Living Reviews in Relativity manuscript No.
(will be inserted by the editor)

Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

4.2.2 Bulk acoustic-wave devices

Bulk acoustic-wave (BAW) devices are one of the pillars of frequency control and frequency metrology (Galliou et al., 2013). In its simplest form, a piece of piezoelectric material is sandwiched between two electrodes, converting the acoustic waves inside the material into electrical signals. With its relatively compact size and robustness, this technology gives one of the best levels of frequency stability near one second of integration time. More recently, it was demonstrated that quartz bulk acoustic-wave devices exhibit extremely high-quality factors (up to 8×10^9) at cryogenic temperatures for various overtones of the longitudinal mode covering the frequency range (5–700) MHz (Galliou et al., 2013; Goryachev et al., 2013). For this reason, it was proposed to use the technology for various tests of fundamental physics (Galliou et al., 2013) such as Lorentz invariance tests (Lo et al., 2016), quantum gravity research (Bushev et al., 2019) and search for high-frequency GWs (Goryachev and Tobar, 2014). For the latter purpose, a bulk acoustic-wave device represents a resonant mass detector whose vibration could be read through the piezoelectric effect and Superconducting Quantum Interference Devices (SQUIDs). The approach has the following advantages: highest quality factor (high-sensitivity), internal (piezoelectric) coupling to SQUIDs (Goryachev et al., 2014), allows parametric detection methods, a large number of sensitive modes (>100) in a single device, modes scattered over the wide frequency range (1–700) MHz, well-established and relatively inexpensive technology (mass production), high-precision (insensitive to external influences such as seismic vibration and temperature fluctuations), and possibility of scalation or modifications towards lower frequencies and/or better sensitivities from arrays of detectors. On the other hand, it is shown that at low temperatures identical devices demonstrate significant dispersion in mode frequencies, thus, showing low accuracy. The level of sensitivity of bulk acoustic-wave detectors is estimated at the level of $\sqrt{S_n} \simeq 2 \times 10^{-22}\,\mathrm{Hz}^{-1/2}$ subject to the mode geometry (Goryachev and Tobar, 2014). With additional investment into research and development, this level can be improved and the frequency range extended down to hundreds of kHz range.

A search for high-frequency GWs with single bulk acoustic-wave devices and two modes at $\sim 4\,\mathrm{K}$ has been running at the University of Western Australia since November 2018. Quite recently, two strong rare events were reported in these searches, at different frequencies around few MHz (Goryachev et al., 2021). The origin of these rare events can not be determined with current data (see also (Lasky and Thrane, 2021) regarding the relation of the signal to UHFGWs). However, these results show the extraordinary potential of this direction. This has triggered the interest for further developments. Among them, the possibilities of building an array of BAWs and multimode read-outs are being pursued by the Bulk Acoustic Wave Sensors for a High-frequency Antenna (BAUSCIA) proposal in Milano Biccoca (`https://indico.cern.ch/event/1257532/contributions/5668682/`) and the Multimode Acoustic Gravitational Wave Experiment (MAGE) one in University of Western Australia (Campbell et al., 2023b). From these experiences, one expects to be able to build networks of $O(10)$ BAWs, accessing $O(100)$ frequencies in the rank and sensitivities we described.

Further improvements could come from reaching the quantum ground state of the system (Campbell et al., 2023a), or, in general, counting phonons, performing quantum state tomography or quantum manipulation and characterization of the states of a BAW resonator (Chu et al., 2018; von Lüpke et al., 2022; Bild et al., 2023). Finally, a recent theoretical characterization aiming at optimizing the searches of HFGWs with phonons can be found in (Kahn et al., 2023).

https://indico.cern.ch/event/1257532/timetable/#20231204.detailed

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Ultra-high frequency gravitational waves: where to next ?

Dec 4, 2023, 9:00 AM → Dec 8, 2023, 7:00 PM Europe/Zurich

4/3-006 - TH Conference Room (CERN)

Bulk Acoustic Wave devices for high-frequency gravitational wave antennas

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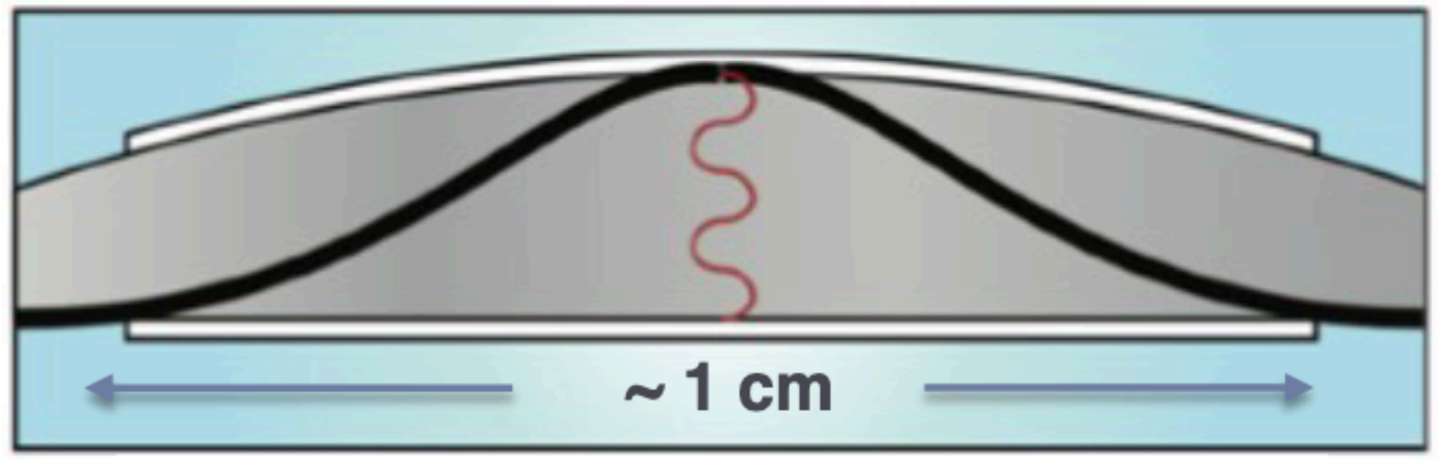
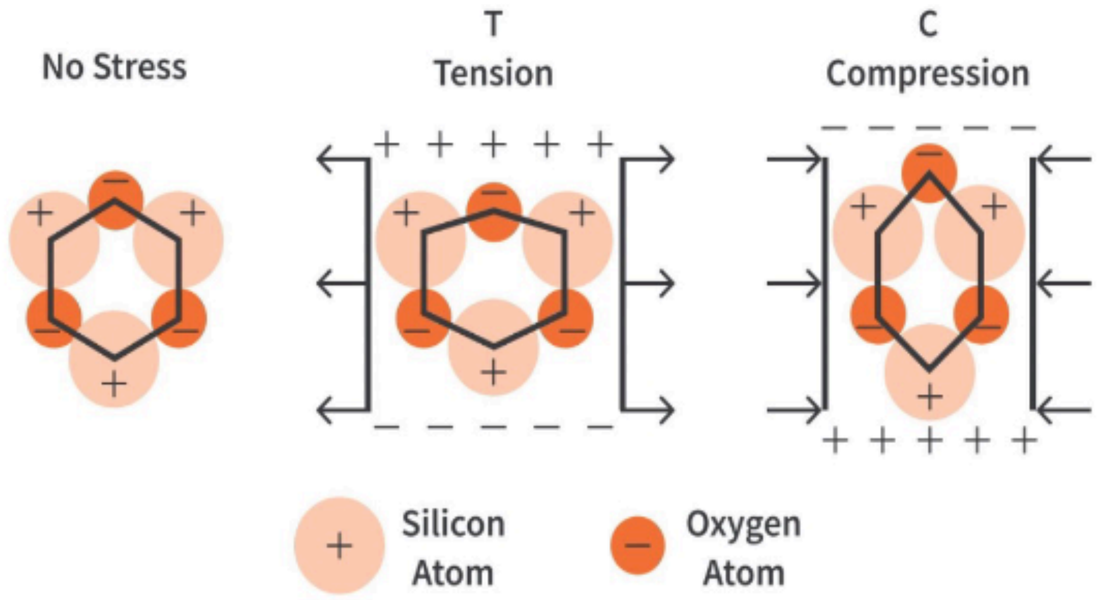
Bulk acoustic wave c

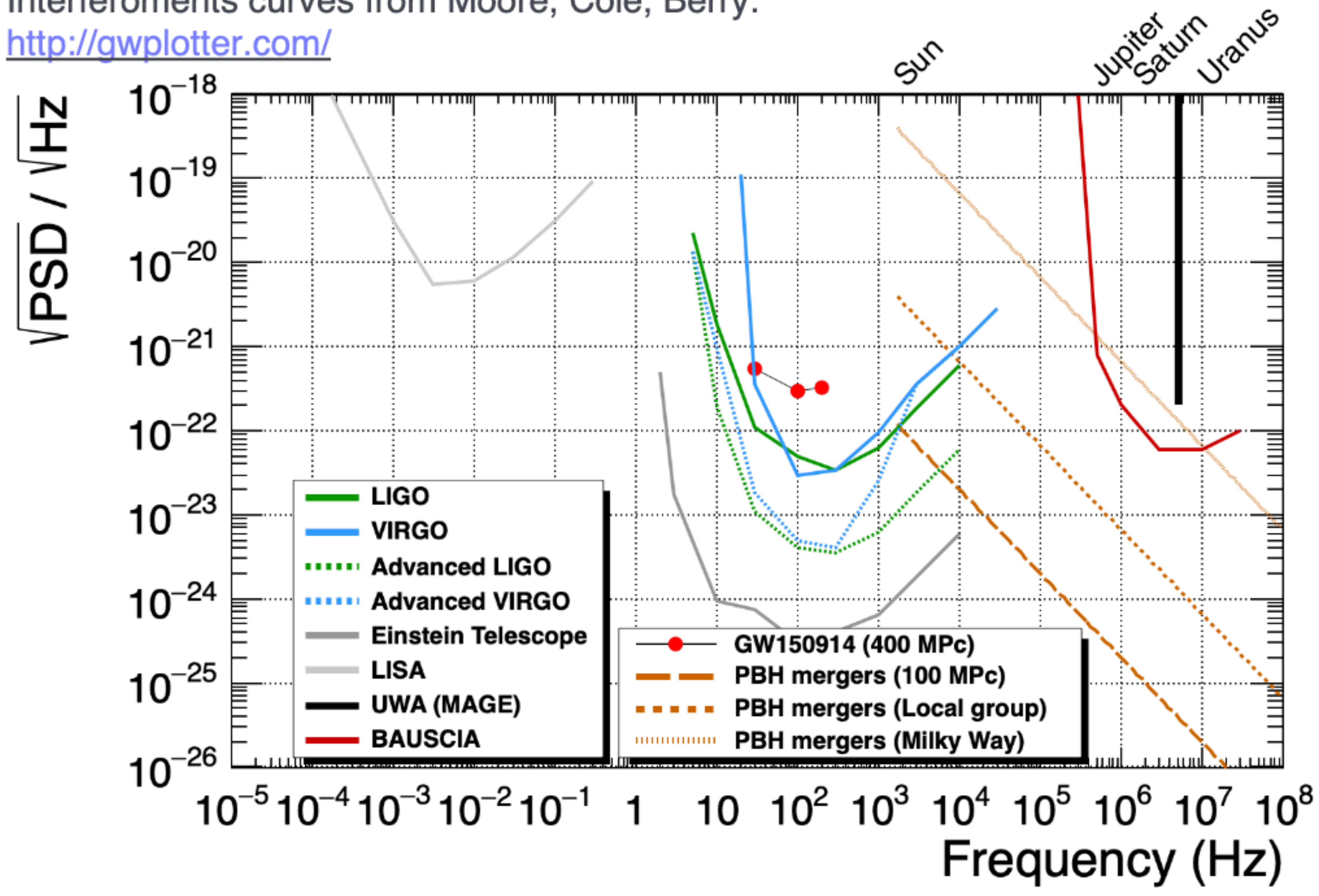
- **Resonant mass detector**
  - **High sensitivity** through high quality factor
  - **Internal** (piezoelectric) **transducer**
    - (only odd overtones audible)
  - **Scalable** technology, established >70 years for precision clock applications

Plano-convex BAW
(minimize mechanical losses)





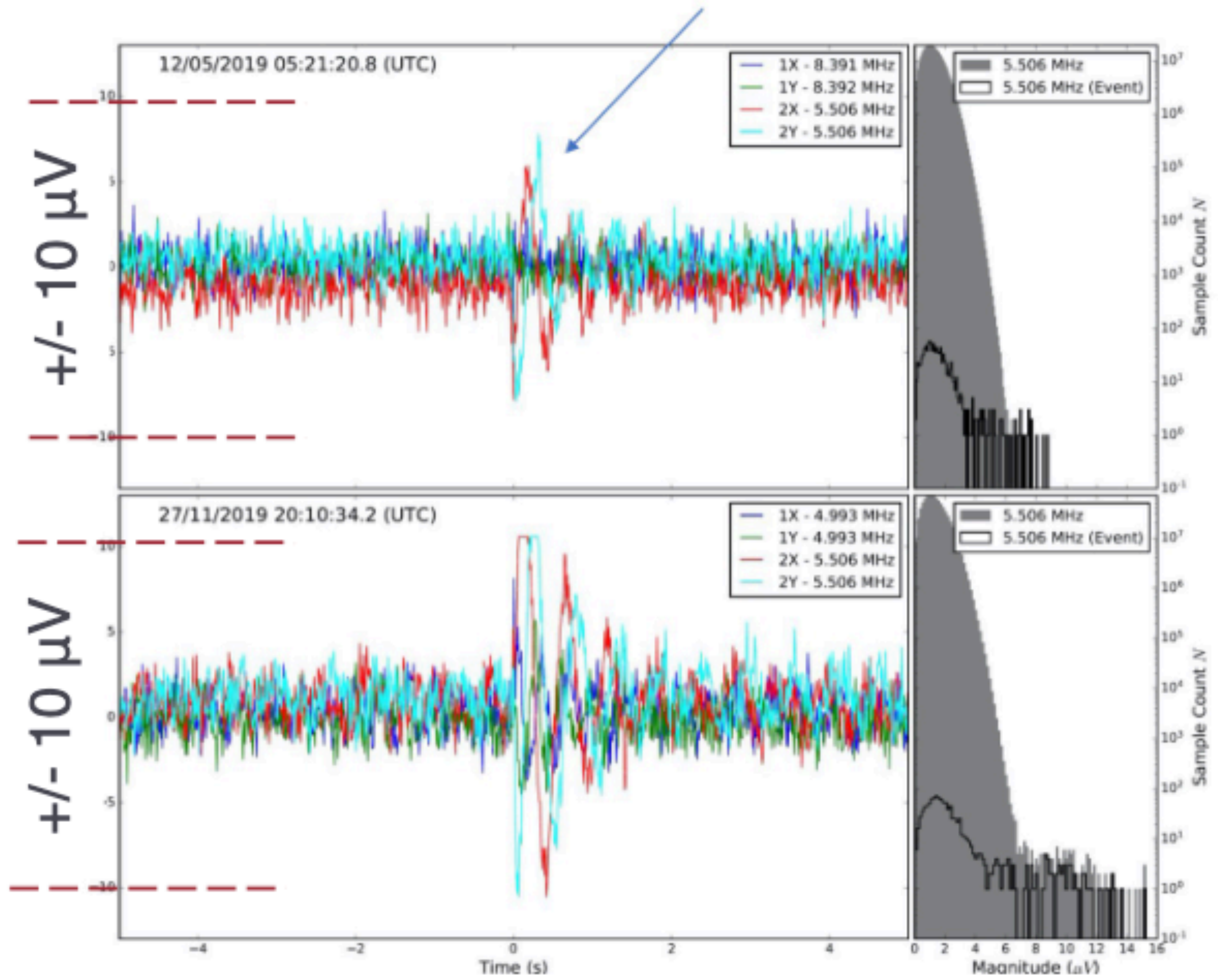
Interferoments curves from Moore, Cole, Berry: http://gwplotter.com/



Sensitivity (envelope) scaling from the MAGE antenna at UWA to an array of multiple BAW cavities of comparable quality

PBH merger signal scaled from GW150914

- **Complementary to large interferometers**
- **Supplementary to MAGE (Univ. Western Australia)**
  - BAW antenna operated for 153 days at 5 MHz (single frequency lock-in readout)
  - Detection of two signals of uncertain origin (*)



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

Equation of motion under GW excitation

$$\ddot{B}_\lambda + \tau_\lambda^{-1}\dot{B}_\lambda + \omega_\lambda^2 B = -c^2 R_{i0j0}\int_{\mathcal{V}} dv\,\frac{\rho}{m_\lambda}U_\lambda^i(\mathbf{x})x^j,$$

GW – cavity coupling

- U_λ = spatial distribution of the mode vibration
- V, ρ, and m_λ = BAW volume, density mode mass
- ω_λ, τ_λ = mode frequency and bandwidth

Coupling coefficient scales with $1/n^2$

- High response to GW only at low overtones

$$\xi_\lambda = h_0\tilde{\xi}_\lambda = \int_{\mathcal{V}} dv\,\frac{\rho}{m_\lambda}U_\lambda^i(\mathbf{x})x^j,$$

$$\tilde{\xi}_{Xn00} = \frac{\xi_{Xn00}}{h_0} = \frac{16}{n^2\pi^2}\frac{\mathrm{Erf}(\sqrt{n}\eta_x)\mathrm{Erf}(\sqrt{n}\eta_y)}{\mathrm{Erf}(\sqrt{2n}\eta_x)\mathrm{Erf}(\sqrt{2n}\eta_y)},$$

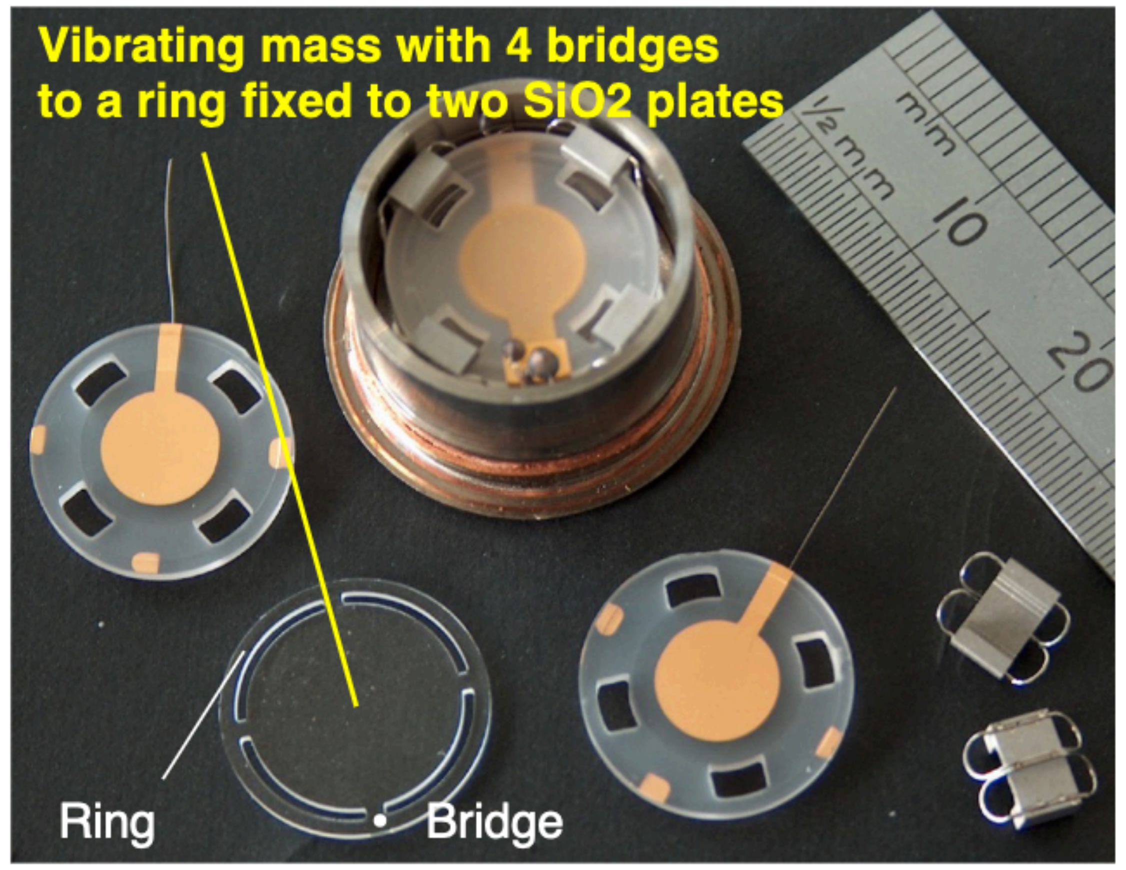
Trapping coefficient

$$\eta_x = \frac{L}{2}\sqrt{\frac{\chi_x}{h_0\sqrt{RL}}}, \qquad \eta_y = \frac{L}{2}\sqrt{\frac{\chi_y}{h_0\sqrt{RL}}}.$$

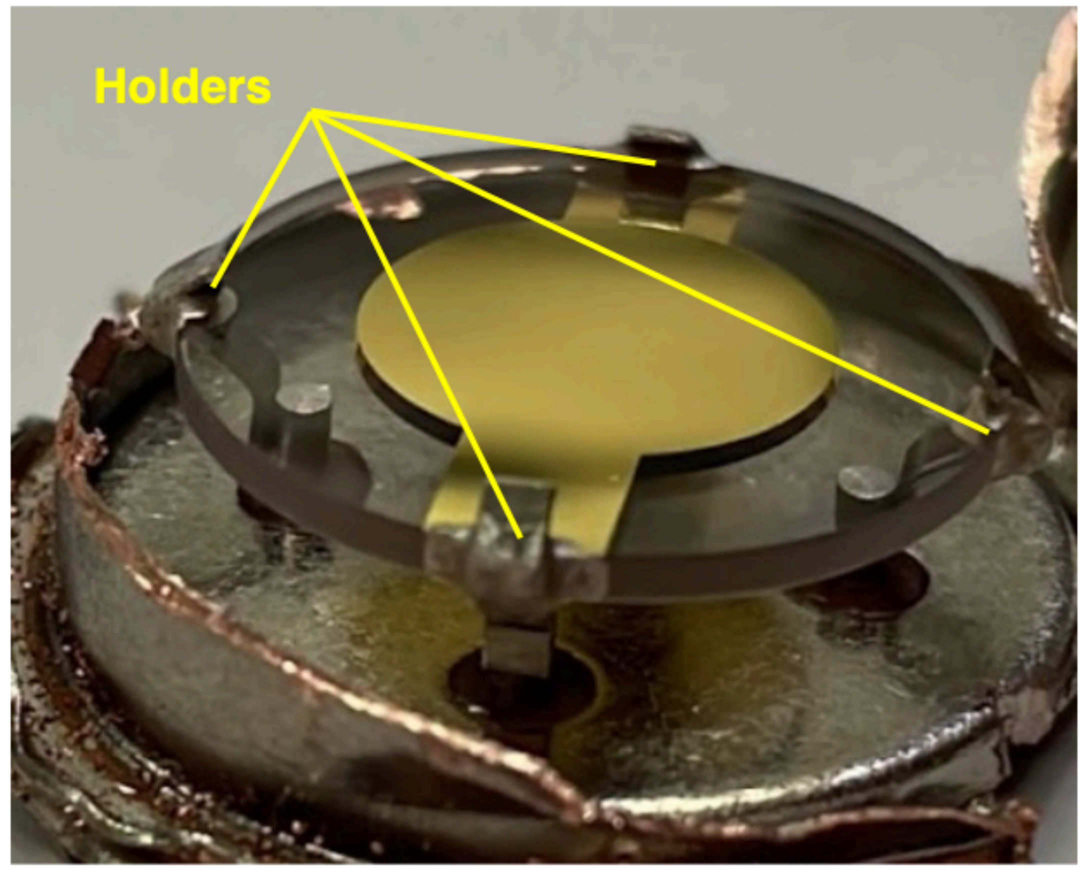
- Depends on the cavity gometry (R, L, h_0) and parameters that can be measured (angular modes)

BAW samples

- **MAGE (UWA)**
  - Two BVA quartz cavities (low-loss design)
  - Plano-convex SiO_2: d~1 mm
  - Electrodes deposited on separated SiO2 plates



- **BAUSCIA (Milano Bicocca)**
  - Off-the-shelf quartz cavities (Rakon XO)
  - SiO_2 crystal with four rigid mounts: d~1 mm
  - *Electrodes deposited on BAW (suboptimal)*



- **Room temperature: Q ~ 10^6**
  - Optimized for the 3rd overtone of the C-mode (slow shear) at ~5 MHz (clock standard)
  - Low Q at n=1 (lwhere the coupling to GW is largest)
- **Cryogenic temperatures: Q > 10^7 (low overtones)**
  - [up to 10^9 at high frequencies but reduced coupling to GW signals]

OTHER??

E.g. ETHZ group