The Plasma Axion Haloscope & the ALPHA Collaboration

Katie Dunne
katherine.dunne@fysik.su.se
on behalf of the ALPHA collaboration

Partikeldagarna 2021
Chalmers University, Gothenberg

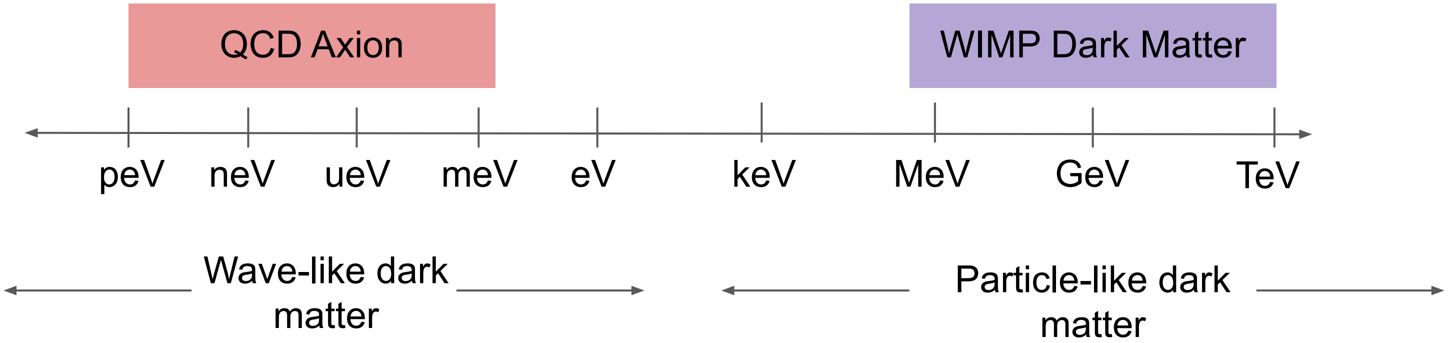
Stockholm University

Oskar Klein centre

alpha

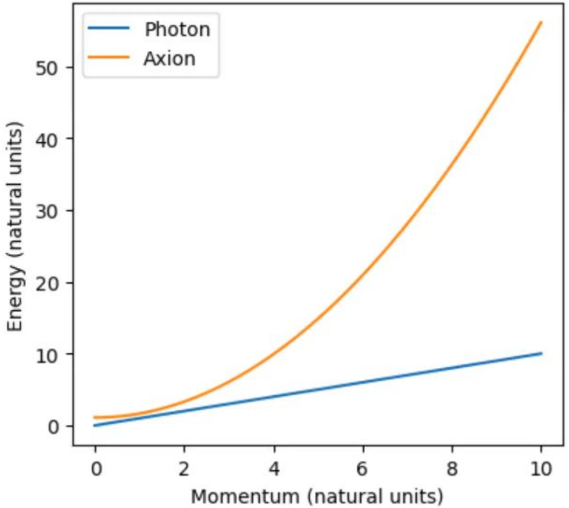
Axion Dark Matter

- Dark Matter parameter space spans 84 orders of magnitude!
- QCD axion proposed by F. Wilczek kills two birds with one stone
  - Solution to Strong CP problem
  - Candidate for dark matter
- Wave-like dark matter: detecting a classical field, very different techniques than what we've discussed at Partikeldagarna so far



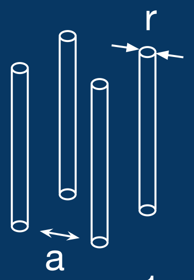
Dispersion Relation

- 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?
  - Traditional cavity experiments must build smaller and smaller cavities to reach higher and higher masses
  - **Give photon a mass** by using an appropriate medium (a plasma)
  - Decouples the volume of the detector from the mass of the axion
  - Using a plasma you can reach **higher masses without sacrificing volume**



Wire Metamaterials

- What do you want in a plasma?
  - Cryogenic temperatures
  - Tuneable plasma frequency
  - Large volume
- 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 set by the mutual inductance of the wires,
  - i.e. inter-wire spacing
- cm spacings → GHz frequencies
- Detector volume limited by coherent volume of the axion: de Broglie wavelength
  - Practically speaking, limited by size of magnet

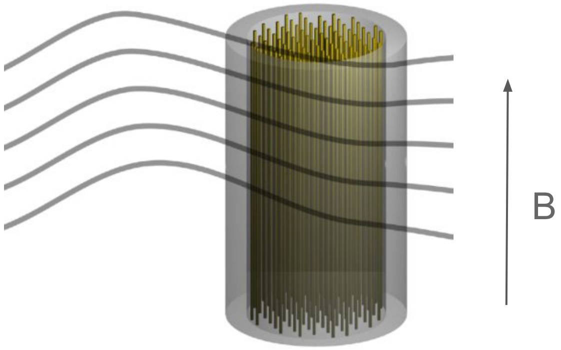


$$\omega_p^2 \propto \frac{1}{a^2\log(a/r)}$$

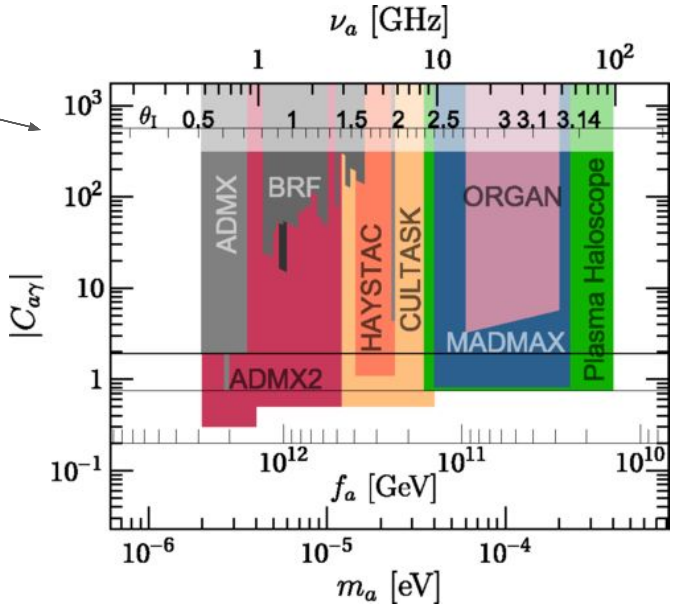
[1] J.B. Pendry et al. J. Phys. Condens. Matter 10, 1998
[2] P. Belov et al. Phys. Rev. B 67, 113103 2003

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
- Assuming T=4K, B=10T, V=0.8m^3, Q=100, 6 years measurement time



A. Millar



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?
- International and multi/inter-disciplinary 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
- Collaborators in condensed matter, high energy physics, CMB experiments, superconductors -> theorists and experimentalists

ALPHA Collaboration - Steering Committee

Matthew Lawson,
Spokesperson

Alexander Millar,
Theory Coordinator

Jón Gudmundsson,
Technical Coordinator

Hiranya Peiris,
Funding Coordinator

Frank Wilczek,
Project Scientist

Pavel Belov (ITMO),
At-Large Member

Karl van Bibber (UC Berkeley),
At-Large Member

ALPHA Collaboration - Working Groups

Antenna and Readout
Group Lead:
Stafford Withington
(Cambridge)

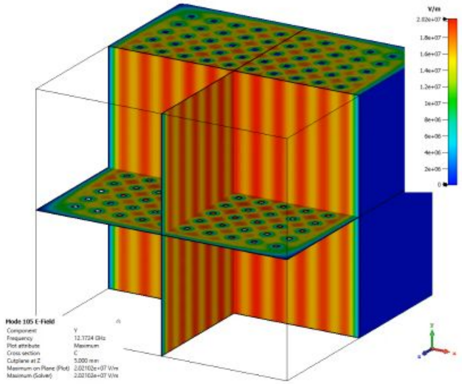
Theory and Simulation
Group Lead:
Alexander Millar
(SU, OKC)

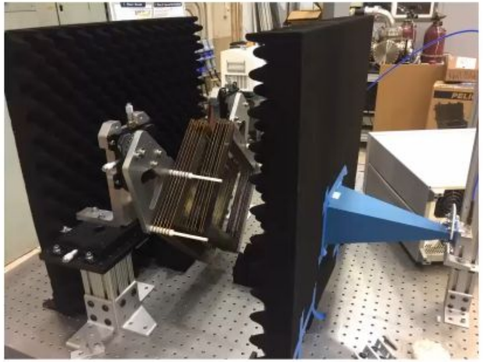
Metamaterials
Group Lead:
Karl van Bibber
(UC Berkeley)

Superconductors
Group Lead:
Steven Anlage
(Univ. Maryland)

Working Groups I

- **Theory and Simulation**
  - Focused on simulations to understand metamaterial properties
  - Show achievable Qs up to 3000, more than odrer of magnitude than assumed for initial paper
  - Novel tuning mechanisms - potentially 30% tunability
- **Metamaterials**
  - Focused on building prototypes
  - 3 prototypes constructed UCB, ITMO, SU
  - ITMO first measurement of wire metamaterial in a cavity
    - measured unloaded Q of 1000





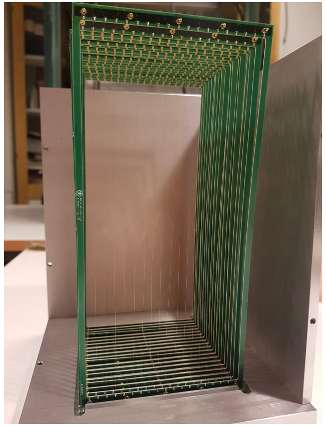
Working Groups II

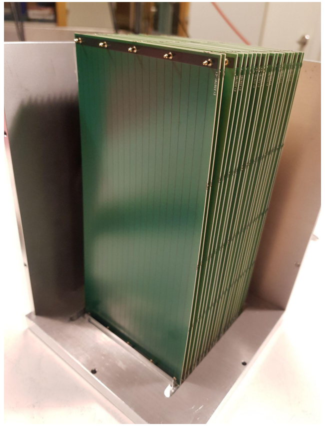
- **Superconductors**
  - Focused on non mechanical tuning by adjusting kinetic inductance of wires
  - Feasibility studies - promising avenue with experimental challenges [3]
- **Antenna and Readout**
  - Focused on understanding mode structure
  - Antenna design that is sensitive to those modes and can pick up just those sensitive to axion
  - SU leading experimental effort

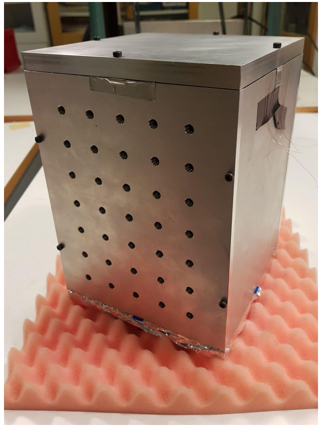
[3] M. Trepanier et al. AIP Advances 9, 105320 (2019)

Prototypes @ Stockholm University Antenna Lab

- Designed and constructing a set of prototypes of fixed frequency to test various antenna solutions
- Two versions
  - Wires (a)
  - PCB traces (b)
- Open Questions
  - Placement and number of antennas
  - Strength of antenna coupling to system (weakly, critically, strongly)
  - Antennas which couple to electric field or magnetic field (e.g. monopole probes, magnetic loops)
  - Method of tuning antenna







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

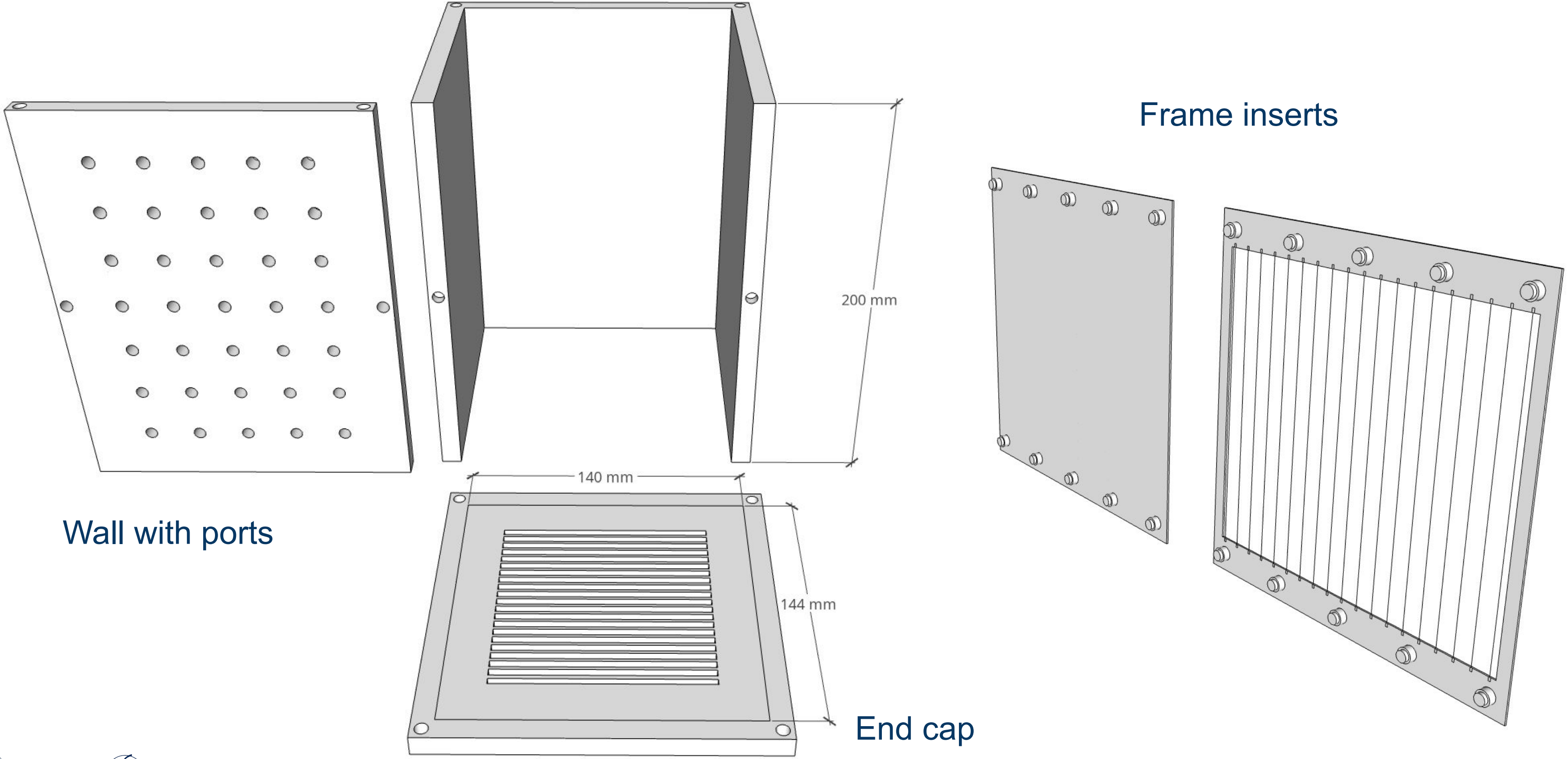
Summary

- 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
- Open to collaborators!

Funded by ERC and VR AxionDM Research Environment

Backup Slides

Cavity - Box Geometry



Axion-plasmon coupling

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

- Primary effect of axion is to act like an oscillating current, driving the system at ω_a.
- Resonance when $\omega_p = \omega_a$
- Enhancement of the E field is not related to boundary conditions
- Limited by losses (Γ)