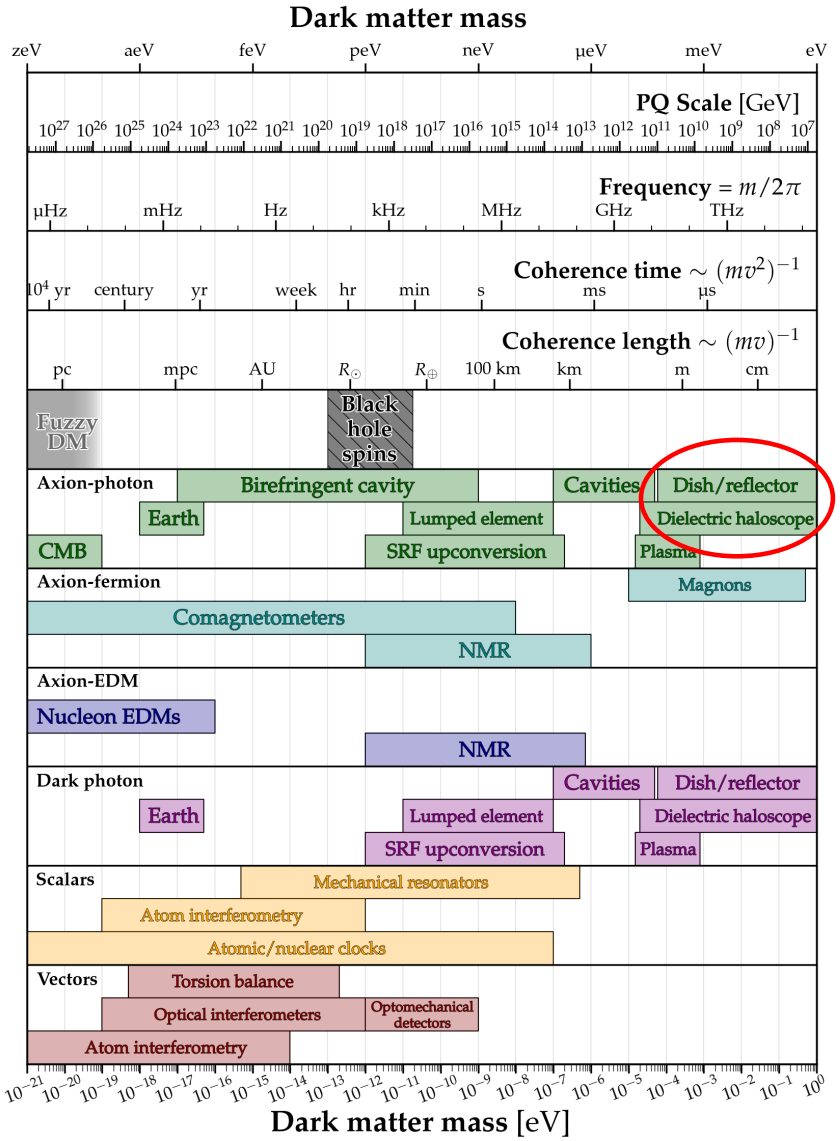
Variety of experimental techniques



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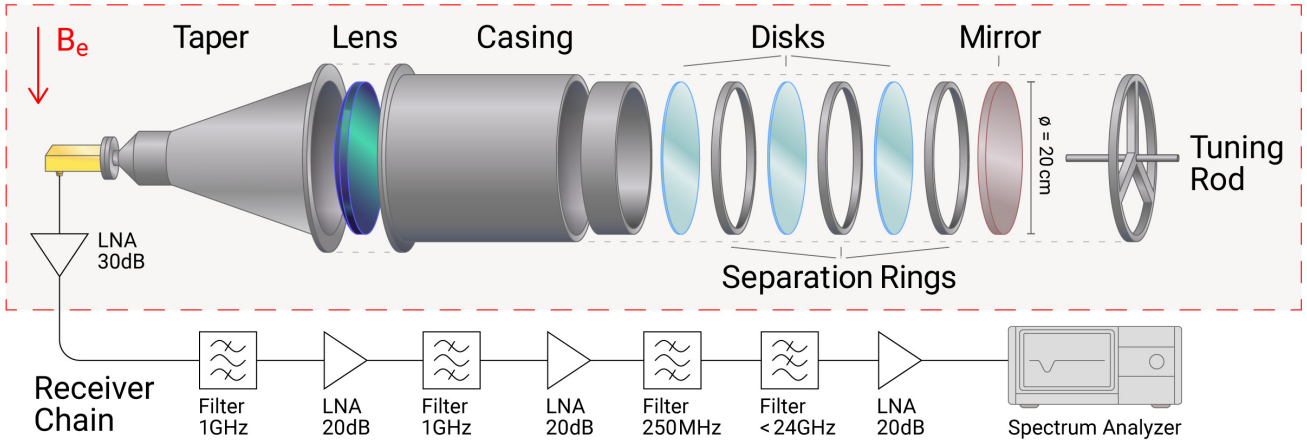
First search published:

PHYSICAL REVIEW LETTERS **135,** 041001 (2025)

First Search for Axion Dark Matter with a MADMAX Prototype

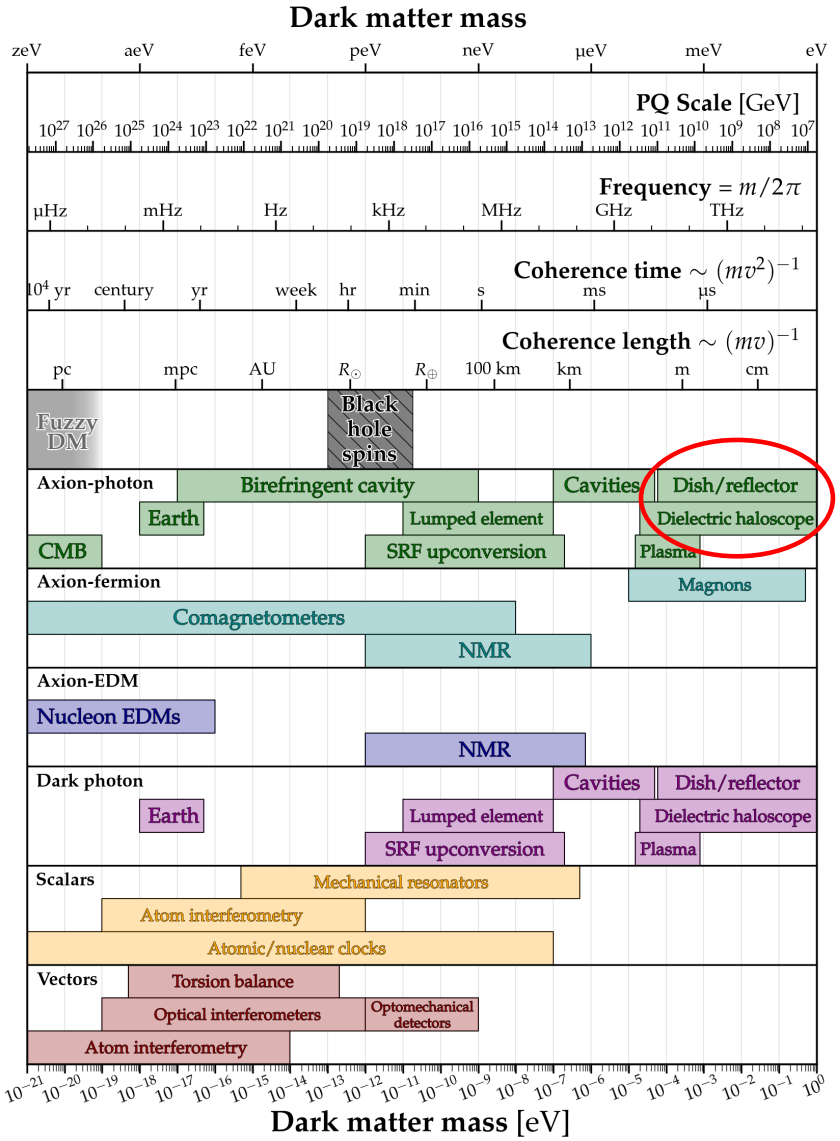
B. Ary dos Santos Garcia,[1] D. Bergermann,[1] A. Caldwell,[2] V. Dabhi,[3] C. Diaconu,[3] J. Diehl,[2] G. Dvali,[2] J. Egge,[4] E. Garutti,[4] S. Heyminck,[5] F. Hubaut,[3] A. Ivanov,[2] J. Jochum,[6] S. Knirck,[7] M. Kramer,[5] D. Kreikemeyer-Lorenzo,[2] C. Krieger,[4] C. Lee,[2,*] D. Leppla-Weber,[8] X. Li,[2,†] A. Lindner,[8] B. Majorovits,[2] J. P. A. Maldonado,[2] A. Martini,[8] A. Miyazaki,[9] E. Öz,[1] P. Pralavorio,[3] G. Raffelt,[2] J. Redondo,[10] A. Ringwald,[8] J. Schaffran,[8] A. Schmidt,[1] F. Steffen,[2] C. Strandhagen,[6] I. Usherov,[6] H. Wang,[1] and G. Wieching[5]

(MADMAX Collaboration)



Axion Dark Matter Experiments

Variety of experimental techniques

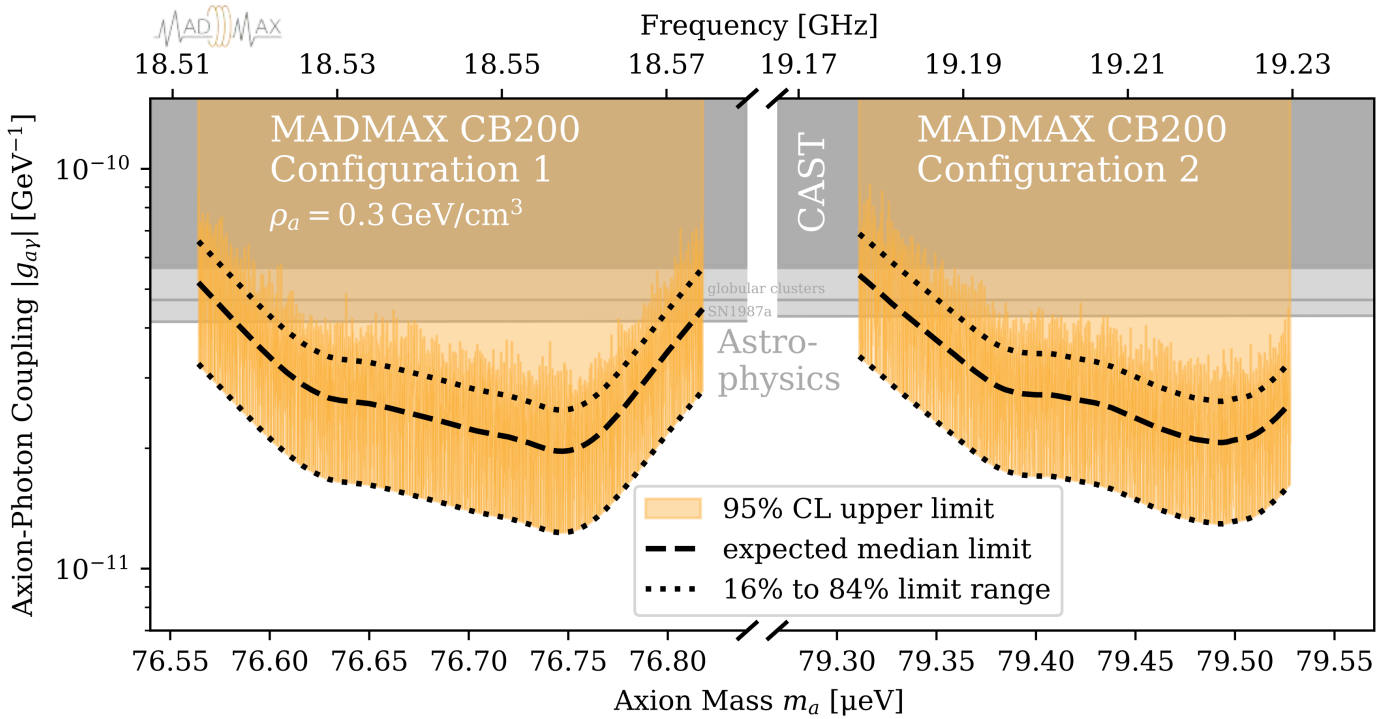


Dielectric haloscope example:

MADMAX [MADMAX Coll., Eur.Phys.J.C 79 (2019) 3, 186]

Prototype tests and science runs with MORPURGO magnet @ CERN

First search published:



[MADMAX Collaboration, PRL 135, 041001 (2025)]

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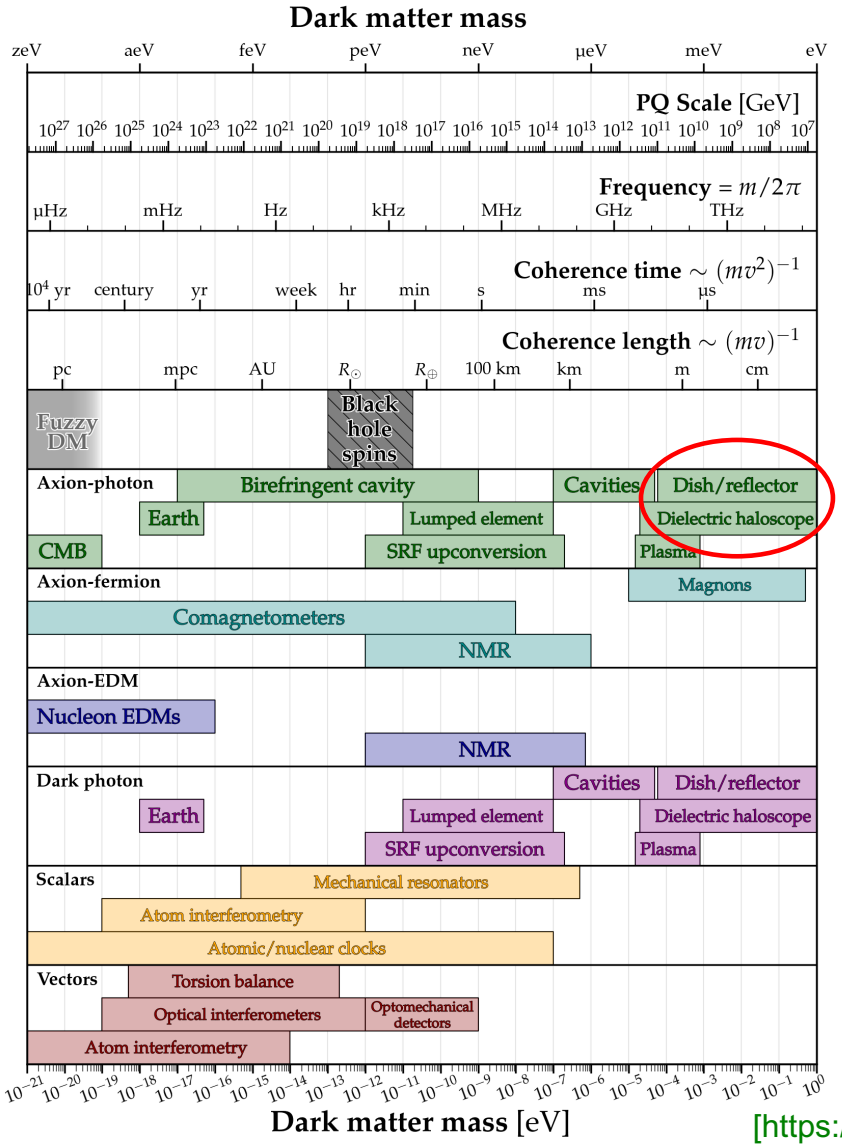
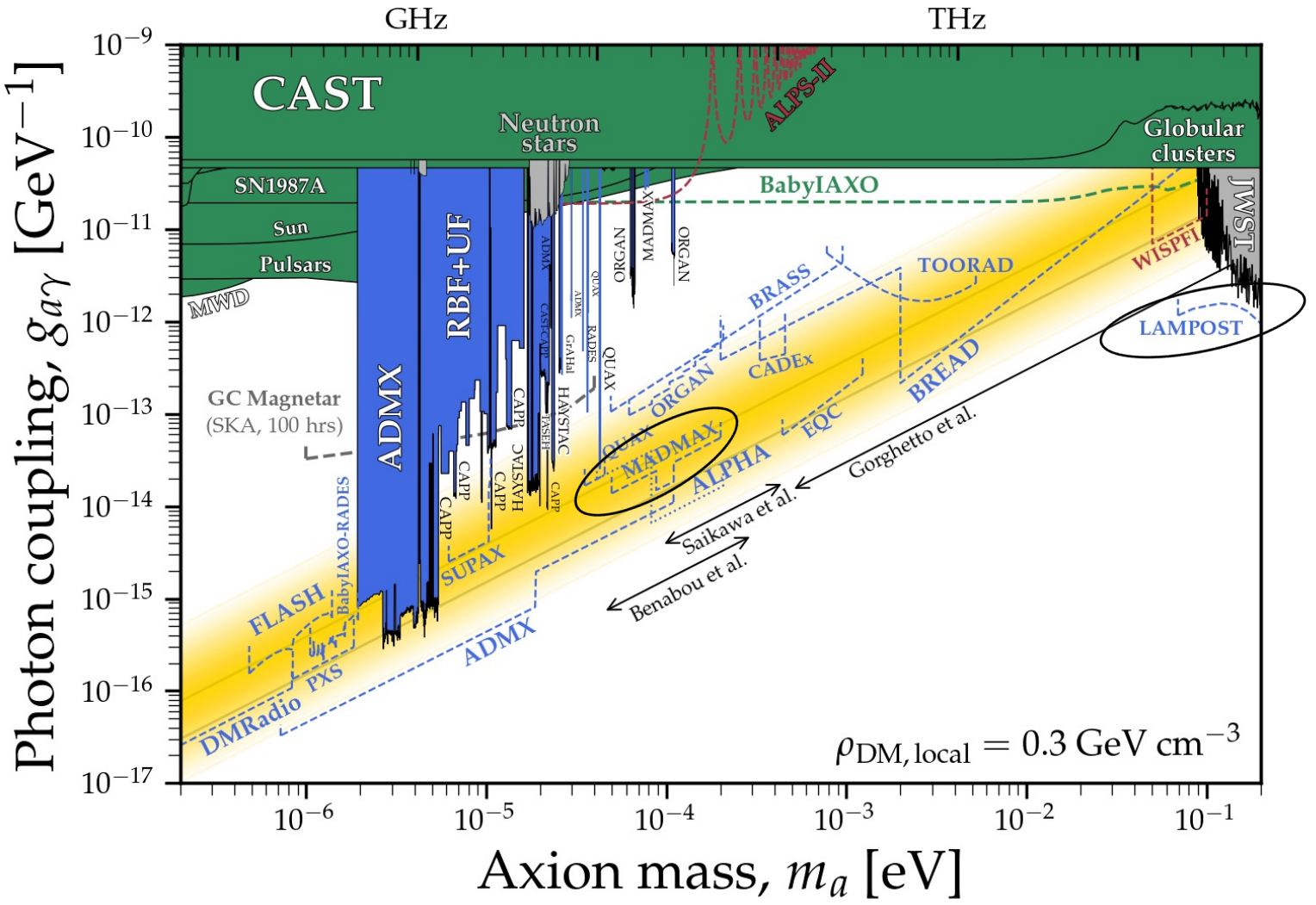


Dielectric haloscope prospects:



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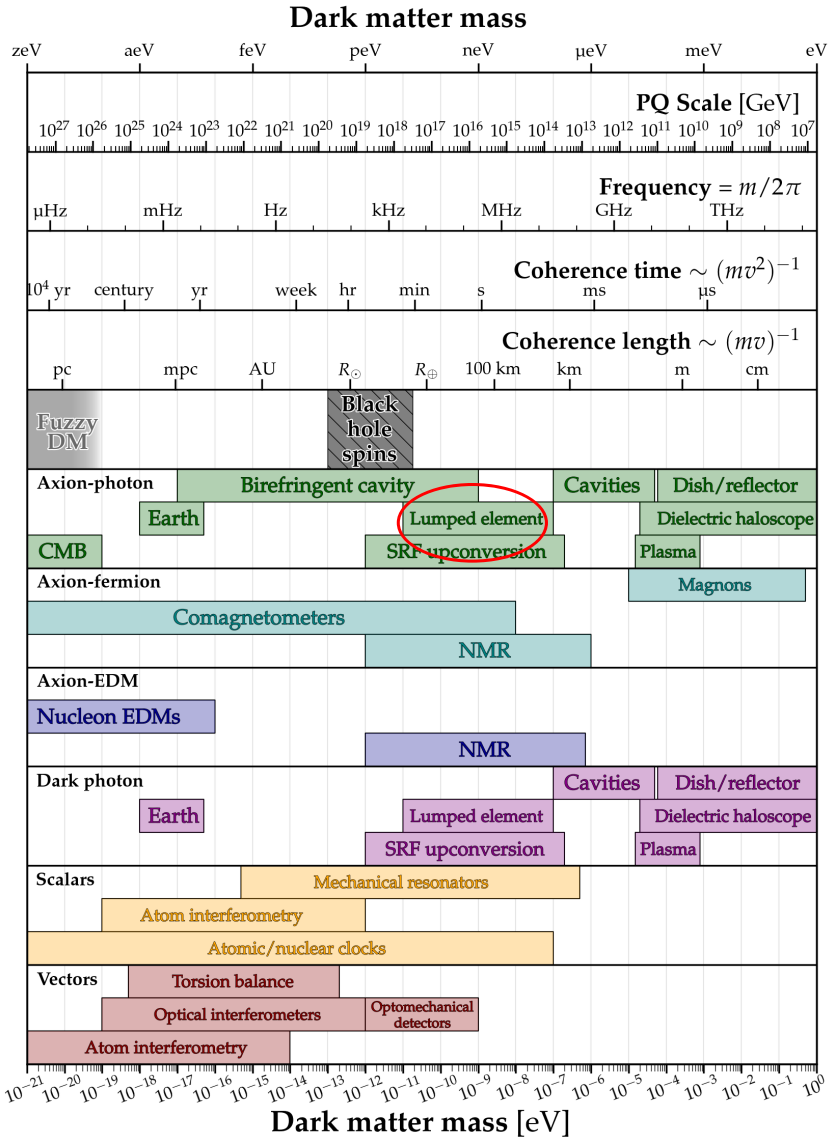


Lumped element concept:

[Sikivie,Sullivan,Tanner 14; Kahn,Safdi,Thaler `16]

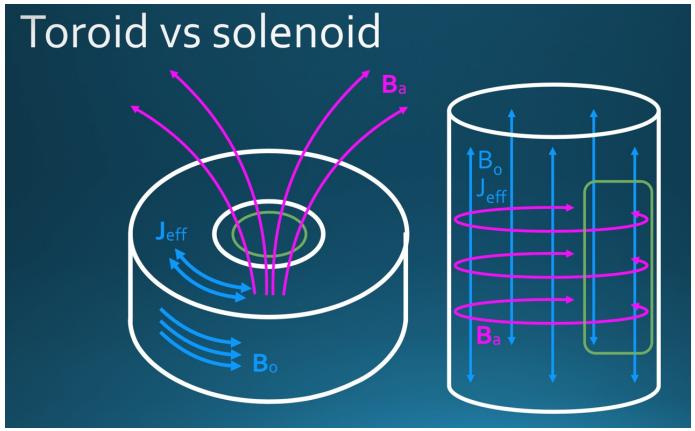
- In a static magnetic field B_0,

  the oscillating axion DM field acts as an effective current density

$$\mathbf{j}_a = -g_{a\gamma}\mathbf{B}_0\,\dot{a}$$

  which, in the magneto-quasistatic limit, sources a tiny oscillating magnetic field $\mathbf{B}_a$, with approximately

$$\nabla \times \mathbf{B}_a = \mathbf{j}_a$$



[Salemi '21]

$$\mathbf{J}_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\mathbf{B}$$

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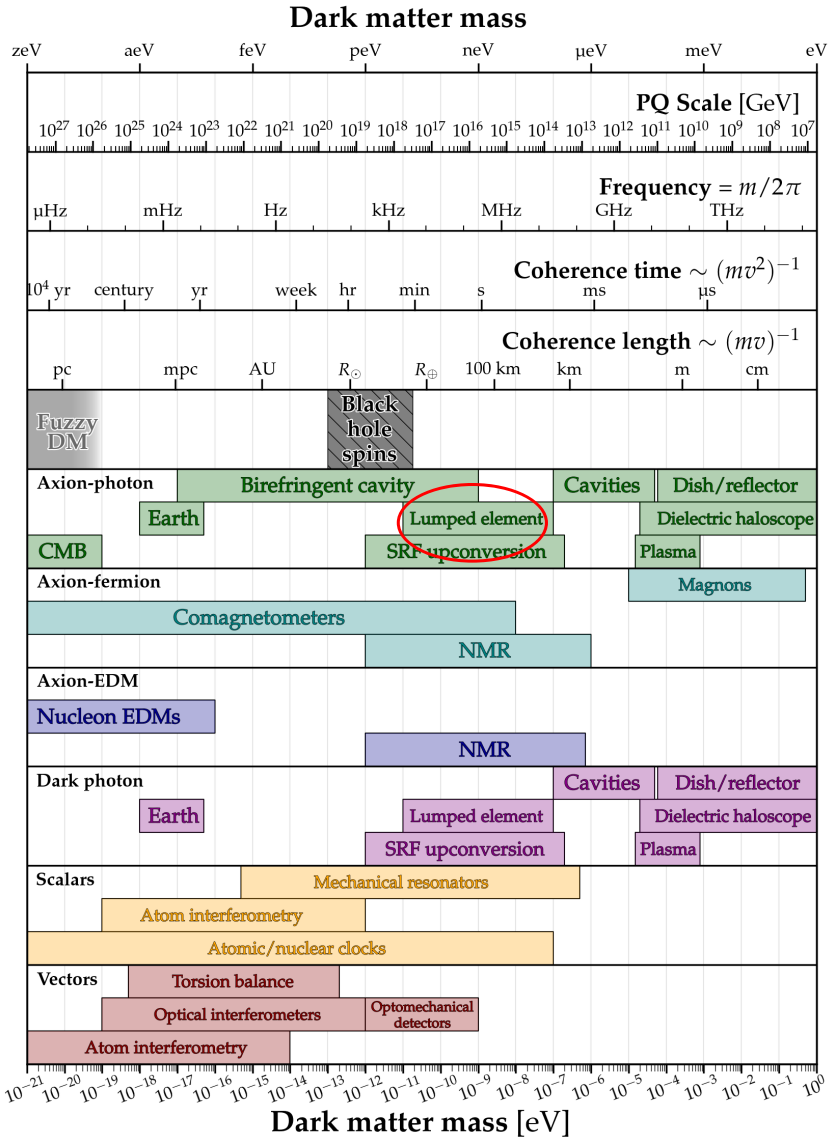

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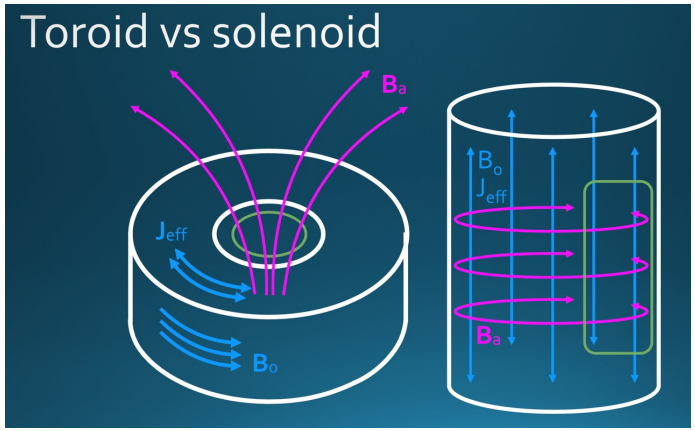
- The induced oscillating flux is

  coupled into a superconducting pickup loop,

  amplified/read out by a lumped-element circuit, and

  detected with a SQUID



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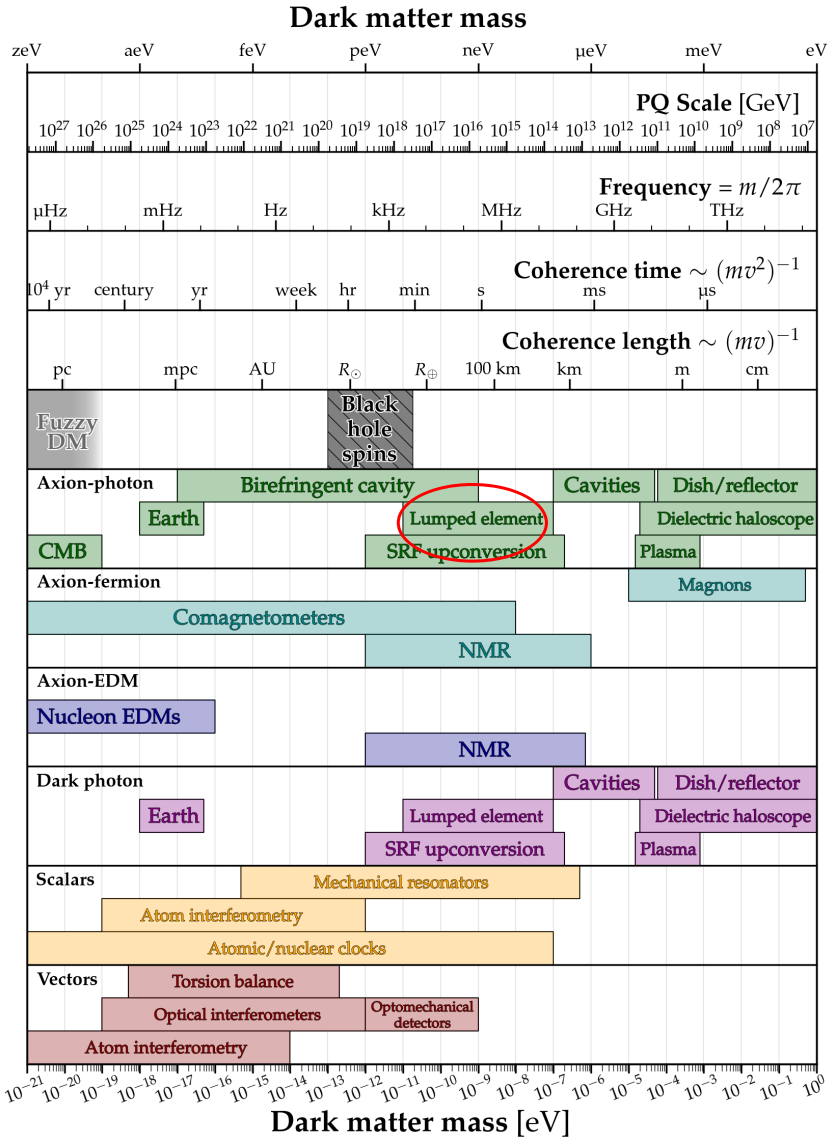
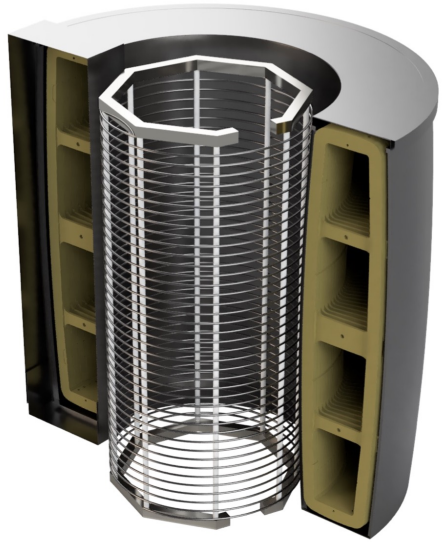


Lumped element examples:

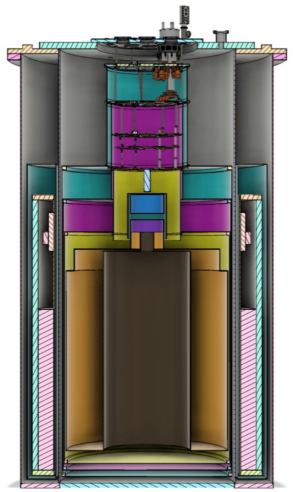
DMRadio

Talk by Andrew Yi on Tue 23/06 at 14:00 in Particles: Dark Matter parallel session

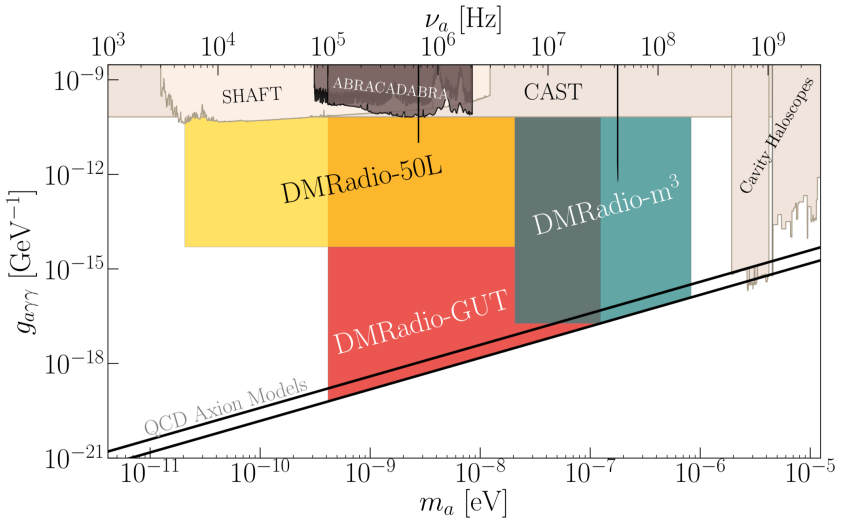
- Ambitious suite of experiments in the US
  - DMRadio-50L
  - DMRadio-m^3
  - DMRadio-GUT



50L



m^3



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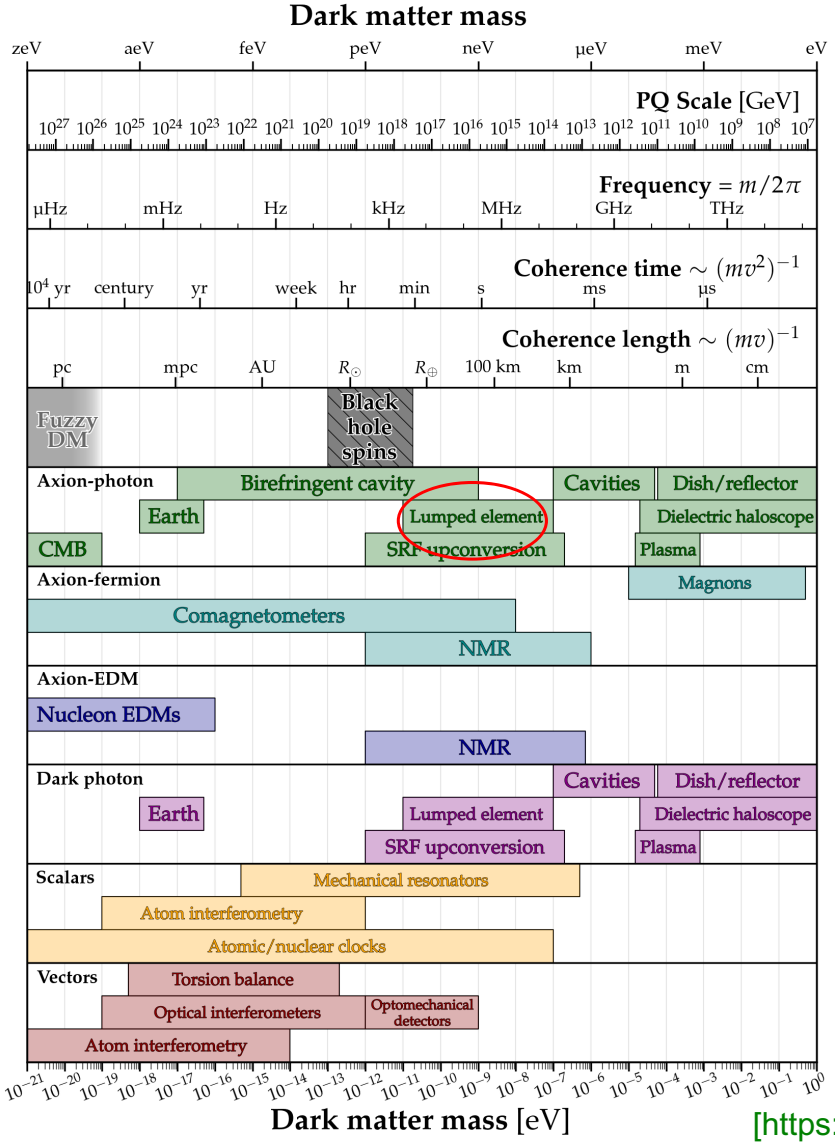
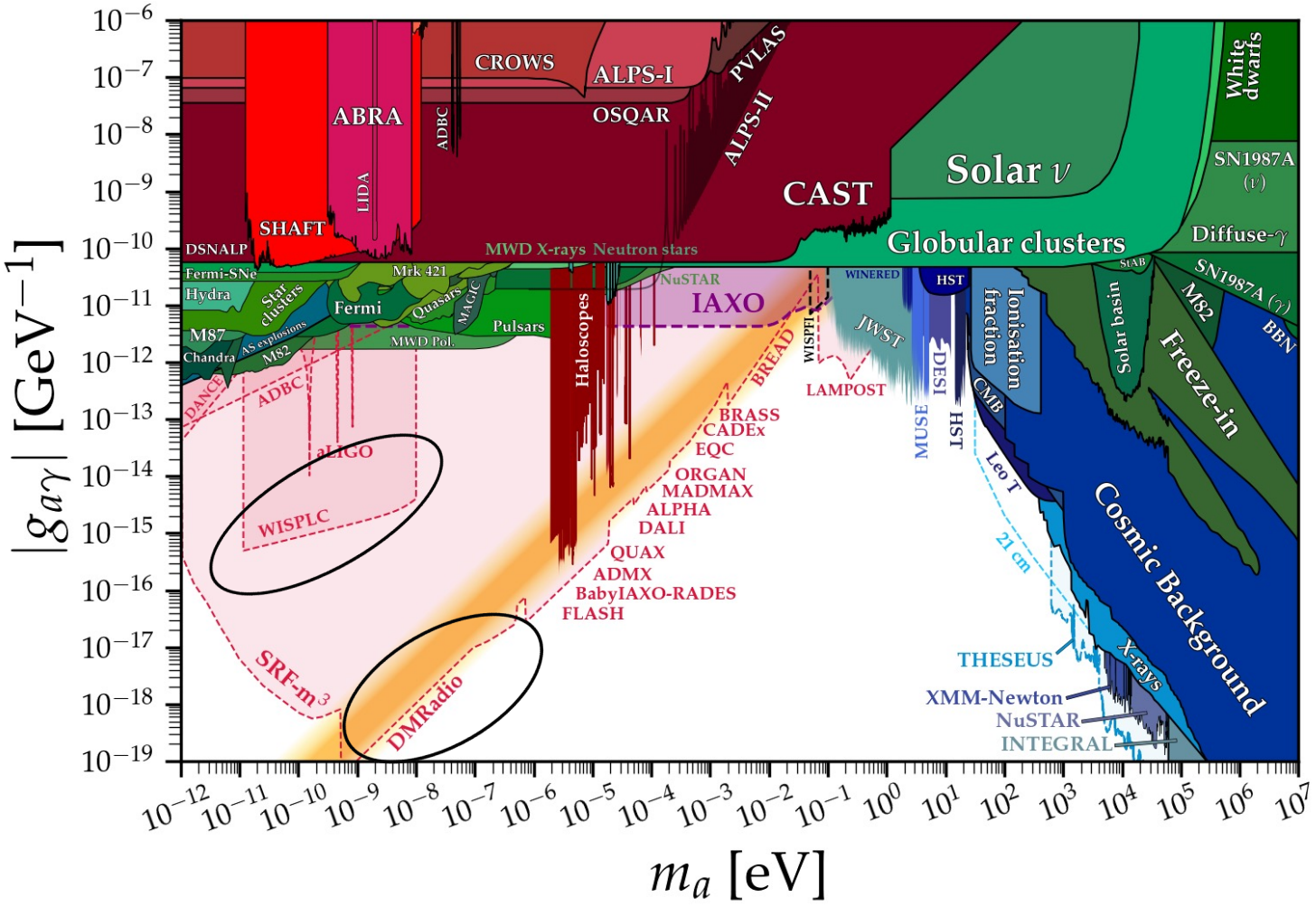


Lumped element prospects:



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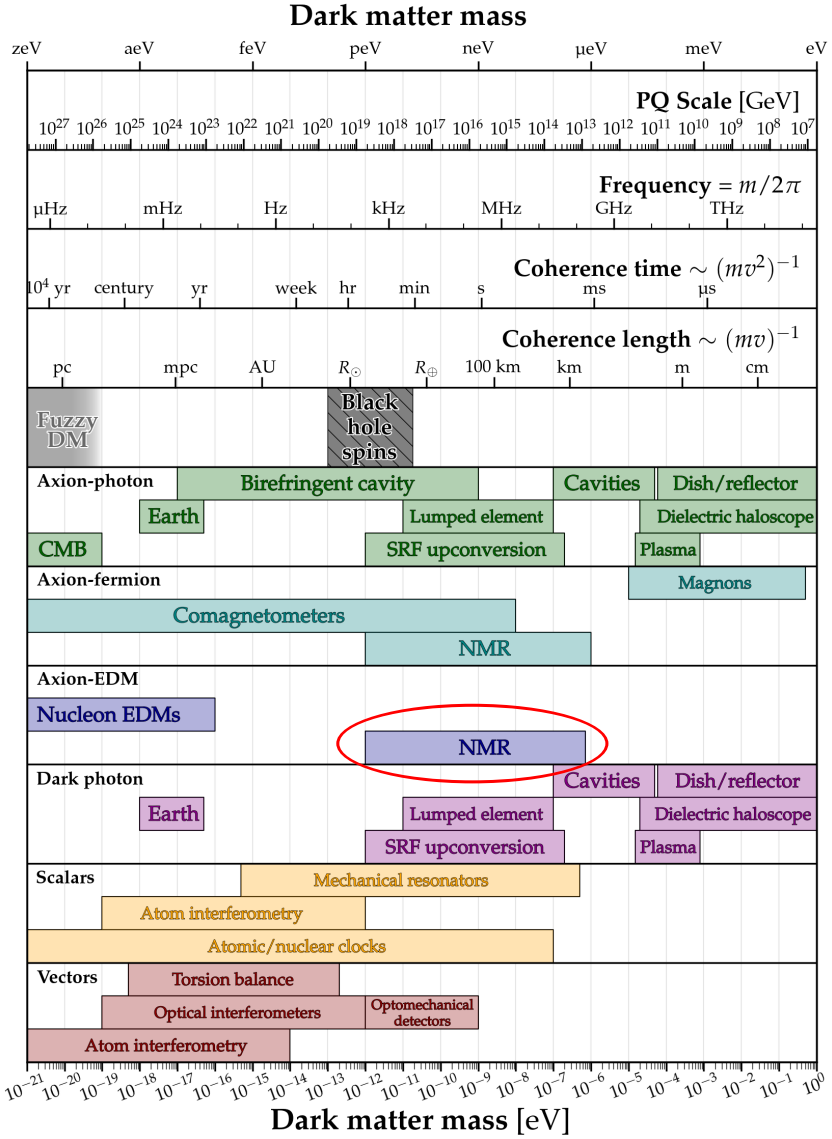

NMR for EDM coupling concept:

[Graham,Rajendran 13; Budker et al. 14]

- Axion DM field acts as an oscillating effective NEDM:

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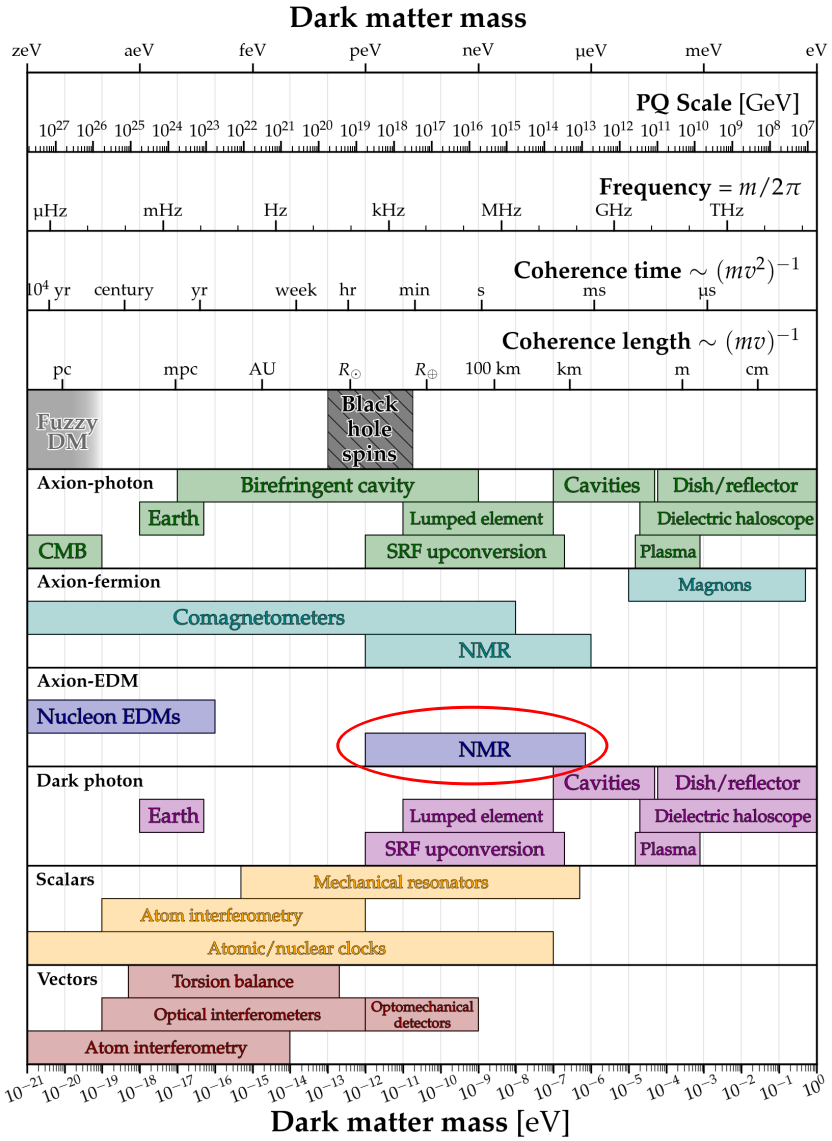

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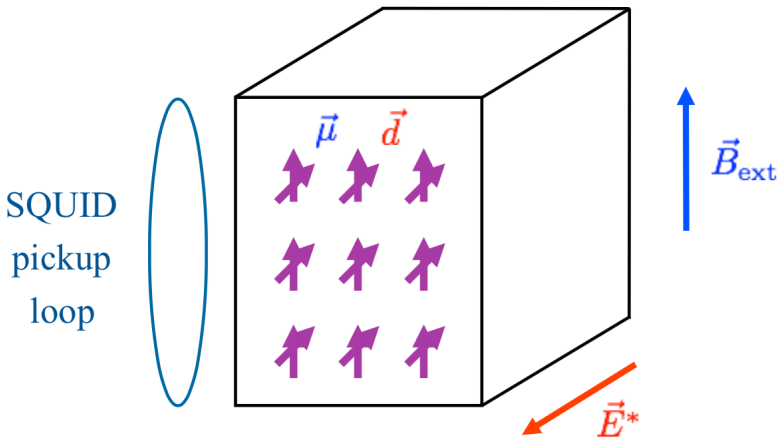

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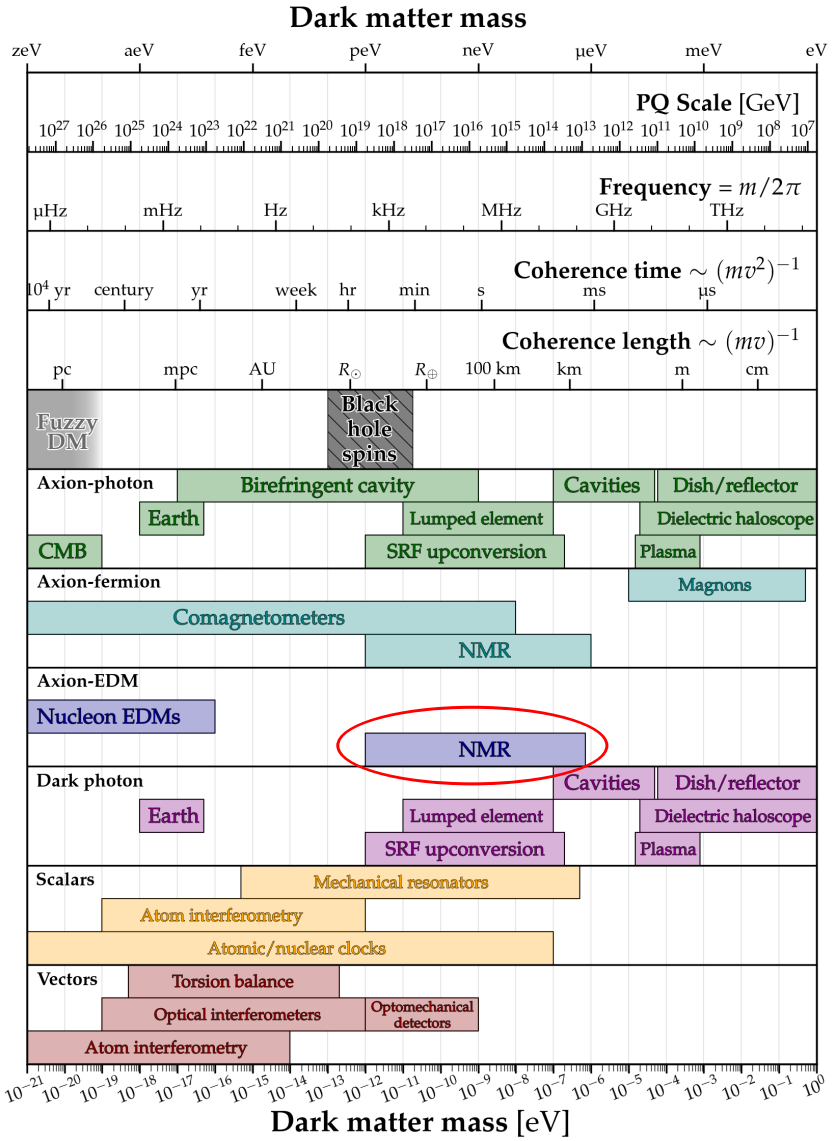

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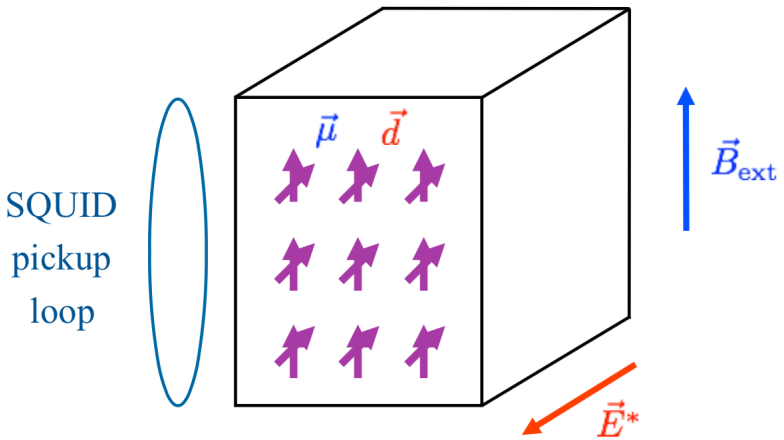

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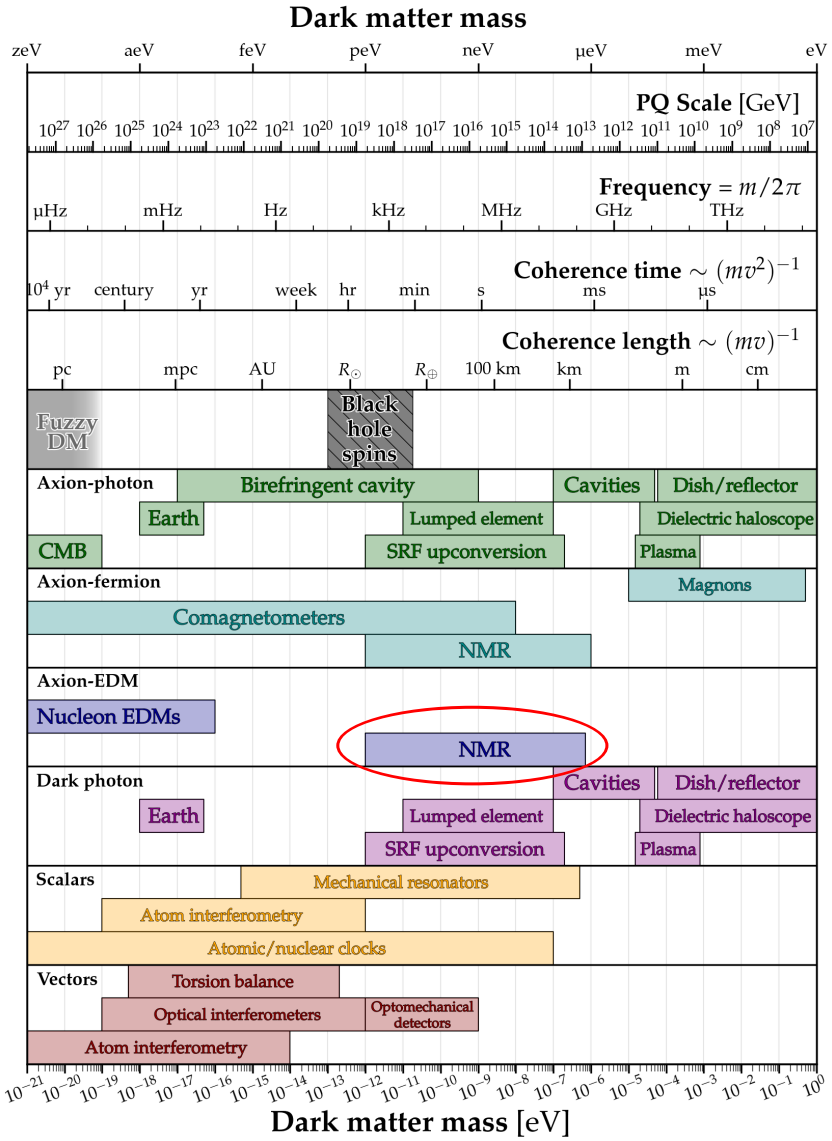

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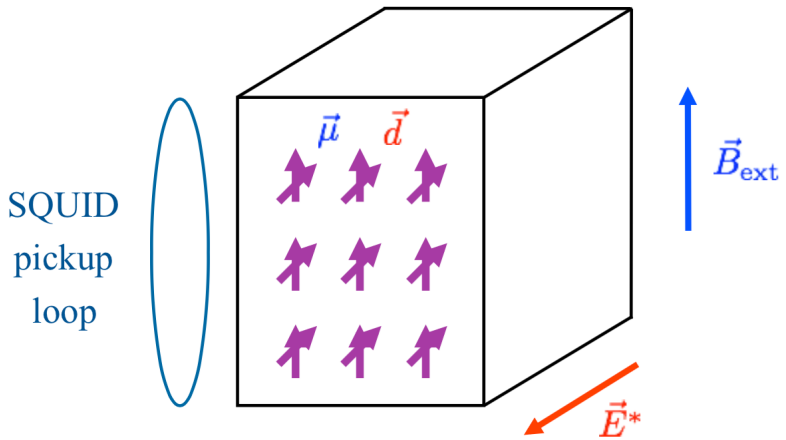
- EDM interaction, $\epsilon_S \vec{d}_N(t) \cdot \vec{E}^*$, drives the spins and resonantly builds up transverse magnetization when $\omega_L \simeq m_a$



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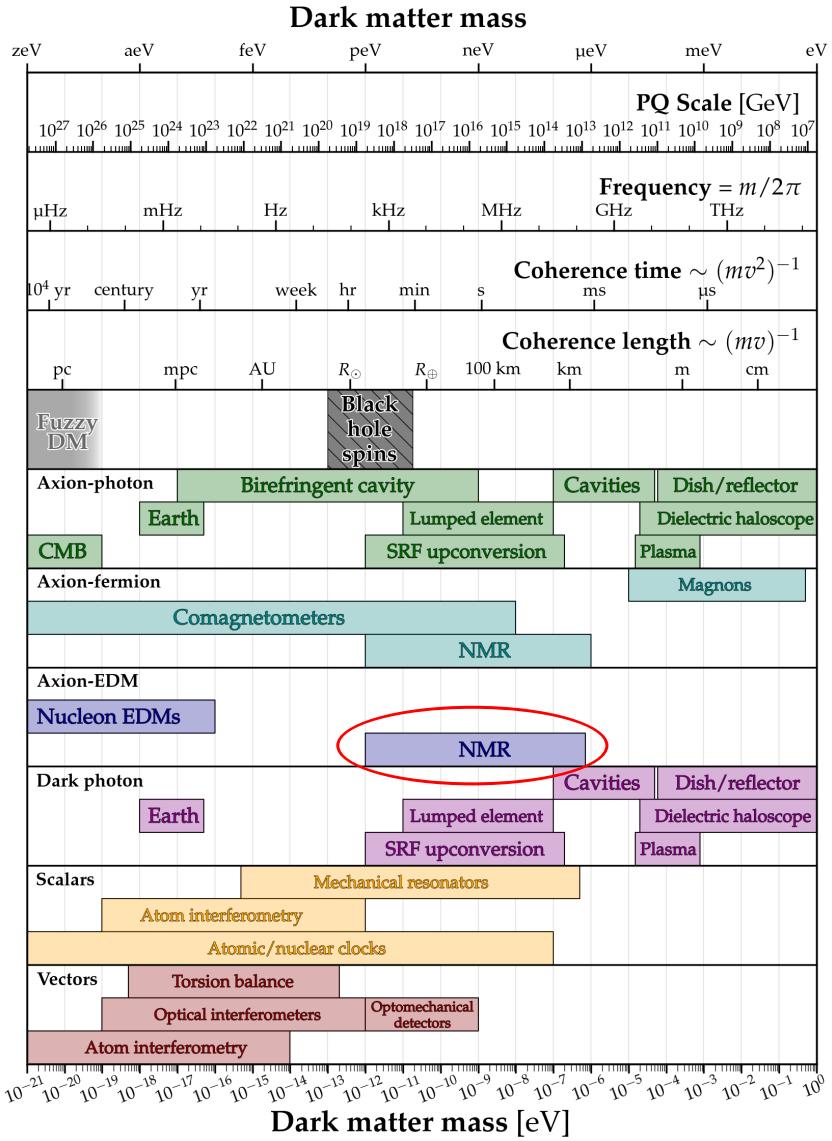

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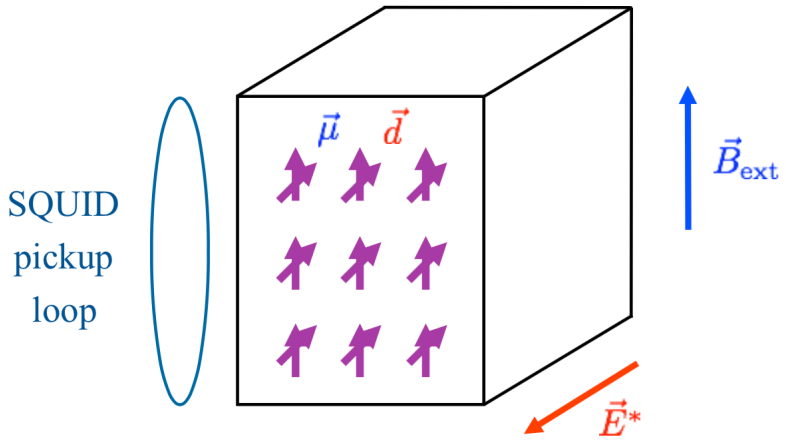
- Sweeping $\vec{B}_{\rm ext}$ scans the axion mass; the transverse magnetization is read out with a pickup loop/SQUID



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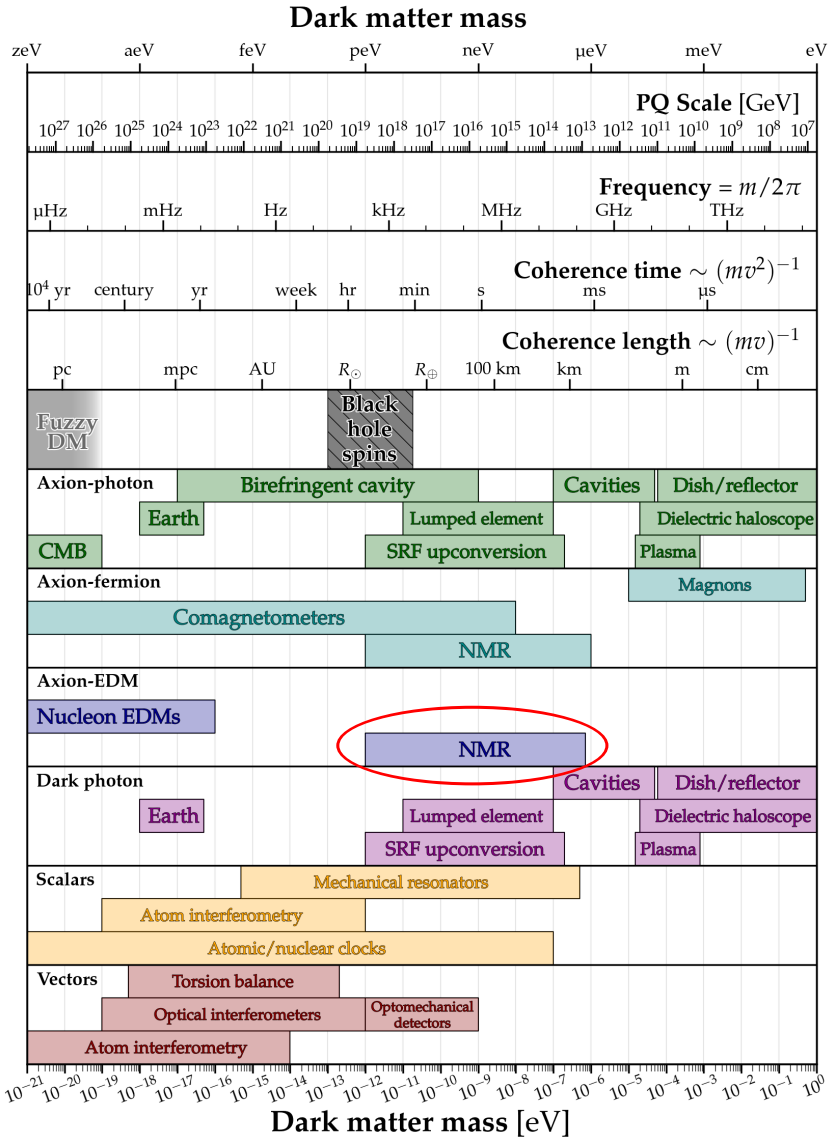
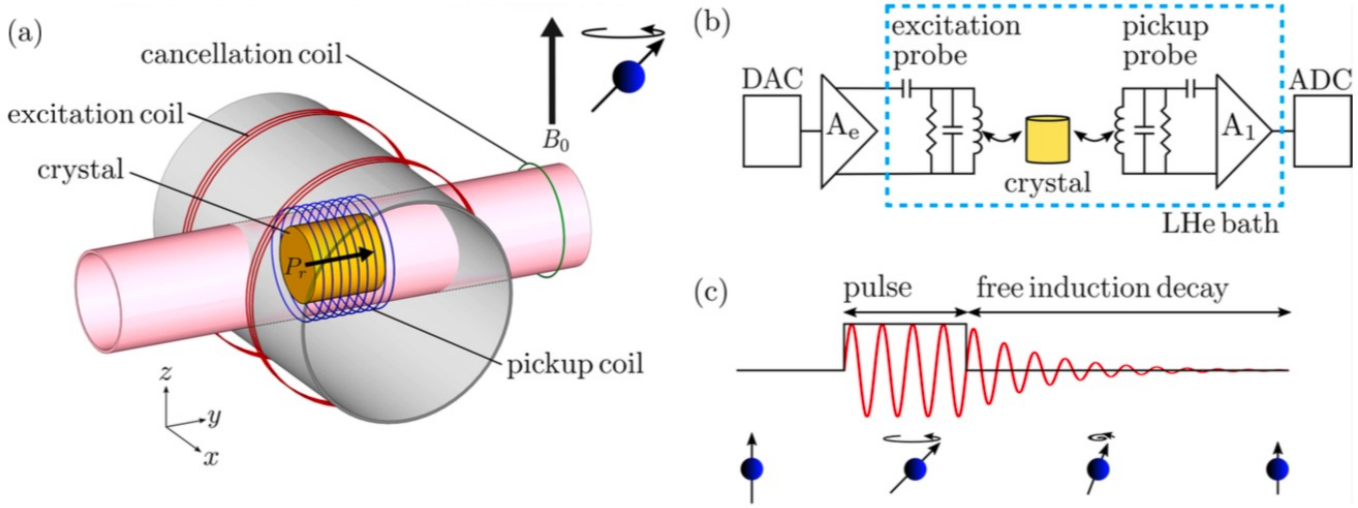


NMR for EDM coupling example:

CASPEr-Electric in Boston

- Initial pathfinder experiment in 2021



[Aybas et al., 2101.01241]

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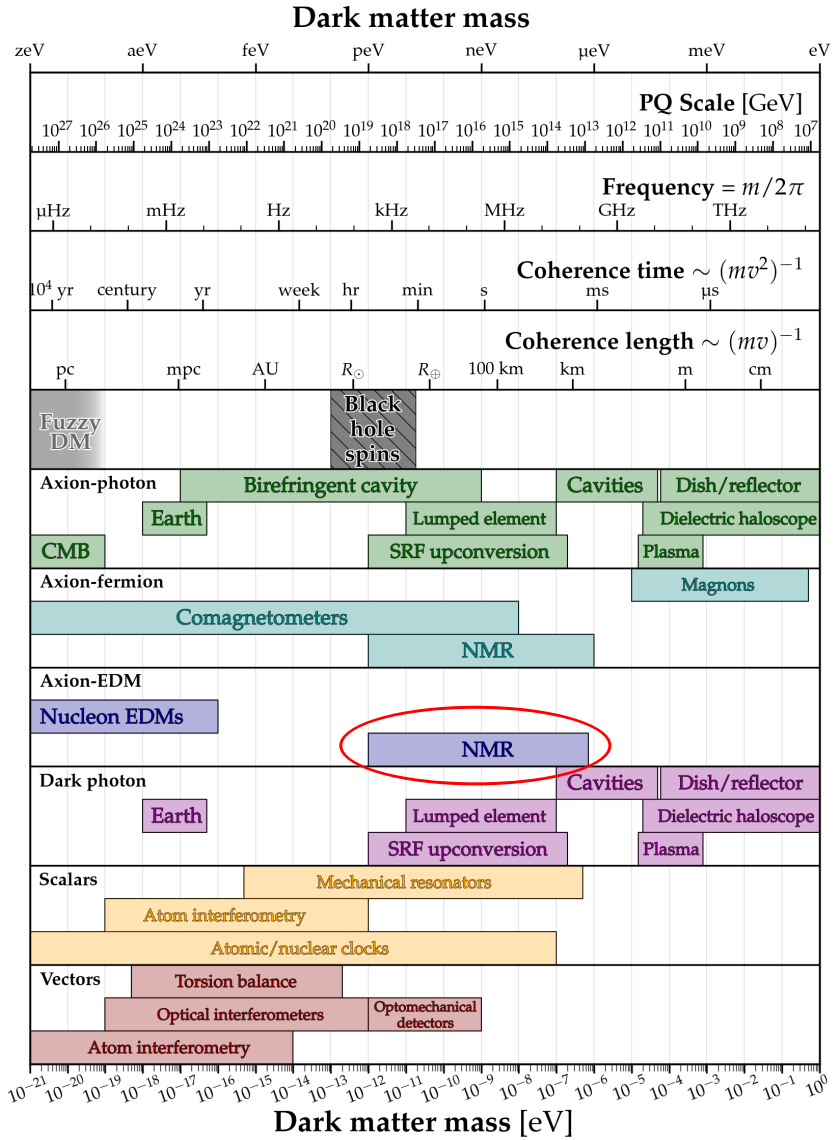
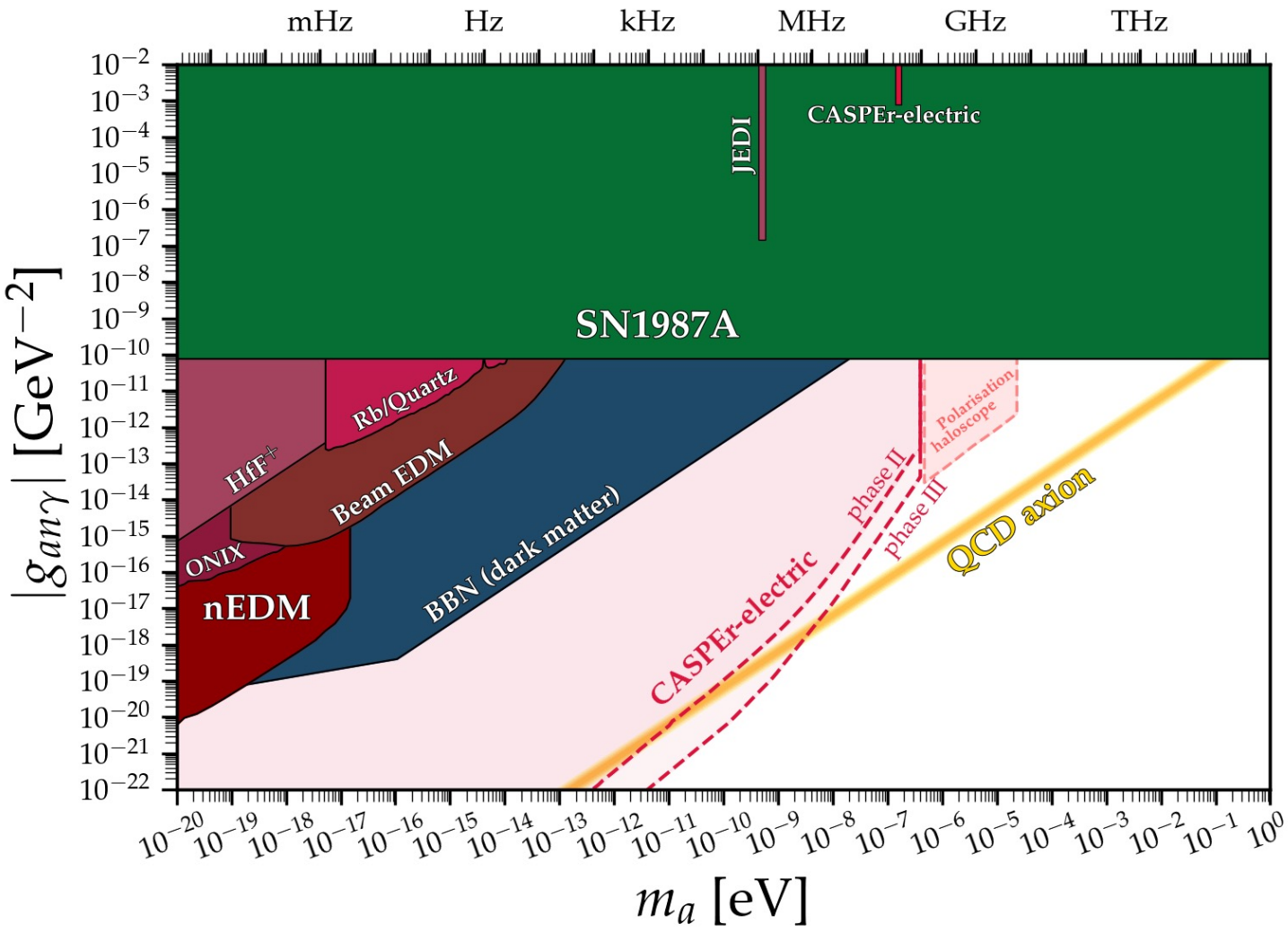


NMR for EDM coupling prospects:



[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionEDM_with_Projections.png]

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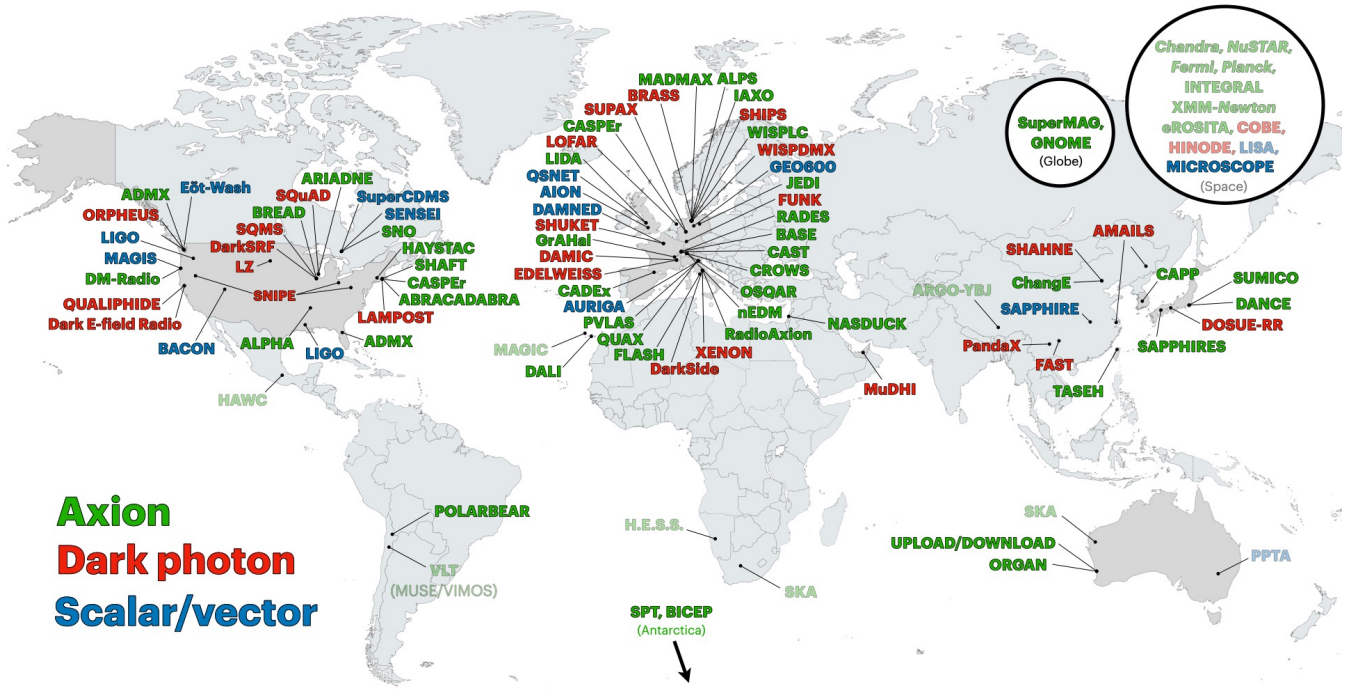

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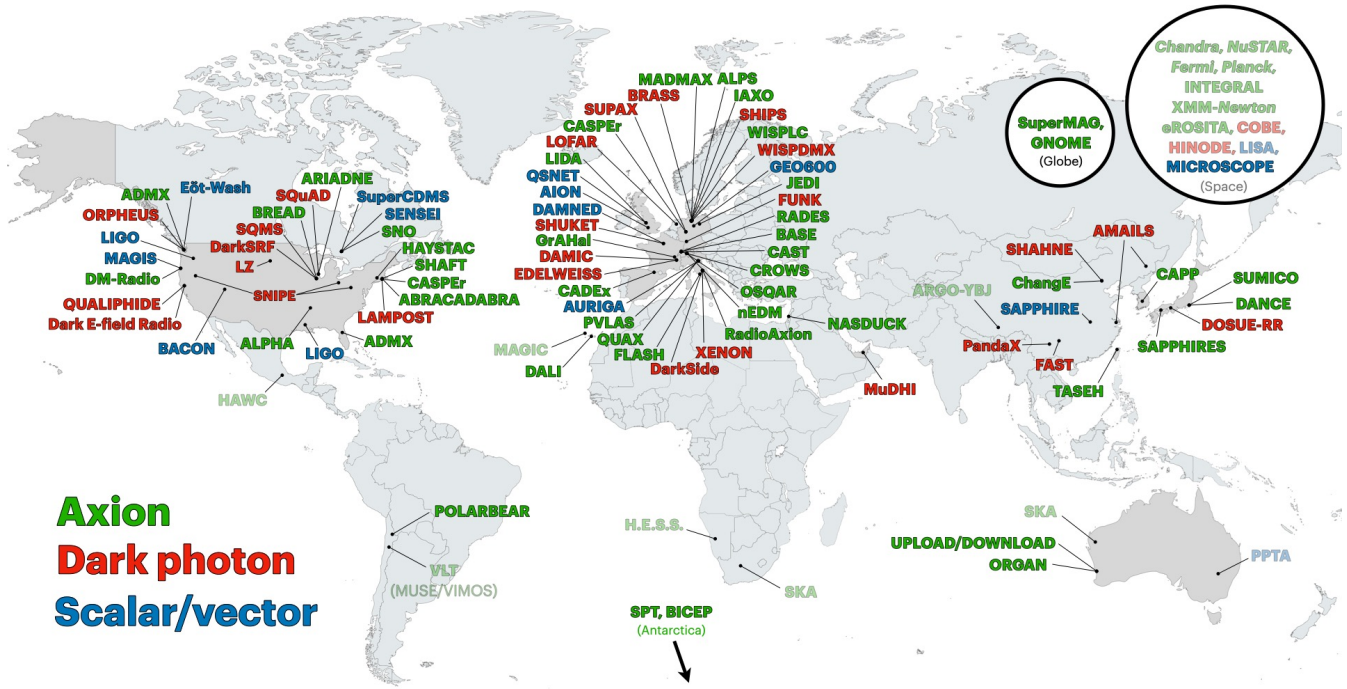

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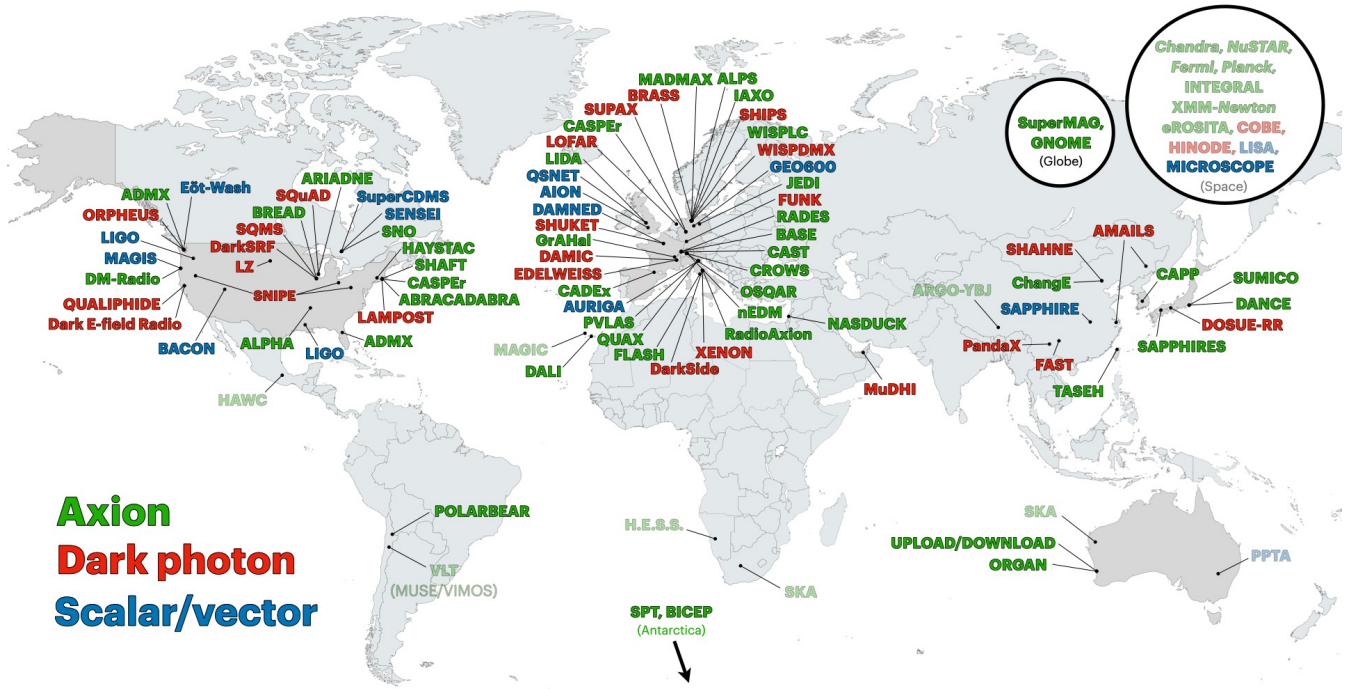

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Stay tuned!

Backup Slides

Axion Experiments Not Relying on Axion Dark Matter

Searching for solar or home-made axions

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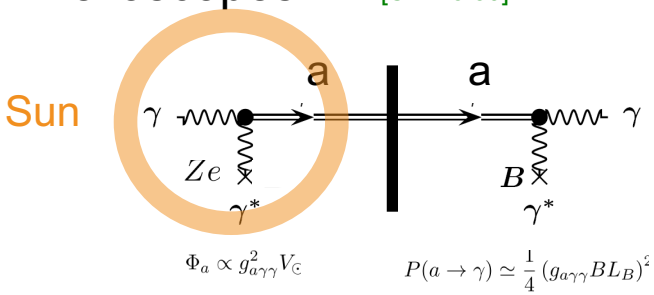
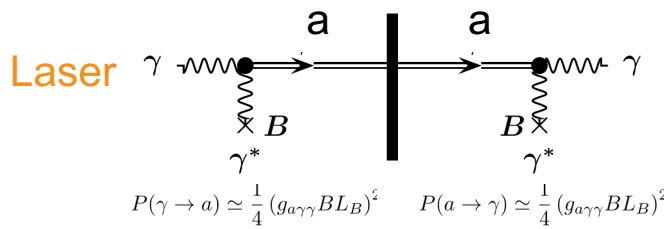
- Helioscopes: [Sikivie 83]



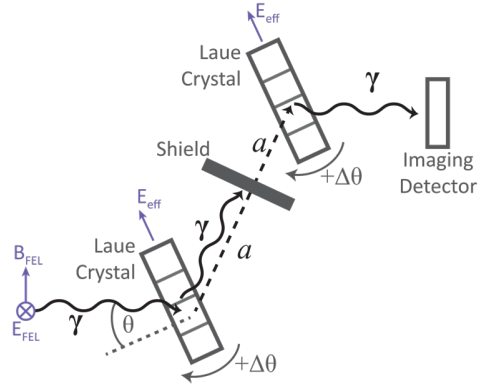
- **Light-shining through walls:** [Anselm 85; van Bibber 87]



Crystal-assisted X-ray LSW concept:

[Buchmüller & Hoogeveen, Phys. Lett. B 237 (1990) 278]

- Use intense X-ray beam instead of an optical laser
- In a crystal, strong microscopic electric field of the lattice acts as external field for Primakoff conversion:



- Coherent conversion occurs when the crystal satisfies a Bragg/Laue momentum-matching condition.
- An absorber blocks ordinary X-rays
- Second aligned crystal converts axions back into X-rays:
- Look for regenerated X-rays downstream of the wall.
- Rotating/detuning the crystals scans the ALP mass.

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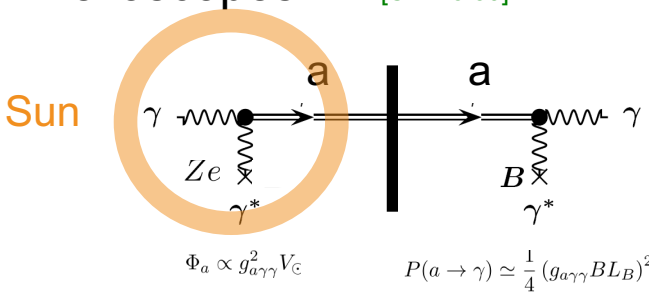

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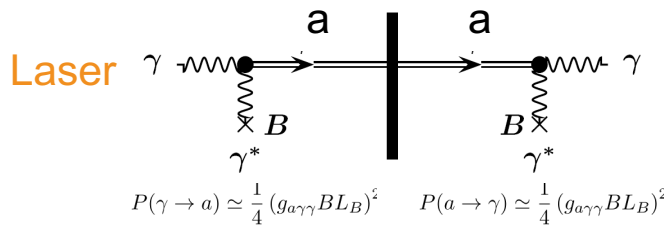
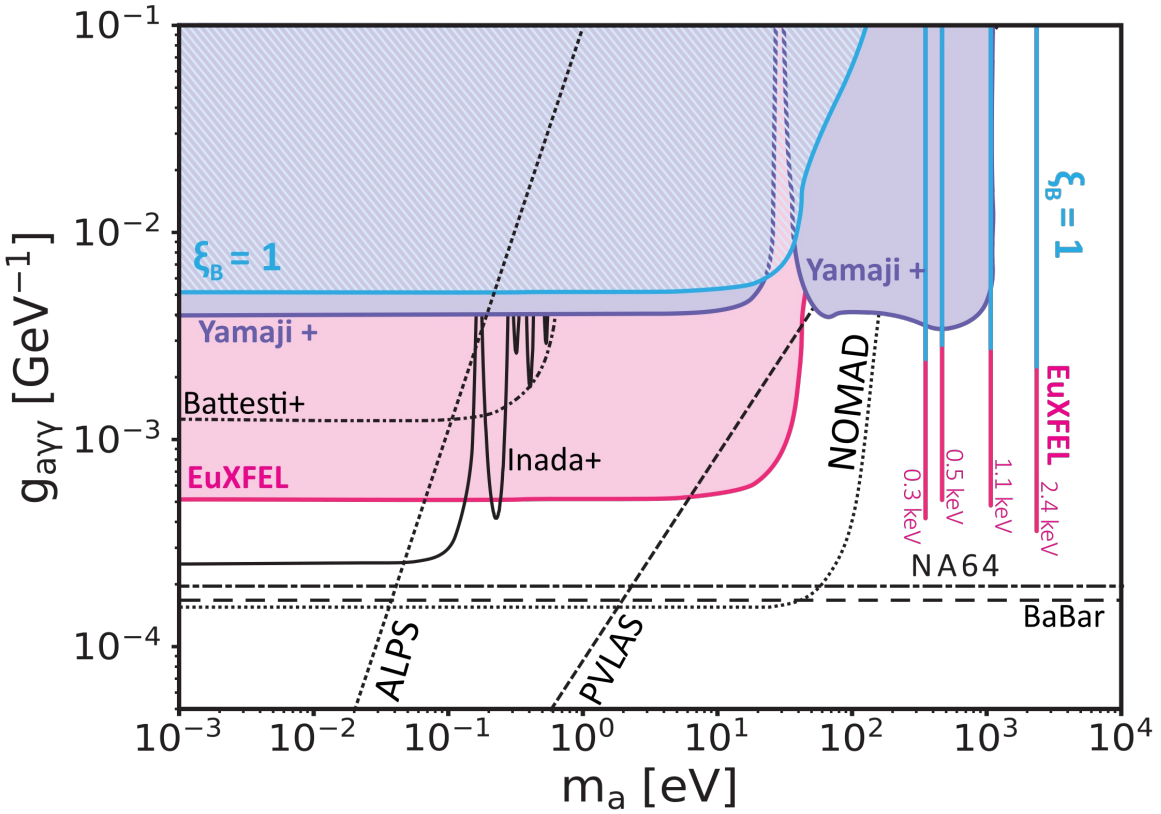


Experimental status of crystal-assisted X-ray LSW:

[Yamaji et al., Phys. Lett. B 782 (2018) 523;
Halliday et al., PRL 134 (2025) 055001;
Heaton et al., 2603.15808]



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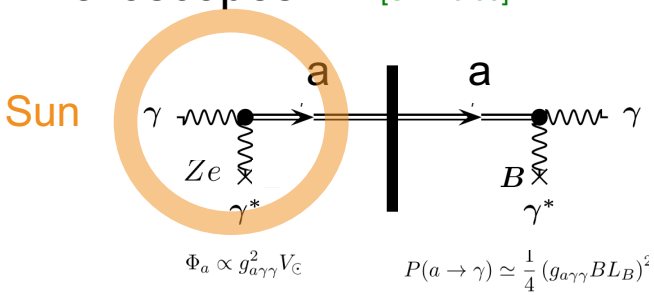

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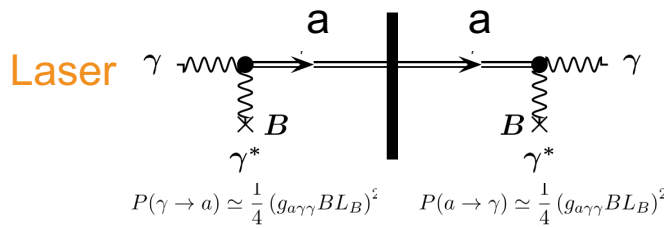

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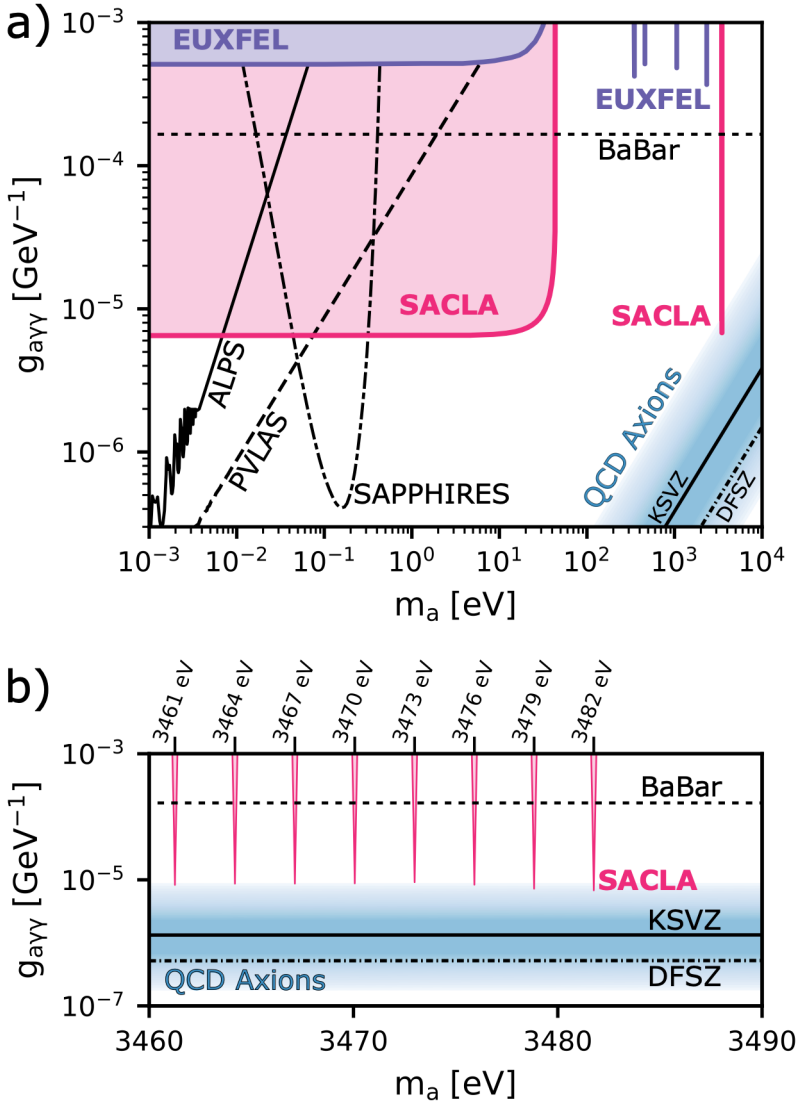

[Heaton et al., 2603.15808]

Axion Experiments Not Relying on Axion Dark Matter

Searches for axion mediated forces

- Experiments searching for axion mediated forces particularly effective in meV mass range
- Monopole-dipole interaction between nucleon and fermion:

$$U_{\rm mon-dip}(r) = \frac{g_{a N \bar{N}}\, g_{a f \bar{f}}}{8\pi m_f} \left(\frac{m_a}{r} + \frac{1}{r^2}\right) e^{-m_a r}\, (\hat{\sigma}\cdot\hat{r})$$

$$\mathcal{L}_{\rm int} = g_{a N \bar{N}}\, a\, \bar{N} N - i\, g_{a f \bar{f}}\, a\, \bar{f}\gamma_5 f$$

- Proposed ARIADNE experiment searches for forces between a rotating cylinder, made of unpolarized material, and a vessel containing hyperpolarized ^{3}He gas
  - Since ^{3}He magnetic moment dominated by neutron contribution: sensitive to monopole-dipole interaction between nucleus and neutrons, $| g_{a N \bar{N}}\, g_{an\bar{n}} |$

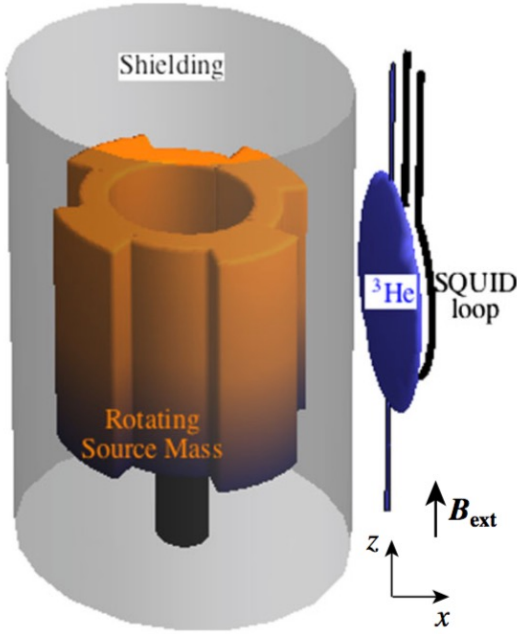

FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency $\omega_{\rm rot}$, which results in a resonance between the frequency $\omega = n\omega_{\rm rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{\rm ext}/\hbar$ of the NMR sample. Superconducting cylinders screen the NMR sample from the source mass and (not shown) the setup from the environment.

[Arvanitaki, Geraci 14]

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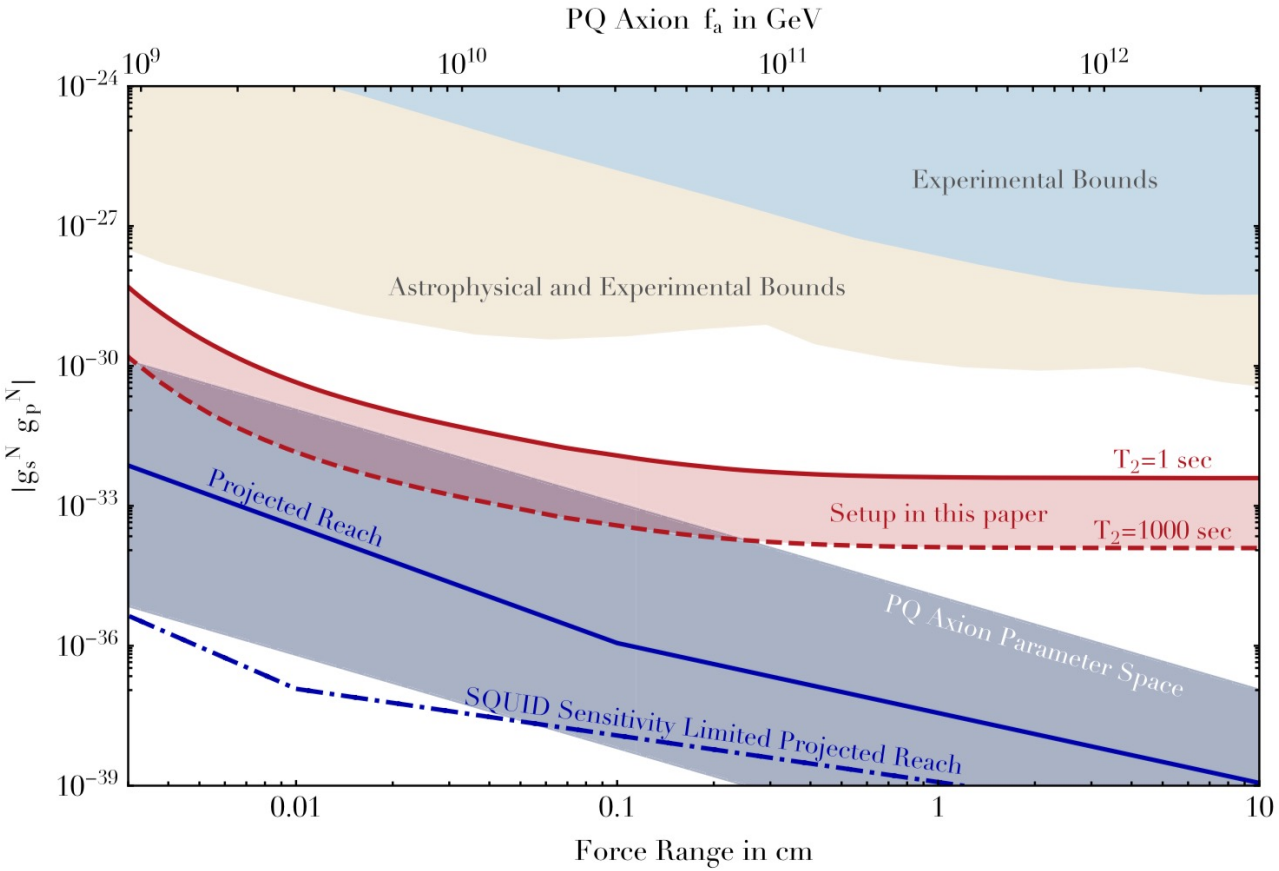

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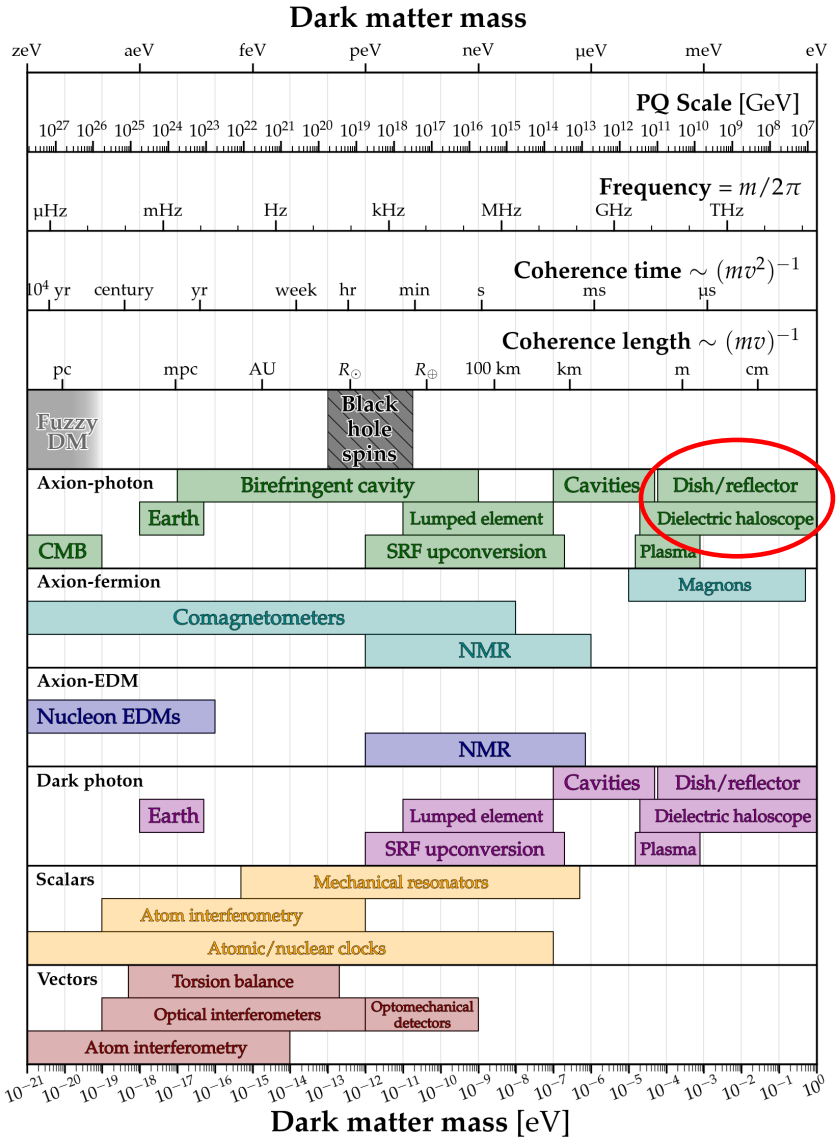
Axion Dark Matter Experiments

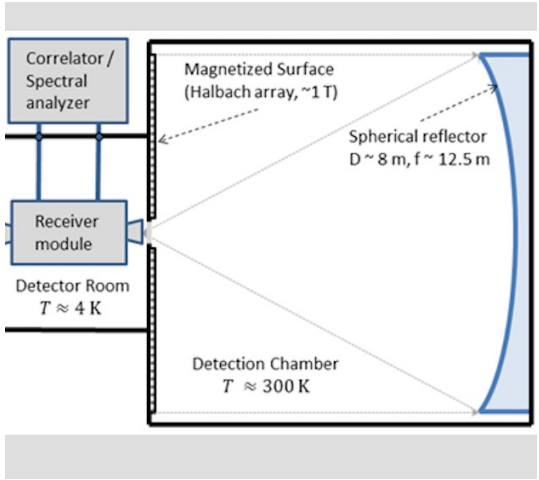
Variety of experimental techniques



Dish/reflector example:

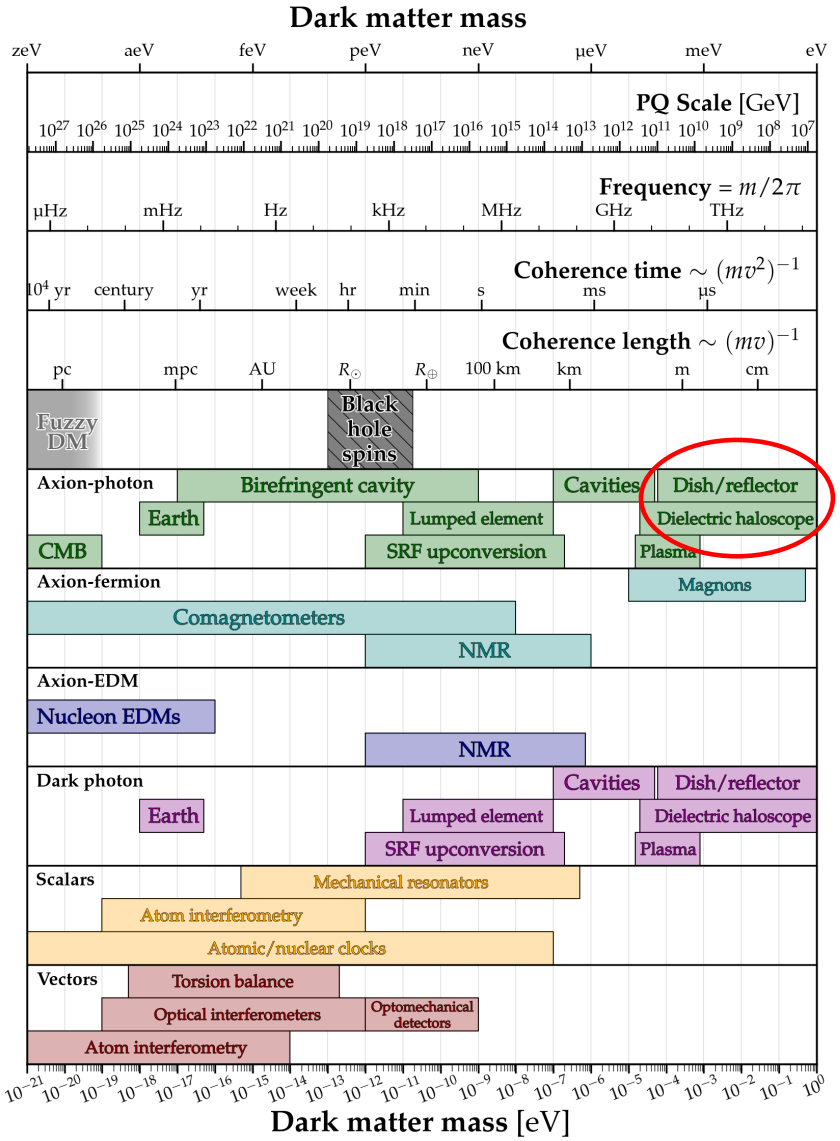
BRASS @ UHH

- Plane permanently magnetized conversion panel
- Spherical reflector



Axion Dark Matter Experiments

Variety of experimental techniques



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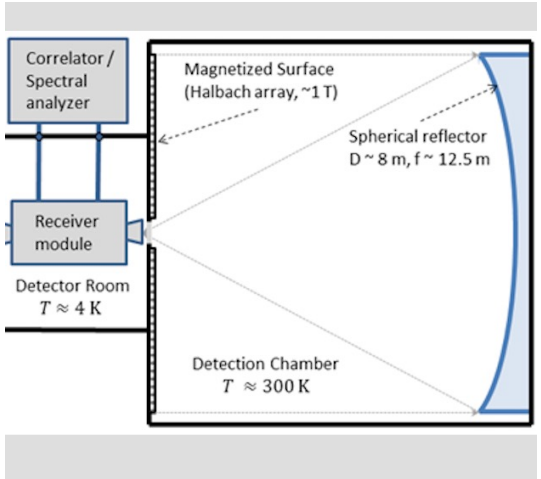
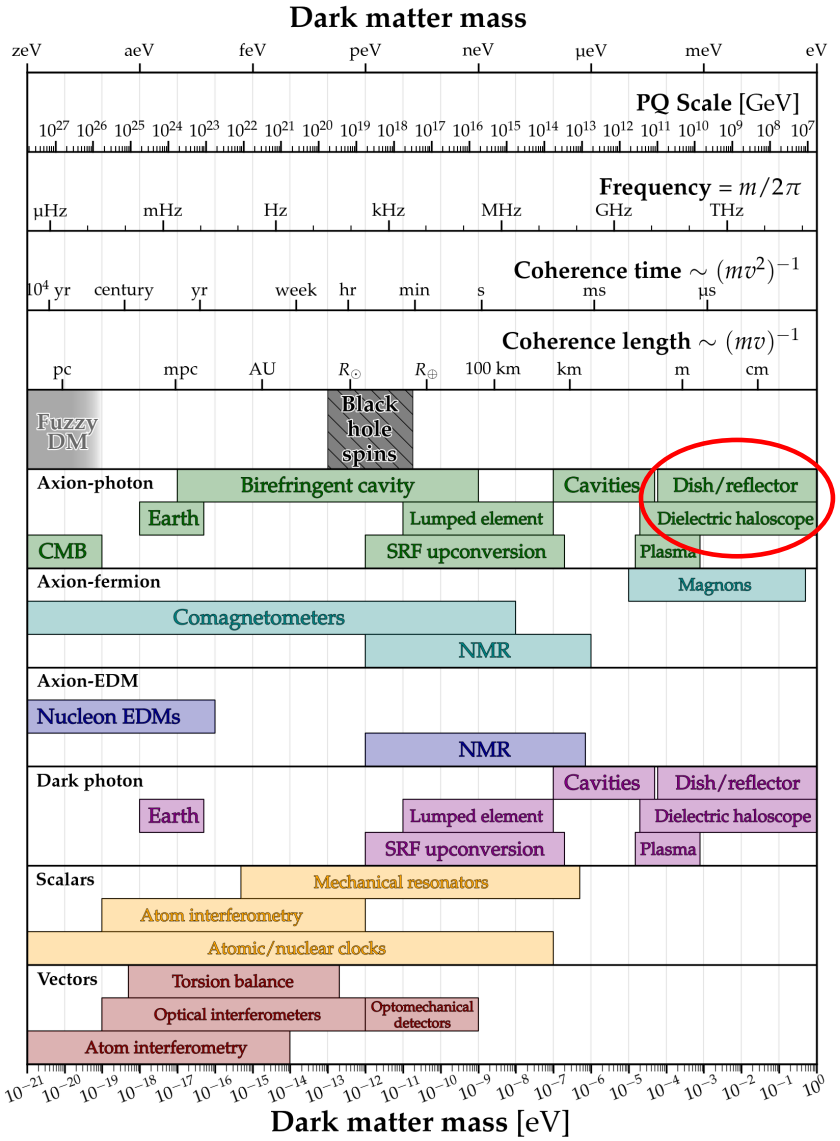


- **BRASS-p** pioneering run
  - Conversion panel not magnetized
  - Dark photon search [Bajjali et al., JCAP 08 (2023) 077]

Axion Dark Matter Experiments

Variety of experimental techniques



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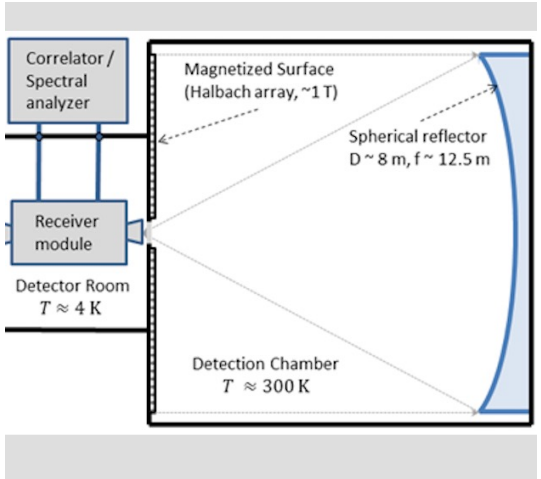

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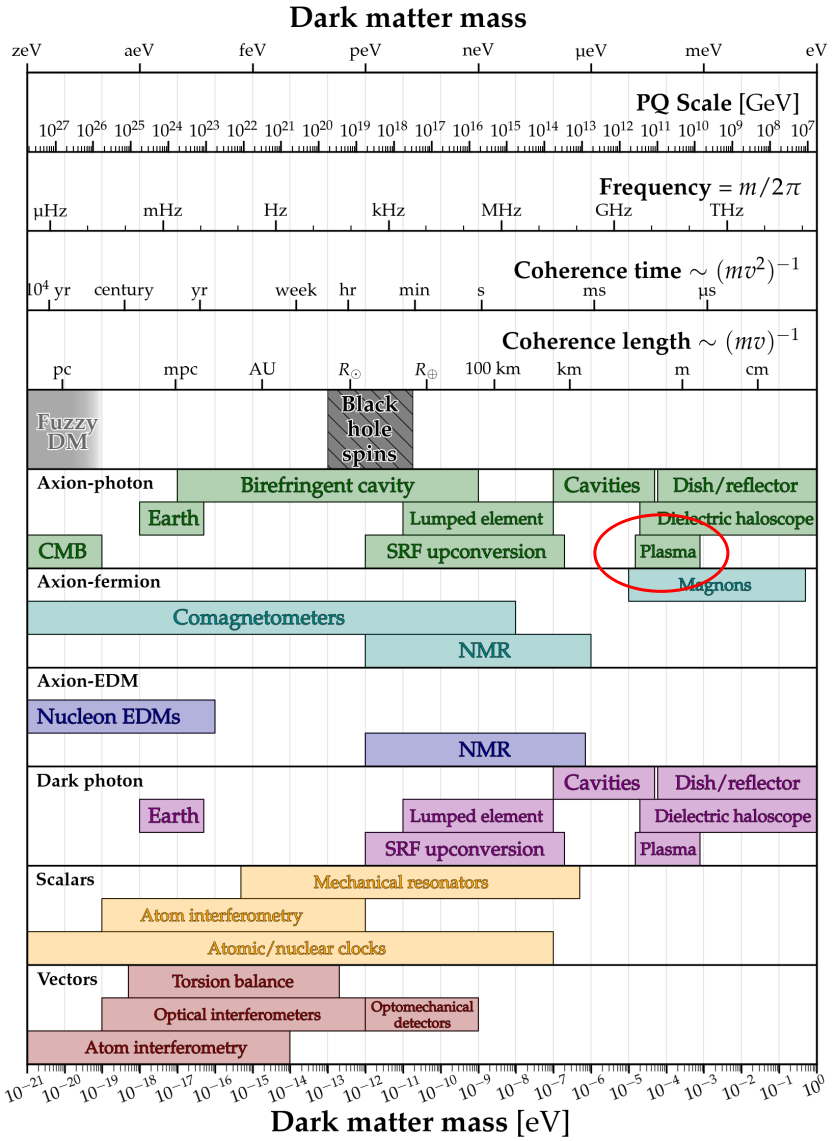
BRASS magnetization on the way ...

Axion Dark Matter Experiments

Variety of experimental techniques



Plasma haloscope concept:

[Lawson, Millar, Pancaldi, Vitagliano, Wilczek, 19]

- In a magnetized plasma, oscillating axion DM induces plasmon excitations,

$$\mathbf{E} = -g_{a\gamma}\mathbf{B}_e a \left(1 - \frac{\omega_p^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$

Axion Dark Matter Experiments

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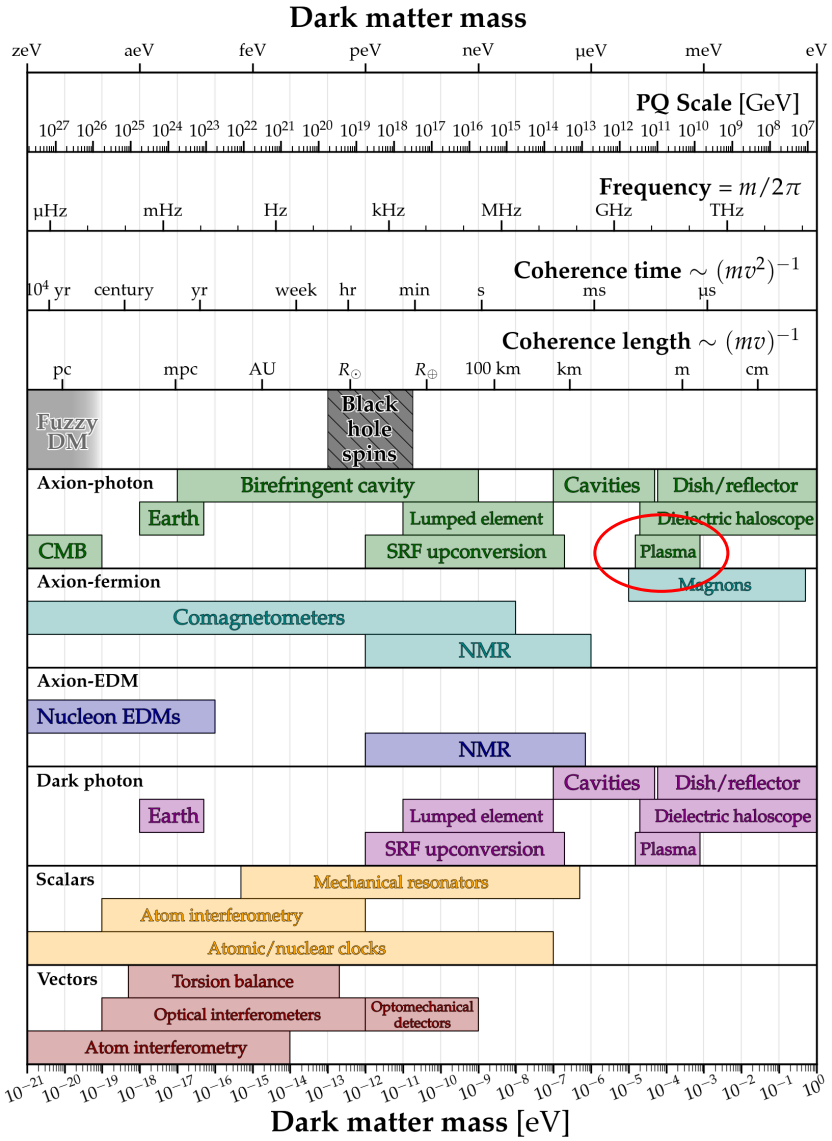

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Axion Dark Matter Experiments

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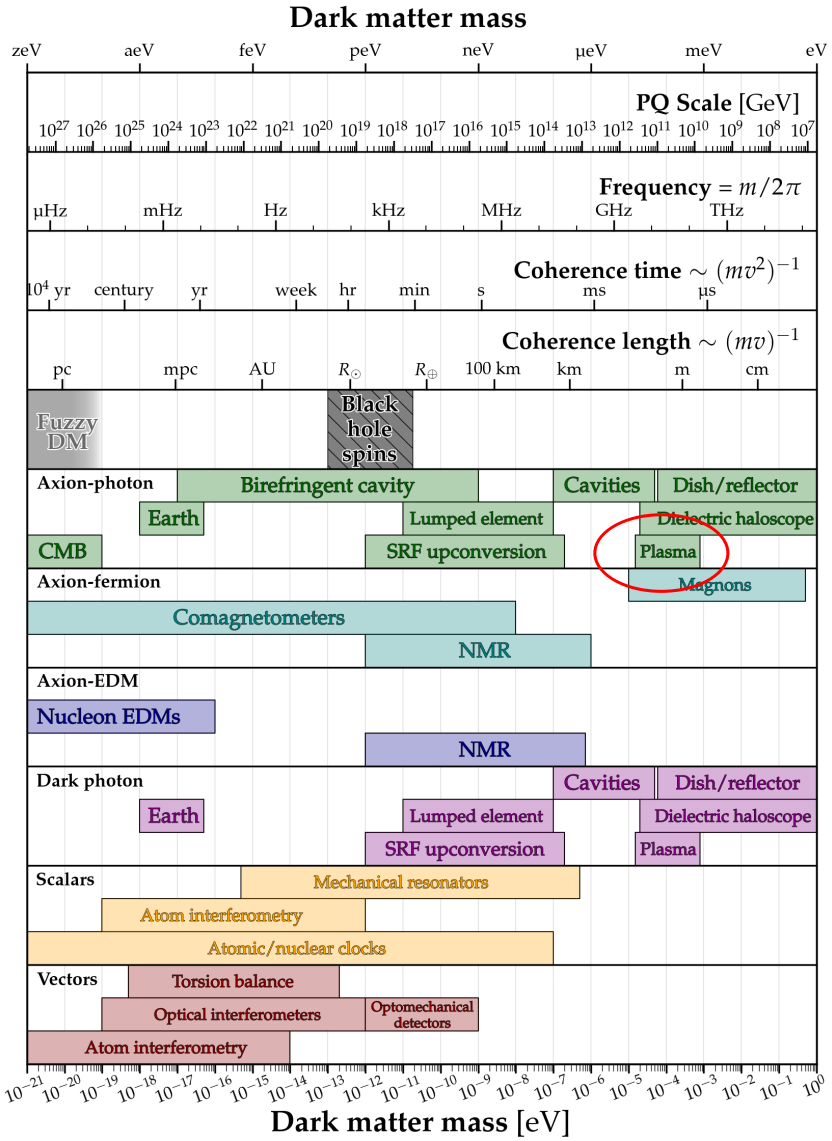

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Axion Dark Matter Experiments

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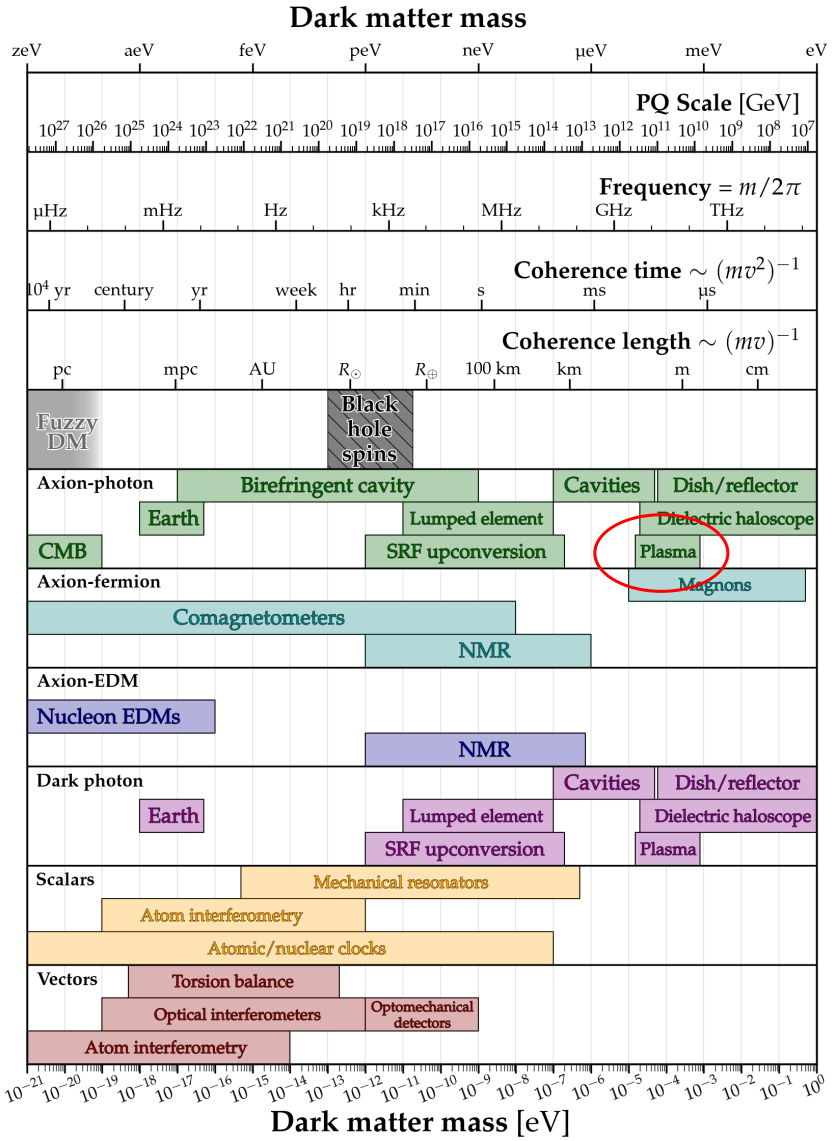

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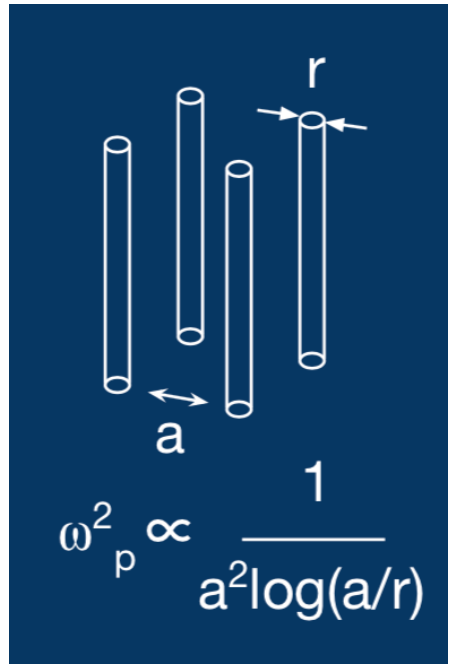
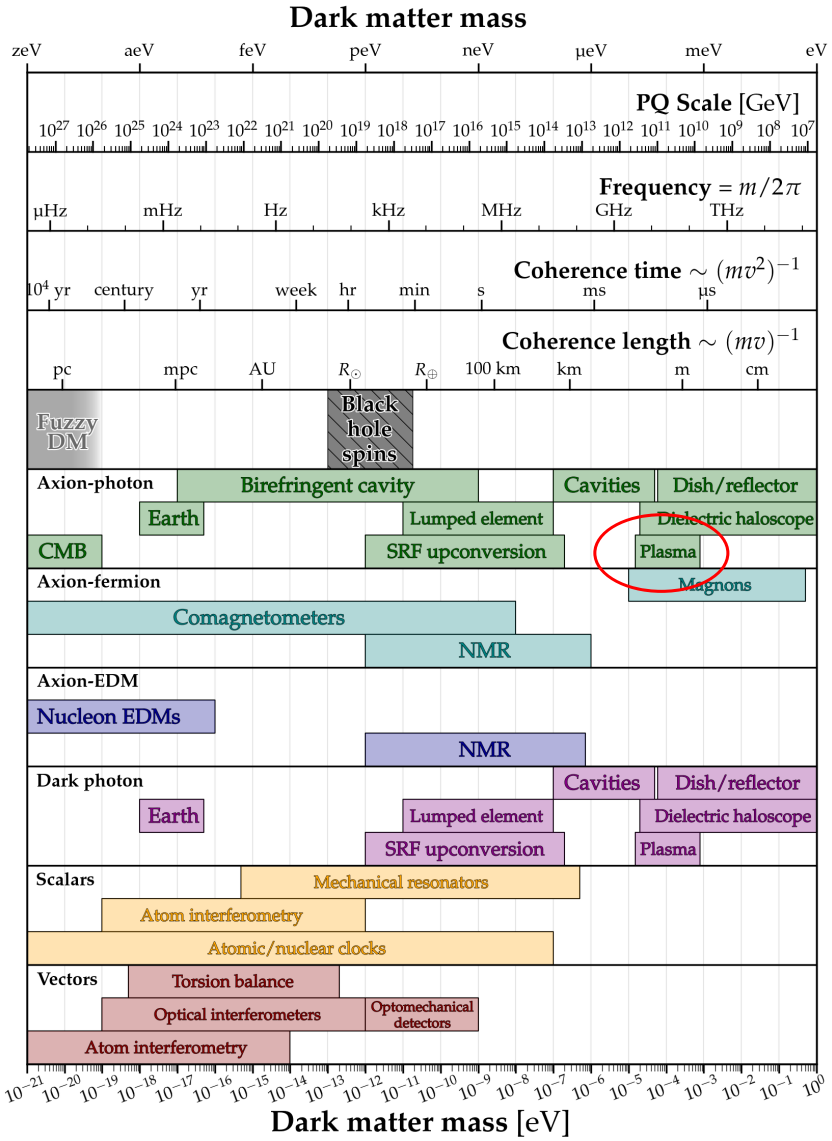
  - limited by losses (Γ)
- A plasma with tunable plasma frequency in the GHz range can be realised by a wire array with variable interwire spacing ("wire metamaterial")



Axion Dark Matter Experiments

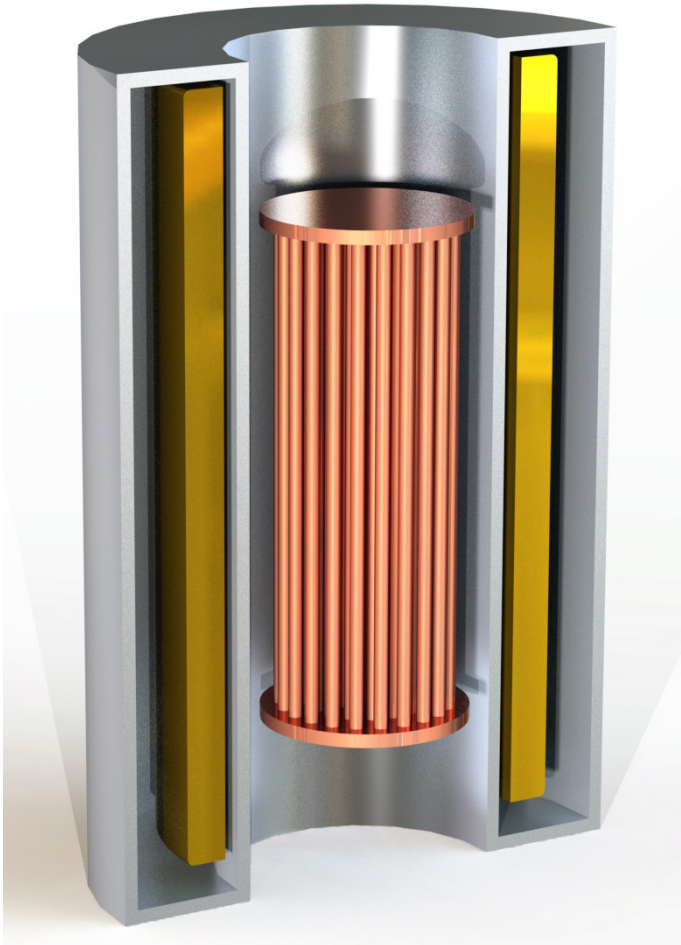
Variety of experimental techniques



Plasma haloscope example:

ALPHA @ Yale

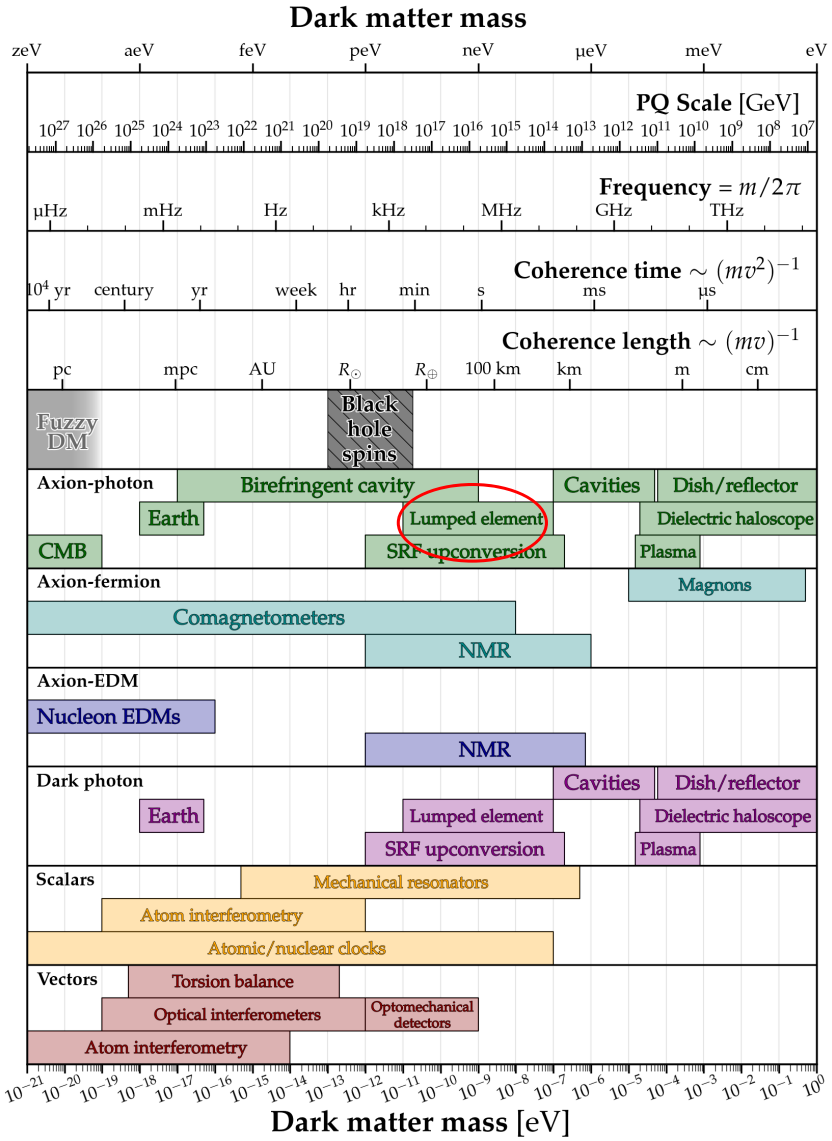
- Goal: building tunable, cryogenic plasma haloscope
- ALPHA Phase I
  - 17 cm bore 9T solenoid
  - dark photon search planned in this year (2026)



[https://axion-dm.yale.edu/alpha-experiment]

Axion Dark Matter Experiments

Variety of experimental techniques



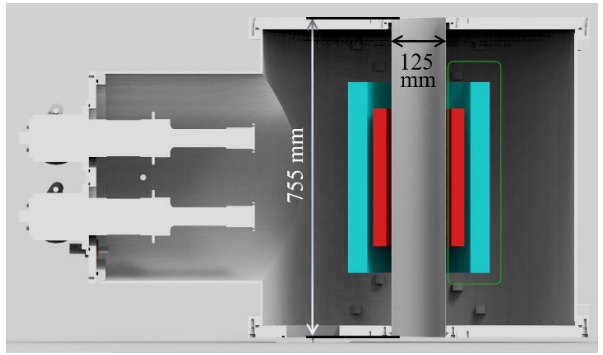
Lumped element examples:

WISPLC @ UHH

- Proposal

  [Zhang,Horns,Ghosh, Phys.Rev.D 106 (2022) 2, 023003]

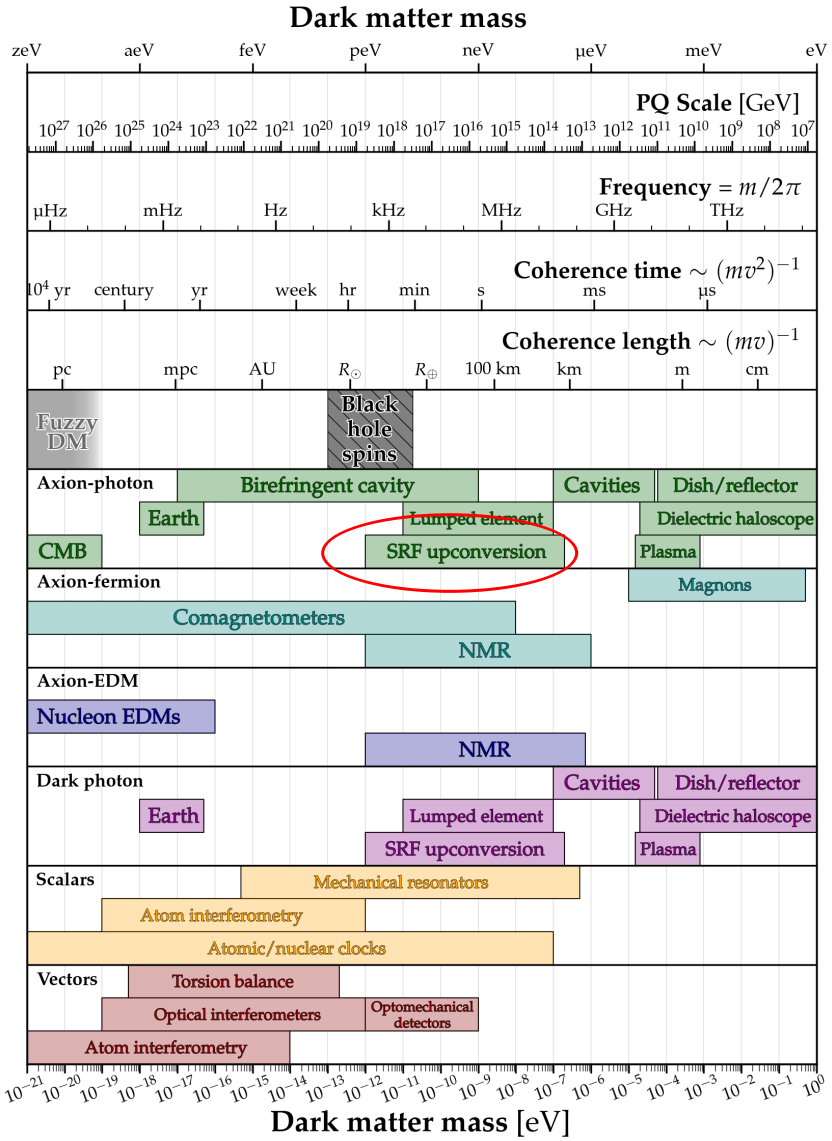
- First pioneering run with WISPLC prototype in 6 T magnet in 2024
- Second run ongoing



[https://www.qu.uni-hamburg.de/research/dark-matter.html]

Axion Dark Matter Experiments

Variety of experimental techniques

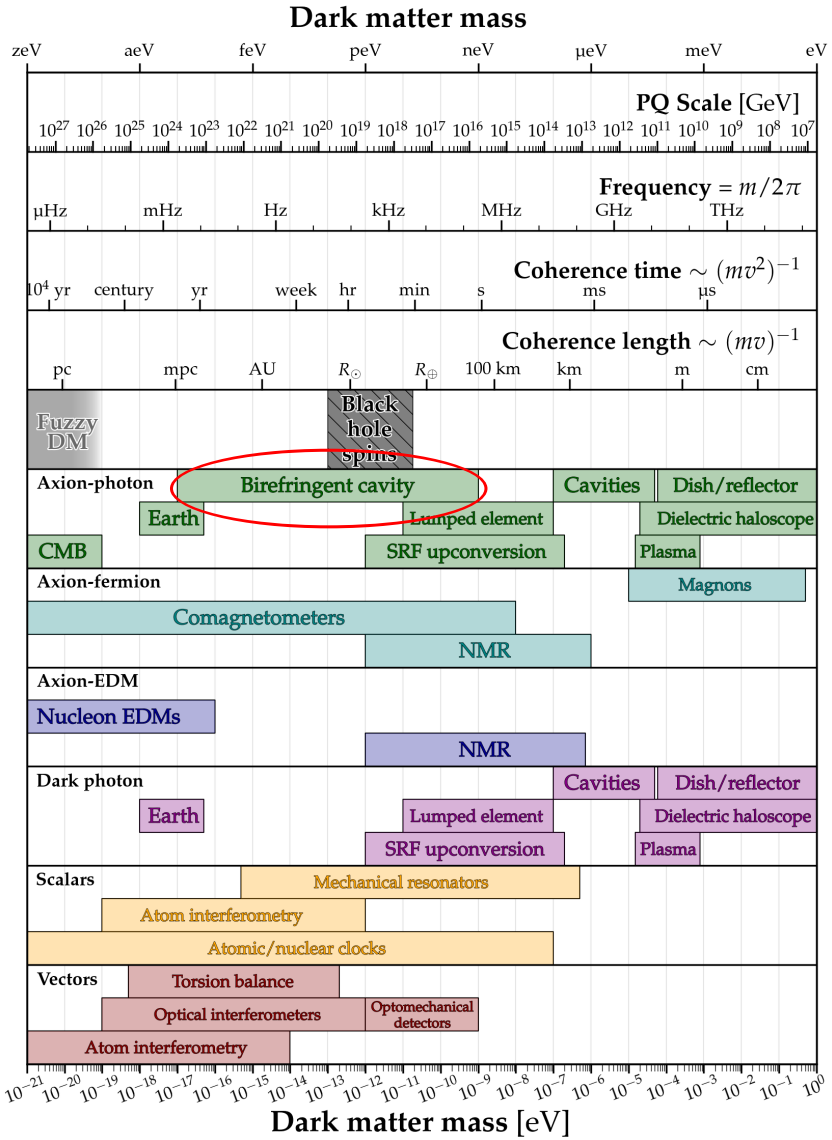


SRF up-conversion /heterodyne concept: [Berlin et al., JHEP 07 (2020) 088; Berlin et al., PRD 104 (2021) L111701; Giaccone et al., 2207.11346]

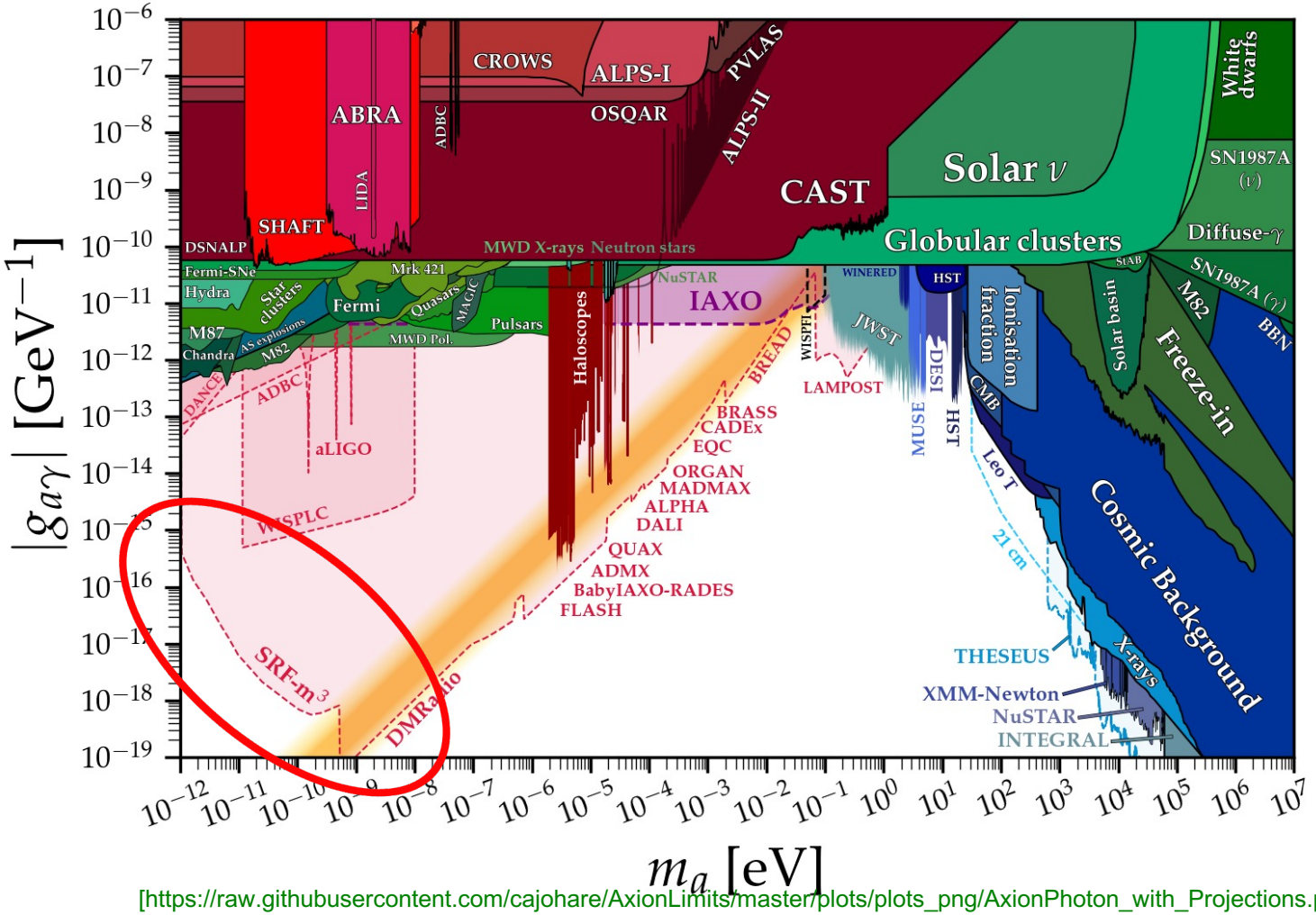
- Axion DM coupled to photons induces transitions between two electro-magnetic cavity modes.
- Drive a high-Q pump mode at frequency ω_0
- Axion DM converts a tiny fraction of the stored pump power into a signal mode at $\omega_1 \simeq \omega_0 \pm m_a$
- The axion mass is encoded in the mode splitting: $m_a \simeq |\omega_1 - \omega_0$
- Using superconducting RF cavities gives ultra-high quality factors, potentially avoiding the large-volume problem of low-mass conventional haloscopes.
- Main challenges: pump leakage, mode mixing, mechanical noise, microphonics, tuning and stability of nearly degenerate modes.
- Experimental R&D is underway in SHADE/SQMS; no published axion-DM limit yet

Axion Dark Matter Experiments

Variety of experimental techniques



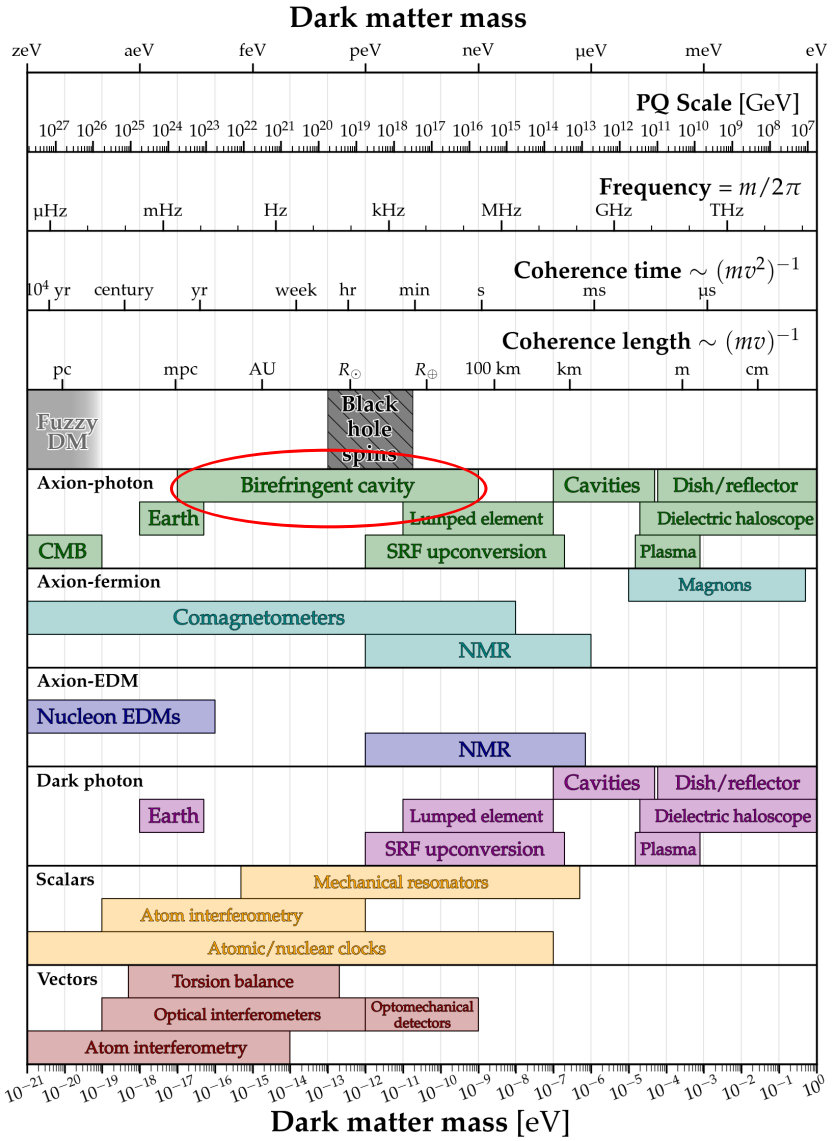
SRF up-conversion /heterodyne prospects:



[https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/AxionPhoton_with_Projections.png]

Axion Dark Matter Experiments

Variety of experimental techniques



Birefringent optical-cavity concept:

[Obata et al.,1805.11753; Liu et al.,1809.01656]

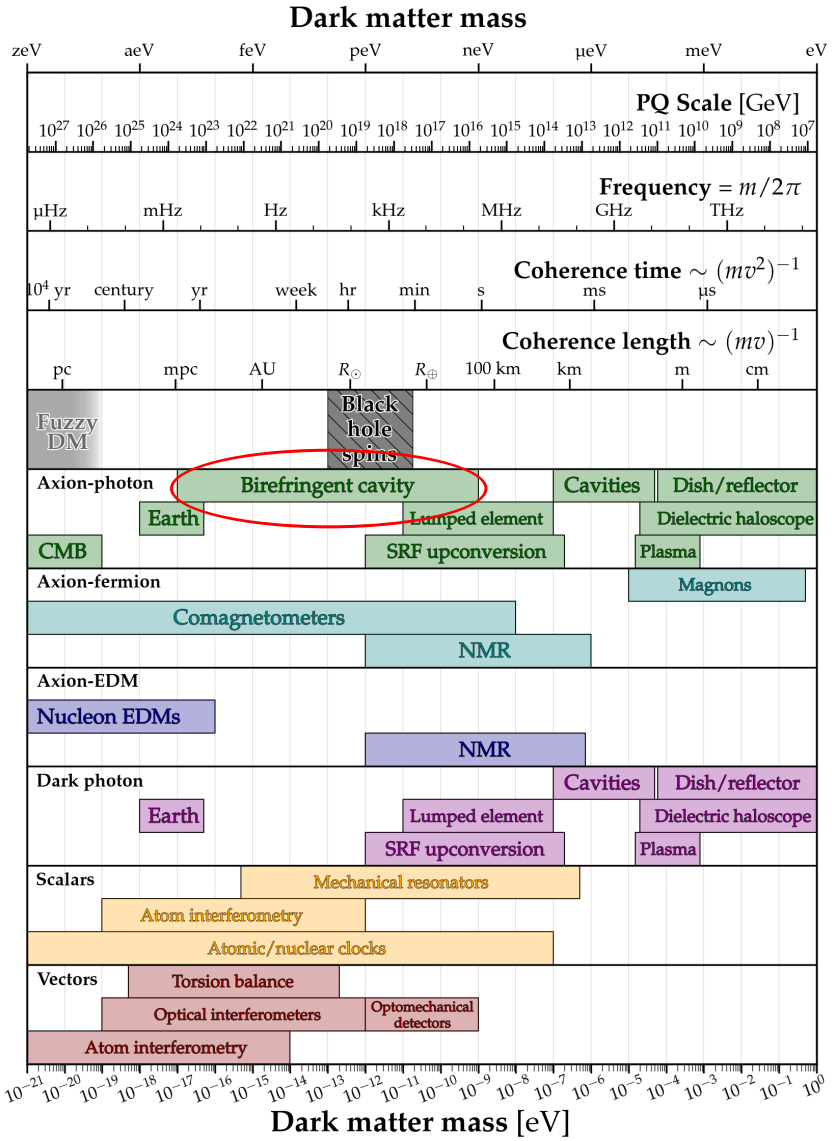
- The axion background acts as a tiny circularly birefringent medium:

$$c_{L/R} = 1 \pm \delta c(t), \qquad \delta c(t) \simeq \frac{g_{a\gamma\gamma}\dot{a}(t)}{2\omega_L}$$

- A linearly polarized laser is a superposition of left- and right-circular polarizations; the axion-induced phase shift rotates its polarization at frequency $\omega_a \simeq m_a$
- Equivalently, the axion converts a strong carrier field at (ω_0) into weak sidebands in the orthogonal polarization at $\omega_0 \pm m_a$
- A high-finesse optical cavity enhances the interaction time / stored optical power; engineered birefringence, ring geometry, or wave plates can make the axion-induced sidebands build up coherently
- Search for a narrow oscillating polarimetric signal — no external magnetic field required.

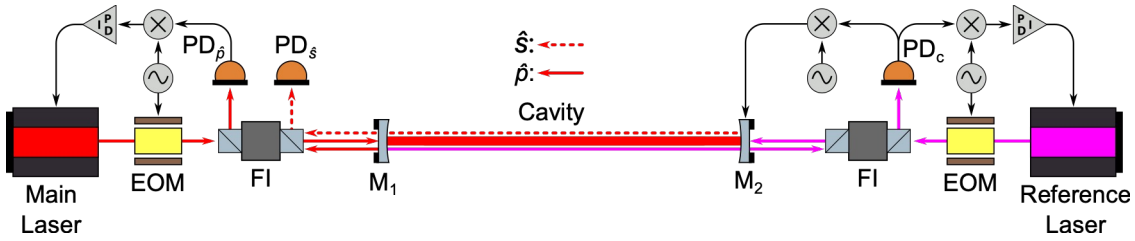
Axion Dark Matter Experiments

Variety of experimental techniques



Example: ALPS II optical cavity as axion-DM polarimeter

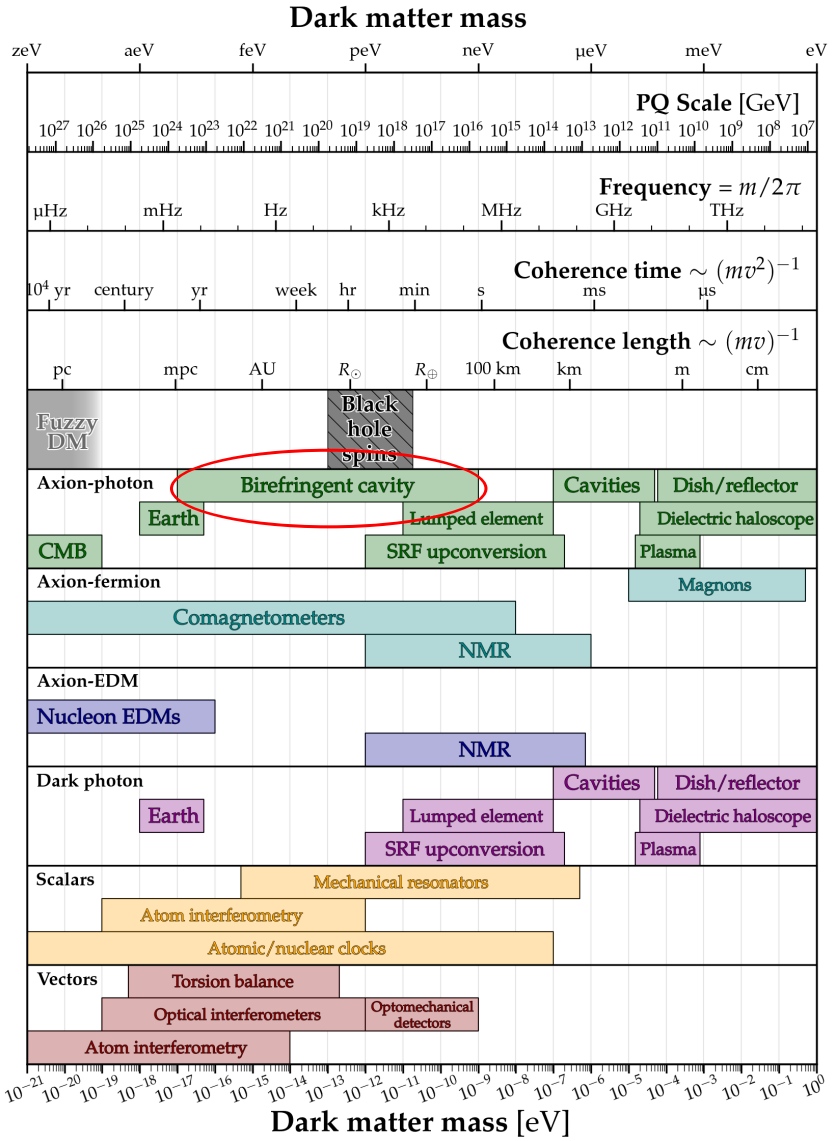
[Garcia-Cely,Marsili,AR,Spector, 2501.08382]



- ALPS II already provides long, high-finesse optical cavities with large stored laser power
- Axion DM would induce a tiny oscillating polarization component orthogonal to the injected laser polarization
- Polarimetric readout of the cavity output searches for sidebands at $\omega_0 \pm m_a$
- Using different ALPS II cavity configurations, including quarter-wave plates, gives resonant or broader sensitivity over $m_a \sim (10^{-9} - 10^{-6})\,\mathrm{eV}$
- Same formalism also applies to high-frequency gravitational-wave backgrounds.

Axion Dark Matter Experiments

Variety of experimental techniques



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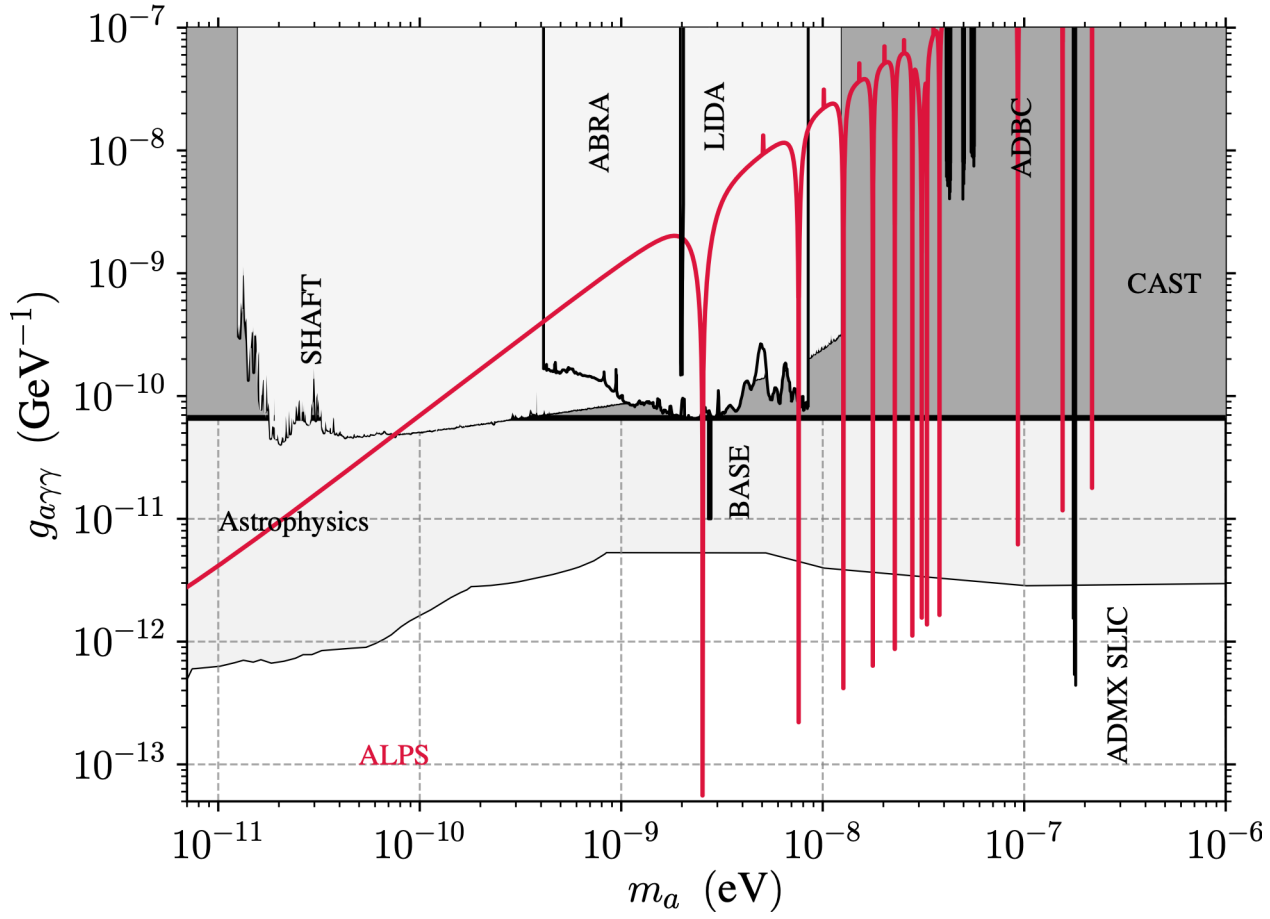

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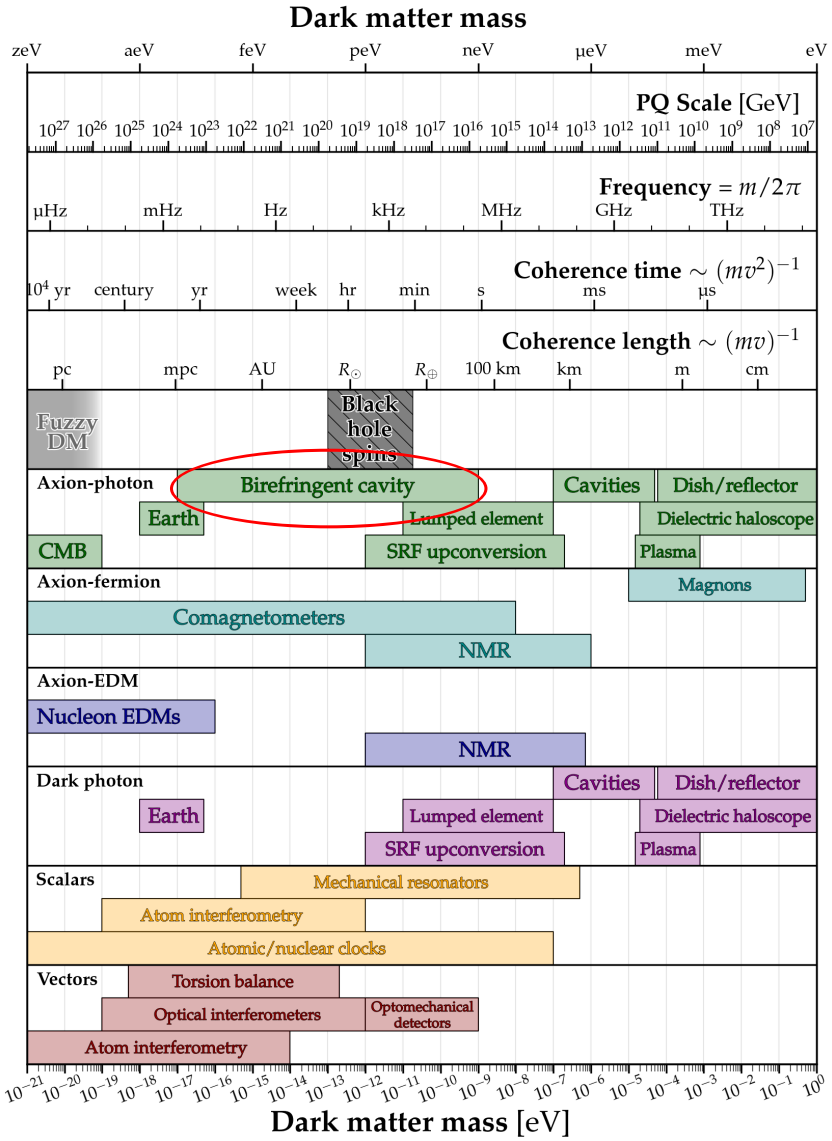
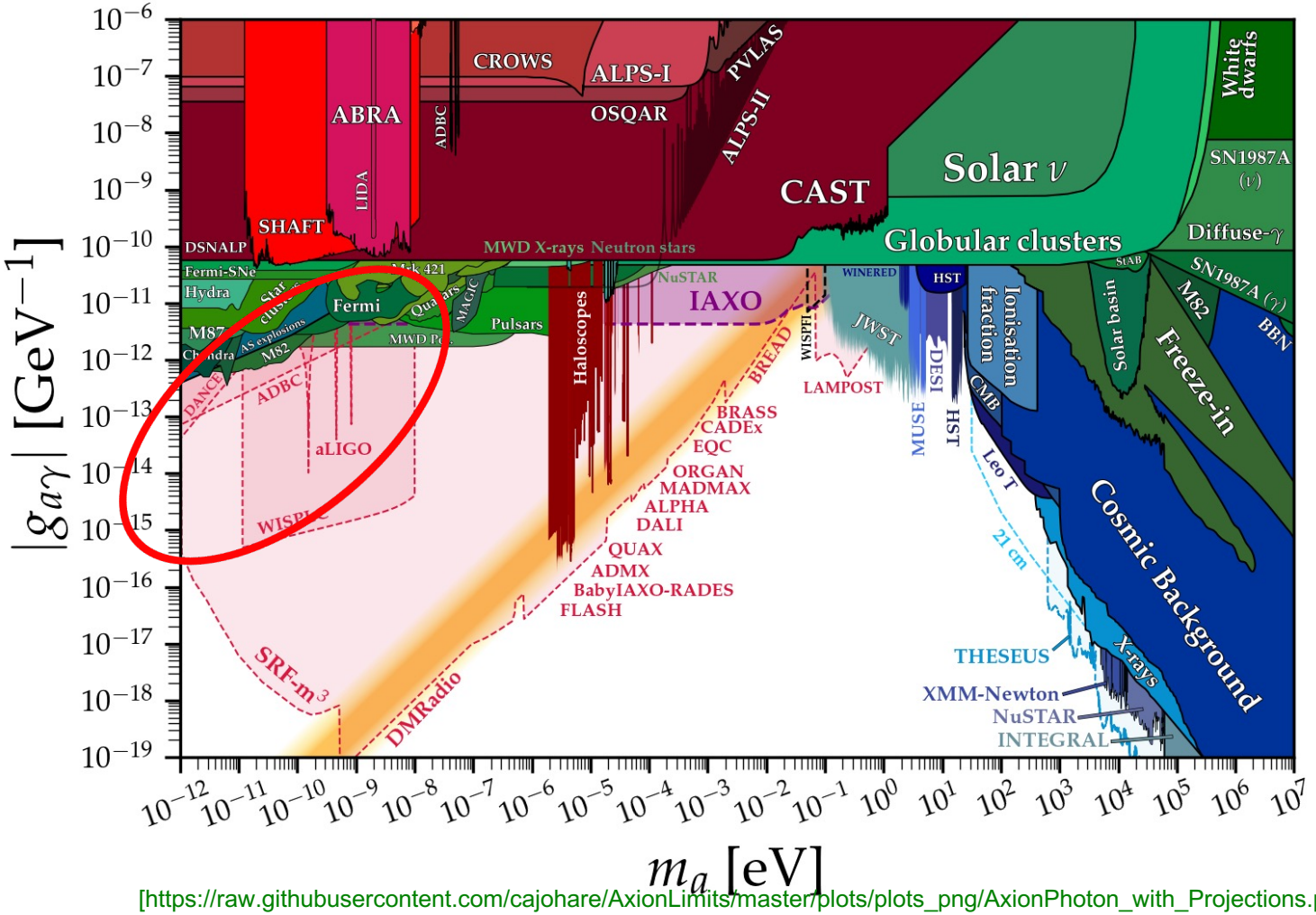


Birefringent cavities prospects:



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