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

The BAUSCIA*) project with BAWs

[BAWSHA: BAW Sensors for High-frequency Antennas]

Tommaso Tabarelli de Fatis

(Dipartimento di Fisica, Università di Milano Bicocca and INFN Milano-Bicocca)

- **Outline**
  - Project context and goals
  - Project status and projected sensitivity
  - Summary and outlook

Contributors:

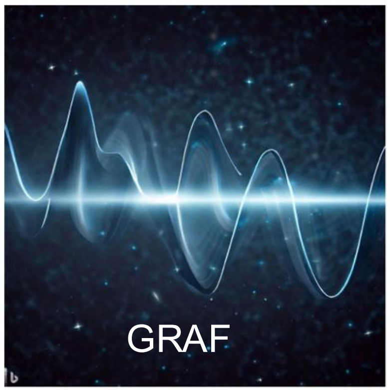
G. Albani, M. Borghesi, L. Canonica, R. Carobene, F. De Guio, M. Faverzani, E. Ferri, R. Gerosa, A. Ghezzi, A. Giachero, C. Gotti, D. Labranca, L. Mariani, A. Nucciotti, G. Pessina, D. Rozza, TTdF

Thanks to:

- W. Campbell, M. Goryachev, and M. Tobar (University of Western Australia)

The BiCoQ Centre

- **Centre of Quantitative Cosmology at Milano Bicocca**
  - Joint effort of astrophysicits, particle physicists, and theorists to understand the nature of gravity, dark matter (DM), dark energy, and the constituents of the universe
  - Program supported by the Italian Ministry of University and Research (MUR)
    - Support for visiting, PhD, and for research (see BiCoQ web page)

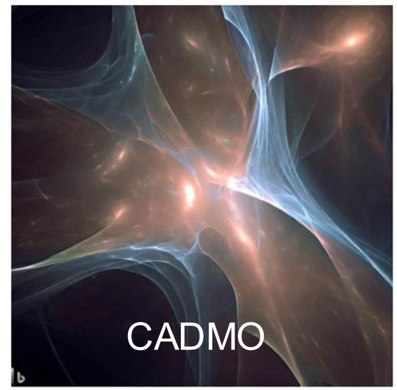


High-precision GW analysis

- LIGO/Virgo, ET (*)
- LISA (*), PTA

High-frequency GW [>100 kHz] (*)

Low-mass and compact objects, DM candidates?



Search for particle DM canditates

Beyond WIMP searches with modified DUNE (*)

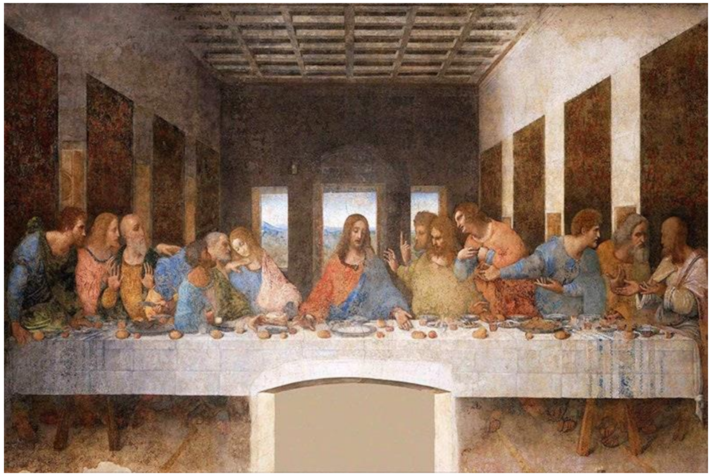
New astrphyiscal observations of DM

Dark galaxies and galaxy filaments; CMB birifrangence (*)

- **(*) Many synergies with astroparticle, gravitational waves, neutrino physics activities supported with long-term programs by INFN**

BiCoQ events

- **"THE NATURE OF MATTER AND GRAVITY: A BICOQ CONFERENCE"**
  - **Milano-Bicocca: 2026, January 26-30**
  - Topics (parallel and plenary sessions):
    - High-precision GW physics and astrophysics
    - Axions, DM and HFGW searches
    - New astrophysical observations of dark matter
  - 1st bulletin to be out soon



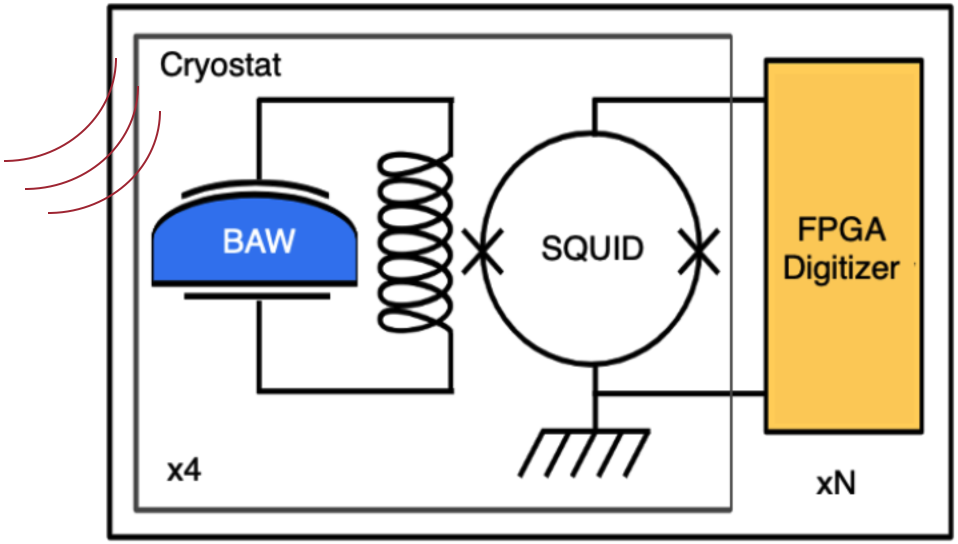
The BAUSCIA project

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

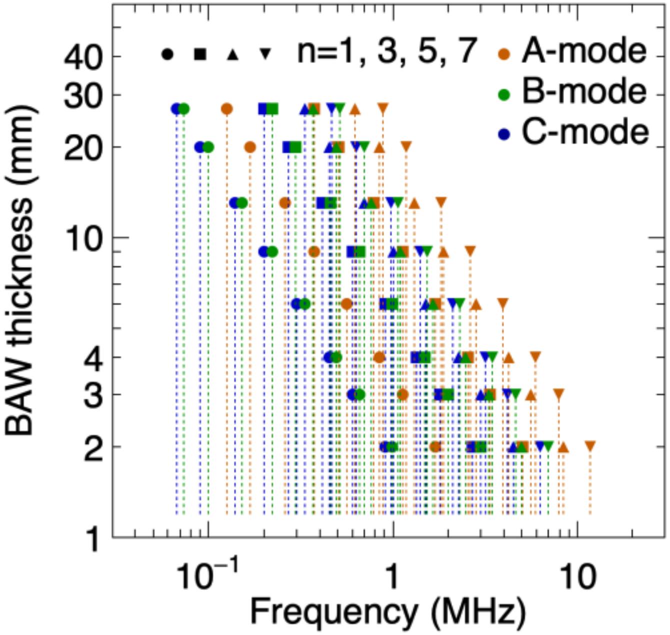
- **A two-stage plan for a resonant mass detector sensitive to multiple frequencies**
  1. Multimode antenna w/ commercially available quartz BAWs → Clock standard 5.175 MHz
  2. Array of customized BAWs to cover a broad spectrum of frequencies → Different thicknesses

$$\ddot{a}_\lambda + \gamma_\lambda \dot{a}_\lambda + \omega_\lambda^2 a_\lambda = -c^2 R_{0i0j} \int_V \frac{\rho}{m_\lambda} U_\lambda^i(\mathbf{x}, t) x^j d\nu$$

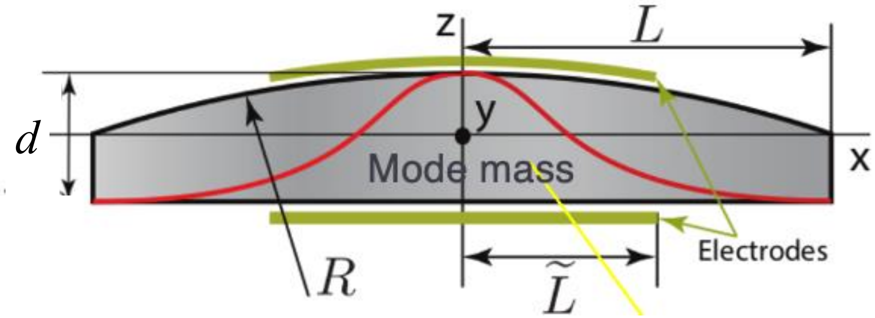
GW-driven resosonator



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



Single-mode peak strain sensitivity



Three modes of vibration with different velocities (quartz)

Longitudinal (A)	Fast shear (B)	Slow shear (C)
v_A= 6760 m/s	v_B= 3970 m/s	v_C= 3610 m/s

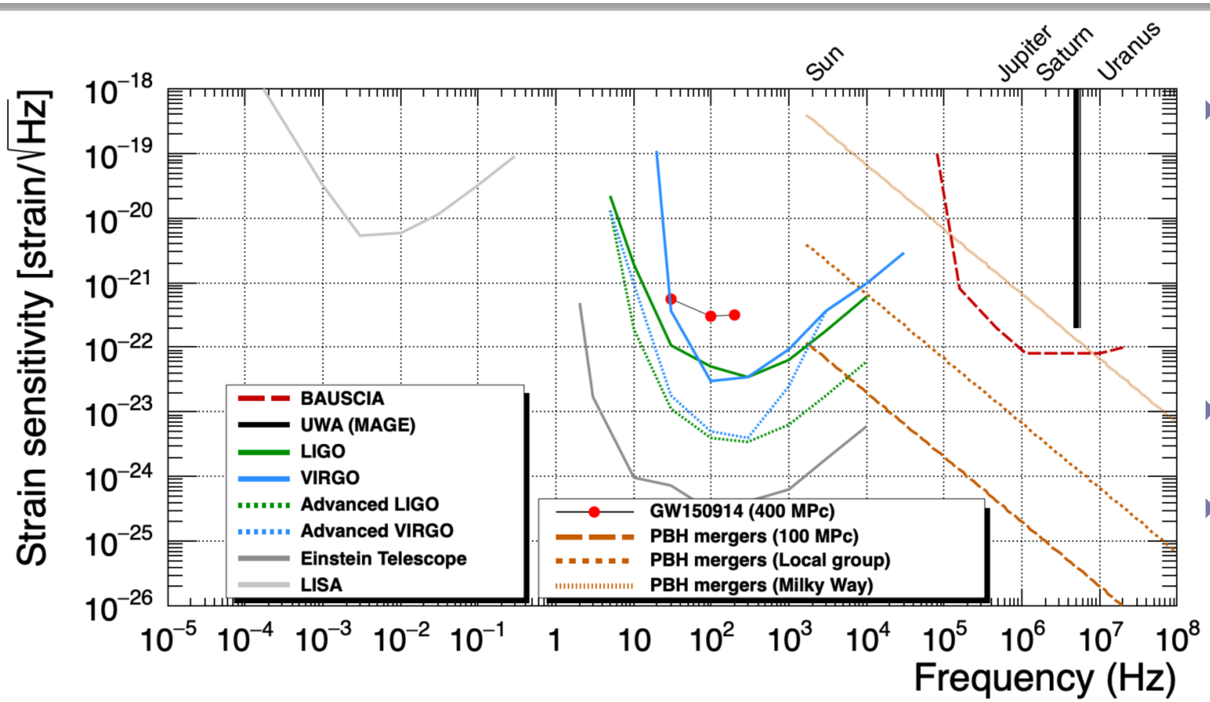
- **Single sided spectral density from spectral density of force fluctuations (Nyquist)**
  - Noise dominated by BAW thermal noise at resonance (SQUID noise negligible)

$$S_h^+(\omega_\lambda) = \frac{2}{\bar{\xi}_\lambda d}\sqrt{\frac{k_b T_\lambda}{m_\lambda Q_\lambda\ \omega_\lambda{}^3}} \quad [\text{strain}/\sqrt{\text{Hz}}], \qquad \propto \frac{n}{L}\sqrt{\frac{k_B T}{Q_\lambda \varrho\ v_\lambda{}^3}}$$

- **Dependency on BAW parameters**
  - **T_λ, Q_λ** and **m_λ** mode temperature, quality factor and vibrating mass
  - **$\omega_\lambda = 2\pi f_\lambda$** mode angular frequency
  - ξ_λ unitless coupling coefficient to the GW $\propto 1/n^2$ through a coefficient of O(1) accounting for the trapping of the vibrational energy in the BAW volume.
  - **n** overtone number

- **Rule of thumb for BAW optimization: large radius, fast crystal, low overtones**
  - And good trapping to achieve high Q factors

- **Potential ground for discoveries**
  - No known astrophysical sources [e.g., beyond stellar black-holes and nuetron star mergers cut-offs]
- **Emission from dark matter candidates**
  - Primary black hole (PBH) binaries (**planetary masses 0.1-10 MHz**) [Franciolini et al (2022)]
  - QCD axions collapsing into a massive black hole (**10-200 kHz**) [A. Arvanitaki et. al (2011)]
- **Post-merger emission from QCD phase transitions in neutron-stars (~600 kHz)**
  - Coincidence with LVK to tag low mass mergers [Casalderrey-Solana et al. (2022)]



- Envelope of estimated peak strain sensitivities of 2x8 custom BAWs x 12 freq./BAW operated at 20 mK
  - Based on the sensitivity of commercial BAWs now in use
- Note: PBH-PBH mergers have a distinctive frequency vs time pattern
- Signal at f_{ISCO} not persistent enough to excite the resonator fully
  - $\Delta t = 1/Qf \sim 1$ s for BAWs

Current status

arXiv > physics > arXiv:2506.17479

Physics > Instrumentation and Detectors

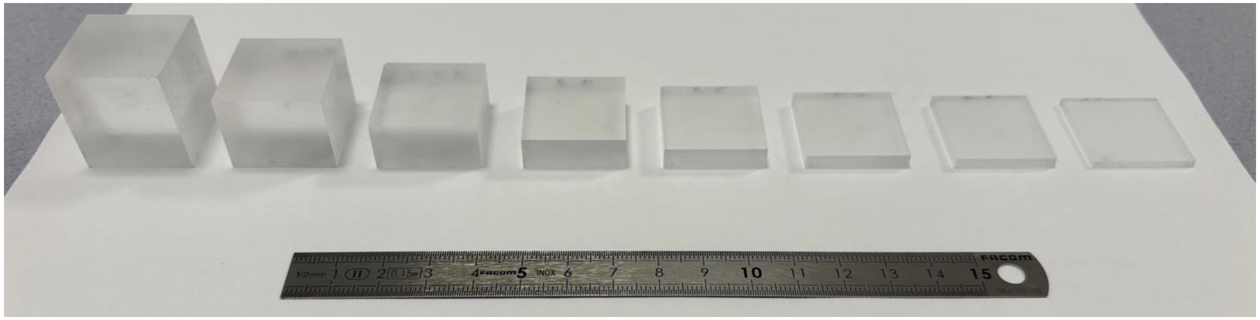
https://arxiv.org/abs/2506.17479

[Submitted on 20 Jun 2025]

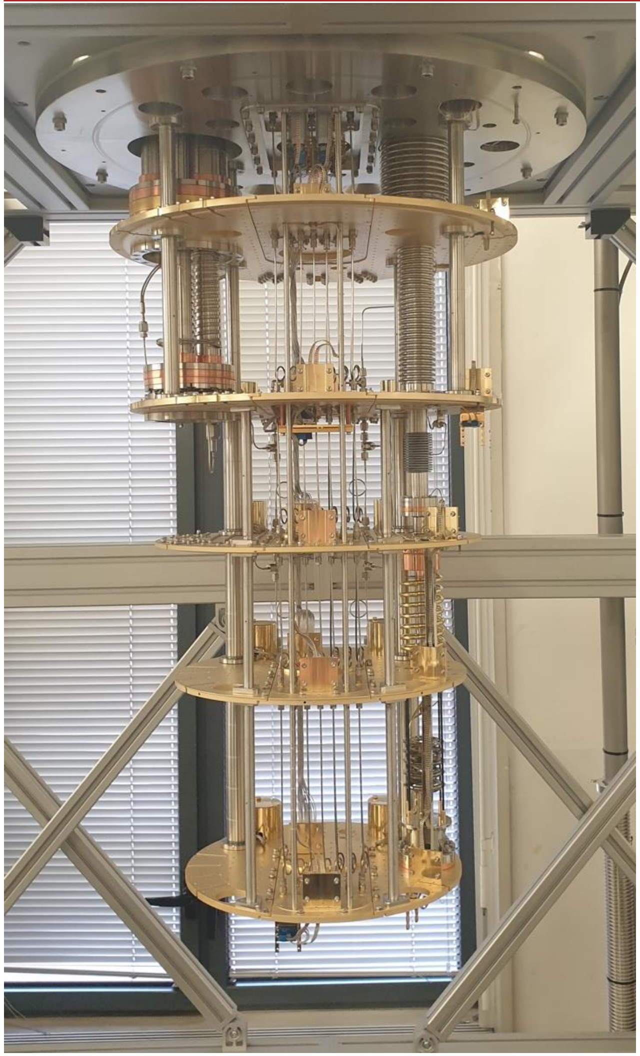
An array of bulk-acoustic-wave sensors as a high-frequency antenna for gravitational waves

G. Albani, M. Borghesi, L. Canonica, R. Carobene, F. De Guio, M. Faverzani, E. Ferri, R. Gerosa, A. Ghezzi, A. Giachero, C. Gotti, D. Labranca, L. Mariani, A. Nucciotti, G. Pessina, D. Rozza, T. Tabarelli de Fatis

- **Stage 1 – ready for data taking by the end of 2025**
  - Commercial BAWs fully characterized (14 mm diameter)
  - Dedicated cryostat installed and commissioned
  - SQUID readout and DAQ commissioning underway
- **Stage 2 – customized BAWs production in progress**
  - SC-cut and AT-cut quartz blanks (25 mm side) ready for post-processing (rounding, grinding, polishing, etc.)

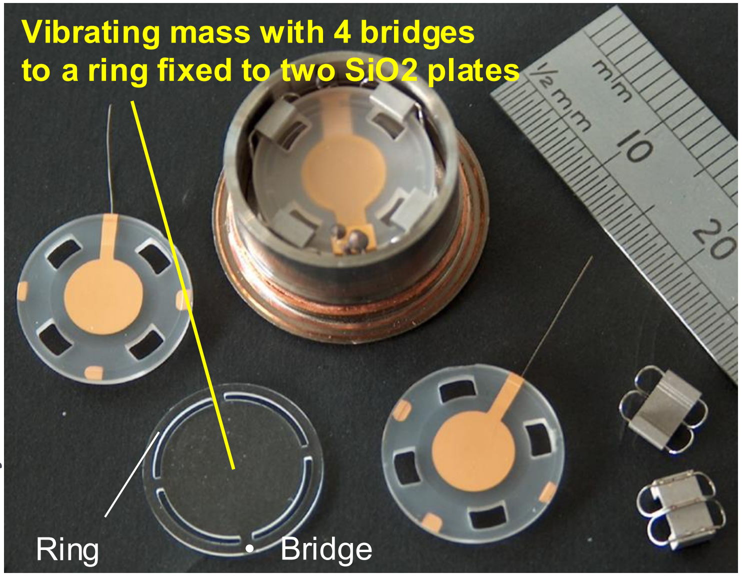


Lab BiCoQ
Dedicated cryostat



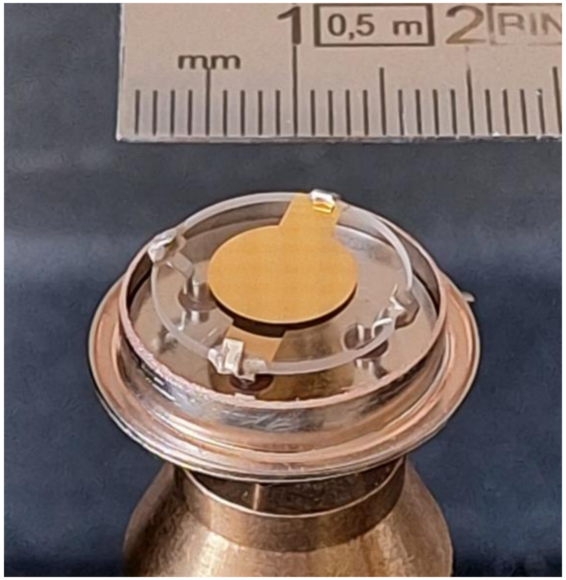
BAW samples for stage 1

- **One BVA sample (courtesy of UWA)**
  - SC-cut, low-loss design
  - SiO_2: **d ~ 1 mm; L = 15 mm**
  - Electrodes deposited on separated SiO2 plates



M. Goryachev et al.

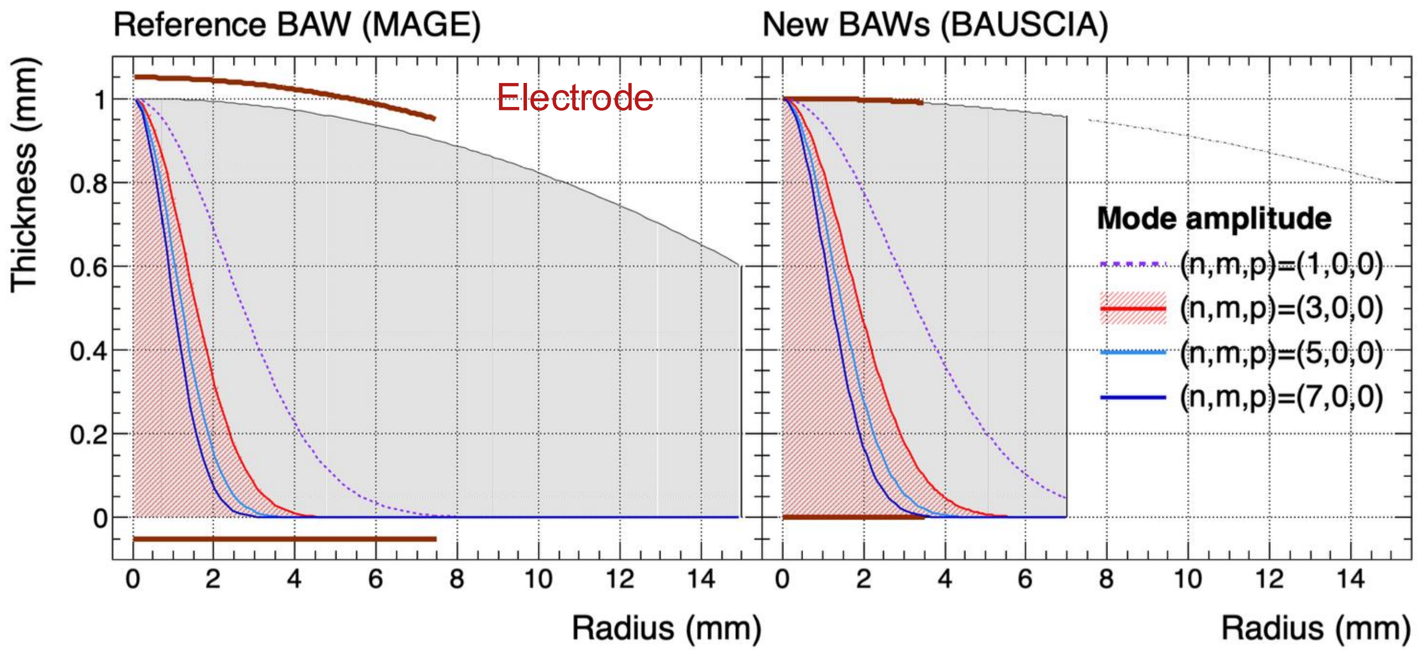
- **Three commercial samples**
  - SC-cut off-the-shelf quartz cavities
  - SiO_2: **d ~ 1 mm; L = 7 mm**
  - *Electrodes deposited on BAW*



Courtesy of Rakon Ltd

- **Plano-convex shape and geometry optimized to 5.175 MHz (clock standard)**
  - 3rd overtone of the C-mode (slow shear)
- **Comparable nominal performance at room temperature (Q ~ 10^6)**
  - Despite different radii and layout

Mode mass and cavity losses



- **Plano-convex shapes minimize mechanical losses through supports**
  - Admits standing waves solutions with Gaussian profile in the transverse direction (n,m,p)=(n,0,0)
  - **Comparable effective (vibrating) mass** because of **different surface curvature (R_C)**

Sample	d (mm)	L (mm)	R_c (mm)	σ_1 (mm)	electrode
Reference	1	15	300	2.3	separated
New	1	7	600	2.8	deposited

$$\sigma_n = (d^3 R_c)^{1/4} / \sqrt{\pi n}$$

→ Effective mass scales as 1/n

BAW characterization: Q at low T

Longitudinal (A)	Fast shear (B)	Slow shear (C)
v_A= 6760 m/s	v_B= 3970 m/s	v_C= 3610 m/s

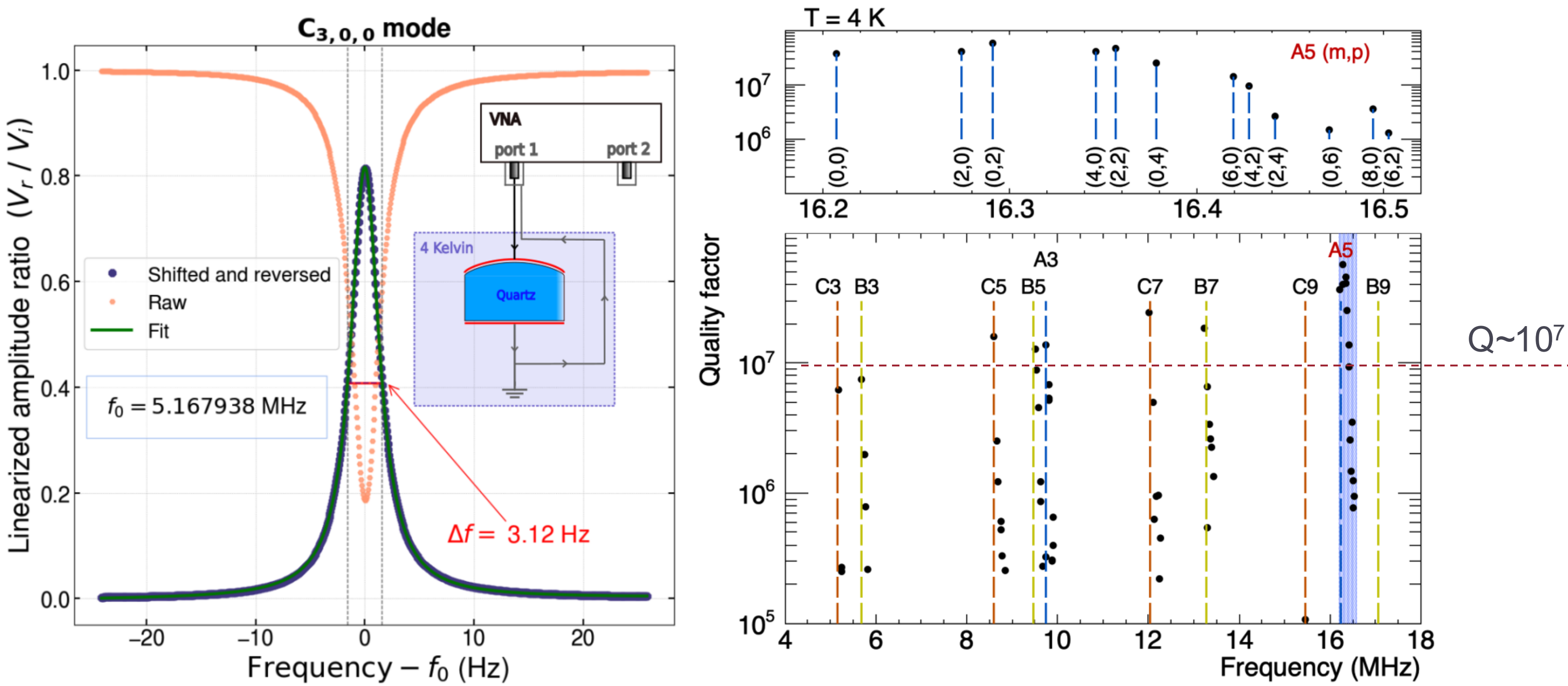
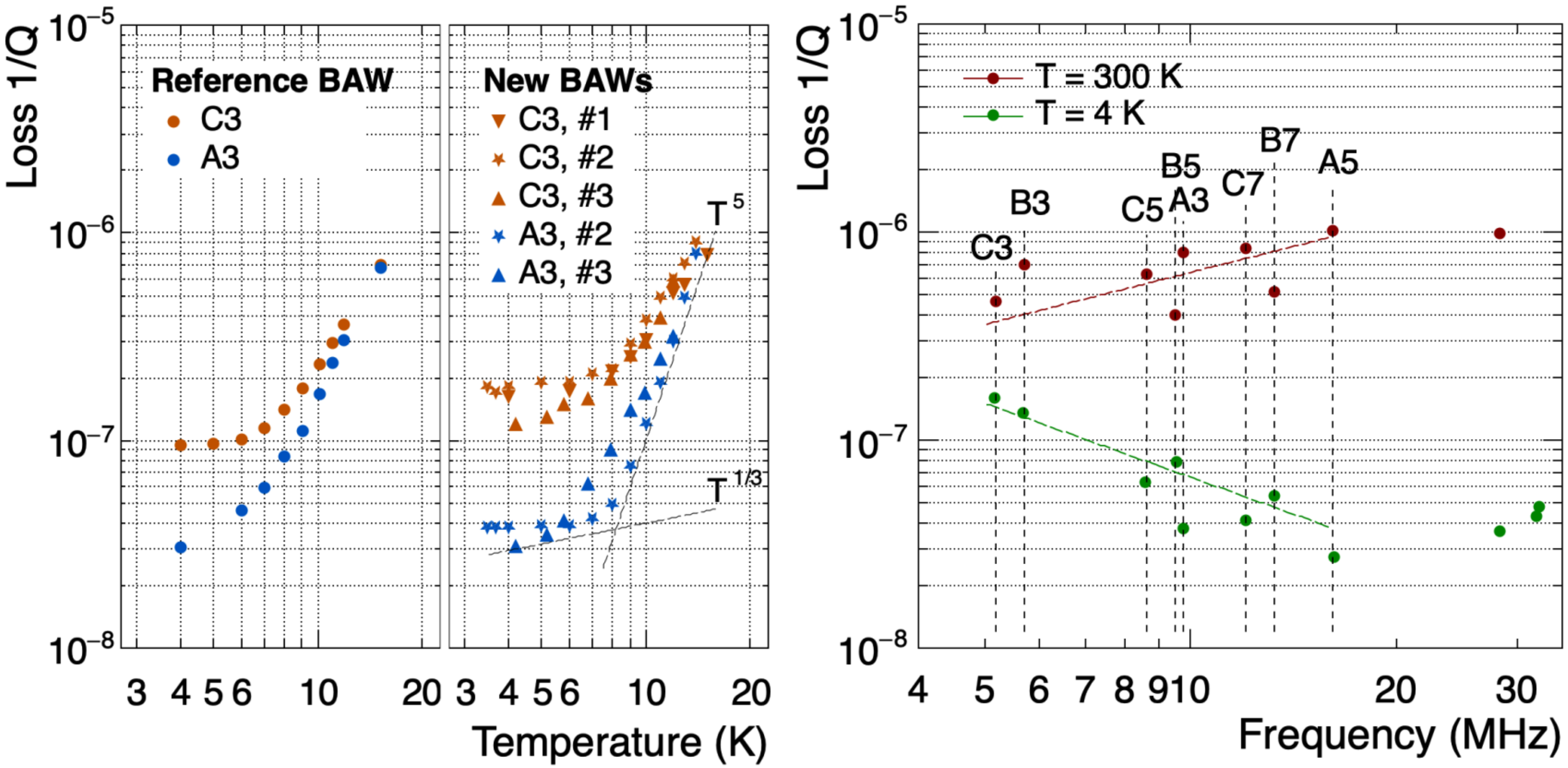


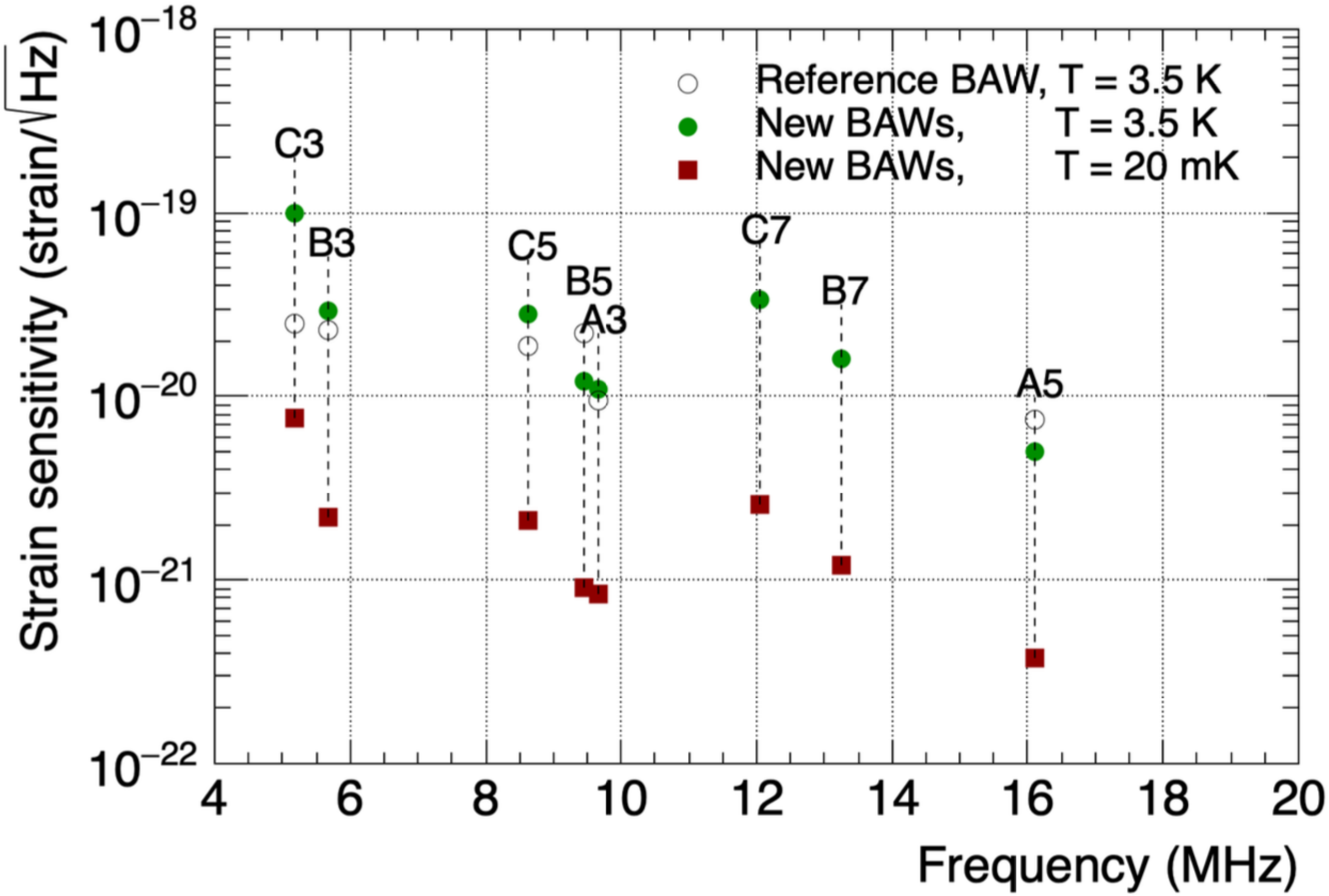
Figure 5: *Left*: Frequency scan around the resonance for the mode $\lambda = \{C, 3, 0, 0\}$ at $T = 3.5$ K. The inset shows the connection to the VNA. *Right*: Identified resonant modes for one BAW sample at $T = 4$ K as a function of the frequency: the main modes ($m = p = 0$) are marked with vertical lines; the top panel shows the frequency pattern of thickness transverse modes for $\lambda = \{A, 5, m, p\}$.

BAW characterization: Q vs T and f



- **Internal losses as a function of temperature compatible with literature:**
  - Two Level System (TLS) losses at low T (crystal impurities): $1/Q \propto T^{13}$
  - Phonon-phonon scattering at higher T: $1/Q \propto T^{\gamma};\ \gamma > 3$
- **Q factor at low-temperature ranges between 10^7 and 10^8 (comparable to MAGE BAWs)**
  - *Q-factor flattens at about 3.5 K (lower temperature still reduces the thermal noise)*

Strain sensitivity



Comparable to MAGE

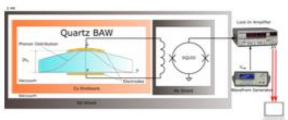
Figure 7: Predicted single-sensor peak spectral strain sensitivity for multiple modes at $T = 3.5$ K for the reference (empty dots) and the new samples (full dots), and for the new samples at $T = 20$ mK (squares).

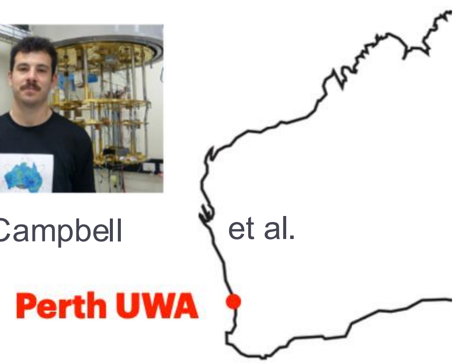
Detector network

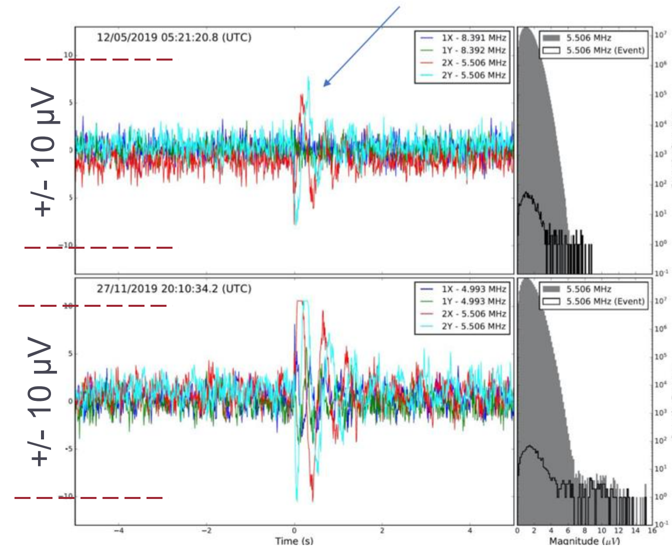
W. Campbell et al, “**The multi-mode acousting gravitational wave exepriment: MAGE**”, [Sci Rep 13, 10638 (2023)](https://www.nature.com/articles/s41598-023-35670-7)

MAGE

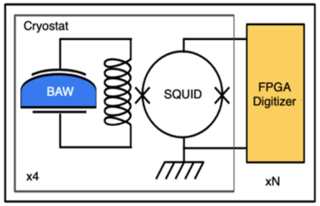
M. Tobar M. Goryachev W. Campbell et al.







M. Goryachev et al, “**Rare events detected with a Bulk Acoustic Wave High Frequency Gravitational Wave Antenna**”, PRL 127, 07102 (2021)



Multi-site detection can confirm the origin of signals (at the ~same frequencies)

Synergies with othe HFGW approaches (GravNET EU) to be explored