The Plasma Axion Haloscope & the ALPHA Collaboration

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on behalf of the ALPHA collaboration

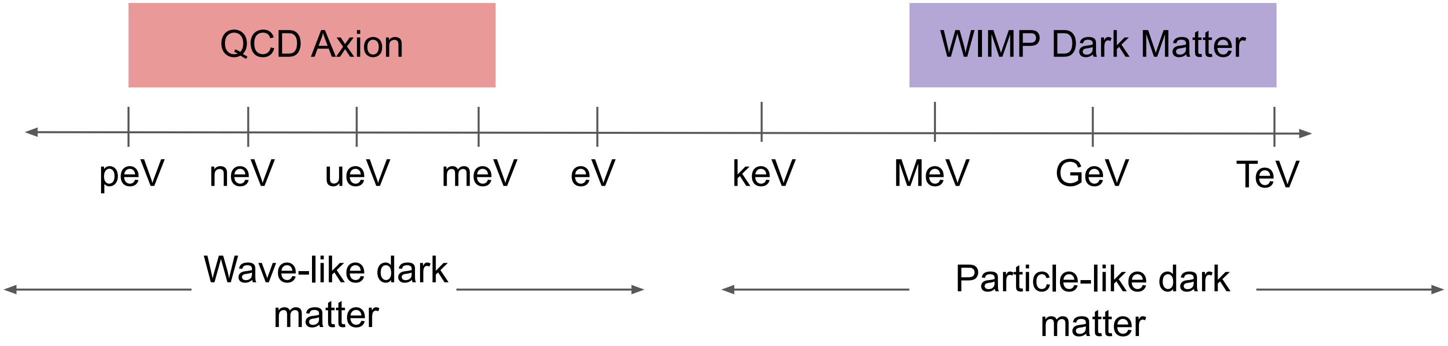
LBNL Instrumentation Brown Bag Seminar

Outline

- Axion Dark Matter
- Experimental methods for axion detection
- Plasmon-axion coupling
- Wire metamaterial plasma haloscope
- ALPHA Collaboration
    - Theory/Simulation
    - Superconductors
    - Metamaterial
    - Antenna and Readout

Axion Dark Matter

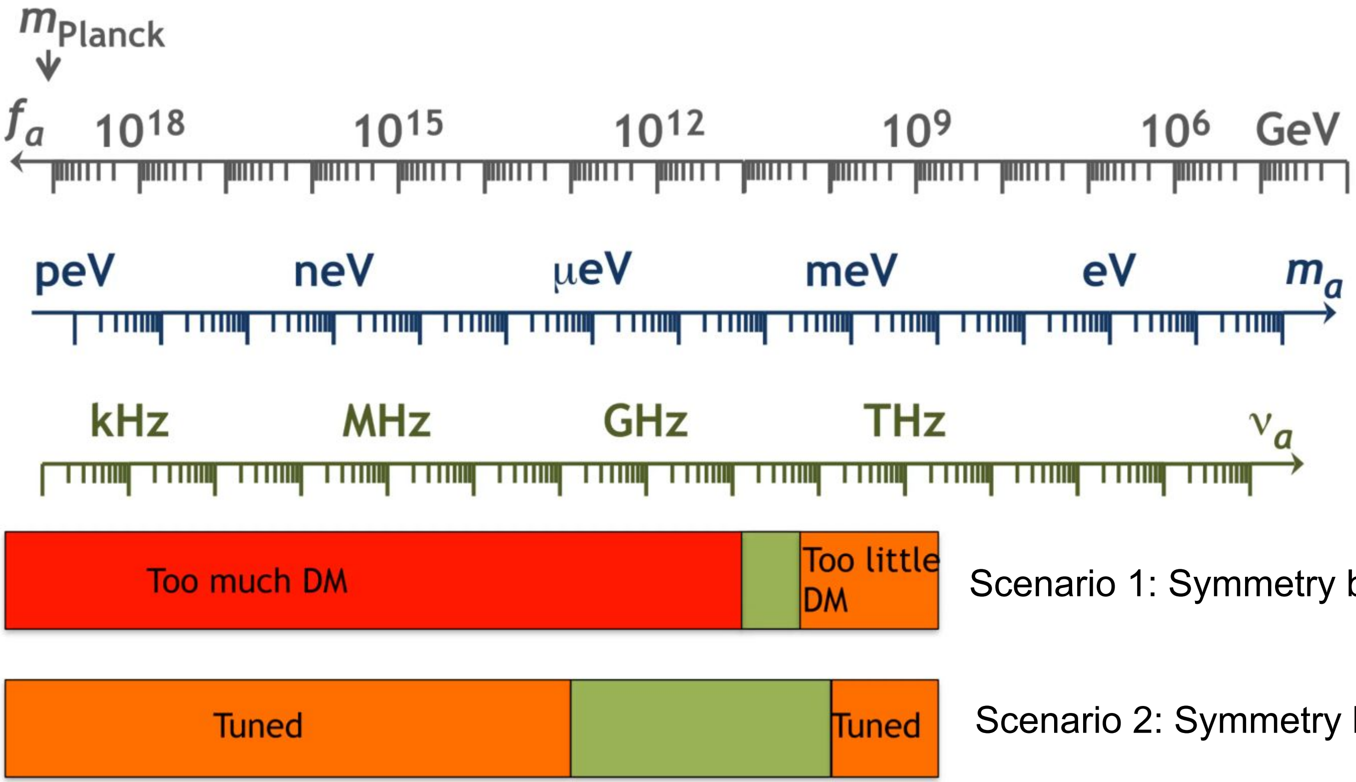
- Dark Matter parameter space spans 84 orders of magnitude!
- QCD axion wave-like, detect as a classical field rather than a single particle



Axion Dark Matter

- QCD axion proposed by F. Wilczek in response to PQ solution to the Strong CP puzzle
- Theta term in the standard model is potentially CP violating
- Problem is that theta is strongly constrained to be close to 0 (10^-10) by nEDM experiments
- PQ solution makes theta dynamical rather than a fixed value
- Result is pseudo-goldstone boson with a small mass - the axion
- Kills two birds with one stone
    - Solution to Strong CP puzzle
    - Candidate for dark matter

Axion Dark Matter



Scenario 1: Symmetry broken after Inflation

Scenario 2: Symmetry broken before Inflation

arXiv:2111.09892
arXiv:2108.05368

Axion Detection

- Common coupling to detect in axion experiments is axion-photon coupling with a mediating magnetic field
- But axion has a mass and the photon doesn’t, How to conserve energy and momentum?

Axion Detection

- Impose boundary conditions on photon modes (Cavity and dielectric haloscopes)
- Relativistic axions (LSW, Helioscopes)
- Probe axions much larger than your system (ABRACADABRA, DM Radio)
- Use another coupling (CASPEr, ARIADNE, QUAX, etc.)
- **Give photon a mass** by using an appropriate medium (ALPHA, TOORAD)
  - Decouples the volume of the detector from the mass of the axion
  - Breaks tyranny of $V \sim 1/\omega^3$ scaling
  - Using a plasma you can reach **higher masses without sacrificing volume**

Axion-plasmon coupling

- In plasma, photon has a tunable mass
- Axion couples to E&M as $aE \cdot B$
- Primary effect of axion is to act like an oscillating current, driving the system at ω_a
- In presence of DC B-field, axion induces plasmon excitations
- Resonance when $\omega_p = \omega_a$
- Enhancement of the E field is not related to boundary conditions
- Limited by losses ($\boldsymbol{\Gamma}$)

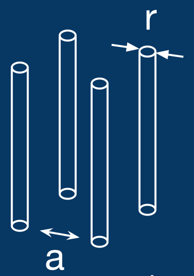
$$\mathbf{E} = -\frac{g_{a\gamma}\mathbf{B}_{\mathrm{e}}a}{\epsilon} = -g_{a\gamma}\mathbf{B}_{\mathrm{e}}a\left(1 - \frac{\omega_p^2}{\omega_a^2 - i\omega_a\Gamma}\right)^{-1}$$

What do you want in a plasma?

- Cryogenic temperatures
- Tunable plasma frequency
- Large volume
- Lower plasma frequency than typically in nature
- Low-losses / long plasmon lifetimes

Wire Metamaterials

- A finite volume of wires with thickness less than the wire spacing acts as an effective medium [1], [2]
    - so-called 'Wire Metamaterial'
- Plasma frequency related to electron density and effective mass of the electrons
- Plasma frequency set by the mutual inductance of the wires,
    - i.e. inter-wire spacing
- cm spacings → GHz frequencies
- Q of resonance depeneds on resistive and radiative losses
- Higher freq -> higher Q
- Volume limited by the coherent volume of the axion
    - Practically speaking limited by volume of magnet you can find

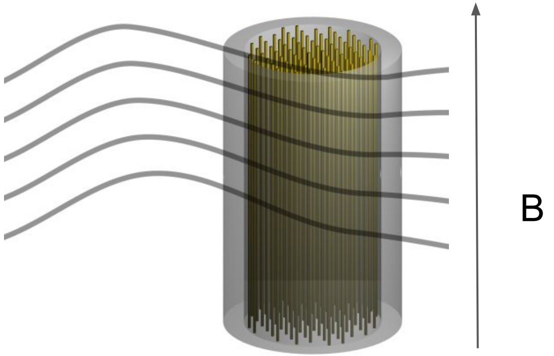


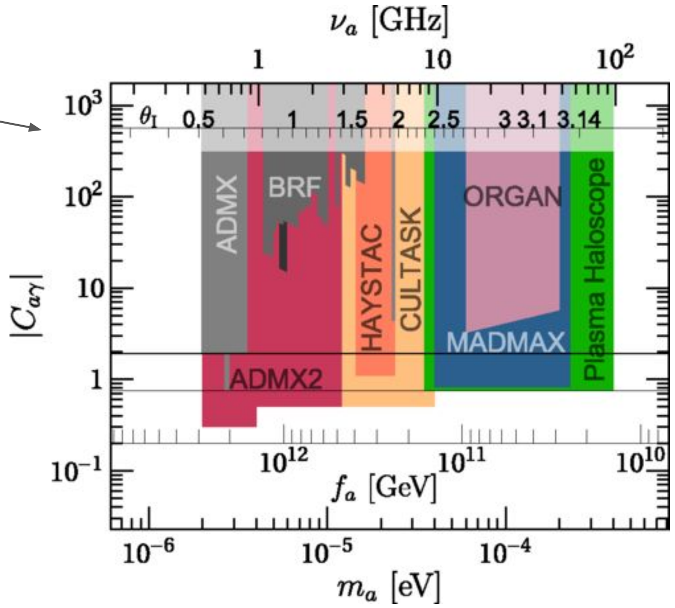
$$\omega^2_p \propto \frac{1}{a^2 \log(a/r)}$$

[1] J.B. Pendry et al. J. Phys. Condens. Matter 10, 1998
[2] P. Belov et al. Phys. Rev. B 67, 113103 2003

Plasma Haloscope

- Proposed in Phys Rev Lett.123.141802 by M. Lawson, A. Millar, M. Pancaldi, E. Vitagliano, F. Wilczek
- Wire metamaterial chosen as target medium
- Competitive in region 10–100 GHz
  - Assuming T=4K, B=10T, V=0.8m^3, Q=100, 6 years measurement time





Open Questions

- Can we get reasonable Q factors for the metamaterial?
- Can we tune the metamaterial?
- Can we effectively couple an antenna to the resonance and read it out?

ALPHA Collaboration

- ALPHA formed with aim to answer these questions and build a tunable, cryogenic plasma haloscope
  - First full-scale demonstrator for the feasibility of the detection of axion-plasmon coupling
- International and multi/inter-disciplinary. Collaborators with broad range of backgrounds
  - Condensed matter
  - High energy physics
  - CMB experiments,
  - Superconductors
- Theorists and experimentalists

ALPHA Collaboration - Steering Committee

Matthew Lawson
Spokesperson

Alexander Millar
Theory Coordinator

Hiranya Peiris
Funding Coordinator

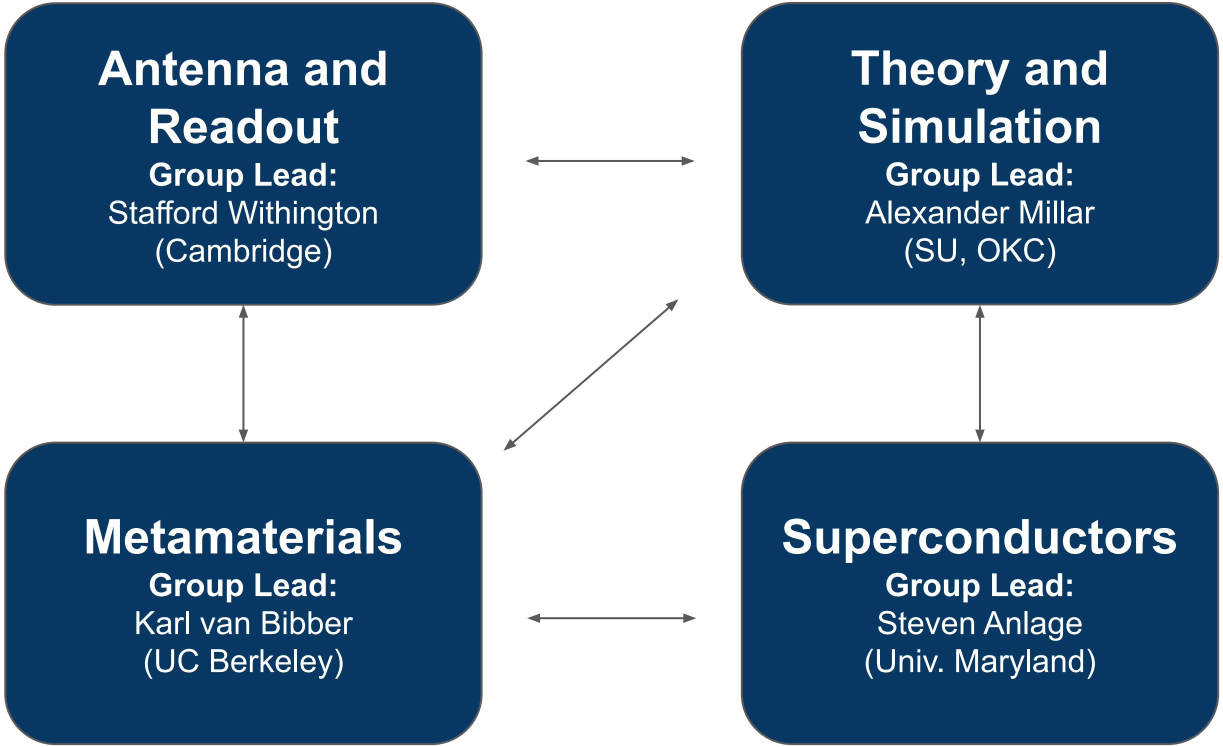
Pavel Belov (ITMO)
At-Large Member

Jón Gudmundsson
Technical Coordinator

Frank Wilczek
Project Scientist

Karl van Bibber (UC Berkeley)
At-Large Member

ALPHA Collaboration - Working Groups



Antenna and Readout
Group Lead:
Stafford Withington
(Cambridge)

Theory and Simulation
Group Lead:
Alexander Millar
(SU, OKC)

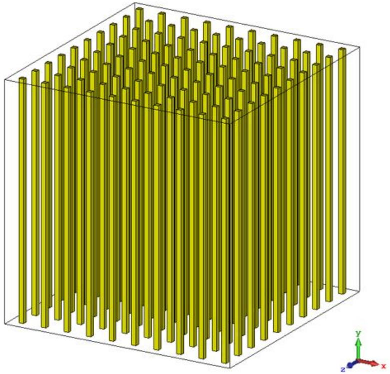
Metamaterials
Group Lead:
Karl van Bibber
(UC Berkeley)

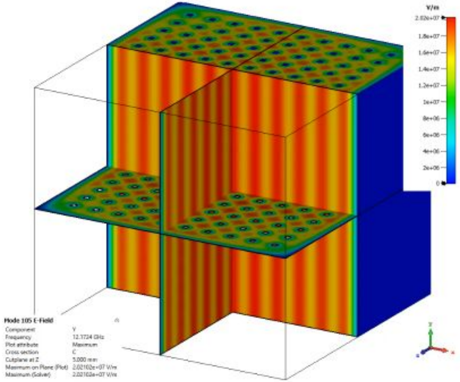
Superconductors
Group Lead:
Steven Anlage
(Univ. Maryland)

Theory and Simulation Working Group

- Focused on simulations to understand metamaterial properties and antenna-system coupling
- Show achievable Qs ~3500, more than an order of magnitude than assumed for initial paper
- Simulations help with identification of modes of interest (TM mode along the axis of the wires) and complications from mode mixing and crowding
- Simulation of tuning mechanism show potentially 30% tunability

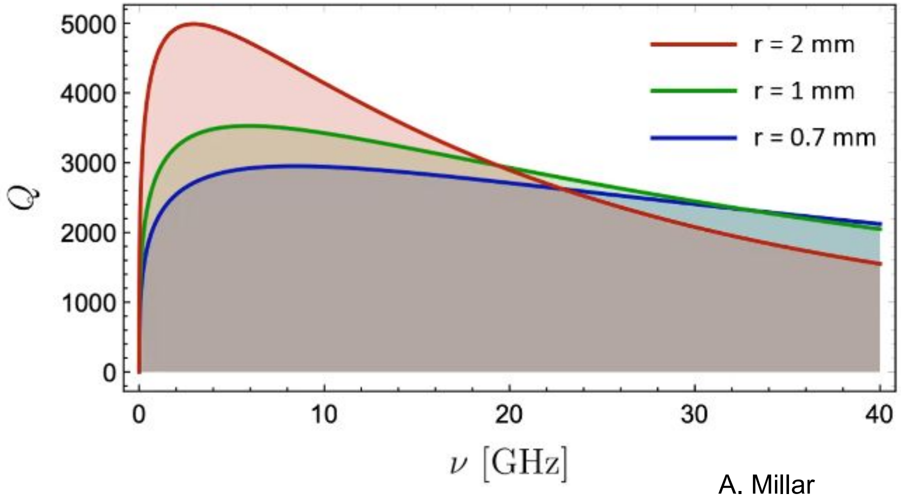
Members	
Pavel Belov (ITMO)	Alex Millar (SU)
Andrea Gallo Rosso (SU)	Tove Klaesson (SU)
Jón Gudmundsson (SU)	Mackenzie Wooten (UCB)
Sid Morampudi (ASU)	Rustam Balafendiev (ITMO)





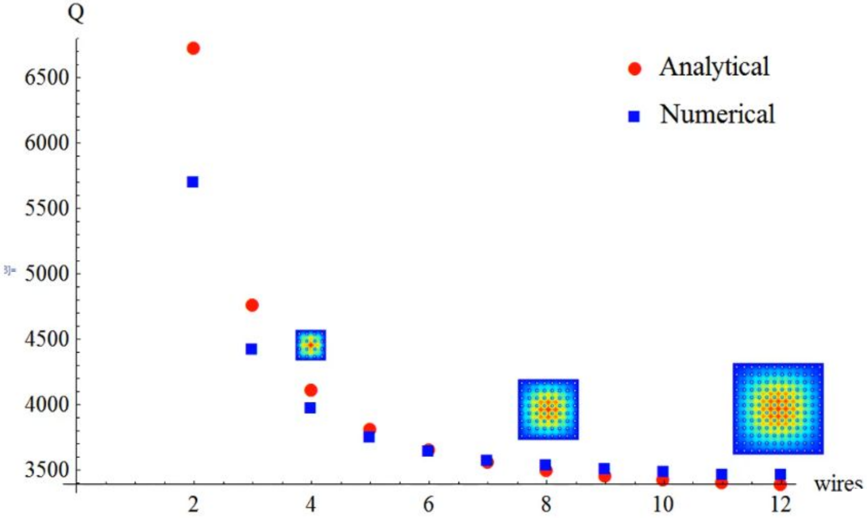
Q Factor Wires

Radius of Wires



A. Millar

Number of Wires



R. Balafendiev

Katie Dunne

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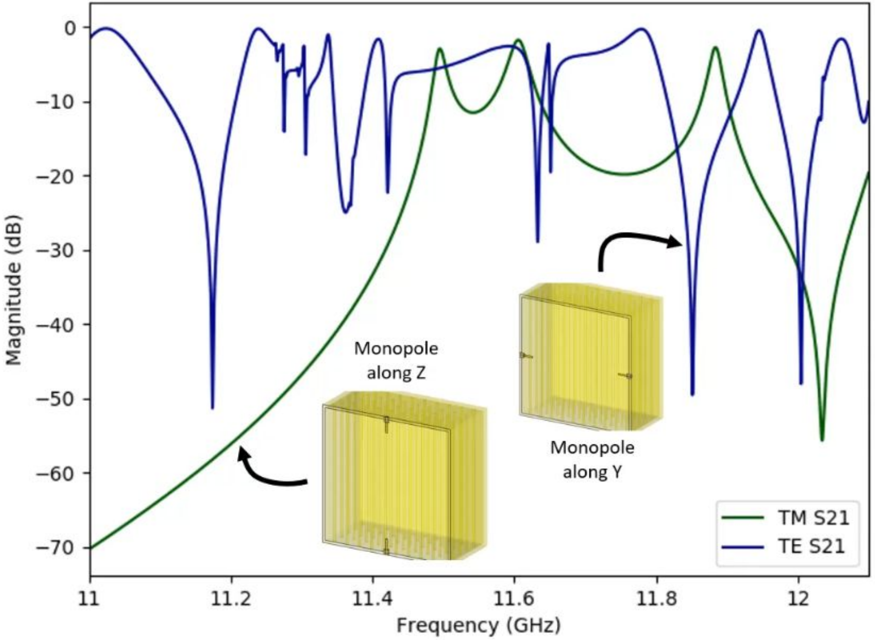
TE and TM Modes

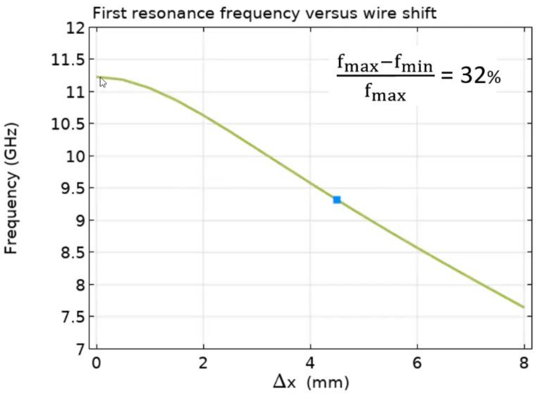
- Other than TM modes, TE modes are present
- Cavity imperfections can cause mixing of modes
- Simulations show TE modes can be ignored with antenna placement

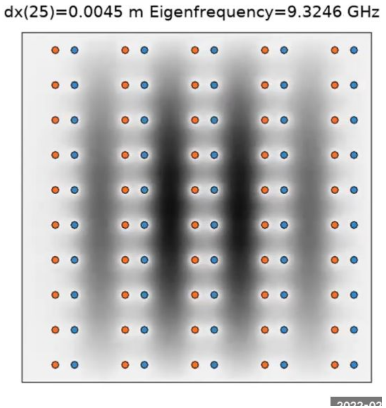


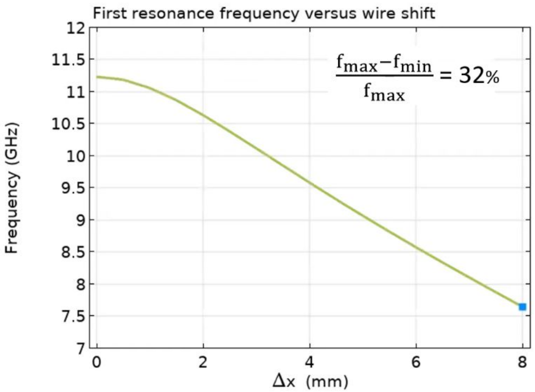
R. Balafendiev

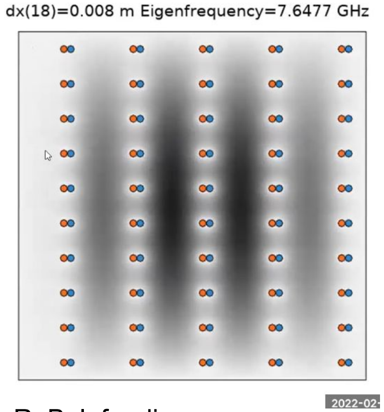
Mechanical Tuning

- Simulation of tuning mechanism with 1D shift of plane spacing
- Show potentially **30% tunability**









R. Balafendiev

Superconductors Working Group

- Focused on non-mechanical tuning by adjusting kinetic inductance of wires
- Feasibility studies - promising avenue with experimental challenges [3]
- Superconducting wires have been demonstrated in the literature with
  - Low ohmic losses at mm-wave frequencies
  - High Q resonance in 6T parallel field
  - Microwave resonance as narrow (<100nm) and thin (<10nm) wires
- Tunability of inductive properties has been demonstrated through:
  - Kinetic inductance by means of temperature, dc current, or dc flux
  - Josephson inductance by means of temp, dc current, or dc flux

Members
Steven Anlage (U. Maryland)
Henrik Røising (SU)
Philip Mauskopf (ASU)
Alex Millar (SU)
Matthew Lawson (SU)

[3] M. Trepanier et al. AIP Advances 9, 105320 (2019)

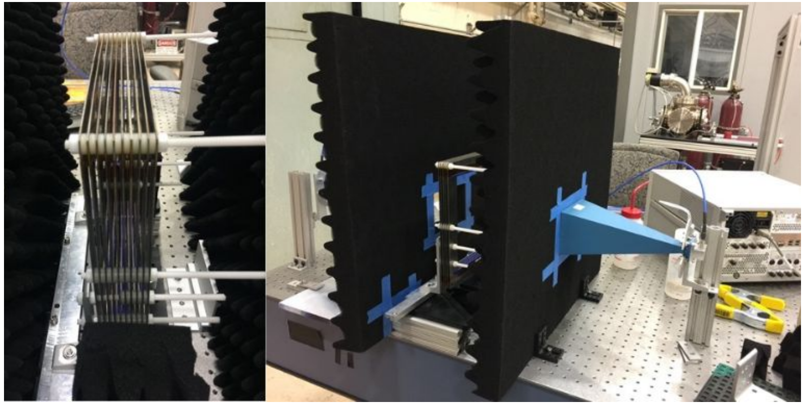
Metamaterials Working Group

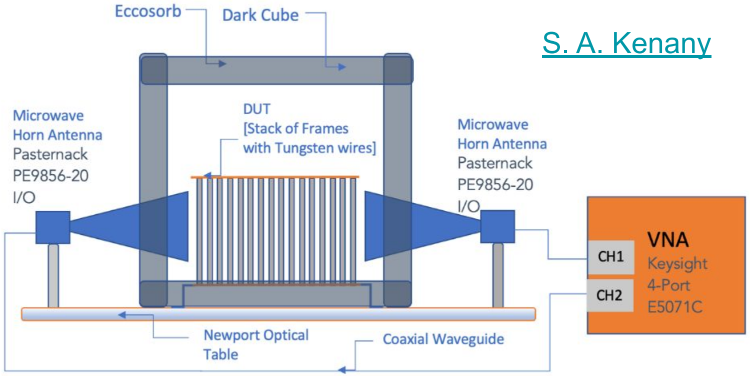
- Focused on building prototypes
- 3 prototypes constructed UCB, ITMO, SU
- Purpose of prototypes
  - Mechanical tuning - Berkeley
  - Metamaterial properties - ITMO
  - Antenna R&D - Stockholm

Members
Pavel Belov (ITMO)
Katie Dunne (SU)
Jón Gudmundsson (SU)
Mackenzie Wooten (UCB)
Alex Millar (SU)
Karl van Bibber (UCB)
Matthew Lawson (SU)

Berkeley Prototype

- Goals
  - S21 measurements on wire metamaterials
  - Determine parameters compare with sim
  - Investigate mechanical tuning schemes
  - Build tunable engineering prototype
- 40 frames
- 20 50um Tungsten wires each frame





S. A. Kenany

Katie Dunne

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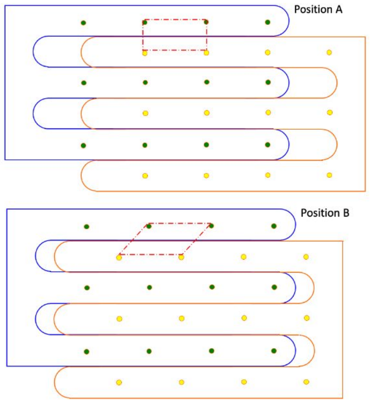
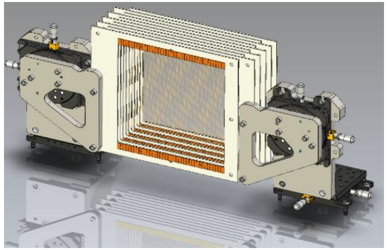
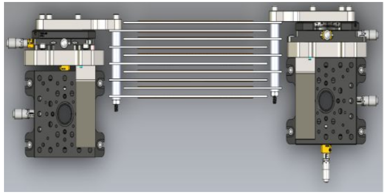
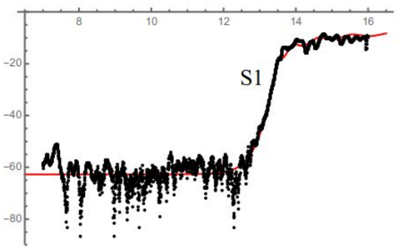
Plane Spacing and Plasma Frequency

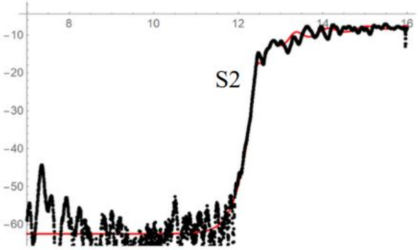
- Metamaterial behavior observed
- Working on implementing new frame geometries for sliding frames relative to one another

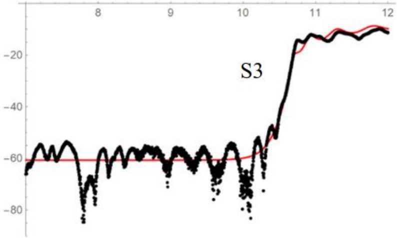


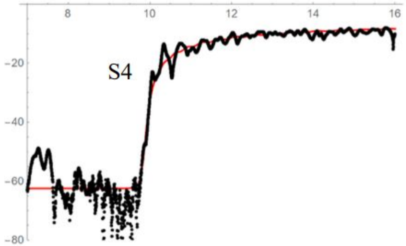








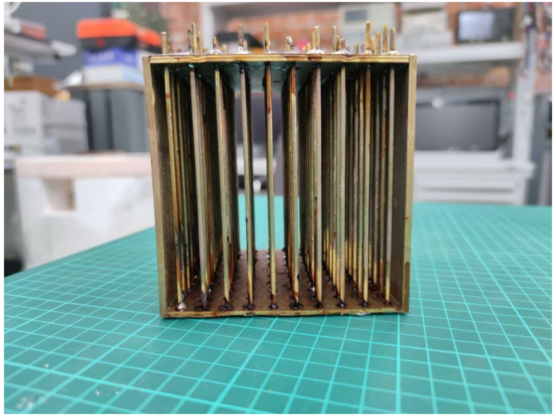




spacing: 3.58 mm 4.18 mm 5.38 mm 5.98 mm

S. A. Kenany

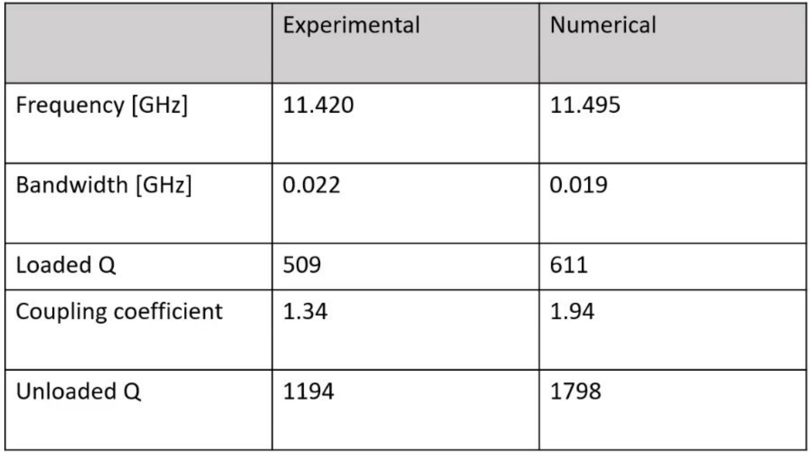
ITMO Prototype



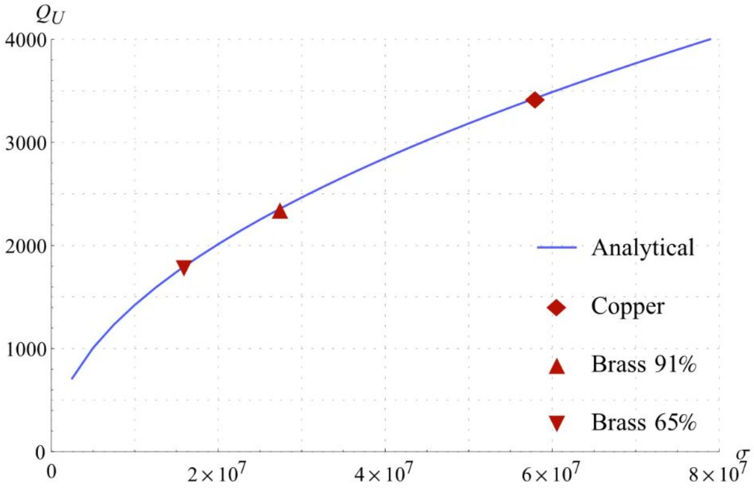
R. Balafendiev

- Goals
  - Measure Q values of wire metameterial in a cavity
  - Compare results with simulations
- Geometry
  - 10 x 10 3mm brass wire rods
  - Welded cavity
  - SMA connector for e-field monopole probe inserted parallel to wires

ITMO Prototype

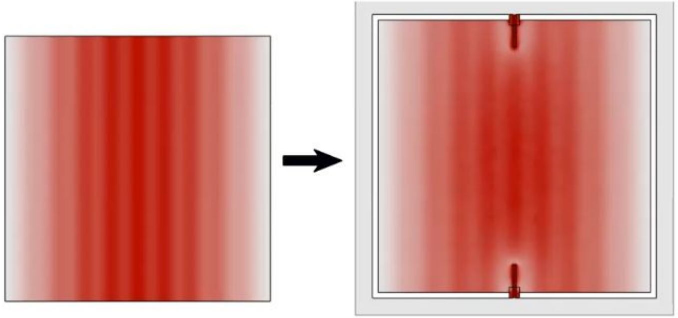


	Experimental	Numerical
Frequency [GHz]	11.420	11.495
Bandwidth [GHz]	0.022	0.019
Loaded Q	509	611
Coupling coefficient	1.34	1.94
Unloaded Q	1194	1798



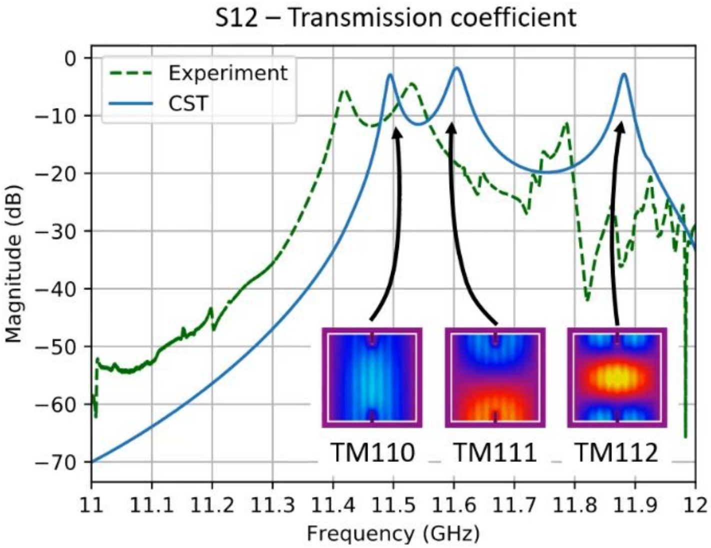
R. Balafendiev

ITMO Prototype



Because of how the probes are placed there is no excitation of the TE modes

Might not be the case in a less ideal system

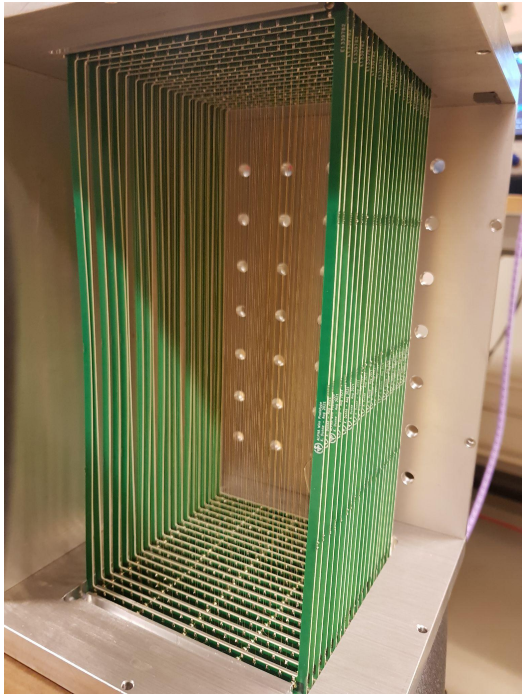


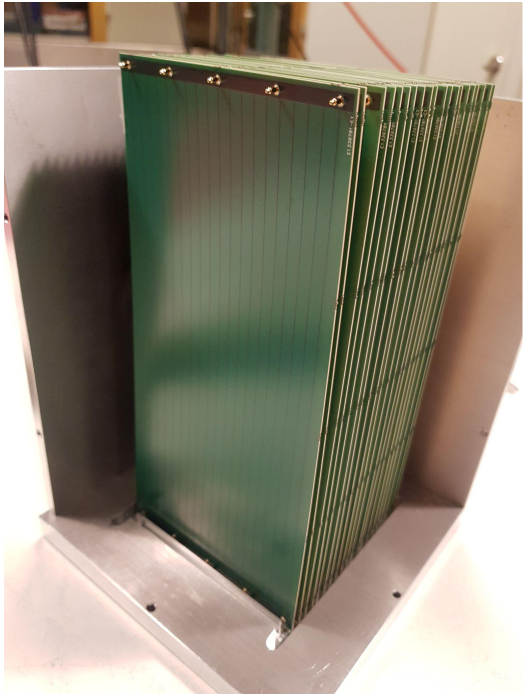
R. Balafendiev

Stockholm Prototypes

- Designed and constructed a set of prototypes of fixed frequency
- Purpose: test various antennae
- Two versions
  - Wires
  - PCB traces
- Inside aluminum cavity

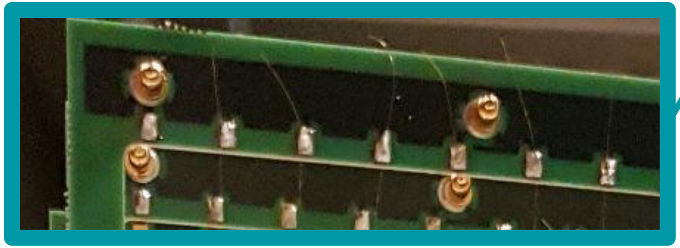
Prototype	Wire	PCB
Conductor Spacing [mm]	5	5
Conductor Thickness [um]	50	100
f_p [GHz]	11	12
Lambda [cm]	2.7	2.5

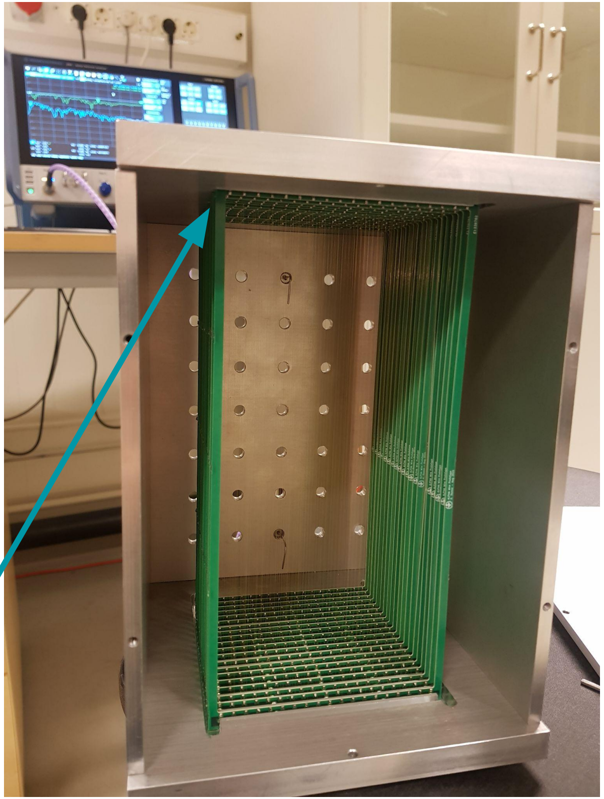

Wires


PCBs

Wire Prototype at SU

- 20 frames of 20 wires each
- Gold plated Tungsten 50 um
- Electrically connected to reduce capacitances that alter mode structure
- Walls with ports allow inserting antennae at various positions to map mode map





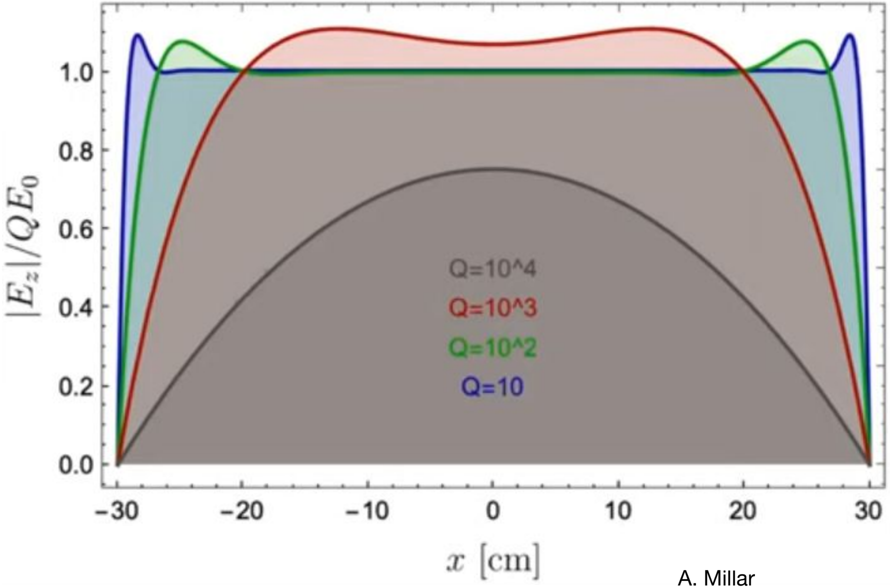
Antenna & Readout Working Group

- Focused on understanding mode structure and how to read it out
- Antenna design that is sensitive to those modes and can pick up just those that couple to axion
- Open Questions
    - Placement and number of antennas
    - Strength of antenna coupling to system (weakly, critically, strongly)
    - Types of antennas
    - Method of tuning antenna

Members
Stafford Withington (Cambdrige)
Tony Tyson (UC Davis)
Jón Gudmundsson (SU)
Philip Mauskopf (ASU)
Alex Millar (SU)
Katie Dunne (SU)
Matthew Lawson (SU)

Readout vs. Q

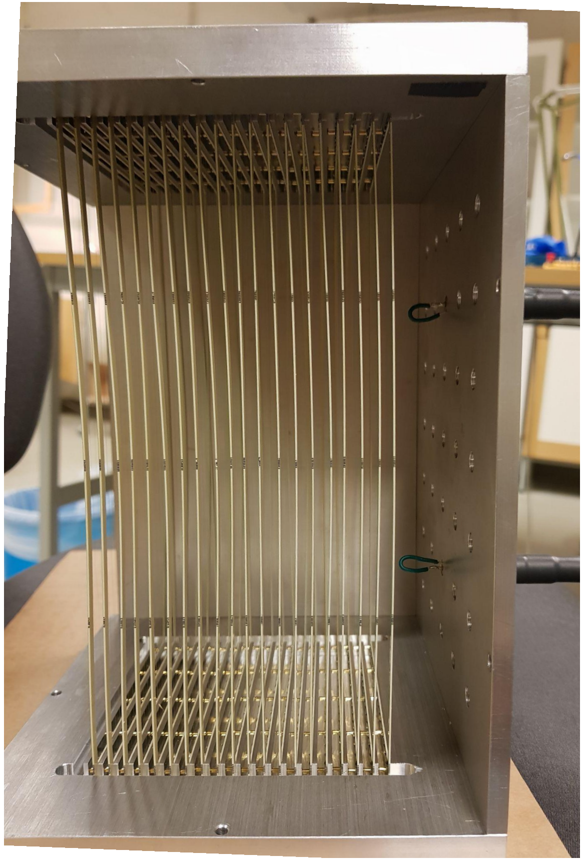
- Low Q: read out in the bulk of the material
- High Q: read out at the boundaries - i.e. cavity walls
- Low Q: degenerate system - mode mixing
- High Q: single moded system



A. Millar

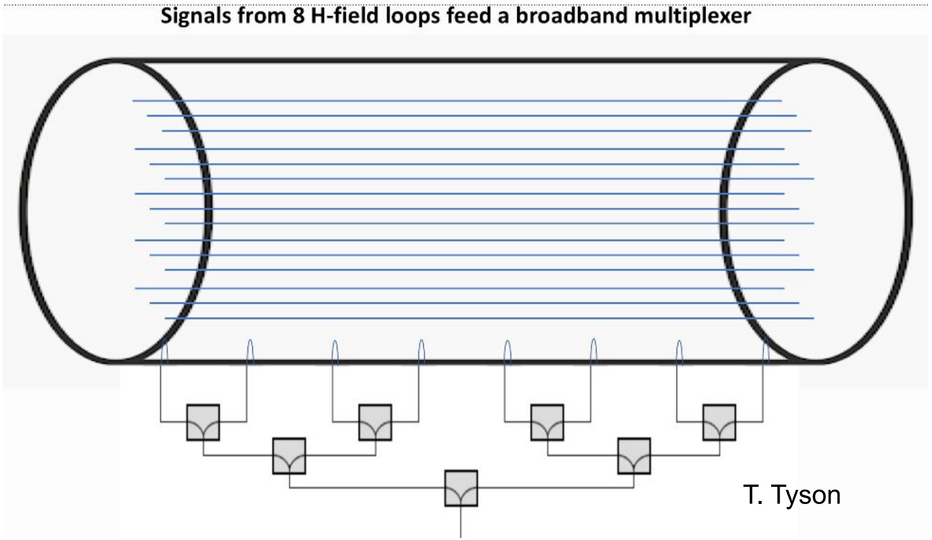
Antenna

- E-field antenna perturbs the system
  - Must be inserted with some depth into the material
- Magnetic field antenna can pick up field close to the walls
- Just constructed two prototypes and measurements are ongoing with magnetic field antennas
- Will compare simulation and empty cavity measurements with metamaterial to verify we are seeing the modes we expect
- Would also like to take experimental data of antennas near to each other



Readout

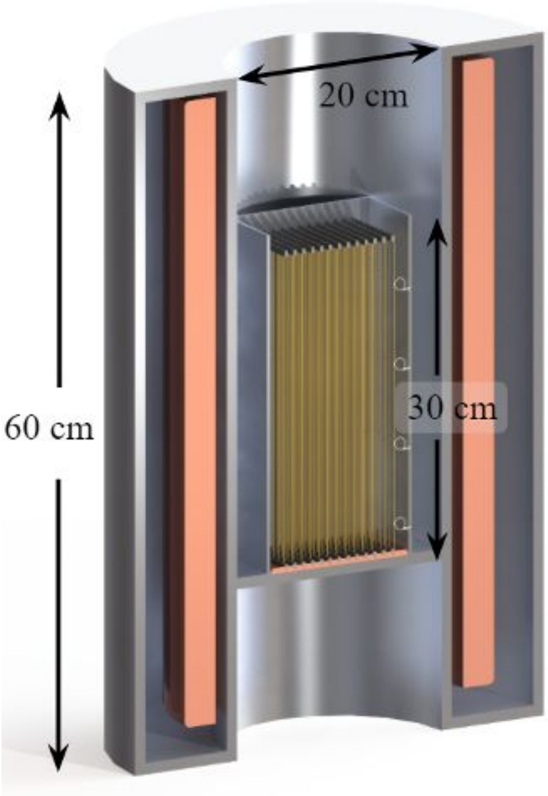
- Baseline is preamplification with cold HEMTs followed by room temperature linear amplifiers
- Loops can be placed at the cavity walls separated by a compton wavelength
- Future work on designing such a network will come after antenna choice



T. Tyson

ALPHA Pathfinder

- R&D efforts are towards a large-scale pathfinder experiment
- 20 cm bore 8T solenoid
- Sensitive to mass range around 10–20 GHz
- Tuning with low power piezoelectric translation stages
- Warm/cryogenic tests expected 2024/2025
- Data run expected ~2026



Conclusions

- Axion-plasma mixing a promising new avenue for axion detection
- Plasma haloscopes are novel way to get to higher axion masses
- ALPHA collaboration recently formed with goal of building tunable, cryogenic plasma haloscope
- Deal breakers have not broken any deals
- Prototyping stage towards ALPHA Pathfinder
- Open to collaborators!

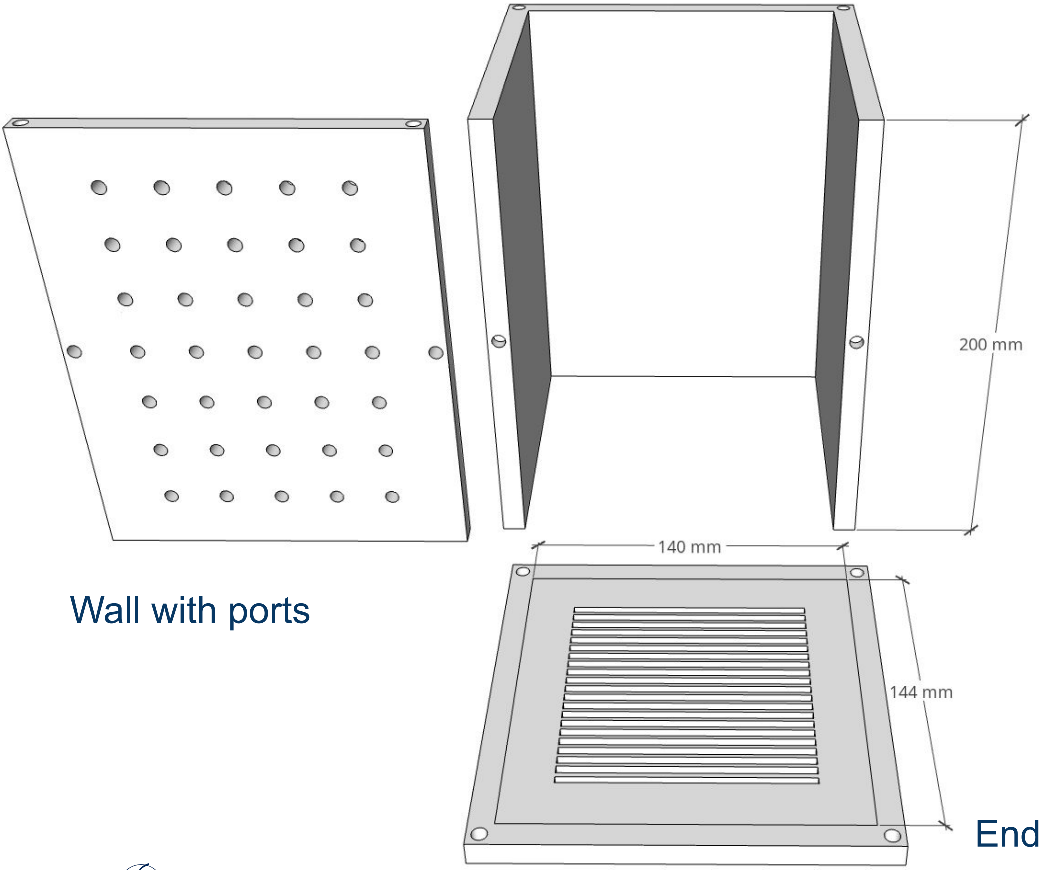
Funded by ERC and VR AxionDM Research Environment

European Research Council
Established by the European Commission

Swedish
Research Council

Backup Slides

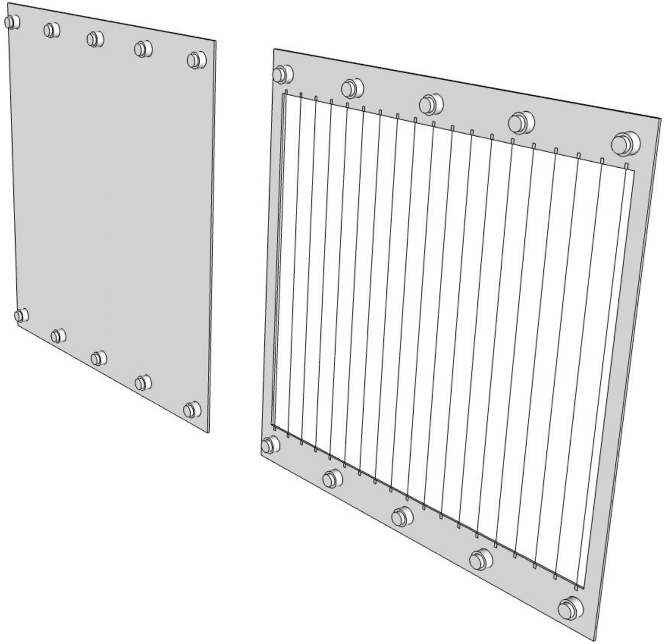
Stockholm Prototypes



Wall with ports

End cap

Frame inserts



$$SNR = \frac{P_a}{P_N}\sqrt{Bt} = \frac{P_a}{k_B T_s}\sqrt{\frac{t}{B}}$$

$$\text{scan rate} \propto (B_0^2 V)^2 \frac{1}{T_s^2}$$

$$g_{\alpha\gamma\gamma} \propto \frac{T_s}{B_0^2 V} \tag{7}$$

Equations 6 and 7 show that it is critical to minimize the system noise temperature T_s. Doing so allows ADMX to scan faster while maintaining sensitivity, or scan at the same rate while increasing sensitivity.