Precision Metrology with Photons, Phonons and Spins: Answering Major Unsolved Problems in Physics and Advancing Translational Science

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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

The QDM Lab: https://www.qdmlab.com/

QUANTUM TECHNOLOGIES AND DARK MATTER RESEARCH LAB

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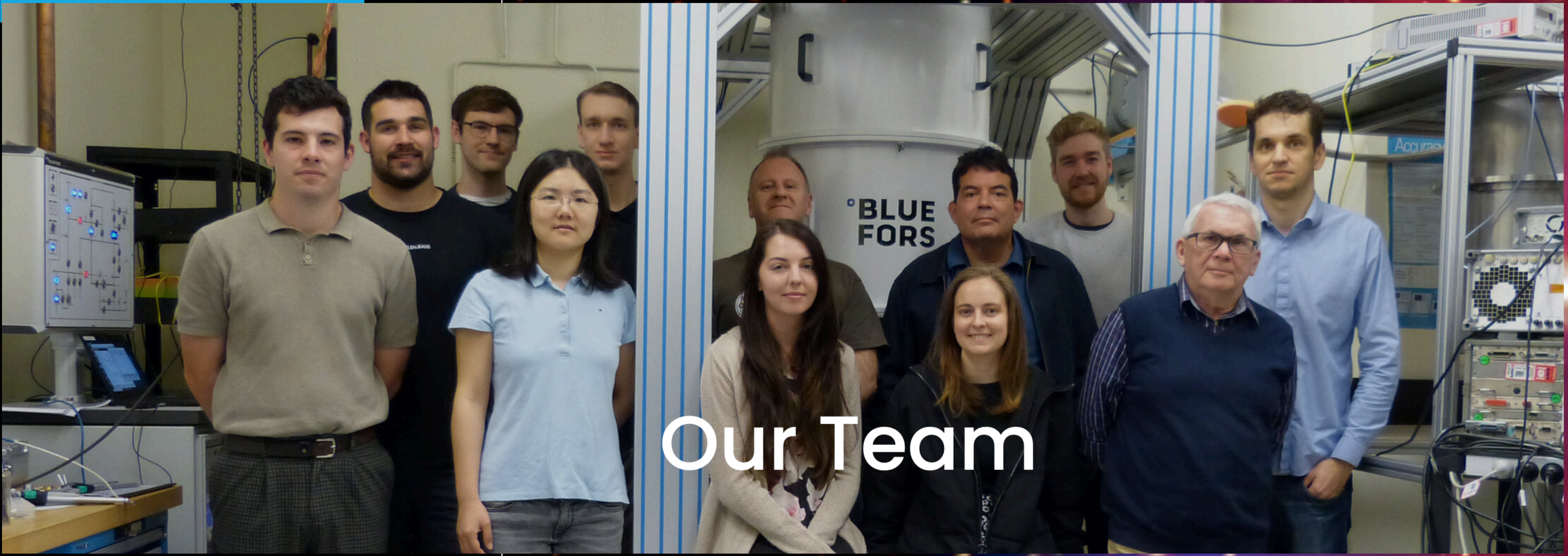

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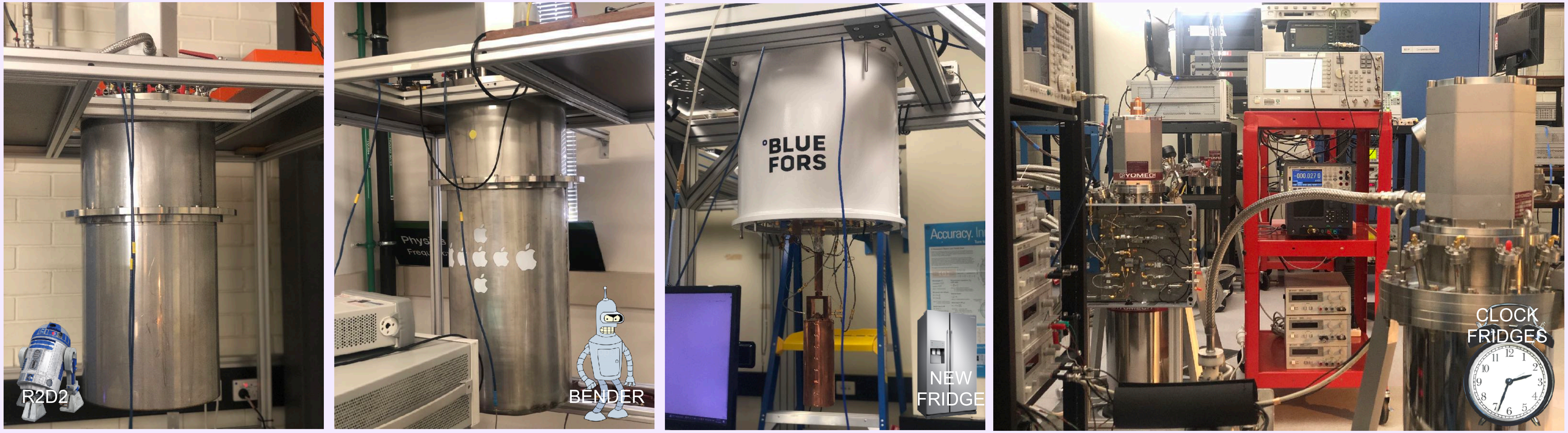
QDM Laboratory

Welcome to the Quantum Technology and Dark Matter Laboratory at UWA!
Come inside and check out our world class facilities, home to nodes of the ARC Centre of Excellence for Engineered Quantum Systems, and the ARC Centre of Excellence for Dark Matter Particle Physics.

QDM Quantum Technologies and Dark Matter Research Lab

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

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Physics: An experimental science

White, Harvey Elliott

Note: This is not the actual book cover

Physics: An experimental science

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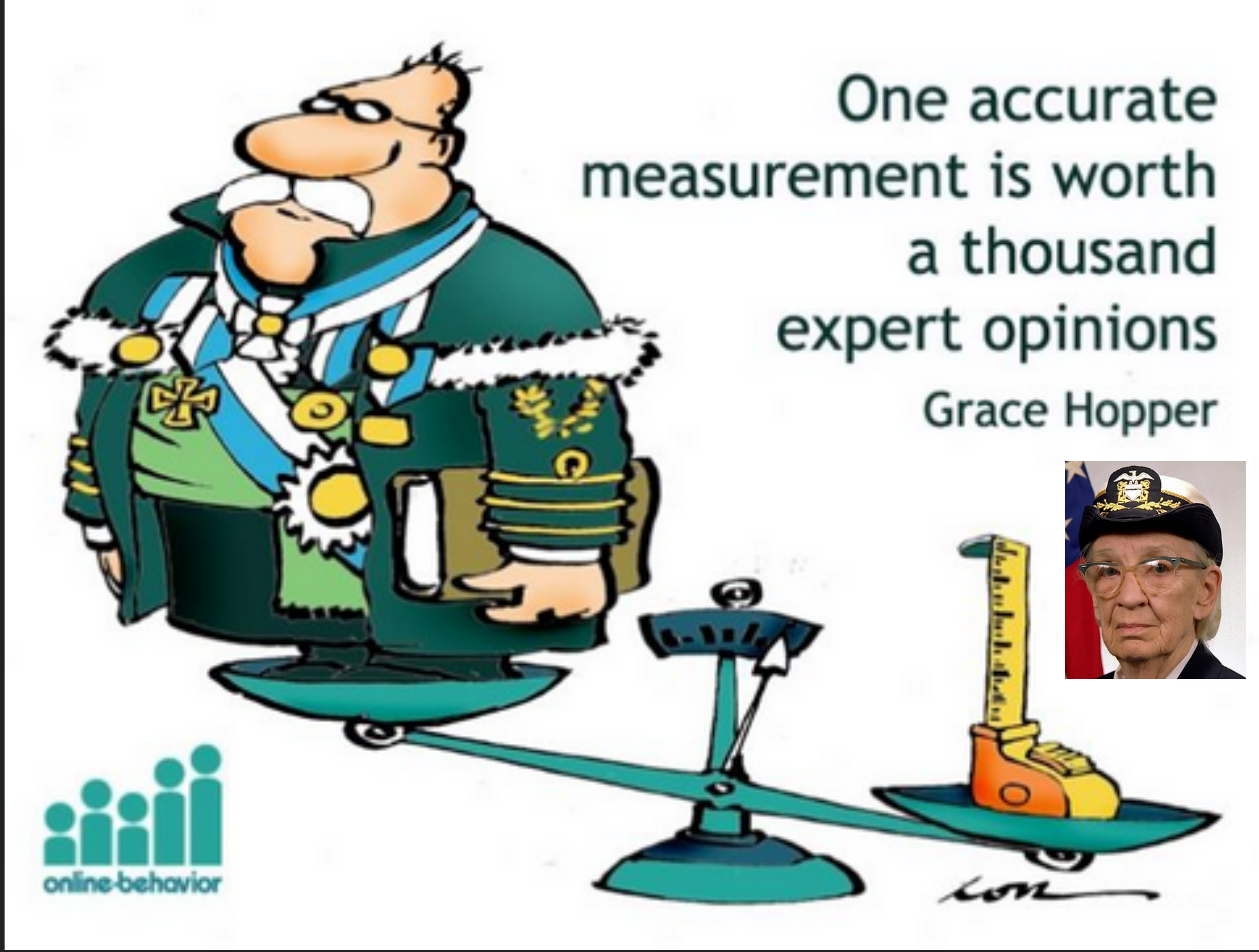

Physics: An experimental science

White, Harvey Elliott

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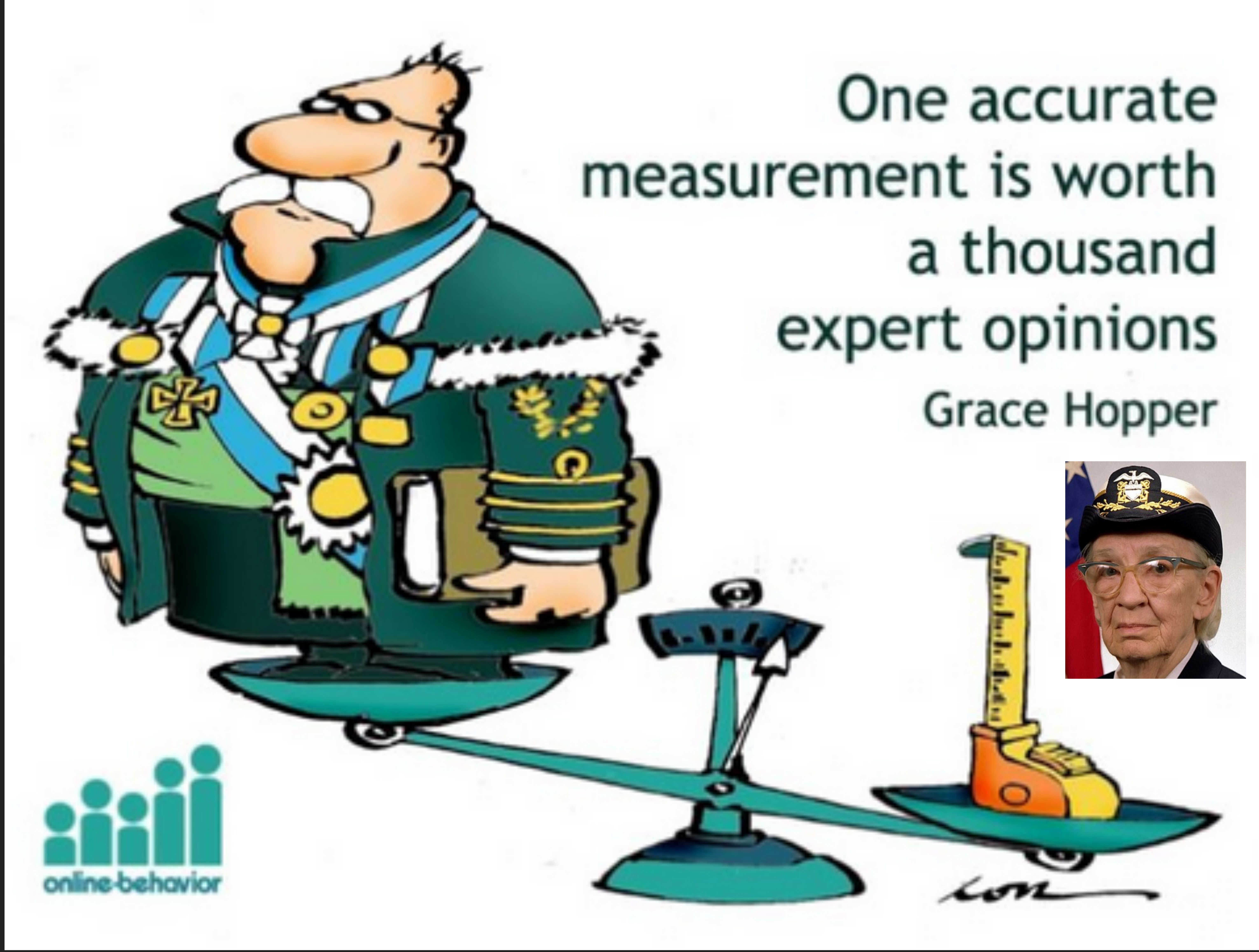
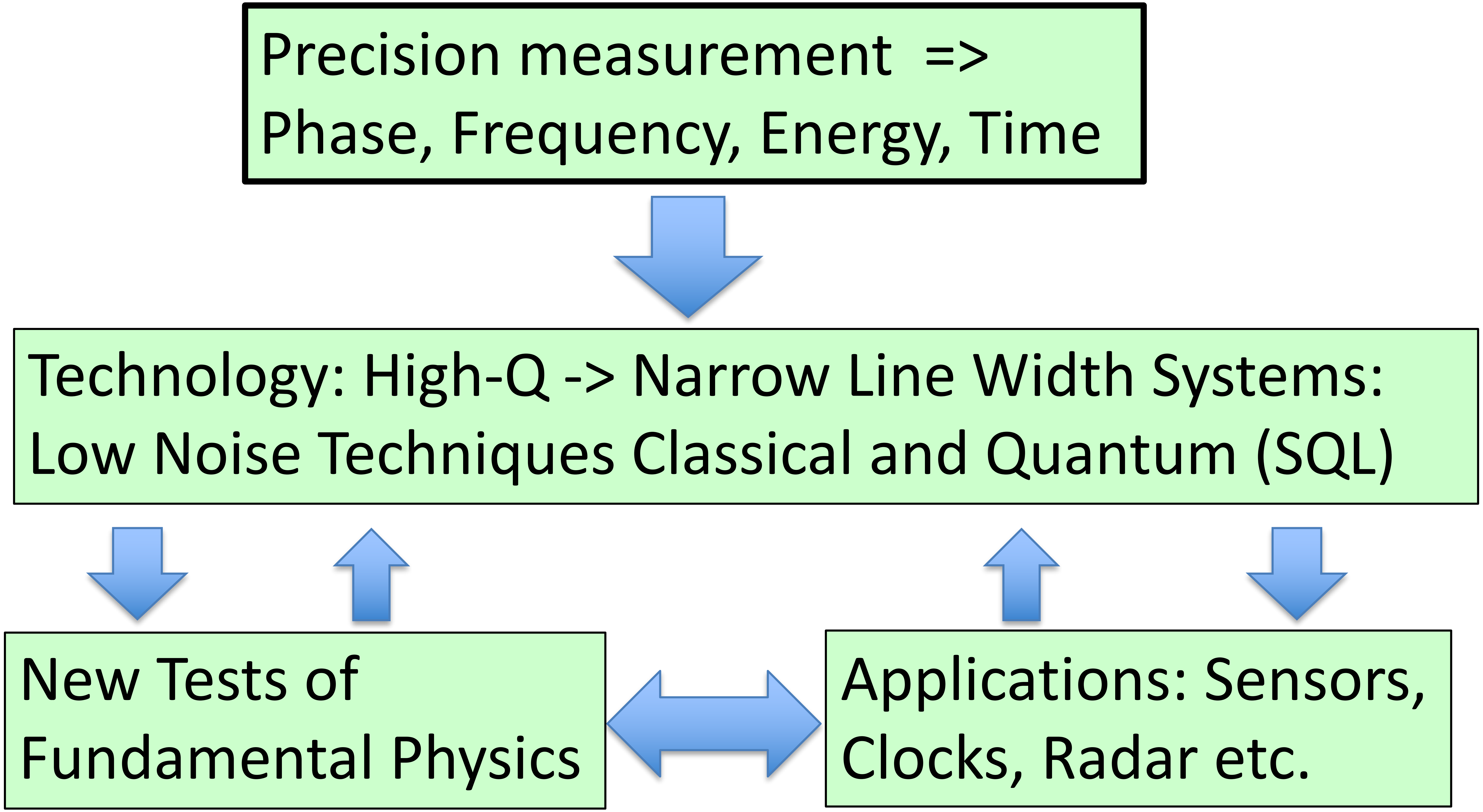


Computer Scientist
Invented COBOL

Precision Measurements @ QDM Lab Uni of Western Australia



QDM has realised many best tests on Dark Matter, Quantum Gravity and Relativity

12 Patents: Radar, Gradiometer, Sensing, Oscillators

Organisation

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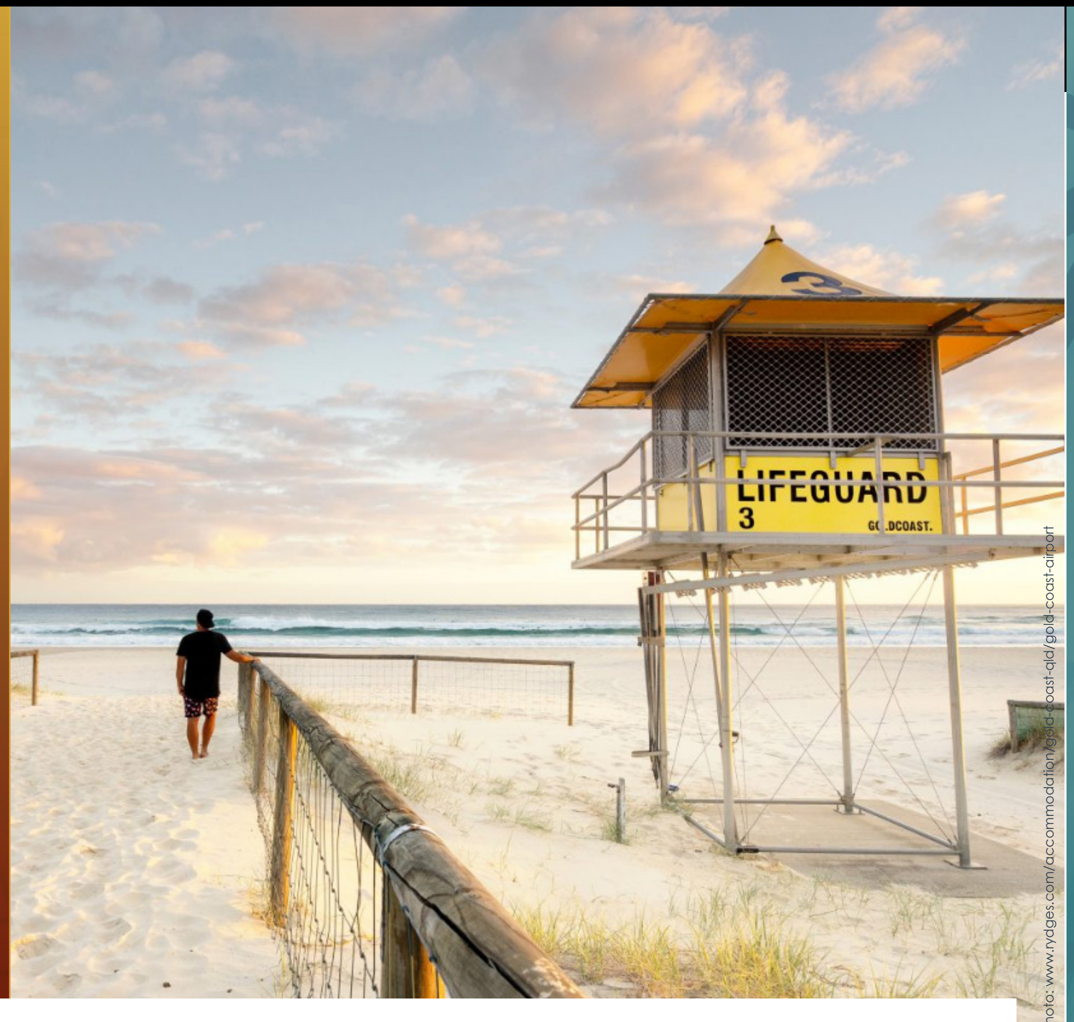
EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

The 9th Symposium on Frequency Standards and Metrology

Summer School on Frequency Standards, Precision and Quantum Measurement

Rydges Gold Coast Airport Hotel, Gold Coast, QLD, Australia

9–13 October 2023



The week before 9FSM we are presenting a Summer School on Frequency Standards, Precision and Quantum Measurement for students, early career researchers, and those professionals who want to learn more on the subject.

Confirmed Speakers

John Close, Professor of Physics, Leader of the Atom Laser Group, Australian National University, Canberra, Australia
Topic: Using Atoms for Precision and Quantum Measurements

Tara Fortier, Project Leader, Time and Frequency Division, National Institute of Standards and Technology, Colorado, USA
Topic: Optical and Microwave Metrology

Anna Grassellino, Director, Superconducting Quantum Materials and Systems Center, Fermilab, Illinois, USA
Topic: High-Q Super Conducting Cavities, and Application to Quantum Measurements and Tests of Fundamental Physics

Eugene Ivanov, Research Professor, University of Western Australia, Dept. Physics, Perth, Australia.
Topic: Low Noise Frequency Stable Microwave Oscillators and Metrology

John Kitching, Group Leader and Fellow, Time and Frequency Division, National Institute of Standards and Technology, Colorado, USA.
Topic: Vapor cell clocks, CSACs and quantum sensing

Helen Margolis, Head of Science for Time & Frequency and NPL Fellow in Optical Frequency Standards and Metrology, National Physical Laboratory, London, UK.
Topic: Optical clocks for international timekeeping

Ekkehard Peik, Head of Time and Frequency Department, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
Topic: Nuclear Clocks

Piet Schmidt, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
Topic: Highly Charged Ion Clocks and testing Fundamental Physics.

Patrizia Tavella, Director of Department of Time, Bureau International des Poids et Mesures, Paris, France.
Topic: UTC time scales or mathematical and statistical methods for time and frequency standards

Nora Tischler, ARC DECRA Fellow, Centre for Quantum Dynamics, Griffith University, Brisbane, Australia.
Topic: The physics of light detection and correlation measurements.

Michael Wouters, Head of Time and Frequency National Measurement Institute Australia, Sydney, NSW, Australia.
Topic: Advanced time and frequency, time-transfer methods, analysis of Time and Frequency data

Sébastien Bize, Head of the optical frequency group, Sytèmes de Référence Temps Espace, Observatoire de Paris.
Topic: Optical lattice clocks.

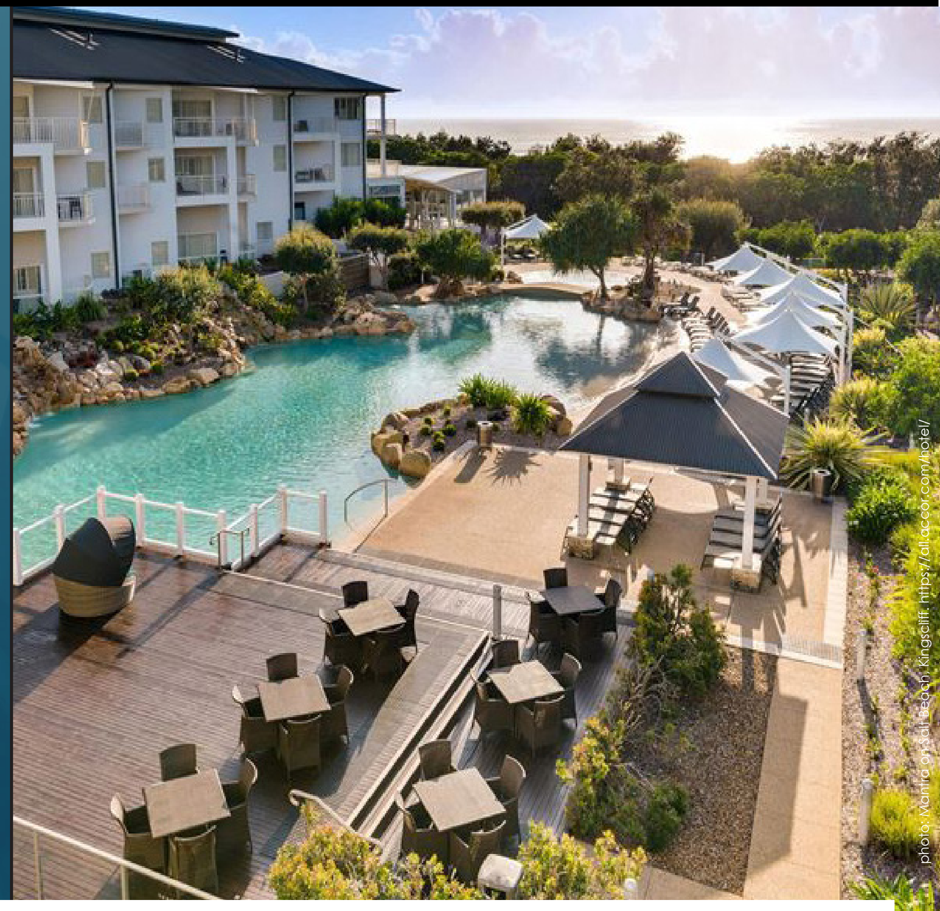
Tanya Zelevinsky, Professor of Physics, Columbia University, New York City, USA.
Topic: Precision molecular clocks and systems

https://www.qdmlab.com/9fsm/summer-school
(+61) 0404872944
9fsm@uwa.edu.au

The 9th Symposium on Frequency Standards and Metrology

Mantra on Salt Beach Resort, Kingscliff, NSW, Australia

16–20 October 2023



An international discussion forum on precision frequency standards throughout the electromagnetic spectrum, and associated precision and quantum metrology.

https://www.qdmlab.com/9fsm
(+61) 0404872944
9fsm@uwa.edu.au

Confirmed Invited Speakers

Alexander Romaneko, Fermilab, Illinois, USA.
Andrei Derevianko, University of Nevada, Reno, USA.
Andrew Ludlow, National Institute of Standards and Technology, Boulder, USA.
Andrey Matsko, Jet Propulsion Laboratory, Pasadena, USA.
Anna Grassellino, Fermilab, Illinois, USA.
Anne Amy-Klein, Université Université Sorbonne, Paris Nord, France.
Davide Calonico, Istituto Nazionale di Ricerca Metrologica, Torino, ITALY.
Dmitry Budker, Helmholz Institute, Mainz, Germany.
Ekkehard Peik, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
Eric Burt, Jet Propulsion Laboratory, Pasadena, USA.
Eugene Ivanov, University of Western Australia, Perth, Australia.
Helen Margolis, National Physical Laboratory, Teddington, London, UK.
Hidetoshi Katori, RIKEN, Saitama, Japan.
Jacques Vanier, University of Montreal, Canada.
James Chin-wen Chou, National Institute of Standards and Technology, Boulder, USA.
Jian-Wei Pan, University of Science and Technology of China, Hefei, China.
John Kitching, National Institute of Standards and Technology, Boulder, USA.
Jun Ye, JILA, Boulder Colorado, USA.
Krzysztof Szymaniec, National Physical Laboratory, Teddington, London, UK.
Mark Kasevich, Stanford, USA.
Maxim Goryachev, University of Western Australia, Perth, Australia.
Murray Barett, National University of Singapore, Singapore.
Nan Yu, Jet Propulsion Laboratory, Pasadena, USA.
Nathan Newbury, National Institute of Standards and Technology, Boulder, USA.
Patrick Gill, National Physical Laboratory, Teddington, London, UK.
Piet Schmidt, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
Scott Papp, National Institute of Standards and Technology, Boulder, USA.
Sébastien Bize, Sytèmes de Référence Temps Espace, Paris Observatory, France
Tanja Mehlstäubler, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany.
Tanya Zelevinsky, Columbia University, New York City, USA
Tara Fortier, National Institute of Standards and Technology, Boulder, USA.
Tetsuya Ido, National Institute of Information and Communications Technology, Japan.
Thomas Udem, Max Planck Institute of Quantum Optics, Garching, Germany.
Uwe Sterr, Low noise optical cavities and transportable clock laser systems
Victor Flambaum, University of New South Wales, Sydney, Australia.
Yannick Bidel, ONERA, The French Aerospace Lab, France.

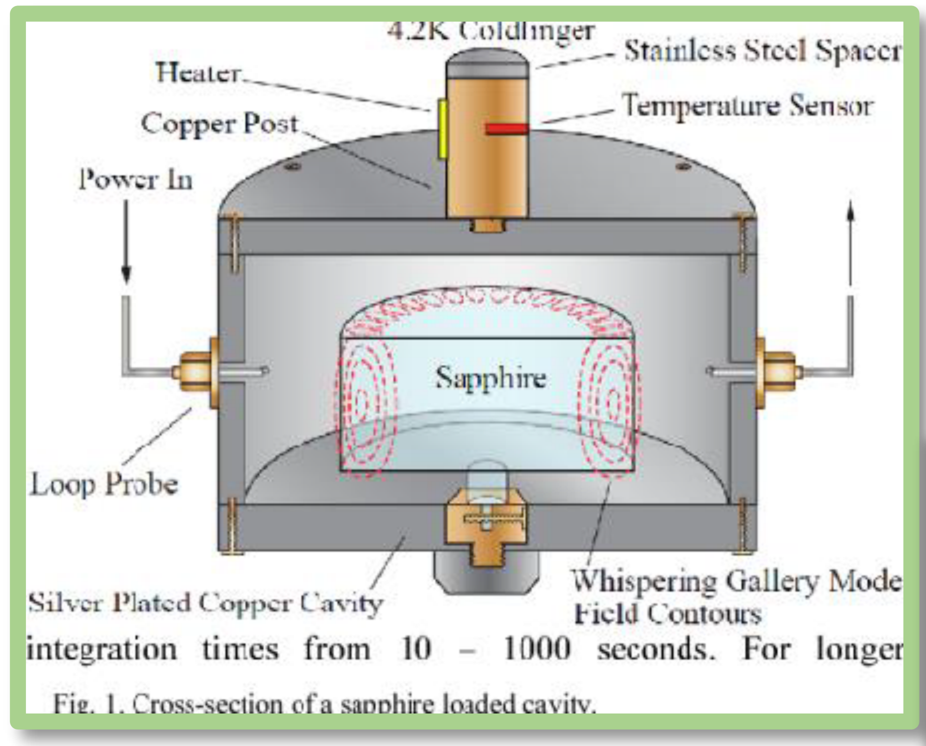
QDM Lab Precision Metrology: See www.qdmlab.com

Science of precise measurement → Physics at low energies

Metrological Systems:

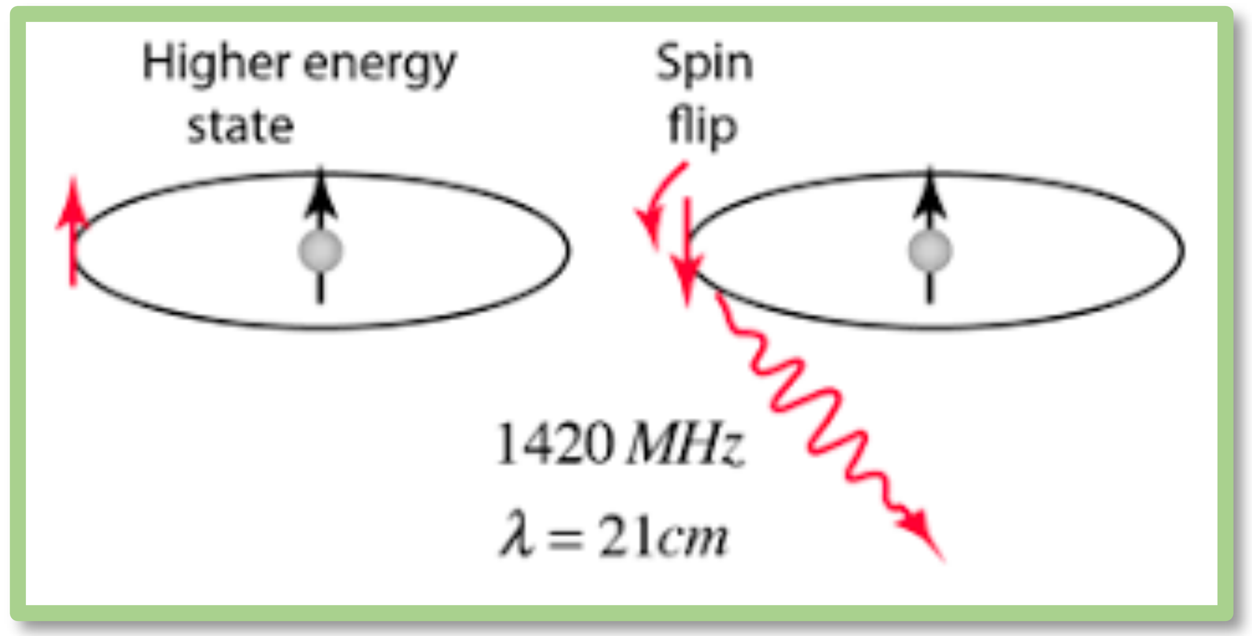
Photonic

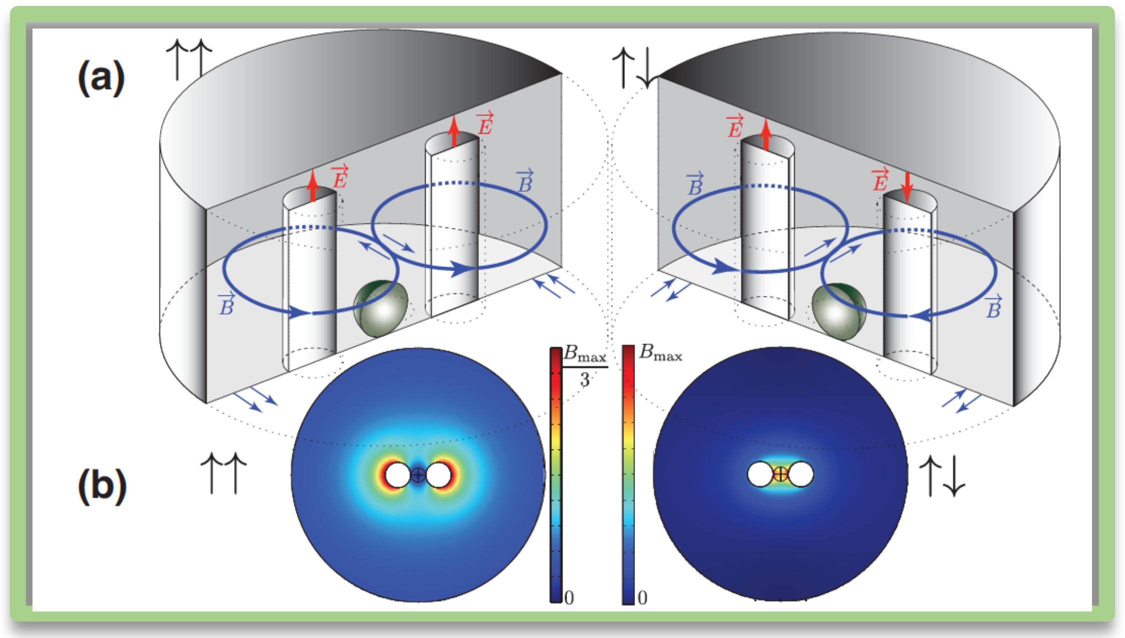
- WGM Resonators
- Novel Microwave Cavities



Atomic/Spins

- H - Maser
- Atomic Clocks
- Spin Waves



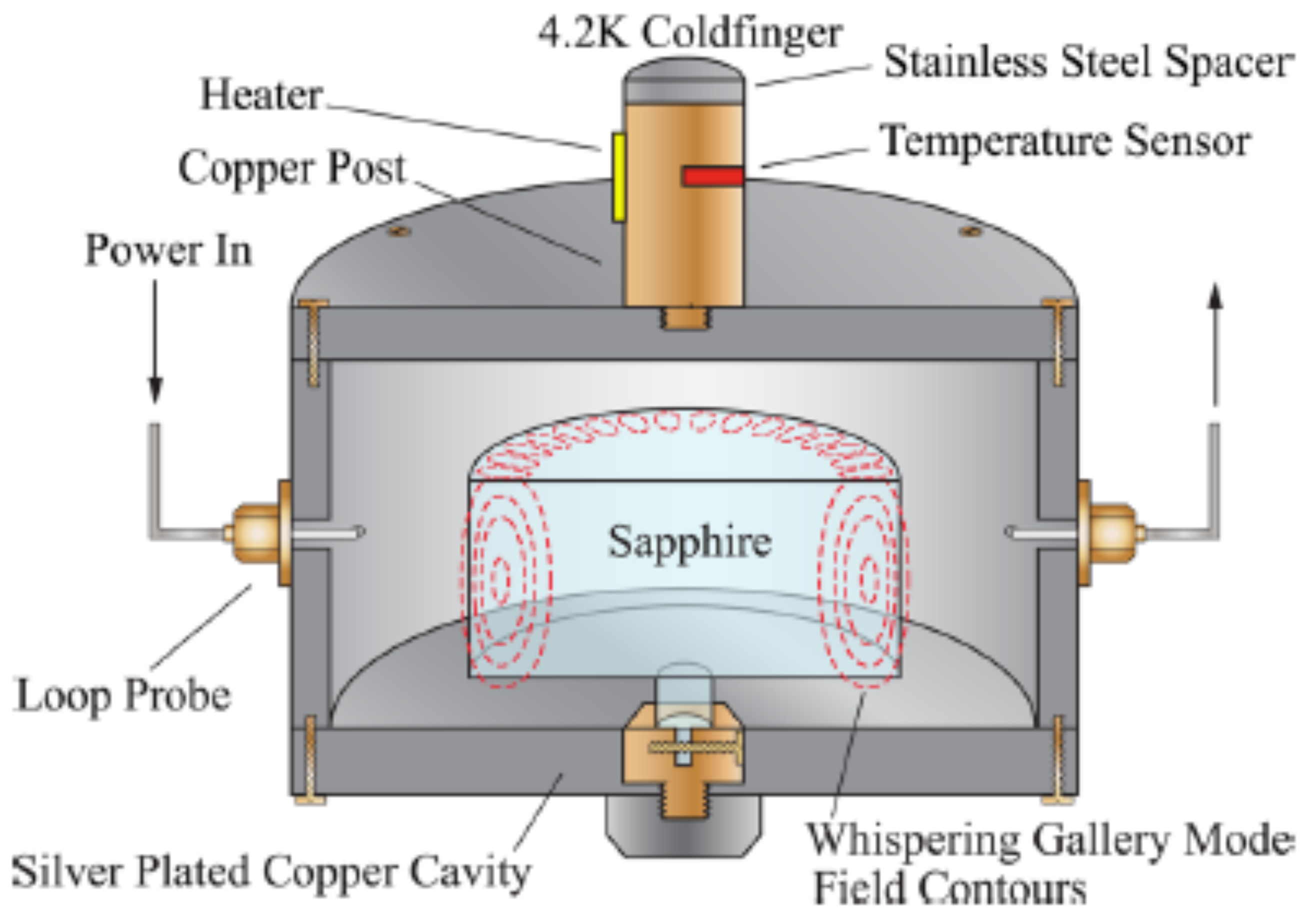


Acoustic

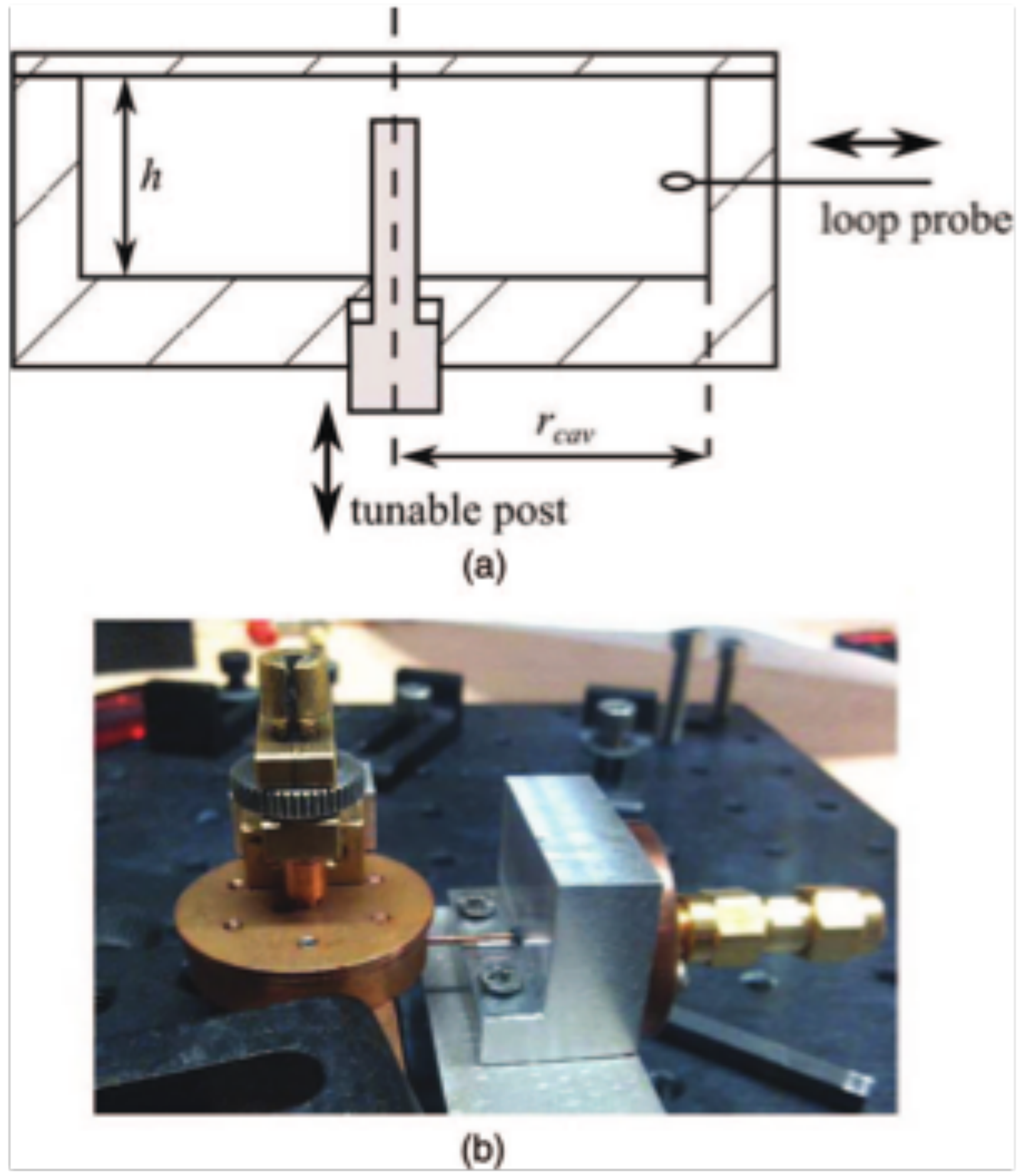
- Superfluid
- BAW Resonator

Types of Photonic Cavities to Couple to Spins, Phonons etc.

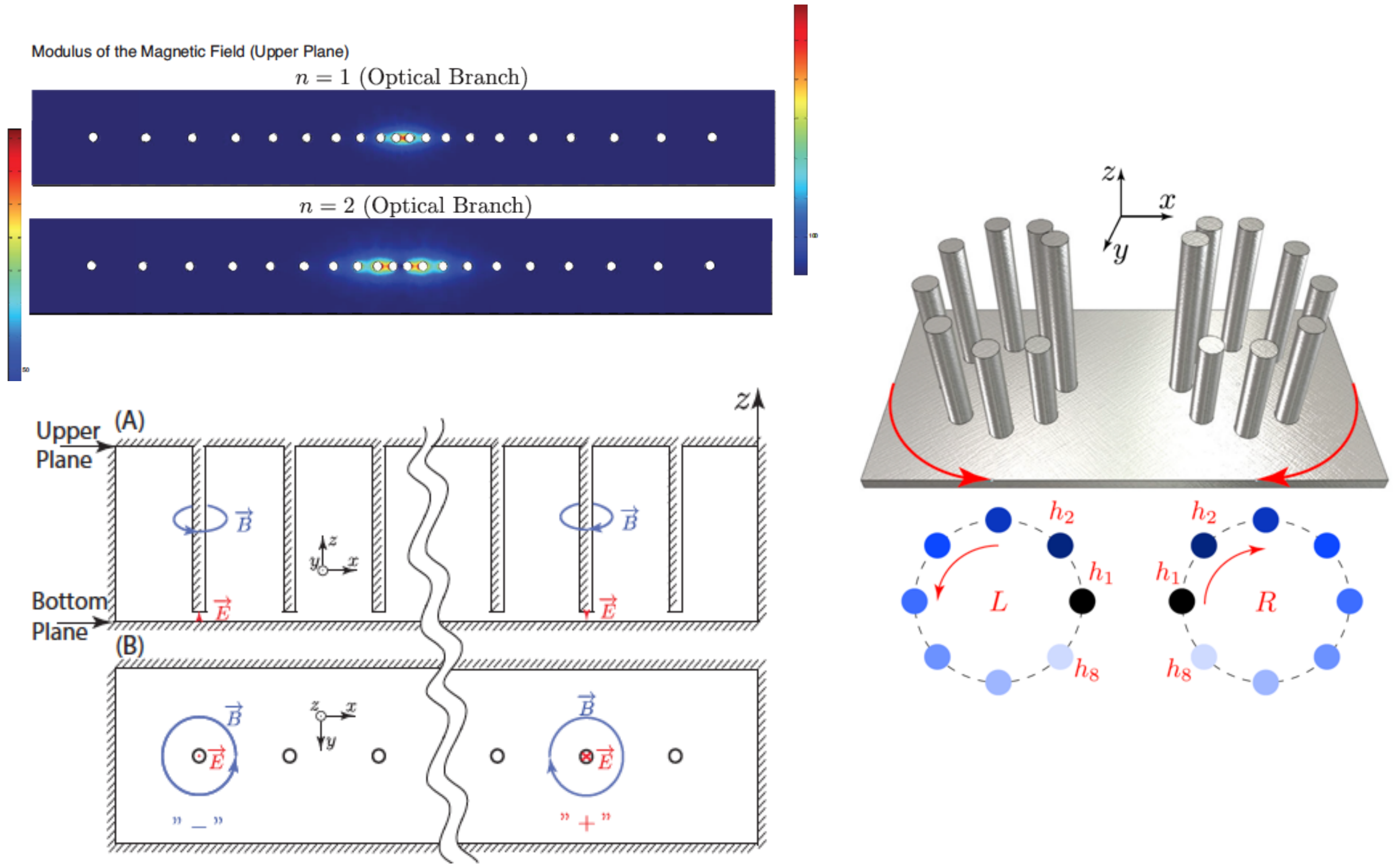
WG Modes



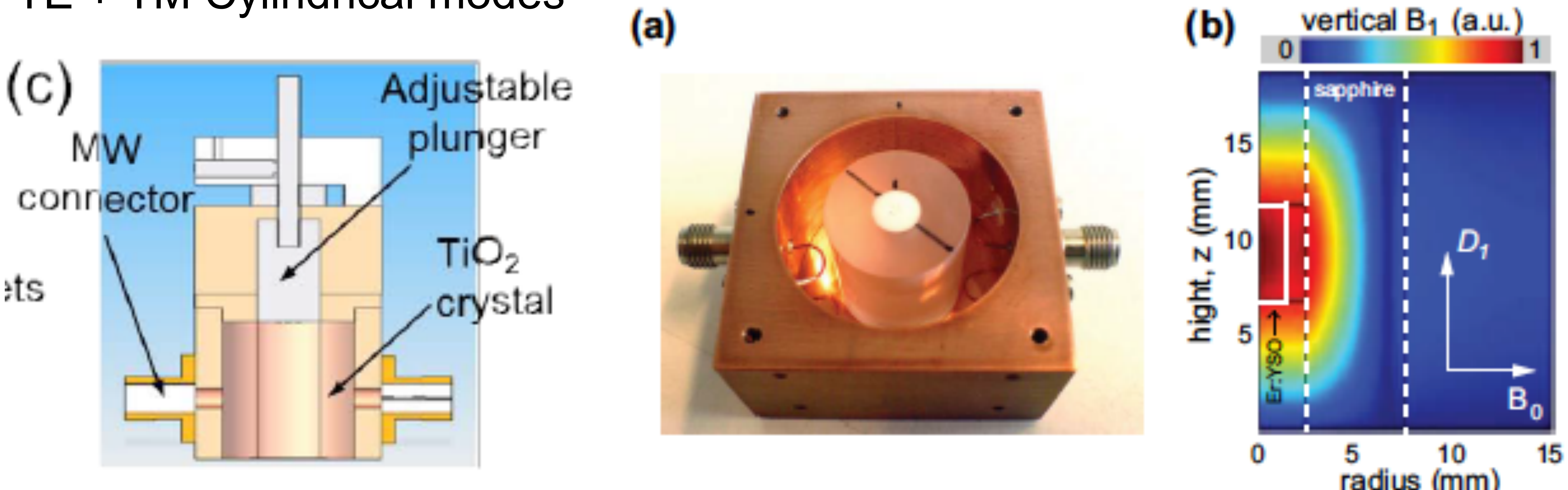
Reentrant: 3D LC



Reentrant Lattice



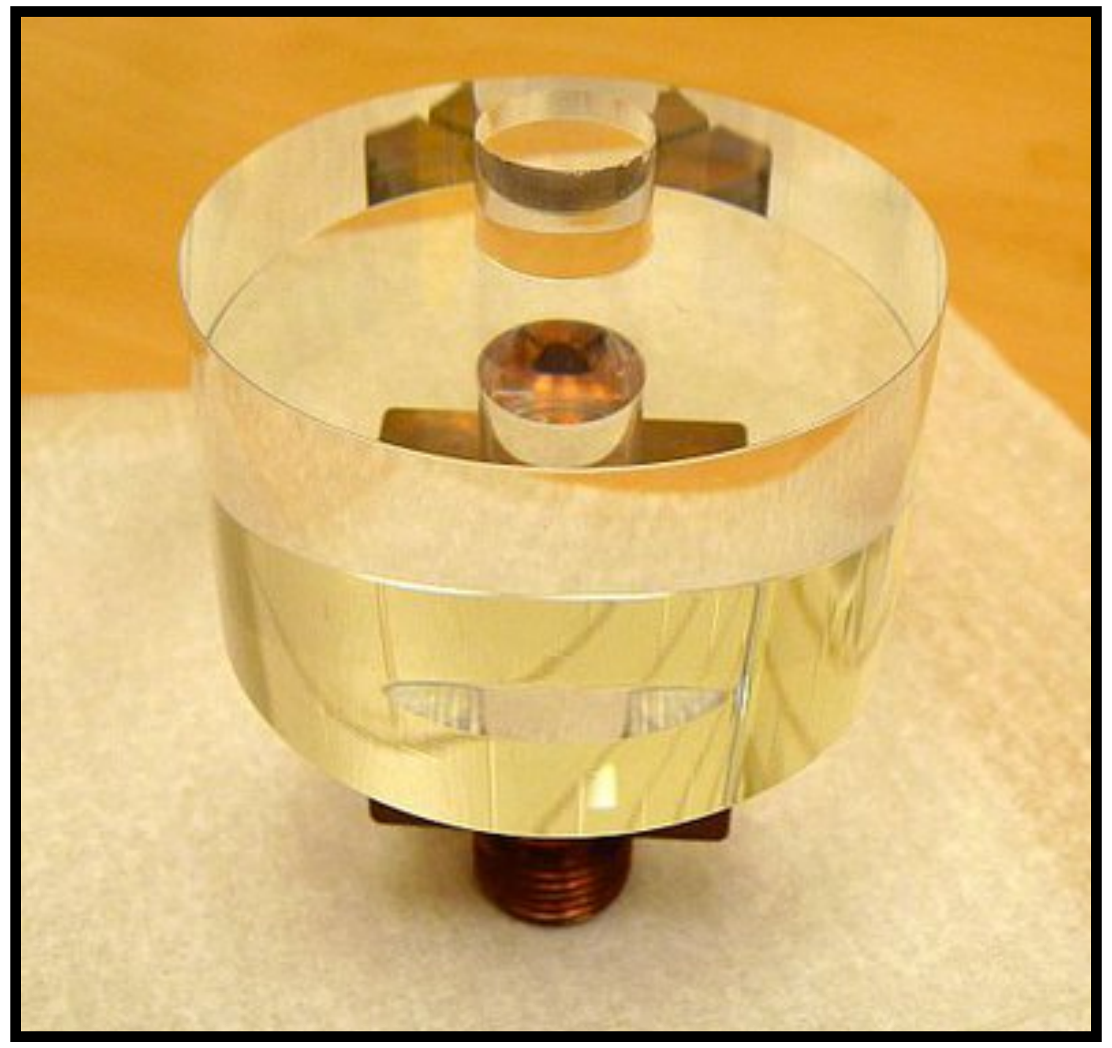
TE + TM Cylindrical modes

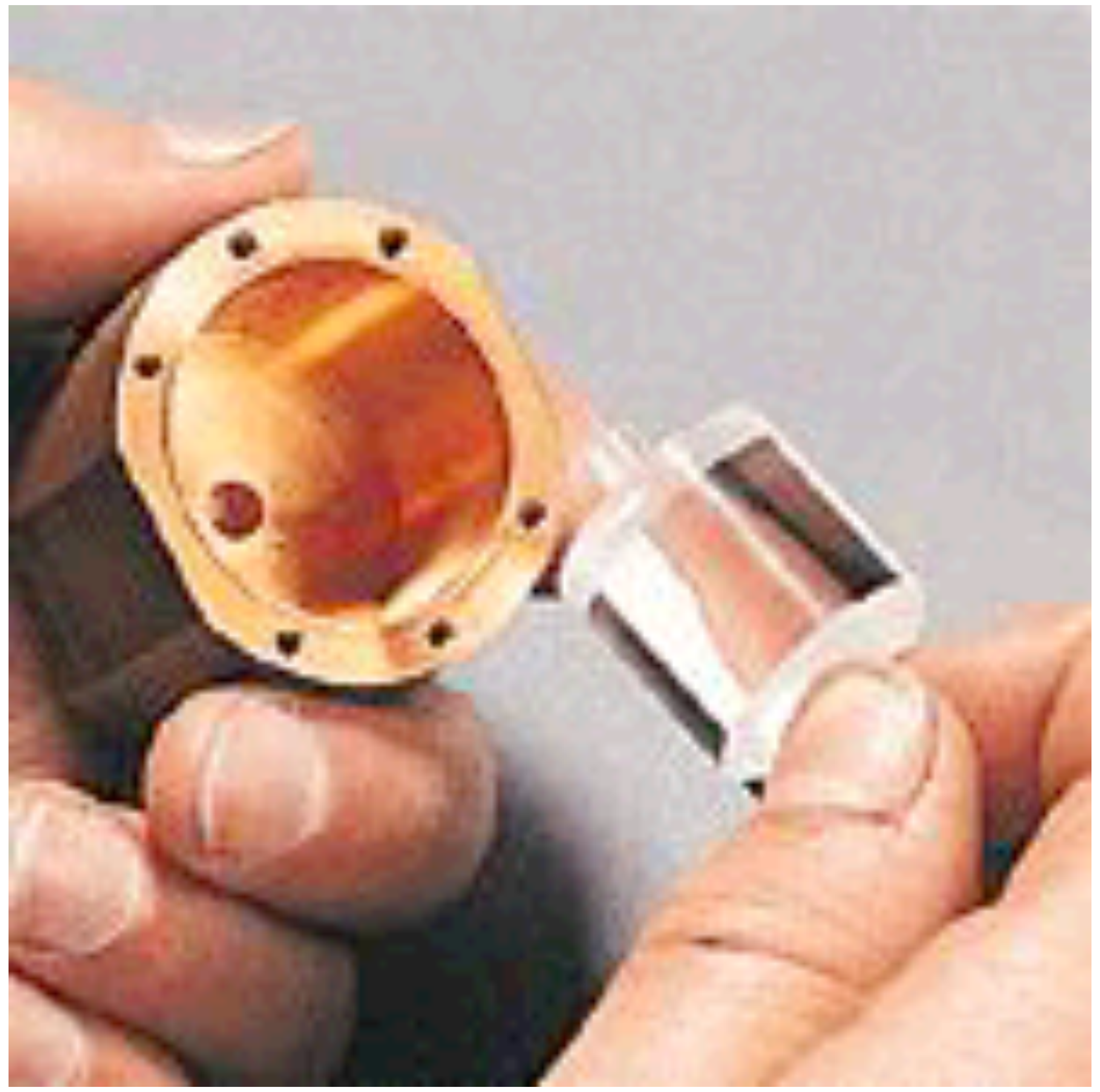


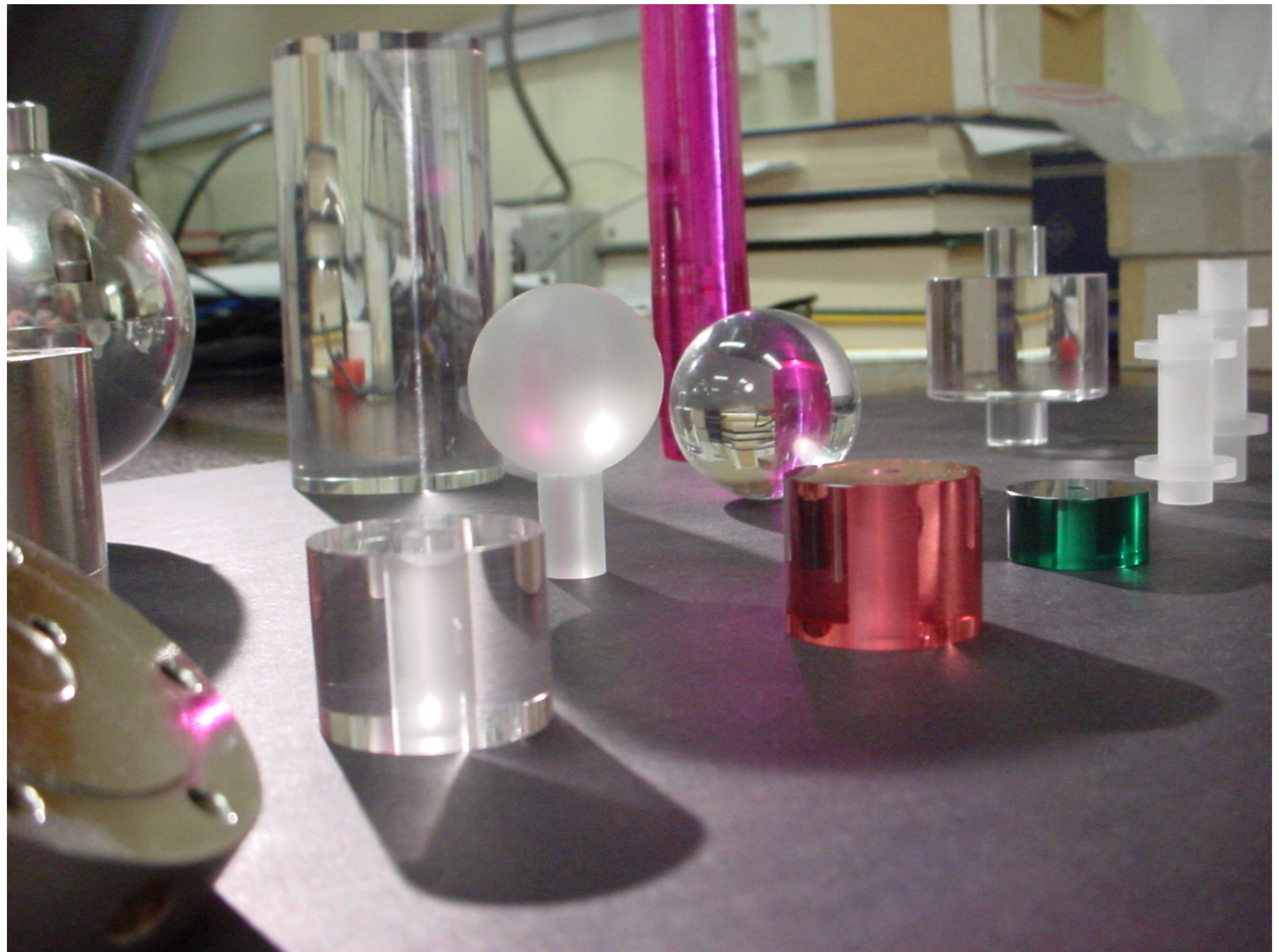
The Anyon Cavity Resonator

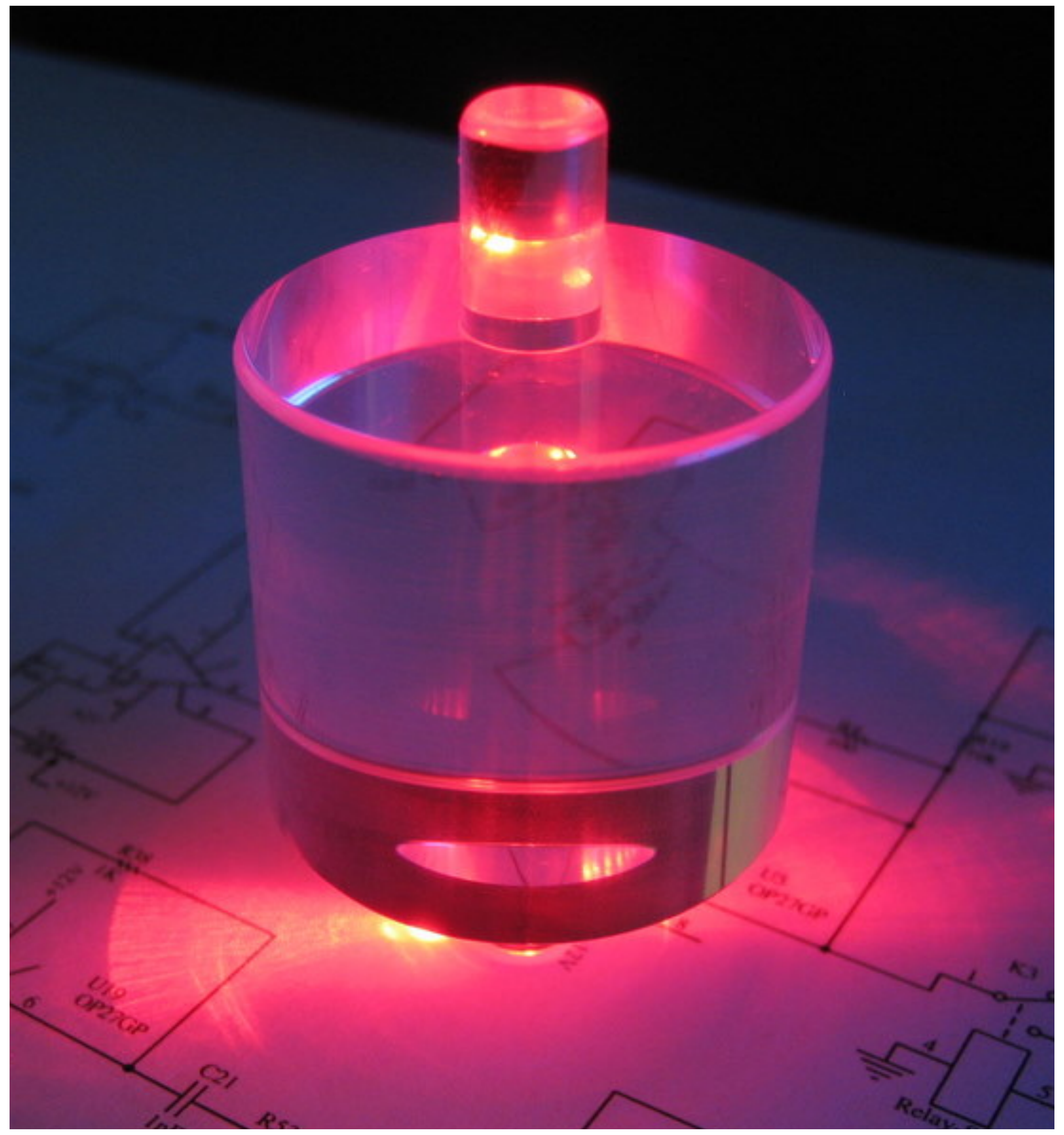
@ UWA: Photonic High-Q Sapphire Resonators

- Crystal Dielectric Resonators
  - In general low loss tangent and anisotropic
  - High-Q
  - Permittivity ~ 10 -> Whispering Gallery Mode (WGM)

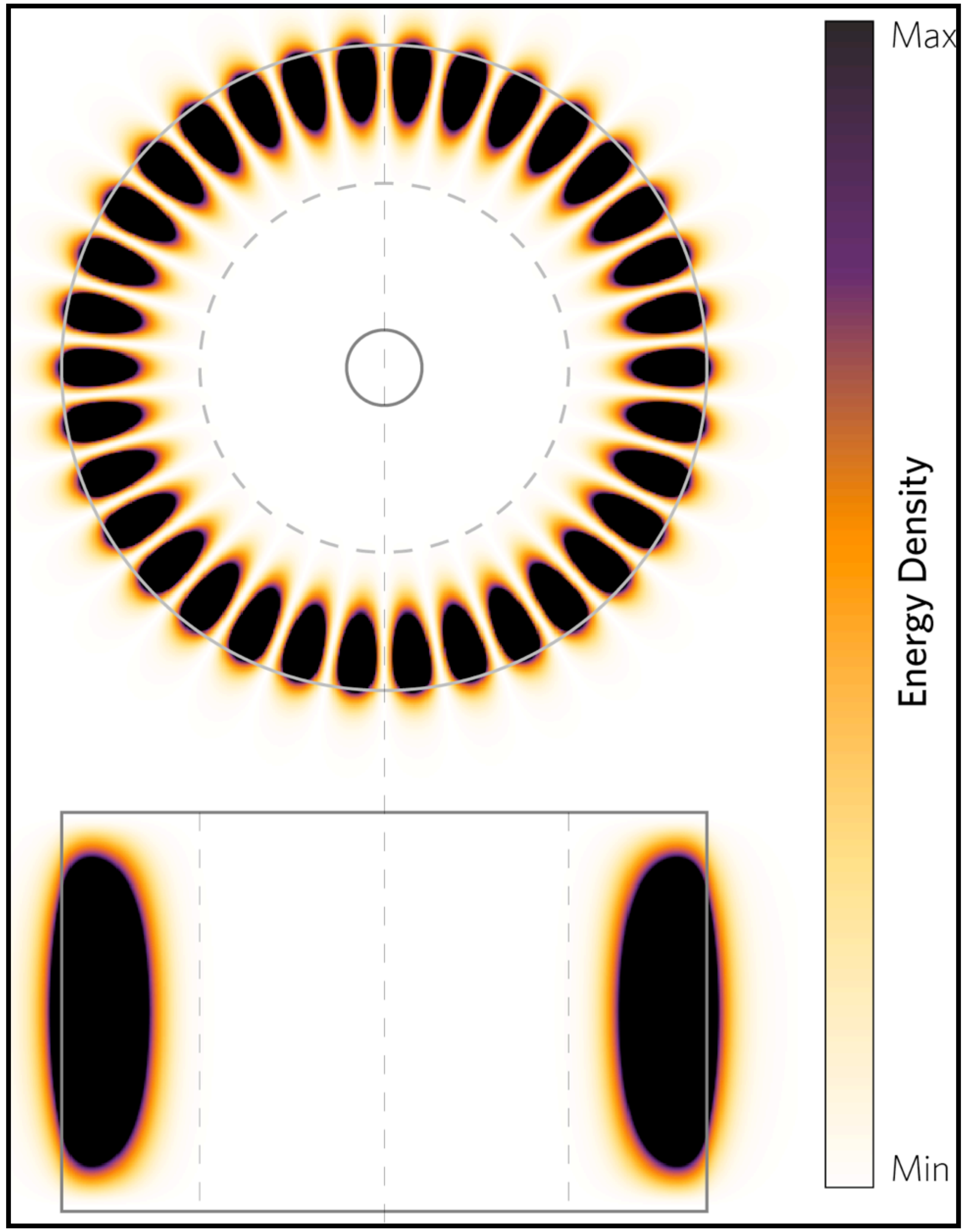








Whispering Gallery Modes: m>0



$WGH_{m,1,1}$ – transverse magnetic, Ez and Hr

$WGE_{m,1,1}$ – transverse electric, Hz and Er

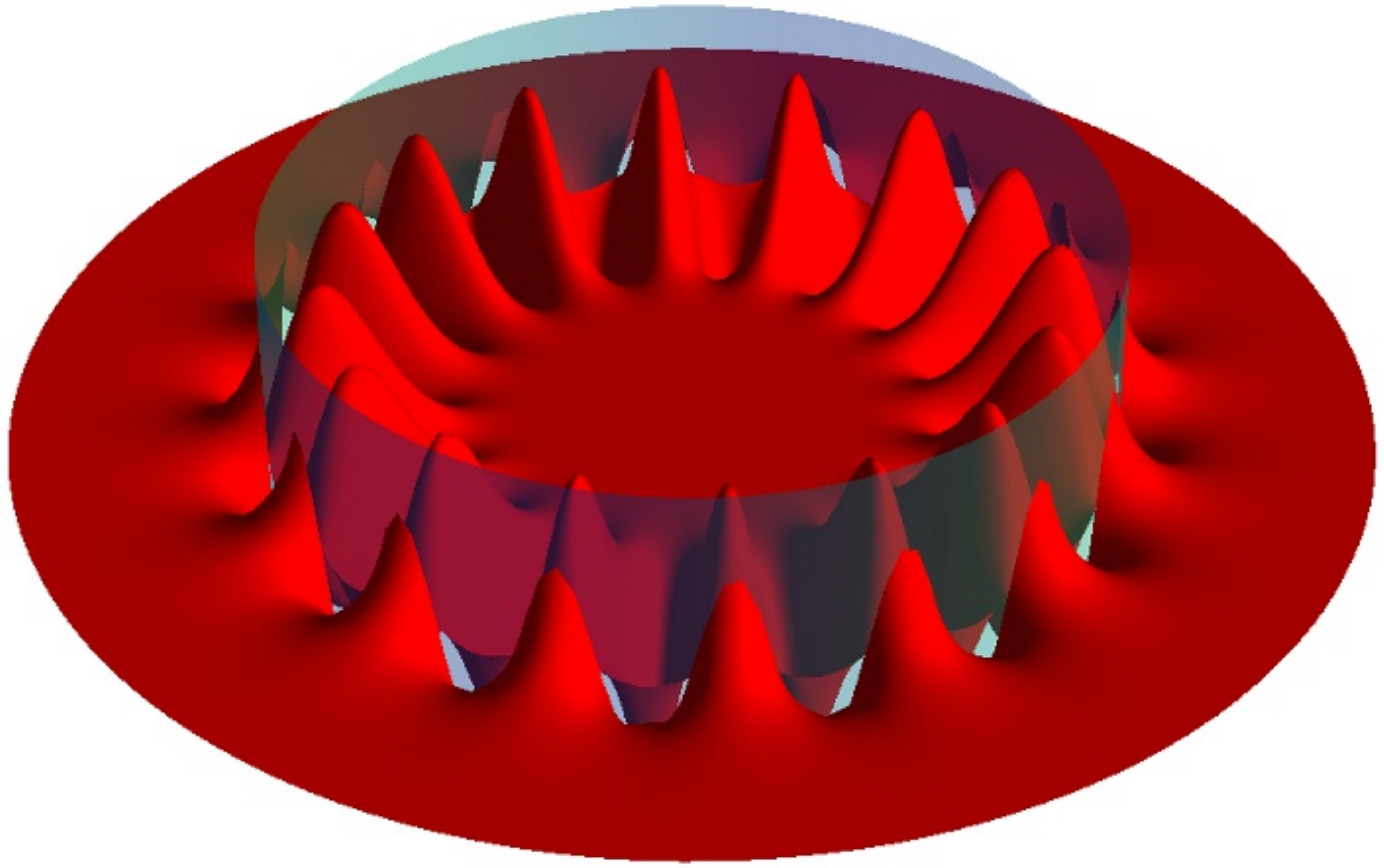
High-Q low temperature sensitivity

-> High stability oscillators

-> Low phase noise oscillators

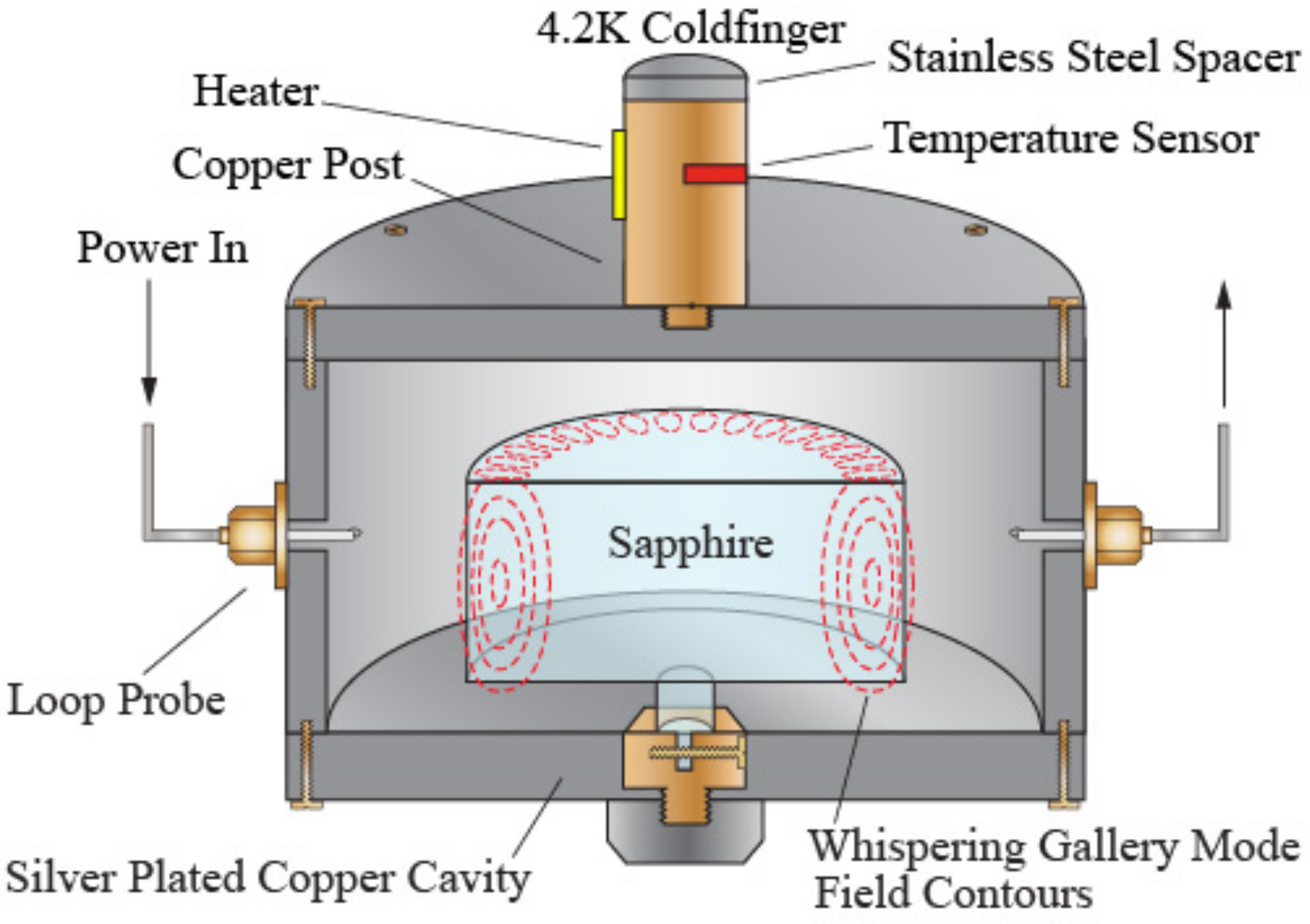
-> Test fundamental physics

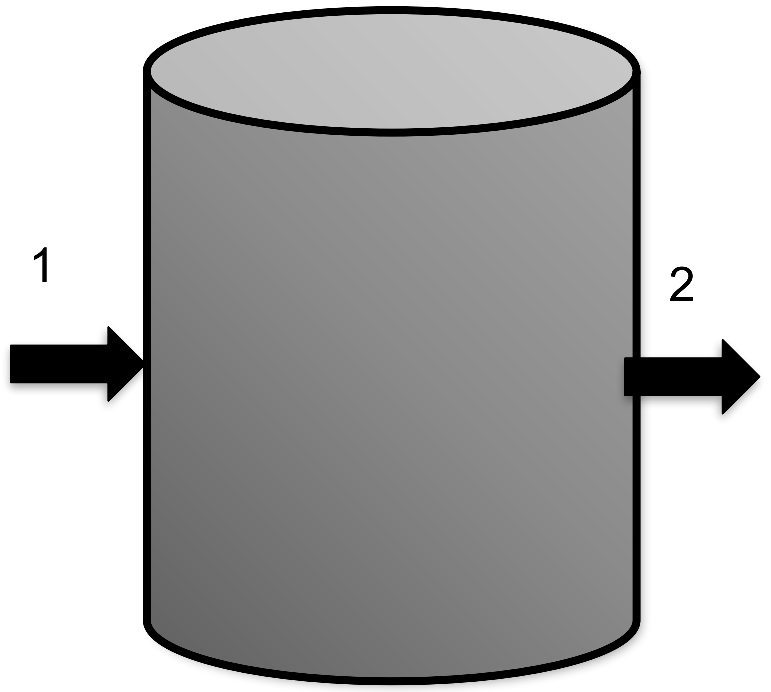
-> Engineered Quantum Systems



ME Tobar and AG Mann, "Resonant frequencies of higher order modes in cylindrical anisotropic dielectric resonators" IEEE Trans. on MTT, vol 39, no. 12, pp. 2077-2083, Dec. 1991.

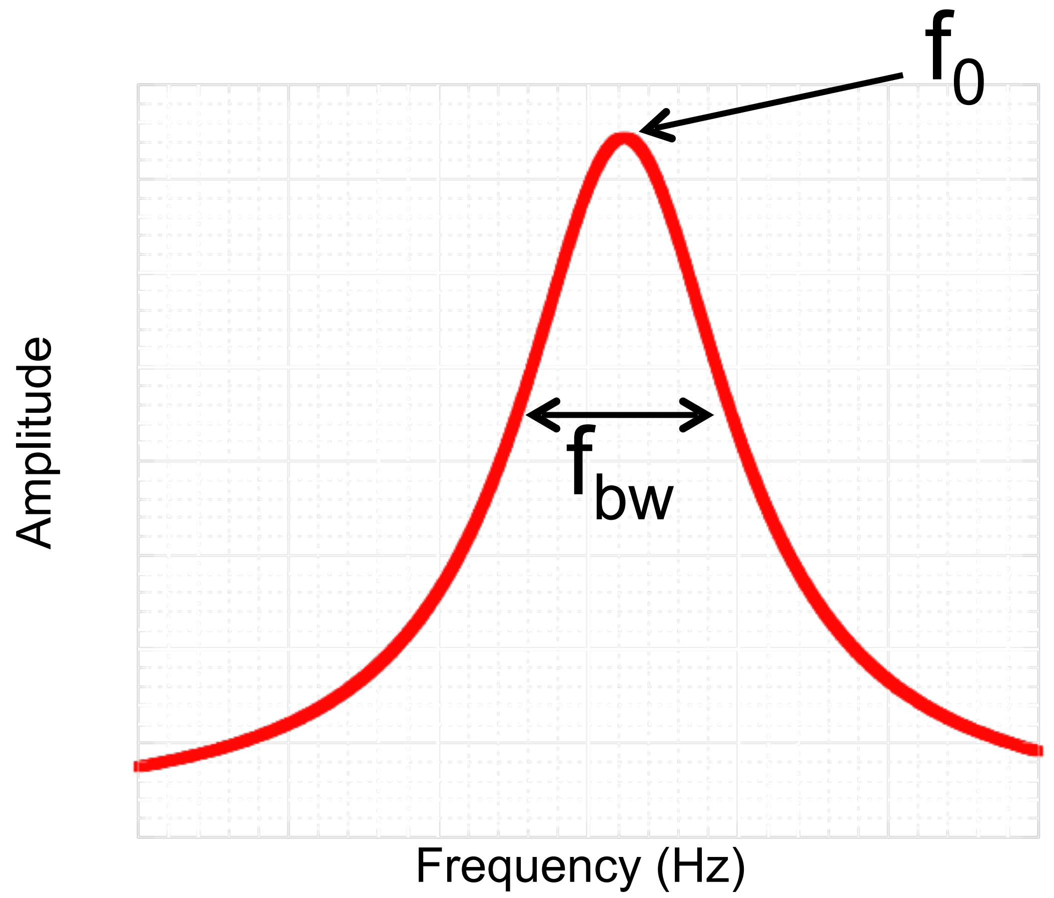
Example: Cryogenic Sapphire Oscillators (CSO) based on WGM Precision Frequency, Phase and Time





$Q_L = f_0 / f_{bw}$

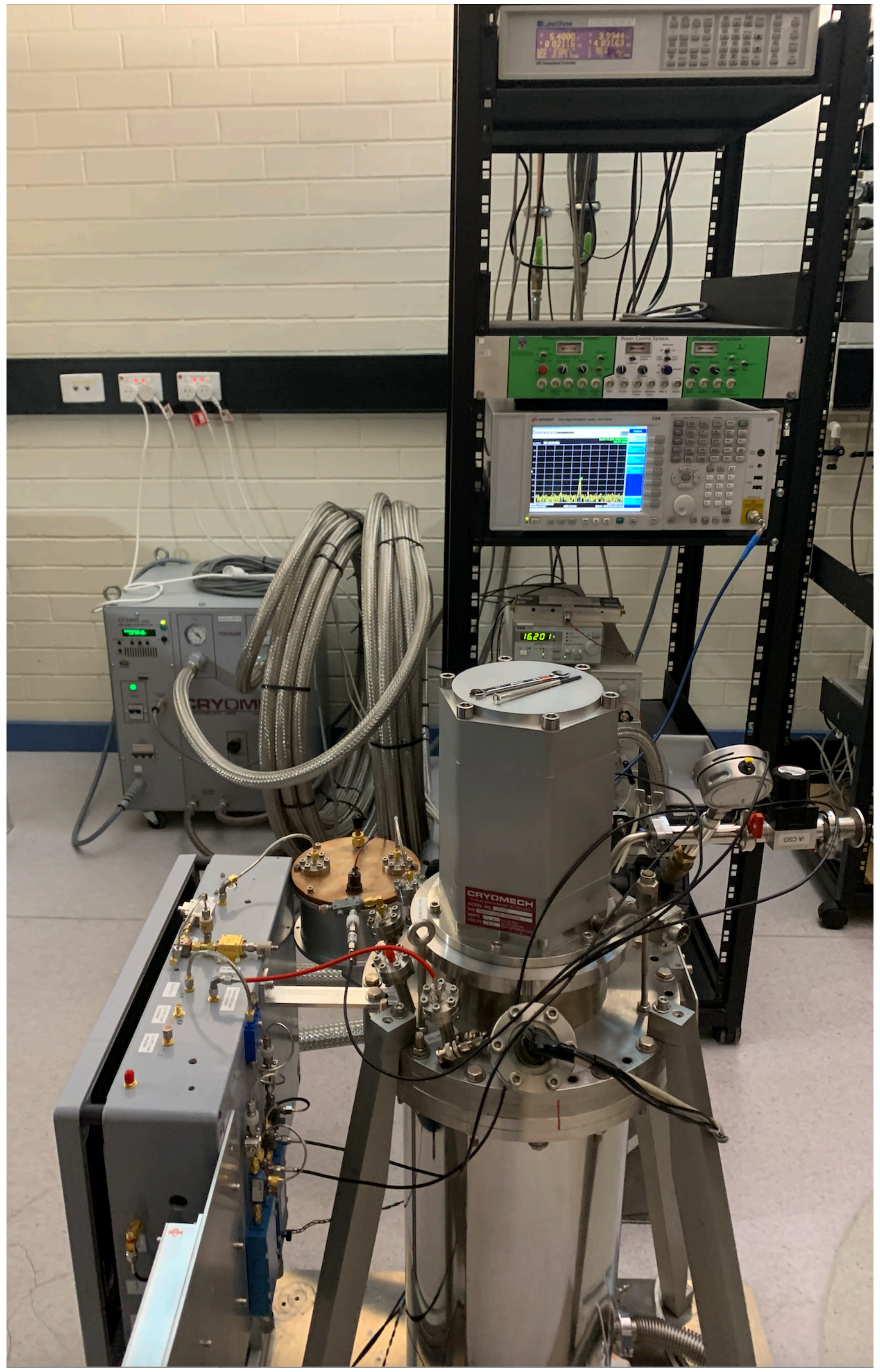
S_{21}: Transmission Spectrum



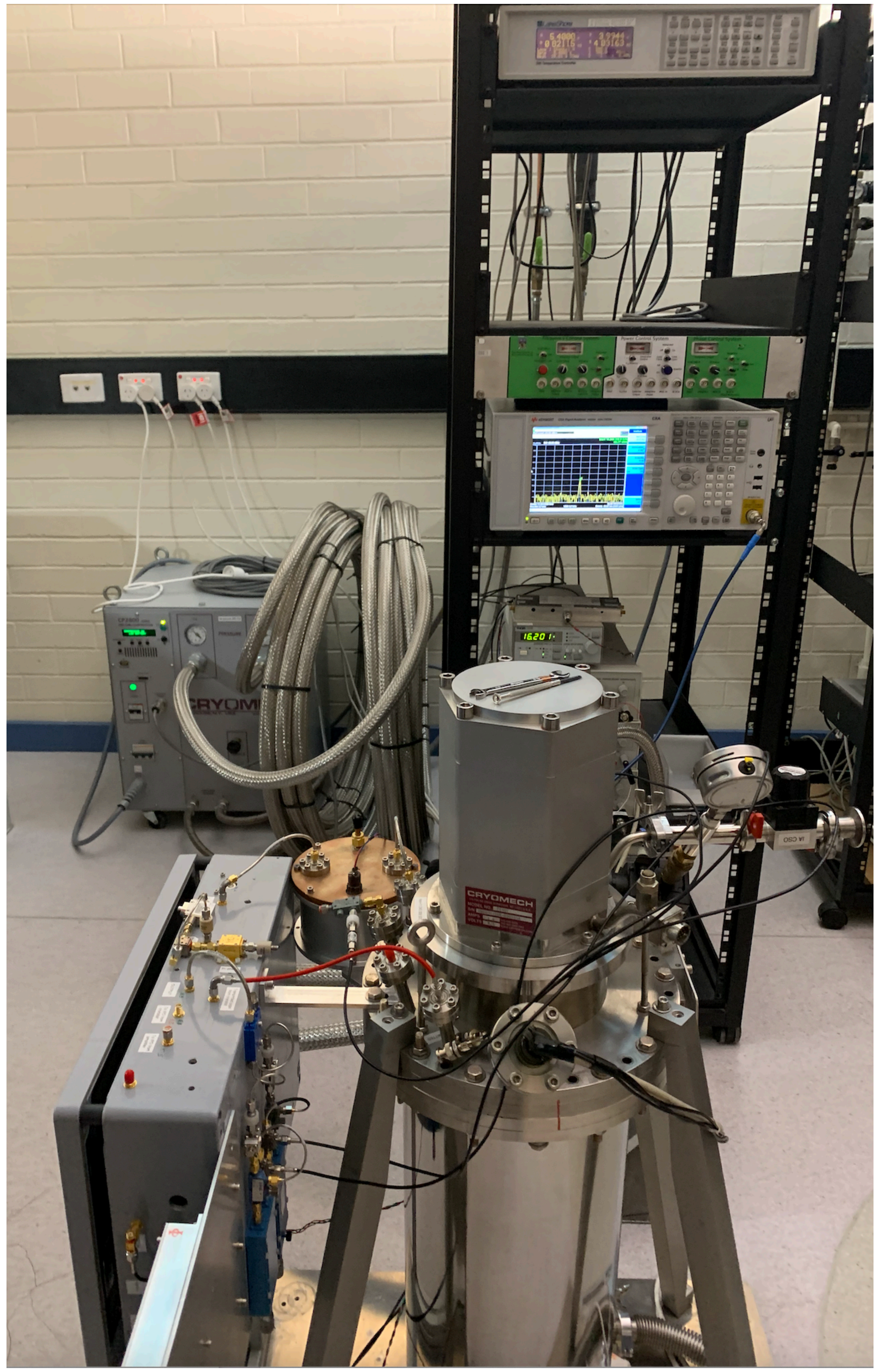
$Q_L = 10^9$ $f_0 = 10$ GHz $f_{bw} = 10$ Hz

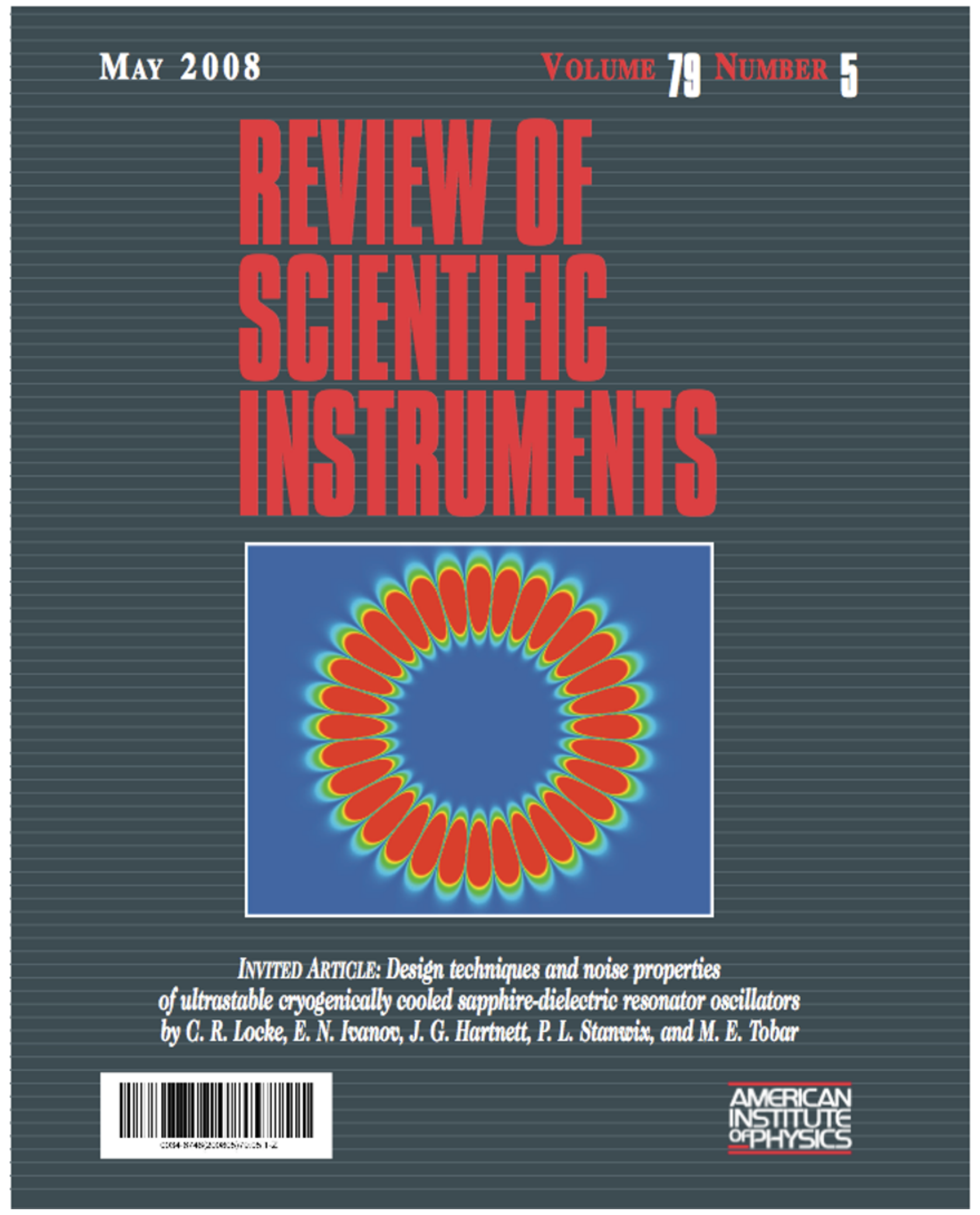
Q-factor Greater than one billion Q-factor at microwave frequencies

Cryogenic Sapphire Oscillators (CSO) 1989-Now

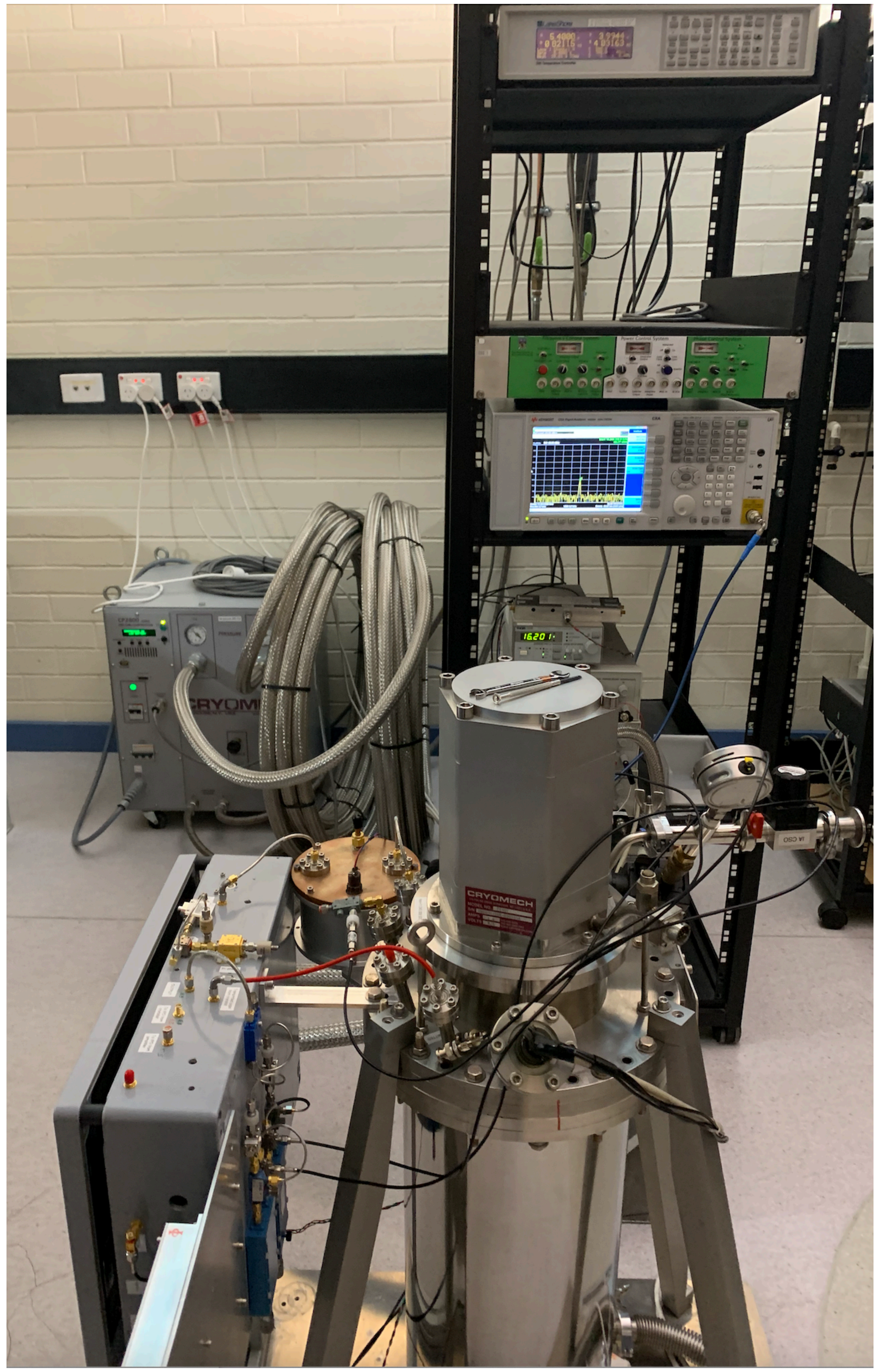


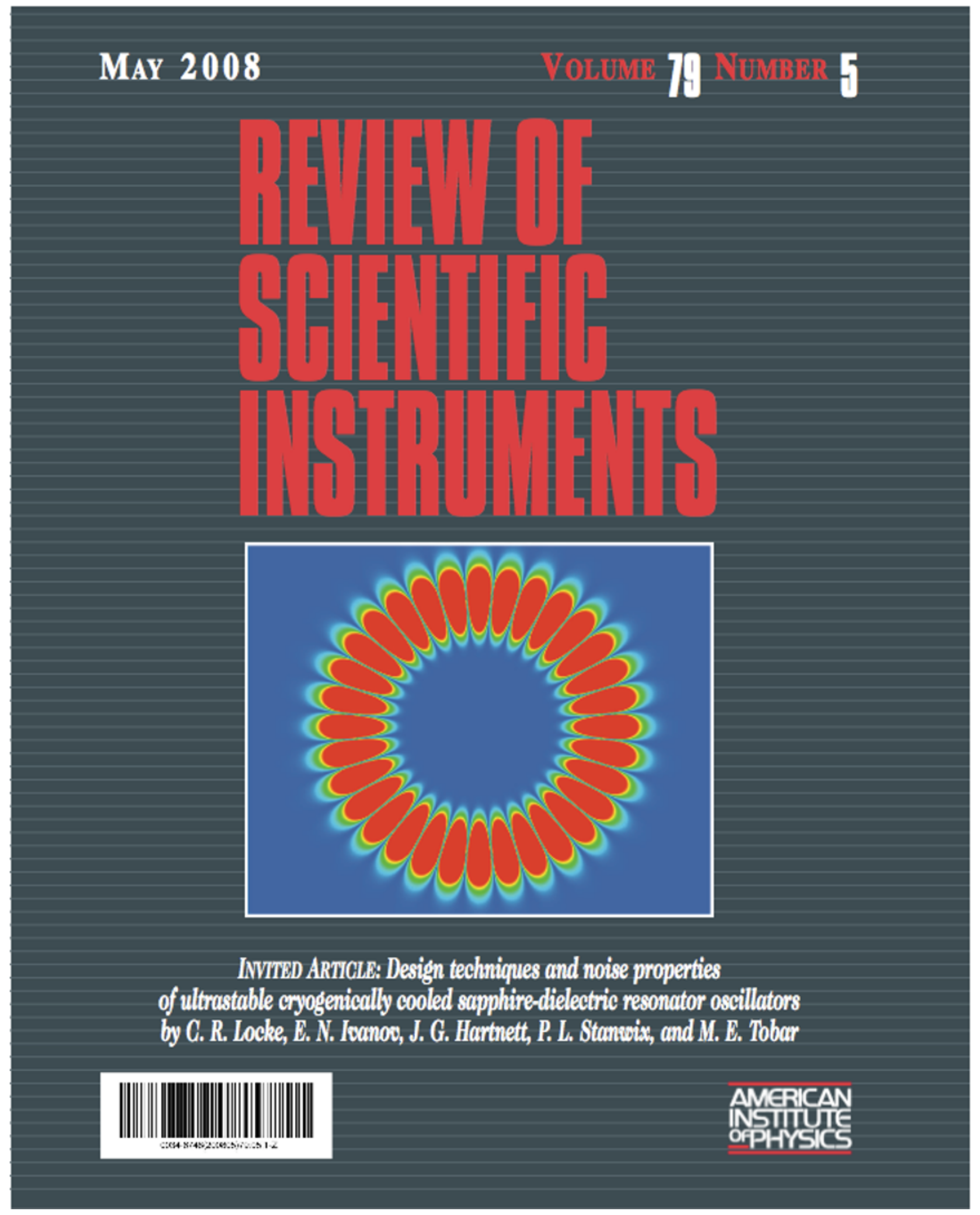
Cryogenic Sapphire Oscillators (CSO) 1989-Now

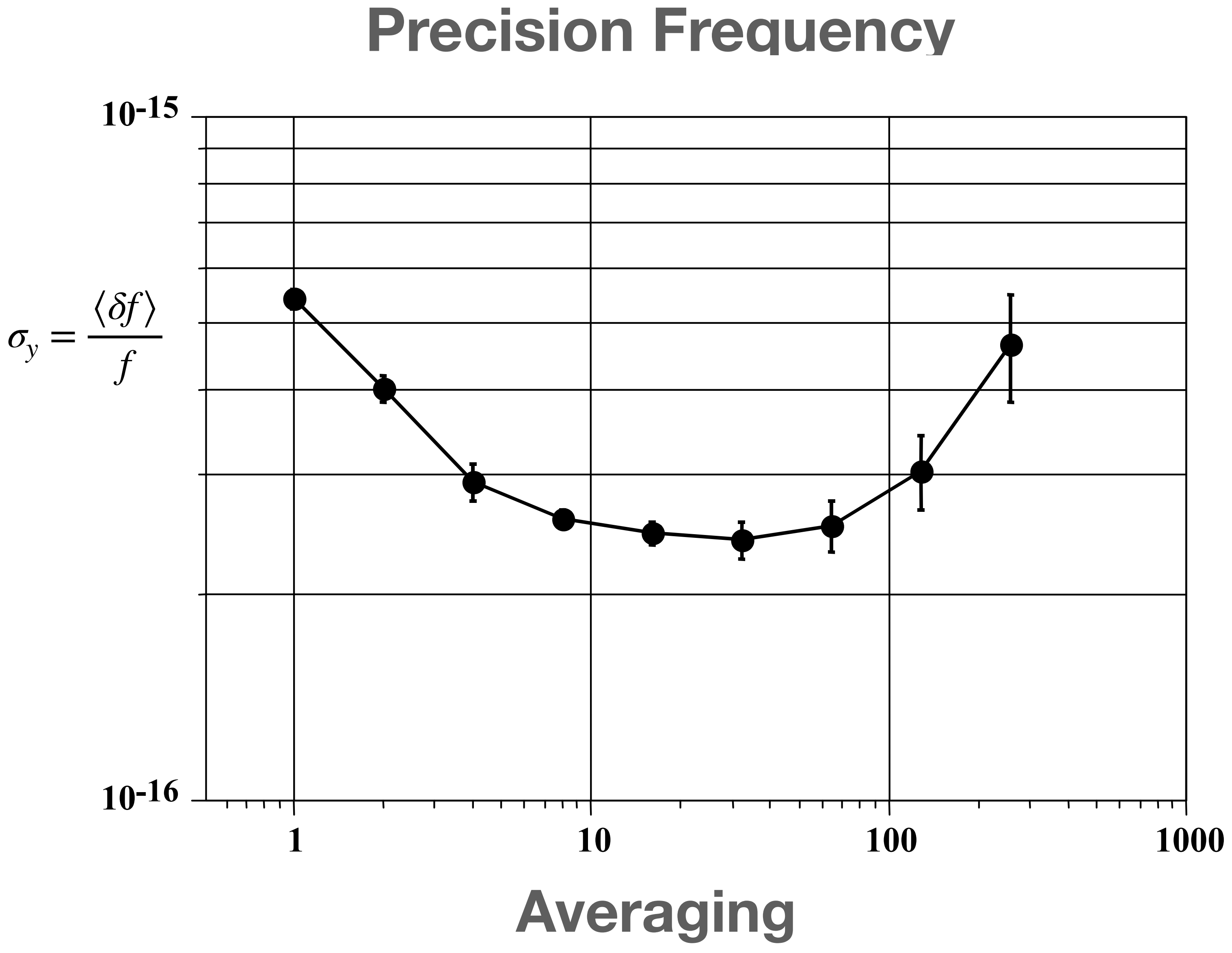




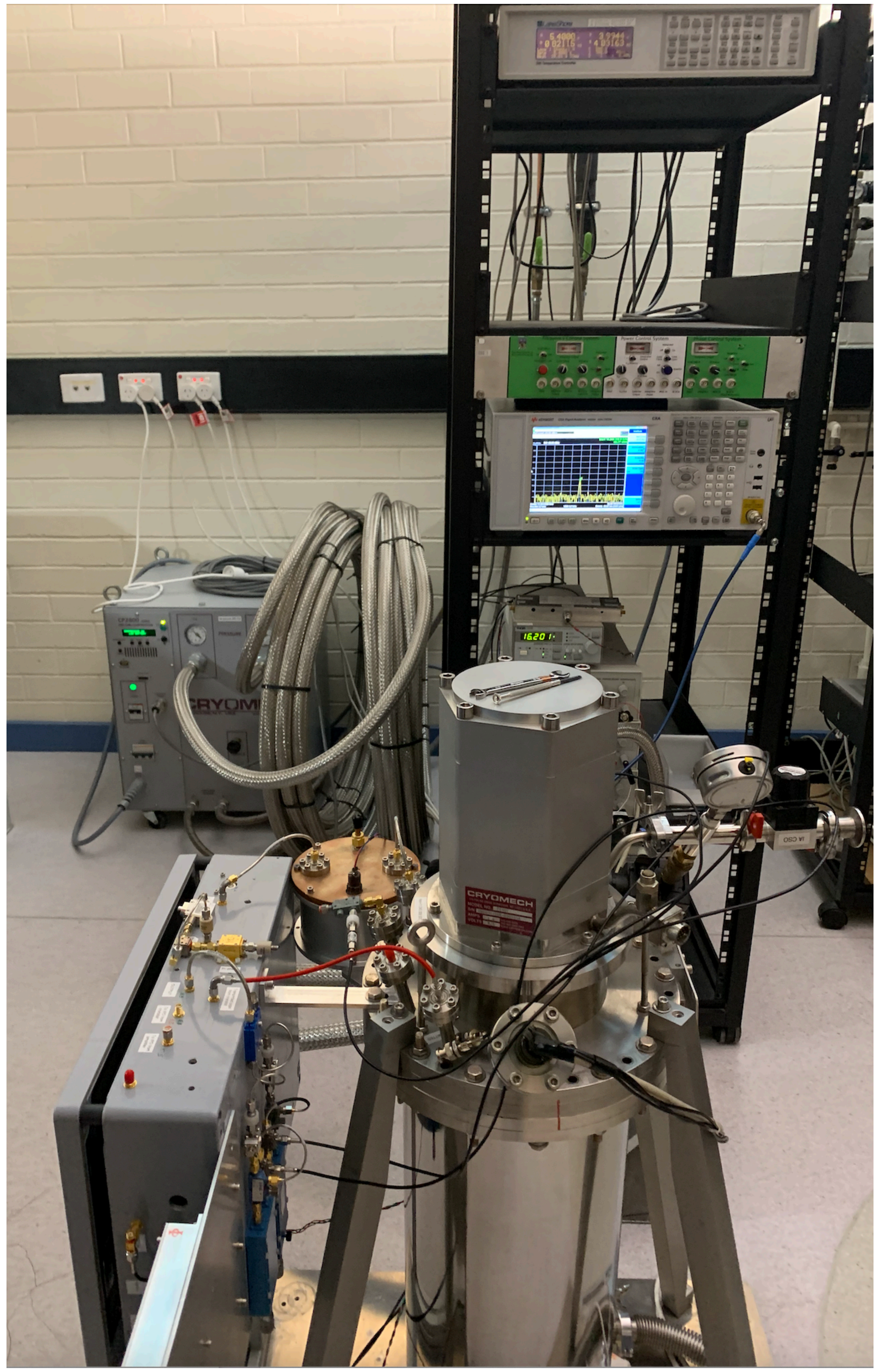
Cryogenic Sapphire Oscillators (CSO) 1989-Now

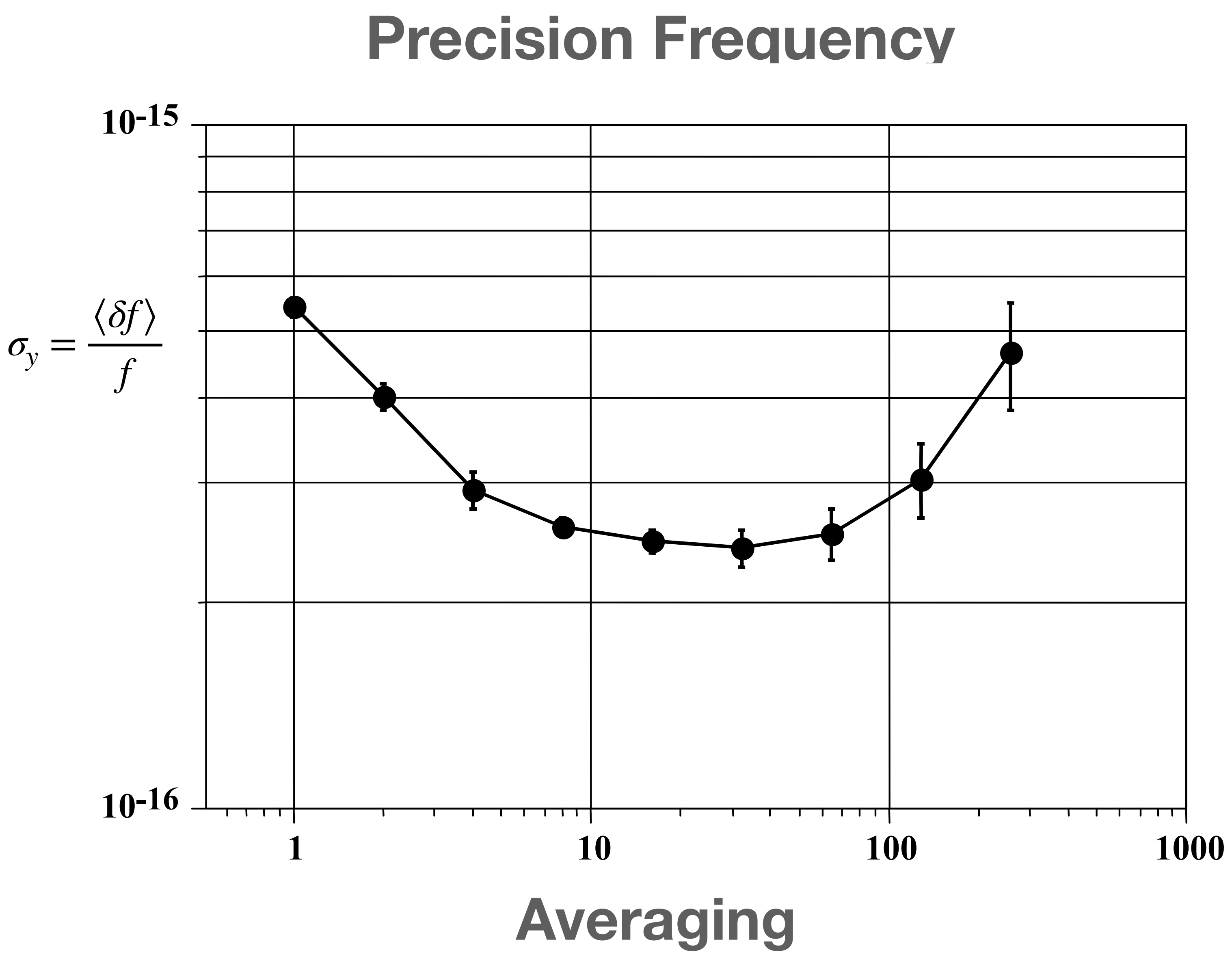


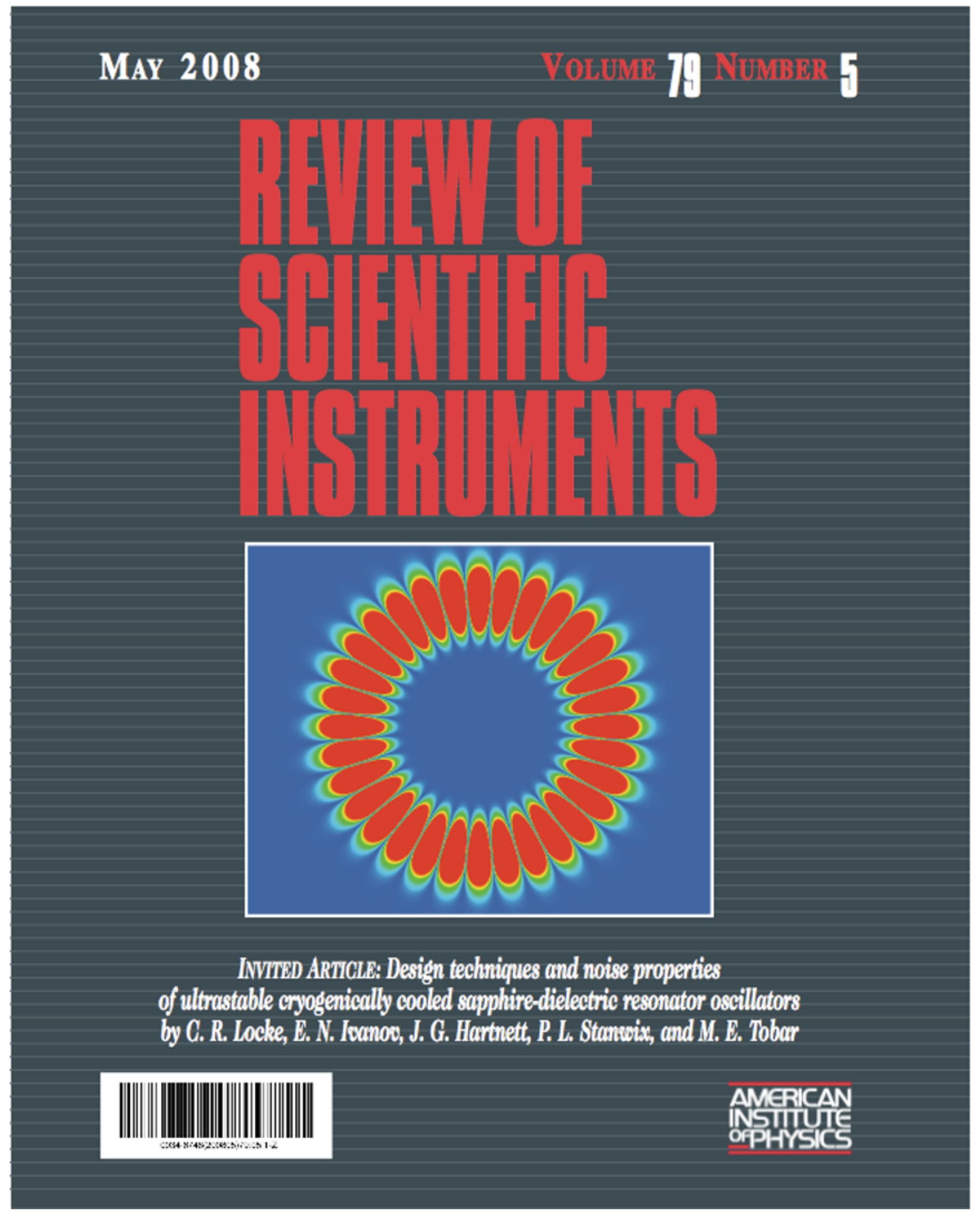


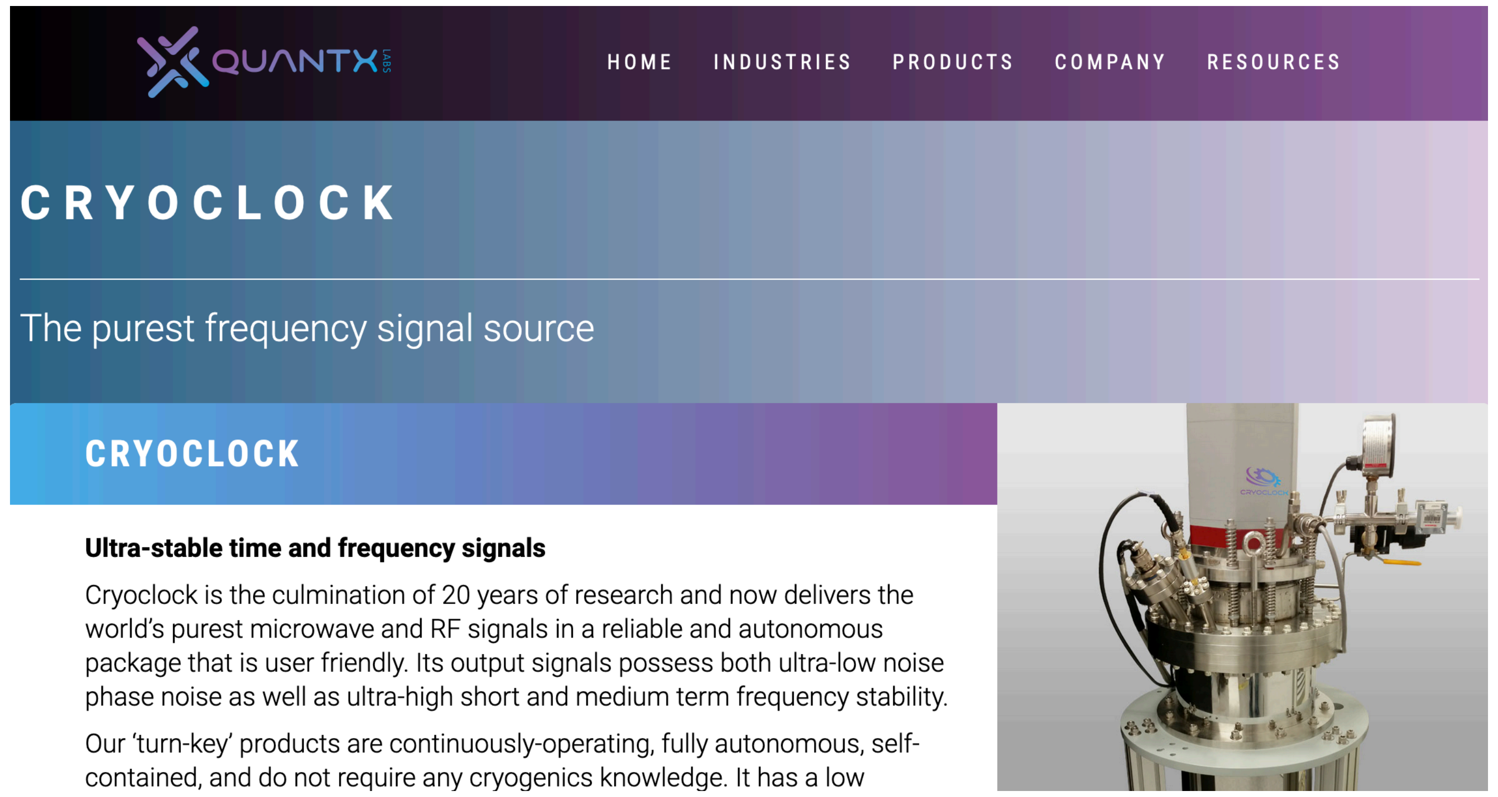


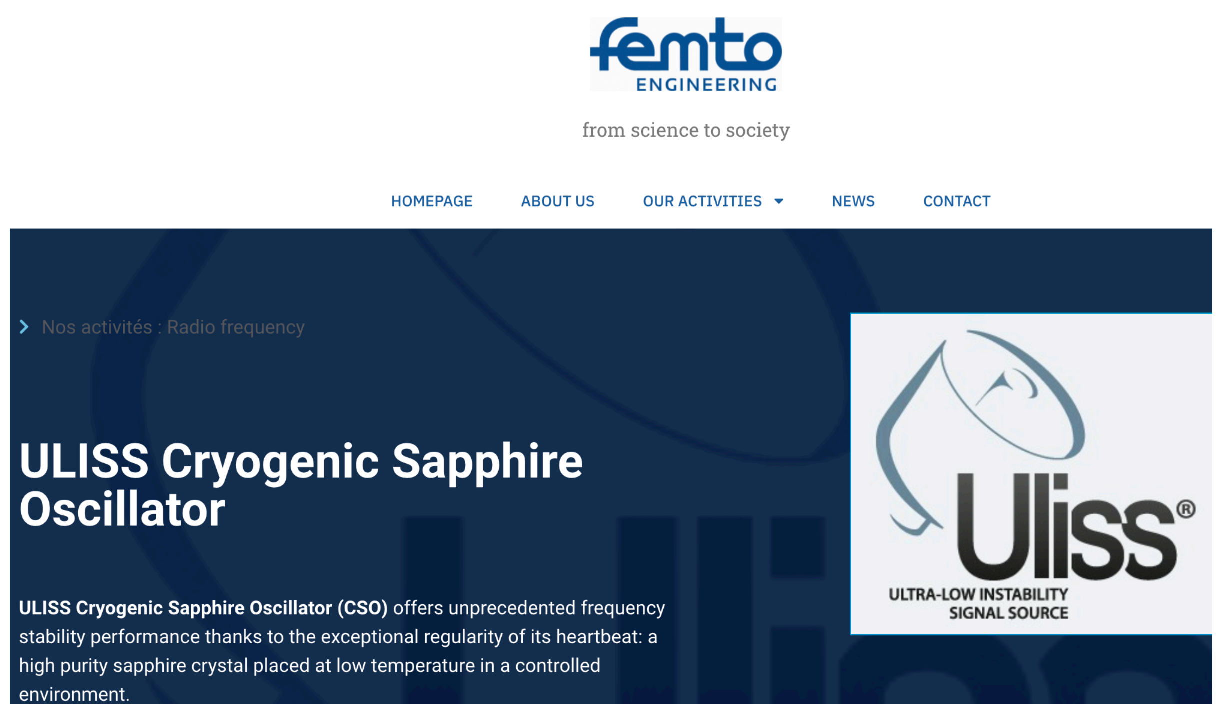
Cryogenic Sapphire Oscillators (CSO) 1989-Now



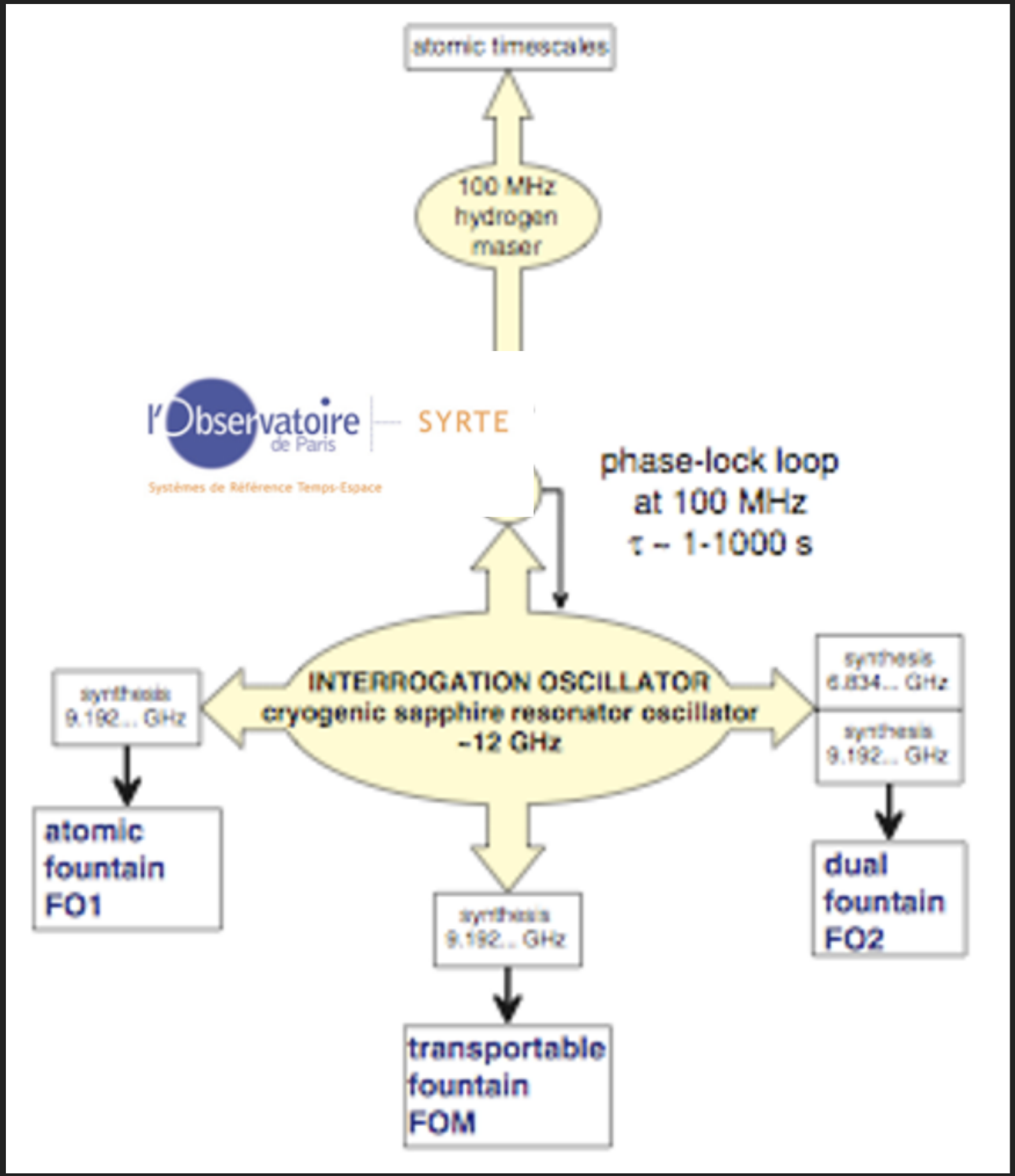




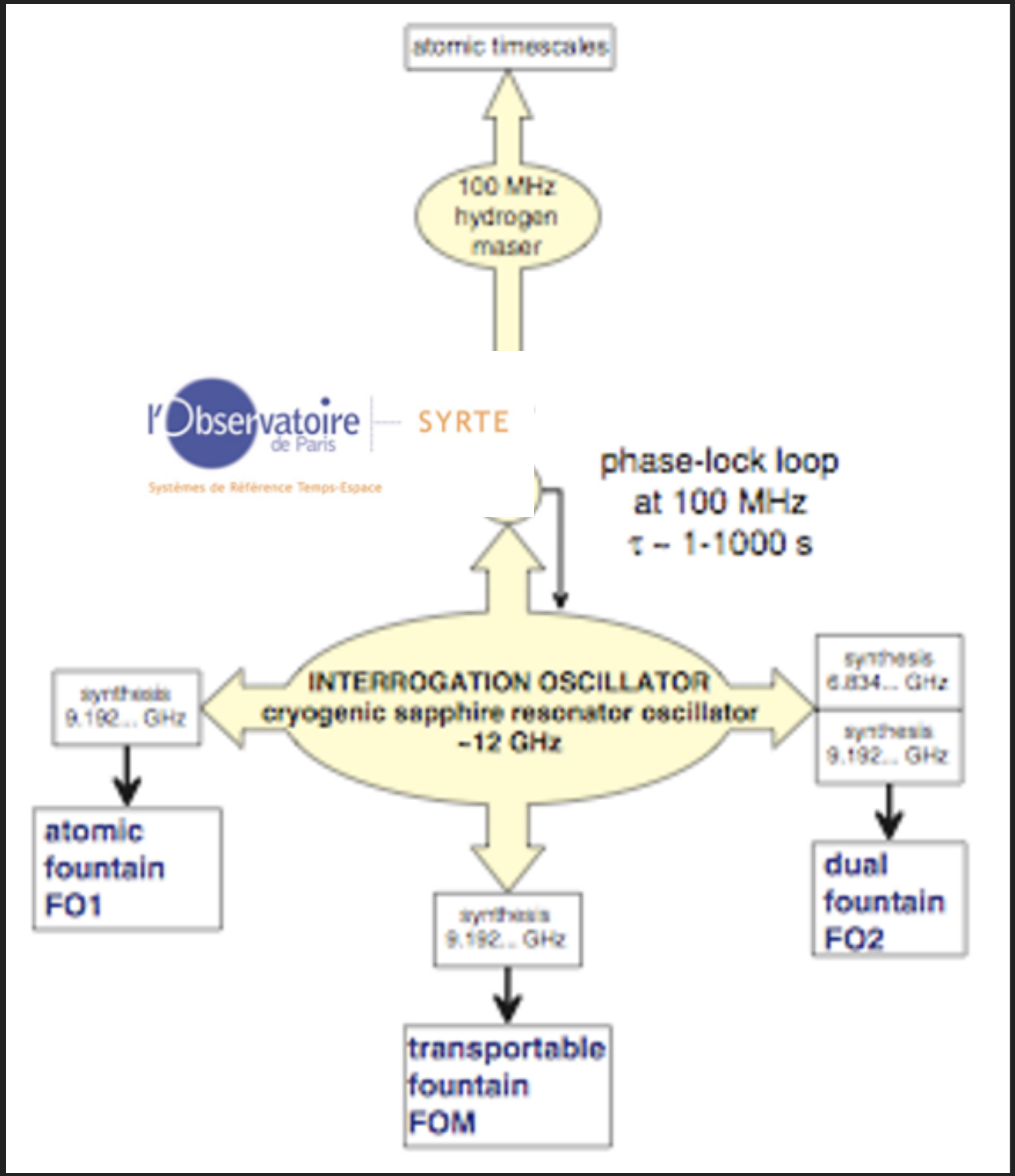




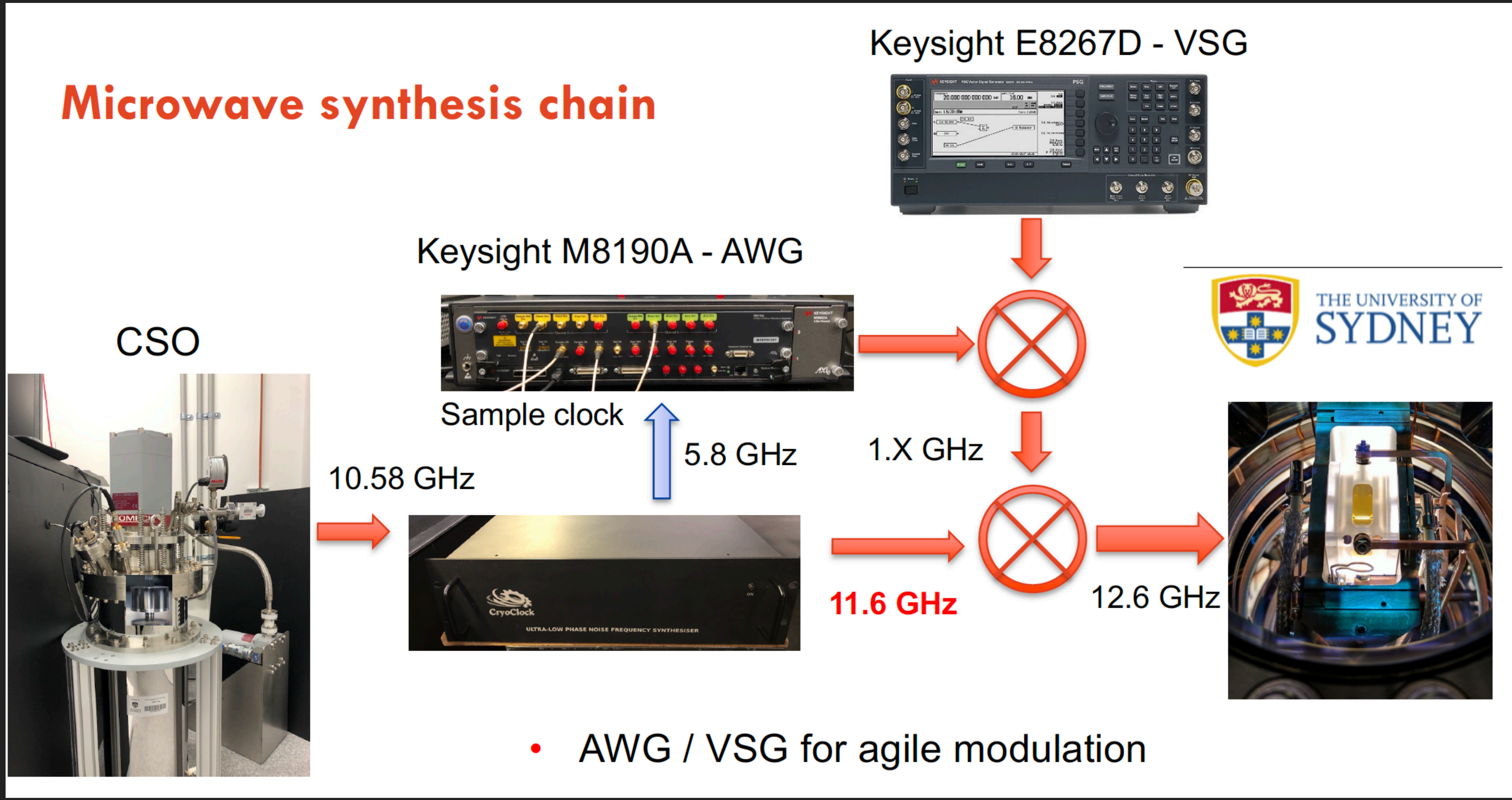
CSO Operates Atomic Clock @ the Projection Noise Limit: Paris Observatory SYRTE since 1999



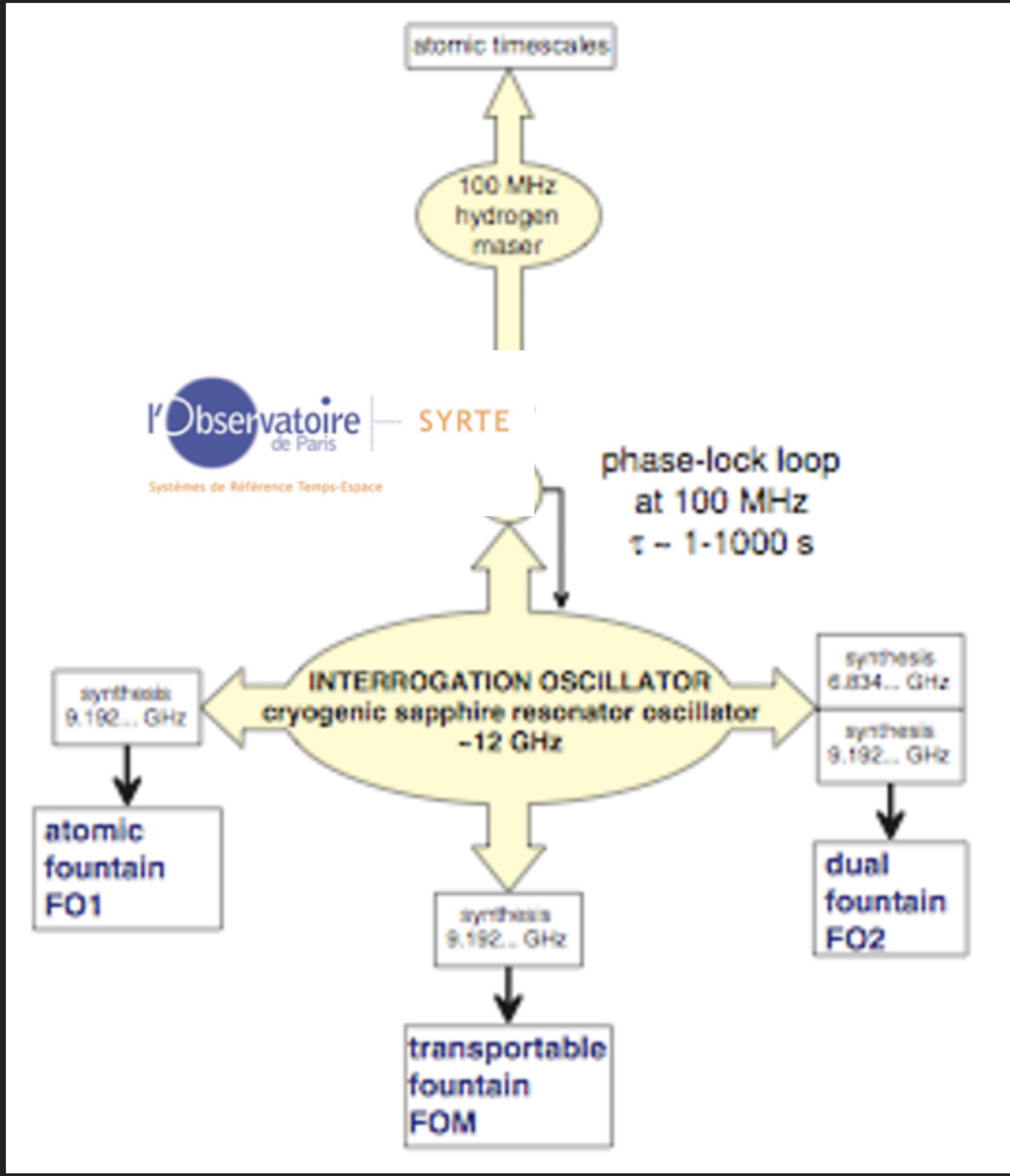
CSO Operates Atomic Clock @ the Projection Noise Limit: Paris Observatory SYRTE since 1999



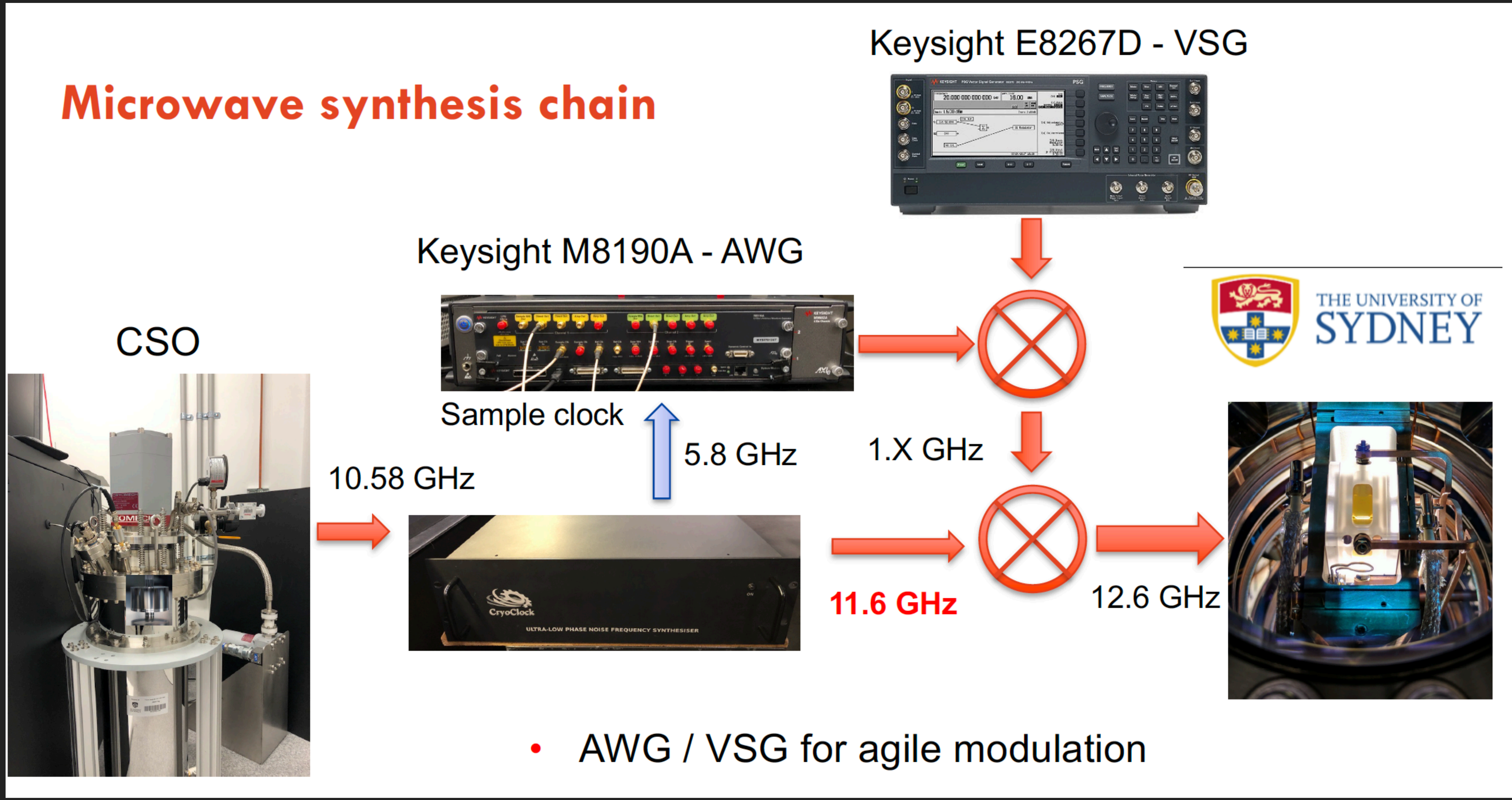
Now: Atomic or Spin Qubits at the Quantum Limit



CSO Operates Atomic Clock @ the Projection Noise Limit: Paris Observatory SYRTE since 1999



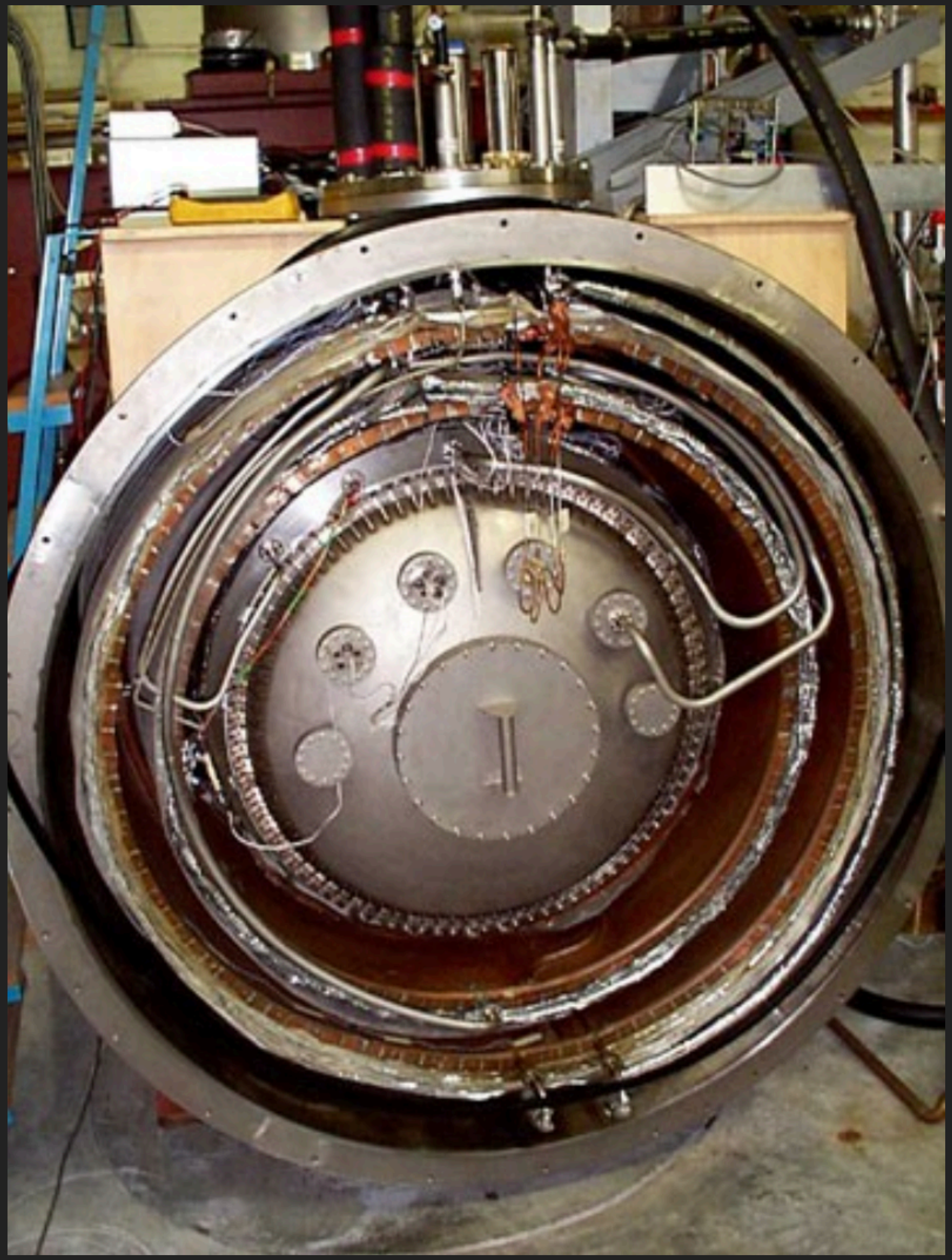
Now: Atomic or Spin Qubits at the Quantum Limit



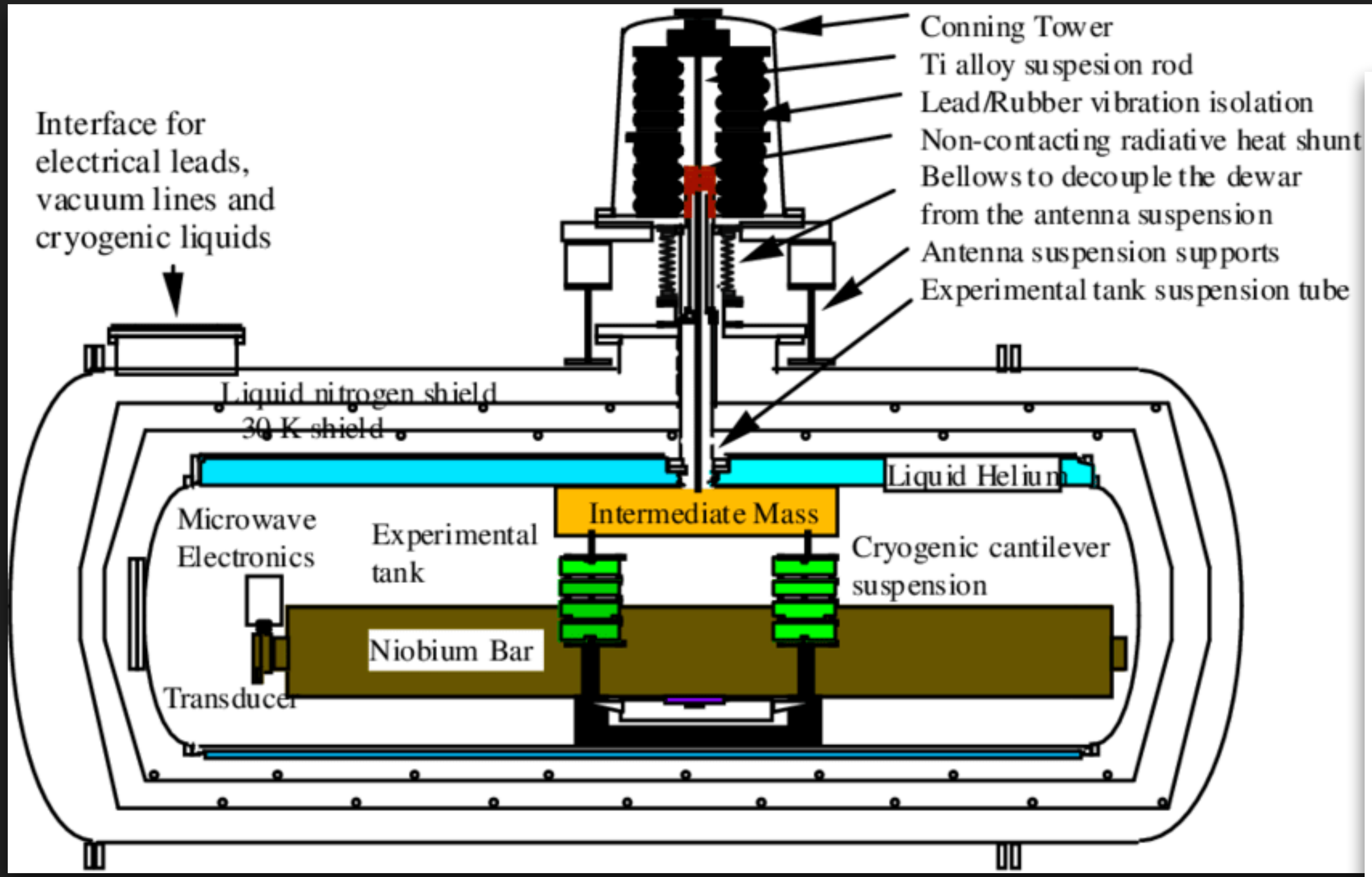
Yb ion qubits.

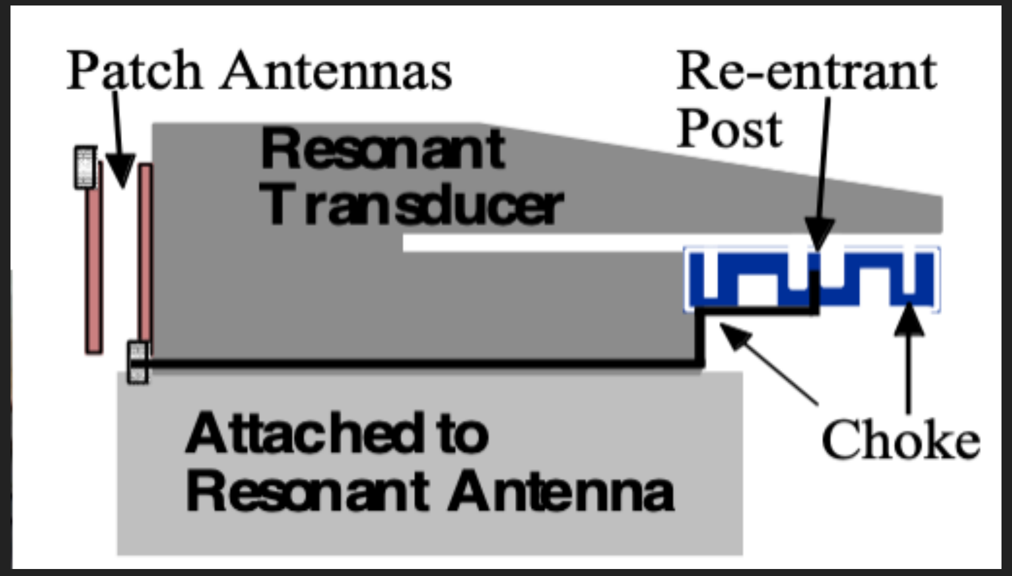
Also, other systems will need low phase noise pump oscillators

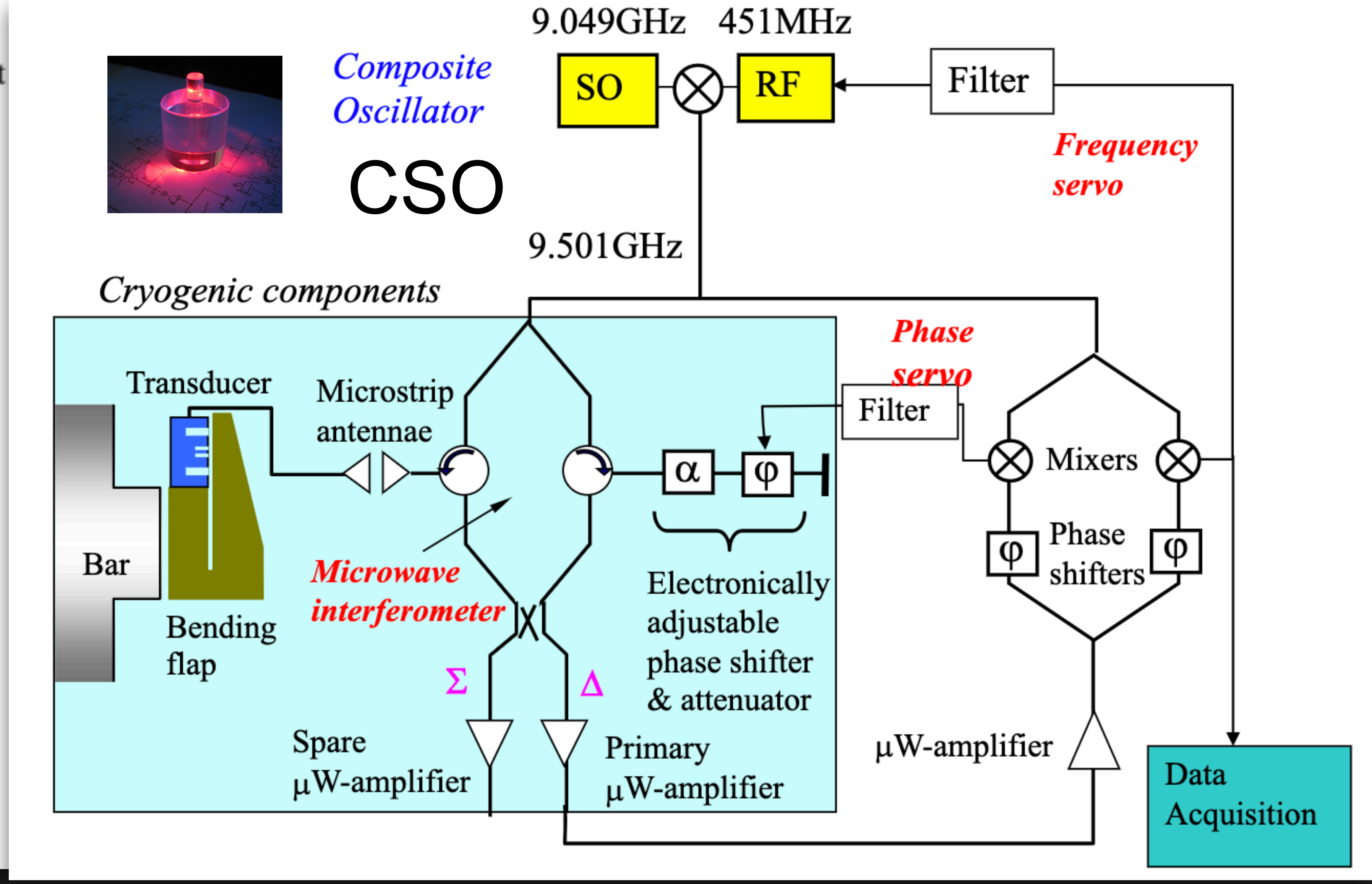
Cryogenic Resonant Bar Gravity Wave Detectors: ultra precise optomechanical displacement measurement: needs low phase noise oscillator



Phys. Rev. Lett 74, 1908 (1995)







My PhD project 1989 ->1993 UWA PhD

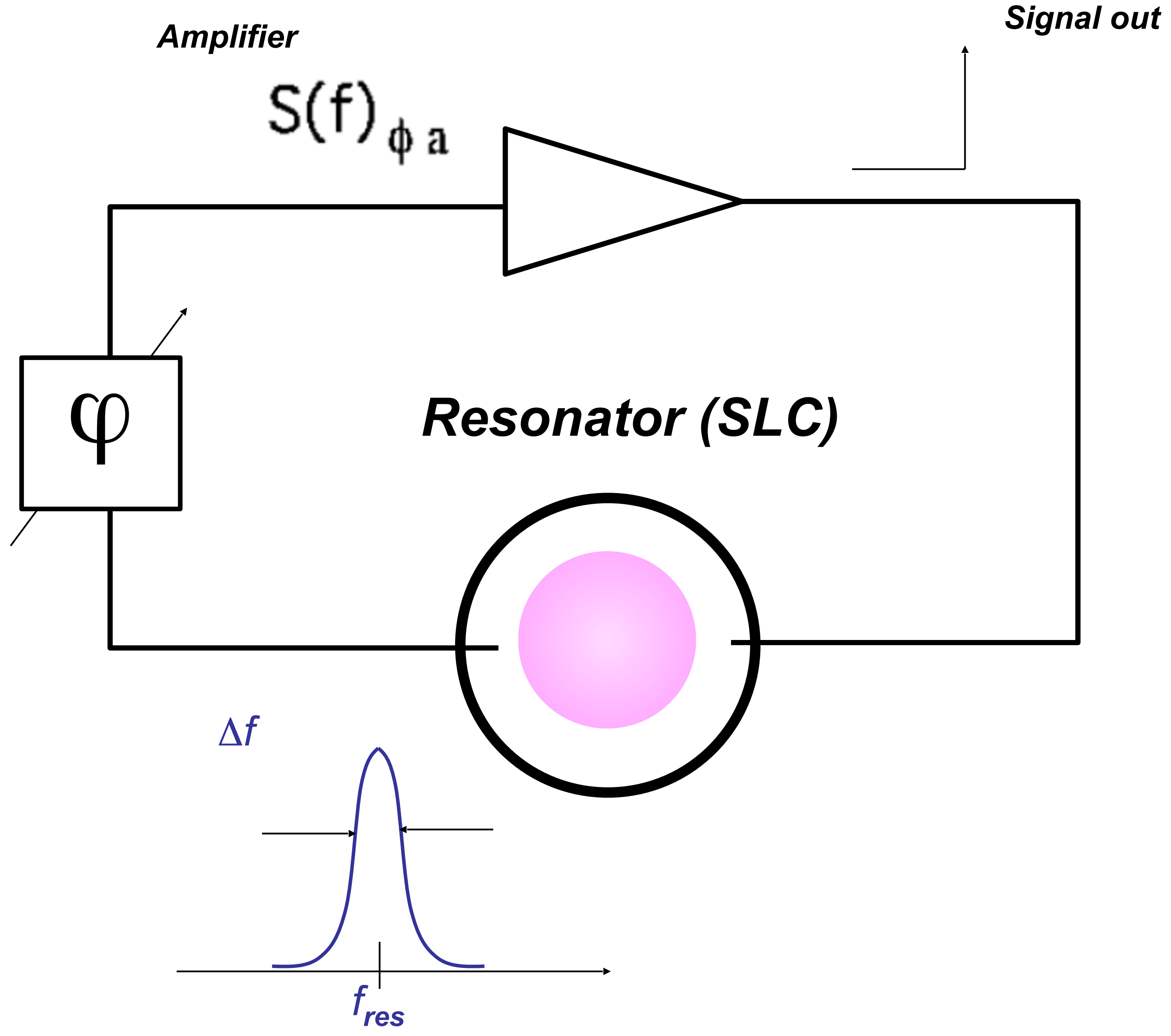
Low Phase Noise Oscillators

Lesson's Model

Noise in oscillator depends on the amplifier phase noise

and Cavity Q-factor = $f_0/\Delta f$

(f is Fourier frequency)



$$S_{\phi c} = S(f)_{\phi a}\left(1 + (\Delta f/2f)^2\right)$$

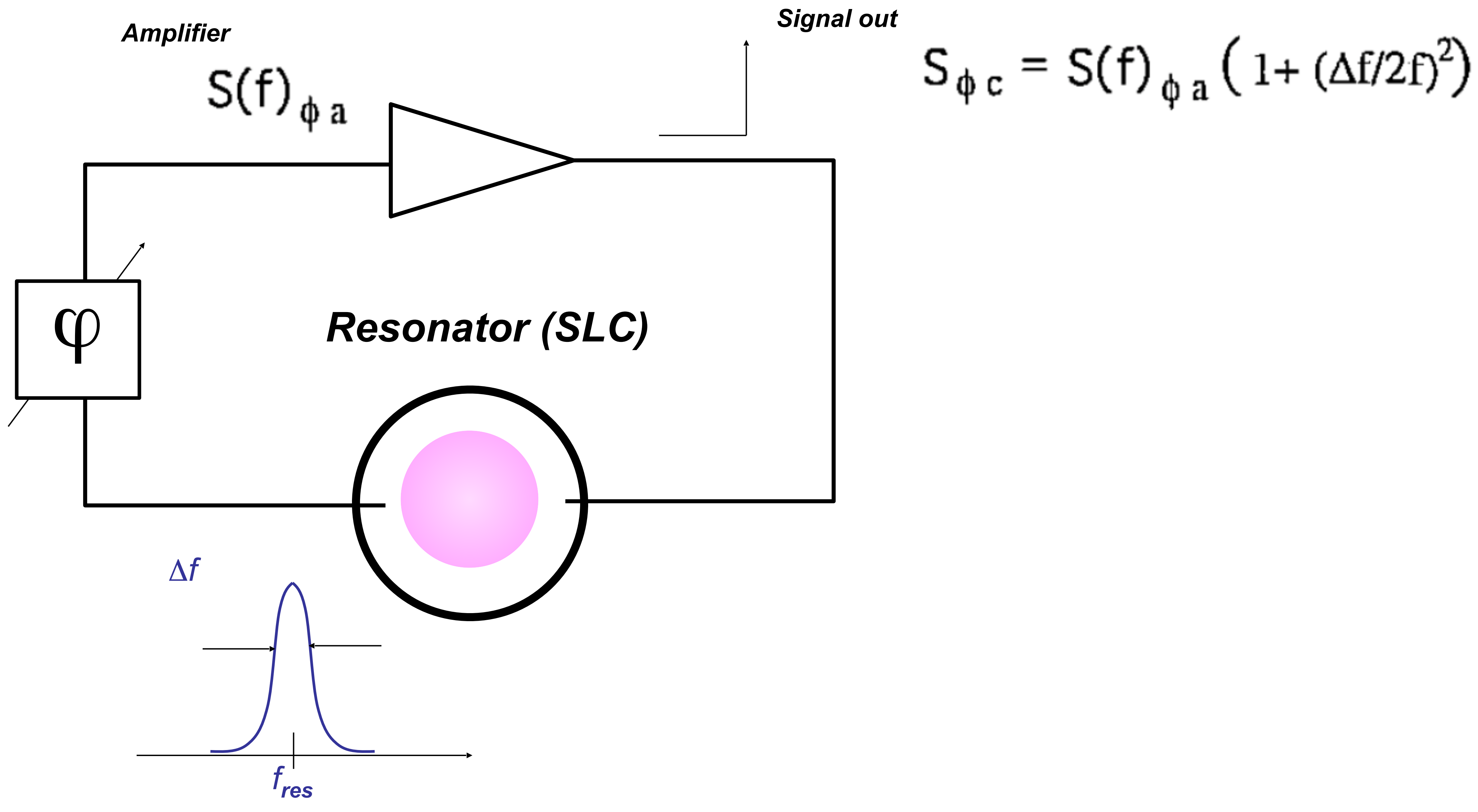
Low Phase Noise Oscillators

Noise in oscillator depends on the amplifier phase noise

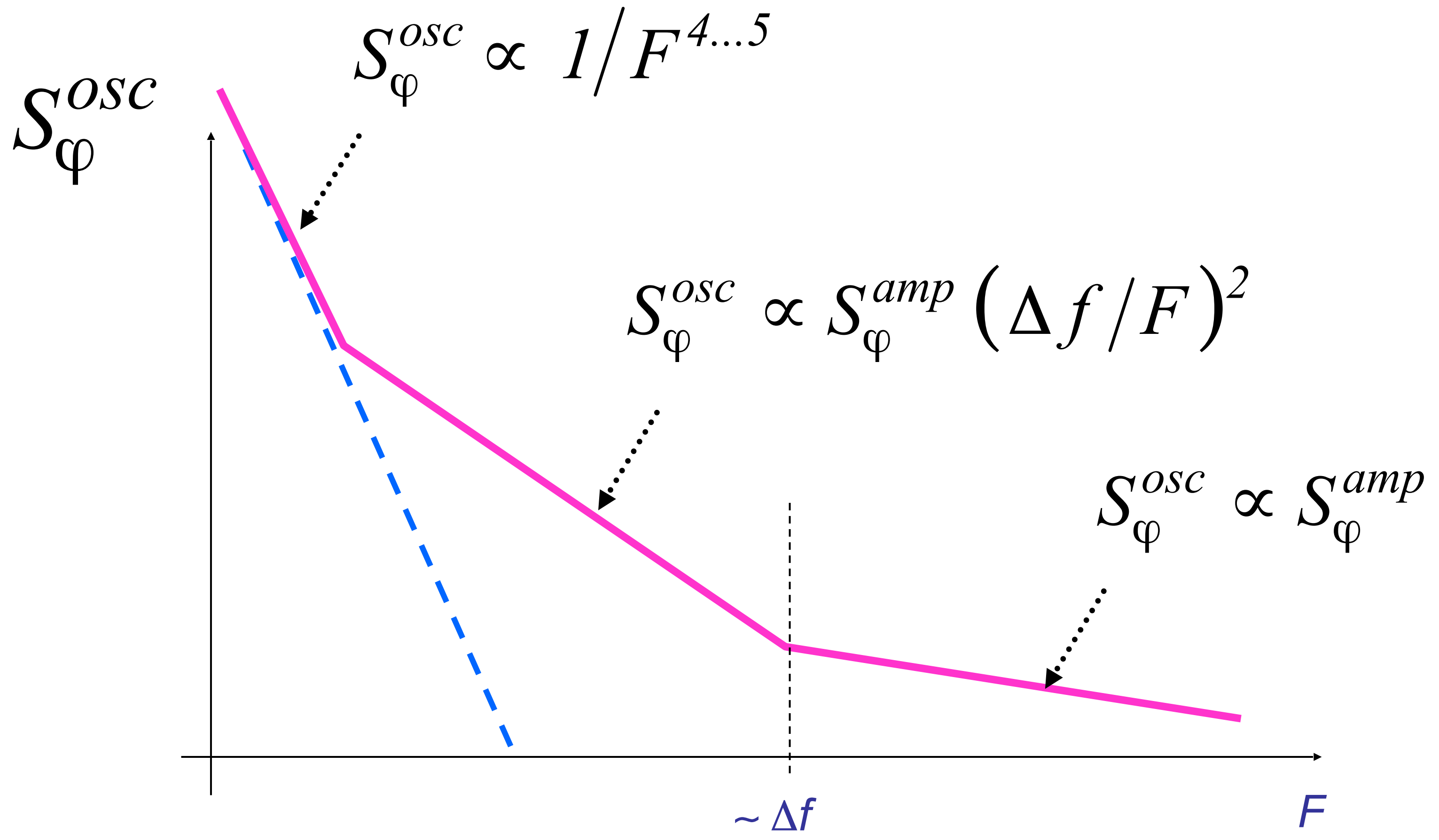
and Cavity Q-factor = $f_0/\Delta f$

(f is Fourier frequency)

Lesson's Model



Oscillator phase noise spectrum



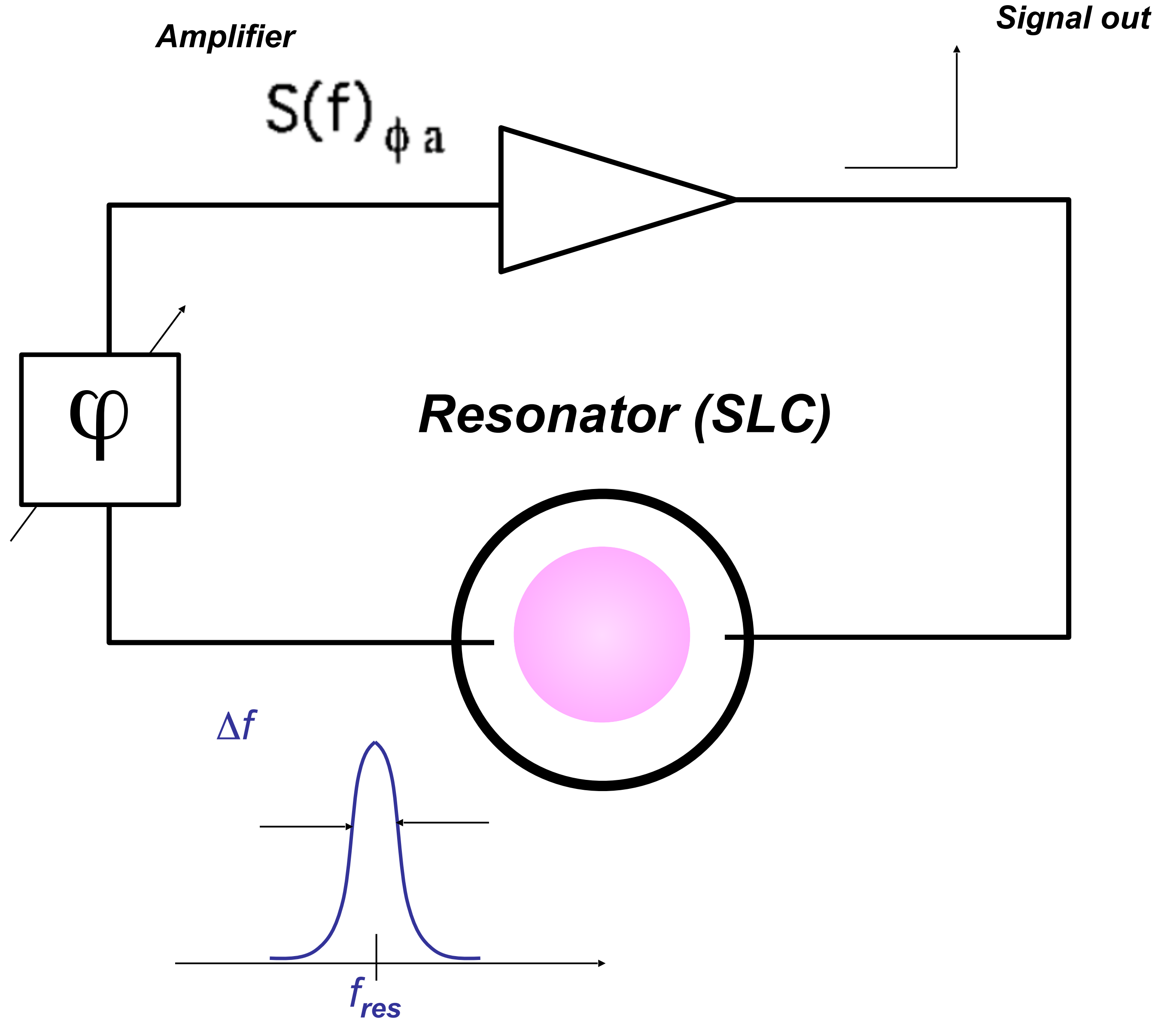
Low Phase Noise Oscillators

Lesson's Model

Noise in oscillator depends on the amplifier phase noise

and Cavity Q-factor = $f_0/\Delta f$

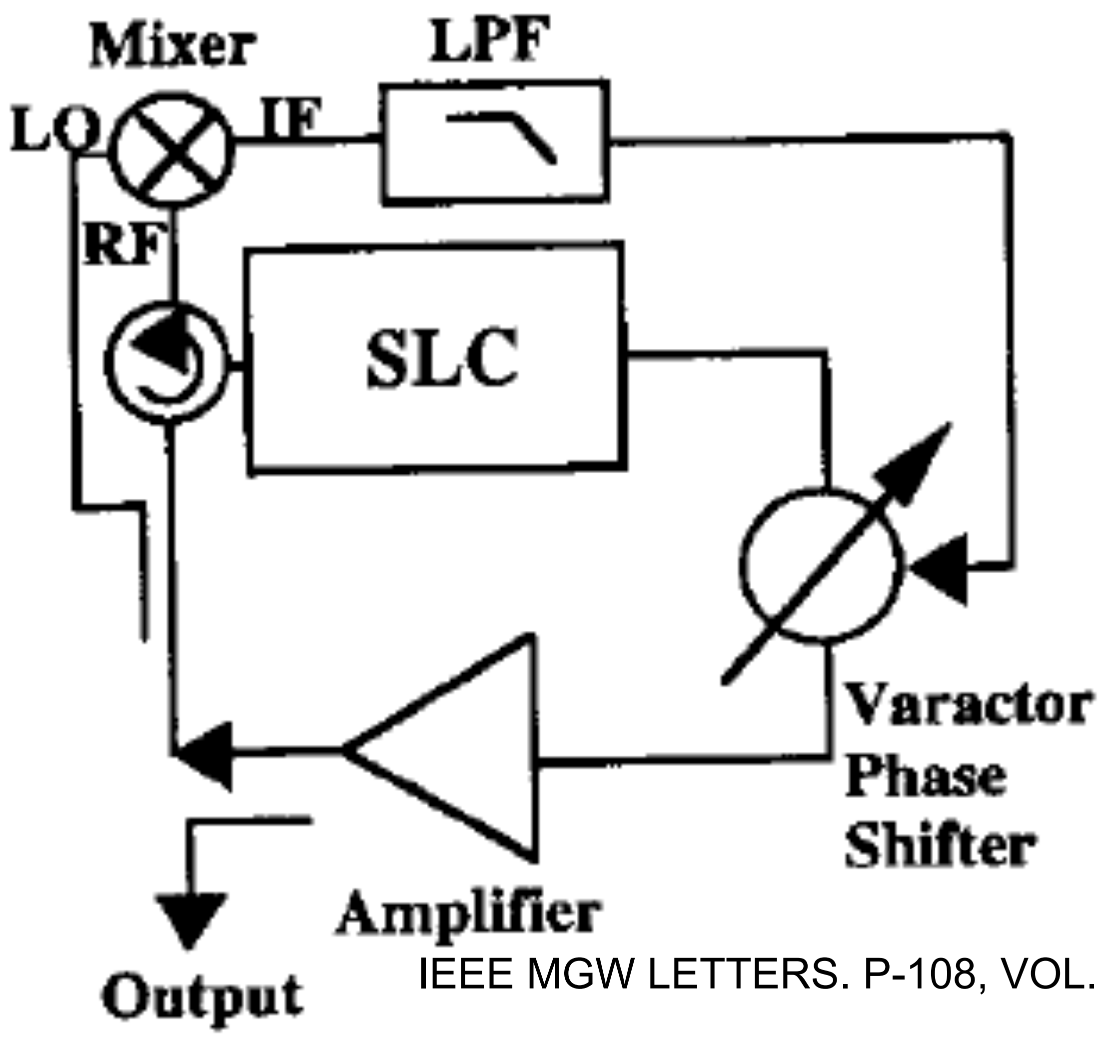
(f is Fourier frequency)



$$S_{\phi c} = S(f)_{\phi a}\left(1 + (\Delta f/2f)^2\right)$$

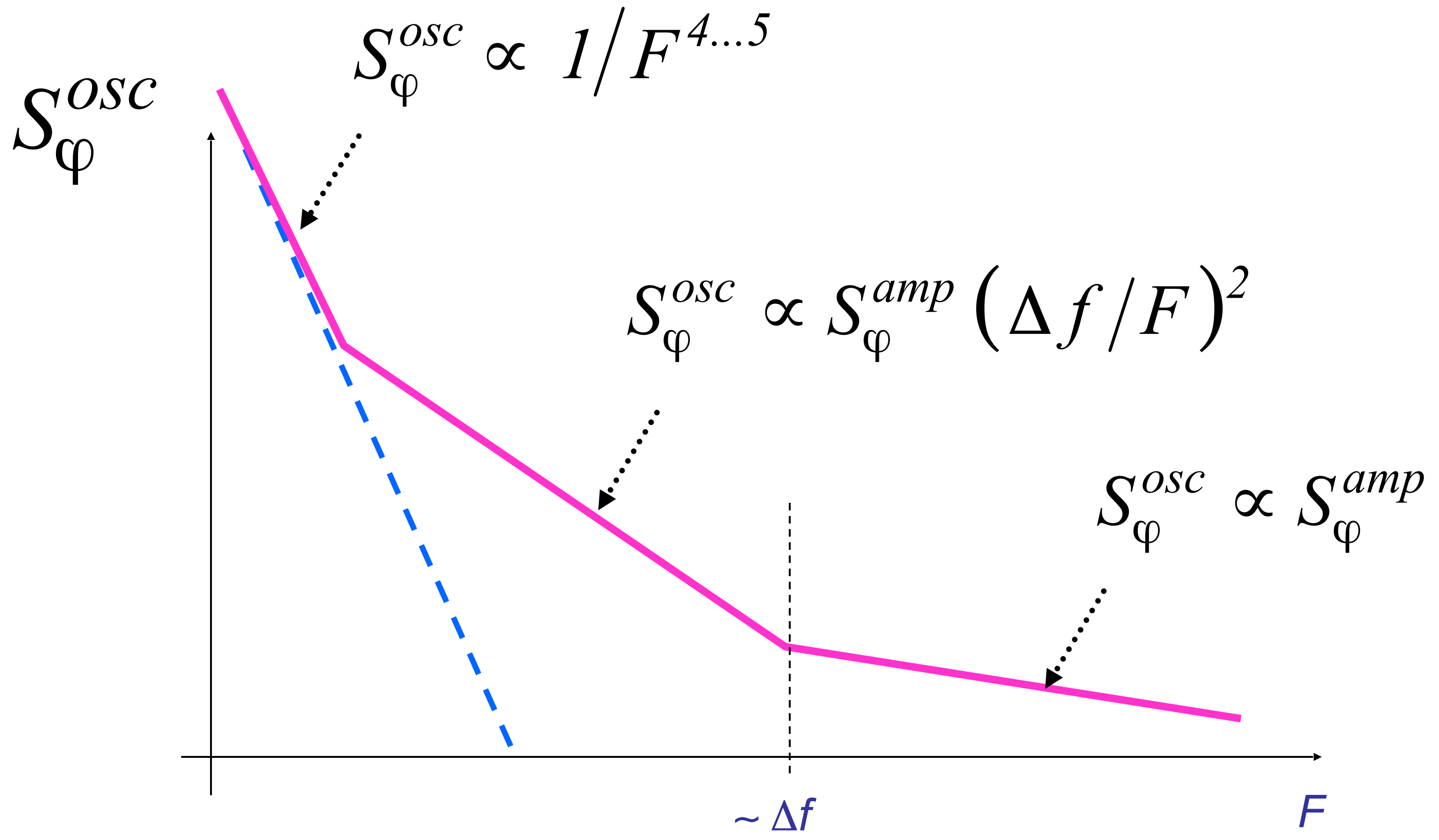
Cancel Noise with Phase Detector

Mixer phase detector



IEEE MGW LETTERS. P-108, VOL. 5. NO. 4, APRIL 1995

Oscillator phase noise spectrum



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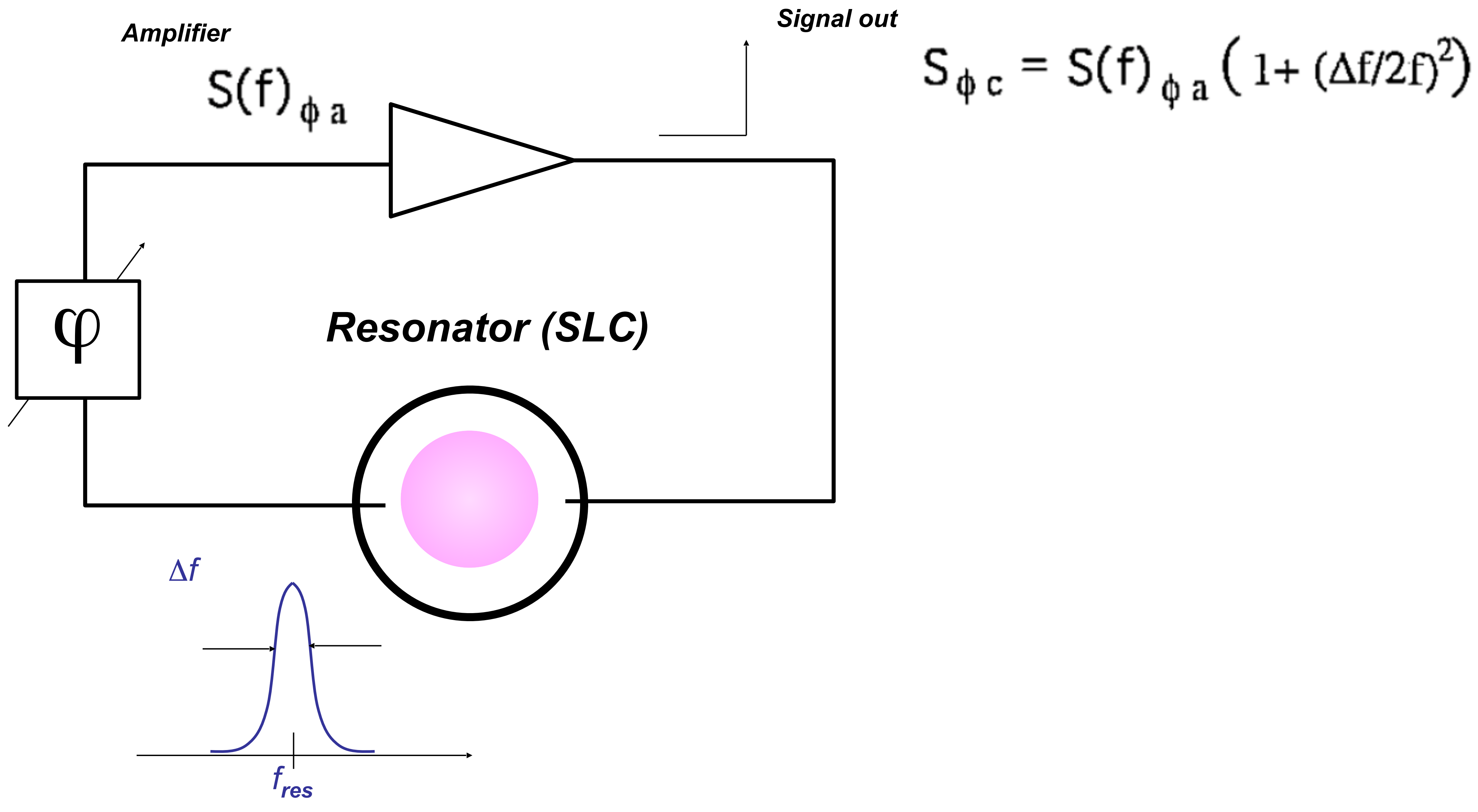

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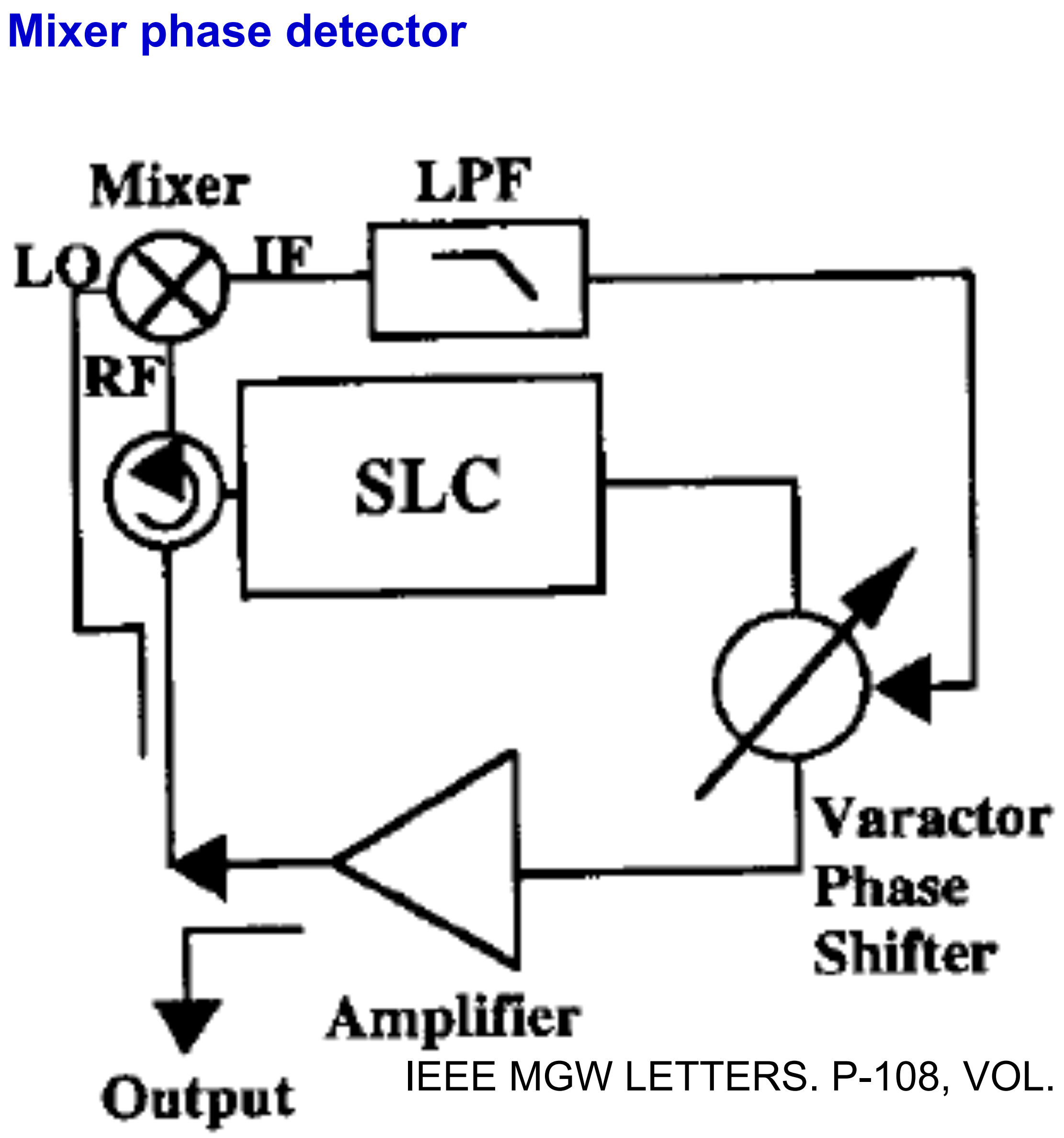

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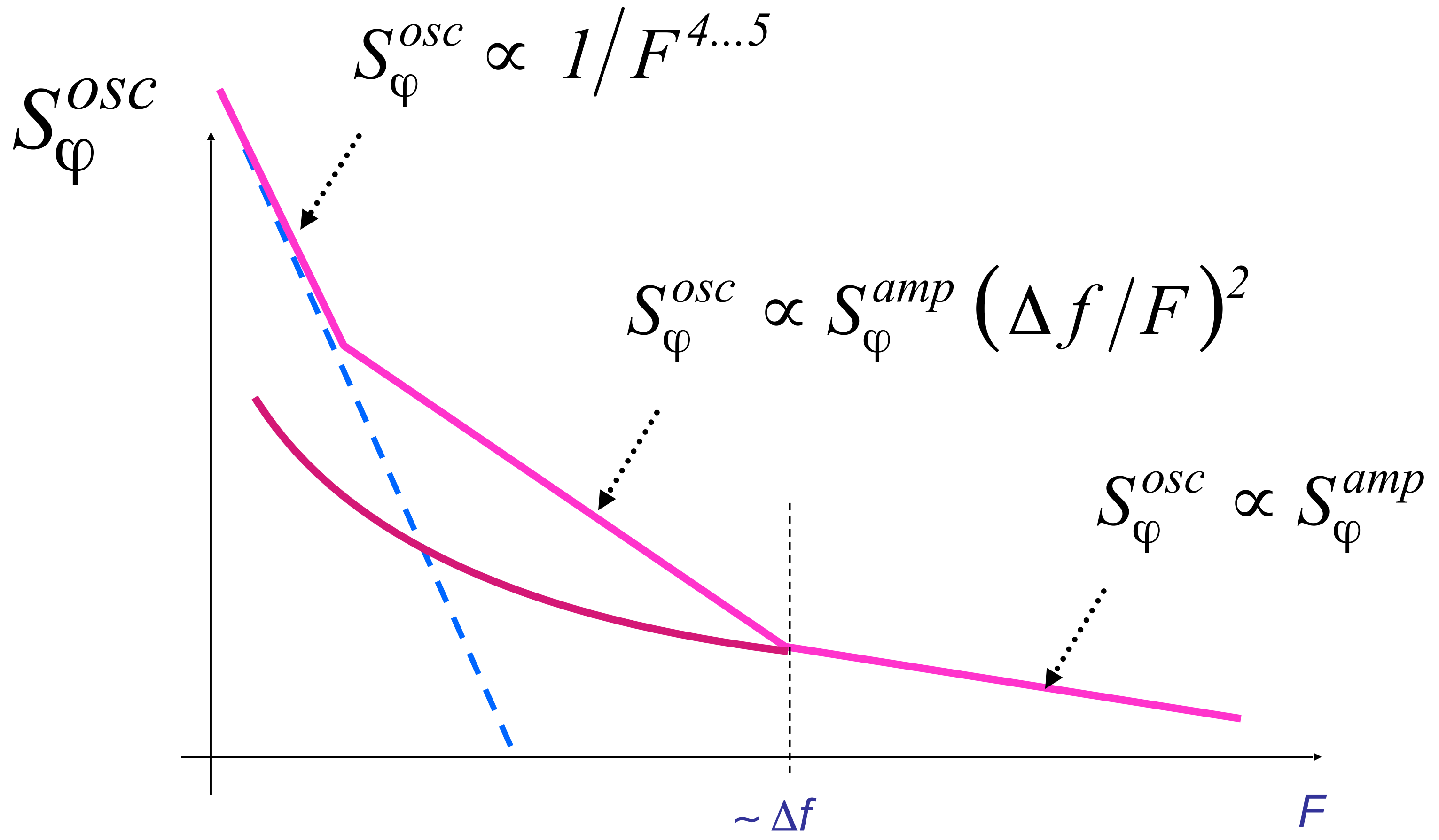


A MAJOR BREAK THROUGH IN MICROWAVE SENSING AND LOW-NOISE OSCILLATORS

CARRIER SUPPRESSION INTERFEROMETER

In 1993 we developed the interferometer as a phase detector, only limited by basic fundamental thermal noise if designed properly

The novel technique is covered by several international patent applications and granted patents
-> UWA licensed technology to PSI Pty. Ltd. delayed publication.

1526 IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 45, NO. 6, NOVEMBER 1998

Microwave Interferometry: Application to Precision Measurements and Noise Reduction Techniques

Eugene N. Ivanov, M. E. Tobar, *Member, IEEE*, and R. A. Woode

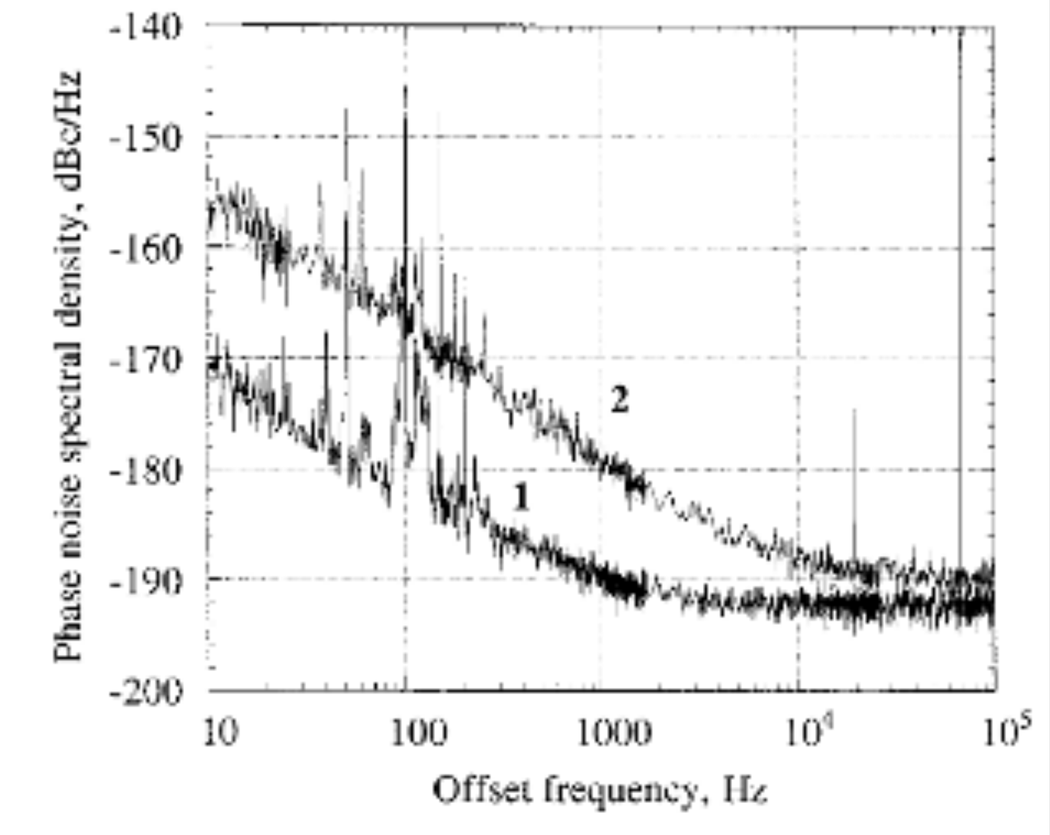


Fig. 2. The phase noise floor of interferometric noise measurement system (curve 1), phase noise of 6 microwave isolators connected in series (curve 2). Input power is 20 dBm, carrier frequency 9 GHz.

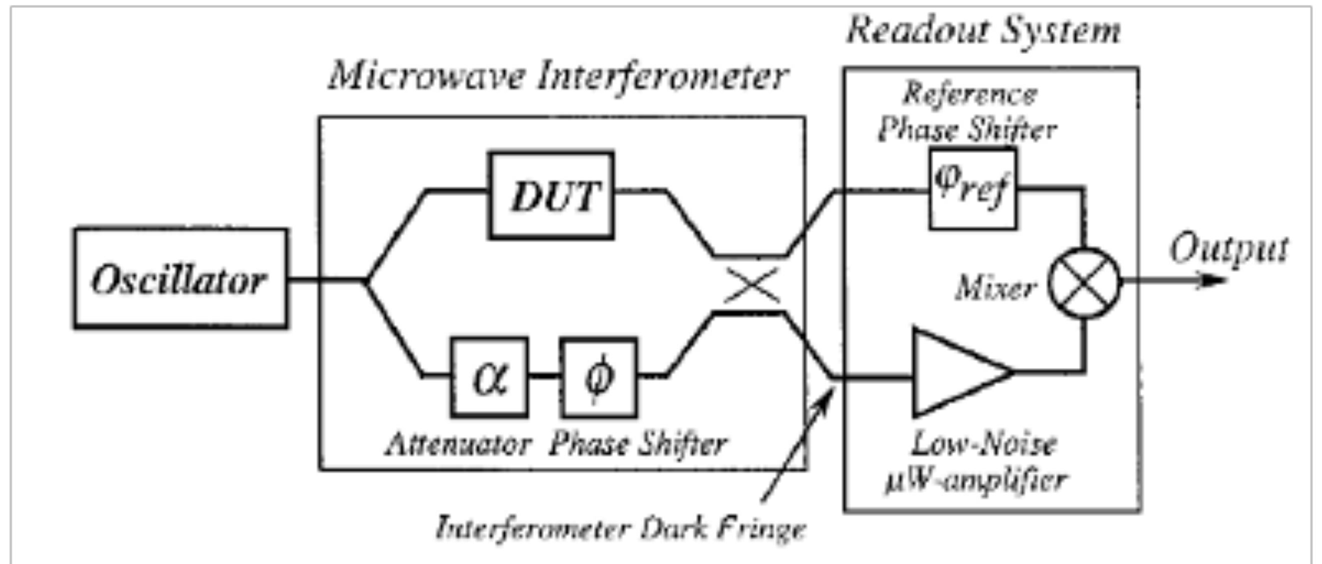


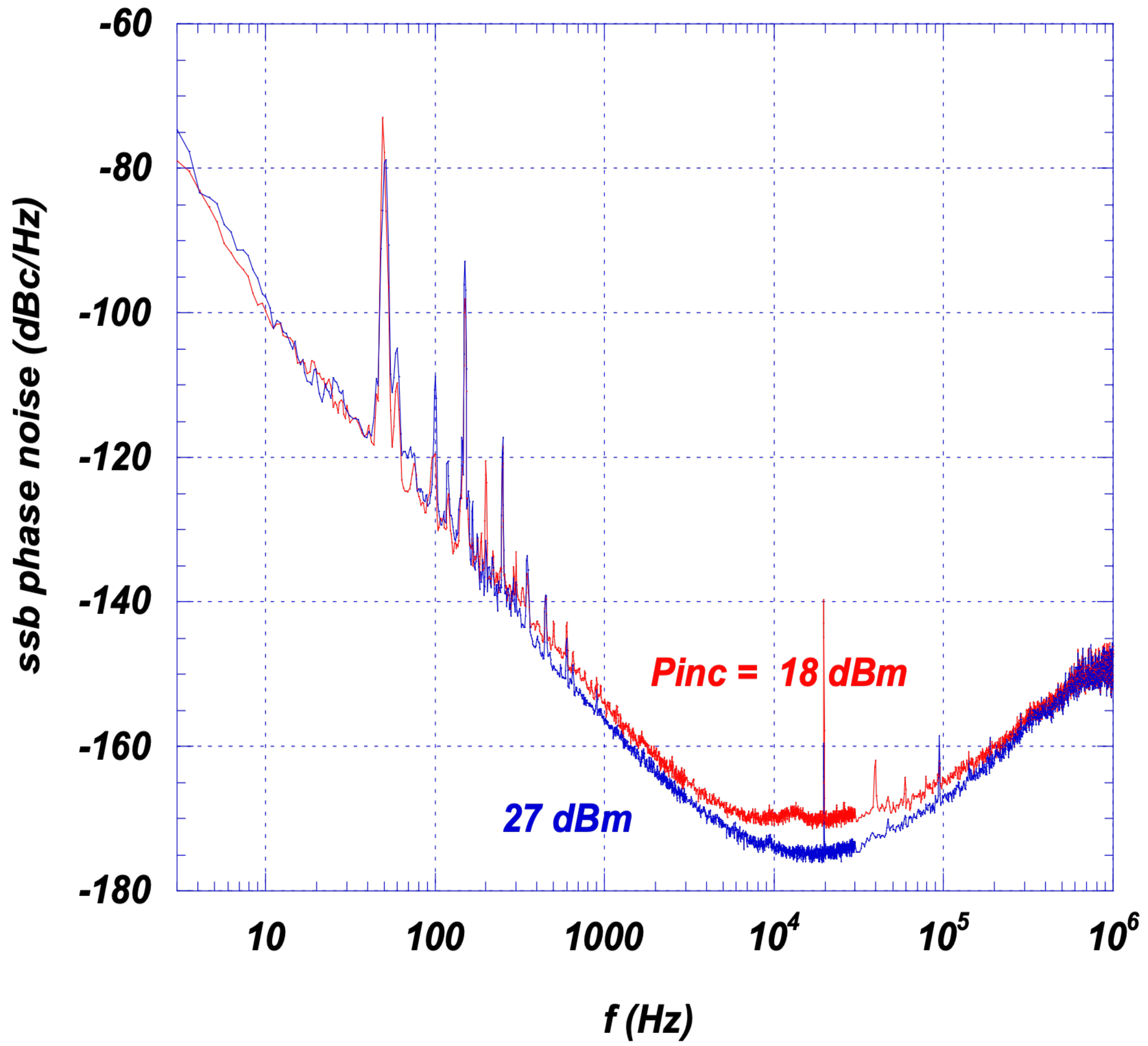
Fig. 1. Interferometric noise measurement system.

$$\mathcal{L}_{\varphi}^{n/f(1)}(f) = \mathcal{L}_{\text{AM}}^{n/f(1)}(f) = \frac{k_B T_{\text{RS}}}{P_{\text{inp}} L_{\text{DUT}}}, \quad (1)$$

IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 56, NO. 2, FEBRUARY 2009 263

Low Phase-Noise Sapphire Crystal Microwave Oscillators: Current Status

Eugene N. Ivanov and Michael E. Tobar, *Senior Member, IEEE*

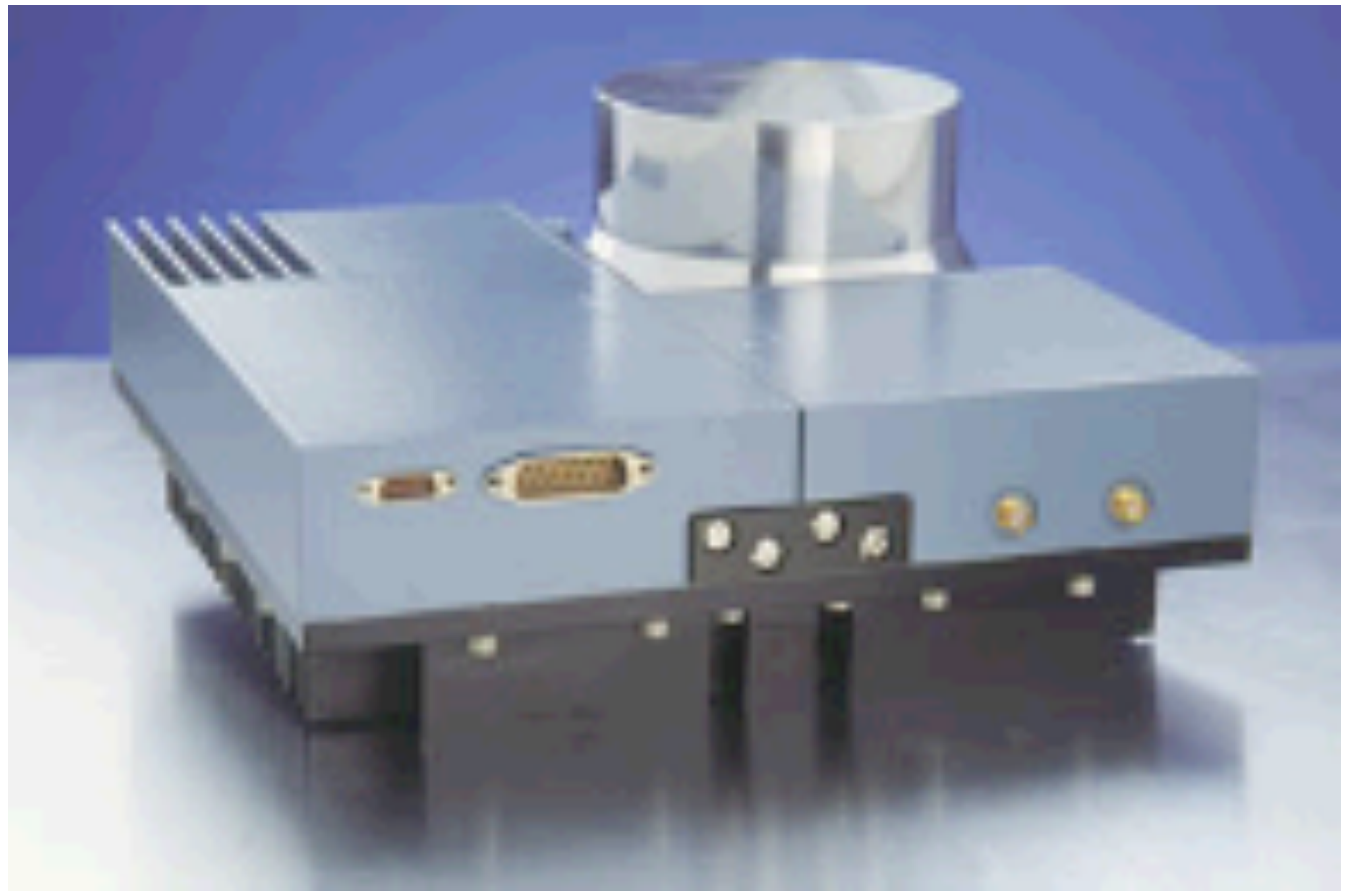


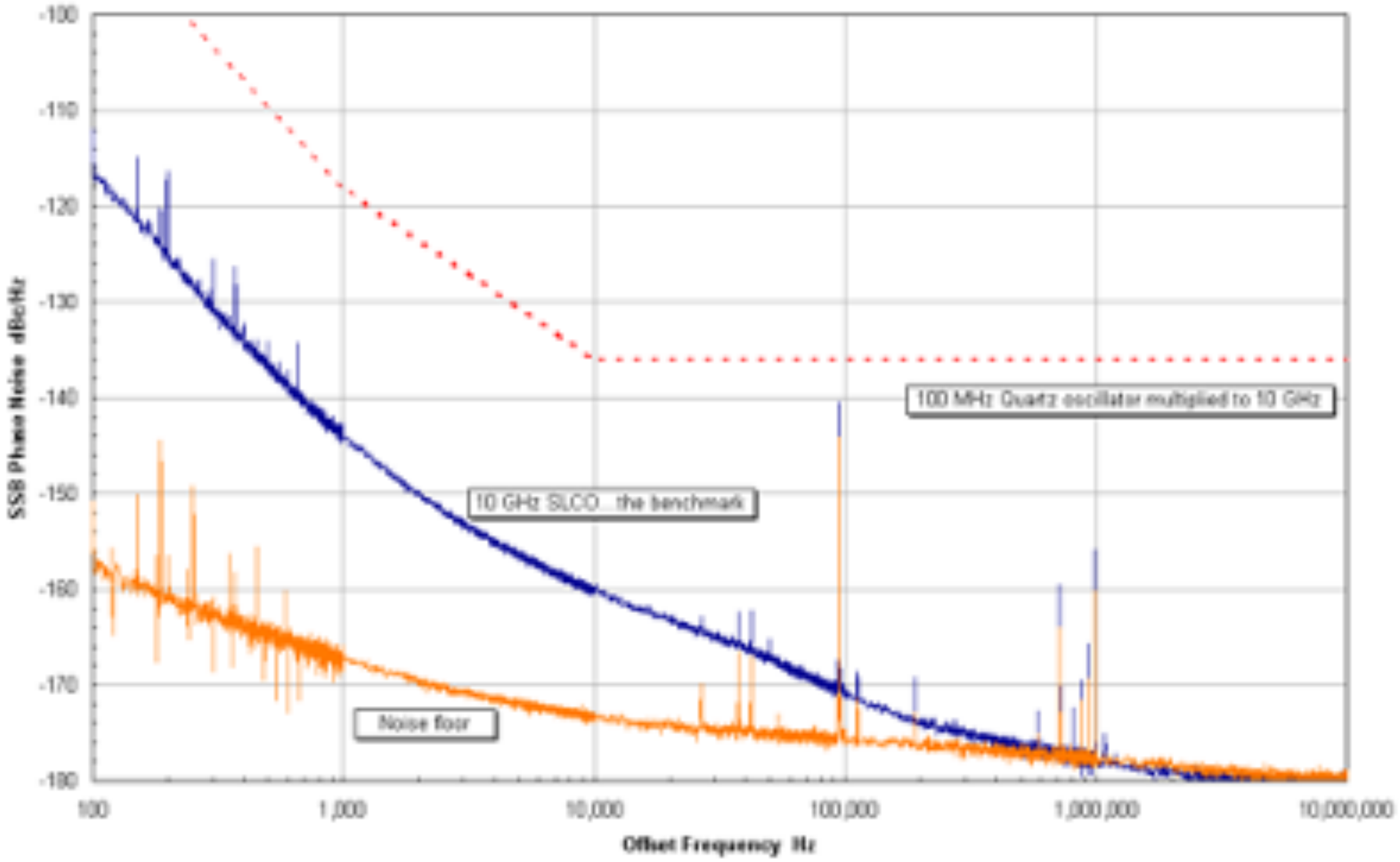
IEEE TRANSACTIONS ON MTT, VOL. 54, NO. 8, P 3284, AUGUST 2006

ROOM TEMPERATURE LOW NOISE SAPPHIRE OSCILLATORS: CAN BE MADE COMPACT OR RACK MOUNT

PSI
PoseidonScientificInstruments

Lowest phase and amplitude noise
Exceptional spectral purity
Low spurious content
Low vibrational sensitivity
Unequalled short-term stability.





SAPPHIRE LOADED CAVITYOSCILLATORS

Compact low noise oscillator: Defence Radar Applications

Microwave Stripline Components: Compact Design

History of Commercialization

- 10 UWA Patents to do with low noise oscillators

Raytheon
Australia

Raytheon Australia Acquires Poseidon Scientific Instruments

Raytheon Australia has acquired Poseidon Scientific Instruments in order to enhance Raytheon's suite of world leading technology and defence capabilities. Poseidon Scientific Instruments brings to Raytheon a depth of technical expertise in ultra low phase noise signal generation and measurement. Terms of the transaction are not being disclosed.

Products include:

- The SBO Class of Ultra Low Phase Noise Oscillators
  - SBO-XPL Compact Sapphire Oscillator
  - SBO-HS Compact and High-Speed Sapphire Oscillator
  - SBO Accessories
- The SKO Class of Sapphire Loaded Oscillator
- The SLCO Class of Sapphire Loaded Cavity Oscillator
  - Sapphire Loaded Cavity Oscillator (SLCO-BCS)
  - Sapphire Loaded Cavity Oscillator (SLCO NCS)
- Low Noise Dielectric Resonator Oscillators (DRO)
- Low Noise Divider Ensemble
- Low Noise Regenerative Divider
- DENA-5A Rack Mount Divider
- Oscillator Accessories
- Phase Noise Analysers and Receiver Modules
  - ODIN-320AS Phase Noise Analyser
  - OR-101A – 6GHz to 12GHz Receiver Module
  - OR-102A – 5MHz to 1GHz Receiver Module
  - OR-105A – 1GHz to 18GHz Receiver Module
  - OD-103B – Delay Line
  - OC-104A – Calibration Modules

For more information, please contact: PSIProgram@raytheon.com.au

Corporate Communications
Raytheon Australia
4 Brindabella Circuit
Brindabella Business Park
Canberra Airport ACT 2609
Contact Us

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- Resurgence ->Now low noise oscillators necessary to drive quantum qubits to work at Quantum Limit

Raytheon Australia: PSI Program http://www.raytheon.com.au/businesses/integrated_solutions/cap...

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QUANTX LABS

X-LNO

Ultra-Low-Noise Microwave Oscillator

The X-LNO is a microwave reference oscillator that produces world-leading ultra-low phase noise reference signal in the X-band region. By exploiting the remarkably high Q of sapphire, the oscillator delivers a +10 dBm signal with phase noise below -165 dBc/Hz at 10 kHz offset.

The X-LNO has a standard 3U package that is suited to rack-mounting although other OEM configurations are available on request. A key application for the X-LNO is the master oscillator in microwave communications and radar systems, including Precision Approach Radars and surface detection radars. The ultra-low phase noise of the X-LNO will enable significantly greater sensitivity in these radar systems when compared to quartz-based systems

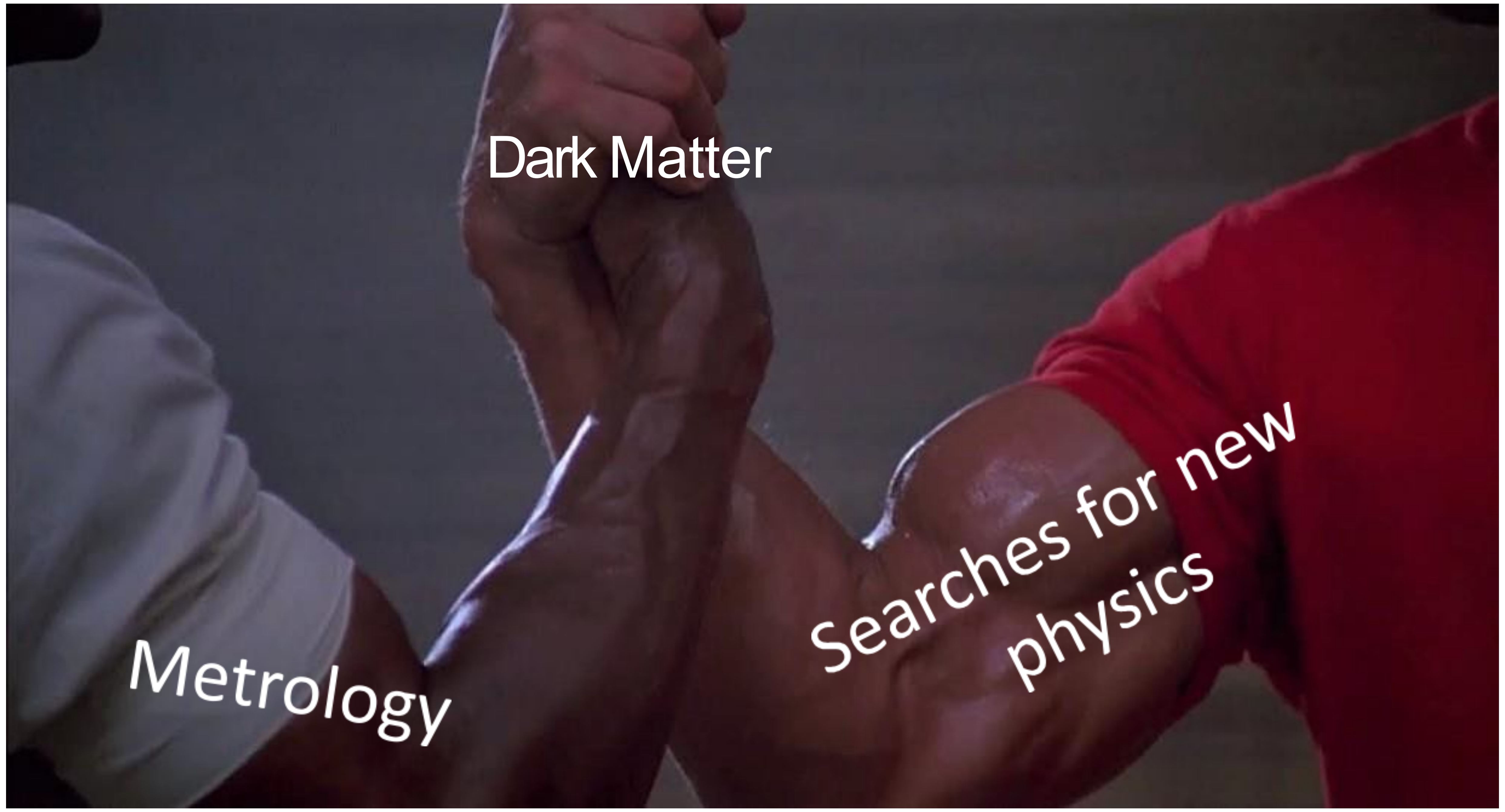
This product can be configured to provide any frequency outputs between 8 to 12 GHz and wider ranges are possible on request.

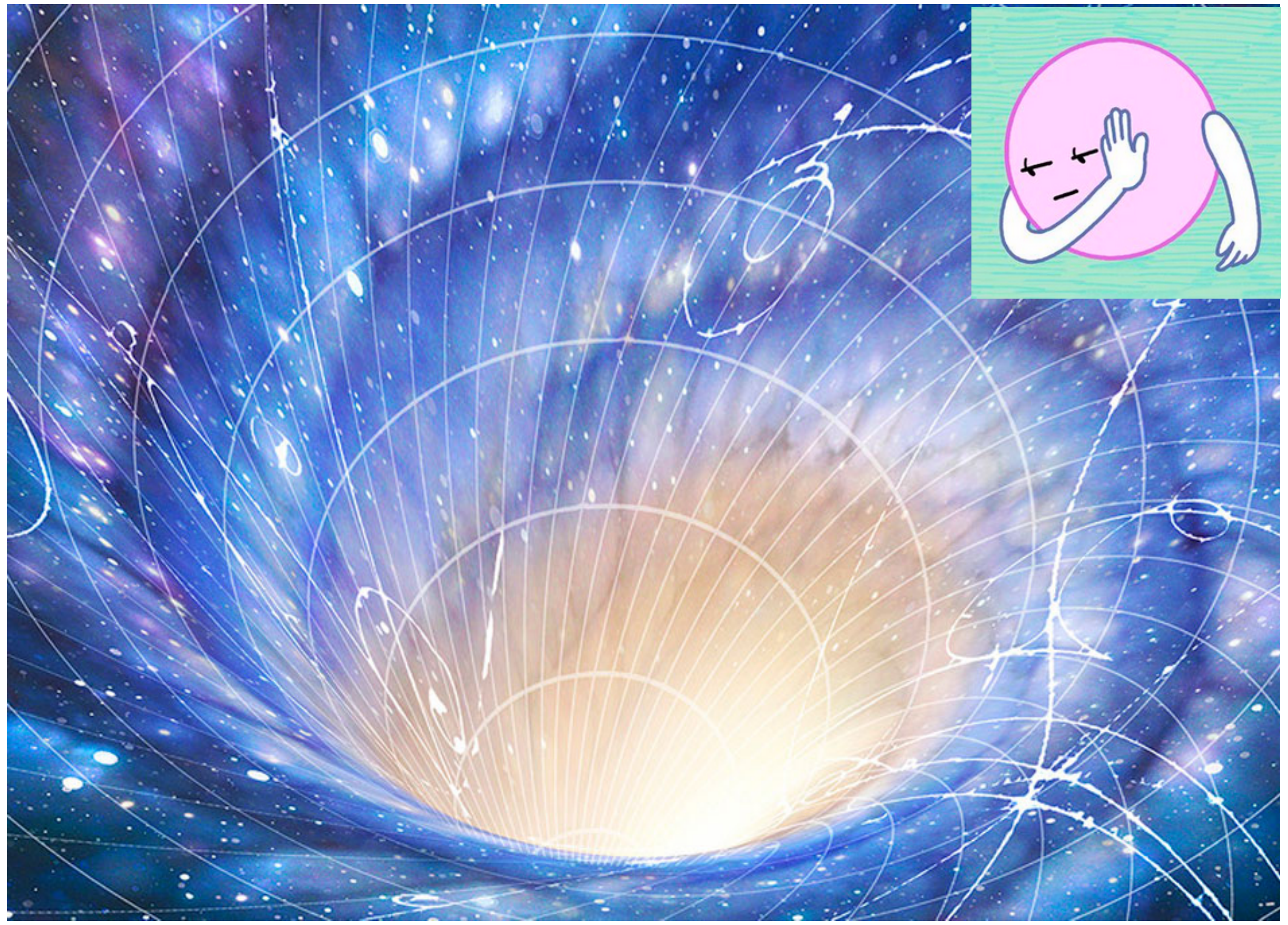
KEY APPLICATIONS:

- Civilian and military radar
- Wind/gust monitoring near civilian airports
- Detection and tracking of fast-moving objects at a distance

Precision Metrology

Science of precise measurement → Physics at low energies



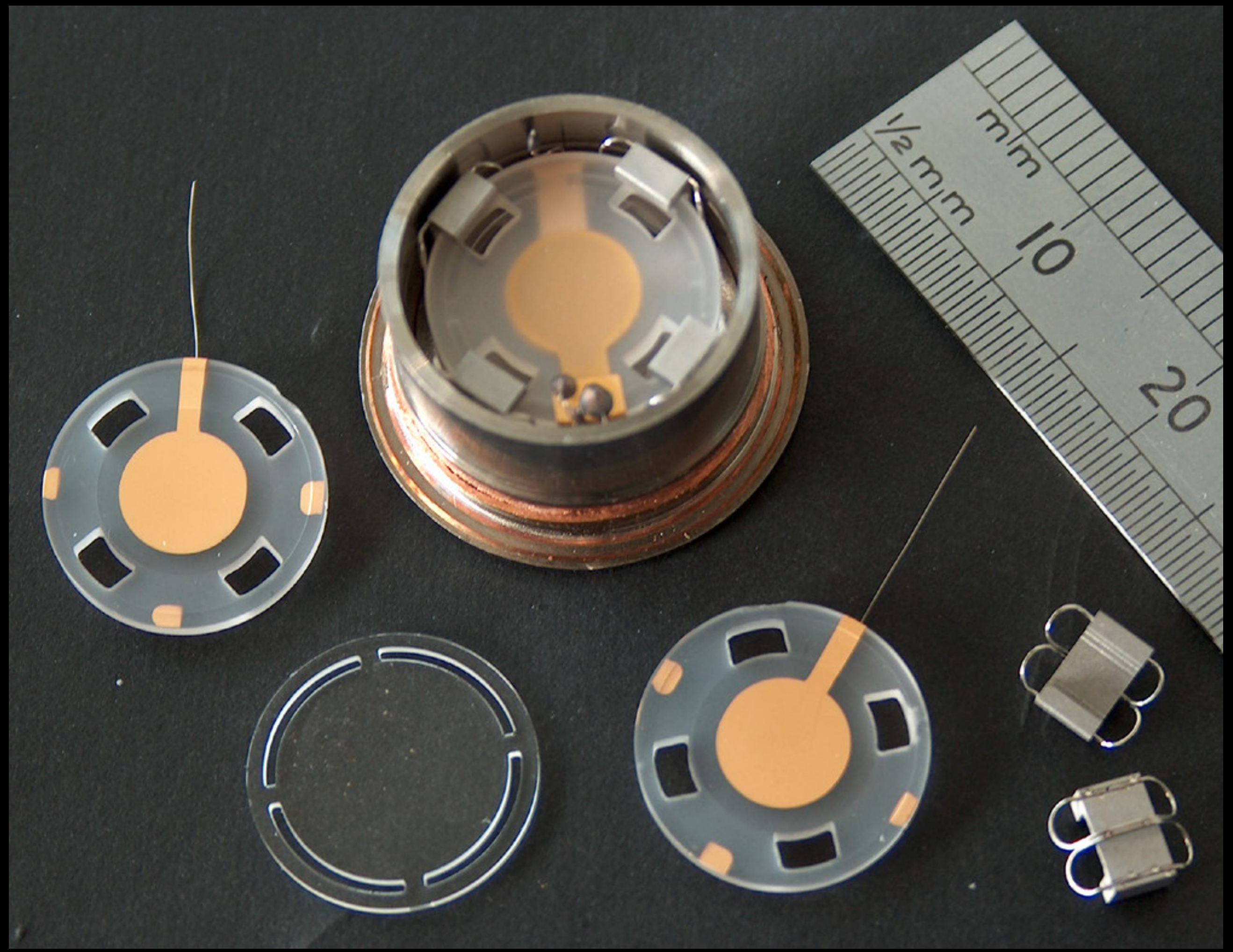


Metrology helps us search for physics beyond the standard model

Lorentz violation, fundamental constant variation, tests of general relativity & gravitation, violations of quantum statistics + more

Bulk Acoustic Wave High-Frequency GW Detectors (A Resonant-Mass Detector)

Prof. Michael Tobar

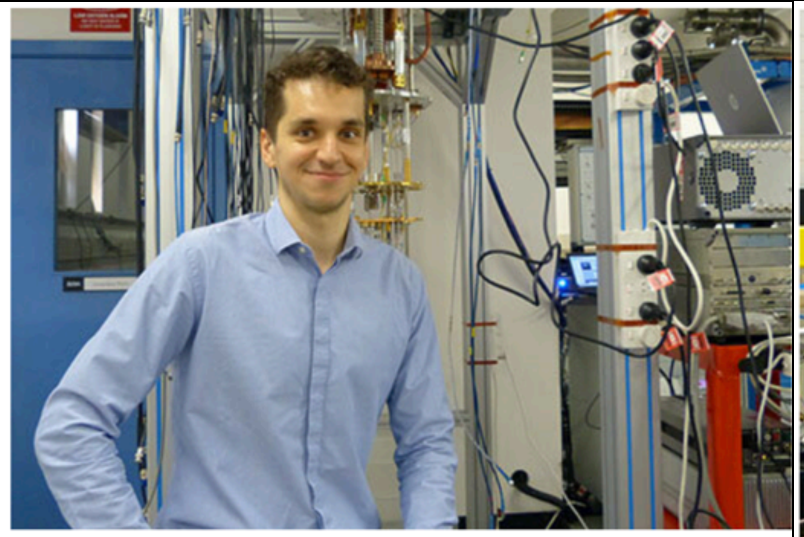



Will Campbell

PhD Student

QDM
Quantum Technologies and Dark Matter Research Lab


Professor Mike Tobar


Dr Maxim Goryachev


Professor Eugene Ivanov

UWA Staff


Ik Siong Heng
Prof. Glasgow

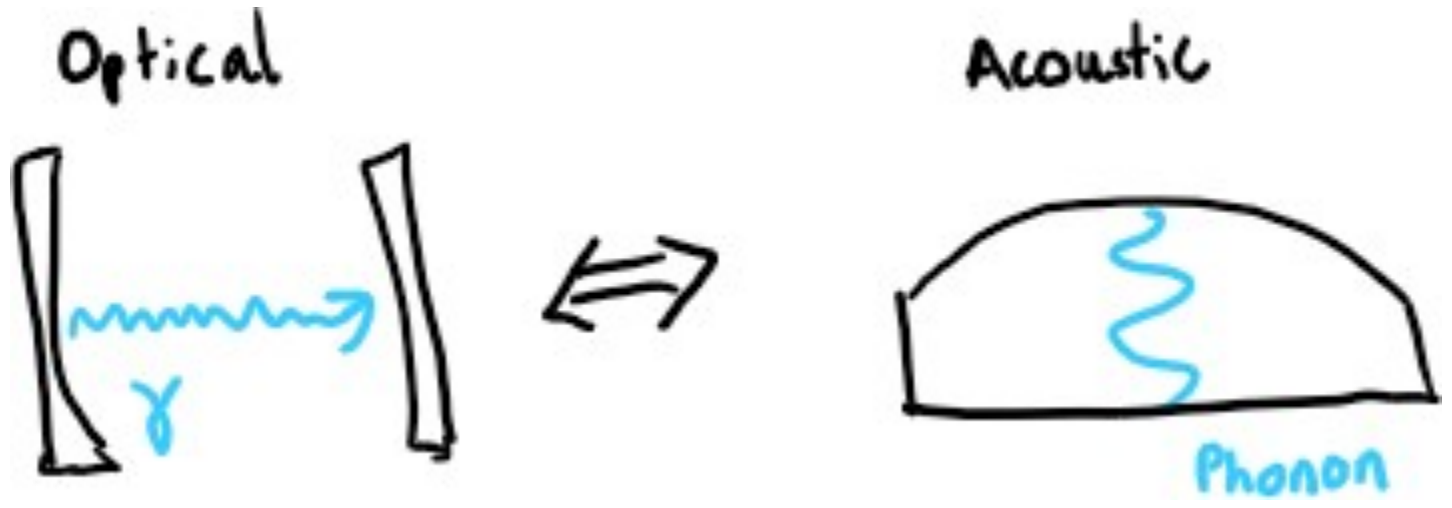

Serge Galliou
Prof. Franche-Comté

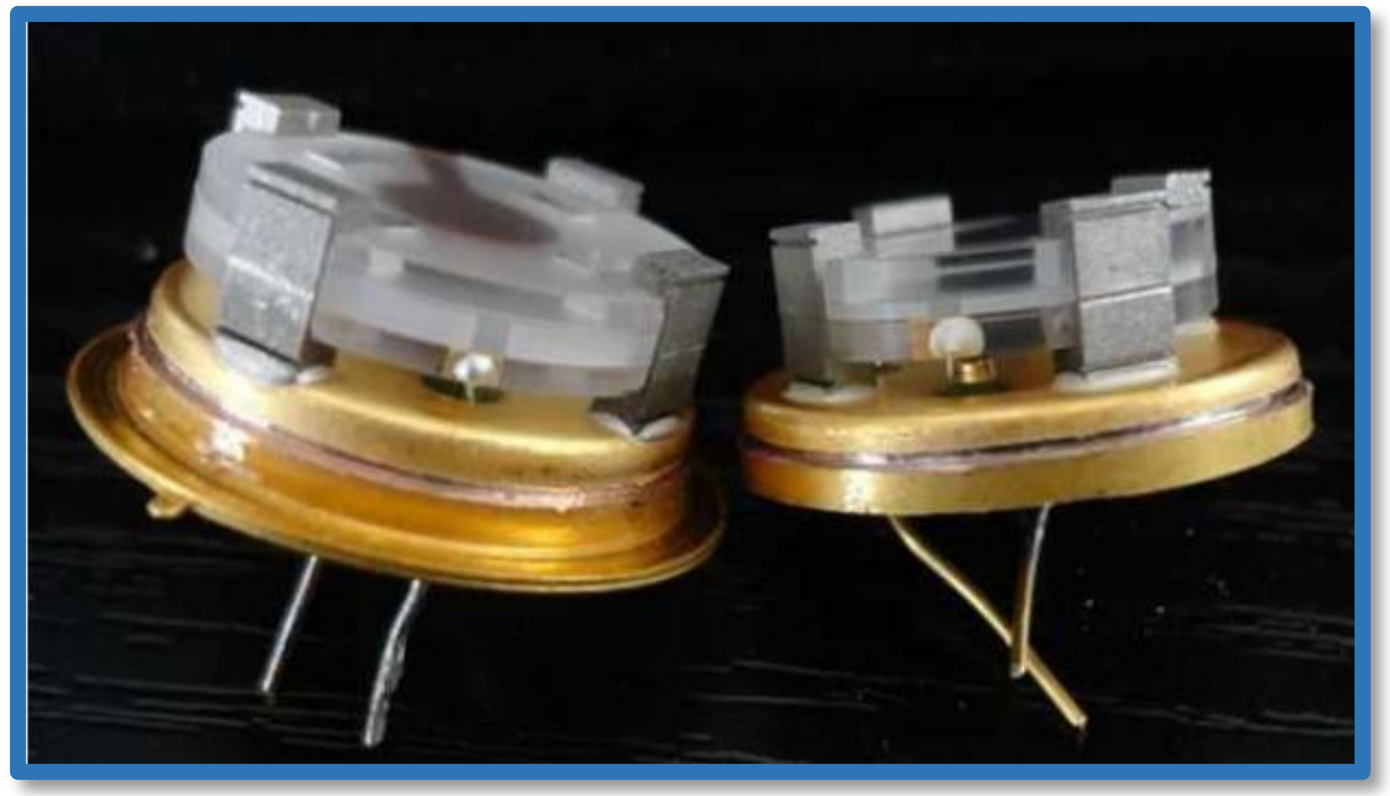
Australian Government
Australian Research Council

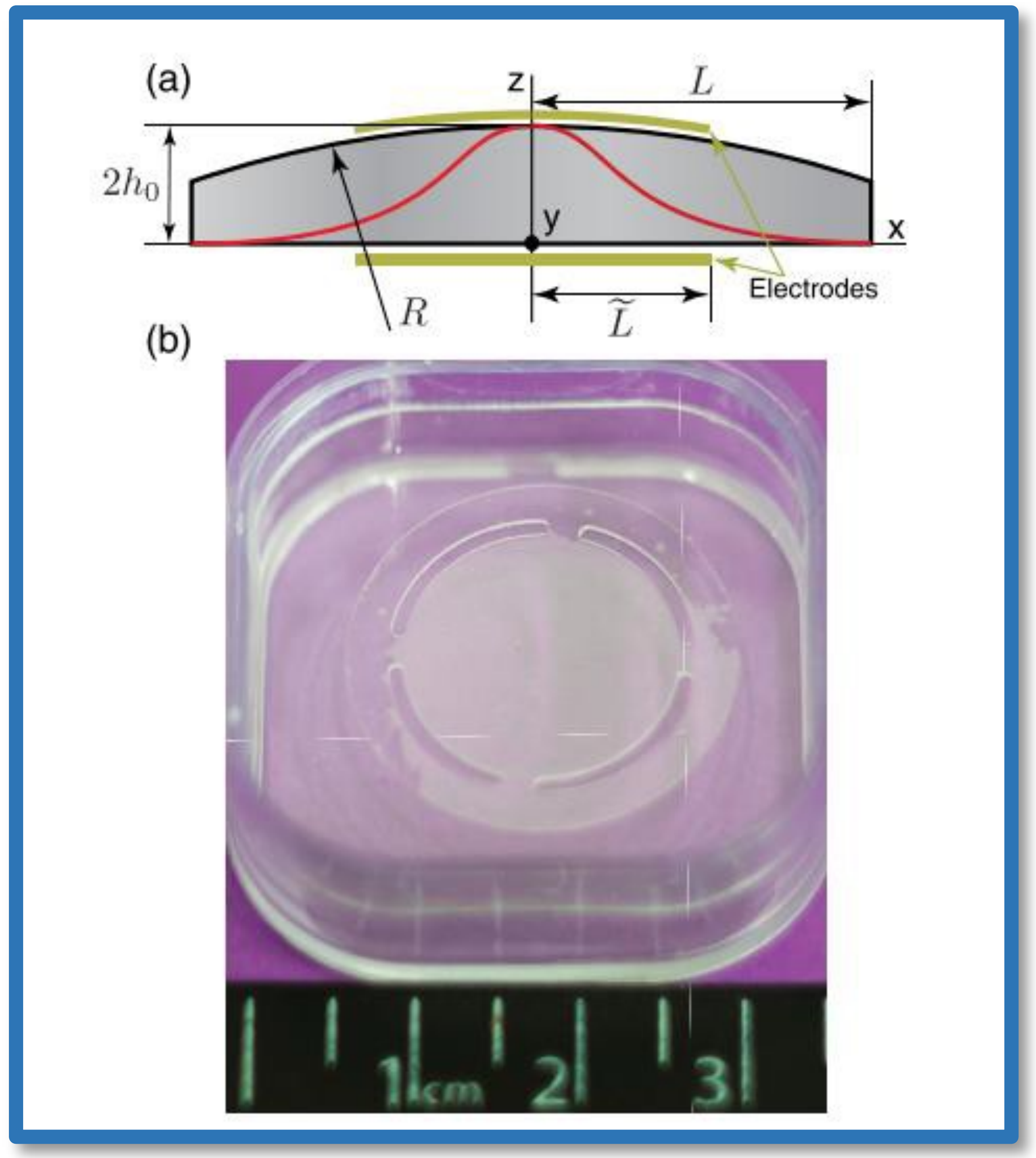
THE UNIVERSITY OF WESTERN AUSTRALIA
SEEK WISDOM

Quartz Bulk Acoustic Wave Resonators

- Acoustic analogue to a Optical Fabry-Perot cavity.

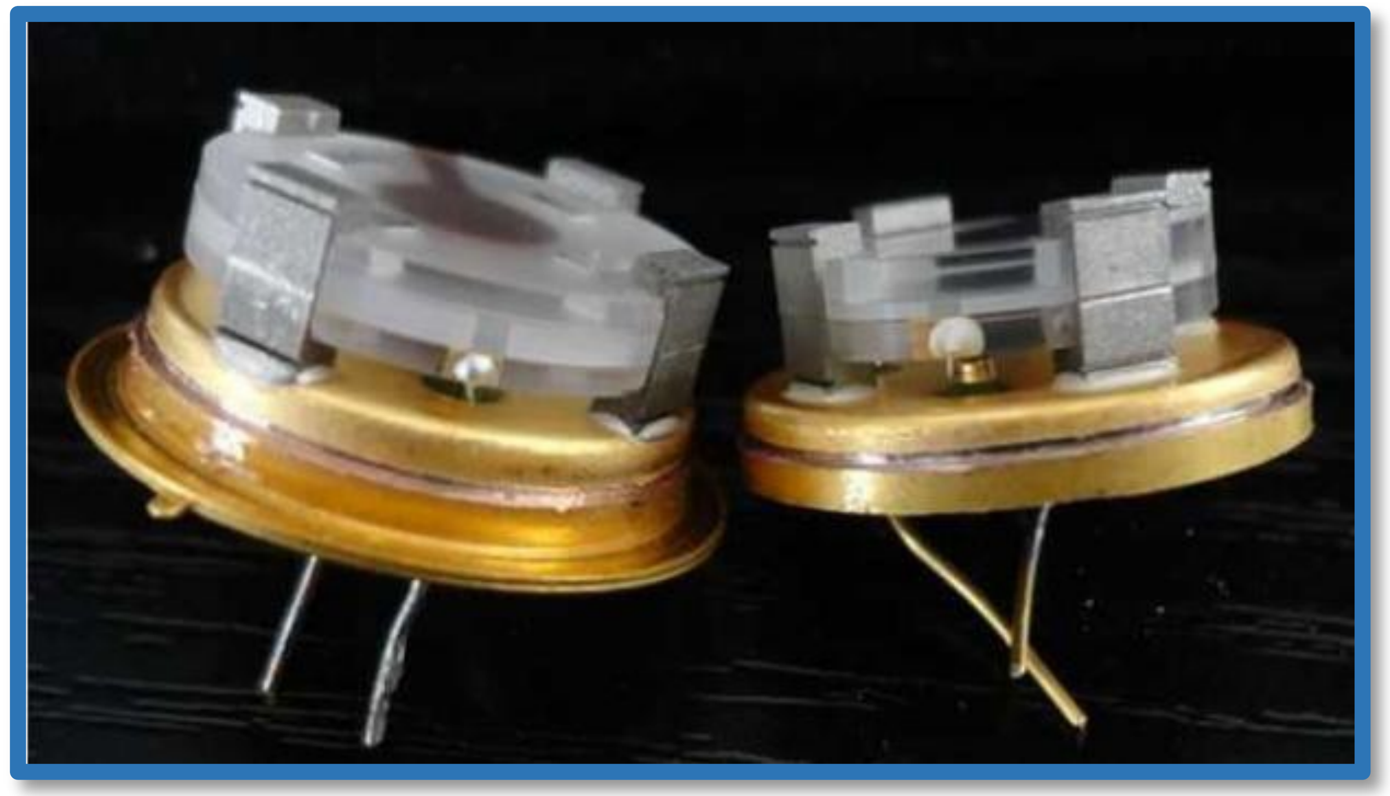


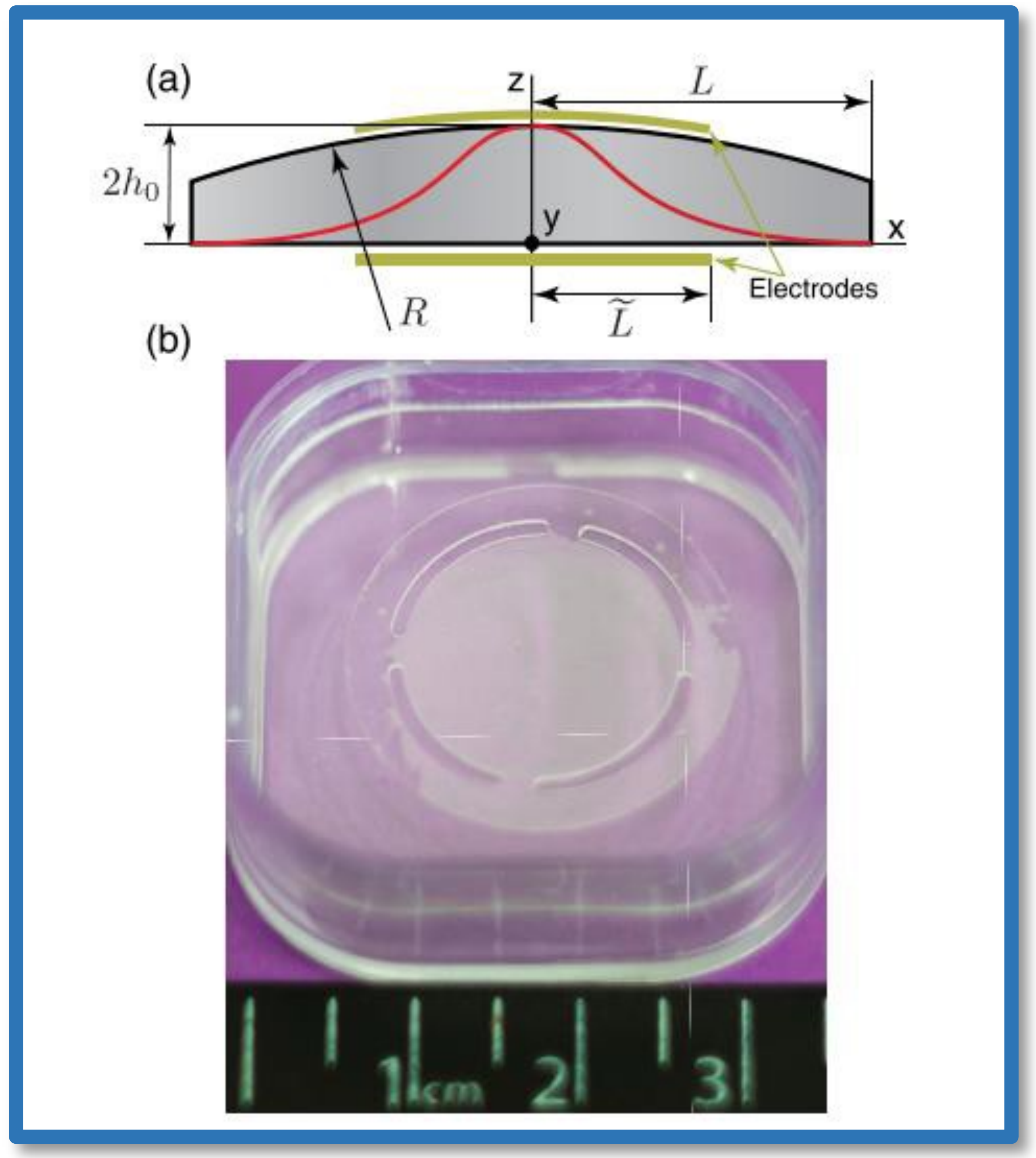




Quartz Bulk Acoustic Wave Resonators

- Acoustic analogue to a Optical Fabry-Perot cavity.
- Already a well established technology
- Gram scale mode mass, macroscopic resonator





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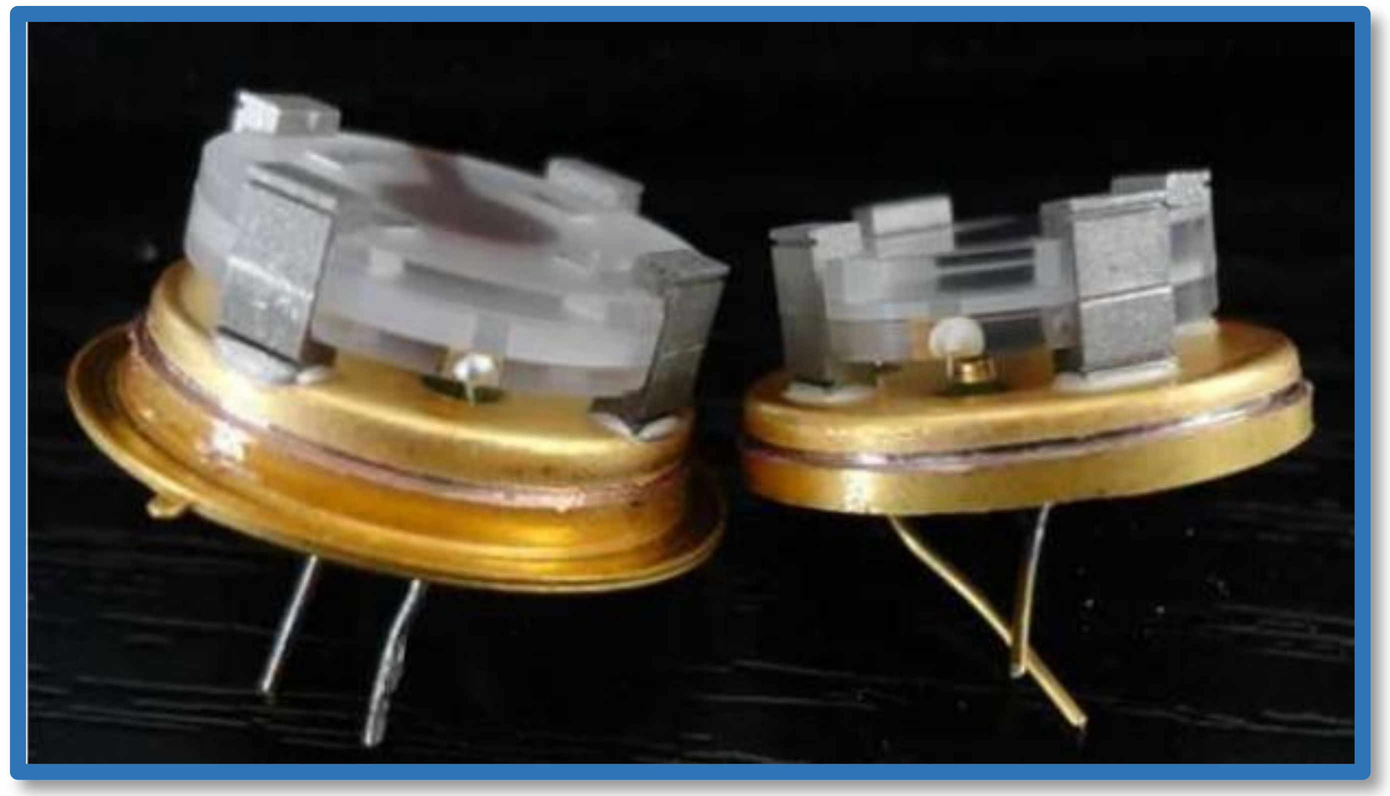
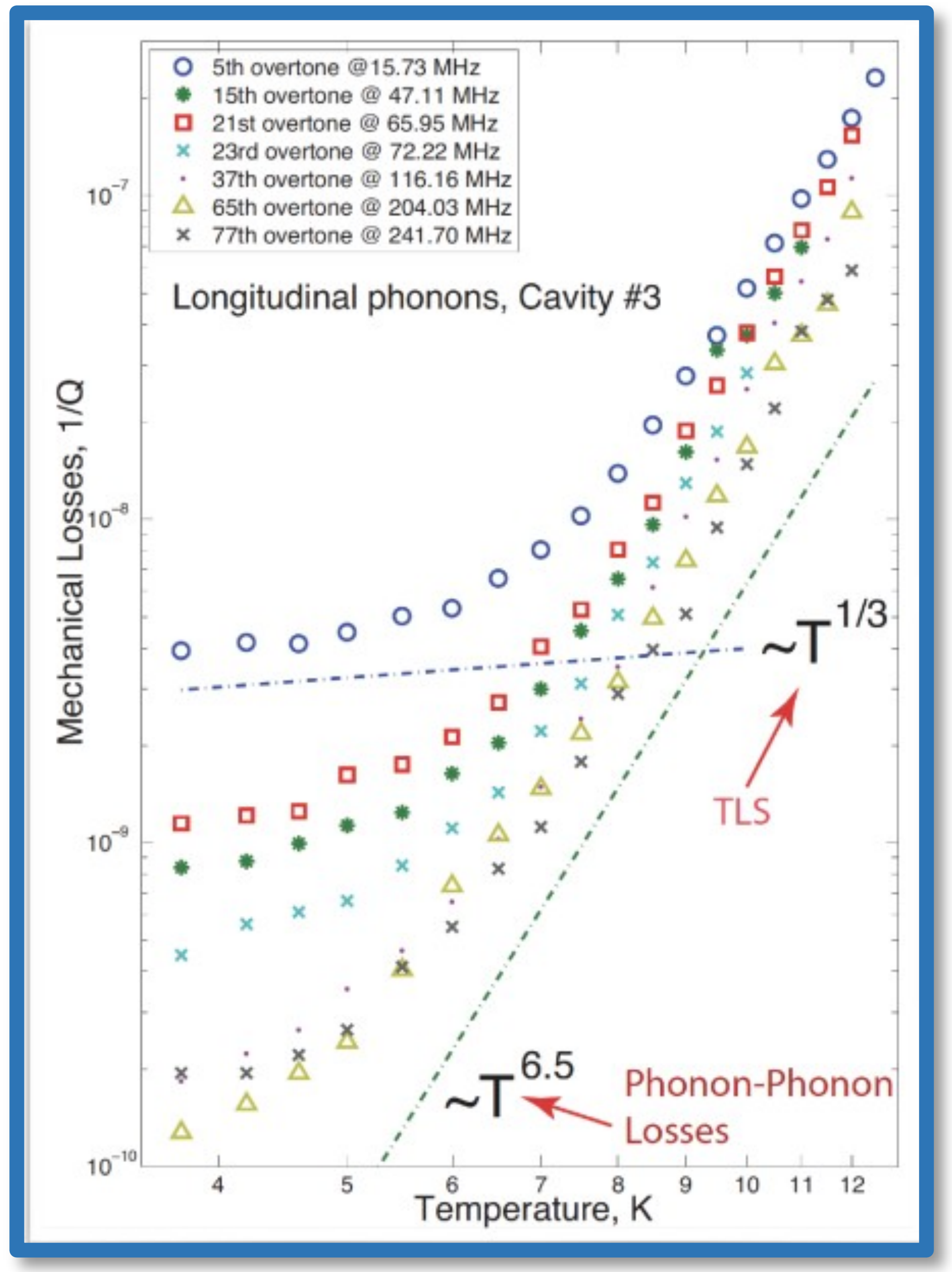
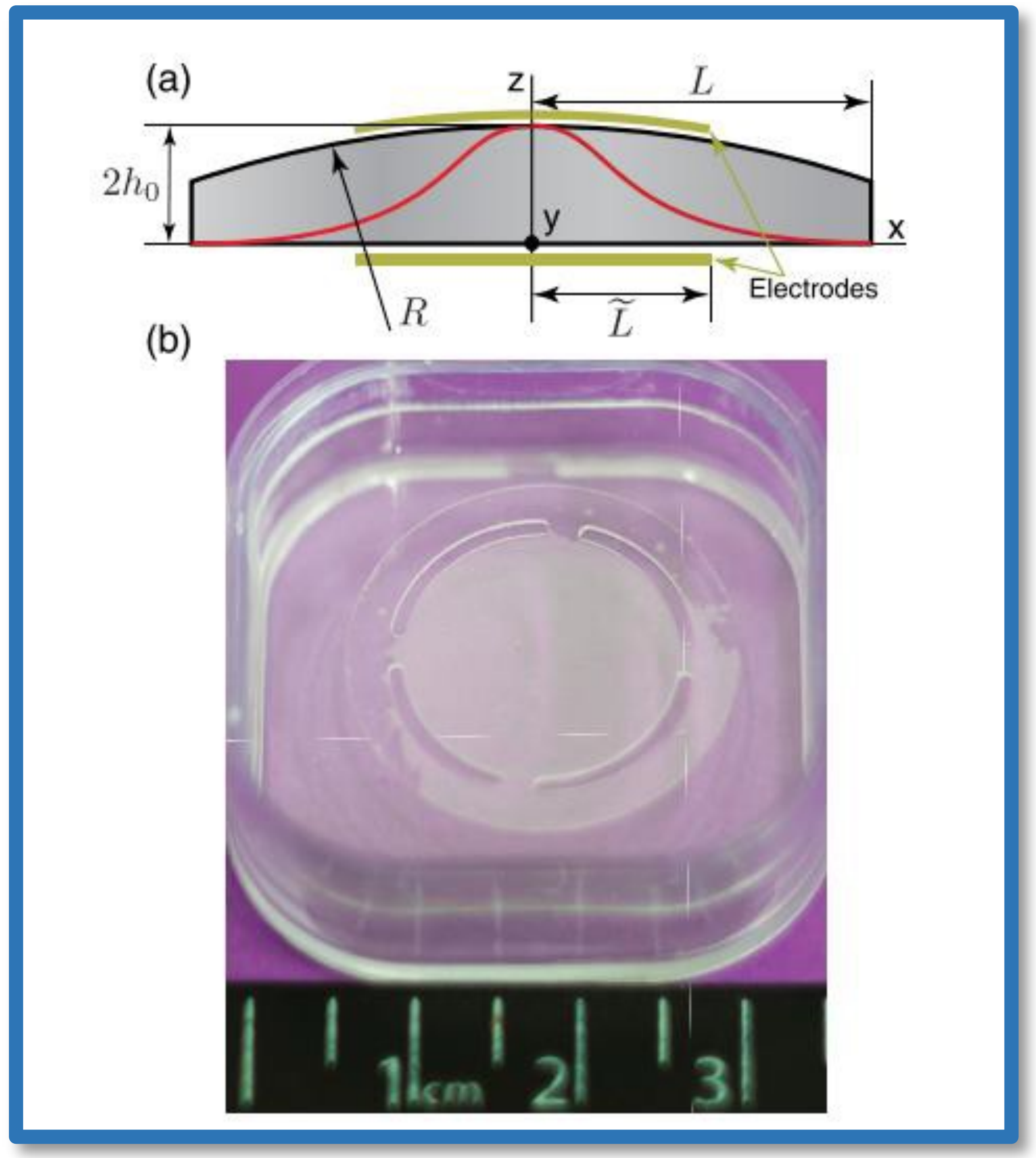




Scientific Reports Vol. 3, 2132 (2013)



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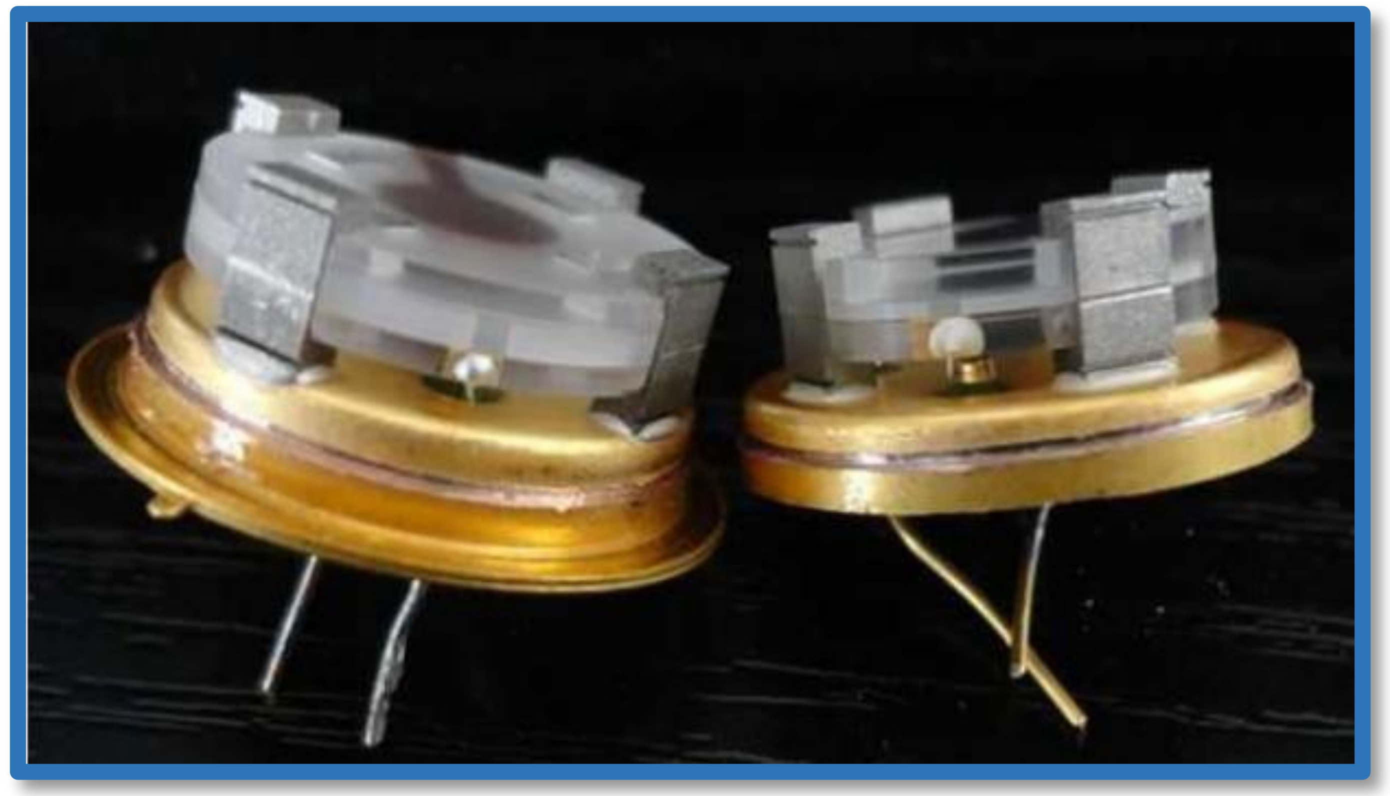

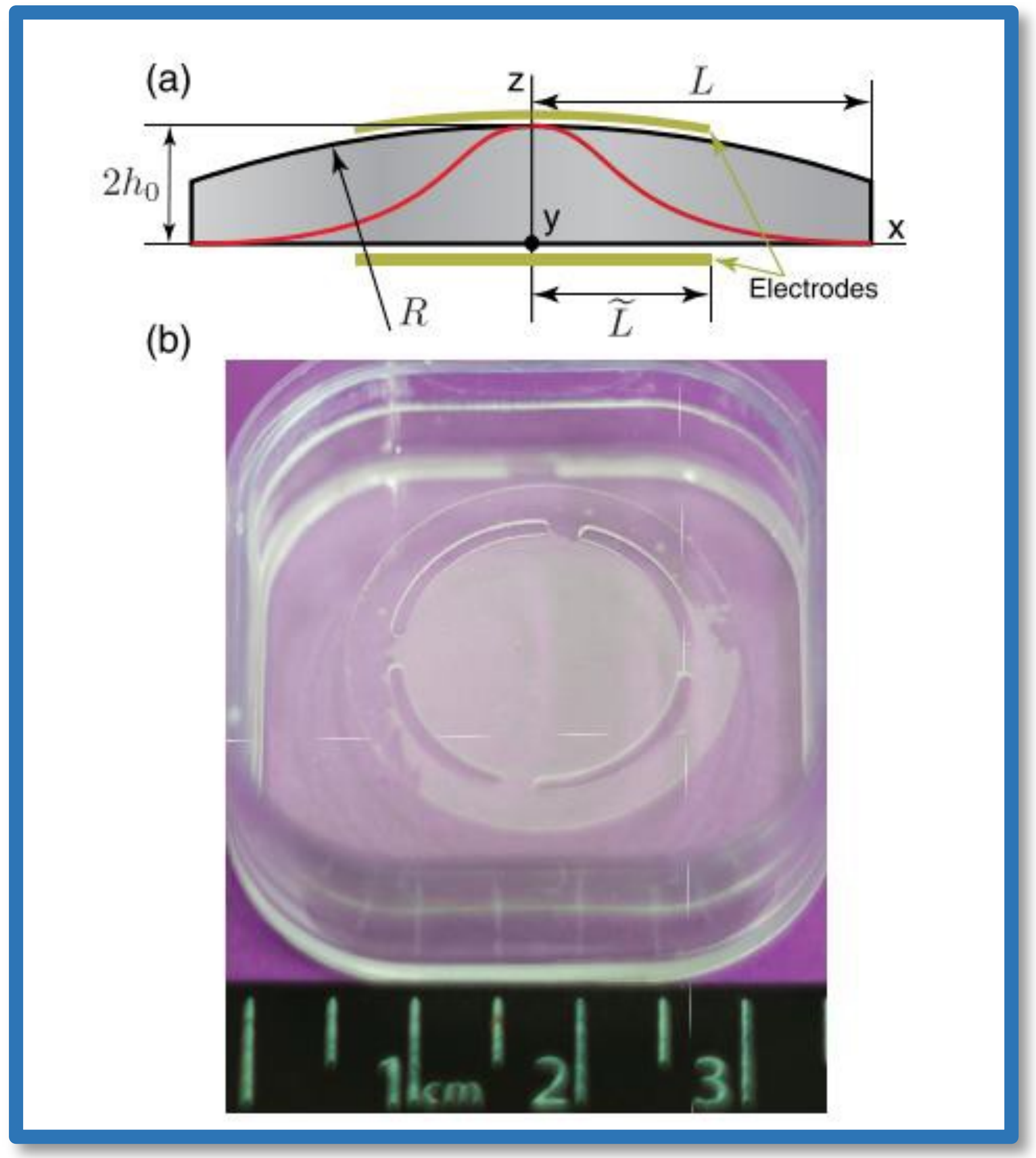

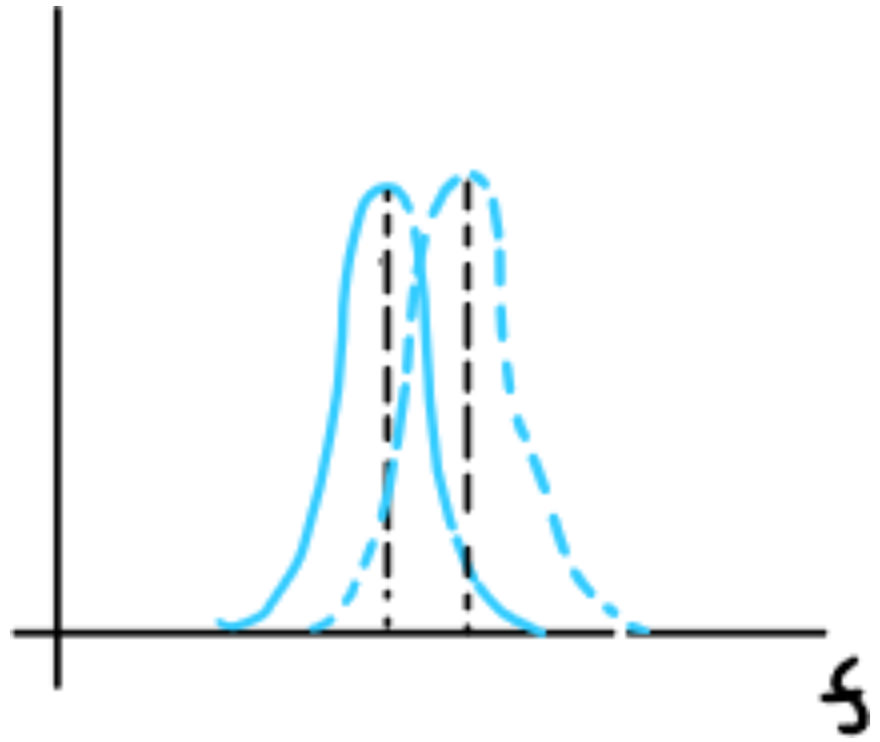

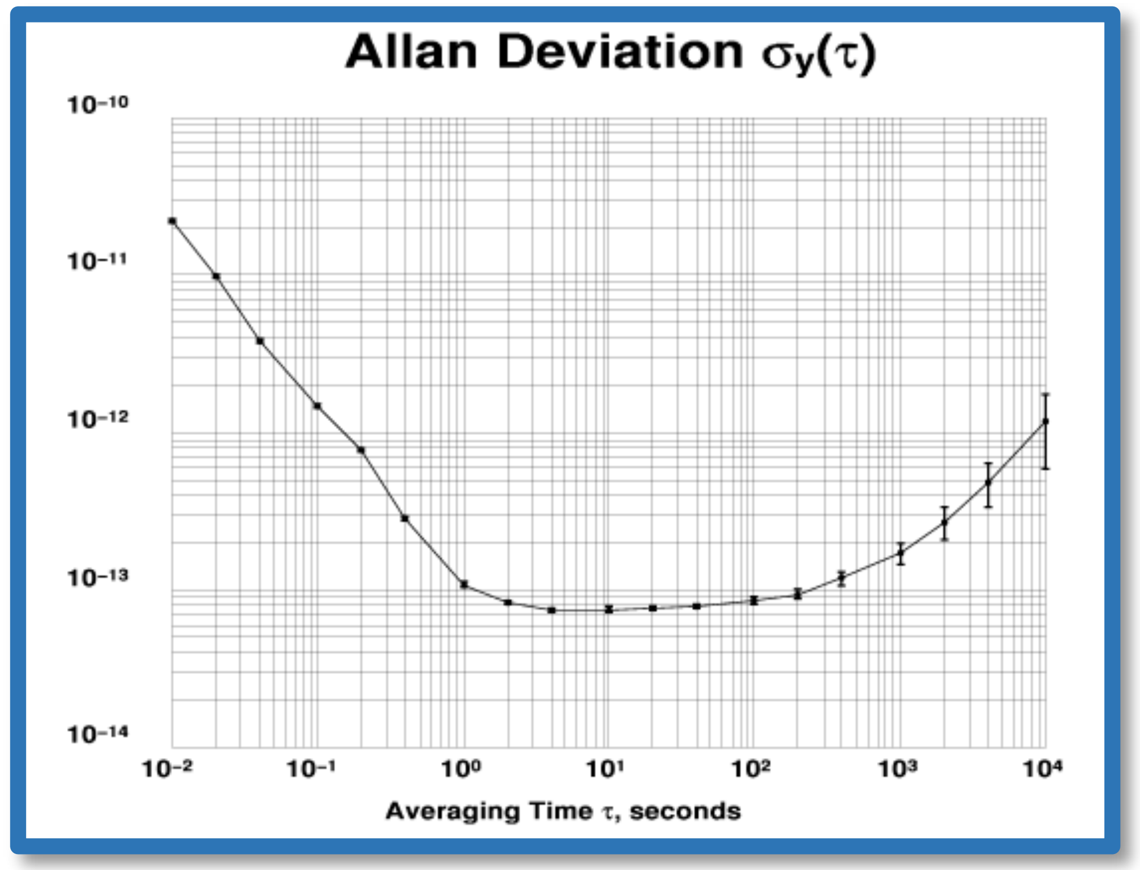

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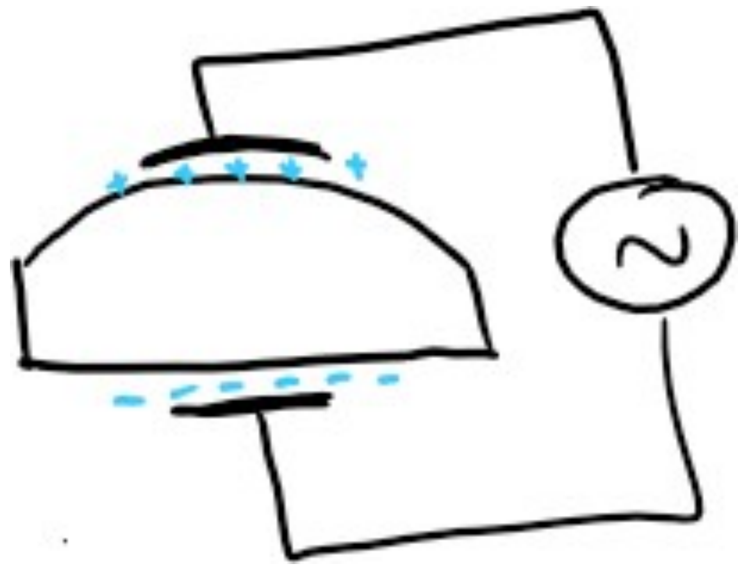

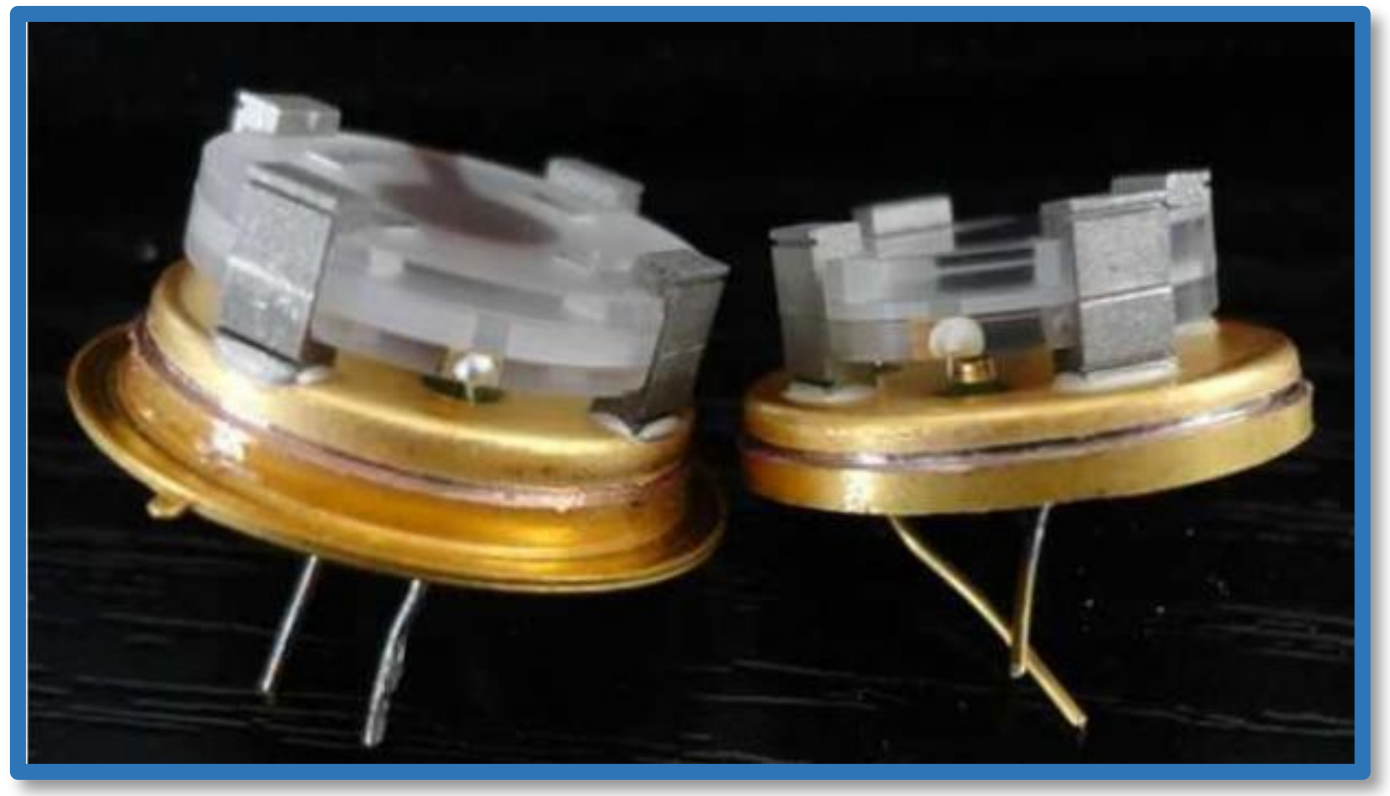

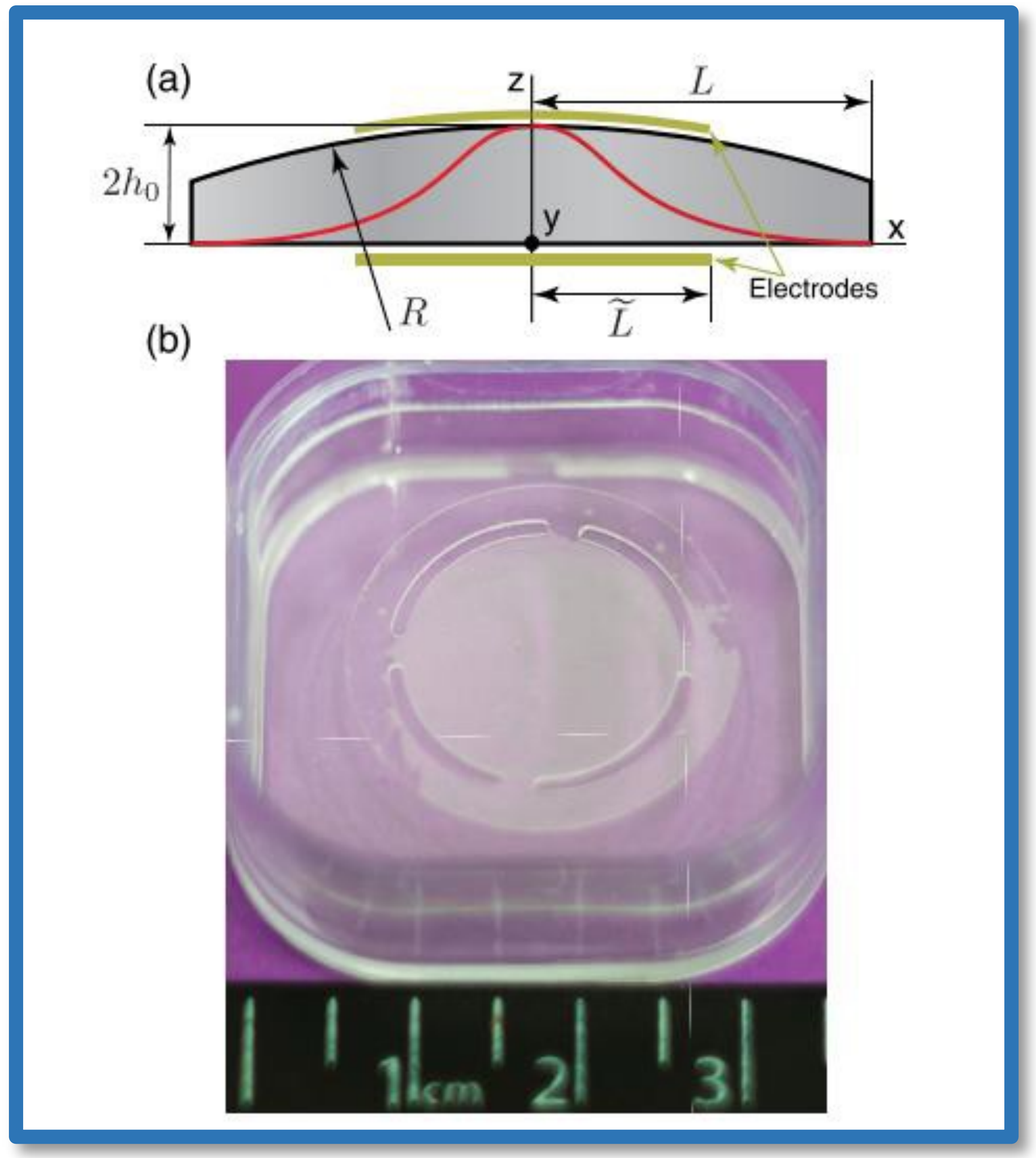

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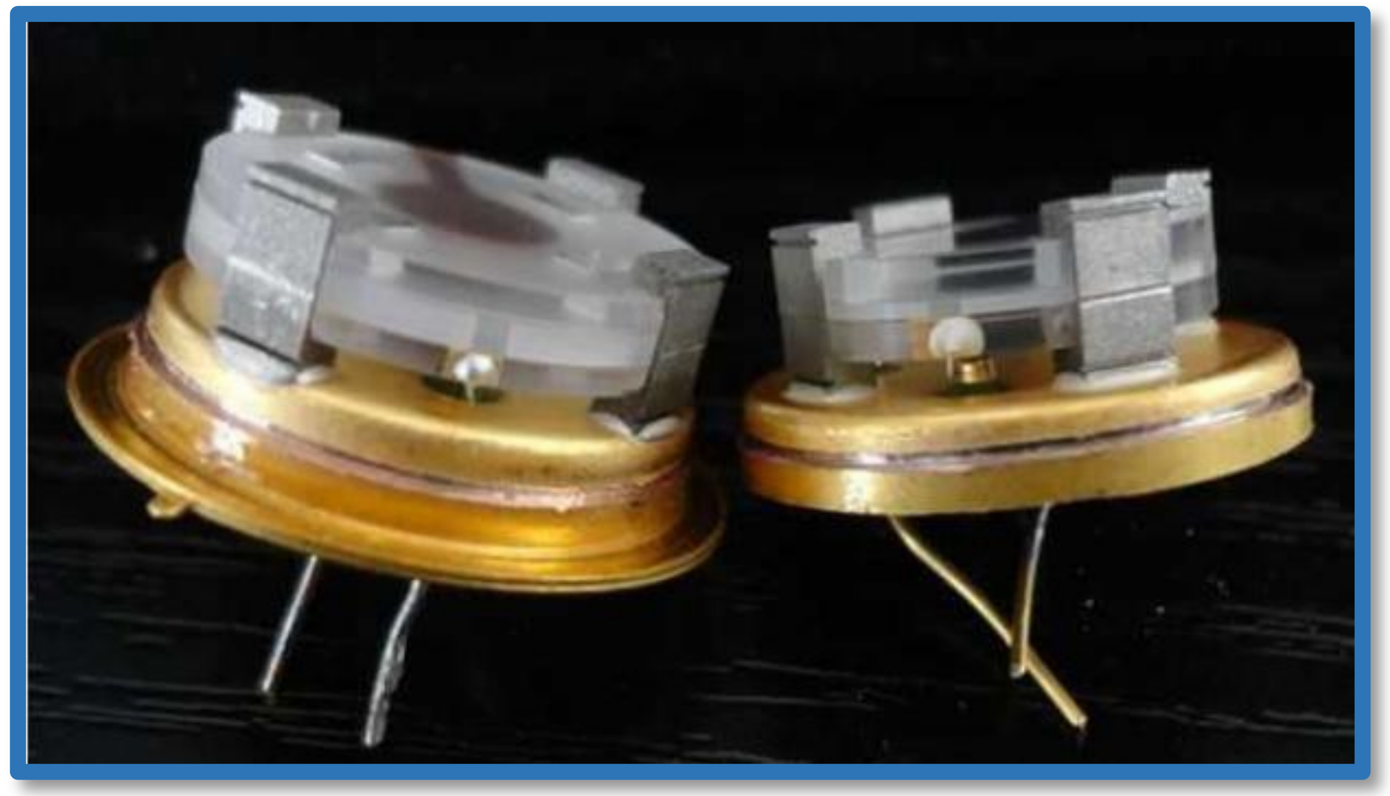

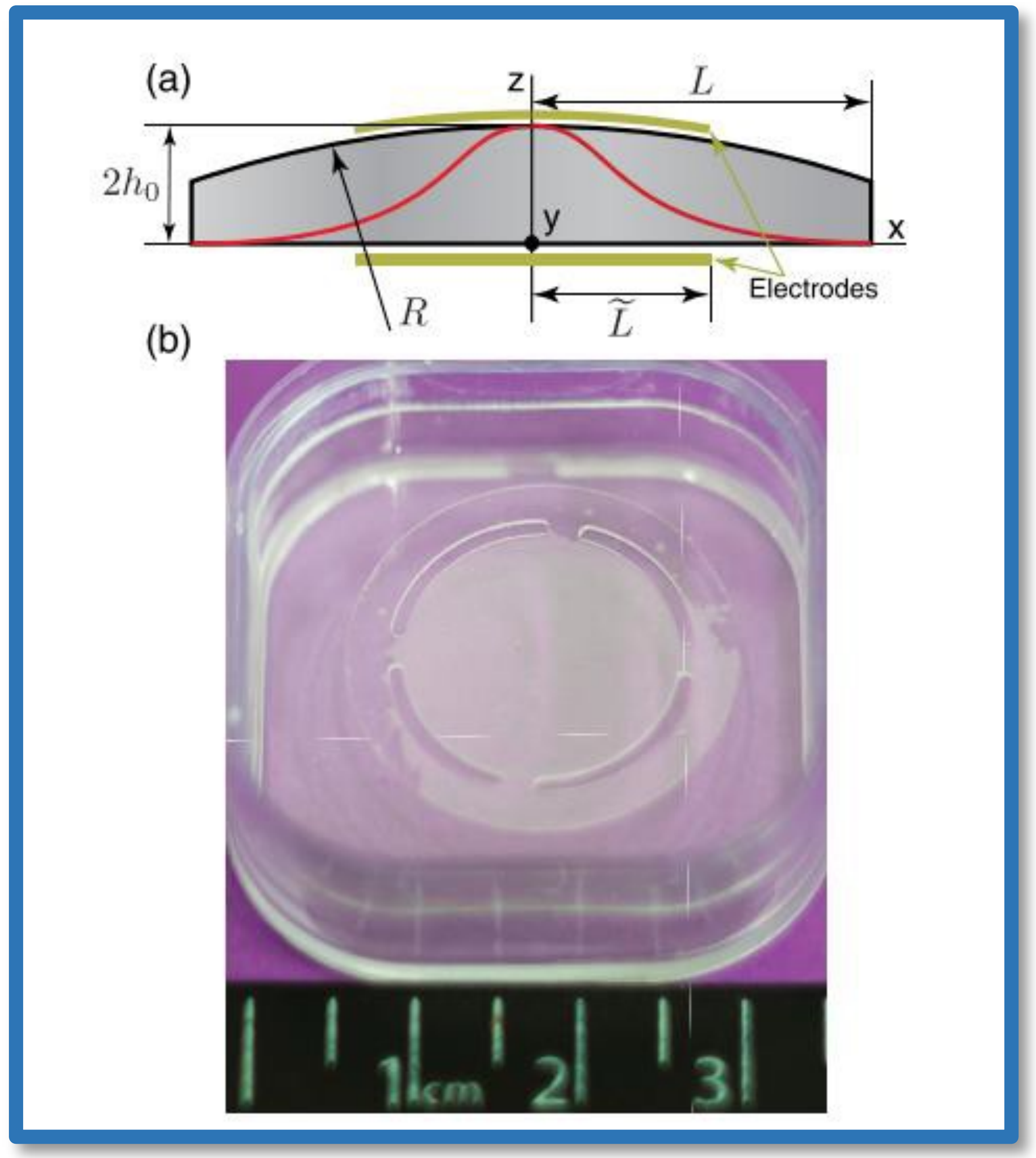

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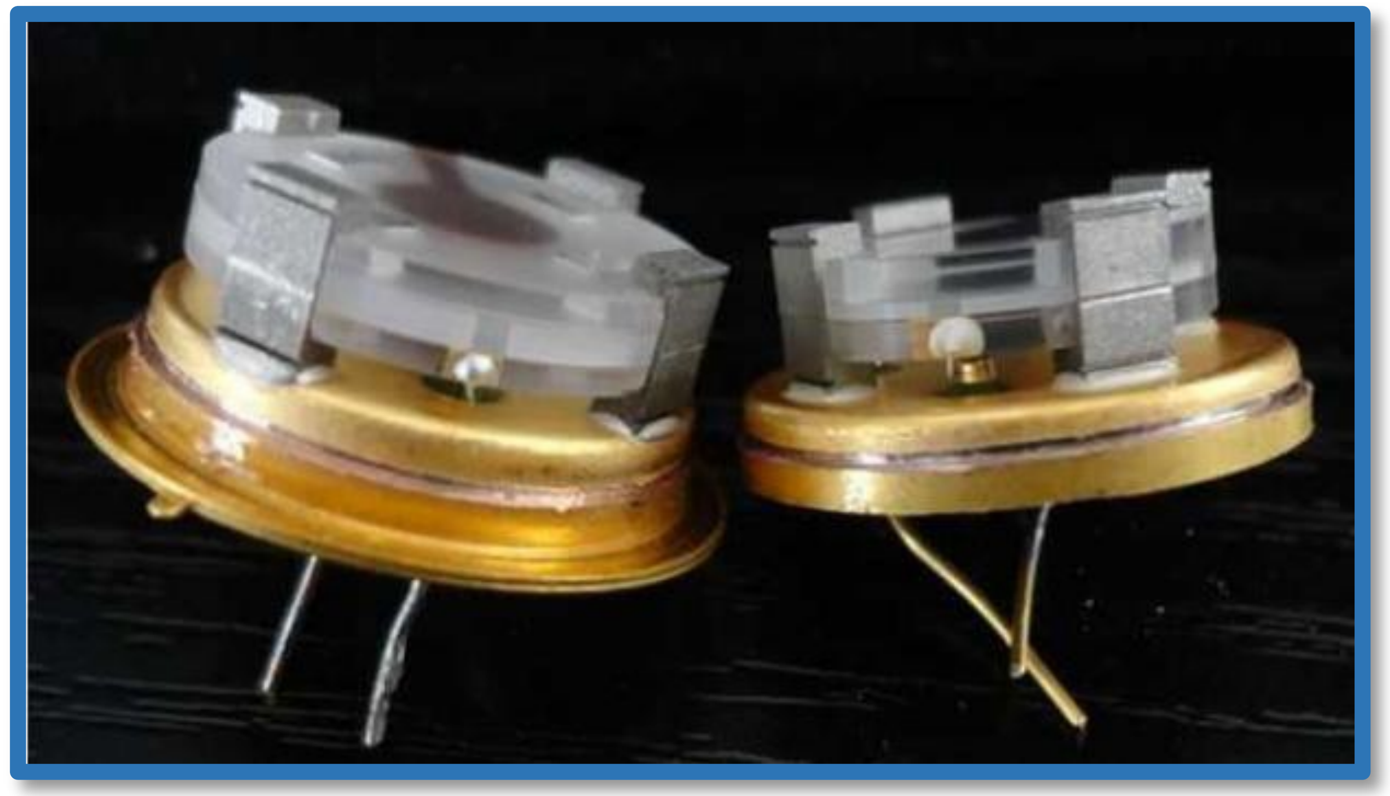
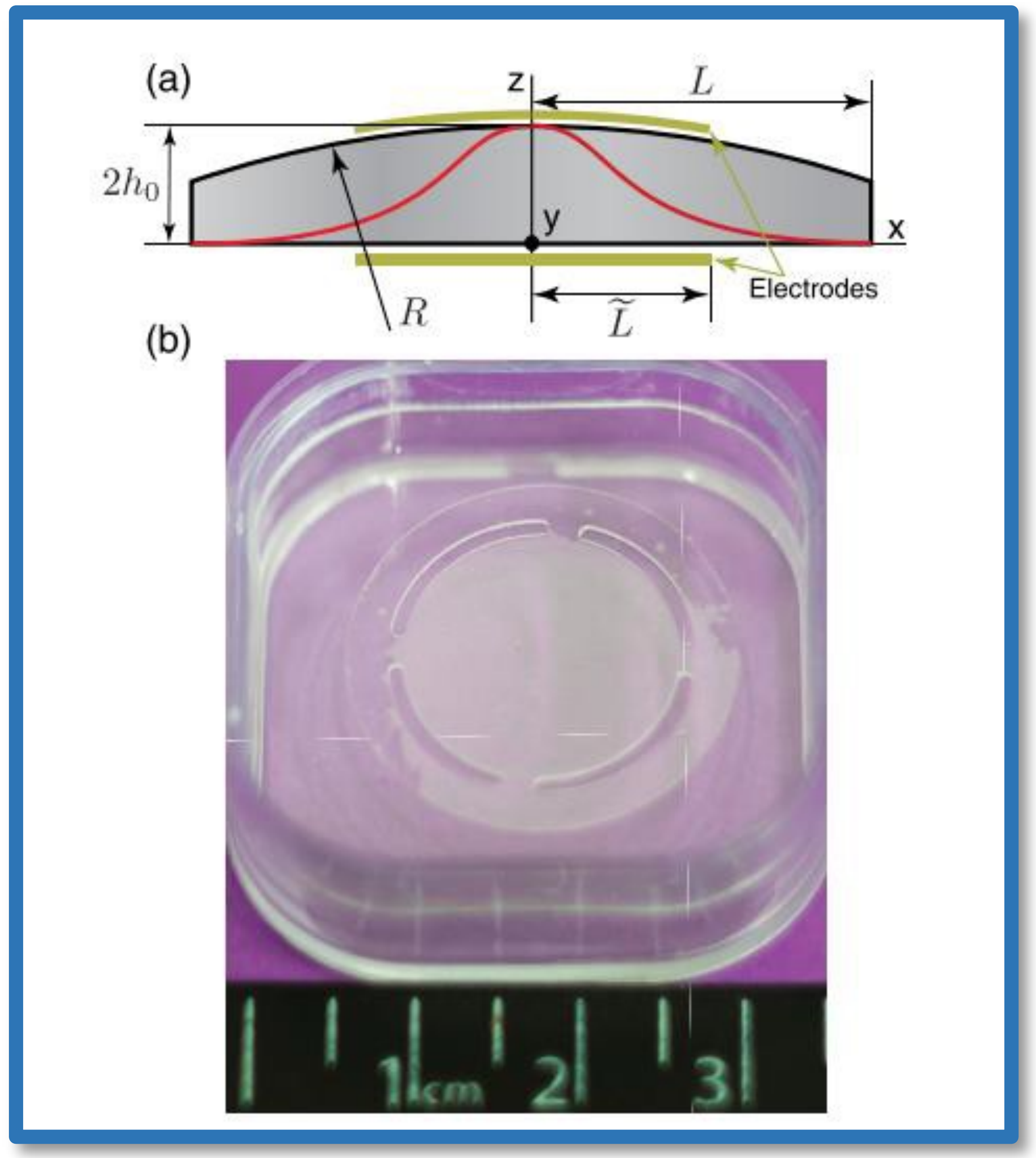
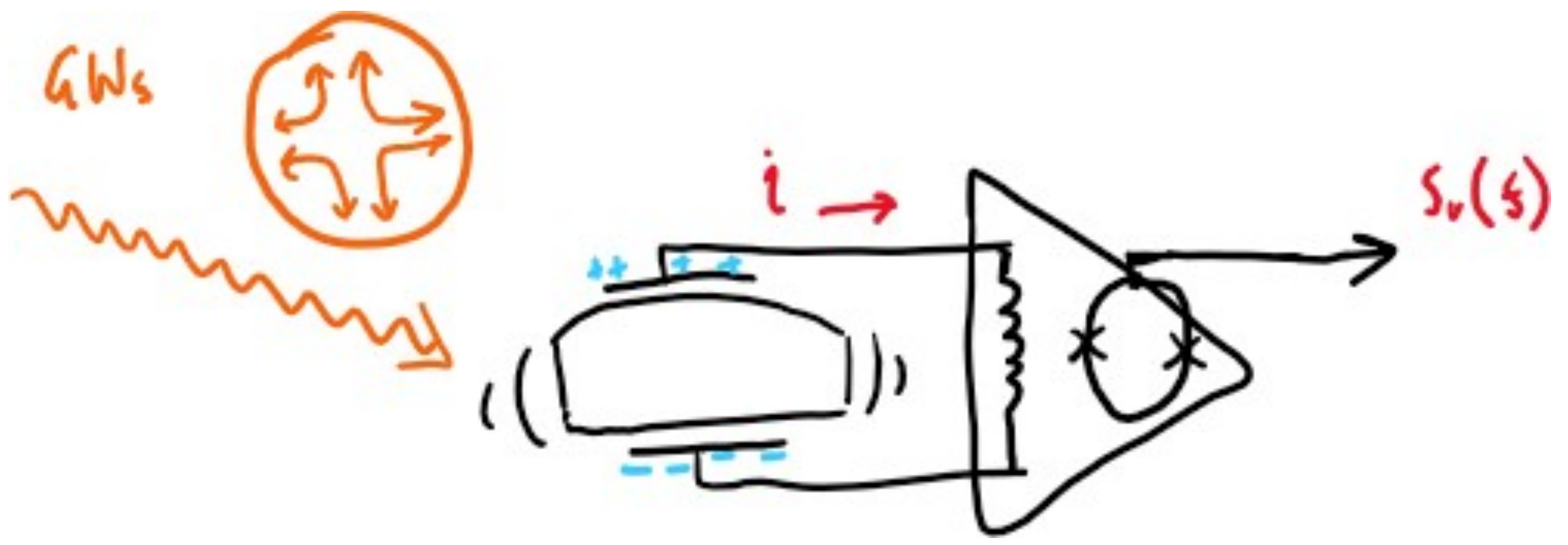
- High density of modes from 1-1000 MHz
- Ongoing studies of behaviour at cryogenic temperatures



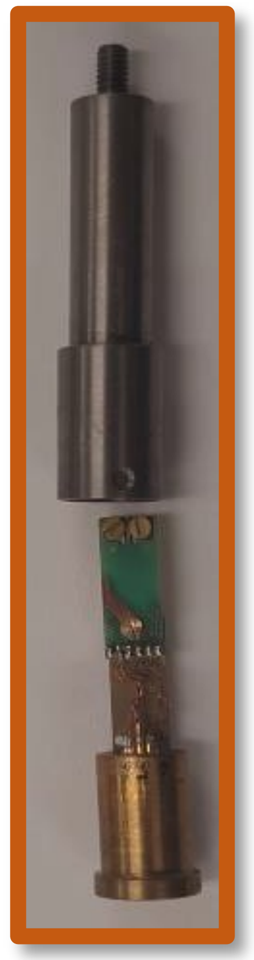


MAGE – Searching for new physics

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



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



Primary target:

High frequency gravitational waves (MHz)

PRD 90, 102005 (2014)

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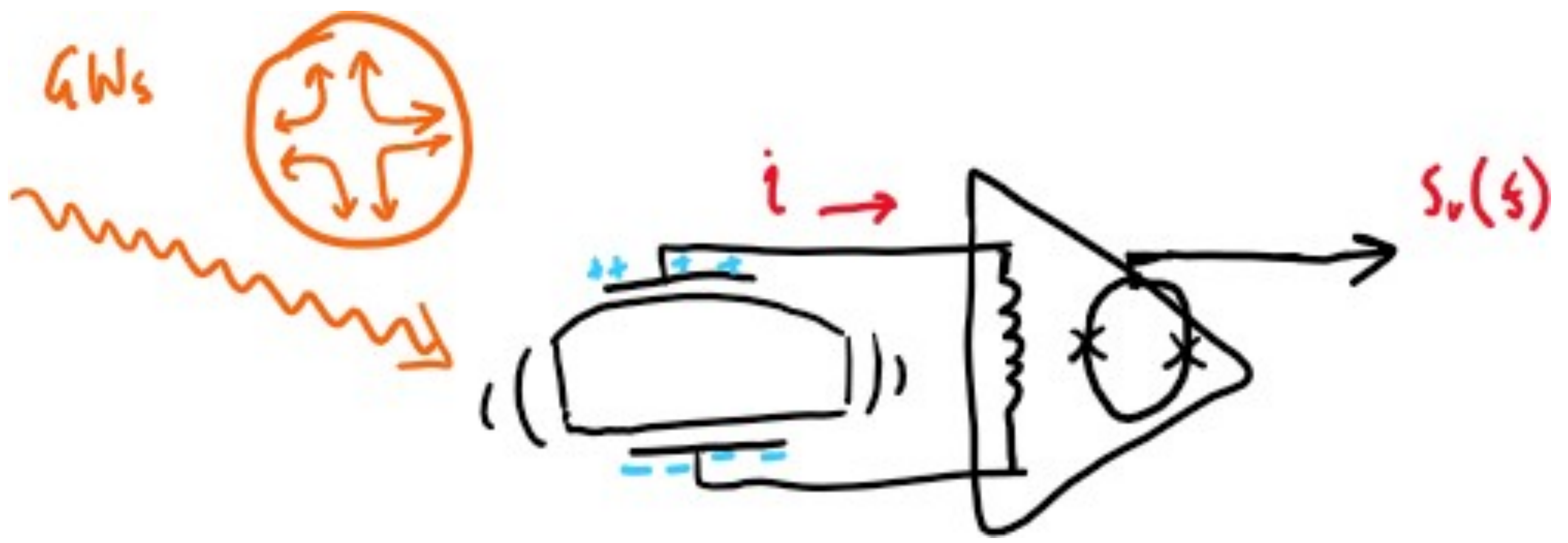

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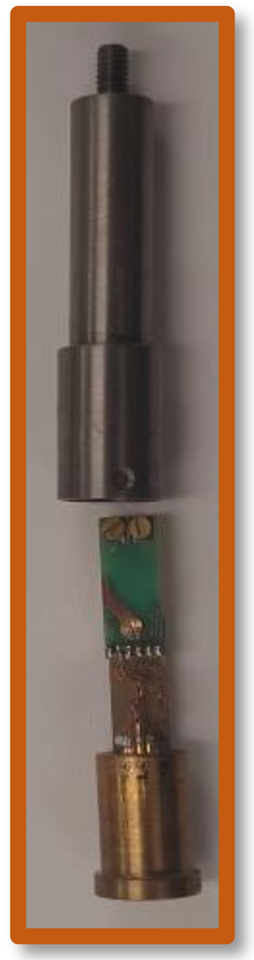

Primary target:

High frequency gravitational waves (MHz) → No known astrophysical sources exist at these frequencies

PRD 90, 102005 (2014)

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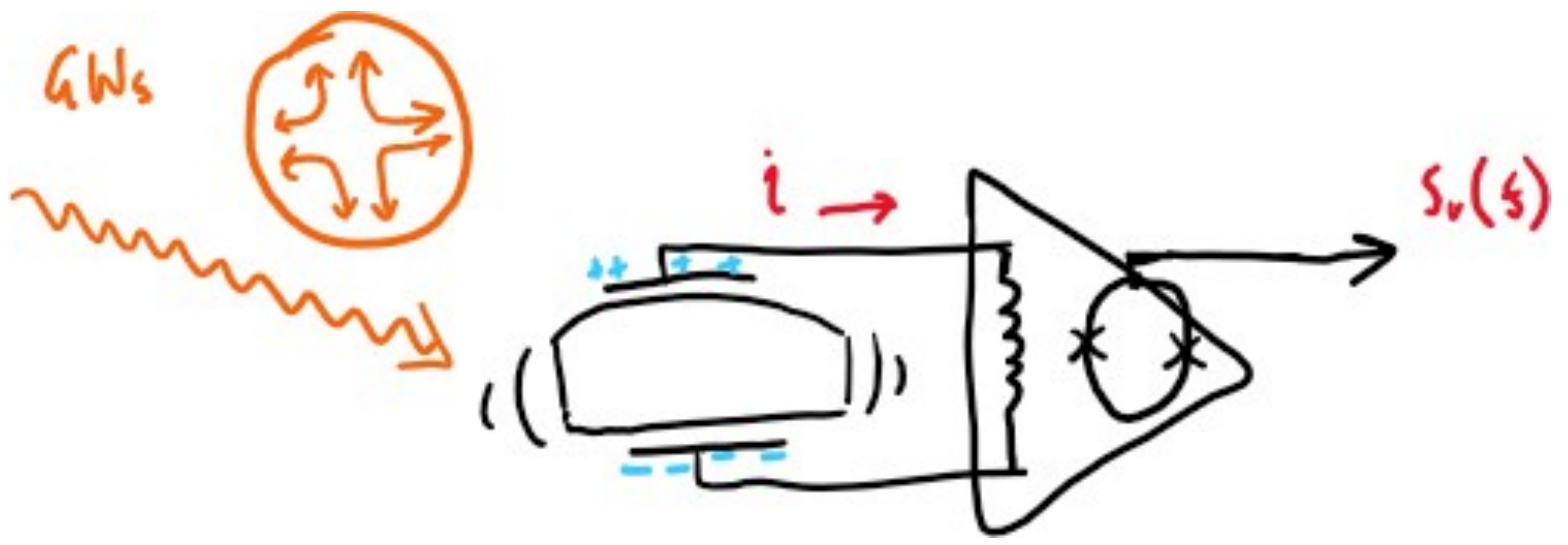

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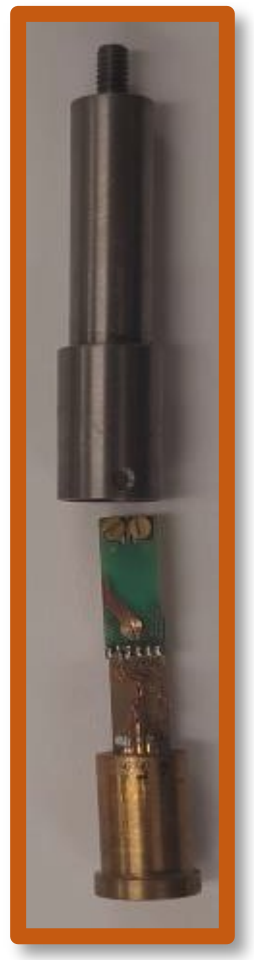

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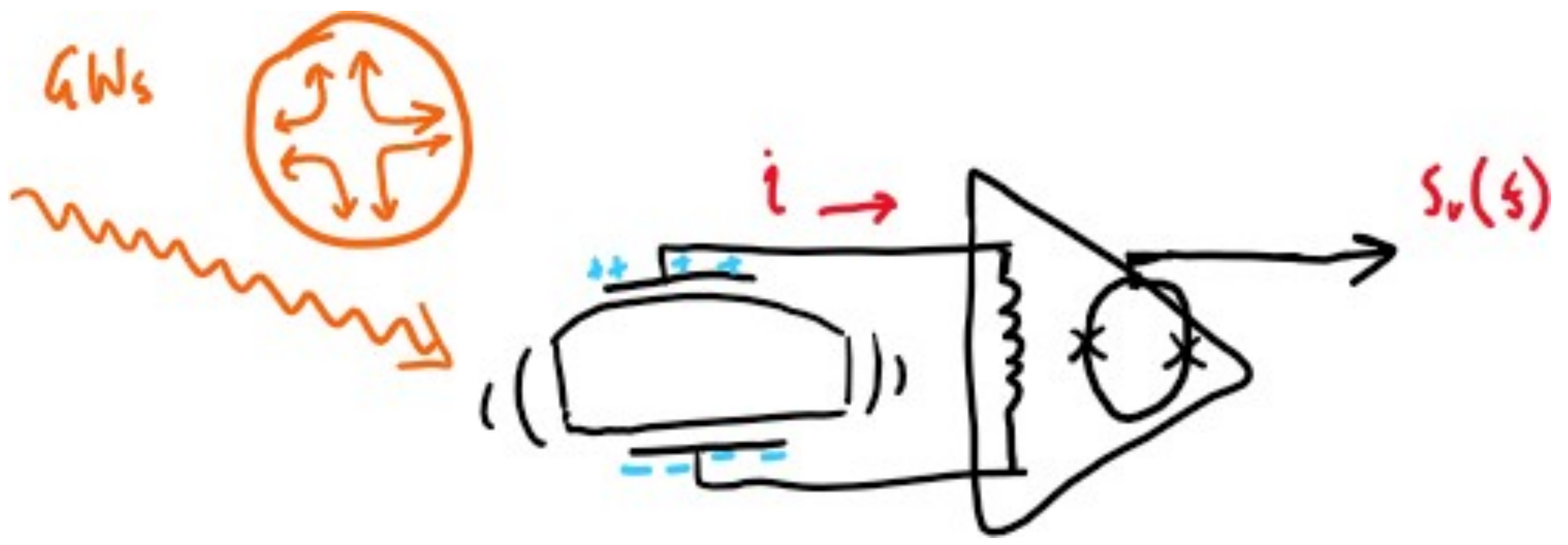
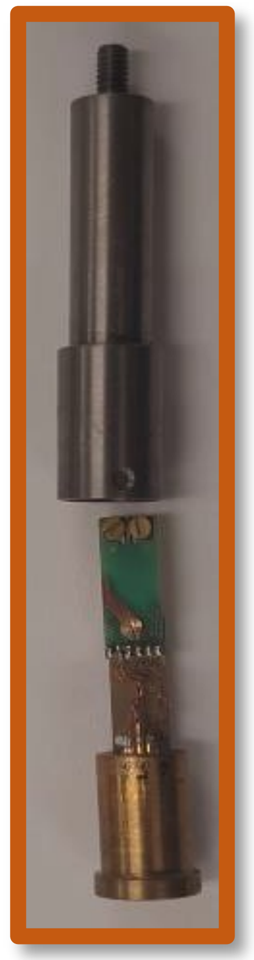
Any potential detection points to new physics outside the standard model !

MAGE – Searching for new physics

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

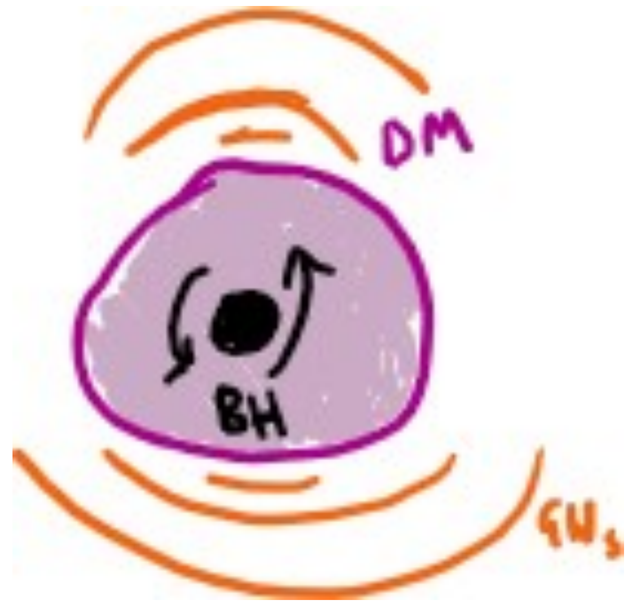


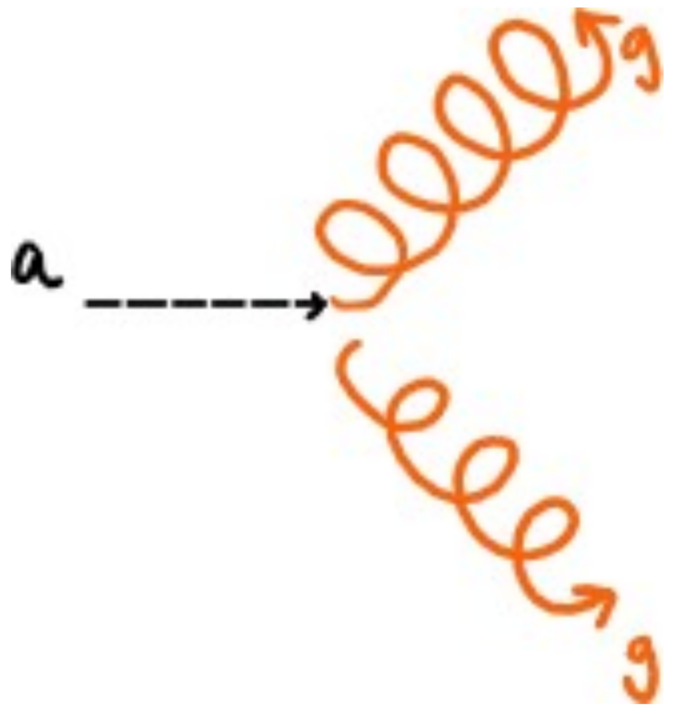
$$\ddot{B}_\lambda + \tau_\lambda^{-1}\dot{B}_\lambda + \omega_\lambda^2 B = -c^2 R_{i0j0}\int_V dv\, \frac{\rho}{m_\lambda} U^i_\lambda(\mathbf{x}) x^j$$



HFGWs due to DM:

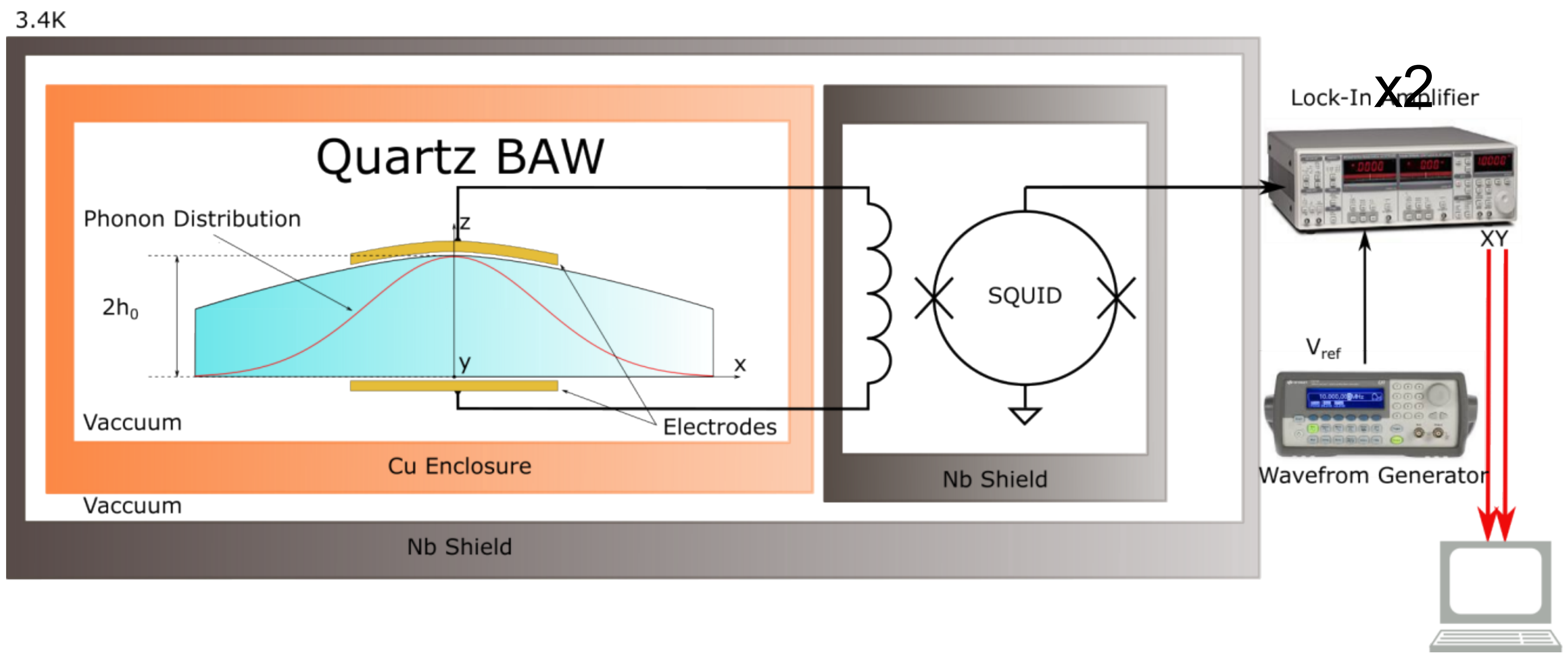
Sub – solar black hole mergers, black hole super radiance, axion decay into gravitons

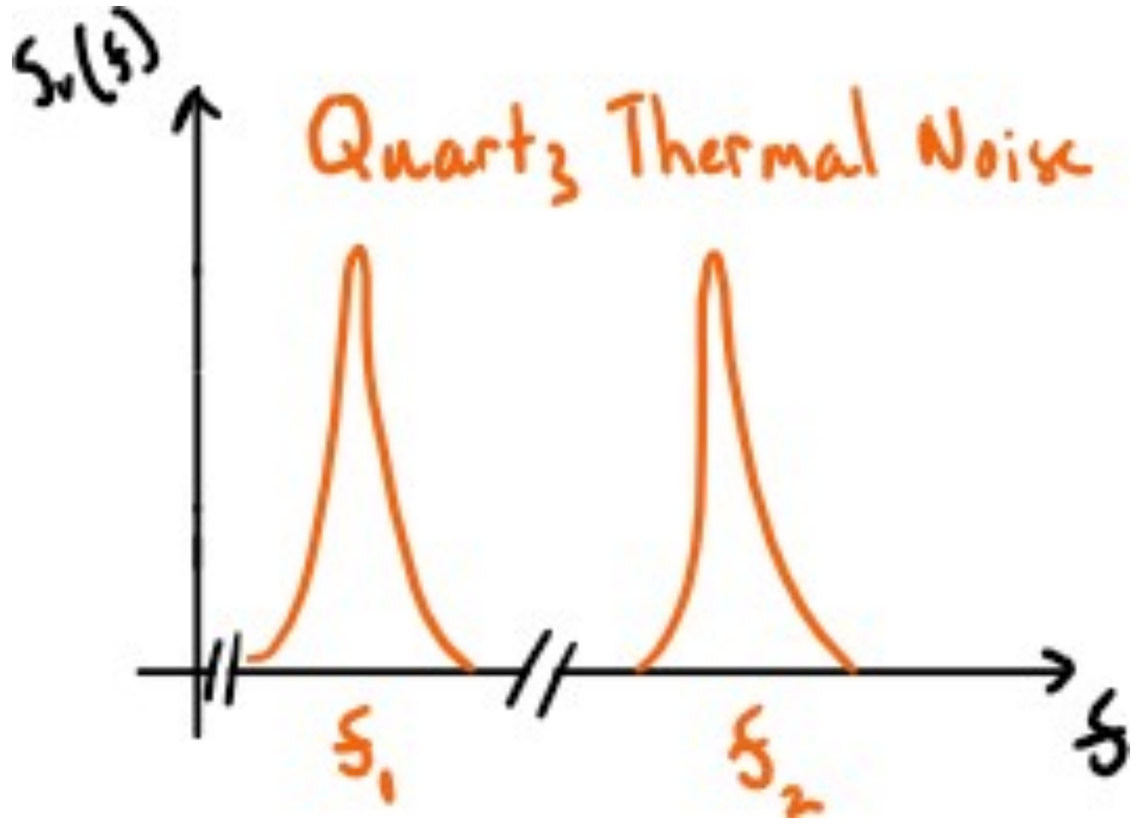




MAGE – Searching for new physics

First Observational Period → GEN 1 & GEN 2, *153 days* of data, *two modes*

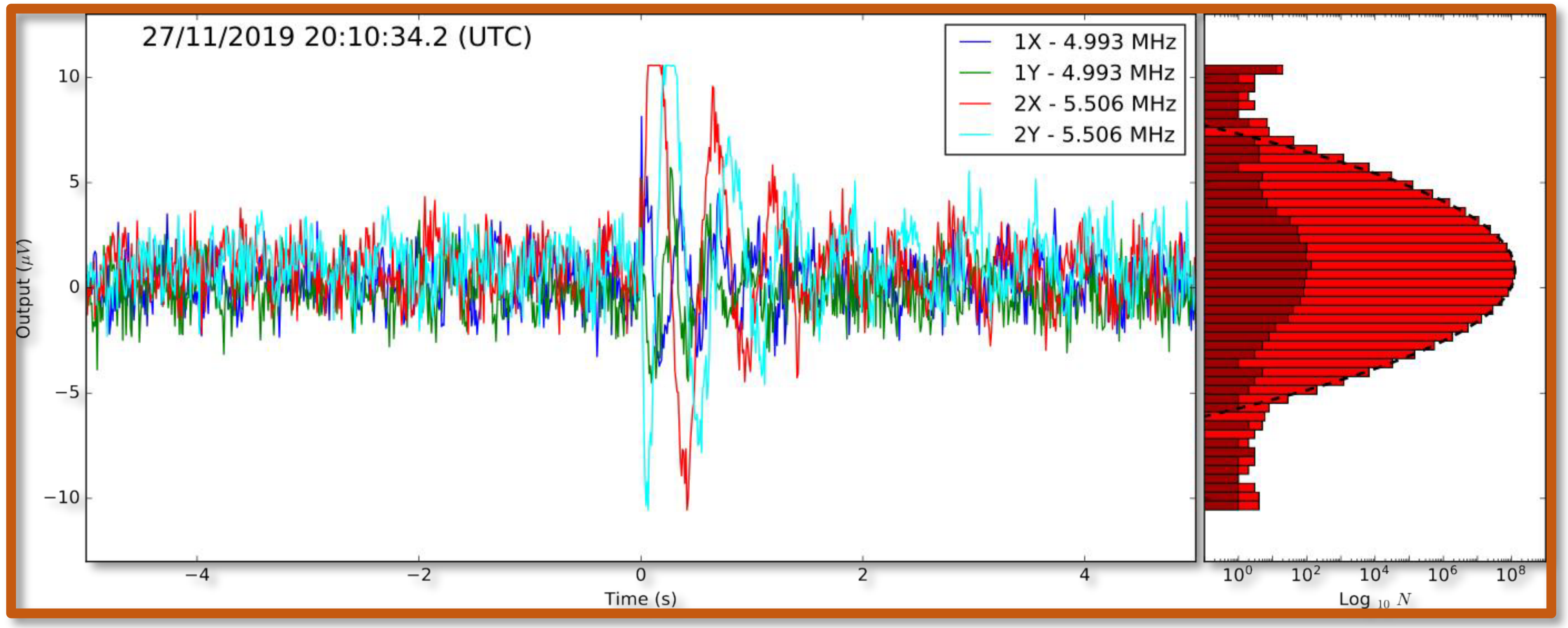




Data Analysis:

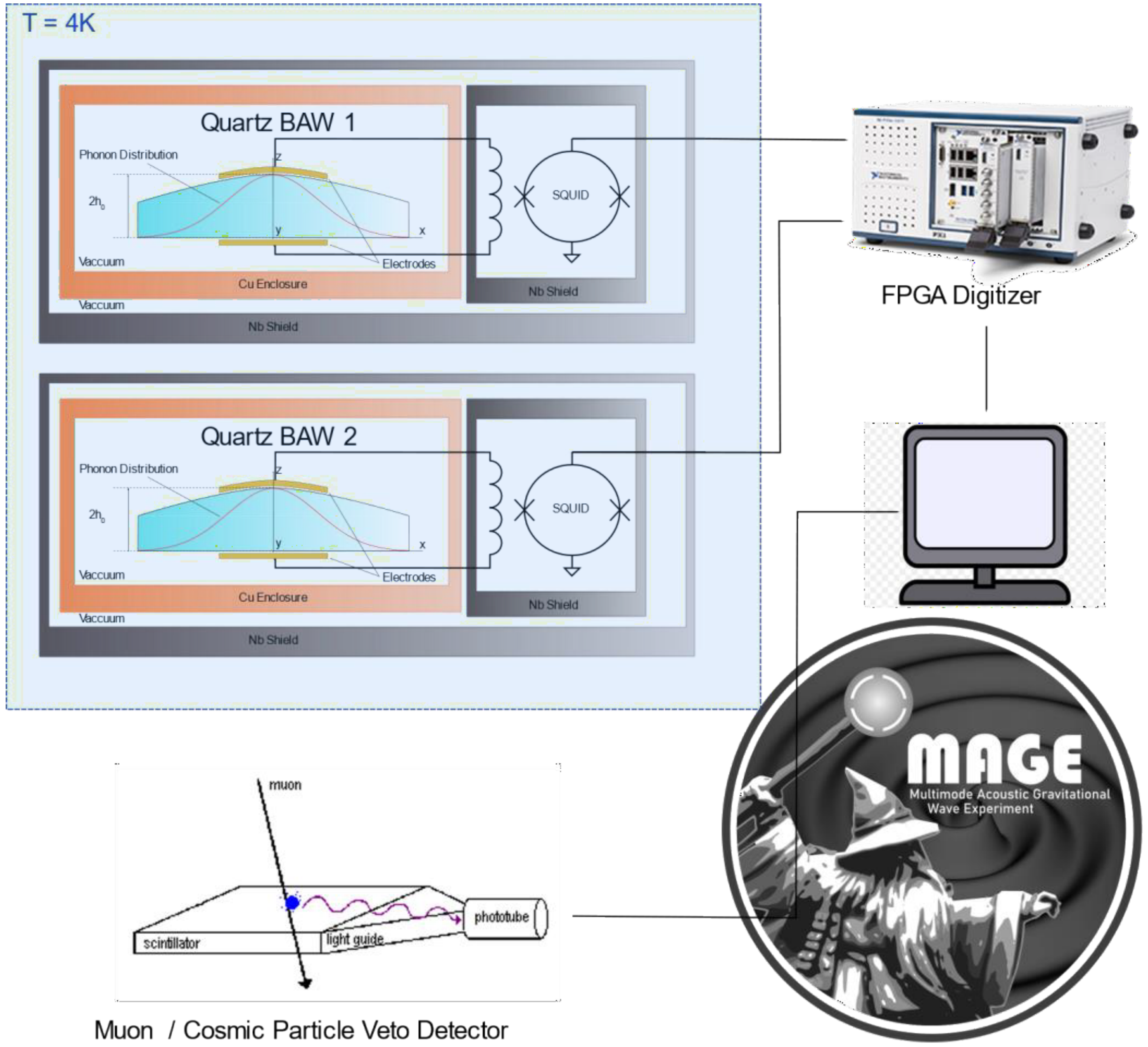
Two significantly strong, rare events

Phys. Rev. Lett. **127**, 071102



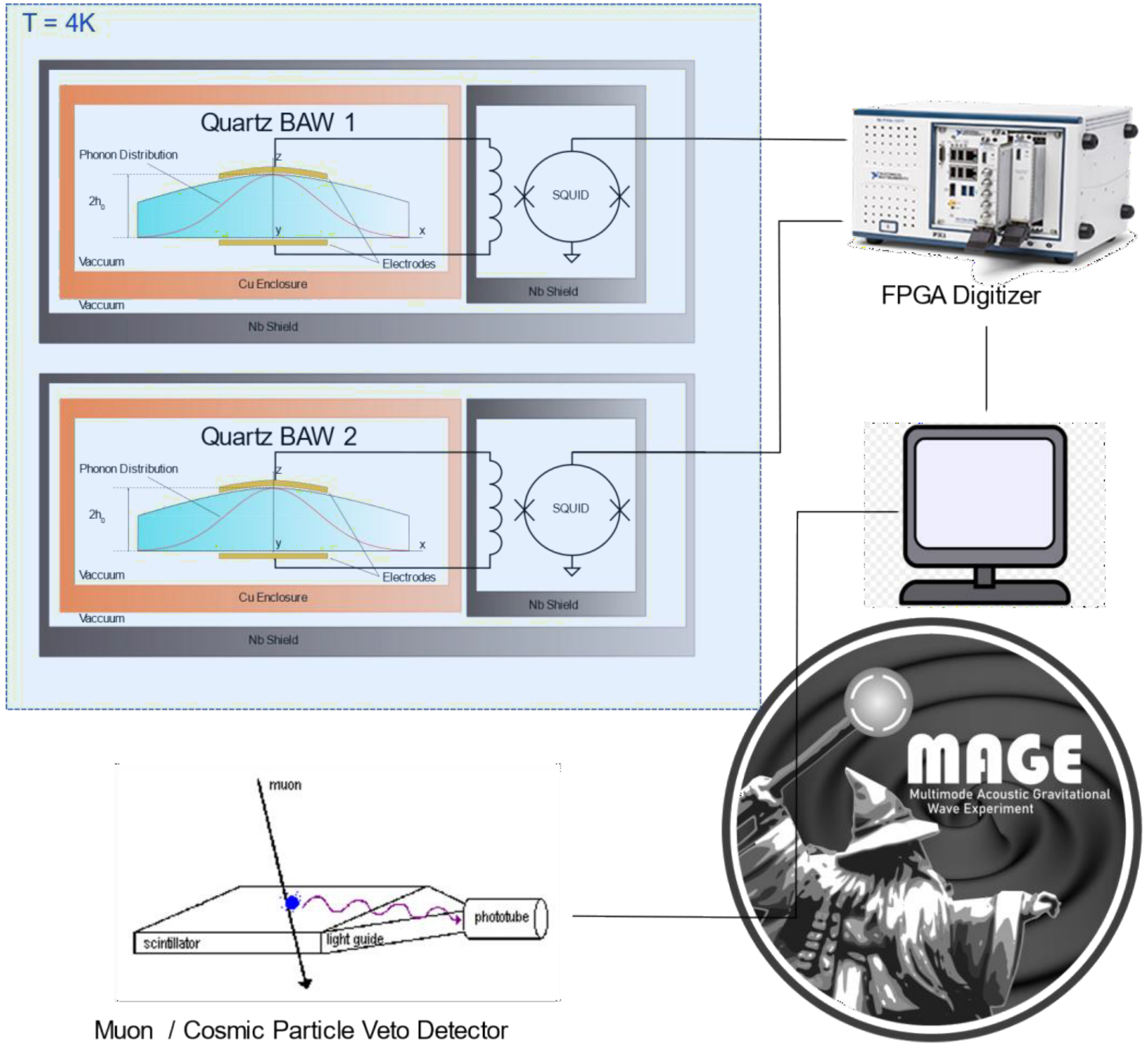
MAGE – Searching for new physics

What's next ? → **M**ultimode **A**coustic **G**ravitational Wave **E**xperiment



MAGE – Searching for new physics

<u>What's next ?</u> → **<u>M</u>**ultimode **<u>A</u>**coustic **<u>G</u>**ravitational Wave **<u>E</u>**xperiment

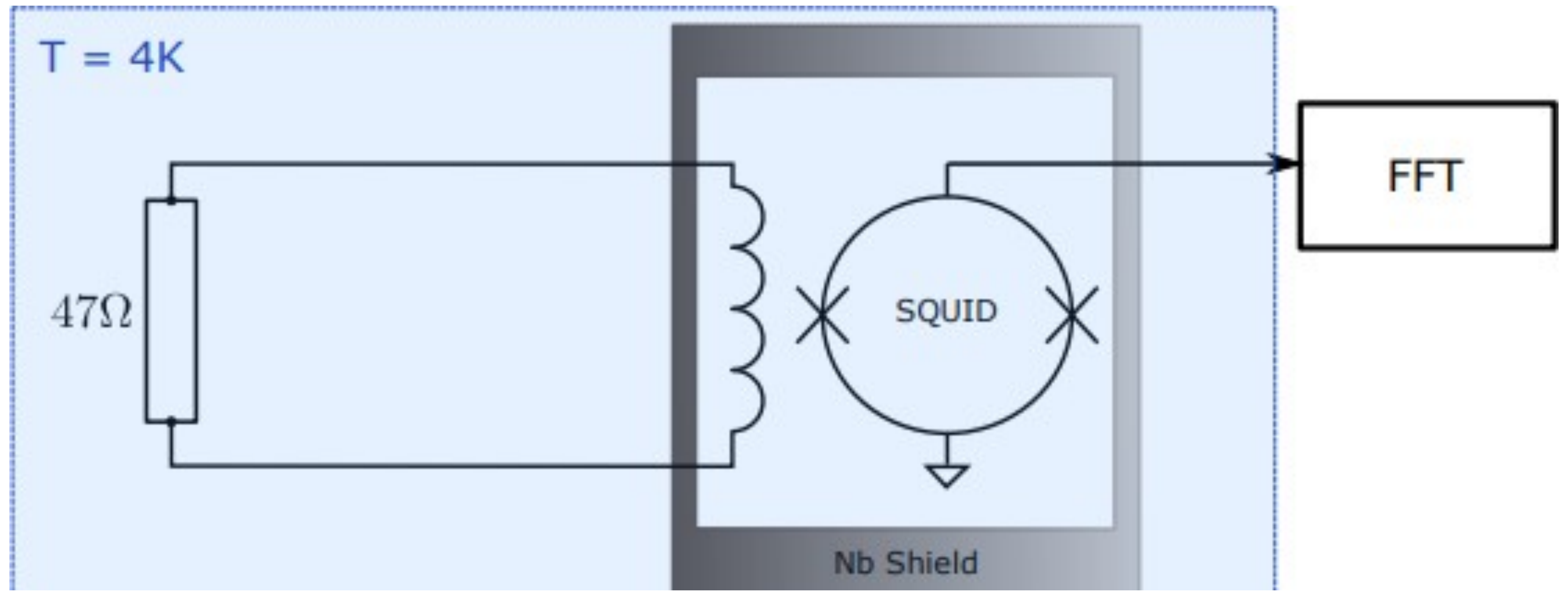


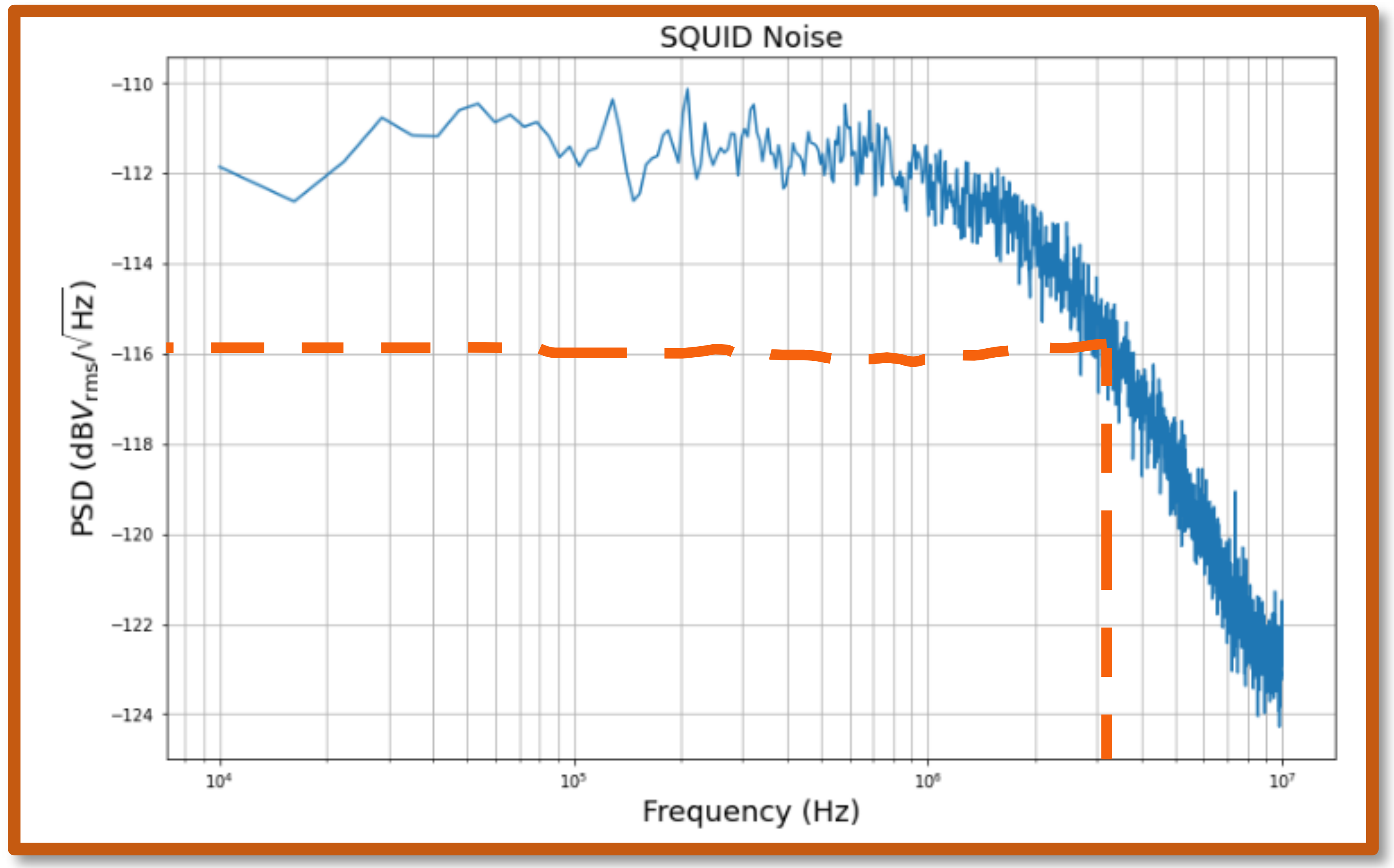
- 2 x Quartz BAW crystals
- 2 x DC SQUID amplifiers
- FPGA DAQ
- Cosmic particle veto (coming soon)

<u>Exclude potential sources of events:</u>

MAGE – Searching for new physics

Calibration of 2nd detector



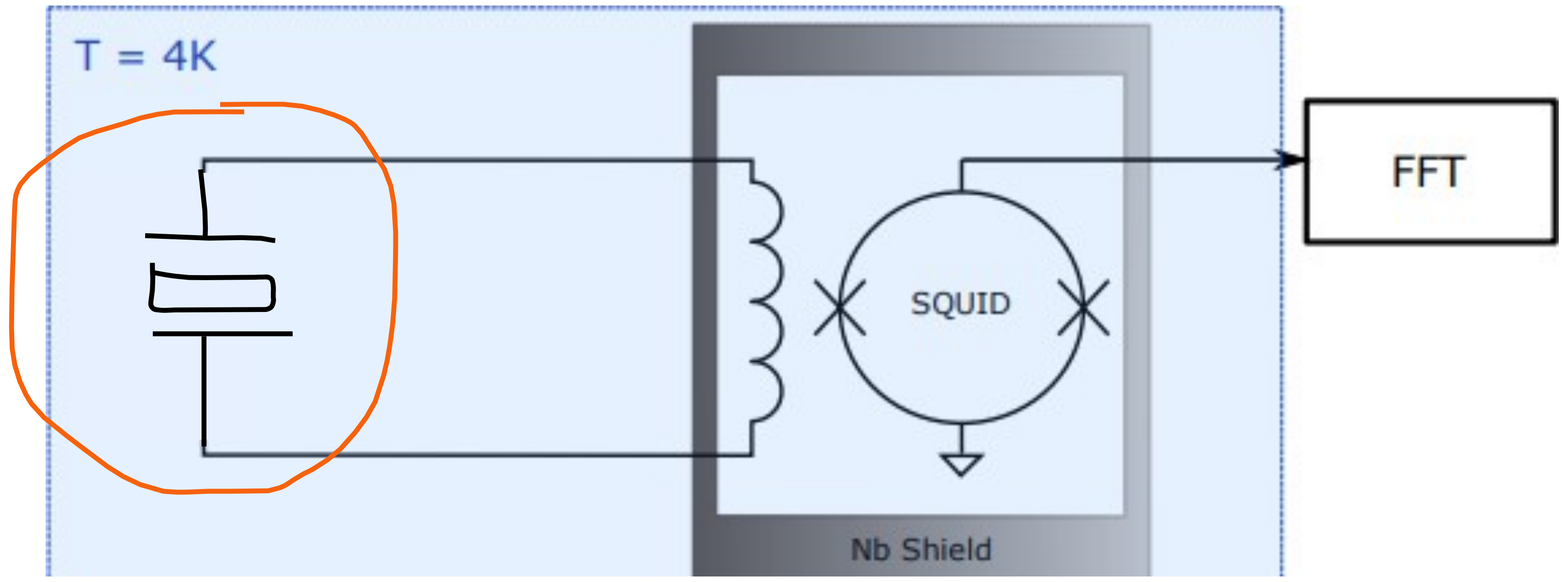


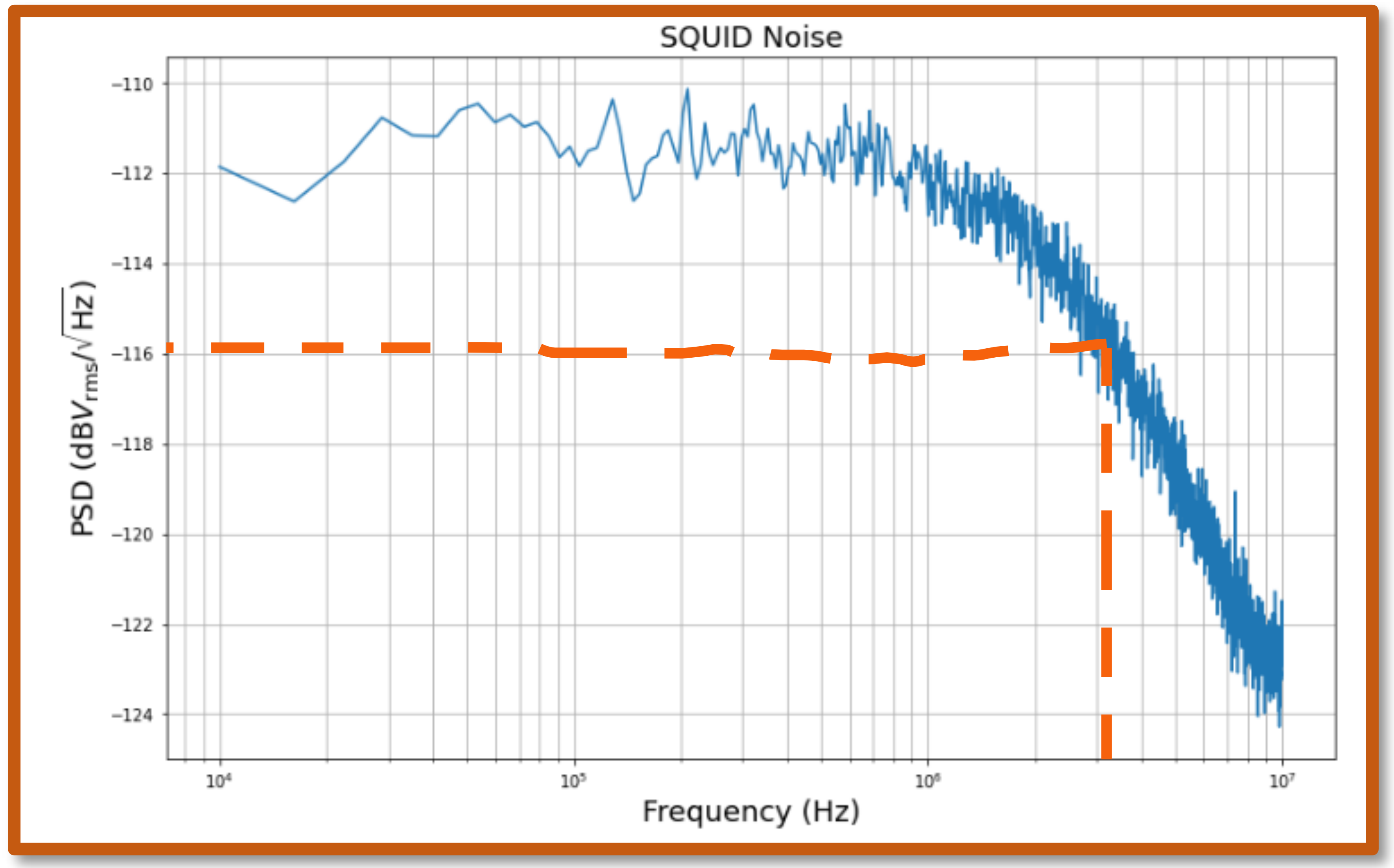
f_{3dB}~3 MHz

Limited by SQUID electronics

MAGE – Searching for new physics

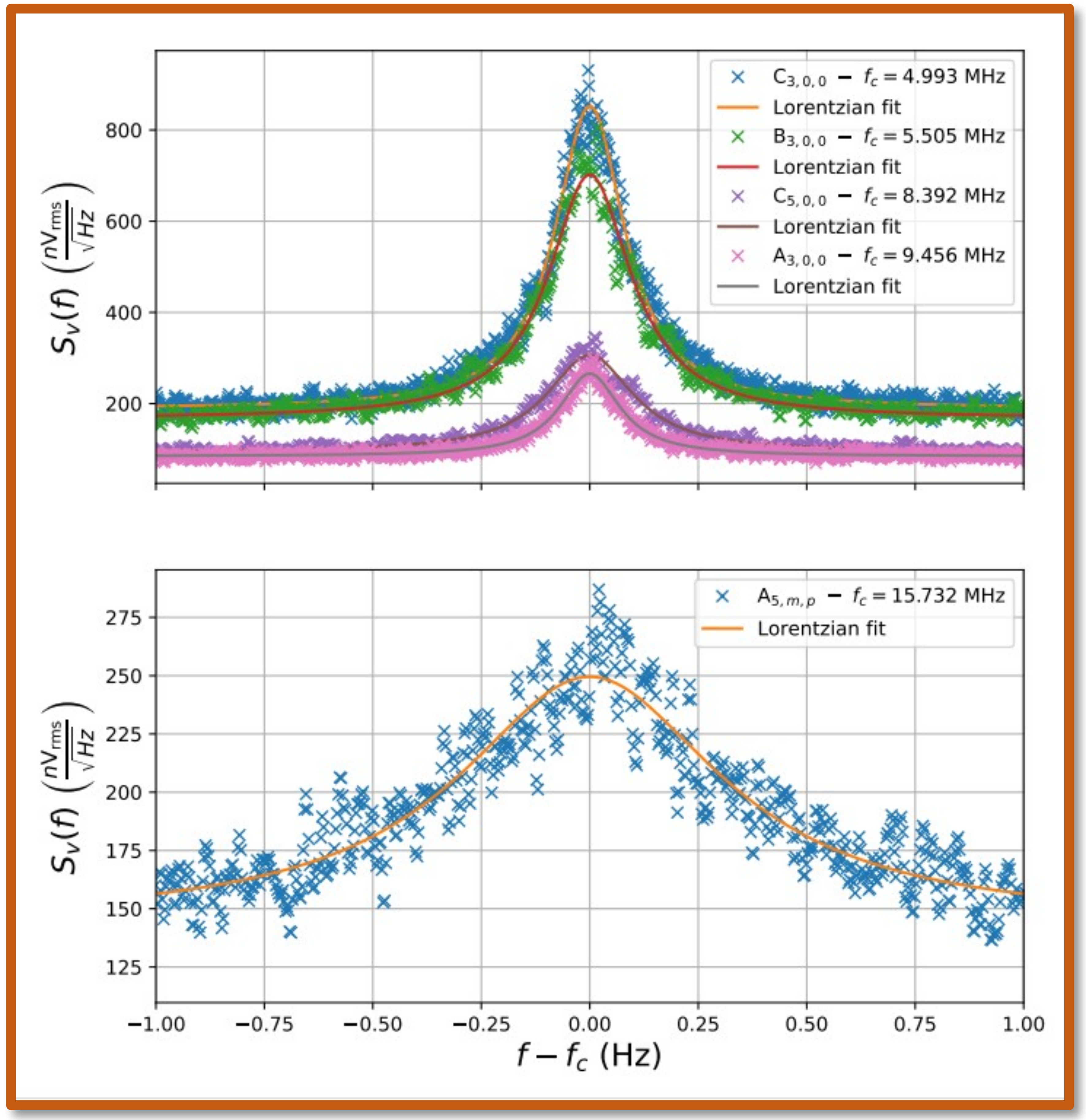
Calibration of 2nd detector





f_{3dB}~3 MHz

Modes up to 20 MHz are still observable



MAGE – Searching for new physics

Development of FPGA data acquisition

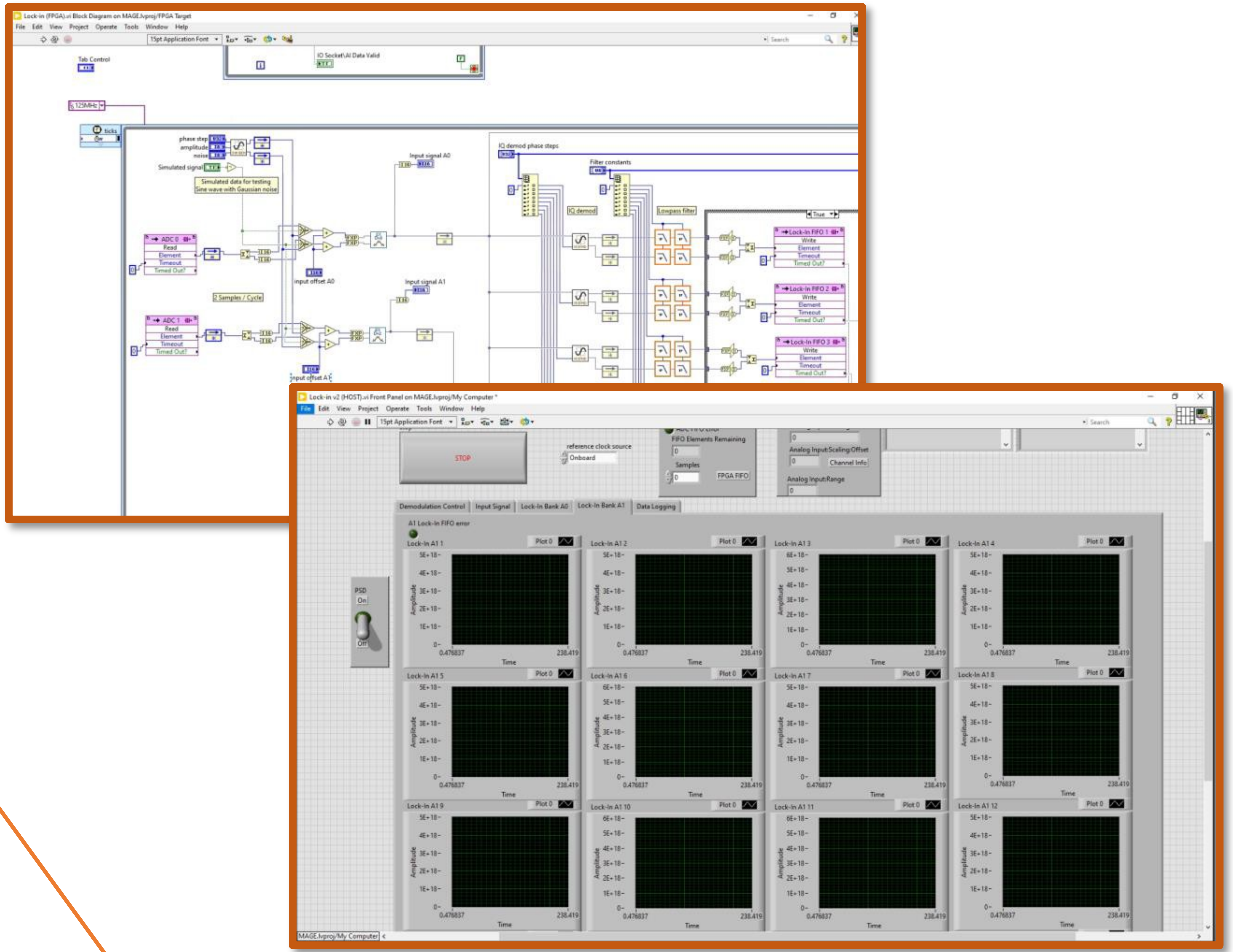
National Instruments – 5763 Digitizer
LabVIEW

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

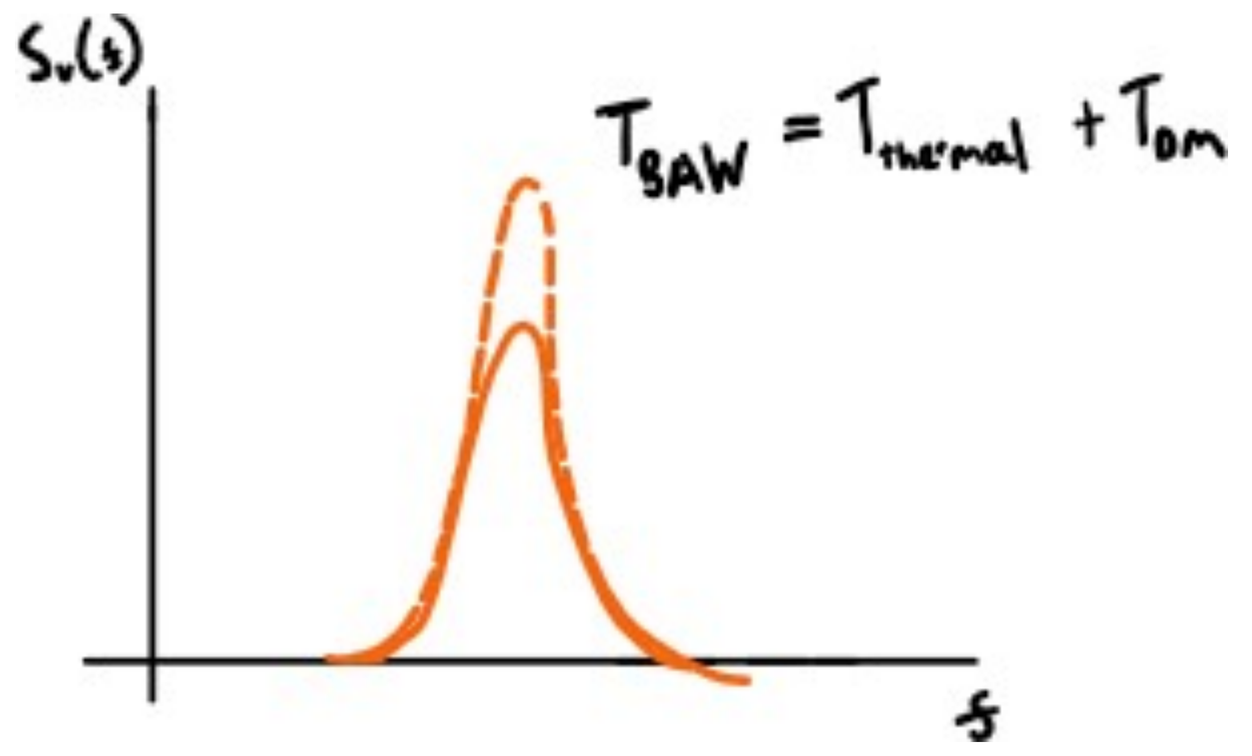


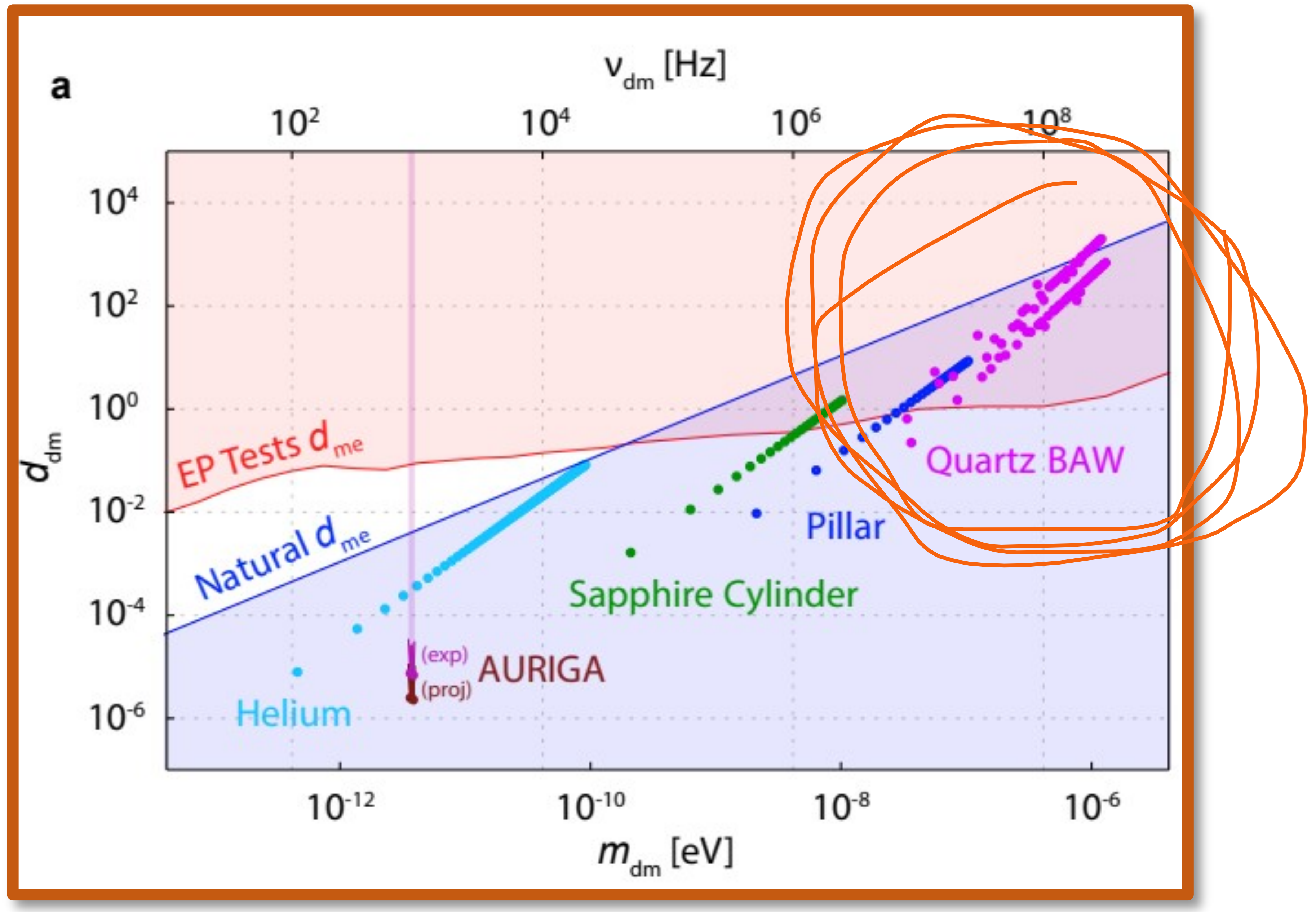
16 modes in each crystal
Currently taking data

MAGE – Searching for new physics

Other possibilities for MAGE:

Scalar DM -> Isotropic strain signal



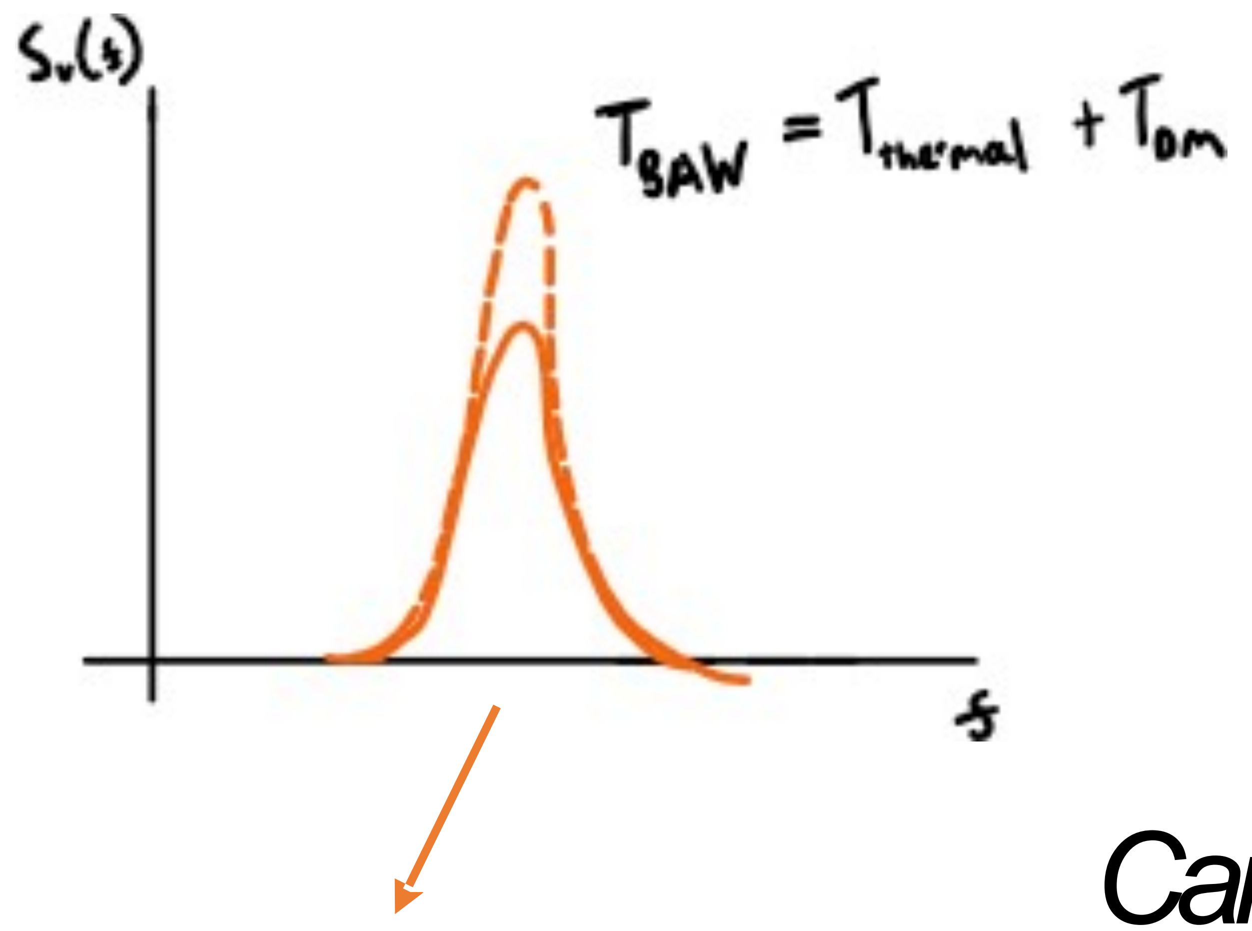


Phys. Rev. Lett. **124**, 151301

MAGE – Searching for new physics

<u>*Other possibilities for MAGE:*</u>

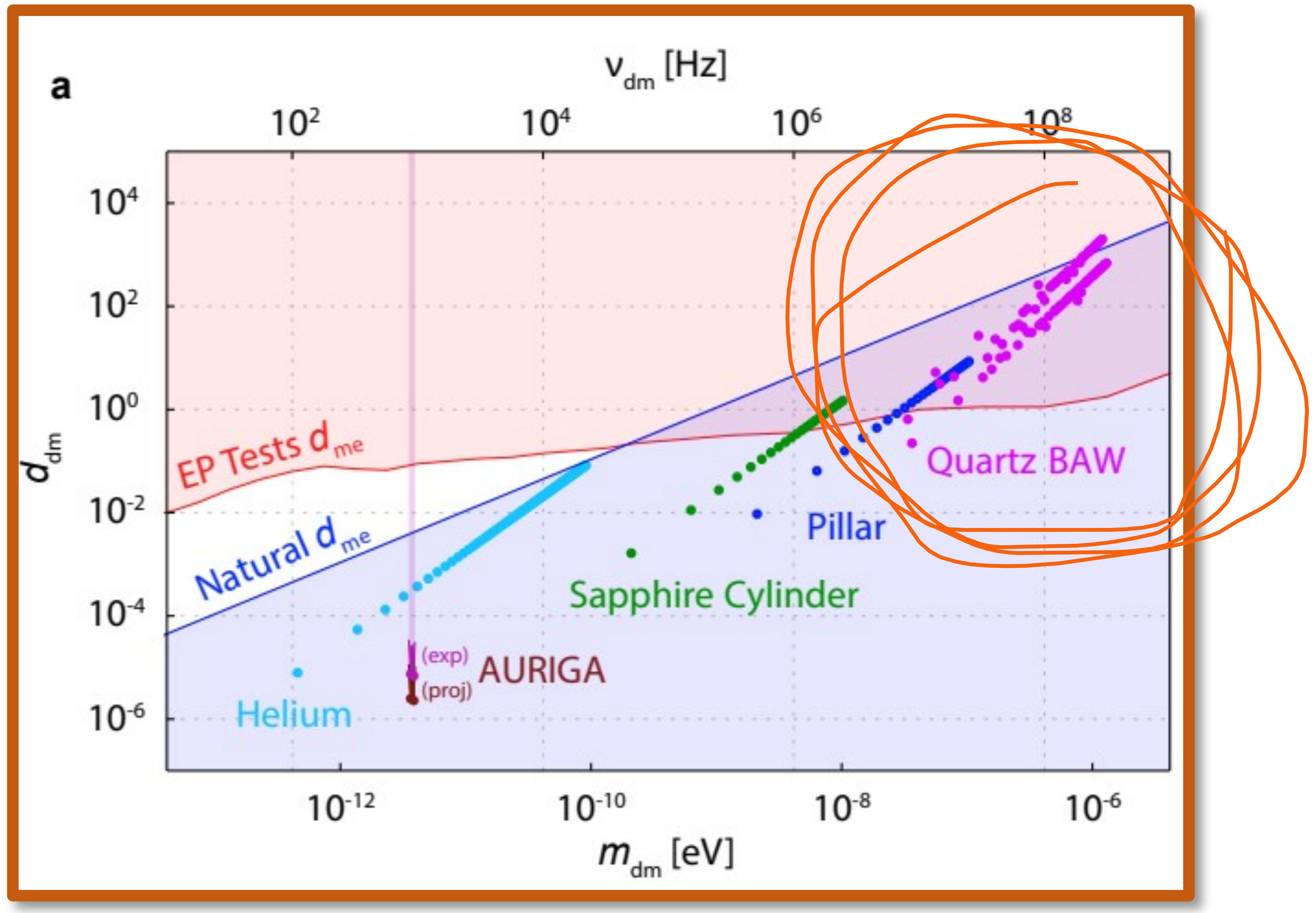
Scalar DM -> Isotropic strain signal



Nontrivial DM signal

<u>*Can exclude*</u>:
Transient flows
Daily modulation

<u>*Ongoing work*</u>:
Resonance tuning



Phys. Rev. Lett. **124**, 151301

MAGE – Searching for new physics

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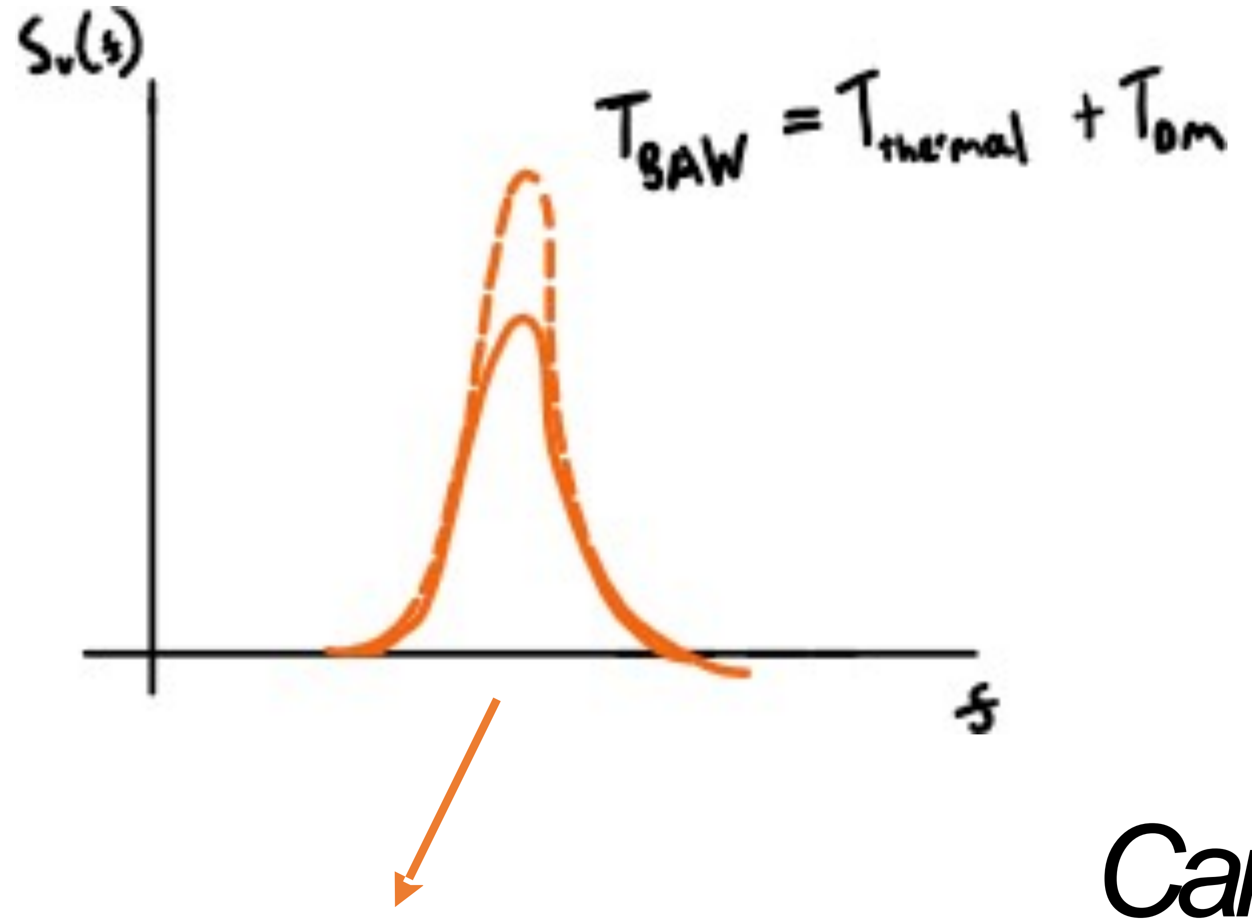


Nontrivial DM signal

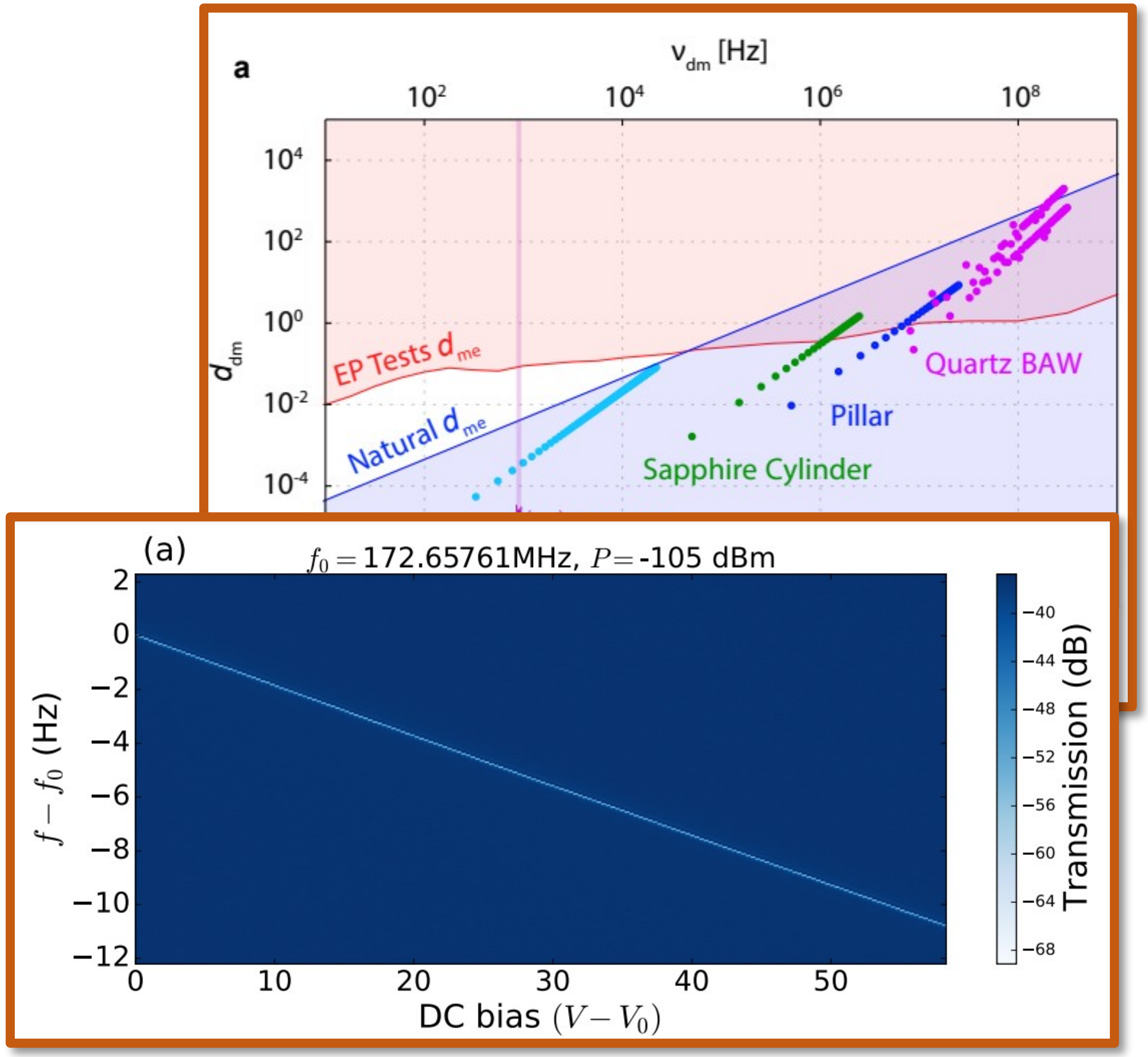
Can exclude:

Transient flows

Daily modulation

Ongoing work:

Resonance tuning → 2207.01176

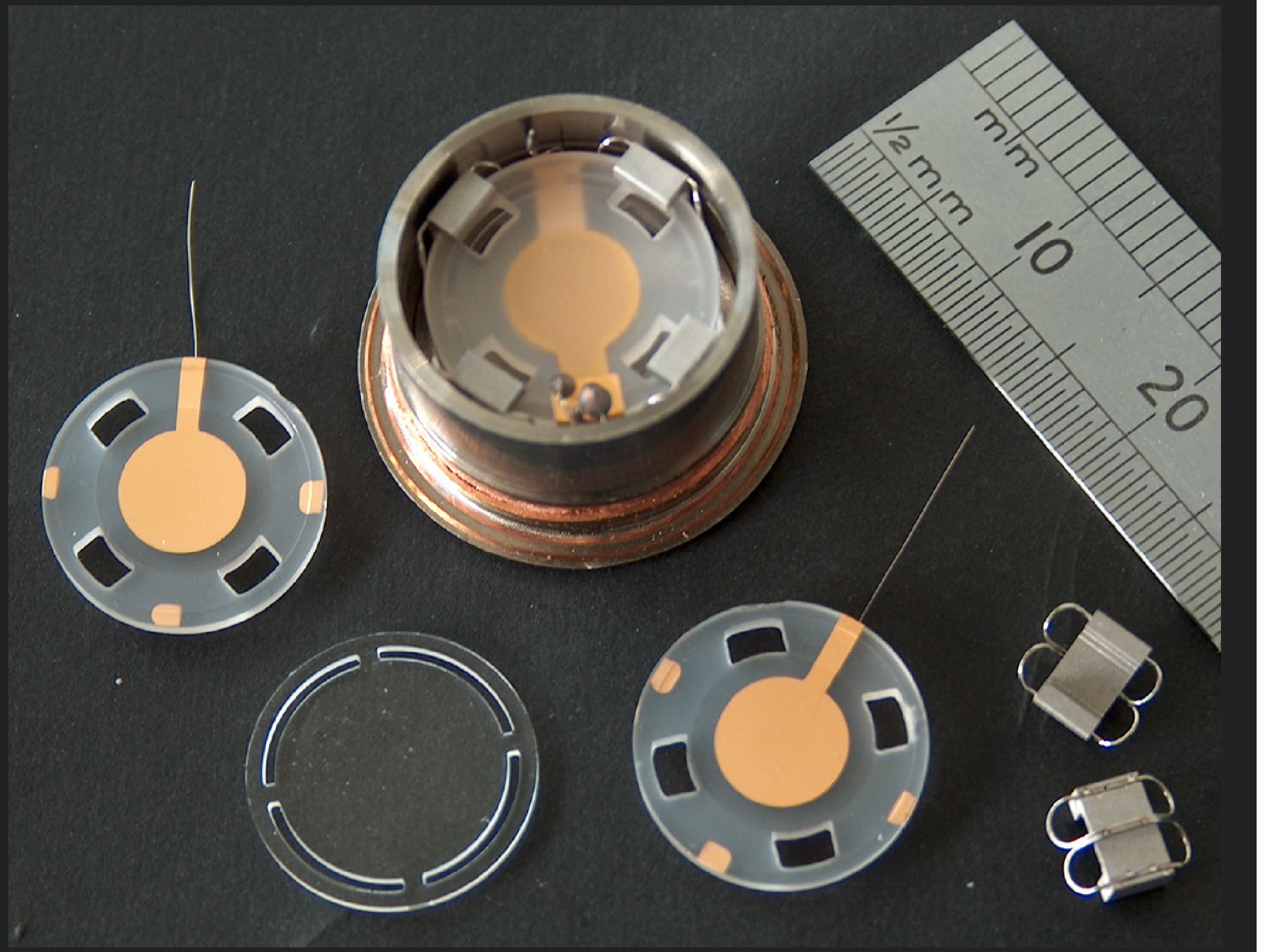


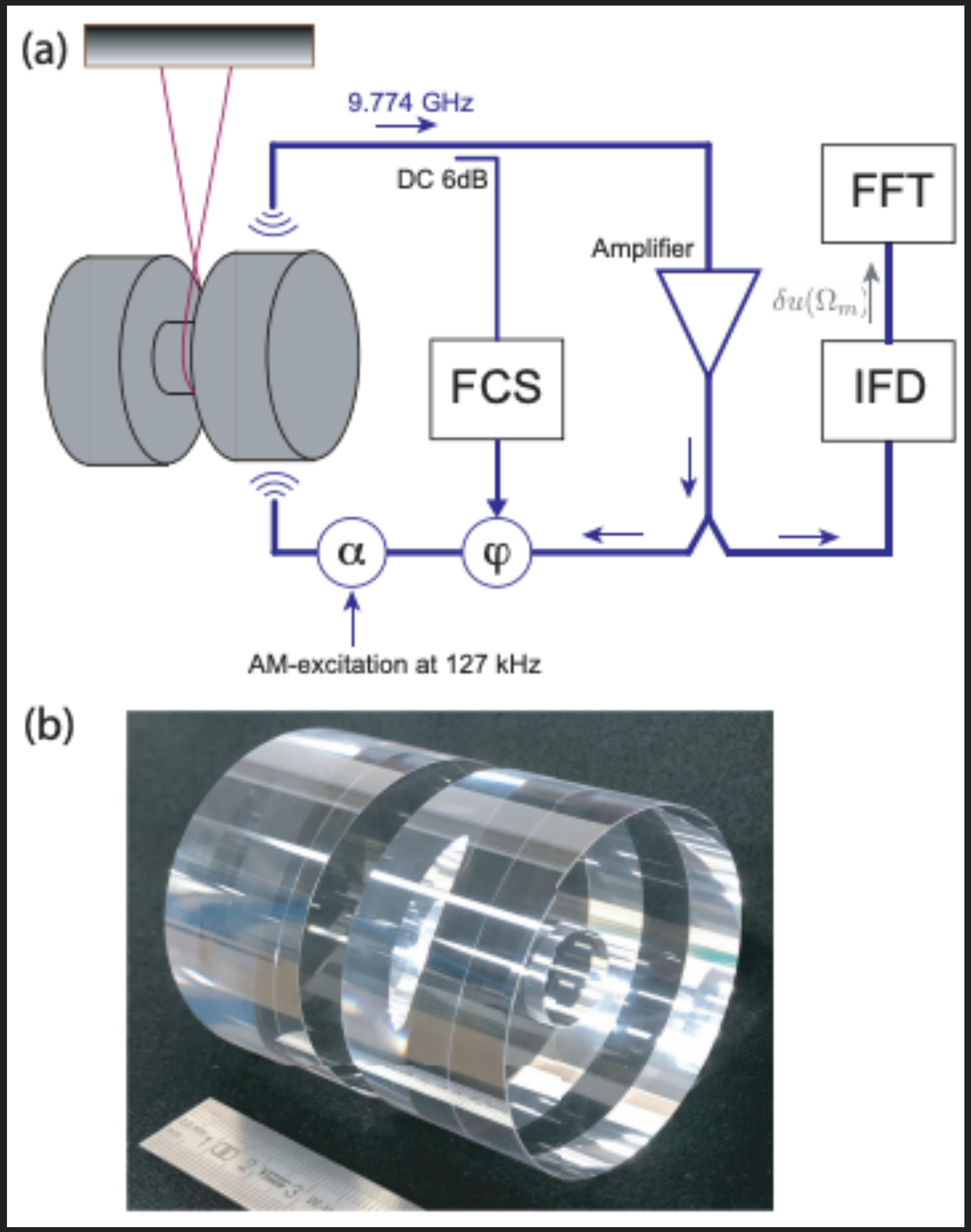
Acoustic Tests of Quantum Gravity

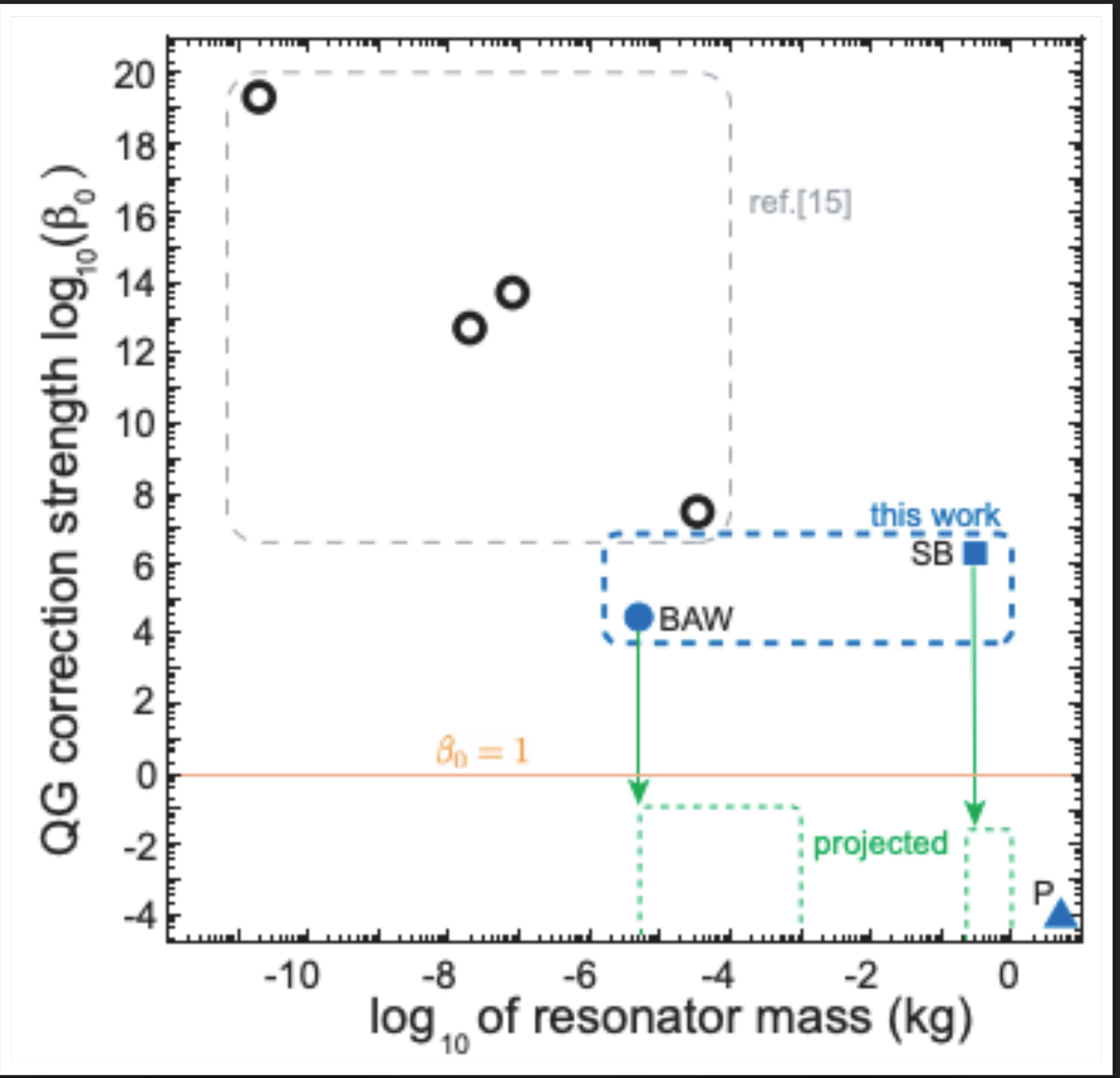
Testing the generalized uncertainty principle with macroscopic mechanical oscillators and pendulums

P. A. Bushev, J. Bourhill, M. Goryachev, N. Kukharchyk, E. Ivanov, S. Galliou, M. E. Tobar, and S. Danilishin

Phys. Rev. D **100**, 066020 – Published 20 September 2019







EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

ARC CENTRE OF EXCELLENCE FOR
DARK MATTER

Minimum Length

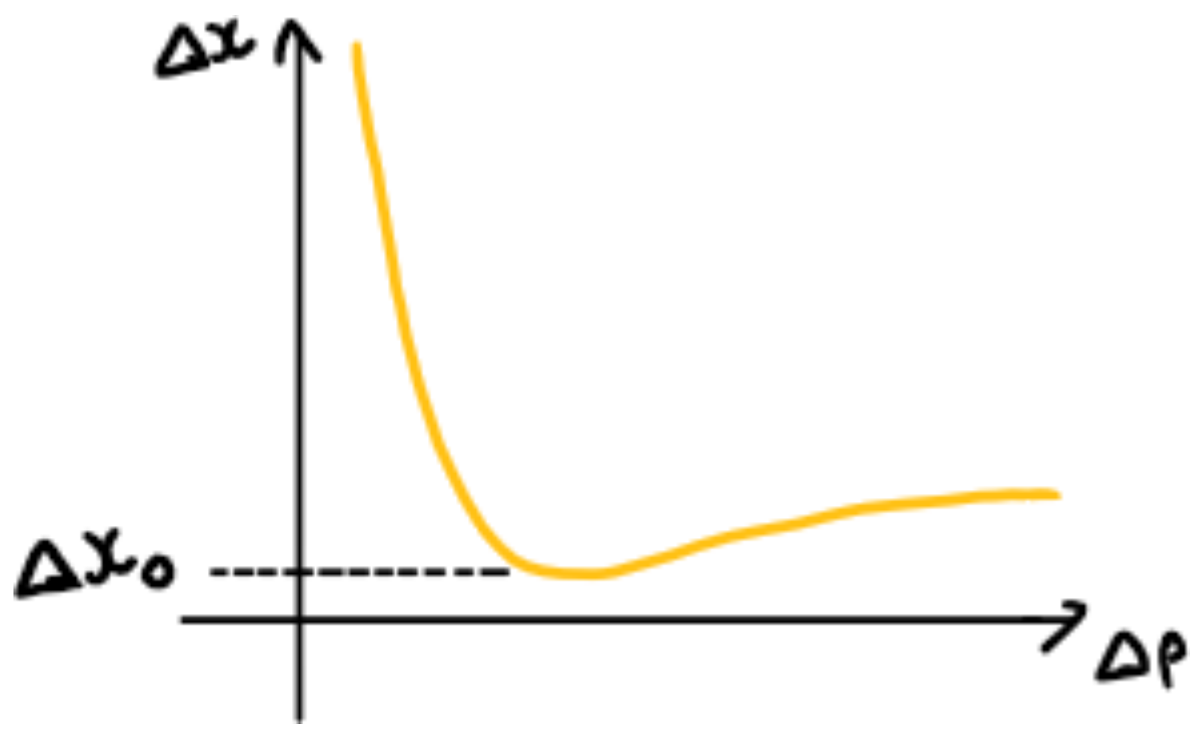
Quantum gravity models

↓

Fundamental minimum length scale $\sim l_{planck}$

↓

Generalized uncertainty principle ⟶ $$\Delta x \Delta p \geq \frac{\hbar}{2}\left[1+\beta_0\left(\frac{l_p \Delta p}{\hbar}\right)^2\right],$$

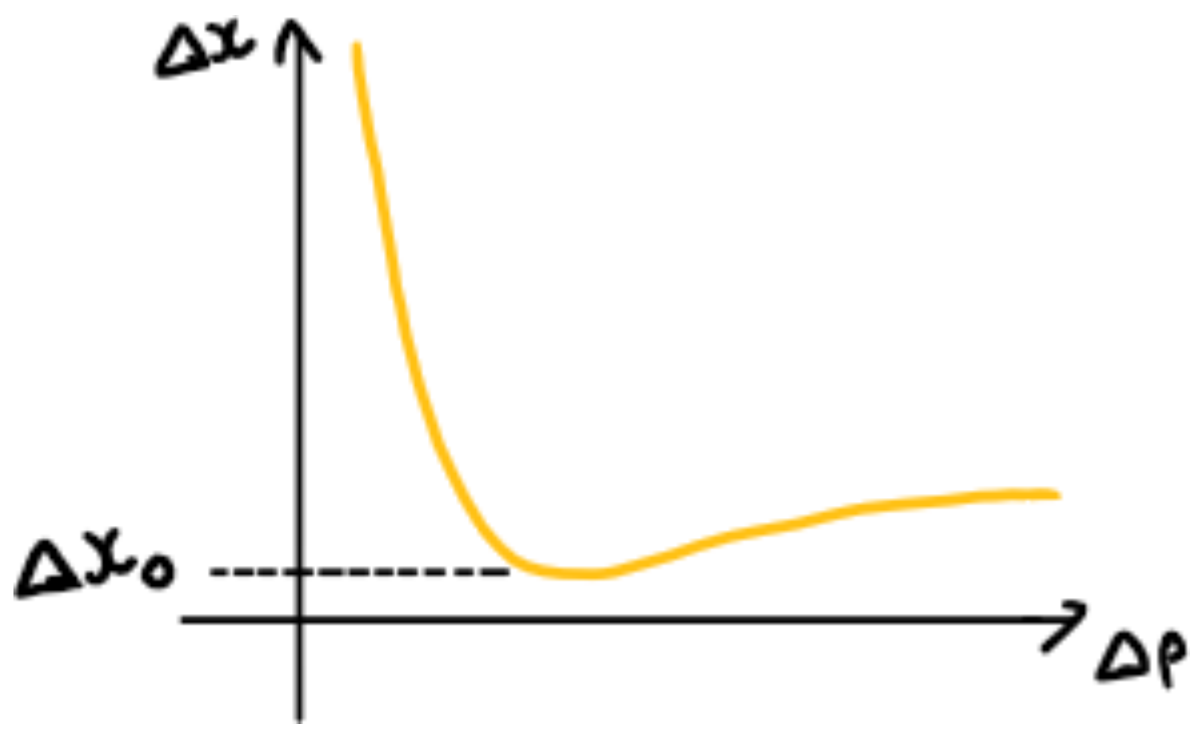


Minimum Length

How can we test it ?

$l_{planck} = 1.62 \times 10^{-35}$ m

$E_{planck} = 1.2 \times 10^{9}$GeV



Minimum Length

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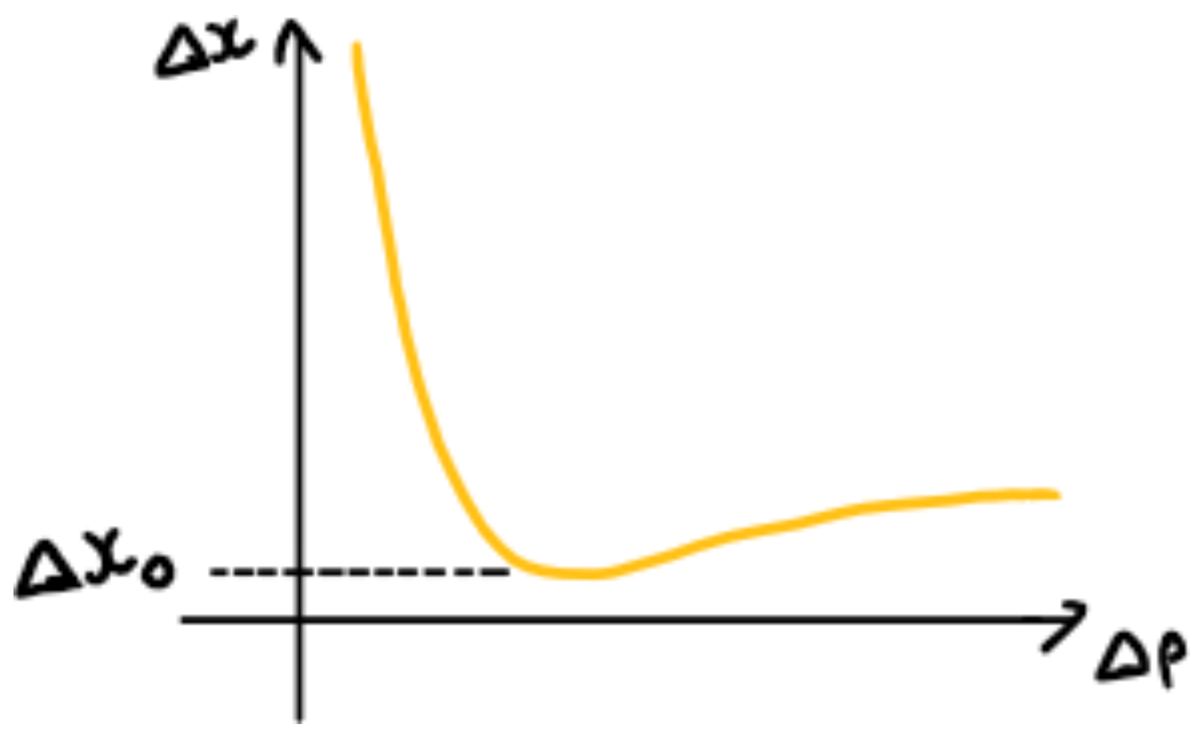

Consider *deformed* Heisenberg algebra of harmonic oscillator

$$[\hat{x}, \hat{p}] = i\hbar\left(1 + \beta_0\left(\frac{l_p}{\hbar}\hat{p}\right)^2\right)$$

Equations of motion of harmonic oscillator

$$Q = Q_0\left[\sin(\tilde{\omega}t) + \frac{\beta}{8}Q_0^2\sin(3\tilde{\omega}t)\right],$$

$$\tilde{\omega} = (1 + \frac{\beta}{2}Q_0^2)\omega_0.$$

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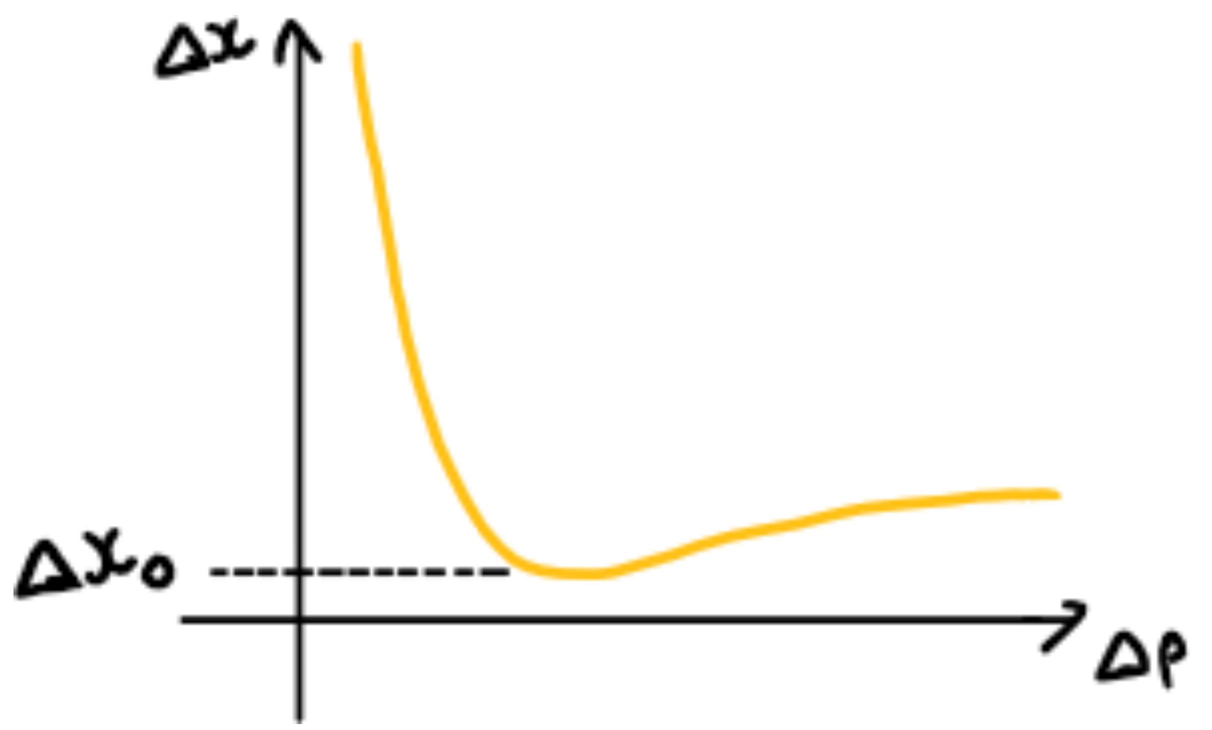
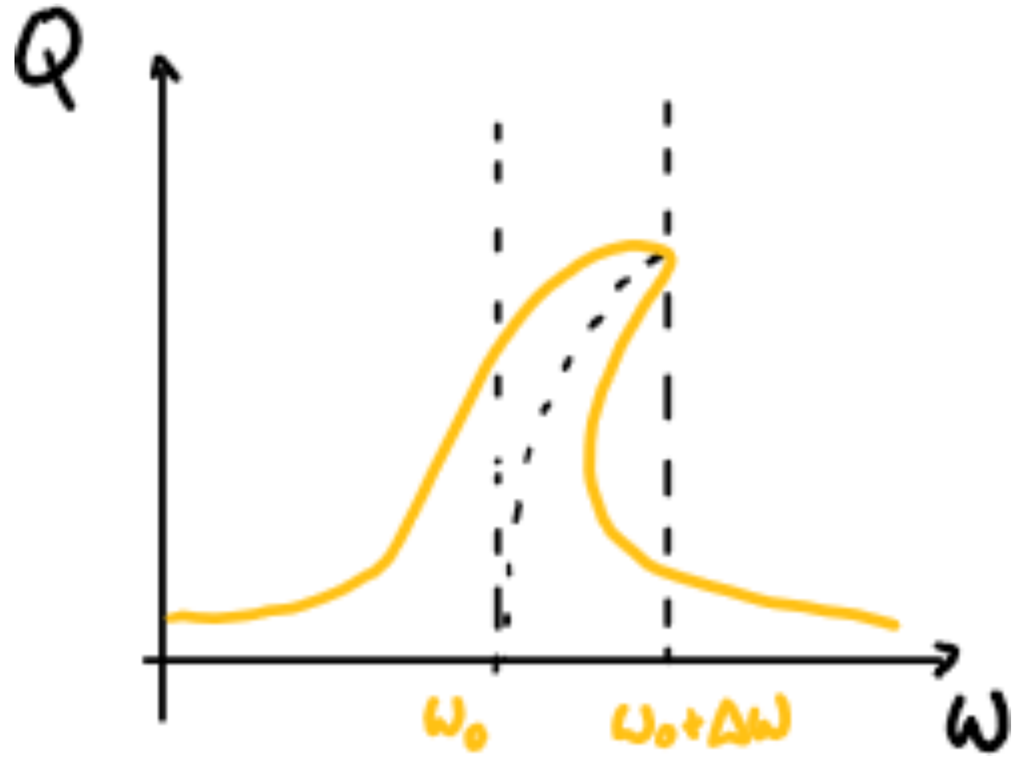
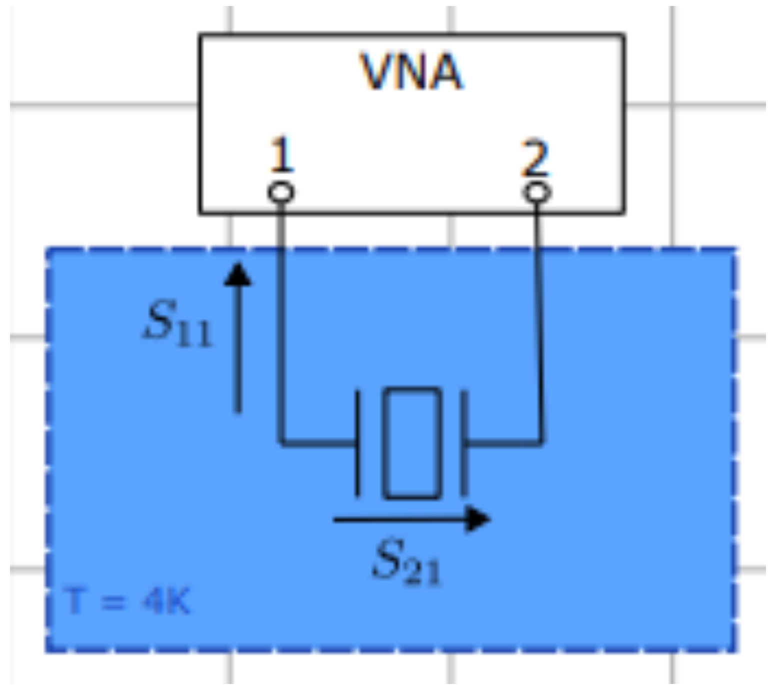
$\Delta\omega_0$

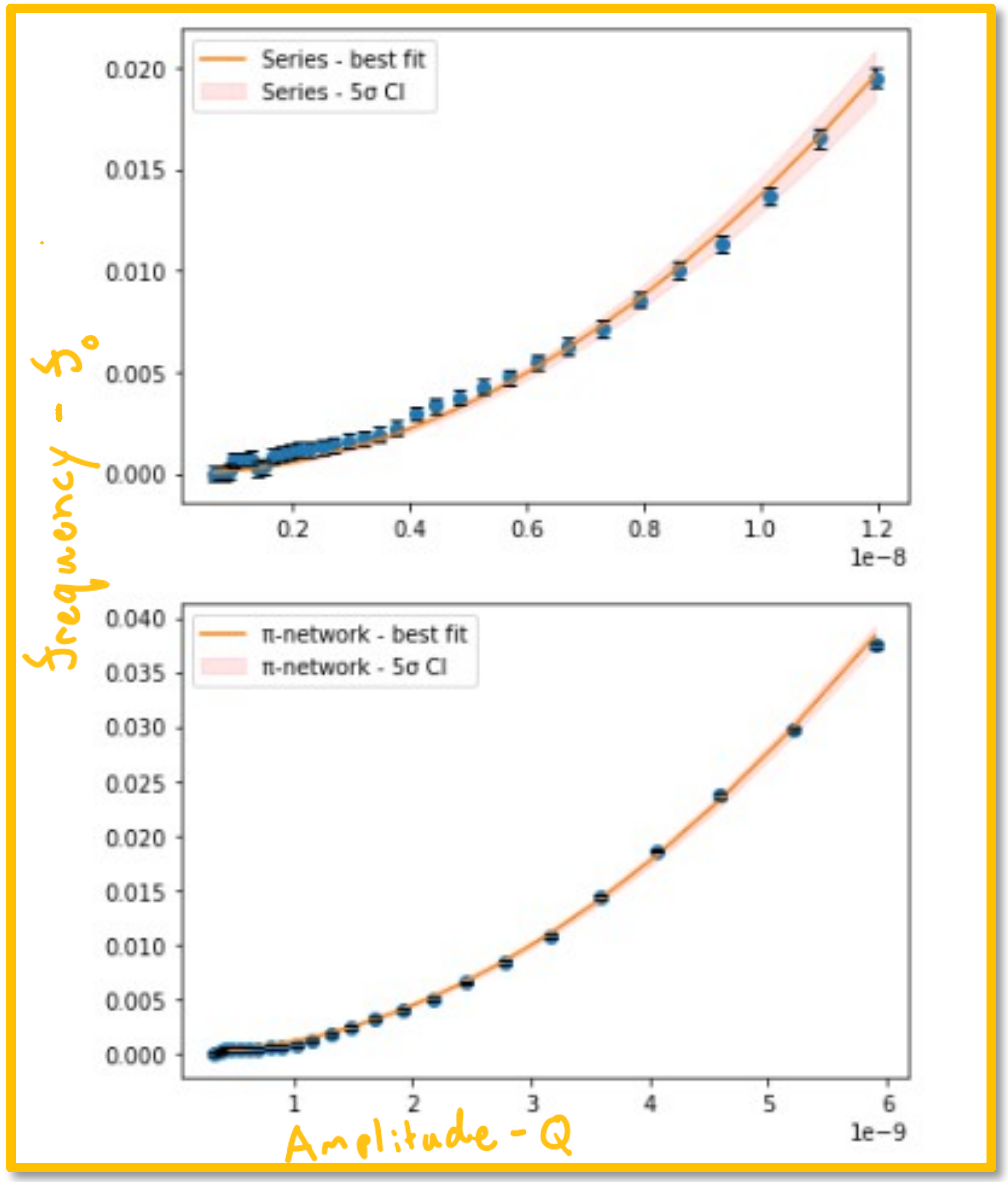


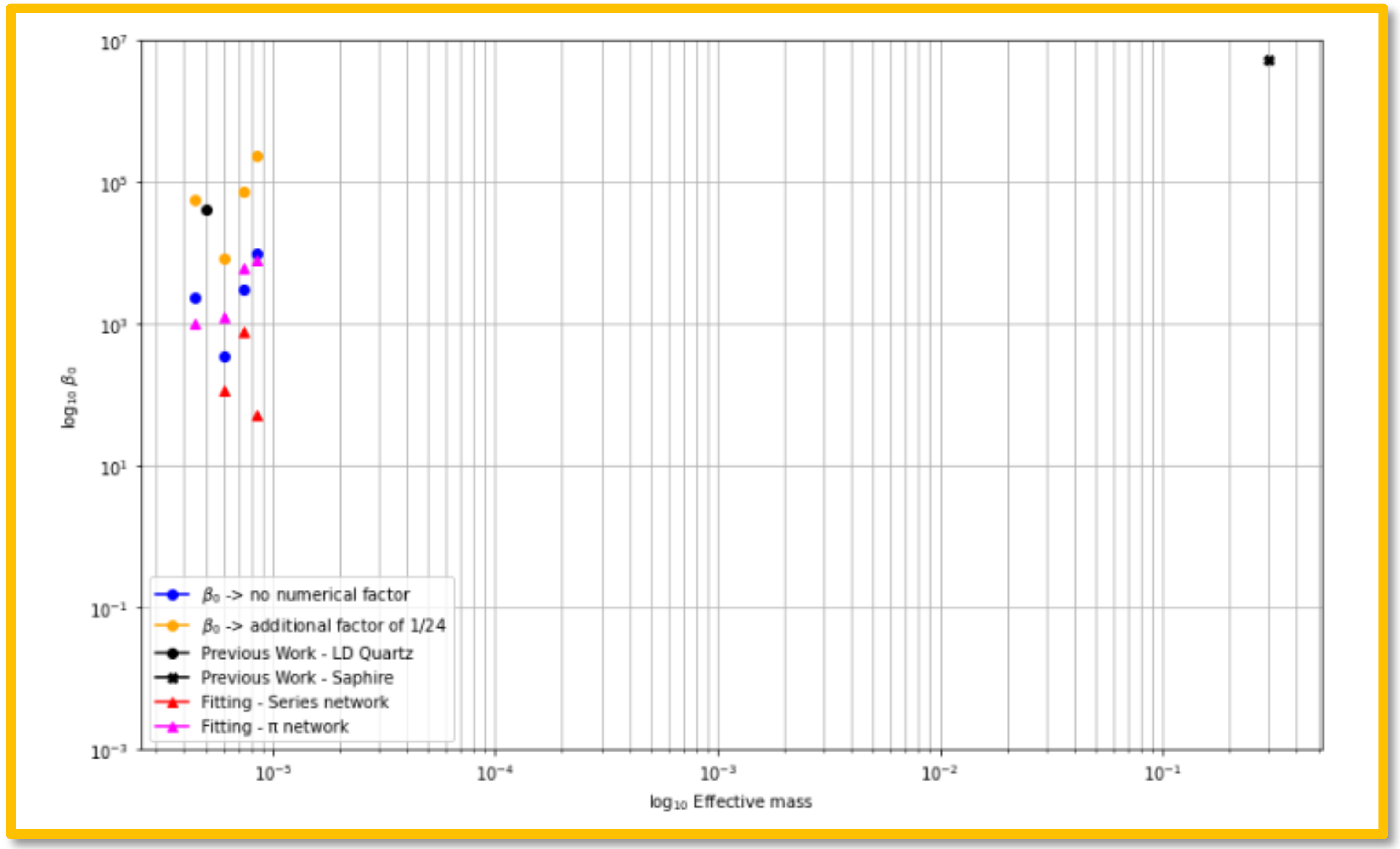


Minimum Length

Using quartz resonator







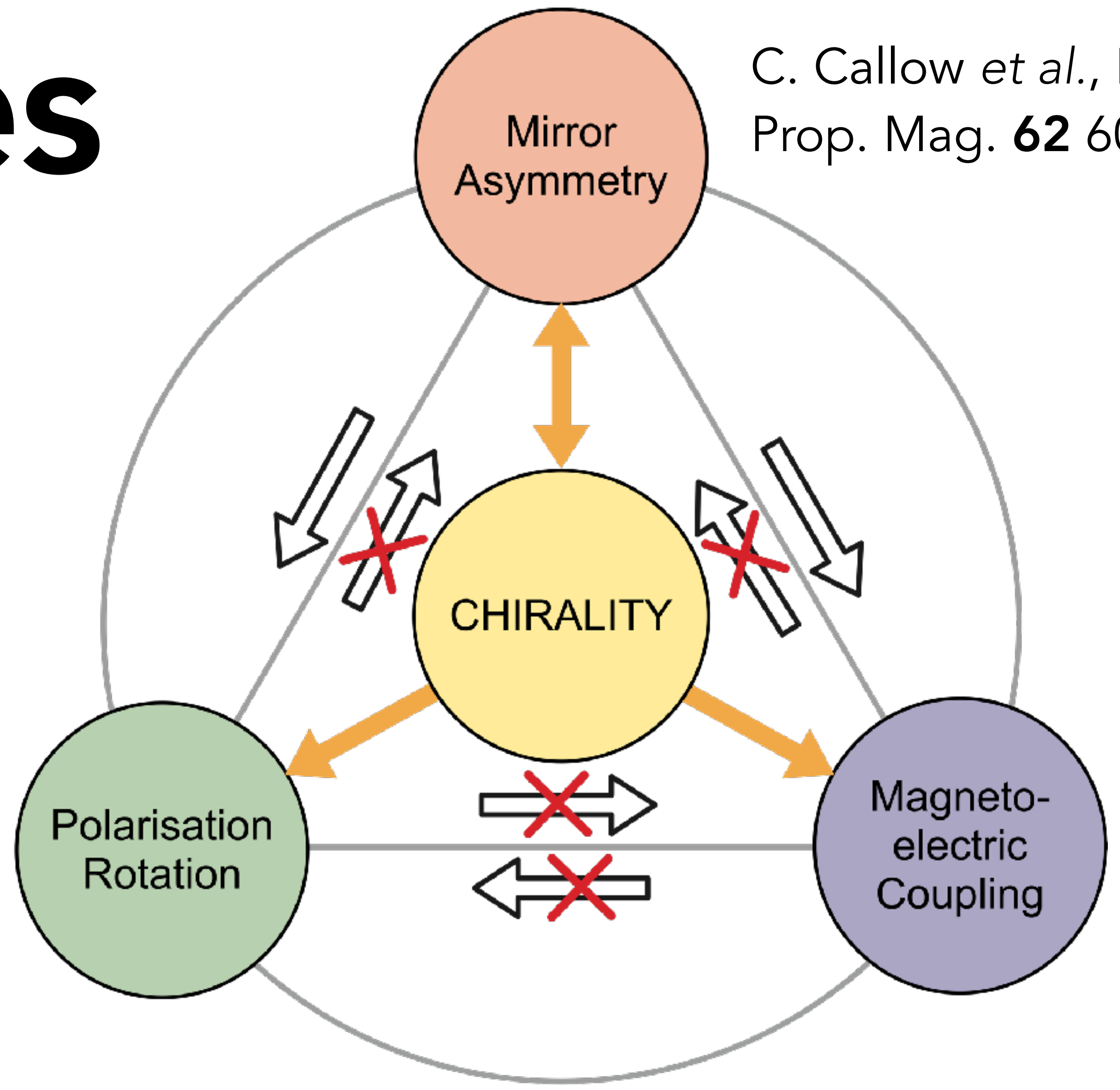
Twisted "anyon" microwave cavities

Engineered electromagnetic helicity *in vacuo*

Twisted "anyon" microwave cavities

Engineered electromagnetic helicity *in vacuo*

- **Chirality** is an inherent property of a particle, just like your left and right hands

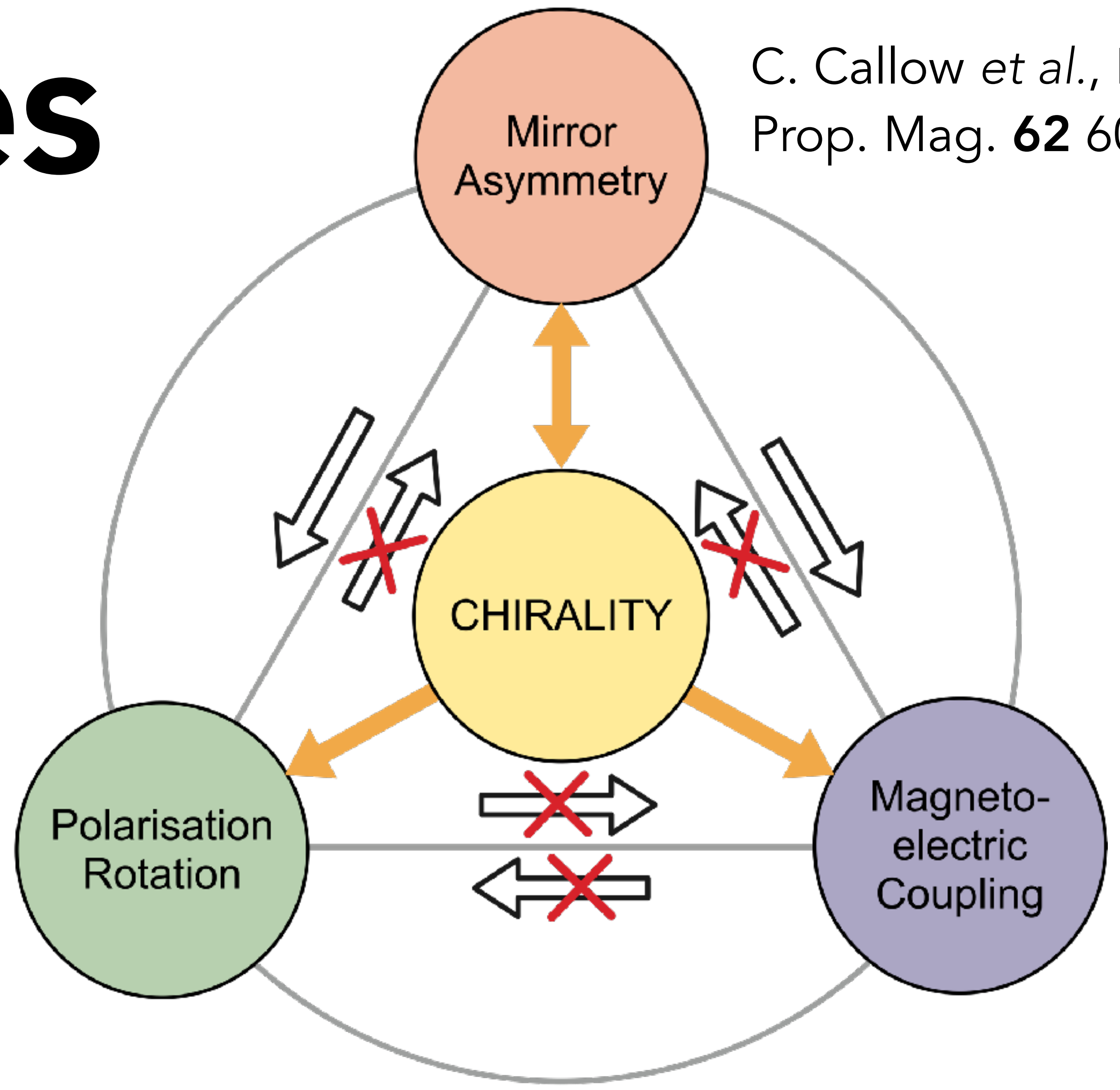


C. Callow *et al.*, IEEE Ant. And Prop. Mag. **62** 60 (2020)

Twisted "anyon" microwave cavities

Engineered electromagnetic helicity *in vacuo*

- **Chirality** is an inherent property of a particle, just like your left and right hands
- **Helicity** depends on if a particle's spin is aligned or anti-aligned with its momentum



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

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

Twisted “anyon” microwave cavities

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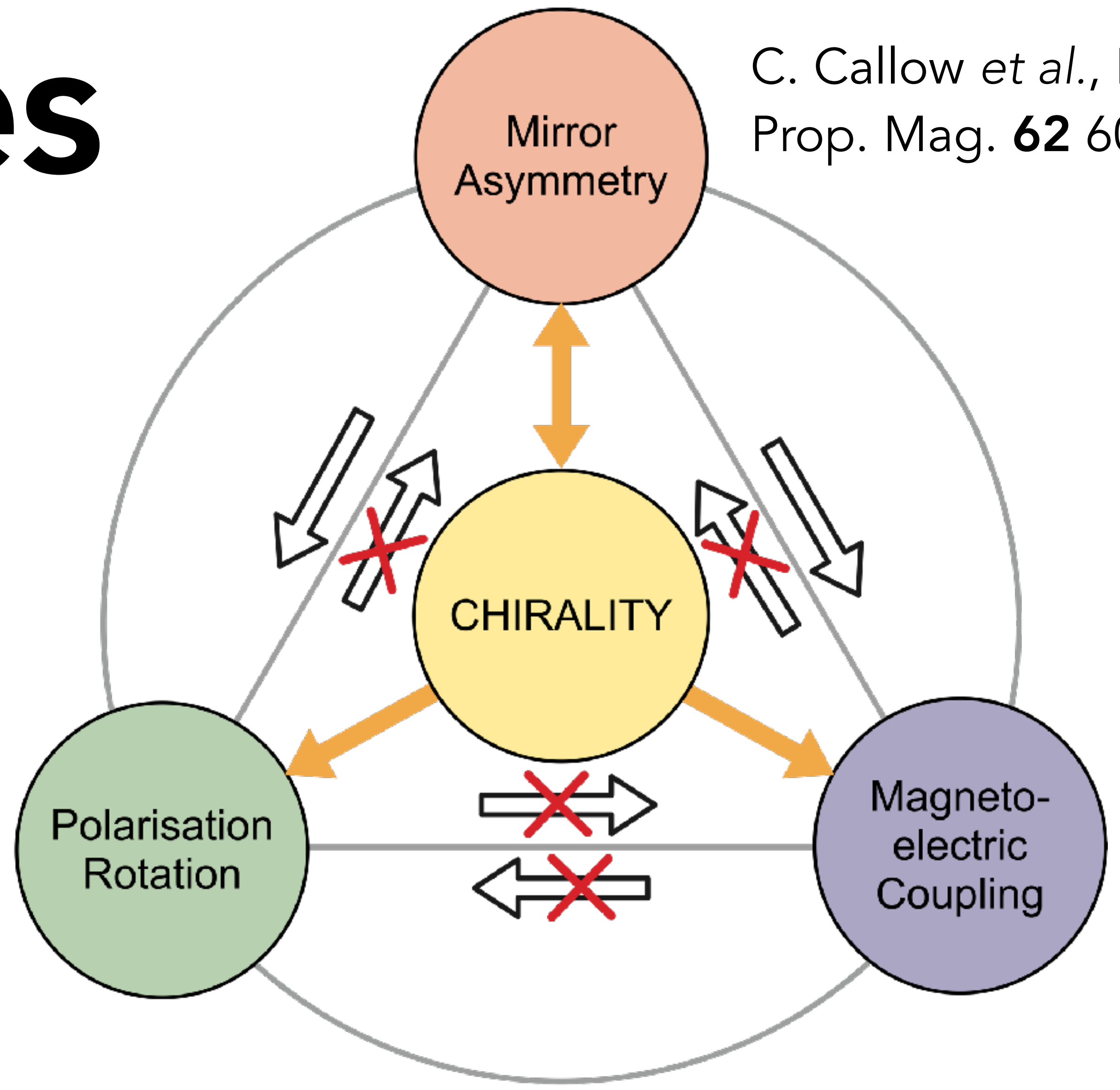

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- M*assless* particle -> unable to alter helicity by changing frames -> If particle is chiral right-handed it will have right handed helicity

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

Twisted "anyon" microwave cavities

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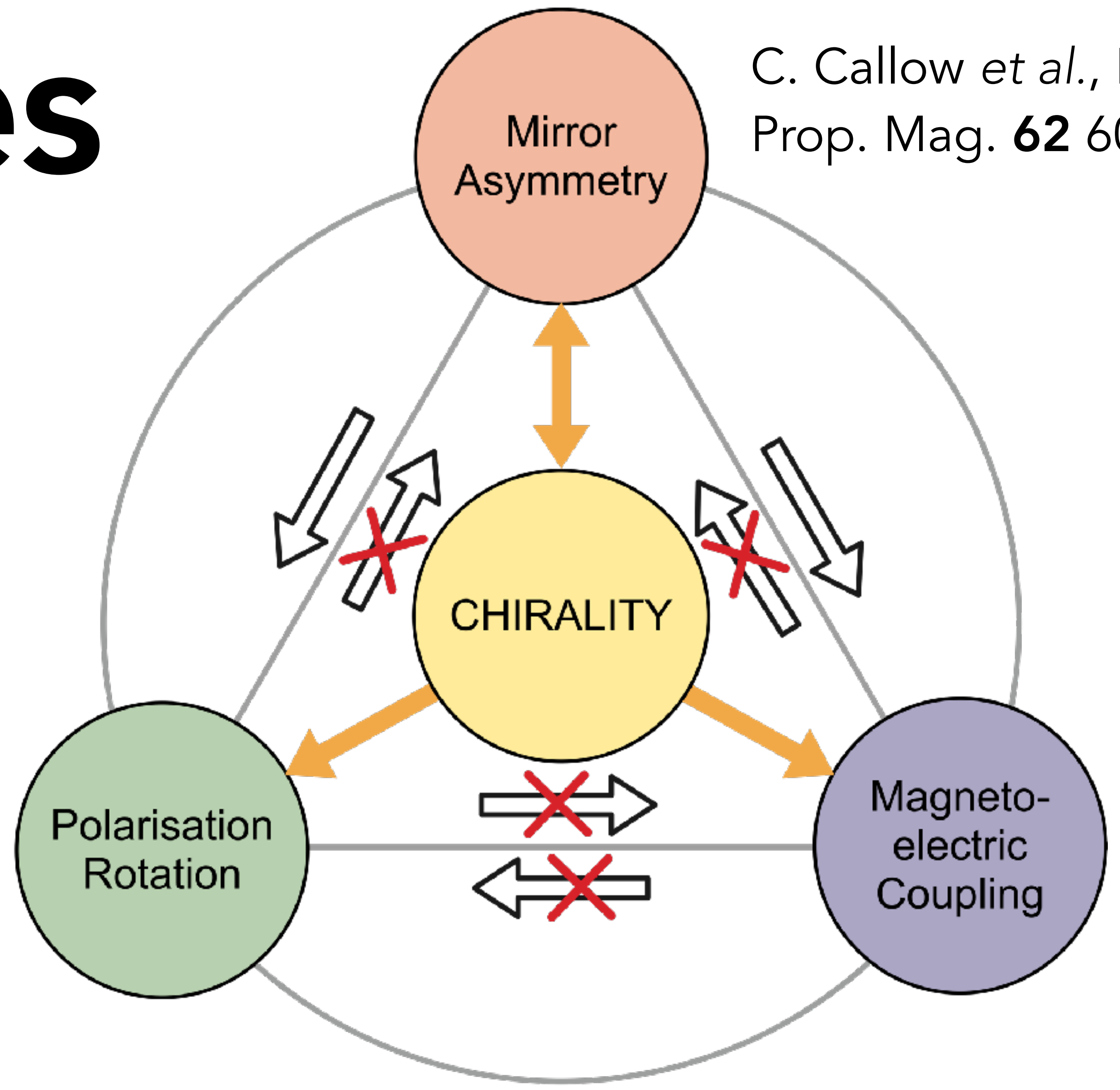

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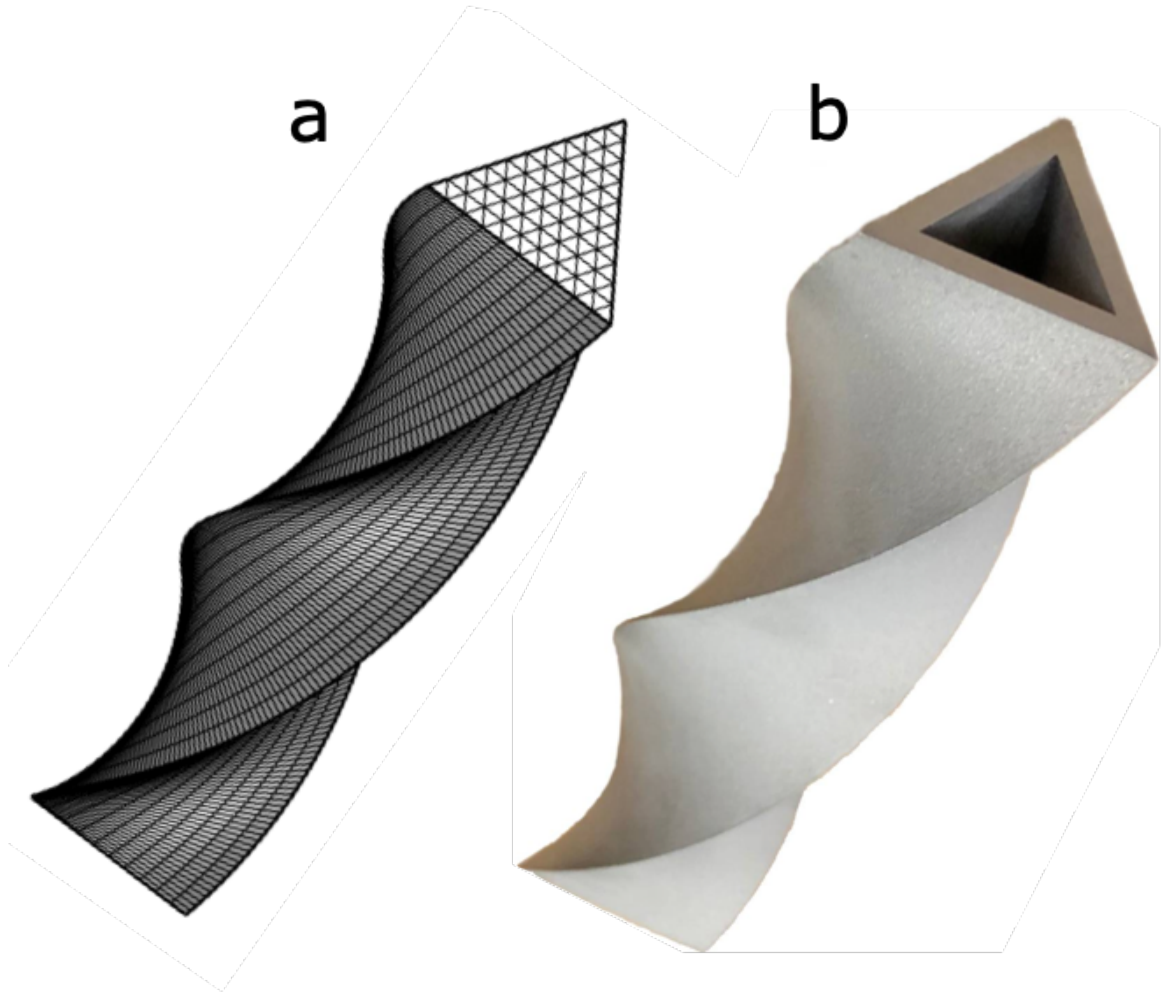


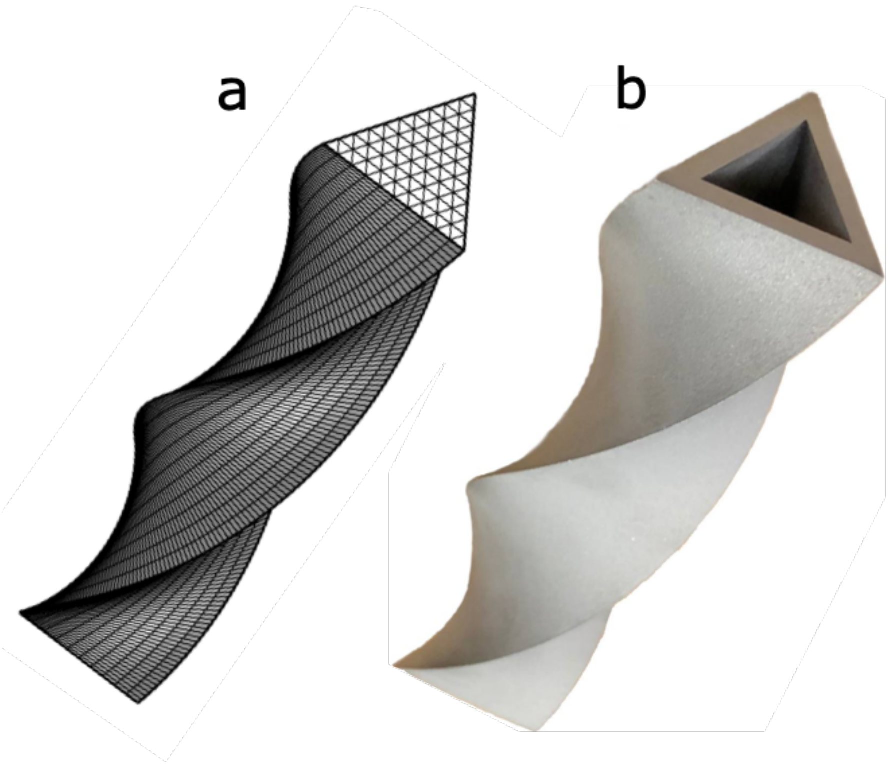
Twisted “anyon” microwave cavities

So why a triangle cross-section?

Quantum Technologies and Dark Matter Research Lab

Twisted “anyon” microwave cavities

So why a triangle cross-section?

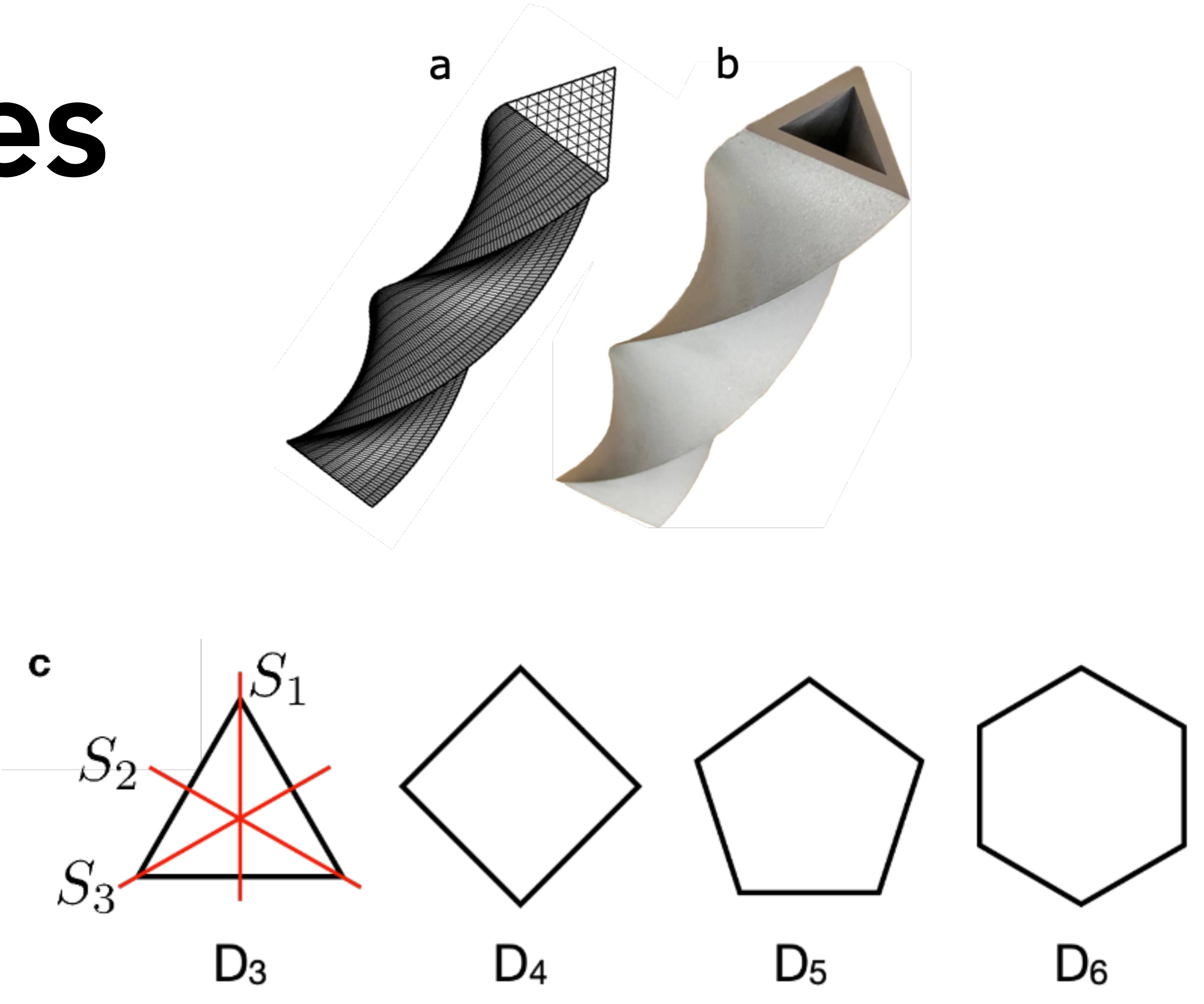


- Cavity **mirror asymmetry** from the clockwise or counter-clockwise twist

Twisted "anyon" microwave cavities

So why a triangle cross-section?

- Cavity **mirror asymmetry** from the clockwise or counter-clockwise twist
- If cross-section a regular polygon, as we increase the number of planes of symmetry, we further approximate a circle -> which shows no mirror asymmetry



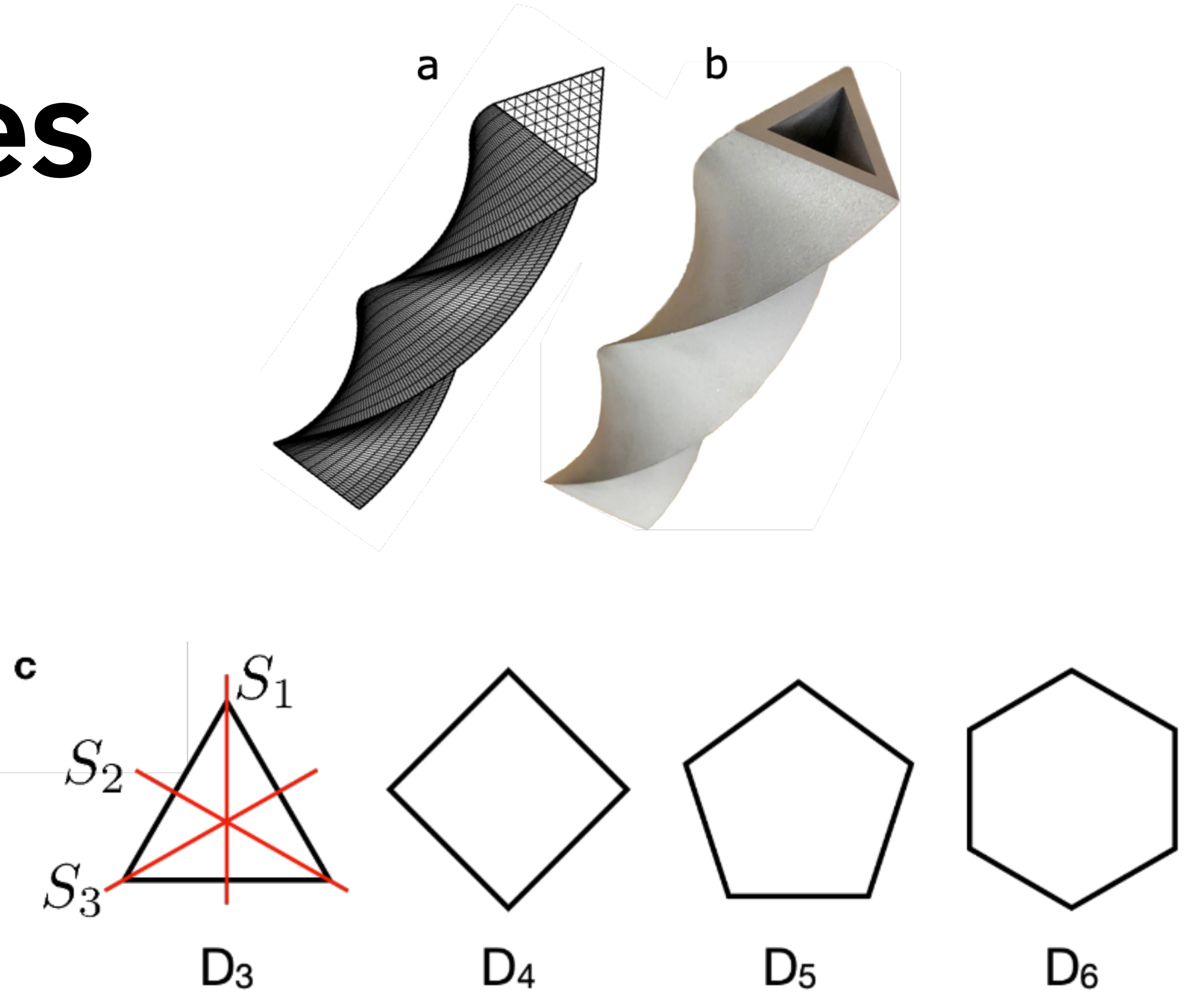
Twisted "anyon" microwave cavities

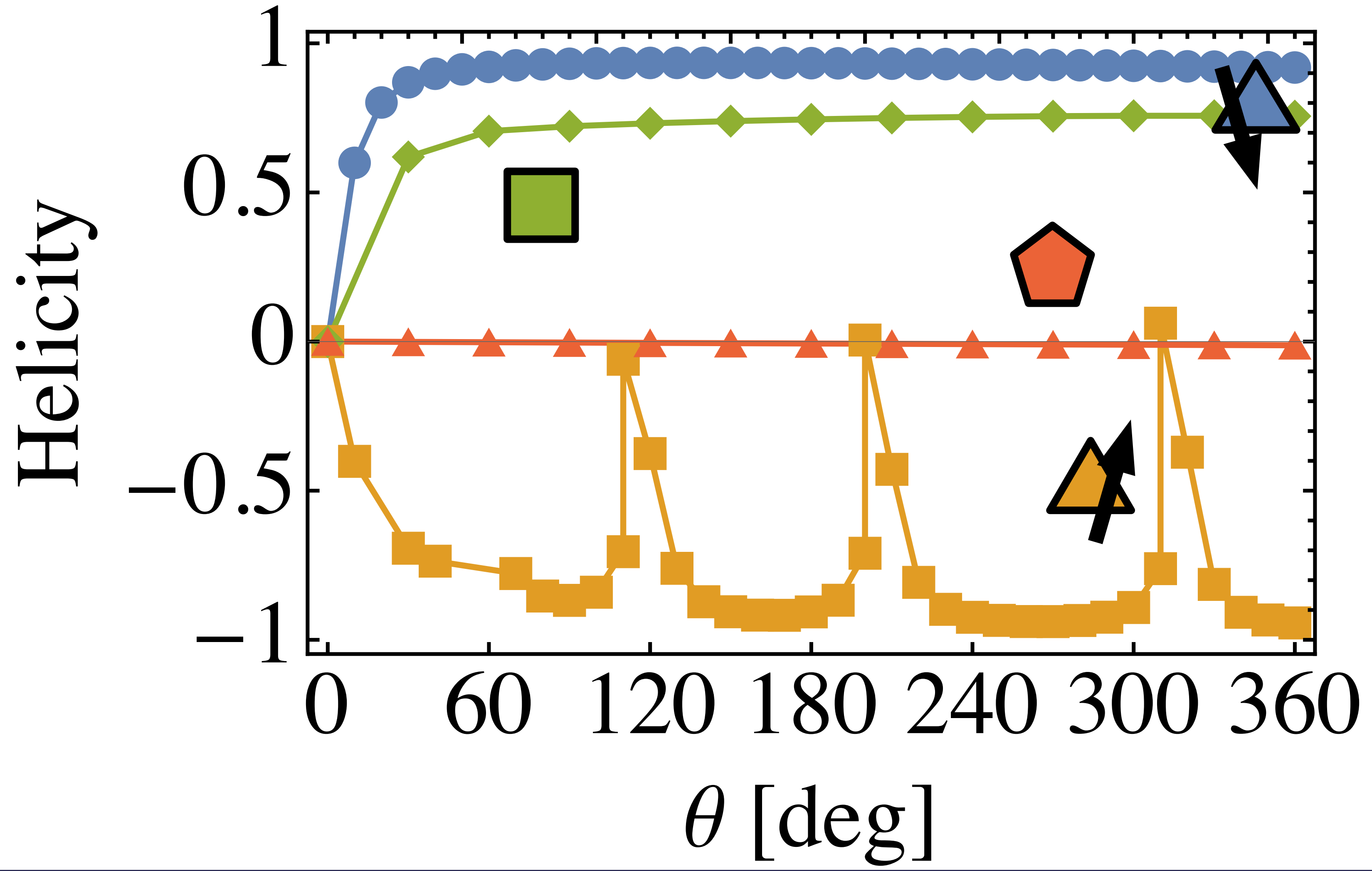
So why a triangle cross-section?

- Cavity **mirror asymmetry** from the clockwise or counter-clockwise twist

- If cross-section a regular polygon, as we increase the number of planes of symmetry, we further approximate a circle -> which shows no mirror asymmetry

- The least amount of symmetry lines -> greatest helicity





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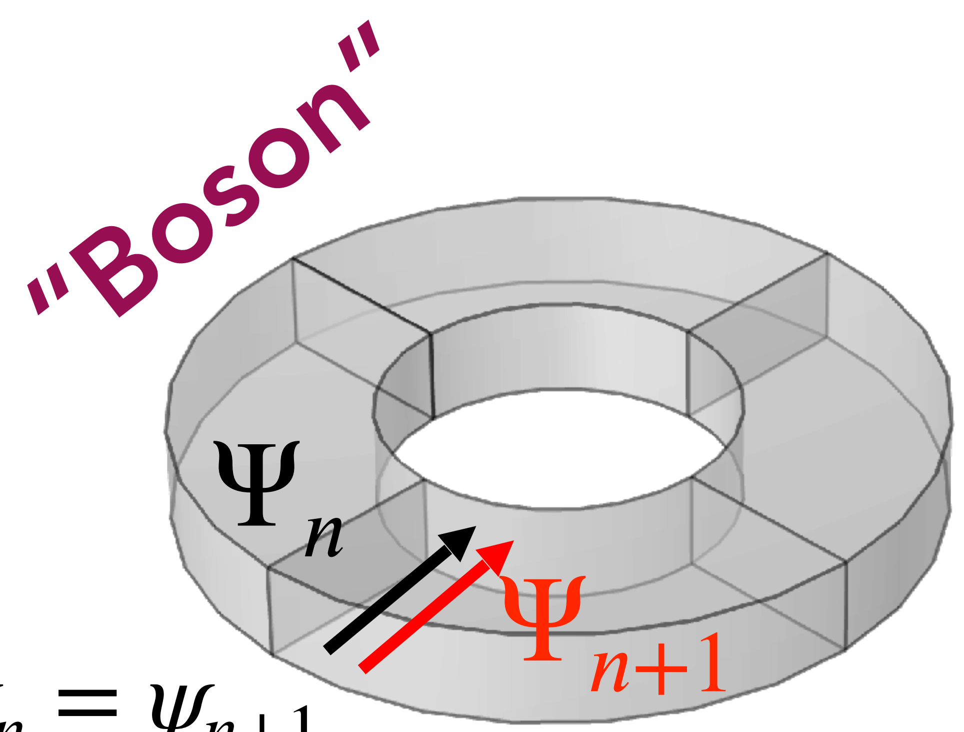
Twisted "anyon" microwave cavities

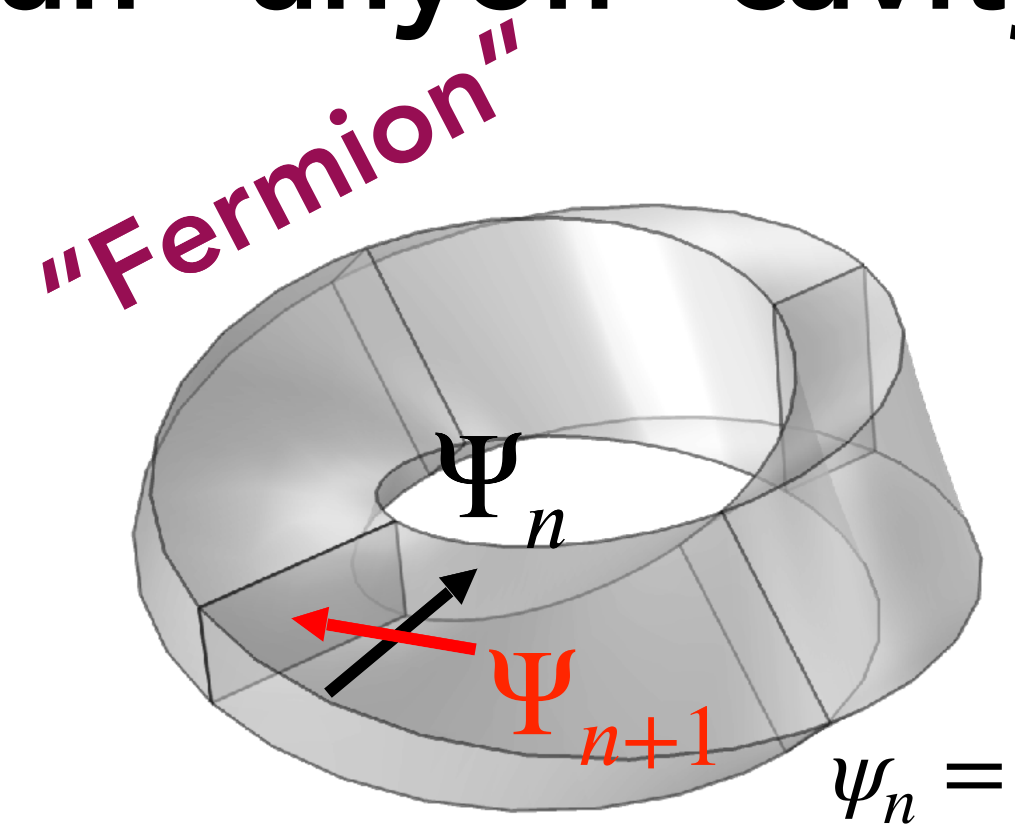
Why is it called an "anyon" cavity?

Twisted “anyon” microwave cavities

Why is it called an “anyon” cavity?



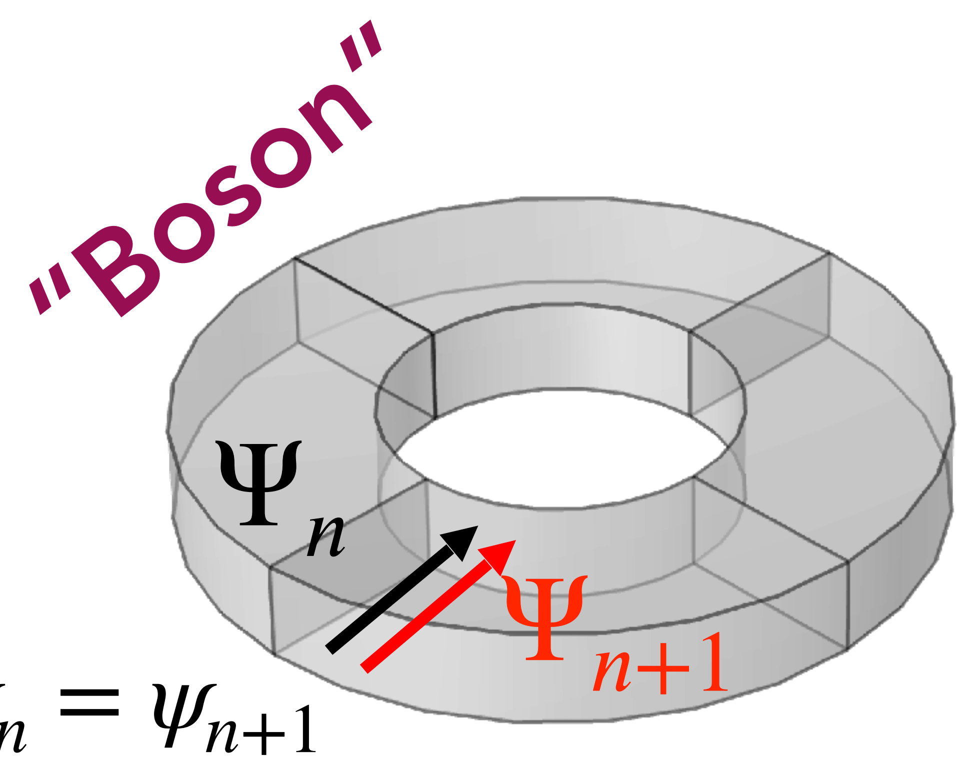
$\psi_n = \psi_{n+1}$
$\psi_n = \psi_{n+N}$
$\theta = 0$



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

Twisted "anyon" microwave cavities

Why is it called an "anyon" cavity?



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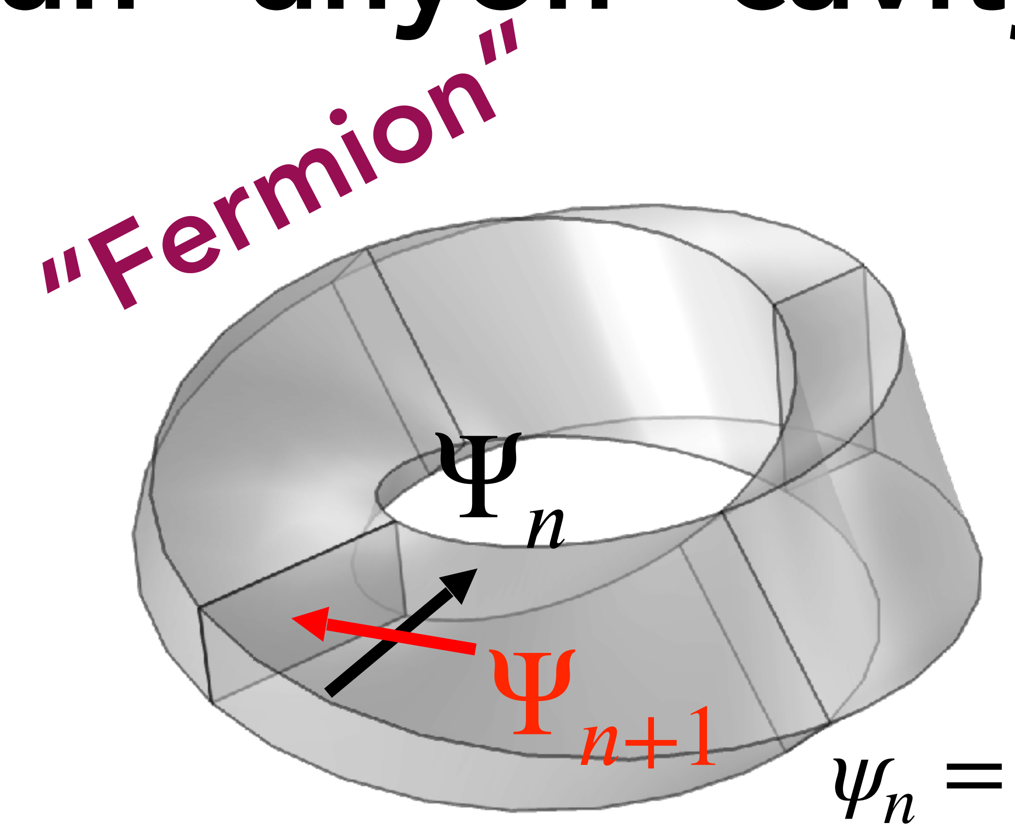

$\psi_n = -\psi_{n+1}$
$\psi_n = \psi_{n+2N}$
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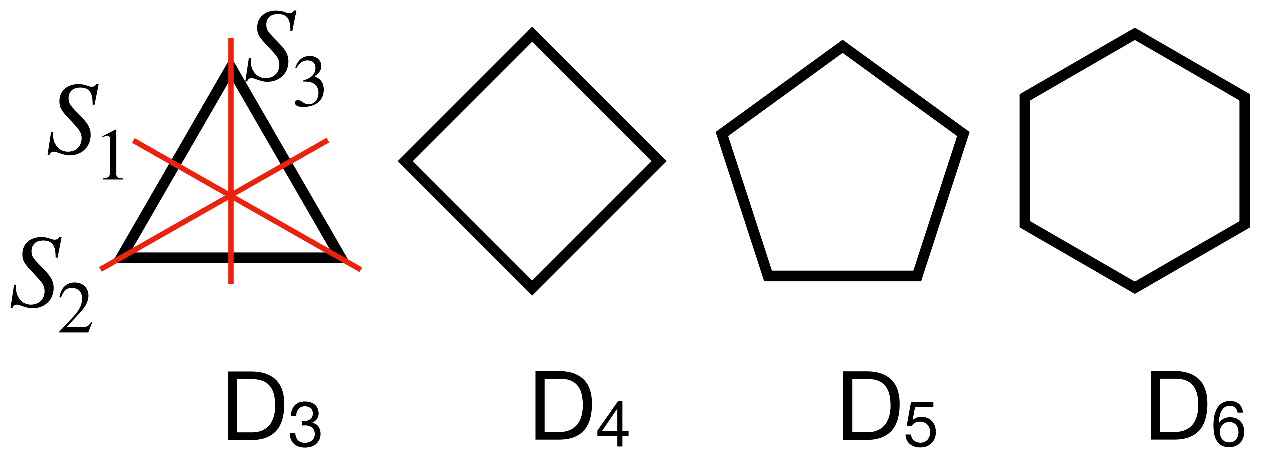
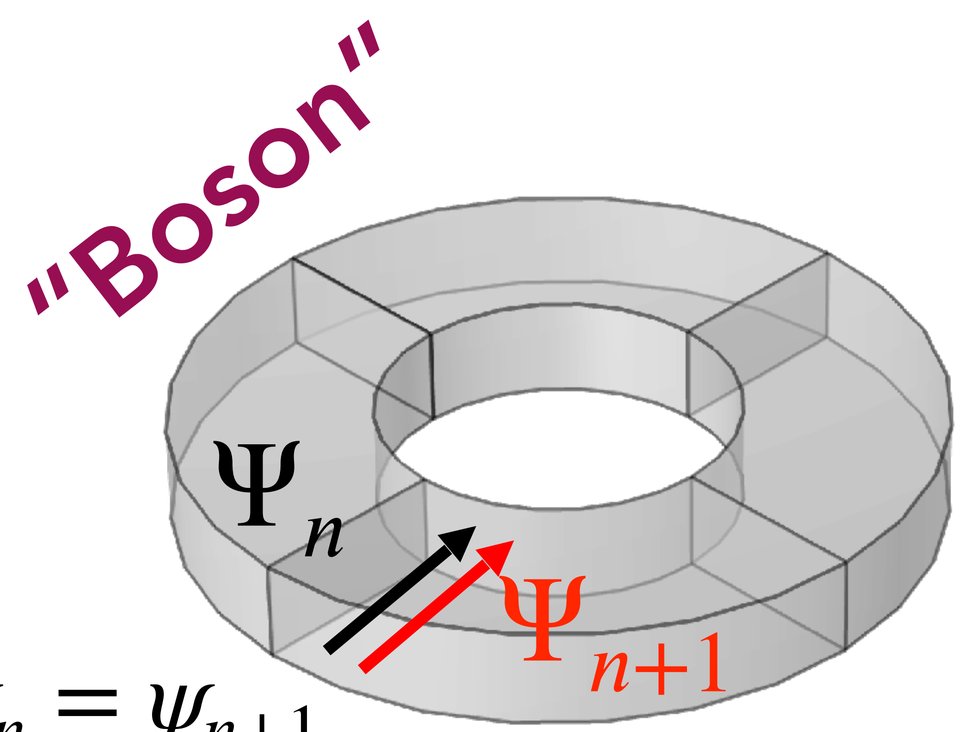
Dihedral group of regular convex polygons: D_p



Twisted "anyon" microwave cavities

Why is it called an "anyon" cavity?



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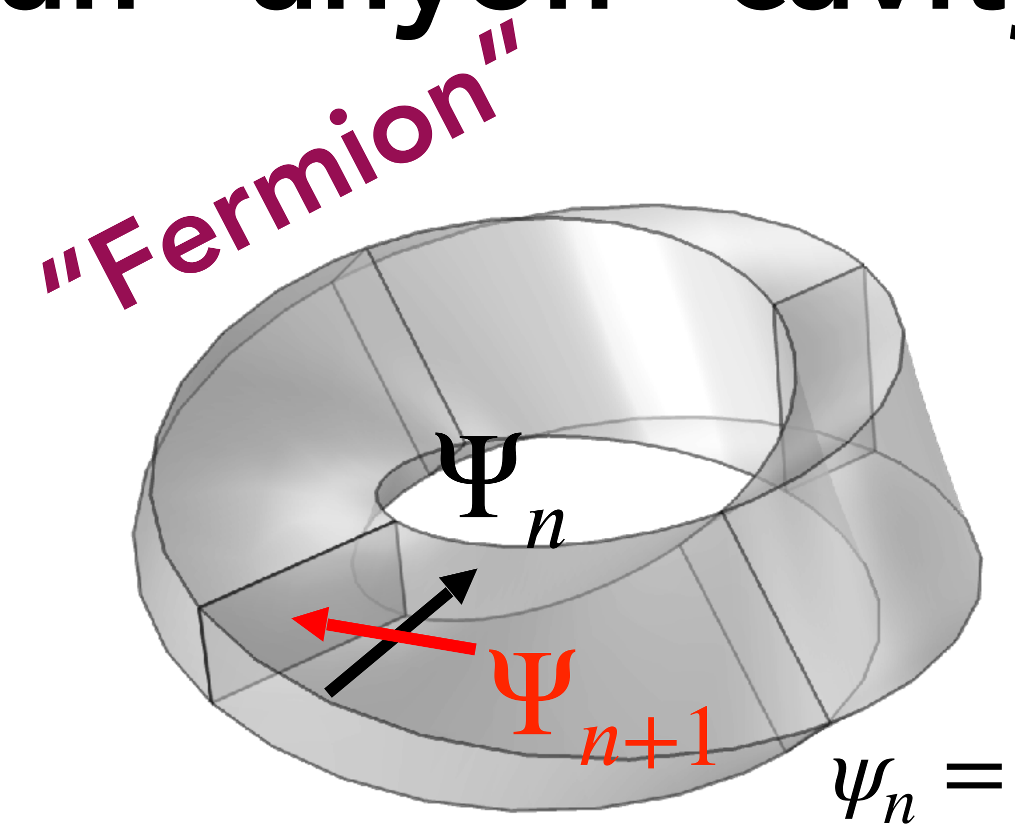
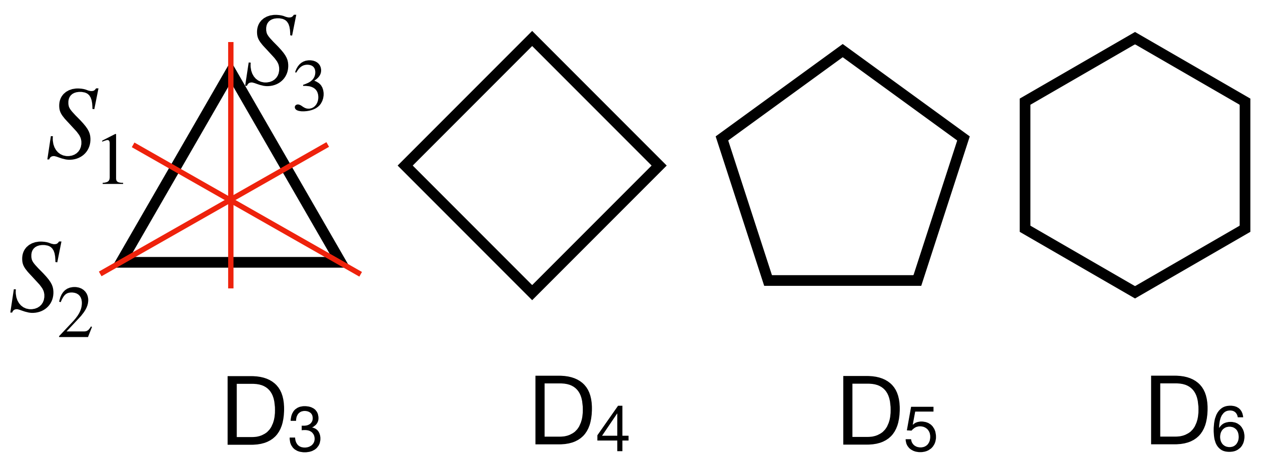


$\psi_n = -\psi_{n+1}$
$\psi_n = \psi_{n+2N}$
$\theta = \pm\pi$

Dihedral group of regular convex polygons: D_p

$2p$ symmetries:
p rotational + p reflection



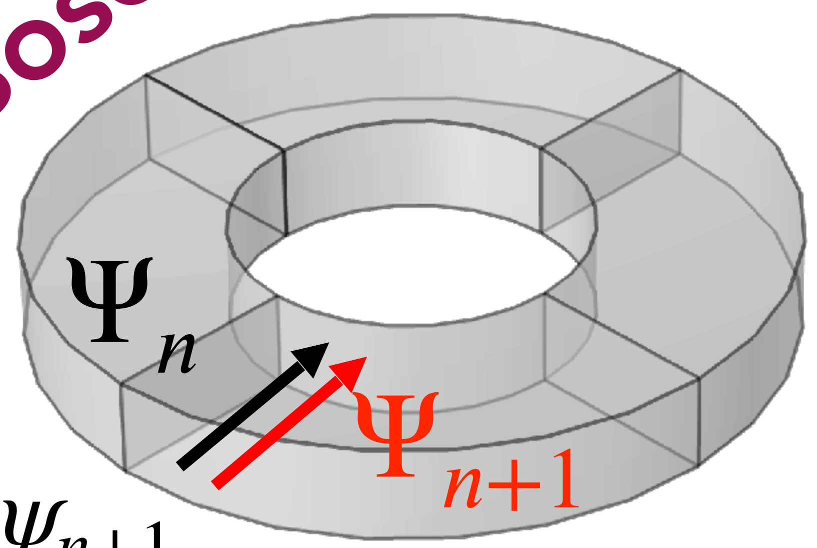
Rotation by 2π/p preserves the object

QDM
Quantum Technologies and Dark Matter Research Lab

Twisted "anyon" microwave cavities

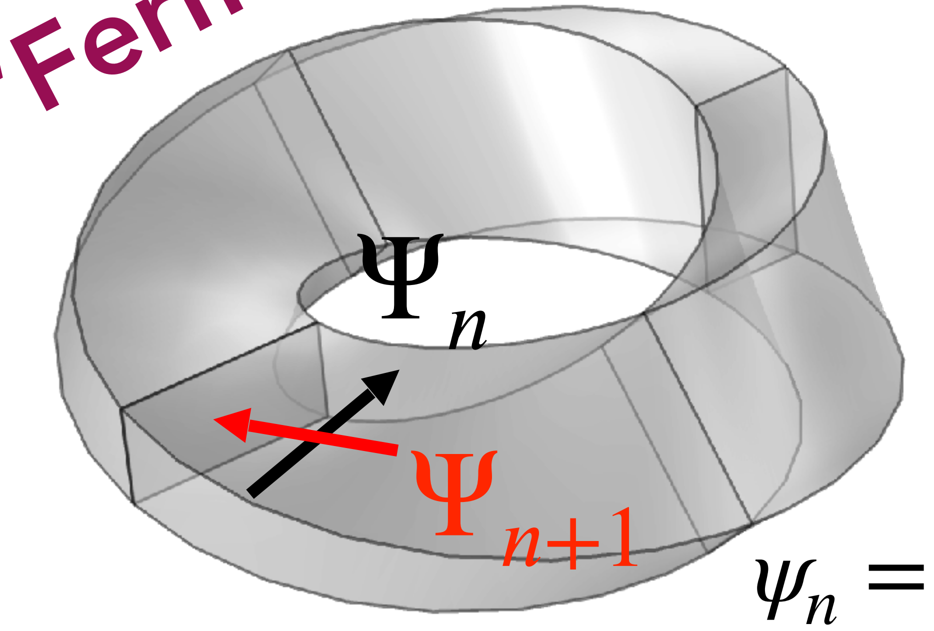
Why is it called an "anyon" cavity?

"Boson"



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

"Fermion"



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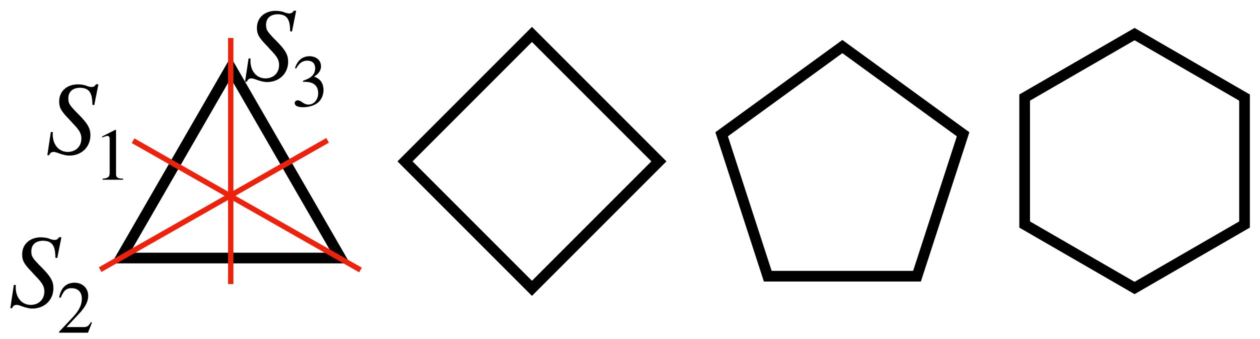
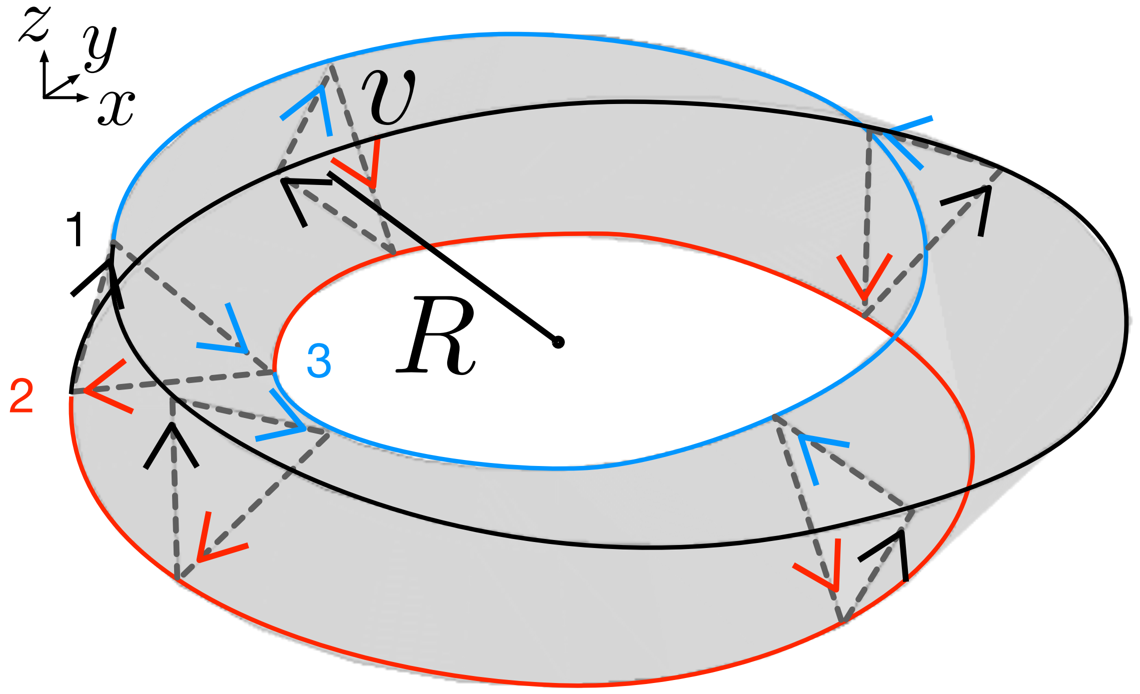
$2p$ symmetries:
p rotational + p reflection

Dihedral group of regular convex polygons: D_p

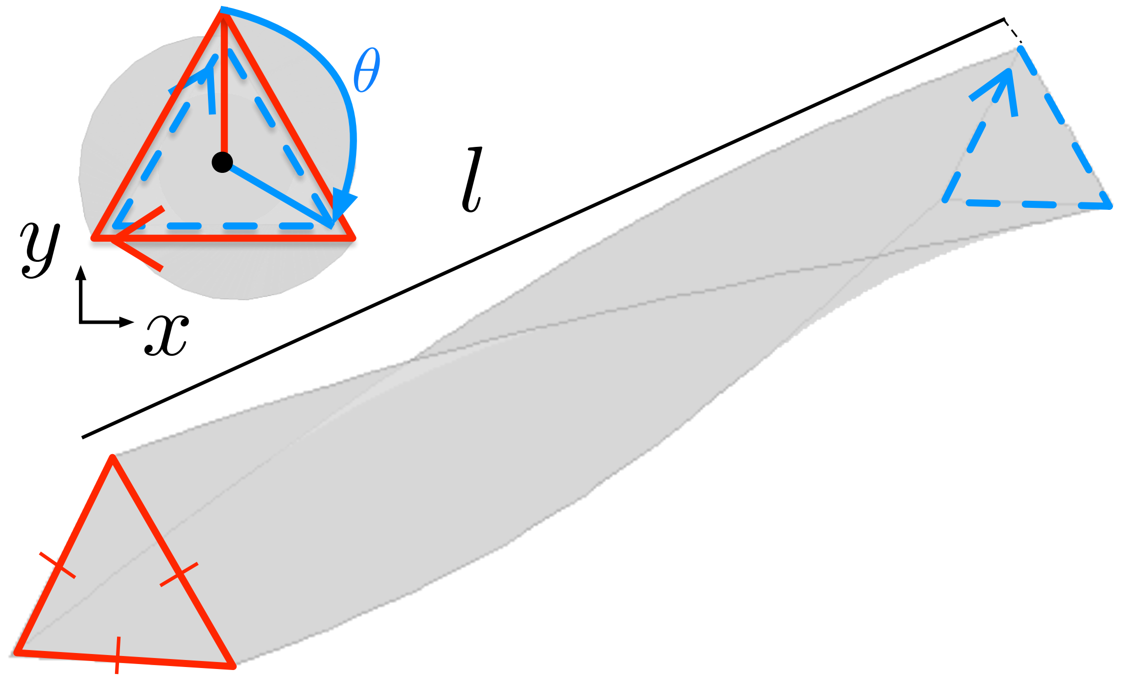


D_3 D_4 D_5 D_6

Rotation by 2π/p preserves the object



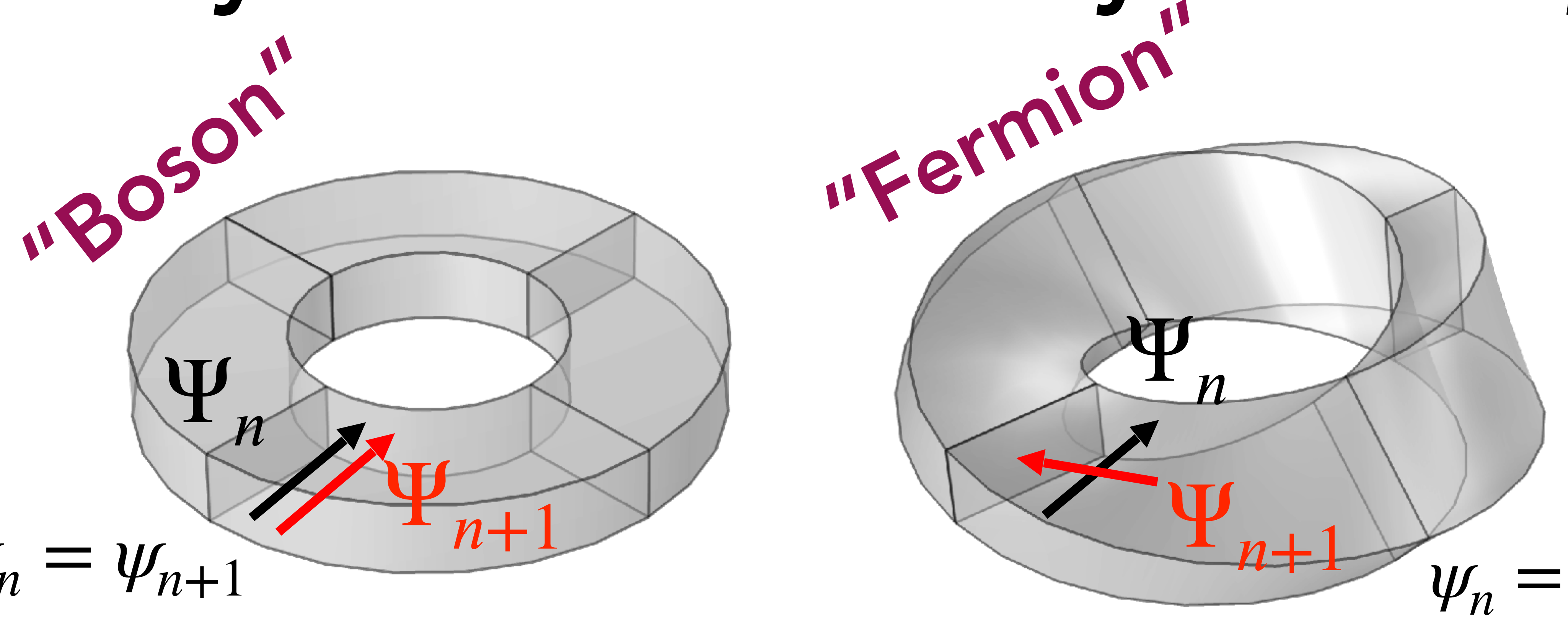
$$\psi_n = e^{i\theta}\psi_{n+1}$$
$$\theta = (2\pi/p)Z$$
$$Z \in \pm\mathbb{Z}$$



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

Twisted “anyon” microwave cavities

Why is it called an “anyon” cavity?

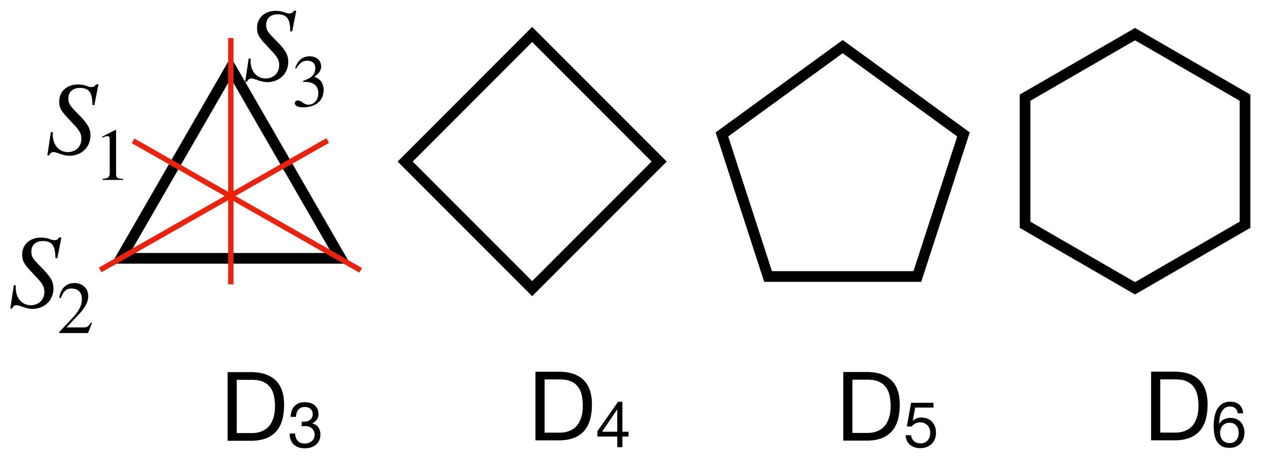


$\psi_n = \psi_{n+1}$
$\psi_n = \psi_{n+N}$
$\theta = 0$

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

Dihedral group of regular convex polygons: D_p

2*p* symmetries:
p rotational + *p* reflection



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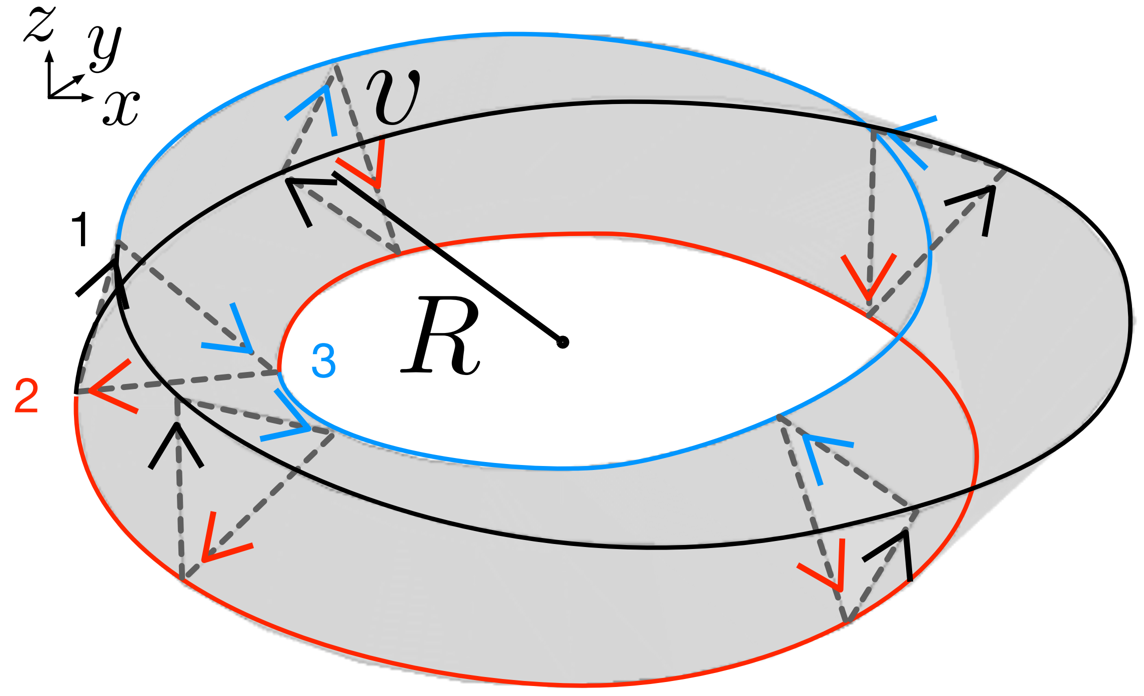

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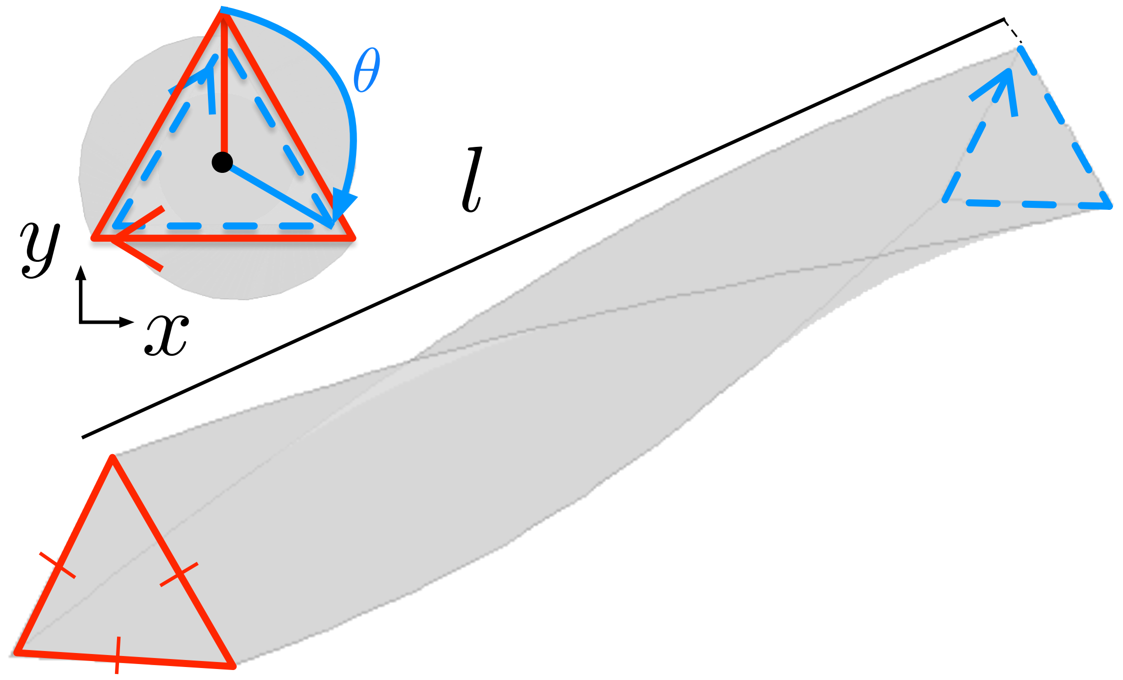

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Classical Möbius-Ring Resonators Exhibit Fermion-Boson Rotational Symmetry

Douglas J. Ballon and Henning U. Voss
Phys. Rev. Lett. **101**, 247701 – Published 9 December 2008

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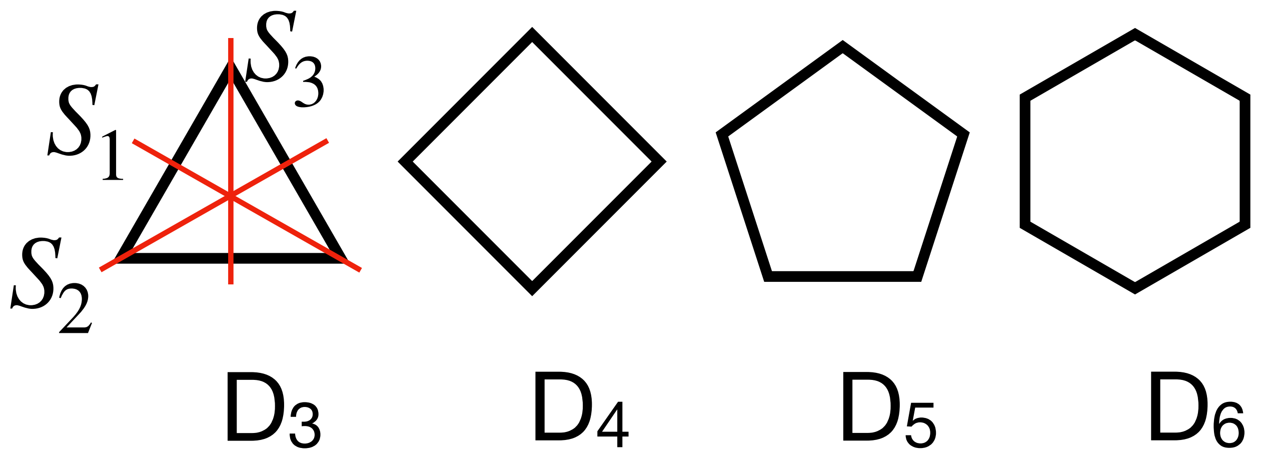
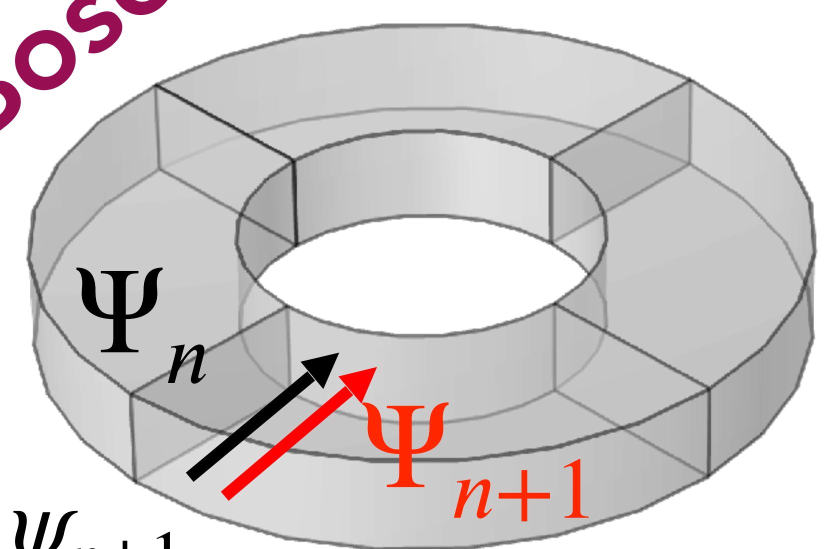


$2p$ symmetries:
p rotational + p reflection

"Boson"



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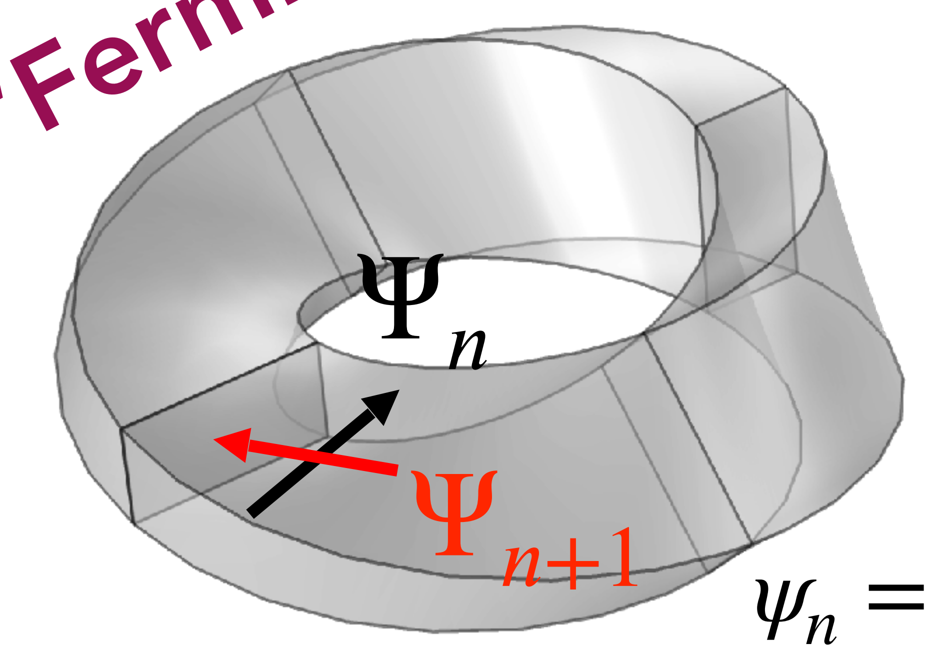
"Fermion"



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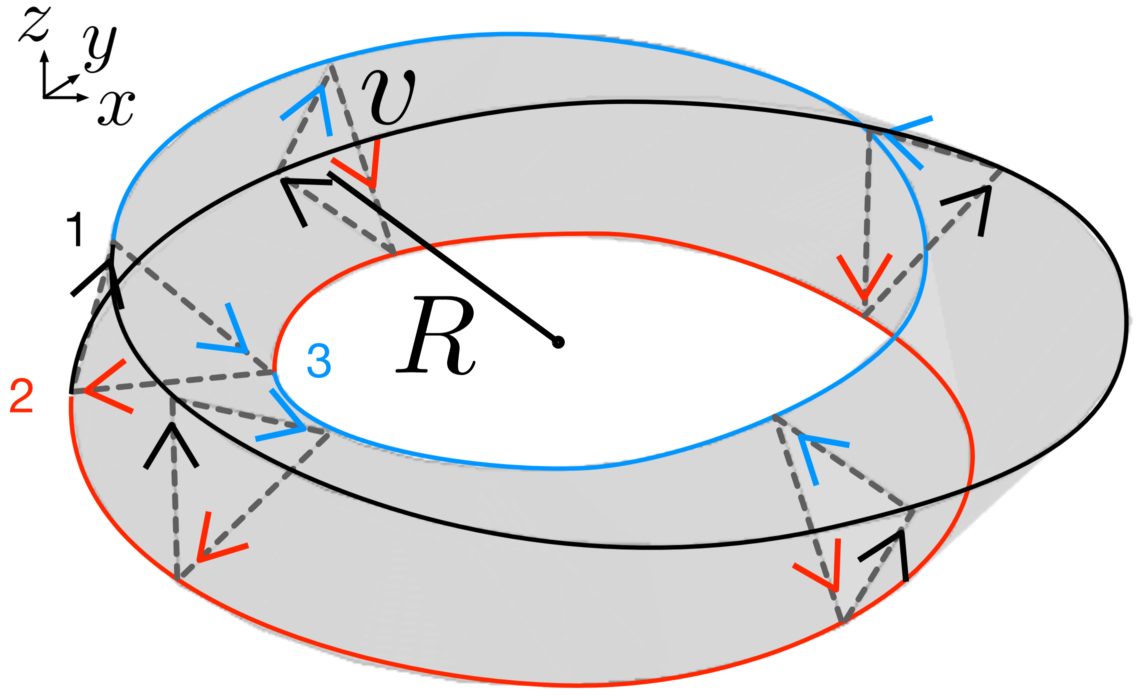
Rotation by 2π/p preserves the object



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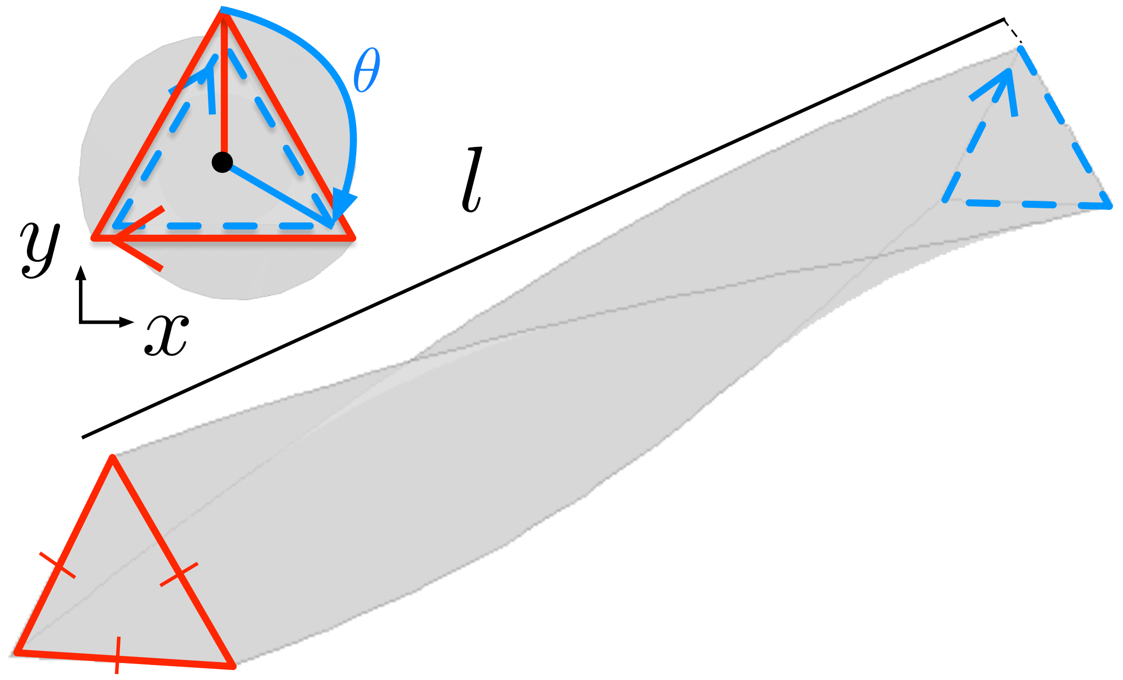

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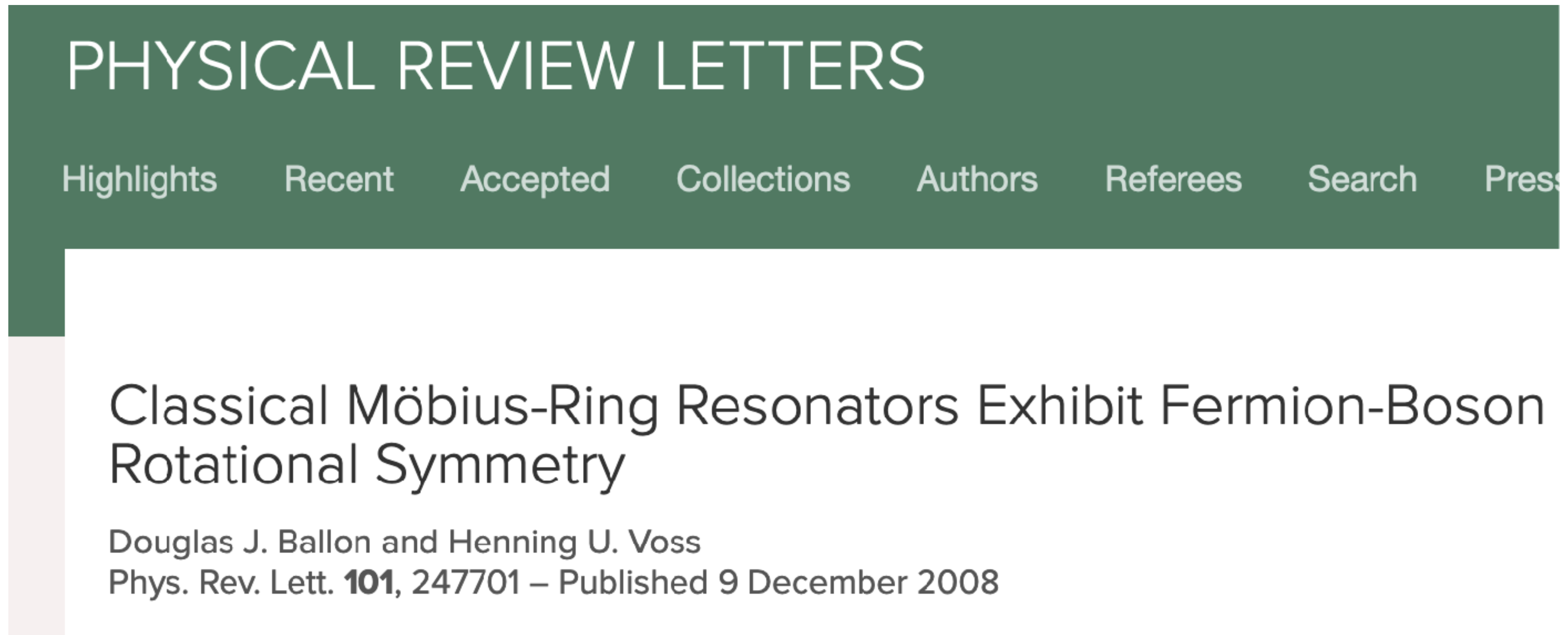
"Anyon"



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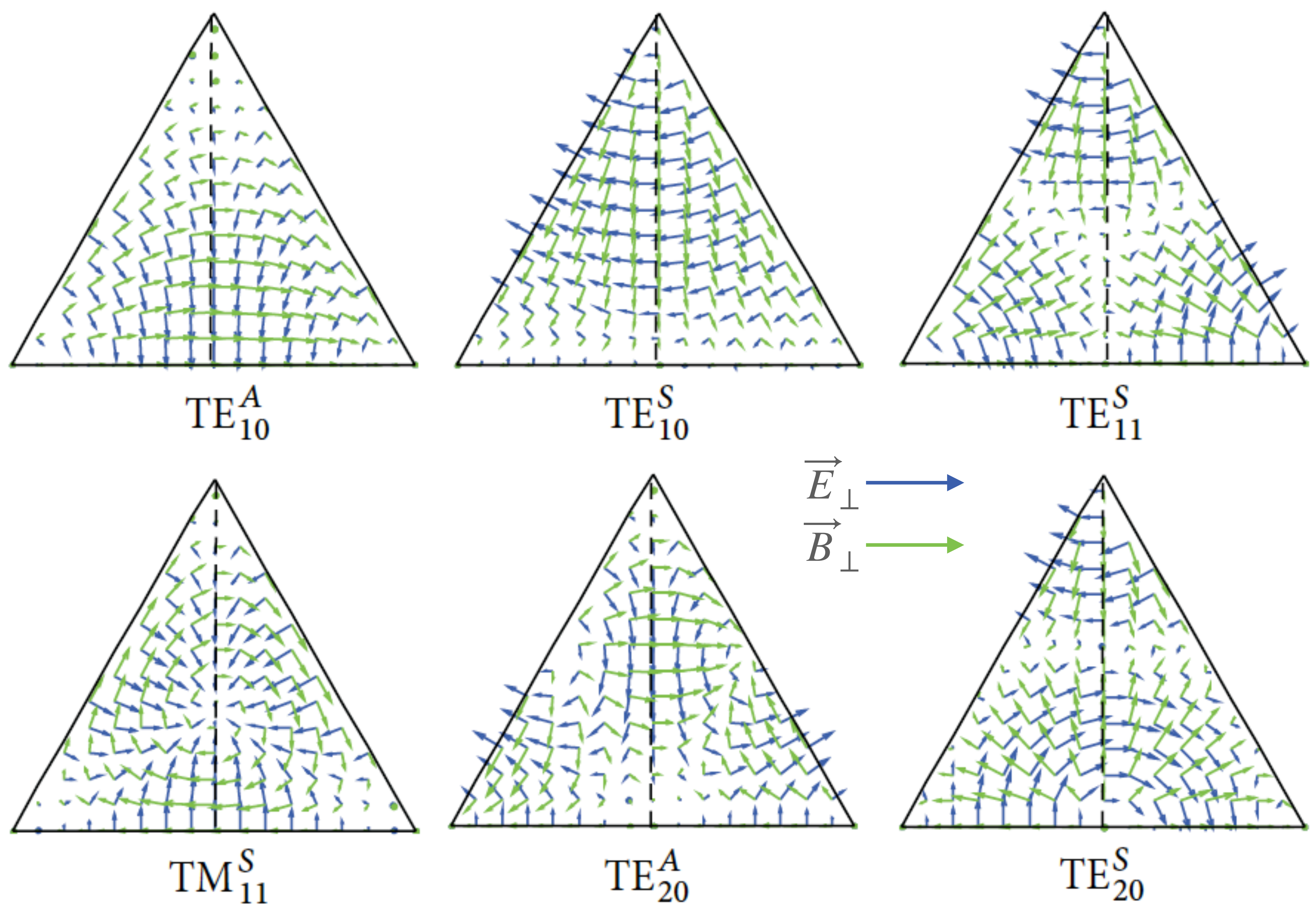
Twisted “anyon” microwave cavities

How do these geometries generate helicity?



A. Moran-Lopez *et al.* Adv. Math. Phys., 2016, 2974675 (2016)

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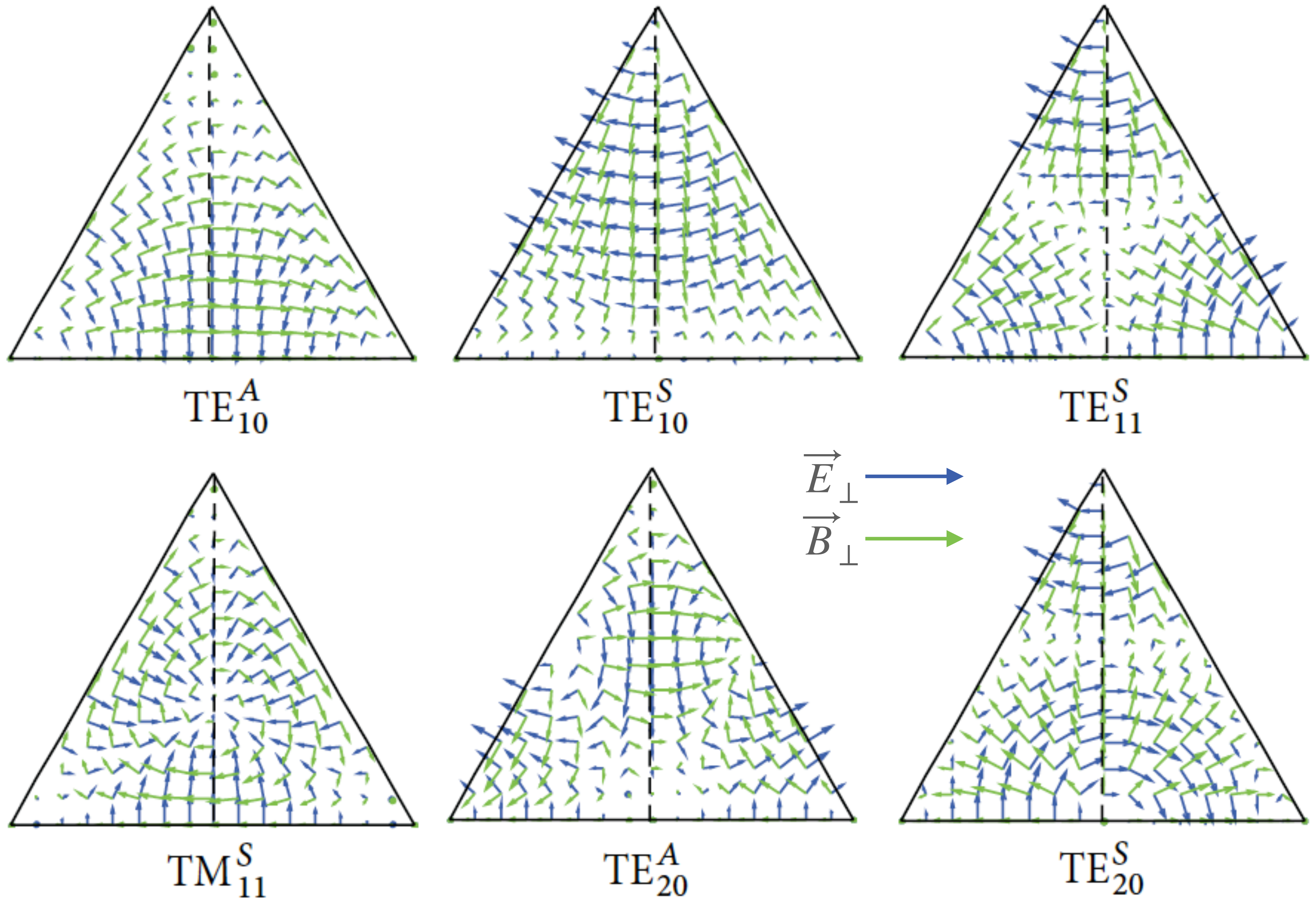

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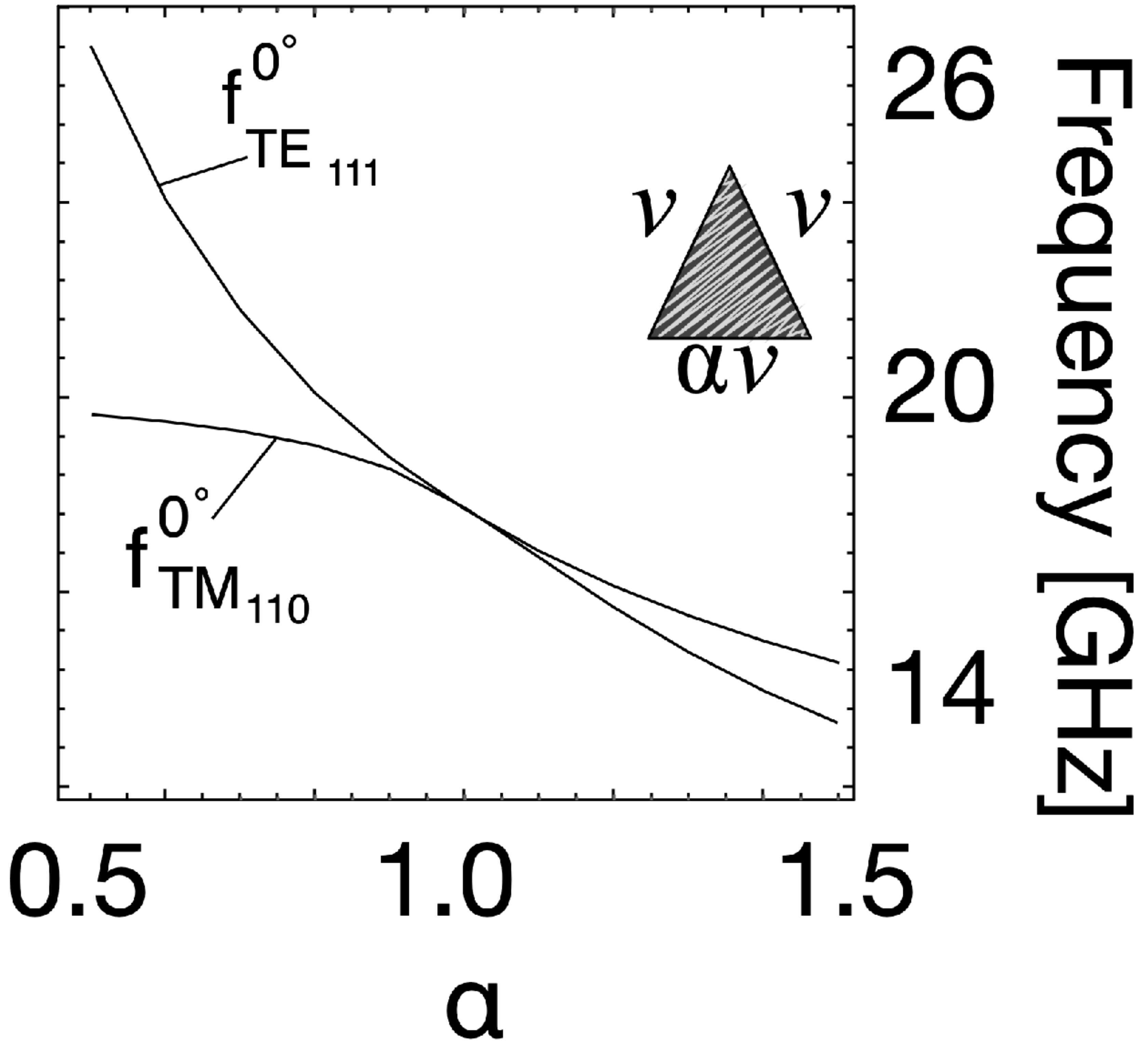

Quantum Technologies and Dark Matter Research Lab

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Quantum Technologies and Dark Matter Research Lab

Twisted “anyon” microwave cavities

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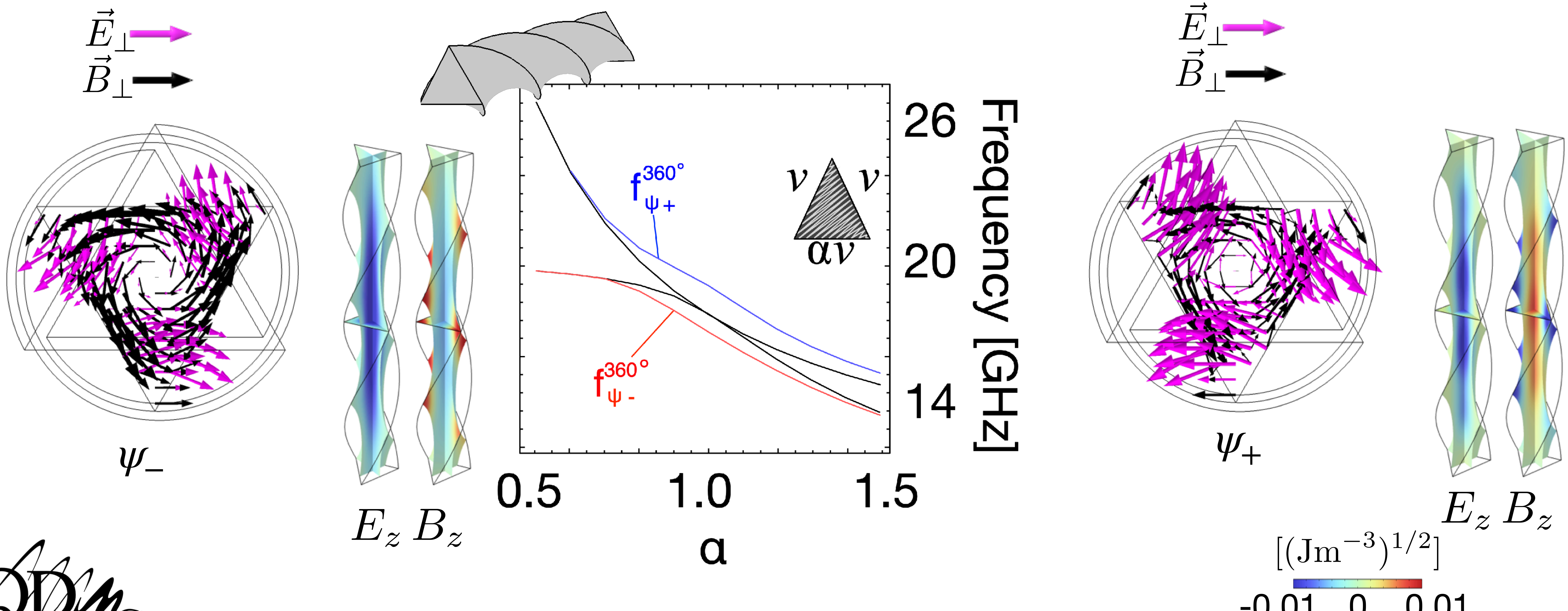

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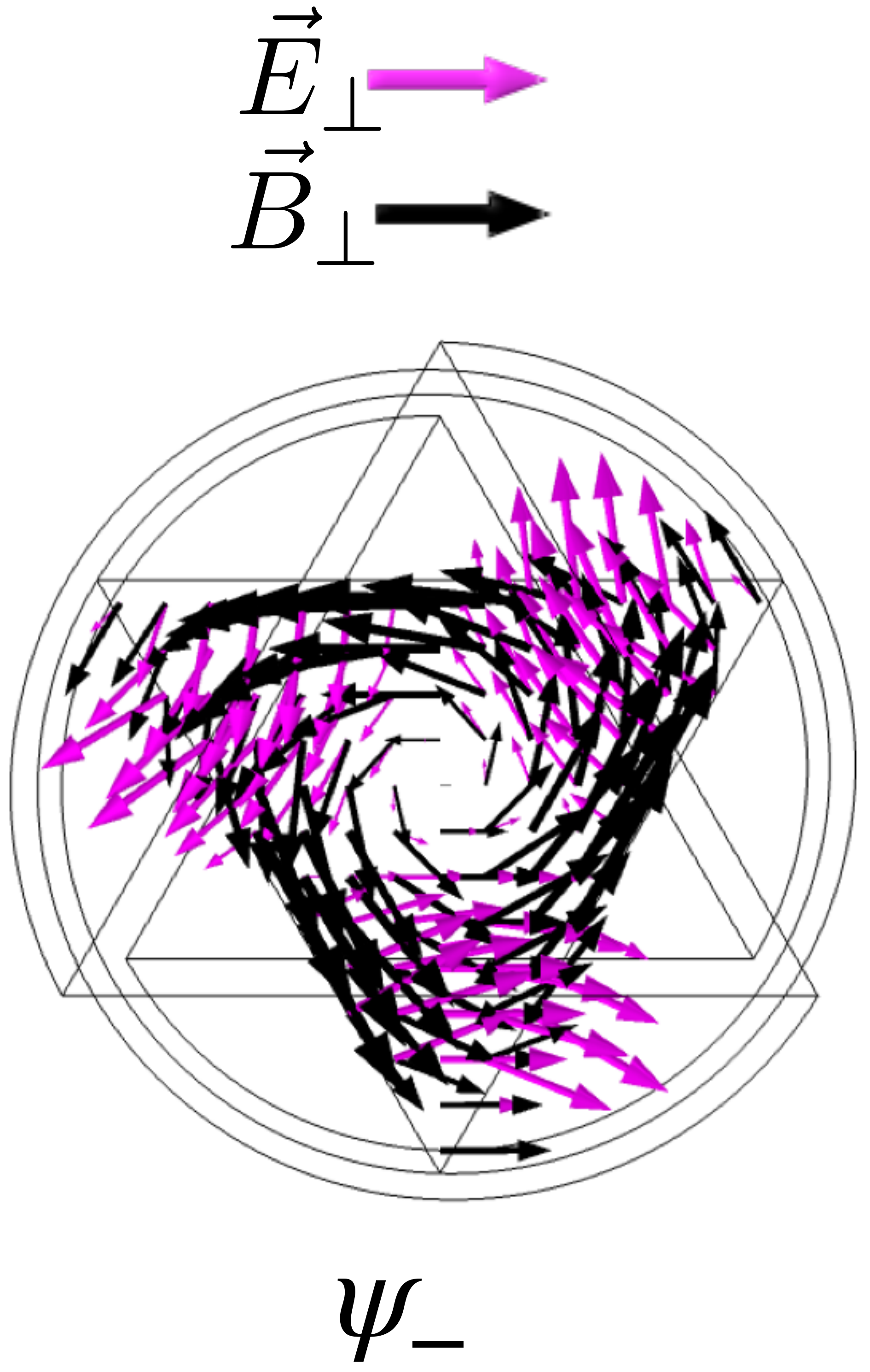

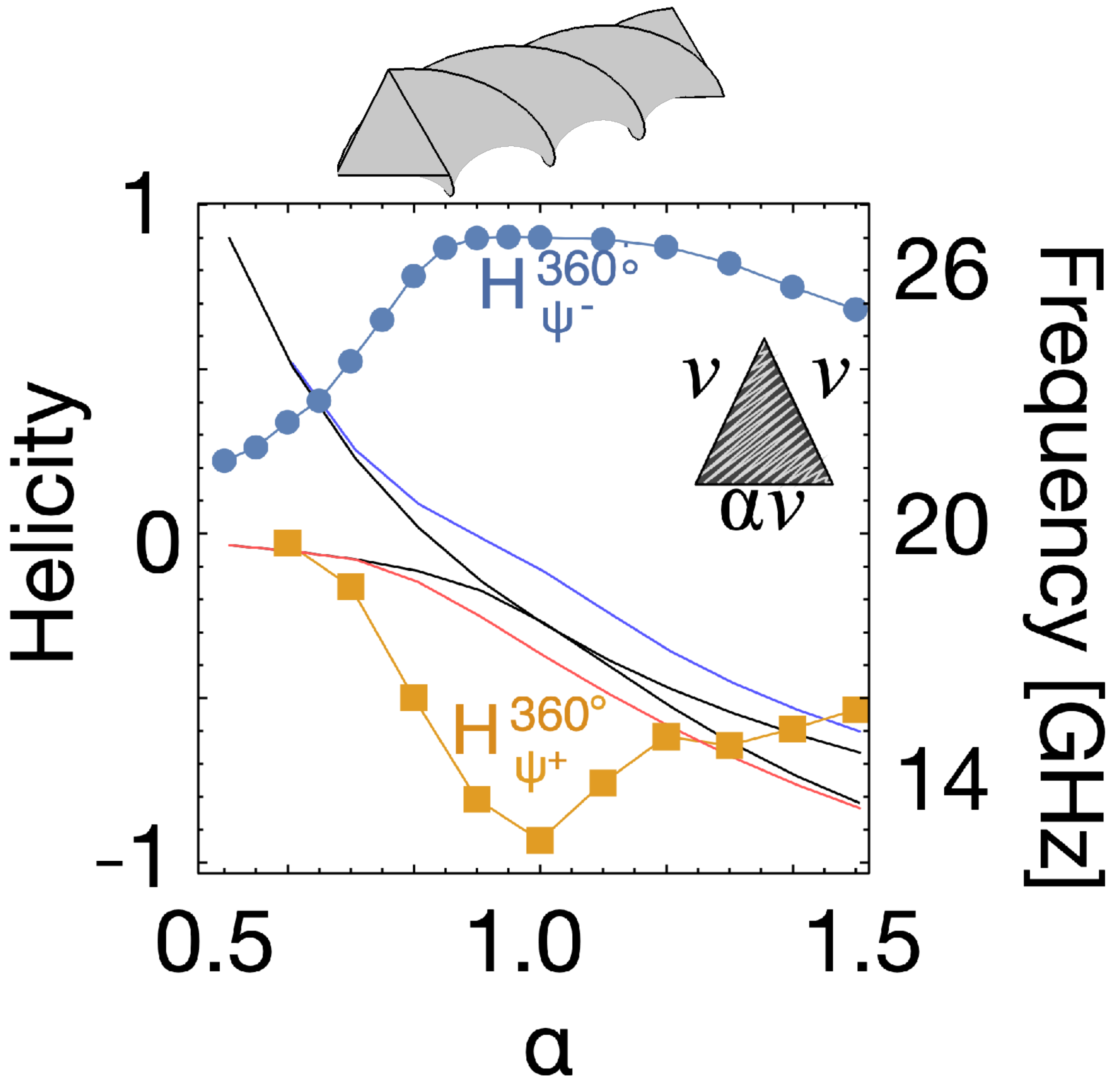

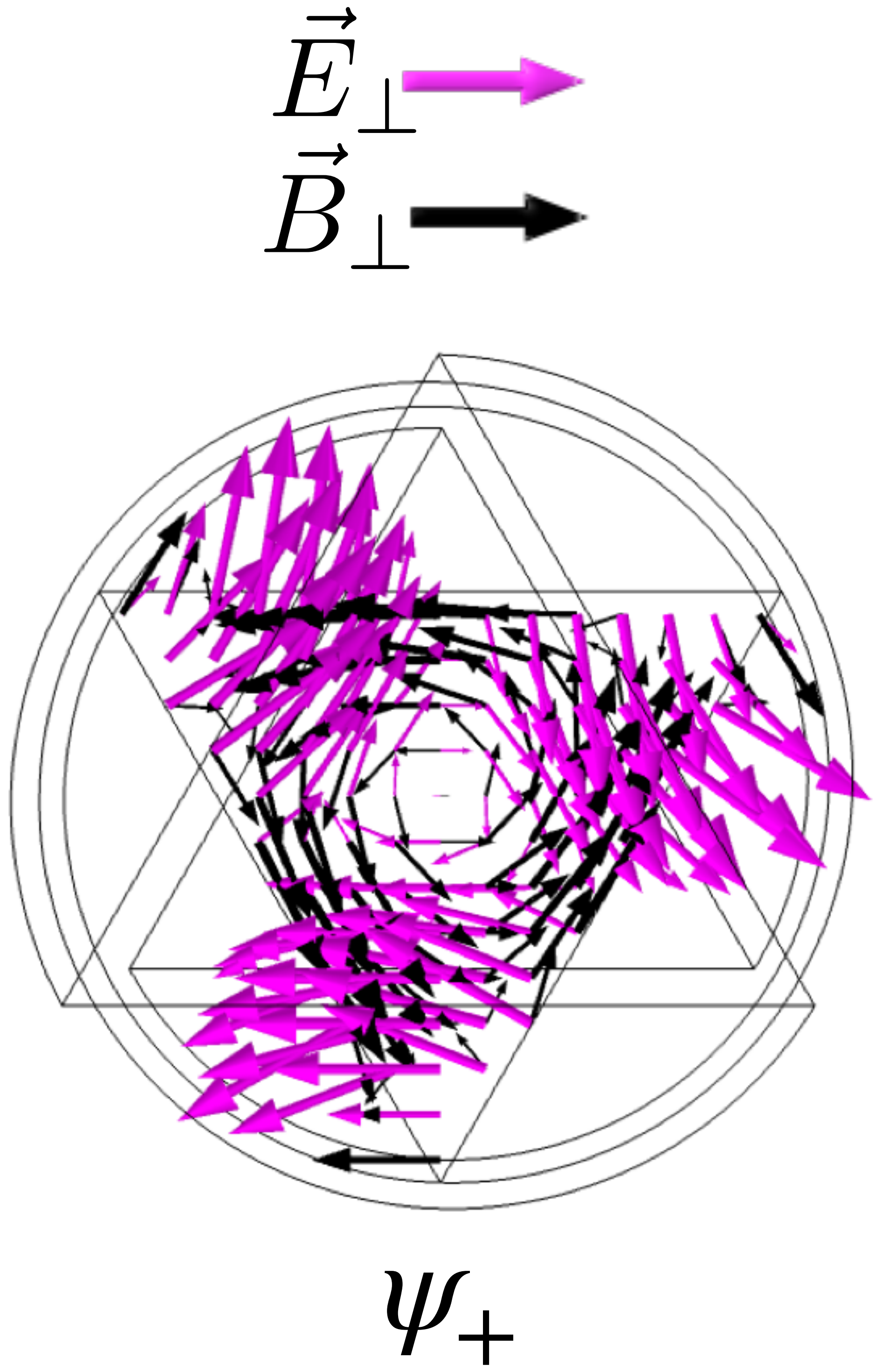

Twisted “anyon” microwave cavities

Can we build these geometries?

Twisted “anyon” microwave cavities

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- 3D printed using Selective Laser Melting printers and Al-Si powder

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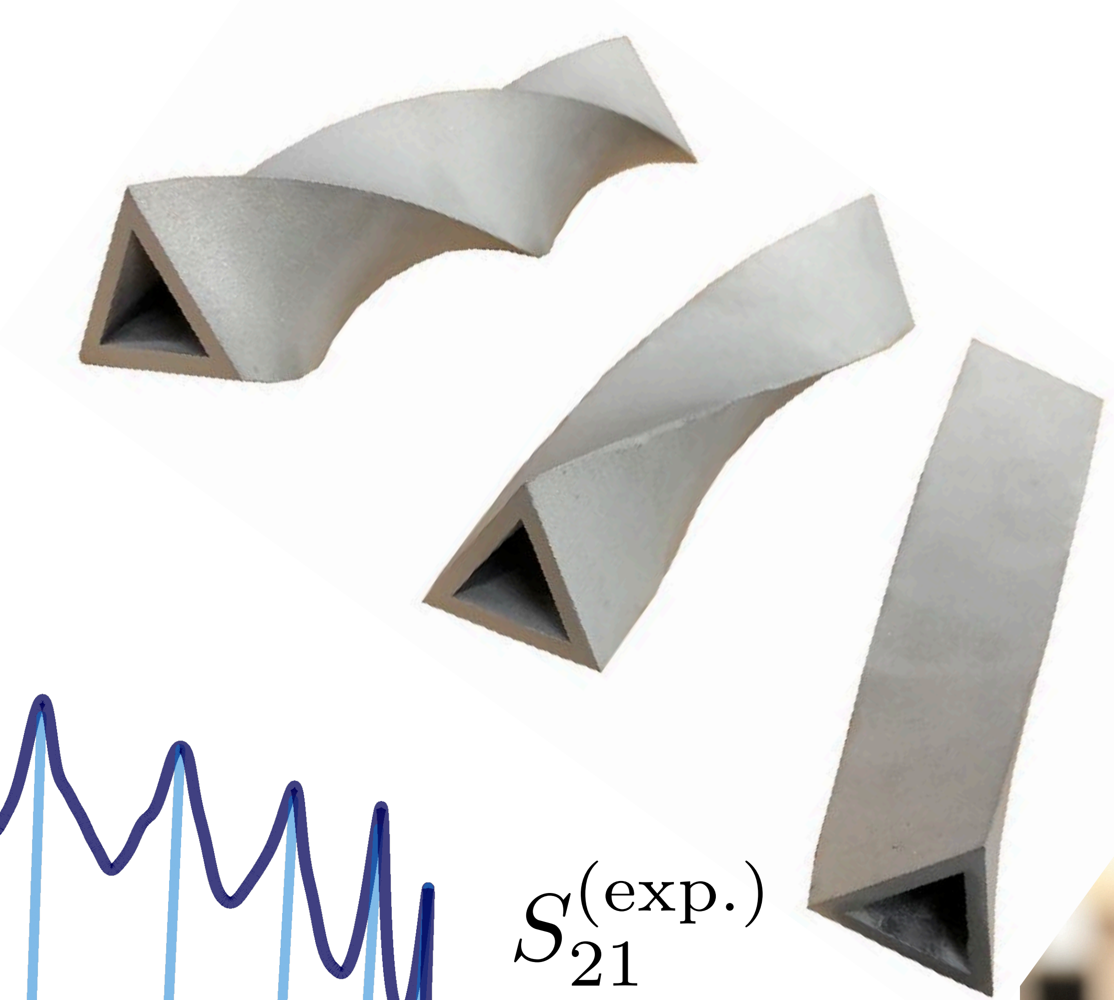
Resonator	Mode	f (GHz)	G (Ω)	$\mathscr{H}$
Ring	ψ_0^-	17.221	6200	0.933
Ring	ψ_1^-	17.297	6570	0.9166
Ring	ψ_0^+	17.895	7290	-0.820
Linear	ψ_0^-	17.214	1950	0.932
Linear	ψ_1^-	17.278	2030	0.896
Linear	ψ_0^+	17.859	1920	-0.884

Twisted "anyon" microwave cavities

Can we build these geometries?

- 3D printed using Selective Laser Melting printers and Al-Si powder
- Measured mode frequencies to confirm simulation results



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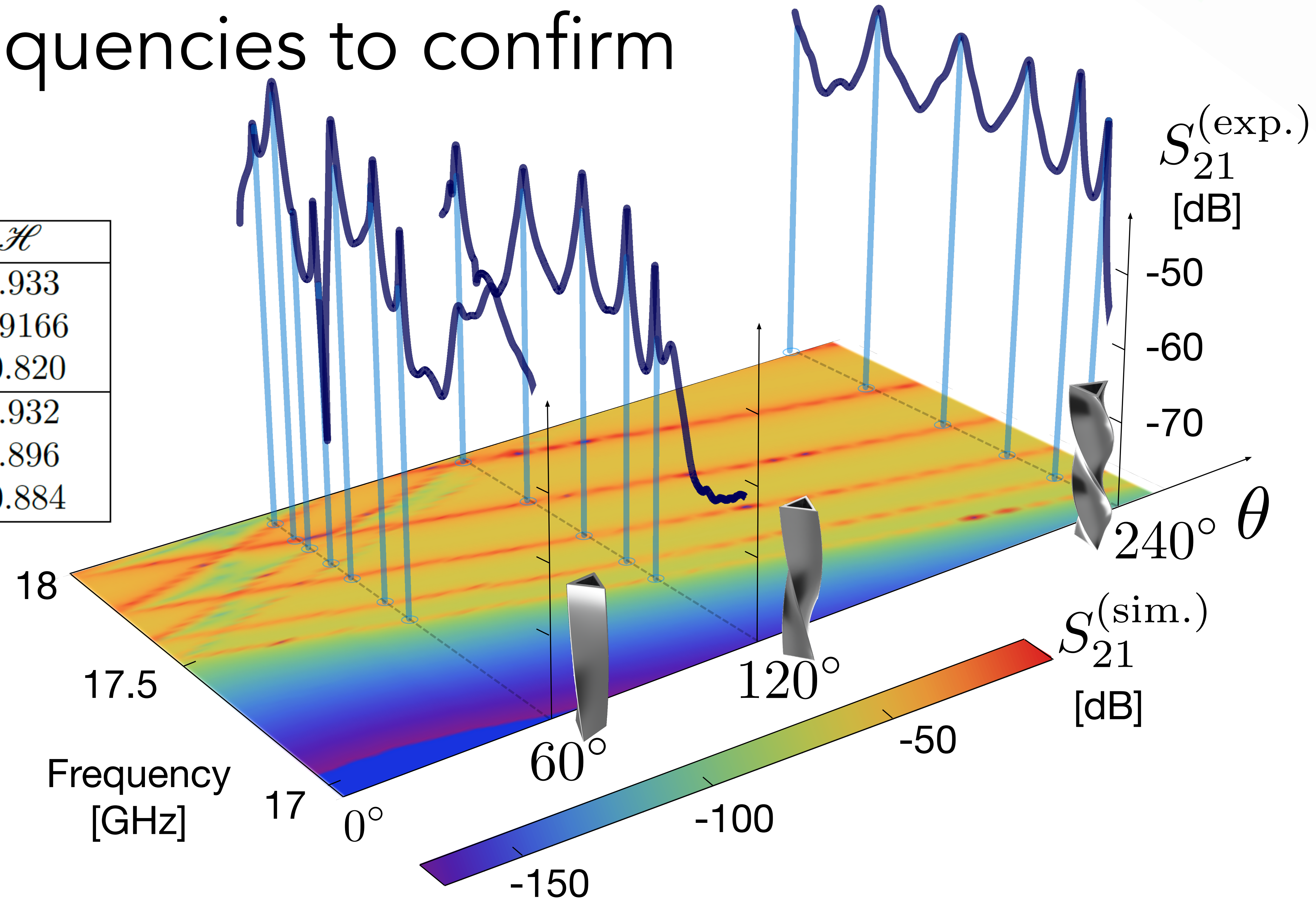


Twisted "anyon" microwave cavities

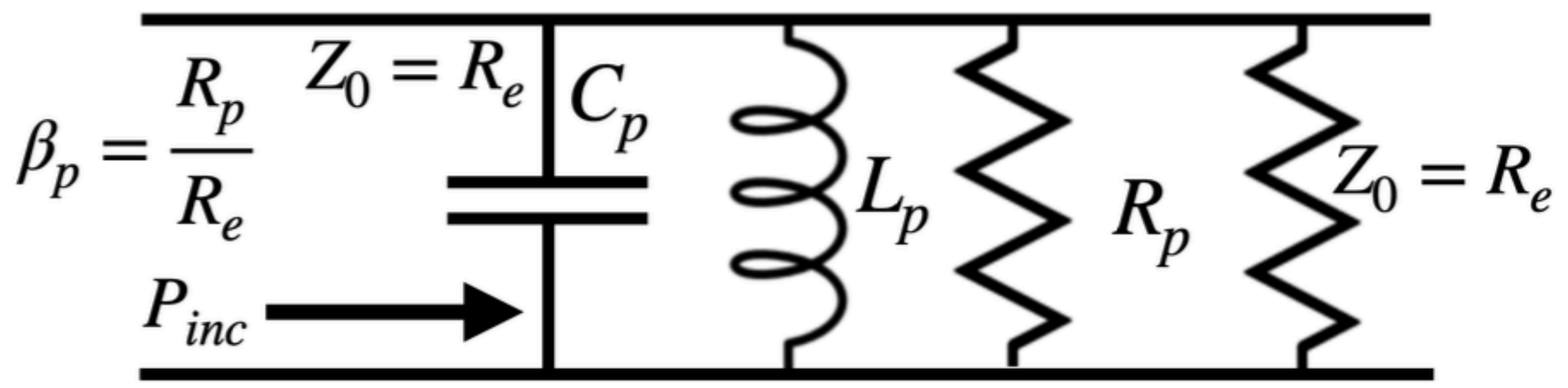
Dark matter detection thanks to helicity

arXiv:2208.01640v2

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



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

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

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

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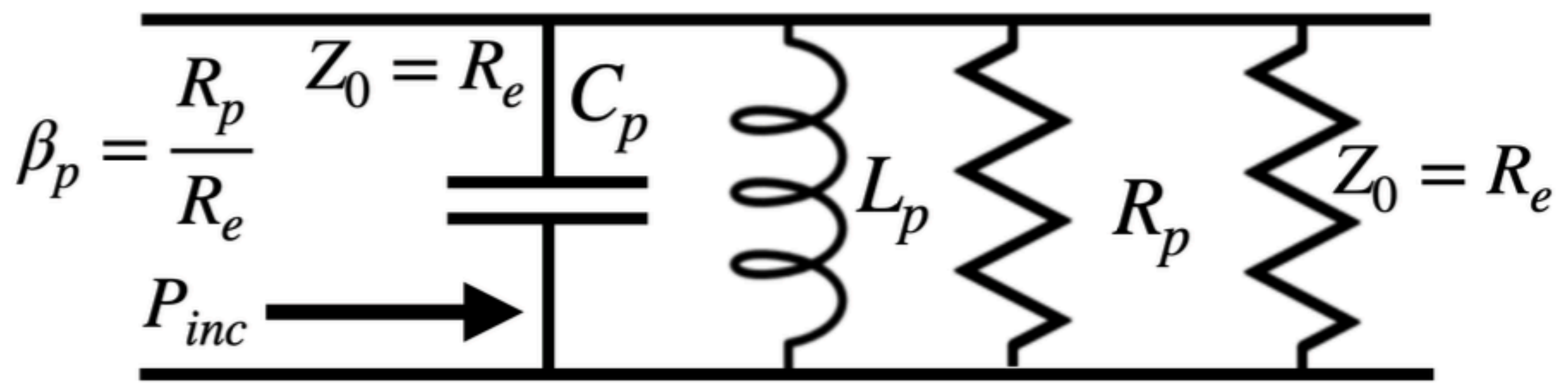

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Axion Photon Coupling ($g_{a\gamma\gamma}$)

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})

arXiv:2208.01640v2

Twisted “anyon” microwave cavities

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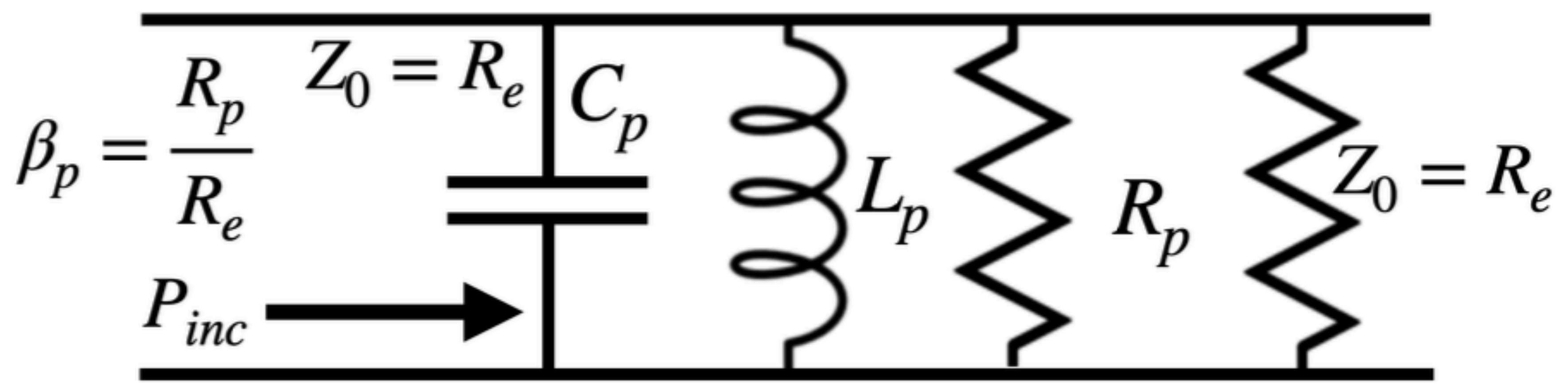
- Due to the helicity, **ultra-light dark matter axions**, whose mass range falls within the cavity bandwidth will amplitude modulate the cavity mode

- The frequency of the AM will be proportional to the axion mass



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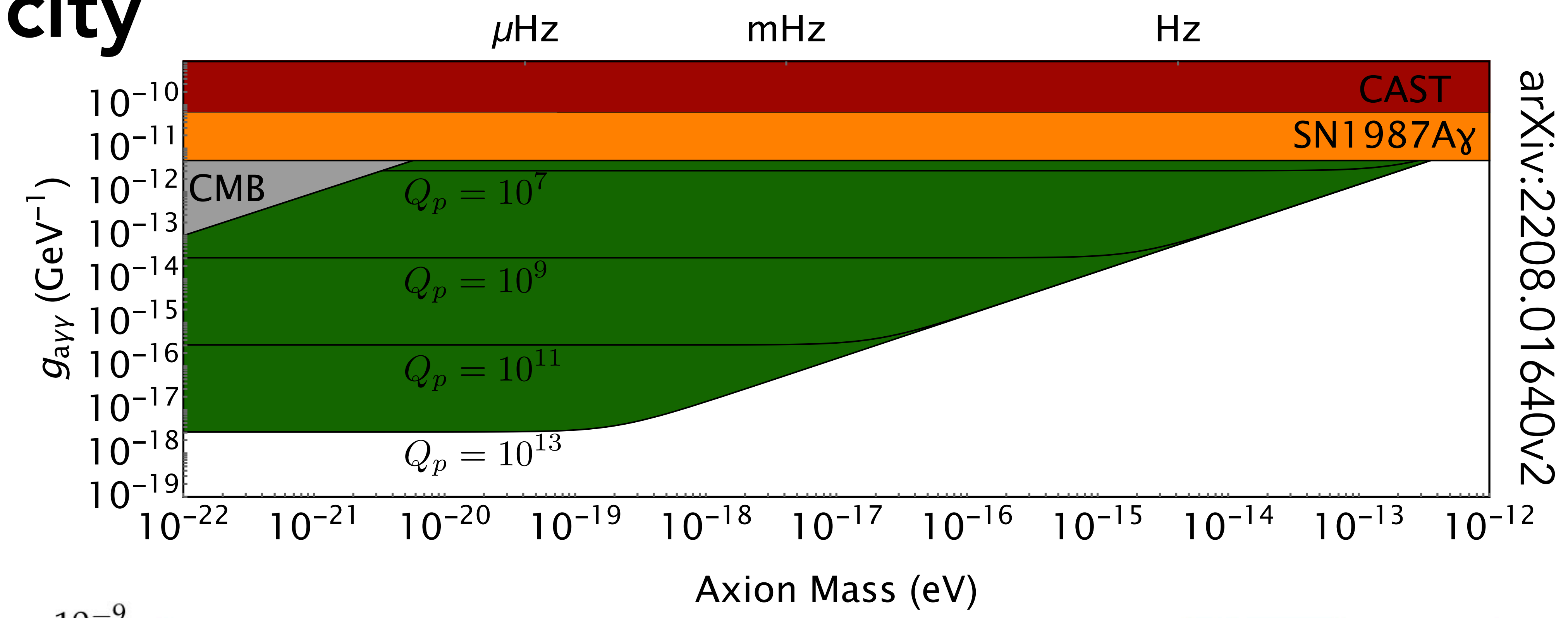
Twisted "anyon" microwave cavities

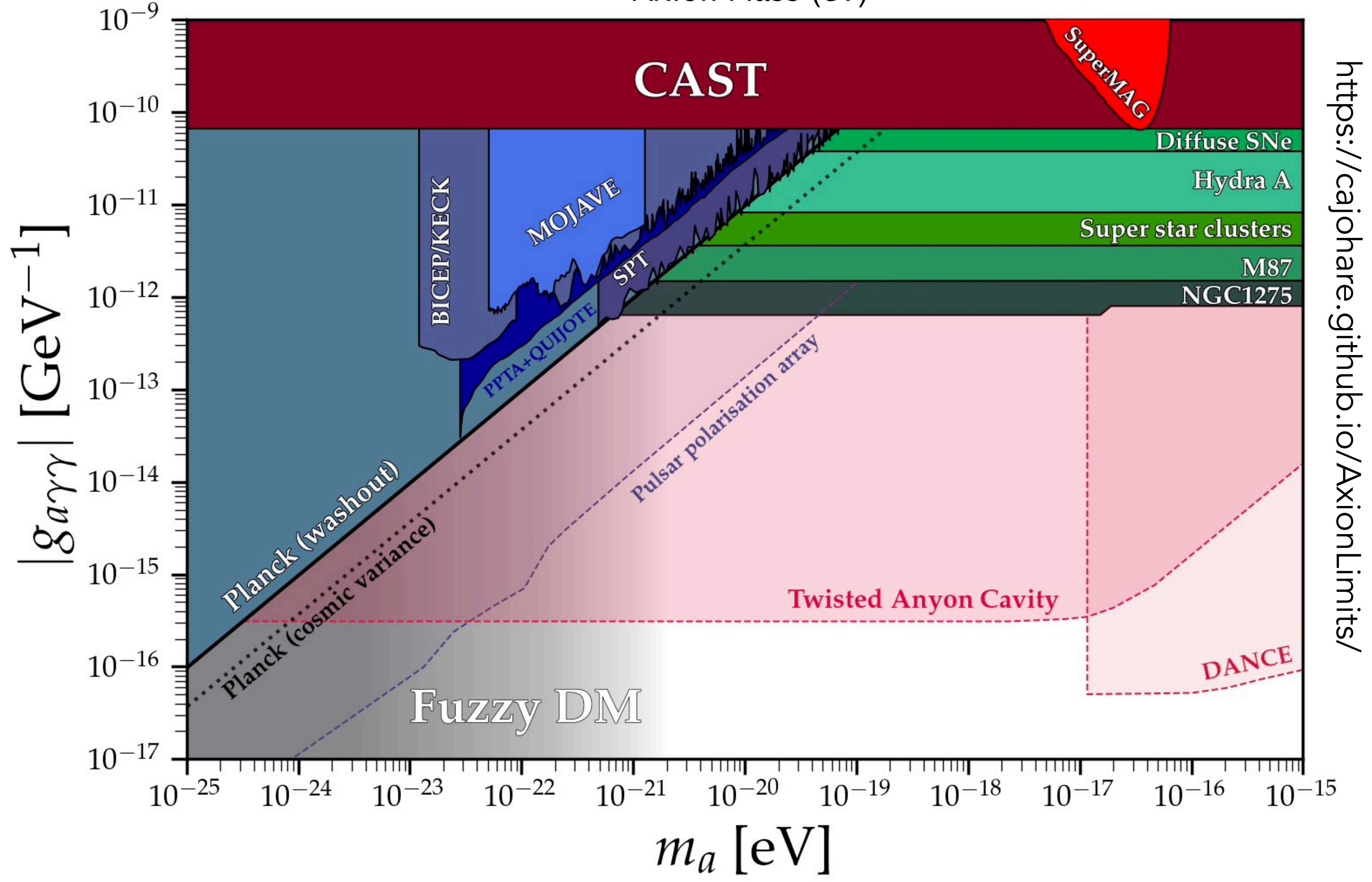
Dark matter detection in a single mode thanks to helicity

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

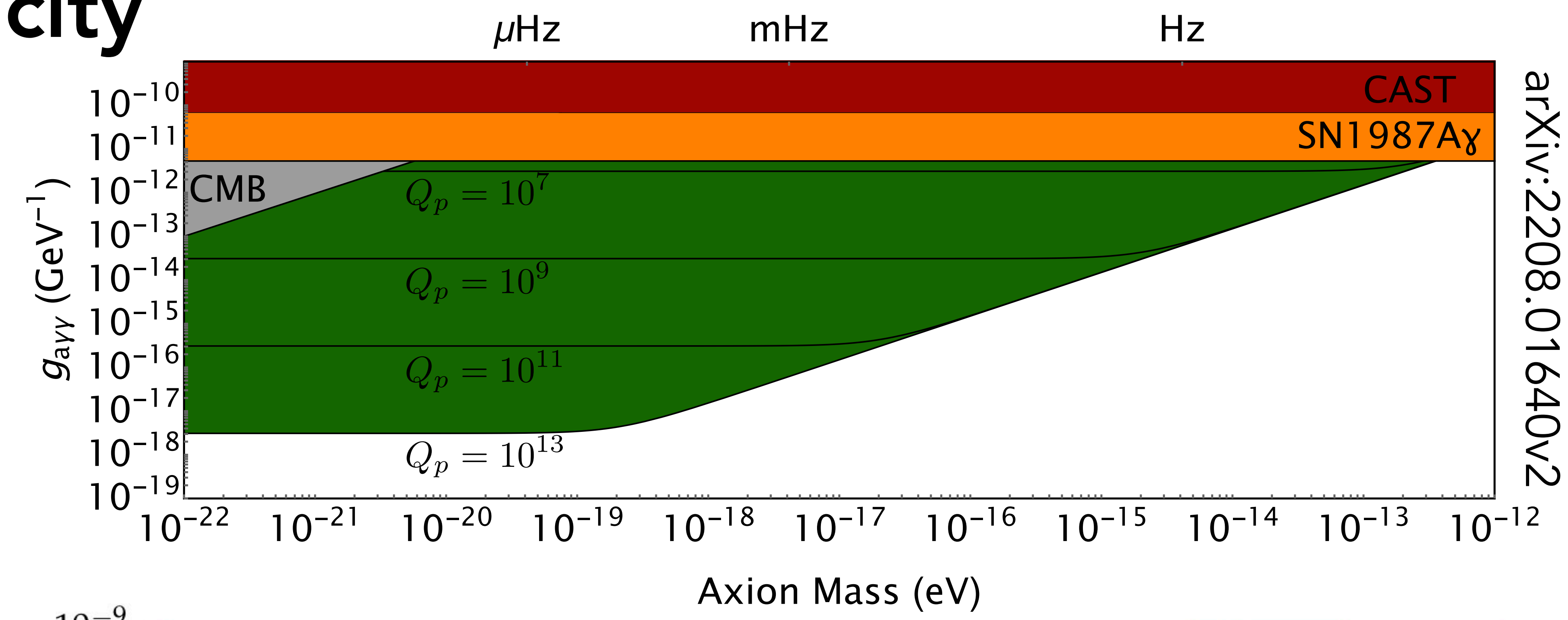




Twisted "anyon" microwave cavities

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**



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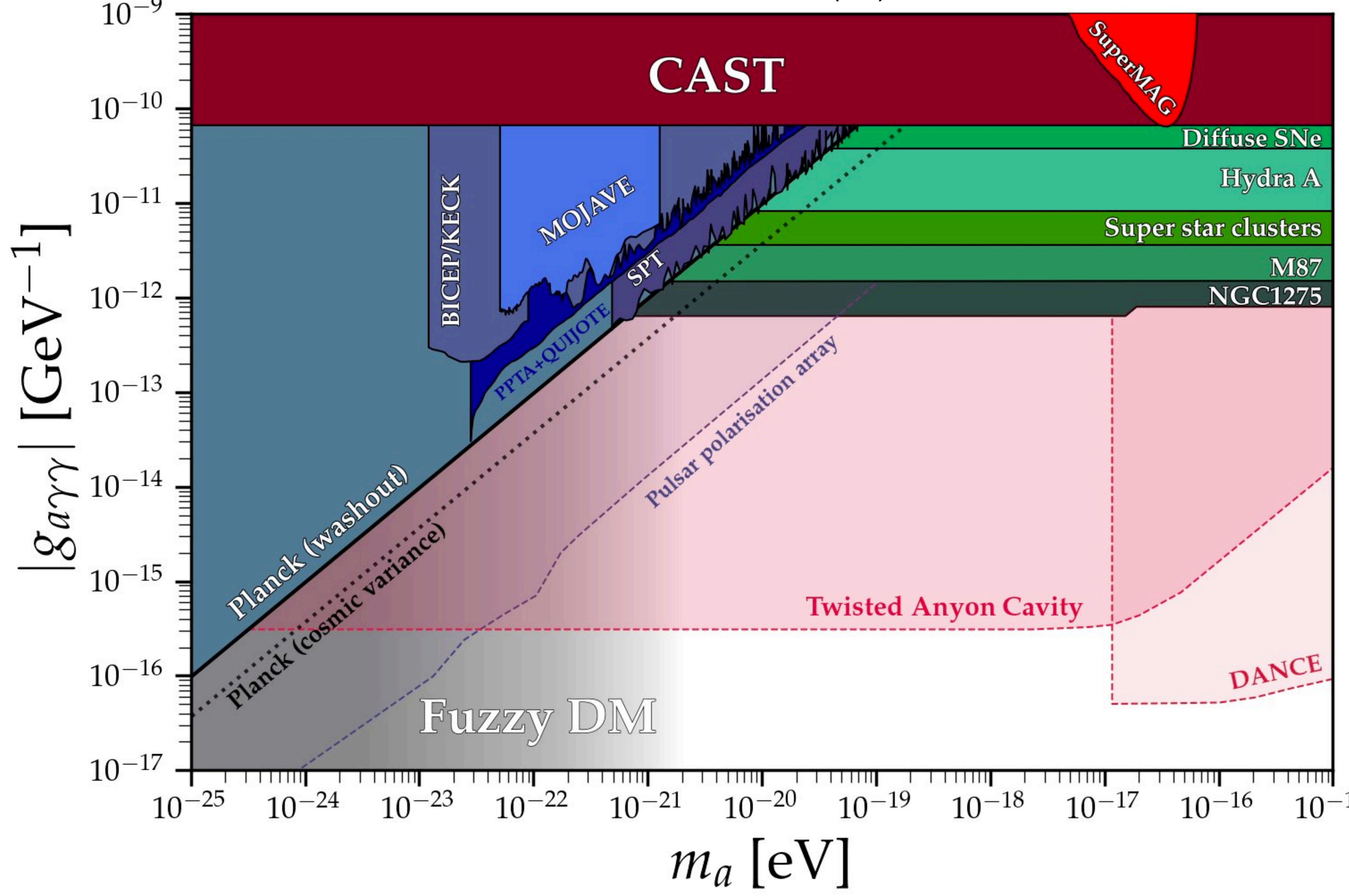

https://cajohare.github.io/AxionLimits/

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Twisted "anyon" microwave cavities

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- Accesses an axion mass range very difficult to search
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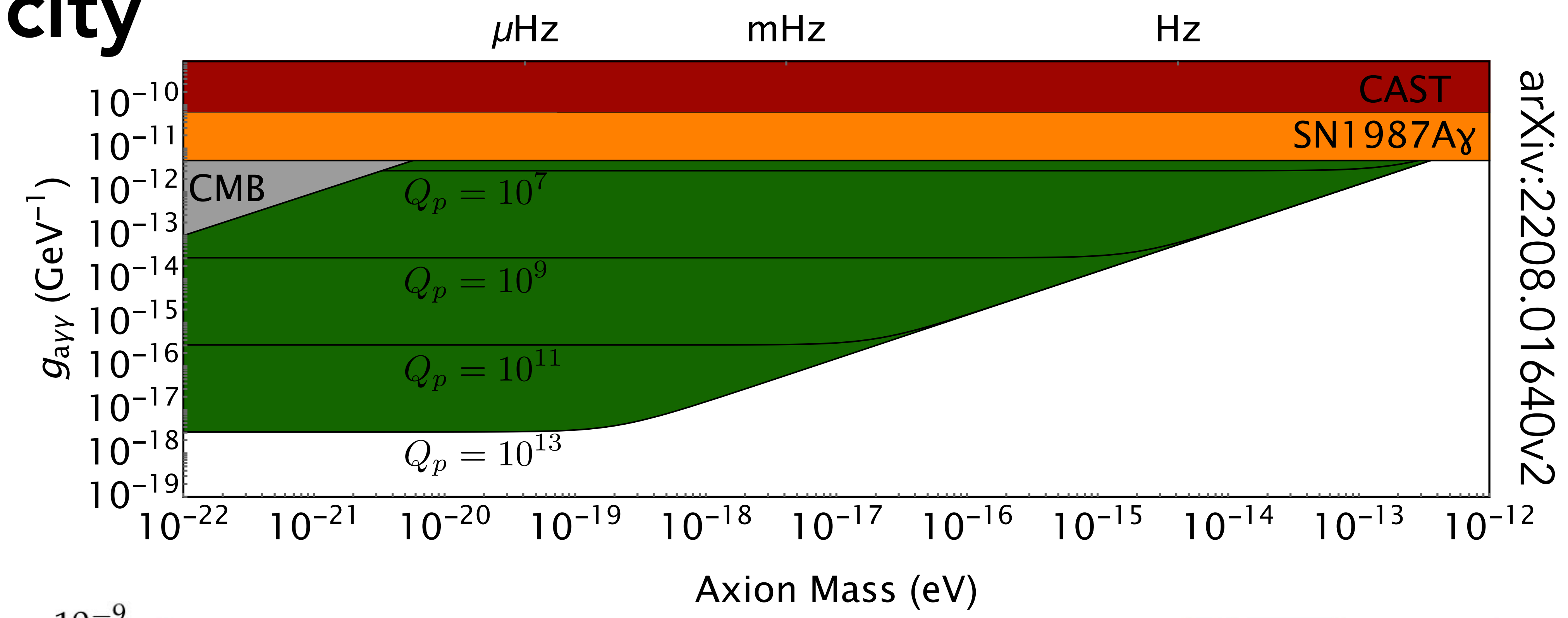

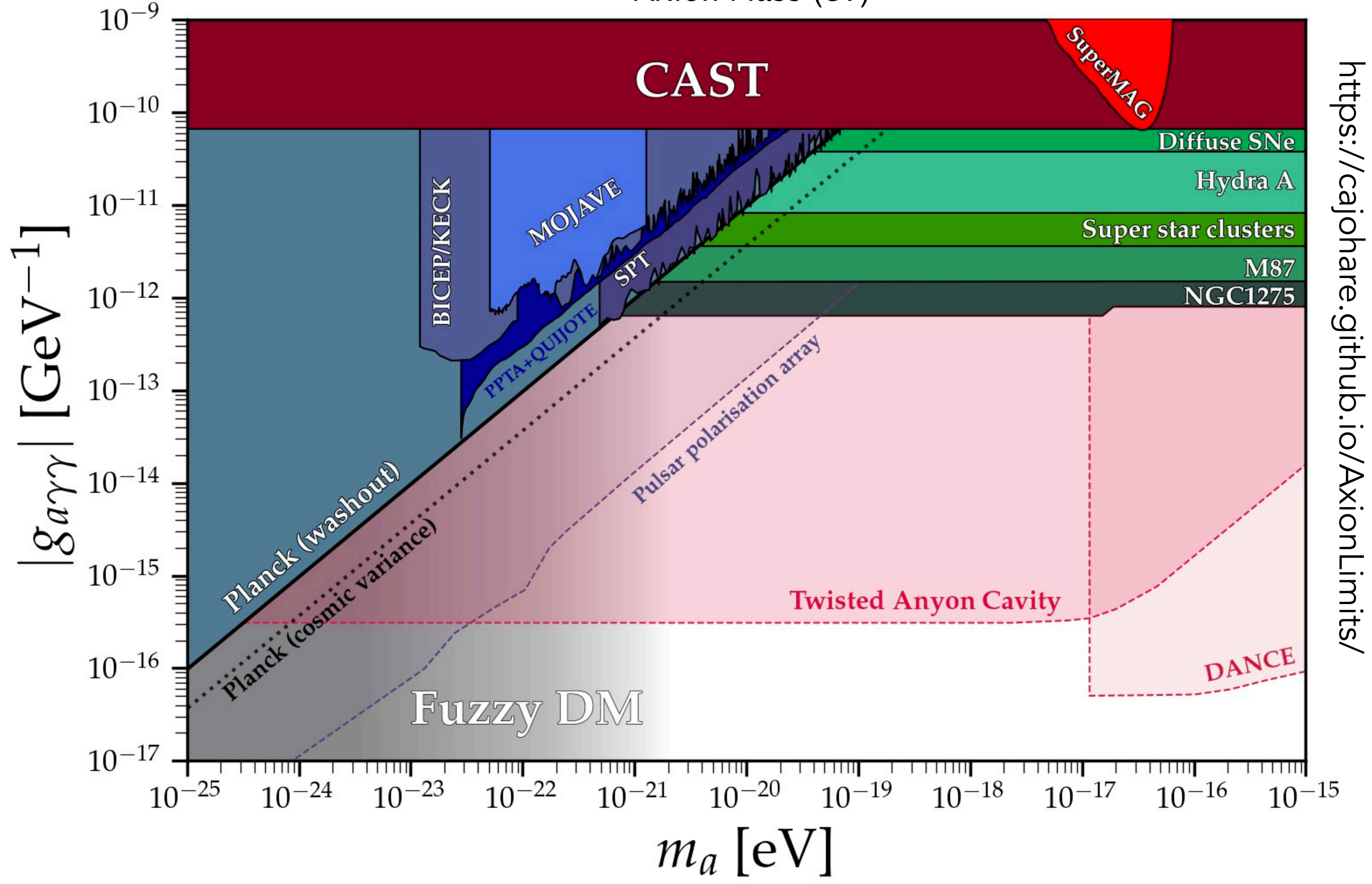

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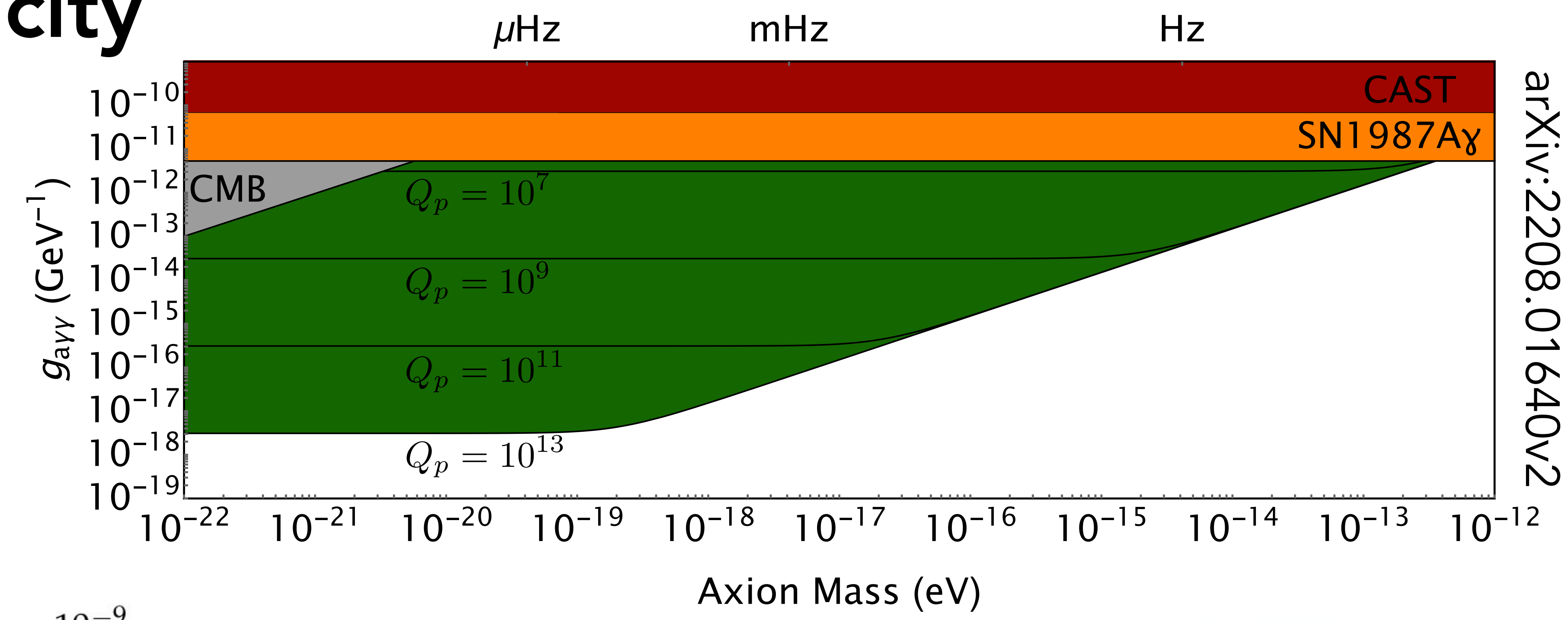

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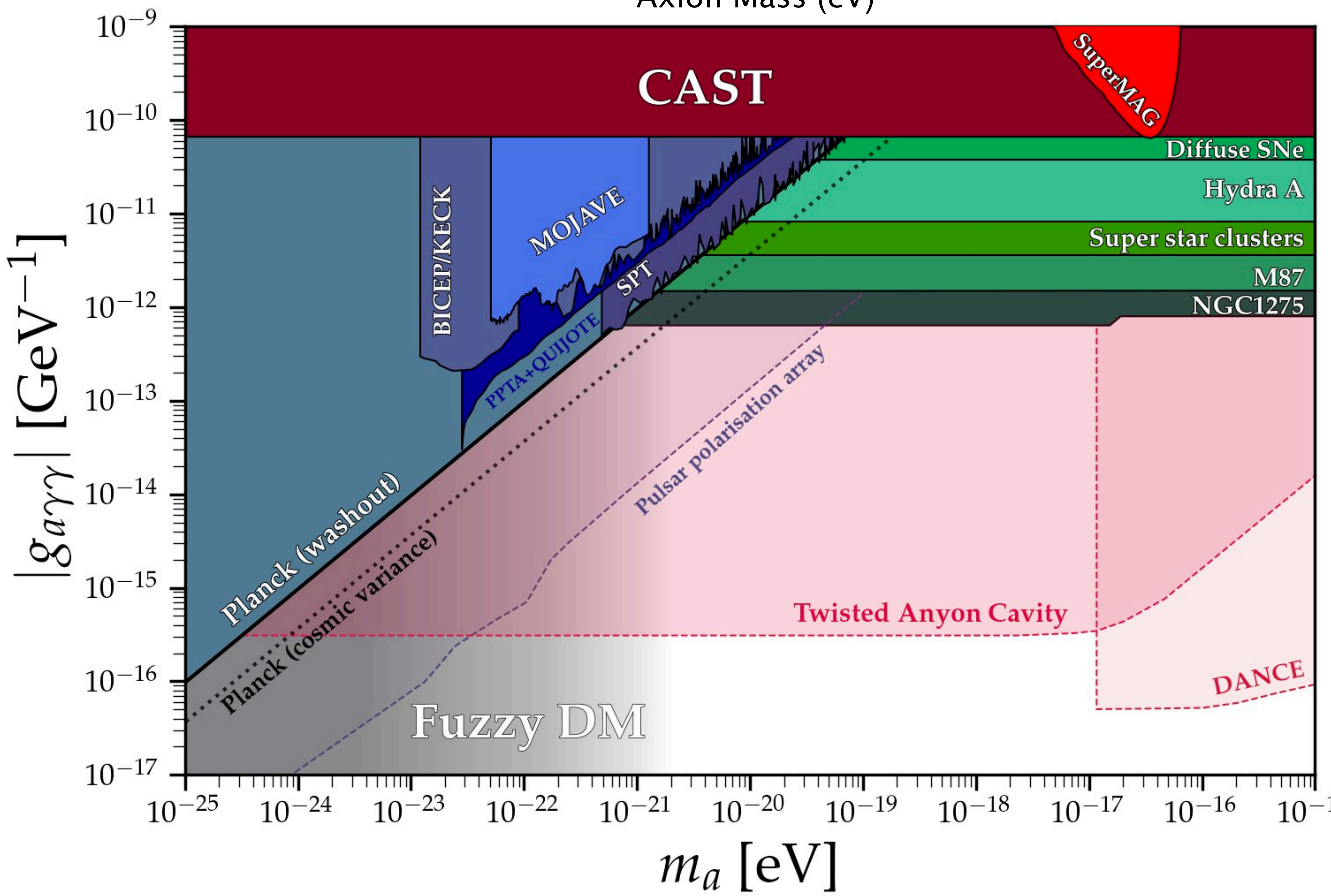

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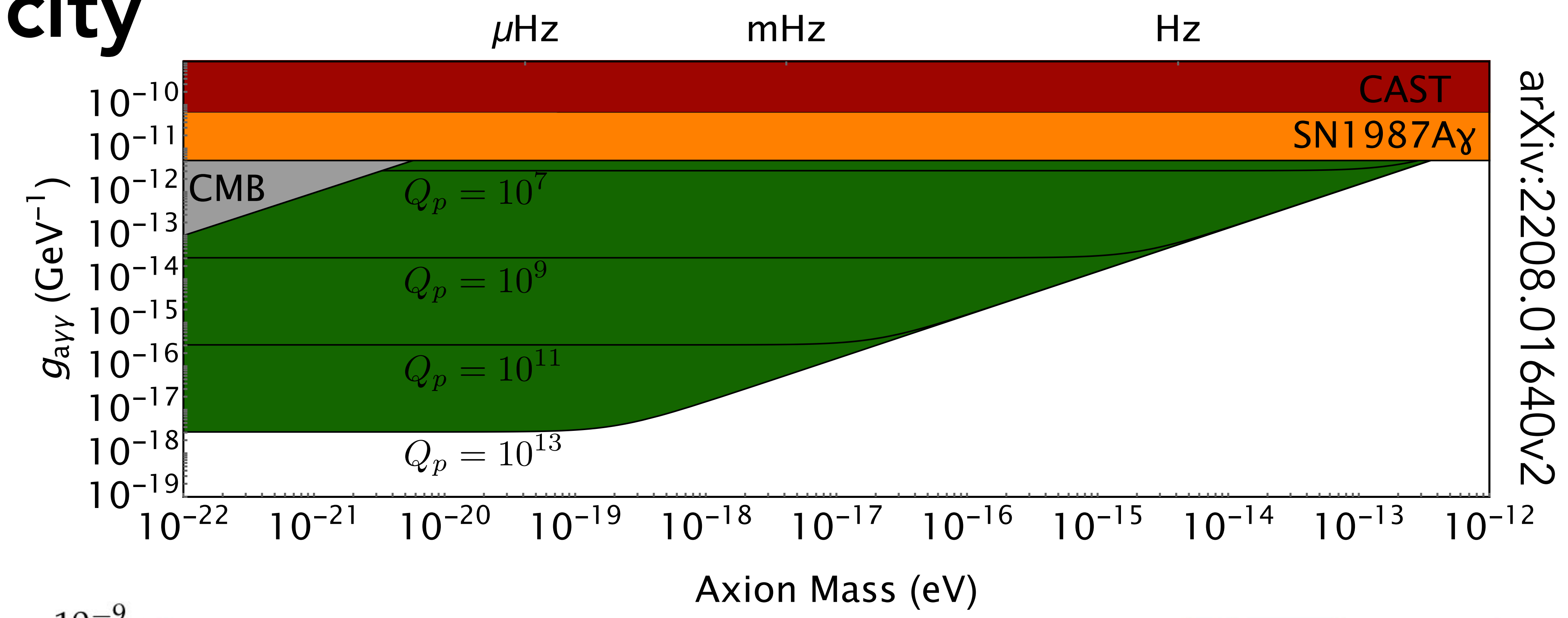

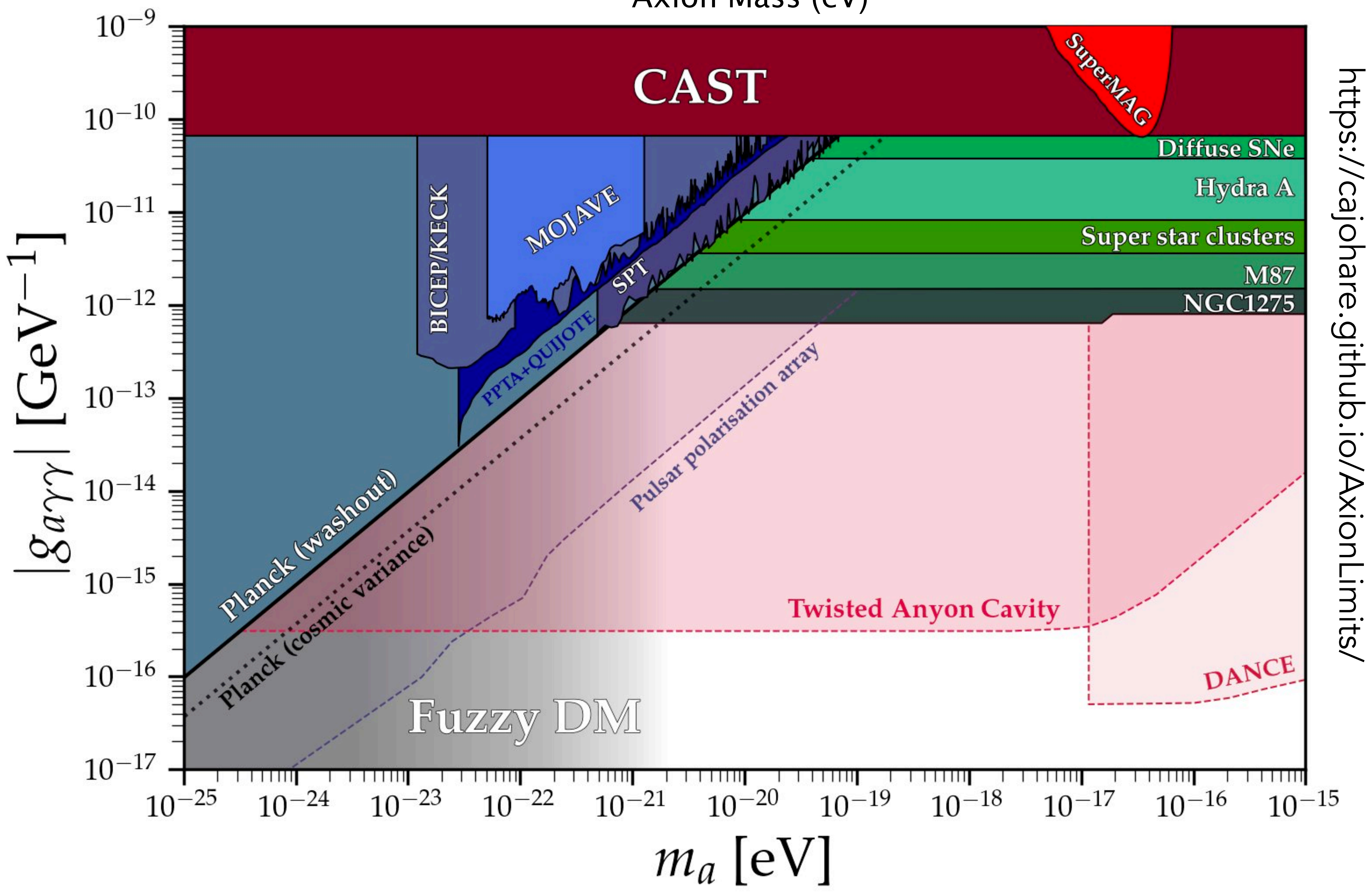

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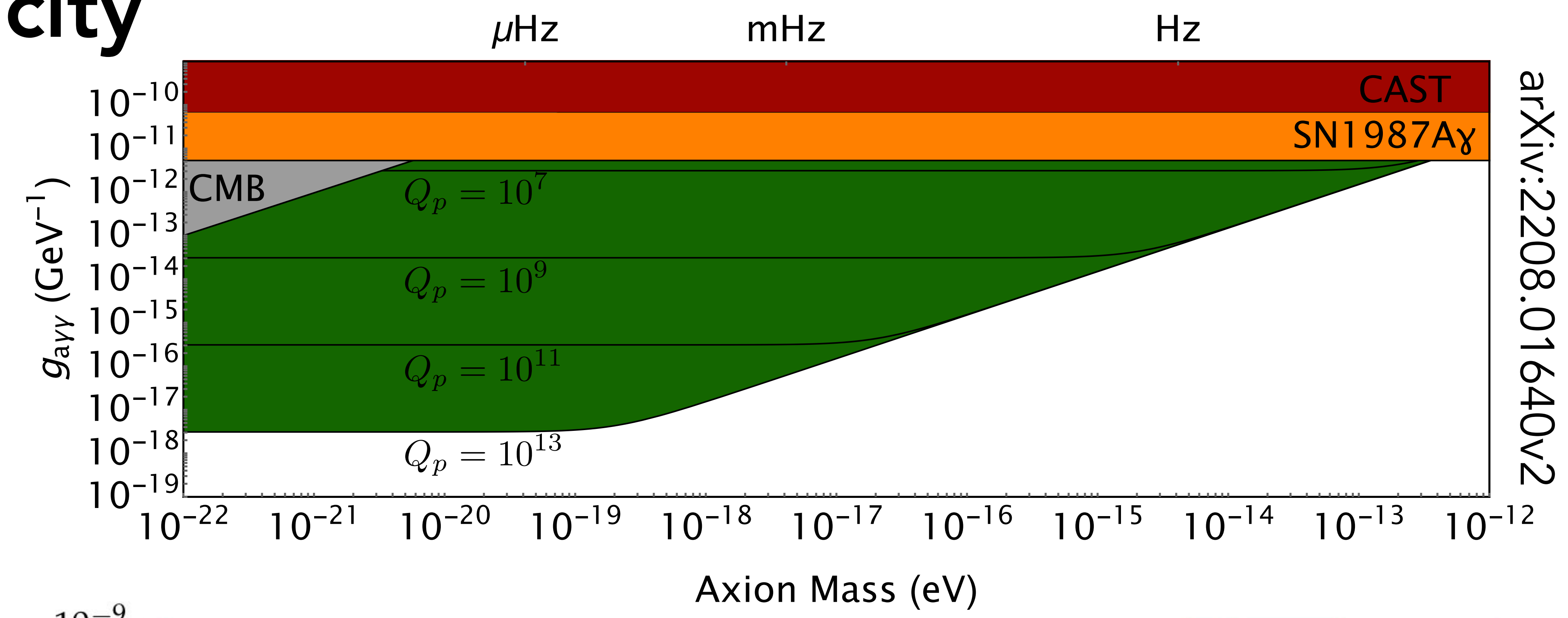

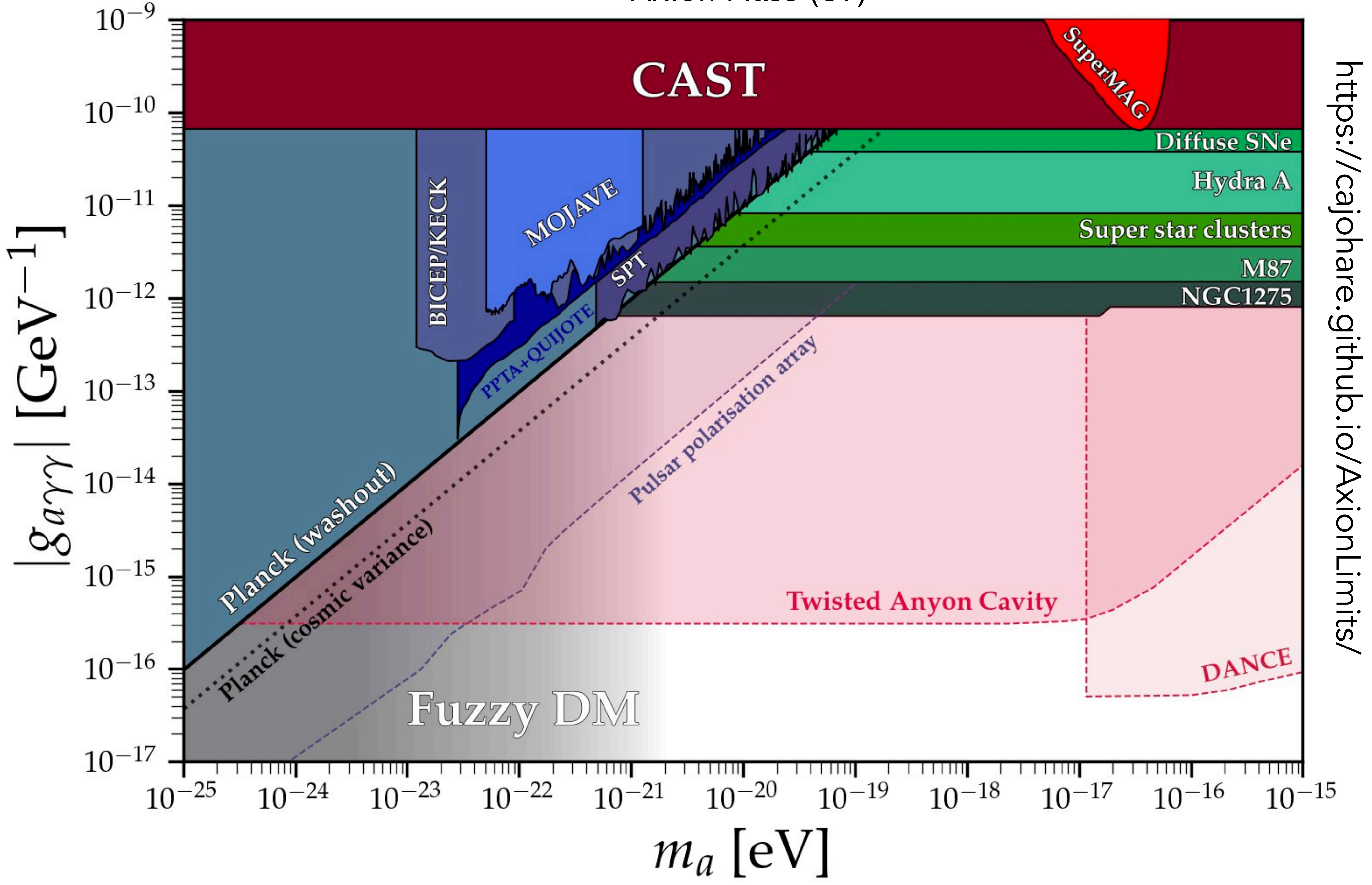

See poster #82 by Jeremy Bourhill

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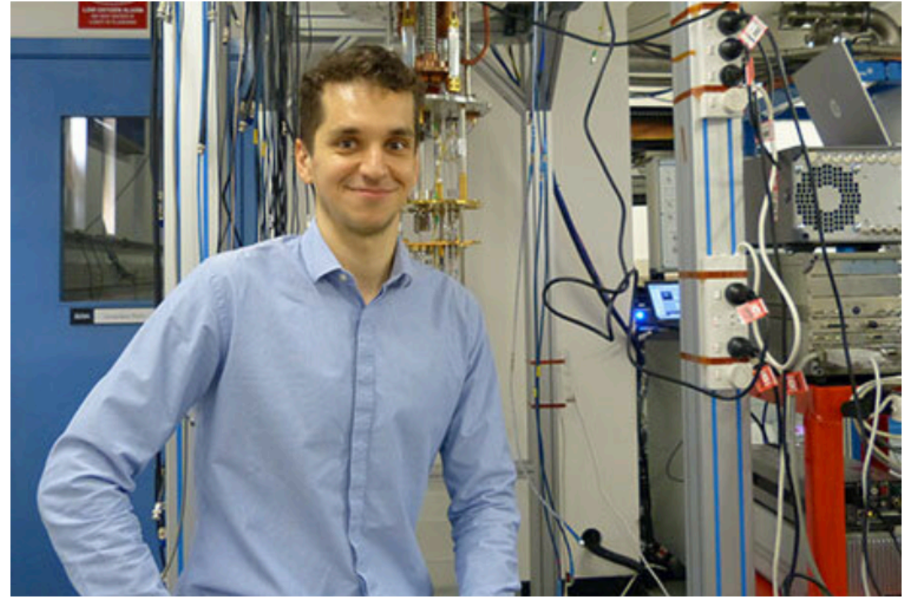
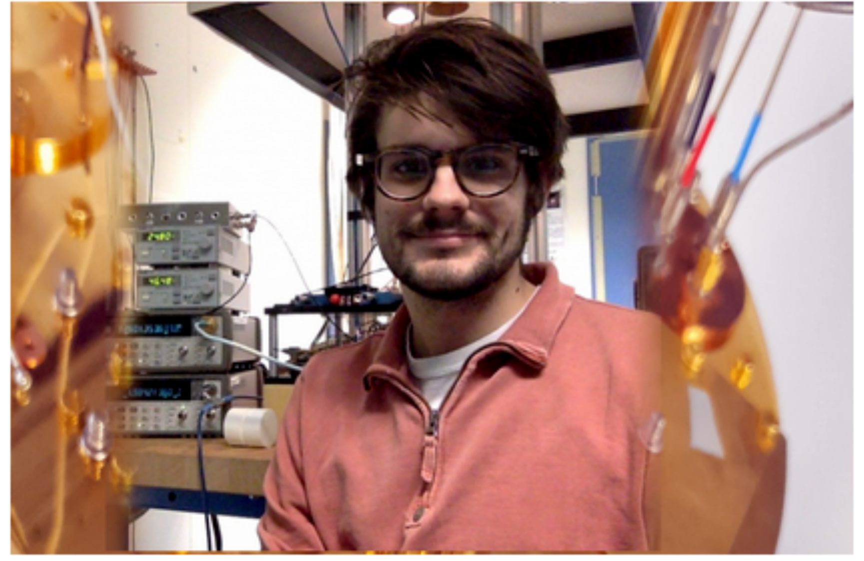
Professor Mike Tobar
Director



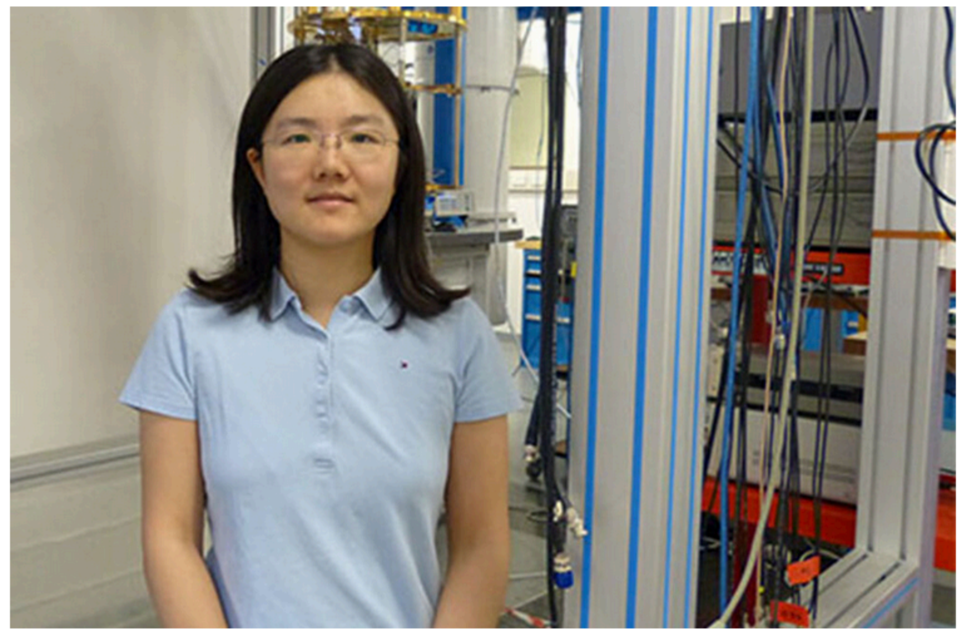
Dr Maxim Goryachev
Research Associate

Dr Ben McAllister
Research Associate

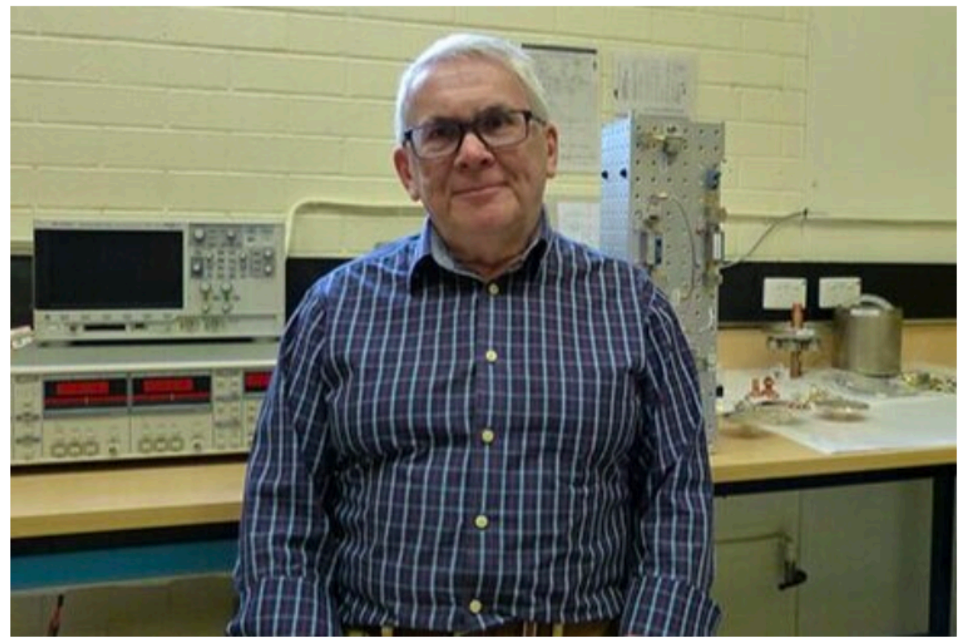
Professor Eugene Ivanov
Winthrop Research Professor—Dept of Physics



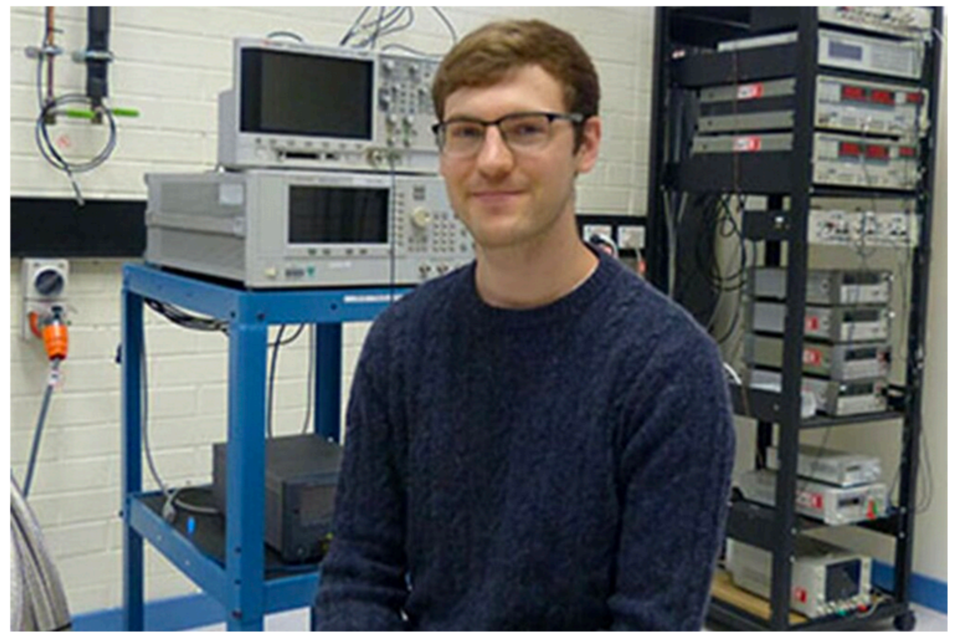
Dr Jeremy Bourhill
Postdoctoral Research Associate



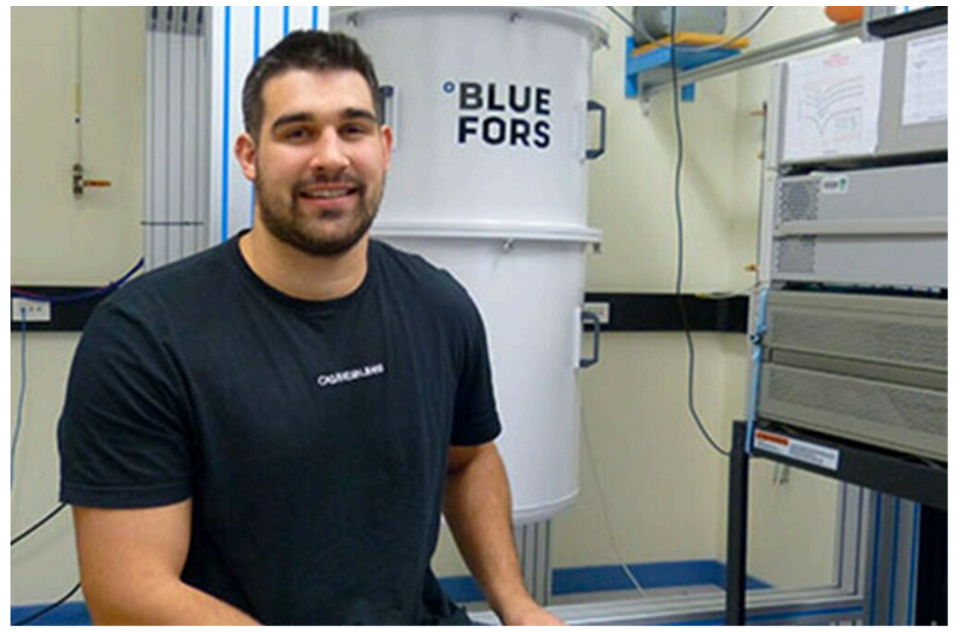
Dr Cindy Zhao
Deborah Jin Fellow—EQUS



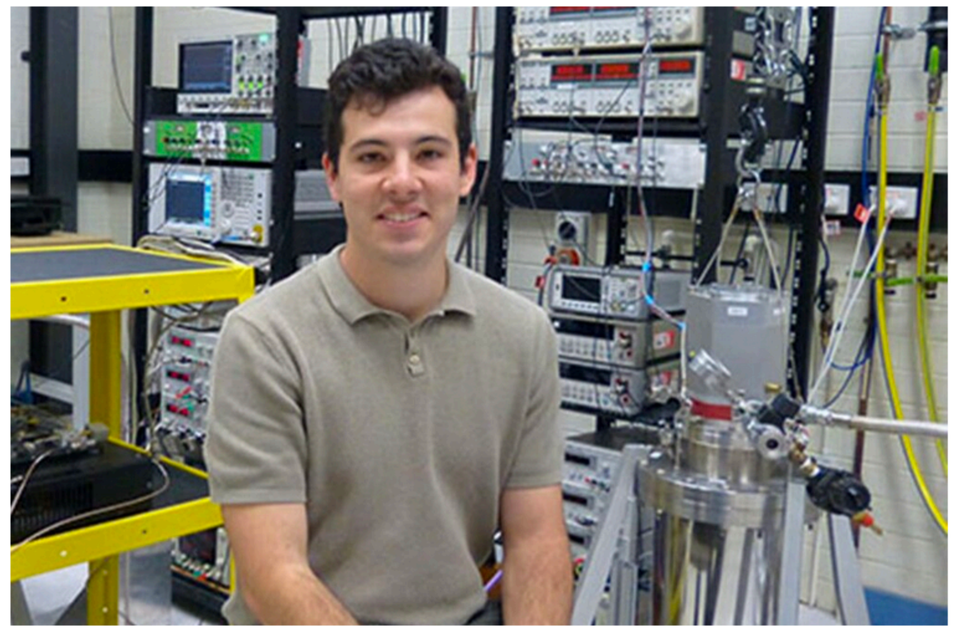
Professor Alexey Veryaskin
Adjunct Professor



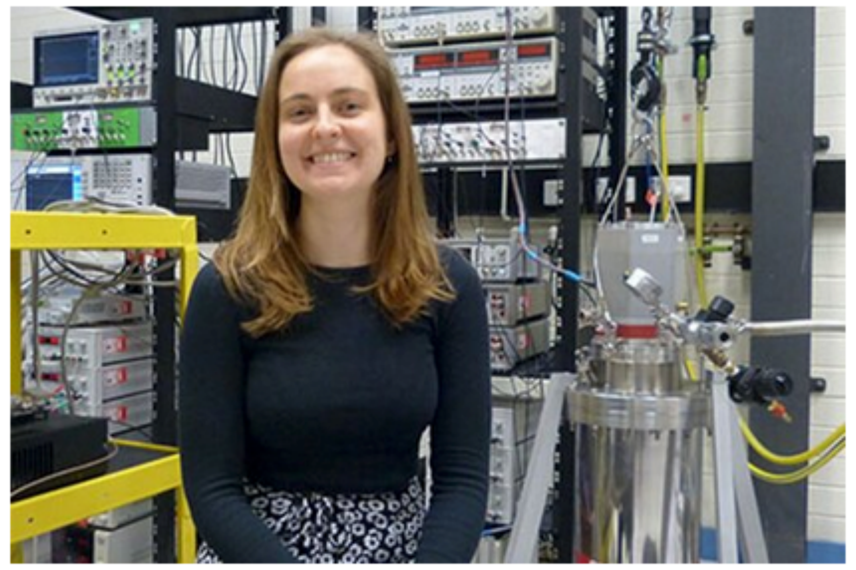
Graeme Flower
PhD



Aaron Quiskamp
PhD

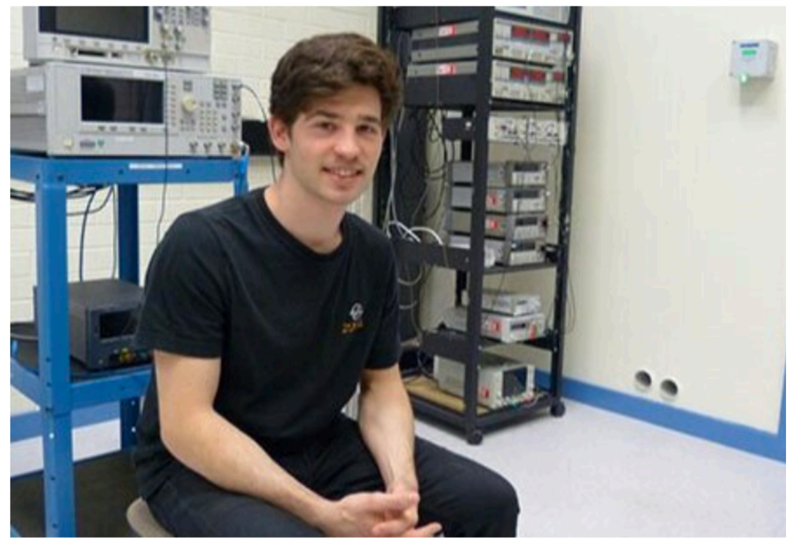


Will Campbell
PhD



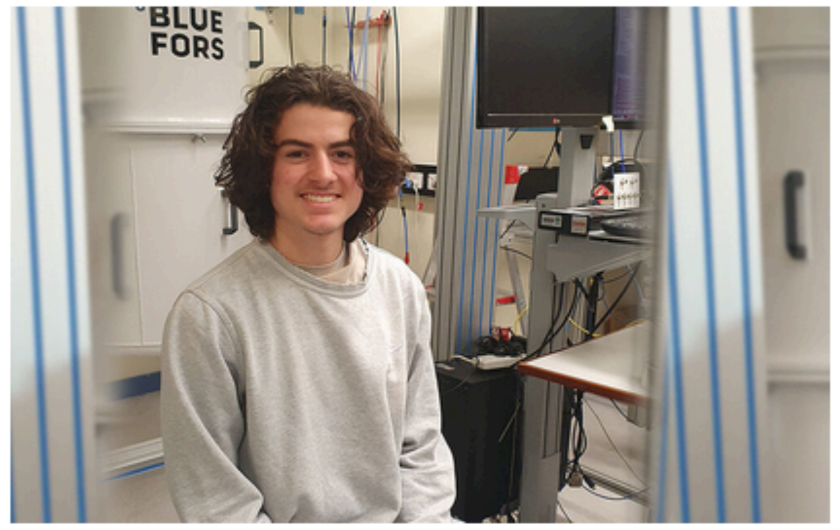
Catriona Thomson
PhD

Elrina Hartman
PhD

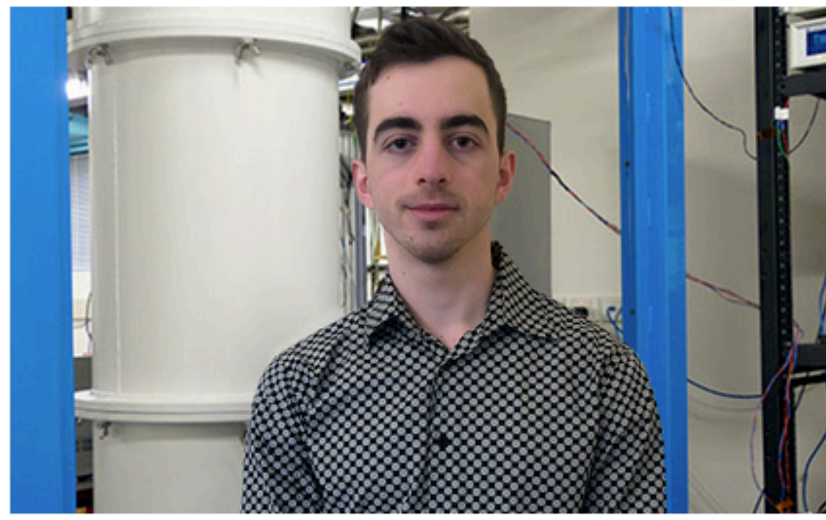


Jay Mummery
Masters

Robert Crew
BPhil (Hons) Placement



Daniel Tobar
BPhil (Hons) Placement



Michael Hatzon
BPhil (Hons)Placement

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Steve Osborne
Technician

THE END
THE
TEAM

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