New techniques to search for wave-like dark matter and test fundamental physics using precision low-energy measurements.

Michael Tobar Quantum Technologies and Dark Matter Laboratory

ACADEMIC (3)	POSTDOCS (5)	PHD STUDENTS (4)	UNDERGRAD STUDENTS (6)
Michael Tobar	Cindy Zhao	Elrina Hartman	Sonali Parashar (MSc)
Eugene Ivanov	Jeremy Bourhill	Steven Samuels	Michael Hatzon (Hons)
Maxim Goryachev	Graeme Flower	Emma Paterson	Emily Waterman (Hons)
	William Campbell	Robert Crew	Ashley Johnson (MSc)
	Aaron Quiskamp		Tim Holt (MSc)
			Teehani Ralph (MPE)

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

19th PATRAS
19th Sept 2024

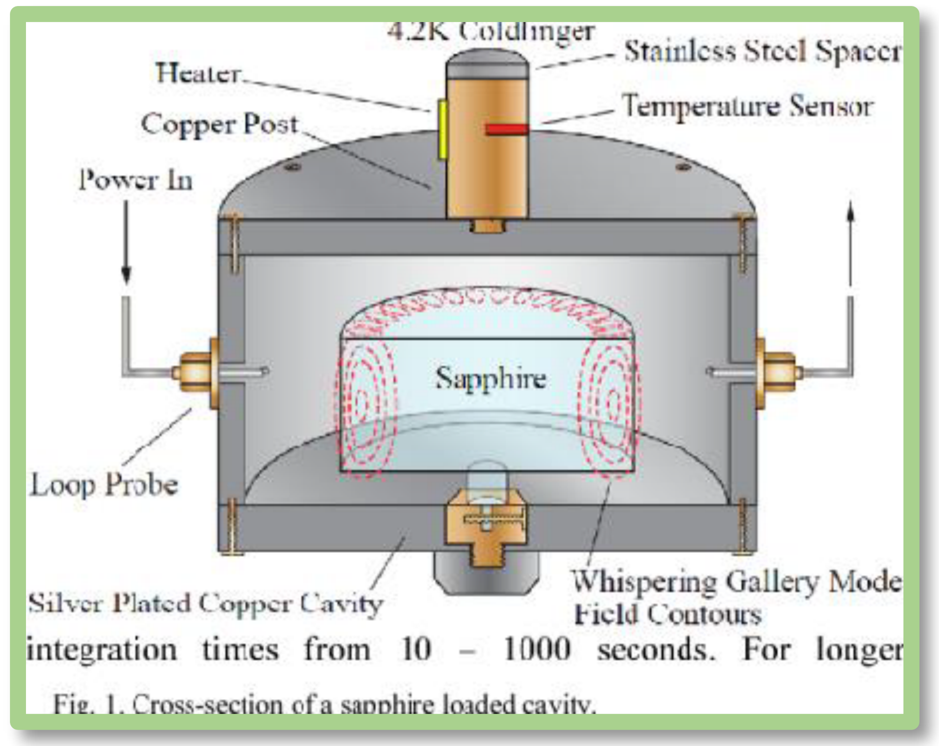
QDM Lab Precision Metrology: See www.qdmlab.com

Metrological Systems:

Science of precise measurement → **Physics at low energies**

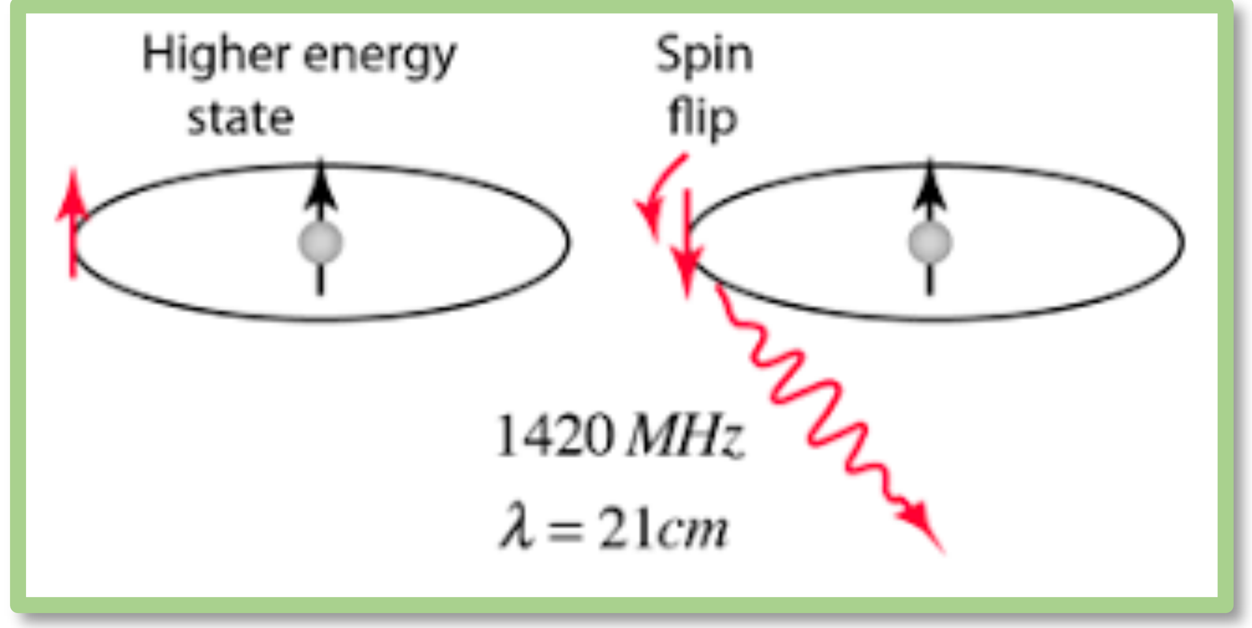
Photonic

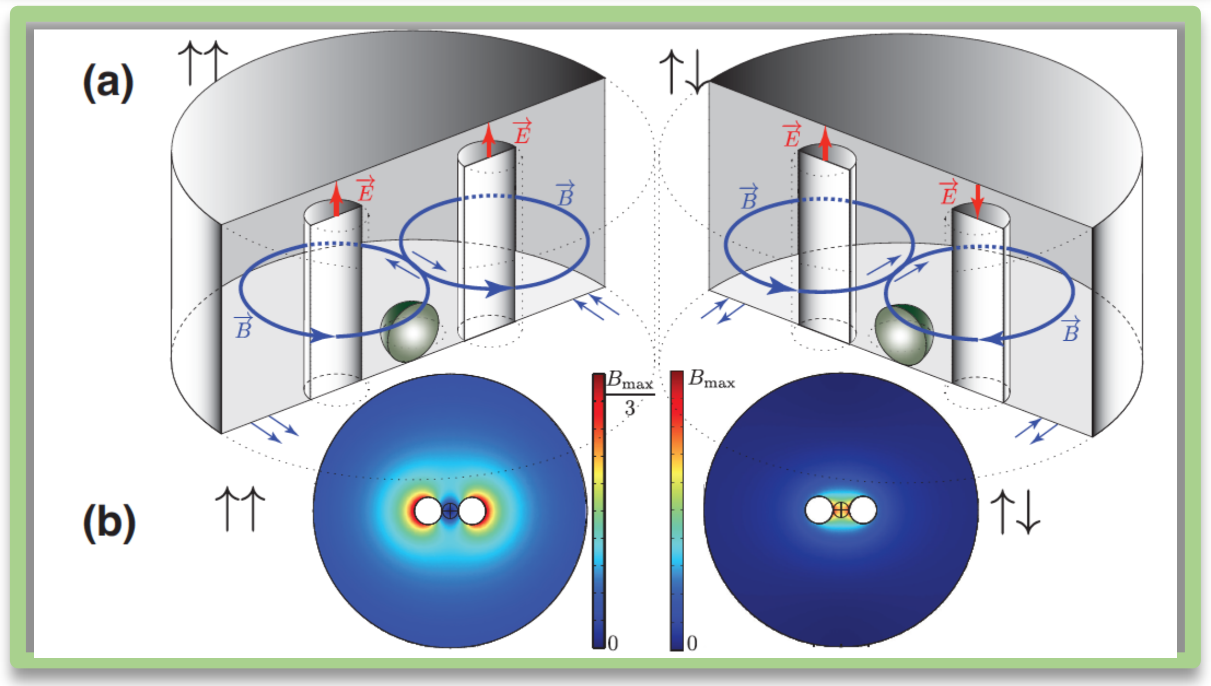
- WGM Resonators
- Specially Designed Microwave Cavities



Atomic/Spins

- H - Maser
- Atomic Clocks
- Spin Waves
- Spin Ensembles in Solids



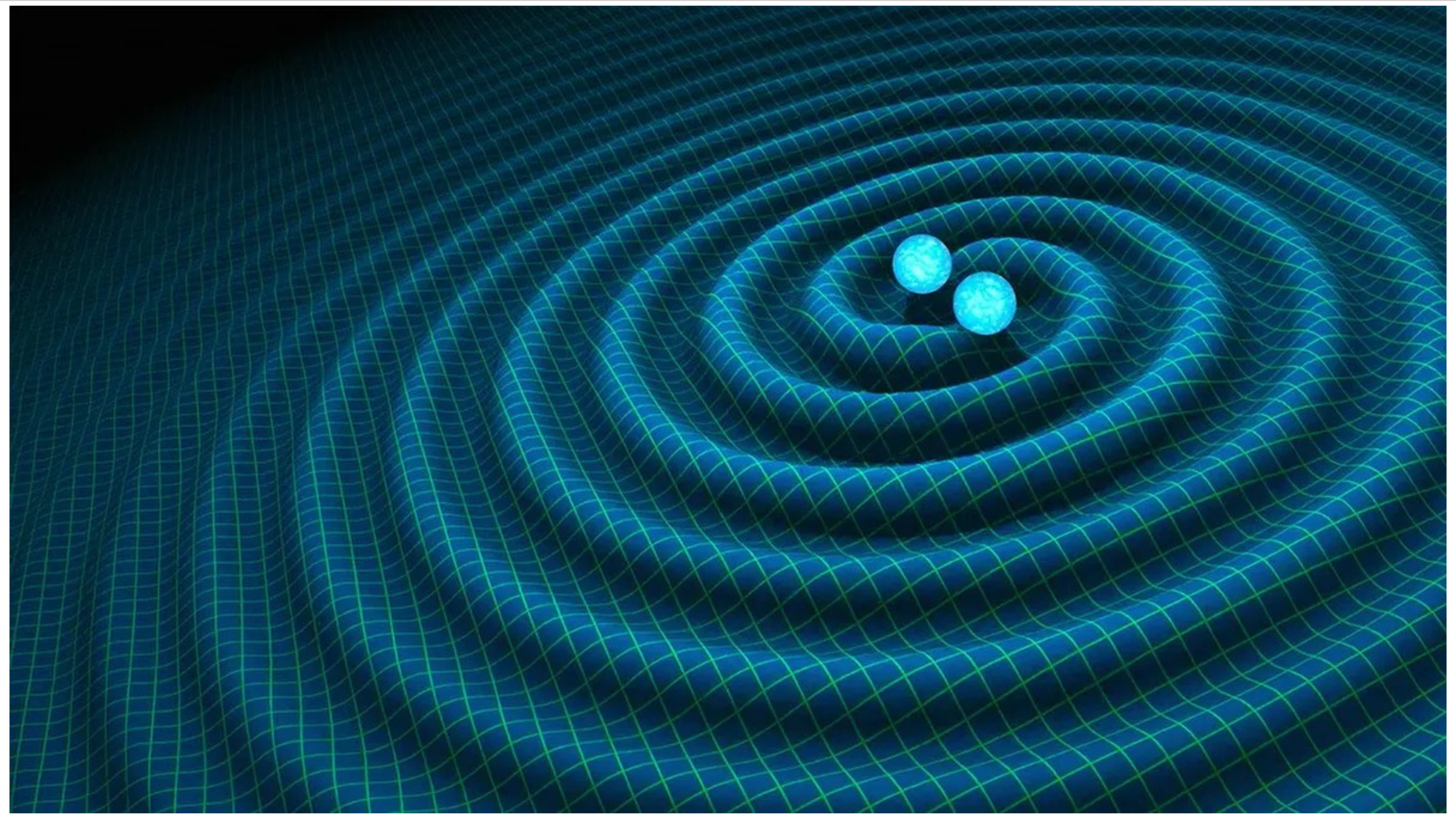


Acoustic

- Superfluid
- BAW Resonator

Motivation: Fundamental Physics

General Relativity



Quantum gravity

Dark Matter

High frequency gravitational waves

Lorentz invariance violations

Minimum length

Metrology helps us search for physics beyond the standard model

The standard model

Science of precise measurement → Physics at low energies

ORGAN: Axion Dark Matter

RECENT PUBLICATIONS

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]*

arXiv > hep-ex > arXiv:2407.18586

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High Energy Physics – Experiment

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PHYSICAL REVIEW LETTERS **132,** 031601 (2024)

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

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ANYON AXION Helicity

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

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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

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PHYSICAL REVIEW D **105**, 045009 (2022)

Poynting vector controversy in axion modified electrodynamics

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

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

Axion ED Poynting Theorem: Standardised way of Calculating Sensitivity

Low Noise Oscillators

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1642 IEEE MICROWAVE AND WIRELESS TECHNOLOGY LETTERS, VOL. 33, NO. 12, DECEMBER 2023

Frequency Stable Microwave Sapphire Oscillators

Eugene N. Ivanov and Michael E. Tobar, *Fellow, IEEE*

1090 IEEE MICROWAVE AND WIRELESS TECHNOLOGY LETTERS, VOL. 33, NO. 7, JULY 2023

Power-to-Frequency Conversion in Cryogenic Sapphire Resonators

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Tests of Quantum Mechanics / Gravity

PHYSICAL REVIEW A **107**, 042209 (2023)

Energy-level shift of quantum systems via the scalar electric Aharonov-Bohm effect

R. Y. Chiao,[1,*] H. Hart,[1,†] M. Scheibner,[1,‡] J. Sharping,[1,§] N. A. Inan,[1,2,3,||] D. A. Singleton,[3,¶] and M. E. Tobar[4,#]
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Scalar gravitational Aharonov–Bohm effect: Generalization of the gravitational redshift

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PHYSICAL REVIEW D **108,** 102006 (2023)

Improved constraints on minimum length models with a macroscopic low loss phonon cavity

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Detect Gravitons?

arXiv > astro-ph > arXiv:2406.16898

Detecting kHz gravitons from a neutron star merger with a multi-mode resonant bar

Germain Tobar,[1] Igor Pikovski,[1,2] and Michael E. Tobar[3]
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RECENT PUBLICATIONS

Low Noise Oscillators

1642 IEEE MICROWAVE AND WIRELESS TECHNOLOGY LETTERS, VOL. 33, NO. 12, DECEMBER 2023

Frequency Stable Microwave Sapphire Oscillators

Eugene N. Ivanov and Michael E. Tobar, *Fellow, IEEE*

1090 IEEE MICROWAVE AND WIRELESS TECHNOLOGY LETTERS, VOL. 33, NO. 7, JULY 2023

Power-to-Frequency Conversion in Cryogenic Sapphire Resonators

Eugene N. Ivanov and Michael E. Tobar, *Fellow, IEEE*

Detect Gravitons?

arXiv > astro-ph > arXiv:2406.16898

Detecting kHz gravitons from a neutron star merger with a multi-mode resonant bar

Germain Tobar,[1] Igor Pikovski,[1,2] and Michael E. Tobar[3]
[1] *Department of Physics, Stockholm University, SE-106 91 Stockholm, Sweden*
[2] *Department of Physics, Stevens Institute of Technology, Hoboken, New Jersey 07030, USA*
[3] *Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Hwy, 6009 Crawley, Western Australia.*

Detecting UHF GWs? MAGE

www.nature.com/scientificreports

scientific reports

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OPEN **The multi-mode acoustic gravitational wave experiment: MAGE**

William M. Campbell, Maxim Goryachev & Michael E. Tobar

Tests of Quantum Mechanics / Gravity

PHYSICAL REVIEW A **107**, 042209 (2023)

Energy-level shift of quantum systems via the scalar electric Aharonov-Bohm effect

R. Y. Chiao,[1,*] H. Hart,[1,†] M. Scheibner,[1,‡] J. Sharping,[1,§] N. A. Inan,[1,2,3,||] D. A. Singleton,[3,¶] and M. E. Tobar[4,#]
[1] *University of California, School of Natural Sciences, P.O. Box 2039, Merced, California 95344, USA*
[2] *Clovis Community College, 10309 N. Willow, Fresno, California 93730, USA*
[3] *Department of Physics, California State University Fresno, Fresno, California 93740-8031, USA*
[4] *Quantum Technologies and Dark Matter Laboratories, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*

Scalar gravitational Aharonov–Bohm effect: Generalization of the gravitational redshift

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Published Online: 28 August 2024

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Michael E. Tobar,[a)] Michael T. Hatzon, Graeme R. Flower, and Maxim Goryachev

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Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, Crawley, Washington 6009, Australia

PHYSICAL REVIEW D **108**, 102006 (2023)

Improved constraints on minimum length models with a macroscopic low loss phonon cavity

William M. Campbell,[*] Michael E. Tobar, and Maxim Goryachev[†]
Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Washington 6009, Australia

Serge Galliou
SUPMICROTECH-ENSMM, CNRS, Institut FEMTO-ST, 26 Rue de l'Épitaphe 25000 Besançon, France

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

MAGE

NEW SCALAR DM PROGRAM

ELECTROMAGNETIC TECHNIQUES

Resonant Axion Haloscopes @ UWA

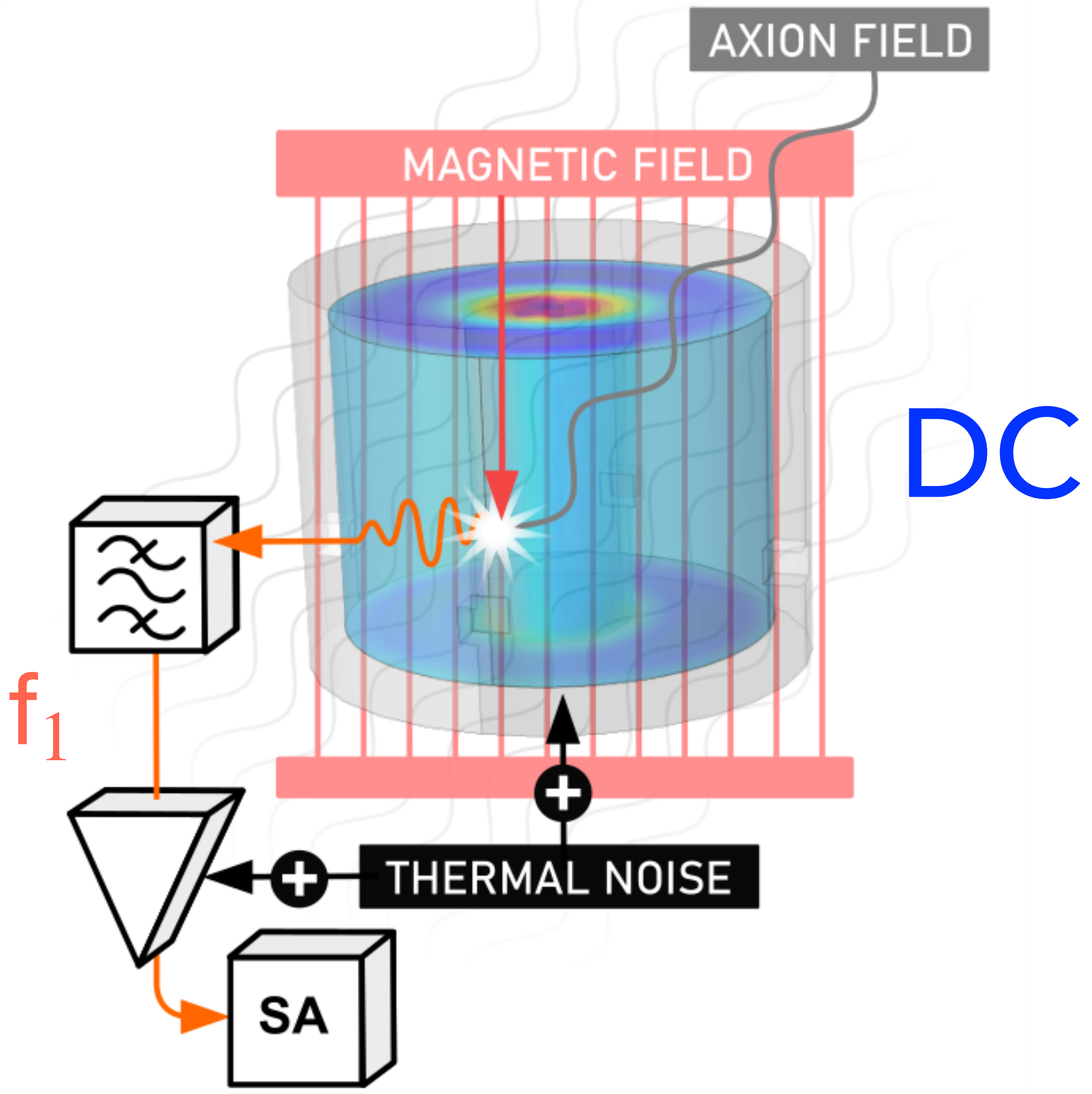
$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

- ORGAN
- UPLOAD

Resonant Axion Haloscopes @ UWA

$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

- ORGAN



- UPLOAD

Resonant Axion Haloscopes @ UWA

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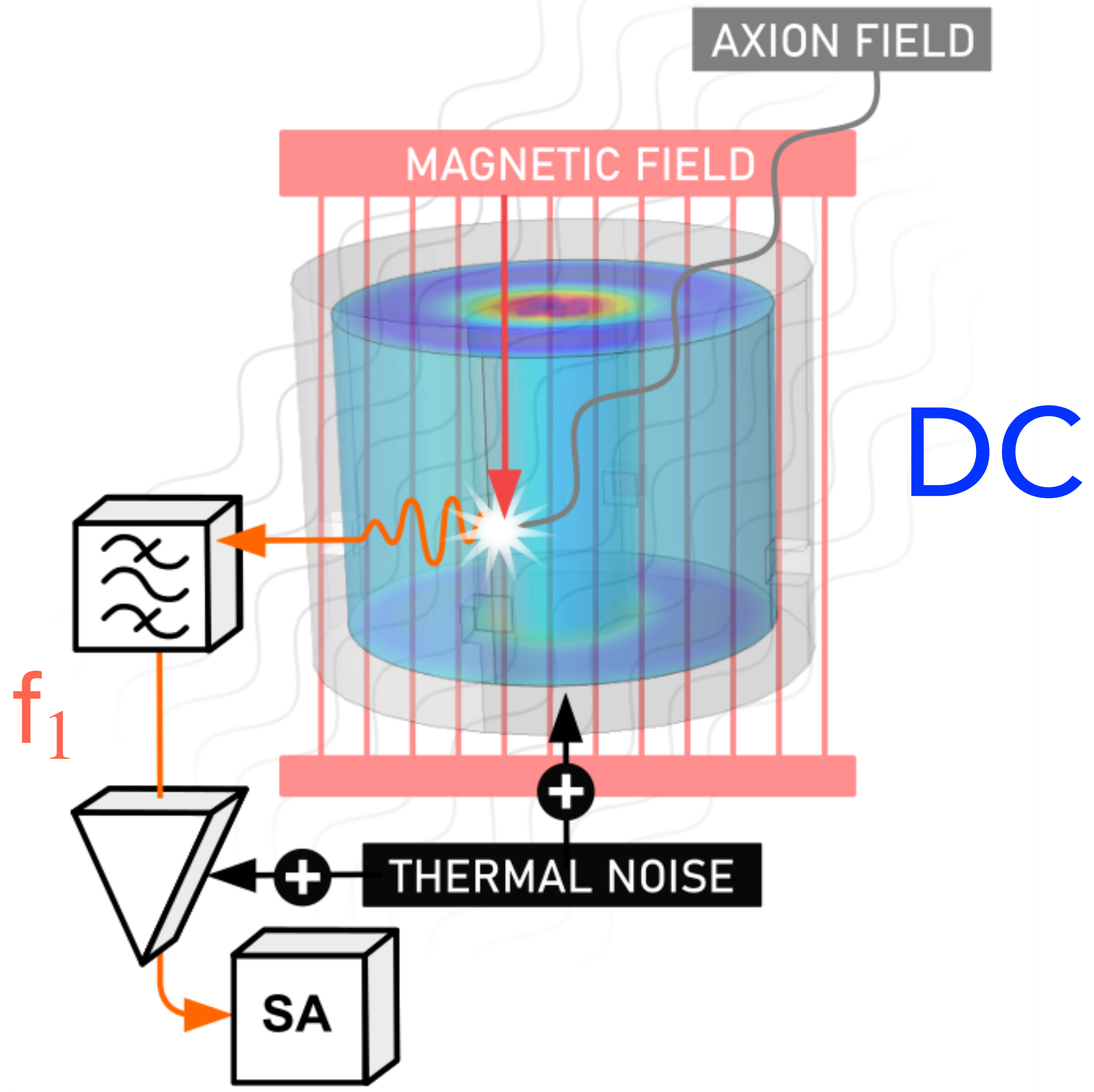
- UPLOAD



Photon 0, Back ground DC B field of surrounding magnet

Resonant Axion Haloscopes @ UWA

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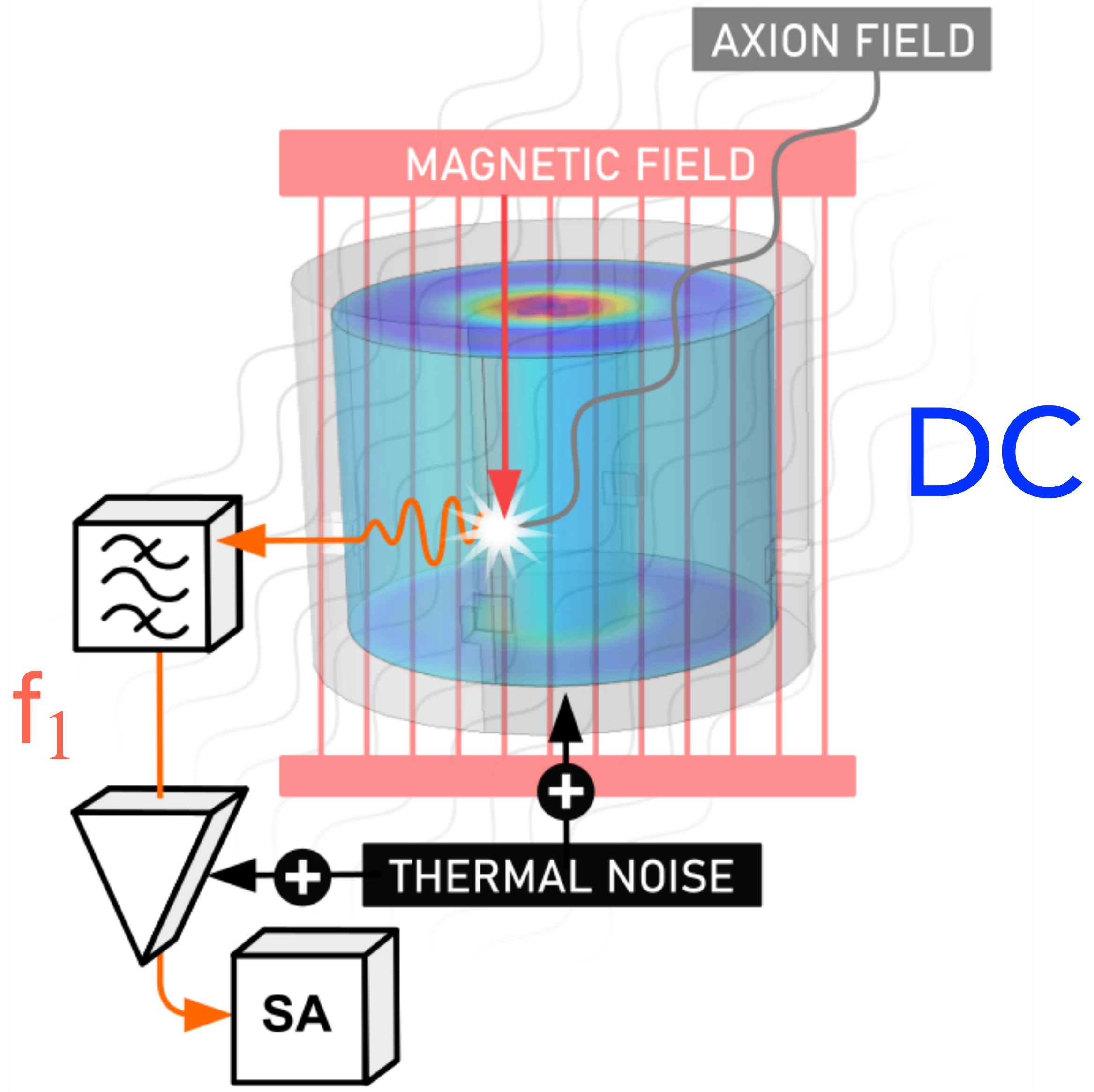
- ORGAN
- UPLOAD



Photon 0, Back ground DC B field of surrounding magnet

Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

Resonant Axion Haloscopes @ UWA

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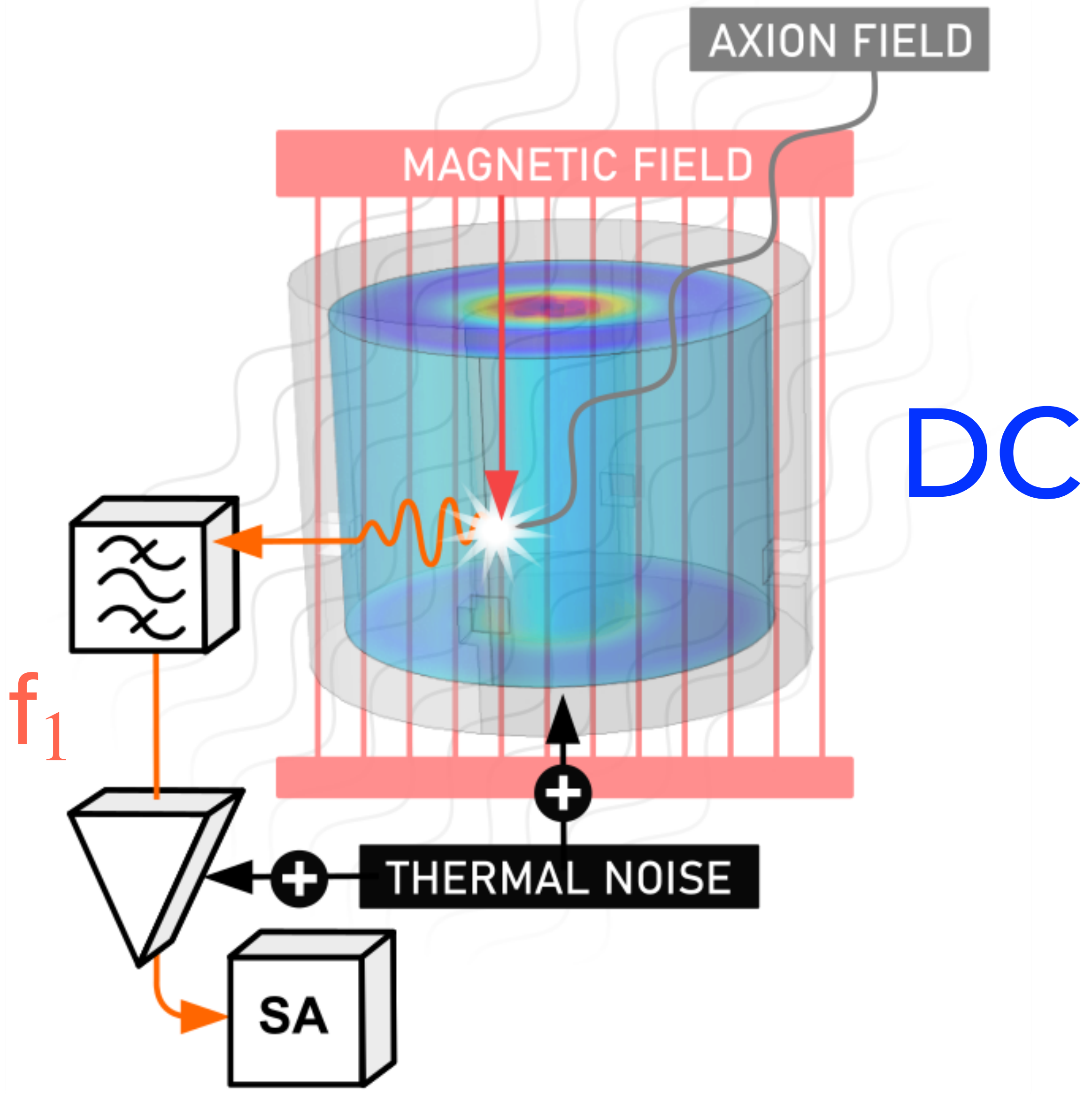

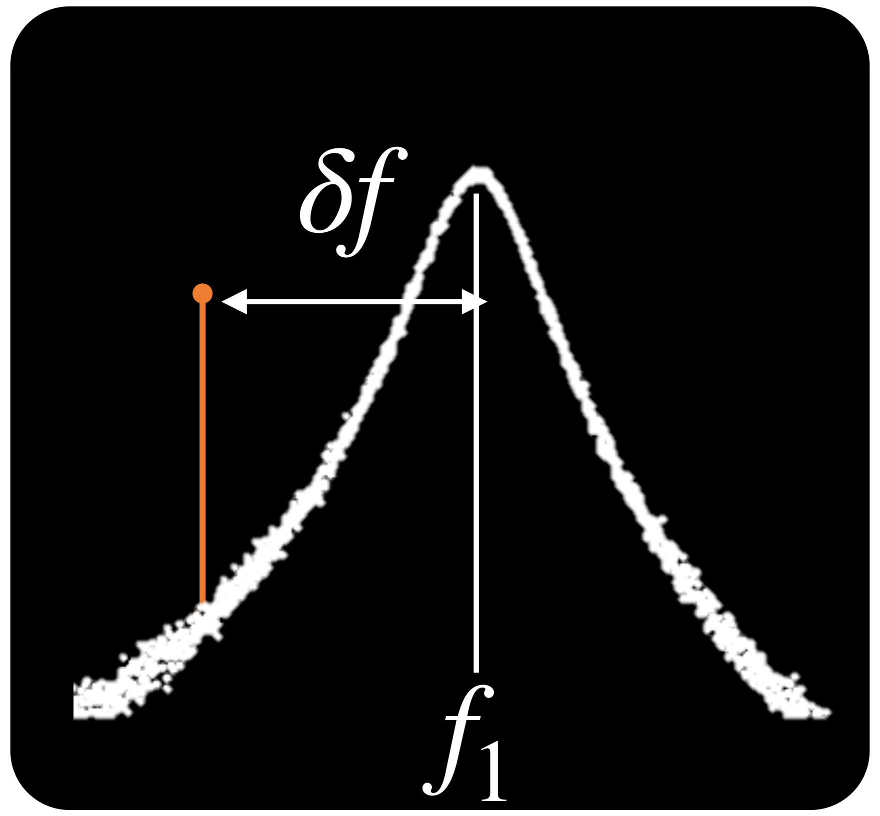

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- UPLOAD

Resonant Axion Haloscopes @ UWA

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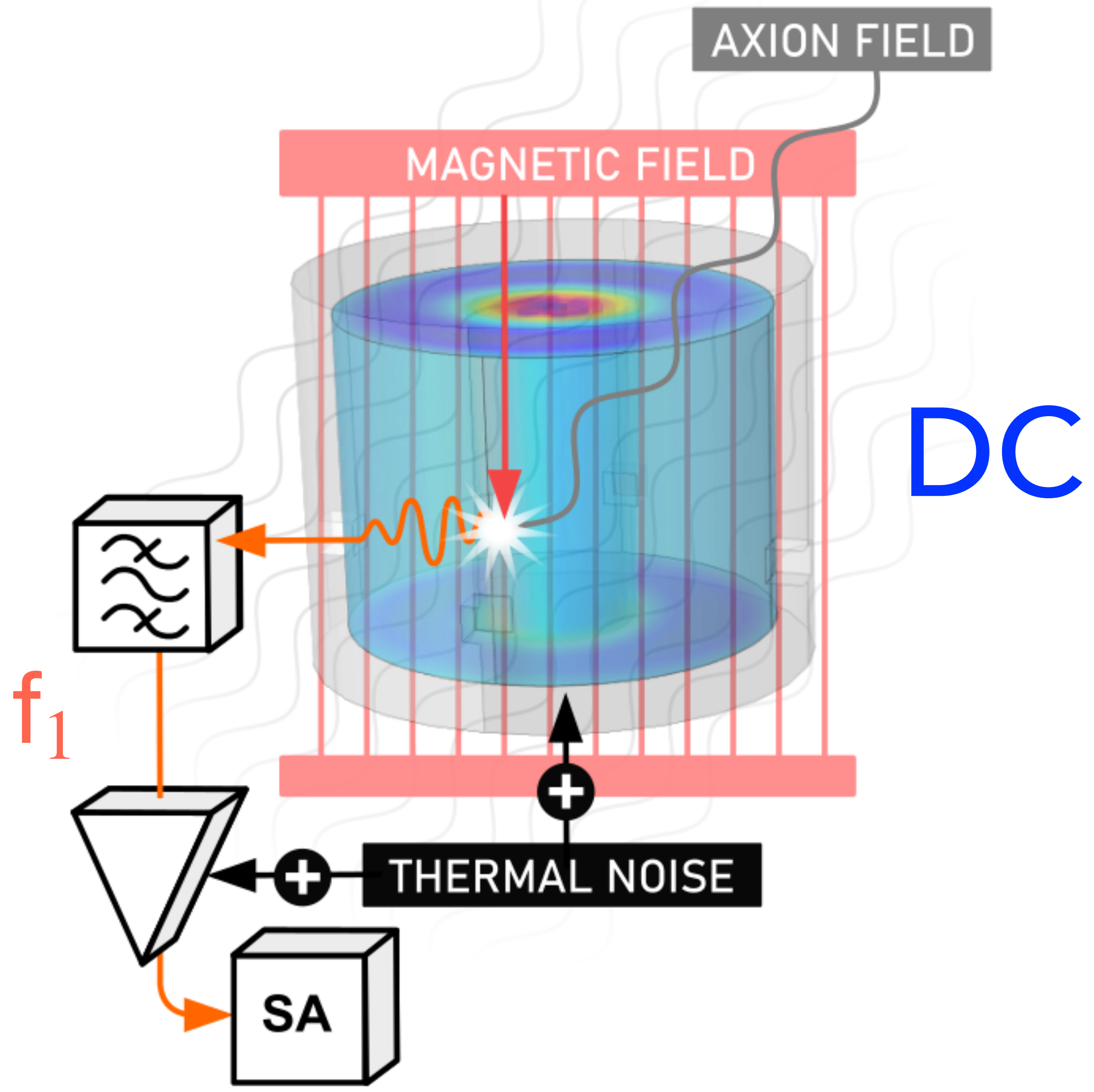
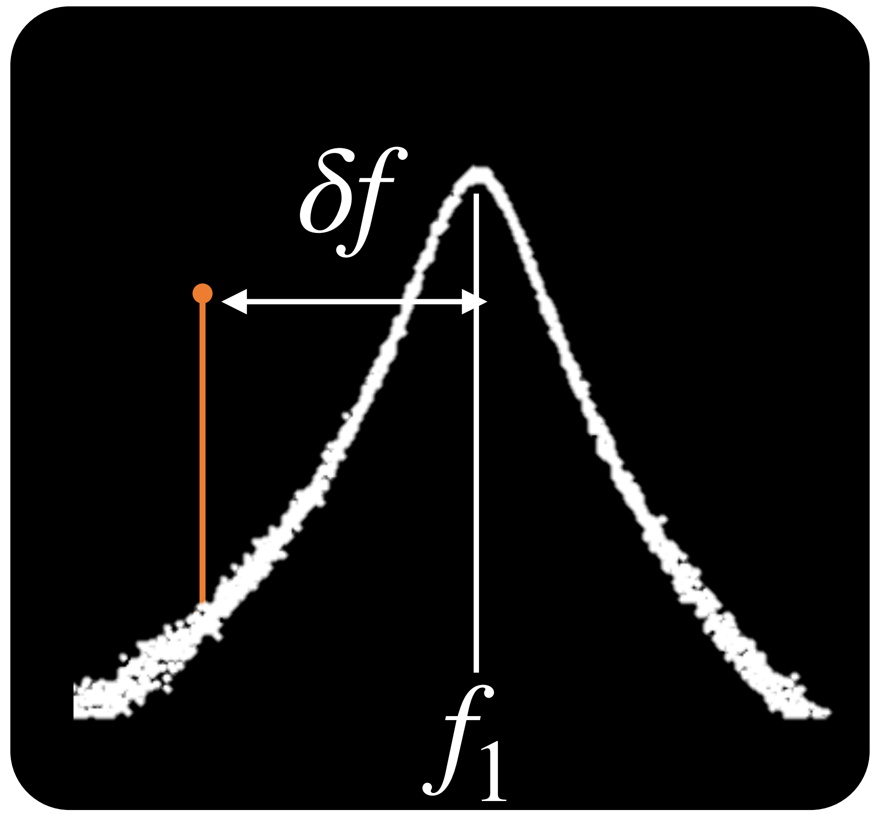
•ORGAN





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Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

eg.
- ADMX
- ORGAN (UWA)
- CAPP
- HAYSTAC

•UPLOAD

Resonant Axion Haloscopes @ UWA

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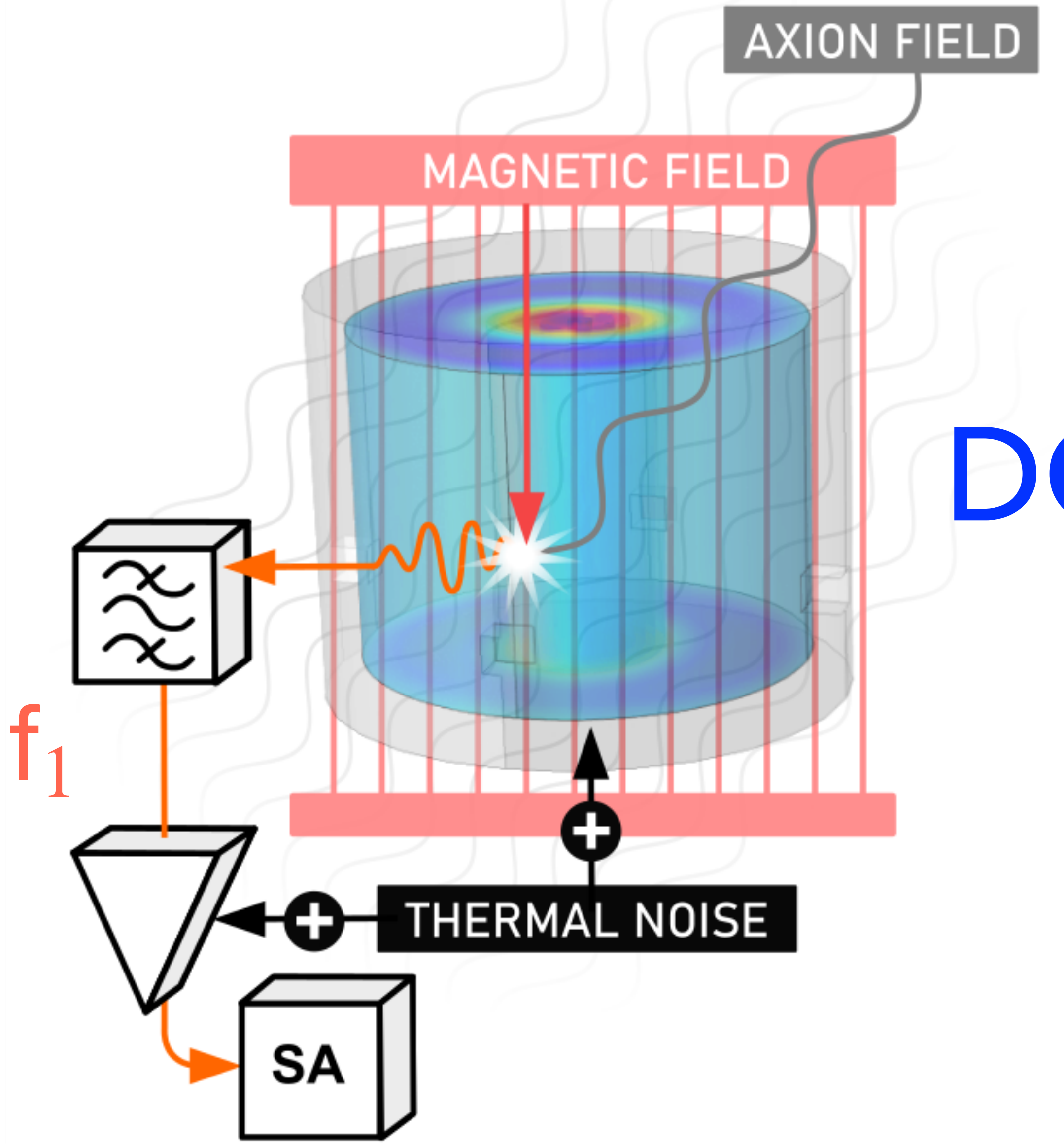
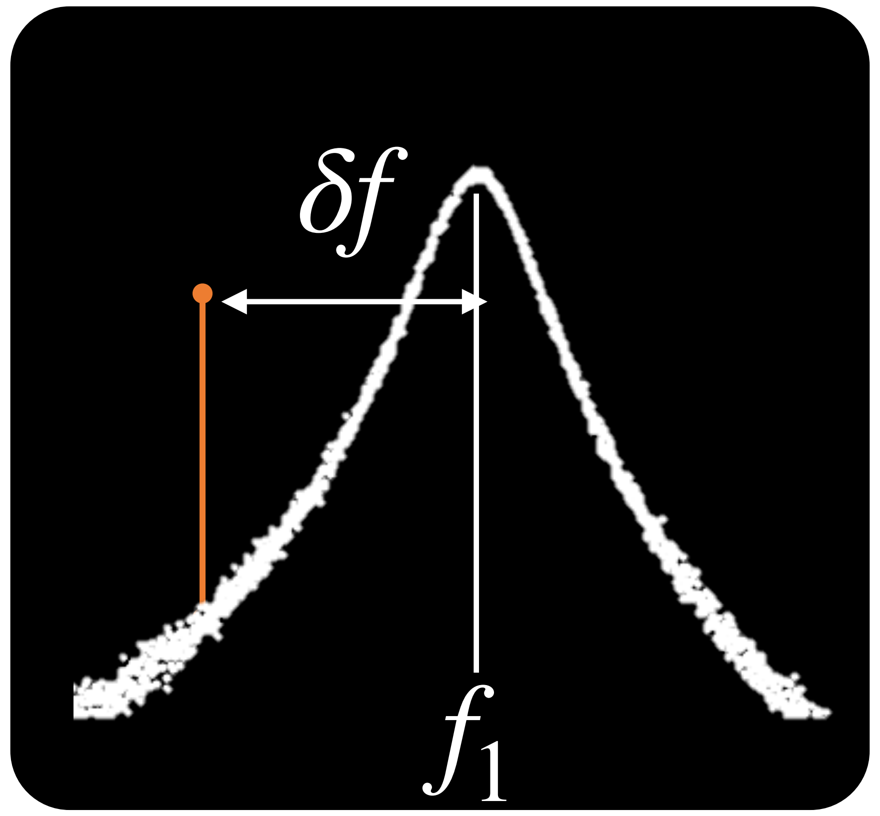
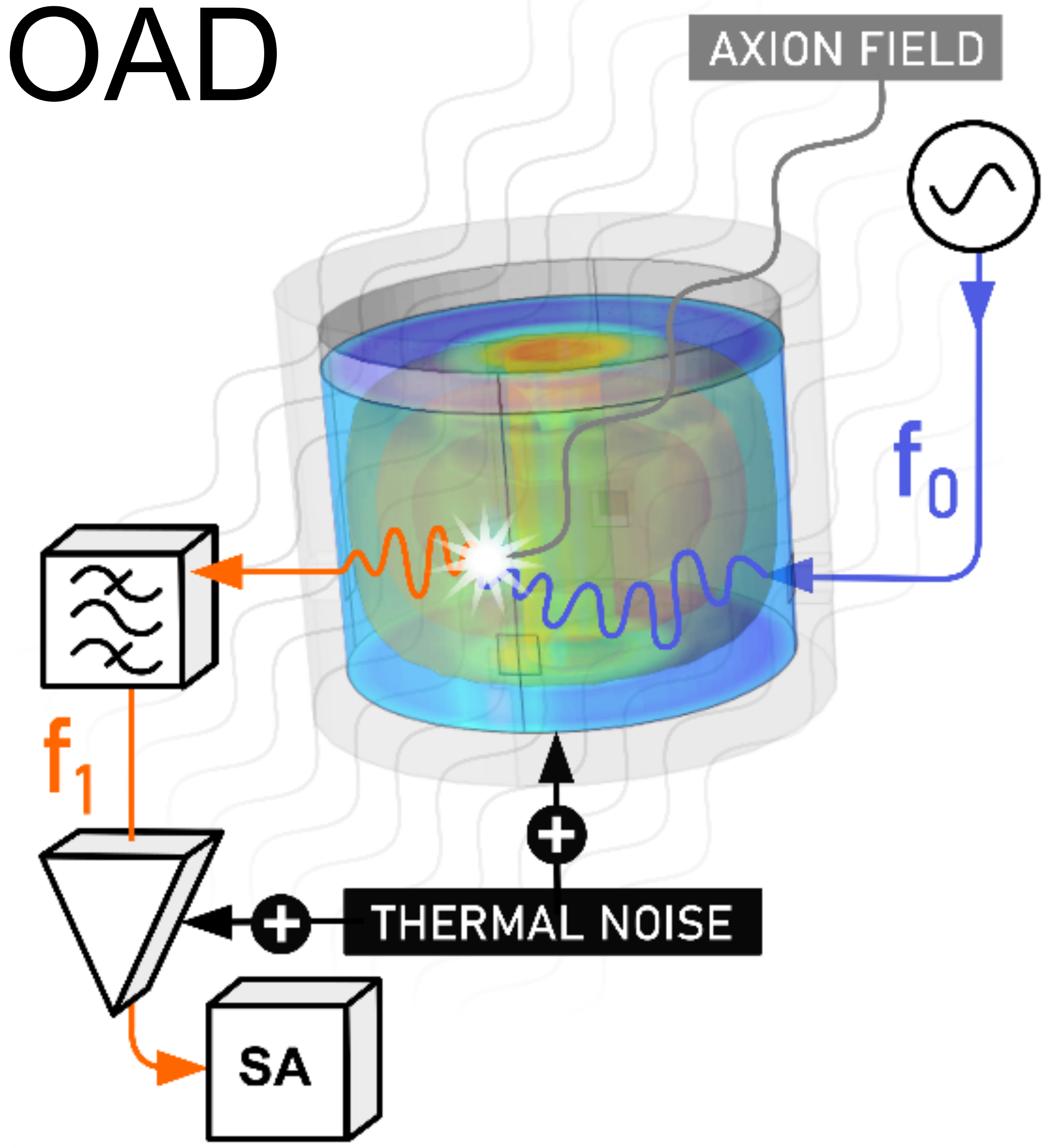


DC



- UPLOAD



AC

Photon 0, Back ground DC B field of surrounding magnet

Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

eg.
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- ORGAN (UWA)
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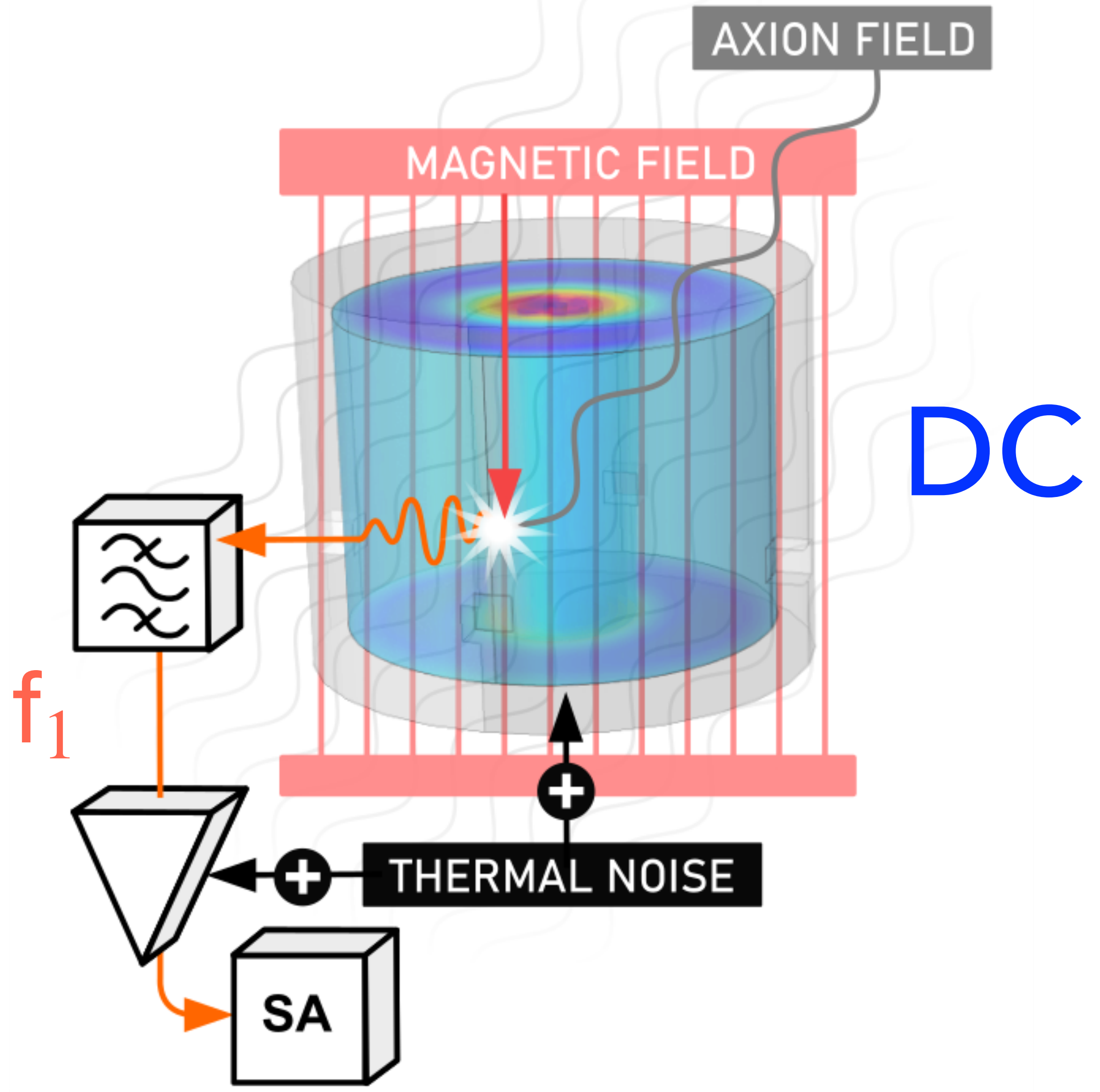
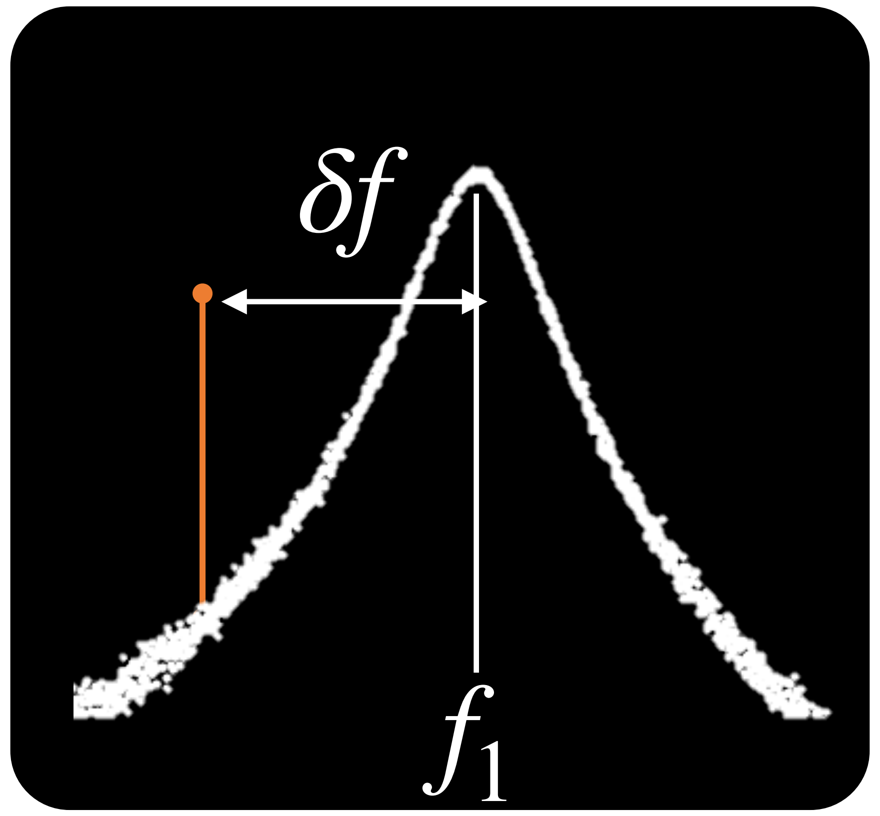
Resonant Axion Haloscopes @ UWA

$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

- ORGAN





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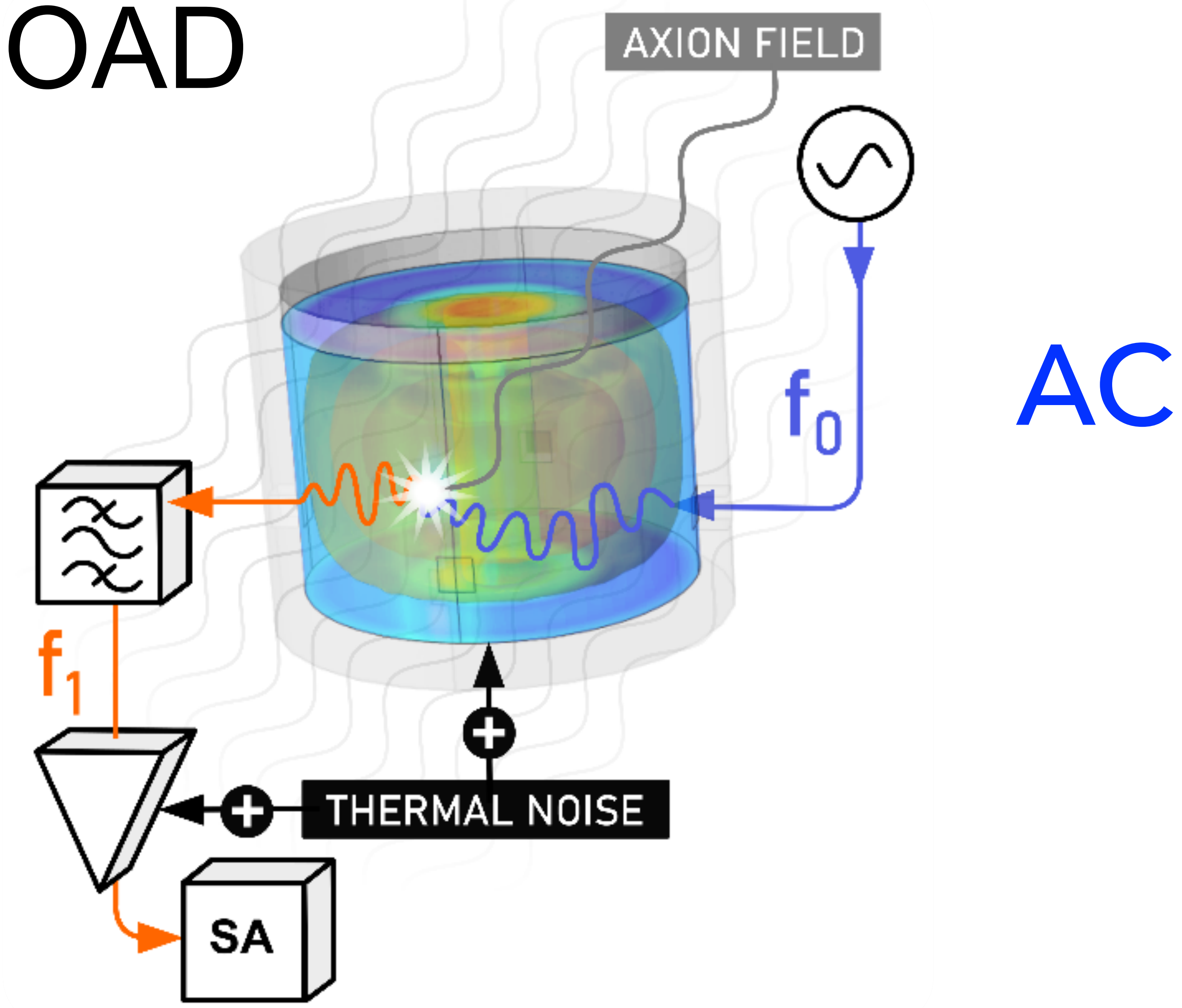


Photon 0, Back ground DC B field of surrounding magnet

Photon 1: E field of cavity's resonant transverse magnetic mode, $m_a = f_1 + \delta f$

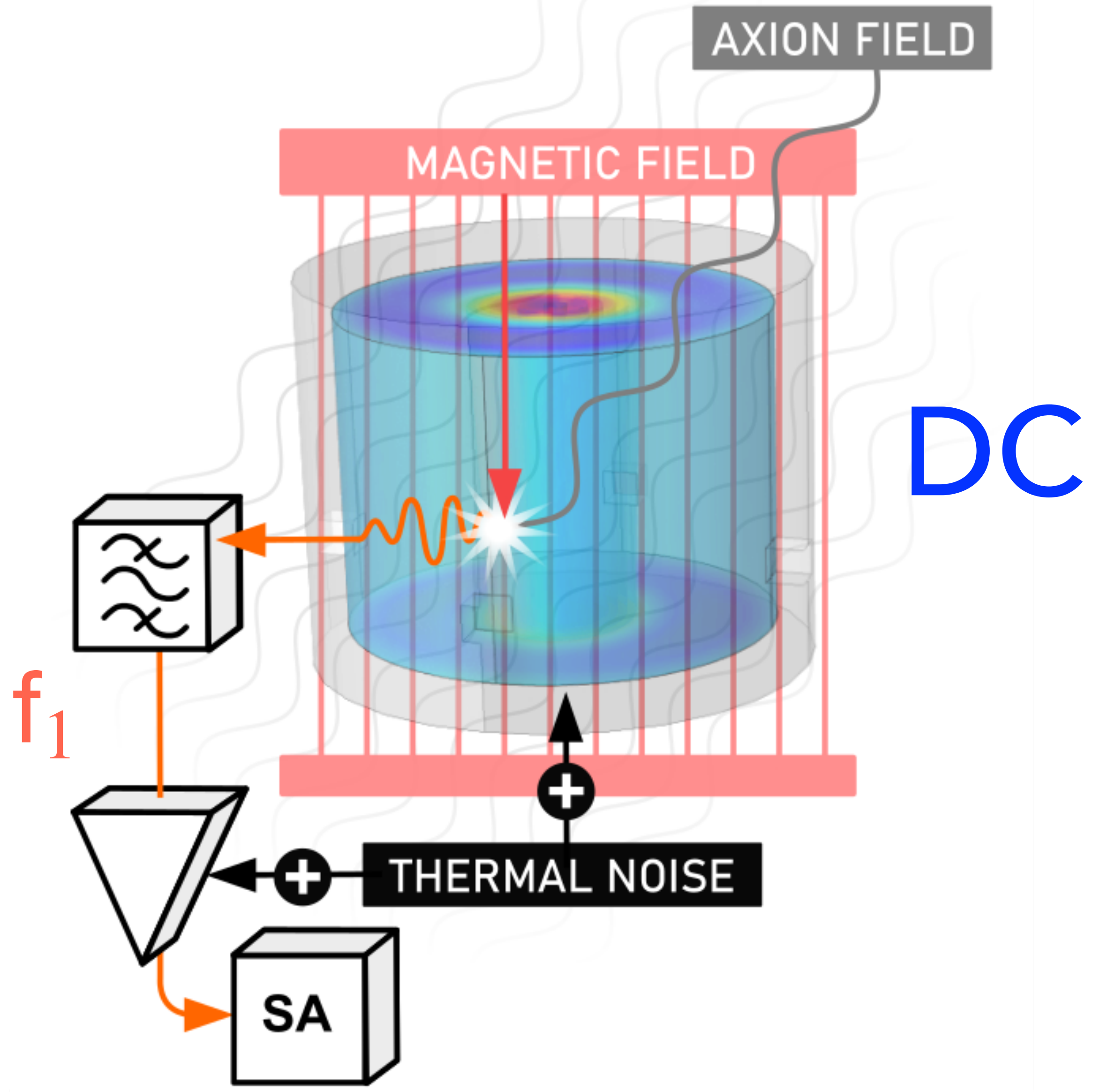
eg.
- ADMX
- ORGAN (UWA)
- CAPP
- HAYSTAC

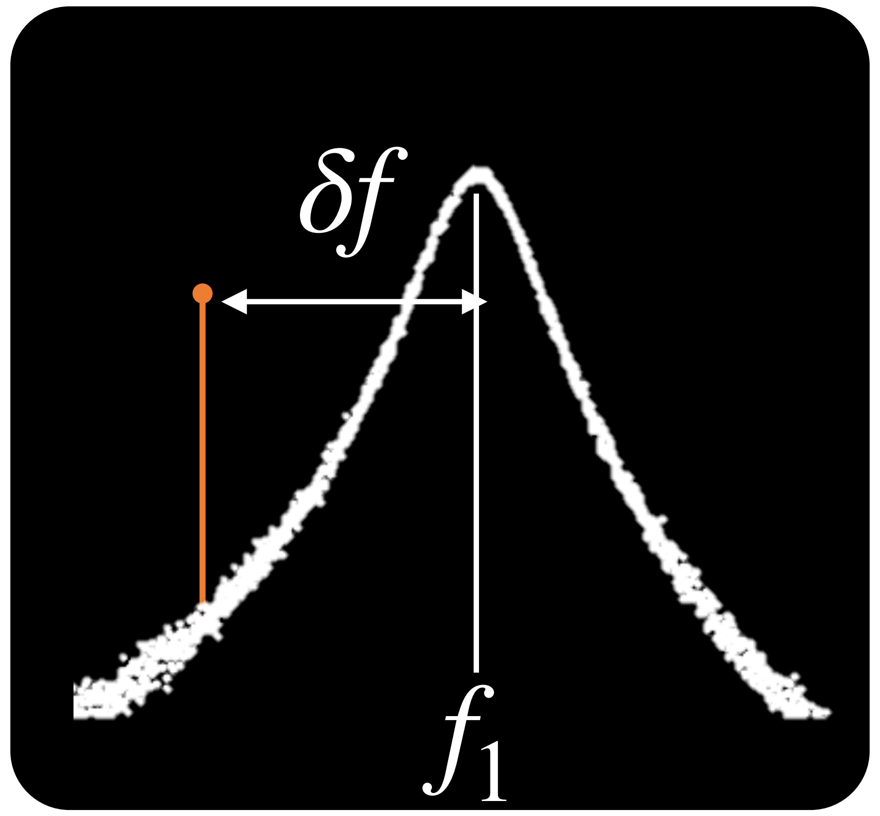
- Use a mode 0 as the background "magnetic field" AC source
- Two modes in one cylindrical cavity
- Upconversion limit $m_a = |f_1 - f_0| + \delta f$

Resonant Axion Haloscopes @ UWA

$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

•ORGAN





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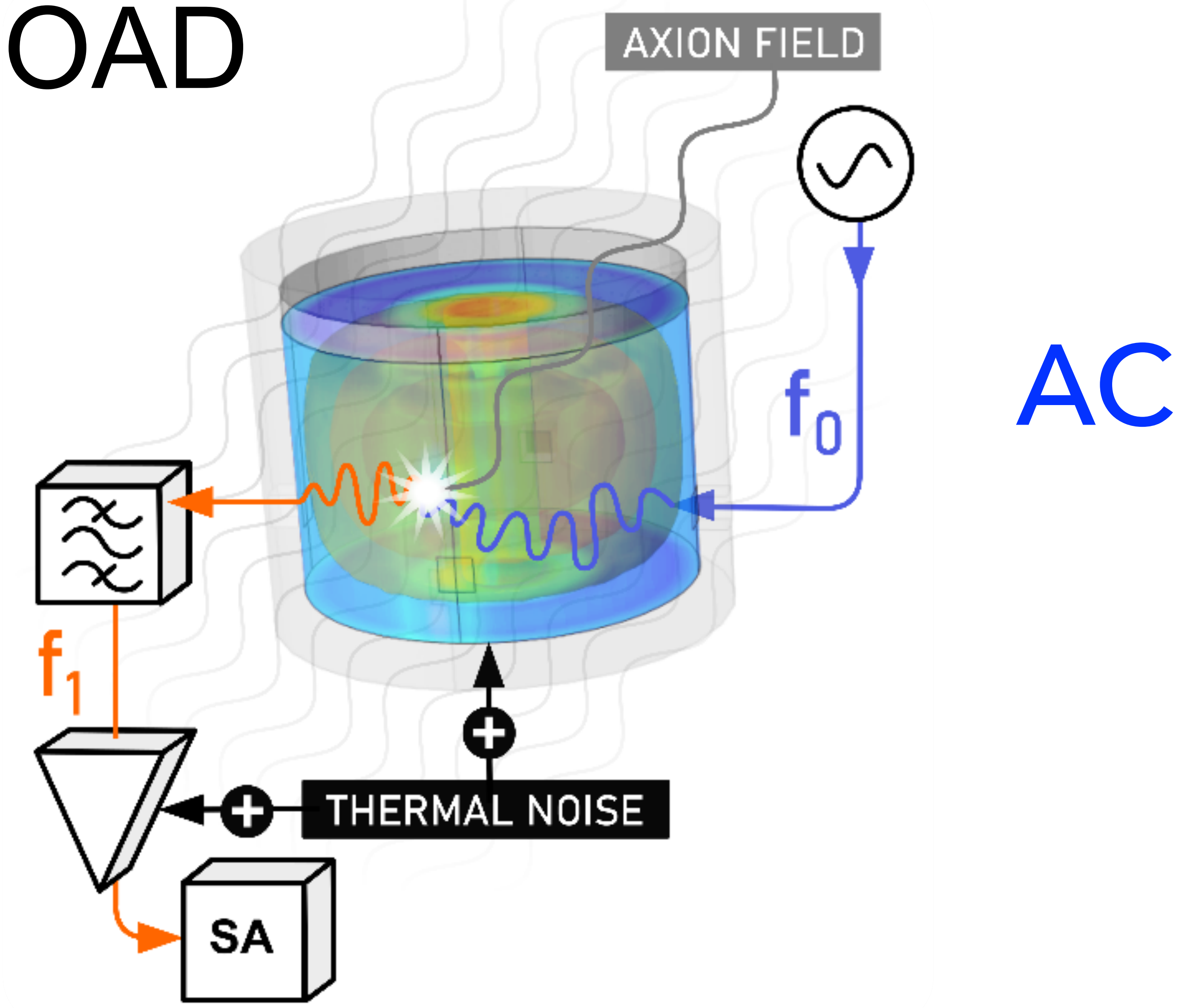

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eg.
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•ORGAN (UWA)
•CAPP
•HAYSTAC

Photon 1: Transverse Magnetic Mode

(Longitudinal Electric Ez)

Resonant Axion Haloscopes @ UWA

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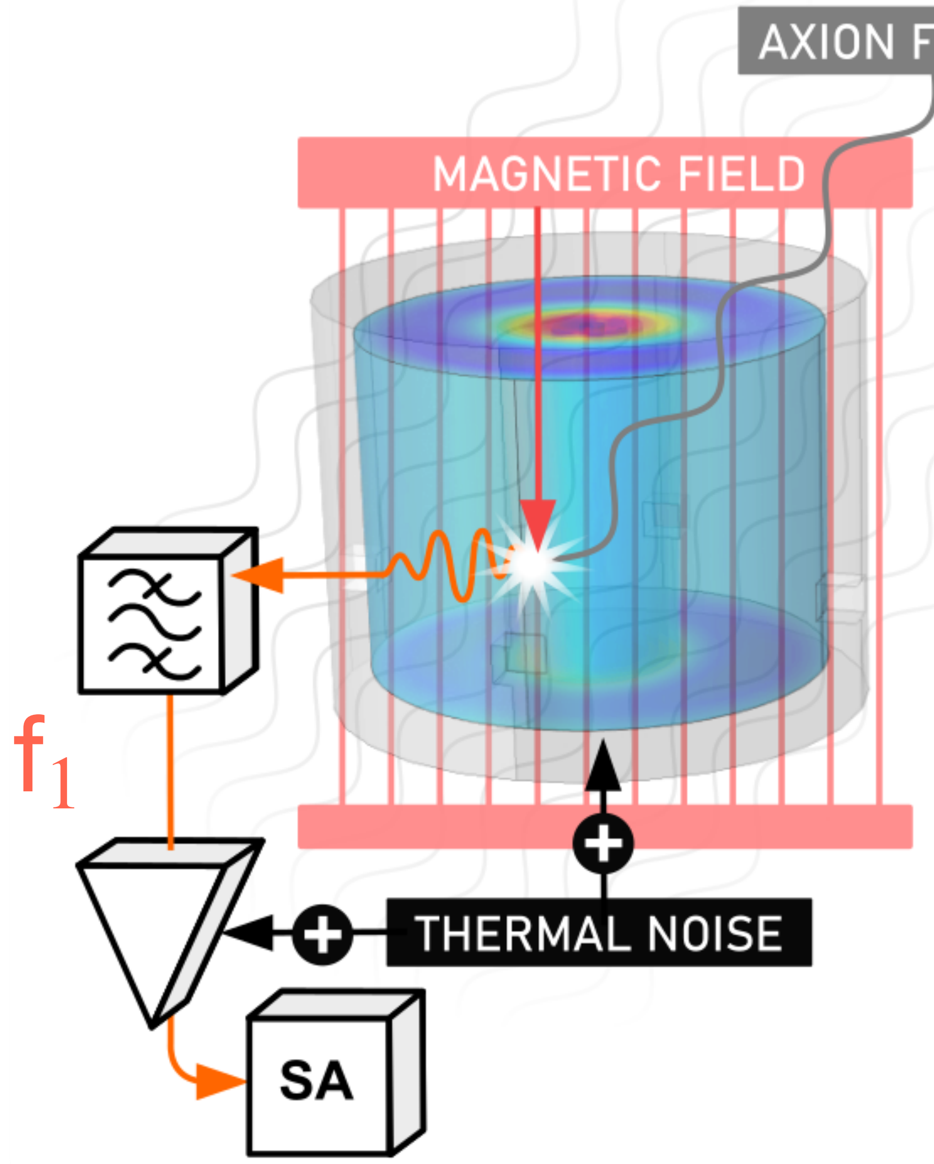

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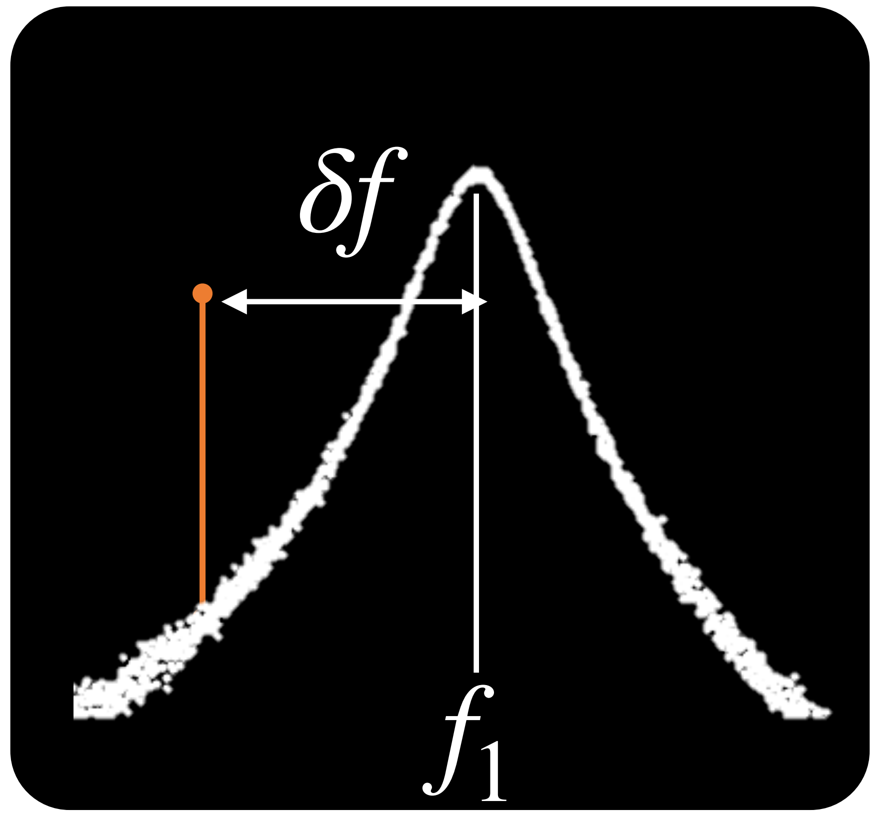

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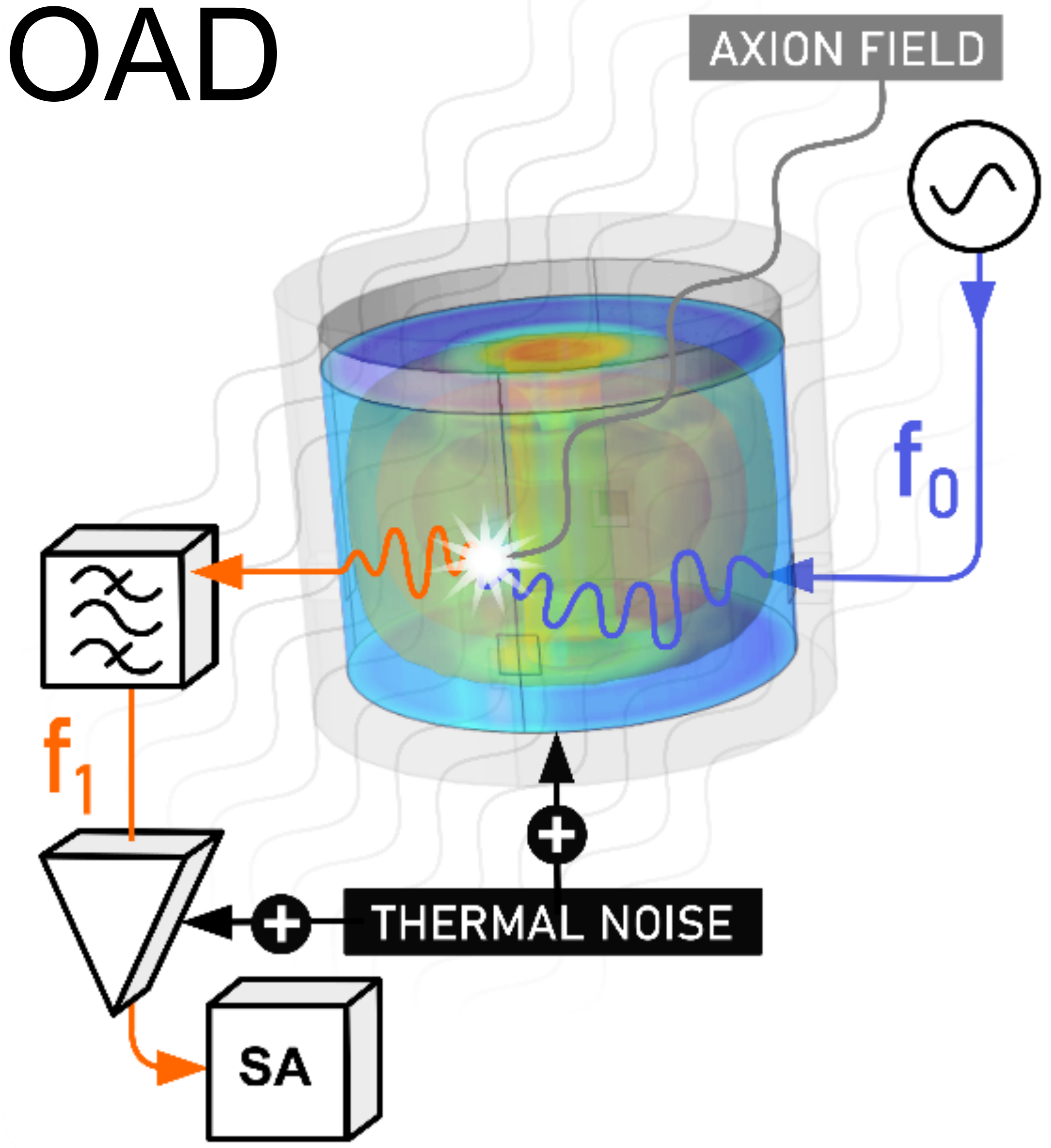

AC

- Use a mode 0 as the background "magnetic field" AC source
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- Upconversion limit $m_a = |f_1 - f_0| + \delta f$

Photon 1: Transverse Magnetic Mode

(Longitudinal Electric Ez)

Photon 0: Transverse Electric Mode

(Longitudinal Magnetic Bz)

Resonant Axion Haloscopes @ UWA

$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

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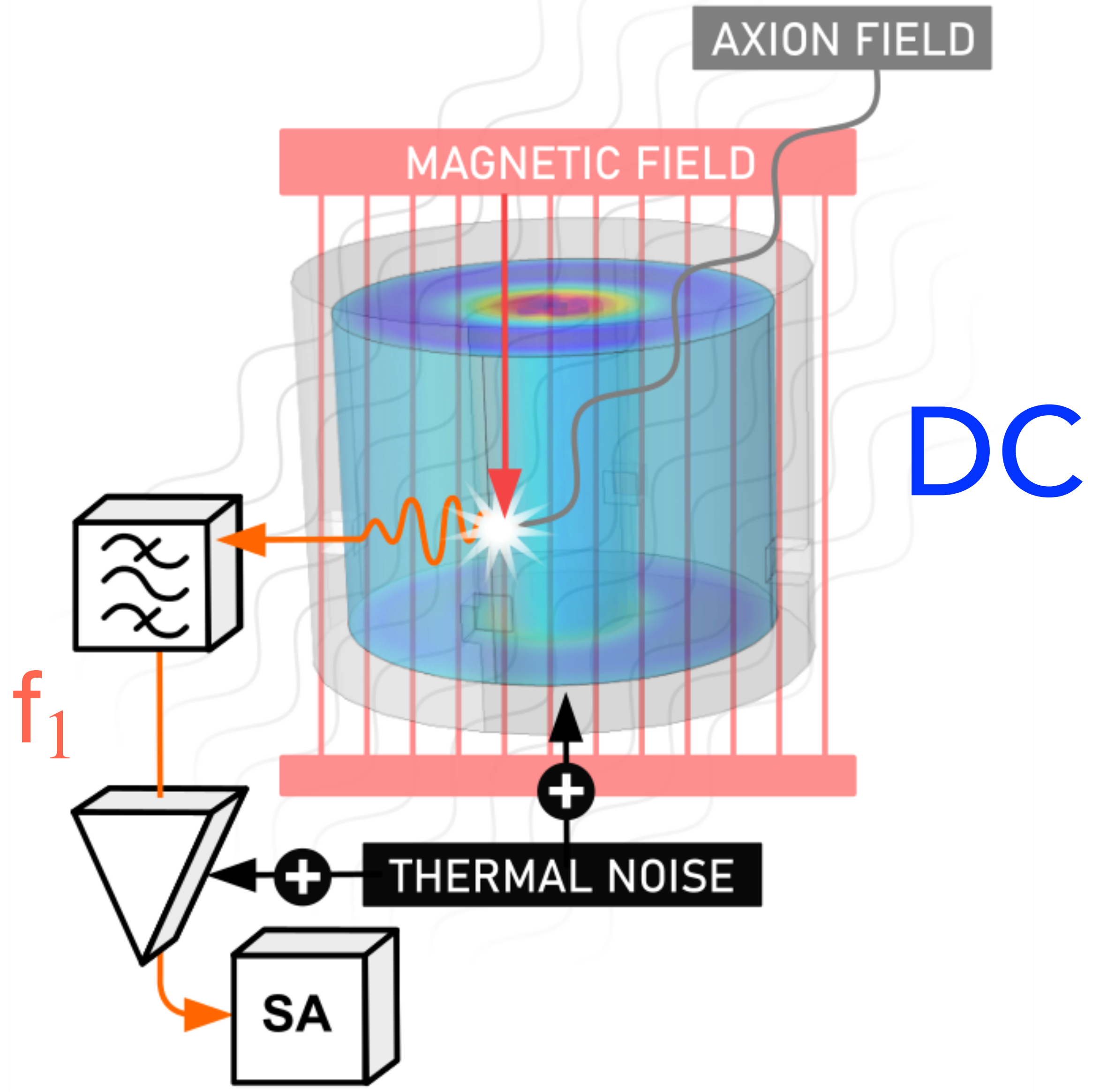

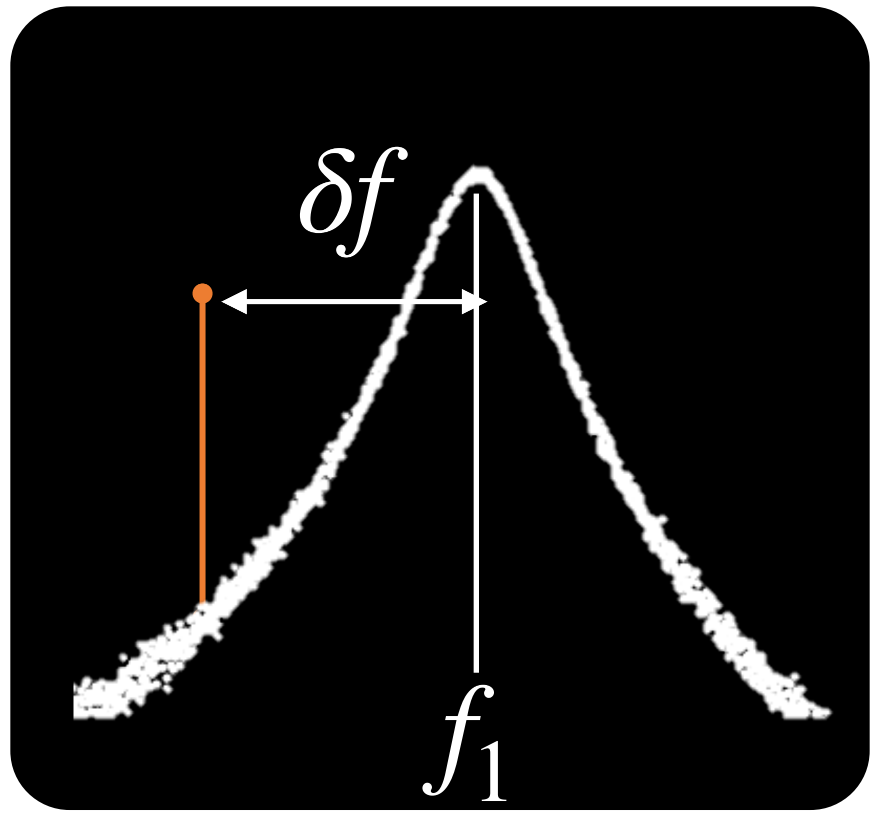

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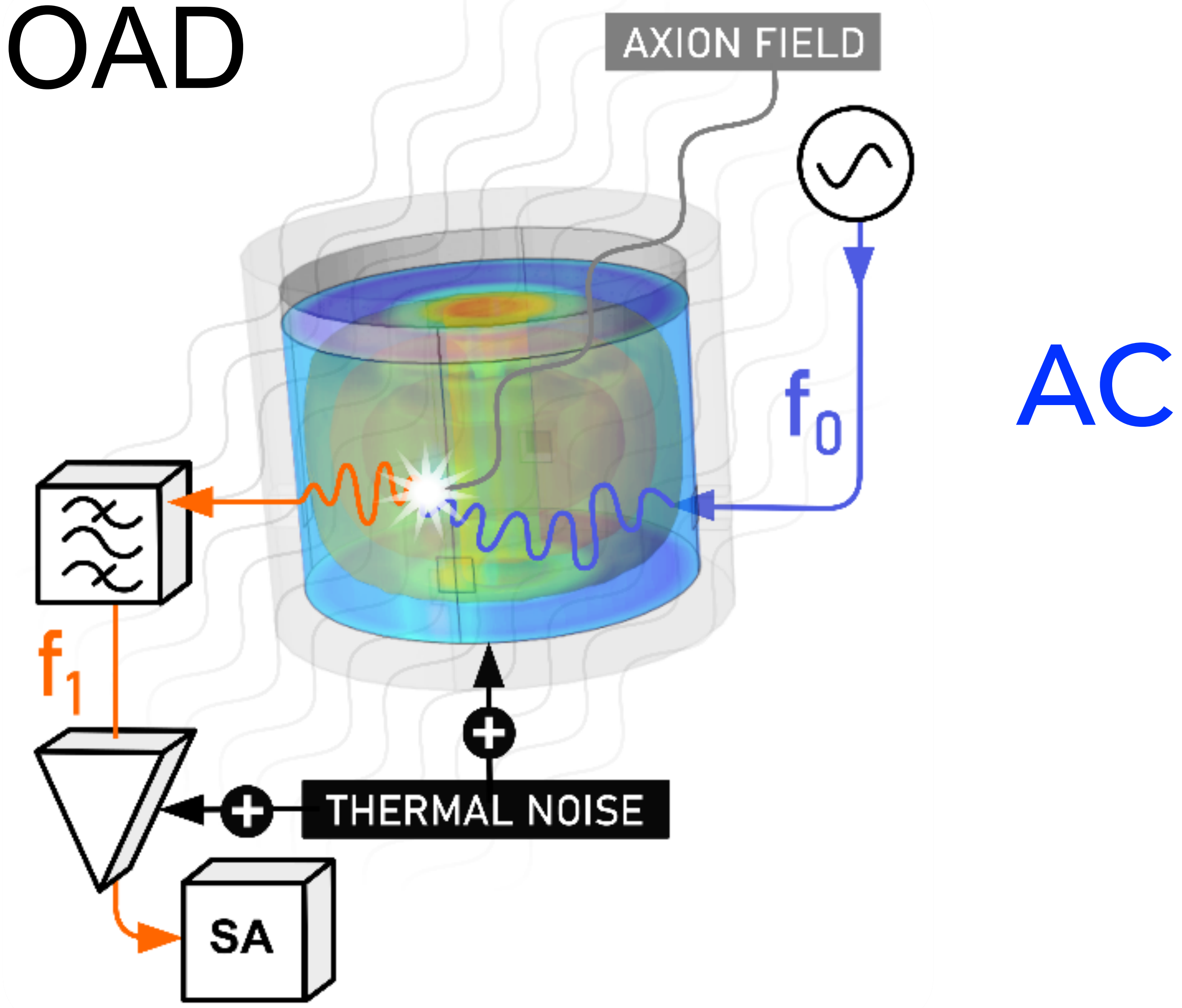

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Photon 1: Transverse Magnetic Mode

(Longitudinal Electric Ez)

Photon 0: Transverse Electric Mode

(Longitudinal Magnetic Bz)

DC: Excite B_0: Measure f_1 Power Fluctuation Spectrum: $m_a = f_1 + \delta f$

AC: Excite f_0: Measure f_1 Power Fluctuation Spectrum: $m_a = |f_1 - f_0| + \delta f$

Single Mode Sensitivity to Axions?



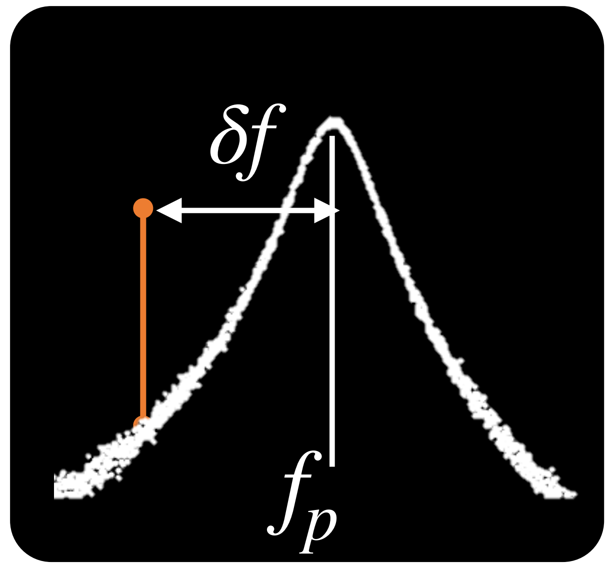

PHYSICAL REVIEW D **108,** 052014 (2023)

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

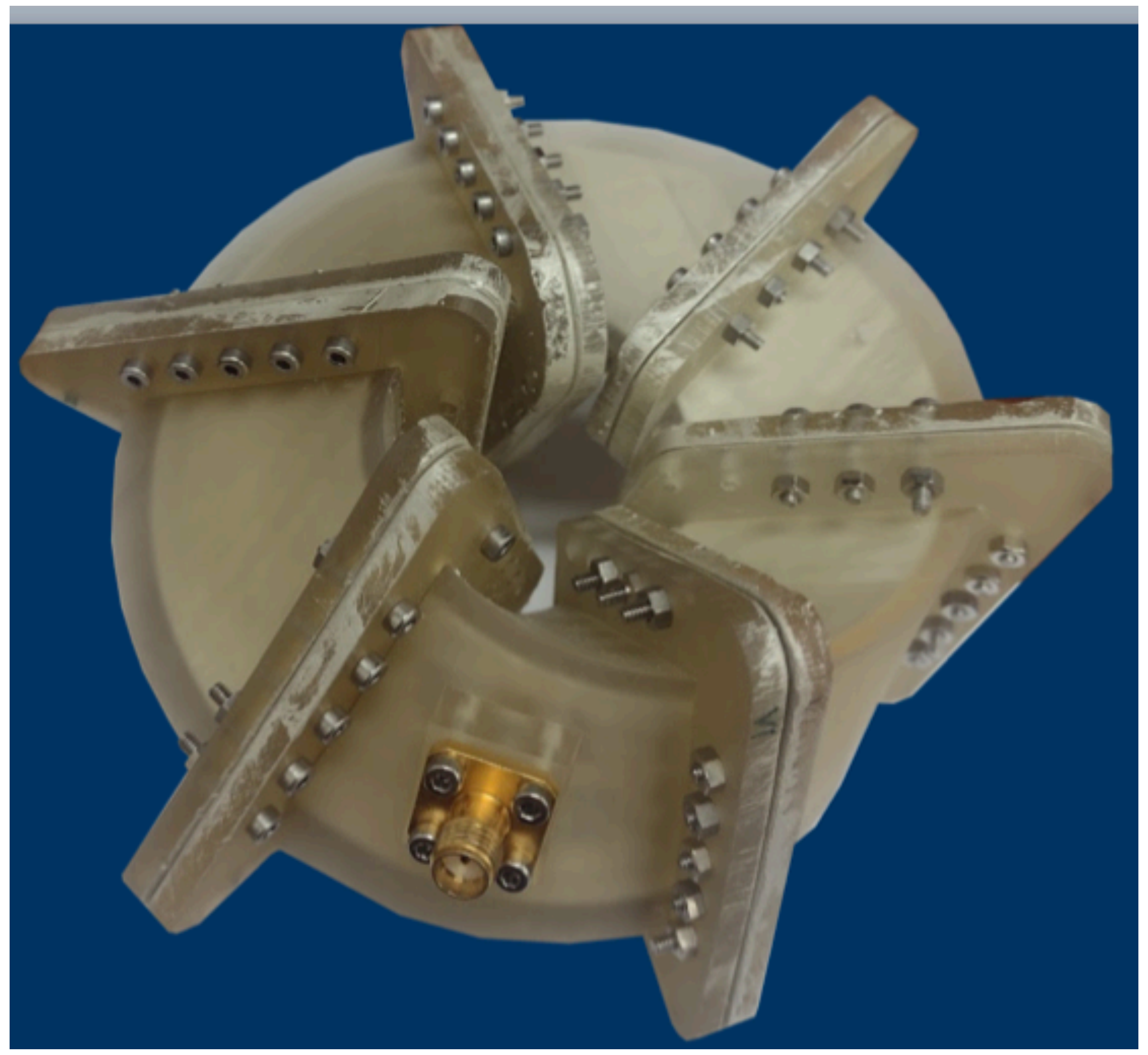
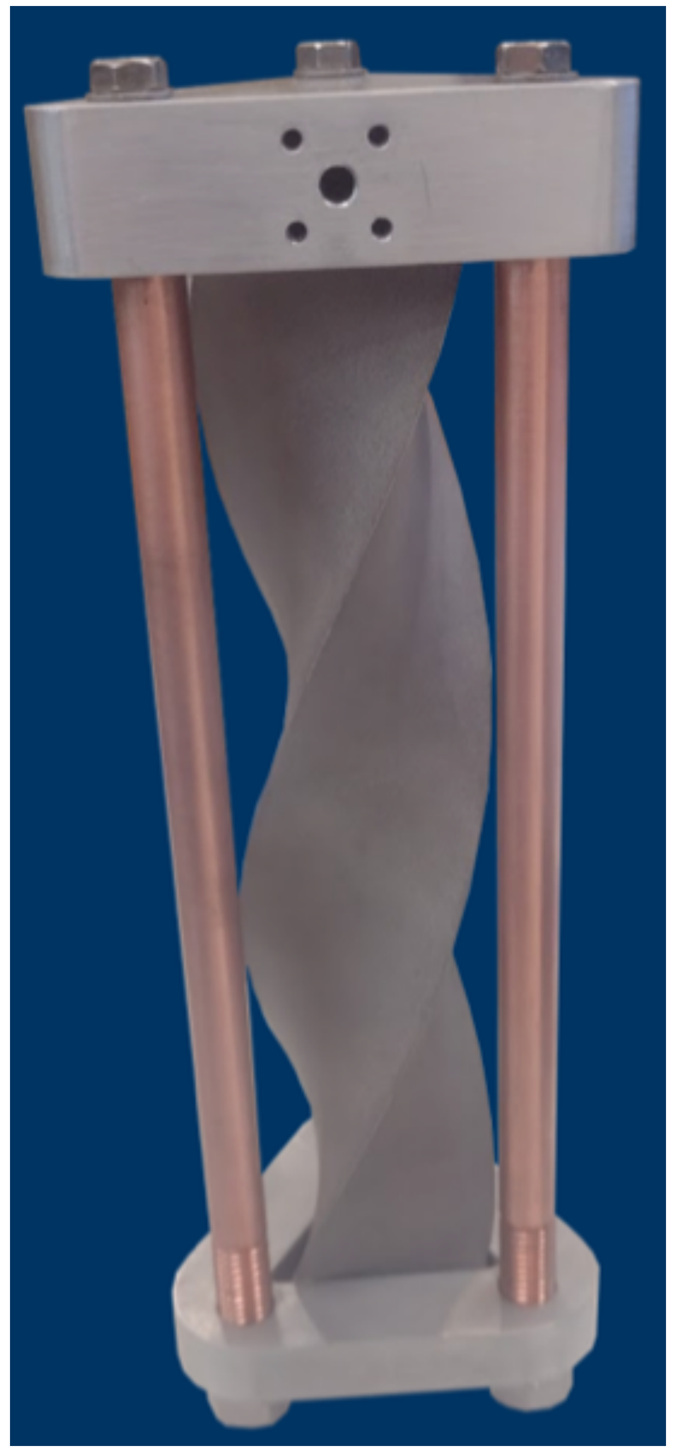
- Twisted ANYON Cavity
- Upconversion limit $m_a = \delta f$



Helicity: Single Mode with non-zero $\int \mathbf{B}_p(\vec{r}) \, . \, \mathbf{E}_p^*(\vec{r}) d\tau$

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

Acts as both background and output mode

Electromagnetic Helicity in Twisted Cavity Resonators

E. C. I. Paterson,[1] J. Bourhill,[1] M. Goryachev,[1] and M. E. Tobar[1]

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

(Dated: September 19, 2024)

By introducing mirror-asymmetry (chirality) to the conducting boundary conditions of an equilateral triangular cross-section electromagnetic resonator through left- or right-handed twisting, we generate eigenmodes with non-zero electromagnetic helicity as a result of the mixing of near degenerate $\mathrm{TE}_{11(p+1)}$ and TM_{11p} modes. This can be interpreted as an emergence of magneto-electric coupling, which in turn produces a measurable shift in resonant mode frequency as a function of twist angle. We show that this coupling mechanism is equivalent to introducing a non-zero chirality material parameter κ_{eff} or axion field θ_{eff} to the radiation. Our findings demonstrate the potential for real-time, macroscopic manipulation of chirality.

Electromagnetic Helicity in Twisted Cavity Resonators

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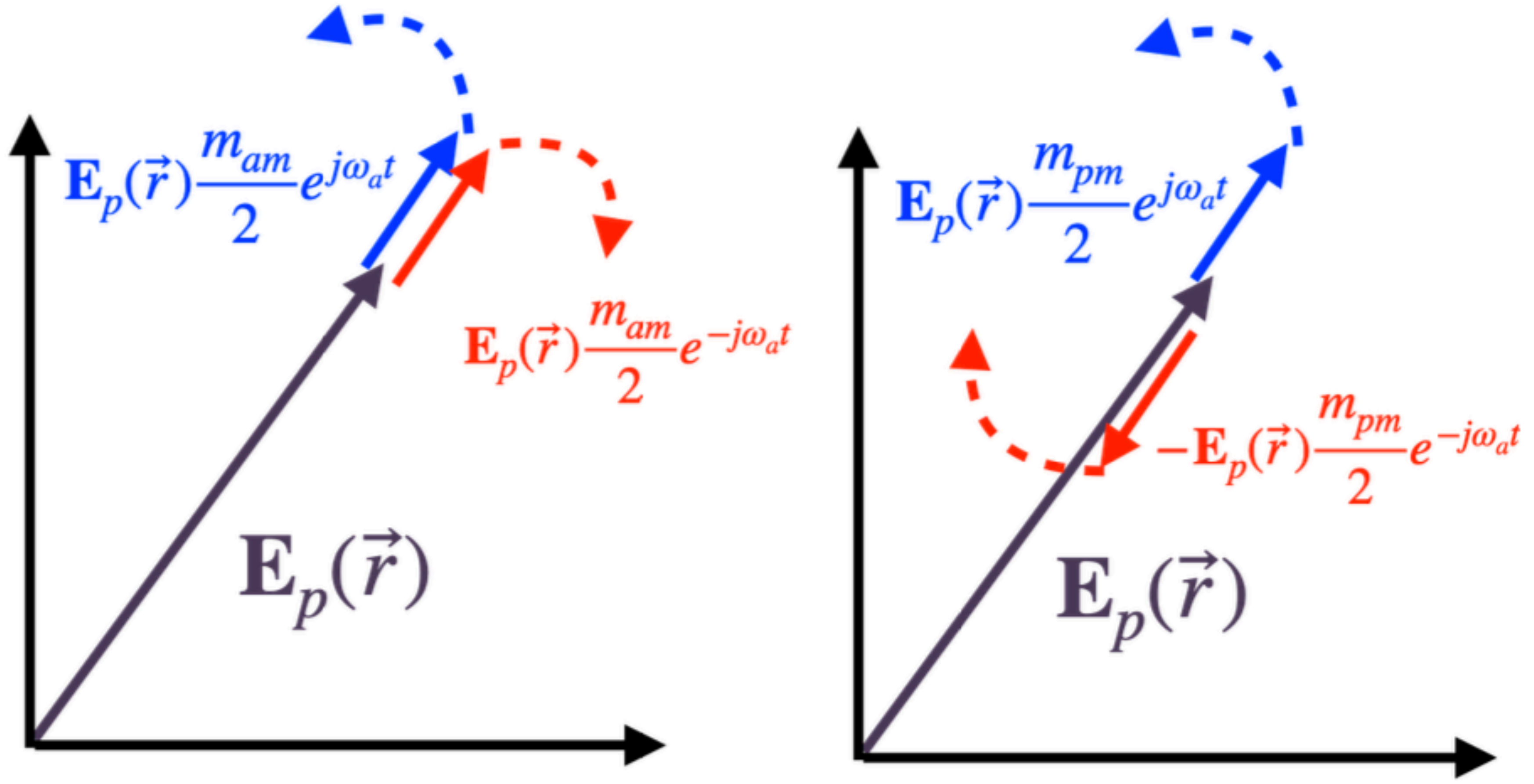
Twisted “anyon” microwave cavities

Dark matter detection thanks to helicity

- Due to the helicity, **ultra-light dark matter axions**, whose mass range falls within the cavity bandwidth will amplitude modulate the cavity mode
- Apply Poynting Theorem + Rotating Wave Approximation
- Calculate that the frequency of the AM sidebands -> proportional to the axion mass



Sensitivity ~ $|\mathscr{H}|(g_{a\gamma\gamma} + g_{aBB})$

Axion-Photon Chiral anomaly coupling

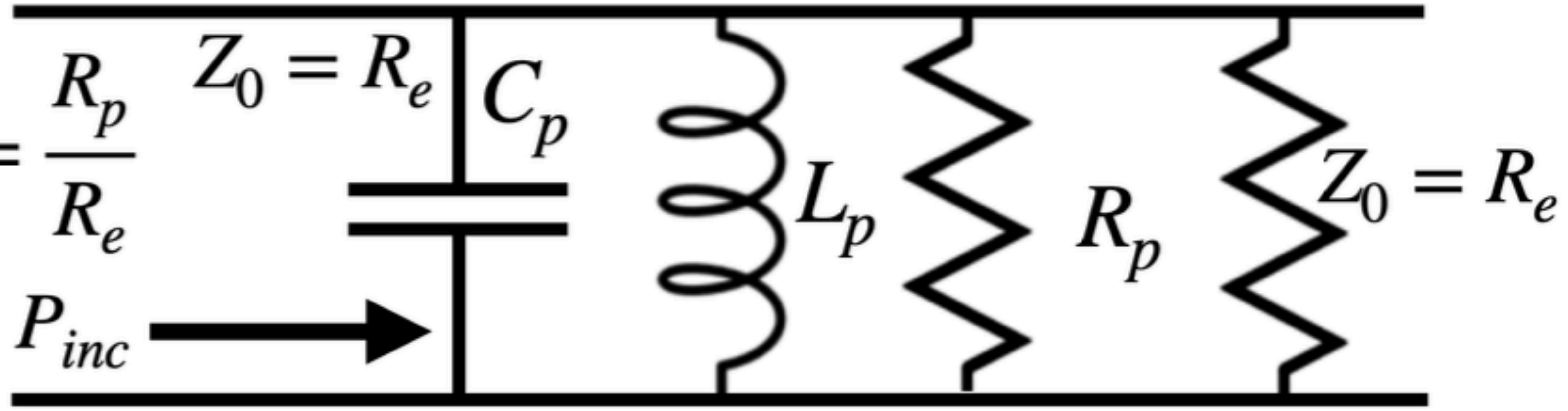
Extra coupling if high energy monopole exists

$$P_p = \frac{\beta_p P_d}{\beta_p + 1} = \frac{4\beta_p^2}{(1+\beta_p)^2} P_{inc}.$$

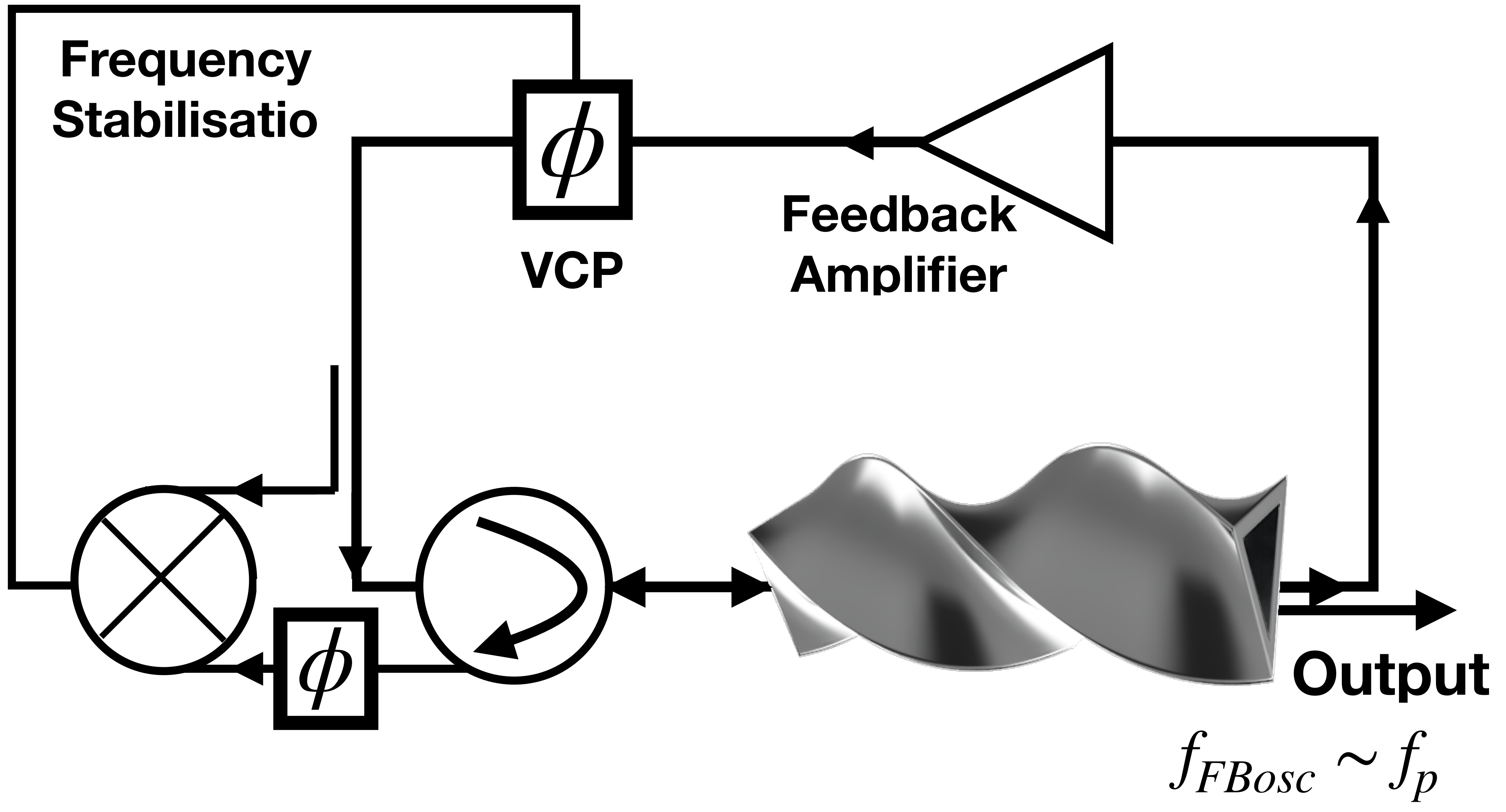
$$\frac{P_{am}}{P_{inc}} = \frac{m_{am}^2 P_p}{P_{inc}} = Q_p^2 \frac{4\beta_p^2}{(1+\beta_p)^2}\left(\frac{\omega_a}{\omega_p}\right)^2 \frac{\langle\theta_0\rangle^2}{8}\mathscr{H}_p^2.$$

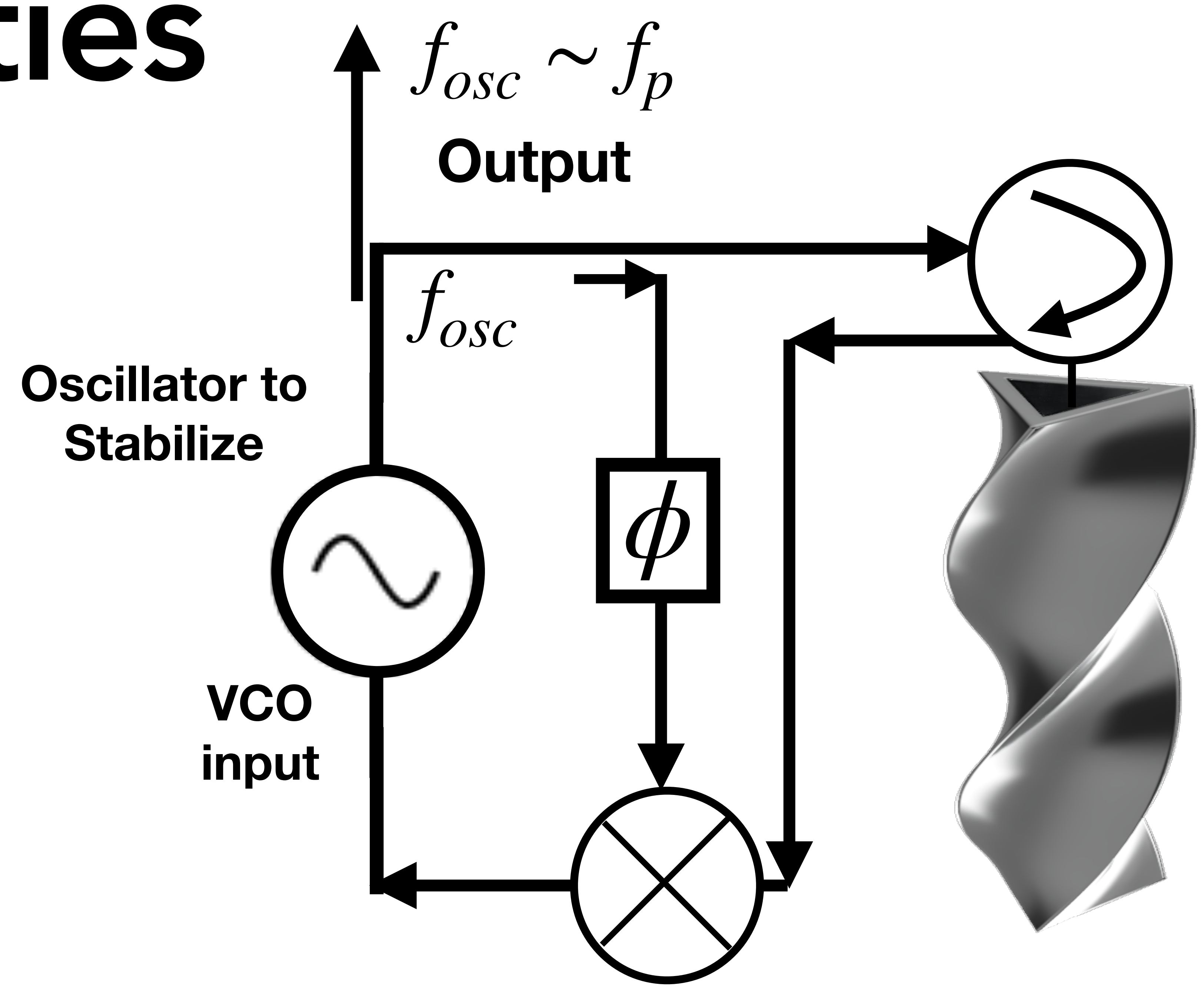
$$SNR = \frac{g_{a\gamma\gamma}\beta_p|\mathscr{H}_p|}{\sqrt{2}(1+\beta_p)} \frac{Q_p}{\sqrt{1+4Q_p^2(\frac{\omega_a}{\omega_p})^2}} \frac{\left(\frac{10^6 t}{\omega_a}\right)^{\frac{1}{4}}\sqrt{\rho_a c^3}}{\omega_p\sqrt{S_{am}}}$$

$$\beta_p = \frac{R_p}{R_e}$$



Twisted "anyon" microwave cavities





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

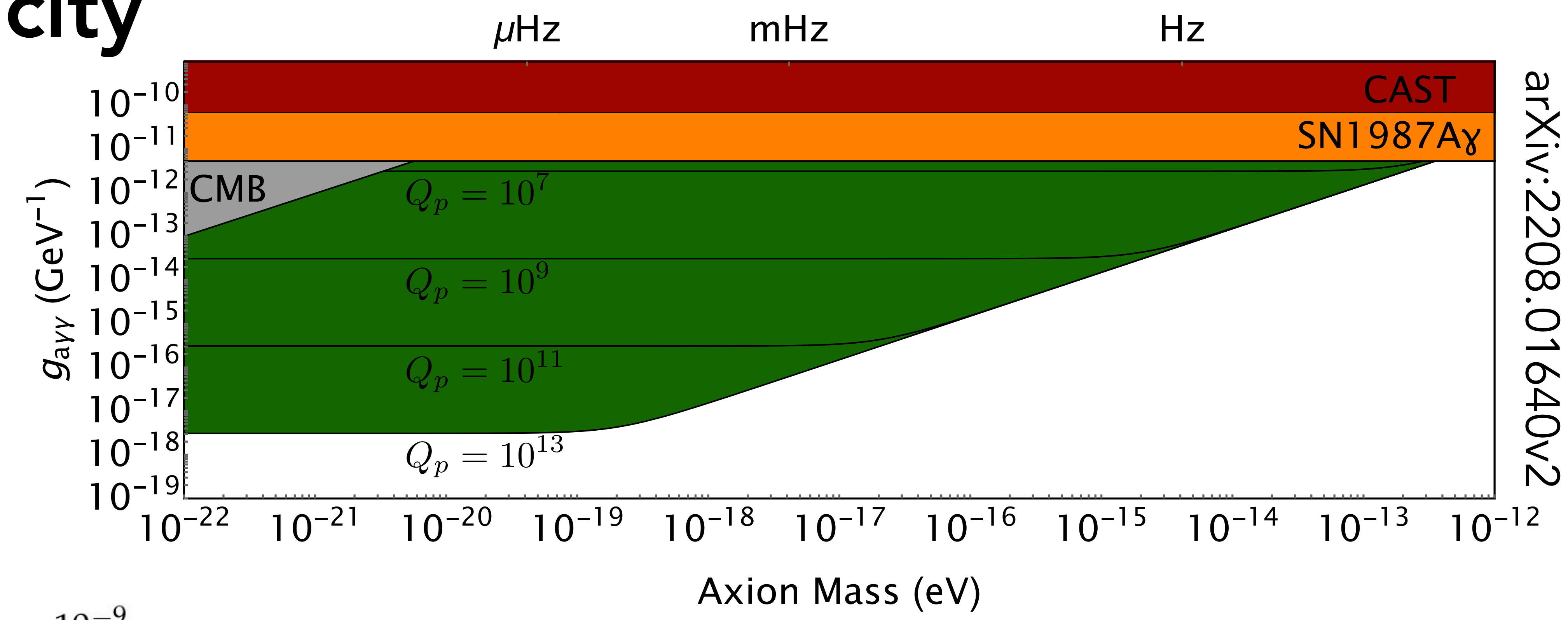
- Axion Photon Coupling ($g_{a\gamma\gamma}$)
- Microwave Probe Coupling (β_p)
- **Helicity** ($|\mathscr{H}_p|$)
- **Q factor** (Q_p)
- Axion Frequency (ω_a)
- Measurement time (1 week) (t)
- Cold dark matter density (8×10^{-22}kgm^{-3}) (ρ_a)
- Speed of light (3×10^8 ms^{-1}) (c)
- Cavity frequency (1 GHz) (ω_p)
- Amplitude noise (-160 dBcHz^{-1}) (S_{am})

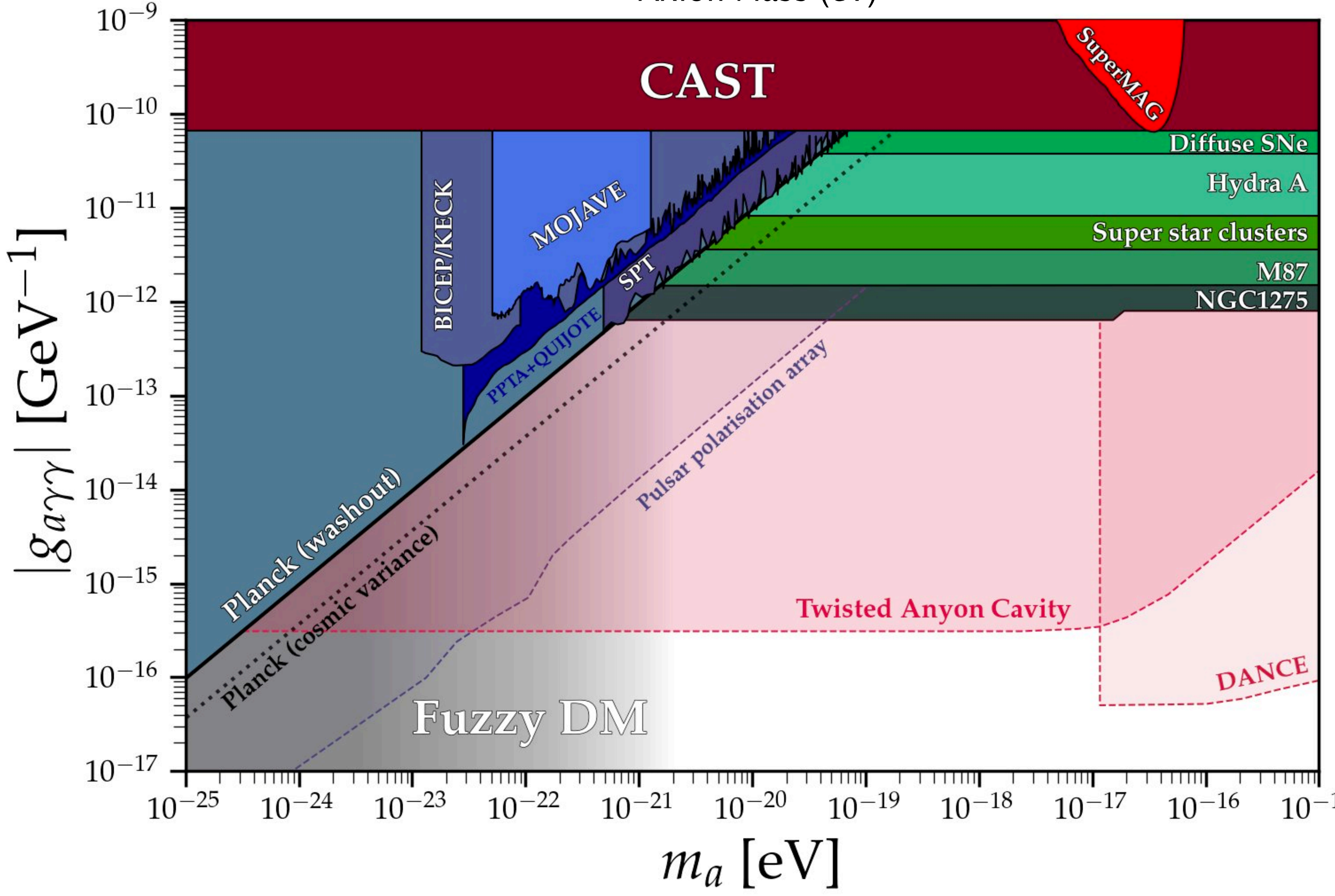
Quantum Technologies and Dark Matter Research Lab

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
- Next: Optimising Q-factors and minimising read-out amplitude modulation noise for a detection run





Quantum Technologies and Dark Matter Research Lab

UPLOAD Cryogenic

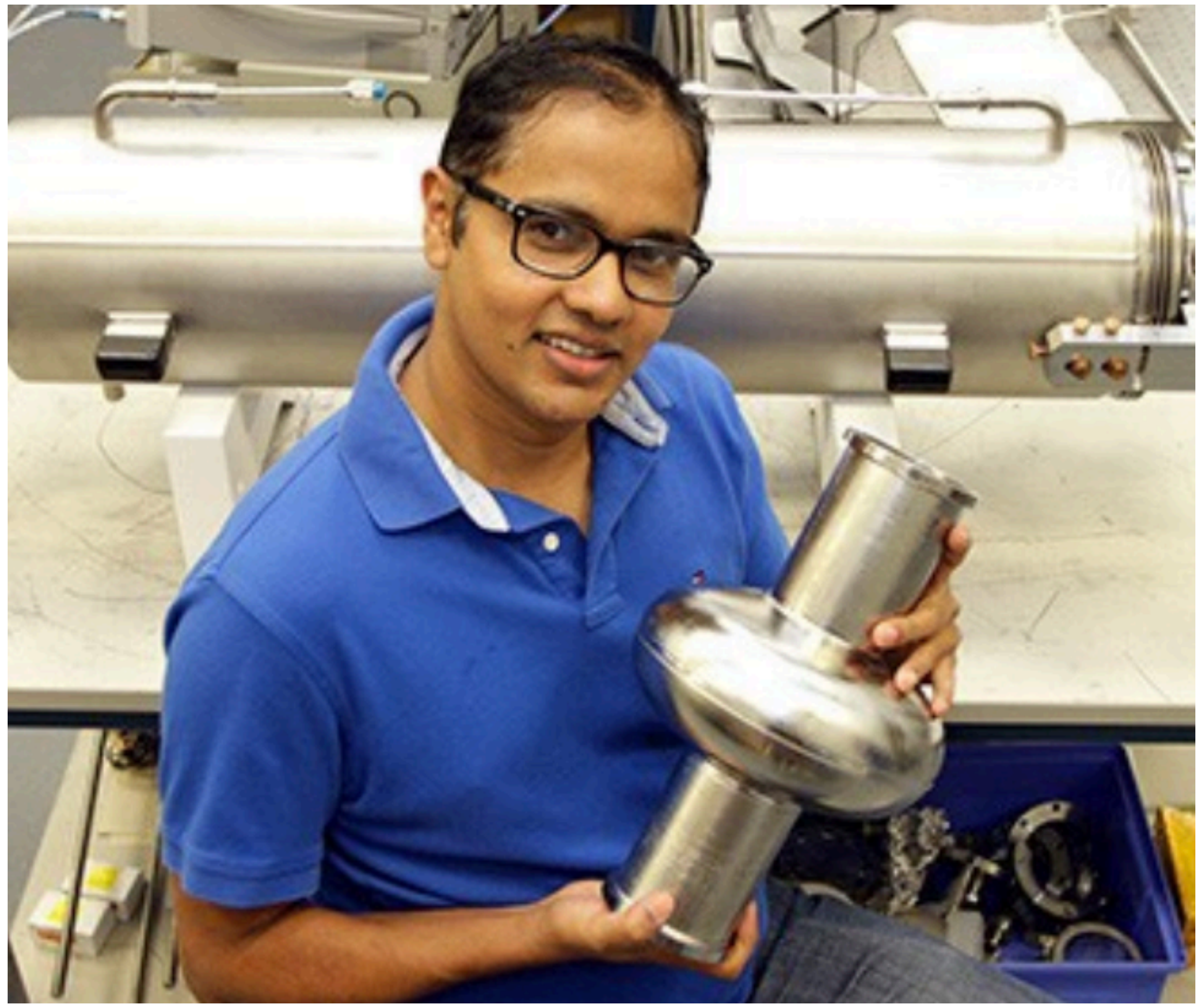
1) **DUAL MODE Operation**

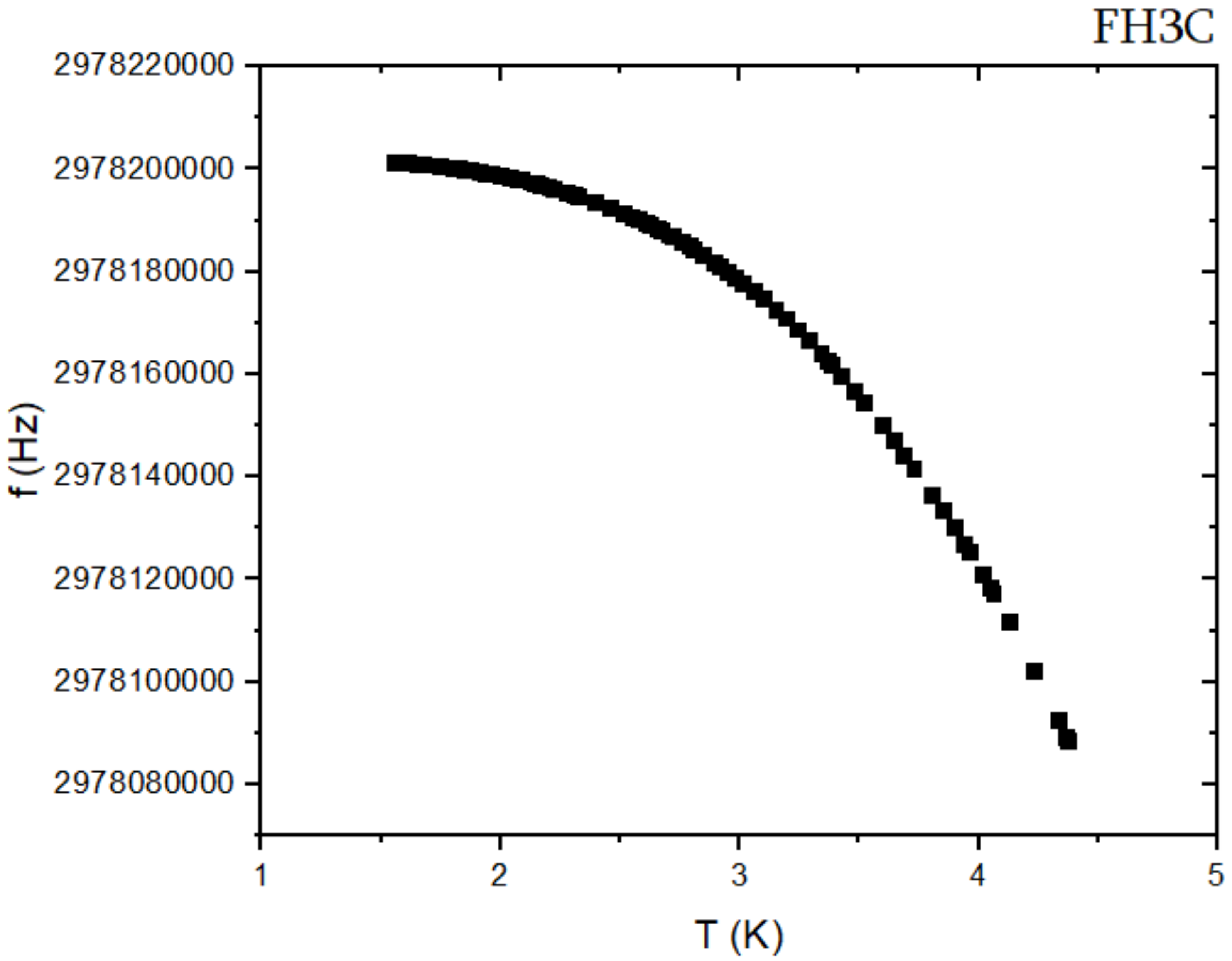
2) **Low-Noise Oscillator as test bed for the ANYON experiment**

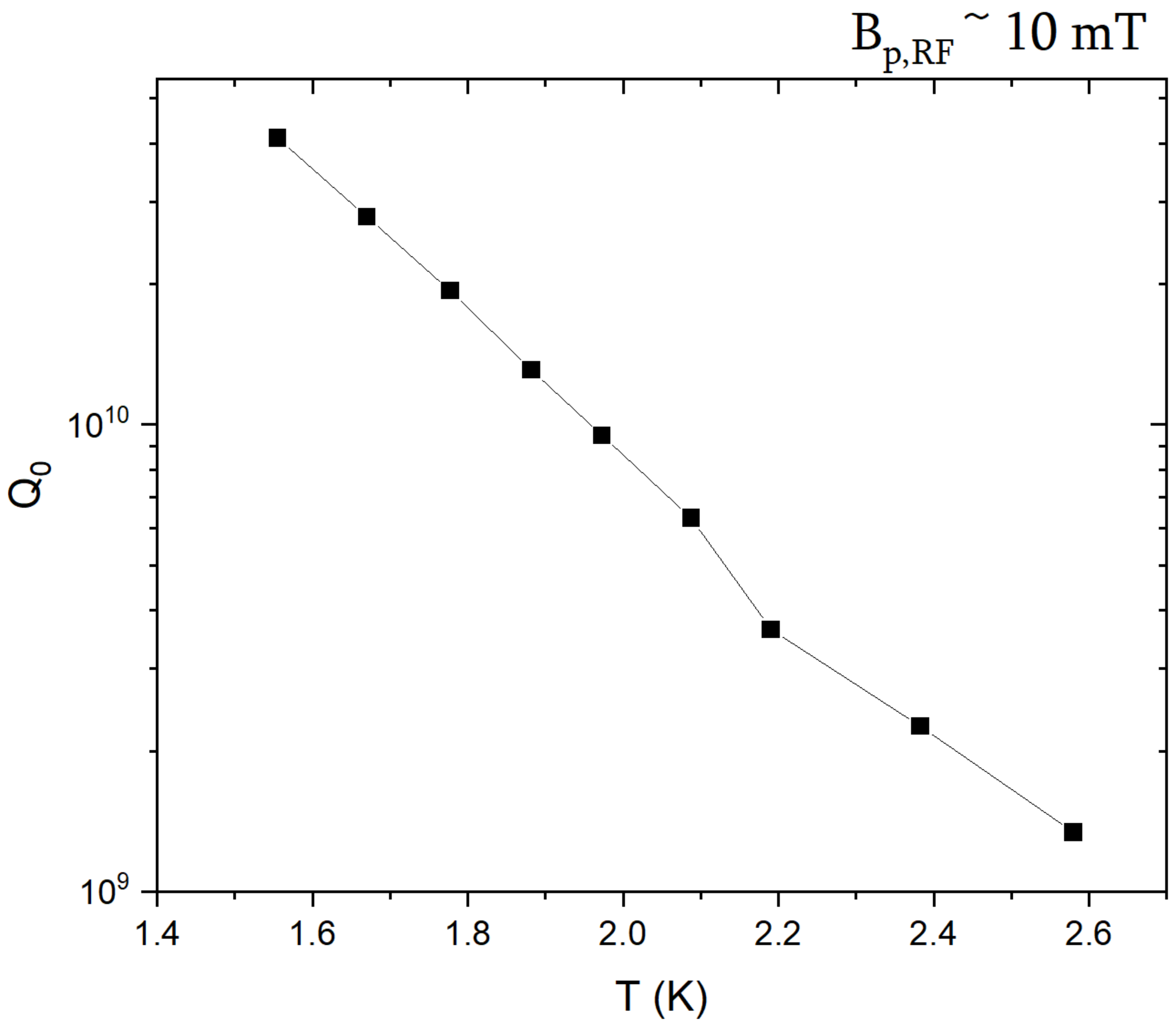
Robert Crew

Pashupati Dhakal

Jefferson Lab







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

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

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

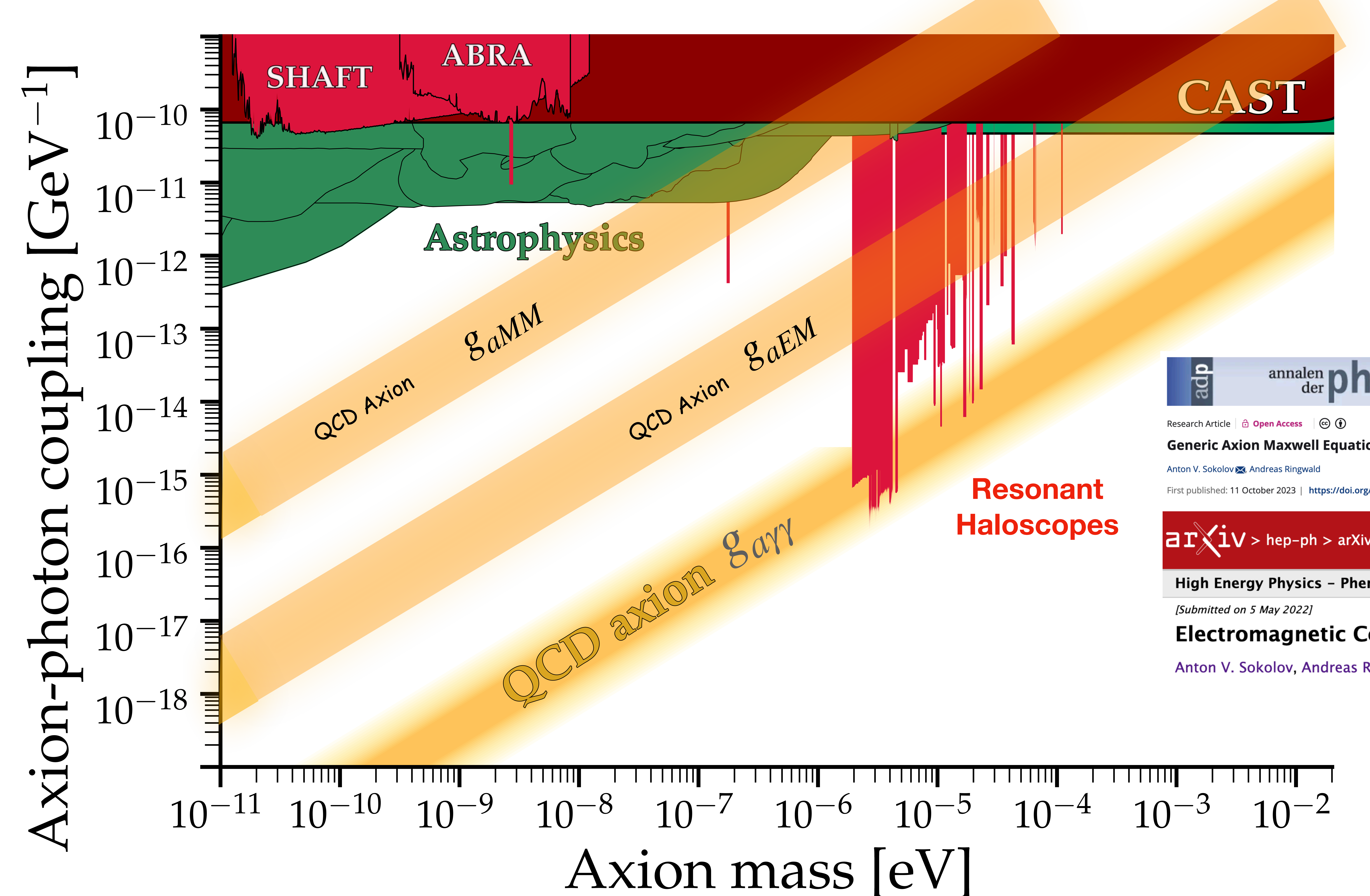
Anton V. Sokolov, Andreas Ringwald

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

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

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

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



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

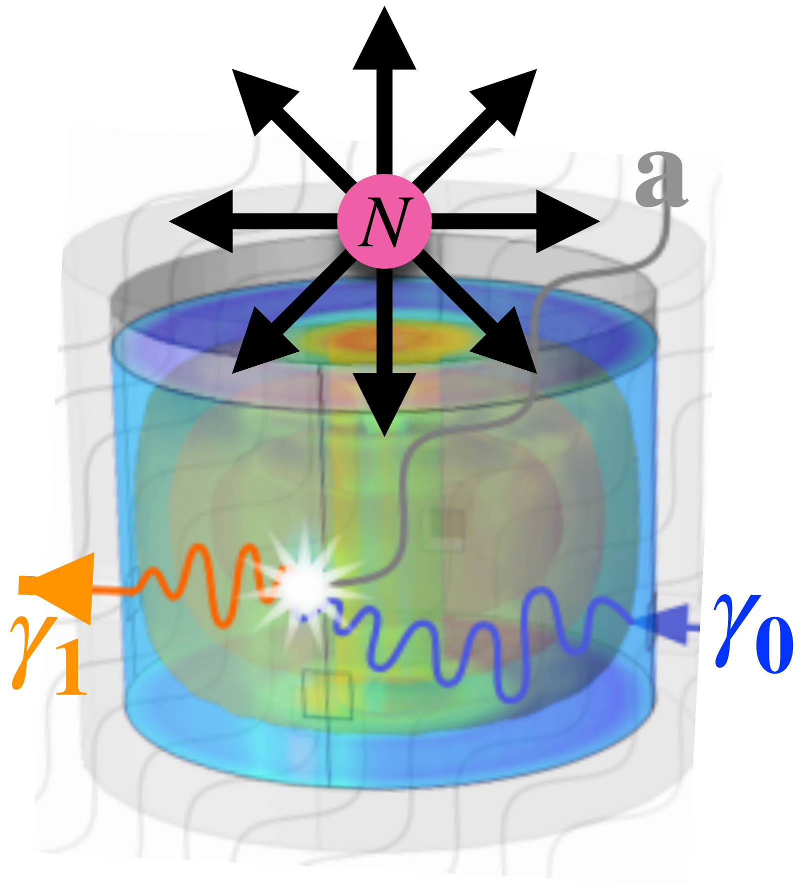
High Energy Physics – Phenomenology

[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



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*

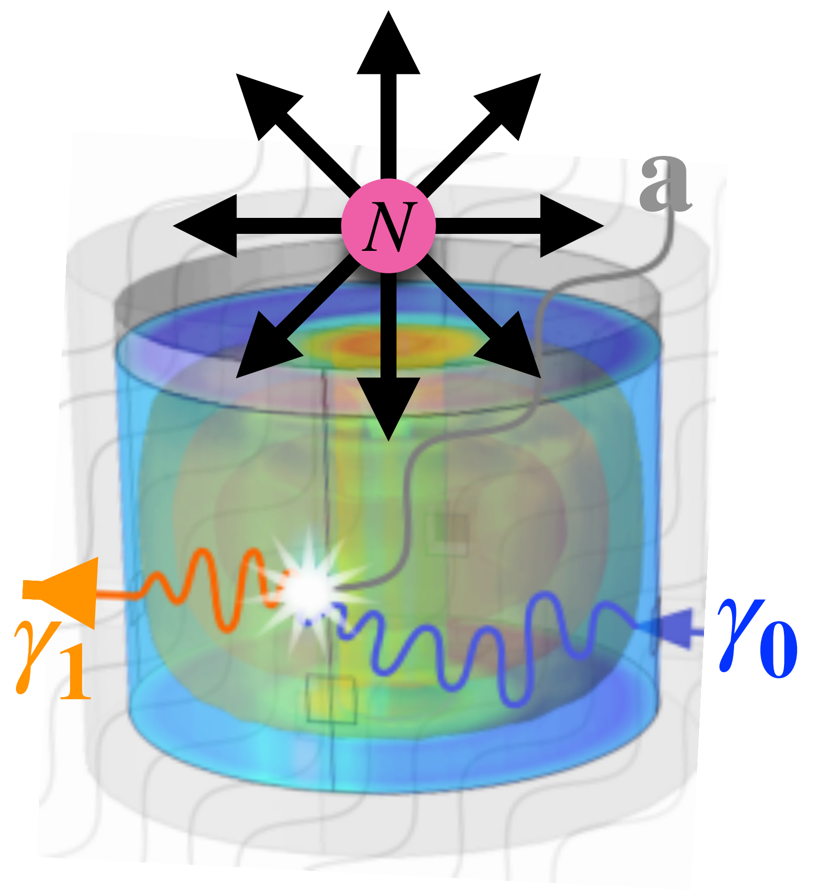
Form Factors

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

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

$g_{aEM} \rightarrow$ Suppressed

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



RESEARCH ARTICLE

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Sensitivity of Resonant Axion Haloscopes to Quantum Electromagnetodynamics

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RESEARCH ARTICLE

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$g_{aEM} \rightarrow$ Suppressed

UPLOAD $\rightarrow g_{aMM}$

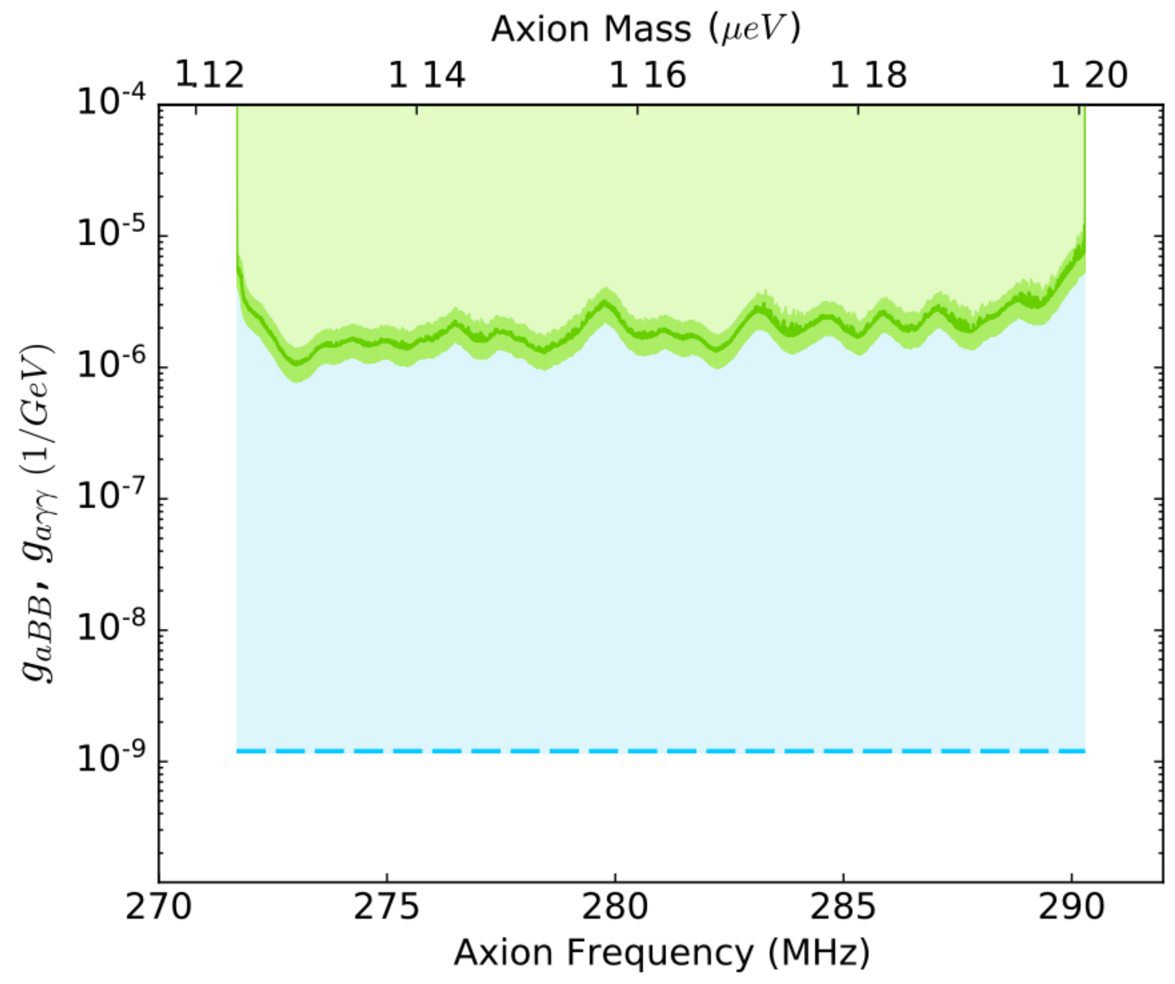
PHYSICAL REVIEW D **107,** 112003 (2023)

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)



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)

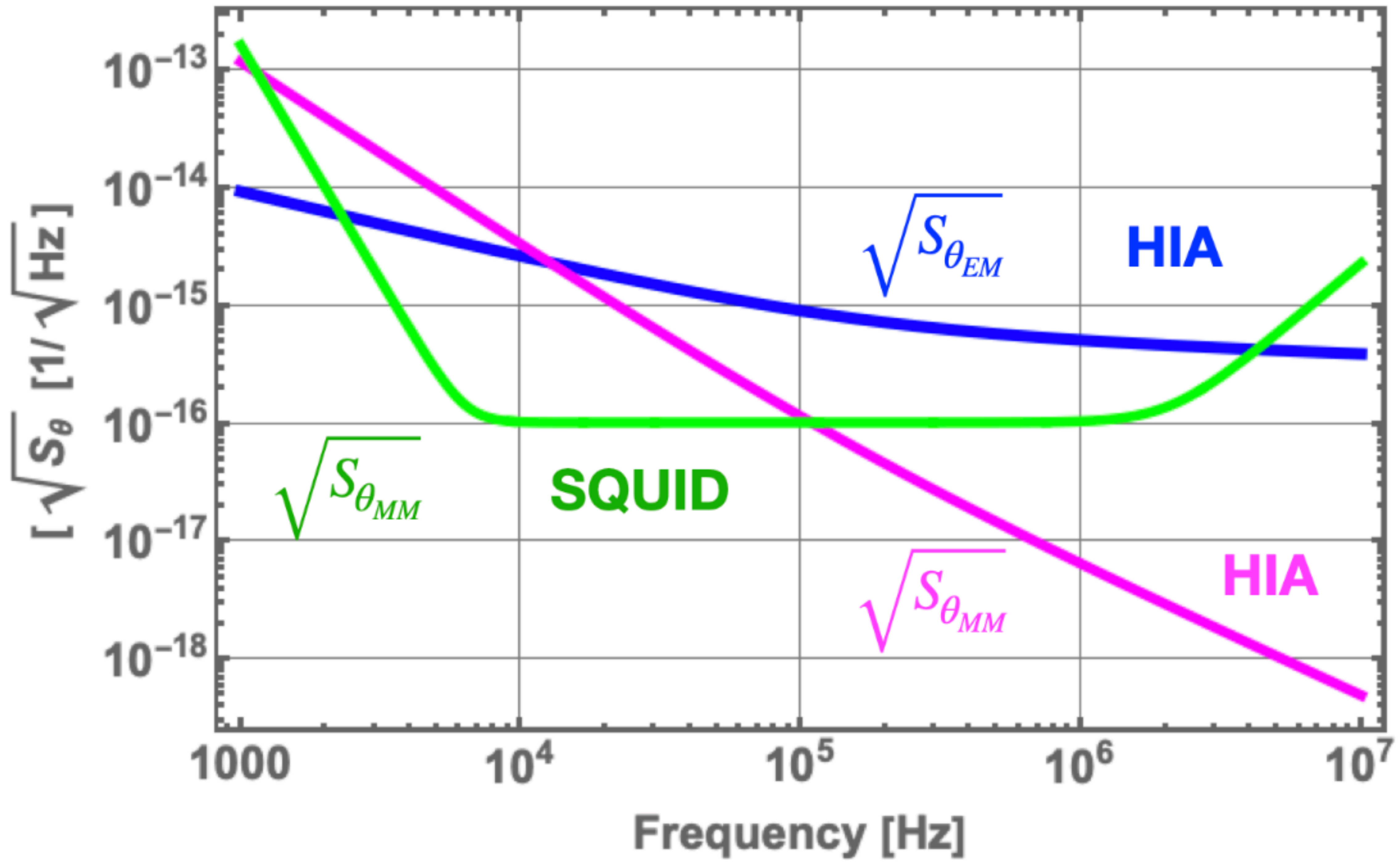
Axion Generated Magnetic Field-> Magnetic Circuit Readout Sensitive to g_{aMM}

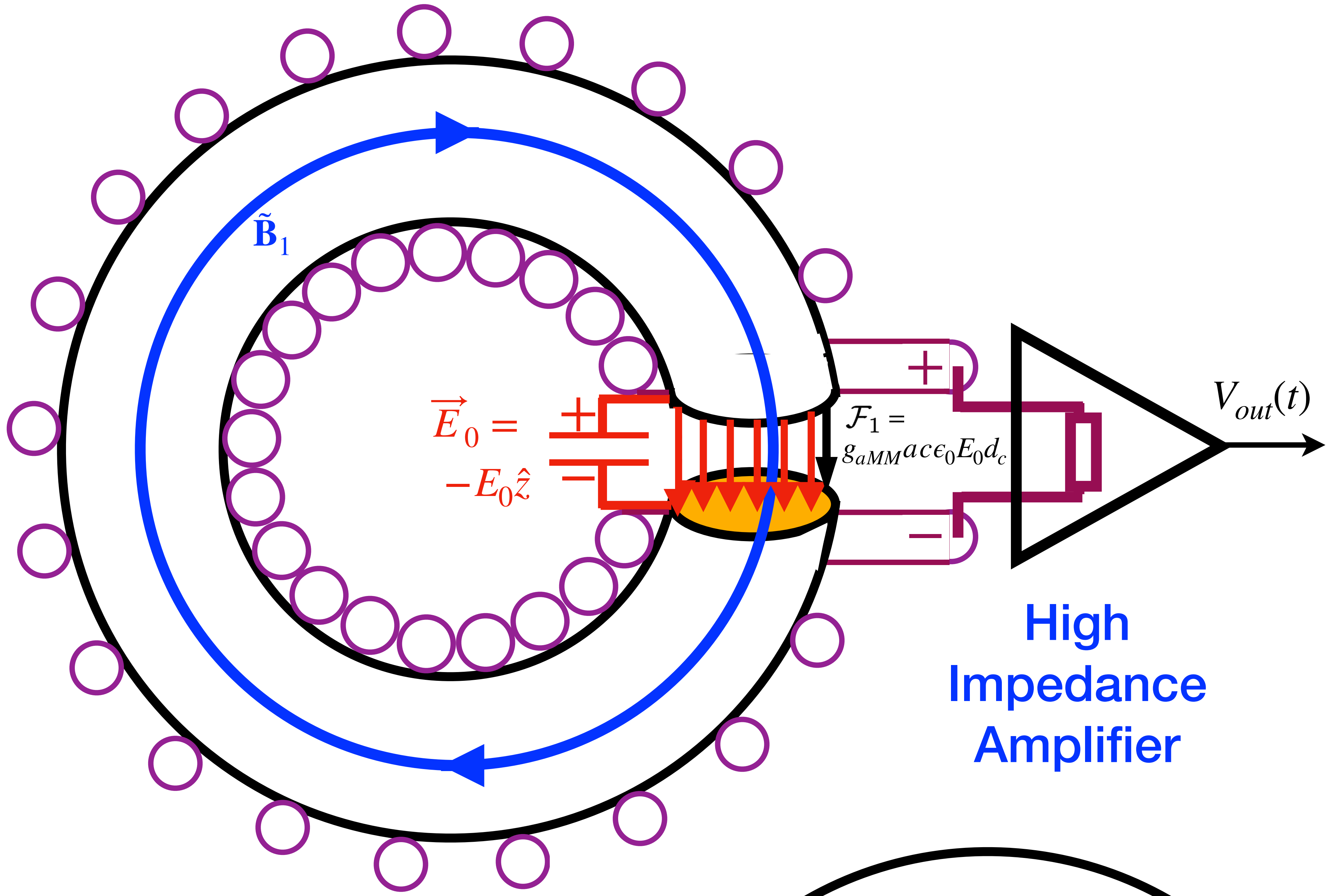
$$\frac{\oint \mathrm{Im}\left(\mathbf{S}_1\right)\cdot \hat{n}ds}{\omega_a} = \int \left(\left(\frac{1}{2\mu_0}\mathbf{B}_1^*\cdot\mathbf{B}_1 - \frac{\epsilon_0}{2}\mathbf{E}_1\cdot\mathbf{E}_1^* \right) - \frac{g_{aEM}a_0\epsilon_0}{4}(\mathbf{E}_1+\mathbf{E}_1^*)\cdot\vec{E}_0 + \frac{g_{aMM}a_0\epsilon_0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

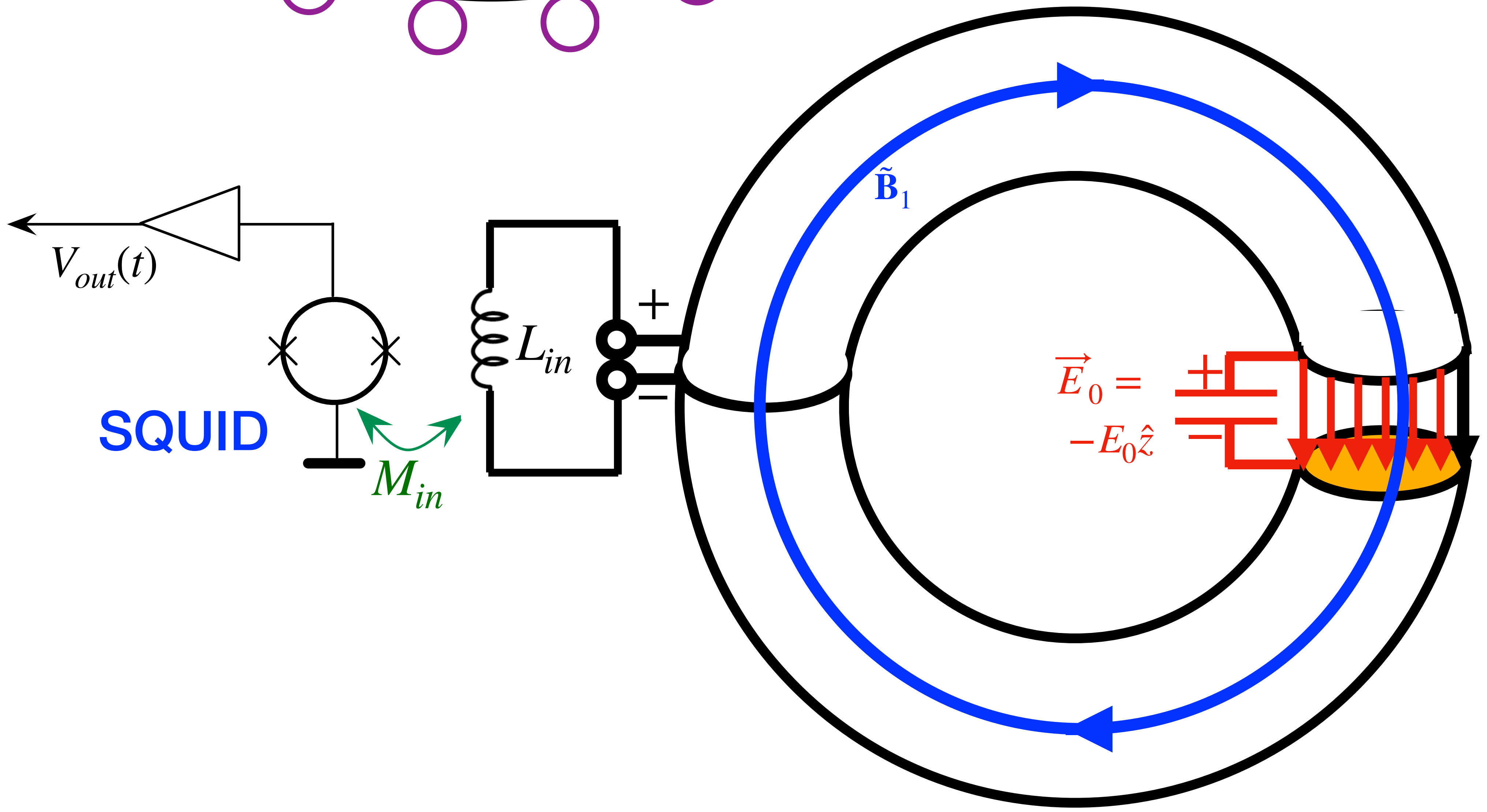
$\mathbf{E}_1+\mathbf{E}_1^* \sim 0 \quad \mathbf{B}_1+\mathbf{B}_1^* \sim 2\mathbf{B}_1$

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

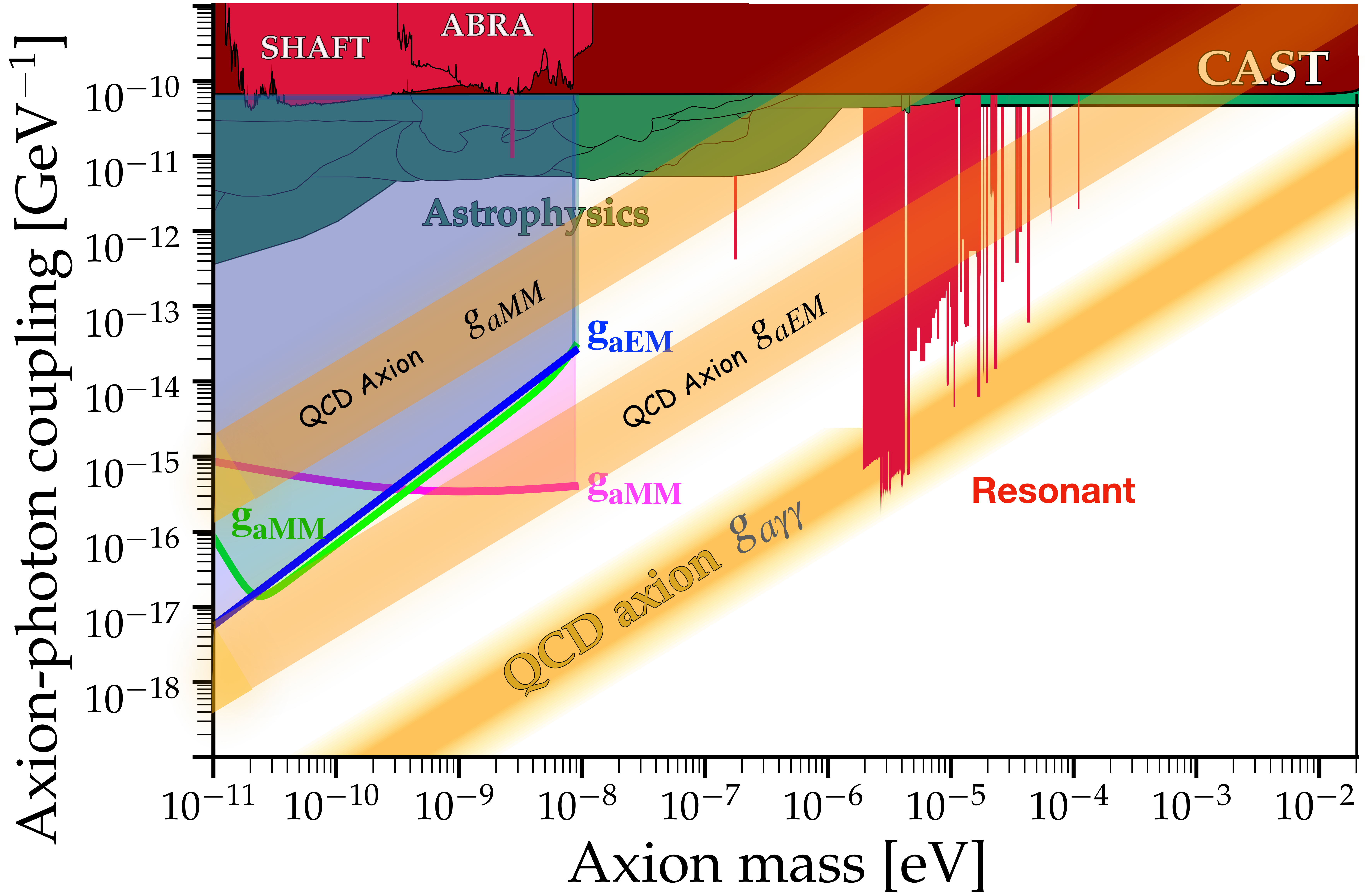
$\theta = a g_{aMM}$





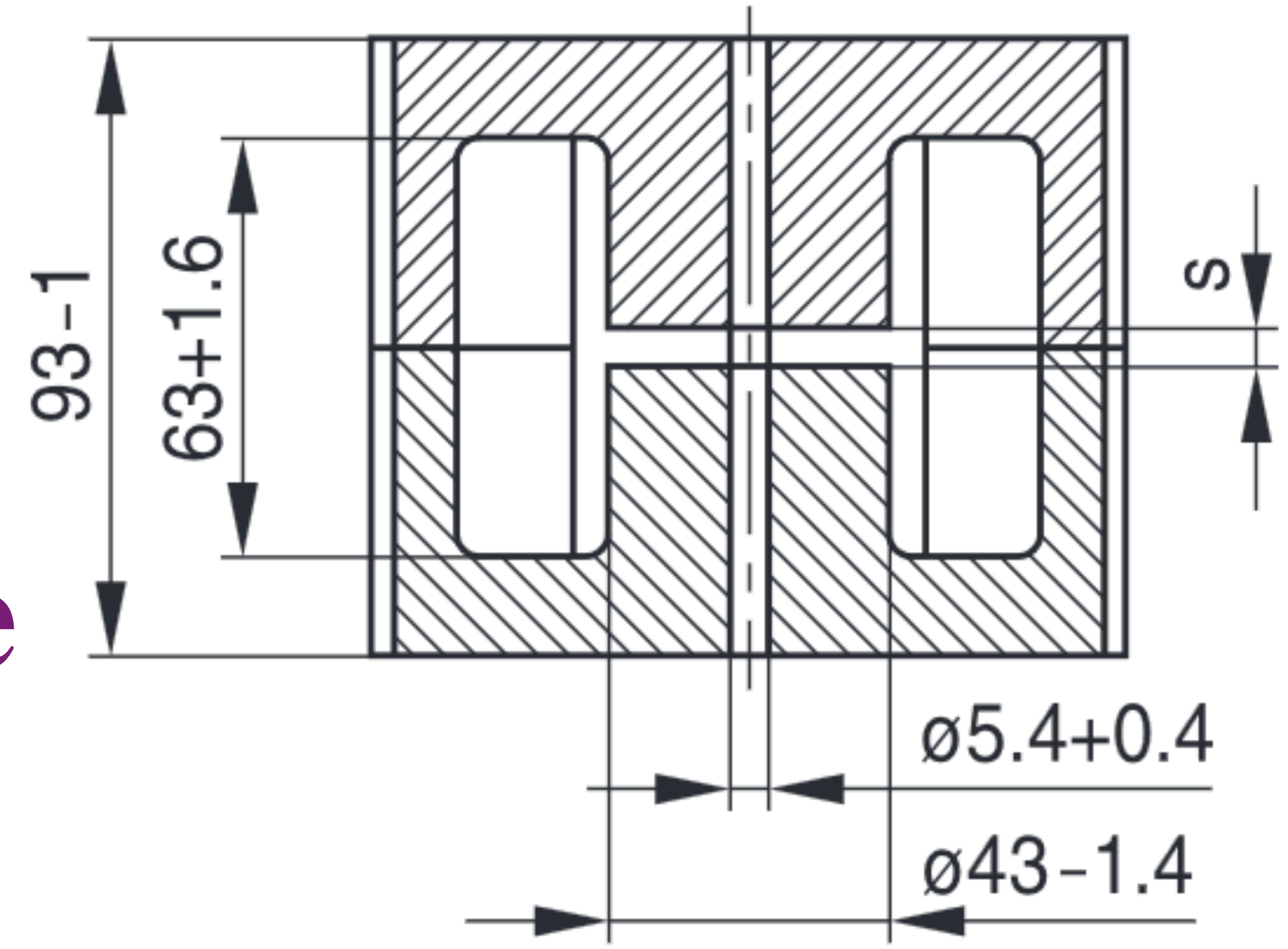


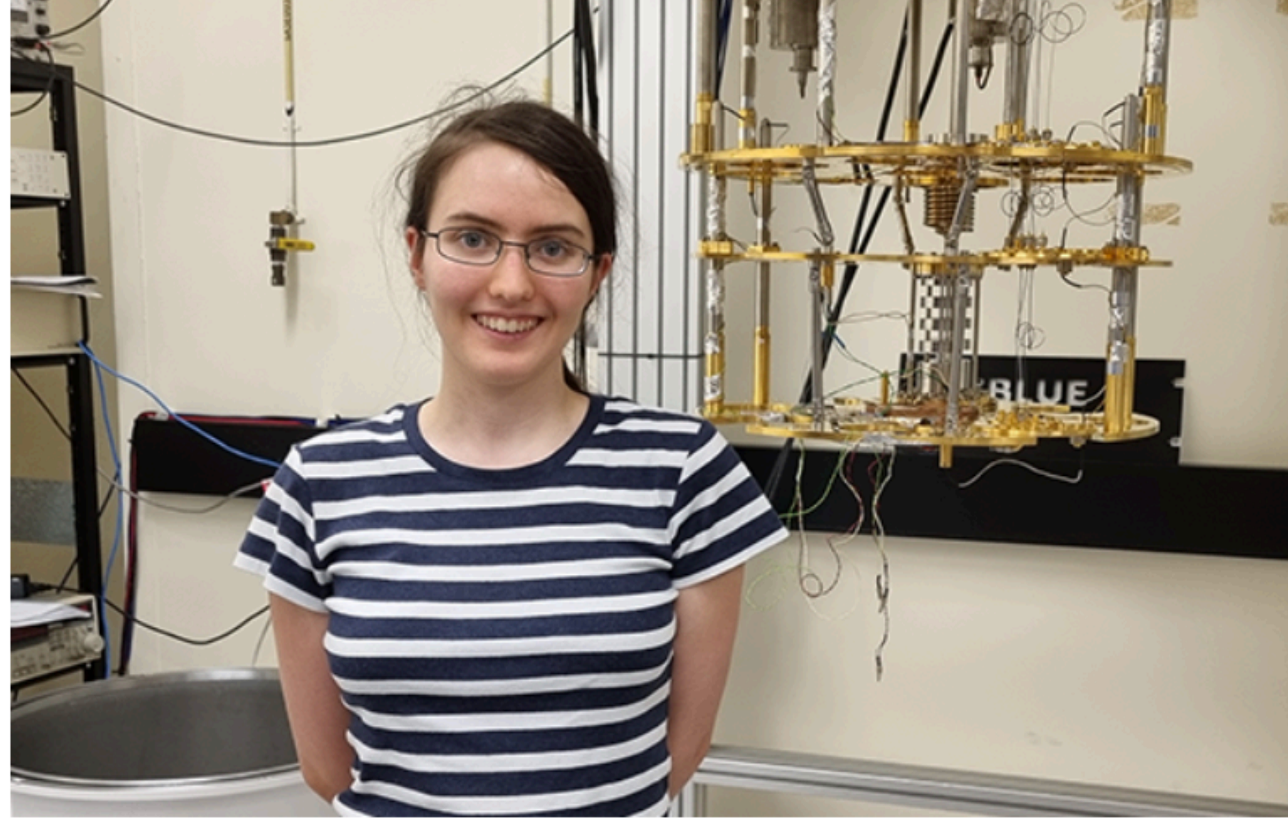
Low-Mass Sensitivity to the QCD Axion ~ 10 cm Scale Assumed



18 days of continuous data taking

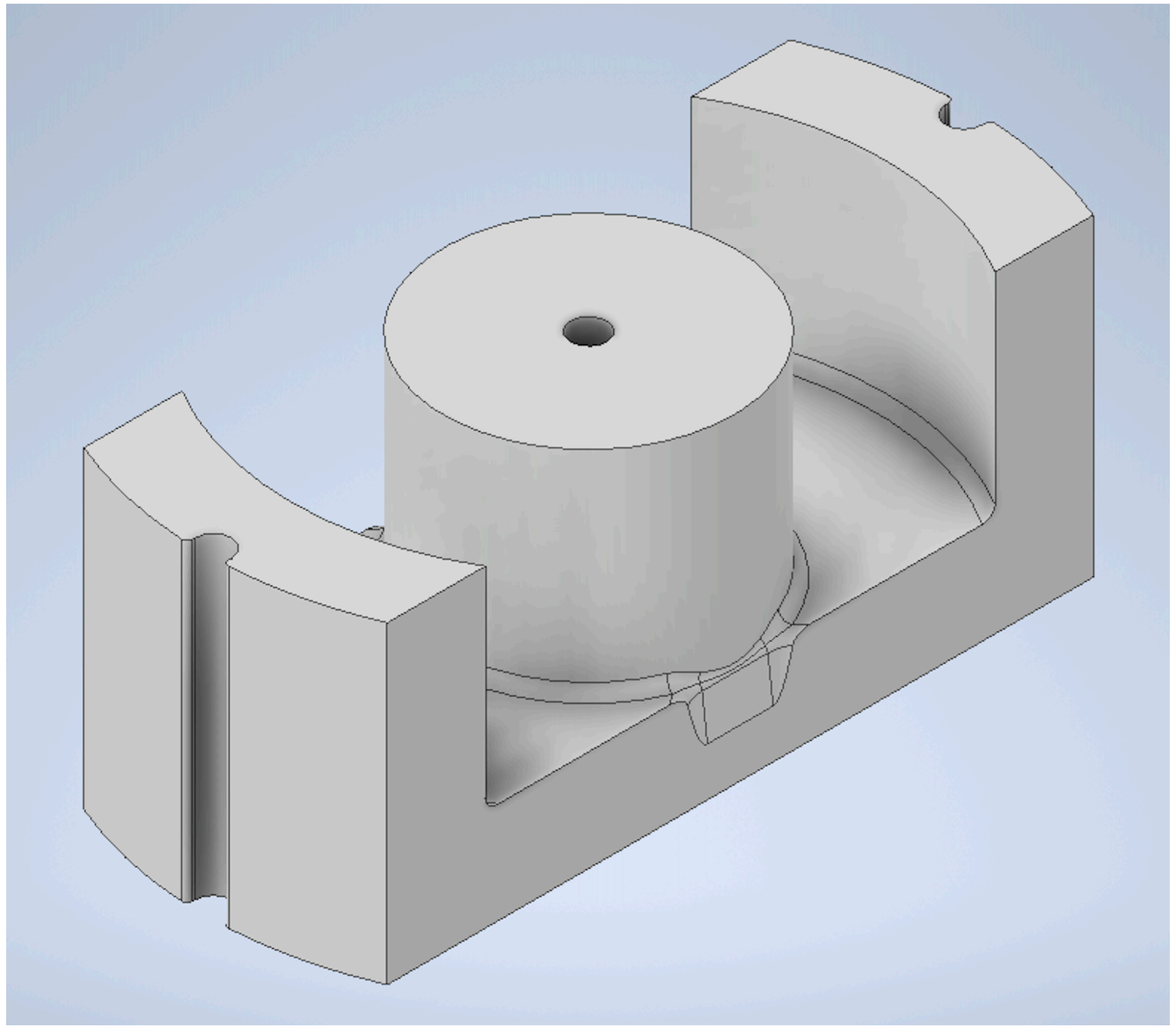
The Axion-MonoPole-Detection (AMPD) Experiment
Initial Prototype ~ 4cm
Purchased Standard Ferrite Core

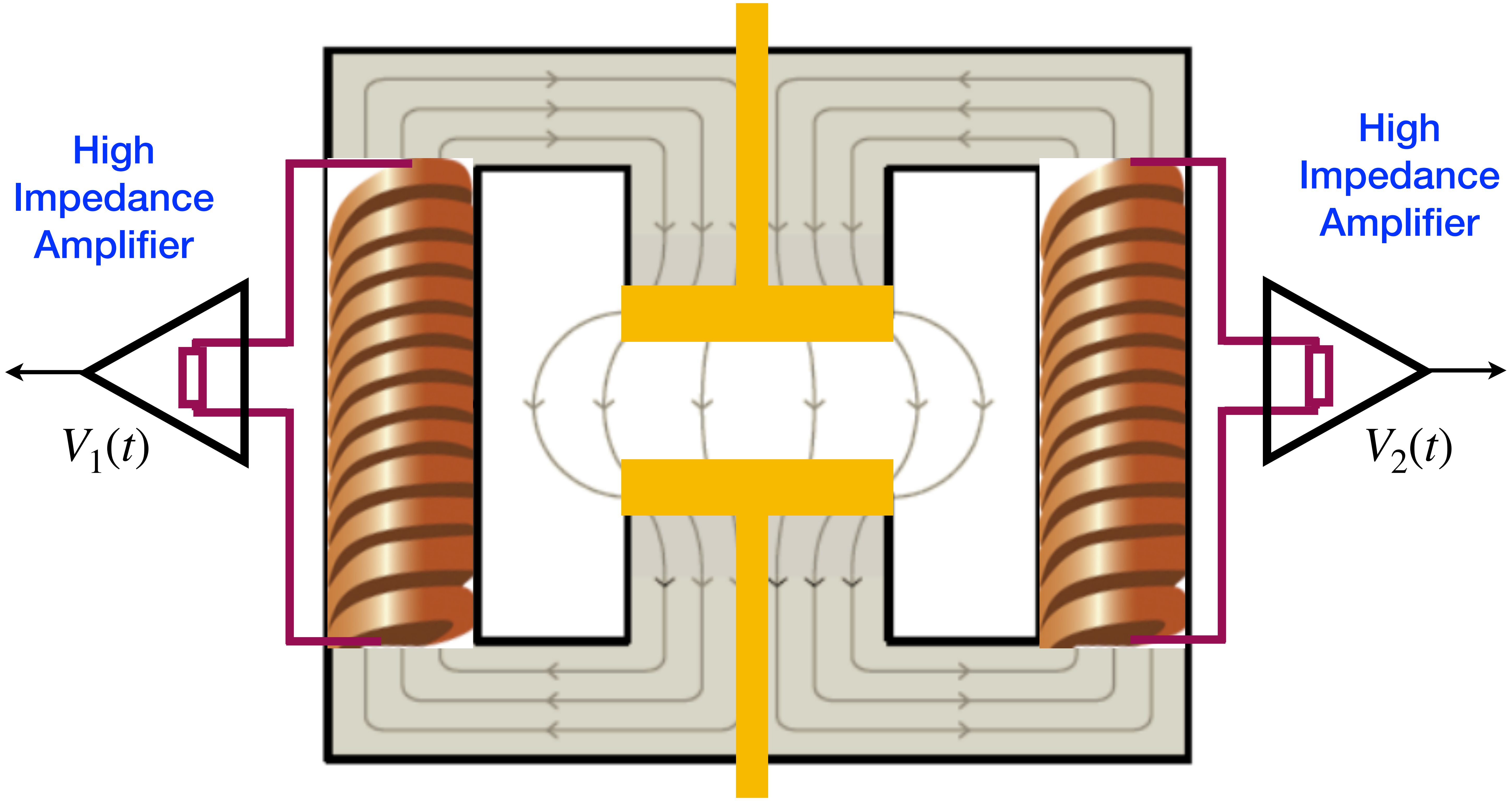


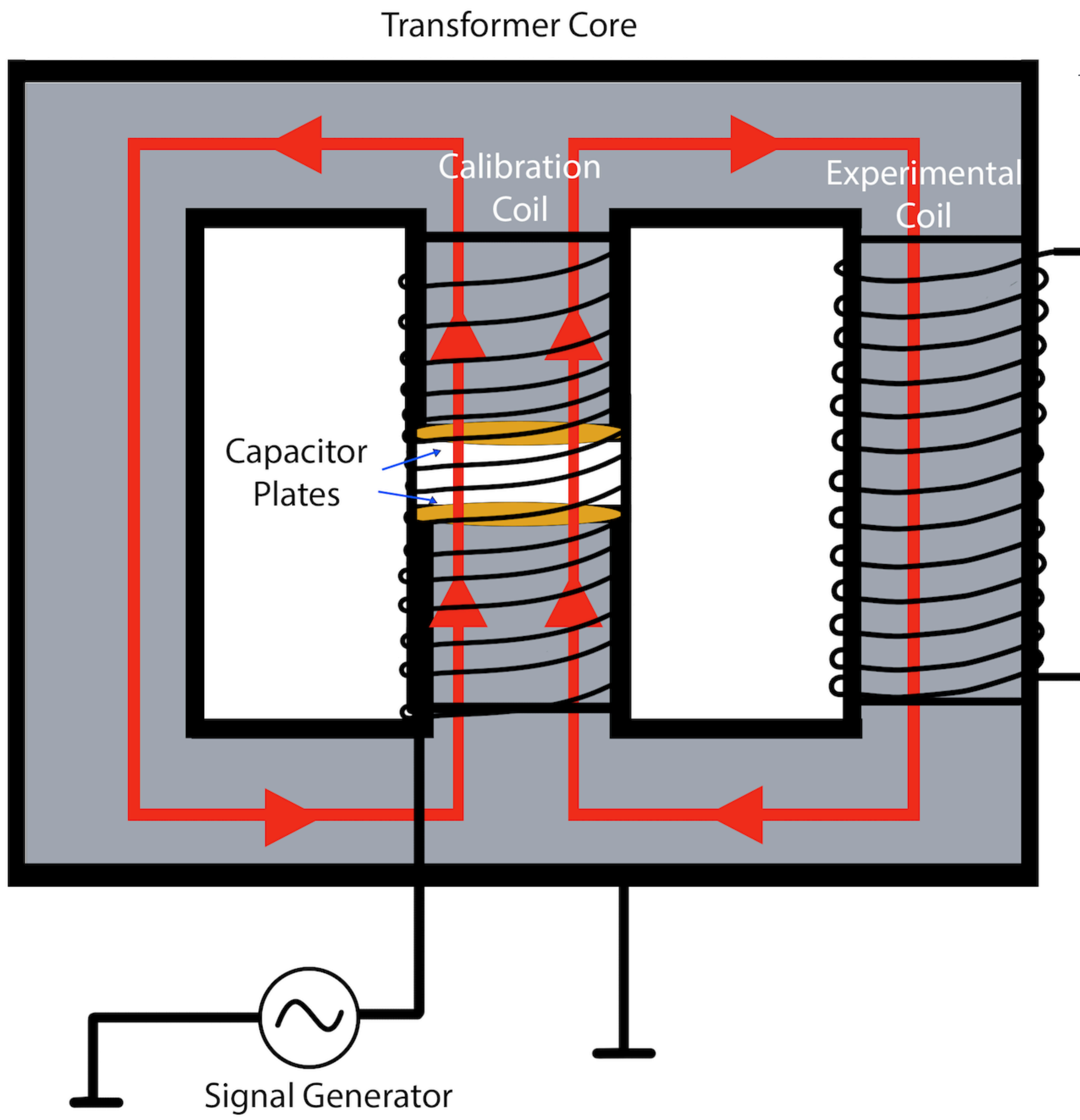


Emily Waterman

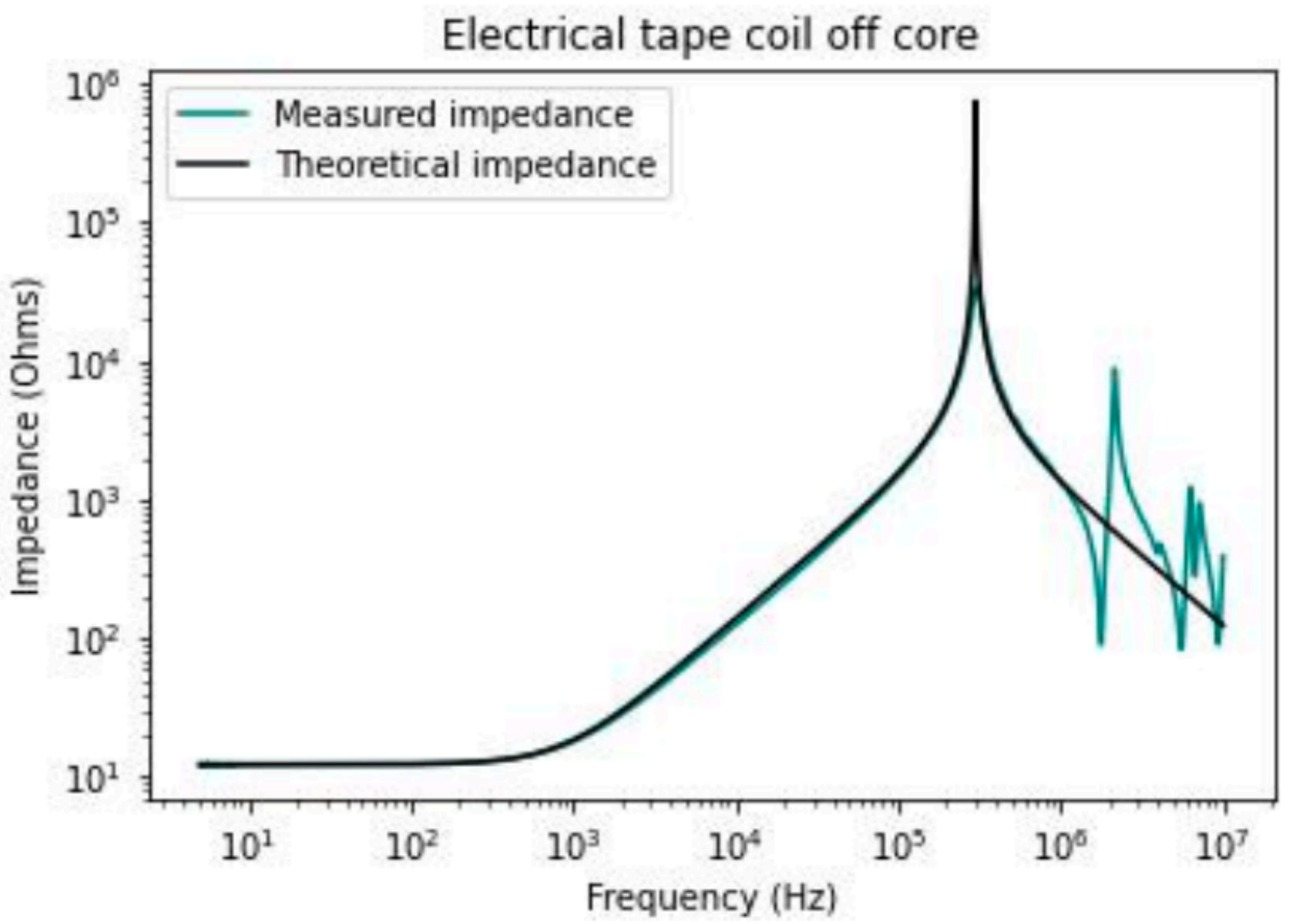
BPhil (Hons) Honours Dissertation

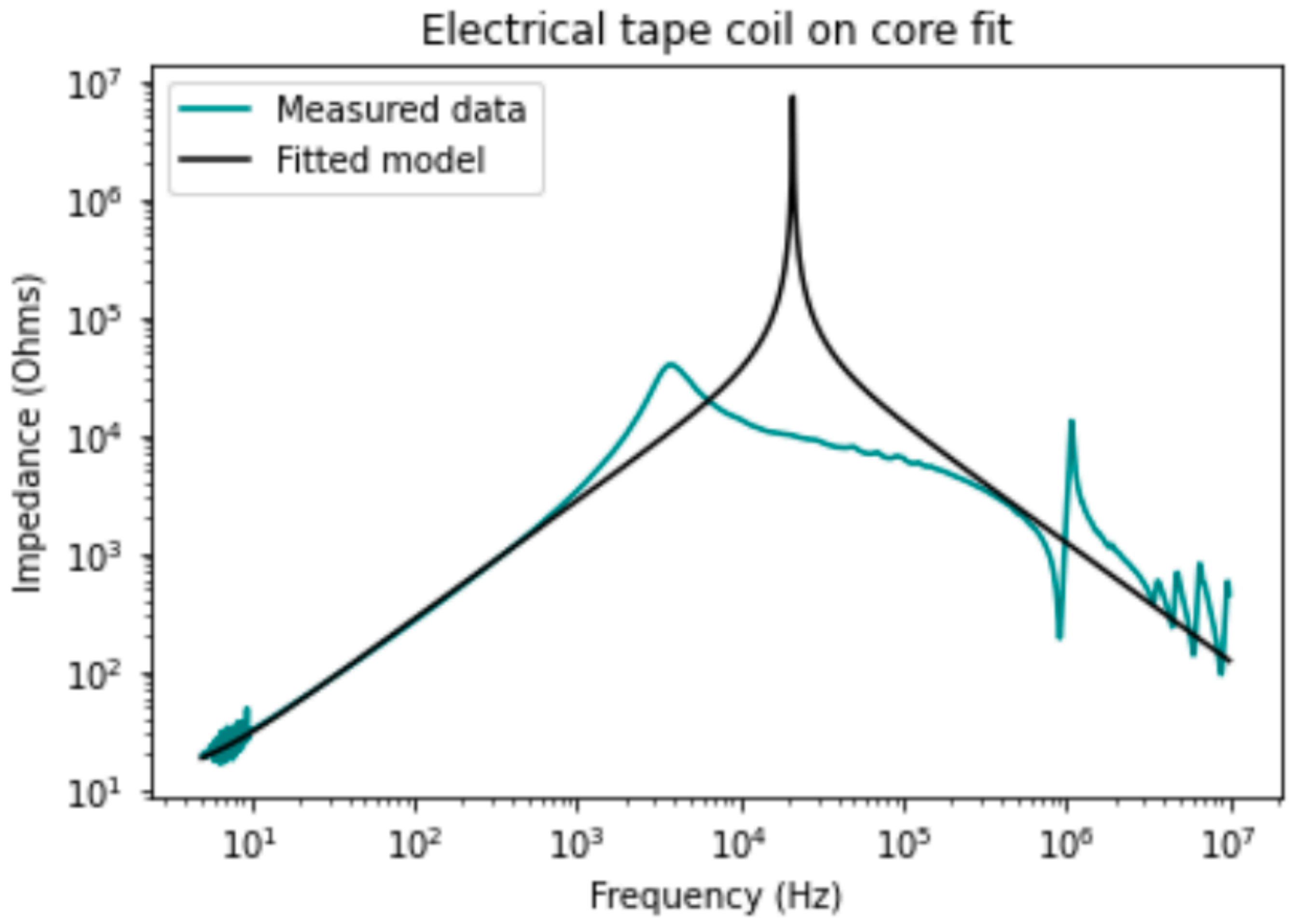


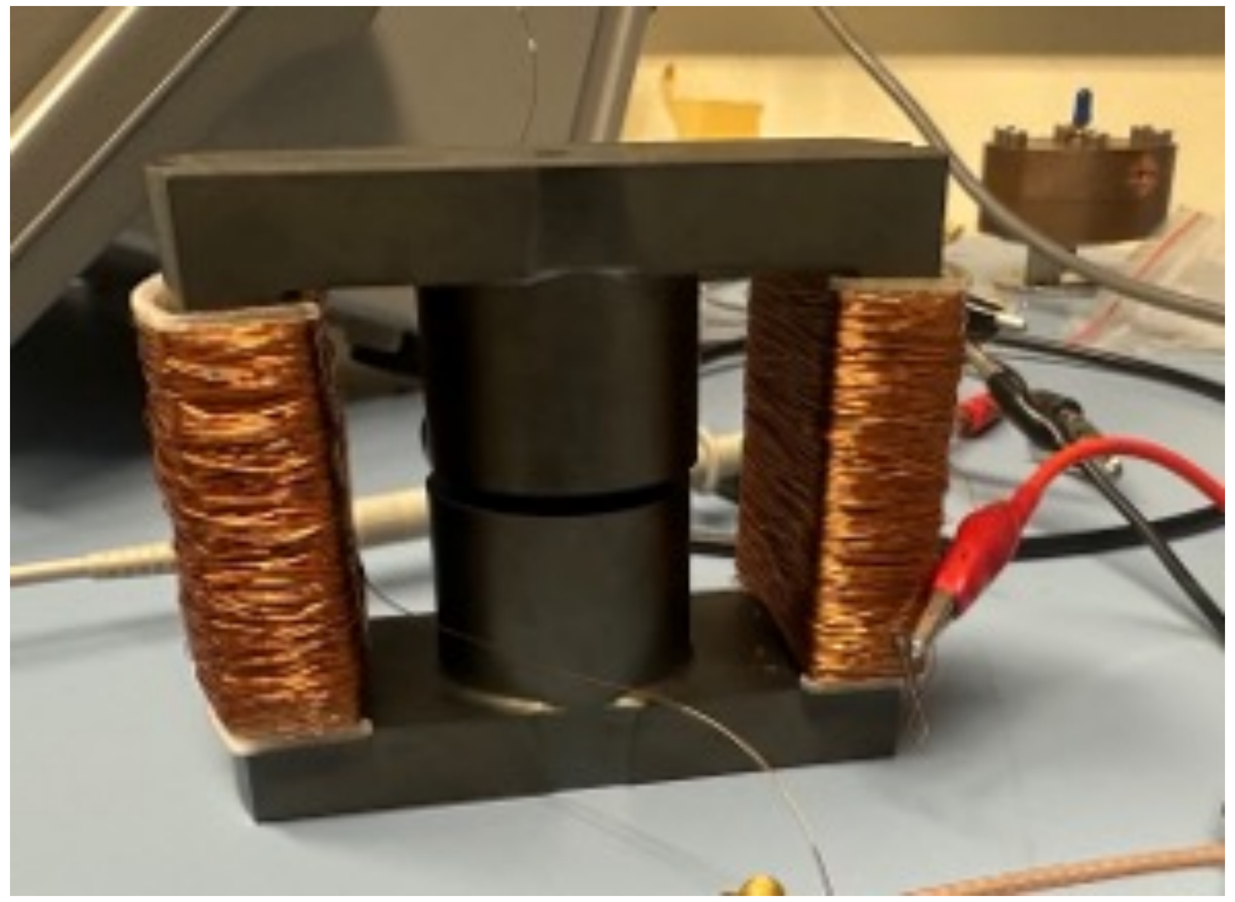


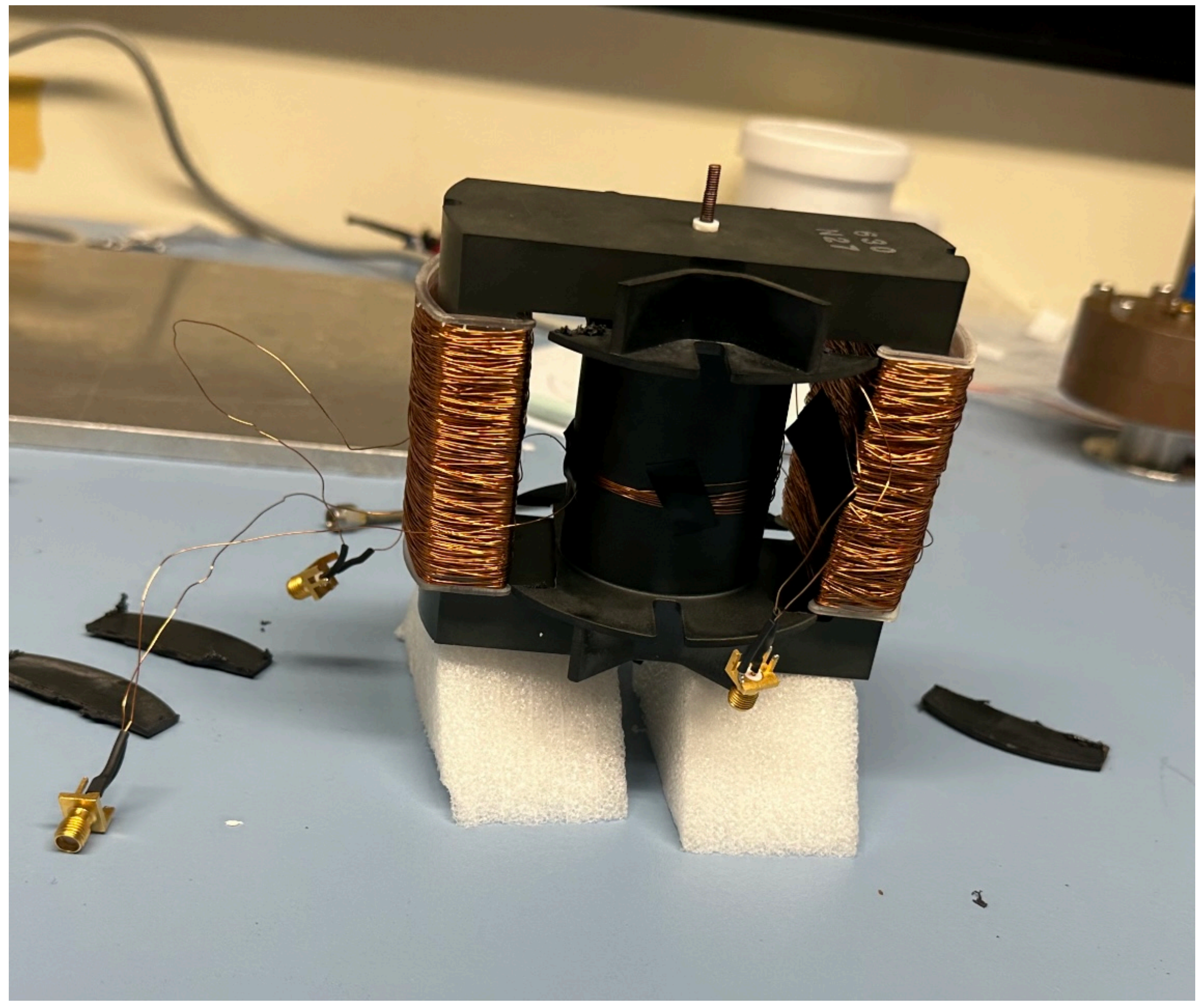

Transformer Core
Calibration Coil
Experimental Coil
Capacitor Plates
Amplifier
Vout
Signal Generator

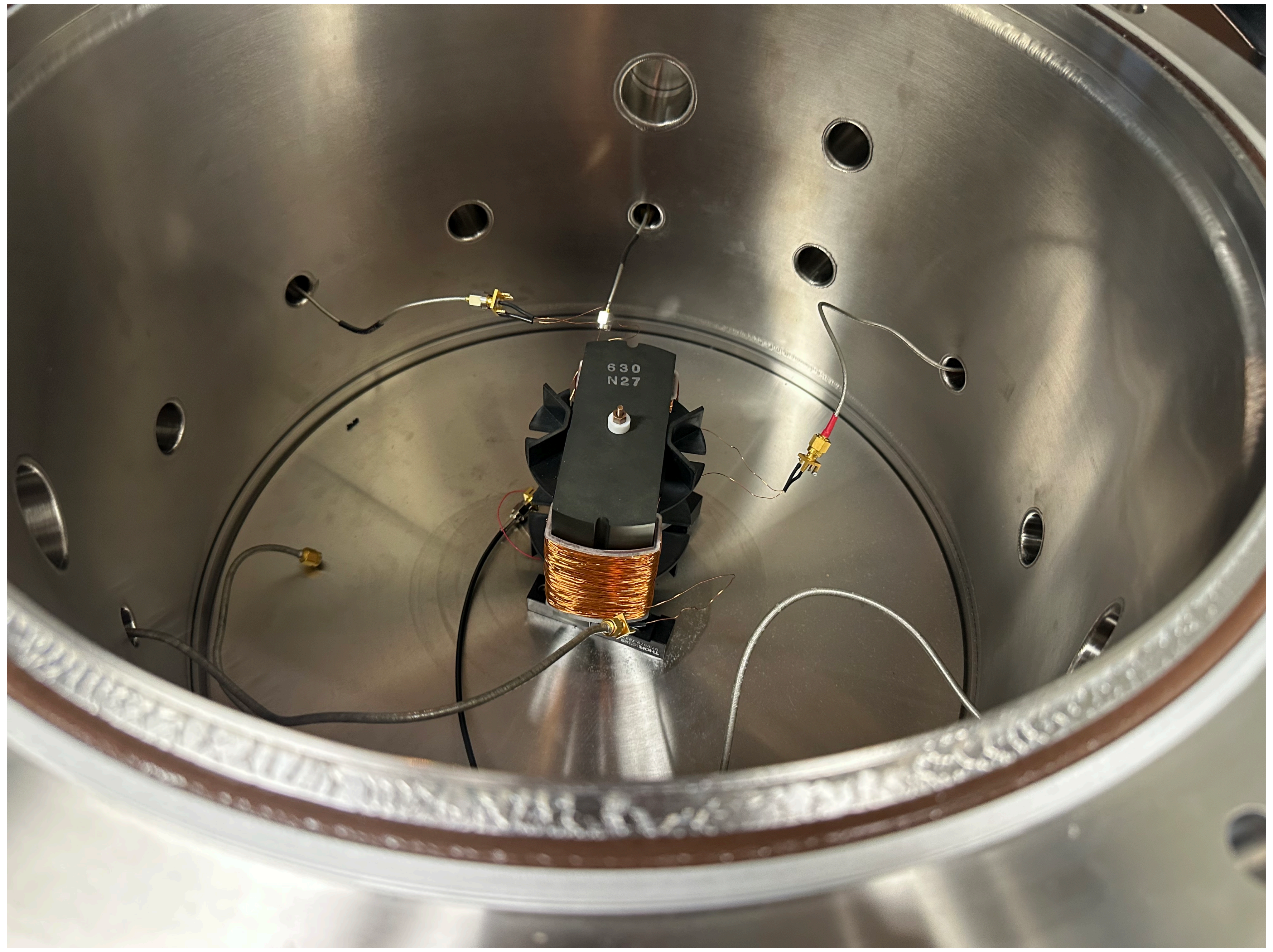
$$L = 309\ mH$$

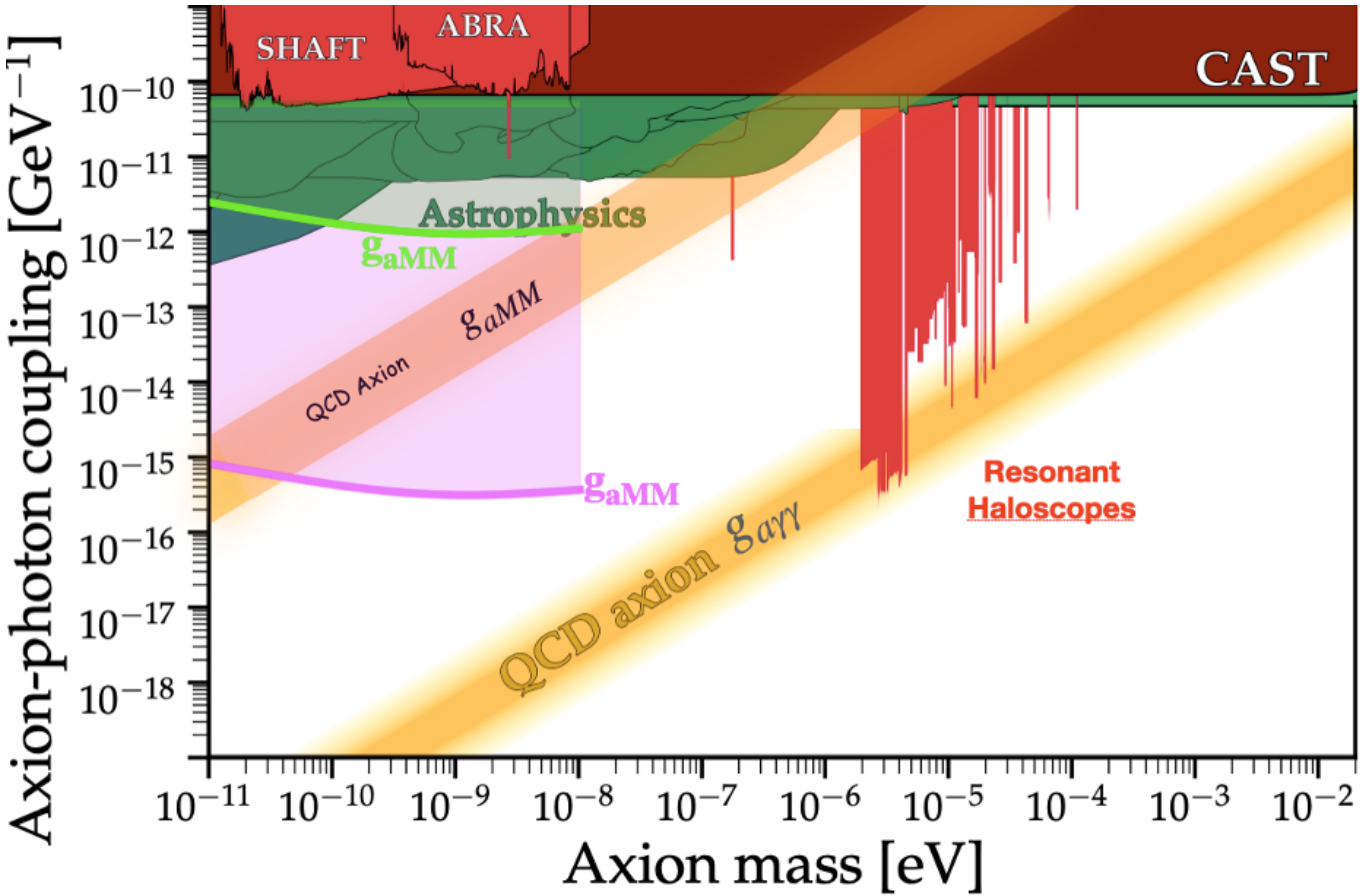

Electrical tape coil off core
Measured impedance
Theoretical impedance
Impedance (Ohms)
Frequency (Hz)


Electrical tape coil on core fit
Measured data
Fitted model
Impedance (Ohms)
Frequency (Hz)





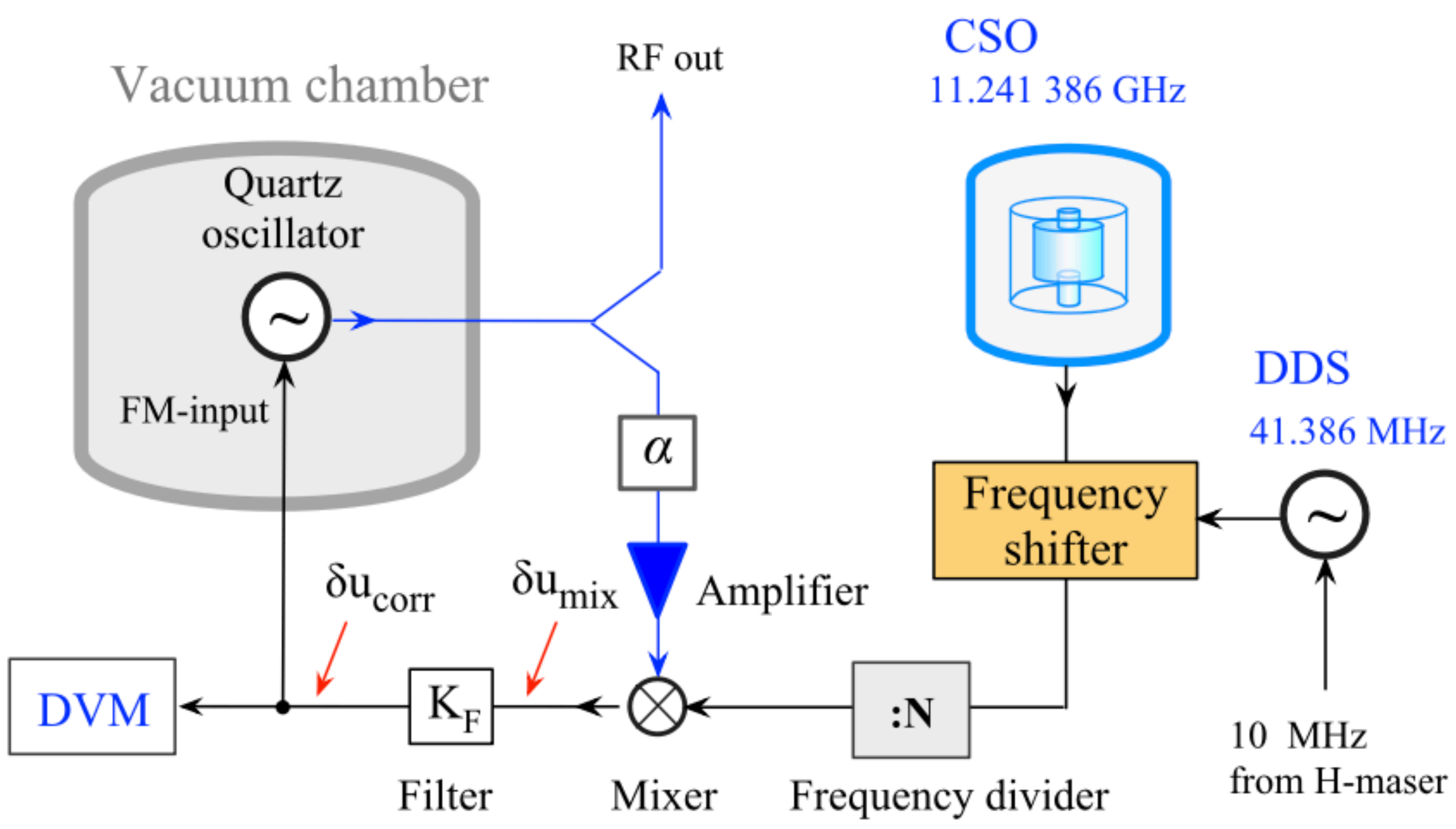


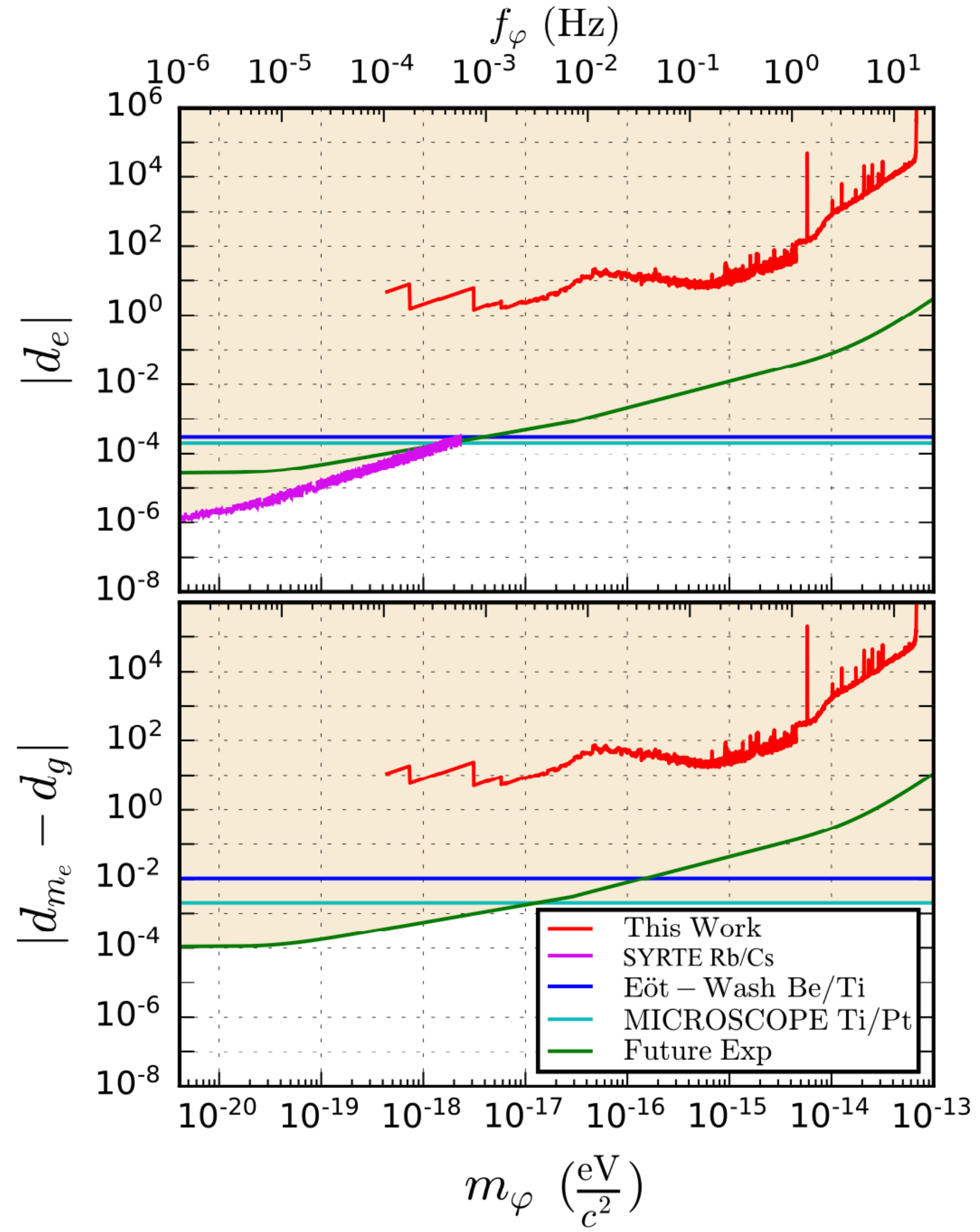


SHAFT
ABRA
CAST
Astrophysics
g_{aMM}
g_{aMM}
QCD Axion
g_{aMM}
Resonant
Haloscopes
QCD axion $g_{a\gamma\gamma}$
Axion-photon coupling [GeV^{-1}]
Axion mass [eV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}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

Searching for Scalar Dark Matter via Coupling to Fundamental Constants with Photonic, Atomic, and Mechanical Oscillators

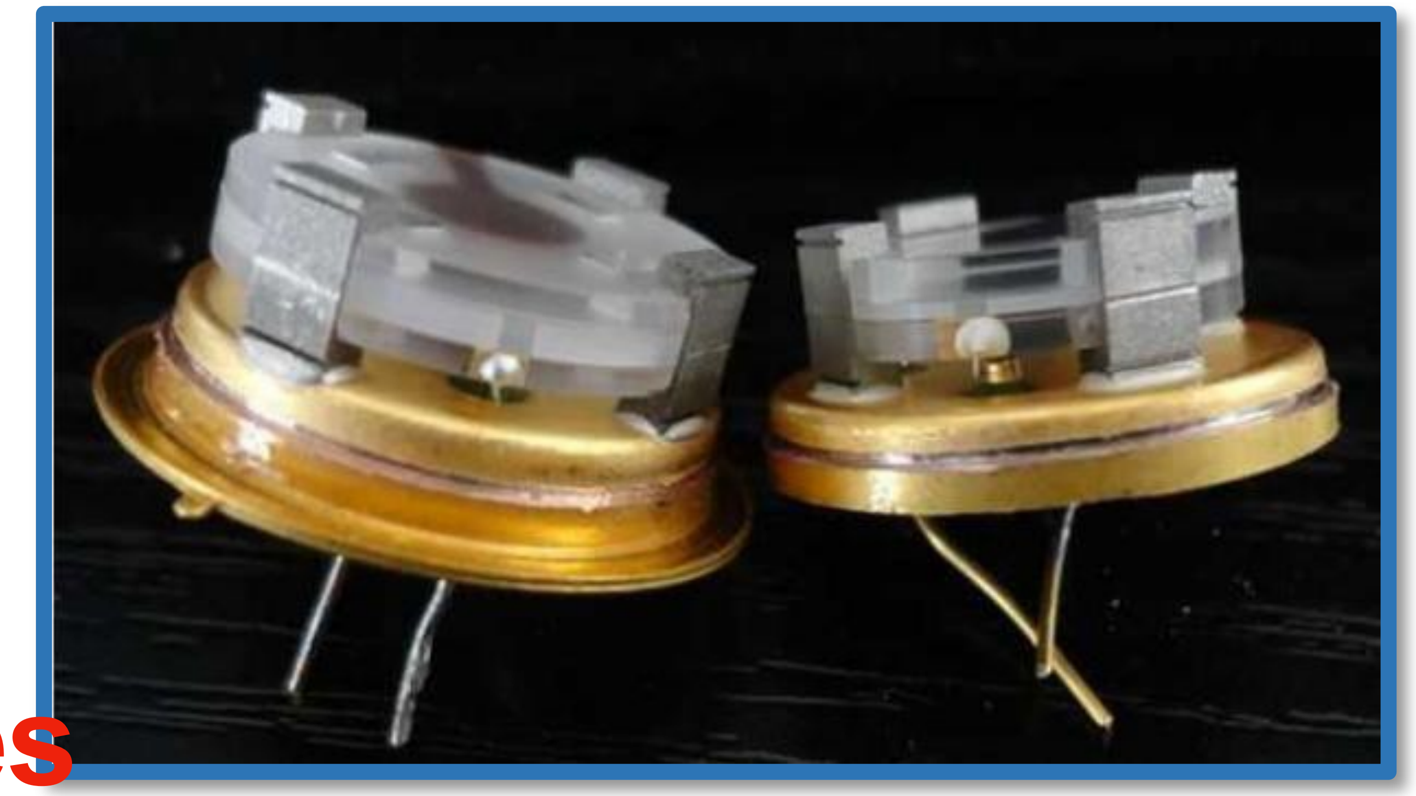
William M. Campbell, Ben T. McAllister, Maxim Goryachev, Eugene N. Ivanov, and Michael E. Tobar*
ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia

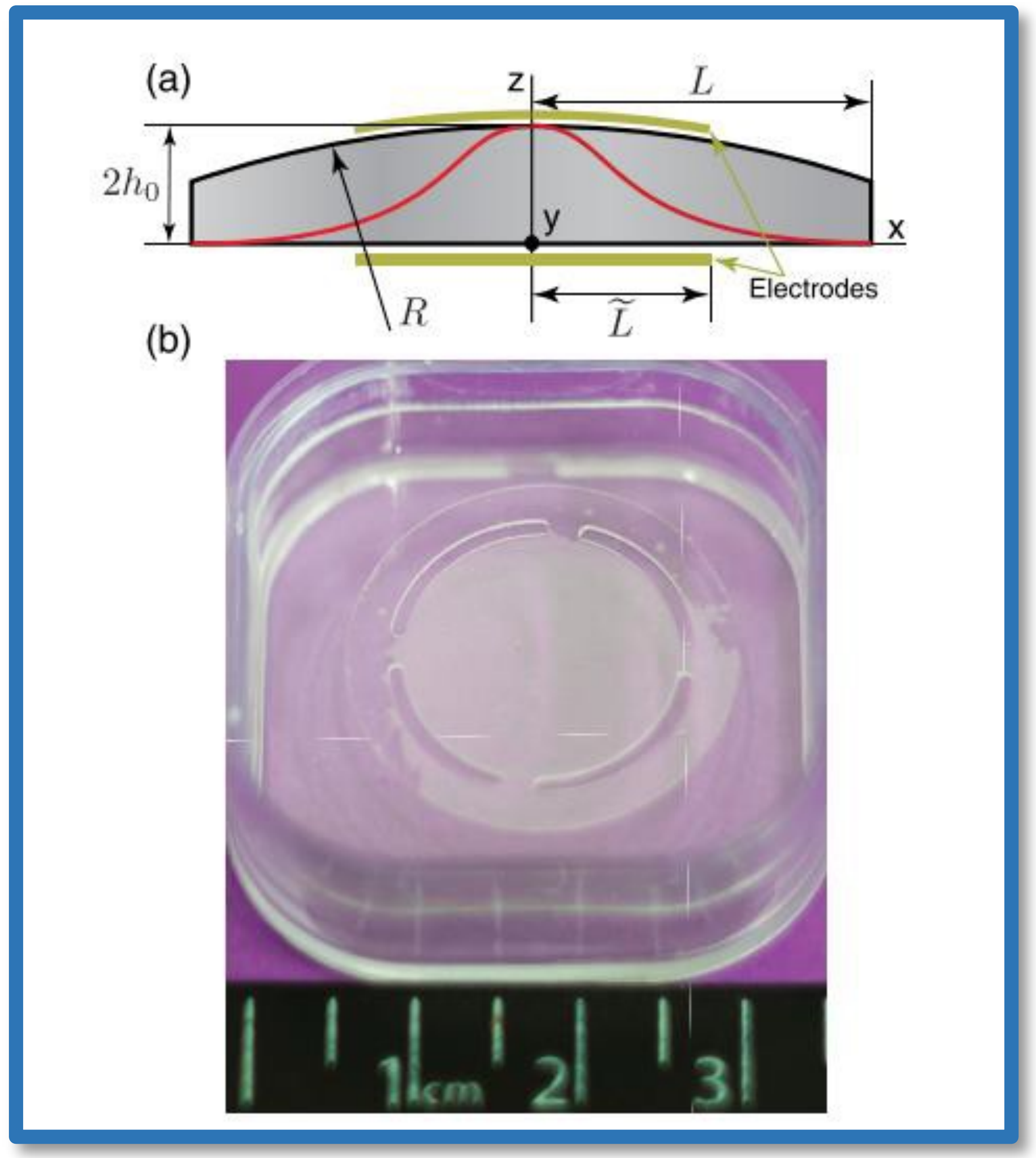




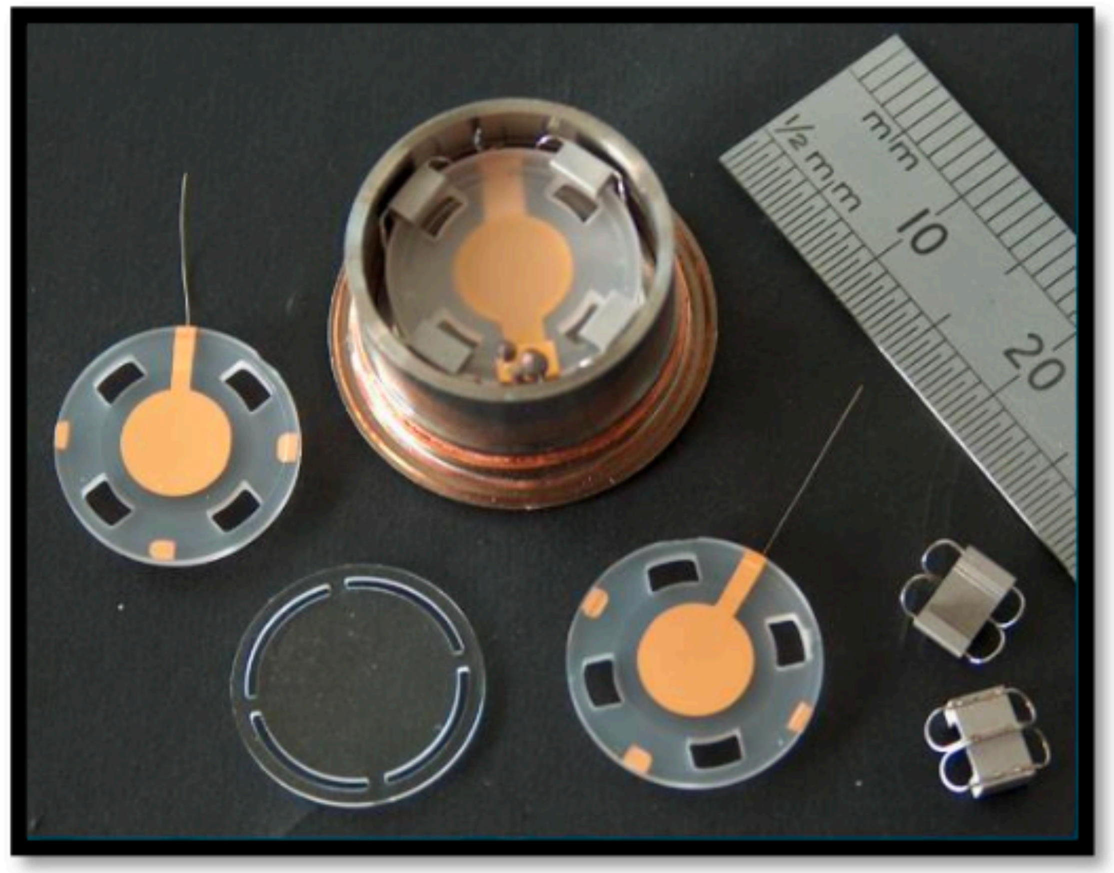
Quartz Bulk Acoustic Wave Resonators

- Acoustic analogue to a Optical Fabry-Perot cavity.
- Already a well established technology
- Gram scale mode mass, macroscopic resonator
- Extraordinarily high quality factors at cryogenic temperatures ($\sim 10^{10}$)
- Impressive short - mid term frequency stability
- Piezoelectric coupling provides excitation & readout
- High density of modes from 1-1000 MHz





The Multimode Acoustic Gravitational Wave Experiment: MAGE



MAGE
Multimode Acoustic Gravitational Wave Experiment

THE UNIVERSITY OF WESTERN AUSTRALIA

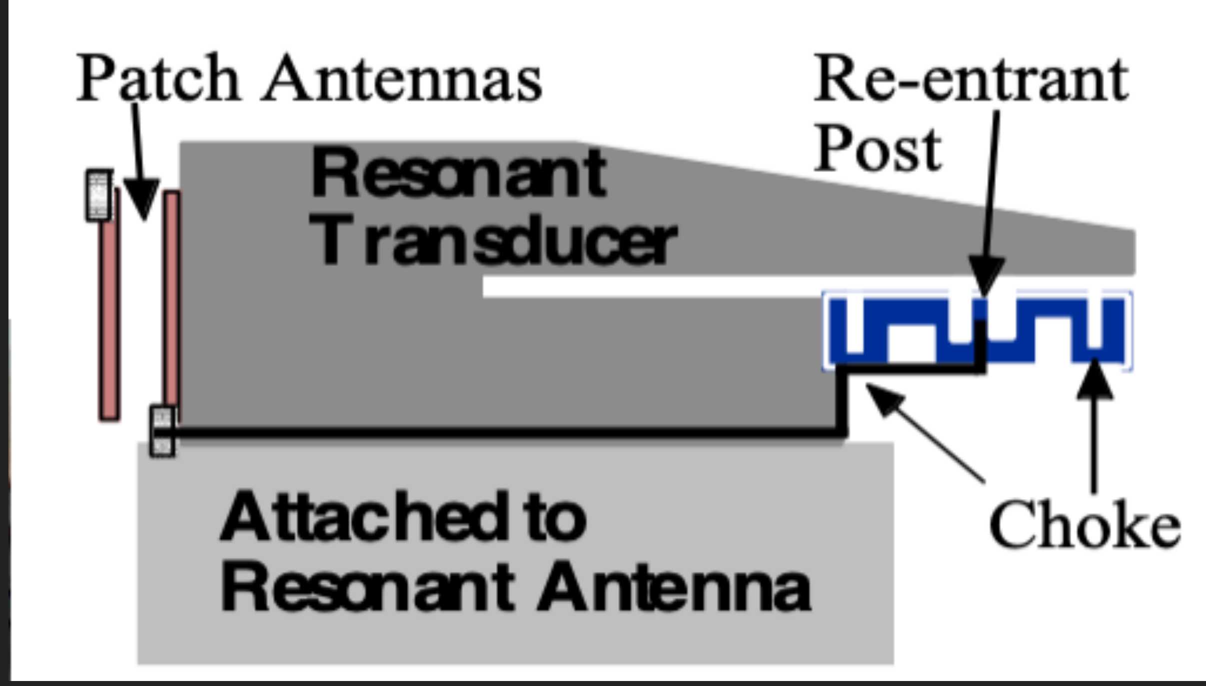
SEEK WISDOM

EQUS

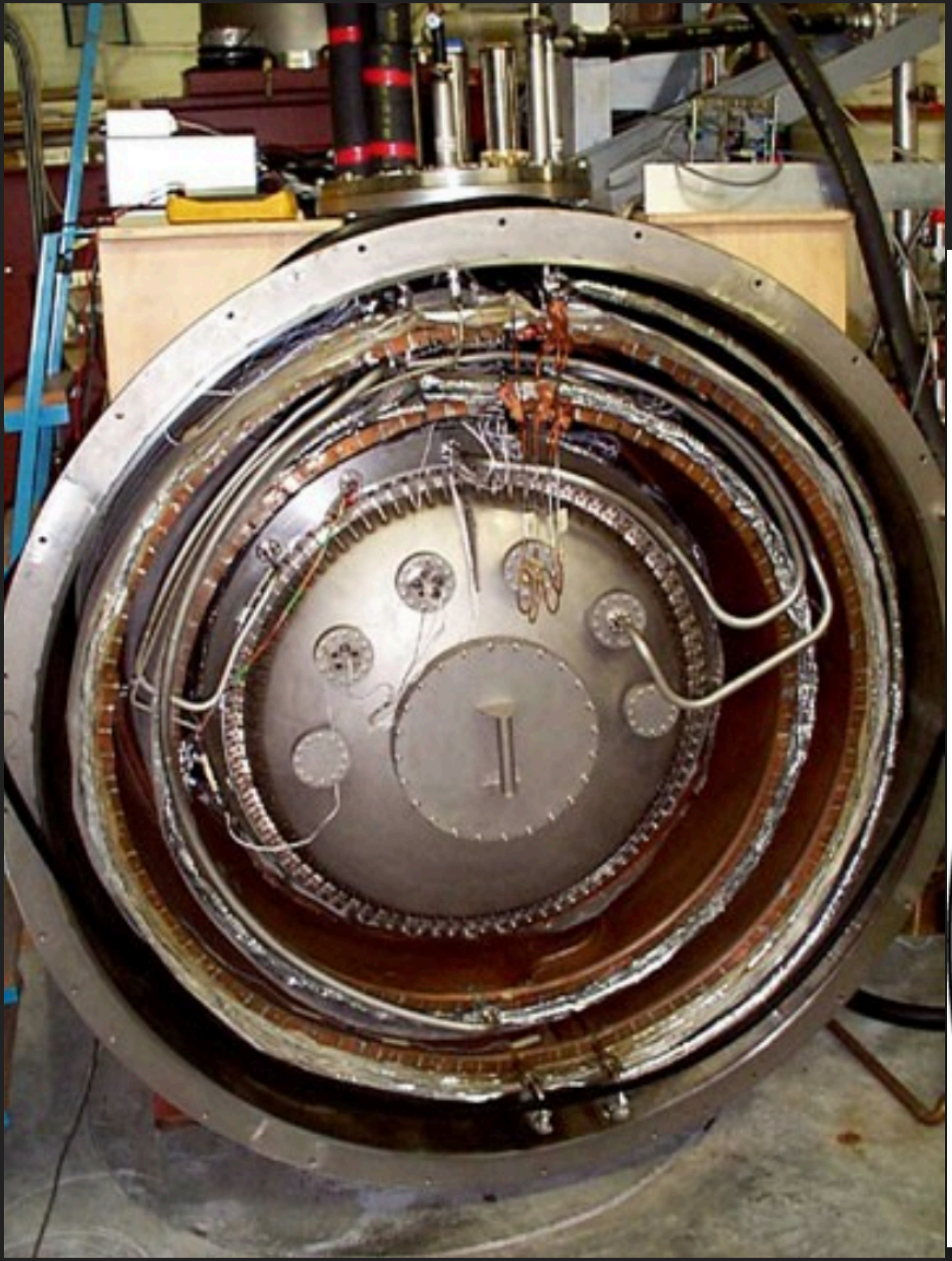
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

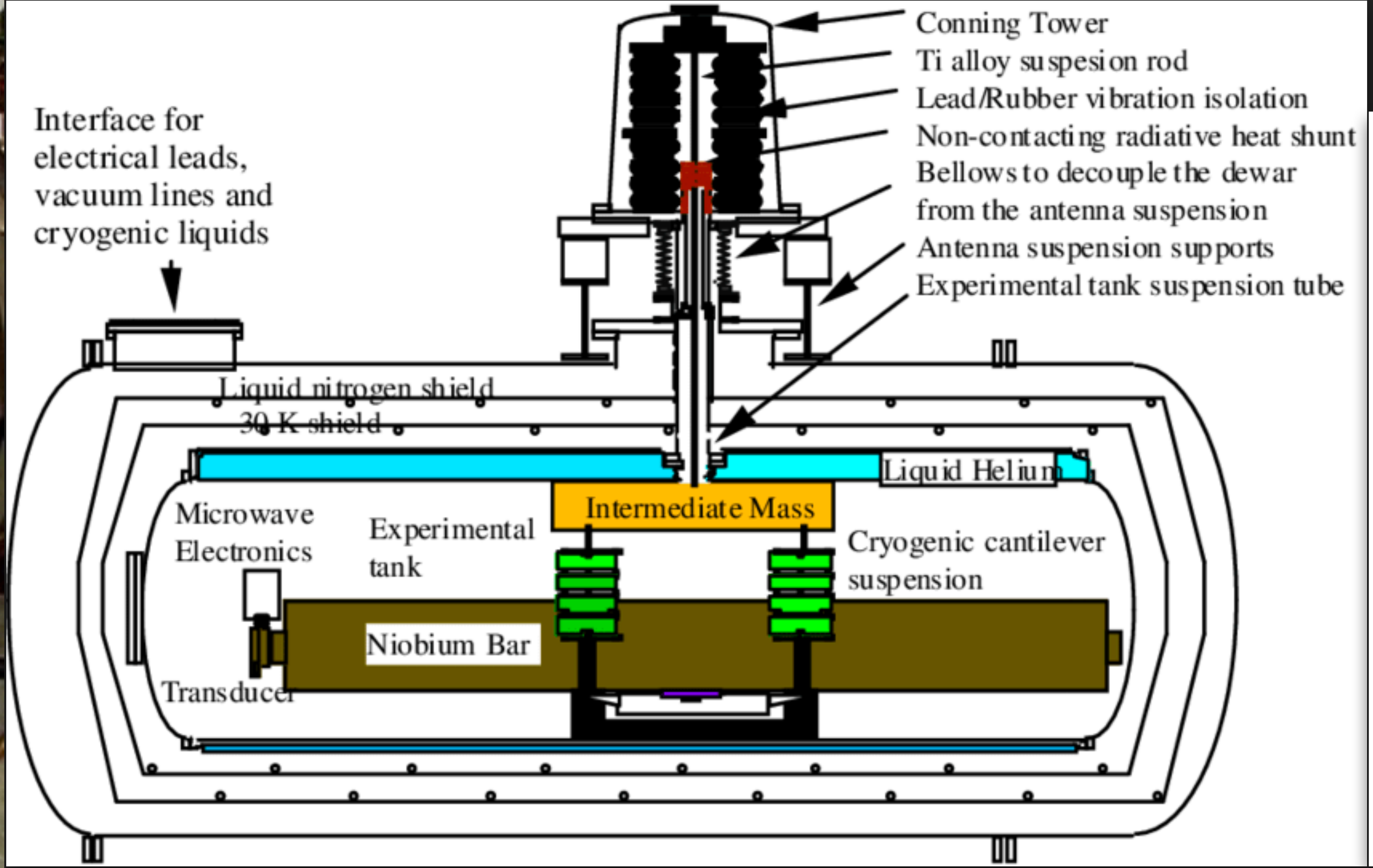
Cryogenic Resonant Bar Gravity Wave Detectors
-> Ultra precise optomechanical position measurement
-> Low phase noise read-out and pump oscillator

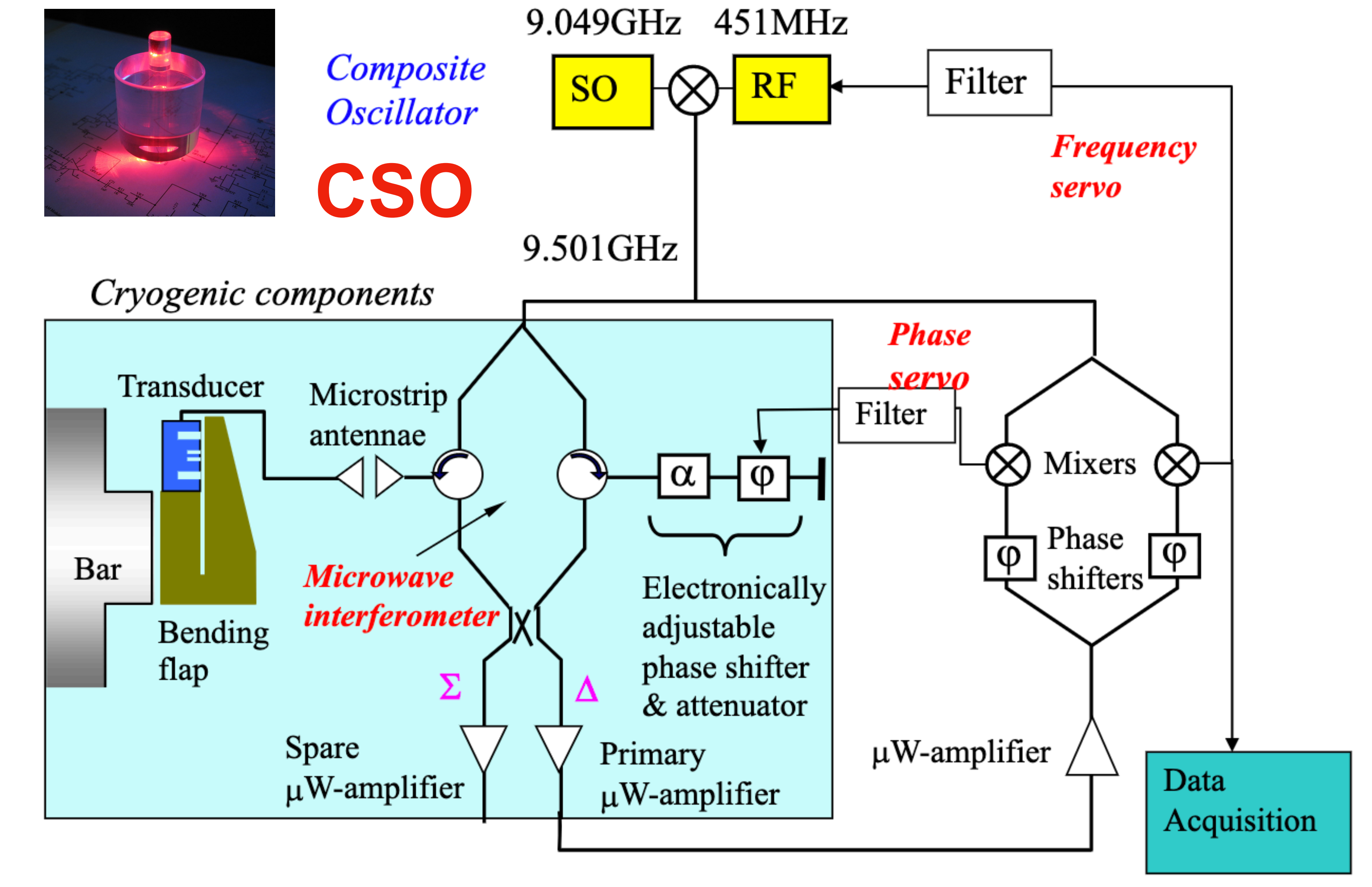
* **Photons**
* **Ponons**
* **Spins**



J. Phys. D: App. Phys, 26, 2276-2291, 1993
J.Phys D: App. Phys, 28, 1729-1736, 1995
Phys. Rev. Lett, 74, 1908, 1995
Rev. of Sci. Instrum., 67(7), 2435-2442, 1996





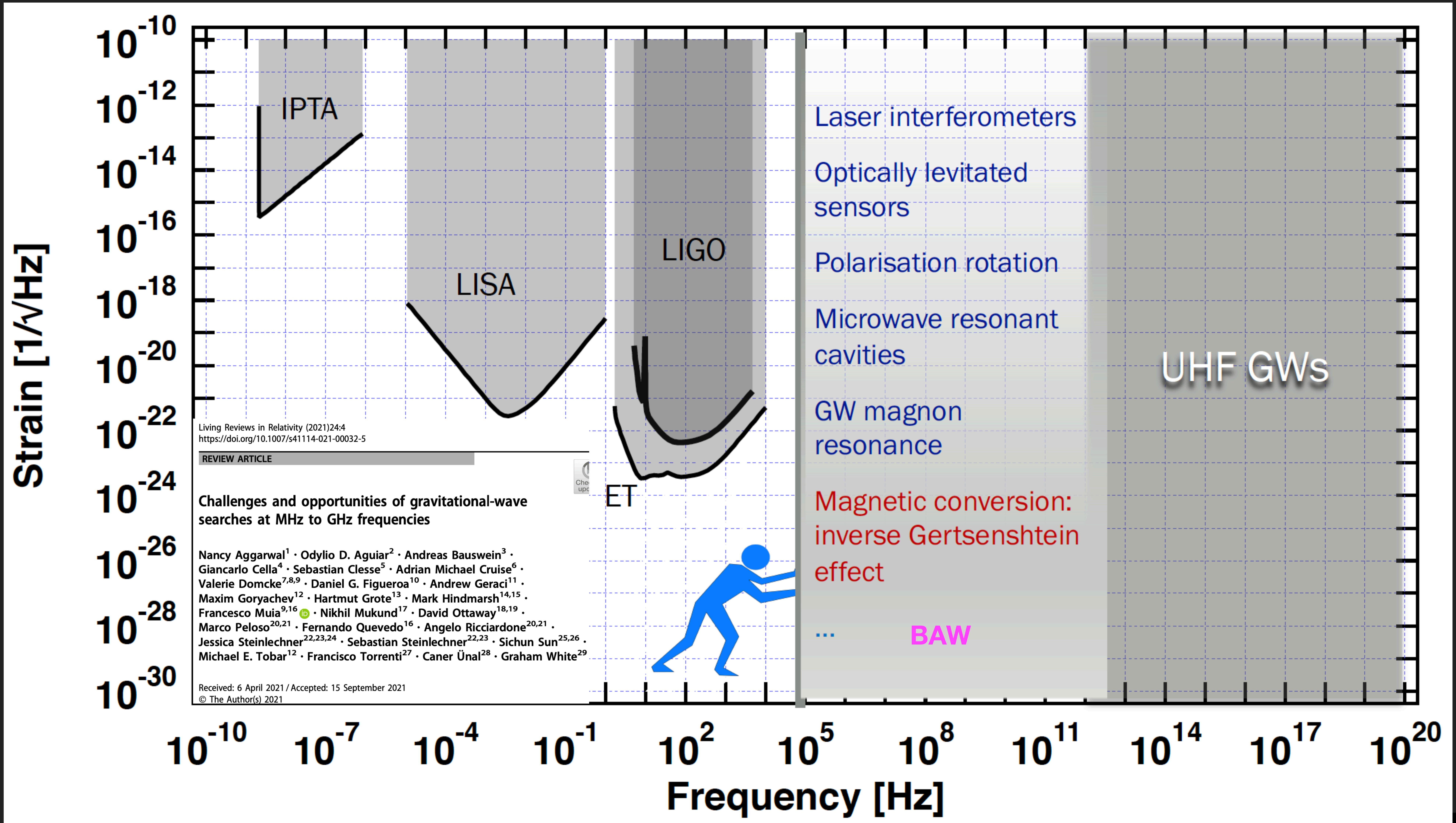


EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

My PhD project 1989 ->1993 UWA PhD
Searching GW Signal Burst at 720 Hz

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Gravitation Wave Instrument Sensitivity



Aldo Ejlli

Ultra-High-Frequency GWs: A Theory and Technology Roadmap

13/10/2021

symmetry

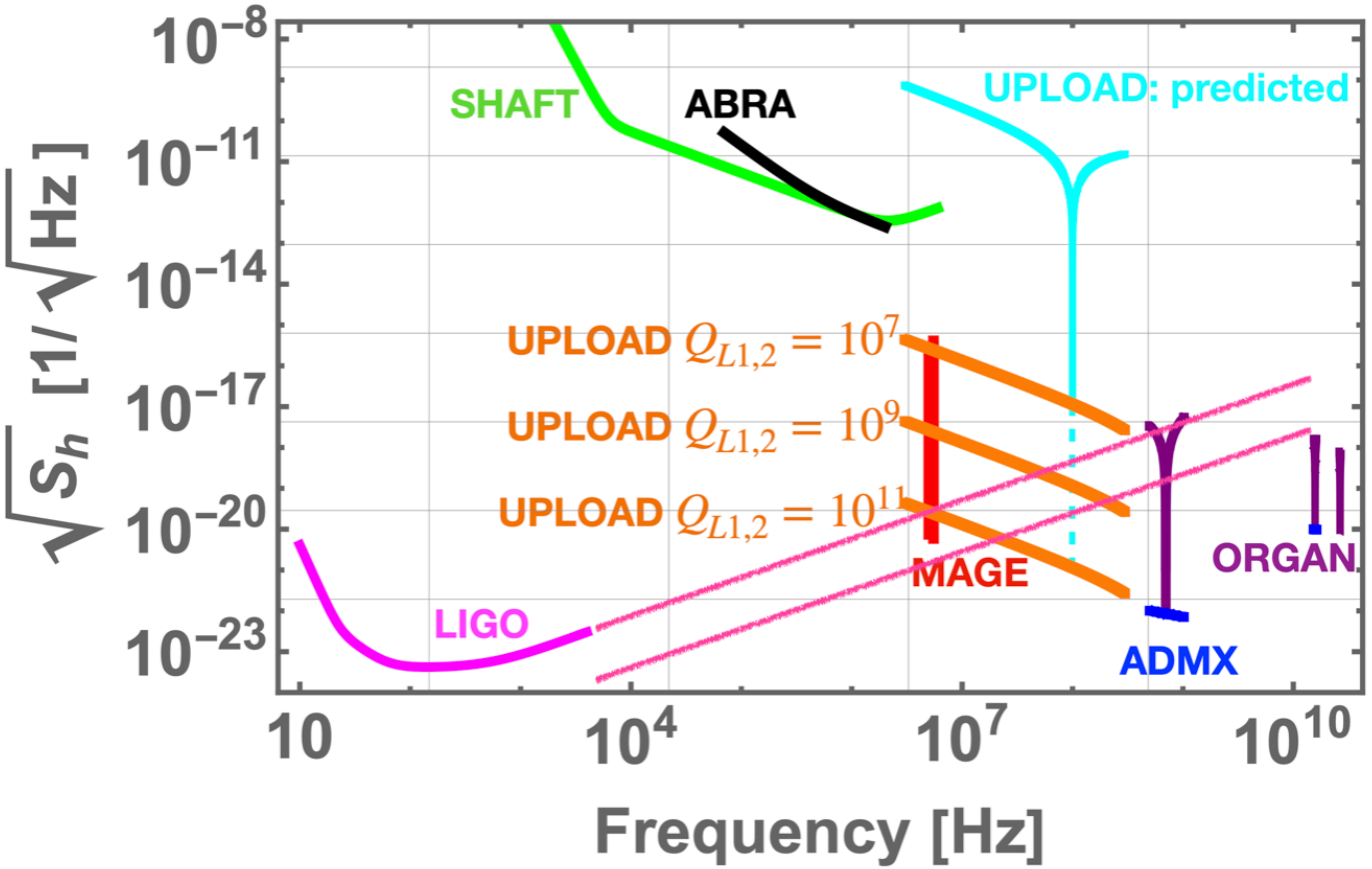
Comparing Instrument Spectral Sensitivity of Dissimilar Electromagnetic Haloscopes to Axion Dark Matter and High Frequency Gravitational Waves

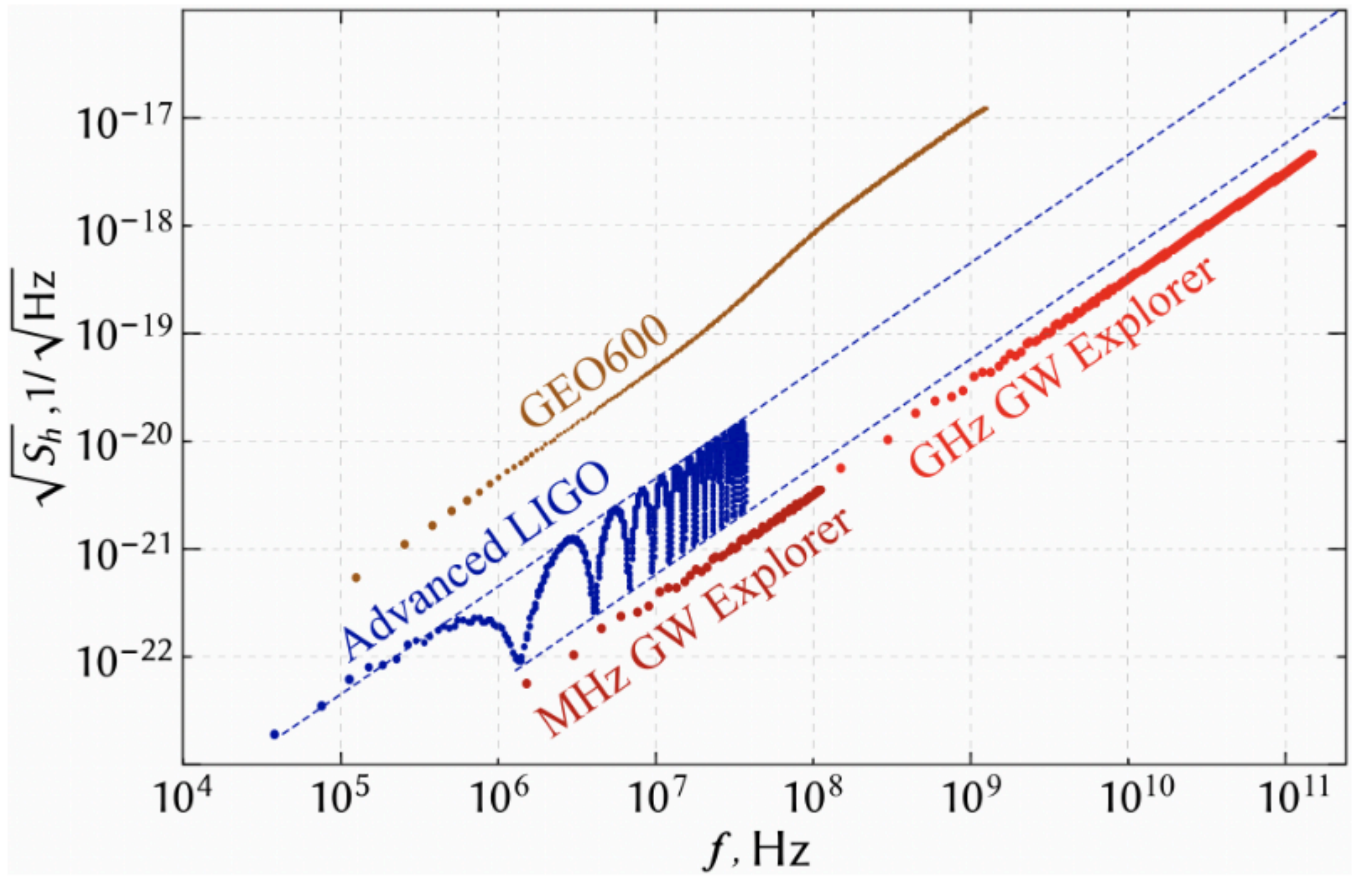
Michael E. Tobar *, Catriona A. Thomson, William M. Campbell, Aaron Quiskamp, Jeremy F. Bourhill, Benjamin T. McAllister, Eugene N. Ivanov and Maxim Goryachev

Special Issue

The Dark Universe: The Harbinger of a Major Discovery

Edited by
Prof. Konstantin Zioutas





arXiv:2409.03019 Schnabel and Korobko

$$\theta_a = g_{a\gamma\gamma} a \sim h_g$$

$$SNR = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{\Theta_a(j\omega)^2}{S_{\theta_N}(\omega)} d\omega = 4\int_{0}^{\infty} \frac{\Theta_a(f)^2}{S^{+}_{\theta_N}(f)} df$$

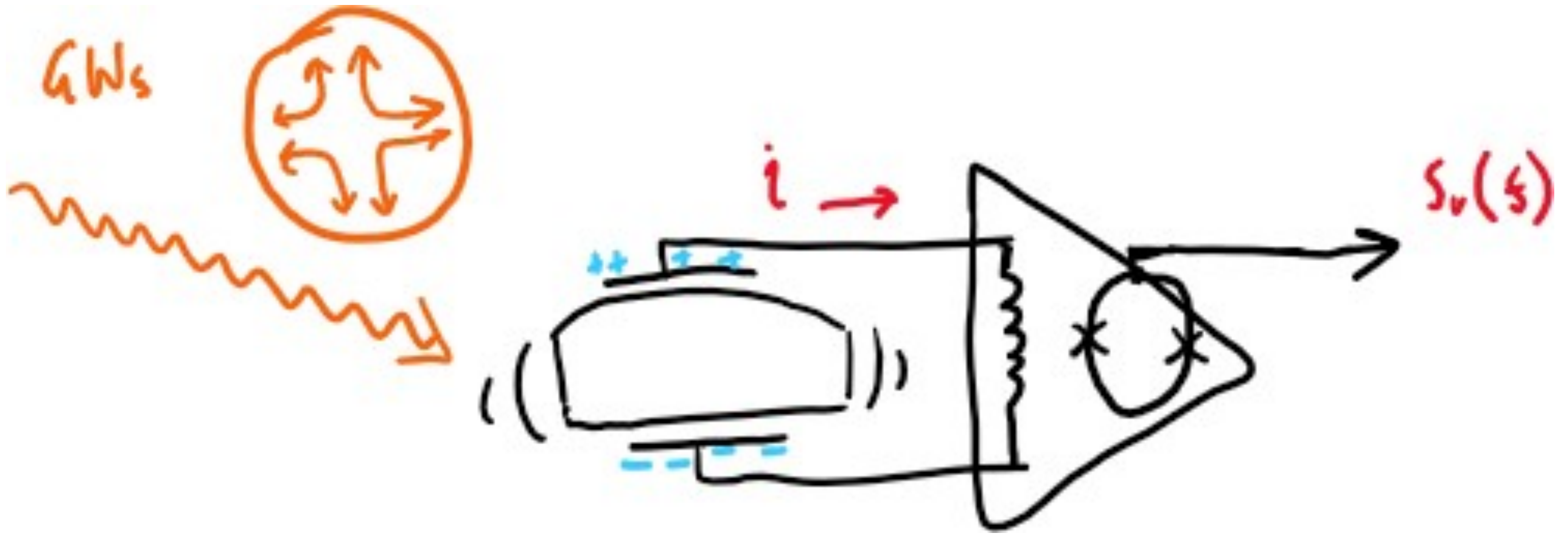
ADMX and ORGAN (purple) with current tuning locus (blue); 0.6-1.2 GHz for ADMX and 15.2 to 16.2 GHz for ORGAN

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

symmetry

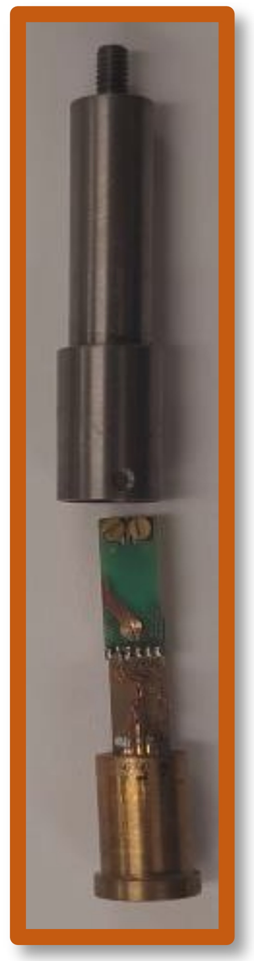
MAGE – Searching for new physics

Quartz BAW coupled to a DC SQUID amplifier



$$\ddot{B}_\lambda + \tau_\lambda^{-1}\dot{B}_\lambda + \omega_\lambda^2 B = -c^2 R_{i0j0}\int_V dv\, \frac{\rho}{m_\lambda} U_\lambda^i(\mathbf{x})x^j.$$

Highly sensitive resonant mass antenna



PHYSICAL REVIEW D **90,** 102005 (2014)

Gravitational wave detection with high frequency phonon trapping acoustic cavities

Maxim Goryachev and Michael E. Tobar*

ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia

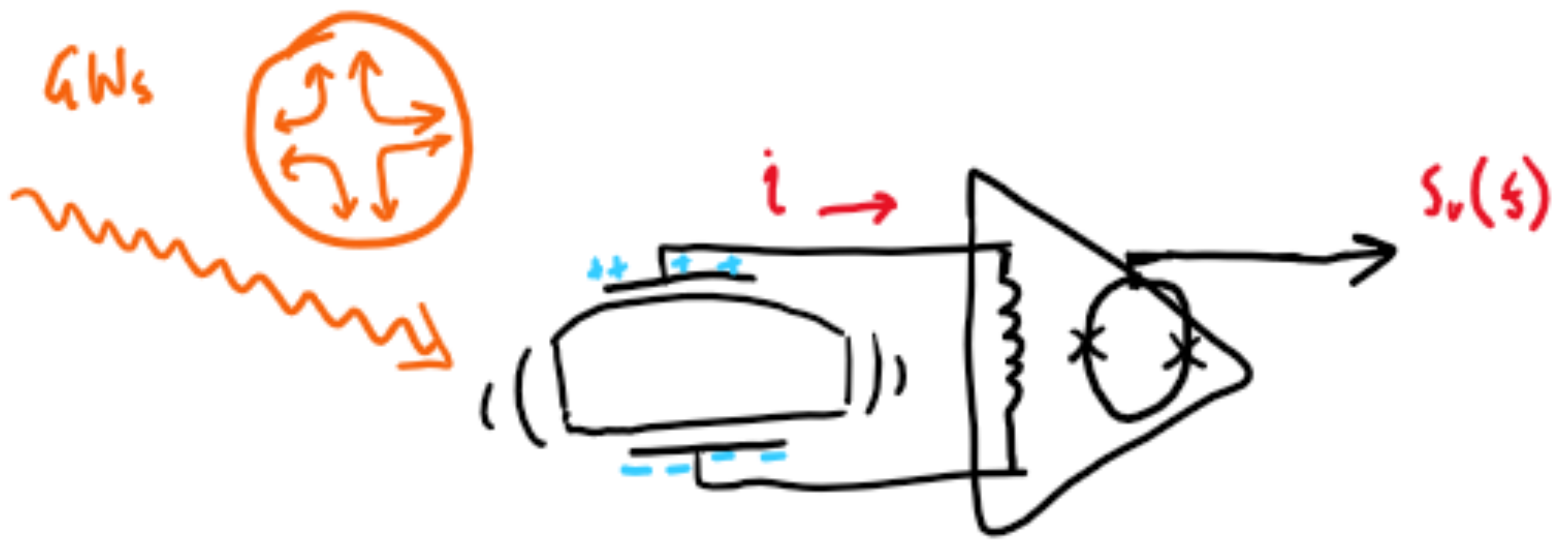
(Received 25 September 2014; published 24 November 2014)

Primary target:

High frequency gravitational waves (MHz)

MAGE – Searching for new physics

Quartz BAW coupled to a DC SQUID amplifier → *Highly sensitive resonant mass antenna*



Mode Temperature

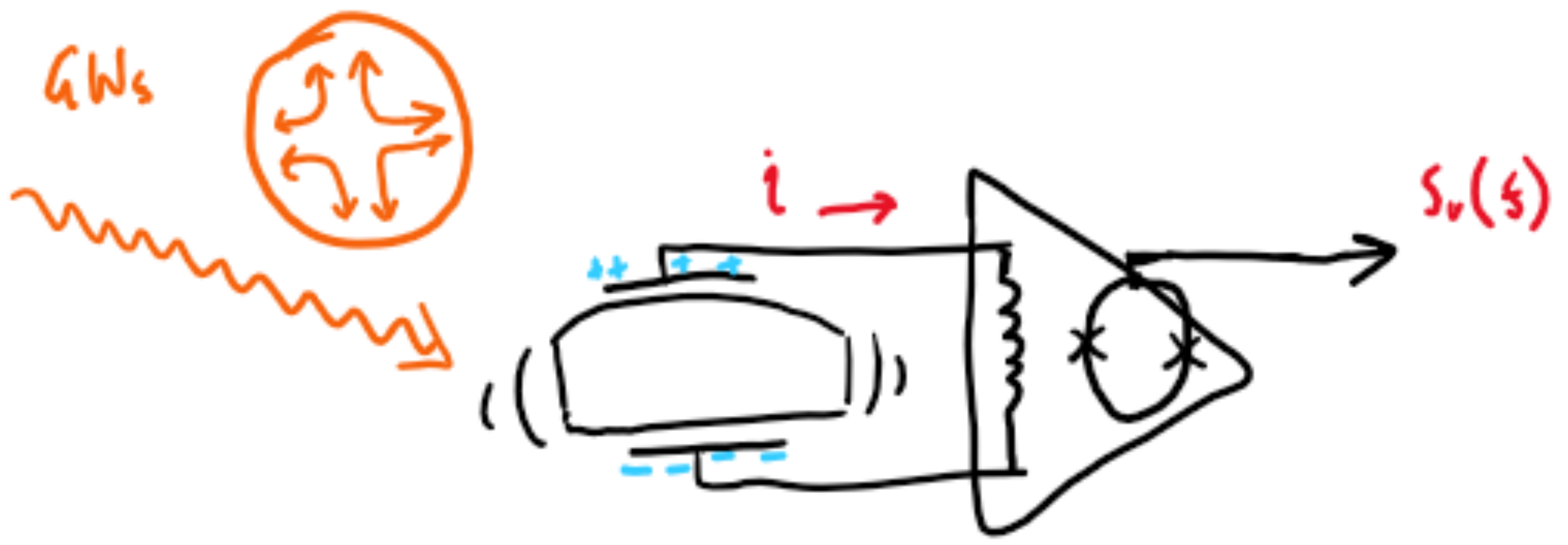
$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}} \left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right)$$

Quality Factor

Gravitational Coupling

MAGE – Searching for new physics

Quartz BAW coupled to a DC SQUID amplifier → *Highly sensitive resonant mass antenna*

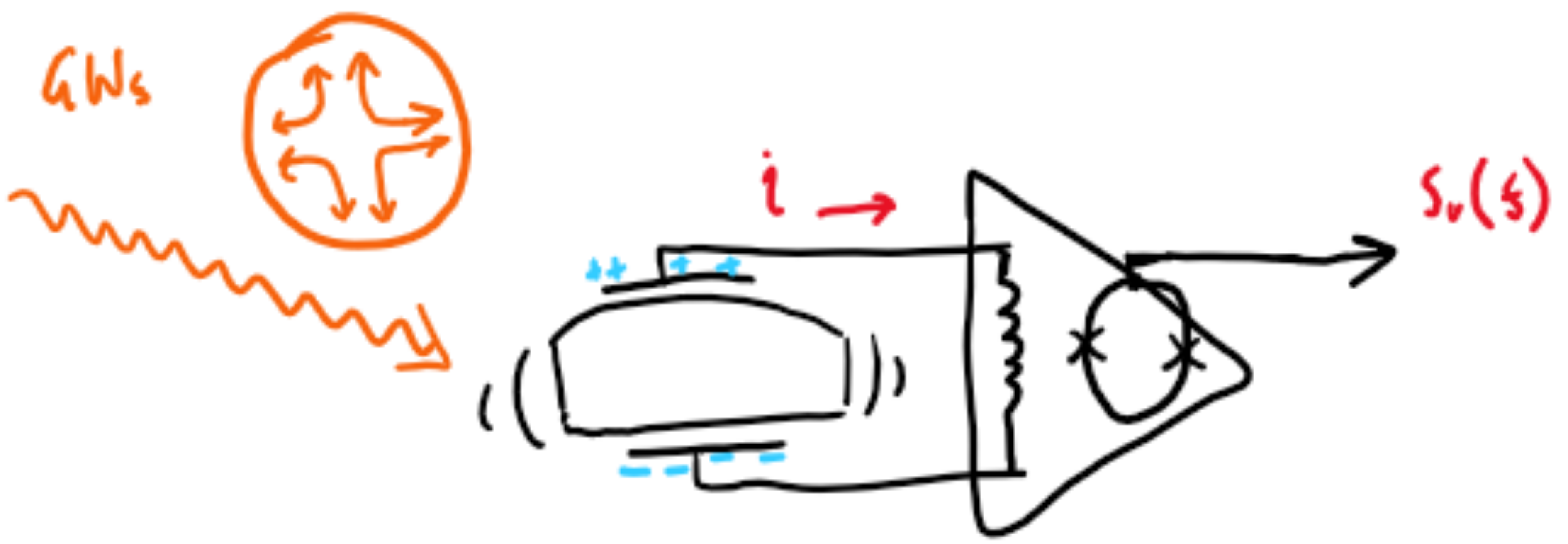


$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right) \qquad \xi_\lambda = h_0 \tilde{\xi}_\lambda = \int_V dv \frac{\rho}{m_\lambda} U_\lambda^i(\mathbf{x}) x^j$$

Gravitational Coupling

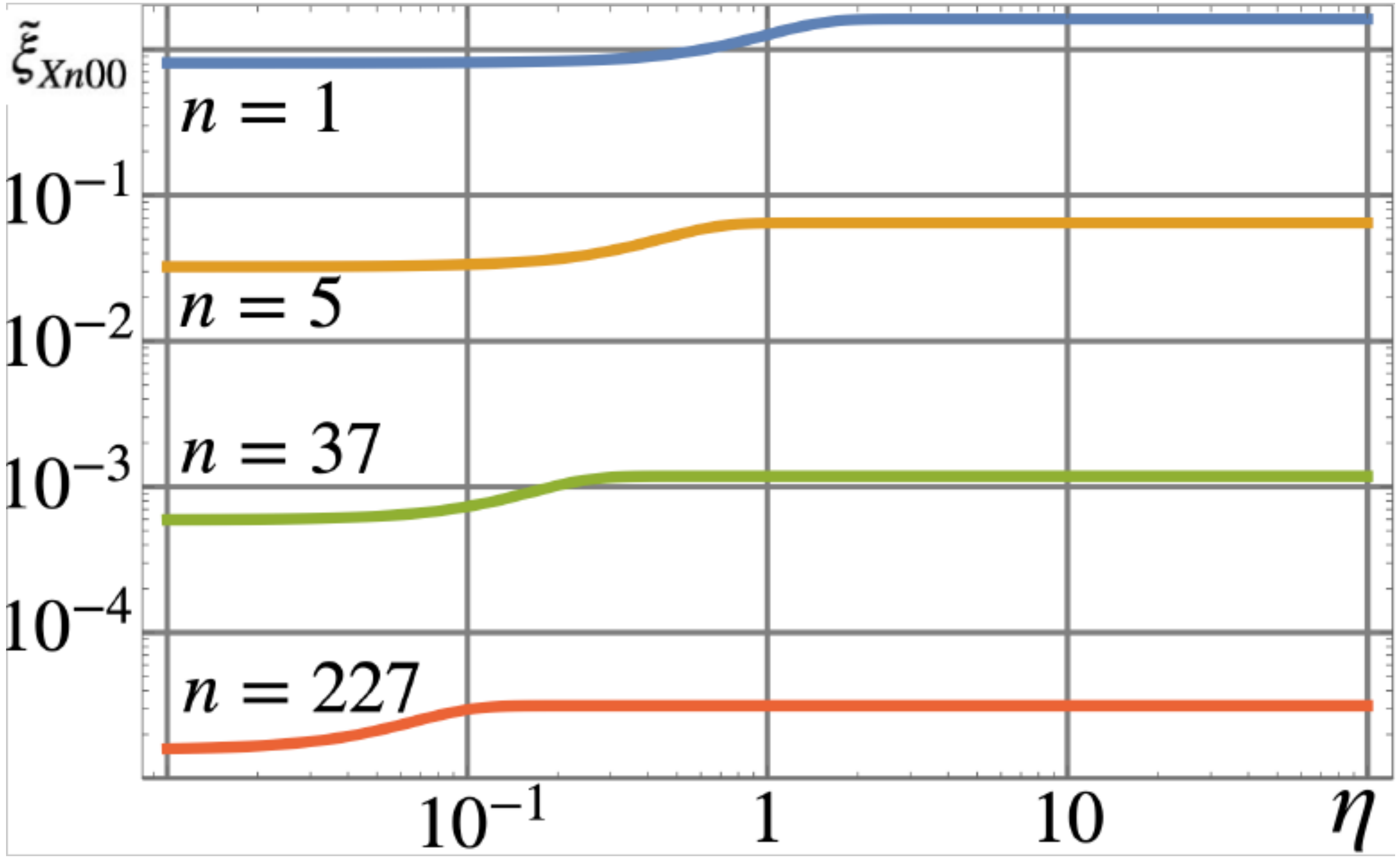
MAGE – Searching for new physics

Quartz BAW coupled to a DC SQUID amplifier → *Highly sensitive resonant mass antenna*



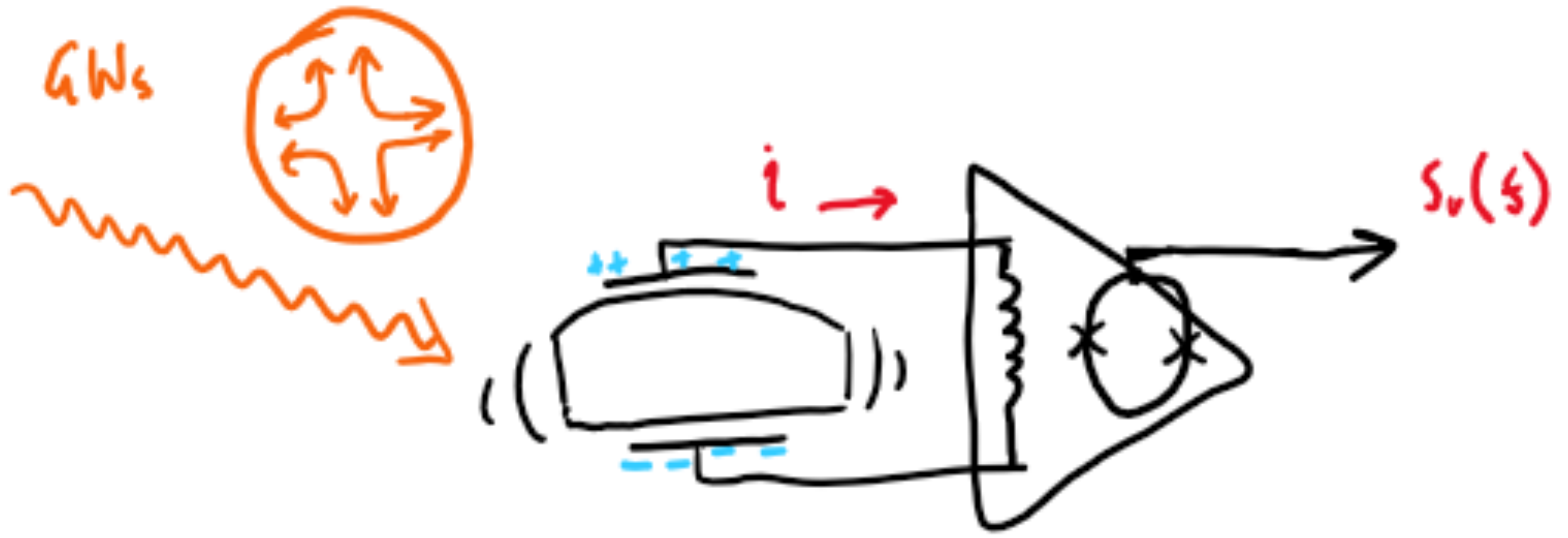
$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right)$$

Gravitational Coupling

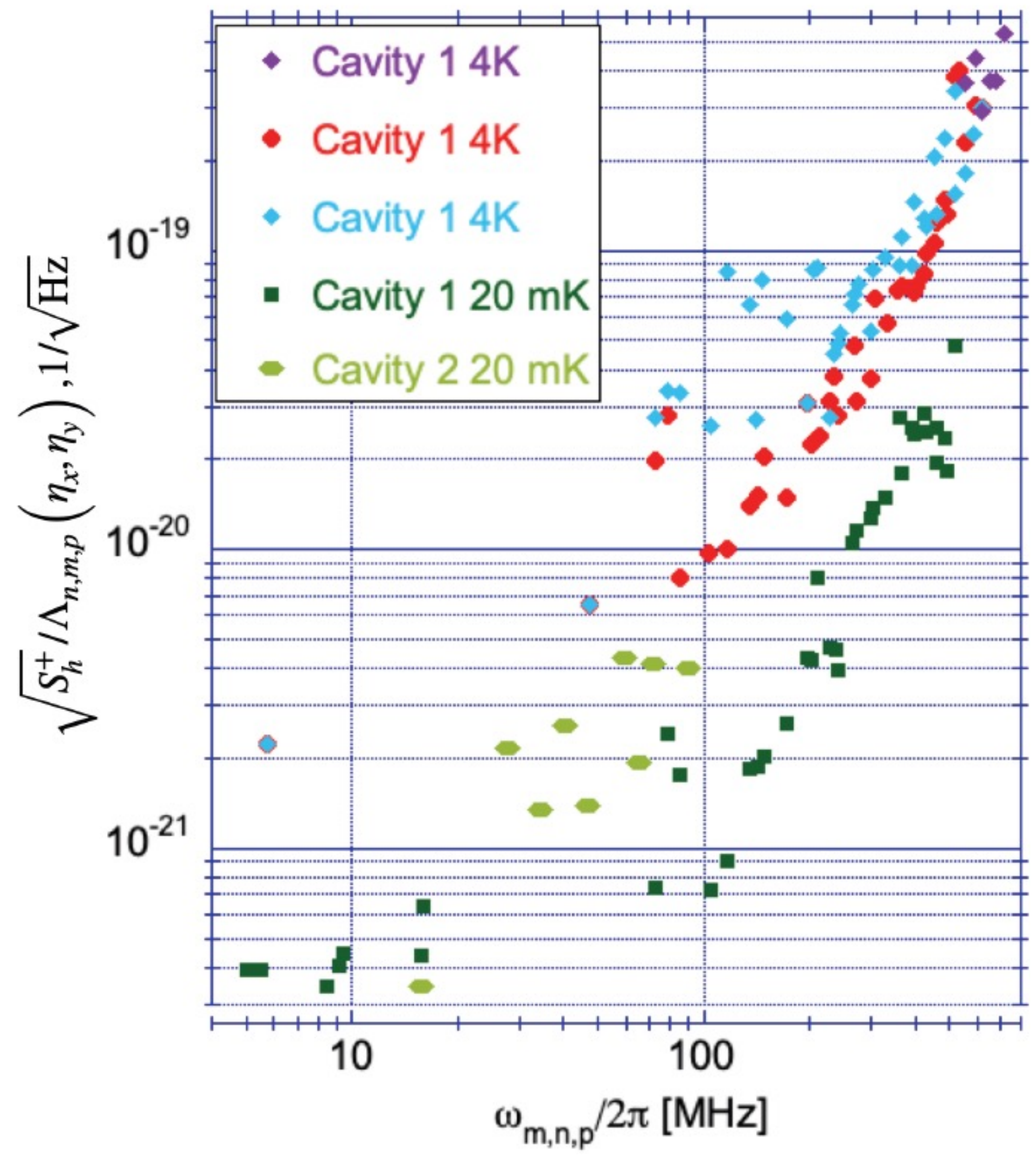


MAGE – Searching for new physics

Quartz BAW coupled to a DC SQUID amplifier → ***Highly sensitive resonant mass antenna***



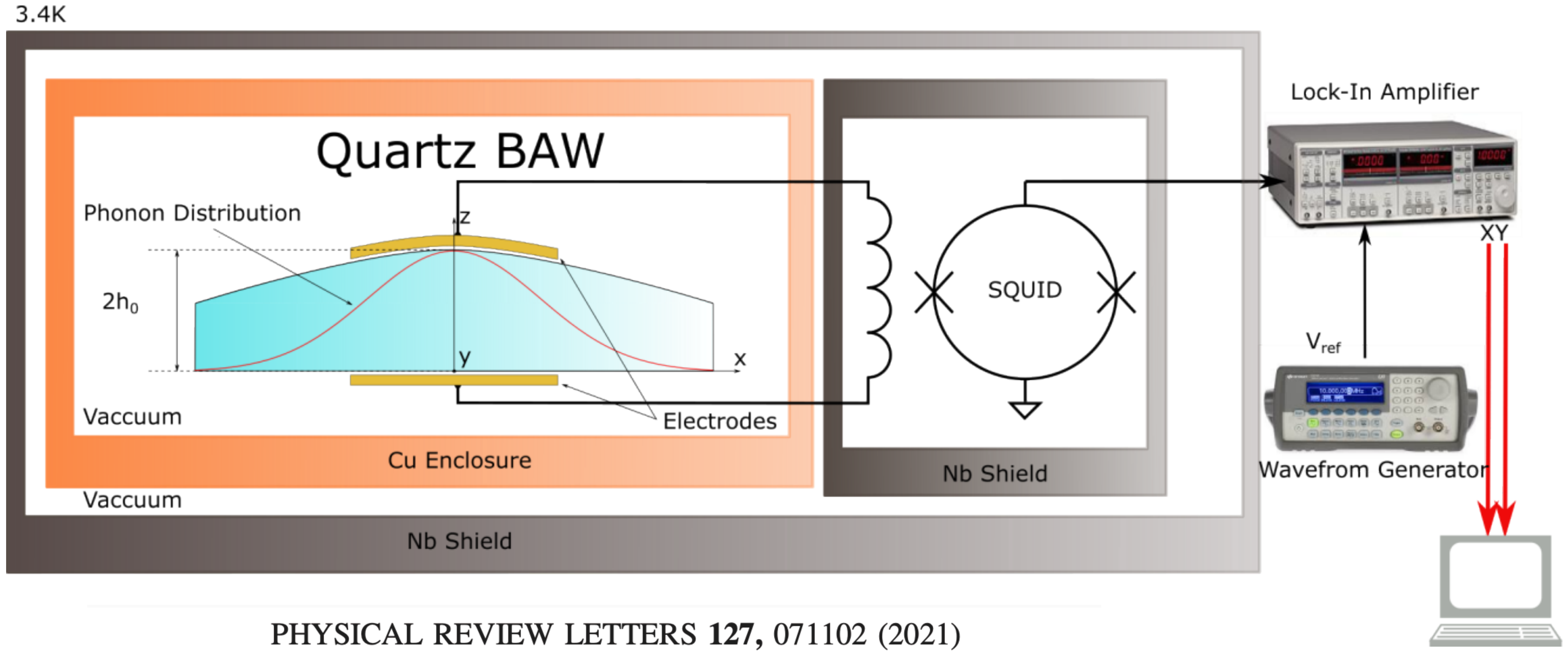
$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right)$$

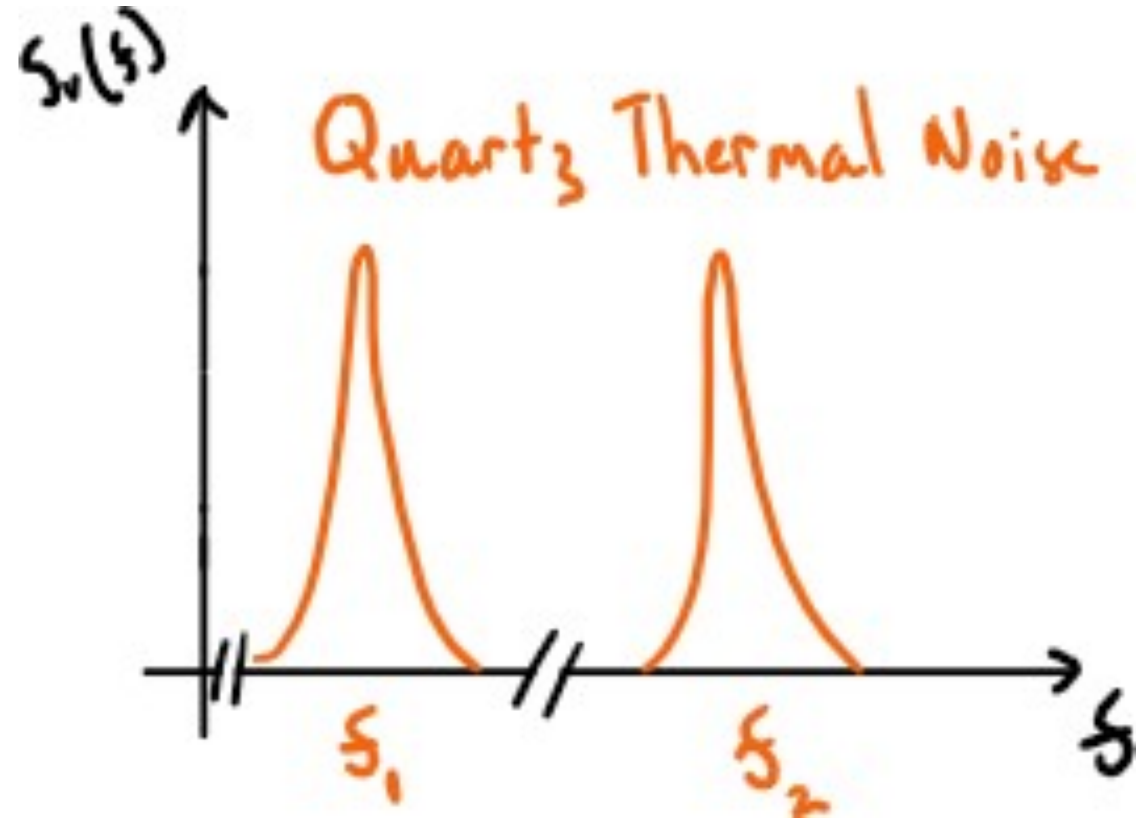


MAGE – Searching for new physics

First Observational Period

GEN 1 & GEN 2, *153 days* of data, *two modes*

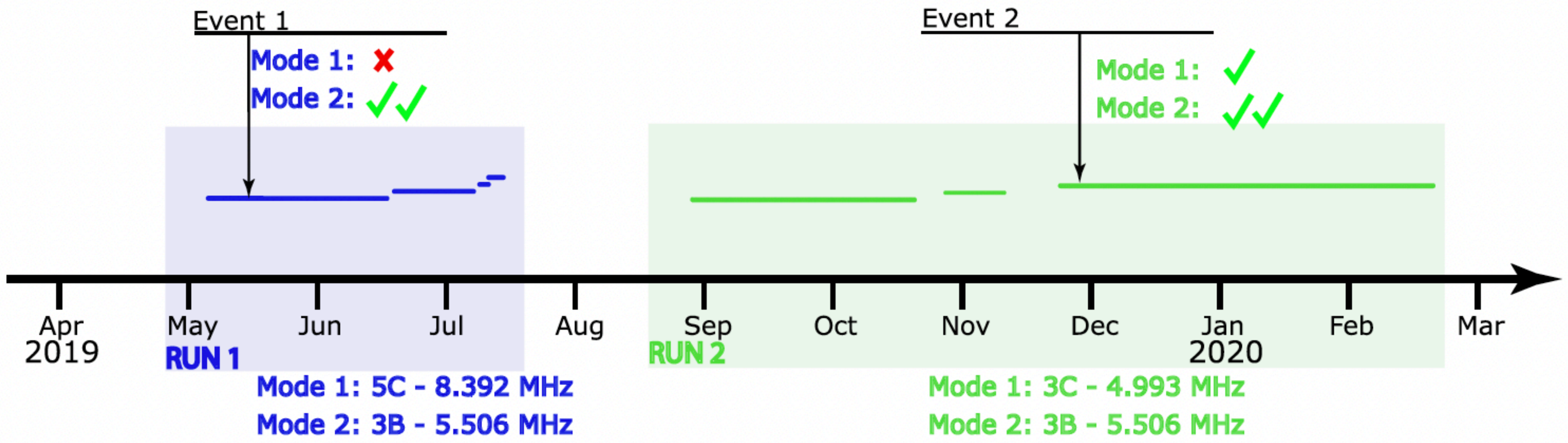




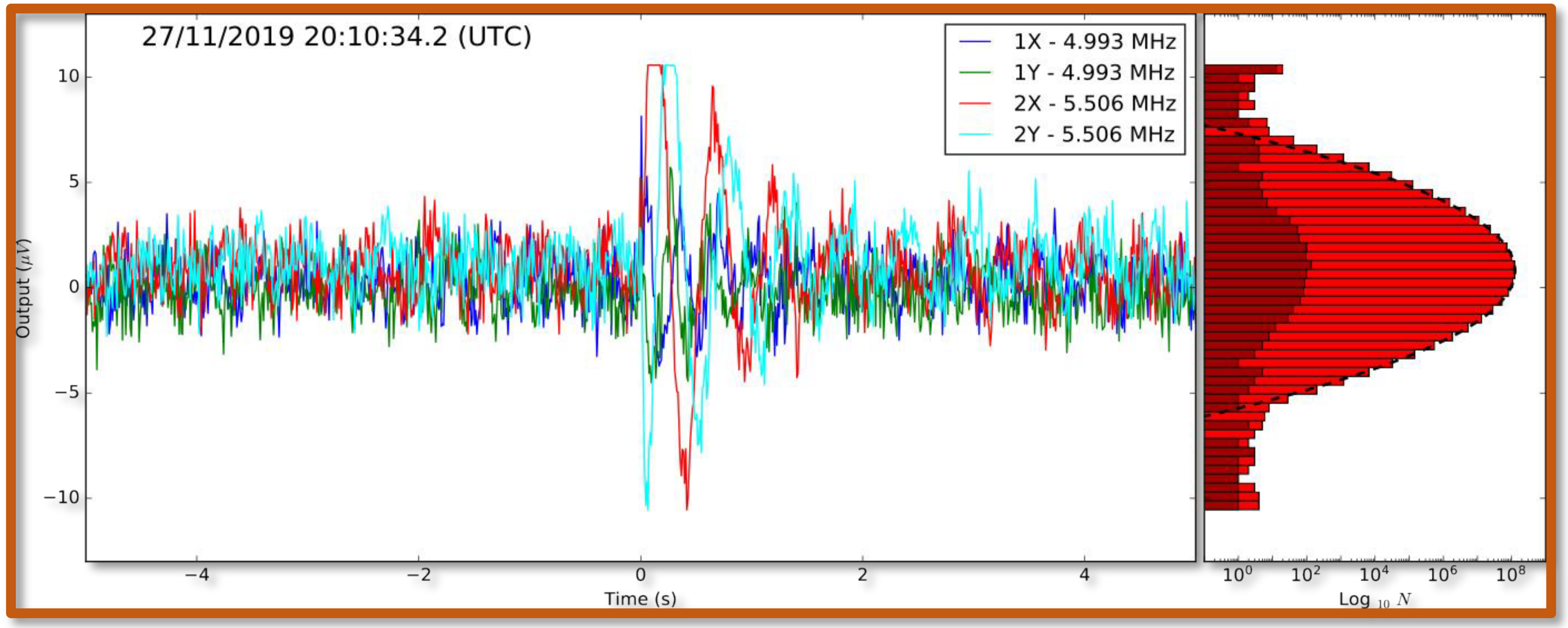
PHYSICAL REVIEW LETTERS **127,** 071102 (2021)

Rare Events Detected with a Bulk Acoustic Wave High Frequency Gravitational Wave Antenna

Maxim Goryachev,[1] William M. Campbell,[1] Ik Siong Heng,[2] Serge Galliou,[3] Eugene N. Ivanov,[1] and Michael E. Tobar[1,*]



Data Analysis:



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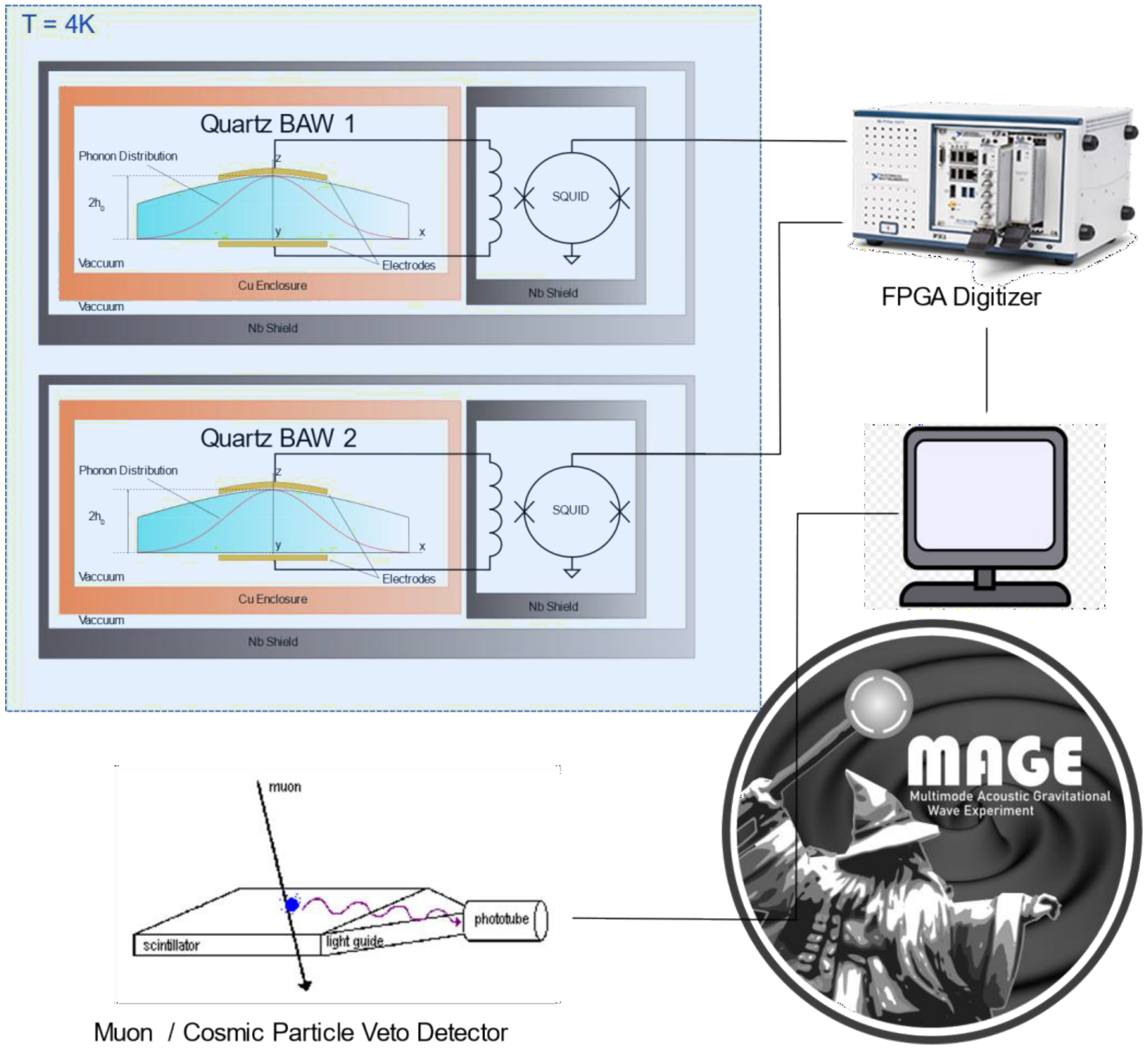
What's next ? → Multimode Acoustic Gravitational Wave Experiment



- 2 x Quartz BAW crystals
- 2 x DC SQUID amplifiers
- FPGA DAQ
- Cosmic particle veto (coming soon)

Exclude potential sources of events:

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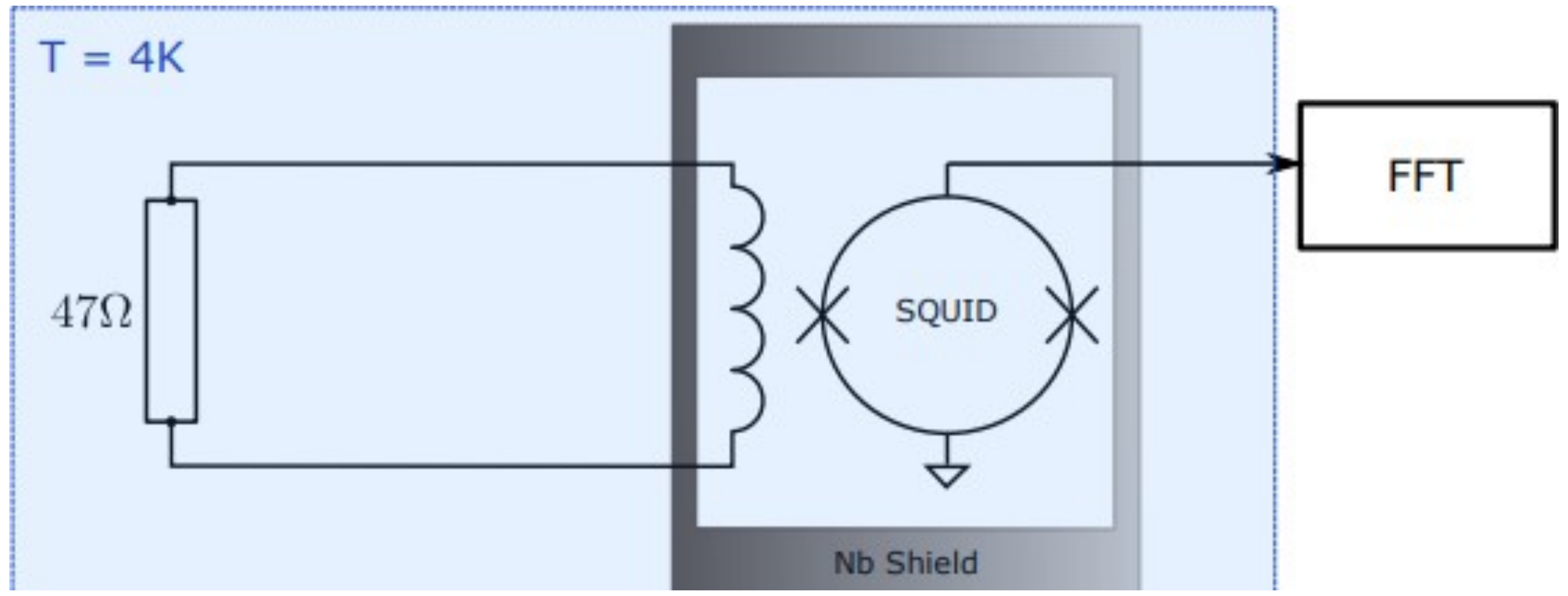
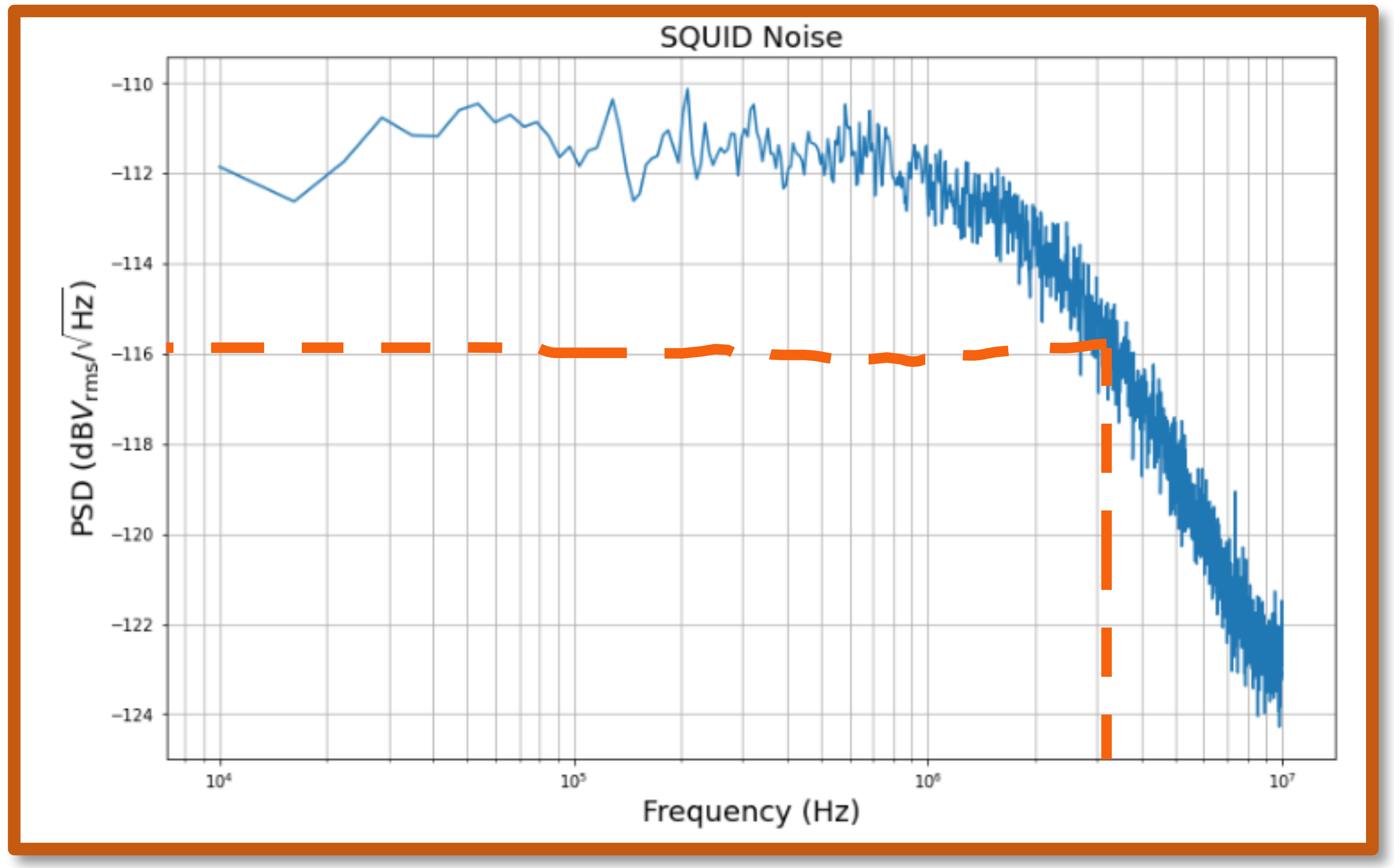
Calibration of 2nd detector





Limited by SQUID electronics

f_{3dB}~3 **MHz**

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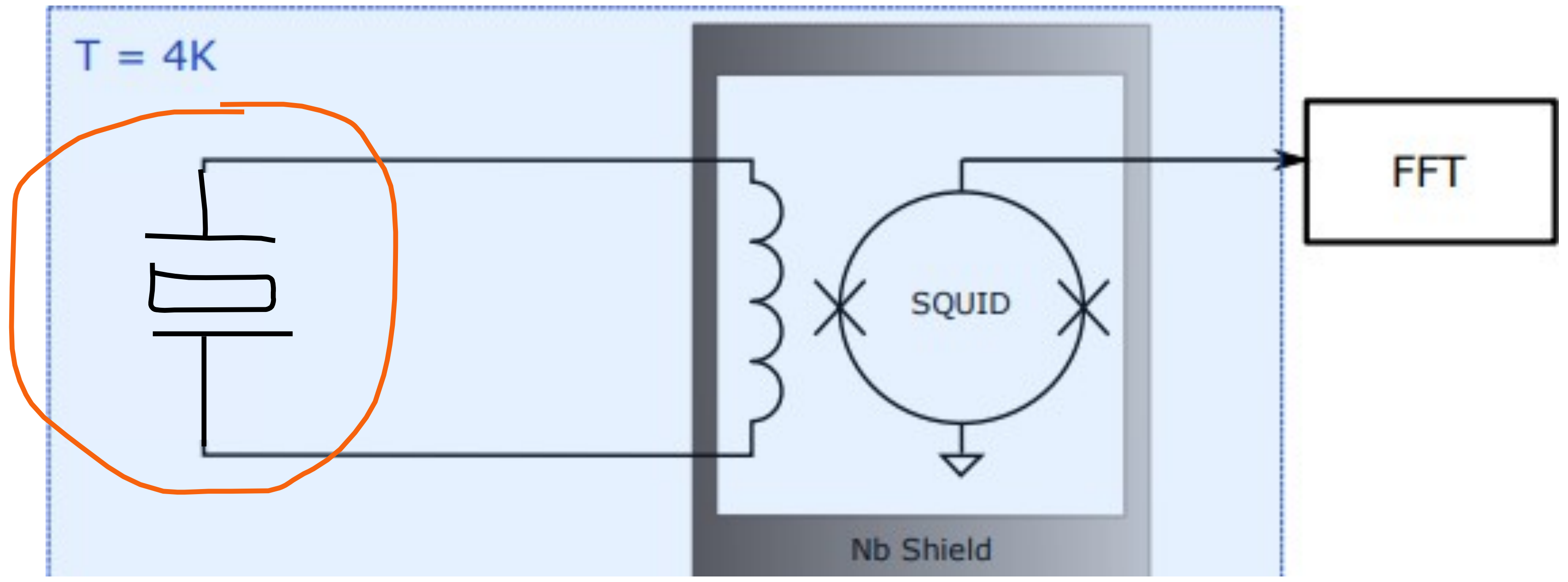
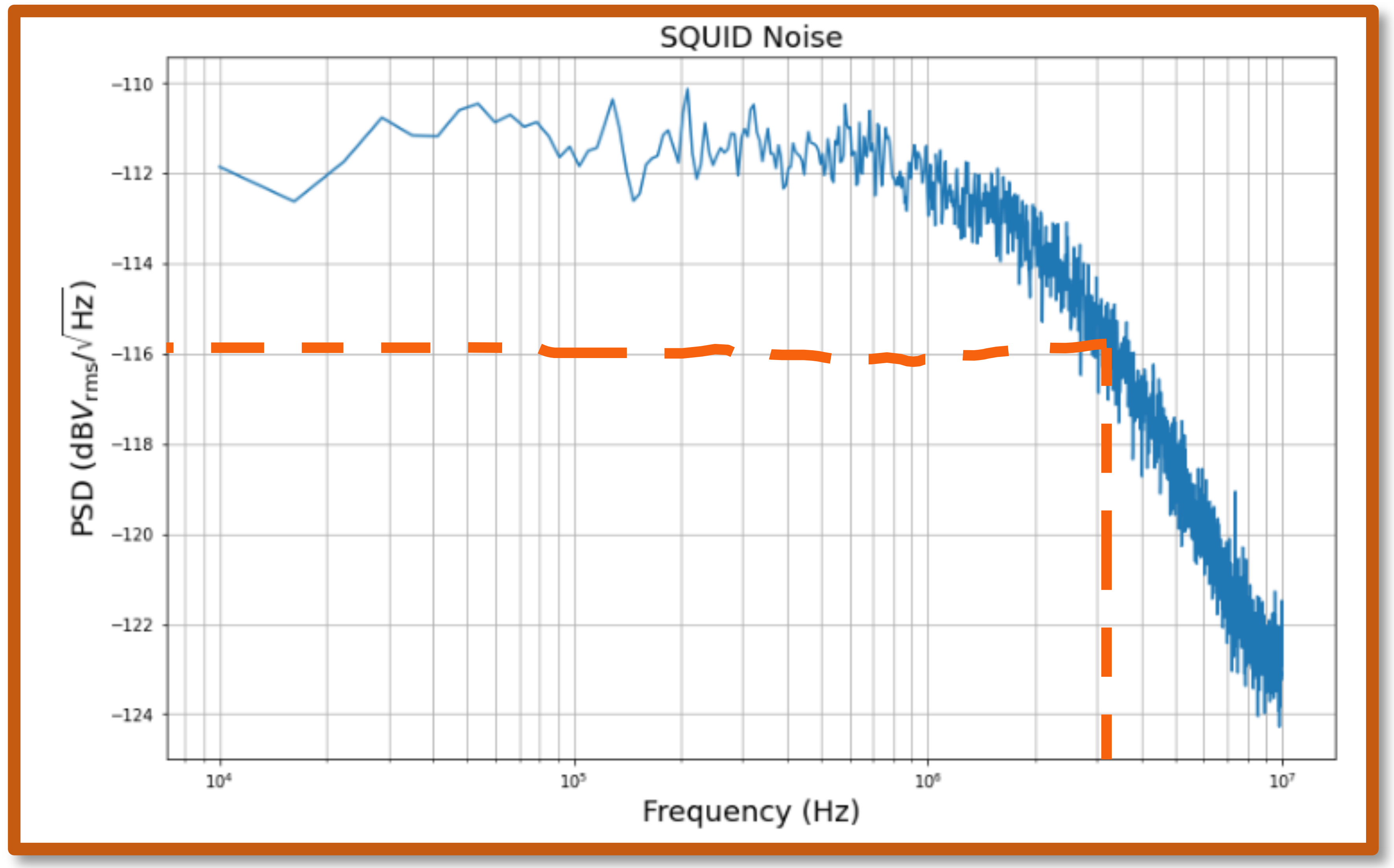
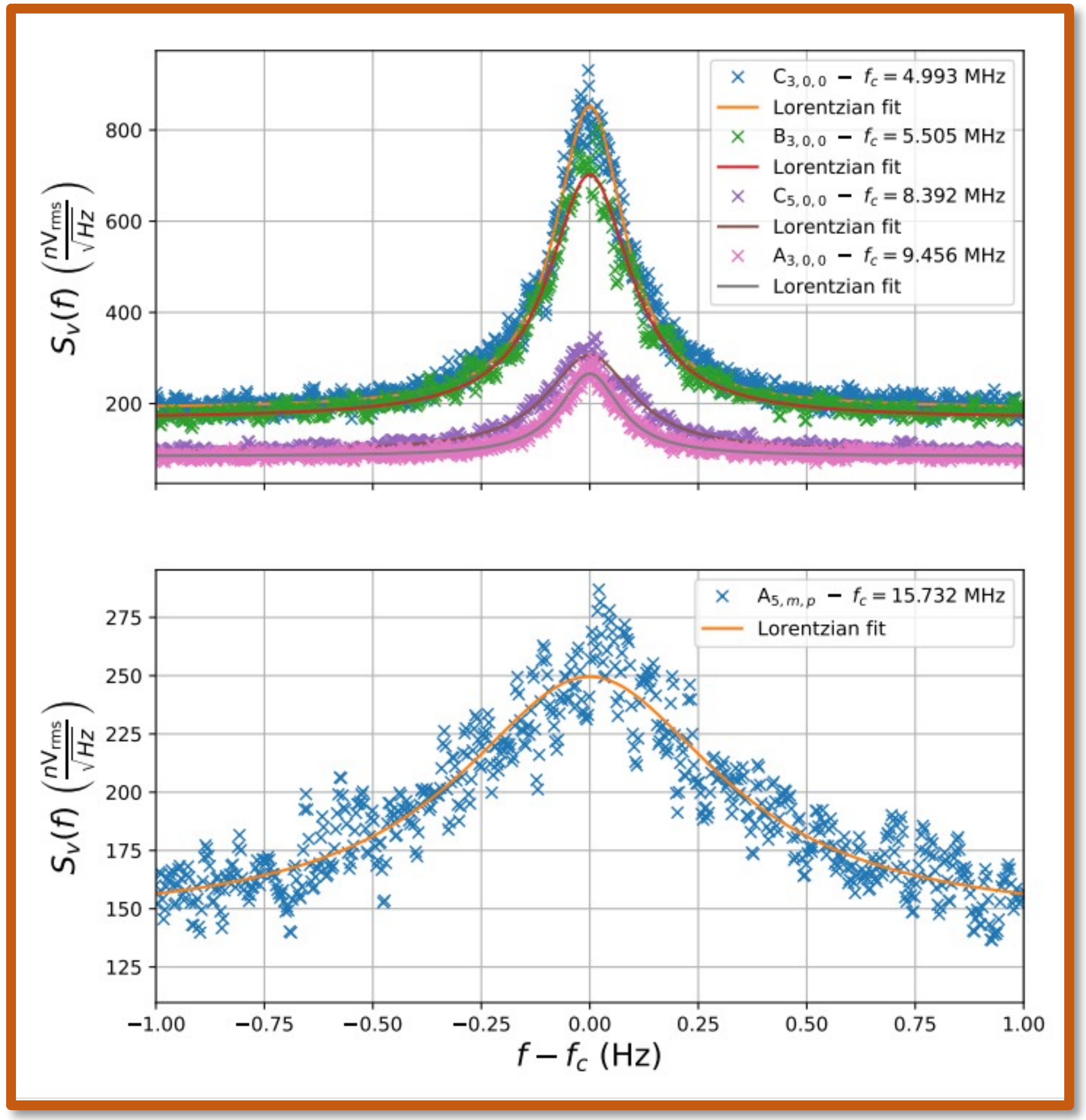
Calibration of 2nd detector





f_{3dB}~3 **MHz**



Modes up to 20 MHz are still observable

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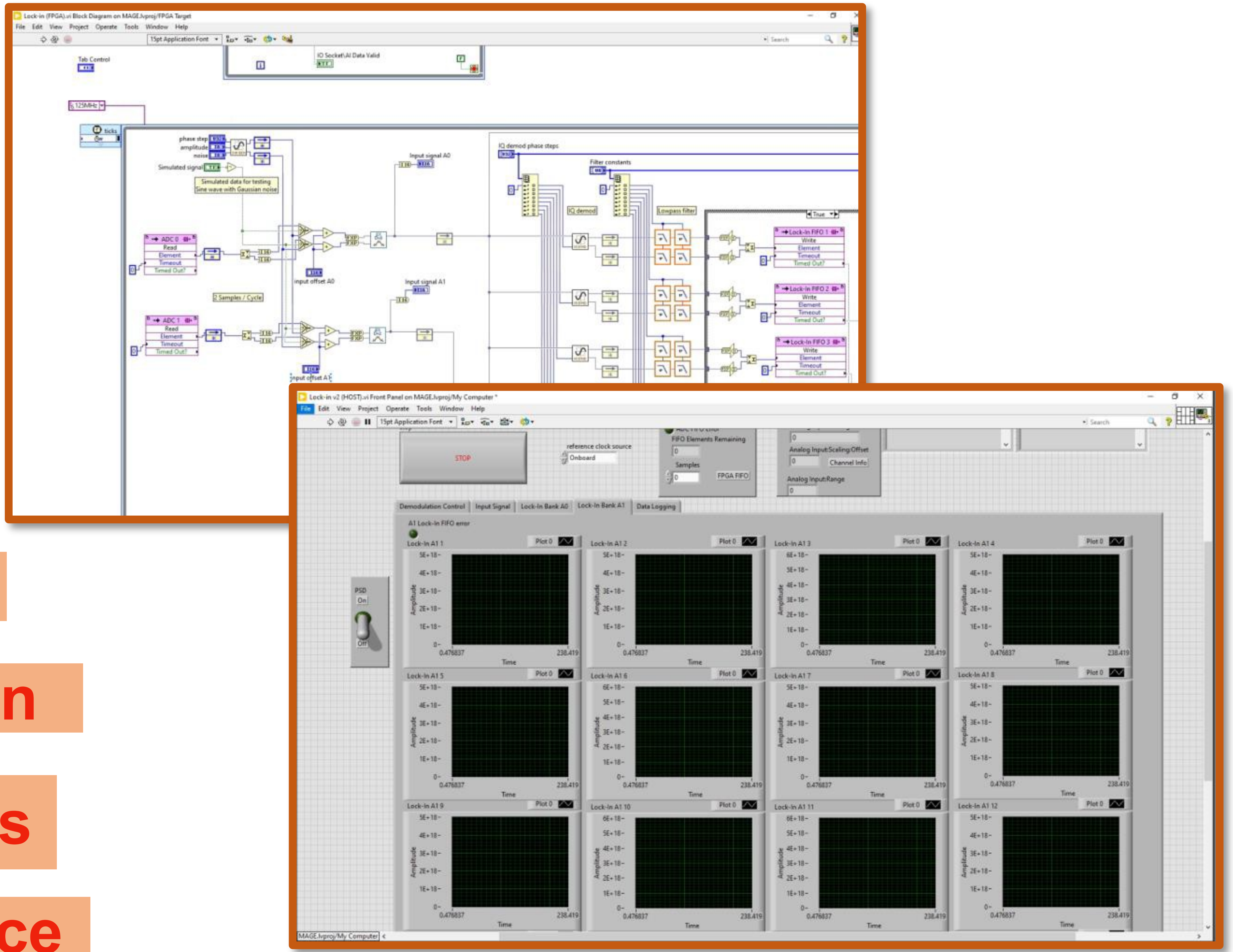

Development of FPGA data acquisition

National Instruments – 5763 Digitizer
LabVIEW

32 Lock-in amplifiers across two inputs

Continuous data streaming & acquisition

In real time w/strict timing & zero data loss

Yet to reach hardware limitation of device

16 modes in each crystal. [MHz]

4.993050, 5.080854, 5.088263, 5.505426, 5.576835, 8.392272, 9.151802, 9.409902, 9.452381, 5.603804, 6.4326464, 8.297581, 8.400189, 9.224931, 9.246863, 9.526448, 15.731899

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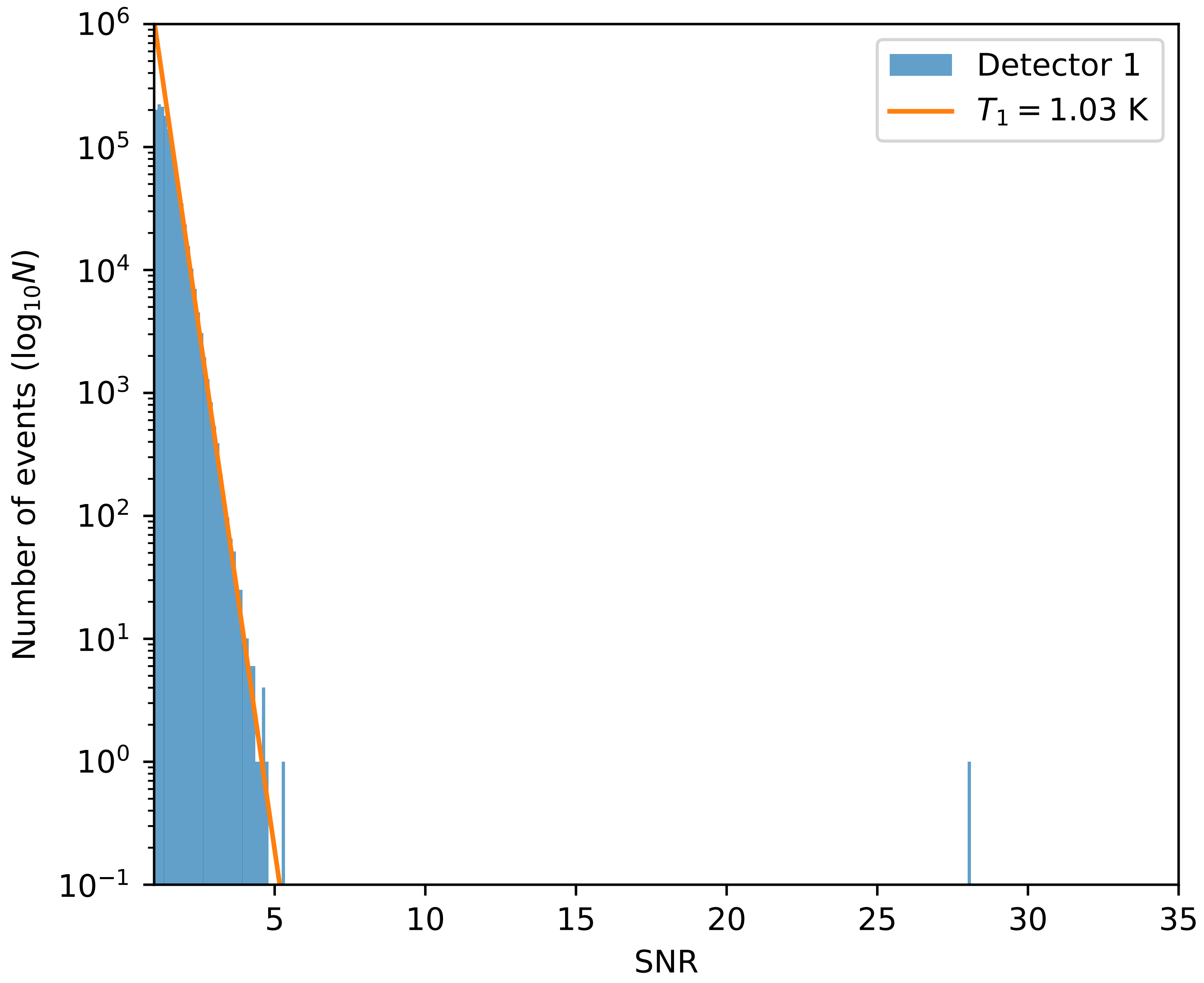
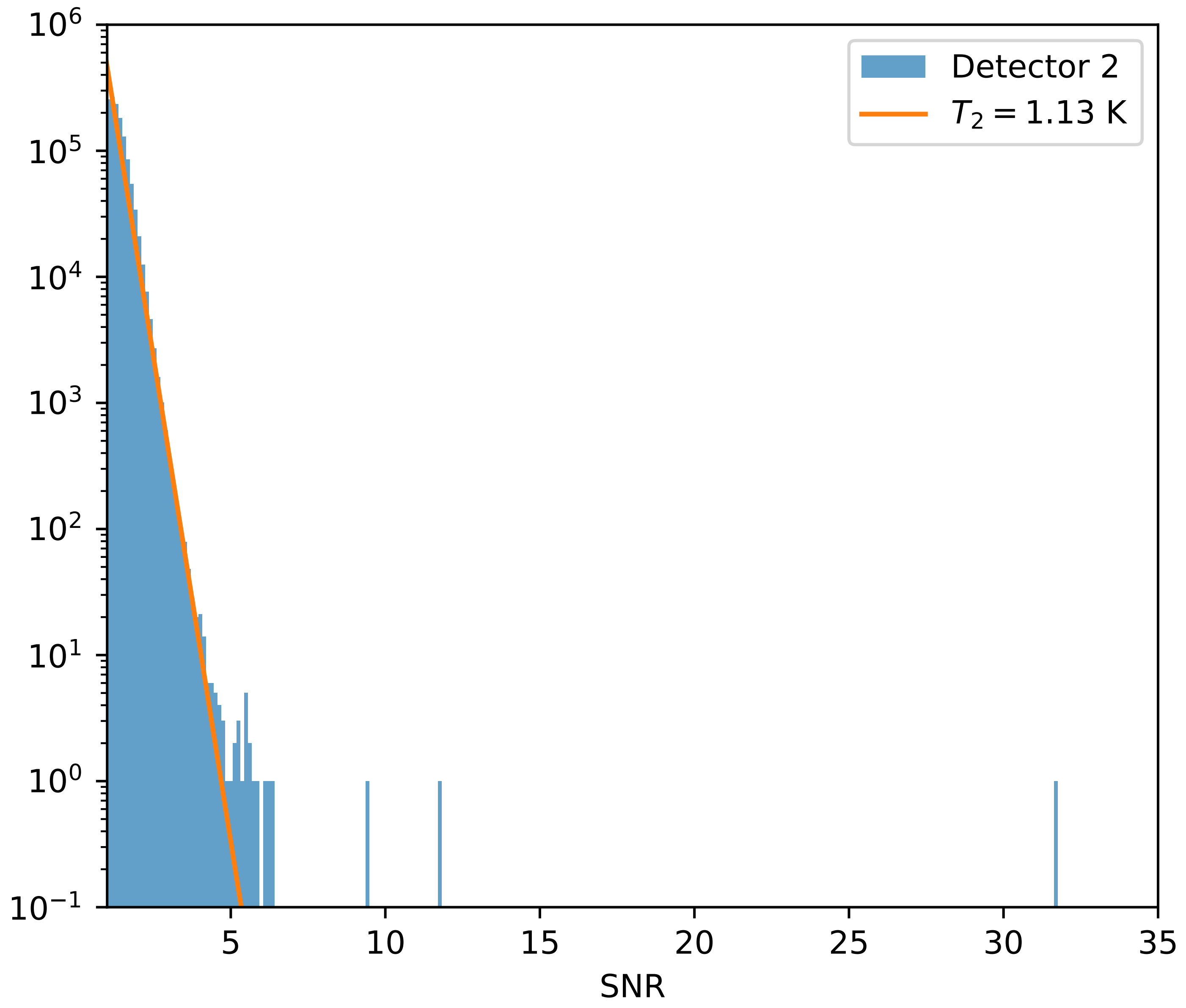
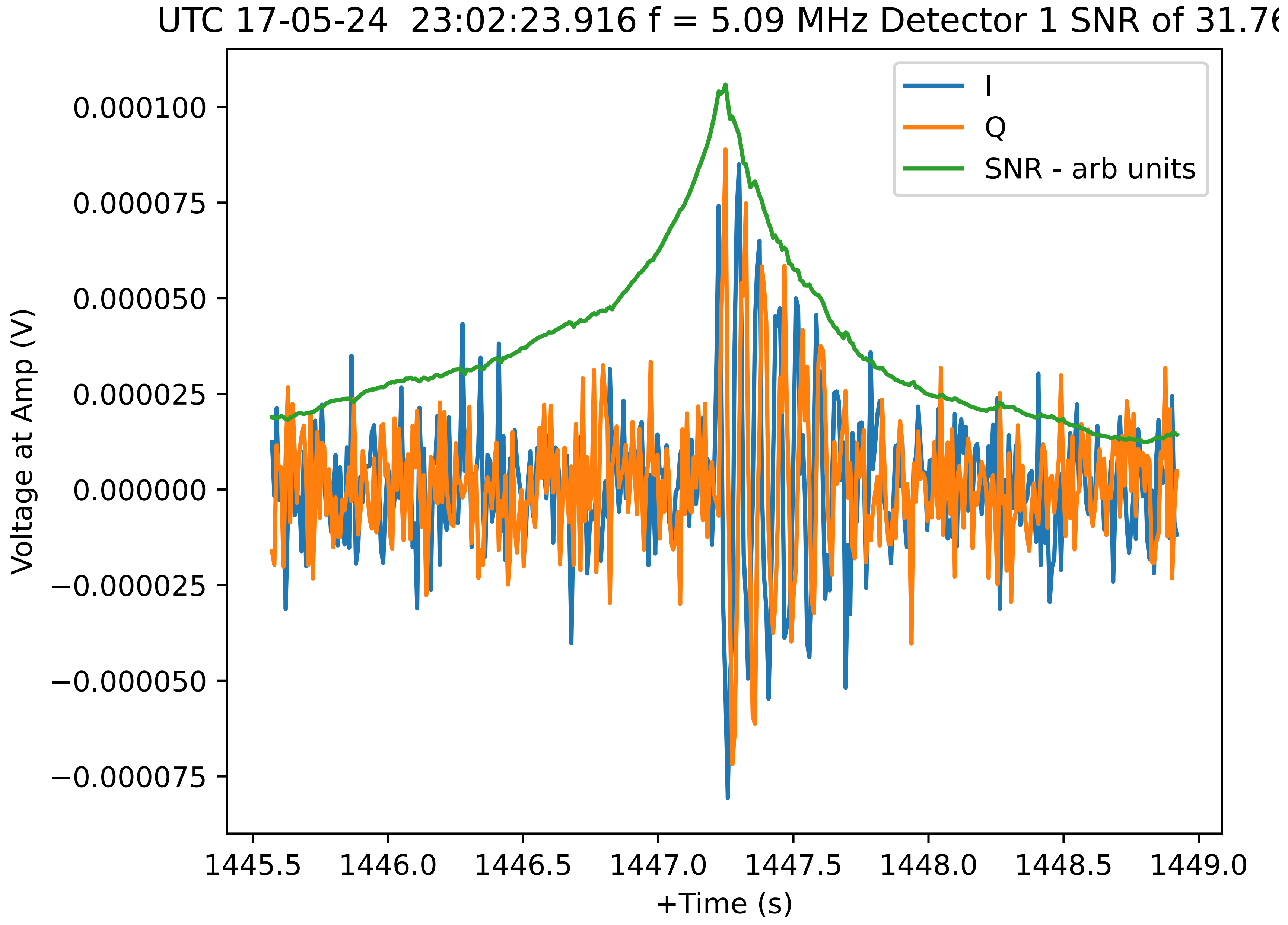
Currently have new data!

Optimal FIltering → Search for transient events corresponding to quartz decay

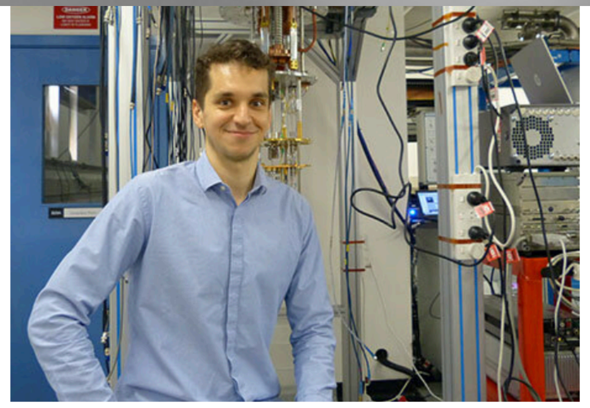






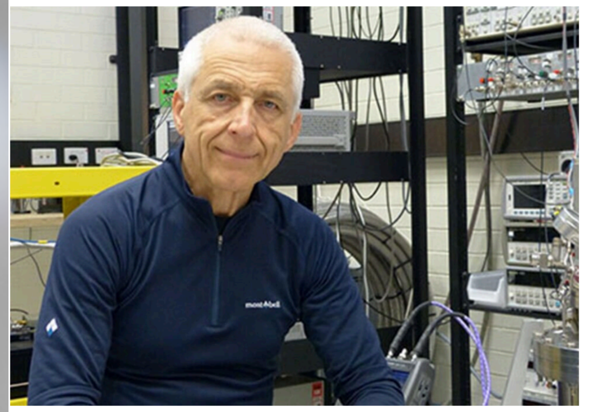
The Team

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

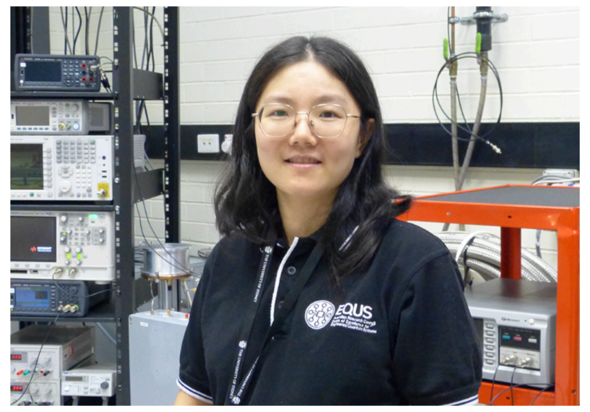


Dr Maxim Goryachev
EQUS Chief Investigator, CDM Chief Investigator, Lecturer—Research Intensive

Dr Ben McAllister
Adjunct Research Fellow



Winthrop Professor Eugene Ivanov
Senior Principle Research Fellow



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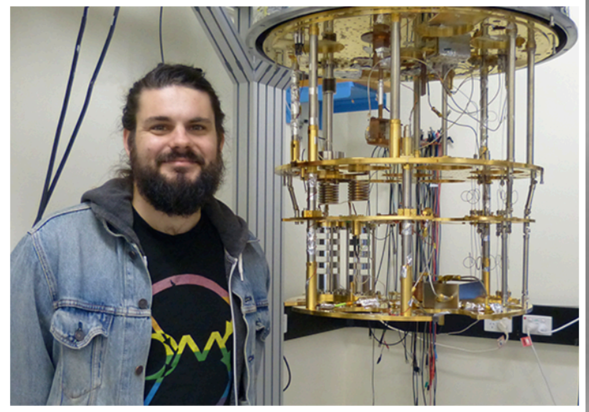
Deborah Jin Fellow—EQUS



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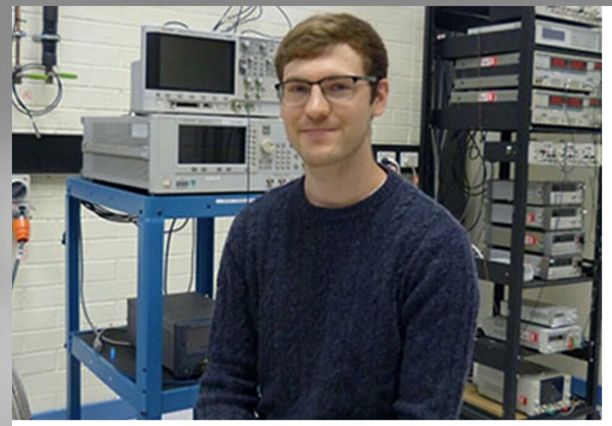
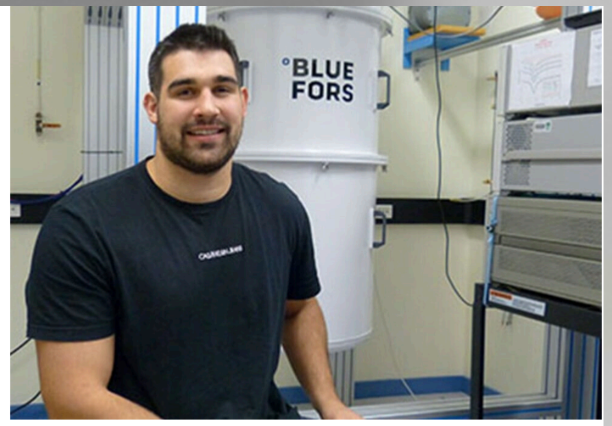
Postdoctoral Research Associate



Dr Graeme Flower
Research Associate

Will Campbell
Research Associate—Clock Flagship



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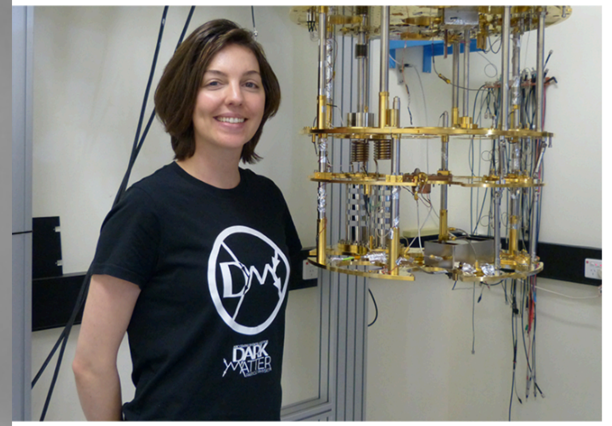

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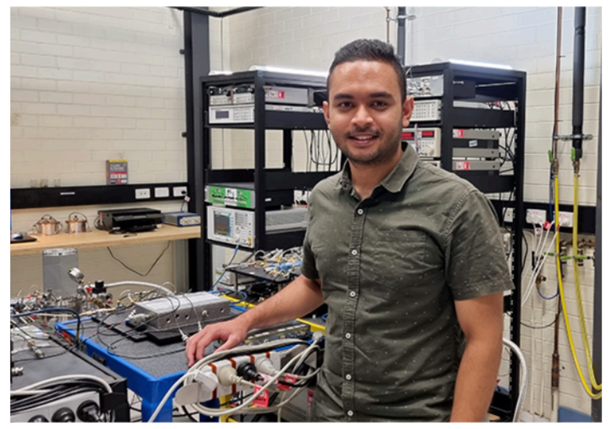

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Robert Crew
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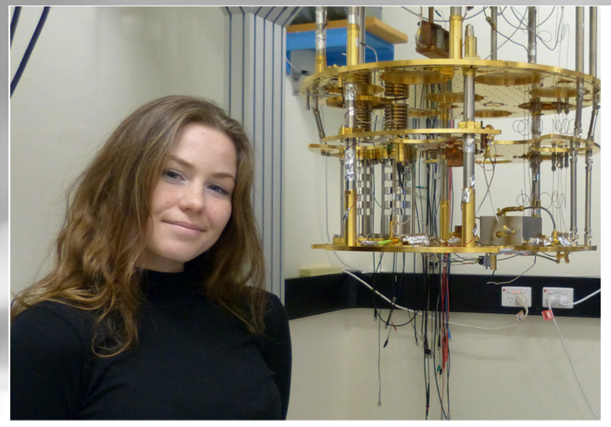

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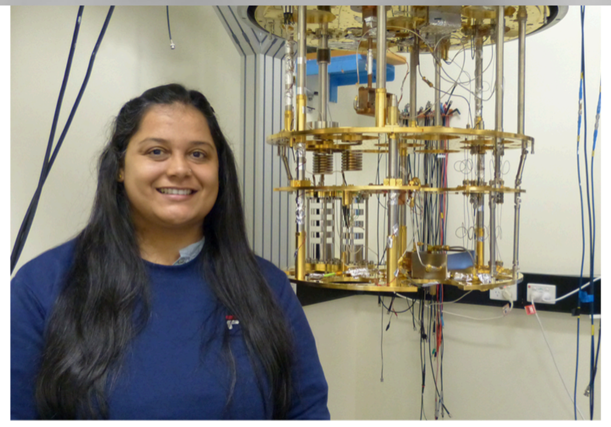
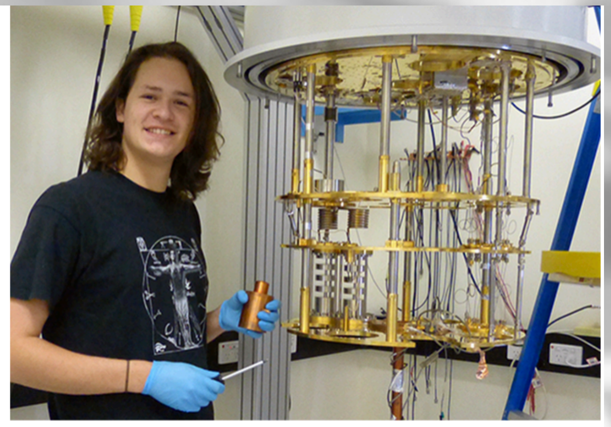
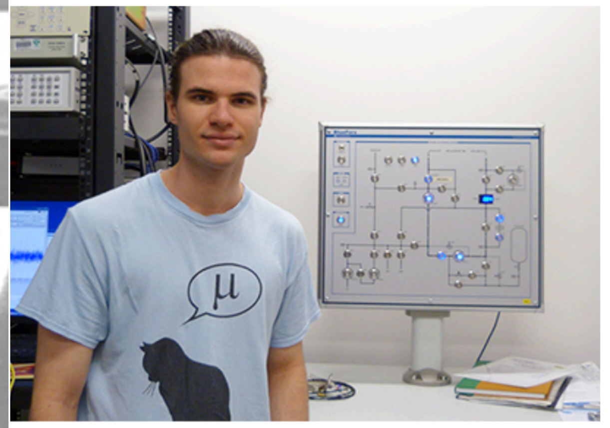
PhD



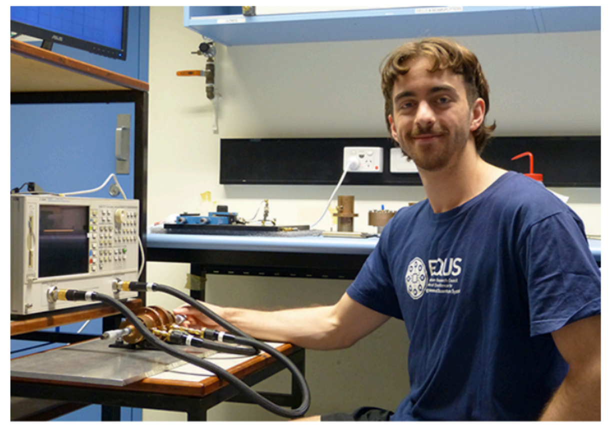
Sonali Parashar
Master of Physics—Coursework and Dissertation



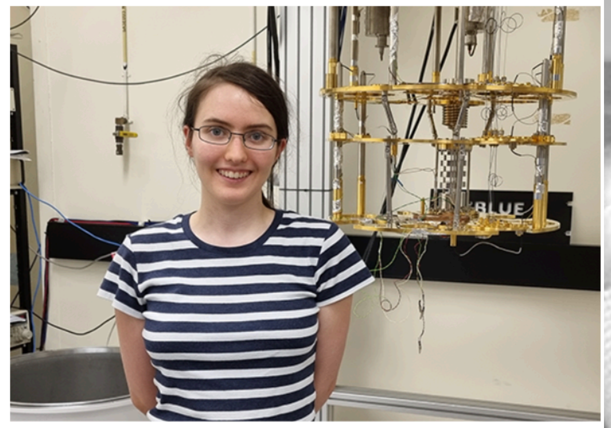
Tim Holt
BSc (Frontier Physics) and Master of Physics



Ashley Johnson
BSc (Frontier Physics) and Master of Physics



Michael Hatzon
BPhil (Hons) Honours Dissertation



Emily Waterman
BPhil (Hons) Honours Dissertation

Teehani Ralph
Master of Professional Engineering

QDM Quantum Technologies and Dark Matter Research Lab

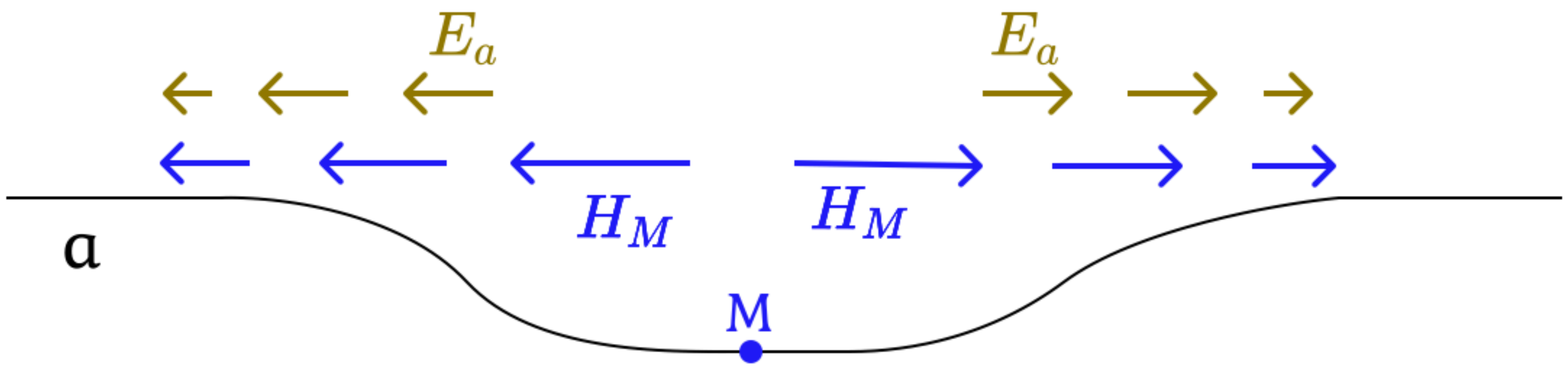
EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

ARC Centre of Excellence for Dark Matter Particle Physics

The University of Western Australia
Seek Wisdom

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