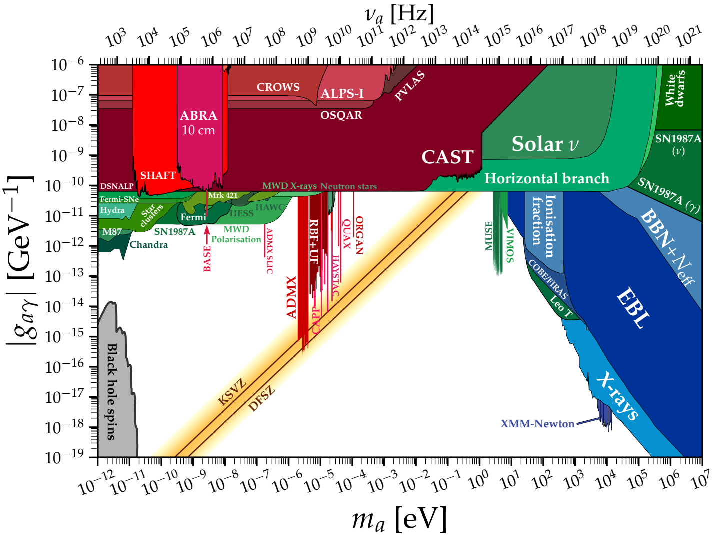
Searching for axions with metamaterials
the ALPHA haloscope

A. Gallo Rosso and ALPHA Consortium
UCLA Dark Matter 2023

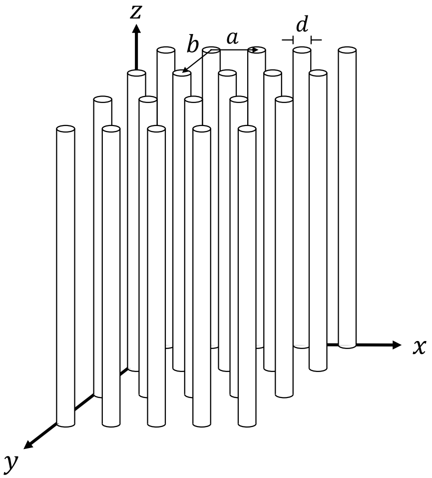
AXION-PHOTON COUPLING



[1]O' Hare, cajohare/AxionLimits: AxionLimits.

WIRE METAMATERIALS

Metamaterials
Composite materials with different properties than their single parts

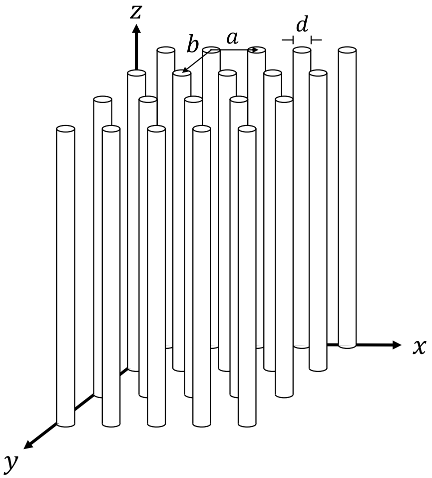


[2]M. Lawson *et al.*, PRL 123 (2019) 14, 141802.

WIRE METAMATERIALS

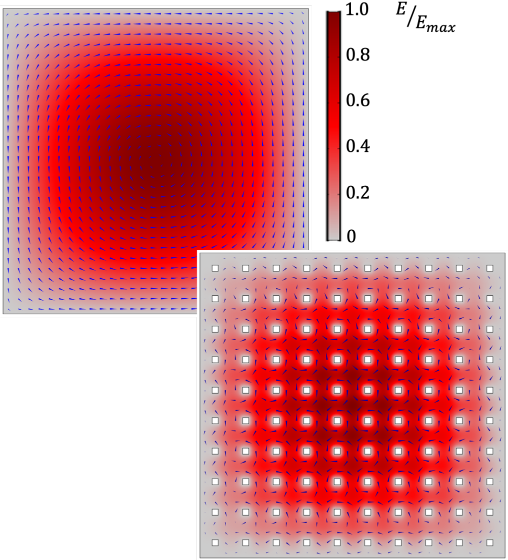
$$\frac{\omega_p^2}{c^2} = \frac{2\pi}{ab}\left[\log\left(\frac{\sqrt{a\,b}}{\pi\,d}\right) + F\left(\frac{a}{b}\right)\right]^{-1}$$

$$F(u) = -\frac{\log u}{2} + \sum_{n=1}^{\infty}\left(\frac{\coth(\pi n u) - 1}{n}\right) + \frac{\pi u}{6}$$



[3] P.A. Belov *et al.*, J. Electromagn. Waves. Appl. 16, 8 (2002).

WIRE METAMATERIALS



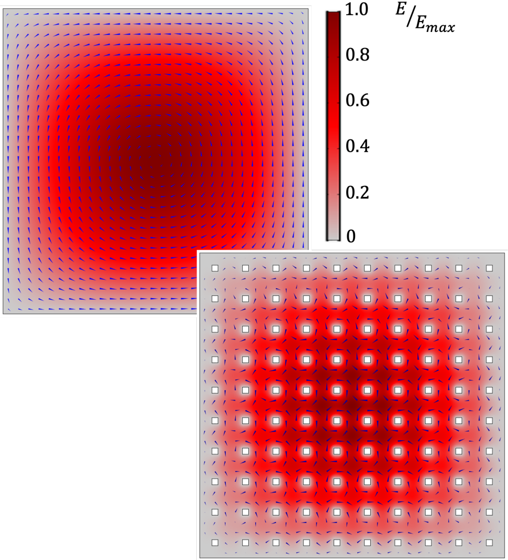
TM$_{110}$ mode structure

Behavior as an effective medium

Field distortion near wires might complicate readout

[4]A. Millar *et al.*, PRD 107 (2023) 5, 055013.

WIRE METAMATERIALS



PROs

- Cryogenic
- Solenoidal magnet
- Much larger volume than cavities

CONs

- ~~Behind on R&D~~

[4] A. Millar *et al.*, PRD 107 (2023) 5, 055013.

Searching for dark matter with plasma haloscopes

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(Endorsers)

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Arizona State University	Niels Bohr Institute	UC Davis
Fermilab	Nordita, KTH Stockholm	UCL London
IIT Chicago	Oak Ridge National Labs	University of Iceland
IIT Kanpur	Shanghai Jiao Tong University	University of Maryland
MIT Cambridge	Stockholm University & OKC	University of Oxford
Narxoz University	UC Berkeley	Uppsala University

POWER IN THE DETECTOR

$$P_s = \left(\frac{\rho_a}{m_a} g_{a\gamma}^2\right) \kappa B_e^2 Q \mathcal{G} V$$

Quality factor Q

System dampening

$$Q = \frac{\omega \mathcal{U}}{P_{\text{loss}}} = \frac{\omega}{c\,\Gamma_p}$$

Geometry factor $\mathcal{G}$

Normalization of stored energy

$$\mathcal{G} = \frac{1}{a_0^2 g_{a\gamma}^2 B_e^2 V Q^2} \int |\boldsymbol{E}|^2 \, \mathrm{d}V$$

Volume V

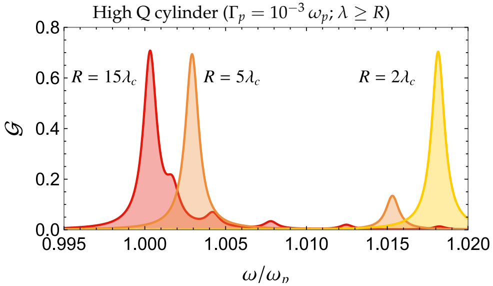
GEOMETRY FACTOR

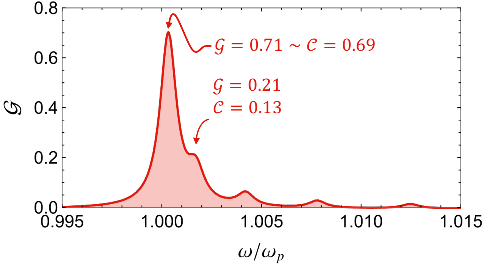
For single-mode systems

$$\mathcal{G} = \mathcal{C} = \frac{1}{\overline{B}_e^2 V^2} \left(\int B_e \mathcal{E}_i \, \mathrm{d}V \right)^2$$

For multi-mode systems

SINGLE CAVITY MODE BREAKS DOWN
MORE THAN ONE ANTENNA NEEDED

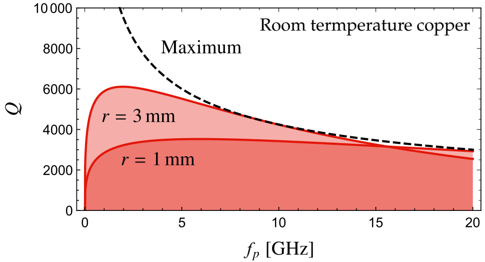


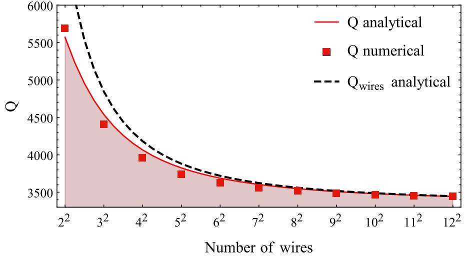


[4] A. Millar *et al.*, PRD 107 (2023) 5, 055013.

QUALITY FACTOR

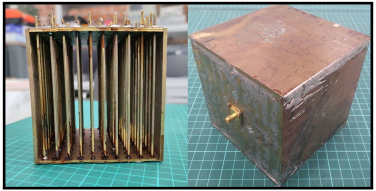
- Tightly bound to design
  - ↪ $Q = Q(\omega_p) = Q(\omega_p(r))$
  - ↪ Theory ✓ Simulation ✓ Experiment
- $Q \sim$ some 1000s
  - ↪ $\times 10$ than previously quoted
  - ↪ $\times 3$ more if cryogenic
- Wire losses > surface
  - ↪ Asymptotically $P_s \propto V$



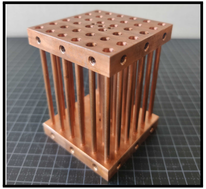


[5] R. Balafendiev *et al.*, PRB 106, 075106 (2022).

PROTOTYPE I

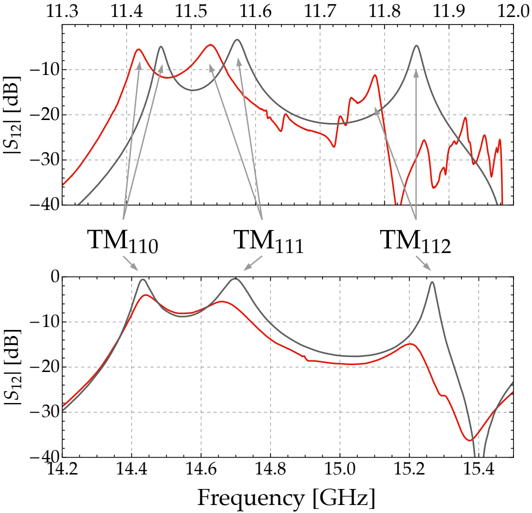


PROTOTYPE II

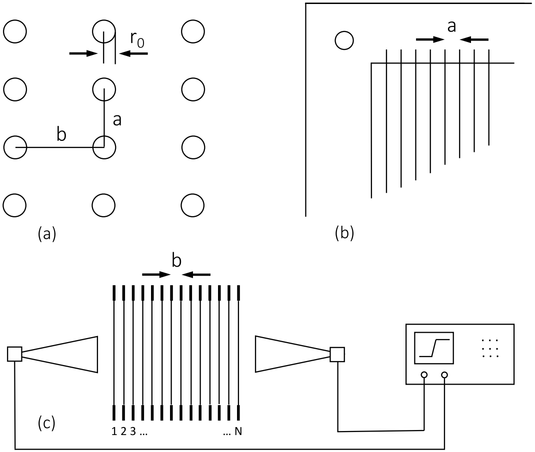


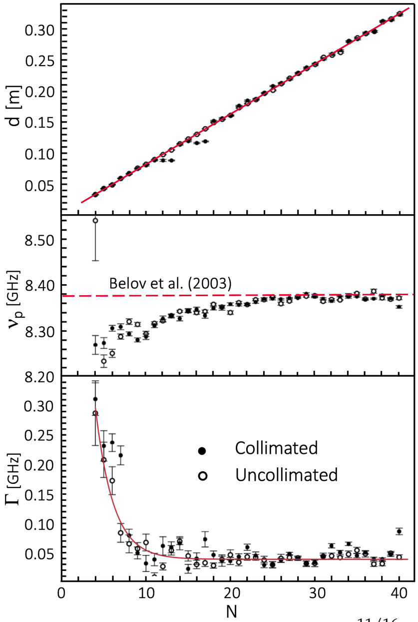
Experiment

CST simul.



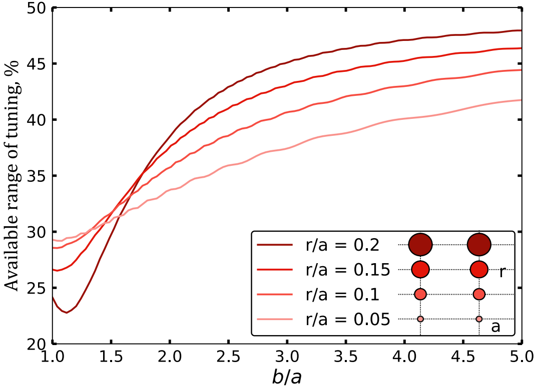
[5] R. Balafendiev *et al.*, PRB 106, 075106 (2022).

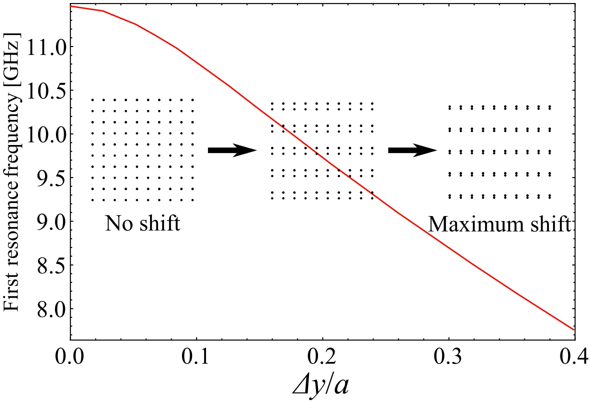




[6] M. Wooten *et al.*, Annalen der Physik (2022) 00479.

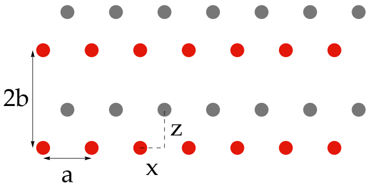
TUNING

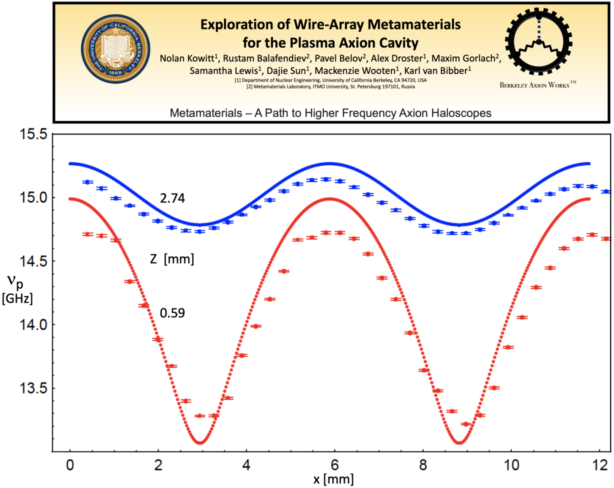




[4] A. Millar *et al.*, PRD 107 (2023) 5, 055013.

- Smaller freq. range
- More practical
- Few % agreement





[7]Data: N. Kowitt, Simulation: R. Balafendiev (see poster).

DISCOVERY REACH

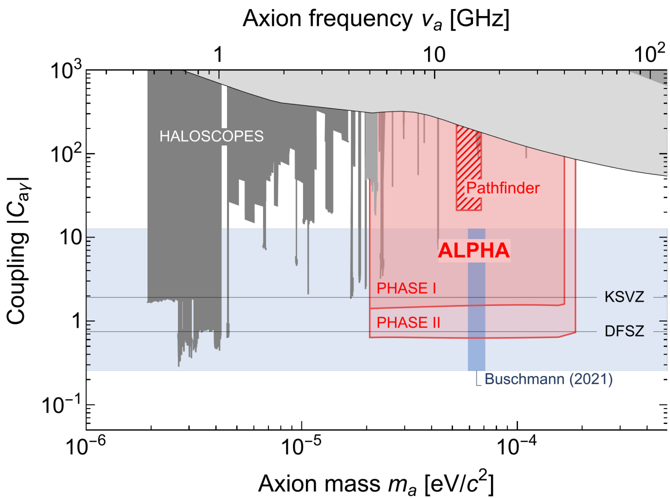
ALPHA PHASE I

- 2 years run
- $(5 \div 40)$ GHz
- HEMT amplifiers
- Single scan (see [8])

ALPHA PHASE II

- 2 years run
- $(5 \div 45)$ GHz
- Quantum limited
- Single scan (see [8])

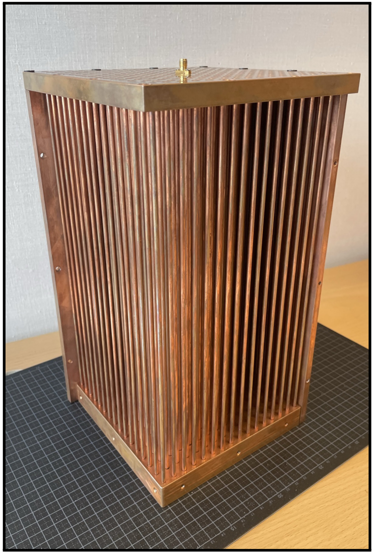
$(Q \sim 10^4,\, B \sim 10\,\mathrm{T},\, V \approx 0.3\,\mathrm{m}^3)$



[8] A. Gallo Rosso *et al.*, arXiv:2210.16095.

CONCLUSIONS

- Overall design validation
  - ✓ Theory/simulation/experiment
  - ✓ Feasible tuning
- Pathfinder on the way
  - ✓ First data in 2026
- KSVZ and DFSZ at reach
  - ✓ $2 + 2$ yrs full scale experiment



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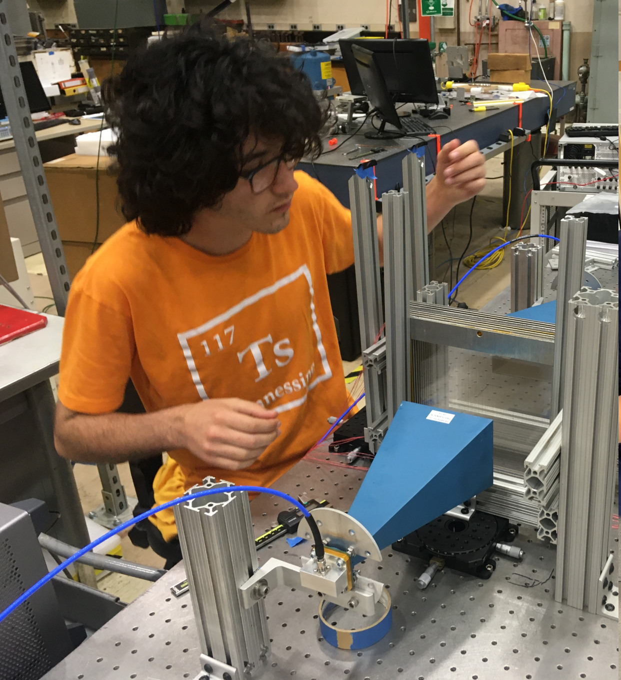
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