The ALPHA axion dark matter experiment

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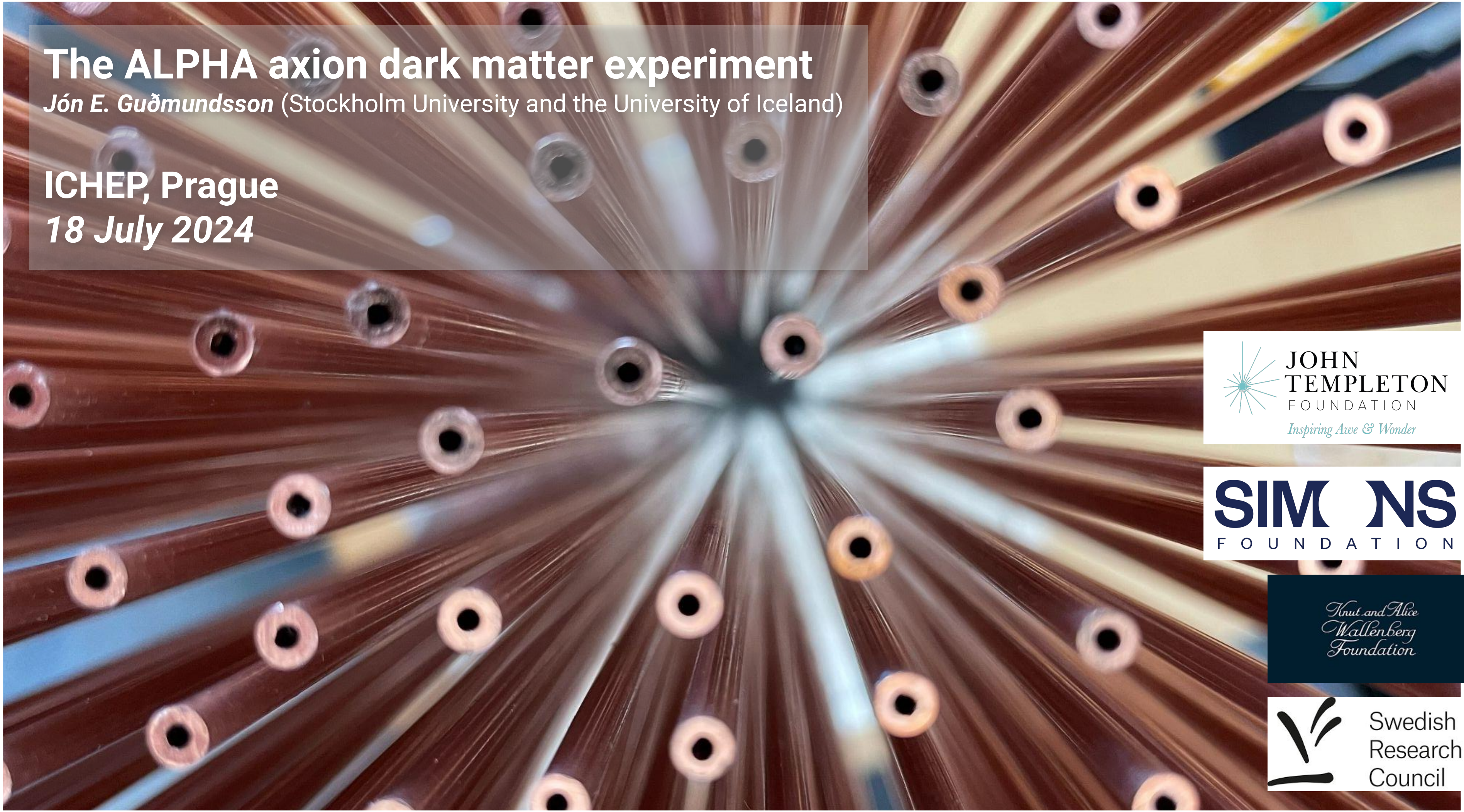
ICHEP, Prague

18 July 2024



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The axion

- The neutron’s electric dipole moment (EDM) constrained to $d_n = 0 \pm 1.3 \times 10^{-28}$ e m
- Axions, a solution to the strong CP problem, explains the vanishing EDM Peccei & Quinn (1977) Weinberg, Wilczek (1978)
- Abbott & Sikivie; Dine & Fischler; Preskill, Wise & Wilczek (1983): **the axion could be dark matter**
- *Experimental tests of the “invisible” axion*, P. Sikivie, *PRL* (1983): the haloscope needs a strong magnetic field, cryogenic cooling, resonant cavities, sensitive microwave antennas
  - AC current term: $g_{a\gamma}\mathbf{B}_\mathrm{e}\,\dot{a}$
- A QCD axion model with m_a = 20 µeV gives $n_a \approx 2 \times 10^{13}$ /cm^3

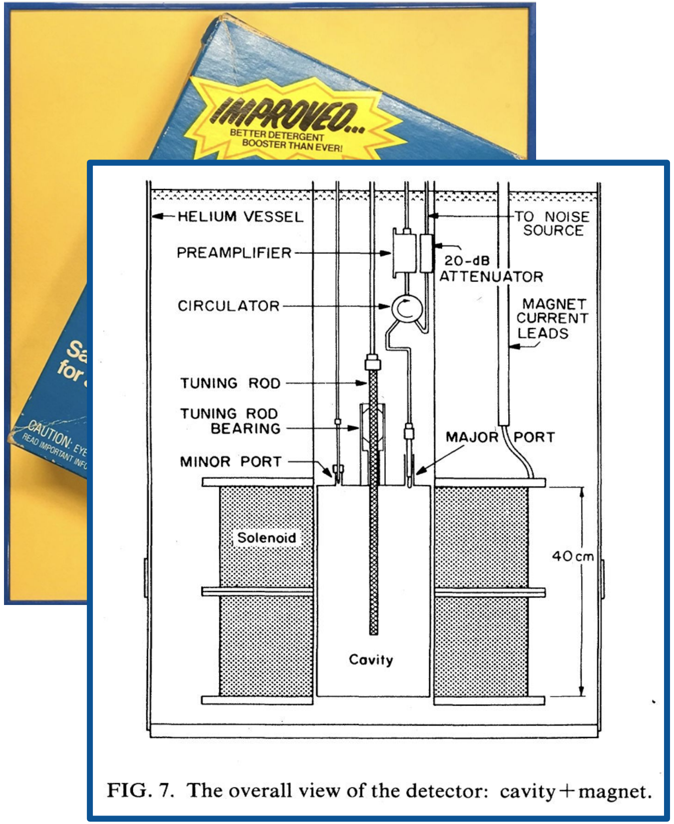


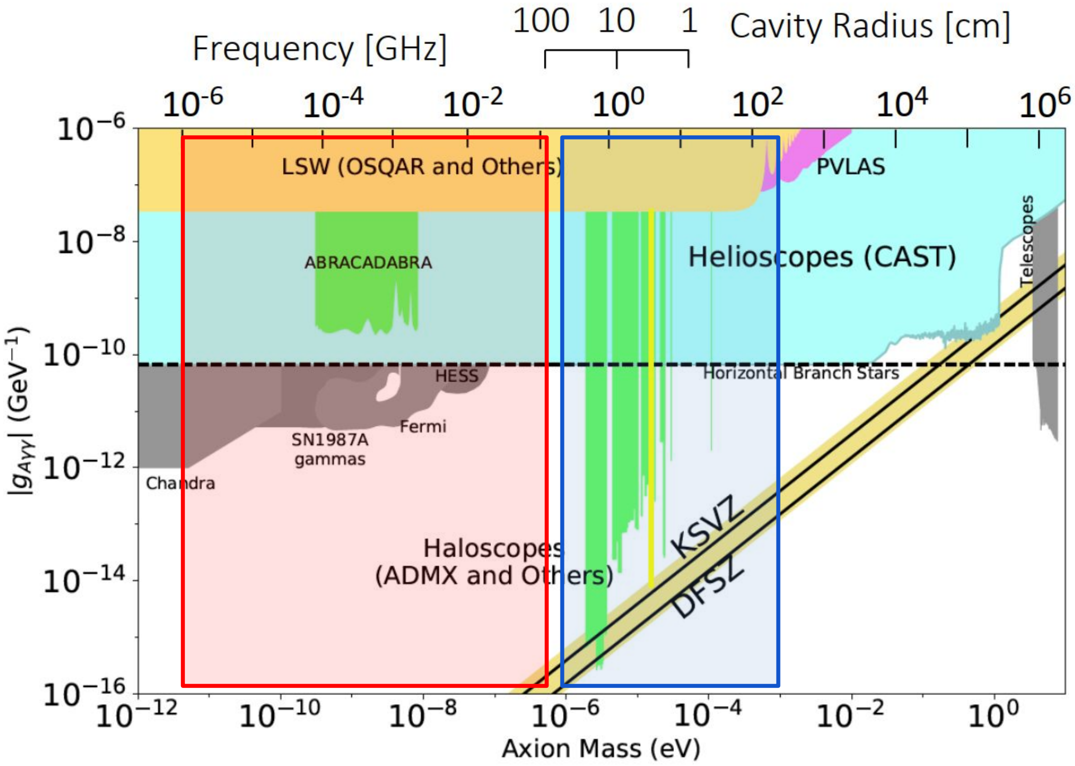
FIG. 7. The overall view of the detector: cavity + magnet.

Wuensch et al. (1989)

The RBF experiment produced impressive constraints on axion coupling factors in the 1-4 GHz (4-16 µeV) range using **11 different** cavities

Axion classification

Pre-inflation axion w/ mass range 20 peV – 1 μeV (~GUT scale), see e.g. lumped element detectors such as DMRadio. Wide range of viable masses.



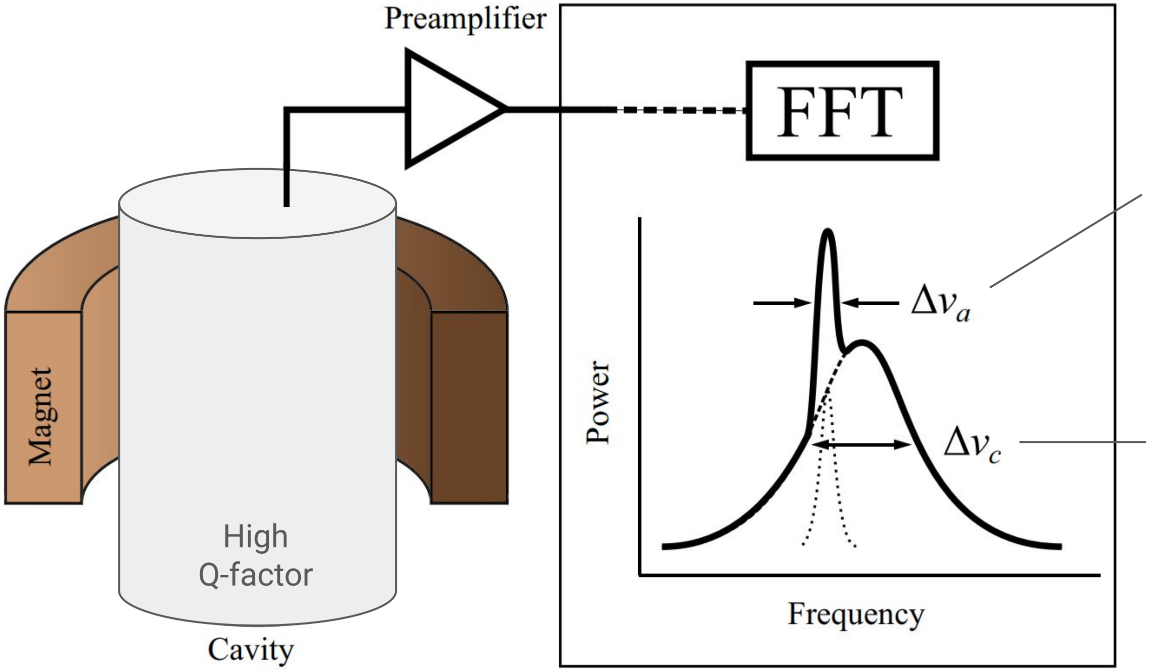
Post-inflation axion w/ mass range 1 μeV – 1 meV, can in theory be explicitly derived. Typically probed with **cavity haloscopes**.

Credit: PDG 2020 review of axion particle physics

The axion haloscope

A conceptual schematic of a microwave-cavity

We want photons produced through axion-photon conversion to survive in the cavity, hence the need for high Q-factors



Axion line broadening due to virial velocity of dark matter in our galaxy

Cavity band pass

Figure: Kowitt, Balafendiev et al. (2023)
Tunable wire metamaterials for an axion haloscope

Axion signal strength

The **power** expected from an axion induced signal:

$$P \propto B^2 C V Q$$

For a typical axion haloscope operating in the O (10 GHz) range, we expect:

$$P_{\rm ax} \approx 10^{-23}{\rm W}$$

This corresponds to a tens of photons per second!!

"Compare this with the signals received on earth from the 4-watt transmitter aboard the Voyager spacecraft at the periphery of our solar system — a whopping 10^{-17} Watts." **L. J. Rosenberg and K. van Bibber**

System noise temperature (Dicke equation): Ability to measure a signal in the presence of noise sources

$$\mathrm{SNR} = \frac{P}{k_{\rm B} T_{\rm Sys}} \sqrt{\frac{t}{\Delta\nu}}$$

$$k_{\rm B} T_{\rm Sys} = h\nu \left(\frac{1}{e^{h\nu/k_{\rm B}T} - 1} + \frac{1}{2} \right) + k_{\rm B} T_{\rm A}$$

Form factor: The overlap between the cavity mode and the magnetic field.

$$\mathcal{C} = \frac{1}{B_e^2 V^2} \left(\int dV\, B_e \mathcal{E}_i \right)^2$$

For a cylindrical cavity, the TM$_{010}$ mode gives $C_{010} \approx 0.7$

Scanning rate: The rate with which we can scan through frequency in search for an axion signal

$$\frac{d\nu}{dt} \propto V^2 B^4 C^2 Q$$

Figure of merit: The combined effects that experimentalists can (hope to) control:

$$\mathrm{FoM} \propto \frac{V^2 B^4 C^2 Q}{T_{\rm Sys}}$$

Does not include: axion physics, coupling strengths, dark matter clustering, mode purity, tuning range, duty cycle, etc.

Axions and decay of cosmic strings

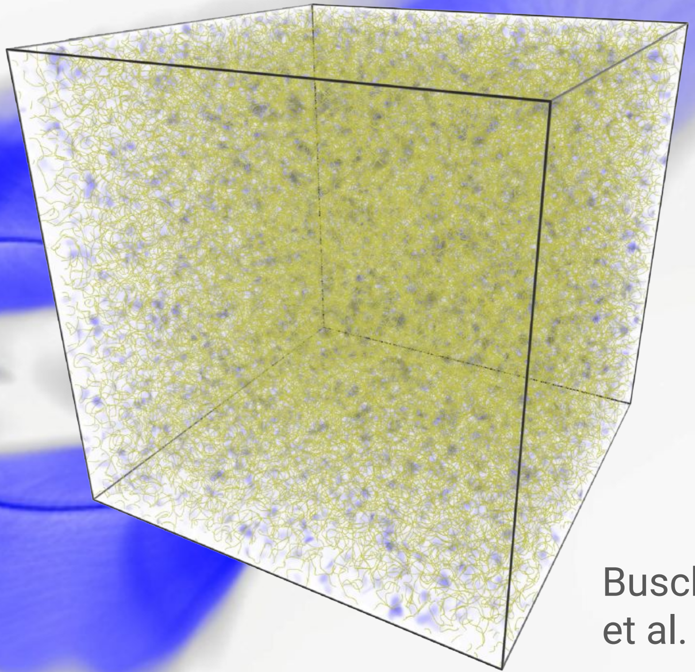
If the axion is generated after inflation, there is a **unique mass** that gives rise to the observed dark matter abundance, but these calculations are challenging

Borsanyi et al. (2016)
PQ symmetry broken after inflation: $m_a > 10\ \mu\text{eV}$

Klaer & Moore (2017)
$m_a = 26.2 \pm 3.4\ \mu\text{eV}$

Buschmann et al. (2022)
$m_a = 65 \pm 6\ \mu\text{eV}$

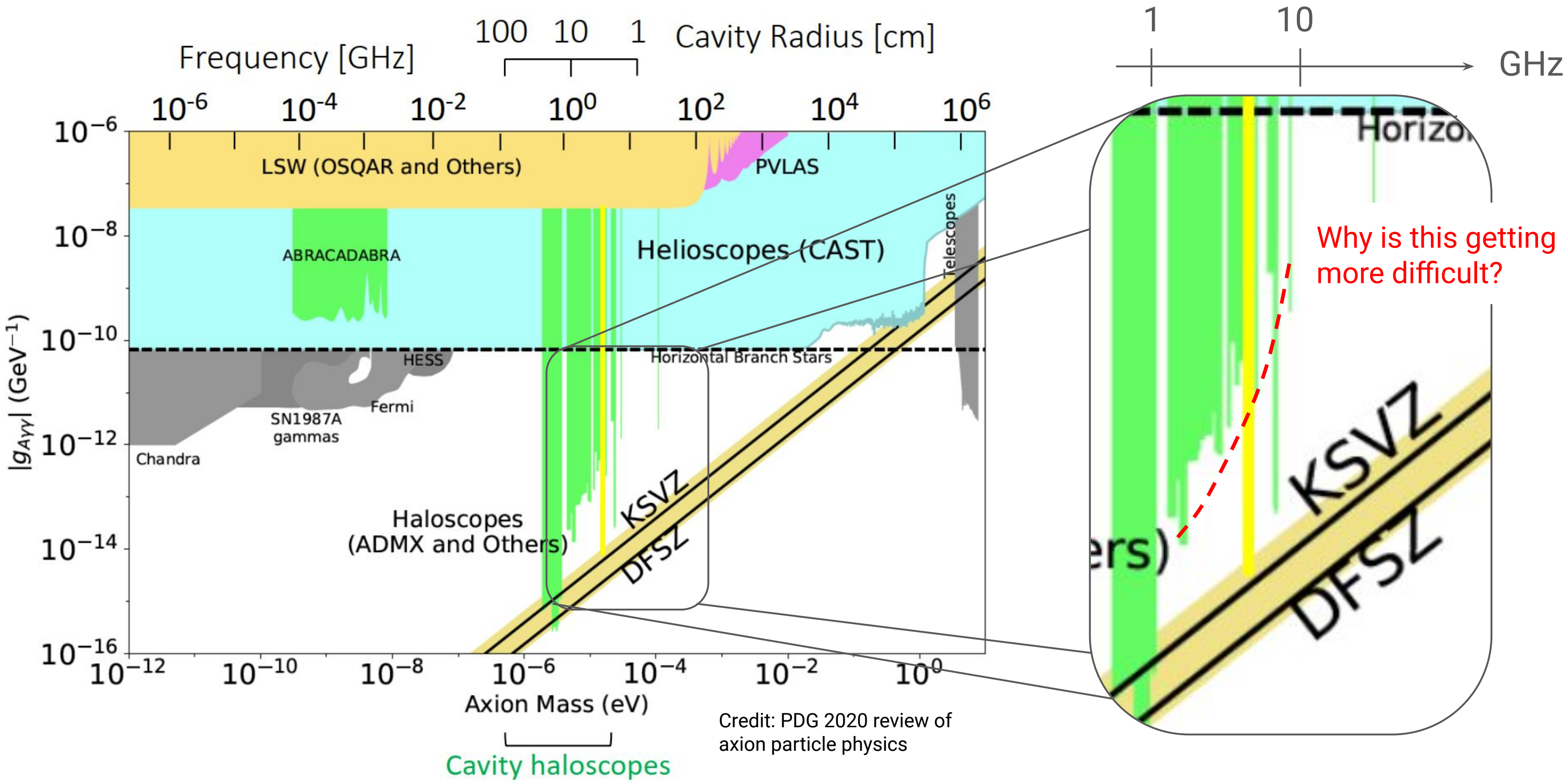
Saikawa et al. (2024)
$m_a \approx 95\text{–}450\ \mu\text{eV}$



Buschmann et al. (2022)

Cold dark matter axions produced in the post-inflationary Peccei-Quinn symmetry breaking scenario serve as clear targets for their experimental detection, since it is in principle possible to give a sharp prediction for their mass once we understand precisely how they are produced from the decay of global cosmic strings in the early Universe. — Saikawa et al.

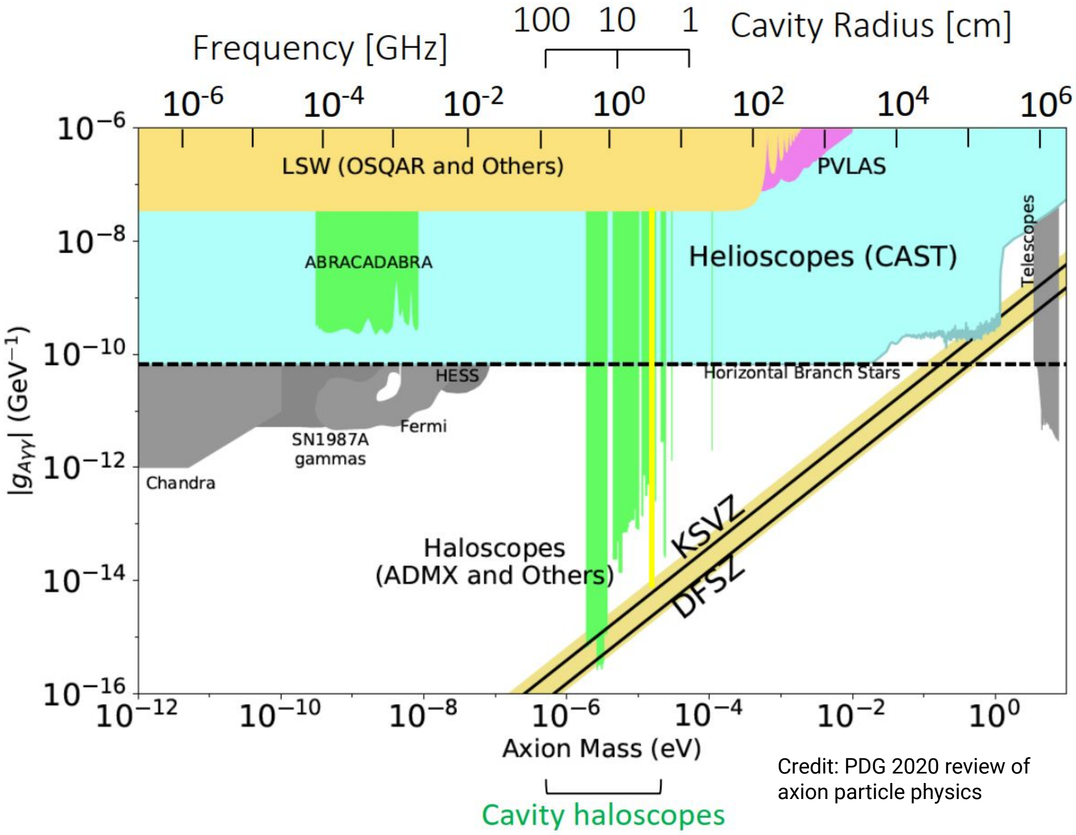
Large mass → small volume



Why is this getting more difficult?

Credit: PDG 2020 review of axion particle physics

Large mass → small volume

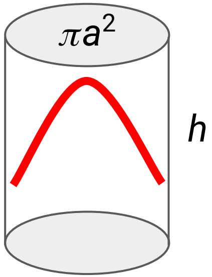


Credit: PDG 2020 review of axion particle physics

The power produced in a haloscope:

$$P \propto B^2 C_{nml} V Q$$

Volume = $h\pi a^2$



$$(f)_{\mathrm{TM}_{010}} = \frac{1.202}{\pi}\frac{c}{a} = \frac{0.115}{a}\ \mathrm{GHz}$$

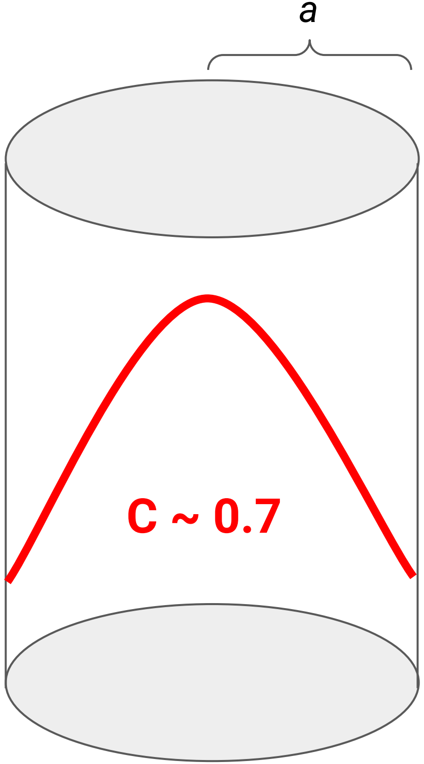
For a = 1.15 cm, we get f = 10 GHz

m_a = (4.1 μeV) ✕ (f / GHz)

= 41 μeV (if f = 10 GHz)

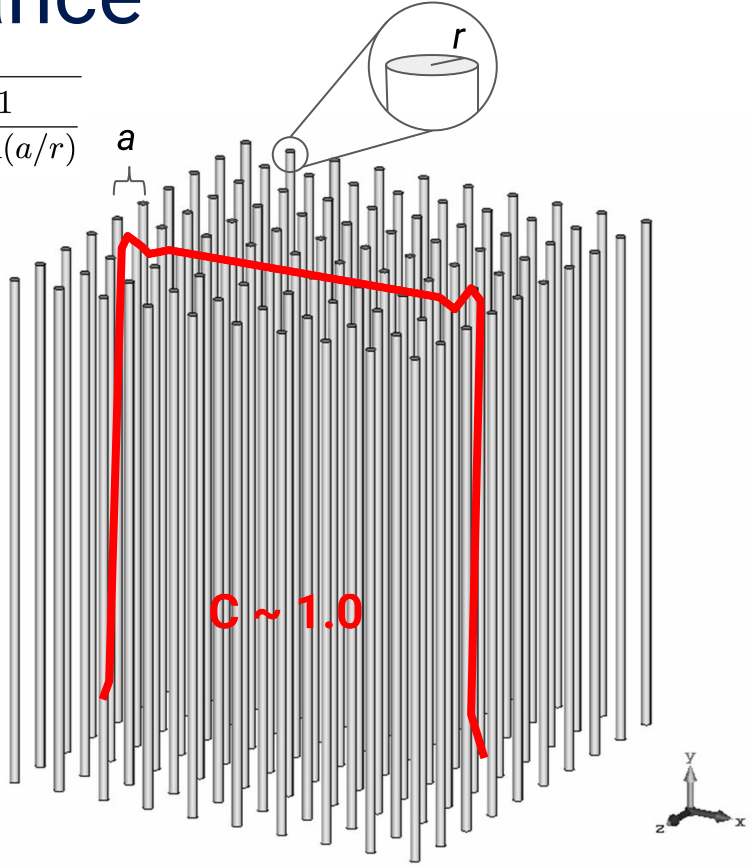
Solution: plasmonic resonance

$$f = \frac{1.202}{\pi}\frac{c}{a}$$



Sikivie (1983), PRL

$$f = \frac{c}{a}\sqrt{\frac{1}{2\pi\ln(a/r)}}$$

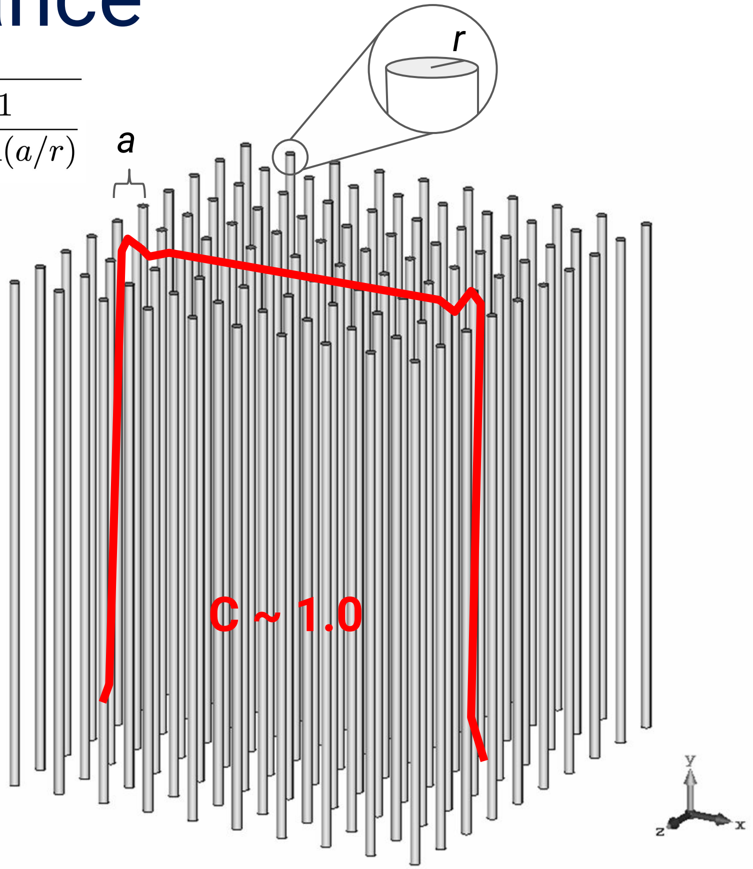


Lawson et al. (2019), PRL

Solution: plasmonic resonance

- Wires mutually induct, changing the plasma frequency
- Resonant frequency is decoupled from the size of the system
- Resonance when axion and plasma frequencies match
- Theory of wire metamaterial:
  Pendry (1998)
  Belov, et al. (2003)
- A wire-spacing of 1 cm gives a plasma frequency of ~10 GHz

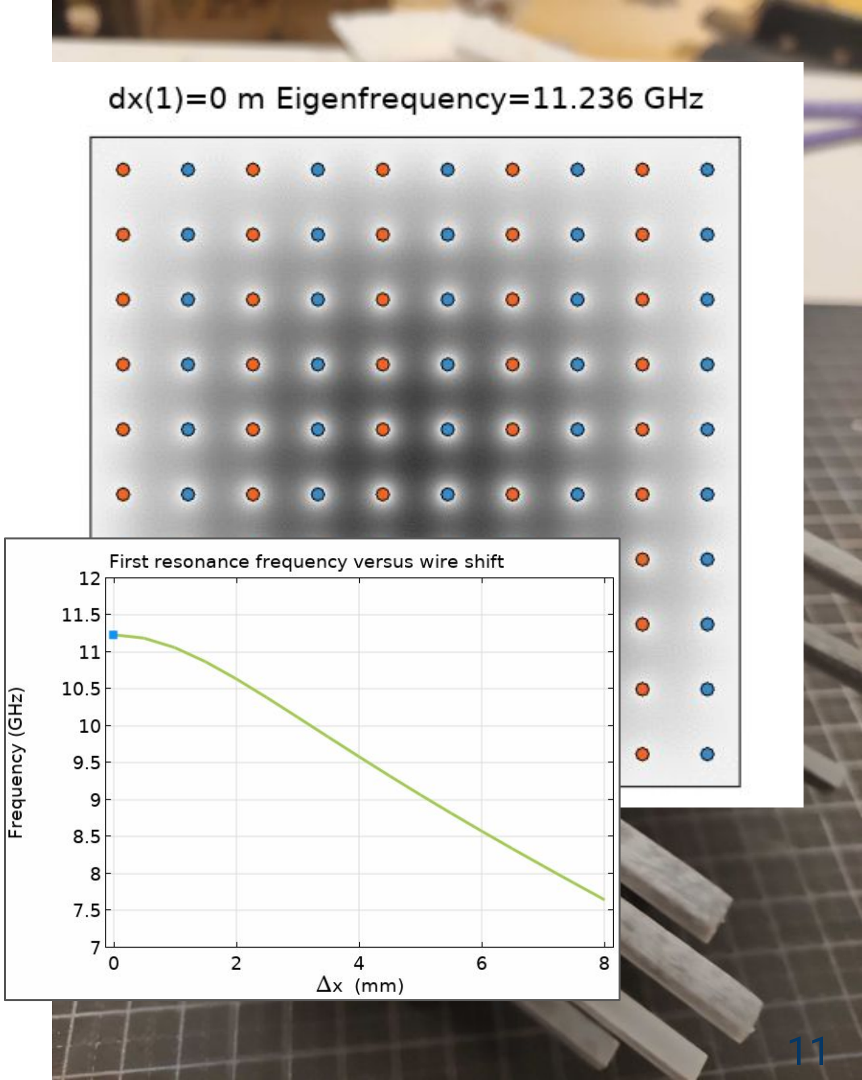
$$f = \frac{c}{a}\sqrt{\frac{1}{2\pi \ln(a/r)}}$$



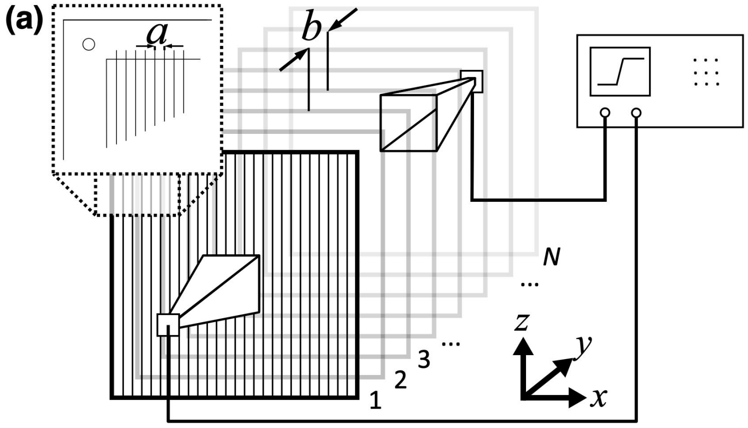
Lawson et al. (2019), PRL

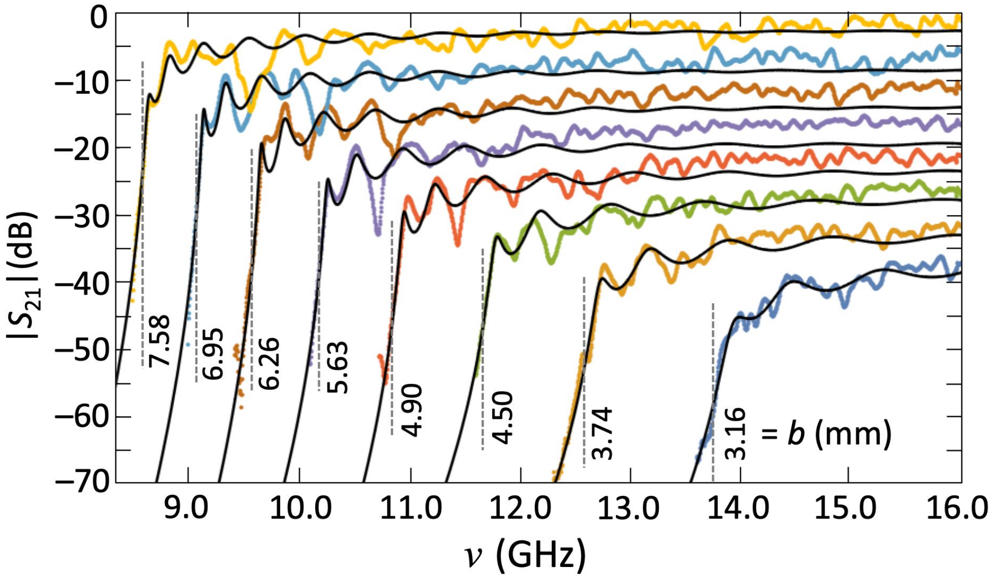
Towards tuning

- Early 2021: *Can this system be tuned?*
- Answer: Yes (in theory)
  - See Balafendiev et al., PRB (2022) and the ALPHA White paper (2022)
- Lateral translation works, but its implementation in closed cavities is not trivial
  - See Dr. Gagandeep Kaur’s talk tomorrow afternoon in session on *Detectors for Future Facilities, R&D, Novel Techniques*



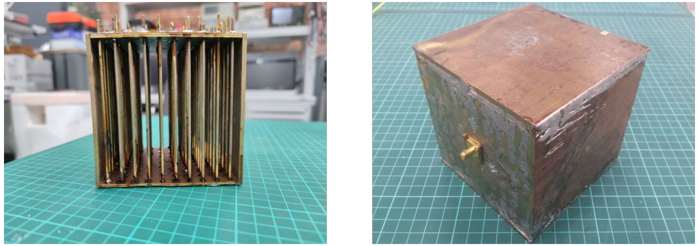
Kowitt et al. (2022)

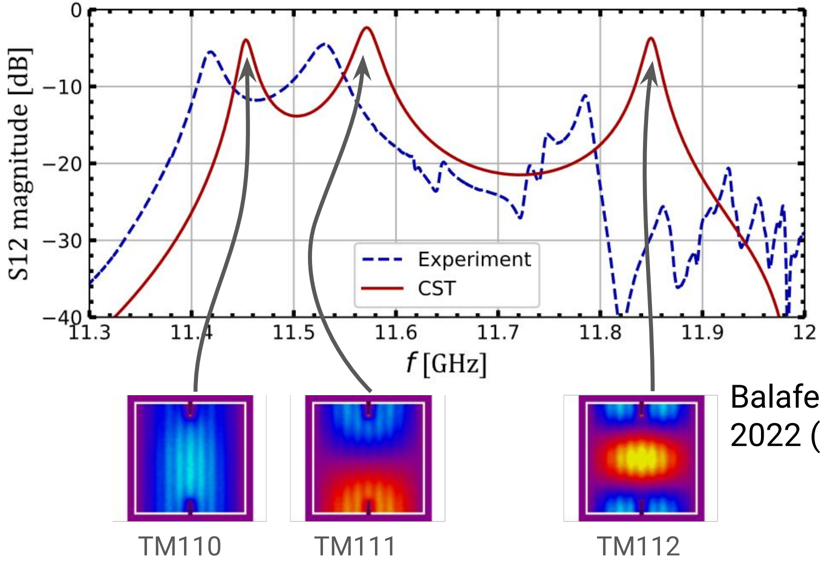




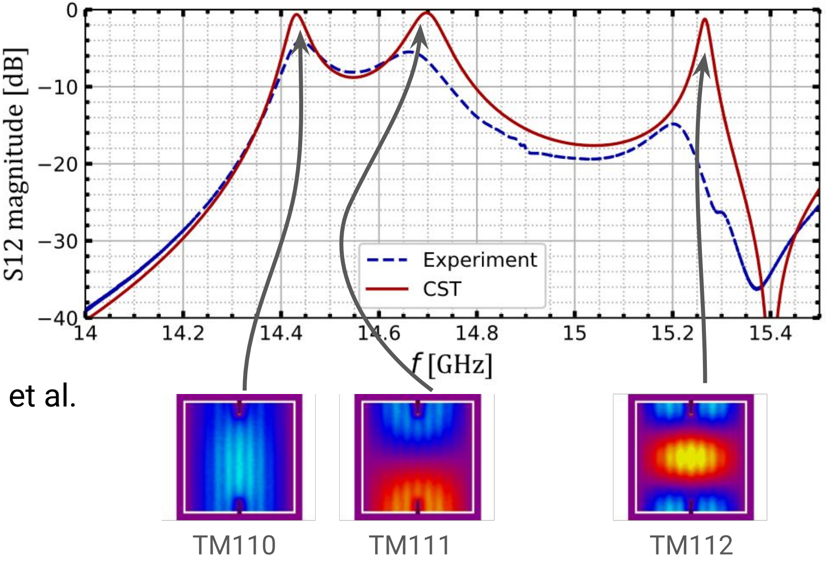
The onset of plasmonic resonance matches theory expectation
Tuning achieved through changing the frame spacing

Comparing simulations with experiment



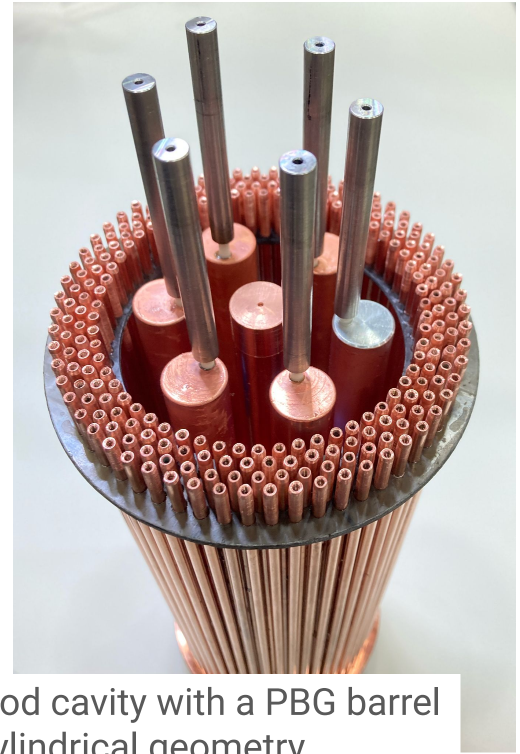


Balafendiev et al. 2022 (PRB)



Building on Haystack resonator development

Resonator development led by K. van Bibber (Berkeley Axion Works)



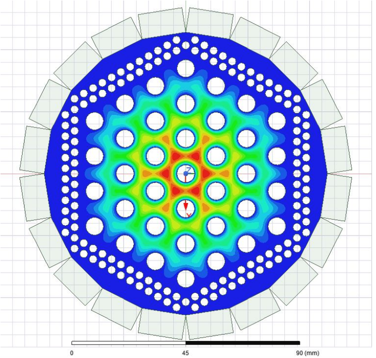
Multirod cavity with a PBG barrel in a cylindrical geometry

Aarav Sindhwad and Pablo Castaño

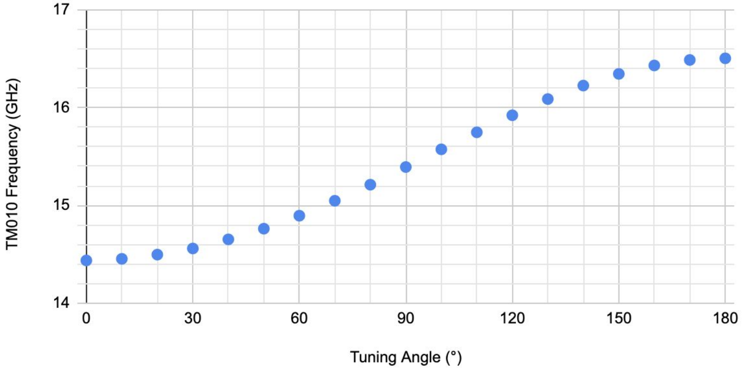
Credit: K. van Bibber

ALPHA Phase Ia resonator

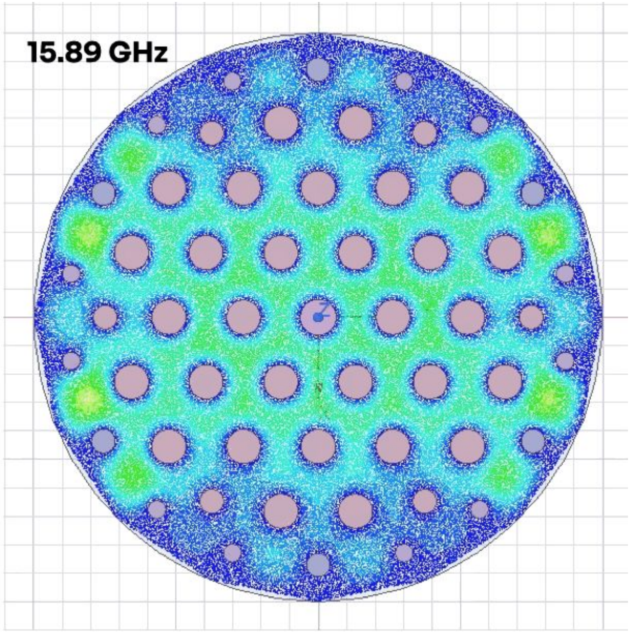
will build on UC Berkeley’s experience with tunable lattice & photonic band gap structures; first prototype to be constructed and tested 2024-25



37-rod triangular lattice: Rod: ∅~7.1mm, Res: ∅~95.3mm



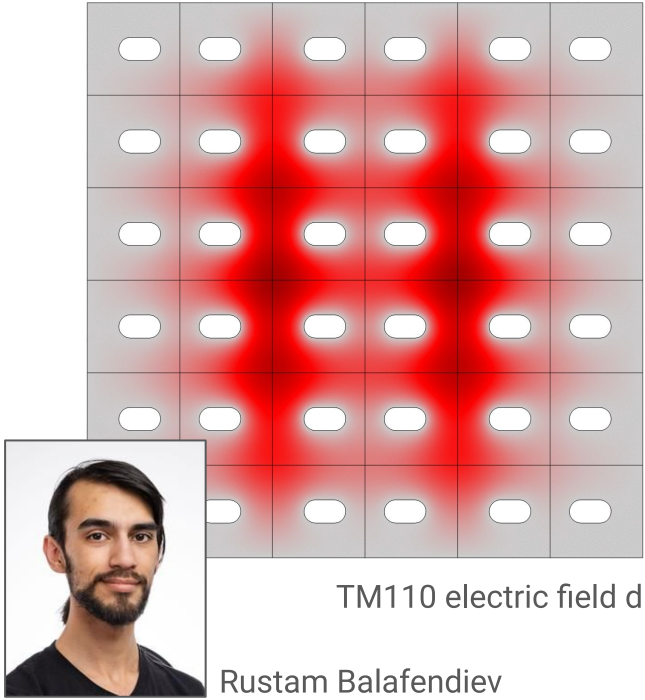
55-rod triangular lattice: 10.2 cm ID, 25.4 cm long



Credit:
H. Jackson
K. van Bibber

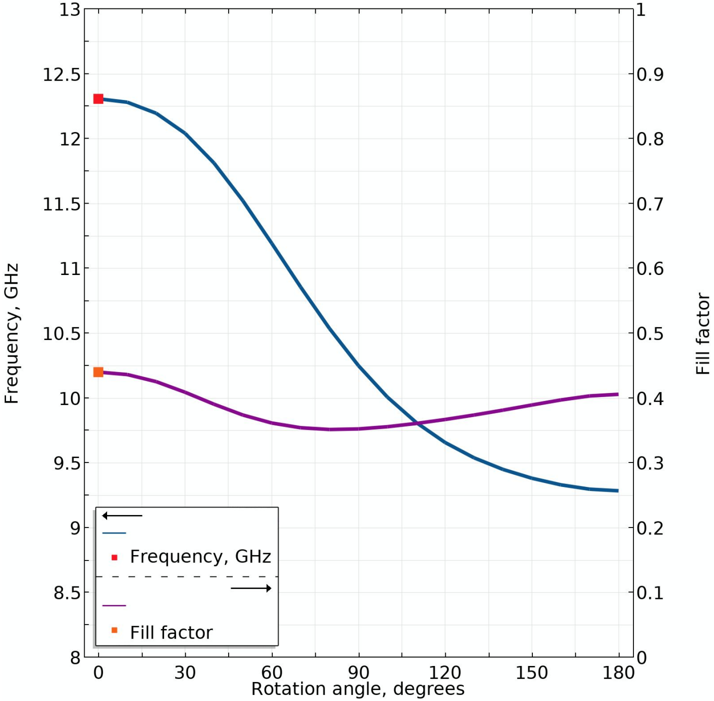
R&D towards phase Ib resonator –Tuning with sails

R&D towards optimized FOM actively pursued at Stockholm University, guided by theory and simulations from the ITMO/St. Petersburg group (**R. Balafendiev, P. Belov**, M. Gorlach, et al.)

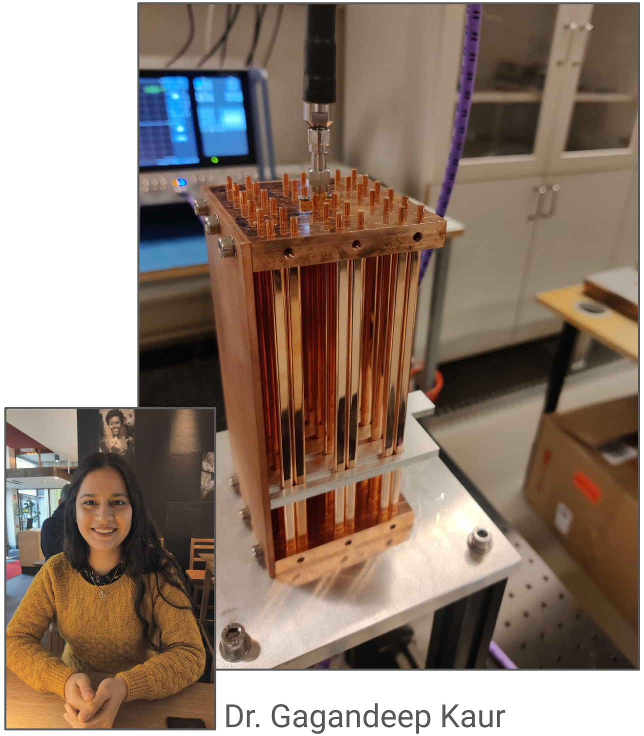


TM110 electric field distribution

Rustam Balafendiev

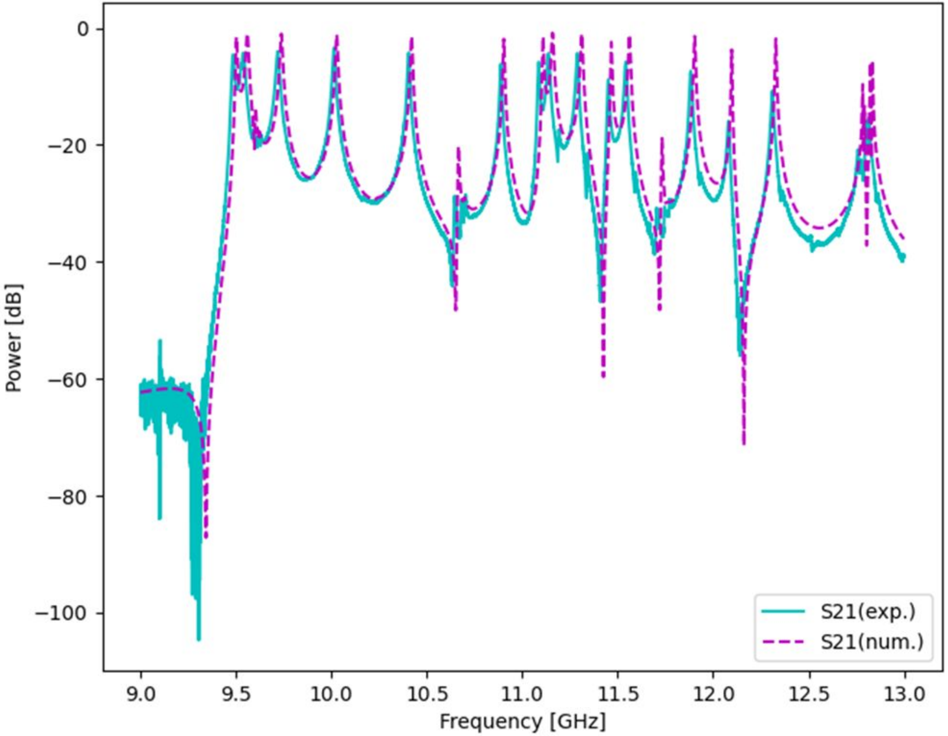


R&D towards phase Ib resonator



Dr. Gagandeep Kaur

θ = 180 deg

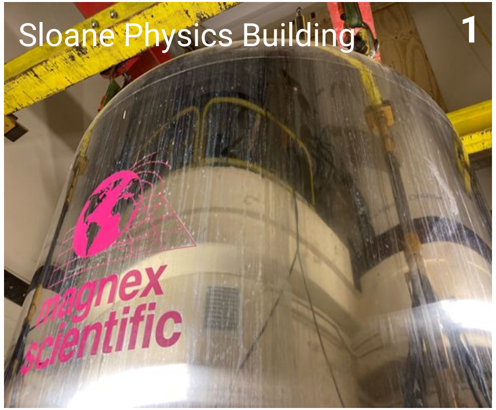


September 2023, Yale University

The first ALPHA Collaboration Meeting

Prospective space for ALPHA Experiment

alpha



1

Sloane Physics Building

2

3

4

Magnet Flyover!

5

ALPHA Magnet move
Saturday, March 9, 2024

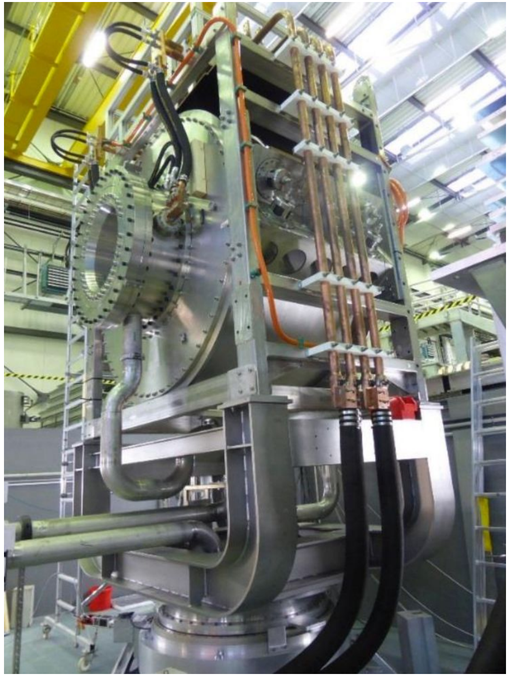
6

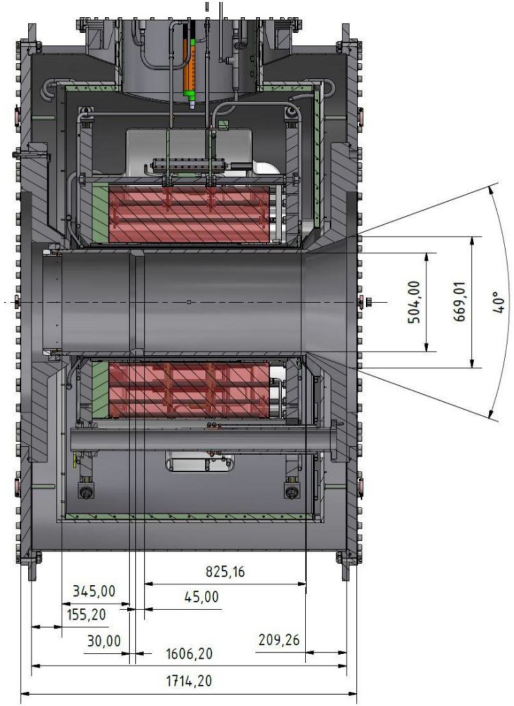
Wright Laboratory

7

Future phase of ALPHA – Oak Ridge

A future phase of ALPHA may use a large superconducting magnet from the Helmholtz Zentrum Berlin





- A 13-T magnet w/ 50-cm ⌀ × 170 cm
- Arriving at ORNL in 2024
- >10 years of scientific use

Collaboration status

alpha

Support is gratefully acknowledged from:

JOHN TEMPLETON FOUNDATION
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SIMONS FOUNDATION

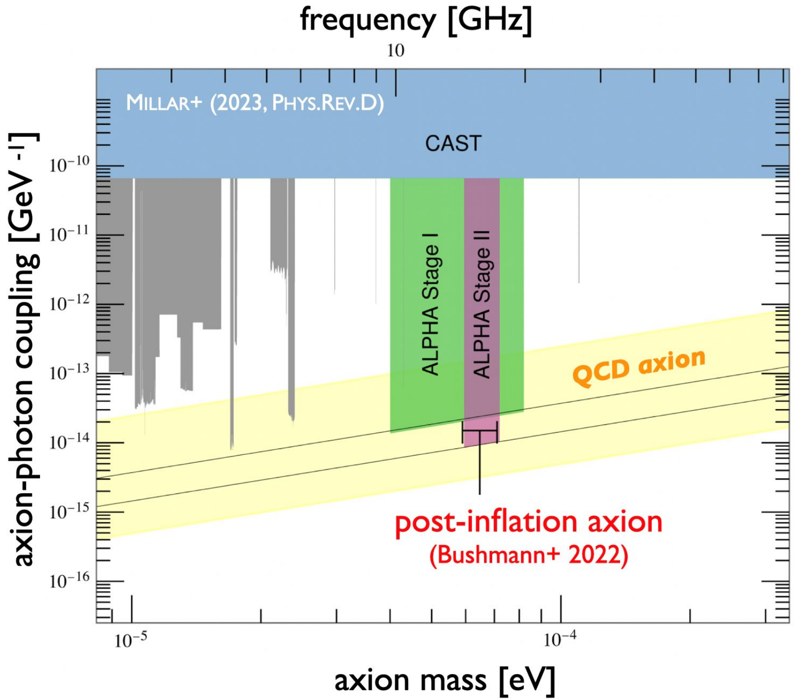
Knut and Alice Wallenberg Foundation

Swedish Research Council

Collaboration Institutions:
Yale University (Host)
Arizona State University
University of California Berkeley
University of Cambridge
Colorado University
Iceland University
ITMO University
Johns Hopkins University
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Stockholm University
Wellesley College

Project Scientist:
F. Wilczek (MIT/Stockholm University)
Project PI:
K. van Bibber (Berkeley)
Project Technical Director:
M. Jewell (Yale)
Spokes / deputy persons:
J. Gudmundsson (Stockholm University)
R. Maruyama (Yale)

Conclusions



Credit: Hiranya Peiris and Alex Millar

- Post-inflation axion one of two well-motivated mass ranges
- Recent calculations: ~15 GHz, 65 µeV (Buschmann et al., 2022)
- Out of reach of conventional haloscopes, but accessible to plasma haloscopes
- ALPHA to focus initially on 40-80 µeV
- Construction of ALPHA under way, experiment hosted at Yale in high-field superconducting magnet (16.4 Tesla)
- Commissioning 2026-27

Thank you!