

Dark matter across all scales · Odense, May 2026

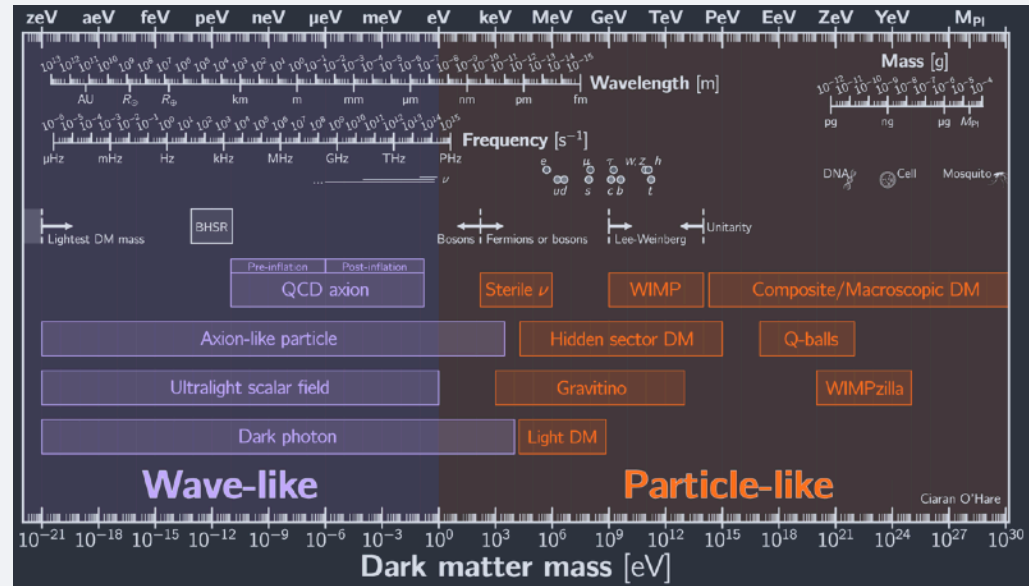
Axion haloscopes: resonator design & quantum-enhanced readout

Jacob Egge

DESY Hamburg

Dark matter

- ~27% of the universe's energy density is dark matter
- For masses below ~200 eV, DM particle must be bosonic
- Wavelike dark matter particle candidate
 - Axions
 - Dark photons
 - Scalar fields
 - Massive gravitons



<https://cajohare.github.io/AxionLimits/>

The axion

STRONG CP PROBLEM

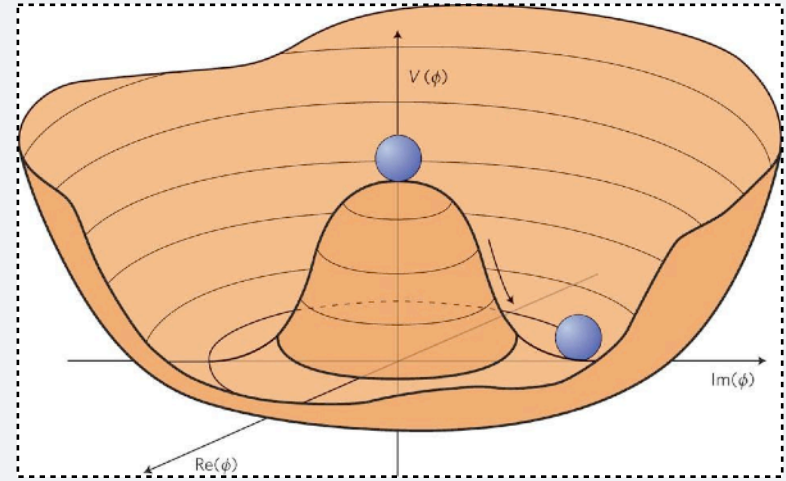
QCD permits a CP-violating term $\theta \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$
 Experiment: $|\theta| < 10^{-10}$. Why?

PECCEI-QUINN MECHANISM

New global $U(1)_{PQ}$ symmetry broken at scale f_a . The pseudo-Goldstone boson is the axion – drives $\theta \rightarrow 0$ dynamically.

AXION AS DARK MATTER

Produced non-thermally; cold, coherent. Post-inflation scenario favours $m_a \sim \mu\text{eV}$.

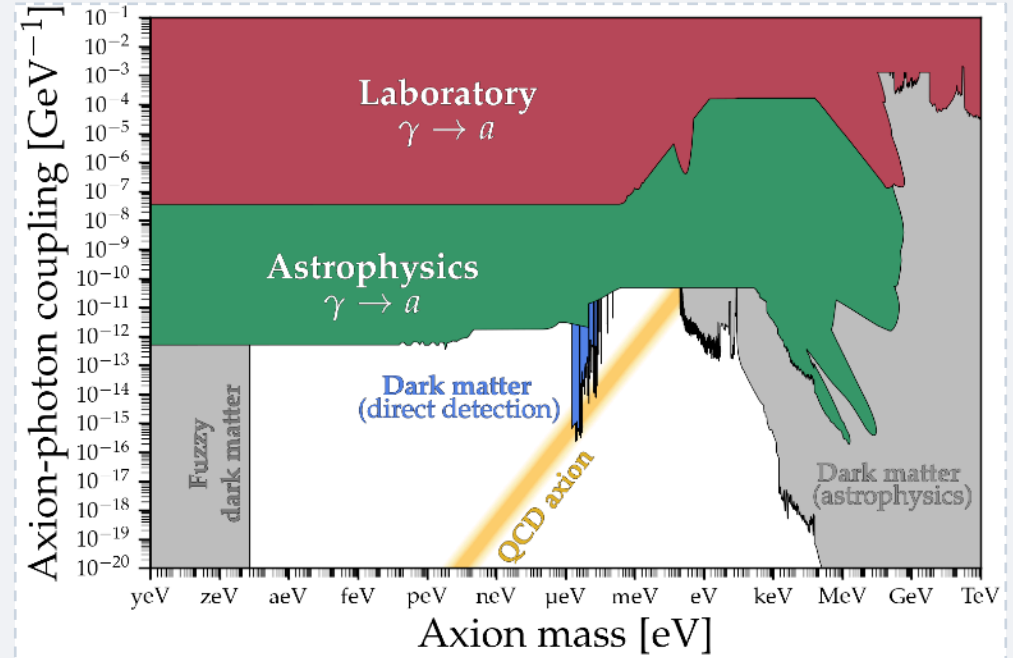
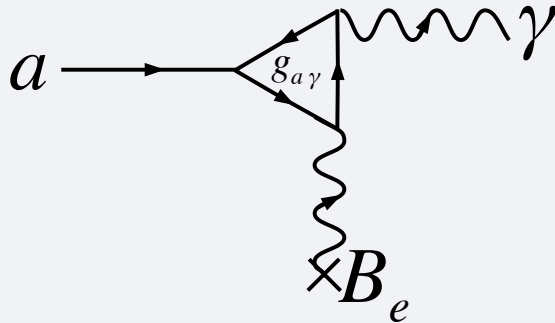


$$m_a \simeq 5.7 \mu\text{eV} \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$$

Axion–photon coupling

- Axion couples to two photons:

$$\mathcal{L} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$
- $g_{a\gamma} = \frac{\alpha}{\pi f_a} \left| \frac{E}{N} - 1.92 \right|$ – model-dependent coefficient
- KSVZ and DFSZ are the two benchmark QCD models
- In external static magnetic field, axion DM converts to a photon via the inverse Primakoff effect
- This is the detection handle exploited by all haloscopes

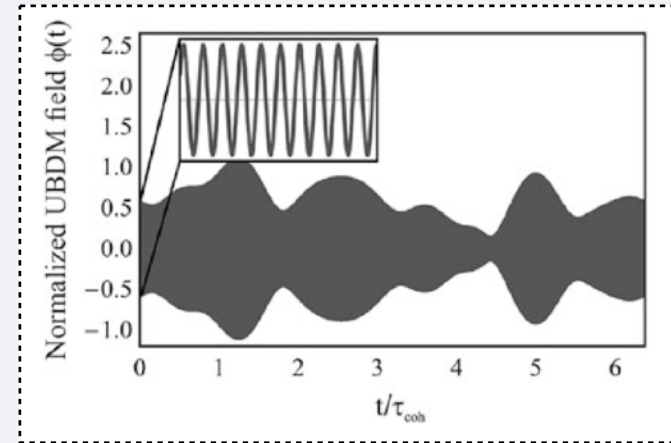


<https://cajohare.github.io/AxionLimits/>

The classical axion field

- DM axions form a classical coherent field:
- $a(t) = a_0 \cos(\omega_a t)$
- Local DM density $\rho_{\text{DM}} \sim 0.45 \text{ GeV/cm}^3$ sets amplitude a_0
- Oscillation frequency: $\hbar\omega_a \approx m_a c^2$ GHz for μeV axions
- Coherence time $\tau_{\text{coh}} \sim \frac{10^6}{f}$ from small velocity effects
- Highly monochromatic signal
- Axion-modified Maxwell's equations

$$\nabla \times B - \dot{E} = g_{a\gamma} \dot{a} B_e$$

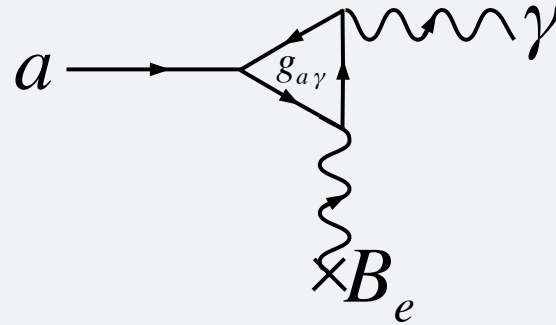


Simanovskaia, M., Carosi, G., Bibber, K.v. (2023). Microwave Cavity Searches

Axion–photon conversion in a magnetic field

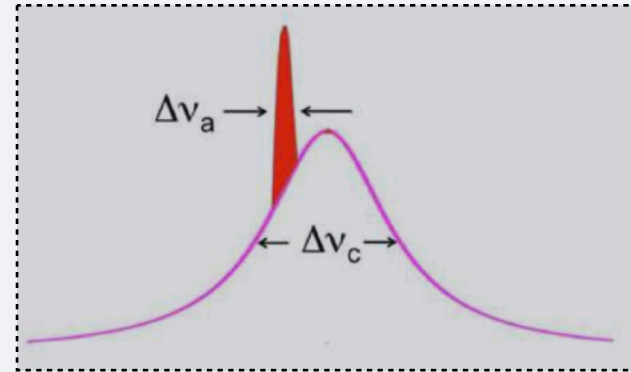
- External magnetic field drives an effective current: $\mathbf{J}_{\text{eff}} = g_{a\gamma} \dot{\mathbf{a}} \mathbf{B}_e$
- This current excites EM modes of the resonator
- Resonant enhancement when $\omega_{\text{res}} \sim \omega_a$

$$P_{\text{sig}} \propto g_{a\gamma}^2 \cdot B_e^2 \cdot V \cdot C \cdot Q_L \cdot \frac{\rho_{\text{DM}}}{m_a}$$

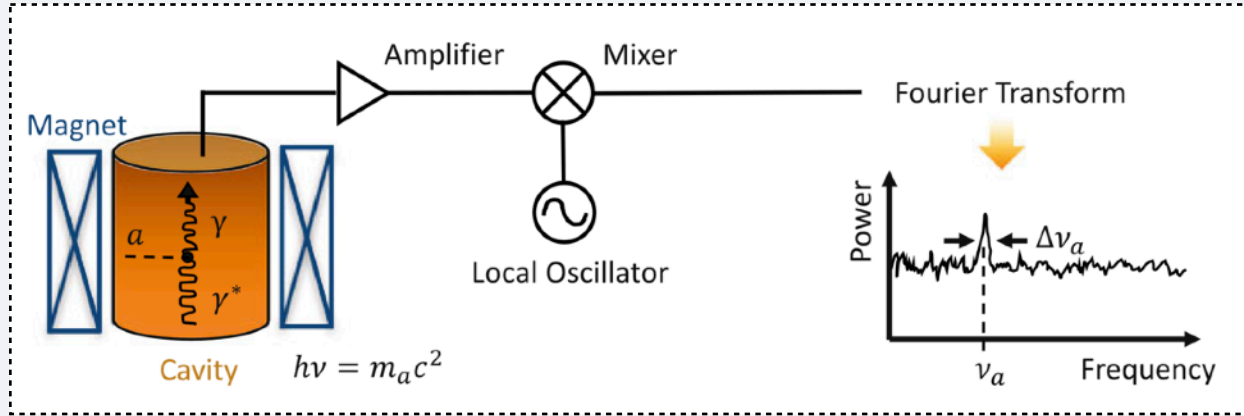


Signal signature & scan strategy

- Signal: narrow excess power at $\nu = m_a/h$ above noise floor
- Linewidth $\Delta\nu_a \approx \frac{\nu}{10^6}$ (set by DM velocity dispersion)
- m_a unknown \rightarrow must scan: tune, integrate, step, repeat
- Step size set by cavity linewidth $\Delta\nu_{\text{cav}} = \frac{\nu}{Q_L}$



Anatomy of a haloscope



Simanovskaia, M., Carosi, G., Bibber, K.v. (2023). Microwave Cavity Searches

MAGNET

Strong static B_0 (5–14 T). Solenoid for cavities, dipole for large-aperture designs.

RESONATOR

High-Q tunable resonator matched to axion mass. Coherently amplifies conversion signal.

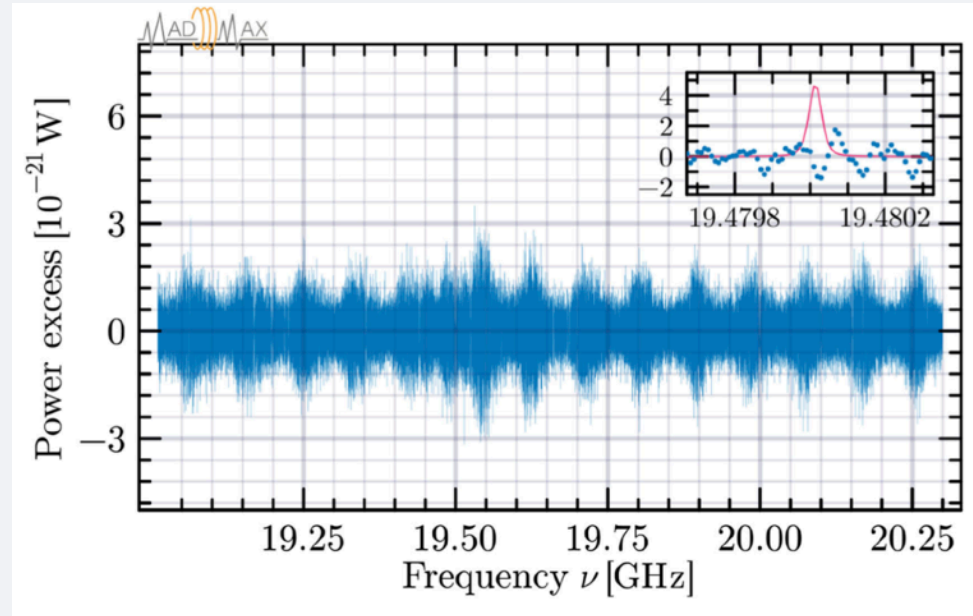
RECEIVER CHAIN

Cryogenic parametric amplifier near SQL, followed by heterodyne receiver, digitizer.

$$P_{sig} \propto g_{a\gamma}^2 \cdot B_e^2 \cdot V \cdot C \cdot Q_L \cdot \frac{\rho_{DM}}{m_a}$$

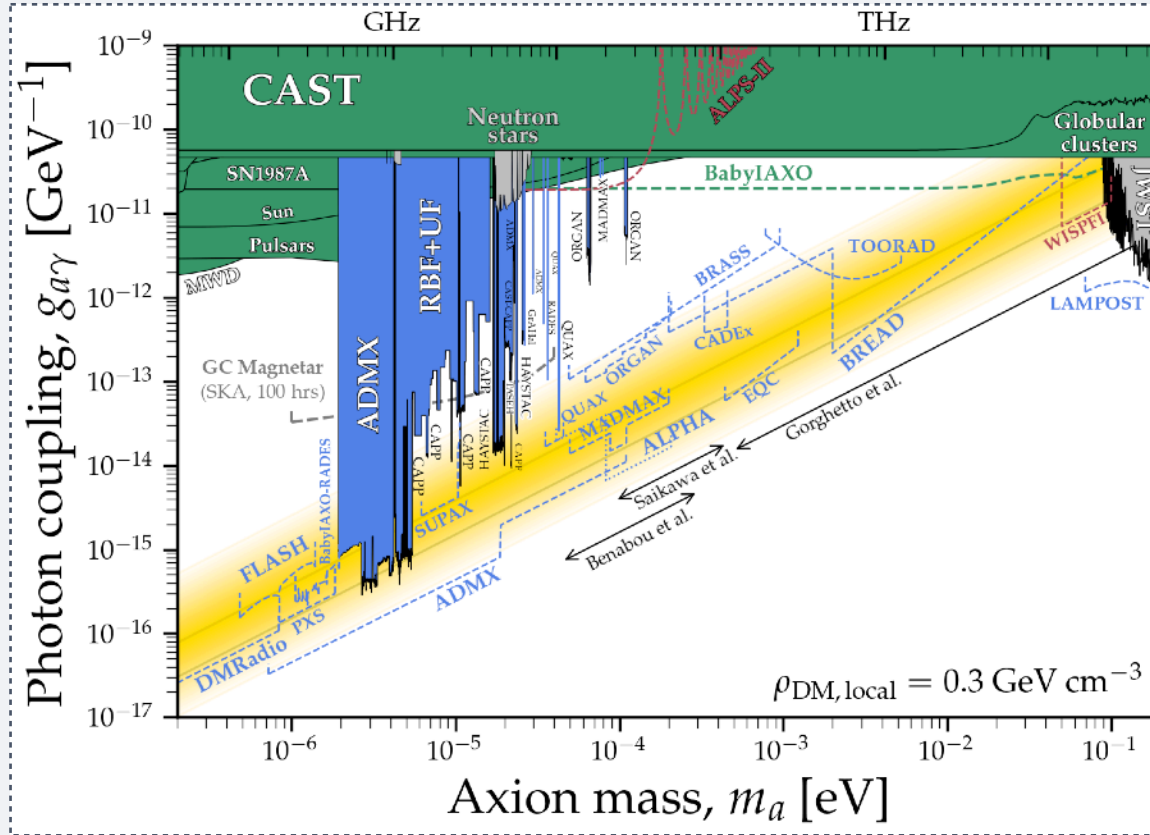
Noise & thermal background

- Dominant noise: thermal photon occupation in resonator + amplifier added noise
- Thermal occupation: $\bar{n} = (e^{\hbar\omega/k_B T} - 1)^{-1}$
- At 1 GHz, 100 mK: $\bar{n} \approx 0.5$ – approaching quantum regime
- Linear amplifier adds 1 photon of noise (standard quantum limit)
- Total: $T_{\text{sys}} = T_{\text{phys}} + T_{\text{add}}$
- Frequency dependent



Phys. Rev. Lett. **134**, 151004

The haloscope landscape

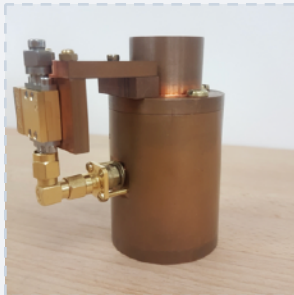


<https://cajohare.github.io/AxionLimits/>

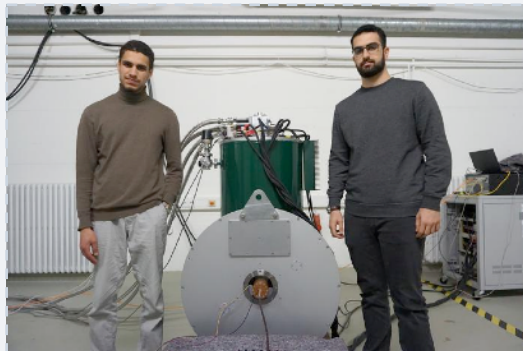
Cavity haloscopes

- Original Sikivie concept (1983): high-Q cylindrical cavity in solenoidal magnet
- Tuning: metal or dielectric rod moved across cavity diameter
- Natural mass range: $\sim 1\text{--}40 \mu\text{eV}$ (0.25–10 GHz)
- Most sensitive technology to date — DFSZ reached at few μeV

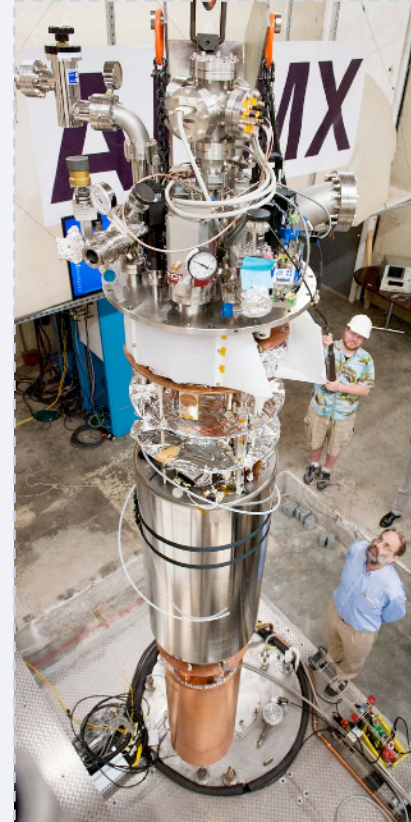
Nabil Salama & Agit Akgümüs



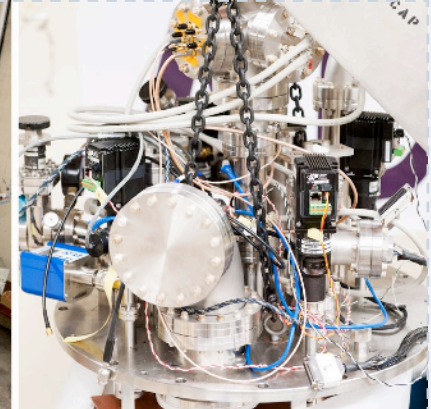
ORGAN @26 GHz



SPACE @4 GHz
JCAP04(2026)054



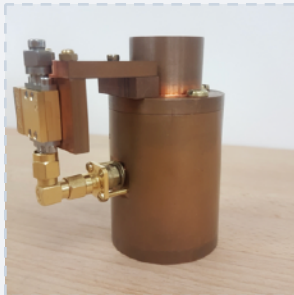
ADMX @1 GHz



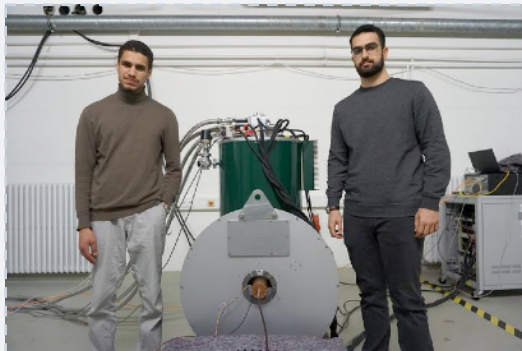
The volume scaling problem

- Cavity volume scales $V \propto 1/\nu^3$
- Signal power $P \propto V$ — tiny cavities at high frequency kill sensitivity
- Above $\sim 50 \mu\text{eV}$ (10 GHz), single cavities too small for DFSZ

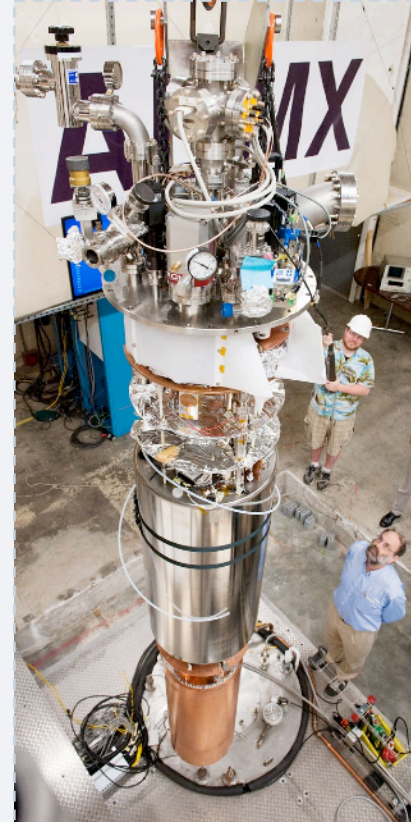
Nabil Salama & Agit Akgümüs



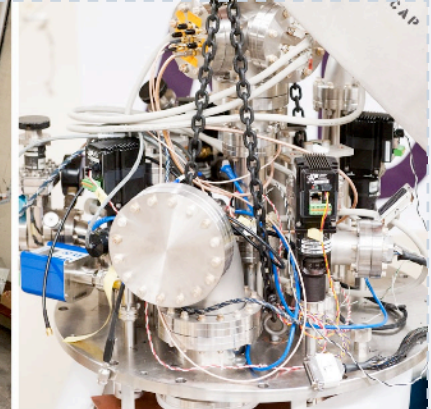
ORGAN @26 GHz



SPACE @4 GHz
 JCAP04(2026)054



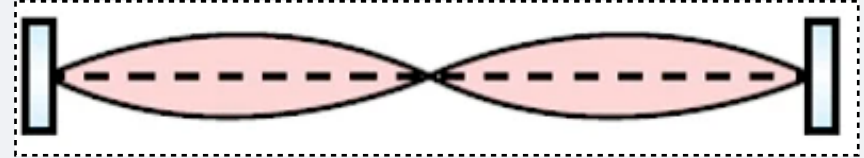
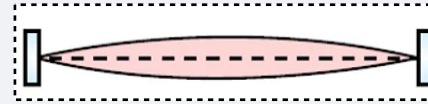
ADMX @1 GHz



The volume scaling problem: Overlap

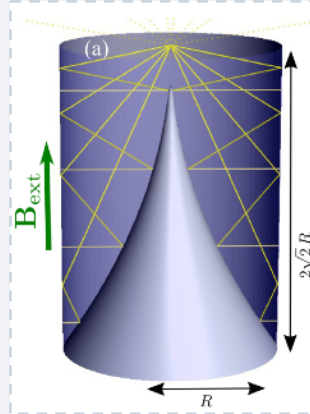
- Why can't we just make the resonator bigger?
- Resonators have higher order modes at higher frequencies
- But: Resonating photon mode needs to have non-zero overlap with axion field and magnetic field
- Axion field and magnetic field are nearly uniform \rightarrow negligible overlap in practice

$$C_{mnl} = \frac{\left| \int_V \vec{E}_{mnl}(\vec{r}) \cdot \vec{B}_0(\vec{r}) d^3r \right|^2}{B_0^2 V \int_V \epsilon_r(\vec{r}) |\vec{E}_{mnl}(\vec{r})|^2 d^3r}$$



Dish antenna & broadband haloscopes

- One solution: Remove the resonator!
- Conducting mirror in magnetic field: axion DM drives surface currents
- no resonator, no tuning needed
- Emitted power $P \propto g_{ay} B_e^2 A$ where A is the mirror area
- No resonant enhancement ($Q = 1$)
->compensated by large area



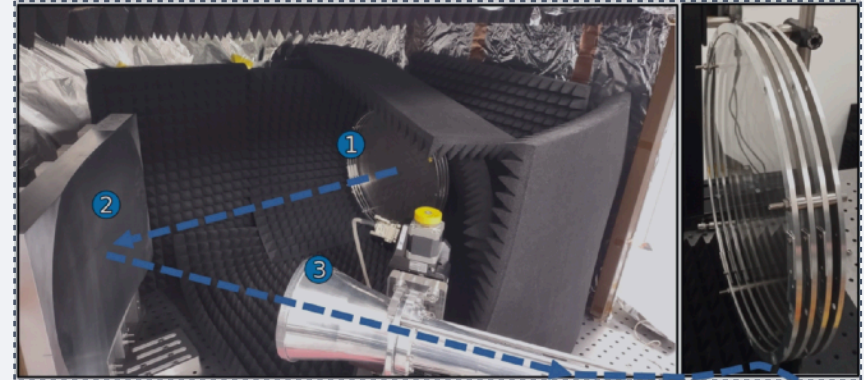
BREAD



BRASS

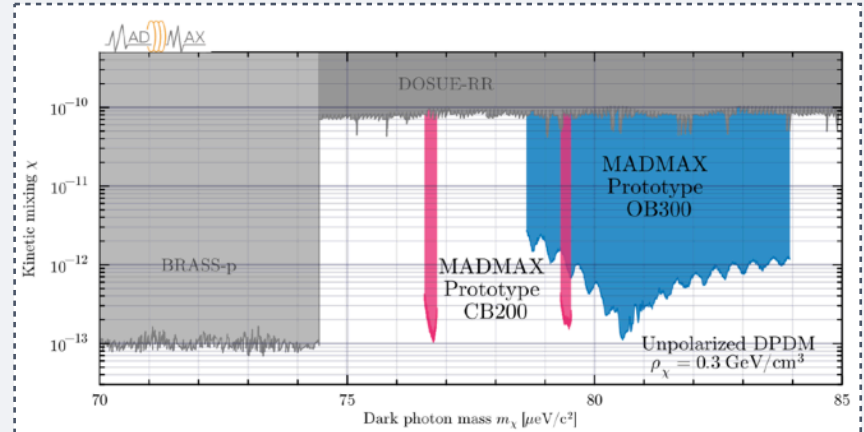
Dielectric haloscopes

- Can we add more emitting interfaces?
- Stack of dielectric discs in dipole magnet: axion-induced E at each boundary
- Moderate Q-factor and large volume
- Decouples aperture area from frequency: large A at high mass
- Target mass range: $\sim 40\text{--}400\ \mu\text{eV}$ (10–100 GHz)



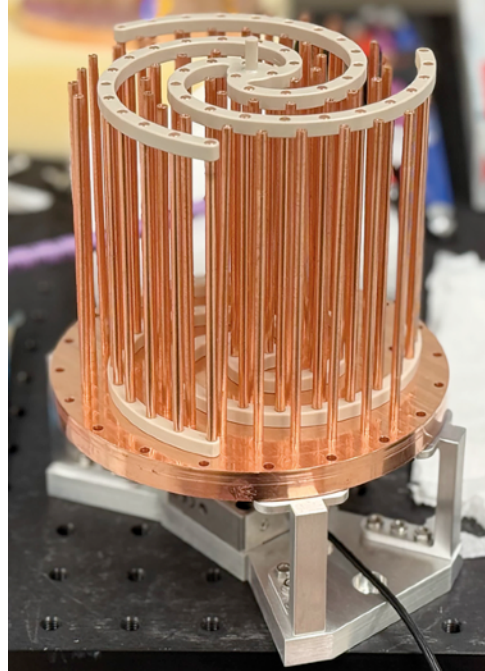
MADMAX

$$P \propto g_{a\gamma}^2 \cdot B_e^2 \cdot A \cdot \beta^2(\omega)$$

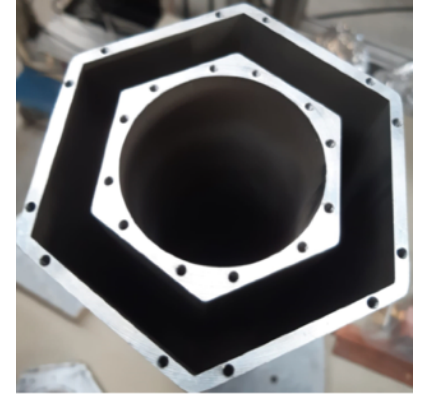


More designs

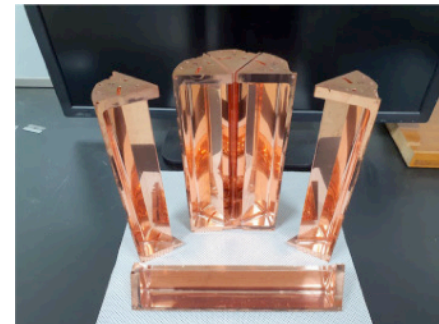
- Many more innovative designs to reduce the frequency dependency of detector volume
- Generally adds complexity and requires precise alignment and control of interfaces



ALPHA



QUAX

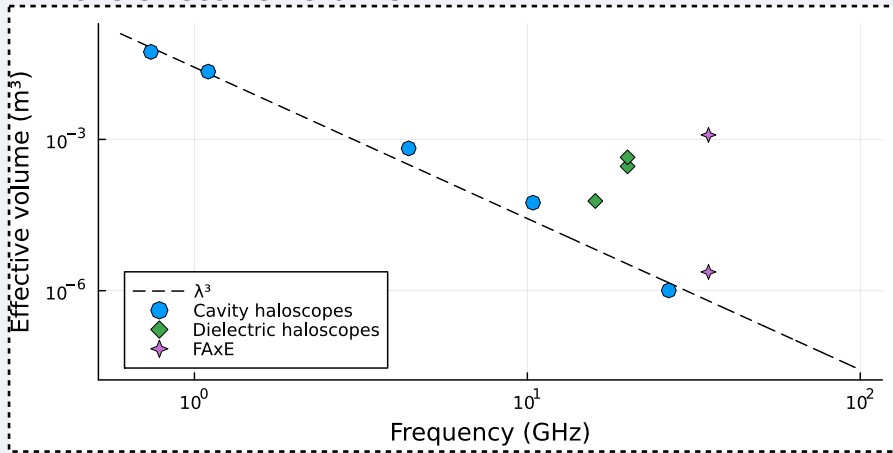
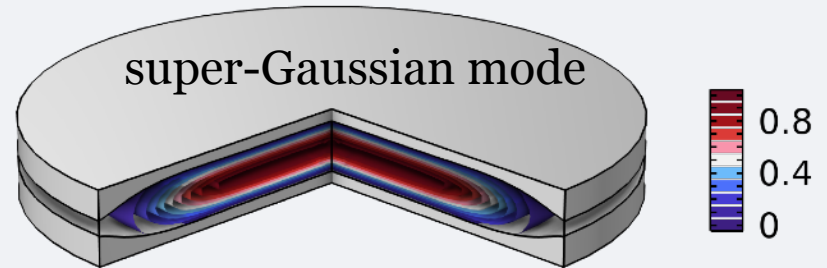
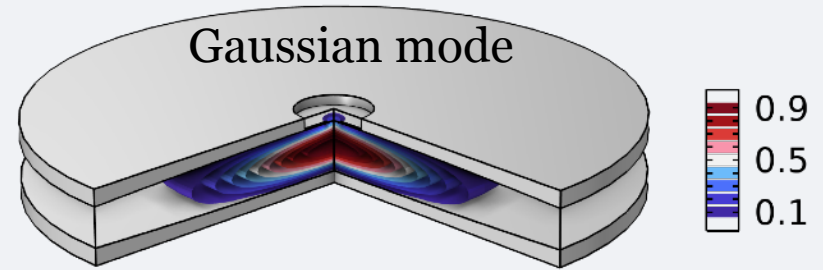


CAPP

FAXE — Fabry-Pérot Axion Experiment



- Can we have high Q-factor and large volume area independent of resonance frequency?
- Simple solution: Two parallel mirrors separated by $\lambda/2$
- Volume $V \sim \lambda$
- More advanced mirror geometry can double the effective volume

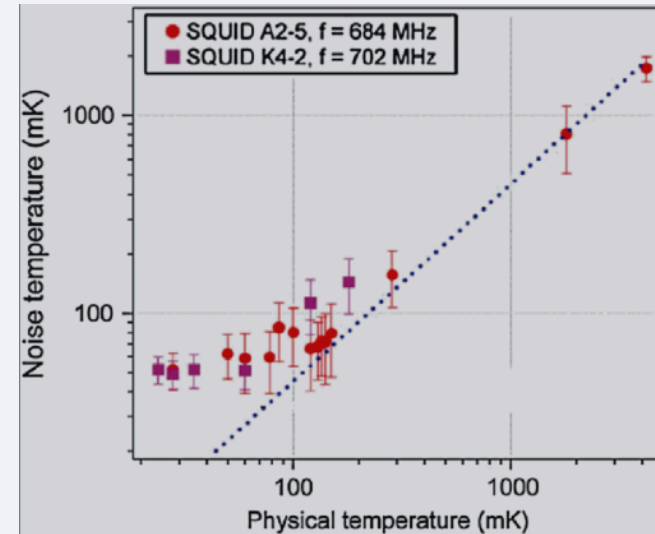


The standard quantum limit

- Higher frequency adds another challenge: The standard quantum limit
- Any phase-preserving linear amplifier must add $\geq 1/2$ photon of noise per quadrature
- At 5 GHz: 240 mK — comparable to fridge temperature
- Parametric amplifiers reach within factor ~ 2 of SQL in practice
- The SQL is not fundamental — it can be beaten with non-classical states

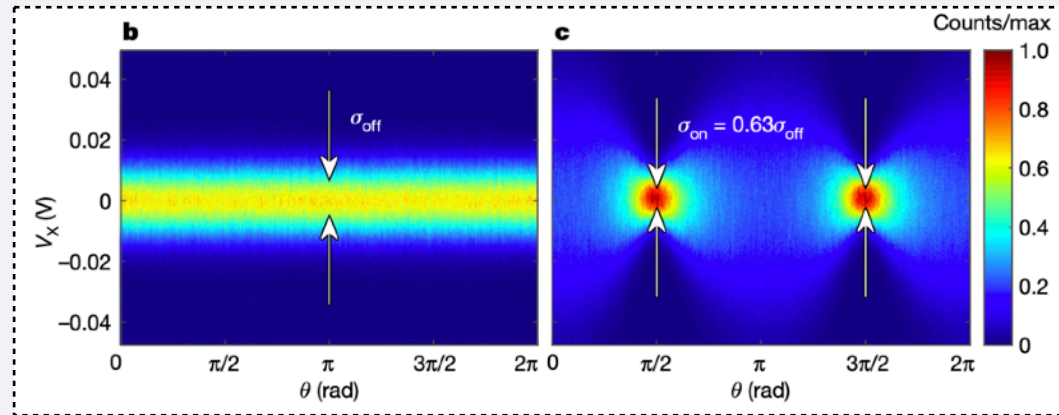
$$T_{SQL} = \frac{\hbar\omega}{k_B} \approx 48 \text{ mK} \times \frac{\nu}{1 \text{ GHz}}$$

SQUID-based amplifier



Squeezing: beating the SQL and its limits

- Squeezed states: $\Delta X_1 \cdot \Delta X_2 = \frac{1}{4}$, $\Delta X_1 < \frac{1}{2}$
 - noise below SQL in one quadrature
- If axion signal in amplified quadrature, effective added noise is reduced
- Demonstrated in axion searches: $\sim 2\times$ improvement in scan rate
- Practical limit: lossy circulators between squeezer and cavity degrade squeezing
- Lossless integration and direct injection remain active R&D challenges



Nature **590**, 238–242 (2021)

Beyond the SQL: photon counting

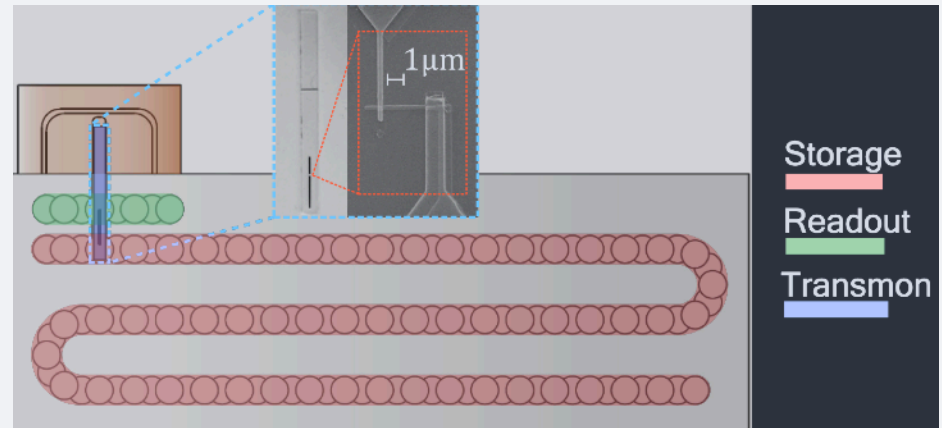
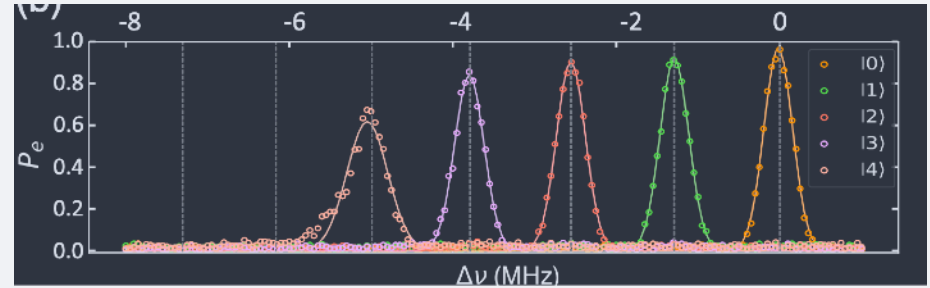
- Linear amplifiers measure field amplitude — noise from Heisenberg uncertainty of conjugate quadrature
- Photon number \hat{n} can be QND observable: measuring it does not destroy the signal photon
- Ideal photon counter adds zero noise to \hat{n}
- In practice, dark counts add additional noise
- Advantageous only if thermal photon population $\bar{n} < 1$ and dark count rate small enough

$$\frac{P_\ell}{P_{sp}} = \left[\sqrt{\bar{n}} + \frac{1}{\sqrt{\bar{n}}} \right] \sqrt{\frac{Q_c}{2\pi\eta Q_a}}$$

Qubit-based microwave photon detection

$$\mathcal{H}/\hbar = \omega_s a^\dagger a + \frac{1}{2} (\omega_q + \chi a^\dagger a) \sigma_z$$

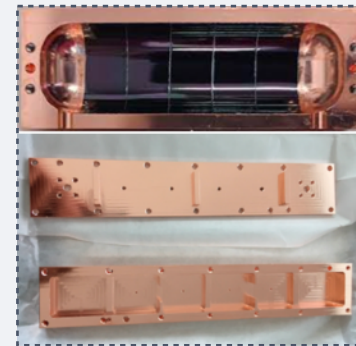
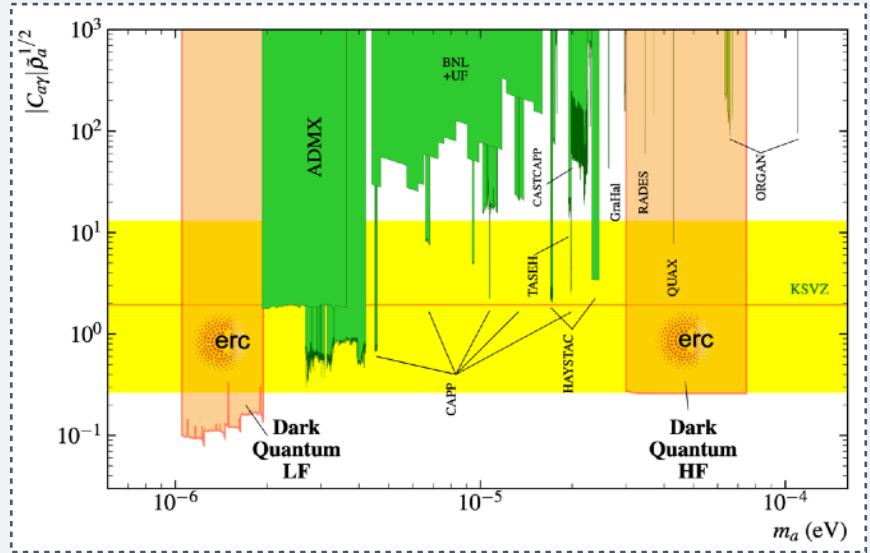
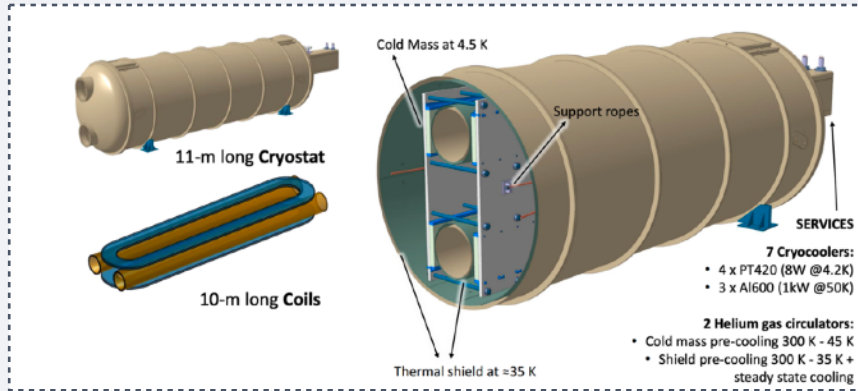
- Transmon qubit dispersively coupled to cavity: qubit frequency shifts by χ per photon
- QND measurement: probe qubit state without absorbing the cavity photon
- Demonstrated 20 \times improvement in scan rate over SQL linear amplifier @ 5 GHz



PhysRevLett.132.140801

Dark Quantum Project

- Two haloscope designs within RADES collaboration
- sidecar experiment within babyIAXO magnet
- Low frequency (200-500 MHz): Traditional design, quantum limited read-out using SQUID amplifiers
- High frequency (8-18 GHz): Single photon detection using Transmon Qubits



Open challenges

RESONATOR ENGINEERING

Broadband tuning, high-Q, and large volumes remain active challenges.

DETECTOR TECHNOLOGY

Single photon counting is maturing and can significantly speed up the search. Extension to higher frequencies is actively being pursued.

TAKE HOME MESSAGE

Reaching axion QCD sensitivity is hard and requires a combination of novel technologies.

But exploring new parameter space is actually easy with standard equipment. So just built it and see!