Precision Low-Energy Experiments to Search for signs of Quantum Gravity and Dark Matter Particles

Michael Tobar Quantum Technologies and Dark Matter Laboratory

ACADEMIC (3)
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- Eugene Ivanov
- Maxim Goryachev

POSTDOCS (4)
- Cindy Zhao
- Jeremy Bourhill
- Graeme Flower
- William Campbell

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- Elrina Hartman
- Steven Samuels
- Emma Paterson
- Robert Crew

UNDERGRAD STUDENTS (6)
- Sonali Parashar (MSc)
- Michael Hatzon (Hons)
- Emily Waterman (Hons)
- Ashley Johnson (MSc)
- Tim Holt (MSc)
- Teehani Ralph (MPE)

QDM

QDM Quantum Technologies and Dark Matter Research Lab

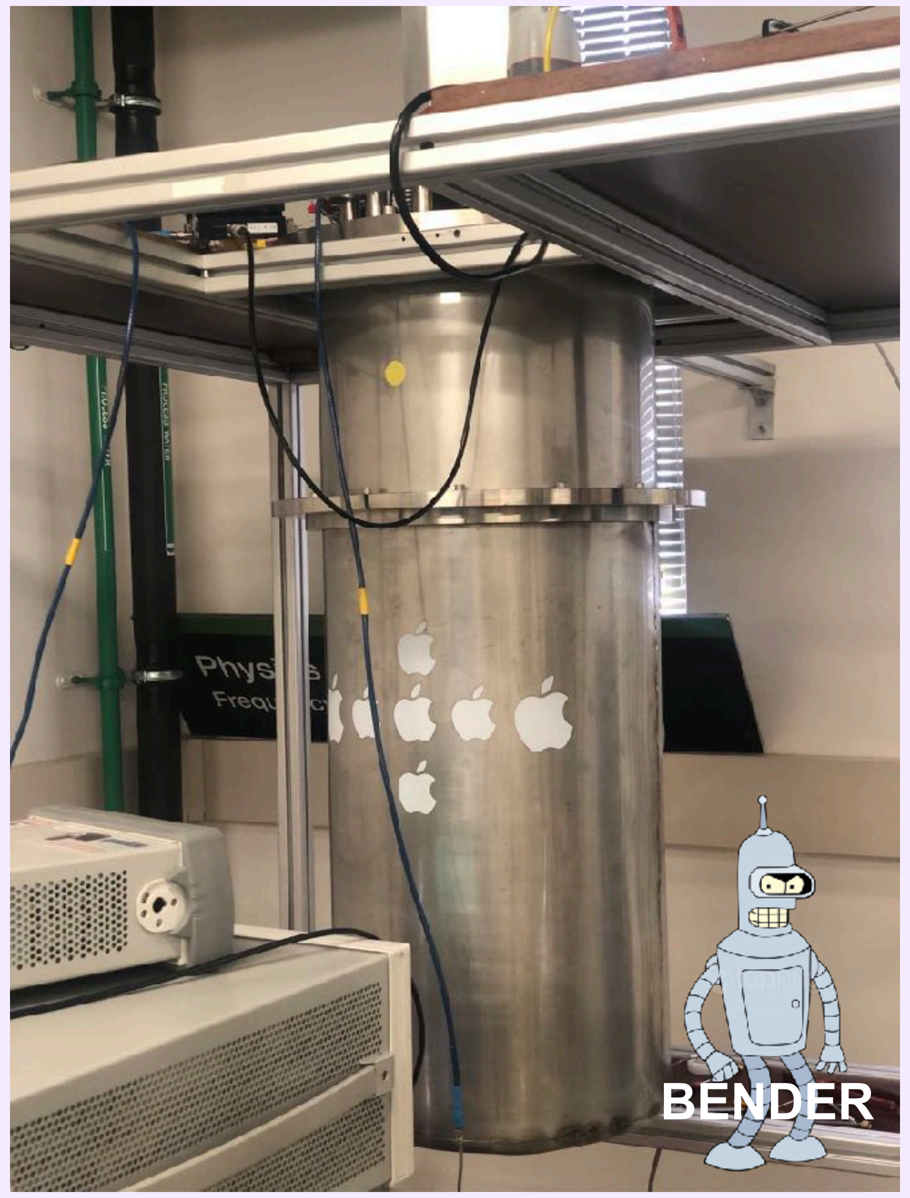
EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

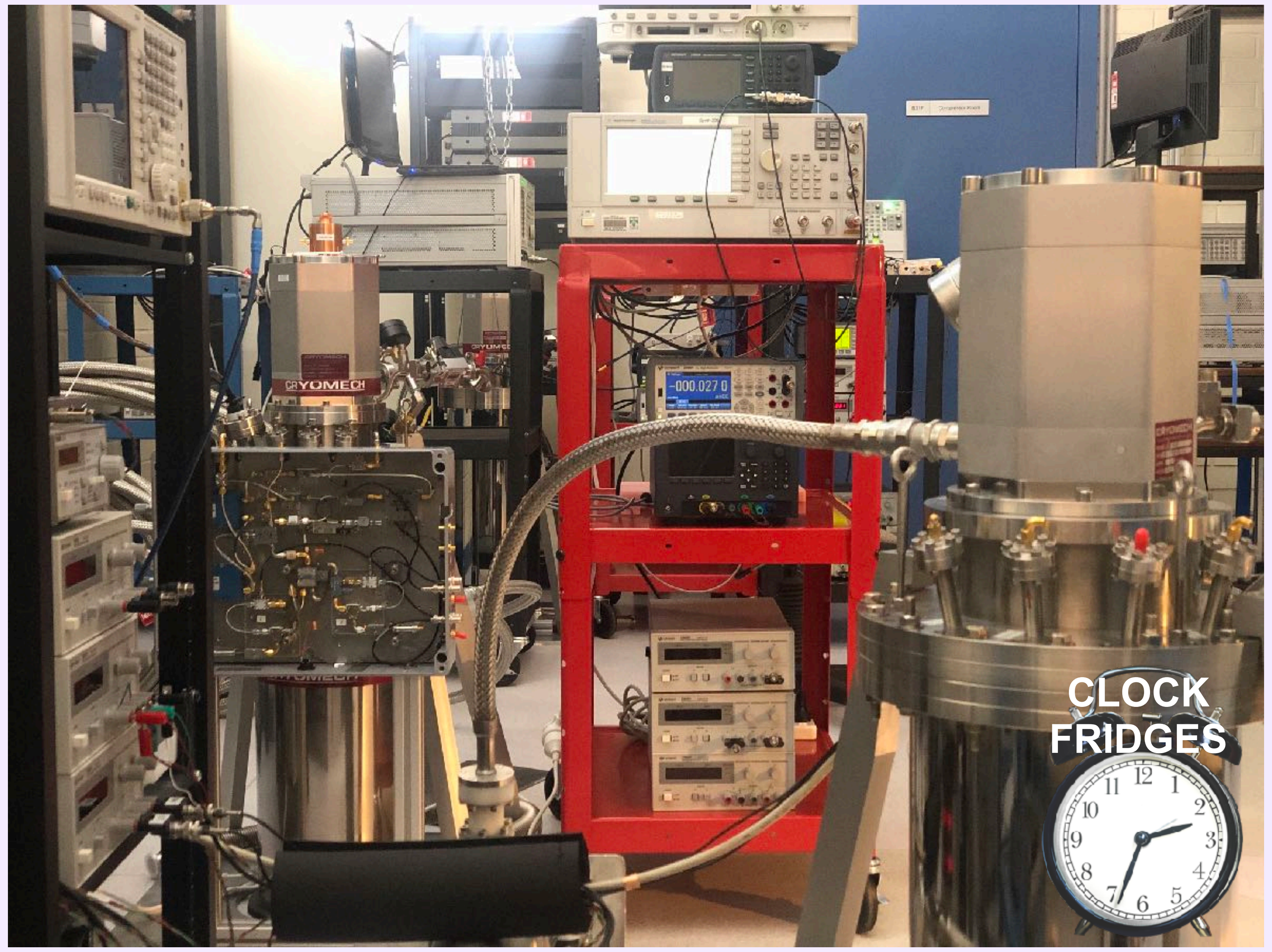
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

THE UNIVERSITY OF WESTERN AUSTRALIA — SEEK WISDOM

IGARSS 2024
8th July 2024

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

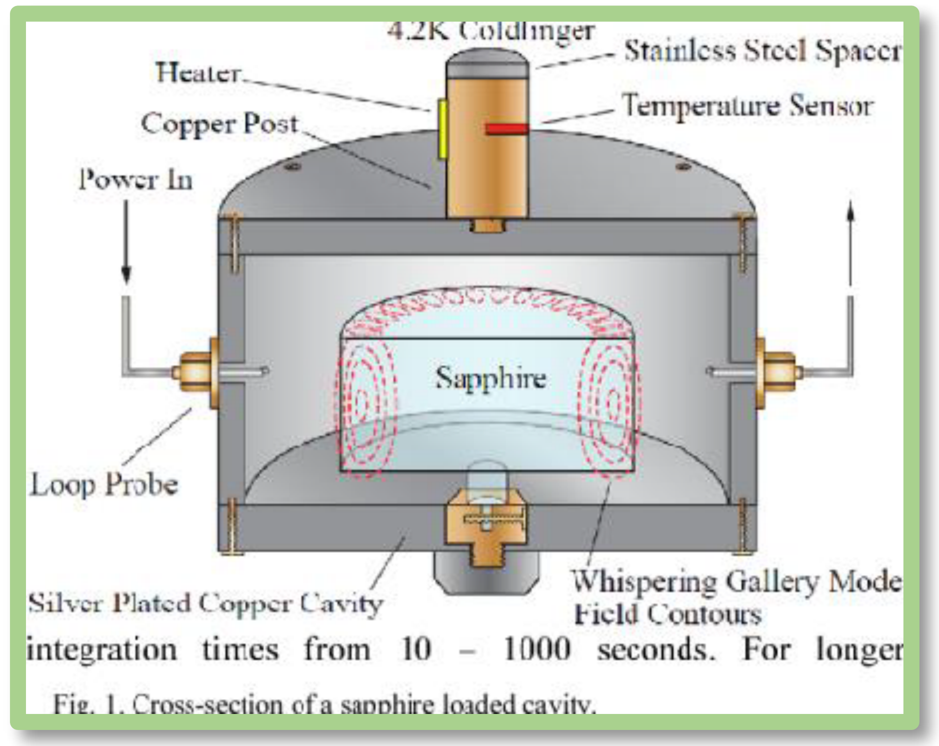
QDM Lab Precision Metrology: See www.qdmlab.com

Metrological Systems:

Science of precise measurement → Physics at low energies

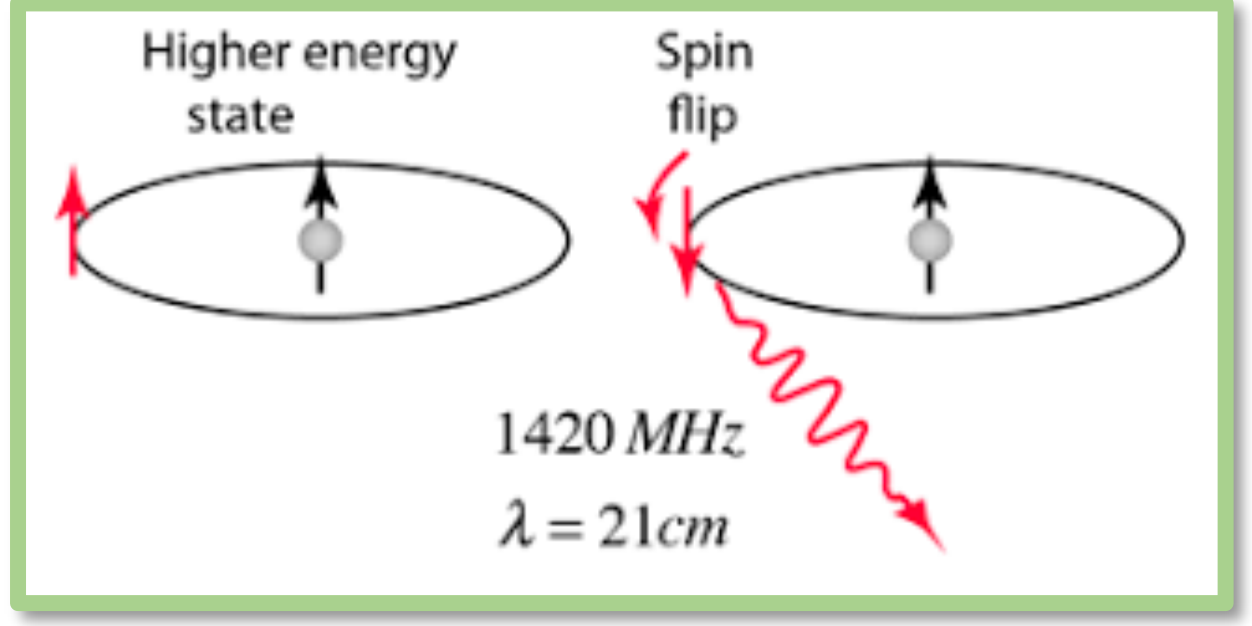
Photonic

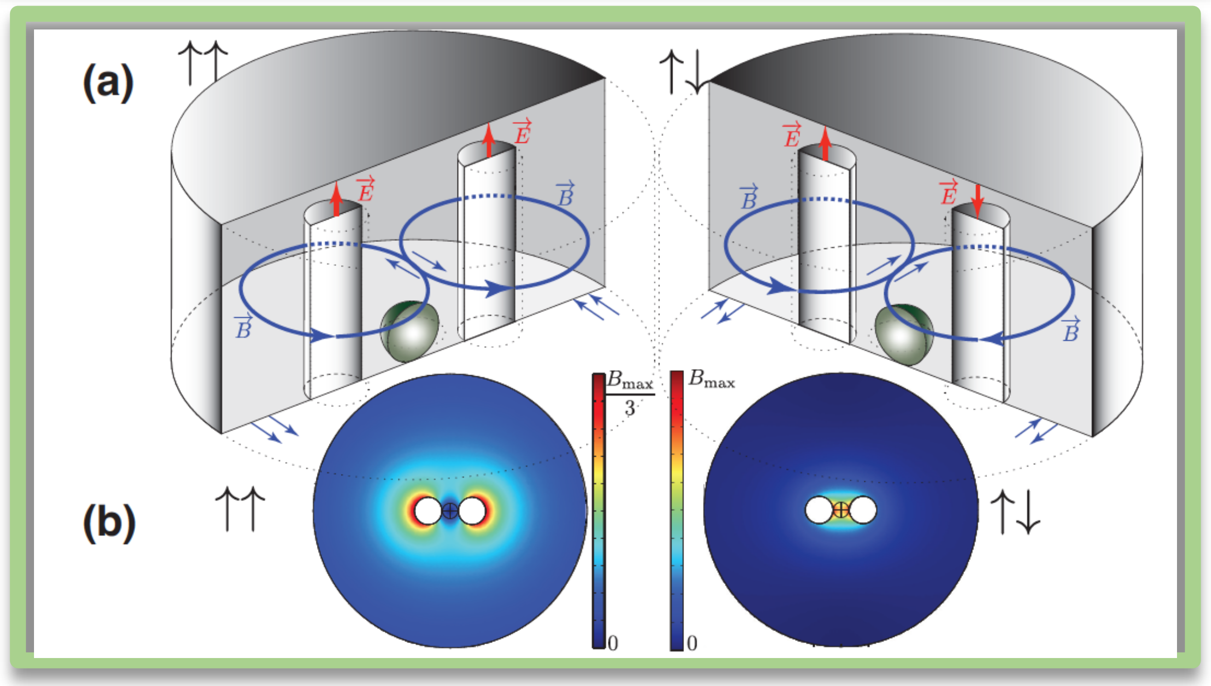
- WGM Resonators
- Specially Designed Microwave Cavities



Atomic/Spins

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



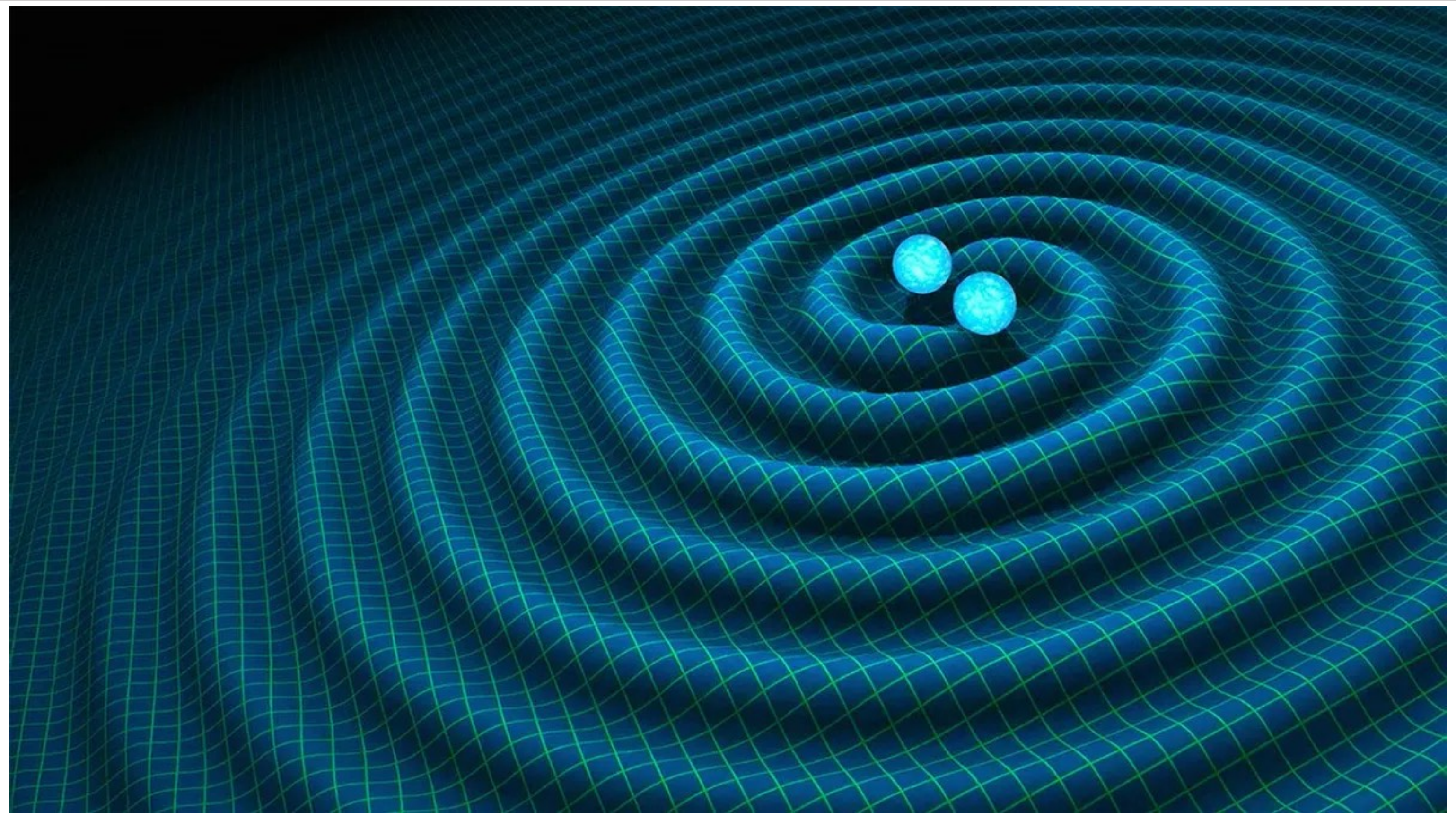


Acoustic

- 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

High Energy Physics – Experiment

[Submitted on 26 Jul 2024 (v1), last revised 1 Aug 2024 (this version, v2)]

Near-quantum limited axion dark matter search with the ORGAN experiment around 26 μeV

Aaron P. Quiskamp, Graeme Flower, Steven Samuels, Ben T. McAllister, Paul Altin, Eugene N. Ivanov, Maxim Goryachev, Michael E. Tobar

PHYSICAL REVIEW LETTERS 132, 031601 (2024)

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

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

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

UPLOAD Low-mass Axions

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*
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[3]*ARC Centre of Excellence For Engineered Quantum Systems, The Australian National University, Canberra, Australian Capital Territory 2600 Australia*

ANYON AXION Helicity

PHYSICAL REVIEW D 108, 052014 (2023)

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

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

Scalar Field Dark Matter

PHYSICAL REVIEW D 106, 055037 (2022)

Searching for scalar field dark matter using cavity resonators and capacitors

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

Axions and Magnetic Charge

PHYSICAL REVIEW D 108, 035024 (2023)

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

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

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

symmetry — MDPI

Article

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

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

PHYSICAL REVIEW D 105, 045009 (2022)

Poynting vector controversy in axion modified electrodynamics

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

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

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

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

Axion ED Poynting Theorem: Standardised way of Calculating Sensitivity

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*

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

Cite as: Appl. Phys. Lett. **125**, 094002 (2024); doi: 10.1063/5.0226310
Submitted: 1 July 2024 · Accepted: 9 August 2024 ·
Published Online: 28 August 2024

View Online Export Citation CrossM

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

AFFILIATIONS

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

Axions: ADMX

PHYSICAL REVIEW LETTERS **131**, 101002 (2023)

Search for a Dark-Matter-Induced Cosmic Axion Background with ADMX

T. Nitta,[1,*,†] T. Braine,[1] N. Du,[1] M. Guzzetti,[1] C. Hanretty,[1] G. Leum,[1] L. J. Rosenberg,[1] G. Rybka,[1] J. Sinnis,[1] John Clarke,[2] I. Siddiqi,[2] M. H. Awida,[3] A. S. Chou,[3] M. Hollister,[3] S. Knirck,[3] A. Sonnenschein,[3] W. Wester,[3] J. R. Gleason,[4] A. T. Hipp,[4] P. Sikivie,[4] N. S. Sullivan,[4] D. B. Tanner,[4] R. Khatiwada,[5,3] G. Carosi,[6] N. Robertson,[6] L. D. Duffy,[7] C. Boutan,[8] E. Lentz,[8] N. S. Oblath,[8] M. S. Taubman,[8] J. Yang,[8] E. J. Daw,[9] M. G. Perry,[9] C. Bartram,[10] J. H. Buckley,[11] C. Gaikwad,[11] J. Hoffman,[11] K. W. Murch,[11] M. Goryachev,[12] E. Hartman,[12] B. T. McAllister,[12,13] A. Quiskamp,[12] C. Thomson,[12] and M. E. Tobar[12]

(ADMX Collaboration)

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

Check for updates

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

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

Searching for Axion Dark Matter

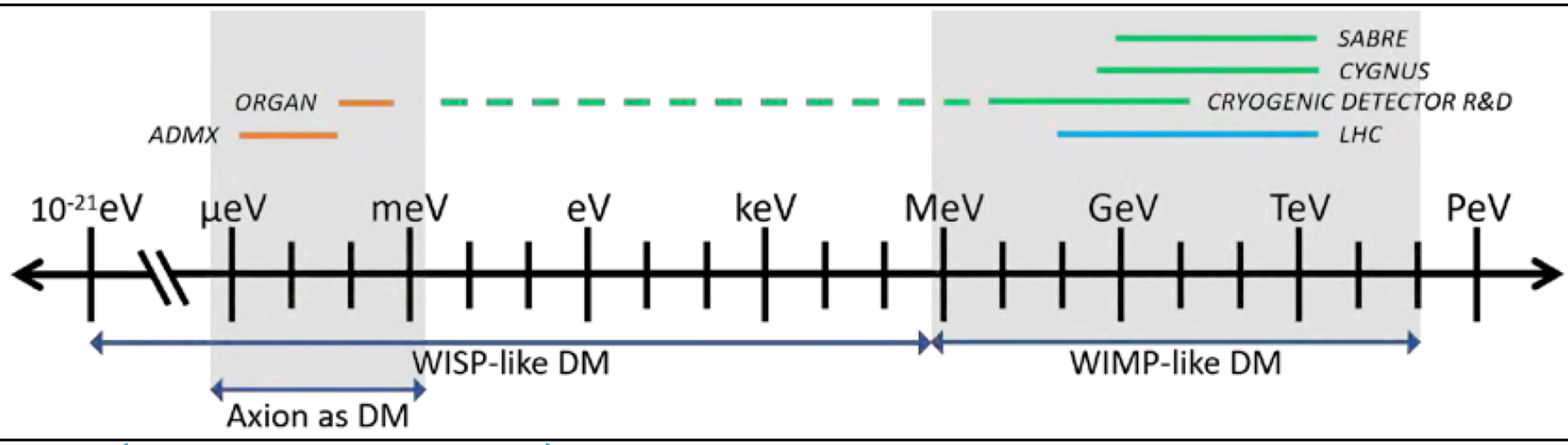


Figure 4: Dark matter mass ranges to be searched in Centre WIMP and WISP direct detection experiments and the LHC Program.

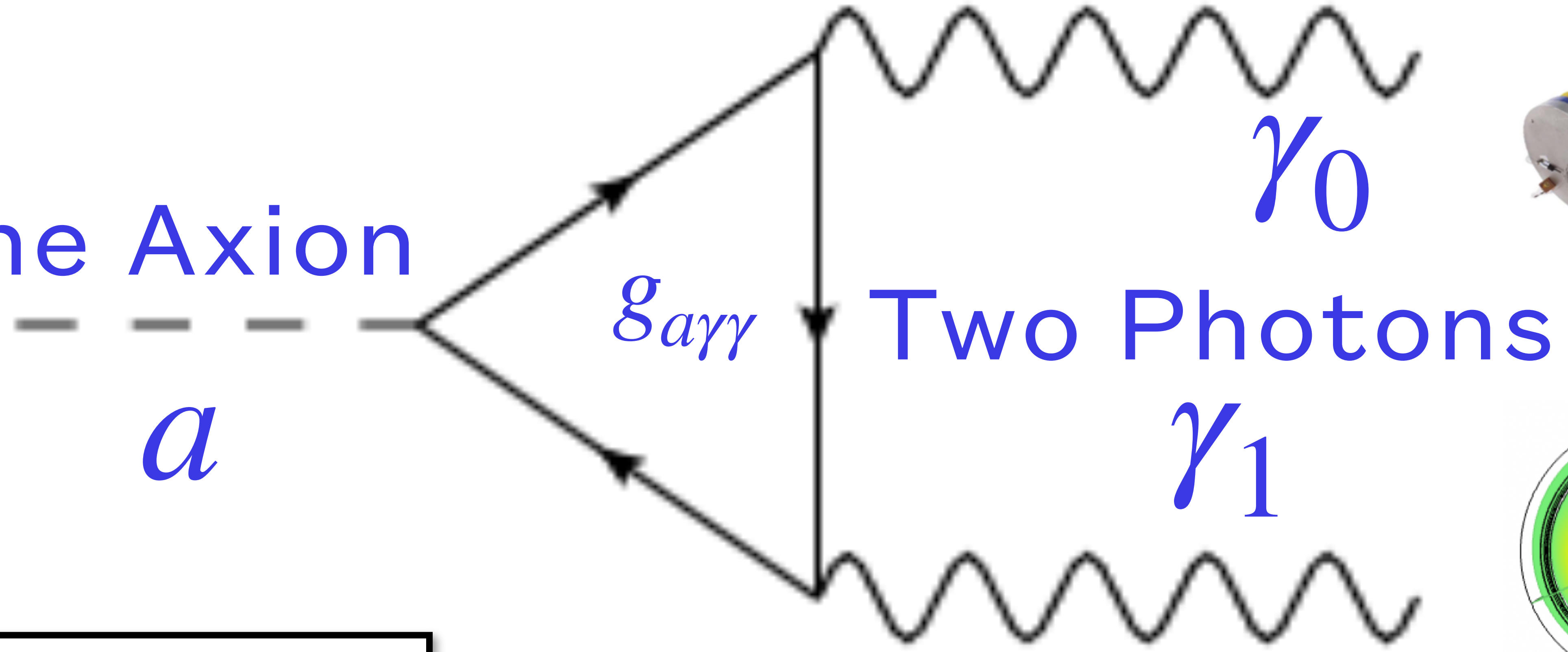
WLDM: Wave Like Dark Matter

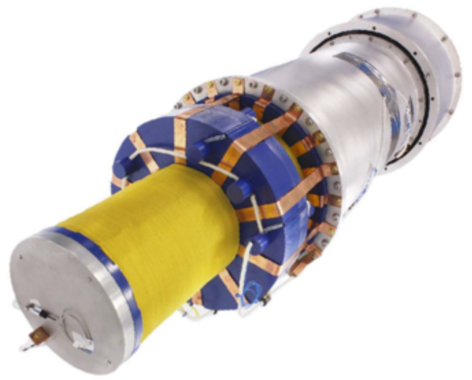
The Axion Particle Should Exist!

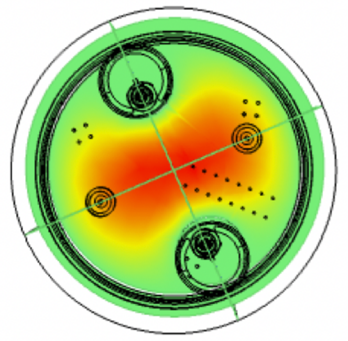
1) Solves Strong CP Problem
2) Predicted to form in Early Universe
3) Is Dark Matter the Axion?

Frank Wilczek

axion-photon coupling $g_{a\gamma\gamma}$ -> chiral anomaly







$$\mathcal{H}_{int} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E}_1 \cdot \mathbf{B}_0$$

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

Measure

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

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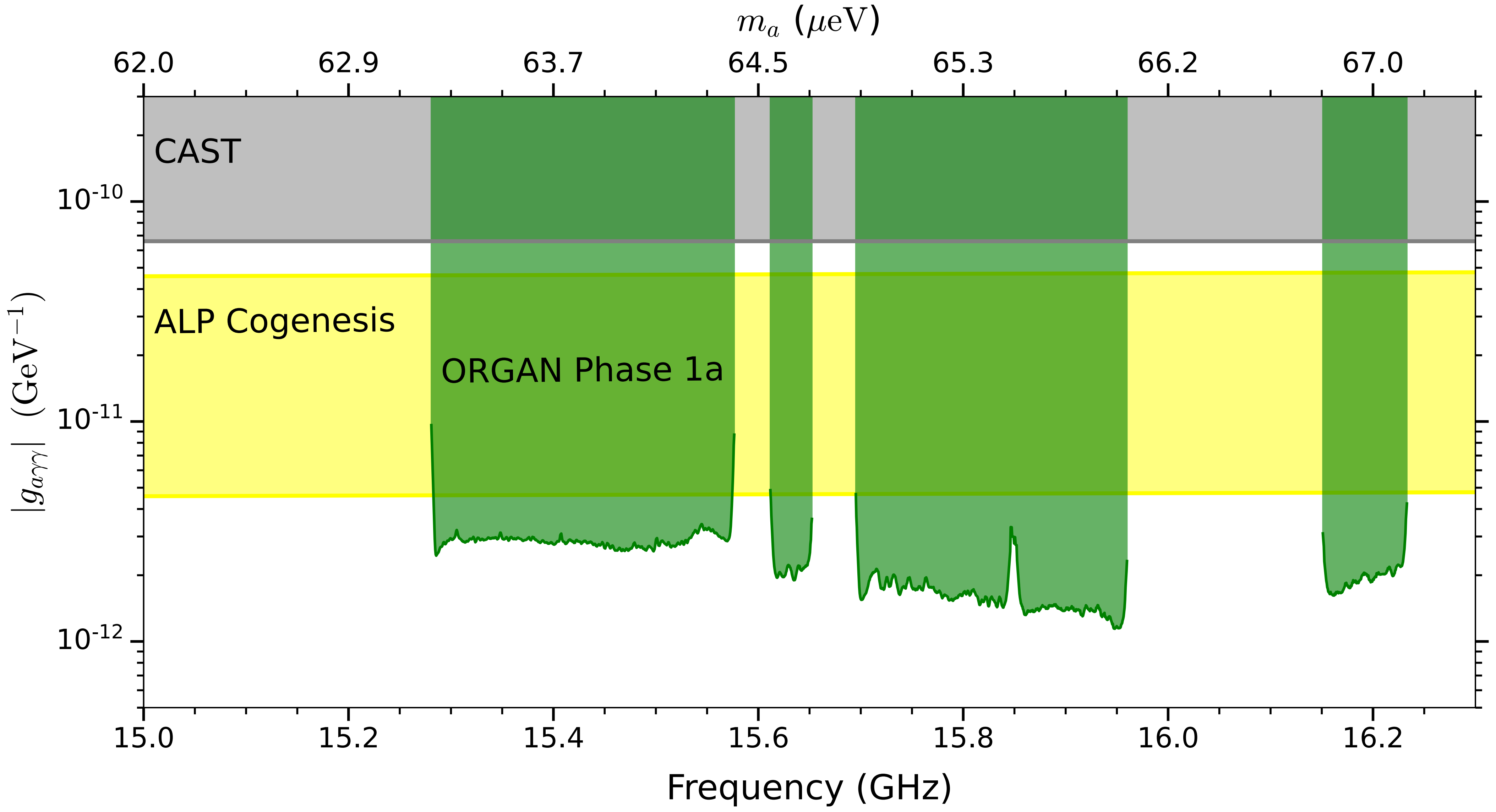

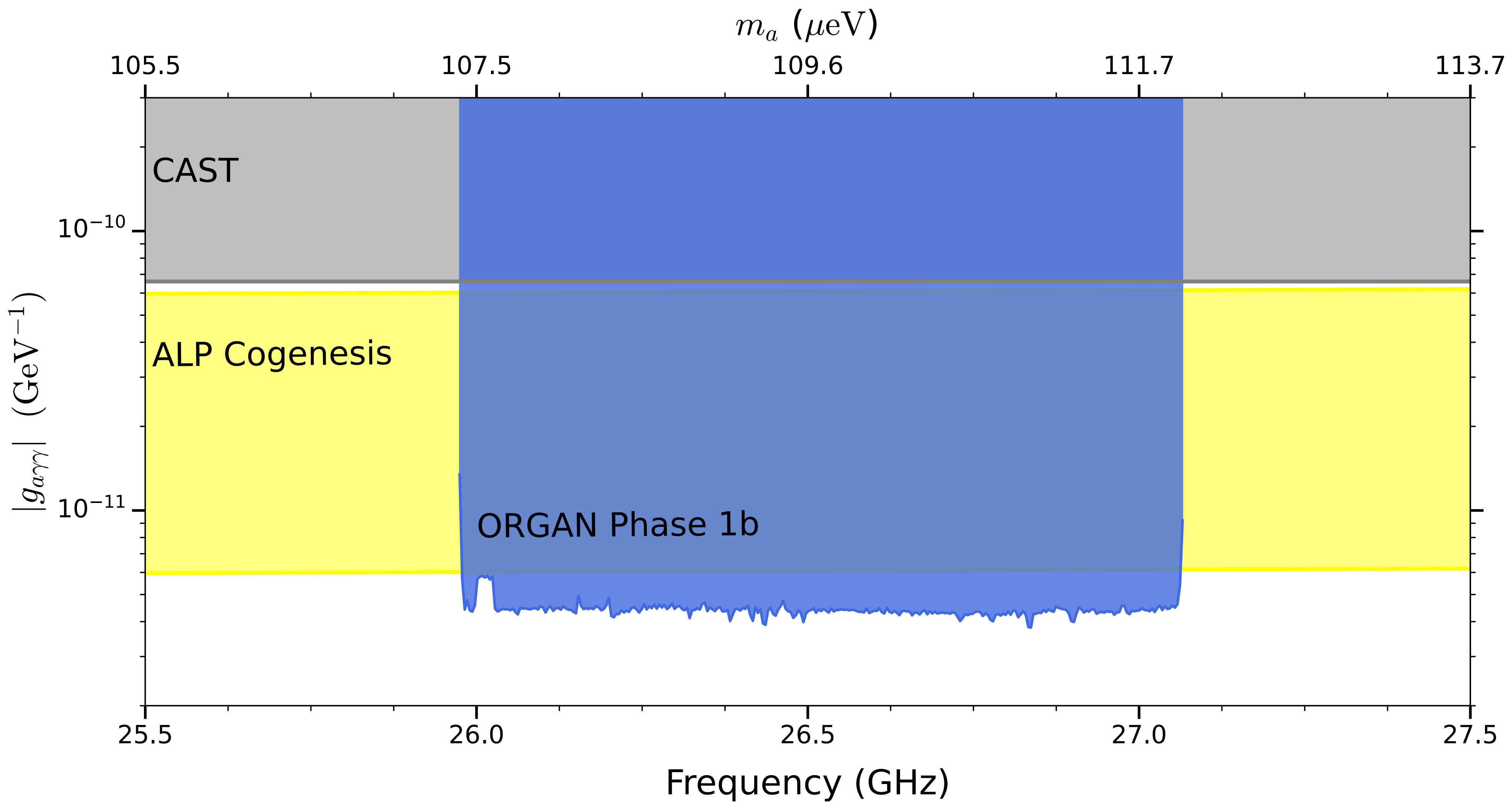

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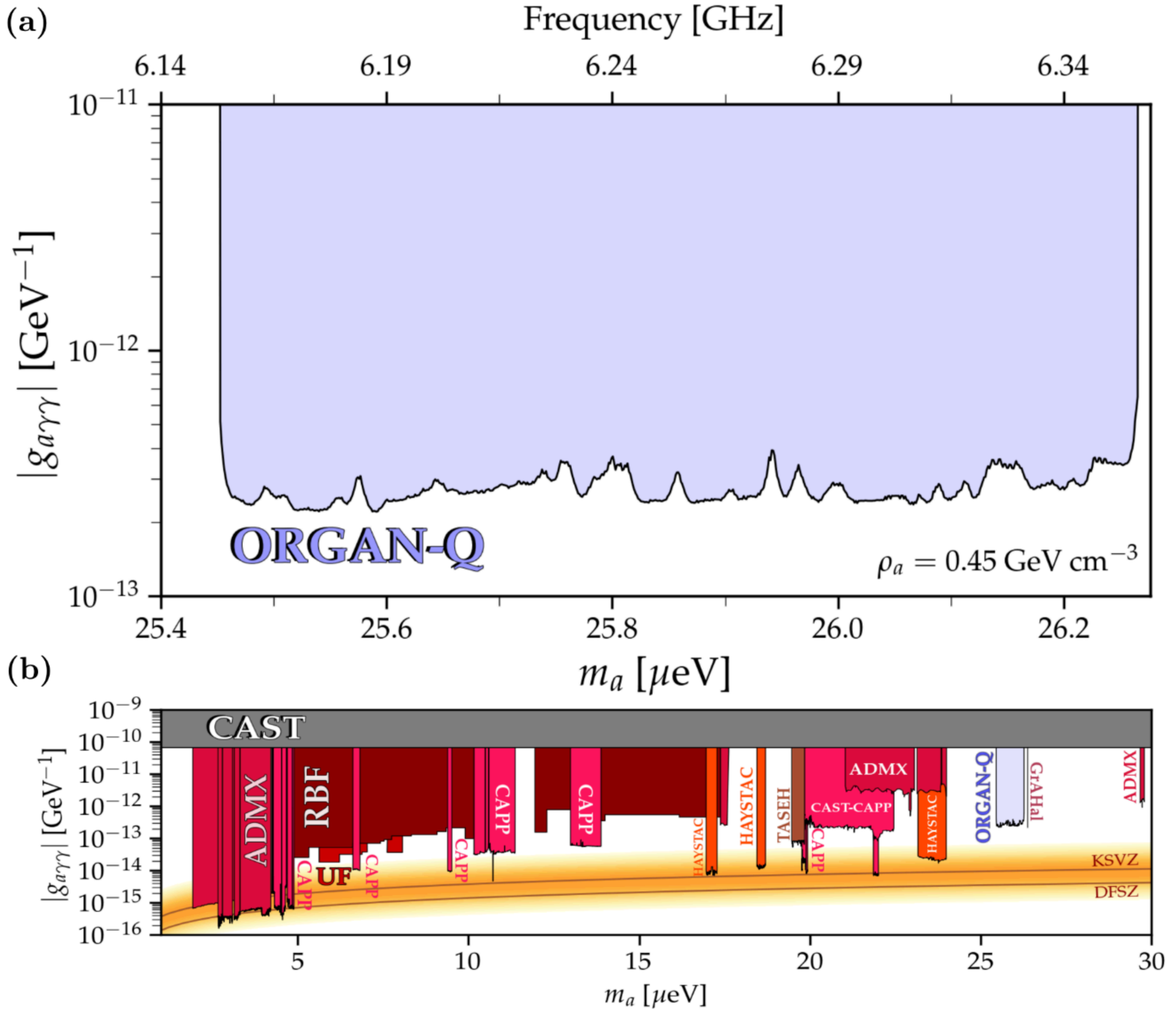

PHYSICAL REVIEW LETTERS **132,** 031601 (2024)

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

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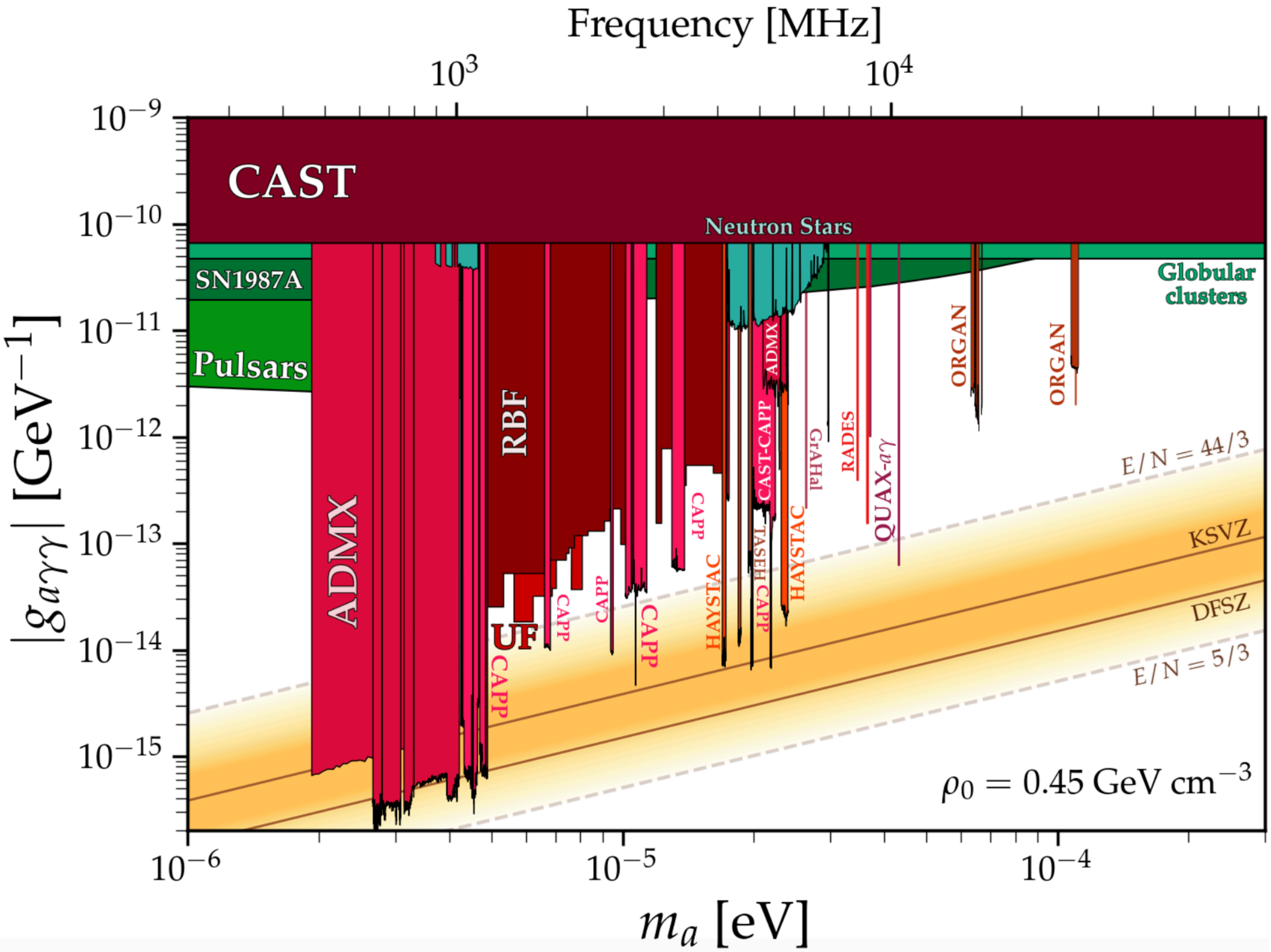
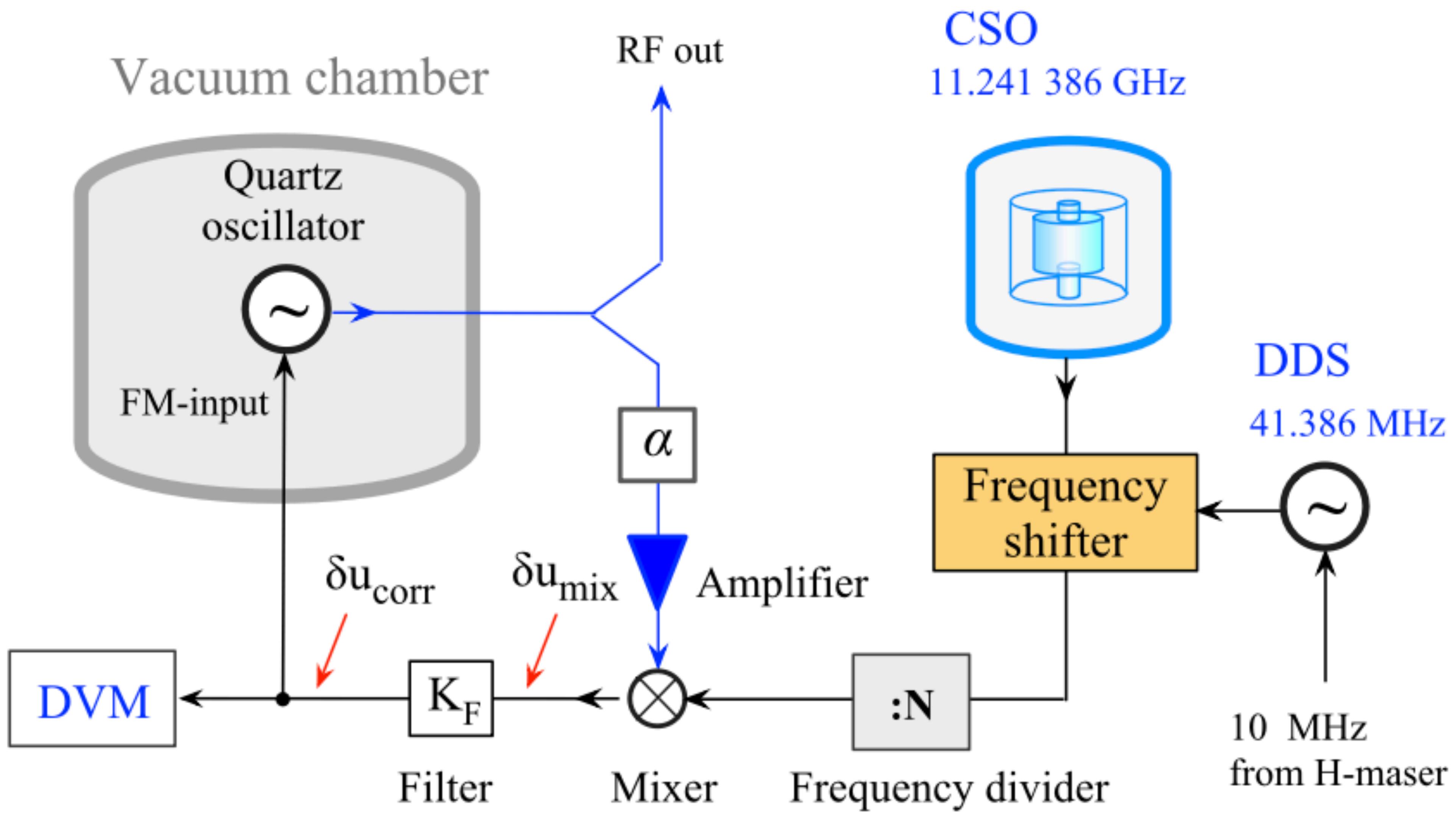
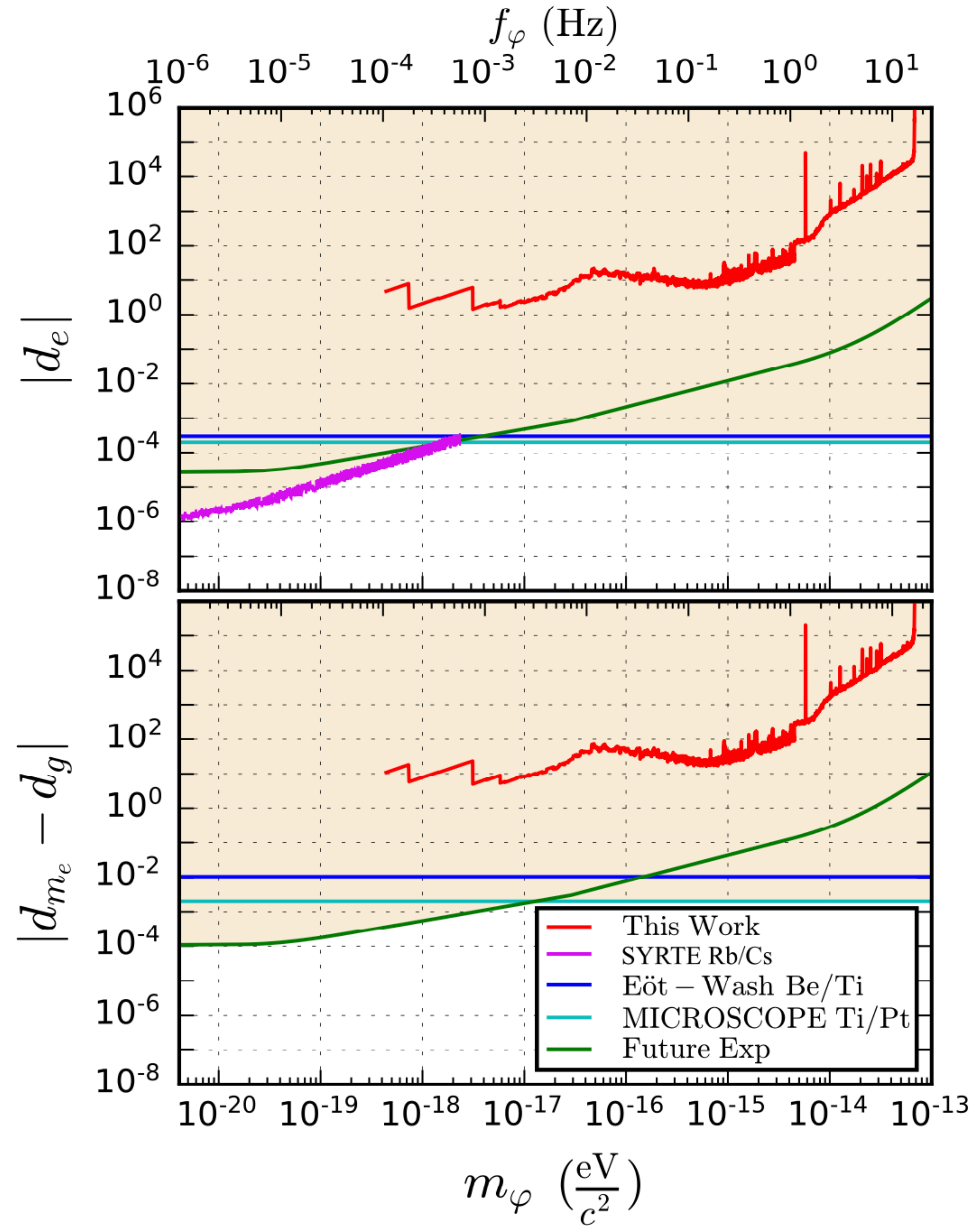

Frequency [MHz]
10^3
10^4
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
CAST
Neutron Stars
SN1987A
Pulsars
Globular clusters
ADMX
RBF
UF
CAPP
CAPP
CAPP
CAPP
CAPP
HAYSTAC
TASEH
CAPP
CAST-CAPP
ADMX
HAYSTAC
GrAHal
RADES
QUAX-$a\gamma$
ORGAN
ORGAN
E/N = 44/3
KSVZ
DFSZ
E/N = 5/3
$\rho_0 = 0.45$ GeV cm^{-3}
10^{-6}
10^{-5}
10^{-4}
m_a [eV]

PHYSICAL REVIEW LETTERS **126,** 071301 (2021)

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

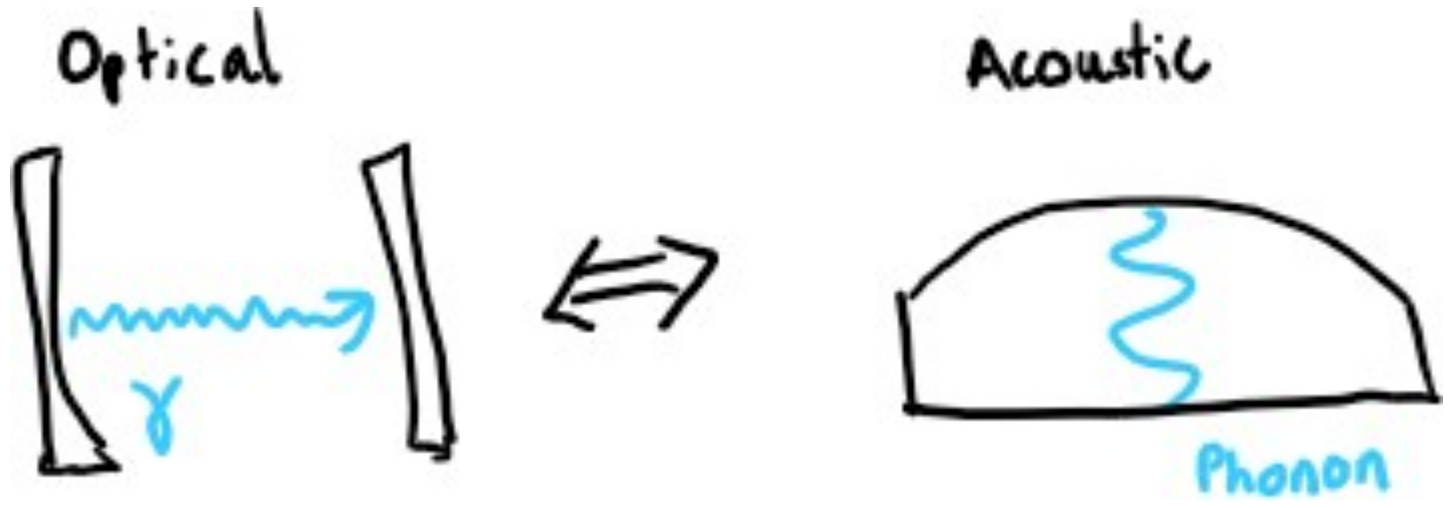
William M. Campbell, Ben T. McAllister, Maxim Goryachev, Eugene N. Ivanov, and Michael E. Tobar*
ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley,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

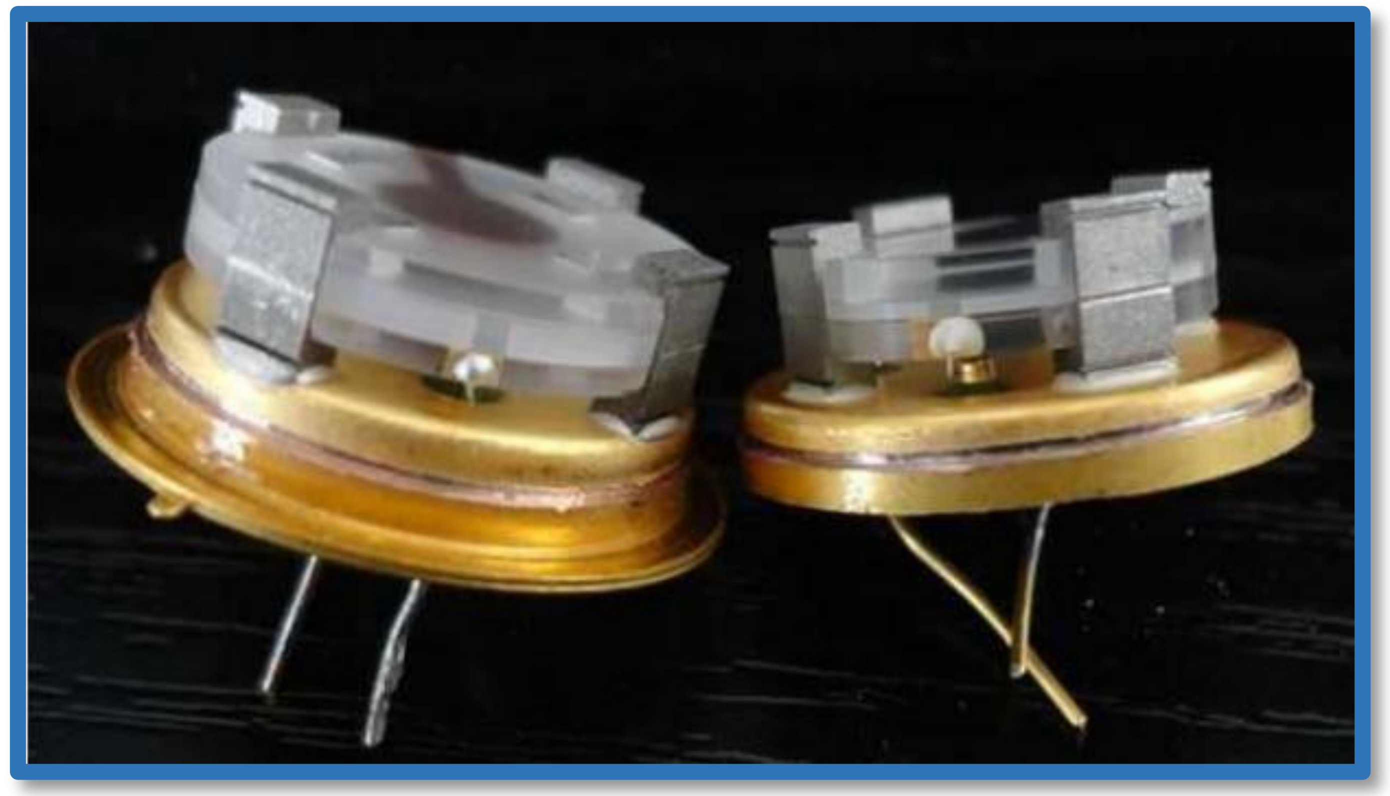




Quartz Bulk Acoustic Wave Resonators

- **Acoustic analogue to a Optical Fabry-Perot cavity.**





***RESEARCH WITH ACOUSTIC RESONATORS @ UWA**

***Search for High frequency GWs**

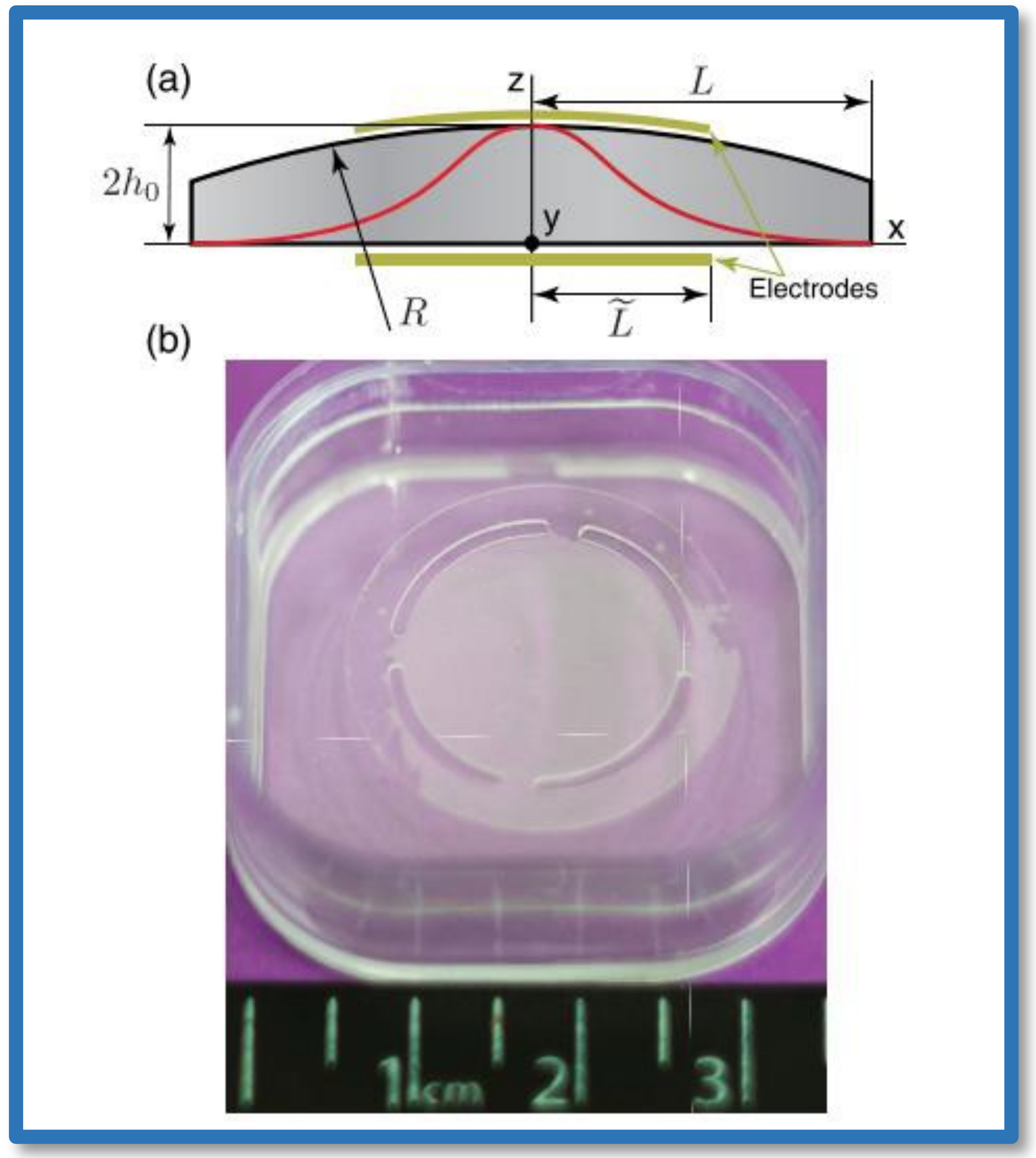
***Detection of a Graviton**

***Search for Scalar DM:**

***Search for Lorentz invariance violations**

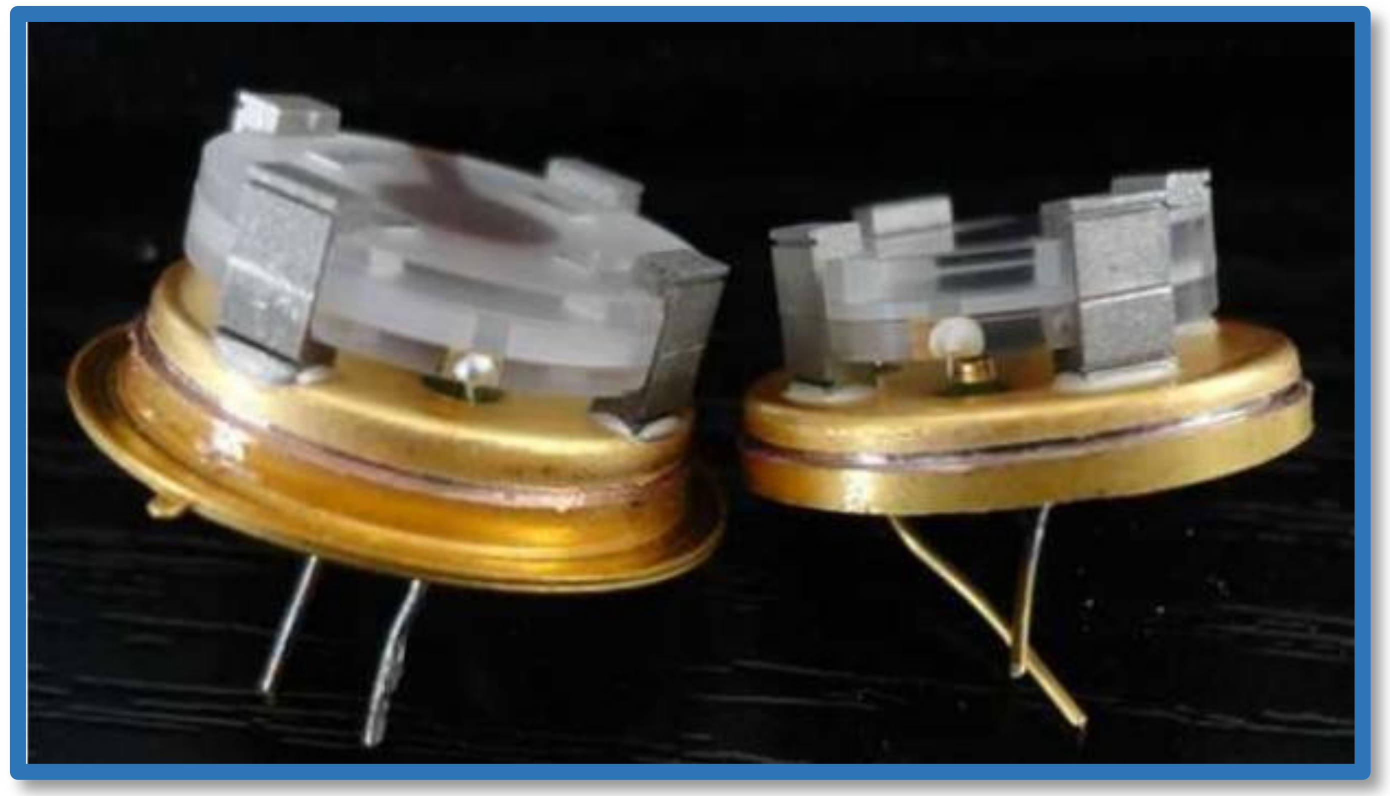
***Improved constraints on minimum length models or Generalized Uncertainty Principle (GUP)**

***Gravitational Aharonov-Bohm Effect**

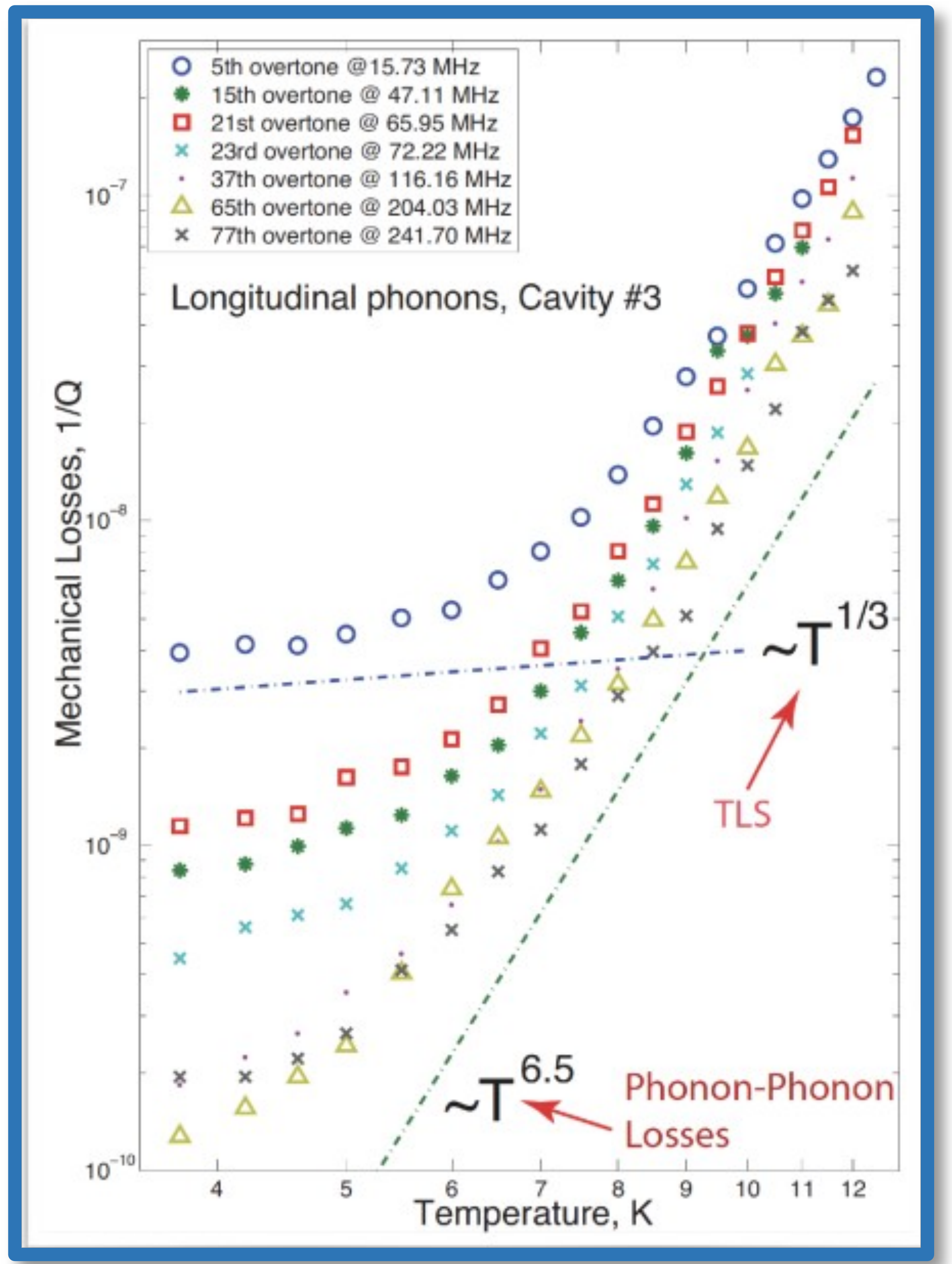


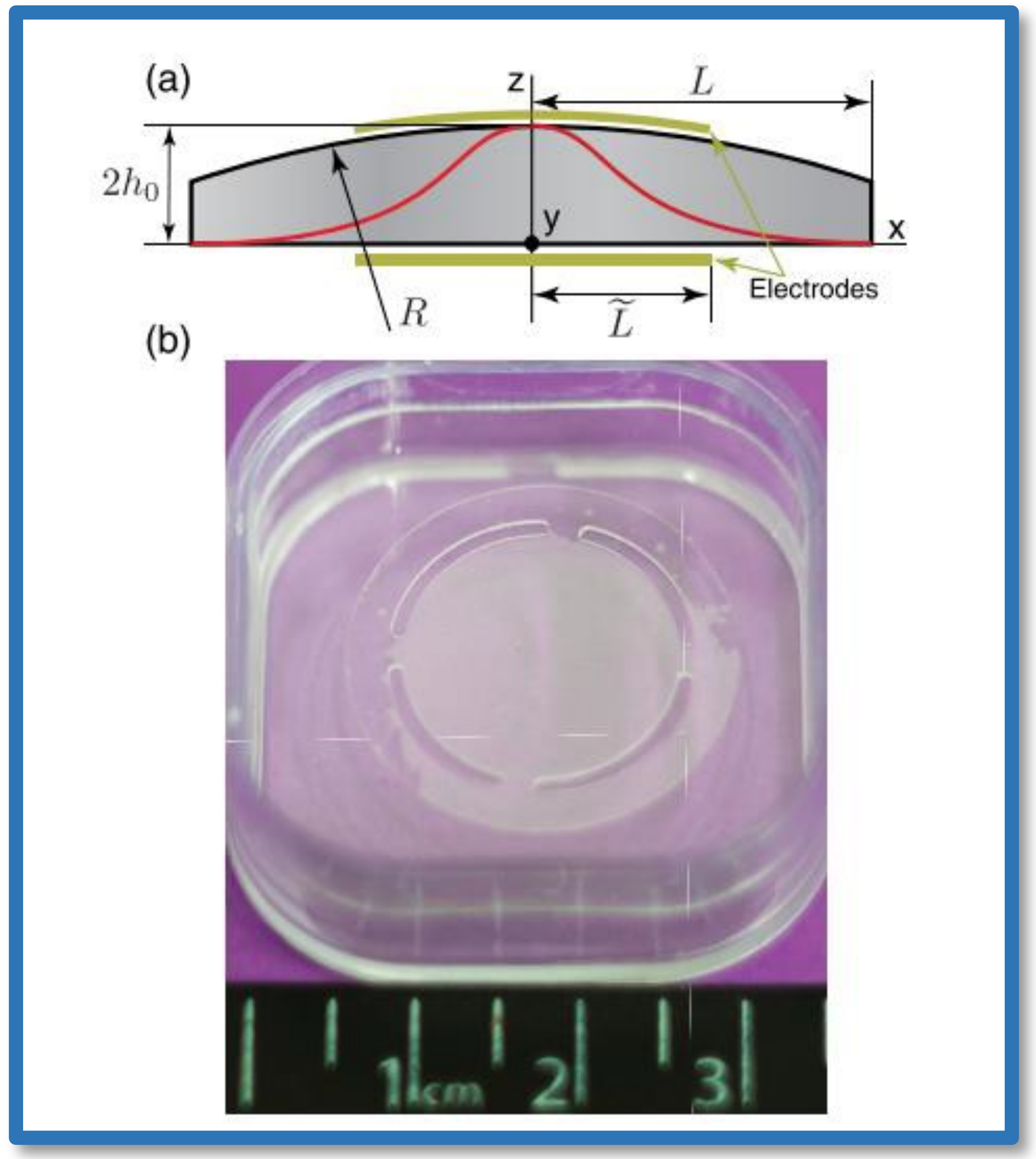
Quartz Bulk Acoustic Wave Resonators

- **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 (~10^{10})**



Scientific Reports Vol. 3, 2132 (2013)





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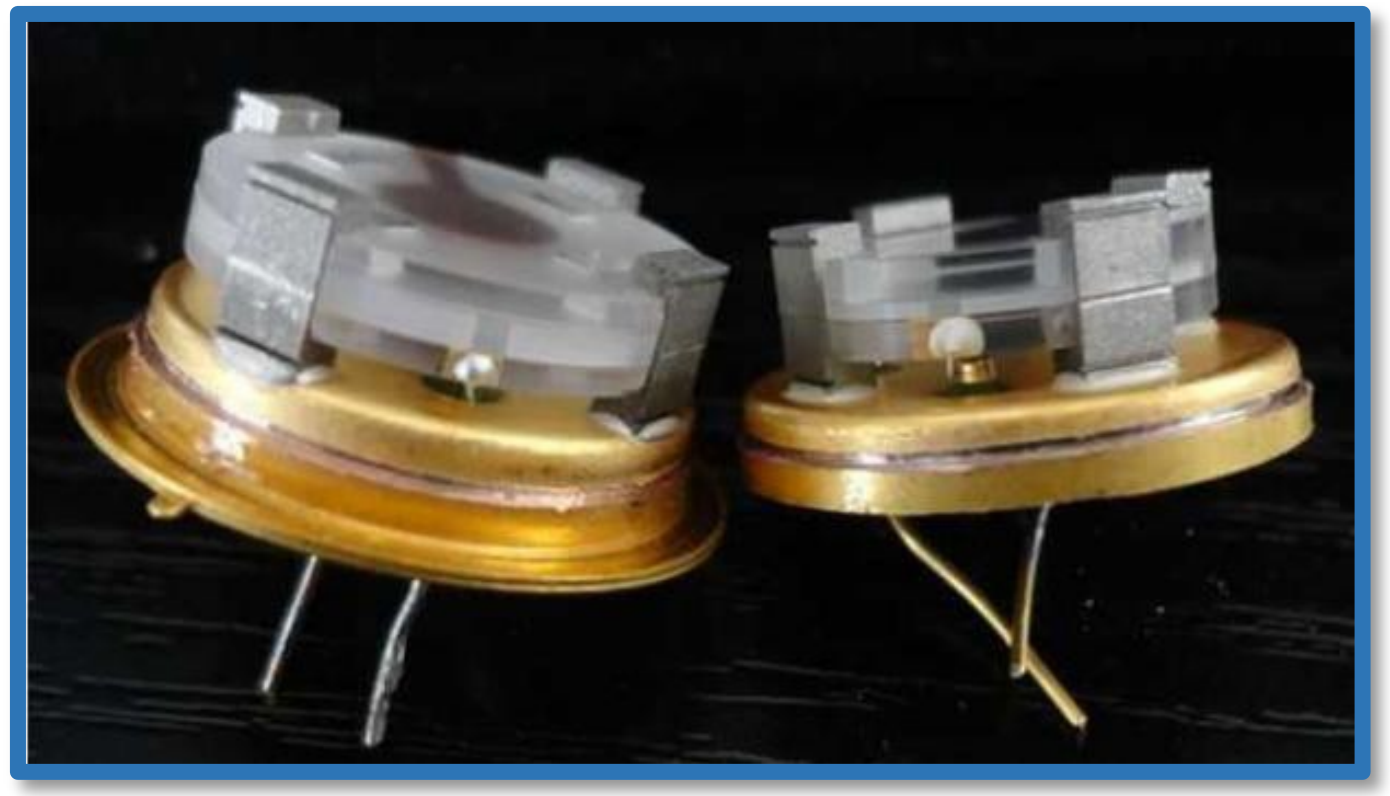

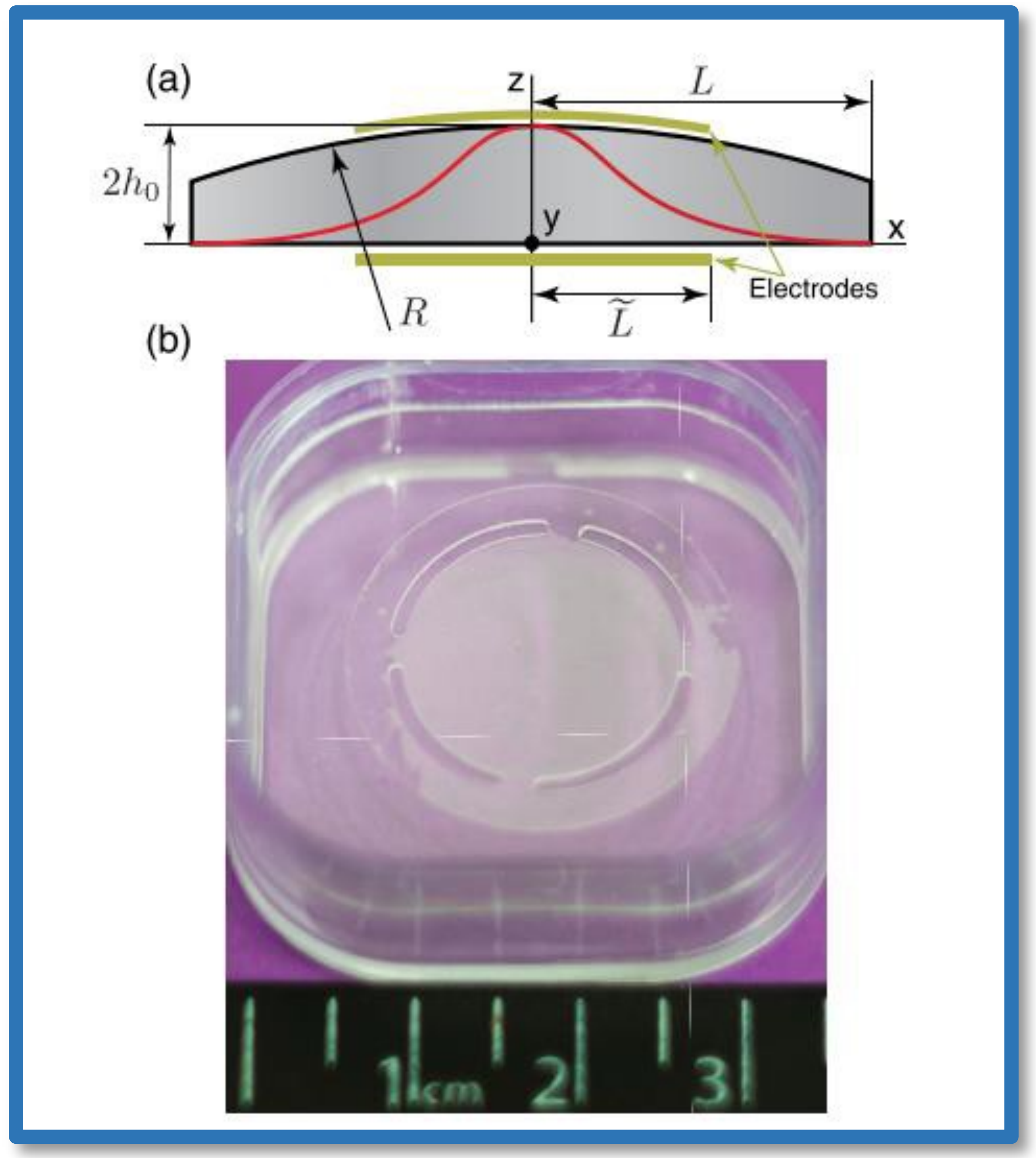

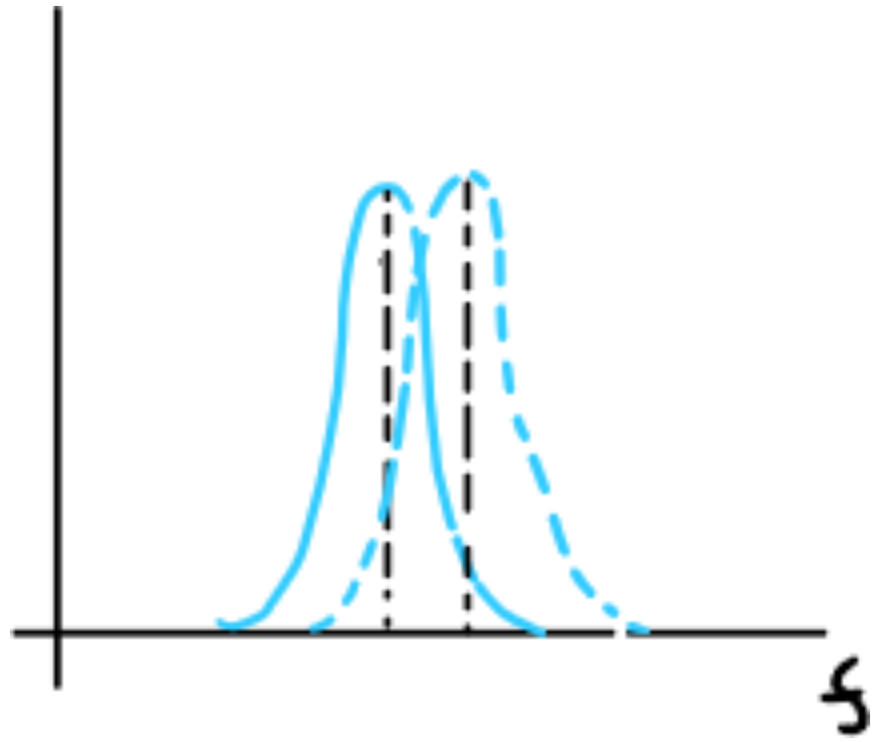

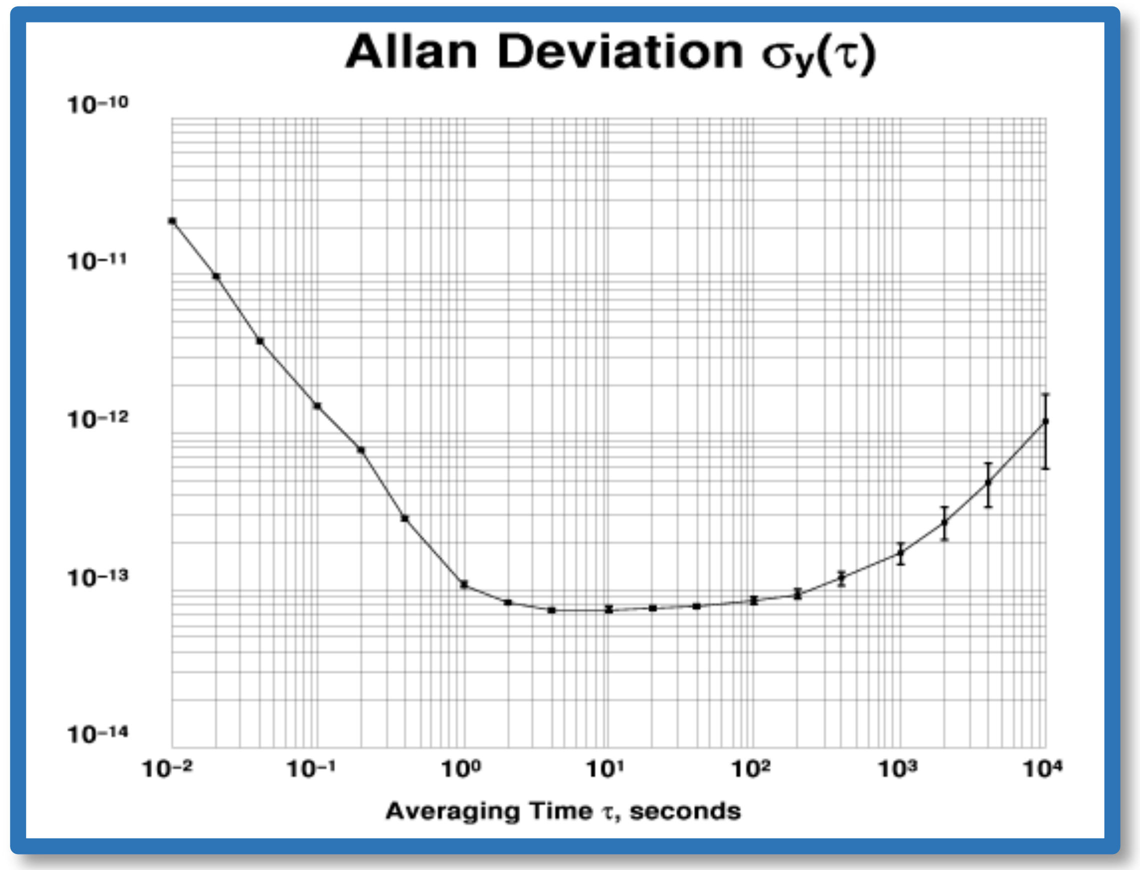

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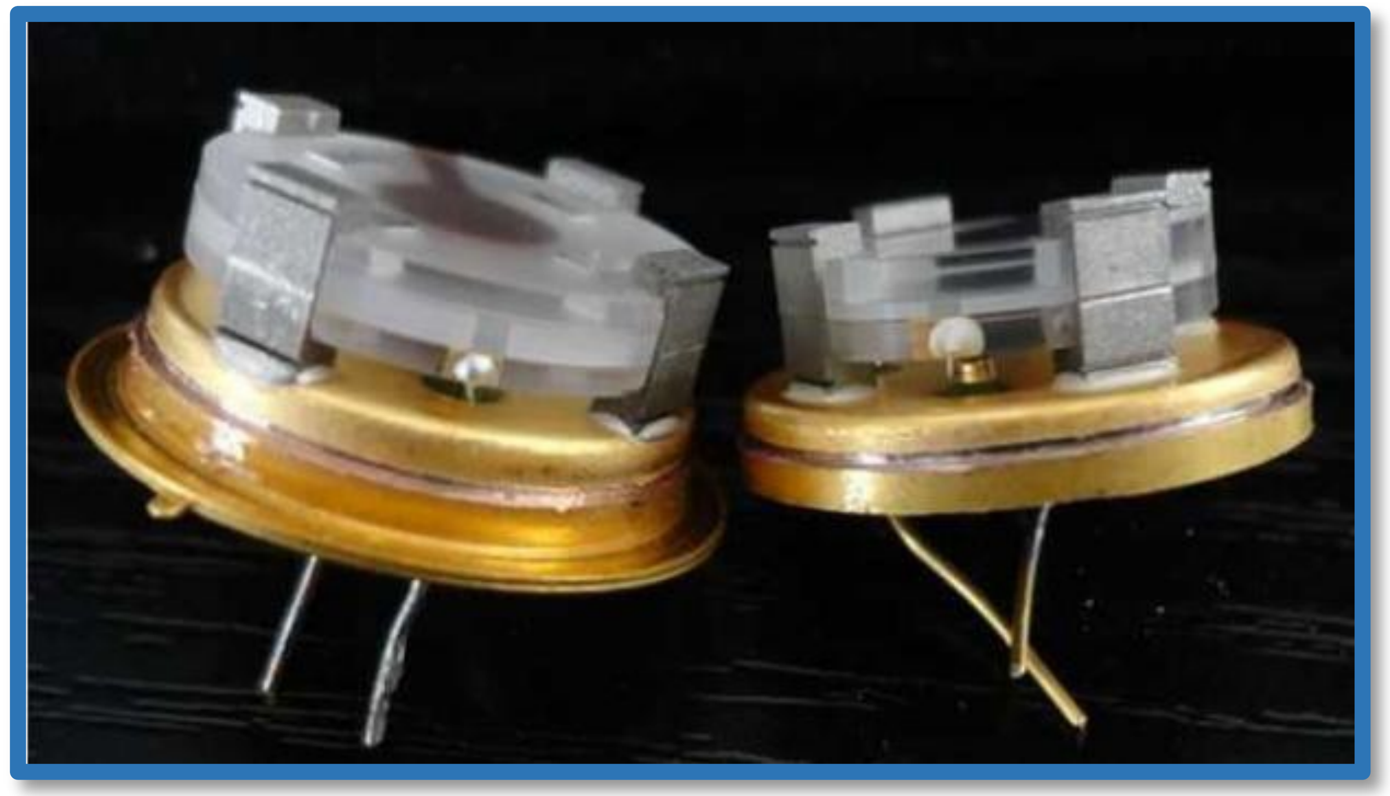
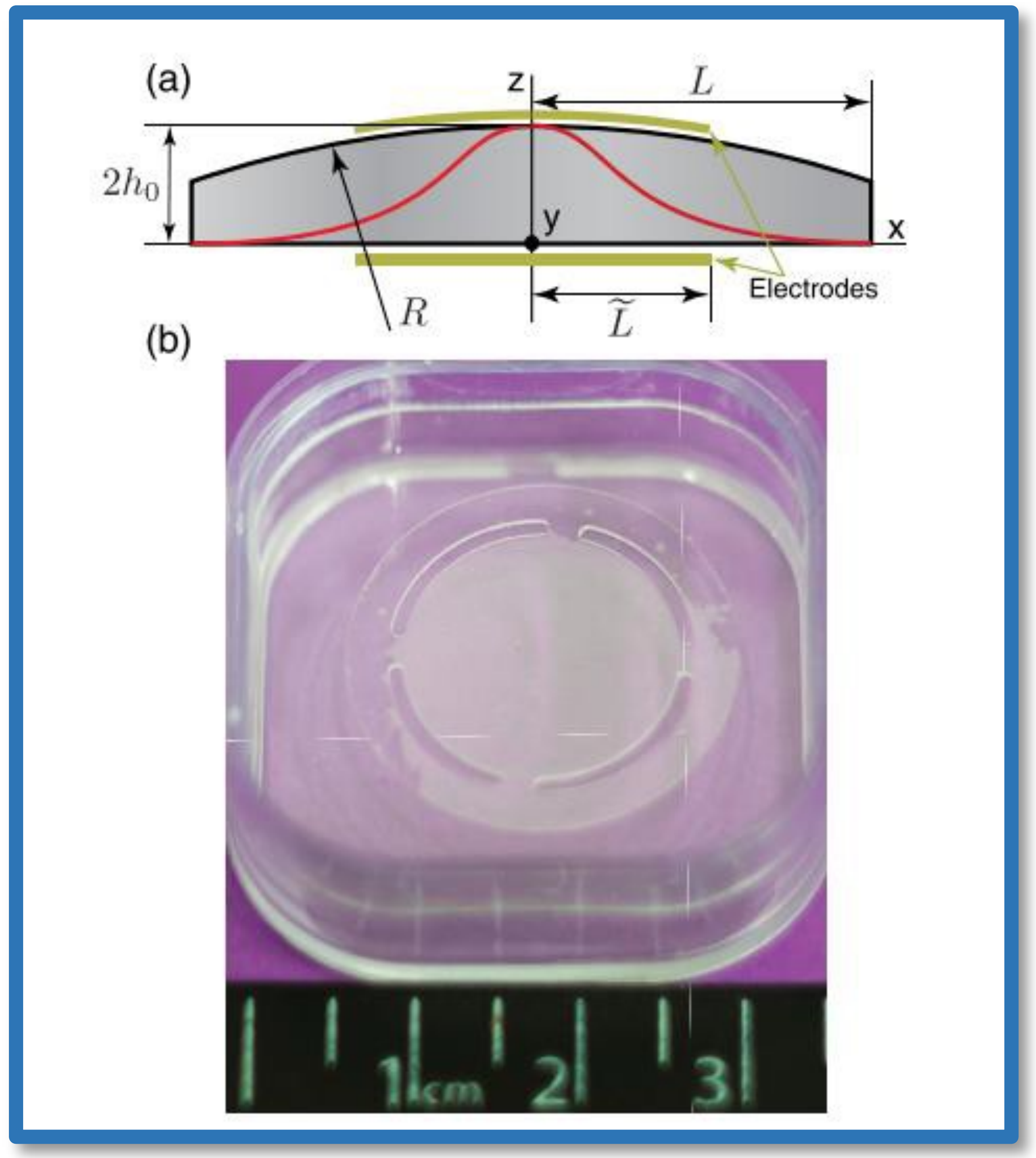
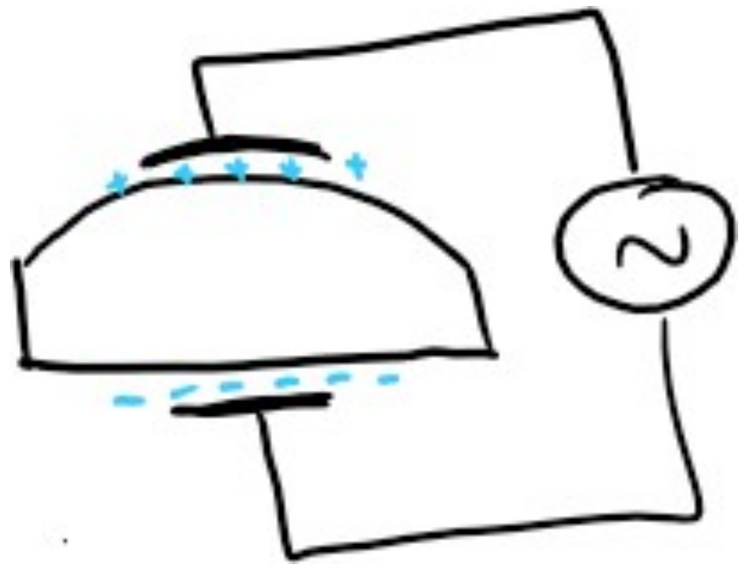
- **Impressive short - mid term frequency stability**
- **Piezoelectric coupling provides excitation & readout**

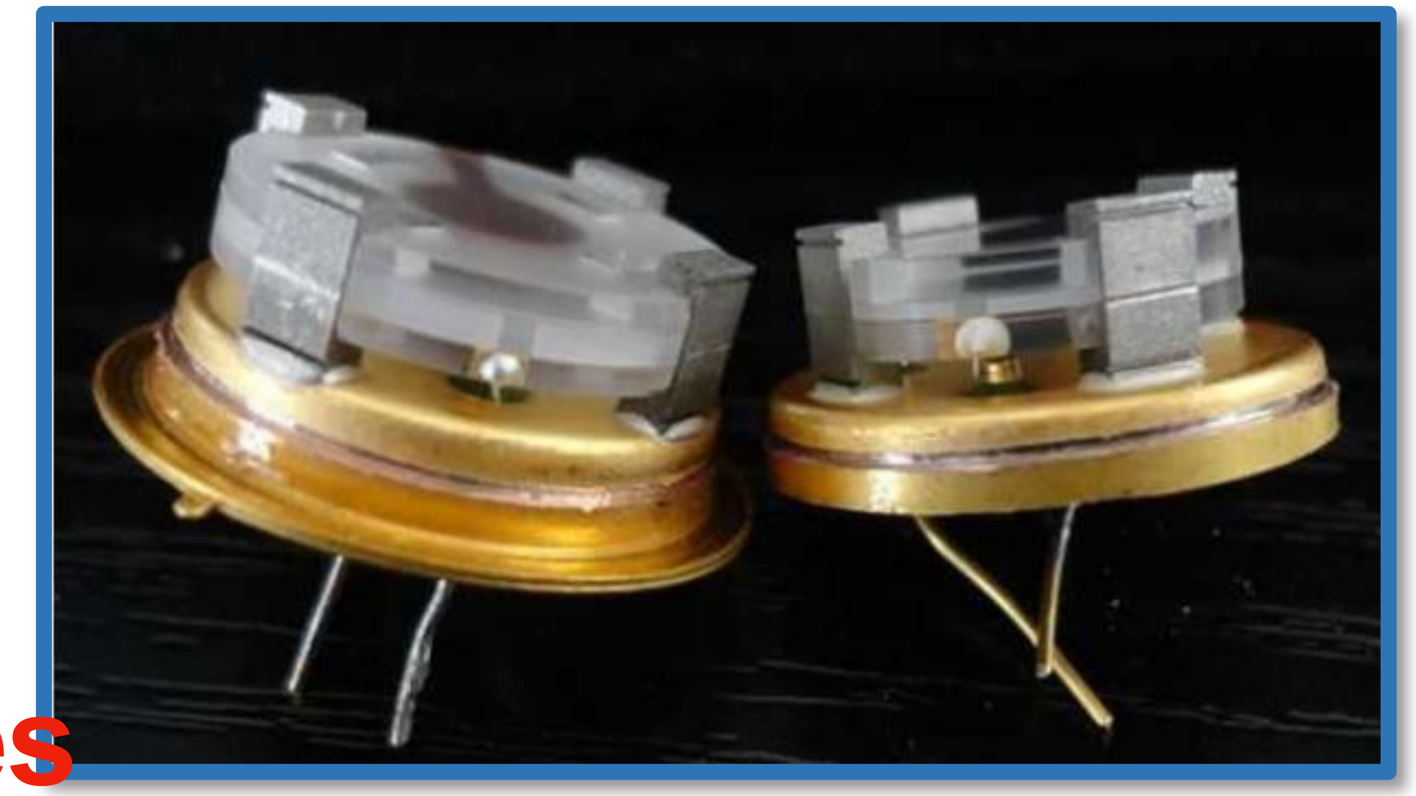


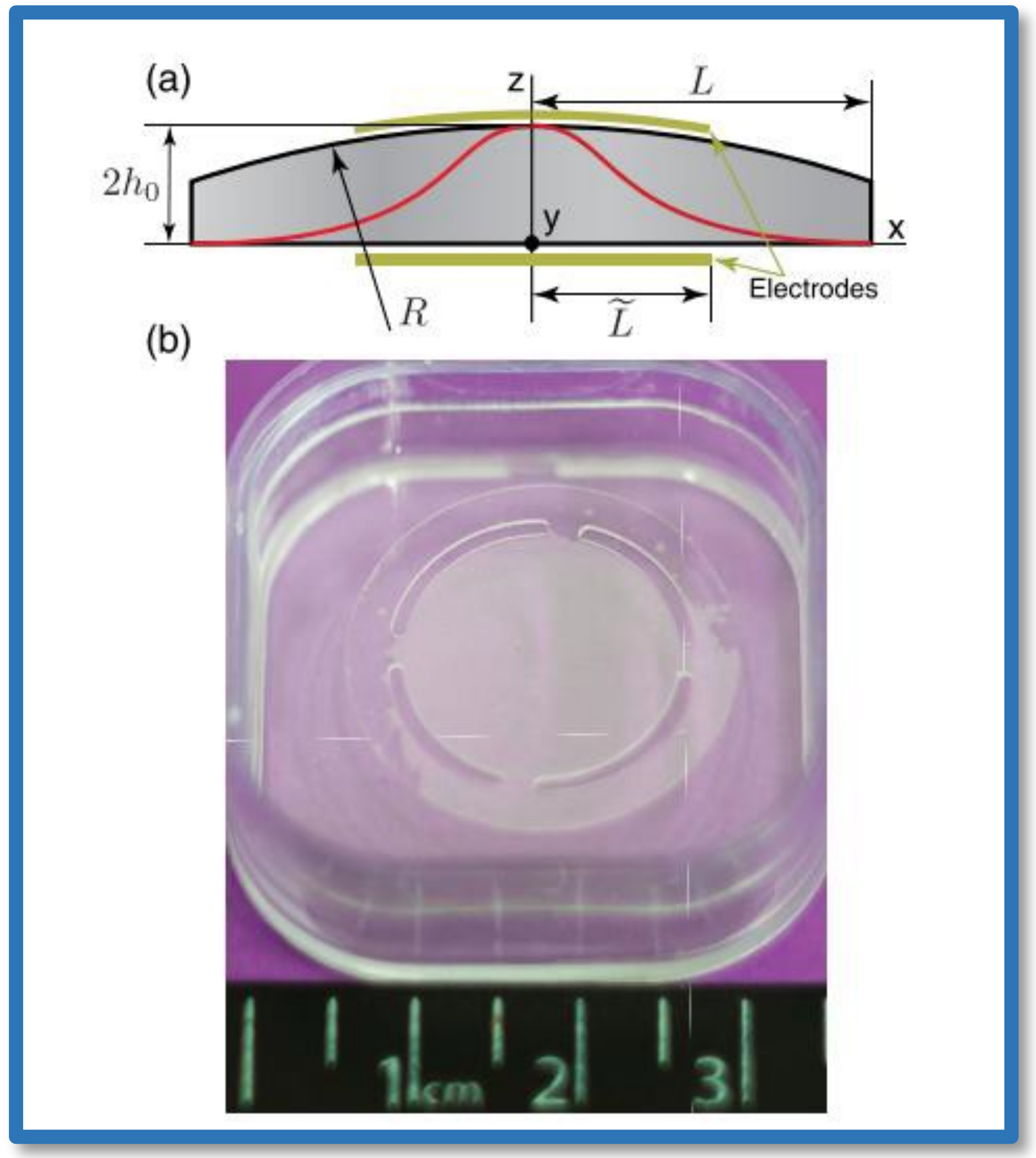




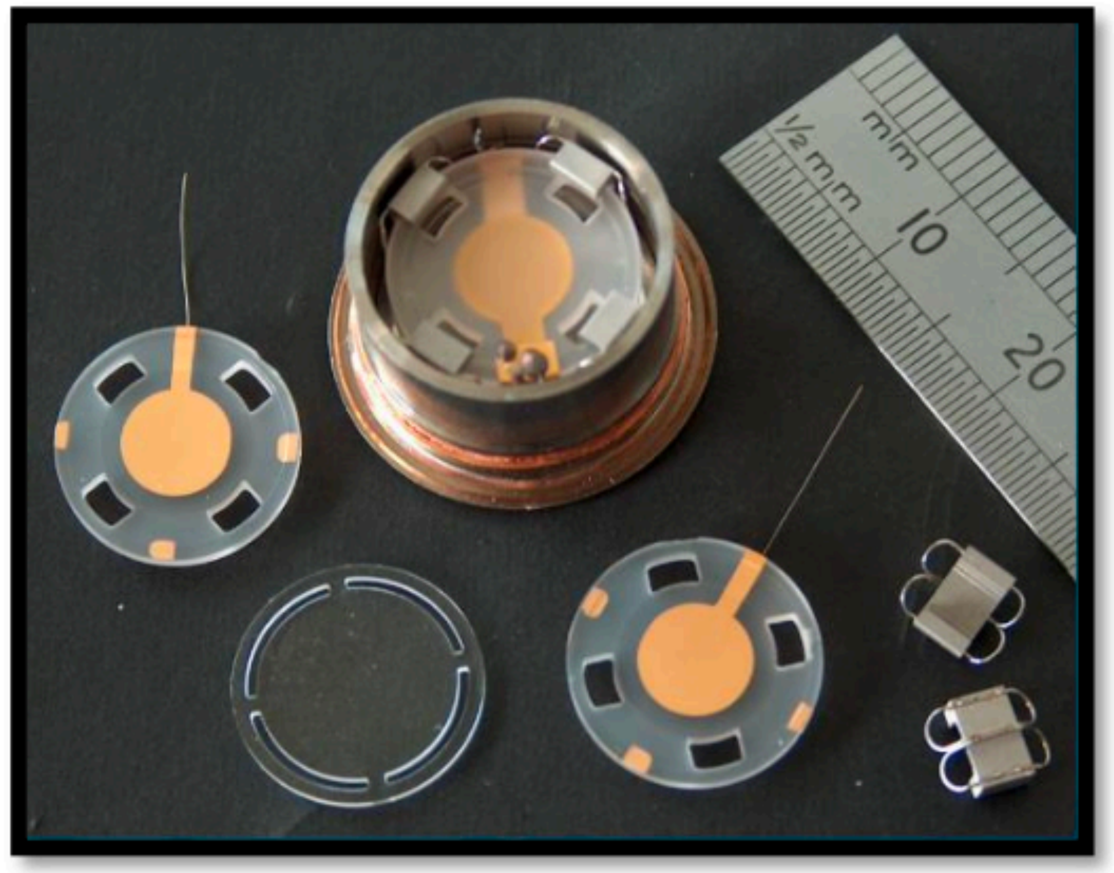
Quartz Bulk Acoustic Wave Resonators

- 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



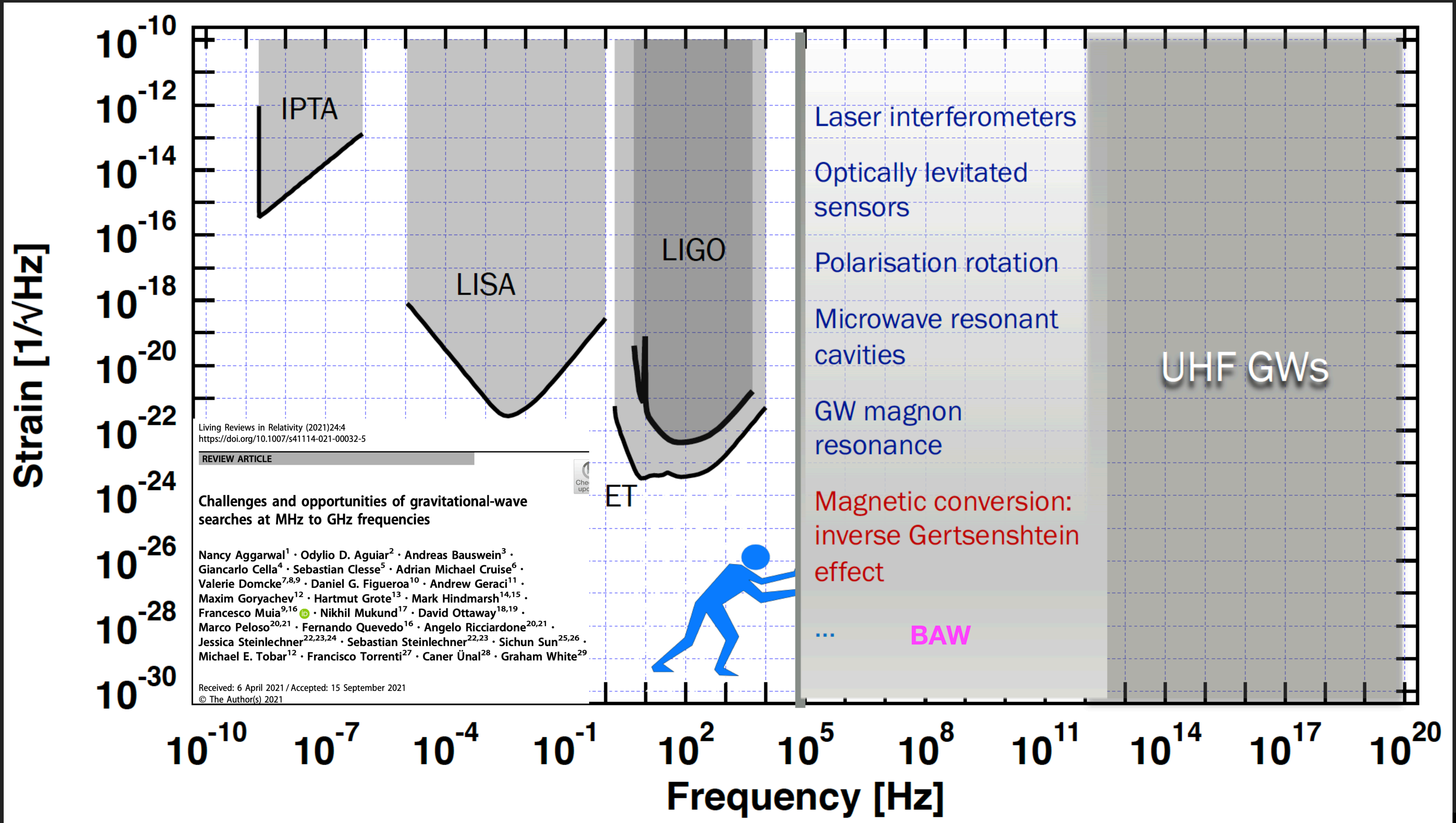
MAGE
Multimode Acoustic Gravitational Wave Experiment

THE UNIVERSITY OF WESTERN AUSTRALIA

EQUS

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

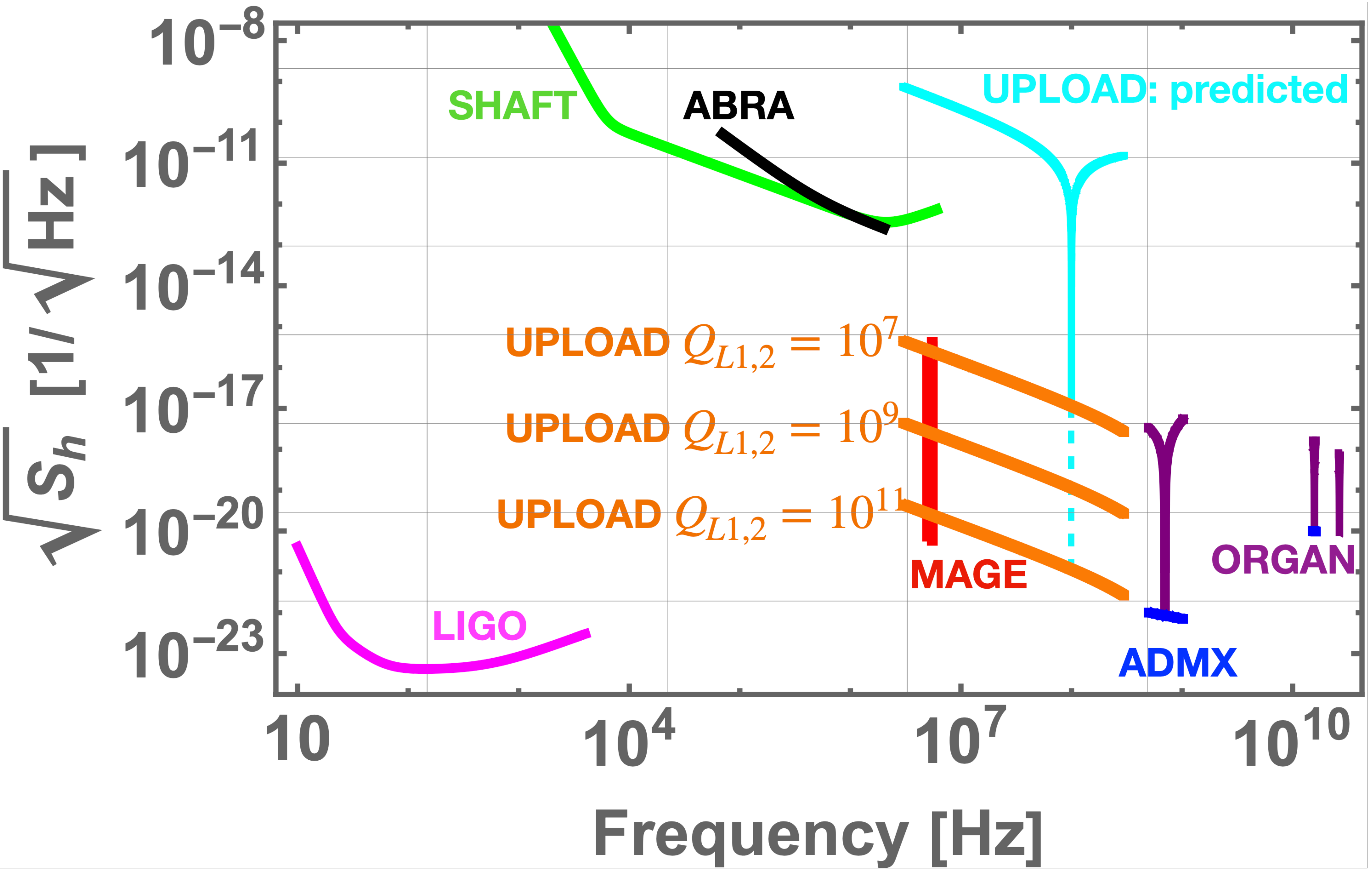
Gravitation Wave Instrument Sensitivity



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

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

$$SNR = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{\Theta_a(j\omega)^2}{S_{\theta_N}(\omega)} d\omega = 4\int_0^{\infty} \frac{\Theta_a(f)^2}{S^+_{\theta_N}(f)} df$$

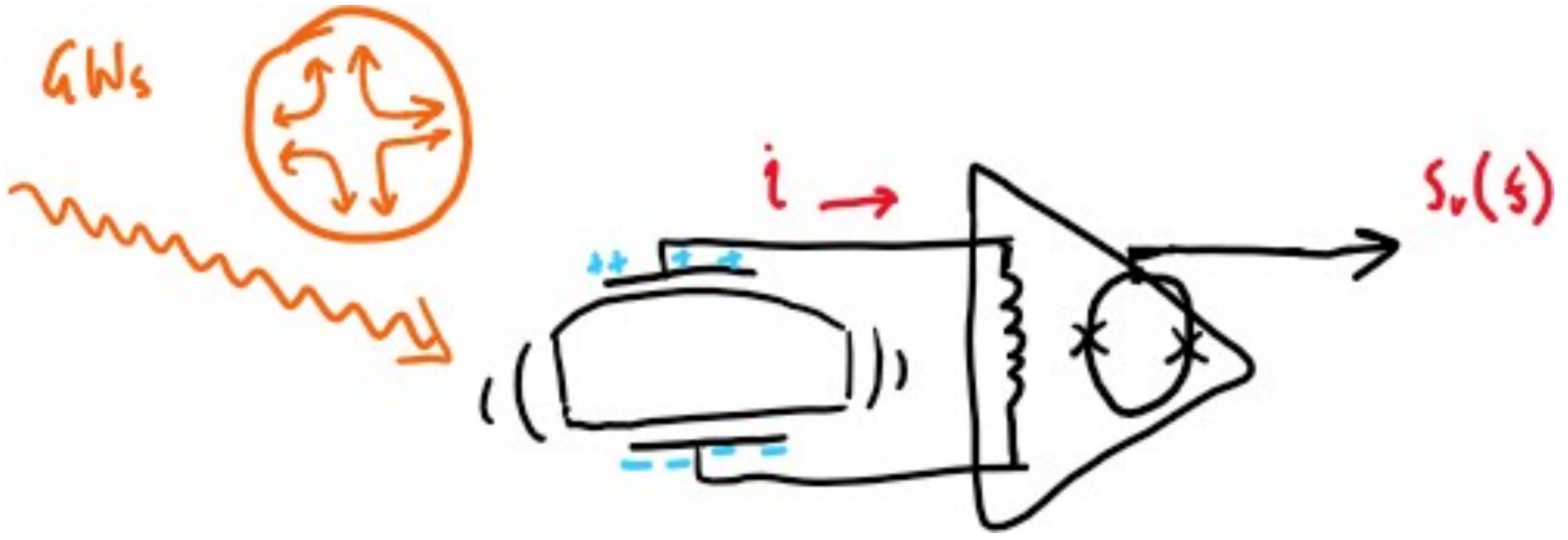
ADMX and ORGAN (purple) with current tuning locus (blue);
0.6-1.2 GHz for ADMX and 15.2 to 16.2 GHz for ORGAN

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

symmetry

MAGE – Searching for new physics

Quartz BAW coupled to a DC SQUID amplifier

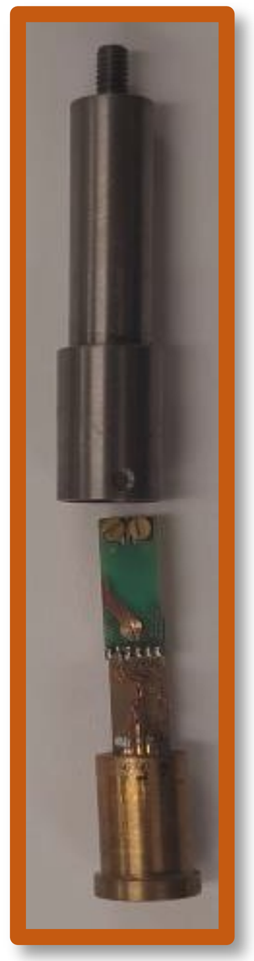


$$\ddot{B}_\lambda + \tau_\lambda^{-1}\dot{B}_\lambda + \omega_\lambda^2 B = -c^2 R_{i0j0}\int_V dv \frac{\rho}{m_\lambda} U_\lambda^i(\mathbf{x}) x^j.$$

Primary target:

High frequency gravitational waves (MHz)

Highly sensitive resonant mass antenna



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

Gravitational wave detection with high frequency phonon trapping acoustic cavities

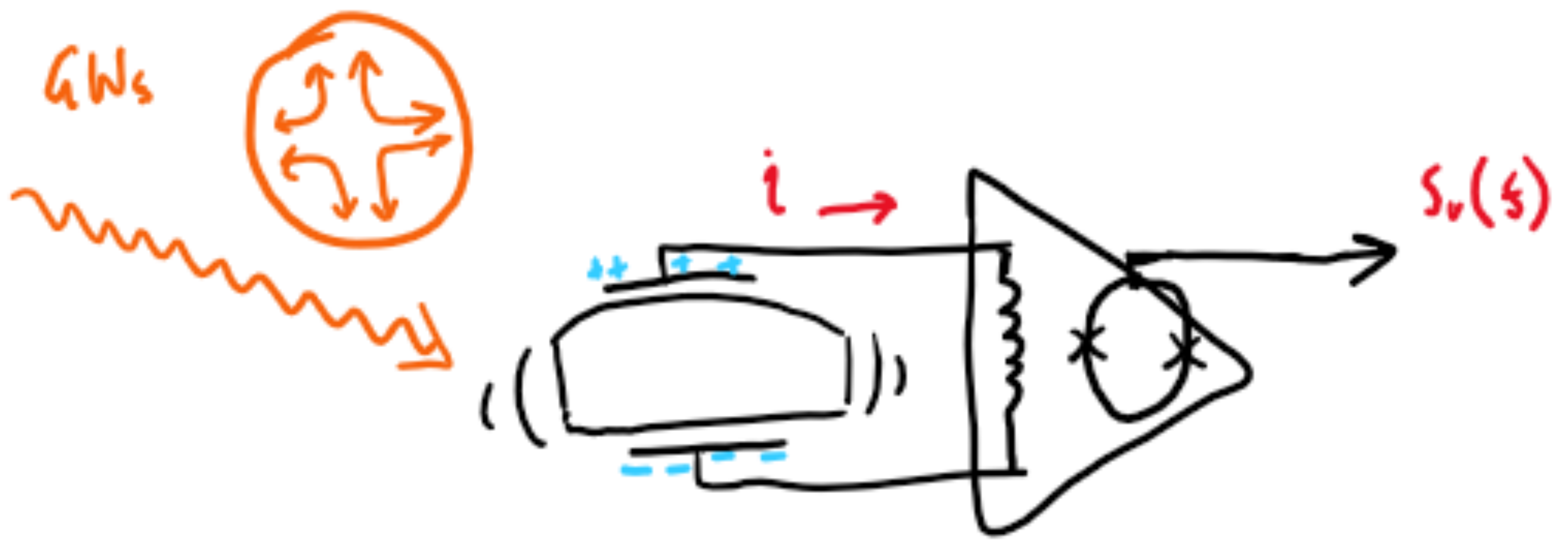
Maxim Goryachev and Michael E. Tobar*

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)

MAGE – Searching for new physics

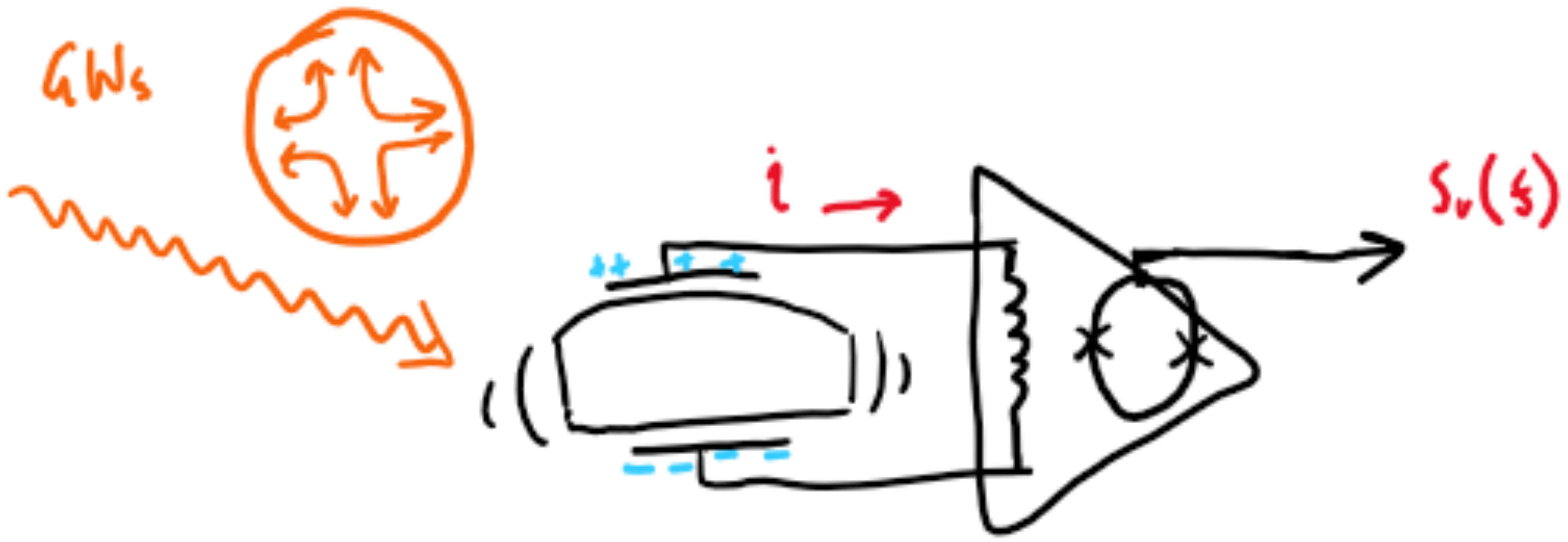
Quartz BAW coupled to a DC SQUID amplifier → *Highly sensitive resonant mass antenna*



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

MAGE – Searching for new physics

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

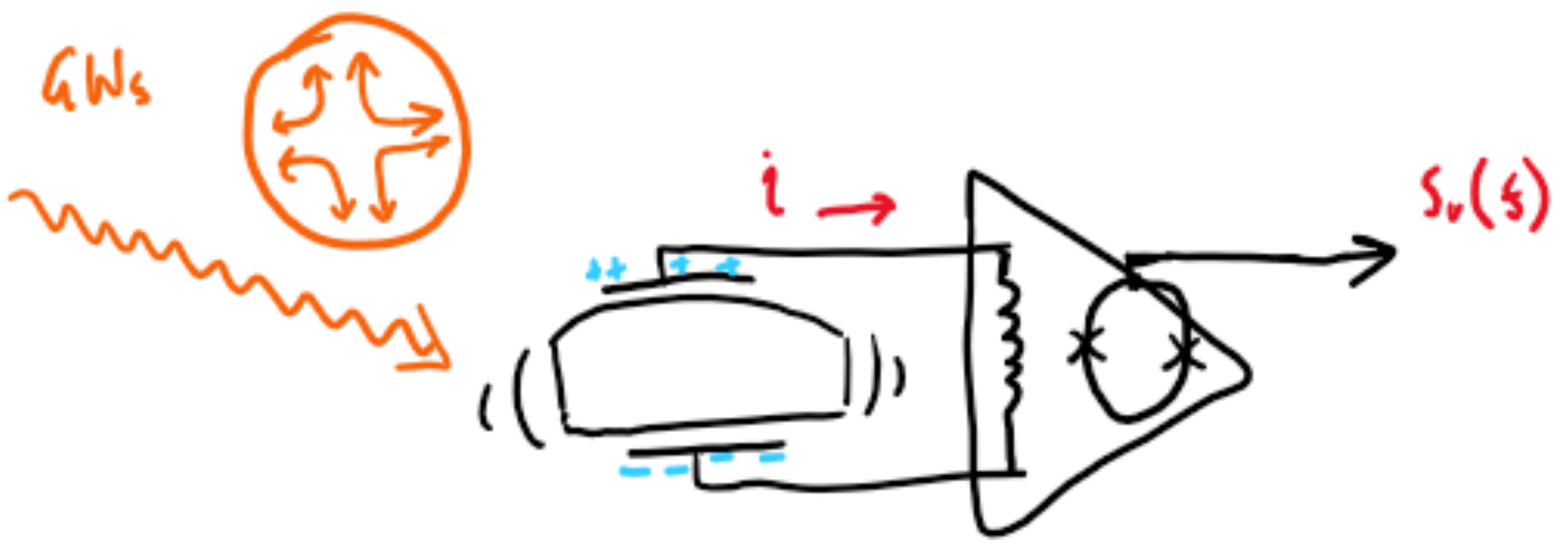


Mode Temperature

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

MAGE – Searching for new physics

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



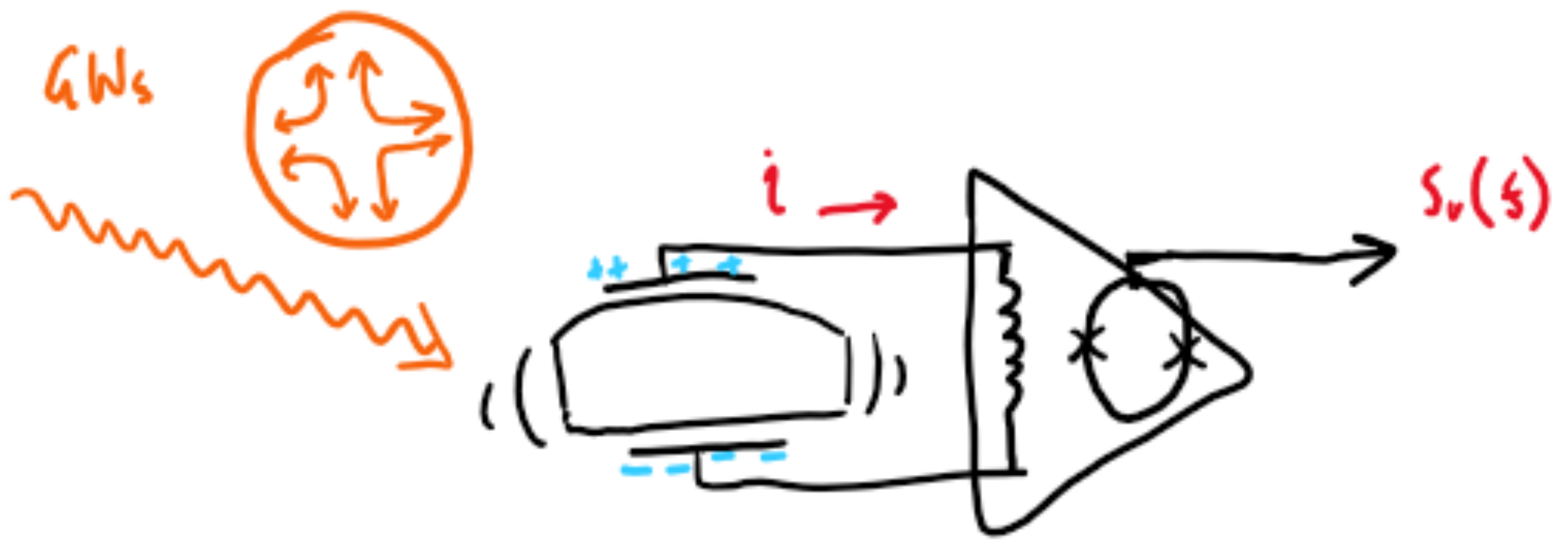
Mode Temperature

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

Quality Factor

MAGE – Searching for new physics

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



Mode Temperature

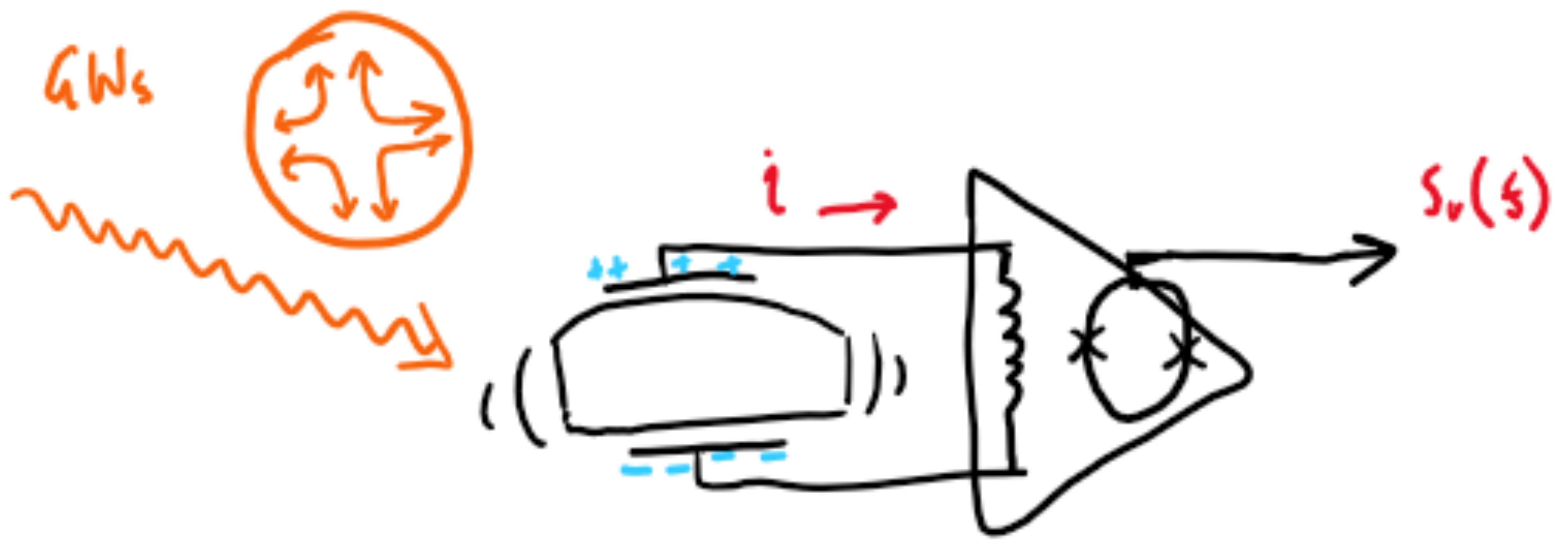
$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right)$$

Quality Factor

Gravitational Coupling

MAGE – Searching for new physics

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

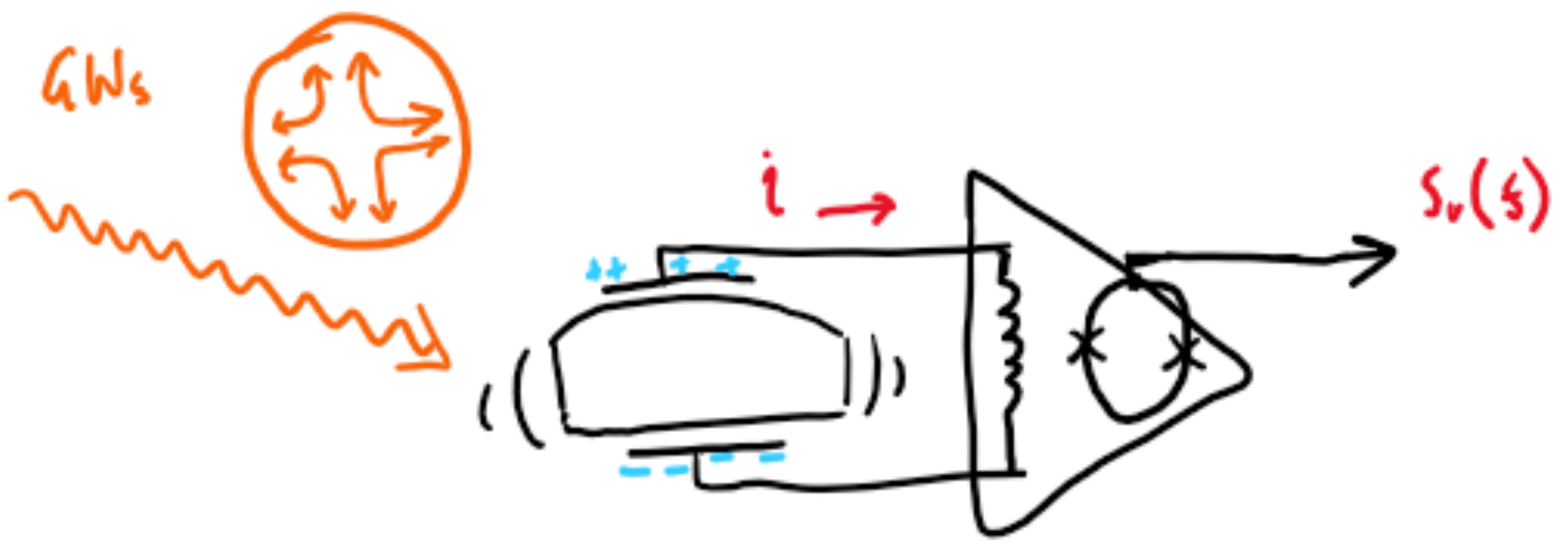


$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right) \qquad \xi_\lambda = h_0\tilde{\xi}_\lambda = \int_V dv\,\frac{\rho}{m_\lambda}U_\lambda^i(\mathbf{x})x^j$$

Gravitational Coupling

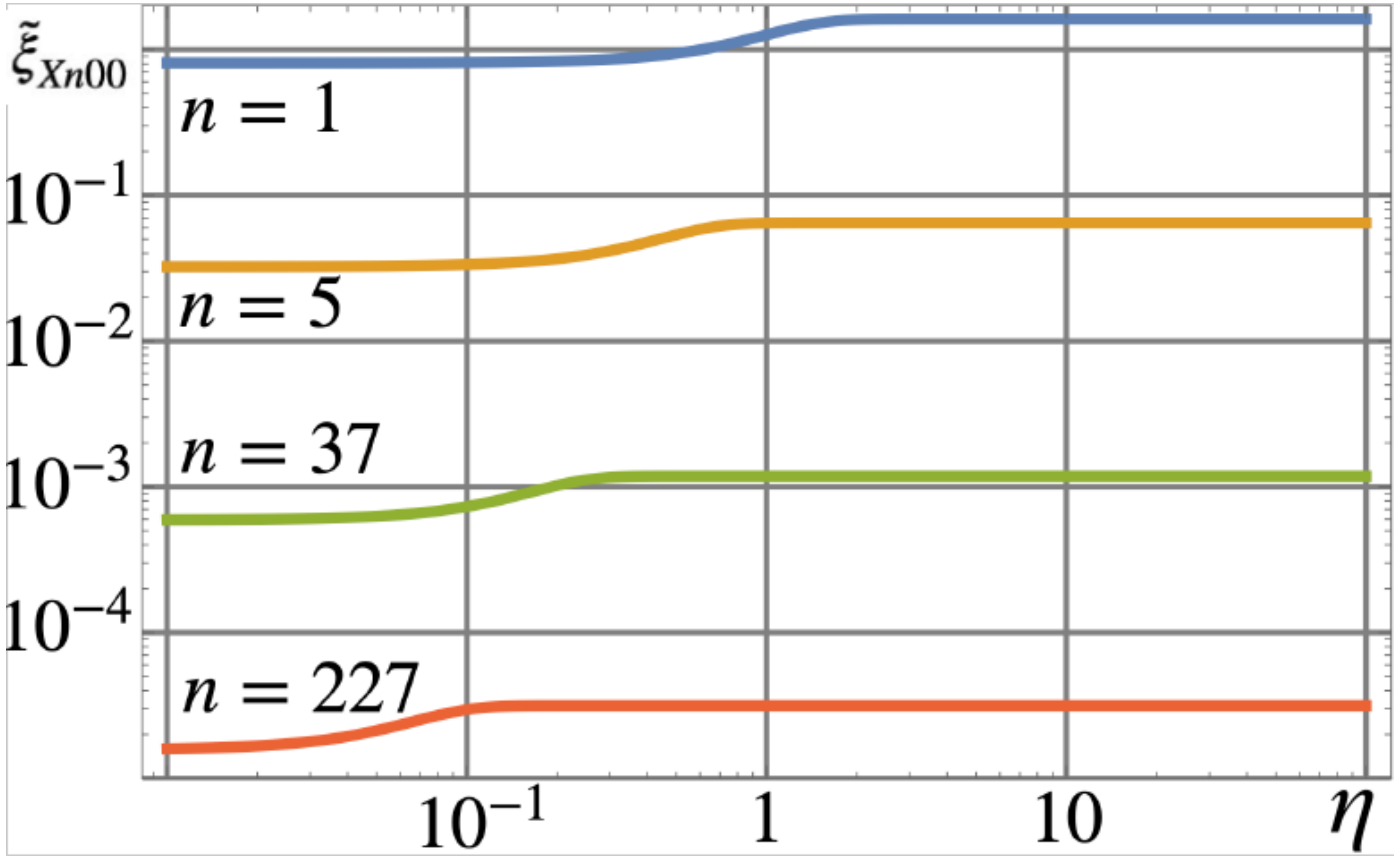
MAGE – Searching for new physics

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



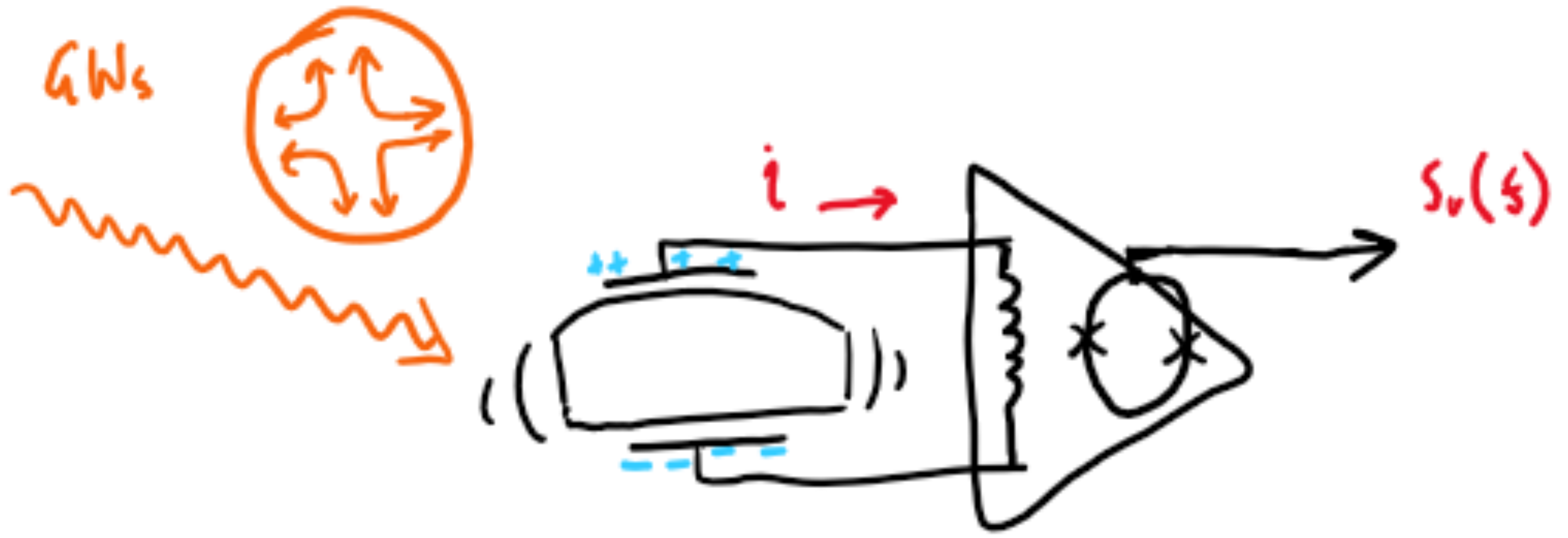
$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_bT_\lambda\,\omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right)$$

Gravitational Coupling

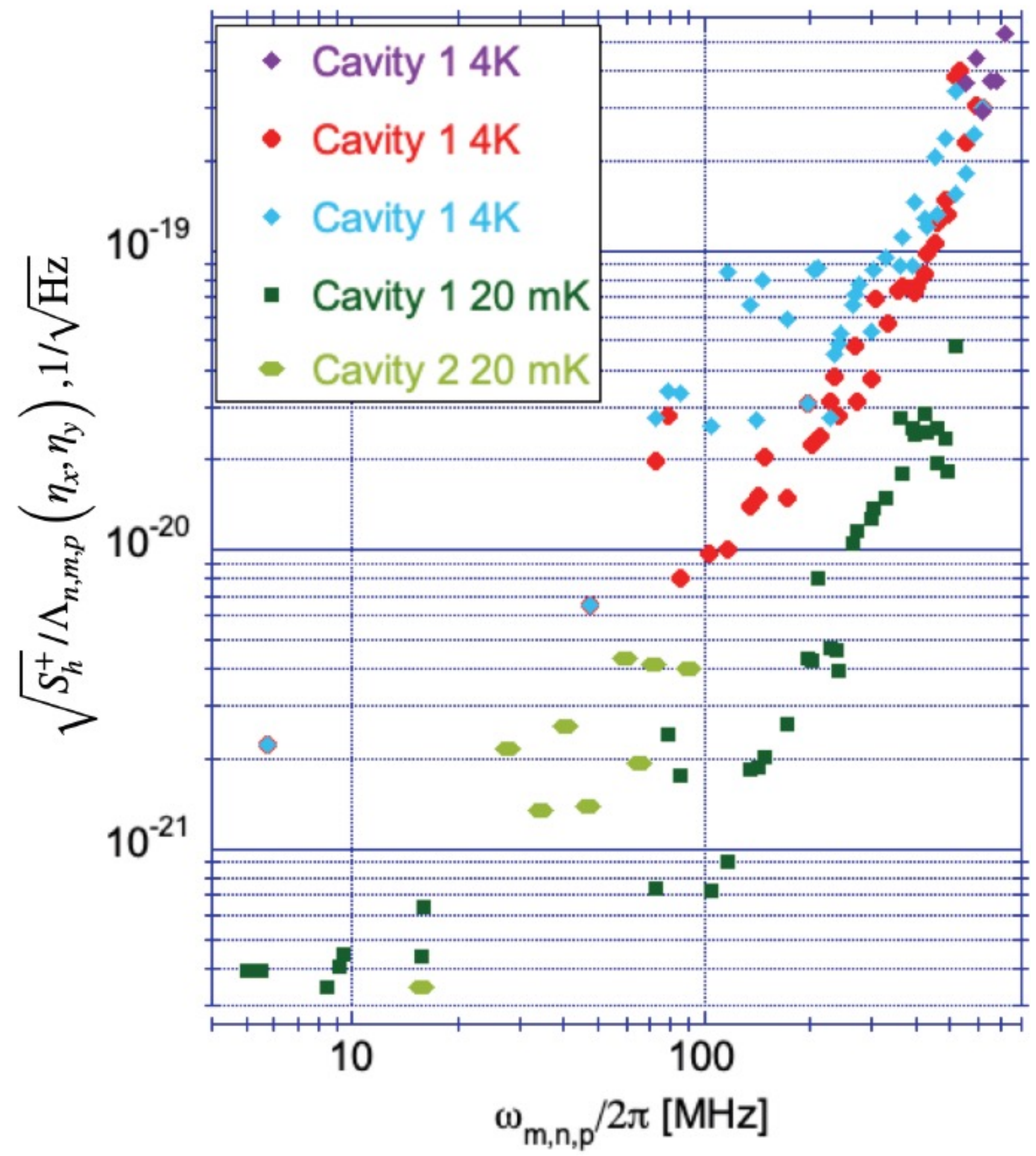


MAGE – Searching for new physics

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



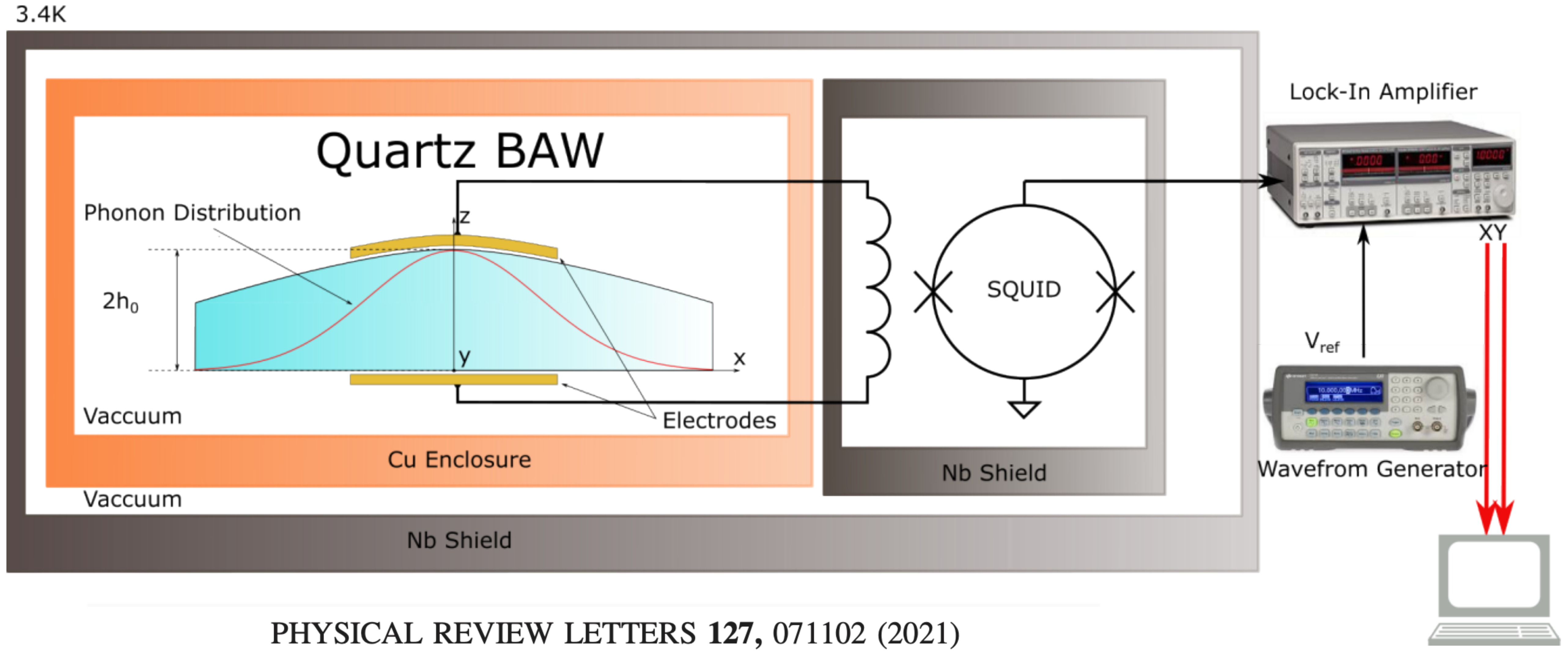
$$S_h^+(\omega)\Big|_{\omega=\omega_\lambda} = \sqrt{\frac{4k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 h_0 \xi}\right)$$

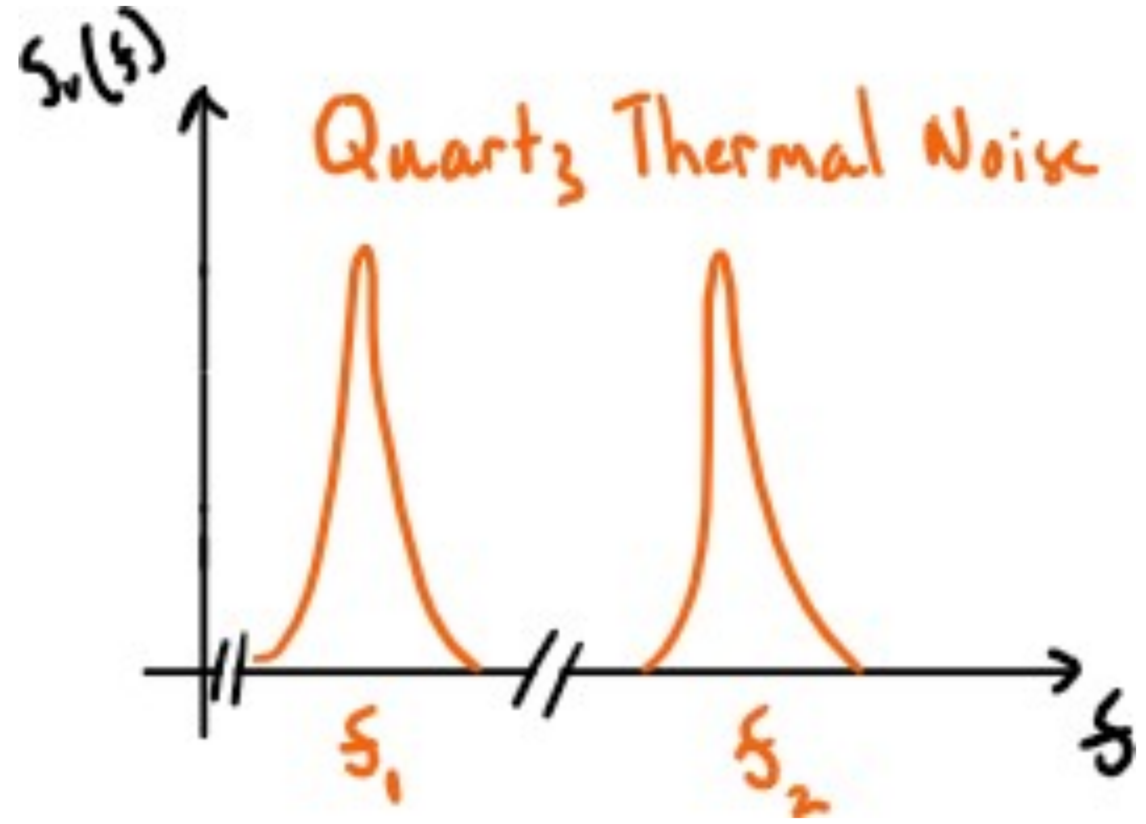


MAGE – Searching for new physics

First Observational Period

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

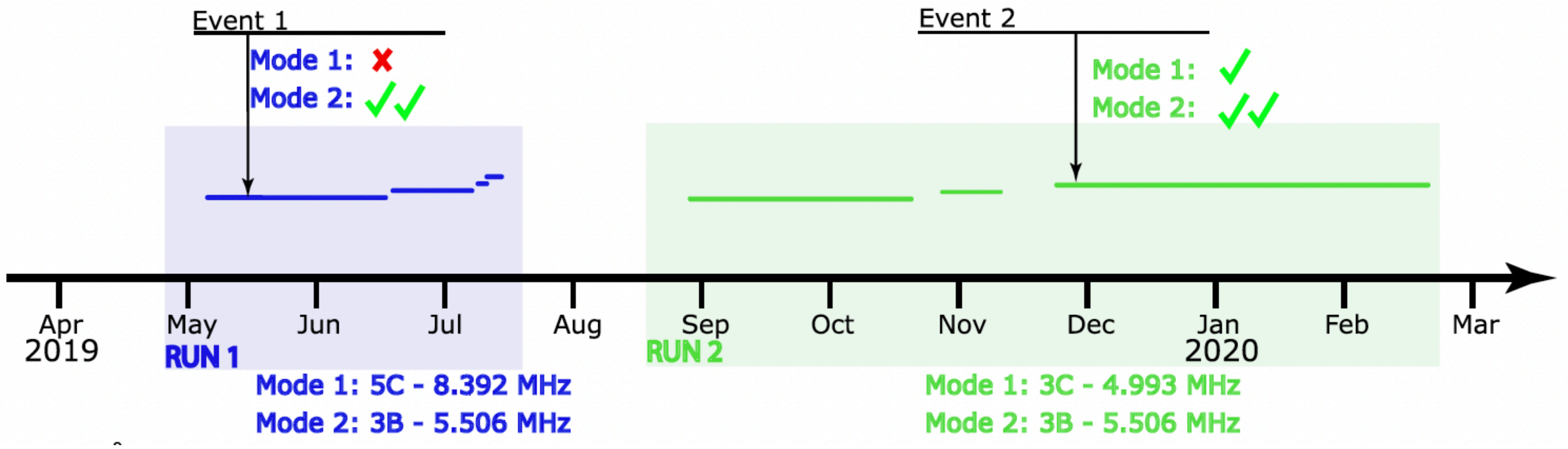




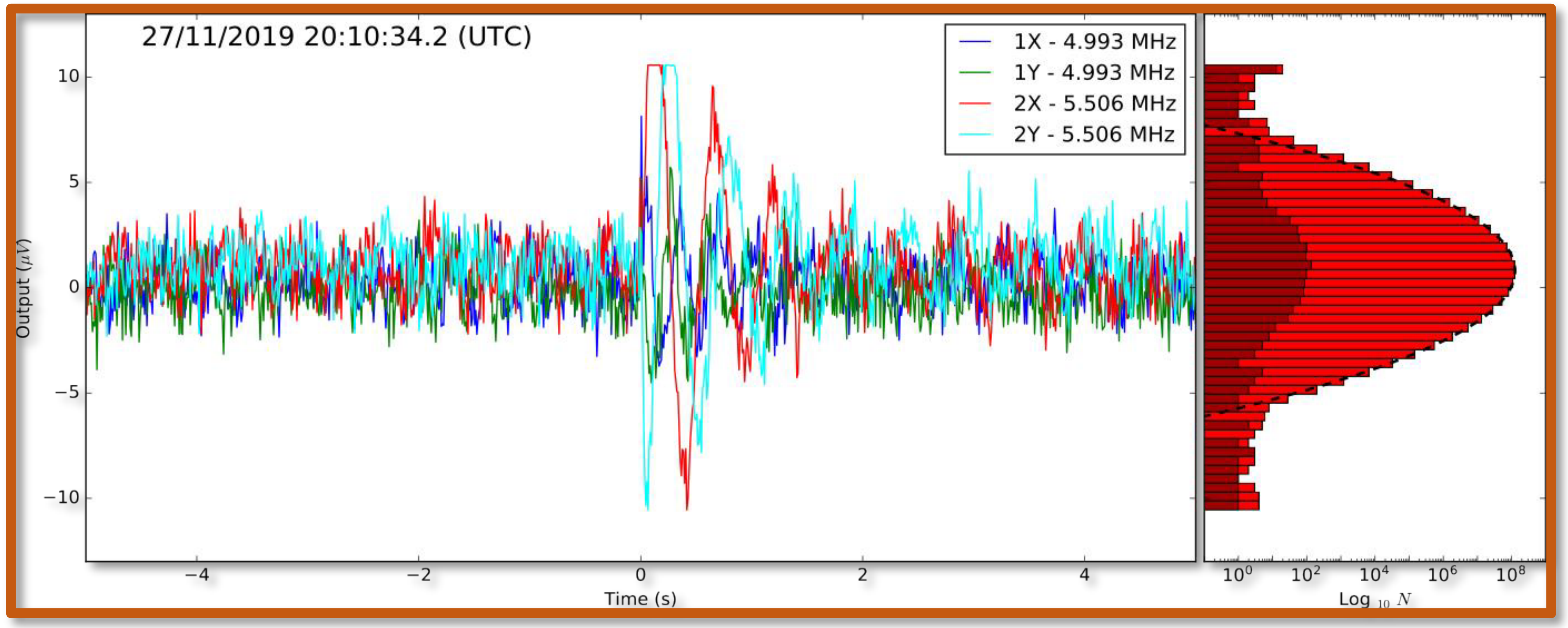
PHYSICAL REVIEW LETTERS **127,** 071102 (2021)

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,*]



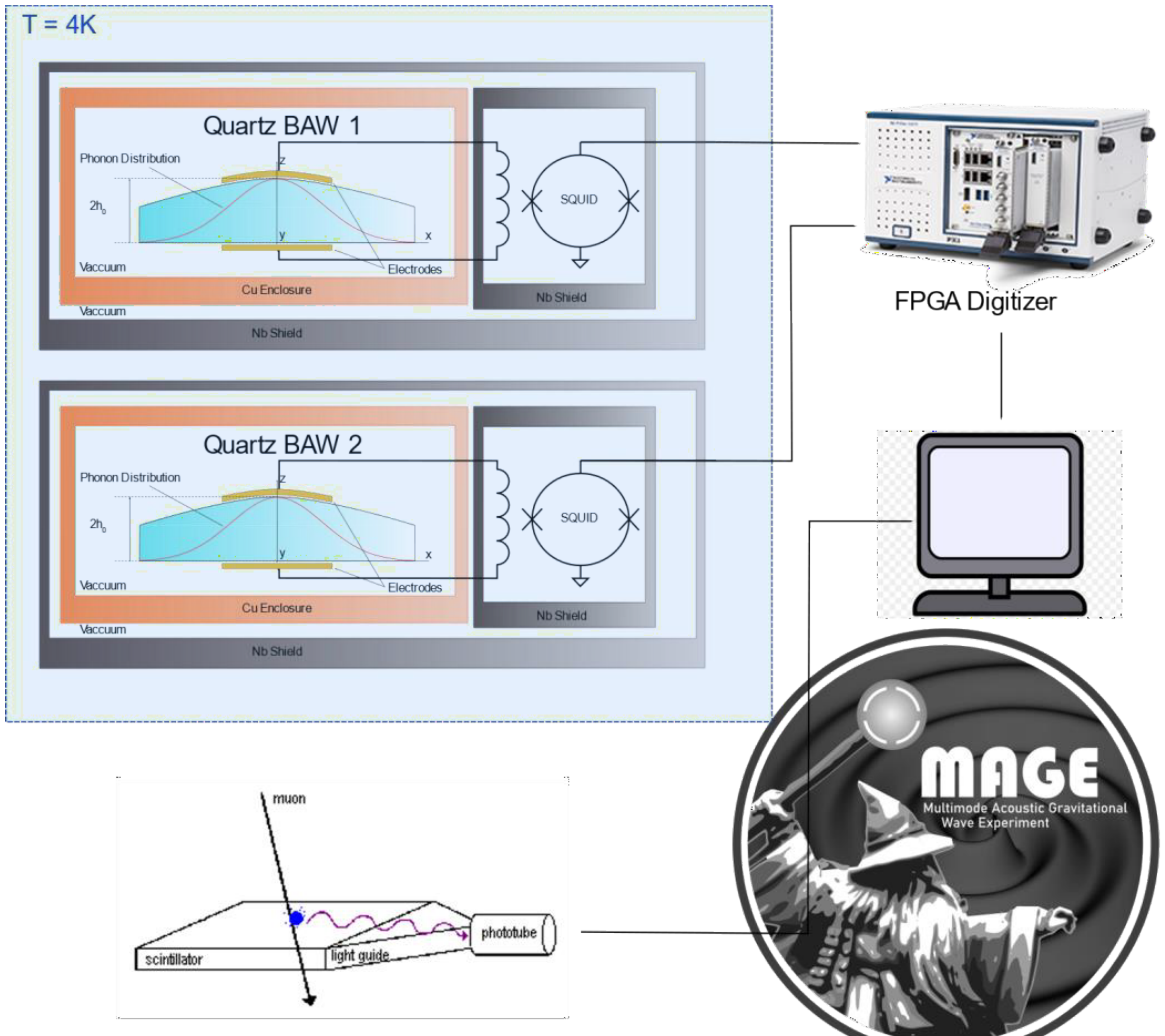
Data Analysis:



MAGE – Searching for new physics

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

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

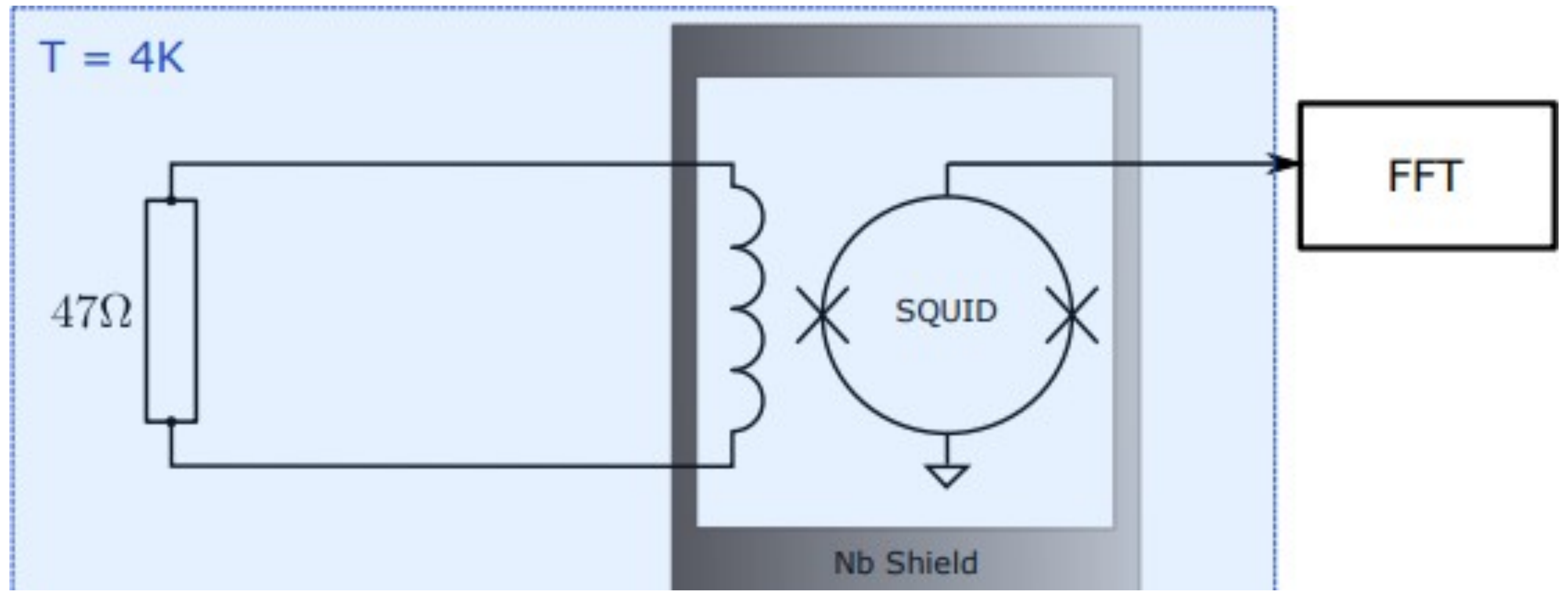


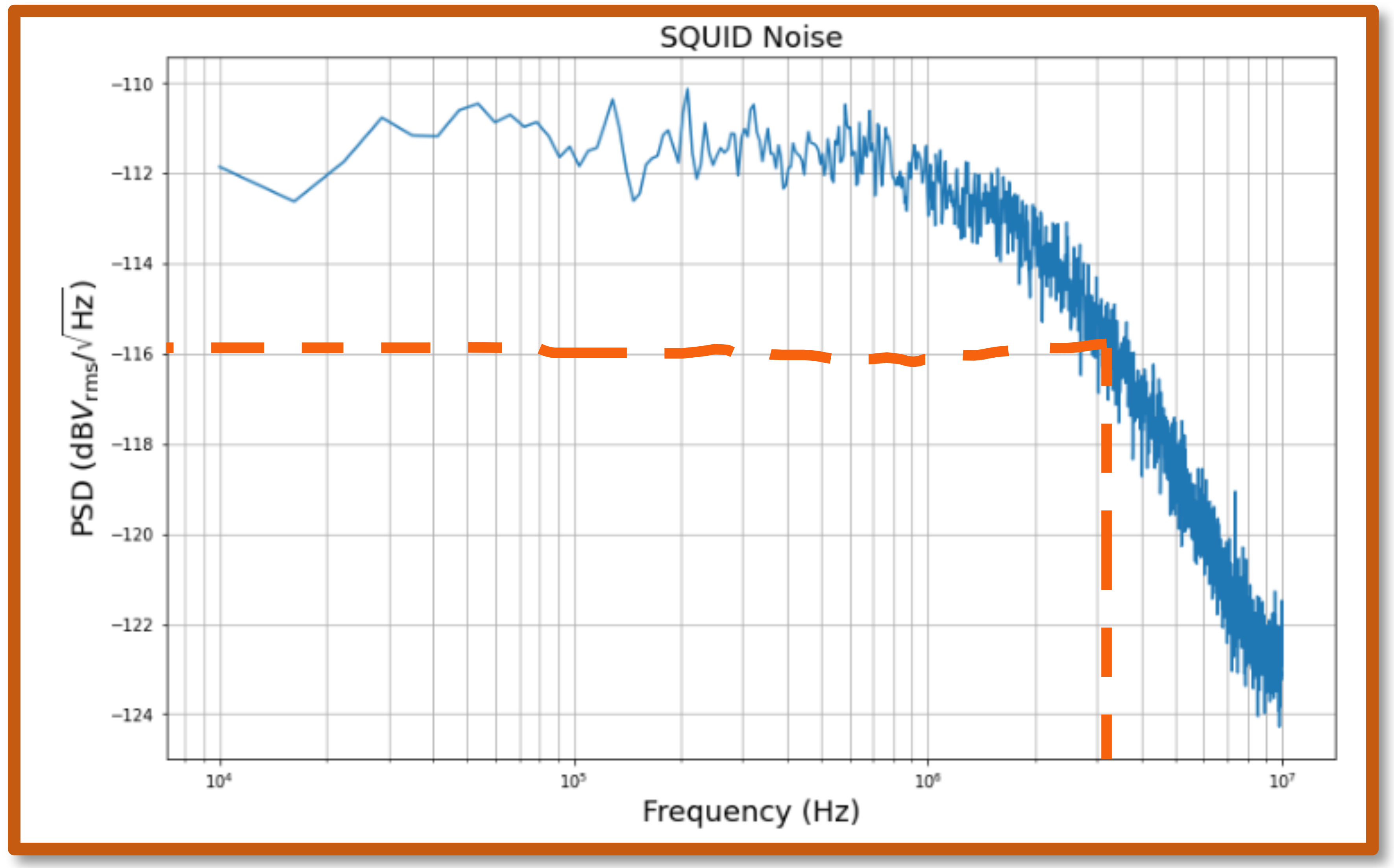
Muon / Cosmic Particle Veto Detector

Exclude potential sources of events:

MAGE – Searching for new physics

Calibration of 2nd detector



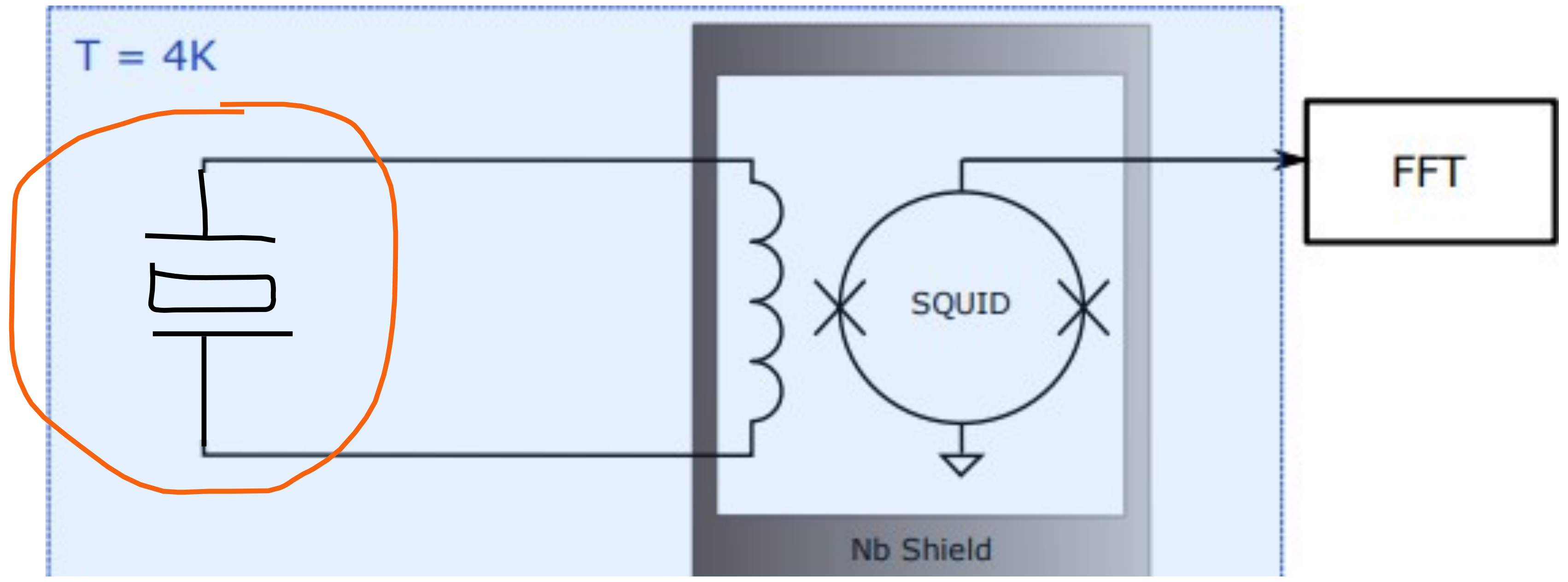


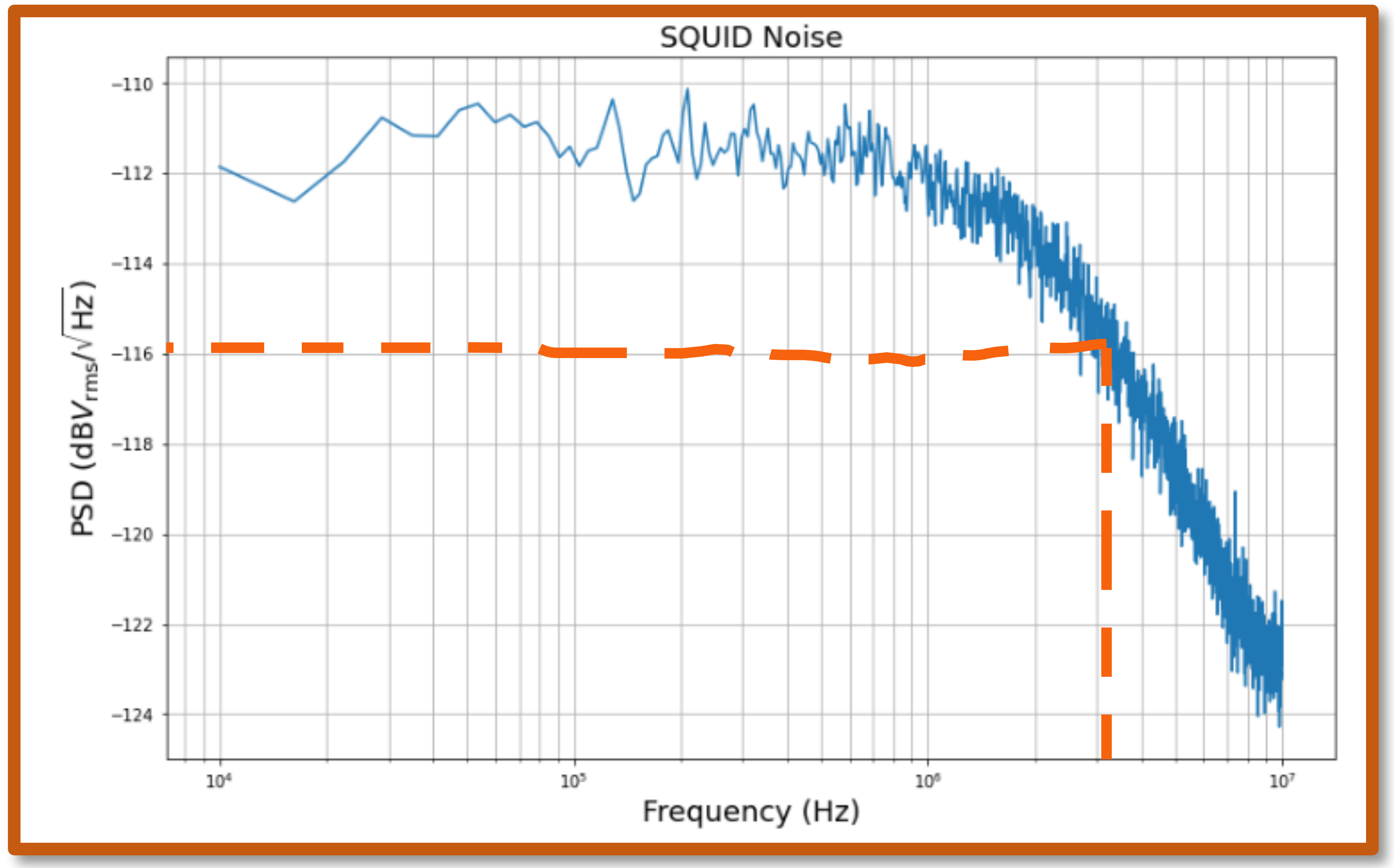
Limited by SQUID electronics

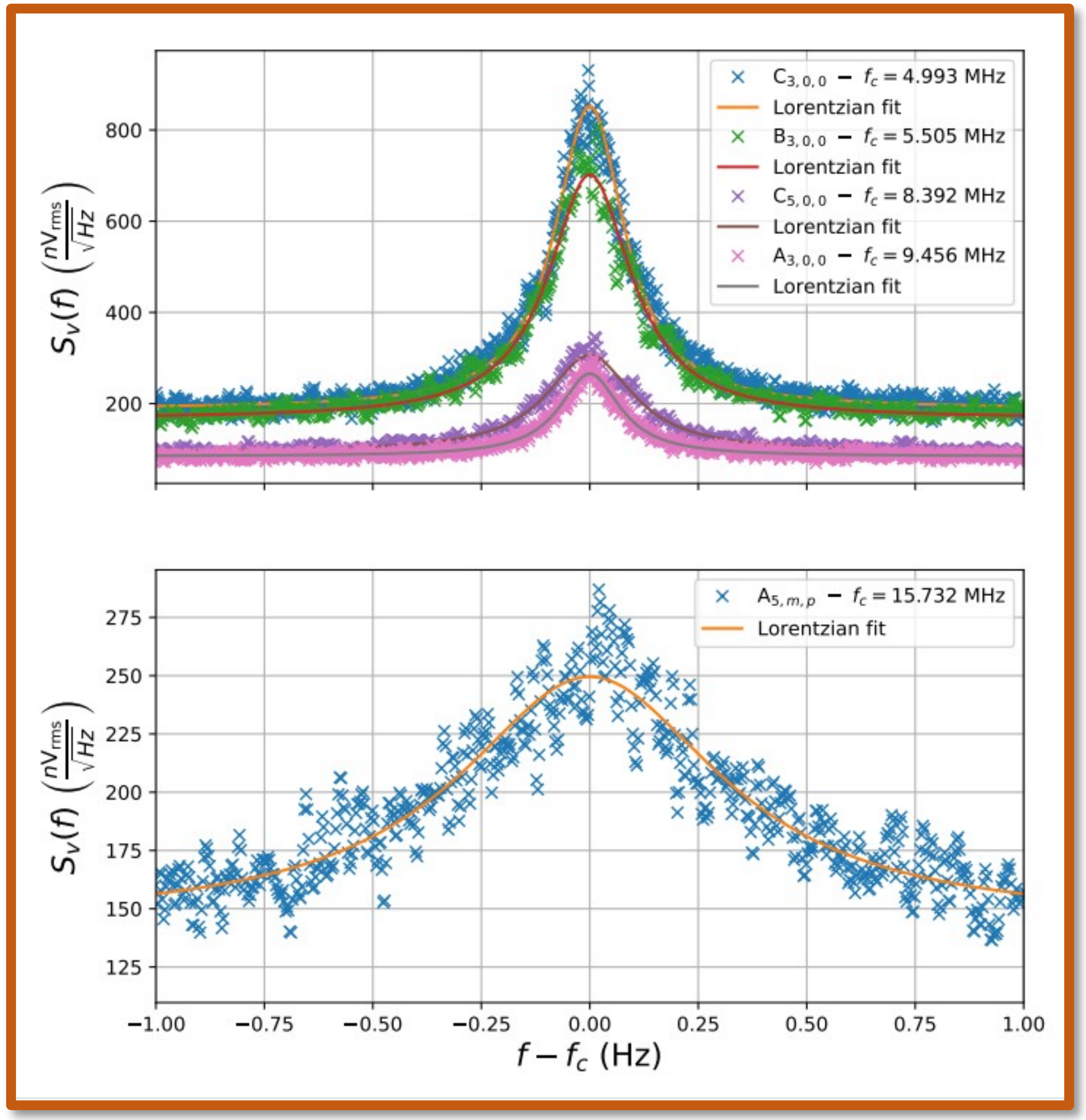
$f_{3dB} \sim 3$ **MHz**

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

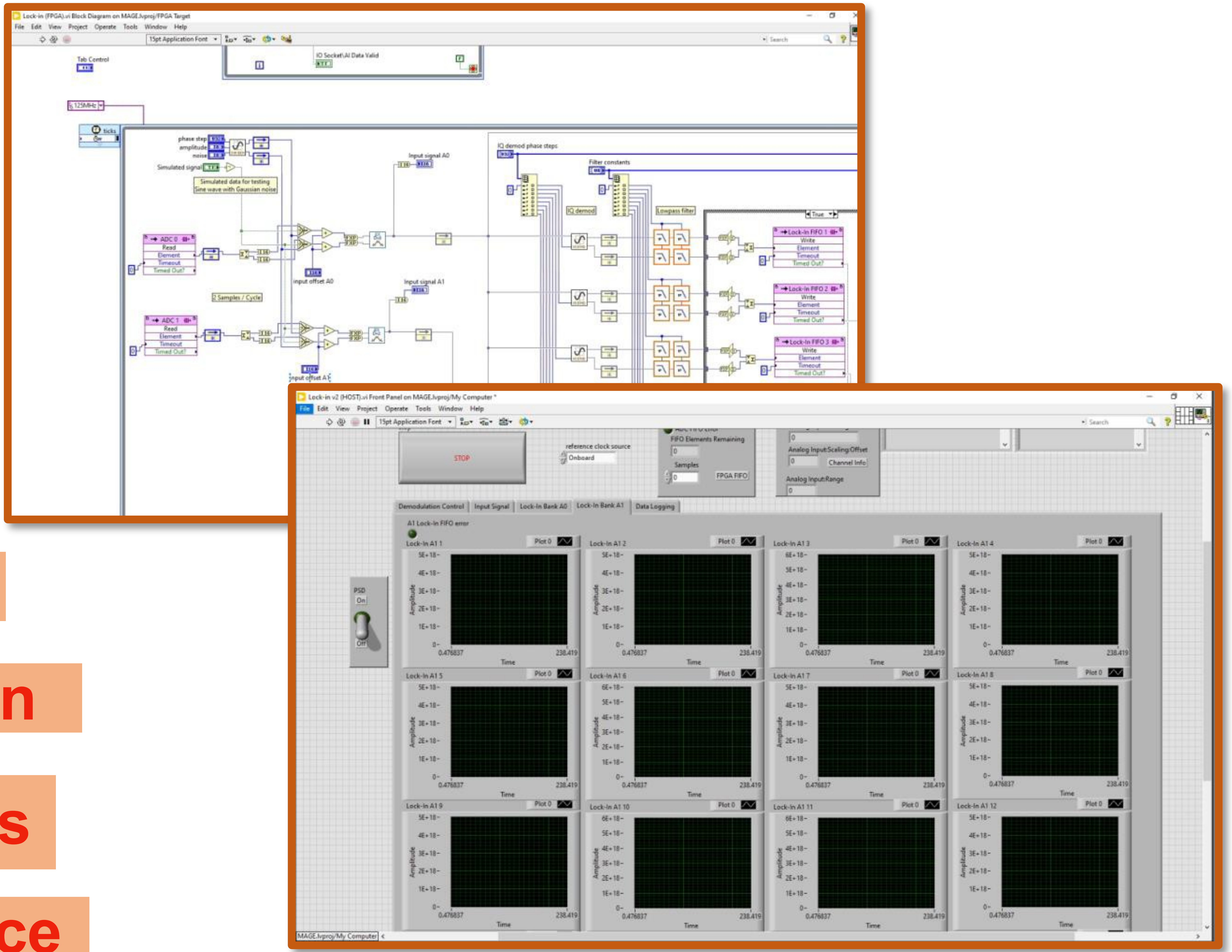
National Instruments – 5763 Digitizer
LabVIEW

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



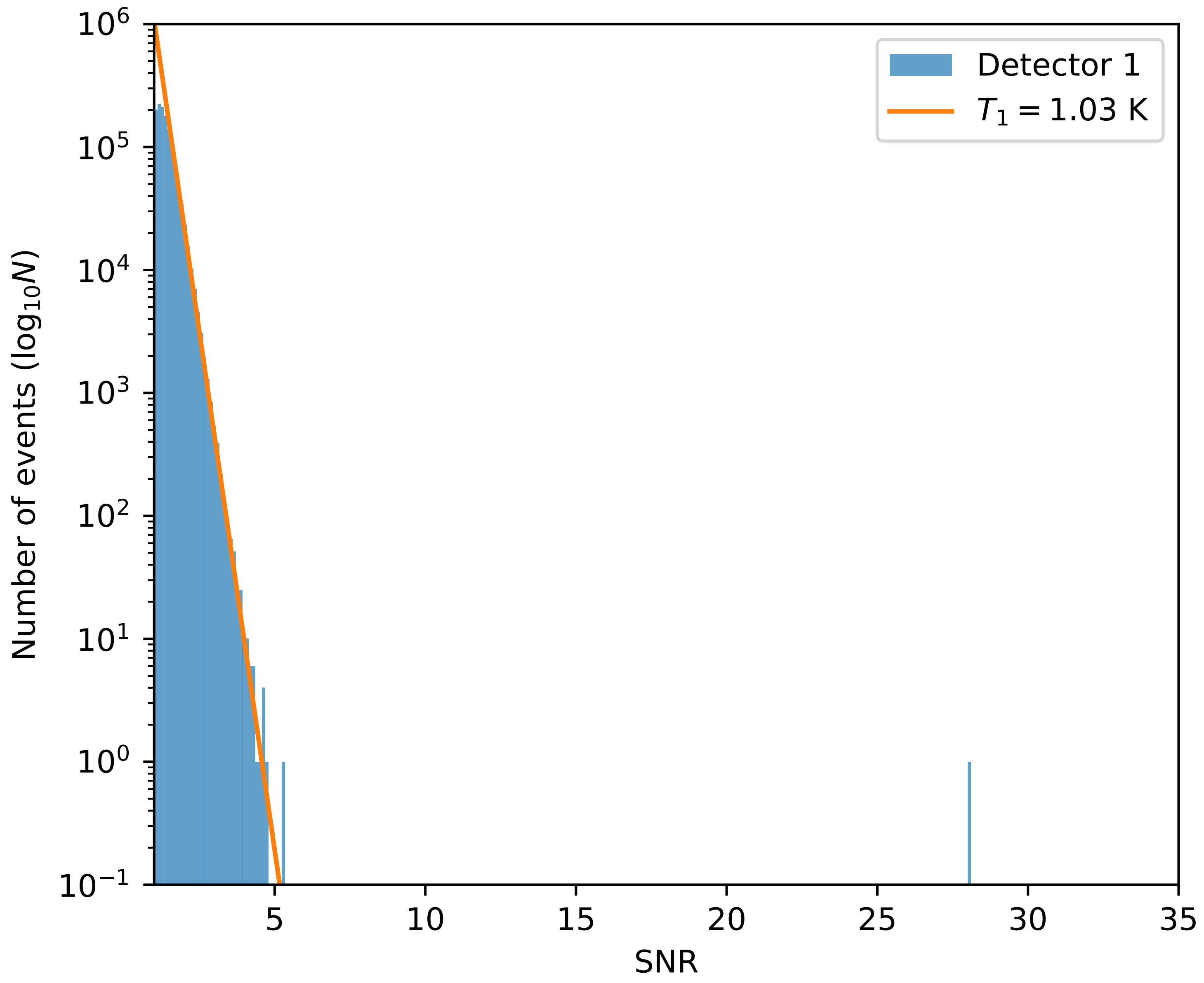
16 modes in each crystal. [MHz]

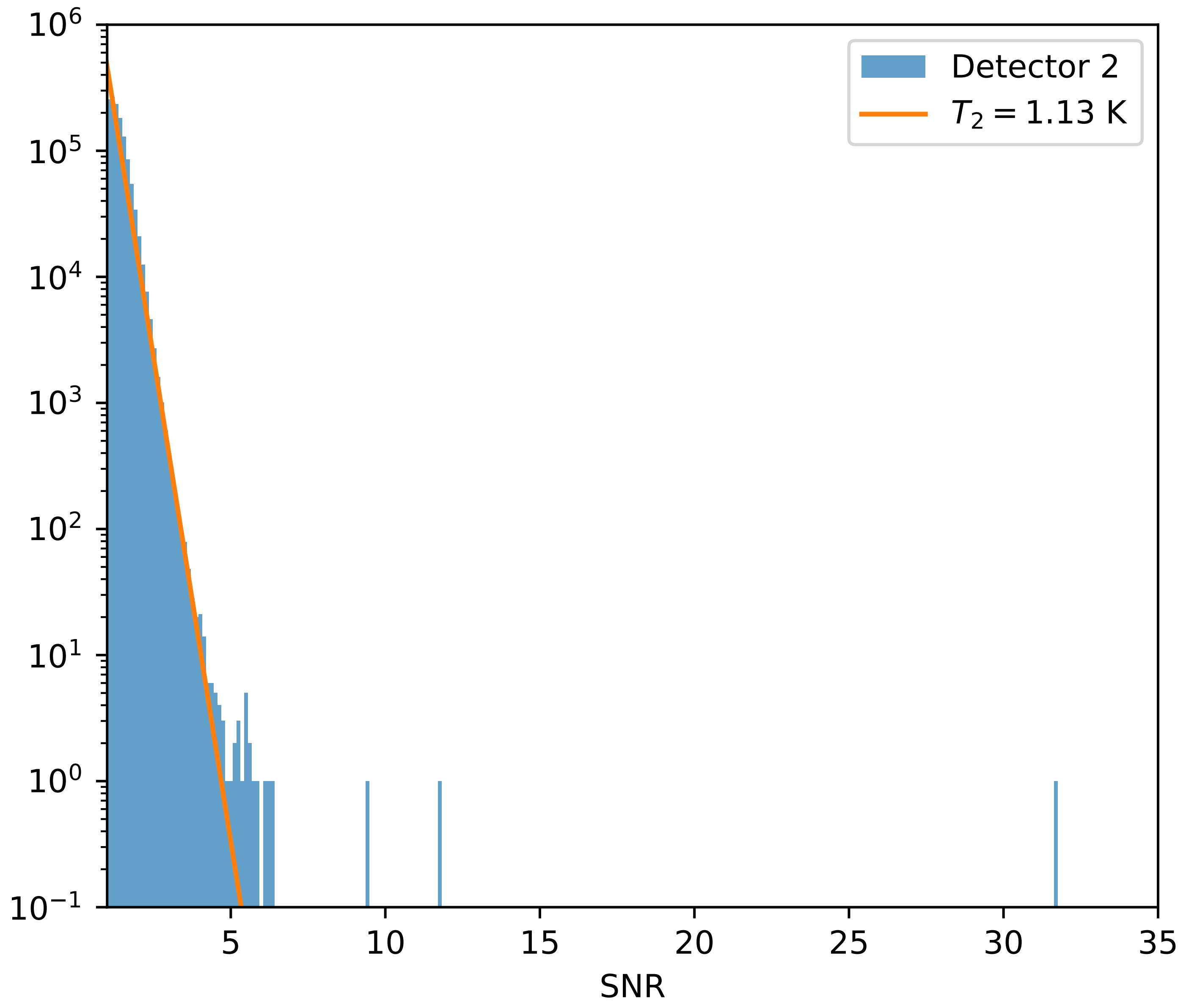
4.993050, 5.080854, 5.088263, 5.505426, 5.576835, 8.392272, 9.151802, 9.409902, 9.452381, 5.603804, 6.4326464, 8.297581, 8.400189, 9.224931, 9.246863, 9.526448, 15.731899

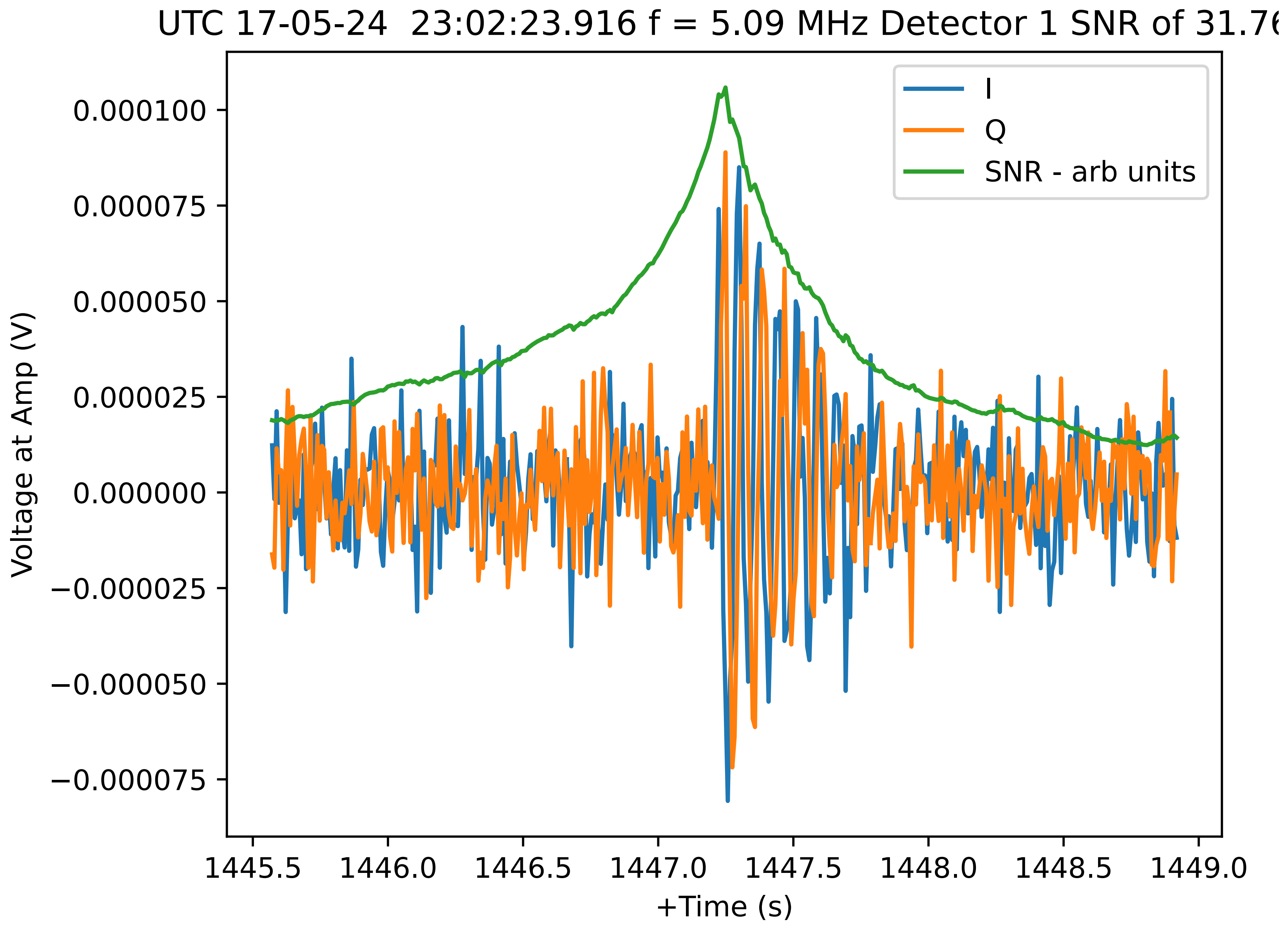
MAGE – Searching for new physics

Currently have new data!

Optimal FIltering → Search for transient events corresponding to quartz decay

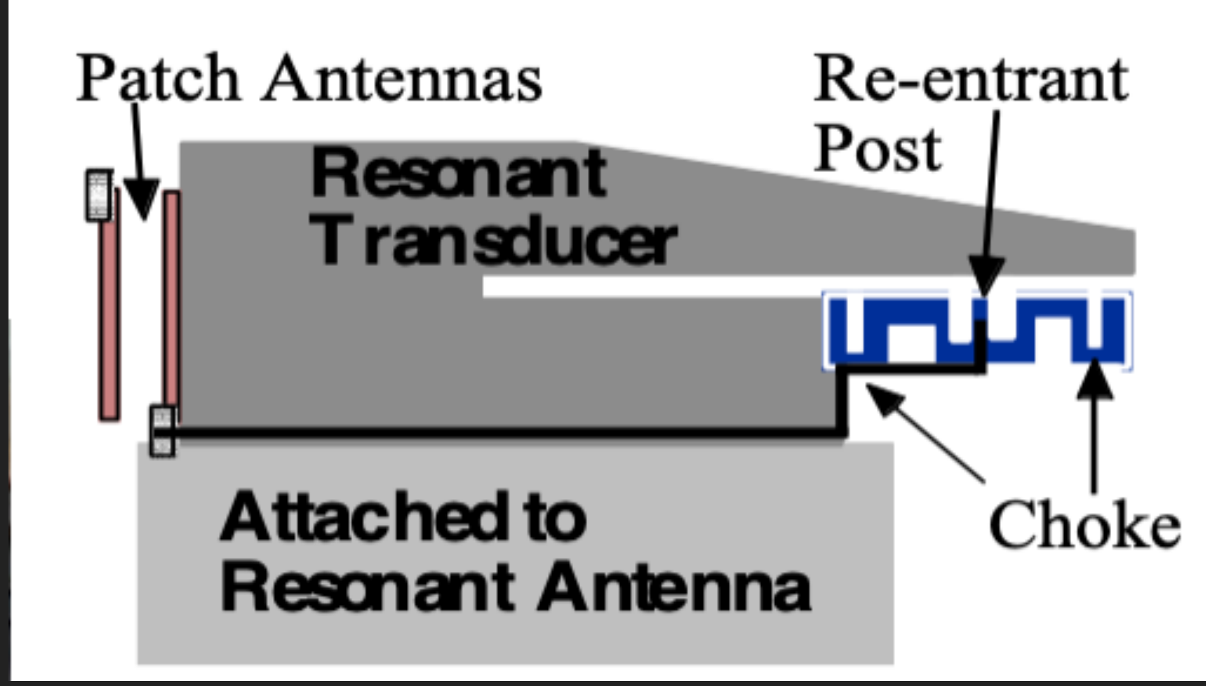




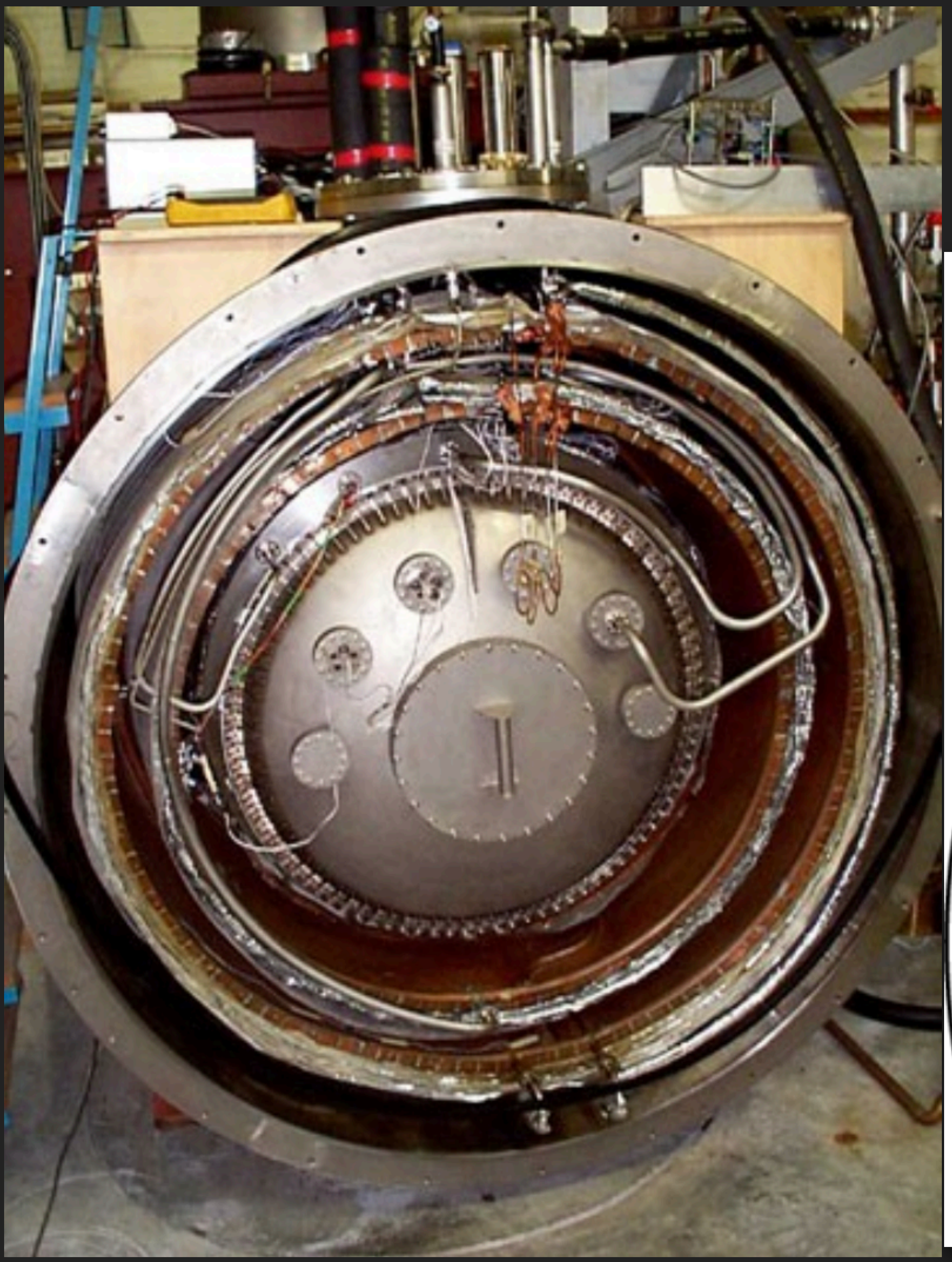


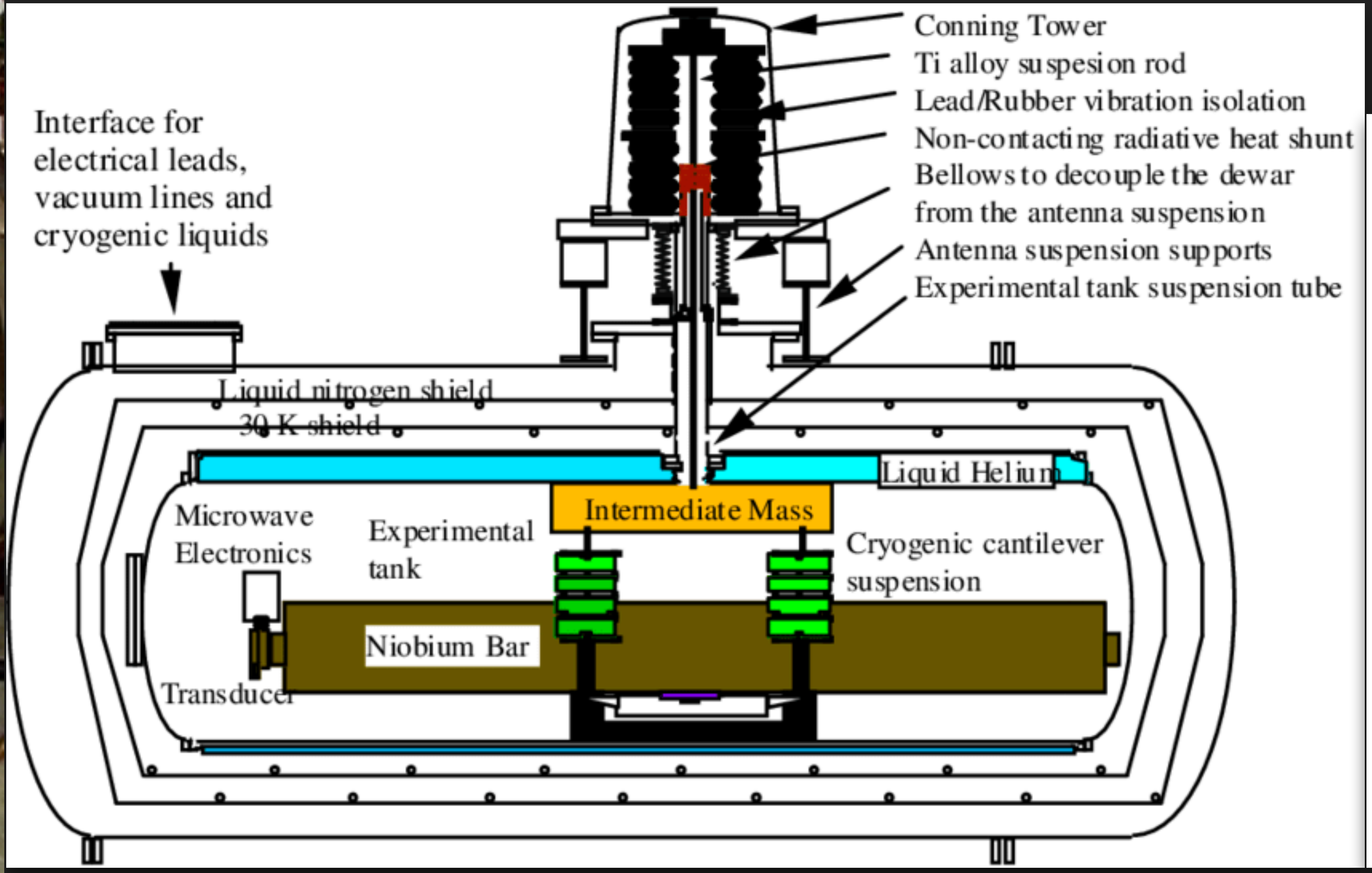
Cryogenic Resonant Bar Gravity Wave Detectors
-> Ultra precise optomechanical position measurement
-> Low phase noise read-out and pump oscillator

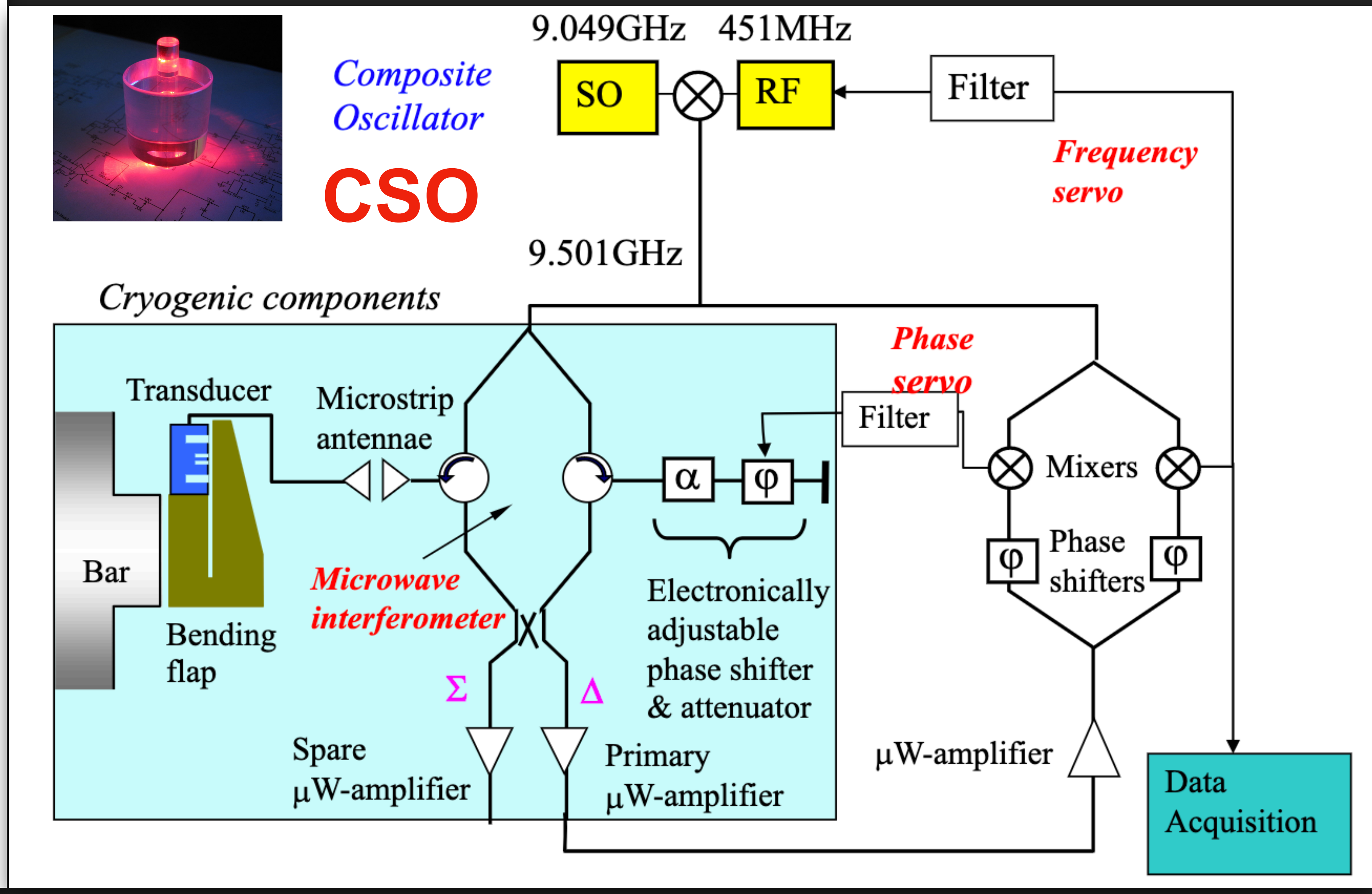
* **Photons**
* **Ponons**
* **Spins**



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

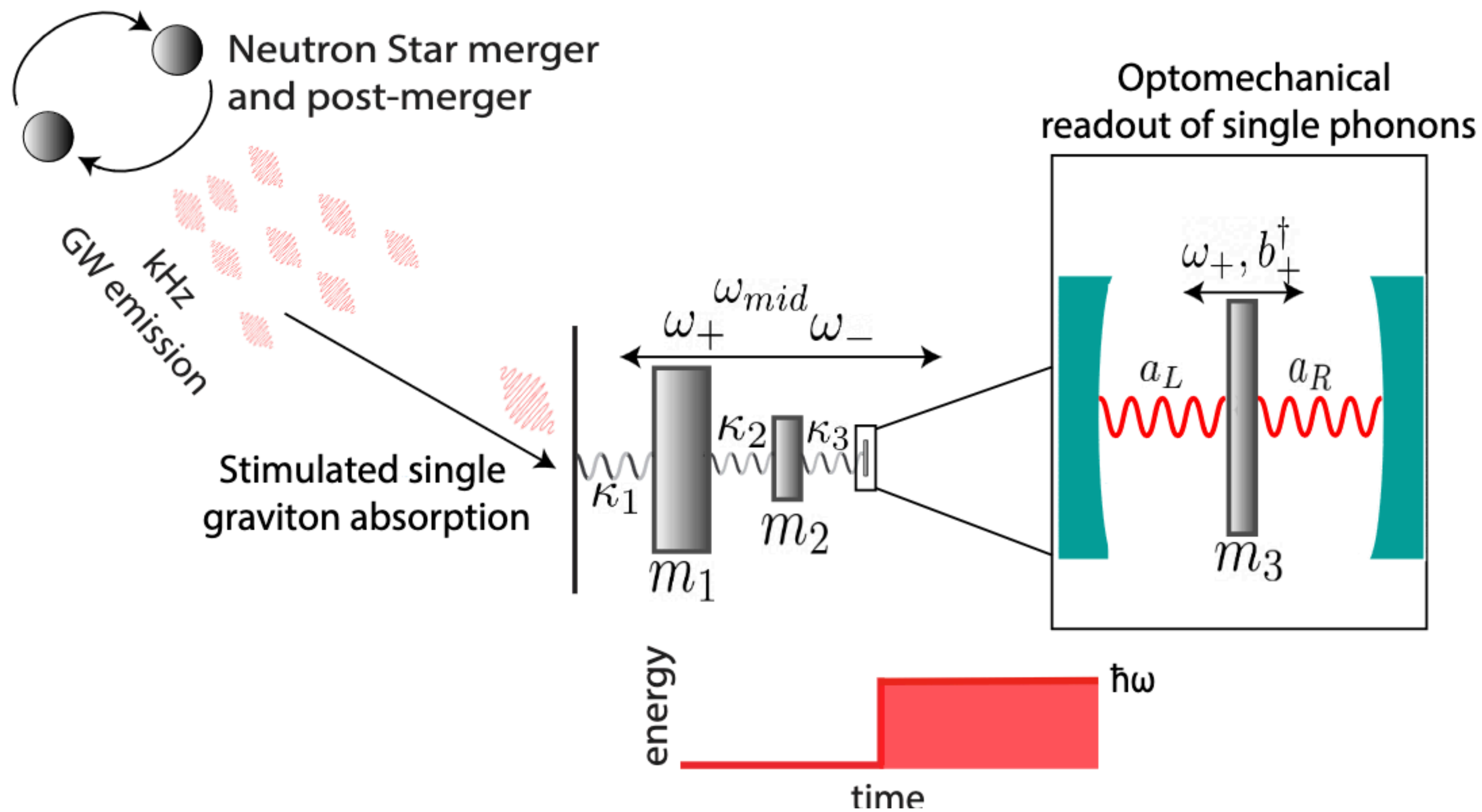
My PhD project 1989 ->1993 UWA PhD
Searching GW Signal Burst at 720 Hz

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

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.*



J. Phys. D: Appl. Phys. **28** (1995) 1729–1736. Printed in the UK

Characterizing multi-mode resonant-mass gravitational wave detectors

Michael E Tobar

Department of Physics, University of Western Australia, Nedlands 6009, Western Australia

Received 29 November 1994

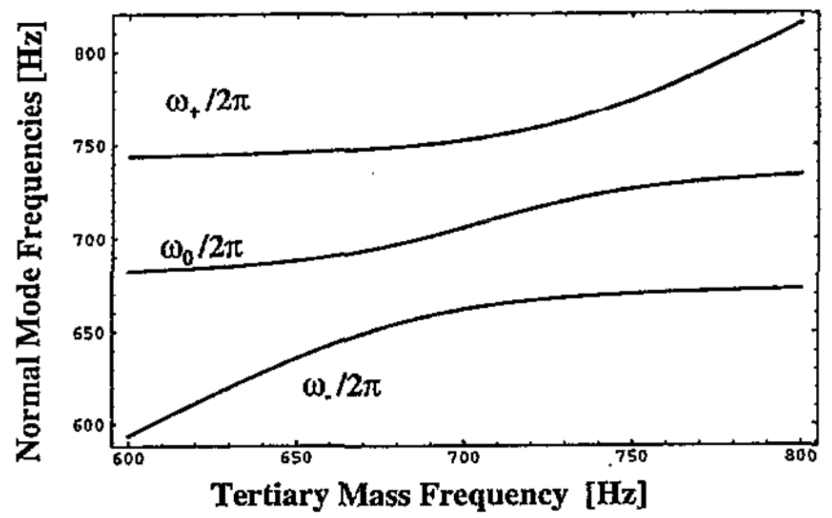


Figure 4. Normal mode frequencies against tertiary mass frequency for the UWA antenna with the proposed two-mode sapphire transducer.

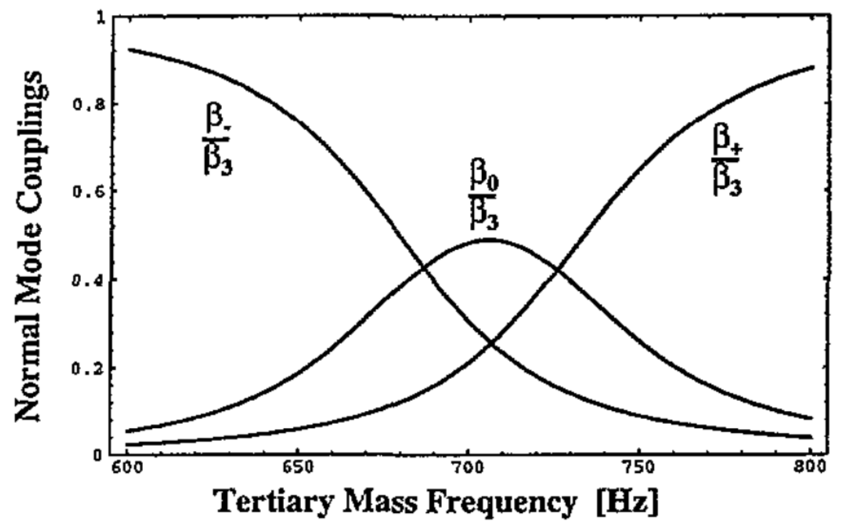


Figure 6. Normalized electromechanical couplings of the normal modes against tertiary mass frequency for the UWA antenna with the proposed two-mode sapphire transducer.

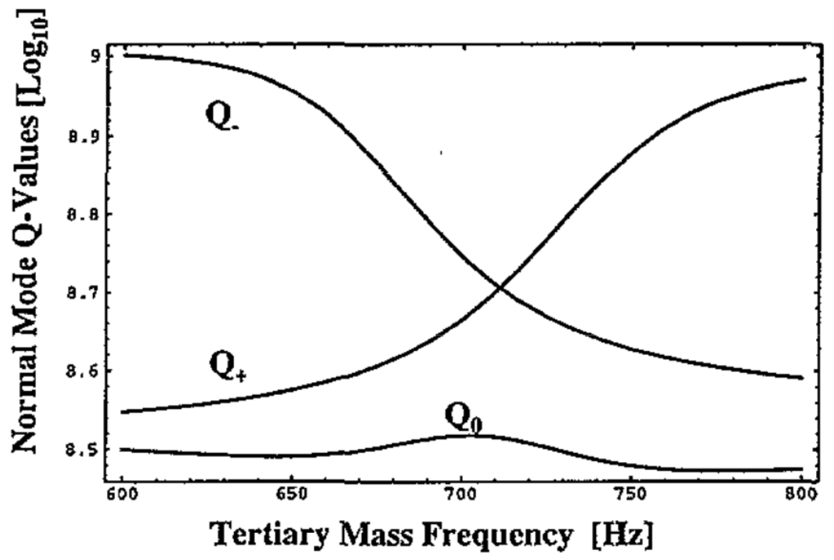


Figure 5. Normal mode *Q* values against tertiary mass frequency for the UWA antenna with the proposed two-mode sapphire transducer.

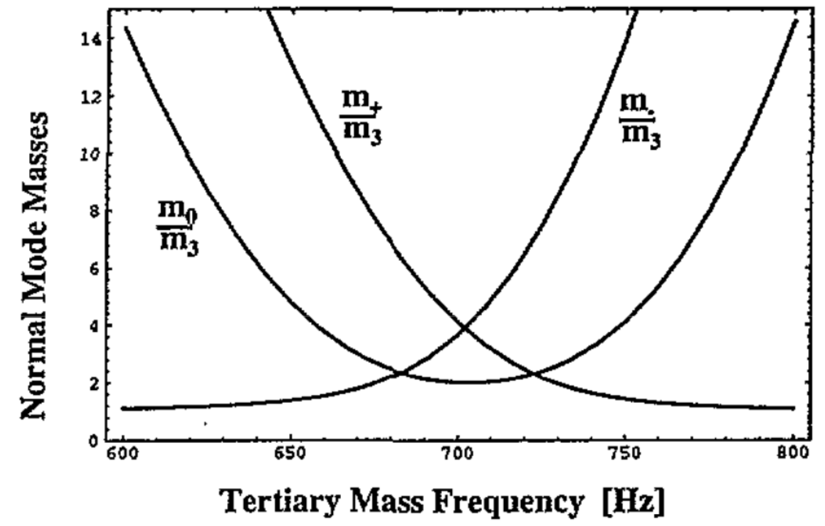
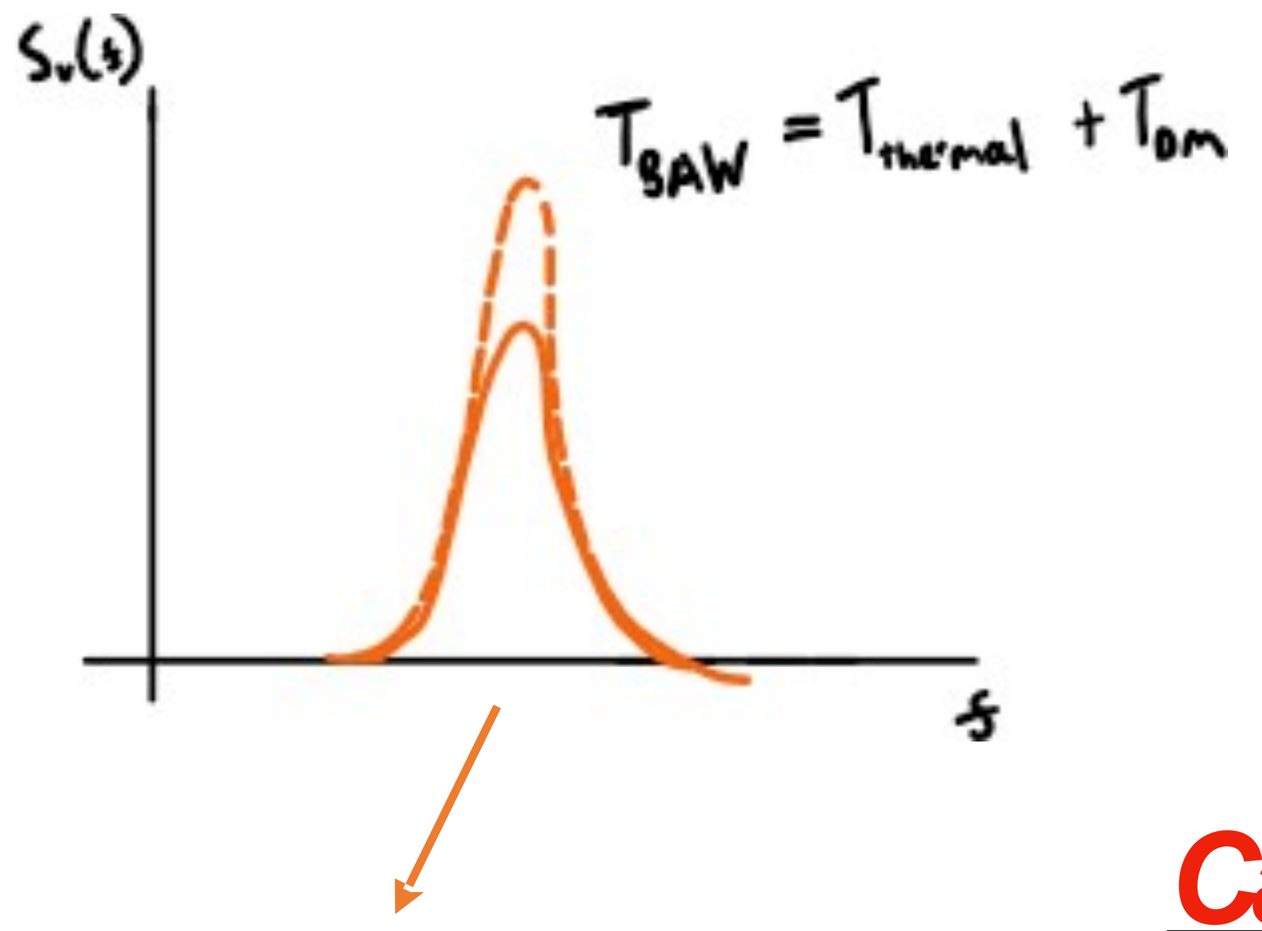


Figure 7. Normalized normal mode masses versus tertiary mass frequency for the UWA antenna with the proposed two-mode sapphire transducer.

MAGE – Searching for new physics

Other possibilities for MAGE:

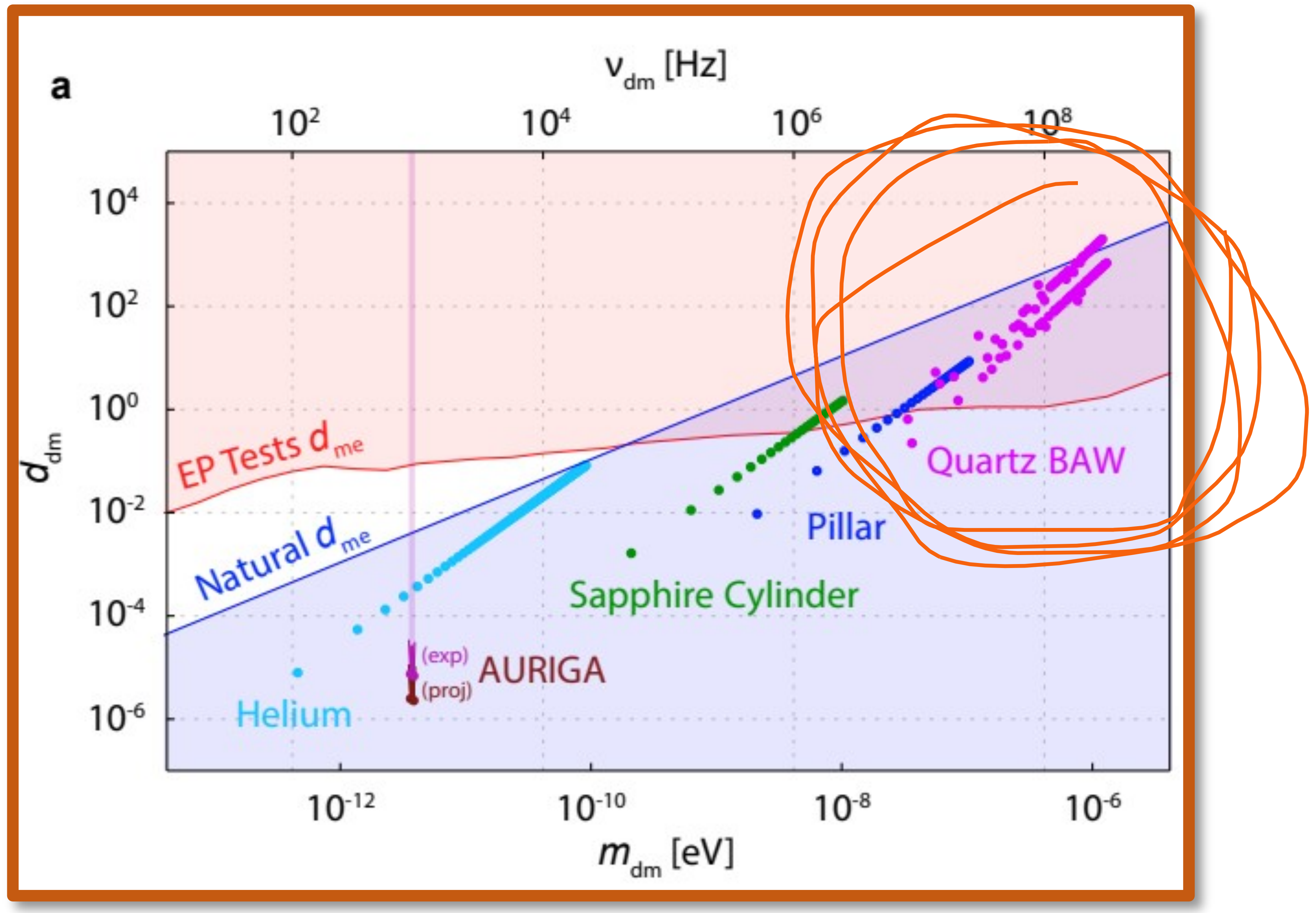
Scalar DM -> Isotropic strain signal



Nontrivial DM signal

***Can exclude*:**
Transient flows
Daily modulation

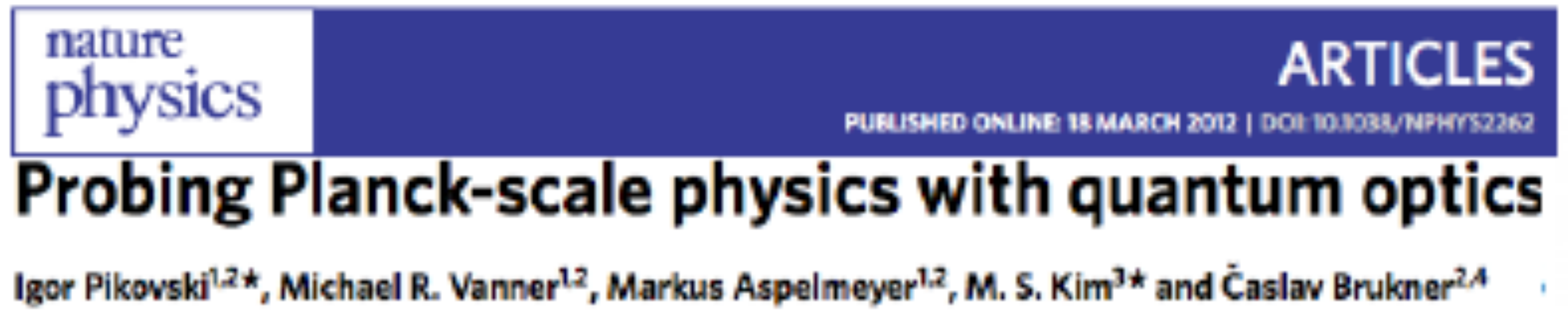
***Ongoing work*:**
Resonance tuning



Phys. Rev. Lett. 124, 151301

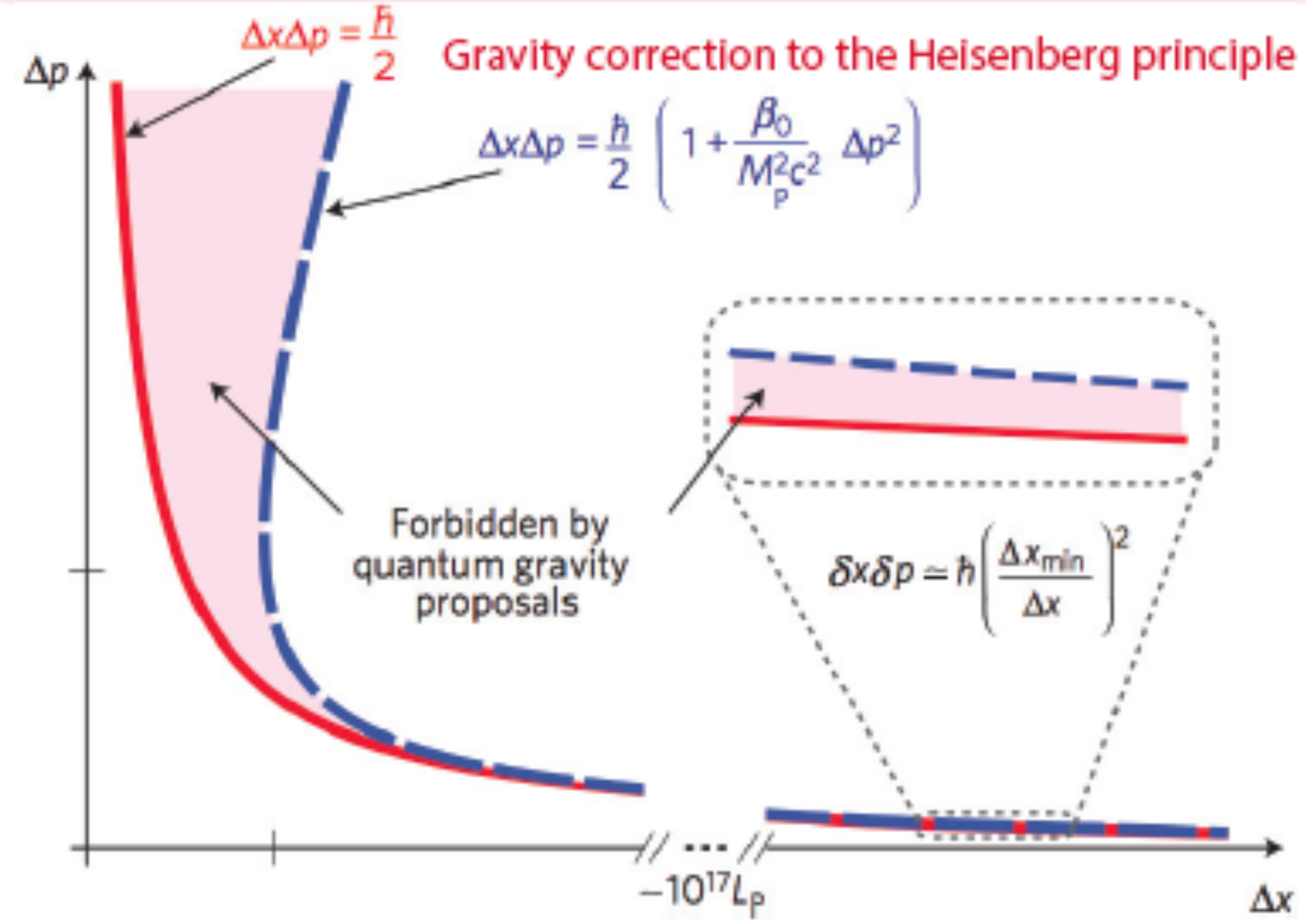
Does Gravity Modify Quantum Mechanics? Is there a Theory of Quantum Gravity?

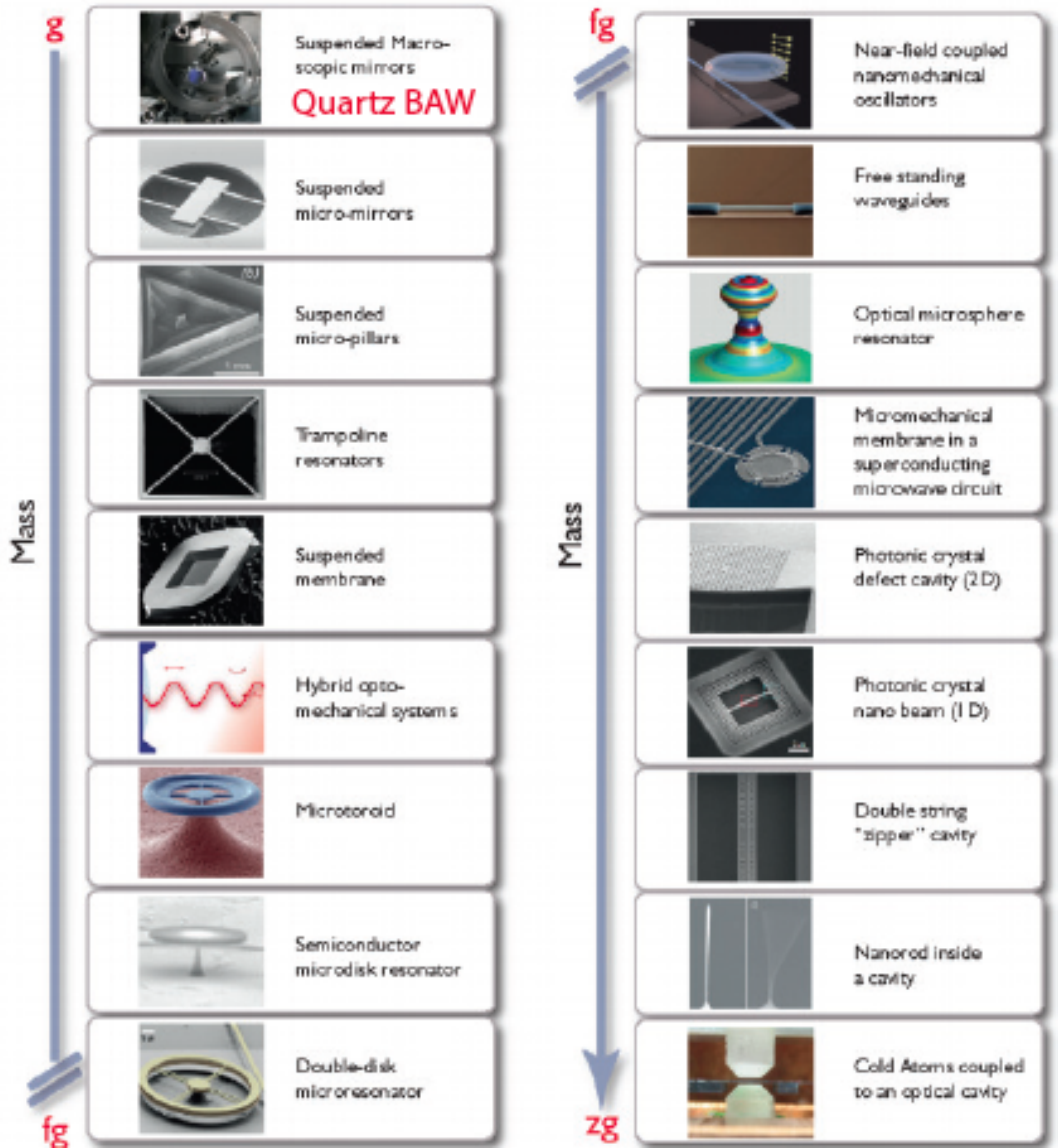
Quantum Gravity


nature physics | ARTICLES
PUBLISHED ONLINE: 18 MARCH 2012 | DOI: 10.1038/NPHYS2262
Probing Planck-scale physics with quantum optics
Igor Pikovski[1,2]*, Michael R. Vanner[1,2], Markus Aspelmeyer[1,2], M. S. Kim[3]* and Časlav Brukner[2,4]

Theoretically proposed modification:

$$[x,p] = i\hbar\sqrt{1 + 2\eta_0 \frac{(p/c)^2 + m^2}{M_p^2}}$$





Quantum Mechanics Possible with Macroscopic Masses?

* Does mass modify the position and momentum commutator relations?
* QG theories predict a nonlinear correction to the canonical commutation relation between x, and p.

(Minimum Length Theories)

* Can test with precision opto-mechanics?

Quantum Gravity

Testing the generalized uncertainty principle with macroscopic mechanical oscillators and pendulums

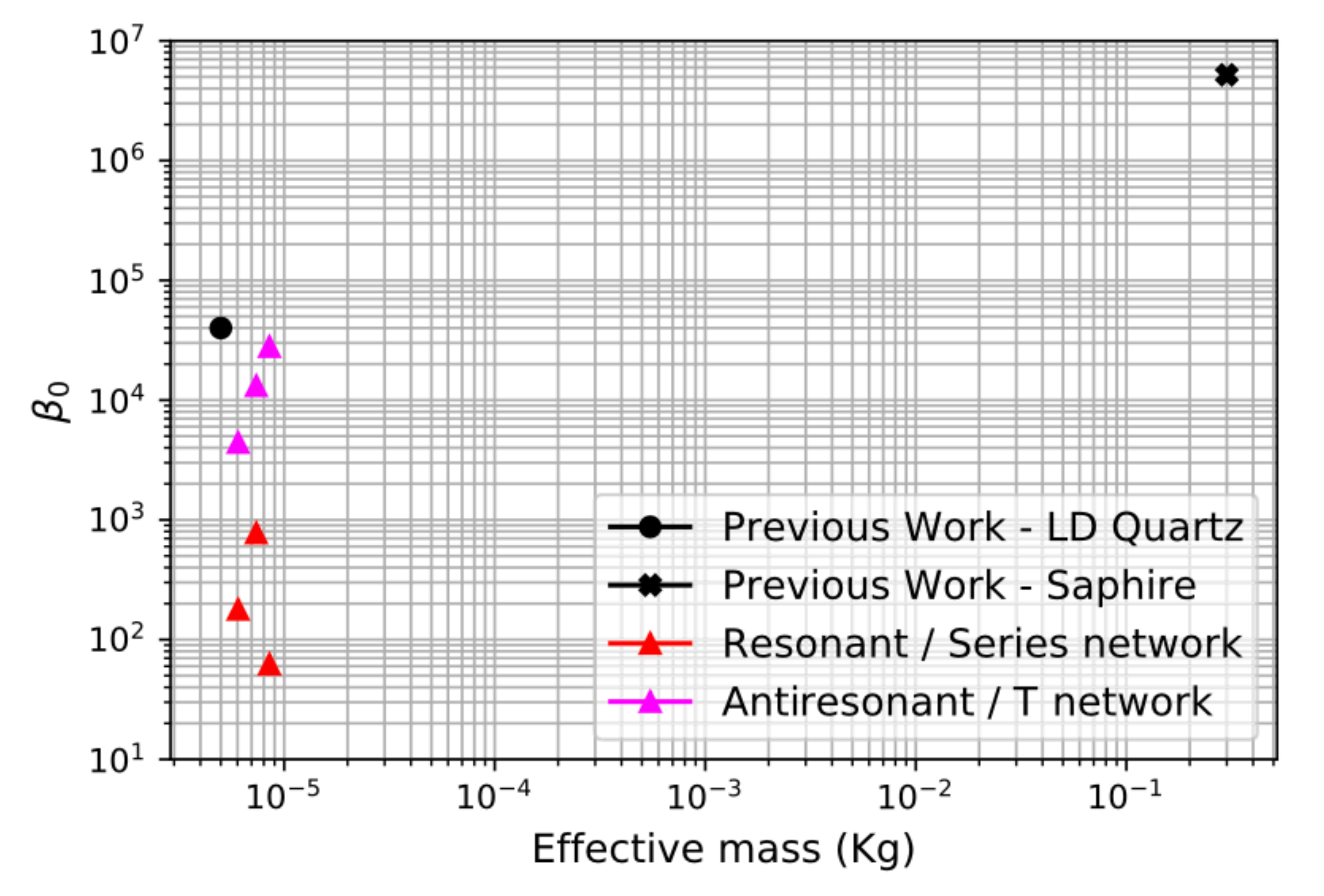
P. A. Bushev, J. Bourhill, M. Goryachev, N. Kukharchyk, E. Ivanov, S. Galliou, M. E. Tobar, and S. Danilishin
Phys. Rev. D **100**, 066020 – Published 20 September 2019

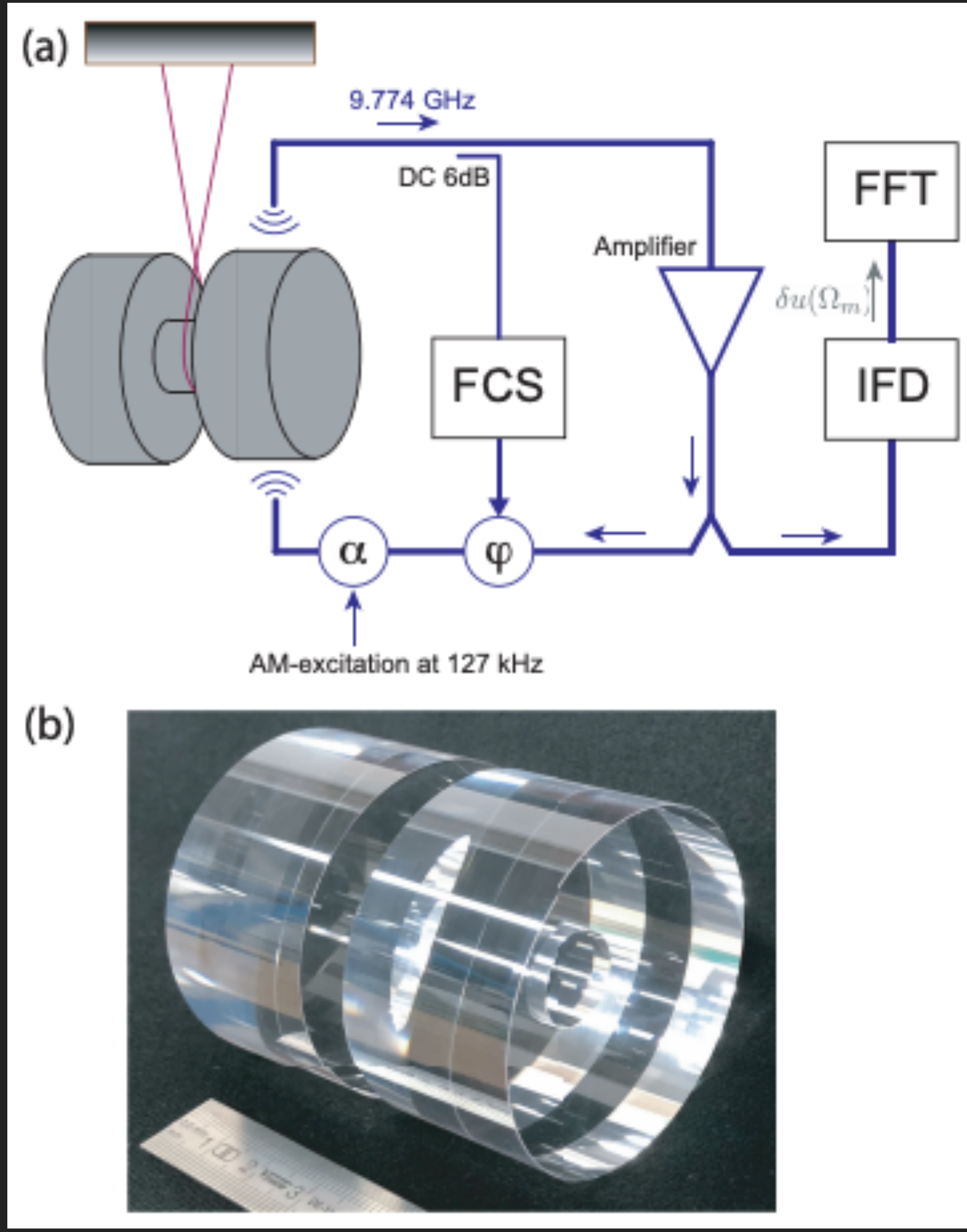
PHYSICAL REVIEW D **108,** 102006 (2023)

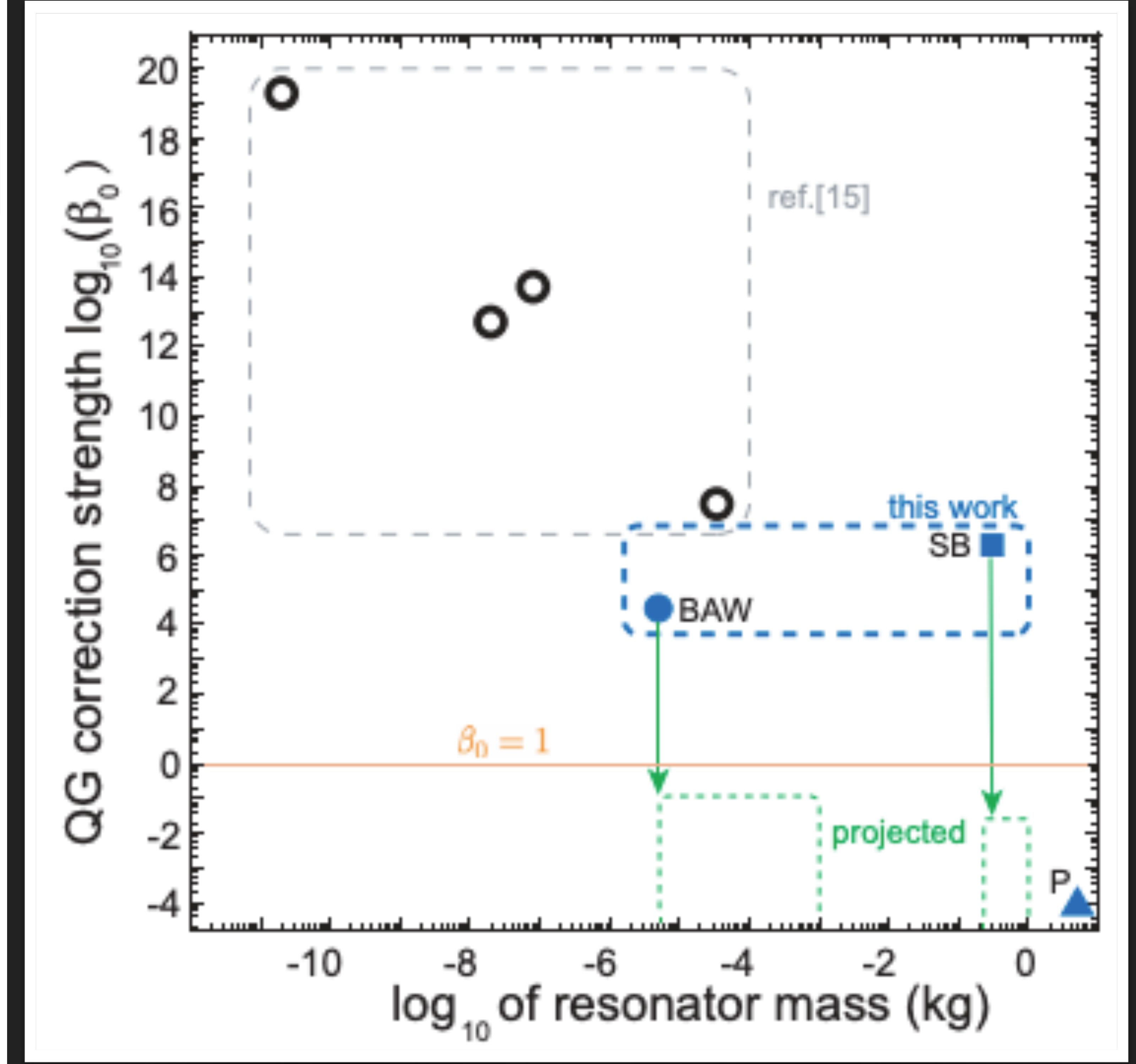
Improved constraints on minimum length models with a macroscopic low loss phonon cavity

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

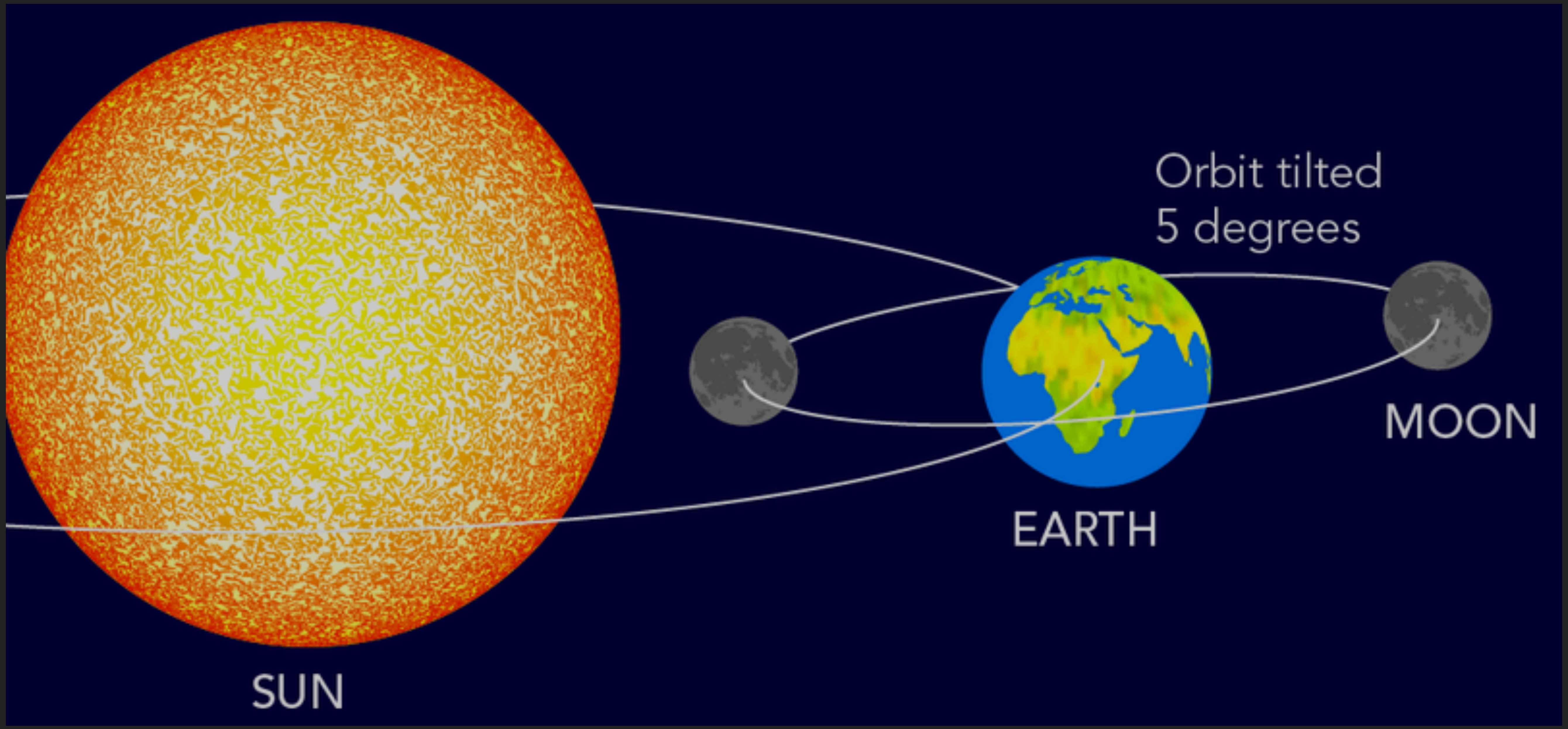
Serge Galliou
SUPMICROTECH-ENSMM, CNRS, Institut FEMTO-ST, 26 Rue de l'Épitaphe 25000 Besançon, France

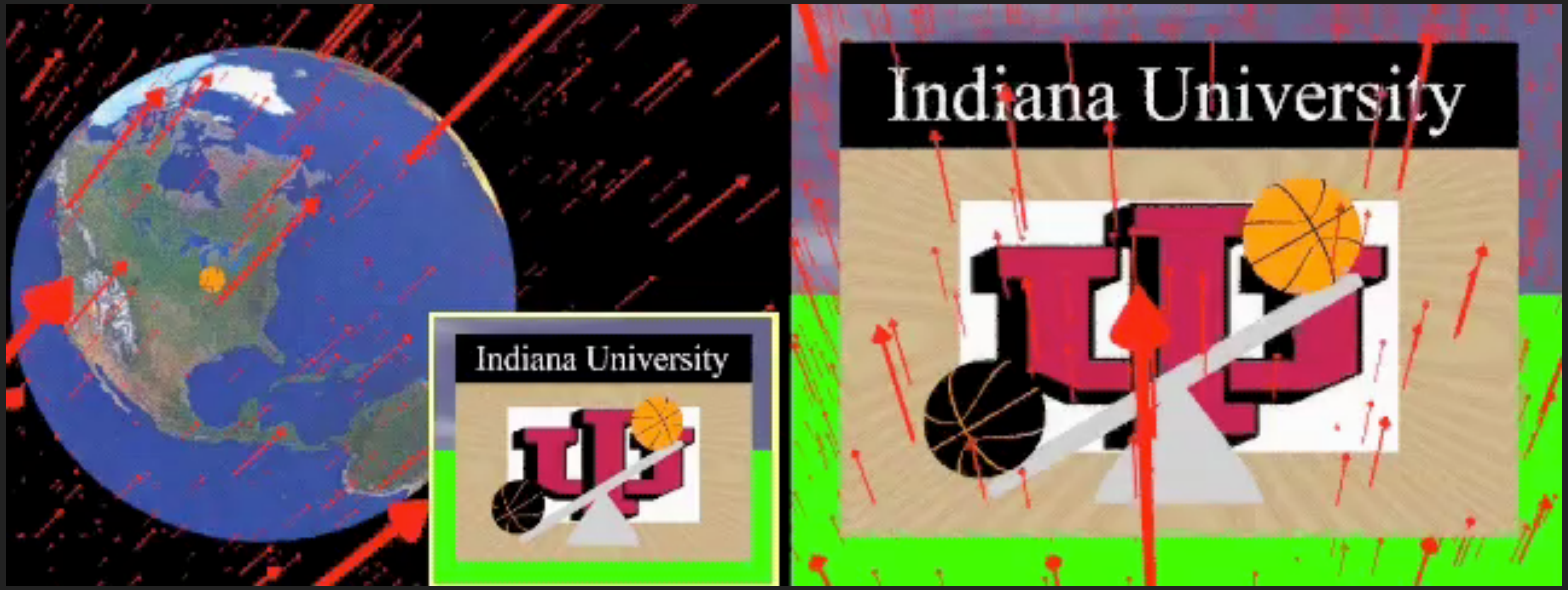






Large Acoustic Systems





Electric and Gravitational Scalar Aharonov-Bohm Effects

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*

(Received 21 November 2022; accepted 3 April 2023; published 13 April 2023)

PHYSICAL REVIEW D **109**, 064073 (2024)

Gravitational Aharonov-Bohm effect

R. Y. Chiao,[1,*] N. A. Inan,[2,1,3,†] M. Scheibner,[1,‡] J. Sharping,[1,§] D. A. Singleton,[3,‖] and M. E. Tobar[4,¶]

[1] *University of California, Merced, School of Natural Sciences, P.O. Box 2039, Merced, California 95344, USA*
[2] *Clovis Community College, 10309 N. Willow, Fresno, California 93730 USA*
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Scalar gravitational Aharonov–Bohm effect: Generalization of the gravitational redshift

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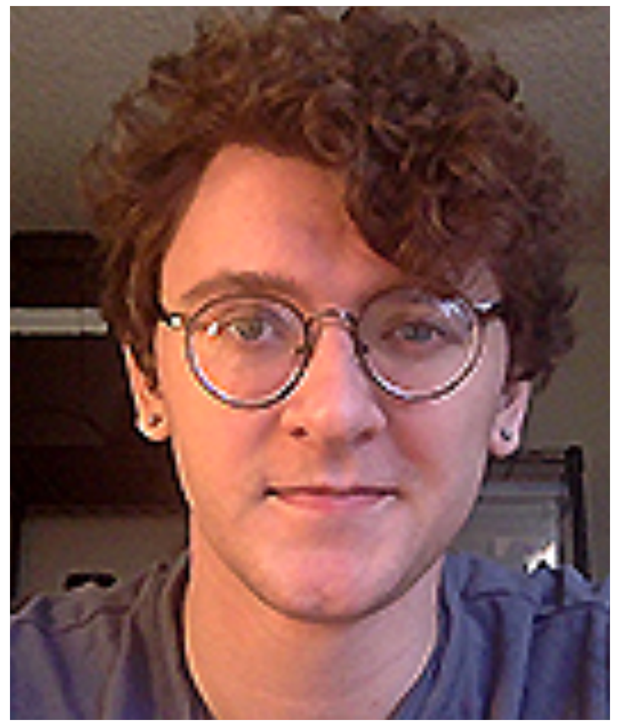
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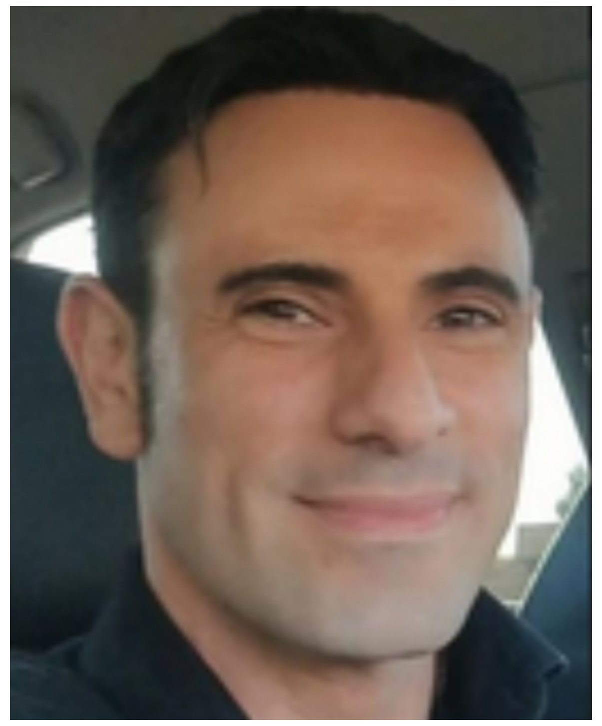
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Electromagnetic Aharonov-Bohm (AB) Effect: Geometric or Berry Phase

Vector Potential Effect (Magnetic and Spatial)

Static AB phase: Vector Magnetic AB Effect

$$\phi_{B_{AB}} = \frac{q}{\hbar}\oint_{\mathscr{P}} \mathbf{A}\cdot d\mathbf{l}$$

$$= \frac{q}{\hbar}\int_S \nabla \times \mathbf{A}\cdot d\mathbf{S}$$

$$= \frac{q}{\hbar}\int_S \mathbf{B}\cdot d\mathbf{S}$$

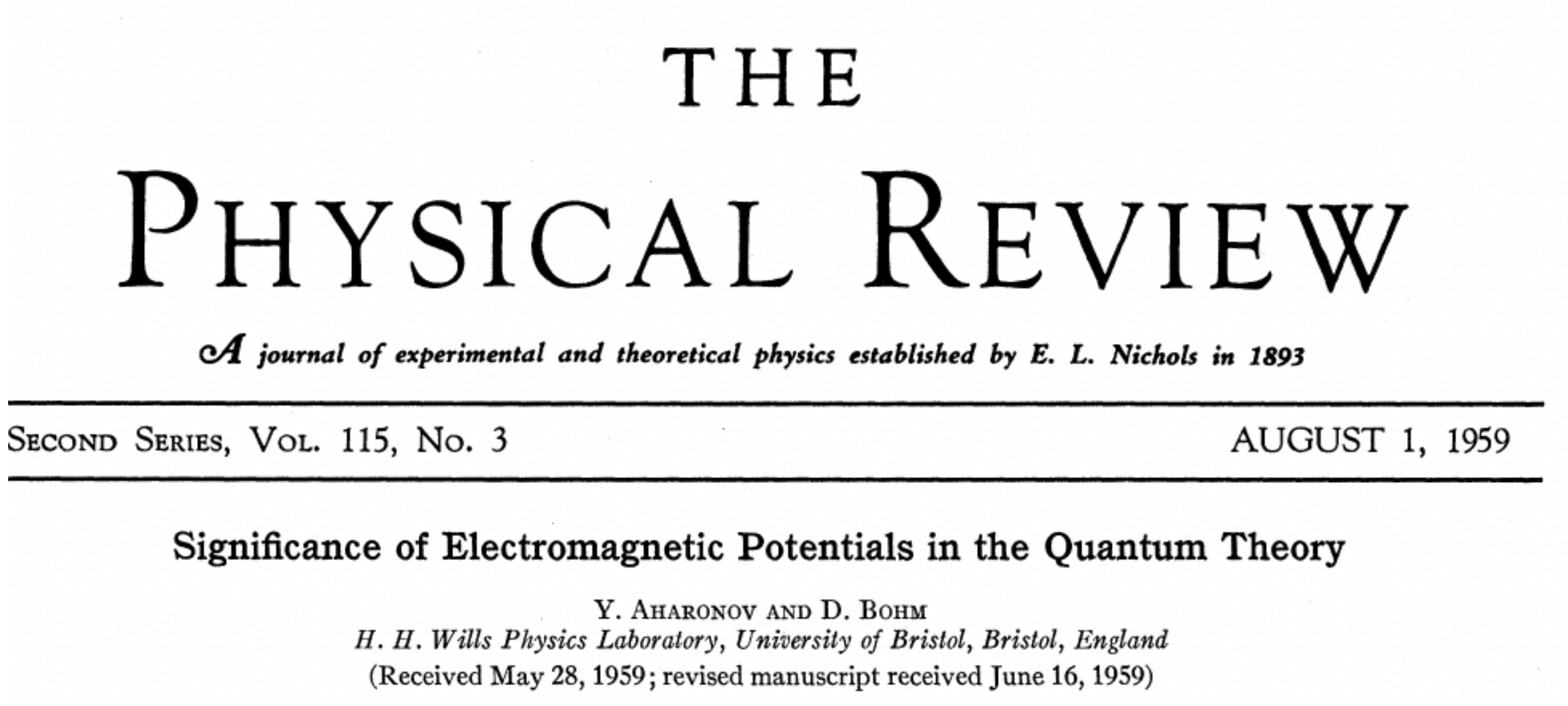
for a superconducting system with n Cooper pairs (q=2e)

$$\int_S \mathbf{B}\cdot d\mathbf{S} = n\Phi_0 = \frac{nh}{2e}$$

normal conductor with free electrons (q=e)

$$= 2n\Phi_0 = \frac{nh}{e}$$

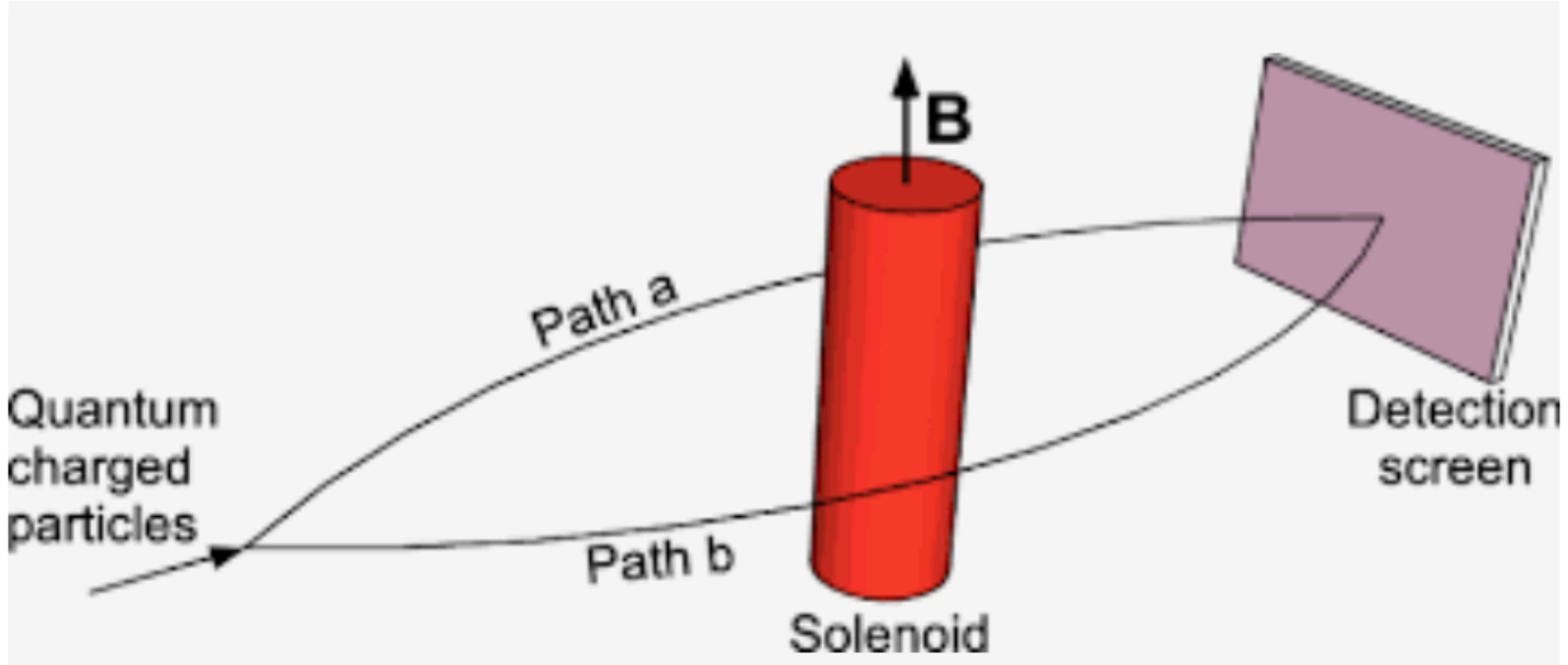
$$\phi_{B_{AB}} = 2n\pi$$

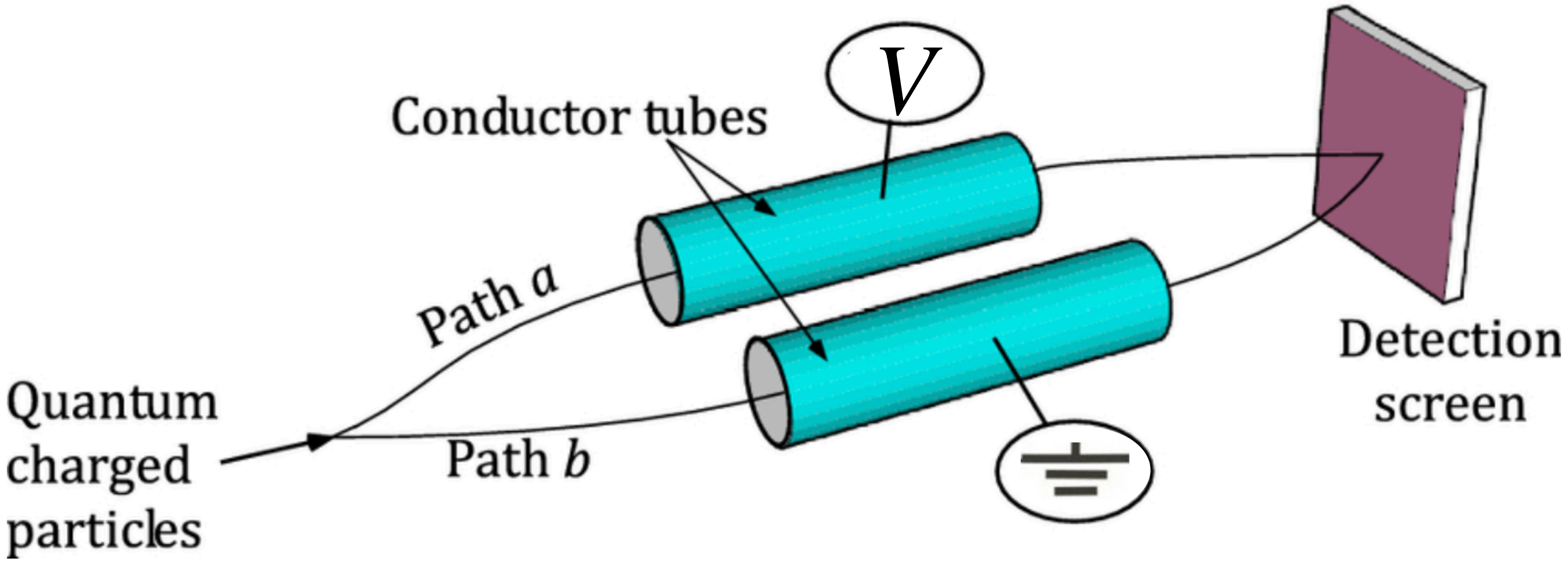


Scalar Potential Effect (Electric and Temporal)

Time dependent AB phase: Scalar Electric AB effect

$$\varphi_E(t) = \frac{e}{\hbar}\int V(t)dt \qquad \mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t} = 0$$





Energy-Level Shift of QM System via Electric AB Effect

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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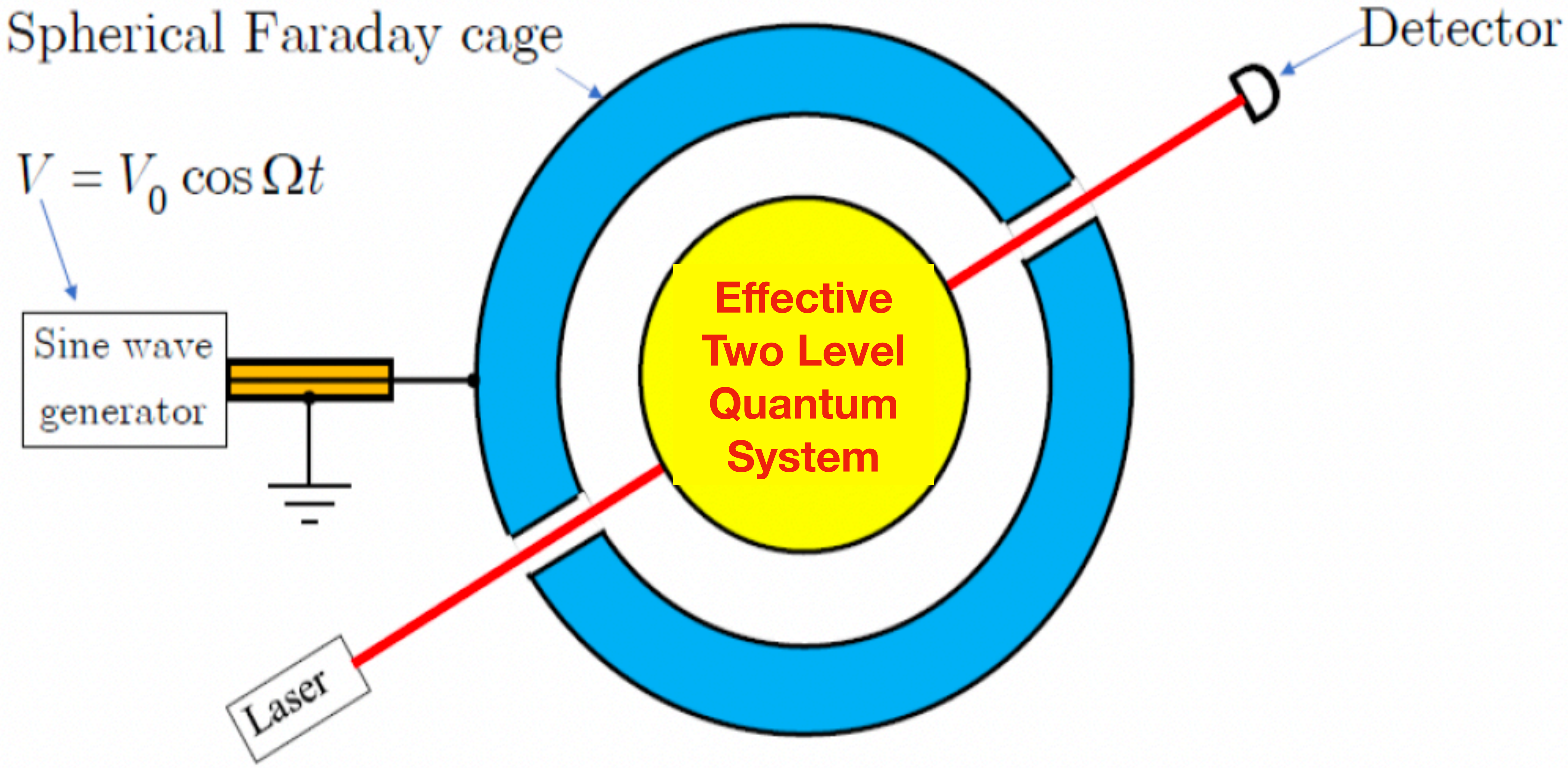
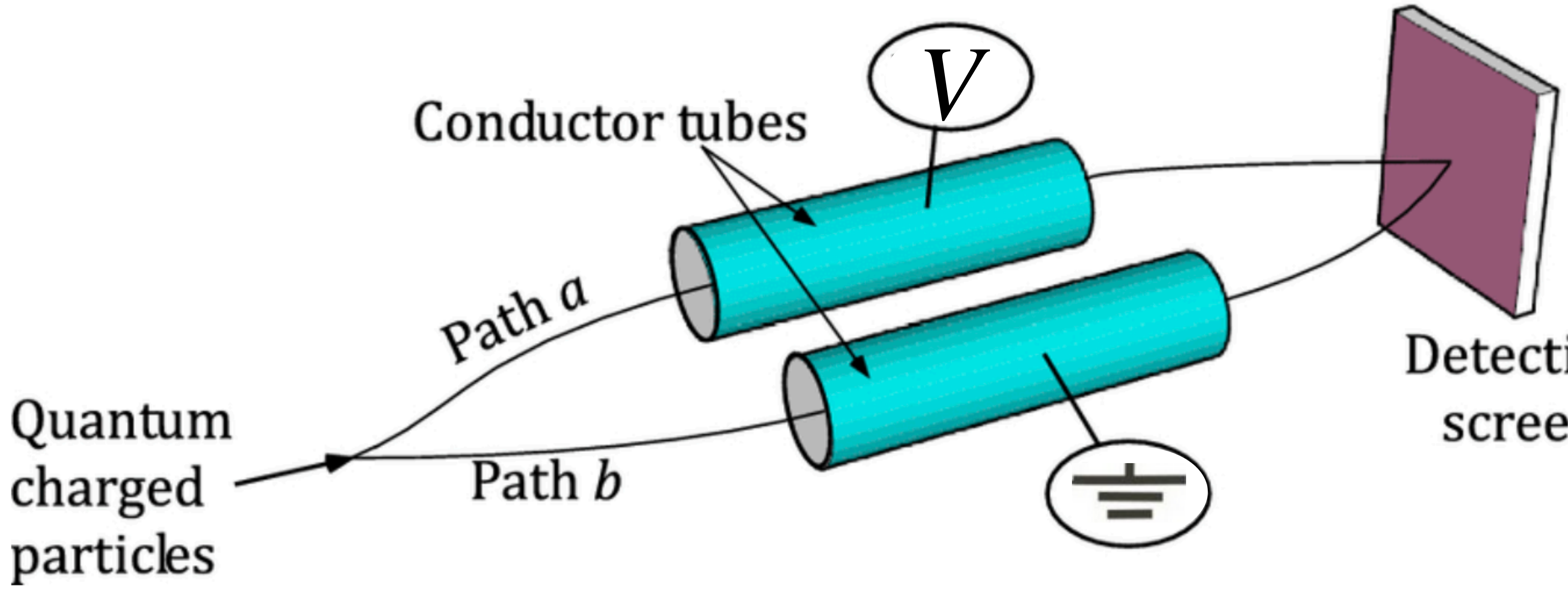


$$\mathbf{E} = -\nabla V(t) = 0$$

- We put a quantum system under a time varying, spatial uniform potential, $V(t)$.
- Original proposal had two different static fields.

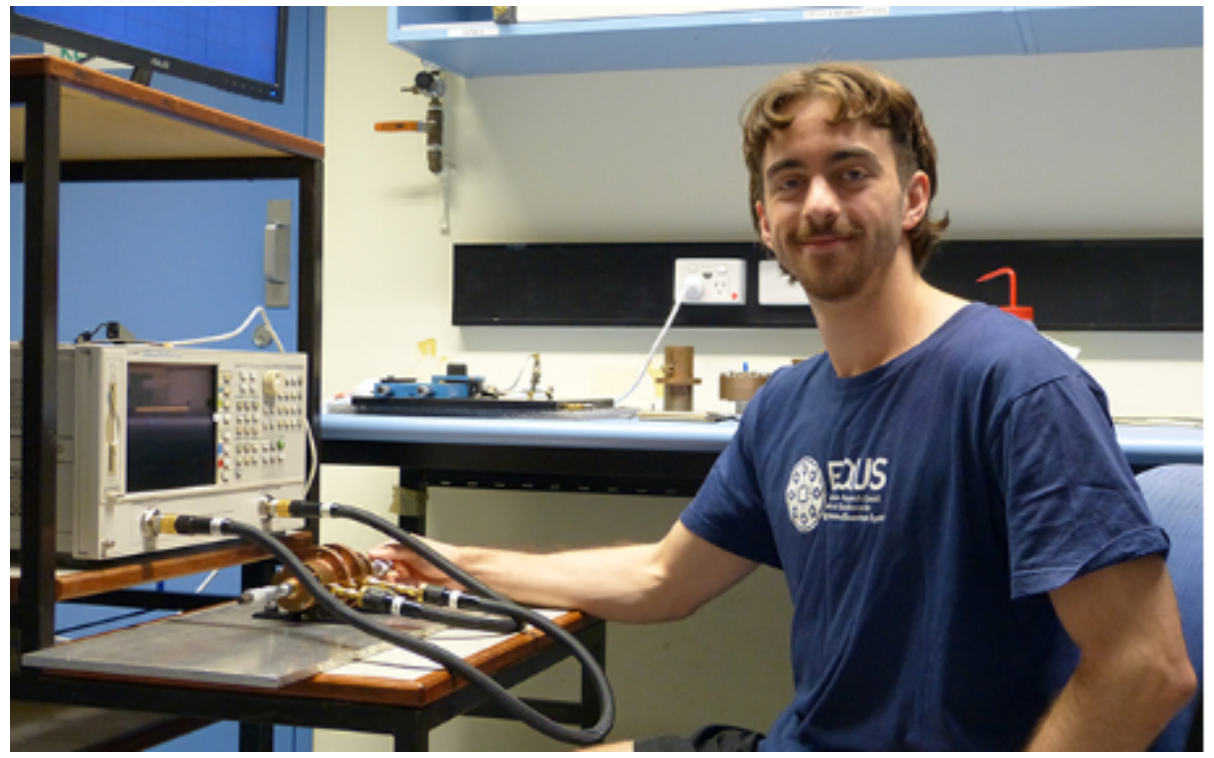


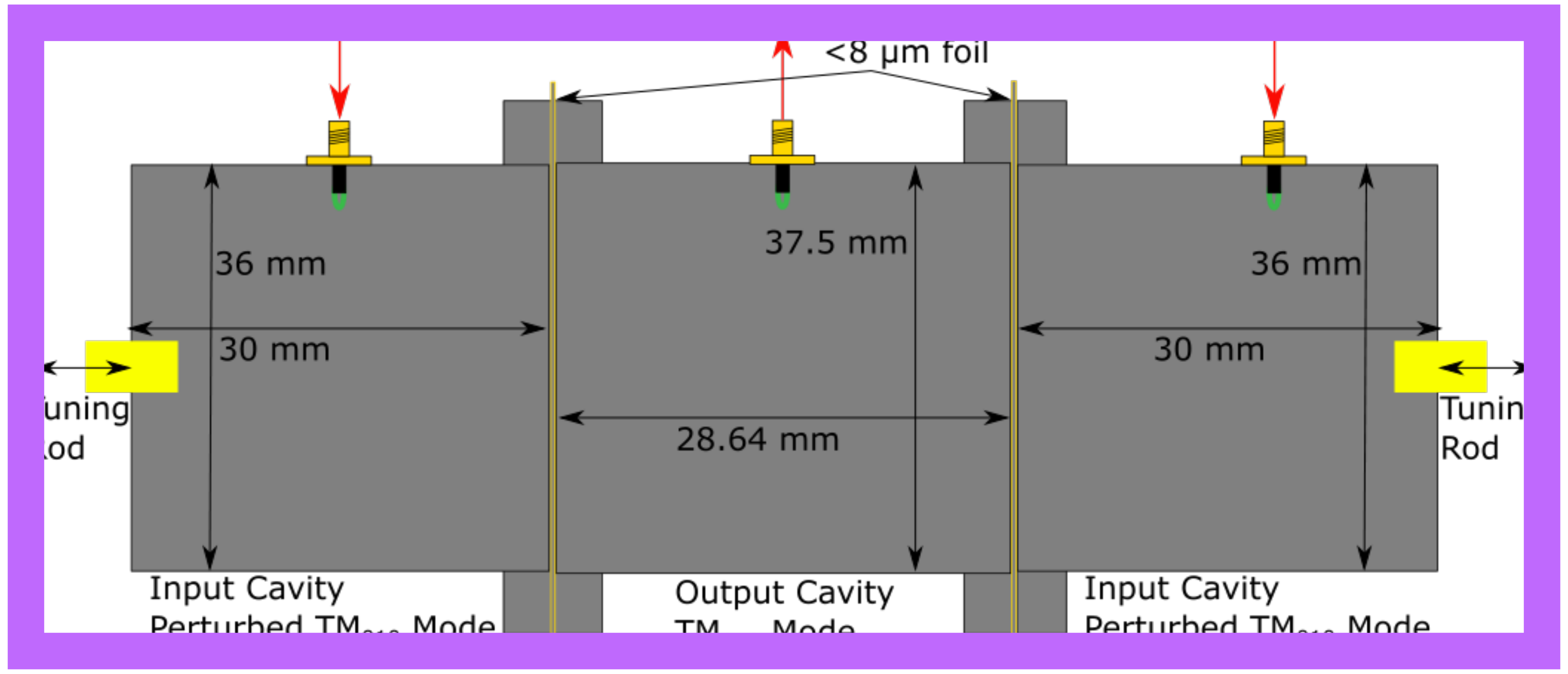
Possible Systems

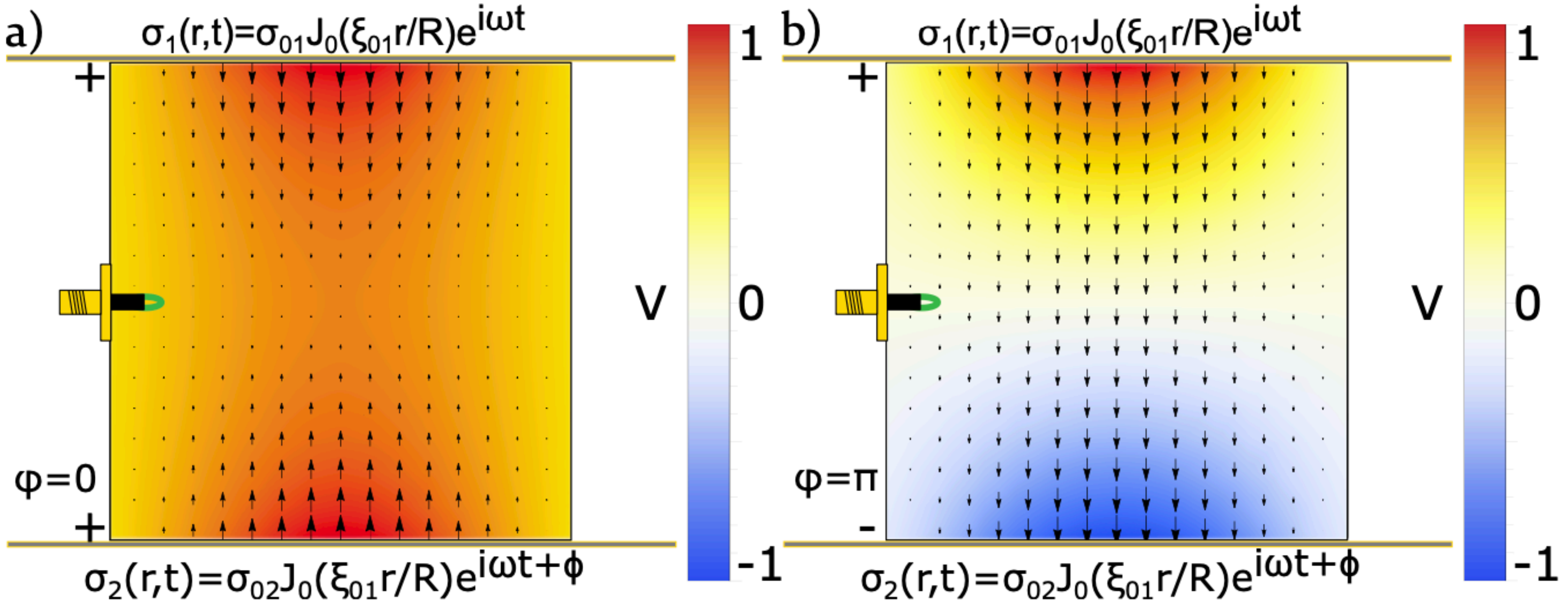
- **Atom valence electrons**
- **Ion**
- **Quantum Dot**
- **Charge/Transmon Qubit**

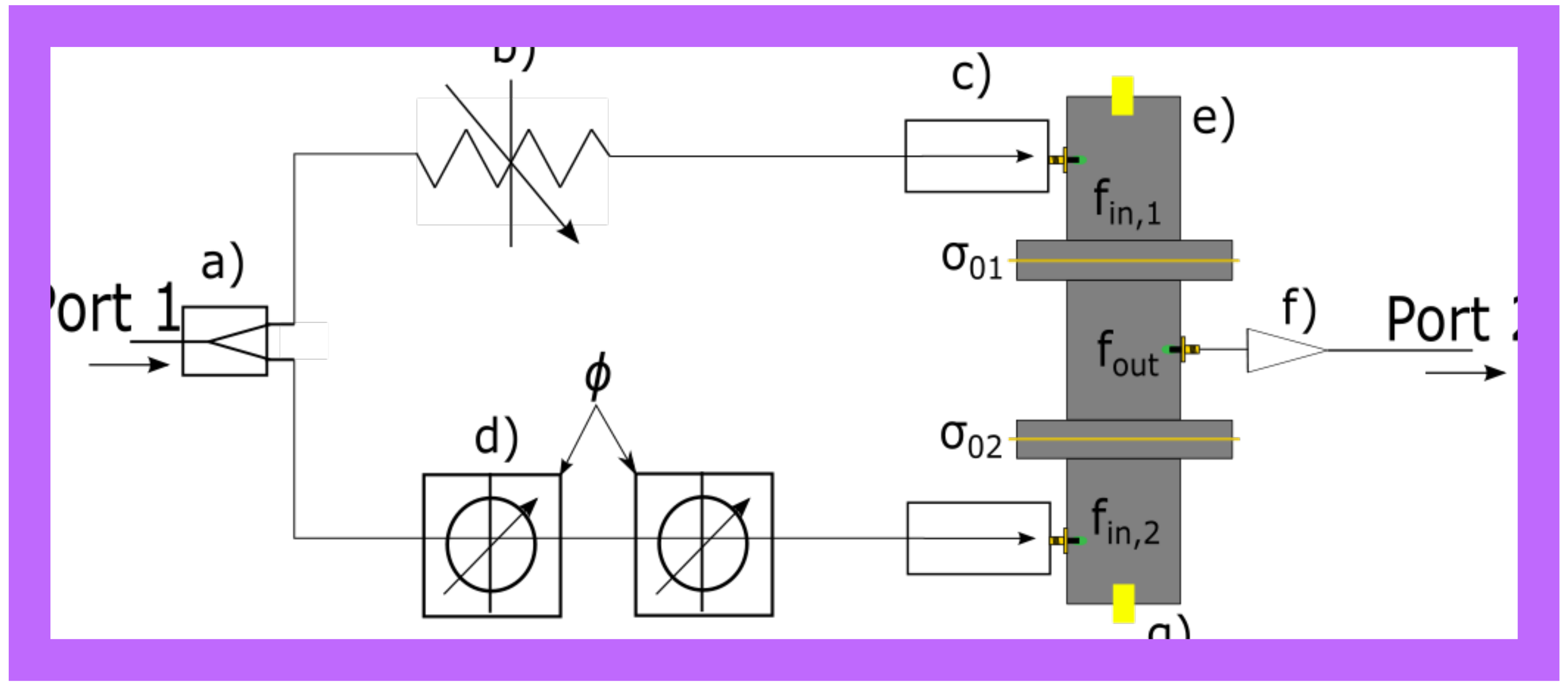
Microwave Cavity Resonator with Extreme Dispersion to Enable a Test of the Electric-Scalar Aharonov-Bohm Effect

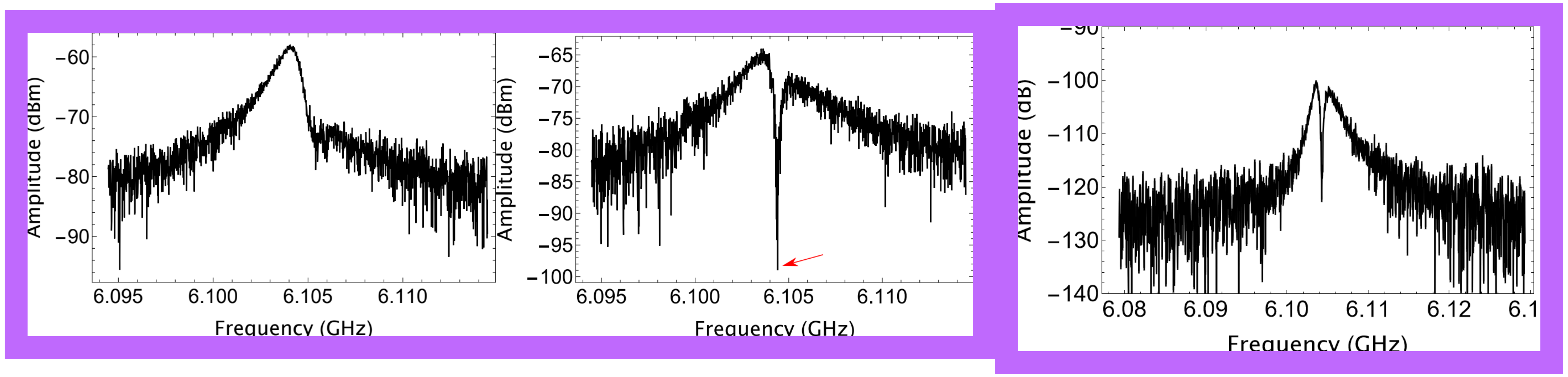
Exciting a Resonator with: $V(t) \neq 0,\ \overrightarrow{E} \sim 0$











Gravitational Scalar Aharonov-Bohm Effects: Matter Interferometer

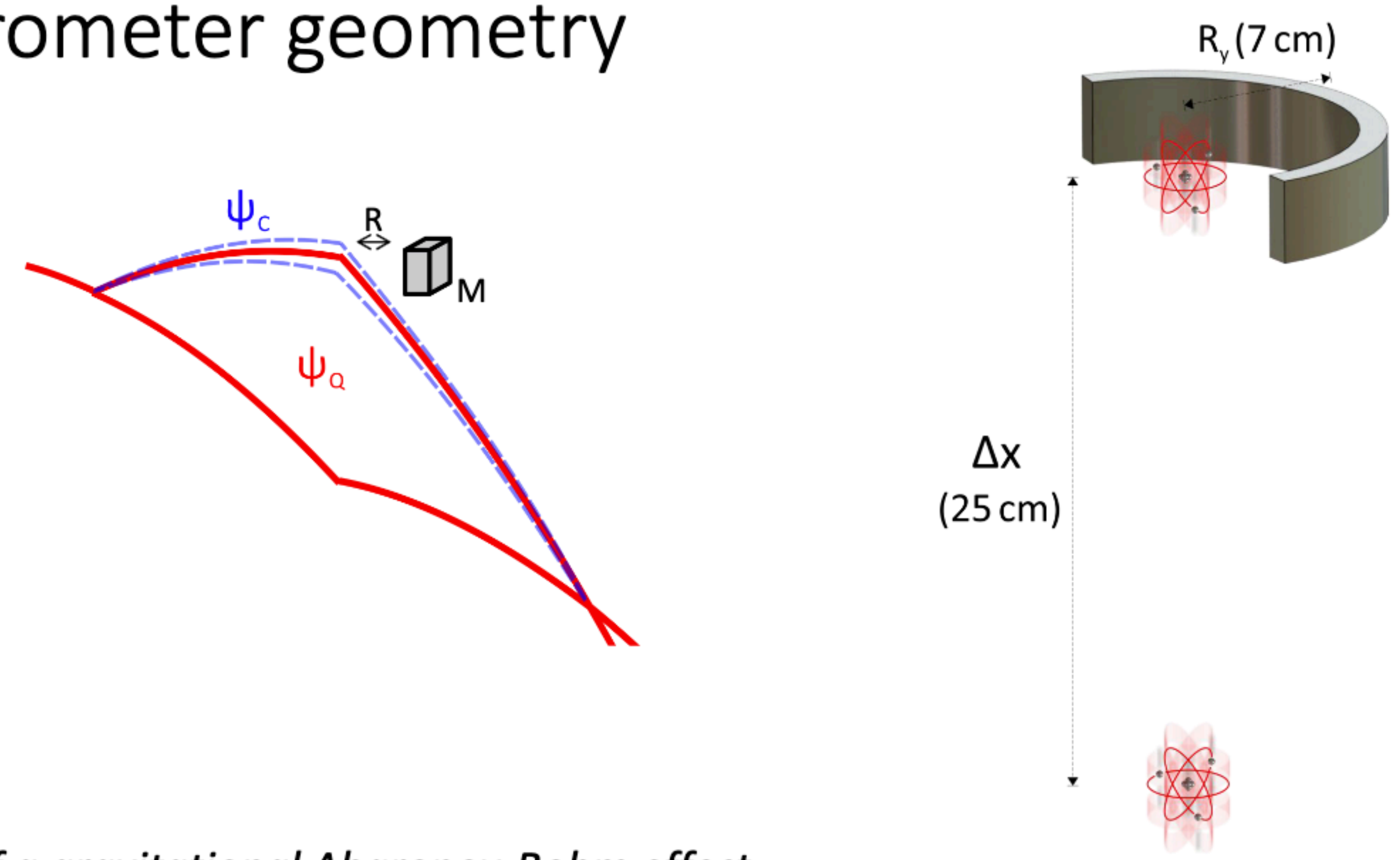
PHYSICS

Observation of a gravitational Aharonov-Bohm effect

Chris Overstreet[1]†, Peter Asenbaum[1,2]†, Joseph Curti[1], Minjeong Kim[1], Mark A. Kasevich[1]*

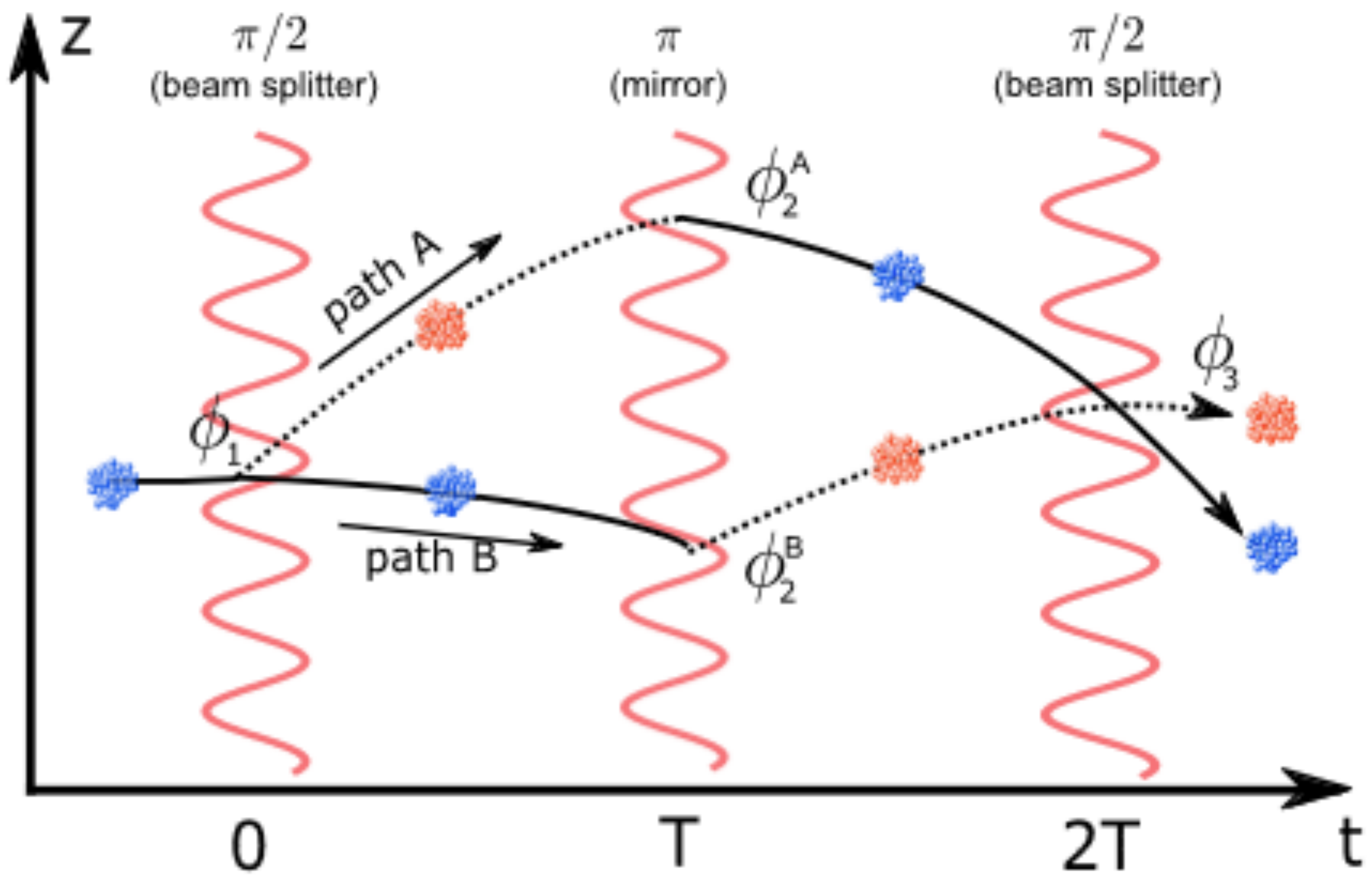
Gravity curves space and time. This can lead to proper time differences between freely falling, nonlocal trajectories. A spatial superposition of a massive particle is predicted to be sensitive to this effect. We measure the gravitational phase shift induced in a matter-wave interferometer by a kilogram-scale source mass close to one of the wave packets. Deflections of each interferometer arm due to the source mass are independently measured. The phase shift deviates from the deflection-induced phase contribution, as predicted by quantum mechanics. In addition, the observed scaling of the phase shift is consistent with Heisenberg's error-disturbance relation. These results show that gravity creates Aharonov-Bohm phase shifts analogous to those produced by electromagnetic interactions.

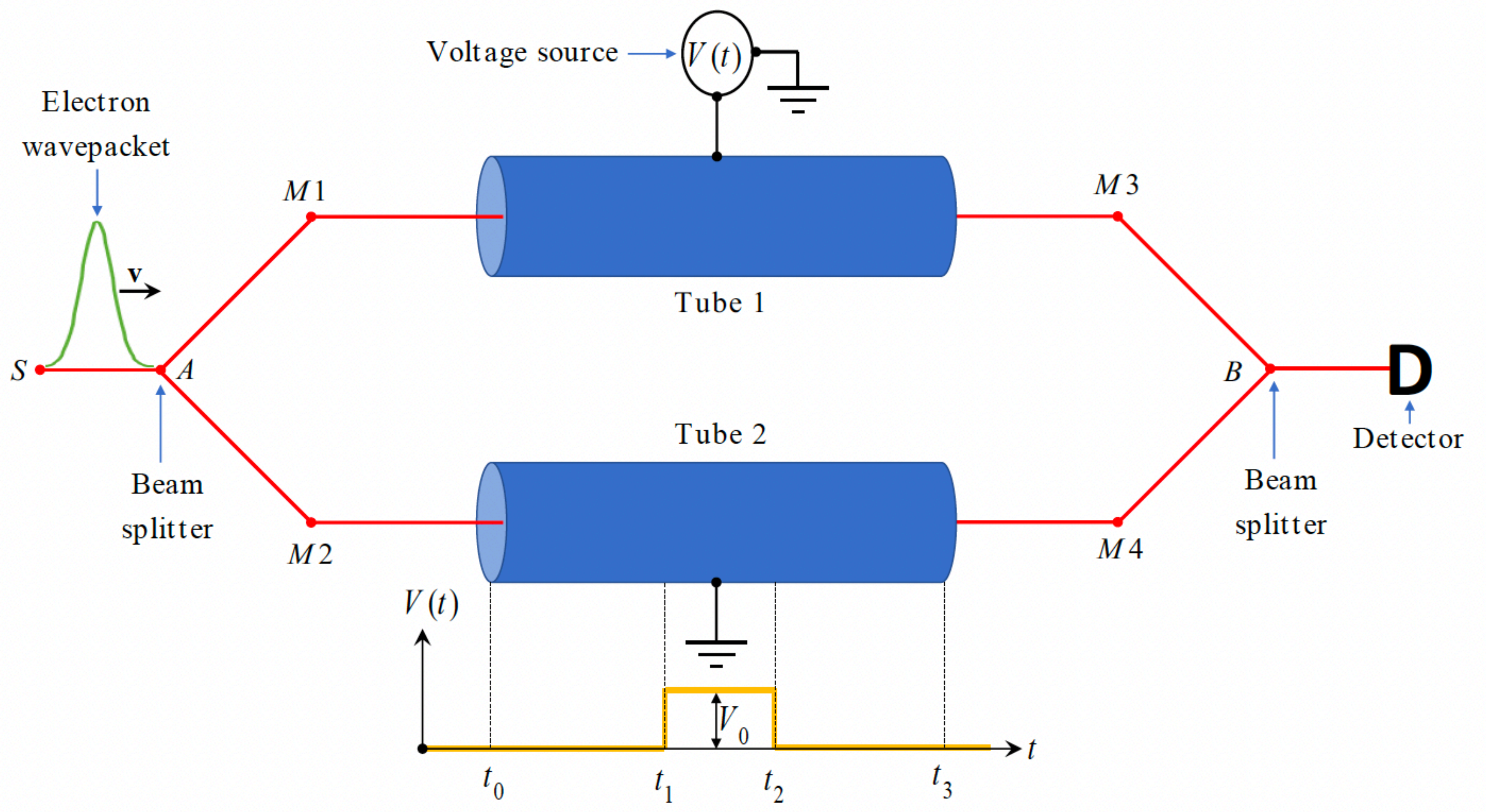
Interferometer geometry



Observation of a gravitational Aharonov-Bohm effect
Science **375**, 226 (2022)

Atom interferometers measure the difference in phase between atomic matter waves along different paths.





PHYSICAL REVIEW D **109**, 064073 (2024)

Gravitational Aharonov-Bohm effect

R. Y. Chiao,[1,*] N. A. Inan,[2,1,3,†] M. Scheibner,[1,‡] J. Sharping,[1,§] D. A. Singleton,[3,∥] and M. E. Tobar[4,¶]
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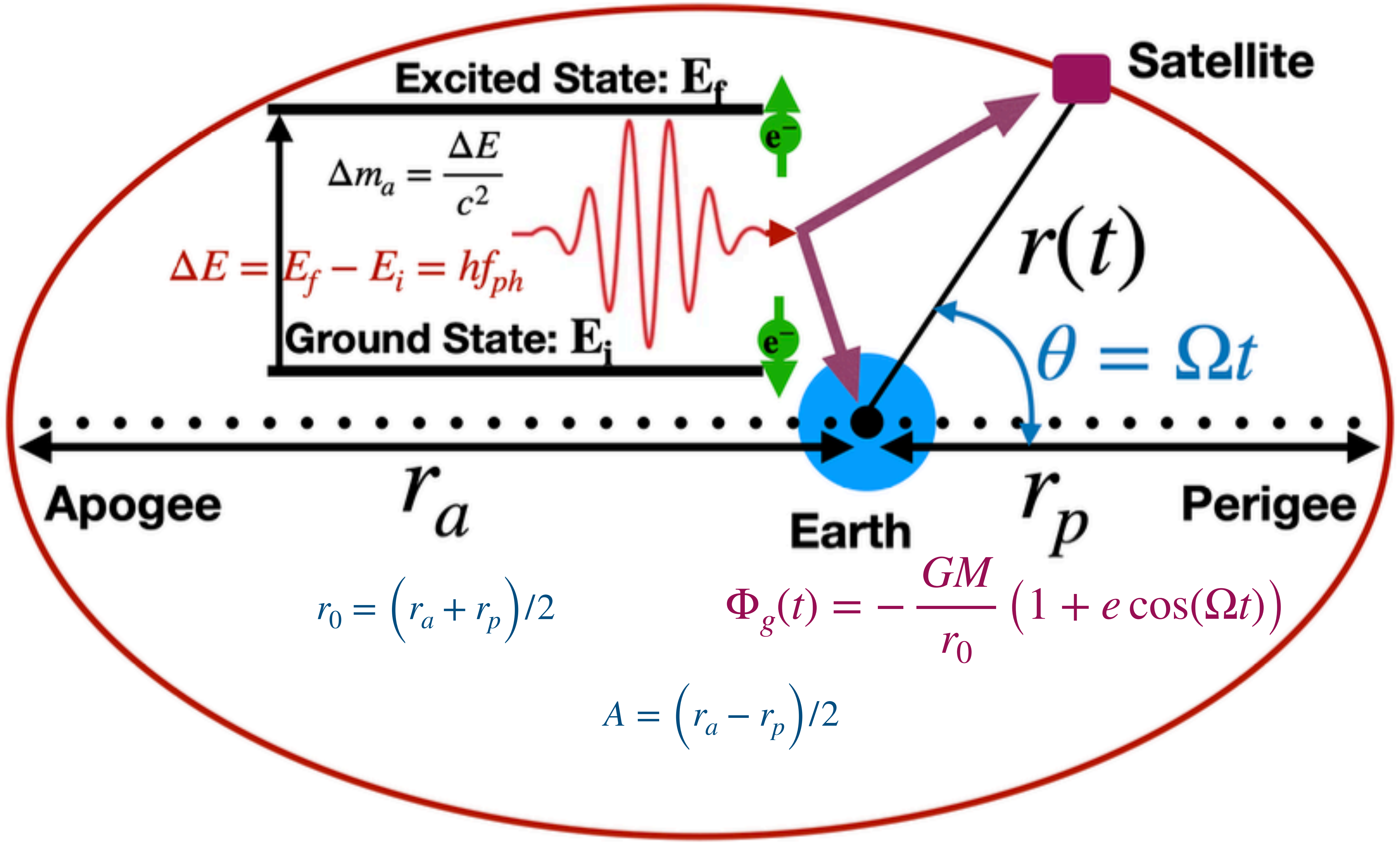
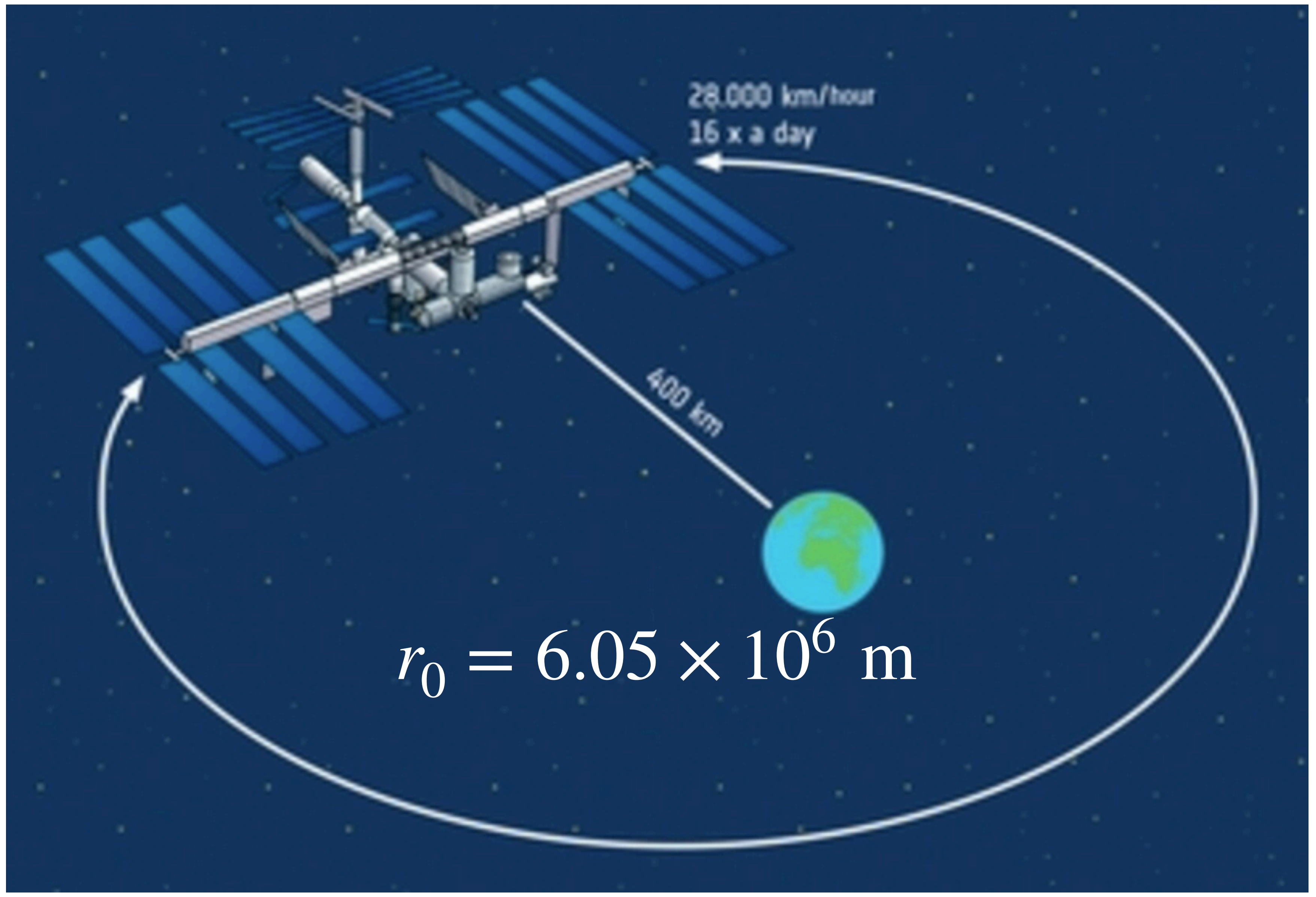
(Received 1 November 2023; accepted 4 March 2024; published 25 March 2024)

$$H = H_0 + m\Phi_g(t) \qquad i\hbar\frac{\partial\psi}{\partial t} = H\psi = \left(H_0 + m\Phi_g(t)\right)$$





Atomic Clock Ensemble in Space (ACES) Mission on the ISS

$$e_{ISS} = 7.34 \times 10^{-4} \qquad f_{ISS} = 1.85 \times 10^{-4}\ \text{Hz}$$

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

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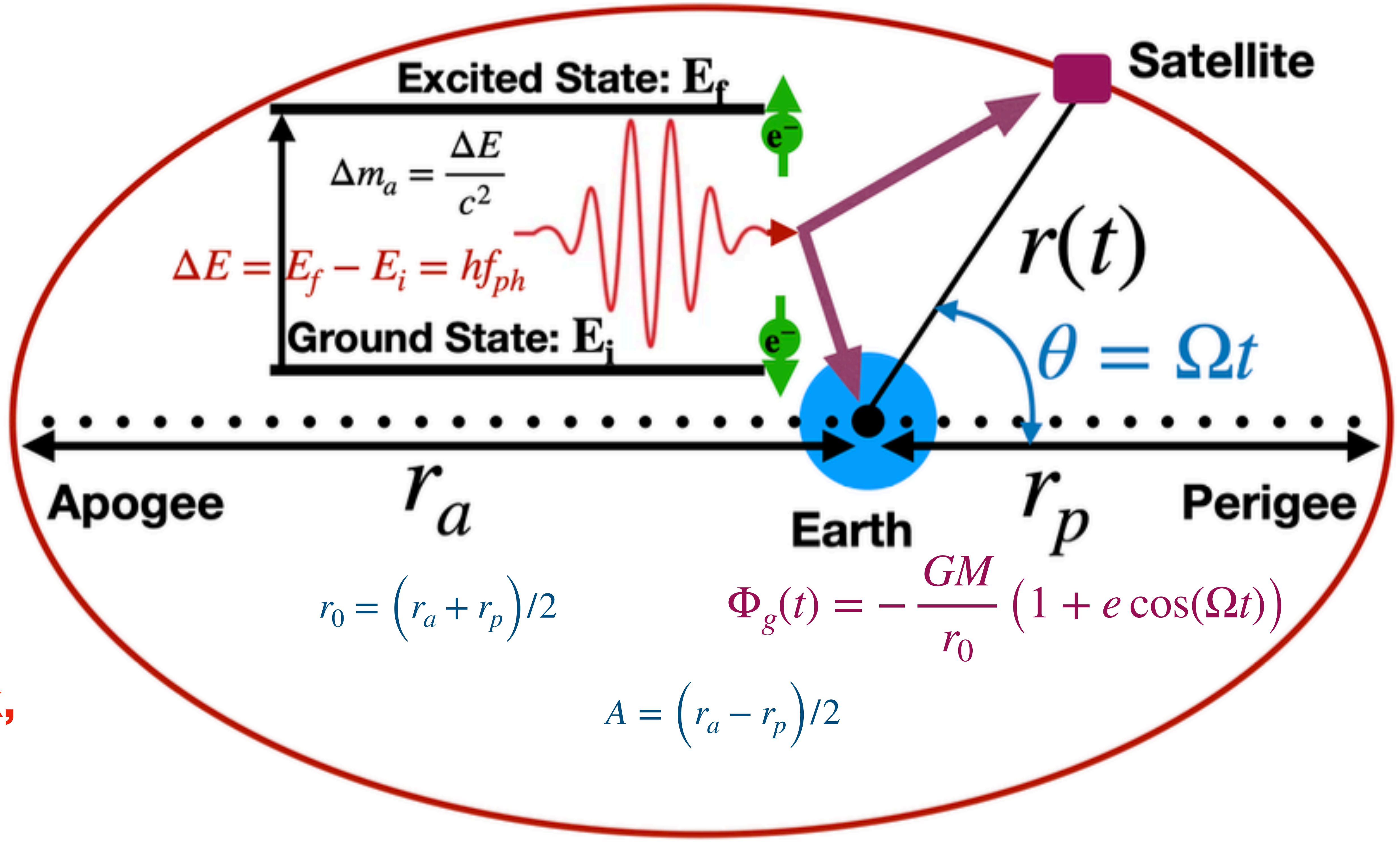


* Mass-energy equivalence principle
* Excited atom gains mass: Rabi Oscillations modulates mass
* Atomic clock in an eccentric orbit
* Time-varying gravitational potential
* Predict constant frequency redshift relative to a ground clock,
* Additional, modulation sidebands

$$\psi(t) = e^{i\left(-\frac{E_{i0}(t)}{\hbar} - \varphi_i(t)\right)}\left(c_i\left|\psi_i\right\rangle + e^{i\left(-\frac{\Delta E_0}{\hbar}t - \left(\varphi_g^*(t) - \varphi_g(t)\right)\right)}c_f\left|\psi_f\right\rangle\right)$$

$$\psi(t) = \left(c_i\left|\psi_i\right\rangle + e^{-i\left(\frac{\Delta E_0 t}{\hbar} + \Delta\varphi_g(t)\right)}c_f\left|\psi_f\right\rangle\right)$$

$$\Delta\varphi_g(t) = -\frac{\Delta E_0 GM}{\hbar r_0 c^2}\int_0^t \left(1 + e\cos(\Omega t')\right)dt' = \alpha\sin(\Omega t)\,.$$

$$\Psi_f(\mathbf{r}, t) = \Psi_f(\mathbf{r})\sum_{n=-\infty}^{\infty}(-1)^n J_n(\alpha)\exp\left(-\frac{i\left(\Delta E_0(1 + \frac{GM}{r_0c^2}) - n\hbar\Omega\right)t}{\hbar}\right)$$

Satellites GSAT-0201 and GSAT-0202 of the European GNSS

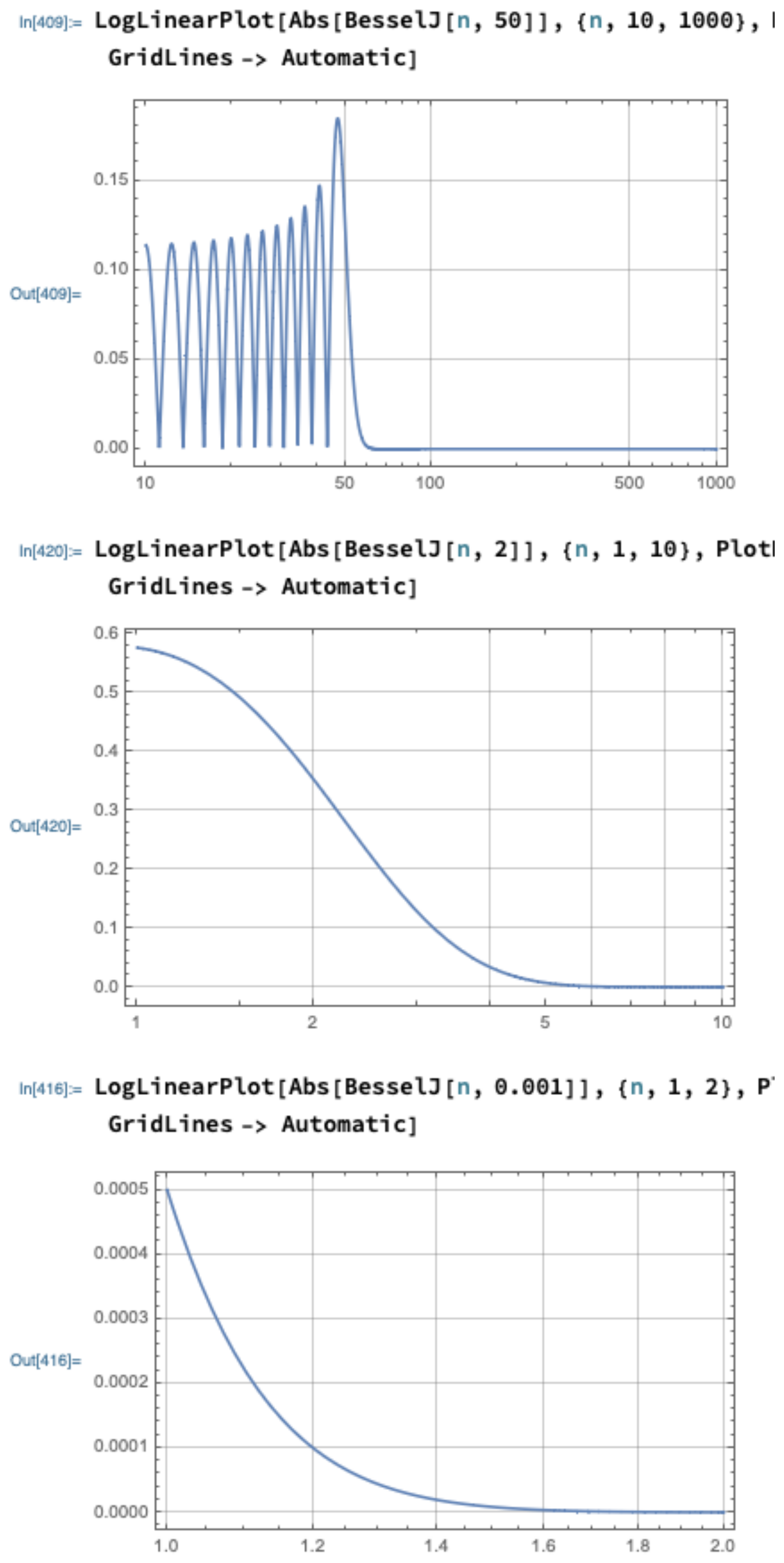
$e_G = 0.162 \quad f_G = 0.215\times10^{-4}\ \mathrm{Hz} \quad r_0 = 27.98\times10^6\ \mathrm{m}$

$$\alpha \equiv e\left(\frac{GM}{r_0c^2}\right)\left(\frac{\omega_{ph}}{\Omega}\right) \qquad \frac{\alpha_G}{\alpha_{ISS}} \sim 460$$

Jacobi–Anger expansion

In mathematics, the **Jacobi–Anger expansion** (or **Jacobi–Anger identity**) is an expansion of exponentials of trigonometric functions in the basis of their harmonics. It is useful in physics (for example, to convert between plane waves and cylindrical waves), and in signal processing (to describe FM signals). This identity is named after the 19th-century mathematicians Carl Jacobi and Carl Theodor Anger.

Modulation index	Sideband amplitude																
	Carrier	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0.00	1.00																
0.25	0.98	0.12															
0.5	0.94	0.24	0.03														
1.0	0.77	0.44	0.11	0.02													
1.5	0.51	0.56	0.23	0.06	0.01												
2.0	0.22	0.58	0.35	0.13	0.03												
2.40483	0.00	0.52	0.43	0.20	0.06	0.02											
2.5	−0.05	0.50	0.45	0.22	0.07	0.02	0.01										
3.0	−0.26	0.34	0.49	0.31	0.13	0.04	0.01										
4.0	−0.40	−0.07	0.36	0.43	0.28	0.13	0.05	0.02									
5.0	−0.18	−0.33	0.05	0.36	0.39	0.26	0.13	0.05	0.02								
5.52008	0.00	−0.34	−0.13	0.25	0.40	0.32	0.19	0.09	0.03	0.01							
6.0	0.15	−0.28	−0.24	0.11	0.36	0.36	0.25	0.13	0.06	0.02							
7.0	0.30	0.00	−0.30	−0.17	0.16	0.35	0.34	0.23	0.13	0.06	0.02						
8.0	0.17	0.23	−0.11	−0.29	−0.10	0.19	0.34	0.32	0.22	0.13	0.06	0.03					
8.65373	0.00	0.27	0.06	−0.24	−0.23	0.03	0.26	0.34	0.28	0.18	0.10	0.05	0.02				
9.0	−0.09	0.25	0.14	−0.18	−0.27	−0.06	0.20	0.33	0.31	0.21	0.12	0.06	0.03	0.01			
10.0	−0.25	0.04	0.25	0.06	−0.22	−0.23	−0.01	0.22	0.32	0.29	0.21	0.12	0.06	0.03	0.01		
12.0	0.05	−0.22	−0.08	0.20	0.18	−0.07	−0.24	−0.17	0.05	0.23	0.30	0.27	0.20	0.12	0.07	0.03	0.01



Comparison with Experiment

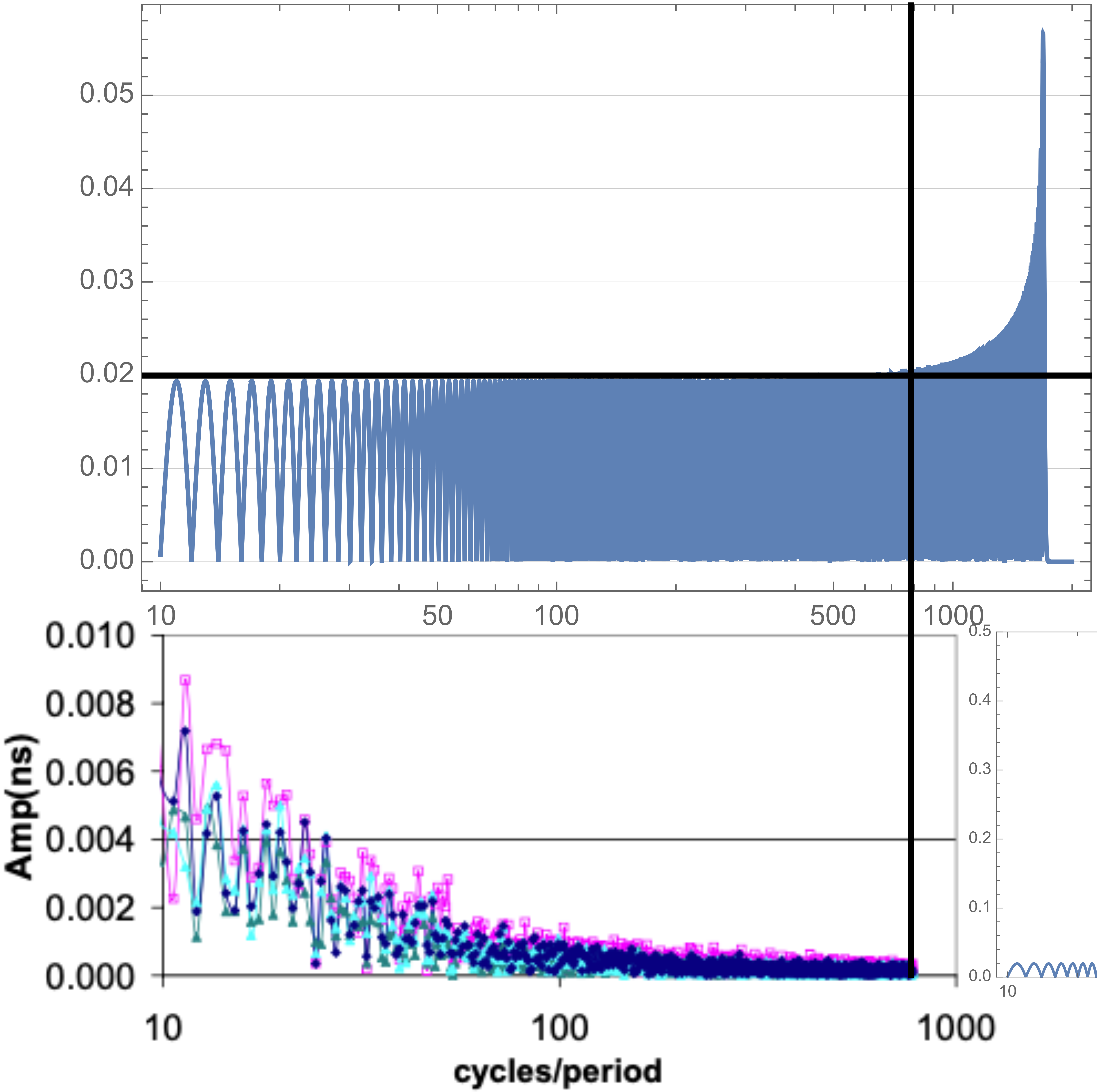
GPS Solutions (2021) 25:139
https://doi.org/10.1007/s10291-021-01174-3

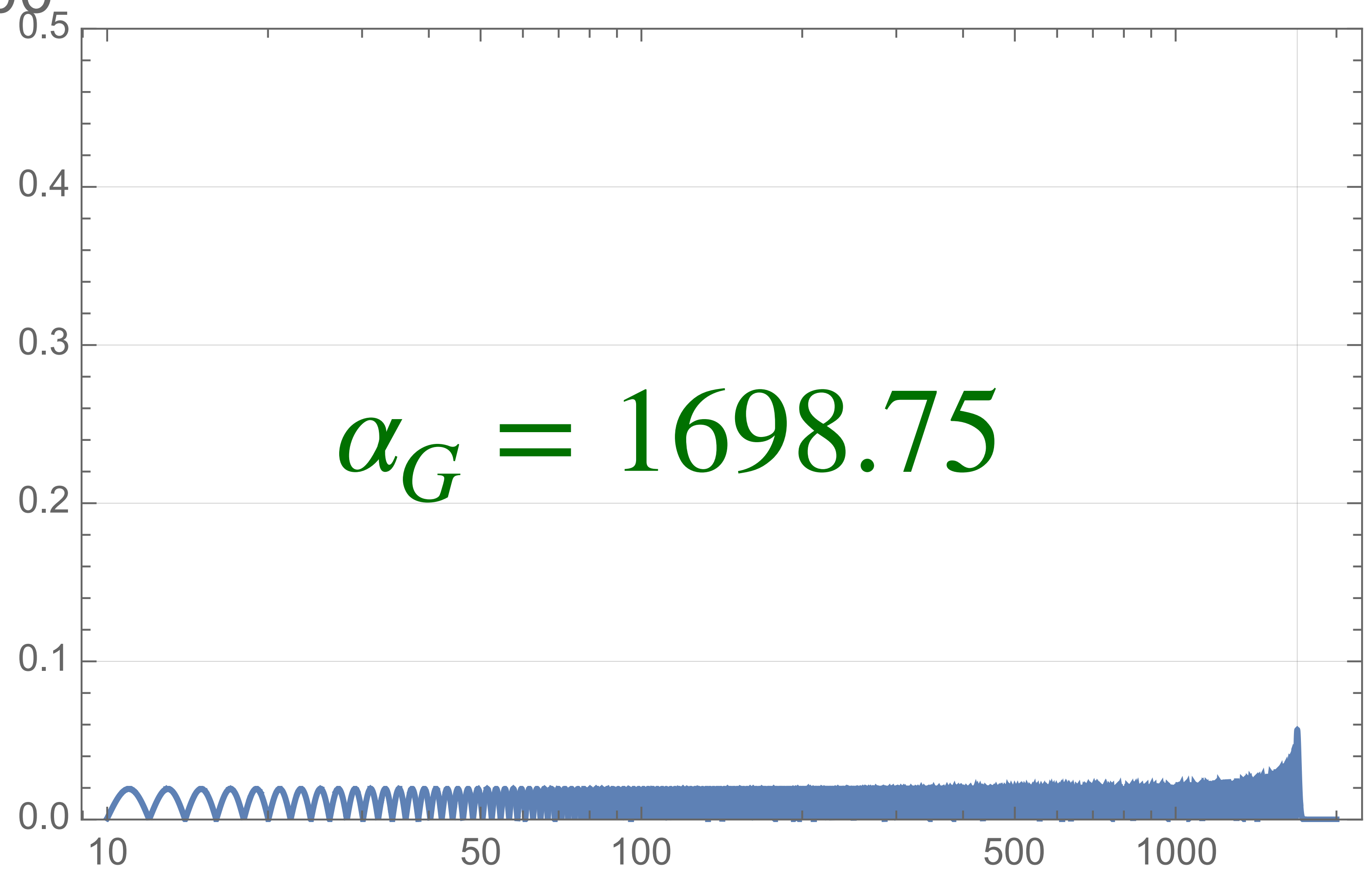
ORIGINAL ARTICLE

Testing of general relativity with two Galileo satellites in eccentric orbits

J. Kouba[1]

$$\alpha \equiv e \left(\frac{GM}{r_0 c^2}\right)\left(\frac{\omega_{ph}}{\Omega}\right)$$





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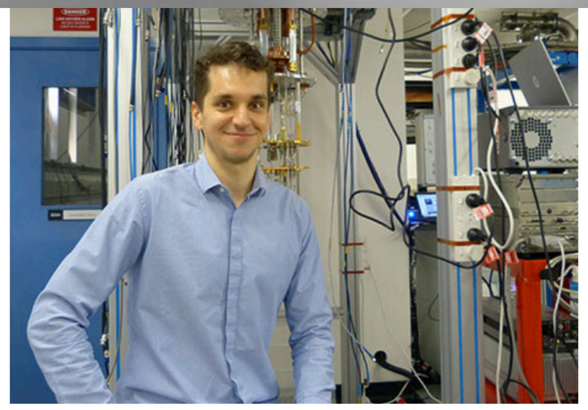

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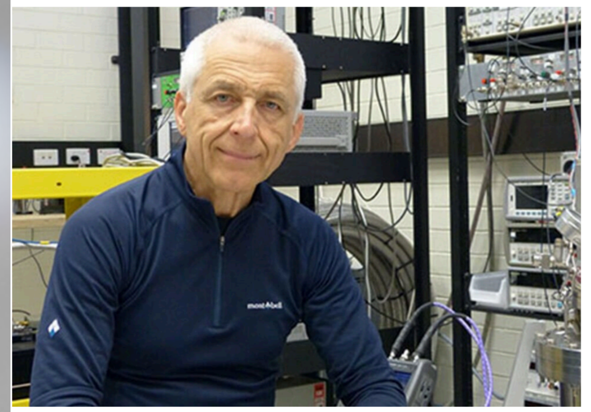

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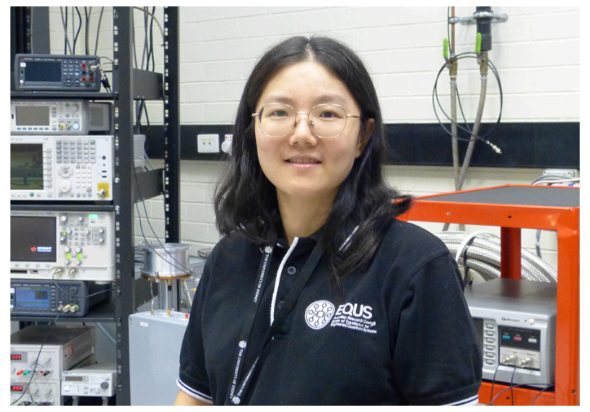

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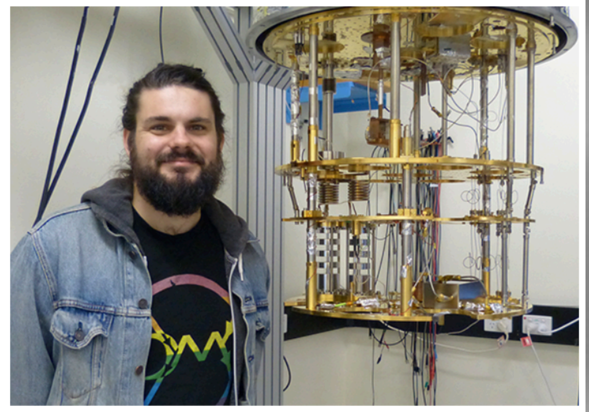

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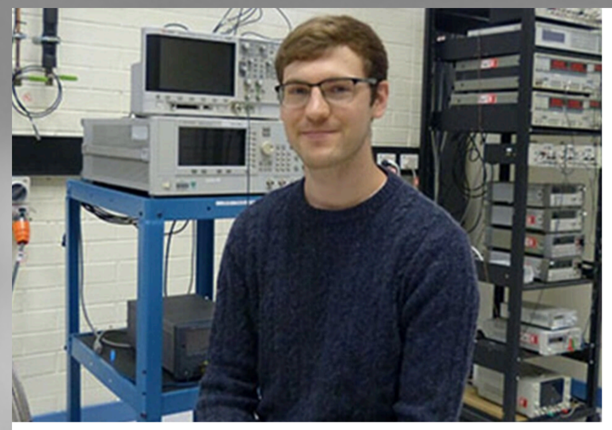

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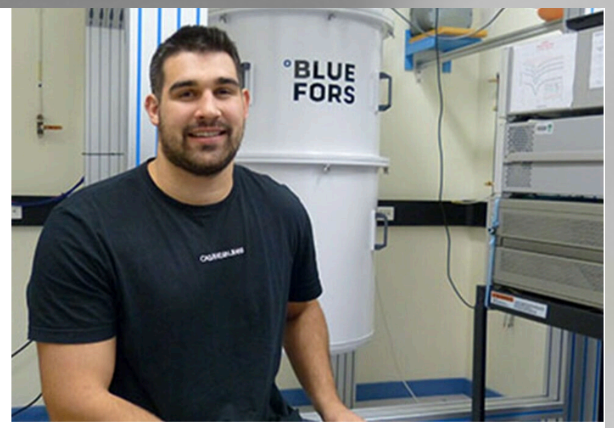

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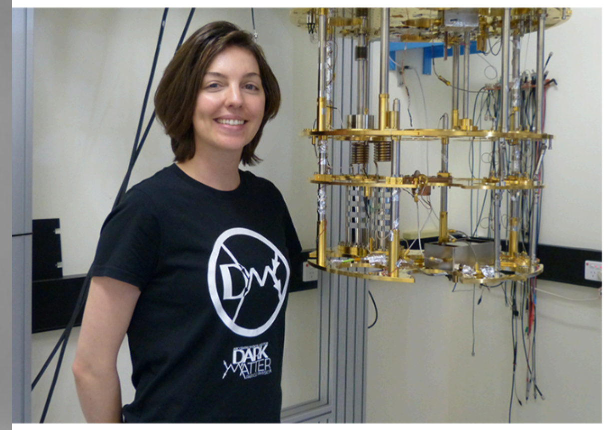
PhD



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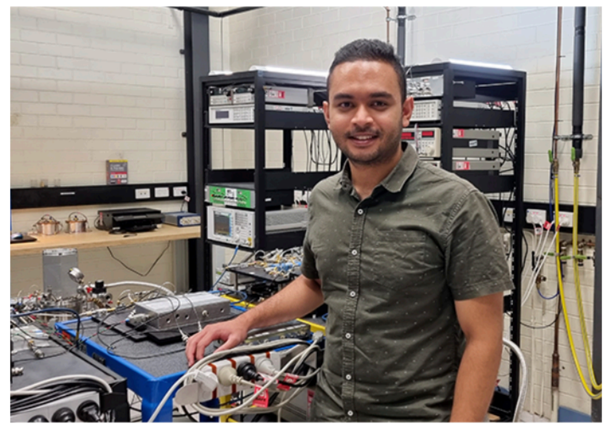

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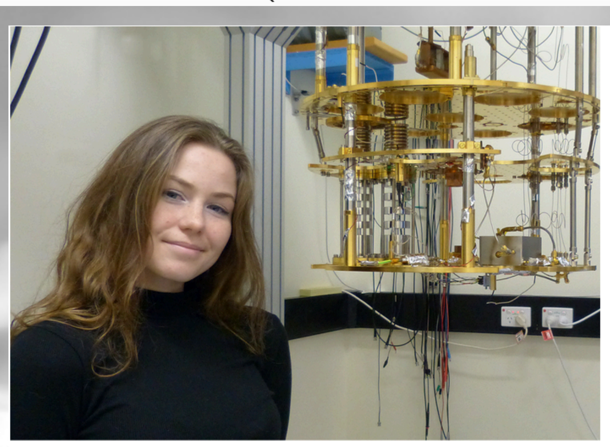

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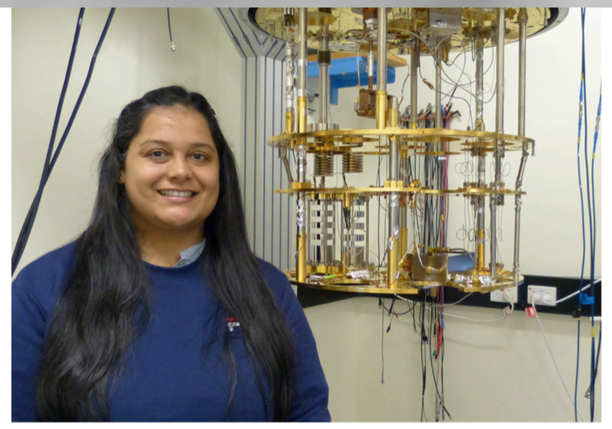

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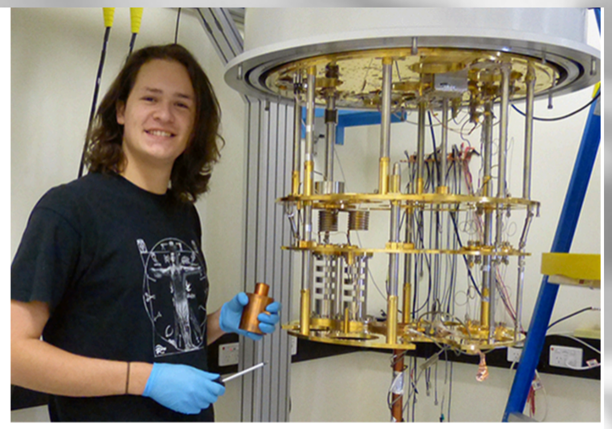
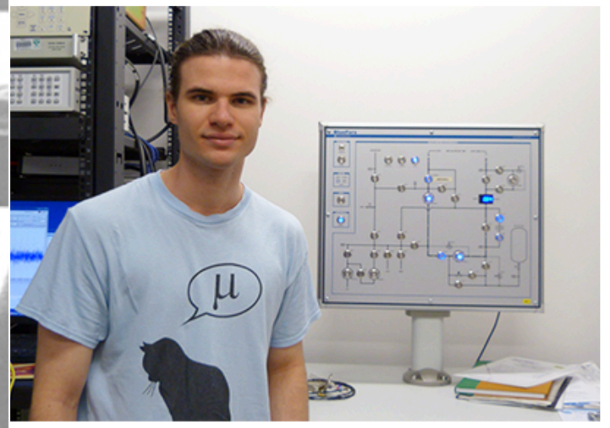
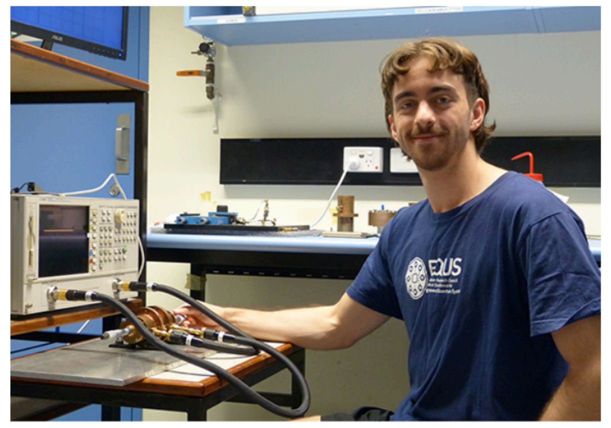


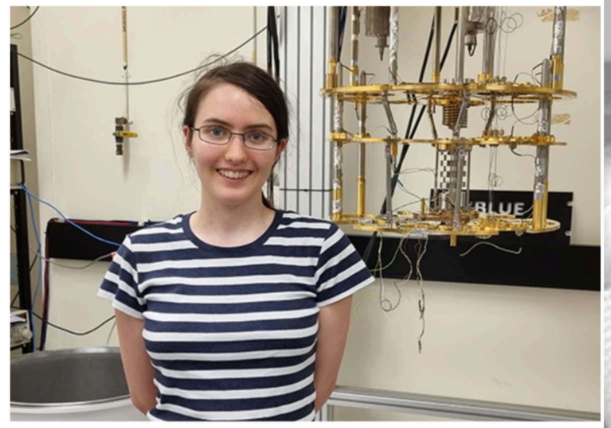
Tim Holt
BSc (Frontier Physics) and Master of Physics



Ashley Johnson
BSc (Frontier Physics) and Master of Physics



Michael Hatzon
BPhil (Hons) Honours Dissertation



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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

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