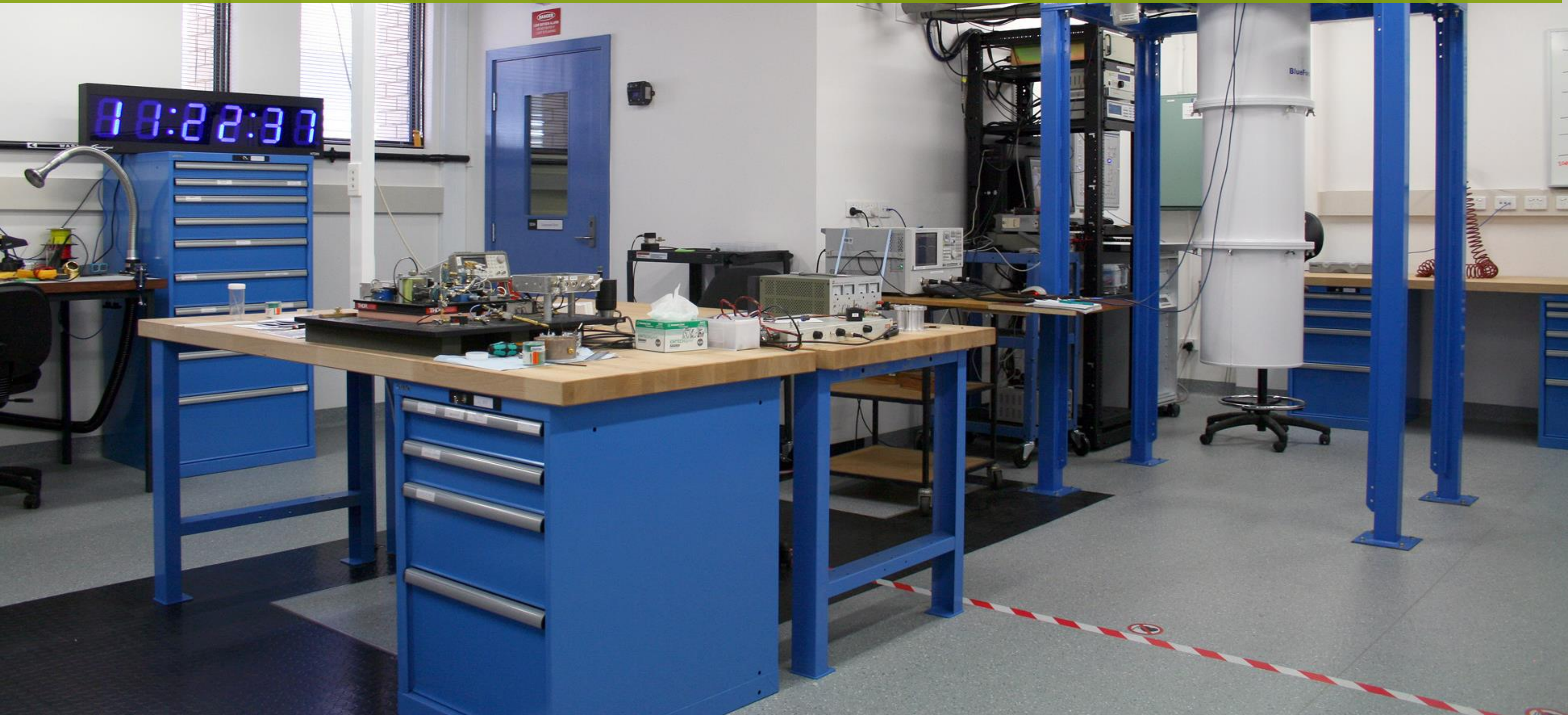
The University of Western Australia

Precision Low Temperature Experiments with Photons, Phonons and Spins and Application to Experiments that Test Fundamental Physics

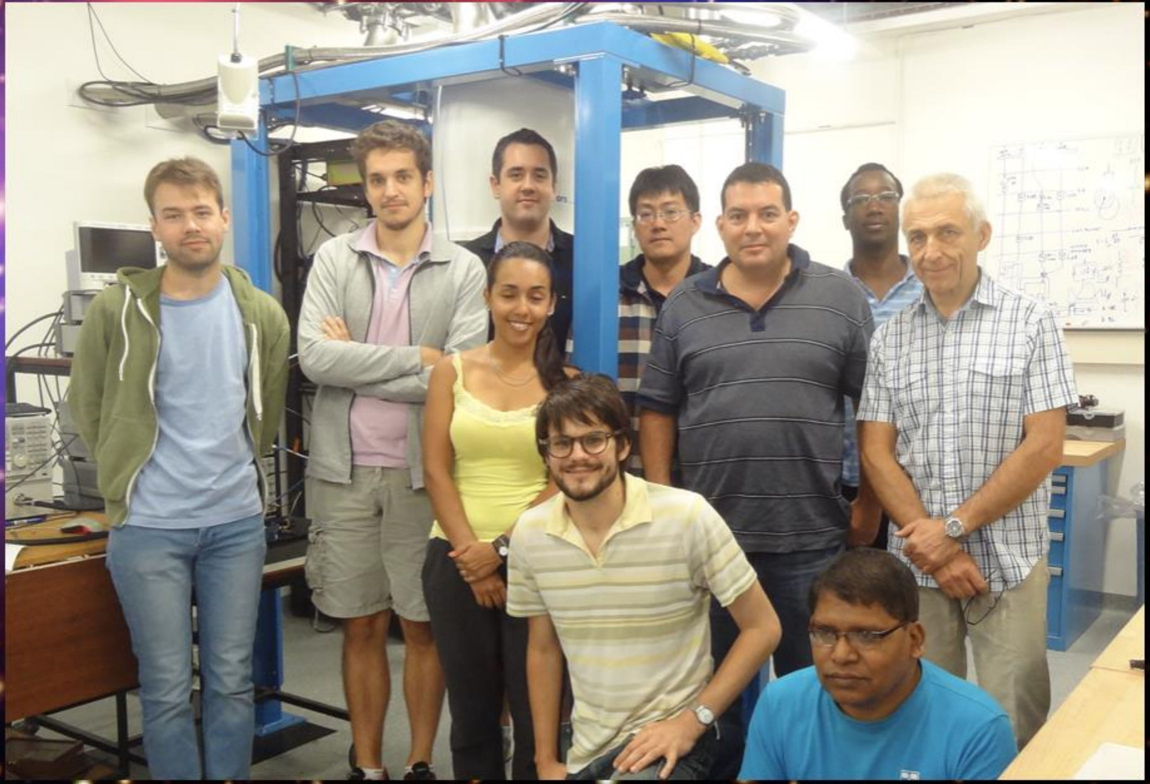
Perth, Australia



Frequency and Quantum Metrology Research Group

- **Research Staff**
- Michael Tobar
- Eugene Ivanov
- John McFerran
- Alexey Veryaskin
- Sascha Schediwy
- Maxim Goryachev
- Jeremy Bourhill

- **Students**
- Ben McAllister
- Akhter Hoissan
- Graeme Flower
- Scott Hardie
- Lewis Teixeira
- Catriona Thomas



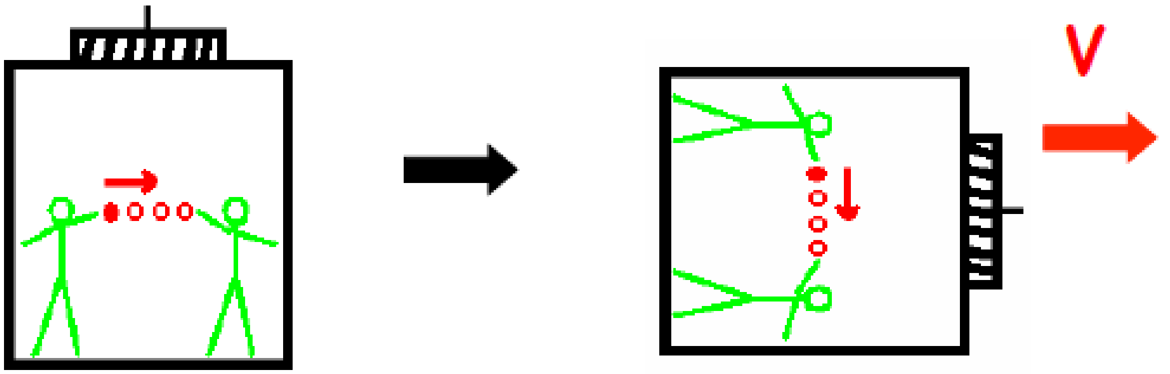
Searching For new Physics

- Unsolved problems in Physics
  - Dark Matter (search for dark sector particles)
  - Dark Energy
  - Theory of Quantum Gravity (search for break down in relativity of Lorentz Invariance violations)
- Can use low energy precision experiments (at UWA)
  - Phonons (search scalar dark matter particles, LIV of oscillating masses)
  - Spins (search spin interaction with axions)
  - Photons (search dark matter particles, LIV of photon and constancy of speed of light)

Local Lorentz Invariance

- Local Lorentz symmetry
  - Two kinds of transformations: **Rotations** and **Boosts**

- Experimental outcomes are the same when the **apparatus** undergoes (local) Lorentz transformations



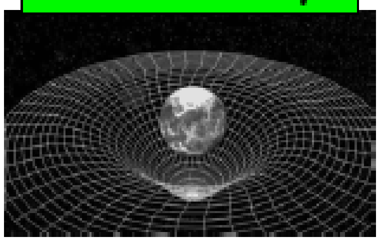
- General framework for studying Lorentz violation

Standard-Model Extension (SME)

(Developed by Kostelecký and collaborators in the 90s)

- Basic Idea:

General Relativity



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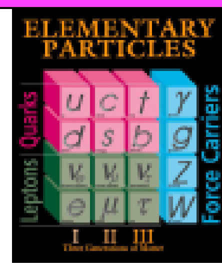
Standard Model



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All possible forms of Lorentz violation

Background fields interacting with known matter

SME - effective field theory with lagrangian:

$$\mathcal{L}_{SME} = \mathcal{L}_{GR} + \mathcal{L}_{SM} + \mathcal{L}_{LV} + \ldots$$

Usual GR lagrangian ($\mathcal{L}_{GR}$)

Usual SM fields ($\mathcal{L}_{SM}$)

All possible Lorentz-violating terms constructed from SM & GR fields and background coefficients ($\mathcal{L}_{LV}$)

Tested Across Many Different Particle Sectors

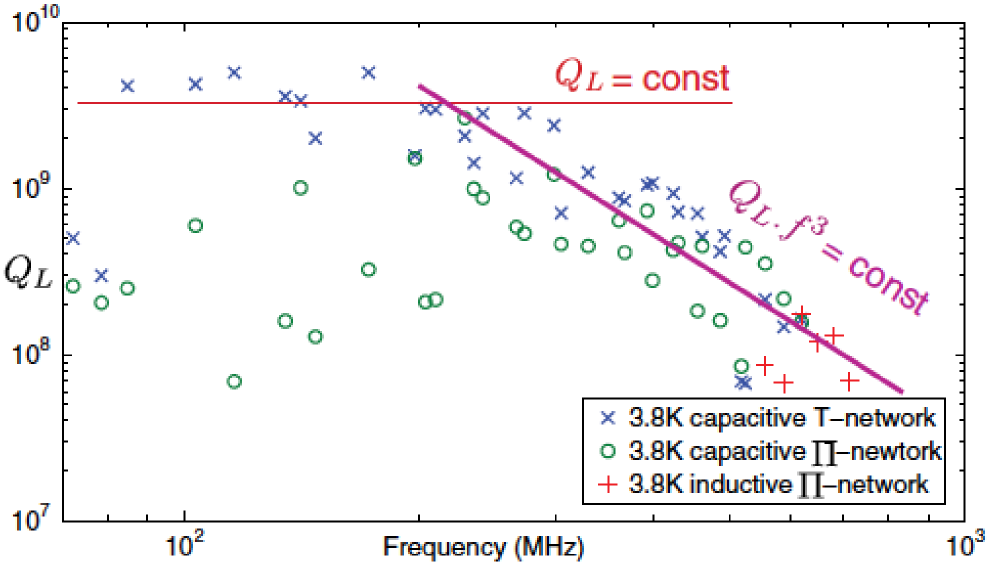
-> Photon
-> Matter (neutron, proton, electron, neutrino..)
-> Gravity

http://www.physics.indiana.edu/~kostelec/

Phonons in BAW Resonators

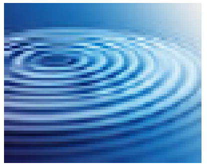
- HIGH-Q PHONON MODES 20mK

PRL **111**, 085502 (2013)



Qxf ~ 10^{18}

Quartz Phonon Trapping Technology

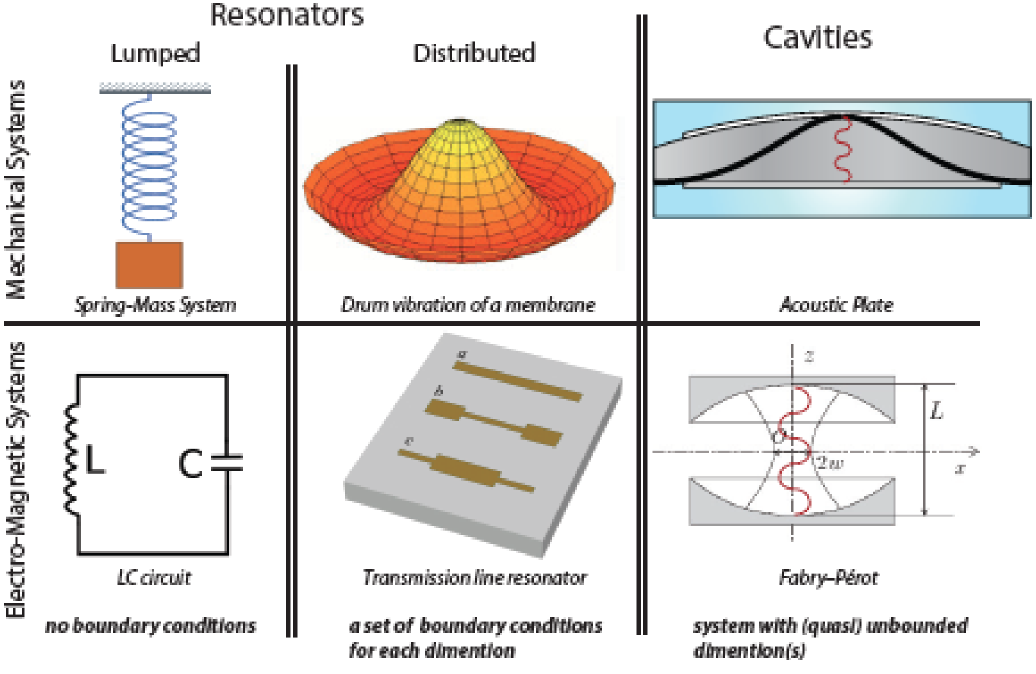


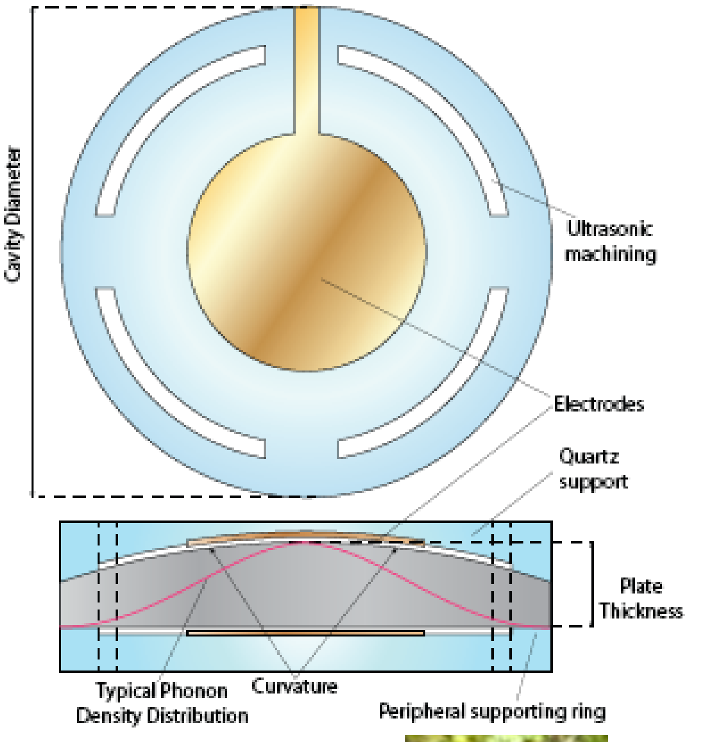
Tabletop experiment could detect gravitational waves

Oct 17, 2014 10 comments

Tiny device could beat LIGO to detecting ripples in space–time, say physicists

Acoustic analog of optical Fabry-Pérot:





Features:

- phonon wavelengths $\sim 8 - 1000\ \mu\text{m}$ ($f \to 1$ GHz),
- (quasi)-longitudinal and (quasi)-transverse polarizations,
- effective phonon trapping (BVA-technology),
- extremely long acoustic phonon life times ($Q \to 10^{10}$)...

PHYSICAL REVIEW X 6, 011018 (2016)

Acoustic Tests of Lorentz Symmetry Using Quartz Oscillators

Anthony Lo, Philipp Haslinger, Eli Mizrachi, Loïc Anderegg, and Holger Müller[*]
Department of Physics, University of California, Berkeley, California 94720, USA

Michael Hohensee[†]
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

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 8 December 2014; revised manuscript received 6 July 2015; published 24 February 2016)

We propose and demonstrate a test of Lorentz symmetry based on new, compact, and reliable quartz oscillator technology. Violations of Lorentz invariance in the matter and photon sector of the standard model extension generate anisotropies in particles' inertial masses and the elastic constants of solids, giving rise to measurable anisotropies in the resonance frequencies of acoustic modes in solids. A first realization of such a "phonon-sector" test of Lorentz symmetry using room-temperature stress-compensated-cut crystals yields 120 h of data at a frequency resolution of 2.4×10^{-15} and a limit of $\tilde{c}^n_Q = (-1.8 \pm 2.2) \times 10^{-14}$ GeV on the most weakly constrained neutron-sector c coefficient of the standard model extension. Future experiments with cryogenic oscillators promise significant improvements in accuracy, opening up the potential for improved limits on Lorentz violation in the neutron, proton, electron, and photon sector.

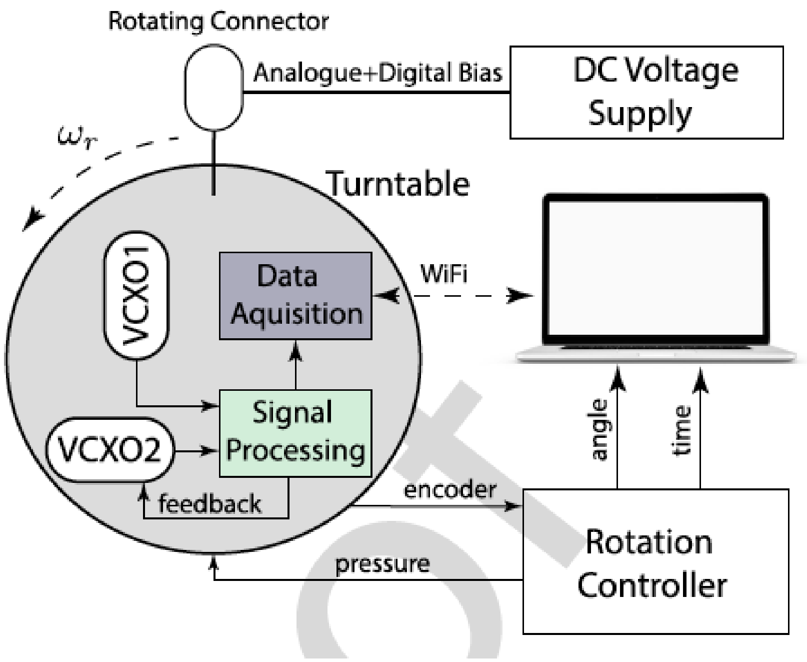
DOI: 10.1103/PhysRevX.6.011018

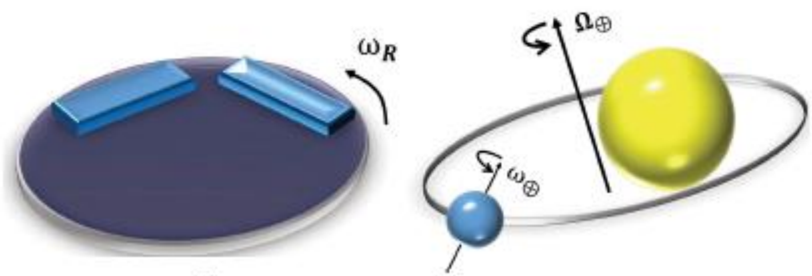
Subject Areas: Acoustics, Atomic and Molecular Physics, Electronics

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

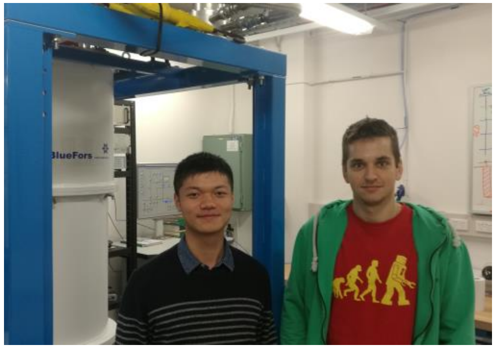
Maxim Goryachev, Zeyu Kuang, Eugene N. Ivanov, Philipp Haslinger, Holger Müller, and Michael E. Tobar, *Fellow, IEEE*

***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.**

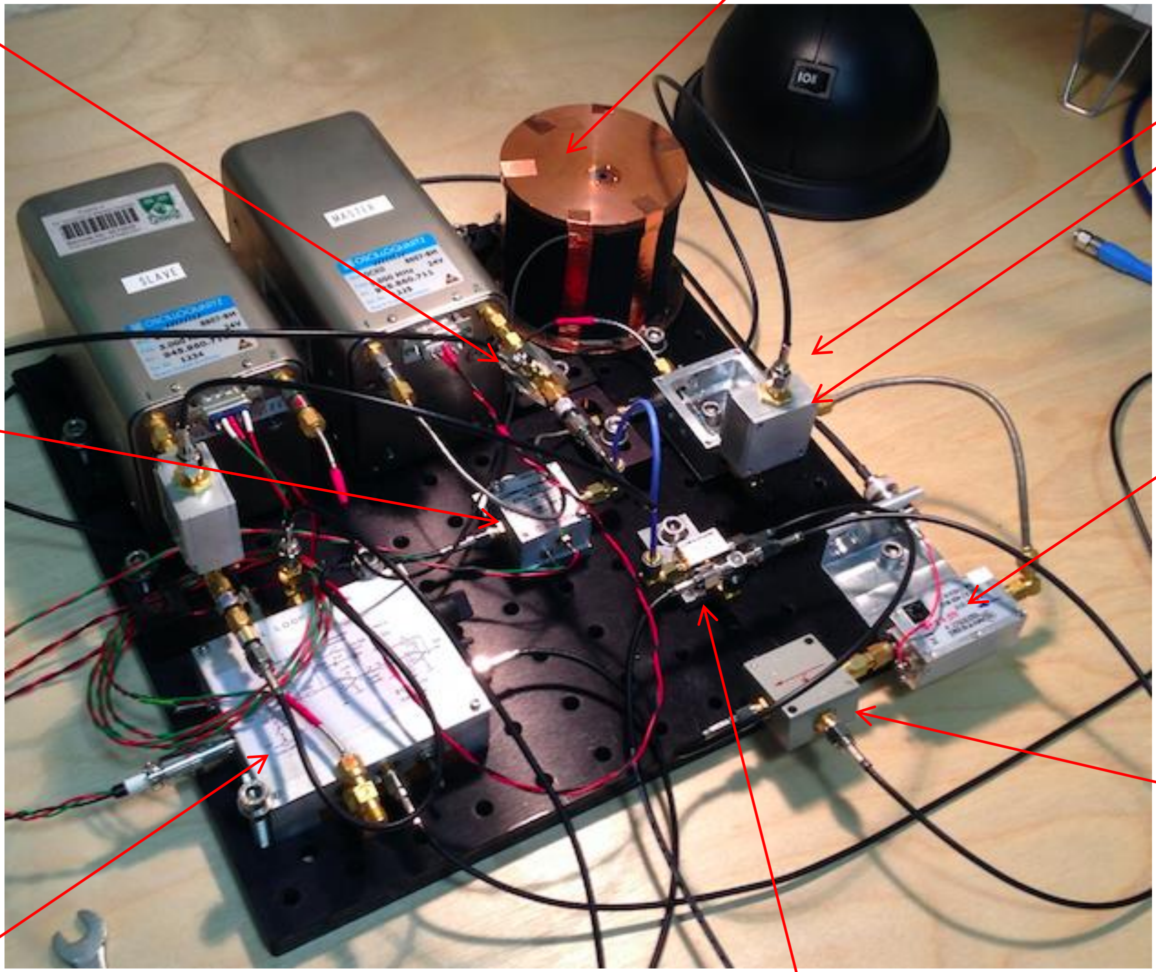




(a) (b)



PLL with Interferometric Readout



PLL mixer

Delay line: Δφ ~ 76 deg at 5 MHz

Attenuator

Power combiner

Isolation/booster amplifier

LNA (1.3 dB NF)

10 dB coupler

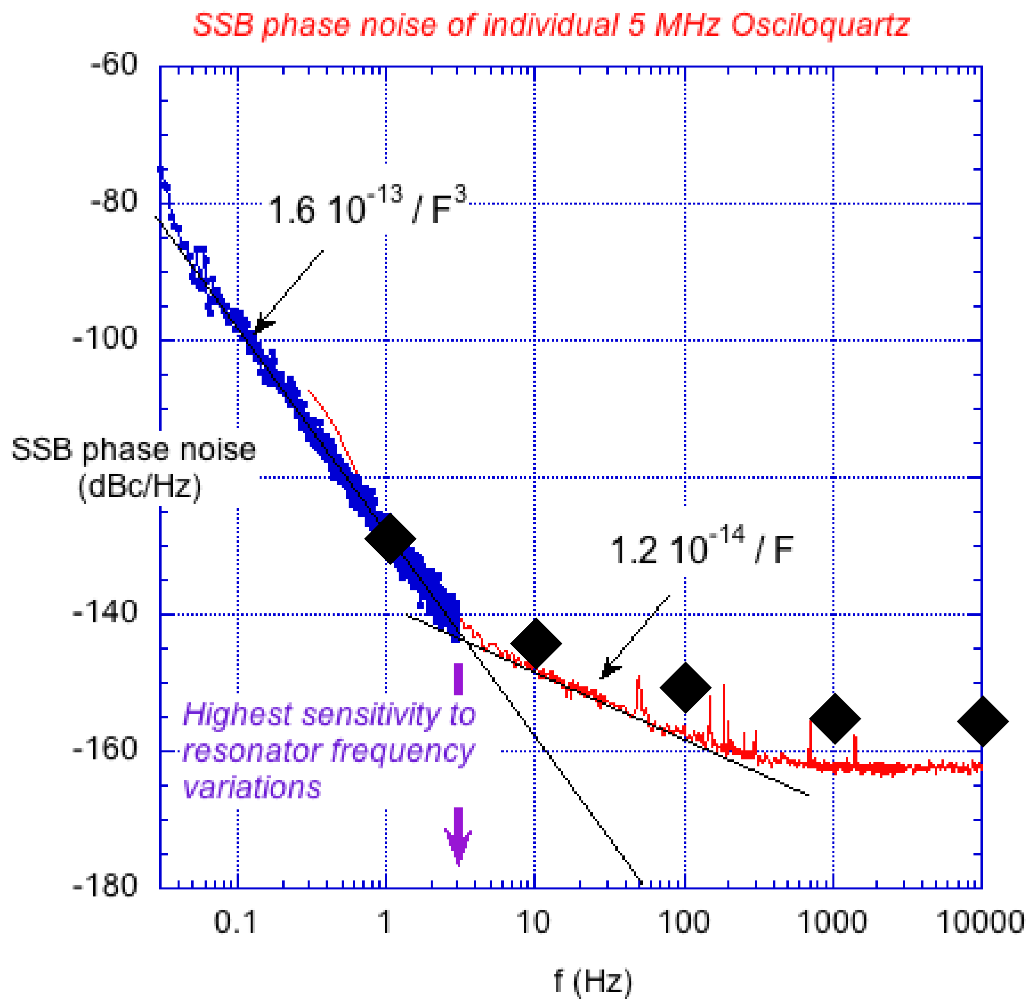
PLL loop filter

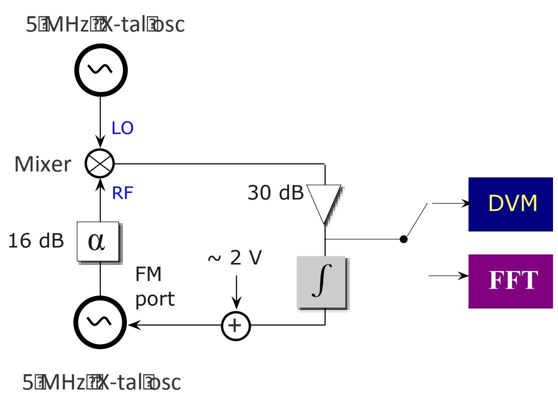
Mixer of readout system

Phase Noise Spectrum of 5 MHz Oscilloquartz oscillator

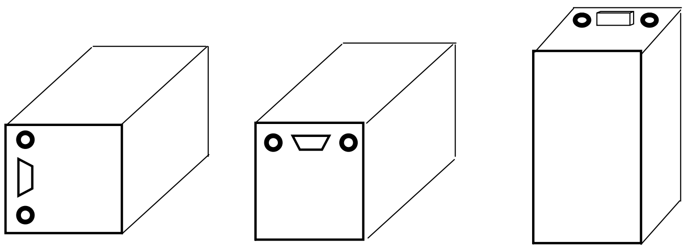
Phase noise (BW = 1 Hz) Options

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





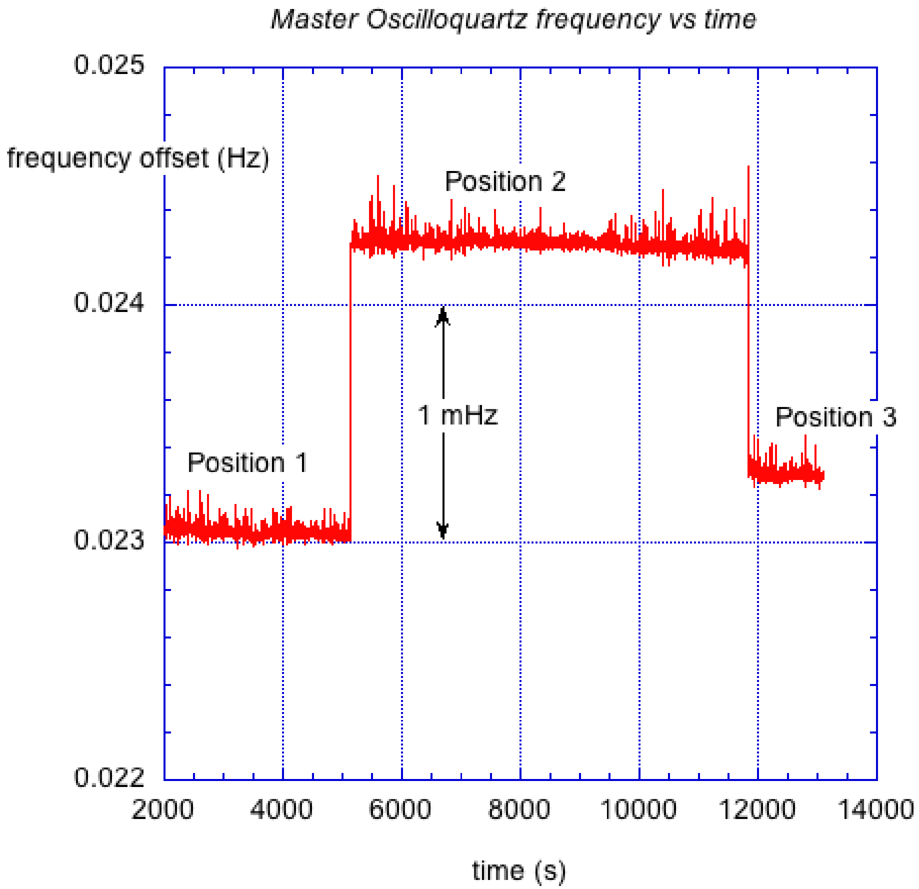
Effect of Rotation on Oscillator Frequency: 2



1 position
(φ = 270)

2nd position
(φ = 0)

3rd posi) on



Rotating Quartz Oscillators

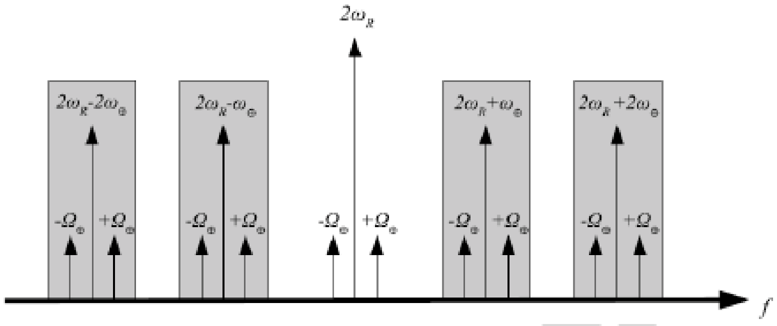
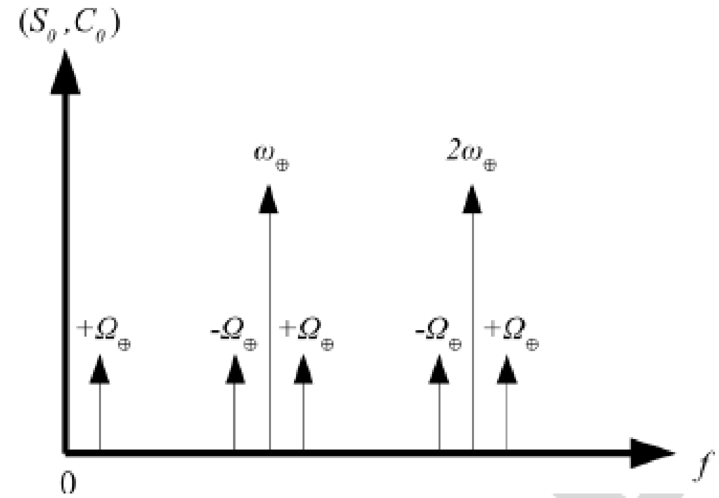
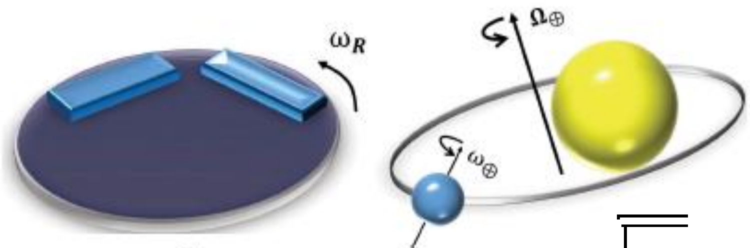


Fig. 5. Illustration of frequency components of $(\Delta f)/f$ caused by putative LIV coefficients.

Demodulate Data by averaging over number of Rotations





(a) (b)

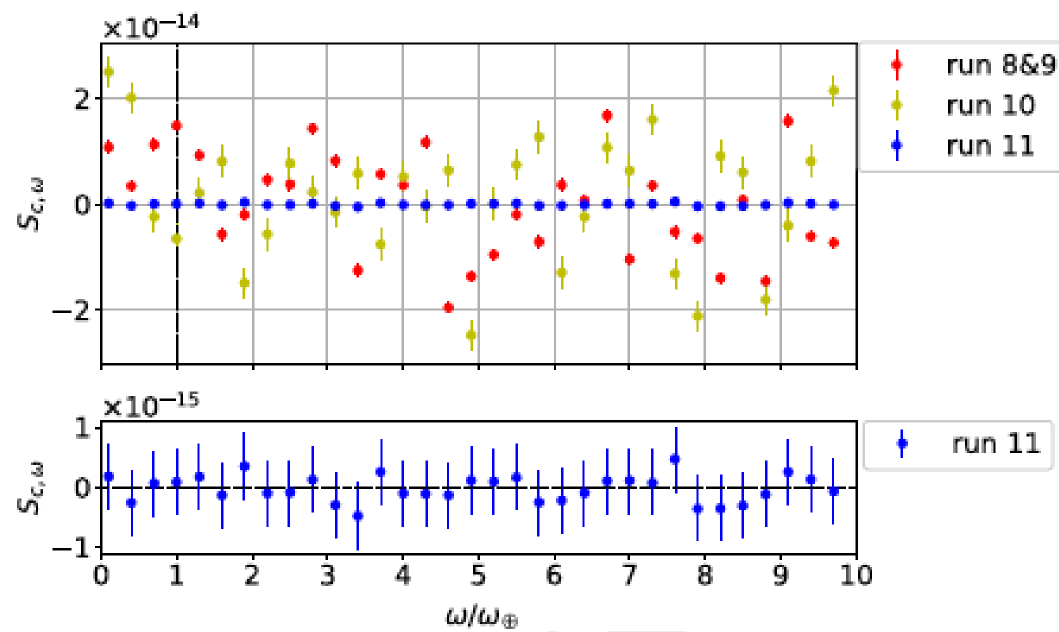
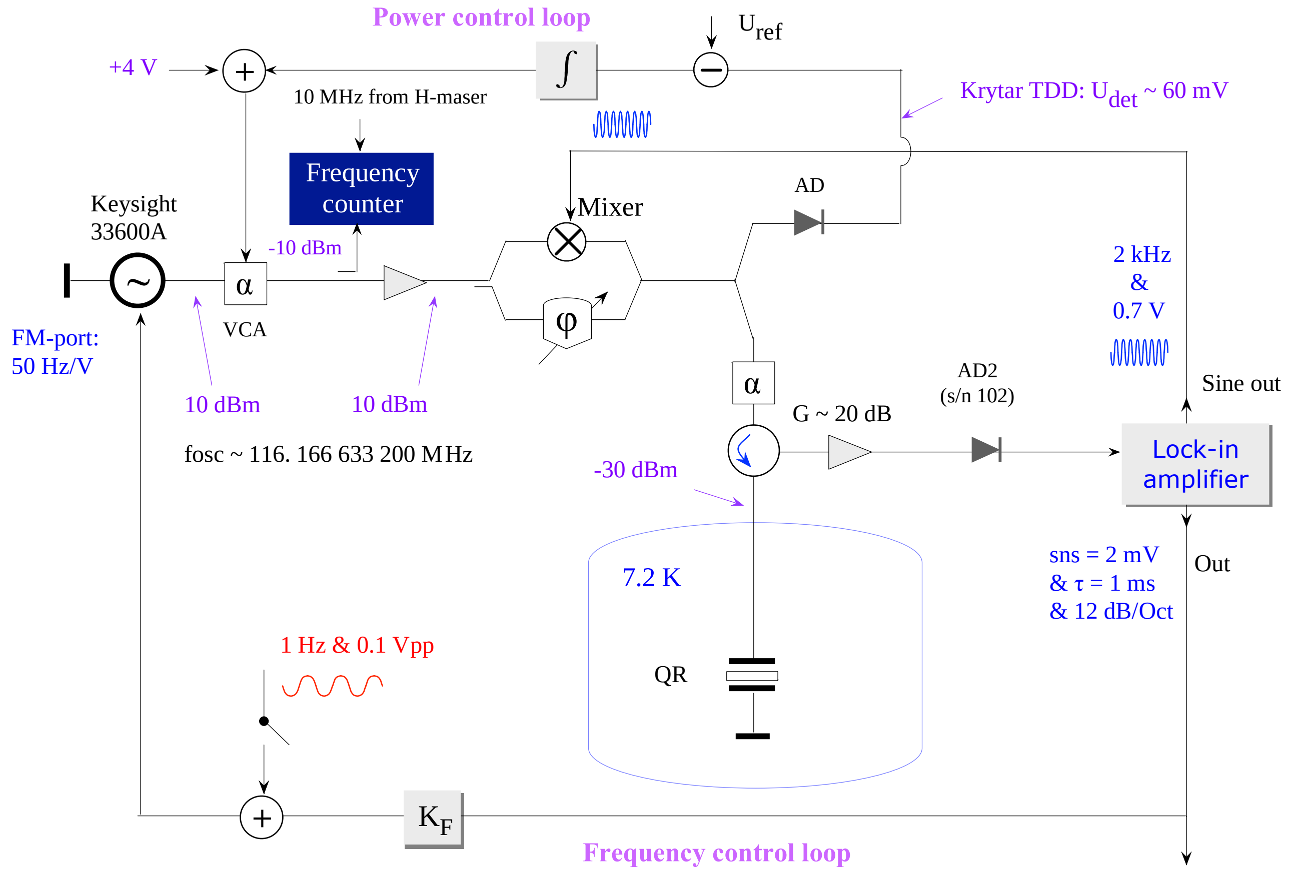


Fig. 10. Fitted $S_{c,\omega}$ coefficient with $N_r = 10$ as a function of normalized frequency $\omega/\omega_\oplus$ for the different experimental runs.

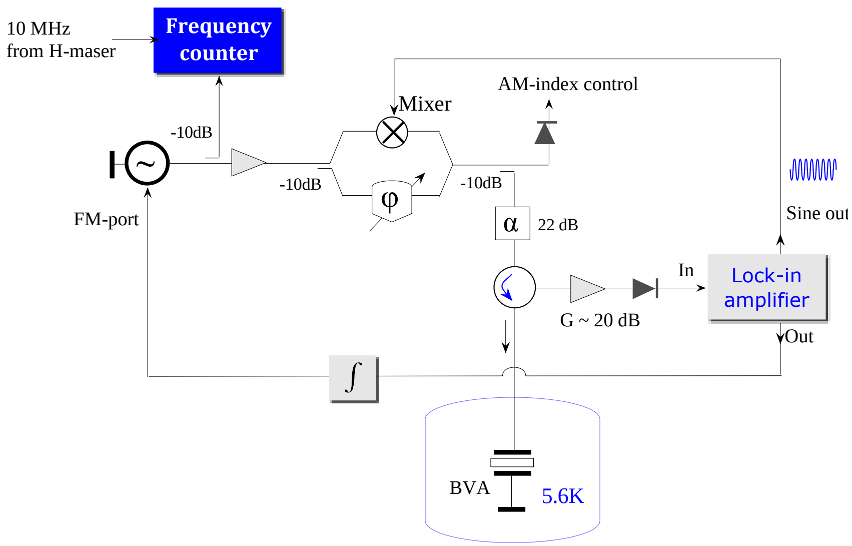
Pound Stabilized Cryogenic Bulk Acoustic Wave Resonator-Oscillator

Eugene N Ivanov, Maxim Goryachev, Michael E Tobar
Centre for Engineered Quantum Systems, School of Physics, University of Western Australia, Crawley, WA 6009, Australia
michael.tobar@uwa.edu.au

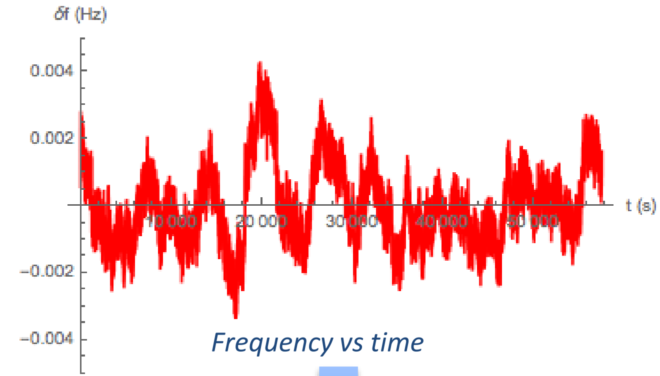
Serge Galliou
FEMTO-ST Institute, CNRS, Univ. Bougogne Franche-Comté, Time and Frequency Department, ENSMM 25000 Besançon, France



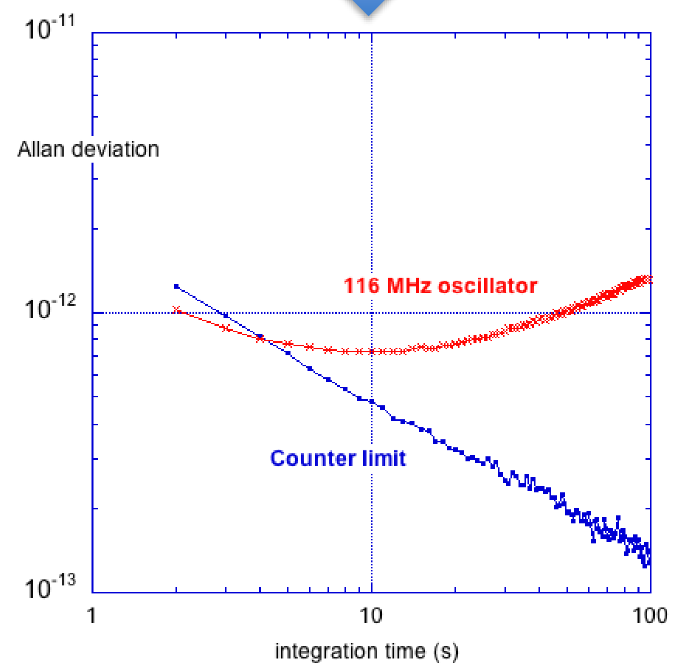
Frequency Stability Measurements



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



Frequency vs time



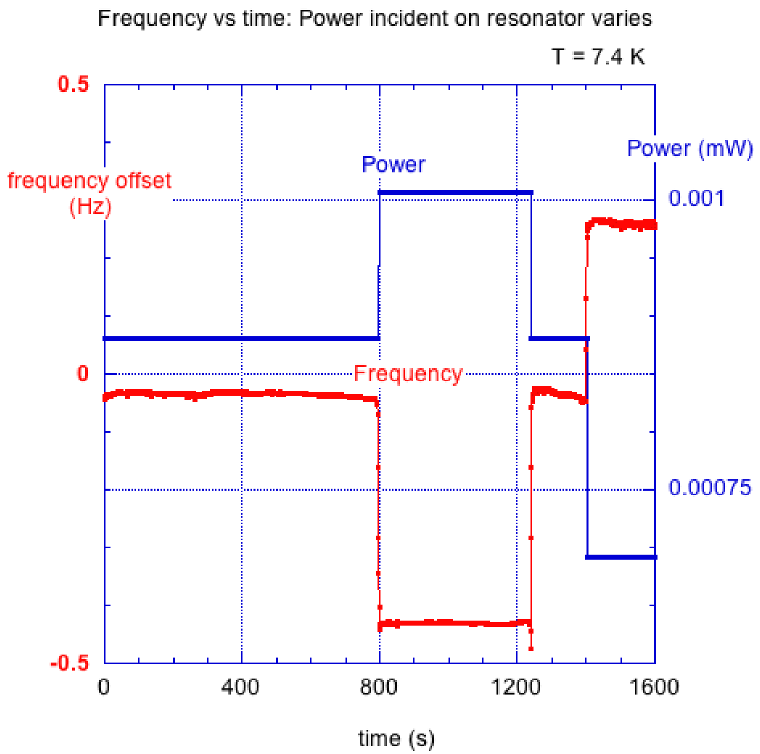
Allan deviation of fractional frequency fluctuations averaged over time τ

NB

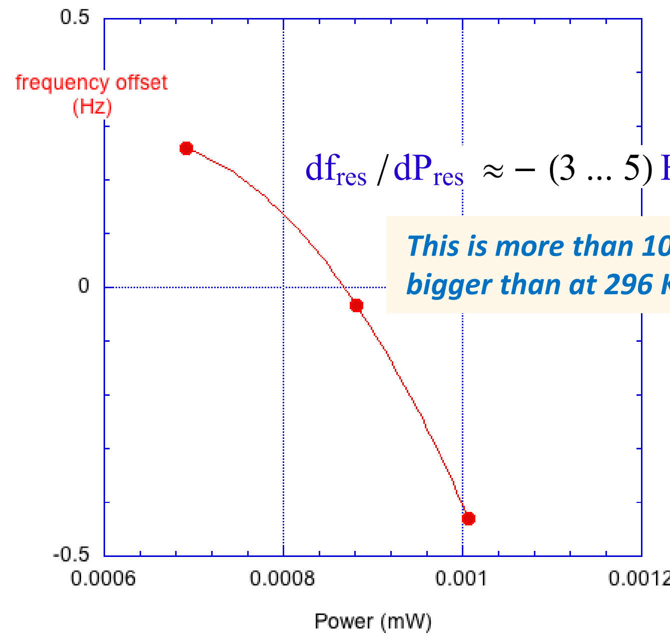
1. There is no noticeable frequency drift despite the use of room temperature detection system.

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

Cryogenic Quartz Oscillator: Power-to-Frequency Conversion



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

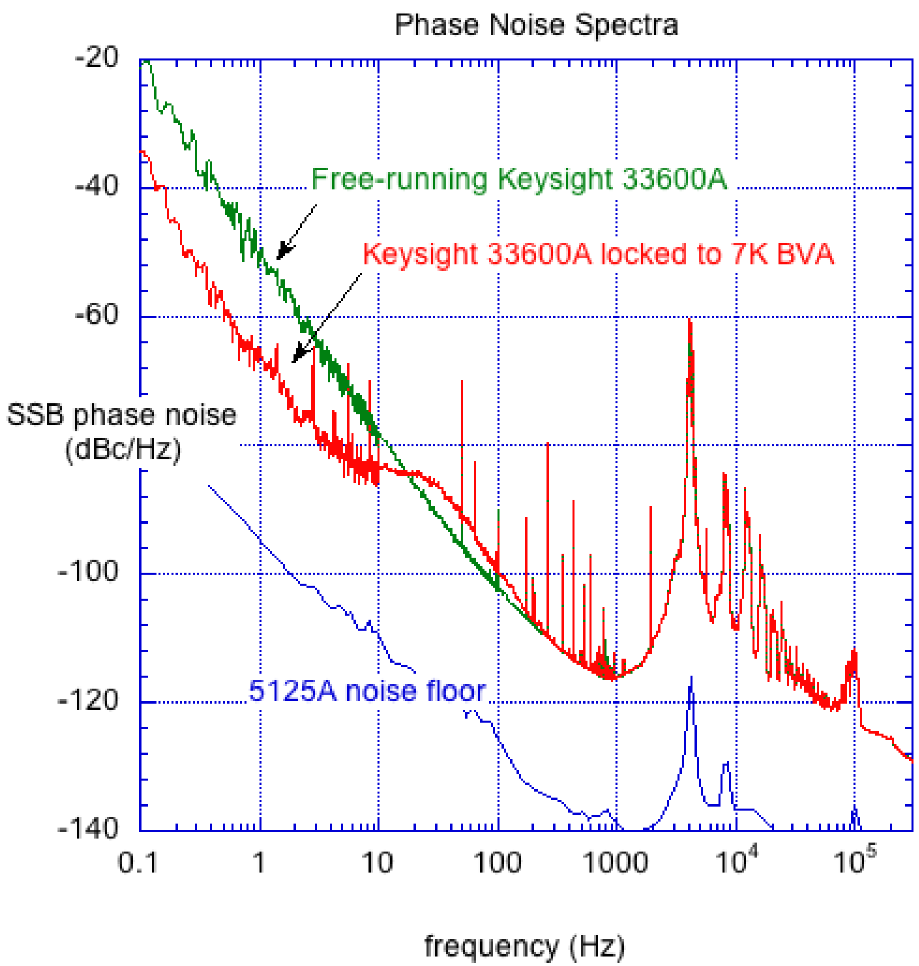


$$df_{res} / dP_{res} \approx -(3 \ldots 5)\ \mathrm{Hz}/\mu\mathrm{W}$$

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

Oscillator frequency vs power

Cryogenic Quartz Oscillator: Phase Noise



APPLIED PHYSICS LETTERS **105**, 153505 (2014)

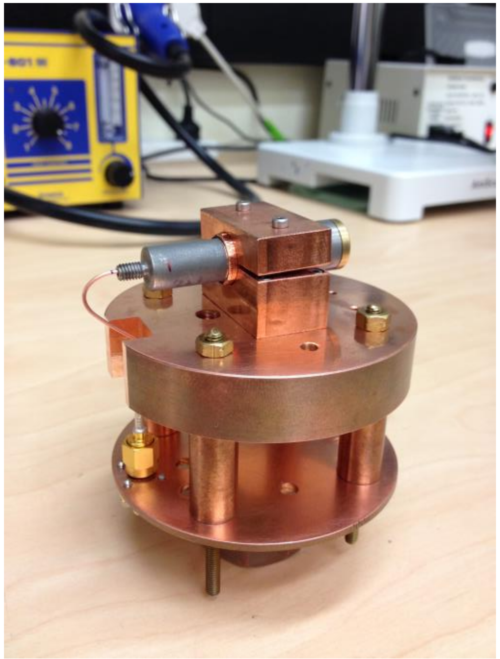
Observation of the fundamental Nyquist noise limit in an ultra-high *Q*-factor cryogenic bulk acoustic wave cavity

Maxim Goryachev,[1,a)] Eugene N. Ivanov,[1] Frank van Kann,[2] Serge Galliou,[3] 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]*School of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*
[3]*Department of Time and Frequency, FEMTO-ST Institute, ENSMM, 26 Chemin de l'Épitaphe, 25000 Besançon, France*

(Received 22 August 2014; accepted 9 October 2014; published online 17 October 2014)

Thermal Nyquist noise fluctuations of high-*Q* bulk acoustic wave cavities have been observed at cryogenic temperatures with a DC superconducting quantum interference device amplifier. High *Q* modes with bandwidths of few tens of milliHz produce thermal fluctuations with a signal-to-noise ratio of up to 23 dB. The estimated effective temperature from the Nyquist noise is in good agreement with the physical temperature of the device, confirming the validity of the equivalent circuit model and the non-existence of any excess resonator self-noise. The measurements also confirm that the quality factor remains extremely high ($Q > 10^8$ at low order overtones) for very weak (thermal) system motion at low temperatures, when compared to values measured with relatively strong external excitation. This result represents an enabling step towards operating such a high-Q acoustic device at the standard quantum limit.
[http://dx.doi.org/10.1063/1.4898813]

Resonator with Squid Output



DC SQUID in a copper holder to be attached to the “cold finger” of the pulse-tube cryocooler

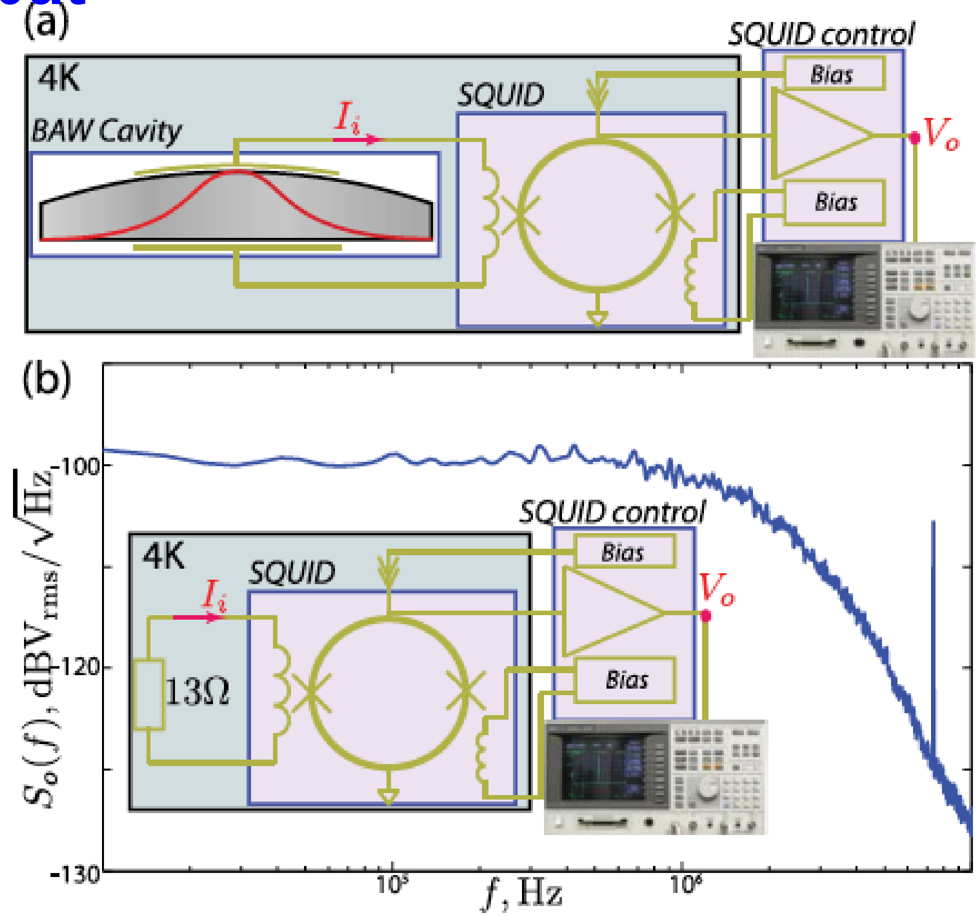


FIG. 1. (a) BAW thermal noise measurement setup for frequencies below 10 MHz. The curvature of one of the plate faces is employed to achieve the phonon trapping with the acoustic energy distribution along the plate denoted by the red curve. (b) Resistive load measurements for system calibration.

Calibration: Use resistors instead of resonators
-> Derive SQUID transimpedance ~ 1.2 MΩ

Calculate Mode Temperature

(i) Measurements of the SQUID voltage noise
(ii) Estimation of the RMS current through resonator (known SQUID impedance from calibration)
(iii) Calculation of power dissipated in resonator for evaluation of mode temperature.

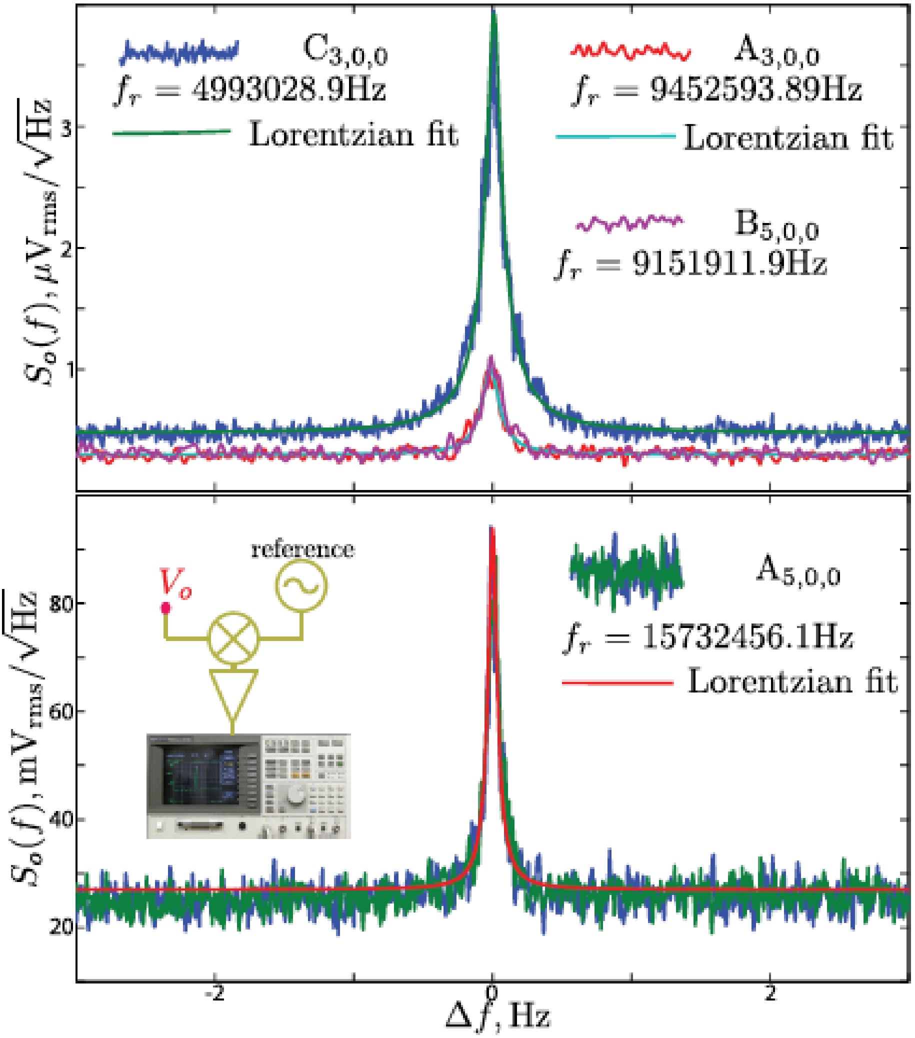


FIG. 2. Results of noise measurements for $C_{3,0,0}$, $A_{3,0,0}$, $B_{5,0,0}$, and $A_{5,0,0}$. The latter is measured using the downconversion as shown in the inset.

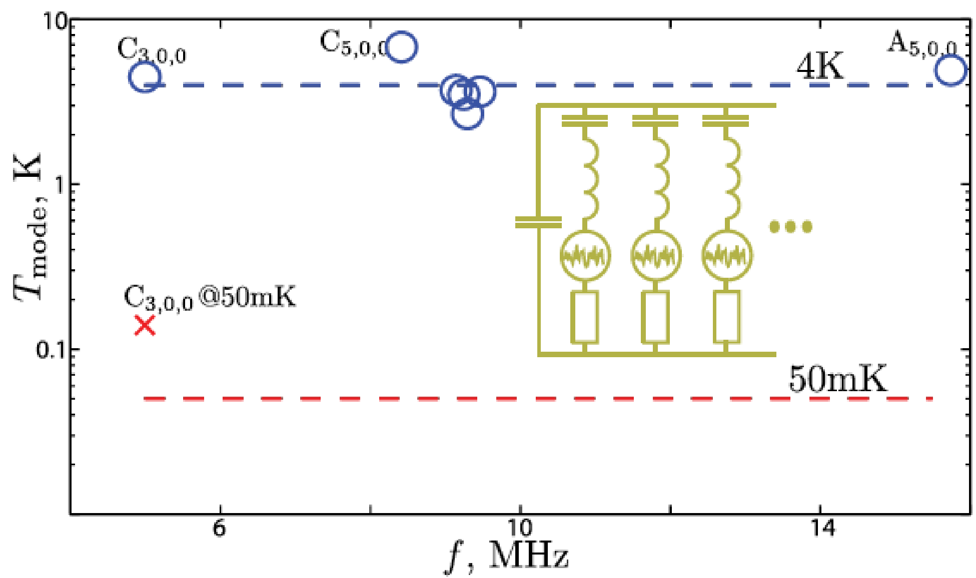
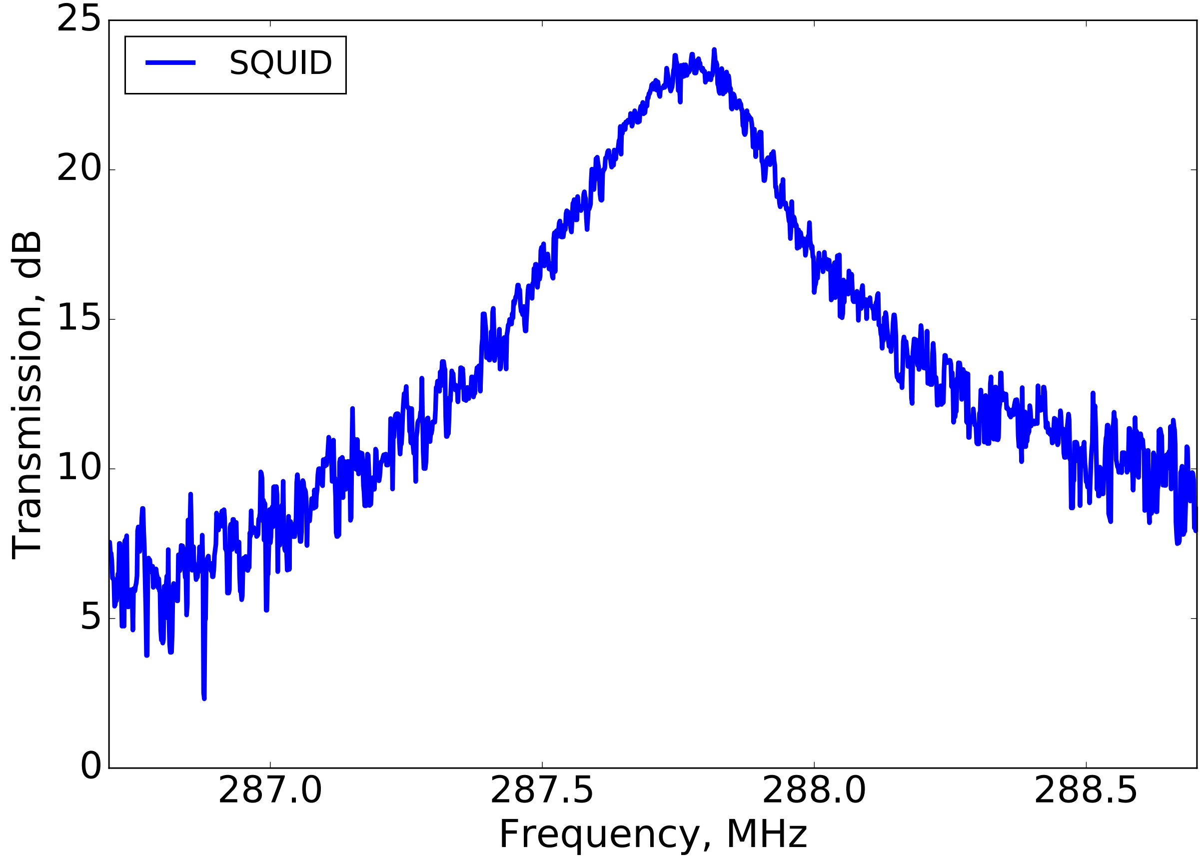


FIG. 3. Estimations of the mode temperatures compared to the ambient values. The inset shows the equivalent circuit model.

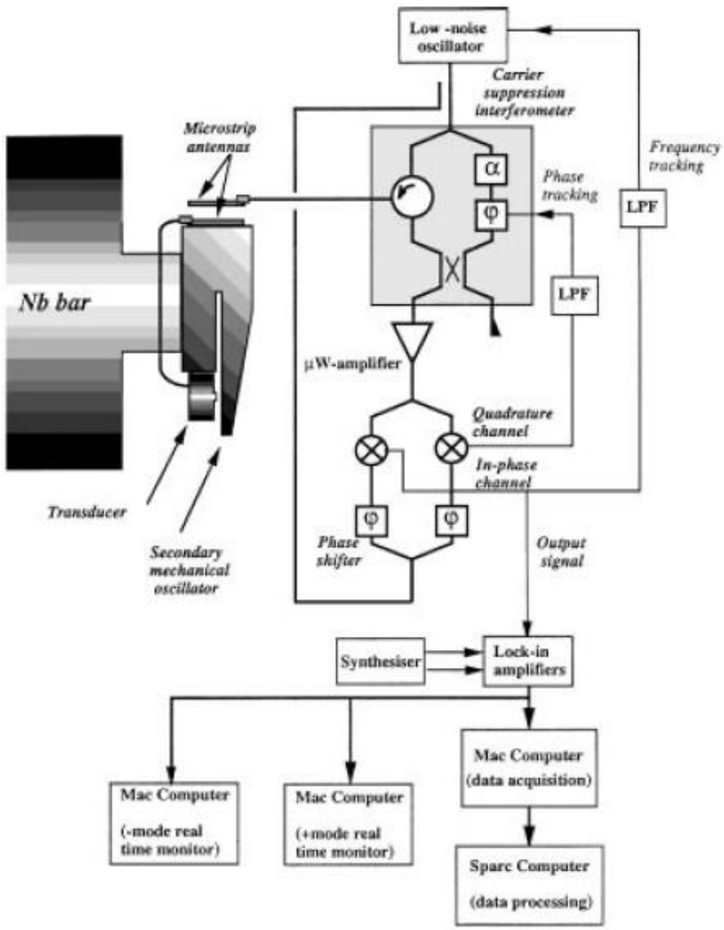
Measured at UWA at 20 mK



- Most of our resonators are identical 5MHz SC cut. -> do not have good modes around 300MHz where the mode density is sparse.

- 5MHz AT cut crystal (we have only one) has a good mode around this frequency, to be measured soon (varactor?), close to Ground State.

System is a sensitive GW Detector



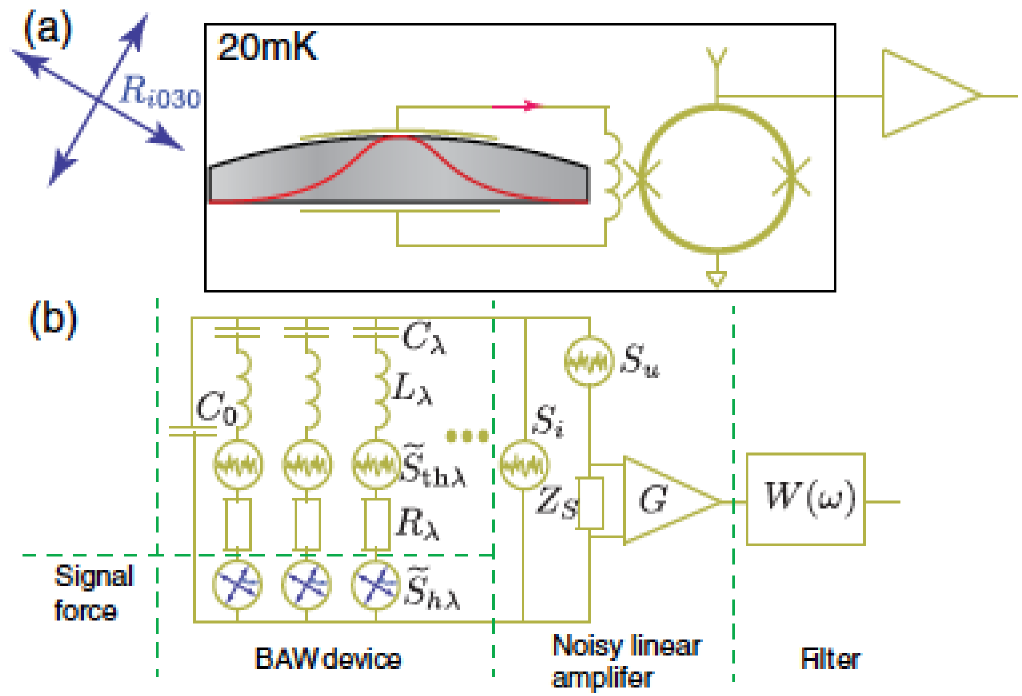
Old Resonant Bar Detector

Mass = 1.5 tonne

Q = 10^7

F = 710 Hz

T = 5 K



Quartz

Mass = Gram Scale

Q = 10^9

f = 5 MHz to 700 MHz

T = 15 mK

System is a sensitive GW Detector (PRD)

PHYSICAL REVIEW D 90, 102005 (2014)

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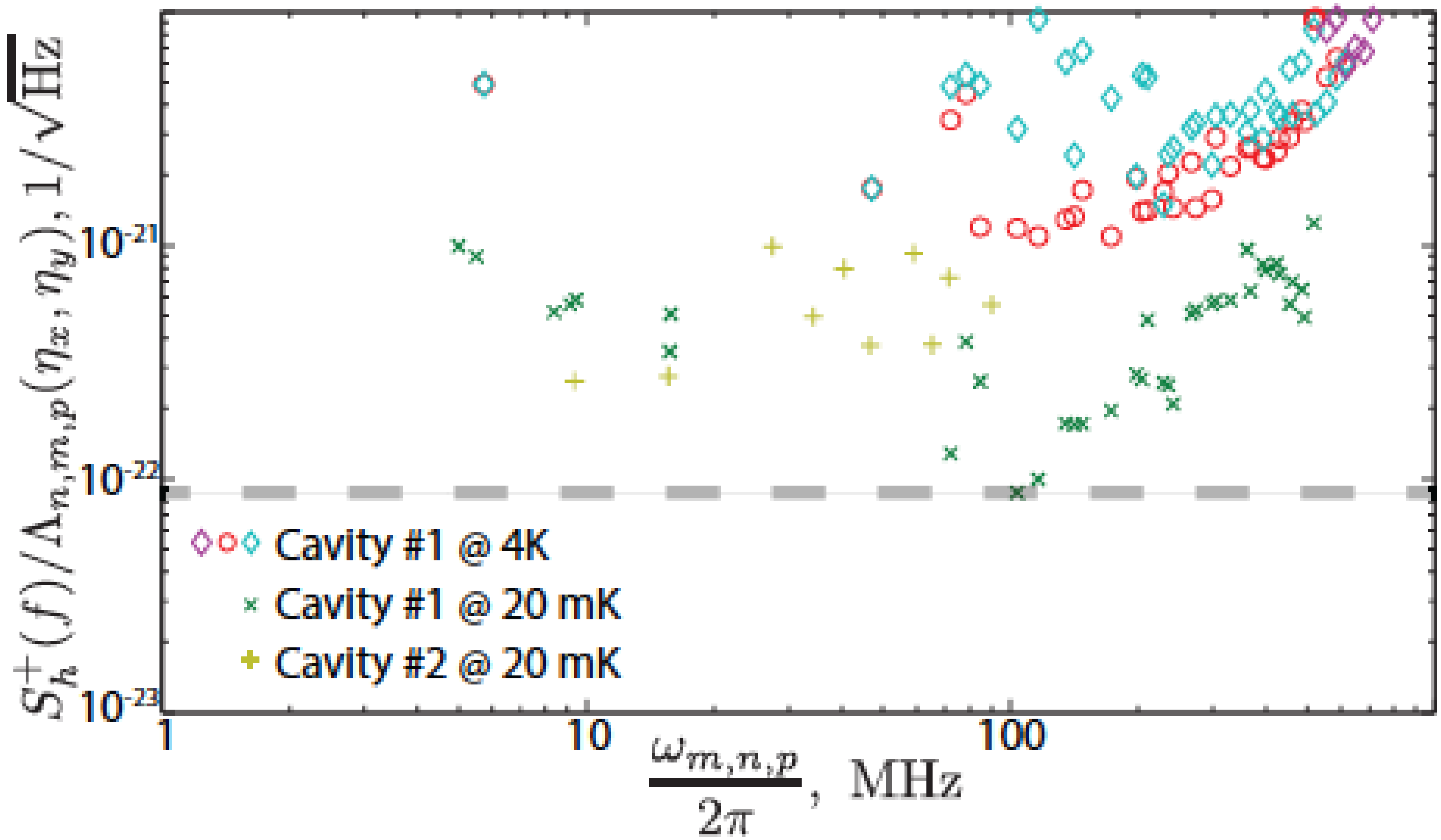

FIG. 5: Normalised the single sided power spectral density of the strain sensitivity for various OTs of the longitudinal mode of two acoustical cavities at 4K and 20mK.

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multiple
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- High frequency region has physically understood processes of generation of GWs
  - thermal gravitational radiation from stars
  - Radiation from low mass primordial black holes
  - gravitational modes of plasma flows
- Tests for many emerging theories predicting GW radiation at such frequencies.
  - stochastic sources in the early Universe
  - GW background from quintessential inflation
  - cosmic strings
  - Dilation
  - pre–big bang scenarios
  - Superinflation in loop quantum gravity
  - Postinflationary phase transitions
  - parametric resonance at the end of inflation or preheating
  - braneworld black holes associated with extra dimensions
  - clouds of axions (super radiance)
  - quark nuggets
  - One hypothetical sources (due to the Galactic center shadow brane) comes within the sensitivity of the proposed single detector

The 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, CA 94305, USA*

(Dated: August 11, 2015)

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 antennae. Existing and proposed resonant-mass detectors can probe dark matter moduli with frequencies between 1 kHz and 1 GHz, with much better sensitivity than force measurements.

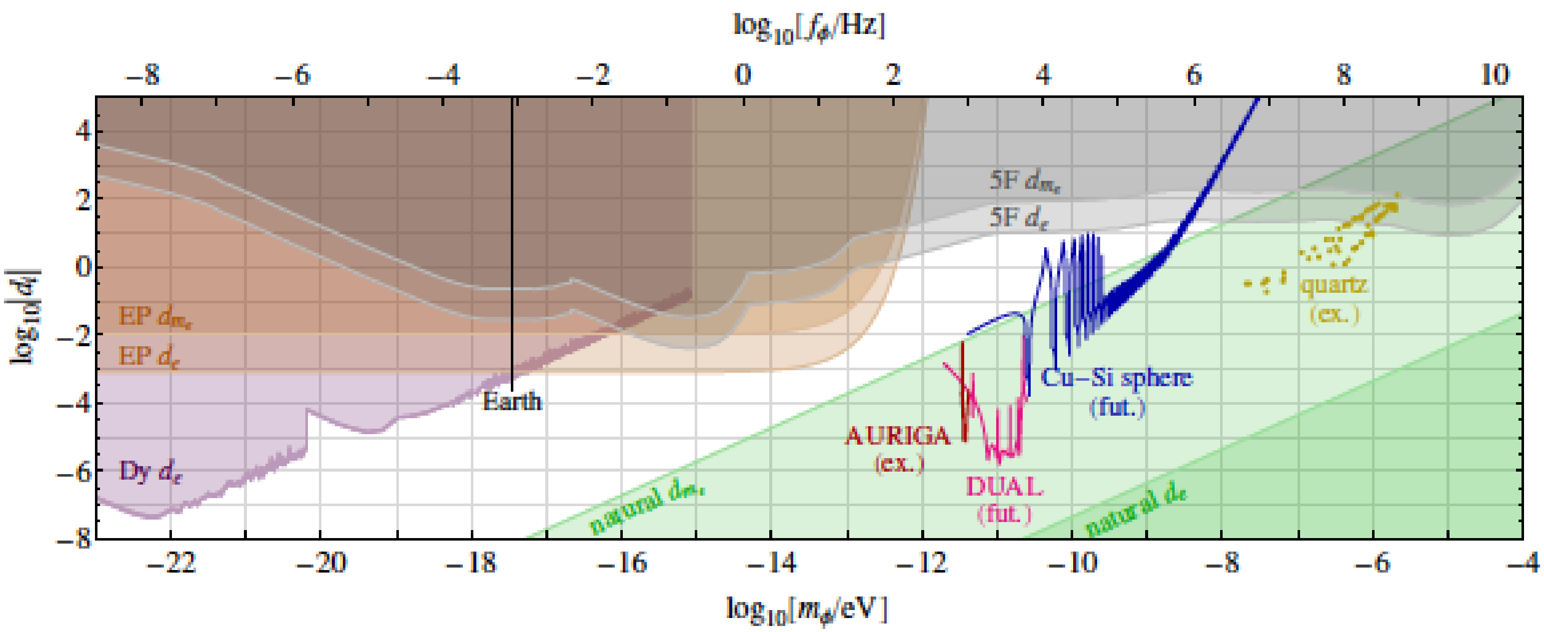
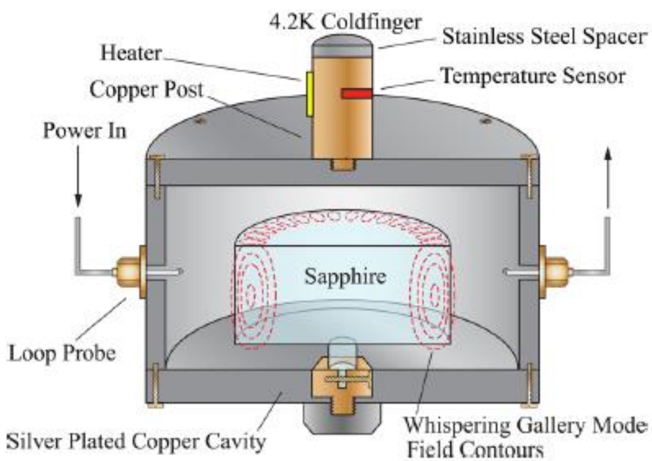


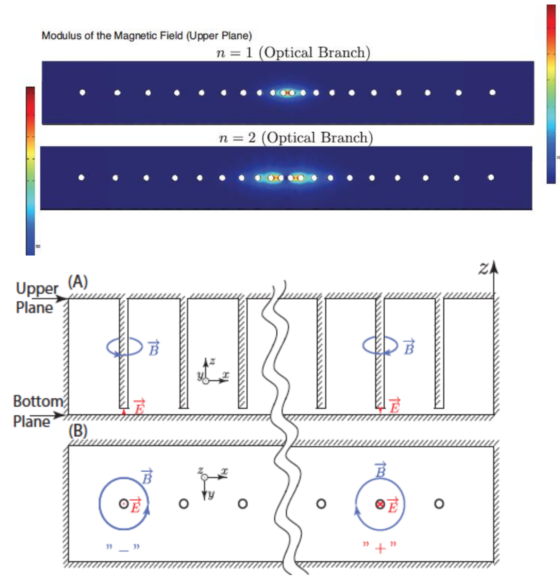
FIG. 1. Scalar field parameter space, with mass m_ϕ and corresponding DM oscillation frequency $f_\phi = m_\phi/2\pi$ on the bottom and top horizontal axes, and couplings of both an electron mass modulus ($d_i = d_{m_e}$) and electromagnetic gauge modulus ($d_i = d_e$) on the vertical axis. Natural parameter space for a 10 TeV cutoff is depicted by the green regions, while the other regions represent 95% CL limits from fifth-force tests ("5F", gray), equivalence-principle tests ("EP", orange), atomic spectroscopy in dysprosium ("Dy", purple), and low-frequency terrestrial seismology ("Earth", black). The blue curve shows the projected SNR = 1 reach of a proposed resonant-mass detector—a copper-silicon (Cu-Si) sphere 30 cm in radius—after 1.6 y of integration time, while the red curve shows the reach for the current AURIGA detector with 8 y of recasted data. Rough estimates of the 1-year reach of a proposed DUAL detector (pink) and several harmonics of two piezoelectric quartz resonators (gold points) are also shown.

High-Q and Novel Cavity Structures for Photon-Spin Strong Coupling and testing Fundamental Physics

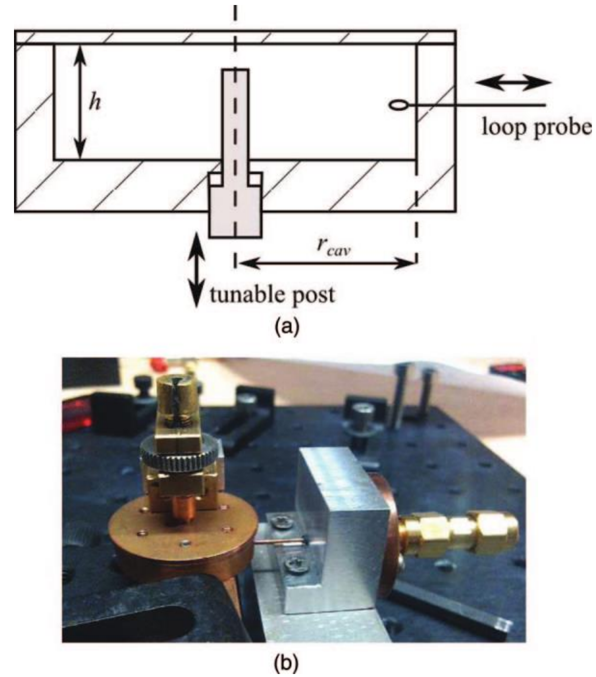
WG Modes



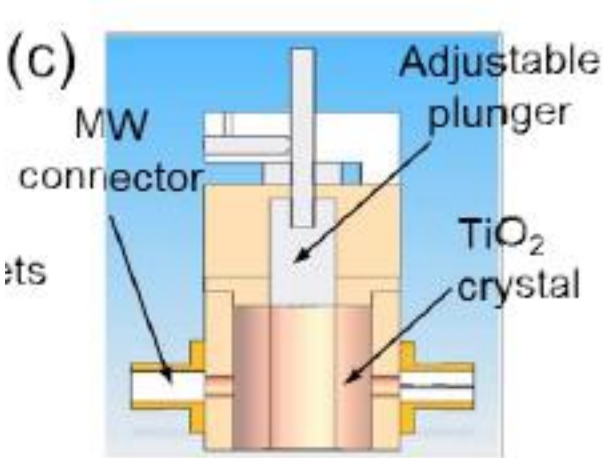
Reentrant Lattice

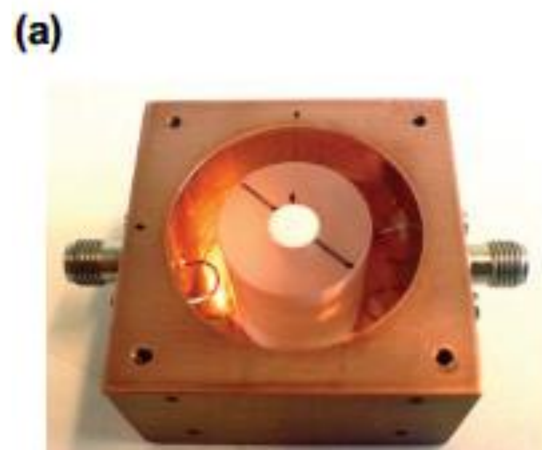


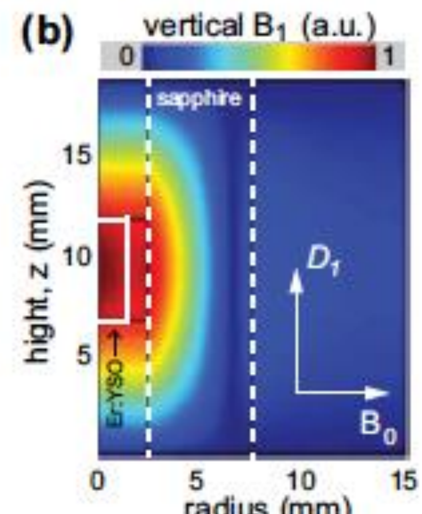
TE + TM Cylindrical modes



Reentrant







nature COMMUNICATIONS

ARTICLE

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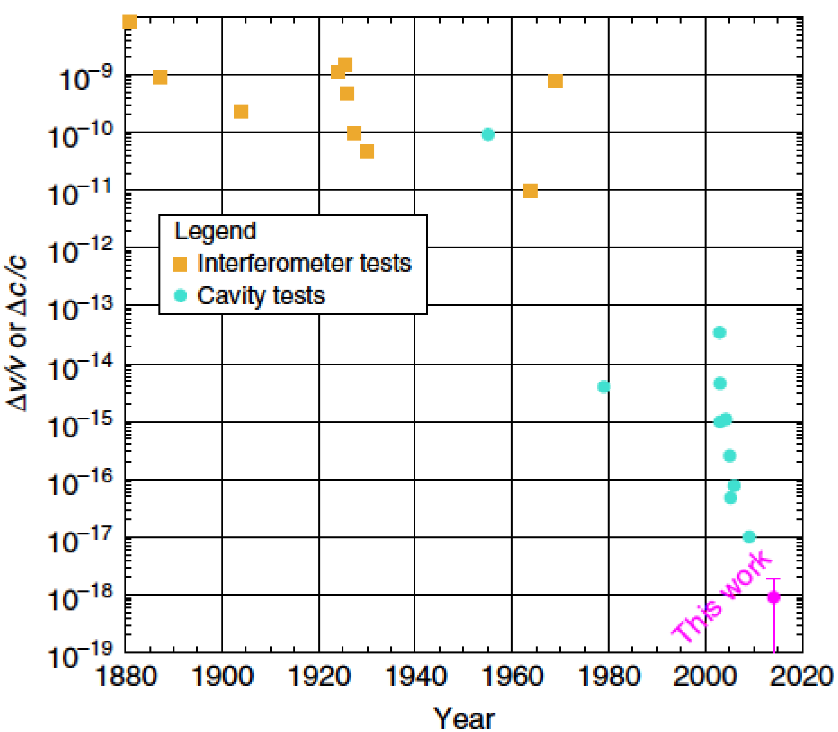
DOI: 10.1038/ncomms9174

OPEN

Direct terrestrial test of Lorentz symmetry in electrodynamics to 10^{-18}

Moritz Nagel[1,*], Stephen R. Parker[2,*], Evgeny V. Kovalchuk[1], Paul L. Stanwix[2], John G. Hartnett[2,3], Eugene N. Ivanov[2], Achim Peters[1] & Michael E. Tobar[2]



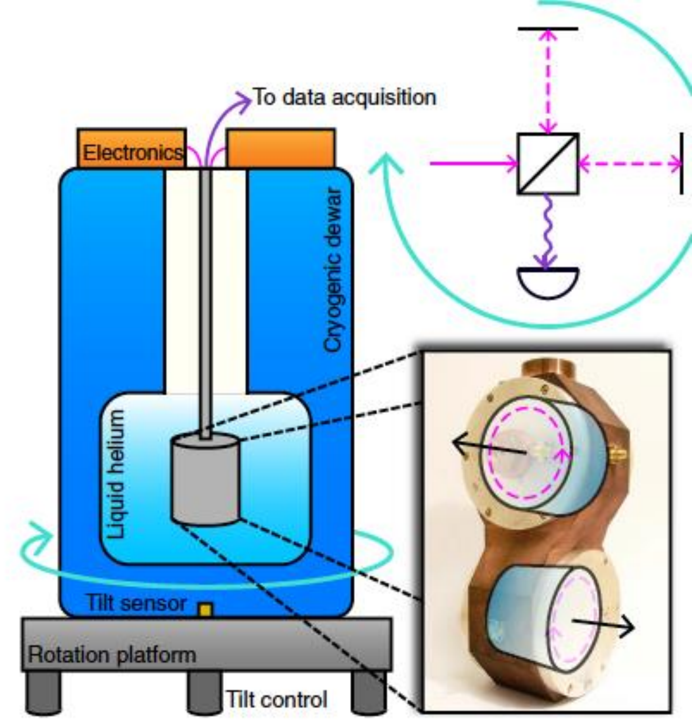


Table 1 | Bounds on non-birefringent photon-sector coefficients of the minimal SME.

Coefficient	Bound (Error)
$\tilde{\kappa}_{e-}^{XY}$	− 0.7 (1.6)
$\tilde{\kappa}_{e-}^{XZ}$	− 5.5 (4.0)
$\tilde{\kappa}_{e-}^{YZ}$	− 1.9 (3.2)
$\tilde{\kappa}_{e-}^{XX} - \tilde{\kappa}_{e-}^{YY}$	− 1.5 (3.4)
$\tilde{\kappa}_{e-}^{ZZ}$	− 286 (279)
$\tilde{\kappa}_{o+}^{XY}$	− 3.0 (3.4)
$\tilde{\kappa}_{o+}^{XZ}$	0.2 (1.7)
$\tilde{\kappa}_{o+}^{YZ}$	− 2.0 (1.6)
$\tilde{\kappa}_{tr}$	− 6.0 (4.0)

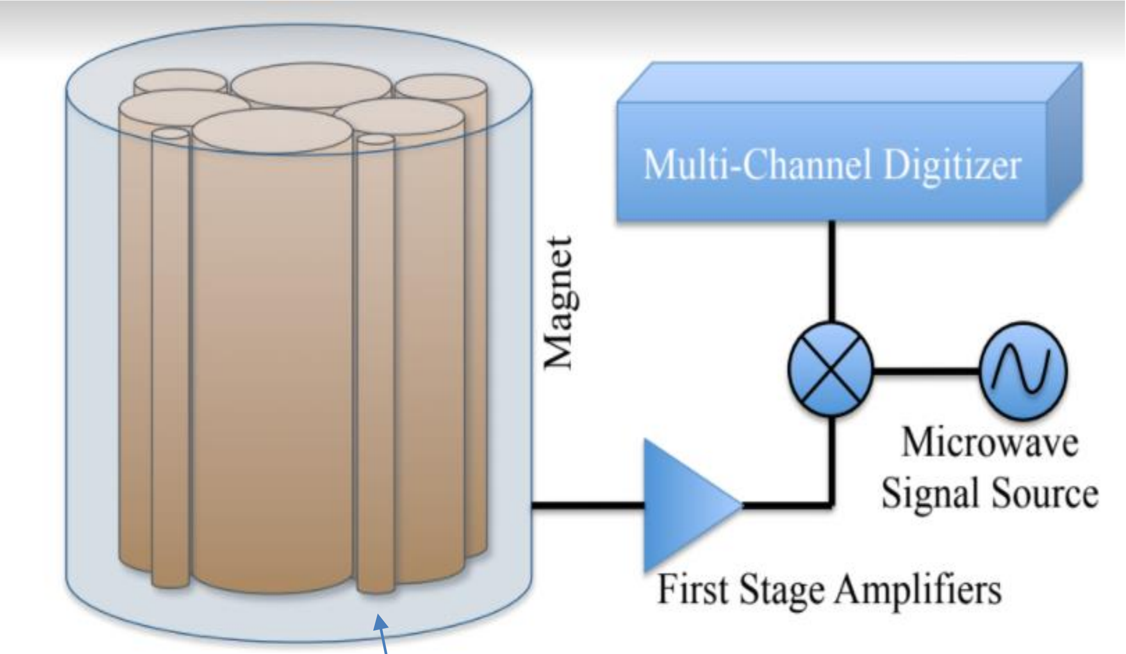
SME, standard model extension.
Errors are standard 1σ of statistical origin. Values for $\tilde{\kappa}_{e-}$ are given in 10^{-18}, $\tilde{\kappa}_{o+}$ in 10^{-14} and $\tilde{\kappa}_{tr}$ in 10^{-10}.

THE ORGAN EXPERIMENT CONCEPT

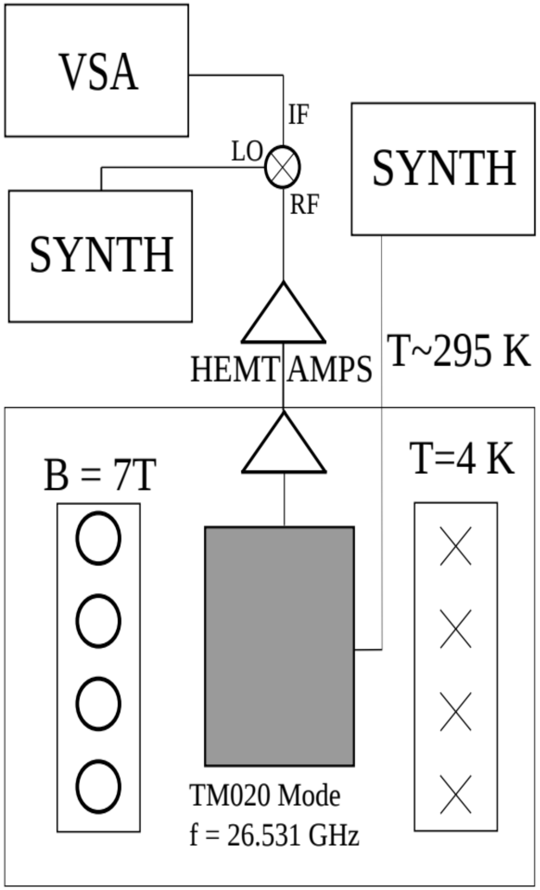
Oscillating Resonant Group AxioN experiment

McGillivary Organ at UWA

Project funded by the ARC CoE for Engineered Quantum Systems
2018-2024: LIEF Application for dedicated Dil Fridge + 14 T Magnet + 50 GHz VNA Recently Successful!



Multiple cylindrical resonators to scan over multiple frequencies



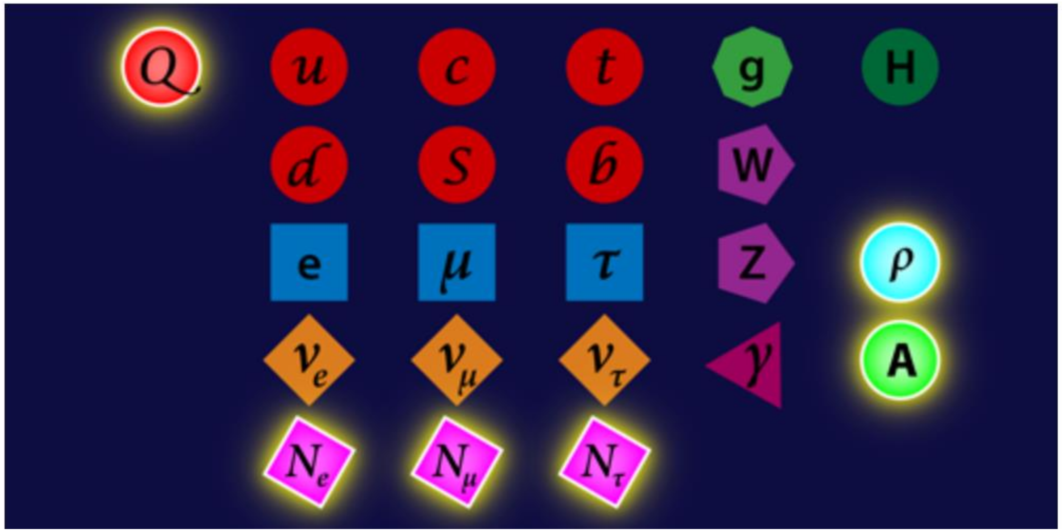
First Experiment

ORGAN

- High frequency haloscope at UWA (>15 GHz), known as the **ORGAN Experiment**
  Oscillating **R**esonant **G**roup **A**xio**N Experiment**
- Multi-stage project:
  →Narrow Search around 26-27 GHz (short term plan)
  → Wider scan at high frequency (15-50 GHz – long term goal)
- Lots of motivation for high frequency searches:
  →SMASH model
  →Claimed results in Josephson Junctions
  →**No one is looking there with a haloscope**

Group introduces six new particles to standard model to solve five enduring problems

February 20, 2017 by Bob Yirka report



Feb 2017

Standard Model-Axion-Seesaw-Higgs Portal Inflation. Five problems of particle physics and cosmology solved in one stroke

Guillermo Ballesteros [1] , Javier Redondo [2, 3] , Andreas Ringwald [4] , Tamarit Carlos Details

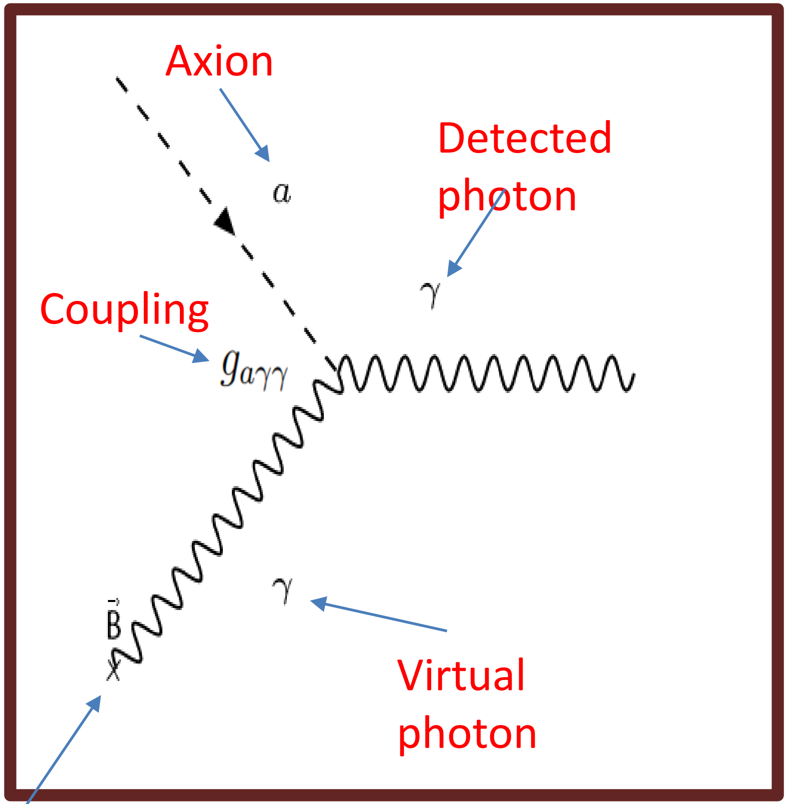
1 IPHT - Institut de Physique Théorique - UMR CNRS 3681
2 Universidad Zaragosa [Zaragoza]
3 MPI-P - Max-Planck-Institut für Physik
4 DESY - Deutsches Elektronen-Synchrotron [Hamburg]

Abstract : We present a minimal extension of the Standard Model (SM) providing a consistent picture of particle physics from the electroweak scale to the Planck scale and of cosmology from inflation until today. Three right-handed neutrinos Ni, a new color triplet Q and a complex SM-singlet scalar σ, whose vacuum expectation value vσ~10^11 GeV breaks lepton number and a Peccei-Quinn symmetry simultaneously, are added to the SM. At low energies, the model reduces to the SM, augmented by seesaw generated neutrino masses and mixing, plus the axion. The latter solves the strong CP problem and accounts for the cold dark matter in the Universe. The inflaton is comprised by a mixture of σ and the SM Higgs and reheating of the Universe after inflation proceeds via the Higgs portal. Baryogenesis occurs via thermal leptogenesis. Thus, five fundamental problems of particle physics and cosmology are solved at one stroke in this unified Standard Model - Axion - Seesaw - Higgs portal inflation (SMASH) model. It can be probed decisively by upcoming cosmic microwave background and axion dark matter experiments.

How do you detect them

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

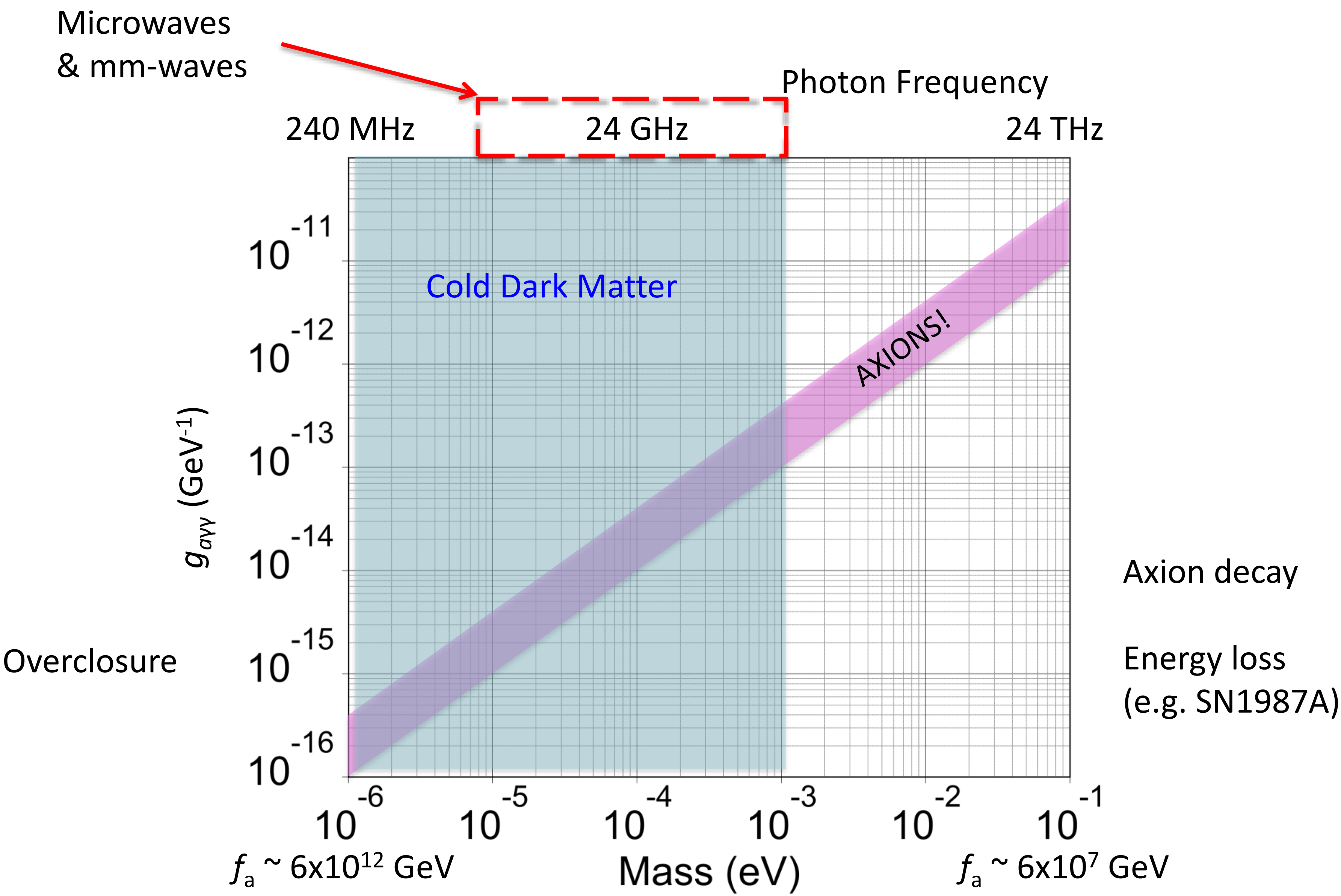
Lagrangian gives effective strength



From an external DC magnetic field

Resonant cavity

Axion Mass / Photon Coupling



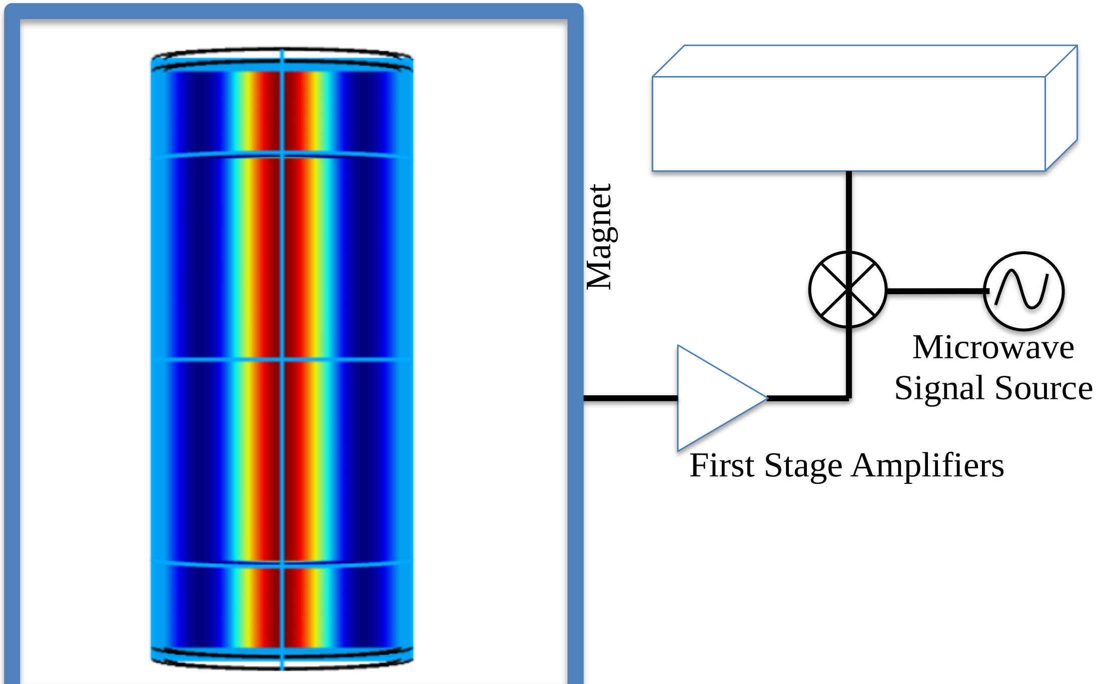
FIRST STEP

Oscillating **R**esonator **G**roup **A**xio**N** **P**athf**I**nder **P**roj**E**ct

ORGAN PIPE

Start with 1 cavity borrow equipment from other projects…

1) Check Detection Claim
2) Show proof of concept at higher masses
3) Test novel noise reduction and signal enhancing techniques



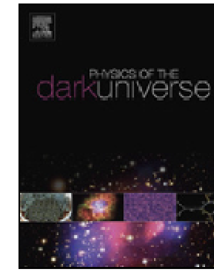
First Path finding Run Reported with strategy for Improvements

Physics of the Dark Universe 18 (2017) 67–72

Contents lists available at ScienceDirect

Physics of the Dark Universe

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



The ORGAN experiment: An axion haloscope above 15 GHz

Ben T. McAllister [a,*], Graeme Flower [a], Eugene N. Ivanov [b], Maxim Goryachev [a], Jeremy Bourhill [a], Michael E. Tobar [a]

[a] ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
[b] School of Physics, The University of Western Australia, Crawley 6009, Australia

A R T I C L E I N F O

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Keywords:
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Dark matter
Haloscope
ORGAN

A B S T R A C T

We present first results and future plans for the Oscillating Resonant Group AxioN (ORGAN) experiment, a microwave cavity axion haloscope situated in Perth, Western Australia designed to probe for high mass axions motivated by several theoretical models. The first stage focuses around 26.6 GHz in order to directly test a claimed result, which suggests axions exist at the corresponding mass of 110 μeV. Later stages will move to a wider scan range of 15–50 GHz (62–207 μ eV). We present the results of the pathfinding run, which sets a limit on $g_{a\gamma\gamma}$ of 2.02×10^{-12} eV^{-1} at 26.531 GHz, or 110 μeV, in a span of 2.5 neV (shaped by the Lorentzian resonance) with 90% confidence. Furthermore, we outline the current design and future strategies to eventually attain the sensitivity to search for well known axion models over the wider mass range.

First run complete

TM_{020} mode

sampling frequency of the digitizer is 1GHz, the 26.54GHz

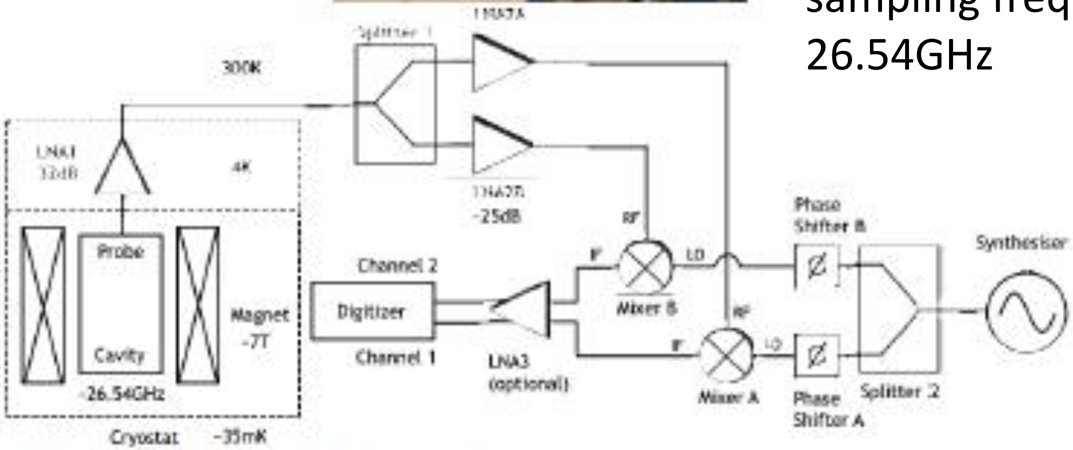
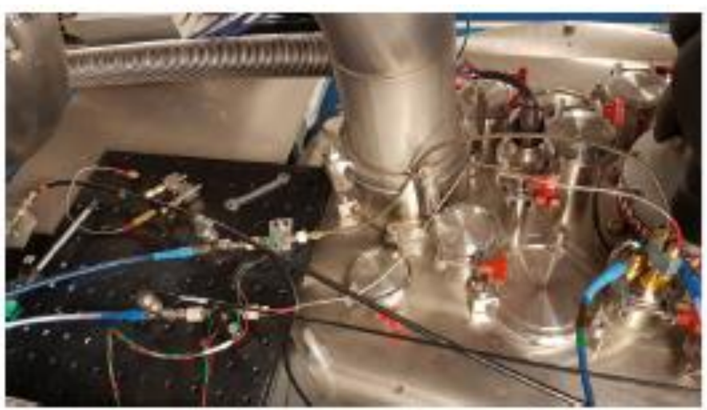
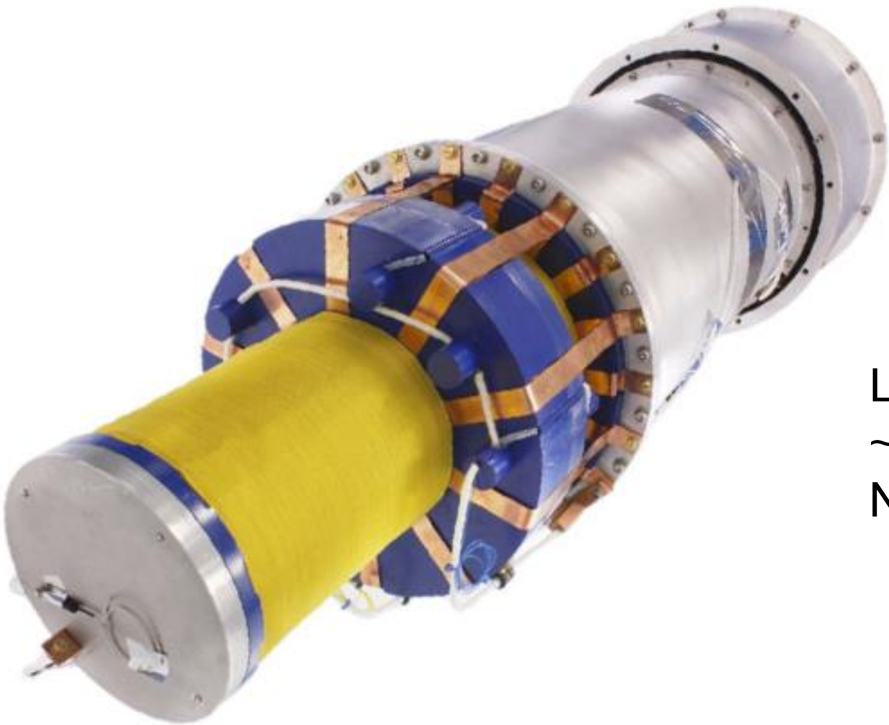


Figure 3.1: **ORGAN configuration.** The copper microwave cavity being used in the initial experiment (top) and a current ORGAN hardware diagram (bottom).



Magnet & readout

ARC CENTRE OF EXCELLENCE FOR ENGINEERED QUANTUM SYSTEMS

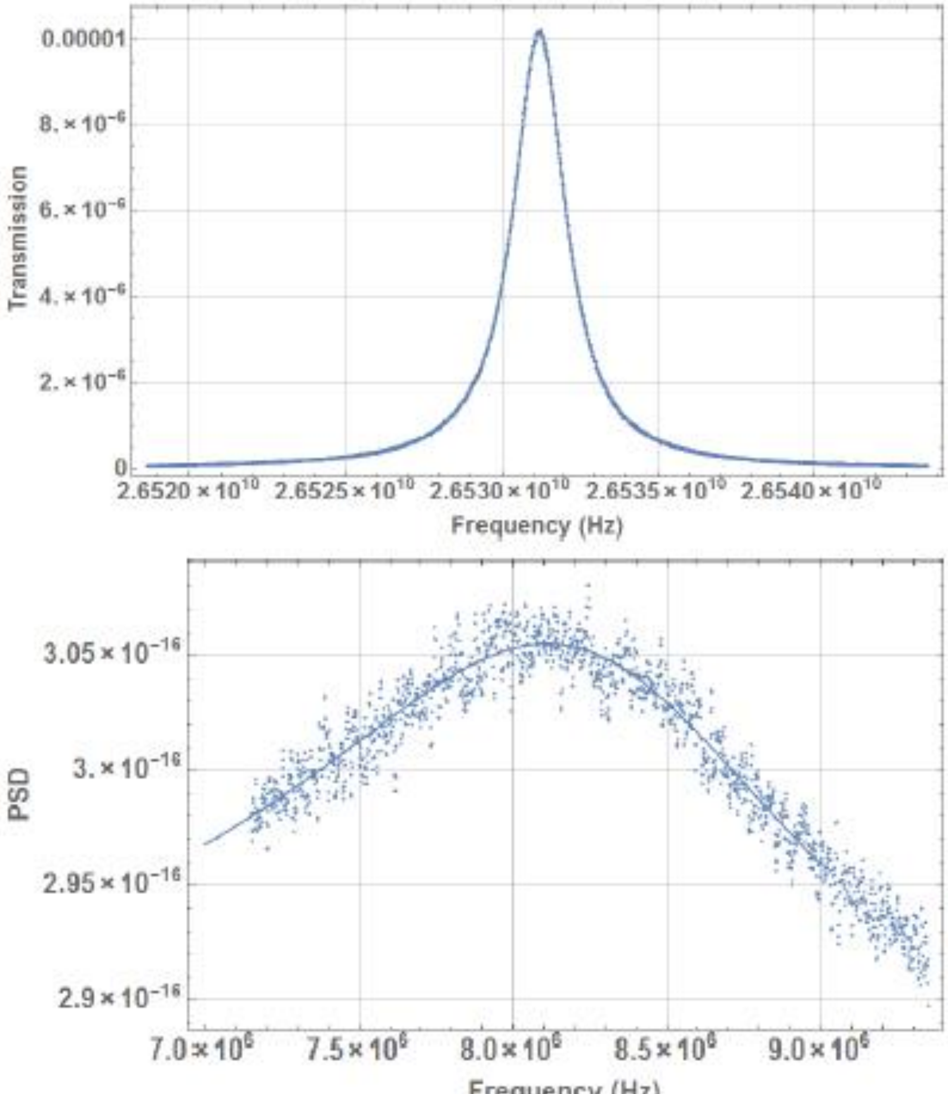


7 T Magnet (10 cm bore)

LNF Cryo HEMTS
~10 K Noise temp (15 – 29 GHz)
Need to develop JPA's at high frequency

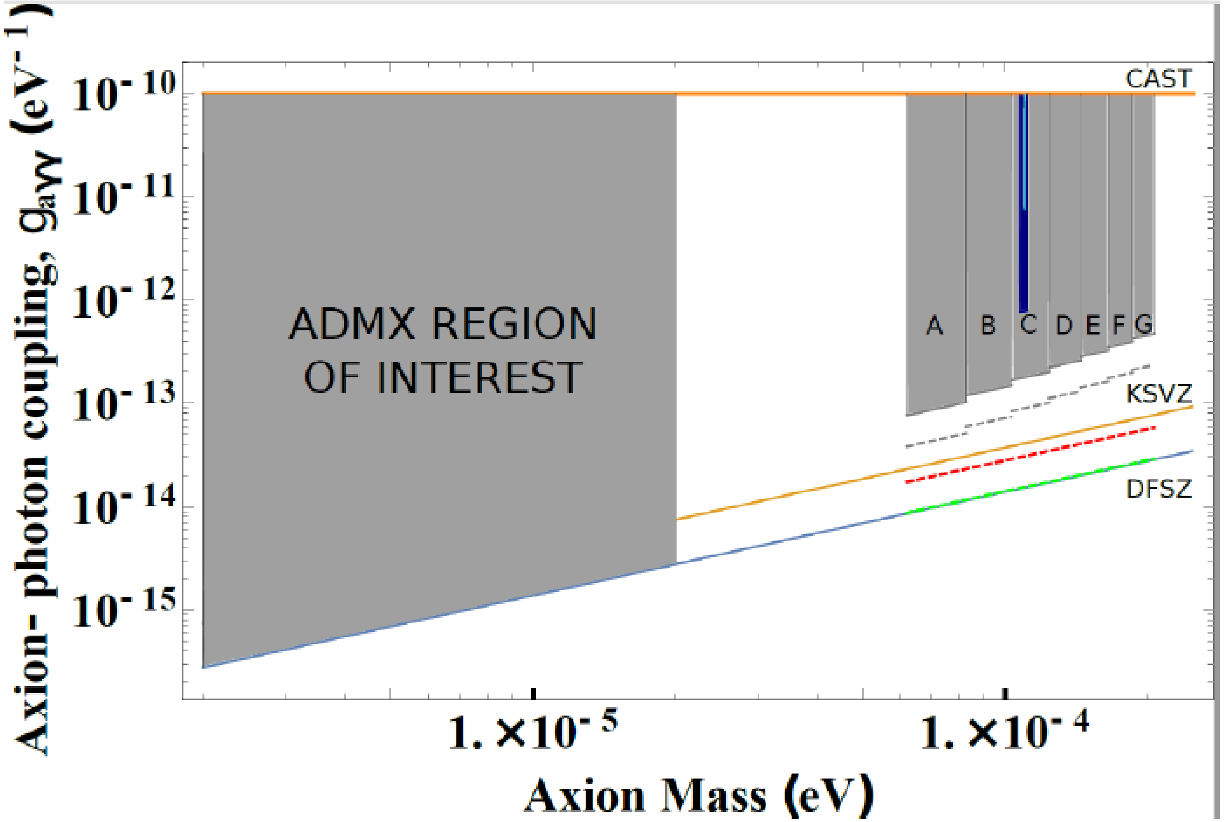
2-channel digitizer
Keysight U5303A

ORGAN



0.00001
8.×10⁻⁶
6.×10⁻⁶
4.×10⁻⁶
2.×10⁻⁶
0
Transmission
2.6520×10¹⁰ 2.6525×10¹⁰ 2.6530×10¹⁰ 2.6535×10¹⁰ 2.6540×10¹⁰
Frequency (Hz)
3.05×10⁻¹⁶
3.×10⁻¹⁶
2.95×10⁻¹⁶
2.9×10⁻¹⁶
PSD
7.0×10⁶ 7.5×10⁶ 8.0×10⁶ 8.5×10⁶ 9.0×10⁶
Frequency (Hz)

Sensitivity Projections



- Narrow aqua bar is pathfinder result
- Wider navy bar is 2018 run, 26-27 GHz
- A→G are the 2018-2025 runs, with 14 T magnet and SQL Amps
- Dashed limits depend on new technology and R&D ie Squeezed vacuum to beat SQL, upgrade magnet again to 28 T

Novel Resonator Designs

PHYSICAL REVIEW APPLIED **9**, 014028 (2018)

Tunable Supermode Dielectric Resonators for Axion Dark-Matter Haloscopes

Ben T. McAllister,[1,*] Graeme Flower,[1] Lucas E. Tobar,[1,2] and Michael E. Tobar[1,†]
[1]*ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia*
[2]*Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3800, Australia*

(Received 16 June 2017; revised manuscript received 19 September 2017; published 26 January 2018)

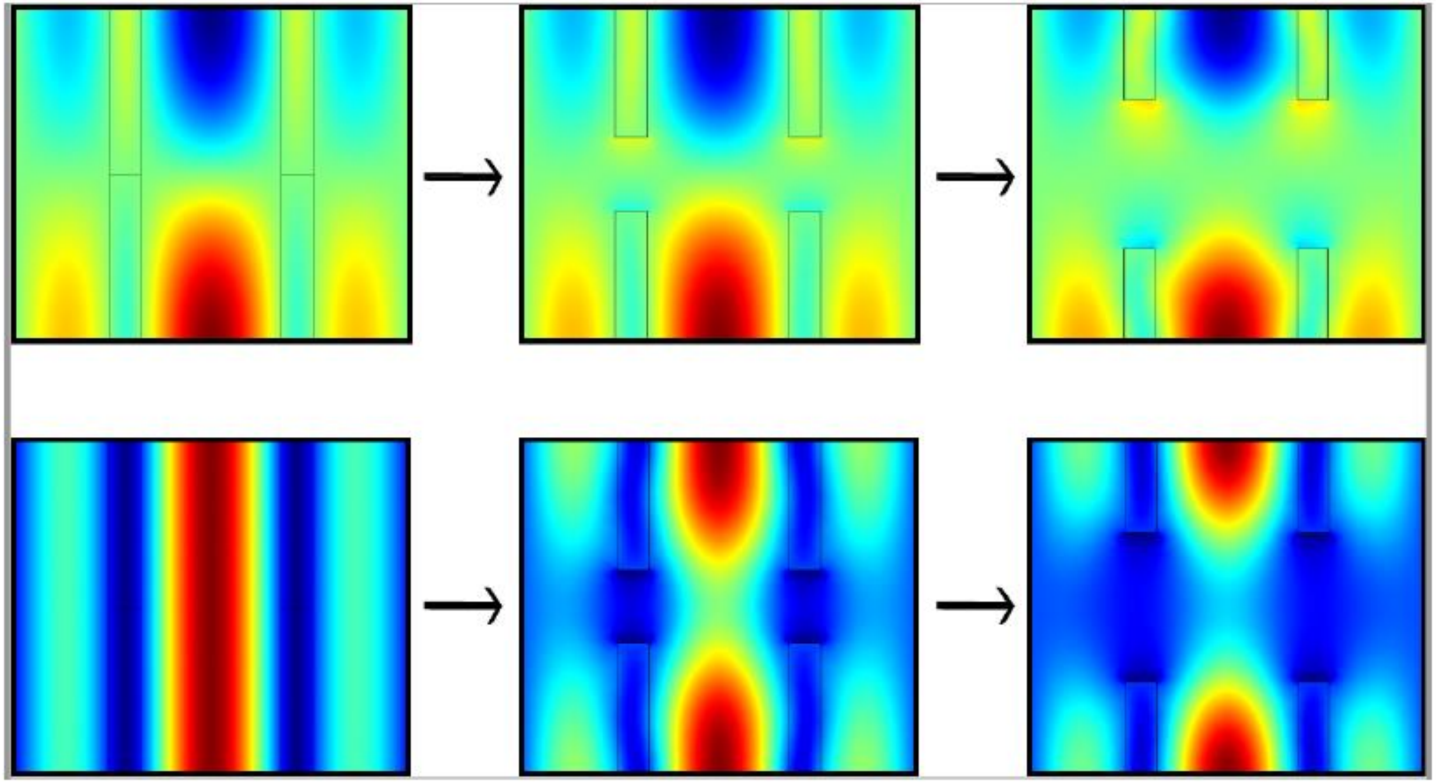
We present frequency-tuning mechanisms for dielectric resonators, which undergo "supermode" interactions as they tune. The tunable schemes are based on dielectric materials strategically placed inside traditional cylindrical resonant cavities, necessarily operating in transverse-magnetic modes for use in axion haloscopes. The first technique is based on multiple dielectric disks with radii smaller than that of the cavity. The second scheme relies on hollow dielectric cylinders similar to a Bragg resonator, but with a different location and dimension. Specifically, we engineer a significant increase in form factor for the TM_{030} mode utilizing a variation of a distributed Bragg reflector resonator. Additionally, we demonstrate an application of traditional distributed Bragg reflectors in TM modes which may be applied to a haloscope. Theoretical and experimental results are presented showing an increase in Q factor and tunability due to the supermode effect. The TM_{030} ring-resonator mode offers a between 1 and 2-order-of-magnitude improvement in axion sensitivity over current conventional cavity systems and will be employed in the forthcoming ORGAN experiment.

DOI: 10.1103/PhysRevApplied.9.014028

arXiv:1705.06028 [physics.ins-det]

Axion-Bragg Resonator

- We can tune this structure, similar to the disk structure
- Axial "supermodes"
- TM030 and TM031 modes



Conclusion

- ORGAN Experiment Pathfinding run complete
- 7 years of funding through ARC Centre of Excellence for Engineered Quantum Systems
- Several phases planned
  → 26-27 GHz tunable run 2018
  → 15-50 GHz 2019-2025
- Novel resonator designs to be employed
  → Dielectric Disks
  → Bragg resonators
  → Axion-Bragg resonators
- Tuning via “supermode” interaction

New Grant Application for 5 more Dark Matter Experiments

Precision Low Energy Experiments to Search for New Physics

Number	Name	Participant Type	Current Organisation(s)	Relevant Organisation
1	Prof Michael Tobar	Chief Investigator	The University of Western Australia	The University of Western Australia
2	Dr Maxim Goryachev	Chief Investigator	The University of Western Australia	The University of Western Australia
3	Prof Eugene Ivanov	Chief Investigator	The University of Western Australia	The University of Western Australia
4	Prof Frank Wilczek	Partner Investigator	Massachusetts Institute of Technology	Massachusetts Institute of Technology
5	Asst Prof Gray Rybka	Partner Investigator	University of Washington, Seattle	University of Washington, Seattle
6	Prof Ik Siong Heng	Partner Investigator	University of Glasgow, UK	University of Glasgow, UK

- Centre of Excellence Application for 7 years of funding
- Short Listed 10 out of 20 to be funded
- Headed by Prof. Elisabetta Barberio Univ. Melb

New Ideas for DM Searches

Search for Scalar particles with phonons
(Resonant GW Detectors)

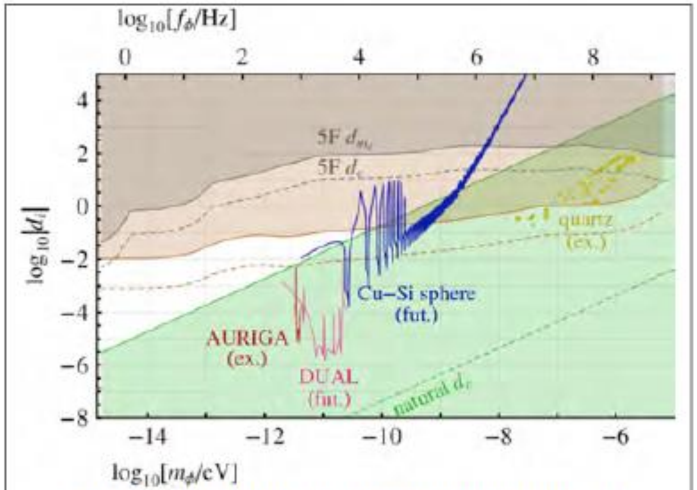


Fig. 4. Scalar field limits, with mass m_ϕ and corresponding DM oscillation frequency on the bottom and top horizontal axes, and couplings of the electron mass modulus (d_i=d_{me}) and electromagnetic gauge modulus (d_i =d_e) on the vertical axis. [51] Possible limits for this experiment are labeled quartz.

Search for Spin 0 Bosons (axions) interaction with spins

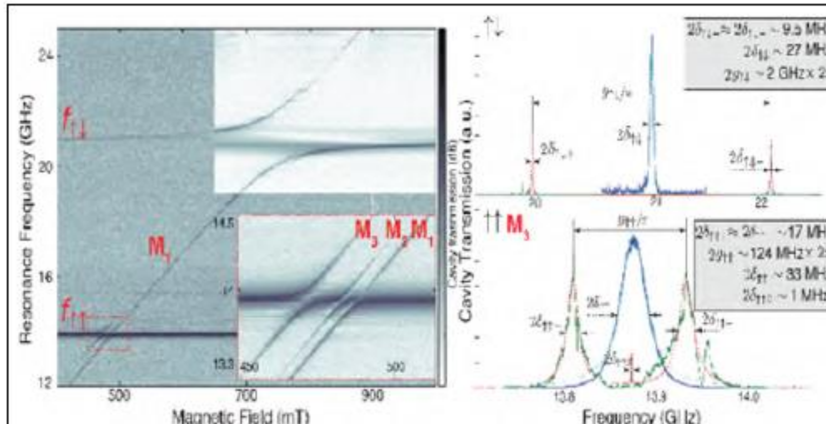
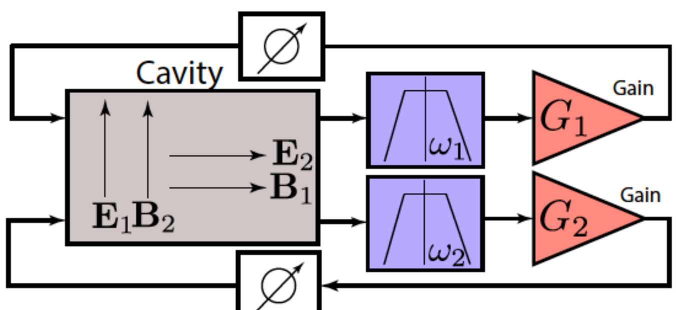


Fig.2 Ultra-strong coupling of magnons to cavity photons [15].



Dual-Mode Oscillator coupled to axions

5th idea

PHYSICAL REVIEW D 94, 042001 (2016)

3D lumped LC resonators as low mass axion haloscopes

Ben T. McAllister,* Stephen R. Parker, and Michael E. Tobar†
ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, 35 Stirling Highway, Crawley 6009, Western Australia, Australia
(Received 18 May 2016; published 11 August 2016)

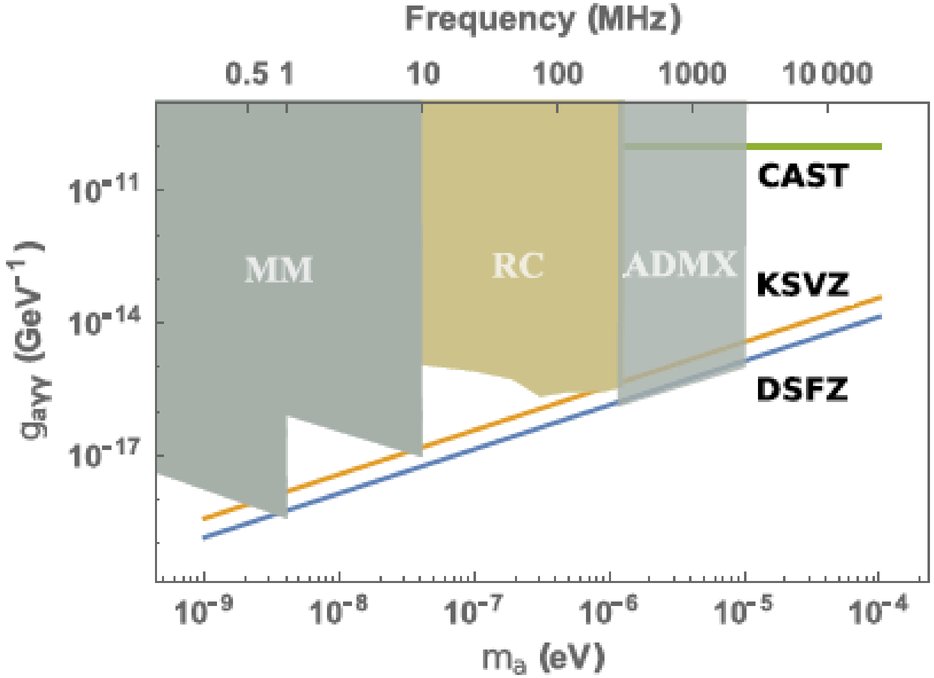
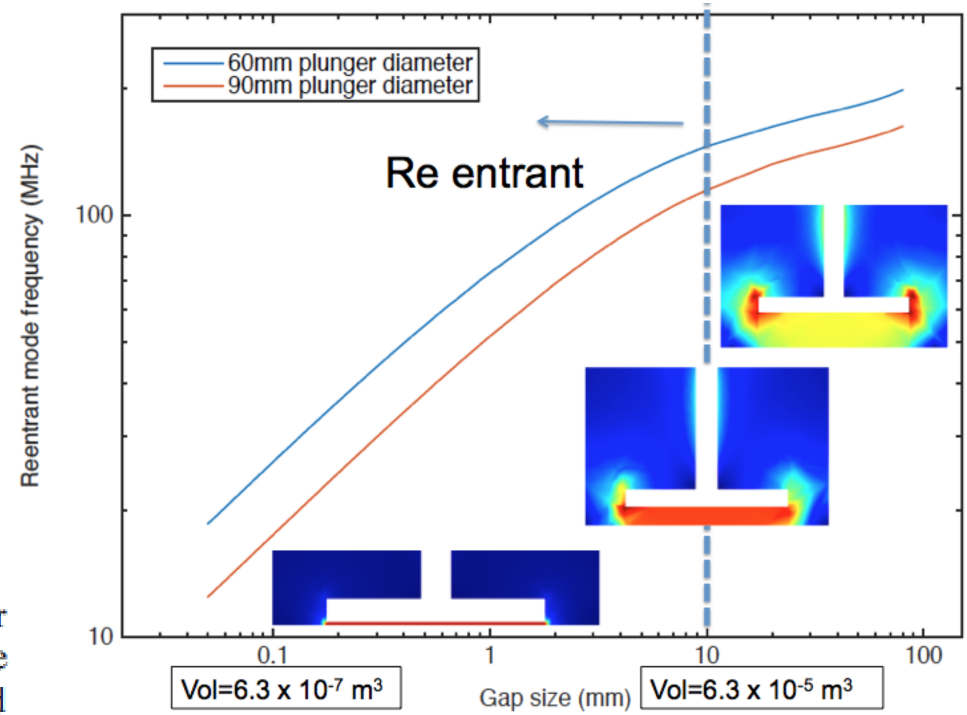


FIG. 6. Predicted axion-photon coupling exclusion limits for the reentrant cavity designs, using the assumptions outlined in the main text (RC). Current and future bounds from ADMX and CAST are shown for comparison, along with the predicted exclusion limits for magnetometer experiments (MM) presented in Ref. [21].



Modified Axion Electrodynamics through Oscillating Vacuum Polarization and Magnetization and Low Mass Detection

Michael Edmund Tobar, Ben T. McAllister, Maxim Goryachev

(Submitted on 5 Sep 2018 (v1), last revised 16 Oct 2018 (this version, v3))

We present a reformulation of axion modified electrodynamics where the equations maintain a similar form Maxwell's, with all modifications redefined within the constitutive relations between $\vec{D}$, $\vec{H}$, $\vec{B}$ and $\vec{E}$ fields. In this reformulation the axion induced bound charge density, polarization current density and bound current density are identified along with the associated induced vacuum polarization and magnetization, which are shown to satisfy the charge-current continuity equation. The reformulation is important when considering conversions of axions into photons, relevant in many experimental contexts. For example, when a DC $\vec{B}$-field is applied, oscillating bound vacuum charges and polarization currents are induced at a frequency equivalent to the axion mass. In contrast, when a large DC $\vec{E}$ field is applied, an oscillating bound current or magnetization of the vacuum is induced at a frequency equivalent to the axion mass. Moreover, the integral forms of the equations can be used to clearly define the boundary conditions between distinct media either with or without axion induced vacuum polarization or magnetization. This provides clarity when considering experiments sensitive to axion induced electric and/or magnetic effects inside or outside the high DC field region. For example, we show how the axion induced oscillating polarization under a DC magnetic field is analogous to a permanent polarised electret oscillating at the frequency of the axion's Compton mass. The oscillating electret sources an EMF which acts to change the Lorentz Force acting on conducting electrons as well bound electrons in a dielectric. This means that conductors and capacitors in a high DC magnetic field can act as a detector for low-mass axions without suppression of the signal due to electromagnetic shielding.

Comments: Calculation of axion modification to the Lorentz Force Included. Included Electret analogy. Deleted Errors

Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Astrophysics of Galaxies (astro-ph.GA); General Relativity and Quantum Cosmology (gr-qc); Instrumentation and Detectors (physics.ins-det)

Cite as: arXiv:1809.01654 **[hep-ph]**

(or arXiv:1809.01654v3 **[hep-ph]** for this version)

Reformulate Modified Electrodynamics

$$\vec{\nabla} \cdot \overrightarrow{D_a} = \rho_f$$

$$\vec{\nabla} \times \overrightarrow{H_a} = \vec{J_f} + \frac{\partial \overrightarrow{D_a}}{\partial t}$$

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

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Similar to Standard Model Extension Modifications for Lorentz Invariance Violations

Modification in the Constitutive Relations

$$\overrightarrow{D_a} = \epsilon_0 \vec{E} + \vec{P} + \overrightarrow{P_a}$$

$$\vec{P}_a = -g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{B})$$

$$\overrightarrow{H_a} = \frac{1}{\mu_0}\vec{B} - \vec{M} - \overrightarrow{M_a}$$

$$\vec{M}_a = g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}(a\vec{E})$$

PHYSICAL REVIEW LETTERS

VOLUME 58 | 4 MAY 1987 | NUMBER 18

Two Applications of Axion Electrodynamics

Frank Wilczek

Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106

(Received 27 January 1987)

$$\Delta\mathcal{L} = \kappa a \mathbf{E}\cdot\mathbf{B}, \tag{1}$$

where κ is a coupling constant. The resulting equations are

$$\nabla\cdot\mathbf{E} = \tilde{\rho} - \kappa\nabla a\cdot\mathbf{B}, \tag{2}$$

$$\nabla\times\mathbf{E} = -\partial\mathbf{B}/\partial t, \tag{3}$$

$$\nabla\cdot\mathbf{B} = 0, \tag{4}$$

$$\nabla\times\mathbf{B} = \partial\mathbf{E}/\partial t + \tilde{\mathbf{j}} + \kappa(\dot{a}\mathbf{B} + \nabla a\times\mathbf{E}), \tag{5}$$

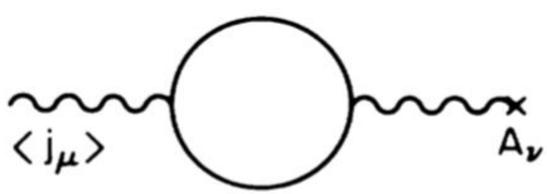


FIG. 3. Expectation of the current in a background field is derived from the vacuum polarization.

PHYSICAL REVIEW D **66**, 056005 (2002)

Signals for Lorentz violation in electrodynamics

V. Alan Kostelecký and Matthew Mewes
Physics Department, Indiana University, Bloomington, Indiana 47405
(Received 20 May 2002; published 23 September 2002)

$$\vec{\nabla}\times\vec{H}-\partial_0\vec{D}=0, \quad \vec{\nabla}\cdot\vec{D}=0,$$

$$\vec{\nabla}\times\vec{E}+\partial_0\vec{B}=0, \quad \vec{\nabla}\cdot\vec{B}=0.$$

$$\begin{pmatrix}\vec{D}\\ \vec{H}\end{pmatrix}=\begin{pmatrix}1+\kappa_{DE} & \kappa_{DB}\\ \kappa_{HE} & 1+\kappa_{HB}\end{pmatrix}\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix}$$

PHYSICAL REVIEW D **71**, 025004 (2005)

New methods of testing Lorentz violation in electrodynamics

Michael Edmund Tobar,[1,*] Peter Wolf,[2,3] Alison Fowler,[1] and John Gideon Hartnett[1]
[1]*University of Western Australia, School of Physics, M013, 35 Stirling Highway, Crawley 6009 WA, Australia*
[2]*Bureau International des Poids et Mesures, Pavillon de Breteuil, 92312 Sèvres Cedex, France*
[3]*BNM-SYRTE, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris, France*
(Received 1 September 2004; published 7 January 2005)

$$\begin{pmatrix}\boldsymbol{D}\\ \boldsymbol{H}\end{pmatrix}=\begin{pmatrix}\epsilon_0(\tilde{\epsilon}_r+\kappa_{DE}) & \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{DB}\\ \sqrt{\frac{\epsilon_0}{\mu_0}}\kappa_{HE} & \mu_0^{-1}(\tilde{\mu}_r^{-1}+\kappa_{HB})\end{pmatrix}\begin{pmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{pmatrix}$$

$$g_{a\gamma\gamma}a \sim \kappa_{DB} \quad \kappa_{HE}$$

Axion Interaction similar to odd parity Lorentz Invariance Violation

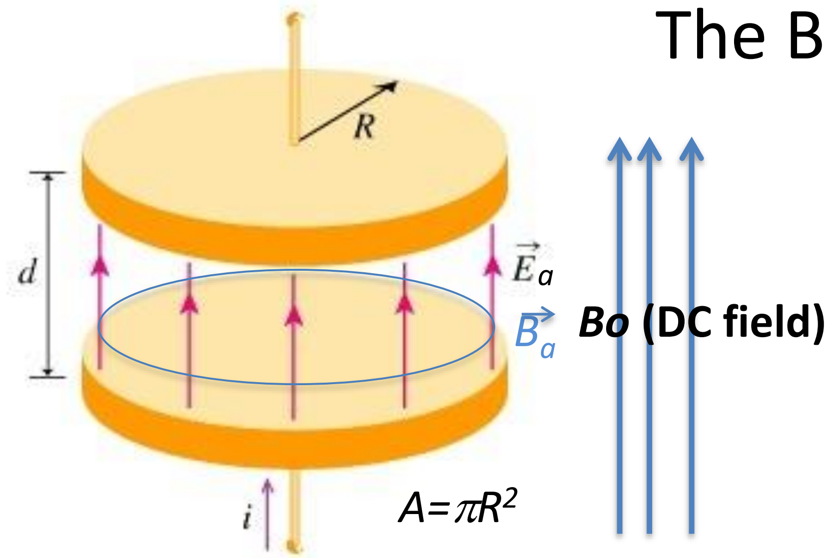
Ben T. McAllister, Maxim Goryachev, Jeremy Bourhill, Eugene N. Ivanov, Michael E. Tobar

(Submitted on 21 Mar 2018 (v1), last revised 5 Sep 2018 (this version, v3))

The mass of axion dark matter is only weakly bounded by cosmological observations, necessitating a variety of detection techniques over several orders of magnitude of mass ranges. Axions haloscopes based on resonant cavities have become the current standard to search for dark matter axions. Such structures are inherently narrowband and for low masses the volume of the required cavity becomes prohibitively large. Broadband low-mass detectors have already been proposed using inductive magnetometer sensors and a gapped toroidal solenoid magnet. In this work we propose an alternative, which uses electric sensors in a conventional solenoidal magnet aligned in the laboratory z-axis, as implemented in standard haloscope experiments. In the presence of the DC magnetic field, the inverse Primakoff effect causes a time varying electric vacuum polarization (or displacement current) in the z-direction to oscillate at the axion Compton frequency. We propose non-resonant techniques to detect this oscillating polarization by implementing a capacitive sensor or an electric dipole antenna coupled to a low noise amplifier. We present the first experimental results and discuss the foundations and potential of this proposal. Preliminary results constrain $g_{a\gamma\gamma} >\sim 2.35\times10^{-12}$ GeV^{-1} in the mass range of 2.08×10^{-11} to 2.2×10^{-11} eV, and demonstrate potential sensitivity to axion-like dark matter with masses in the range of 10^{-12} to 10^{-8} eV.

Comments: 8 pages, 4 figures. V3: Updated figures/text/appendices
Subjects: **Instrumentation and Detectors (physics.ins-det)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph)
Cite as: arXiv:1803.07755 **[physics.ins-det]**
(or arXiv:1803.07755v3 **[physics.ins-det]** for this version)

The BEAST Experiment



$$I_a(t) = g_{a\gamma\gamma} a_0 \sqrt{\frac{\epsilon_0}{\mu_0}} A B_0 \omega_a \sin(\omega_a t)$$

$$V_a(t) = -\frac{F_a d}{q_a} = g_{a\gamma\gamma} d \frac{c}{\epsilon_r} B_0 \cos(\omega_a t)$$

$$I_a^{\mathrm{RMS}} = g_{a\gamma\gamma} A \sqrt{\frac{\epsilon_0}{\mu_0}} B_0 \sqrt{\rho_{\mathrm{DM}} c^3}$$

$$V_a^{\mathrm{RMS}} = \frac{1}{\epsilon_r} g_{a\gamma\gamma} d \left(\frac{c}{\omega_a}\right) B_0 \sqrt{\rho_{\mathrm{DM}} c^3}$$

Measure with SQUID (current) or
High Impedance Amplifier (Voltage)

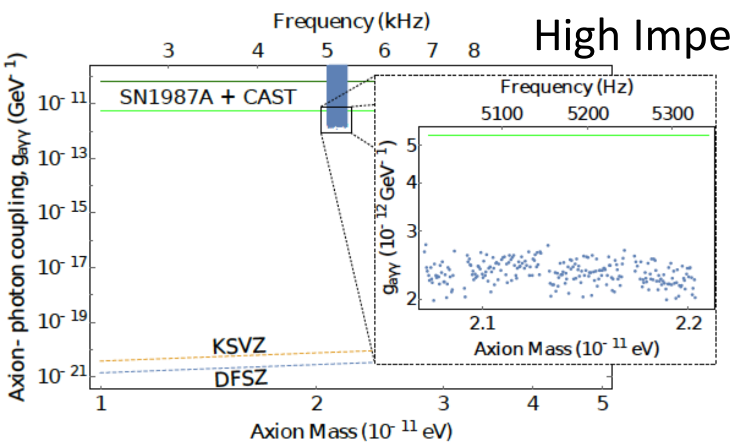


FIG. 3: Exclusion limits from the proof of concept experiment with a single capacitor coupled to a SQUID. Previous best limits in the region from CAST (green) SN1987A (light green) are also plotted. Also shown are popular axion model bands, KSVZ (gold, dashed) and DFSZ (blue, dashed). The inset shows the actual limit as a function of mass, including the narrow regions where limits could not be placed due to large noise sources.

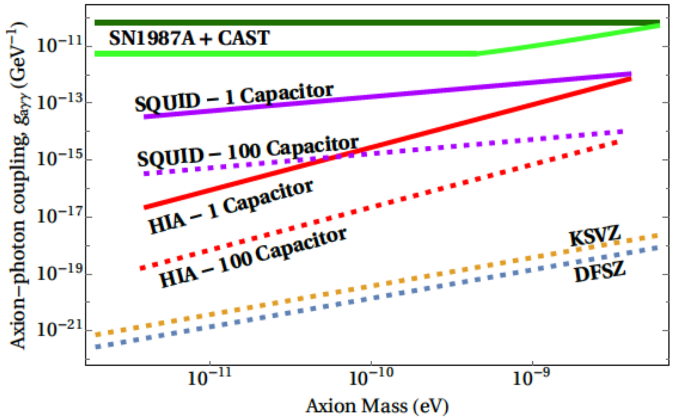


FIG. 1: Projected limits for the BEAST experiment, utilizing: a single capacitor (purple) and 100 capacitors (purple, dashed) coupled to a SQUID, and a single capacitor (red) and 100 capacitors (red, dashed) coupled to a high-impedance amplifier. Current best limits in the region from CAST (green) SN1987A (light green) are also plotted. Also shown are popular axion model bands, KSVZ (gold, dashed) and DFSZ (blue, dashed).

Axion Detection with Precision Frequency Metrology

Maxim Goryachev, Ben McAllister, Michael E. Tobar

(Submitted on 19 Jun 2018 (v1), last revised 26 Jun 2018 (this version, v2))

We investigate a new class of galactic halo axion detection techniques based on precision frequency and phase metrology. Employing equations of axion electrodynamics, it is demonstrated how a dual mode cavity exhibits linear mode-mode coupling mediated by the axion upconversion and axion downconversion processes. The approach demonstrates phase sensitivity with an ability to detect axion phase with respect to externally pumped signals. Axion signal to phase spectral density conversion is calculated for open and closed loop detection schemes. The fundamental limits of the proposed approach come from the precision of frequency and environment control electronics, rather than fundamental thermal fluctuations allowing for table-top experiments approaching state-of-the-art cryogenic axion searches in sensitivity. Practical realisations are considered, including a TE-TM mode pair in a cylindrical cavity resonator and two orthogonally polarised modes in a Fabry-Perot cavity.

Subjects: **Instrumentation and Detectors (physics.ins-det)**; Other Condensed Matter (cond-mat.other); High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph); Quantum Physics (quant-ph)

Cite as: arXiv:1806.07141 **[physics.ins-det]**
(or arXiv:1806.07141v2 **[physics.ins-det]** for this version)

Frequency Metrology in Paraphoton Detection

New alternative to Light Shining through a Wall

PHYSICAL REVIEW D **87,** 115008 (2013)

Hidden sector photon coupling of resonant cavities

Stephen R. Parker,[1,*] Gray Rybka,[2] and Michael E. Tobar[1]
[1]*School of Physics, The University of Western Australia, Crawley 6009, Australia*
[2]*University of Washington, Seattle, Washington 98195, USA*
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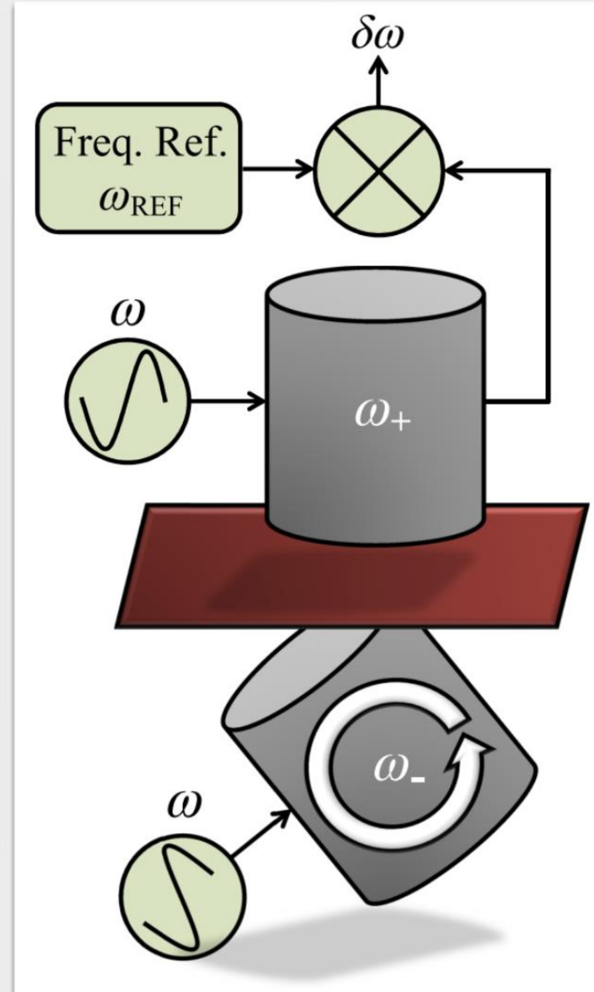
Many beyond the standard model theories introduce light paraphotons, a hypothetical spin-1 field that kinetically mixes with photons. Microwave cavity experiments have traditionally searched for paraphotons via transmission of power from an actively driven cavity to a passive receiver cavity, with the two cavities separated by a barrier that is impenetrable to photons. We extend this measurement technique to account for two-way coupling between the cavities and show that the presence of a paraphoton field can alter the resonant frequencies of the coupled cavity pair. We propose an experiment that exploits this effect and uses measurements of a cavity's resonant frequency to constrain the paraphoton-photon mixing parameter χ. We show that such an experiment can improve the sensitivity to χ over existing experiments for paraphoton masses less than the resonant frequency of the cavity, and that it can eliminate some of the most common systematics for resonant cavity experiments.



coupled mode system

$$\omega_\pm \approx \omega_0\left(\frac{1}{1-\frac{x^2}{2}}\left(1+\frac{1}{2Q_1Q_2}+\frac{x^2}{4}+\boxed{\frac{m_{\gamma'}^2\chi^2}{\omega_0^2}-\frac{m_{\gamma'}^4\chi^2 G_S}{\omega_0^4}}\pm\left(\frac{1}{Q_1Q_2}+x^2+\boxed{\frac{2m_{\gamma'}^2x^2\chi^2}{\omega_0^2}-\frac{2m_{\gamma'}^4x^2\chi^2G_S}{\omega_0^4}+\frac{m_{\gamma'}^8\chi^4G}{\omega_0^8}}\right)^{\frac{1}{2}}\right)\right)^{\frac{1}{2}},$$

Paraphoton coupling to the 2nd cavity modulate resonance frequency

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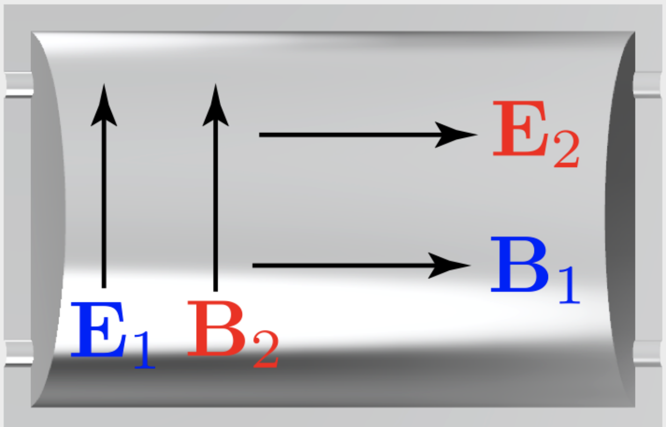
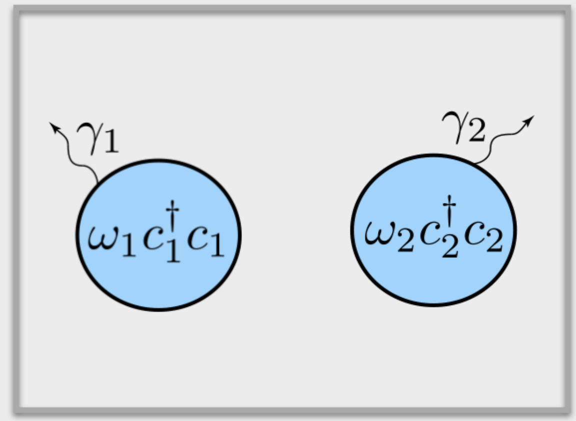
System for Axion Detection

photonic cavity with two mutually orthogonal modes

optical or microwave





Axion Electrodynamics

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}{m_a}^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Hamiltonian Density

$$\mathcal{H} = \mathcal{H}_{\text{EM}} + \mathcal{H}_a + \mathcal{H}_{\text{int}}$$

$$\mathcal{H}_{\text{EM}} = \frac{\varepsilon_0}{2}\left[\mathbf{E}^2 + c^2\mathbf{B}^2\right]$$

normal ED

$$\mathcal{H}_{\text{a}} = \frac{\phi^2}{2m_a} + V(\theta)$$

axion

$$\mathcal{H}_{\text{int}} = \varepsilon_0 c g_{a\gamma\gamma}\theta \; \mathbf{E}\cdot\mathbf{B}$$

interaction

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arXiv:1806.07141

Axion Mediated Mode-Mode Interaction

based on axion Electrodynamics we derive axion induced coupling between two cavity modes

$$H_{\text{int}} = i\hbar g_{\text{eff}}\theta\Big[\xi_-(c_1c_2^\dagger - c_1^\dagger c_2) + \xi_+(c_1^\dagger c_2^\dagger - c_1c_2)\Big]$$

Dimensionless Orthogonality Form Factors

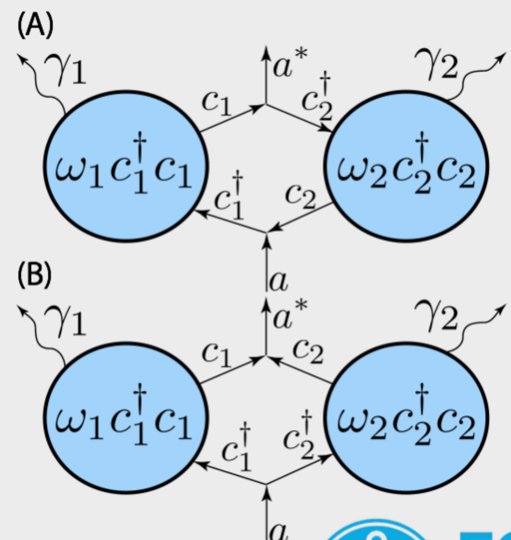
$$\xi_1 = \frac{1}{\sqrt{V_1V_2}}\int_V d^3r(\mathbf{e}_1\cdot\mathbf{b}_2),$$

$$\xi_2 = \frac{1}{\sqrt{V_1V_2}}\int_V d^3r(\mathbf{e}_2\cdot\mathbf{b}_1).$$

$$\xi_\pm = \xi_1 \pm \xi_2$$

Effective Coupling

$$g_{\text{eff}} = \frac{g_{a\gamma\gamma}}{2}\sqrt{\omega_1\omega_2}$$



Rotating Wave Approximation

Axion UpConversion

$$\omega_a = \omega_2 - \omega_1$$

$$H_{\text{U}} = i\hbar g_{\text{eff}}\xi_-(a^*c_1c_2^\dagger - ac_1^\dagger c_2)$$

beam splitter

allows optical search at microwaves and mm-wave

Axion DownConversion

$$\omega_a = \omega_2 + \omega_1$$

$$H_{\text{D}} = i\hbar g_{\text{eff}}\xi_+(ac_1^\dagger c_2^\dagger - a^*c_1c_2)$$

parametric amplification

allows microwave search at mm-wave

arXiv:1806.07141

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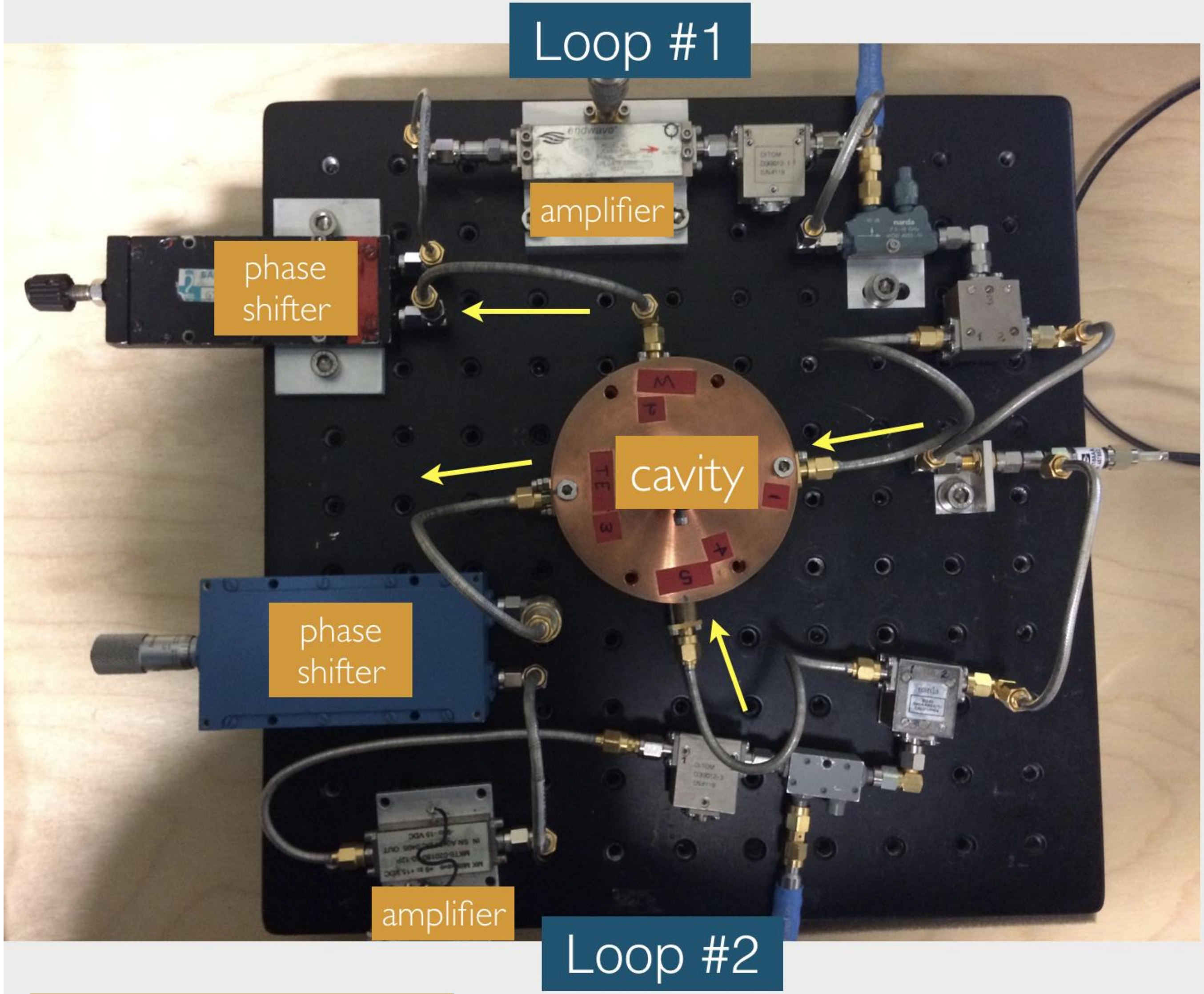
Experiment

Dual Loop Oscillator



R=22mm, H = 18.5-83.6 mm cylindrical copper cavity

TM_{022} mode (9GHz)
TM_{011} mode (6.5-9GHz)

$$\xi_- = -0.39..-0.5$$
$$\xi_+ = -0.46..-0.57$$

Catriona Thomson

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Probing Dark Universe with Exceptional Points

Maxim Goryachev, Ben McAllister, Michael E. Tobar

(Submitted on 28 Aug 2018)

It is demonstrated that detection of putative particles such as paraphotons and axions constituting the dark sector of the universe can be reduced to detection of extremely weak links or couplings between cavities and modes. This method allows utilisation of extremely sensitive frequency metrology methods that are not limited by traditional requirements on ultra low temperatures, strong magnetic fields and sophisticated superconducting technology. We show that exceptional points in the eigenmode structure of coupled modes may be used to boost the sensitivity of dark matter mediated weak links. We find observables that are proportional to fractional powers of fundamental coupling constants. Particularly, in case of axion detection, it is demonstrated that resonance frequency scaling with $\sim \sqrt{g_{a\gamma\gamma}}$ and $\sim \sqrt[3]{g_{a\gamma\gamma}}$ dependencies can be realised in a ternary photonic cavity system, which is beneficial as these coupling constants are extremely small.

Subjects: **High Energy Physics - Experiment (hep-ex)**; Instrumentation and Detectors (physics.ins-det); Quantum Physics (quant-ph)
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THE END