BAUSCIA: challenge of high frequency gravitational waves detection

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Università and INFN Milano Bicocca

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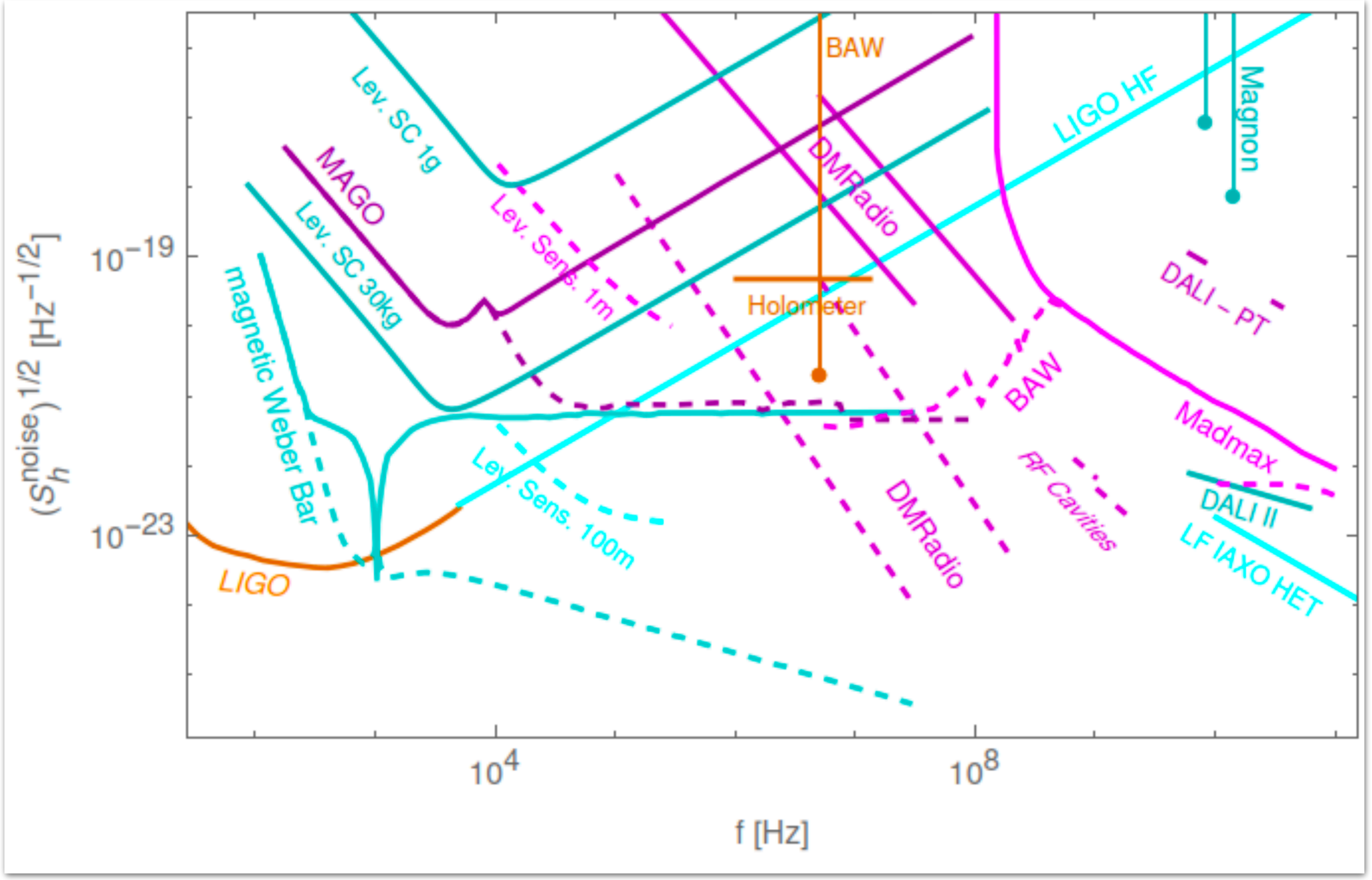
One more year of BiCoQ: status and prospects

Physics case

Why searching for GW @ kHz-GHz

- Sensitivity beyond the capabilities of traditional interferometers like LIGO and Virgo.
- Potential **coherent sources** include:
    - mergers of primary black hole binaries (Franciolini et al. 2022)
    - superradiant emission from axions collapsing into a massive black hole (A. Arvanitaki et al., 2011)
    - post-merger emission from QCD phase transitions in neutron-star (J. Casalderrey-Solana et al., 2022).
- Effort of using BAW devices pioneered by the MAGE (Multimode Acoustic Gravitational-wave Experiment), based at the University of Western Australia (UWA, M. Tobar research group).
- **Complementary** to LF GW interferometers
- **Supplementary** to MAGE at UWA (and in coincidence with it)



N. Aggarwal et al., summary of the workshop “Challenges and opportunities of high-frequency gravitational wave detection” held at CERN in December 2023.

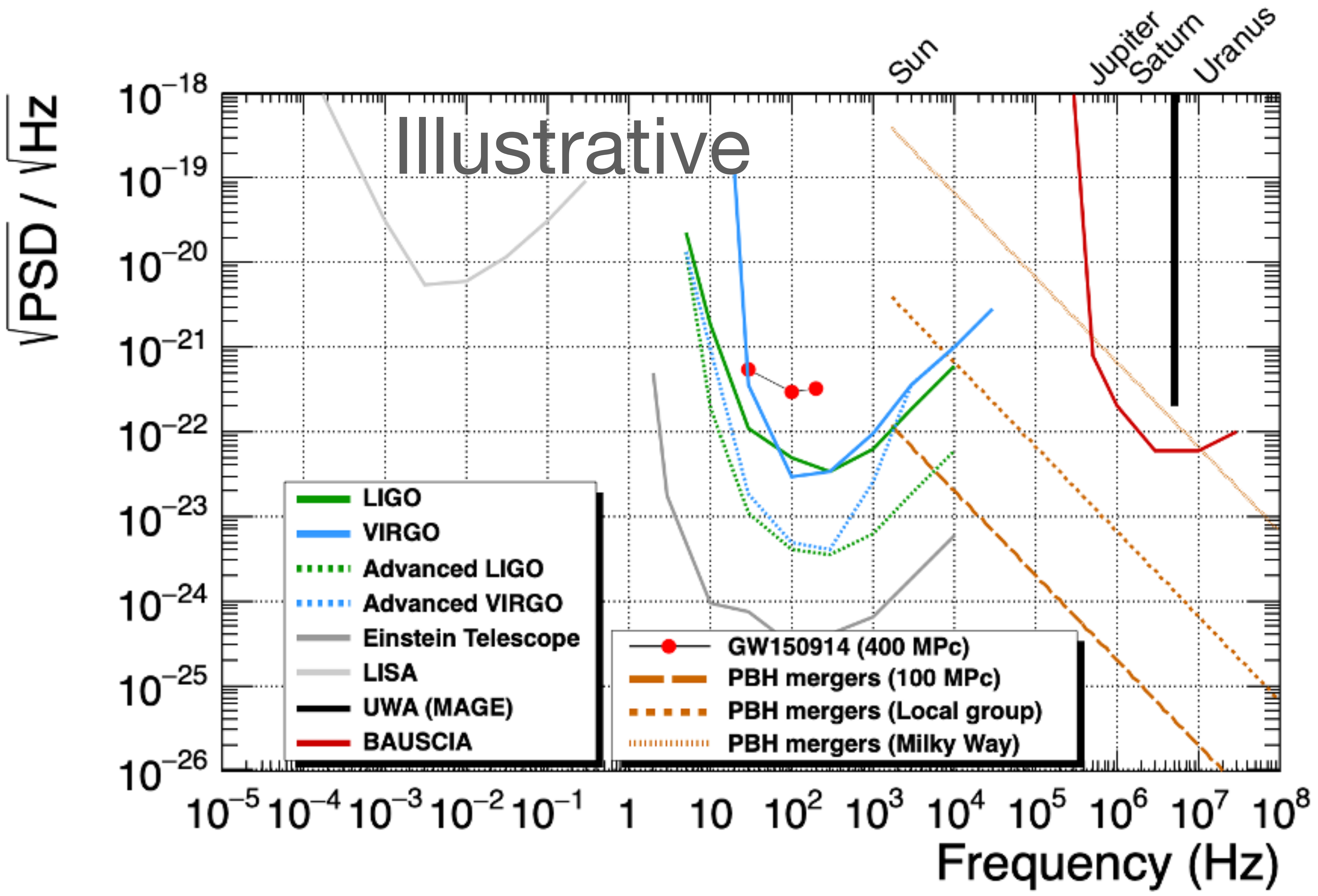
BAUSCIA objectives

A two stage plan

1. Within the third year of the project (end of 2025) we aim at building a multimode antenna based on commercially available BAWs (optimized at 5 MHz and a few overtones)

2. By the end of the five-year plan (end of 2027), we plan to build an array a O(10) BAWs spanning over O(100) frequencies from 100 kHz to 10 MHz.

Estimated power spectral density (PSD) sensitivity at the resonant frequencies achieves about 2×10^{-22} Hz$^{-1/2}$ (subject to the mode geometry)

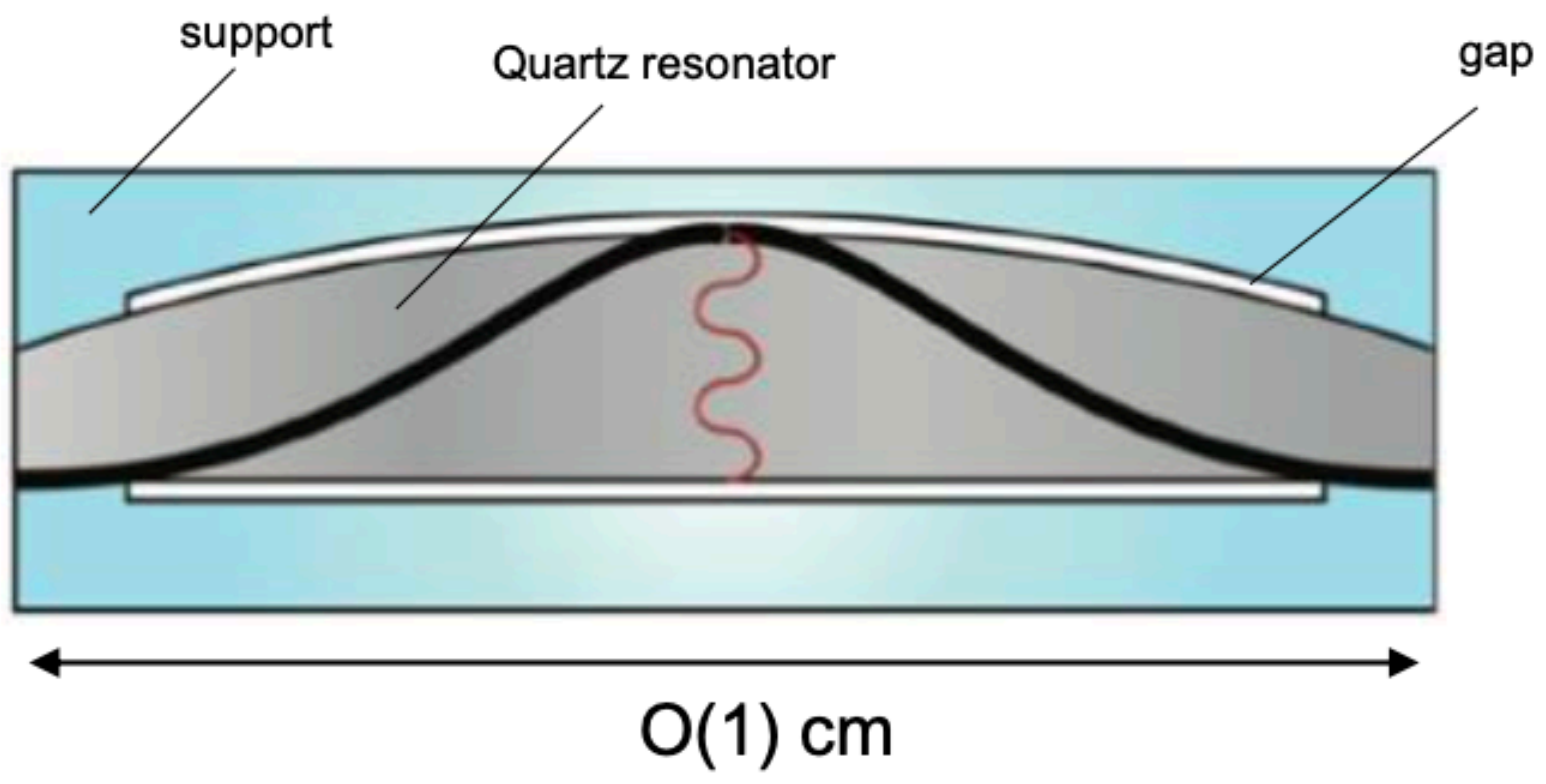


Detection principle

Bulk Acustic Wave

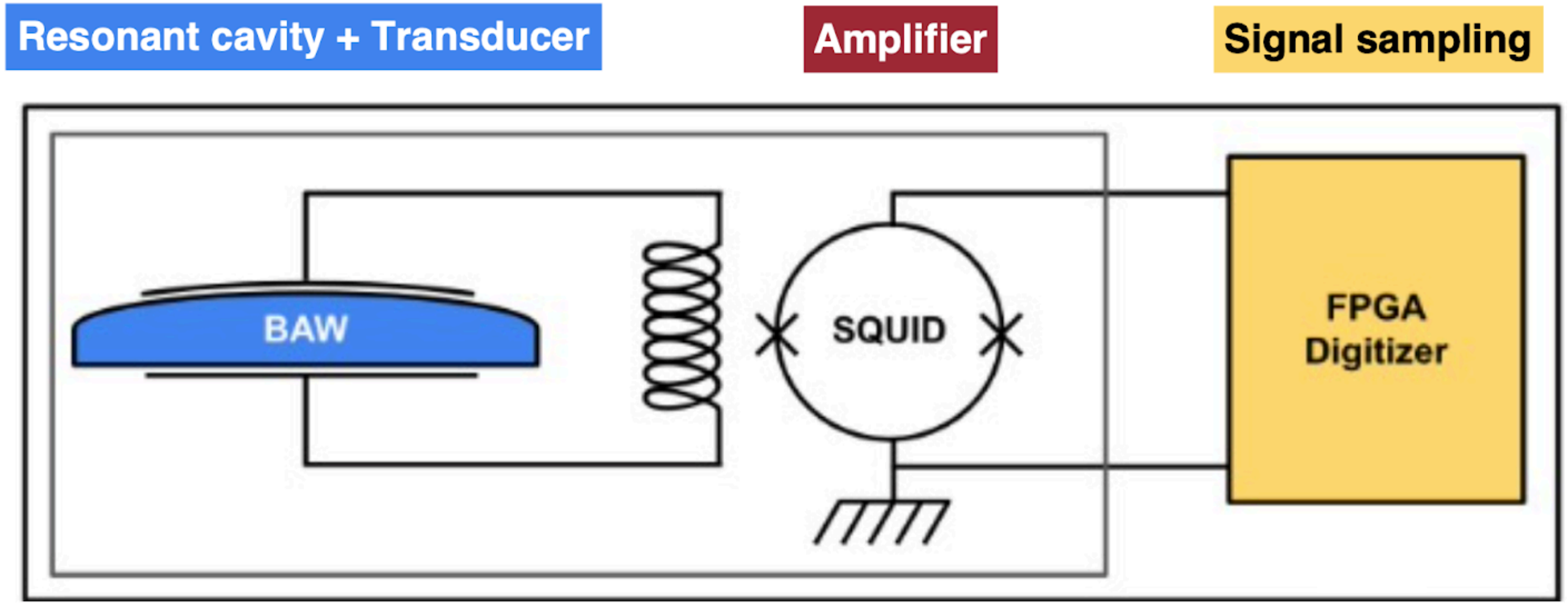
- Use of **B**ulk **A**coustic **W**ave (**BAW**) resonators: piezoelectric transducer
- Resonant Mass Detection Mechanism:
  - GWs passing through a BAW device induce tidal forces that cause finite distortions in the material.
  - Length variation only detectable at the resonant frequency of the vibration mode(s)
  - Narrow band sensitivity
- High sensitivity through high quality factor (>10^6).

From www.minigrail.nl/



BAWSHA

Bulk Acoustic Wave Sensors for a High frequency Antenna (BAUSCIA, in Milan's dialect)



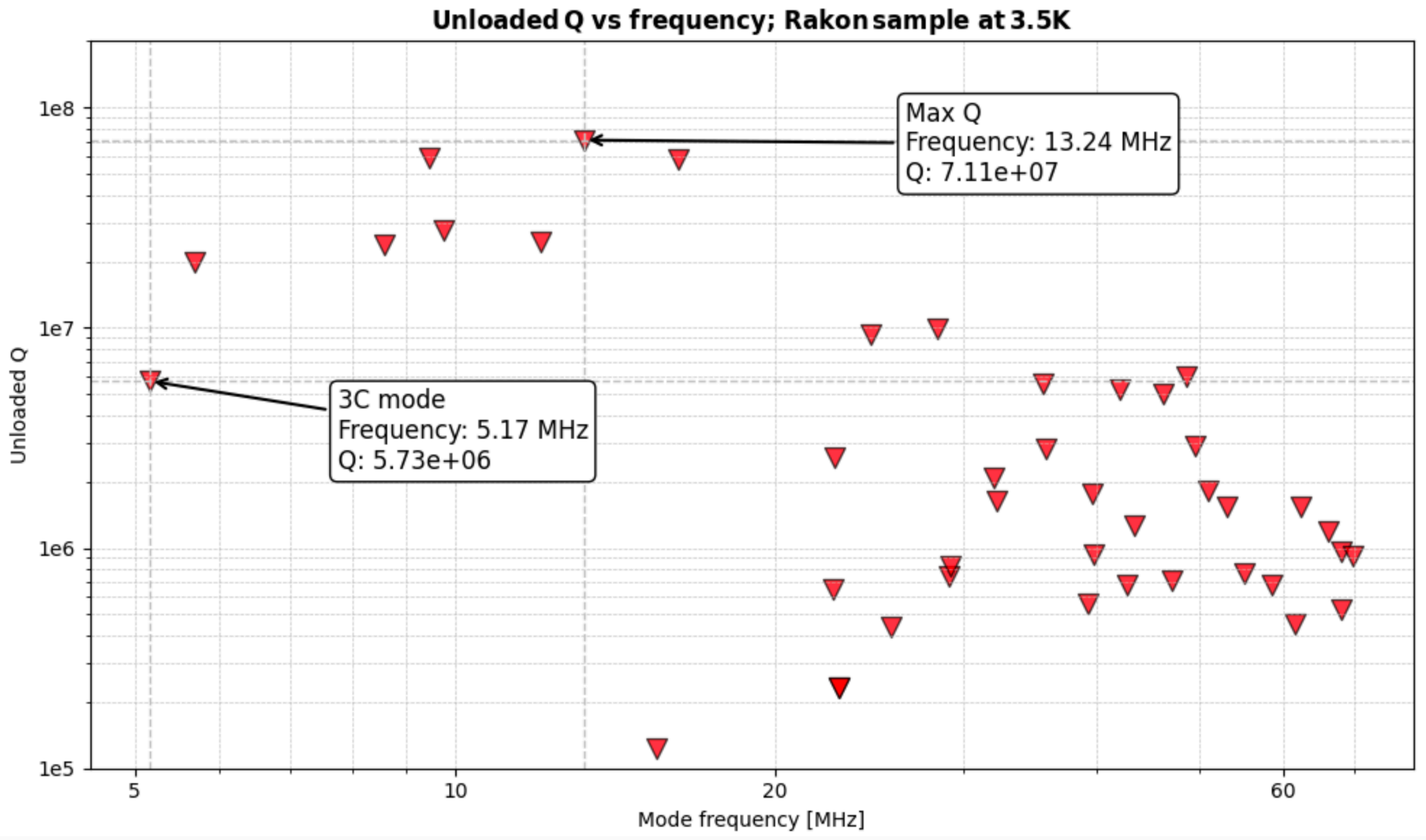
- The "broadband" sensitivity provided by:
  - Multiple overtones sensing per BAW
  - Array of many BAWs tuned to different frequency
    - Requires specific R&D on BAWs

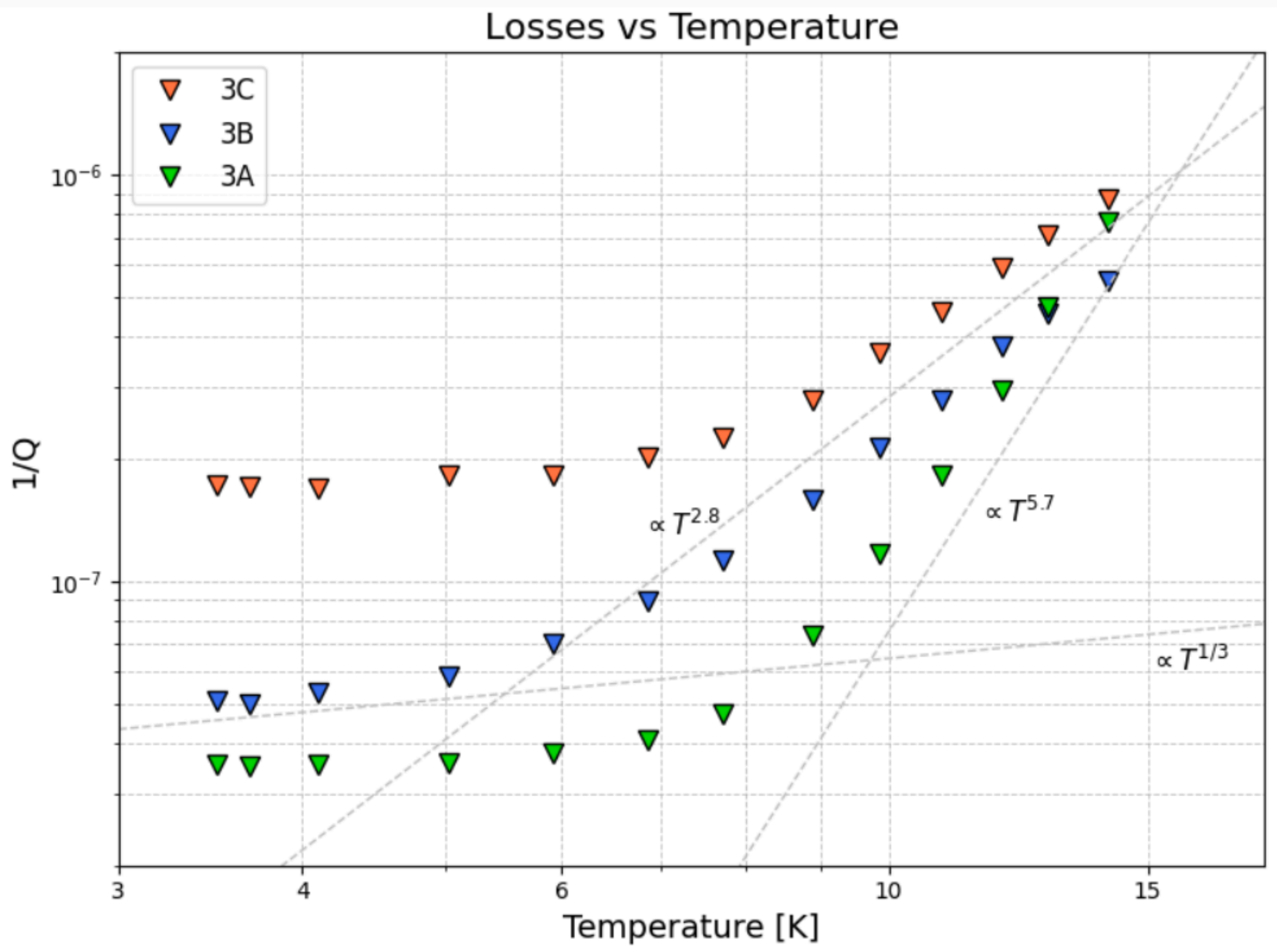
- Operation at low temperature (Q-factor improves at low temperatures)
- Superconducting Quantum Interference Devices (SQUIDs) for amplification.

Current status

and short term plan

- We acquired and characterized **commercial SiO_2 BAW resonators,** from RAKON (FR) conducting tests at both room and cryogenic temperatures.
- Device optimized for ~5 MHz (clock standard)
- **Q-factor > 10^7** at 4 K, comparable to devices in use at MAGE
- Performance meets the requirements necessary for a prototype gravitational wave detector at the MHz scale.
- SQUIDs and Cryostat will be delivered in the upcoming weeks.
- **We will be ready soon to put in operation the prototype HFGW detector with commercial BAWs.**





Plots from L. Mariani, Master Student currently @ UWA

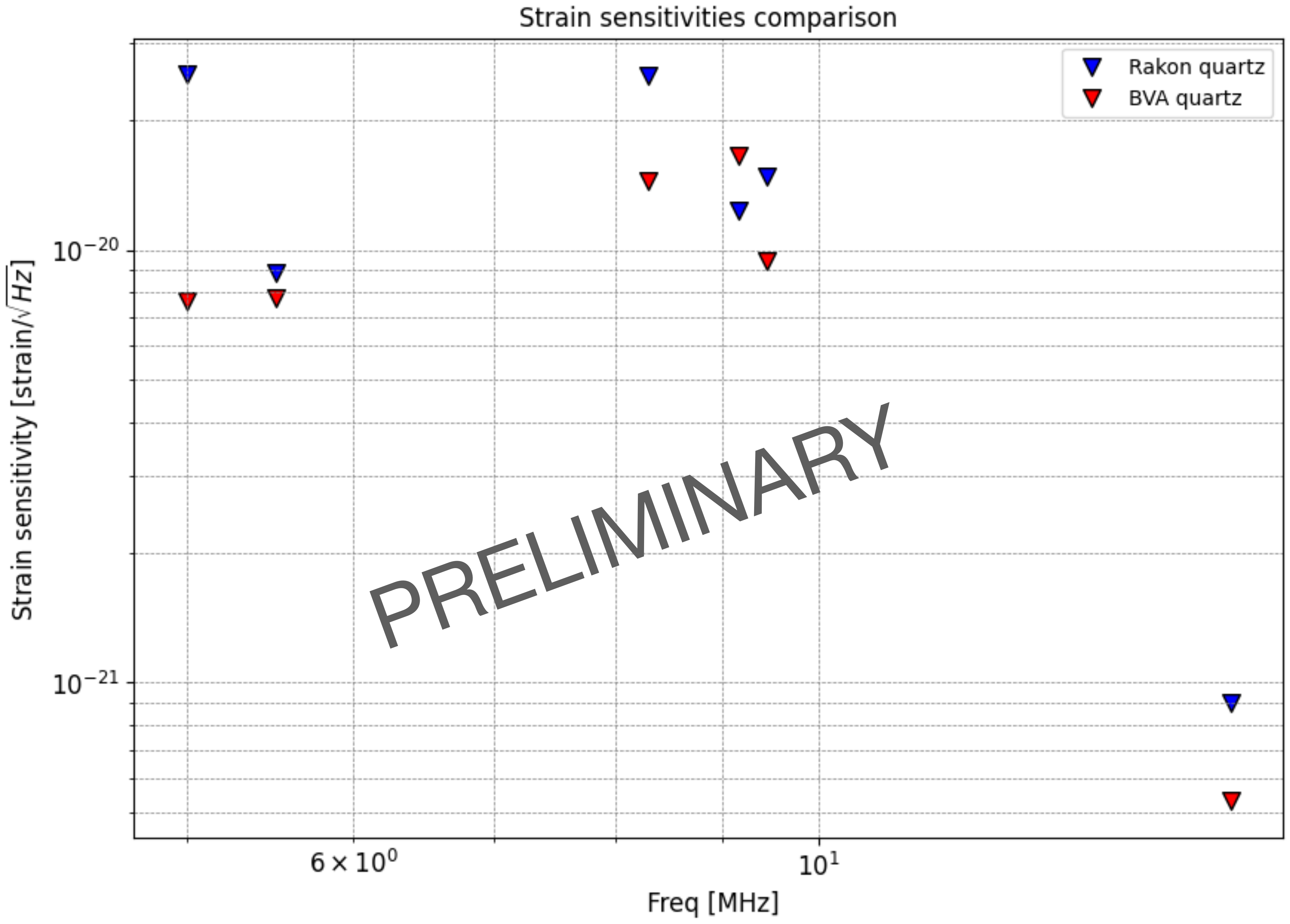
Strain sensitivity

And detection limit

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

$$\sqrt{S_h^+(f)} = \frac{2}{\pi h_0 \bar{\xi}_\lambda f}\sqrt{\frac{w(\omega)\, k_B T}{Q_\lambda \omega_\lambda m_\lambda}} \quad \left[\frac{strain}{\sqrt{Hz}}\right]$$

- Expected **sensitivity comparable to MAGE** at UWA

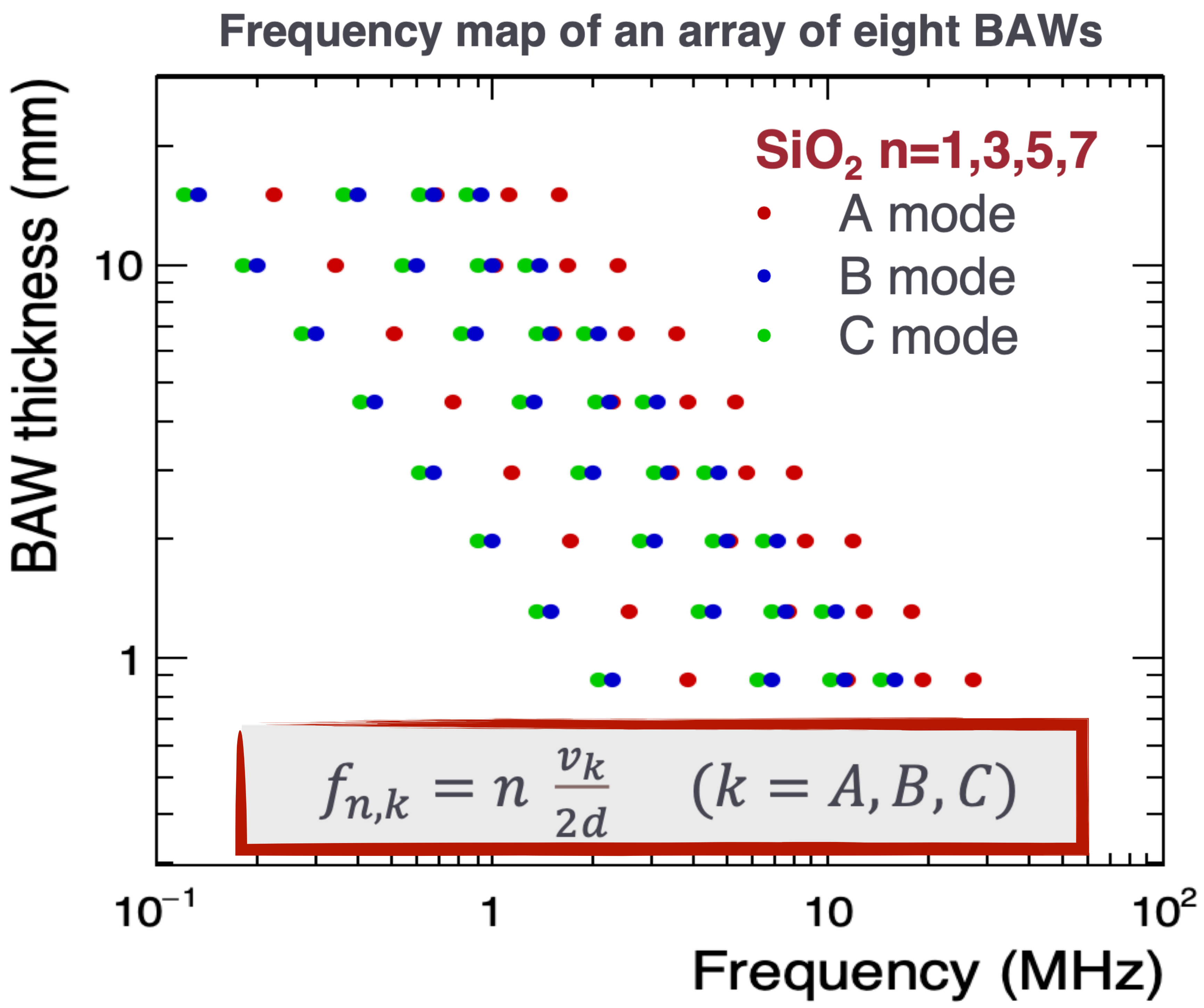


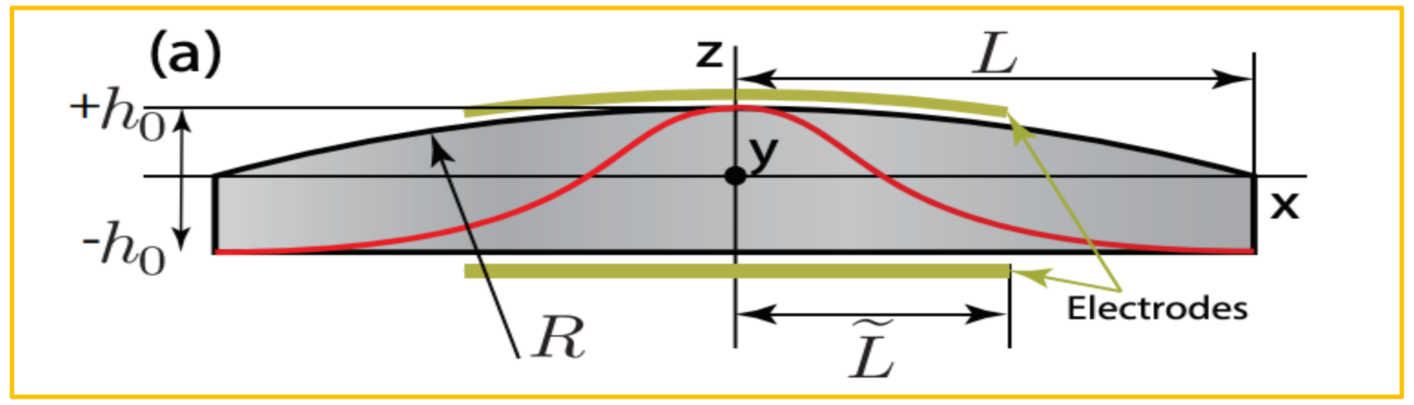
Plot from L. Mariani, Master Student currently @ UWA

From narrowband to broadband

Custom BAW for a multi-frequency detector

- BAW resonators can support multiple resonant modes, 1 longitudinal (A) and 2 transverse (B,C)
- They supports also multiple higher-order harmonic overtones, *n* (only sensitive to odd overtones)
- Adjusting the thickness of the resonator, specific mechanical resonance frequencies can be targeted
- Using different piezoelectric materials, each with distinct acoustic velocities, several resonant frequencies can be supported.
- Critical sensitivity dependencies: $\sqrt{S(f)} \sim \frac{\sqrt{2n}}{L}\sqrt{\frac{k_B T}{Q_\lambda \rho \nu^3}}$
- **Wide frequency range of sensitive modes with improved sensitivity is possible**

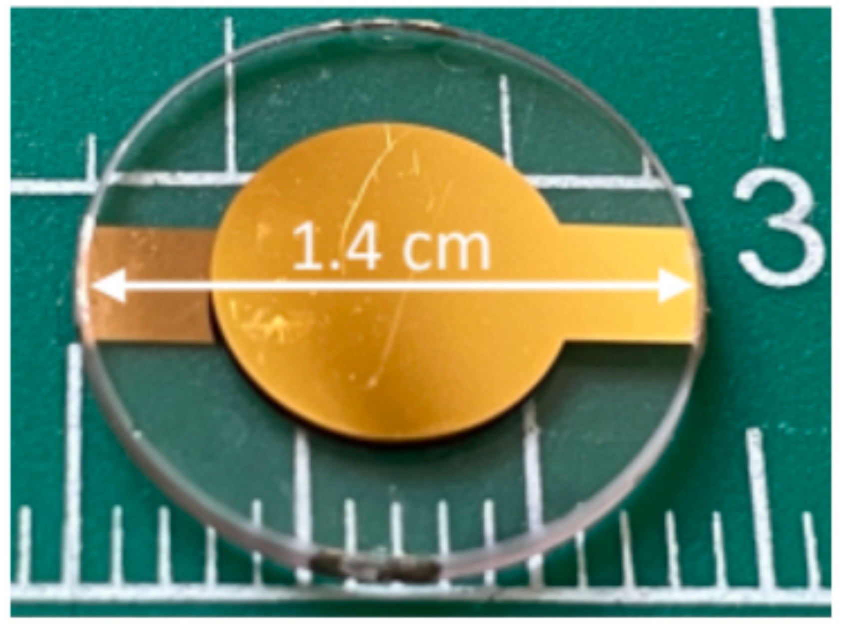


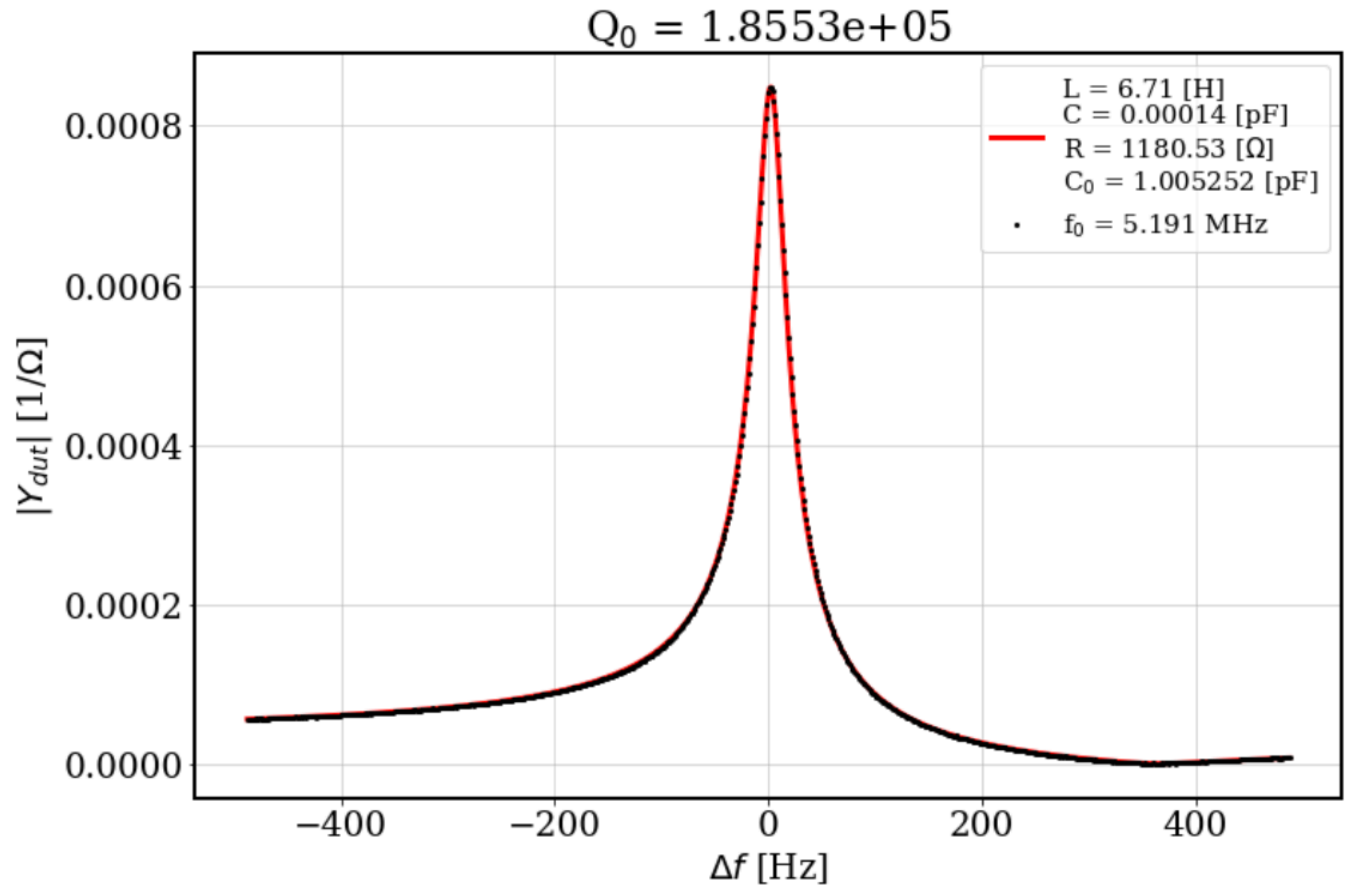


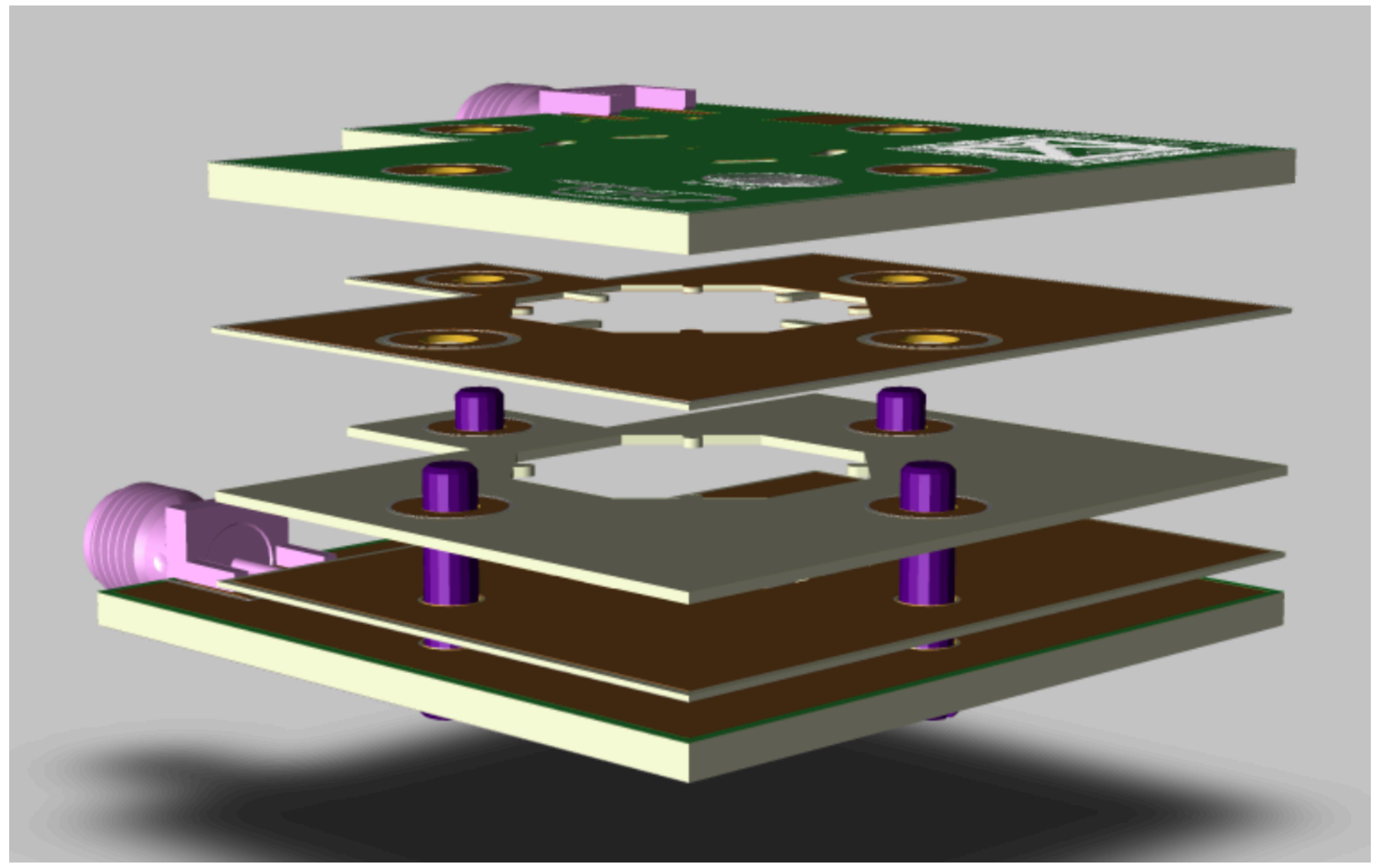
Current activities

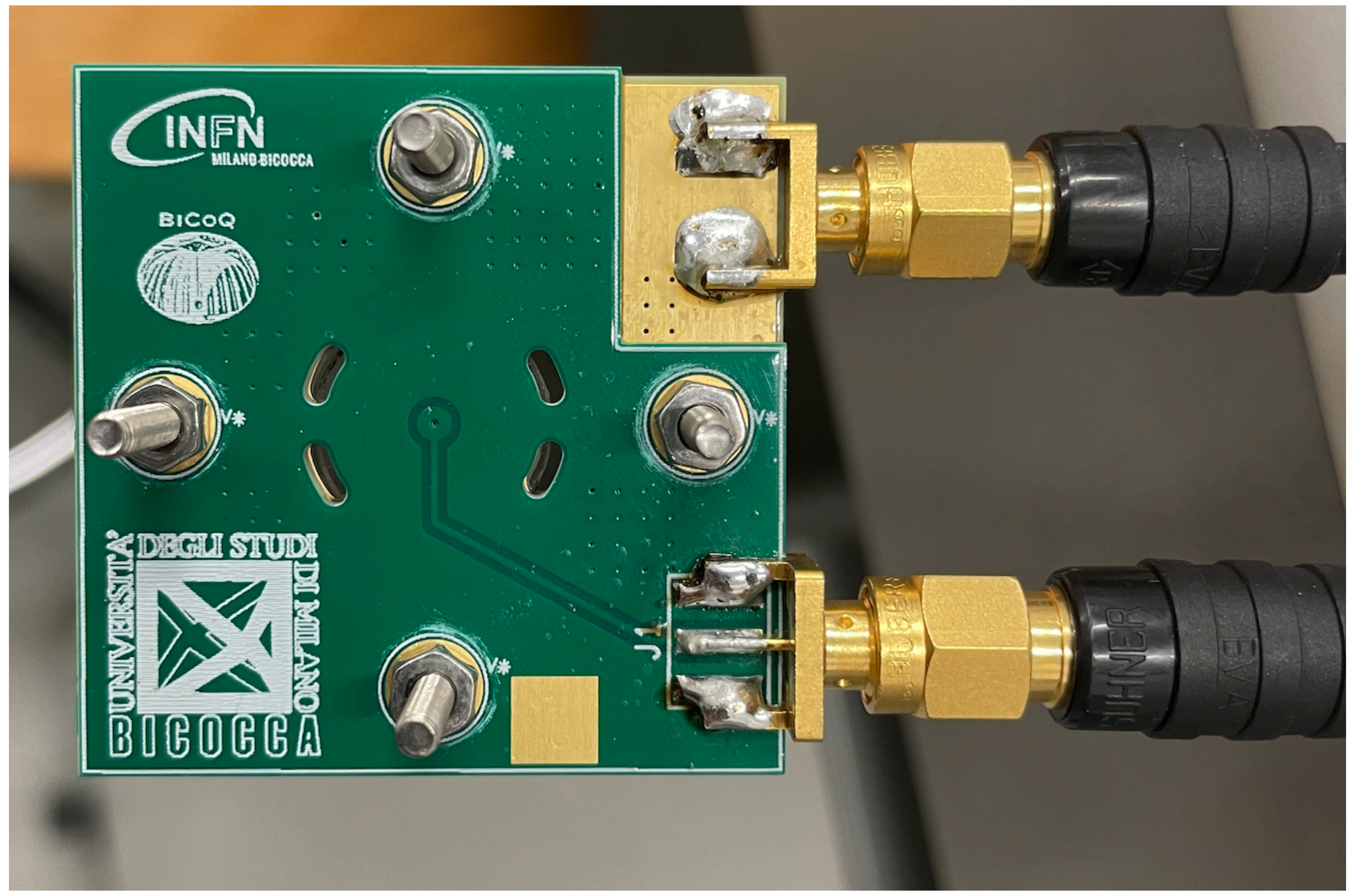
Towards a high multi-frequency detector

- Collaboration initiated with with suppliers (e.g., CristalInnov, FR, and Kingwin Optics, China) to create **BAW with custom designs**, i.e. different shapes and thicknesses.
- Preliminary measurements on bare quartz crystals and other piezoelectric materials (like $LiNbO_3$)
- Custom **mechanical holders** to test crystals of various sizes.



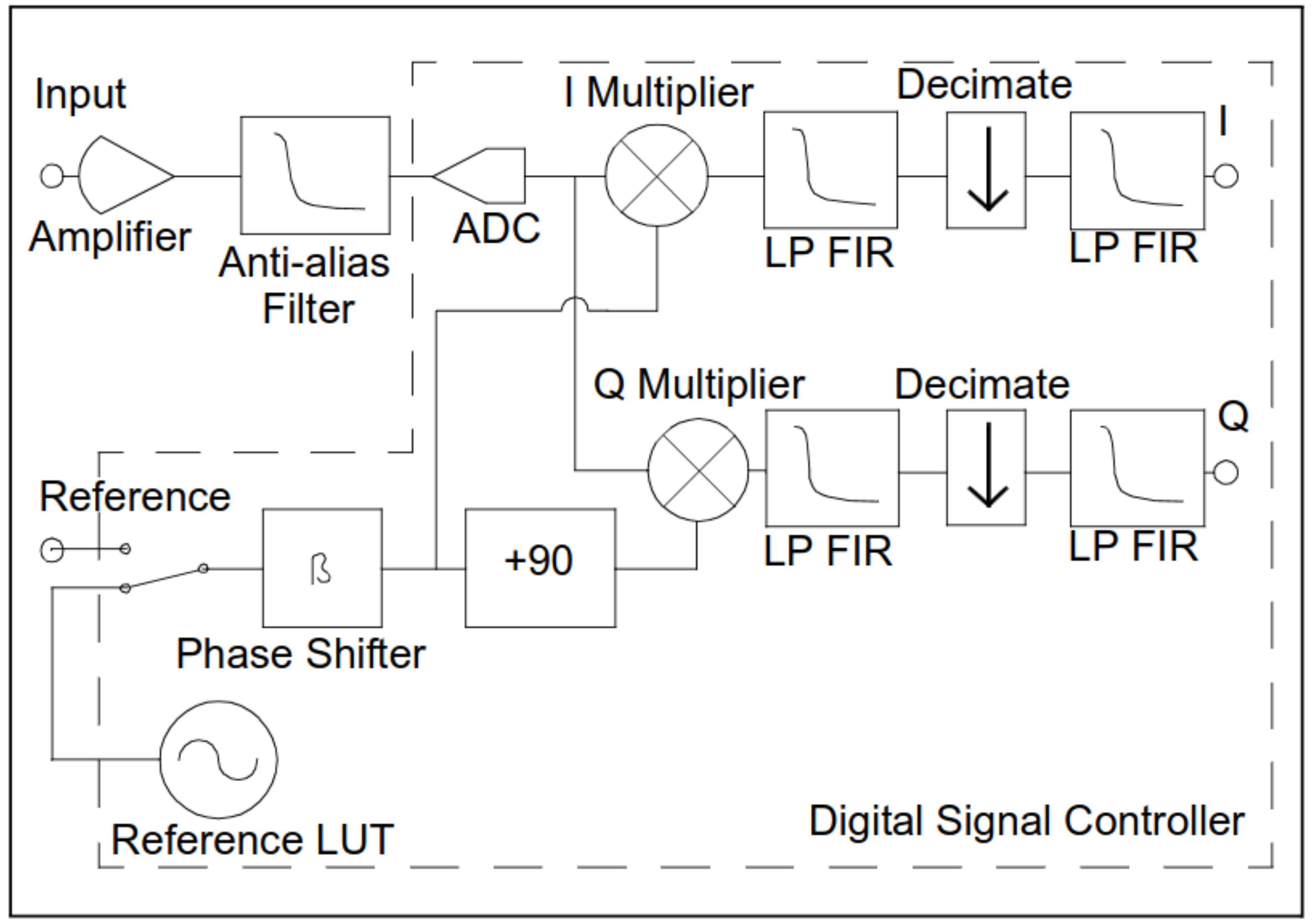




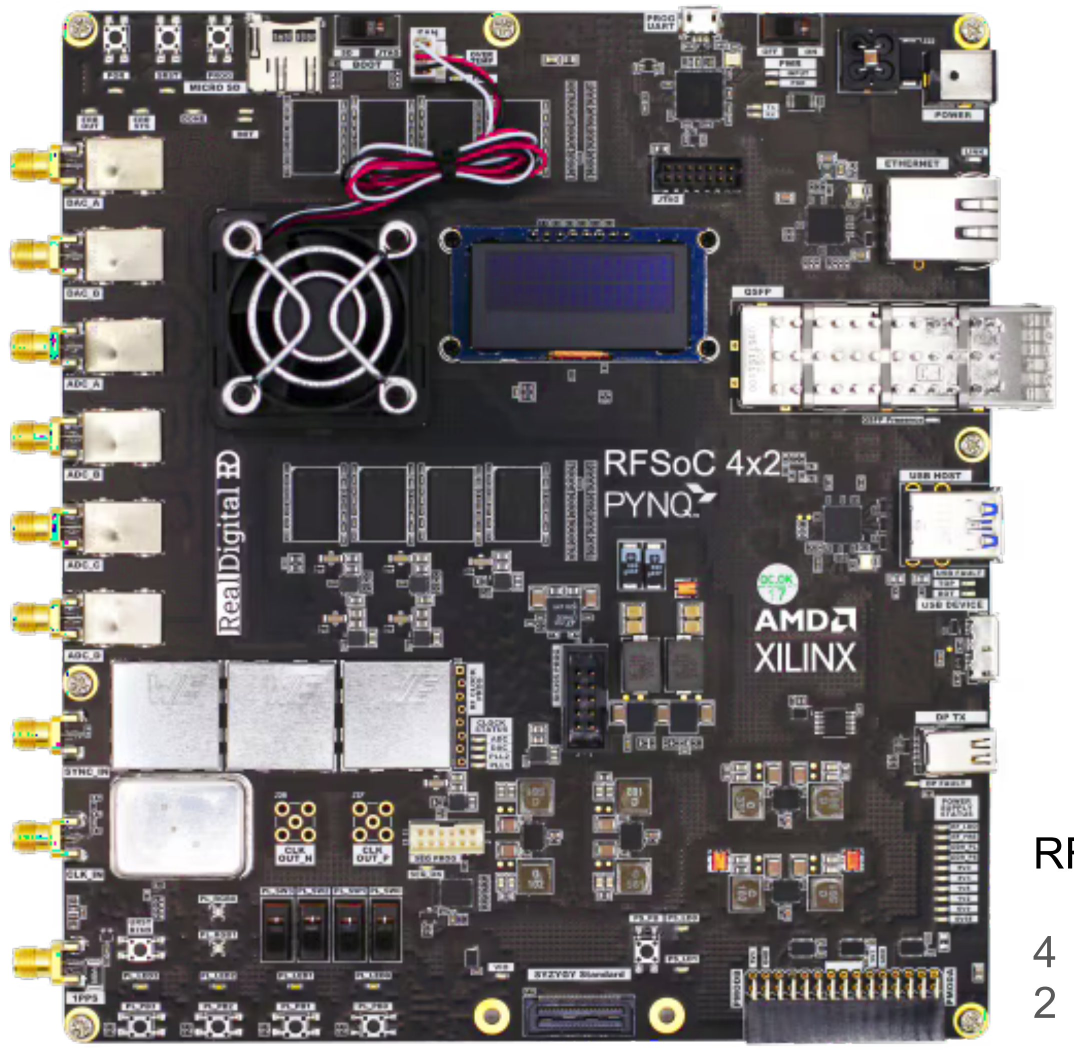


Readout and DAQ
Development in progress

- Objectives:
  - Realization of a **full-digital lock-in amplifier** to analyze multiple frequencies from one BAW 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 and 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)

Procurement and criticalities

- **SQUIDS**:
  - The purchase order was placed in October 2023.
  - Faulty components in the electronic control boards caused vendor delays of several months.
  - The delivery of SQUIDs is now expected **before the end of the year.**

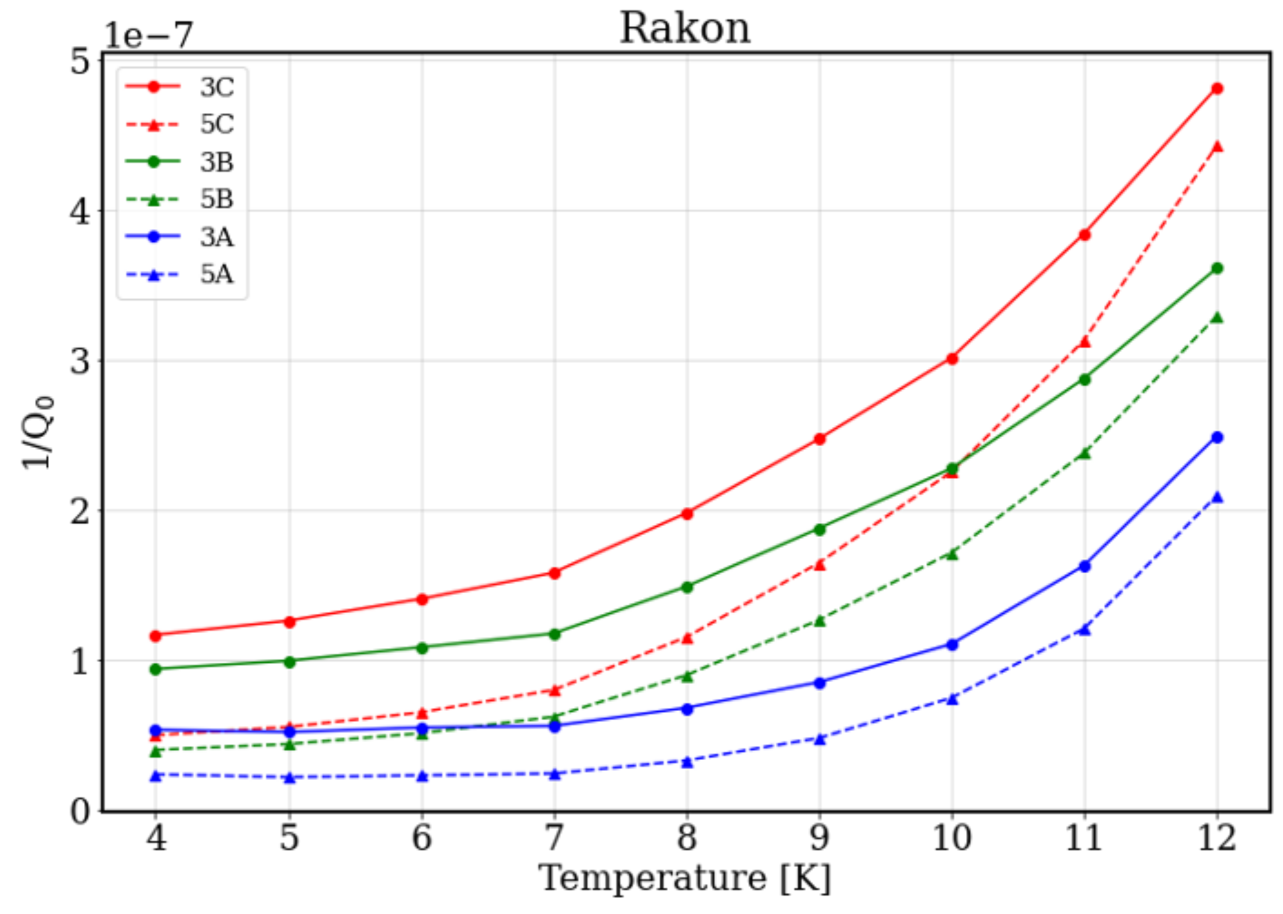
- **Cryostat:**
  - Delivery scheduled for Feb. 2025 (only a few months' delay relative to the initial schedule)
  - For the R&D phase, we are relying on cryogenic setups available at the cryogenic laboratory of INFN and the Physics Department
  - **Access to measurement slots is highly limited.**

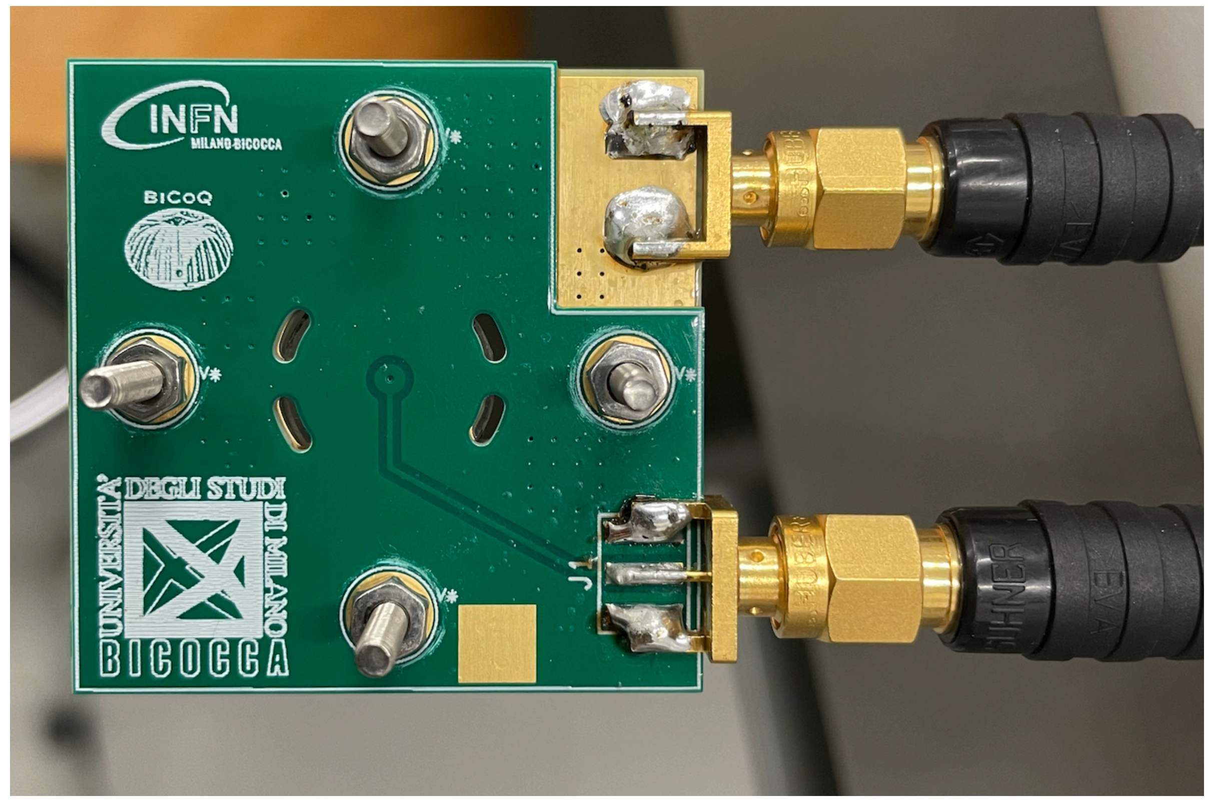
- **Space for laboratory**
  - New experimental area for BiCoQ Laboratory (LaBiCoQ) located in U19
  - Construction timeline incompatible with the experiment's schedule.
  - **Urgent identification of a temporary space for the refrigerator installation.**

Summary

And prospects

- BAW technology is suited for the detection of HFGW
- Broad range sensitivity requires many BAWs of different sizes
    - Dedicated BAWs being developed with crystal manufacturers
- Setting up a 2nd detection site at Milano-Bicocca with off-the-shelf BAWs
    - Expected sensitivity comparable to MAGE





Further reference

Scientific output

- **Conferences**
  - T. Tabarelli de Fatis, “Bulk Acoustic Wave cavities for high frequency gravitational wave antennas”, talk, “GWADW2023: Gravitational-Wave Advanced Detector Workshop”, La Biodola, Isola d’Elba, Italy, 21-27 May 2023.
  - T. Tabarelli de Fatis, “Bulk Acoustic Wave devices”, invited talk, “Ultra High-Frequency Gravitational Waves (UHFGW) Workshop”, CERN, Switzerland, 4-8 December, 2023.
  - M. Faverzani, “Bulk Acoustic Wave cavities for high-frequency gravitational wave antennas”, poster, “16th Pisa Meeting on Advanced Detectors”, La Biodola, Isola d’Elba, Italy, May 26-June 1, 2024.
  - L. Canonica “Bulk Acoustic Wave devices for high-frequency gravitational wave antennas”, poster, “IDM2024 - Identification of Dark Matter Conference”, L’Aquila Italy, 8–12 July 2024.
- **Bachelor thesis at University of Milano-Bicocca:**
  - Riccardo Maifredi (2023), Lisa Paradossi (2023), Alberto Costanzo (2023), Alessia Pozzi (2024), Francesco Butà (2024), Ivan Piergianni (in progress), Camilla Ruiu (in progress);
- **Master thesis at UWA and University of Milano-Bicocca:**
  - Leonardo Mariani (2024 in progress)