

Search for high-frequency gravitational waves with acoustic resonators

Università di Milano Bicocca, End of 1st year PhD seminar, cycle XLI, 10/09/2026

BAWSHA: Bulk Acoustic Wave Sensors for a High-frequency Antenna (BAUSCIA*)!

*) Bauscia /ba' uʃa/: braggart, boaster,
used mockingly to refer to the Milanese



- ❖ **Experiment overview**
- ❖ **Motivation**
- ❖ **BAWs: the acoustic sensors**
 - Physics of the piezoelectric resonators
 - (Preliminary) characterization work
- ❖ **DC SQUIDS: the superconducting amplifiers**
 - Calibration work (Johnson thermometry)
- ❖ **Analysis of a prototype detection line**
 - Resonator thermal noise
 - Measurement of modal effective temperatures
 - Backaction exclusion and fundamental thermal limit
 - Sensitivity projections
 - Readout chain
- ❖ **Current status and next steps**
- ❖ **Conclusions & other activities**



Detection concept

- Follows the concept of a seminal proposal by M. Goryachev and M. Tobar, [PRD 90,102005 \(2014\)](#)

◆ A two-stage plan for a resonant mass detector sensitive to multiple frequencies

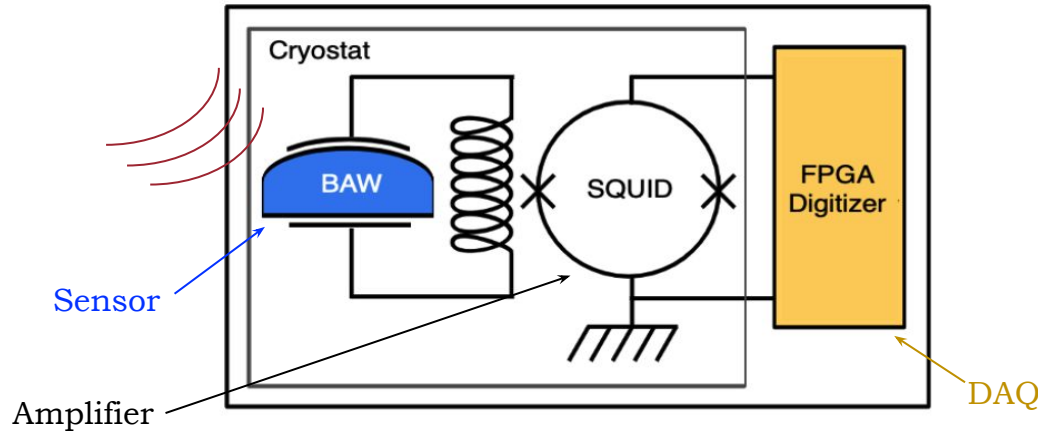
- Multimode antenna w/ commercially available quartz BAWs
- Array of customized BAWs to cover a broad spectrum of frequencies

- Clock standard 5.175 MHz
- Different thicknesses



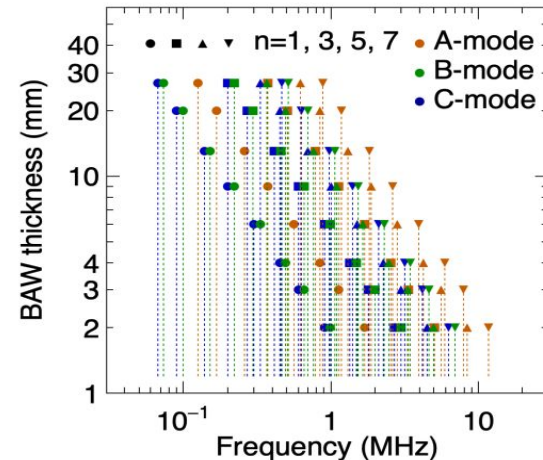
EOM for
mode λ

$$\ddot{a}_\lambda + \gamma_\lambda \dot{a}_\lambda + \omega_\lambda^2 \underbrace{a_\lambda}_{\propto \text{Resonator displacement}} = -c^2 \underbrace{R_{0i0j}}_{\text{GW}} \int_V \frac{\rho}{m_\lambda} \underbrace{U_\lambda^i(\mathbf{x}, t)}_{\text{resonator displacement}} \underbrace{x^j}_{\text{mode mass}} dV$$



$$f_{n,X} = n \frac{v_X}{2d}, \quad (n = 1, 3, 5, \dots; X = A, B, C)$$

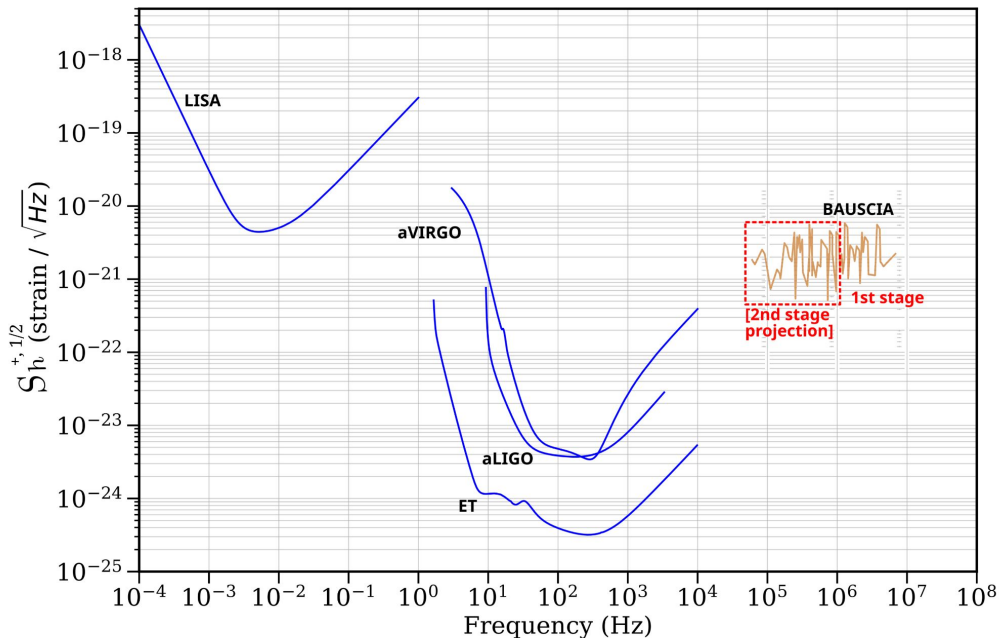
GW-driven **cryogenic,**
piezoelectric resonator



Why? GW sources at 0.1-10 MHz

◆ Potential ground for discoveries

- No known astrophysical sources [e.g., beyond stellar black-holes and neutron star mergers cut-offs]



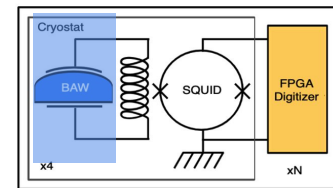
◆ Hypothetical sources include

- **Primordial black hole (PBH) binary mergers** [[Franciolini et al \(2022\)](#), [Haque et al \(2026\)](#)]
- **Axion clouds** collapsing into a massive black hole [[A. Arvanitaki et. al \(2011\)](#)]
- **QCD phase transition** in supernovae [[K. Bleau et al \(2026\)](#)]
- **Post-merger emission** from QCD phase transitions in neutron-star binaries (~600 kHz) [[Casalderrey-Solana et al. \(2022\)](#)]
- **Non-GW events:** ultralight DM candidates [[Manley et al. \(2020\)](#), [Trickle \(2025\)](#), [Arvanitaki et al. \(2024\)](#)]

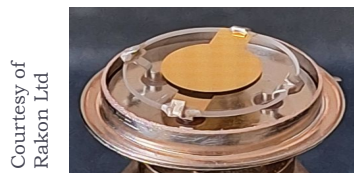
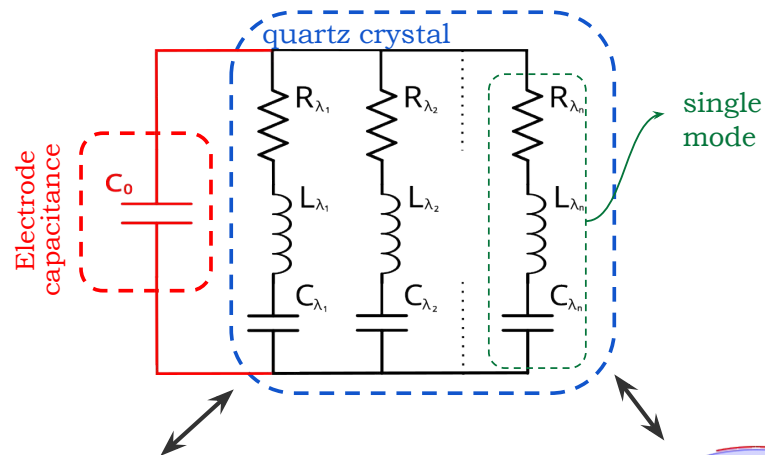
BAW: the strain sensor

❖ Quartz BAW → multi-resonant device

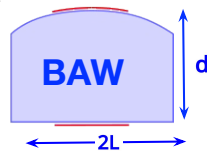
- sustains **longitudinal (A)**, **fast shear (B)** and **slow shear (C)** acoustic modes
- piezoelectrically transduces odd overtones ($n=1, 3, 5, \dots$) of each mode ($X=A,B,C$); $\lambda=X_n$ indexes the mode



❖ Electrical-equivalent model (BVD)



Plano-convex shape
(mode confinement)



❖ BAW's thermal noise constrains sensitivity (until well below $T=100$ mK)

Strain sensitivity for mode λ (on resonance, thermal limit):

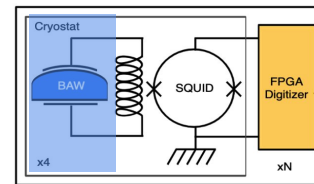
$$S_h^{+1/2}(\omega_\lambda) = \frac{8}{d\xi_\lambda} \sqrt{\frac{k_B T_\lambda}{m_\lambda Q_\lambda \omega_\lambda^3}} \propto \frac{n}{L} \sqrt{\frac{k_B T_\lambda}{Q_\lambda \rho v_\lambda^3}}$$

$\xi \rightarrow$ GW coupling: $O(1)$ $d \rightarrow$ BAW thickness $m \rightarrow$ effective mass $\rho \rightarrow$ mass density
 $\omega \rightarrow$ (angular) resonance $Q \rightarrow$ Quality factor $T \rightarrow$ effective temperature $v \rightarrow$ sound velocity
 $n \rightarrow$ overtone $L/2 \rightarrow$ BAW radius

❖ Rule of thumb [important for stage 2]:

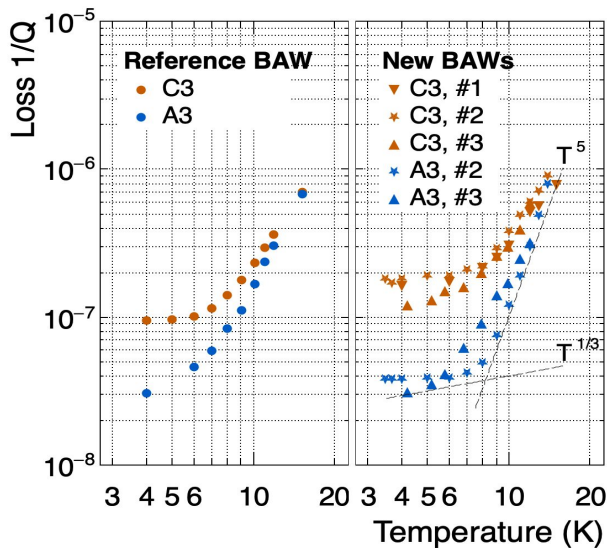
- Large radius (L)
- Fast crystal (v)
- Low overtones (n)

Stage 1: BAW characterization

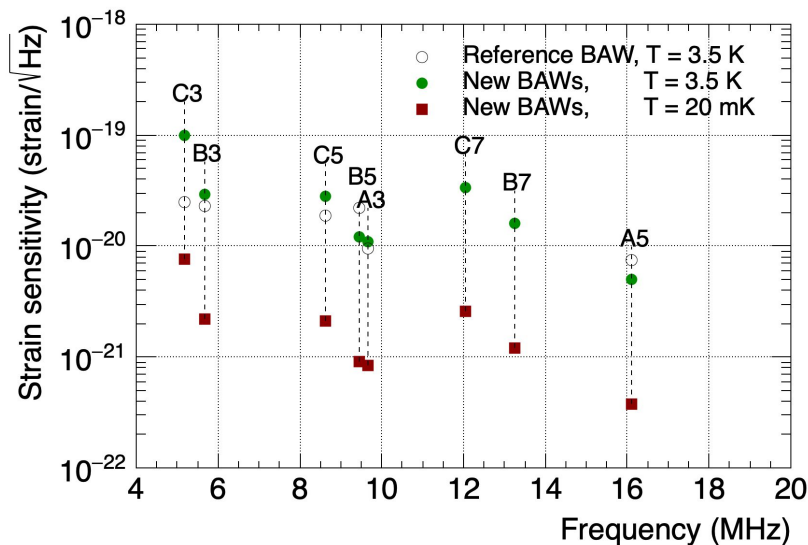


◆ Preliminary BAW characterization on commercial resonators is described in [\[Albani et al. 2025\]](#)

- Comparable performance wrt a reference BAW provided by collaborators at UWA (MAGE experiment, [W Campbell et al. 2024](#))

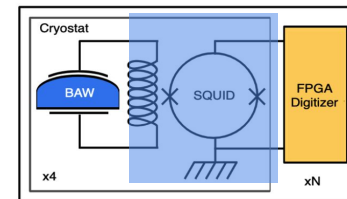


- Comparable losses ($Q \lesssim 10^7$) and temperature scaling



- Sensitivity improvement at mK temperatures

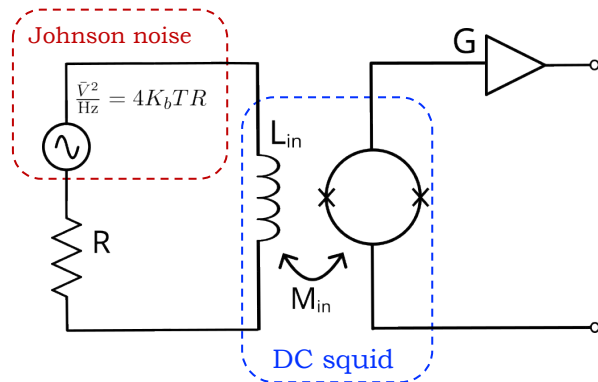
DC SQUID calibration



❖ Observation of Johnson spectrum of a 100 mΩ resistor

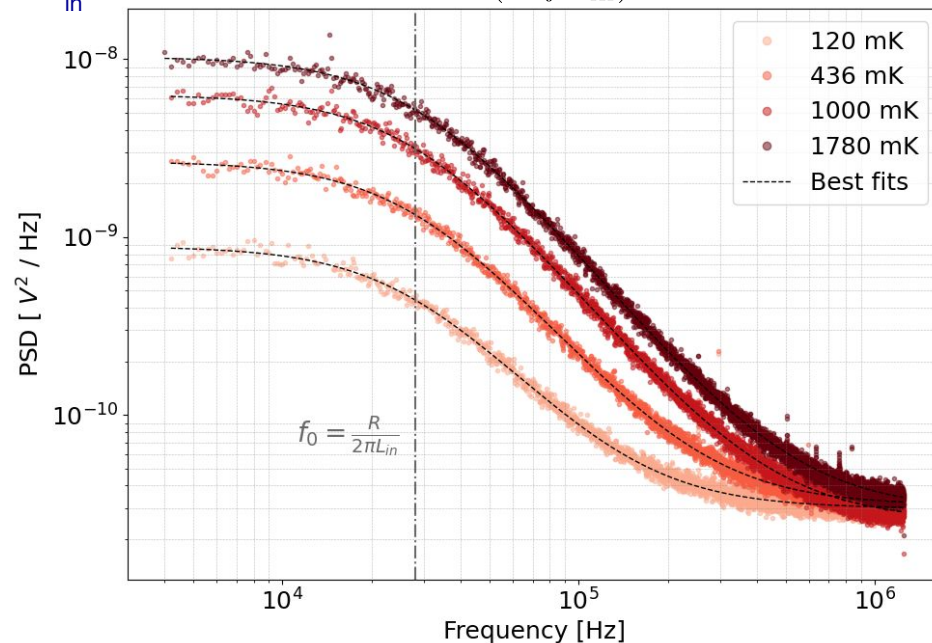
- White Johnson noise, RL cutoff at $f_0 = R / 2\pi L_{in} \approx 30$ kHz
- Independent measurement of SQUID's input coil L_{in} !

$$S_{vv}(f) = \frac{(GV_{\Phi} M_{in})^2 4K_b T R}{(2\pi f L_{in})^2 + R^2} + N_{\text{squid}}^2$$

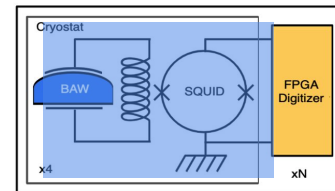


$$L_{in} = (560 \pm 10) \text{ nH}$$

(against a nominal value of 400 nH)

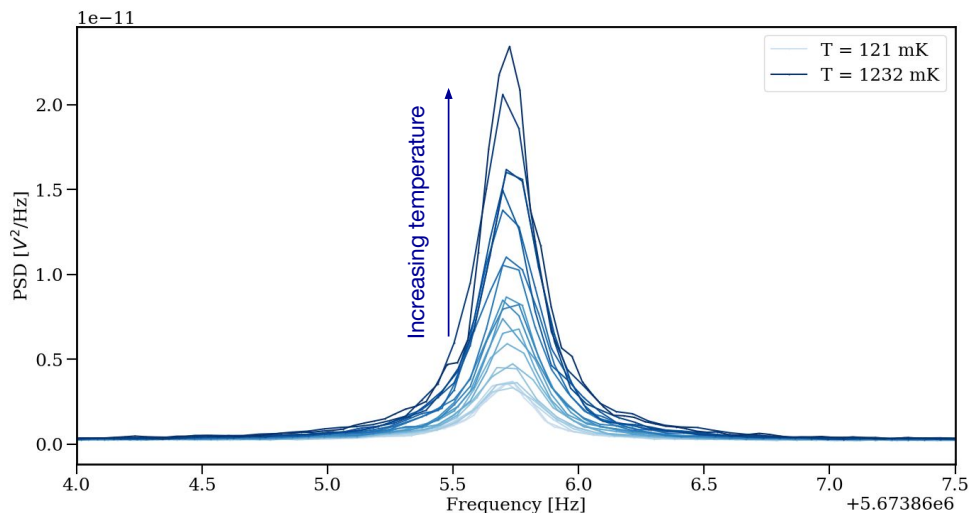
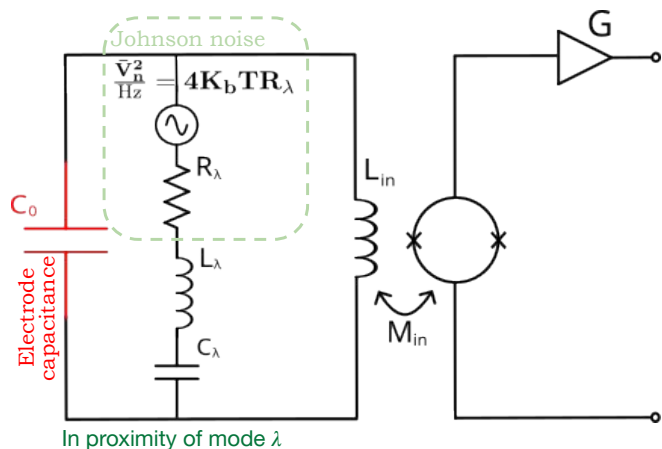


BAW's thermal noise



Tone 3B

- ❖ Varied cryostat temperature and monitored thermal peaks



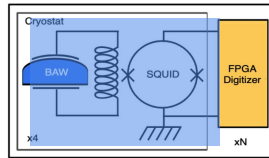
- ❖ Circuit model for measured PSD:

$$S_{vv}(\omega) \approx \frac{(M_{in} G V_{\Phi})^2 4K_b T R_{\lambda}}{\left| R_{\lambda} + j \left(\omega (L_{\lambda} + L_{in}) - \frac{1}{\omega C_{\lambda}} \right) \right|^2}, \quad \text{for } \omega \ll 2\pi \times 200\text{MHz}$$

$$\frac{A^2}{1 + [(f - f_0)/\Gamma]^2} + b g^2$$

Analytical Lorentzian re-parametrization!

Modes' effective temperatures



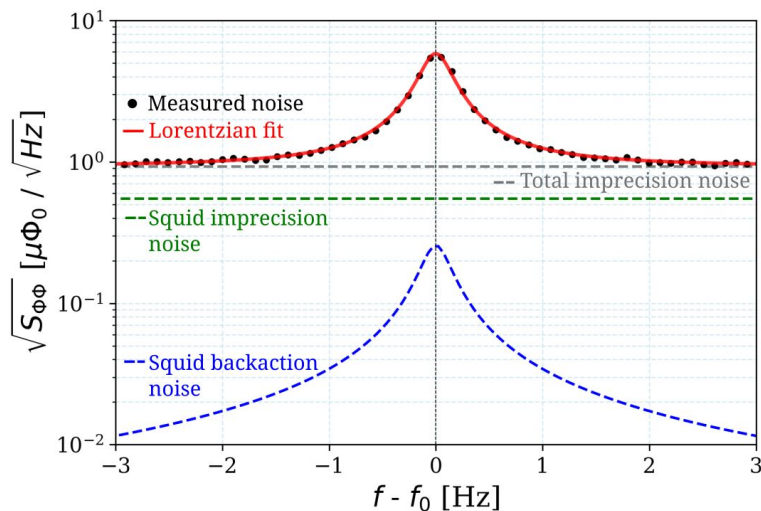
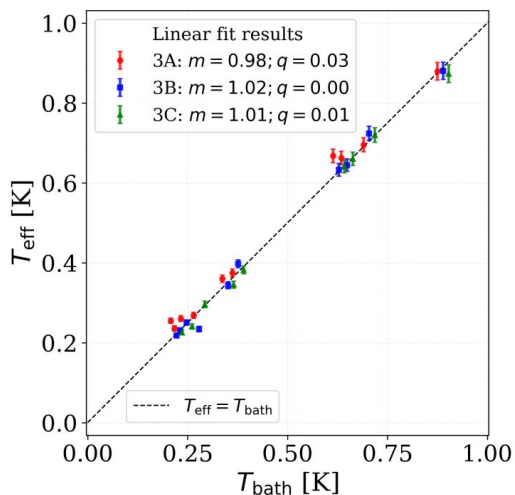
Estimation of Lorentzian's parameters □ info about resonator's thermal state:

∝ peak height! $A^2 = (GV_\Phi M_{in})^2 4K_b \frac{T_{eff}}{R_\lambda}$

- R_λ known from previous impedance analysis → retrieve T_{eff}

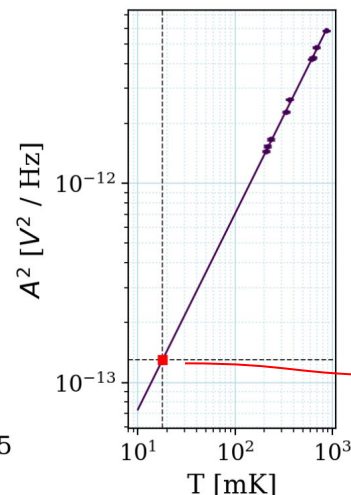
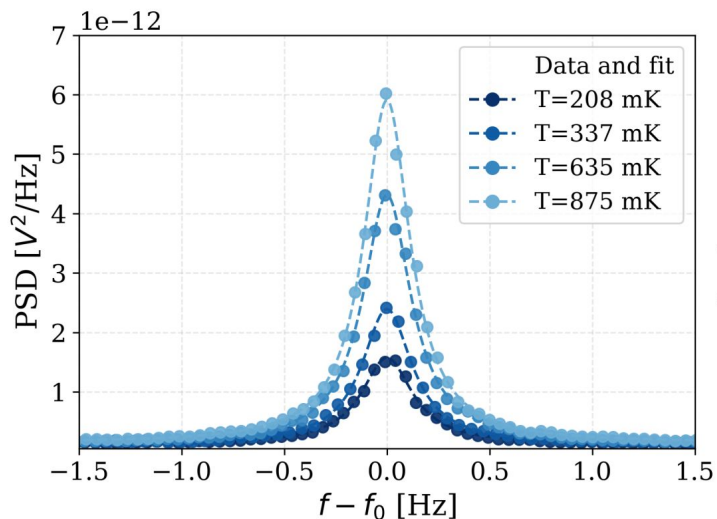
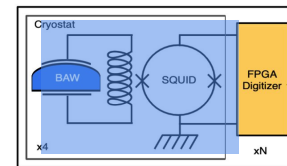
➤ Experimental **exclusion of SQUID backaction** on our BAW!

Tesche-Clarke theory predicts SQUID noise [[Ankel et al, 2025](#)]



- Imprecision: total noise
- Backaction: SQUID noise reflected back in input circuit (BAW)
→ would alter our signals!
- Both experiment (plot 1) and theory (plot 2) exclude backaction in our system!

Operation temperature and fundamental thermal limit



❖ Left
Lorentzian fit on 3B mode

❖ Right
Extrapolation of Lorentzian peak height towards lower temperatures (3B mode).

❖ **Red marker** ■
temperature $T_{\min}$ where the peak height (thermal noise) equals the flat background (readout imprecision noise)

Mode	Frequency [MHz]	Q -factor $\times 10^7$	$T_{\min}$ [mK]
3C	5.167945	0.5	71
3B	5.689657	1.9	18
5C	8.593922	3.4	18
5B	9.464173	10.3	8
3A	9.741681	3.2	31
5A	16.218829	6.4	55

At 10 mK (cryostat base temperature)

some modes would start to deviate from the sensitivity **fundamental thermal limit!** (see next slide)

Sensitivity projection

Strain Sensitivity
[strain / Hz^{1/2}]

$$S_h^{+1/2}(\omega_\lambda) = \sqrt{S_{h,T}^+(\omega_\lambda) + S_{h,R}^+(\omega_\lambda)} = \frac{4}{d\tilde{\xi}_\lambda} \sqrt{\frac{4k_B T_\lambda}{m_\lambda Q_\lambda \omega_\lambda^3} + \frac{S_{\Phi\Phi}}{\kappa_L^2 M_{in}^2 Q_\lambda^2 \omega_\lambda^2}}$$

Resonator thermal noise
(strain-referred) PSD

Readout imprecision noise
(strain-referred) PSD

$\xi \rightarrow$ GW coupling: O(1)

$d \rightarrow$ BAW thickness

$m \rightarrow$ effective mass

$\omega \rightarrow$ (angular) resonance

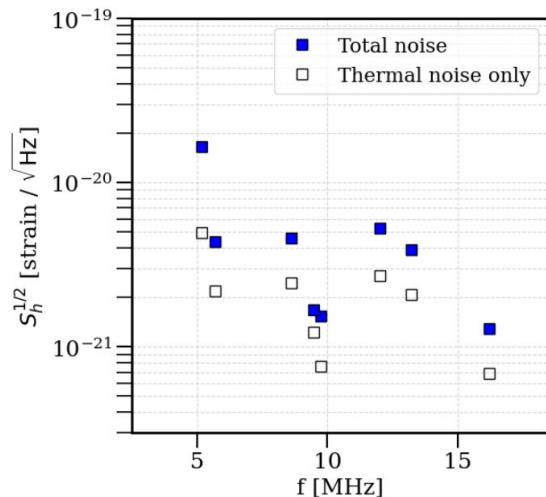
$Q \rightarrow$ Quality factor

$T \rightarrow$ effective temperature

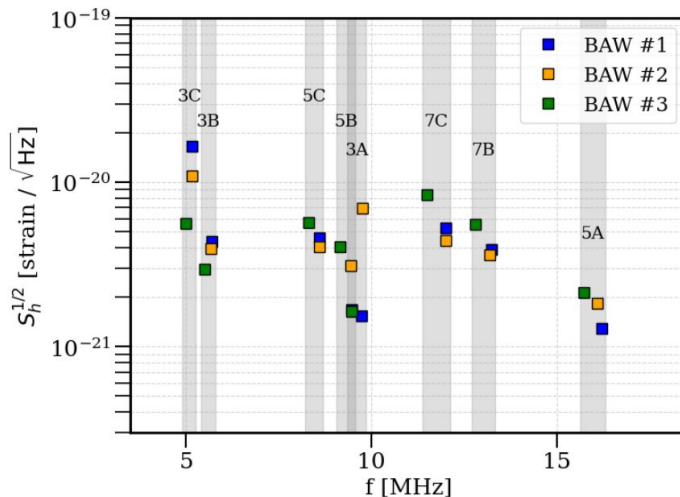
$S_{\Phi\Phi} \rightarrow$ Readout flux noise PSD

$M_{in} \rightarrow$ Squid coupling

$\kappa_L \rightarrow$ BAW electro-mechanical coupling



20 mK projections for the measured prototype line (T=20 mK)



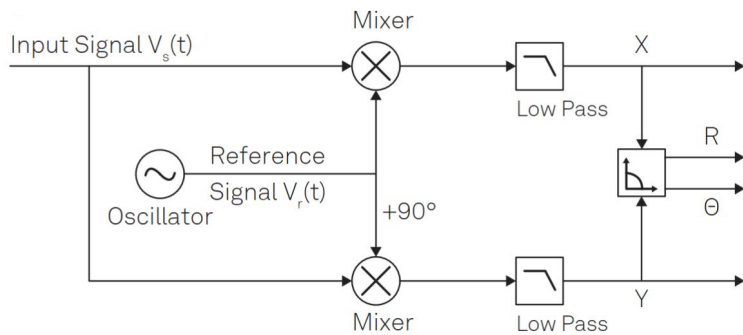
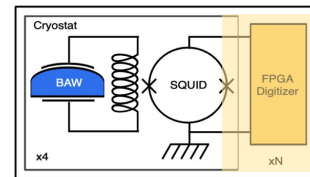
Sensitivity projections for the BAUSCIA array (3 channels) which is currently running :D (Again, T = 20 mK)

Left:

Full sensitivity (thermal + readout noises) vs thermal limit; no more than ~2x discrepancy.

- Operating **near fundamental limit**
- upgrade to **lower-noise readout** will help us gain something!

Readout chain



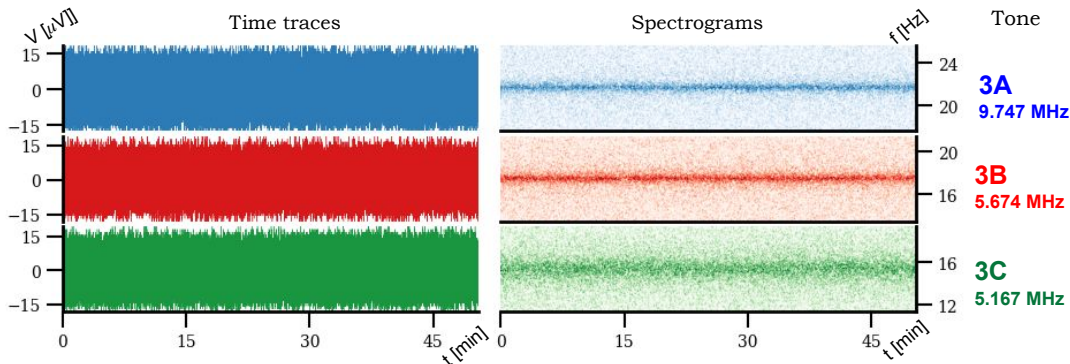
LOCK-IN amplification

- Quadrature readout scheme
- Shifts signal at $f_{\text{sig}} - f_{\text{LO}}$ and $f_{\text{sig}} + f_{\text{LO}}$ filtered out
- Effectively: demodulation of RF signal near DC

RFSoc-based DAQ (Xilinx Zynq FPGA RFSoc4x2)

- Customizable number of lock-ins on each of the 4 ADC inputs
- Parallel readout of multiple tones for each BAW!
- In-house developed firmware!
- GPS synced clock! (OCXO)

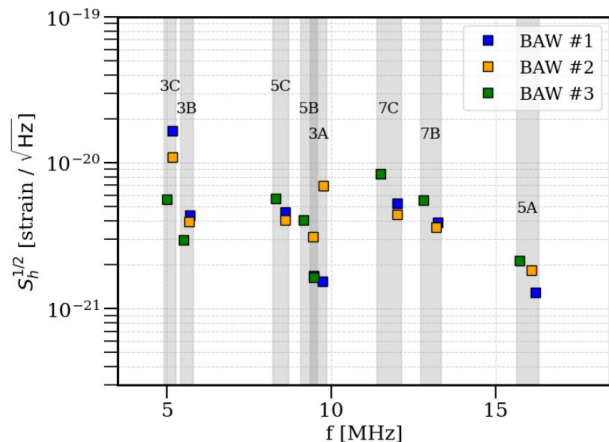
DAQ stability recently tested



Next steps

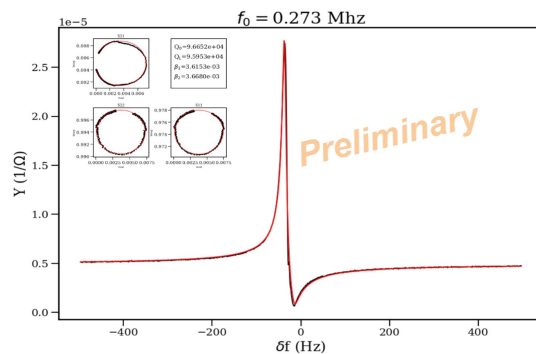
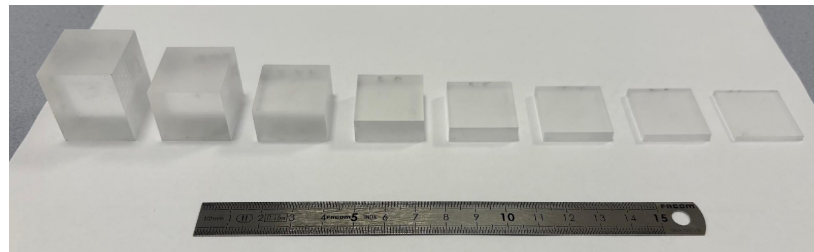
❖ Ongoing experimental run!

- 3 characterized BAWs, 3 characterized squids



- **Multi-site detection** with MAGE at the University of Western Australia [currently running!]
- Possible synergies with other HFGW approaches like Gravnet EU ([Amaral et al. 2026](#))

❖ Working on 2nd stage of experiment!



Customization of thicker quartz crystals for lower frequency coverage!

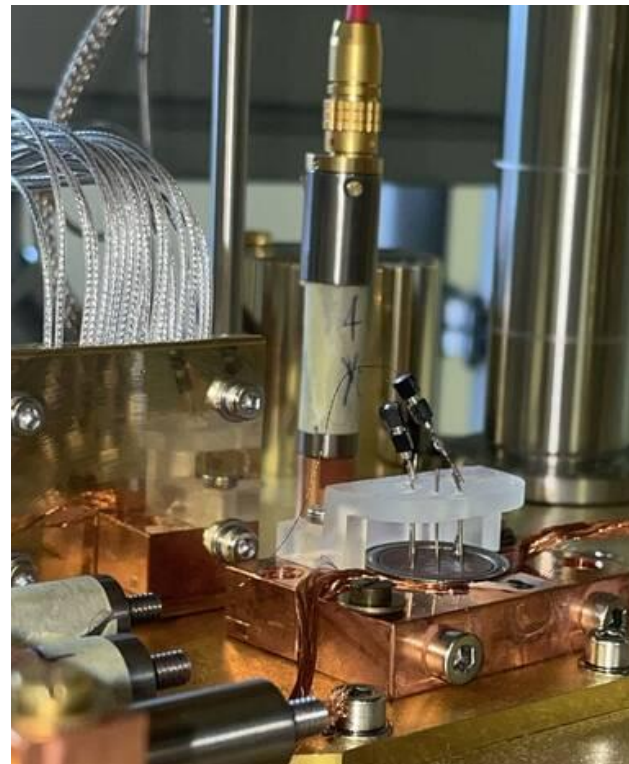
❖ Thinking of a quantum readout to enhance sensitivity!

Conclusions

- First stage resonators → characterized ✓ [[Albani et al. 2025](#)]
- DC squids → calibrated ✓
- Prototype channel → characterized and well understood ✓
- Experimentally excluded squid backaction ✓
- Currently measuring w/ MAGE at UWA! ✓

- Data analysis pipeline 
- Thicker crystals 
- Quantum readout 

Thank You



Other activities

◆ Conferences

- 1st BiCoQ Conference: from Gravity to particles, 15–19 June 2026

◆ Schools

- Quantum sensing for fundamental physics, CERN, 24-28 Aug 2026

◆ Courses

- Multidisciplinary
 - Productivity tools for (young) researchers (1 ects)
 - Philosophy of AI and robotics (1 ects)
 - Transferable competences and professional transitions (1 ects)
- Specific (Physics)
 - Microwave engineering (2 ects)

◆ Teaching assistance

- Tutoring classes for the “FISICA II” course (2nd year undergraduate)
- Academic tutor for “Teaching and Learning of Algebra” course
- Subject Matter Expert on the Teacher Licensing Examination Board