Update on the ALPHA experiment
Phase 1

June 2, 2026
Axion Searches – IDM 2026

WELLESLEY
PHYSICS & ASTRONOMY

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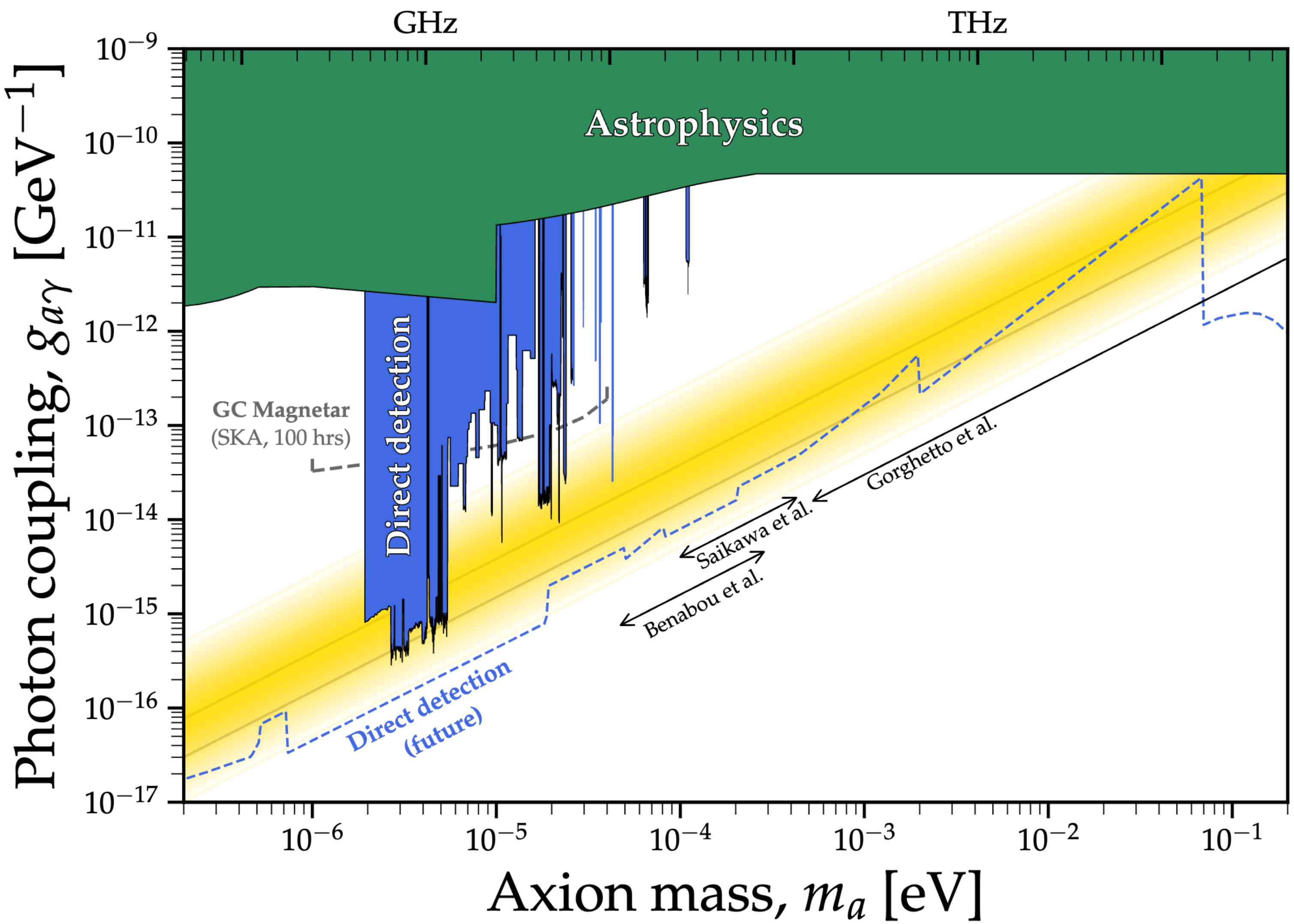
alpha

Post-inflationary axion

- Post-inflationary axion: PQ symmetry broken after inflation
- Major computational efforts to model and predict axion mass
- Recent results favor masses above 40 μeV e.g.:
    - Saikawa *et al.*, JCAP (2024)
    - Benabou *et al.*, PRL (2025)
- Search lower region via resonant haloscopes

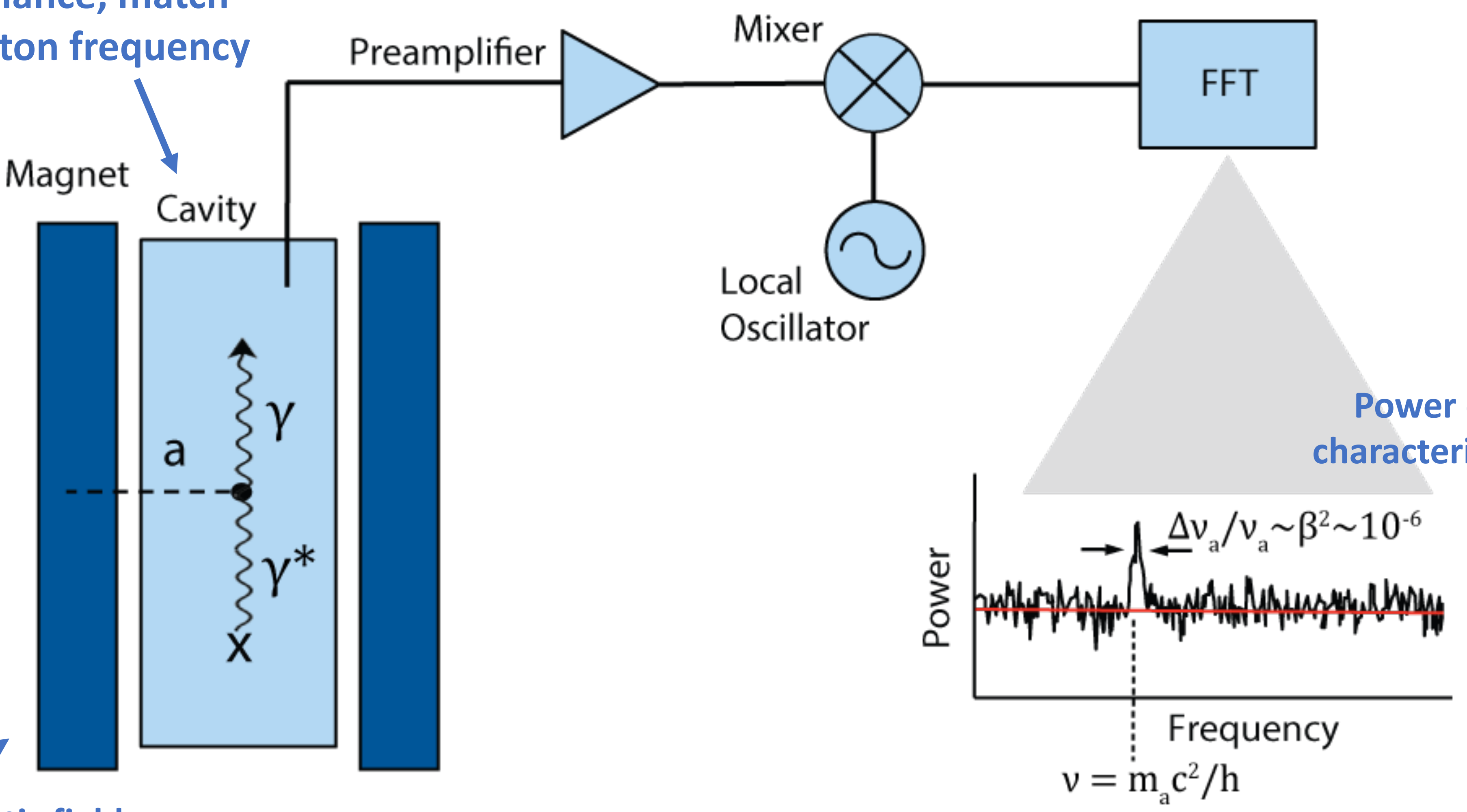
From Ciaran O'Hare, Axion Limits, https://github.com/cajohare



Haloscope overview

Tunable resonance, match converted photon frequency

Low noise readout chain



Power excess with characteristic lineshape

Strong magnetic field

Signal power and scan rate

- Haloscope signal power and scan rate depend strongly on cavity performance

Quality factor

$$P \propto B^2 \boldsymbol{V} \boldsymbol{Q}_{\boldsymbol{L}} \boldsymbol{C}_{\boldsymbol{nm\ell}} g_{a\gamma\gamma}^2$$

Cavity volume

Mode form factor

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

System noise temperature

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

System noise temperature

- Converted photon is polarized along the magnetic field direction
- Maximize signal power by using cavity mode with the same electric field direction
- Utilize TM_{010} cylindrical cavity mode

$$C_{nm\ell} = \frac{\left(\int E_z dV\right)^2}{V \int \varepsilon E^2 dV}$$

The high frequency challenge

- TM_{010} frequency scales inversely with radius:
  - 1 GHz cavity, ~11 cm radius
  - 10 GHz cavity, ~1 cm radius
- Cylindrical cavity volume *at minimum* scales as r^{-2}
- Reality is much worse, length must also decrease

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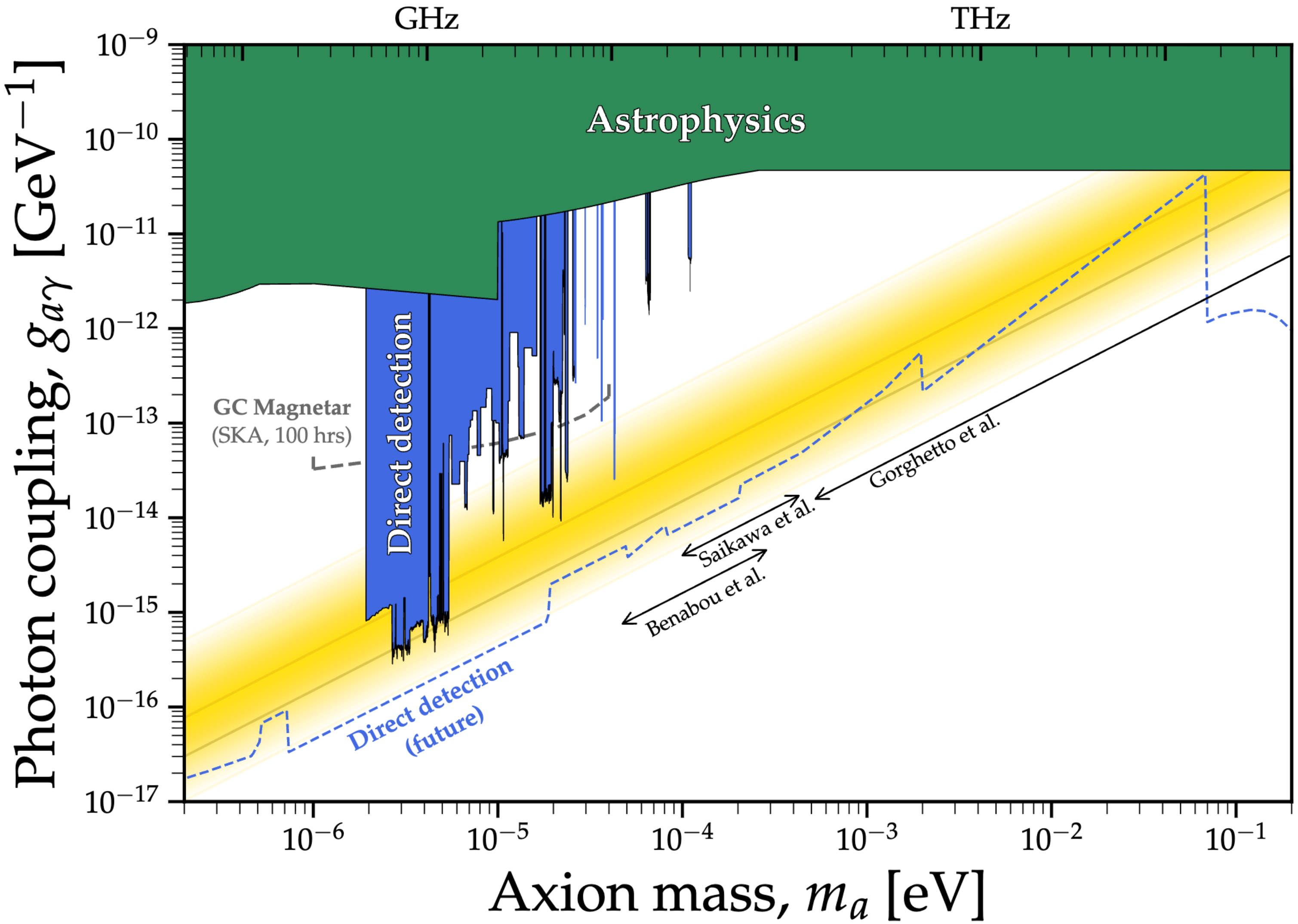
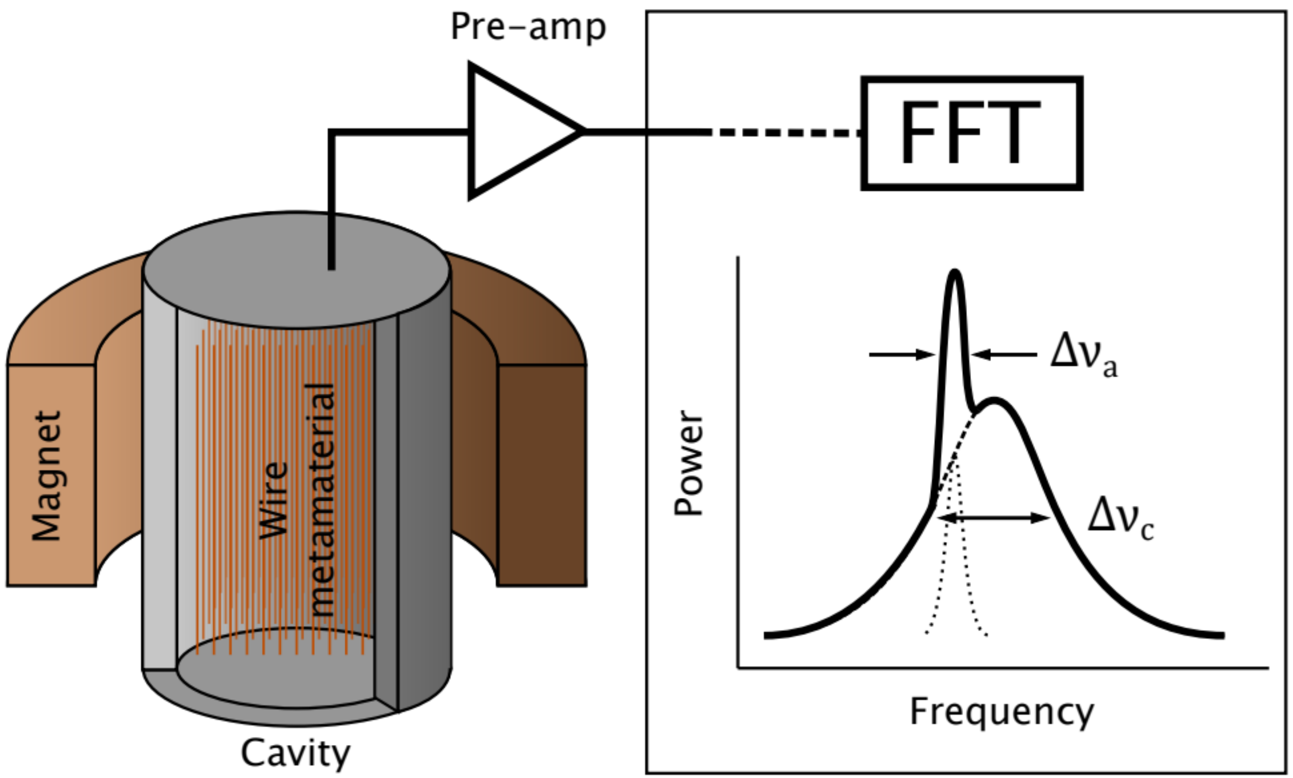


ALPHA (Axion Longitudinal Plasma HAloscope)

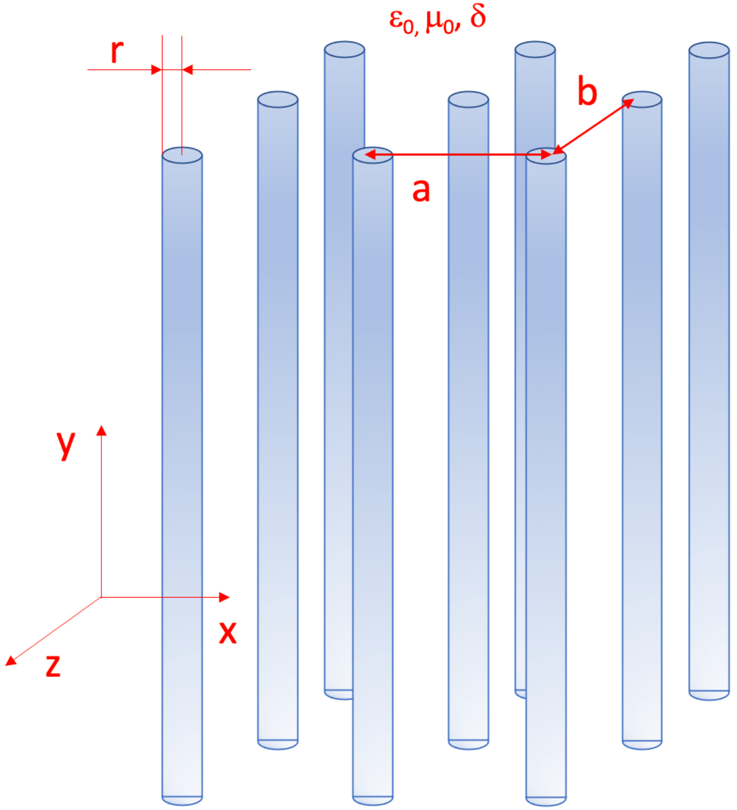
- ALPHA: metamaterial haloscope aimed at searching for the post-inflationary axion
- Metamaterial resonators: achieve large volume at high frequency
- Originally proposed in M. Lawson *et al.*, PRL **123** (2019), wire array metamaterial; white paper published in 2023: A. Millar *et al.*, PRD **107** (2023).
- Builds on expertise from HAYSTAC, see X. Bai *et al.*, PRD **113** (2026) and X. Bai *et al.*, PRL **134** (2025).
- Under construction at Yale University



N. Kowitt *et al.*, Phys. Rev. Applied **20** (2023)

Plasma resonator principle

- Wire-array metamaterial: period arrangement gives rise to a bulk mode
- Described by a plasma resonance determined by wire size and spacing
- Analytical model: P. A. Belov *et al.*, PRB **67** (2003)
- Haloscope proposal: M. Lawson *et al.*, PRL **123** (2019)



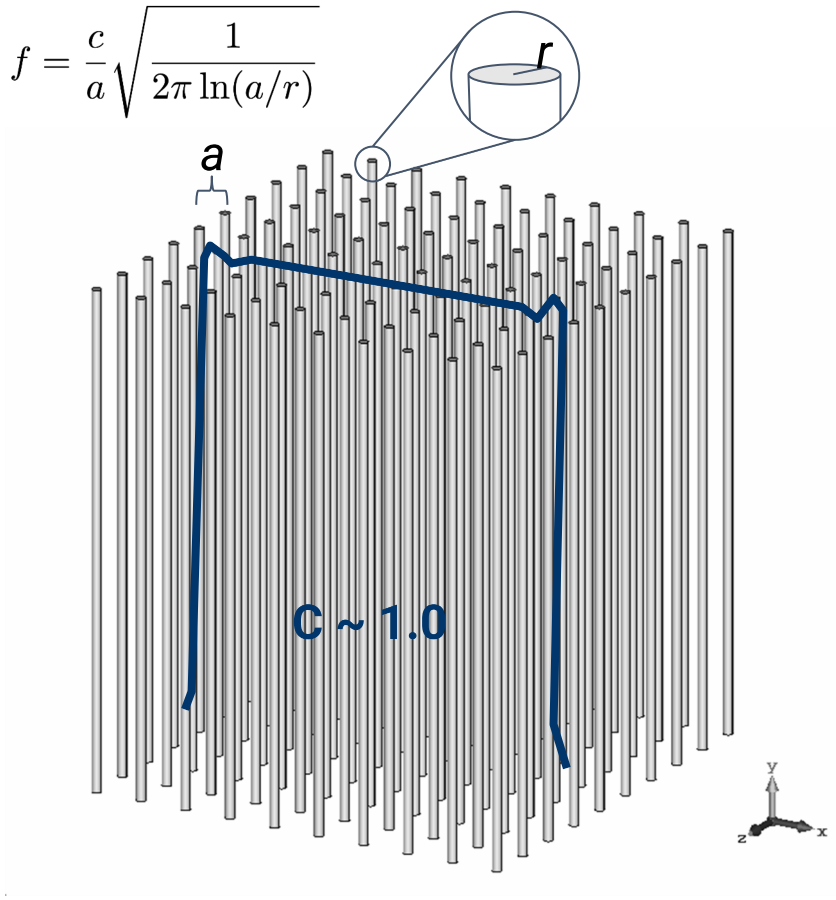
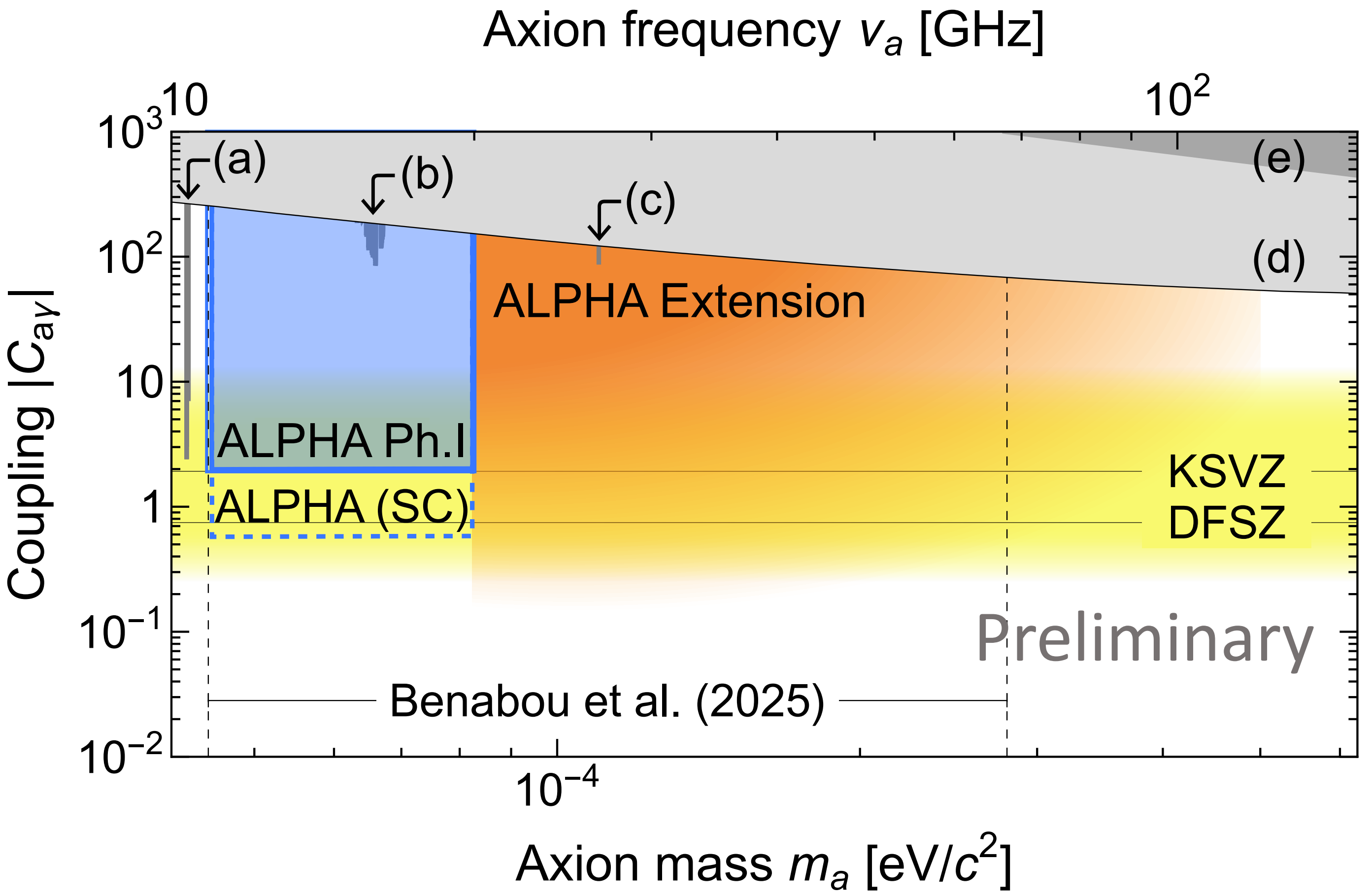


Figure by Jon Gudmundsson

ALPHA Phase 1

- Phase 1 targets the frequency range 10-20 GHz (~40-80 μeV)
- Will use a custom 9 T magnet from Cryogenic Limited; bore diameter 200 mm and length 1000 mm
- Multiple resonator designs/tuning mechanisms under development
- Low noise JPAs being developed to cover full range



Phase 1 resonator design

Rinnegan design: nested spiral of moving and fixed rods, all tuning from central post

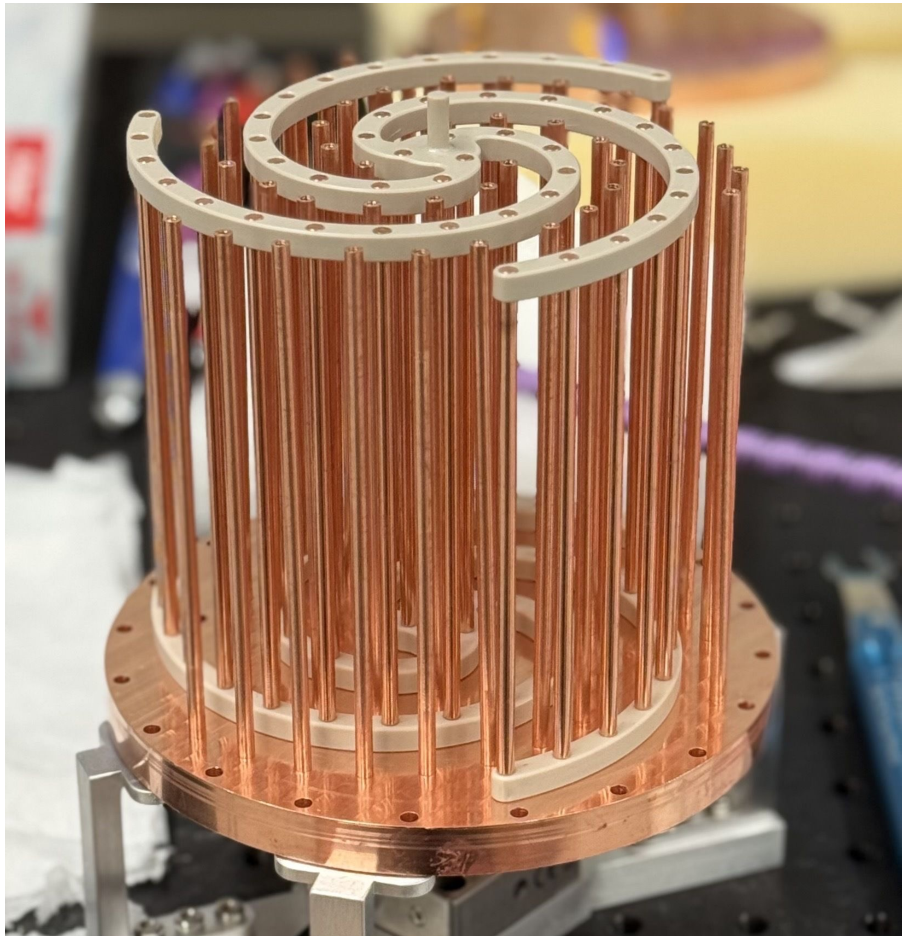
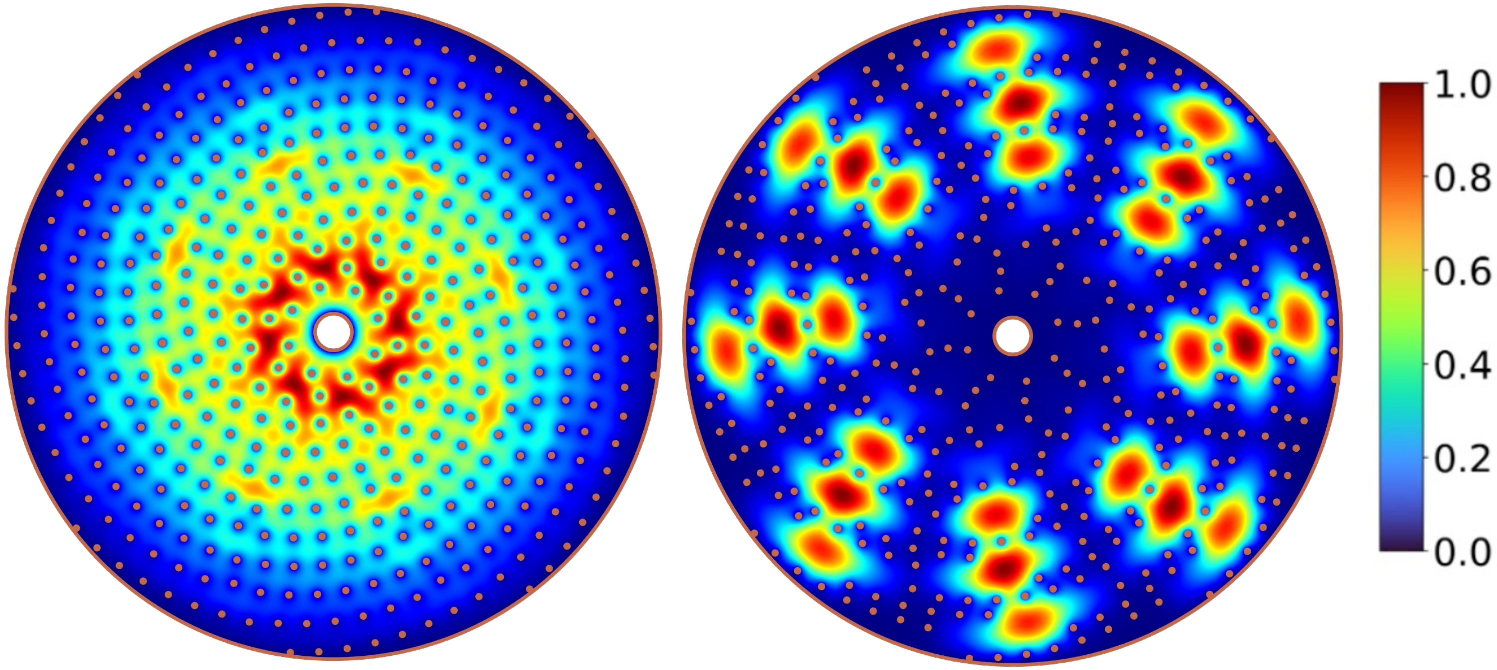


Photo courtesy Junu Jeoung

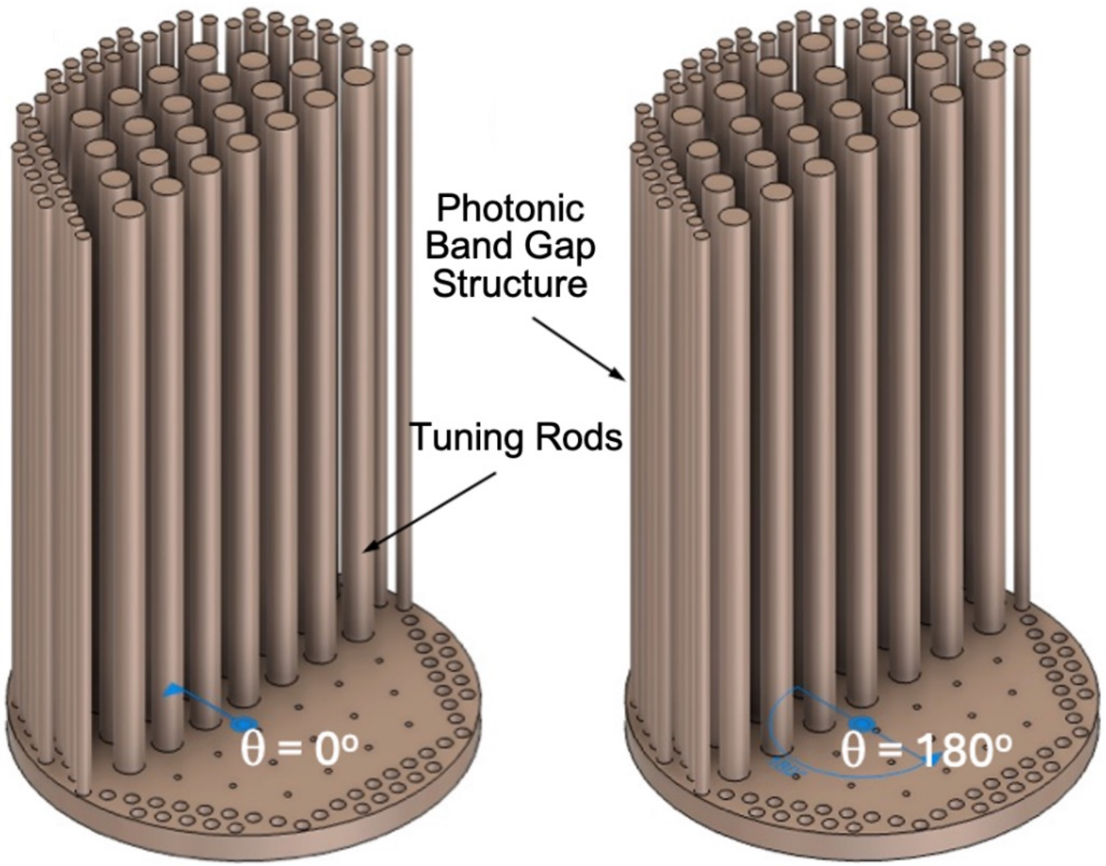


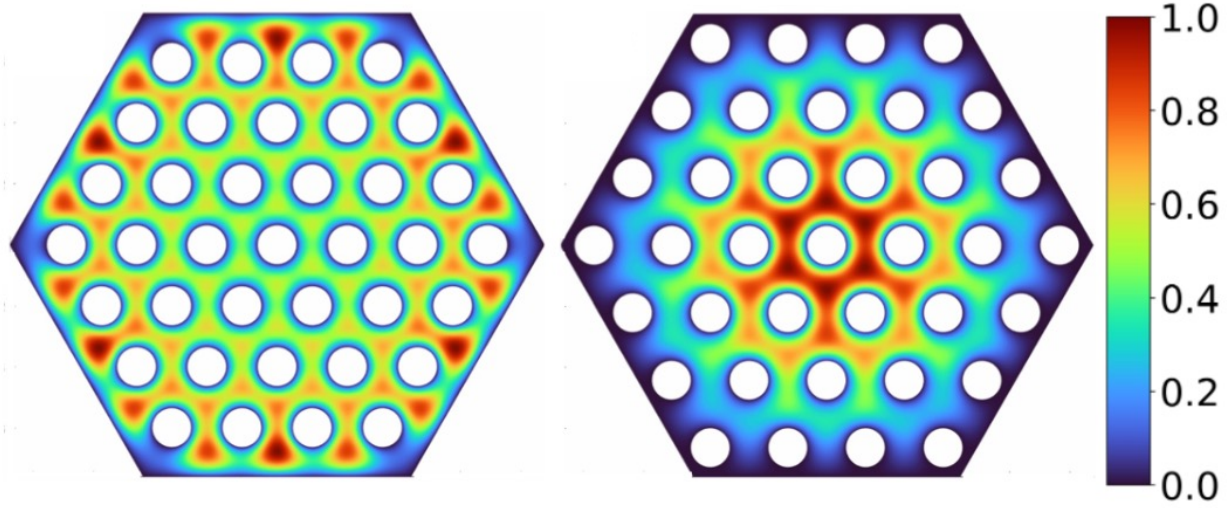
Increasing rotation

See talk by Jianyang Qi, Thursday at 12:45

Phase 1 resonator design

Symmetric lattice: rods with off-axis axles driven by one tuner, maintains triangular symmetry



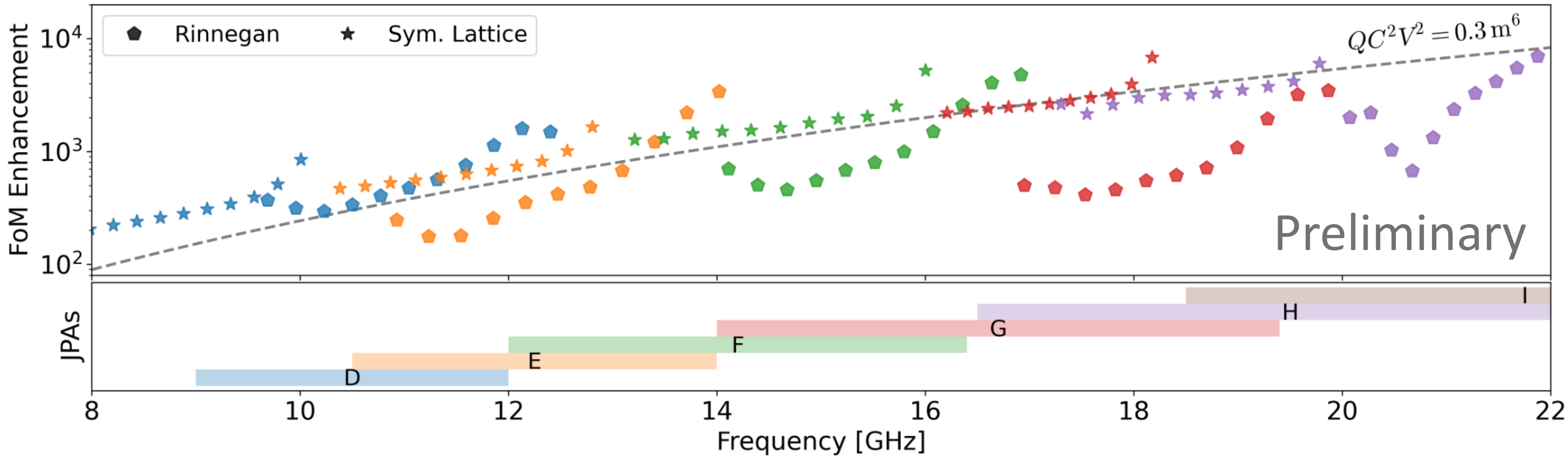


Builds off of HAYSTAC 7-rod tuning mechanism, uses PBG boundary to eliminate unwanted modes

(see D. Goulart *et al.*, RSI **96** (2025))

Resonator capabilities

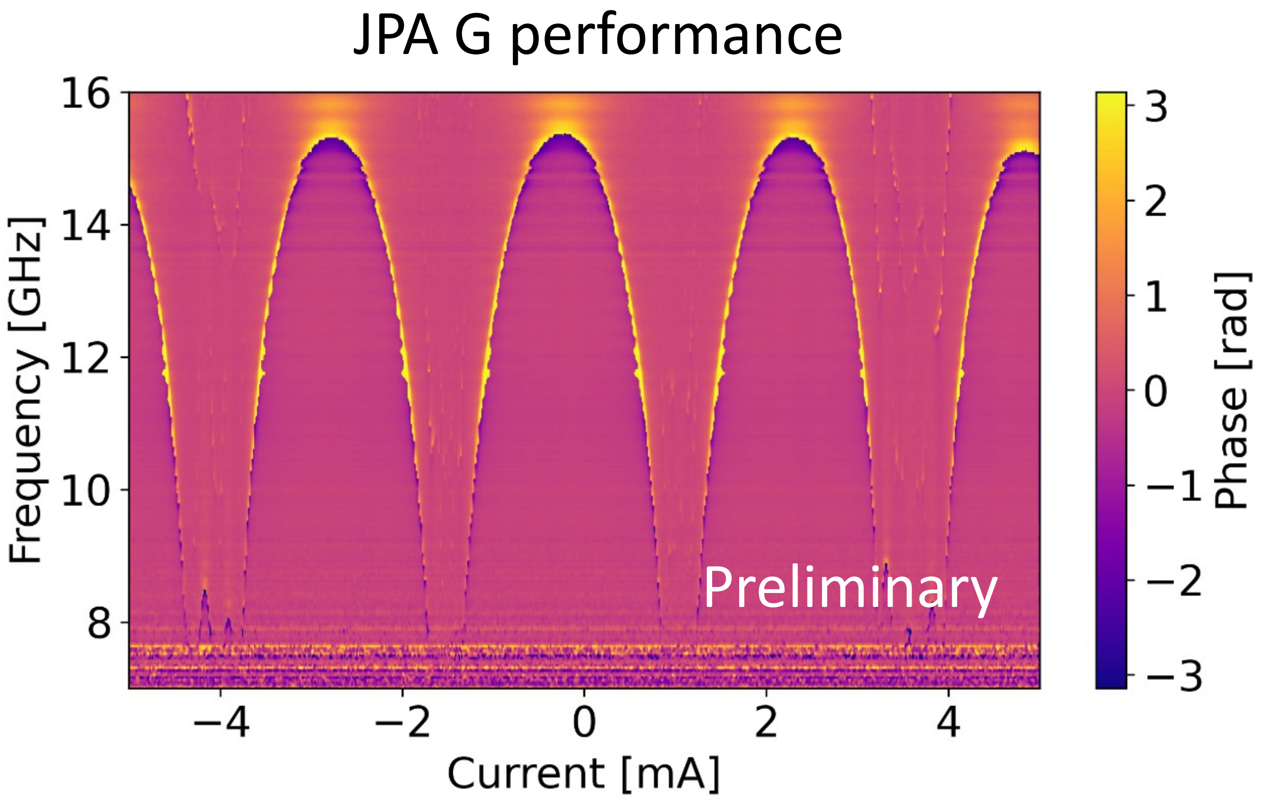
- Designs optimized based on V^2C^2Q figure of merit, assuming 500 mm heights
- Both designed to use as much of the magnet bore radius as possible
- Possible to scale designs, several cavities used to cover 10-20 GHz range



Readout

- Several JPA designs to cover full frequency range:

JPA	Design Freq. (GHz)
D	9.0—12.0
E	10.5—14.0
F	12.0—16.4
G	14.0—19.4
H	16.5—22.5
I	18.5—25.0



- Magnetic shielding design uses the same technique as HAYSTAC: active field cancellation coil, persistent superconducting coils, multi-layer shielding can

Current status

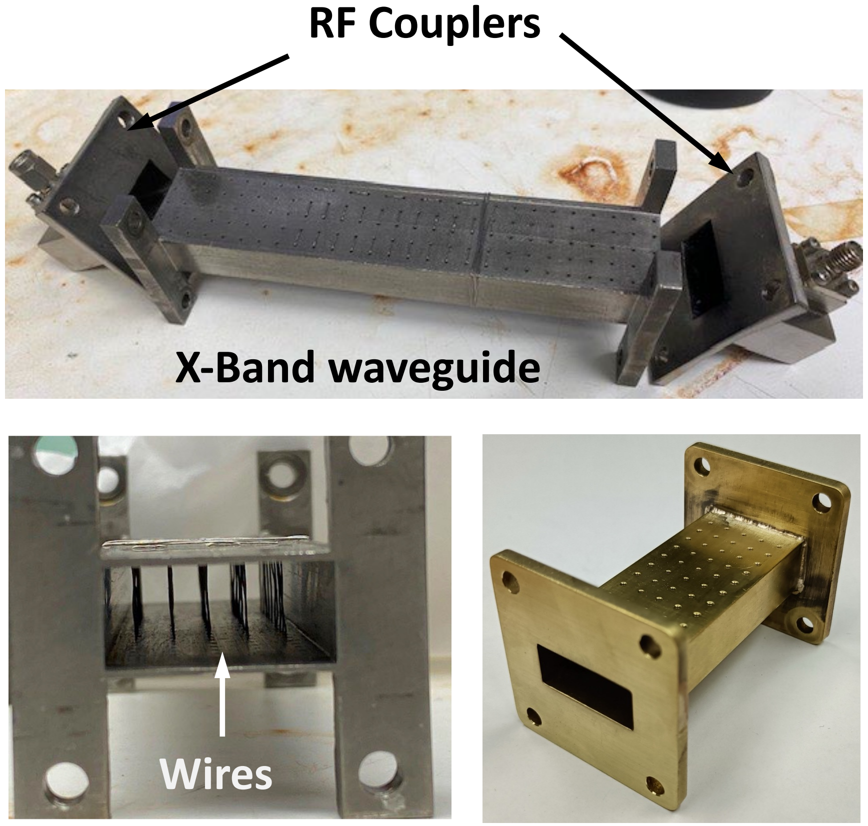
- Construction is underway at Yale Wright Lab!
- Currently commissioning for dark photon run using a prototype cavity with spiral tuner design
- Resonator design being finalized, beginning production soon
- Magnet delivery and full commissioning in 2027
- Physics data taking to begin in 2028

Beyond Phase 1: R&D for higher frequency reach

- ALPHA is already thinking beyond 20 GHz! New technology is needed:

- Readout technology:
  - JPA development above 20 GHz is extremely challenging
  - Exploring kinetic inductance-based devices for frequency downconversion
  - Rydberg atom-based photon detection, E. Graham *et al*., PRD **109** (2024)

- Resonator technology:
  - Above 20 GHz would require true wire arrays, high surface area to volume ratio and greater losses
  - Exploring MgB_2 superconducting wire arrays to achieve high Q



Tests with waveguide-mounted wire-array metamaterials: Cu, Nb, MgB_2 (250 μ wires)
(Photos courtesy Karl van Bibber)

ALPHA Collaboration

First collaboration meeting in 2023

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:
Frank Wilczek (MIT/Stockholm University)
Project PI:
Karl van Bibber (Berkeley)
Project Technical Director:
Max Silva-Feaver (Yale)
Spokes / deputy persons:
R. Maruyama (Yale)
J. Conrad (Stockholm University)

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ALFRED P. SLOAN FOUNDATION
GORDON AND BETTY MOORE FOUNDATION
Knut and Alice Wallenberg Foundation
Swedish Research Council
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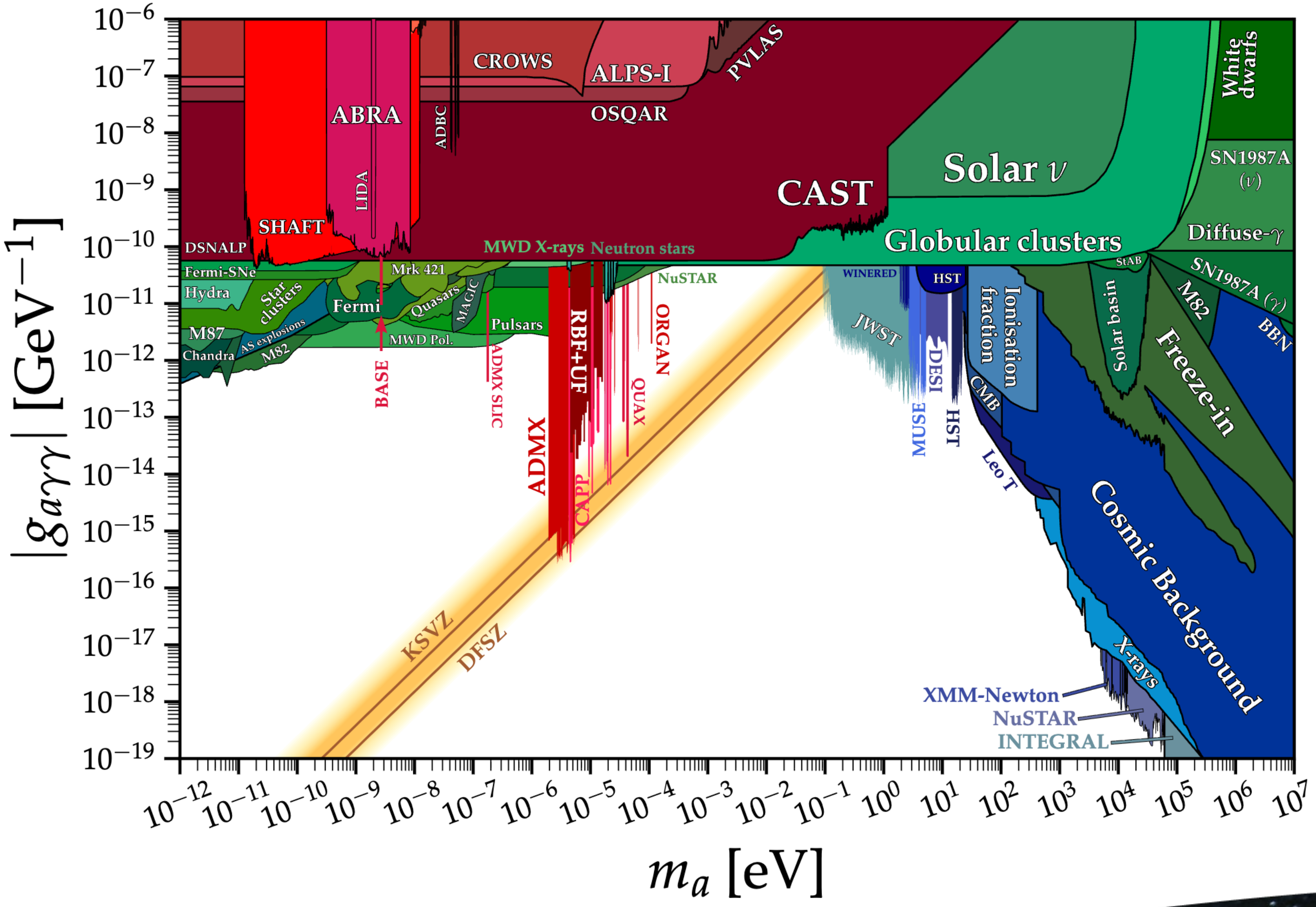
Questions?

Email: sl128@wellesley.edu

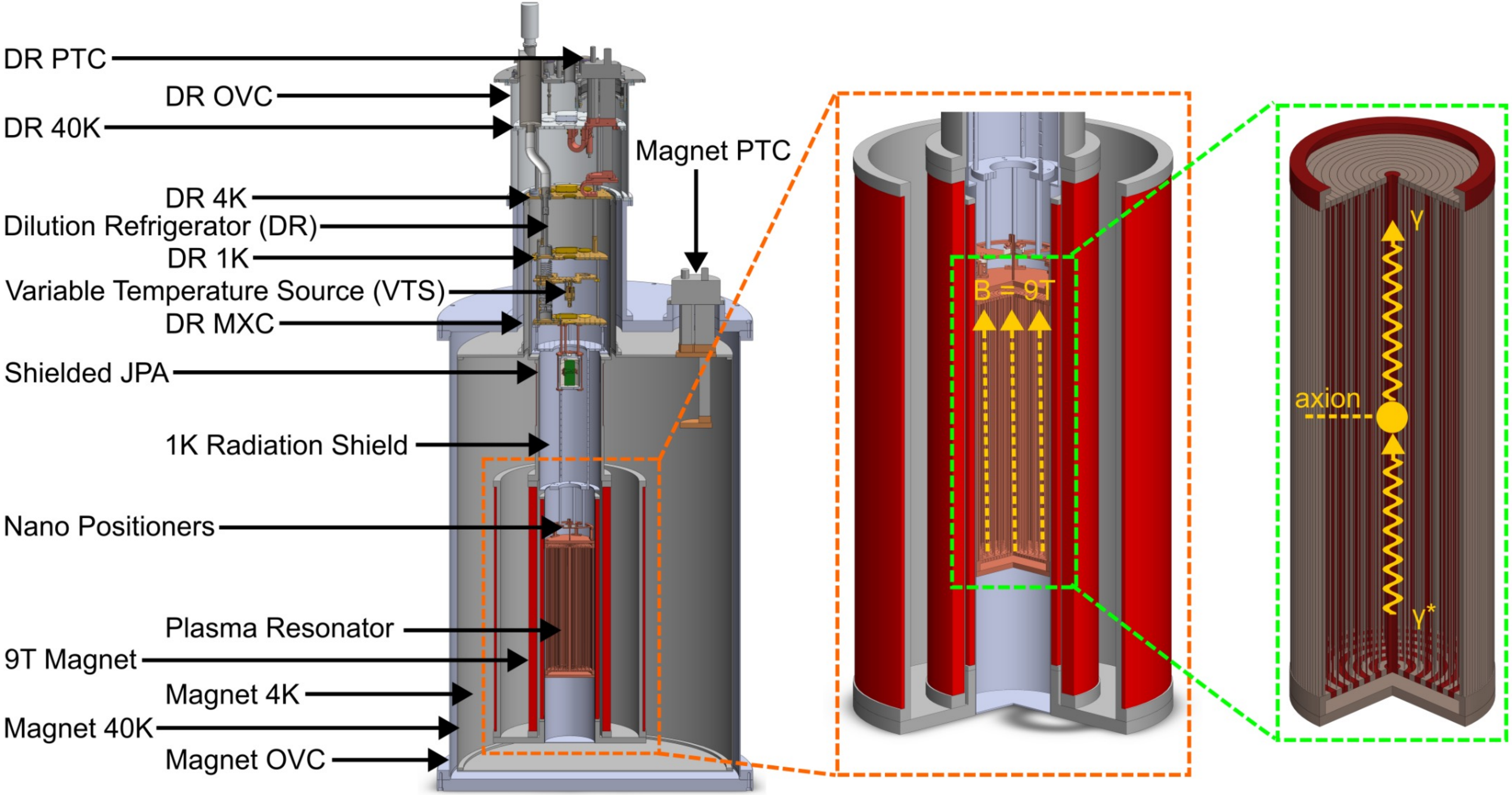
Backup slides

Axion-photon coupling parameter space

From Ciaran O'Hare, Axion Limits, https://github.com/cajohare



Magnet and cryostat design



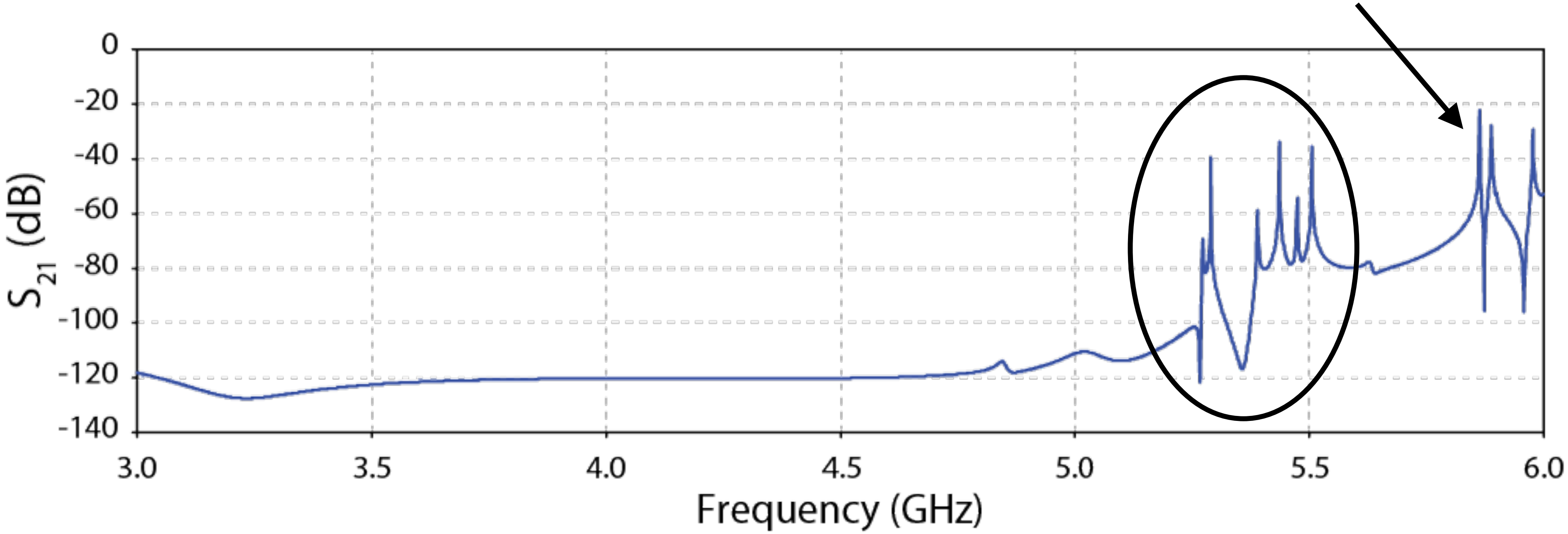
Mode crossing problem

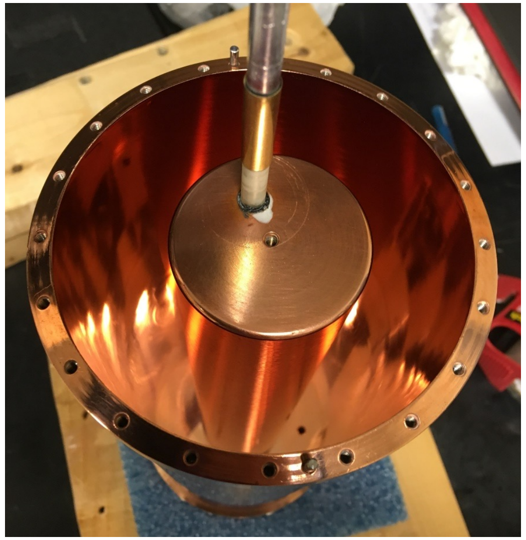
Mode crossings

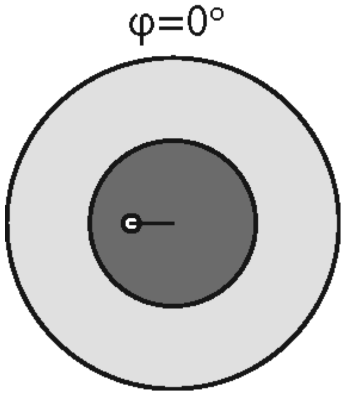
- Tuning rod does not affect TE/TEM modes
- Modes hybridize, reducing form factor
- Regions of tuning range become unusable for data collection

Rod in center (maximum frequency)

TM$_{010}$ mode







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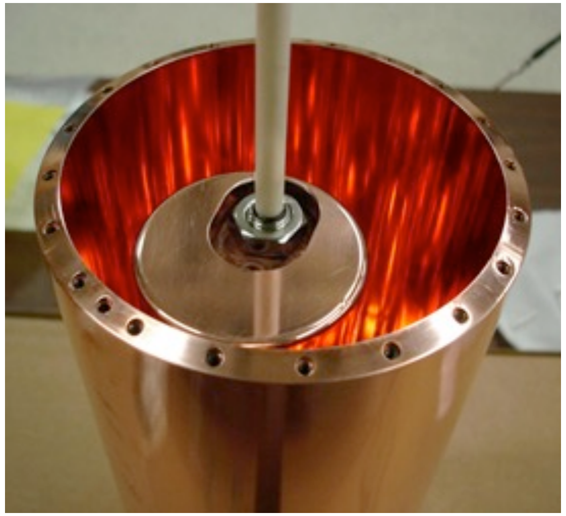
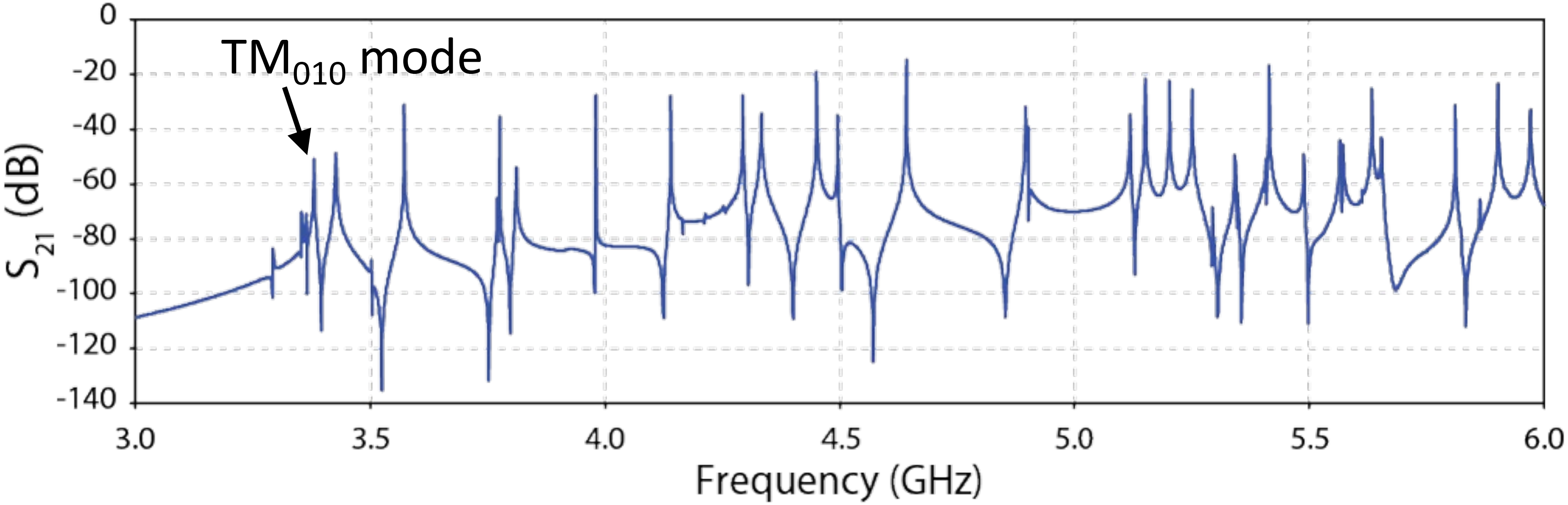
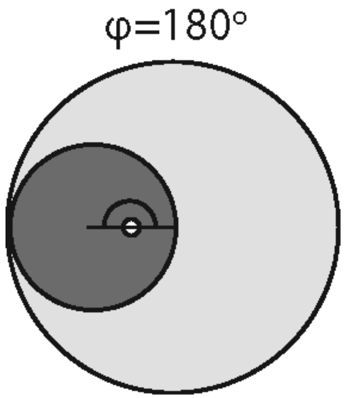


Rod at wall (minimum frequency)





Photonic band gap structures

- Photonic band gap (PBG) resonators: selective mode confinement based on lattice design
- Multiple phases of study:
  - Demonstration of simple tuning
  - Simplified single rod structure
  - Multi rod tuning
  - Exploration of limits of operation