Bulk Acoustic Wave devices for high-frequency gravitational wave antennas

Tommaso Tabarelli de Fatis
(Dipartimento di Fisica, Università di Milano Bicocca and INFN Milano-Bicocca)

- **Outline**
  - Potential GW sources at high-frequencies
  - Detection approach
  - Status (at Milano Bicocca)
  - Summary

Contributors:

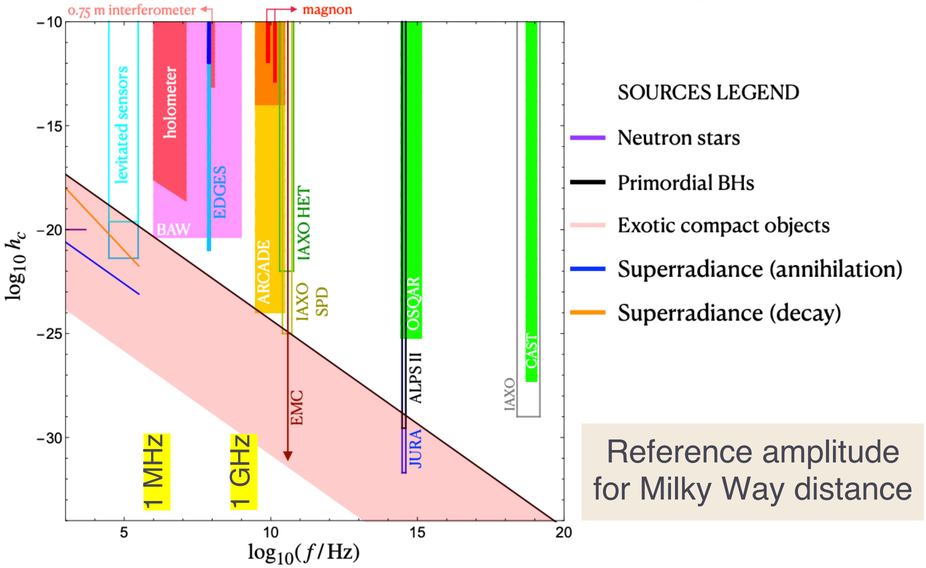
- L. Mariani and R. Maifredi (BSc. In Physics at Milano Bicocca);
- M. Borghesi, M. Benaglia, G. Conenna, F. De Guio, M. Faverzani, E. Ferri, A. Ghezzi, R. Gerosa, B. Giacomazzo, A. Giachero, M. Malberti, A. Nucciotti, G. Pessina (Milano Bicocca)

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

Potential GW sources at high-frequency

- N. Aggarwal et al., “Challenges and opportunities of Gravitational Wave searches at MHz to GHz frequencies”, Living Reviews in Relativity volume 24, Article number: 4 (2021)

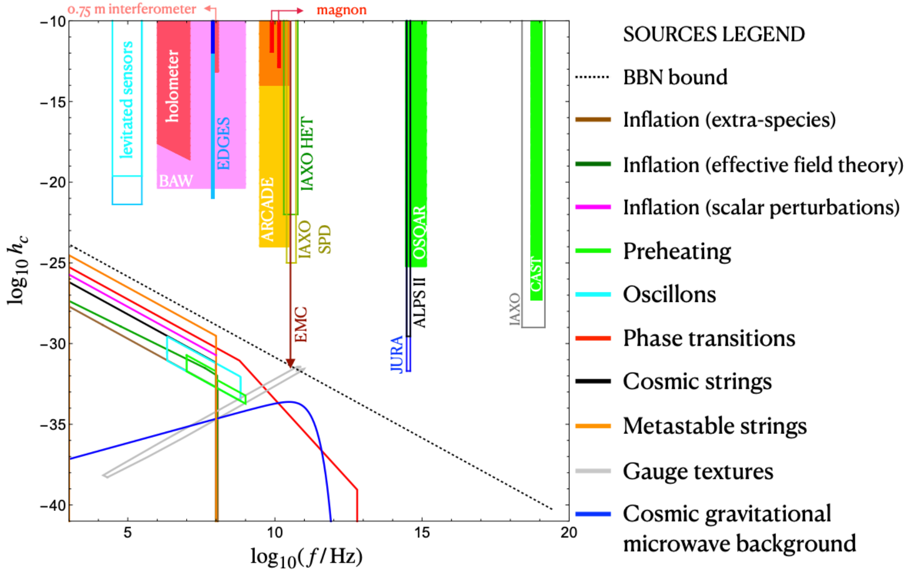
Coherent sources (distinctive signature)



Reference amplitude for Milky Way distance

Figure 1: Examples of coherent sources of GWs, see text for details. Details about the various detector concepts are given in Sec. 4.1.2 for the 0.75 m interferometer and the holometer experiment, Sec. 4.2.1 for the optically levitated sensors, Sec. 4.2.2 for IAXO Single Photon Detector (SPD), IAXO Heterodyne radio receiver (HET), OSQAR, CAST, ALPS II, JURA, EDGES and ARCADE, Sec. 4.2.5, Sec. 4.2.6 for the Bulk Acoustic Wave Devices (BAW) and Sec. 4.2.9 the graviton-magnon resonance effect.

Incoherent sources



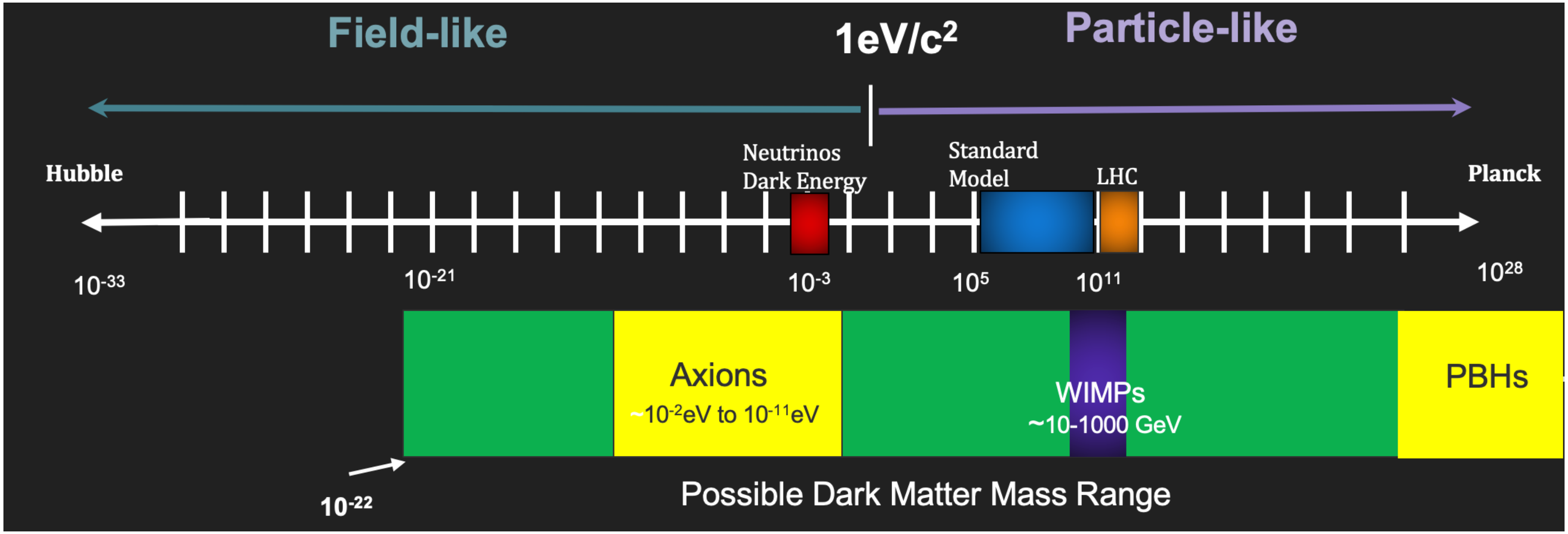
igure 2: Examples of stochastic sources of GWs, see text for details and the caption of Fig. 1 for the reference to ie various detector concept sections.

- **Bulk Acoustic Wave devices (purple) have some sensitivity to <u>coherent signals</u>**
  - *Standard* devices (*) responsive over a wide range of frequencies (1 MHz - 1 GHz)
  - Customization at lower frequencies (larger signals) is possible (and sought)

(*) Precision clock for PLL, GPS, networks applications, etc

Astrophysical coherent sources (I)

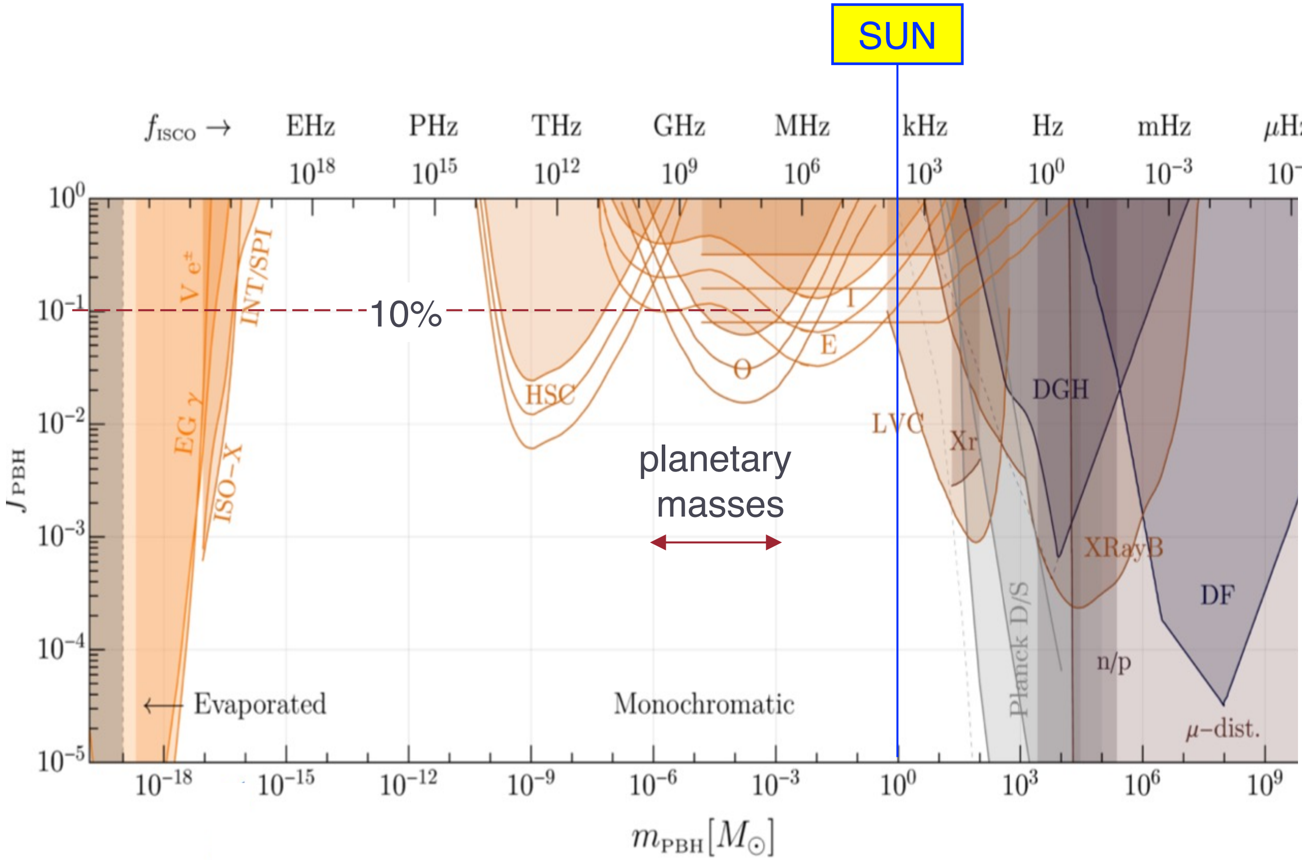
- **Inspirals and mergers of compact binary objects: distinctive frequency vs time pattern**
  - Primordial black holes (PBH) can contribute up to about 10% of the dark matter at planetary masses, which would give an emission at f_{ISCO} in the window of sensitivity of *established* BAWs
- **Black hole superradiance** A. Arvanitaki et. al PRD 83, 044026 (2011)
  - QCD axion annihilations to gravitons in cloud around black holes
  - Requires detection sensitivity around 10-100 kHz (see plot in previous page)
    - Marginal for *established* BAWs but coverable with customized BAWs



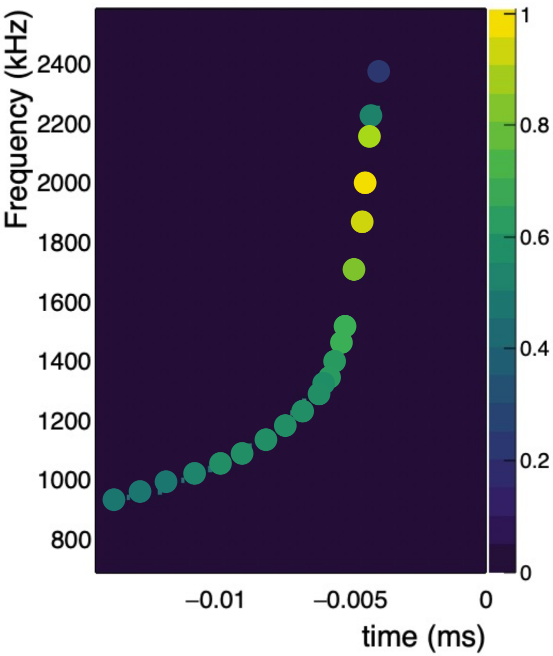
Cartoon from Andrew Geraci's talk at Challenges and opportunities of HFGW, Trieste 2019

Astrophysical coherent sources (II)

- **Inspirals and mergers of compact binary objects: distinctive frequency vs time pattern**
  - Primordial black holes (PBH) can contribute up to about 10% of the dark matter at planetary masses, which would give an emission at f_{ISCO} in the window of sensitivity of *established* BAWs



M ~ 3×10^{-4} $M_\odot$
f_{ISCO} ~ 2 MHz

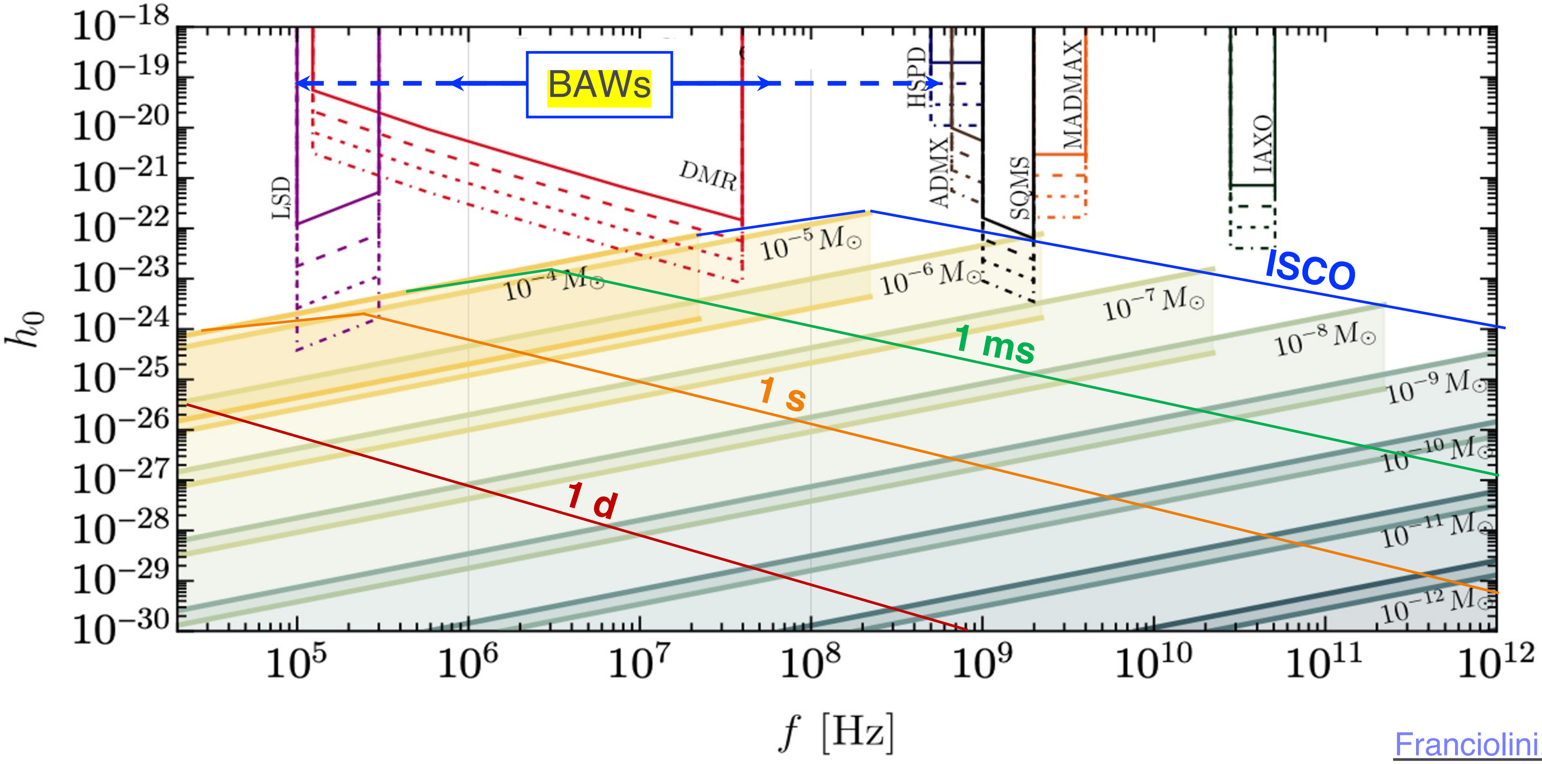


Saturn-mass
PBH-PBH merger

Gravitational lensing: https://doi.org/10.1103/PhysRevD.106.103520

Emission history of PBH binaries

- **BAWs can probe the last day or seconds of planetary-mass PBH binaries**
  - Binaries collapsing in the late universe were formed in early universe
    - Emission for over 10 Gy time at lower frequencies
  - Emission frequency spans several order of magnitudes in the last day
- **Signal correlations in amplitude, time, and frequency can be exploited in GW detectors designed for broadband (or multiple frequency) response**



GW amplityde for signals from distance giving 1 event/day

Bands are for $f_{DM} = 1$ and spans different hypotheses about binaries formation

Franciolini, Maharana, Muia
Phys. Rev. D 106, 103520

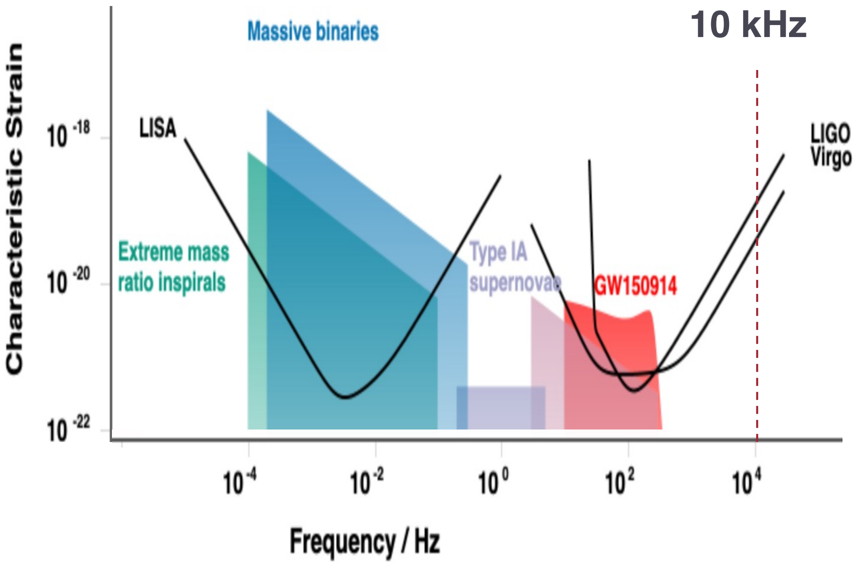
GW detectors: two main classes

- **Interferometers**
  - GWs stretch and squeeze the space between test masses
  - Strain h = ΔL/L very small
    - A few 10^{-21} in GW150914 (1st LIGO chirp)

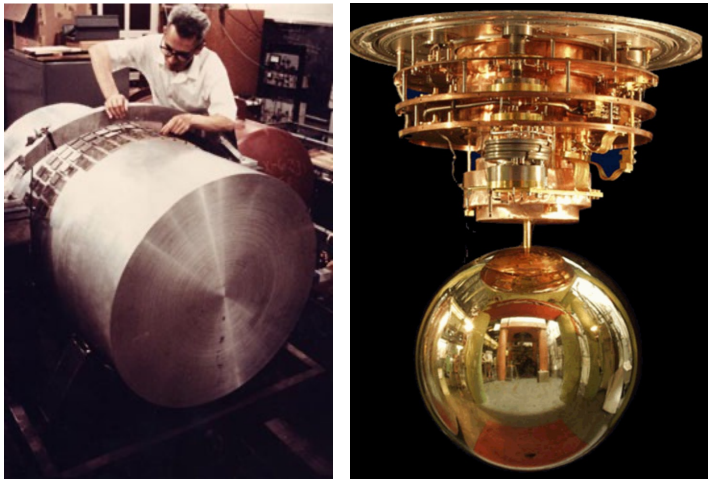
- **Resonant mass detectors**
  - GW tidal forces stretch and squeeze the mass
  - Length variation only detectable at the resonant frequency of the vibration mode(s)
    - Achieved ~ 10^{-22} / √Hz sensitivities

- **Broad band sensitivity**
  - Key to chirp detector (signal pattern)
  - Limited at high frequency by laser shot noise

- **Narrow band sensitivity (high Q)**
  - Bars' resonant frequency ~ **O(1) kHz**

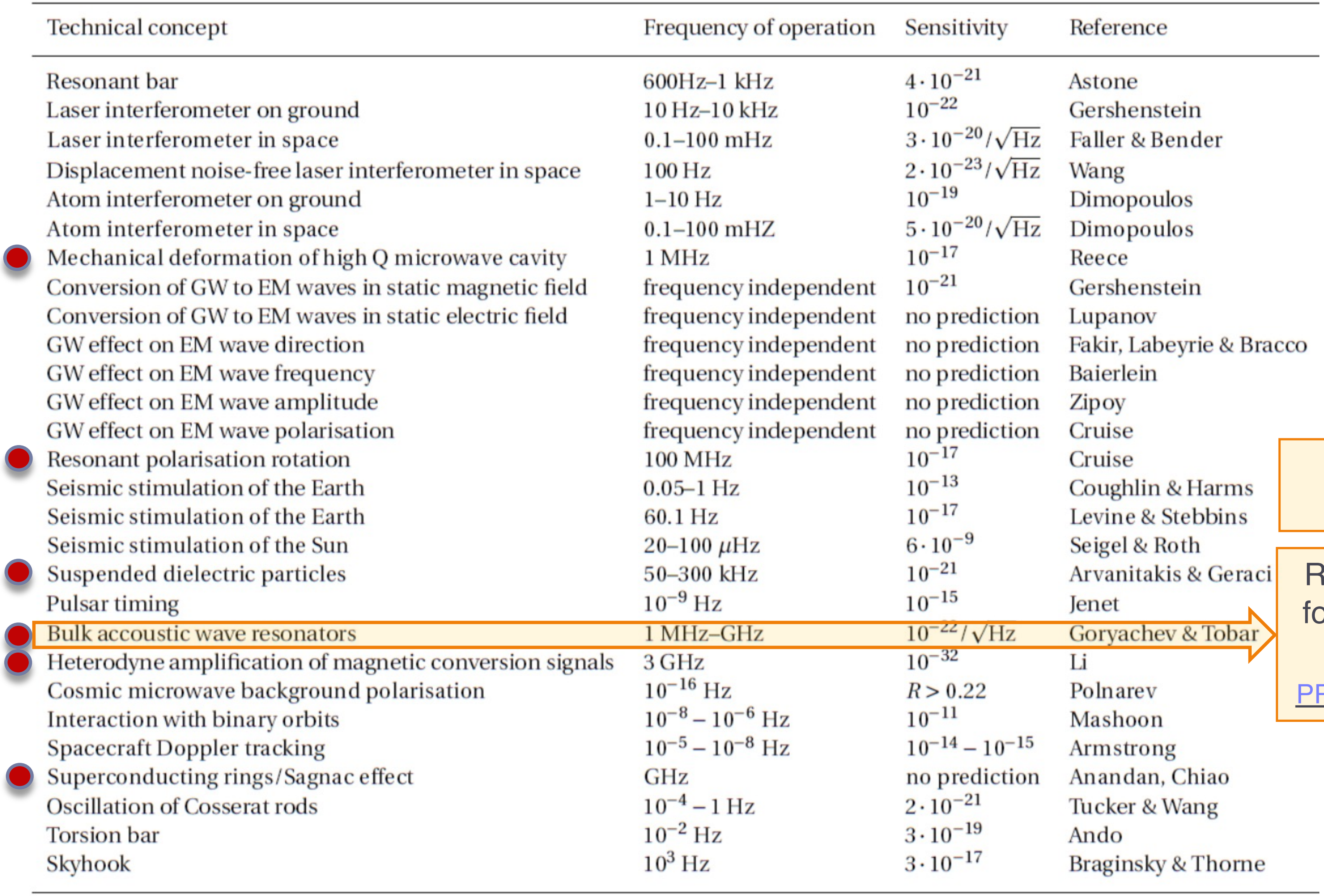


Moore, Cole, Berry: http://gwplotter.com/



K. Thorne: "*A xylophone is needed to detect the entire symphony of the universe*"

GW detectors: many flavours



	Technical concept	Frequency of operation	Sensitivity	Reference
	Resonant bar	600Hz–1 kHz	$4\cdot 10^{-21}$	Astone
	Laser interferometer on ground	10 Hz–10 kHz	10^{-22}	Gershenstein
	Laser interferometer in space	0.1–100 mHz	$3\cdot 10^{-20}/\sqrt{\mathrm{Hz}}$	Faller & Bender
	Displacement noise-free laser interferometer in space	100 Hz	$2\cdot 10^{-23}/\sqrt{\mathrm{Hz}}$	Wang
	Atom interferometer on ground	1–10 Hz	10^{-19}	Dimopoulos
	Atom interferometer in space	0.1–100 mHZ	$5\cdot 10^{-20}/\sqrt{\mathrm{Hz}}$	Dimopoulos
●	Mechanical deformation of high Q microwave cavity	1 MHz	10^{-17}	Reece
	Conversion of GW to EM waves in static magnetic field	frequency independent	10^{-21}	Gershenstein
	Conversion of GW to EM waves in static electric field	frequency independent	no prediction	Lupanov
	GW effect on EM wave direction	frequency independent	no prediction	Fakir, Labeyrie & Bracco
	GW effect on EM wave frequency	frequency independent	no prediction	Baierlein
	GW effect on EM wave amplitude	frequency independent	no prediction	Zipoy
	GW effect on EM wave polarisation	frequency independent	no prediction	Cruise
●	Resonant polarisation rotation	100 MHz	10^{-17}	Cruise
	Seismic stimulation of the Earth	0.05–1 Hz	10^{-13}	Coughlin & Harms
	Seismic stimulation of the Earth	60.1 Hz	10^{-17}	Levine & Stebbins
	Seismic stimulation of the Sun	20–100 μHz	$6\cdot 10^{-9}$	Seigel & Roth
●	Suspended dielectric particles	50–300 kHz	10^{-21}	Arvanitakis & Geraci
	Pulsar timing	10^{-9} Hz	10^{-15}	Jenet
●	Bulk accoustic wave resonators	1 MHz–GHz	$10^{-22}/\sqrt{\mathrm{Hz}}$	Goryachev & Tobar
●	Heterodyne amplification of magnetic conversion signals	3 GHz	10^{-32}	Li
	Cosmic microwave background polarisation	10^{-16} Hz	$R > 0.22$	Polnarev
	Interaction with binary orbits	$10^{-8}-10^{-6}$ Hz	10^{-11}	Mashoon
	Spacecraft Doppler tracking	$10^{-5}-10^{-8}$ Hz	$10^{-14}-10^{-15}$	Armstrong
●	Superconducting rings/Sagnac effect	GHz	no prediction	Anandan, Chiao
	Oscillation of Cosserat rods	$10^{-4}-1$ Hz	$2\cdot 10^{-21}$	Tucker & Wang
	Torsion bar	10^{-2} Hz	$3\cdot 10^{-19}$	Ando
	Skyhook	10^{3} Hz	$3\cdot 10^{-17}$	Braginsky & Thorne

BAW: Resonant mass detector

Reported evidence for rare events with BAWs at 5 MHz

PRL 127, 07102 (2021)

- Sensitivity beyond the “cut-off” frequency of current laser interferometers of a few kHz

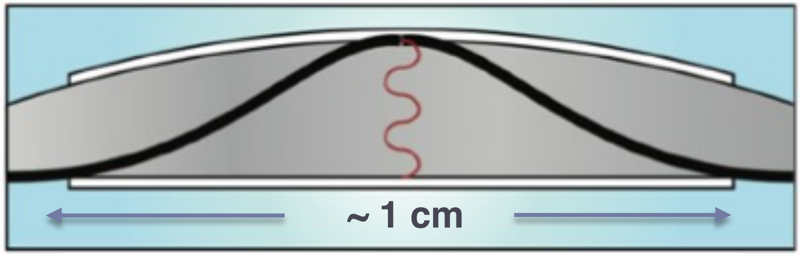
Bulk acoustic wave devices

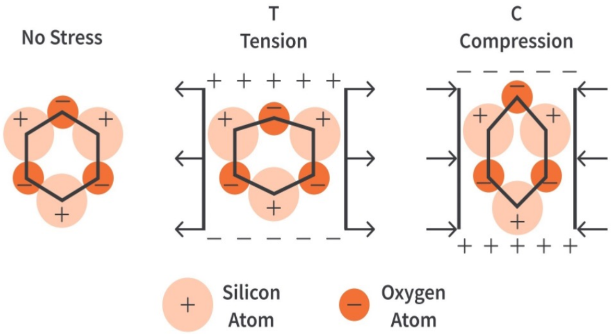
- **Resonant mass detector**
  - **High sensitivity** through high quality factor
  - **Internal** (piezoelectric) **transducer**
    - (only odd overtones audible)
  - **Scalable** technology, established >70 years for precision clock applications

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

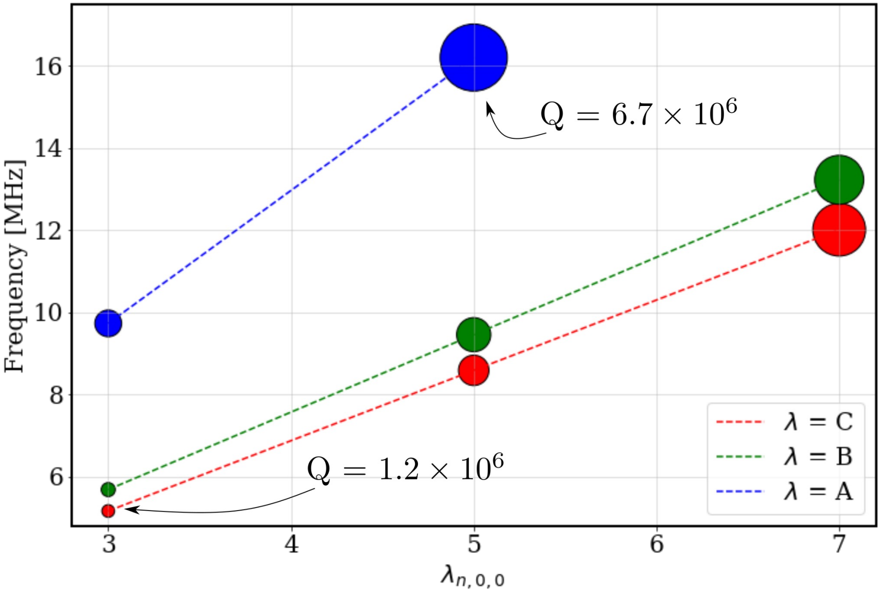
$$f_{n,k} = n\,\frac{v_k}{2d} \qquad (k = A, B, C)$$

Plano-convex BAW
(minimize mechanical losses)





Example: frequency vs overtone for n = 3, 5, 7



Readout concept

displacement | current | voltage | data

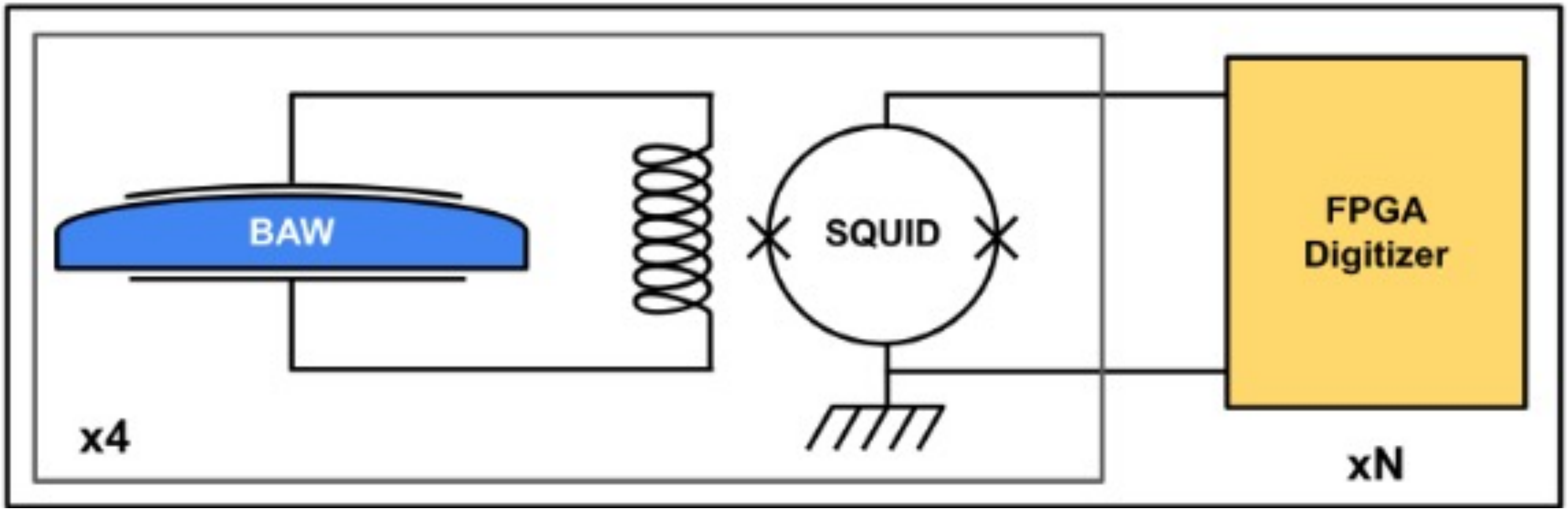
$$h(t) \longrightarrow u(t) + n \longrightarrow i(t) + n \longrightarrow A(i(t) + n) + n_A \longrightarrow A(i(\tau) + n) + n_A$$

Resonant cavity + Transducer

Amplifier

Signal sampling

Data logging

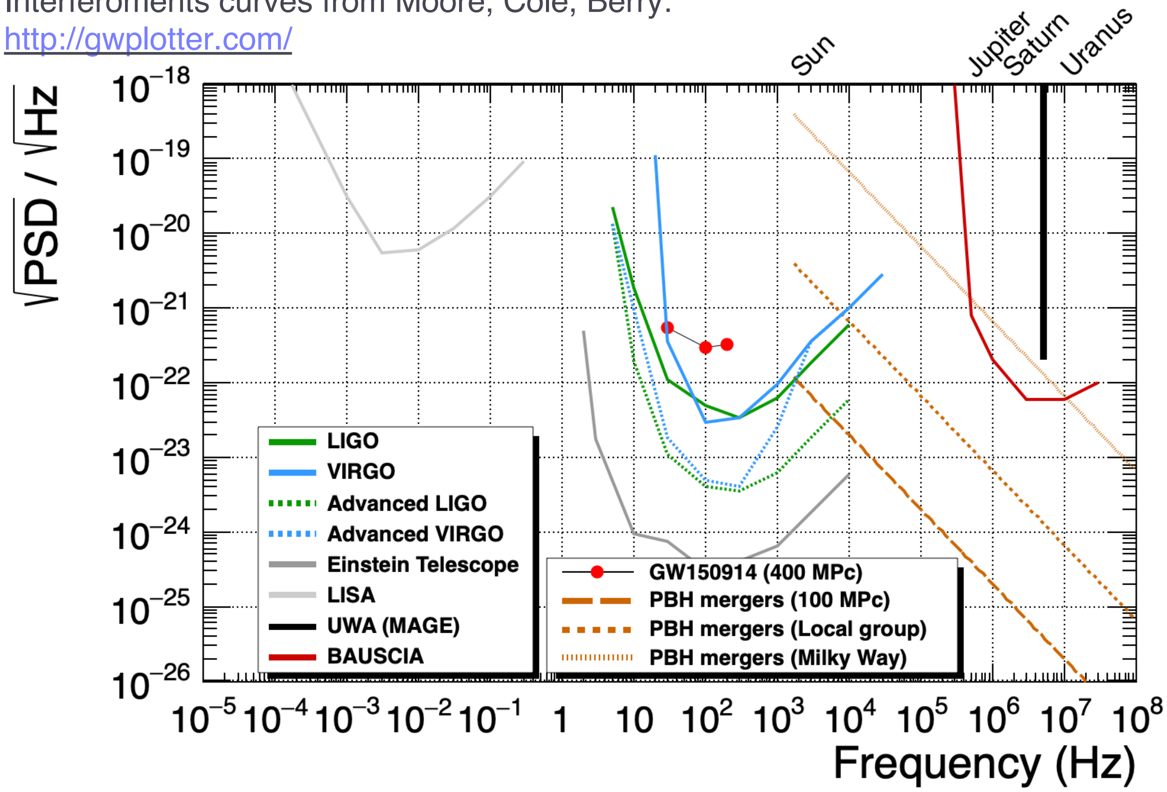


  - Seminal proposal by M. Goryachev and M. Tobar, PRD 90,102005 (2014)

- **"Broadband" sensitivity provided by**
  - Multiple overtones sensing per BAW (see W. Campbell talk about MAGE)
  - Array of many BAWs tuned to different frequencies → requires specific R&D on BAWs
- **Bulk Acoustic Wave Sensors for a High frequency Antenna (*BAUSCIA, in Milan's dialect*)**

Sensitivity (illustrative)

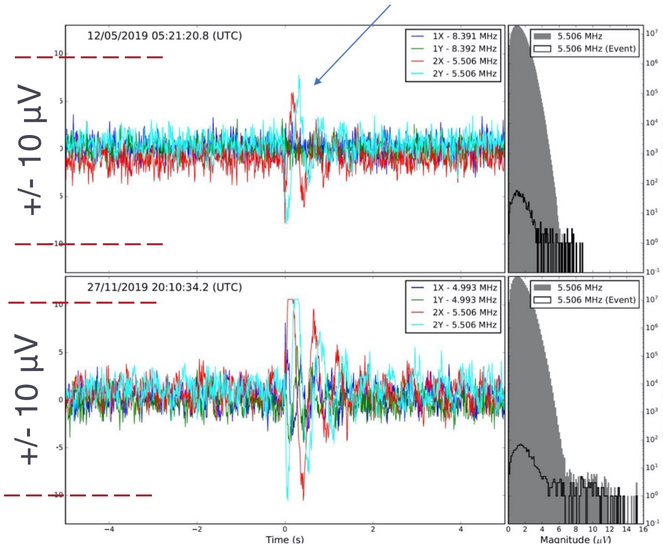
Interferoments curves from Moore, Cole, Berry:
http://gwplotter.com/



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)

BAW cavity as a GW antenna

- **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

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

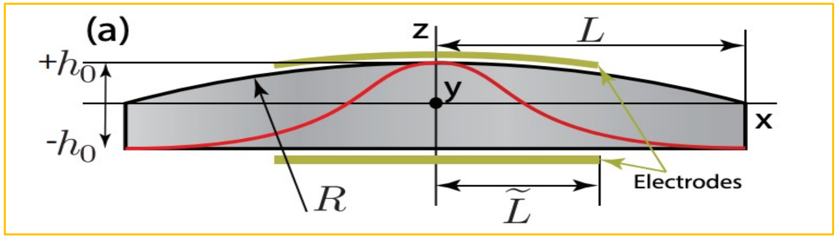
$$\tilde{\xi}_{Xn00} = \frac{\xi_{Xn00}}{h_0} = \frac{16}{n^2\pi^2}\,\frac{\mathrm{Erf}(\sqrt{n}\eta_x)\mathrm{Erf}(\sqrt{n}\eta_y)}{\mathrm{Erf}(\sqrt{2n}\eta_x)\mathrm{Erf}(\sqrt{2n}\eta_y)},$$

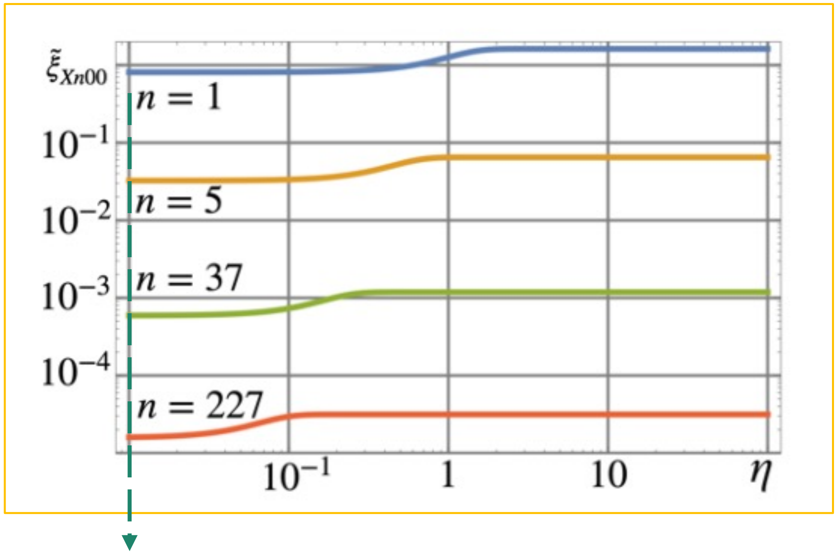
- **Trapping coefficient**

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

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

M. Goryachev and M. Tobar, PRD 90, 102005 (2014); Erratum: Submitted to PRD 2023





- **Resonant bar (infinite R): $\bar{\xi}_n = 8/(n\pi)^2$**
  - Curvature only mildly enhances coupling *[but it reduced losses through supports]*

Detection limit and strain sensitivity

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

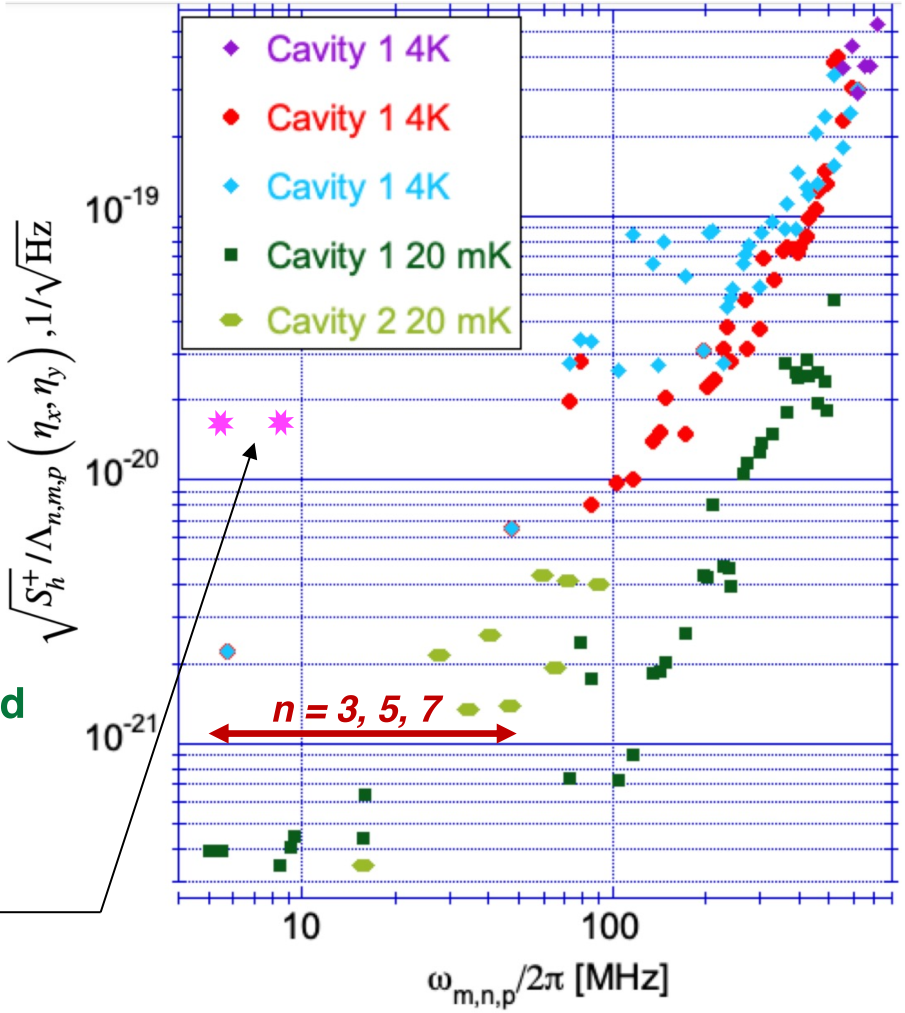
$$\sqrt{S_h^+(f)} = \frac{2}{\pi h_0 \bar{\xi}_\lambda f}\sqrt{\frac{w(\omega)\, k_B T}{Q_\lambda \omega_\lambda m_\lambda}} \left[\frac{strain}{\sqrt{Hz}}\right]$$

  - w(ω) = phonon statistic distribution weight

→ **Max sensitivity at cold and low overtones**
  - **Driven by coupling coefficient: $\bar{\xi}_\lambda f \propto 1/n$**
  - Q_λ also improves at high frequency and low temperatures

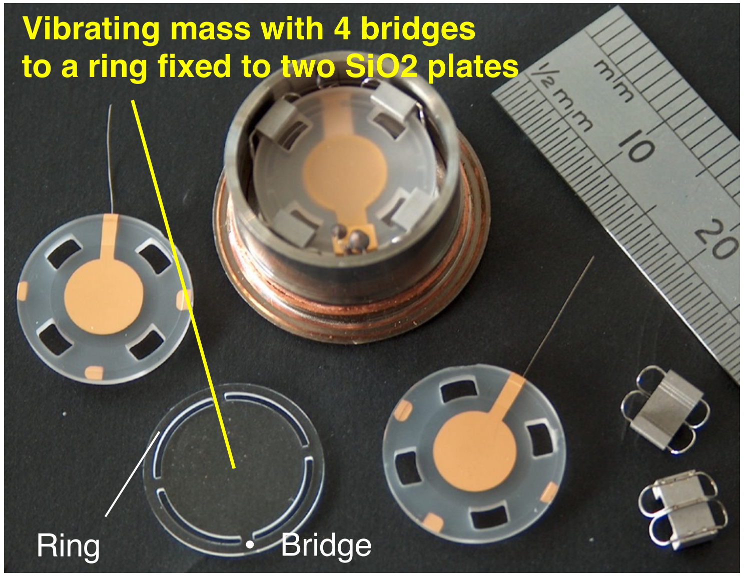
- **Projected single-sided spectral density around $10^{-21}/\sqrt{Hz}$ at T = 20 mK (Q ~ 10^9) for n = 3, 5, 7**
  - Optimal sensitivity limited to ~ 5 – 50 MHz
  - ✳ Current MAGE experiment at 4K [W. Campbell et al. ArXiv: 2307.00715]

- PRD 90,102005 (2014)
- Appl.Phys.Lett. 105, 153505
- M. Goryachev and M. Tobar, Erratum, 2023



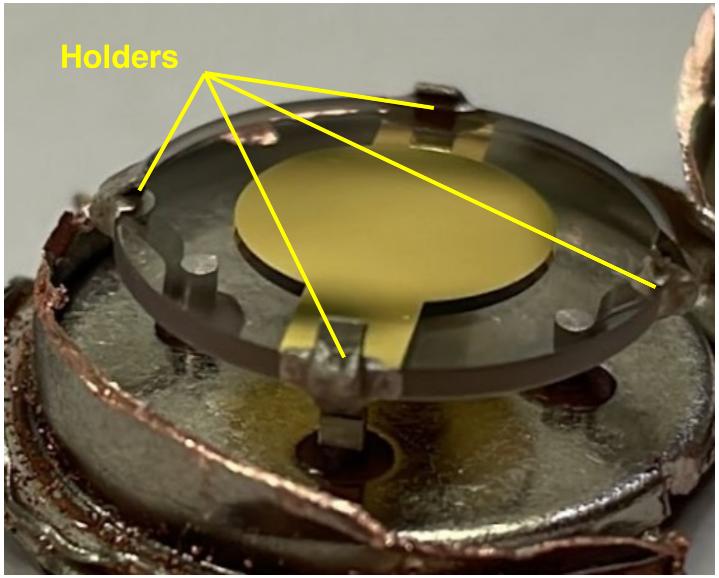
BAW samples

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



Vibrating mass with 4 bridges to a ring fixed to two 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)*

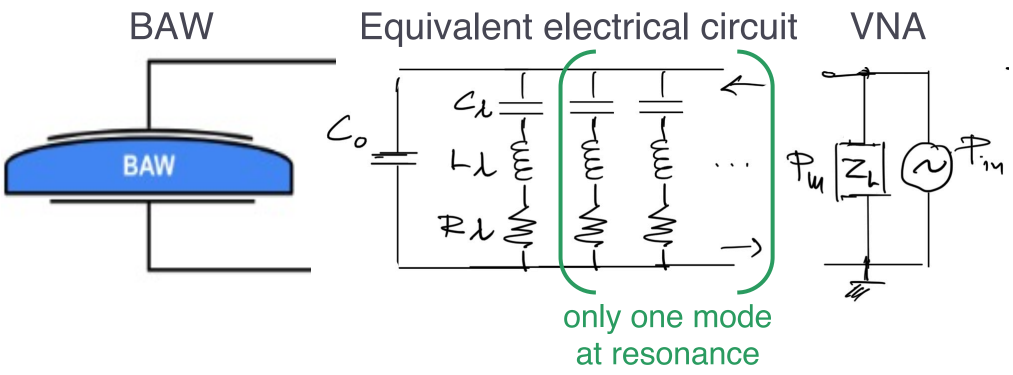


Holders

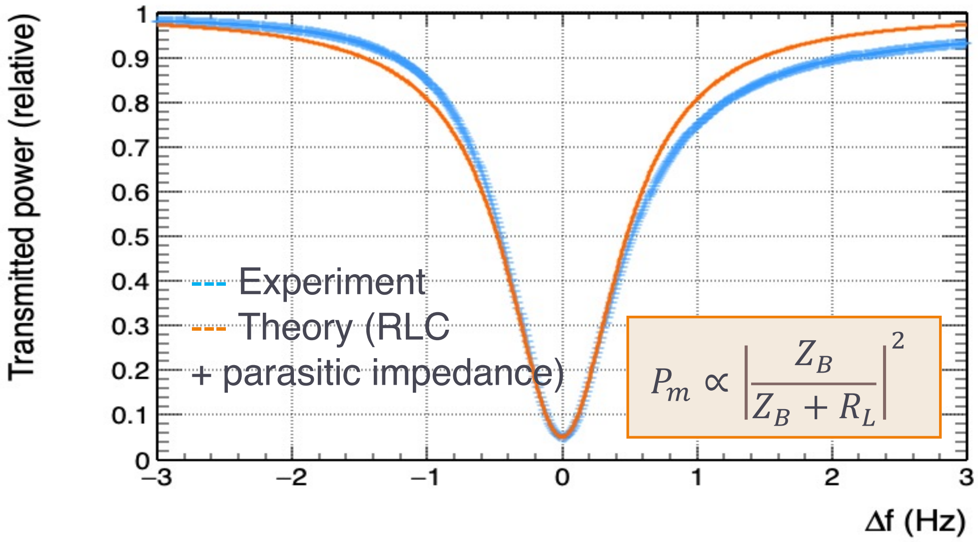
- **Room temperature: Q ~ 10^6**
  - Optimized for the 3rd overtone of the C-mode (slow shear) at ~5 MHz (clock standard)
  - Low Q at n=1 (lwhere the coupling to GW is largest)
- **Cryogenic temperatures: Q > 10^7 (low overtones)**
  - [up to 10^9 at high frequencies but reduced coupling to GW signals]

BAW characterization

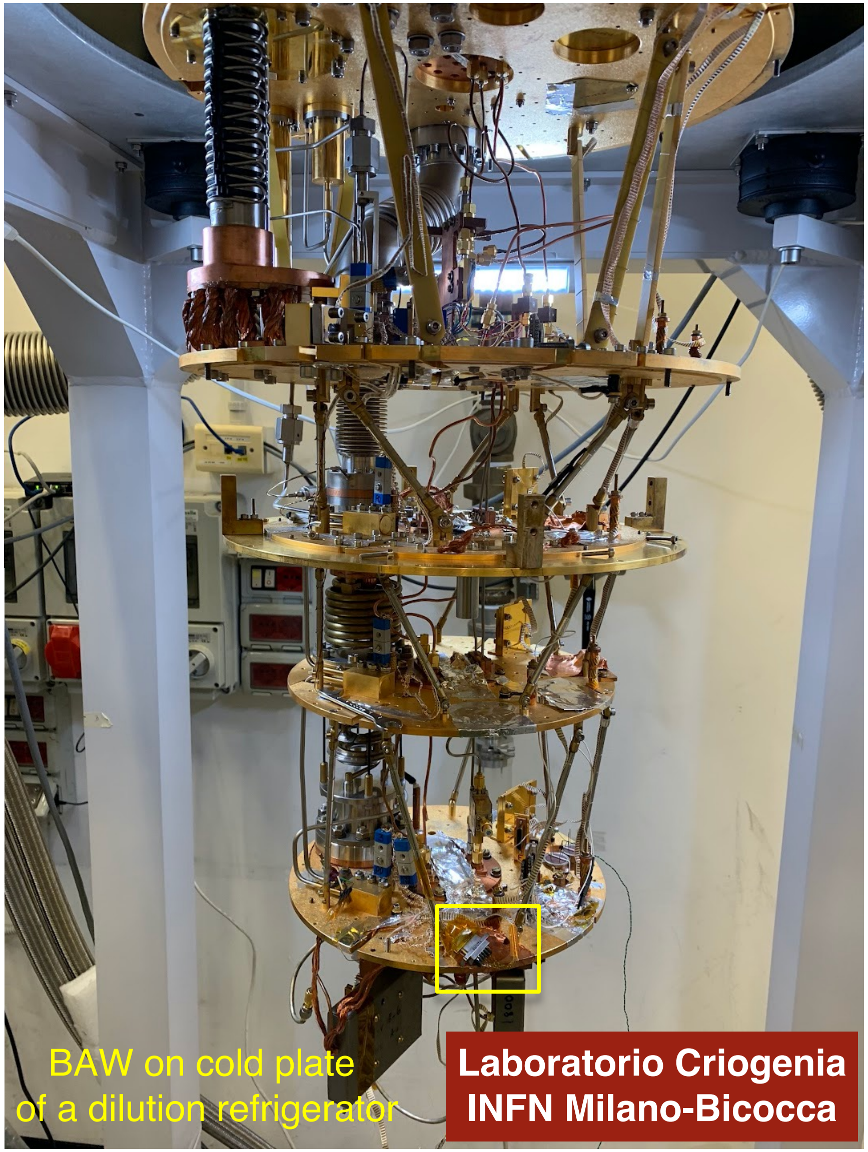
- **Acoustical coupling to electromagnetic response from impedance analysis**



T = 0.1 K, f = 8.6 MHz, Q = 3.8x10^7



$$P_m \propto \left| \frac{Z_B}{Z_B + R_L} \right|^2$$



BAW on cold plate of a dilution refrigerator

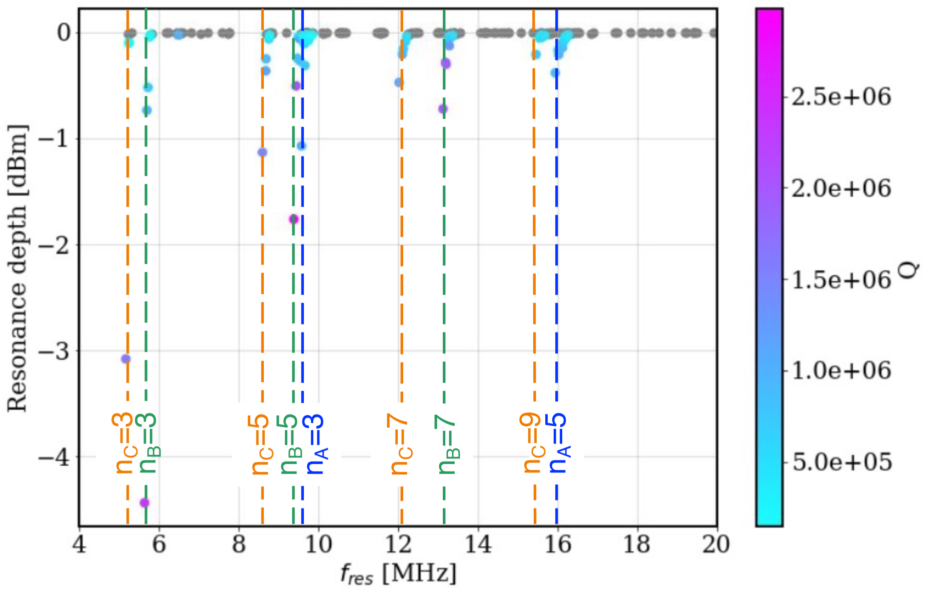
Laboratorio Criogenia INFN Milano-Bicocca

T = 300 K - off-the-shelf BAWs

- **Observed modes**
  - High Q = high phonon trapping and low losses

$$\omega^2_{n,m,p} = \frac{n^2\pi^2\hat{c}_z}{4h_0^2\rho}\left(1+\frac{\chi_x\cdot(2m+1)}{n}+\frac{\chi_y\cdot(2p+1)}{n}\right)$$

Commericial SiO_2 BAW: **T = 300 K**

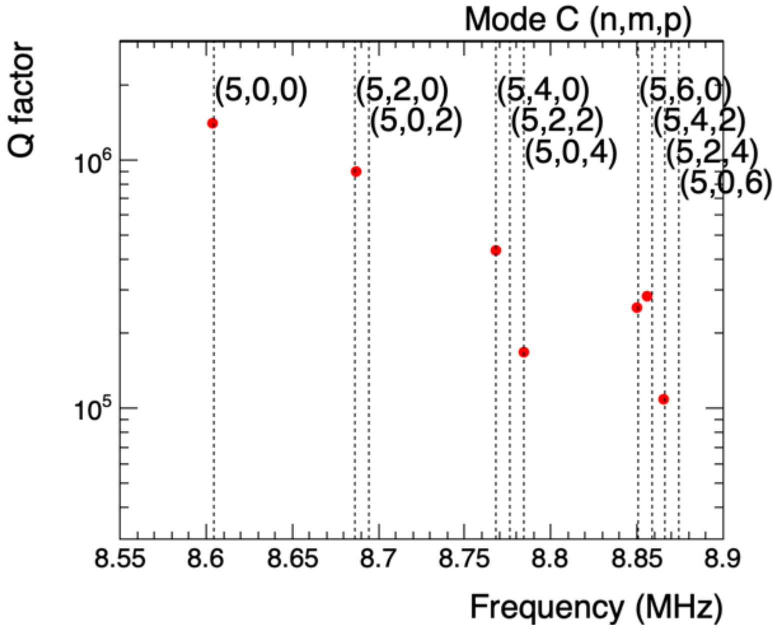


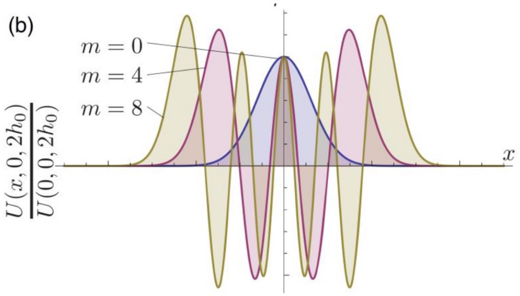
- Q-factors up to a few 10^6 *[for n>1]*

Slow shear (C)
v_C= 3610 m/s

Fast shear (B)
v_B= 3970 m/s

Longitudinal (A)
v_A= 6760 m/s

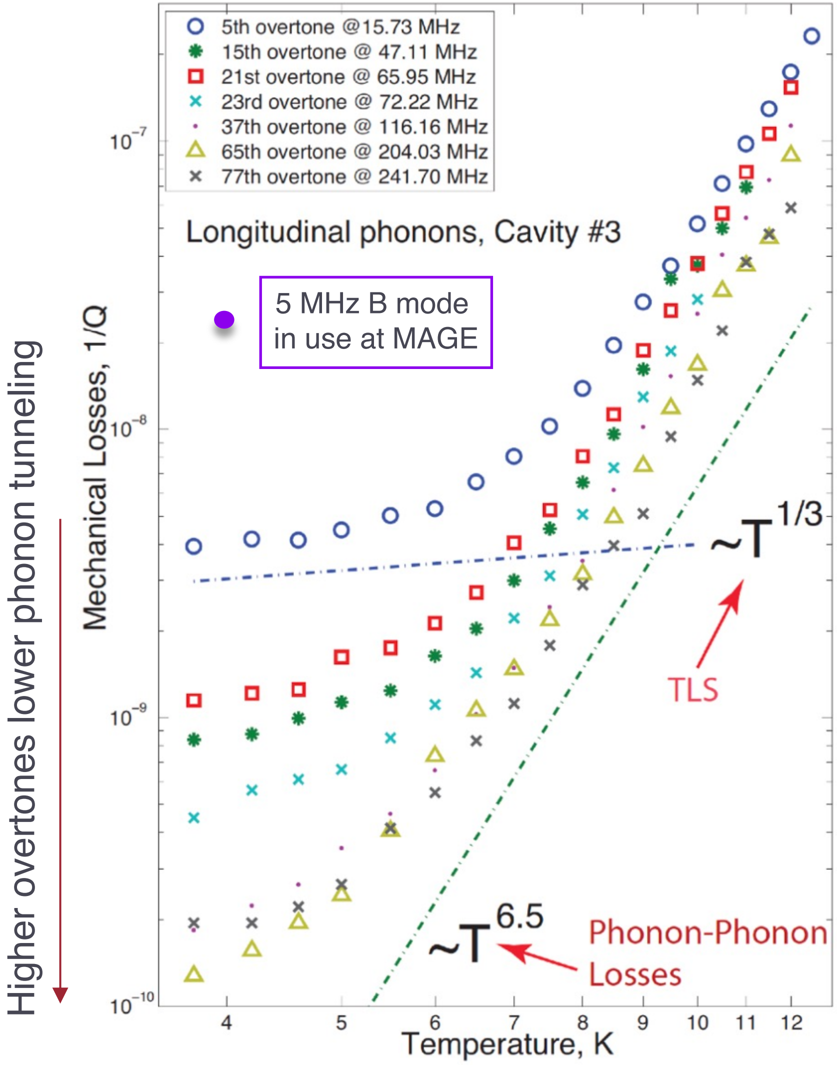




Wave distribution in the transverse plane

Type of losses and Q at low temperature

M. Goryachev *et al*, Sci. Rep. Vol.3, 2132 (2013)
M. Goryaachev *et al*, PRL, III, 085502 (2013)



5 MHz B mode in use at MAGE

Higher overtones lower phonon tunneling

Phonon-tunneling to the environment

- Losses due to phonon-tunnelung through electrodes, supports, etc.
- Cavities available at UWA optimized for low-losses to the environment (n>1)

Residual losses:

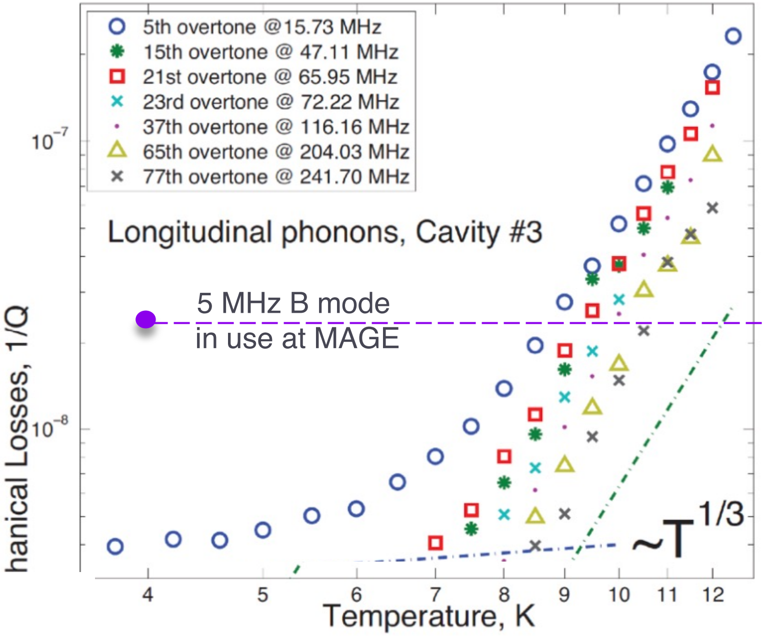
- phonon-phonon dissipation due to acoustic phonon scattering by thermal phonons (Landau-Rumer) $\propto T^{6.5}$
- Two-Level-System (TLS) absorption attributed to ion impurities $\propto T^{1/3}$
- Scattering losses on surface roughness and bulk impurities (Rayleigh scattering)
- Thermoelastic dissipation from thermal flow following compression/decompression

Very high Q at high overtones

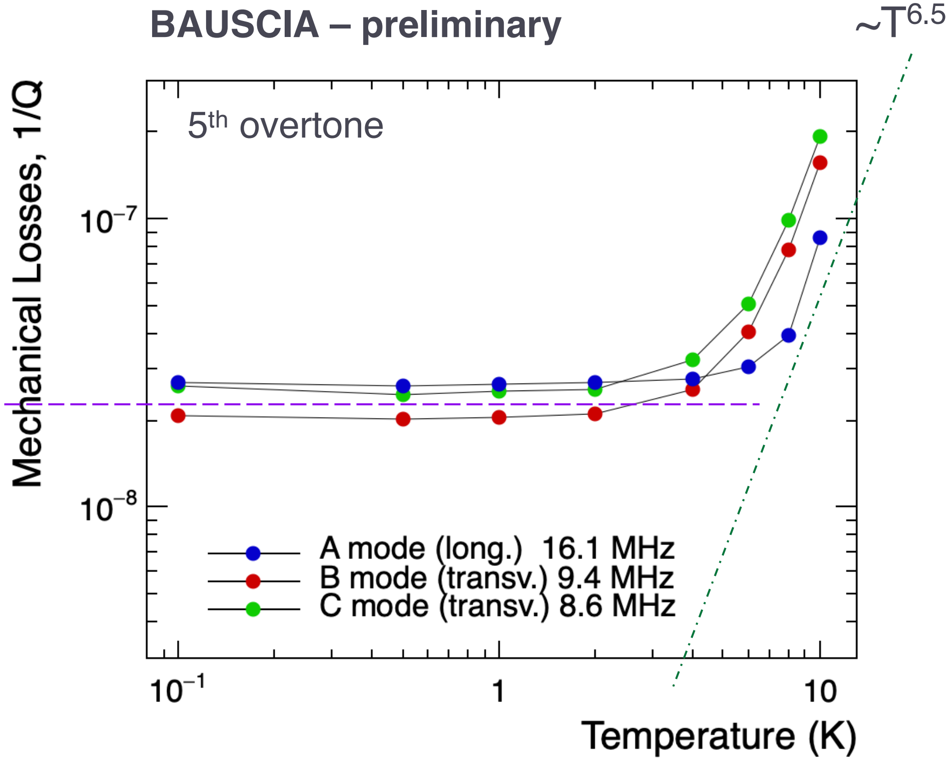
- *Coupling to GW good only at low overtones*

Low T behaviour - off-the-shelf BAWs

M. Goryachev *et al*, Sci. Rep. Vol.3, 2132 (2013)
M. Goryaachev *et al*, PRL, III, 085502 (2013)



BAUSCIA – preliminary



- **Q-factor comparable to devices in use at the MAGE experiment**
  - Thorough characterization at **n=3, 5 and 7**, and cross-comparison with UWA devices in progress
  - Saturation at low T tentatively ascribed to manufacturing differences (holder and electrodes)
- **Setting up a GW detector to supplement MAGE measurements**
  - Readout SQUIDs expected by late spring 2024 (long lead time at vendor)
  - Expected sensitivity sufficient to compare measurements

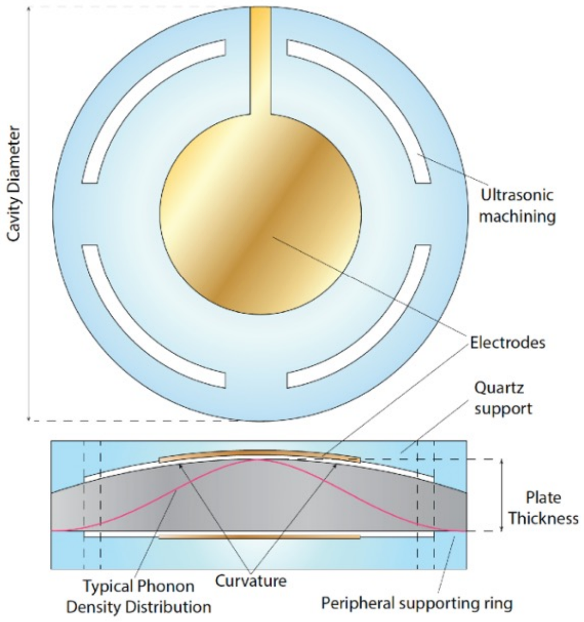
Next step: BAW optimiztion

In collaboration with UWA

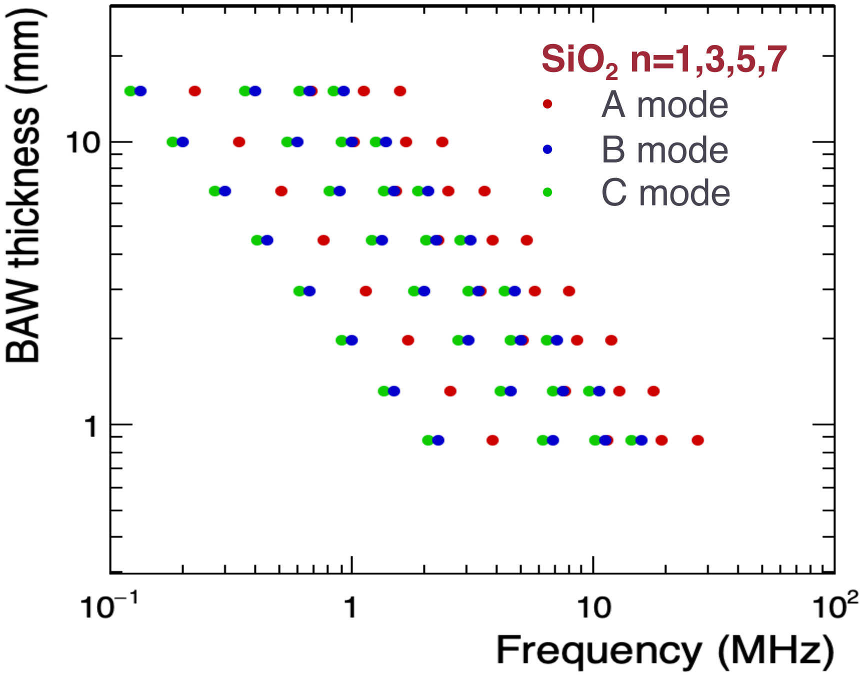
- **BAWs with customized shape (curvature) and thickness**
  - Design to minimize mechanical losses for n=1 (maximal coupling to GW)
  - Thinckness between 0.5- and 20-mm match the region of interest for coherent sources
- **Material type and quality**
  - SiO_2, $LiNbO_3$ $^{(*)}$, etc. in discussion with crystal manufactures

Current BVA reference design

d = 1 mm
D = 1 cm
f_1 = 1.725 MHz
f_3 = 5.175 MHz
m ~ 0.2 g



Frequency map of an array of eight BAWs



(*) See, e.g., M. Kemp et al. Nature Comm. 1715 (2019) for a $LiNbO_3$ bar of 10 cm (40 kHz) showing Q~10^6

Summary

From the summary of M. Goryachev's talk at
Challenges and opportunities of HFGW, Trieste 2019

Easy
- Increase number of modes/channels/crystals
- Improvements in signal processing
- Shifting to 20 mK (dilution fridge)
- mK higher frequency SQUIDs

Hard
- Design of Dedicated BAW cavities
- Multisite Detection

- **Broad range sensitivity requires many BAWs of different thicknesses**
  - Sensitivity scales as ~ 1/n (n = overtone)
  - Optimal sensitivity at n=1
- **Dedicated BAWs under development**
- **Setting up a 2nd detection site at Milano-Bicocca with off-the-shelf BAWs**
  - Expected sensitivity comparable to MAGE

*A xylophone is being designed to detect
the high-frequency symphony of the universe*