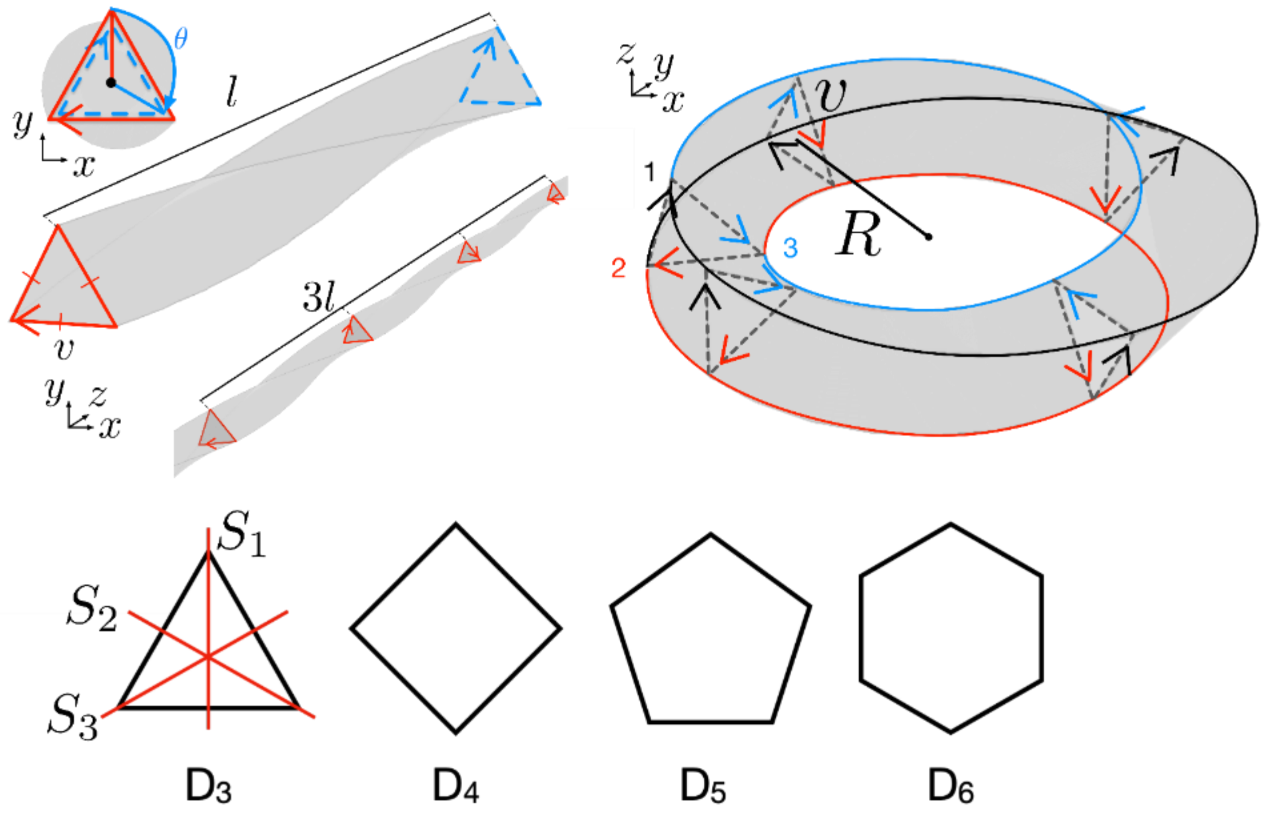
Anyon Cavity Resonator and Ultra-Light Axions

Jeremy F. Bourhill, Emma C. I. Paterson, Maxim Goryachev, Michael E. Tobar

Twisted Anyon Cavity Resonators



- Twisted hollow structures
- Monochromatic bulk chiral modes at microwave frequencies
- Near unity helicity
- Magneto-electric coupling

Regular (DC) Cavity Haloscope

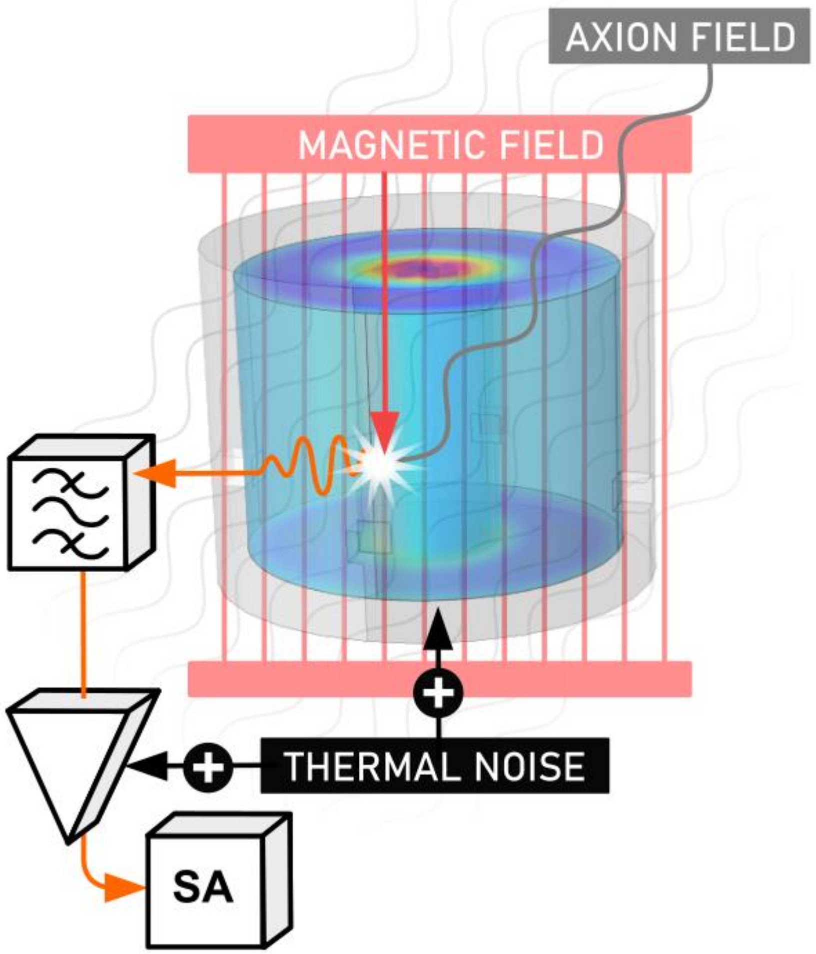
- ADMX and ORGAN (UWA)
- TM_{020}

Two-photon axion interaction

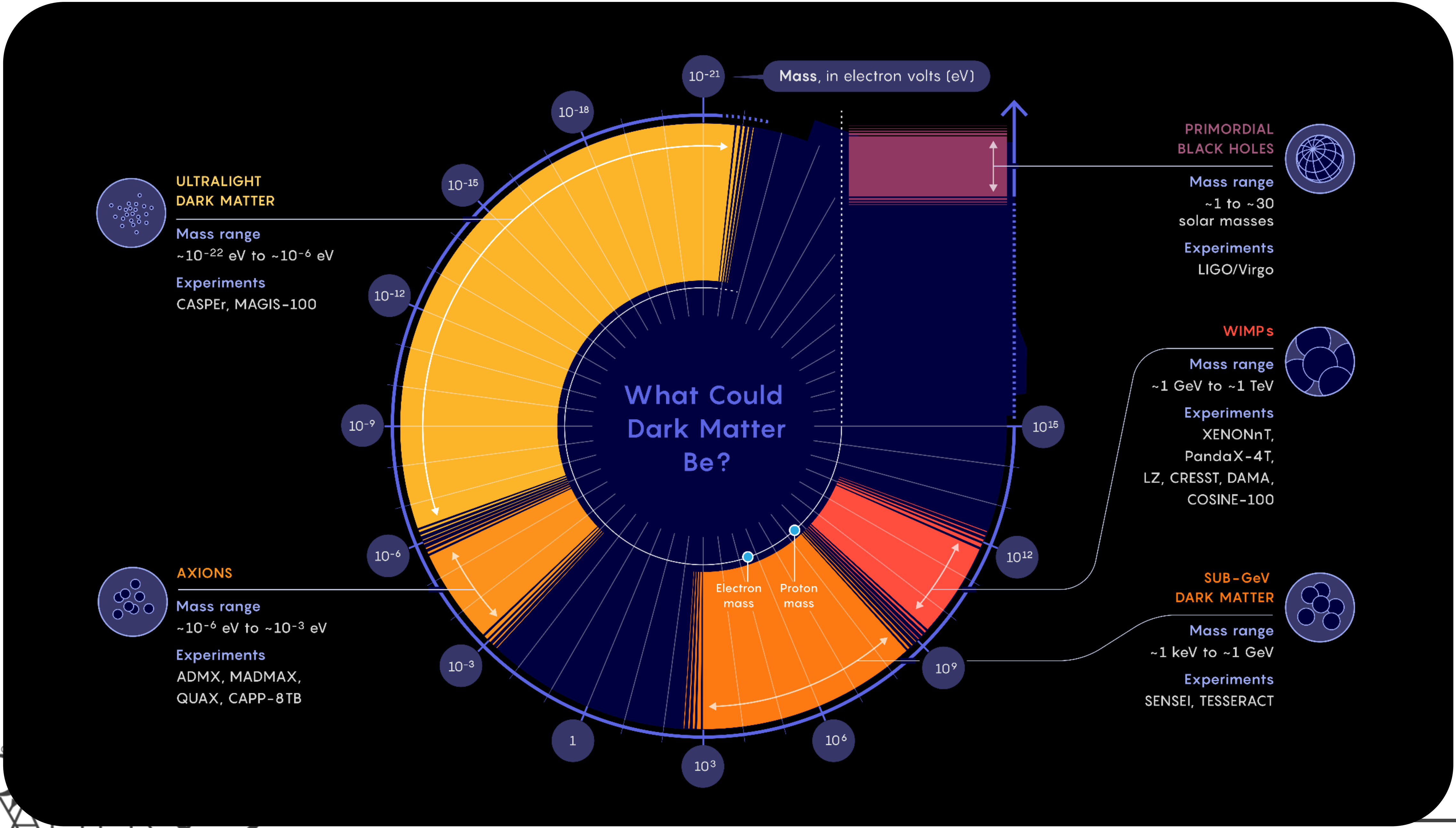
$$H_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

Photon 1: E field of cavity's resonant transverse magnetic mode

Photon 2: B field of surrounding magnet



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS



PARTICLE PHYSICS

Axion detection method limitation

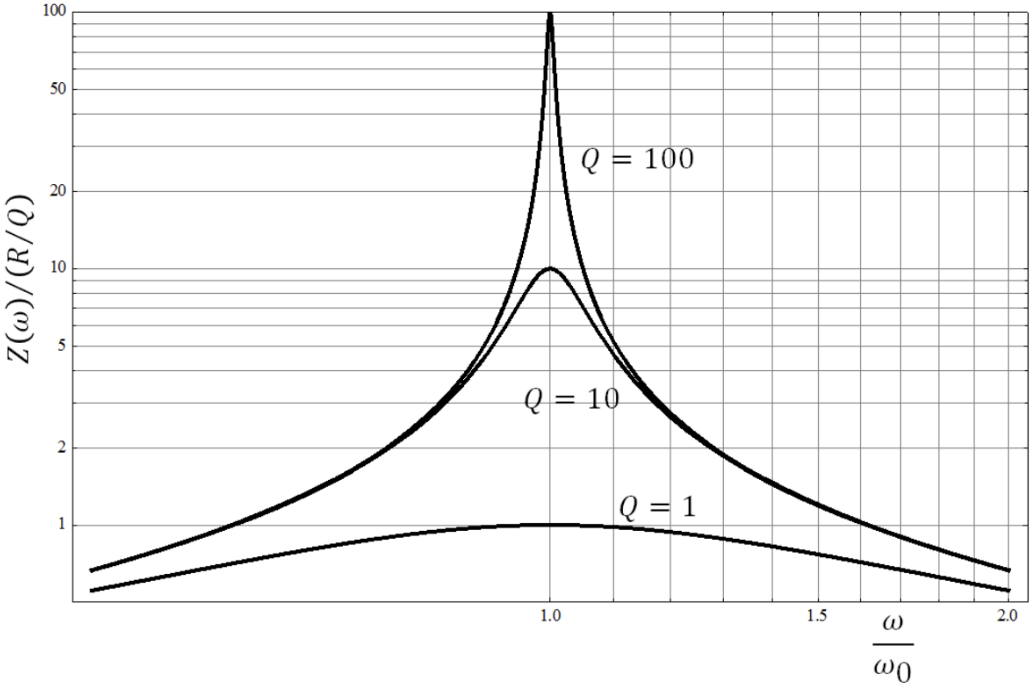
Haloscopes

- GHz frequencies
- Requires external magnetic field

  Superconductive incompatible

  ➜ Limited Q

  ➜ Limited Sensitivity



Improved Detection Method

- How can we eliminate the need for an external magnet?
- How can we search lower frequencies?

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Axion detection method limitation

Haloscopes

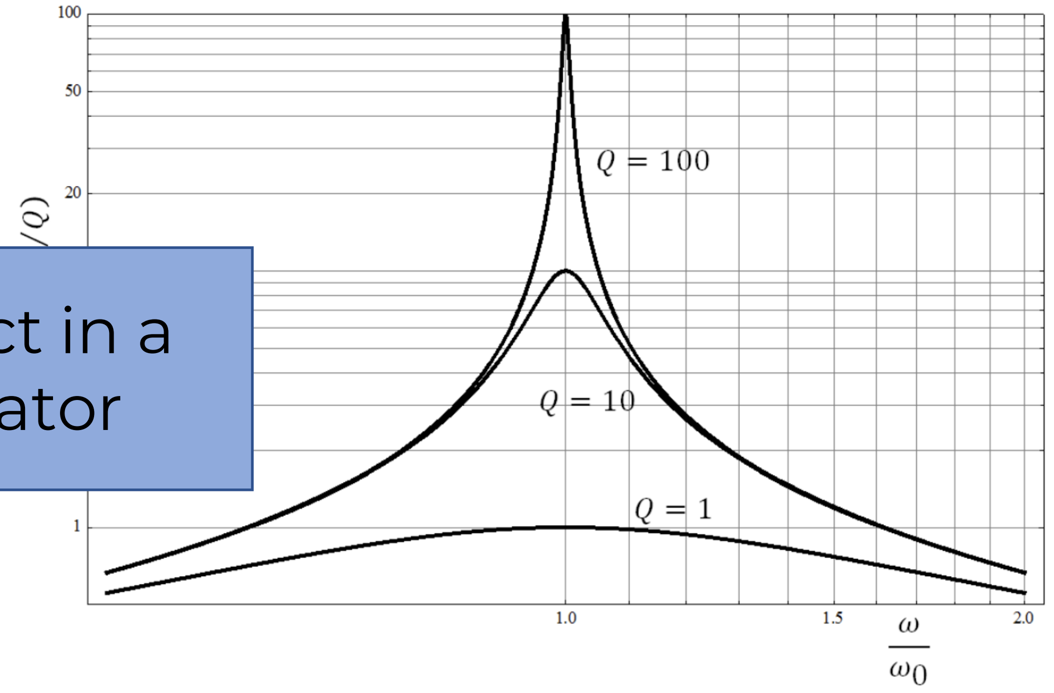
- GHz frequencies
- Requires external

Superconduct

➔ Limited Q

➔ Limited Sensitivity

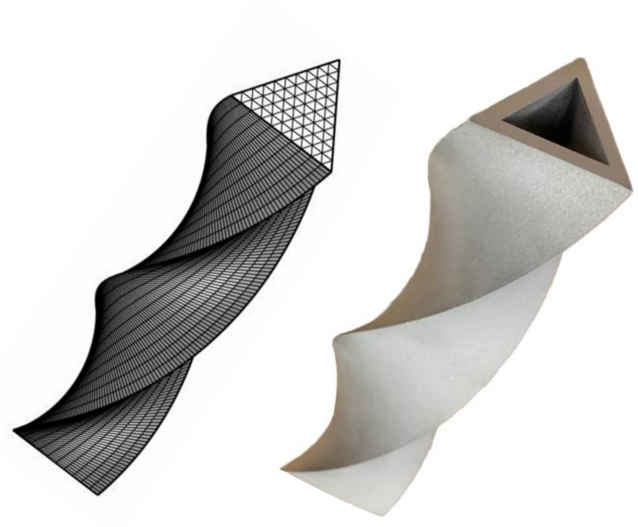
Non-zero E·B product in a single mode resonator

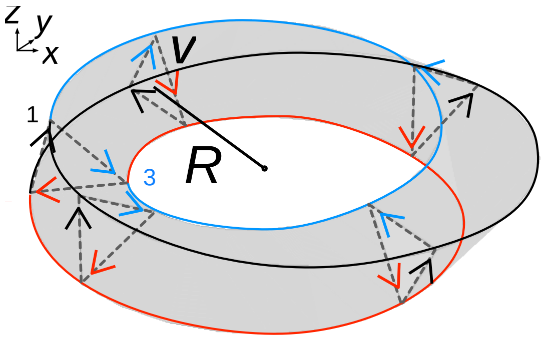


Improved Detection Method

- How can we eliminate the need for an external magnet?
- How can we search lower frequencies?

Twisted Anyon Cavity Resonators



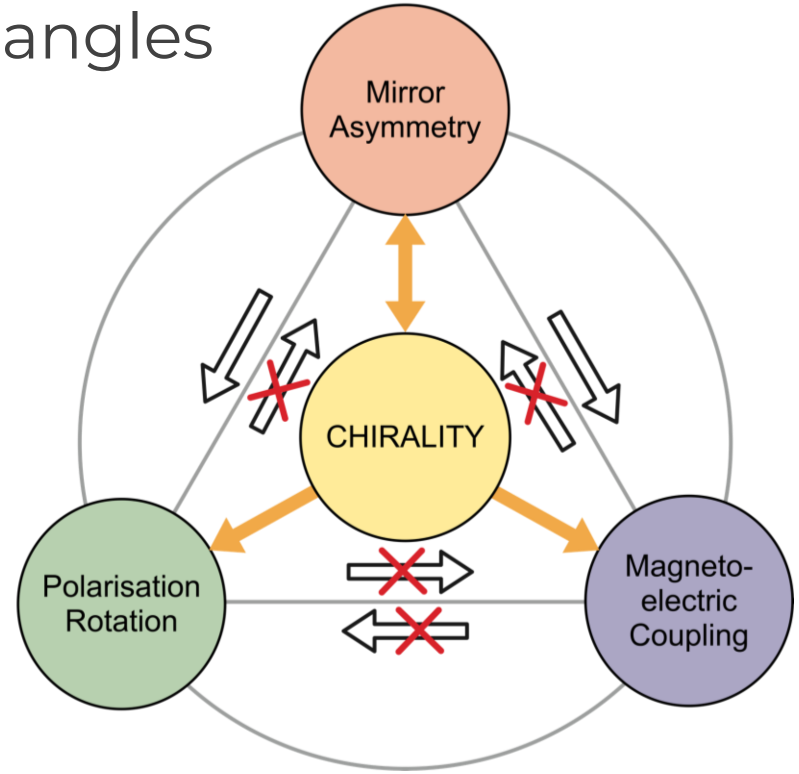


Types

1) Twisted Waveguide with conducting end caps
   - Allowing all possible twist angles

2) Twisted ring (Möbius strip)
   - Restricted twist angles

- Geometrically-induced high helicity cavity modes
- Single mode coupling to axions via non-zero helicity



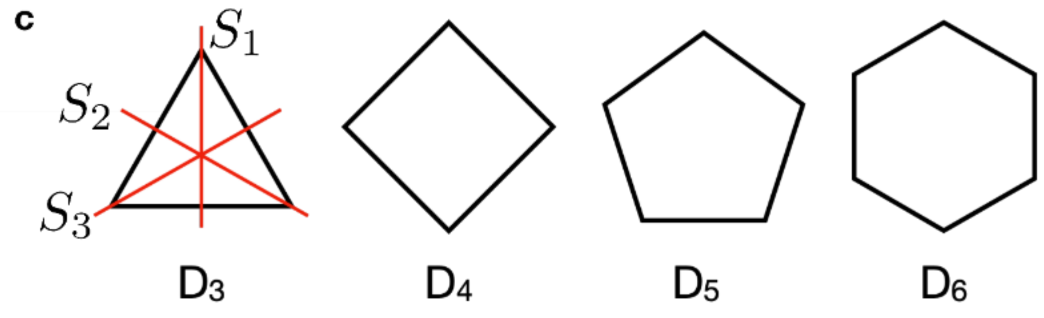
Callow C. Et al., IEEE Ant. And Prop. Mag. **62** 60 (2020)

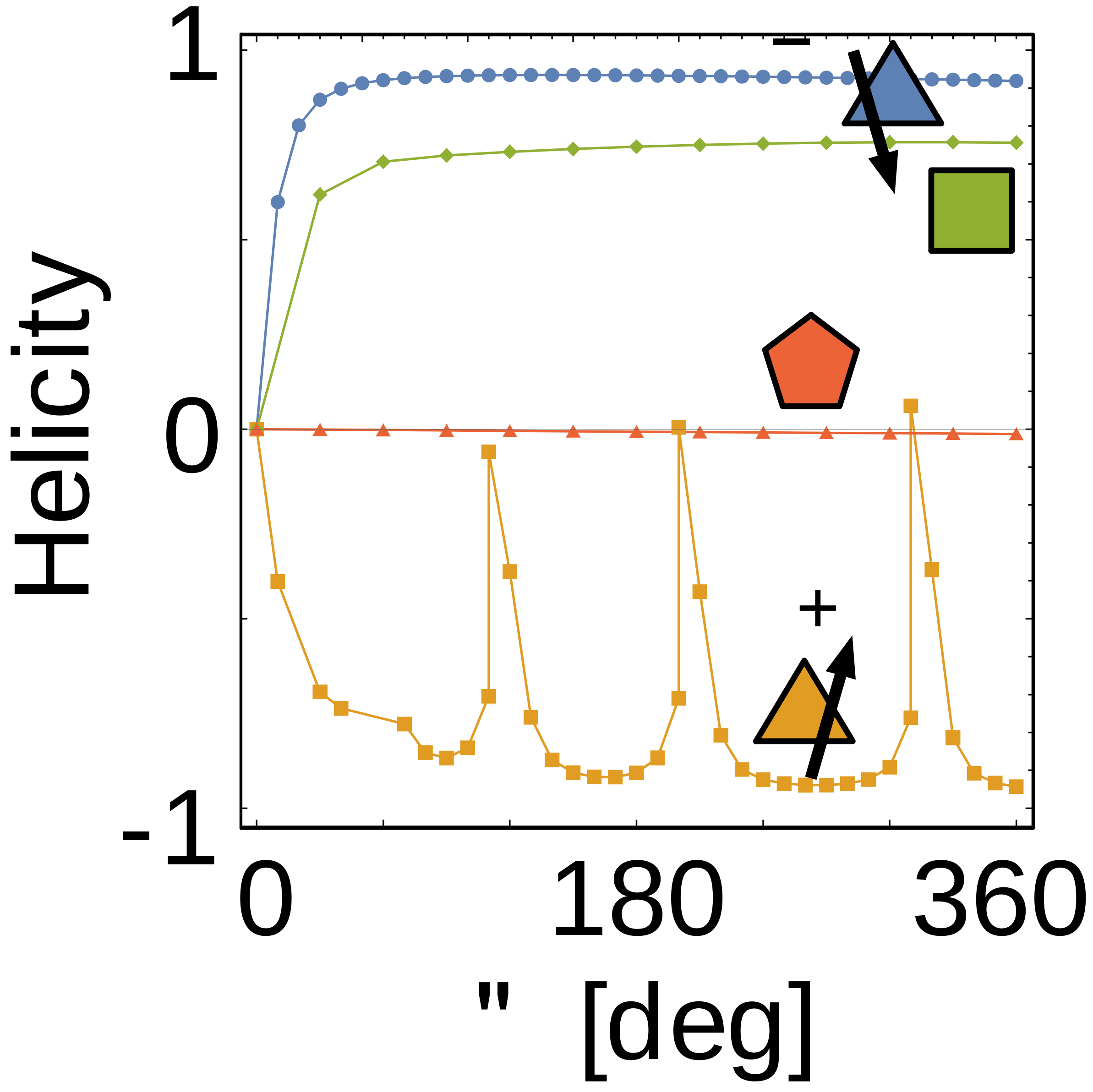
Advantages

- No external magnetic field
- Ability to use superconducting materials
- No need for cryogenics
- Sensitivity to Ultralight axions (10^{-15} eV)
- Möbius cavity has high achievable Q-factors and large numbers of high helicity modes across a range of frequencies

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Cross-section



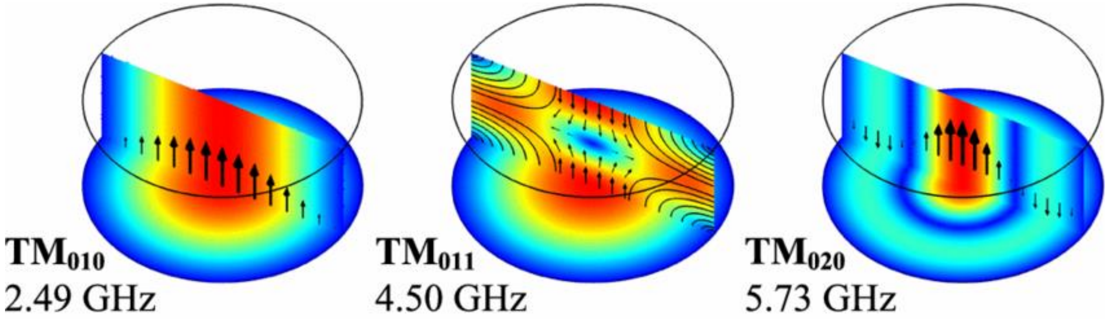


- Triangular cross-section shows greatest helicity (order unity)

Cause of Helicity

Usual Haloscope Modes

H=0



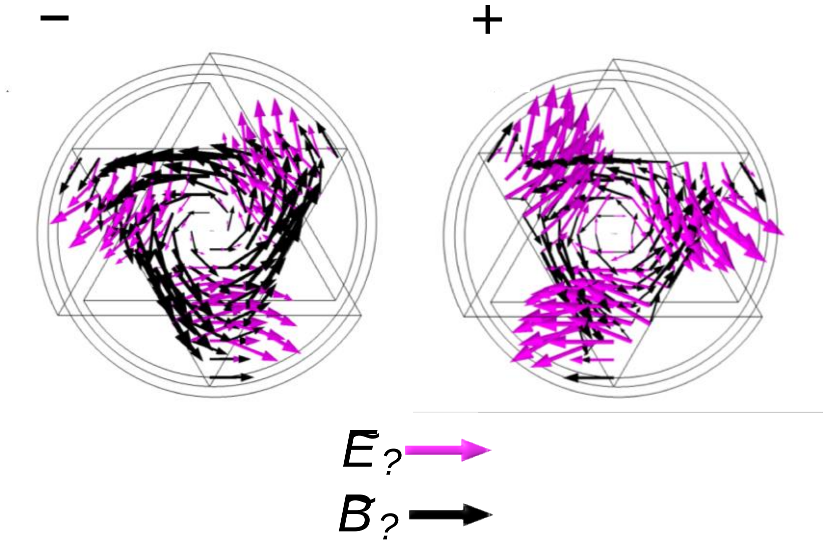
Twisted Anyon Cavity Modes

H≠0

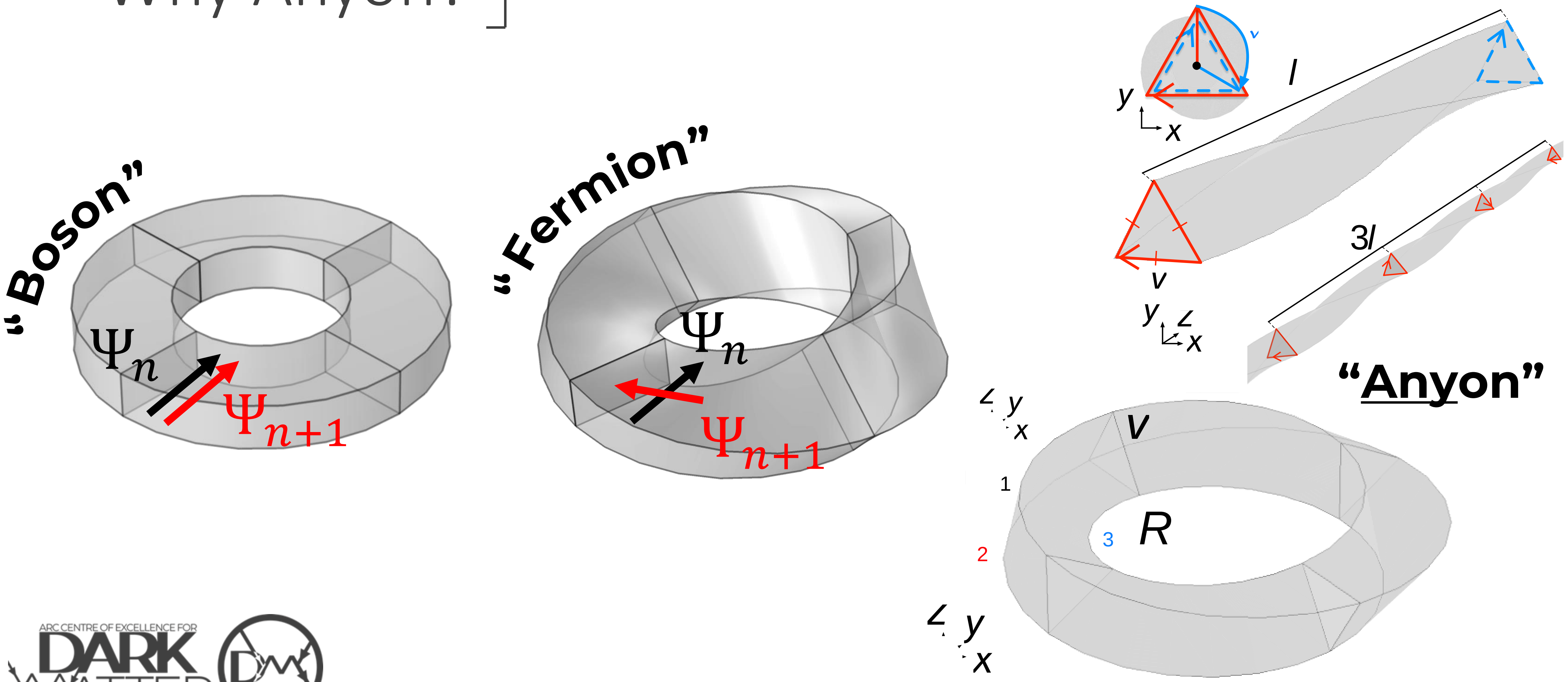
Circularly polarized

Two modes: TE & TM modes

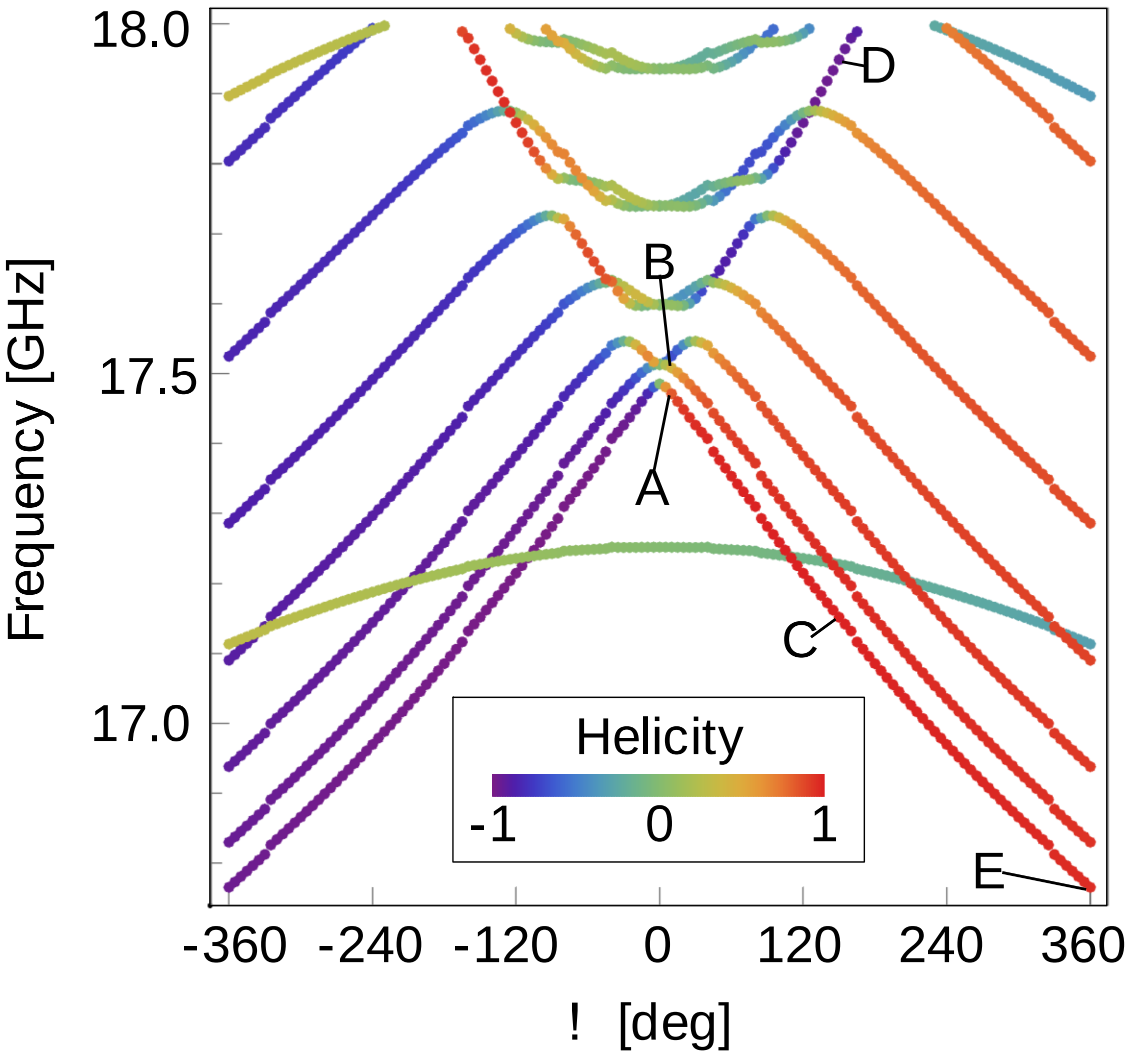
- Non-degenerate
- Magneto-electric coupling



Why Anyon?



"Boson"
Ψ_n
Ψ_{n+1}
"Fermion"
Ψ_n
Ψ_{n+1}
"Anyon"
y
x
l
v
y
z
x
3l
y
z
x
V
1
2
3
R
z
y
x



COMSOL

- Helicity is calculated via finite element analysis

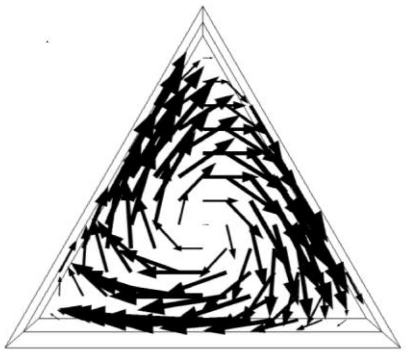
$$H_p = \frac{2Im[\int \mathbf{B}_p(\overrightarrow{r}) \cdot \mathbf{E}_p^*(\overrightarrow{r}) d\tau]}{\sqrt{\int \mathbf{E}_p(\overrightarrow{r}) \cdot \mathbf{E}_p^* d\tau \int \mathbf{B}_p(\overrightarrow{r}) \cdot \mathbf{B}_p^*(\overrightarrow{r}) d\tau}}$$

COMSOL

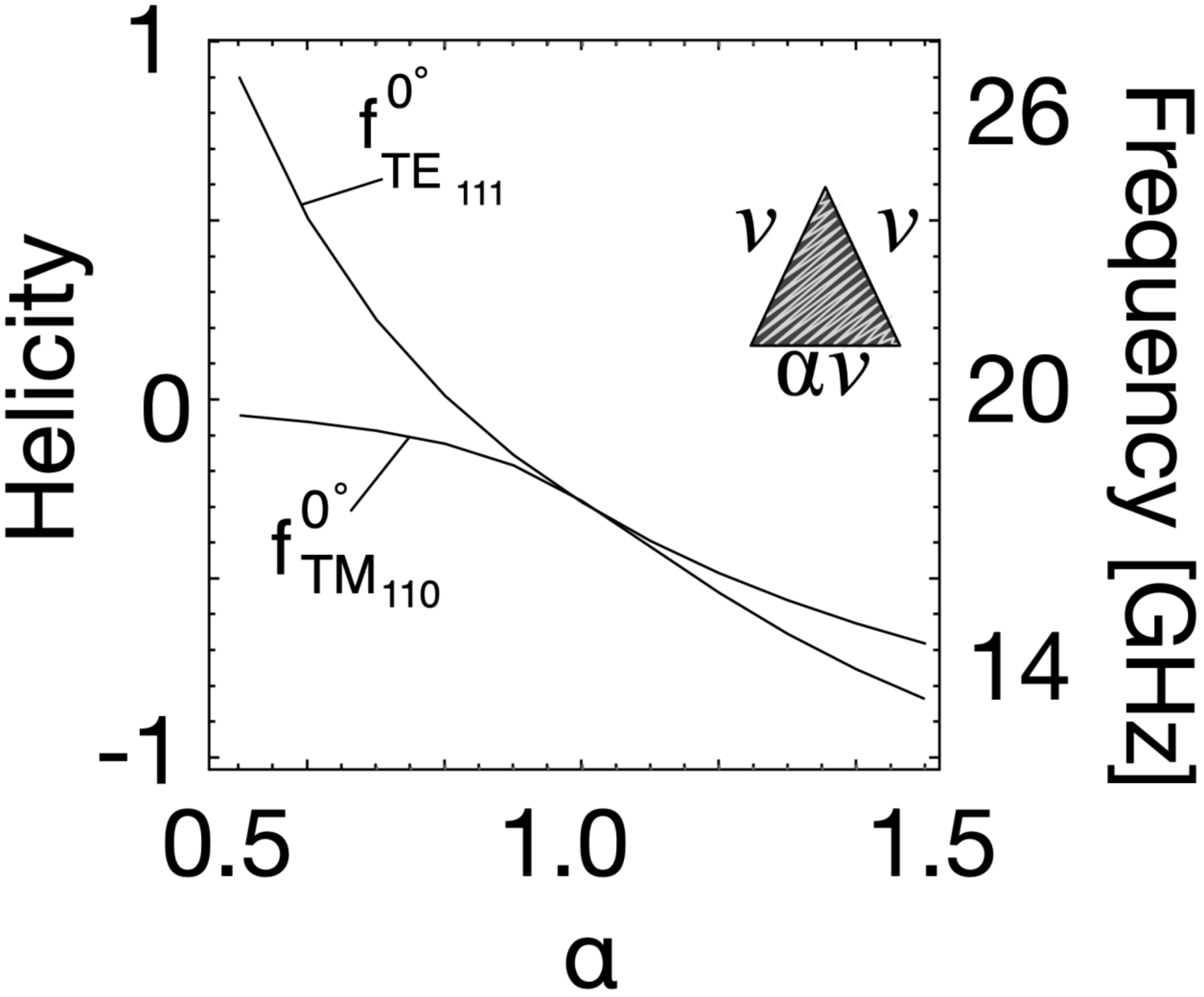
- With twist
  - Eigenmodes tune in frequency
  - Helicity increases
- Confirm theoretical predictions

E? →
B? →

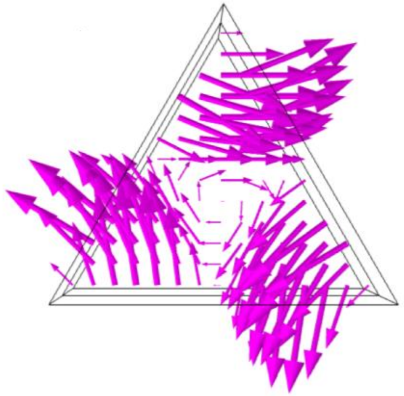
−



Transverse Magnetic (TM)



+

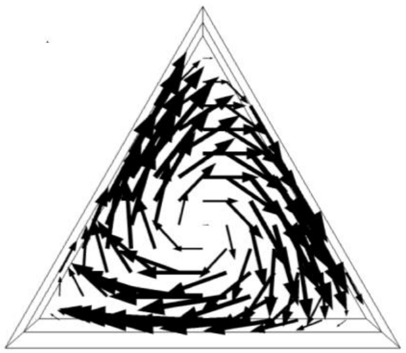


Transverse Electric (TE)

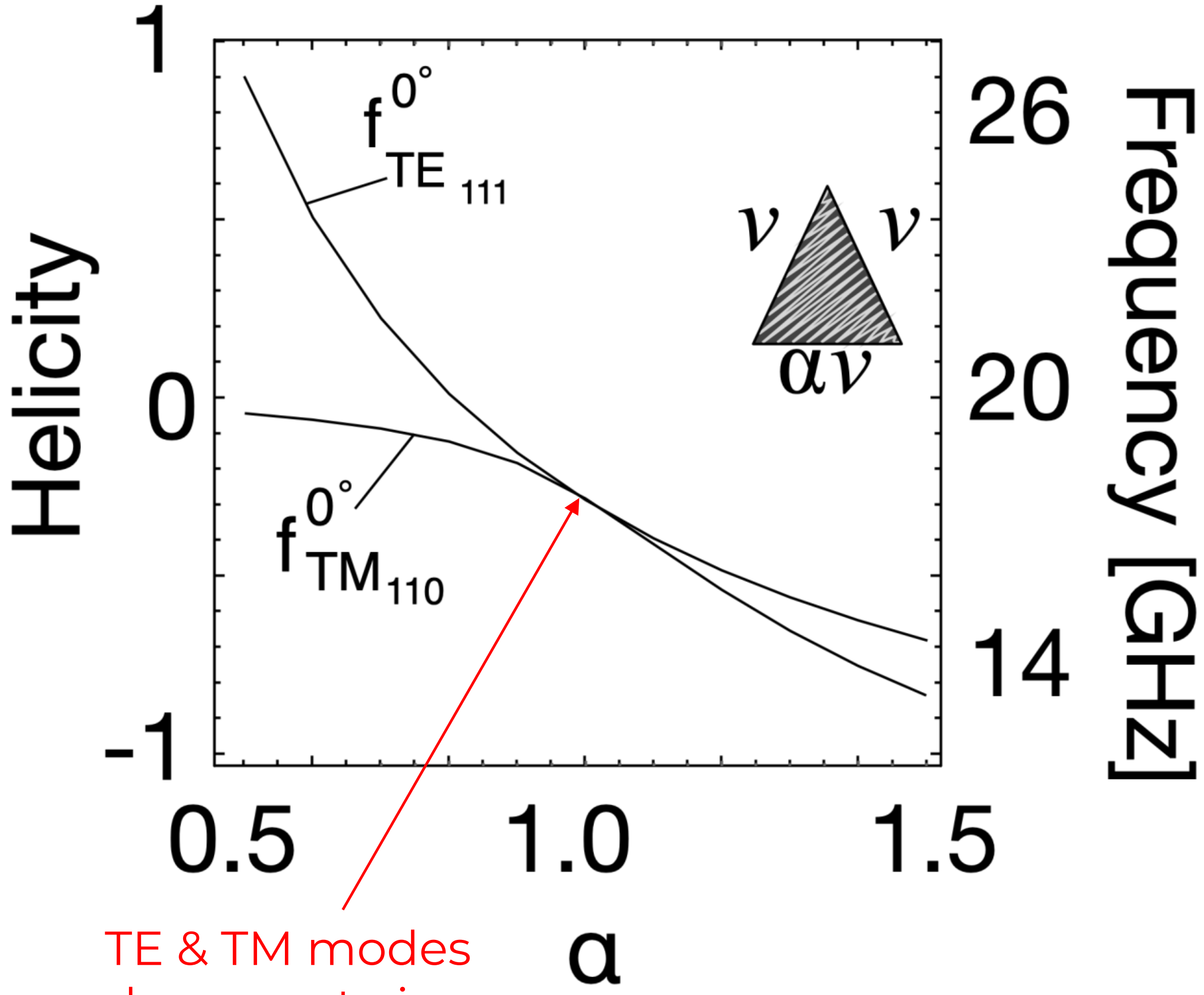
$\vec{E}$?

$\vec{B}$?

−

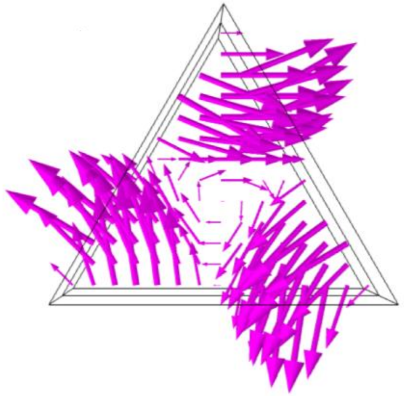


Transverse Magnetic (TM)



TE & TM modes degenerate in frequency

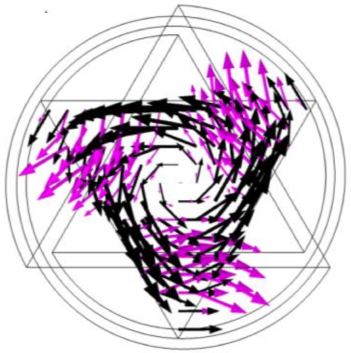
+

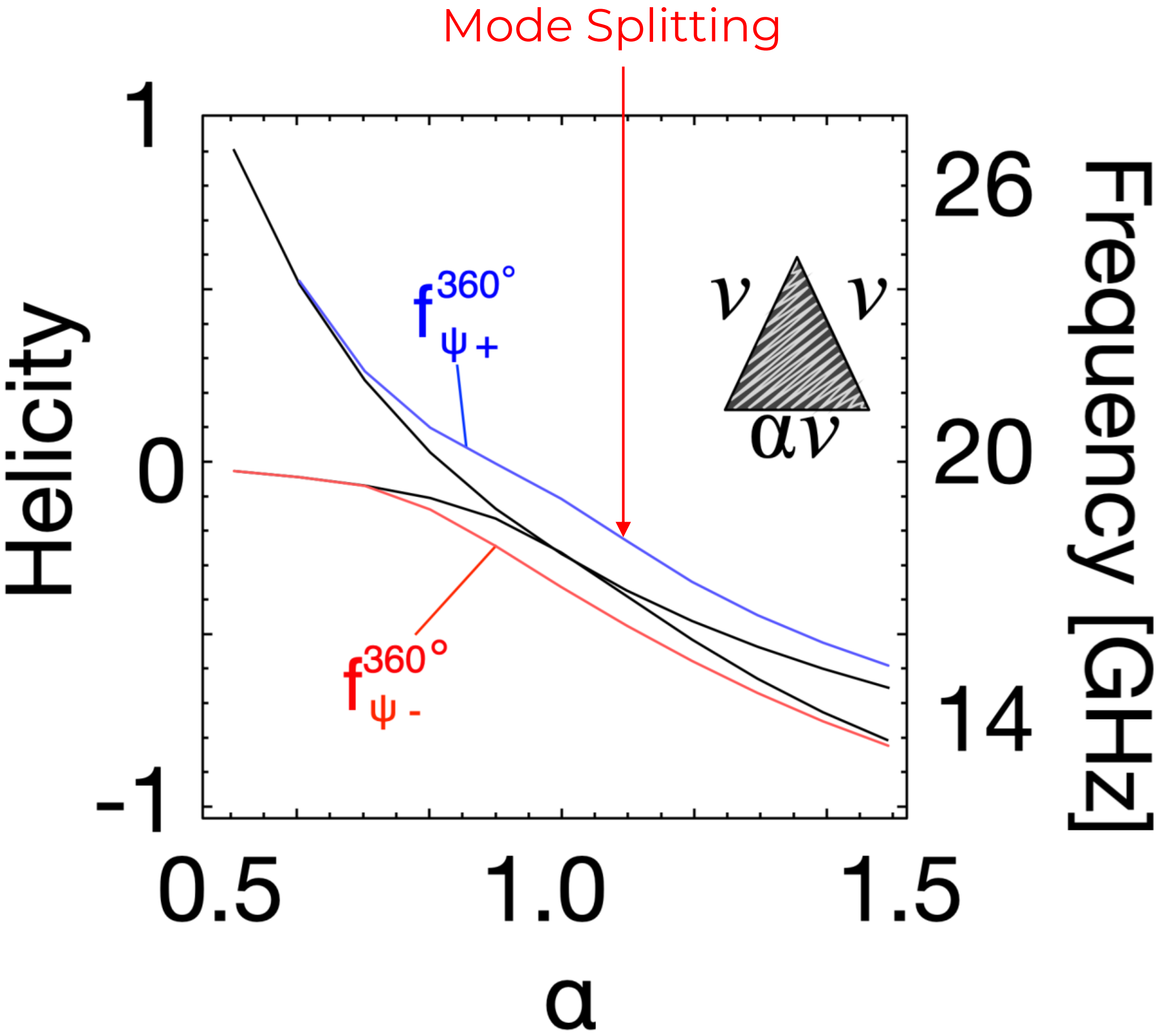


Transverse Electric (TE)

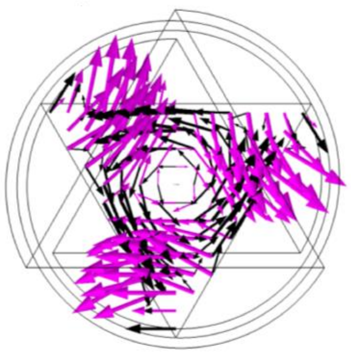
E?
B?

−

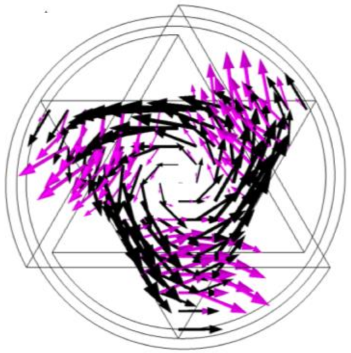


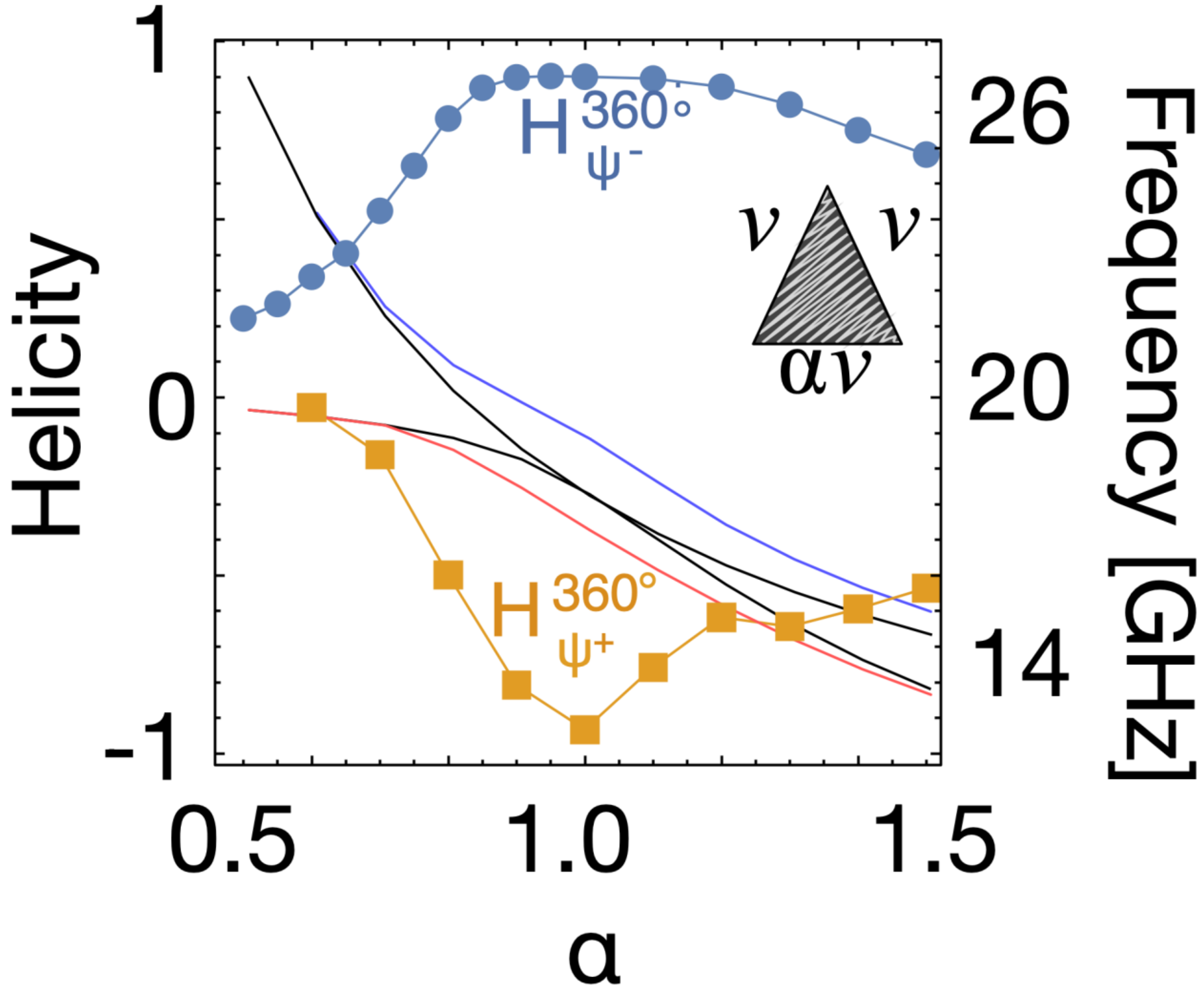

Mode Splitting
1
0
-1
Helicity
26
20
14
Frequency [GHz]
0.5
1.0
1.5
α
$f^{360°}_{\psi+}$
$f^{360°}_{\psi-}$
ν
ν
αν

+

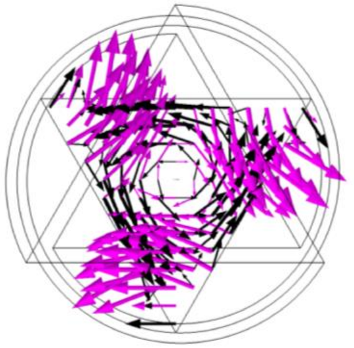


E?
B?





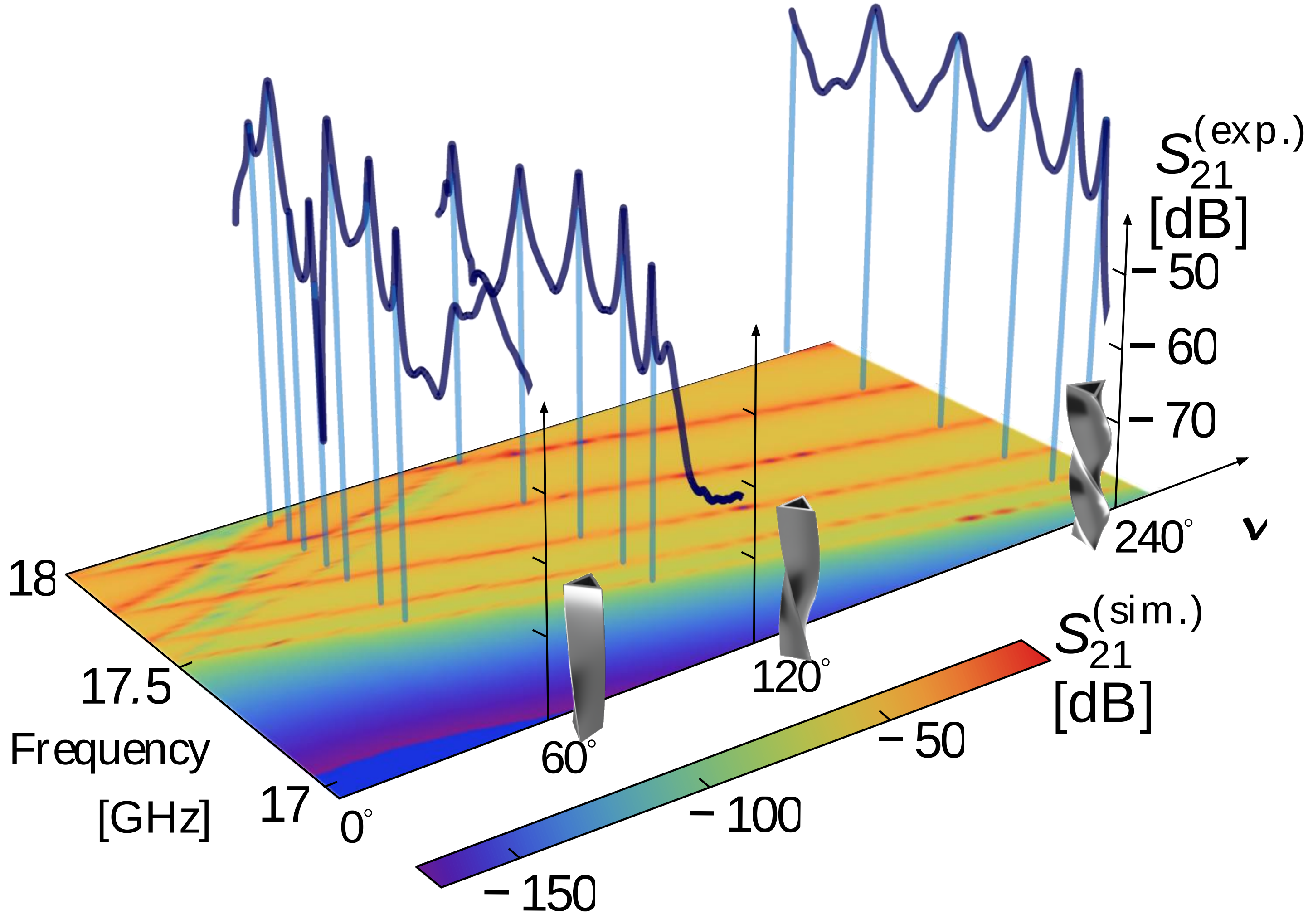
1
0
-1
Helicity
0.5
1.0
1.5
α
26
20
14
Frequency [GHz]
H 360° ψ-
H 360° ψ+
ν
ν
αν



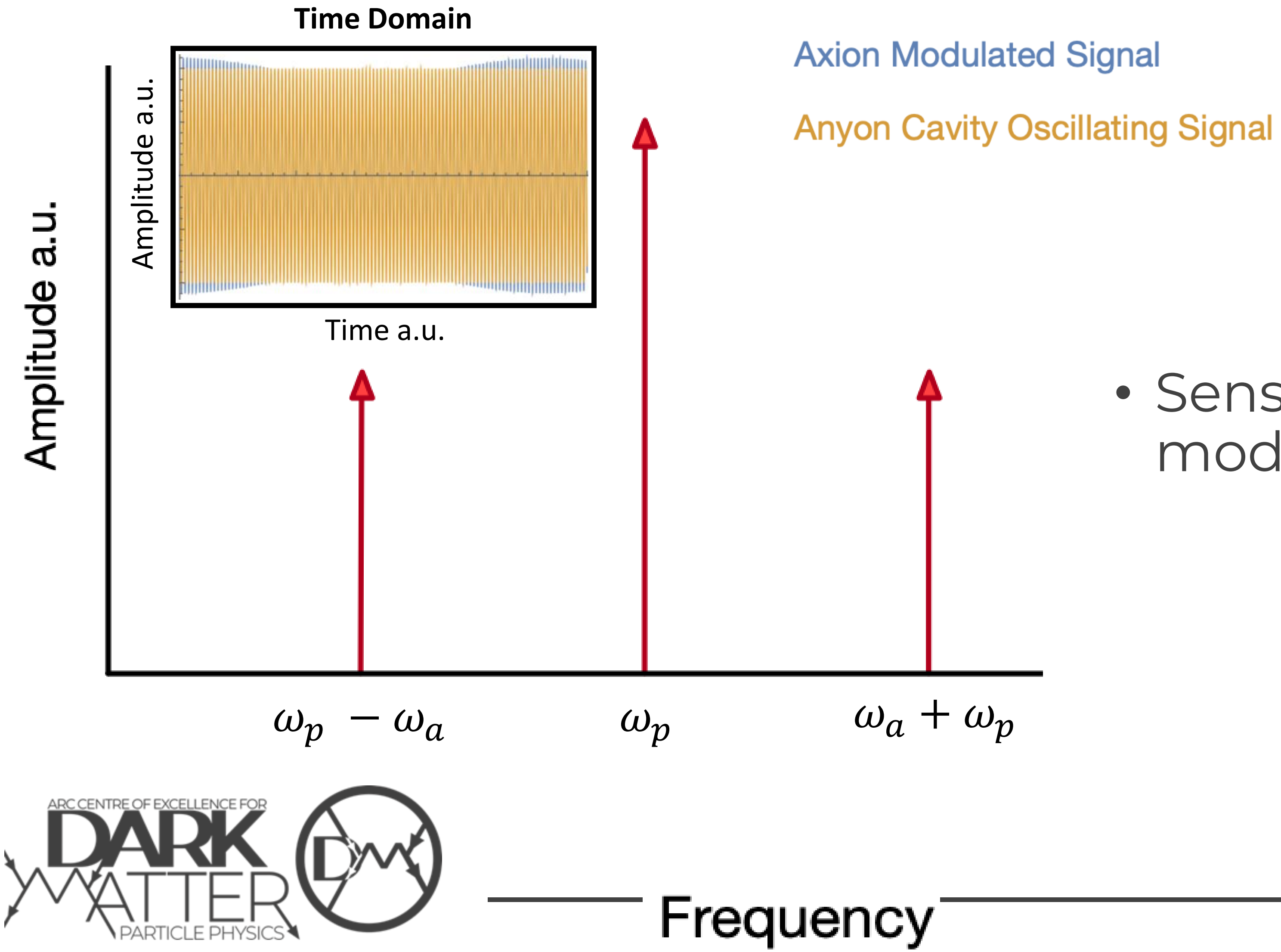
3D Printed

3D printed aluminium

Simulation and Experimental Results Agree



Amplitude Modulated Sidebands



- Sensitive to amplitude modulation of our carrier signal

Sensitivity

$$SNR = \frac{g_{a\gamma\gamma}\beta_p|H_p|}{\sqrt{2}(1+\beta_p)} \frac{Q_p}{\sqrt{1+4Q_p^2(\frac{\omega_a}{\omega_p})^2}} \frac{(\frac{10^6 t}{\omega_a})^{\frac{1}{4}}\sqrt{\rho_a c^3}}{\omega_p\sqrt{S_{am}}}$$

arXiv:2208.01640v2

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Sensitivity

Axion Photon Coupling

Microwave Probe Coupling

Helicity

Q factor

Axion Frequency

Measurement time (1 week)

Cold dark matter density (8×10^{-22}kgm^{-3})

$$SNR = \frac{g_{a\gamma\gamma}\beta_p|H_p|}{\sqrt{2}(1+\beta_p)}\frac{Q_p}{\sqrt{1+4Q_p^2(\frac{\omega_a}{\omega_p})^2}}\frac{(\frac{10^6 t}{\omega_a})^{\frac{1}{4}}\sqrt{\rho_a c^3}}{\omega_p\sqrt{S_{am}}}$$

Speed of light (3×10^{8} ms^{-1})

Cavity frequency (1 GHz)

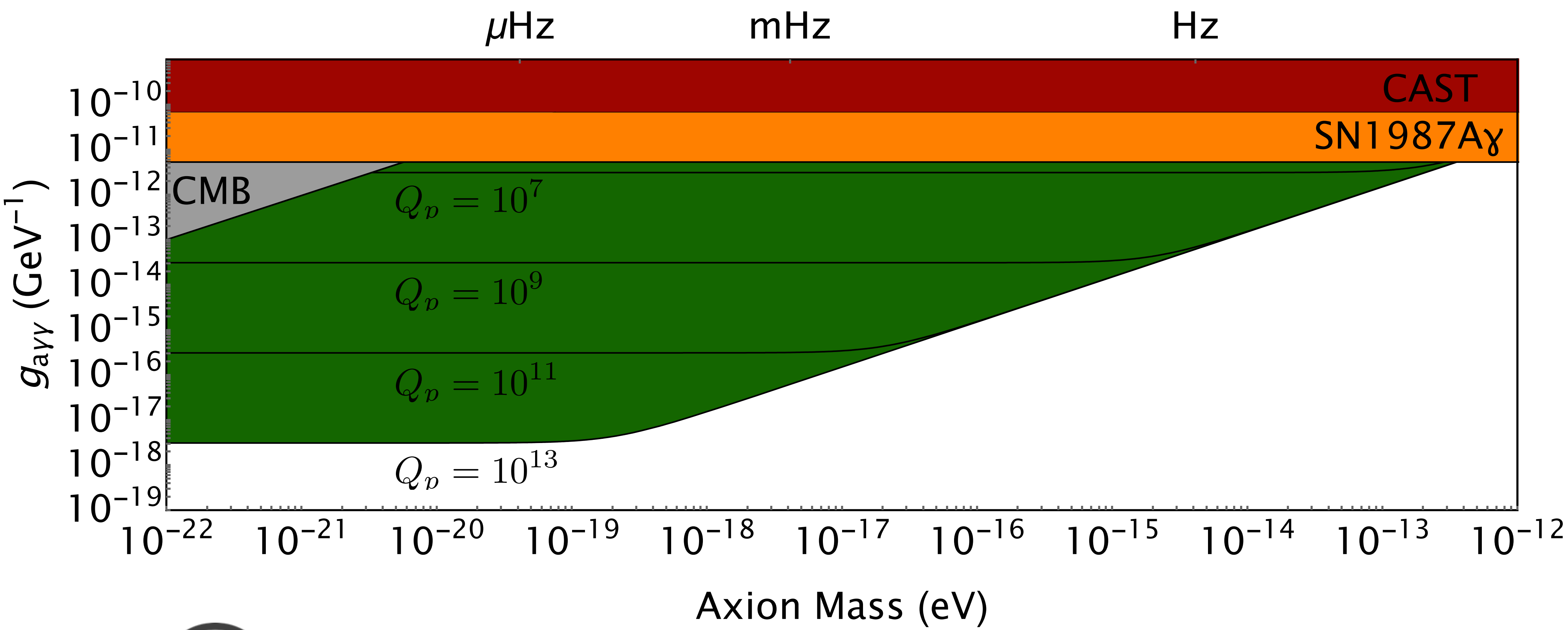
Amplitude noise (-160 dBcHz^{-1})

$$\omega_\alpha \ll \omega_p$$

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

arXiv:2208.01640v2

Projections



Twisted Anyon Cavity Resonators with Bulk Modes of Chiral Symmetry and Sensitivity to Ultra-Light Axion Dark Matter

J. F. Bourhill, E. C. I. Paterson, M. Goryachev, and M. E. Tobar
ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Hwy, 6009 Crawley, Western Australia.

(Dated: 9 August 2022)

In this work we invent the Anyon Cavity Resonator. The resonator is based on twisted hollow structures, which allow select resonant modes to exhibit non-zero helicity. Depending on the cross section the cavity, the modes have more general symmetry than that has been studied before. For example, with no twist the mode is the form of a boson, while with a 180^o twist the symmetry is in the form of a fermion. We show that the general twisted resonator is in the form of an anyon. The non-zero helicity couples the mode to axions, and we show in the upconversion limit the mode couples to ultra-light axions within the bandwidth of the resonator. The coupling adds amplitude modulated sidebands and allows a simple sensitive way to search for ultra-light axions using only a single mode within the bandwidth of the resonator.

Available at arXiv: 2208.01640v2
Under Review at Physical Review Letters

In Conclusion

- Invention of a new class of resonator

- Simulation results have been conducted and show this new class of cavity has great sensitivity to ultra-light dark matter

Next Steps

- Optimising Q-factors and minimising read-out amplitude modulation noise

Questions?