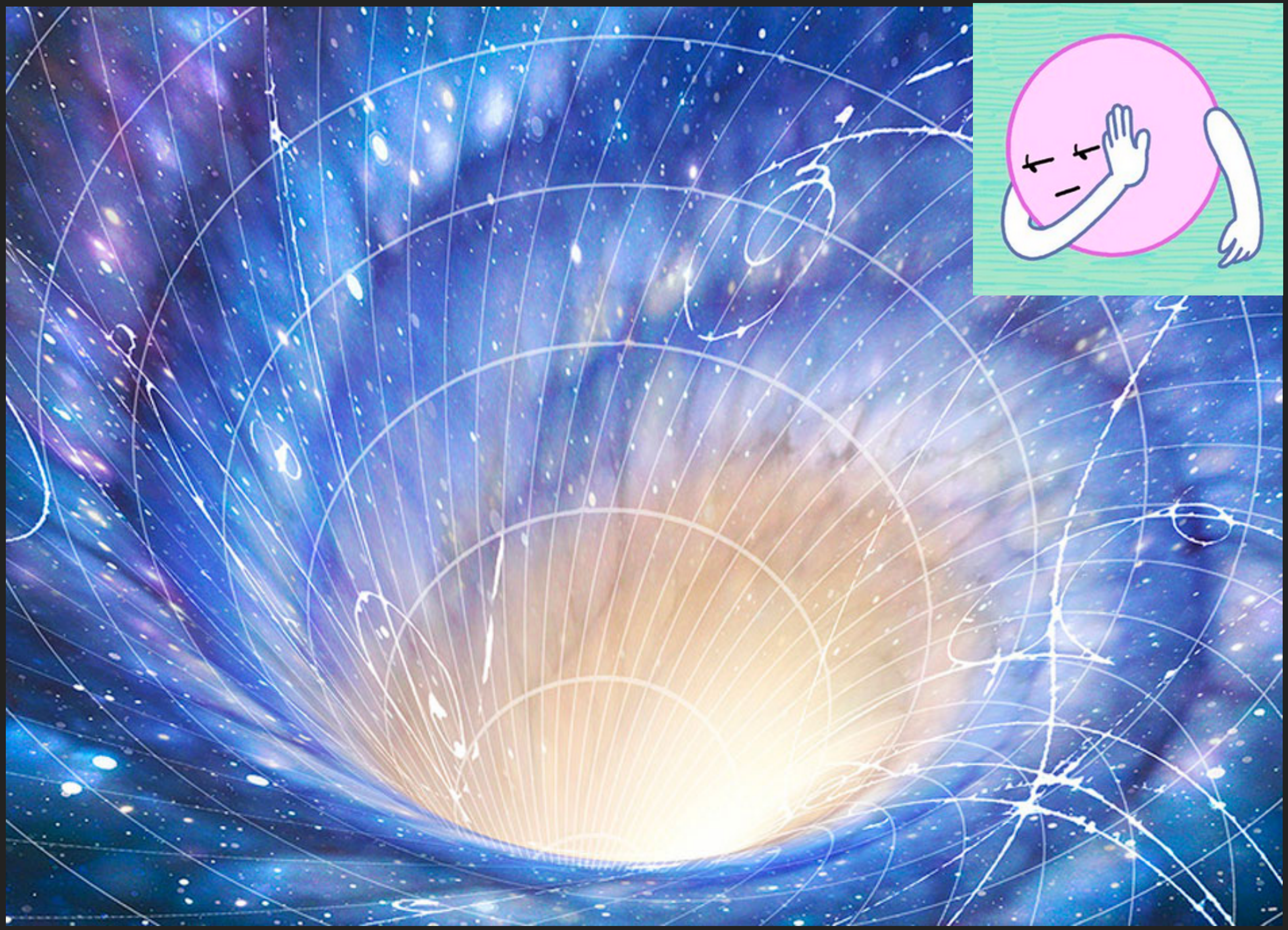
Searching for dark matter using precision oscillators

Prof. Michael Tobar

THE UNIVERSITY OF WESTERN AUSTRALIA

QDM Quantum Technologies and Dark Matter Research Lab

PATRAS 2021



ARC CENTRE OF EXCELLENCE FOR DARK MATTER

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

Searching for dark matter using precision oscillators

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

Quantum Technologies and Dark Matter Research Lab

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Australian Research Council
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Engineered Quantum Systems

The University of Western Australia

QDM
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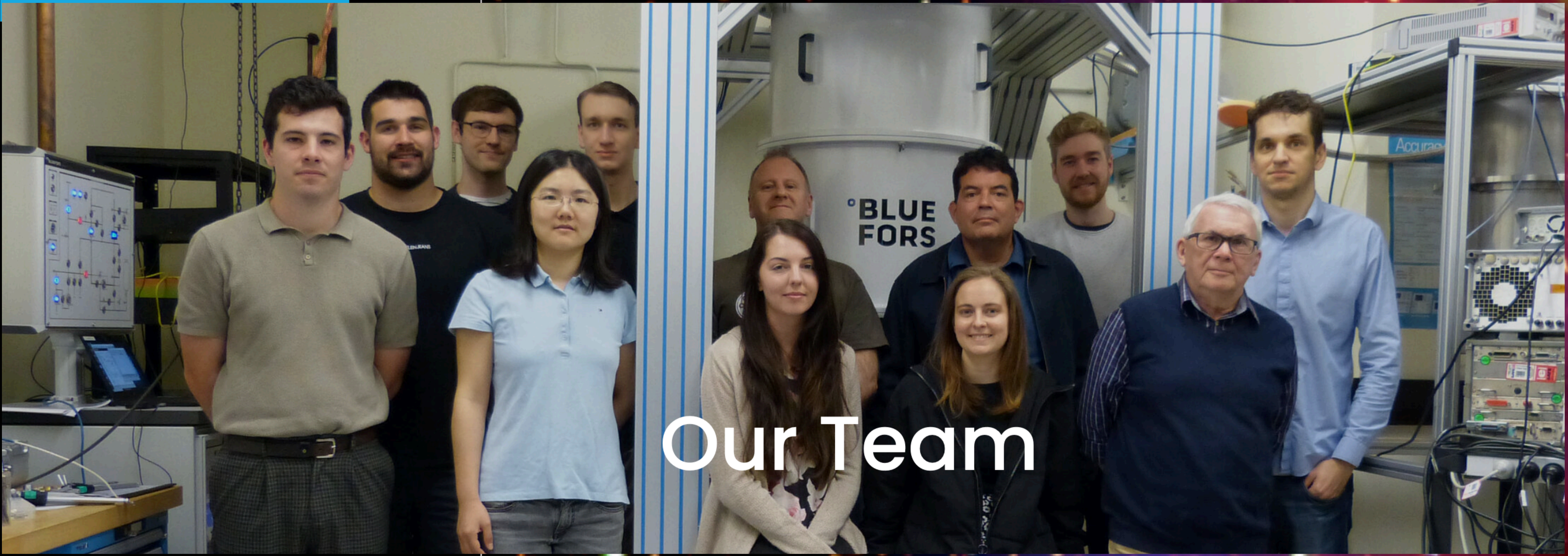
ARC Centre of Excellence for Dark Matter



HDR/PHD STUDENTS
Graeme Flower
Catriona Thomson
William Campbell
Aaron Quiskamp
Elrina Hartman

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Jay Mummery (Masters)
Robert Crew (BPhil)
Daniel Tobar (BPhil)
Michael Hatzon (BPhil)

ACADEMIC
Michael Tobar
Eugene Ivanov
Maxim Goryachev

POSTDOCS
Ben McAllister
Cindy Zhao
Jeremy Bourhill

TECHNICIAN
Steven Osborne

ADJUNCT
Alexey Veryaskin (Trinity Labs)

Physics: An experimental science

White, Harvey Elliott

Note: This is not the actual book cover

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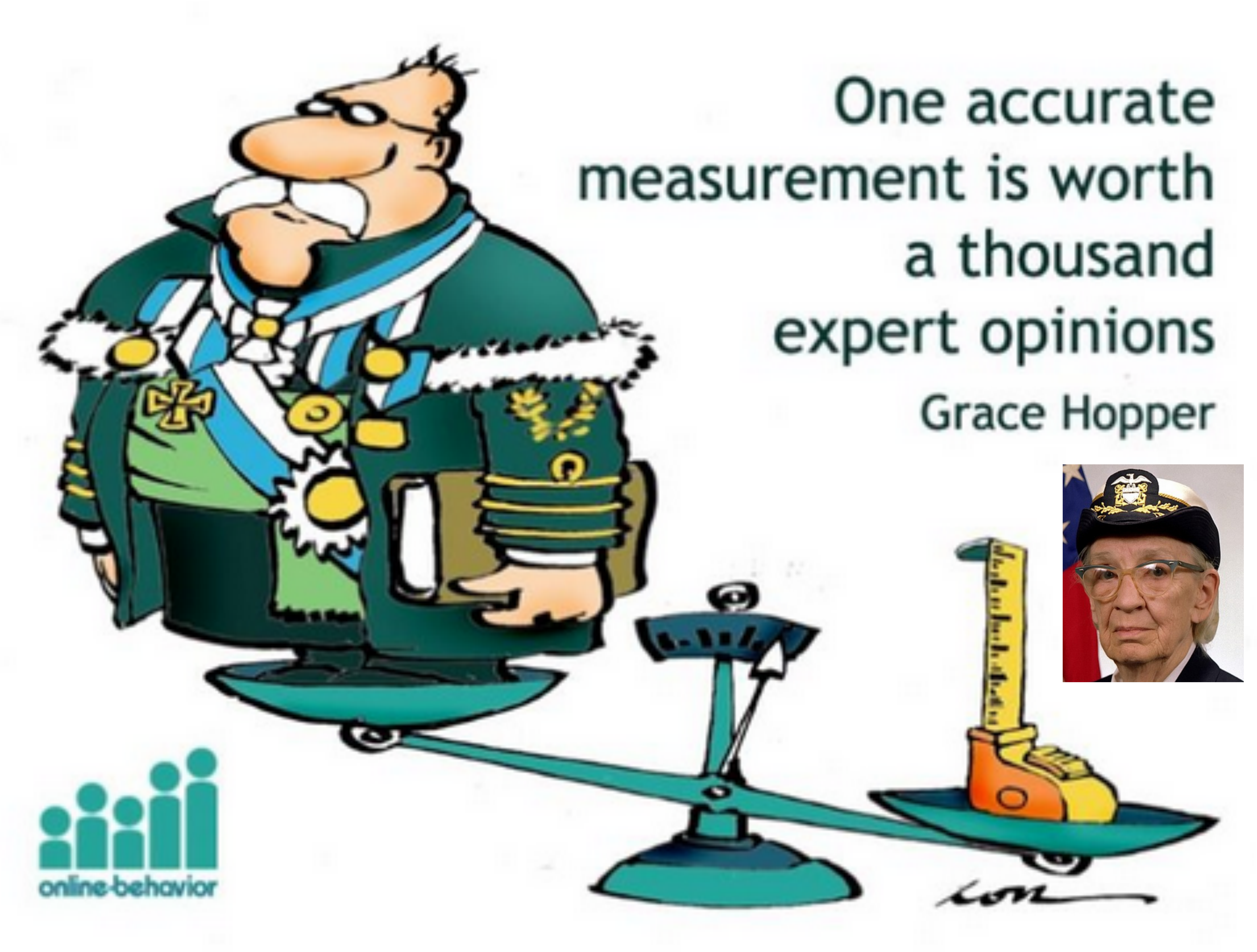

Physics: An experimental science

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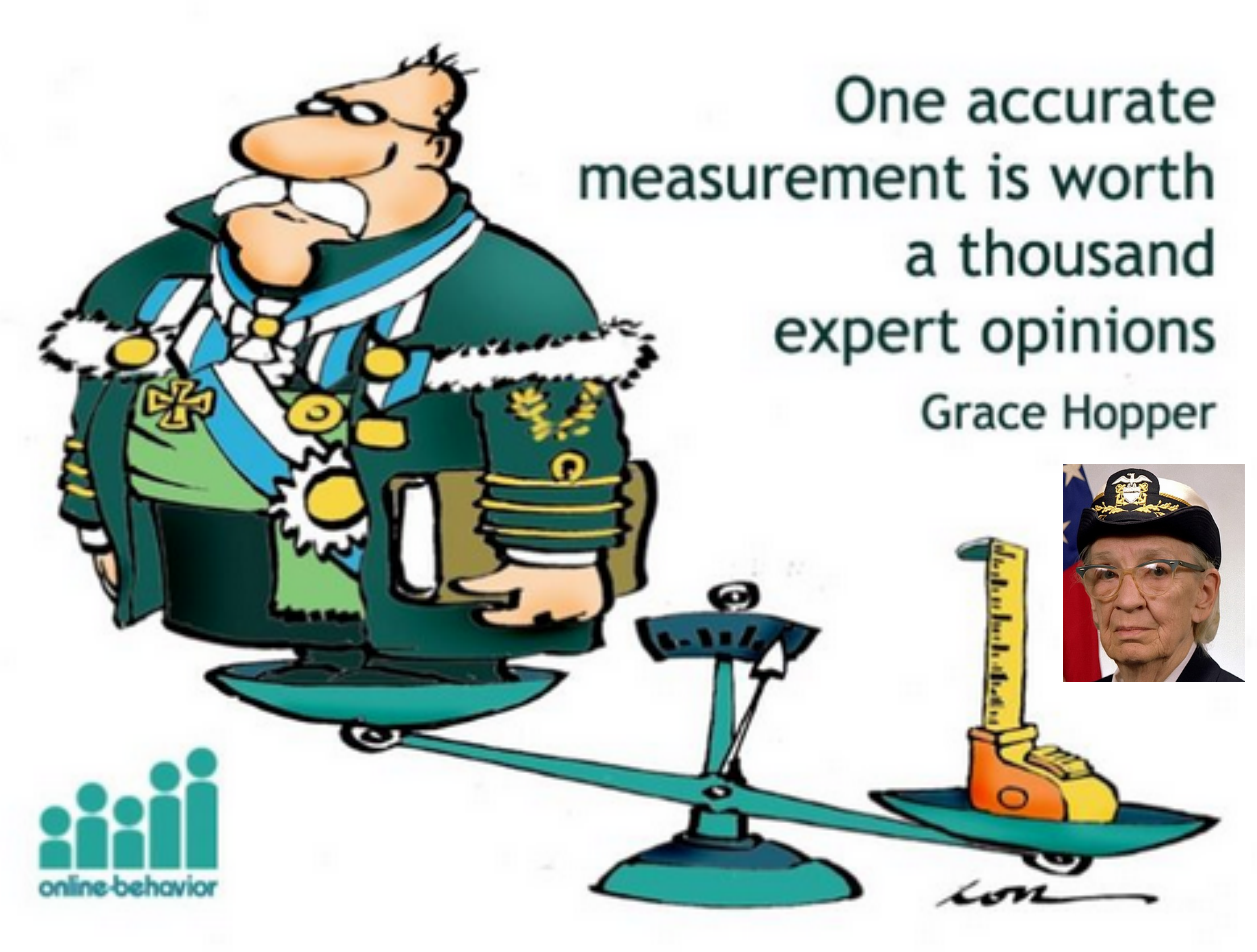
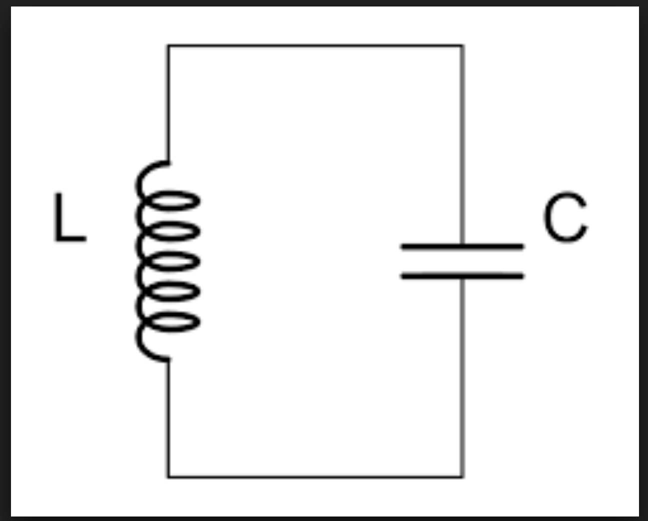
Computer Scientist
Invented COBOL

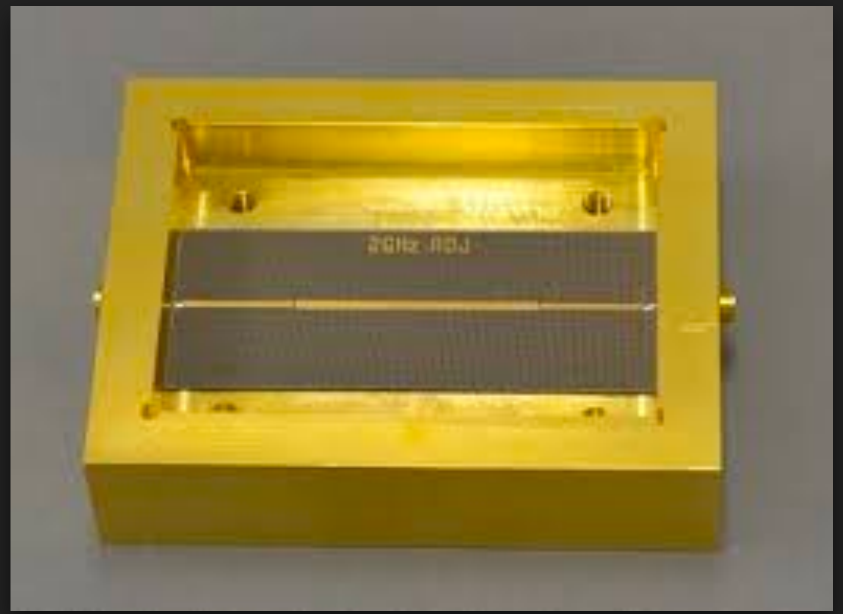


Frequency Metrology

PHOTONS



LC-circuits



Metallic Cavities

Dielectric Cavities

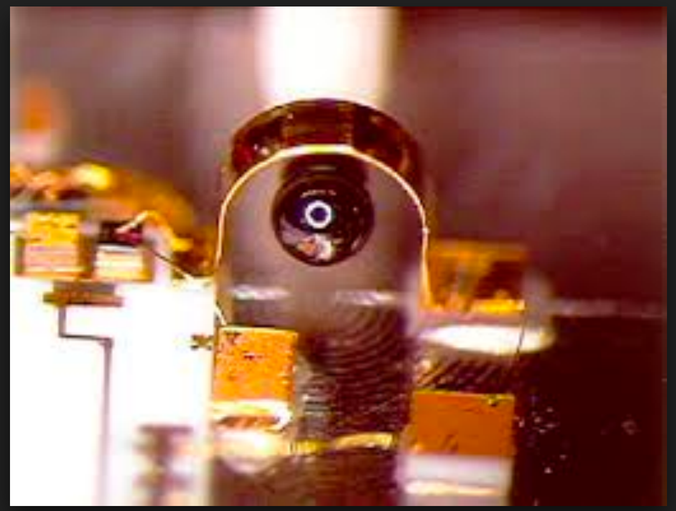
PHONONS

SAW

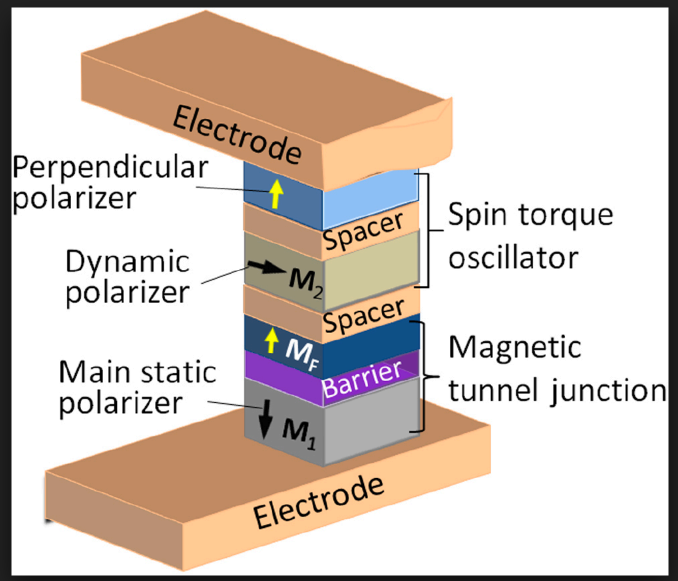
BAW

Structures

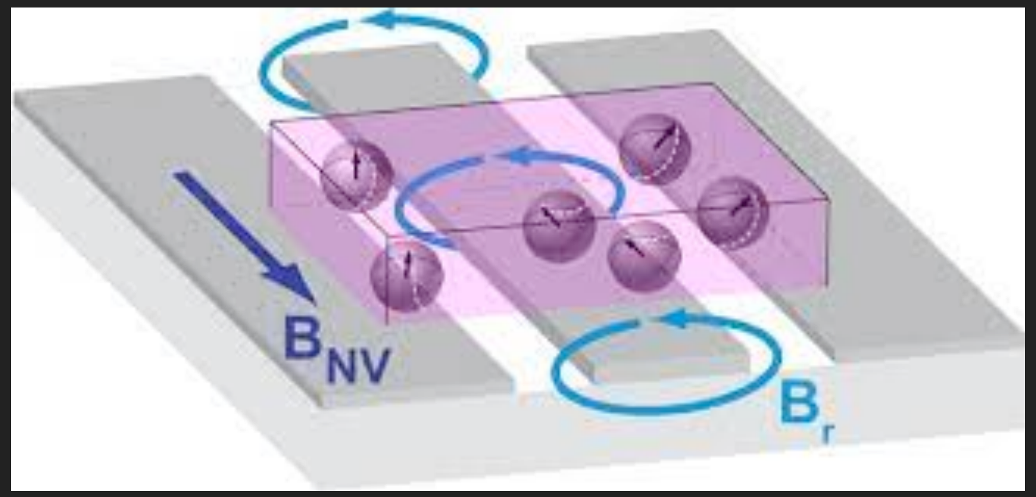
MAGNONS/SPINS



Bulk

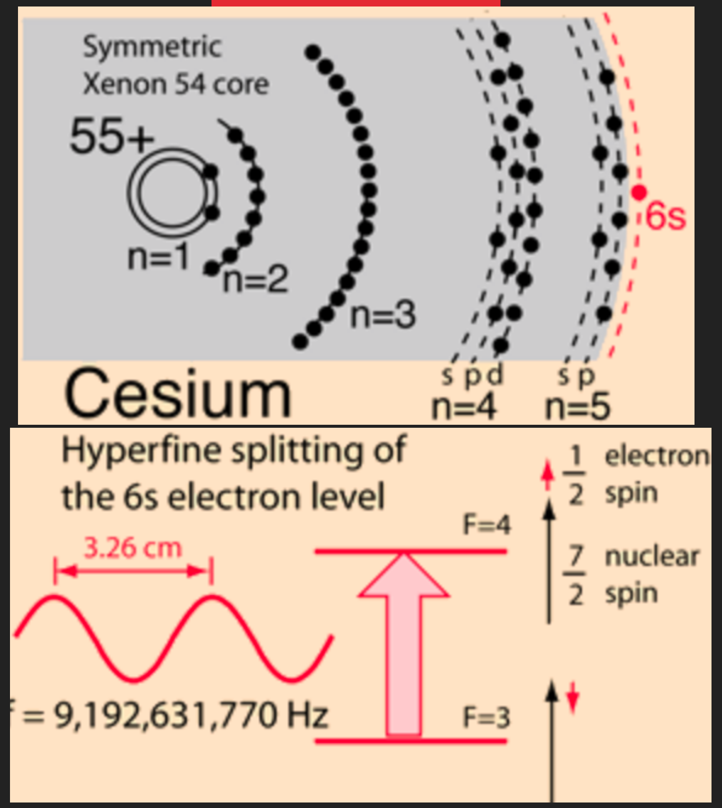


Spin-Torque

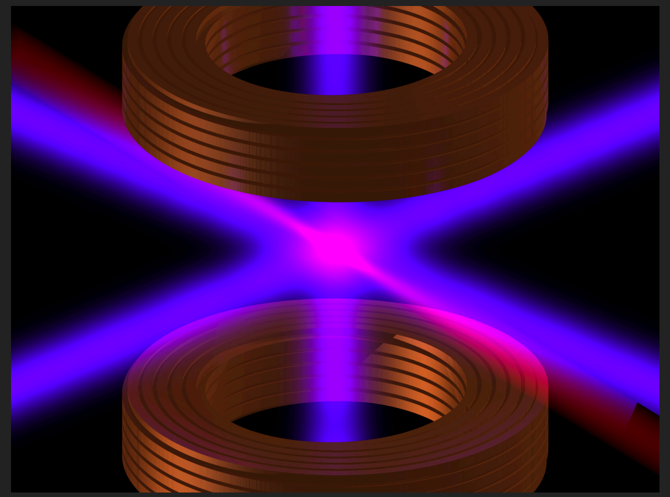


Spin Ensembles

ATOMS



Hyperfine transitions



Electron transitions

Nuclear transitions

WIDE RANGE OF PHYICAL PHENOMENA

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Sapphire Low Noise Oscillators under Development at UWA

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*

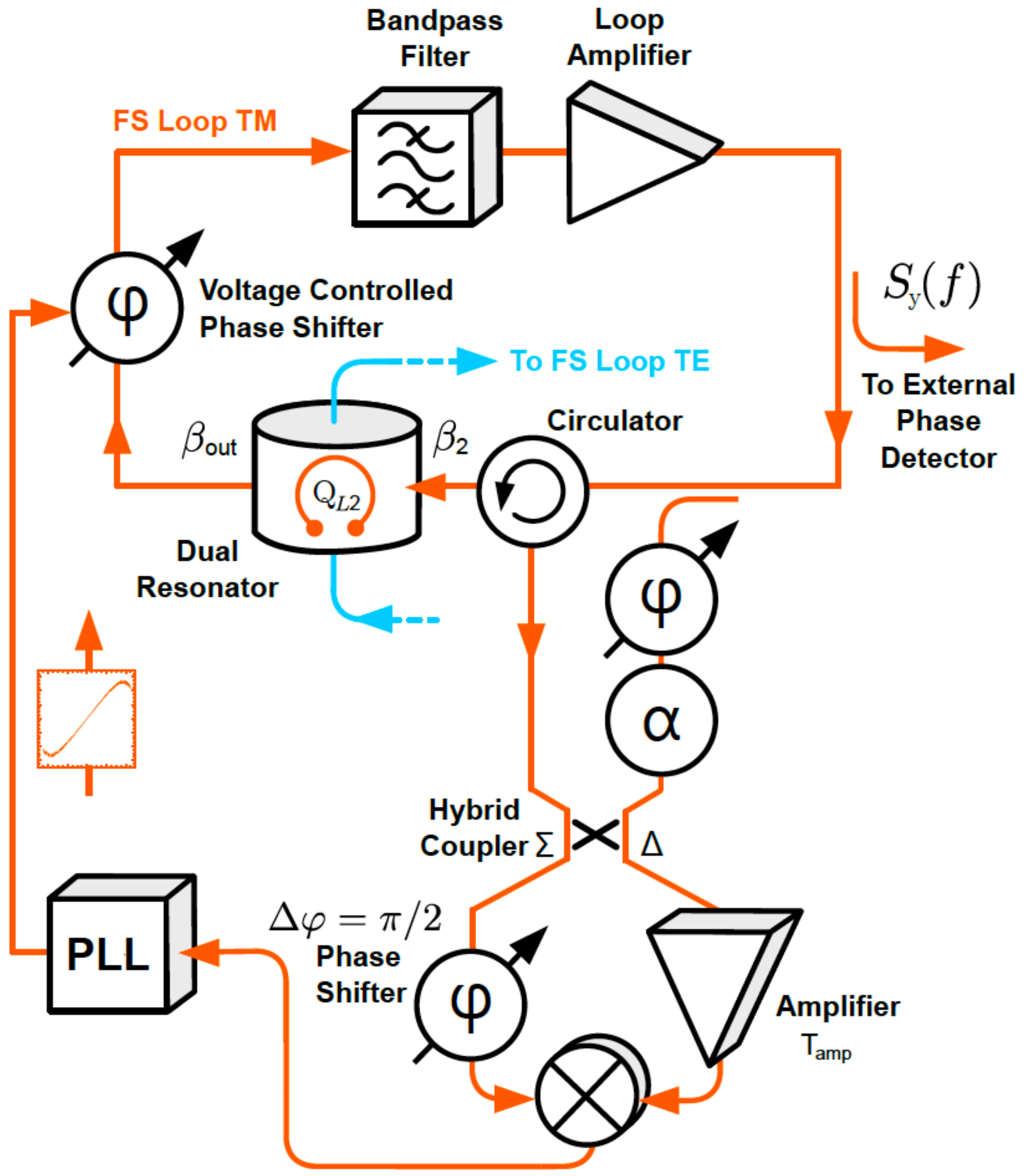


FIG. 5: Schematic of a frequency stabilized (FS) feedback oscillator with interferometric signal processing.

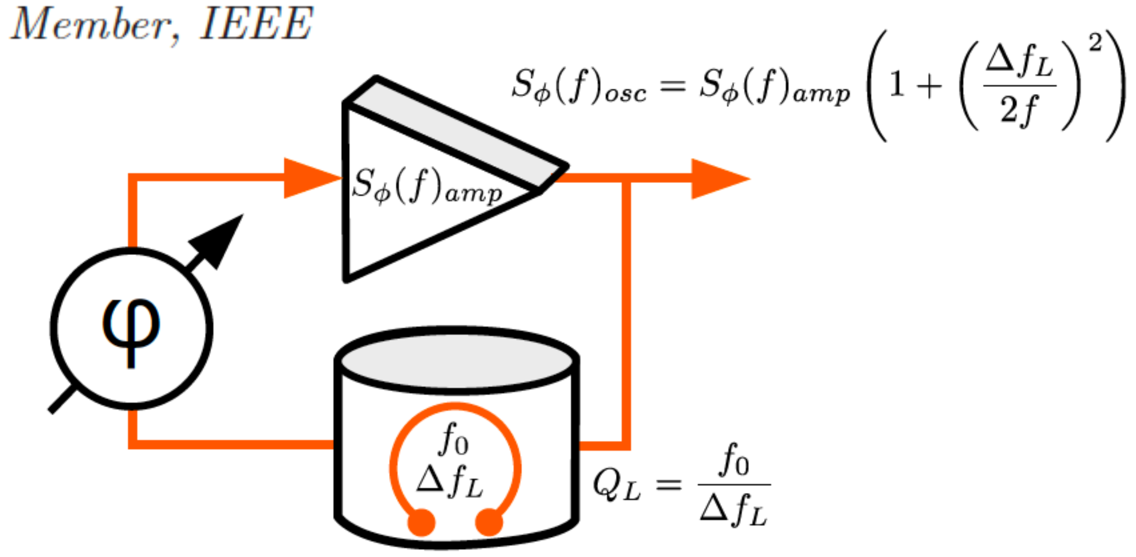
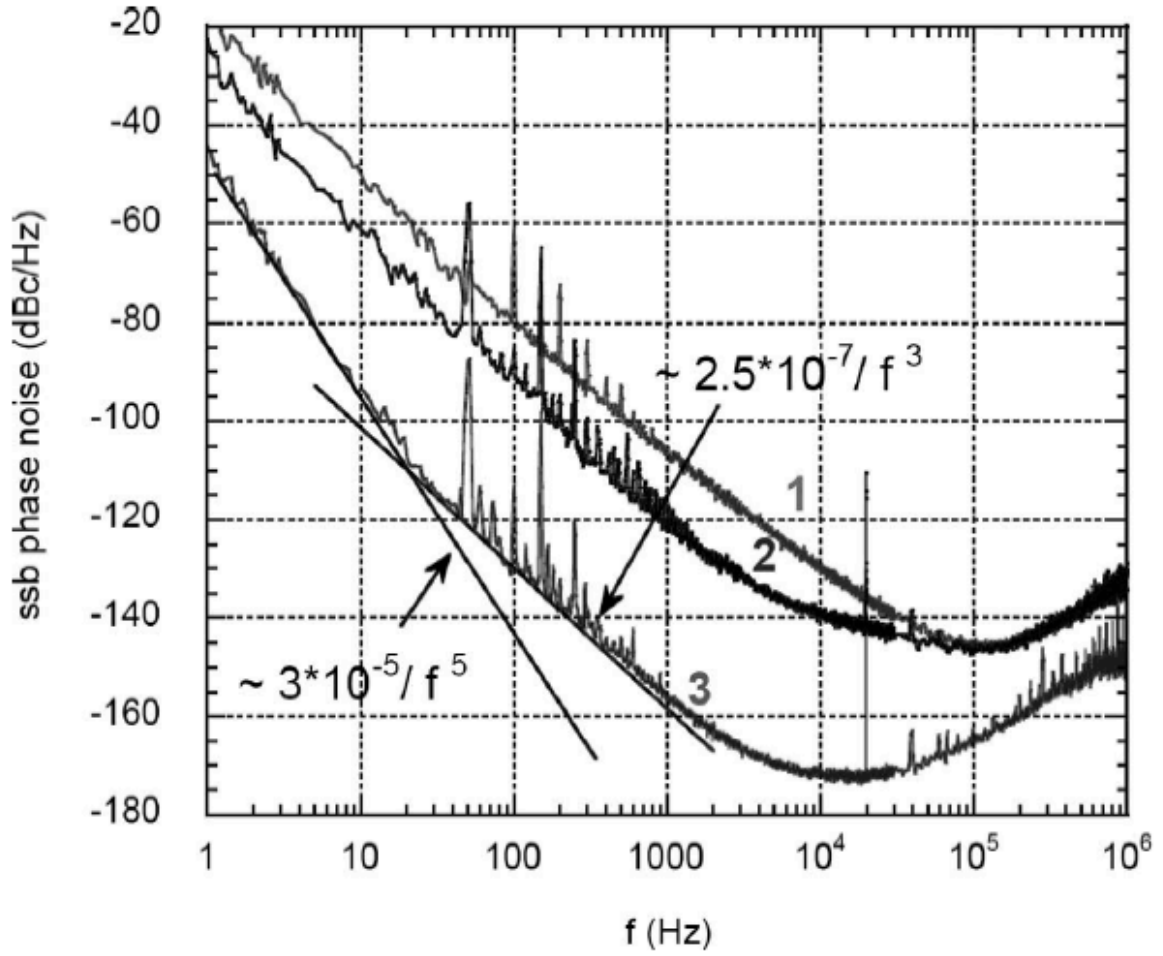


FIG. 4: Schematic of a simple feedback oscillator, with resonator loaded Q-factor Q_L, and amplifier phase noise of $S_\phi(f)_{amp}$. Shown is the simple relation to the oscillator phase noise, $S_\phi(f)_{osc}$.



E. N. Ivanov and M. E. Tobar, "Noise Suppression with Cryogenic Resonators," in IEEE Microwave and Wireless Components Letters, doi: 10.1109/LMWC.2021.3059291 , 2021

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Cryogenic Version Under development < -180 dBc/Hz.

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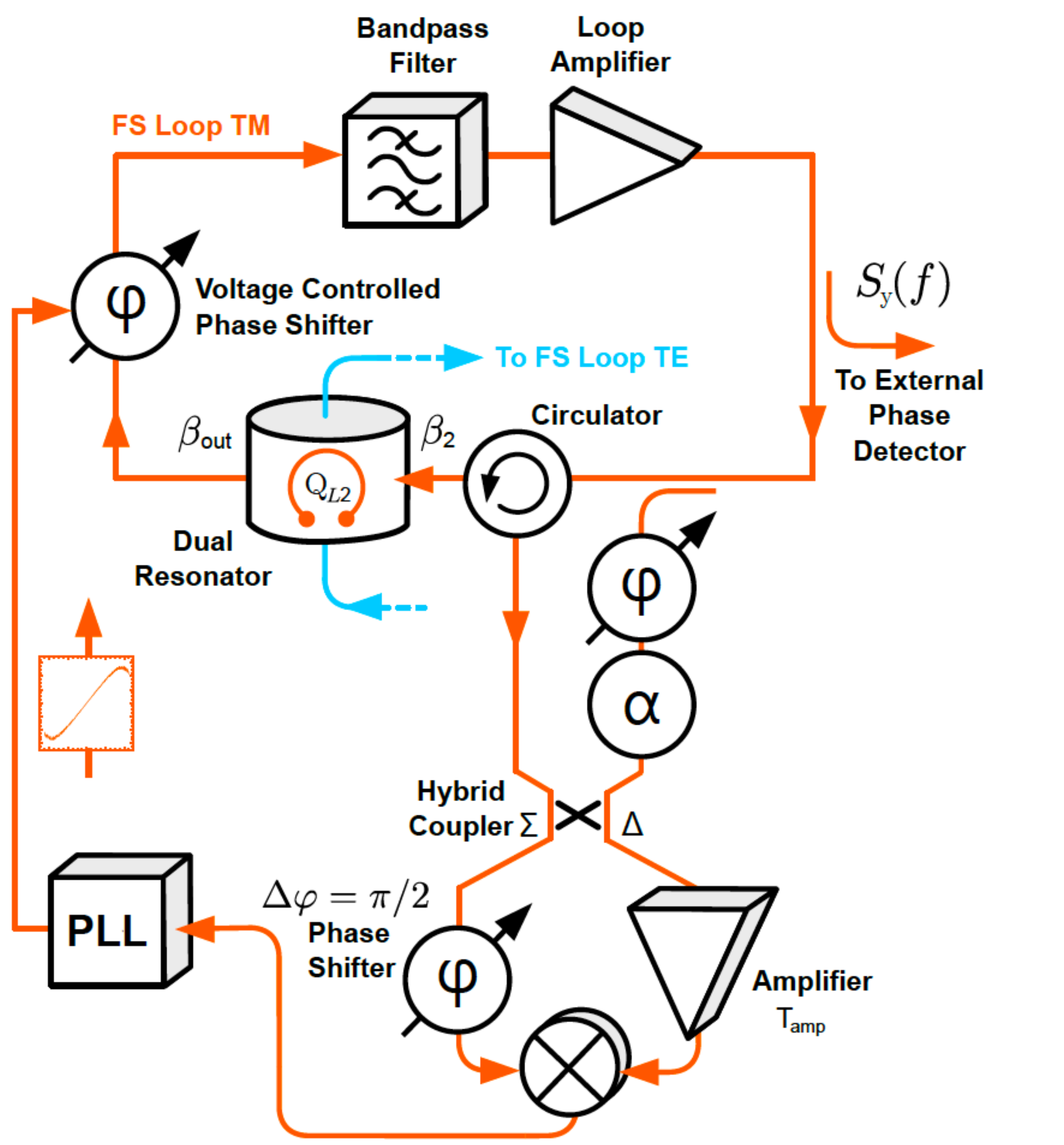

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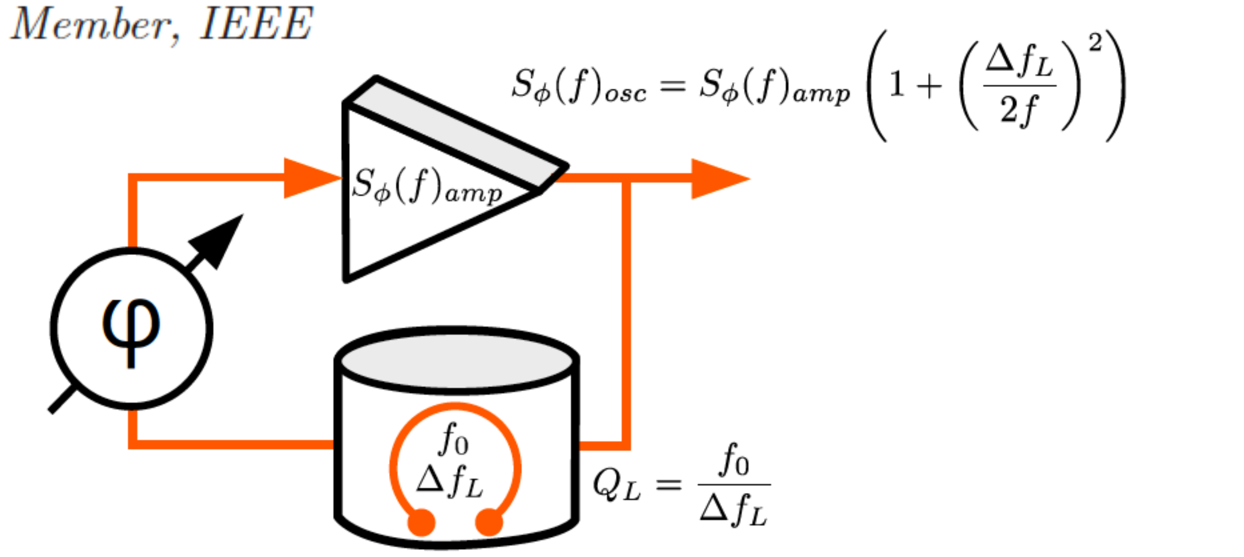

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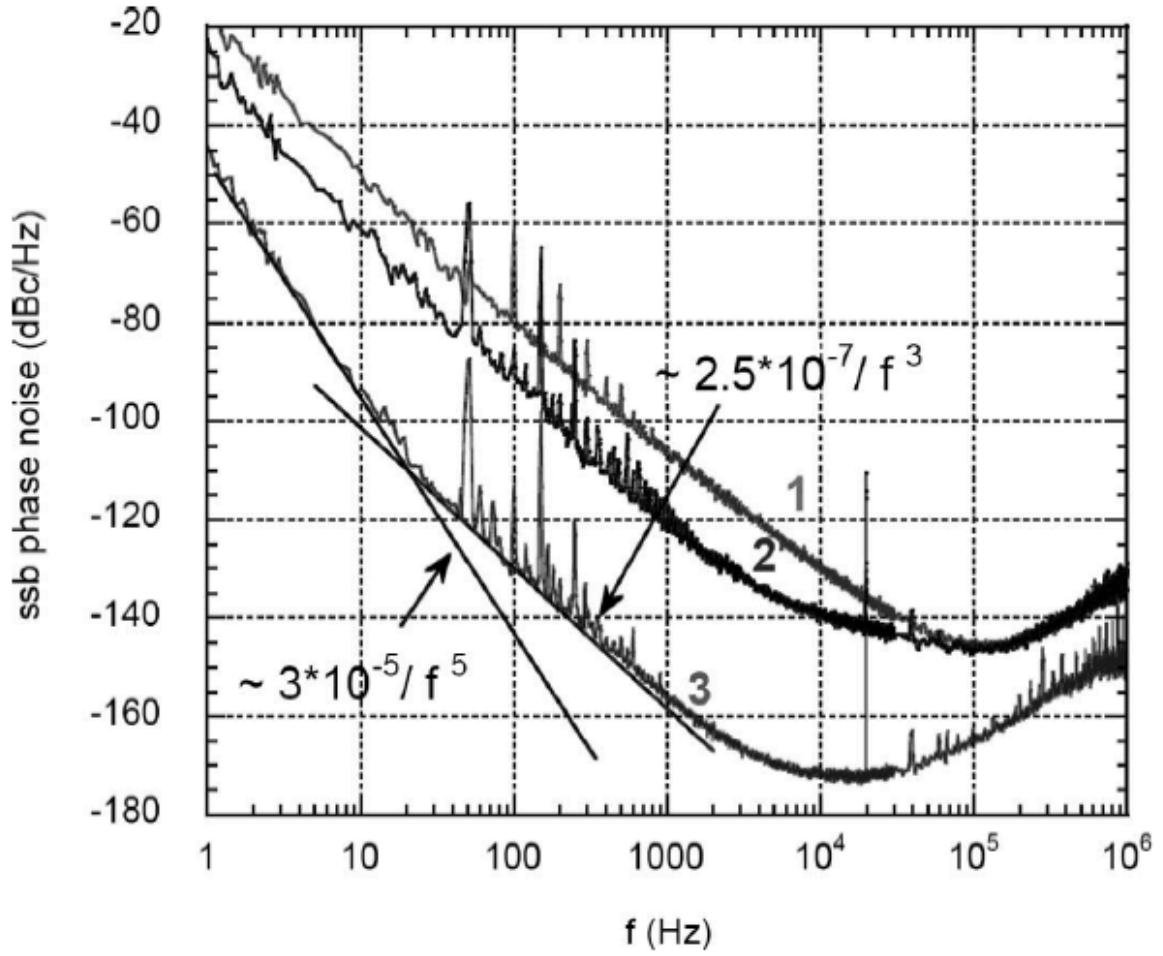

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IEEE MICROWAVE AND WIRELESS COMPONENTS LETTERS, VOL. 31, NO. 4, APRIL 2021

Noise Suppression With Cryogenic Resonators

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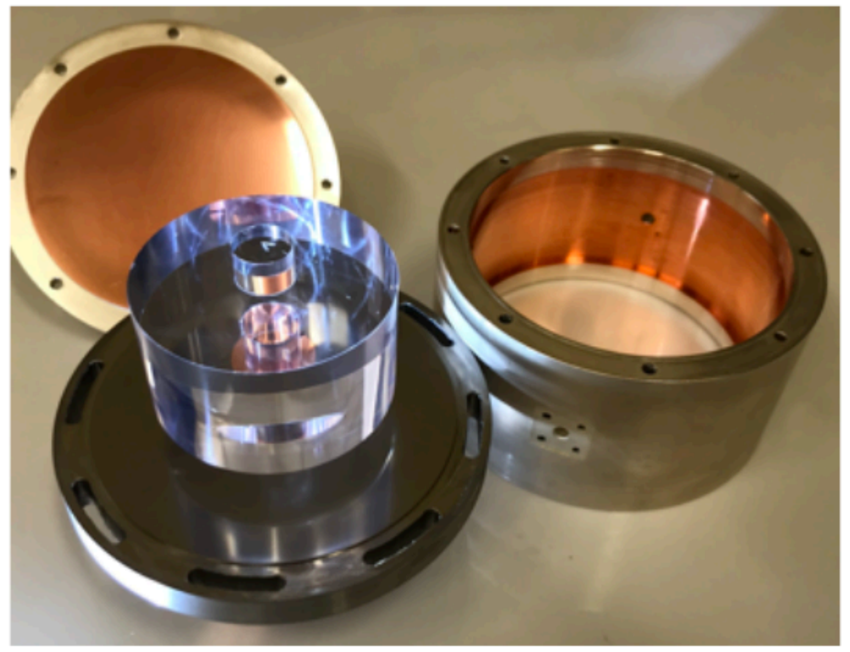

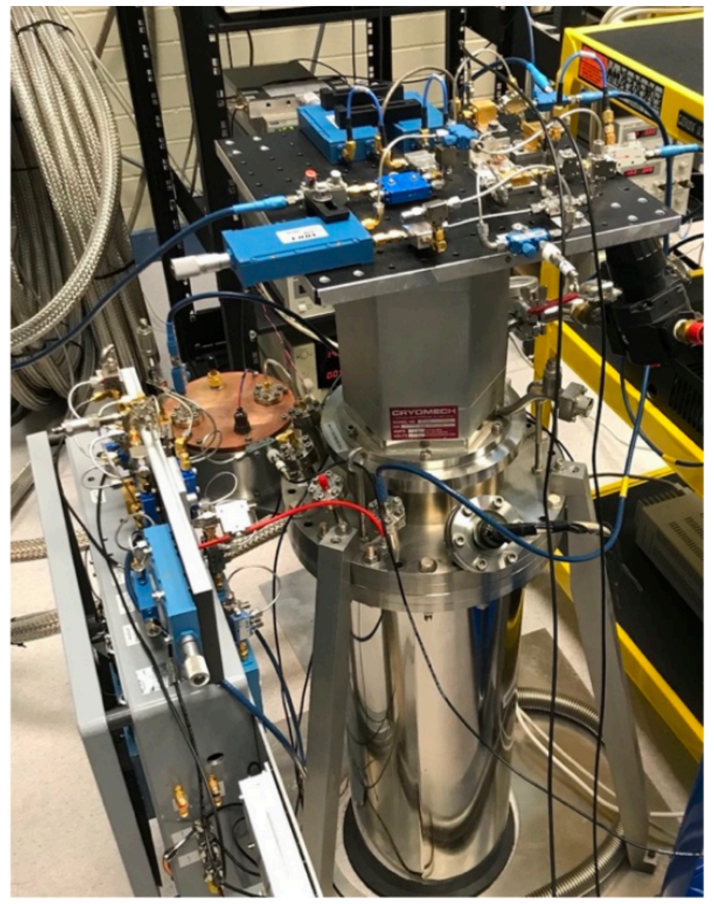

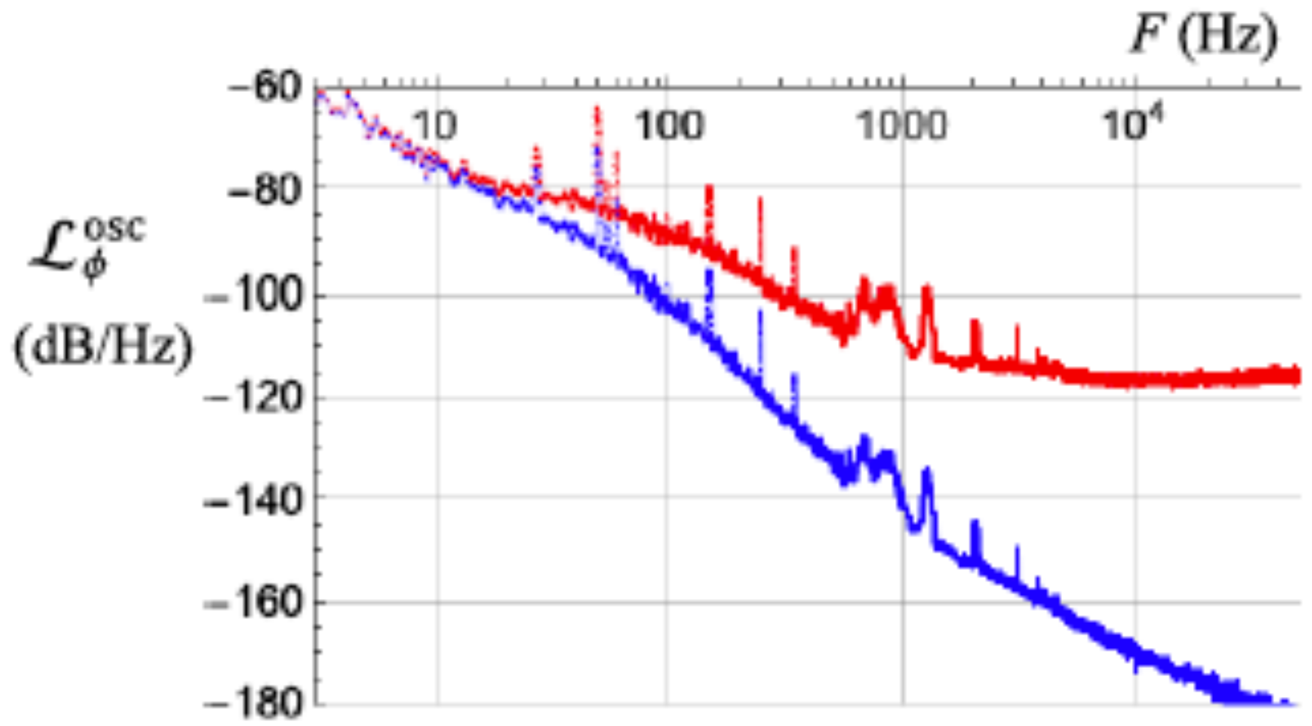

Fig. 7. SSB phase noise spectra of the E8257D at 11.2 GHz: top trace is the measured phase noise of the incident signal; bottom trace is the inferred phase noise of the transmitted signal.

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

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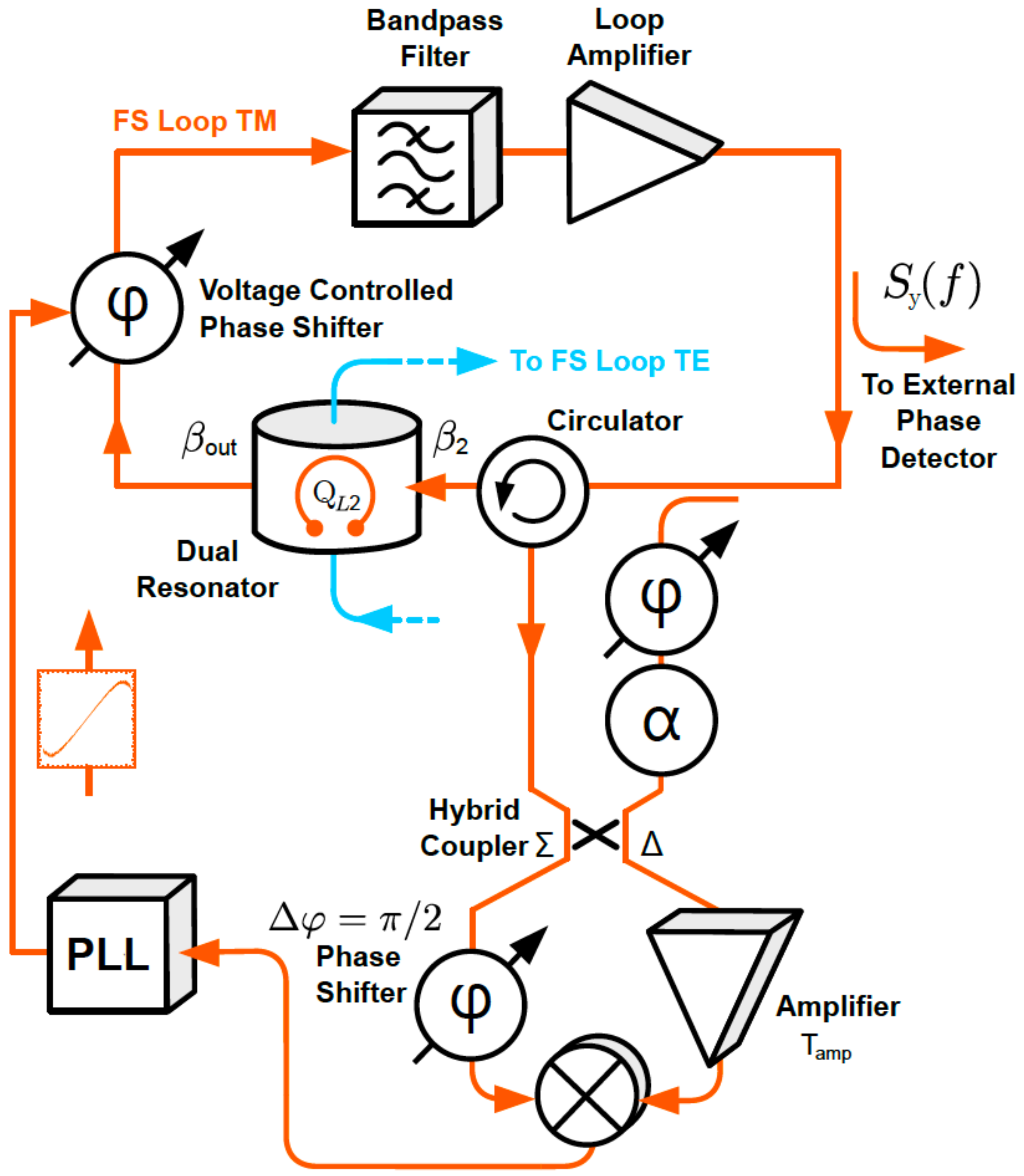

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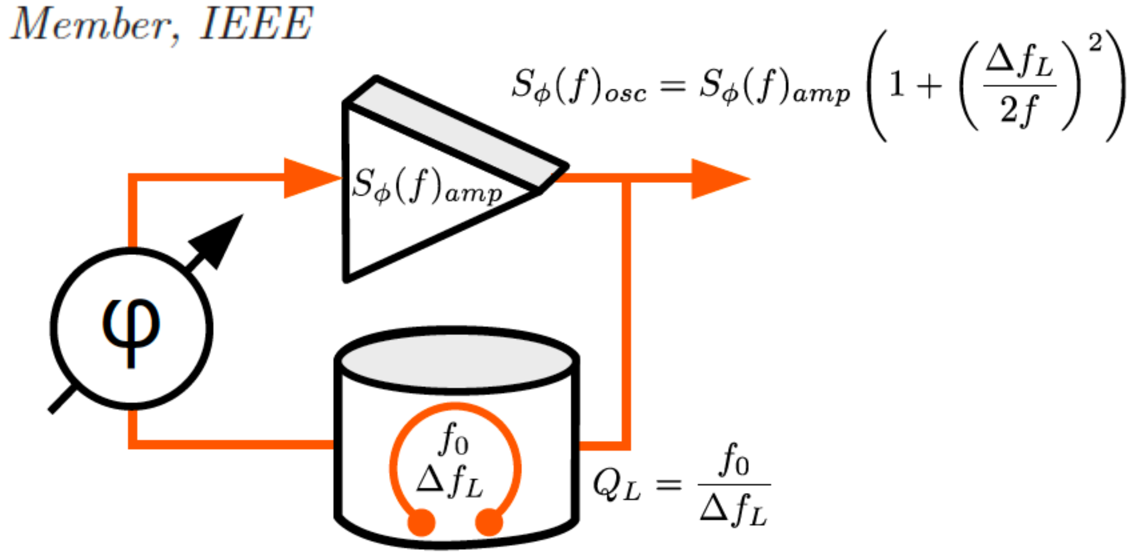

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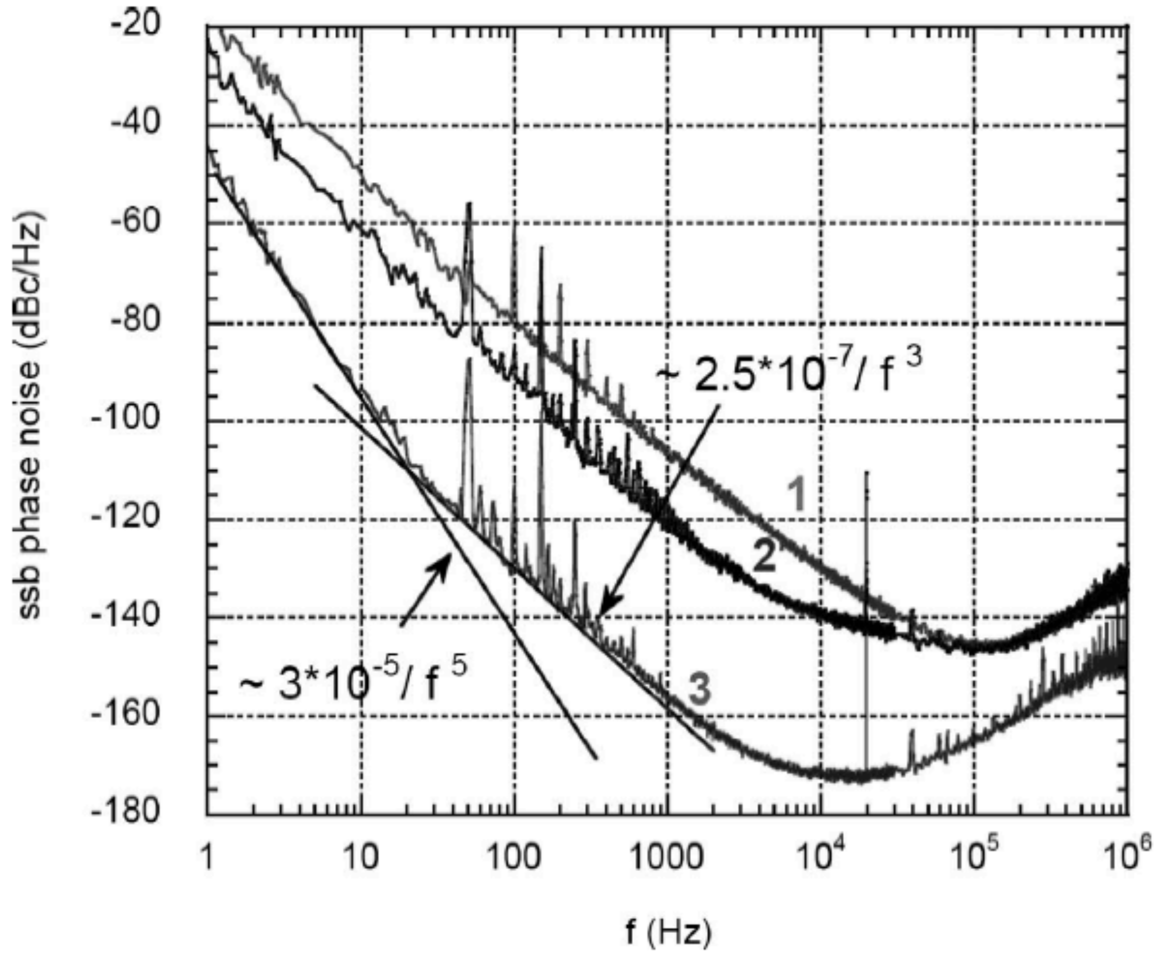

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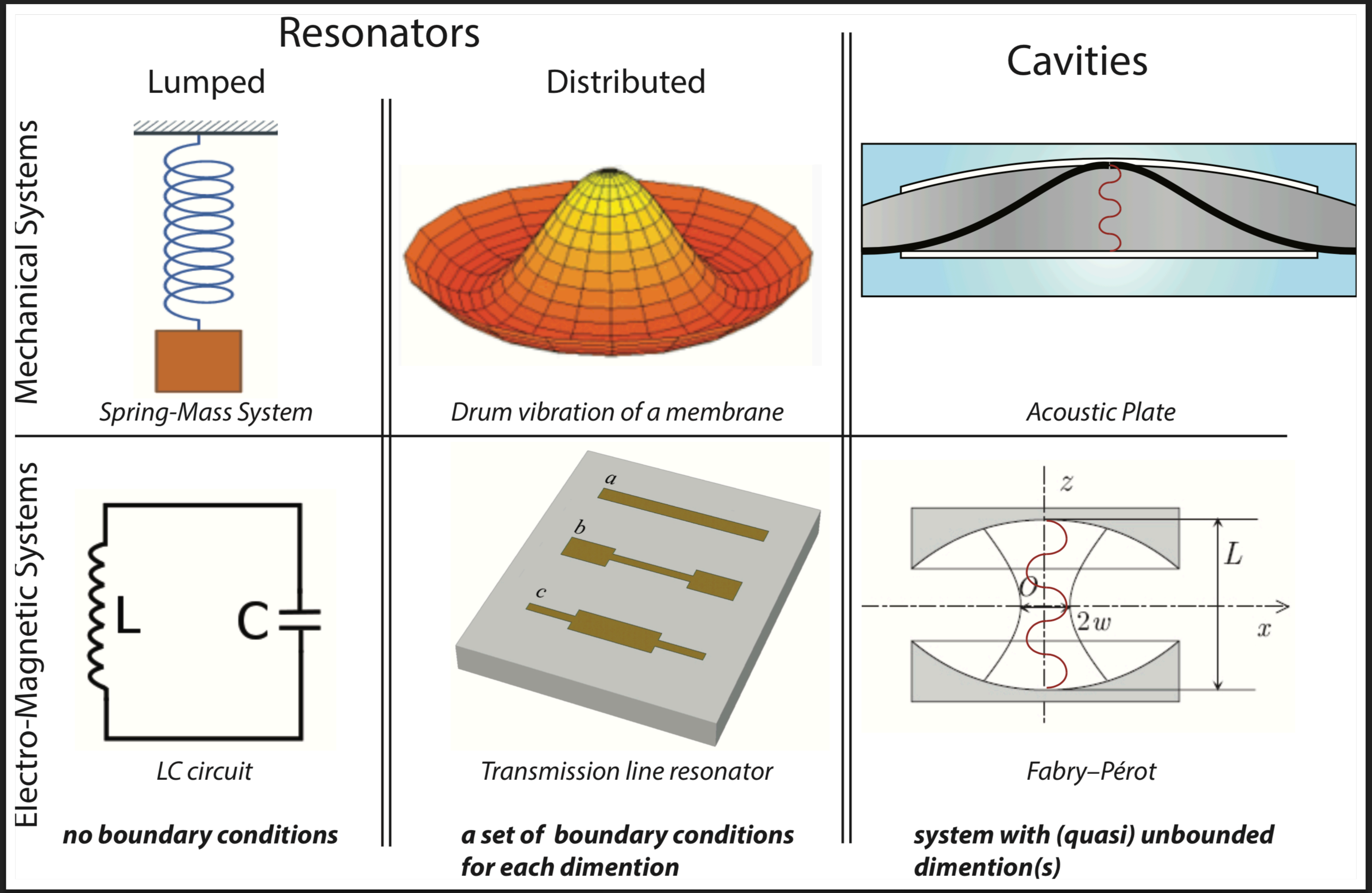
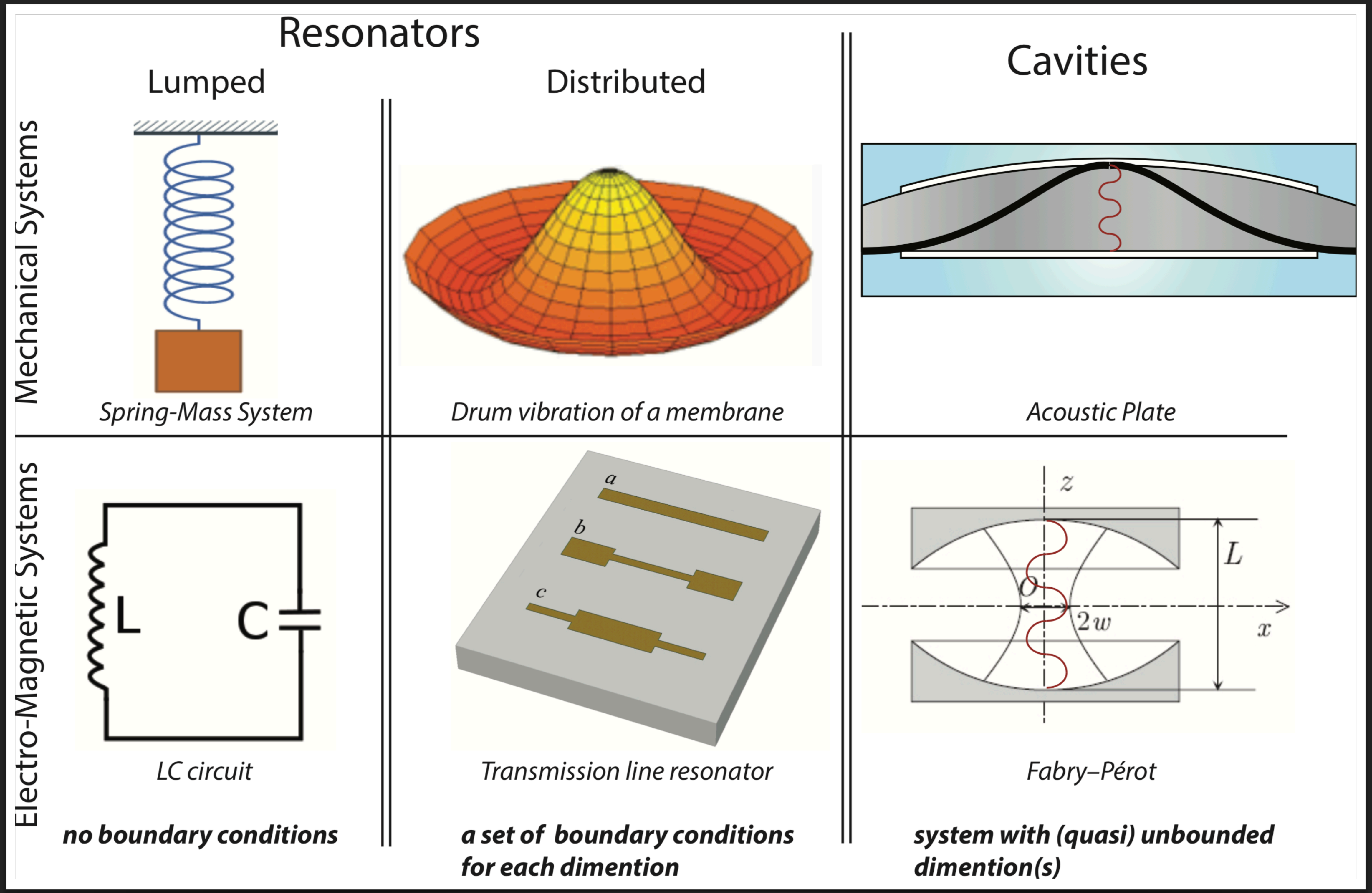
Photons (Electromagnetic) vs Phonons (Acoustic)



Photons (Electromagnetic) vs Phonons (Acoustic)

BAW Cavities



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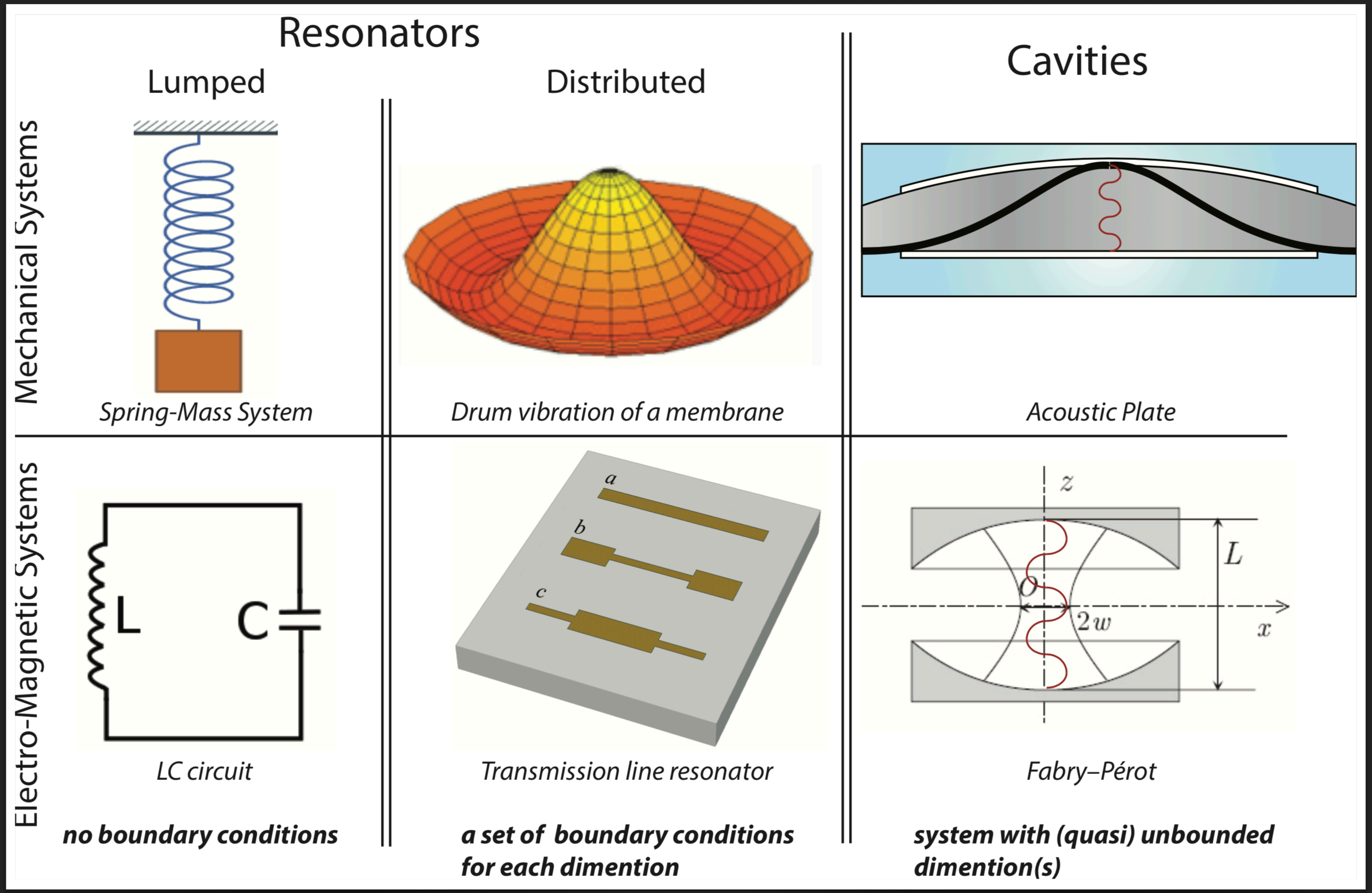

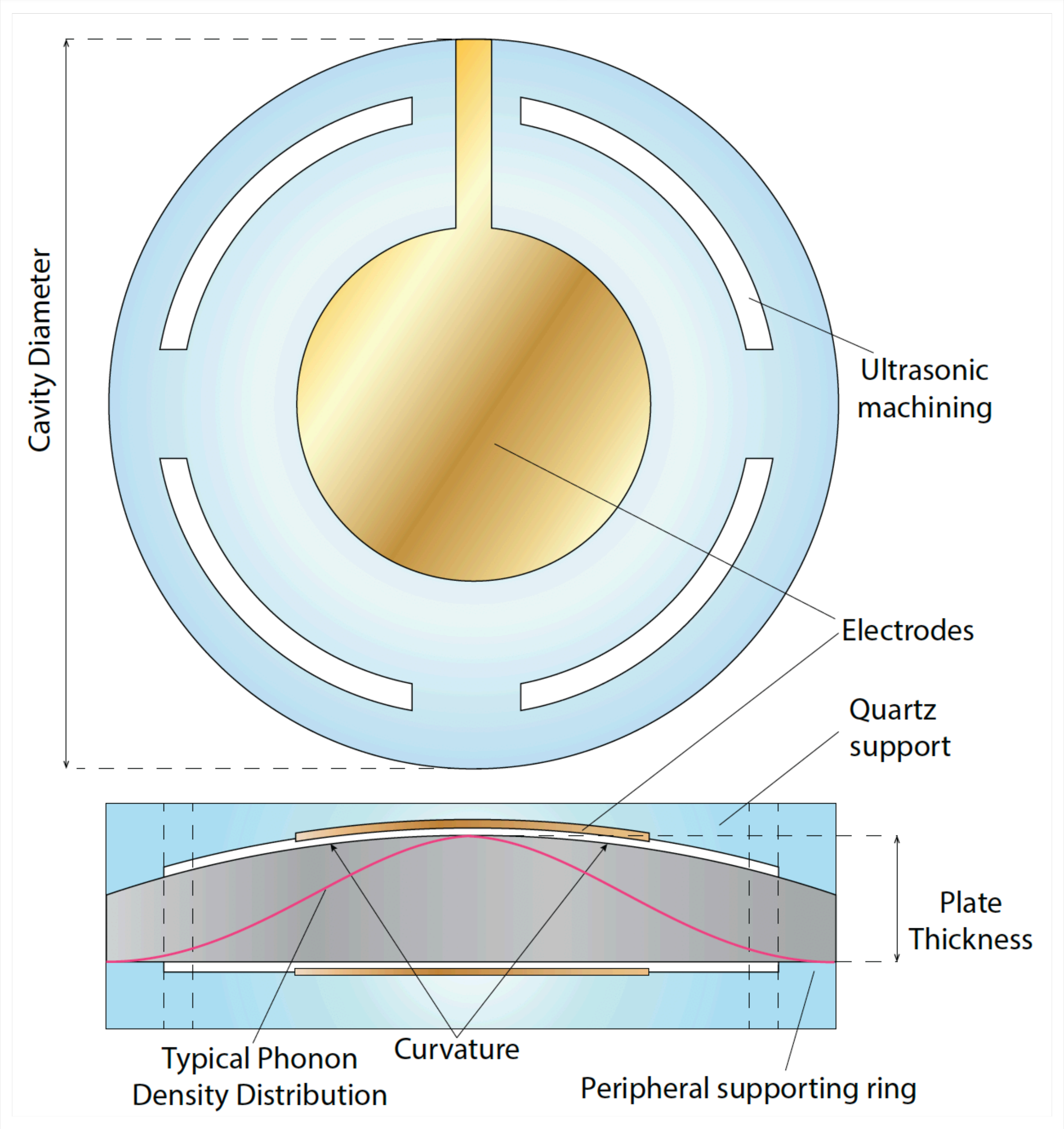

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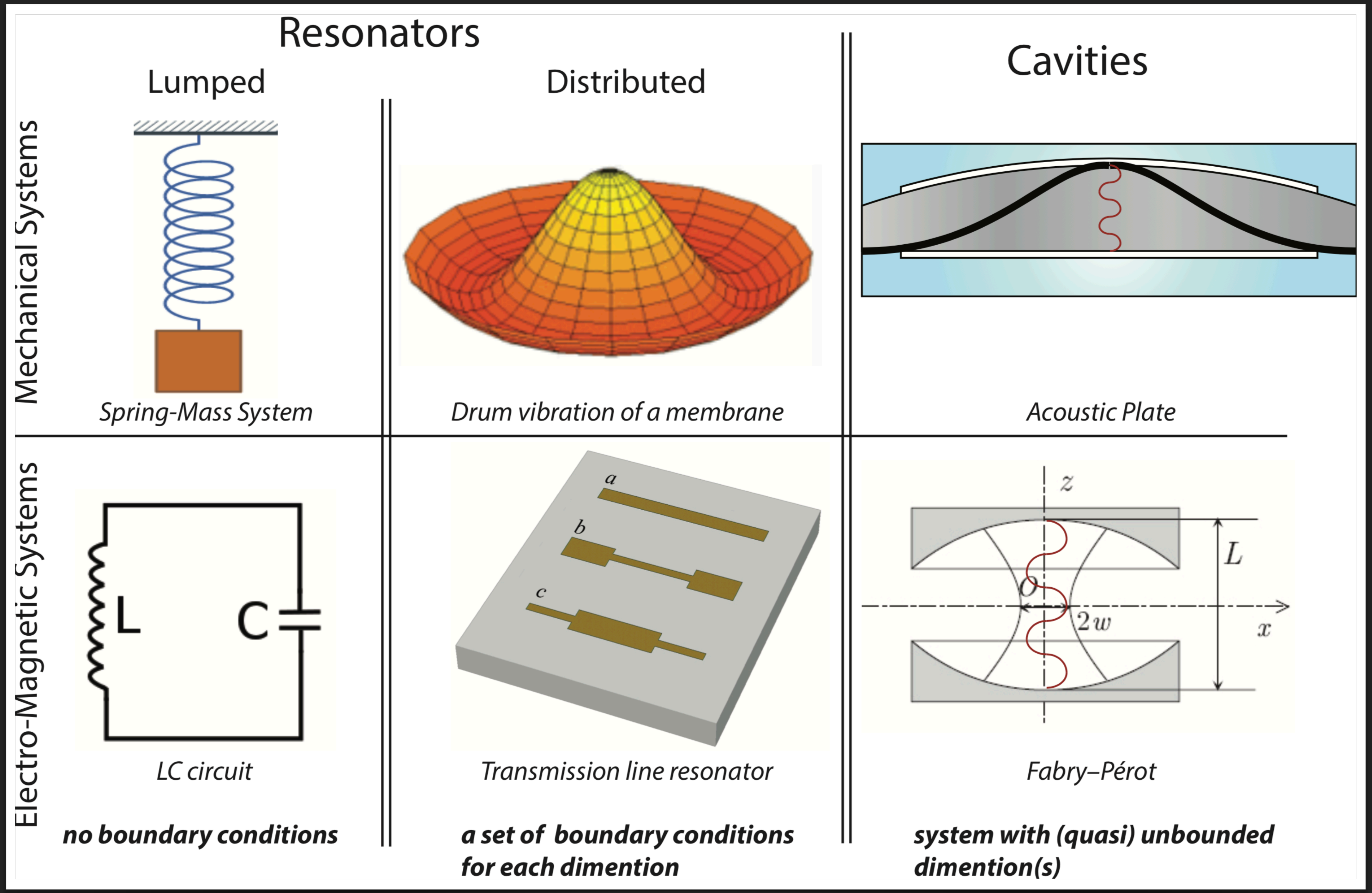

APPLIED PHYSICS LETTERS 100, 243504 (2012)

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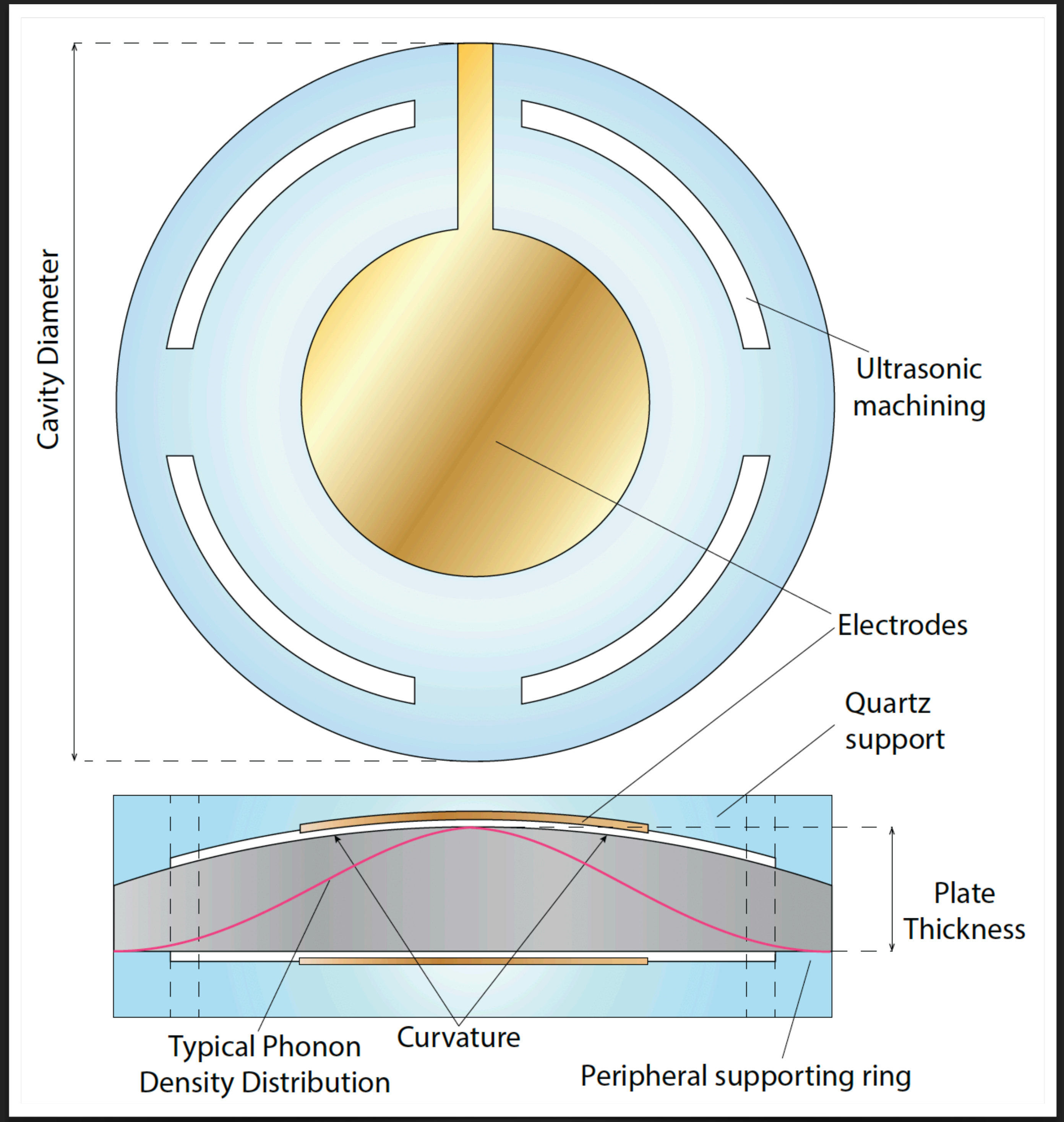
Scientific Reports Vol. 3, 2132 (2013)



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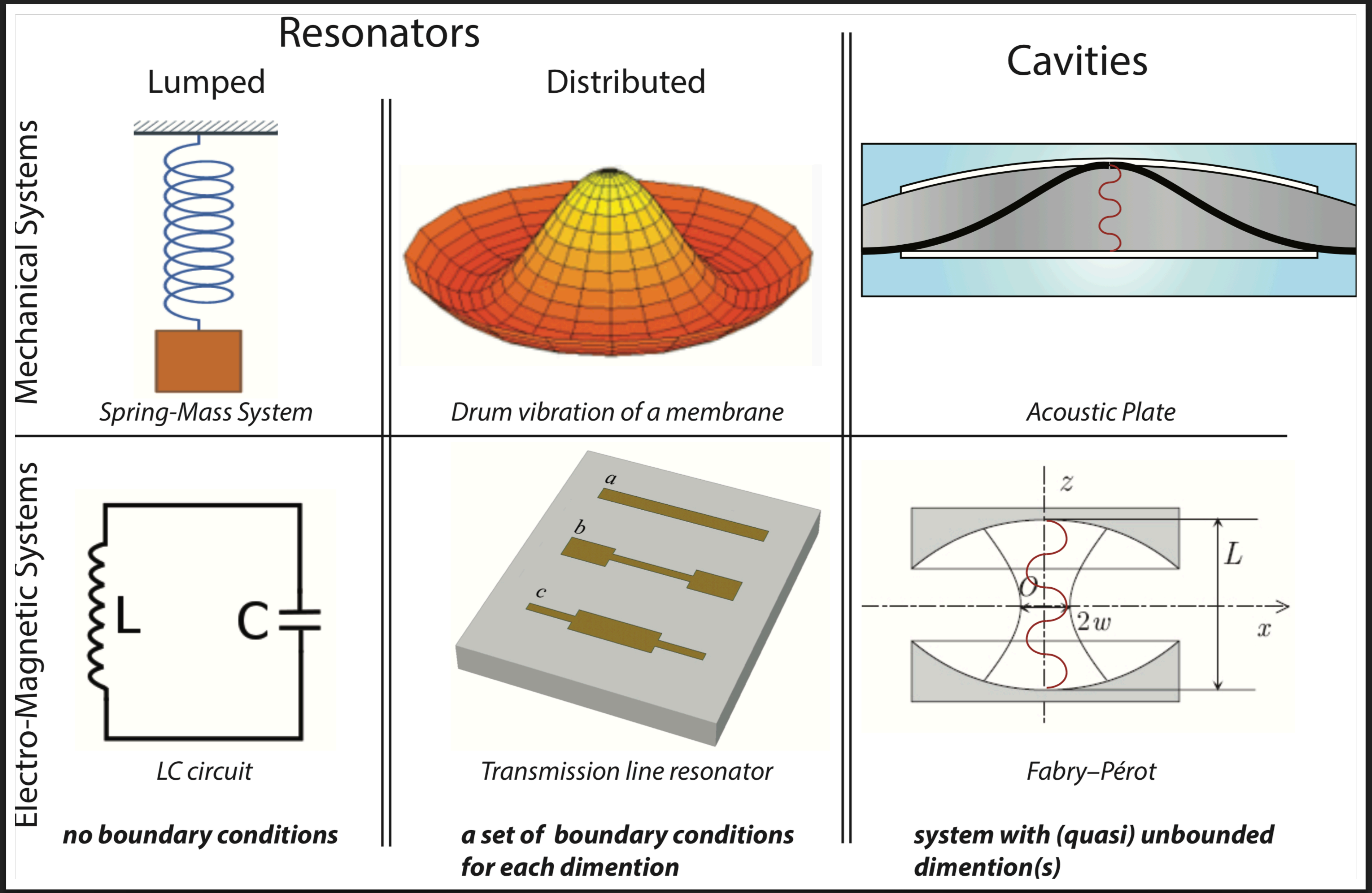

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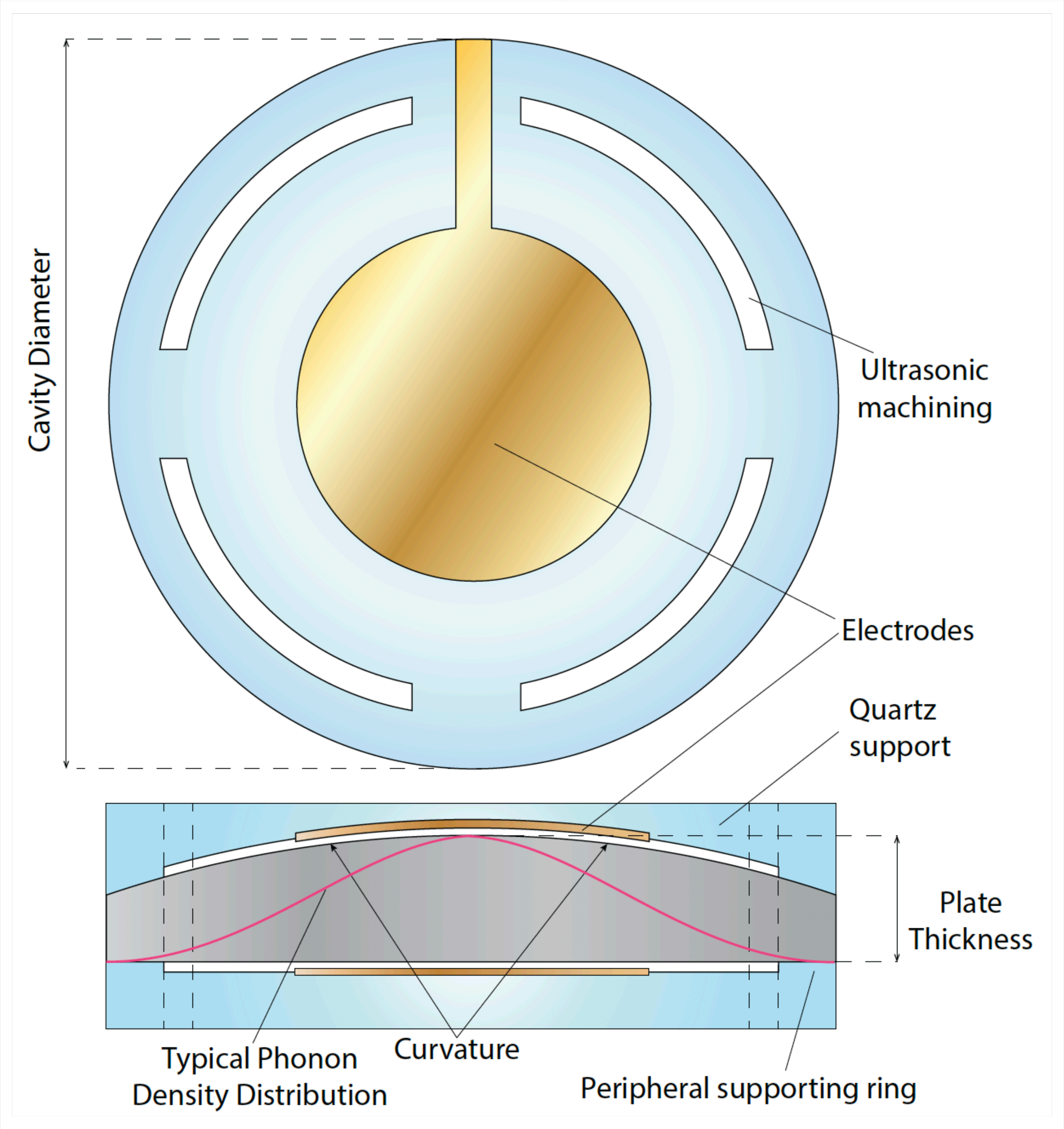

- Frequency range: 1-1000 MHz
- Three mode family types: 2 transverse and 1 longitudinal
- Piezoelectric Coupling
- Established technology (>70 years for time keeping applications)
- Record high Quality factors ~ 10^{10}

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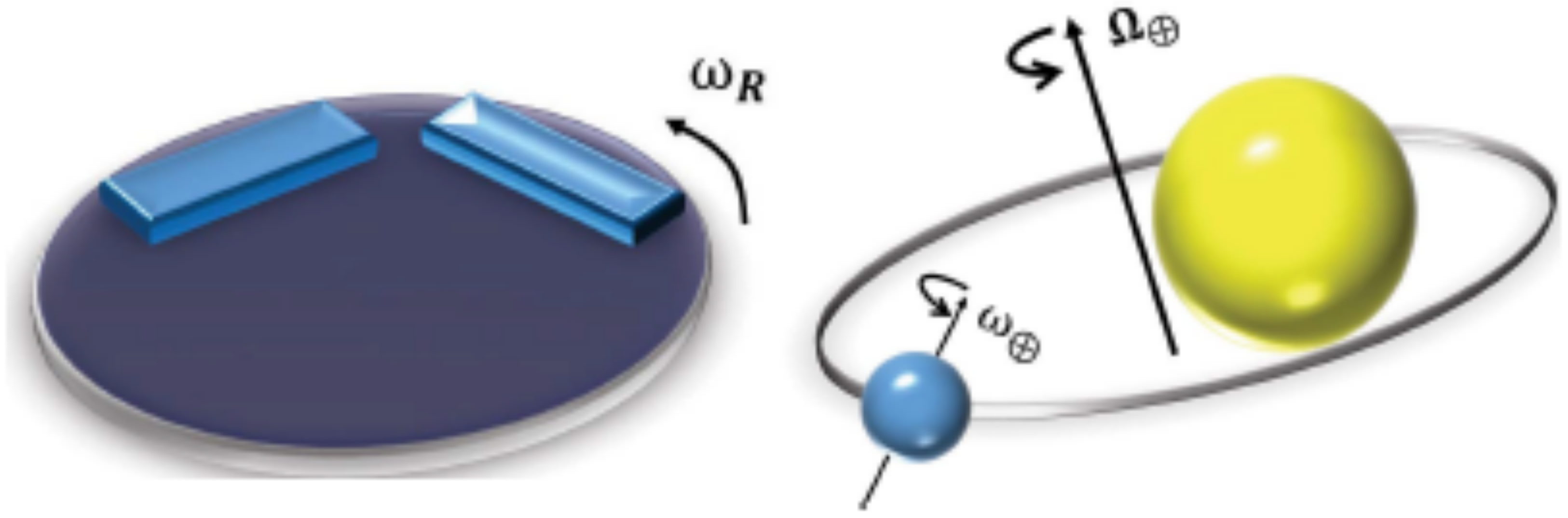
IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 65, NO. 6, JUNE 2018 991

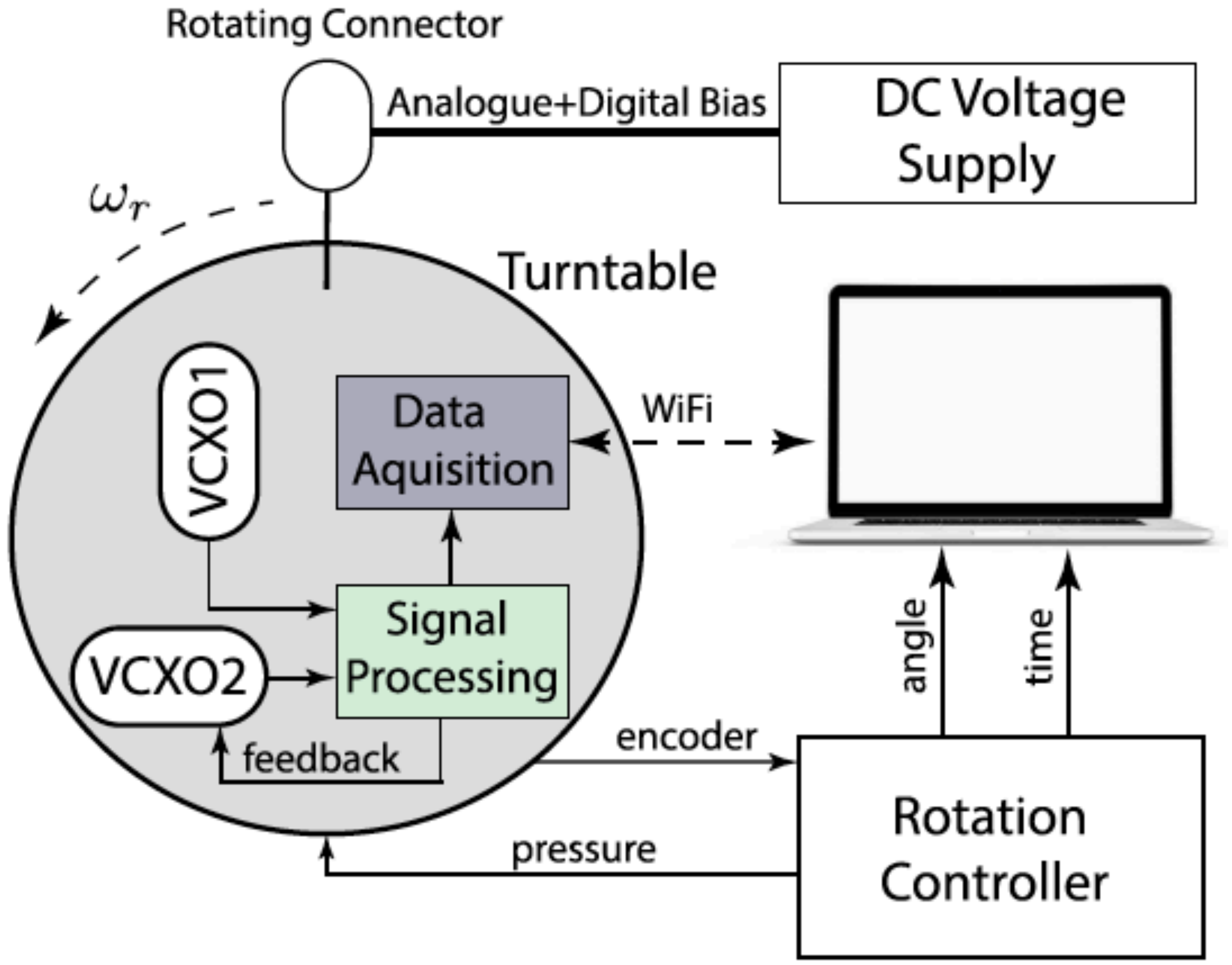
Next Generation of Phonon Tests of Lorentz Invariance Using Quartz BAW Resonators

Maxim Goryachev, Zeyu Kuang, Eugene N. Ivanov, Philipp Haslinger,
Holger Müller, and Michael E. Tobar, *Fellow, IEEE*

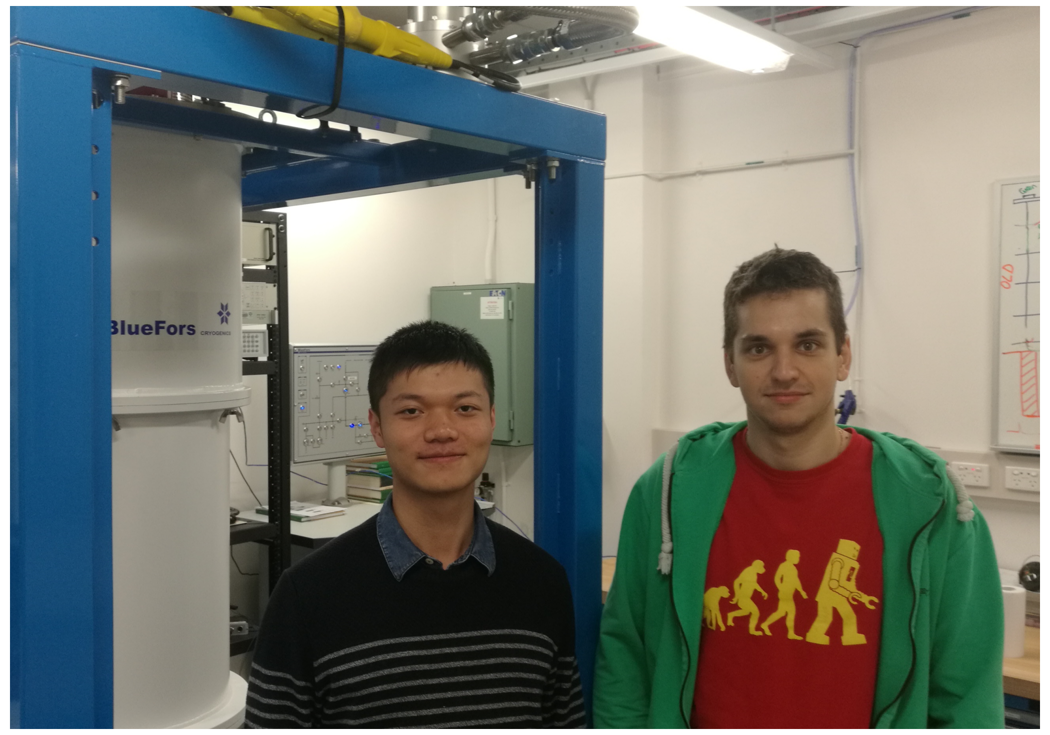
Abstract—**We demonstrate technological improvements in phonon sector tests of the Lorentz invariance that implement quartz bulk acoustic wave oscillators. In this experiment, room temperature oscillators with state-of-the-art phase noise are continuously compared on a platform that rotates at a rate of order of a cycle per second. The discussion is focused on improvements in noise measurement techniques, data acquisition, and data processing. Preliminary results of the second generation of such tests are given, and indicate that standard model extension coefficients in the matter sector can be measured at a precision of order 10^{-16} GeV after taking a year's worth of data. This is equivalent to an improvement of two orders of magnitude over the prior acoustic phonon sector experiment.**



(a) (b)

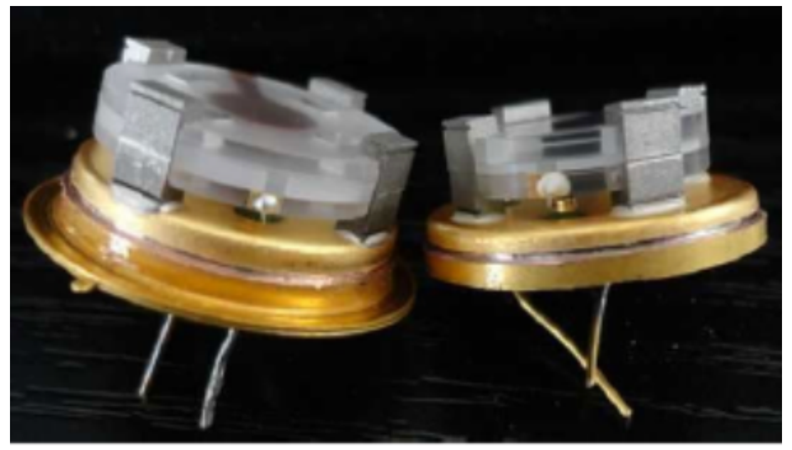


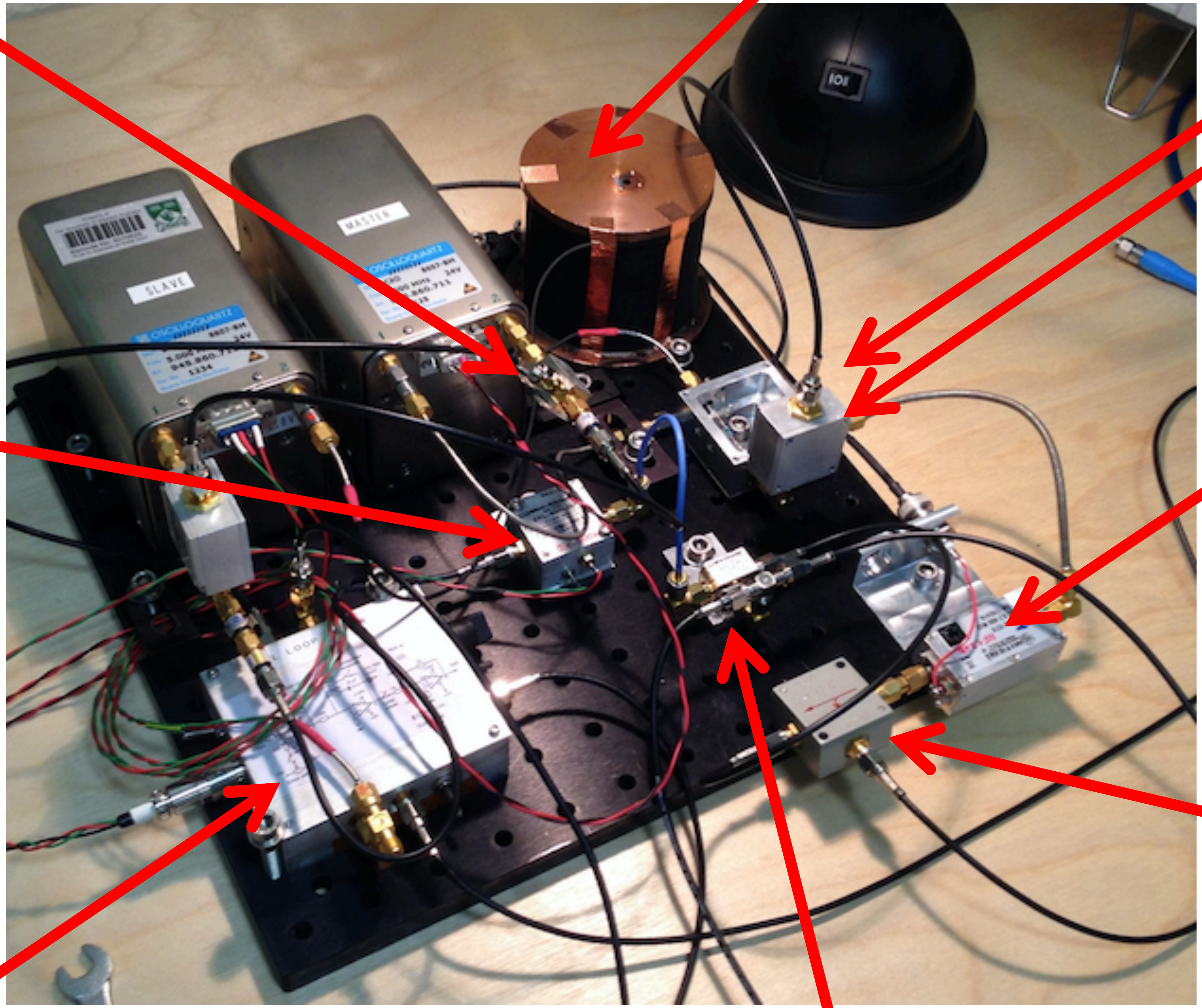
Current Status: Data taking Finished
-> ~ 2 years of data
-> Multiple Coefficients, Higher Dimensions



Room Temperature Resonator-Oscillators using Quartz BAWs

Q~10^6



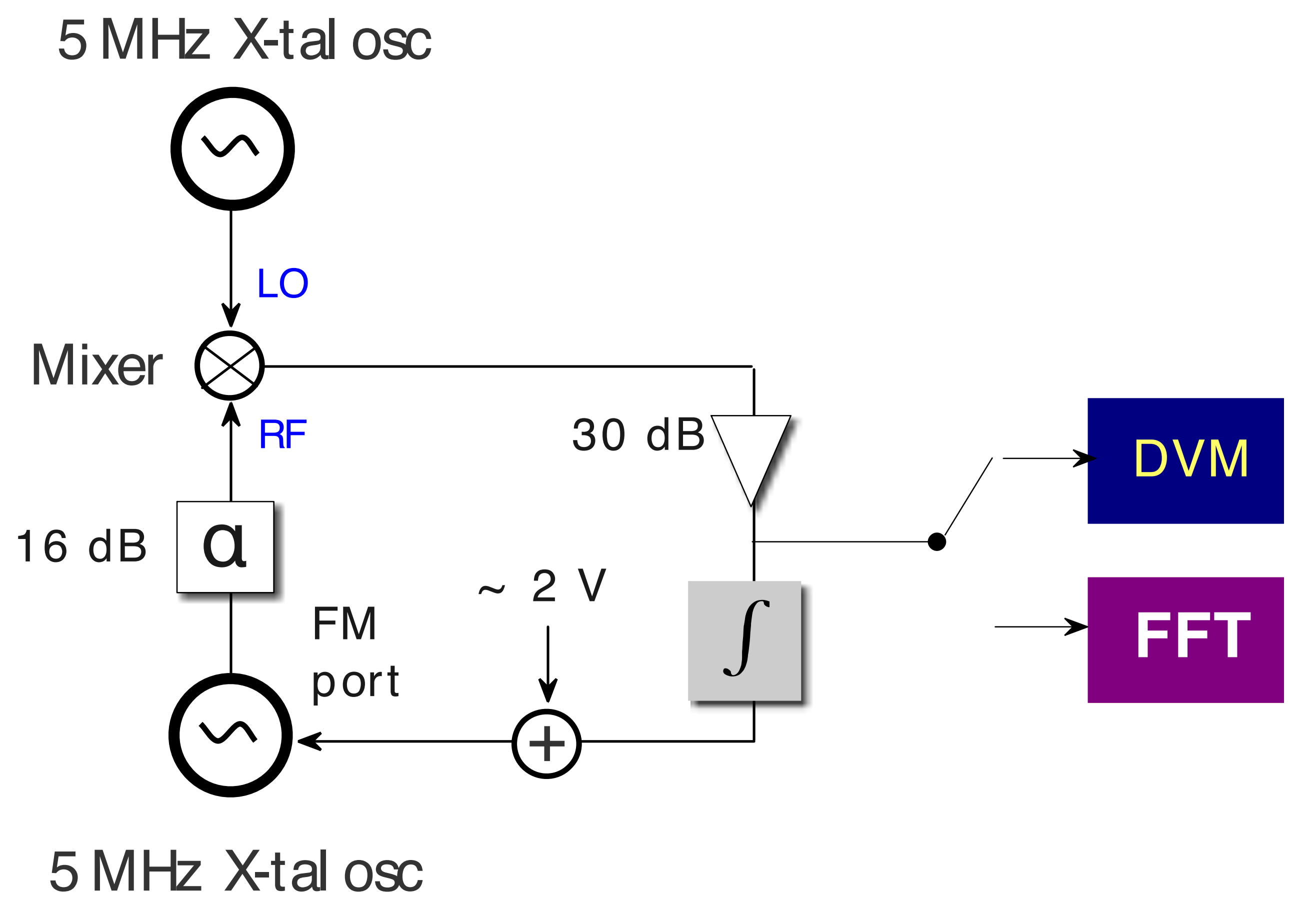


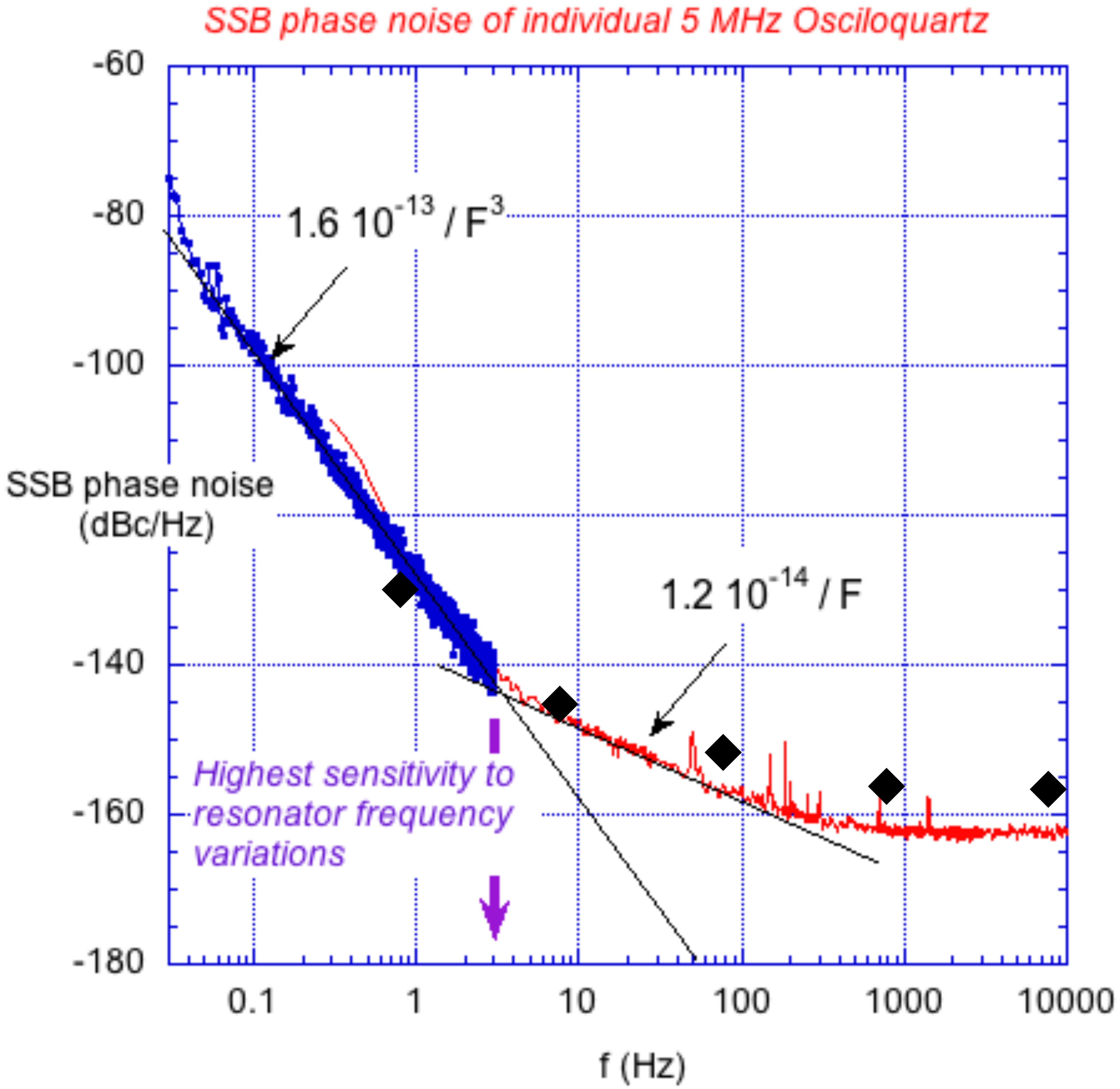
5 MHz Oscilloquartz

Phase Noise Spectrum of 5 MHz Oscilloquartz

Phase noise (BW = 1 Hz) Options

Frequencies	5 MHz		10 MHz	
Standard / Option L	Standard	Option L	Standard	Option L
Phase noise 1 Hz	- 125 dBc	- 130 dBc	-118 dBc	- 122 dBc
10 Hz	- 145 dBc	- 145 dBc	-137 dBc	- 137 dBc
100 Hz	- 153 dBc	- 153 dBc	-143 dBc	- 143 dBc
1'000 Hz	- 156 dBc	- 156 dBc	-145 dBc	- 145 dBc
10'000 Hz	- 156 dBc	- 156 dBc	- 145 dBc	- 145 dBc





Used to test fundamental Physics - LLI, Dark Matter
Can we Improve Using a Cryogenic Oscillator???

Searching for Scalar Dark matter from Oscillating Fundamental Constants

Atomic ionization by scalar dark matter and solar scalars

H. B. Tran Tan, A. Derevianko, V. Dzuba, V.V. Flambaum

hhu.

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Limits on oscillating fundamental constants from laser spectroscopy of molecular ensembles

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Heinrich-Heine-Universität Düsseldorf (Germany)

N. L. Figueroa, Ke Zhang, O. Tretiak, D. Antypas, D. Budker*
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Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung (Germany)

A. Banerjee, G. Perez
epartment of Particle Physics and Astrophysics, Weizmann Institute of Science (Israel)

* *also: Department of Physics, University of California, Berkeley (USA)*

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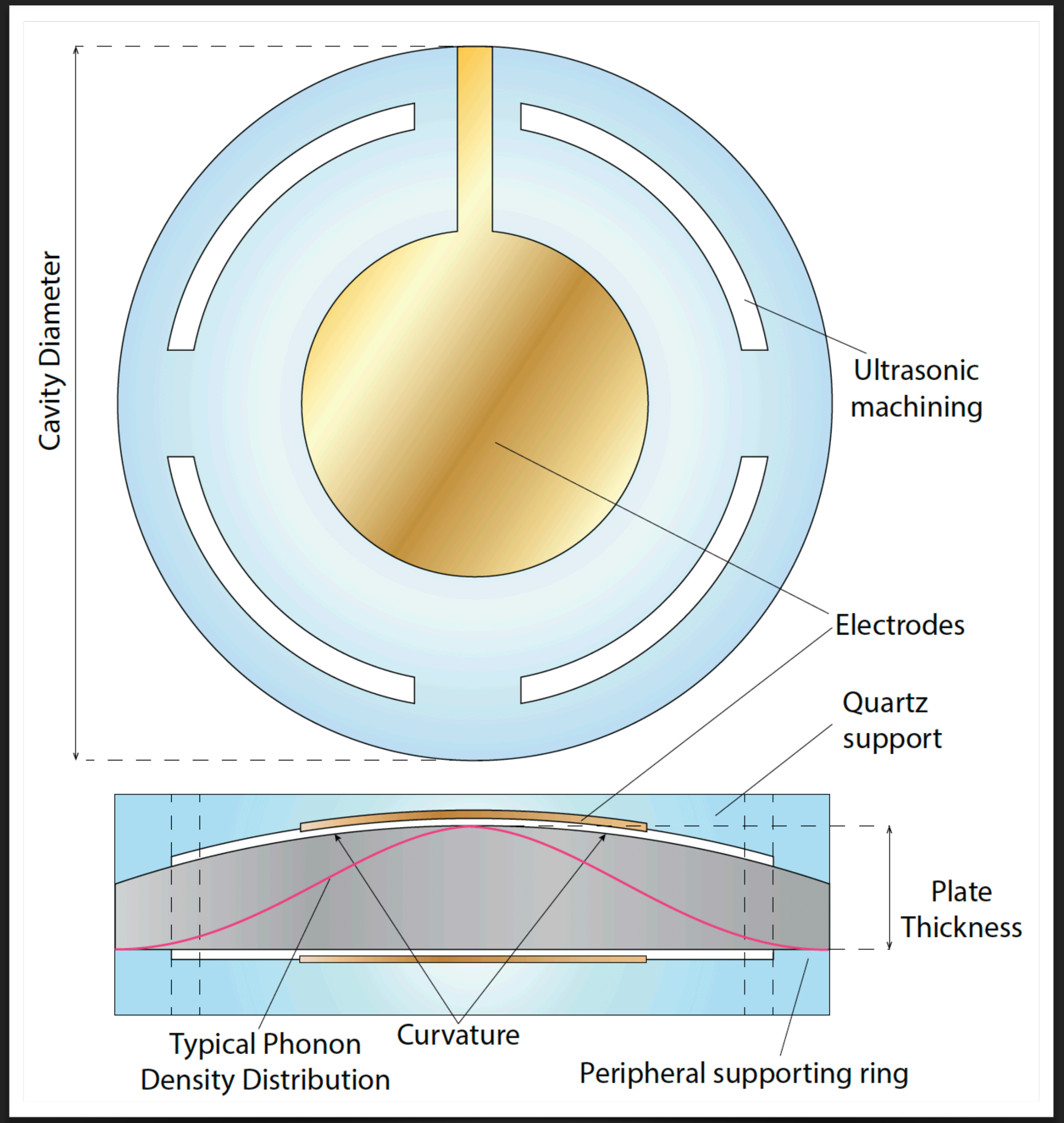
Some dependencies

- Optical transition frequency $f \propto m_e c^2 \alpha^2 H(\alpha)$
- Hyperfine transition frequency $f \propto m_e c^2 \alpha^4 F(\alpha) \left(\frac{m_e}{m_p}\right) \mu_{nuc}$
- Molecular vibrational transition frequency $f \propto m_e c^2 \alpha^2 \left(\frac{m_e}{M_{nuc}}\right)^{\frac{1}{2}} G\left(\frac{m_e}{M_{nuc}}\right)$
- Electromagnetic cavity mode frequency (empty cavity) $f \propto m_e c^2 \alpha$
- Mechanical mode frequency $f \propto m_e c^2 \alpha^2 \left(\frac{m_e}{M_{nuc}}\right)^{\frac{1}{2}}$

$$\frac{\delta M_{\rm nuc}}{M_{\rm nuc}} = \frac{\delta \Lambda_{\rm QCD}}{\Lambda_{\rm QCD}} + 0.093\frac{\delta \hat{m}}{\hat{m}} + 0.043\frac{\delta m_s}{m_s}, \quad \hat{m} = (m_u + m_d)/2$$

$\mu_{\rm nuc}$ has a small/modest dependence on m_s (~0.01) and on $\hat{m}$ (~0.1)

Bulk Acoustic Wave (BAW) Oscillator Fundamental Constant Dependence Quartz Oscillator Limits the Experiment Stability: 10^{-13} to 10^{-16} possible



$$f = \frac{nv}{L}$$

vis the speed of sound in the material
L resonator length parameter
n is a constant.

$$f \propto \sqrt{\frac{KL}{m}} \propto \sqrt{\frac{\alpha^4 {m_e}^3}{m_p}} \propto m_e \alpha^2 \sqrt{\frac{m_e}{m_p}}.$$

Scalar Dark Matter

PHYSICAL REVIEW D **98**, 064051 (2018)

Violation of the equivalence principle from light scalar dark matter

Aurélien Hees,[1,*] Olivier Minazzoli,[2,3] Etienne Savalle,[1] Yevgeny V. Stadnik,[4] and Peter Wolf[1]

[1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire 75014 Paris, France*

[2]*Centre Scientifique de Monaco, 8 Quai Antoine 1er, 98000 Monaco, Monaco*

[3]*Laboratoire Artemis, Université Côte d'Azur, CNRS, Observatoire Côte d'Azur, BP4229, 06304, Nice Cedex 4, France*

[4]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany*

(Received 11 July 2018; published 25 September 2018)

Fine structure constant

$$\alpha_{\mathrm{EM}}(\varphi) = \alpha_{\mathrm{EM}}\left(1 + d_e^{(i)}\frac{\varphi^i}{i}\right),$$

Masses of particles

$$m_j(\varphi) = m_j\left(1 + d_{m_j}^{(i)}\frac{\varphi^i}{i}\right) \quad \text{for } j = e, u, d,$$

QCD mass scale

$$\Lambda_3(\varphi) = \Lambda_3\left(1 + d_g^{(i)}\frac{\varphi^i}{i}\right),$$

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Scalar Dark Matter

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

Phys. Rev. Lett. **126**, 071301 – Published 18 February 2021

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We present a way to search for light scalar dark matter (DM), seeking to exploit putative coupling between dark matter scalar fields and fundamental constants, by searching for frequency modulations in direct comparisons between frequency stable oscillators. Specifically we compare a cryogenic sapphire oscillator (CSO), hydrogen maser (HM) atomic oscillator, and a bulk acoustic wave quartz oscillator (OCXO). This work includes the first calculation of the dependence of acoustic oscillators on variations of the fundamental constants, and demonstration that they can be a sensitive tool for scalar DM experiments. Results are presented based on 16 days of data in comparisons between the HM and OCXO, and 2 days of comparison between the OCXO and CSO. No evidence of oscillating fundamental constants consistent with a coupling to scalar dark matter is found, and instead limits on the strength of these couplings as a function of the dark matter mass are determined. We constrain the dimensionless coupling constant d_e and combination $|d_{m_e} - d_g|$ across the mass band $4.4 \times 10^{-19} \lesssim m_\varphi \lesssim 6.8 \times 10^{-14}$ eV c^{-2}, with most sensitive limits $d_e \gtrsim 1.59 \times 10^{-1}$, $|d_{m_e} - dg| \gtrsim 6.97 \times 10^{-1}$. Notably, these limits do not rely on maximum reach analysis (MRA), instead employing the more general coefficient separation technique. This experiment paves the way for future, highly sensitive experiments based on state-of-the-art acoustic oscillators, and we show that these limits can be competitive with the best current MRA-based exclusion limits.

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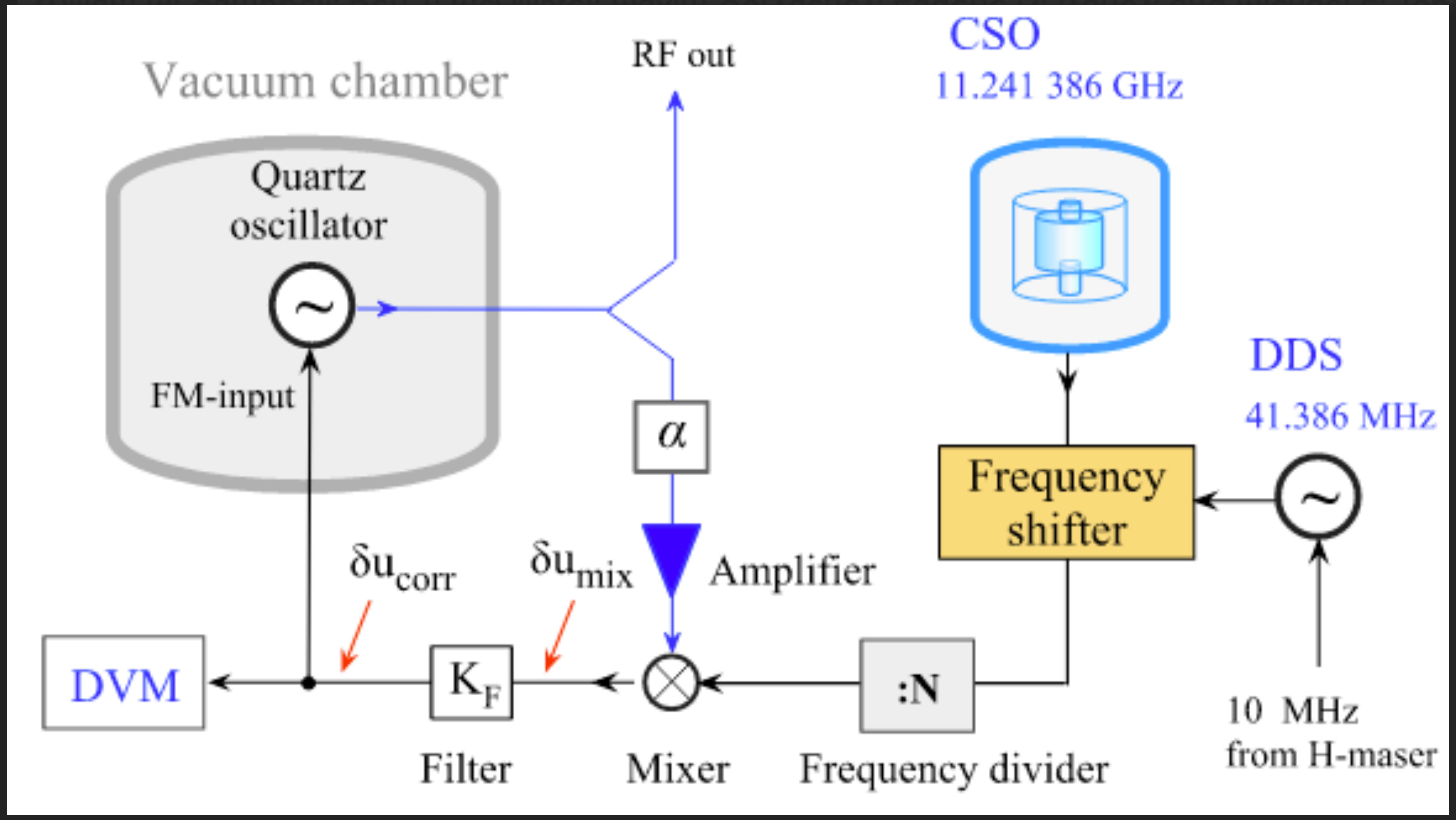
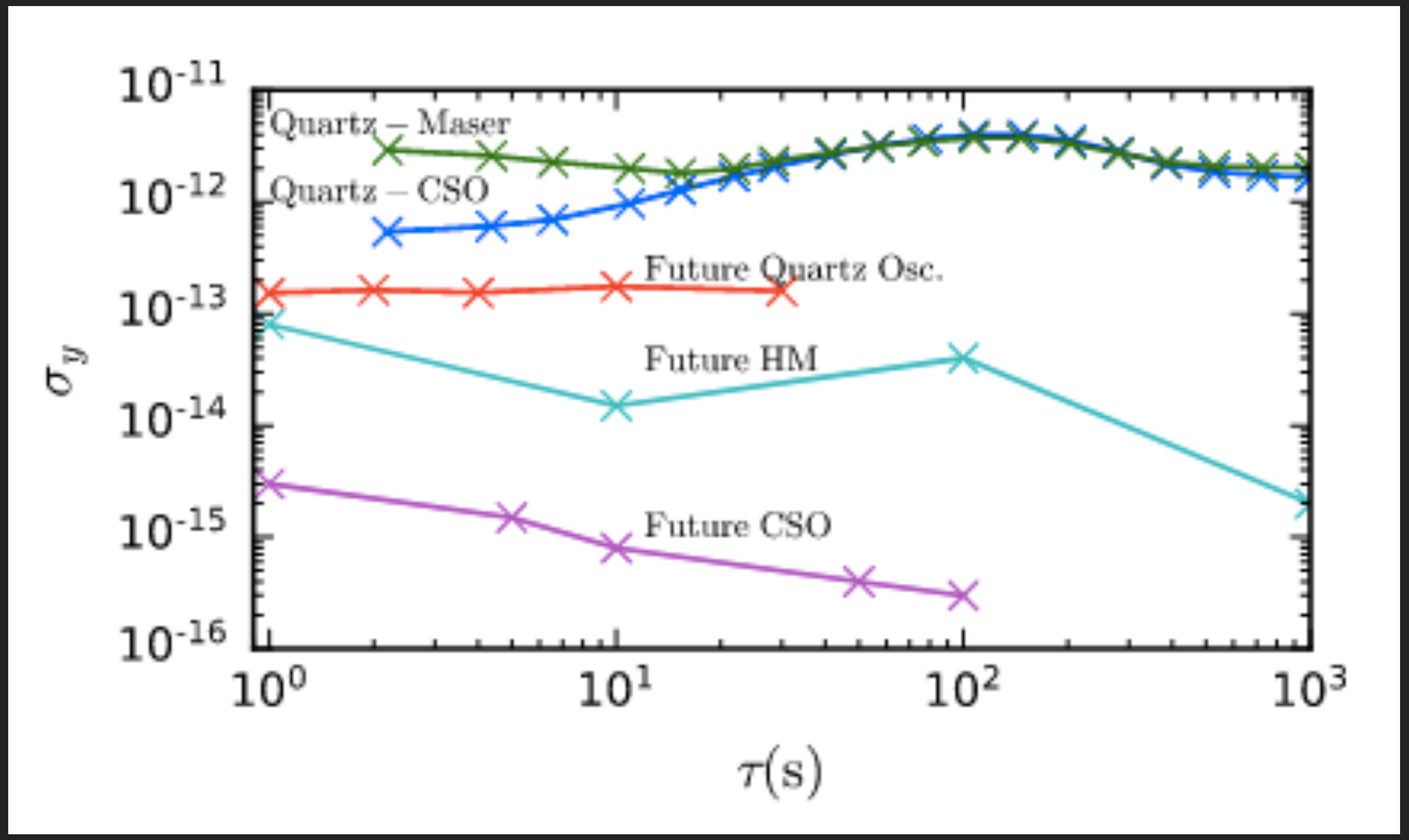
Scalar Dark Matter

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

Phys. Rev. Lett. **126**, 071301 – Published 18 February 2021





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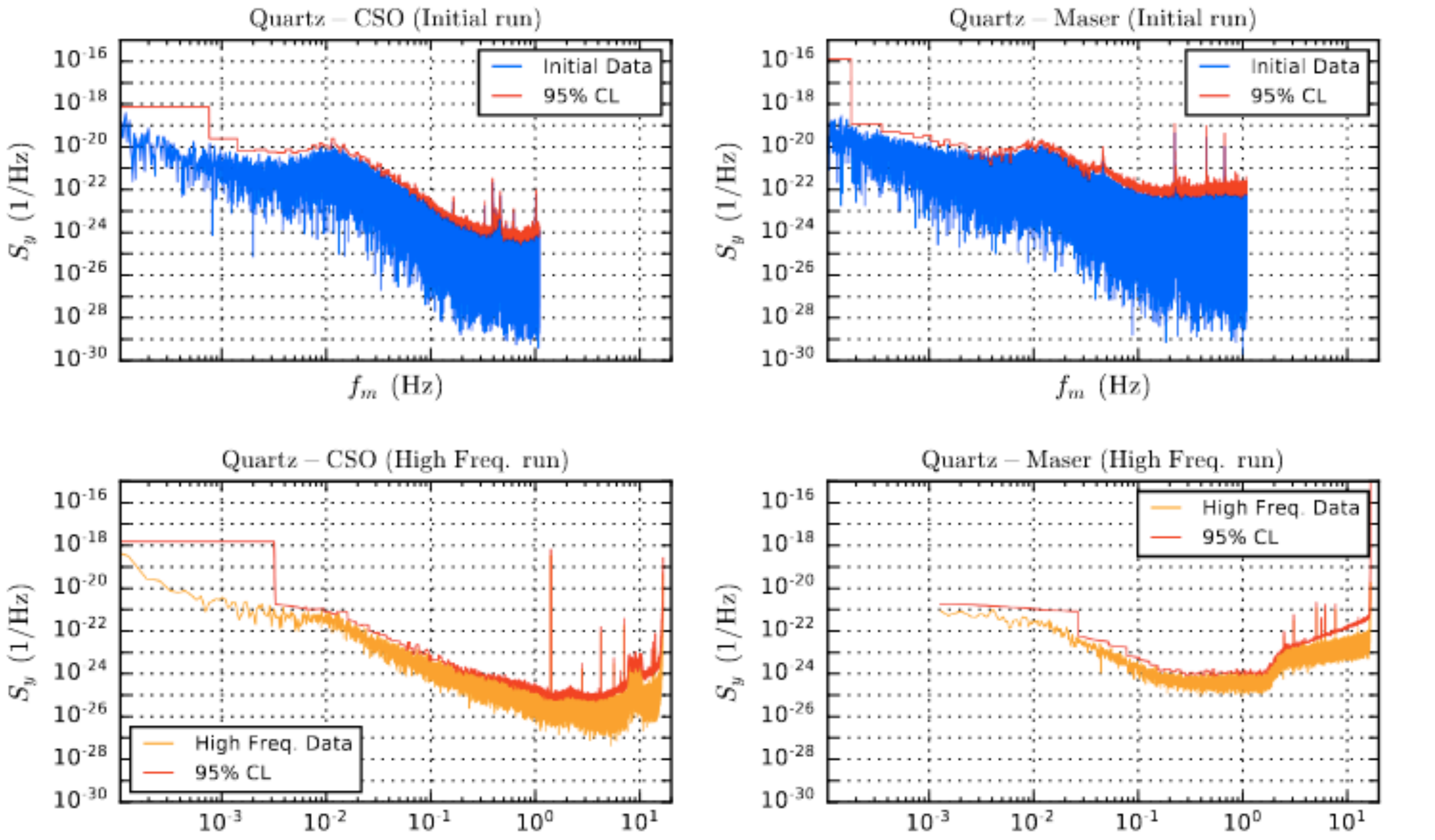
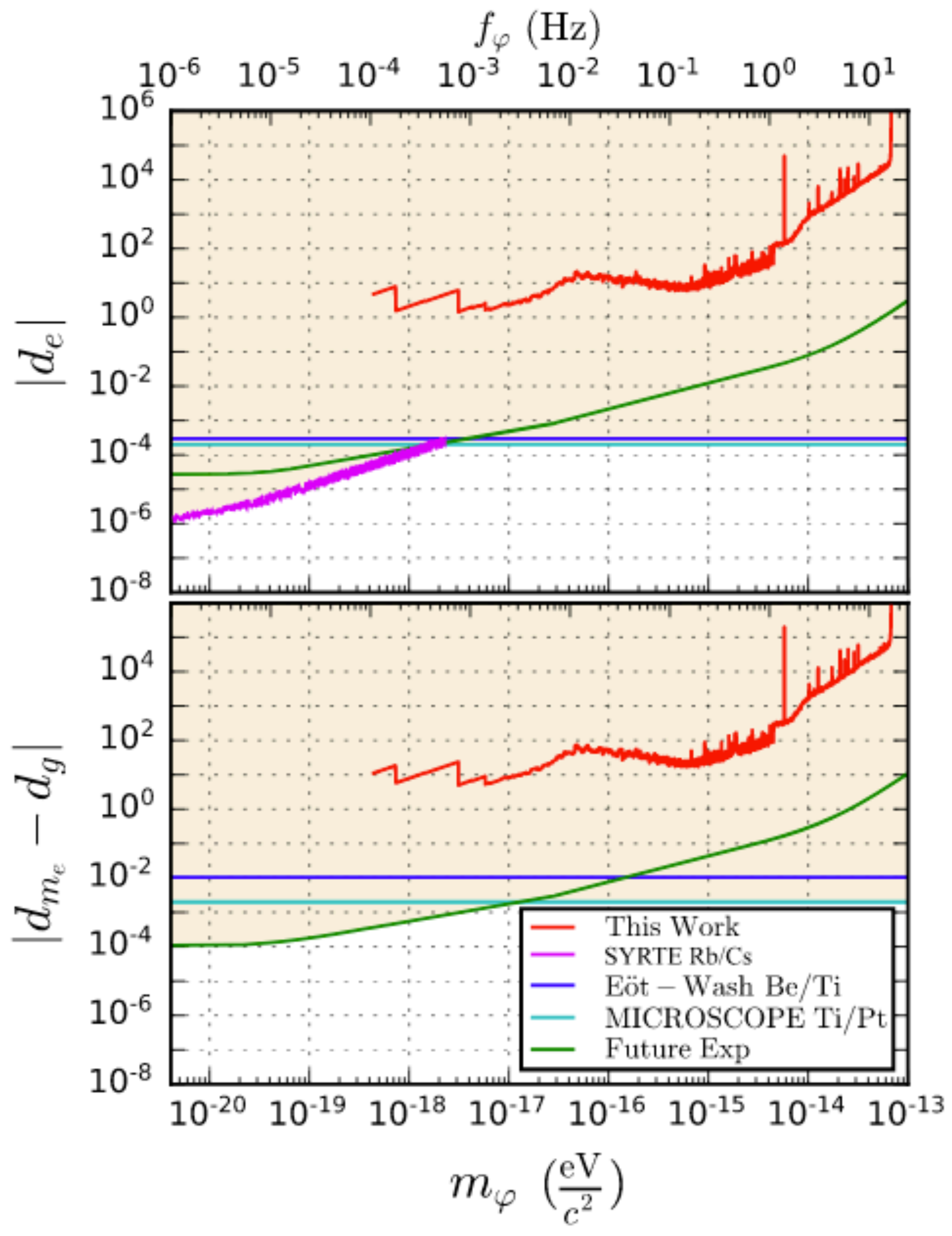
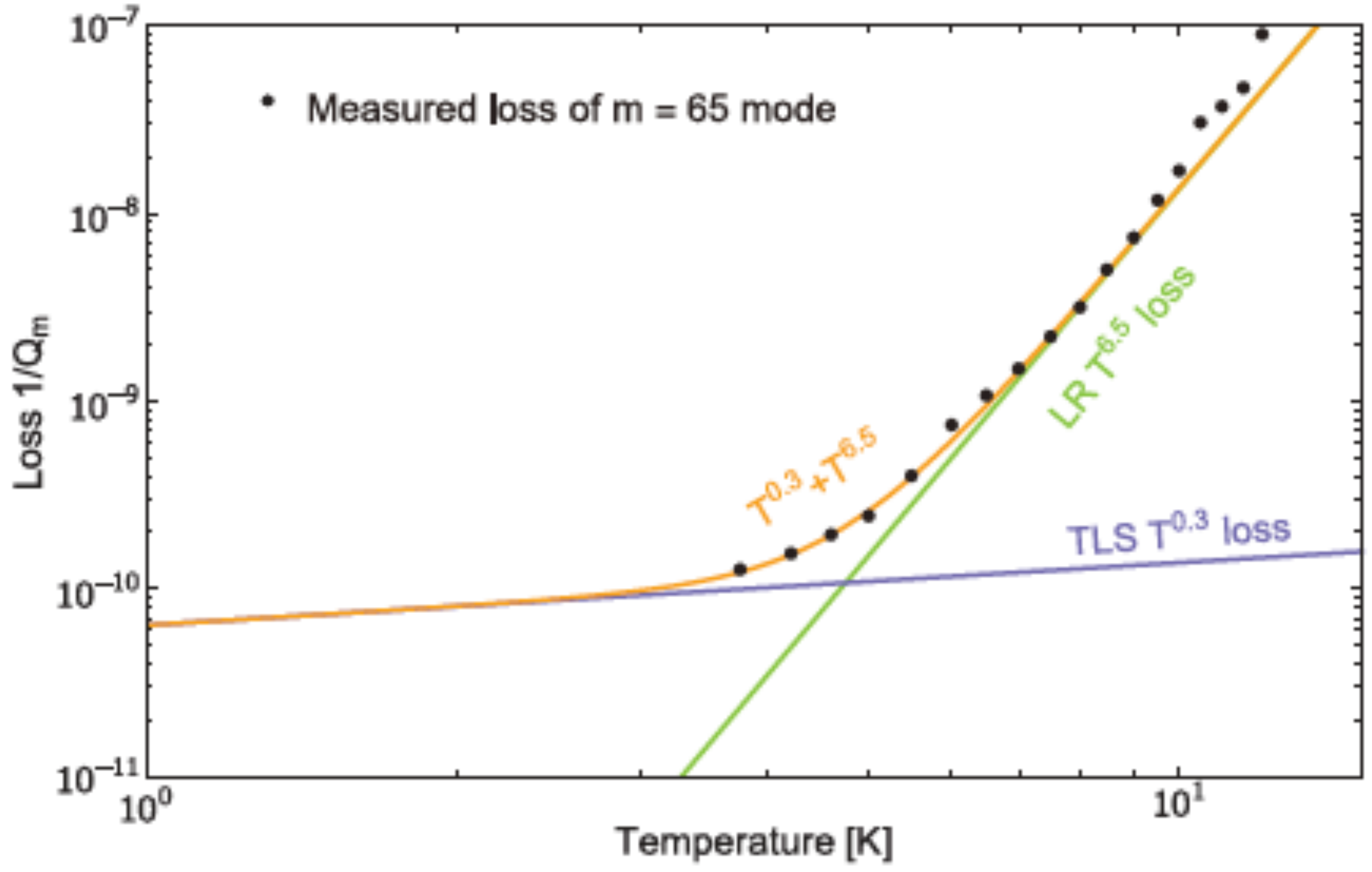


FIG. 6. PSD of frequency noise for all initial and later runs are shown by the blue and orange traces respectively. Also shown in Red is the excluded power to 95% confidence.



Next Generation Experiment? Cryogenic BAW (4K) ->Q~10^{10}
4 orders better than room temp



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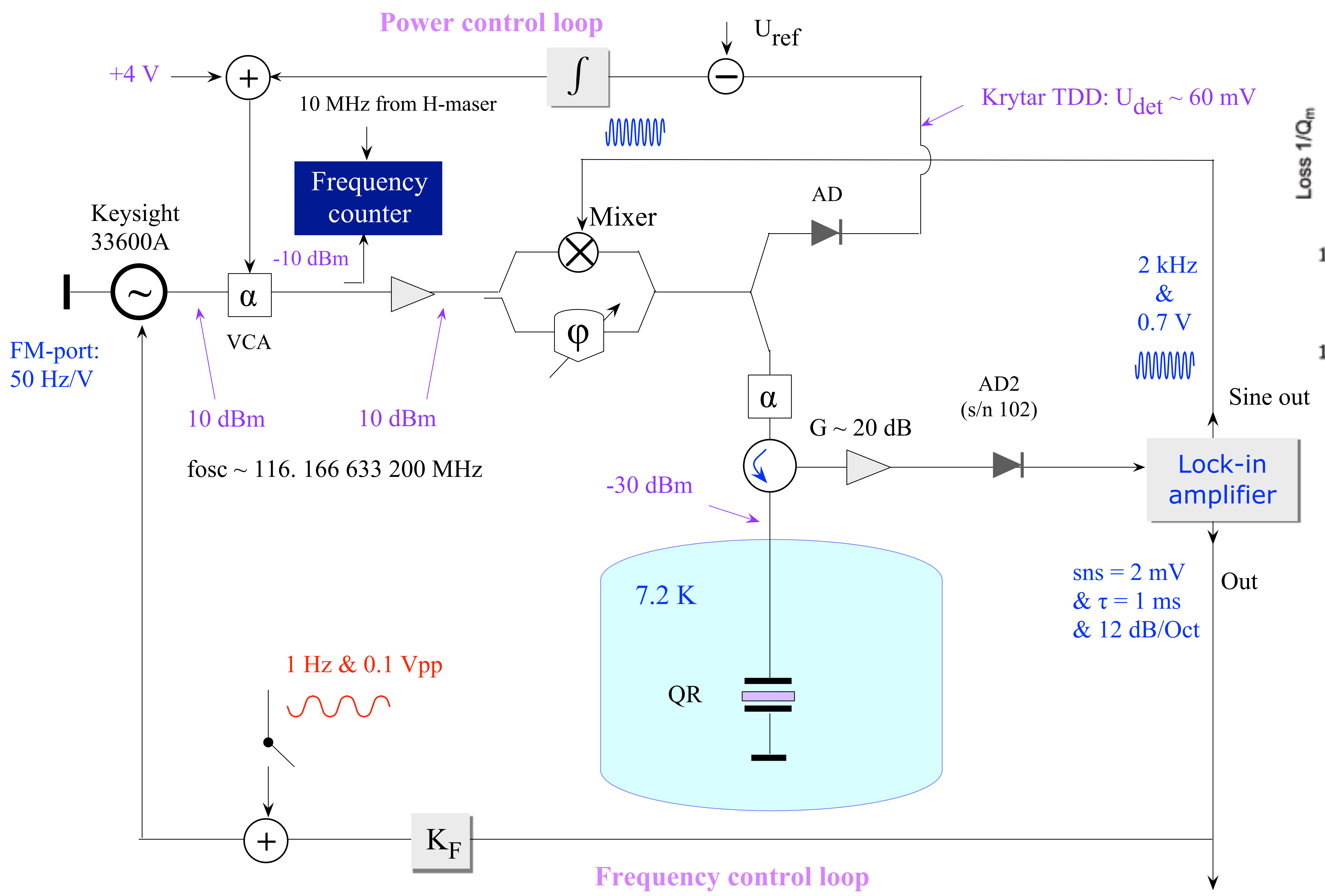

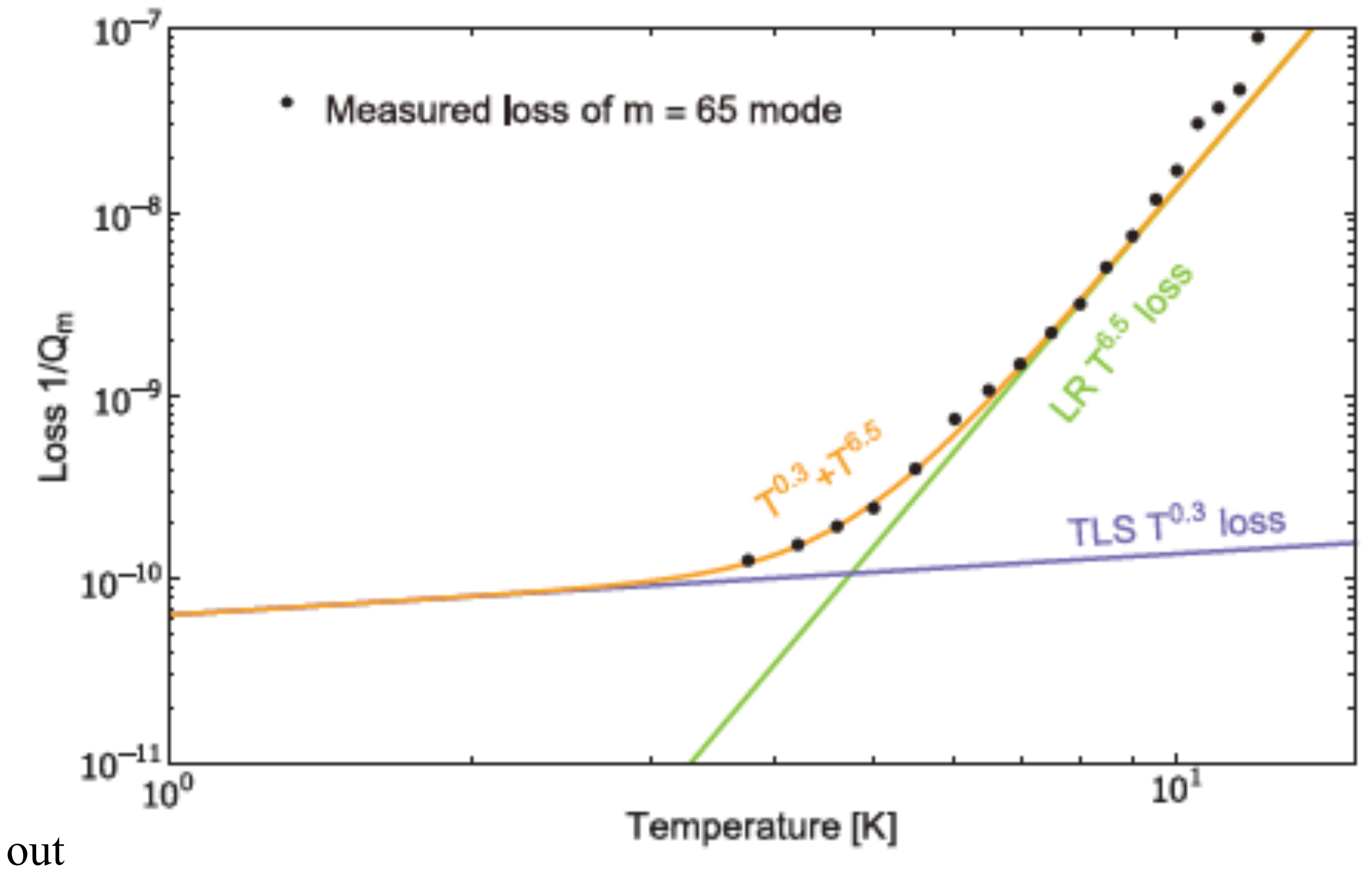

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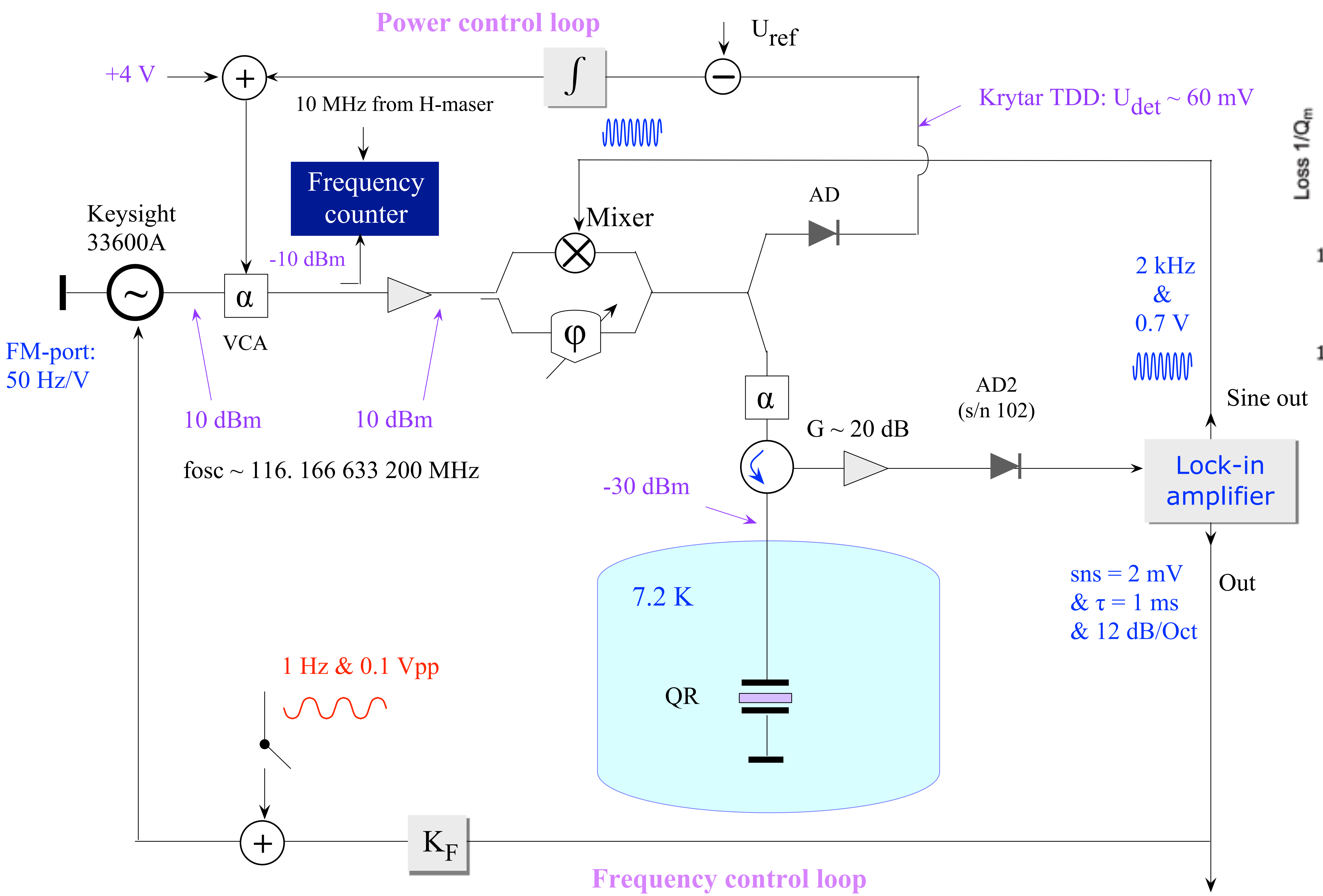
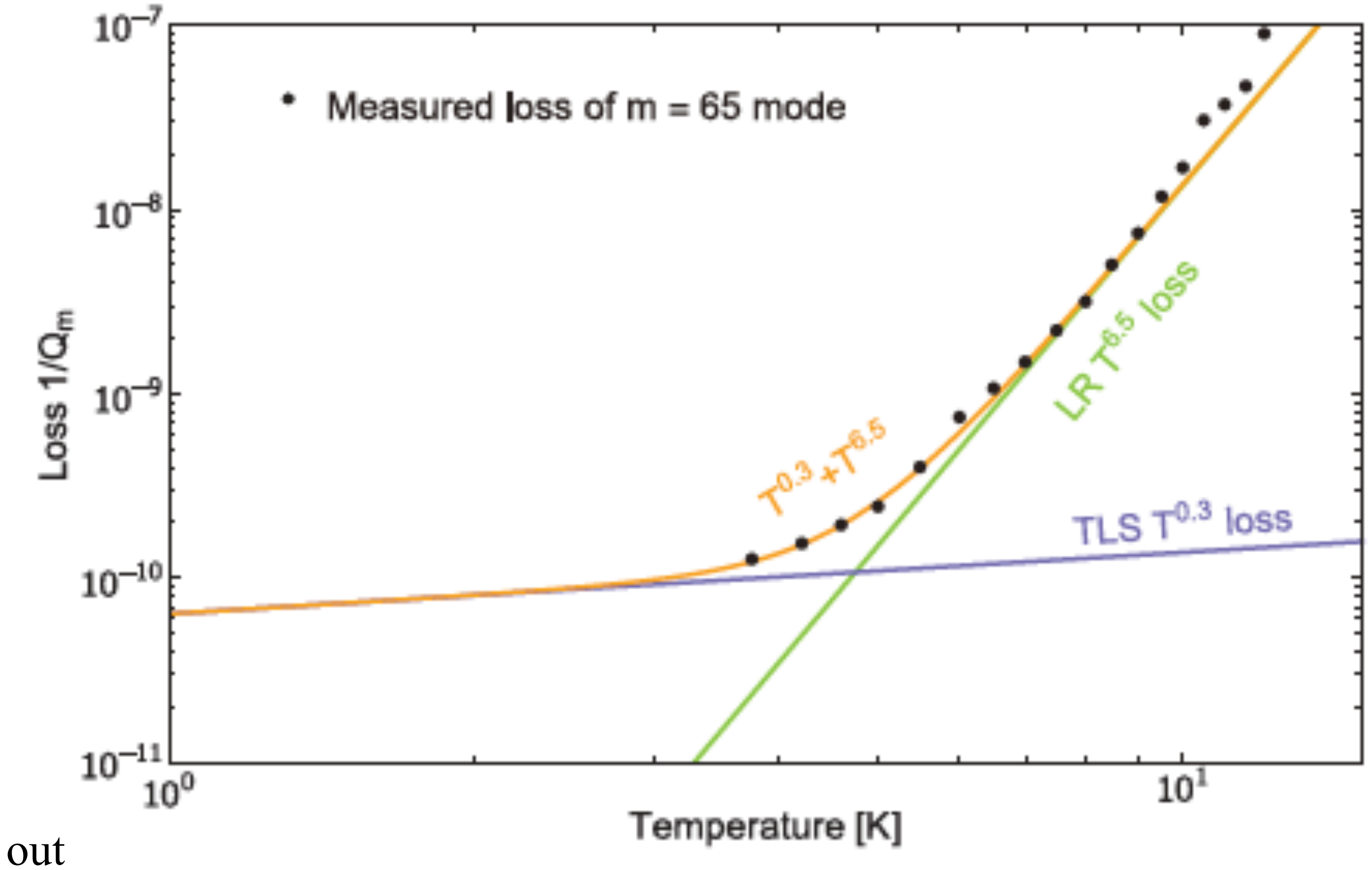
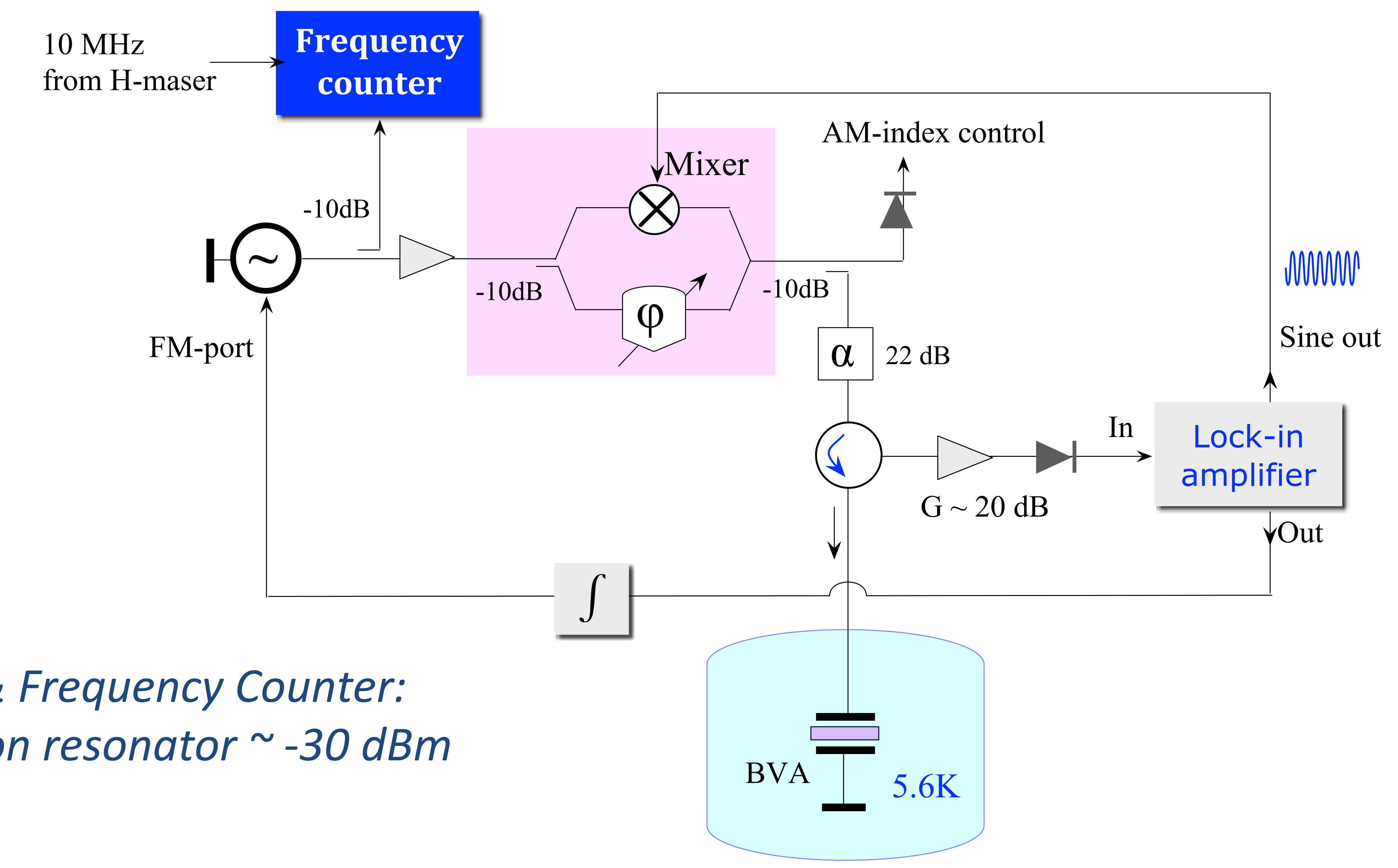
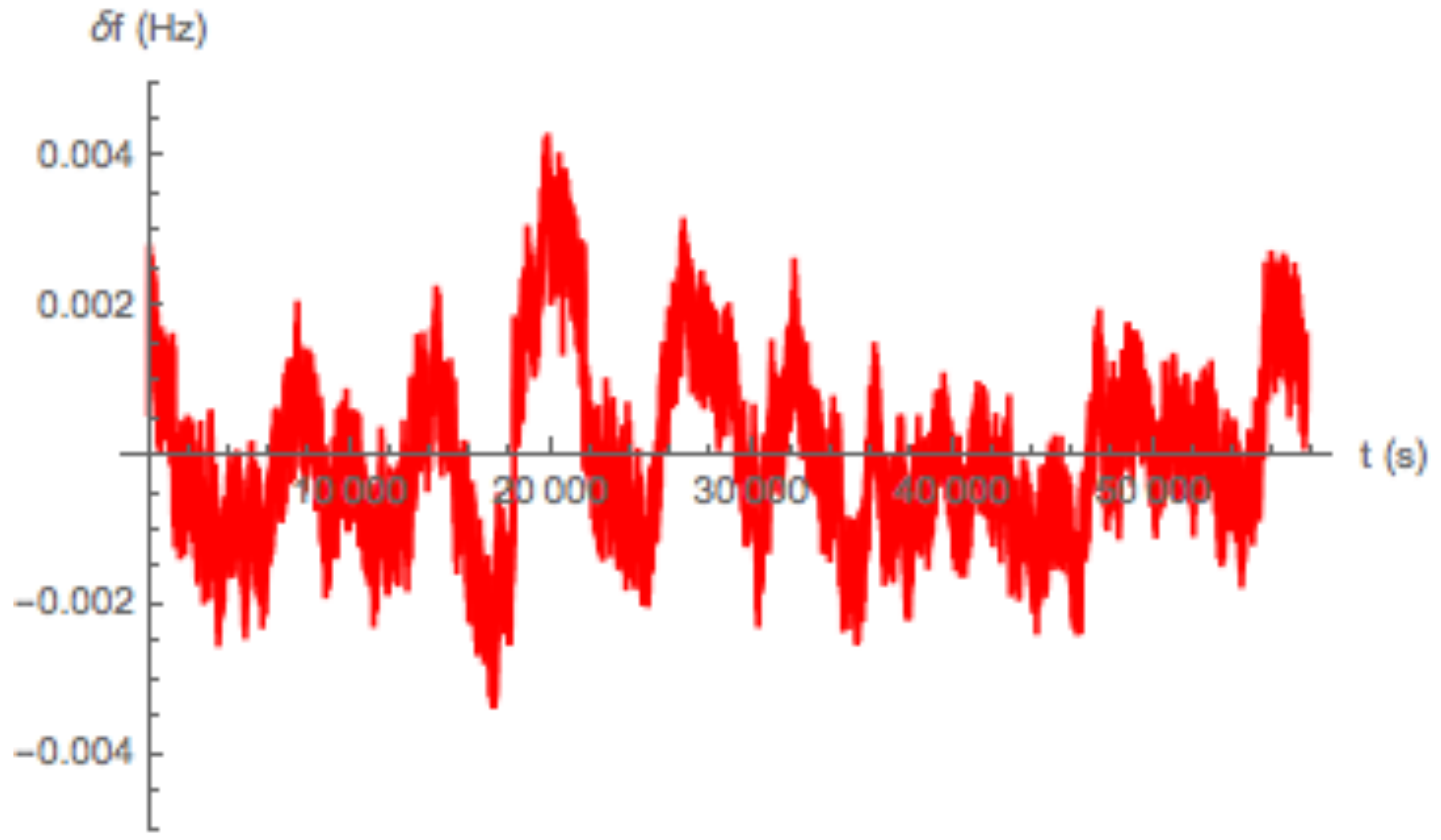


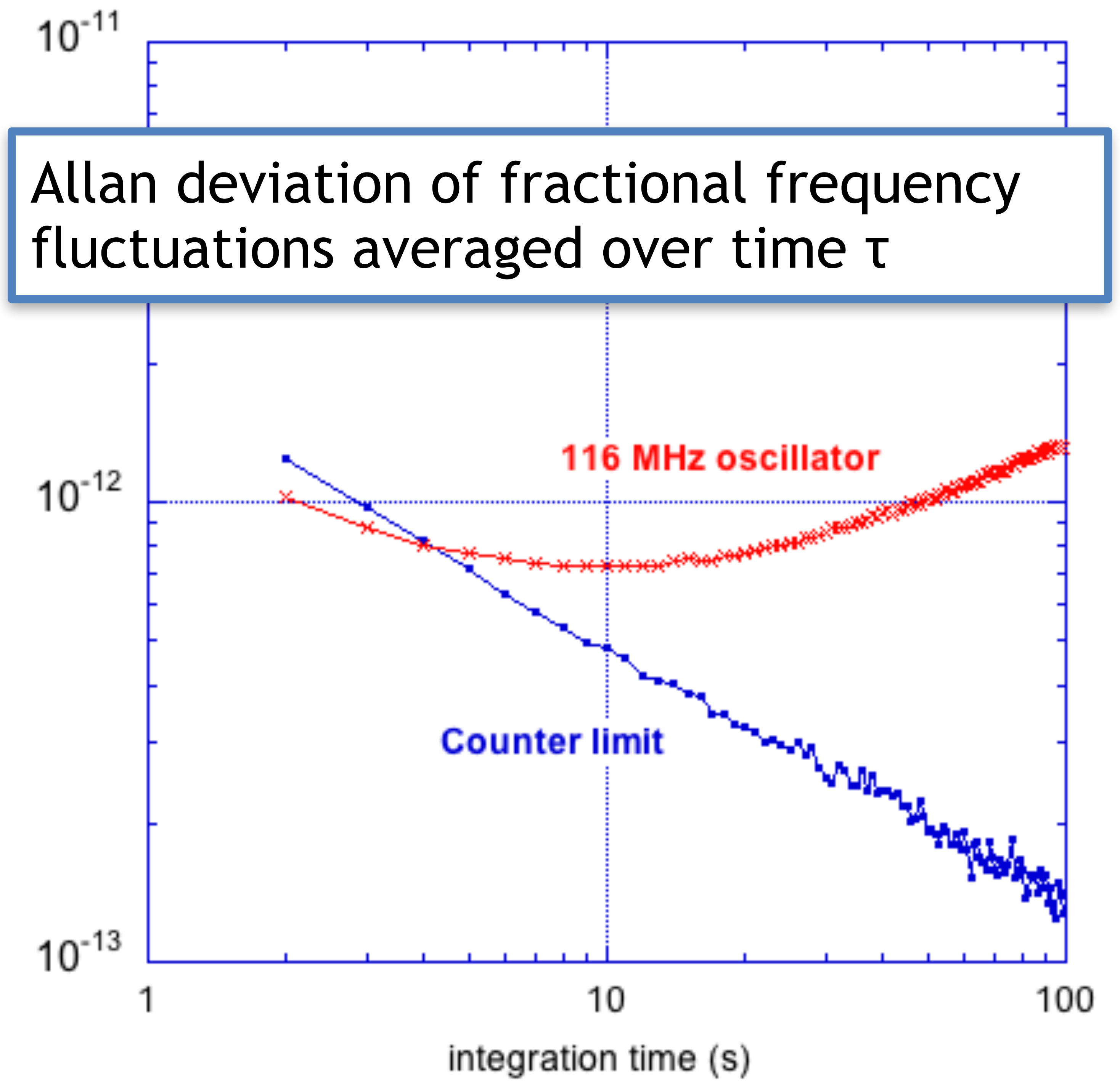


Frequency Stability Measurements



RF oscillator & Frequency Counter:
Power incident on resonator ~ -30 dBm



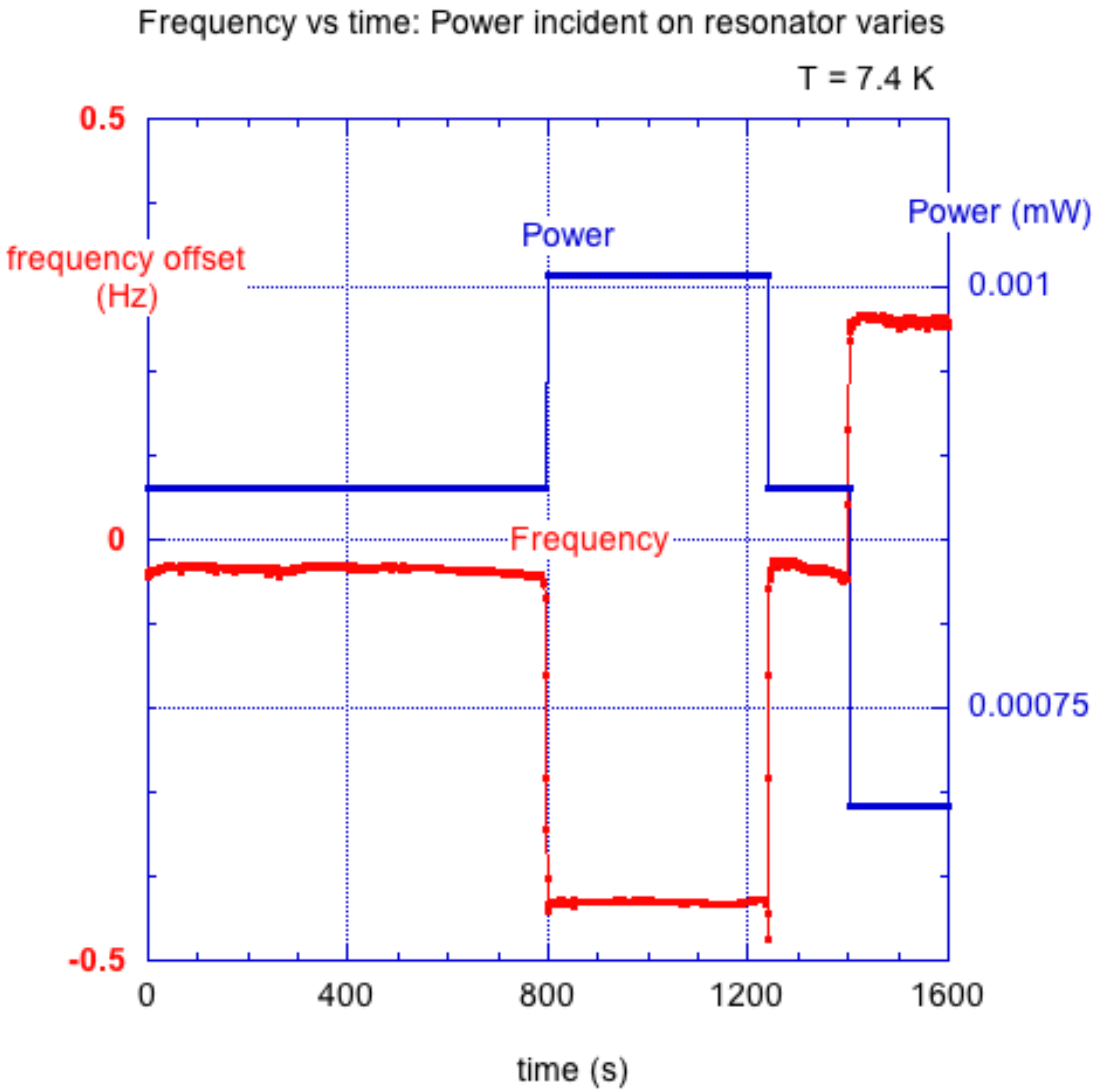


NB

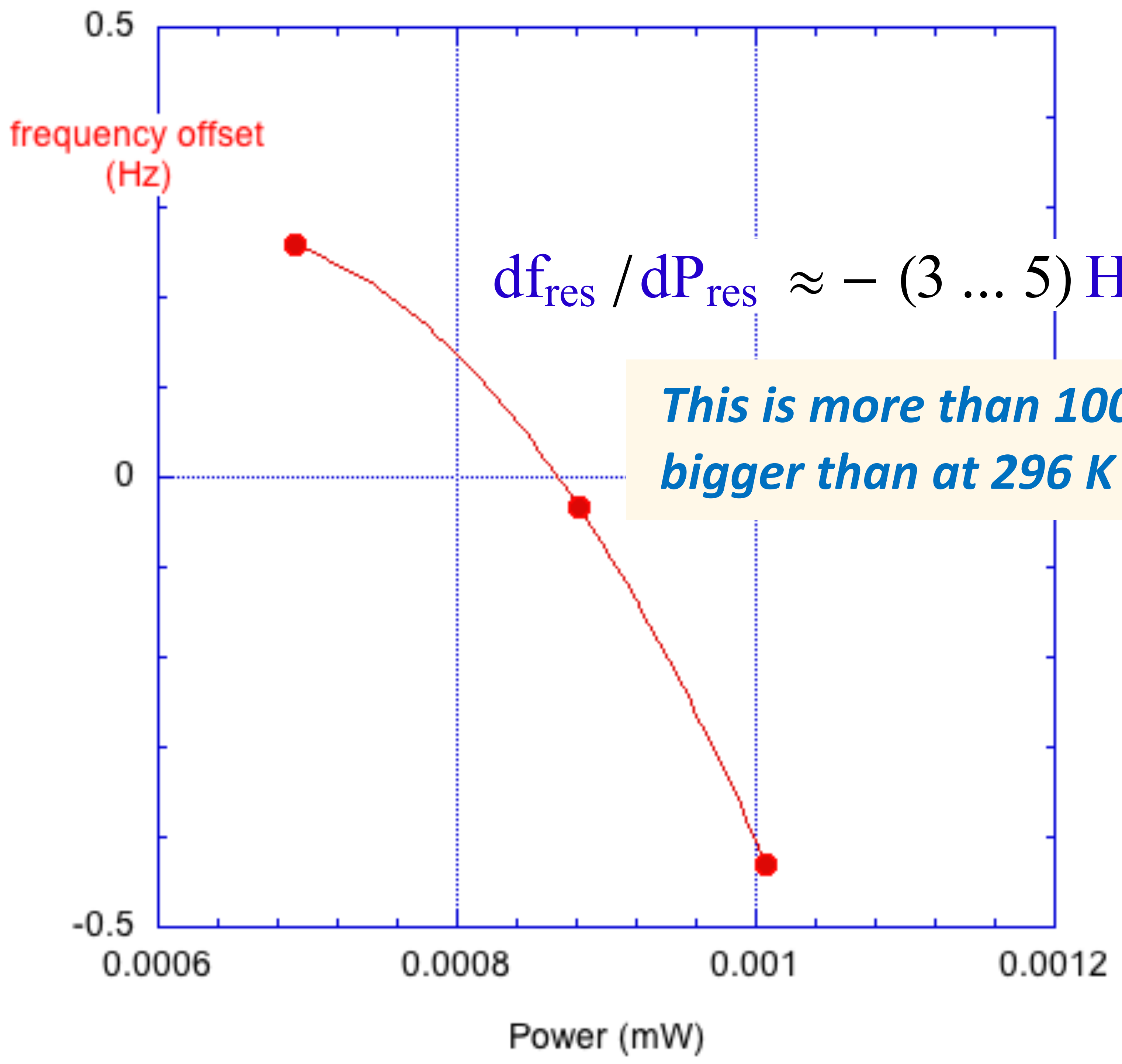
1. There is no noticeable frequency drift despite the use of room temperature detection system.

2. Frequency stability improves by ~ 10% when LA sensitivity increases from 20 to 5 mV

Cryogenic Quartz Oscillator: Power-to-Frequency Conversion: Duffing Nonlinearity



Power incident on cryogenic BVA resonator (blue) and oscillator frequency (red) vs time

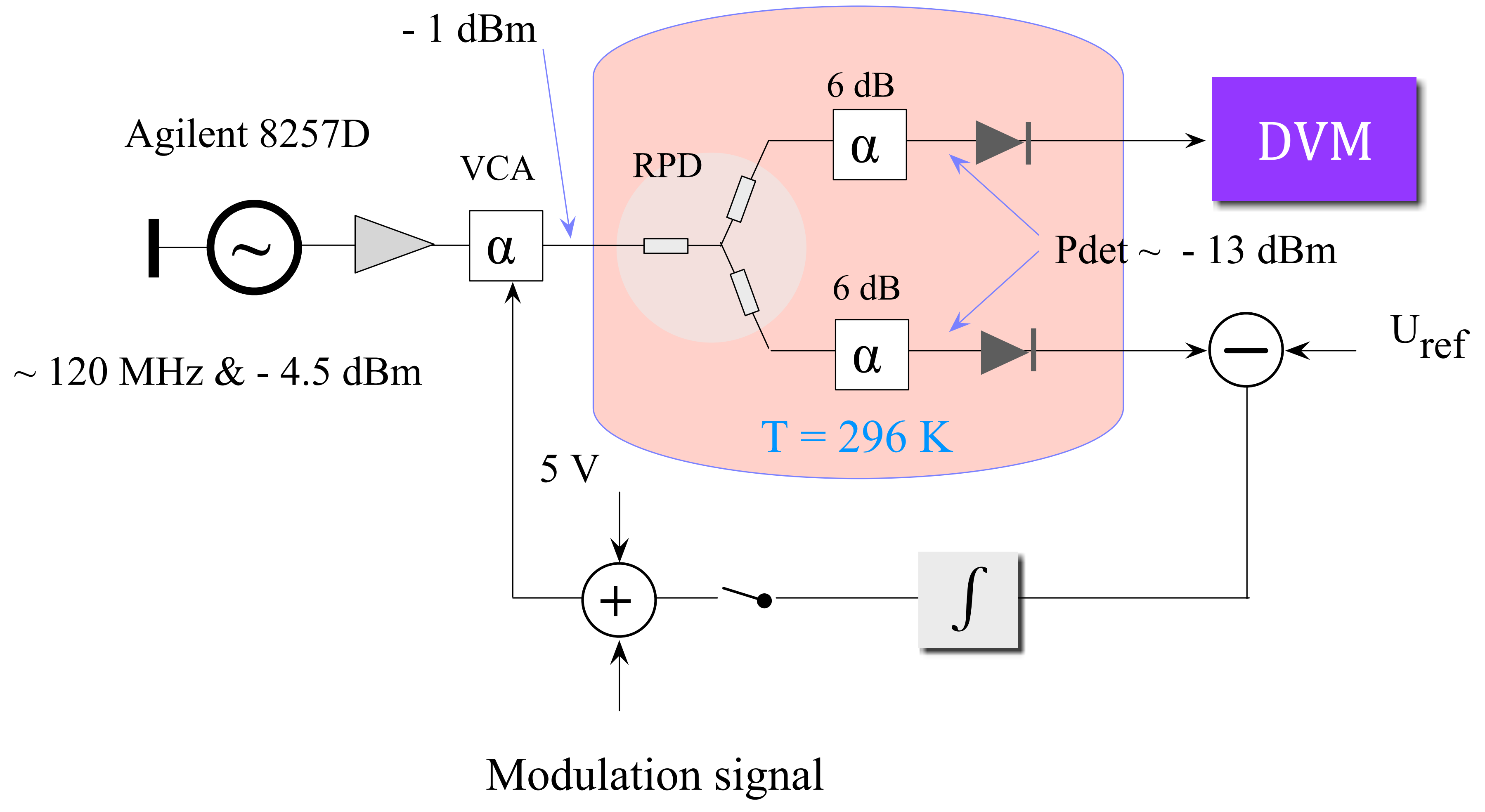


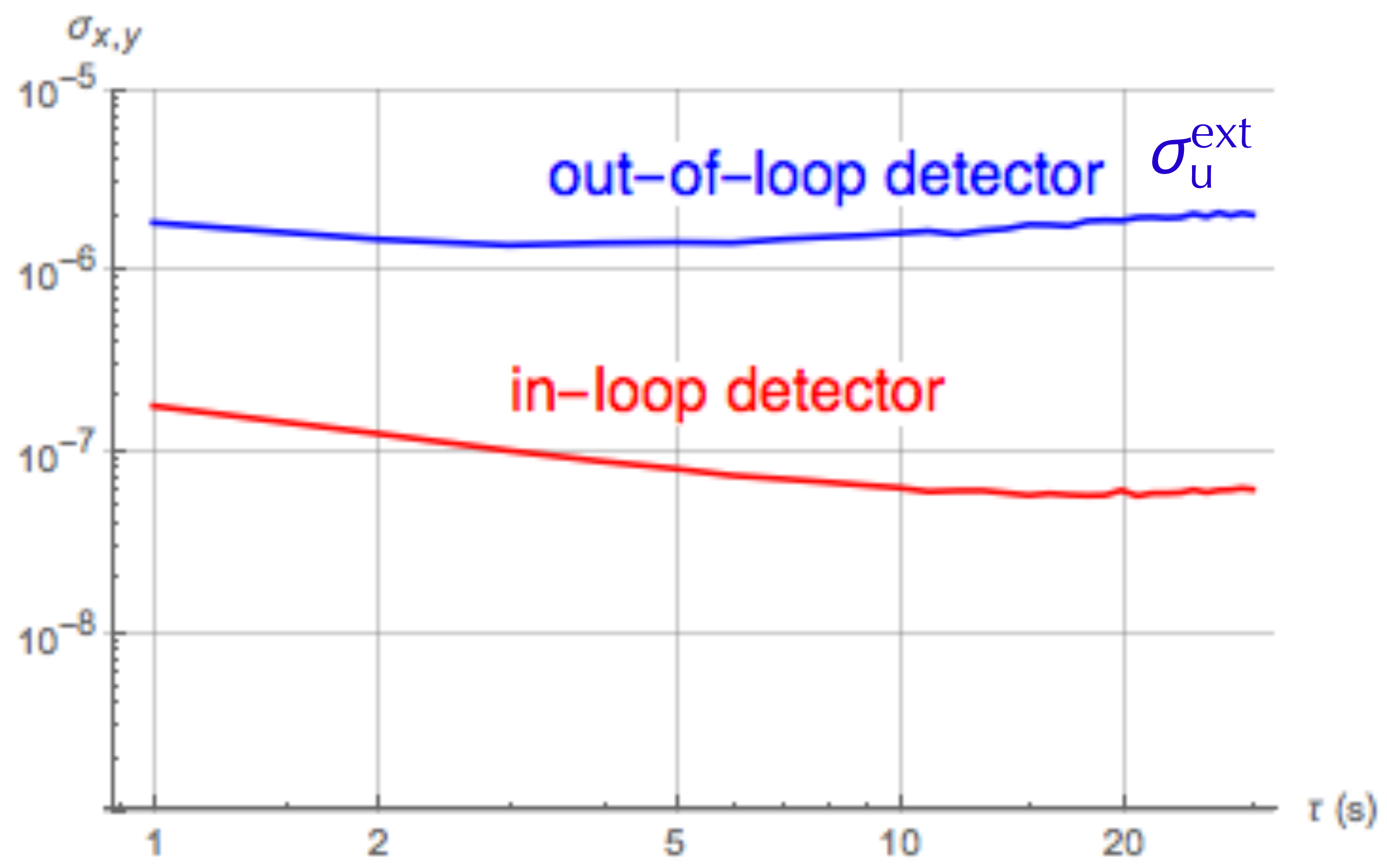
$$df_{res} / dP_{res} \approx -(3 \ldots 5)\, \mathrm{Hz}/\mu\mathrm{W}$$

This is more than 1000 times bigger than at 296 K !

Oscillator frequency vs power

Oscillator Frequency Stability due to Power Fluctuations





Oscillator fractional frequency stability due to power fluctuations

$$\eta = P_{res} / P_{det} \ll 1$$

Allan deviation of fractional voltage fluctuations at the output of out-of-loop detector

$$\sigma_y = \frac{1}{f_{res}} \frac{df_{res}}{dP_{res}} \eta \frac{\sigma_u^{ext}}{\sqrt{\left(S_{AD}^{in-loop}\right)^2 + \left(S_{AD}^{ext}\right)^2}}$$

Power-to-Voltage conversions of amplitude detectors (see next slides)

Oscillator parameters:

$P_{det} = -10$ dBm

$P_{res} = -30$ dBm

$df_{res} / dP_{res} \approx -(3 \dots 5)$ Hz/μW

$du / dP_{det} \approx 1000$ mV/mW

σ_u^{ext} (1 ... 30 s) $\approx 2 \times 10^{-6}$

σ_y (1 ... 30 s) $\approx 5 \dots 7 \times 10^{-13}$

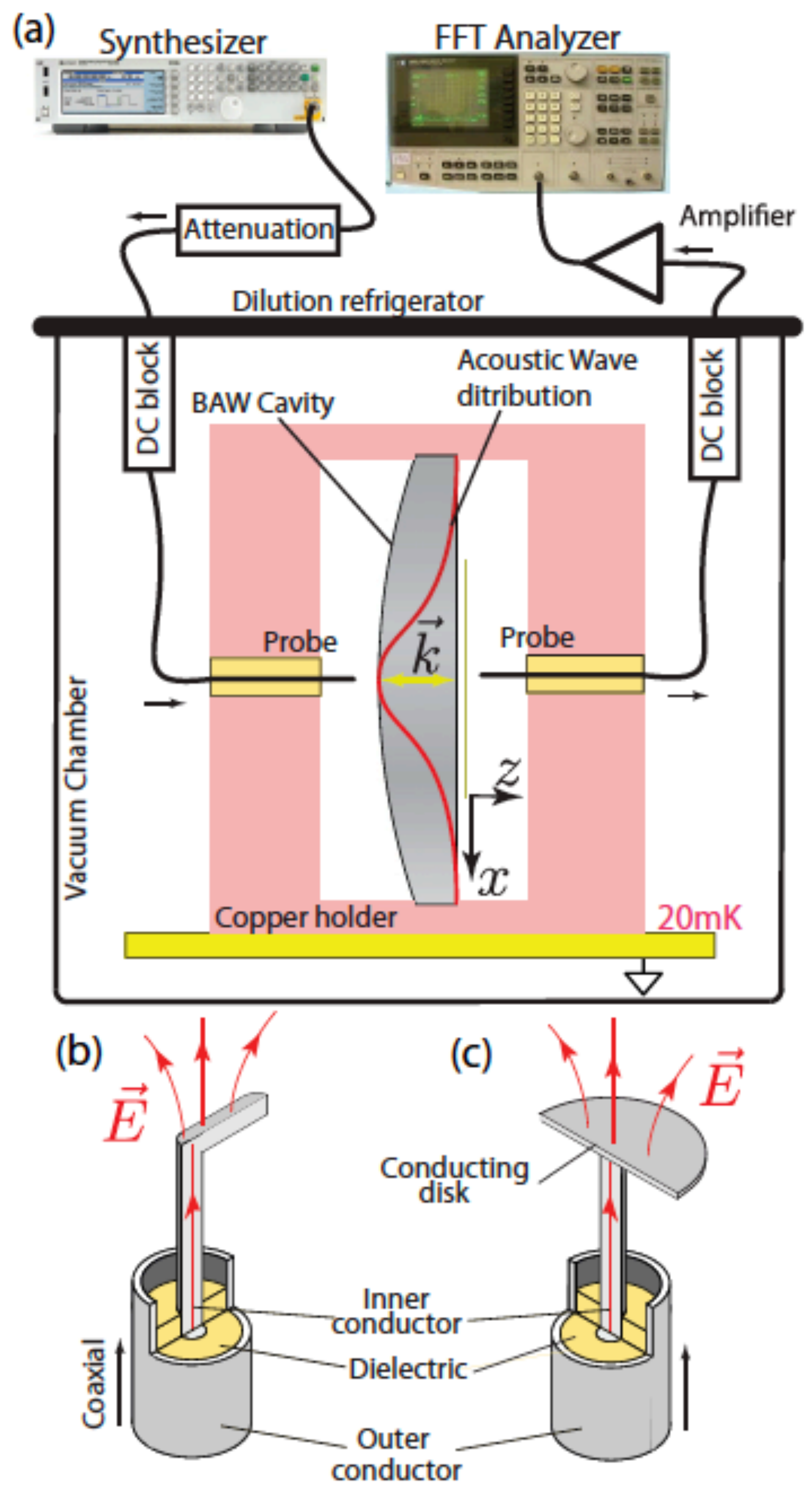
PHYSICAL REVIEW RESEARCH **2**, 023035 (2020)

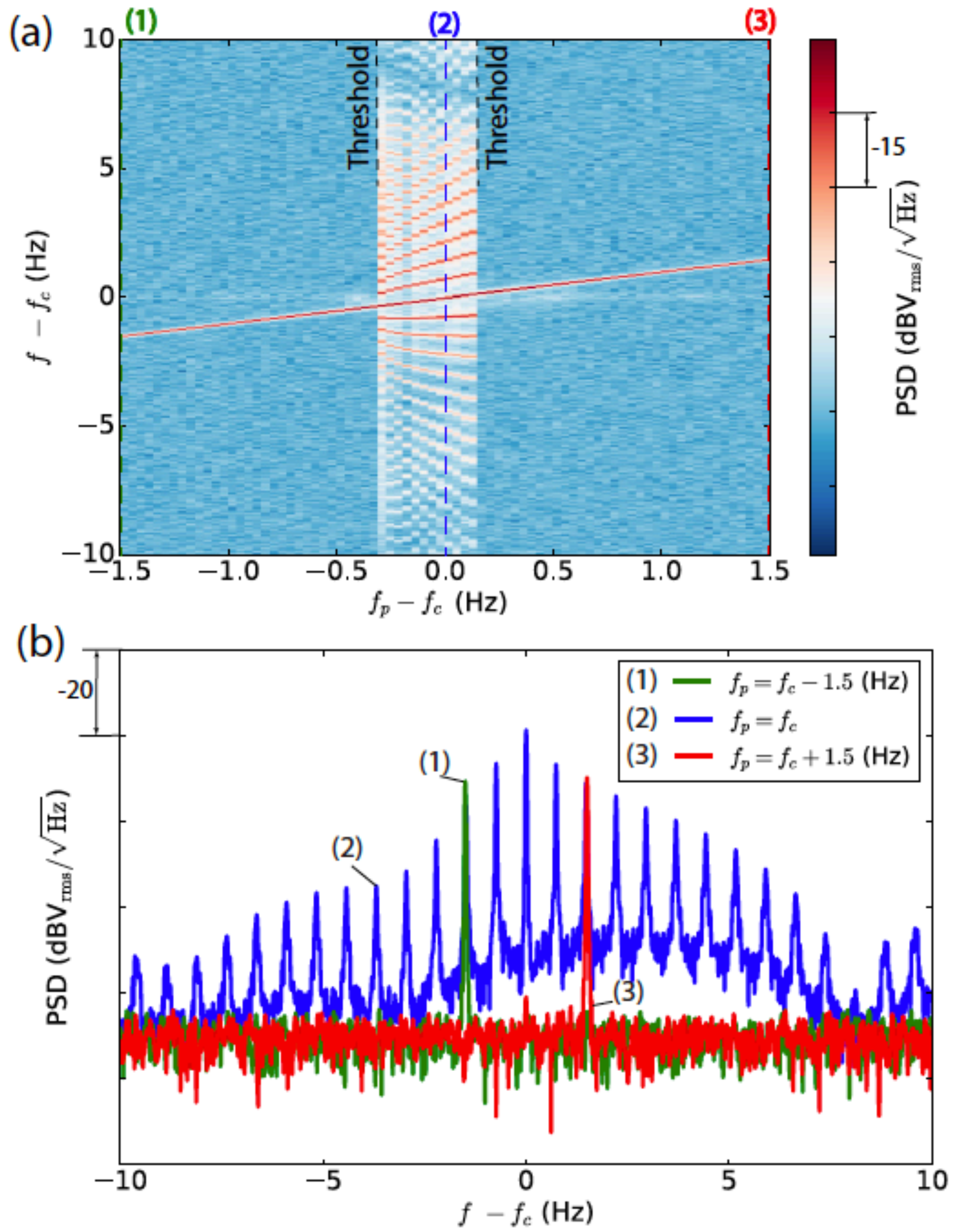
Generation of ultralow power phononic combs

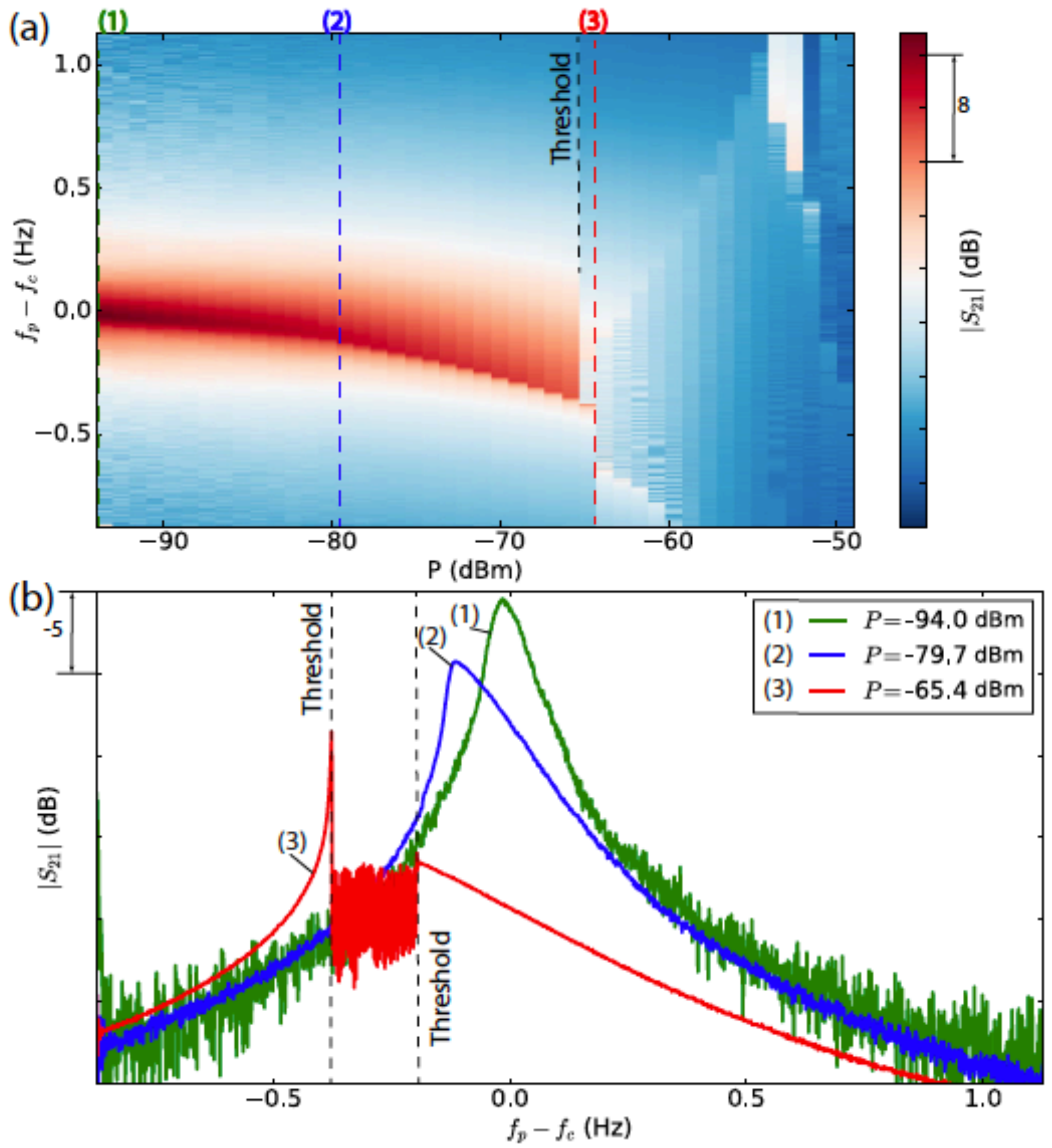
Maxim Goryachev,[1,*] Serge Galliou,[2] and Michael E. Tobar[1]

[1]*ARC Centre of Excellence for Engineered Quantum Systems, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*

[2]*FEMTO-ST Institute, Université Bourgogne Franche-Comté, Centre National de la Recherche Scientifique, ENSMM, 26 Rue de lÉpitaphe, 25000 Besançon, France*







applied sciences

MDPI

Article

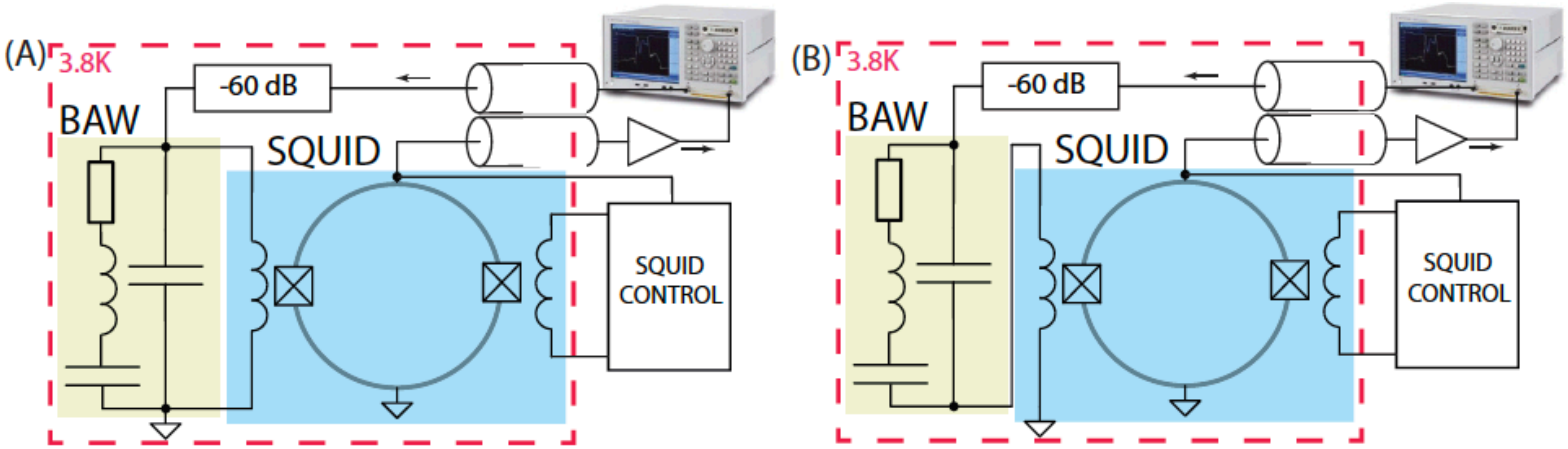
Inducing Strong Non-Linearities in a Phonon Trapping Quartz Bulk Acoustic Wave Resonator Coupled to a Superconducting Quantum Interference Device

Maxim Goryachev [1], Eugene N. Ivanov [1], Serge Galliou [2] and Michael E. Tobar [1,*]

1 ARC Centre of Excellence for Engineered Quantum Systems, University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia; maxim.goryachev@uwa.edu.au (M.G.); eugene.ivanov@uwa.edu.au (E.N.I.)
2 FEMTO-ST Institute, CNRS, Univ. Bourgogne Franche Comte, ENSMM, 26 Chemin de l'Épitaphe, 25000 Besançon, France; serge.galliou@ens2m.fr
* Correspondence: michael.tobar@uwa.edu.au

Received: 22 March 2018; Accepted: 4 April 2018; Published: 11 April 2018

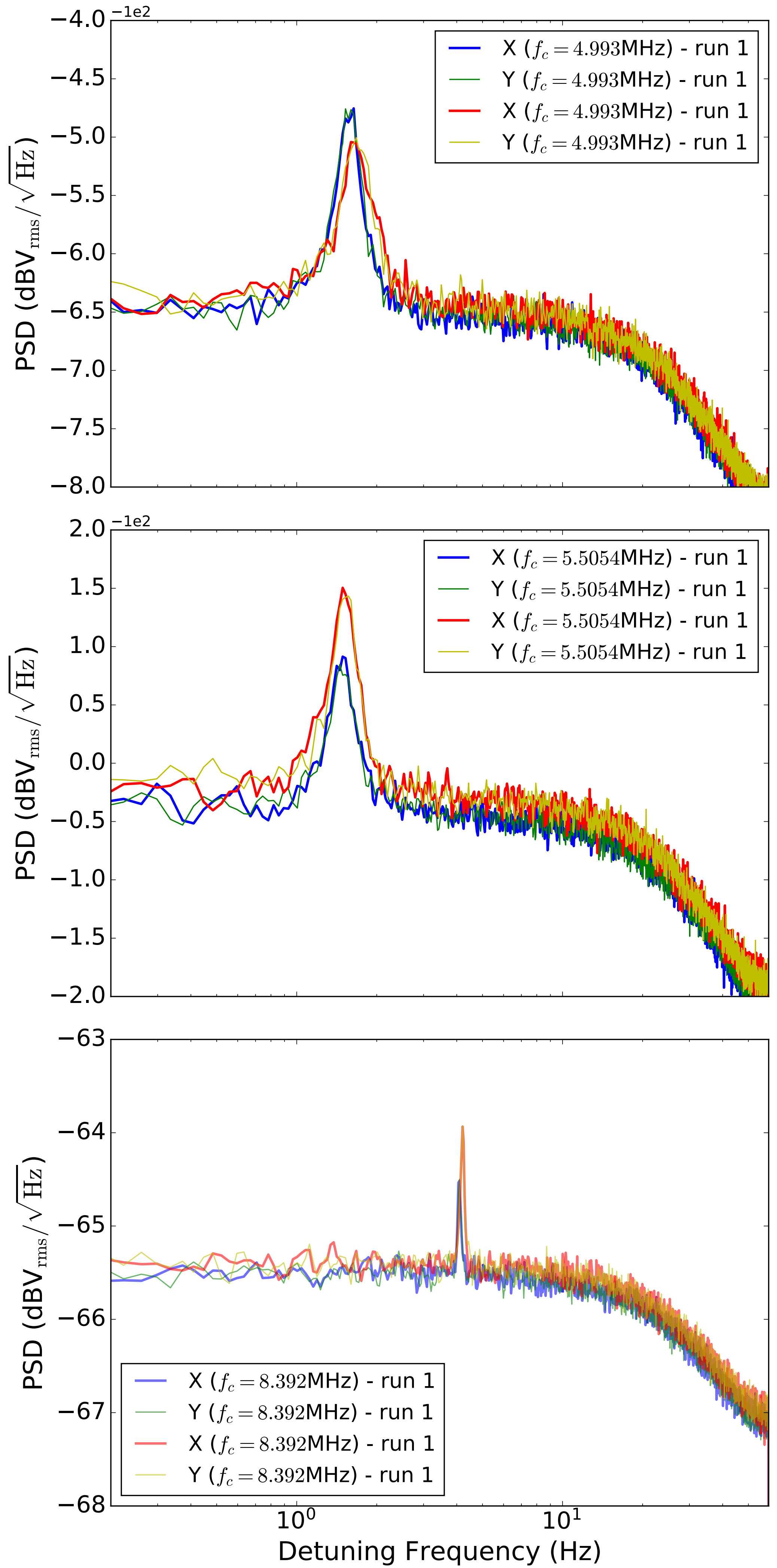
check for updates

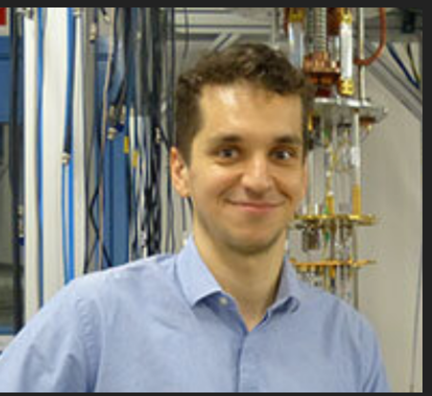


Passive Bulk Acoustic Wave Resonators at Low Temperatures

* Avoid the non-linear regime
* Measuring Thermal Noise; Continuous; ~ 1 year
* Search: GWs; Scalar Dark Matter; Test Quantum Gravity

20 mK





High Frequency Gravitational Waves

Gravitational wave detection with high frequency phonon trapping acoustic cavities

Maxim Goryachev and Michael E. Tobar
Phys. Rev. D **90**, 102005 – Published 24 November 2014

arXiv.org > gr-qc > arXiv:2102.05859

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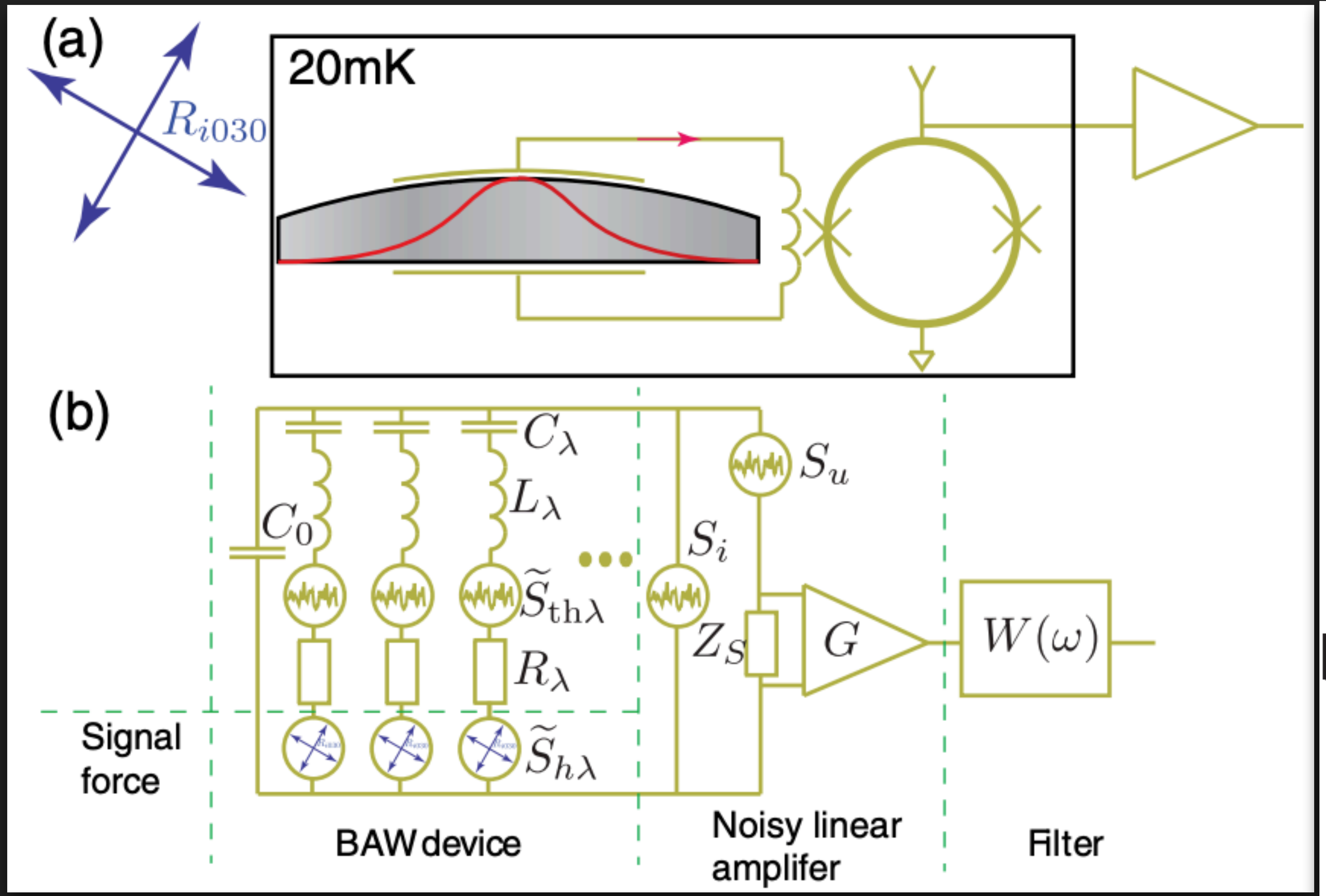
General Relativity and Quantum Cosmology

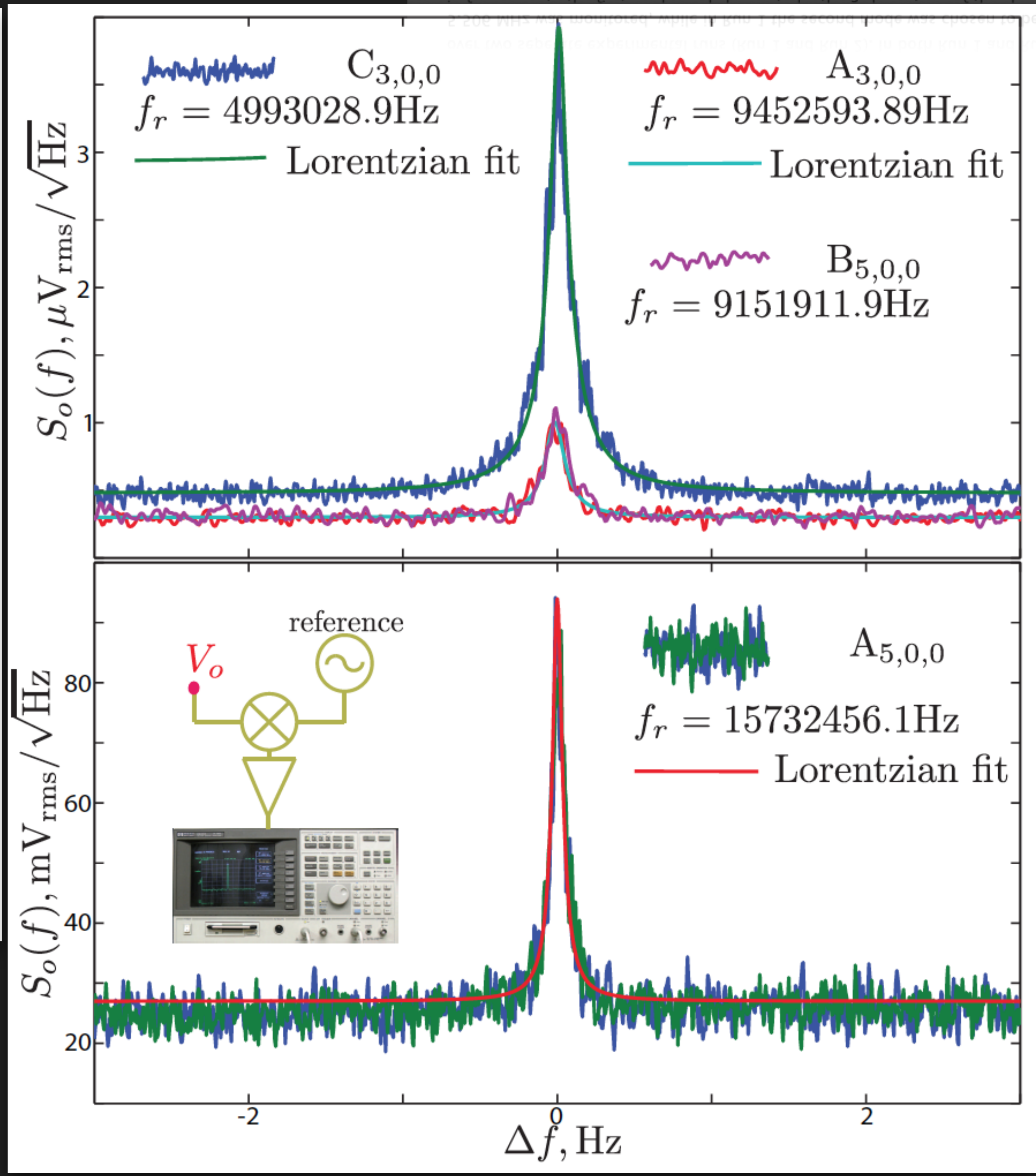
[Submitted on 11 Feb 2021]

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

Maxim Goryachev, William M. Campbell, Ik Siong Heng, Serge Galliou, Eugene N. Ivanov, Michael E. Tobar

This work describes the operation of a High Frequency Gravitational Wave detector based on a cryogenic Bulk Acoustic Wave (BAW) cavity and reports observation of rare events during 153 days of operation over two seperate experimental runs (Run 1 and Run 2). In both Run 1 and Run 2 two modes were simultaneously monitored. Across both runs, the 3rd overtone of the fast shear mode (3B) operating at 5.506 MHz was monitored, while in Run 1 the second mode was chosen to be the 5th OT of the slow shear mode (5C) operating at 8.392 MHz. However, in Run 2 the second mode was selected to be closer in frequency to the first mode, and chosen to be the 3rd overtone of the slow shear mode (3C) operating at 4.993 MHz. Two strong events were observed as transients responding to energy deposition within acoustic modes of the cavity. The first event occurred during Run 1 on the 12/05/2019 (UTC), and was observed in the 5.506 MHz mode, while the second mode at 8.392 MHz observed no event. During Run 2, a second event occurred on the 27/11/2019(UTC) and was observed by both modes. Timing of the events were checked against available environmental observations as well as data from other detectors. Various possibilities explaining the origins of the events are discussed.





- *Neutron star mergers*
- *Light primordial black hole mergers*
- *Exotic compact objects*
- *Black hole superradiance*
- *Inflation*
- *Preheating*
- *Phase transitions*
- *Topological defects*
- *Evaporating primordial black holes*

Appl. Phys. Lett. 105, 153505 (2014)

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Scalar Dark Matter

Problem, Quartz Q larger than Viralized Dark matter

Search For Cold Flows?

PRL 116, 031102 (2016) PHYSICAL REVIEW LETTERS week ending 22 JANUARY 2016

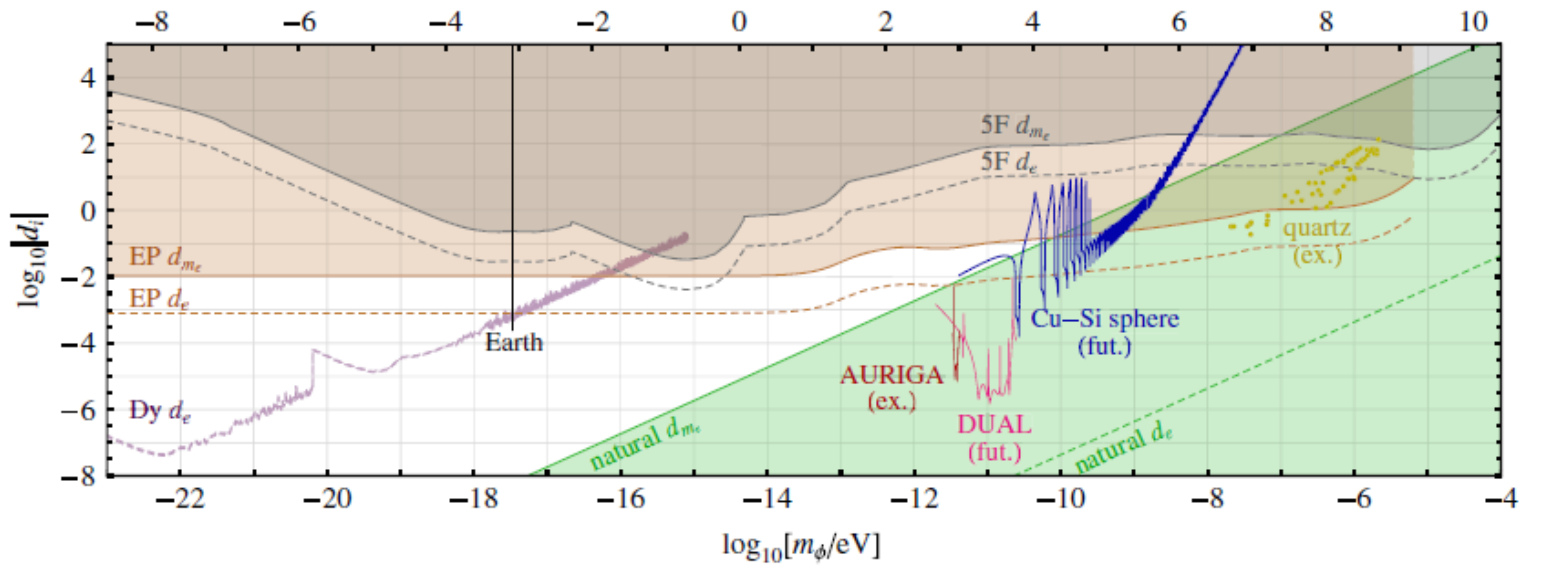
Sound of Dark Matter: Searching for Light Scalars with Resonant-Mass Detectors

Asimina Arvanitaki,[1,*] Savas Dimopoulos,[2,†] and Ken Van Tilburg[2,‡]
[1]Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada
[2]Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA

(Received 23 August 2015; revised manuscript received 17 October 2015; published 22 January 2016)

The fine-structure constant and the electron mass in string theory are determined by the values of scalar fields called moduli. If the dark matter takes on the form of such a light modulus, it oscillates with a frequency equal to its mass and an amplitude determined by the local dark-matter density. This translates into an oscillation of the size of a solid that can be observed by resonant-mass antennas. Existing and planned experiments, combined with a dedicated resonant-mass detector proposed in this Letter, can probe dark-matter moduli with frequencies between 1 kHz and 1 GHz, with much better sensitivity than searches for fifth forces.

DOI: 10.1103/PhysRevLett.116.031102



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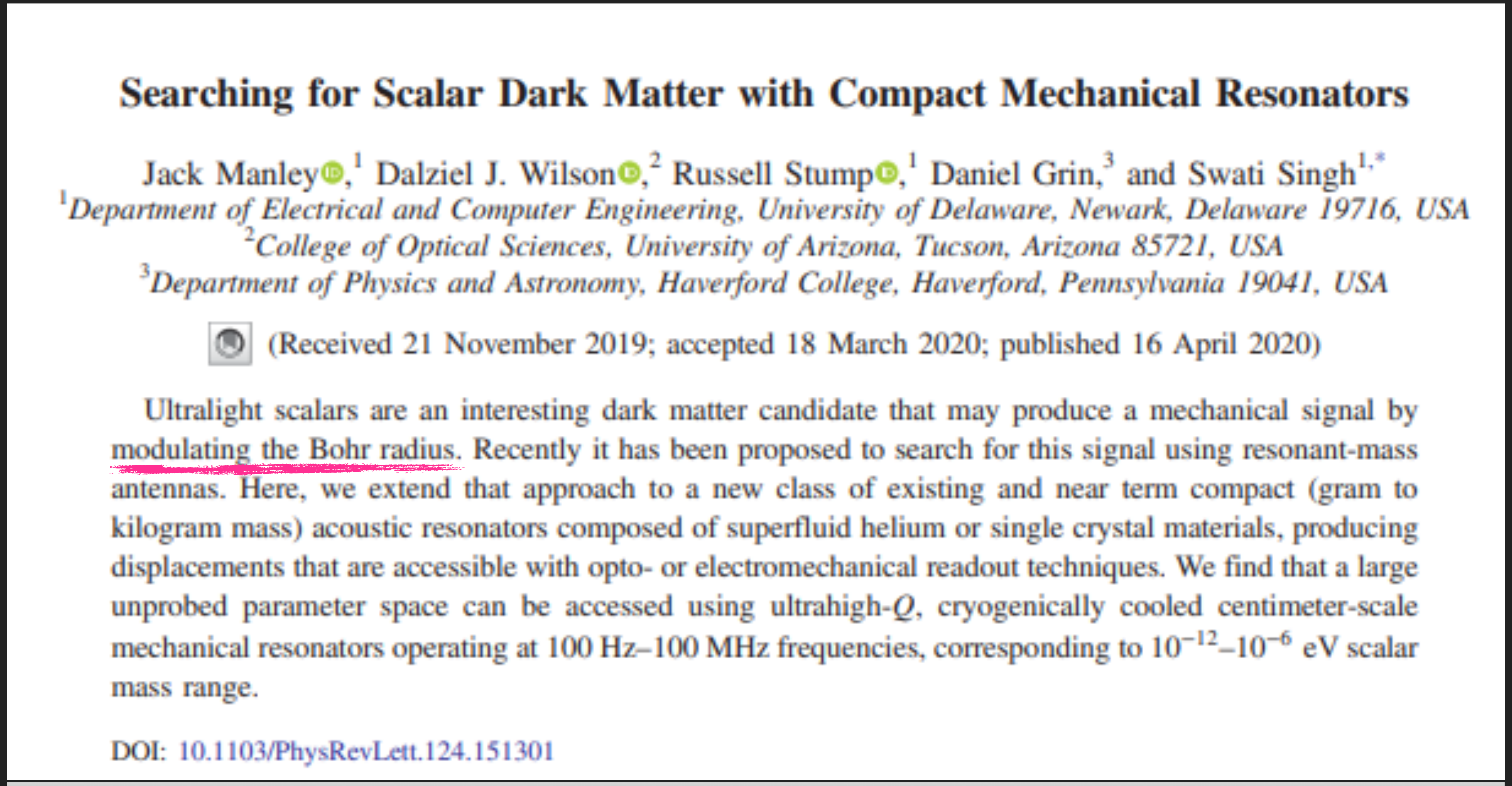
Scalar Dark Matter



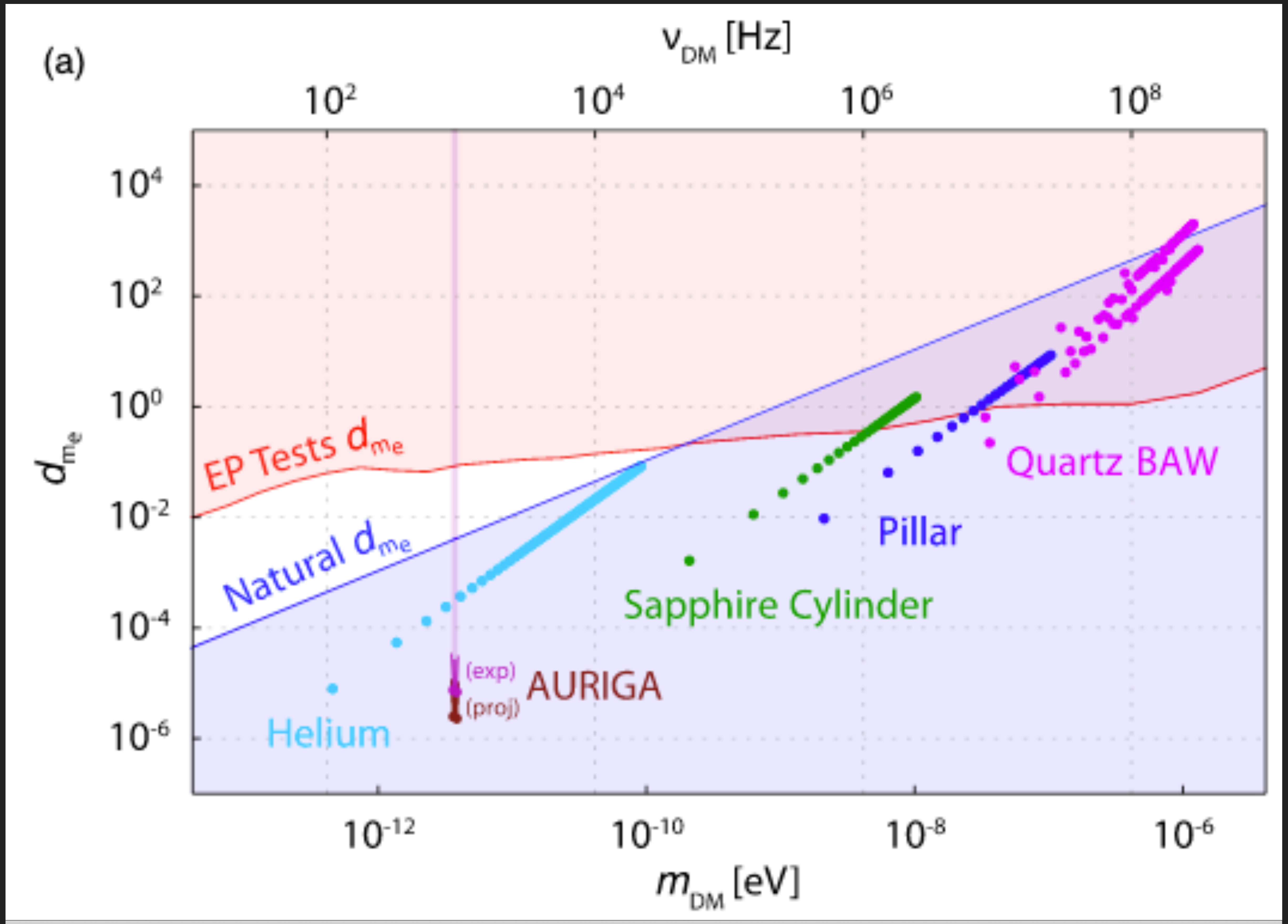
Searching for Scalar Dark Matter with Compact Mechanical Resonators

Jack Manley,[1] Dalziel J. Wilson,[2] Russell Stump,[1] Daniel Grin,[3] and Swati Singh[1,*]
[1]Department of Electrical and Computer Engineering, University of Delaware, Newark, Delaware 19716, USA
[2]College of Optical Sciences, University of Arizona, Tucson, Arizona 85721, USA
[3]Department of Physics and Astronomy, Haverford College, Haverford, Pennsylvania 19041, USA

(Received 21 November 2019; accepted 18 March 2020; published 16 April 2020)

Ultralight scalars are an interesting dark matter candidate that may produce a mechanical signal by modulating the Bohr radius. Recently it has been proposed to search for this signal using resonant-mass antennas. Here, we extend that approach to a new class of existing and near term compact (gram to kilogram mass) acoustic resonators composed of superfluid helium or single crystal materials, producing displacements that are accessible with opto- or electromechanical readout techniques. We find that a large unprobed parameter space can be accessed using ultrahigh-Q, cryogenically cooled centimeter-scale mechanical resonators operating at 100 Hz–100 MHz frequencies, corresponding to 10^{-12}–10^{-6} eV scalar mass range.

DOI: 10.1103/PhysRevLett.124.151301



$$\left(d_{\mathrm{DM}}\right)_{\min} \approx \sqrt{\frac{c^2}{8\pi G\rho_{\mathrm{DM}}}}\,\omega_n h_{\min}$$

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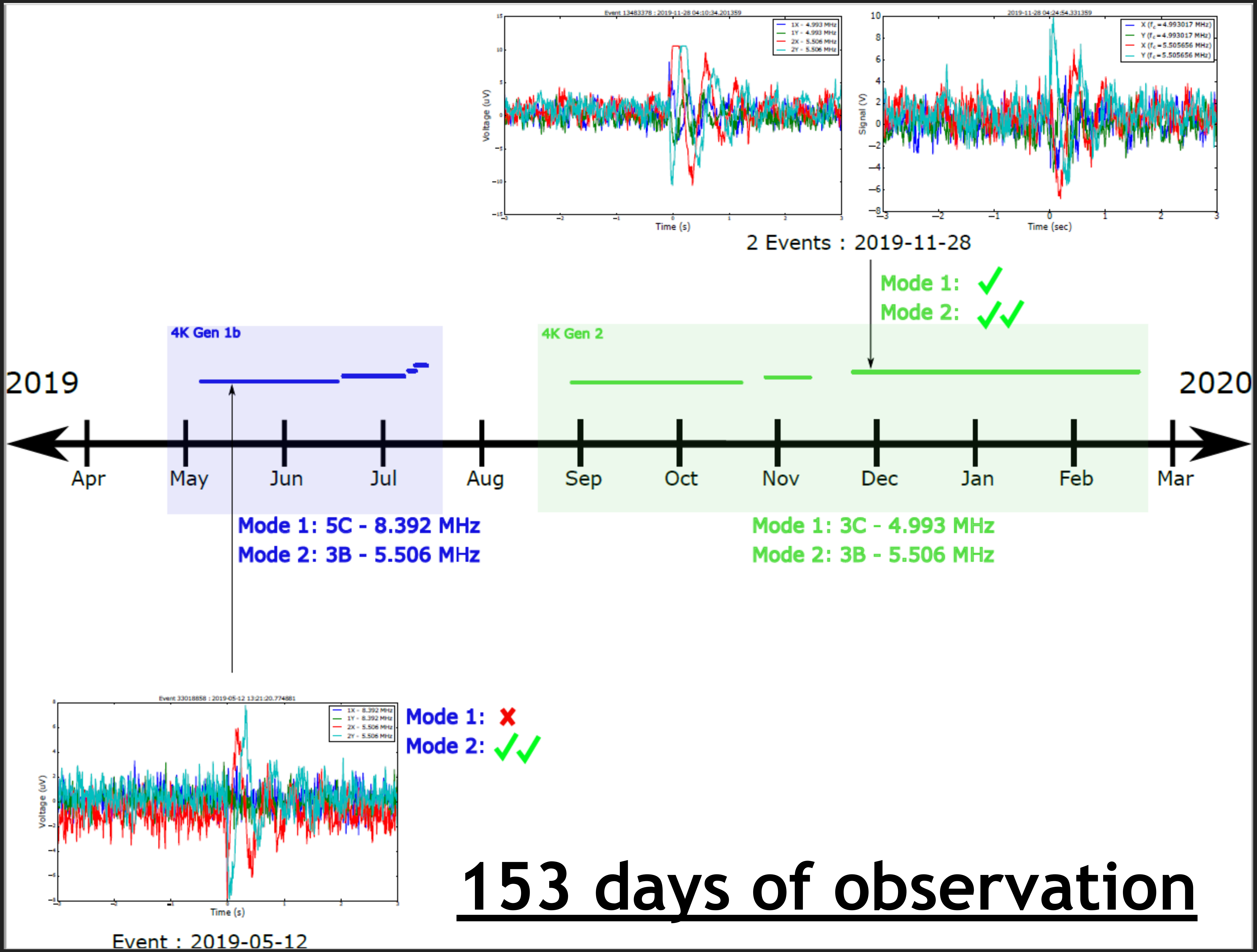
First Detection



153 days of observation

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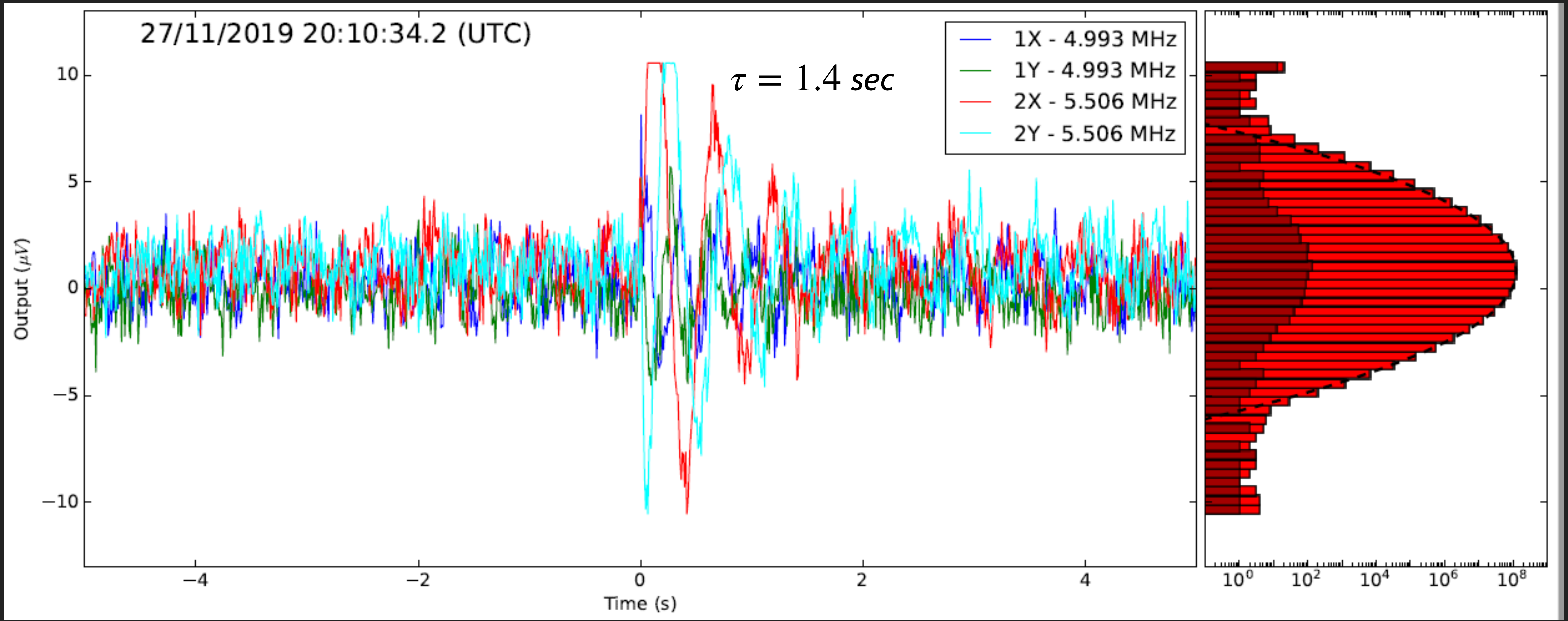
First Detection



Excluded sources:
LIGO/VIRGO event catalogue, weather perturbations, earthquakes, meteor events / cosmic showers, FRBs

Possible sources:
Internal solid state processes, internal radioactive events, cosmic ray events, HFGW sources, domain walls, WIMPs, dark matter

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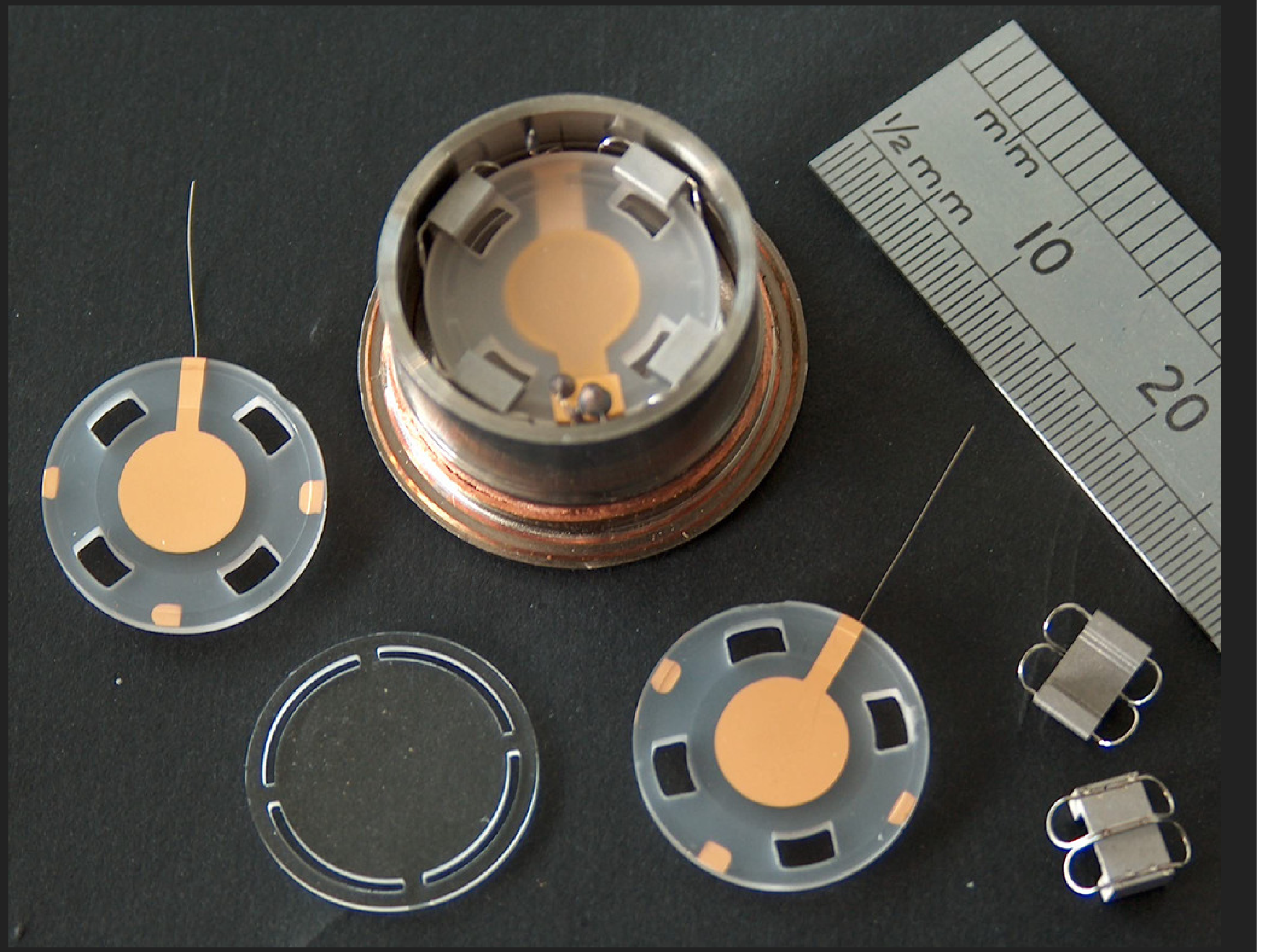
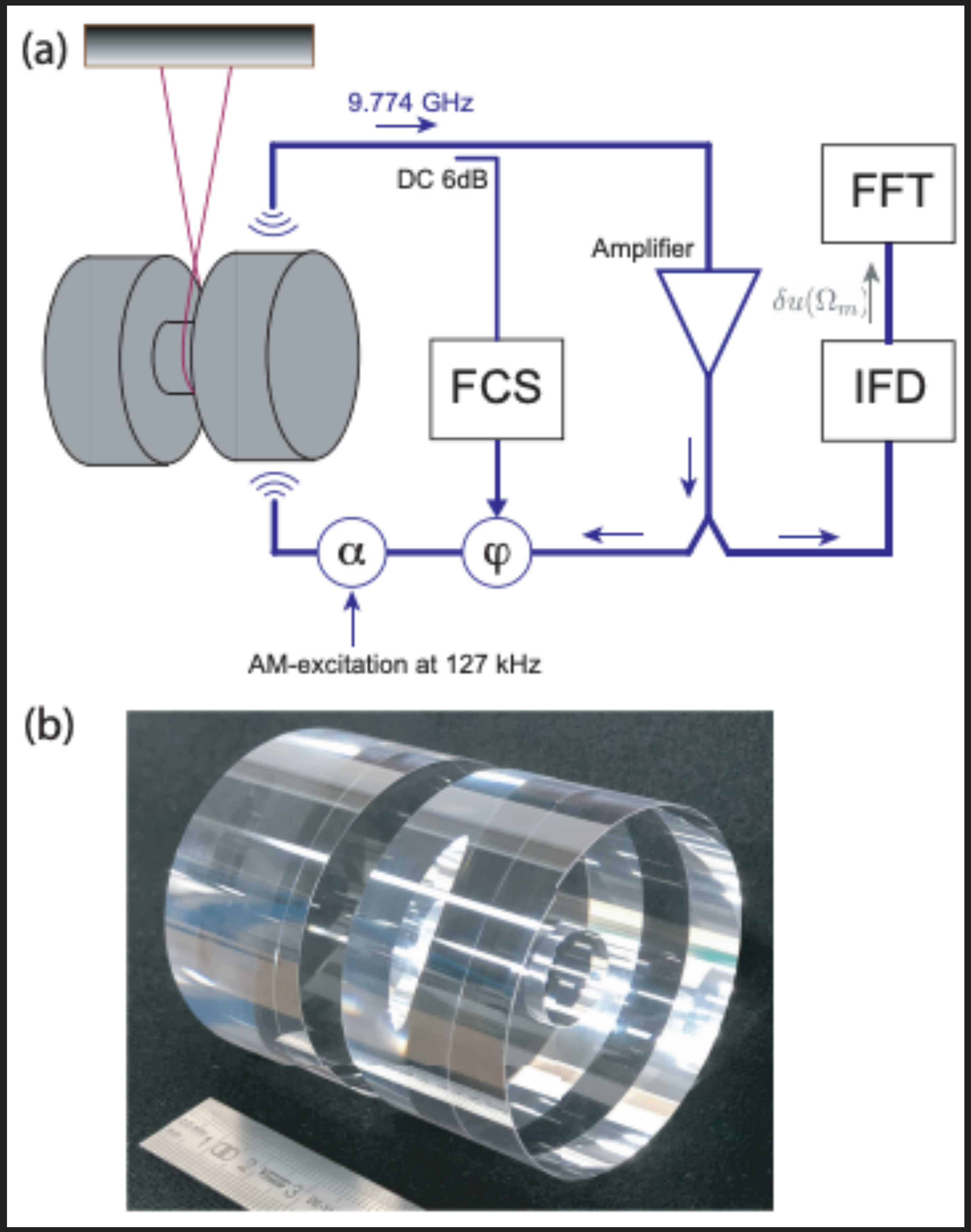
Quantum Gravity

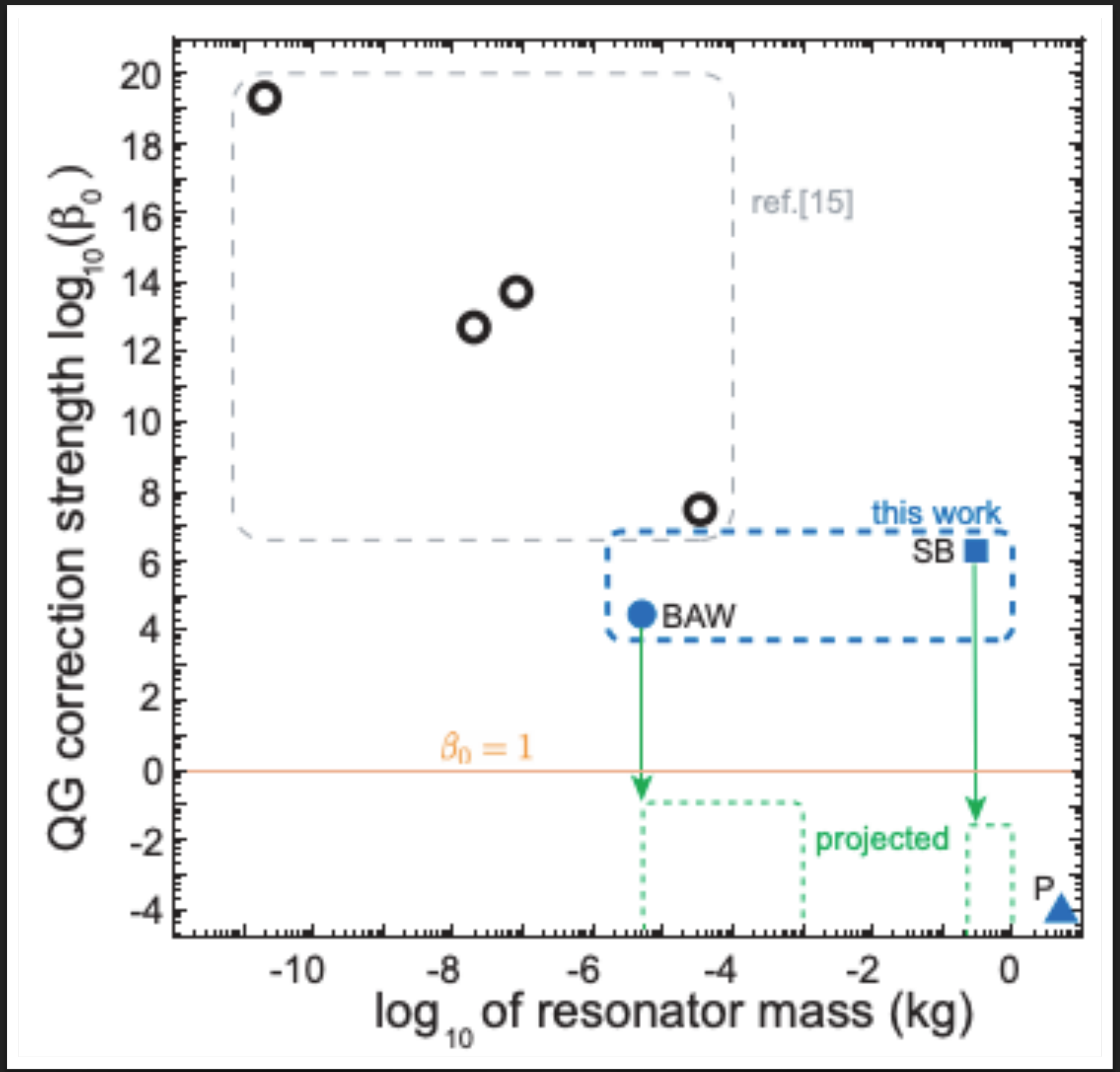
Testing the generalized uncertainty principle with macroscopic mechanical oscillators and pendulums

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







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PHYSICAL REVIEW LETTERS **126,** 081803 (2021)

Upconversion Loop Oscillator Axion Detection Experiment: A Precision Frequency Interferometric Axion Dark Matter Search with a Cylindrical Microwave Cavity

Catriona A. Thomson,* 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

Physics of the Dark Universe 26 (2019) 100345

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

Axion detection with precision frequency metrology

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

First Proposed in 2018
arXiv:1806.07141 [physics.ins-det]:
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(Dated: June 10, 2021)

We are very grateful to Kevin Zhou for meticulously going through our paper and finding our mistake, and reading this correction making sure of its validity. This work was funded by the ARC Centre of Excellence for Engineered Quantum Systems, CE170100009, and Dark Matter Particle Physics, CE200100008.

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QDM

Heterodyne Detection of Axion Dark Matter in an RF Cavity

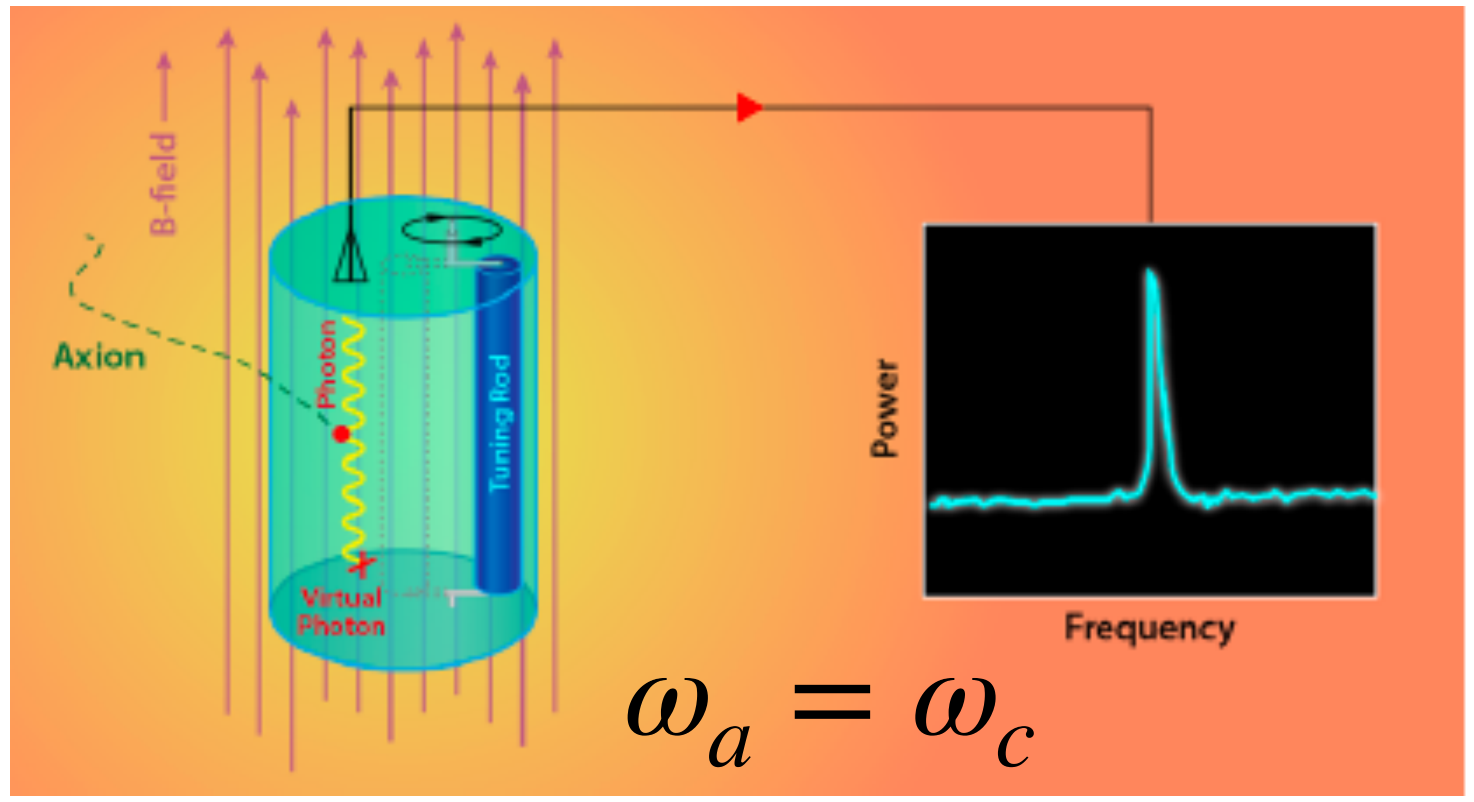
Sebastian Ellis

Axion-Photon Coupling to Search for Axion

The Axion Haloscope Technique

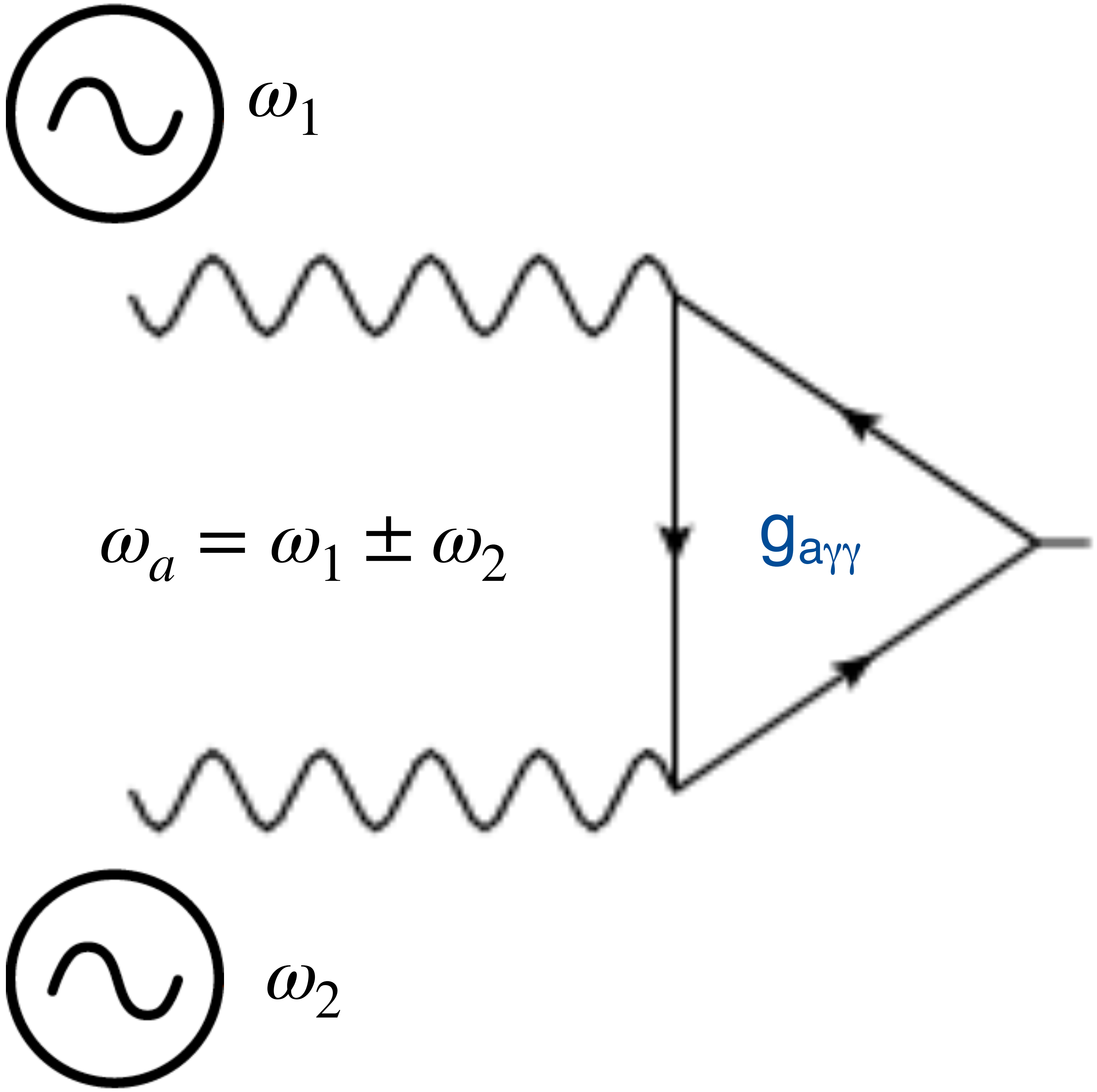
$$\mathscr{L} \propto a g_{a\gamma\gamma} \overrightarrow{E}_{cavity} \bullet \overrightarrow{B}_{ext}$$

Lagrangian gives effective strength

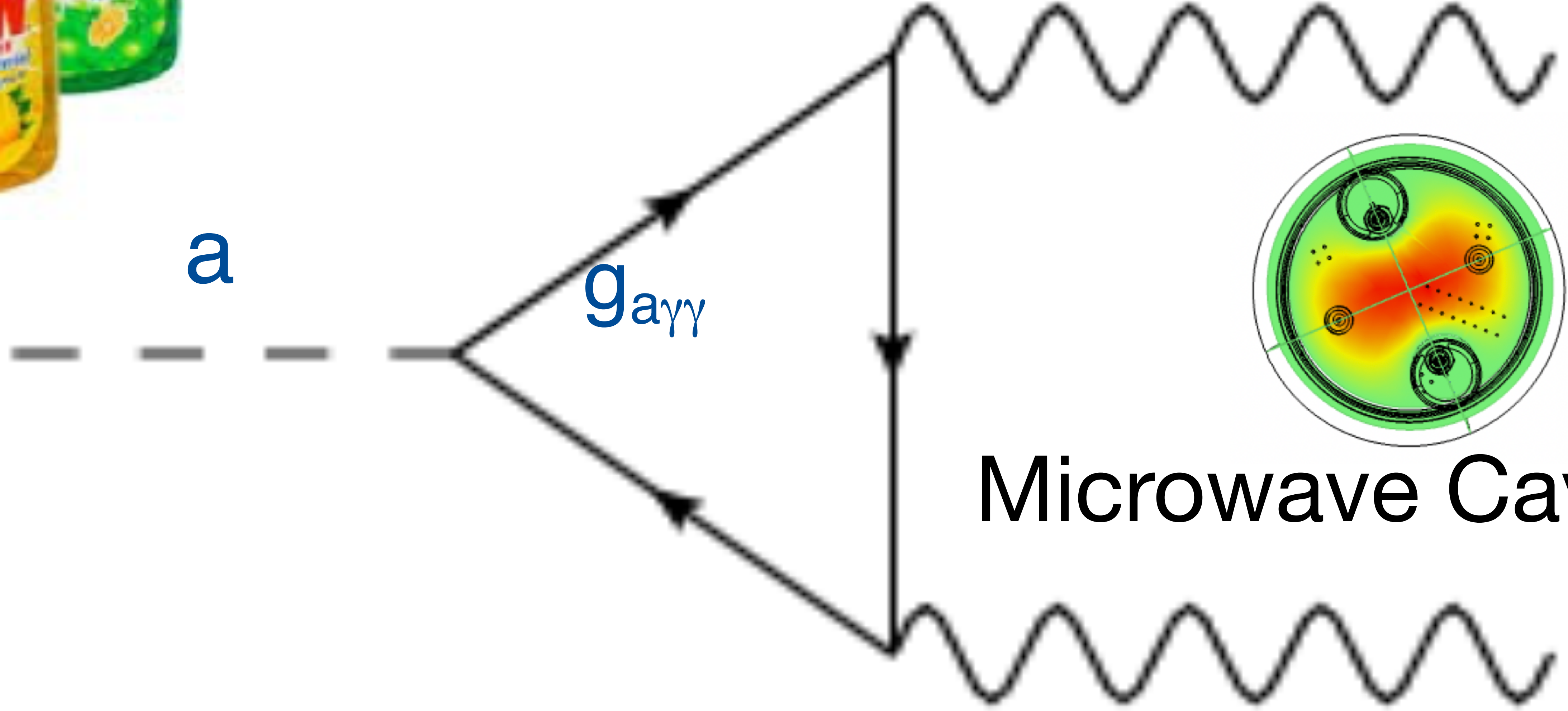


$\omega_a = \omega_c$

The AC Axion Haloscope Technique

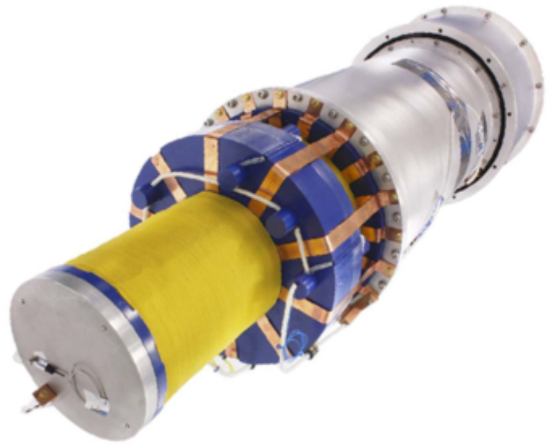


$\omega_a = \omega_1 \pm \omega_2$

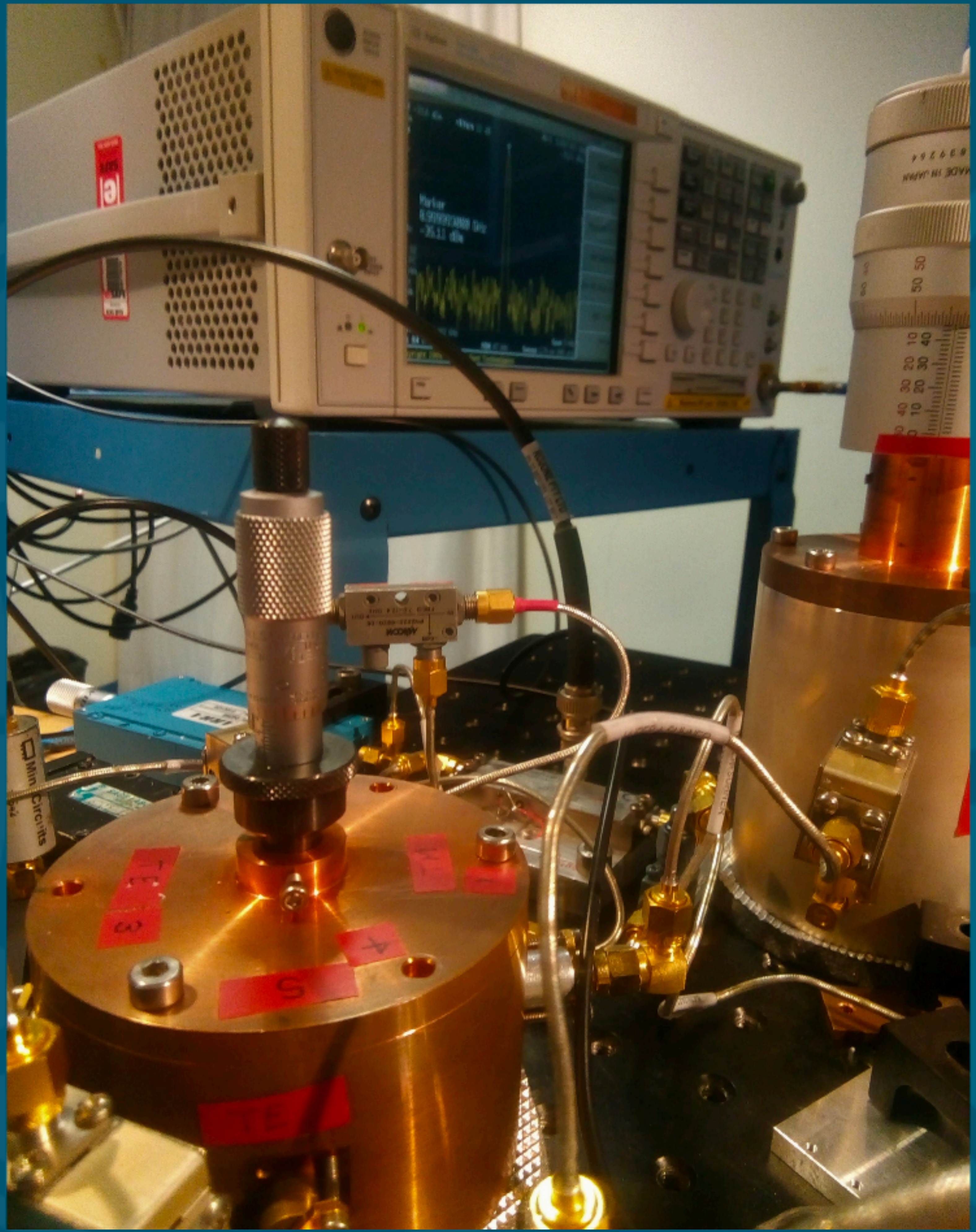


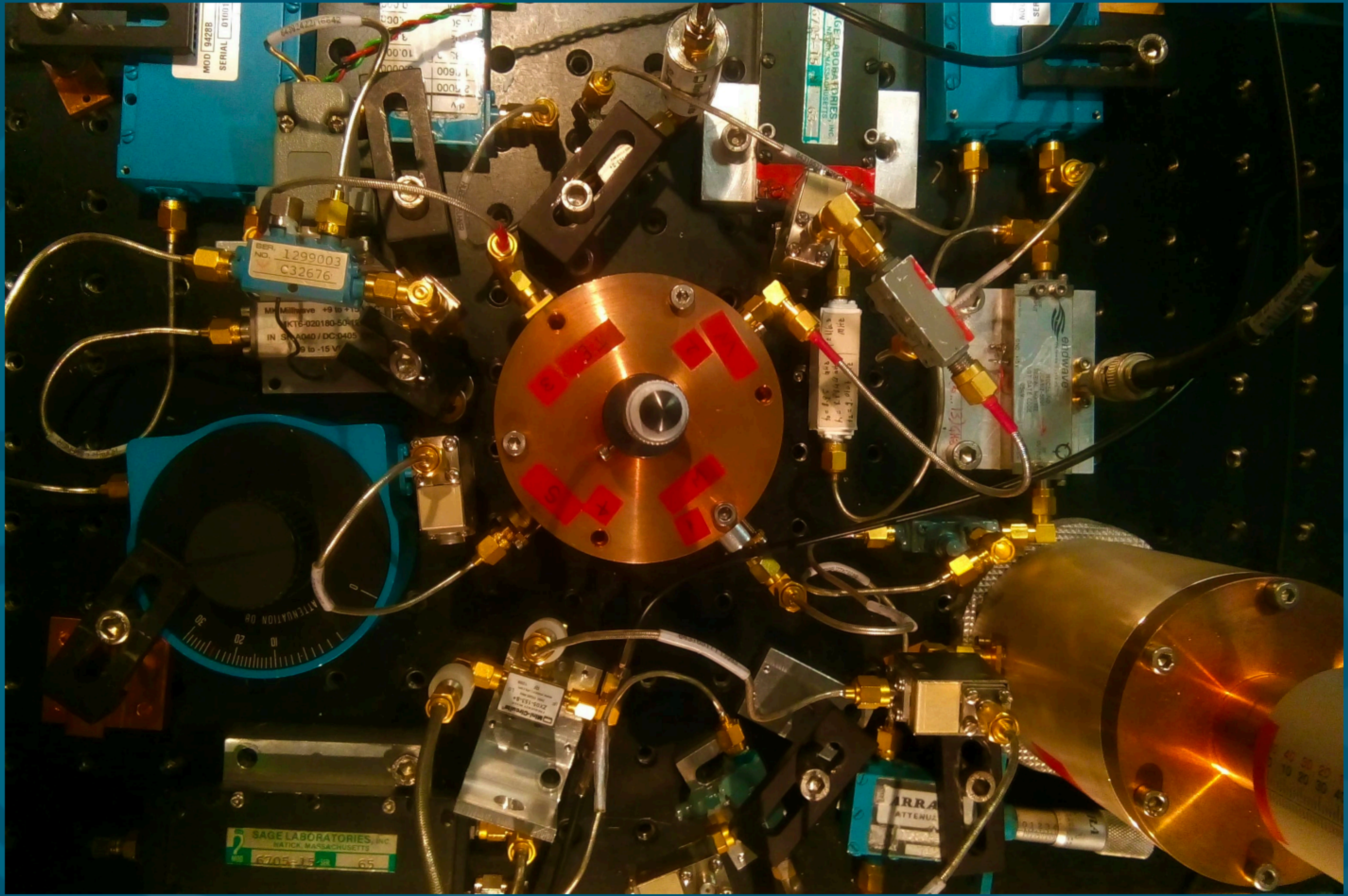
Microwave Cavity

DC B-field



Construct Dual-Mode Loop Oscillator with Phase Noise Measurement System: What is the Signal to Noise Ratio?





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Australian Research Council
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Engineered Quantum Systems

Two mode axion electrodynamics: Interaction Hamiltonian

TABLE I: Experimental Microwave Oscillator Parameters

	$TE_{0,1,1}$ (Mode 1 Fig. 1)	$TM_{0,2,0}$ (Mode 2 Fig. 1)
Q_L	6000	4200
β_{in}	0.9	0.95
P_{inc}	10 dBm	6 dBm
P_c	48 dBm	42 dBm
f_0	9.00168 - 9.00256 GHz	8.9988765 GHz
k_{a-}	$8.4 \times 10^{-4} - 1.1 \times 10^{-3}$	$8.4 \times 10^{-4} - 1.1 \times 10^{-3}$
k_{a+}	5.5	5.5

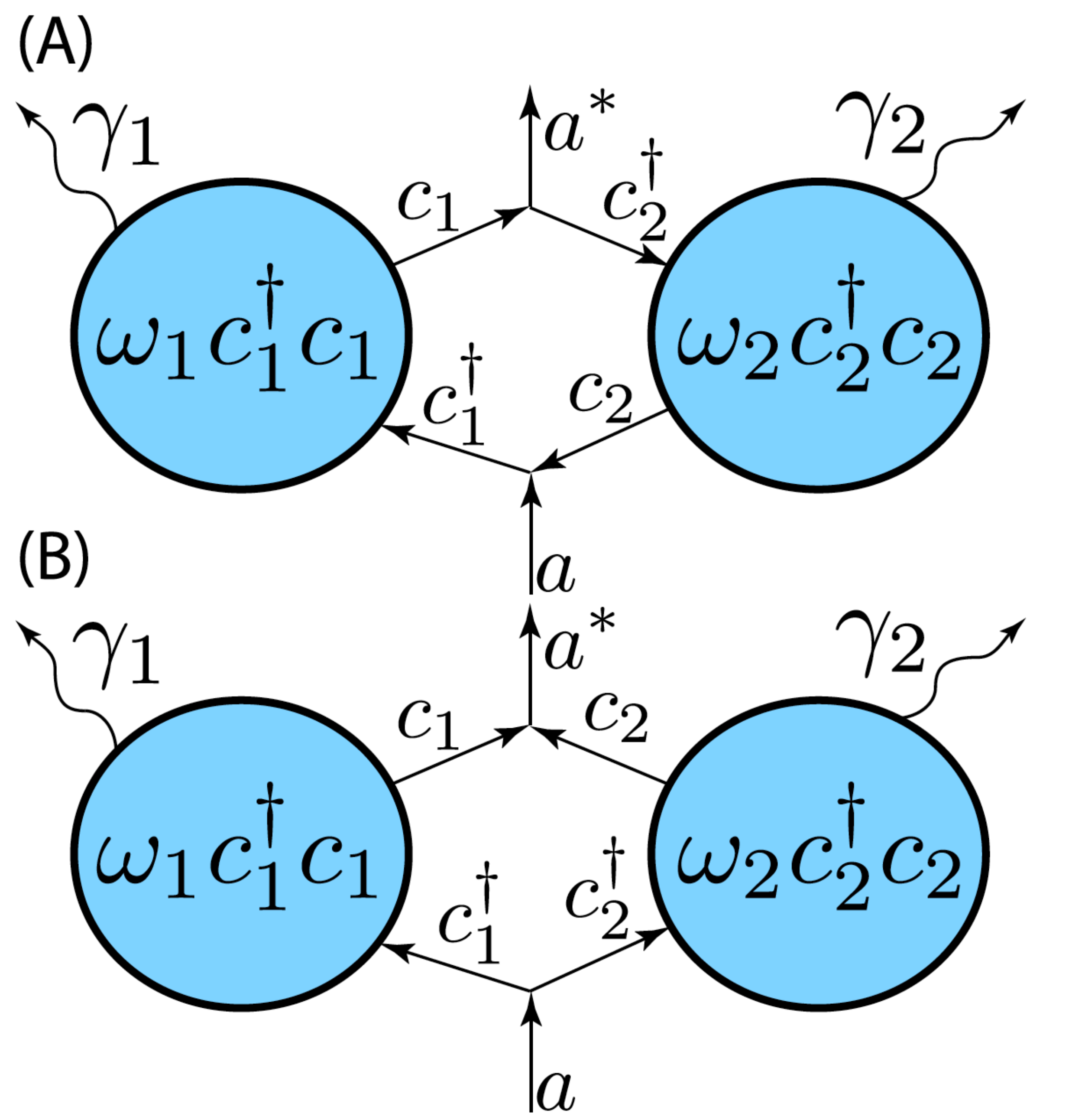


Fig. 1. Graphical representation of the two modes interacting through axion coupling in (A) upconversion and (B) downconversion cases.

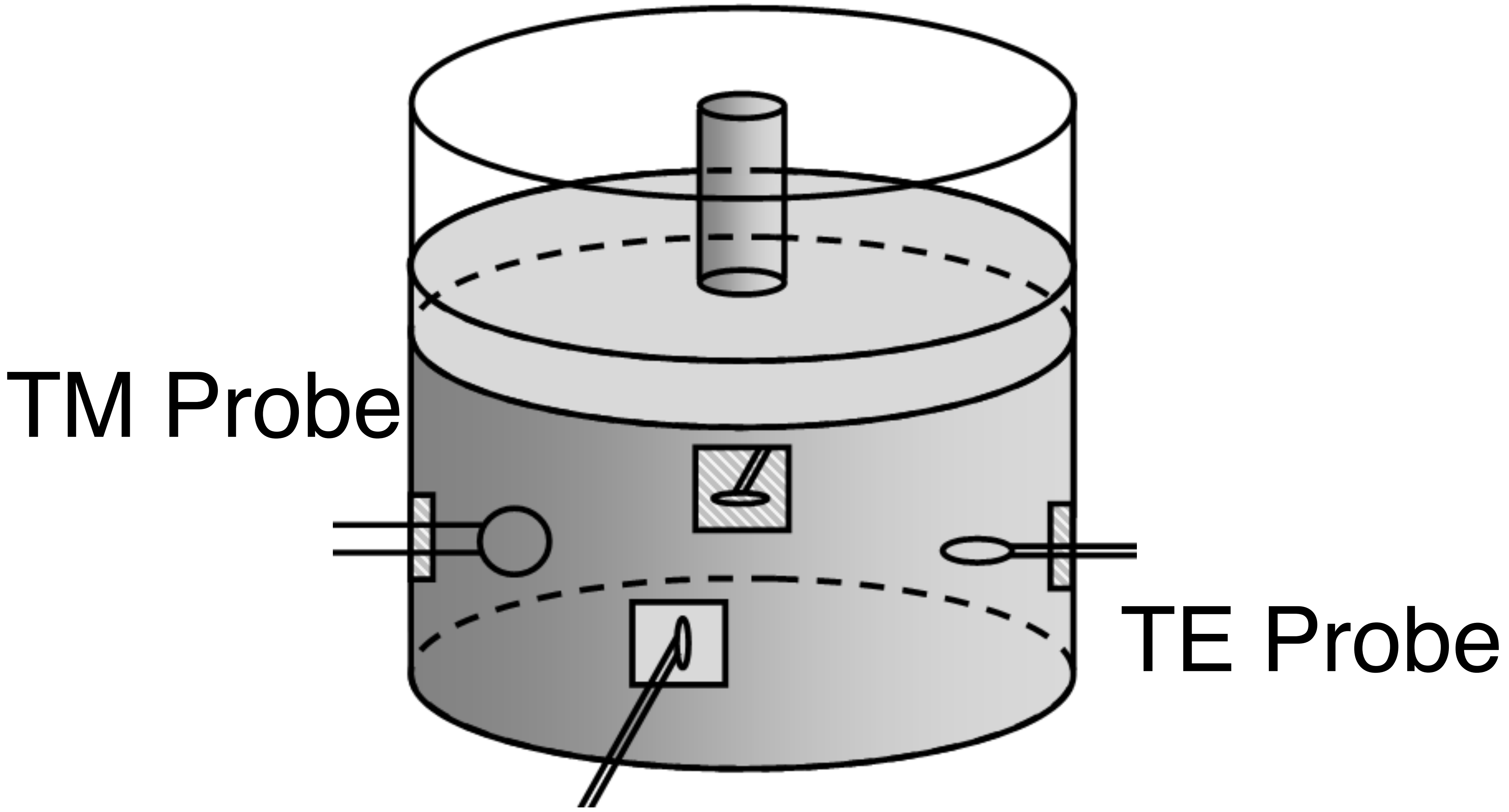
$$\mathcal{H}_{\text{int}} = \epsilon_0 c g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

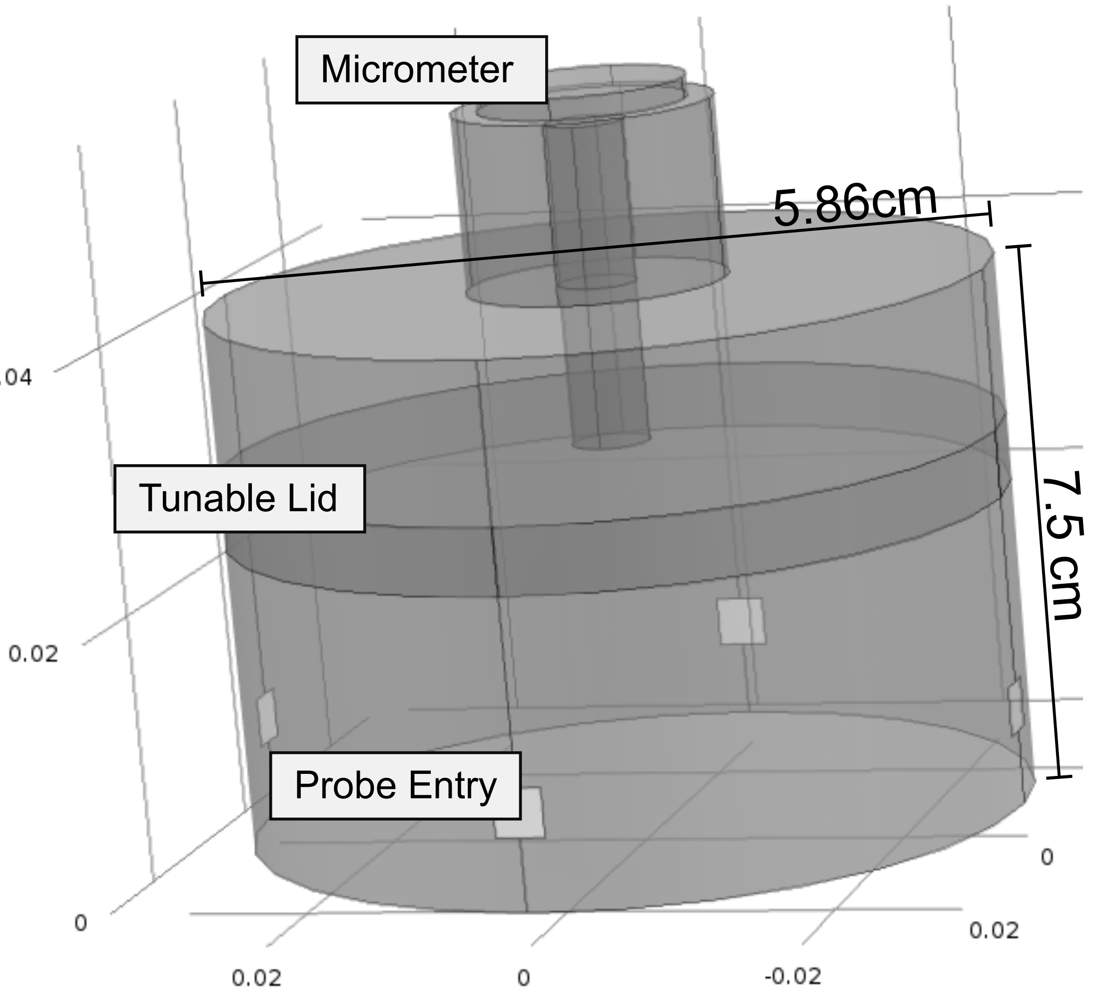
$$H_{\text{int}} = i\pi\hbar g_{a\gamma\gamma} a \sqrt{f_1 f_2}[\xi_-(c_1 c_2^\dagger - c_1^\dagger c_2) + \xi_+(c_1^\dagger c_2^\dagger - c_1 c_2)],$$

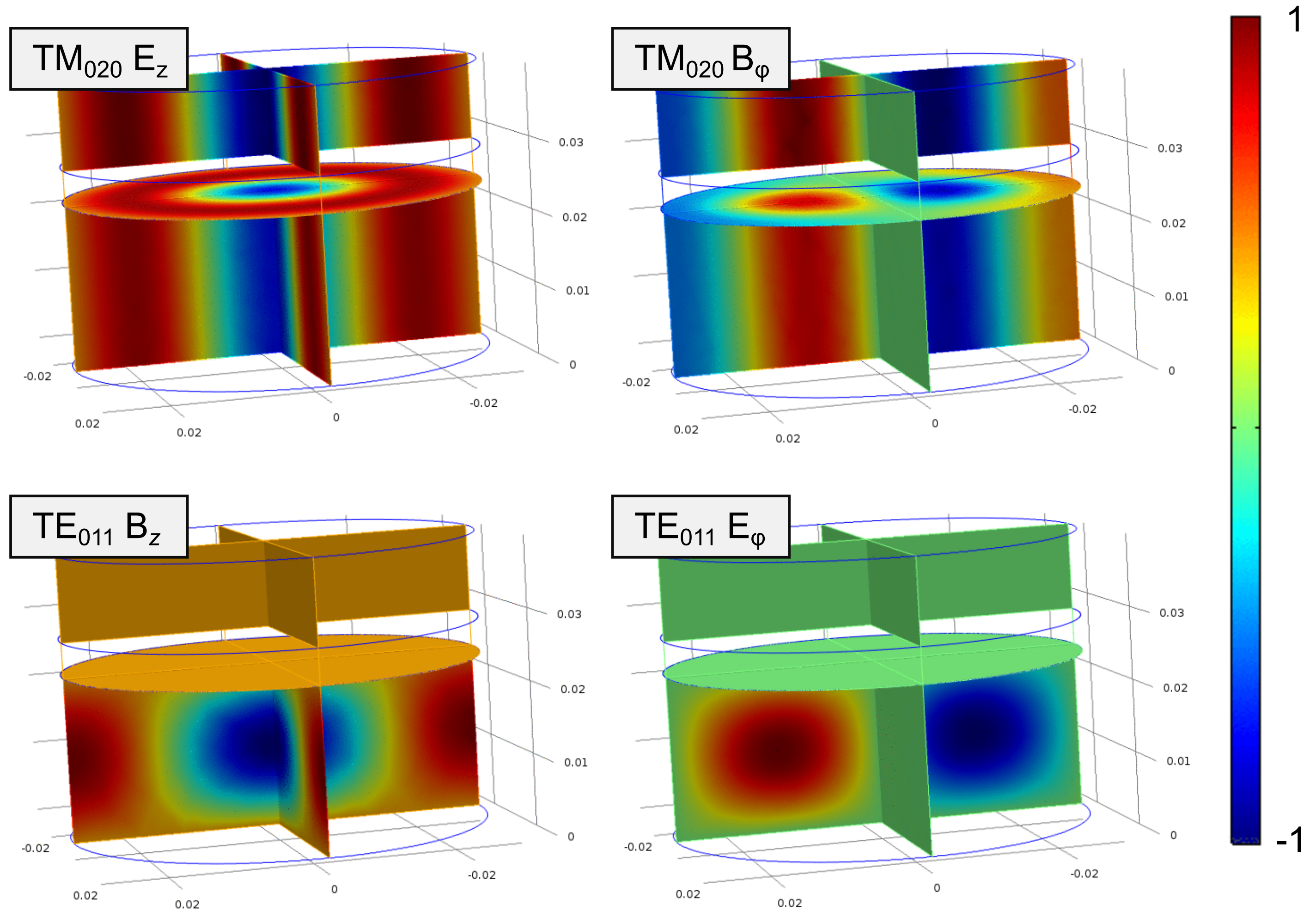
$$SNR_- = g_{a\gamma\gamma} \frac{3.9 \left(\frac{10^6 t}{f_{a\_}}\right)^{\frac{1}{4}} \sqrt{\rho_{DM} c^3}}{2\pi f_{a\_}} \sqrt{\frac{Q_{L1} P_1}{k_b T_{RS}}} \sqrt{\frac{\beta_2 Q_{L2}}{\left(2Q_{L2}\frac{f}{f_2}\right)^2 + 1}} \left(\frac{|\delta f_{12}|}{\sqrt{2} f_2}\right)$$

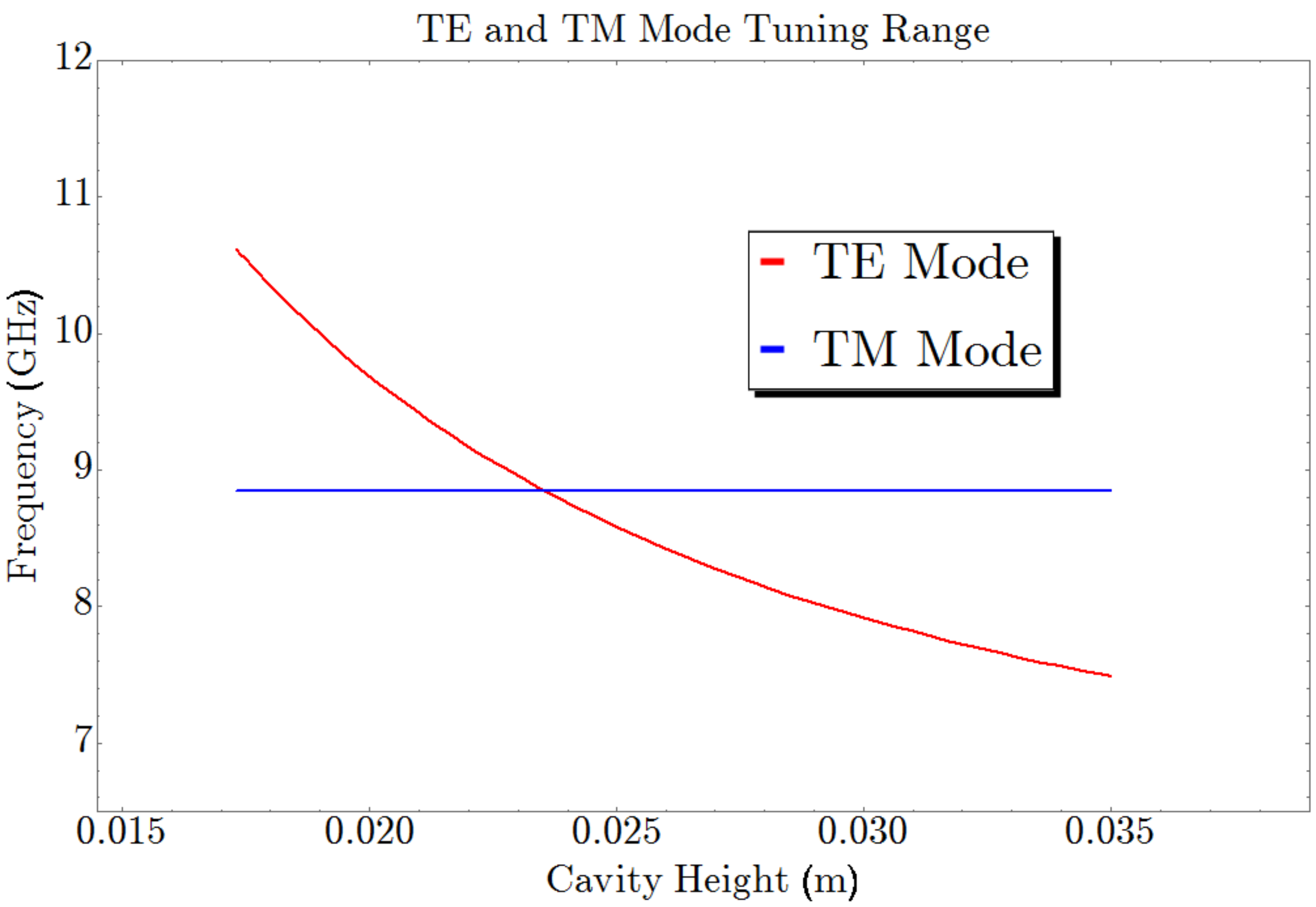
First Realisation: Cylindrical Microwave Cavity

- Tuneable cavity height (lid attached to micrometer)
- TM020 mode frequency <u>fixed</u> by cavity radius
- TE011 mode frequency <u>tuned</u> by cavity height





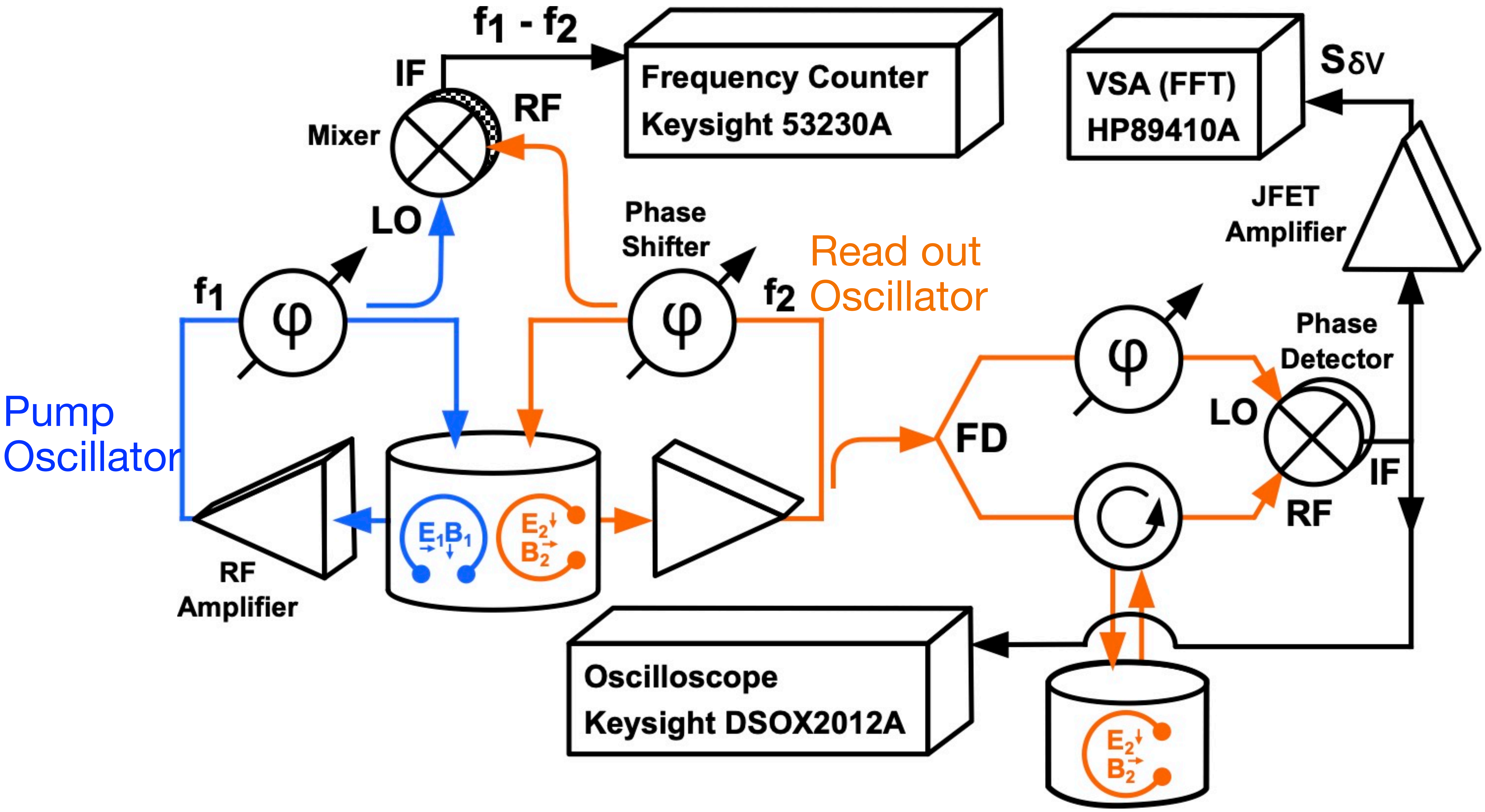




Down Conversion: $f_a \approx f_2 + f_1 \approx$ 18 GHz

Up Conversion: $f_a \approx |f_2 - f_1| \rightarrow$ Low Mass

Schematic of the Experimental Setup



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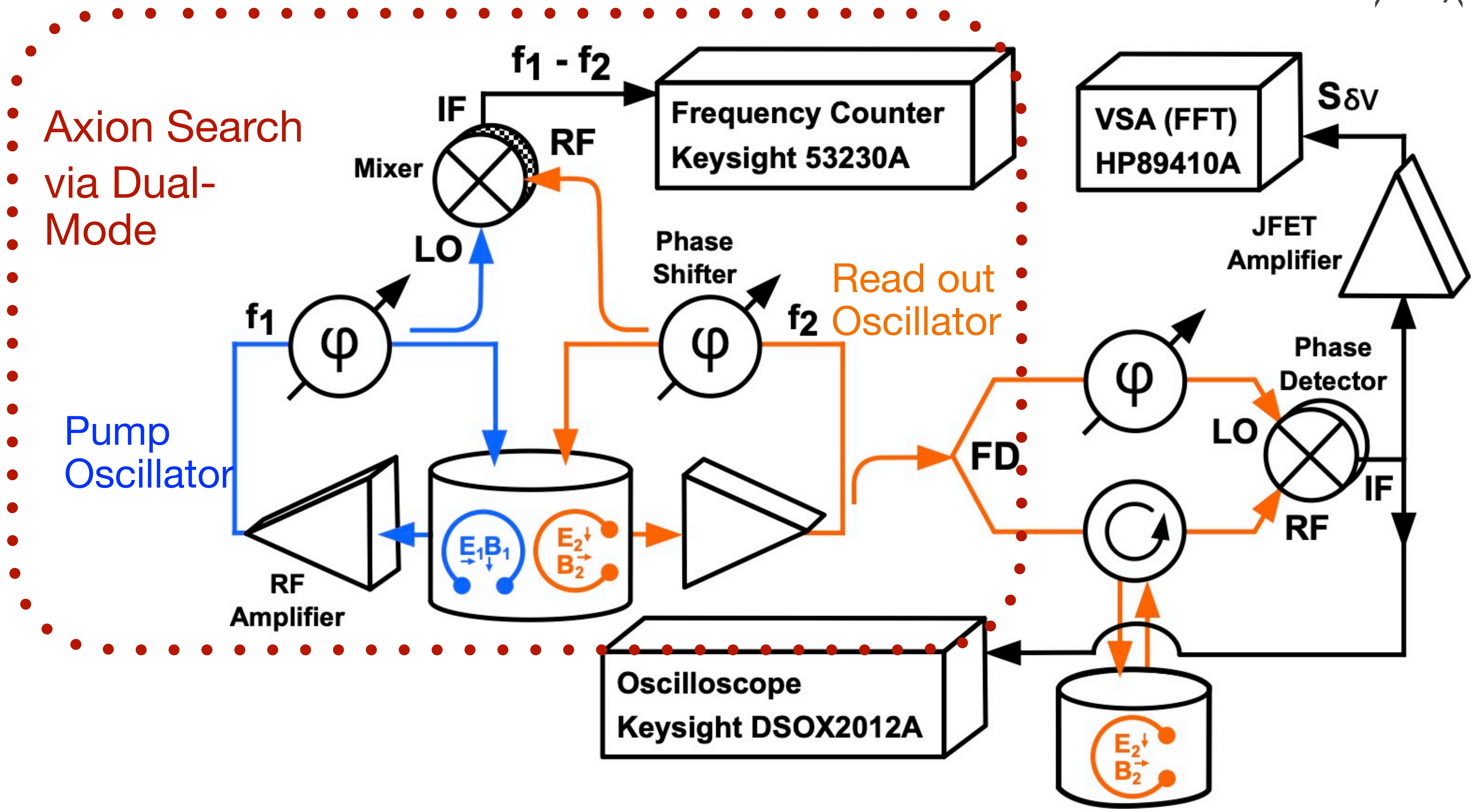
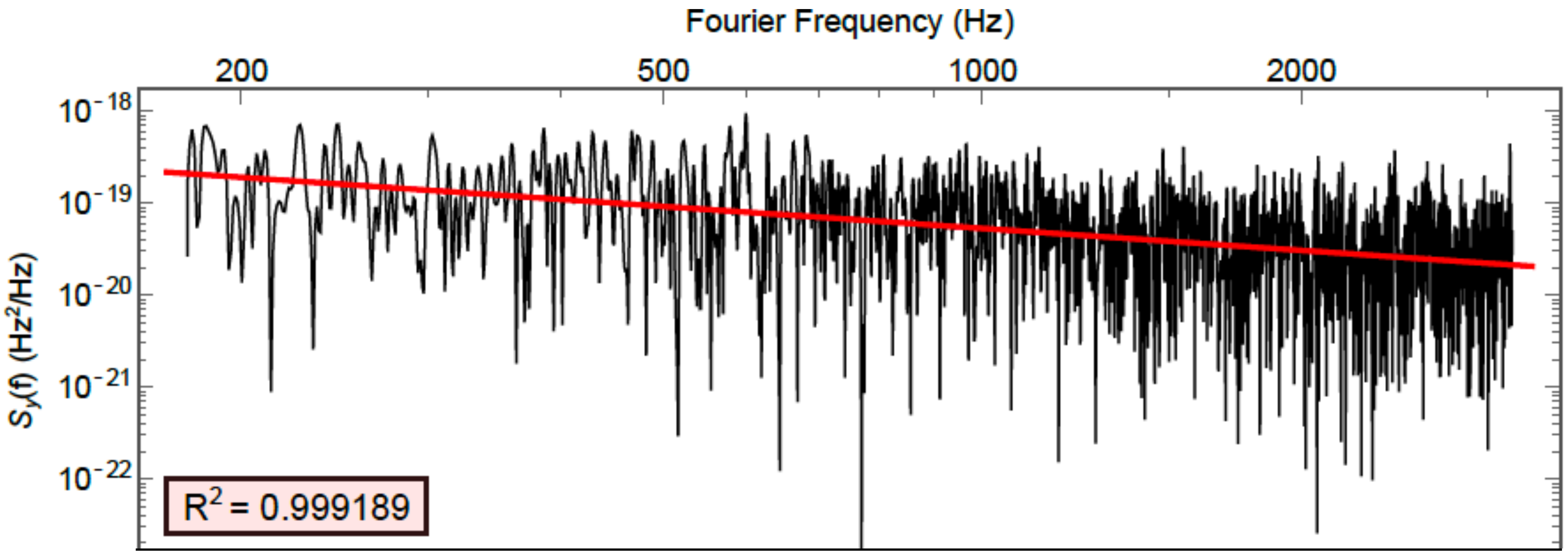


Schematic of the Experimental Setup

Oscillator Fractional Frequency Noise

Search Fourier Frequency of read out oscillator for axions, relation becomes $f_a = f_2 + f_1 \pm f$ or $f_a = |f_2 - f_1| \pm f$.



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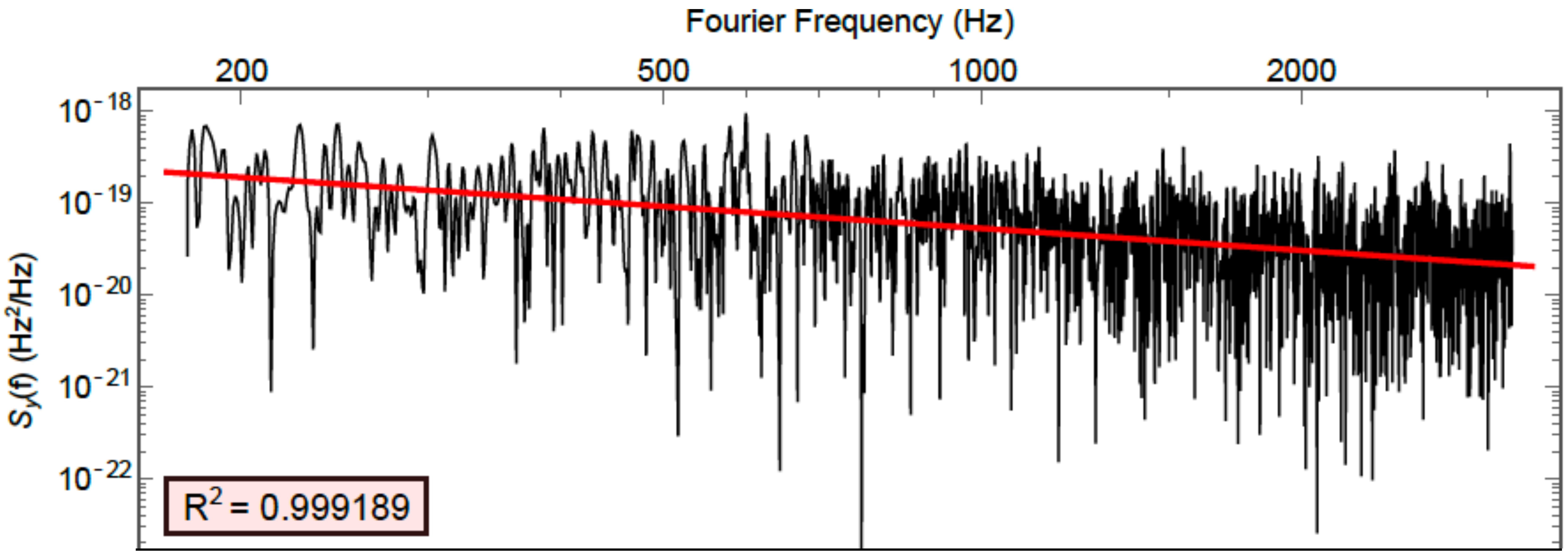
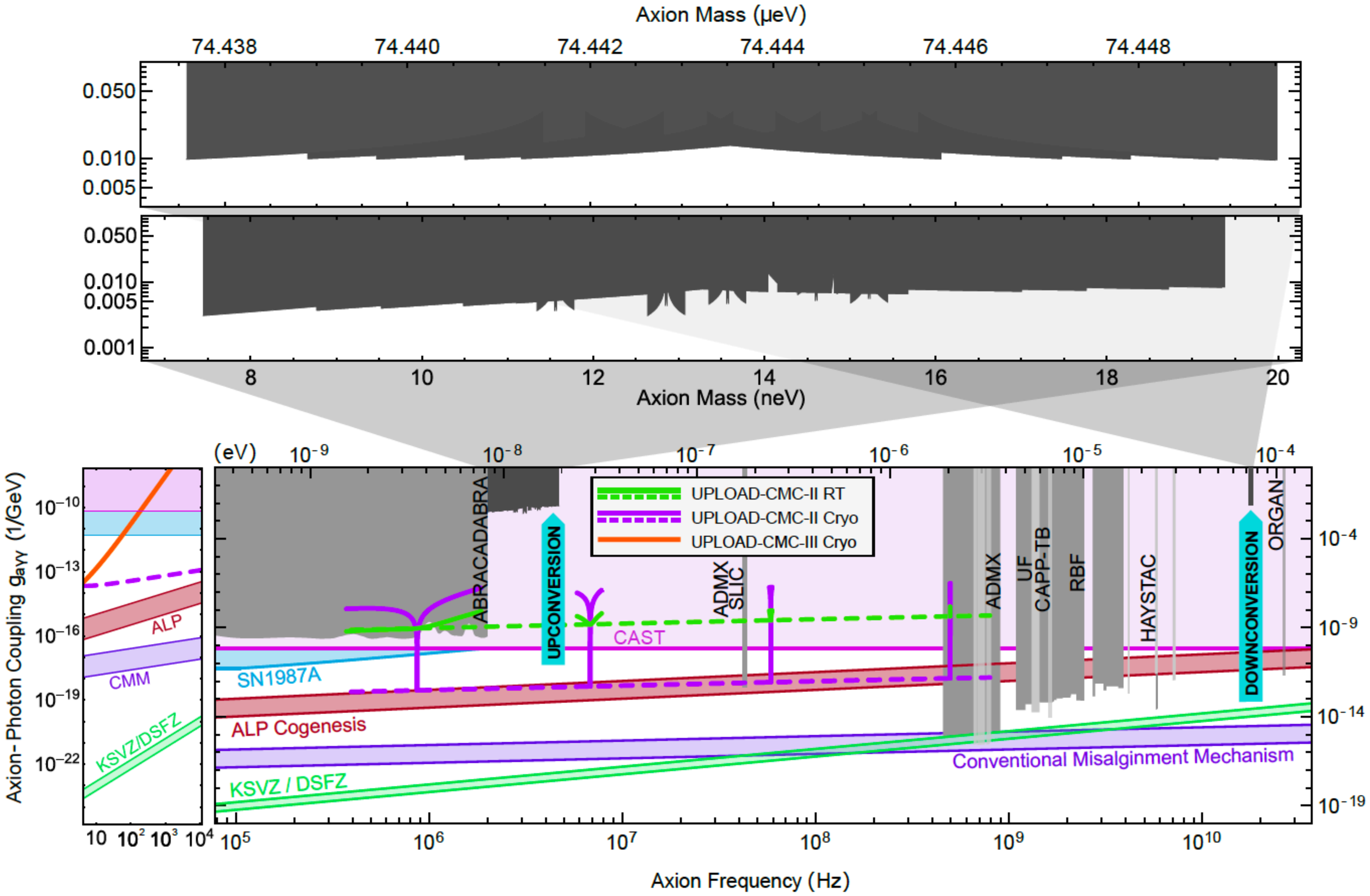


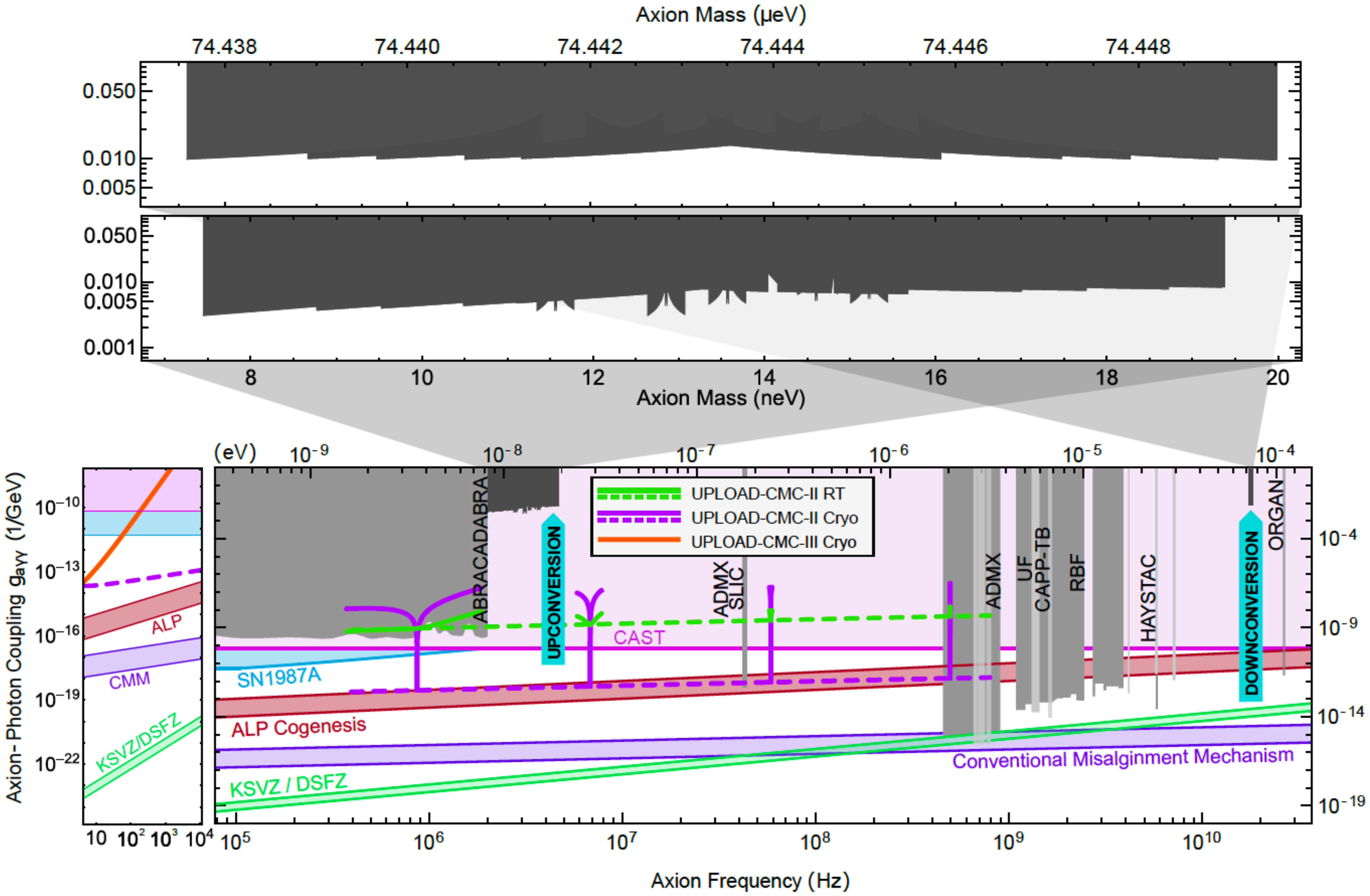
Searching at $\pm f$, Fourier frequencies at the same time

Next: What is the Signal that the Axion will imprint on the Phase Noise?

Sensitivity Limits



Sensitivity Limits



- Puts limits 7.44-19.38 neV with only 5 positions of cavity tuning

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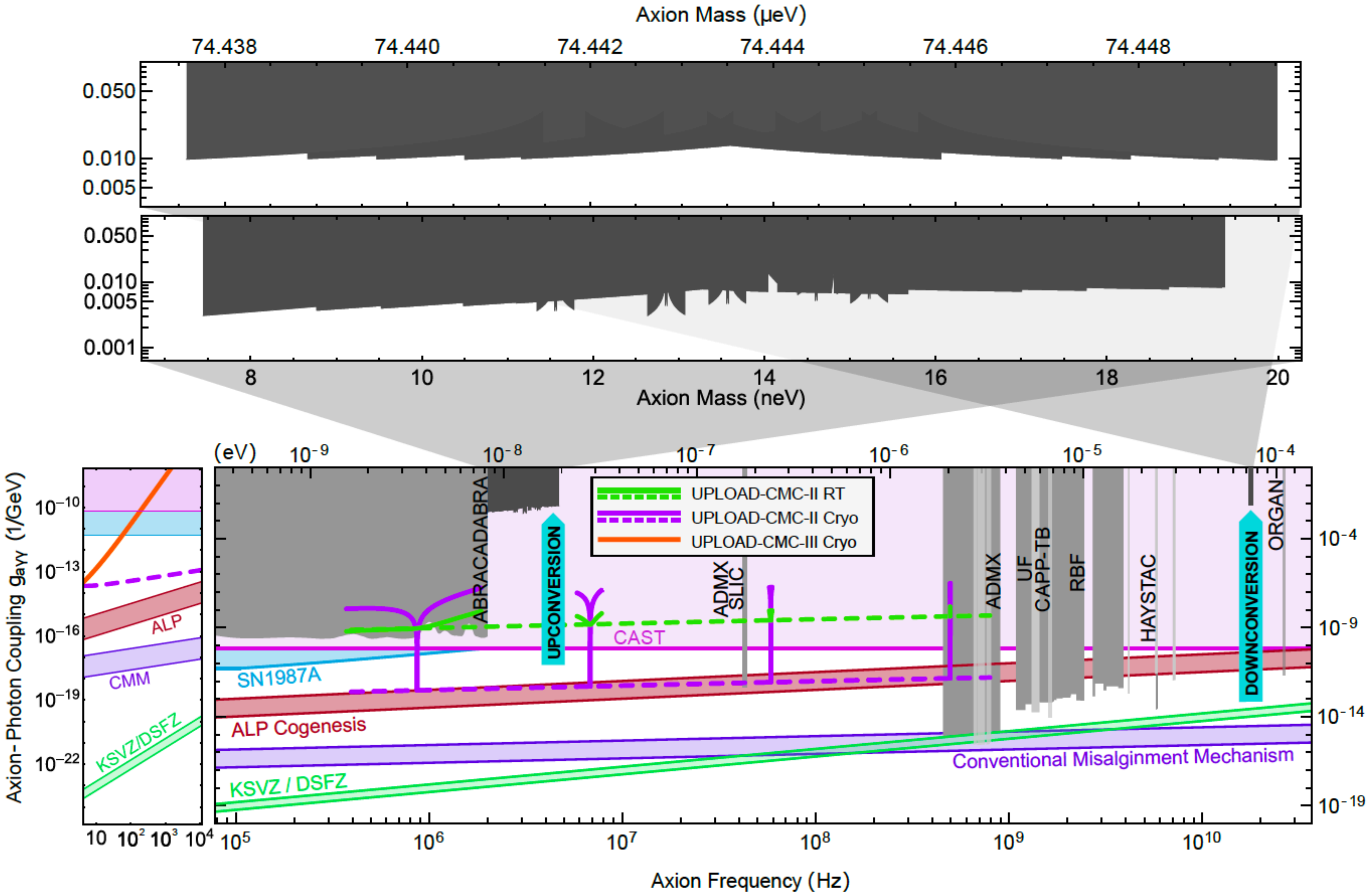

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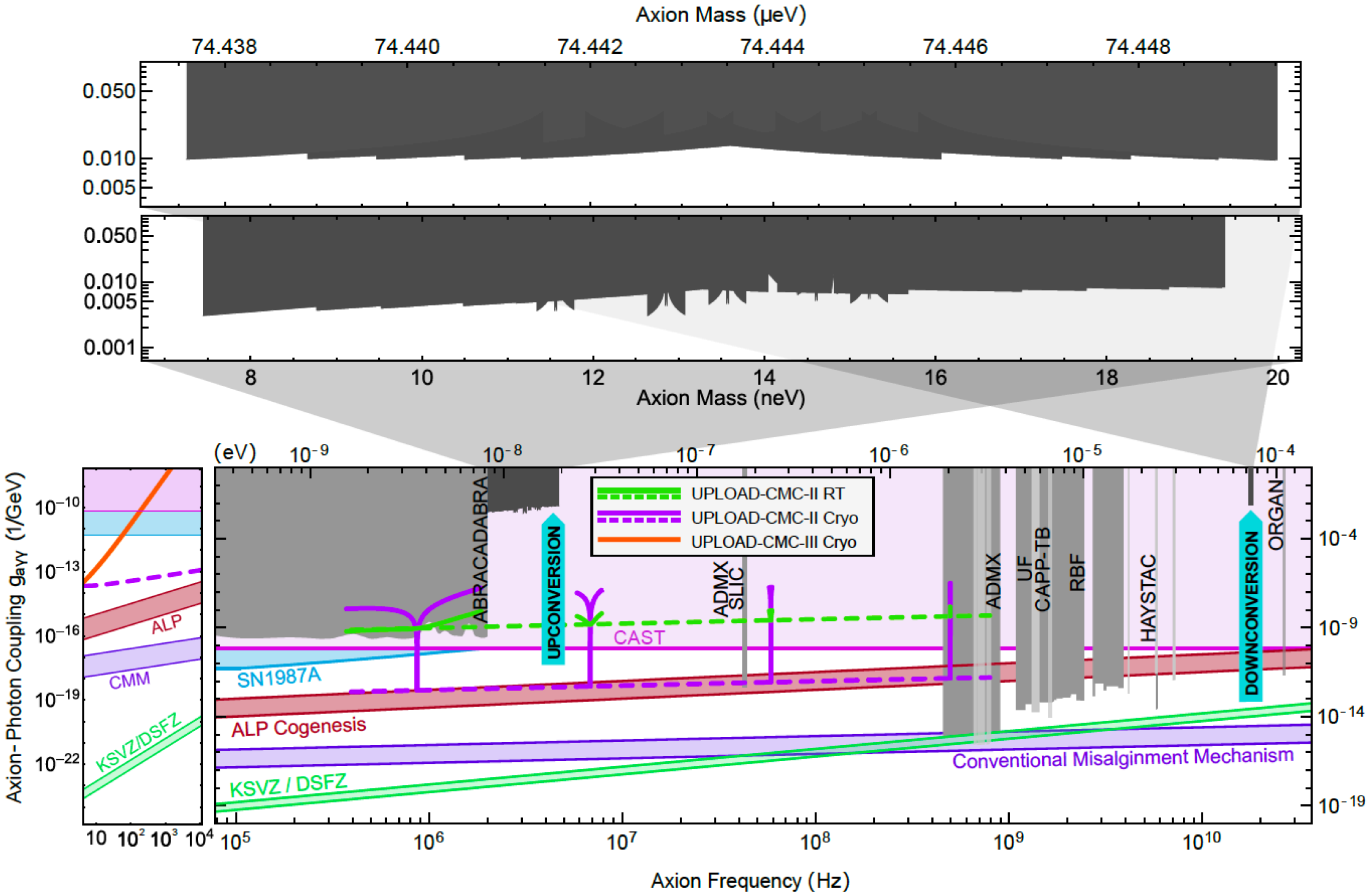

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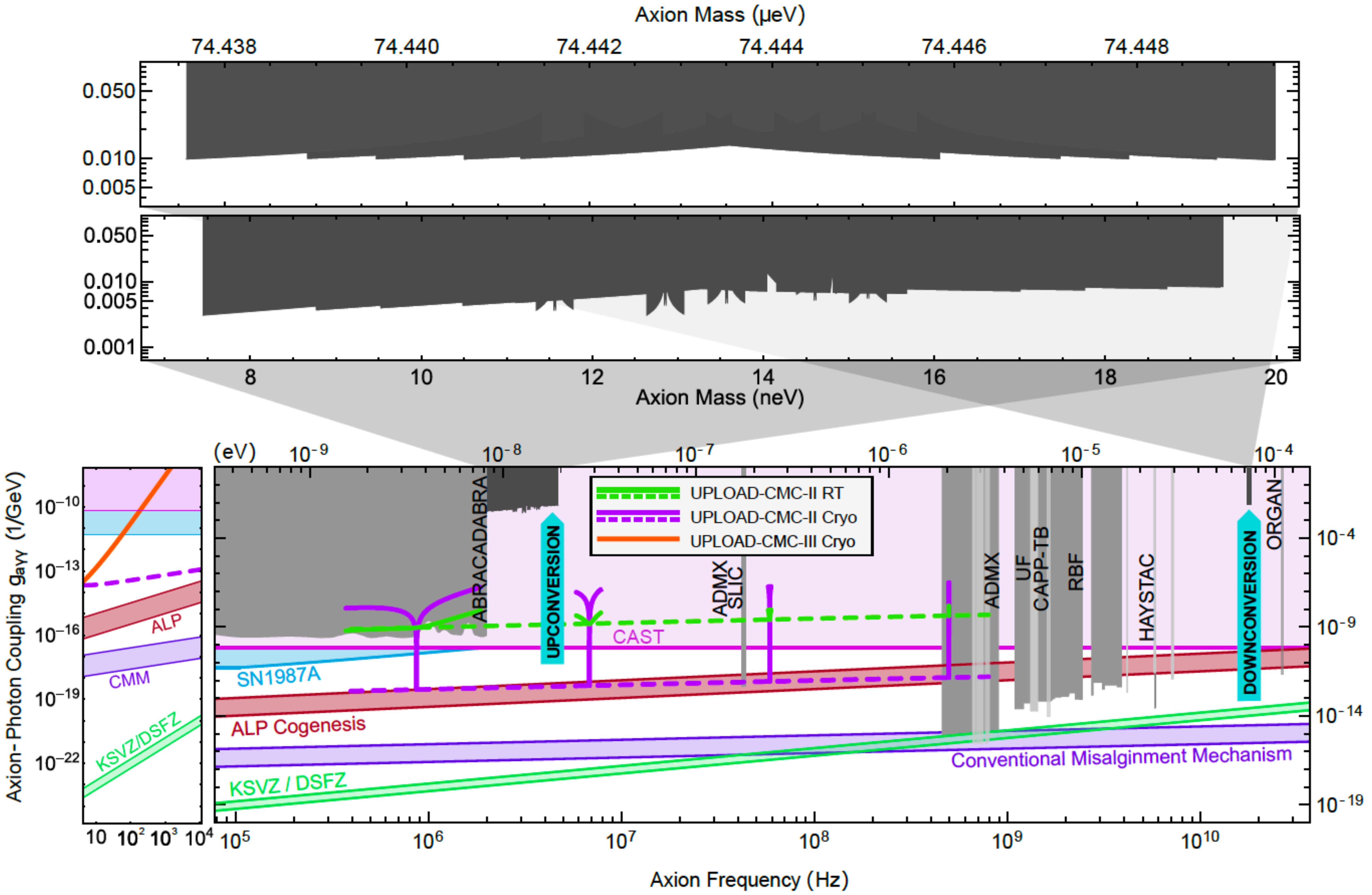

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- Looking at a few different schemes, injection locking etc. and power measurement schemes

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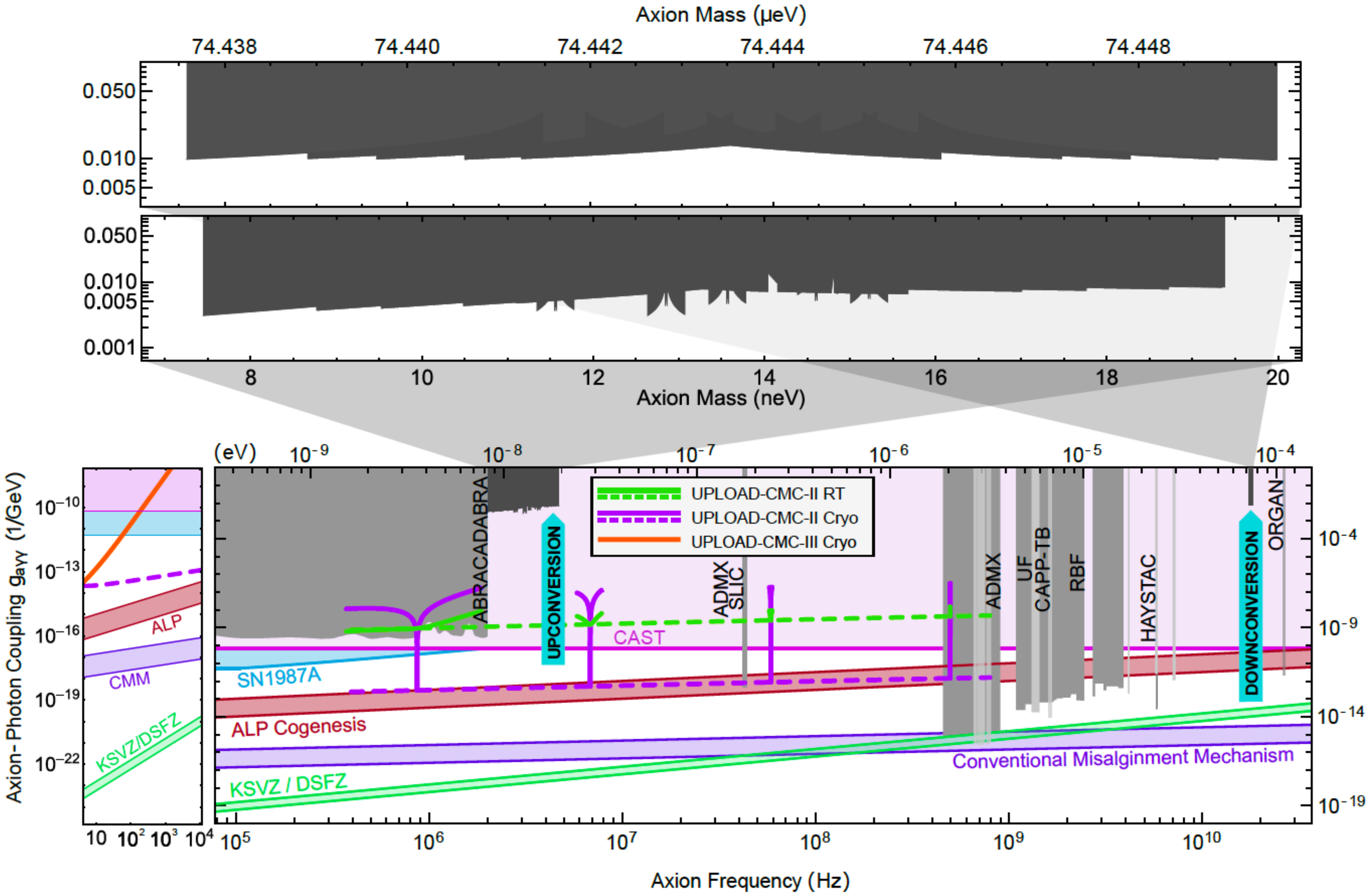

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Heterodyne Detection of Axion Dark Matter in an RF Cavity

Sebastian Ellis

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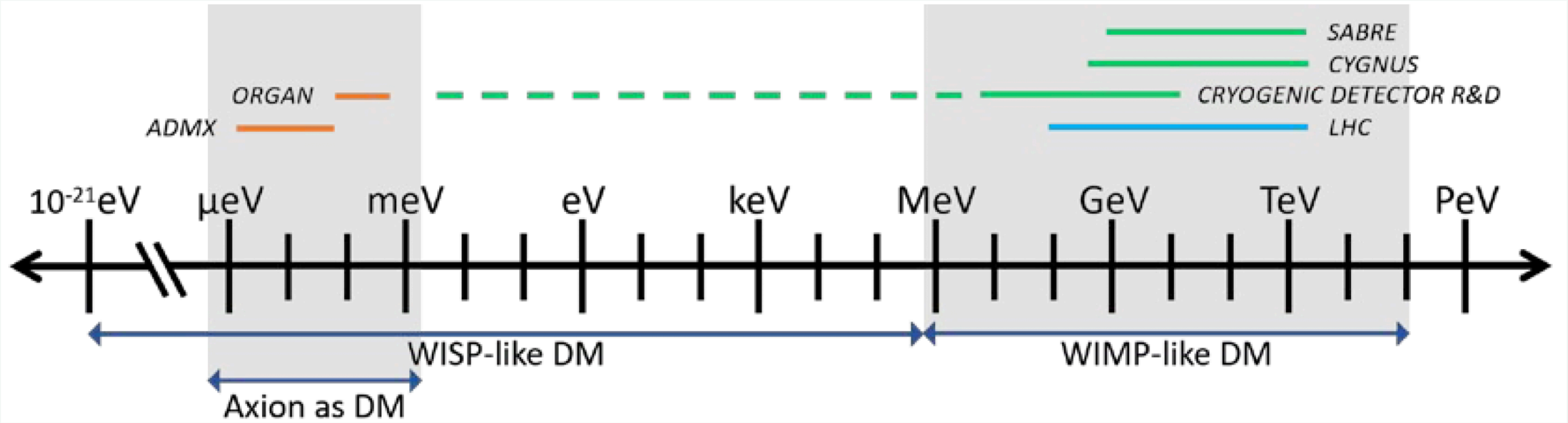
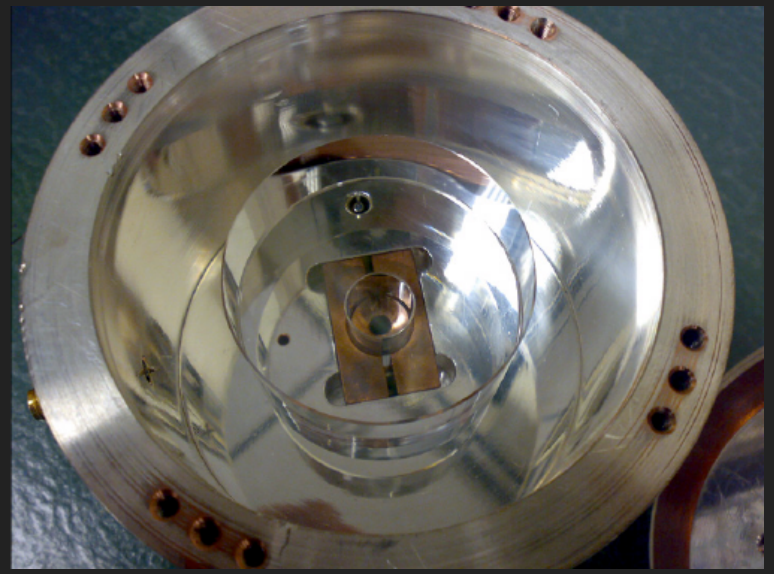
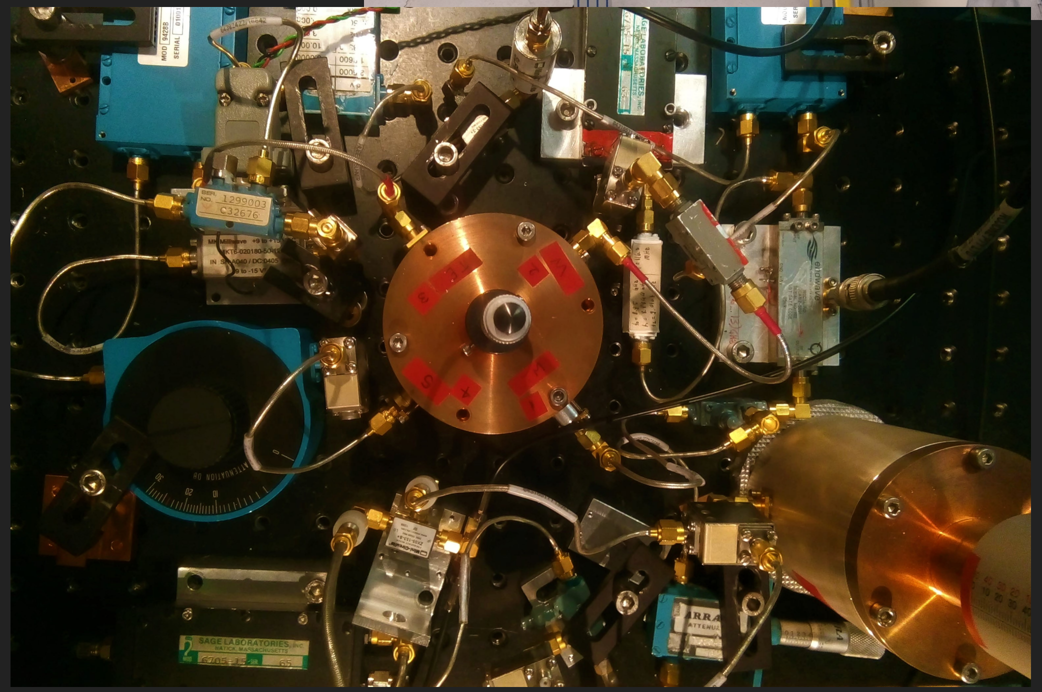
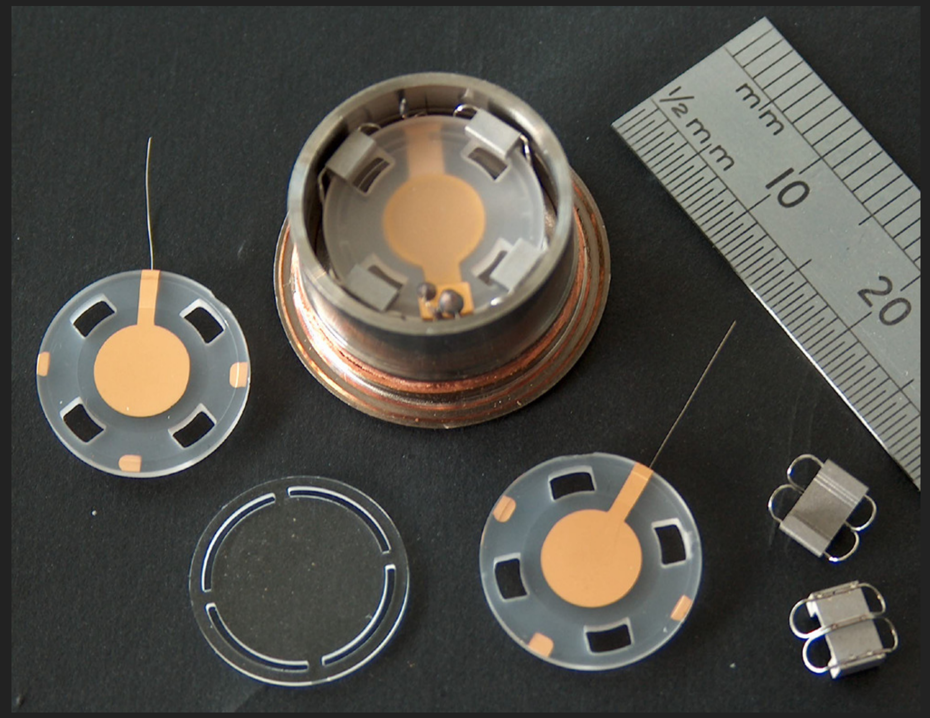
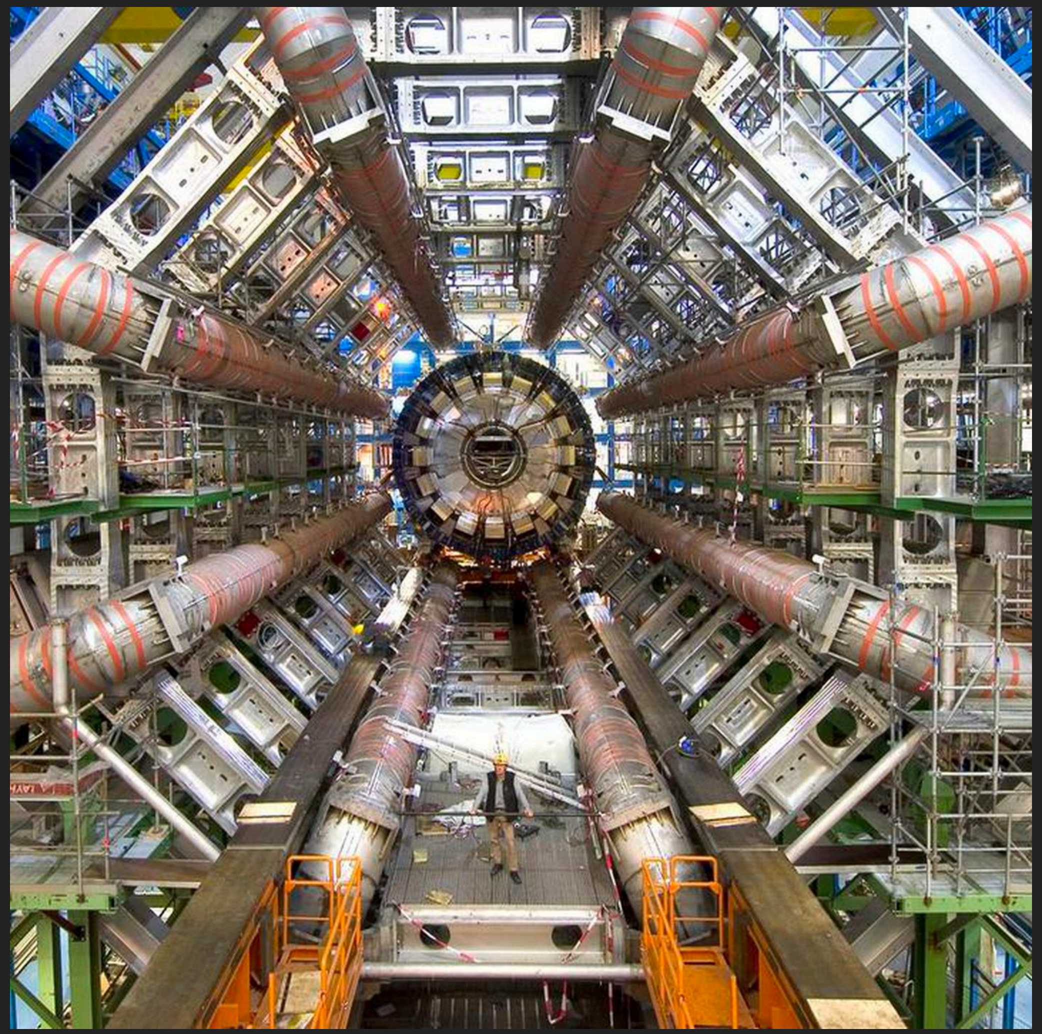
Centre Vision





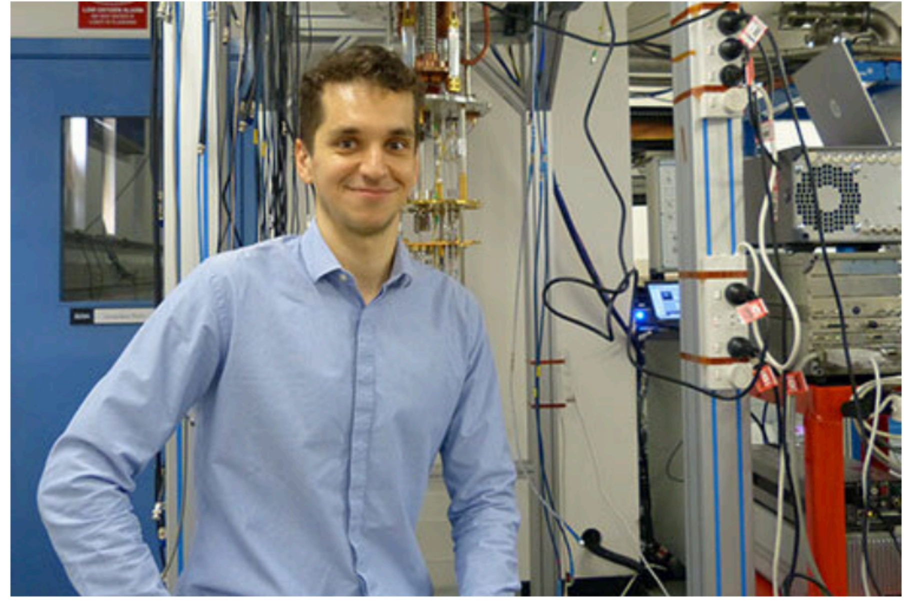






Precision and quantum metrology makes small scale experiments well suitable for searches of new physics

Professor Mike Tobar
Director



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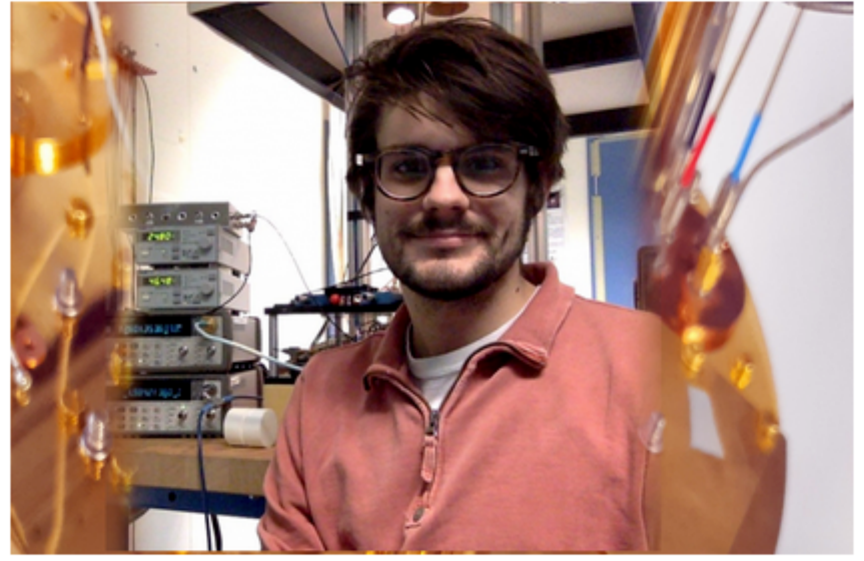
Research Associate

Dr Ben McAllister
Research Associate

Professor Eugene Ivanov
Winthrop Research Professor—Dept of Physics



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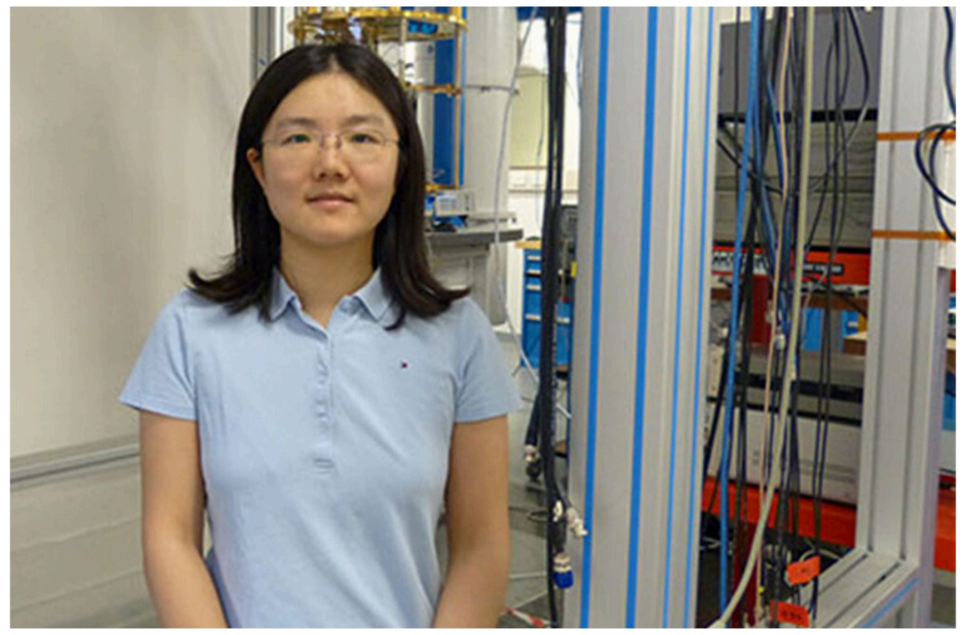
Postdoctoral Research Associate



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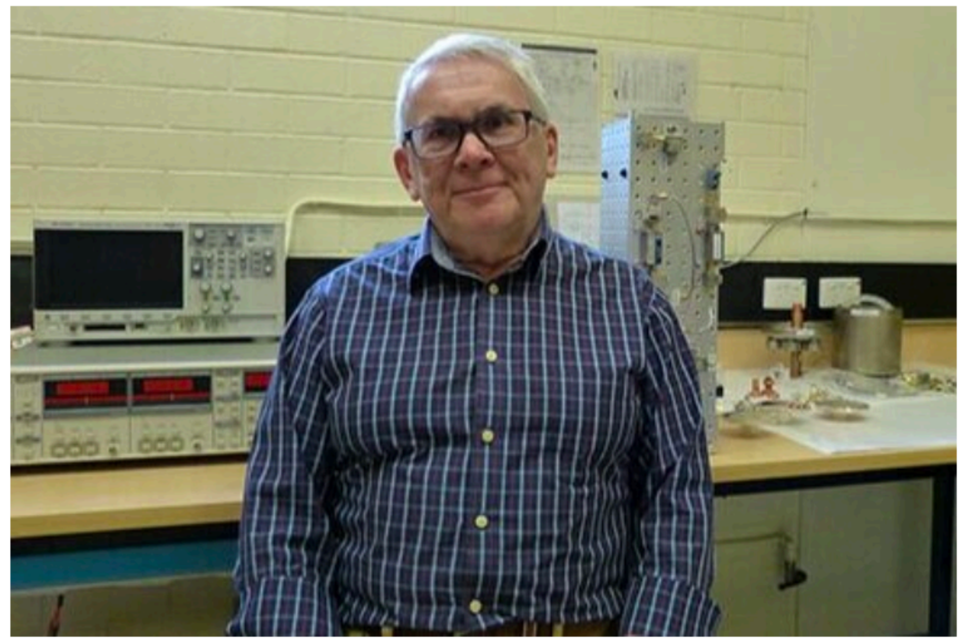
Deborah Jin Fellow—EQUS



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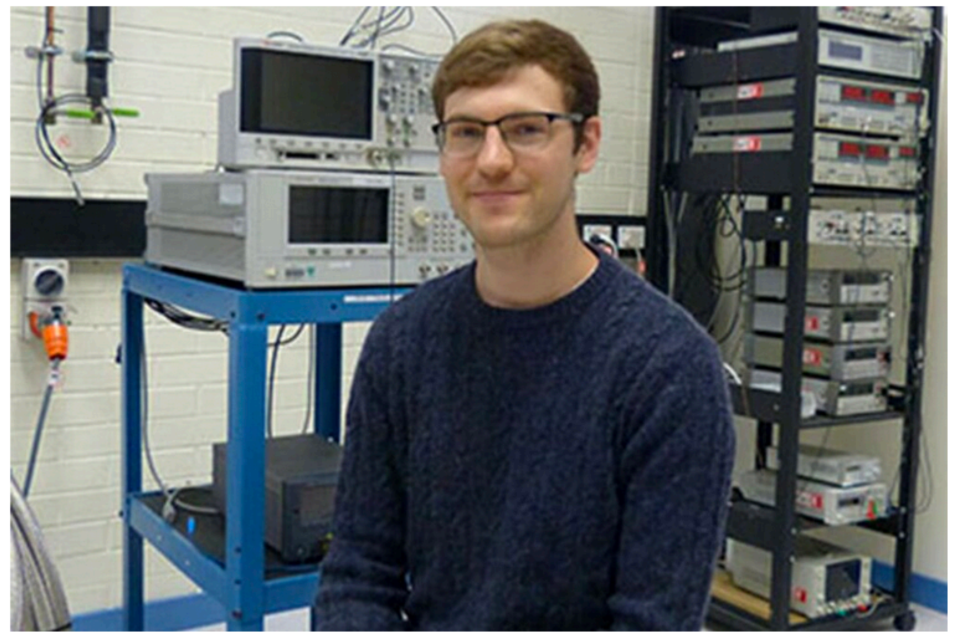
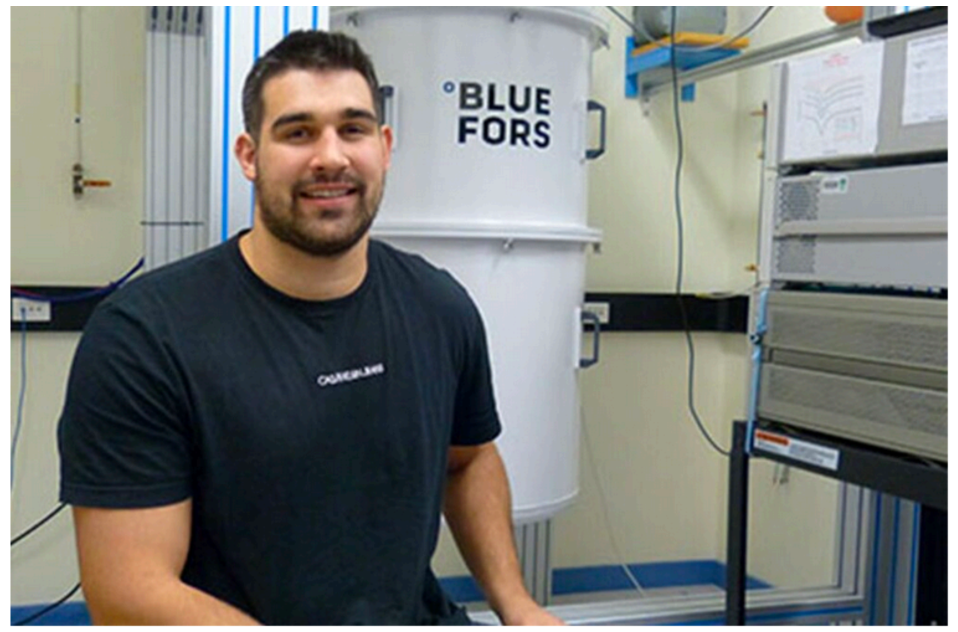
Adjunct Professor



Graeme Flower
PhD



Aaron Quiskamp
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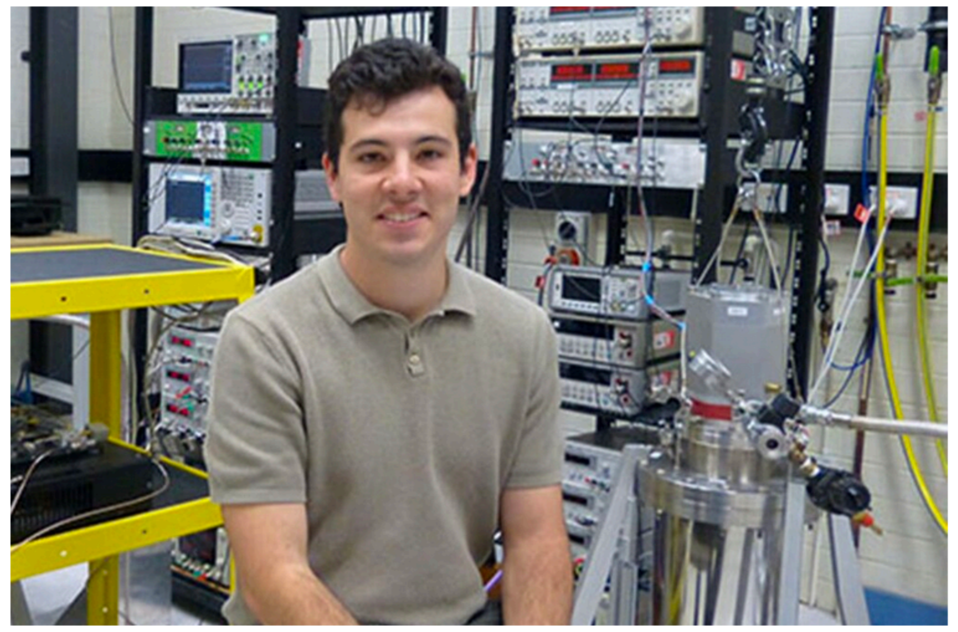

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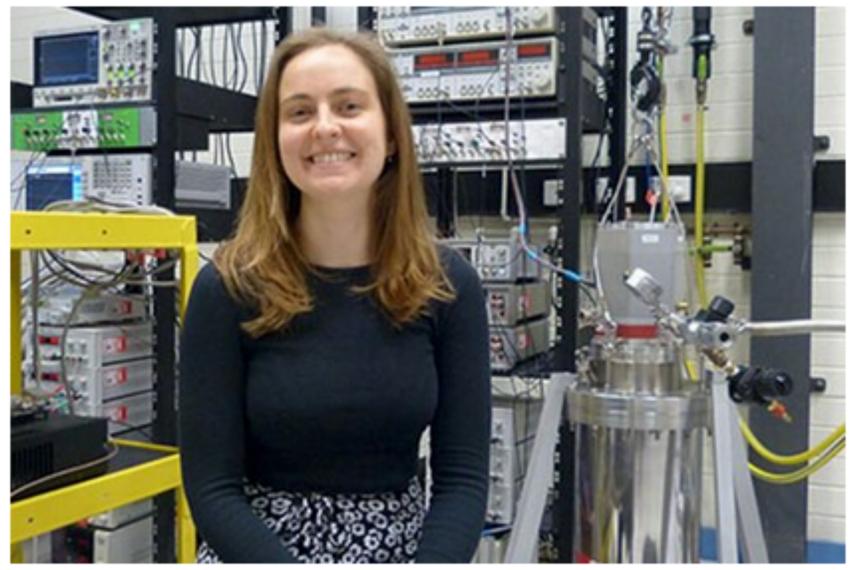

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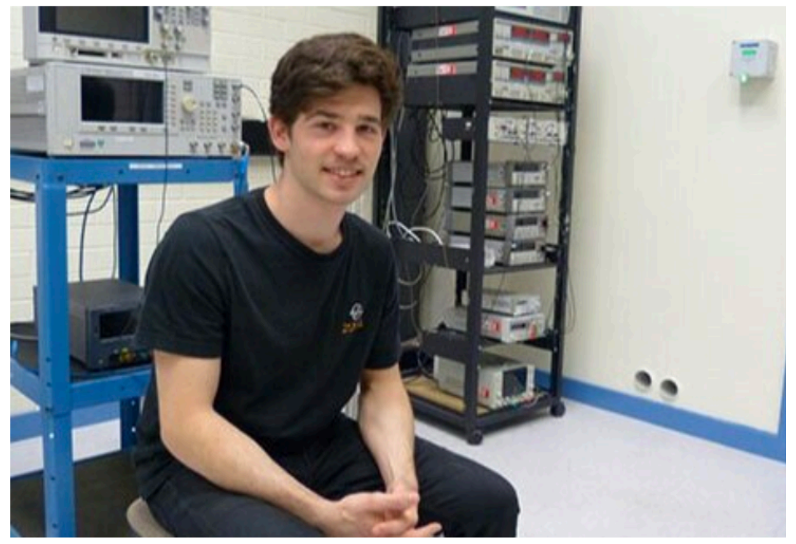
Elrina Hartman
PhD



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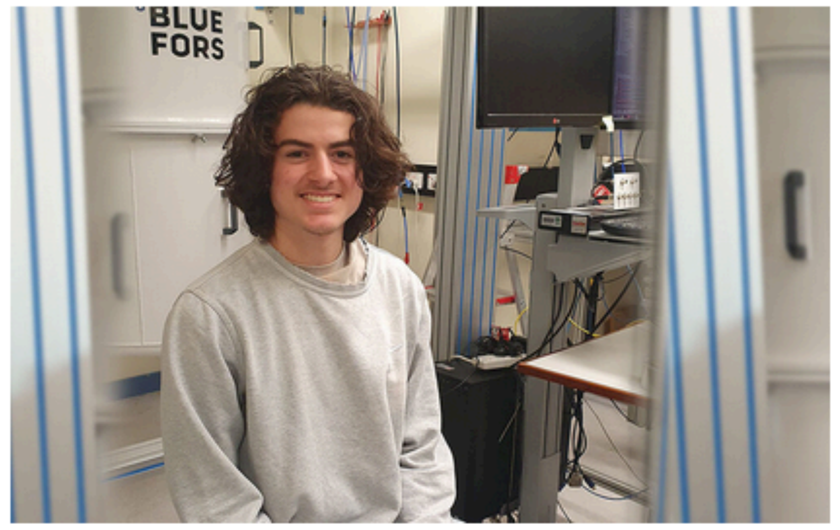
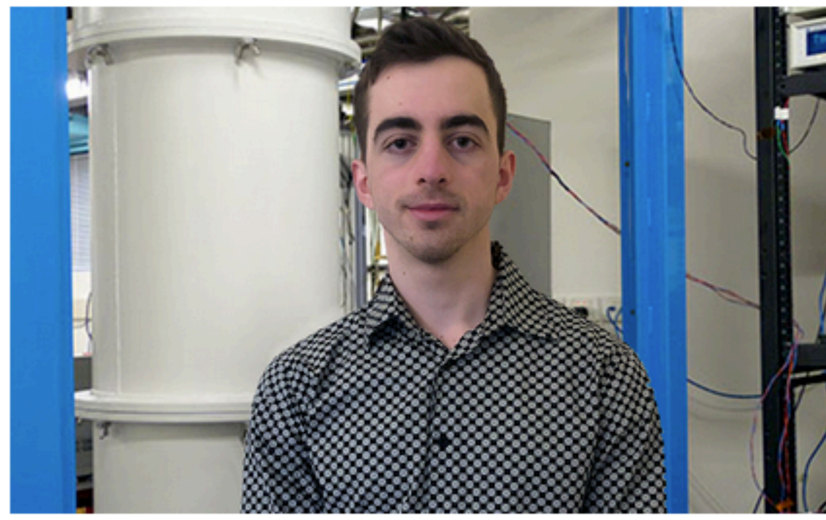
Masters

Robert Crew
BPhil (Hons) Placement



Daniel Tobar
BPhil (Hons) Placement



Michael Hatzon
BPhil (Hons)Placement

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Technician

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