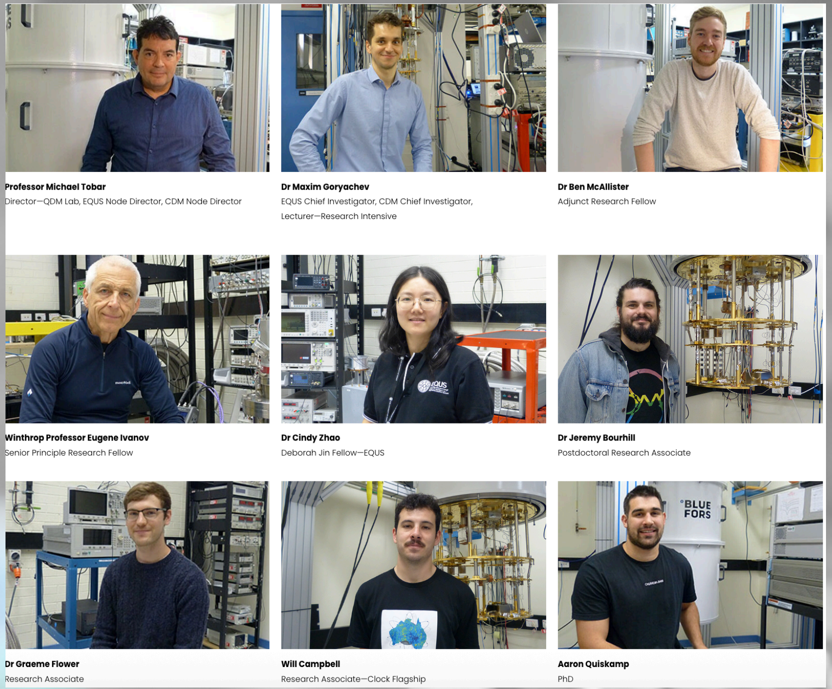
Multi-mode Acoustic Gravitational-wave Experiment (MAGE)



https://www.qdmlab.com/

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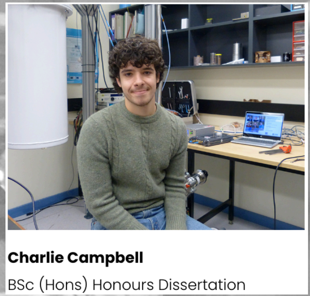


QDM Quantum Technologies and Dark Matter Research Lab

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

ARC Centre of Excellence for Dark Matter Particle Physics

The University of Western Australia — Seek Wisdom

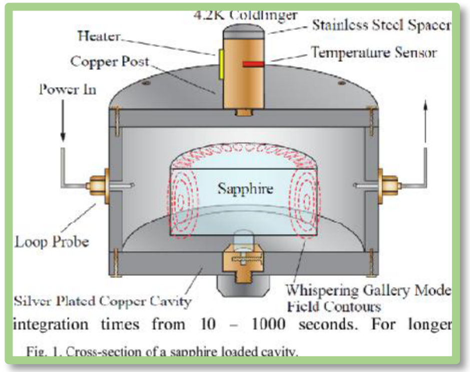
QDM Lab Precision Metrology

Metrological Systems:

Science of precise measurement → **Physics at low energies**

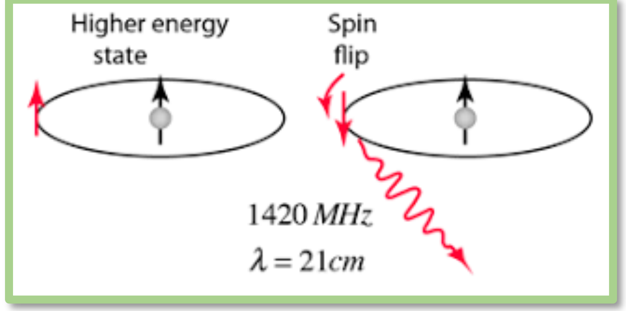
Photonic

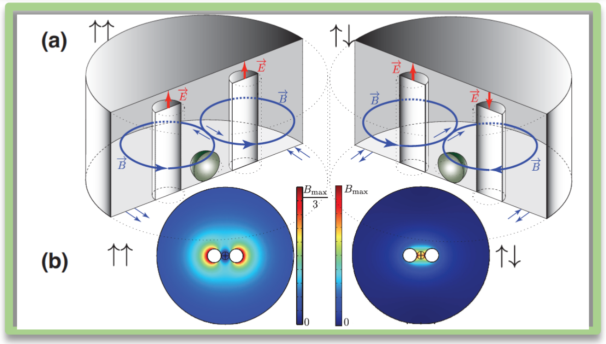
- WGM Resonators
- Specially Designed Microwave Cavities



Atomic/Spins

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



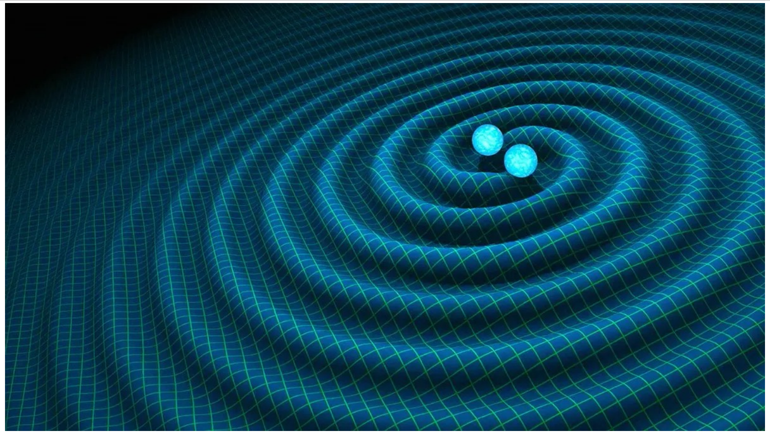


Acoustic

- Superfluid
- BAW Resonator

Motivation: Fundamental Physics

General Relativity



Quantum gravity

Dark Matter

High frequency gravitational waves

Lorentz invariance violations

Minimum length

Metrology helps us search for physics beyond the standard model

The standard model

Science of precise measurement → Physics at low energies

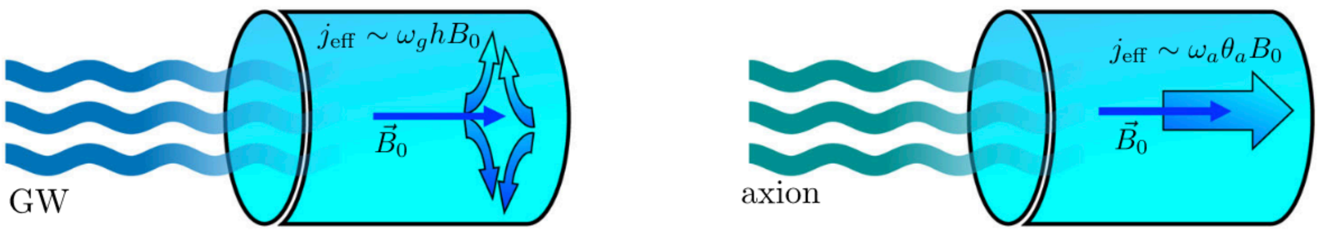
Axion Detector are Sensitive to Ultra-High Frequency GWs (UHFGWs)

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'Agnolo,[6] Sebastian A. R. Ellis,[7,6]
Roni Harnik,[2,3] Yonatan Kahn,[8,9,3] and Jan Schütte-Engel[8,9,3]



$$j_{\rm eff} \supset g_{a\gamma\gamma}\partial_t a \mathbf{B}_0 \simeq \omega_a \theta_a \mathbf{B}_0 \qquad \mathbf{E}_a = g_{a\gamma\gamma} a \mathbf{B}_0 = \theta_a \mathbf{B}_0$$

$$j^{\mu}_{\rm eff} \equiv \partial_\nu \left(\frac{1}{2} h F^{\mu\nu} + h^{\nu}_{\alpha} F^{\alpha\mu} - h^{\mu}_{\alpha} F^{\alpha\nu} \right)$$

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

identifying $\theta_a \sim h$

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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

REVIEW ARTICLE

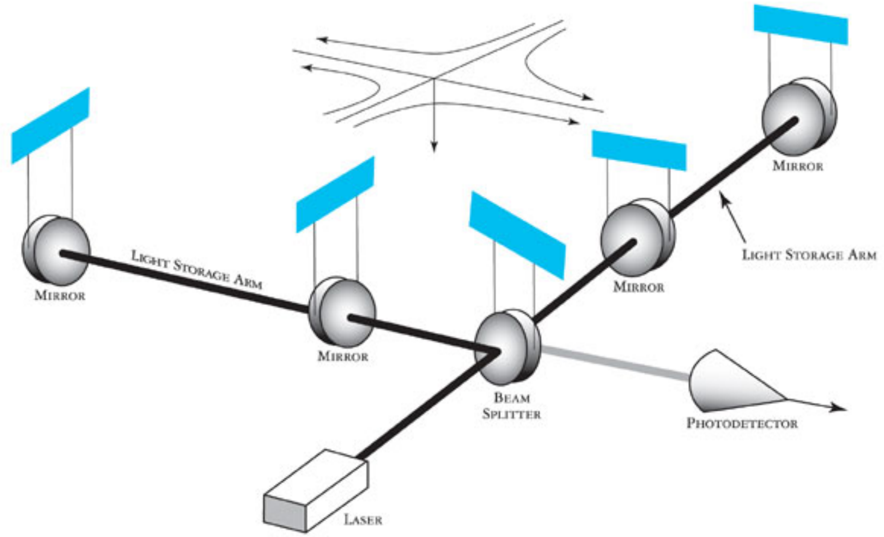
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

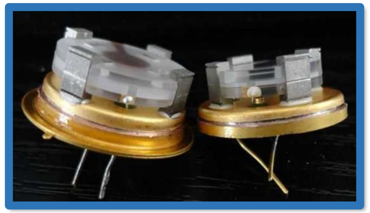
Nancy Aggarwal[1] · Odylio D. Aguiar[2] · Andreas Bauswein[3] · Giancarlo Cella[4] · Sebastian Clesse[5] · Adrian Michael Cruise[6] · Valerie Domcke[7,8,9] · Daniel G. Figueroa[10] · Andrew Geraci[11] · Maxim Goryachev[12] · Hartmut Grote[13] · Mark Hindmarsh[14,15] · Francesco Muia[9,16] · Nikhil Mukund[17] · David Ottaway[18,19] · Marco Peloso[20,21] · Fernando Quevedo[16] · Angelo Ricciardone[20,21] · Jessica Steinlechner[22,23,24] · Sebastian Steinlechner[22,23] · Sichun Sun[25,26] · Michael E. Tobar[12] · Francisco Torrenti[27] · Caner Ünal[28] · Graham White[29]

Received: 6 April 2021 / Accepted: 15 September 2021

Precision Detectors: Sensitive to New Physics

comparing sensitivities



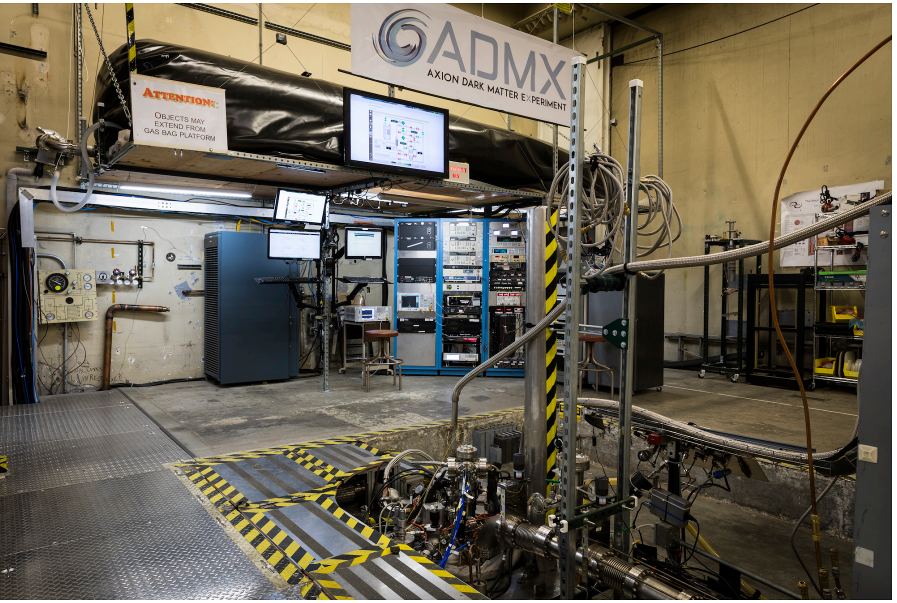


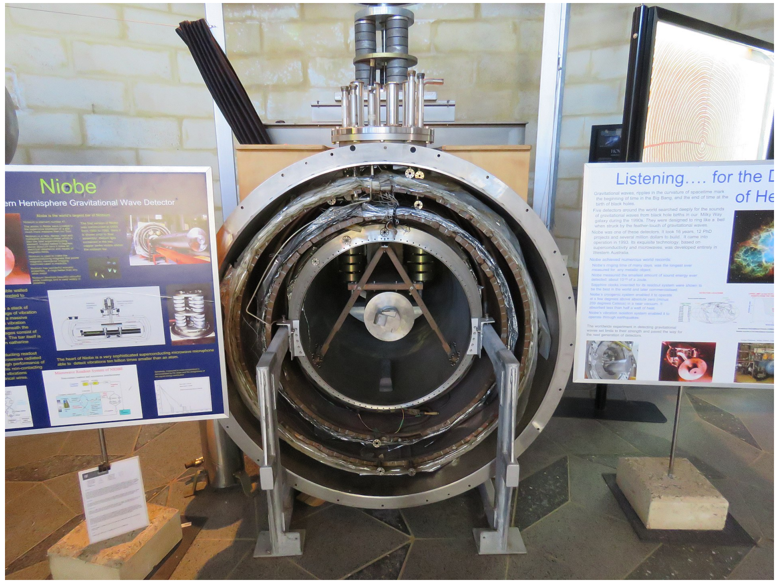
MAGE
Multimode Acoustic Gravitational Wave Experiment

NIOBE

UPLOAD
UPconversion Low-Noise Oscillator Axion Detector

ORGAN
Oscillating Resonant Group AxioN Experiment





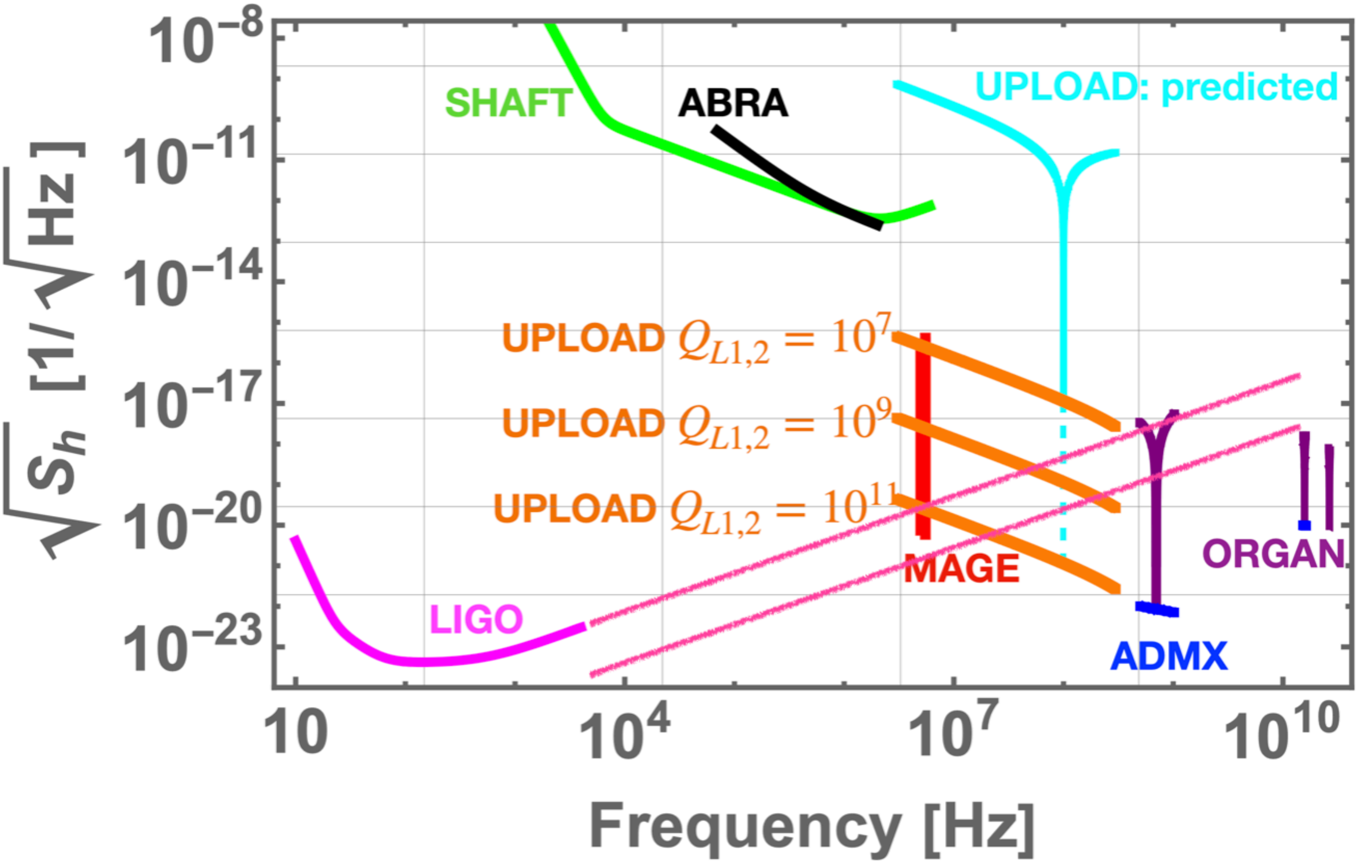
DETECTOR COMPARISON: Defining Instrument Sensitivity independent of signal (Spectral): Also sensitive to GWs

symmetry

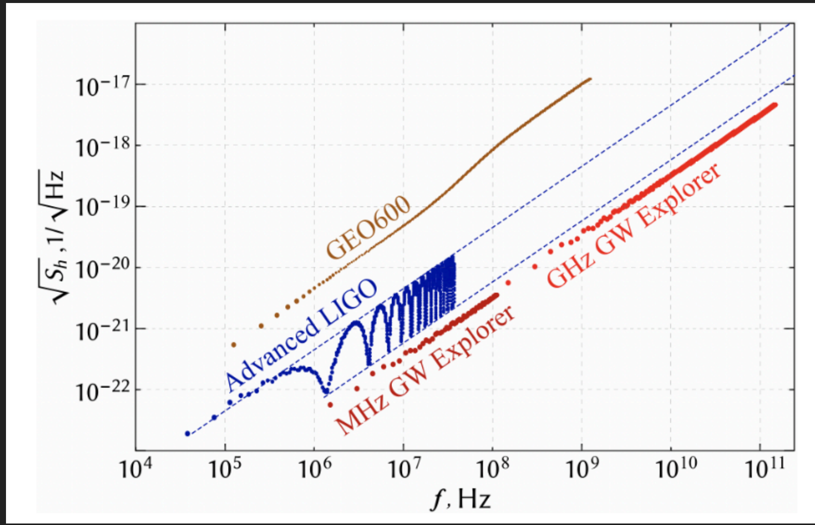
Comparing Instrument Spectral Sensitivity of Dissimilar Electromagnetic Haloscopes to Axion Dark Matter and High Frequency Gravitational Waves

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

Special Issue
The Dark Universe: The Harbinger of a Major Discovery
Edited by
Prof. Konstantin Zioutas
Symmetry, vol. 14, no. 10, 2165, 2022



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



arXiv:2409.03019 Schnabel and Korobko

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

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

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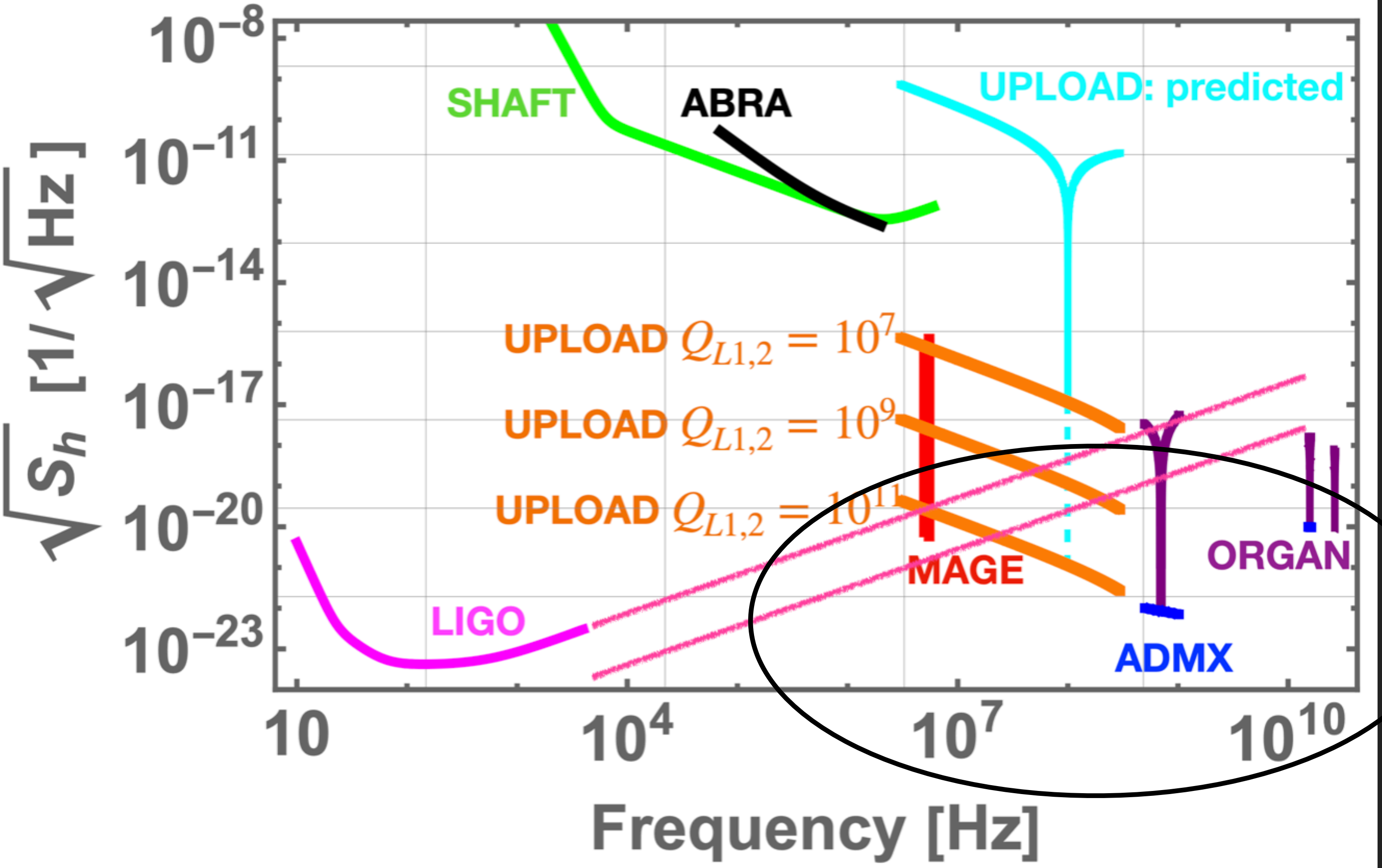

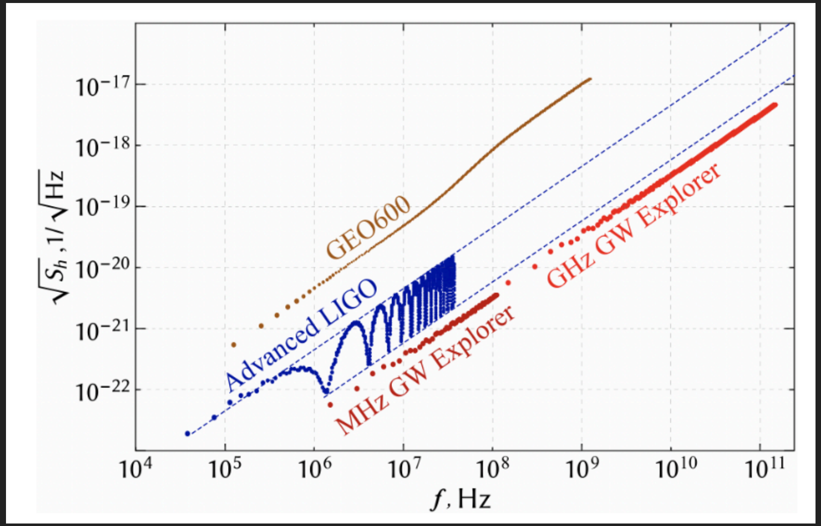

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ADMX and ORGAN (purple) with current tuning locus (blue);

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

MAGE

Excluding PBH Binaries

arXiv > gr-qc > arXiv:2506.03609

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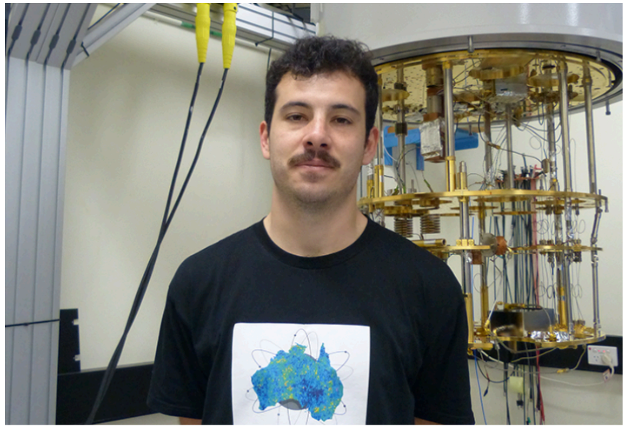
General Relativity and Quantum Cosmology

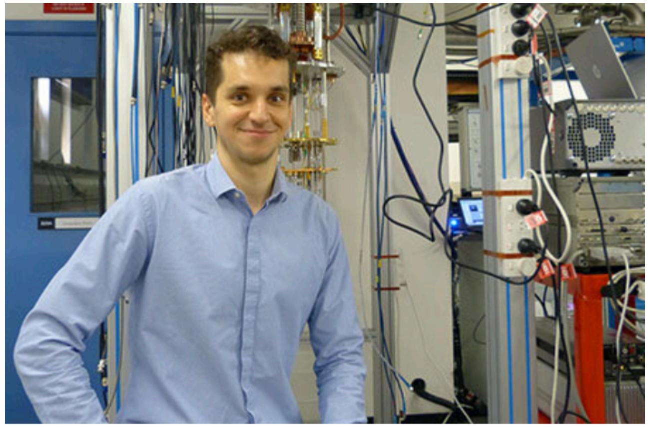
[Submitted on 4 Jun 2025]

Experimental Exclusion of Planetary Mass Primordial Black Hole Mergers

William M. Campbell, Leonardo Mariani, Michael E. Tobar, Maxim Goryachev

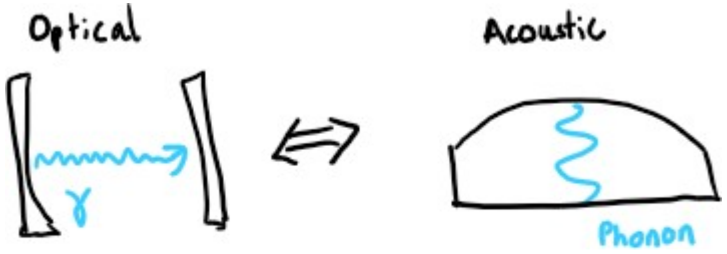
The multi-mode acoustic gravitational wave experiment (MAGE) is a high-frequency gravitational wave detection experiment featuring cryogenic quartz bulk acoustic wave resonators operating as sensitive strain antennas in the MHz regime. After 61 days of non-continuous data collection, we present bounds 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 $\mathcal{R} > 1.3 \times 10^{18}\ \mathrm{kpc}^{-3}\mathrm{yr}^{-1}$ which corresponds to constraining yearly mergers to a distance of reach on the order of the solar system, or 1.0×10^{-6} kpc during the observational period. In addition, we exclude significantly rare and strong events similar to those observed in previous predecessor experiments as non-gravitational background signals, utilising coincident analysis between multiple detectors.

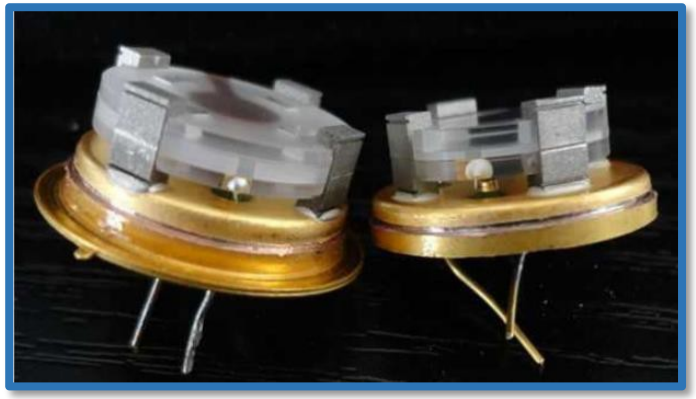




Quartz Bulk Acoustic Wave Resonators

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





***RESEARCH WITH ACOUSTIC RESONATORS @ UWA**

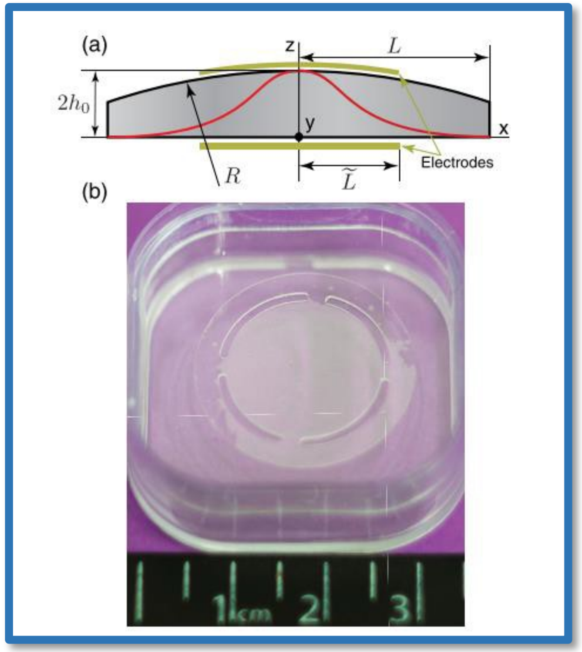
***Search for High frequency GWs**

***Detection of a Graviton**

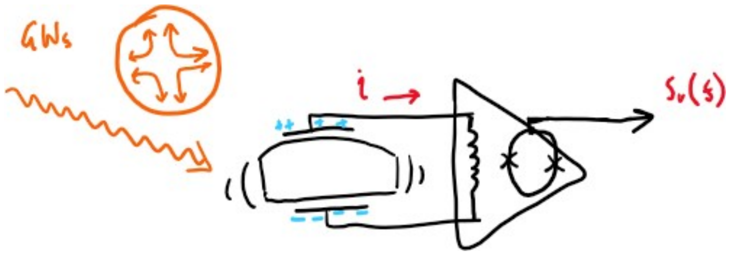
***Search for Scalar DM:**

***Search for Lorentz invariance violations**

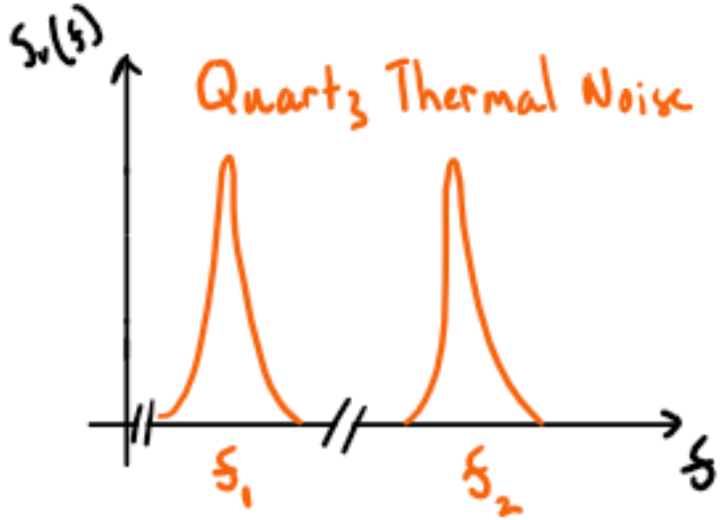
***Improved constraints on minimum length models or Generalized Uncertainty Principle (GUP)**



Scientific Reports Vol. 3, 2132 (2013)

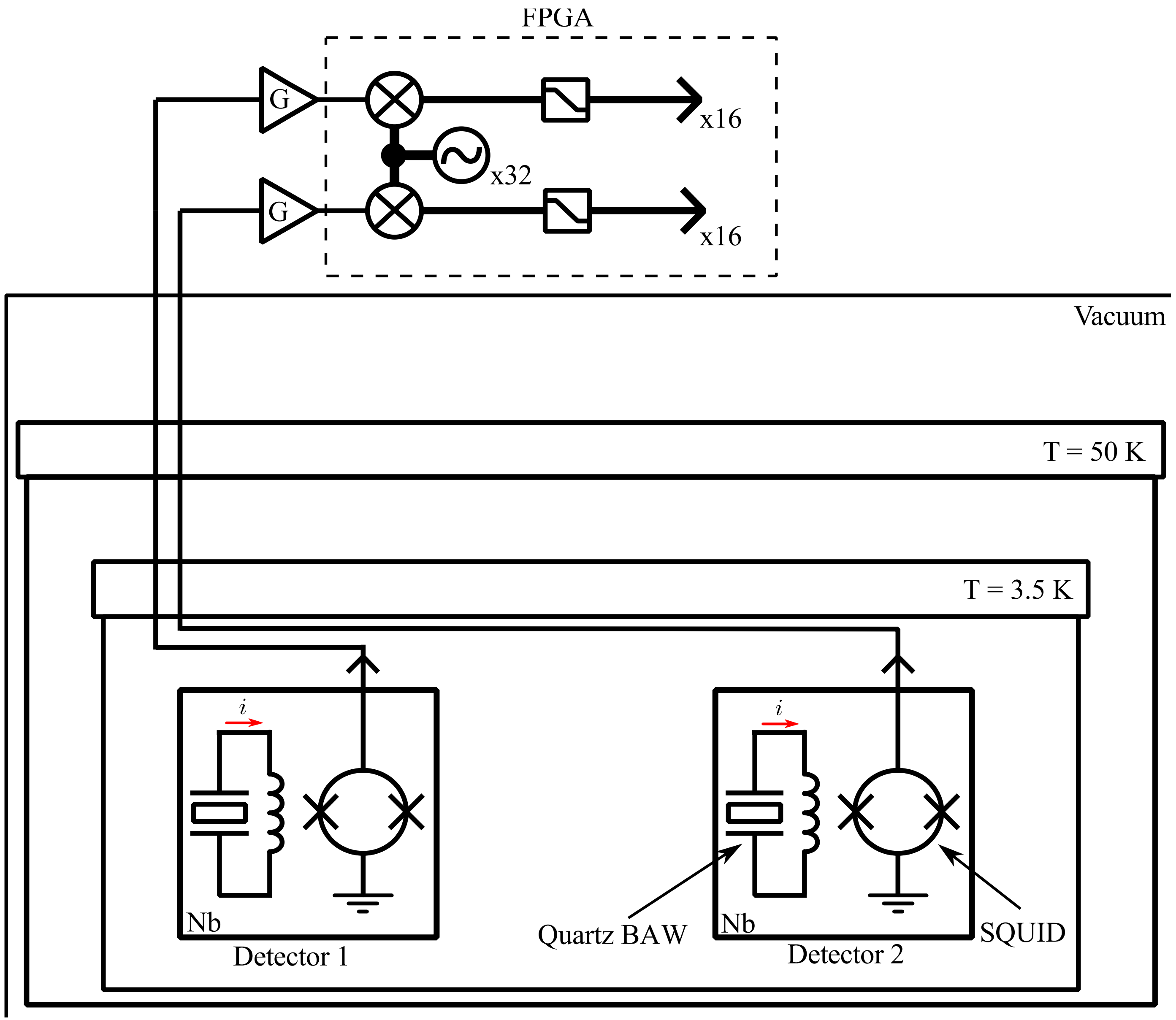


The Experiment



- 61 days of non-continuous data collection
- 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

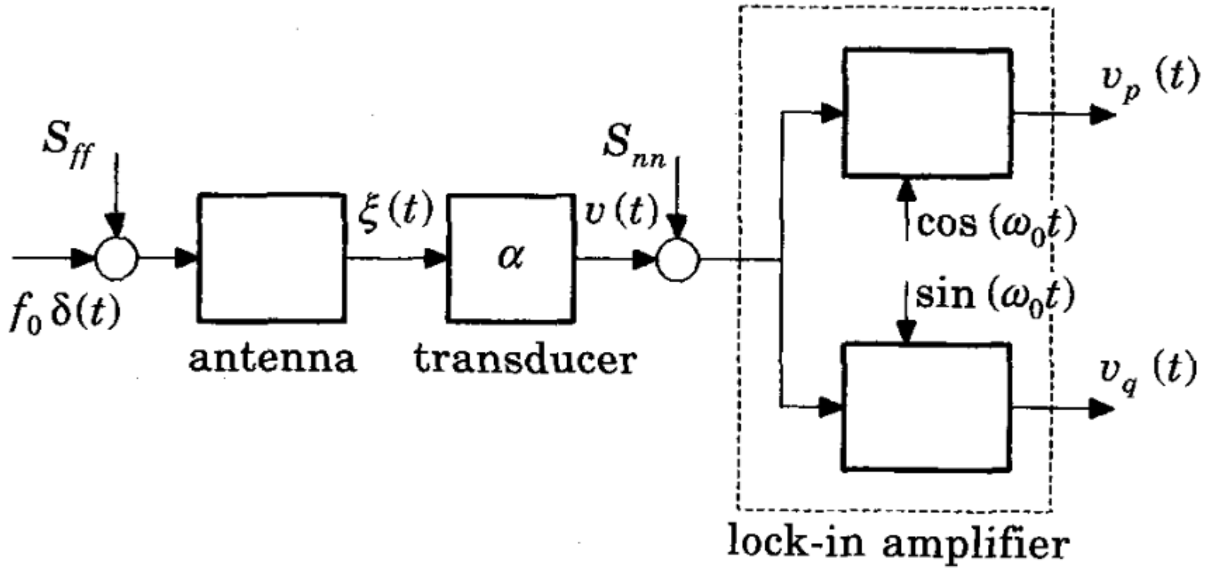
Complex DAQ Chain.



What does the data look like ?

$$v_s(t) = V_s \exp[-\beta_1 t] \sin \omega_0 t\,,$$

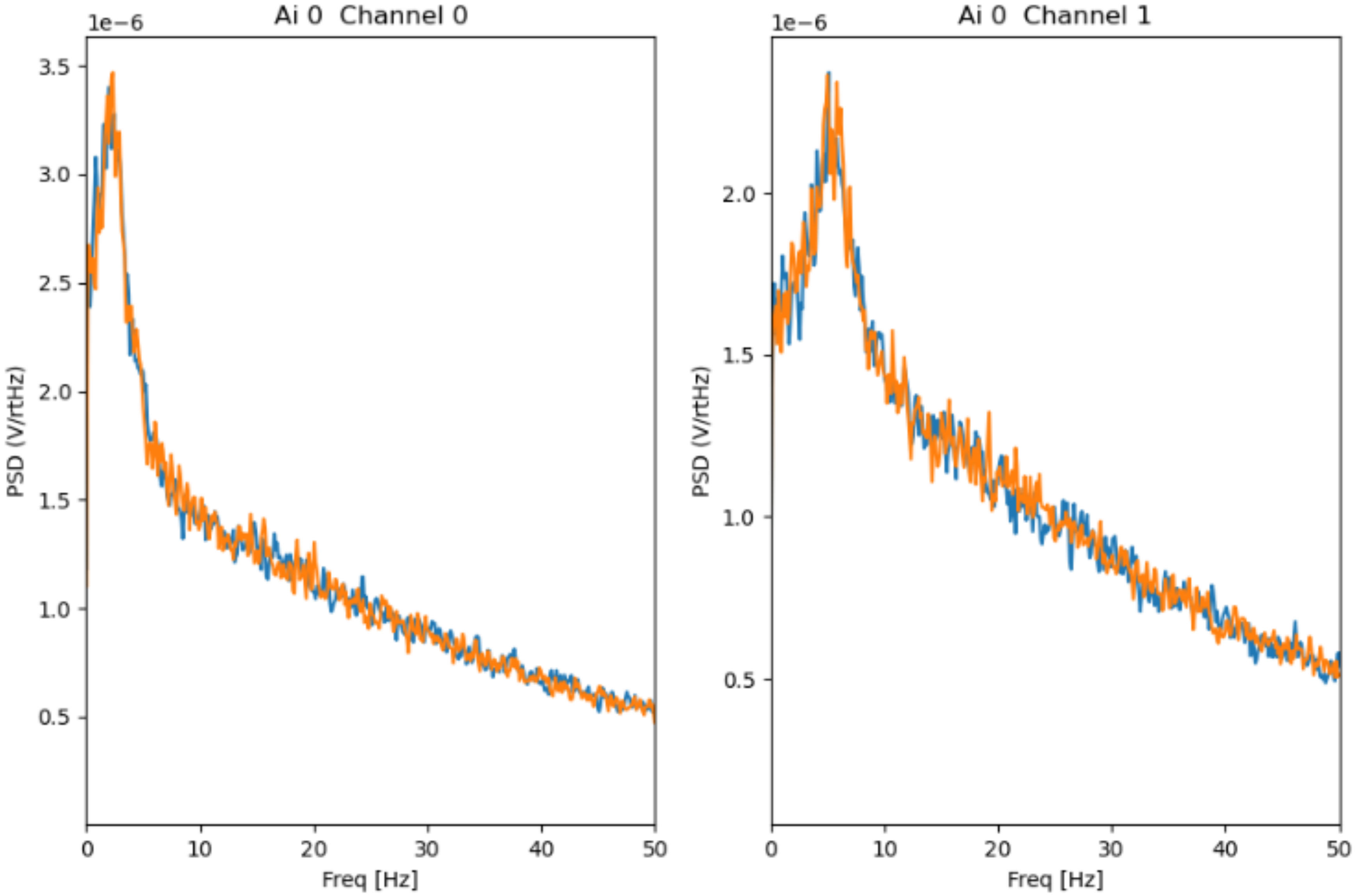
We expect GWs to drive an acoustic mode -> decaying sinusoidal



$$p_s(t) = \frac{V_s}{\sqrt{2}} \frac{\beta_2}{\beta_2 - \beta_1} (\exp[-\beta_1 t] - \exp[-\beta_2 t]) \cos \phi\,,$$

$$q_s(t) = \frac{V_s}{\sqrt{2}} \frac{\beta_2}{\beta_2 - \beta_1} (\exp[-\beta_1 t] - \exp[-\beta_2 t]) \sin \phi\,,$$

- 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 ~ 23 minutes of data

What does the signal look like ?

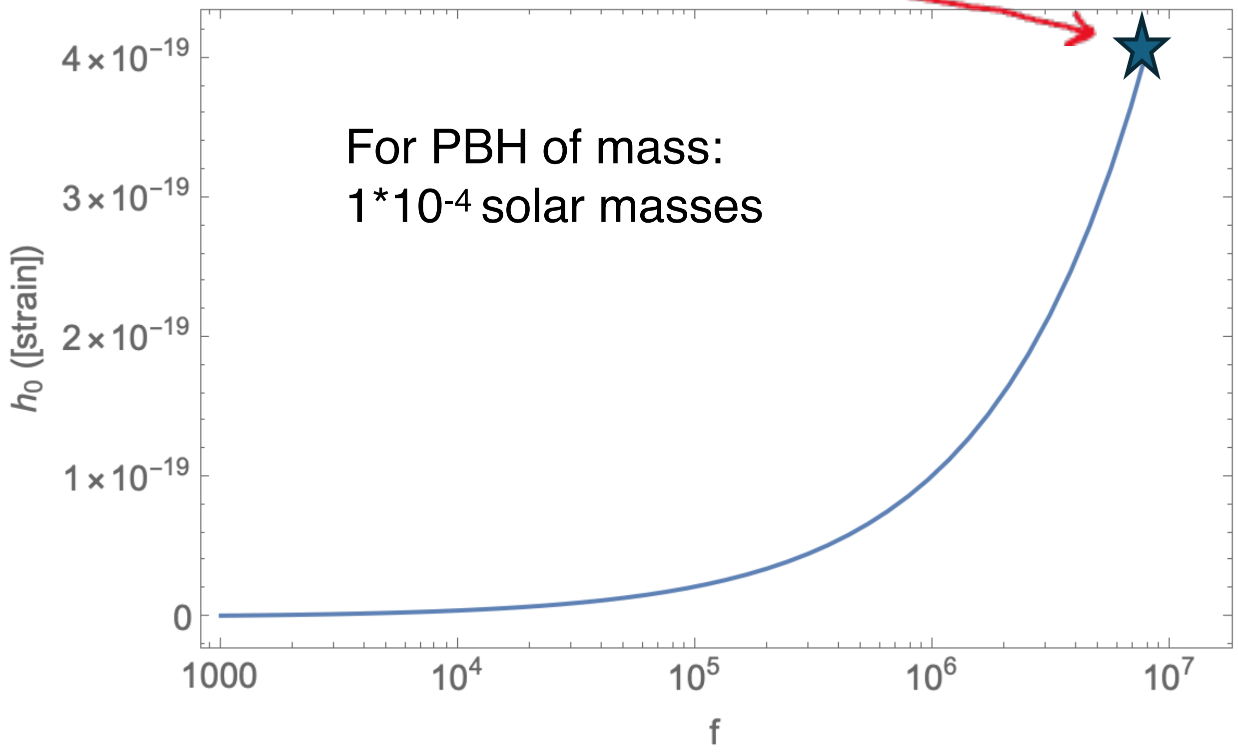
Innermost Stable Circular Orbit

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

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

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

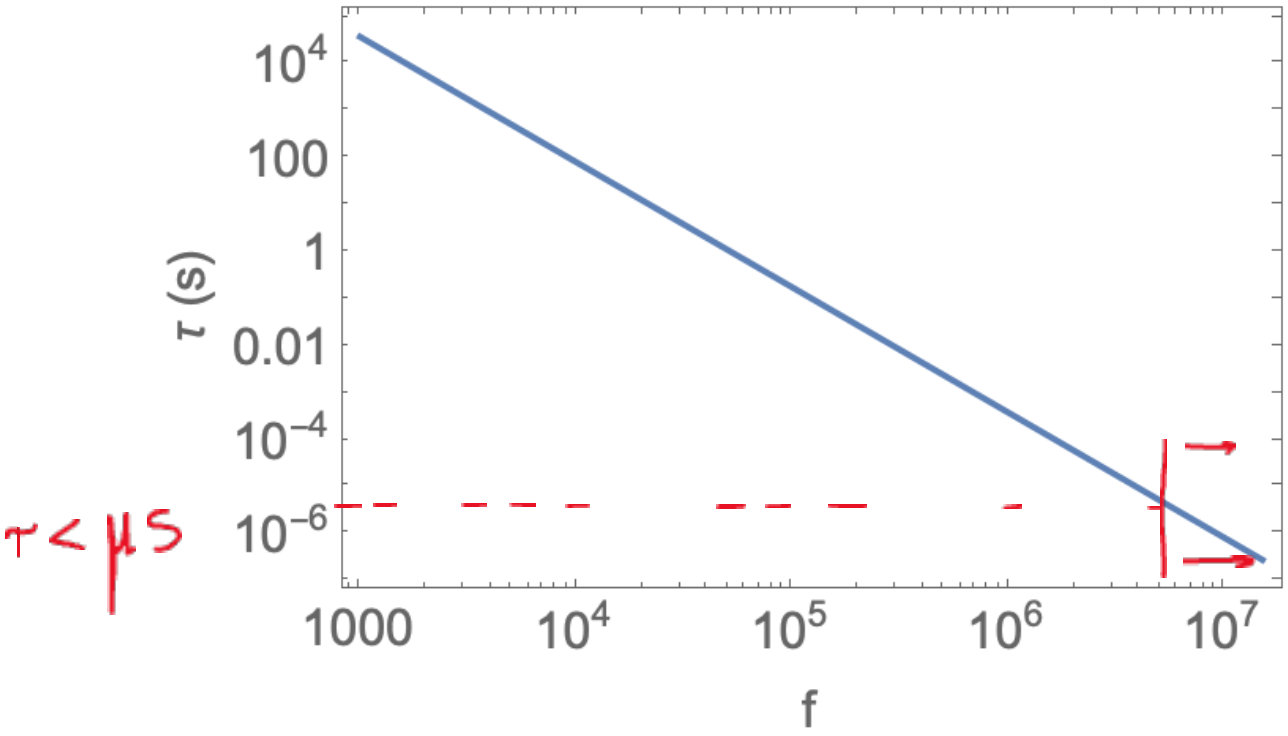
$$h_0 \approx \frac{2}{D}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}$$



$\mathcal{M}$ Reduced mass of binary system

Be careful of signal duration

Time to coalescence at 15 MHz



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

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

MAGE operates in narrow bands in the MHz spectrum

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

Introduce *characteristic strain*

Dimensionless quantity introduced to account for the frequency evolution of a strain signals. It is more convenient to use than strain $h_{0.}$

The characteristic strain, h_c, excluded by the detector can be related to the strain amplitude h_0 of a PBH in-spiral of binary chirp mass $\mathcal{M}$ by;

$$h_c^2 = (2f\tilde{h}(f))^2 = 2h_0^2 N_{\text{cycles}}(\mathcal{M}, f)$$

$$h_0 \approx \frac{2}{d}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3}$$

Searching for a signal in a noisy detector output

Well known / solved problem in the case of stationary gaussian noise -> ***optimal / matched filter.***

$$s(t) = h(t) + n(t)$$

We wish to still be able to detect a signal in the case where the noise is larger than the signal contribution

$$|h(t)| \ll |n(t)|$$

Matched filter

Introduce some filter function K(t)

It is critical we know / assume the form of our signal h(t)

$$\hat{s} = \int_{-\infty}^{\infty} dt\, s(t) K(t)$$

Then ask: “what is the form of K(t) that maximises the ratio of our signal expectation value to the noise”

The signal-to-noise ratio (in amplitude) is defined as S/N, where S is the expected value of $\hat{s}$ when the signal is present, and N is the rms value of $\hat{s}$ when the signal is absent. Since $\langle n(t) \rangle = 0$, we have

$$\begin{aligned} S &= \int_{-\infty}^{\infty} dt \langle s(t) \rangle K(t) \\ &= \int_{-\infty}^{\infty} dt\, h(t) K(t) \\ &= \int_{-\infty}^{\infty} df\, \tilde{h}(f) \tilde{K}^*(f)\,, \end{aligned}$$

F

$$\begin{aligned} N^2 &= \left[\langle \hat{s}^2(t) \rangle - \langle \hat{s}(t) \rangle^2 \right]_{h=0} \\ &= \langle \hat{s}^2(t) \rangle_{h=0} \\ &= \int_{-\infty}^{\infty} dt dt'\, K(t) K(t') \langle n(t) n(t') \rangle \\ &= \int_{-\infty}^{\infty} dt dt' K(t) K(t') \int_{-\infty}^{\infty} df df'\, e^{2\pi i f t - 2\pi i f' t'} \langle \tilde{n}^*(f) \tilde{n}(f') \rangle\,. \end{aligned} \quad (7.4$$

= PSD

Matched filter

We have:

$$\frac{S}{N} = \frac{\int_{-\infty}^{\infty} df\, \tilde{h}(f)\tilde{K}^*(f)}{\left[\int_{-\infty}^{\infty} df\, (1/2) S_n(f) |\tilde{K}(f)|^2\right]^{1/2}}.$$

PSD

What is the K(f) that gives maximum S/N for a given h(t) ?

$$\tilde{K}(f) = \text{const.}\, \frac{\tilde{h}(f)}{S_n(f)}$$

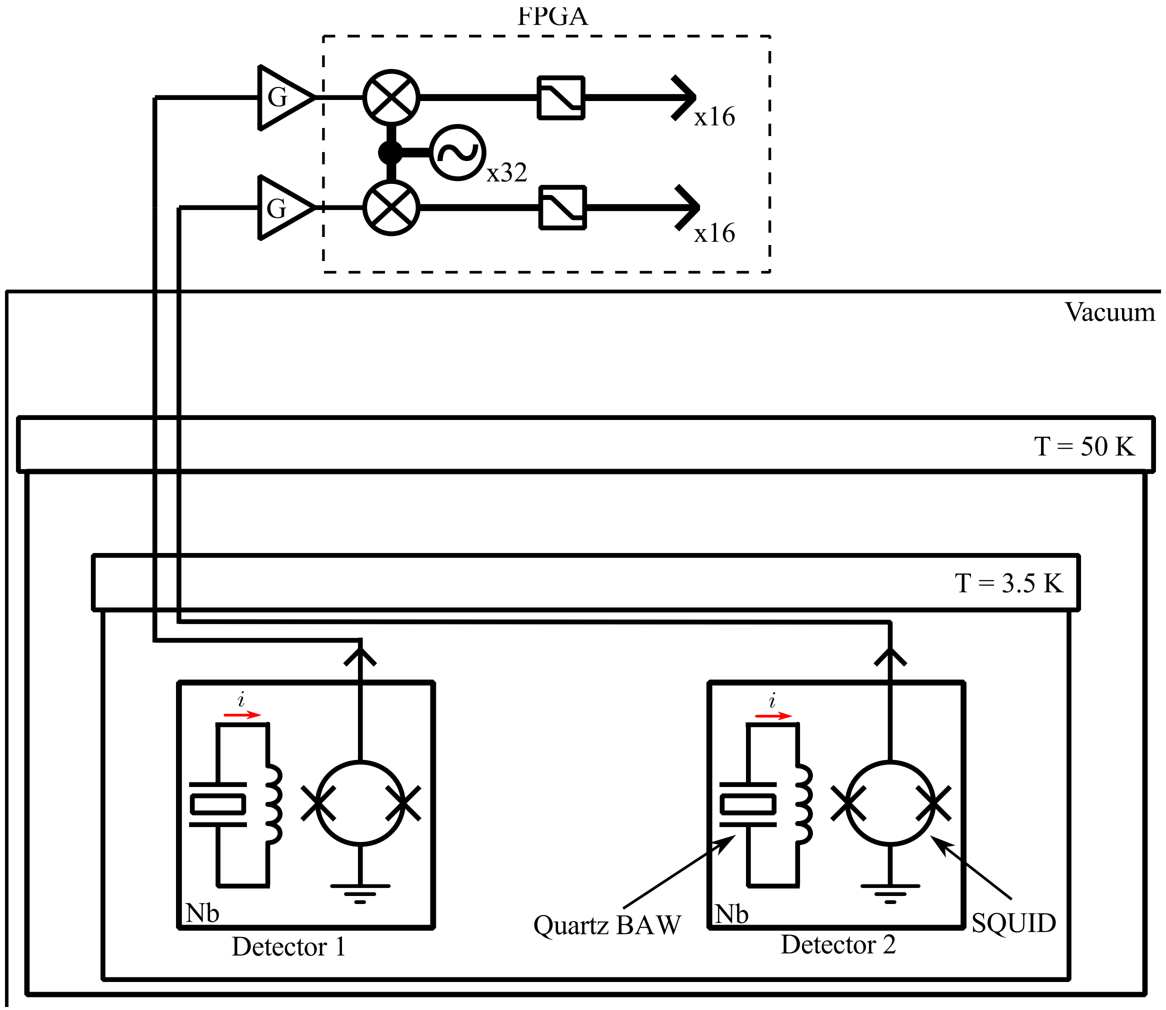
$$\left(\frac{S}{N}\right)^2 = 4 \int_0^{\infty} df\, \frac{|\tilde{h}(f)|^2}{S_n(f)}$$

Substitute K(f) back in to get this equation for the most optimal SNR

Filter effectively weights the noisier detector regions

Determining detector strain

$$x(t) = \mathcal{F}^{-1}\left(\mathcal{F}\left(\frac{\sqrt{X(t)^2 + Y(t)^2}}{2\pi f_\lambda \kappa_\lambda G_s}\right)\right)$$



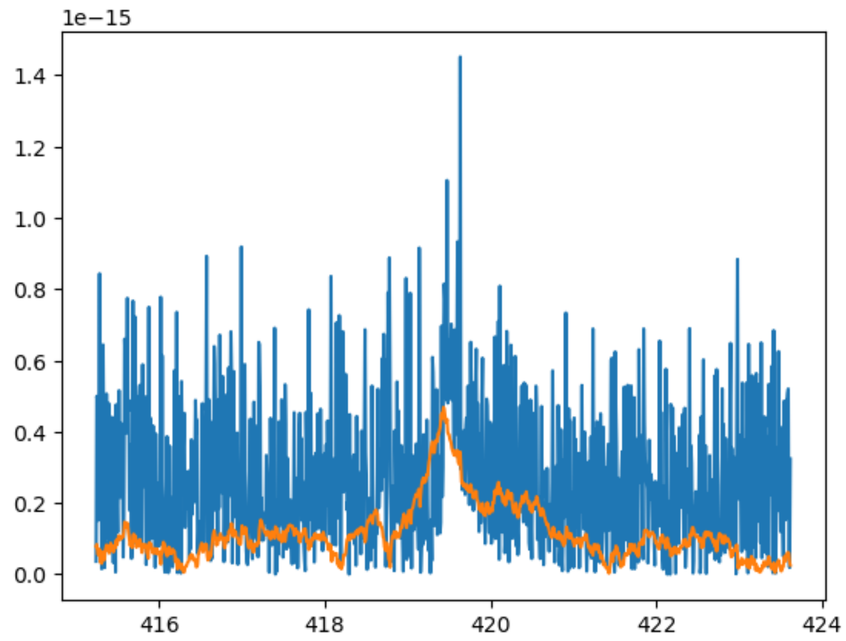
Implementing the matched filter.

```
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

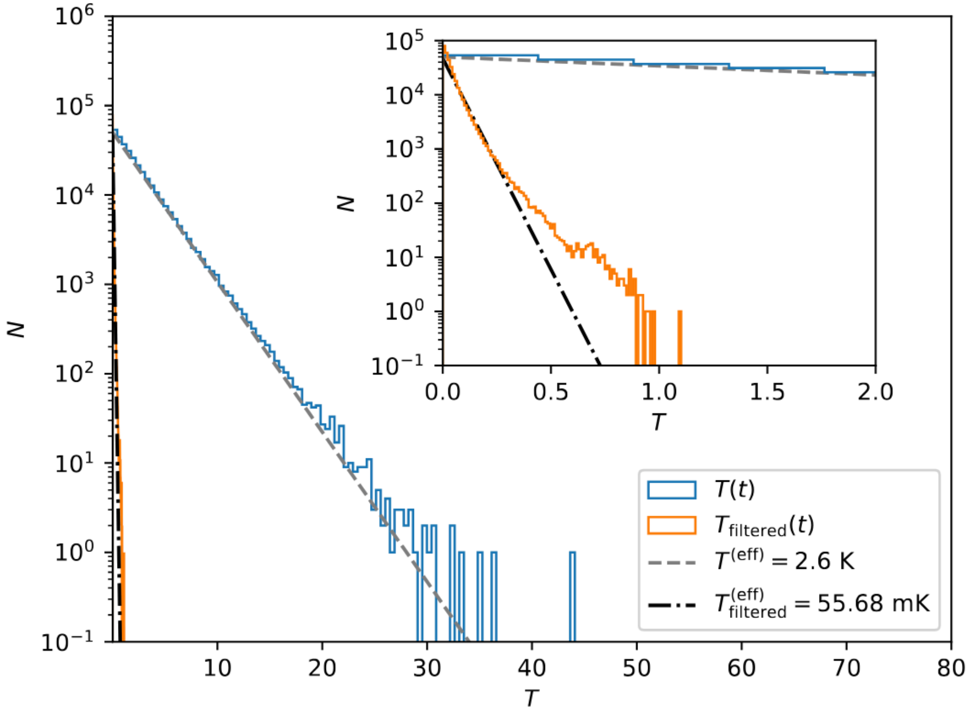
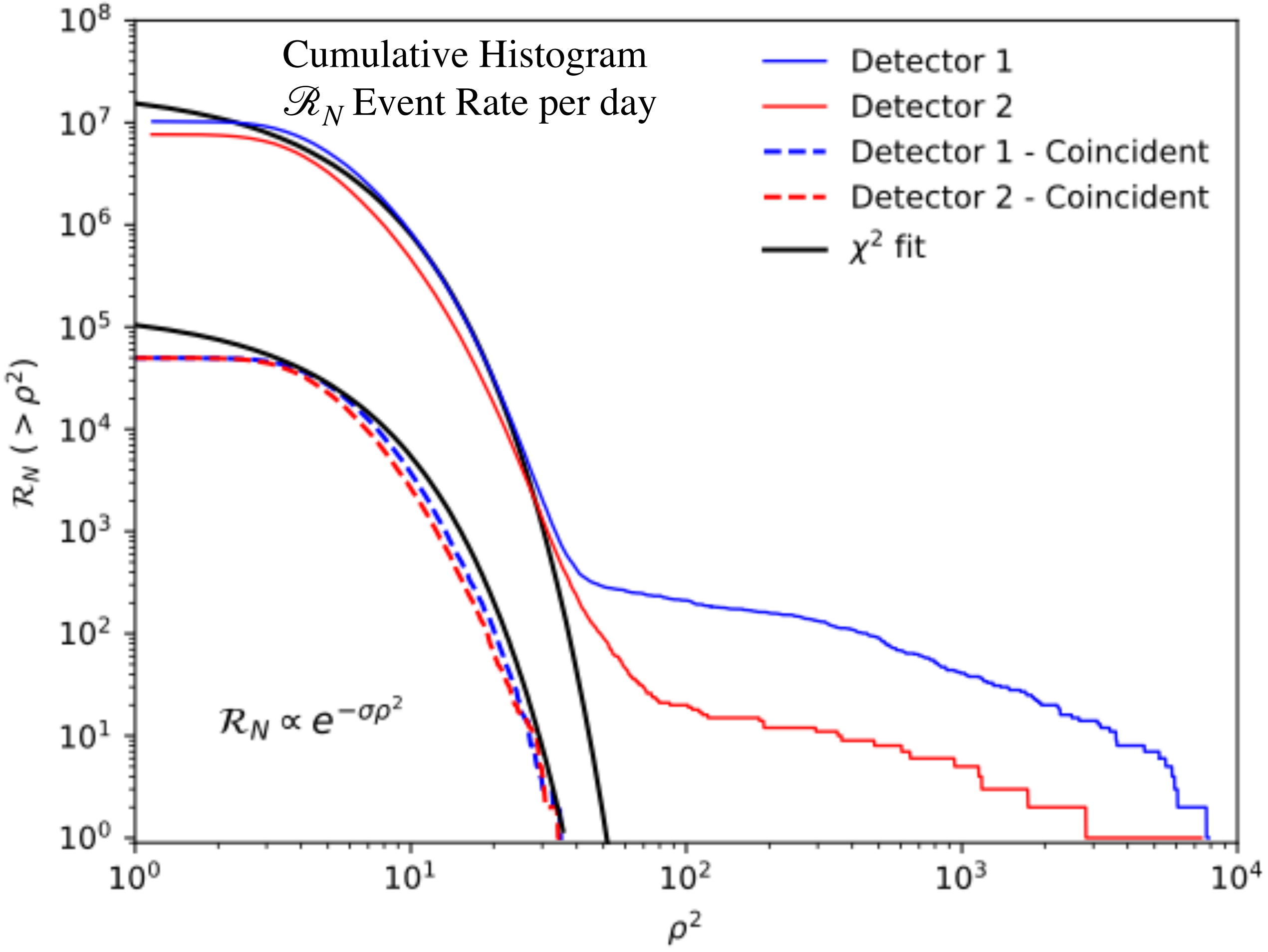
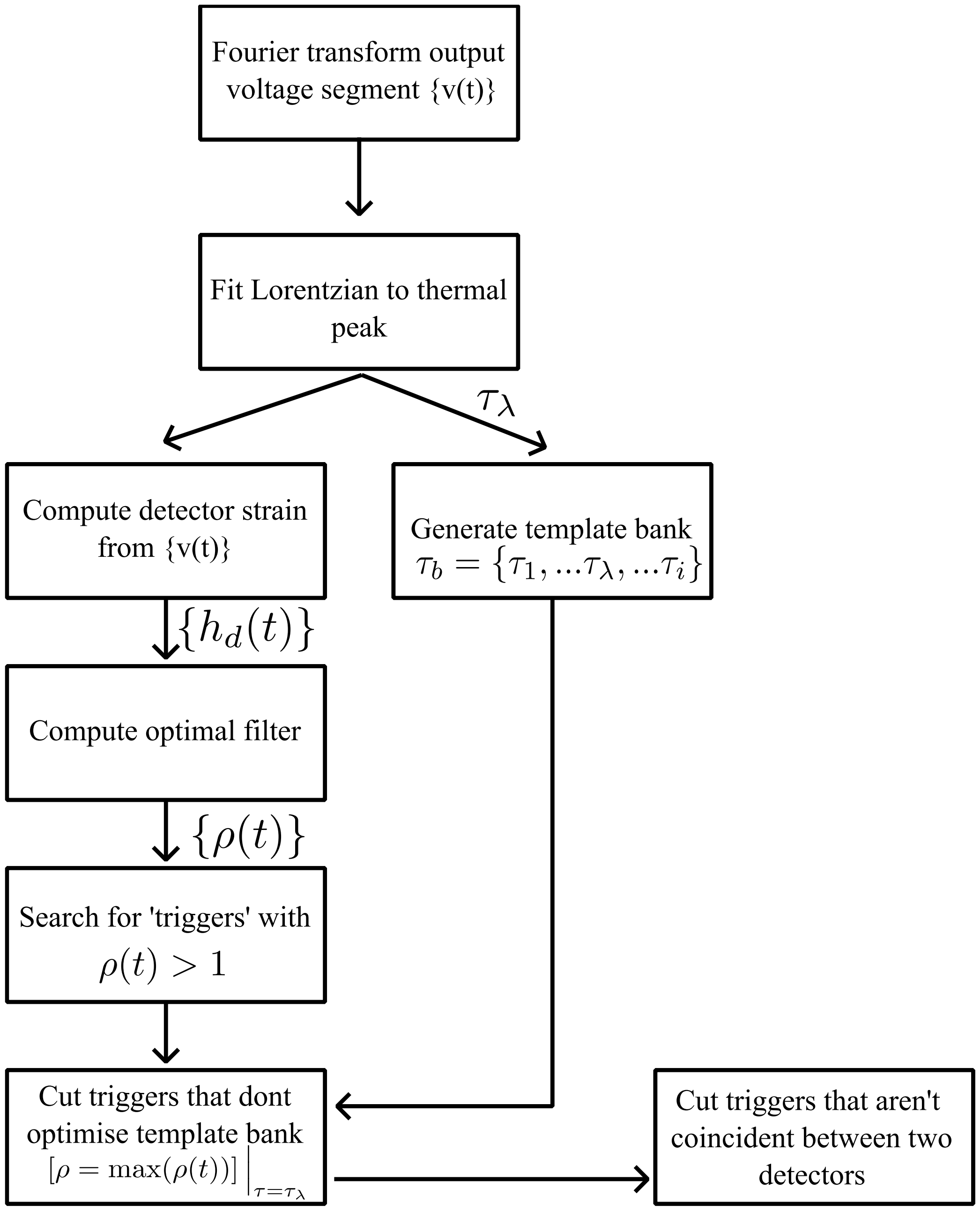


FIG. 2. Instantaneous vibrational energy of a single mode is plotted as a histogram for a 23 minute segment of data. The blue (orange) histogram represents the energy distribution before (after) optimal filtering. Both histograms clearly follow an expected χ^2 distribution, however the effect of optimal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

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

Data analysis pipeline





Applying the optimal filter

-> SNR as a time series ρ(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?

$P(t)$ ⇕

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

For a single mode

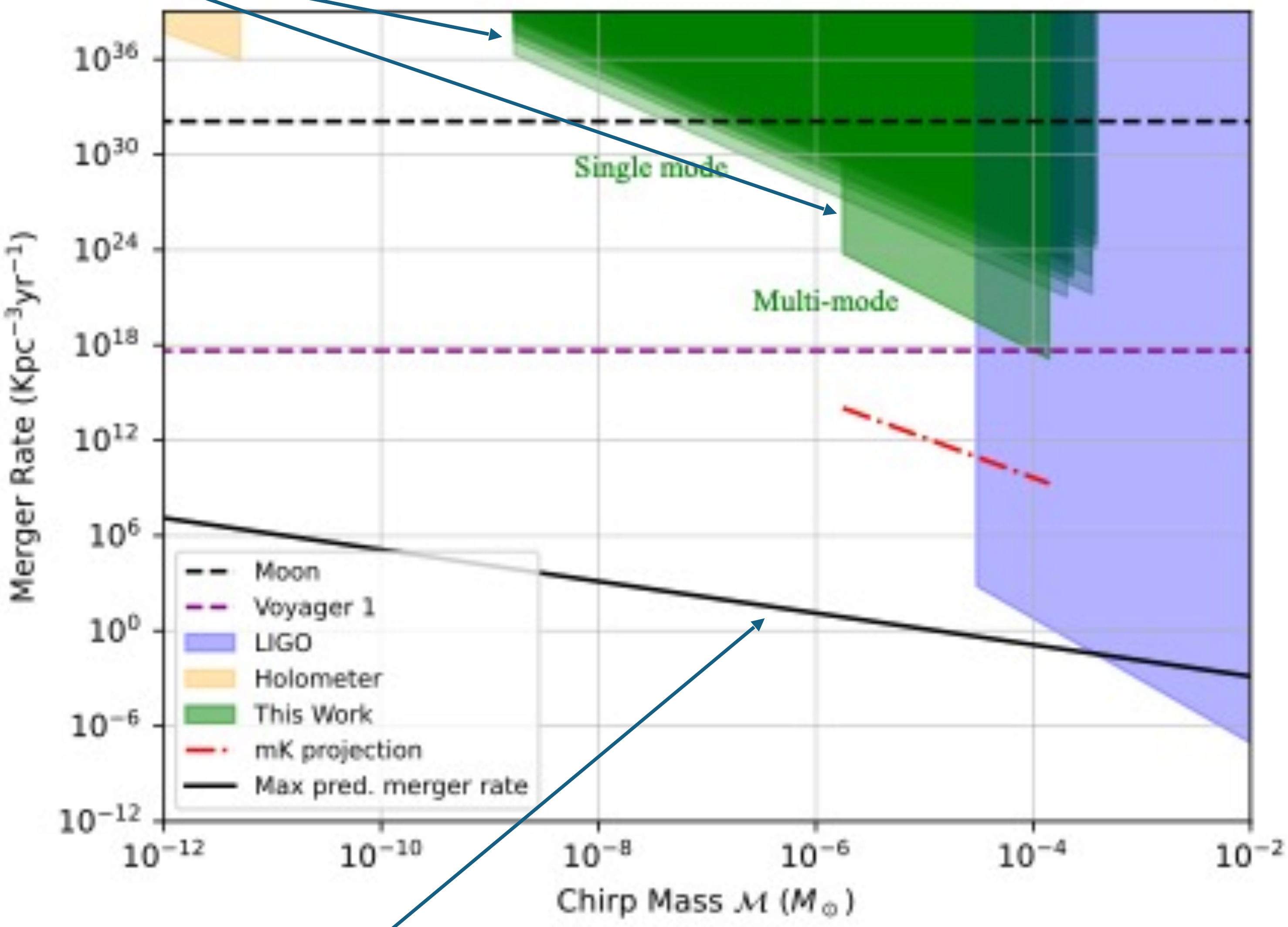
However, we can exploit the multi-mode nature of MAGE and consider an in spiral signal that passes Through the band of *every* mode in both detectors

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

Choosing a threshold 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

Lower bounds determined by sampling rate



Binary system of equal PBH mass ~ $4.4 \times 10^{-3} M_\odot$ Emits maximal HFGW at f = 5 MHz during its innermost stable circular orbit (ISCO)

Maximum predicted merger rate for 100% PBH dark matter

ORGAN (Oscillating Resonant Group AxioN Experiment)

RECENT PUBLICATIONS

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PHYSICS

Direct search for dark matter axions excluding ALP cogenesis in the 63- to 67-μeV range with the ORGAN experiment

Aaron Quiskamp[1]*, Ben T. McAllister[1,2]*, Paul Altin[3], Eugene N. Ivanov[1], Maxim Goryachev[1], Michael E. Tobar[1]*

PHYSICAL REVIEW D 109, 015013 (2024)

Tunable rectangular resonant cavities for axion haloscopes

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[1]*ARC Centre of Excellence for Dark Matter Particle Physics, Swinburne University of Technology, John St, Hawthorn Victoria 3122, Australia*
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(Received 2 October 2023; accepted 28 November 2023; published 16 January 2024)

PHYSICAL REVIEW LETTERS 132, 031601 (2024)

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

Aaron Quiskamp,[1,*] Ben T. McAllister,[1,2,†] Paul Altin,[3] Eugene N. Ivanov,[1] Maxim Goryachev,[1] and Michael E. Tobar[1,‡]
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RESEARCH ARTICLE Ann. Phys. (Berlin)2023,2200594
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Sensitivity of Resonant Axion Haloscopes to Quantum Electromagnetodynamics

Michael E. Tobar, Catriona A. Thomson, Benjamin T. McAllister, Maxim Goryachev, Anton V. Sokolov, and Andreas Ringwald*

RESEARCH ARTICLE Ann. Phys. (Berlin)2023,2200622
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Limits on Dark Photons, Scalars, and Axion-Electromagnetodynamics with the ORGAN Experiment

Ben T. McAllister, Aaron Quiskamp, Ciaran A. J. O'Hare, Paul Altin, Eugene N. Ivanov, Maxim Goryachev, and Michael E. Tobar*

PHYSICAL REVIEW D 111, 095007 (2025)

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

Aaron P. Quiskamp,[1,*] Graeme R. Flower,[1] Steven Samuels,[1] Ben T. McAllister,[1,2,†] Paul Altin,[3] Eugene N. Ivanov,[1] Maxim Goryachev,[1] and Michael E. Tobar[1,‡]
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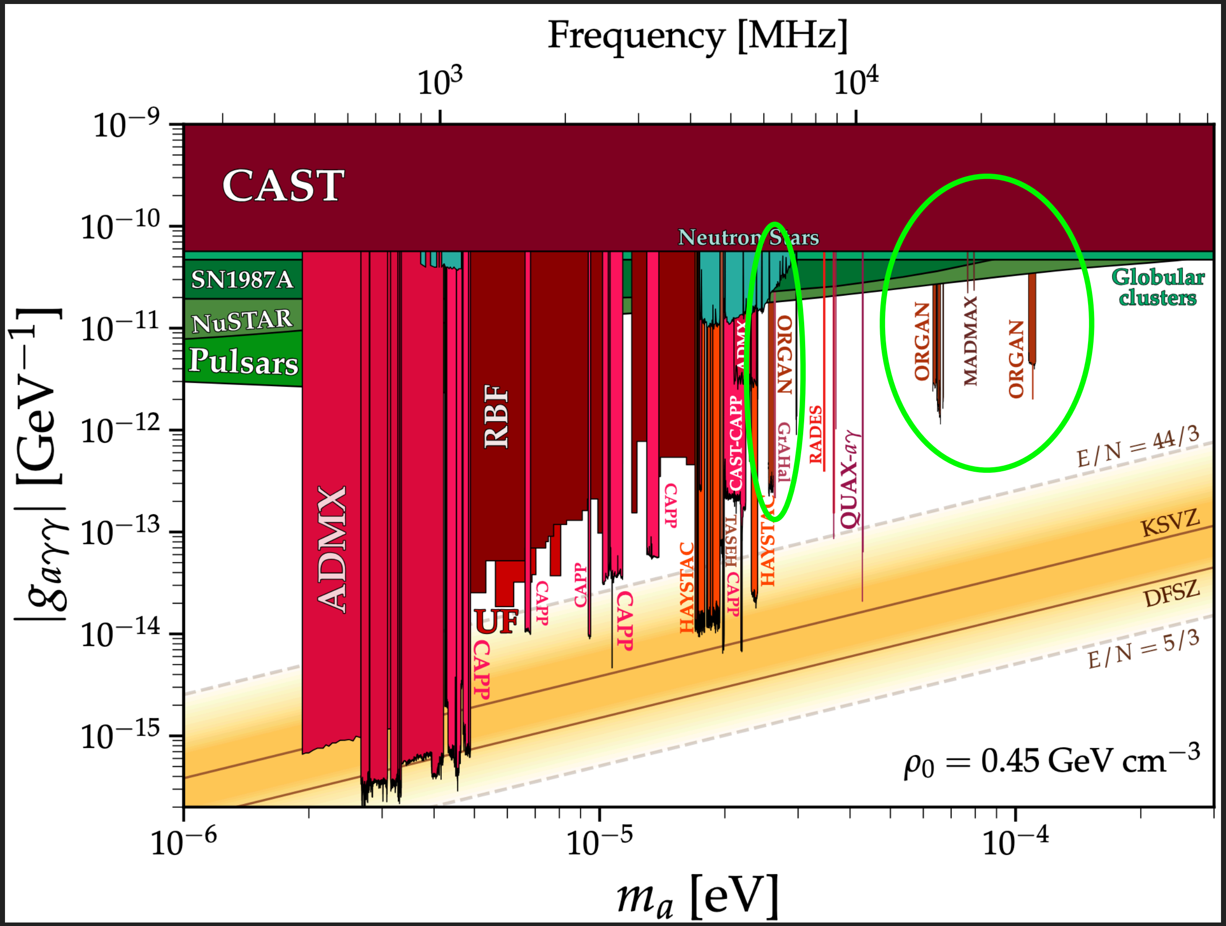
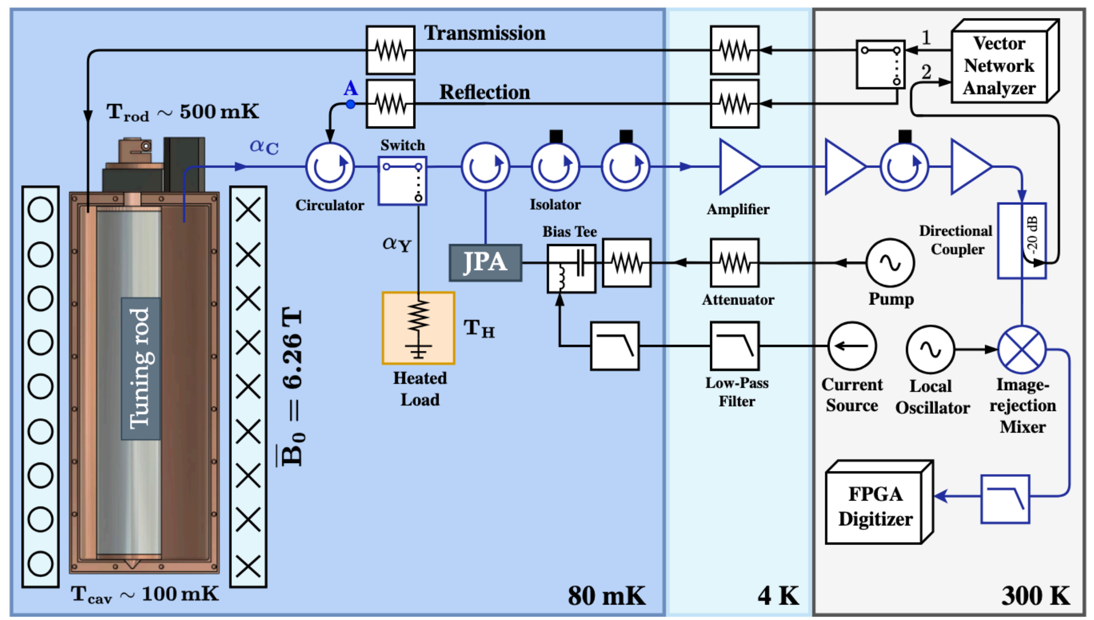
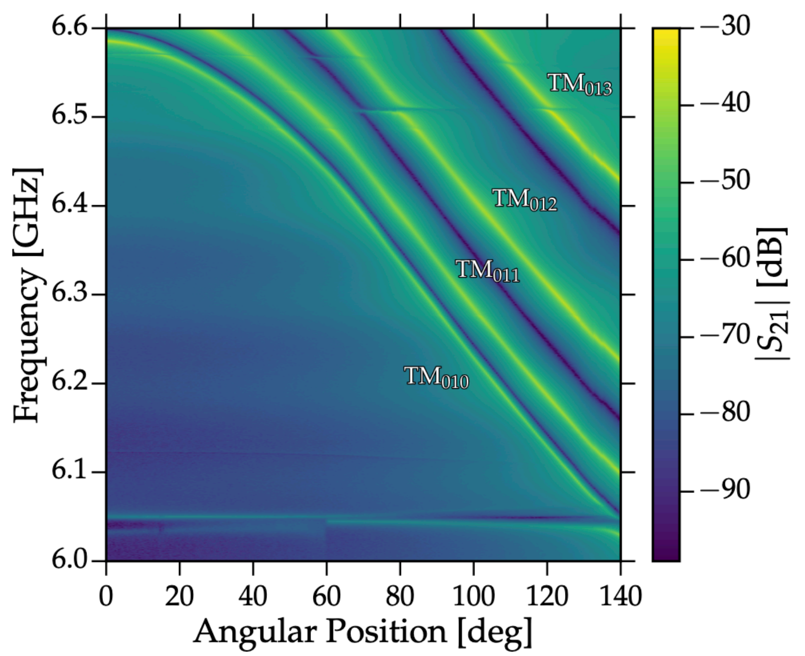
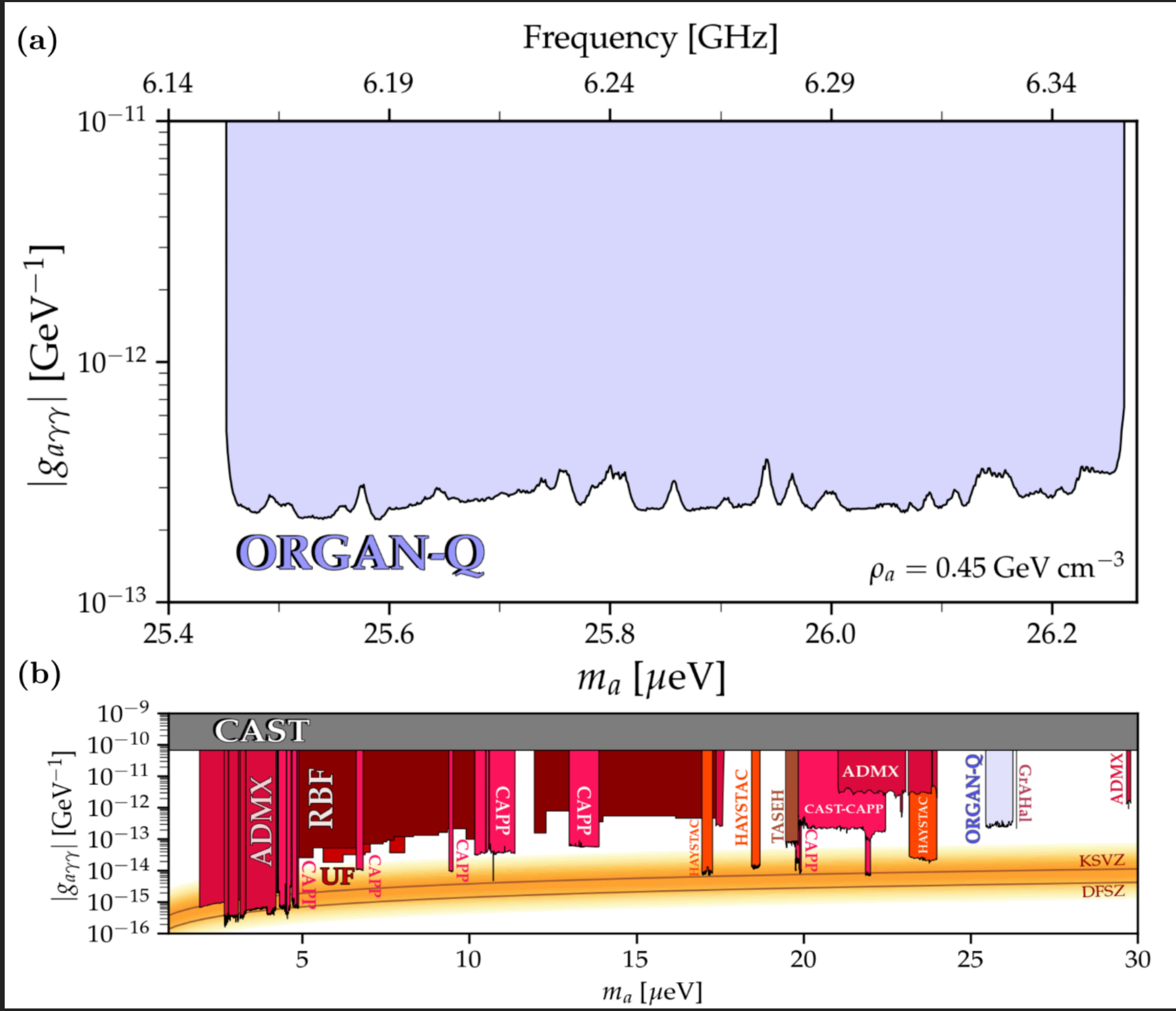
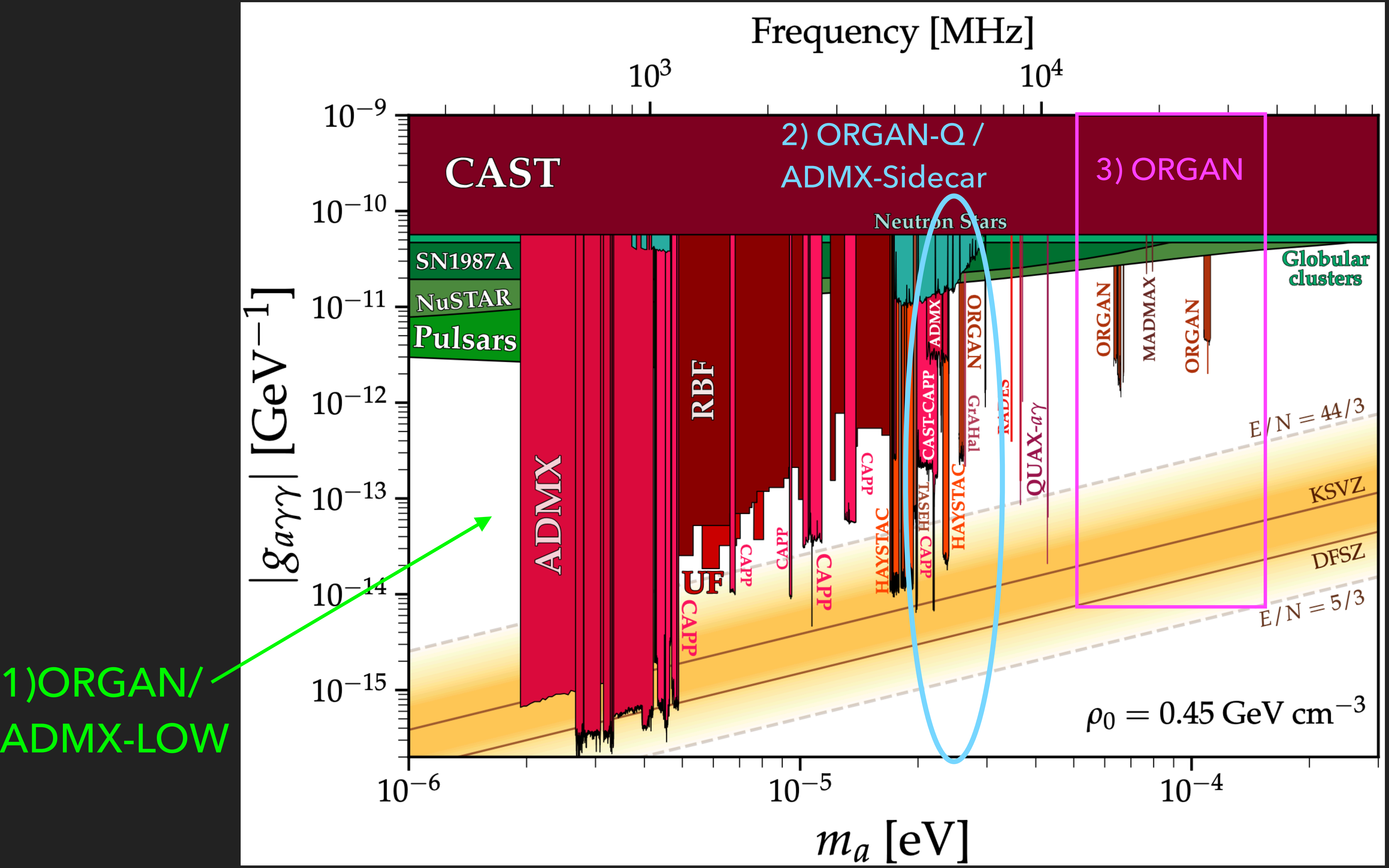


ORGAN -Q


Transmission
Reflection
Vector Network Analyzer
$T_{rod} \sim 500$ mK
Tuning rod
Circulator
Switch
Isolator
Amplifier
Directional Coupler
Bias Tee
JPA
Attenuator
Pump
Heated Load
T_H
Low-Pass Filter
Current Source
Local Oscillator
Image-rejection Mixer
FPGA Digitizer
$B_0 = 6.26$ T
$T_{cav} \sim 100$ mK
80 mK
4 K
300 K

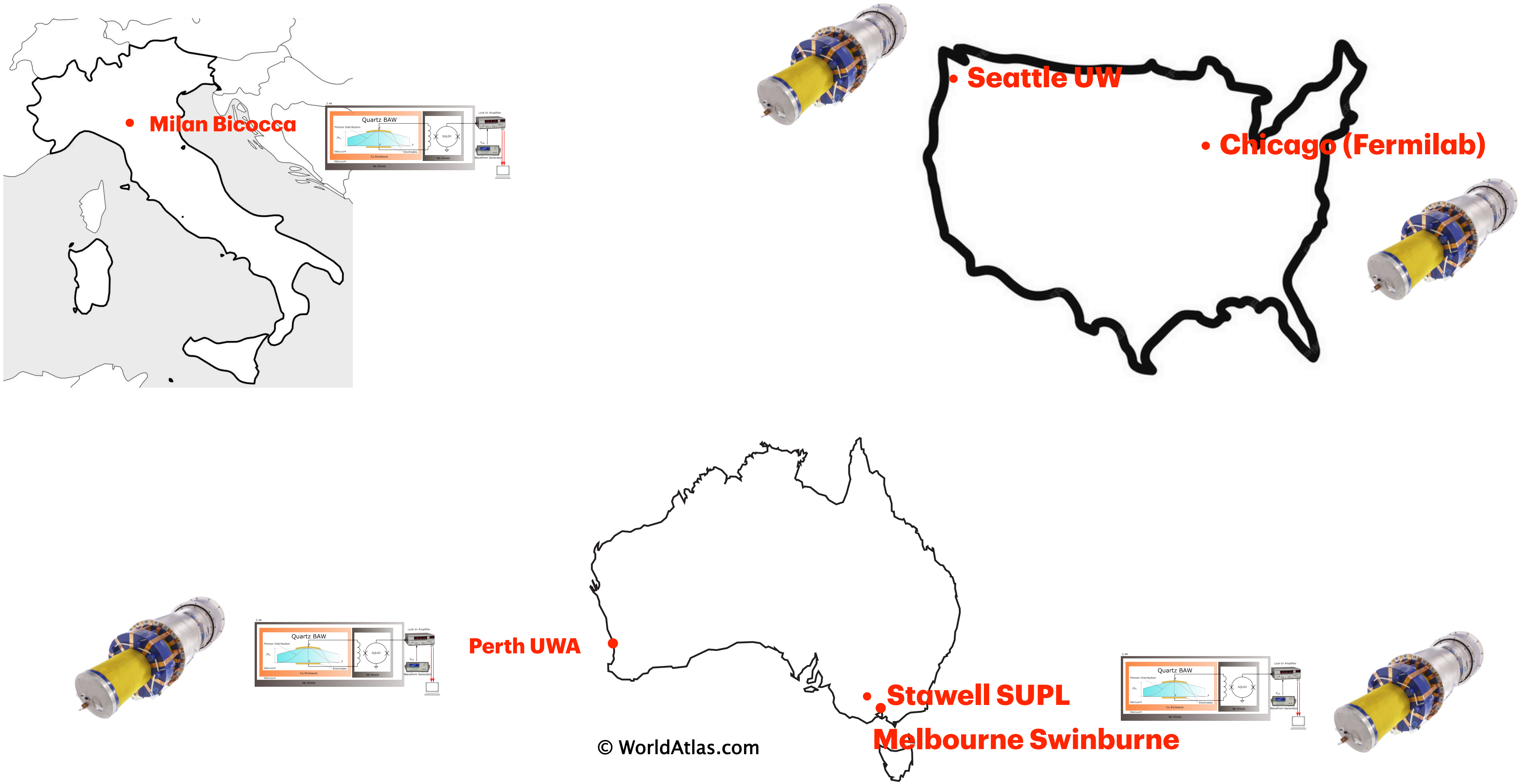

Frequency [GHz]
Angular Position [deg]
$|S_{21}|$ [dB]
TM_{013}
TM_{012}
TM_{011}
TM_{010}


(a)
Frequency [GHz]
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
ORGAN-Q
$\rho_a = 0.45$ GeV cm^{-3}
m_a [μeV]
(b)
CAST
ADMX
RBF
UF
CAPP
HAYSTAC
TASEH
CAST-CAPP
ORGAN-Q
GrAHal
KSVZ
DFSZ



Frequency [MHz]
CAST
2) ORGAN-Q / ADMX-Sidecar
3) ORGAN
Neutron Stars
SN1987A
NuSTAR
Pulsars
Globular clusters
ADMX
RBF
UF
CAPP
CAST-CAPP
HAYSTAC
TASEH
GrAHal
QUAX-aγ
MADMAX
ORGAN
E/N = 44/3
KSVZ
DFSZ
E/N = 5/3
$\rho_0 = 0.45$ GeV cm^{-3}
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]
1)ORGAN/ ADMX-LOW

Future Detector Networks



Linkage Infrastructure Equipment and Facilities

Applicants may seek funding for:

- infrastructure, equipment and facility purchases, construction and installation
- salaries directly associated with creating and installing infrastructure, equipment or facilities
- leasing of infrastructure, equipment or facilities
- consortium membership costs, in the case of Australia's participation in the use of significant international-scale or national research facilities
- specialised computing facilities and software compilations, catalogues, clearing houses or bibliographies.

The objectives of the LIEF scheme are to:

- support excellent basic and applied research and research training through the acquisition of research equipment and infrastructure and access to national and international research facilities
- encourage Eligible Organisations to develop collaborative arrangements with other Eligible Organisations and/or Partner Organisations for the acquisition and use of research equipment and infrastructure or access to national and international facilities.

The LIEF scheme provides project funding of a minimum of $150,000 per year to a maximum of 75% of the total direct cost of the eligible budget items. The grant duration is one year; or one to 5 years if the application is for leasing infrastructure, equipment or facilities, the construction of research infrastructure, or subscription or coordinated access to international facilities and major national facilities.