Bulk Acoustic Wave cavities for high-frequency gravitational wave antennas

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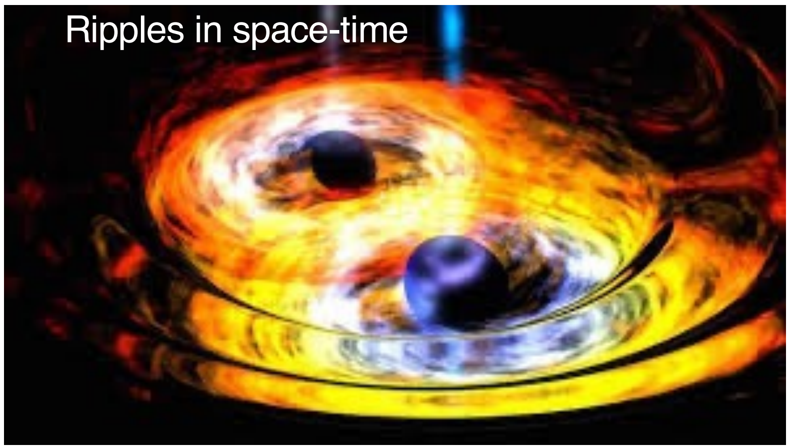
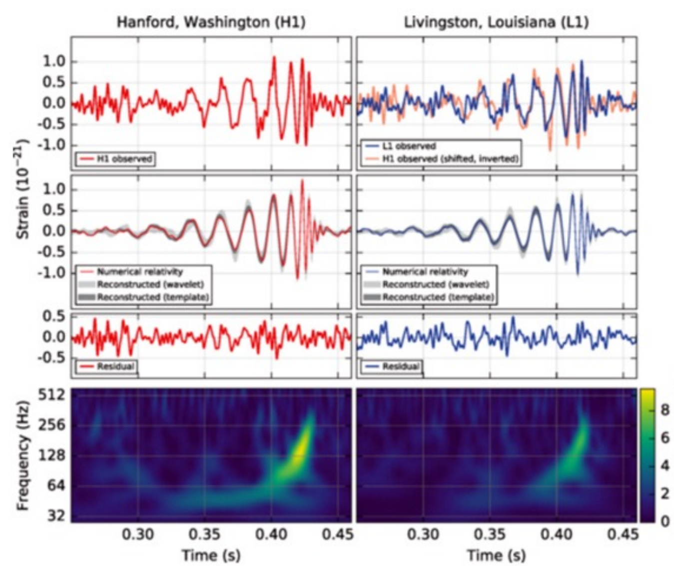
- **Outline**
  - Motivation for GW searches at high-frequencies
  - Proposed approach and status of the project at Milano-Bicocca
  - Instead of a summary

Contributions:
- 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, B. Giacomazzo, R. Gerosa, M. Malberti, A. Nucciotti, G. Pessina (Milano Bicocca)
- W. Campbell, M. Goryachev, and M. Tobar (University of Western Australia)

Gravitational waves

- **Sources**
  - Inspirals of astrophysical object ("late universe signals")
  - Inflation, phase tramsitions, etc. ("early universe signals")





B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102 (2016).

- **First detected on Septembr 2015**
  - Massive compact object inspirals
  - Characteristic time/frequency pattern (chirp)
  - ν_{max} ~ 130 Hz (~peak sensitivity)

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)

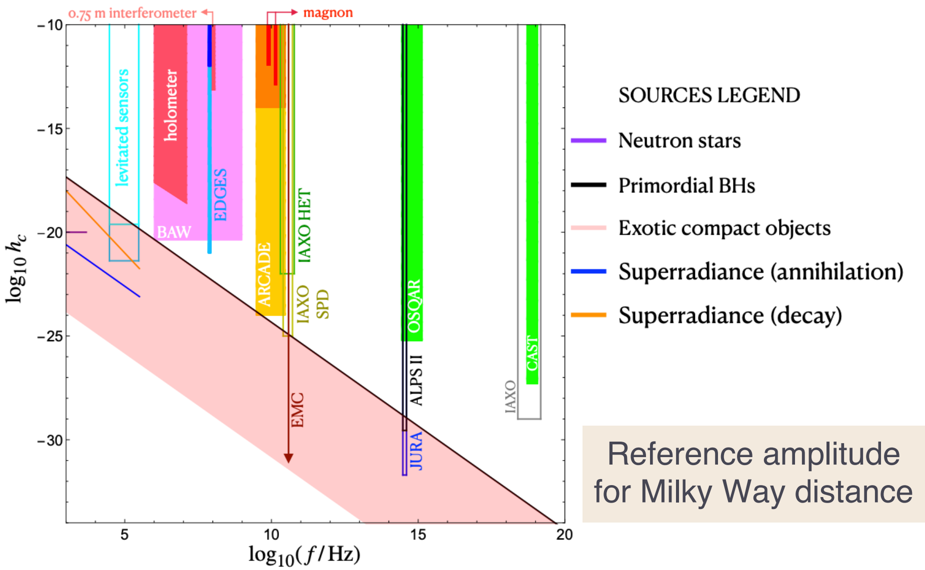
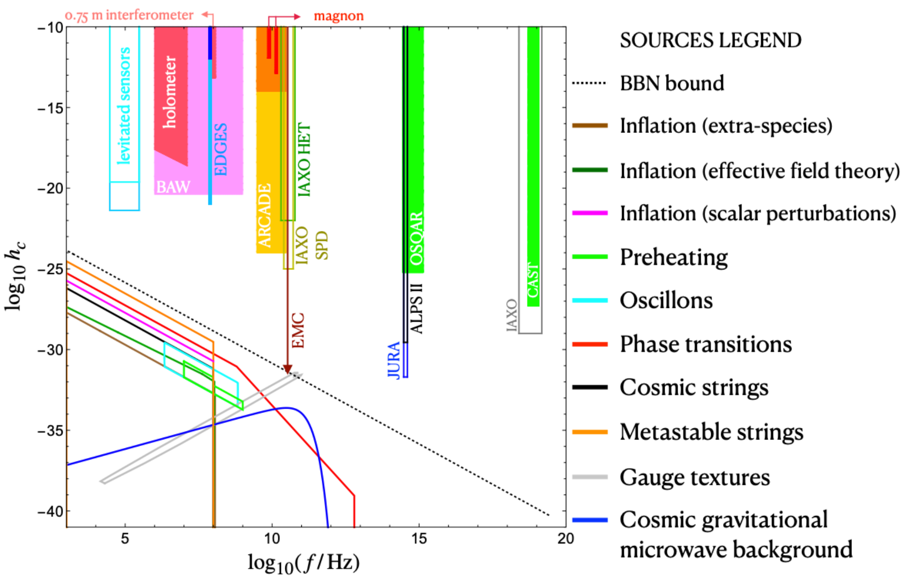


Figure 1: Examples of coherent sources of GWs, see text for details. Details about the various detector concepts are given in Sec. 4.1.2 for the 0.75 m interferometer and the holometer experiment, Sec. 4.2.1 for the optically levitated sensors, Sec. 4.2.2 for IAXO Single Photon Detector (SPD), IAXO Heterodyne 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

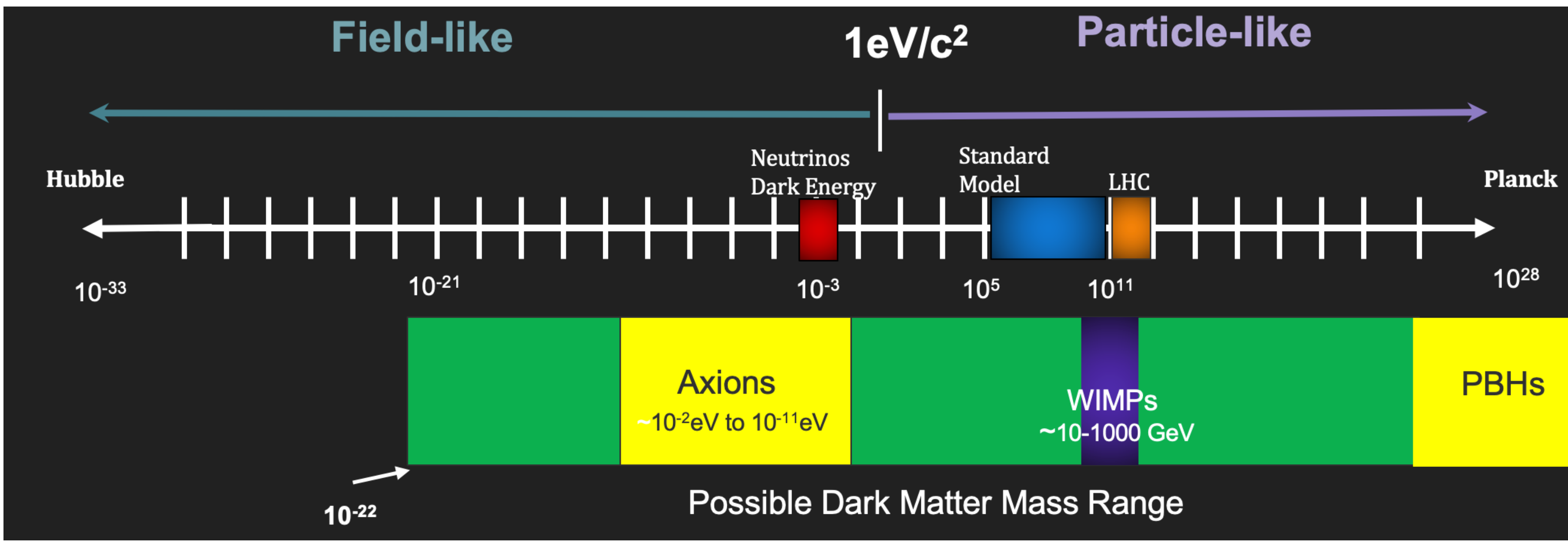


igure 2: Examples of stochastic sources of GWs, see text for details and the caption of Fig. 1 for the reference to ıe various detector concept sections.

- **Output of a first workshop of a series**
  - Next in line: "Ultra high-frequency gravitational waves: where to next?", CERN, December 2023
  - https://indico.cern.ch/event/1257532/

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
- **Black hole superradiance (beyond standard model)**
  - QCD axion annihilations to gravitons in cloud around black holes: emissions at O(<1 MHz)
    A. Arvanitaki et. al PRD 83, 044026 (2011)



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

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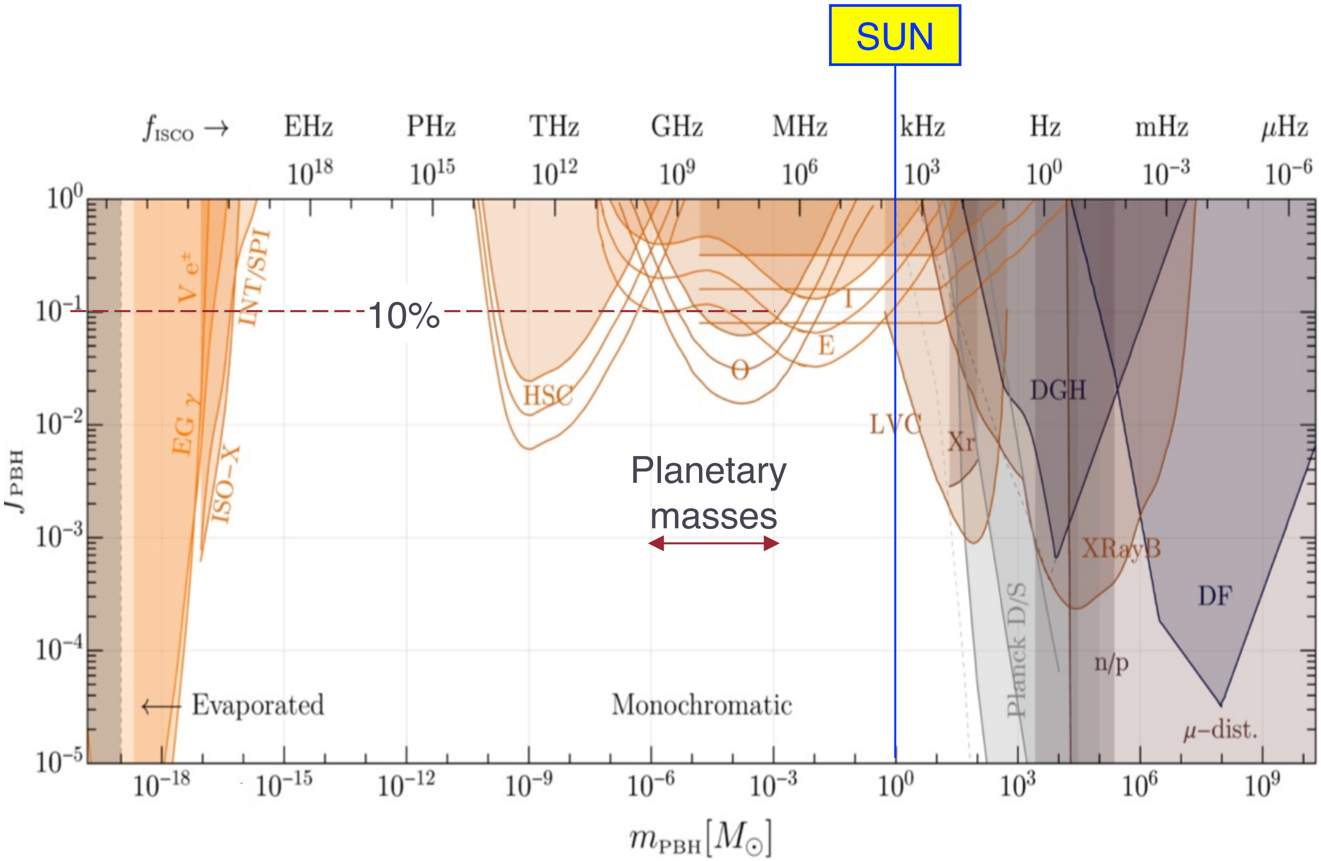
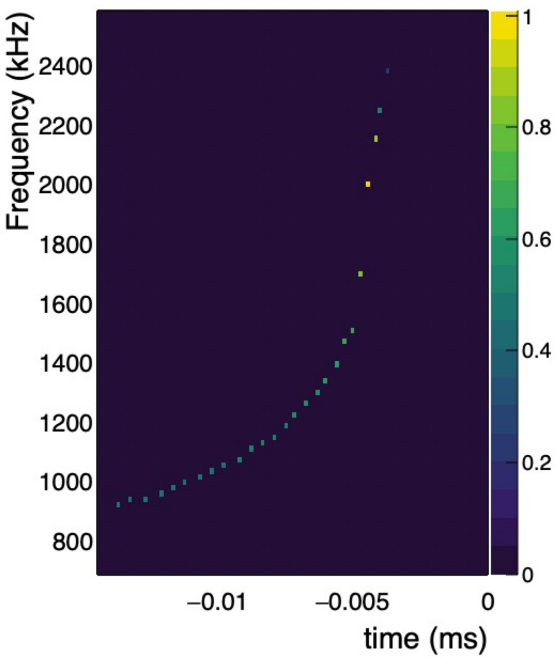


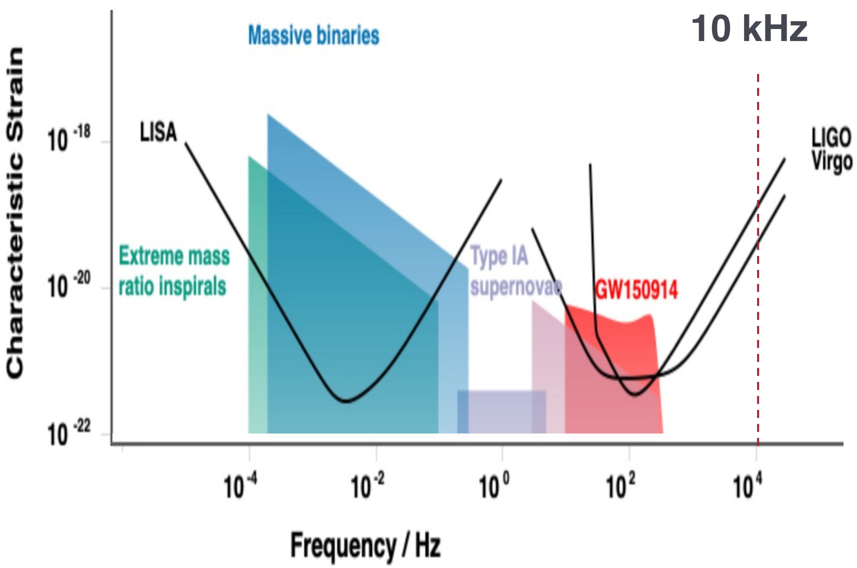


Saturn-mass
PBH-PBH merger

Gravitational lensing: https://doi.org/10.1103/PhysRevD.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 event)
- **Resonant mass detectors**
  - GW tidal forces stretch and squeeze the mass
  - Length variation only detectable at the resonant frequency of the longitudinal vibration mode(s)
    - Achieved ~ 10^{-22} / √Hz sensitivities
- **Broad band sensitivity**
  - Limited at high frequency by laser shot noise
- **Narrow band sensitivity (high Q)**
  - Resonant frequency ~ **O(1) kHz**



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

Who (has been) is thinking to GW detection?

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

Reported evidence for rare events with BAWs at 5 MHz

PRL 127, 07102 (2021)

- High or ultrahigh frequency (beyond the "cut-off" frequency of current laser interferometers of a few kHz)

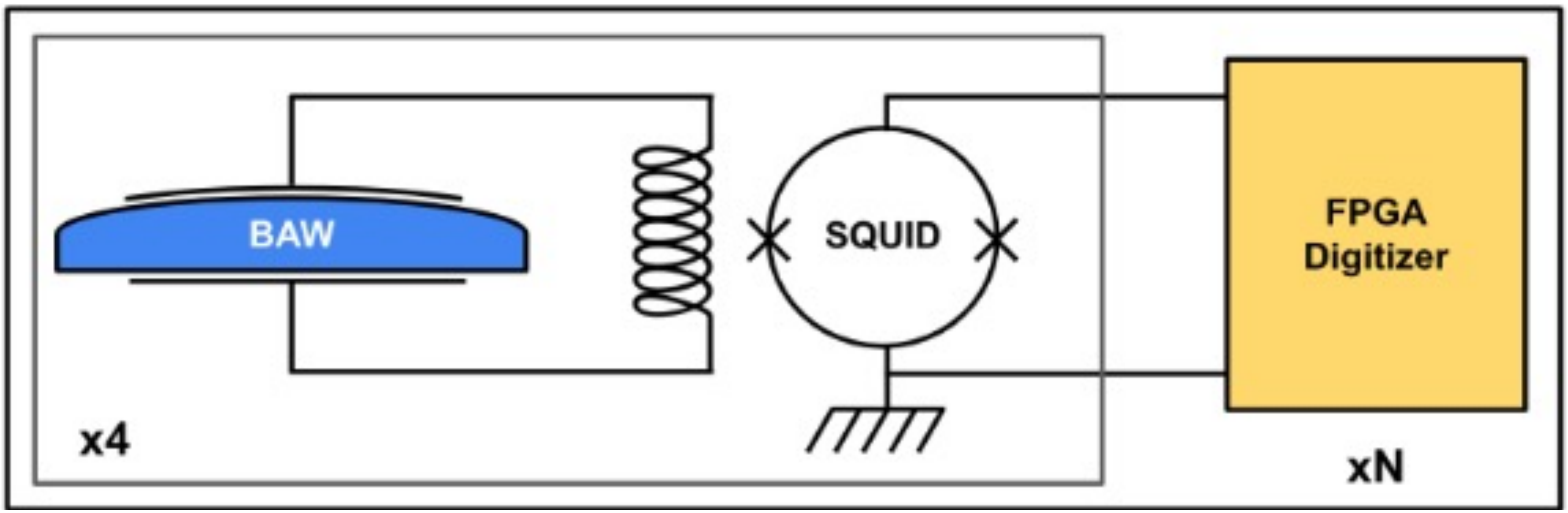
Detection approach

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

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 (down conversion)** | **Data logging**



- **Broadband sensitivity provided by**
  - Multiple overtones sensing per BAW
  - Array of many BAWs tuned at different frequency → requires specific R&D
    - Seminal proposal by M. Goryachev and M. Tobar, PRD 90,102005 (2014)

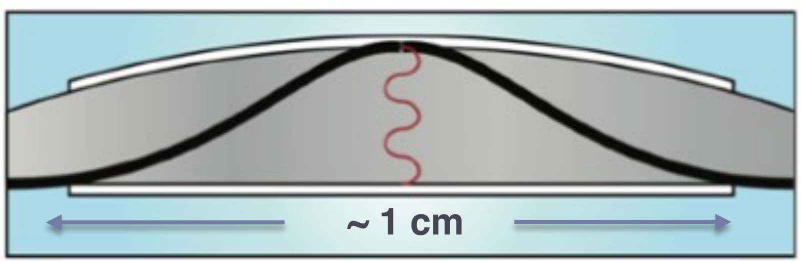
Bulk acoustic wave sensors

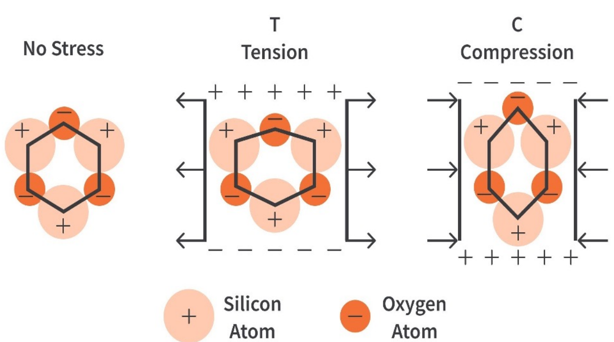
- **Resonant mass detector**
  - **High sensitivity** through high quality factor
  - **Internal** (piezoelectric) **coupling** to SQUIDs
    - (only odd overtones audible)
  - **Scalable** technology established >70 years for precision clock applications

- **Wide frequency range of sensitive modes**
  - Three family types with different velocities
    - 2 transverse and 1 longitudinal
  - Multiple overtones

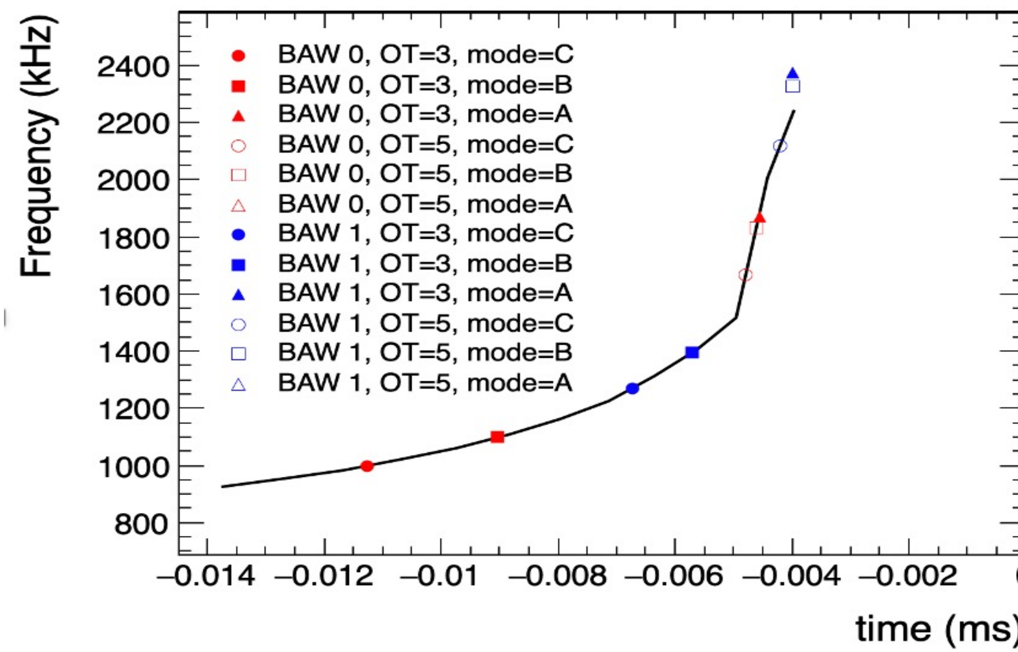
$$f_{n,k} = n \frac{v_k}{2d} \qquad (k = 1, 2, 3)$$

Plano-convex BAW
(minimize mechanical losses)

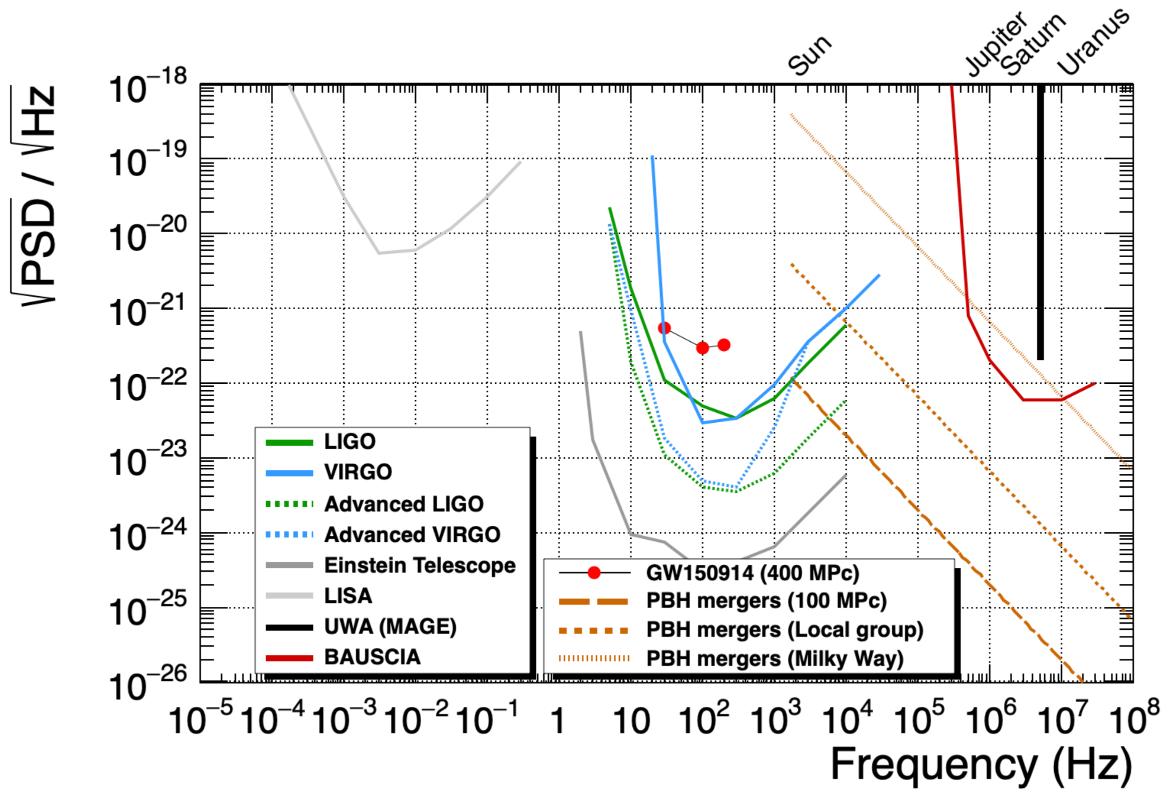




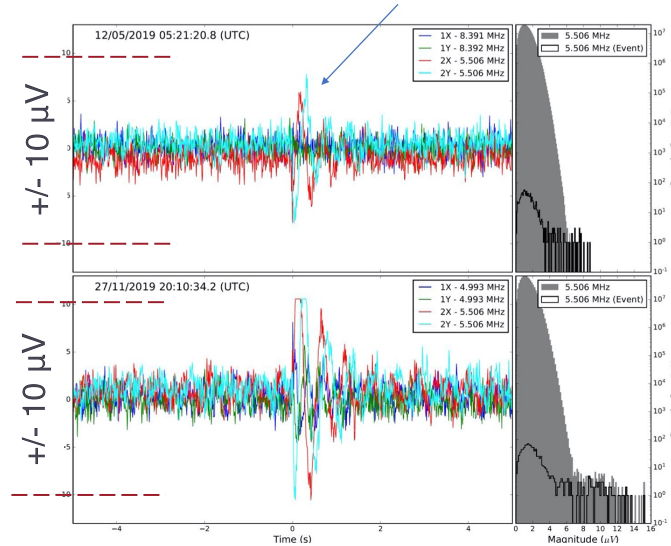
Saturn-mass PBH-PBH merger sampled with two BAWs and multiple overtones



Sensitivity (illustrative)



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



Scaling from the sensitivity of current antenna at UWA
to an array of multiple BAW cavities of comparable quality

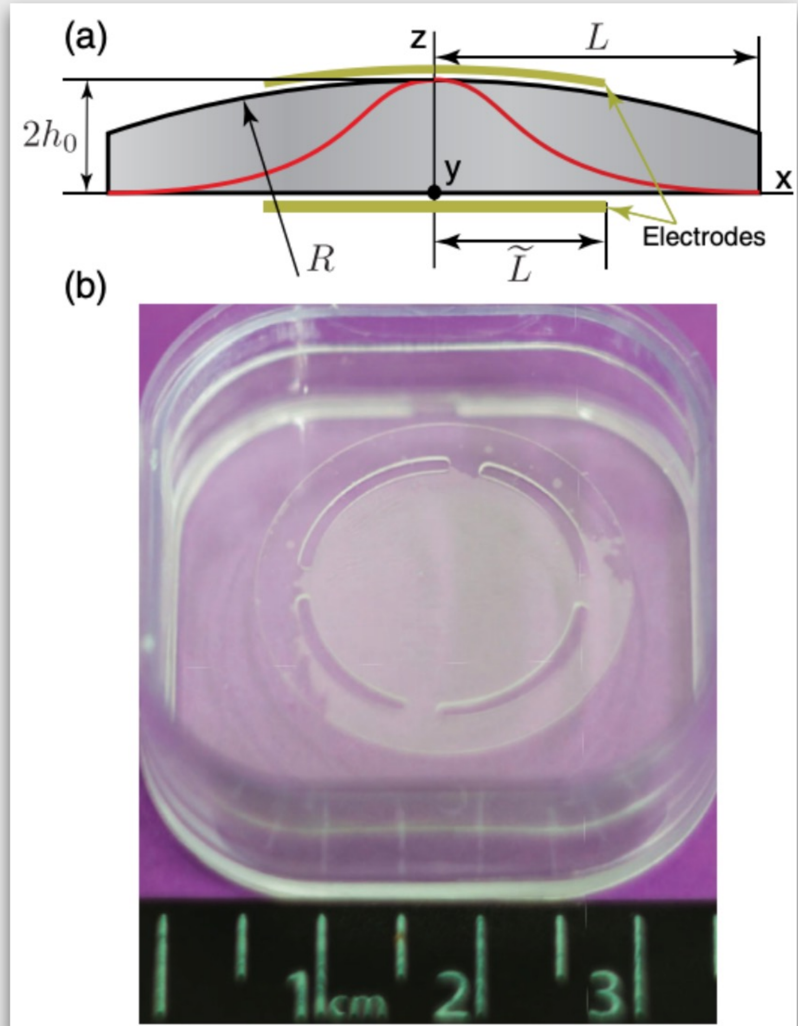
PBH merger strangth scaled from GW150914

(*) 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

- Ref: M. Goryachev and M. Tobar, PRD 90, 102005 (2014)

Admittedly, not yet fully digested



- **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:**

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

$$\tilde{\xi}_{Xn00} = \frac{\xi_{Xn00}}{h_0} = \frac{8}{n\pi}\frac{\mathrm{Erf}(\sqrt{n}\eta_x)\mathrm{Erf}(\sqrt{n}\eta_y)}{\mathrm{Erf}(\sqrt{2n}\eta_x)\mathrm{Erf}(\sqrt{2n}\eta_y)}.$$

- **Trapping coefficients:**

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

  - Depends on the cavity gometry (R, L, h_0) the parameters $\chi_{x,y}$ that can be measured (angular modes)

Strain sensitivity and detection limit

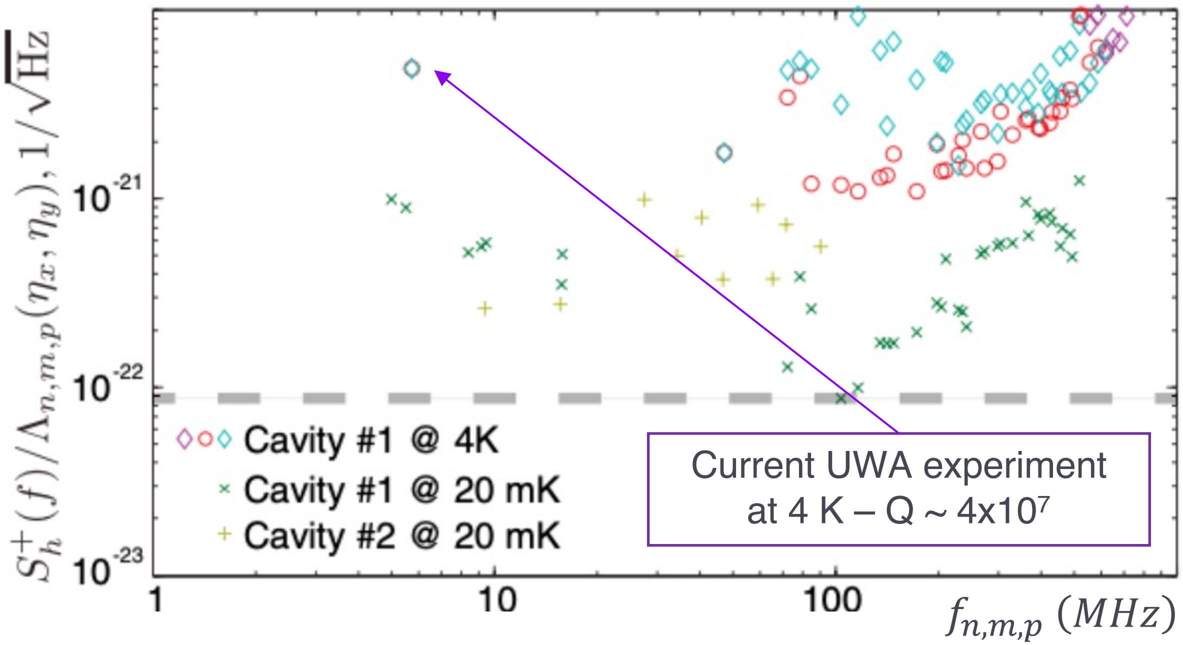
- **Noise sources from SQUID negligible comparted to BAW thermal noise at resonance**
  - Single sided spectral density from spectral density of force fluctuations (Nyquist)

$$S_h^+(f) = \frac{4}{h_0 \bar{\xi}_\lambda f} \sqrt{\frac{w(\omega)\, k_B T}{Q_\lambda \omega_\lambda m_\lambda}}$$

- w(ω) = phonon statistic distribution weight

→ Essentially independent of the frequency (except Q = Q(ω))
  - ω_λ scales with overtone
  - m_λ scales with overtone reciprocal

- **BAW cavity has broadband sensitivity**



Estimated sensitivity for quartz BAW samples at various frequencies

→ Notable dependency on Q factor and temperature

For Q ~ 10^9 and T = 20 mK

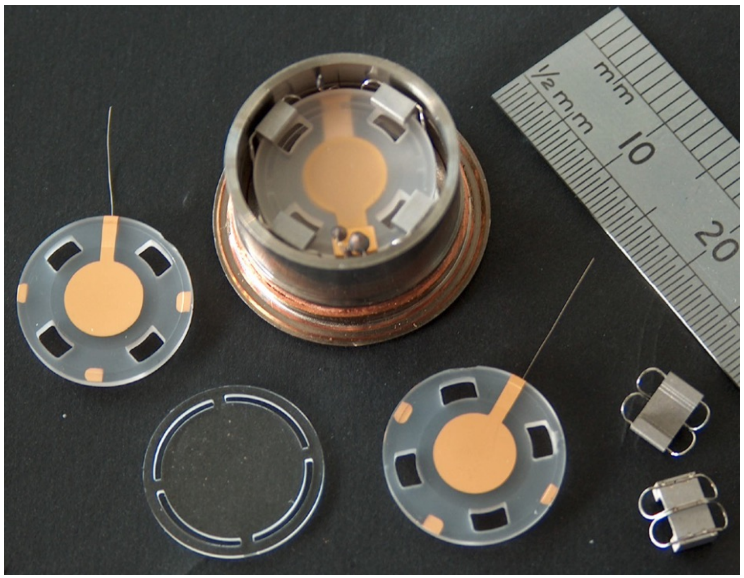
- $S \sim 10^{-22}\ \Lambda_{n,0,0}(\eta_x, \eta_y) / \sqrt{Hz}$

$\Lambda_{n,0,0}(\eta_x, \eta_y) \geq 1$ for large trapping

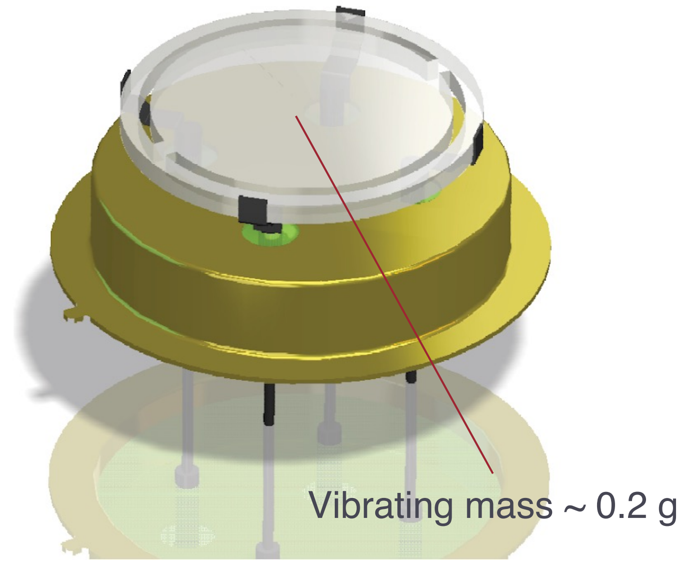
- PRD 90,102005 (2014)
- Appl.Phys.Lett. 105, 153505

BAW samples

- **UWA**
  - Plano-convex quartz crystals d ~ 0.5 mm
  - Electrodes deposited on the support
    - Only two samples available (from specific R&D)



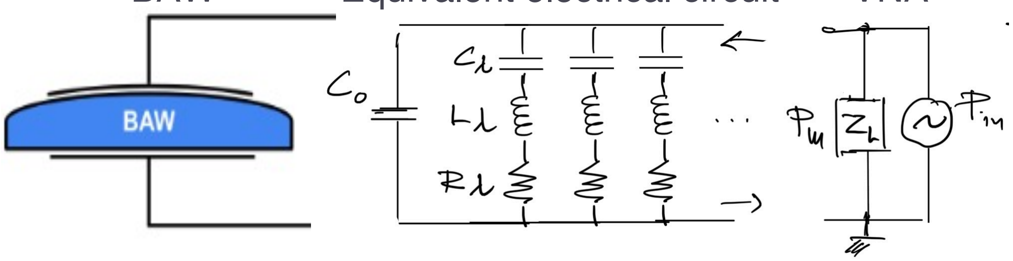
- **Milano Bicocca (BAUSCIA)**
  - Plano-convex quartz crystals d ~ 1 mm
  - *Electrodes deposited on BAW (suboptimal)*
    - Three *off-the-shelf* samples in hands
    - Huge production capability

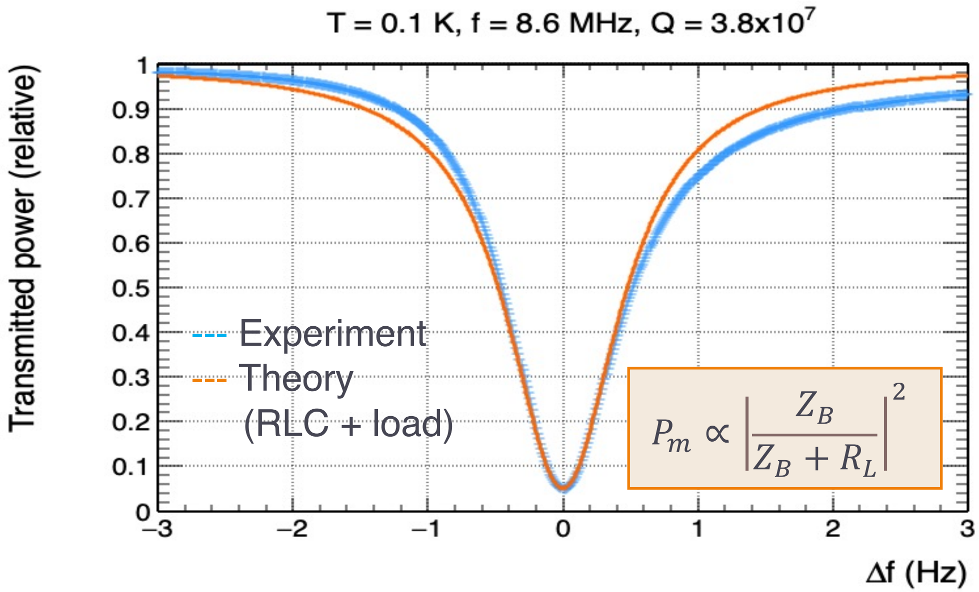


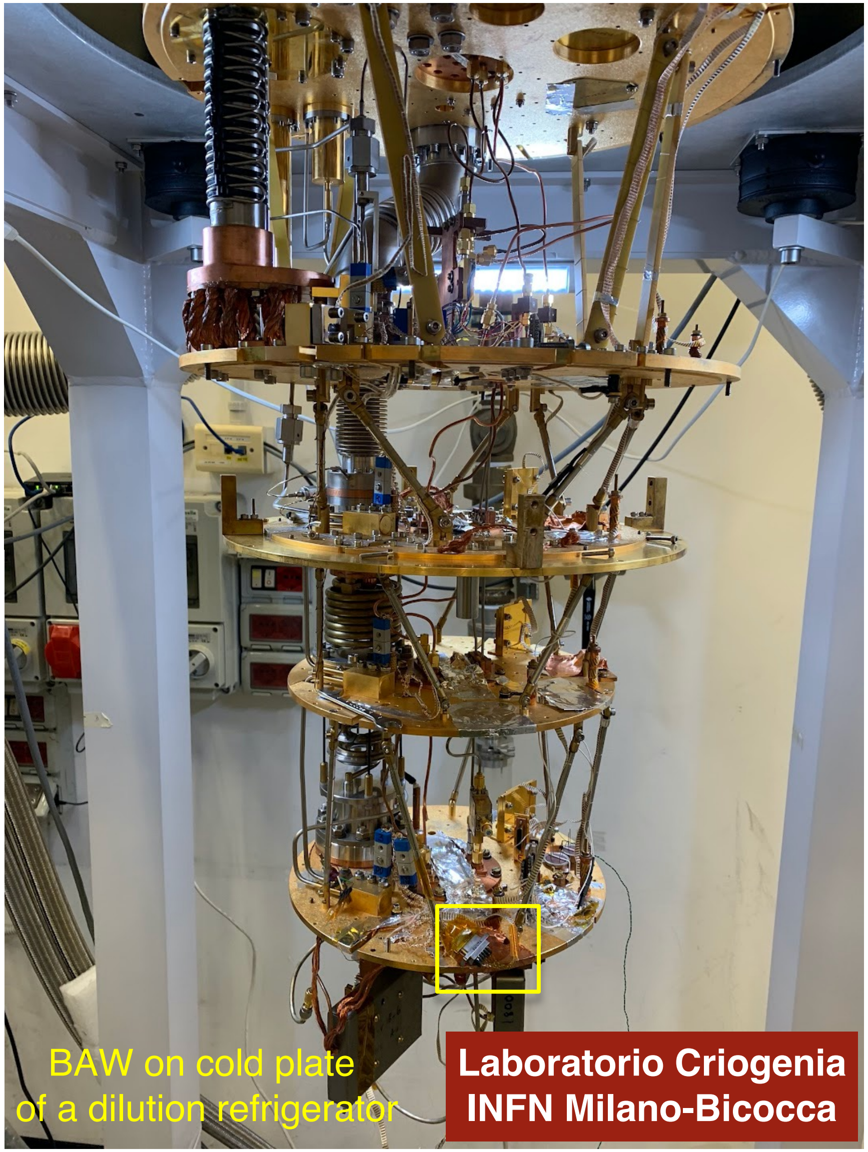
- **Room temperature: Q ~ 10^6**
  - Optimized for 3rd or 5th overtone of the C-mode (slow shear) at 5 MHz (clock/GPS standard)
- **Cryogenic temperatures: Q up to 10^9**
  - Typically higher Q for longitudinally polarized phonons (A-mode) and at higher frequencies

BAW characterization

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



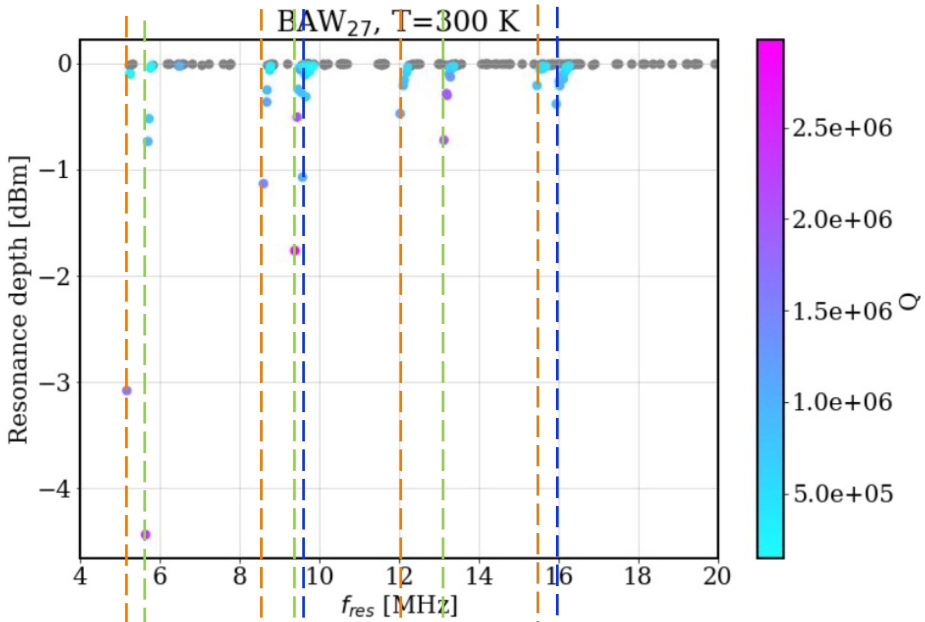


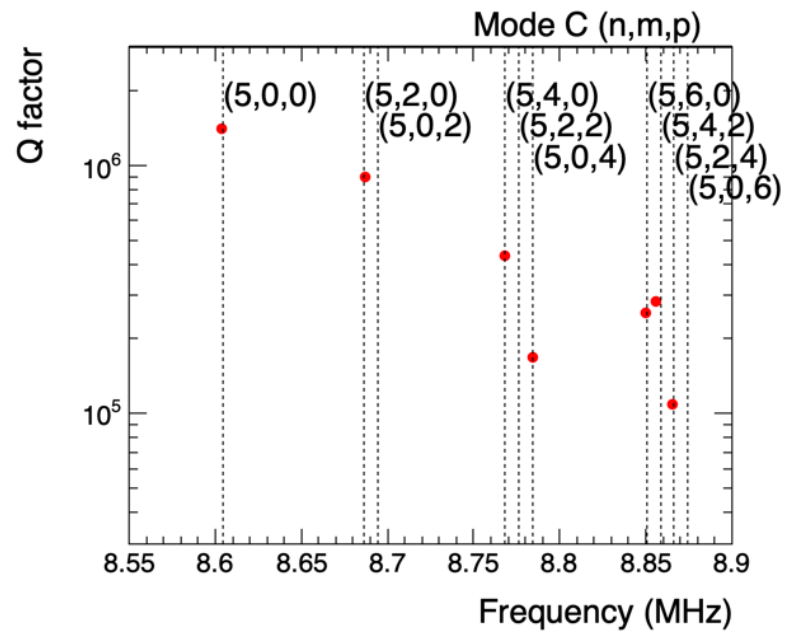


T = 300 K – commercial BAW

- **Modes**
  - High Q = high phonon trapping and low losses

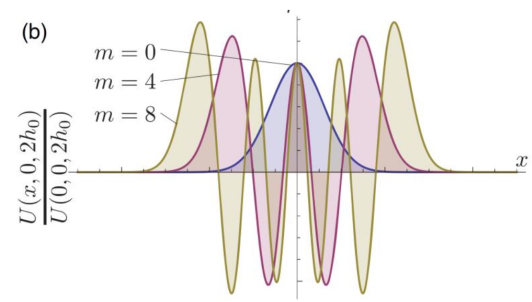
$$\omega^2_{n,m,p} = \frac{n^2\pi^2\hat{c}_z}{4h_0^2\rho}\left(1 + \frac{\chi_x\cdot(2m+1)}{n} + \frac{\chi_y\cdot(2p+1)}{n}\right)$$





- C – 3 5 7 9
- B – 3 5 7 9?
- A – 3 5

longitudinal (A), $V_L = 6757\ m/s$ fast shear (B), $V_{fs} = 3966\ m/s$ slow shear (C) $V_{ss} = 3611\ m/s$



Wave distribution in the transverse plane

Type of losses

When losses due to phonon-tunnelling to the environment are minimised,

$$\frac{1}{Q_{total}} = \frac{1}{Q_{phonon-phonon}} + \frac{1}{Q_{TLS}} + \frac{1}{Q_{scattering}} + \frac{1}{Q_{thermoelastic}} + \text{etc} \qquad (1)$$

Phonon-Phonon Dissipation (Landau-Rumer),

acoustic phonon scattering by thermal phonons over crystal anharmonicity

TLS Absorption

coupling to TLS attributed to impurity ions, e.g. Al^{3+}, Na^{+}, Li^{+}, H^{+}, etc

Scattering Losses

due to acoustic phonon scattering on surface roughness and on small impurities in bulk (Rayleigh scattering)

Thermoelastic Dissipation

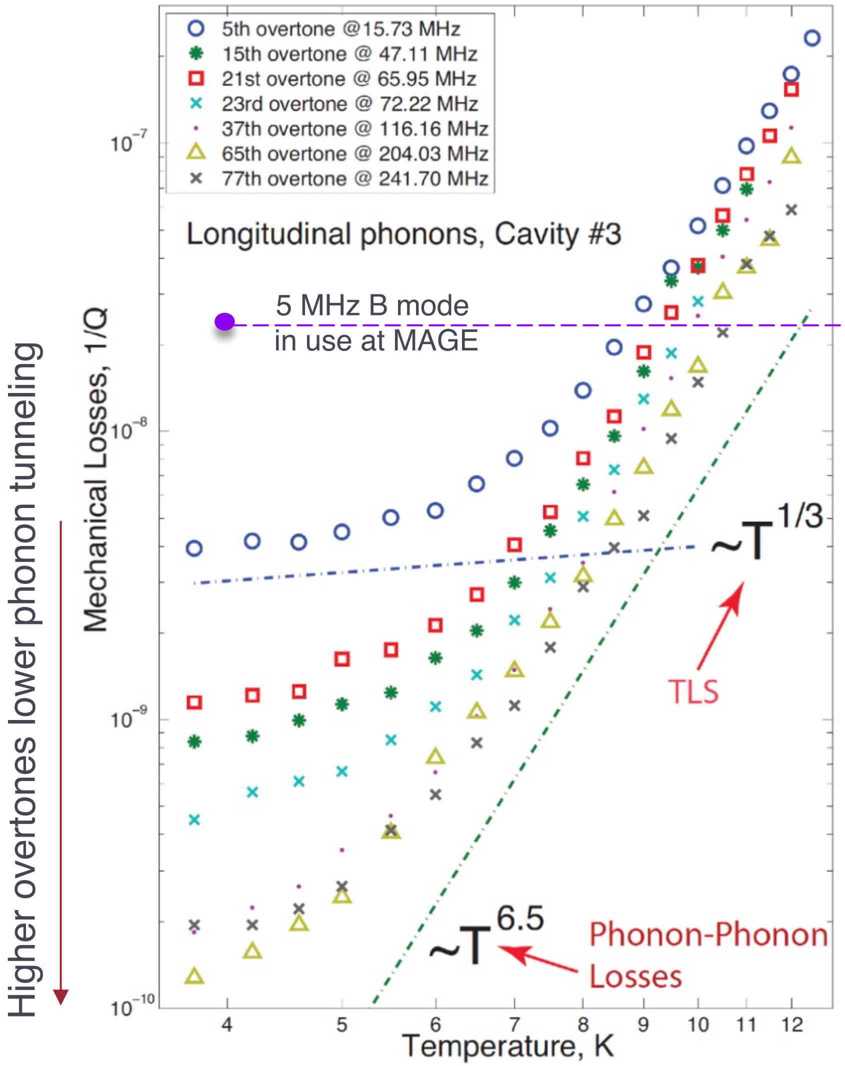
due to thermal currents induced by medium compression/decompression...

Scientific Reports Vol. 3, 2132 (2013)

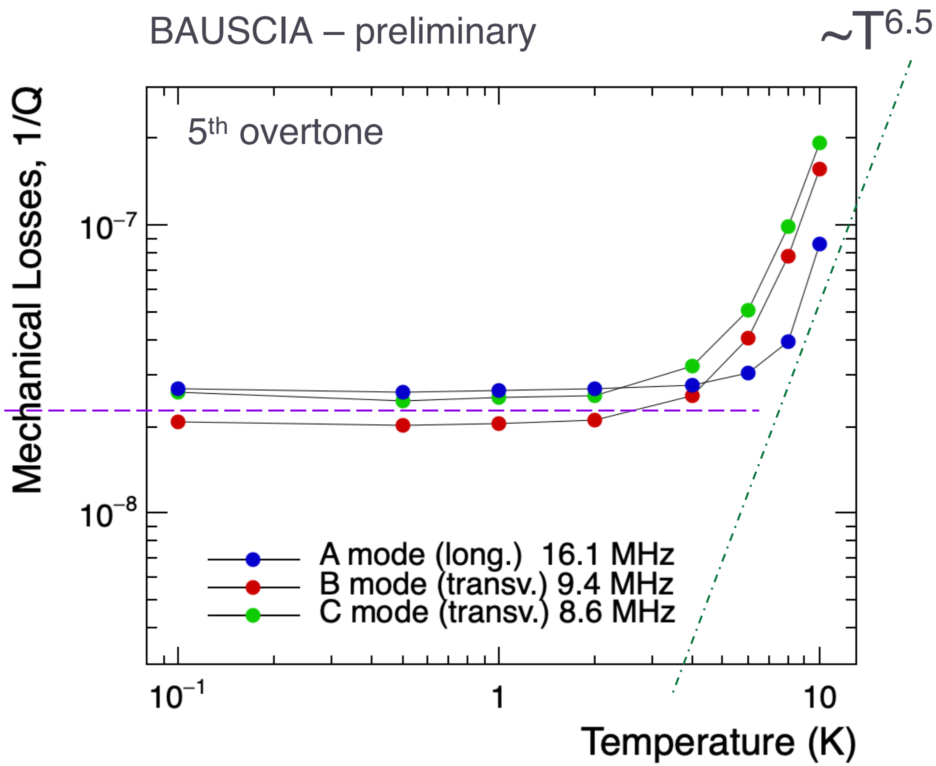
EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

Phonon loss regimes

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



BAUSCIA – preliminary



- **Commercial BAWs tested at Bicocca**
  - >10 gain in Q factor at low temperature
    - 5th overtone (smaller gains at other OTs)
  - Saturation at low temperature tentatively ascribed to surface losses (electrodes)
  - Production of customized BAWs under discussion with a crystal profucer

Instead of a summary

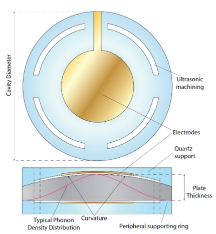
Easy
- Increase number of modes/channels/crystals
- Improvements in signal processing
- Shifting to 20 mK (dilution fridge)
- mK higher frequency SQUIDs

Hard
- Design of Dedicated BAW cavities
- Multisite Detection

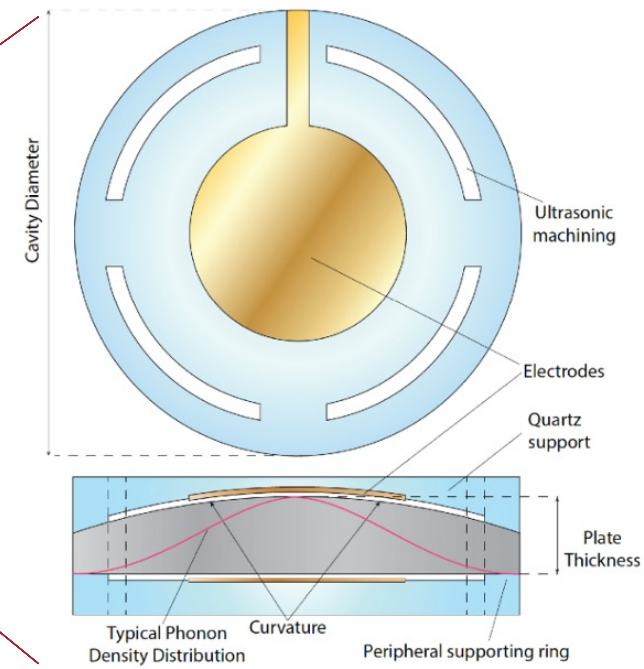
From M. Goryachev talk at
Challenges and opportunities of HFGW, Trieste 2019

- **Dedicated BAWs of larger sizes being developed with a crystal producer**
- **Setting up a 2^{nd} detection site at Milano-Bicocca**

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



x5



d = 5 mm
D = 5 cm
f_1 = 0.345 MHz
f_3 = 1.035 MHz
m ~ 20 g

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