

MAGE: a multimode acoustic detector for high-frequency gravitational waves and an Australian node for GravNet



ACADEMIC (4)

Michael Tobar
Eugene Ivanov
Maxim Goryachev
Jeremy Bourhill

ADJUNCT(1)

Ben McAllister

POSTDOCS (3)

Cindy Zhao
Graeme Flower
Aaron Quiskamp

PHD STUDENTS (7)

Elrina Hartman
Steven Samuels
Emma Paterson
Robert Crew
Michael Hatzon
Sonali Parashar
Ashley Johnson

UNDERGRAD STUDENTS (3)

Tim Holt (MSc)
Evangelos Hajigabriel (Hons)
Charlie Campbell (Hons)

VACATION STUDENTS (3)

Owen Yadell
Jonathan Charlesworth
Div Sharma

<https://www.qdmlab.com/>



EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems



THE UNIVERSITY OF
WESTERN AUSTRALIA

Quantum Technology and Dark Matter Laboratory at UWA



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

Welcome to the QDM Lab

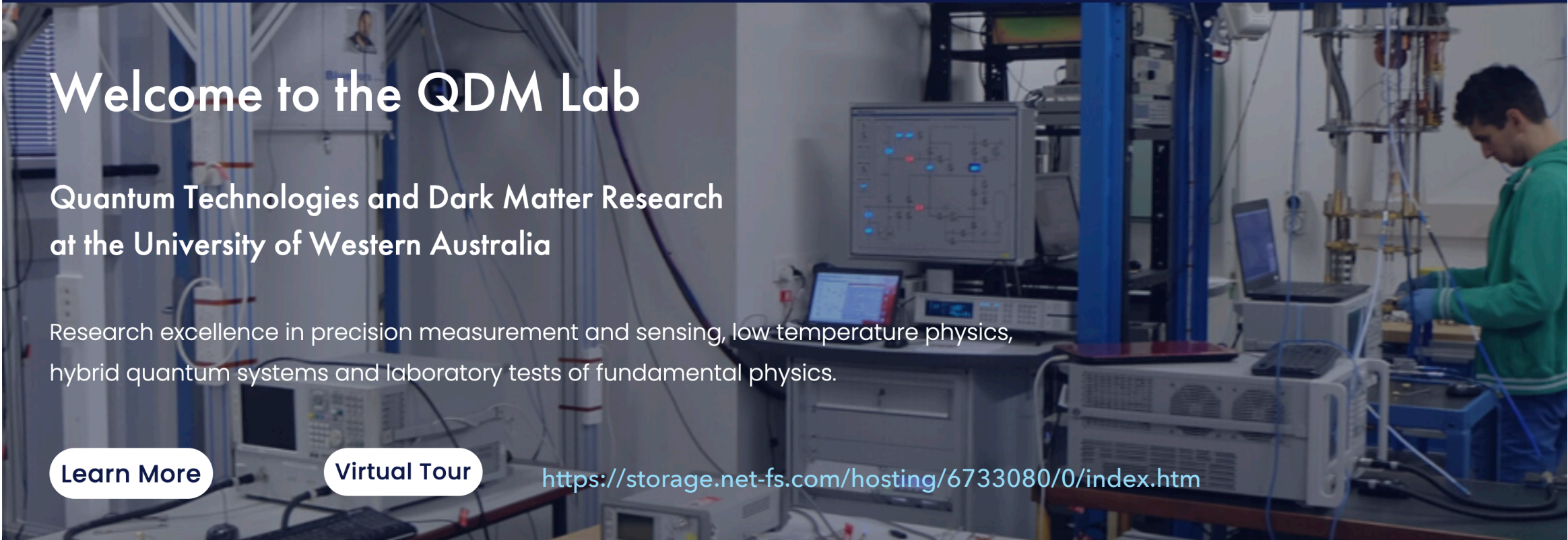
Quantum Technologies and Dark Matter Research
at the University of Western Australia

Research excellence in precision measurement and sensing, low temperature physics, hybrid quantum systems and laboratory tests of fundamental physics.

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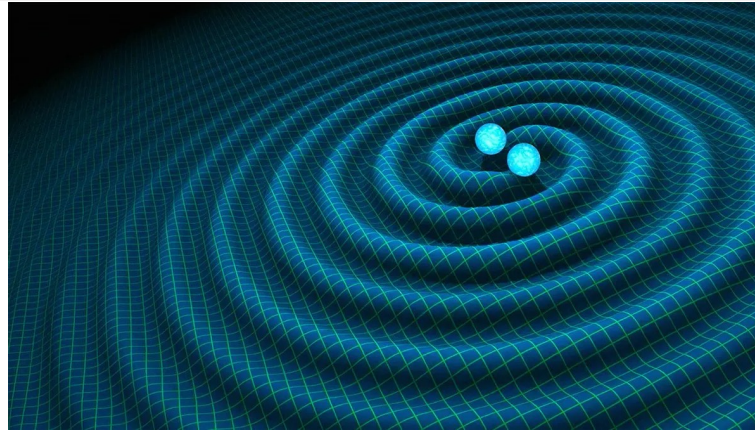
[Virtual Tour](#)

<https://storage.net-fs.com/hosting/6733080/0/index.htm>



Motivation: Fundamental Physics

General Relativity



Fundamental Constants

Quantum gravity

Dark Matter

Quantum Measurement

High frequency gravitational waves

Minimum length

Lorentz invariance violations

Metrology helps us search for physics beyond the standard model

The standard model

Quantum Enabled: Noise $<$ SQL

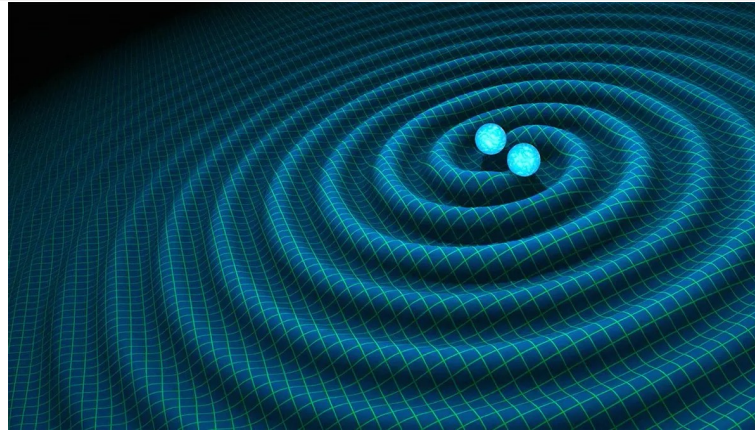
Science of precise measurement



Physics at low energies

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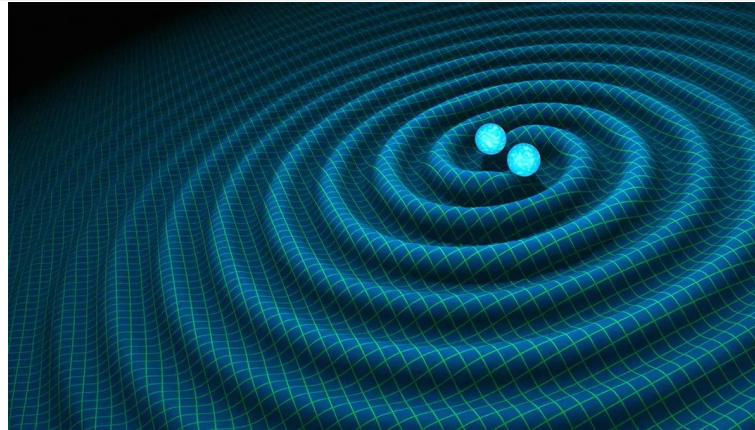
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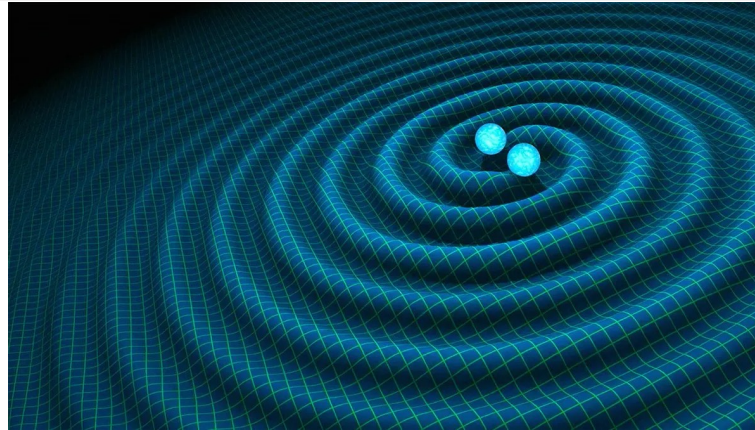
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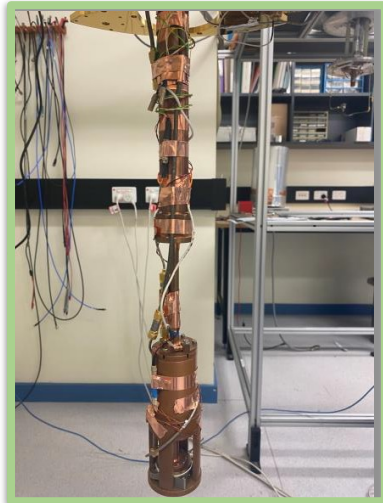
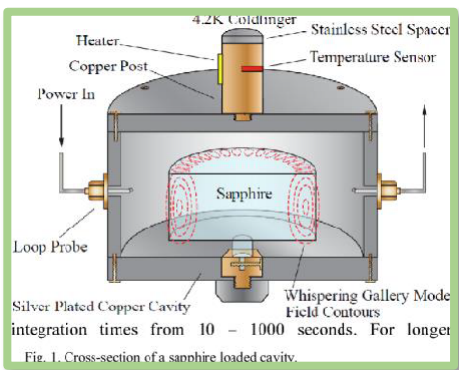
Physics at low energies

QDM Lab Precision Metrology

Metrological Systems:

Photonic

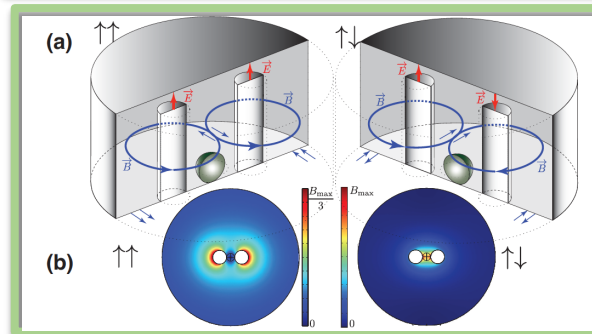
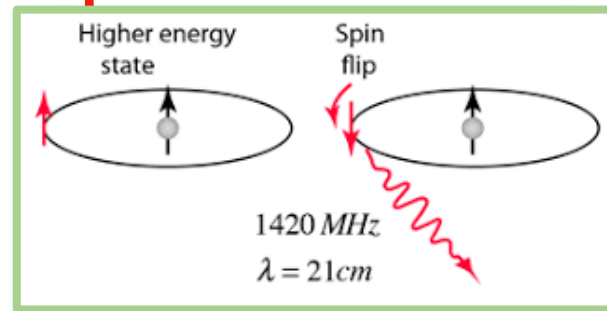
- WGM Resonators
- Specially Designed Microwave Cavities



Science of precise measurement

Atomic/Spins

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



Physics at low energies

Acoustic

- Superfluid
- BAW Resonator



Searching for Axion Dark Matter

The Axion Particle Should Exist!

- 1) Solves Strong CP Problem
- 2) Predicted to form in early Universe
- 3) Can solve inflation
- 4) Can solve matter-antimatter asymmetry
- 5) Is Dark Matter the Axion?

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



Frank Wilczek



One Axion

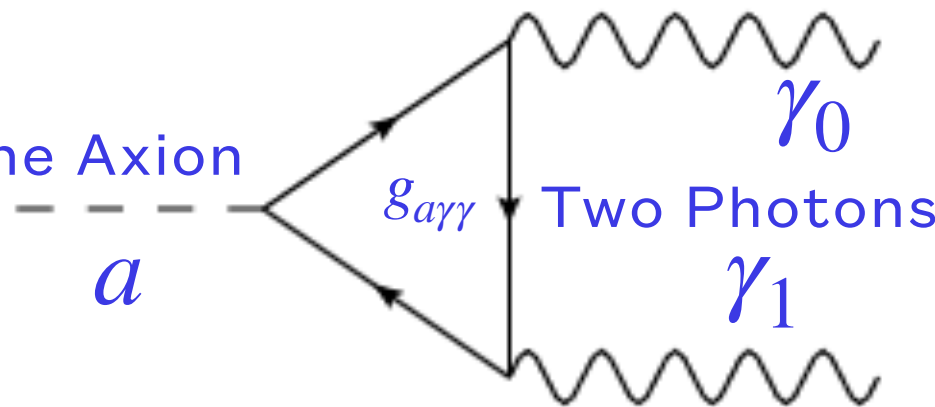
a

$g_{a\gamma\gamma}$

γ_0

Two Photons

γ_1



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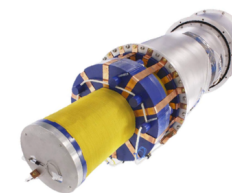
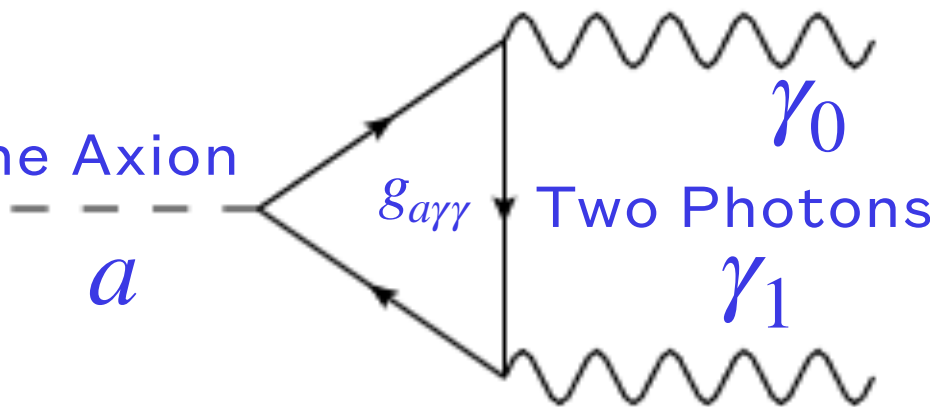
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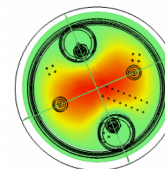
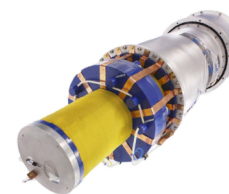
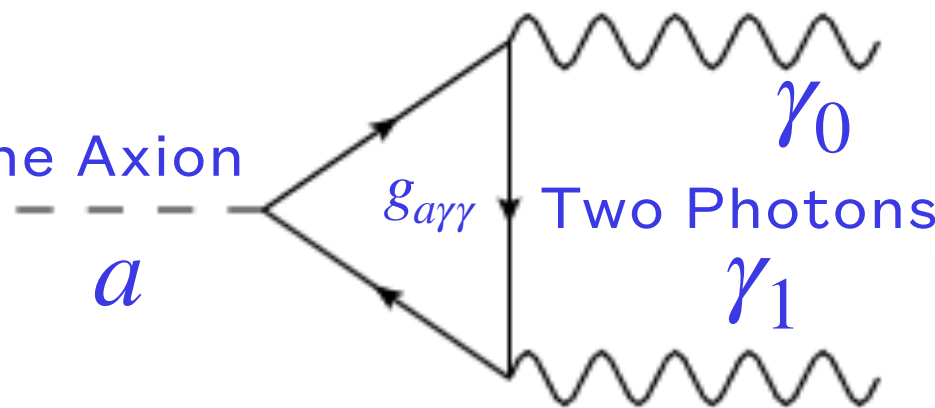
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Measure:
Tunable Cavity

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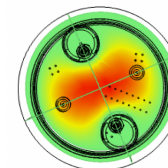
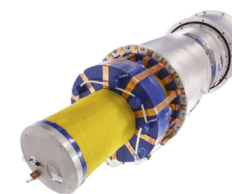
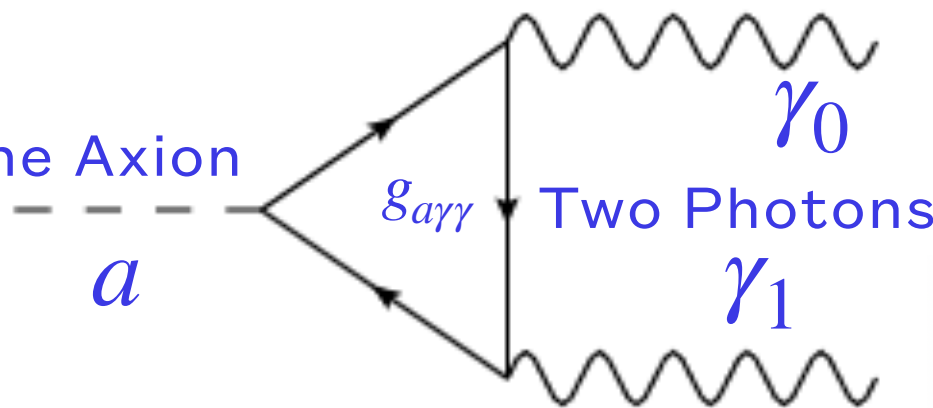


Frank Wilczek



One Axion
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axion-photon coupling $g_{a\gamma\gamma}$ \rightarrow chiral anomaly



Measure:
Tunable Cavity

Axion mass m_a determines ν_a

$$\nu_a = \frac{m_a c^2}{h} \left(1 + \frac{v^2}{2c^2} \right)$$

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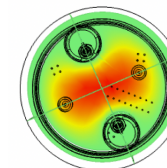
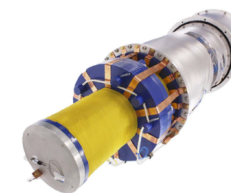
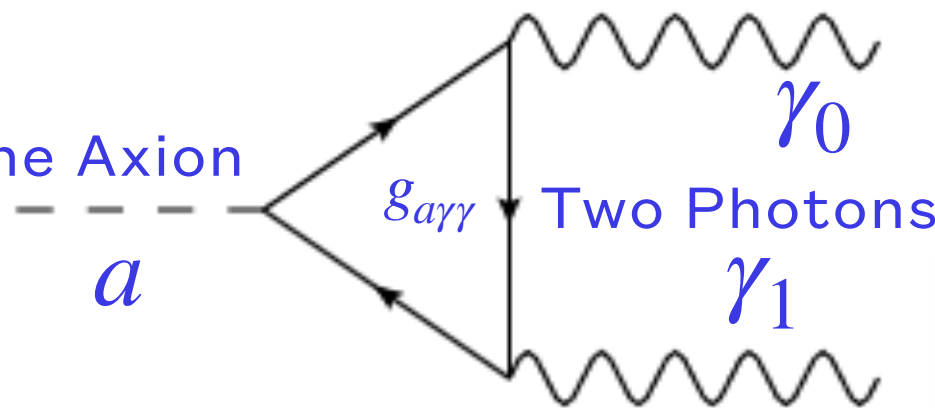


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Sikivie Haloscope



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

Sikivie Haloscope

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



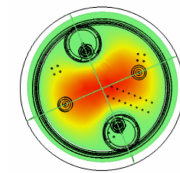
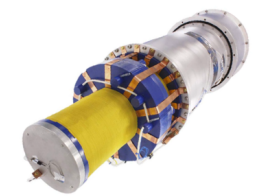
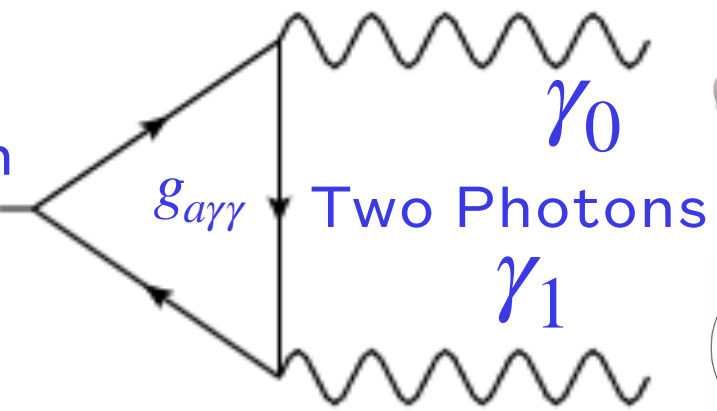
axion-photon coupling $g_{a\gamma\gamma}$ -> chiral anomaly



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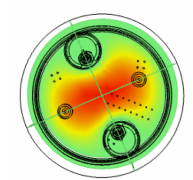
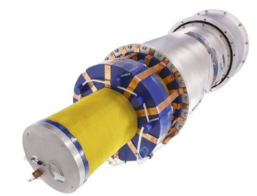
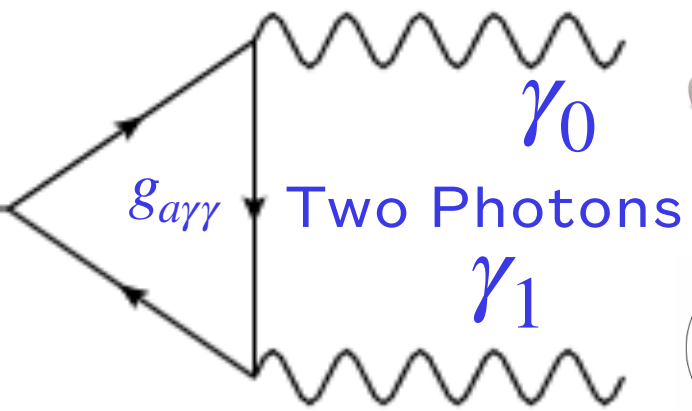
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Measure:
Tunable Cavity

Axion mass m_a determines ν_a

Quantum
Electromagnetodynamics
(QEMD)

$$g_{a\gamma\gamma} \rightarrow (g_{a\gamma\gamma}, g_{aAB}, g_{aBB})$$

$$\nu_a = \frac{m_a c^2}{h} \left(1 + \frac{v^2}{2c^2} \right)$$

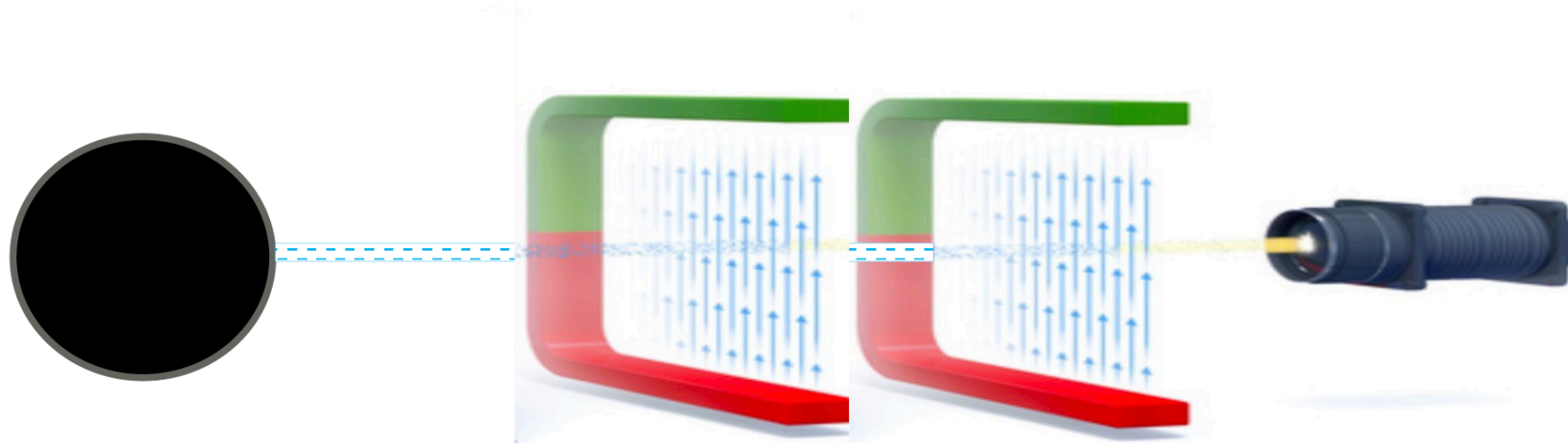
Magnetic conversion (Inverse Gertsenshtein effect)

- Gravitational-wave propagating in magnetic fields convert into photons.
Gertsenshtein, Sov. Phys., JETP 14, 84 (1962), G. A. Lupanov JETP 25, 76 (1967)

Source

Magnetic field

Photon detector



Axion Detector are Sensitive to Ultra-High Frequency GWs (UHFGWs)

Inverse Gertsenshtein effect

PHYSICAL REVIEW D **105**, 116011 (2022)

Detecting high-frequency gravitational waves with microwave cavities

Asher Berlin,^{1,2,3} Diego Blas,^{4,5} Raffaele Tito D’Agnolo⁶, Sebastian A. R. Ellis^{7,6},
Roni Harnik,^{2,3} Yonatan Kahn,^{8,9,3} and Jan Schütte-Engel^{8,9,3}



$$j_{\text{eff}} \supset g_{a\gamma\gamma} \partial_l a \mathbf{B}_0 \simeq \omega_a \theta_a \mathbf{B}_0 \quad \mathbf{E}_a = g_{a\gamma\gamma} a \mathbf{B}_0 = \theta_a \mathbf{B}_0$$

$$j_{\text{eff}}^\mu \equiv \partial_\nu \left(\frac{1}{2} h F^{\mu\nu} + h_a^\nu F^{\alpha\mu} - h_a^\mu F^{\alpha\nu} \right)$$

$$j_{\text{eff}} \sim \omega_g h B_0$$

identifying $\theta_a \sim h$

Living Reviews in Relativity (2021)24:4
https://doi.org/10.1007/s41114-021-00032-5

REVIEW ARTICLE

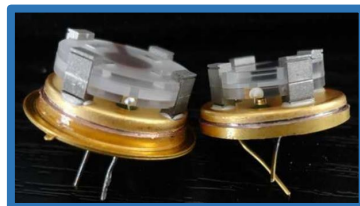
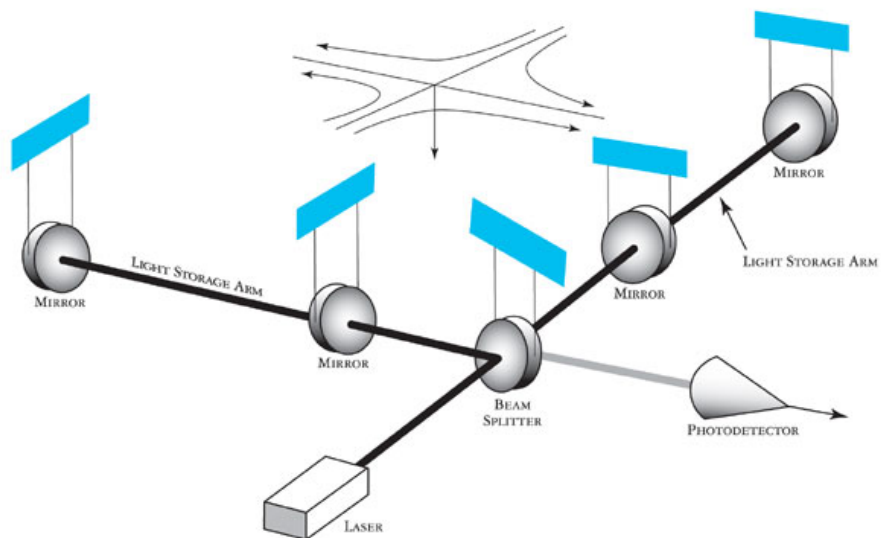
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

Nancy Aggarwal¹ · Odylio D. Aguiar² · Andreas Bauswein³ ·
Giancarlo Cella⁴ · Sebastian Clesse⁵ · Adrian Michael Cruise⁶ ·
Valerie Domcke^{7,8,9} · Daniel G. Figueroa¹⁰ · Andrew Geraci¹¹ ·
Maxim Goryachev¹² · Hartmut Grote¹³ · Mark Hindmarsh^{14,15} ·
Francesco Muia^{9,16} · Nikhil Mukund¹⁷ · David Ottaway^{18,19} ·
Marco Peloso^{20,21} · Fernando Quevedo¹⁶ · Angelo Ricciardone^{20,21} ·
Jessica Steinlechner^{22,23,24} · Sebastian Steinlechner^{22,23} · Sichun Sun^{25,26} ·
Michael E. Tobar¹² · Francisco Torrenti²⁷ · Caner Ünal²⁸ · Graham White²⁹

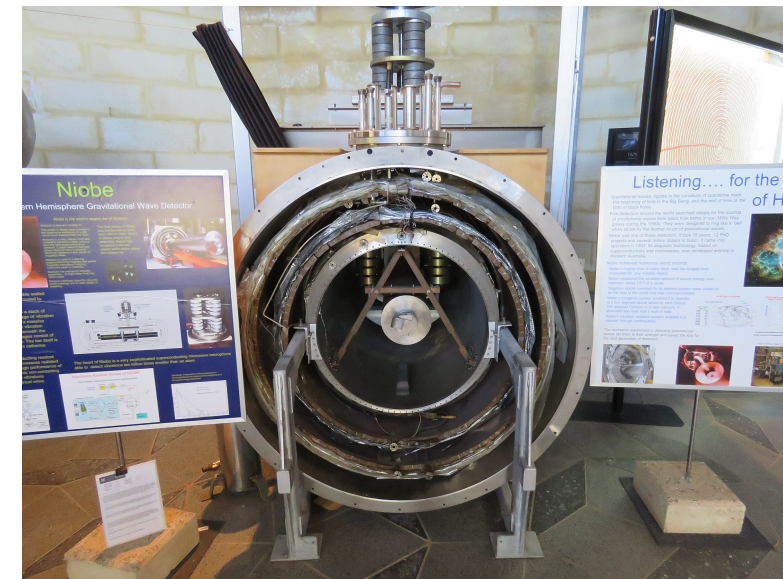
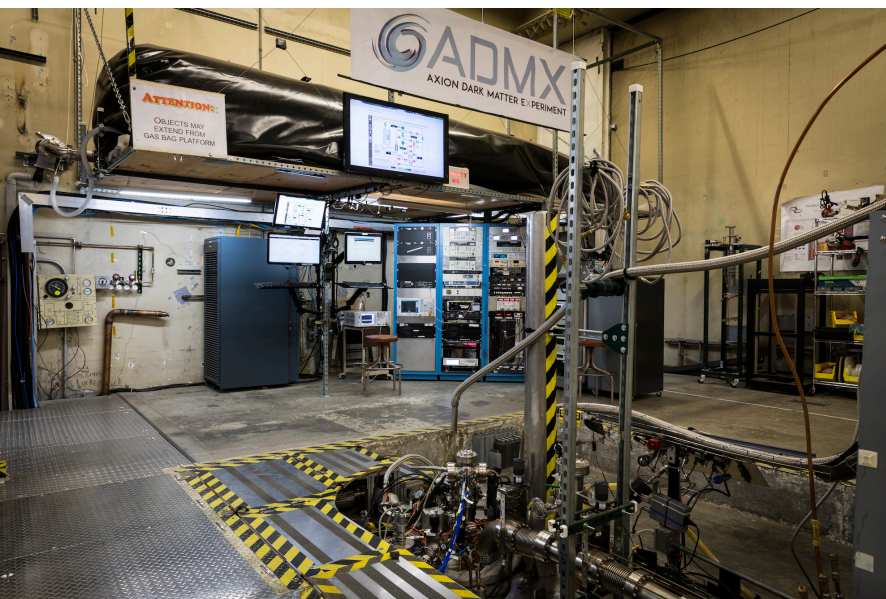
Received: 6 April 2021 / Accepted: 15 September 2021
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Precision Detectors: Sensitive to New Physics

comparing sensitivities



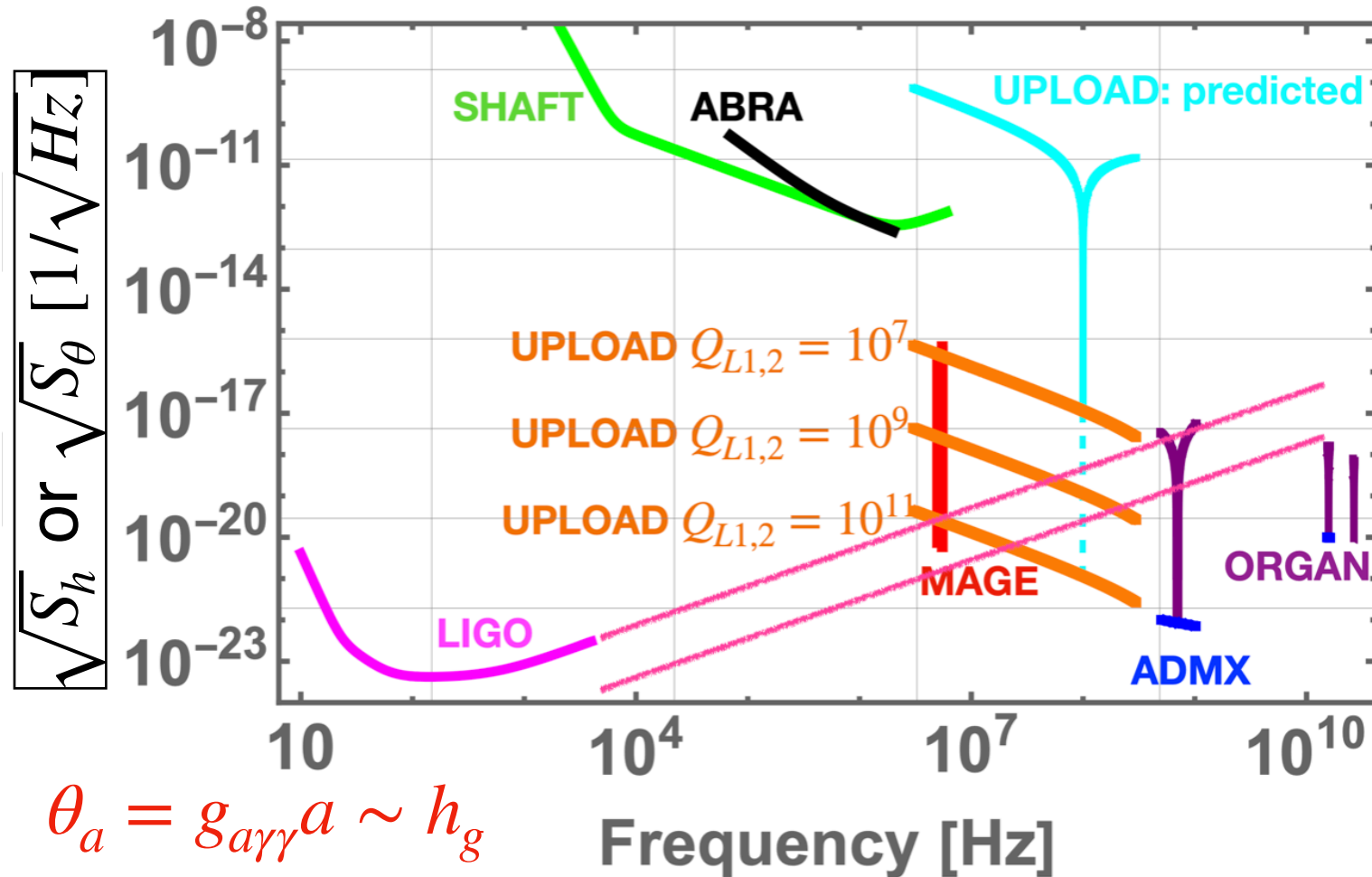
NIOBE





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

Michael E. Tobar *¹, Catriona A. Thomson, William M. Campbell, Aaron Quiskamp, Jeremy F. Bourhill, Benjamin T. McAllister, Eugene N. Ivanov and Maxim Goryachev



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

Frequency [Hz]

ADMX and ORGAN (purple) with current tuning locus (blue);

0.6-1.2 GHz for ADMX and 15.2 to 16.2 GHz for ORGAN

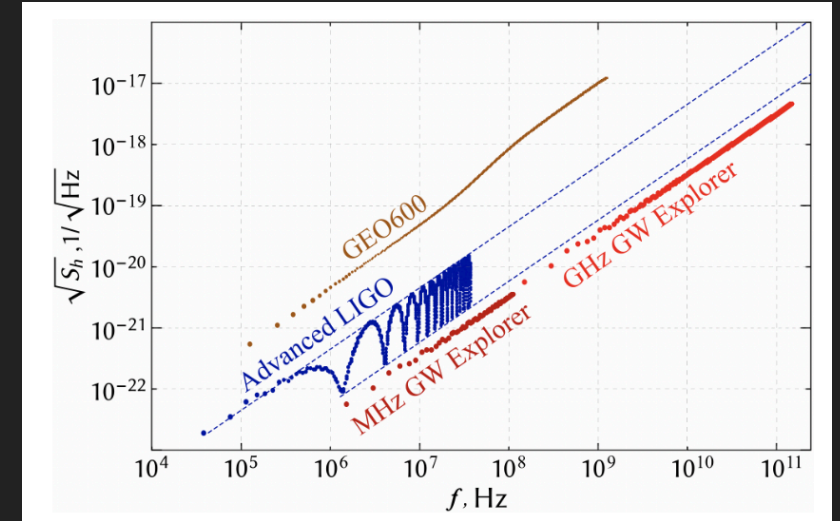
Special Issue

The Dark Universe: The Harbinger of a Major Discovery

Edited by

[Symmetry, vol. 14, no. 10, 2165, 2022](#)

Prof. Konstantin Zioutas



arXiv:2409.03019 Schnabel and Korobko

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

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

Technology at UWA to detect HFGWs

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- 1) Leading Axion Dark Matter Experiments @ UWA (ORGAN) -> utilise the “Inverse Gertsenshtein Effect”

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VOLUME 74, NUMBER 11

PHYSICAL REVIEW LETTERS

13 MARCH 1995

High Sensitivity Gravitational Wave Antenna with Parametric Transducer Readout

D.G. Blair, E. N. Ivanov, M. E. Tobar, P. J. Turner, F. van Kann, and I. S. Heng
Physics Department, University of Western Australia, Nedlands, Western Australia, 6009
(Received 4 April 1994; revised manuscript received 27 September 1994)

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

Gravitational wave detection with high frequency phonon trapping acoustic cavities

Maxim Goryachev and Michael E. Tobar*

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

(Received 25 September 2014; published 24 November 2014)

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

Maxim Goryachev, Eugene N. Ivanov, Frank van Kann, Serge Galliou, and Michael E. Tobar

Citation: *Applied Physics Letters* **105**, 153505 (2014); doi: 10.1063/1.4898813

View online: <http://dx.doi.org/10.1063/1.4898813>

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- Rare Events Detected with a Bulk Acoustic Wave HFGW Antenna: 2021

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

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

Maxim Goryachev,¹ William M. Campbell¹, Ik Siong Heng², Serge Galliou³, Eugene N. Ivanov,¹ and Michael E. Tobar^{1*}

¹ARC Centre of Excellence for Engineered Quantum Systems, ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia

²SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland G12 8QQ, United Kingdom

³Department of Time and Frequency, FEMTO-ST Institute, ENSMM, 26 Chemin de l'Épitaphe, 25000 Besançon, France

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- **The Multi-mode Acoustic GW Experiment (MAGE): First results 2025**

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13 MARCH 1995

High Sensitivity Gravitational Wave Antenna with Parametric Transducer Readout

D.G. Blair, E.N. Ivanov, M.E. Tobar, P.J. Turner, F. van Kann, and I.S. Heng
Physics Department, University of Western Australia, Nedlands, Western Australia, 6009
(Received 4 April 1994; revised manuscript received 27 September 1994)



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

Gravitational wave detection with high frequency phonon trapping acoustic cavities

Maxim Goryachev and Michael E. Tobar*

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

(Received 25 September 2014; published 24 November 2014)

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

Maxim Goryachev, Eugene N. Ivanov, Frank van Kann, Serge Galliou, and Michael E. Tobar

Citation: *Applied Physics Letters* **105**, 153505 (2014); doi: 10.1063/1.4898813

View online: <http://dx.doi.org/10.1063/1.4898813>

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

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

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

¹ARC Centre of Excellence for Engineered Quantum Systems, ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia

²SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland G12 8QQ, United Kingdom

³Department of Time and Frequency, FEMTO-ST Institute, ENSMM, 26 Chemin de l'Épitaphe, 25000 Besançon, France

scientific reports

Sci Rep **13**, 10638, 2023

OPEN The multi-mode acoustic gravitational wave experiment: MAGE

William M. Campbell[✉], Maxim Goryachev & Michael E. Tobar[✉]

PHYSICAL REVIEW LETTERS **135**, 251402 (2025)

Experimental Limits on Planetary Mass Primordial Black Hole Mergers

William M. Campbell^{✉,1,2} Leonardo Mariani^{✉,2} Michael E. Tobar^{✉,1} and Maxim Goryachev¹

¹Quantum Technologies and Dark Matter Labs, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia

²Department of Physics “Giuseppe Occhialini,” University of Milano-Bicocca, Piazza dell’Ateneo Nuovo, 1 - 20126, Milan (Mi), Italy

Cryogenic Resonant Bar Gravity Wave Detectors

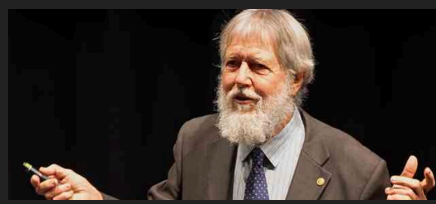
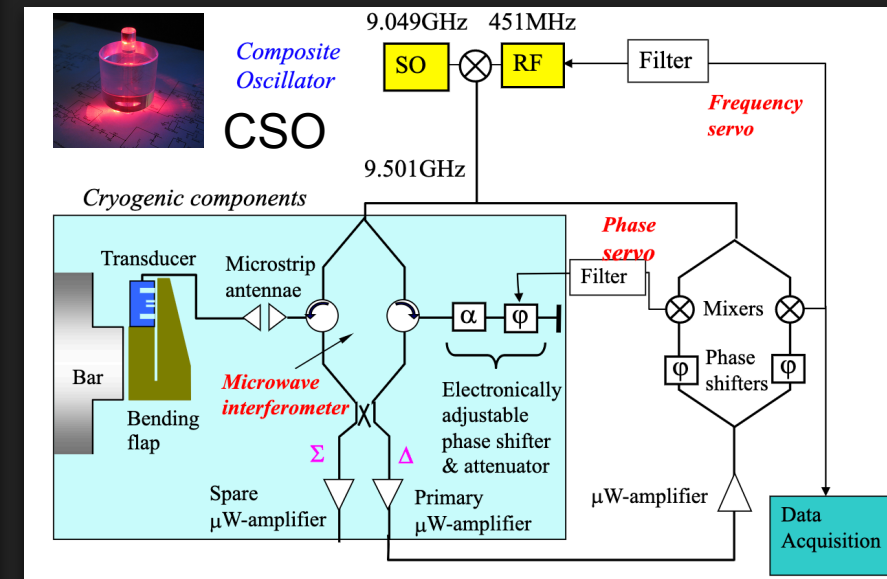
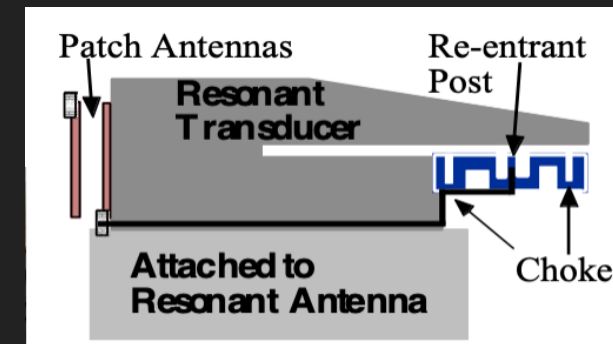
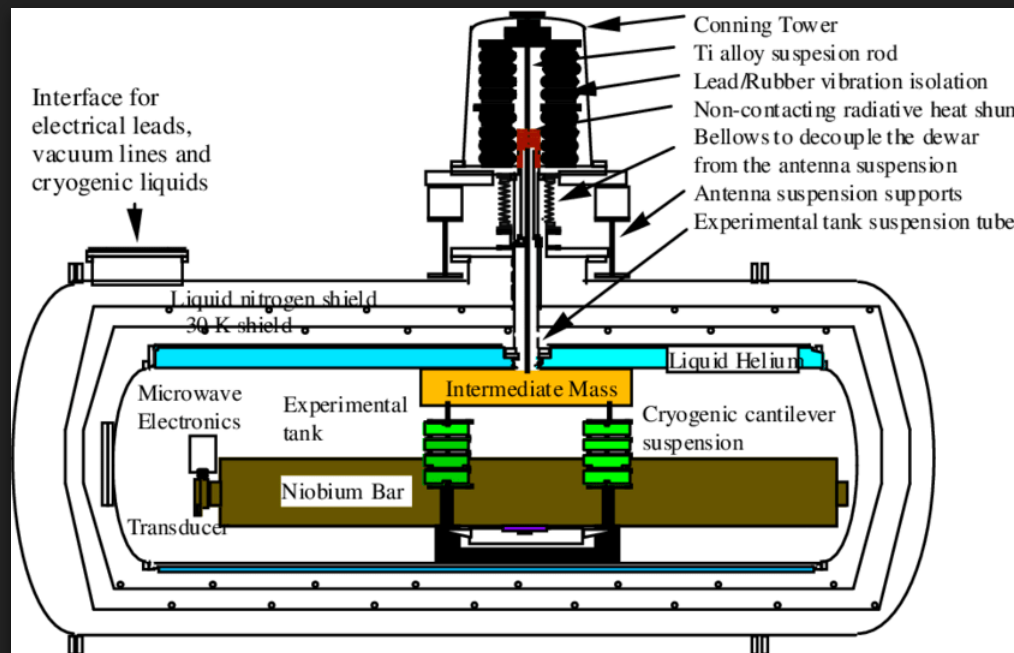
-> Ultra precise optomechanical position measurement

-> Low phase noise read-out and pump oscillator

- * Photons
- * Phonons
- * Spins



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

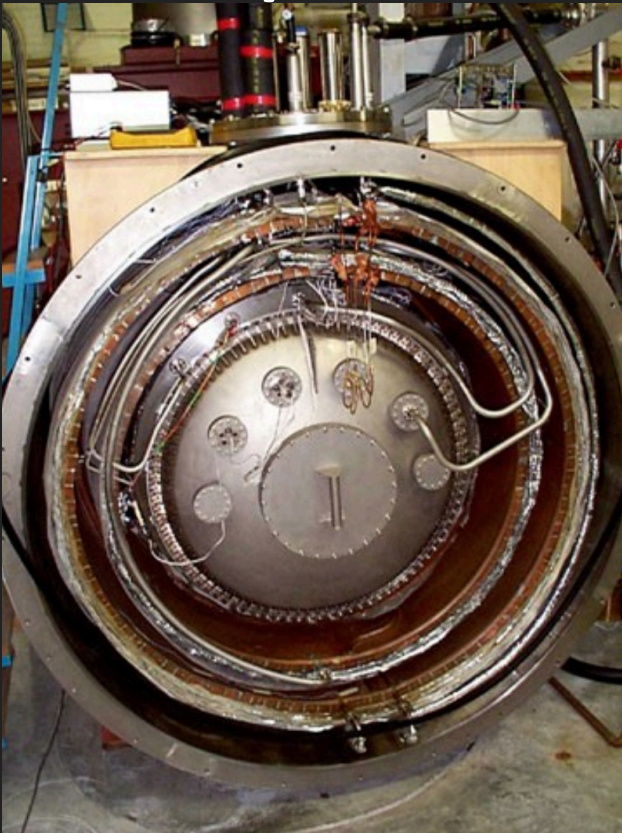


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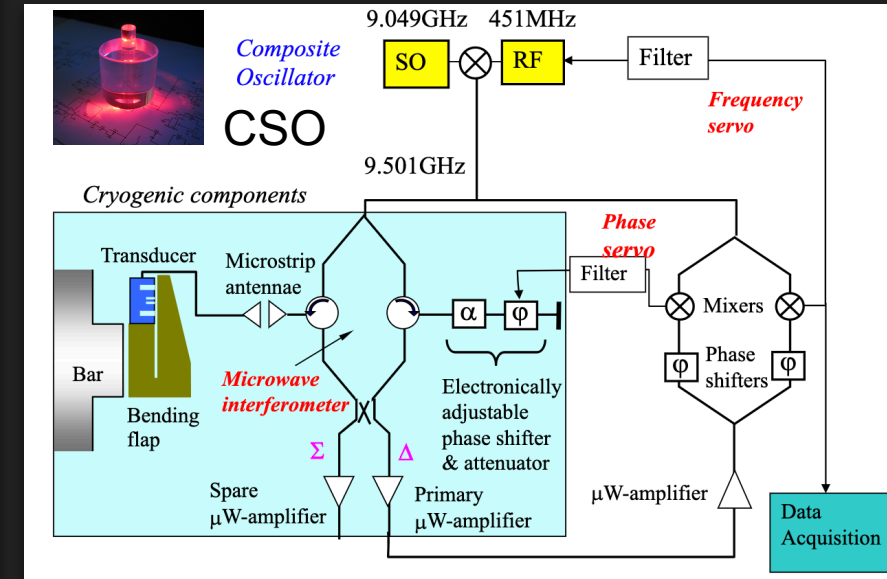
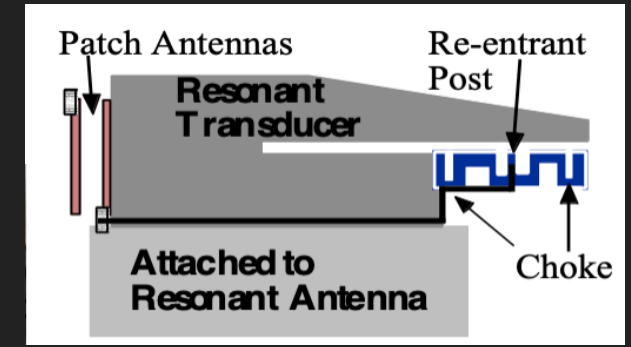
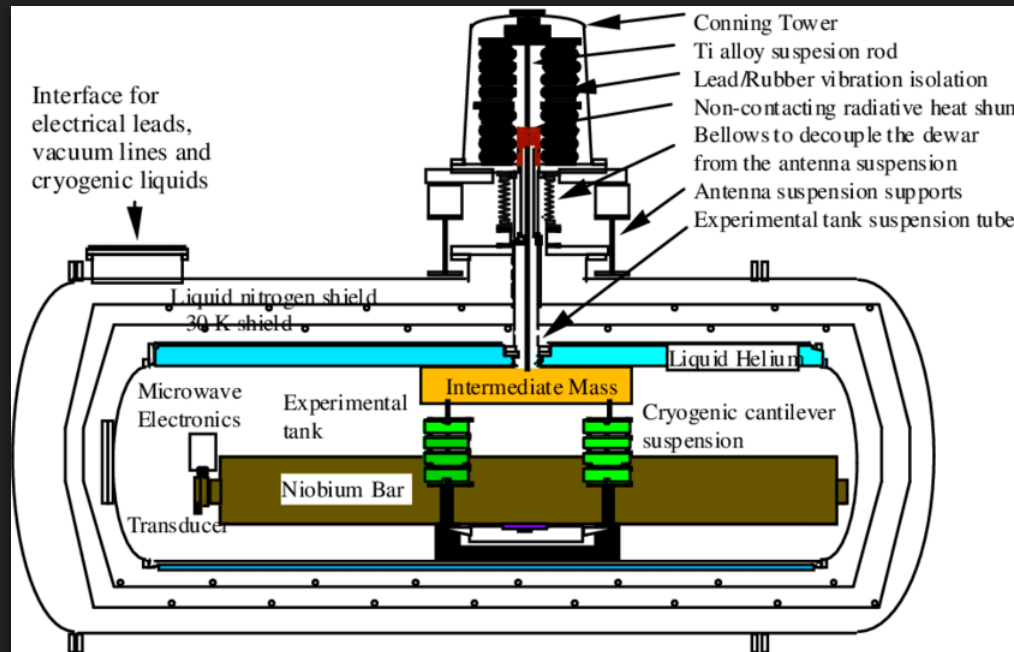
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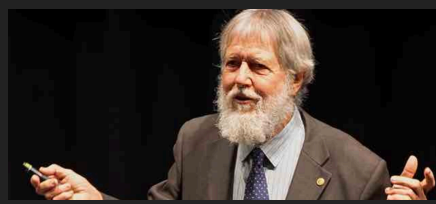
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My PhD project 1989 ->1993 UWA PhD Searching GW Signal Burst at 720 Hz

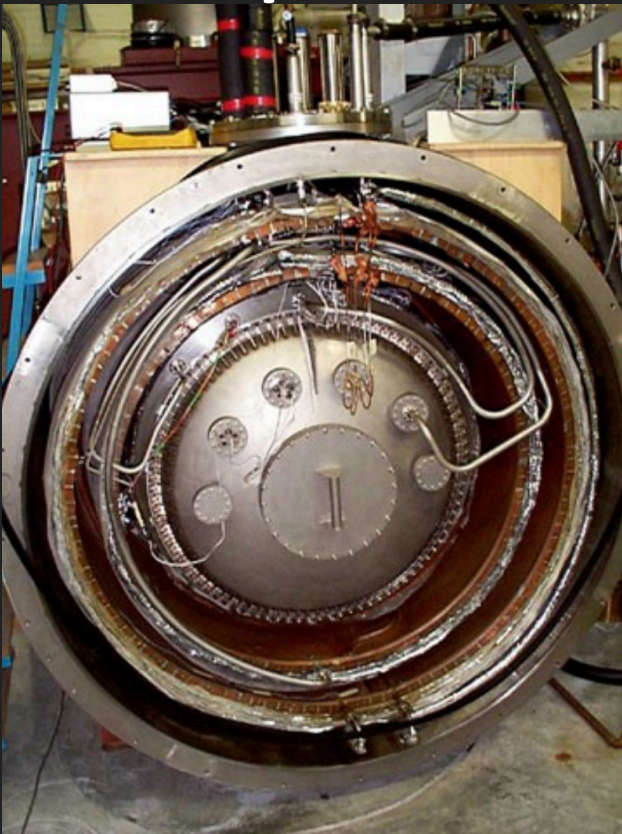


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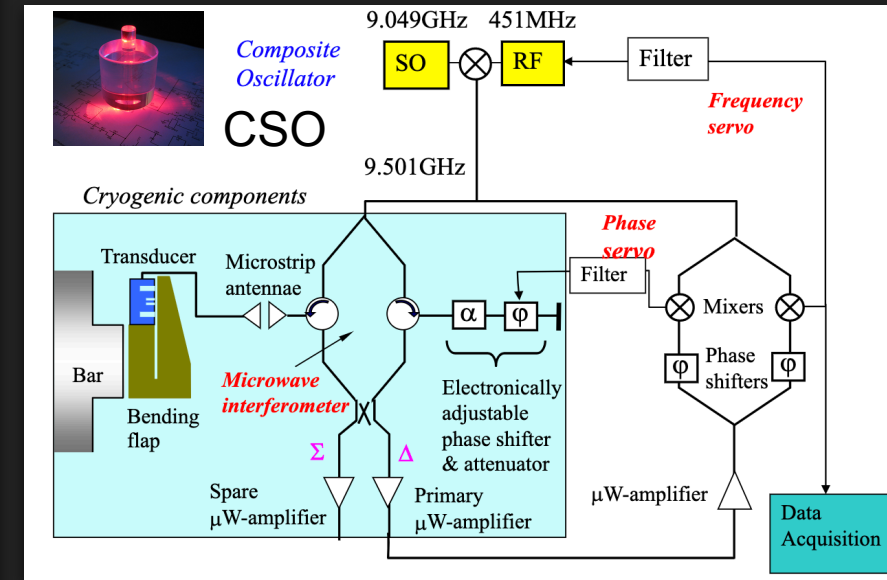
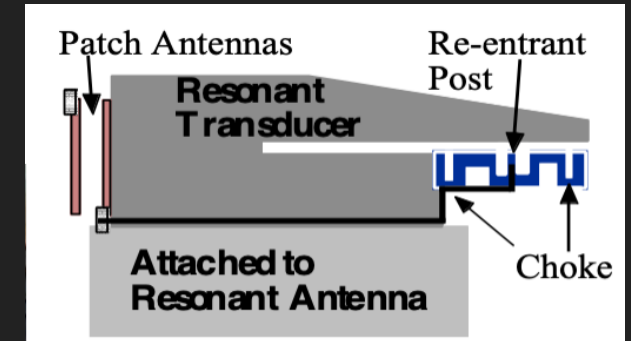
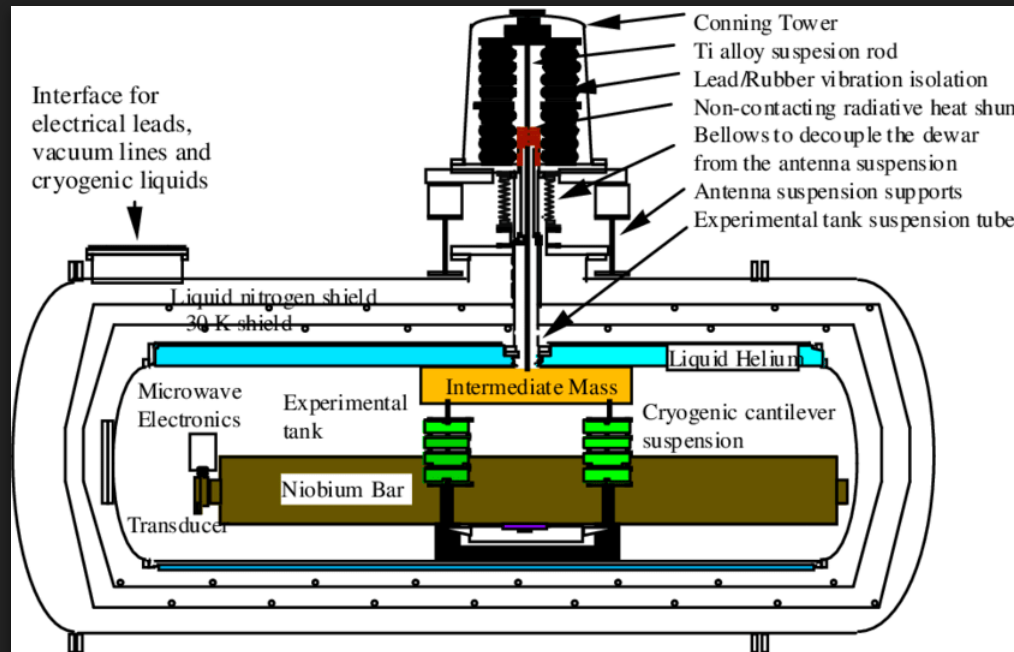
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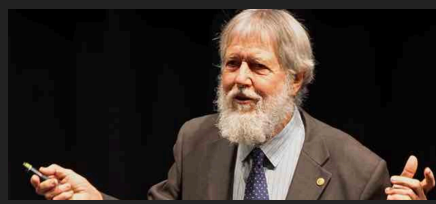


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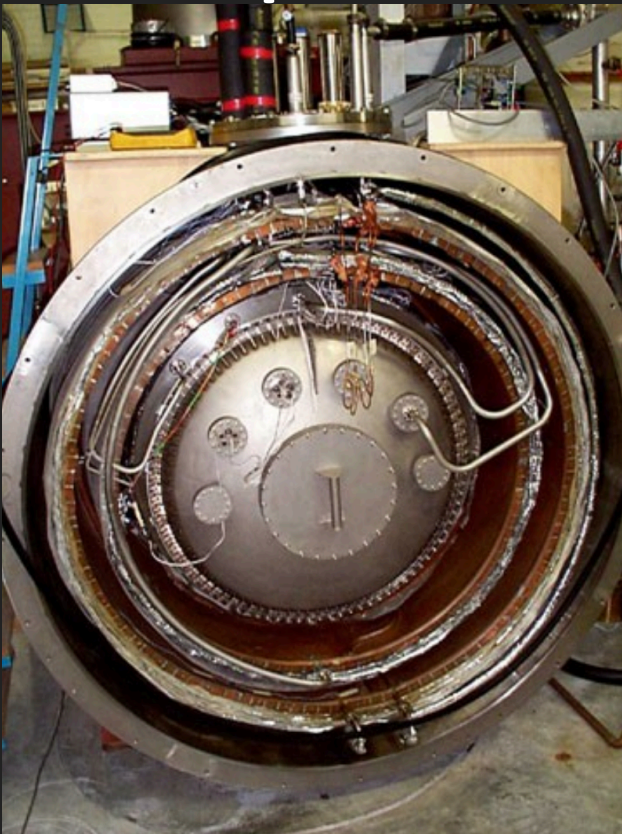


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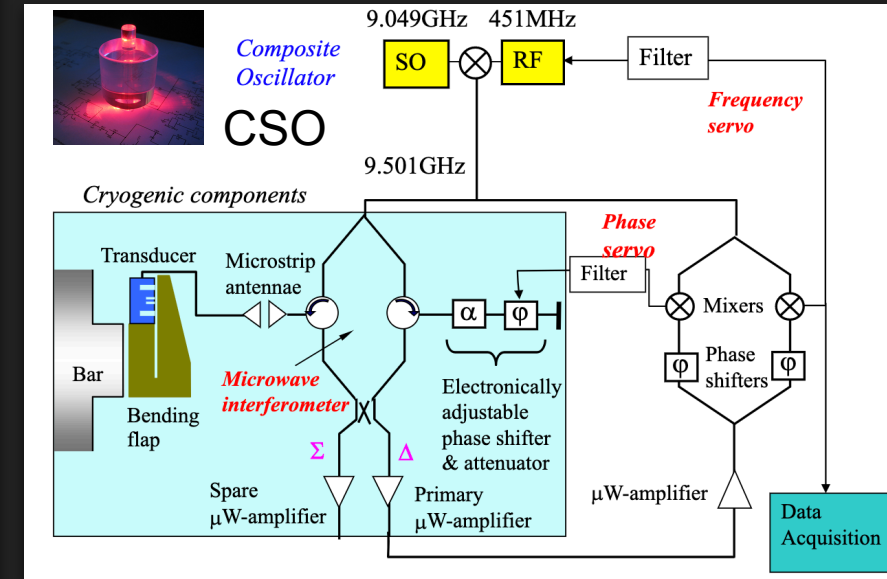
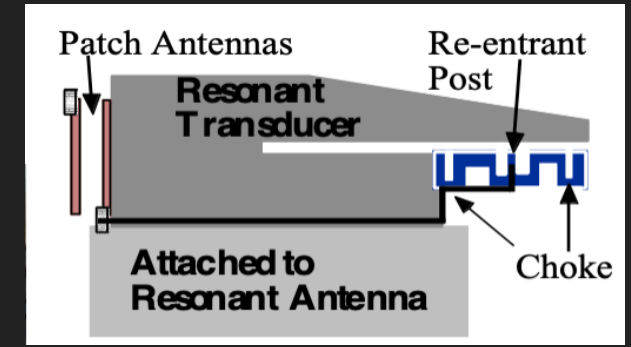
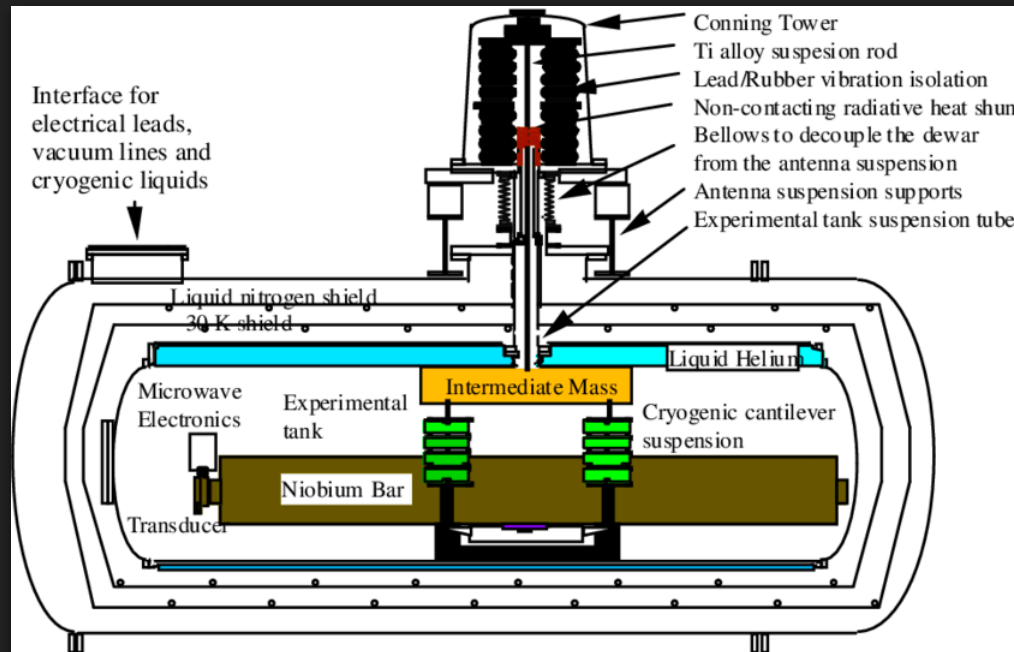
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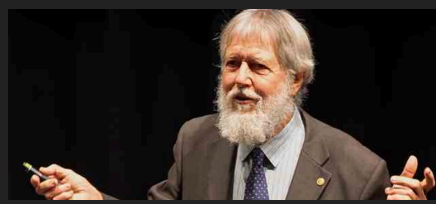
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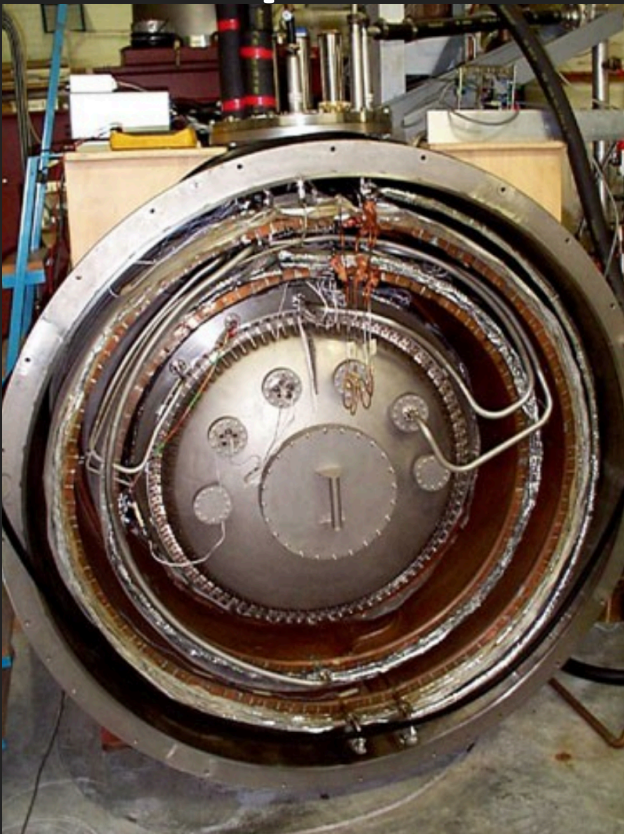
$$\tau = \frac{2Q}{\omega_0} = 1 \text{ day}$$

Cryogenic Resonant Bar Gravity Wave Detectors

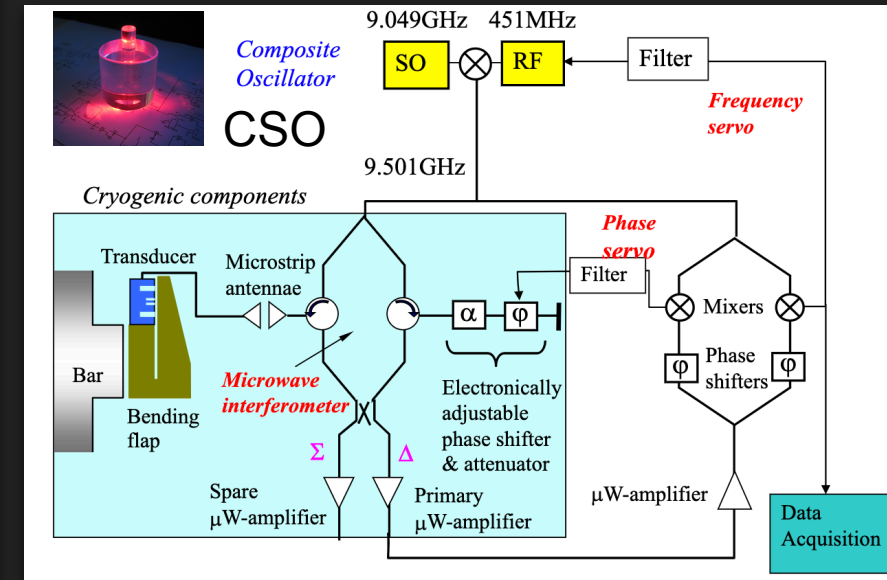
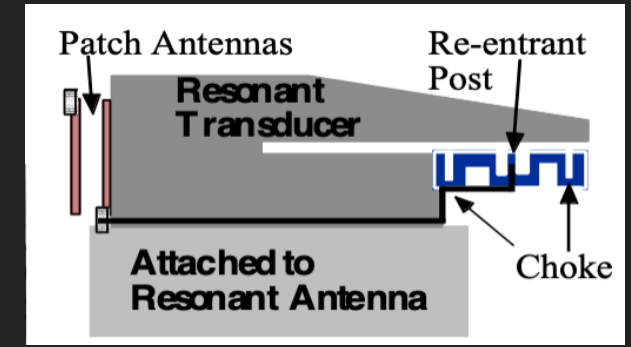
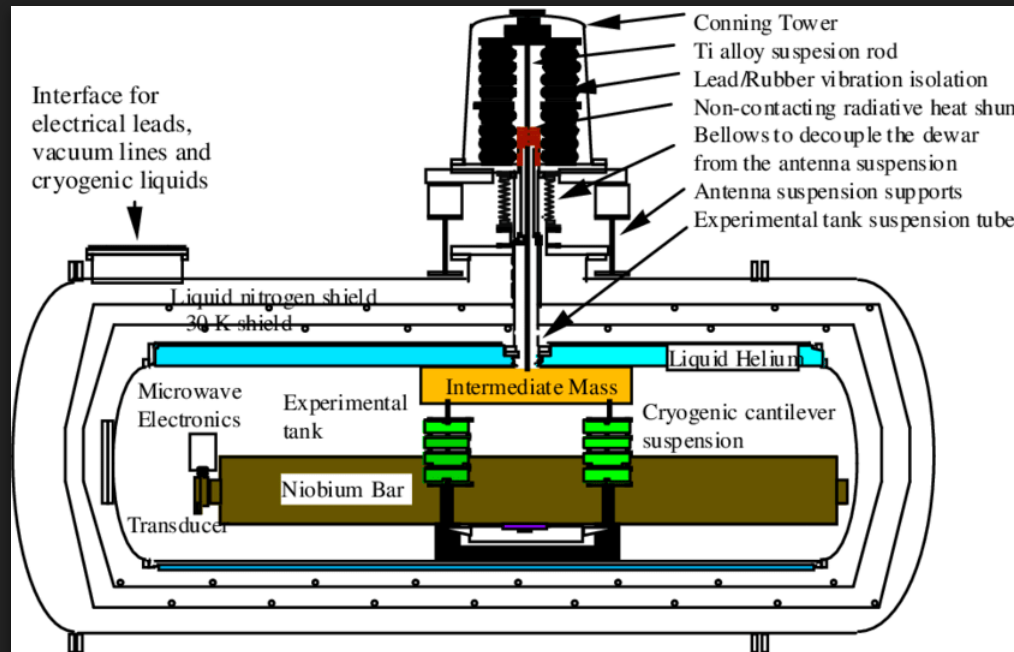
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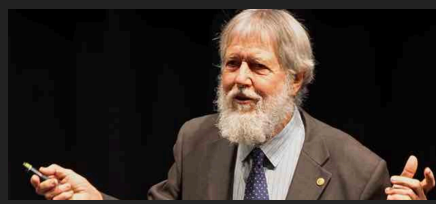
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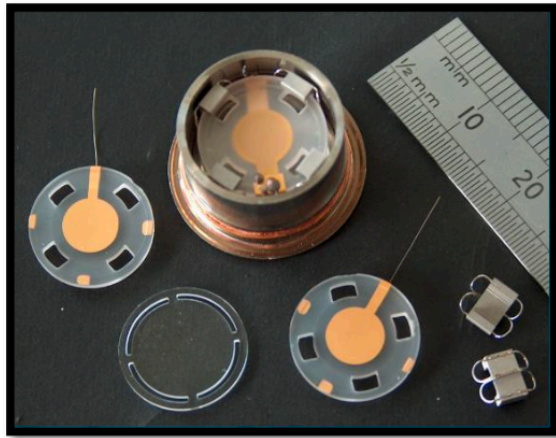
4K->Cold Damped-> 370 mK
 ->Measure quickly 900 μ K

The Multimode Acoustic

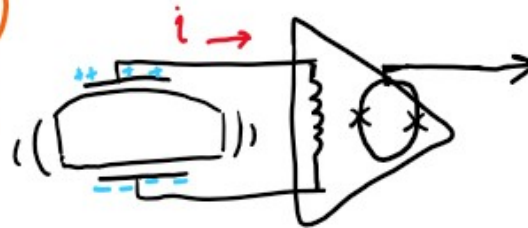
QDM

Gravitational Wave Experiment: MAGE

Tommaso Tabarelli de Fatis (Universita & INFN, Milano-Bicocca (IT))



THE UNIVERSITY OF
**WESTERN
AUSTRALIA**

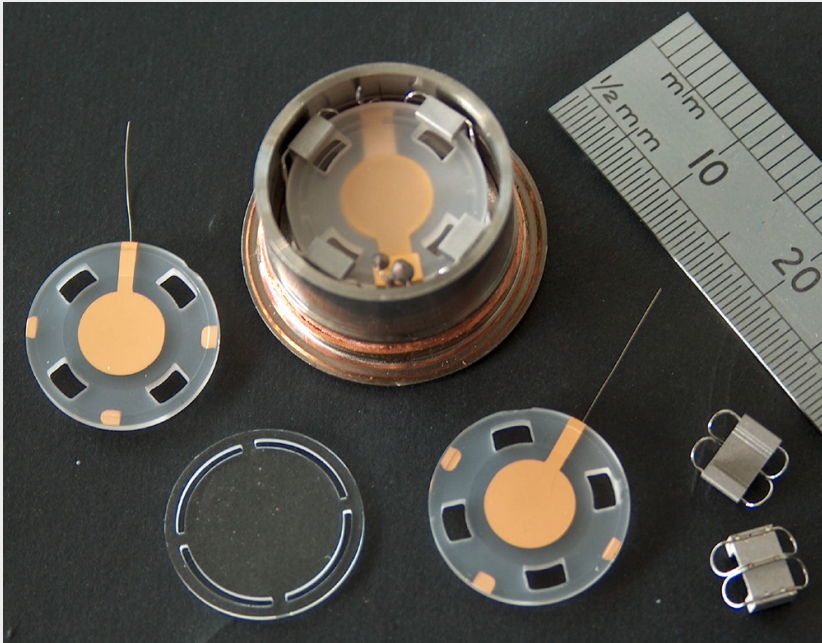


$S_v(s)$

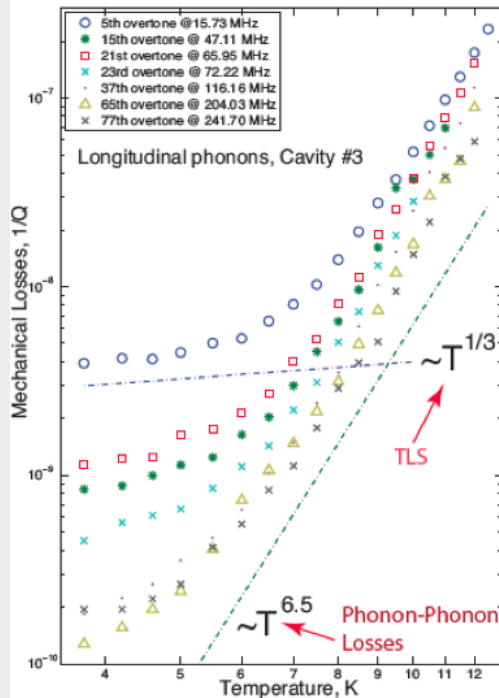
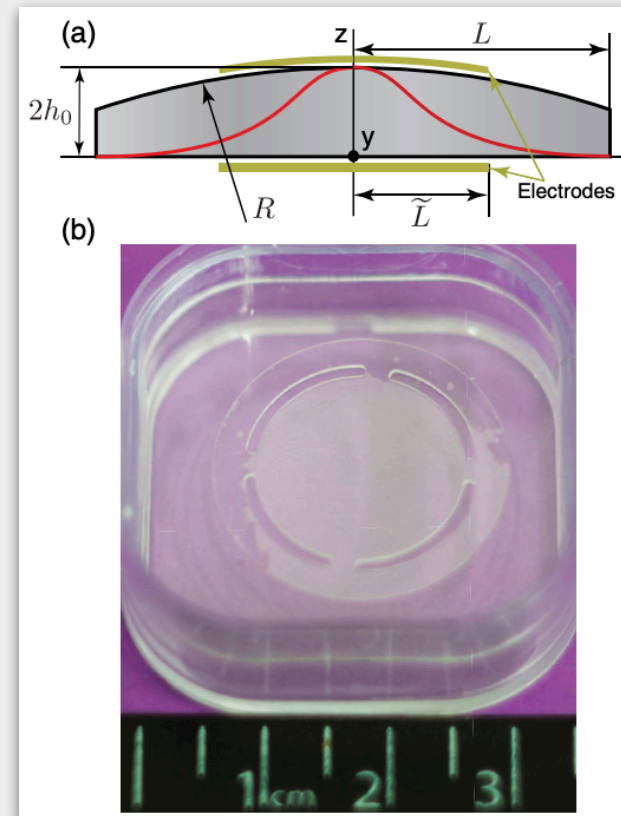
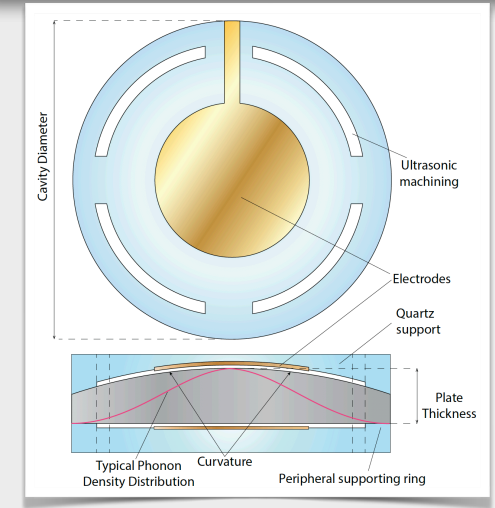
ARC CENTRE OF EXCELLENCE FOR
**DARK
MATTER**
PARTICLE PHYSICS



Bulk Acoustic Wave Devices



- Top High Quality α -quartz,
- BVA-technology,
- SC-cut,
- plano-covex...

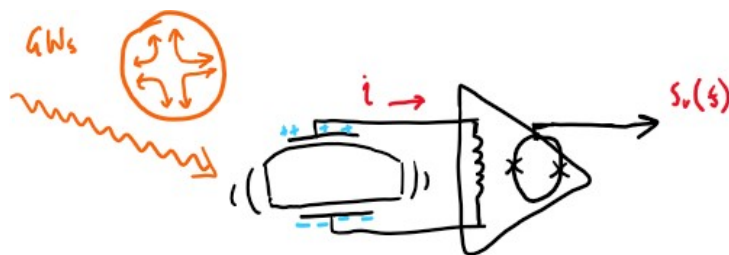
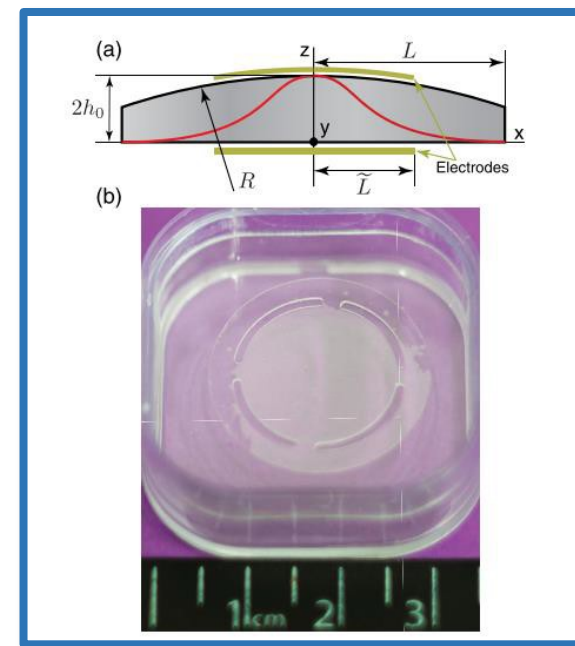
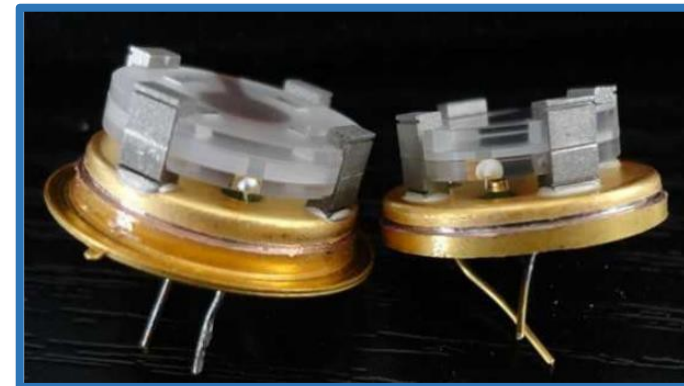
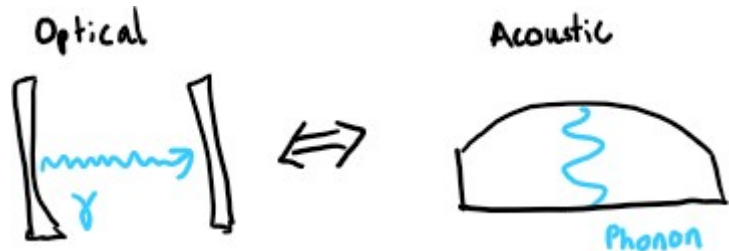


Frequency range: 1-1000 MHz
 Tree mode family types: 2 transverse and 1 longitudinal
 Piezoelectric Coupling
 Established technology (>70 years for time keeping applications)



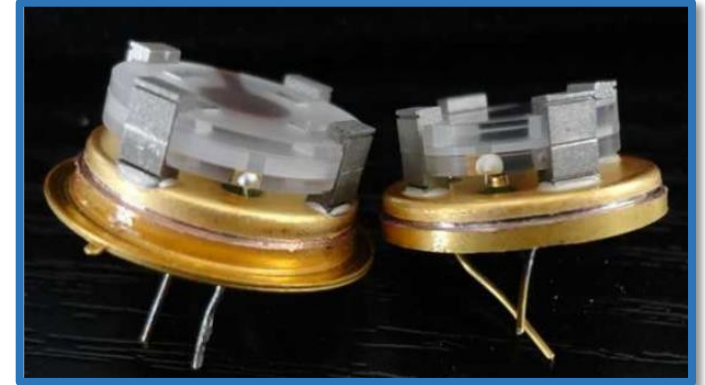
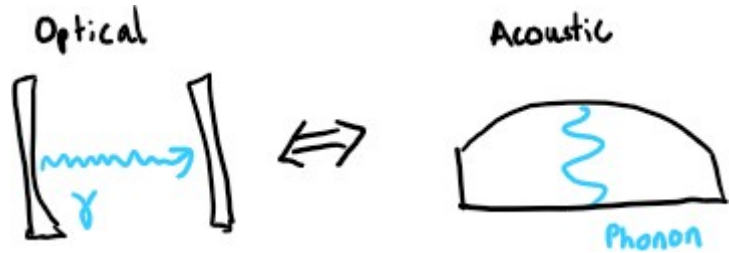
Quartz Bulk Acoustic Wave Resonators

- Acoustic analogue to a Optical Fabry-Perot cavity.

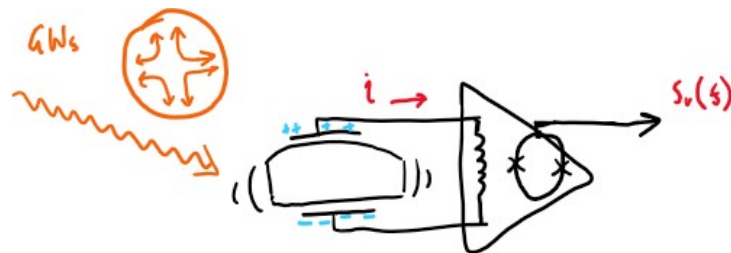
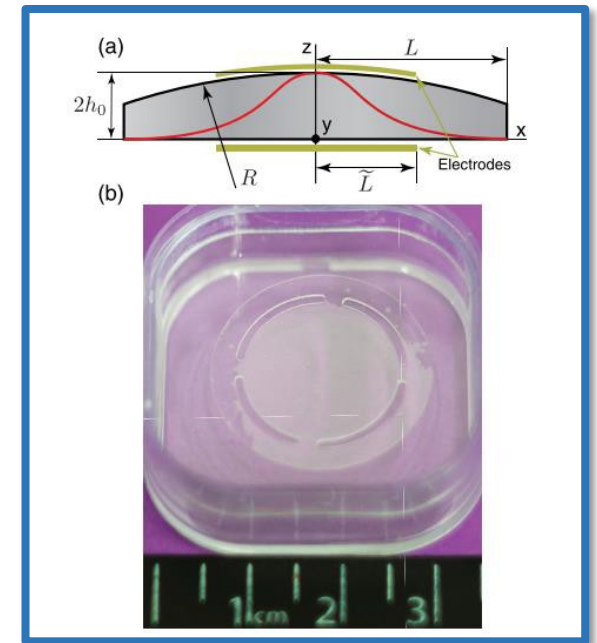


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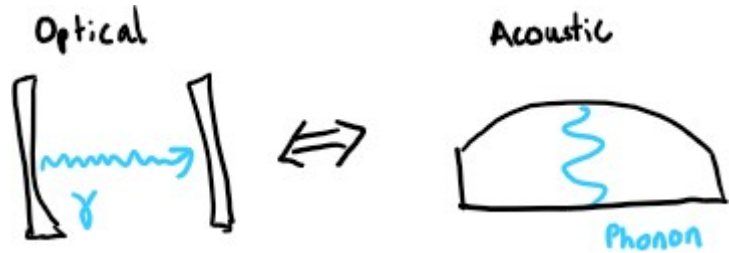


* RESEARCH WITH ACOUSTIC RESONATORS @ UWA



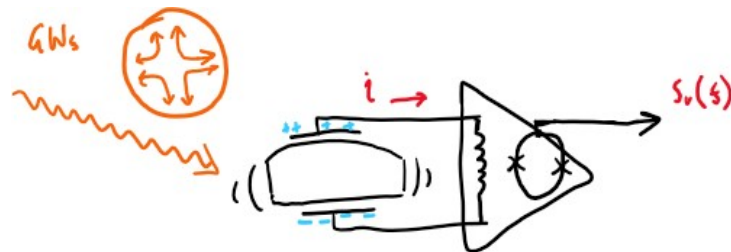
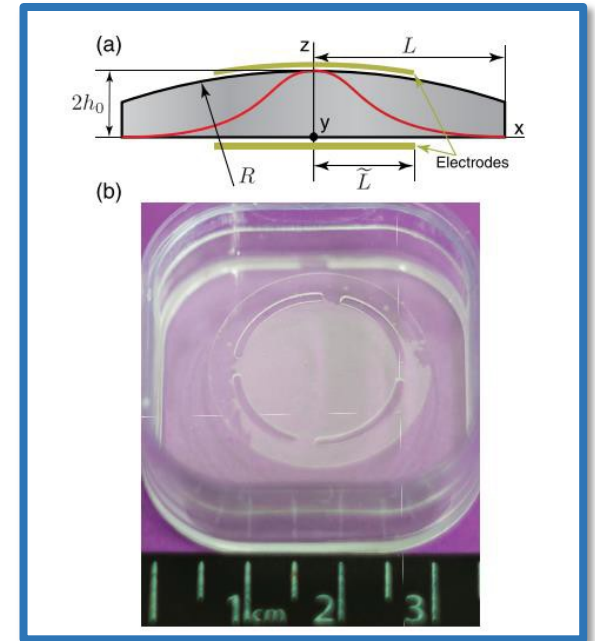
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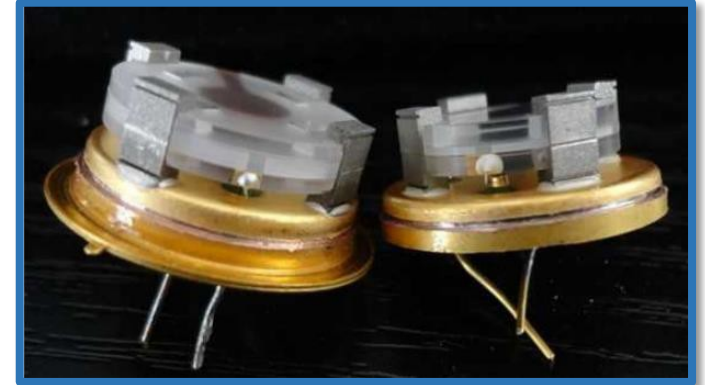
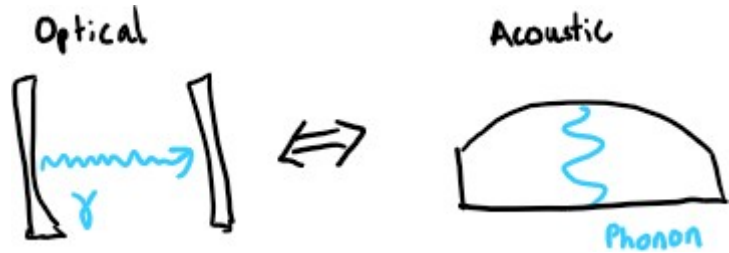
*** RESEARCH WITH ACOUSTIC RESONATORS @ UWA**

*** Search for High frequency GWs**



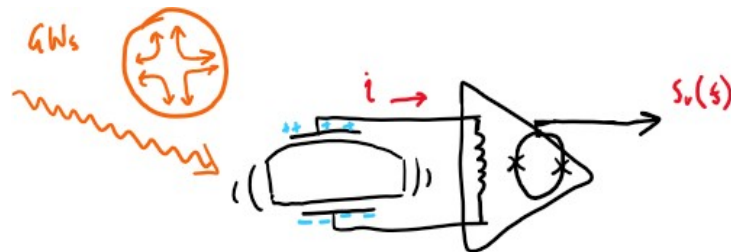
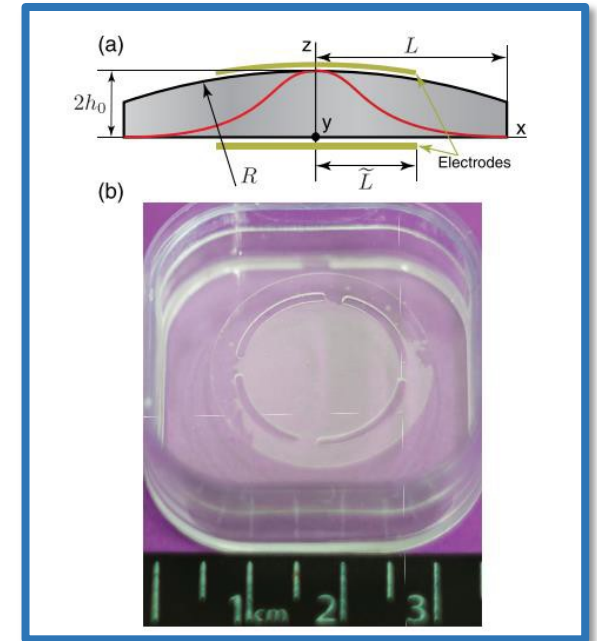
Quartz Bulk Acoustic Wave Resonators

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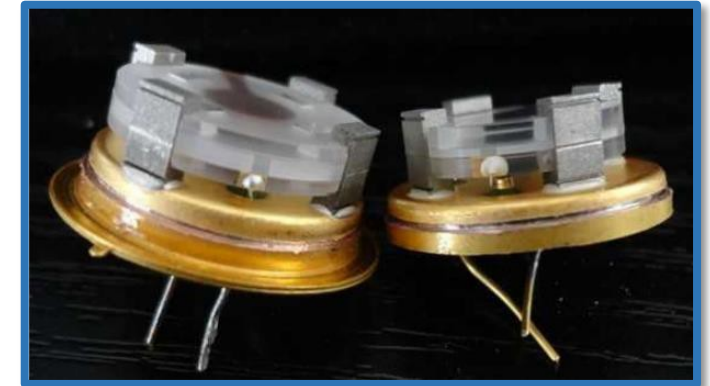
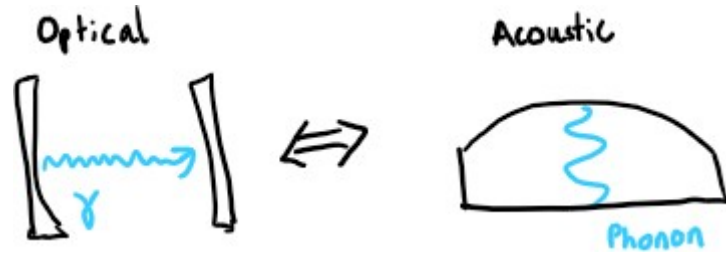
* RESEARCH WITH ACOUSTIC RESONATORS @ UWA

- * Search for High frequency GWs
- * Detection of a Graviton



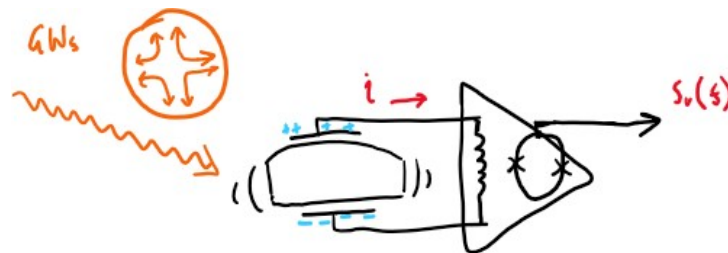
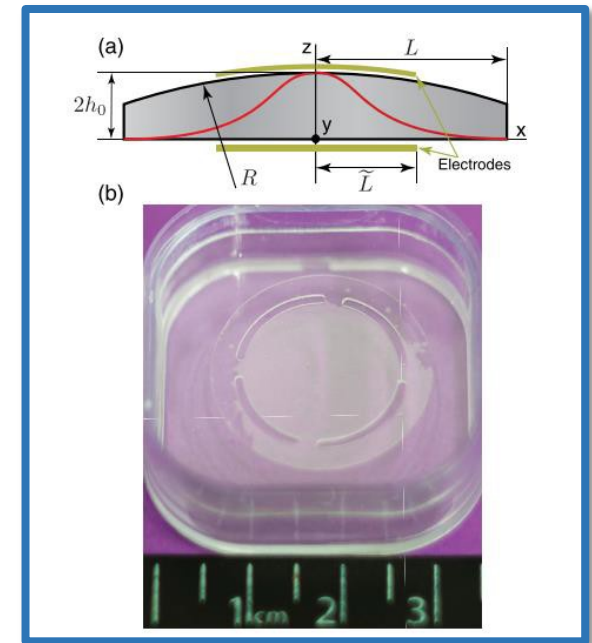
Quartz Bulk Acoustic Wave Resonators

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



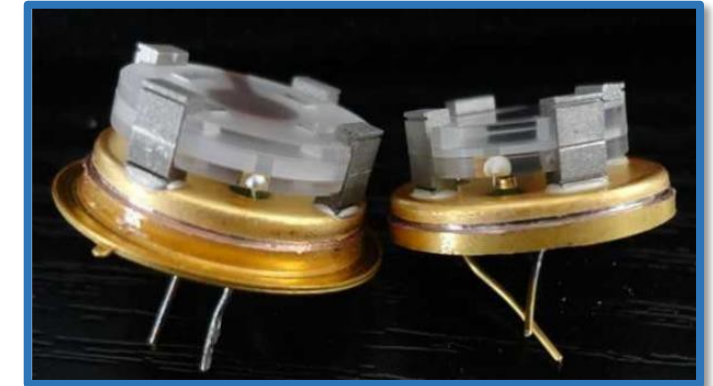
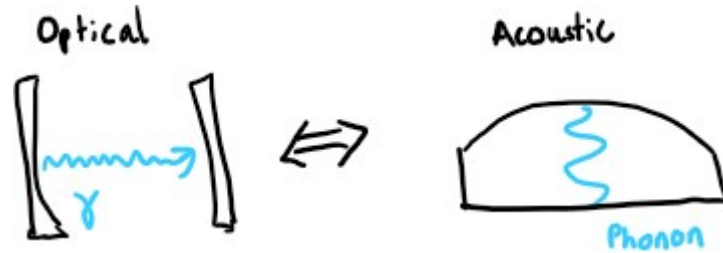
* RESEARCH WITH ACOUSTIC RESONATORS @ UWA

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- * Detection of a Graviton
- * Search for Scalar DM:



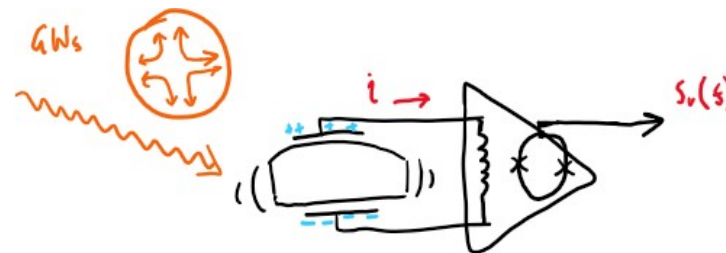
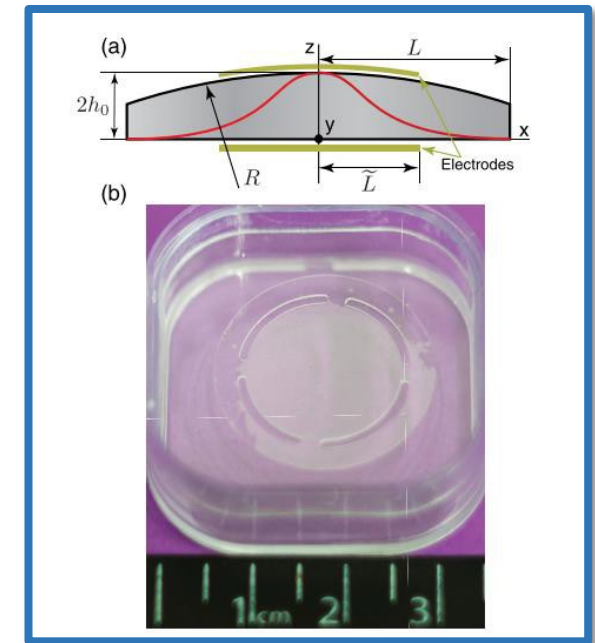
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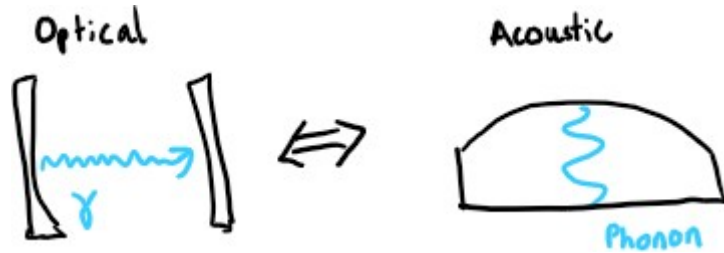
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- * Search for Scalar DM:
- * Search for Lorentz invariance violations



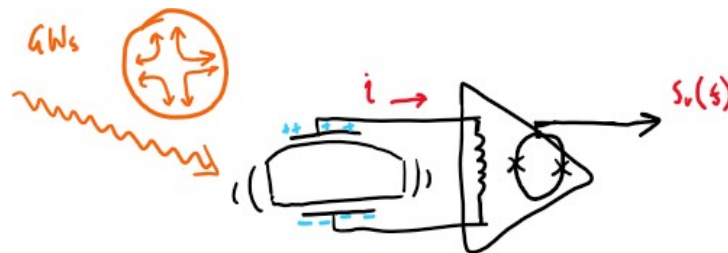
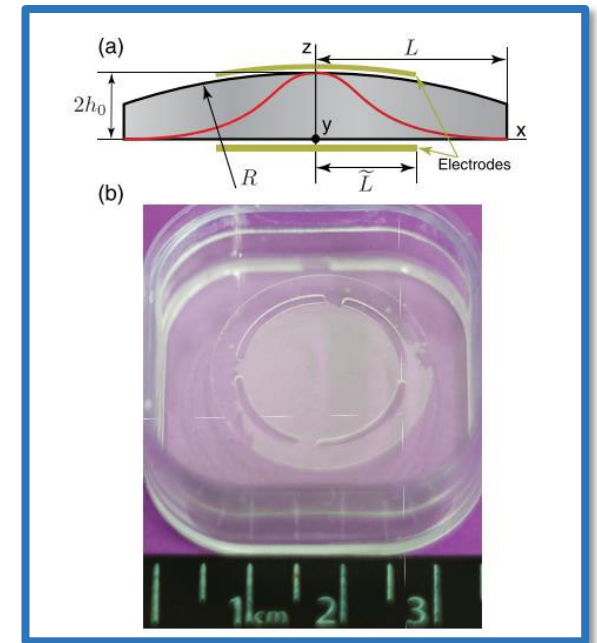
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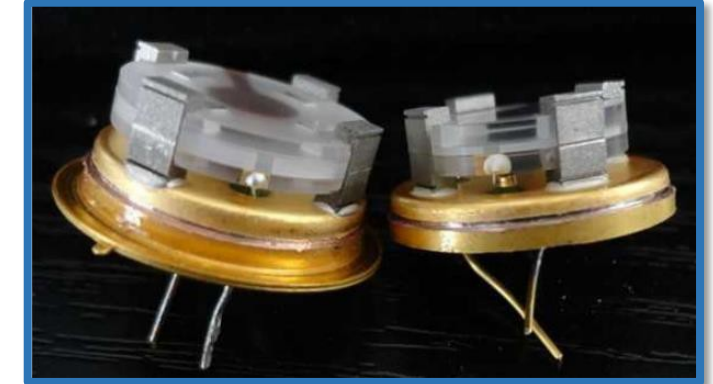
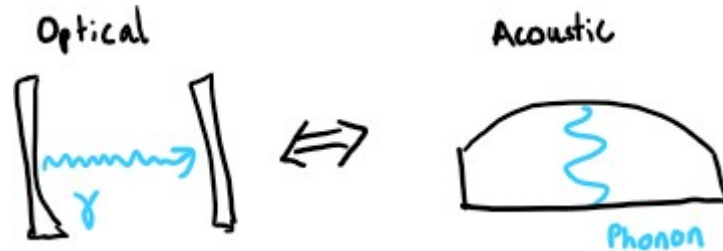
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- * Tests of Quantum Gravity



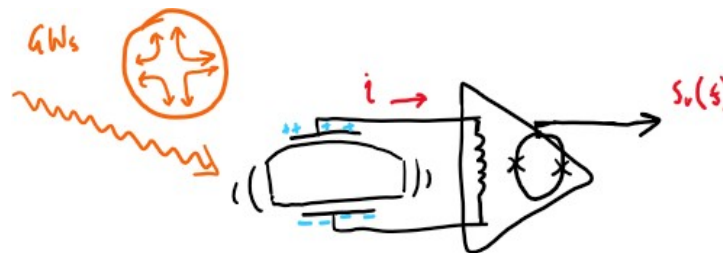
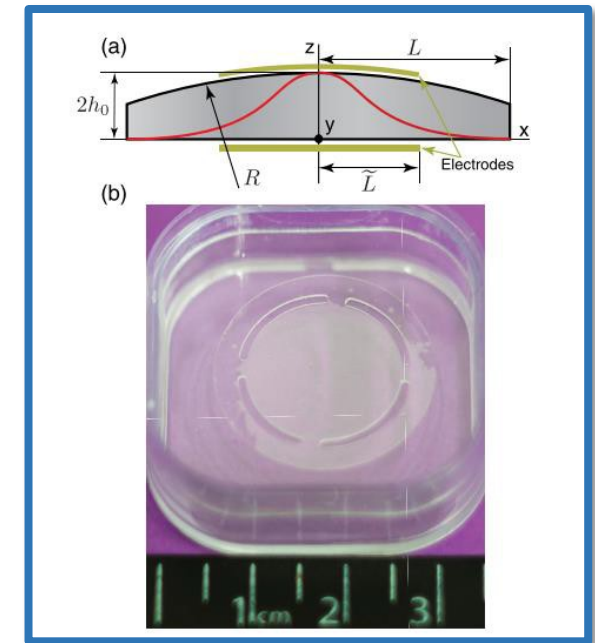
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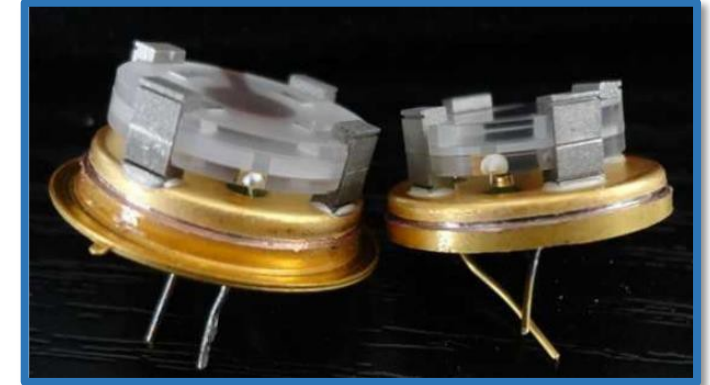
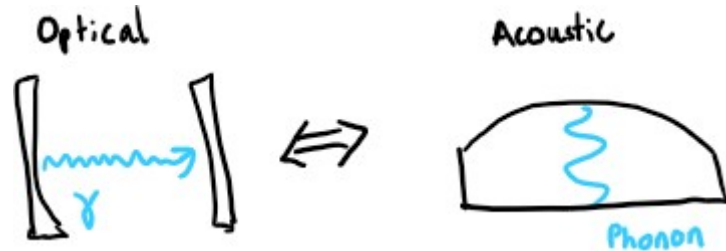
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- * Tests of Quantum Gravity
 - * Improved constraints on minimum length models or Generalized Uncertainty Principle (GUP)



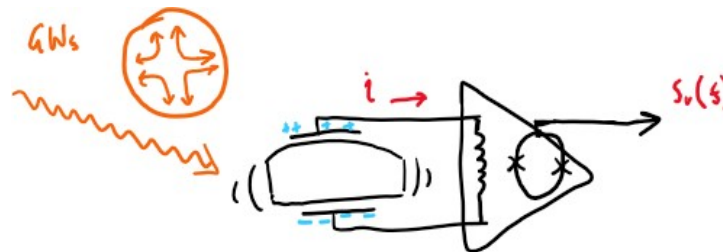
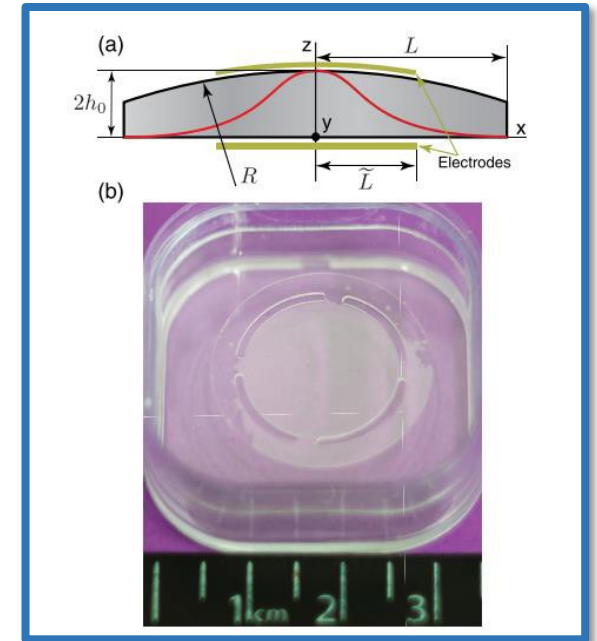
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 - * Test Collapse Models



Quartz BAW coupled to a DC SQUID amplifier

Highly sensitive resonant mass antenna

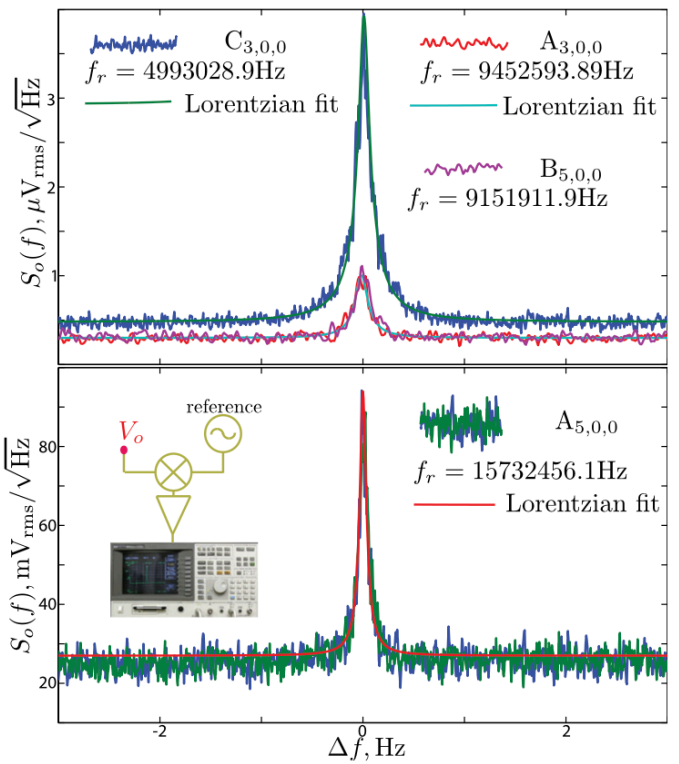
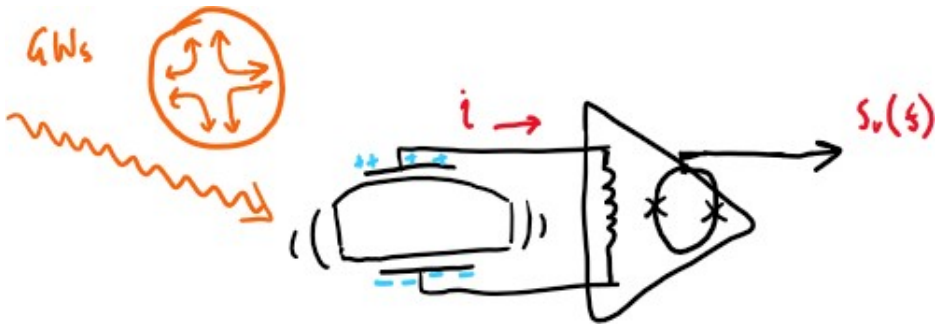
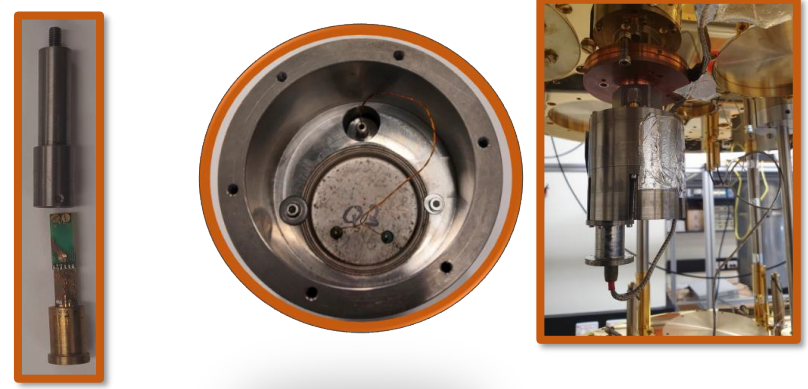
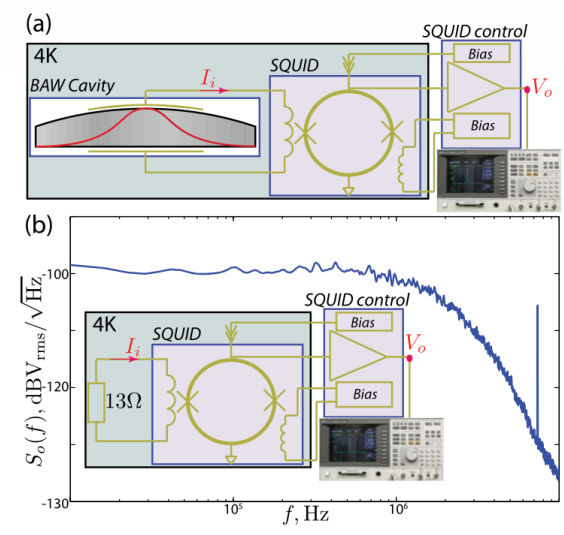


FIG. 2. Results of noise measurements for $C_{3,0,0}$, $A_{3,0,0}$, $B_{5,0,0}$, and $A_{5,0,0}$. The latter is measured using the downconversion as shown in the inset.

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. Tobar¹



Large Unexplained Events

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

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

Maxim Goryachev,¹ William M. Campbell¹,¹ Ik Siong Heng²,² Serge Galliou³,³
Eugene N. Ivanov,¹ and Michael E. Tobar^{1,*}

¹ARC Centre of Excellence for Engineered Quantum Systems, ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia

²SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland G12 8QQ, United Kingdom

³Department of Time and Frequency, FEMTO-ST Institute, ENSMM, 26 Chemin de l'Épitaphe, 25000 Besançon, France



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, domain walls, WIMPs, dark matter



Recent Experiment ?153 days of observation

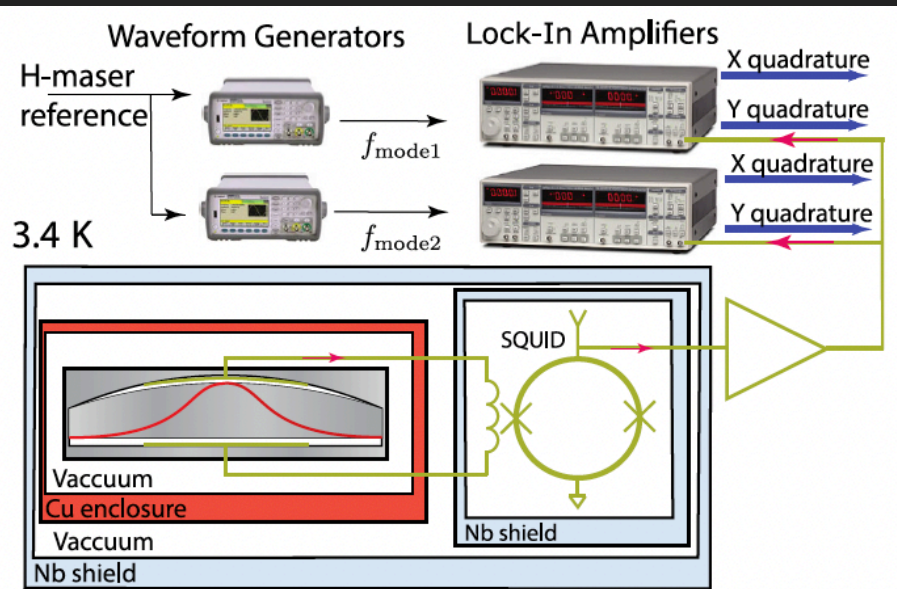


FIG. 1. Experimental setup showing BAW cavity connected to SQUID amplifier and shielding arrangement. Note that 4 and 50 K shields as well as stainless still vacuum chamber not shown.

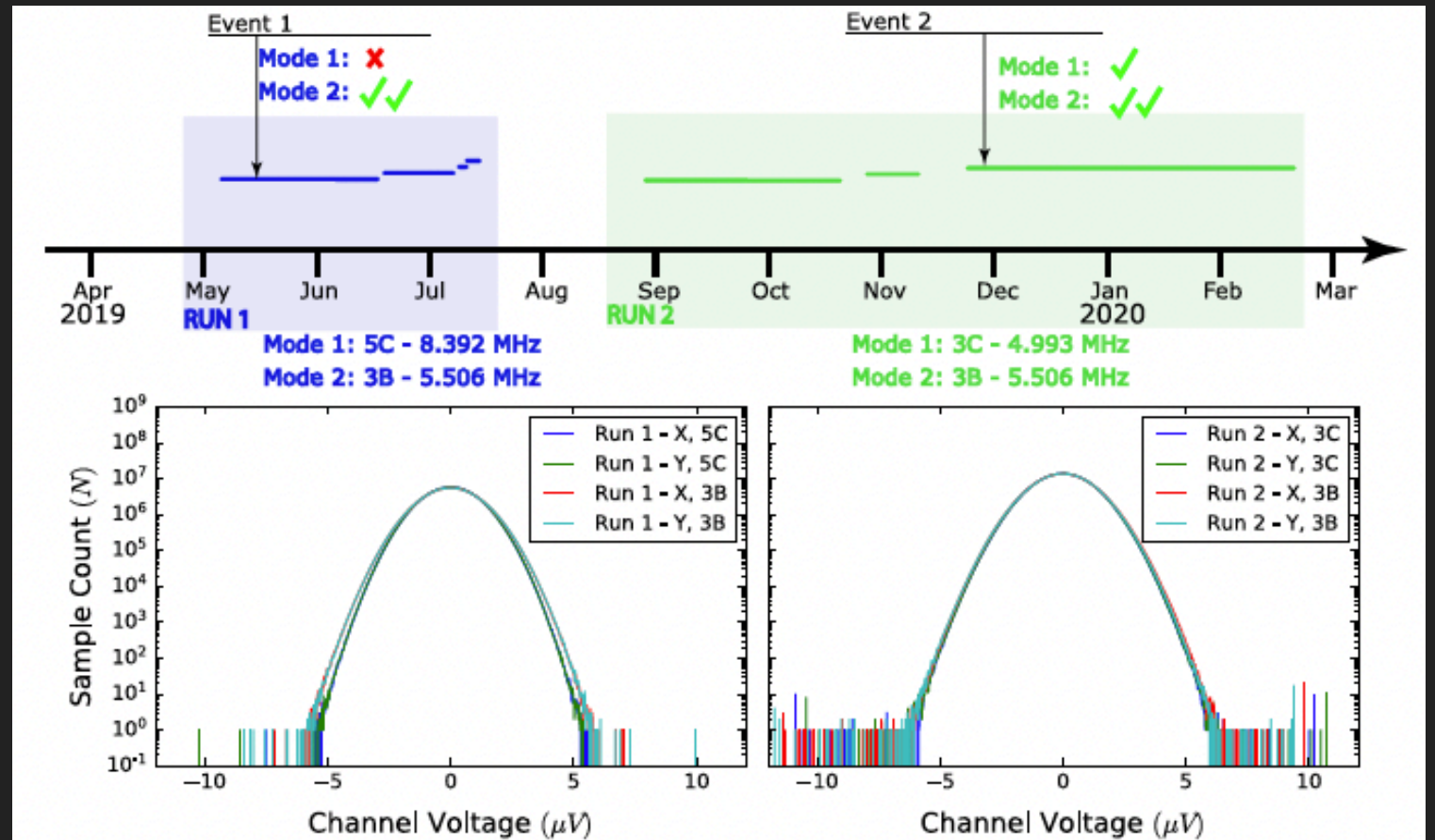


FIG. 2. Timeline of described experiment as well as histogram of total data collection at the detector output. Blue and green lines on timeline show separate data acquisition periods for two runs. Arrows point to the dates of two observed events.

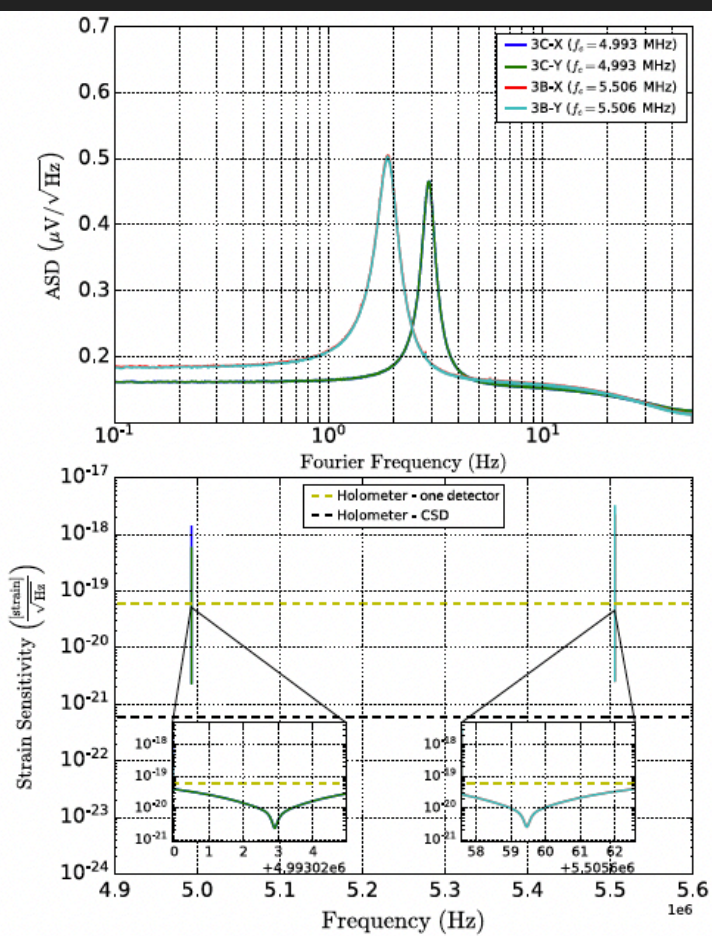


FIG. 3. Top figure displays averaged amplitude spectral density (ASD) of each output channel of lock-ins for longest continuous data taking run; here, each mode has been demodulated from the carrier. Bottom figure shows corresponding spectral strain sensitivity determined for each trace, as well as current best sensitivity in region given by Holometer experiment [6], which uses the cross spectral density (CSD) of two identical interferometers to search for HFGWs.

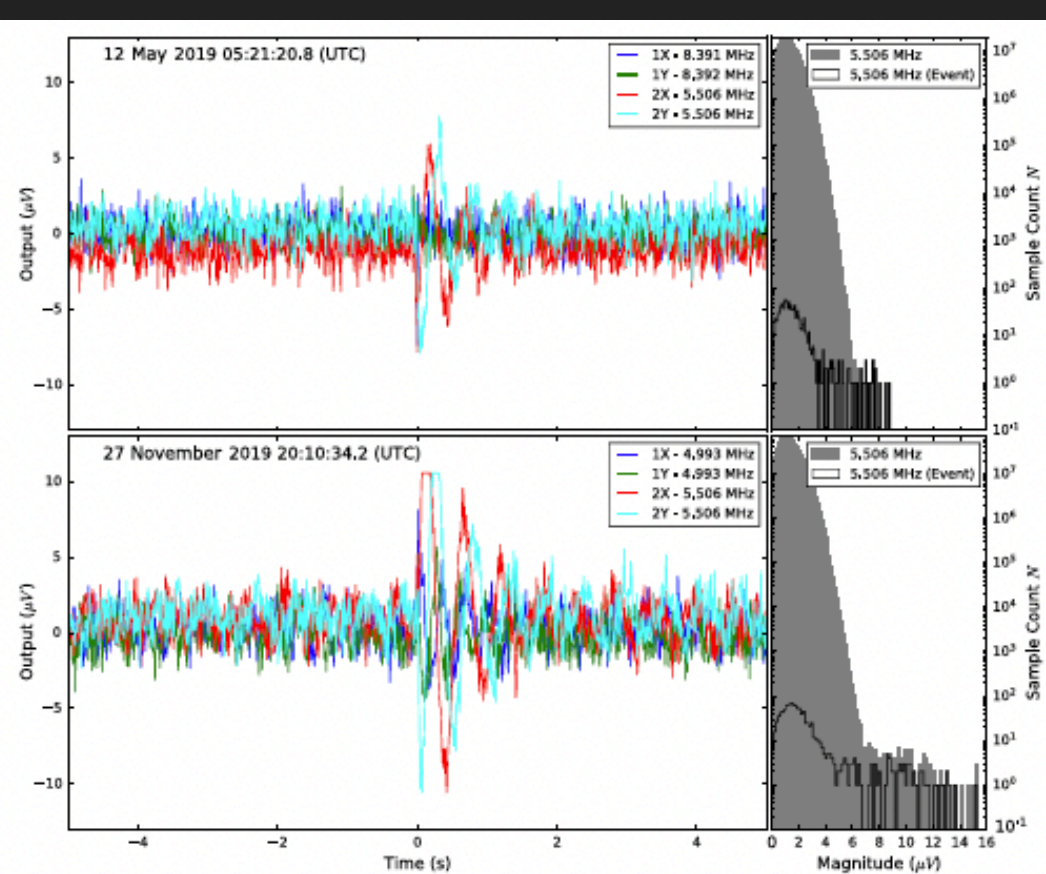
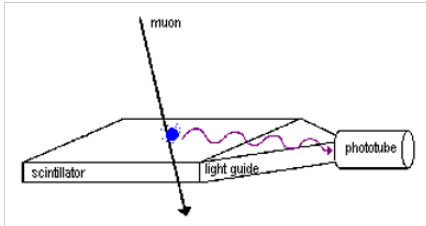
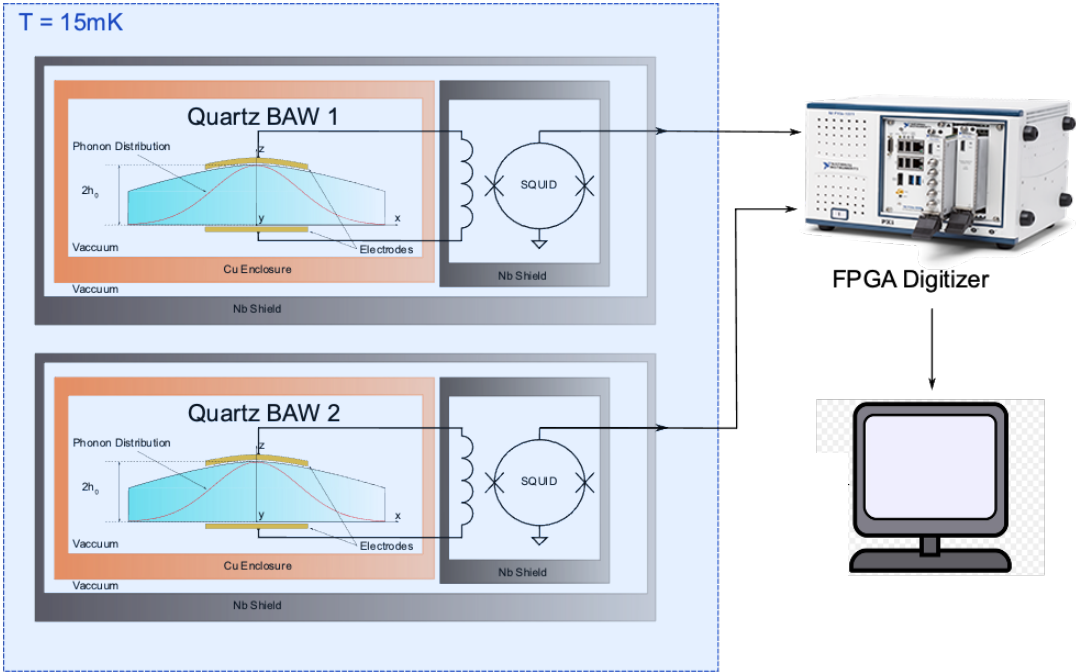


FIG. 4. Time series traces for two event signals detected by system. Each plot shows two quadratures for each mode. Also shown are histograms of output magnitude samples from only the 3B mode from both the entire corresponding run (gray) and just 10 s of data around the event (black). It is clear from this plot that the overwhelming majority of non-Gaussian outliers is due to these signals.

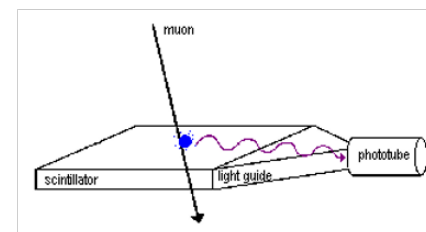
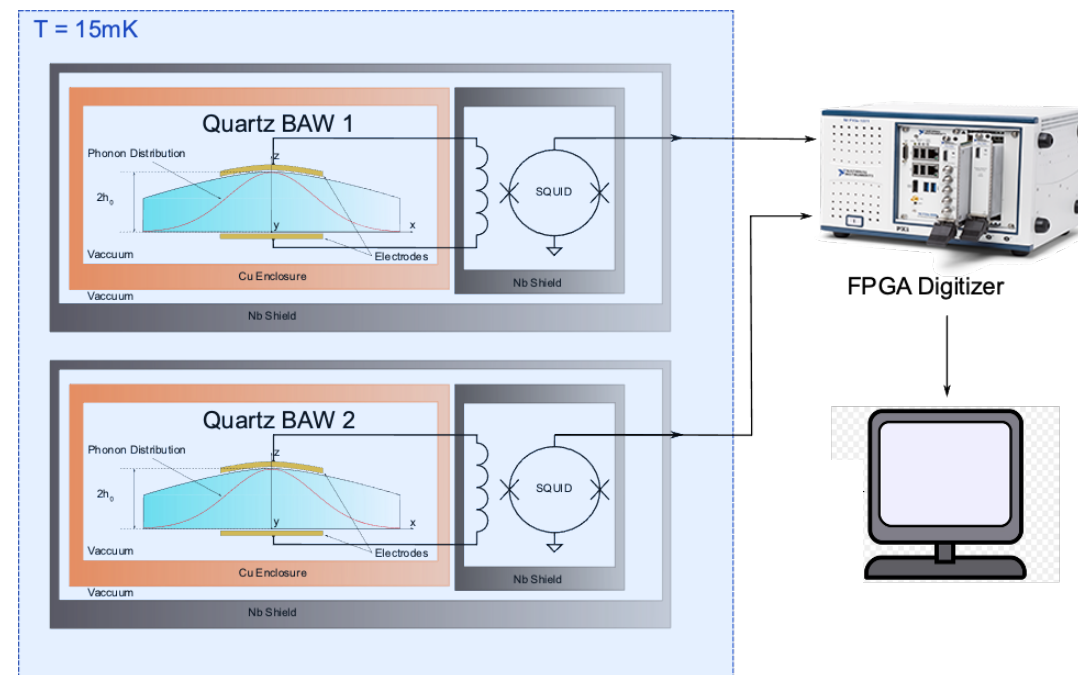
$$H(i\omega) = \frac{\kappa_{\lambda}^2 \omega_{\lambda}^2 Z_{\text{SQUID}}^2 (-\omega^2/2) h_0 \xi}{(i\omega)^2 + \tau_{\lambda}^{-1} i\omega + \omega_{\lambda}^2}$$

Introducing: the Multimode Acoustic Gravitational wave Experiment (MAGE)



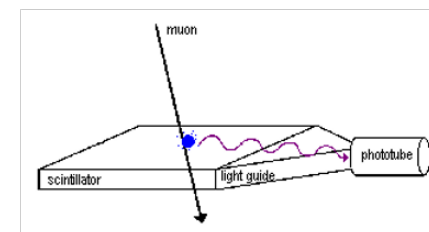
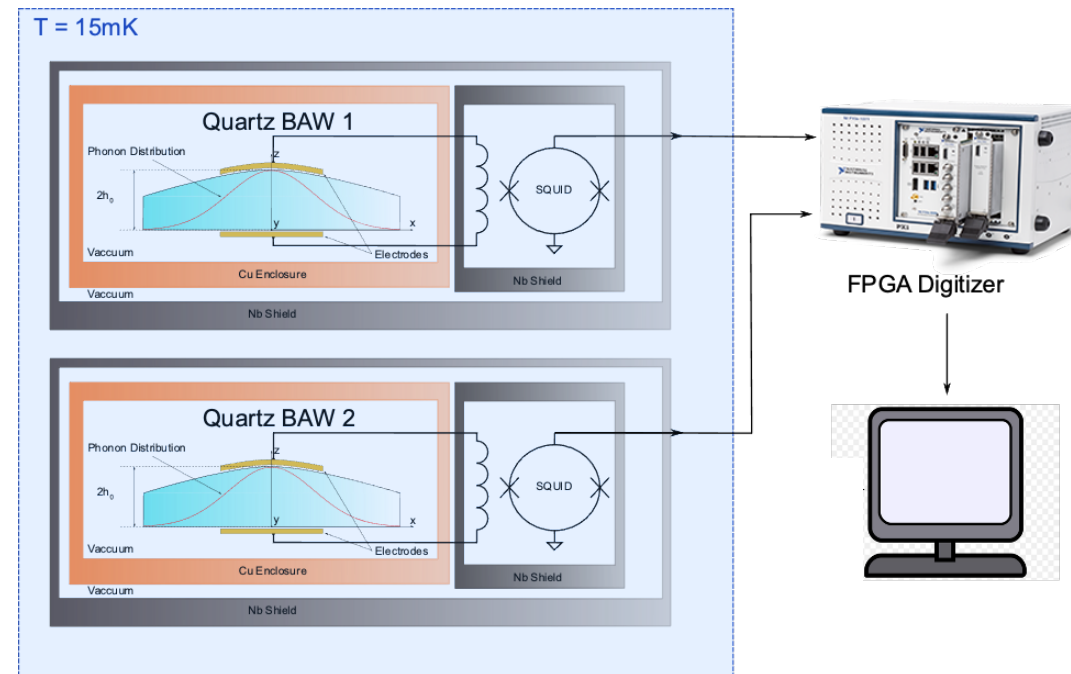
Muon / Cosmic Particle Veto Detector

Introducing: the Multimode Acoustic Gravitational wave Experiment (MAGE)



Muon / Cosmic Particle Veto Detector

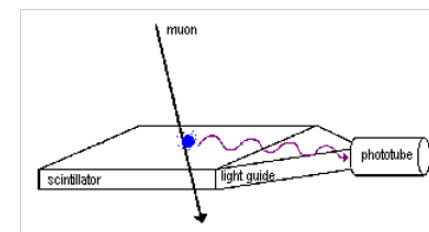
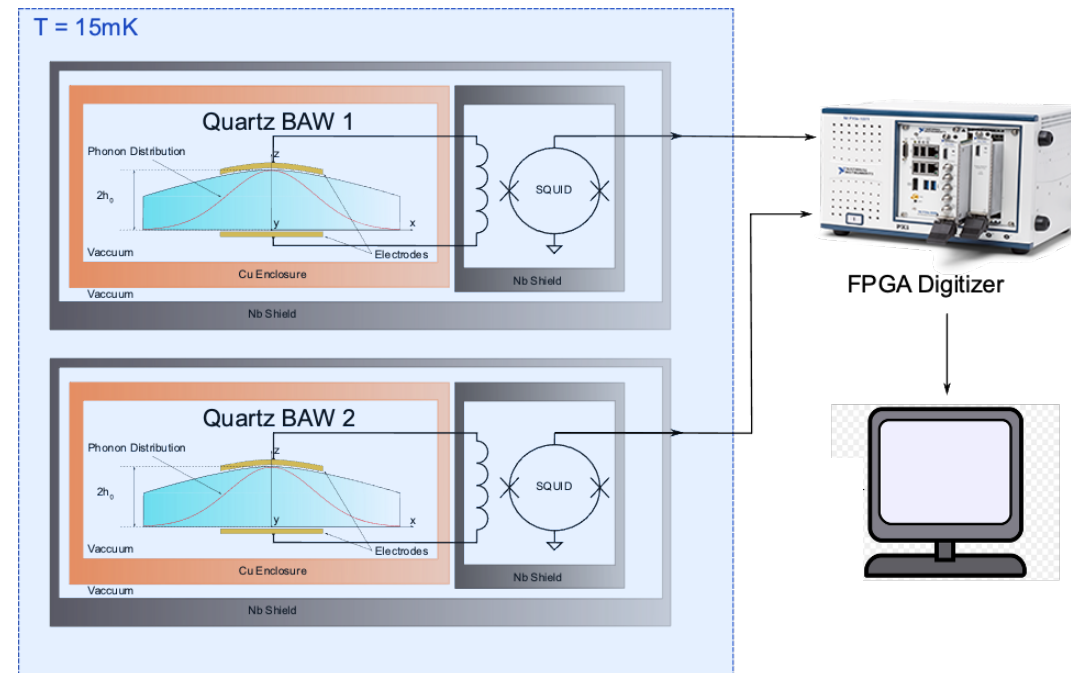
Introducing: the Multimode Acoustic Gravitational wave Experiment (MAGE)



Muon / Cosmic Particle Veto Detector

- MAGE main goals / features:

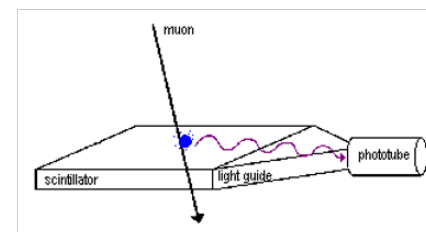
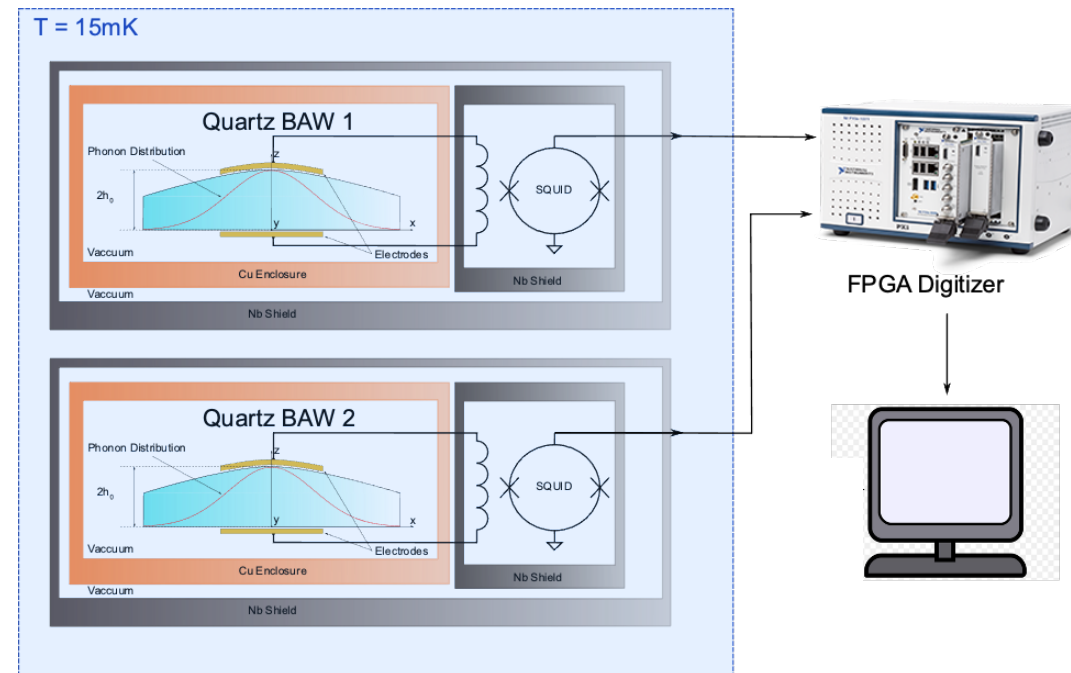
Introducing: the Multimode Acoustic Gravitational wave Experiment (MAGE)



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- Two identical quartz BAW detectors, maybe more? (funding application)

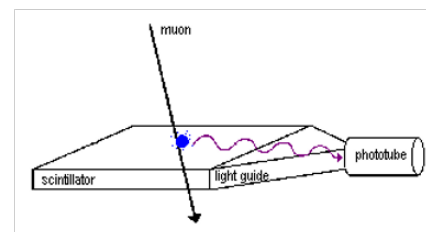
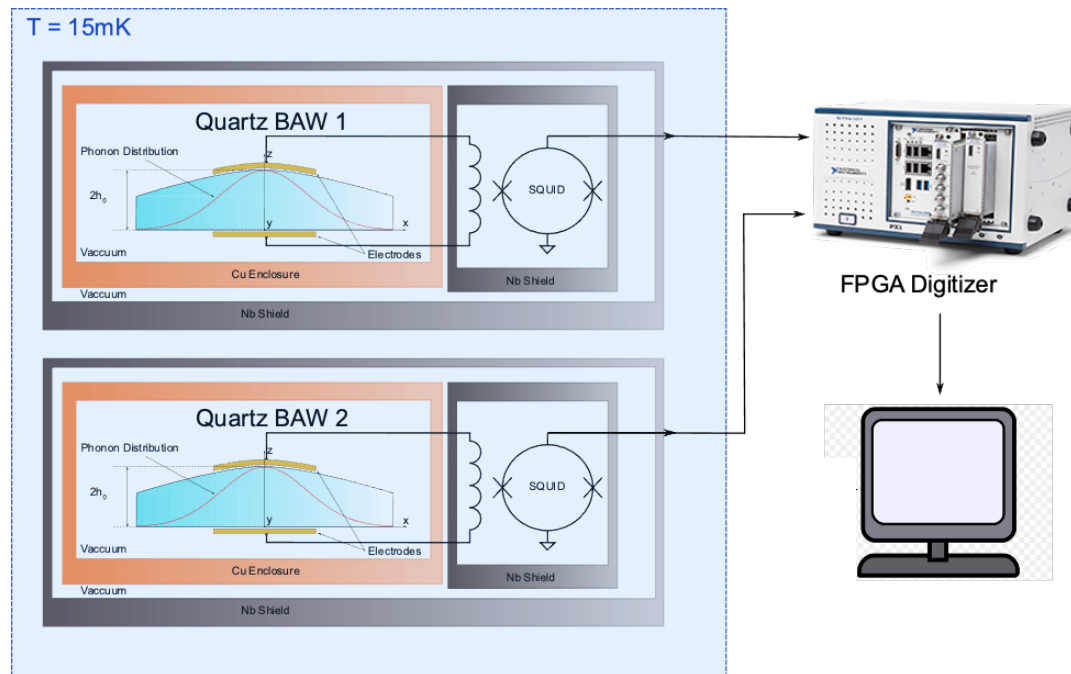
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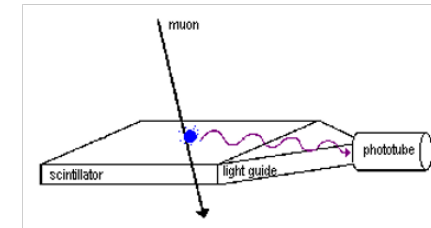
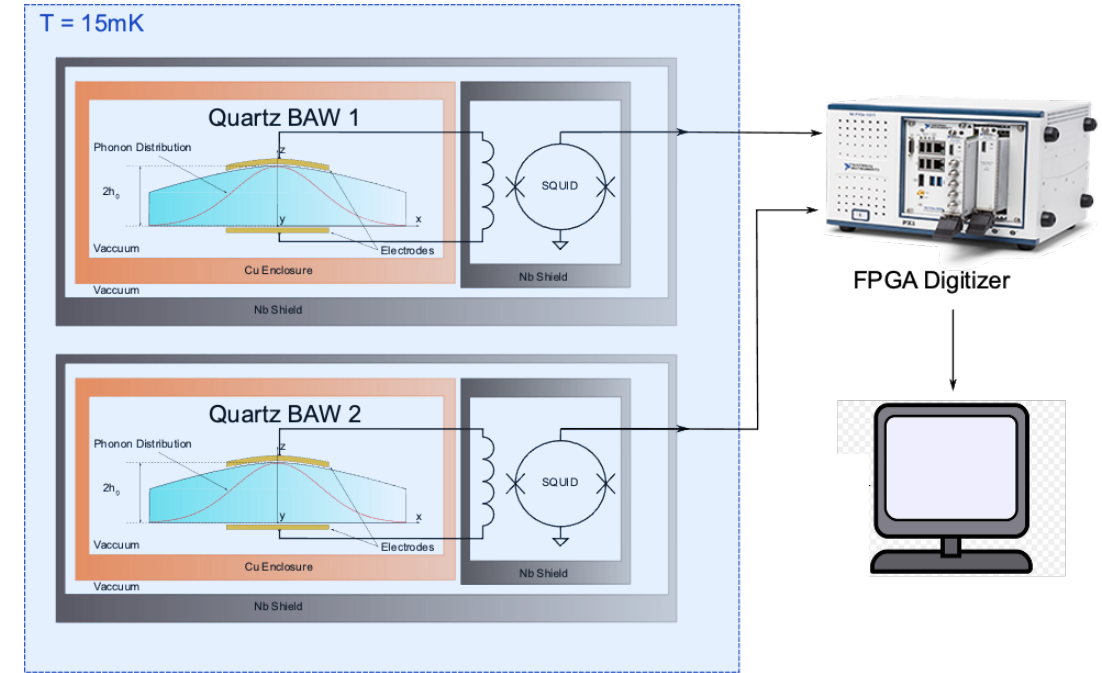
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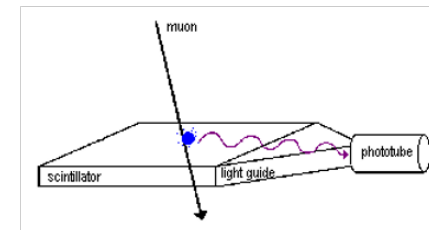
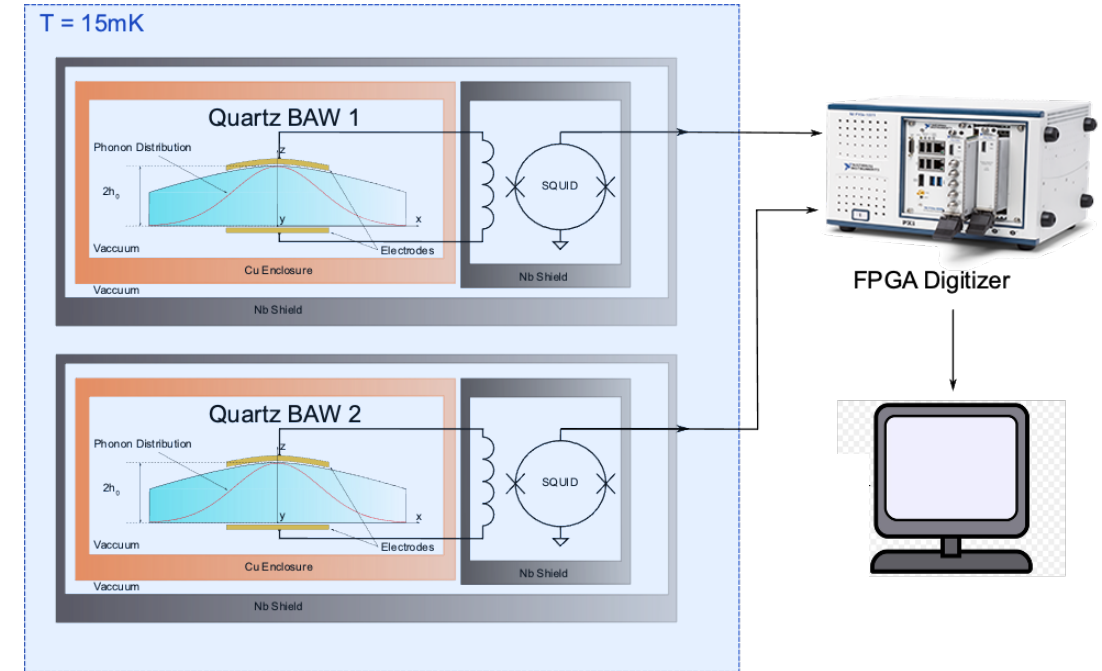
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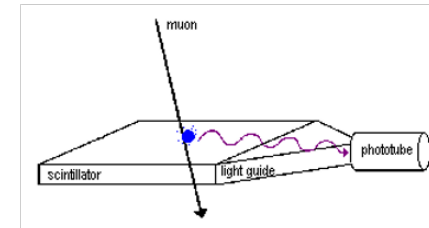
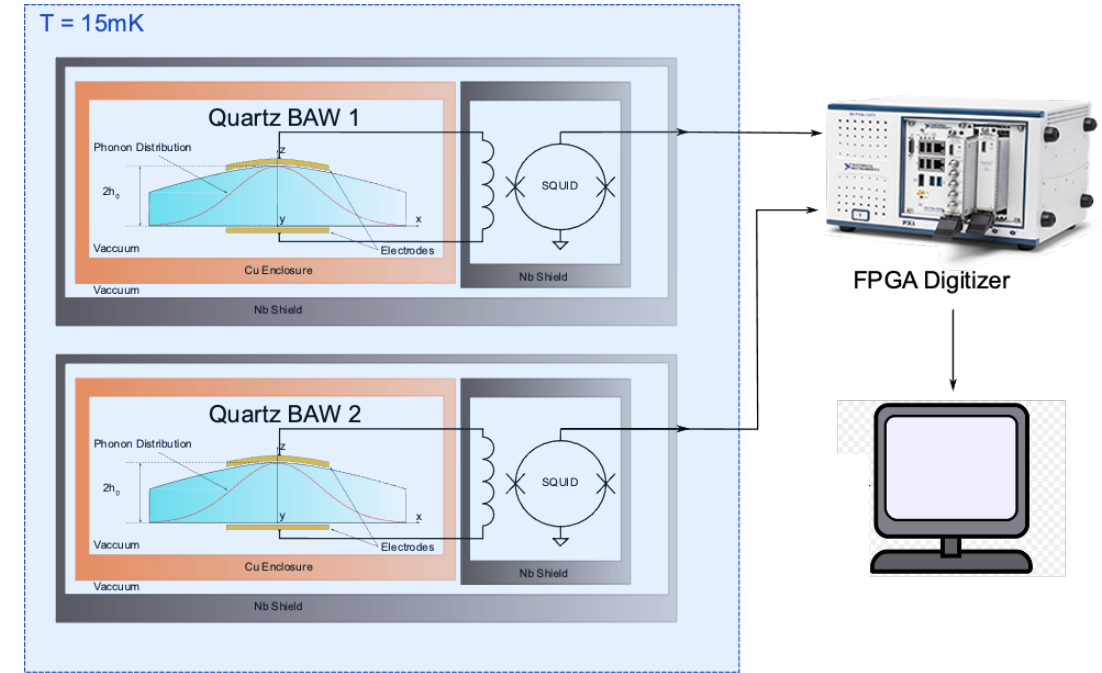
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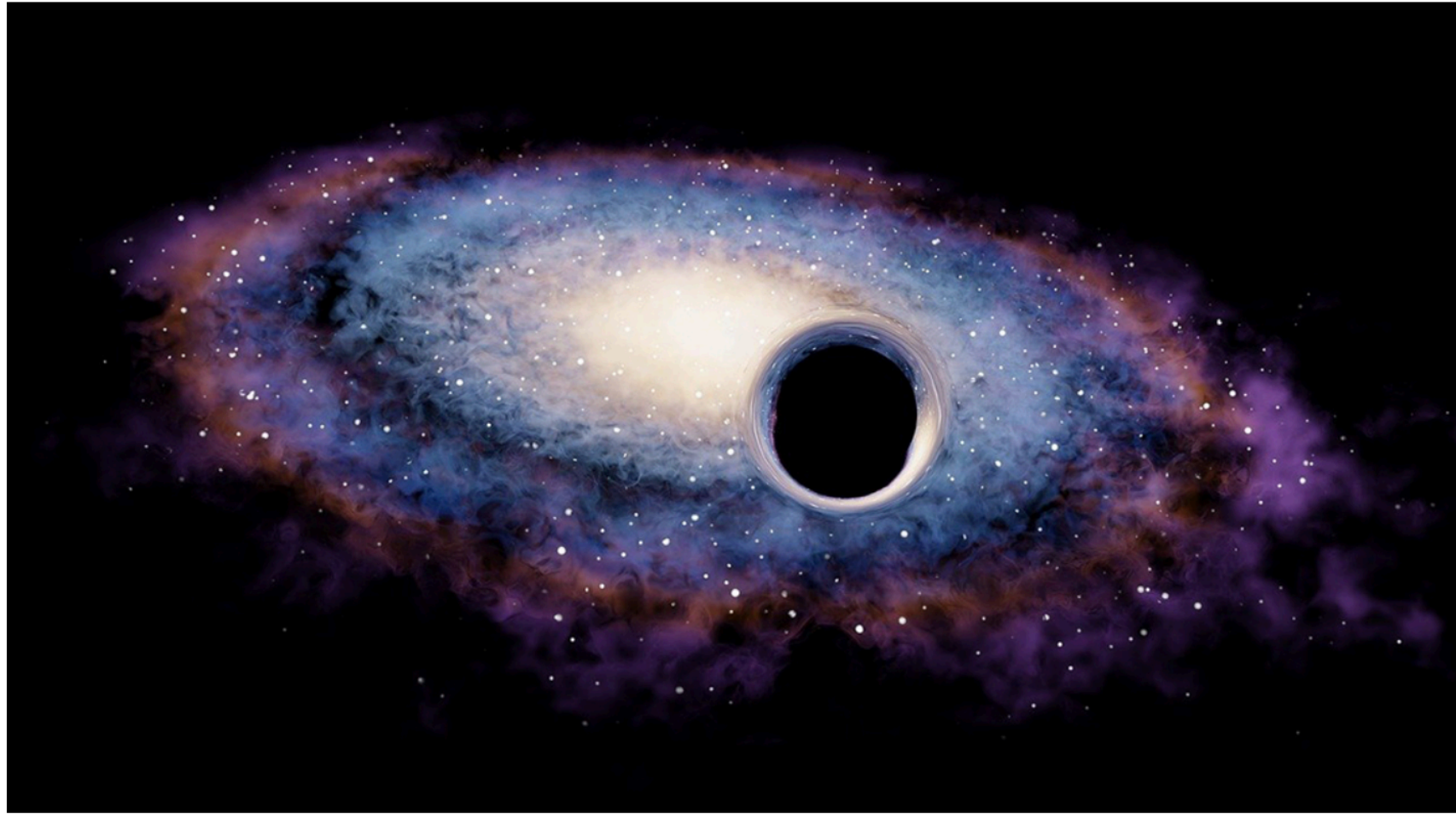
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- Wider bandwidth SQUID; 5 – 200 MHz +
- Cosmic particle veto system. Potentially cryogenic ?
- Sub-Kelvin operation -> quantum limited, higher Qs, Quantum Metrology

Dark matter could be composed of primordial black holes

by Andrey Feldman | Jan 18, 2022

A new theory for the origin and nature of dark matter resolves some inconsistencies between cosmological predictions and astronomical data.



- Sub-solar mass black hole binary systems are yet to be confirmed
- Production mechanism for sub-solar mass black holes confines them to be of primordial origin

MAGE

Excluding PBH Binaries



Experimental Limits on Planetary Mass Primordial Black Hole Mergers

William M. Campbell^{1,*}, Leonardo Mariani², Michael E. Tobar¹, and Maxim Goryachev¹

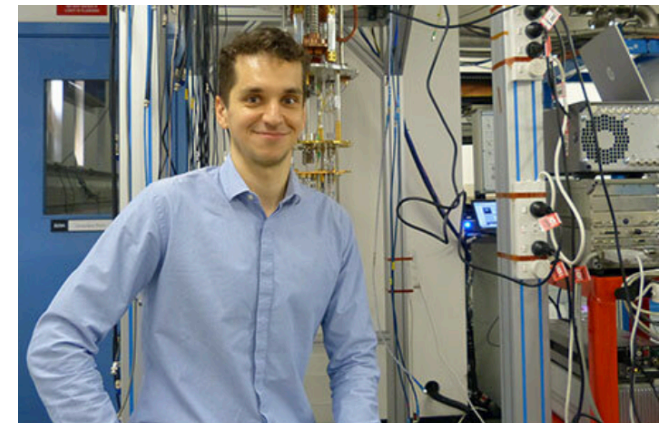
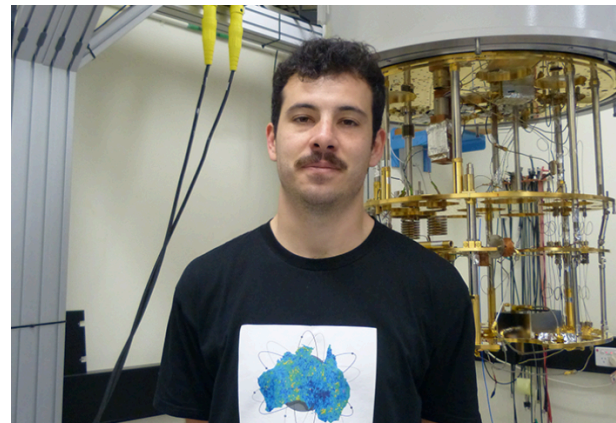
¹*Quantum Technologies and Dark Matter Labs, Department of Physics,
University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*

²*Department of Physics "Giuseppe Occhialini," University of Milano-Bicocca,
Piazza dell'Ateneo Nuovo, 1 - 20126, Milan (Mi), Italy*

(Received 4 June 2025; revised 29 July 2025; accepted 8 December 2025; published 19 December 2025)

The multimode acoustic gravitational wave experiment (MAGE) is a high-frequency gravitational wave detection experiment featuring cryogenic quartz bulk acoustic wave resonators operating as sensitive strain antennas in the MHz regime. After 61 days of noncontinuous data collection, we present bounds on the observable merger rate density of primordial black hole binary systems of chirp mass $1.2 \times 10^{-4} M_{\odot} < \mathcal{M} < 1.7 \times 10^{-9} M_{\odot}$. The maximum achieved limit on the merger rate density is $\mathcal{R} < 1.3 \times 10^{18} \text{ kpc}^{-3} \text{ yr}^{-1}$, which corresponds to constraining yearly mergers to a distance of reach on the order of the Solar System, or $1.0 \times 10^{-6} \text{ kpc}$ during the observational period. In addition, we exclude significantly rare and strong events similar to those observed in previous predecessor experiments as nongravitational background signals, utilising coincident analysis between multiple detectors.

PHYSICAL REVIEW LETTERS 135, 251402 (2025)



MAGE

Excluding PBH Binaries



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William M. Campbell^{1,*}, Leonardo Mariani², Michael E. Tobar¹, and Maxim Goryachev¹

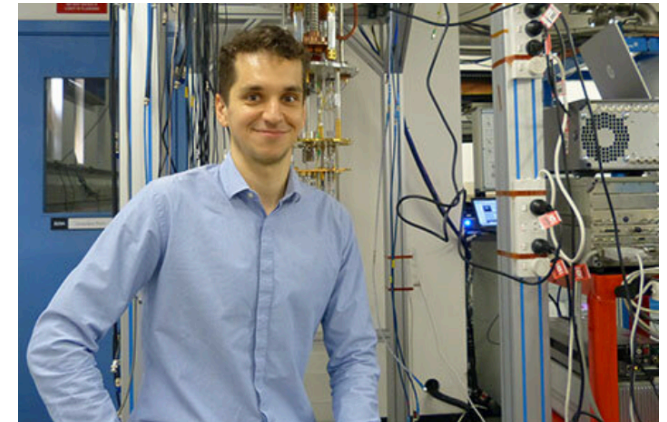
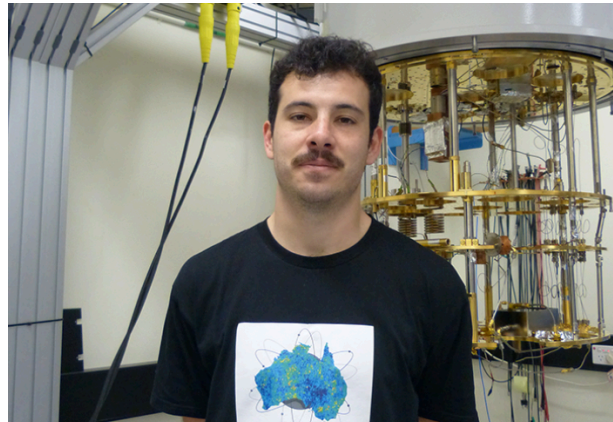
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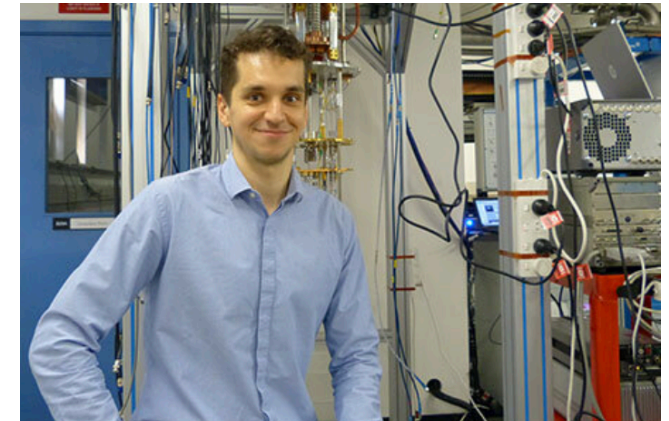
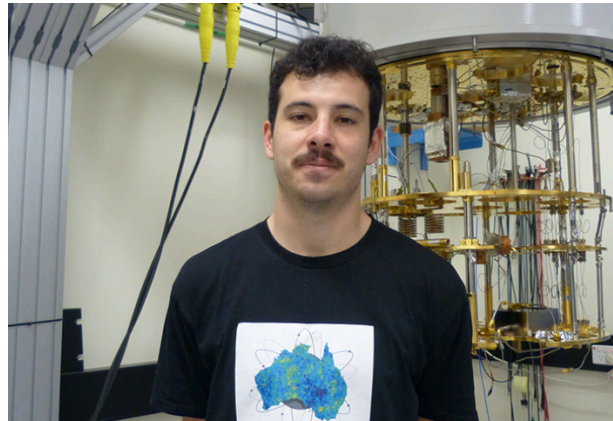
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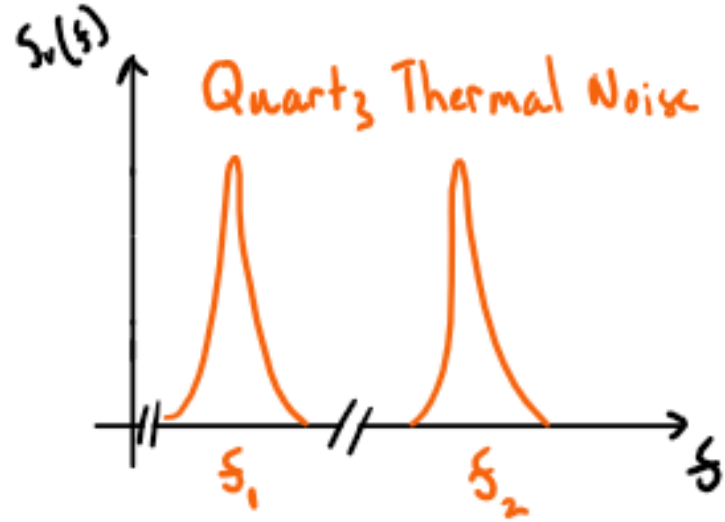
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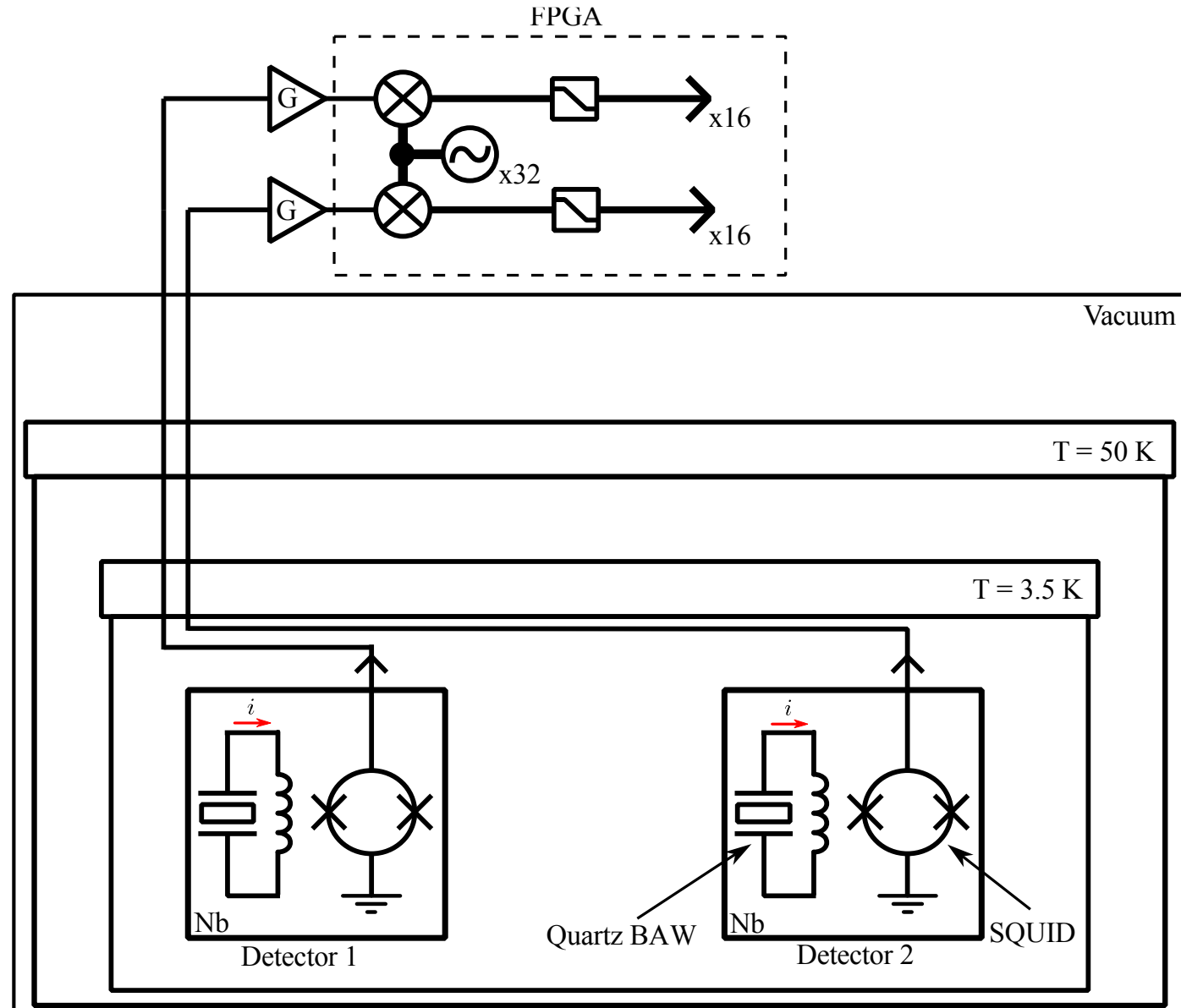


The Experiment

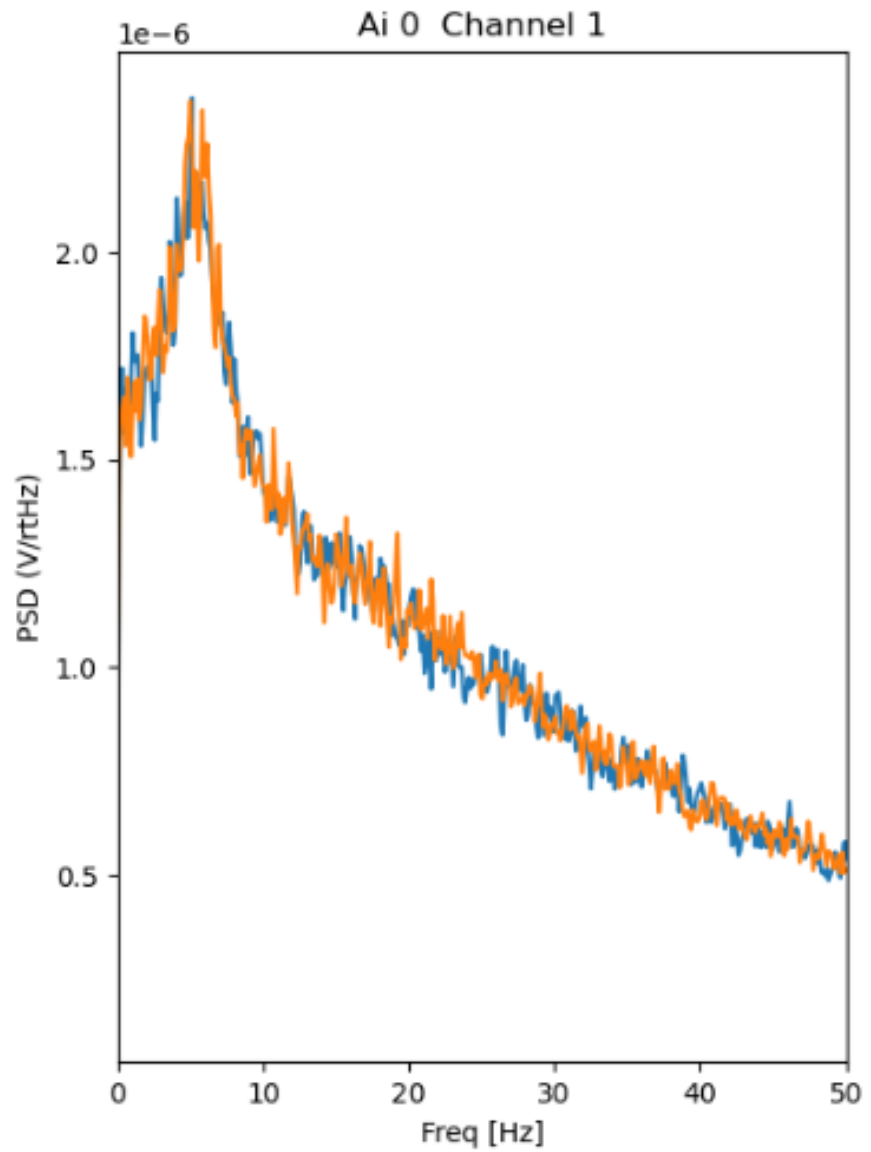
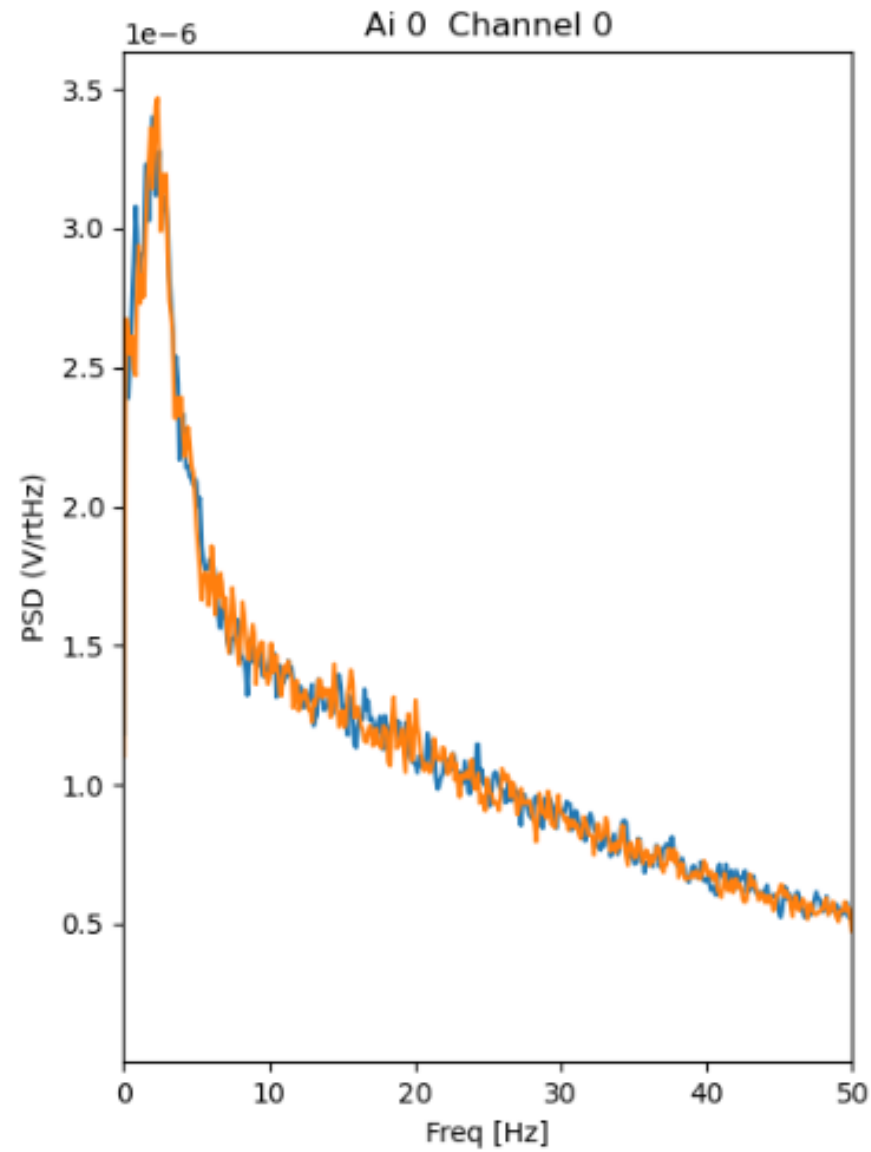


- 61 days of non-continuous data collection Nov 2024–Mar 2025
- Optimal filtering approach
- Coincident with the two MAGE detectors,
- Removes non-gravitational background signals by coincident analysis
- High energy events seen previously observed to never occur in both detectors

Complex DAQ Chain.



- Detector 1 Fourier Transforms
- Channel 0 is 4.993 MHz
- Channel 1 is 5.08 MHz



- FPGAs mimics 32 lockin-amps, Phase is time dependent and equal to 2Hz
- Sampled at a frequency of 238 Hz
- -> data streams, broken into 20×2^{14} samples segments \sim 23 minutes of data

What does the signal look like ?

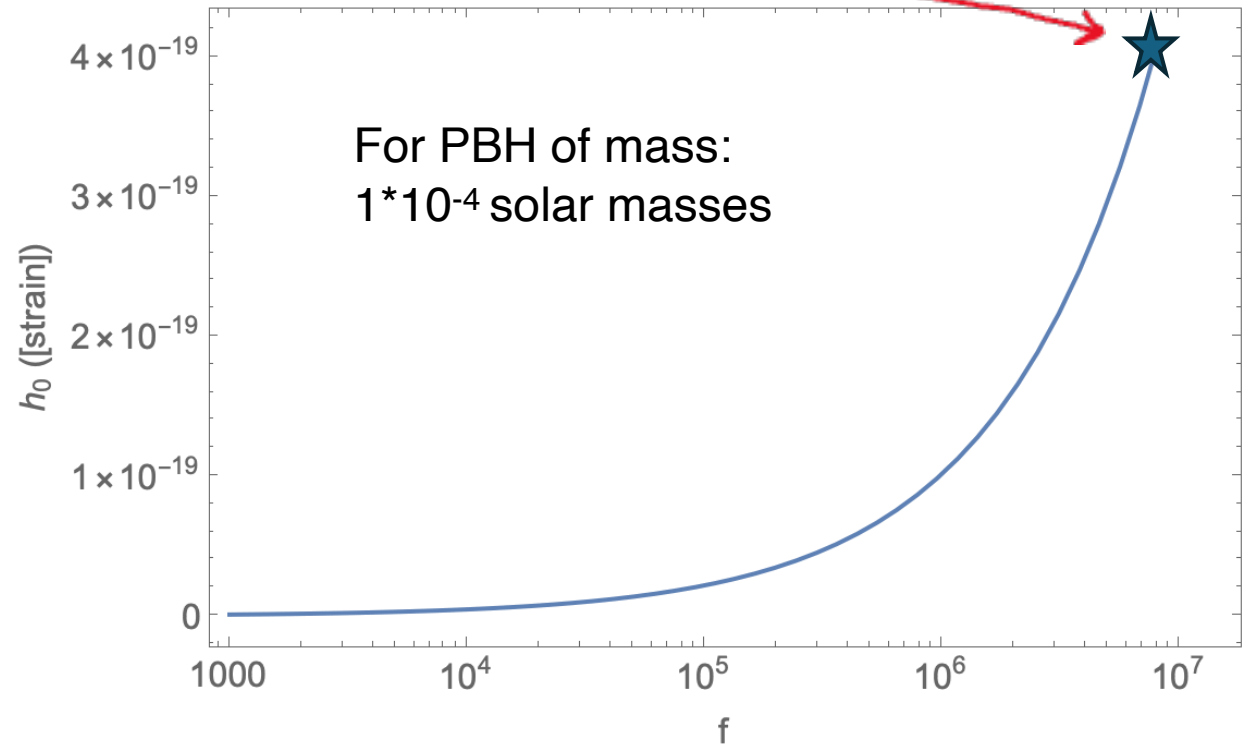
Innermost Stable Circular Orbit

PBH merger ring-up to some frequency f_{ISCO}

$$f_{\text{ISCO}} = 4400 \text{ Hz} \frac{M_{\odot}}{m_1 + m_2},$$

Produces a strain h_0 proportional to the merger mass M and distance D

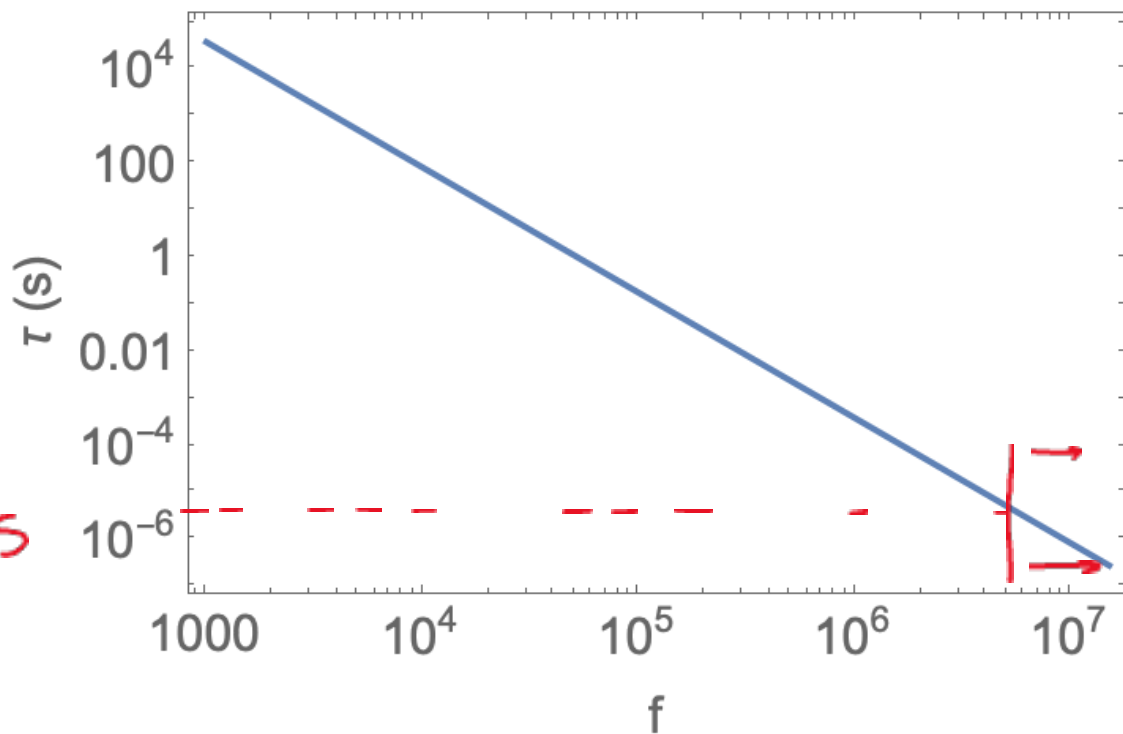
$$h_0 \approx \frac{2}{D} \left(\frac{GM}{c^2} \right)^{5/3} \left(\frac{\pi f}{c} \right)^{2/3}$$



\mathcal{M} Reduced mass of binary system

Be careful of signal duration

Time to coalescence at 15 MHz



$$N_{\text{cycles}} = \frac{f^2}{\dot{f}} \simeq 2.2 \times 10^6 \left(\frac{f}{\text{GHz}} \right)^{-5/3} \left(\frac{m_{\text{PBH}}}{10^{-9} M_{\odot}} \right)^{-5/3},$$

$$\tau(f) \approx 83 \text{ sec} \left(\frac{m_{\text{PBH}}}{10^{-12} M_{\odot}} \right)^{-5/3} \left(\frac{f}{\text{GHz}} \right)^{-8/3}$$

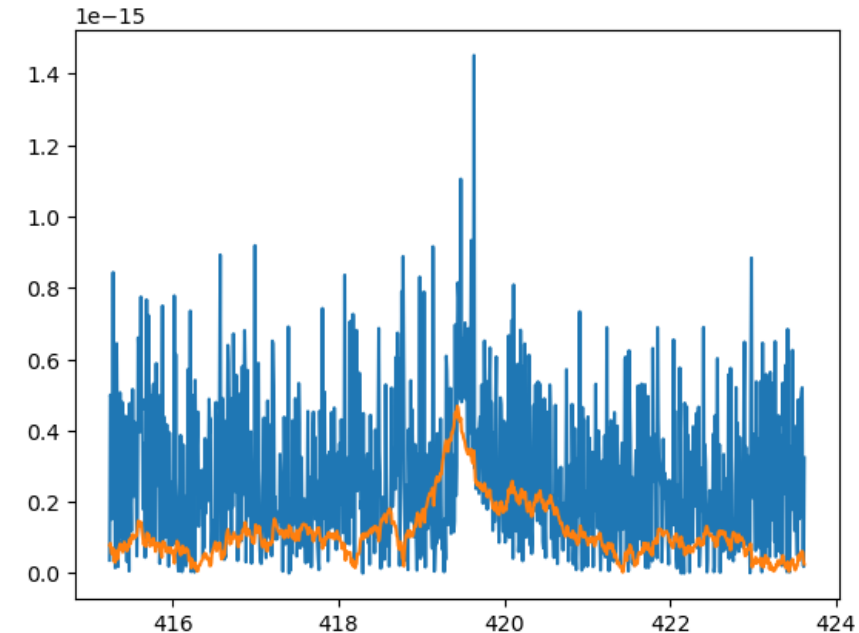
MAGE operates in narrow bands in the MHz spectrum

Signal may only pass through detector band for a VERY brief moment in time.

The expected signature of a short HFGW burst in a high-Q resonator is an **impulsive excitation followed by an exponential ringdown**

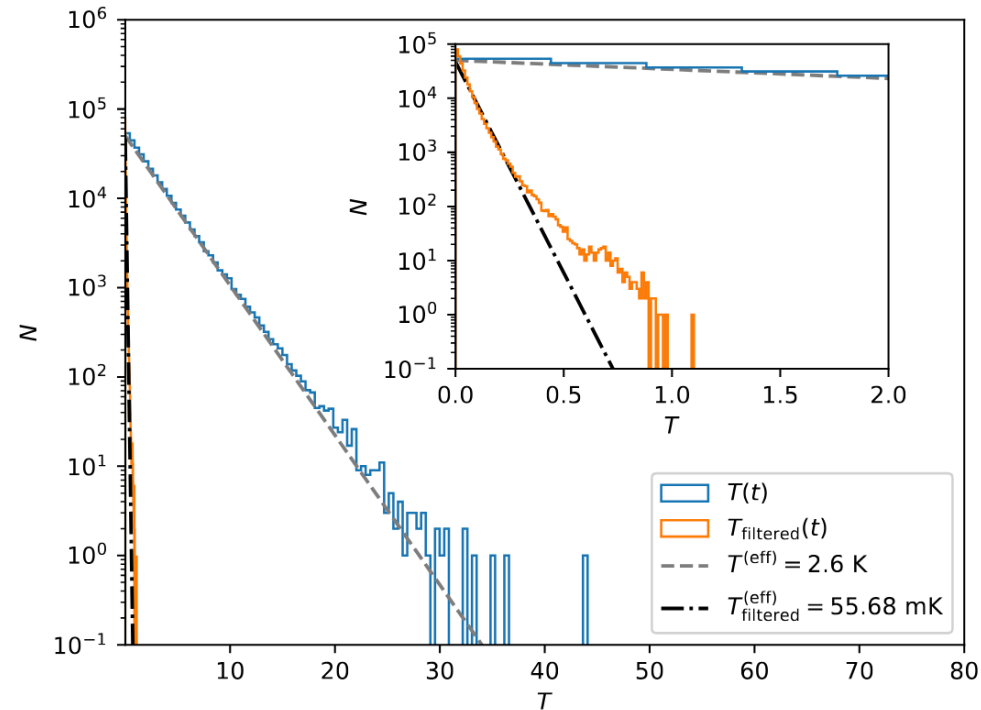
Implementing the matched filter.

```
def optimal_filter(data, template, Fs, NFFT):  
    fft = np.fft.fft(data) # fourier transformed data  
    zero_pad = np.zeros(data.size - template.size) # zero pad template to match data size  
    template_pad = np.append(template, zero_pad)  
    fft_template = np.fft.fft(template_pad) # fourier transformed padded template  
    plt.plot()  
    power_dat, freq_PSD = plt.psd(data, Fs=Fs, NFFT = NFFT, visible = True)  
    freq_dat = np.fft.fftfreq(data.size)*Fs #fourier frequencies corresponding to data partition  
    power_spec = np.interp(freq_dat, freq_PSD, power_dat)  
  
    val_cal = np.max(template)  
    OF = np.fft.ifft(fft_template*fft_template.conjugate()/power_spec).real  
    K = val_cal/np.amax(OF)  
  
    df = np.abs(freq_dat[1] - freq_dat[2])  
    opt_filter = K * fft * fft_template.conjugate() / power_spec #optimal filter  
    dat_filt = np.fft.ifft(opt_filter) #revert to time domain for filter output  
  
    sigmasq = 2*(K**2 * fft_template * fft_template.conjugate() / power_spec).sum() * df  
    sigma = np.sqrt(np.abs(sigmasq))  
    SNR = np.abs(2*dat_filt) / (sigma)  
    return SNR, dat_filt
```



```
signal = 5e-16*np.exp(-t_sig/(tau1))  
template = np.exp(-t_sig/(tau1))  
zero_pad = np.zeros(h.size - signal.size) # zero pad template to match data size  
template_pad = np.roll(np.append(signal, zero_pad),50000)  
  
h_inject = template_pad + np.abs(np.random.normal(0, 1.66*np.std(h), size = len(h)))  
h_inject2 = np.abs(np.random.normal(0, 1.66*np.std(h), size = len(h)))
```

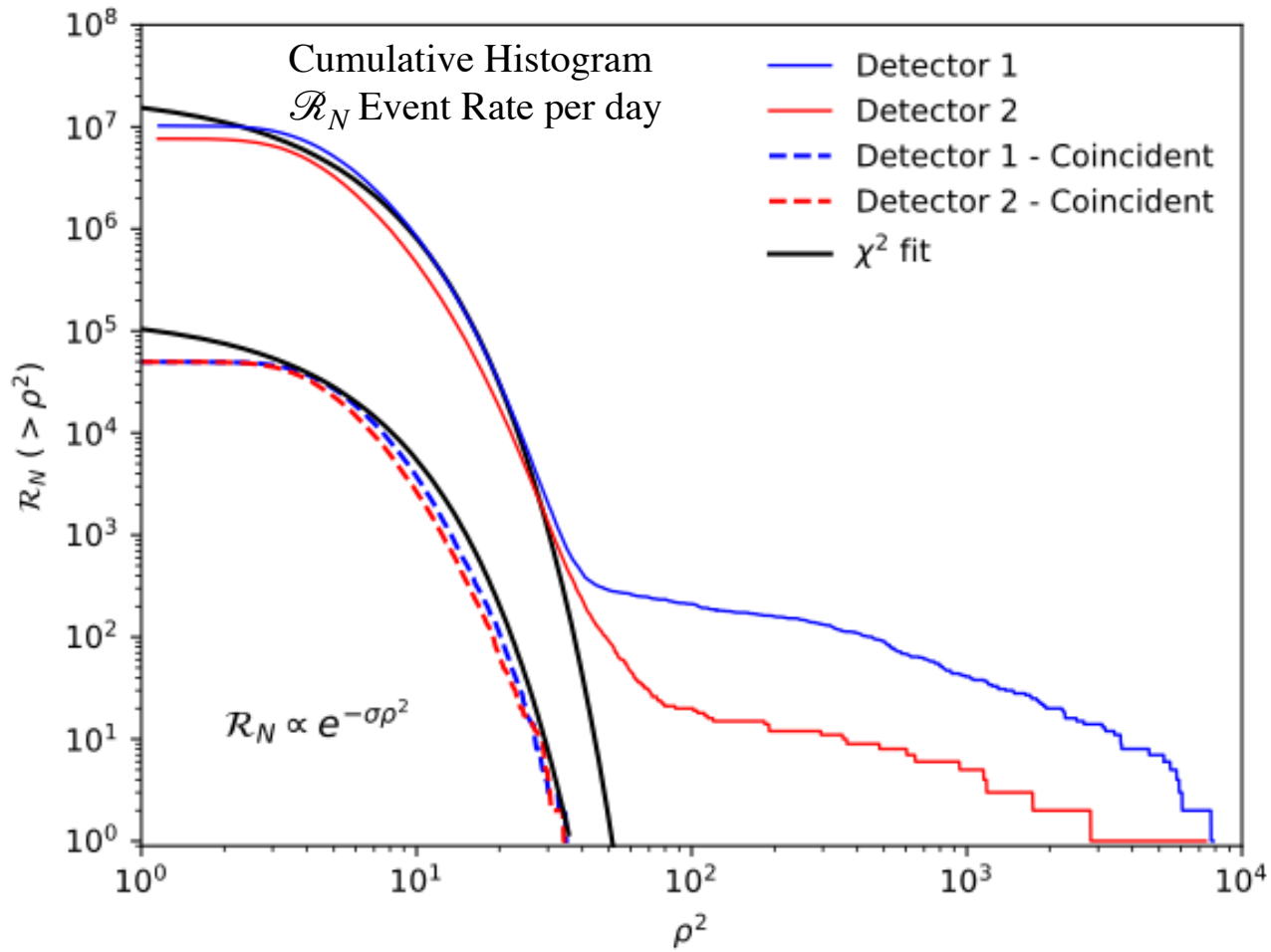
Determining Candidate Events



- Transient energy impulses excite the crystal
- Distinguished from other non-Gaussian noise sources by implementing a template bank with multiple values of decay times $\tau_b = \{\tau_1, \dots, \tau_\lambda, \dots, \tau_i\}$
- Selecting candidate triggers for which ρ is optimised for $\tau \sim \tau_\lambda$

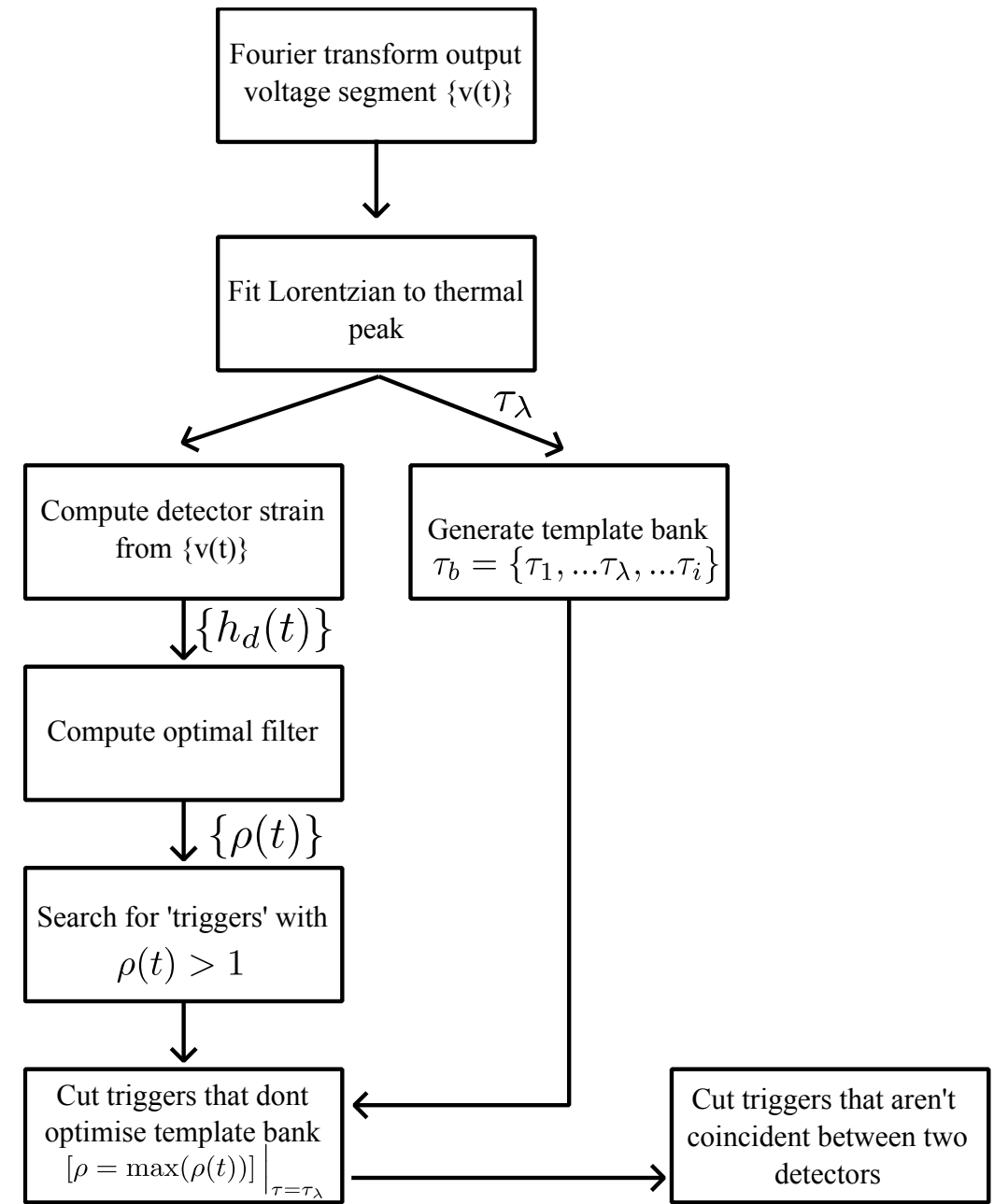
FIG. 2. Instantaneous vibrational energy of a single mode is plotted as a histogram for a 23 minute segment of data. The blue (orange) histogram represents the energy distribution before (after) optimal filtering. Both histograms clearly follow an expected χ^2 distribution, however the effect of optimal filtering greatly reduces the effective temperature at which events can be identified with $\text{SNR} = 1$.

Data analysis pipeline



Applying the optimal filter

- > SNR as a time series $\rho(t)$
- > represents SNR in excess narrowband fluctuations above the thermal Nyquist noise limit of the crystal
- > SNR fits a thermal distribution
- > Statistical coincidences of thermal noise



What characteristic strain can be excluded?

$$h_{c,\lambda} > \underbrace{x_{\max,\lambda}}^{\substack{\mathcal{P}(t) \\ \updownarrow}} \left| \frac{-2\pi^2 f^2 L_z \xi}{(2i\pi f)^2 + \tau_\lambda^{-1} + (2\pi f_\lambda)^2} \right|^{-1} \frac{f_\lambda}{\Delta f_\lambda}$$

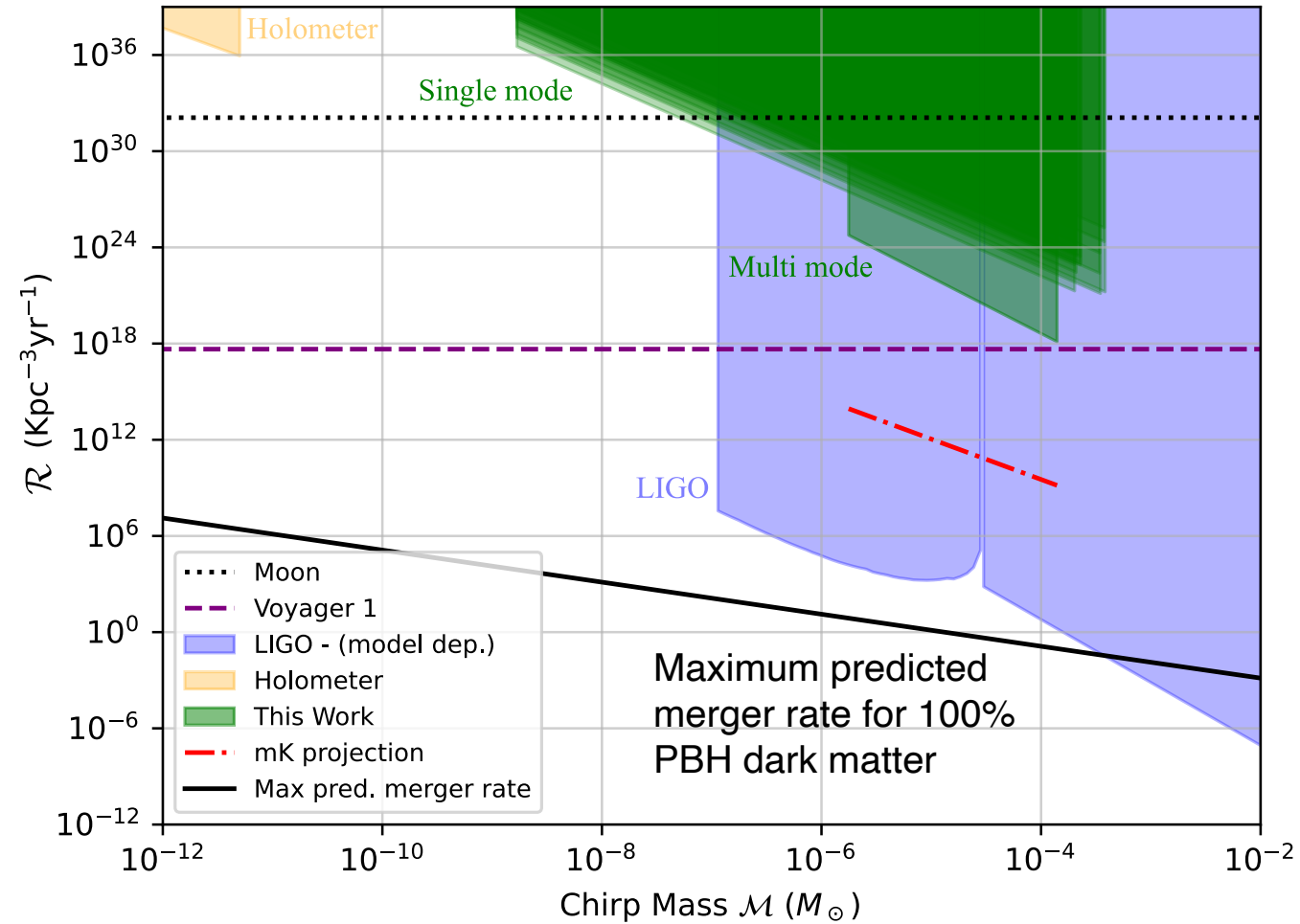
For a single mode

Exploit the multi-mode nature of MAGE
 Consider an inspiral signal that passes through
every mode in both detectors

$$\rho^2 = 2 \int_0^\infty df \frac{N_{\text{cycles}}(f) h_0^2}{f^2 S_n(f)} \sim \frac{h_0^2}{2} \sum_\lambda^{N_\lambda} \frac{\Delta f_\lambda^2 N_{\text{cycles}}(f_\lambda)}{f_\lambda^2 h_n^2(f_\lambda)}$$

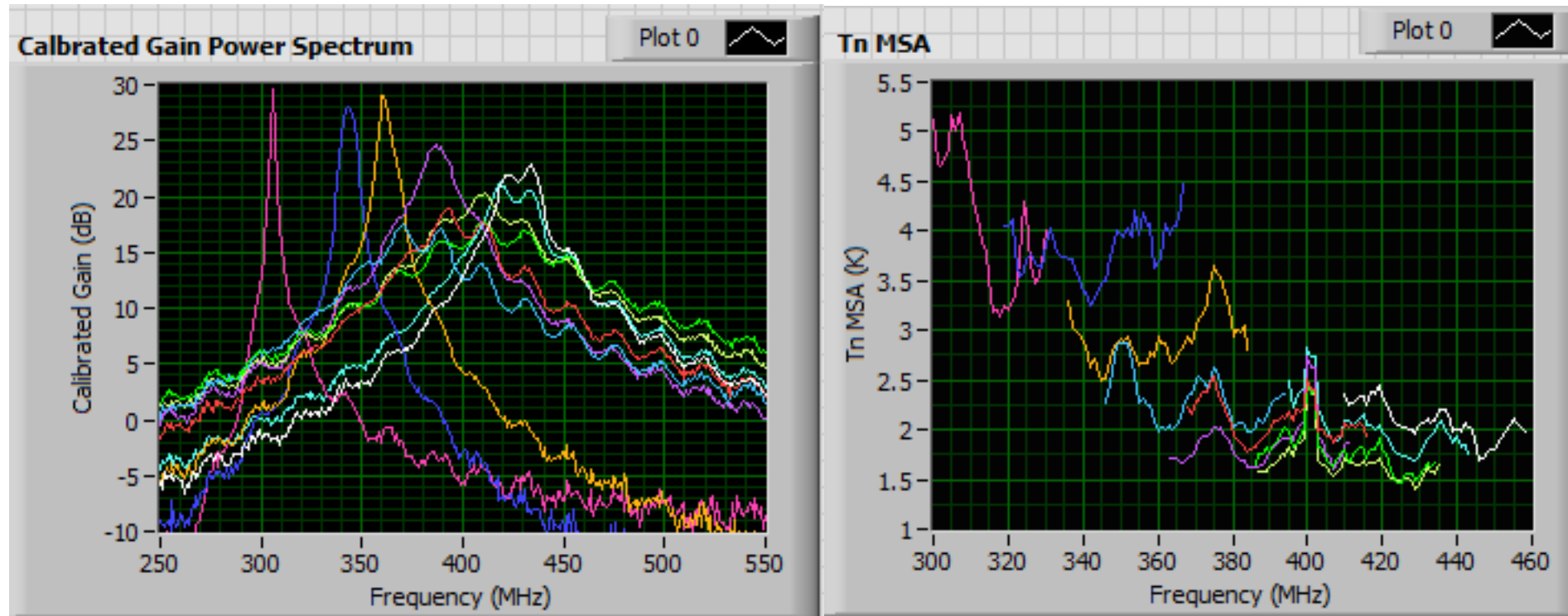
Choosing a threshold $\text{SNR} > 3$ gives an exclusion to
 97.7% confidence on minimum detectable h_0

This can be converted in a corresponding distance of reach D for a PBH system of some mass M
 Constrain yearly mergers to a distance of reach on the order of the solar system

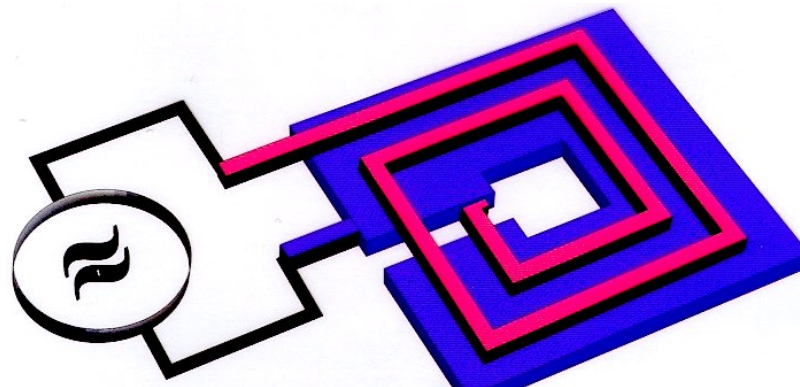
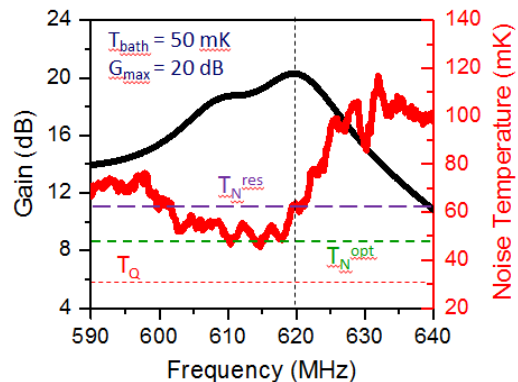


Now Cooled BAW to mK: Tunable Microstrip SQUID Amplifier (MSA)

Maxim Goryachev -> John Clarke Lab Berkeley



ADMX Amplifiers -> Near Quantum limited



Travelling wave Amplifiers from JPL

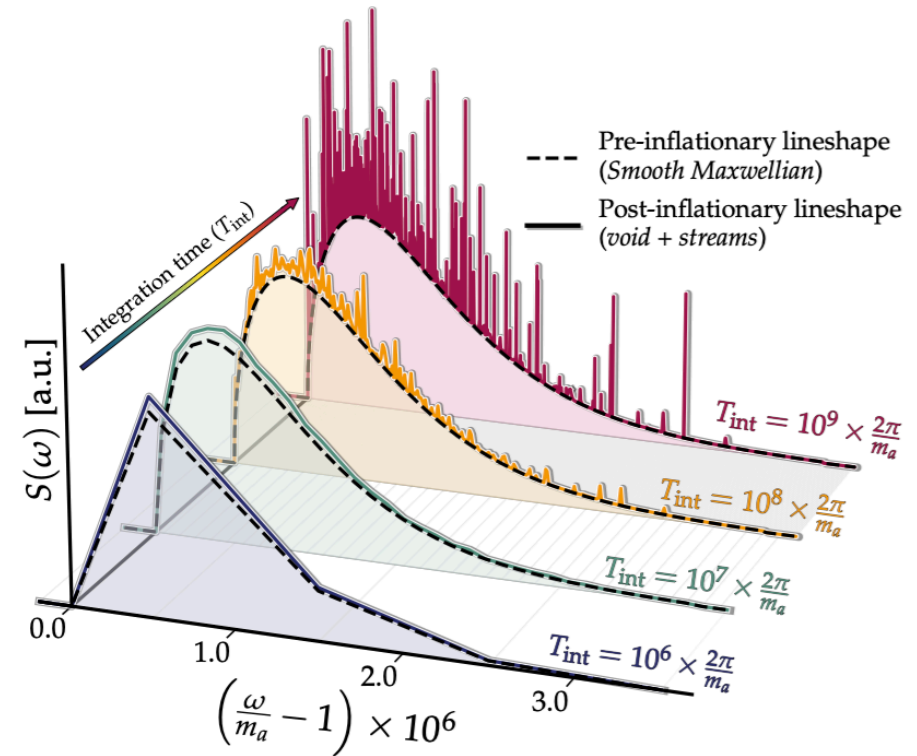
Cooled to BAW mK, readout Nyquist Noise

Axion and GW Networks

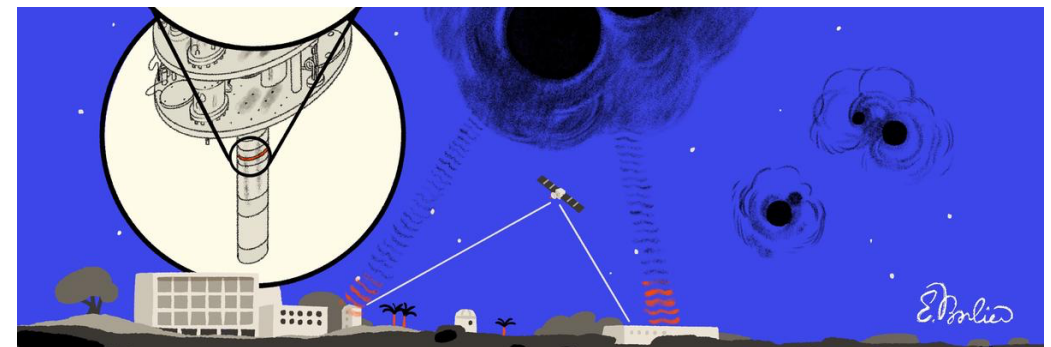
- Expect there to be “fine structure” in the axion distribution
- **Ciaran O’hare** and **Giovanni Pierobon** USYd
- Need to collect “High-Resolution” data (no averaging)
- We collected ~30-TB of data with $\frac{\delta f}{f} \sim 10^{-10}$
- Michael Hatzon (PhD student) is currently analysing this data
- Can also use this data to detect **HF gravity waves**
 - We are part of GravNet -> *A Global Network to Search for High Frequency Gravitational Waves*

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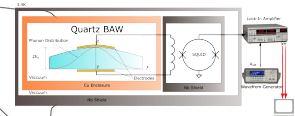
O’Hare, Ciaran A. J., et al. Axion MiniCluster Streams in the Solar Neighbourhood. 2023



Future Detector Networks



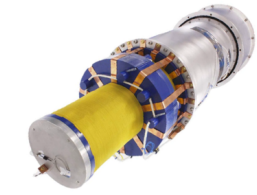
• Milan Bicocca



BAUSCIA

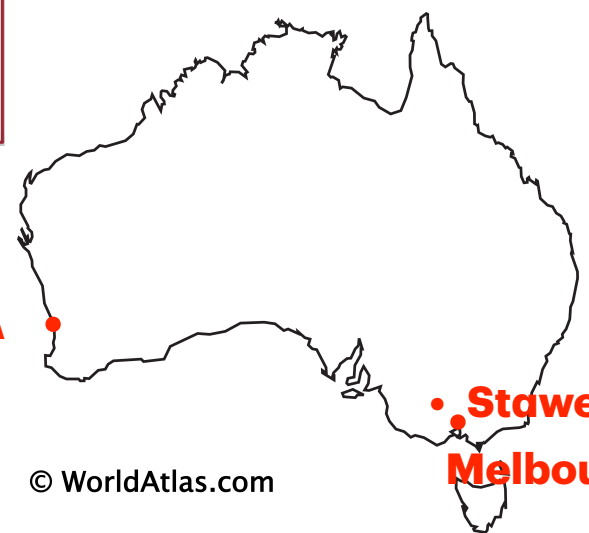
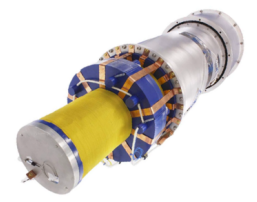
High-frequency GW
>100 kHz (*)

Low-mass and compact objects, DM candidates?

A visualization of a gravitational wave event, showing a black hole or neutron star merger with accretion disks, labeled BAUSCIA.

• Seattle UW

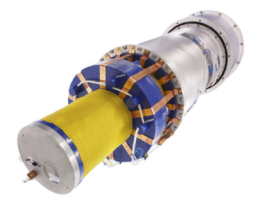
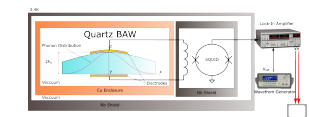
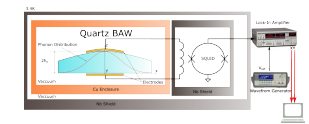
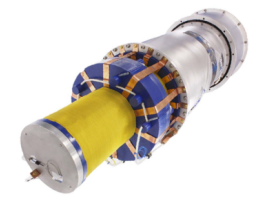
• Chicago (Fermilab)



Perth UWA

• Stawell SUPL

Melbourne Swinburne



Jun 26 – 27, 2025
HIM
Europe/Berlin timezone

GravNet: A Global Network for the Search for High-Frequency Gravitational Waves Receives ERC Synergy Grant 2024

[Overview](#)

[Timetable](#)

[Contribution List](#)

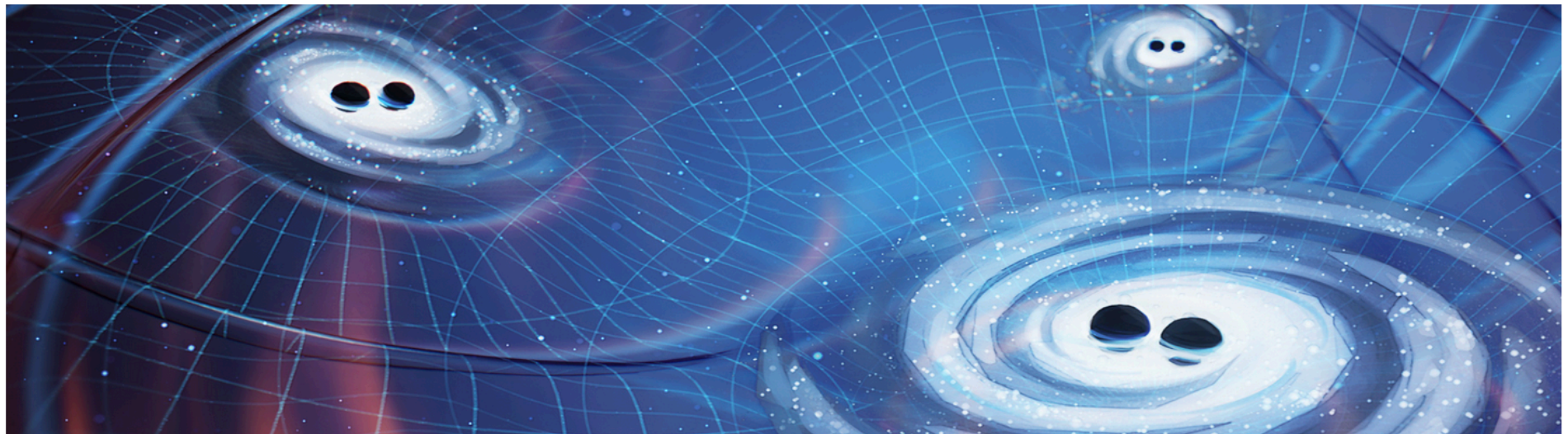
[Registration](#)

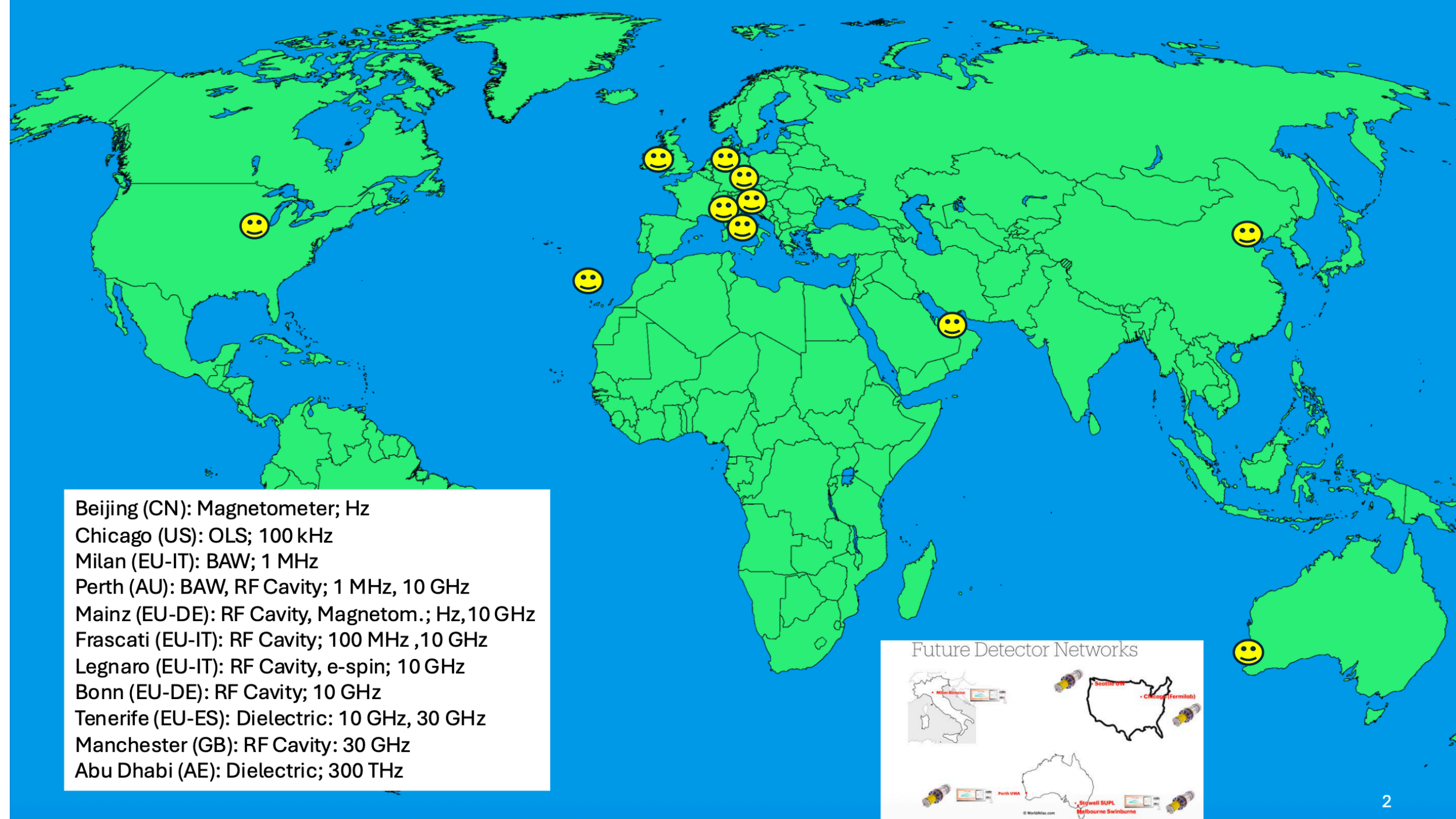
[Participant List](#)

GravNet - Searching for High Frequency Gravitational Waves with a Global Detector Network

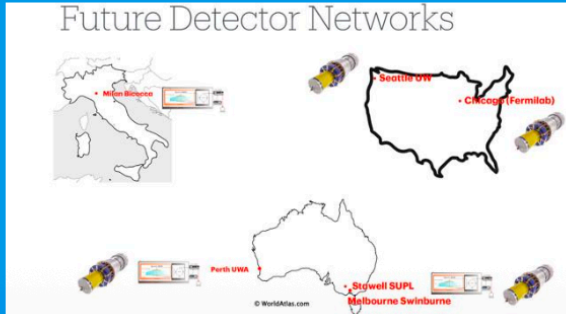
Location: University of Mainz, Germany

Date: Thursday, 26th of June 2025 to Friday, 27th of June 2025





- Beijing (CN): Magnetometer; Hz
- Chicago (US): OLS; 100 kHz
- Milan (EU-IT): BAW; 1 MHz
- Perth (AU): BAW, RF Cavity; 1 MHz, 10 GHz
- Mainz (EU-DE): RF Cavity, Magnetom.; Hz, 10 GHz
- Frascati (EU-IT): RF Cavity; 100 MHz, 10 GHz
- Legnaro (EU-IT): RF Cavity, e-spin; 10 GHz
- Bonn (EU-DE): RF Cavity; 10 GHz
- Tenerife (EU-ES): Dielectric: 10 GHz, 30 GHz
- Manchester (GB): RF Cavity: 30 GHz
- Abu Dhabi (AE): Dielectric; 300 THz



THE END: The QDM Lab



ACADEMIC (4)

- Michael Tobar
- Eugene Ivanov
- Maxim Goryachev
- Jeremy Bourhill
- ADJUNCT(1)**
- Ben McAllister

POSTDOCS (3)

- Cindy Zhao
- Graeme Flower
- Aaron Quiskamp

PHD STUDENTS (7)

- Elrina Hartman
- Steven Samuels
- Emma Paterson
- Robert Crew
- Michael Hatzon
- Sonali Parashar
- Ashley Johnson

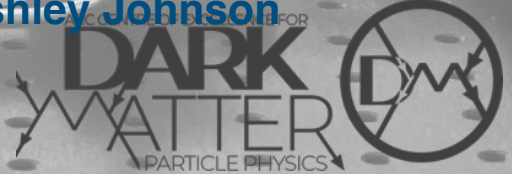
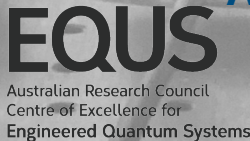
UNDERGRAD STUDENTS (3)

- Tim Holt (MSc)
- Evangelos Hajigabriel (Hons)
- Charlie Campbell (Hons)

VACATION STUDENTS (3)

- Owen Yandell
- Jonathan Charlesworth
- Div Sharma

<https://www.qdmlab.com/>



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