BAWSHA: **B**ulk **A**coustic **W**ave **S**ensors for a **H**igh-frequency **A**ntenna (BAUSCIA*)!)

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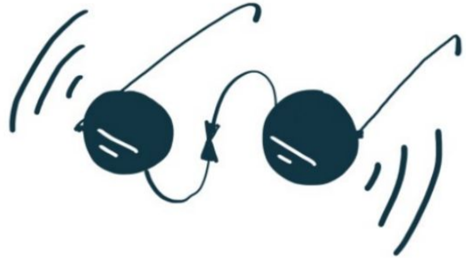
(University of Western Australia)



BAUSCIA!

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*) Bauscia /baˈuʃa/: braggart, boaster, used mockingly to refer to the Milanese

Detection concept

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

❖ A <u>two-stage</u> plan for a resonant mass detector sensitive to multiple frequencies

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

☐ Clock standard 5.175 MHz ✓

☐ Different thicknesses 🚧

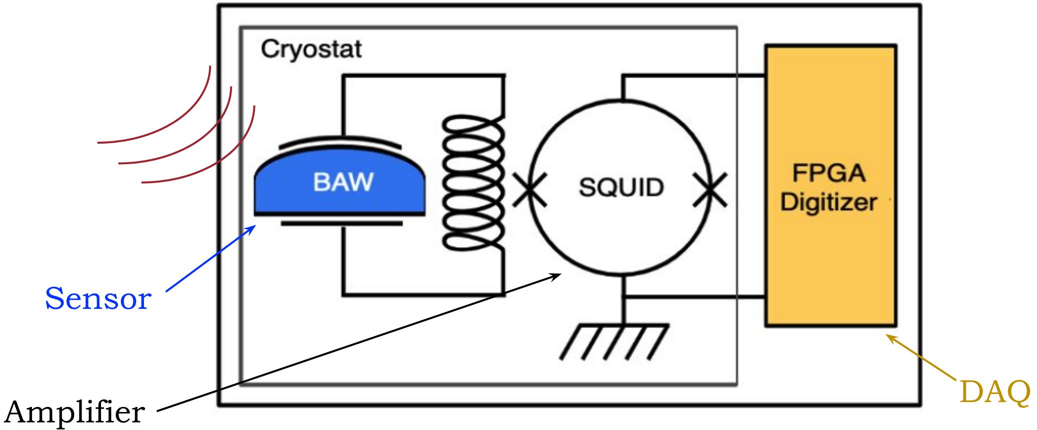
EOM for mode λ

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

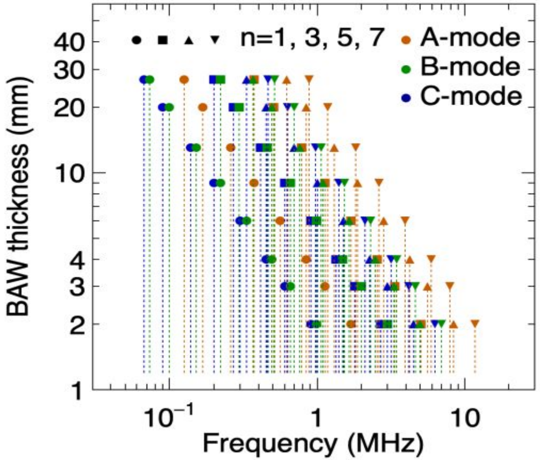
resonator displacement

mode mass

GW-driven **cryogenic**, **piezoelectric** resonator



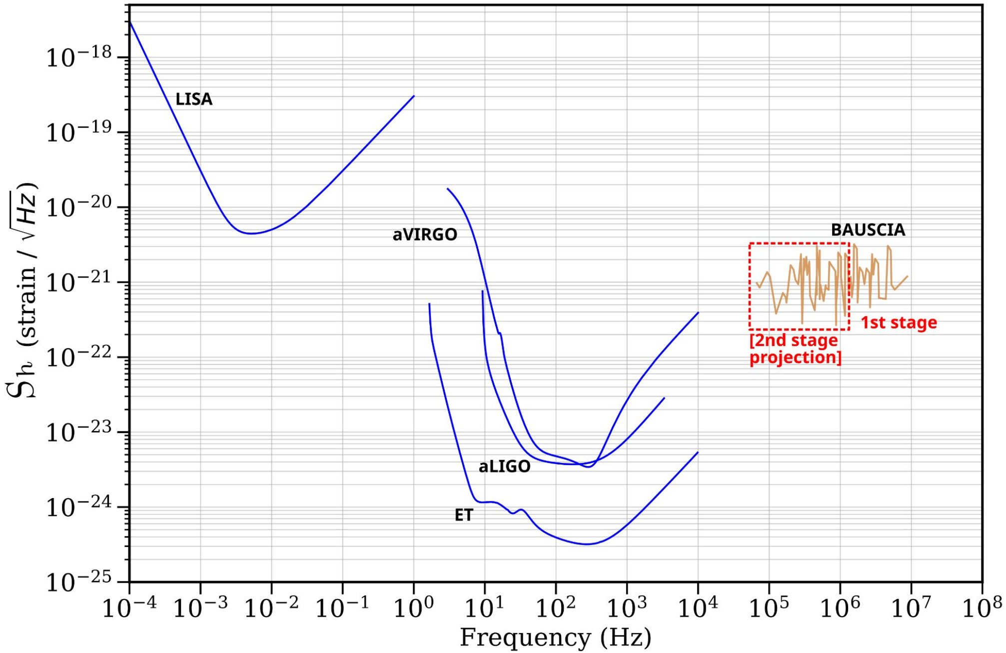
$$f_{n,X} = n\frac{v_X}{2d}, \qquad (n = 1, 3, 5, \ldots; X = A, B, C)$$



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**

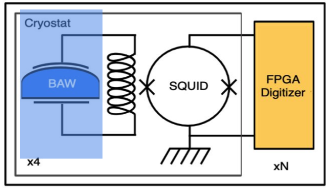
➢ **Primordial black hole** (PBH) binary mergers [Franciolini et al (2022), Haque et al (2026)]

➢ **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)]

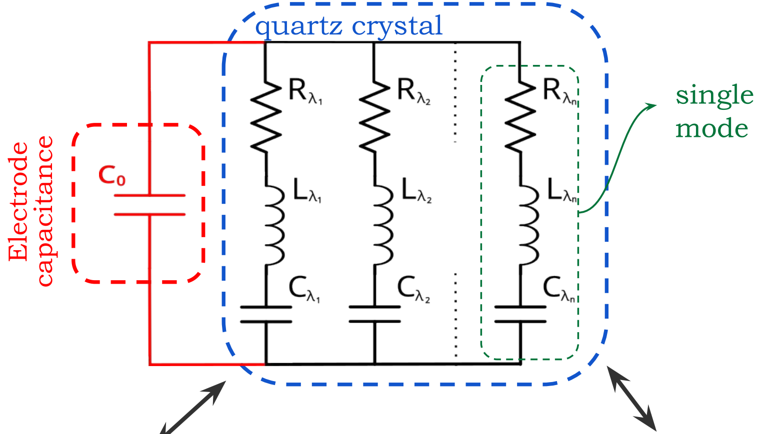
BAW: the strain sensor

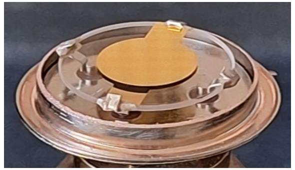


❖ Quartz BAW → multi-resonant device

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

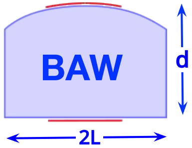
❖ Electrical-equivalent model (BVD)





Courtesy of Rakon Ltd

Plano-convex shape (mode confinement)



❖ BAW's thermal noise dominates over system's noise on resonance

Strain sensitivity for mode λ:

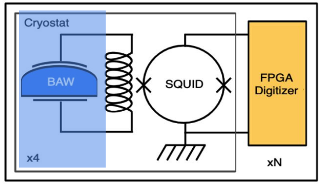
$$S_h^+(\omega) = \frac{2}{\xi_\lambda d}\sqrt{\frac{k_B T_\lambda}{m_\lambda Q_\lambda \omega_\lambda^3}} \left[\frac{\text{strain}}{\sqrt{\text{Hz}}}\right] \propto \frac{n}{L}\sqrt{\frac{k_B T_\lambda}{Q_\lambda\, \rho\, v_\lambda^3}}$$

ξ→ GW coupling: O(1)
ω → (angular) resonance
n → overtone
d → BAW thickness
Q → Quality factor
L/2 → BAW radius
m → effective mass
T → effective temperature
ρ → mass density
v → sound velocit

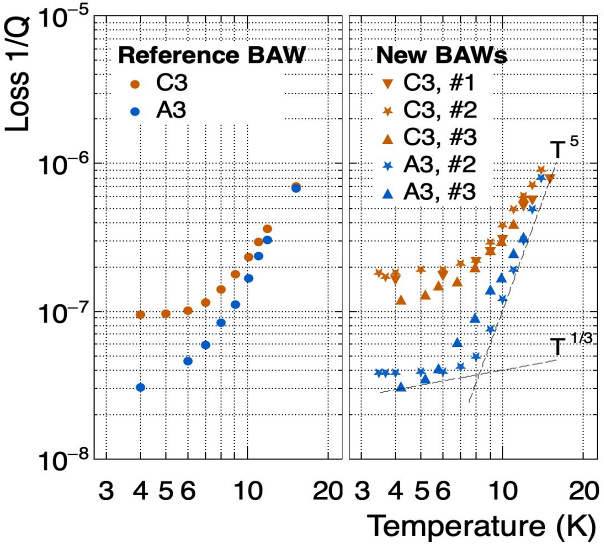
❖ Rule of thumb [important for stage 2]:

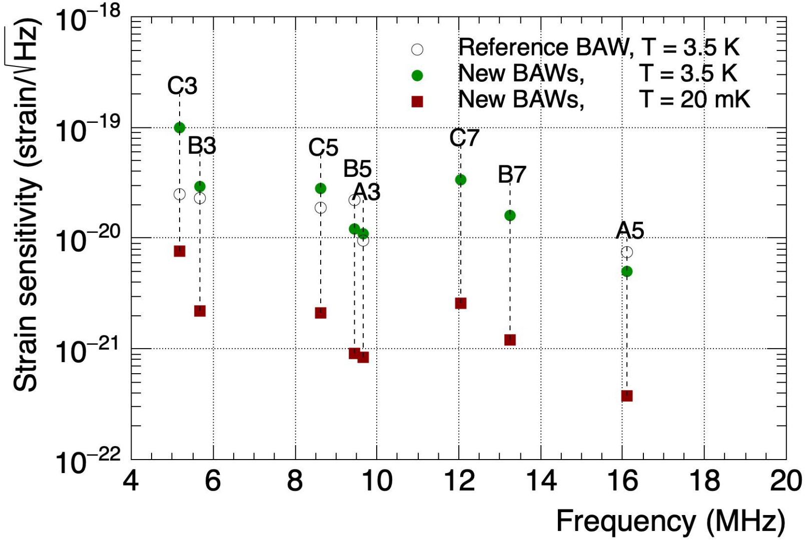
- ➢ Large radius (L)
- ➢ Fast crystal (v)
- ➢ Low overtones (n)

Stage 1: BAW characterization



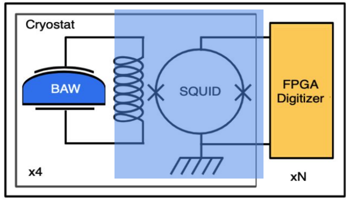
- **Preliminary BAW characterization on commercial resonators is described in [Albani et al, 2025]**
  - ➢ Comparable performance wrt a reference BAW provided by collaborators at UWA (MAGE experiment, W Campbell et al, 2024)





- ➢ Comparable losses ($Q \gtrsim 10^7$) and temperature scaling
- ➢ Sensitivity improvement at mK temperatures

DC Squid calibration

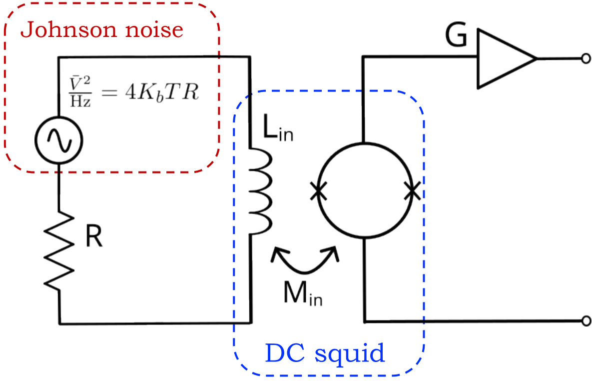


◆

Observation of Johnson spectrum of a 100 mΩ resistor

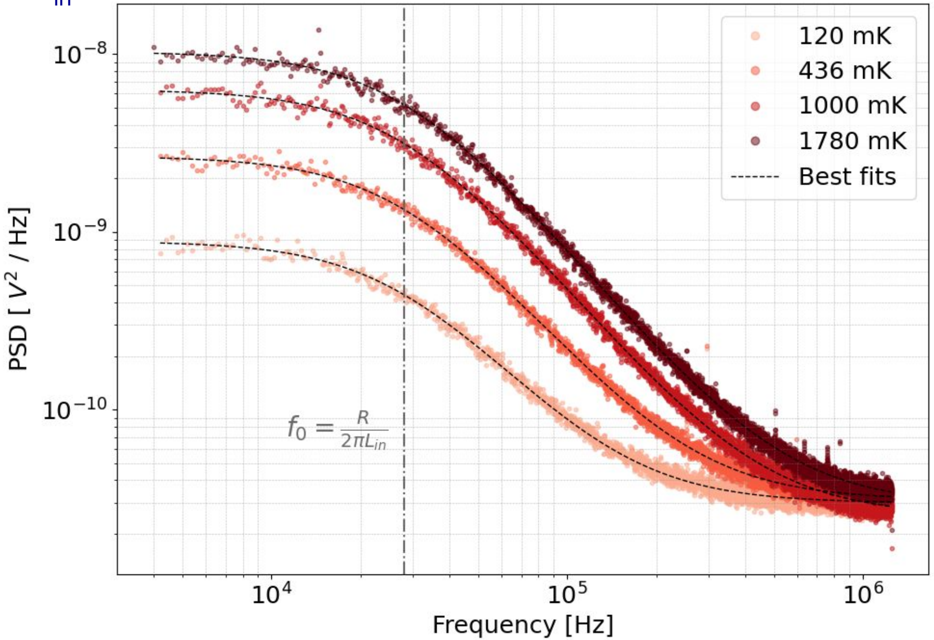
- ➢ White Johnson noise, RL cutoff at $f_0 = R / 2\pi L_{in} \cong 30$ kHz
- ➢ Independent measurement of SQUID's input coil L_{in}!

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

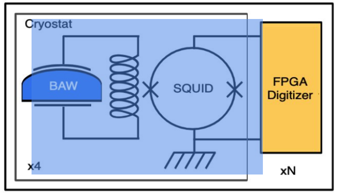


$$L_{\text{in}} = (560 \pm 10)\ \text{nH}$$

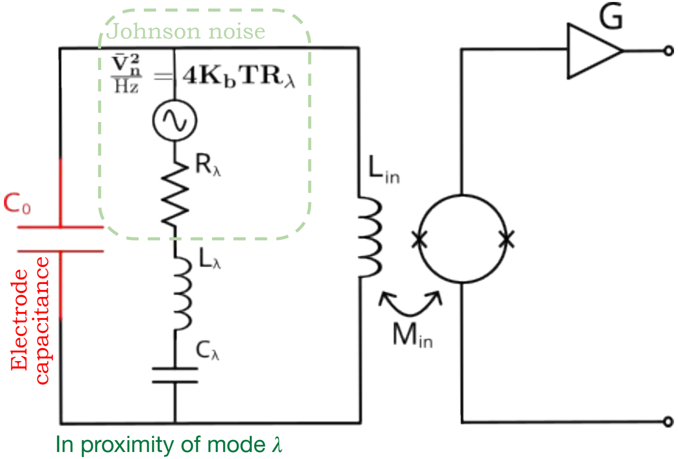
(against a nominal value of 400 nH)

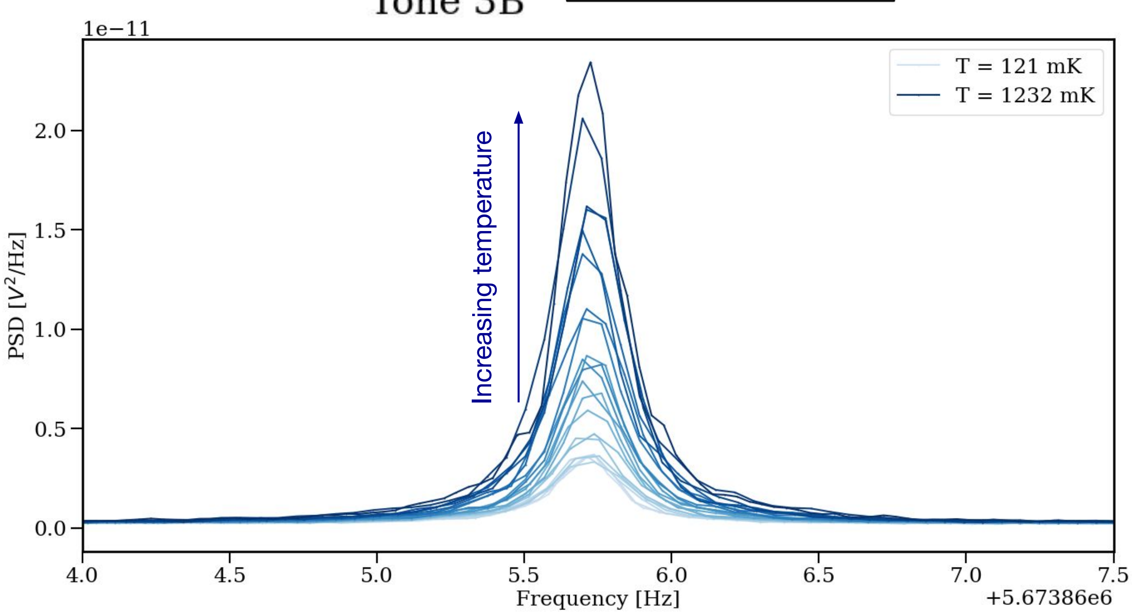


BAW's thermal noise



- **Varied cryostat temperature and monitored thermal peaks**





- **Circuit model for measured PSD:**

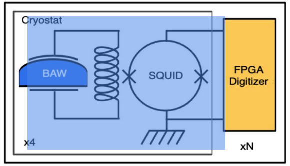
for $\omega \ll 2\pi \times 200$MHz

$$S_{vv}(\omega) \approx \frac{\left(M_{\rm in} G V_\Phi\right)^2 4K_b T R_\lambda}{\left|R_\lambda + j\left(\omega(L_\lambda + L_{\rm in}) - \frac{1}{\omega C_\lambda}\right)\right|^2},$$

↔

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

Analytical Lorentzian re-parametrization!

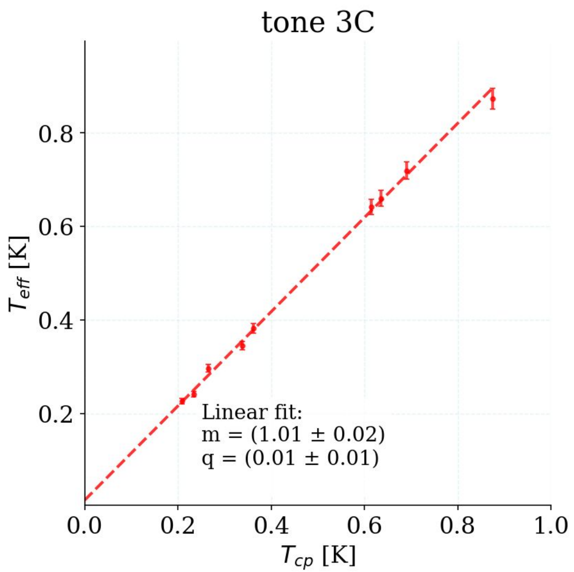


Modes' effective temperatures

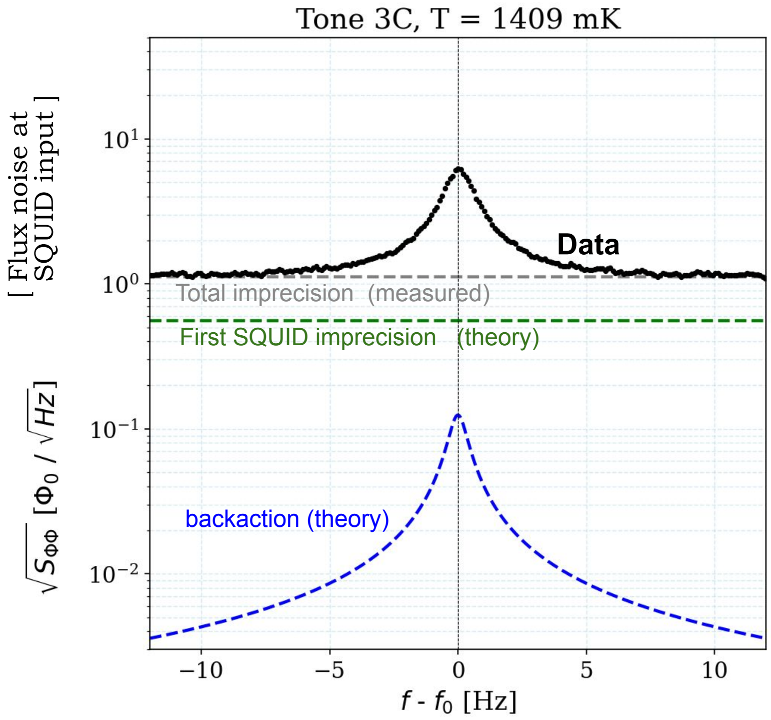
❖ **Estimation of the Lorentzian's parameters gives information about the resonator's thermal state:**

$\propto$ peak height! $$\boxed{A^2} = (G V_\Phi M_{\mathrm{in}})^2 4 K_b \frac{T_{\mathrm{eff}}}{R_\lambda}$$

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



- ➢ Experimental **exclusion of SQUID backaction** on our BAW!

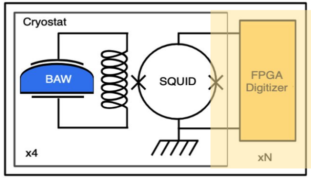


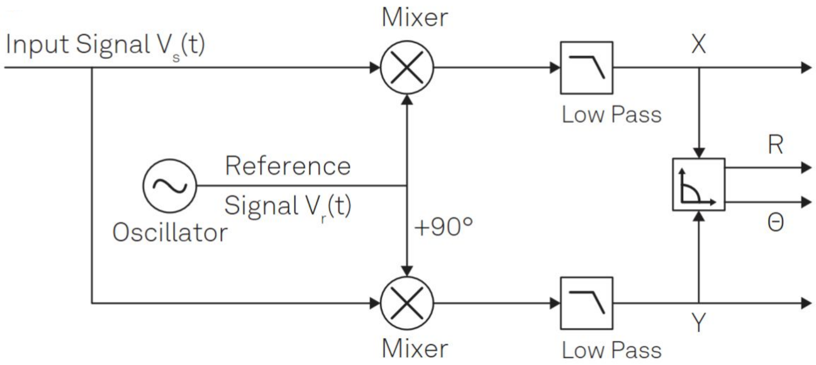
Tesche-Clarke theory predicts SQUID noise [Ankel et al, 2025]

- ➢ 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!

Readout chain





❖ LOCK-IN amplification

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

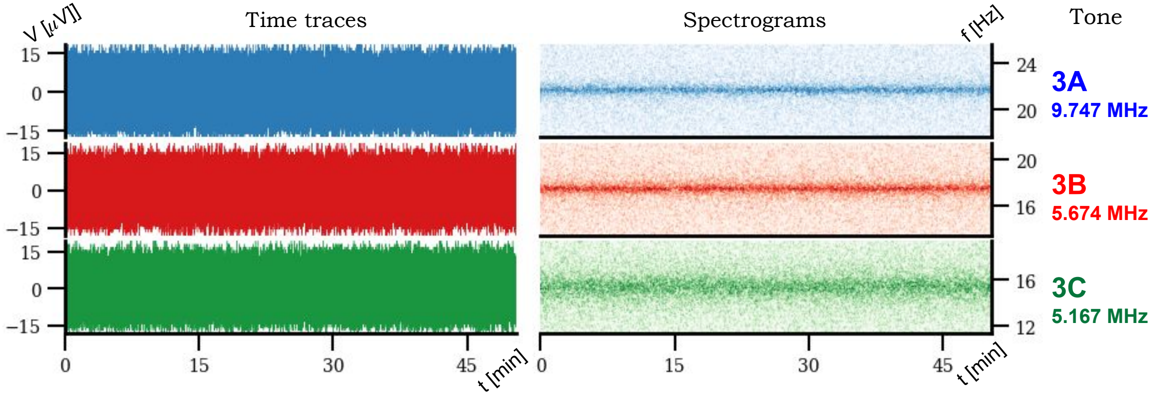
❖ RFSoC-based DAQ

(Xilinx Zynq UltraScale+ 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)

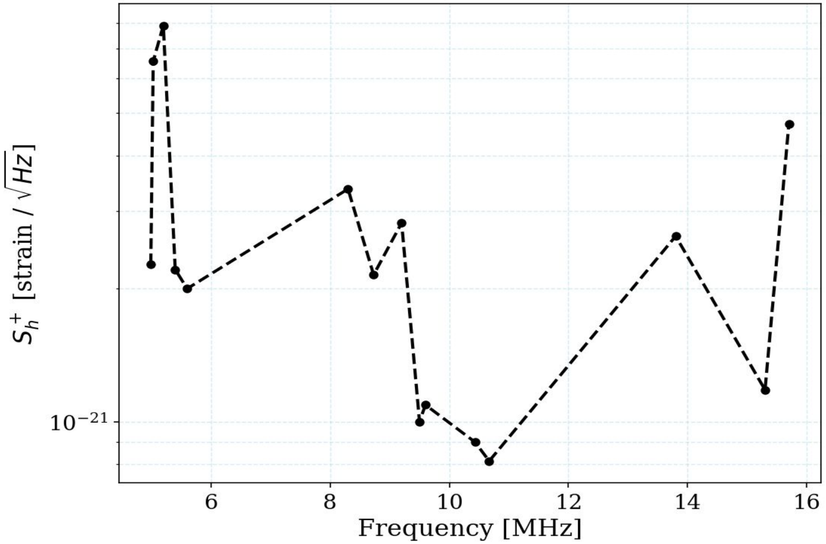
DAQ stability recently tested ✓



Next steps

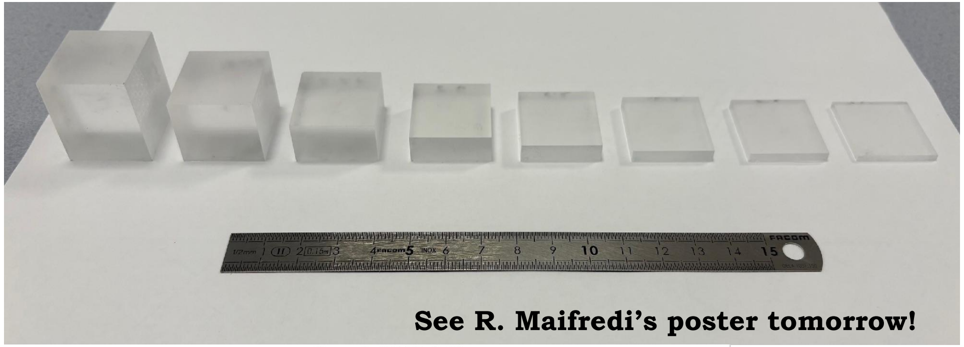
❖ **Ready for a [1st stage] summer run!**

- ➢ 3 characterized BAWs, 3 characterized squids

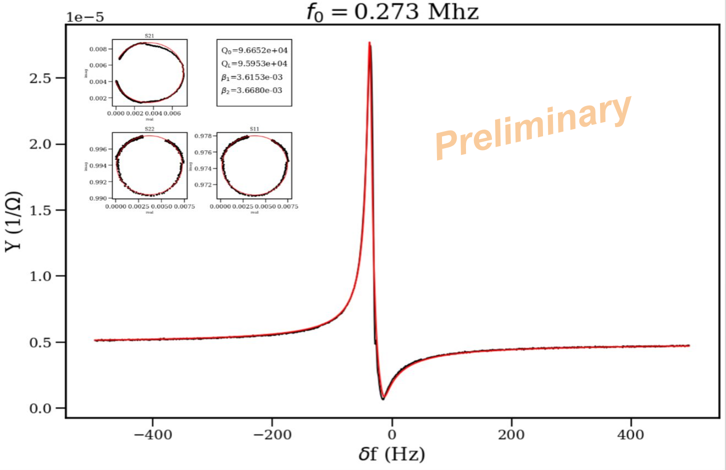


- ➢ Multi-site detection with MAGE at the University of Western Australia [currently running]!
- ➢ Possible synergies with other HFGW approaches like Gravnet EU (Amaral et al, 2026)

❖ **Working on 2nd stage of experiment**



See R. Maifredi's poster tomorrow!

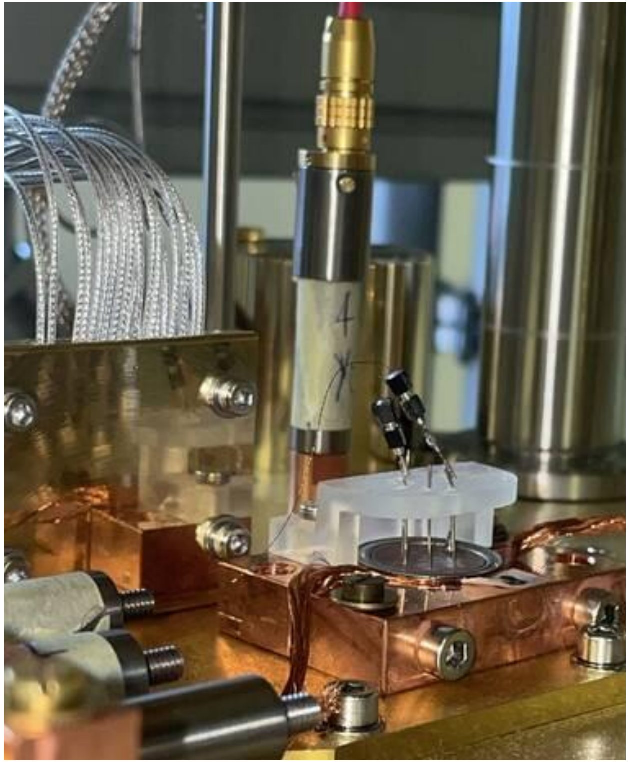


Customization of thicker quartz crystals for lower frequency coverage!

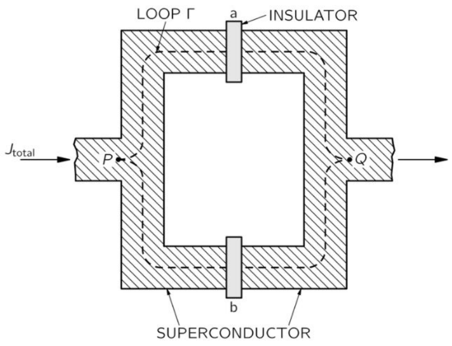
Conclusions

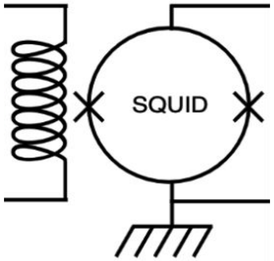
- First stage resonators → characterized ✓ [Albani et al, 2025]
- DC squids → calibrated ✓
- Prototype channel → characterized and well understood ✓
- Experimentally excluded squid backaction ✓

- Ready to start measuring in (northern) summer ‘26!
- Possibility of multi-site detection with MAGE at UWA and GravNet!



backup: DC SQUID

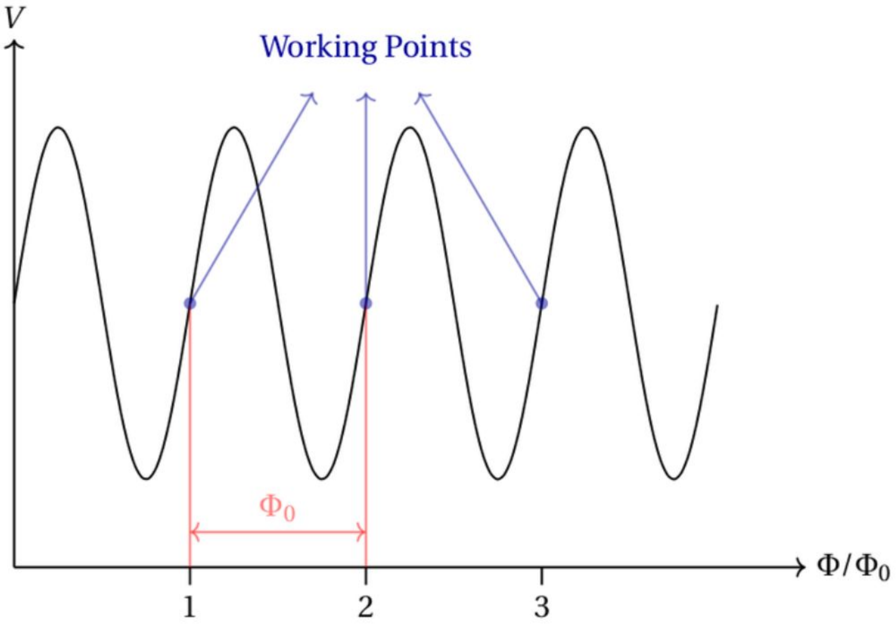




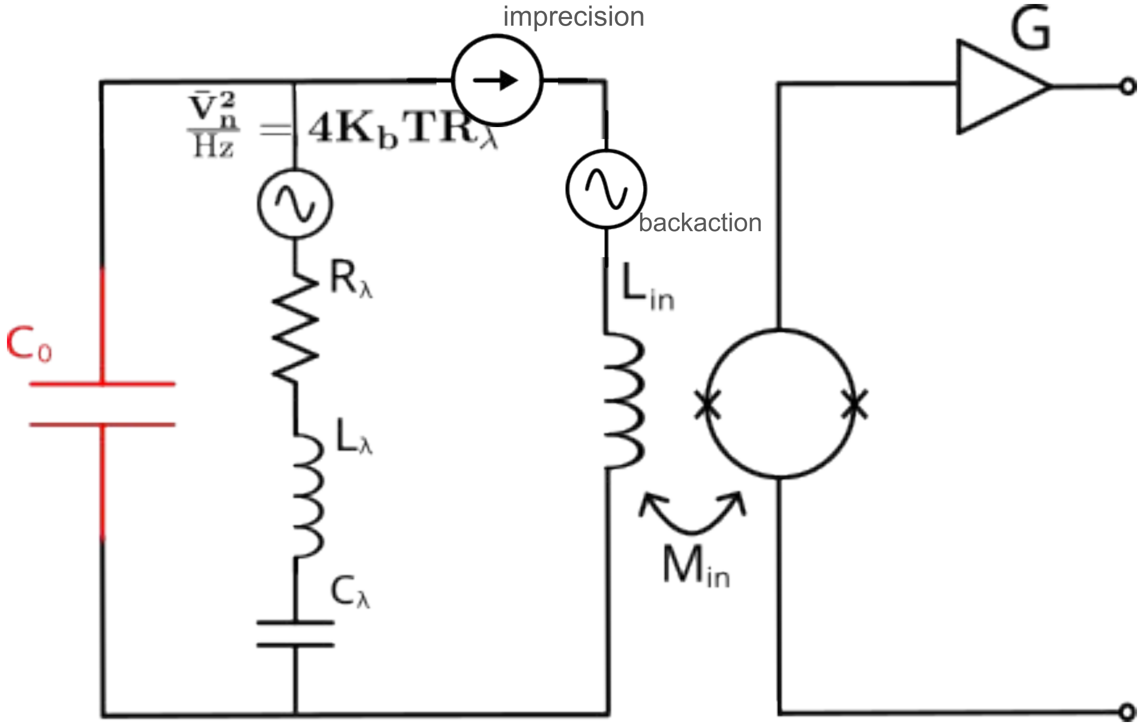
Treated as transimpedance amplifiers (input current into output voltage)

$$V_{\text{out}} = \underbrace{\boxed{M_{\text{in}} V_\Phi}}_{\text{“gain”}} I_{\text{in}}$$

$M_{\text{in}} V_\Phi$ ∝ slope at working point



backup-tion



Imprecision: input referred amplifier noise. Generated by SQUID sensor junctions (1st order contribution), amplifier squid array junctions, preamplifier…
There also when NO INPUT connected.

Backaction: physical current noise circulating in squid loop causes an emf (voltage) back on the input circuit. Still sourced by the squid junctions.