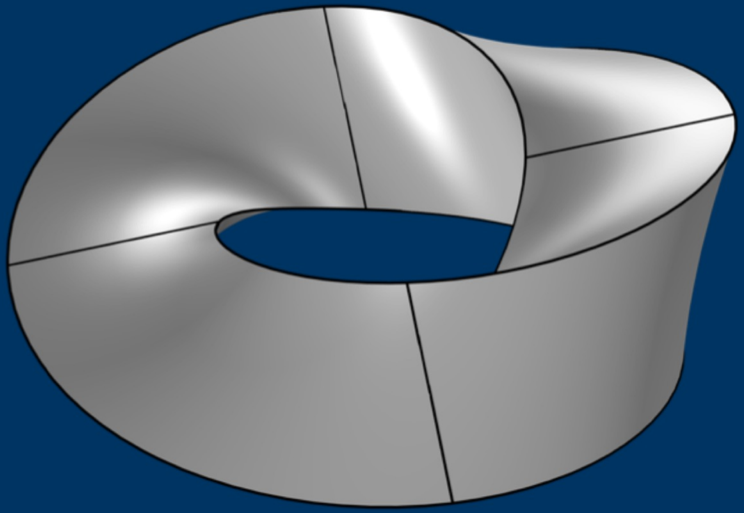
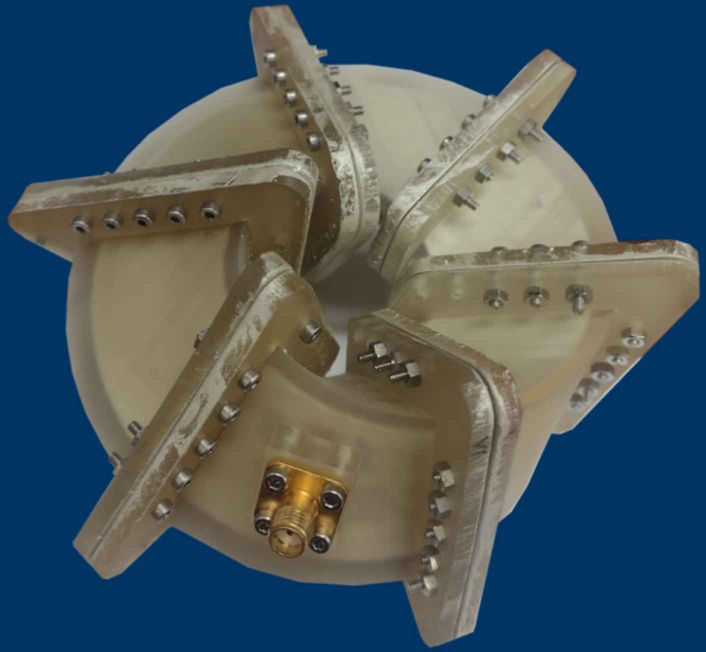
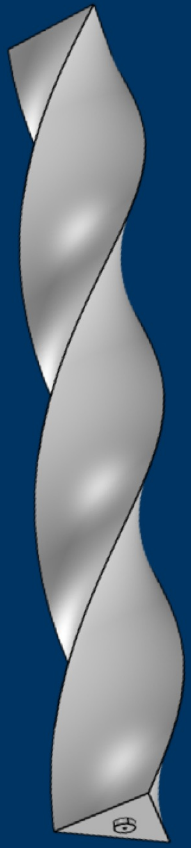




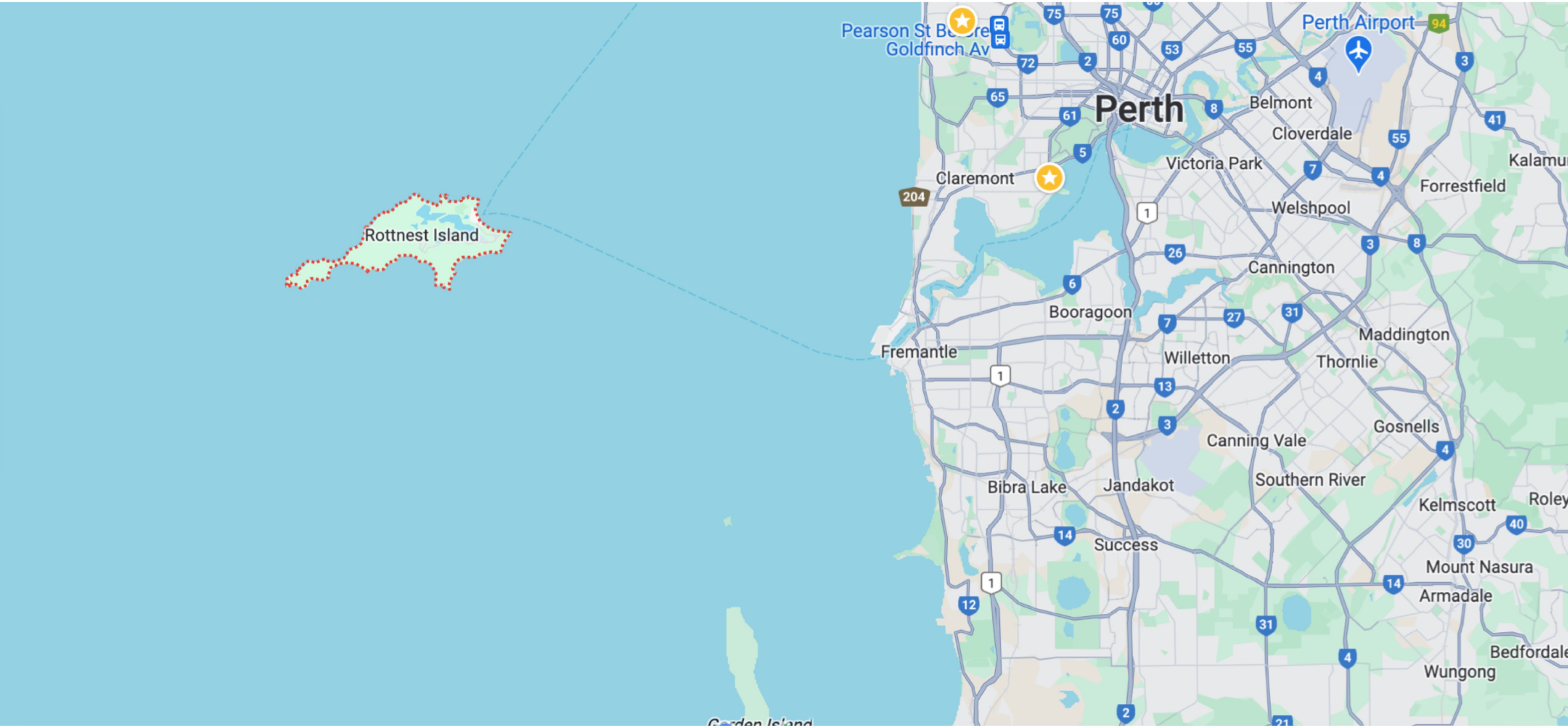


The Twisted Anyon Cavity Resonator as a potential Dark Matter Detector and Sensing device

Emma C. I. Paterson

Supervisor: Dr Jeremy Bourhill

Cultural Snippet



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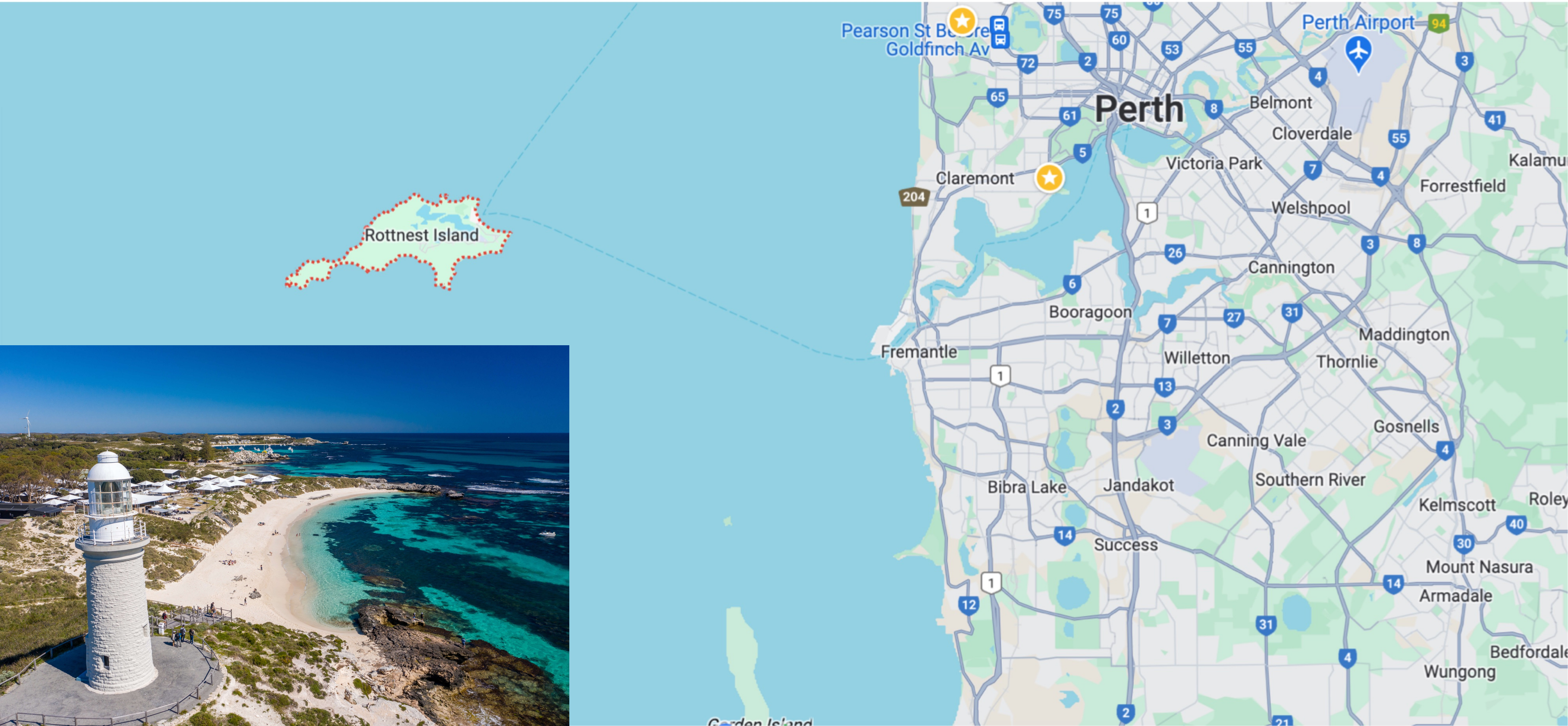
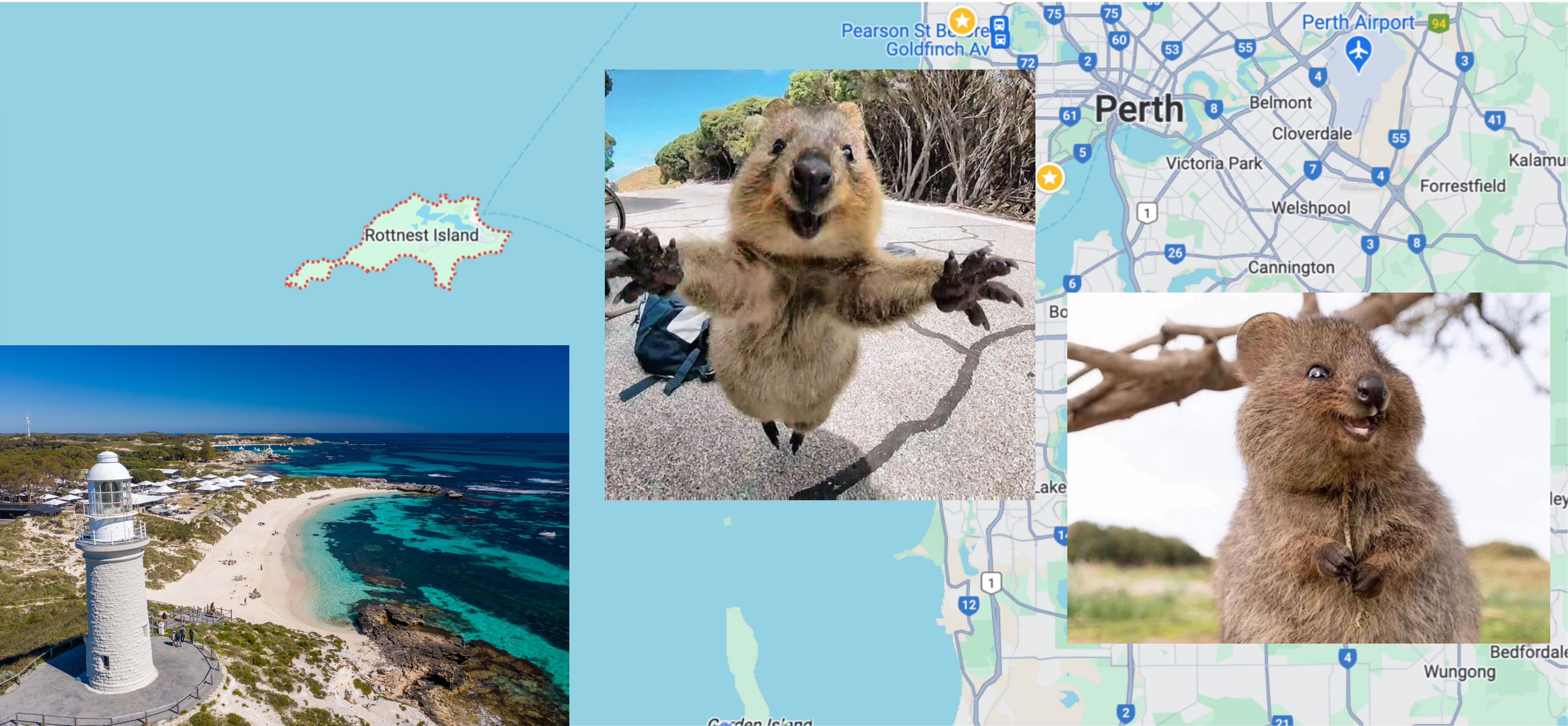
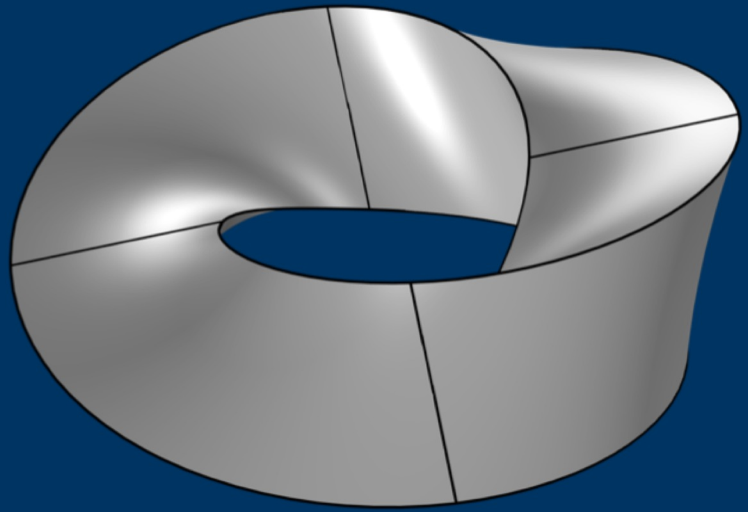
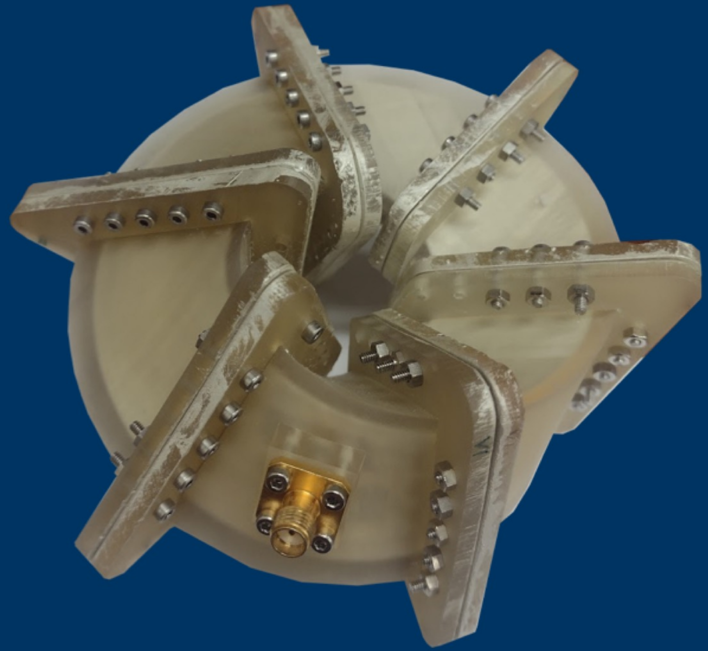
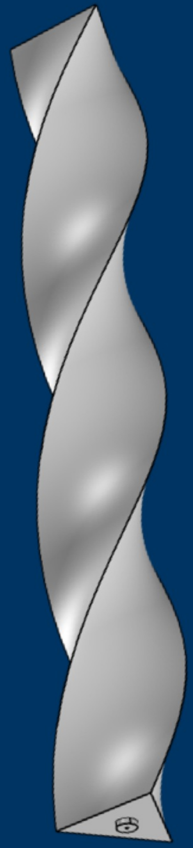


Cultural Snippet




The Twisted Anyon Cavity Resonator as a potential Dark Matter Detector and Sensing device

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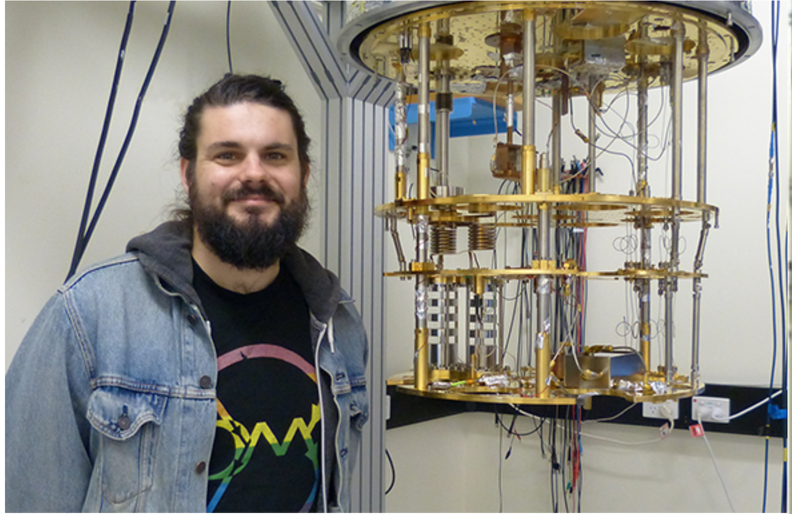
The Team



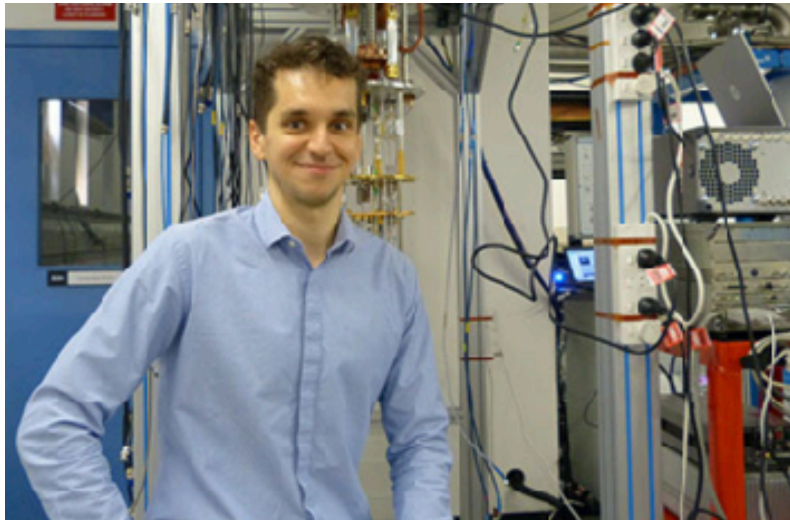
Dr Jeremy Bourhill

Prof Michael Tobar

QDM

Quantum Technologies and Dark Matter Research Lab

THE UNIVERSITY OF
WESTERN
AUSTRALIA



Prof Maxim Goryachev

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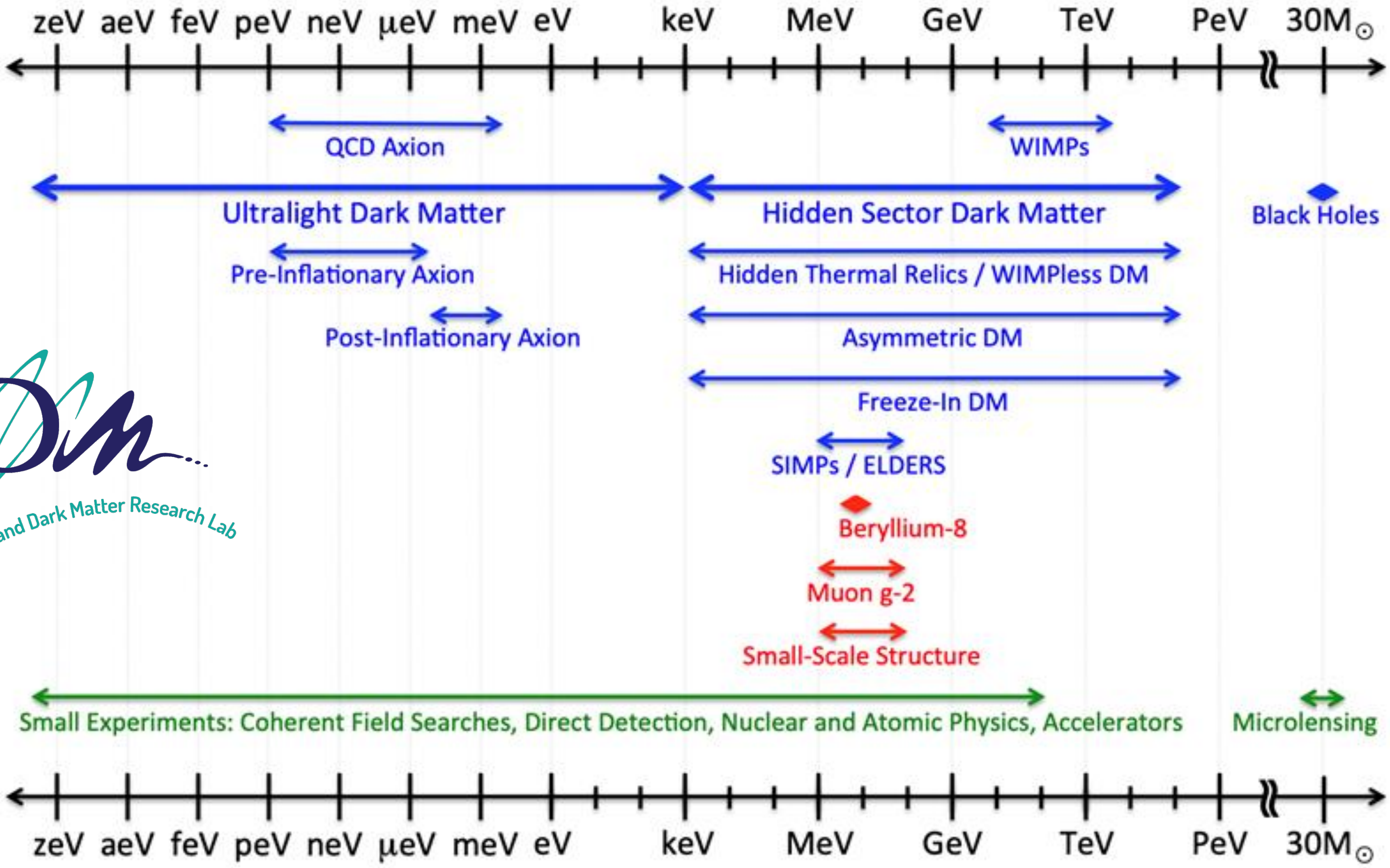
Dark Matter Candidate

- Axion
  - Weak coupling with ordinary matter

Dark Sector Candidates, Anomalies, and Search Techniques



QCD Axion

WIMPs

Ultralight Dark Matter

Hidden Sector Dark Matter

Black Holes

Pre-Inflationary Axion

Hidden Thermal Relics / WIMPless DM

Post-Inflationary Axion

Asymmetric DM

Freeze-In DM

SIMPs / ELDERS

Beryllium-8

Muon g-2

Small-Scale Structure

Small Experiments: Coherent Field Searches, Direct Detection, Nuclear and Atomic Physics, Accelerators

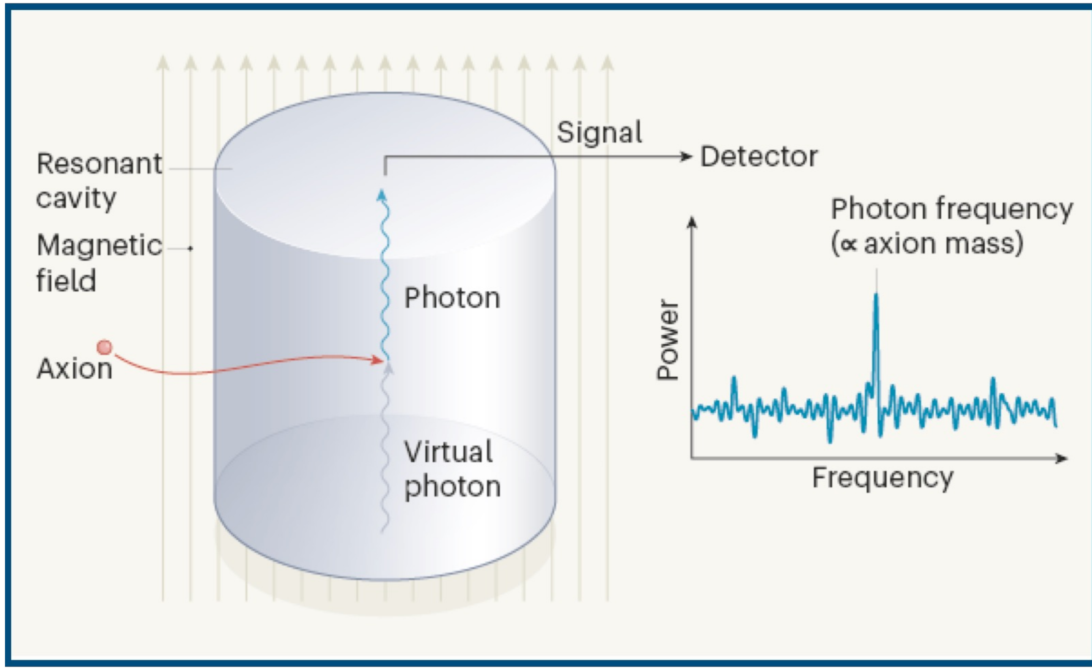
Microlensing

Regular (DC) Cavity Haloscopes

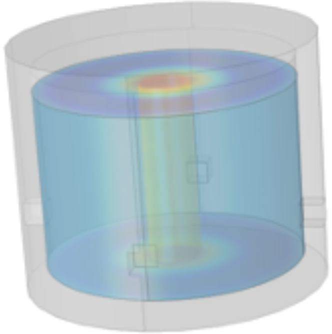
- **Chiral anomaly**: axion 2-photon coupling

$$\mathscr{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a(t) \boxed{\overrightarrow{E} \cdot \overrightarrow{B}}$$

- ORGAN
- DC magnetic field

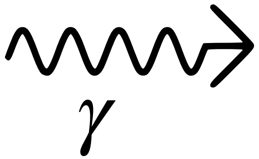


Photon ° of freedom 1:
Cavity TM mode



Photon ° of freedom 2:
Virtual Photon

$$\overrightarrow{B} \equiv$$



Regular (DC) Cavity Haloscopes

- External magnetic field
  - Prohibits the use of superconducting materials
  - Limited Q → **limited sensitivity**

$$Q = 2\pi f \frac{\text{Total stored energy}}{\text{Power Losses}}$$

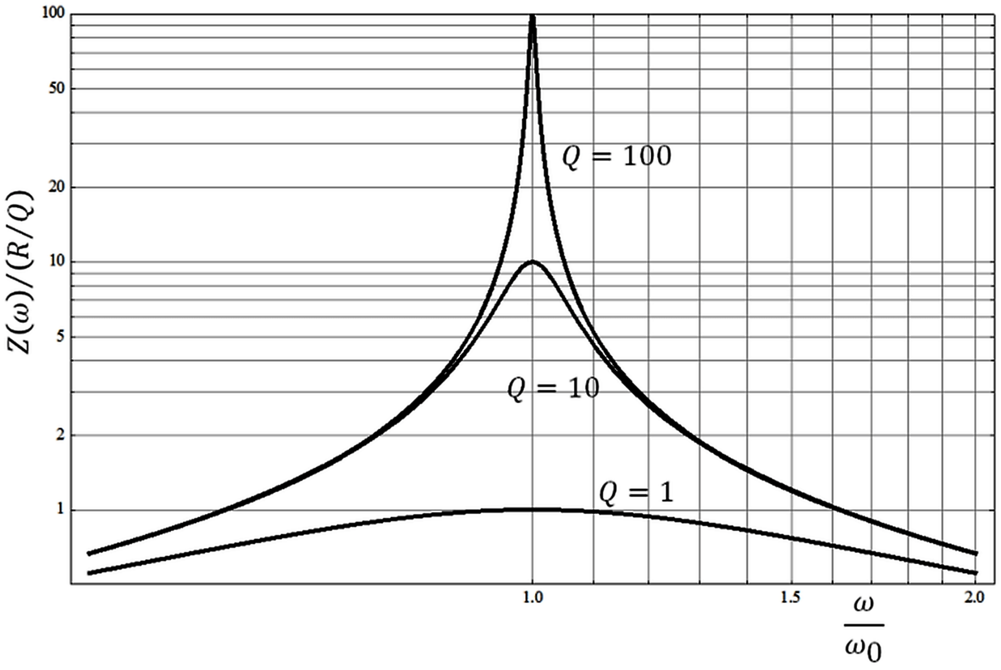
- Resonator Size ↔ minimum mass detectable

$$c = \lambda f$$

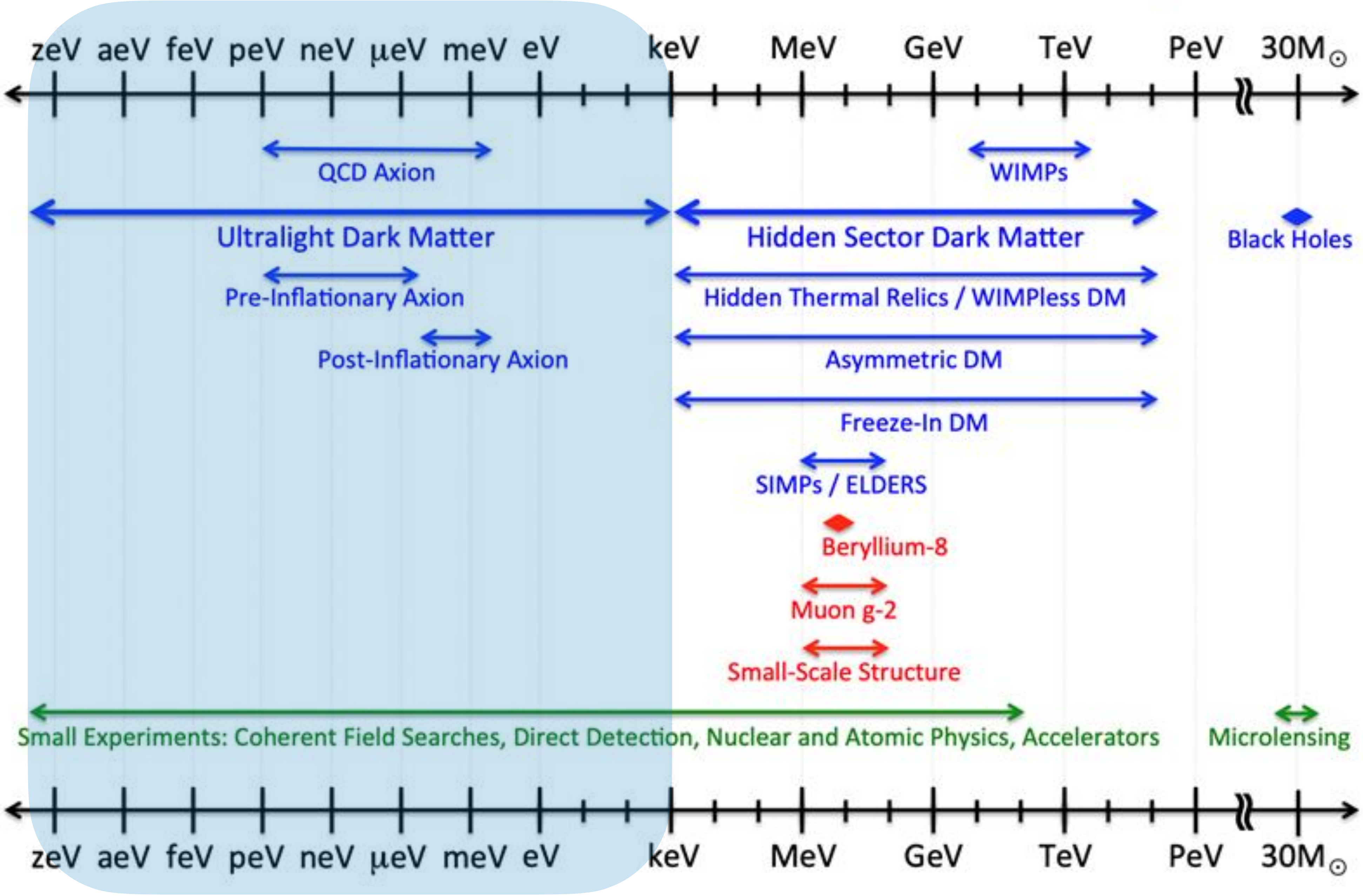
$$f = \boxed{1\ \text{MHz}} \rightarrow \lambda = \boxed{300\ \text{m}}\ !$$

Ultra-light Axions

Haloscope Cavity Size



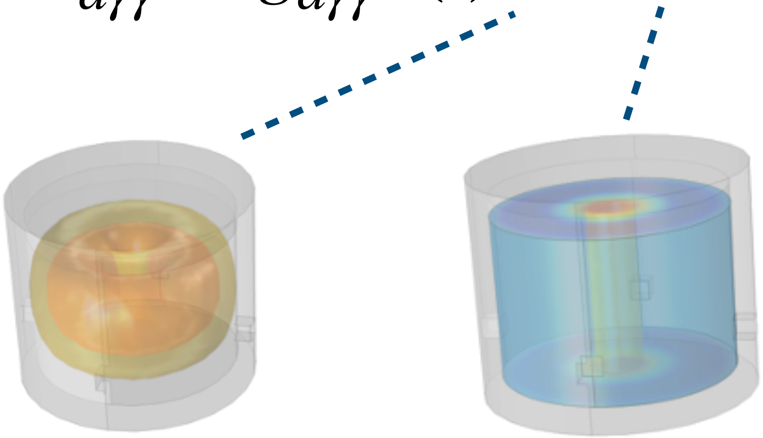
Dark Sector Candidates, Anomalies, and Search Techniques



UPLOAD

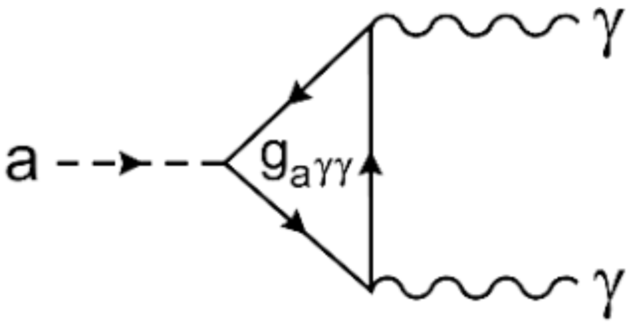
- **Two** electromagnetic **modes**

$$\mathscr{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a(t) \overrightarrow{E} \cdot \overrightarrow{B}$$



Photon ° of freedom 1: **Cavity TE mode**

Photon ° of freedom 2: **Cavity TM mode**



$\omega_a = \omega_2 - \omega_1,$ axion upconversion

$\omega_a = \omega_2 + \omega_1,$ axion downconversion

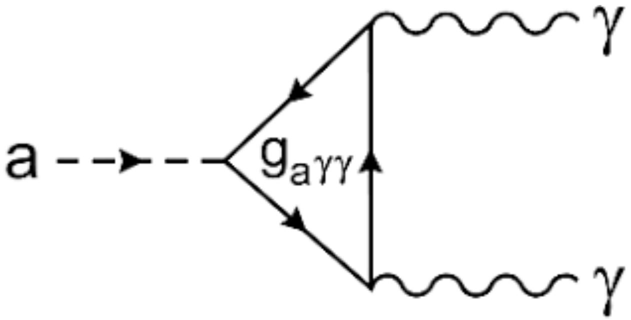
$\omega_a = \omega_1 - \omega_2 \pm \Omega$ where $\Omega \ll \omega_1$

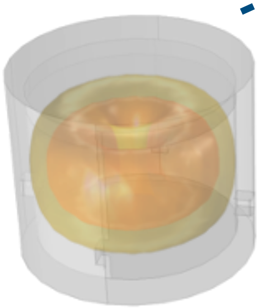
- Detection in a **lower mass range**
- **No** applied DC **magnetic field**

UPLOAD

- **Two** electromagnetic **modes**

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a(t) \overrightarrow{E} \cdot \overrightarrow{B}$$





Photon ° of freedom 1:
Cavity TE mode

2: **Cavity TM mode**

Non-linear effects
Injection Locking
≠
ULDM axions

Lower Limit:
3MHz - 10^{-7}eV

ion upconversion

$\omega_a = \omega_2 + \omega_1$, axion downconversion

$\omega_a = \omega_1 - \omega_2 \pm \Omega$ where $\Omega \ll \omega_1$

- Detection in a **lower mass range**
- **No** applied DC **magnetic field**

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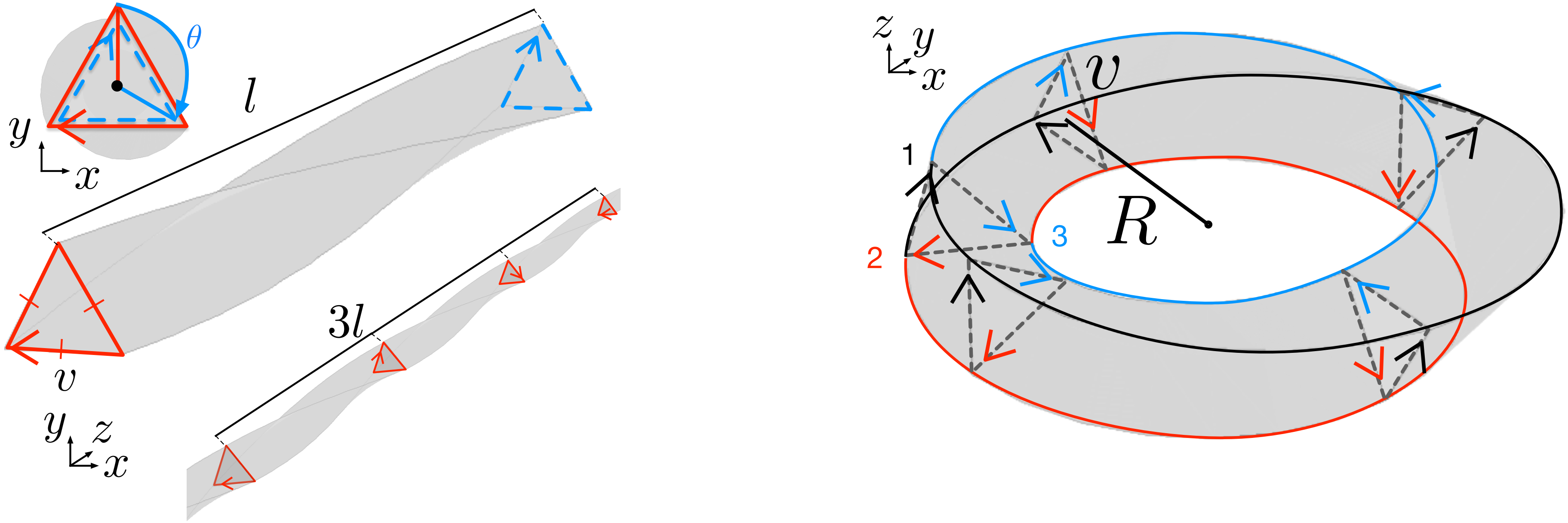
Twisted Anyon Cavity

- Twisted hollow structures
- Chiral modes at microwave frequencies

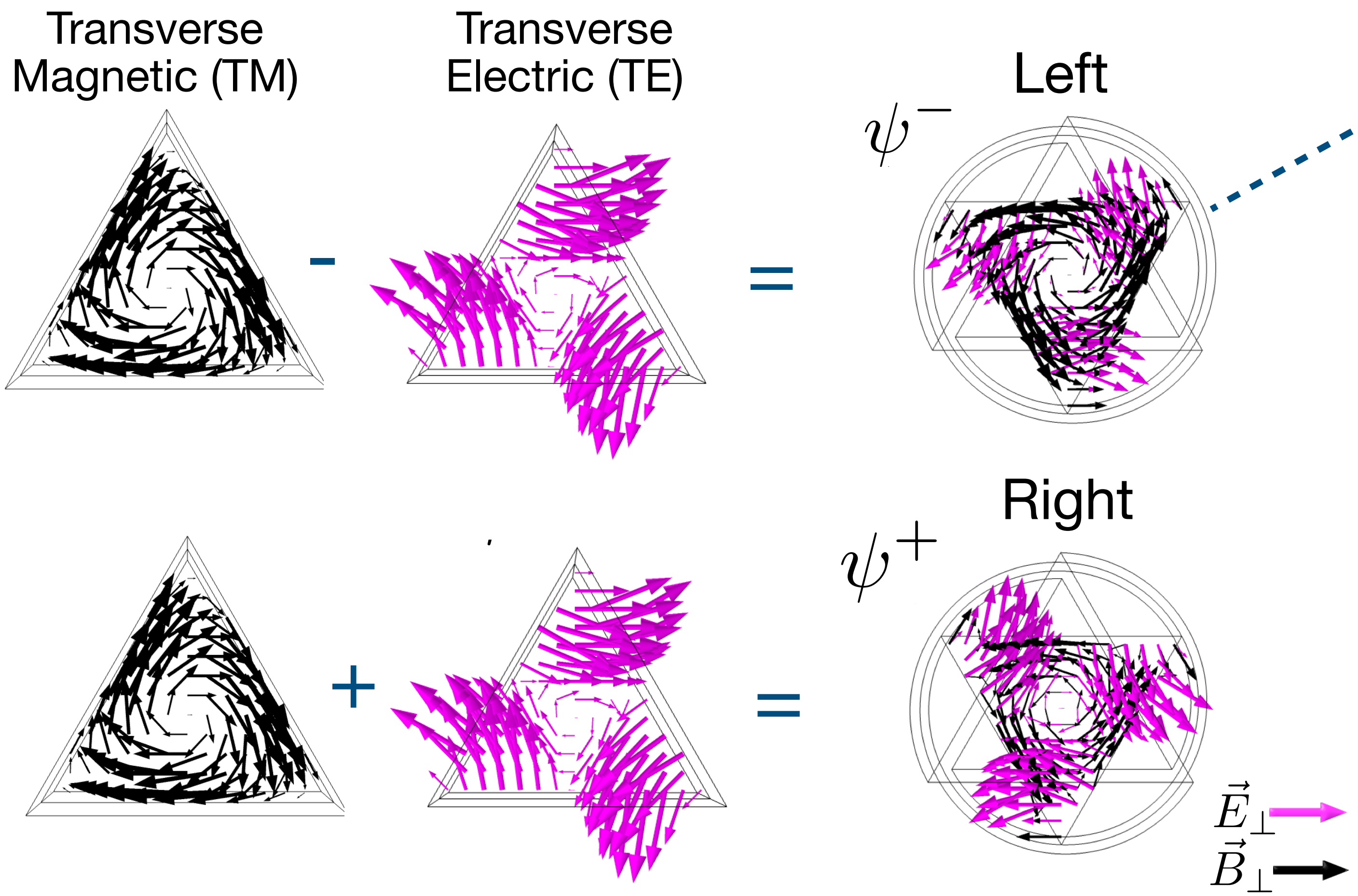


Twisted Anyon Cavity

Mirror Asymmetry → Magneto-electric coupling

New Orthogonality Basis:

Chiral



$$\mathscr{L}_{a\gamma\gamma} = g_{a\gamma\gamma} a(t) \overrightarrow{E} \cdot \overrightarrow{B}$$

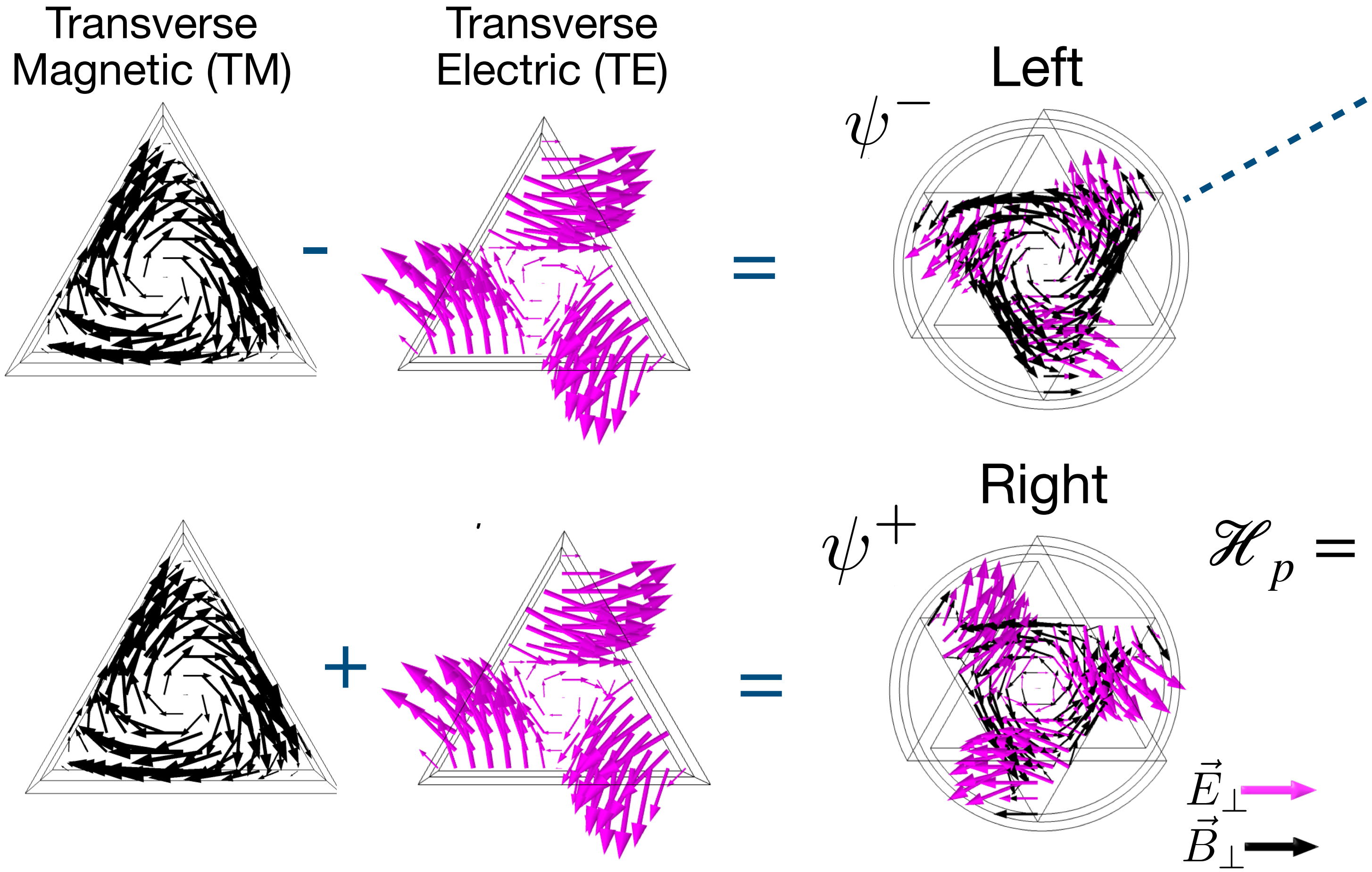
<u>Single</u> electromagnetic mode

Twisted Anyon Cavity

Mirror Asymmetry ⟶ Magneto-electric coupling

New Orthogonality Basis:

Chiral



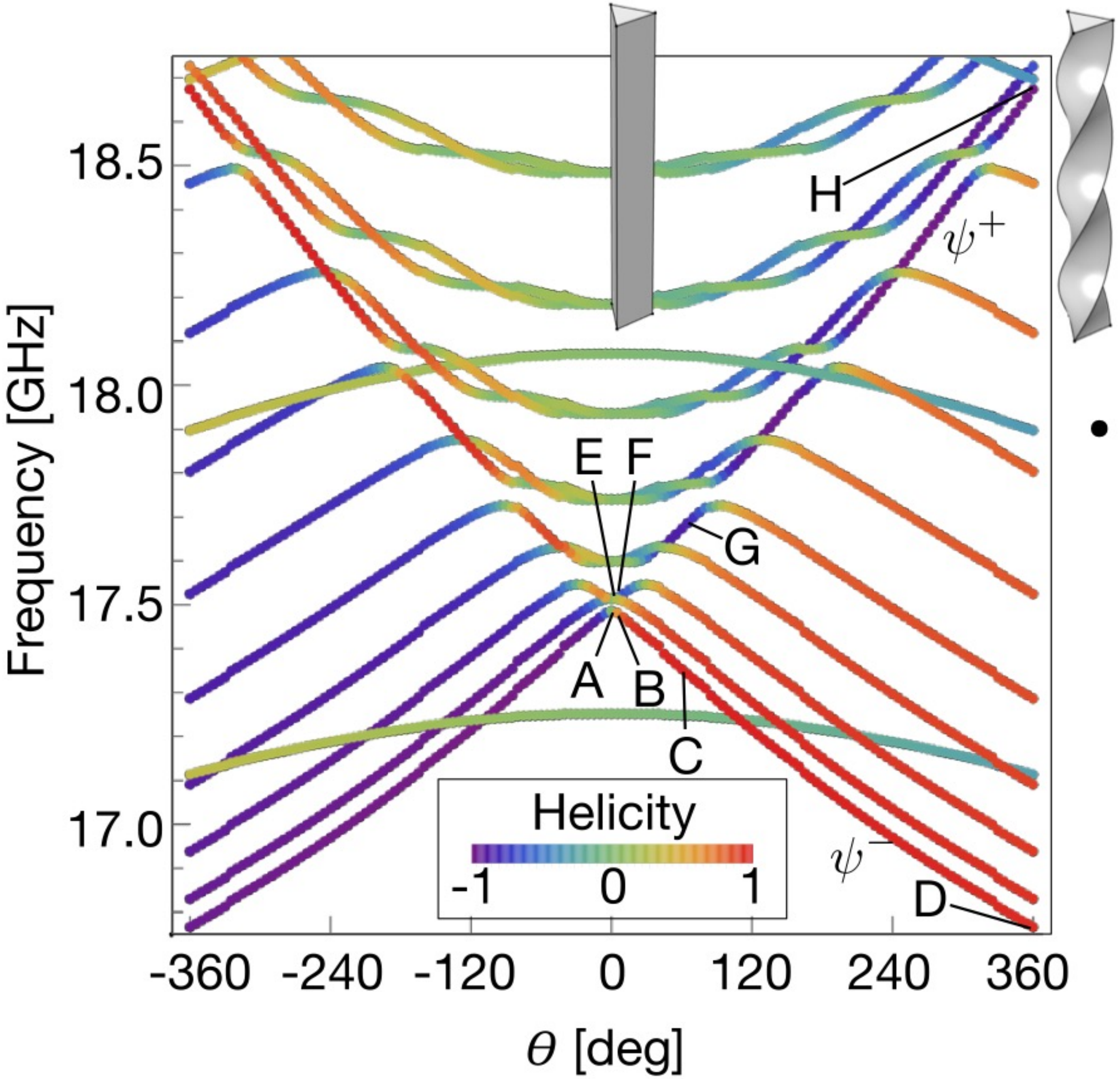
$$\mathscr{L}_{a\gamma\gamma} = g_{a\gamma\gamma}a(t)\,\vec{E}\cdot\vec{B}$$

Single electromagnetic mode

$$\mathscr{H}_p = \frac{2\,\mathrm{Im}\left[\int \mathbf{B}_p^*(\vec{r})\cdot\mathbf{E}_p^{(}\vec{r})d\tau\right]}{\sqrt{\int \mathbf{E}_p(\vec{r})\cdot\mathbf{E}_p^*(\vec{r})d\tau\int \mathbf{B}_p(\vec{r})\cdot\mathbf{B}_p^*(\vec{r})d\tau}}$$

Contents

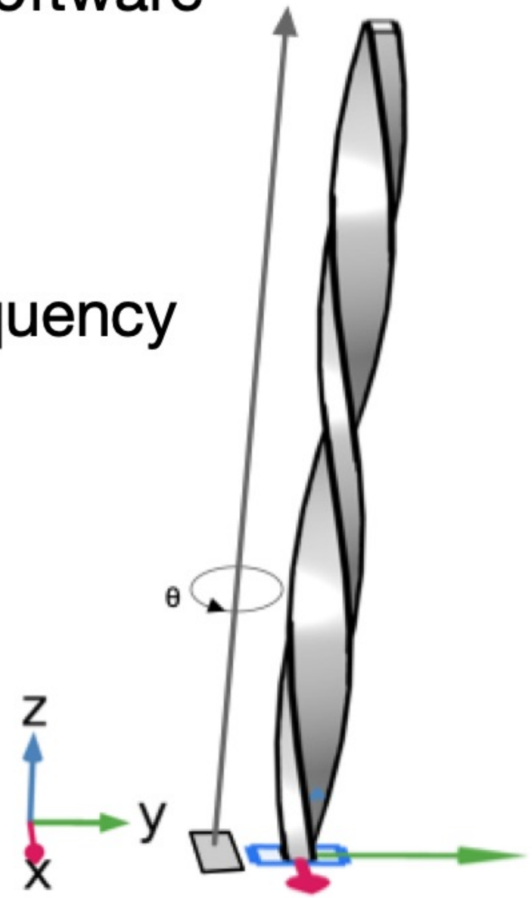
Simulation



Finite element analysis software COMSOL Multiphysics

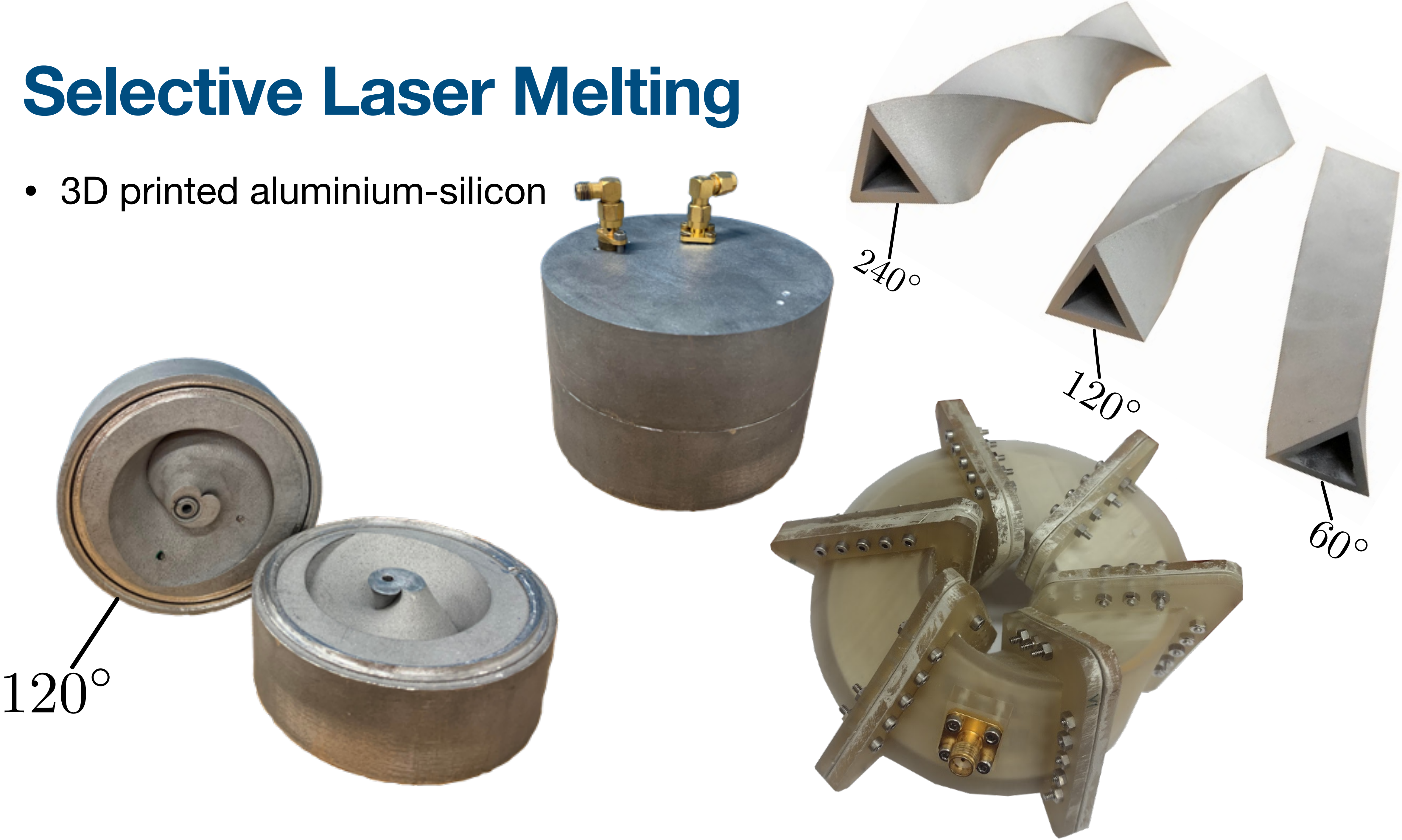
- Increasing twist:
  - Eigenmodes tune in frequency
  - Helicity increases

$$\mathscr{H}_p \approx 1$$

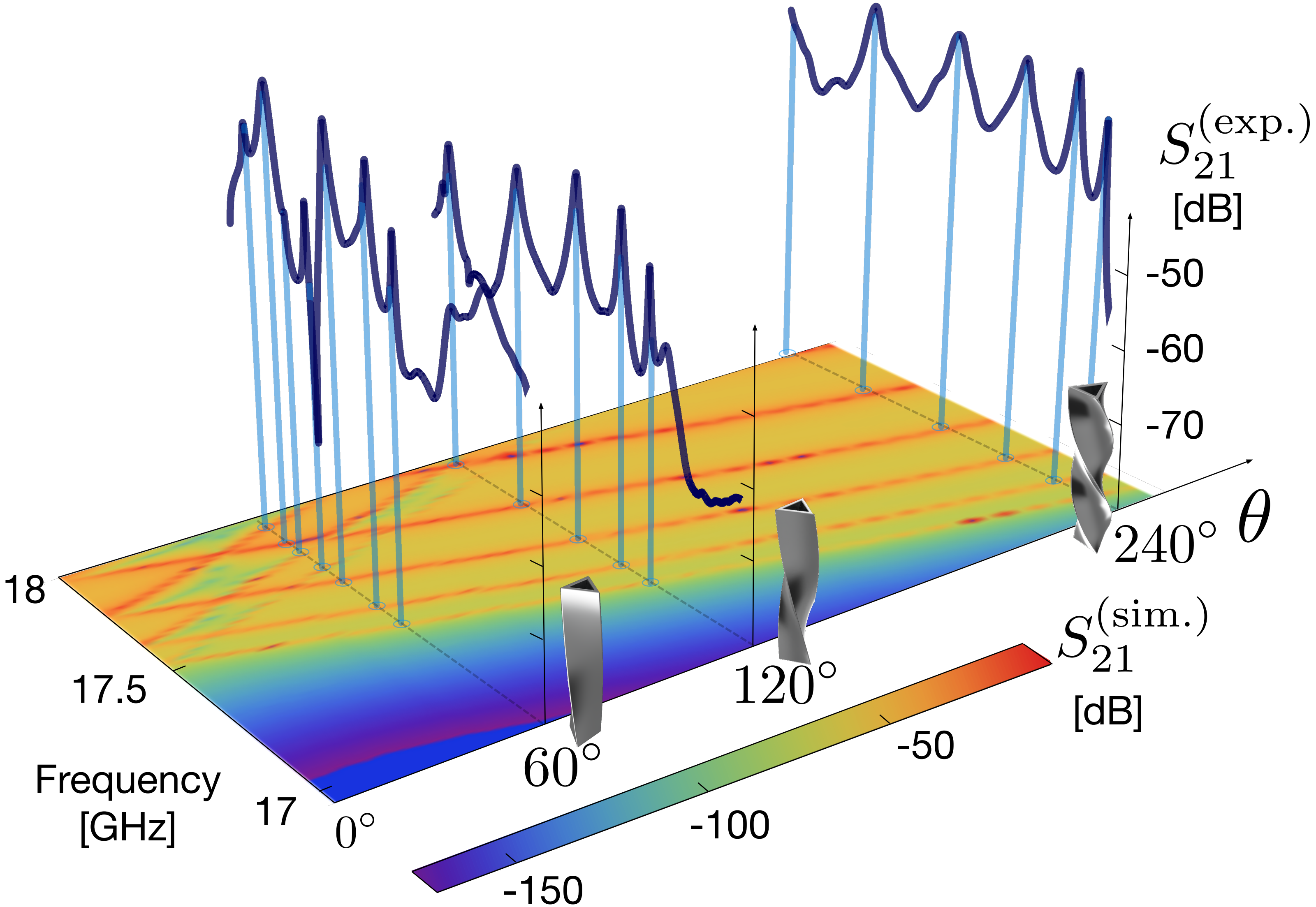


Selective Laser Melting

- 3D printed aluminium-silicon



Simulation and Experimental Results Agree

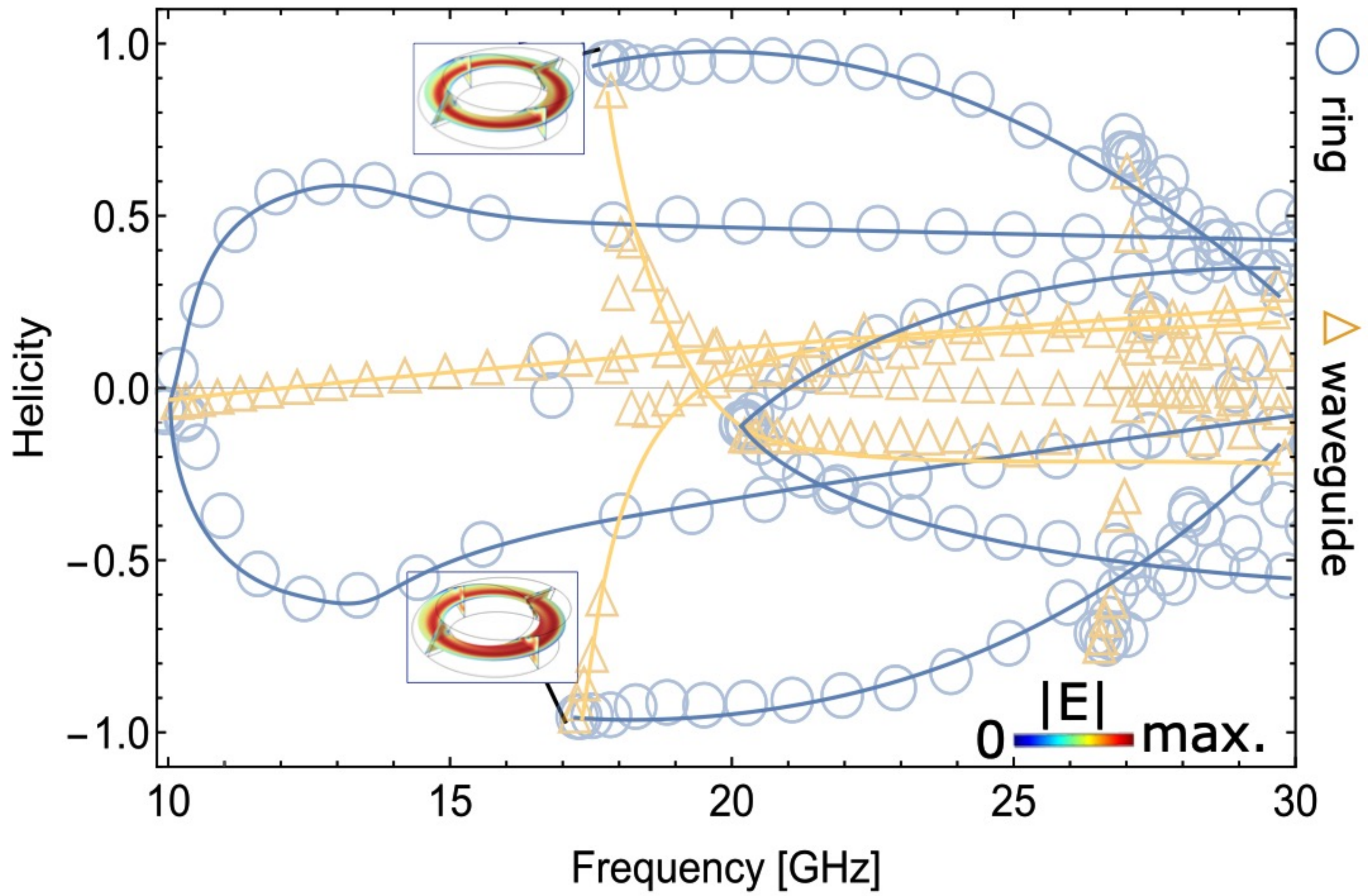


Möbius Resonator

- Increased Q-factor

$$\uparrow Q = 2\pi f \frac{\text{Total stored energy}}{\downarrow \text{Power Losses}}$$

- Multiple high-helicity modes



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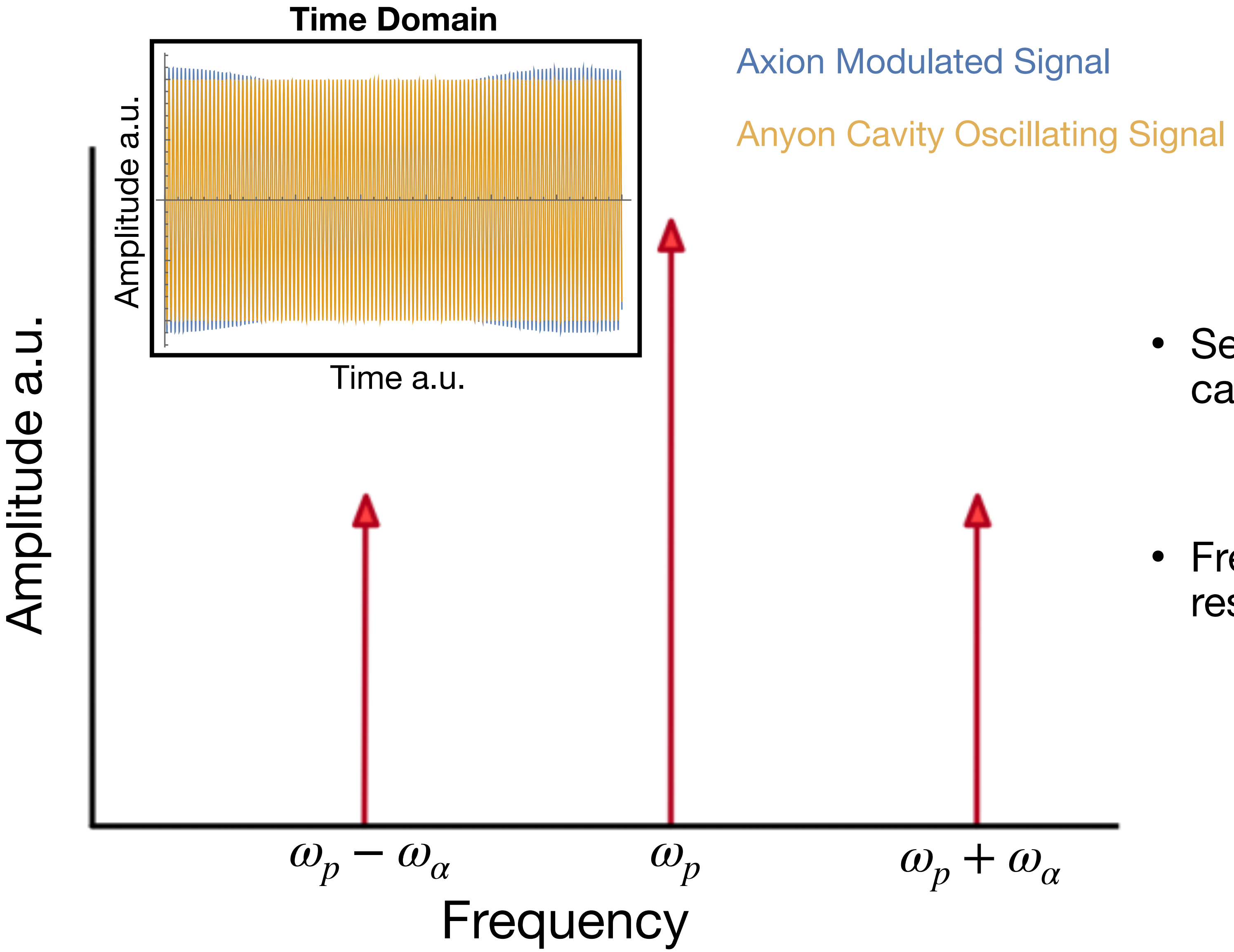
Amplitude Modulated Sidebands



- Sensitive to **amplitude modulation** of our carrier signal
- Frequencies within the **bandwidth** of the resonator

Sensitivity

$$SNR \propto \left|H_p\right| \frac{Q_p}{\sqrt{1 + 4Q_p^2 \left(\frac{\omega_a}{\omega_p}\right)^2}} \frac{\left(\omega_a\right)^{\frac{1}{4}}}{\omega_p}$$

Phys. Rev. D **108**, 052014

Sensitivity

$$SNR \propto \left|H_p\right| \frac{Q_p}{\sqrt{1 + 4Q_p^2 \left(\cancelto{0}{\frac{\omega_a}{\omega_p}}\right)^2}} \frac{\left(\omega_a\right)^{\frac{1}{4}}}{\omega_p}$$

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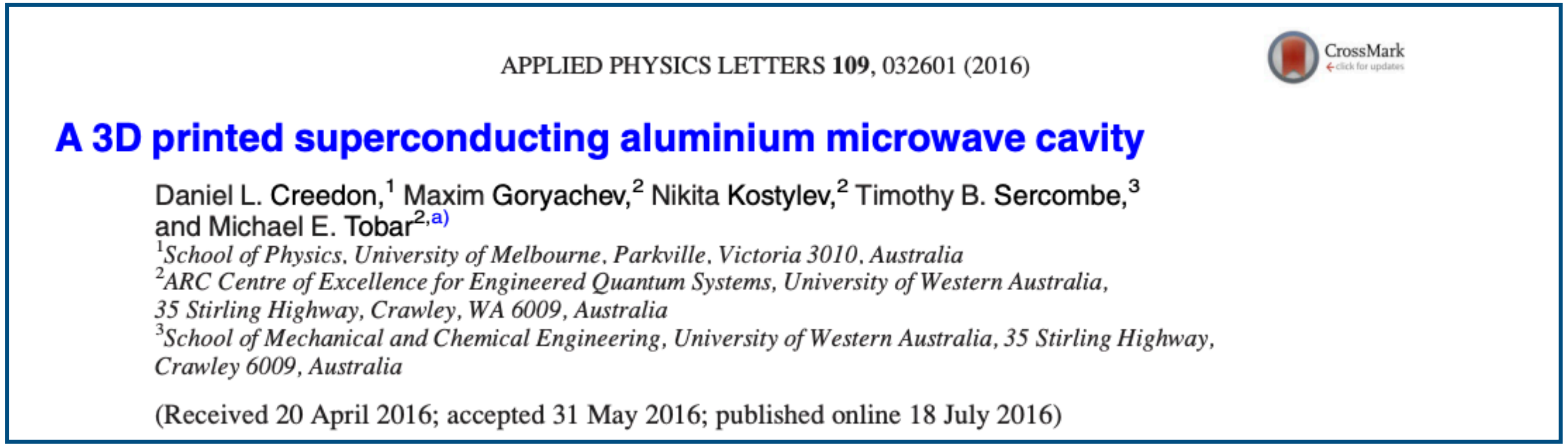


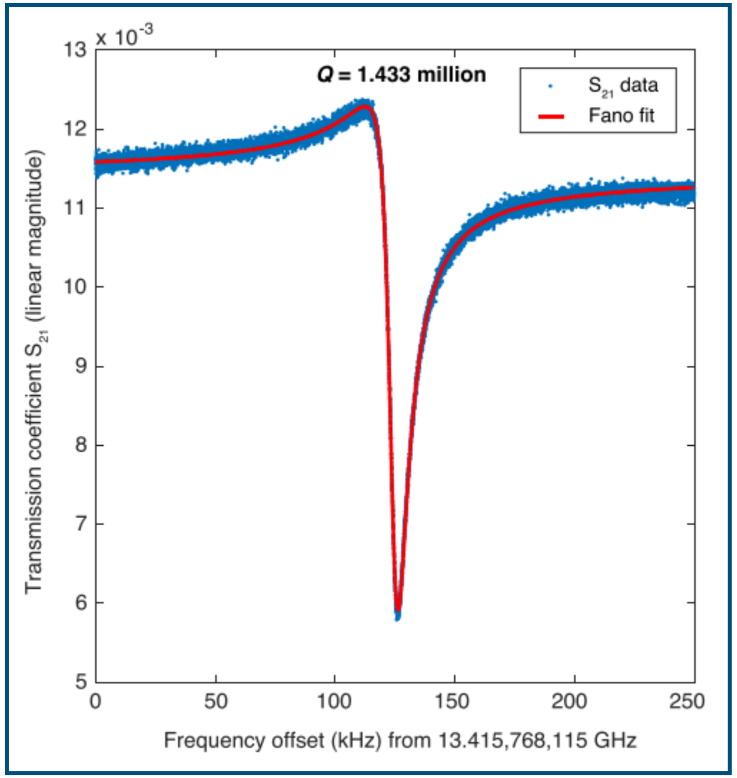
APPLIED PHYSICS LETTERS **109**, 032601 (2016)

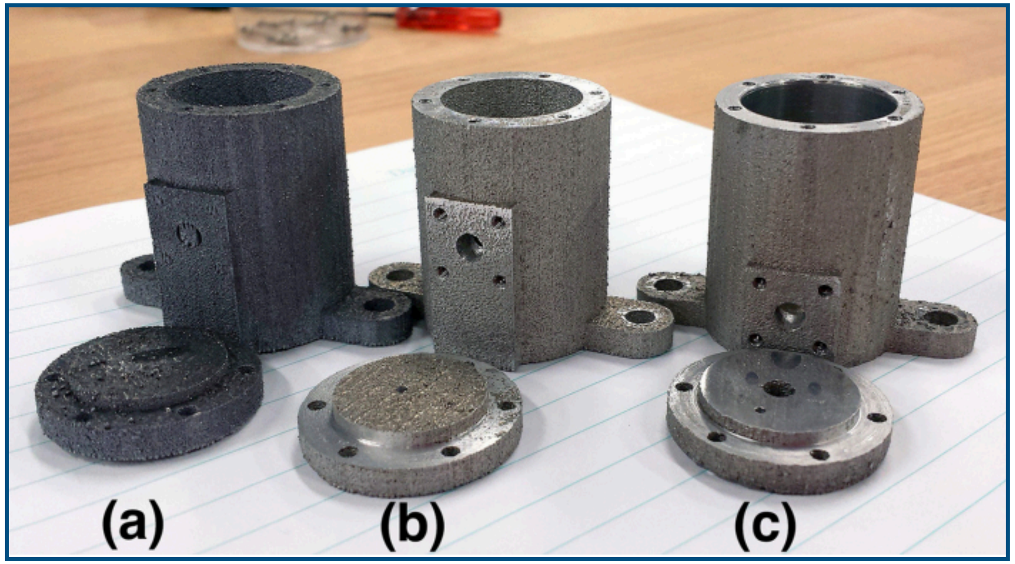
A 3D printed superconducting aluminium microwave cavity

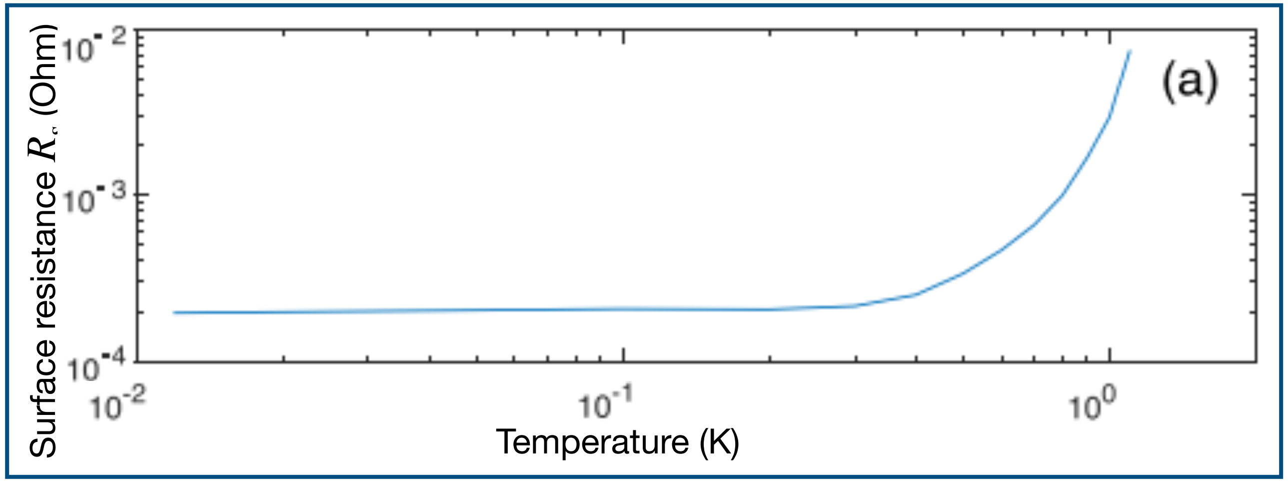
Daniel L. Creedon,[1] Maxim Goryachev,[2] Nikita Kostylev,[2] Timothy B. Sercombe,[3]
and Michael E. Tobar[2,a)]
[1]*School of Physics, University of Melbourne, Parkville, Victoria 3010, Australia*
[2]*ARC Centre of Excellence for Engineered Quantum Systems, University of Western Australia,*
35 Stirling Highway, Crawley, WA 6009, Australia
[3]*School of Mechanical and Chemical Engineering, University of Western Australia, 35 Stirling Highway,*
Crawley 6009, Australia

(Received 20 April 2016; accepted 31 May 2016; published online 18 July 2016)

$$\boxed{Q = \frac{G}{R_s}}$$

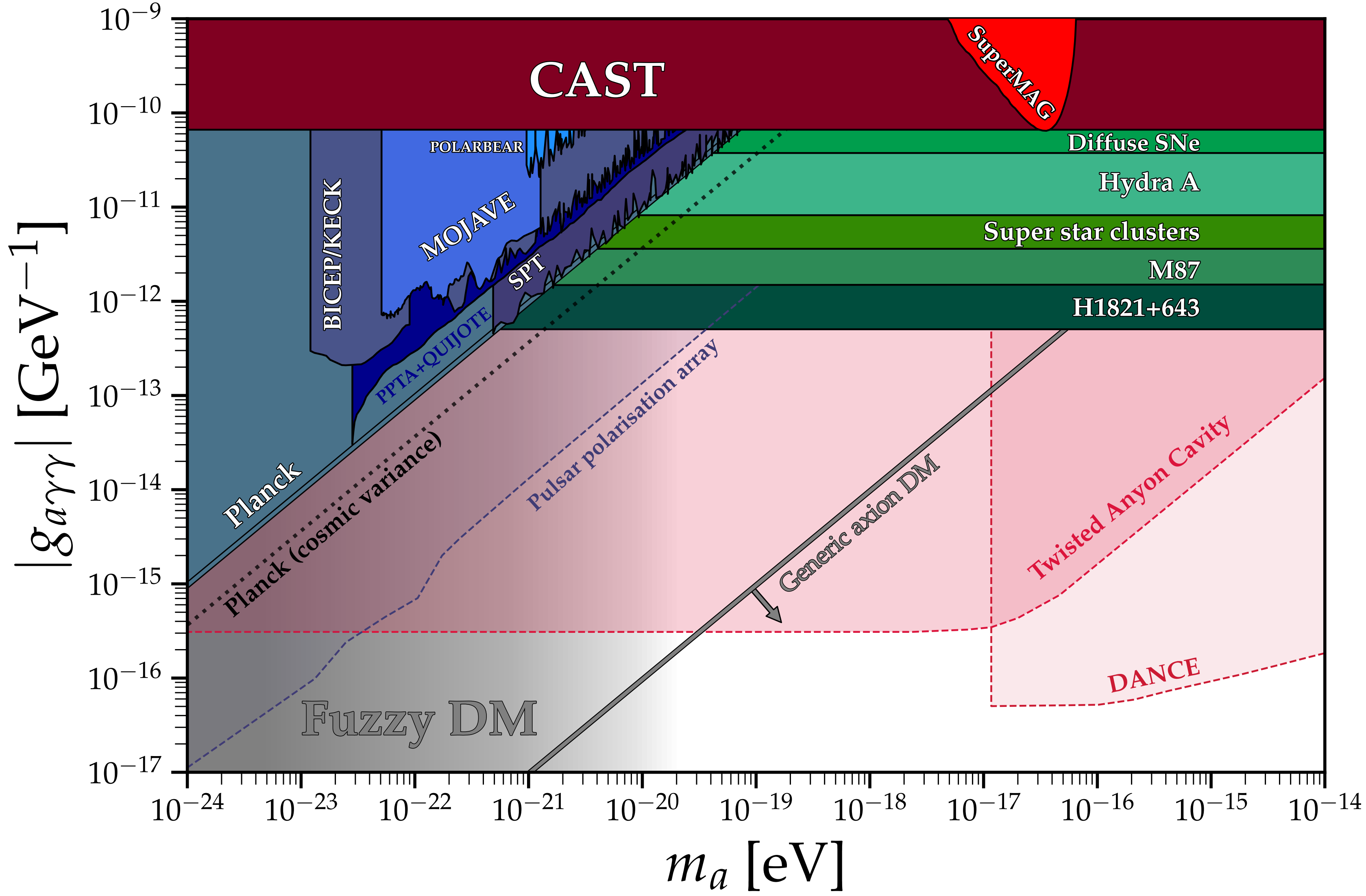






Global Research Efforts

Projections



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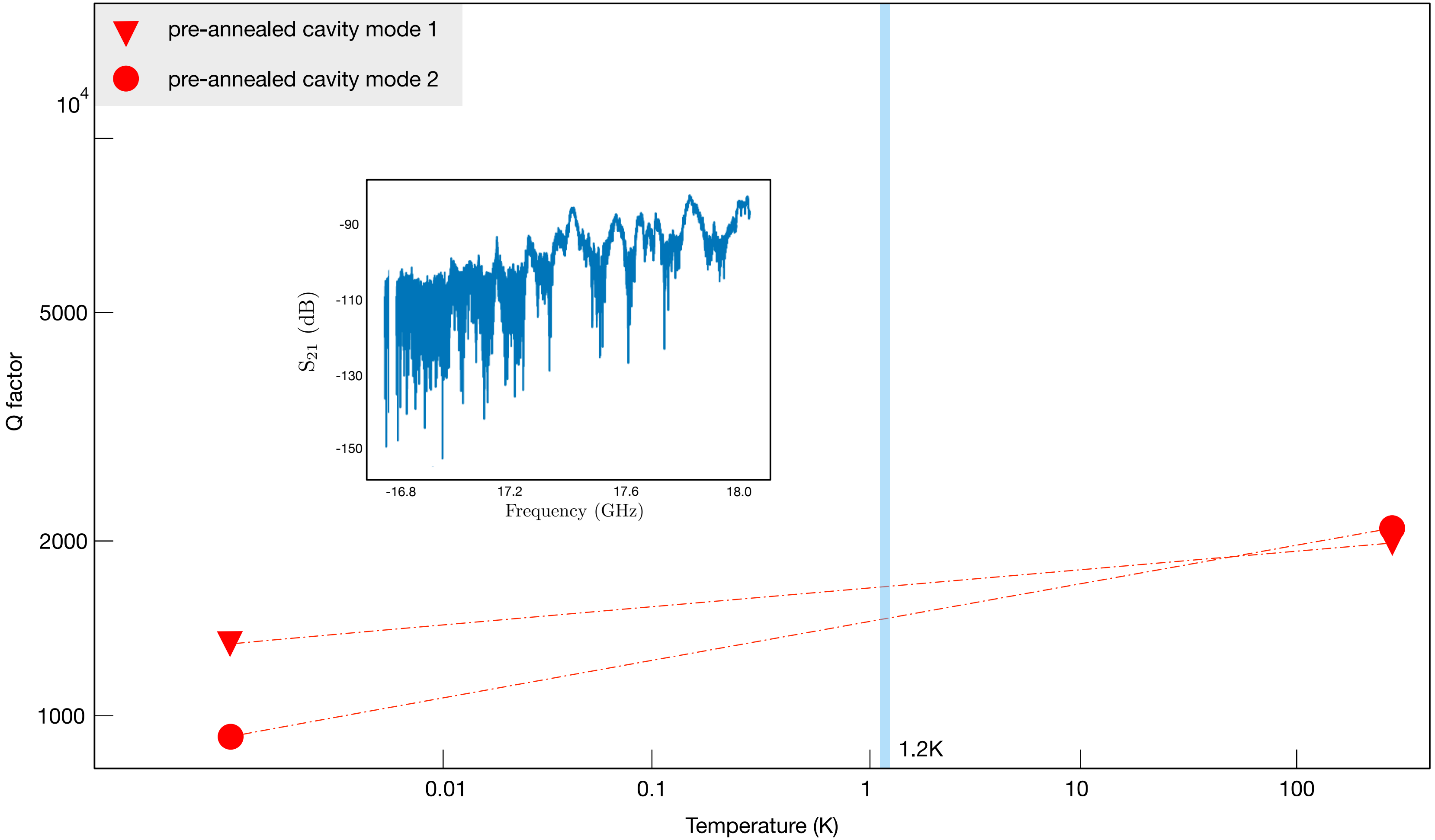
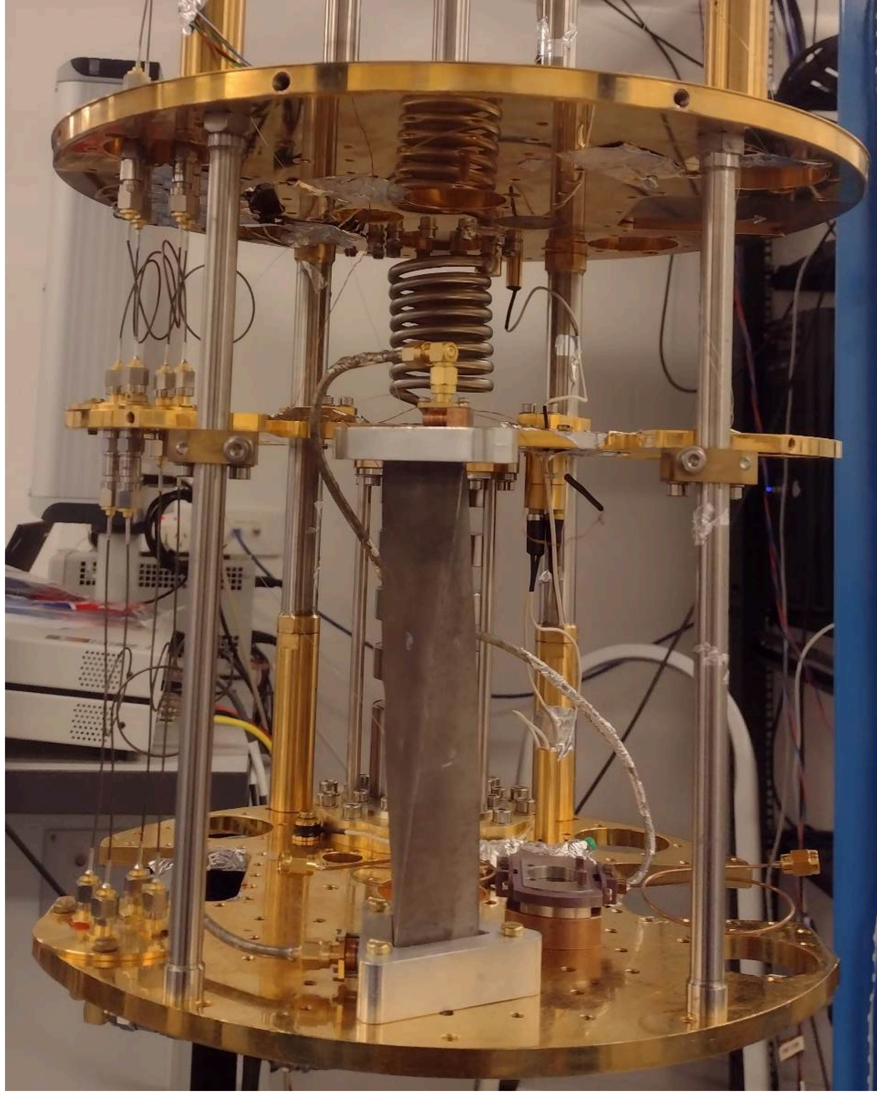
Q-factor Measurements

- Superconducting transition

$$Q = \frac{\omega U}{P_c} \qquad Q = \frac{\omega\mu \int_V |\mathbf{H}|^2 dv}{R_S \int_S |\mathbf{H}|^2 ds}$$

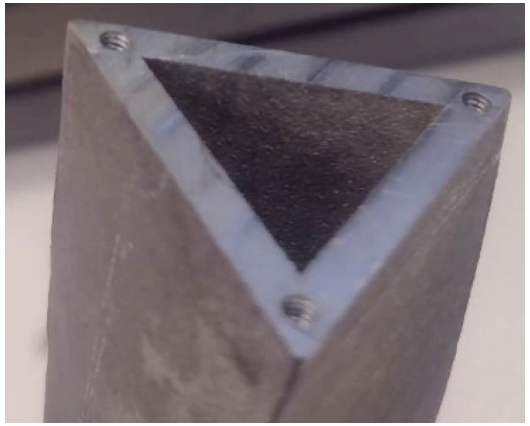




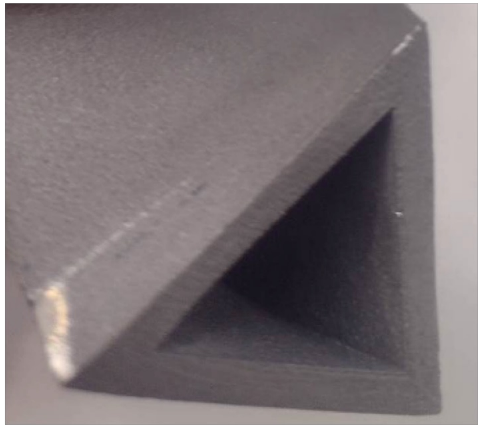
Annealing

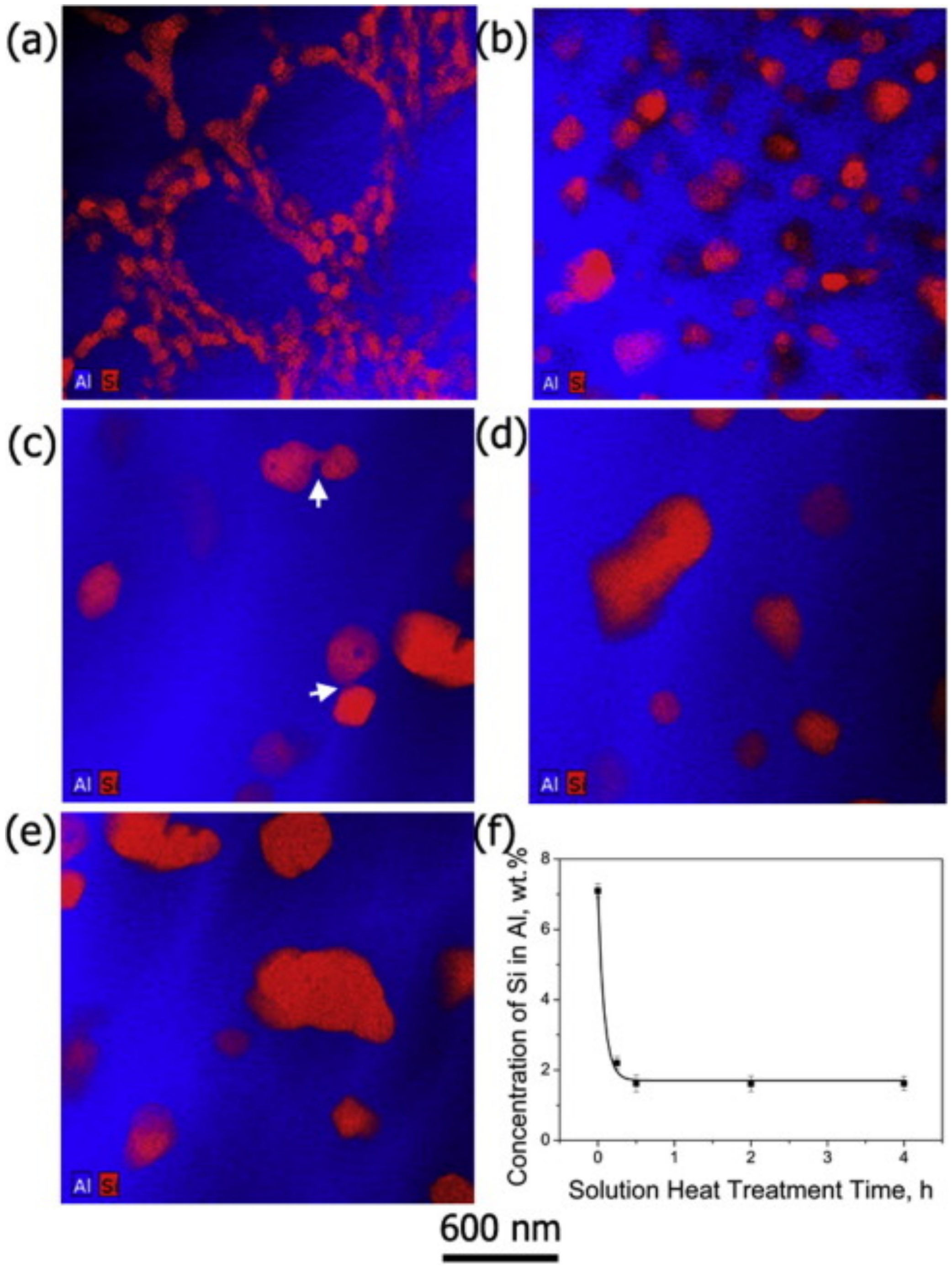
- X.P. Li, Acta Mater. 95:74-82 (2015)
- Extracting Silicon remnants

post-annealing



pre-annealing

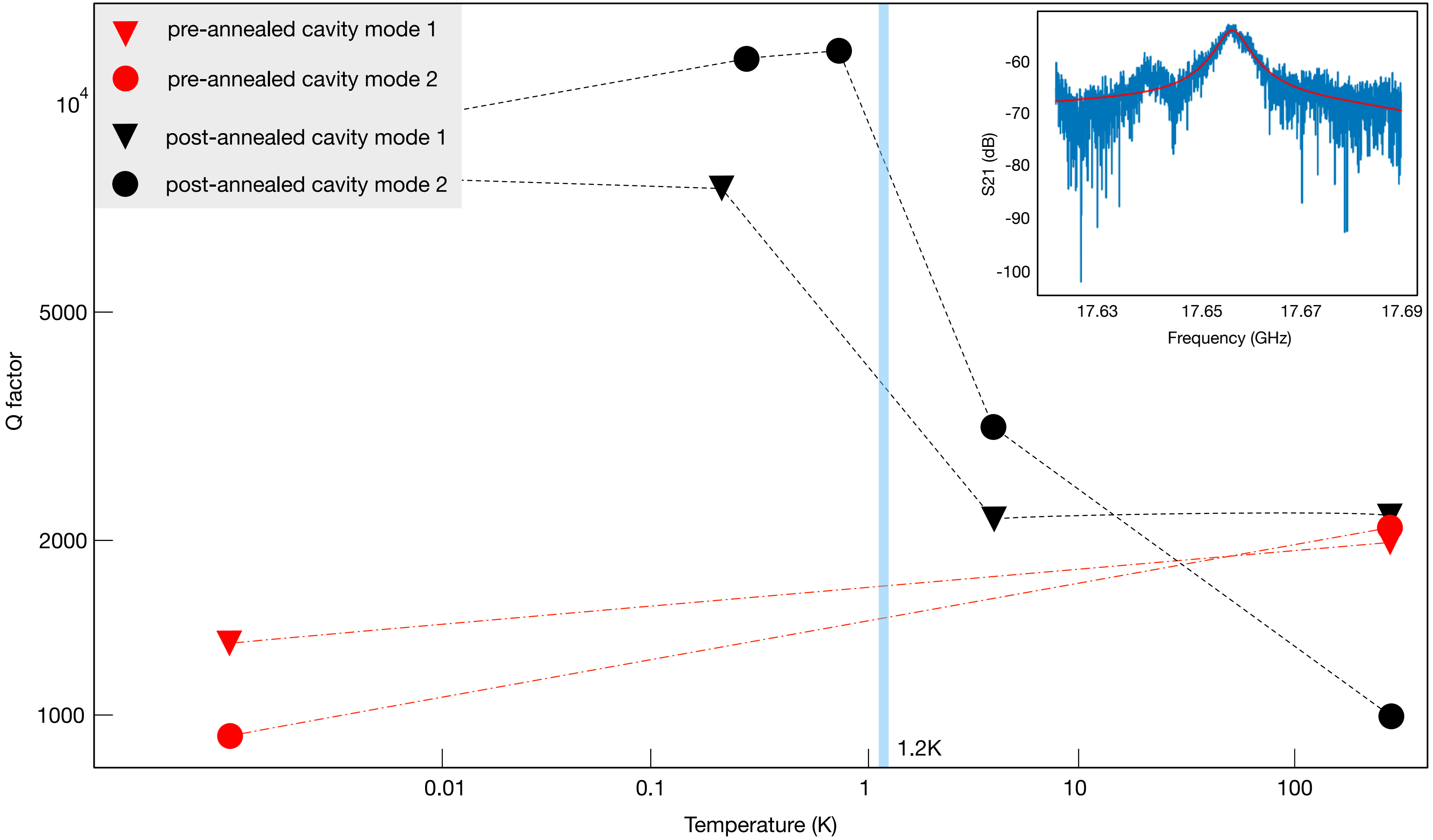


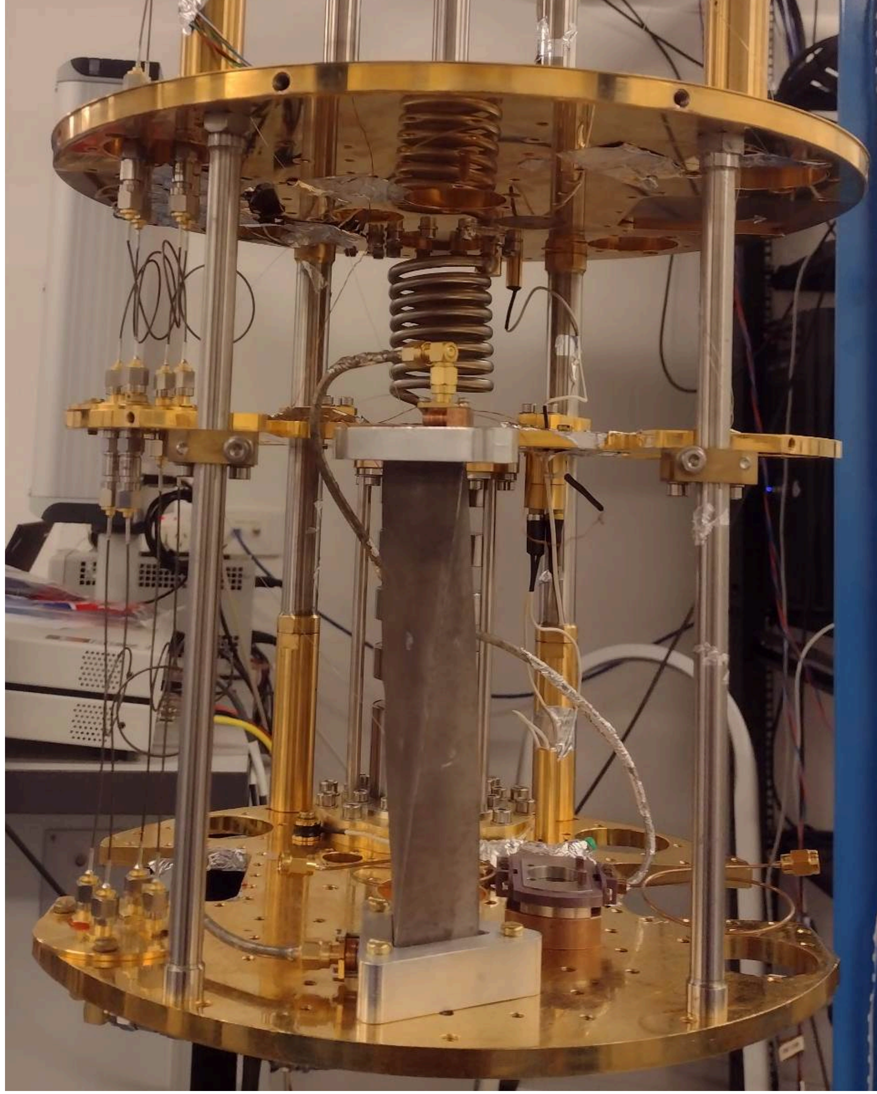


Q-factor Measurements

- Superconducting transition

$$Q = \frac{\omega U}{P_{\mathrm{c}}} \qquad Q = \frac{\omega\mu \int_{\mathrm{V}} |\mathbf{H}|^2 dv}{R_{\mathrm{S}} \int_{\mathrm{S}} |\mathbf{H}|^2 ds}$$





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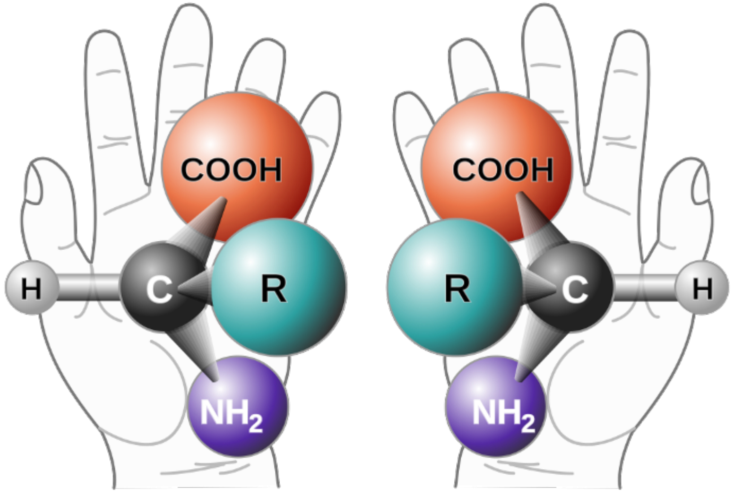
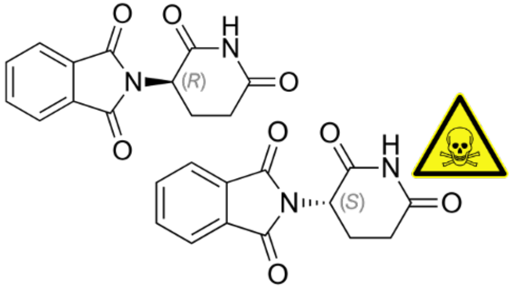
Commercial Application

Commercialization ⟶ Chiral Seperation





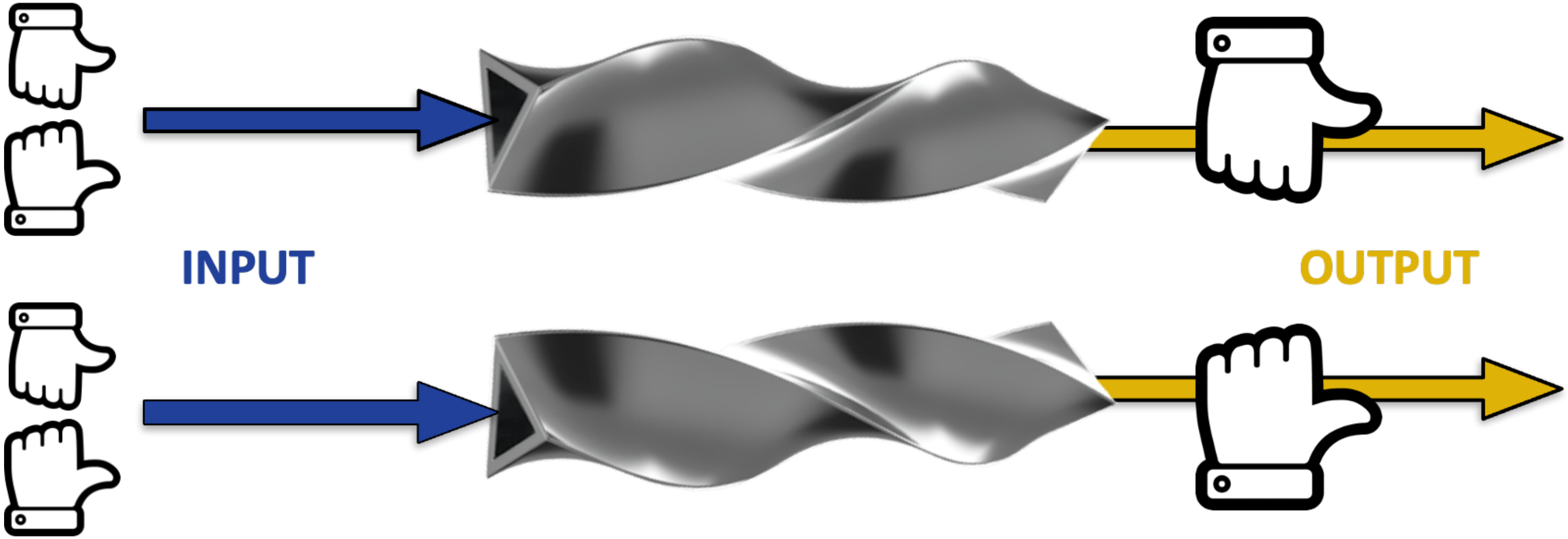
HPLC

Wasteful, inefficient, costly

10’s of mg per day

Commercial Application

Twisted electromagnetic devices



Commercial Application

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

Translational Research Program

Foundry

ON

POWERED BY
CSIRO

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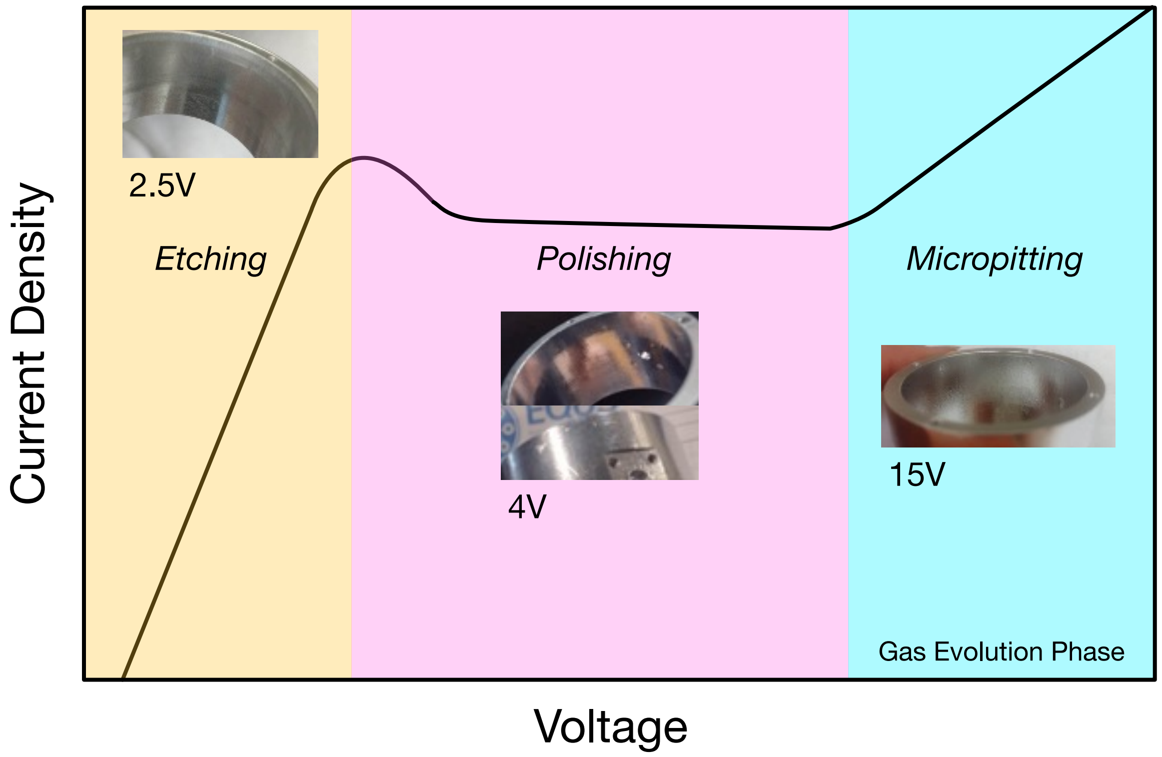
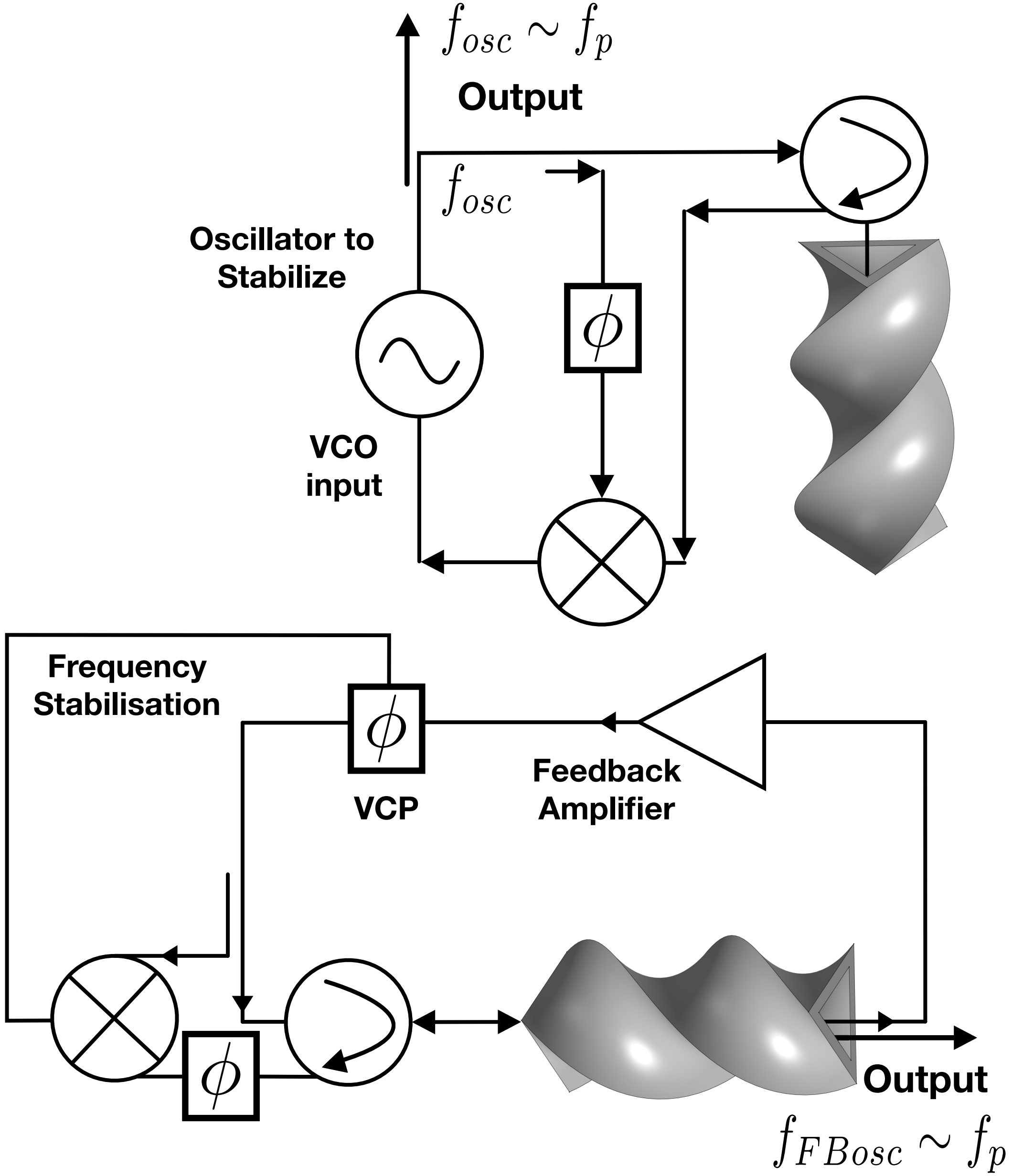
Future Work

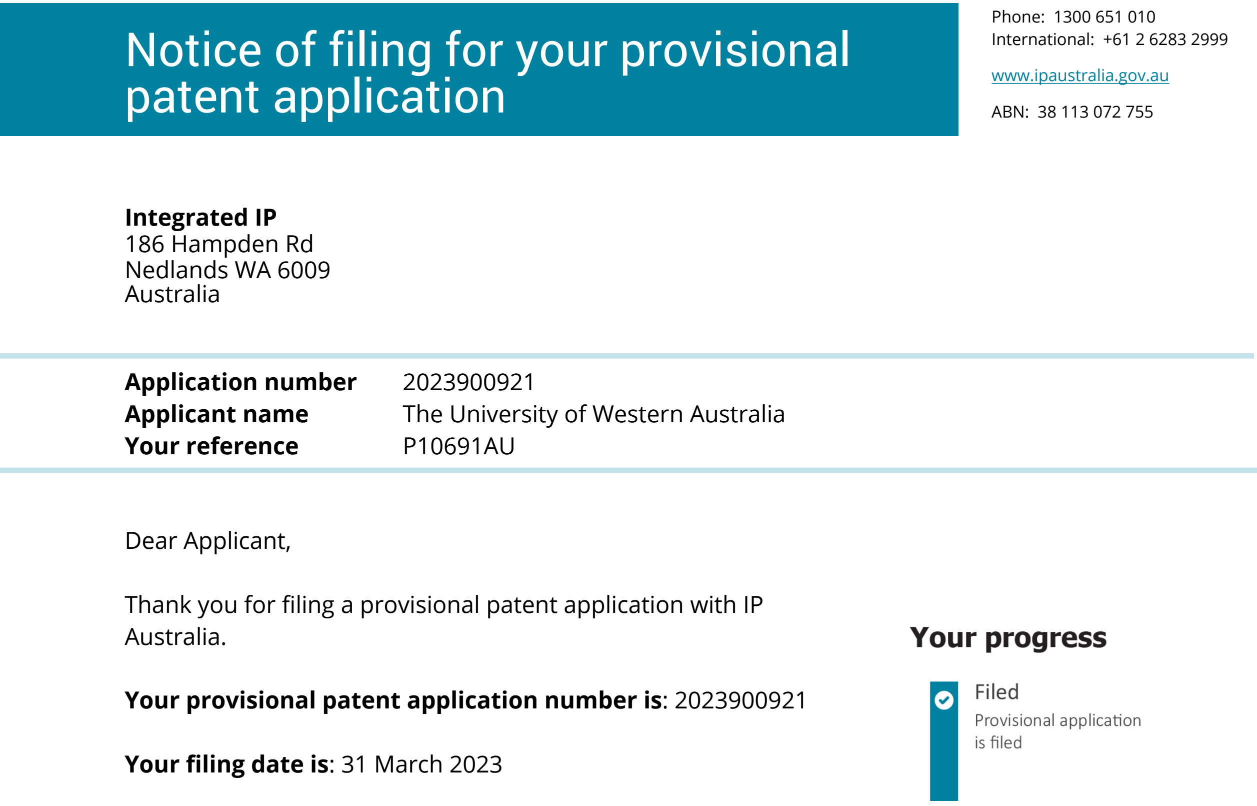
Electropolishing



Axion Detector Oscillator



Questions?



Notice of filing for your provisional patent application

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International: +61 2 6283 2999

www.ipaustralia.gov.au

ABN: 38 113 072 755

Integrated IP
186 Hampden Rd
Nedlands WA 6009
Australia

Application number	2023900921
Applicant name	The University of Western Australia
Your reference	P10691AU

Dear Applicant,

Thank you for filing a provisional patent application with IP Australia.

Your provisional patent application number is: 2023900921

Your filing date is: 31 March 2023

Your progress

✓ Filed
Provisional application is filed

PHYSICAL REVIEW D **108,** 052014 (2023)

Searching for ultralight axions with twisted cavity resonators of anyon rotational symmetry with bulk modes of nonzero helicity

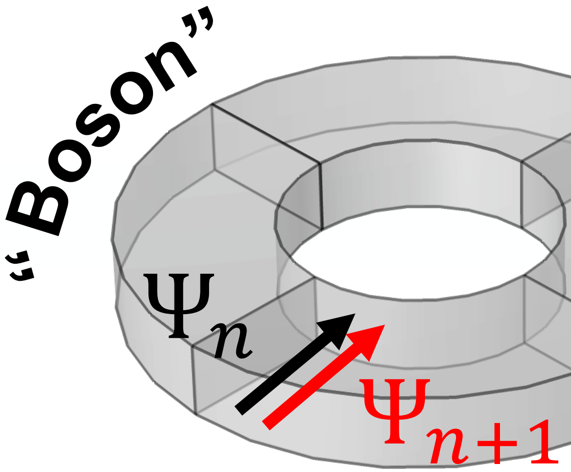
J. F. Bourhill, E. C. I. Paterson, M. Goryachev, and M. E. Tobar
Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, 6009 Crawley, Western Australia

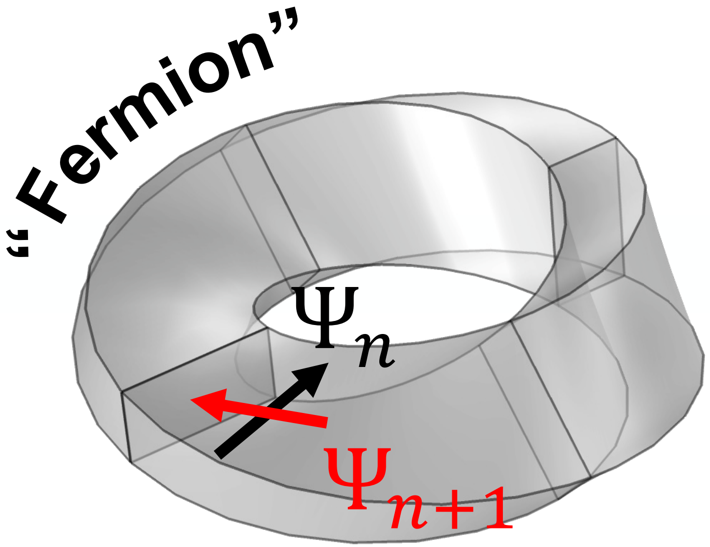
(Received 28 August 2022; revised 19 May 2023; accepted 11 September 2023; published 29 September 2023)

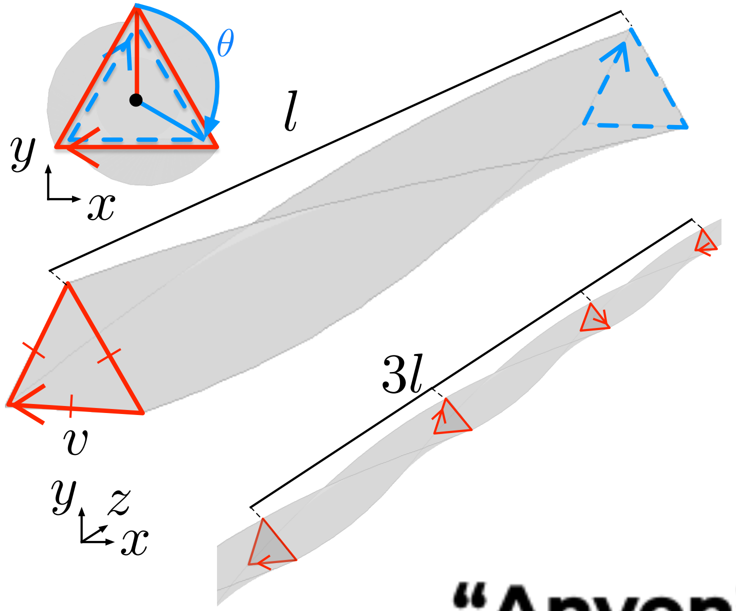
Möbius-ring resonators stem from a well-studied and fascinating geometrical structure which features a one-sided topology, the Möbius strip, and have been shown to exhibit fermion rotational symmetry with respect to a ring resonator with no twist (which exhibits boson rotational symmetry) [Phys. Rev. Lett. **101**, 247701 (2008)]. Here, we present a new type of resonator through the formation of twisted hollow structures using equilateral triangular cross sections, which leads to the realization of a cavity with anyon rotational symmetry. Unlike all previous cavity resonators, the anyon resonator permits the existence of bulk resonant modes that exhibit nonzero electromagnetic helicity in vacuo, with nonzero overlap of the electric and magnetic mode eigenvectors, $\int \mathbf{E}_p \cdot \mathbf{B}_p d\tau$, integrated over the cavity volume. In the upconversion limit, we show that these nonzero helical modes couple naturally to ultralight dark matter axions within the bandwidth of the resonator by adding amplitude modulated sidebands through the axion-photon chiral anomaly. Thus, we show a sensitive ultralight dark matter experiment may be realized by implementing such a resonator in an ultrastable oscillator configuration and searching for signals in the Fourier spectrum of amplitude fluctuations. This removes the typical requirement for an external magnetic field and therefore permits the use of superconducting materials to reduce surface losses and enhance sensitivity to axions.

DOI: 10.1103/PhysRevD.108.052014

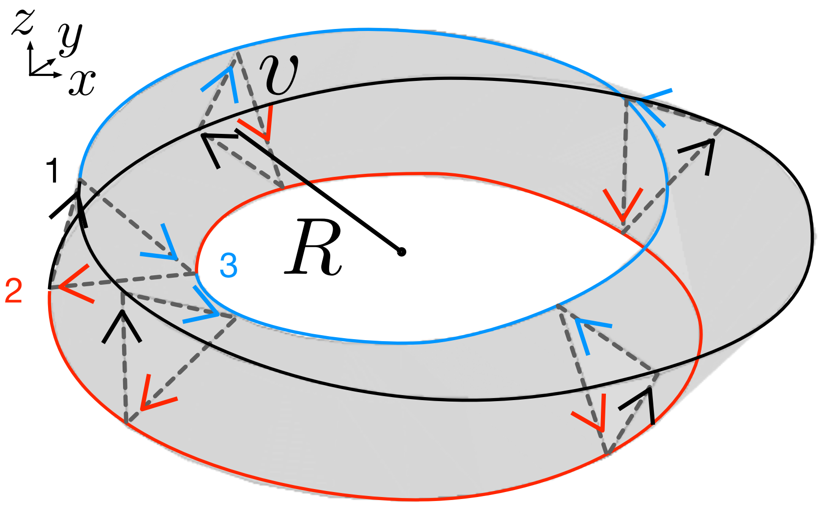
Why Anyon?

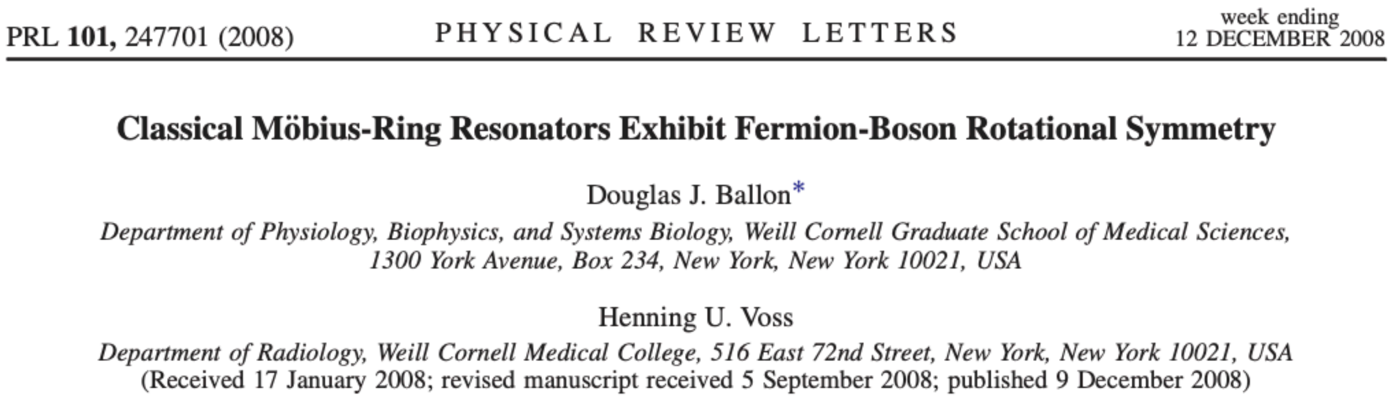






“Anyon”




PRL **101,** 247701 (2008) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2008

Classical Möbius-Ring Resonators Exhibit Fermion-Boson Rotational Symmetry

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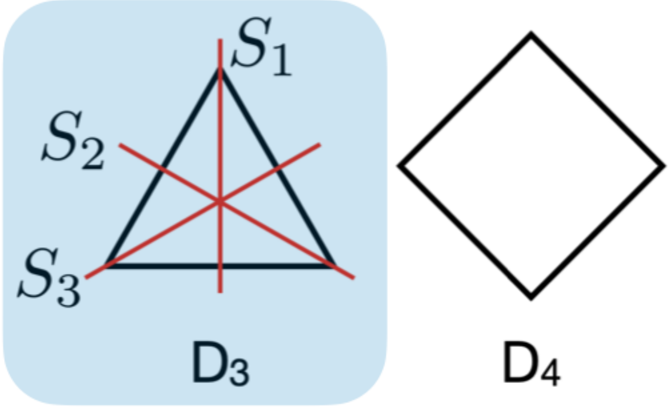
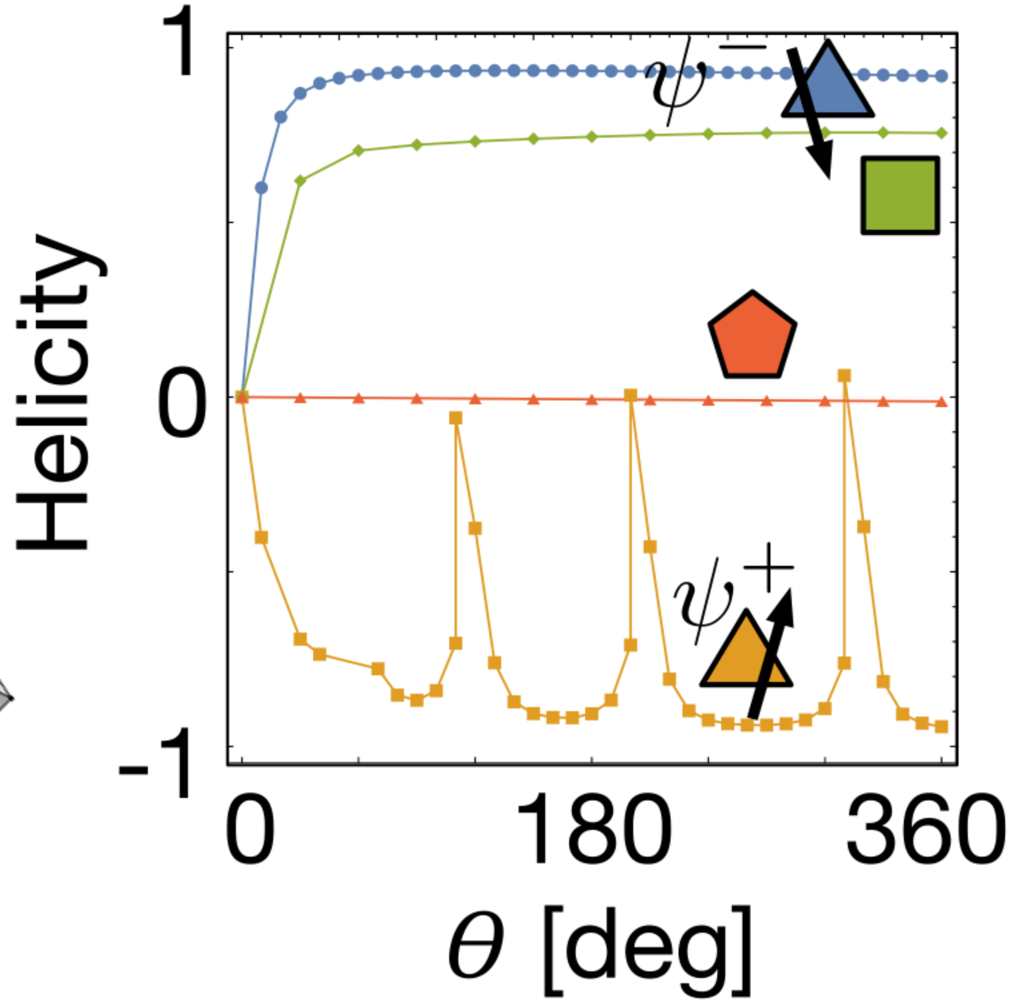
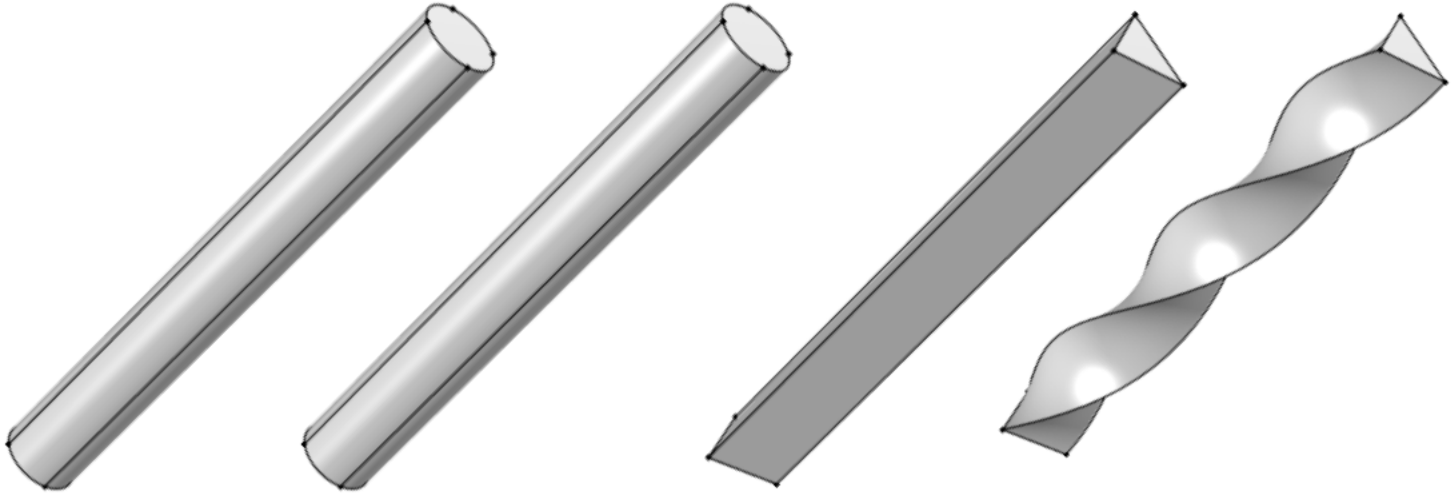
Triangular cross-section

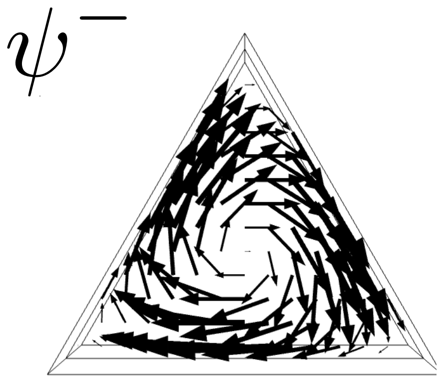


- Greatest mixing effect → greatest helicity

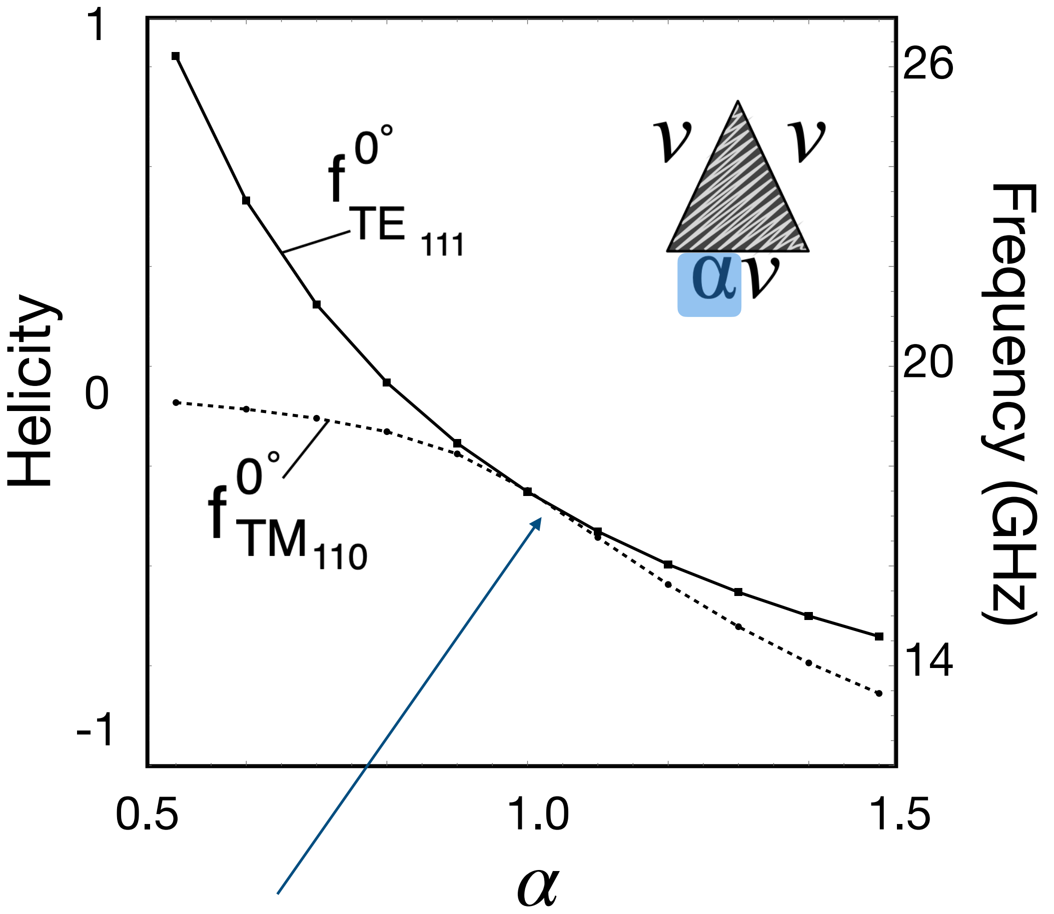




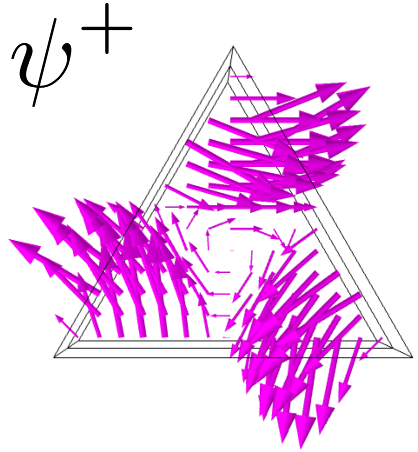
Origin of the High Helicity Modes



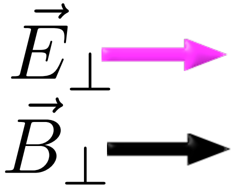
Transverse Magnetic (TM)



TE & TM modes degenerate in frequency

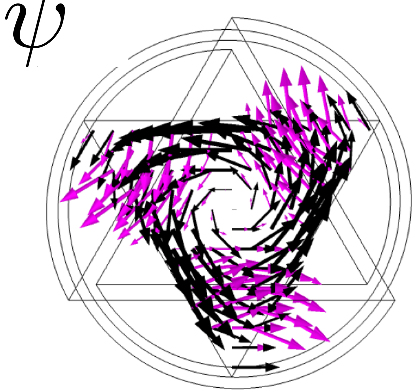


Transverse Electric (TE)

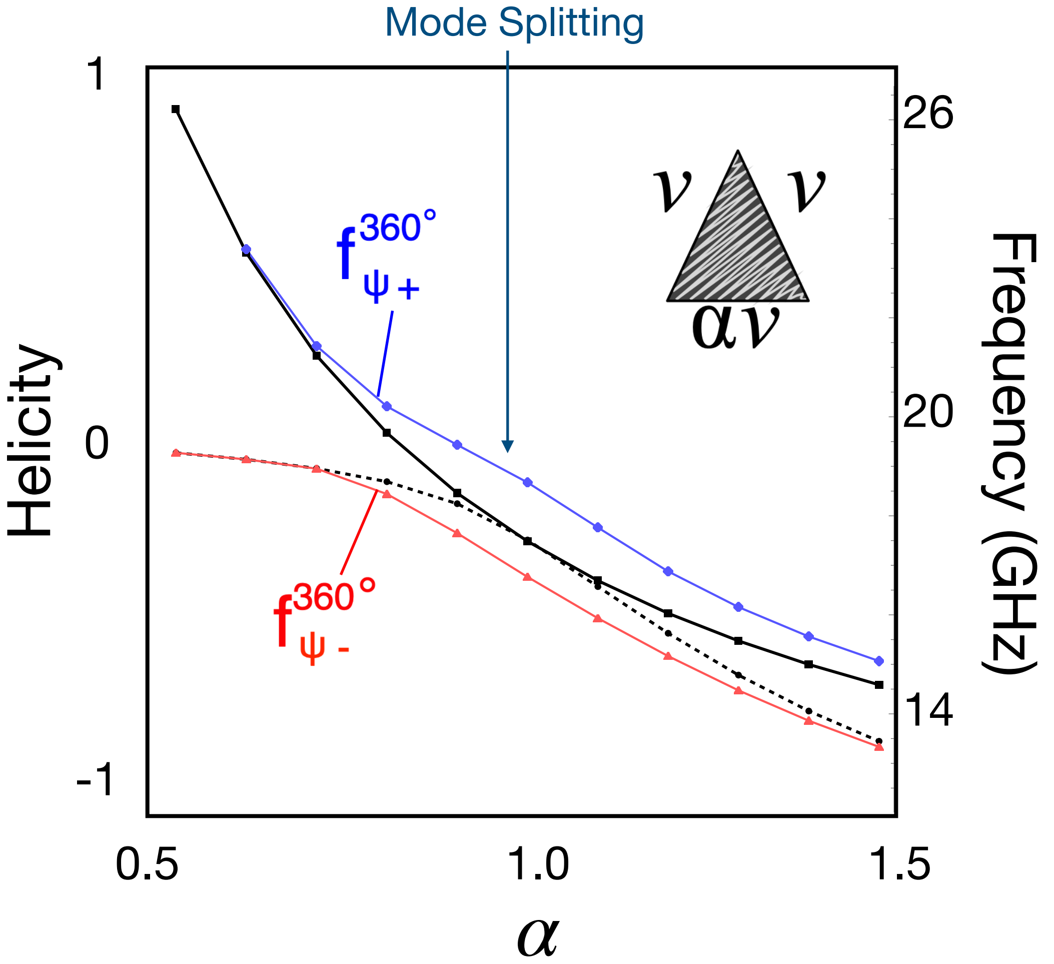


Origin of the High Helicity Modes

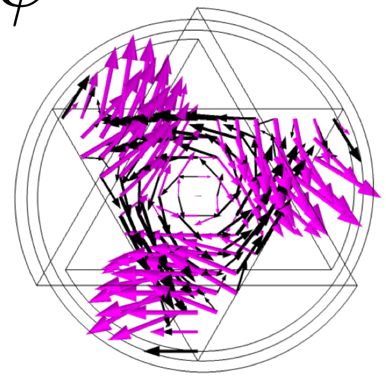
ψ^{-}



Transverse Magnetic (TM)



ψ^{+}



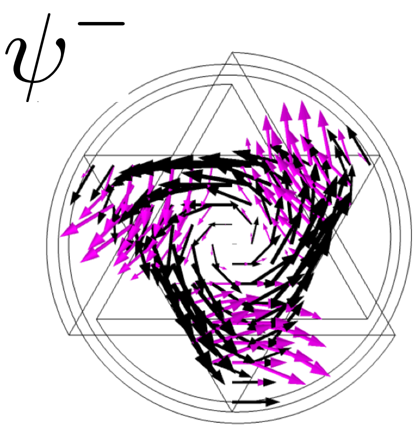
Transverse Electric (TE)

$\vec{E}_\perp$ →

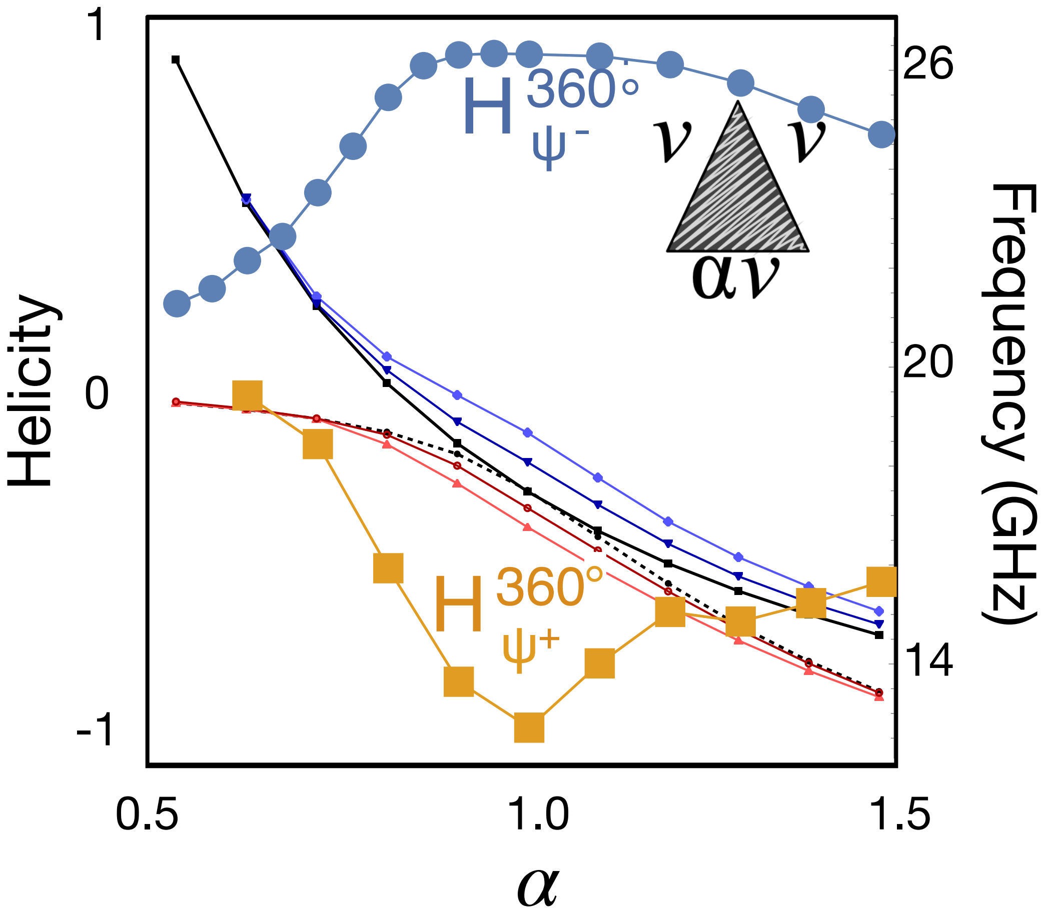
$\vec{B}_\perp$ →

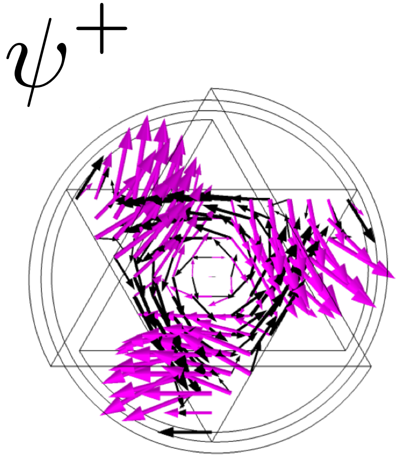
$$\psi^{\pm}\left(\vec{x}_\perp;\vec{q}\right) = E_z\left(\vec{x}_\perp;\vec{q}\right) \pm H_z\left(\vec{x}_\perp;\vec{q}\right)$$

Origin of the High Helicity Modes



Transverse Magnetic (TM)





Transverse Electric (TE)

$\vec{E}_\perp$ →

$\vec{B}_\perp$ →

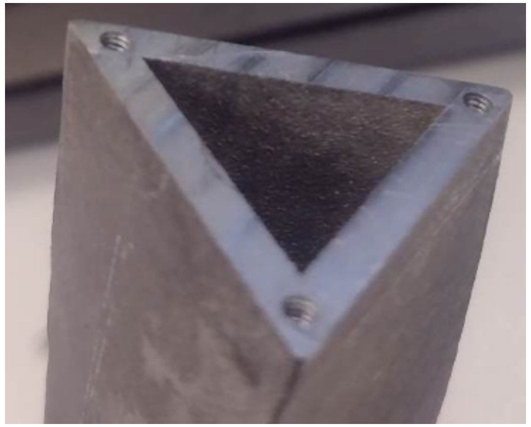
$$\psi^{\pm}\left(\vec{x}_\perp;\vec{q}\right) = E_z\left(\vec{x}_\perp;\vec{q}\right) \pm H_z\left(\vec{x}_\perp;\vec{q}\right)$$

$$\mathscr{H}_p = \frac{2\,\mathrm{Im}\left[\int \mathbf{B}_p^*(\vec{r})\cdot\mathbf{E}_p^{(}\vec{r})d\tau\right]}{\sqrt{\int \mathbf{E}_p(\vec{r})\cdot\mathbf{E}_p^*(\vec{r})d\tau\int \mathbf{B}_p(\vec{r})\cdot\mathbf{B}_p^*(\vec{r})d\tau}}$$

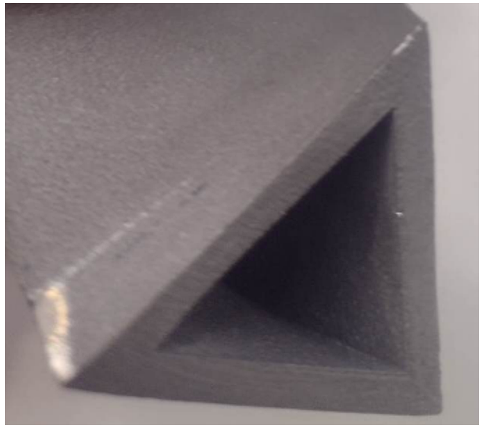
Annealing

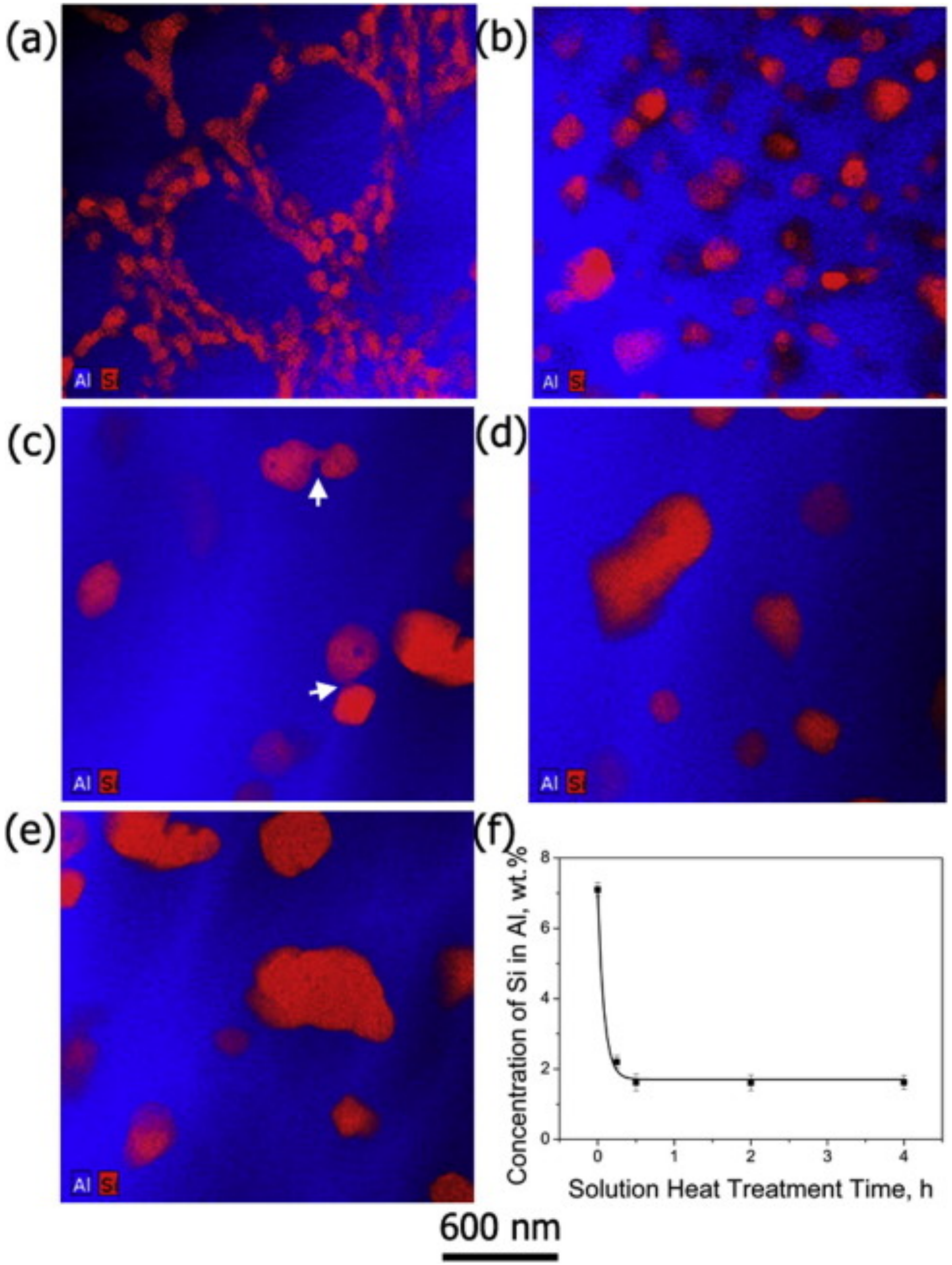
- Baked at $500^\circ C$ for 2 hours in air

post-annealing

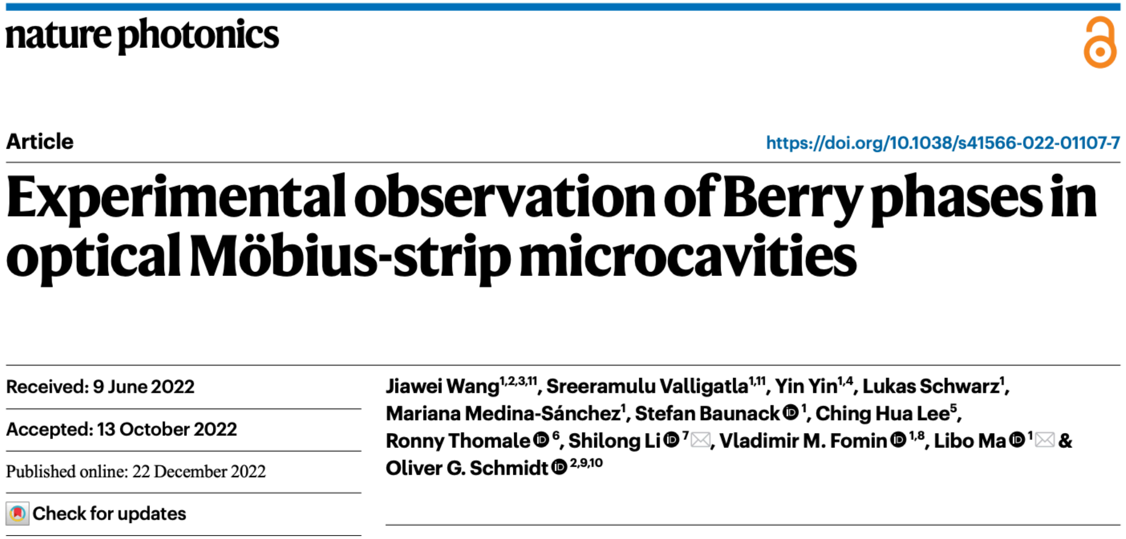


pre-annealing





Berry Phase Generation



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Article

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Experimental observation of Berry phases in optical Möbius-strip microcavities

Received: 9 June 2022

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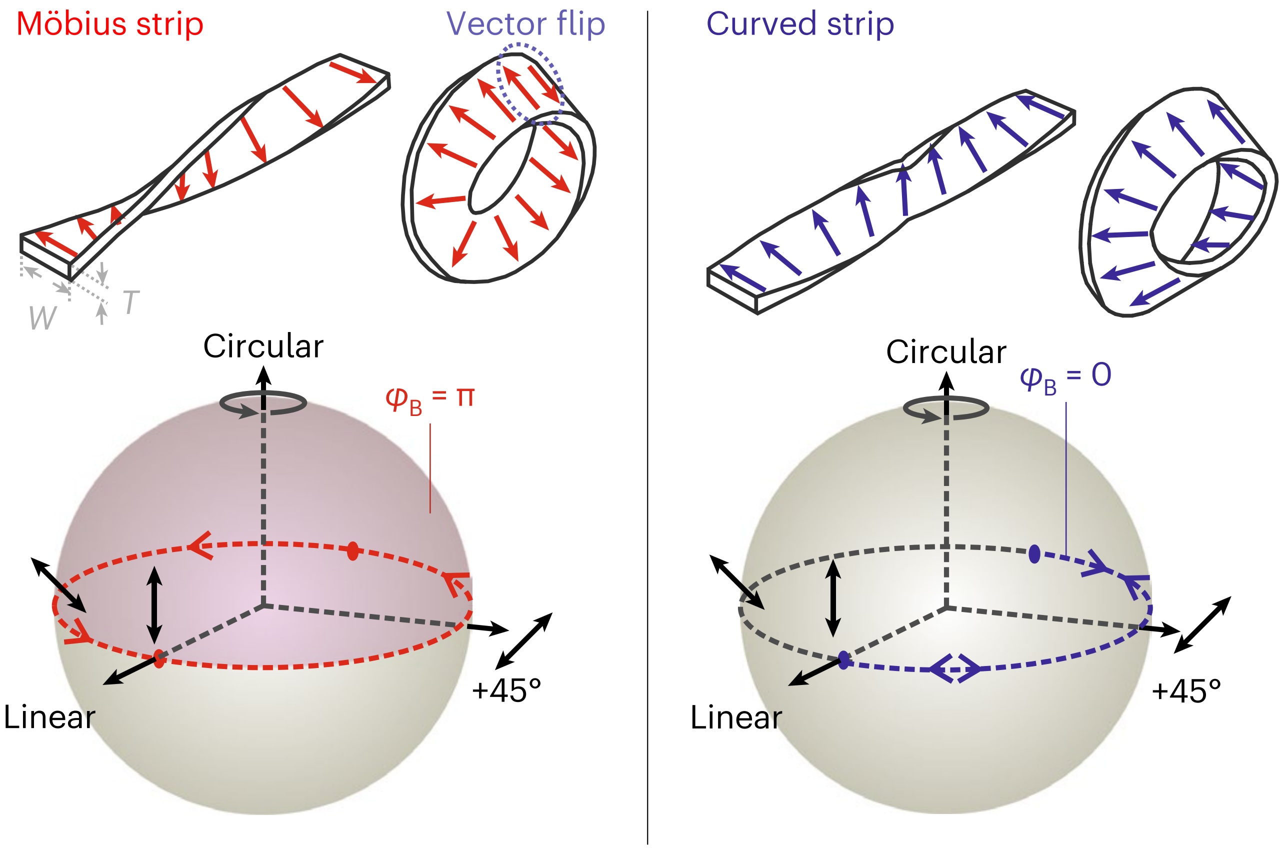
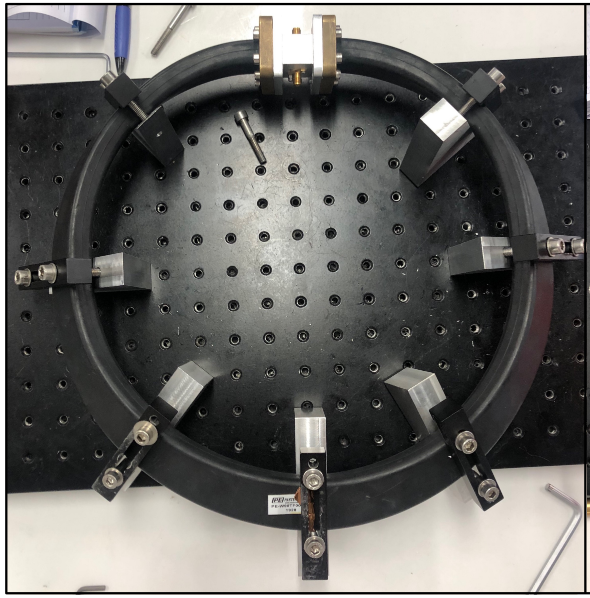
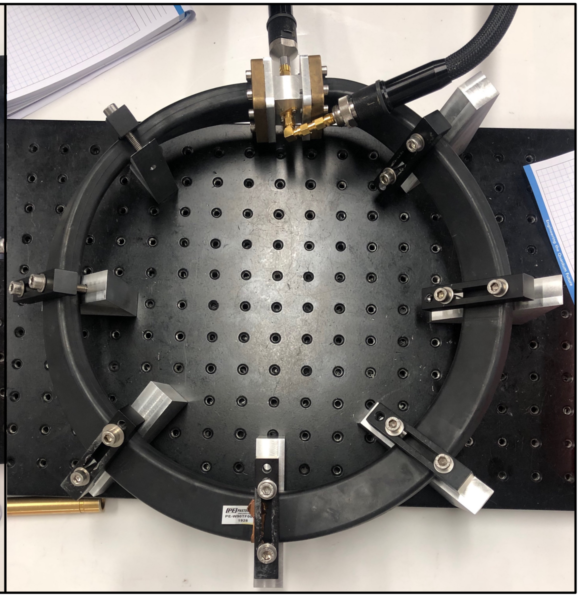


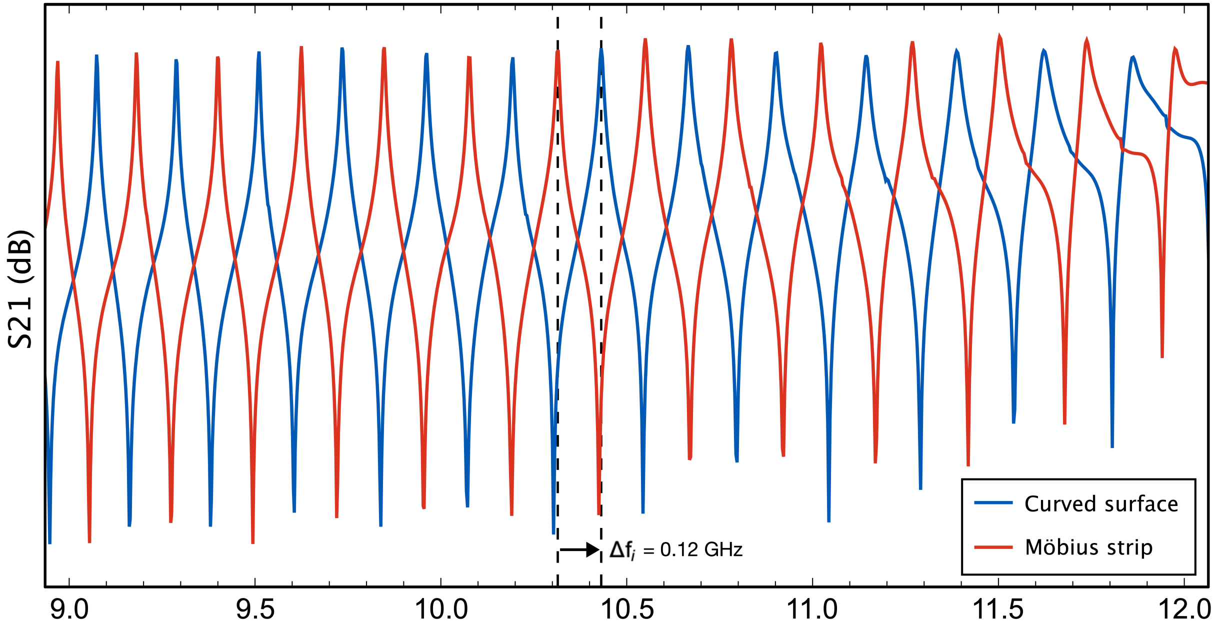
Berry Phase Generation

Curved Strip



Mobius Strip



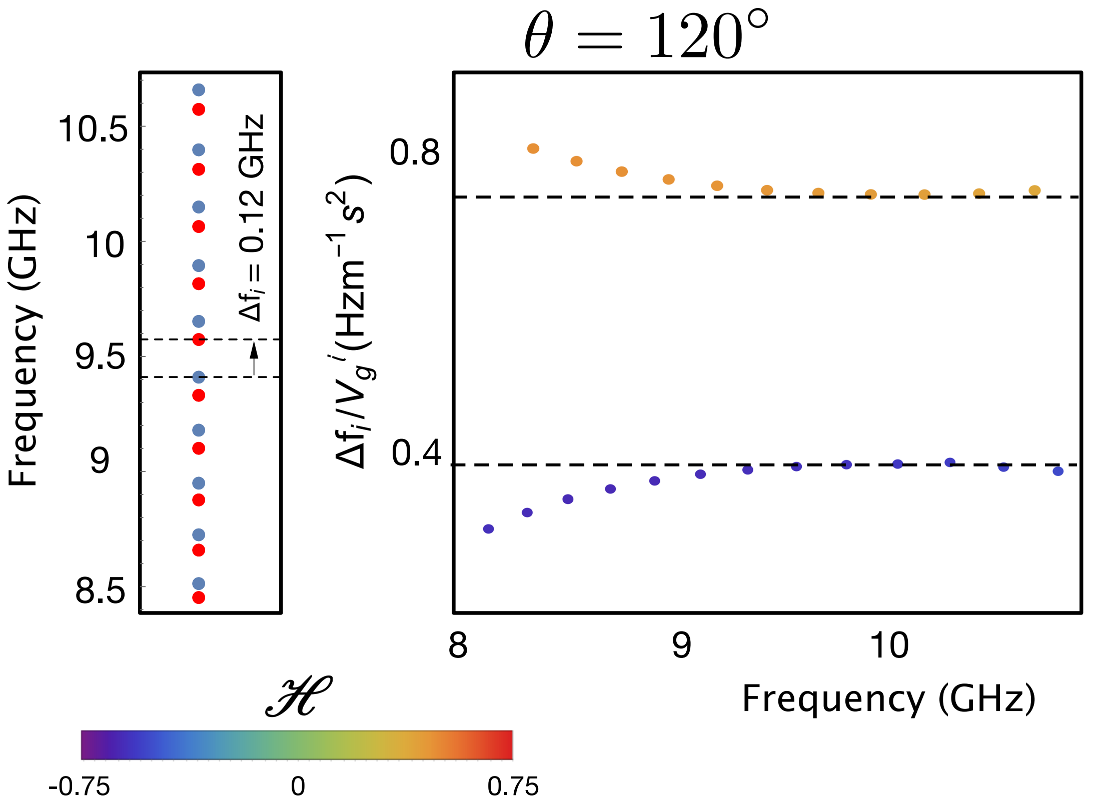


Berry phase

$$\boxed{\frac{\Pi}{\pi}} = \Delta f_i \frac{4\pi^2 R}{c}$$

$$= 0.9463$$

Berry Phase Generation

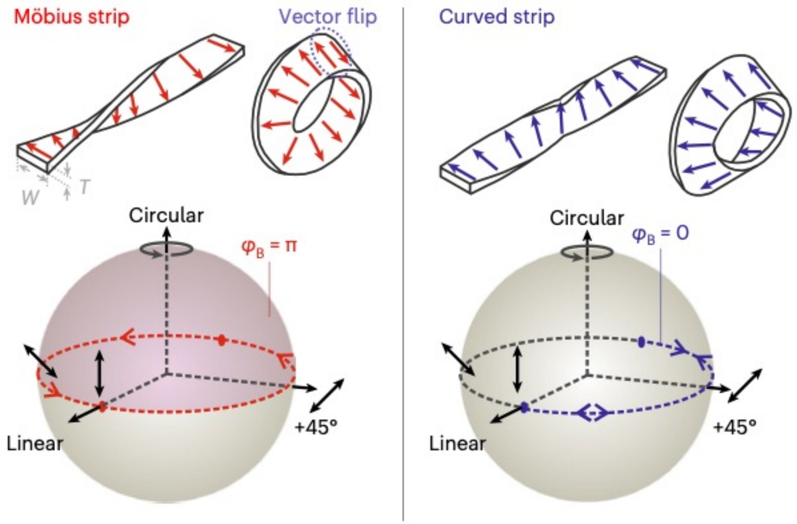


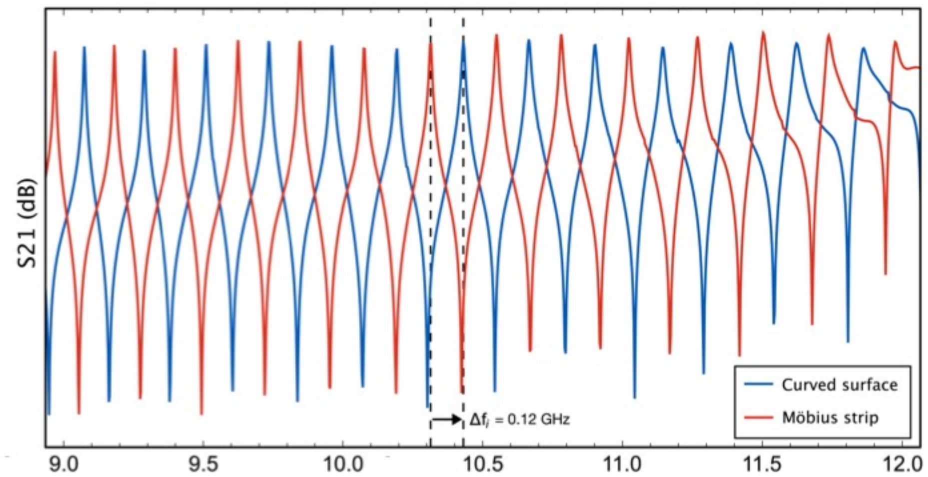
Twist	Berry phase	
120	$2\pi/3$	$4\pi/3$
240	$4\pi/3$	$2\pi/3$
360	0	

Security & robustness of telecommunication

Berry Phase Generation

- Security & robustness of telecommunication

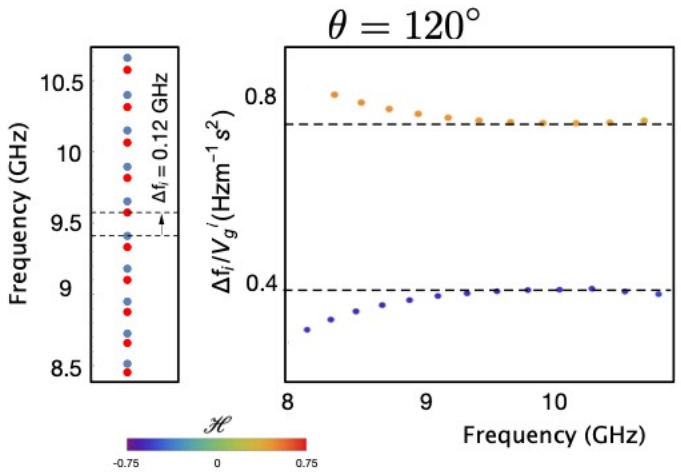




Berry phase

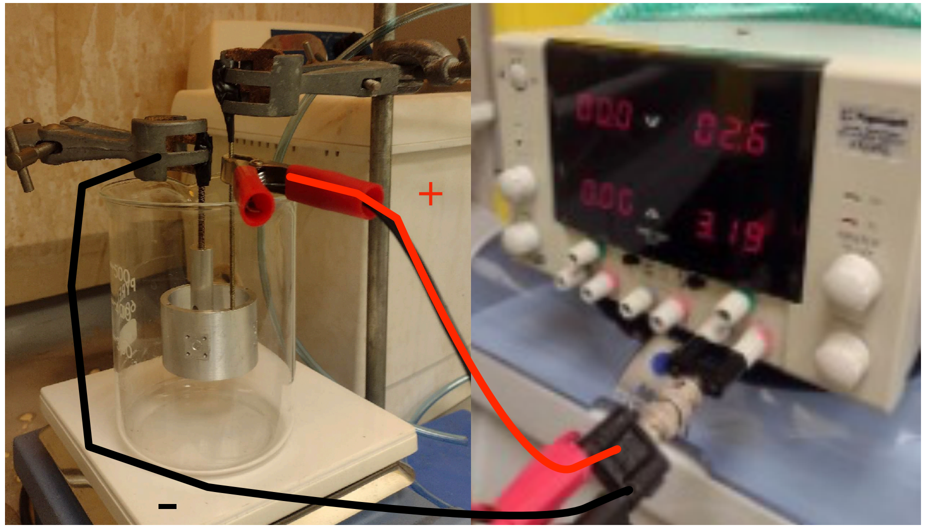
$$\boxed{\frac{\Pi}{\pi}} = \Delta f_i \frac{4\pi^2 R}{c}$$

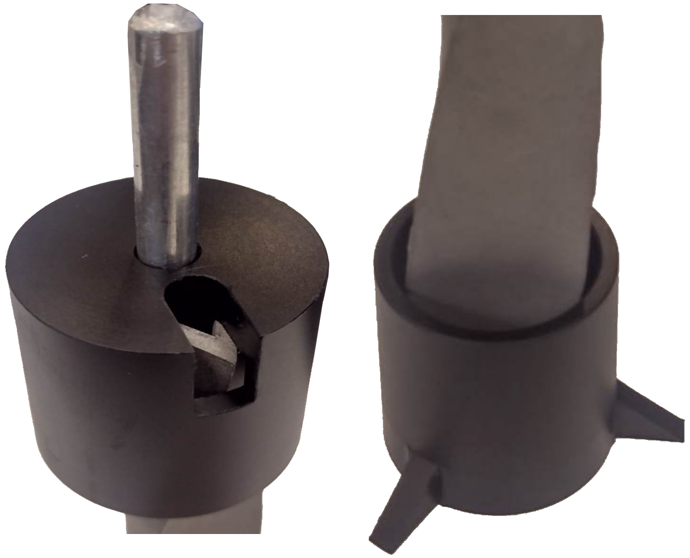
$$= 0.9463$$

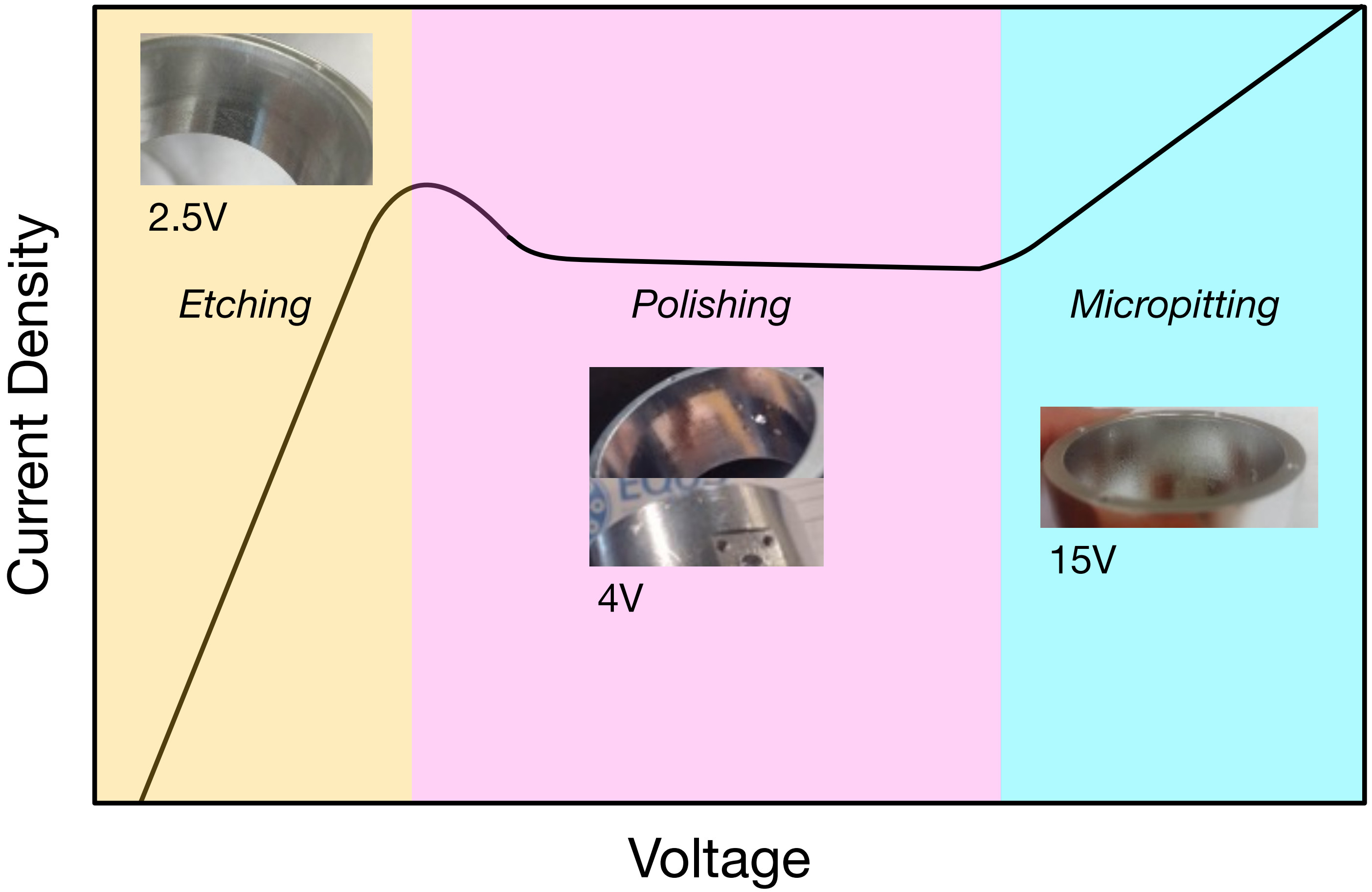


Twist	Berry phase
120	$2\pi/3 \quad 4\pi/3$
240	$4\pi/3 \quad 2\pi/3$
360	0

Electropolishing







Waveguide Configuration

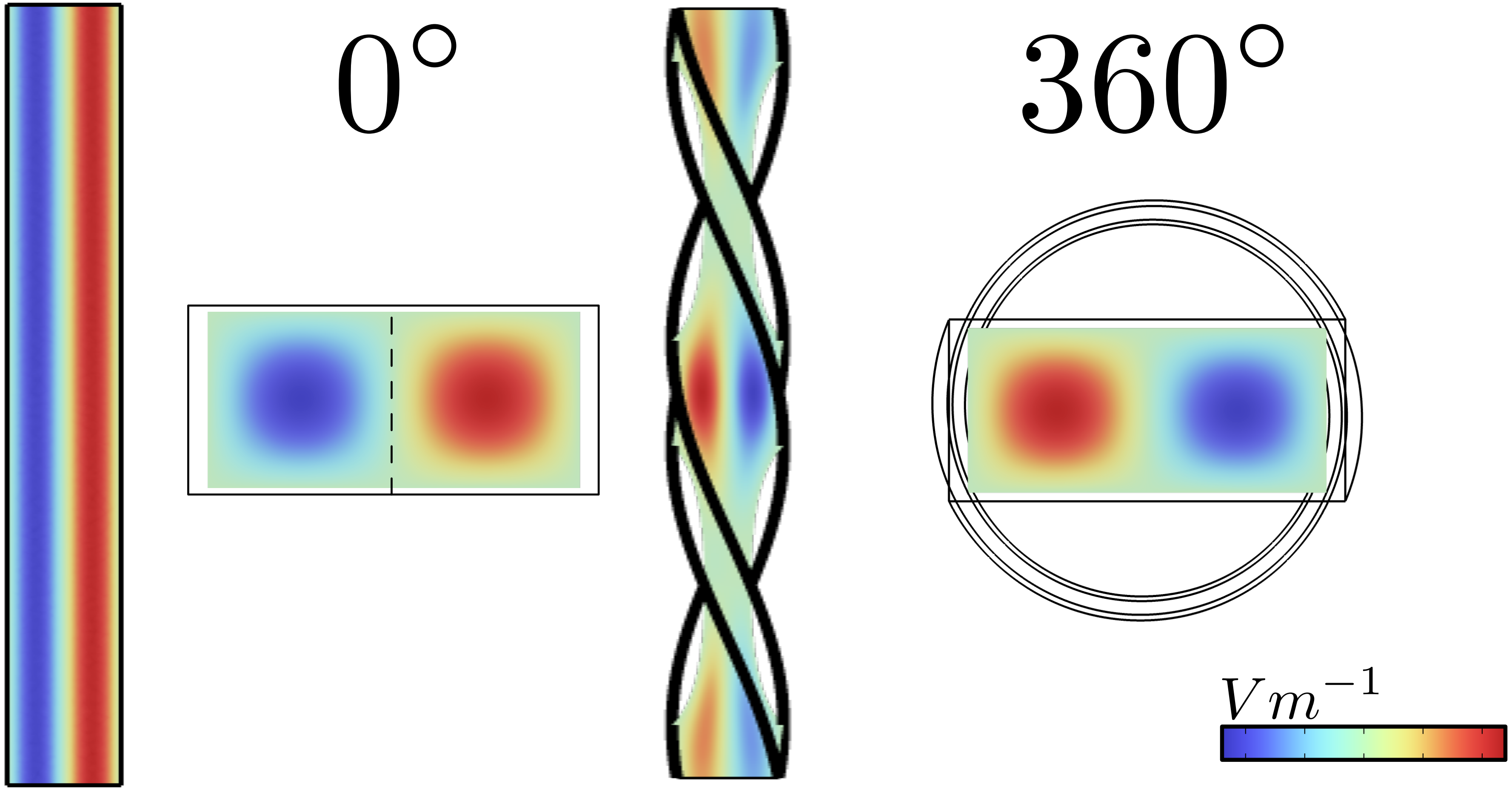
- G-factor and Q-factor are related

$$Q = \frac{\omega U}{P_{\mathrm{c}}}$$

$$Q = \frac{\omega\mu \int_{\mathrm{V}} |\mathbf{H}|^2 dv}{R_{\mathrm{S}} \int_{\mathrm{S}} |\mathbf{H}|^2 ds}$$

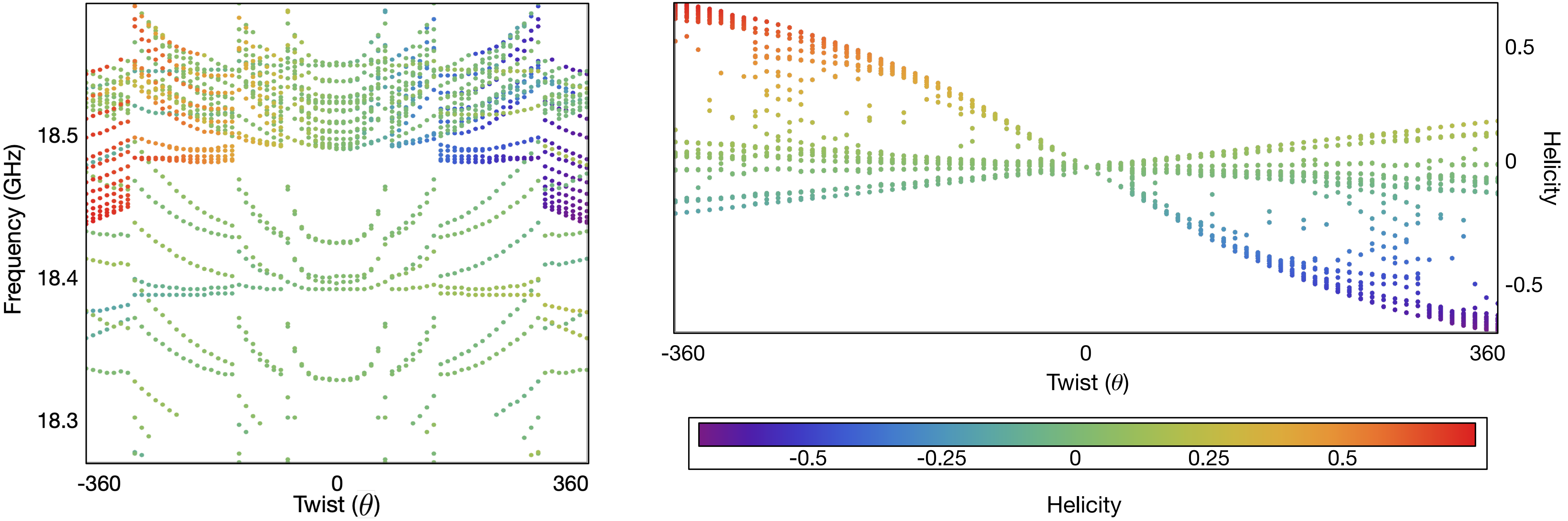
$$G = \frac{\omega\mu \int_{\mathrm{V}} |\mathbf{H}|^2 dv}{\int_{\mathrm{S}} |\mathbf{H}|^2 ds}$$

Twistable Rectangular Resonator

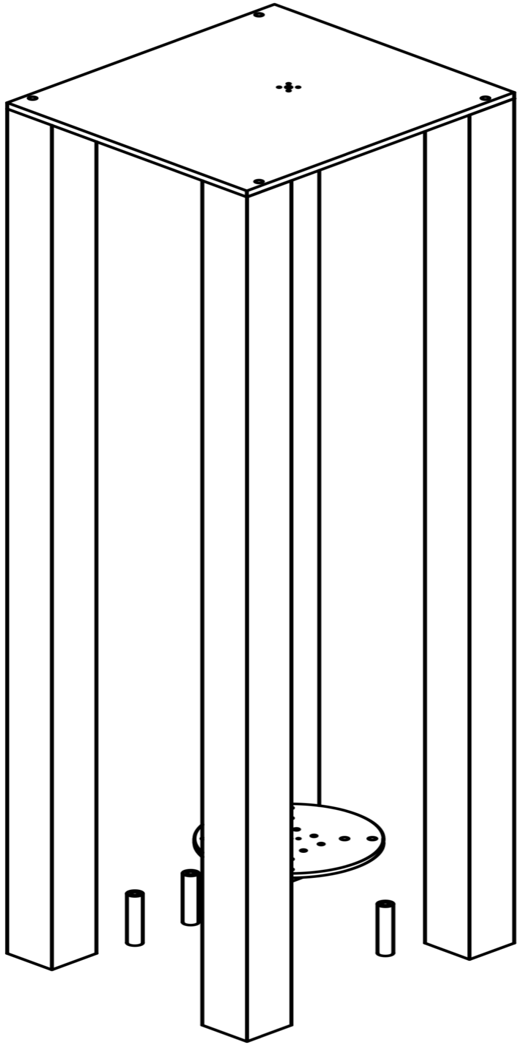


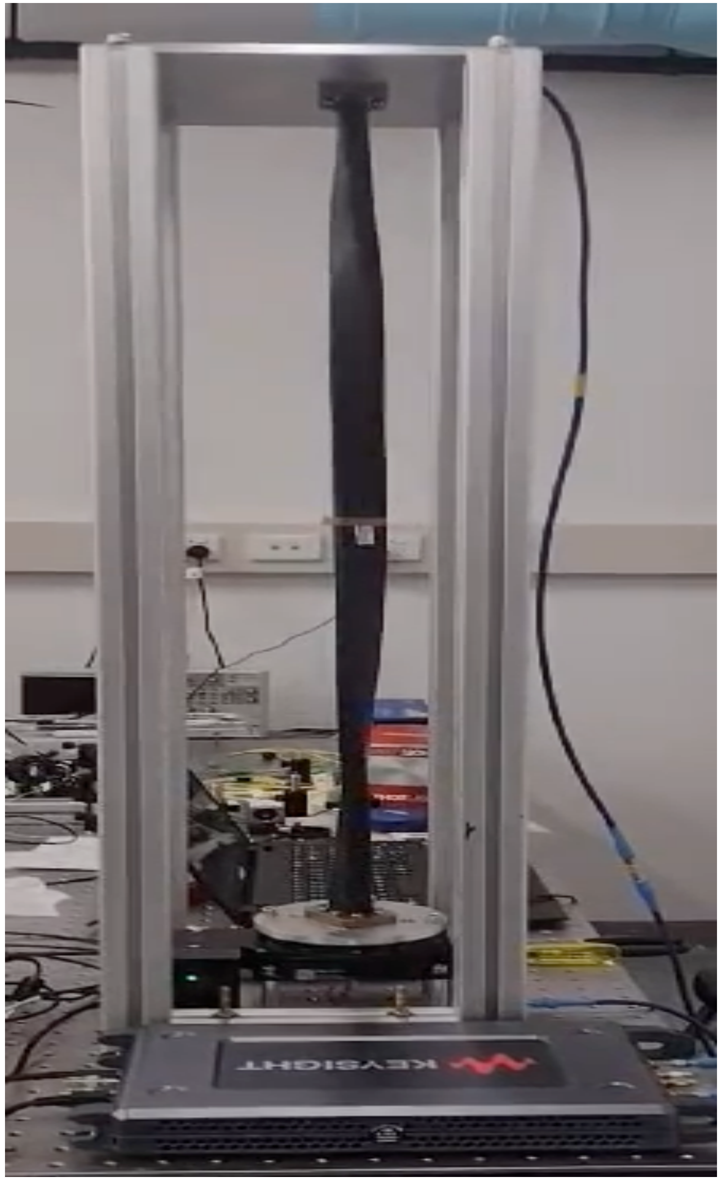
Twistable Rectangular Resonator - Simulation

Flexible Rectangular Waveguide Sweep (-360° to 360°)

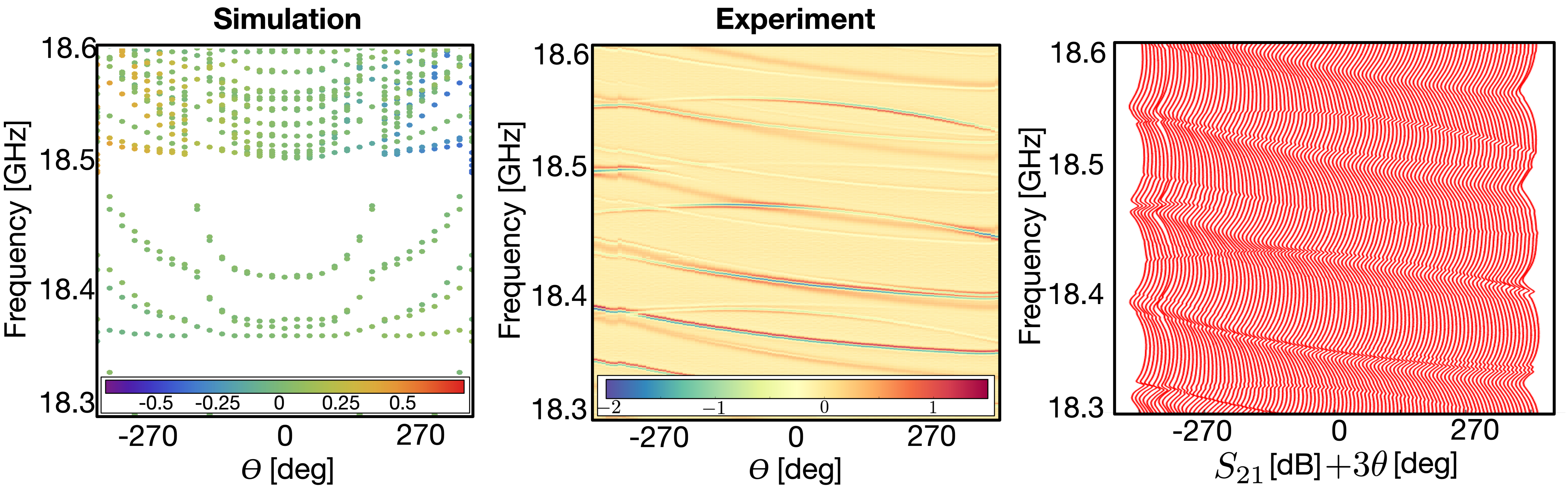


Twistable Rectangular Resonator - Experimental Set-up





Twistable Rectangular Resonator



Simulation

Experiment

Square Resonator