Bulk Acoustic Wave devices for high-frequency gravitational wave antennas

Lucia Canonica

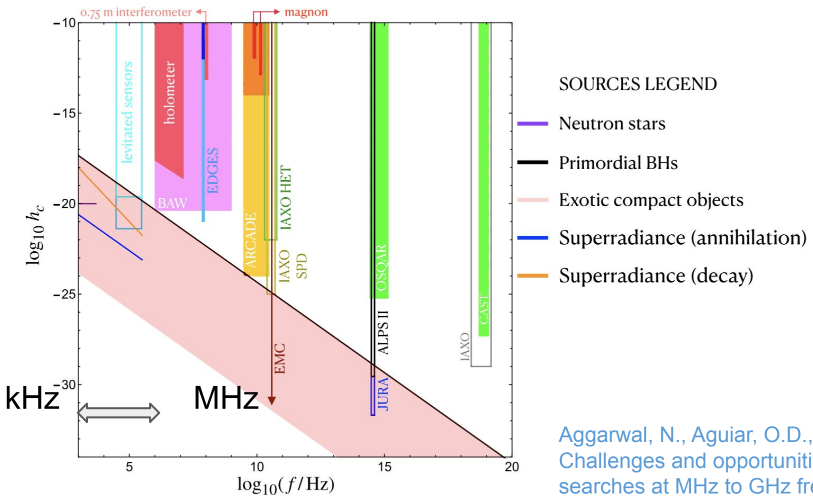
Dipartimento di Fisica, Università di Milano Bicocca and INFN Milano-Bicocca

On behalf of the BAUSCIA team

Physics Case

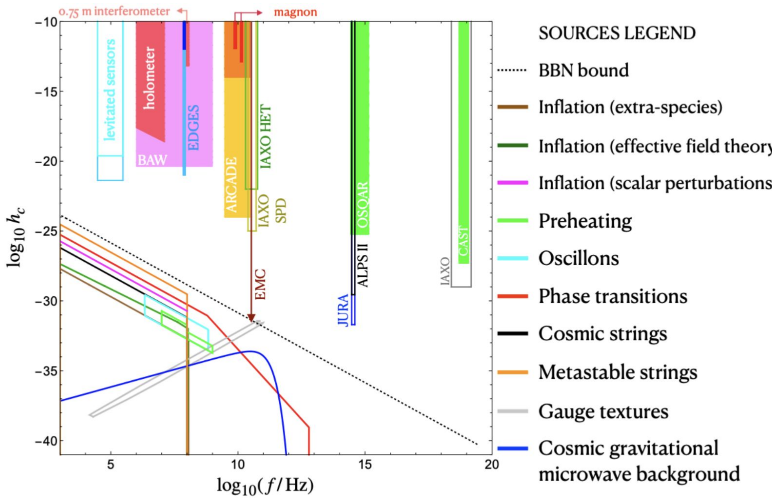
- There are many potential GW sources at frequency higher than those covered by interferometers.
- The identity of dark matter is still unknown. It may hide in HF-GW?
- Search complementary to large interferometers

Coherent sources of GWs

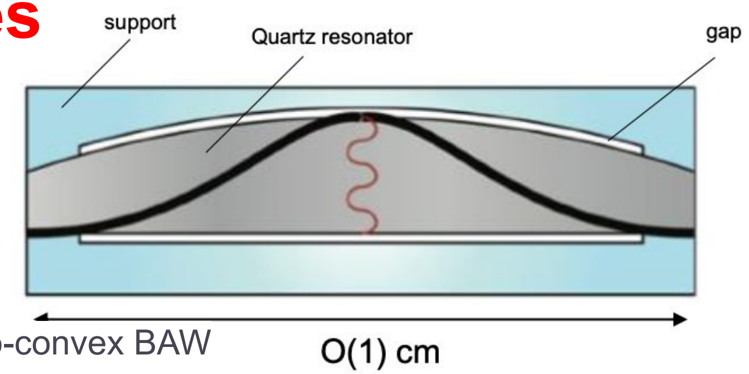


Aggarwal, N., Aguiar, O.D., Bauswein, A. *et al.* Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies. *Living Rev Relativ* **24**, 4 (2021).

Incoherent sources



Bulk acoustic wave (BAW) devices



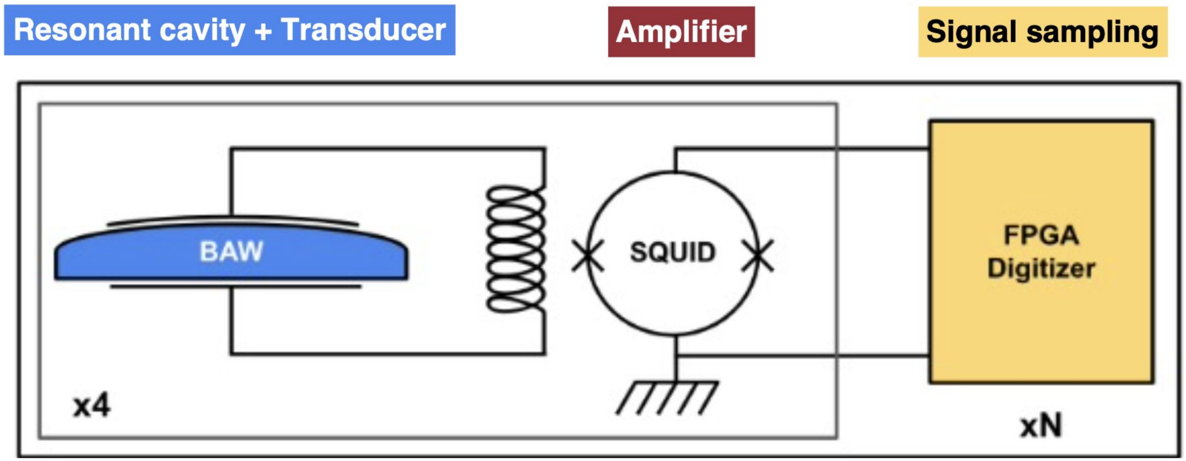
Plano-convex BAW

- High sensitivity through high quality factor (>10^6). Q improves at low temperatures
- Internal (piezoelectric) transducer
  - only odd overtones audible
- Scalable technology, established >70 years for precision clock applications
- GW tidal forces stretches and squeeze the mass: **resonance mass detector**
- Length variation only detectable at the resonant frequency of the vibration mode(s)

$$f_{n,k} = n \frac{v_k}{2d} \qquad (k = A, B, C)$$

- Wide frequency range of sensitive modes
- Three family types with different velocities
  - 2 transverse (B,C) and 1 longitudinal (A) Multiple overtones

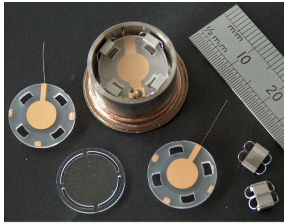
Readout concept



- Multiple overtones sensing per BAW
- Array of many BAWs tuned to different frequency
  - Requires specific R&D on BAWs

Bulk **A**coustic **W**ave **S**ensors for a **H**igh frequency **A**ntenna (*BAUSCIA*, in Milan's dialect)

BAW @ UWA



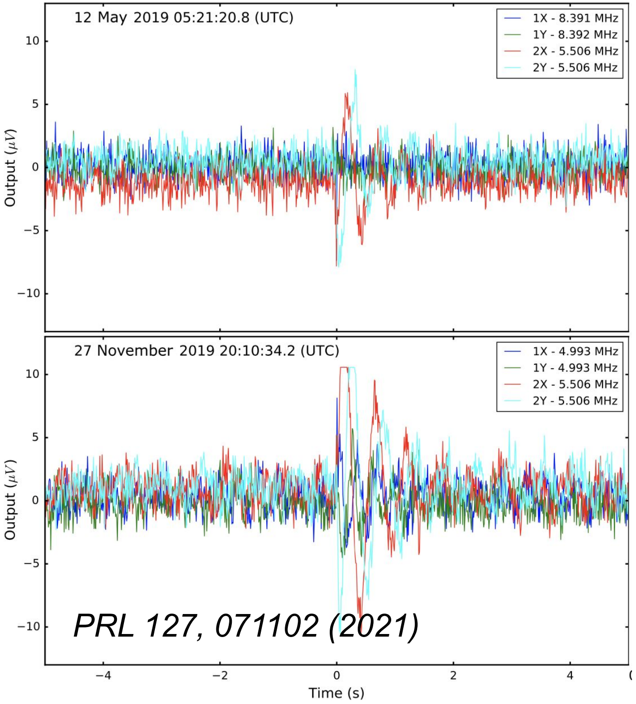
Seminal proposal by M. Goryachev and M. Tobar, PRD 90,102005 (2014)

Multimode Acoustic Gravitational wave Experiment (MAGE):
(University of Western Australia)

In 2021 it detected two signals of uncertain origin.

- **MAGE main goals / features:**
- Two identical quartz BAW detectors, maybe more? (funding application)
- Multi-mode Multi-Detector monitoring with FPGA DAQ
- High number of modes 8-10 modes (5-15 MHz range) per crystal
- Wider bandwidth SQUID; 5 – 200 MHz +
- Cosmic particle veto system. Potentially cryogenic ?
- Sub-Kelvin operation -> quantum limited, higher Qs, Quantum Metrology
- Larger mass quartz resonators? Optimize size and mode for sensitivity?

From M. Tobar's talk @ HFGW workshop
https://indico.cern.ch/event/1074510/



BAUSCIA @ UniMiB

- In close collaboration with Mike Tobar et al., for a multisite detection apparatus
- BAUSCIA receive funds from the MUR - Dipartimento di Eccellenza
- Tender ongoing for the procurement of the dedicated **dilution refrigerator**
  - SQUIDS procurement ongoing
- Preliminary BAW test with the available cryogenic infrastructures

(A fraction of the) BAUSCIA team

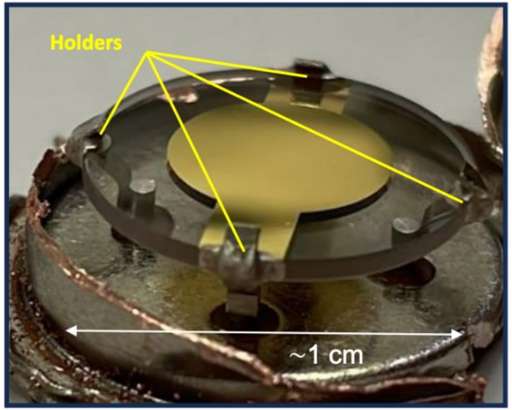
BICOQ

Centro Bicocca di Cosmologia Quantitativa

BAW @ UniMiB

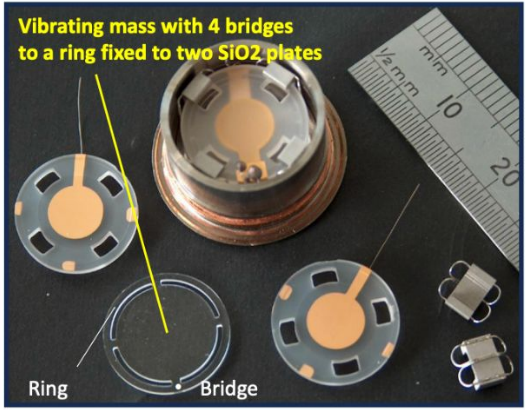
Off-the-shelf quartz BAW (from Rakon)

- Plano convex quartz crystal mounted on 4 rigid clamps
- Gold electrodes deposited
- Optimized at room temperature for the 3rd overtone of the C-mode (~ 5MHz clock standard)



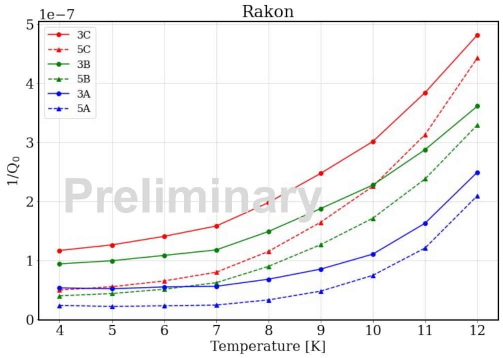
MAGE-like BAW

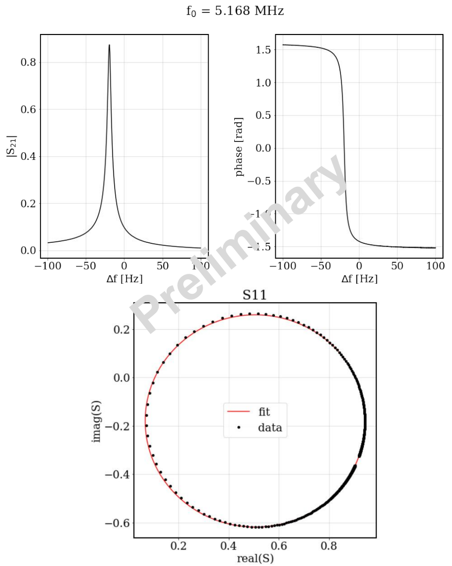
- Plano convex quartz crystal
- Gold electrodes deposited on separated support plate (BVA design, optimez to reduce losses)

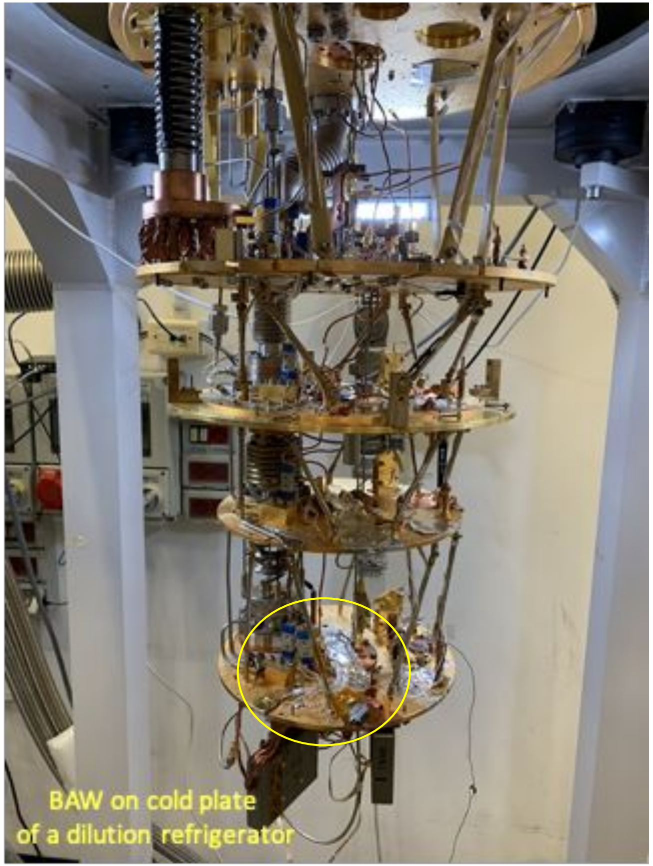


Current activities

- BAW characterized at different temperatures
- Several modes observed, resonance shapes fitted and reconstructed
- Mechanical loss comparable to device in use at MAGE







Readout electronics

Objectives:

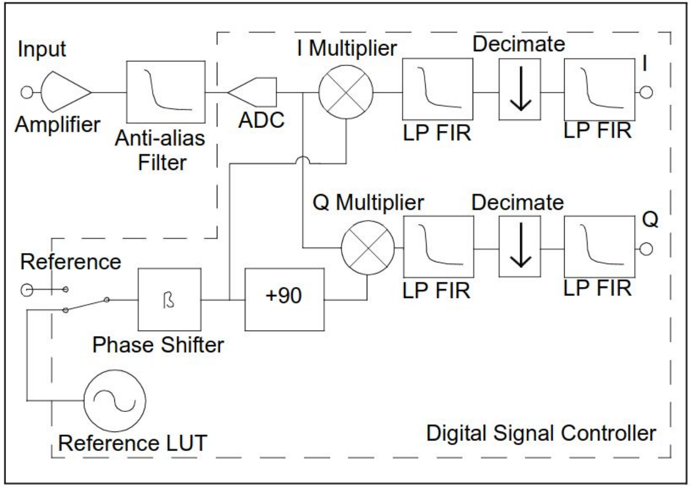
- Realization of a full-digital lock-in amplifier to analyze multiple frequencies (BAWs) on the same line.
- Development of a flexible firmware, usable both with triggers (on signal) and in continuous mode (mainly for characterization).

Current development:

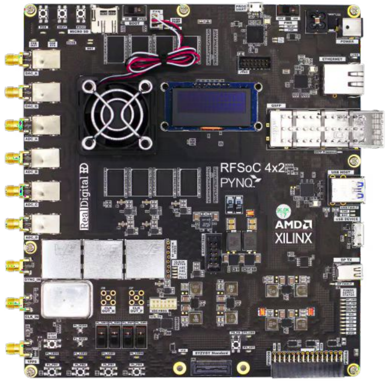
- A firmware that enables continuous acquisition of a single frequency was developed (NCO fully controllable from Python).
- Tested with a RFSoC4x2 using “clean” signals synthesised by a signal generator.

Next steps:

- Test with noisy signals: BAW characterization



Schematics of a digital lock-in amplifier



RFSoC4x2 (by Xilinx)

4 14-bit ADC (5 GSPS)
2 14-bit DAC (9.85 GSPS)

Next steps

- Development of optimized BAWs with customized shape (curvature) and thickness
  - Design to minimize mechanical losses for n=1 (maximal coupling to GW)
  - Thickness between 0.5- and 20-mm match the region of interest for coherent sources (*O*(100kHz))
- Explore different materials and mounting schemes
  - SiO_2, $LiNbO_3$ etc. in discussion with crystal manufactures
- Readout SQUIDs expected by late spring 2024
- Dedicated cryostat available by the end of the year.
  - current R&D work hosted in Holmes or LiteBIRD or Cuore/Cupid cryostats at MiB (*parasitic* running)

Summary

- High Frequency Gravitational Waves can provide sensitivity to dark matter searches complementary to other research lines.
- In close collaboration with Mike Tobar et al. we are setting up a HF-GW detection site at Milano-Bicocca, for a multisite detection apparatus

  ➢ Expected sensitivity comparable to MAGE (UWA)

- Dedicated BAWs under development
- Some synergies with FLASH, possible collaboration is under discussion.