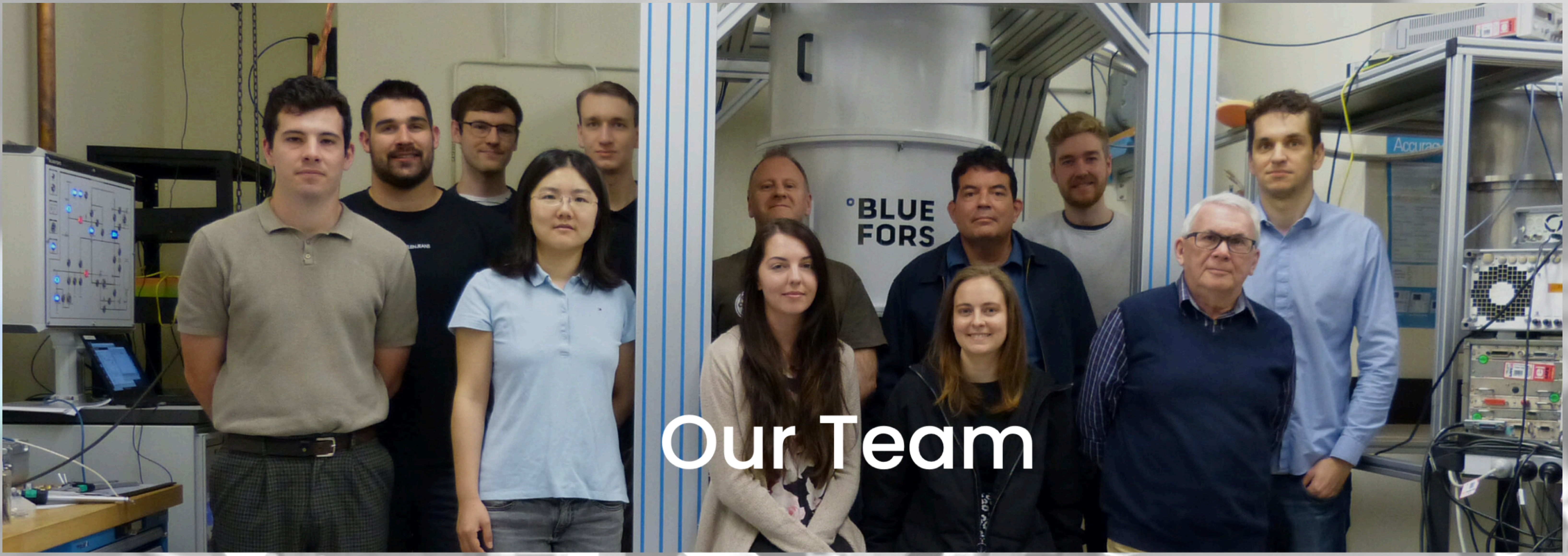
Dark Wave Workshop



ACADEMIC
Michael Tobar
Eugene Ivanov
Maxim Goryachev

POSTDOCS
Cindy Zhao
Jeremy Bourhill
Graeme Flower
William Campbell

PHD STUDENTS
Catriona Thomson
Aaron Quiskamp
Elrina Hartman
Steven Samuels
Emma Paterson
Robert Crew

UNDERGRAD STUDENTS
Sonali Parashar (MSc)
Michael Hatzon (Hons)
Emily Waterman (Hons)
Ashley Johnson (MSc)

Quantum Technologies and Dark Matter Laboratory
QDM-Lab

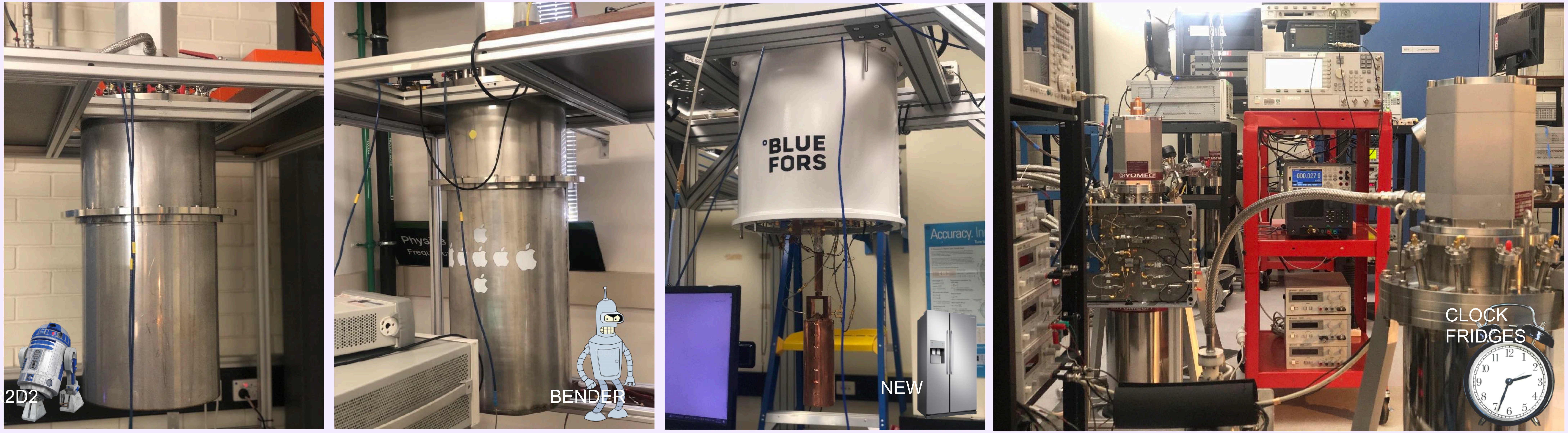
QDM Quantum Technologies and Dark Matter Research Lab

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

ARC Centre of Excellence for Dark Matter Particle Physics

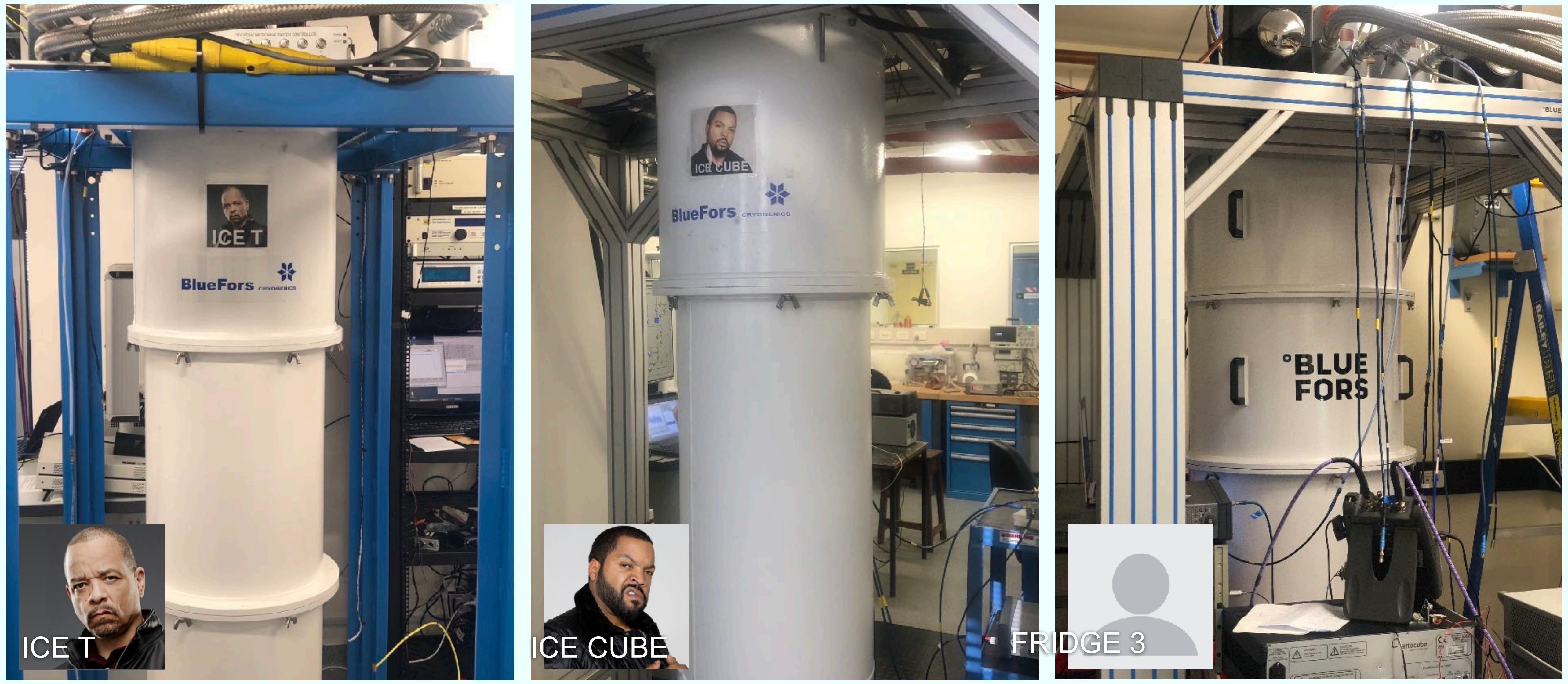
The University of Western Australia

4 Kelvin Systems



- Extensive experience with cryogenic systems
- 3, 7 and 12 T superconducting magnets
- Large collection of microwave (and a some optical) diagnostic equipment and hardware
- Expertise with precision frequency metrology

Dilution Systems



EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

STATUS AND PLANS

STATUS AND PLANS

CURRENT AXION DM PROGRAMS

ORGAN

UPLOAD

ADMX
Collaboration

STATUS AND PLANS

CURRENT AXION DM PROGRAMS	NEW AXION DM PROGRAMS
ORGAN	TWISTED ANYON
UPLOAD	AXION-MONOPOLE COUPLINGS
ADMX Collaboration	

STATUS AND PLANS

CURRENT AXION DM PROGRAMS

ORGAN

UPLOAD

ADMX Collaboration

NEW AXION DM PROGRAMS

TWISTED ANYON

AXION-MONOPOLE COUPLINGS

SCALAR DM PROGRAM

BULK ACOUSTIC WAVE: OSCILLATING FUNDAMENTAL CONSTANTS

STATUS AND PLANS

CURRENT AXION DM PROGRAMS

ORGAN

UPLOAD

ADMX Collaboration

NEW AXION DM PROGRAMS

TWISTED ANYON

AXION-MONOPOLE COUPLINGS

SCALAR DM PROGRAM

BULK ACOUSTIC WAVE: OSCILLATING FUNDAMENTAL CONSTANTS

NEW SCALAR DM PROGRAM

ELECTROMAGNETIC TECHNIQUES

STATUS AND PLANS

CURRENT AXION DM PROGRAMS

ORGAN

UPLOAD

ADMX Collaboration

NEW AXION DM PROGRAMS

TWISTED ANYON

AXION-MONOPOLE COUPLINGS

SCALAR DM PROGRAM

BULK ACOUSTIC WAVE: OSCILLATING FUNDAMENTAL CONSTANTS

NEW SCALAR DM PROGRAM

ELECTROMAGNETIC TECHNIQUES

STATUS AND PLANS

CURRENT AXION DM PROGRAMS

ORGAN

UPLOAD

ADMX Collaboration

NEW AXION DM PROGRAMS

TWISTED ANYON

AXION-MONOPOLE COUPLINGS

SCALAR DM PROGRAM

BULK ACOUSTIC WAVE: OSCILLATING FUNDAMENTAL CONSTANTS

NEW SCALAR DM PROGRAM

ELECTROMAGNETIC TECHNIQUES

RECENT PUBLICATIONS

ORGAN

PHYSICAL REVIEW LETTERS 132, 031601 (2024)

Exclusion of Axionlike-Particle Cogenesis Dark Matter in a Mass Window above 100 μeV

Aaron Quiskamp,[1,*] Ben T. McAllister,[1,2,†] Paul Altin,[3] Eugene N. Ivanov,[1] Maxim Goryachev,[1] and Michael E. Tobar[1,‡]
[1]*Quantum Technologies and Dark Matter Laboratory, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*
[2]*ARC Centre of Excellence for Dark Matter Particle Physics, Swinburne University of Technology, John Street, Hawthorn, Victoria 3122, Australia*
[3]*ARC Centre of Excellence For Engineered Quantum Systems, The Australian National University, Canberra, Australian Capital Territory 2600, Australia*

(Received 3 October 2023; accepted 28 November 2023; published 16 January 2024)

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Direct search for dark matter axions excluding ALP cogenesis in the 63- to 67-μeV range with the ORGAN experiment

Aaron Quiskamp[1]*, Ben T. McAllister[1,2]*, Paul Altin[3], Eugene N. Ivanov[1], Maxim Goryachev[1], Michael E. Tobar[1]*

RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

Limits on Dark Photons, Scalars, and Axion-Electromagnetodynamics with the ORGAN Experiment

Ben T. McAllister, Aaron Quiskamp, Ciaran A. J. O'Hare, Paul Altin, Eugene N. Ivanov, Maxim Goryachev, and Michael E. Tobar*

UPLOAD

PHYSICAL REVIEW D 107, 112003 (2023)

Searching for low-mass axions using resonant upconversion

Catriona A. Thomson,[1,*] Maxim Goryachev,[1] Ben T. McAllister,[1,2] Eugene N. Ivanov,[1] Paul Altin,[3] and Michael E. Tobar[1,†]
[1]*Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*
[2]*Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn, Victoria 3122, Australia*
[3]*ARC Centre of Excellence For Engineered Quantum Systems, The Australian National University, Canberra, Australian Capital Territory 2600 Australia*

ANYON

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

Scalar Field Dark Matter

PHYSICAL REVIEW D 106, 055037 (2022)

Searching for scalar field dark matter using cavity resonators and capacitors

V. V. Flambaum,[1,*] B. T. McAllister,[2,3,†] I. B. Samsonov,[1,‡] and M. E. Tobar[2,§]

Axions with Magnetic Charge

PHYSICAL REVIEW D 108, 035024 (2023)

Searching for GUT-scale QCD axions and monopoles with a high-voltage capacitor

Michael E. Tobar,[1,*] Anton V. Sokolov,[2] Andreas Ringwald,[3] and Maxim Goryachev[1]
[1]*Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*
[2]*Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom*
[3]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany*

DETECTOR COMPARISON: Defining Instrument Sensitivity independent of signal (Spectral)

symmetry MDPI

Article

Comparing Instrument Spectral Sensitivity of Dissimilar Electromagnetic Haloscopes to Axion Dark Matter and High Frequency Gravitational Waves

Michael E. Tobar *, Catriona A. Thomson, William M. Campbell, Aaron Quiskamp, Jeremy F. Bourhill, Benjamin T. McAllister, Eugene N. Ivanov and Maxim Goryachev

Axion ED Poynting Theorem: Standardised way of Calculating Sensitivity

PHYSICAL REVIEW D 105, 045009 (2022)

Poynting vector controversy in axion modified electrodynamics

Michael E. Tobar,* Ben T. McAllister, and Maxim Goryachev
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 Highway, Crawley, Western Australia 6009, Australia

(Received 9 September 2021; accepted 28 January 2022; published 15 February 2022)

PHYSICAL REVIEW D 106, 109903(E) (2022)

Erratum: Poynting vector controversy in axion modified electrodynamics [Phys. Rev. D 105, 045009 (2022)]

If Magnetic Charge Can Exist at High Energy

-> Further Modifications to Axion Electrodynamics

-> Can test the existence of Magnetic Charge through Axions

If Magnetic Charge Can Exist at High Energy

-> Further Modifications to Axion Electrodynamics

-> Can test the existence of Magnetic Charge through Axions

annalen der physik

Research Article | Open Access

Generic Axion Maxwell Equations: Path Integral Approach

Anton V. Sokolov, Andreas Ringwald

First published: 11 October 2023 | https://doi.org/10.1002/andp.202300112

arXiv > hep-ph > arXiv:2205.02605

High Energy Physics – Phenomenology

[Submitted on 5 May 2022]

Electromagnetic Couplings of Axions

Anton V. Sokolov, Andreas Ringwald

If Magnetic Charge Can Exist at High Energy

-> Further Modifications to Axion Electrodynamics

-> Can test the existence of Magnetic Charge through Axions

Axion-photon coupling parameter space is expanded from one parameter to three

$$g_{a\gamma\gamma} \rightarrow (g_{a\gamma\gamma}, g_{aEM}, g_{aMM})$$

adp annalen der physik

Research Article | Open Access

Generic Axion Maxwell Equations: Path Integral Approach

Anton V. Sokolov, Andreas Ringwald

First published: 11 October 2023 | https://doi.org/10.1002/andp.202300112

arXiv > hep-ph > arXiv:2205.02605

High Energy Physics – Phenomenology

[Submitted on 5 May 2022]

Electromagnetic Couplings of Axions

Anton V. Sokolov, Andreas Ringwald

If Magnetic Charge Can Exist at High Energy

-> Further Modifications to Axion Electrodynamics

-> Can test the existence of Magnetic Charge through Axions

Axion-photon coupling parameter space is expanded from one parameter to three

$$g_{a\gamma\gamma} \rightarrow (g_{a\gamma\gamma}, g_{aEM}, g_{aMM})$$

annalen der physik

Research Article | Open Access

Generic Axion Maxwell Equations: Path Integral Approach

Anton V. Sokolov, Andreas Ringwald

First published: 11 October 2023 | https://doi.org/10.1002/andp.202300112

arXiv > hep-ph > arXiv:2205.02605

High Energy Physics – Phenomenology

[Submitted on 5 May 2022]

Electromagnetic Couplings of Axions

Anton V. Sokolov, Andreas Ringwald

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} + g_{a\gamma\gamma} c \epsilon_0 \left(- \vec{\nabla} a \times \vec{E}_0 - \partial_t a \vec{B}_0 \right) + g_{aEM} \epsilon_0 \left(- \vec{\nabla} a \times c^2 \vec{B}_0 + \partial_t a \vec{E}_0 \right),$$

$$\vec{\nabla} \cdot \vec{B}_1 = - \frac{g_{aMM}}{c} \vec{E}_0 \cdot \vec{\nabla} a + g_{aEM} \vec{B}_0 \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 + \frac{g_{aMM}}{c} \left(c^2 \nabla a \times \vec{B}_0 - \partial_t a \vec{E}_0 \right) + g_{aEM} \left(\nabla a \times \vec{E}_0 + \partial_t a \vec{B}_0 \right).$$

If Magnetic Charge Can Exist at High Energy

-> Further Modifications to Axion Electrodynamics

-> Can test the existence of Magnetic Charge through Axions

Axion-photon coupling parameter space is expanded from one parameter to three

$$g_{a\gamma\gamma} \rightarrow (g_{a\gamma\gamma}, g_{aEM}, g_{aMM})$$

adp annalen der physik

Research Article | Open Access

Generic Axion Maxwell Equations: Path Integral Approach

Anton V. Sokolov, Andreas Ringwald

First published: 11 October 2023 | https://doi.org/10.1002/andp.202300112

arXiv > hep-ph > arXiv:2205.02605

High Energy Physics – Phenomenology

[Submitted on 5 May 2022]

Electromagnetic Couplings of Axions

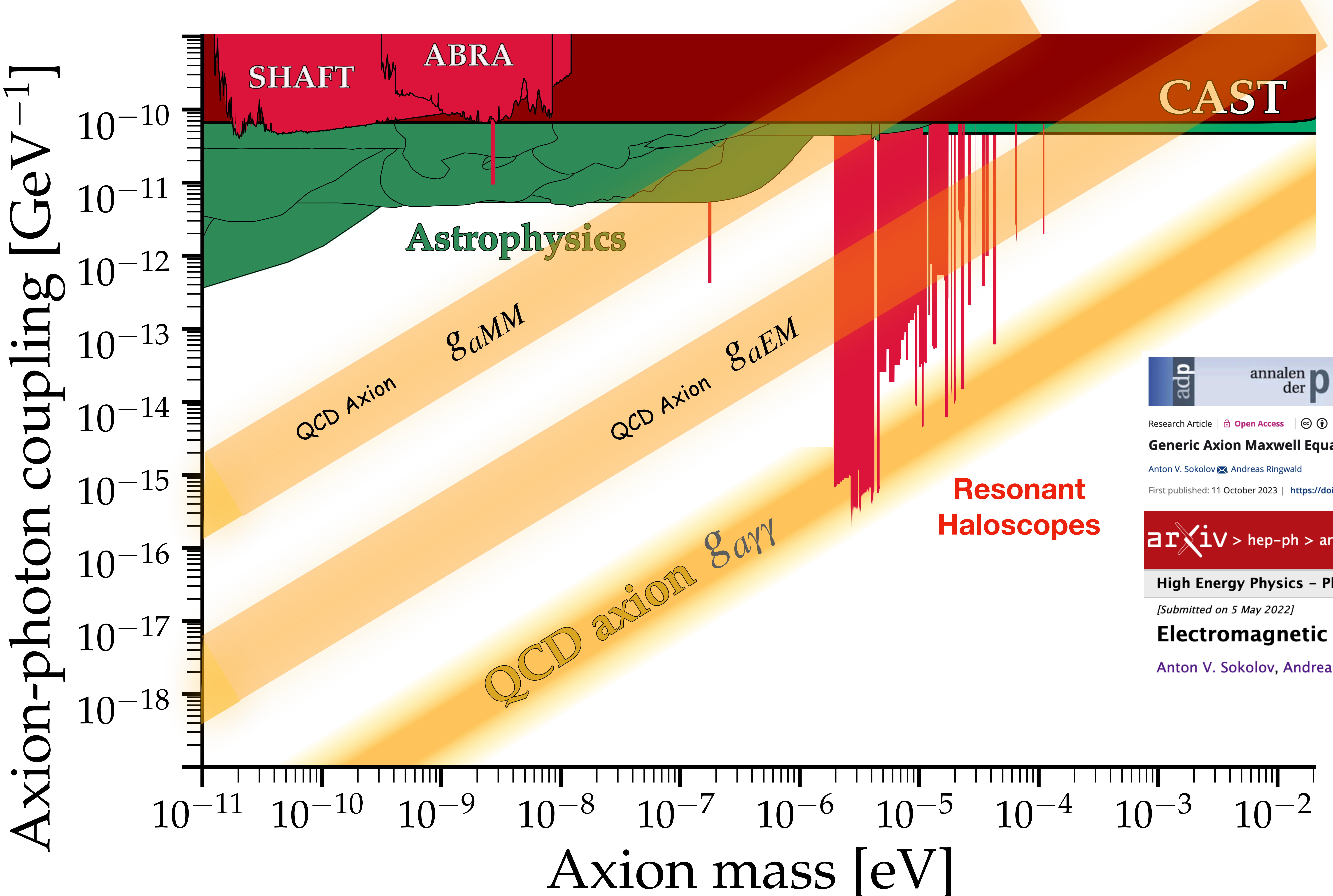
Anton V. Sokolov, Andreas Ringwald

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} + g_{a\gamma\gamma} c \epsilon_0 \left(-\vec{\nabla} a \times \vec{E}_0 - \partial_t a \vec{B}_0 \right) + g_{aEM} \epsilon_0 \left(-\vec{\nabla} a \times c^2 \vec{B}_0 + \partial_t a \vec{E}_0 \right),$$

$$\vec{\nabla} \cdot \vec{B}_1 = -\frac{g_{aMM}}{c} \vec{E}_0 \cdot \vec{\nabla} a + g_{aEM} \vec{B}_0 \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{E}_1 = -\partial_t \vec{B}_1 + \frac{g_{aMM}}{c} \left(c^2 \nabla a \times \vec{B}_0 - \partial_t a \vec{E}_0 \right) + g_{aEM} \left(\nabla a \times \vec{E}_0 + \partial_t a \vec{B}_0 \right).$$



adp annalen der physik

Research Article | Open Access

Generic Axion Maxwell Equations: Path Integral Approach

Anton V. Sokolov, Andreas Ringwald

First published: 11 October 2023 | https://doi.org/10.1002/andp.202300112

arXiv > hep-ph > arXiv:2205.02605

High Energy Physics – Phenomenology

[Submitted on 5 May 2022]

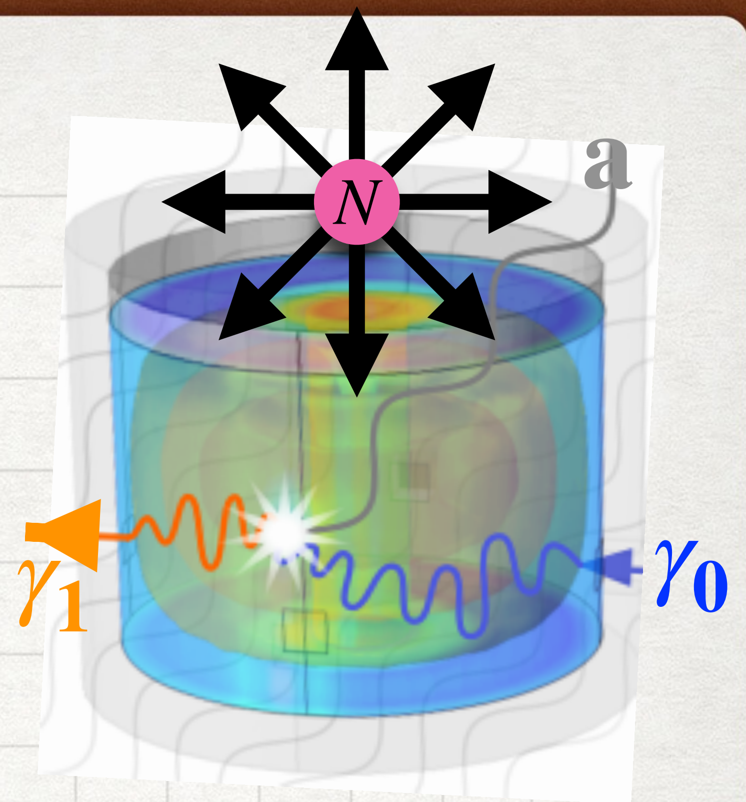
Electromagnetic Couplings of Axions

Anton V. Sokolov, Andreas Ringwald

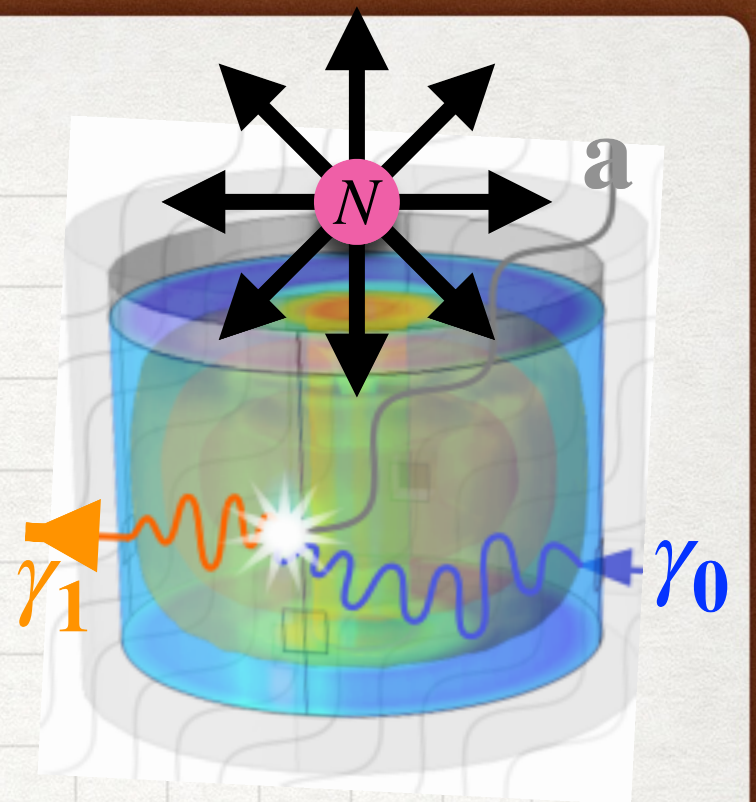
Form Factors for Resonators

-> Static and Time varying Background E + B Fields

-> Calculate from Real Part of Complex Poynting Theorem



Form Factors for Resonators
-> Static and Time varying Background E + B Fields
-> Calculate from Real Part of Complex Poynting Theorem



RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

Sensitivity of Resonant Axion Haloscopes to Quantum Electromagnetodynamics

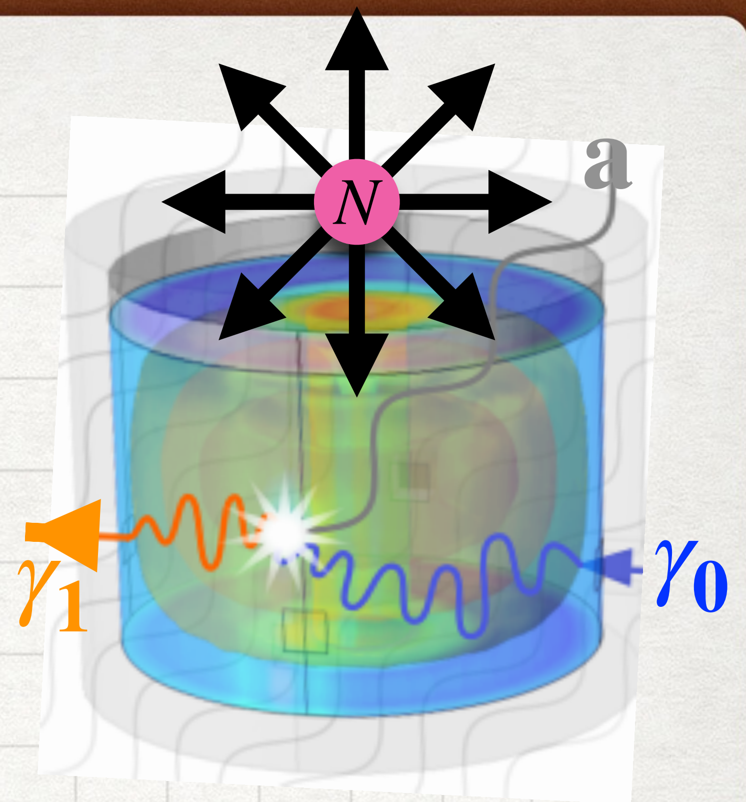
Michael E. Tobar, Catriona A. Thomson, Benjamin T. McAllister, Maxim Goryachev, Anton V. Sokolov, and Andreas Ringwald*

Form Factors

$$C_{1a\gamma\gamma} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{B_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1EM} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{B_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

$$C_{1aEMm} = \frac{(\int \vec{E}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{E_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1aMM} = \frac{(\int \vec{E}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{E_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

Form Factors for Resonators
-> Static and Time varying Background E + B Fields
-> Calculate from Real Part of Complex Poynting Theorem



RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

Sensitivity of Resonant Axion Haloscopes to Quantum Electromagnetodynamics

Michael E. Tobar, Catriona A. Thomson, Benjamin T. McAllister, Maxim Goryachev, Anton V. Sokolov, and Andreas Ringwald*

RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

Limits on Dark Photons, Scalars, and Axion-Electromagnetodynamics with the ORGAN Experiment

Ben T. McAllister, Aaron Quiskamp, Ciaran A. J. O'Hare, Paul Altin, Eugene N. Ivanov, Maxim Goryachev, and Michael E. Tobar*

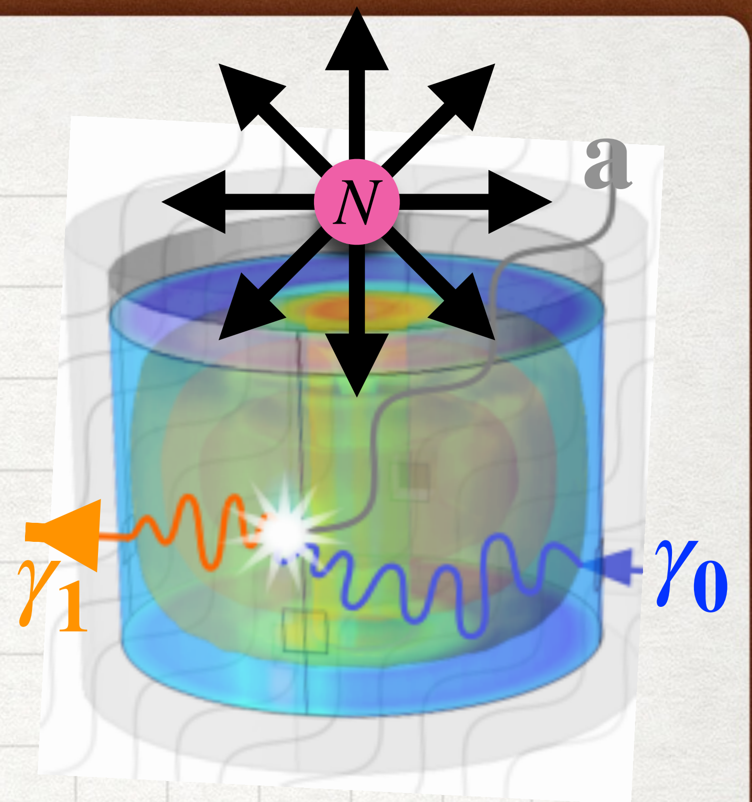
Form Factors

$$C_{1a\gamma\gamma} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{B_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1EM} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{B_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

$$C_{1aEMm} = \frac{(\int \vec{E}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{E_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1aMM} = \frac{(\int \vec{E}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{E_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

$g_{aEM} \rightarrow$ Suppressed

Form Factors for Resonators
-> Static and Time varying Background E + B Fields
-> Calculate from Real Part of Complex Poynting Theorem



RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

Sensitivity of Resonant Axion Haloscopes to Quantum Electromagnetodynamics

Michael E. Tobar, Catriona A. Thomson, Benjamin T. McAllister, Maxim Goryachev, Anton V. Sokolov, and Andreas Ringwald*

RESEARCH ARTICLE

annalen der physik
www.ann-phys.org

Limits on Dark Photons, Scalars, and Axion-Electromagnetodynamics with the ORGAN Experiment

Ben T. McAllister, Aaron Quiskamp, Ciaran A. J. O'Hare, Paul Altin, Eugene N. Ivanov, Maxim Goryachev, and Michael E. Tobar*

Form Factors

$$C_{1a\gamma\gamma} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{B_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1EM} = \frac{(\int \vec{B}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{B_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

$$C_{1aEMm} = \frac{(\int \vec{E}_0 \cdot \mathrm{Re}(\mathbf{E}_1) dV)^2}{E_0^2 V_1 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dV} \qquad C_{1aMM} = \frac{(\int \vec{E}_0 \cdot \mathrm{Re}(\mathbf{B}_1) dV)^2}{E_0^2 V_1 \int \mathbf{B}_1 \cdot \mathbf{B}_1^* dV}$$

PHYSICAL REVIEW D **107**, 112003 (2023)

Searching for low-mass axions using resonant upconversion

Catriona A. Thomson,[1,*] Maxim Goryachev,[1] Ben T. McAllister,[1,2] Eugene N. Ivanov,[1] Paul Altin,[3] and Michael E. Tobar[1,†]

[1] *Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*
[2] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn, Victoria 3122, Australia*
[3] *ARC Centre of Excellence For Engineered Quantum Systems, The Australian National University, Canberra, Australian Capital Territory 2600 Australia*

(Received 17 January 2023; accepted 5 May 2023; published 5 June 2023)

$g_{aEM} \rightarrow$ Suppressed

UPLOAD $\rightarrow g_{aMM}$

Reactive Experiment with Static Background Electric and Magnetic Field -> Imaginary Part of Complex Poynting Theorem

Reactive Experiment with Static Background Electric and Magnetic Field -> Imaginary Part of Complex Poynting Theorem



PHYSICAL REVIEW D **108,** 035024 (2023)

arXiv:2306.13320 [hep-ph]

Searching for GUT-scale QCD axions and monopoles with a high-voltage capacitor

Michael E. Tobar,[1,*] Anton V. Sokolov,[2] Andreas Ringwald,[3] and Maxim Goryachev[1]

[1]*Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*

[2]*Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom*

[3]*Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany*

(Received 20 June 2023; accepted 2 August 2023; published 17 August 2023)

General Equations

General Equations

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

$$\begin{aligned} \mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} \\ + g_{a\gamma\gamma} c \epsilon_0 \left(- \vec{\nabla} a \times \vec{E}_0 - \partial_t a \vec{B}_0 \right) \\ + g_{aEM} \epsilon_0 \left(- \vec{\nabla} a \times c^2 \vec{B}_0 + \partial_t a \vec{E}_0 \right), \end{aligned}$$

$$\vec{\nabla} \cdot \vec{B}_1 = - \frac{g_{aMM}}{c} \vec{E}_0 \cdot \vec{\nabla} a + g_{aEM} \vec{B}_0 \cdot \vec{\nabla} a,$$

$$\begin{aligned} \vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 + \frac{g_{aMM}}{c} \left(c^2 \nabla a \times \vec{B}_0 - \partial_t a \vec{E}_0 \right) \\ + g_{aEM} \left(\nabla a \times \vec{E}_0 + \partial_t a \vec{B}_0 \right). \end{aligned}$$

General Equations

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1}$$
$$+ g_{a\gamma\gamma} c \epsilon_0 \left(- \vec{\nabla} a \times \vec{E}_0 - \partial_t a \vec{B}_0 \right)$$
$$+ g_{aEM} \epsilon_0 \left(- \vec{\nabla} a \times c^2 \vec{B}_0 + \partial_t a \vec{E}_0 \right),$$

$$\vec{\nabla} \cdot \vec{B}_1 = - \frac{g_{aMM}}{c} \vec{E}_0 \cdot \vec{\nabla} a + g_{aEM} \vec{B}_0 \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 + \frac{g_{aMM}}{c} \left(c^2 \nabla a \times \vec{B}_0 - \partial_t a \vec{E}_0 \right)$$
$$+ g_{aEM} \left(\nabla a \times \vec{E}_0 + \partial_t a \vec{B}_0 \right).$$

Background Electric Field $\vec{\nabla} a = 0$

$\nabla \times \vec{E}_0 = 0 \qquad \nabla \cdot \vec{E}_0 = \epsilon_0^{-1} \rho_{e_0} \qquad \vec{B}_0 = 0$

General Equations

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1}$$
$$+ g_{a\gamma\gamma} c \epsilon_0 \left(- \vec{\nabla} a \times \vec{E}_0 - \partial_t a \vec{B}_0 \right)$$
$$+ g_{aEM} \epsilon_0 \left(- \vec{\nabla} a \times c^2 \vec{B}_0 + \partial_t a \vec{E}_0 \right),$$

$$\vec{\nabla} \cdot \vec{B}_1 = - \frac{g_{aMM}}{c} \vec{E}_0 \cdot \vec{\nabla} a + g_{aEM} \vec{B}_0 \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 + \frac{g_{aMM}}{c} \left(c^2 \nabla a \times \vec{B}_0 - \partial_t a \vec{E}_0 \right)$$
$$+ g_{aEM} \left(\nabla a \times \vec{E}_0 + \partial_t a \vec{B}_0 \right).$$

Background Electric Field $\vec{\nabla} a = 0$

$\nabla \times \vec{E}_0 = 0$ $\quad \nabla \cdot \vec{E}_0 = \epsilon_0^{-1} \rho_{e_0}$ $\quad \vec{B}_0 = 0$

$$\vec{\nabla} \cdot \vec{E}_1 = 0,$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} + \vec{J}_{ea1},$$

$$\vec{\nabla} \cdot \vec{B}_1 = 0,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 - \vec{J}_{ma1}.$$

General Equations

$$\vec{\nabla}\cdot\vec{E}_1 = g_{a\gamma\gamma}c\vec{B}_0\cdot\vec{\nabla}a - g_{aEM}\vec{E}_0\cdot\vec{\nabla}a + \epsilon_0^{-1}\rho_{e1},$$

$$\mu_0^{-1}\vec{\nabla}\times\vec{B}_1 = \epsilon_0\partial_t\vec{E}_1 + \vec{J}_{e1} + g_{a\gamma\gamma}c\epsilon_0\left(-\vec{\nabla}a\times\vec{E}_0 - \partial_t a\vec{B}_0\right) + g_{aEM}\epsilon_0\left(-\vec{\nabla}a\times c^2\vec{B}_0 + \partial_t a\vec{E}_0\right),$$

$$\vec{\nabla}\cdot\vec{B}_1 = -\frac{g_{aMM}}{c}\vec{E}_0\cdot\vec{\nabla}a + g_{aEM}\vec{B}_0\cdot\vec{\nabla}a,$$

$$\vec{\nabla}\times\vec{E}_1 = -\partial_t\vec{B}_1 + \frac{g_{aMM}}{c}\left(c^2\nabla a\times\vec{B}_0 - \partial_t a\vec{E}_0\right) + g_{aEM}\left(\nabla a\times\vec{E}_0 + \partial_t a\vec{B}_0\right).$$

Background Electric Field $\vec{\nabla}a = 0$

$$\nabla\times\vec{E}_0 = 0 \qquad \nabla\cdot\vec{E}_0 = \epsilon_0^{-1}\rho_{e_0} \qquad \vec{B}_0 = 0$$

$$\vec{\nabla}\cdot\vec{E}_1 = 0,$$

$$\mu_0^{-1}\vec{\nabla}\times\vec{B}_1 = \epsilon_0\partial_t\vec{E}_1 + \vec{J}_{e1} + \vec{J}_{ea1},$$

$$\vec{\nabla}\cdot\vec{B}_1 = 0,$$

$$\vec{\nabla}\times\vec{E}_1 = -\partial_t\vec{B}_1 - \vec{J}_{ma1}.$$

Effective Axion Current

$$\vec{J}_{ea1} = g_{aEM}\epsilon_0\vec{E}_0\partial_t a$$

General Equations

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} + g_{a\gamma\gamma} c \epsilon_0 \left(- \vec{\nabla} a \times \vec{E}_0 - \partial_t a \vec{B}_0 \right) + g_{aEM} \epsilon_0 \left(- \vec{\nabla} a \times c^2 \vec{B}_0 + \partial_t a \vec{E}_0 \right),$$

$$\vec{\nabla} \cdot \vec{B}_1 = - \frac{g_{aMM}}{c} \vec{E}_0 \cdot \vec{\nabla} a + g_{aEM} \vec{B}_0 \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 + \frac{g_{aMM}}{c} \left(c^2 \nabla a \times \vec{B}_0 - \partial_t a \vec{E}_0 \right) + g_{aEM} \left(\nabla a \times \vec{E}_0 + \partial_t a \vec{B}_0 \right).$$

Background Electric Field $\vec{\nabla} a = 0$

$\nabla \times \vec{E}_0 = 0$ $\quad \nabla \cdot \vec{E}_0 = \epsilon_0^{-1} \rho_{e_0}$ $\quad \vec{B}_0 = 0$

$$\vec{\nabla} \cdot \vec{E}_1 = 0,$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} + \vec{J}_{ea1},$$

$$\vec{\nabla} \cdot \vec{B}_1 = 0,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 - \vec{J}_{ma1}.$$

Effective Axion Current

$$\vec{J}_{ea1} = g_{aEM} \epsilon_0 \vec{E}_0 \partial_t a$$

Effective Axion Magnetic Current

$$\vec{J}_{ma1} = - \frac{g_{aMM}}{c} \vec{E}_0 \partial_t a$$

General Equations

$$\vec{\nabla}\cdot\vec{E}_1 = g_{a\gamma\gamma}c\vec{B}_0\cdot\vec{\nabla}a - g_{aEM}\vec{E}_0\cdot\vec{\nabla}a + \epsilon_0^{-1}\rho_{e1},$$

$$\mu_0^{-1}\vec{\nabla}\times\vec{B}_1 = \epsilon_0\partial_t\vec{E}_1 + \vec{J}_{e1}$$
$$+g_{a\gamma\gamma}c\epsilon_0\left(-\vec{\nabla}a\times\vec{E}_0 - \partial_t a\vec{B}_0\right)$$
$$+g_{aEM}\epsilon_0\left(-\vec{\nabla}a\times c^2\vec{B}_0 + \partial_t a\vec{E}_0\right),$$

$$\vec{\nabla}\cdot\vec{B}_1 = -\frac{g_{aMM}}{c}\vec{E}_0\cdot\vec{\nabla}a + g_{aEM}\vec{B}_0\cdot\vec{\nabla}a,$$

$$\vec{\nabla}\times\vec{E}_1 = -\partial_t\vec{B}_1 + \frac{g_{aMM}}{c}\left(c^2\nabla a\times\vec{B}_0 - \partial_t a\vec{E}_0\right)$$
$$+g_{aEM}\left(\nabla a\times\vec{E}_0 + \partial_t a\vec{B}_0\right).$$

Background Electric Field $\vec{\nabla}a = 0$

$\nabla\times\vec{E}_0 = 0$ $\quad$ $\nabla\cdot\vec{E}_0 = \epsilon_0^{-1}\rho_{e_0}$ $\quad$ $\vec{B}_0 = 0$

$$\vec{\nabla}\cdot\vec{E}_1 = 0,$$

$$\mu_0^{-1}\vec{\nabla}\times\vec{B}_1 = \epsilon_0\partial_t\vec{E}_1 + \vec{J}_{e1} + \vec{J}_{ea1},$$

$$\vec{\nabla}\cdot\vec{B}_1 = 0,$$

$$\vec{\nabla}\times\vec{E}_1 = -\partial_t\vec{B}_1 - \vec{J}_{ma1}.$$

Effective Axion Current

$$\vec{J}_{ea1} = g_{aEM}\epsilon_0\vec{E}_0\partial_t a$$

Effective Axion Magnetic Current

$$\vec{J}_{ma1} = -\frac{g_{aMM}}{c}\vec{E}_0\partial_t a$$

Doing the Calculation This Way -> Can Hide Surface Effects

General Equations

$$\vec{\nabla} \cdot \vec{E}_1 = g_{a\gamma\gamma} c \vec{B}_0 \cdot \vec{\nabla} a - g_{aEM} \vec{E}_0 \cdot \vec{\nabla} a + \epsilon_0^{-1} \rho_{e1},$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} + g_{a\gamma\gamma} c \epsilon_0 \left(- \vec{\nabla} a \times \vec{E}_0 - \partial_t a \vec{B}_0 \right) + g_{aEM} \epsilon_0 \left(- \vec{\nabla} a \times c^2 \vec{B}_0 + \partial_t a \vec{E}_0 \right),$$

$$\vec{\nabla} \cdot \vec{B}_1 = - \frac{g_{aMM}}{c} \vec{E}_0 \cdot \vec{\nabla} a + g_{aEM} \vec{B}_0 \cdot \vec{\nabla} a,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 + \frac{g_{aMM}}{c} \left(c^2 \nabla a \times \vec{B}_0 - \partial_t a \vec{E}_0 \right) + g_{aEM} \left(\nabla a \times \vec{E}_0 + \partial_t a \vec{B}_0 \right).$$

Background Electric Field $\vec{\nabla} a = 0$

$\nabla \times \vec{E}_0 = 0$ $\quad \nabla \cdot \vec{E}_0 = \epsilon_0^{-1} \rho_{e_0}$ $\quad \vec{B}_0 = 0$

$$\vec{\nabla} \cdot \vec{E}_1 = 0,$$

$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \vec{E}_1 + \vec{J}_{e1} + \vec{J}_{ea1},$$

$$\vec{\nabla} \cdot \vec{B}_1 = 0,$$

$$\vec{\nabla} \times \vec{E}_1 = - \partial_t \vec{B}_1 - \vec{J}_{ma1}.$$

Effective Axion Current

$$\vec{J}_{ea1} = g_{aEM} \epsilon_0 \vec{E}_0 \partial_t a$$

Effective Axion Magnetic Current

$$\vec{J}_{ma1} = - \frac{g_{aMM}}{c} \vec{E}_0 \partial_t a$$

Doing the Calculation This Way -> Can Hide Surface Effects

Assumes Total Derivative is Zero and All Surfaces -> Infinity

General Equations

$$\vec{\nabla}\cdot\vec{E}_1 = g_{a\gamma\gamma}c\vec{B}_0\cdot\vec{\nabla}a - g_{aEM}\vec{E}_0\cdot\vec{\nabla}a + \epsilon_0^{-1}\rho_{e1},$$

$$\mu_0^{-1}\vec{\nabla}\times\vec{B}_1 = \epsilon_0\partial_t\vec{E}_1 + \vec{J}_{e1} + g_{a\gamma\gamma}c\epsilon_0\left(-\vec{\nabla}a\times\vec{E}_0 - \partial_t a\vec{B}_0\right) + g_{aEM}\epsilon_0\left(-\vec{\nabla}a\times c^2\vec{B}_0 + \partial_t a\vec{E}_0\right),$$

$$\vec{\nabla}\cdot\vec{B}_1 = -\frac{g_{aMM}}{c}\vec{E}_0\cdot\vec{\nabla}a + g_{aEM}\vec{B}_0\cdot\vec{\nabla}a,$$

$$\vec{\nabla}\times\vec{E}_1 = -\partial_t\vec{B}_1 + \frac{g_{aMM}}{c}\left(c^2\nabla a\times\vec{B}_0 - \partial_t a\vec{E}_0\right) + g_{aEM}\left(\nabla a\times\vec{E}_0 + \partial_t a\vec{B}_0\right).$$

Background Electric Field $\vec{\nabla}a = 0$

$$\nabla\times\vec{E}_0 = 0 \qquad \nabla\cdot\vec{E}_0 = \epsilon_0^{-1}\rho_{e_0} \qquad \vec{B}_0 = 0$$

$$\vec{\nabla}\cdot\vec{E}_1 = 0,$$

$$\mu_0^{-1}\vec{\nabla}\times\vec{B}_1 = \epsilon_0\partial_t\vec{E}_1 + \vec{J}_{e1} + \vec{J}_{ea1},$$

$$\vec{\nabla}\cdot\vec{B}_1 = 0,$$

$$\vec{\nabla}\times\vec{E}_1 = -\partial_t\vec{B}_1 - \vec{J}_{ma1}.$$

Effective Axion Current

$$\vec{J}_{ea1} = g_{aEM}\epsilon_0\vec{E}_0\partial_t a$$

Effective Axion Magnetic Current

$$\vec{J}_{ma1} = -\frac{g_{aMM}}{c}\vec{E}_0\partial_t a$$

Doing the Calculation This Way -> Can Hide Surface Effects

Assumes Total Derivative is Zero and All Surfaces -> Infinity

Impressed Charges and Currents Create Fields, and these Surfaces do not go to infinity

$$\nabla a \cdot \overrightarrow{E}_0 = \nabla \cdot (a\overrightarrow{E}_0) - a(\nabla \cdot \overrightarrow{E}_0)$$

$$\nabla \cdot \overrightarrow{E}_0 = \epsilon_0^{-1}\rho_{e_0}$$

$$\nabla a \cdot \overrightarrow{E}_0 = \nabla \cdot (a\overrightarrow{E}_0) - a(\nabla \cdot \overrightarrow{E}_0)$$ $$\nabla \cdot \overrightarrow{E}_0 = \epsilon_0^{-1} \rho_{e_0}$$

The axion field is strongly repelled by electric charges due to the infinite potential barrier

Willy Fischler and John Preskill. DYON - AXION DYNAMICS. Phys. Lett. B, 125:165–170, 1983

Thus, one has a=0 at the locations of the charged particles, so $a(\nabla \cdot \overrightarrow{E}_0) = 0$,
$\nabla a \neq 0$ in the vicinity of the charge

$$\nabla a \cdot \vec{E}_0 = \nabla \cdot (a\vec{E}_0) - a(\nabla \cdot \vec{E}_0) \qquad \nabla \cdot \vec{E}_0 = \epsilon_0^{-1}\rho_{e_0}$$

The axion field is strongly repelled by electric charges due to the infinite potential barrier

Willy Fischler and John Preskill. DYON - AXION DYNAMICS. Phys. Lett. B, 125:165–170, 1983

Thus, one has a=0 at the locations of the charged particles, so $a(\nabla \cdot \vec{E}_0) = 0$,
$\nabla a \neq 0$ in the vicinity of the charge

$$\vec{\nabla} \cdot \left(\vec{E}_1 + g_{aEM} a \vec{E}_0\right) = \epsilon_0^{-1}\rho_{e1},$$

$$\mu_0^{-1}\vec{\nabla} \times \vec{B}_1 = \epsilon_0 \partial_t \left(\vec{E}_1 + g_{aEM} a \vec{E}_0\right) + \vec{J}_{e1}$$

$$\vec{\nabla} \cdot \left(\vec{B}_1 + \frac{g_{aMM} a \vec{E}_0}{c}\right) = 0,$$

$$\vec{\nabla} \times \vec{E}_1 = -\partial_t \left(\vec{B}_1 + \frac{g_{aMM} a \vec{E}_0}{c}\right).$$

Define Effective Polarization and Magnetization

Define Effective Polarization and Magnetization

$$\overrightarrow{P}_1 = g_{aEM} a \epsilon_0 \overrightarrow{E}_0,$$
$$\overrightarrow{M}_1 = - g_{aMM} a c \epsilon_0 \overrightarrow{E}_0$$

Define Effective Polarization and Magnetization

$$\vec{P}_1 = g_{aEM} a \epsilon_0 \vec{E}_0,$$
$$\vec{M}_1 = - g_{aMM} a c \epsilon_0 \vec{E}_0$$

$$\vec{D}_1 = \epsilon_0 \vec{E}_1 + \vec{P}_1$$
$$\vec{H}_1 = \mu_0^{-1} \vec{B}_1 - \vec{M}_1$$

Define Effective Polarization and Magnetization

$$\vec{P}_1 = g_{aEM} a \epsilon_0 \vec{E}_0,$$
$$\vec{M}_1 = -\, g_{aMM} a c \epsilon_0 \vec{E}_0$$

$$\vec{D}_1 = \epsilon_0 \vec{E}_1 + \vec{P}_1$$
$$\vec{H}_1 = \mu_0^{-1} \vec{B}_1 - \vec{M}_1$$

$$\vec{\nabla} \cdot \vec{D}_1 = \rho_{e1}$$
$$\mu_0^{-1} \vec{\nabla} \times \vec{B}_1 = \partial_t \vec{D}_1 + \vec{J}_{e1}$$
$$\vec{\nabla} \cdot \vec{H}_1 = 0$$
$$\vec{\nabla} \times \vec{E}_1 = -\, \mu_0 \partial_t \vec{H}_1$$

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

$$\oint \mathrm{Im}\left(\mathbf{S}_1\right) \cdot \hat{n} ds = \omega_a \int \left((\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*) - \frac{g_{aEM} a_0 \epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \vec{E}_0 + \frac{g_{aMM} a_0 \epsilon_0}{4}(\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \vec{E}_0) \right) dV .$$

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

$$\oint \mathrm{Im}\left(\mathbf{S}_1\right) \cdot \hat{n} ds = \omega_a \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*\right) - \frac{g_{aEM} a_0 \epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \vec{E}_0 + \frac{g_{aMM} a_0 \epsilon_0}{4}(\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \vec{E}_0 \right) dV .$$

$$U_1 = \frac{\epsilon_0 a_0^2 \left(\int \left(g_{aEM}\left(\mathbf{E}_1^* + \mathbf{E}_1\right) - g_{aMM} c \left(\mathbf{B}_1^* + \mathbf{B}_1\right)\right) \cdot \vec{E}_0 dv \right)^2}{8 \int \left(\left(c^2 \mathbf{B}_1^* \cdot \mathbf{B}_1 - \mathbf{E}_1 \cdot \mathbf{E}_1^* \right) \right) dv}$$

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

$$\oint \mathrm{Im}\left(\mathbf{S}_1\right) \cdot \hat{n} ds = \omega_a \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*\right) - \frac{g_{aEM} a_0 \epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \vec{E}_0 + \frac{g_{aMM} a_0 \epsilon_0}{4}(\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \vec{E}_0 \right) dV .$$

$$U_1 = \frac{\epsilon_0 a_0^2 \left(\int \left(g_{aEM}\left(\mathbf{E}_1^* + \mathbf{E}_1\right) - g_{aMM} c \left(\mathbf{B}_1^* + \mathbf{B}_1\right)\right) \cdot \vec{E}_0 dv \right)^2}{8 \int \left(\left(c^2 \mathbf{B}_1^* \cdot \mathbf{B}_1 - \mathbf{E}_1 \cdot \mathbf{E}_1^* \right) \right) dv}$$

$$\mathbf{B}_1 + \mathbf{B}_1^* \sim 0 \quad \mathbf{E}_1 + \mathbf{E}_1^* \sim 2\mathbf{E}_1$$

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

$$\oint \mathrm{Im}\left(\mathbf{S}_1\right) \cdot \hat{n} ds = \omega_a \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*\right) - \frac{g_{aEM} a_0 \epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \overrightarrow{E}_0 + \frac{g_{aMM} a_0 \epsilon_0}{4}(\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \overrightarrow{E}_0\right) dV .$$

$$U_1 = \frac{\epsilon_0 a_0^2 \left(\int \left(g_{aEM}\left(\mathbf{E}_1^* + \mathbf{E}_1\right) - g_{aMM} c \left(\mathbf{B}_1^* + \mathbf{B}_1\right)\right) \cdot \overrightarrow{E}_0 dv \right)^2}{8 \int \left(\left(c^2 \mathbf{B}_1^* \cdot \mathbf{B}_1 - \mathbf{E}_1 \cdot \mathbf{E}_1^*\right)\right) dv}$$

$$\mathbf{B}_1 + \mathbf{B}_1^* \sim 0 \quad \mathbf{E}_1 + \mathbf{E}_1^* \sim 2\mathbf{E}_1$$

$$U_1 \approx -\frac{g_{aEM}^2 a_0^2 \epsilon_0 \left(\int \mathbf{E}_1 \cdot \overrightarrow{E}_0 dv \right)^2}{2 \int \mathbf{E}_1 \cdot \mathbf{E}_1^* dv}$$

AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

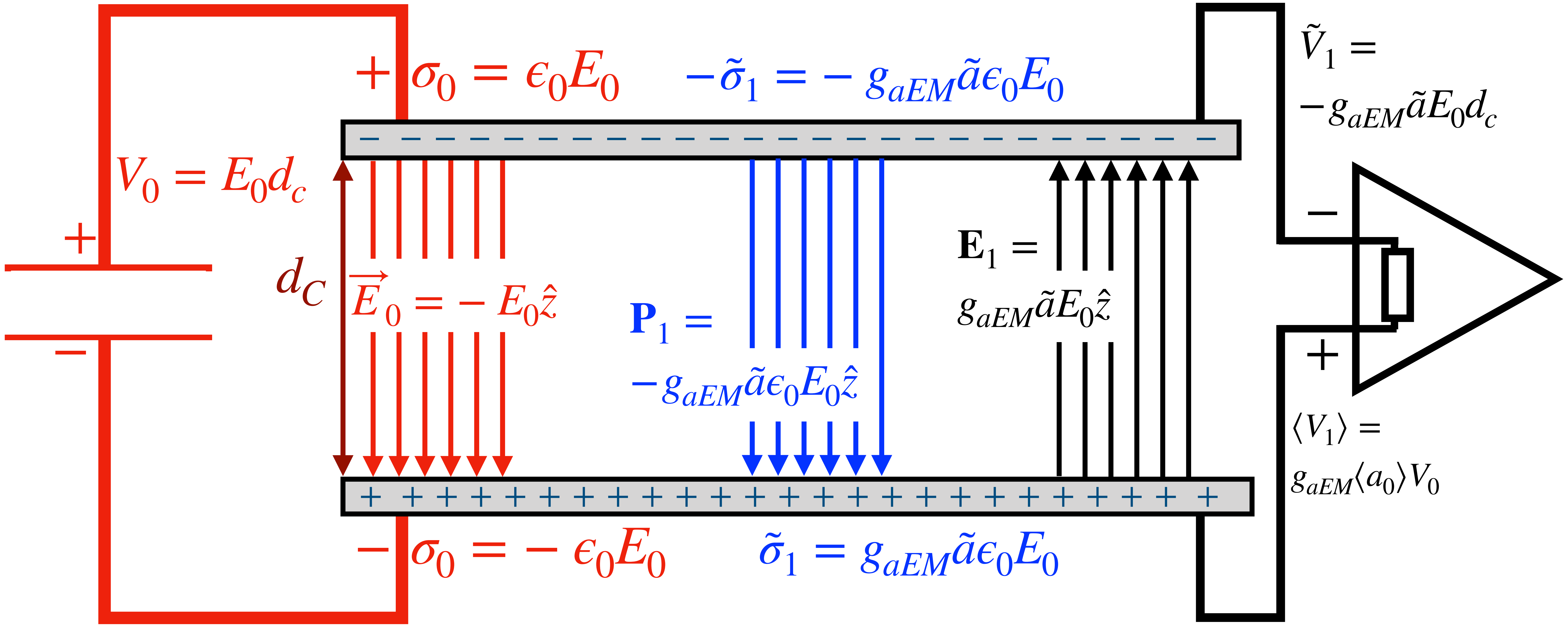
$$\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot\hat{n}ds = \omega_a \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^* \right) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*)\cdot \vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0}{4}(\mathbf{B}_1 + \mathbf{B}_1^*)\cdot \vec{E}_0 \right) dV.$$

$$U_1 = \frac{\epsilon_0 a_0^2 \left(\int \left(g_{aEM}\left(\mathbf{E}_1^* + \mathbf{E}_1\right) - g_{aMM}c\left(\mathbf{B}_1^* + \mathbf{B}_1\right)\right)\cdot \vec{E}_0 dv \right)^2}{8\int \left(\left(c^2\mathbf{B}_1^* \cdot \mathbf{B}_1 - \mathbf{E}_1 \cdot \mathbf{E}_1^* \right) \right) dv}$$

$$\mathbf{B}_1 + \mathbf{B}_1^* \sim 0 \quad \mathbf{E}_1 + \mathbf{E}_1^* \sim 2\mathbf{E}_1$$

$$U_1 \approx -\frac{g_{aEM}^2 a_0^2 \epsilon_0 \left(\int \mathbf{E}_1 \cdot \vec{E}_0 dv \right)^2}{2\int \mathbf{E}_1 \cdot \mathbf{E}_1^* dv}$$

Axion generated Electric Field



AC Capacitor: Apply Poynting Theorem: Sensitive to g_{aEM}

Vector Phasor Amplitudes

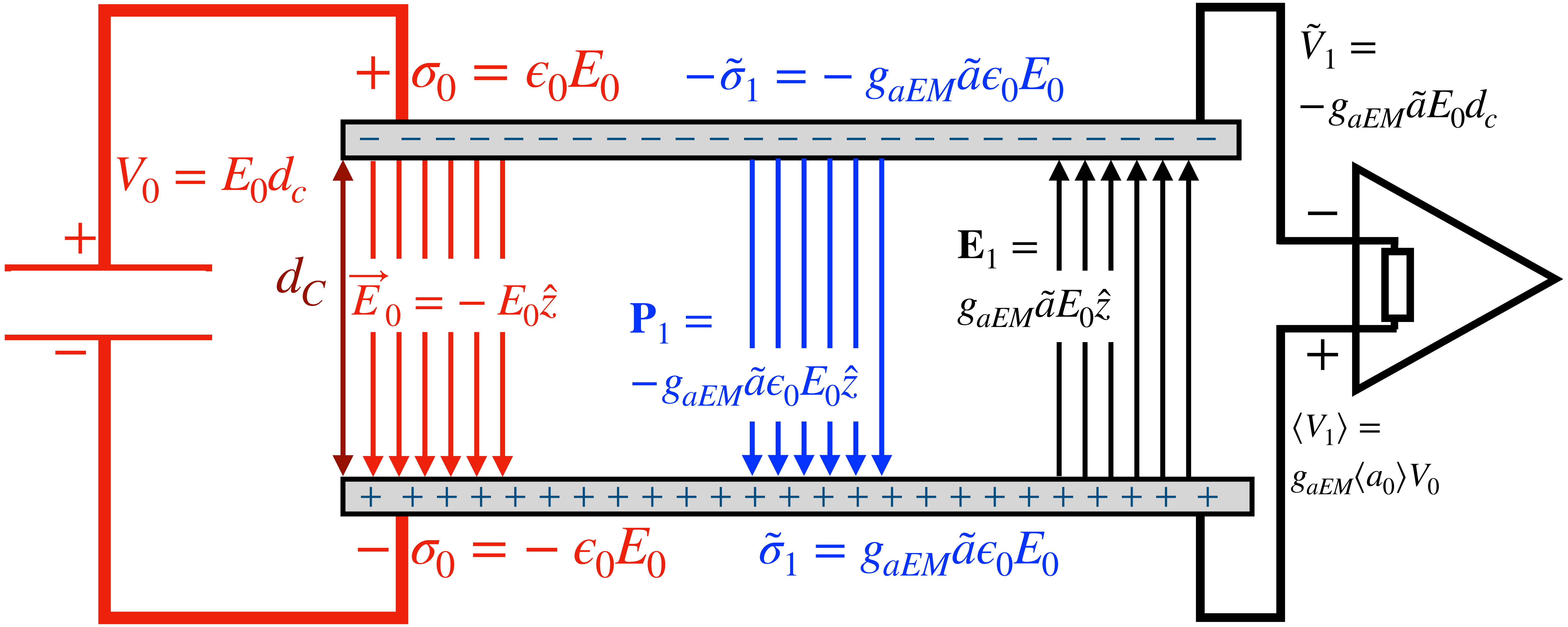
$$\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot \hat{n}ds = \omega_a \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0}{4}(\mathbf{B}_1+\mathbf{B}_1^*)\cdot\vec{E}_0\right) dV\,.$$

$$U_1 = \frac{\epsilon_0 a_0^2\left(\int\left(g_{aEM}\left(\mathbf{E}_1^*+\mathbf{E}_1\right) - g_{aMM}c\left(\mathbf{B}_1^*+\mathbf{B}_1\right)\right)\cdot\vec{E}_0 dv\right)^2}{8\int\left(\left(c^2\mathbf{B}_1^*\cdot\mathbf{B}_1 - \mathbf{E}_1\cdot\mathbf{E}_1^*\right)\right)dv}$$

$$\mathbf{B}_1+\mathbf{B}_1^* \sim 0 \quad \mathbf{E}_1+\mathbf{E}_1^* \sim 2\mathbf{E}_1$$

$$U_1 \approx -\frac{g_{aEM}^2 a_0^2\epsilon_0\left(\int \mathbf{E}_1\cdot\vec{E}_0 dv\right)^2}{2\int \mathbf{E}_1\cdot\mathbf{E}_1^* dv}$$

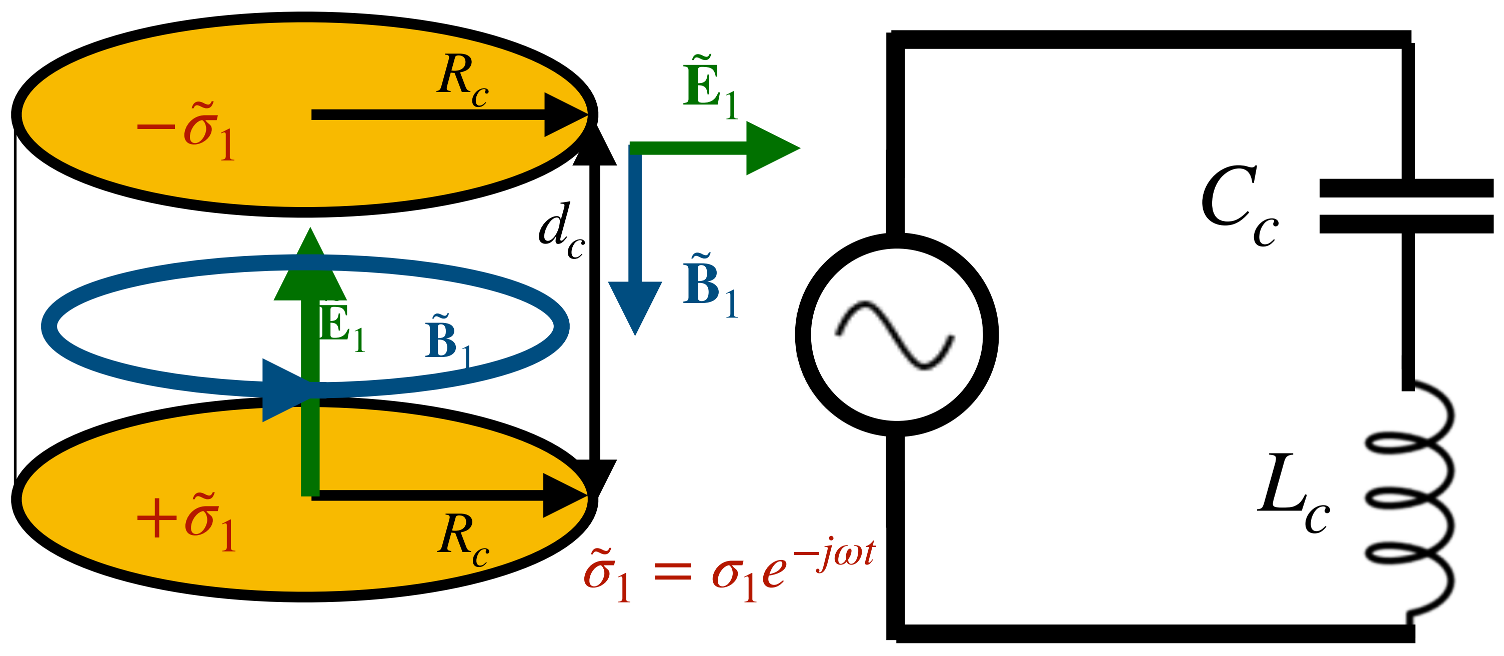
Axion generated Electric Field



Cylindrical // Plate Capacitor

$$\tilde{\mathbf{E}}_1 = \tilde{E}_{01}J_0\left(\frac{\omega_1}{c}r\right)e^{-j\omega_1 t}\hat{z}$$

$$\tilde{\mathbf{B}}_1 = -j\frac{\tilde{E}_{01}}{c}J_1\left(\frac{\omega_1}{c}r\right)e^{-j\omega_1 t}\hat{\varphi} \qquad \tilde{E}_{01} = \frac{\tilde{q}_1}{\pi R_c^2\epsilon_0}$$



SCALAR DARK MATTER: ELECTROMAGNETIC TECHNIQUES

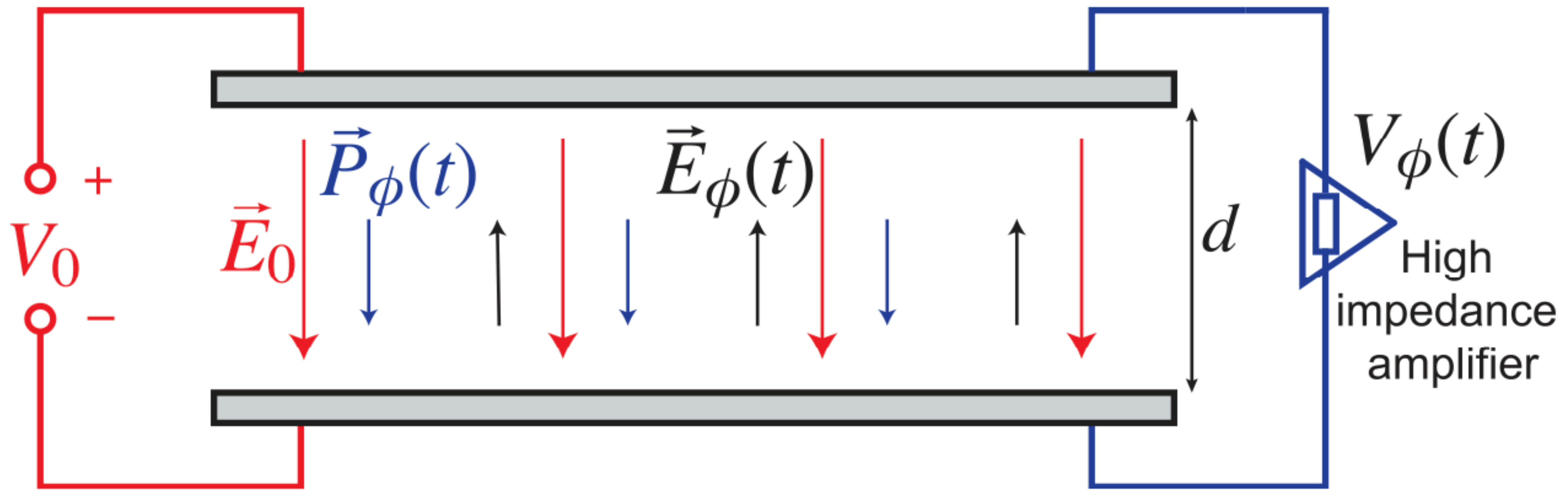
PHYSICAL REVIEW D **106**, 055037 (2022)

Searching for scalar field dark matter using cavity resonators and capacitors

V. V. Flambaum,[1,*] B. T. McAllister,[2,3,†] I. B. Samsonov,[1,‡] and M. E. Tobar[2,§]

[1]*School of Physics, University of New South Wales, Sydney 2052, Australia*
[2]*ARC Centre of Excellence For Engineered Quantum Systems and ARC Centre of Excellence For Dark Matter Particle Physics, QDM Laboratory, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia*
[3]*ARC Centre of Excellence for Dark Matter Particle Physics, Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn VIC 3122, Australia*

$$g_{aEM} \equiv g_{\phi\gamma\gamma}$$



Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

$$\frac{\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot \hat{n}ds}{\omega_a} = \int \left((\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0 c}{4}(\mathbf{B}_1+\mathbf{B}_1^*)\cdot\vec{E}_0) \right) dV$$

$\mathbf{E}_1 + \mathbf{E}_1^* \sim 0 \quad \mathbf{B}_1 + \mathbf{B}_1^* \sim 2\mathbf{B}_1$

Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

$$\frac{\oint \mathrm{Im}\left(\mathbf{S}_1\right) \cdot \hat{n} ds}{\omega_a} = \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*\right) - \frac{g_{aEM} a_0 \epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \vec{E}_0 + \frac{g_{aMM} a_0 \epsilon_0 c}{4}(\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \vec{E}_0 \right) dV$$

$\mathbf{E}_1 + \mathbf{E}_1^* \sim 0 \quad \mathbf{B}_1 + \mathbf{B}_1^* \sim 2\mathbf{B}_1$

$$U_1 = \frac{\left(\frac{g_{aMM} a_0 \epsilon_0 c}{2} \int \mathbf{B}_1 \cdot \vec{E}_0 \, dV \right)^2}{\int \left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^* \right) dV}$$

Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

$$\frac{\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot \hat{n} ds}{\omega_a} = \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*\right) - \frac{g_{aEM} a_0 \epsilon_0}{4}(\mathbf{E}_1 + \mathbf{E}_1^*) \cdot \vec{E}_0 + \frac{g_{aMM} a_0 \epsilon_0 c}{4}(\mathbf{B}_1 + \mathbf{B}_1^*) \cdot \vec{E}_0 \right) dV$$

$$\mathbf{E}_1 + \mathbf{E}_1^* \sim 0 \quad \mathbf{B}_1 + \mathbf{B}_1^* \sim 2\mathbf{B}_1$$

$$U_1 = \frac{\left(\frac{g_{aMM} a_0 \epsilon_0 c}{2} \int \mathbf{B}_1 \cdot \vec{E}_0 \, dV\right)^2}{\int \left(\frac{1}{2\mu_0}\mathbf{B}_1^* \cdot \mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1 \cdot \mathbf{E}_1^*\right) dV}$$

$$U_1 \approx \frac{g_{aMM}^2 a_0^2 \epsilon_0}{2} \frac{\left(\int \mathbf{B}_1 \cdot \vec{E}_0 \, dV\right)^2}{\int \mathbf{B}_1^* \cdot \mathbf{B}_1 \, dV}$$

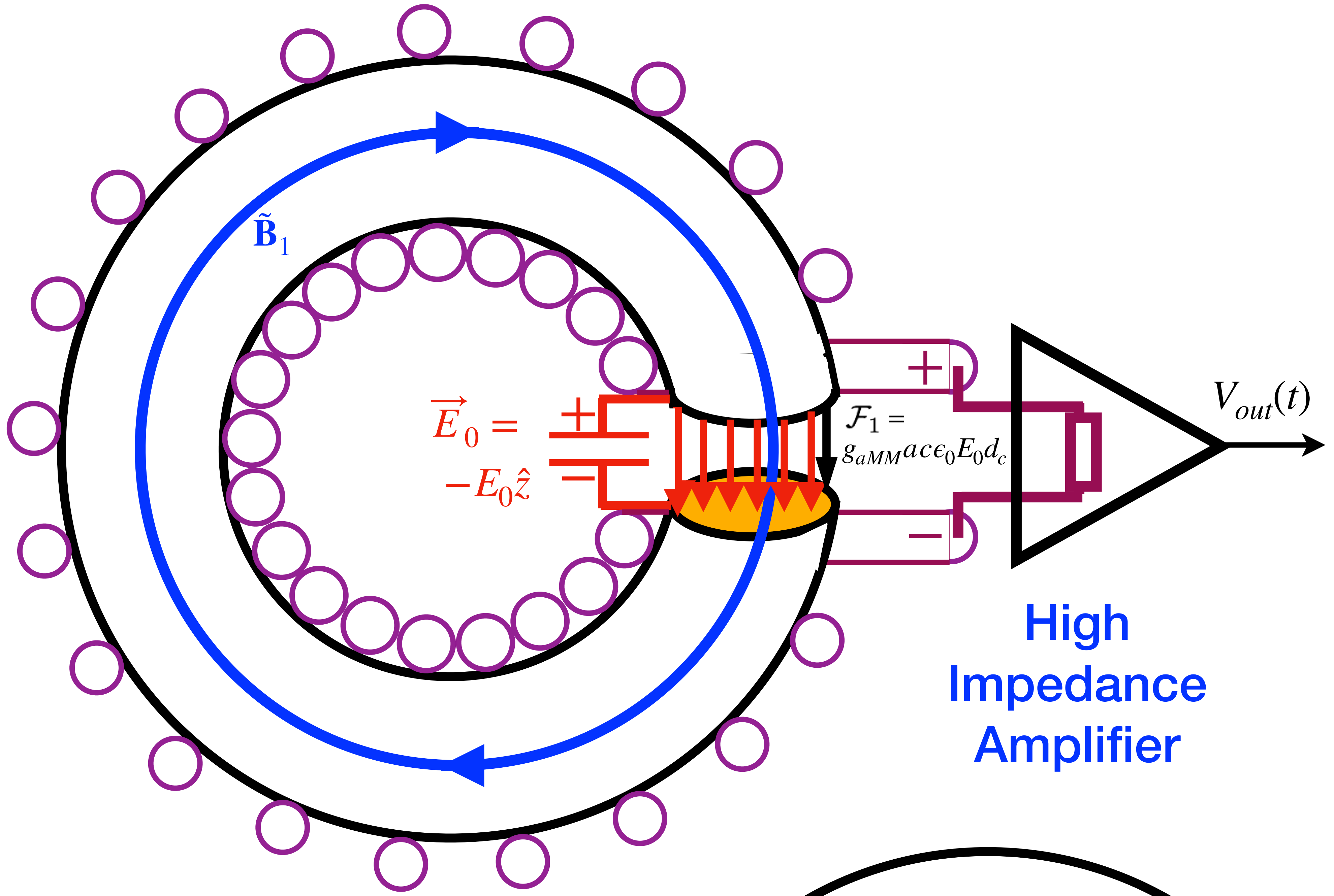
Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

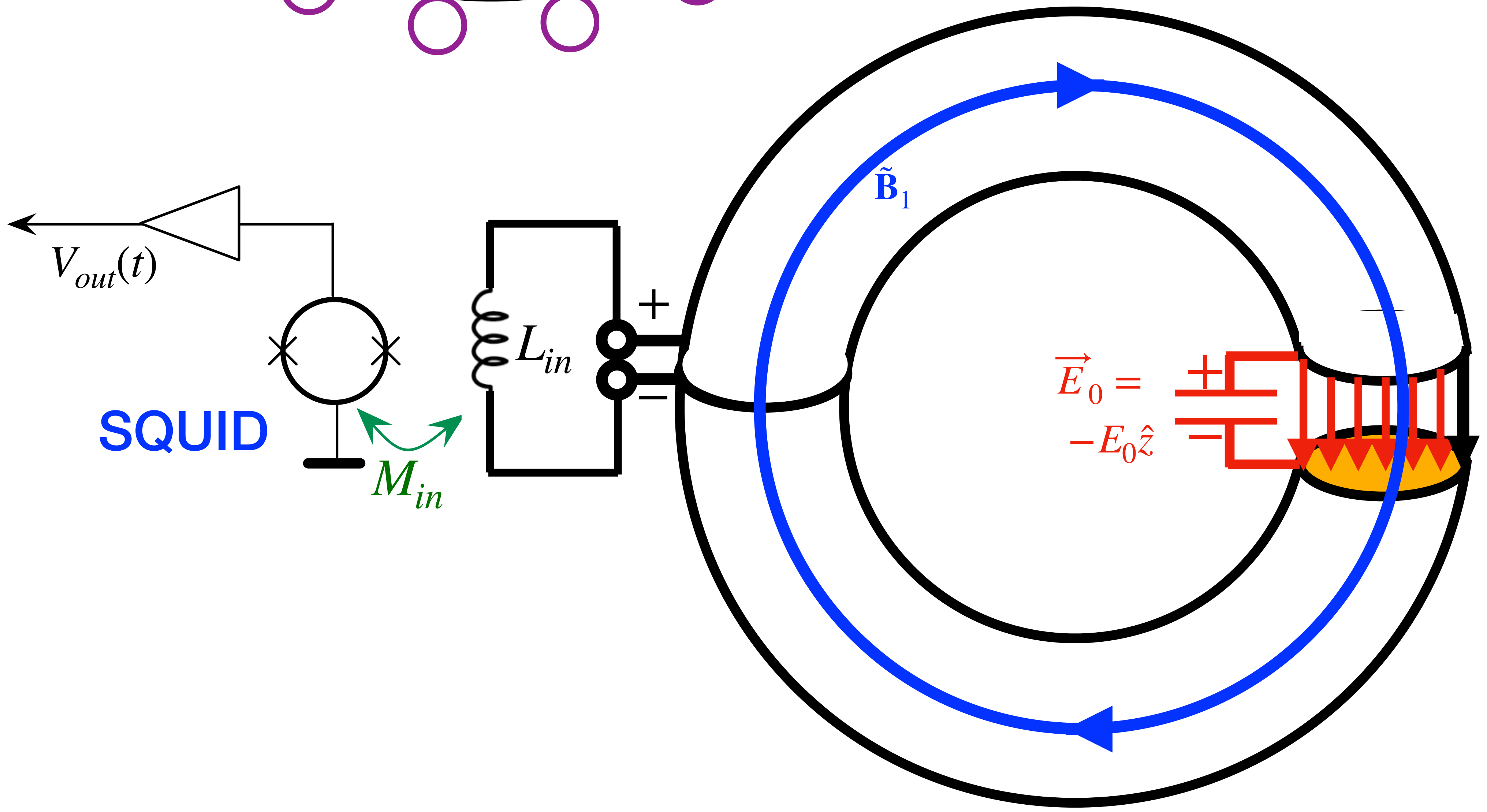
$$\frac{\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot \hat{n}ds}{\omega_a} = \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0 c}{4}(\mathbf{B}_1+\mathbf{B}_1^*)\cdot\vec{E}_0 \right) dV$$

$\mathbf{E}_1 + \mathbf{E}_1^* \sim 0 \quad \mathbf{B}_1 + \mathbf{B}_1^* \sim 2\mathbf{B}_1$

$$U_1 = \frac{\left(\frac{g_{aMM}a_0\epsilon_0 c}{2}\int \mathbf{B}_1\cdot\vec{E}_0\, dV\right)^2}{\int\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right) dV}$$

$$U_1 \approx \frac{g_{aMM}^2 a_0^2\epsilon_0}{2}\frac{\left(\int \mathbf{B}_1\cdot\vec{E}_0\, dV\right)^2}{\int \mathbf{B}_1^*\cdot\mathbf{B}_1\, dV}$$





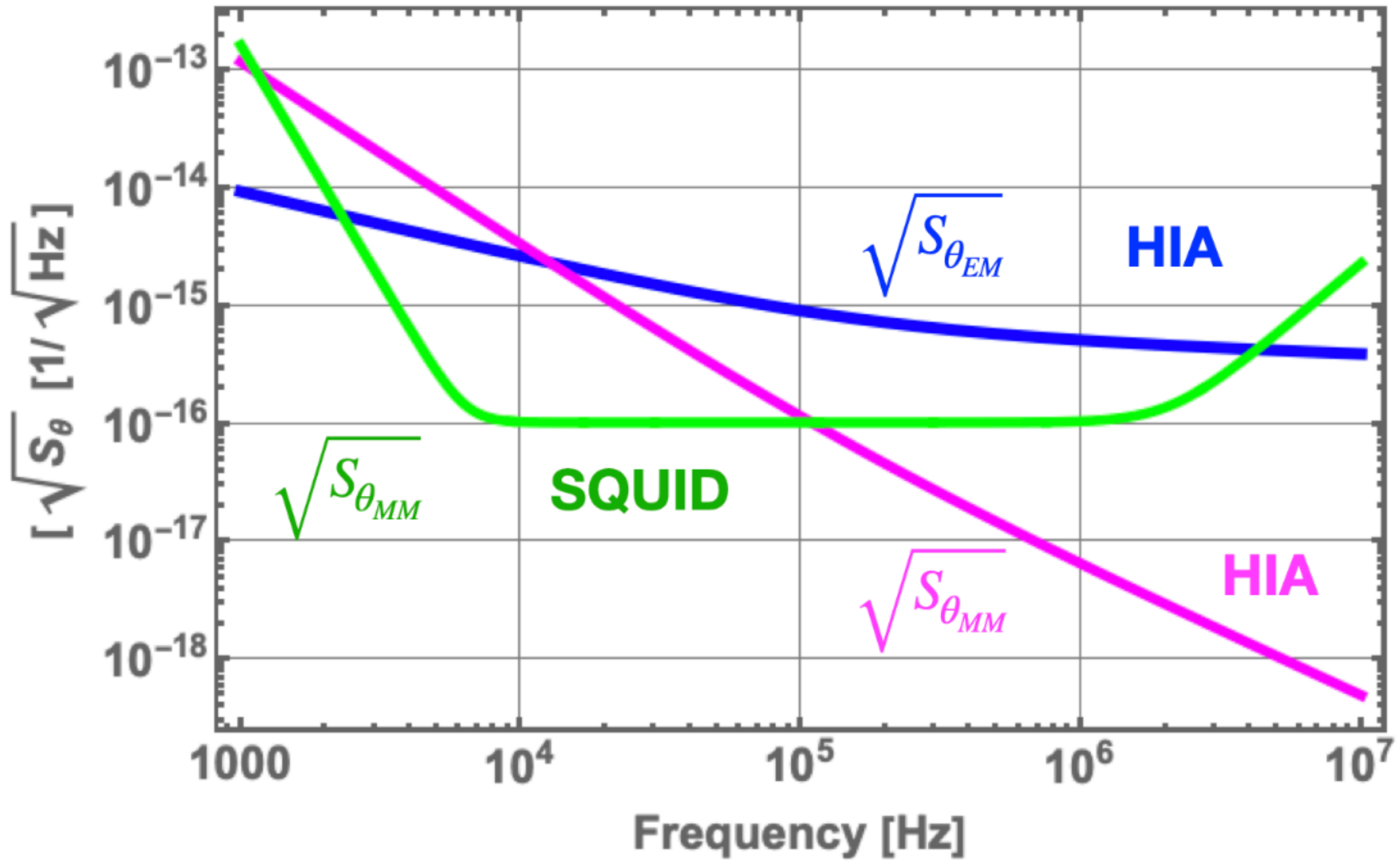
Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

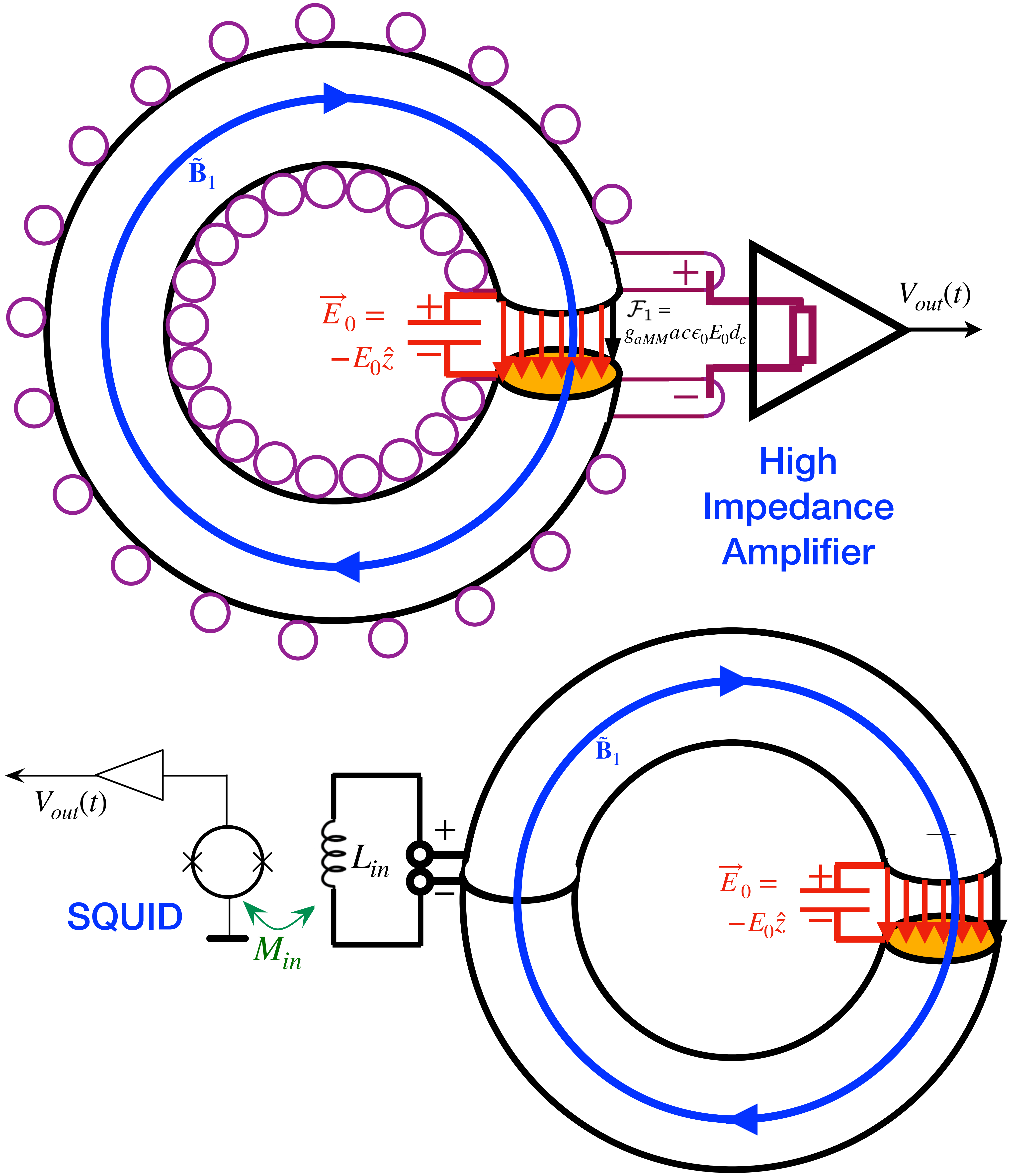
$$\frac{\oint \text{Im}\,(\mathbf{S}_1)\cdot \hat{n} ds}{\omega_a} = \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0 c}{4}(\mathbf{B}_1+\mathbf{B}_1^*)\cdot\vec{E}_0\right) dV$$

$\mathbf{E}_1+\mathbf{E}_1^* \sim 0 \quad \mathbf{B}_1+\mathbf{B}_1^* \sim 2\mathbf{B}_1$

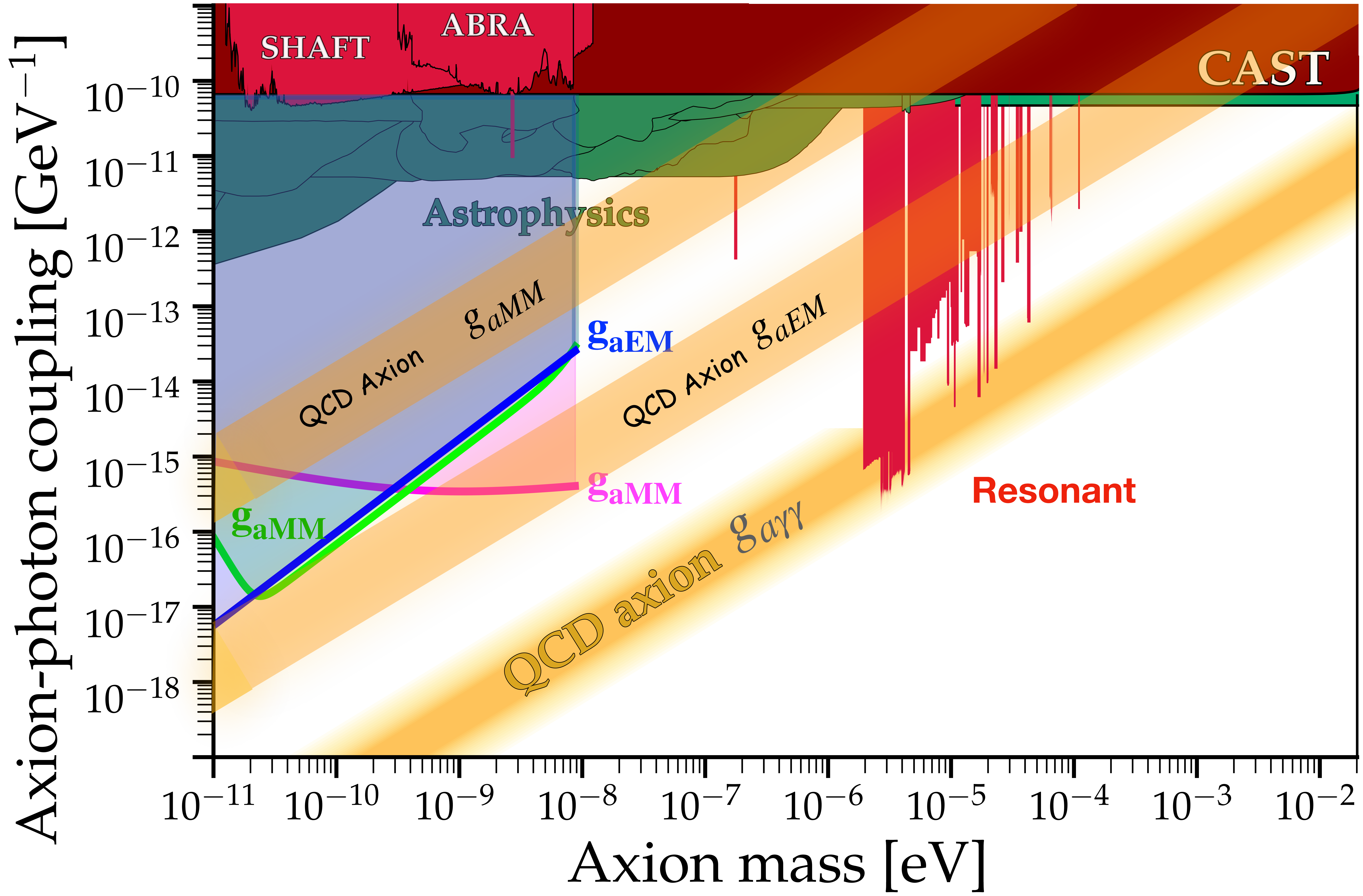
$$U_1 = \frac{\left(\frac{g_{aMM}a_0\epsilon_0 c}{2}\int \mathbf{B}_1\cdot\vec{E}_0\, dV\right)^2}{\int\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^*\right) dV} \qquad U_1 \approx \frac{g_{aMM}^2 a_0^2\epsilon_0}{2}\frac{\left(\int \mathbf{B}_1\cdot\vec{E}_0\, dV\right)^2}{\int \mathbf{B}_1^*\cdot\mathbf{B}_1\, dV}$$

$\theta = a g_{aMM}$



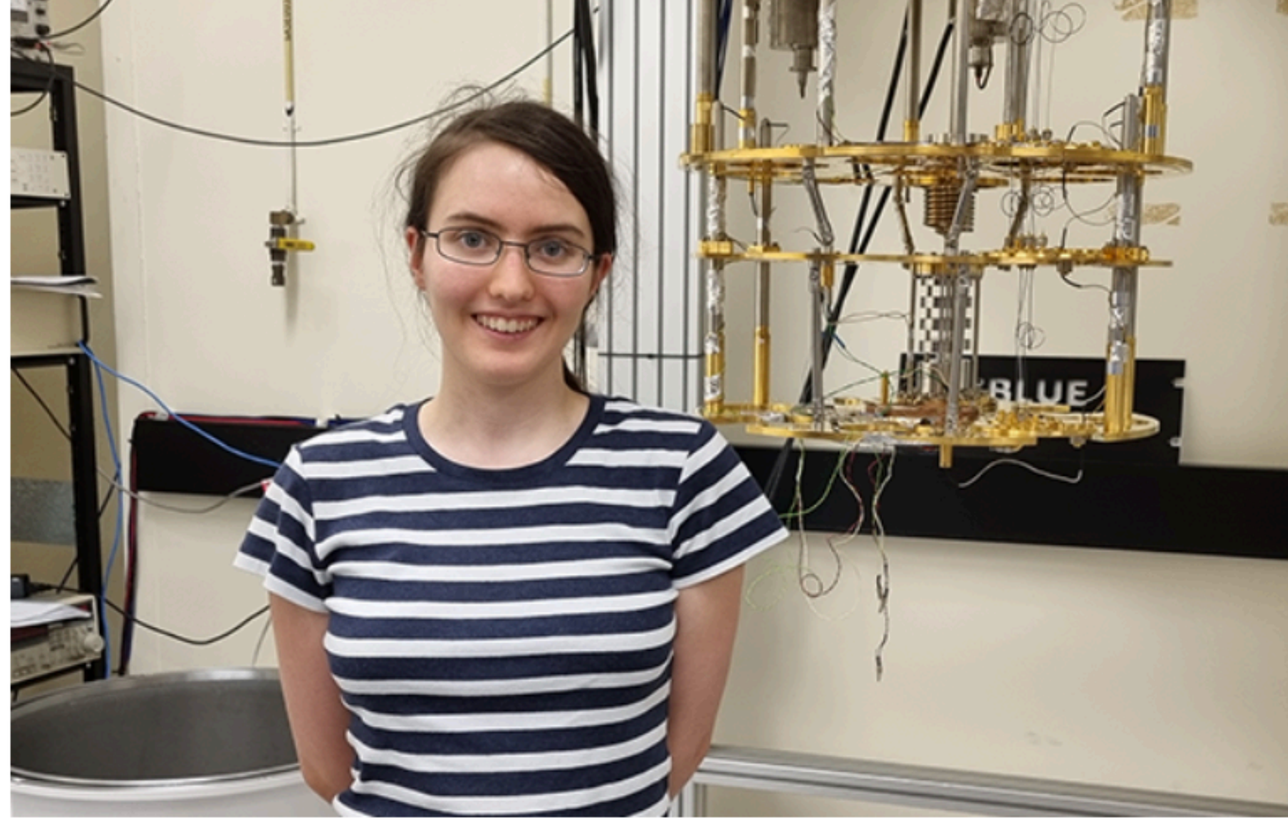


Low-Mass Sensitivity to the QCD Axion ~ 10 cm Scale Assumed



18 days of continuous data taking

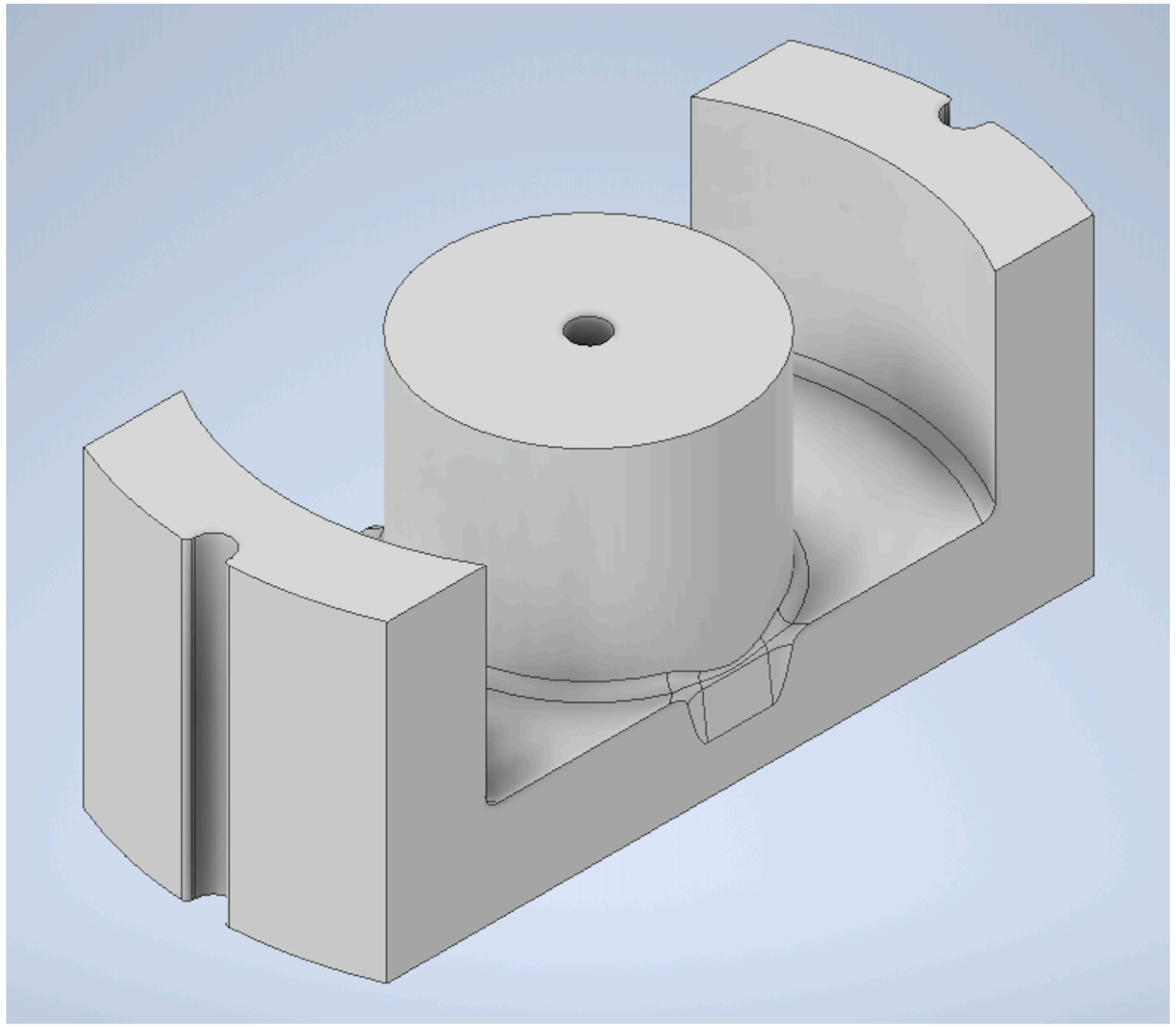
The Axion-MonoPole-Detection (AMPD) Experiment
Initial Prototype ~ 4cm
Purchased Standard Ferrite Core

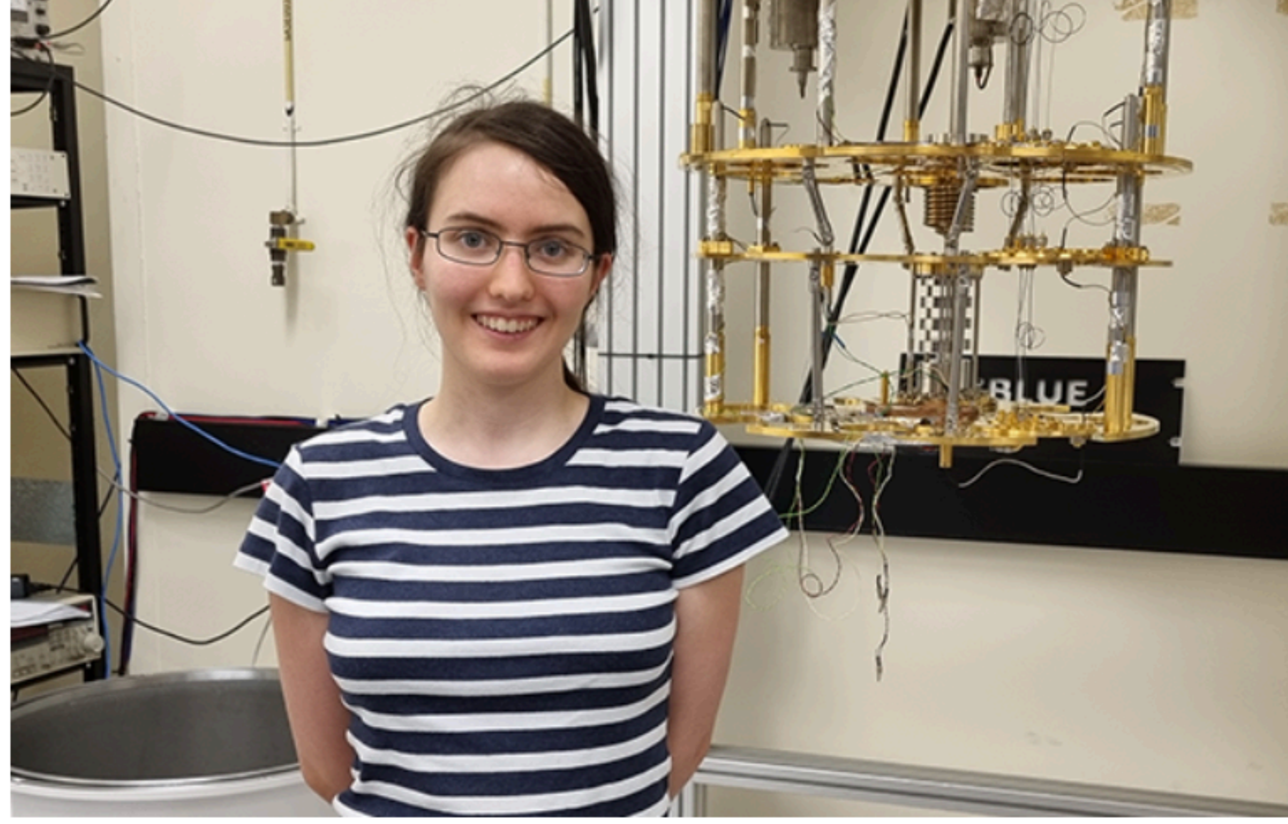


Emily Waterman

BPhil (Hons) Honours Dissertation

The Axion-MonoPole-Detection (AMPD) Experiment
Initial Prototype ~ 4cm
Purchased Standard Ferrite Core

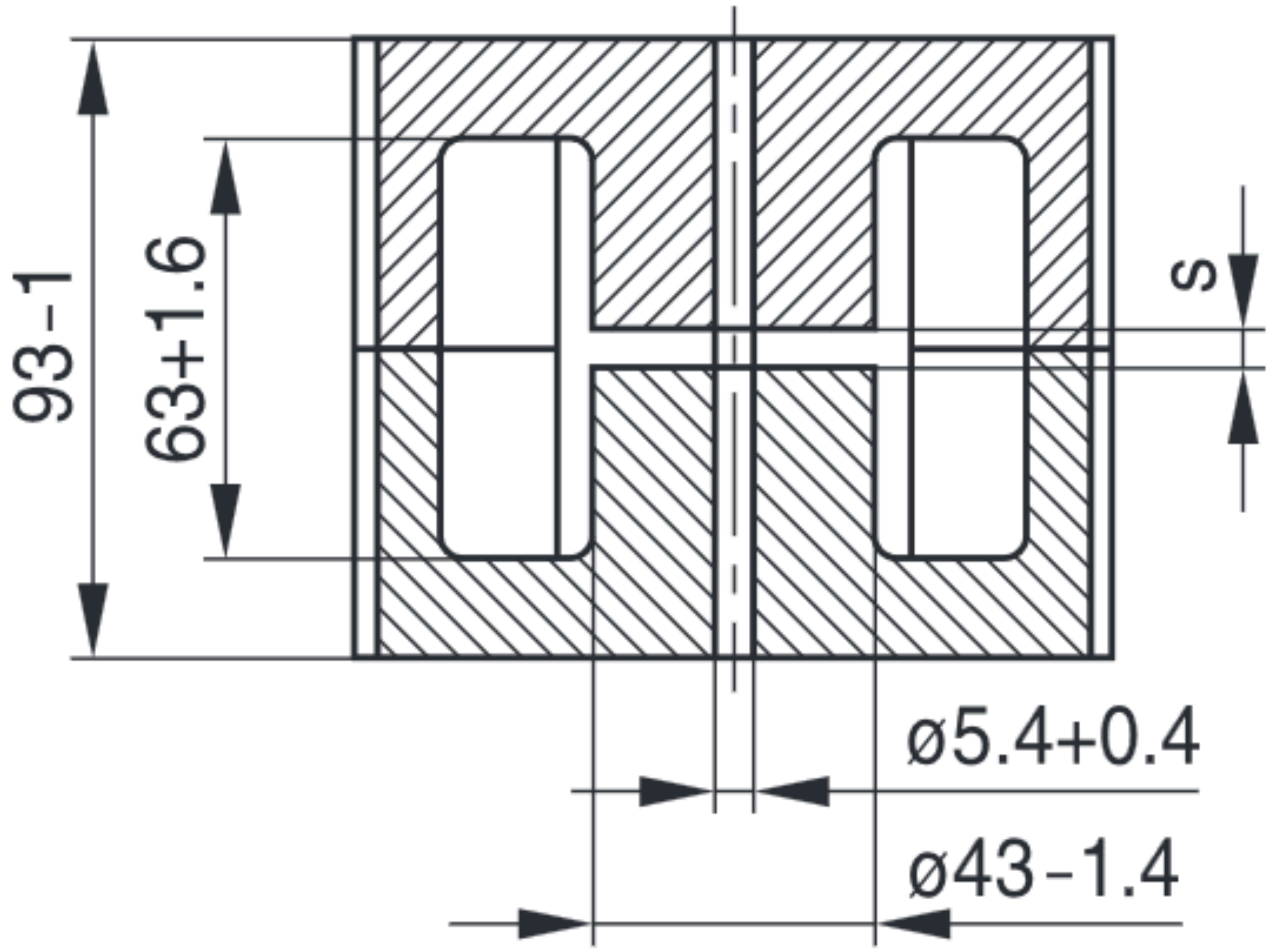


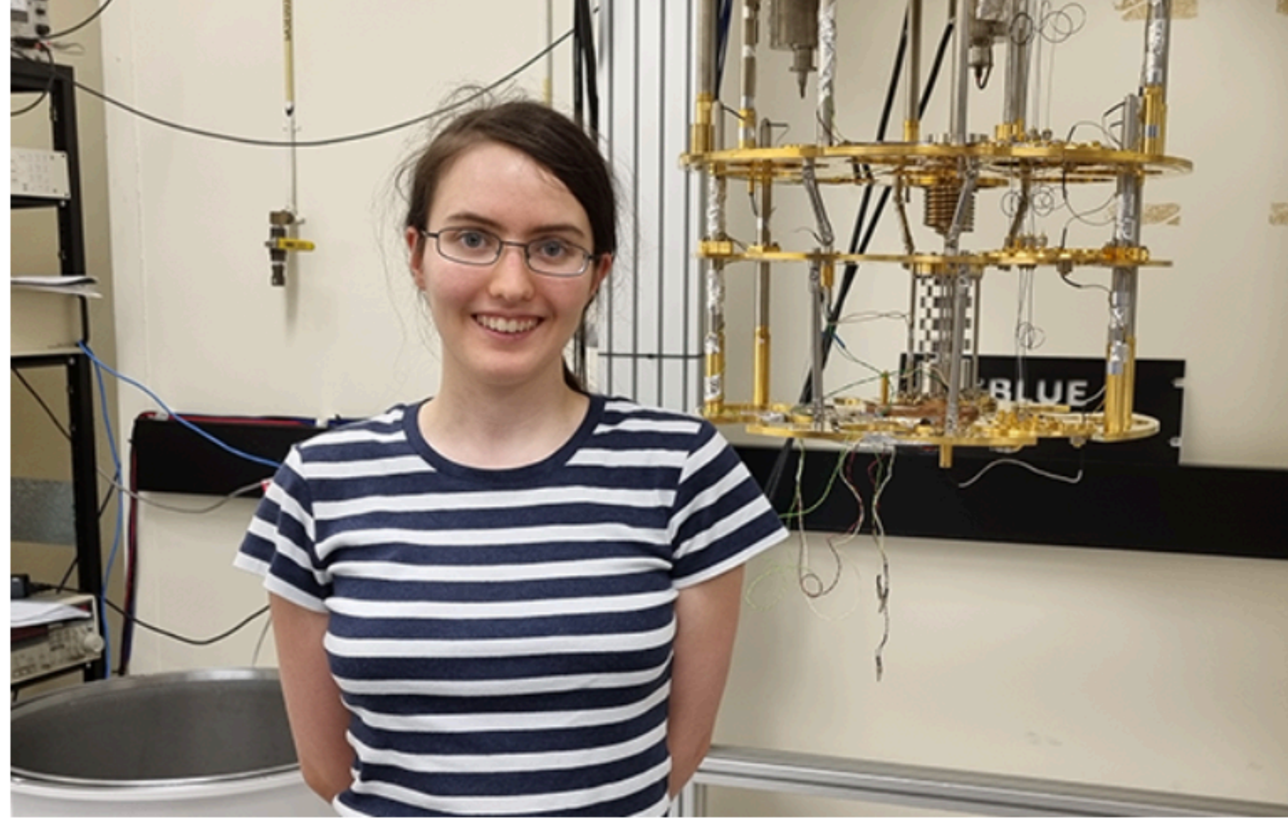


Emily Waterman

BPhil (Hons) Honours Dissertation

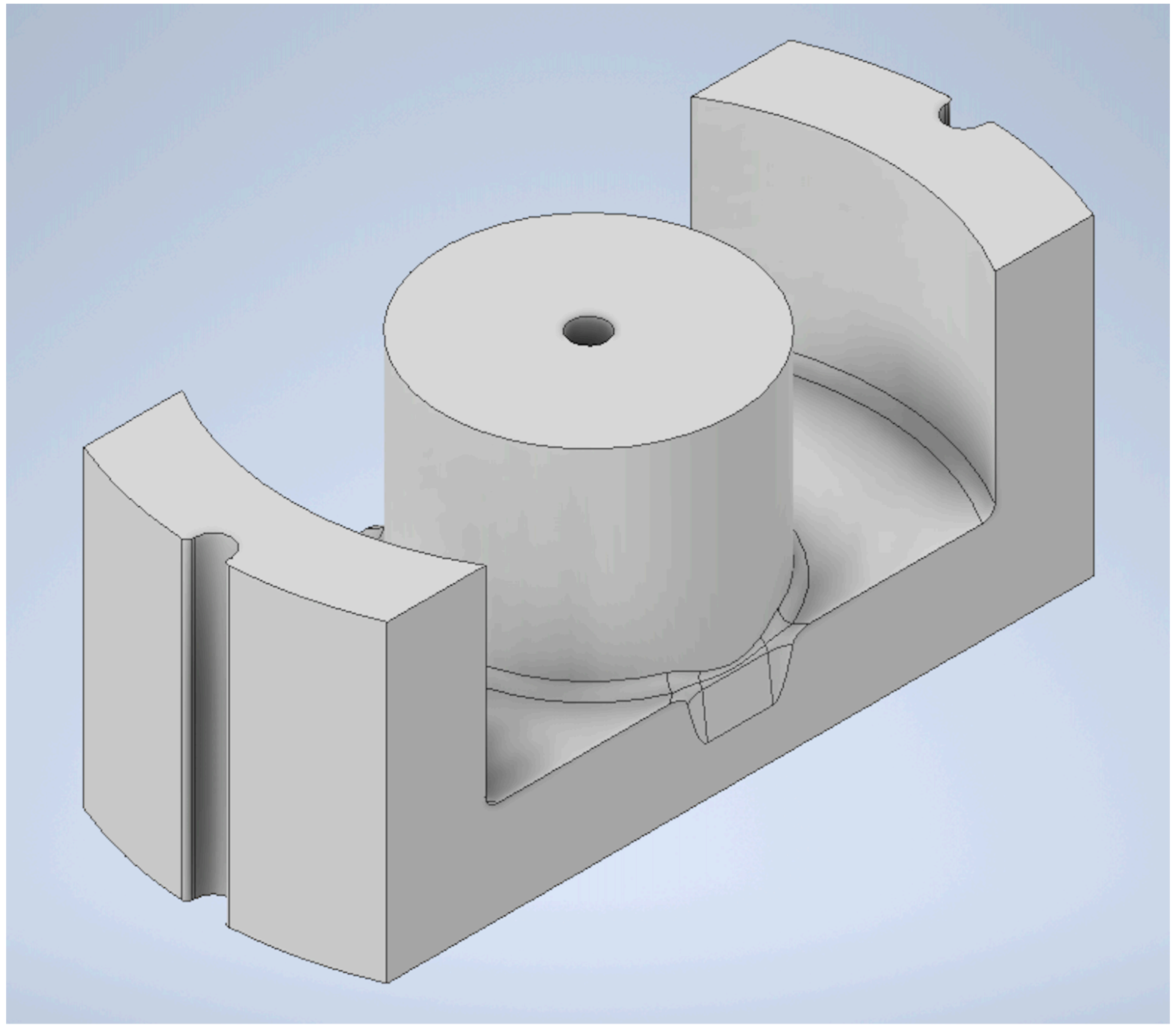
The Axion-MonoPole-Detection (AMPD) Experiment
Initial Prototype ~ 4cm
Purchased Standard Ferrite Core



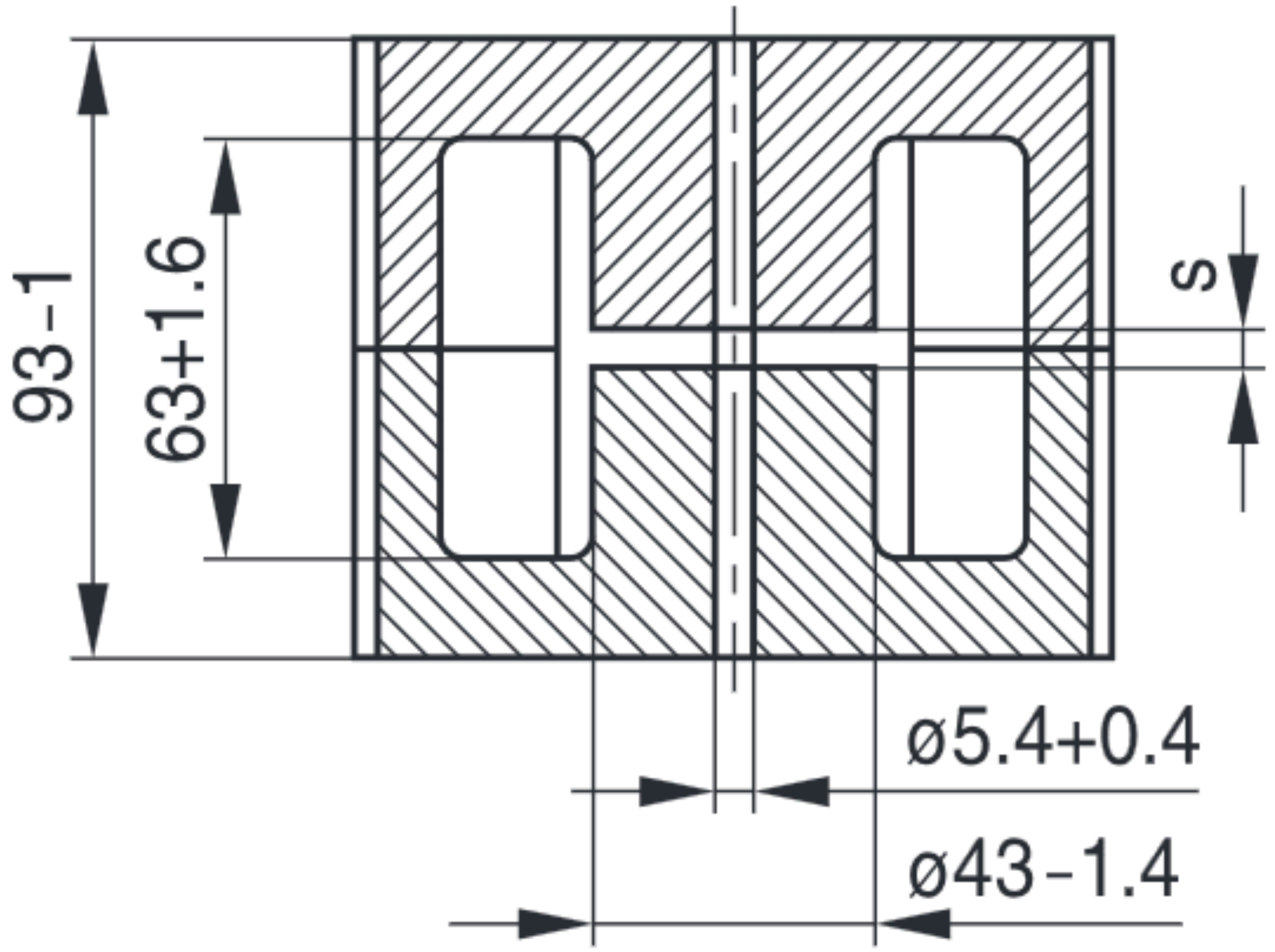


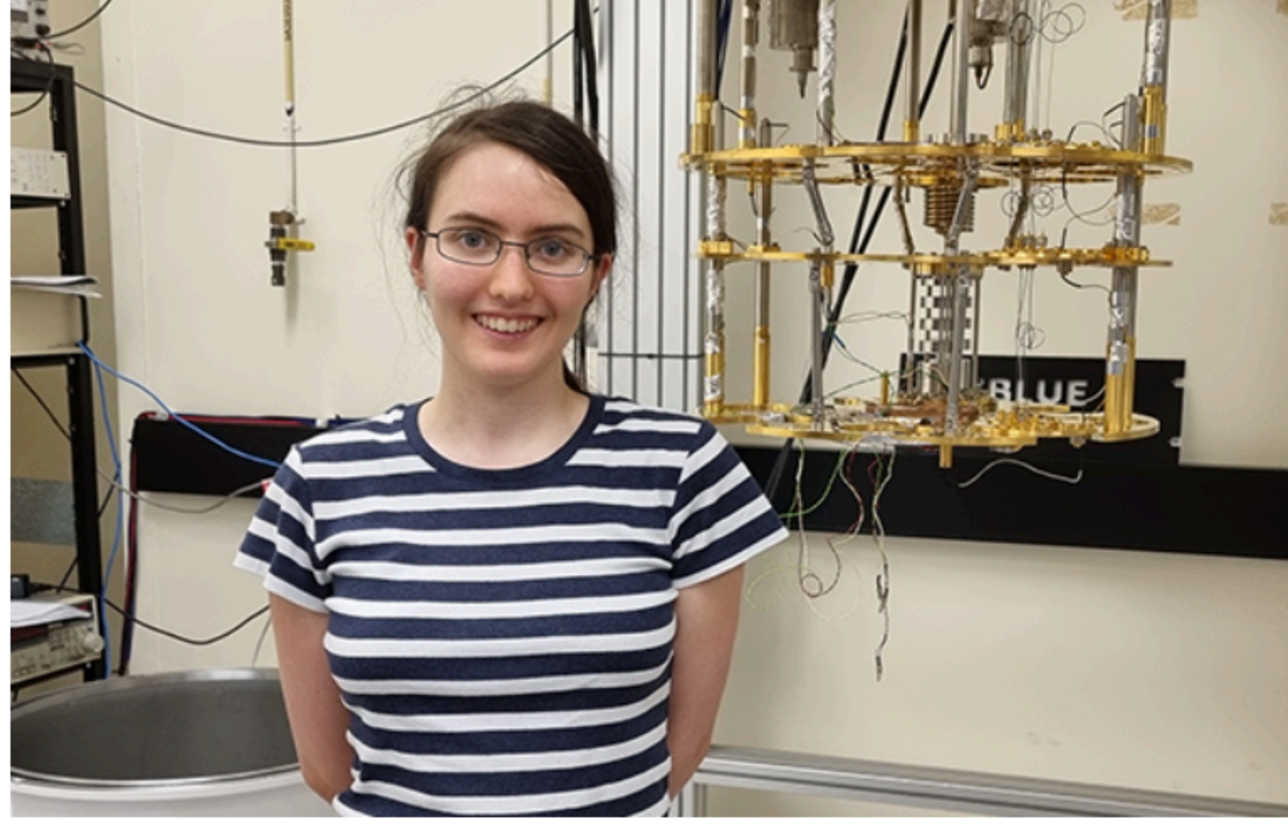
Emily Waterman

BPhil (Hons) Honours Dissertation

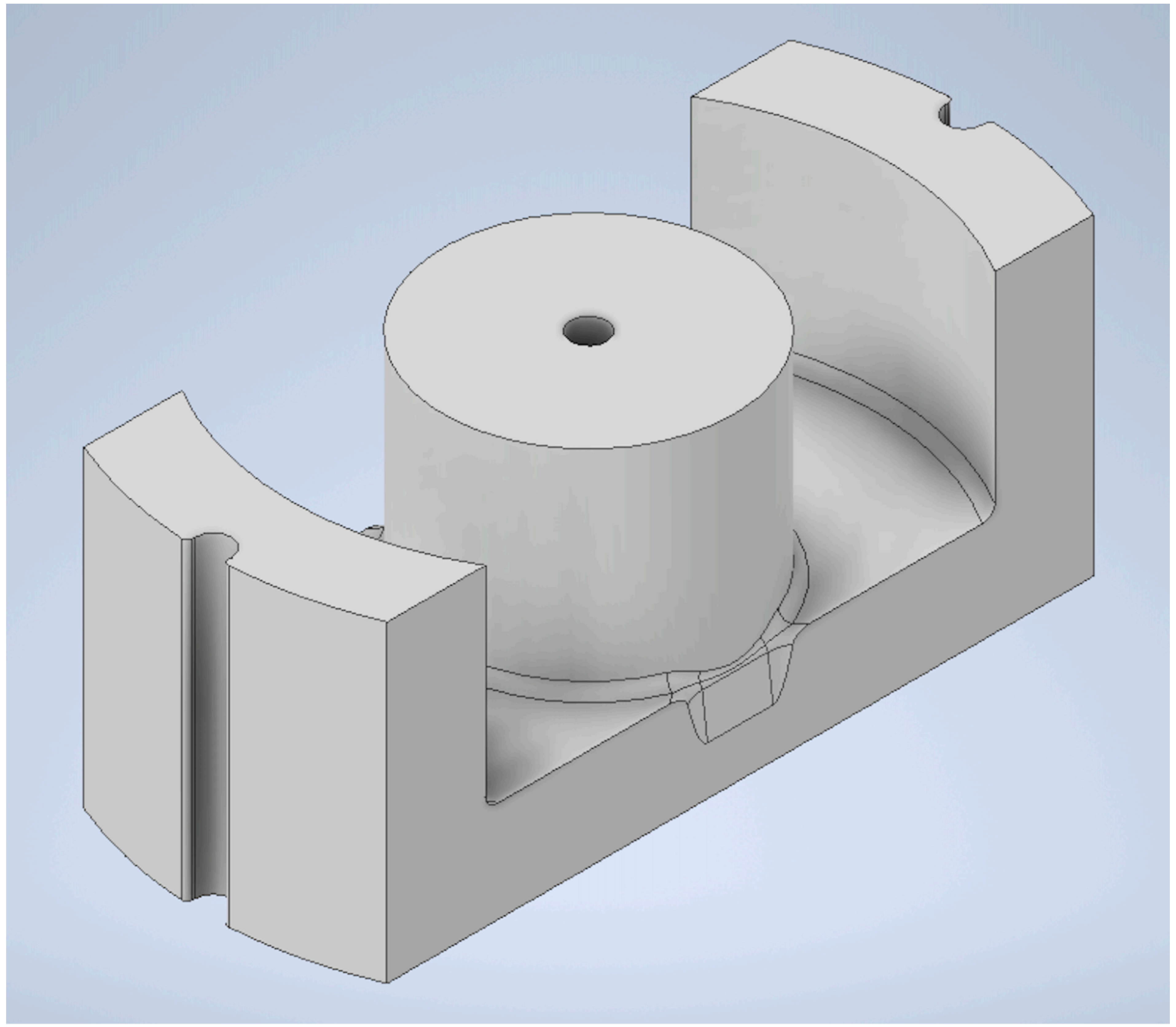


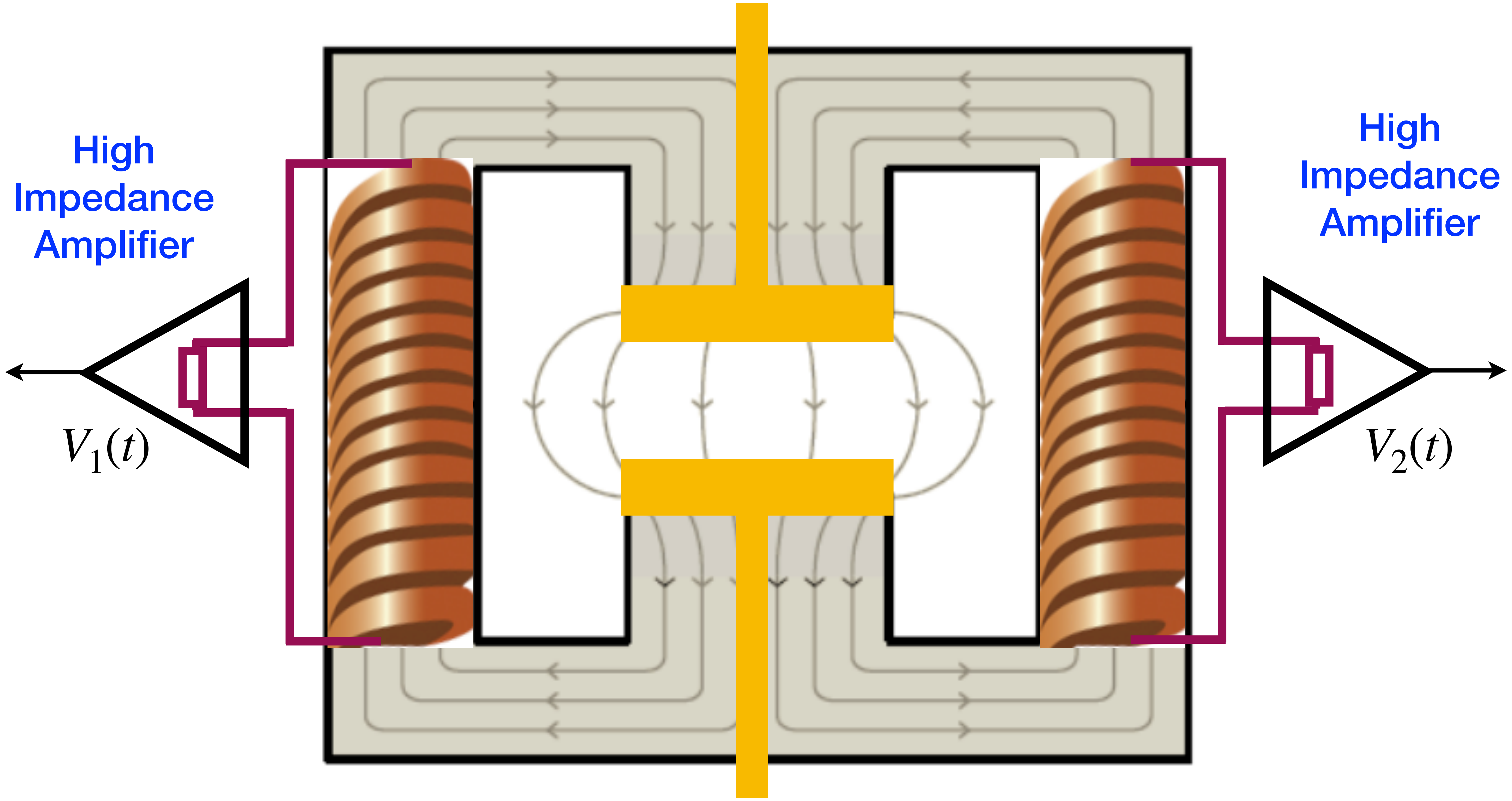
The Axion-MonoPole-Detection (AMPD) Experiment
Initial Prototype ~ 4cm
Purchased Standard Ferrite Core

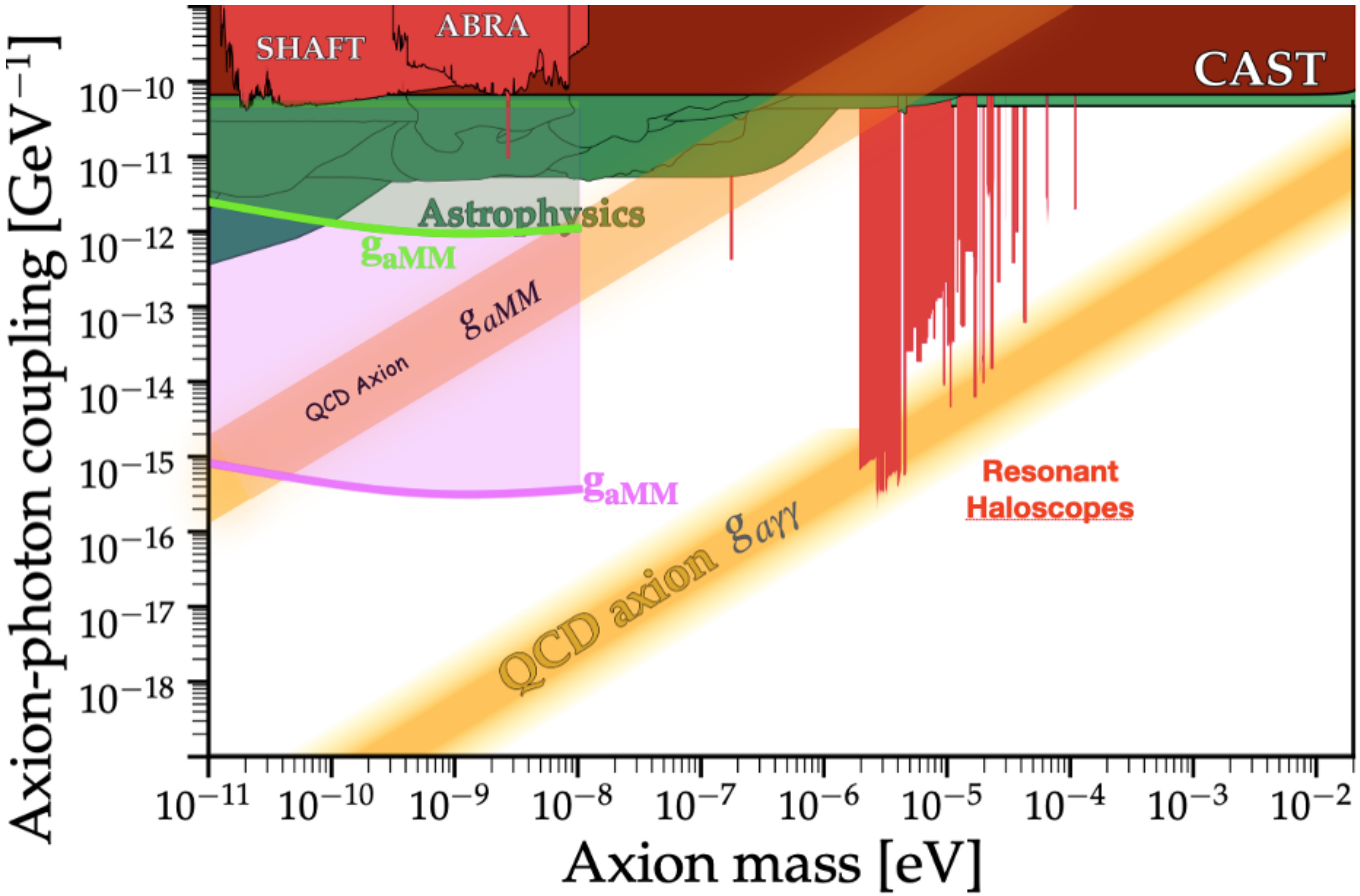




Emily Waterman
BPhil (Hons) Honours Dissertation







SHAFT
ABRA
CAST
Astrophysics
g_{aMM}
g_{aMM}
QCD Axion
g_{aMM}
Resonant
Haloscopes
QCD axion $g_{a\gamma\gamma}$
Axion-photon coupling [GeV^{-1}]
Axion mass [eV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}

Twisted “anyon” microwave cavities

Why is it called an “anyon” cavity?

Twisted "anyon" microwave cavities

Why is it called an "anyon" cavity?

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press

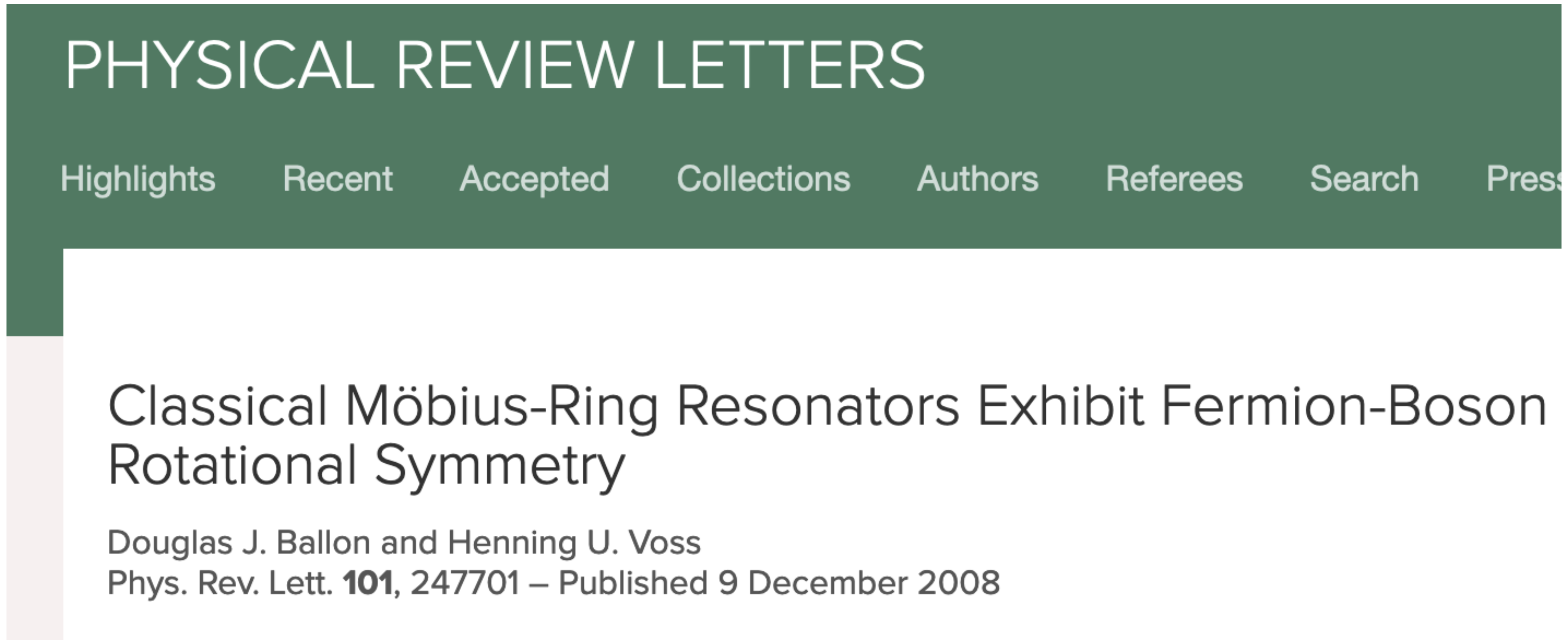
Classical Möbius-Ring Resonators Exhibit Fermion-Boson Rotational Symmetry

Douglas J. Ballon and Henning U. Voss

Phys. Rev. Lett. **101**, 247701 – Published 9 December 2008

Twisted “anyon” microwave cavities

Why is it called an “anyon” cavity?



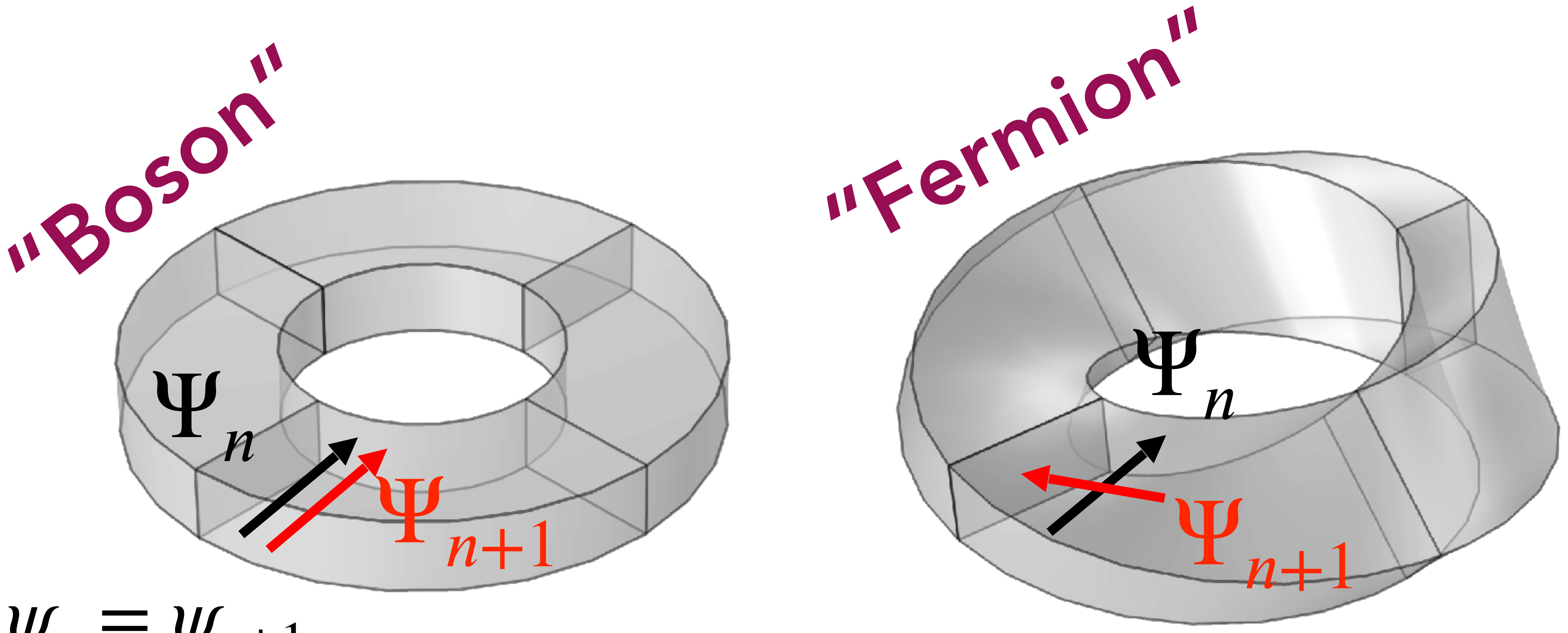
PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press

Classical Möbius-Ring Resonators Exhibit Fermion-Boson Rotational Symmetry

Douglas J. Ballon and Henning U. Voss

Phys. Rev. Lett. **101**, 247701 – Published 9 December 2008



$\psi_n = \psi_{n+1}$

$\psi_n = \psi_{n+N}$

$\theta = 0$

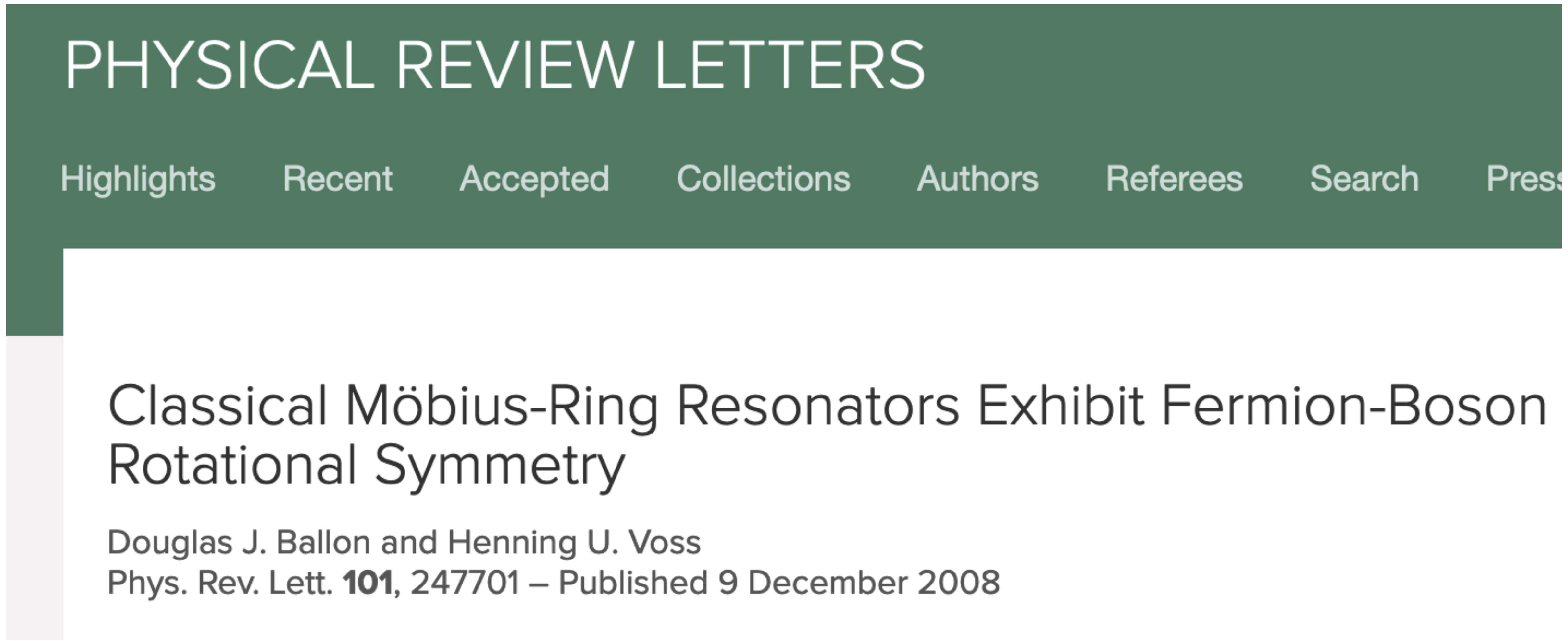
$\psi_n = -\psi_{n+1}$

$\psi_n = \psi_{n+2N}$

$\theta = \pm\pi$

Twisted "anyon" microwave cavities

Why is it called an "anyon" cavity?

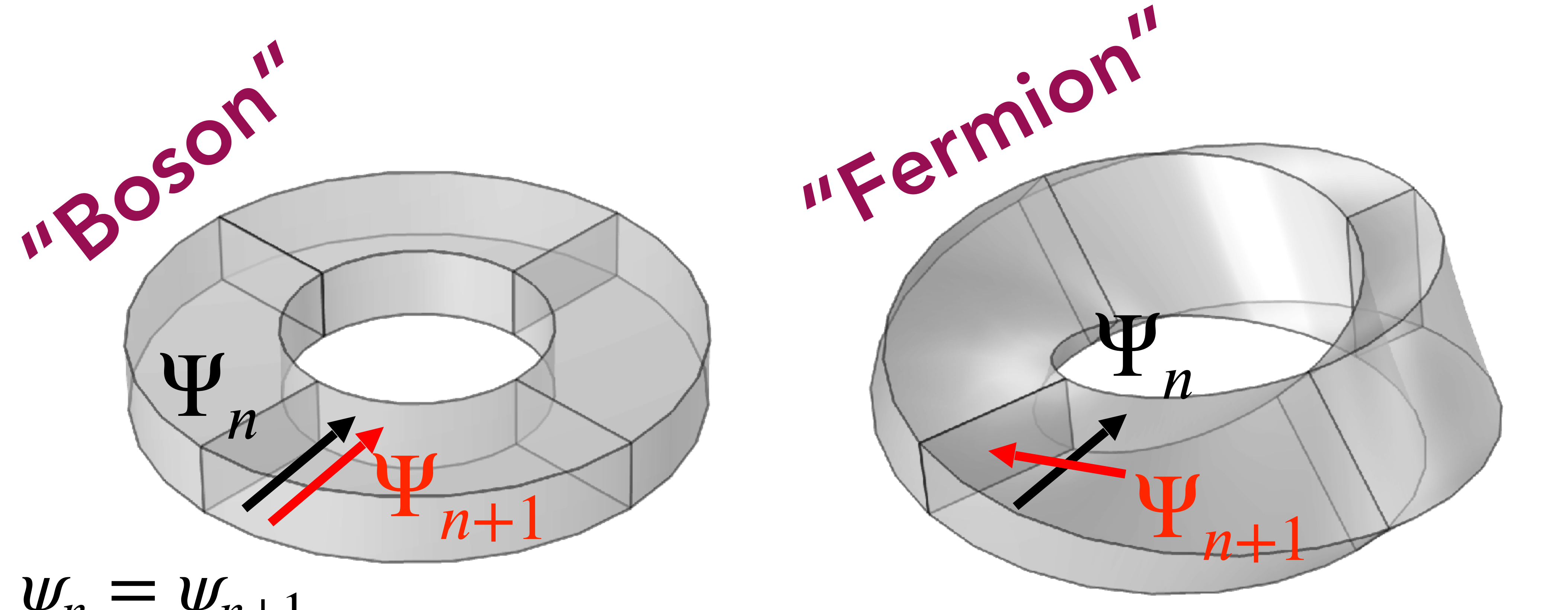

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press

Classical Möbius-Ring Resonators Exhibit Fermion-Boson Rotational Symmetry

Douglas J. Ballon and Henning U. Voss

Phys. Rev. Lett. **101**, 247701 – Published 9 December 2008



$\psi_n = \psi_{n+1}$

$\psi_n = \psi_{n+N}$

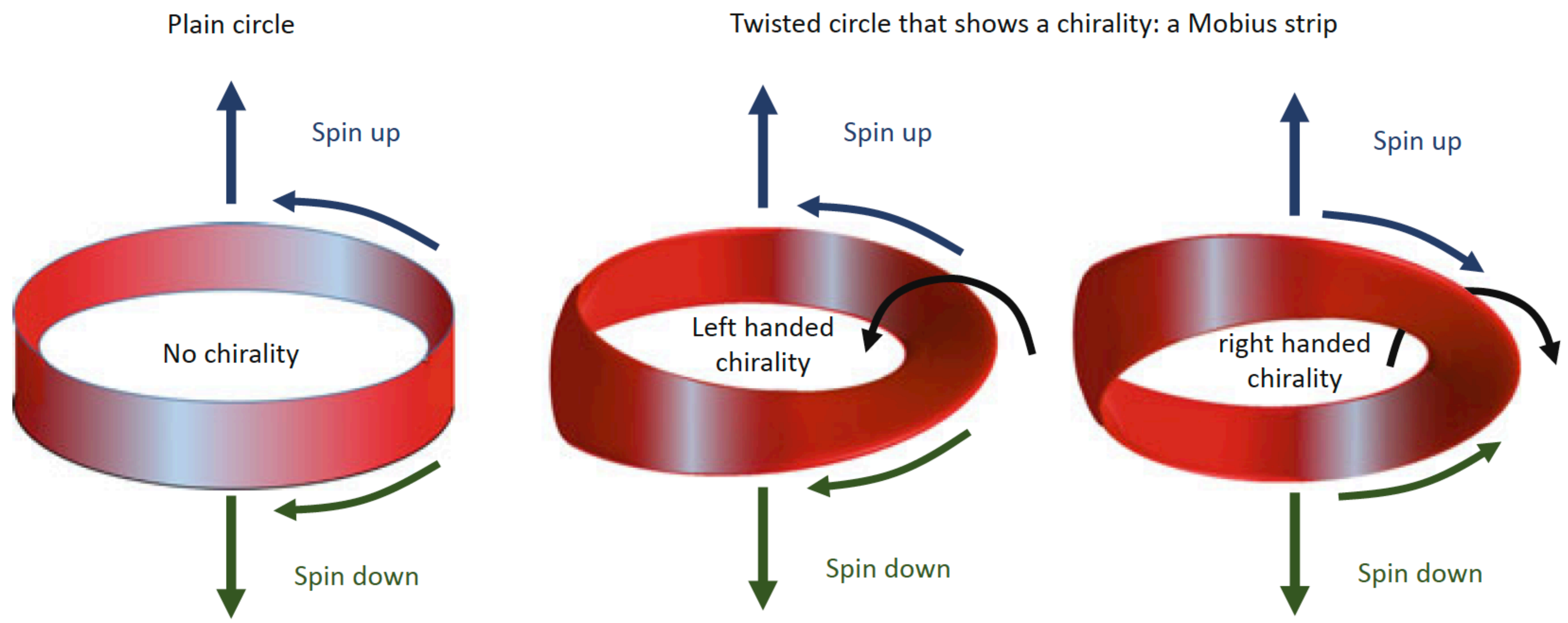
$\theta = 0$

$\psi_n = -\psi_{n+1}$

$\psi_n = \psi_{n+2N}$

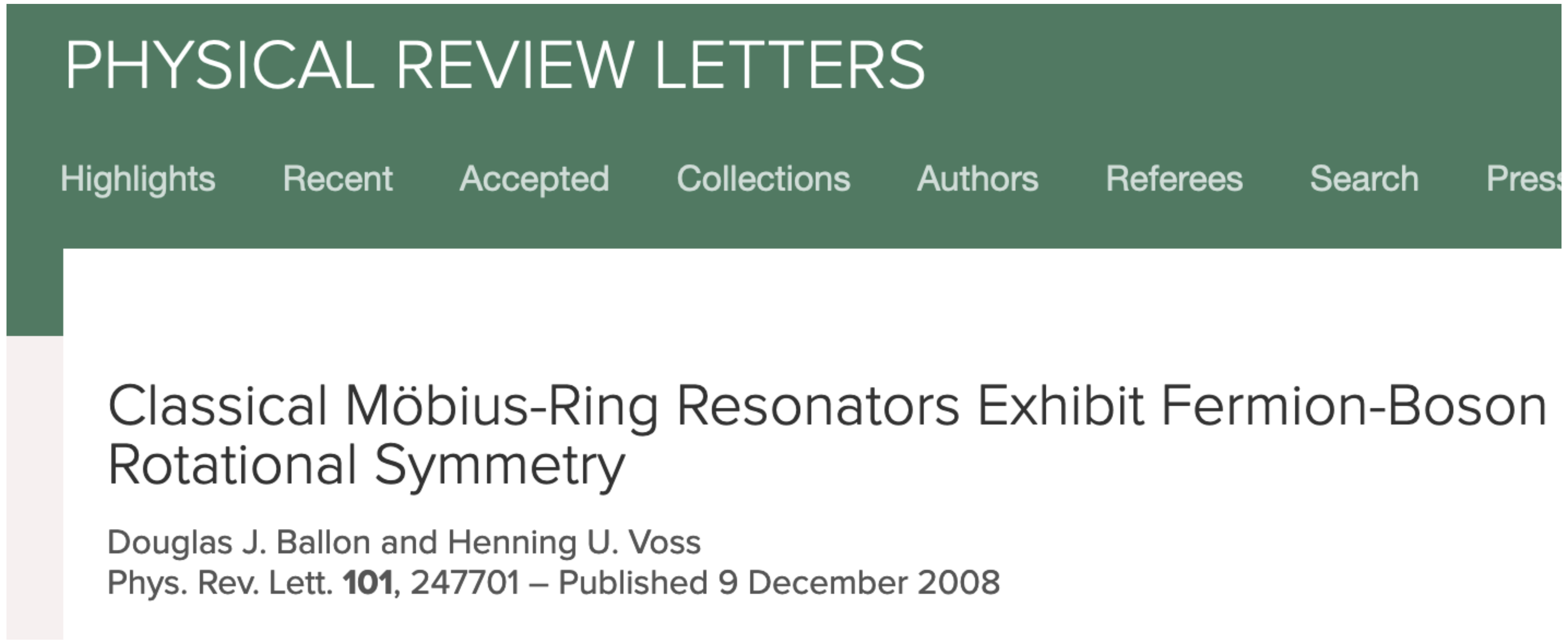
$\theta = \pm\pi$

Fermions Come in Two Chiralities, Called Left and Right. Bosons Do Not



Twisted "anyon" microwave cavities

Why is it called an "anyon" cavity?

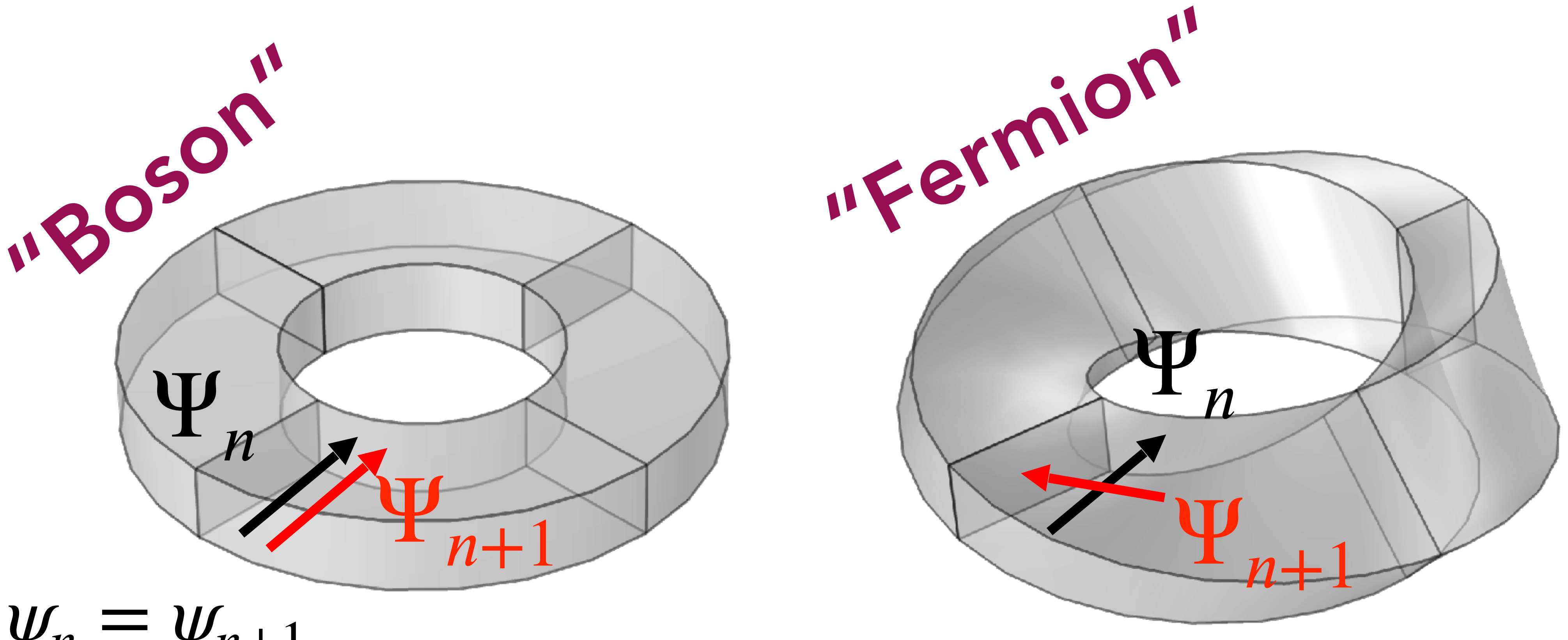

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press

Classical Möbius-Ring Resonators Exhibit Fermion-Boson Rotational Symmetry

Douglas J. Ballon and Henning U. Voss

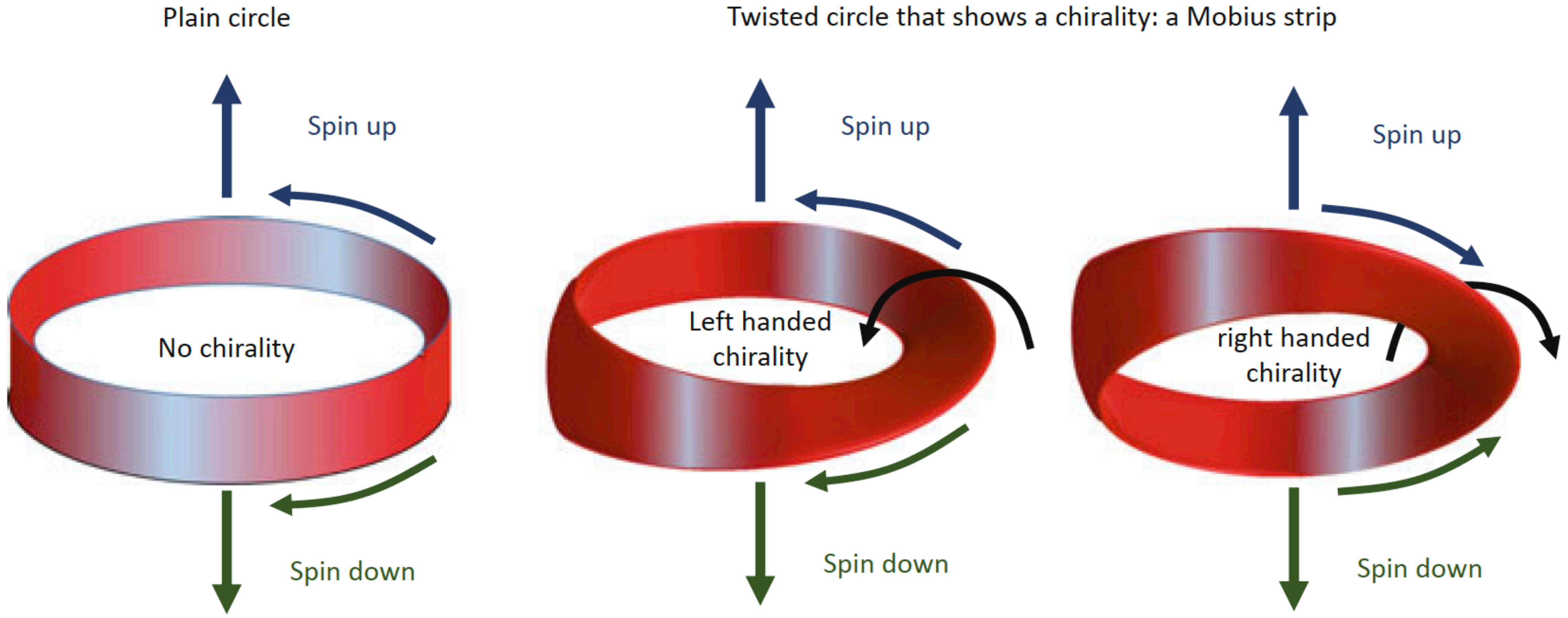
Phys. Rev. Lett. **101**, 247701 – Published 9 December 2008



$\psi_n = \psi_{n+1}$
$\psi_n = \psi_{n+N}$
$\theta = 0$

$\psi_n = -\psi_{n+1}$
$\psi_n = \psi_{n+2N}$
$\theta = \pm\pi$

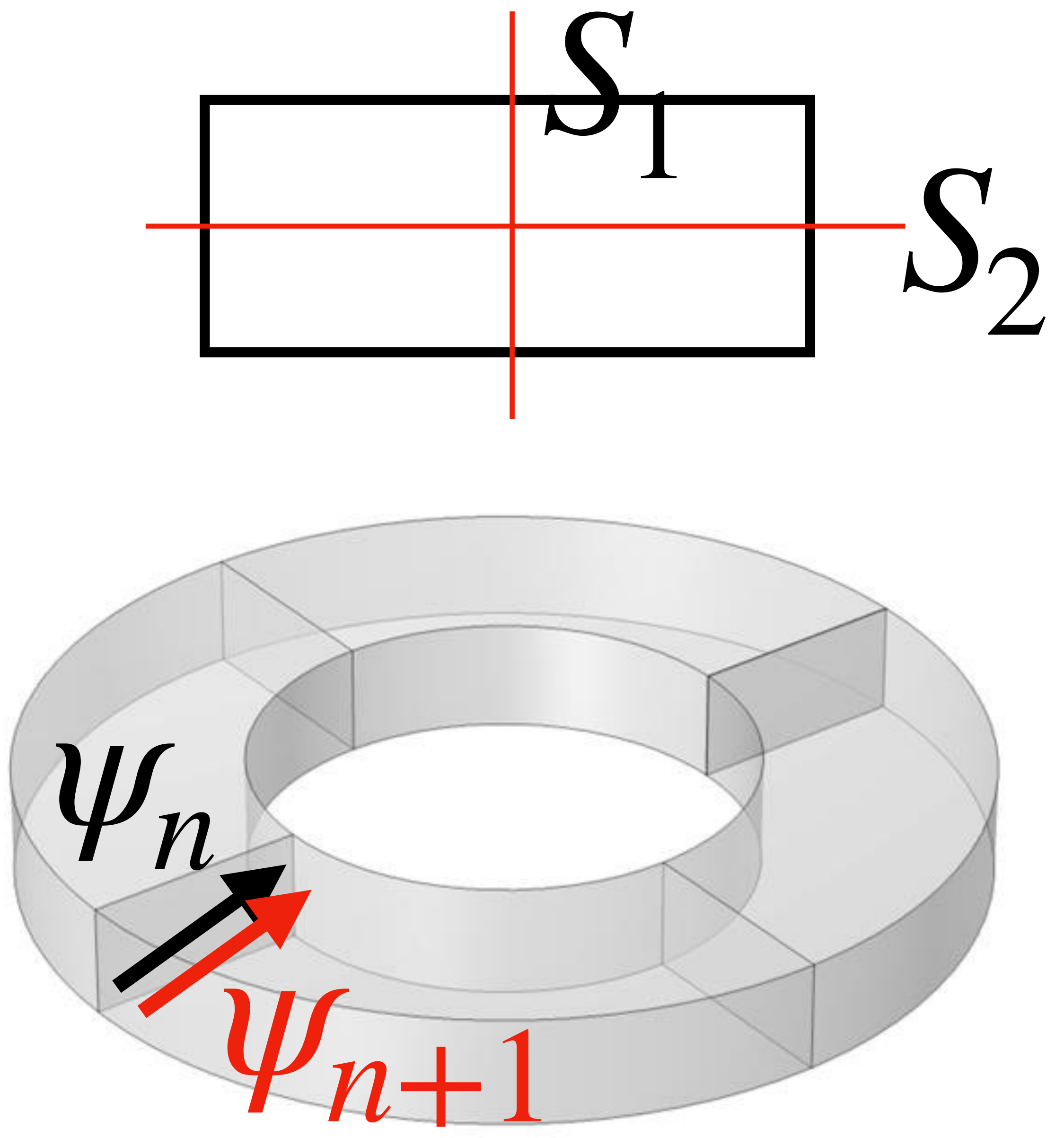
Fermions Come in Two Chiralities, Called Left and Right.
Bosons Do Not



HOWEVER: For Both Cavities

$$\mathscr{H}_p = \frac{2\,\mathrm{Im}[\int \mathbf{B}_p(\vec{r}) \cdot \mathbf{E}_p^*(\vec{r})\, d\tau]}{\sqrt{\int \mathbf{E}_p(\vec{r}) \cdot \mathbf{E}_p^*(\vec{r})\, d\tau \int \mathbf{B}_p(\vec{r}) \cdot \mathbf{B}_p^*(\vec{r})\, d\tau}} \sim 0$$

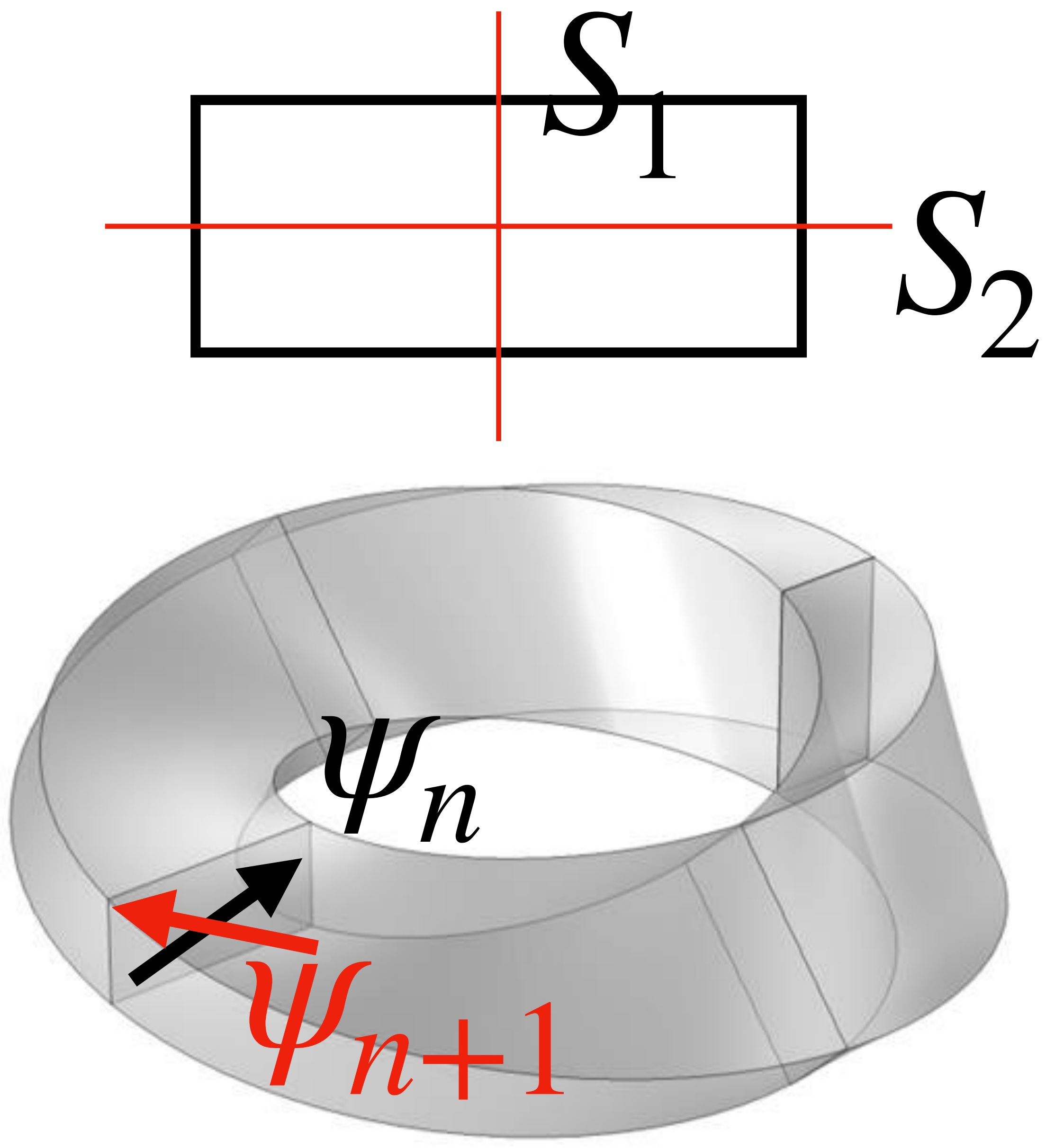
Torus



$$\psi_n = \psi_{n+1}$$
$$\psi_n = \psi_{n+N}$$
$$\theta = 0$$

Boson

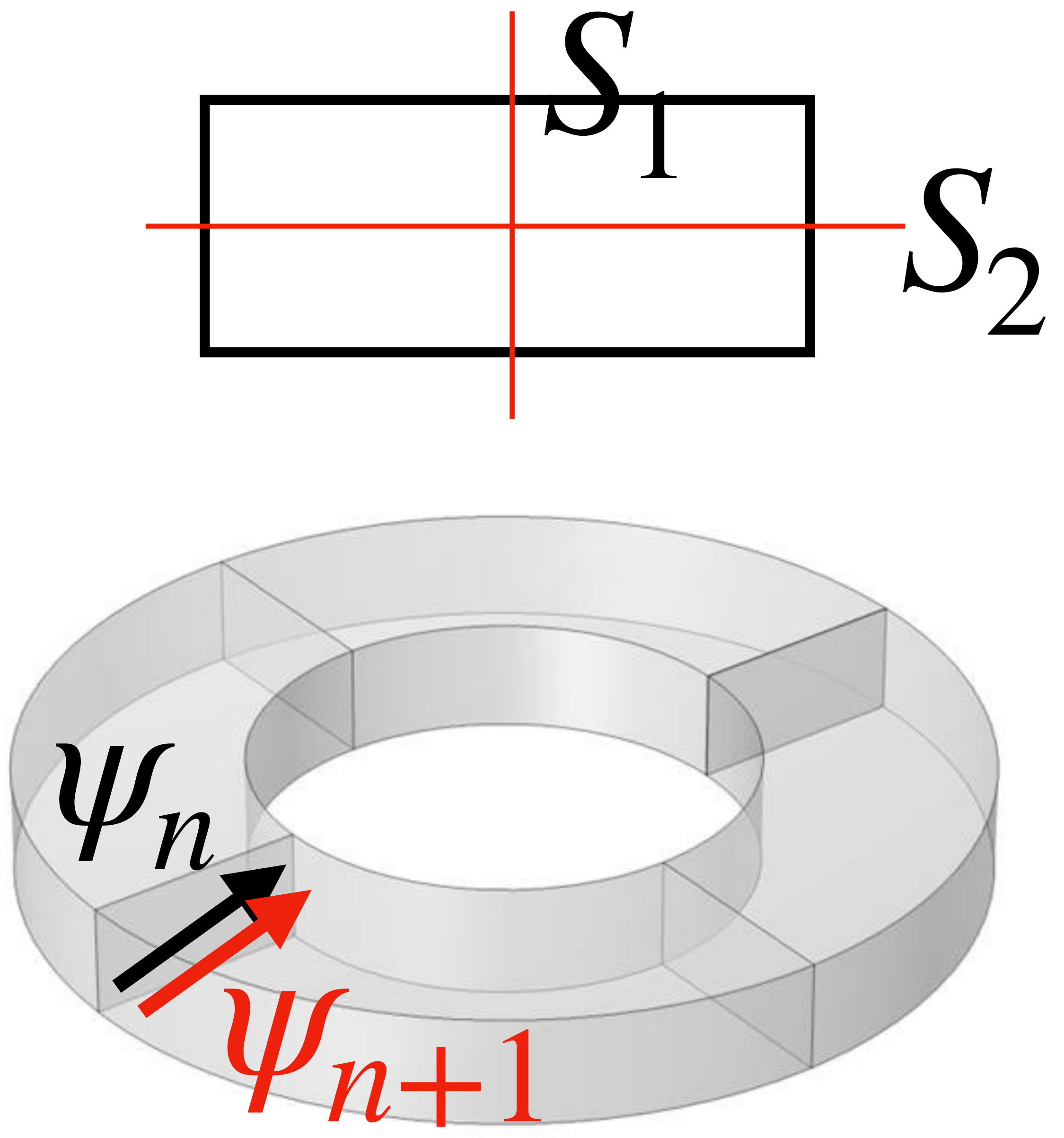
Möbius



$$\psi_n = -\psi_{n+1}$$
$$\psi_n = \psi_{n+2N}$$
$$\theta = \pm\pi$$

Fermion

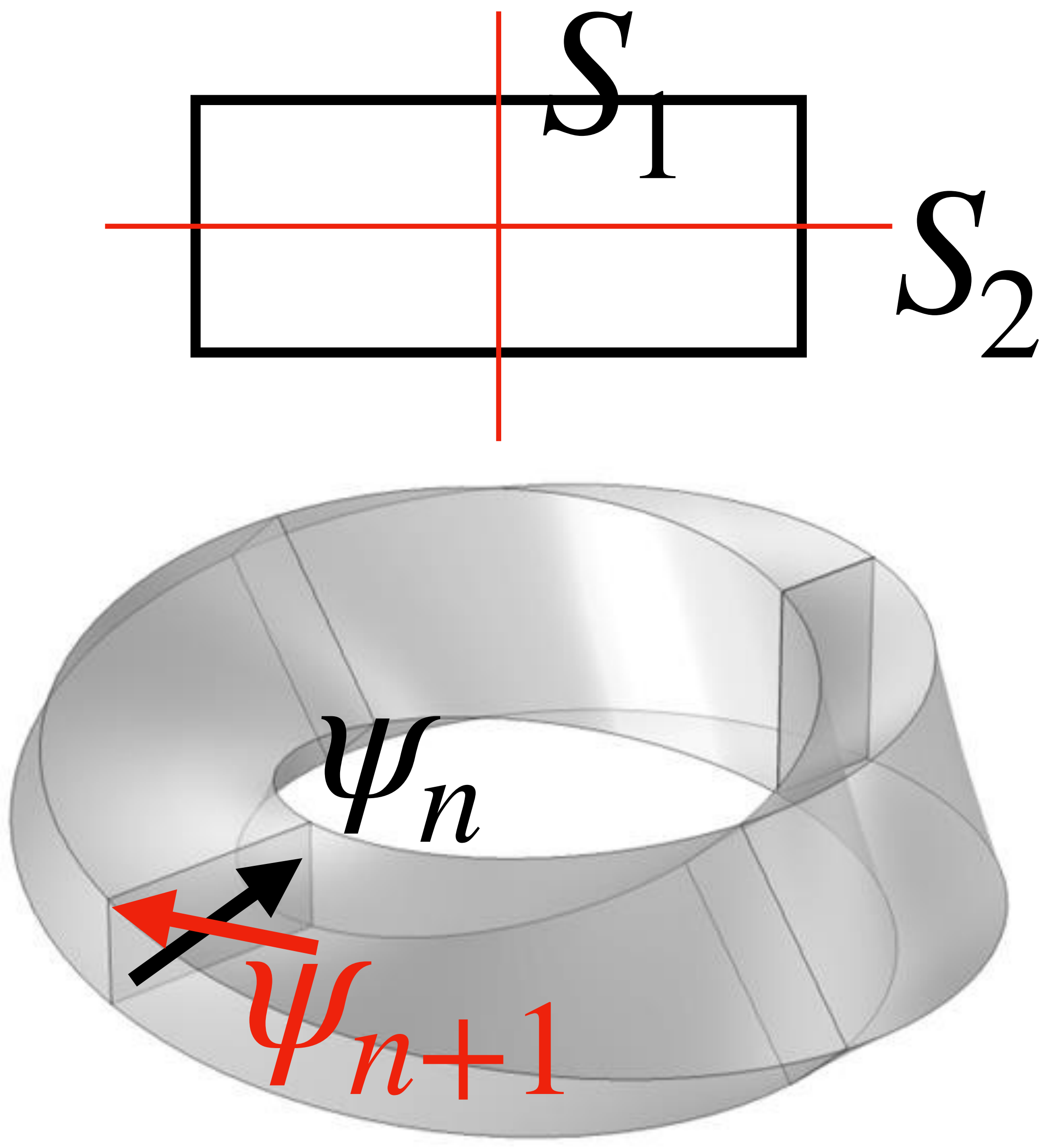
Torus



$$\psi_n = \psi_{n+1}$$
$$\psi_n = \psi_{n+N}$$
$$\theta = 0$$

Boson

Möbius

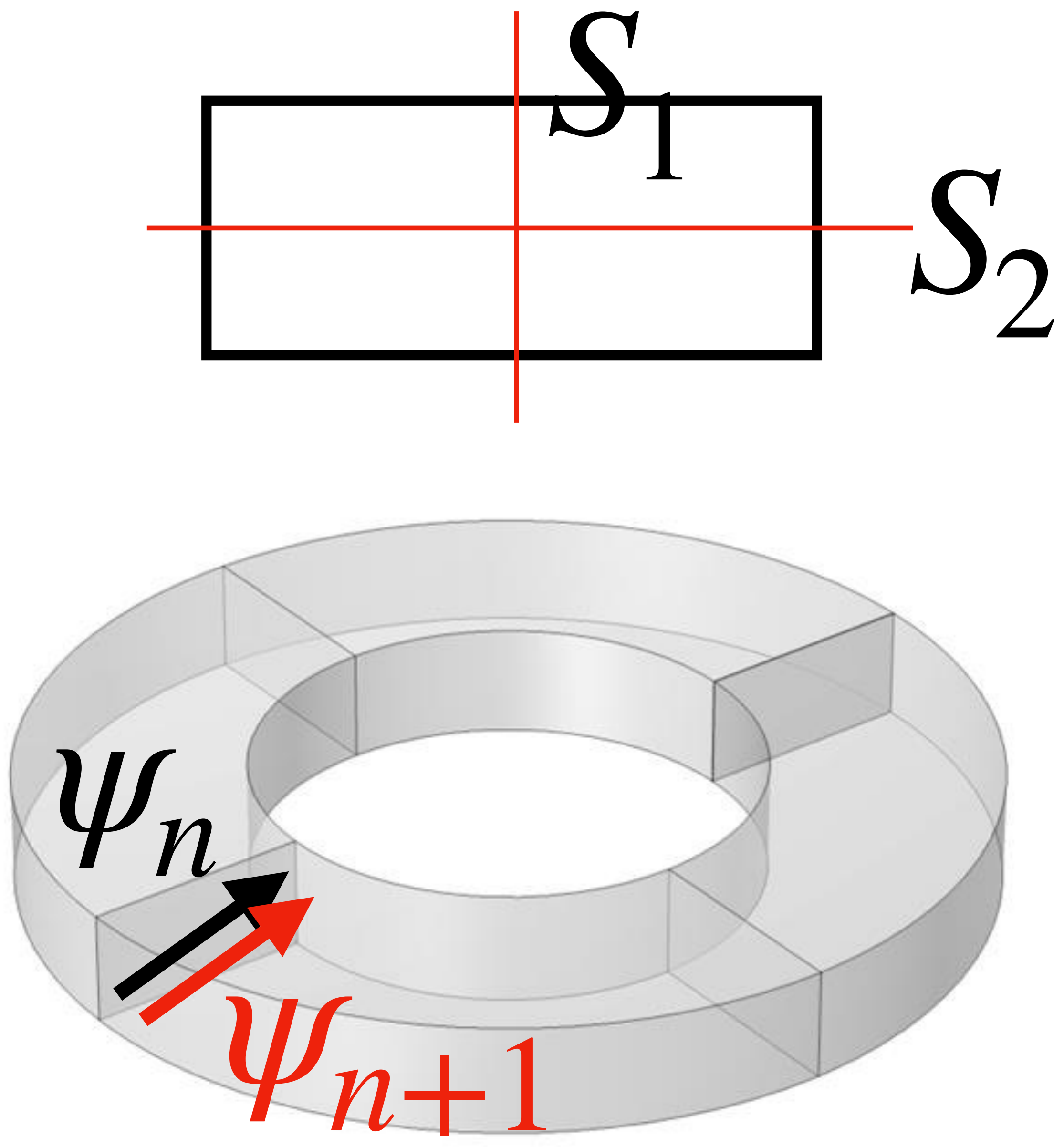


$$\psi_n = -\psi_{n+1}$$
$$\psi_n = \psi_{n+2N}$$
$$\theta = \pm\pi$$

Fermion

Anyon Cavity

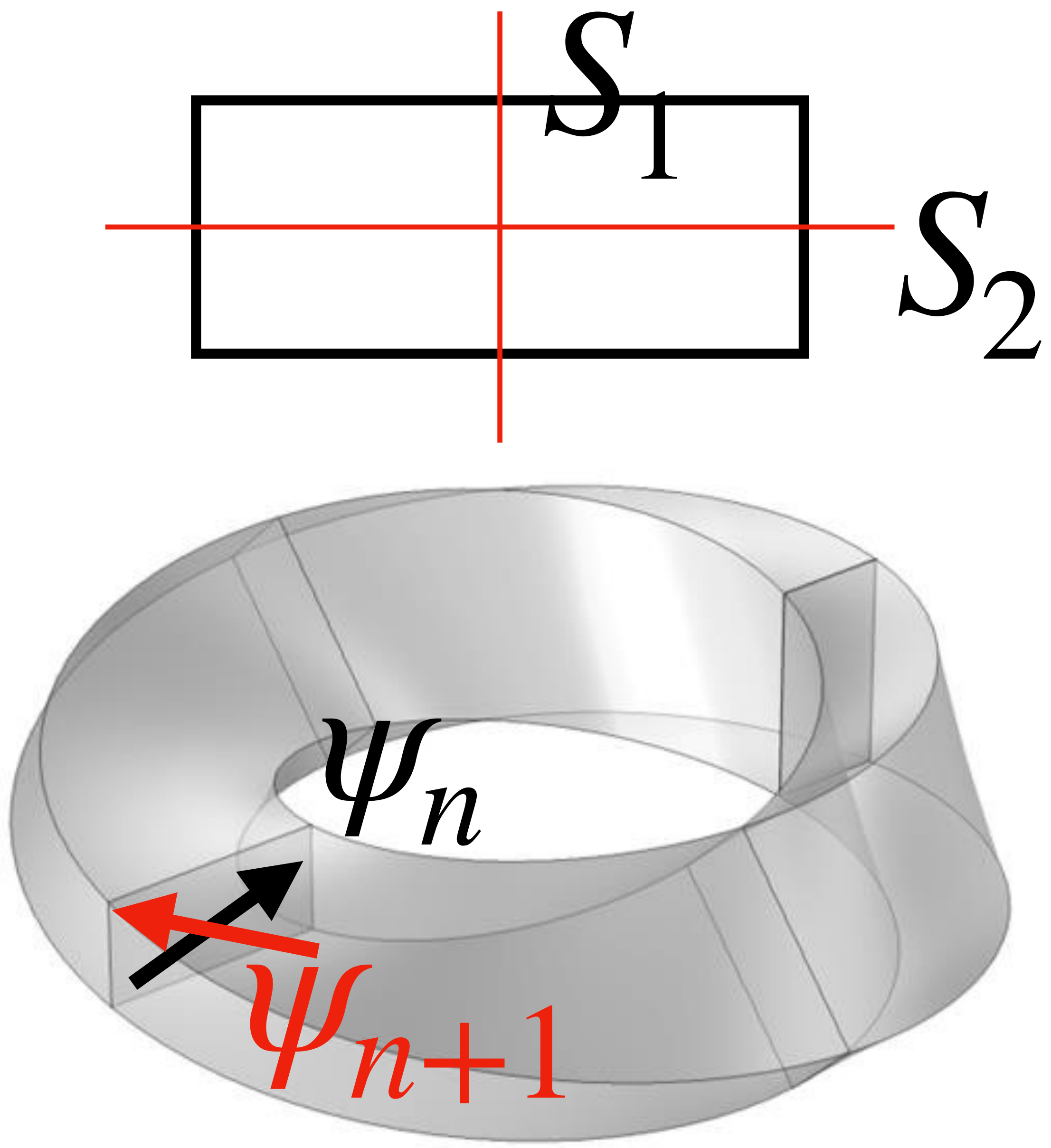
Torus



$$\psi_n = \psi_{n+1}$$
$$\psi_n = \psi_{n+N}$$
$$\theta = 0$$

Boson

Möbius

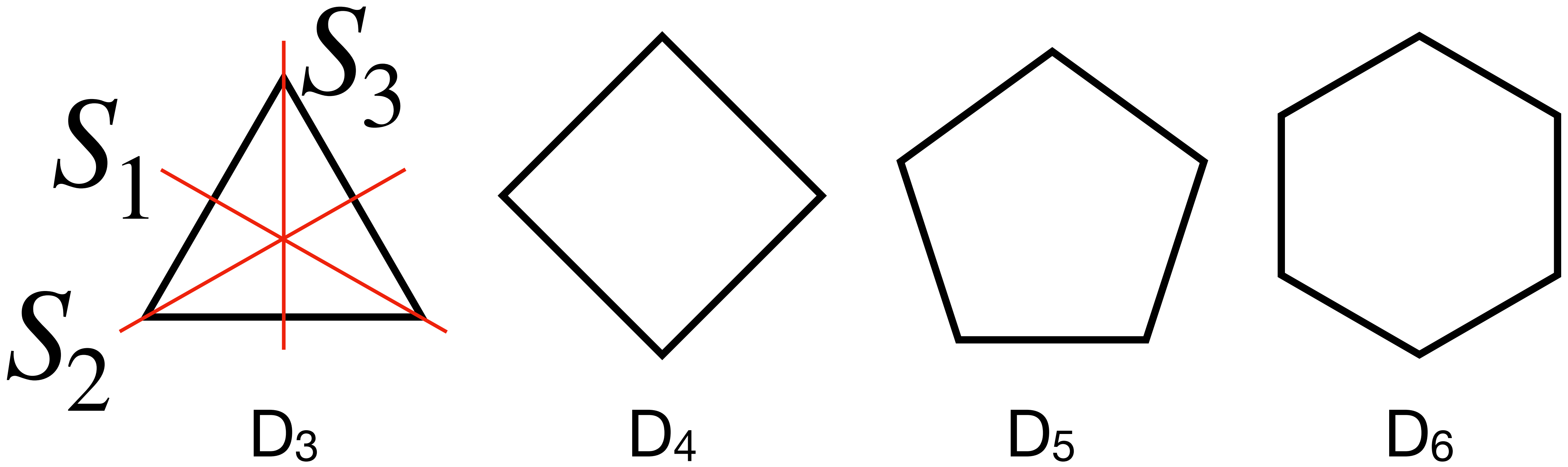


$$\psi_n = -\psi_{n+1}$$
$$\psi_n = \psi_{n+2N}$$
$$\theta = \pm\pi$$

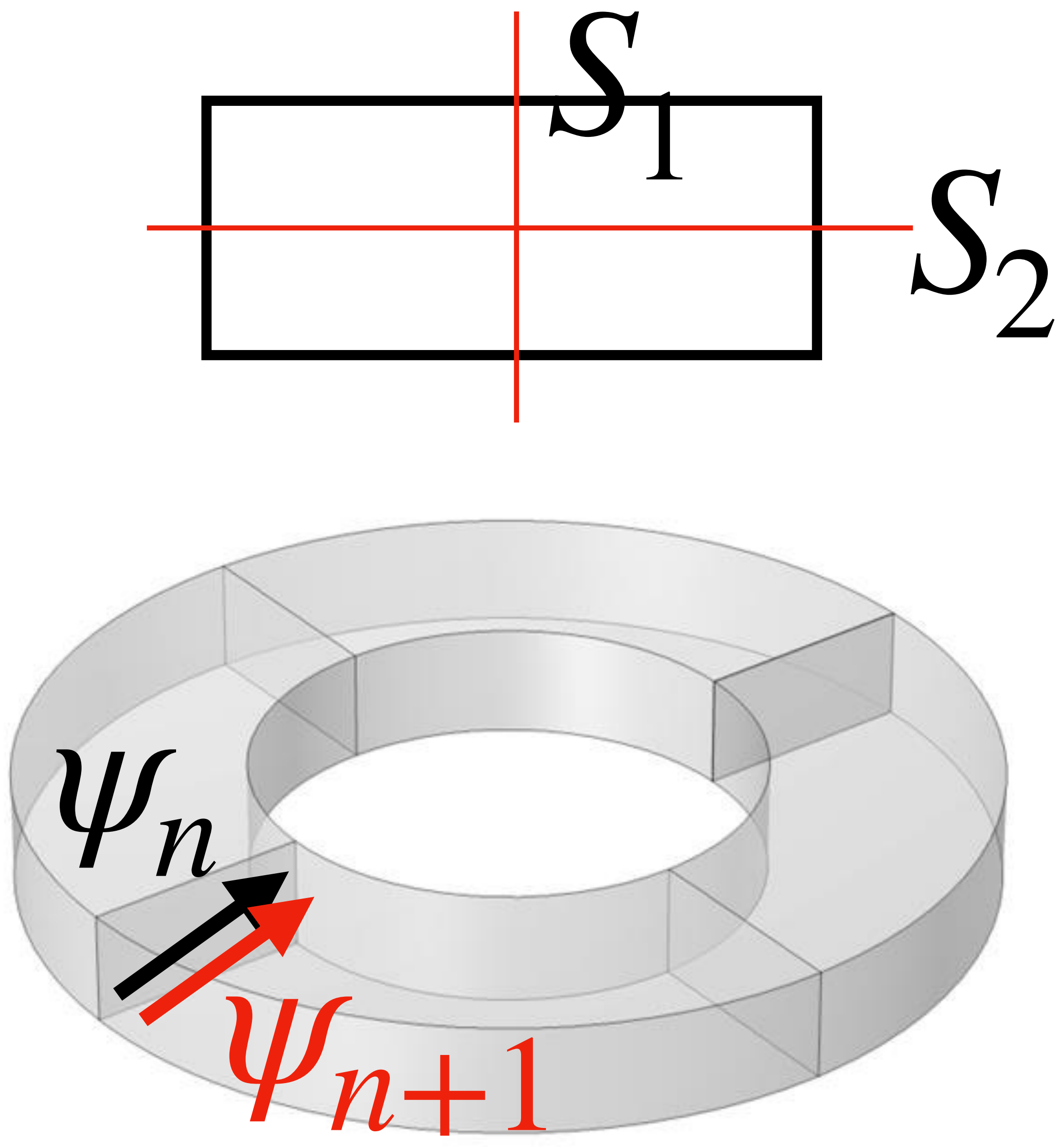
Fermion

Anyon Cavity

Dihedral group of regular convex polygons: D_p



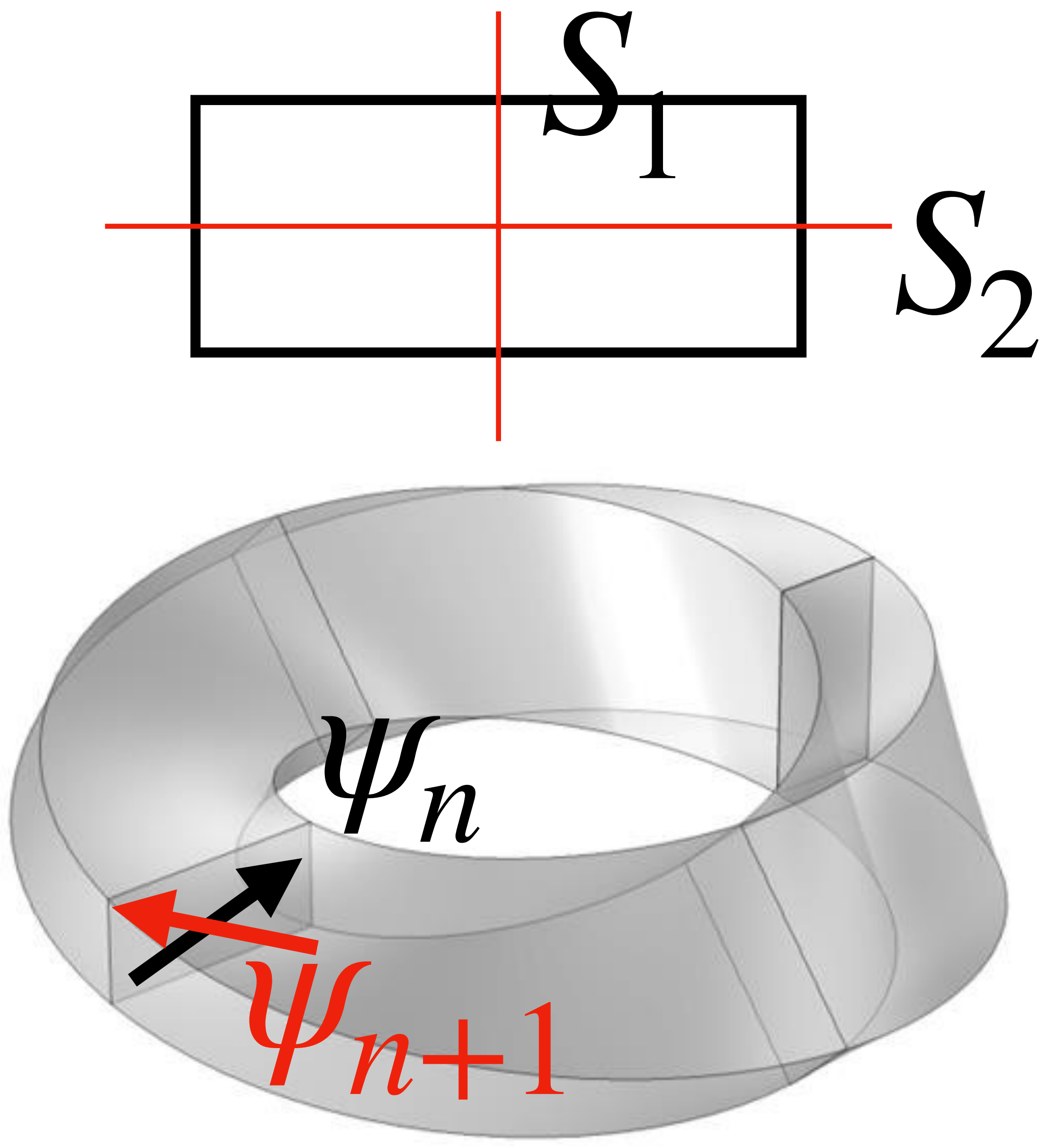
Torus



$$\psi_n = \psi_{n+1}$$
$$\psi_n = \psi_{n+N}$$
$$\theta = 0$$

Boson

Möbius

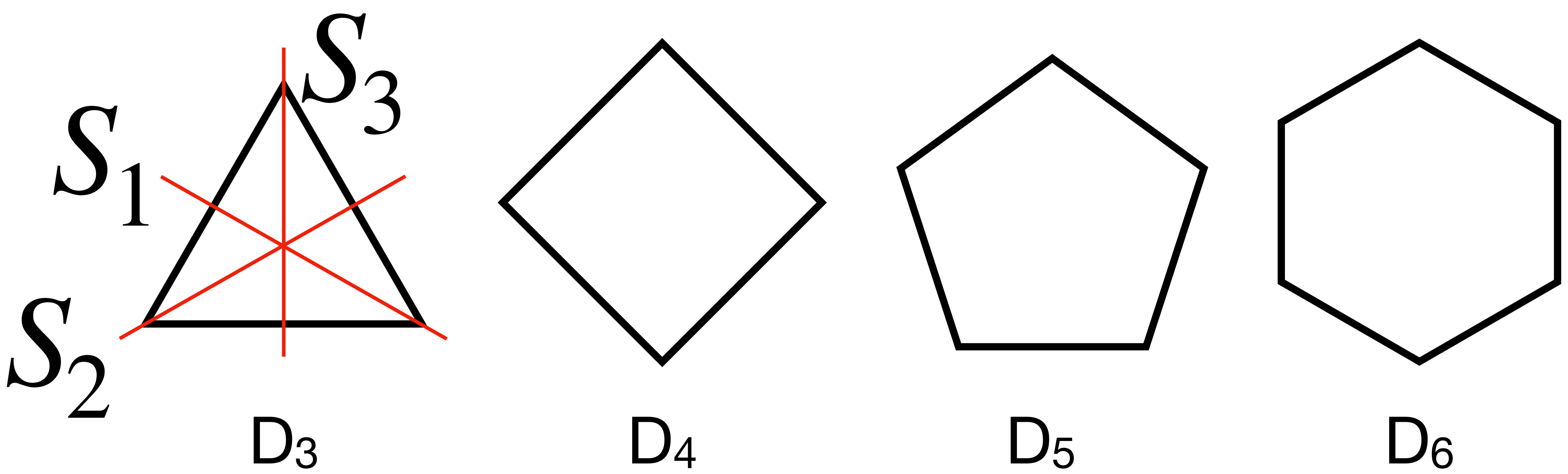


$$\psi_n = -\psi_{n+1}$$
$$\psi_n = \psi_{n+2N}$$
$$\theta = \pm\pi$$

Fermion

Anyon Cavity

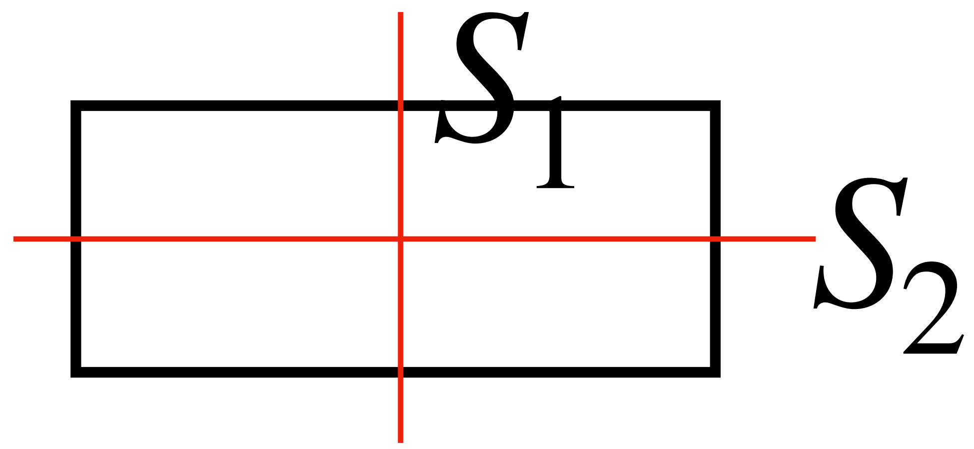
Dihedral group of regular convex polygons: D_p

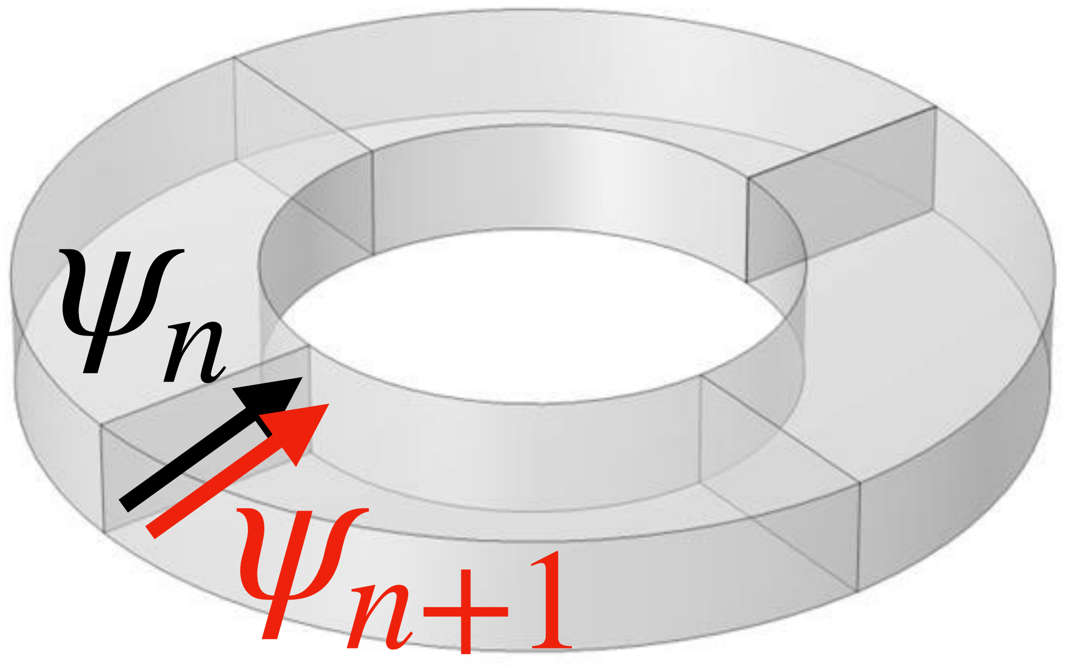


$2p$ symmetries: p rotational + p reflection

Rotation by $2\pi/p$ preserves the object

Torus

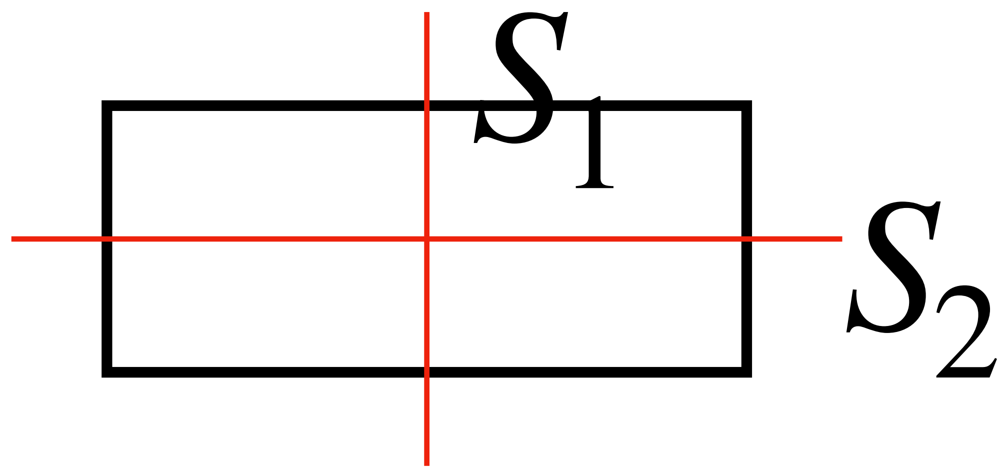


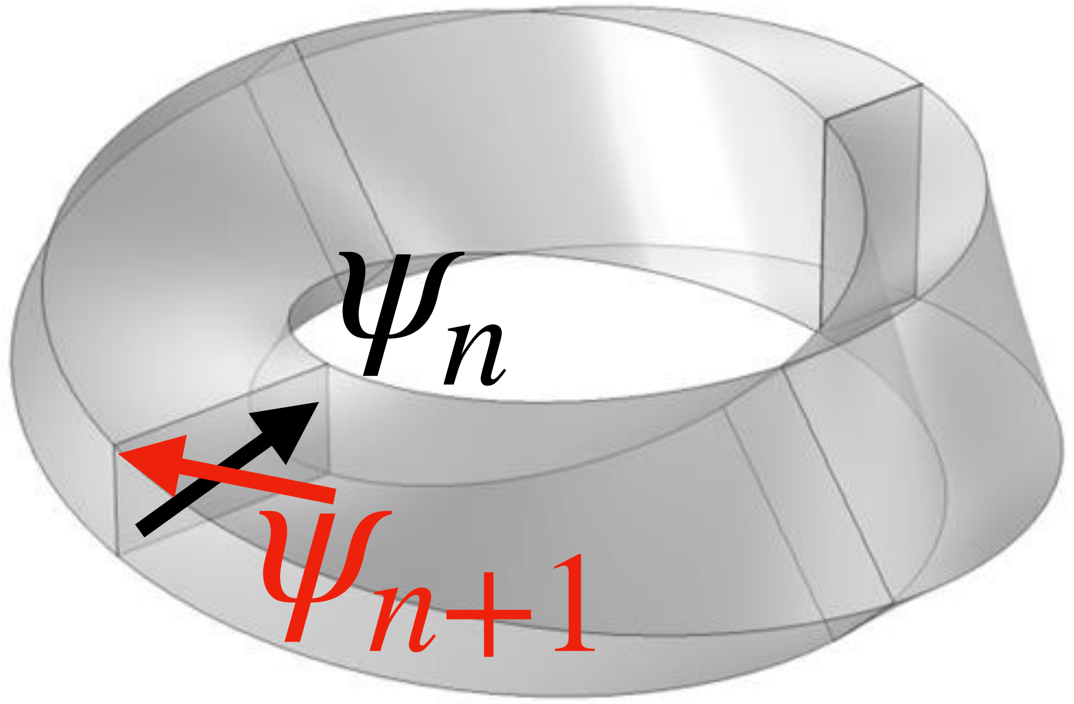


$$\psi_n = \psi_{n+1}$$
$$\psi_n = \psi_{n+N}$$
$$\theta = 0$$

Boson

Möbius



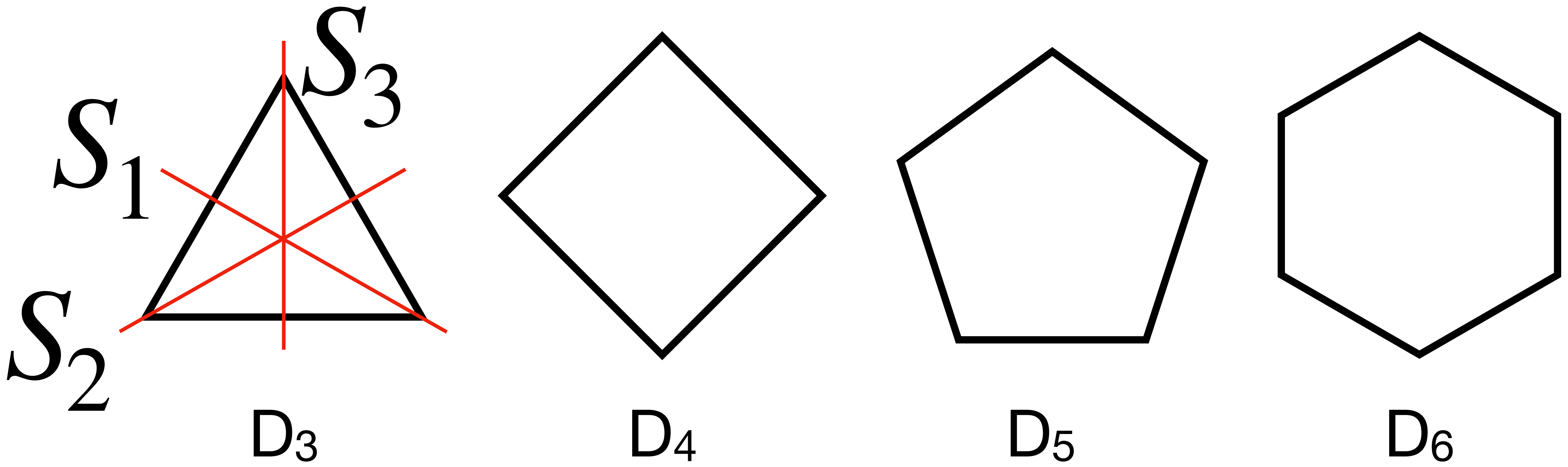


$$\psi_n = -\psi_{n+1}$$
$$\psi_n = \psi_{n+2N}$$
$$\theta = \pm\pi$$

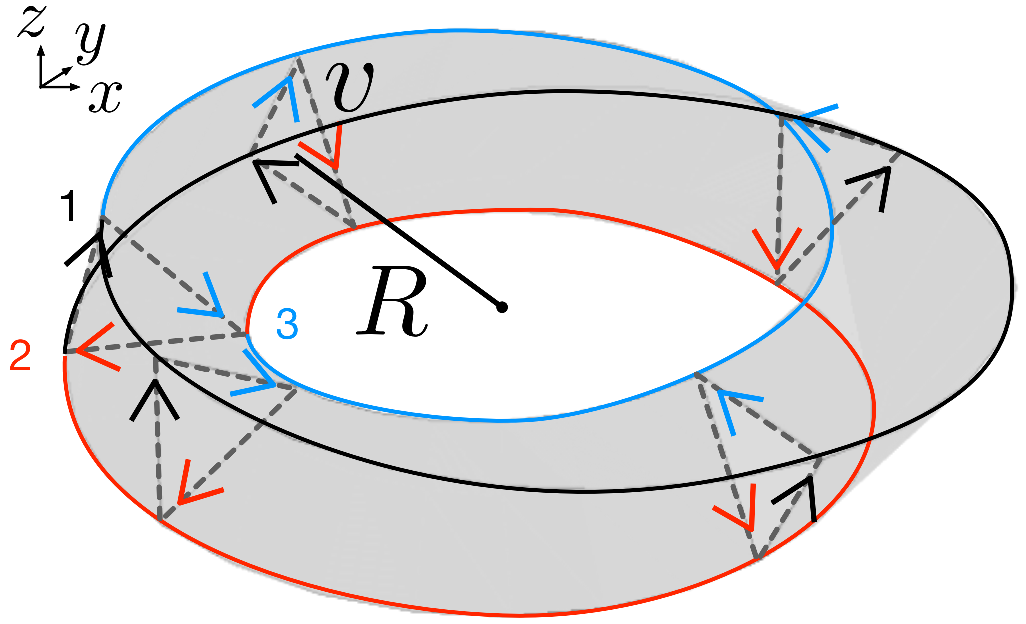
Fermion

Anyon Cavity

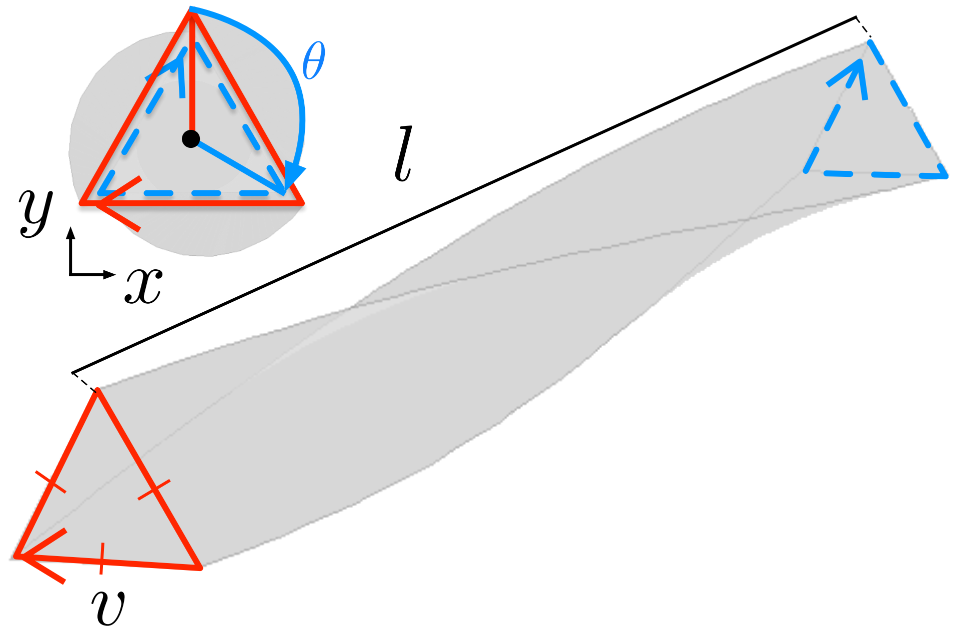
Dihedral group of regular convex polygons: D_p



2p symmetries: p rotational + p reflection
Rotation by $2\pi/p$ preserves the object



$$\psi_n = e^{i\theta}\psi_{n+1}$$
$$\theta = (2\pi/p)Z$$
$$Z \in \pm\mathbb{Z}$$



$$\psi_n = e^{i\theta}\psi_{n+1}$$
$$\theta \in \mathbb{R}$$

Anyon

Twisted "anyon" microwave cavities

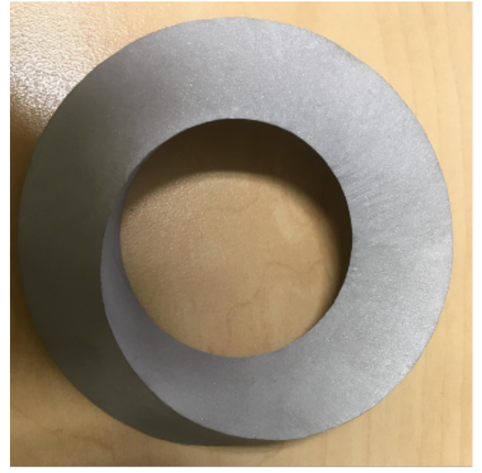

$$\mathscr{H}_p = \frac{2\,\mathrm{Im}\left[\int \mathbf{B}_p(\vec{r}) \cdot \mathbf{E}_p^*(\vec{r})d\tau\right]}{\sqrt{\int \mathbf{E}_p(\vec{r}) \cdot \mathbf{E}_p^*(\vec{r})d\tau \int \mathbf{B}_p(\vec{r}) \cdot \mathbf{B}_p^*(\vec{r})d\tau}}$$

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

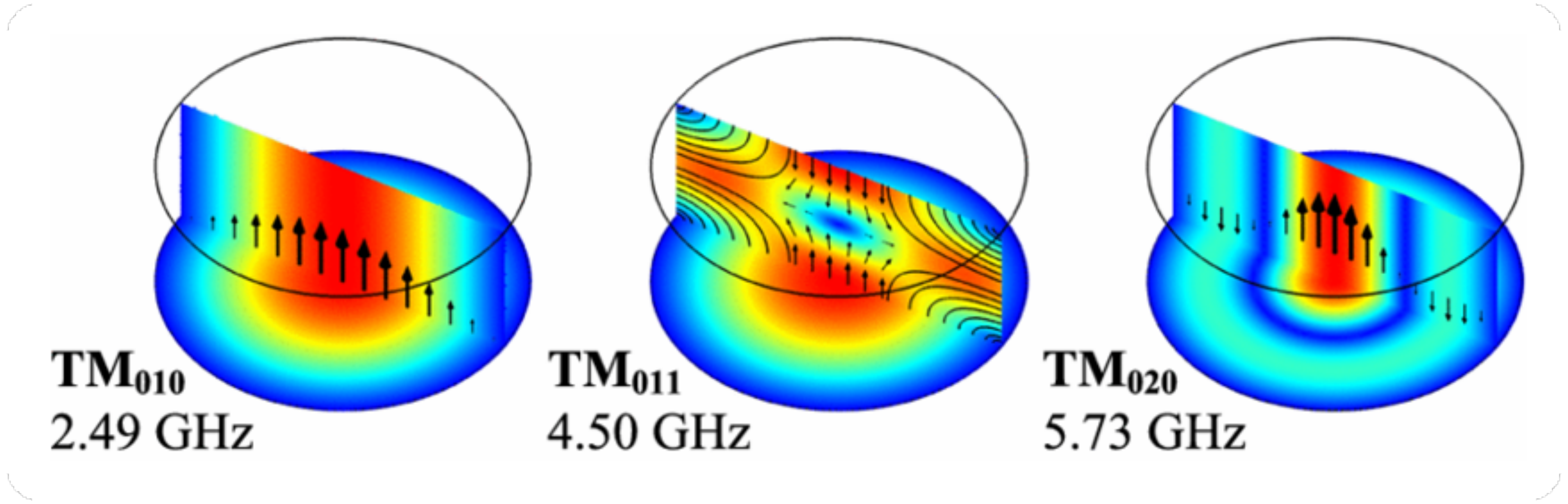


- 3D printed
- Measured mode frequencies to confirm simulation results


Cause of Helicity

Usual Haloscope Modes

$$\mathscr{H} = 0$$



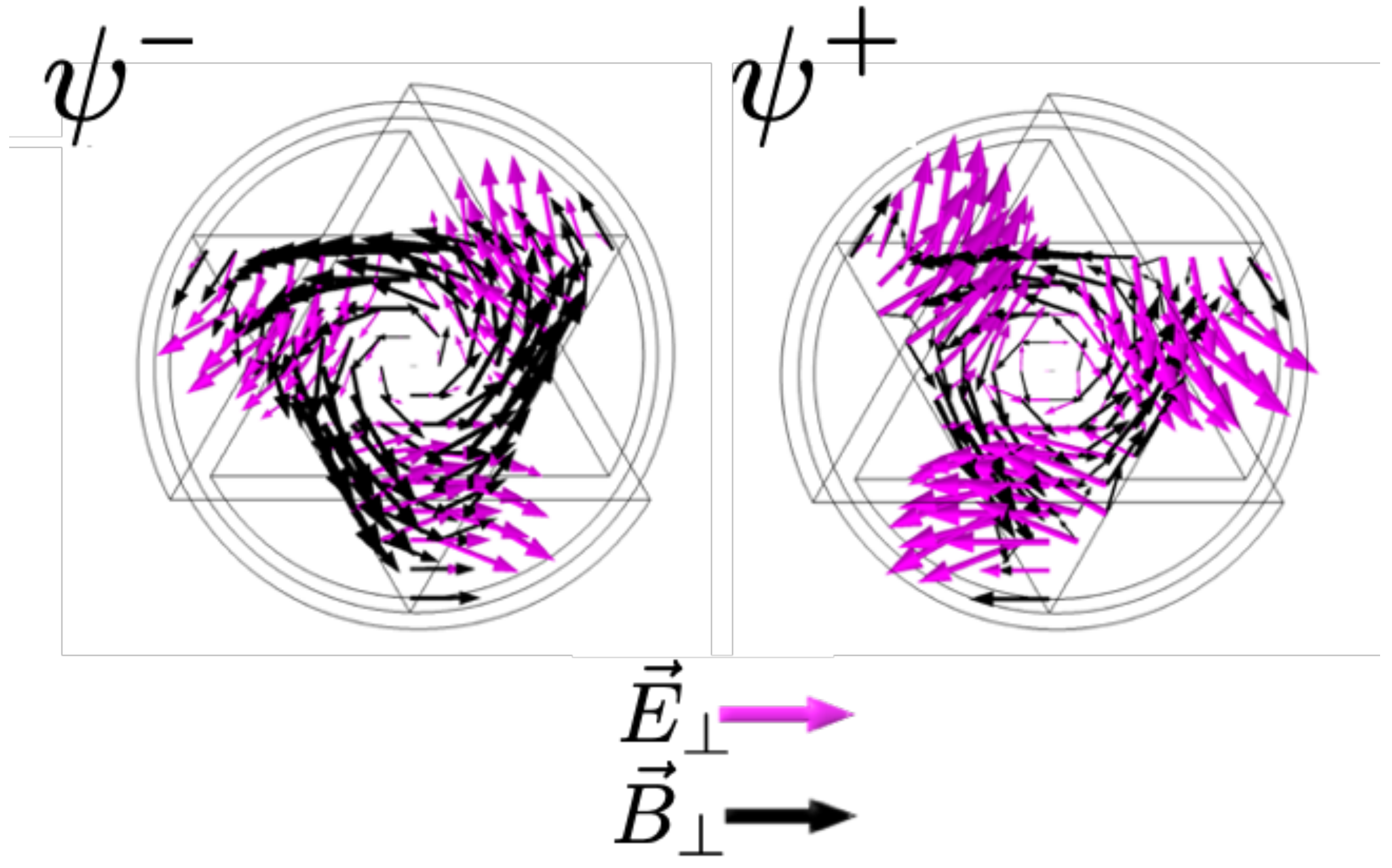
Twisted Anyon Cavity Modes

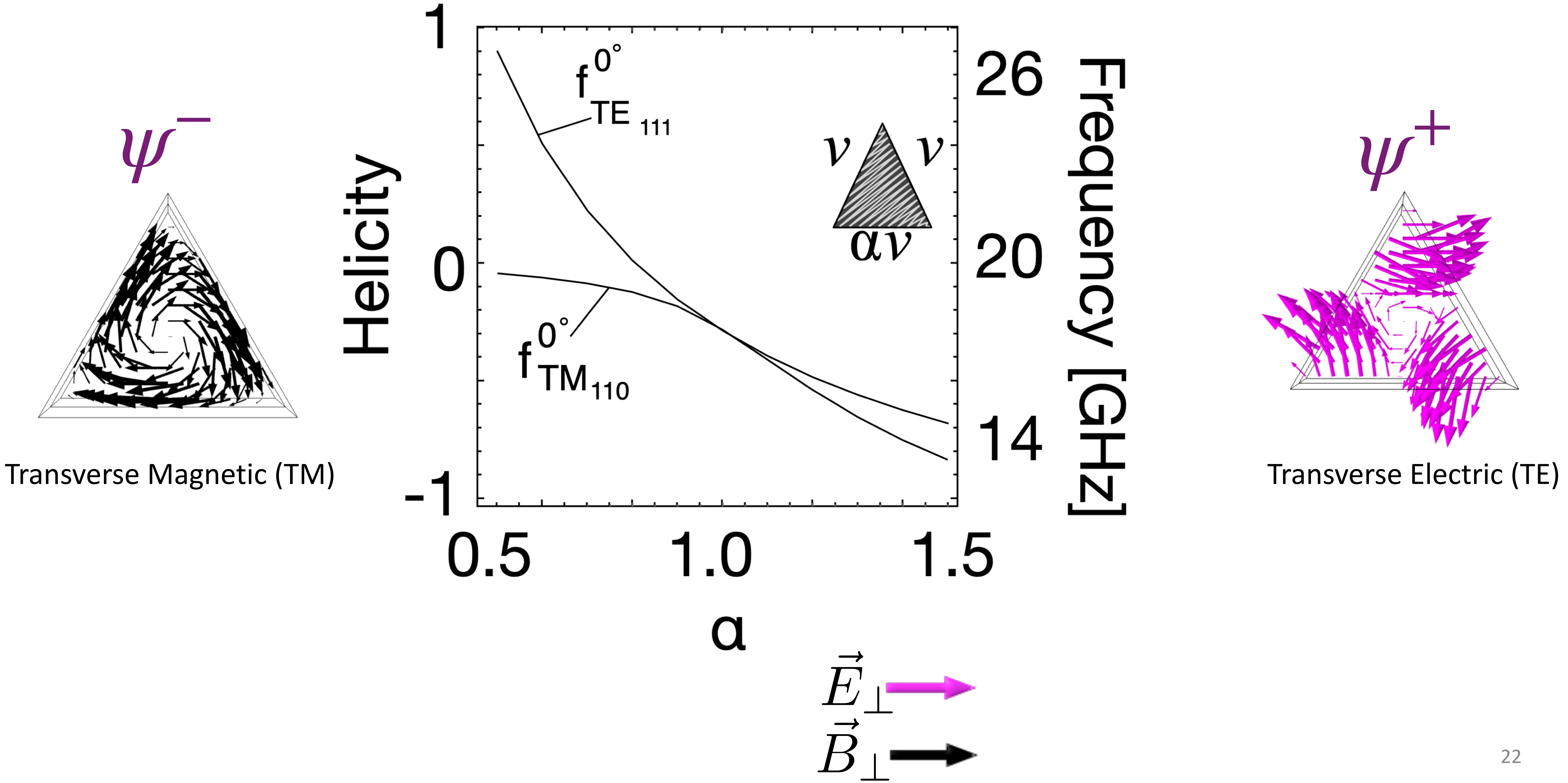
$$\mathscr{H} \neq 0$$

Circularly polarized

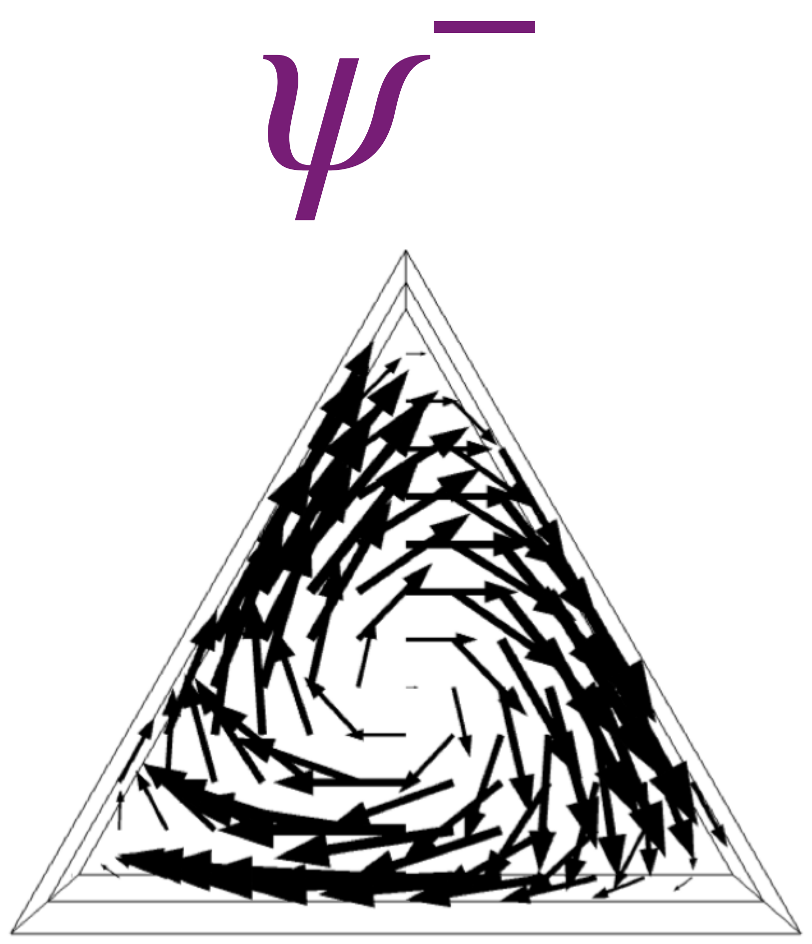
Two modes: TE & TM modes

- Non-degenerate
- Magneto-electric coupling

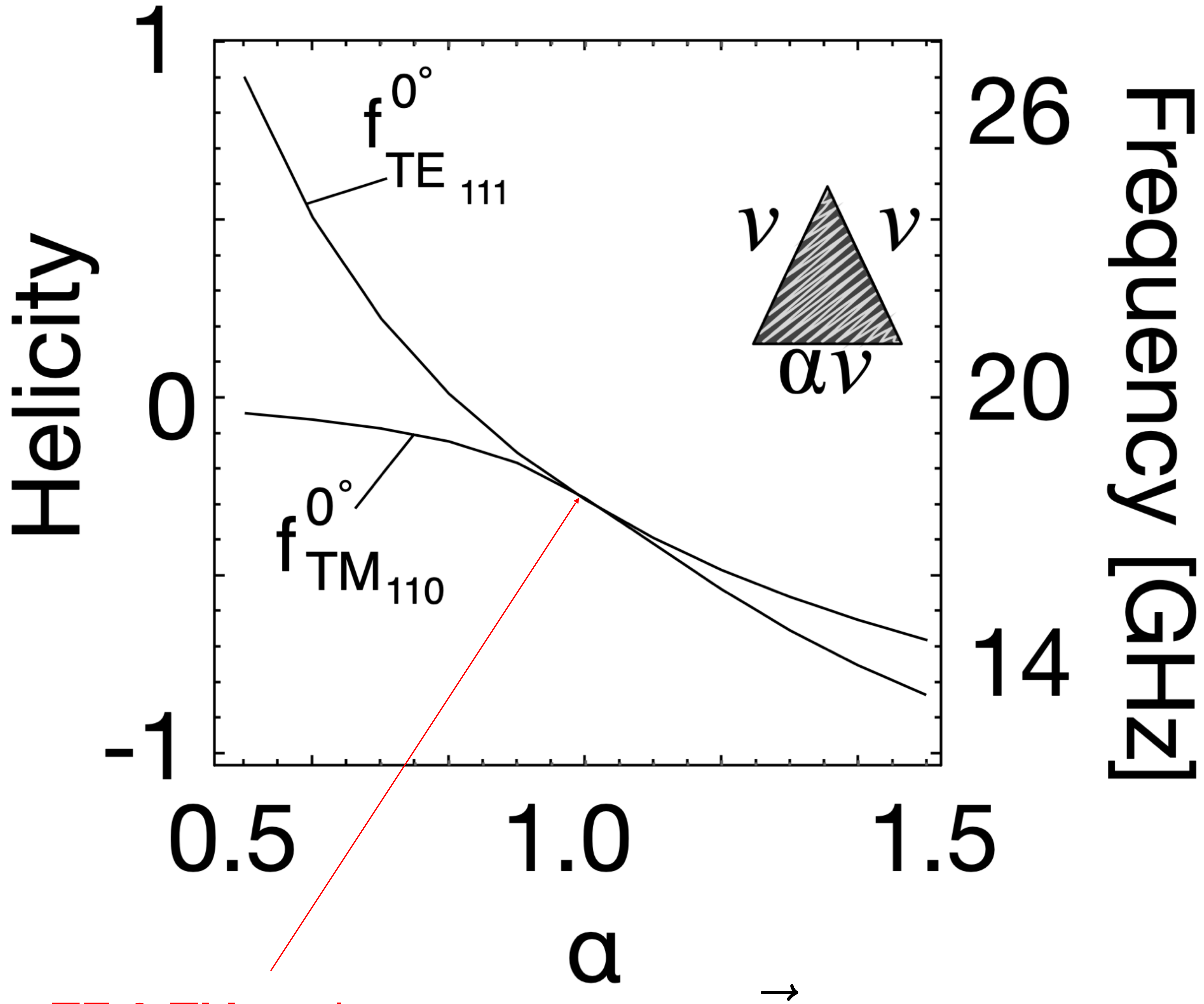


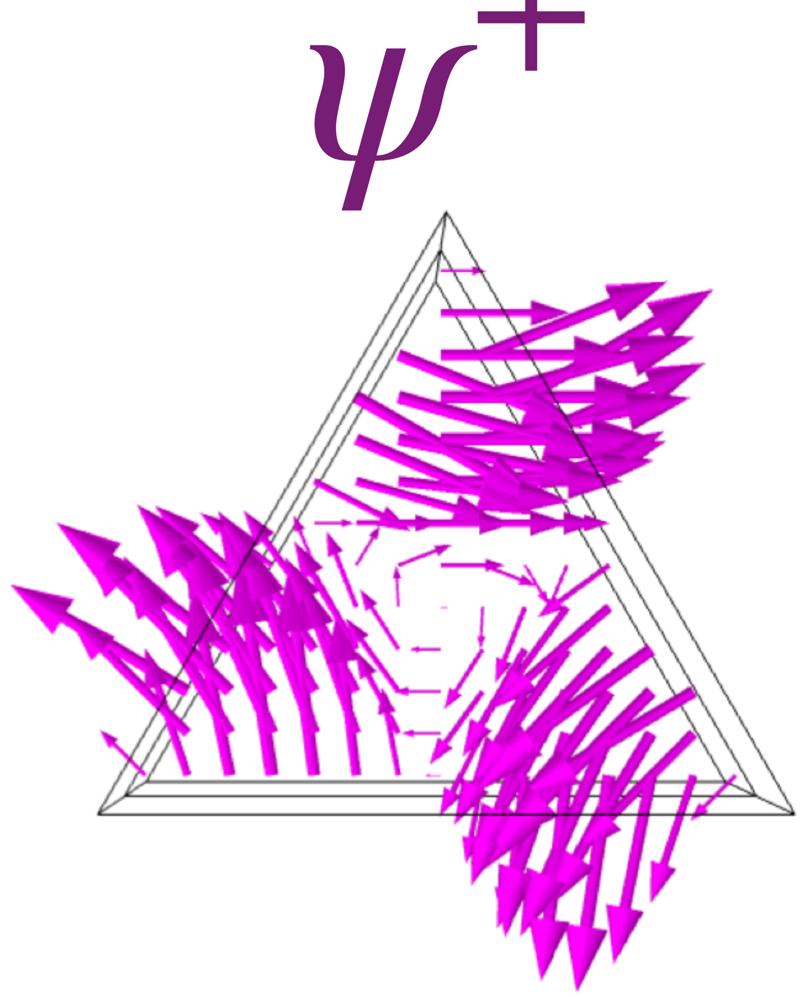


ψ^-
Transverse Magnetic (TM)
1
0
-1
Helicity
$f^{0°}_{TE_{111}}$
$f^{0°}_{TM_{110}}$
ν
ν
$\alpha\nu$
26
20
14
Frequency [GHz]
0.5
1.0
1.5
α
ψ^+
Transverse Electric (TE)
$\vec{E}_\perp$
$\vec{B}_\perp$



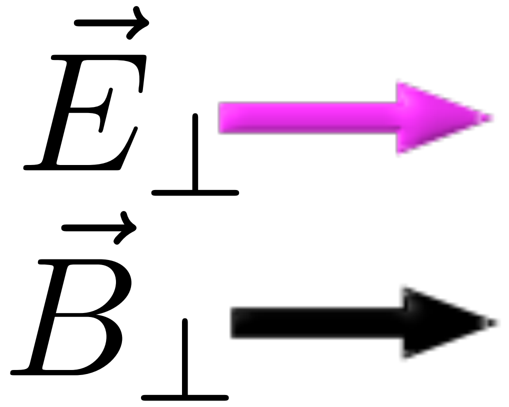
Transverse Magnetic (TM)

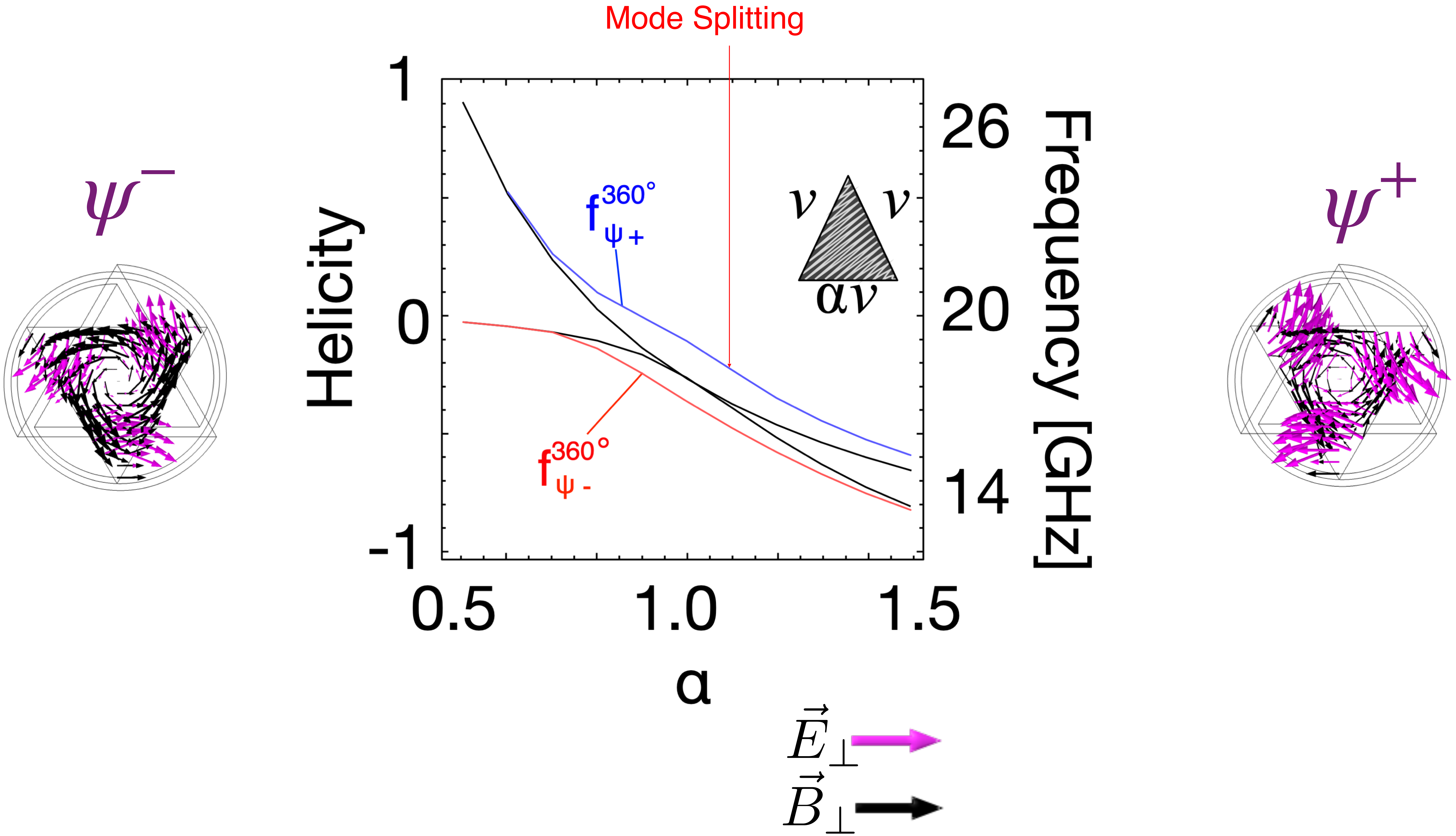




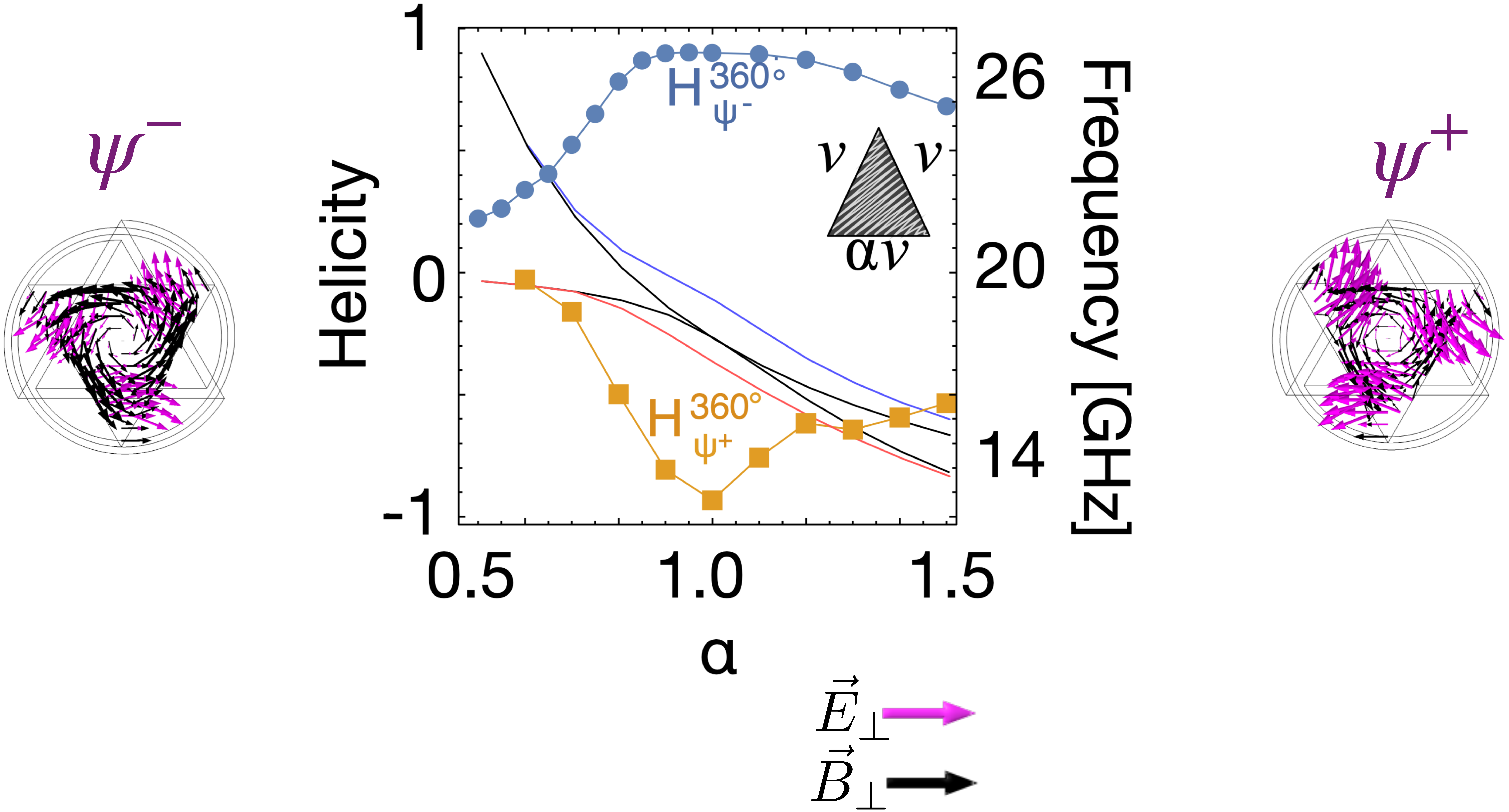
Transverse Electric (TE)

TE & TM modes degenerate in frequency



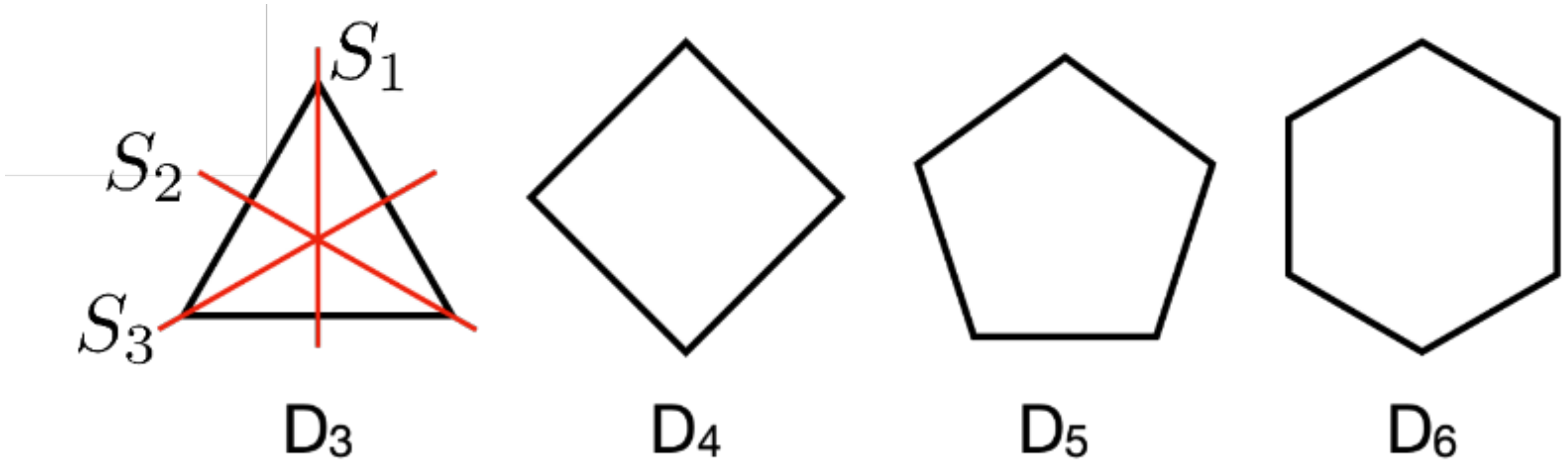


Mode Splitting
1
0
-1
Helicity
26
20
14
Frequency [GHz]
0.5
1.0
1.5
α
$f^{360°}_{\psi+}$
$f^{360°}_{\psi-}$
ν
ν
αν
ψ^{-}
ψ^{+}
$\vec{E}_{\perp}$
$\vec{B}_{\perp}$

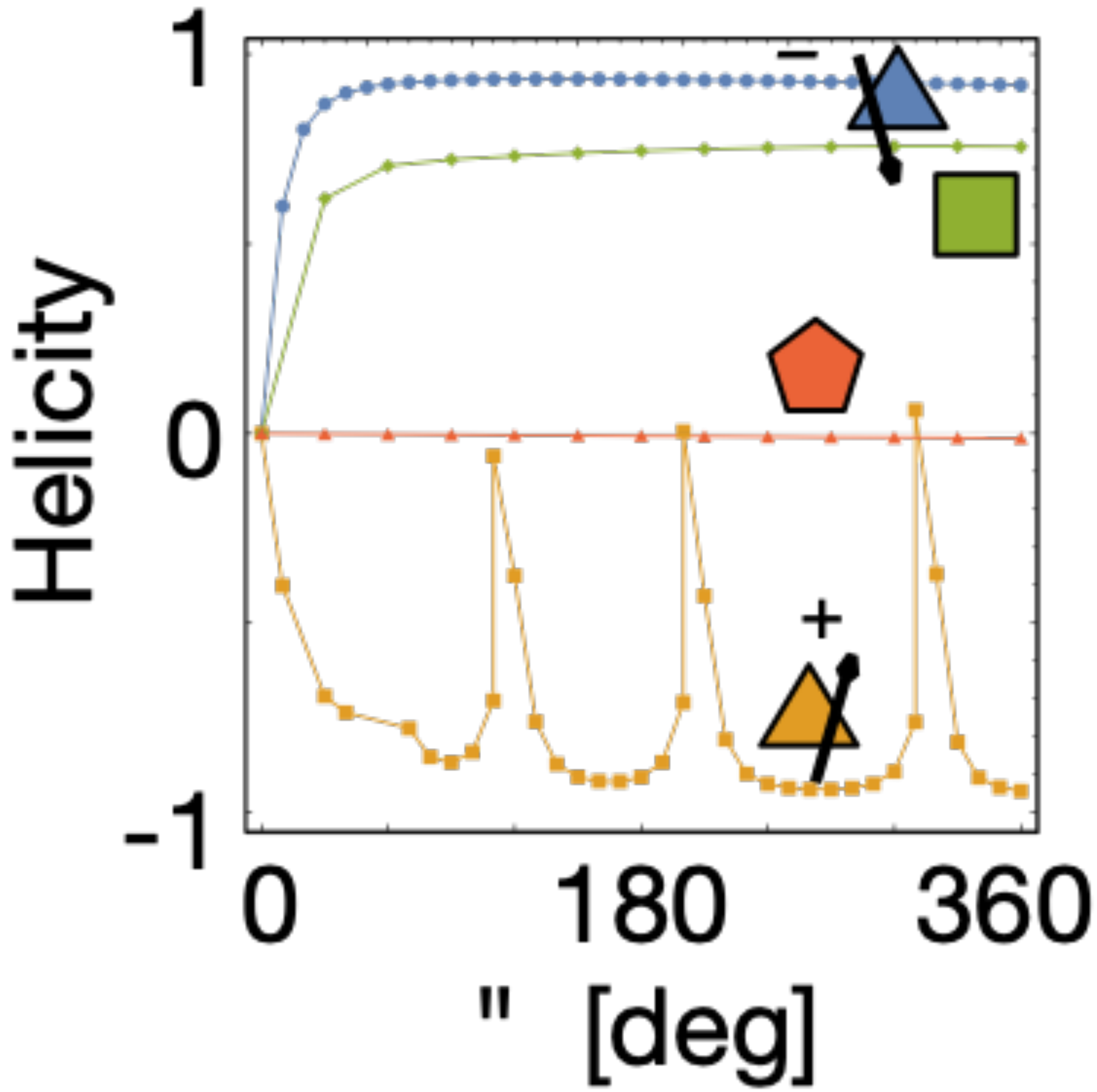


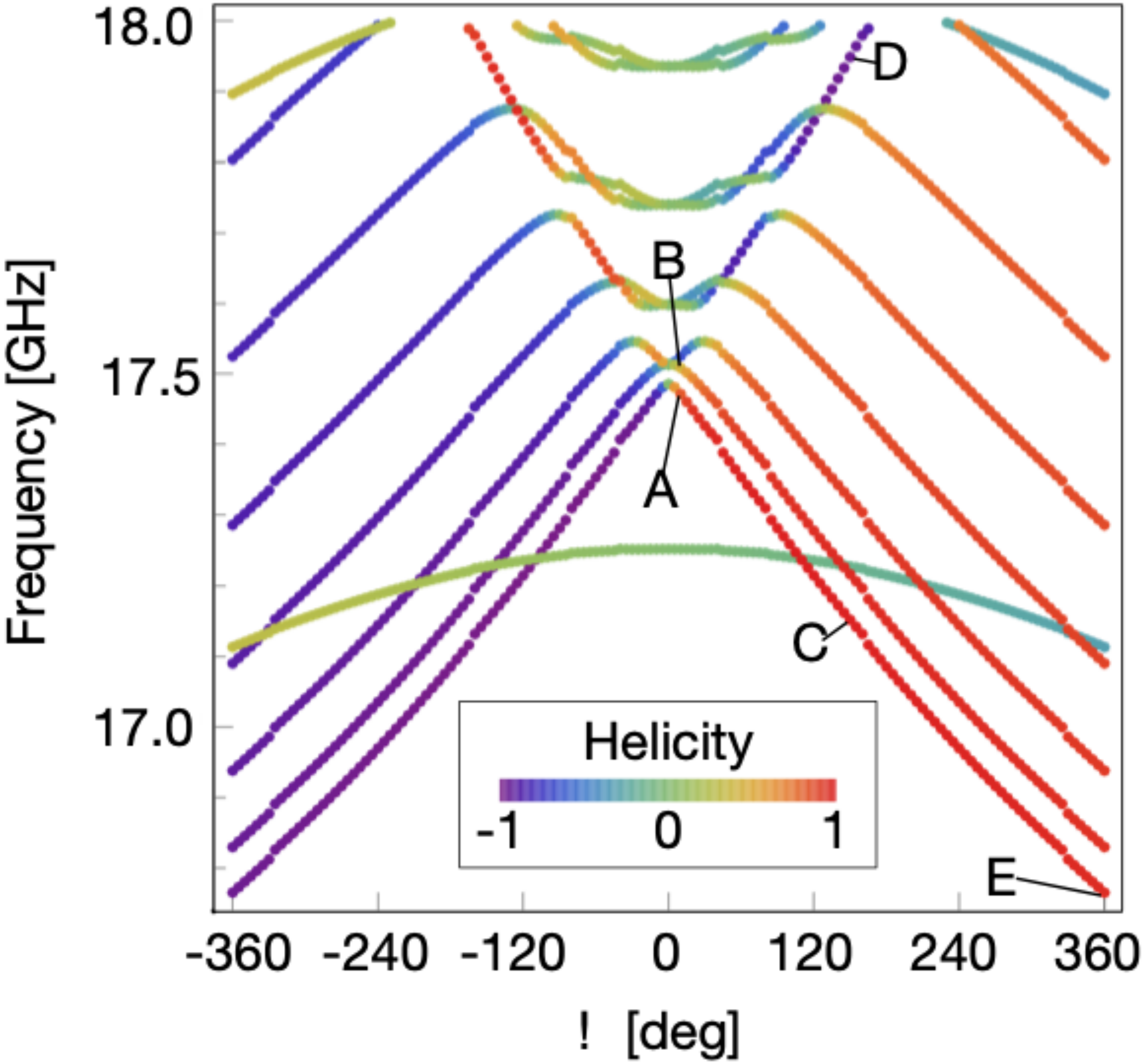
ψ⁻
ψ⁺
Helicity
Frequency [GHz]
1
0
-1
26
20
14
0.5
1.0
1.5
α
H 360° ψ⁻
H 360° ψ⁺
ν ν αν
$\vec{E}_\perp$
$\vec{B}_\perp$

Cross-section



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





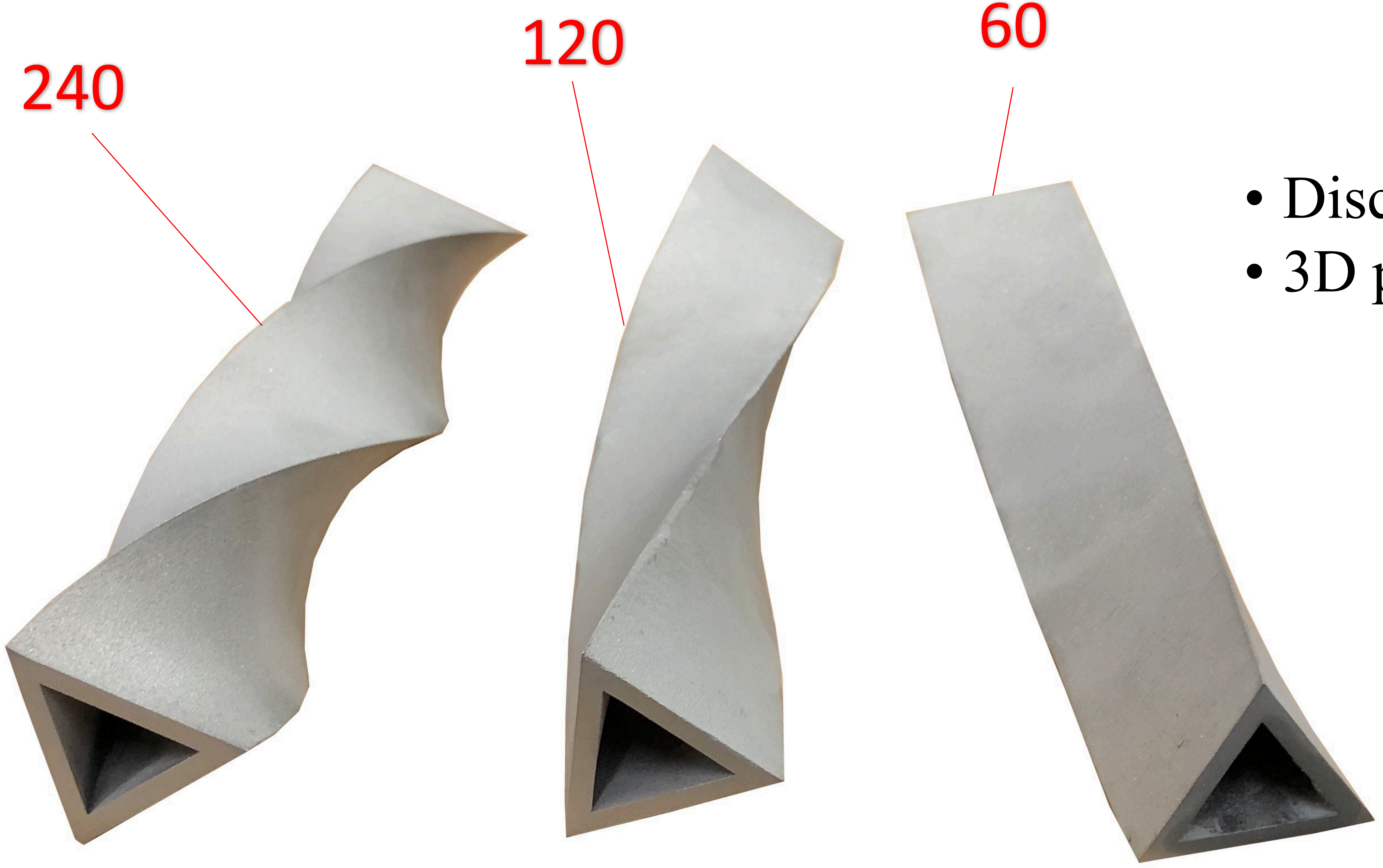
COMSOL

- Helicity is calculated via finite element analysis

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

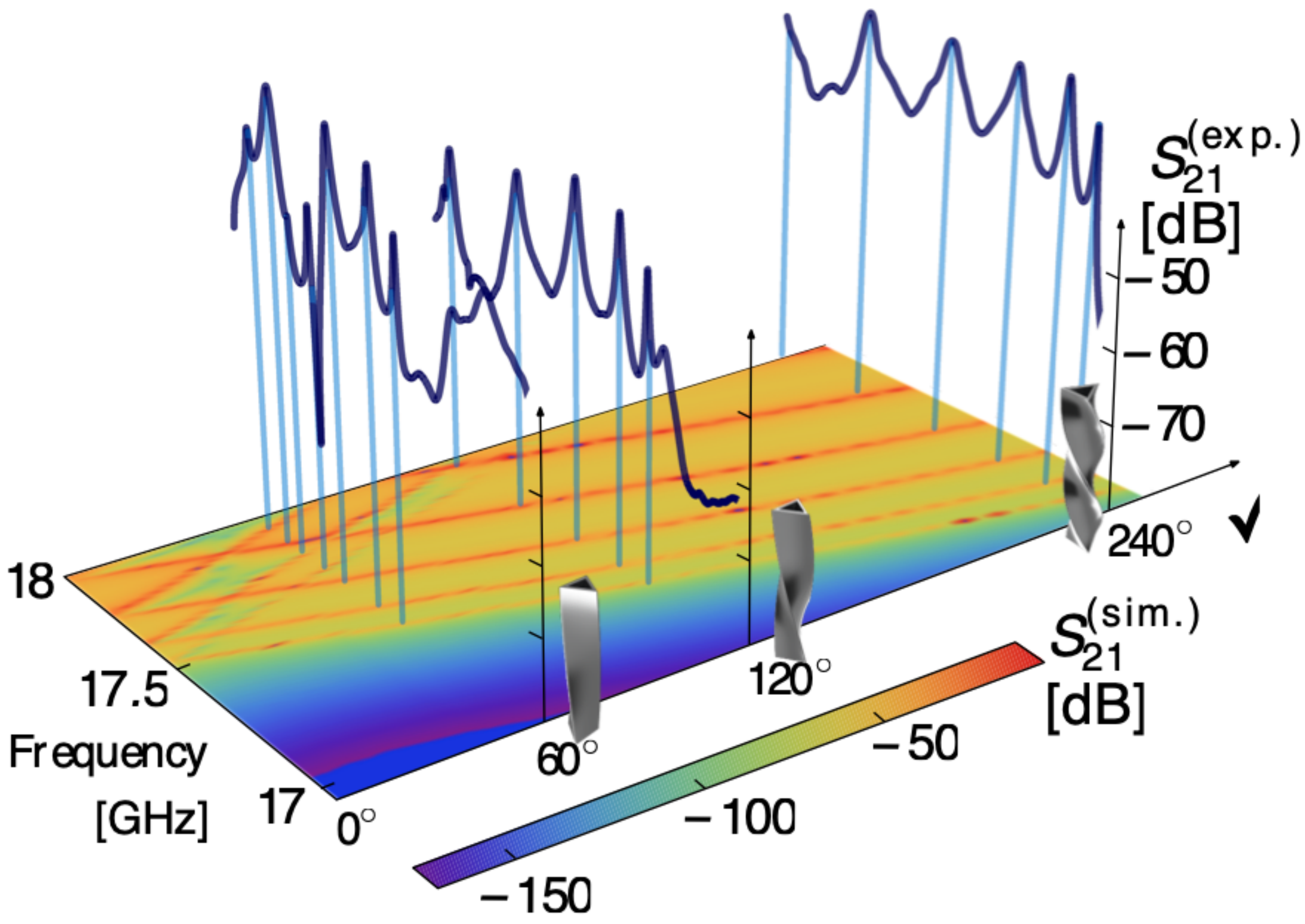
- With twist
  - Eigenmodes tune in frequency
  - Helicity increases
- Confirm theoretical predictions

3D Printed Triangular Waveguide Cavities



- Discrete angles
- 3D printed aluminum

Simulation and Experimental Results Agree



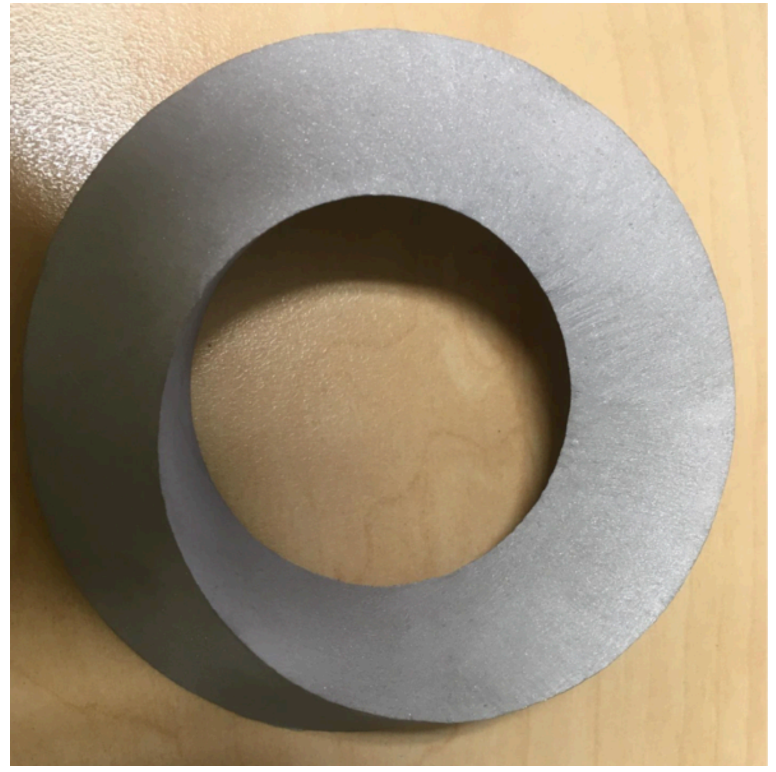
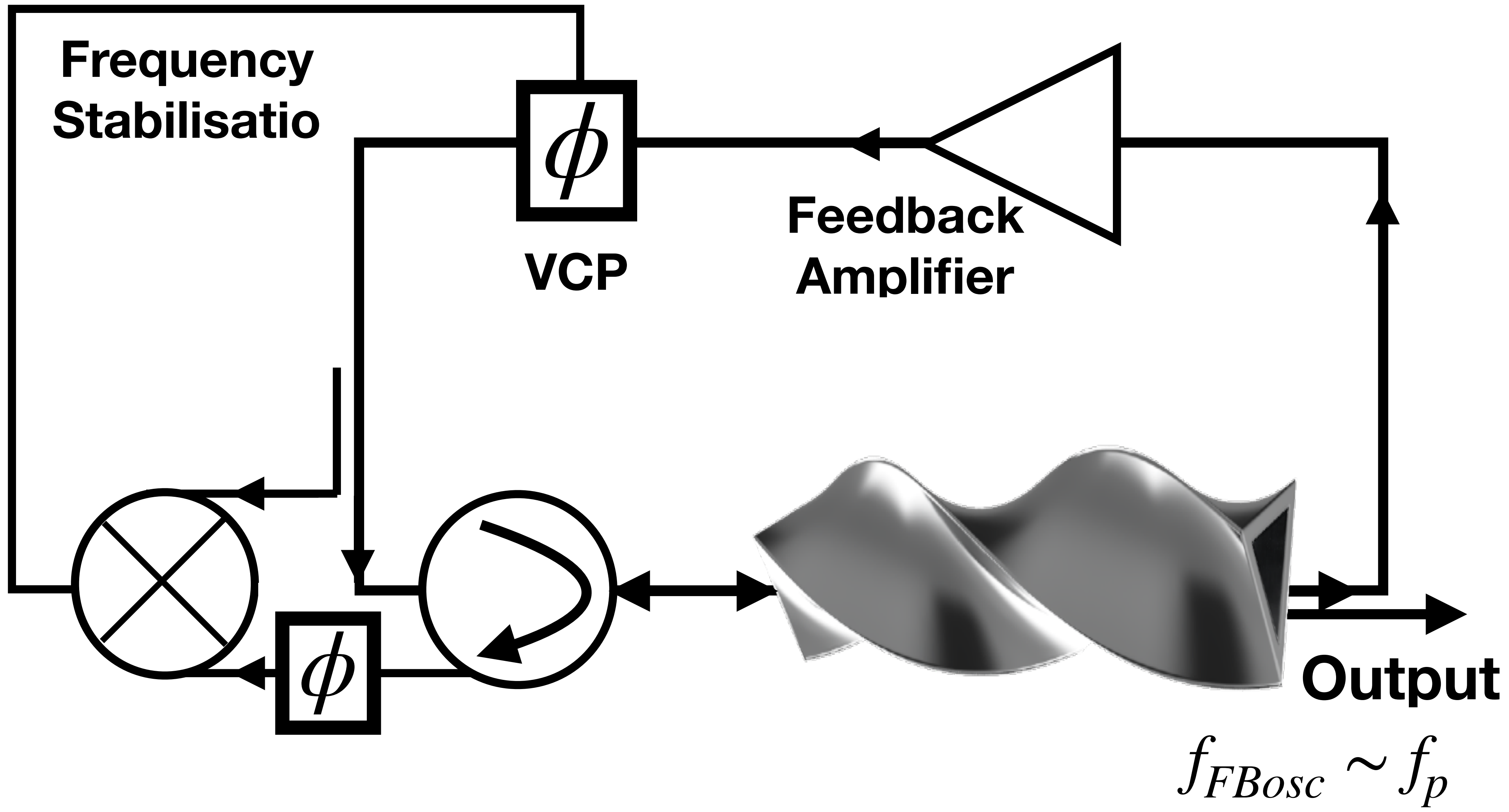
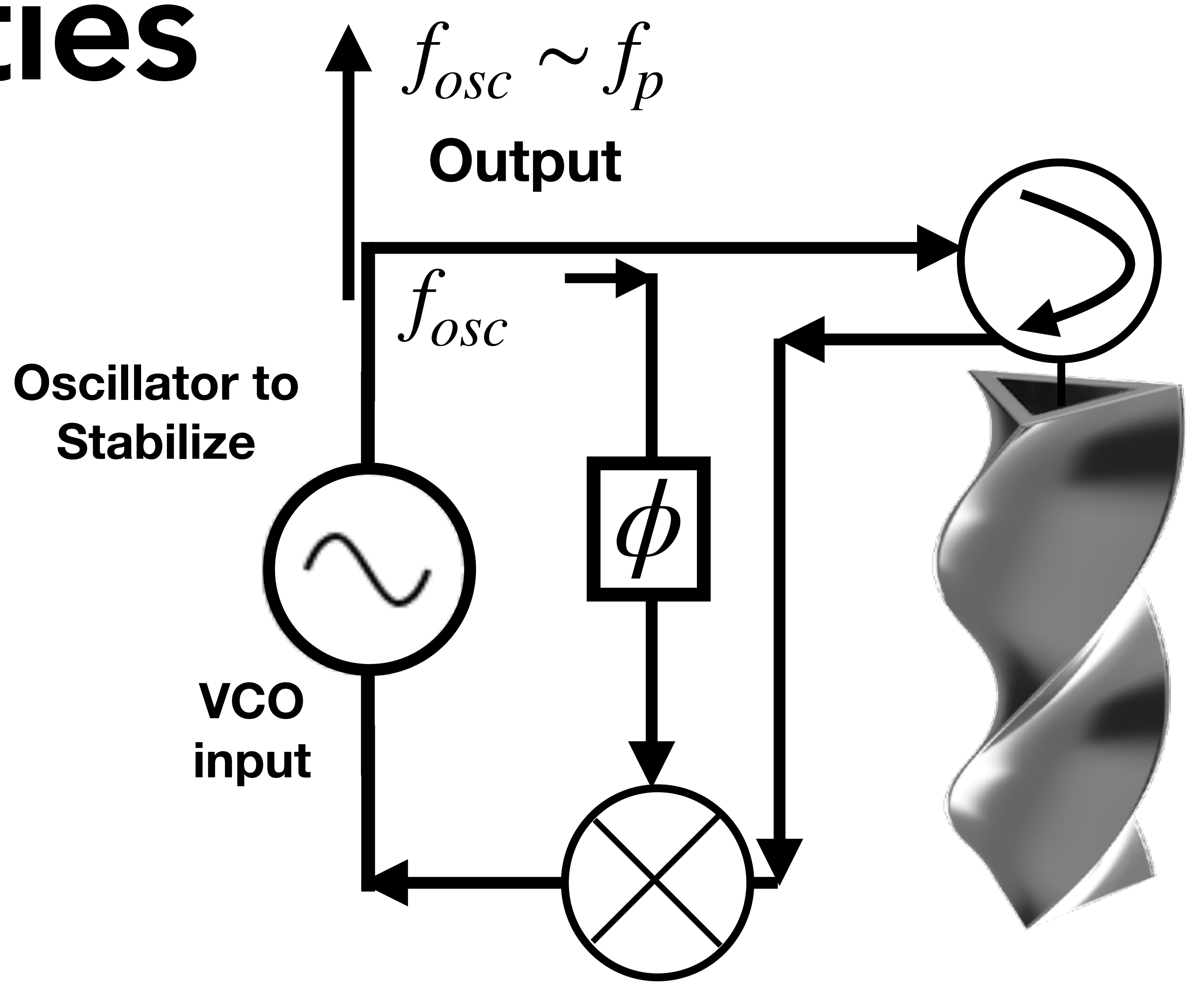


TABLE I. Simulated f_p, G_p and $\mathscr{H}_p$ values for the greatest $|\mathscr{H}_p|$ modes for the linear and ring resonators with $l = 150$ mm, $\nu = 20$ mm, $\alpha = 1$ and $\theta = 120°$.

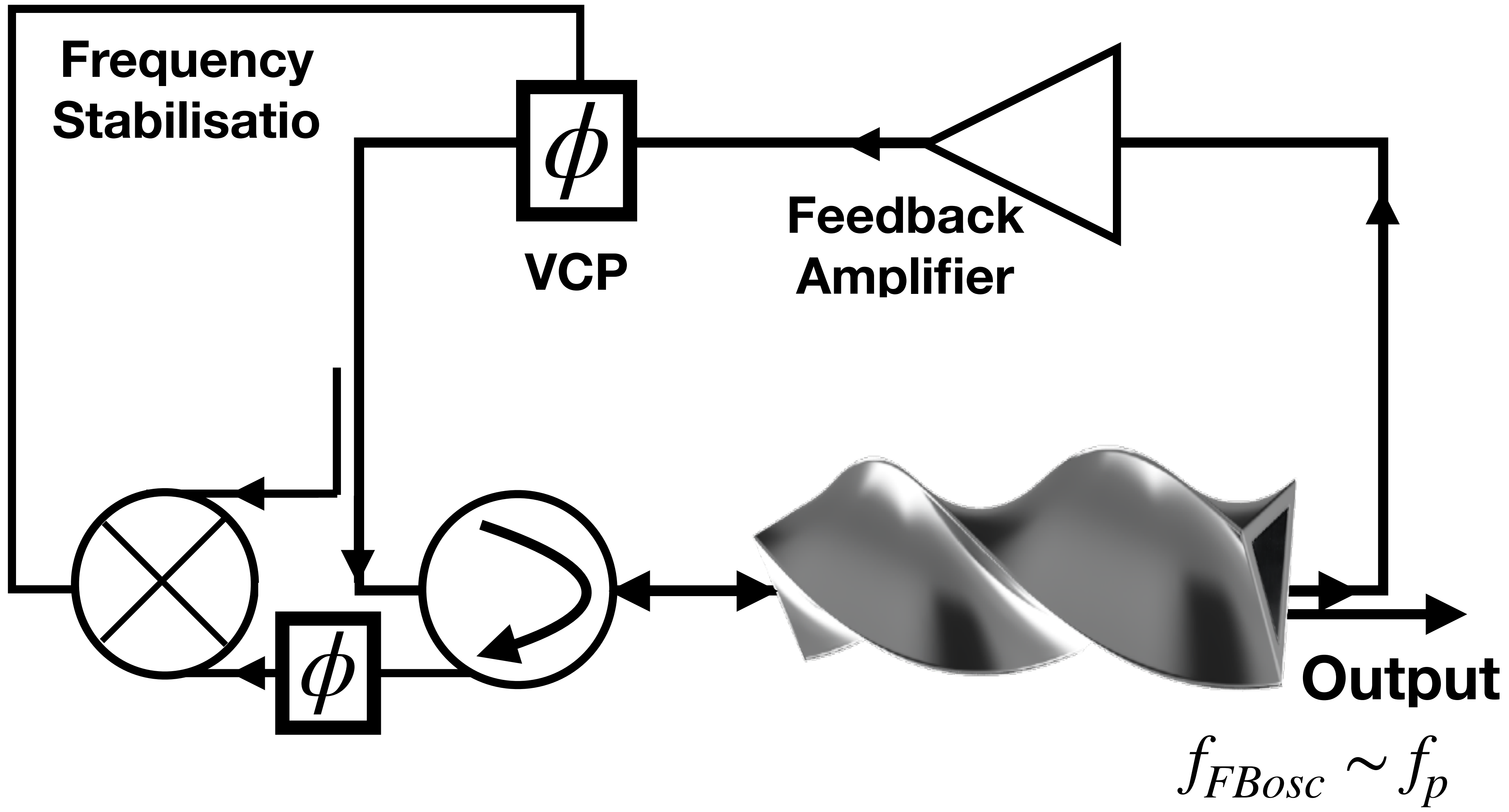
Resonator	f_p (GHz)	G_p (Ω)	$\mathscr{H}_p$
Linear	17.044	1950	−0.931
Linear	17.688	1920	0.8796
Ring	17.022	6200	−0.931
Ring	17.814	7290	0.954

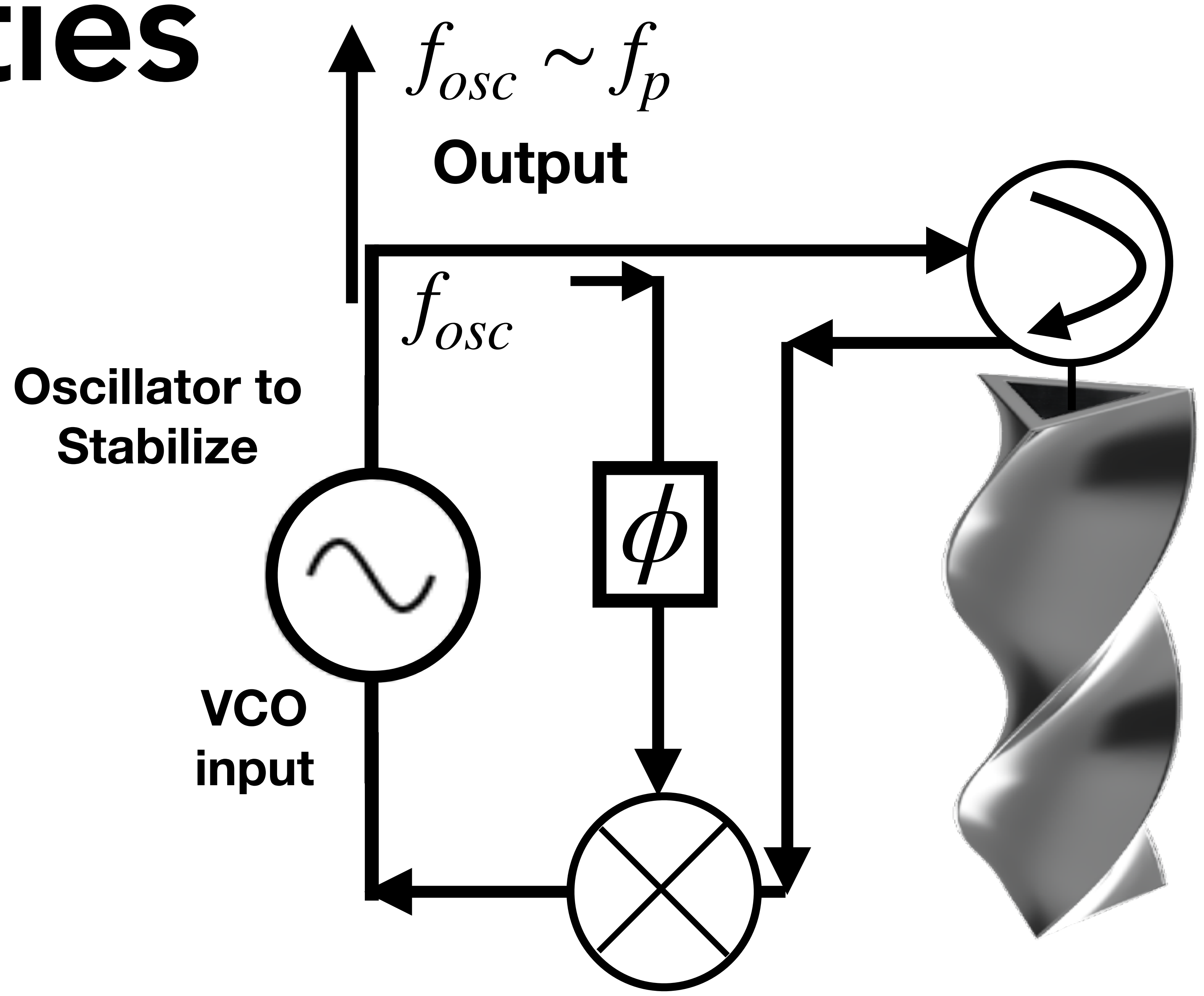
Twisted "anyon" microwave cavities





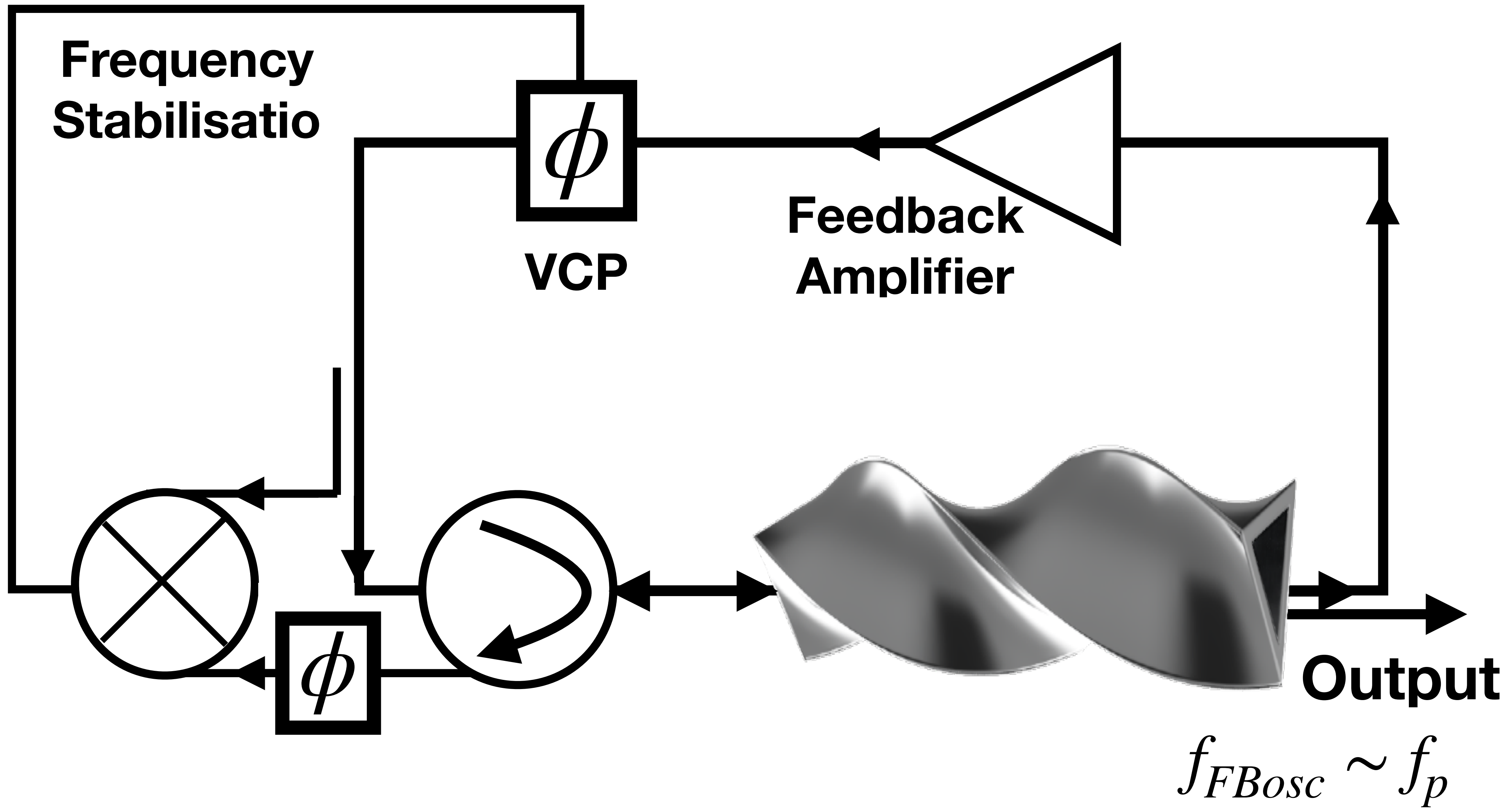
Twisted “anyon” microwave cavities

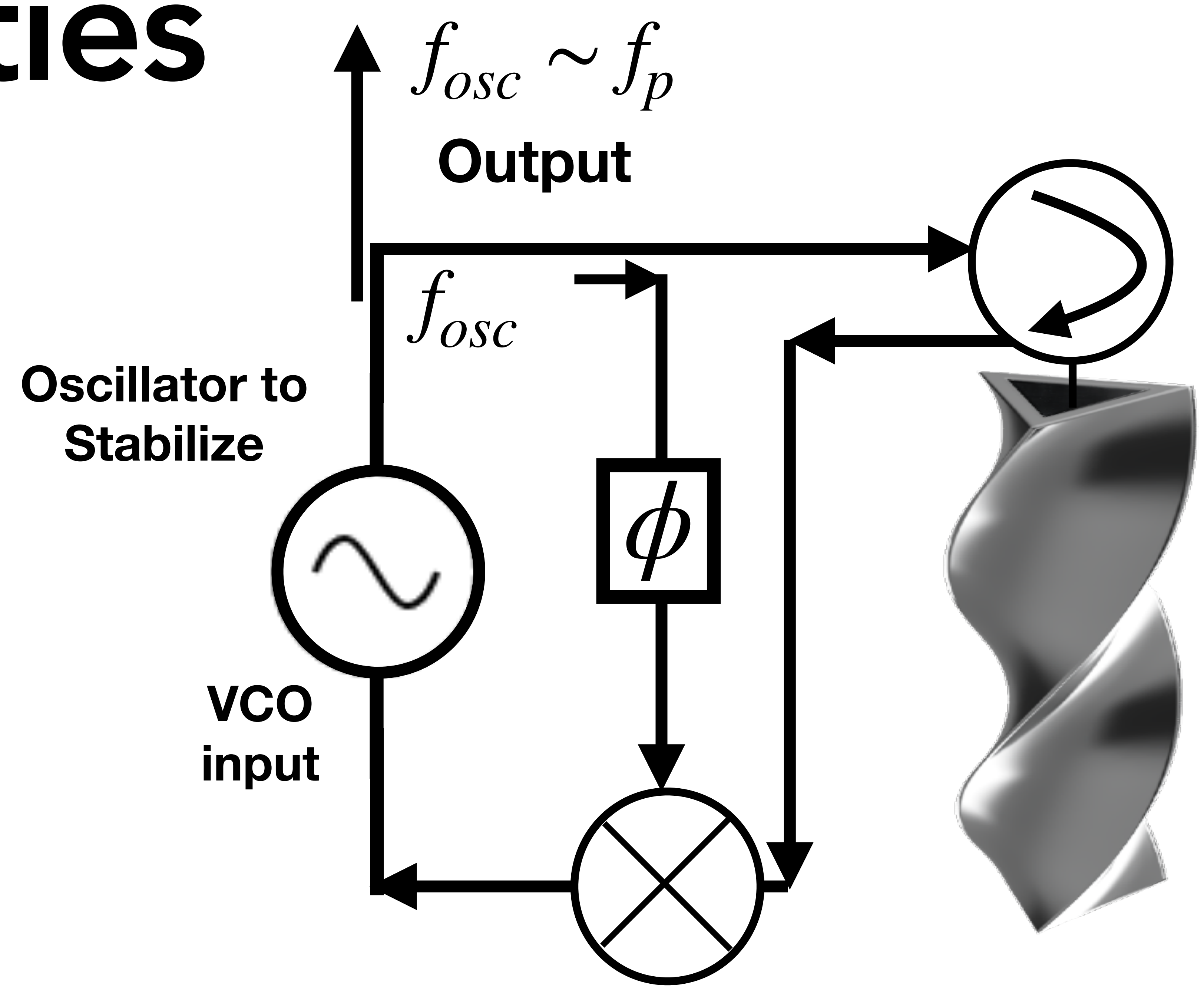




$$SNR = \frac{g_{a\gamma\gamma}\beta_p|\mathscr{H}_p|}{\sqrt{2}(1+\beta_p)} \frac{Q_p}{\sqrt{1+4Q_p^2(\frac{\omega_a}{\omega_p})^2}} \frac{\left(\frac{10^6 t}{\omega_a}\right)^{\frac{1}{4}} \sqrt{\rho_a c^3}}{\omega_p\sqrt{S_{am}}}$$

Twisted "anyon" microwave cavities





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

Axion Photon Coupling

Microwave Probe Coupling

Helicity

Q factor

Axion Frequency

Measurement time (1 week)

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

Speed of light ($3\text{x}10^{8}$ ms^{-1})

Cavity frequency (1 GHz)

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

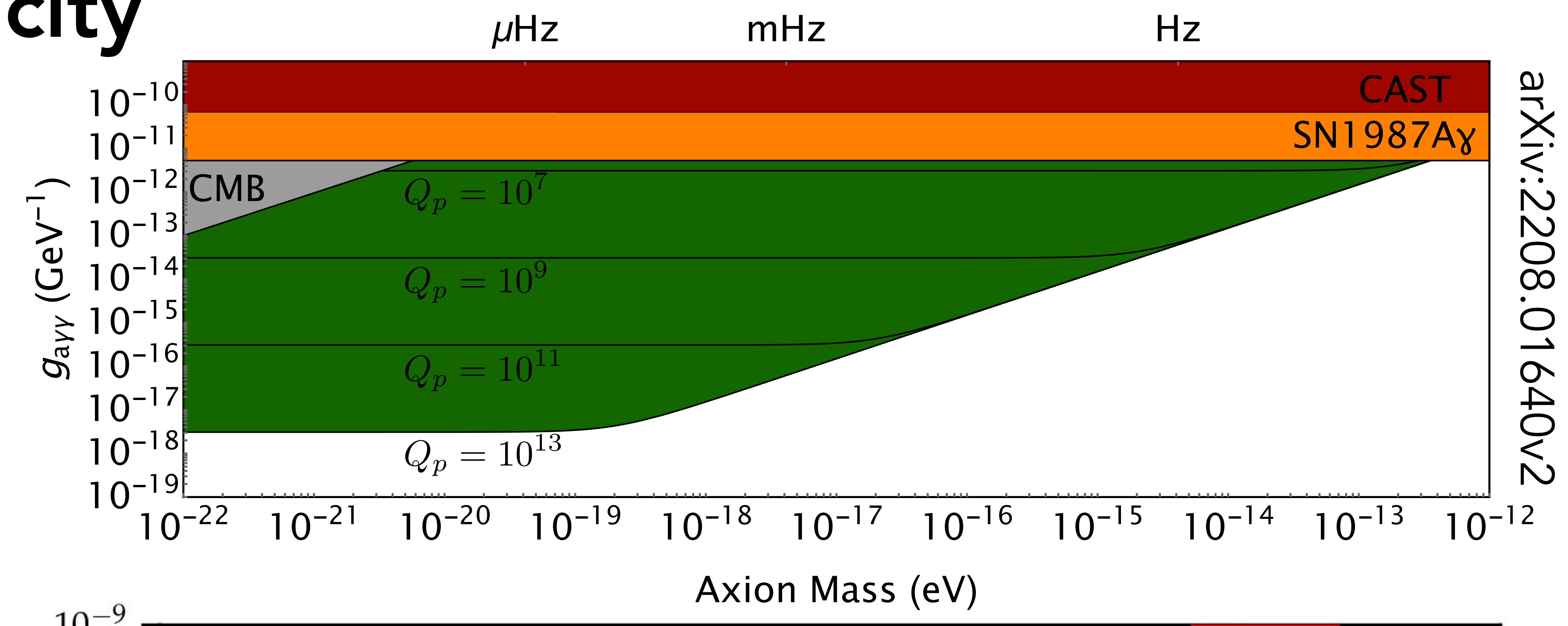
Twisted “anyon” microwave cavities

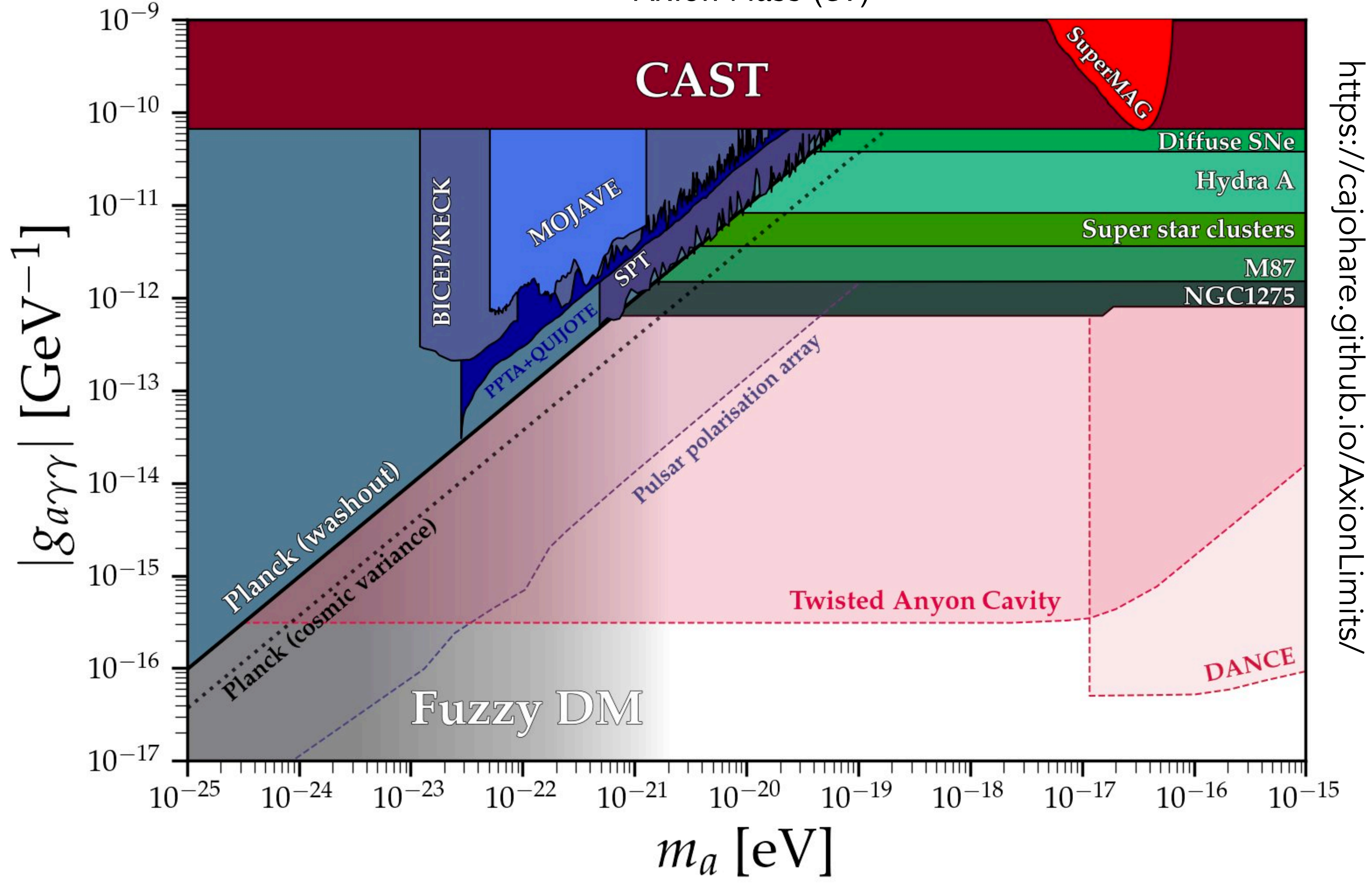
Dark matter detection in a single mode thanks to helicity

Twisted “anyon” microwave cavities

Dark matter detection <u>in a single mode</u> thanks to helicity

- Accesses an axion mass range very difficult to search

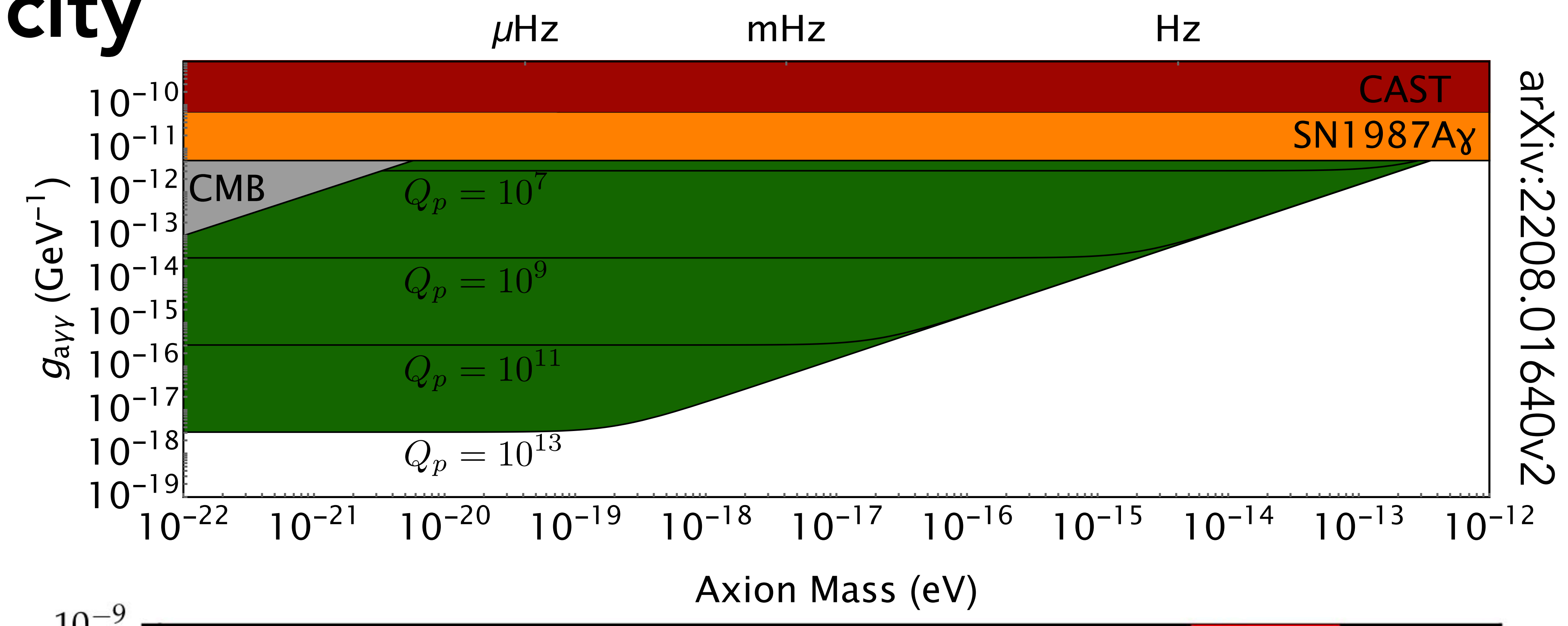


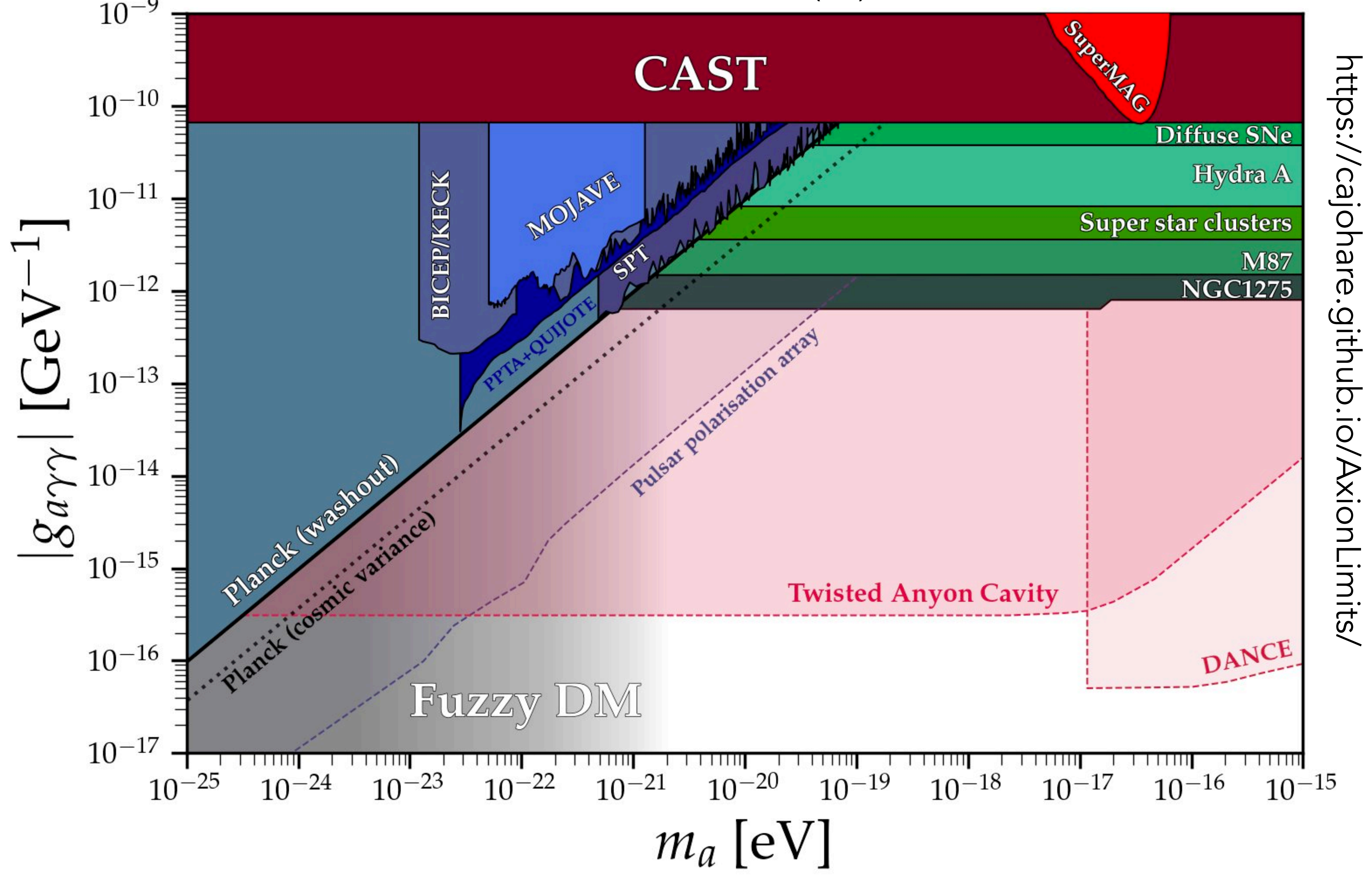


Twisted "anyon" microwave cavities

Dark matter detection <u>in a single mode</u> thanks to helicity

- Accesses an axion mass range very difficult to search
- **No external magnetic field needed**



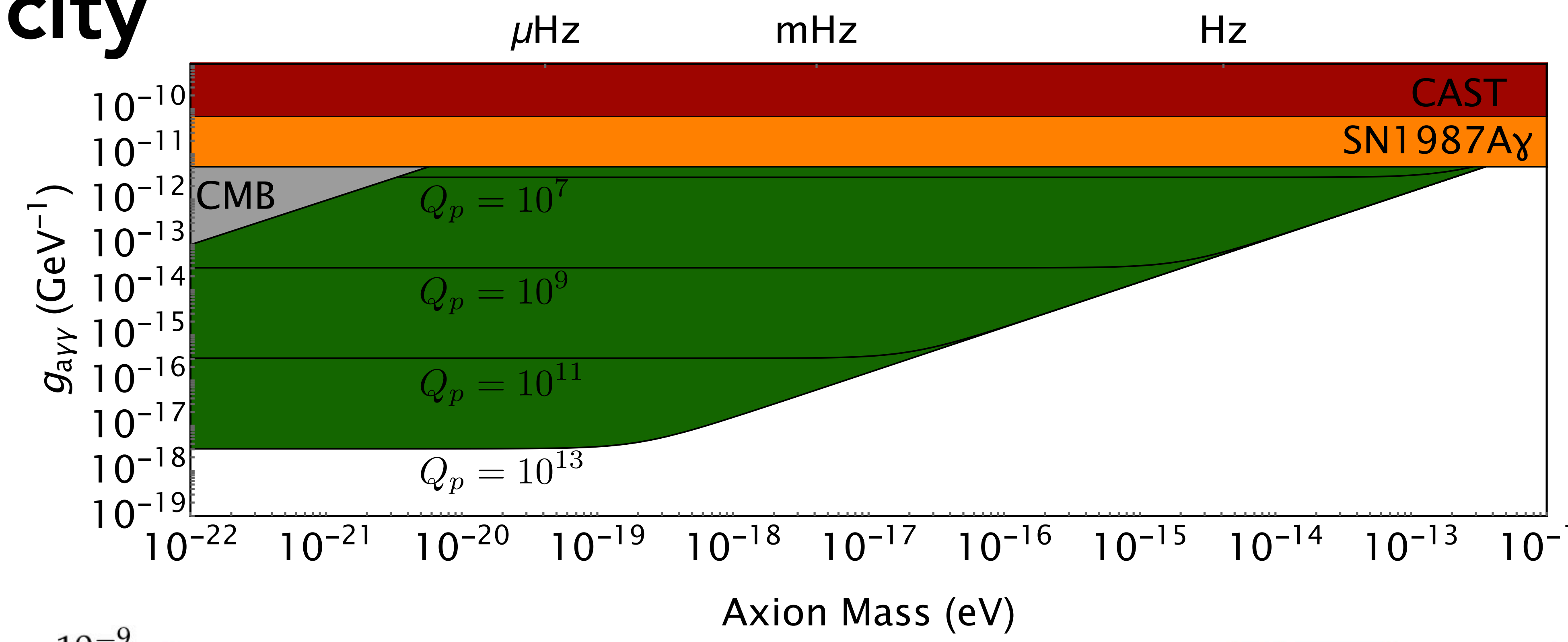


Quantum Technologies and Dark Matter Research Lab

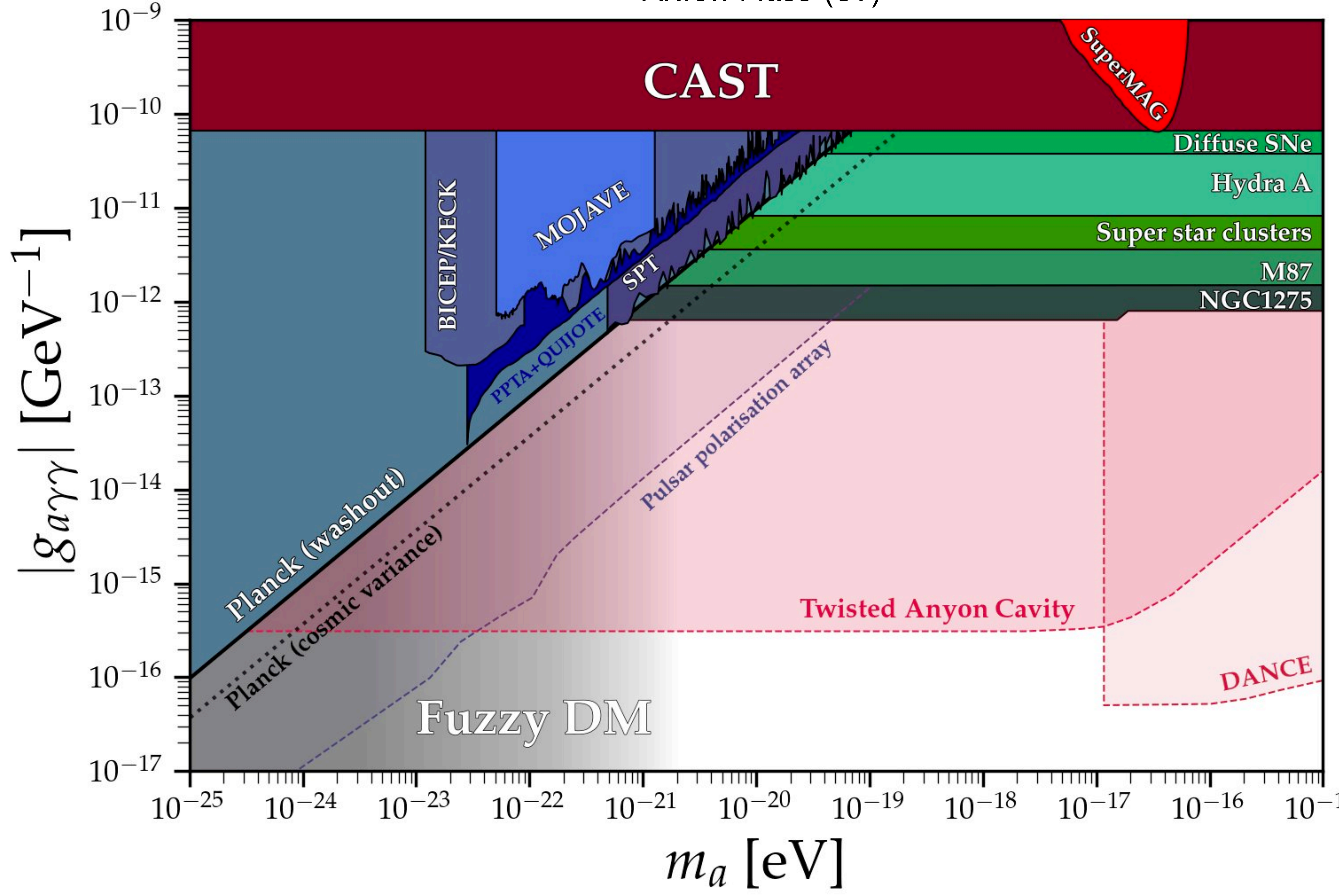
Twisted “anyon” microwave cavities

Dark matter detection <u>in a single mode</u> thanks to helicity

- Accesses an axion mass range very difficult to search
- **No external magnetic field needed**
- Ability to use **superconducting** materials



arXiv:2208.01640v2

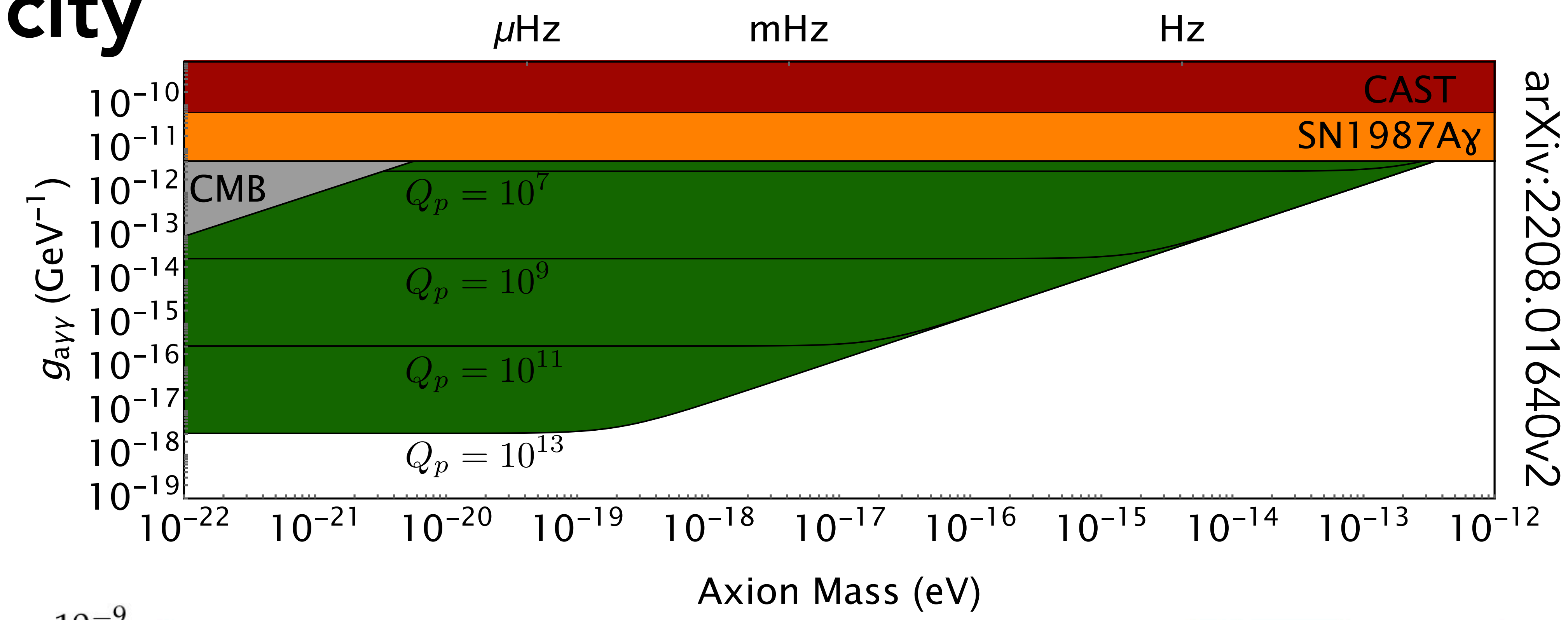


https://cajohare.github.io/AxionLimits/

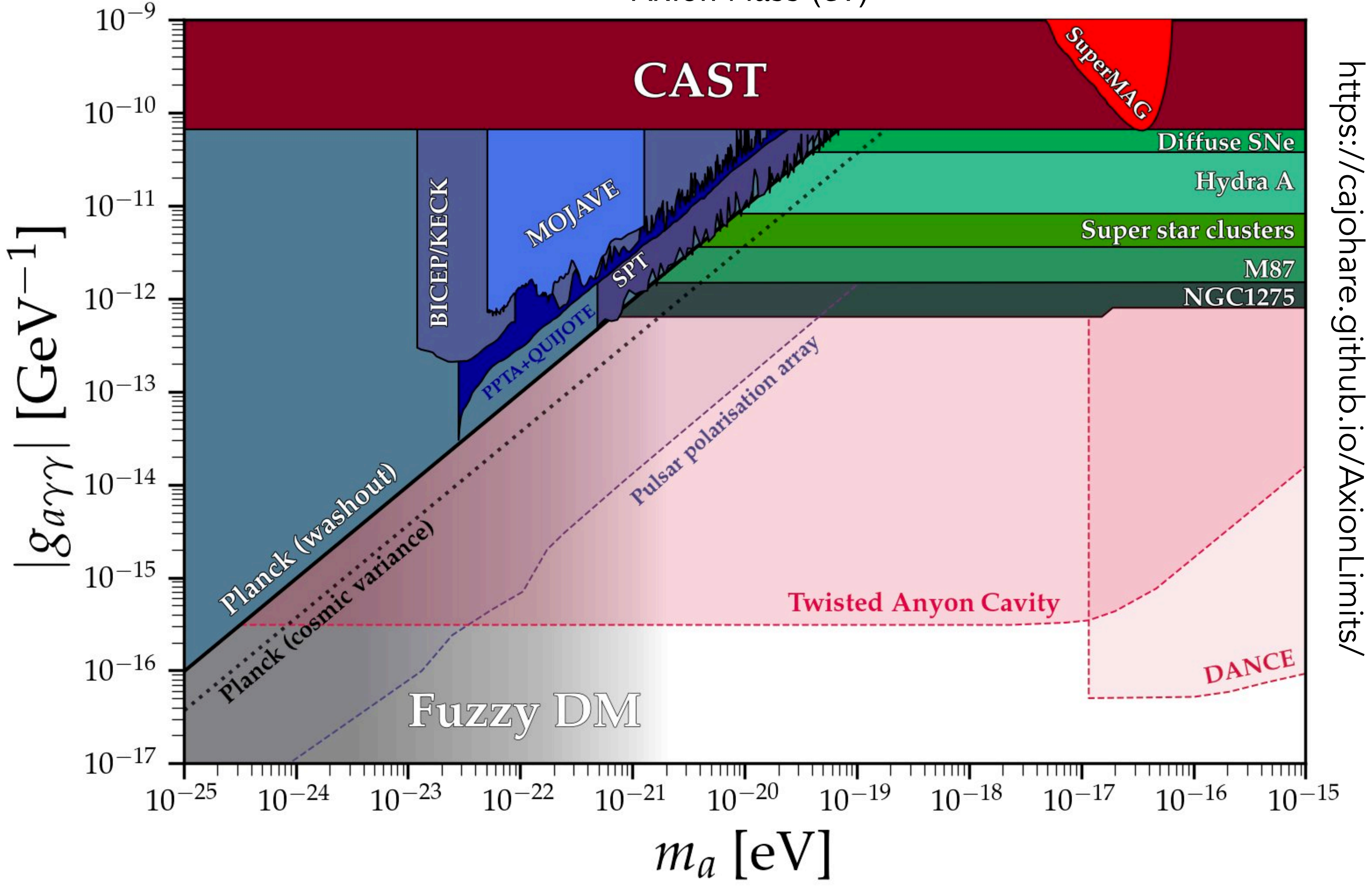
Twisted “anyon” microwave cavities

Dark matter detection in a single mode thanks to helicity

- Accesses an axion mass range very difficult to search
- **No external magnetic field needed**
- Ability to use **superconducting** materials
- Allows high Q-factors and improved sensitivity



arXiv:2208.01640v2



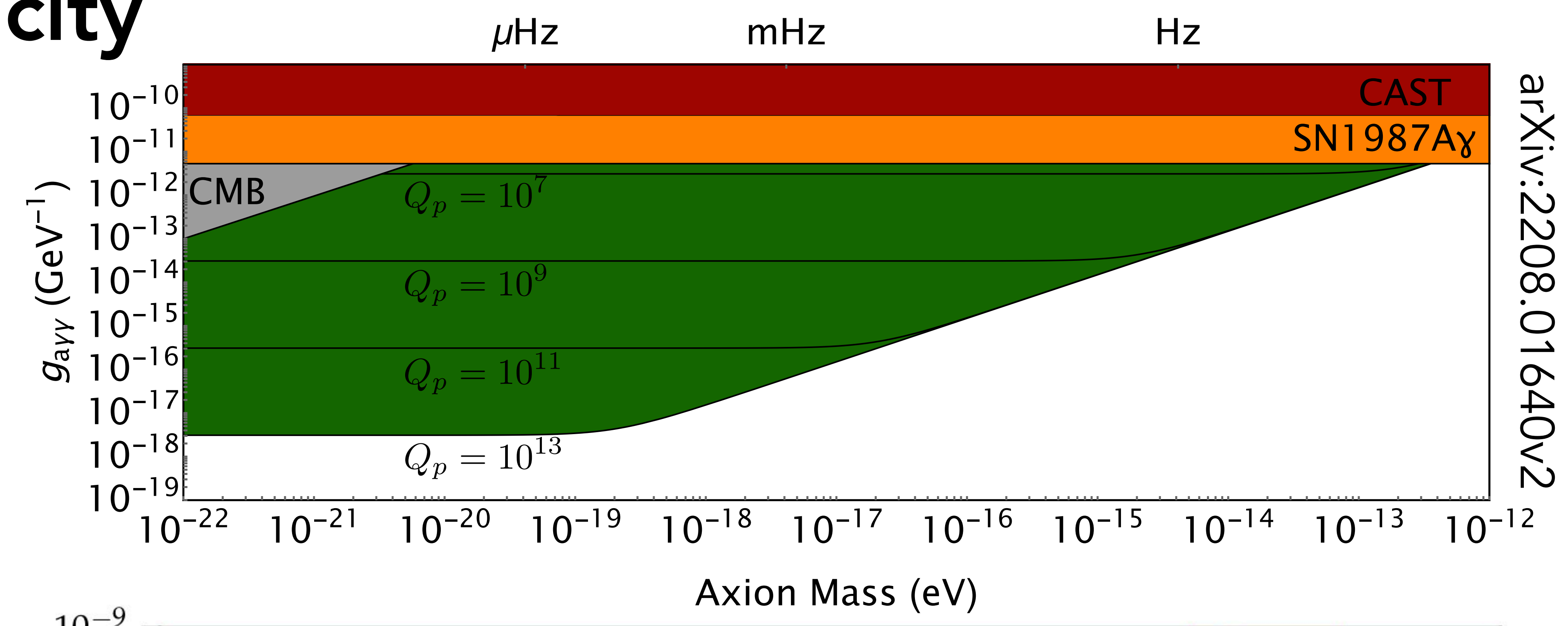
https://cajohare.github.io/AxionLimits/

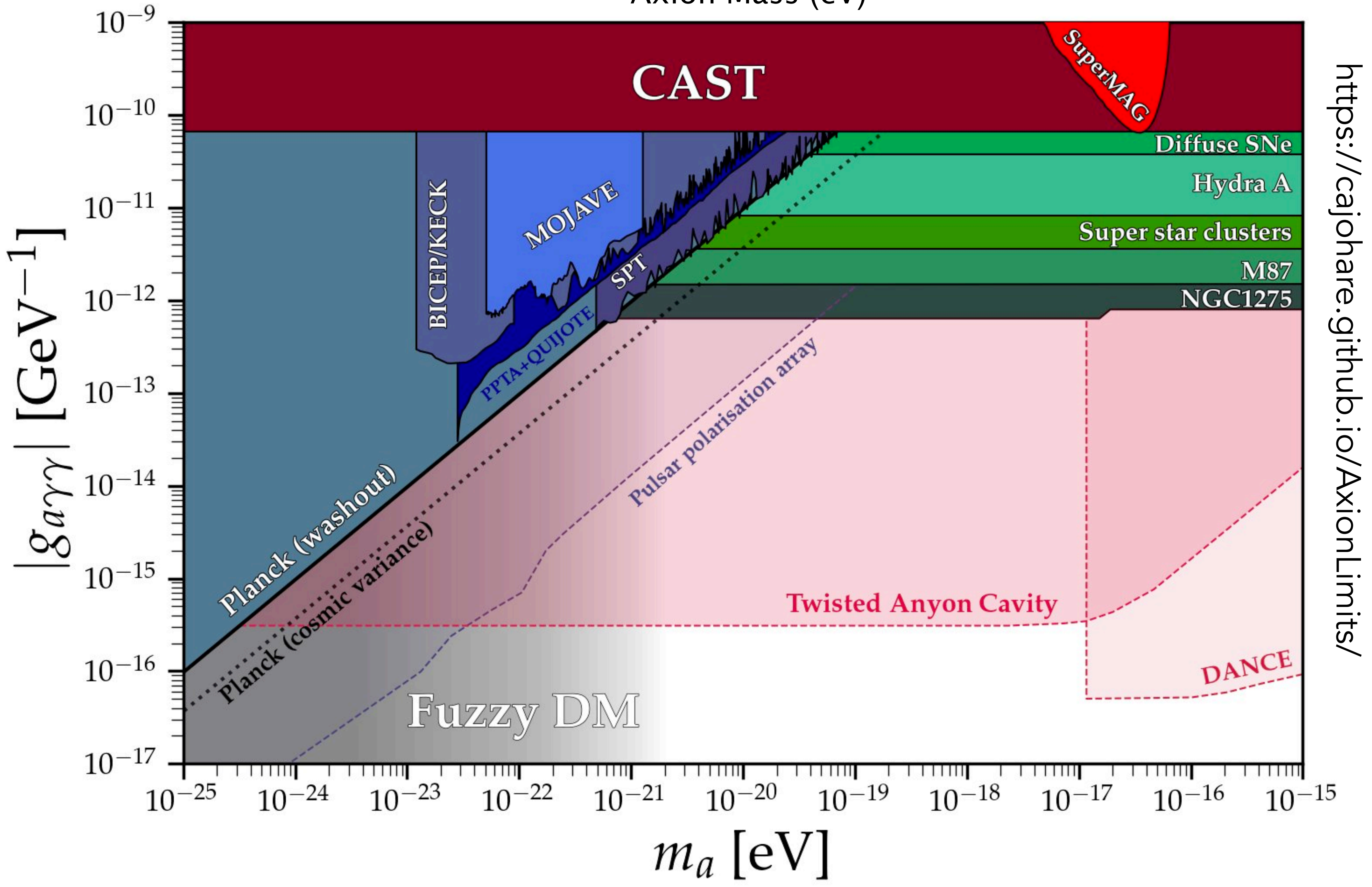
Quantum Technologies and Dark Matter Research Lab

Twisted "anyon" microwave cavities

Dark matter detection <u>in a single mode</u> thanks to helicity

- Accesses an axion mass range very difficult to search
- **No external magnetic field needed**
- Ability to use **superconducting** materials
- Allows high Q-factors and improved sensitivity
- Next: Optimising Q-factors and minimising read-out amplitude modulation noise for a detection run

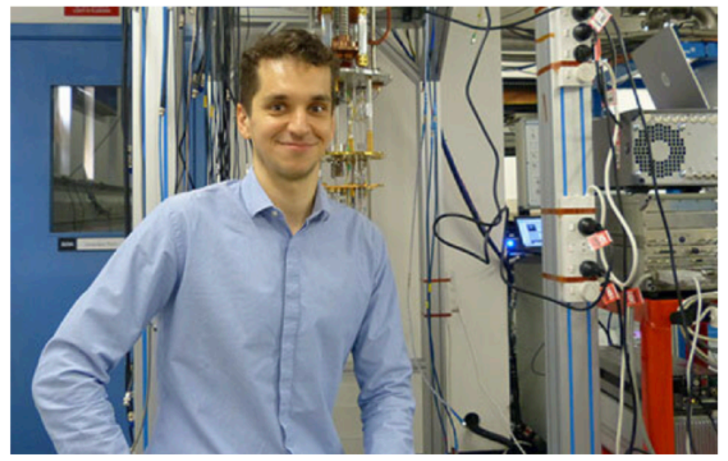




Quantum Technologies and Dark Matter Research Lab

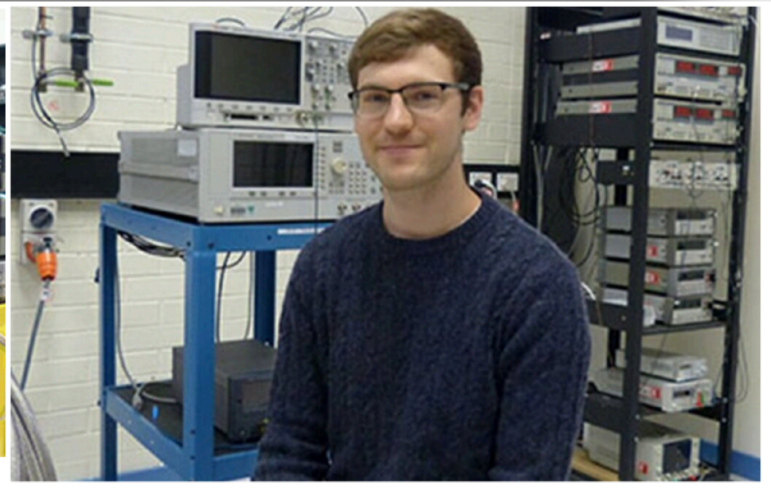
The QDM Team

Professor Michael Tobar
Director—QDM Lab, EQUS Node Director, CDM Node Director

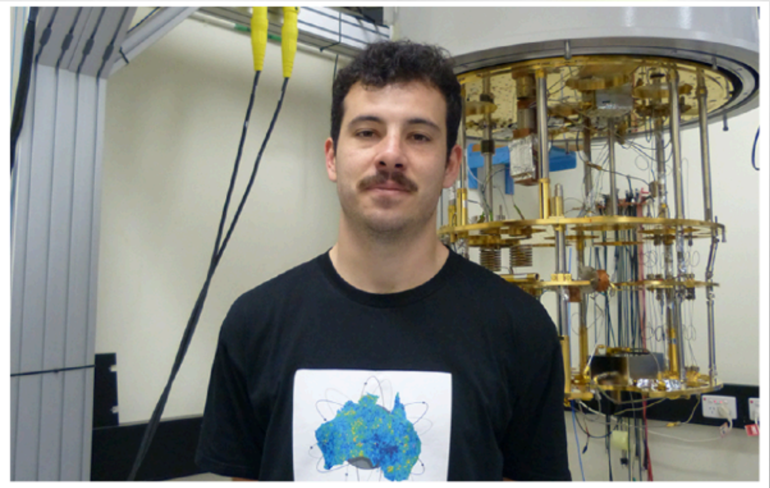


Dr Maxim Goryachev
EQUS Chief Investigator, CDM Chief Investigator, Lecturer—Research Intensive

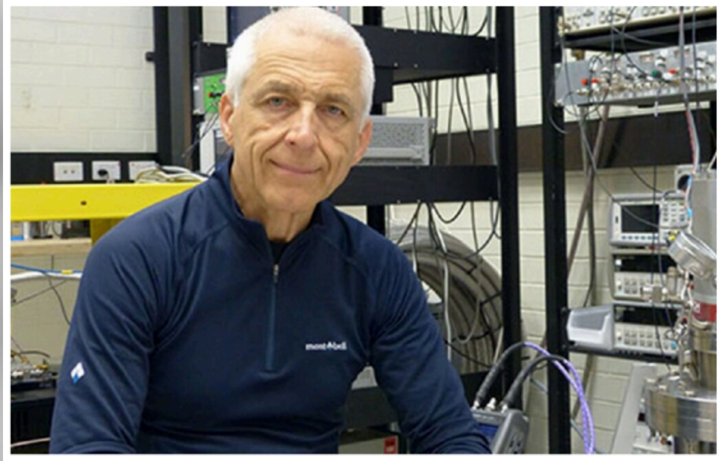
Dr Ben McAllister
Adjunct Research Fellow



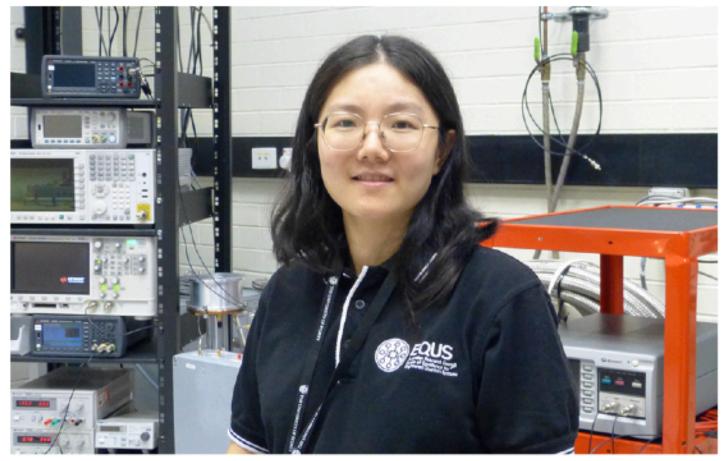
Dr Graeme Flower
Research Associate



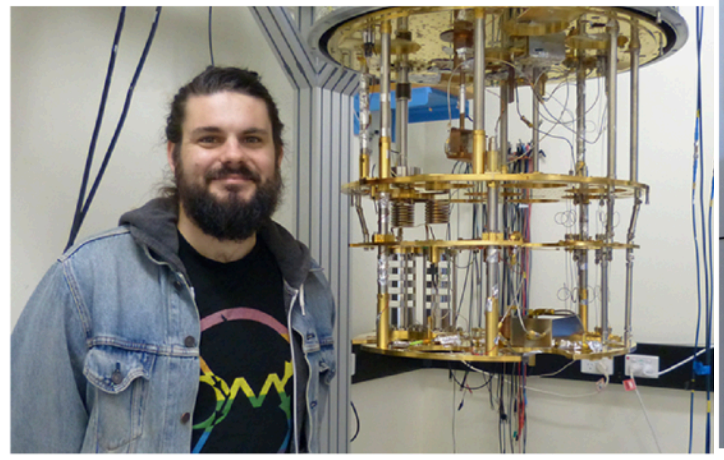
Will Campbell
Research Associate—Clock Flagship



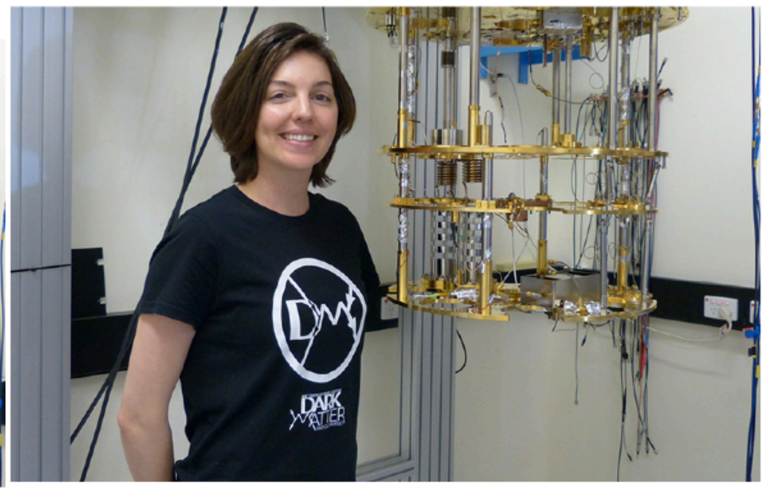
Winthrop Professor Eugene Ivanov
Senior Principle Research Fellow



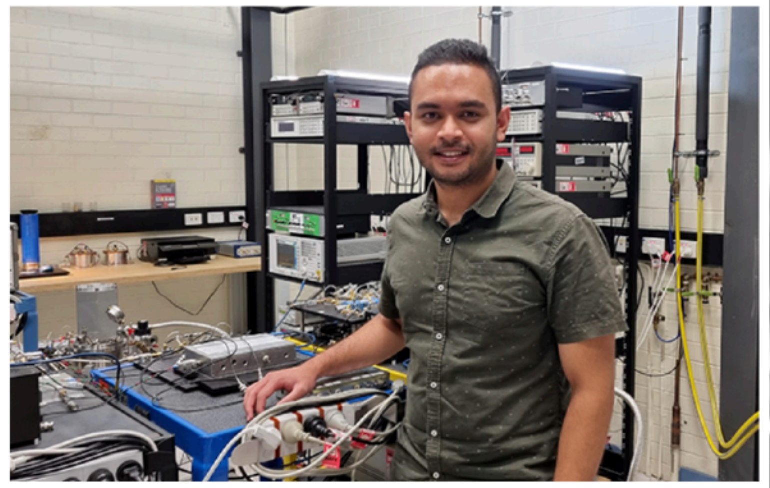
Dr Cindy Zhao
Deborah Jin Fellow—EQUS



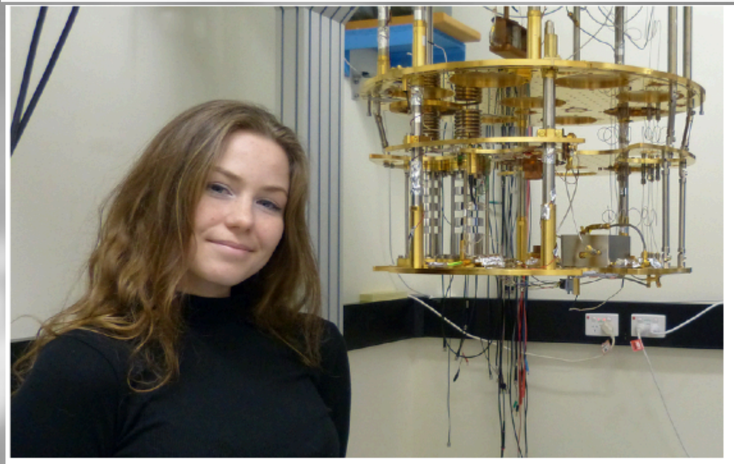
Dr Jeremy Bourhill
Postdoctoral Research Associate



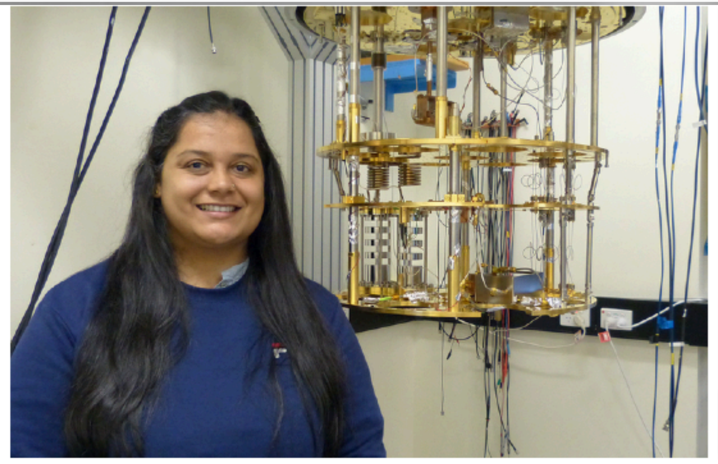
Elrina Hartman
PhD



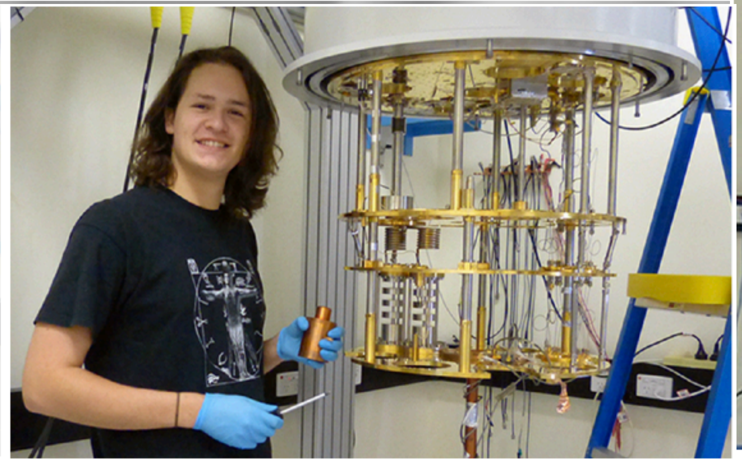
Steven Samuels
PhD



Emma Paterson
PhD



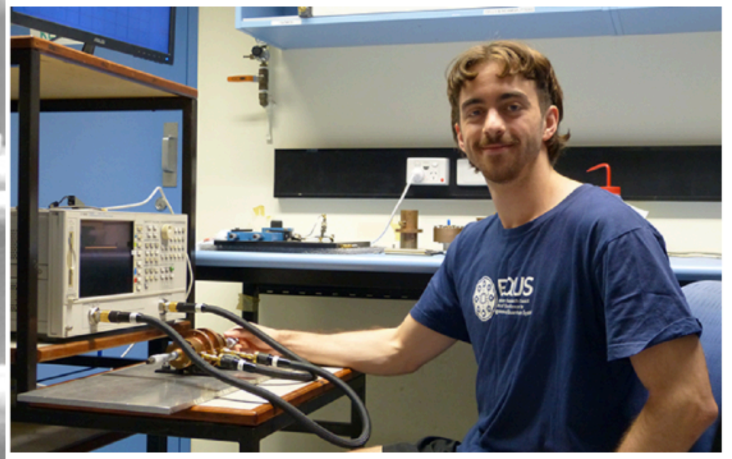
Sonali Parashar
Master of Physics—Coursework and Dissertation



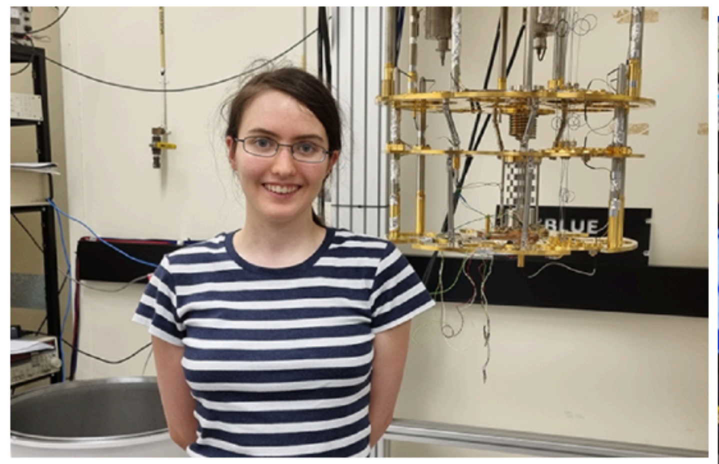
Tim Holt
BSc (Frontier Physics) and Master of Physics

Aaron Quiskamp
PhD

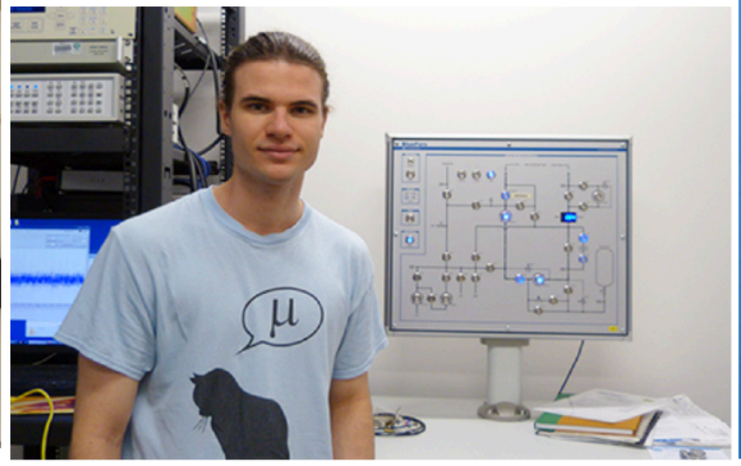
Teehani Ralph
Master of Professional Engineering



Michael Hatzon
BPhil (Hons) Honours Dissertation



Emily Waterman
BPhil (Hons) Honours Dissertation



Ashley Johnson
BPhil (Hons) Honours Dissertation

Robert Crew
PhD

Quantum Technologies and Dark Matter Research Lab

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

ARC Centre of Excellence for Dark Matter Particle Physics

The University of Western Australia — Seek Wisdom

Back up slides

QDM
Quantum Technologies and Dark Matter Research Lab

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

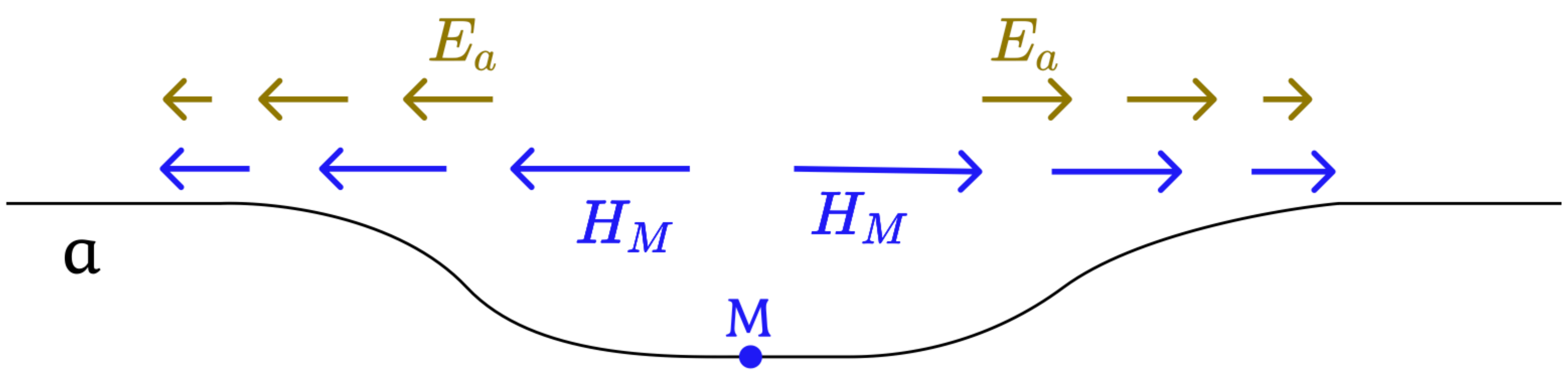
ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

THE UNIVERSITY OF
WESTERN
AUSTRALIA
SEEK WISDOM

Slide From Anton Sokolov

AXION EFFECTS ON CHARGED PARTICLES

- An analogue of the Witten effect in axion electrodynamics:



$$\nabla \cdot \mathbf{E}_a = g_{a\gamma\gamma}\, \mathbf{H}_0 \cdot \nabla a$$

fictitious charge density

- Magnetic monopole looks like a dyon
- No new charged particle states are produced: fictitious charge can only be generated at distance scales $r \gtrsim \omega_a^{-1}$, and so it is never point-like in a given axion EFT
- Axion shift symmetry is preserved since dependence only on ∇a