Search for high frequency gravitational waves with Bulk Acoustic Cavities (BAWs)

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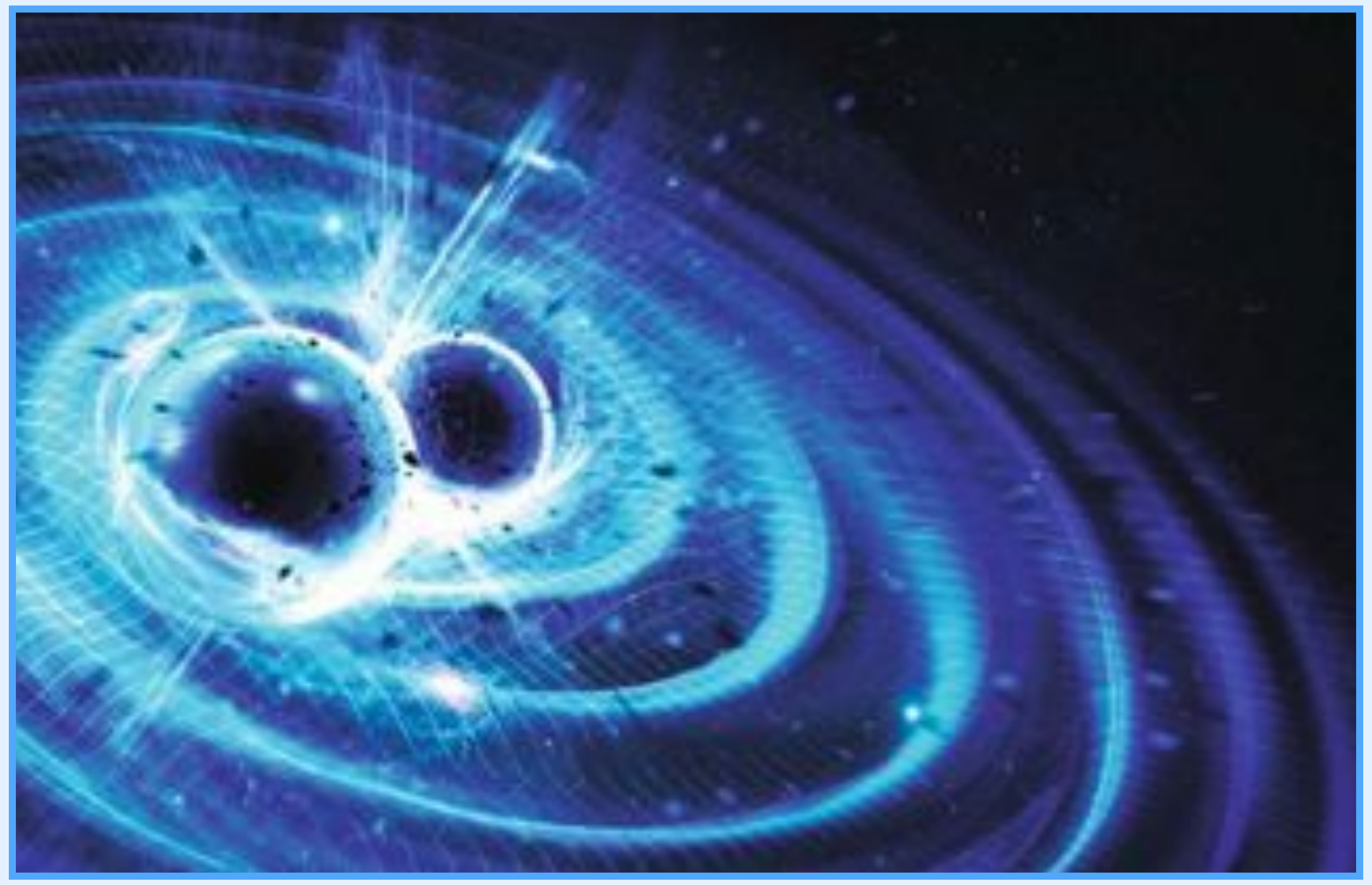
Innovative Detector Technology and Methods (IDTM) Workshop, Lisbon 12th-14th Sept. 2023

Intro to Gravitational Waves

- *Gravitational waves (GWs)* are ripples of space-time generated by the dynamics of massive systems, travel at the speed of light, whose existence is a direct consequence of Einstein's general relativity

Sources of GWs

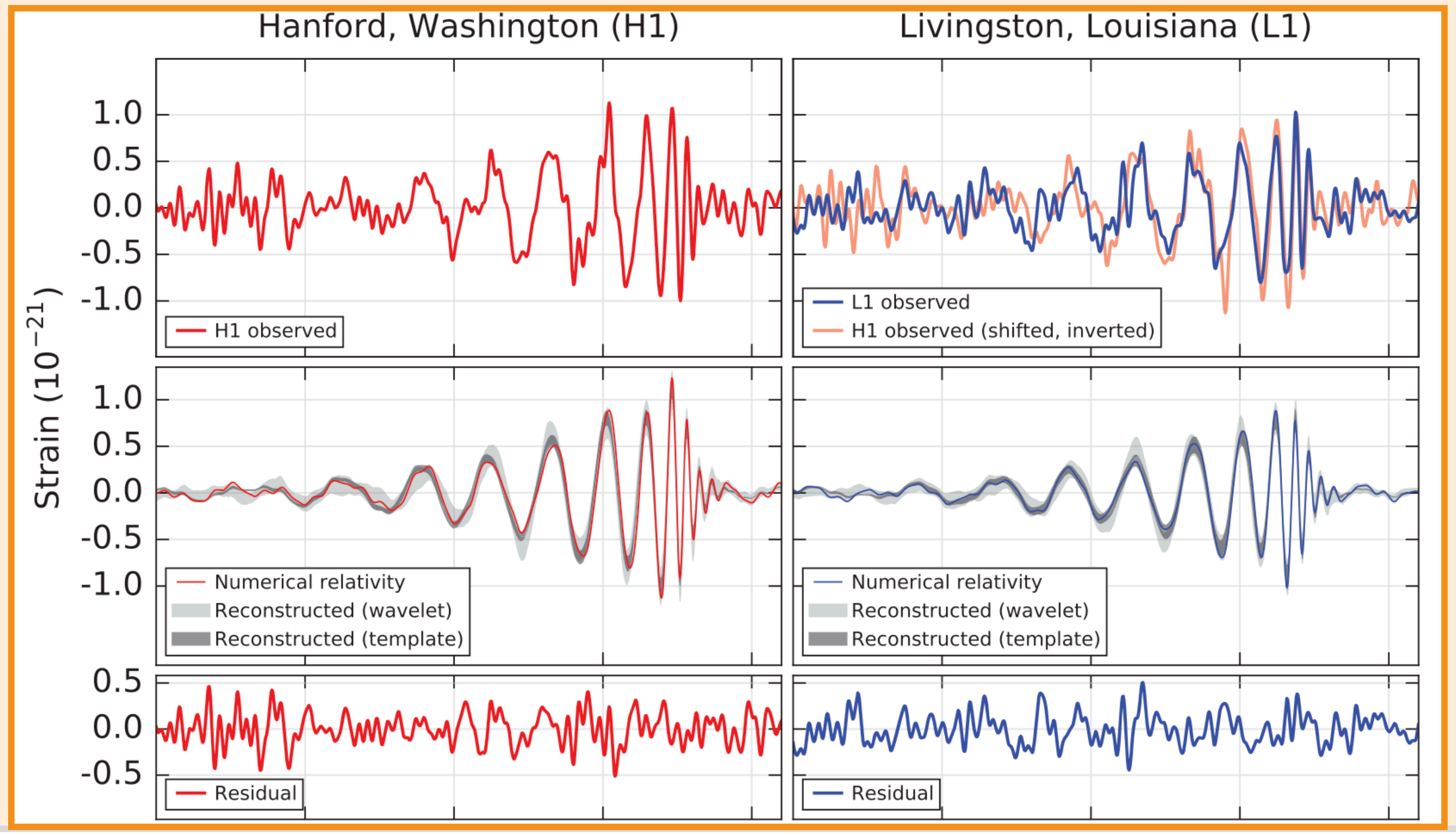
- Inspiral and merger of astrophysical objects → *GWs from late universe dynamics*
- Primordial Black Holes (PHBs) and cosmological sources (inflation, phase-transitions, cloud of axions, etc) → *GWs from early universe*



Experimental observation

- *First detection in 2015* from Ligo and Virgo → Michelson interferometer for GW
- Detected signal produced by *merging of two massive black holes*
- *Characteristic signal pattern (CHIRP)* in time and frequency domains

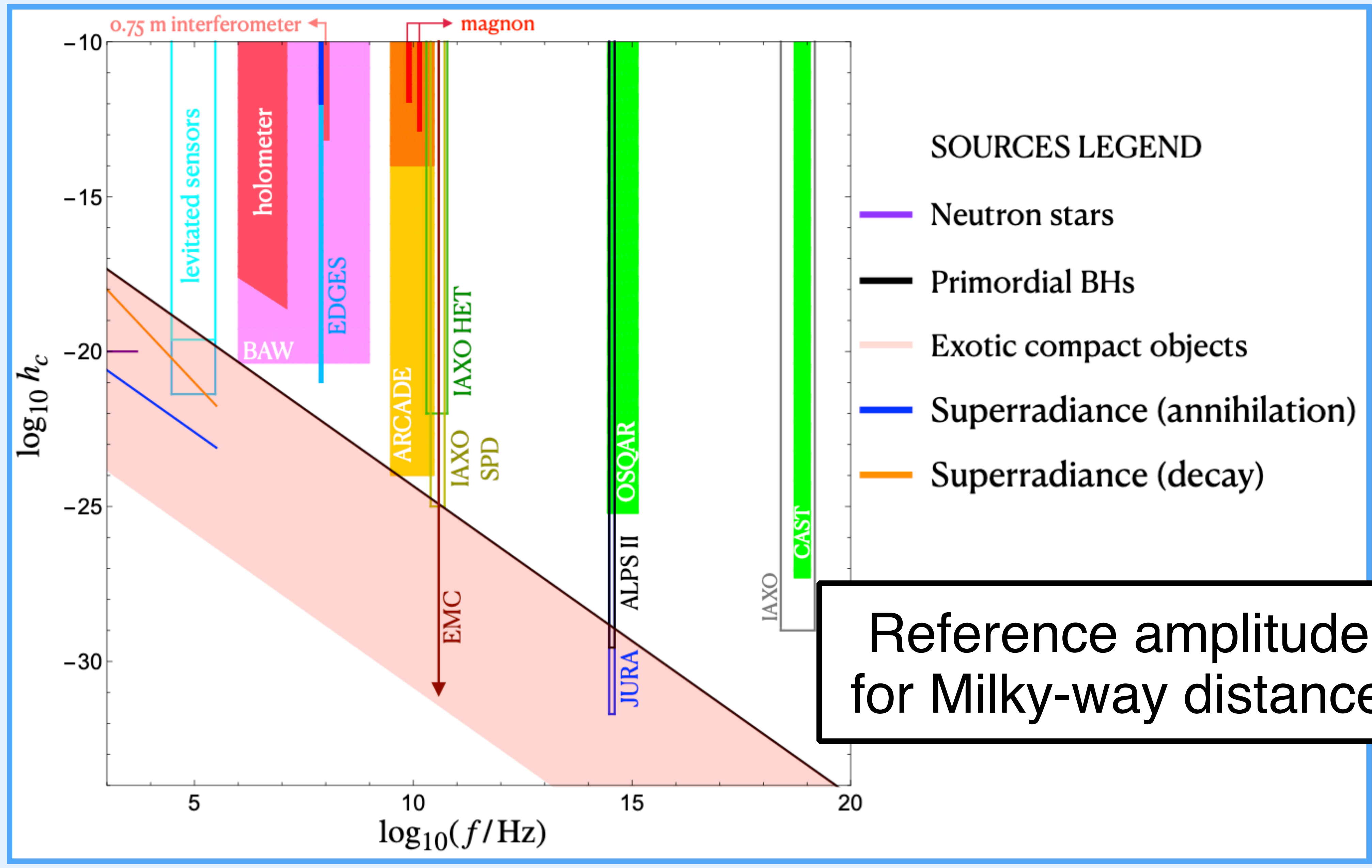
Phys. Rev. Lett. 116, 061102



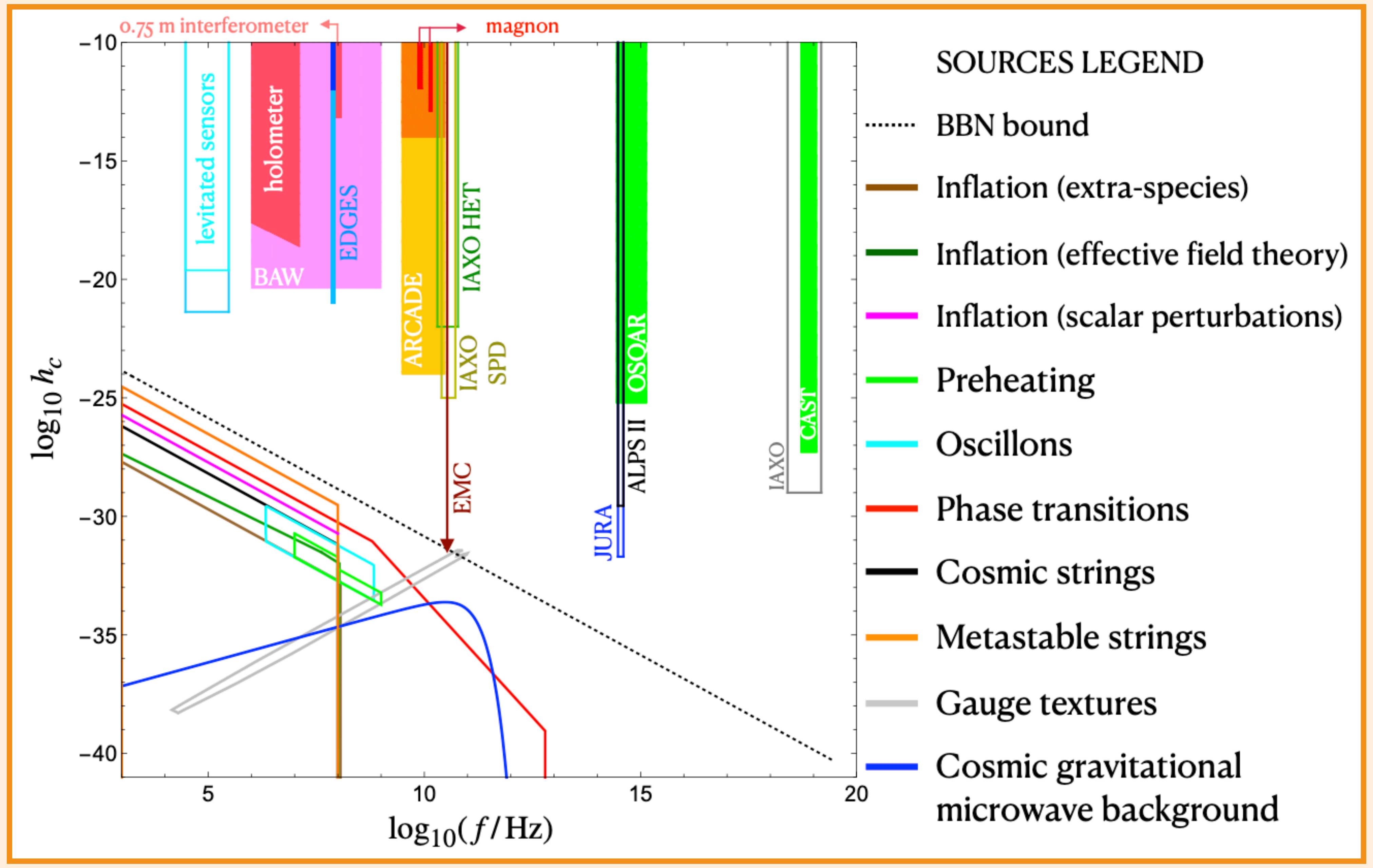
Sources of high frequency GWs

- *High-frequency GWs sources* can be divided into two broad classes
  - *Coherent and/or monochromatic* sources → produced by our cosmological neighbourhood
  - *GWs stochastic background* sources → produced at cosmological distance from earth

Living Rev. Rel. 41114-021-00032-5



Reference amplitude for Milky-way distance



Living Rev. Rel. 41114-021-00032-5

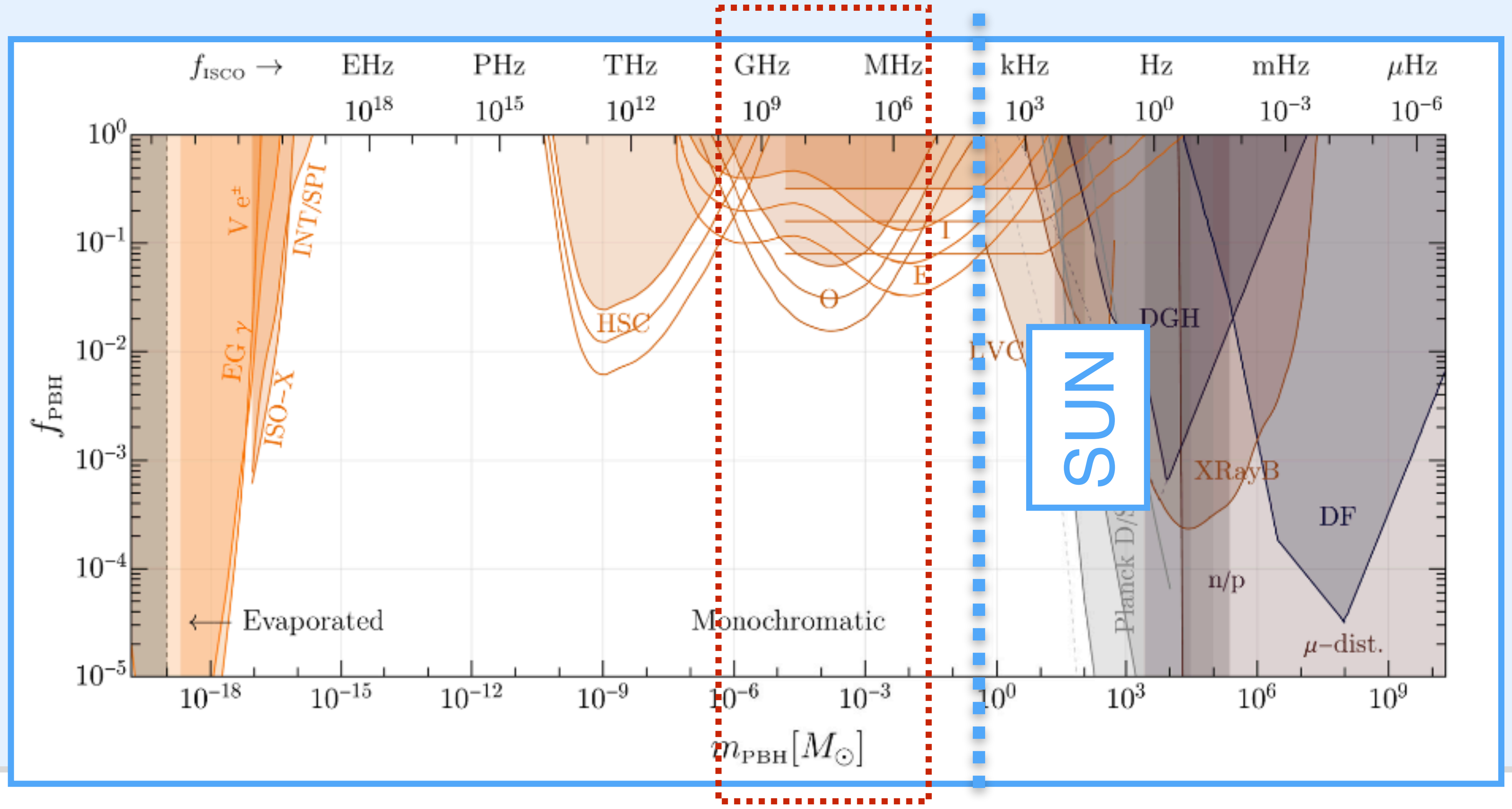
- Dedicated workshop: “Ultra high-frequency gravitational waves: where to next?”, CERN, December 2023
- https://indico.cern.ch/event/1257532/

Coherent sources of high frequency GWs

- *Coherent and/or monochromatic sources* → inspirals and mergers of small mass binary objects
  - These are the potential sources of GWs at high frequencies *easier to probe experimentally*

Primordial black holes (PBHs)

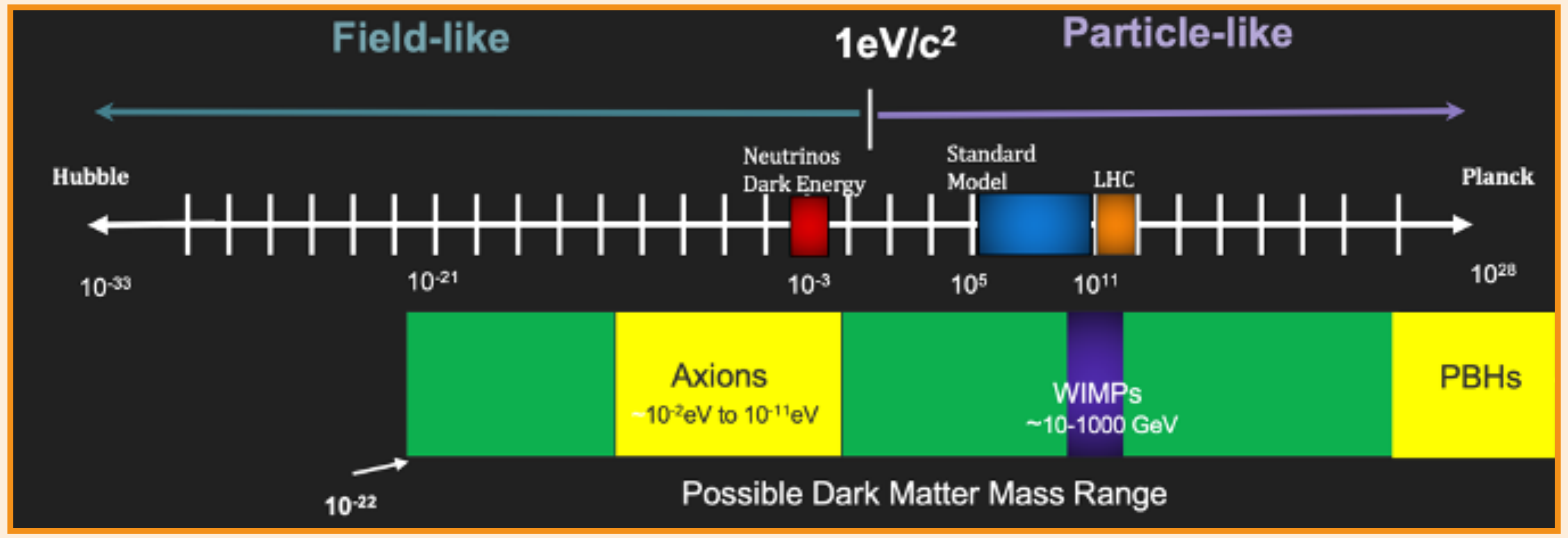
- *Light PBHs* are the most theoretically favourite source of high-frequency GWs
- *Primordial binaries* can take as much as the universe life to merge
- *PBHs* can contribute up to *1-10%* of the *dark-matter* at planetary masses



PhysRevD.106.103520

Black holes Superradiance

- Emission of GWs from *clouds of axions* created by *BHs superradiance*
- *Axions* accumulate outside the BH then *annichilate* into a GW with a frequency dependent on the m_{BH} and m_a
- *Detecting MHz GWs* can be an indirect sign of *axions* as *light DM* candidates



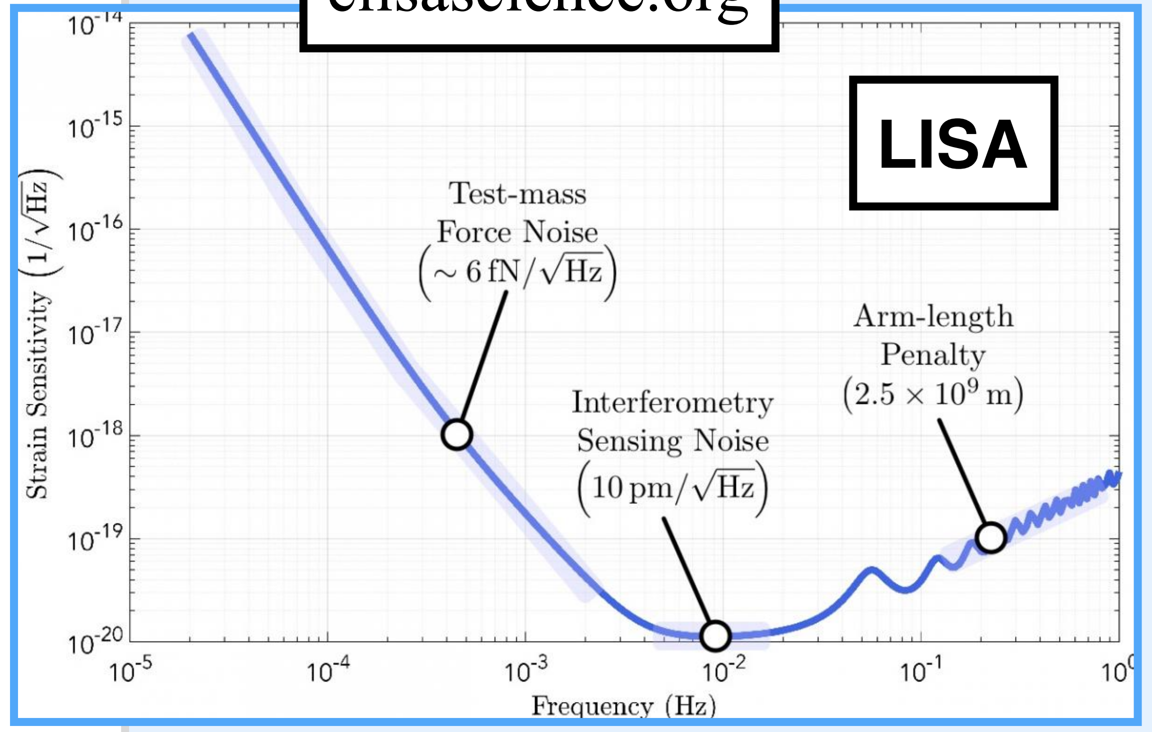
Phys. Rev. D 83, 044026

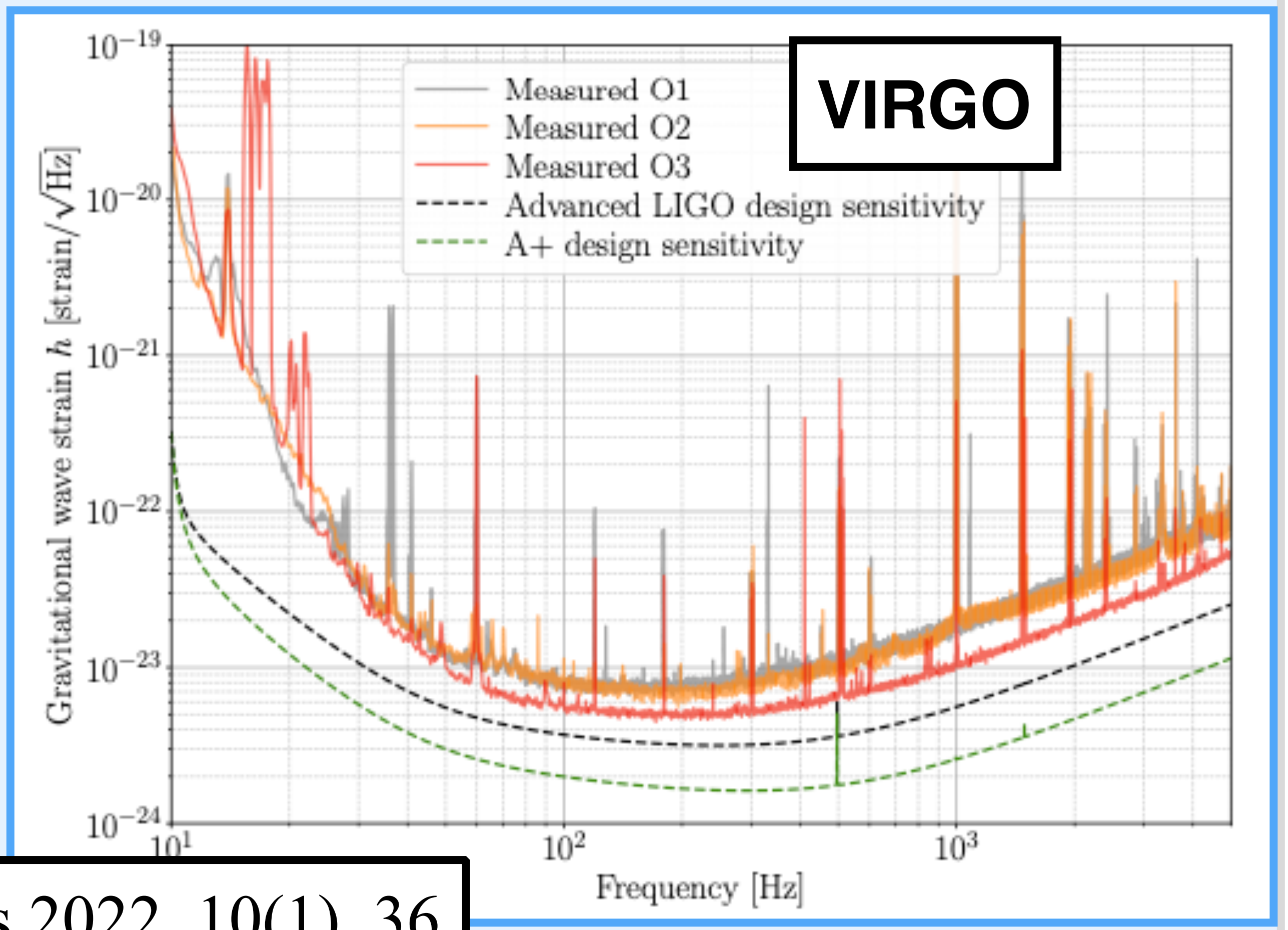
Detecting GWs with "conventional" systems

- *Three classes of GW detectors*: pulse timing arrays (f < 1 μHz), interferometers, and resonant mass

Interferometers for freq. [0.1 mHz,10-kHz]

- *Principle:* GW stretch and squeeze the space-time causing a change in the path length of electromagnetic waves → *interference pattern*
- *Strain amplitude* is very small (ΔL/L) → 10^{-21} in GW150914 that corresponds to the 1st LIGO event
- *Broad band sensitivity* intrinsically limited at high frequencies by the length of the interferometer arms

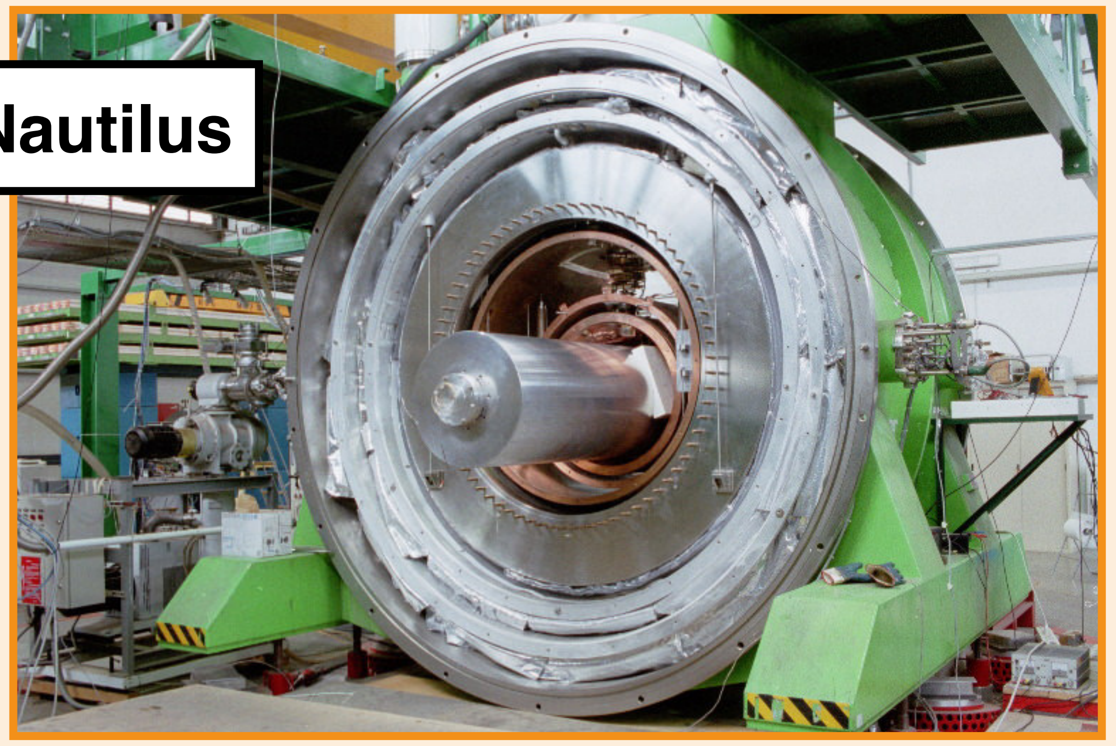




Galaxies 2022, 10(1), 36

Resonant mass detectors for freq. [500 Hz, 5 kHz]

- *Principle:* GW stretch and squeeze the mass and the structure of a physical object
- Length variations in the material detectable only at *discrete resonant frequencies* → *vibration modes*
- Able to reach *strain sensitivities* of ~ few $10^{-22} / \sqrt{\mathrm{Hz}})$
- *High resolution* but *narrow* and *discrete band*
- Two main setups: *resonant bars* or *spheres*



How many systems to detect GWs?

Low frequency < 1 μHz

Average frequency 1 Hz - 10 kHz

High frequency 1 MHz - 1 GHz

pe of detector	Frequency band	Strain sensitivity
Pulse Timing Arrays (PTAs)	10^{-9}–10^{-7} Hz	10^{-15}
Interaction with binary orbits	10^{-8}–10^{-6} Hz	10^{-11}
Sp cecraft Doppler tracking	10^{-8}–10^{-5} Hz	10^{-14}
Interferometer in space	0.1–100 mHz	$10^{-20}/\sqrt{\text{Hz}}$
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tom Interferometer on ground	1–10 Hz	10^{-19}
Laser Interferometer on ground	10 Hz–10 kHz	10^{-22}
esonant bar	0.5–1 kHz	10^{-21}
pended dielectric particles	50–300 kHz	10^{-21}
Q microwave cavities	1 MHz	10^{-17}
Bulk Acustic Wave Resonanters (BAWs)	1 MHz–GHz	$10^{-22}/\sqrt{\text{Hz}}$
Superconducting rings	GHz	–

Pulse Timing Arrays, Doppler Effects, etc.

Interferometers and mechanical mass resonators

Detectors for high frequency GWs beyond the cut-off regime of laser-based interferometers

- *A first evidence for rare resonant events in BAWs around 5 MHz* has been recently reported by UAW group

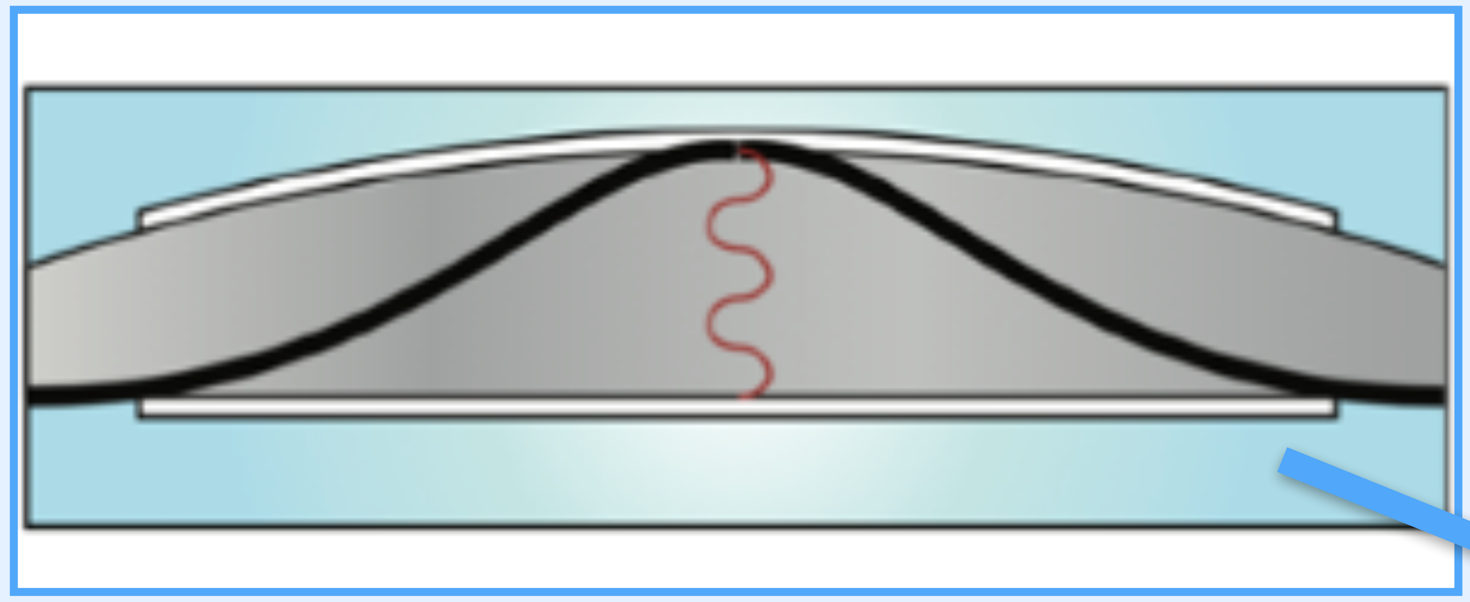
Phys. Rev. Lett. 127, 071102

Bulk Acustic Wave (BAW) resonators

BAWs are resonant detectors for freq. > 1 MHz

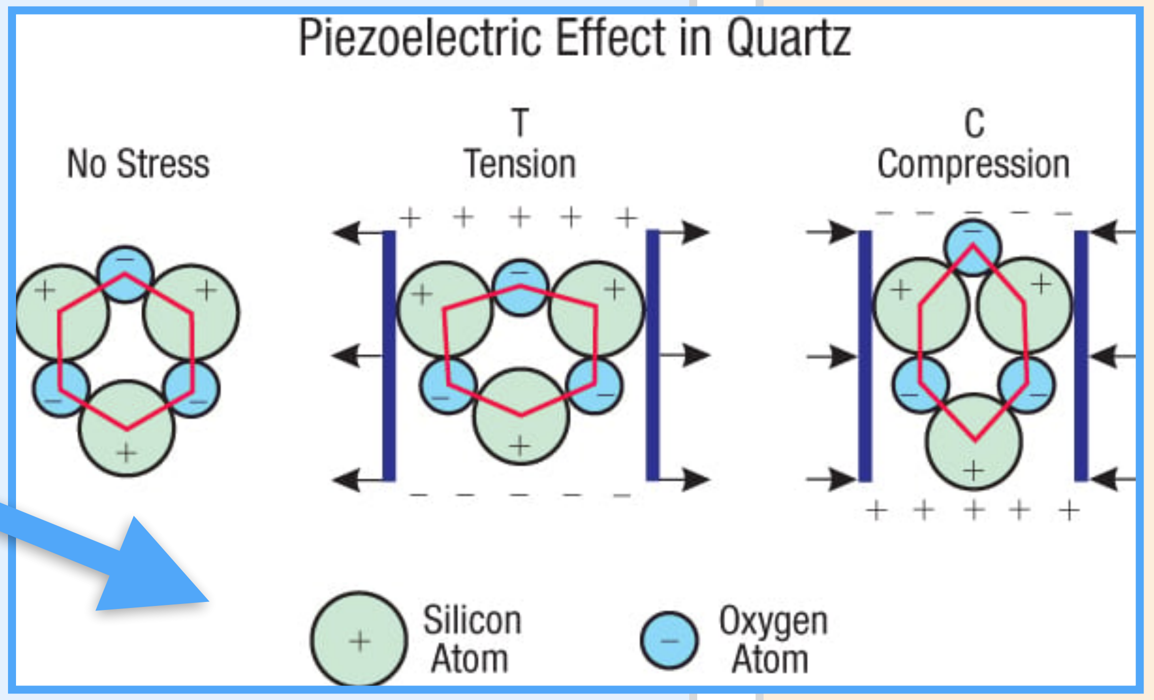
- *Piezoelectric crystals* can be used as mass resonators
- *Large* potential *sensitivity* to GWs due to high Q-factors
- *Piezoelectric properties* allow for a direct conversion of acoustic vibrations to an electric signal
- *Scalable technology* as it is used by > than 60 years for precision clock applications

Piano-Convex BAW trapping phonons



r ≤ 1 cm

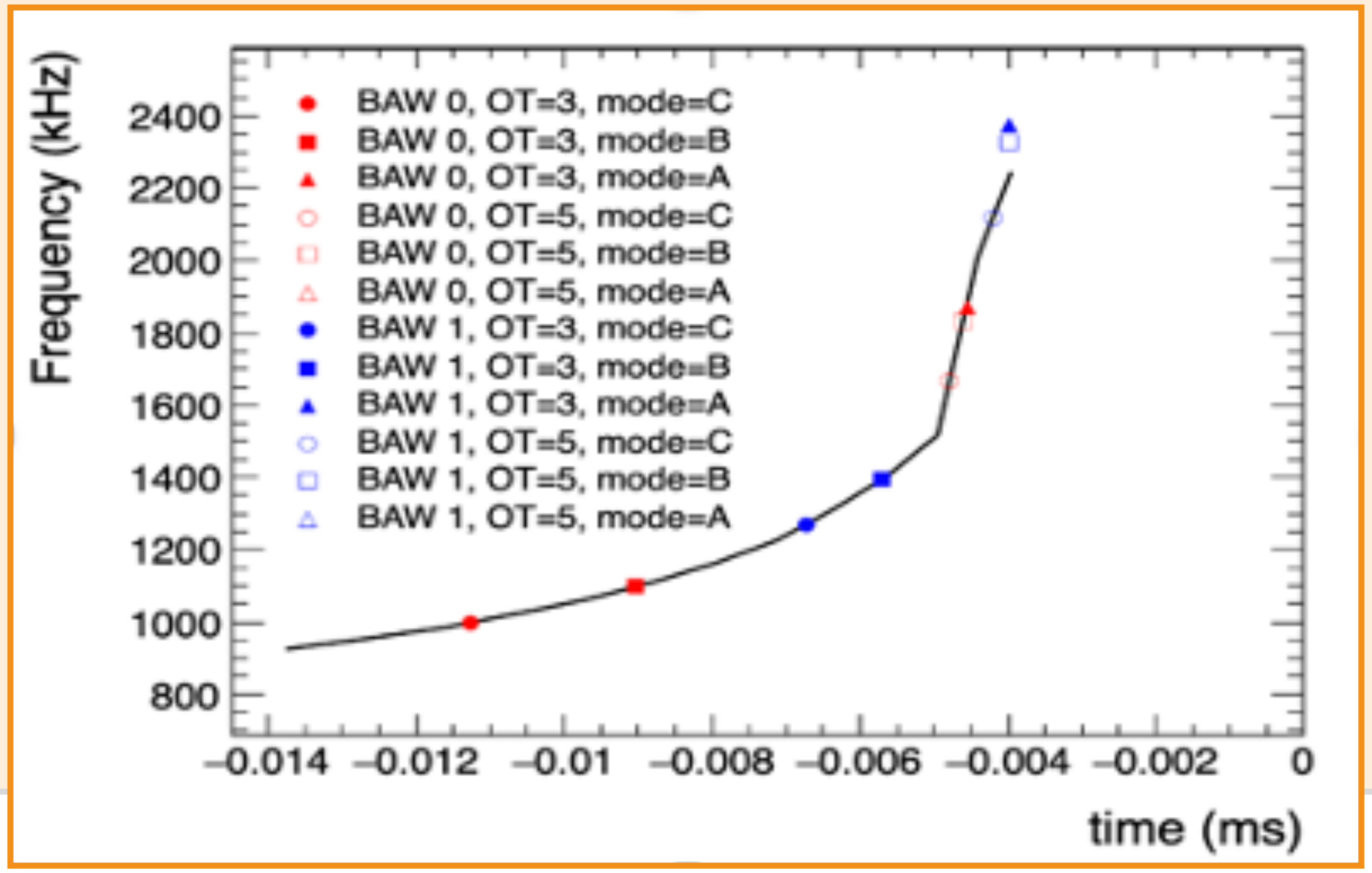
r ~ 1 cm



Discrete resonant modes over a wide freq. range

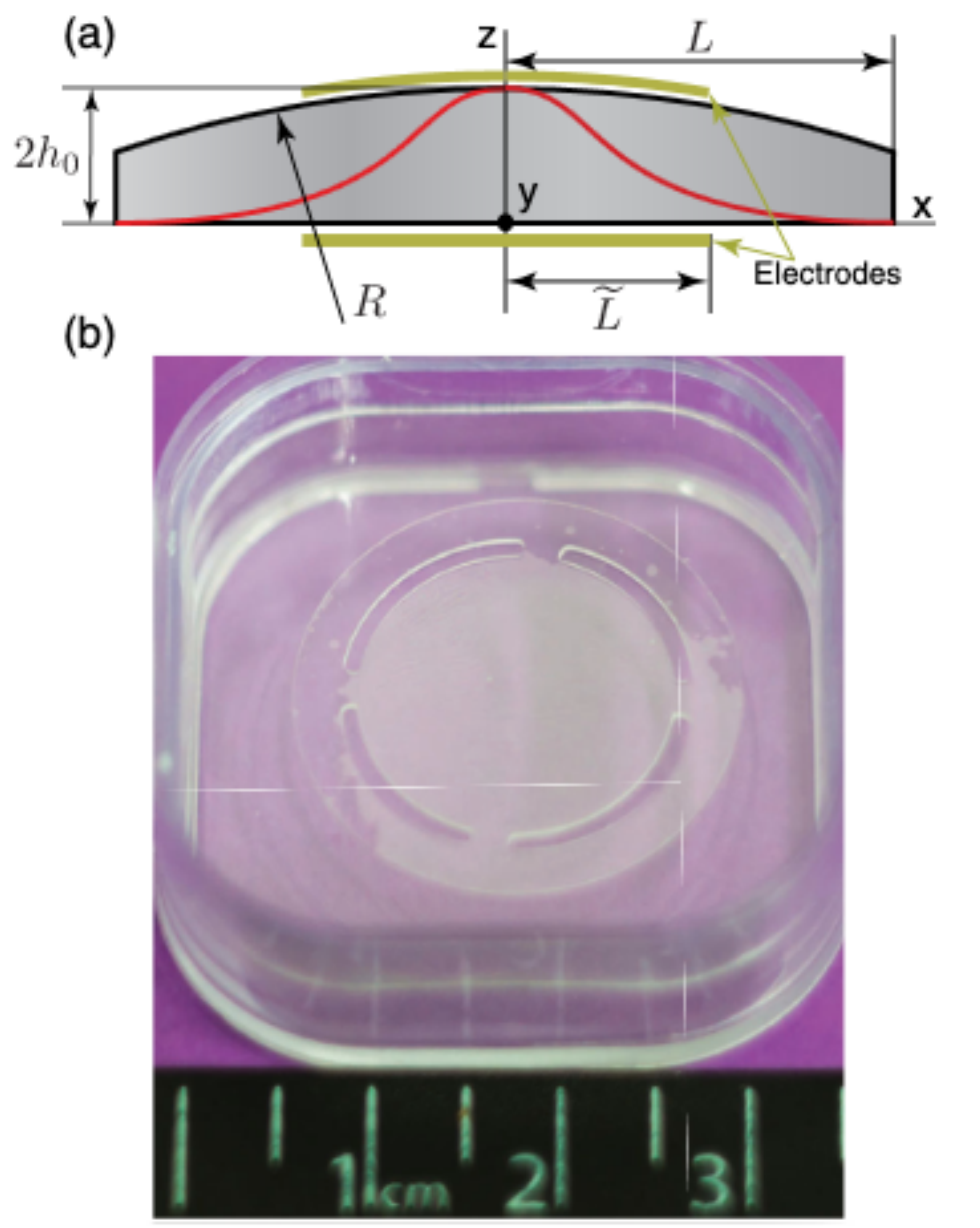
- Within the crystal lattice *three types* of *resonances*
  - Two *transverse* and one *longitudinal* mode
  - Characterised by different *velocities*
- For every type of vibration, *multiple overtones available*

Saturn-mass PBH-PBH merger *signal sampled* with *two BAWs* over multiple overtones



BAW cavities as antenna for GWs

PhysRevD.90.102005



Mathematical description of a BAW in a nutshell

- *Displacement distribution* can be obtained from *Stevens-Tiersten* theory. Dominant component of displacement u_d is a solution of

$$\rho \ddot{u}_d + \frac{\pi^2 n^2 \hat{c}_z}{4h_0^2}\left(1 + \frac{x^2+y^2}{2Rh_0}\right)u_d = M_n \partial_{xx}^2 u_d + P_n \partial_{yy}^2 u_d,$$

- *Solutions provides* three types of vibrations *(A,B,C)*, one *overtone number (n)*, two quantum numbers *(m,p)* related to Hermit poly. in the x-y plane
- *Trapping parameters* depend on cavity geometry (R, L, h_0) and $X_{x,y}$ parameters that can be measured (angular modes)

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

- *BAW response to a GW excitation*

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

U_λ → spatial distribution

V, ρ, m_λ → BAW parameters

ω_λ, τ_λ → mode freq. and bandwidth

BAW: operation and readout

- *Main source of noise* → thermal vibrations → *BAWs* will be operated at *cryogenic temperatures*
- *Detection approach:* trasduce vibrations to electrical signal, amplify + shape, digitalise off-detector, and process it via FPGA

** Superconducting Quantum Interference Device (SQUID) is used to amply and shape the BAW signal

Broad-band setup and its sensitivity

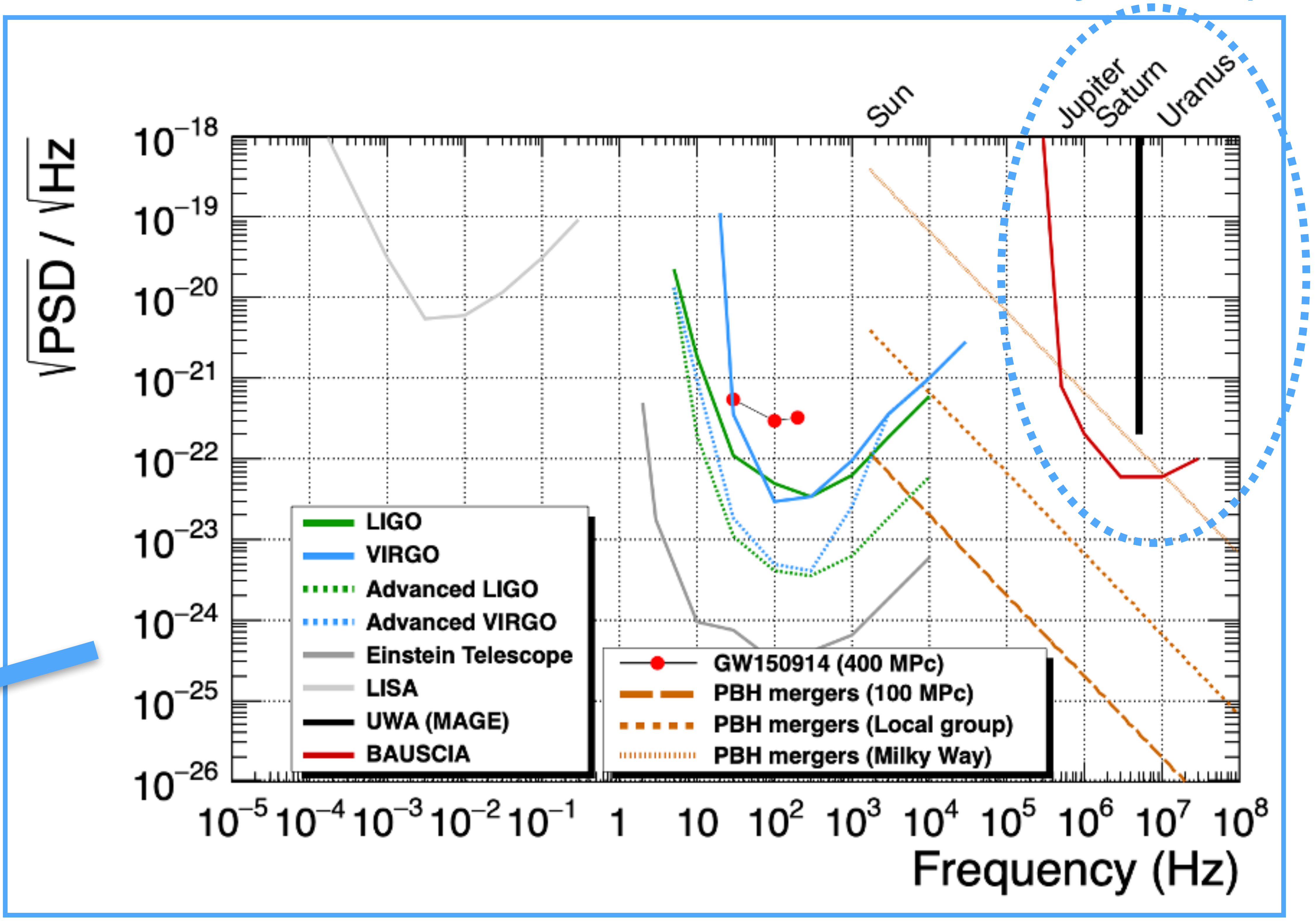
- *Each BAW* is intrinsically a high-Q but *narrow-band antenna* → only sensitive to few overtones of (A,B,C) modes.

How can we obtain a broad-band sensitivity?

- *Use* and *optimise* the Q-factor for as *many overtones* as possible for each single BAW
- *Arrays* of multiple *BAWs* tuned at different frequencies
- Both aspects requires specific R&D ……

- Sensitivity estimate built from *MAGE* at *UAW* described in Phys. Rev. Lett. 127, 071102
- *MAGE* is a *single narrow-band antenna* operated for 153 days looking at signals around *5 MHz*
- *MAGE* sensitivity *scaled* to replicate the performance of an *array* of *BAWs* with same Q-factor → red contour line

Illustrative sensitivity vs freq.



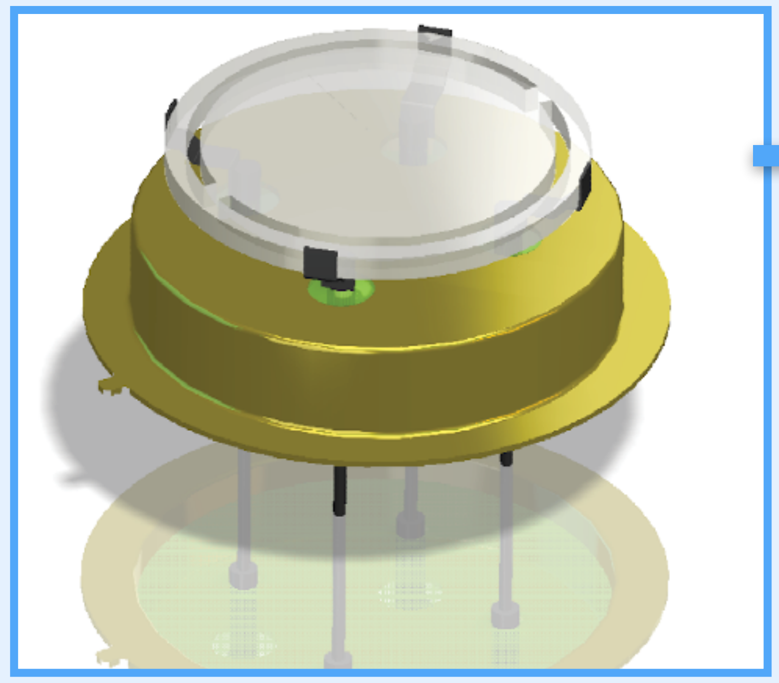
Milano-Bicocca setup: BAUSCIA

- Project name → **B**ulk **A**custic **W**ave **S**ensors for **H**igh frequency **A**ntenna → **BAWSHA** or **BAUSCIA** in Milan's dialect

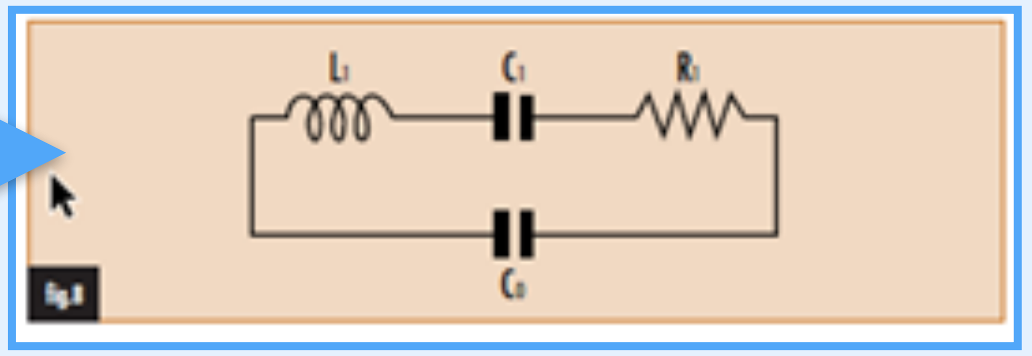
BAW samples

- *Proposal:* use commercial BAWs for a pilot study
- *Plano-convex quartz* crystal with d ~ 1 mm, r ~ 10 mm
  - Three samples with ~similar factory properties
  - Vibrating mass of about 0.2 g

Mechanical layout



Electrical model & params

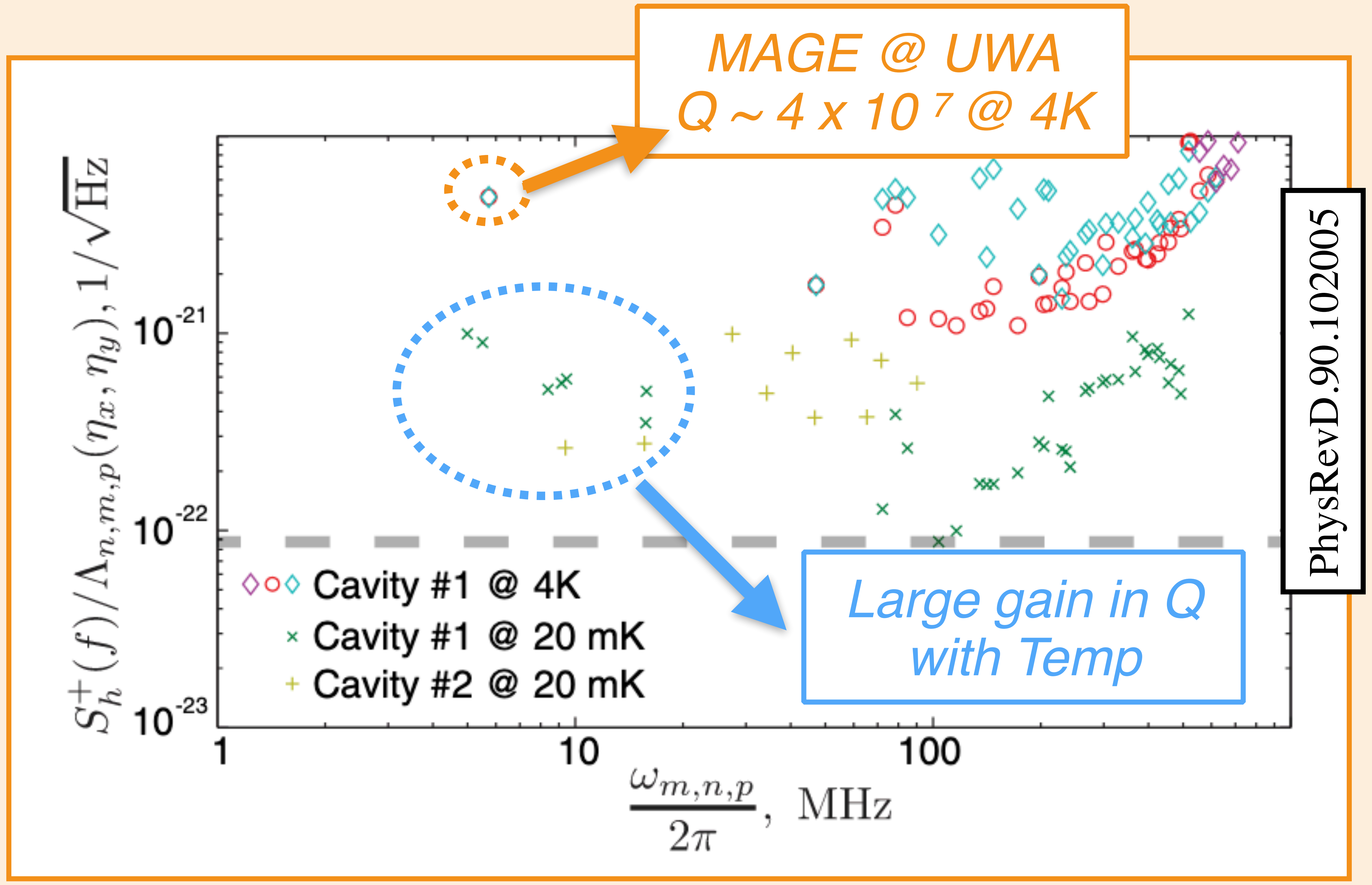


FR	RR	L	C0	C1
Hz	Ohms	mH	pF	fF
5 174 995.40	55.24	3 172.84	2.48	0.30
5 174 993.99	62.13	3 904.36	2.49	0.24
5 174 987.21	48.83	3 434.80	2.49	0.28

- *Room temperature Q factor of* ~ 10^6-10^7

Performance at cryogenic temperatures

- At cryogenic temperatures *Q-factors goes up to* 10^7-10^8
  - Larger gains for longitudinally A-modes and high freq
- *SQUID noise* should be still *smaller* than thermal one



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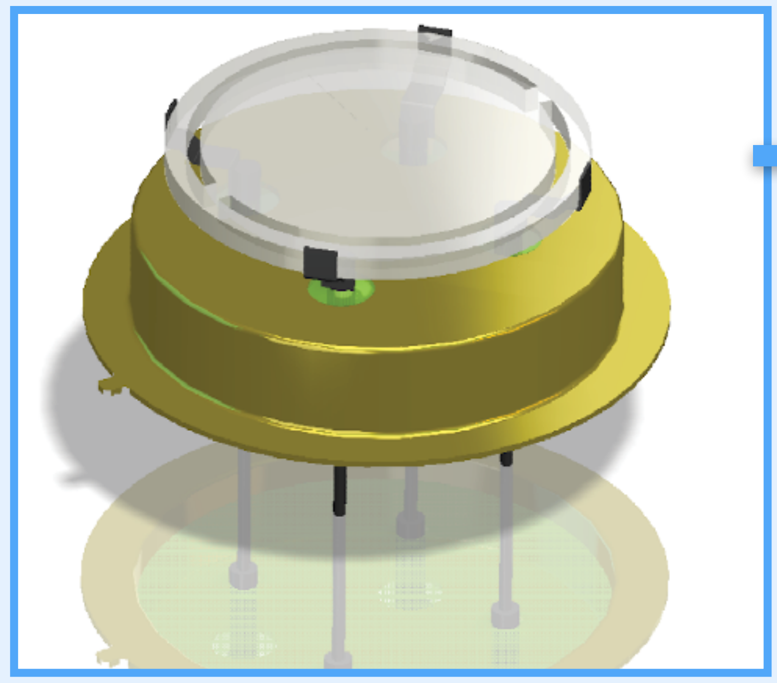

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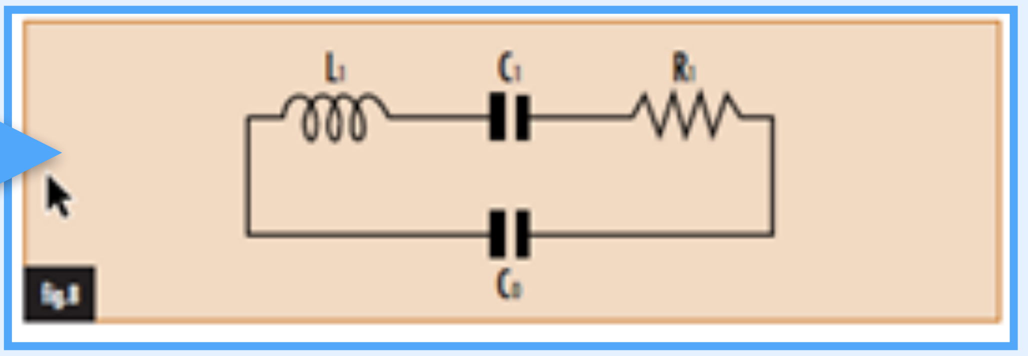

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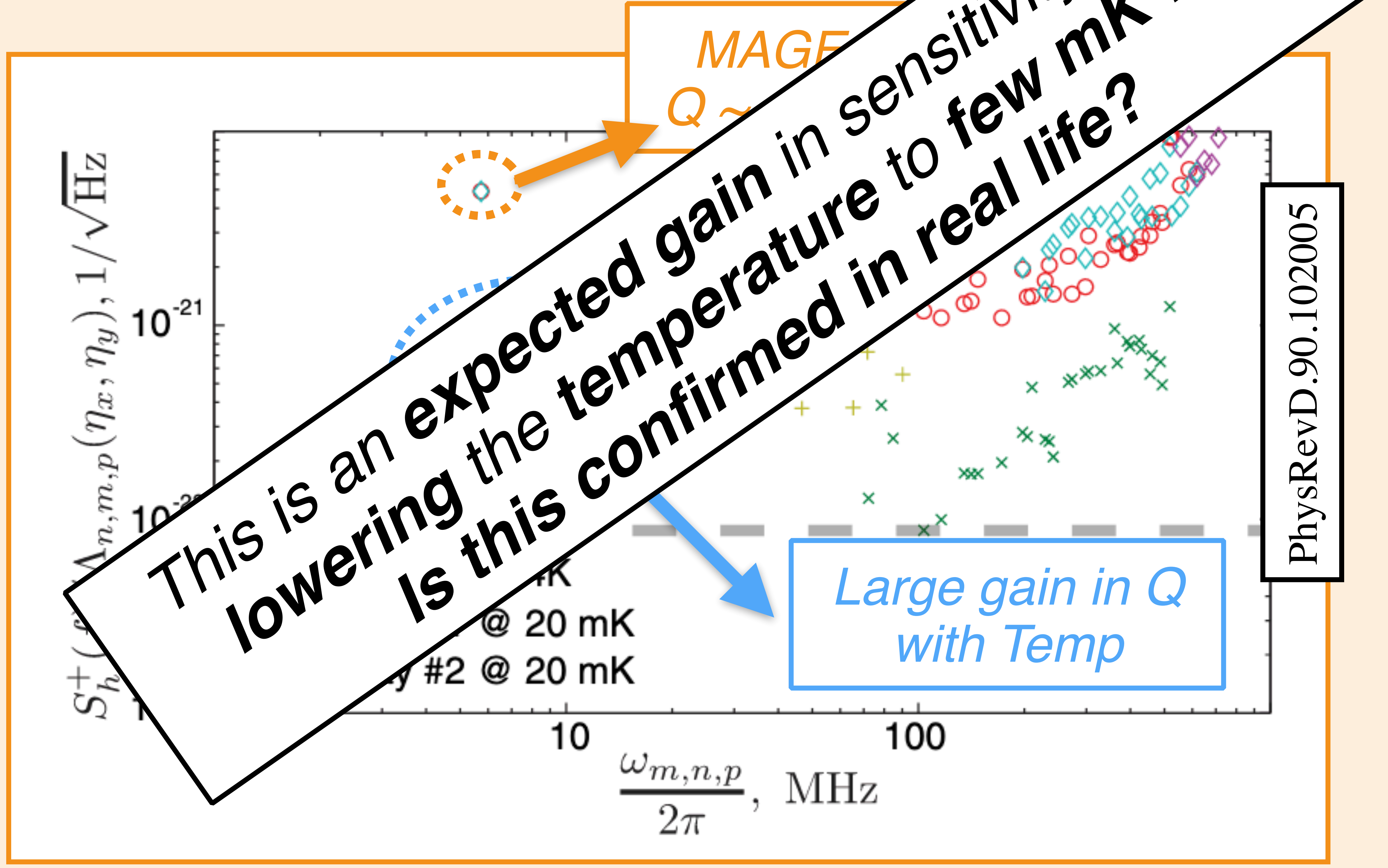
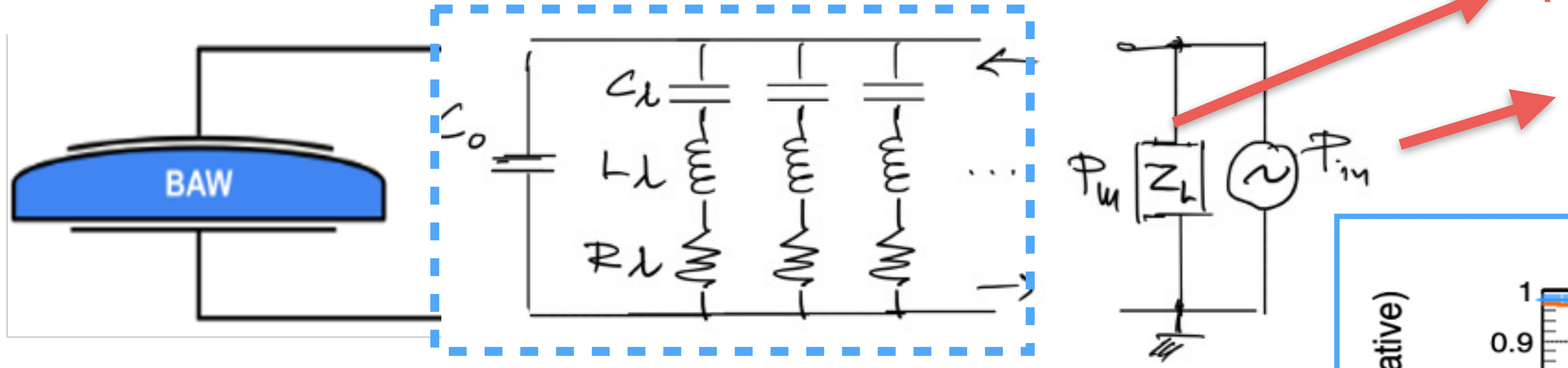


BAWs characterisation at Milano-Bicocca

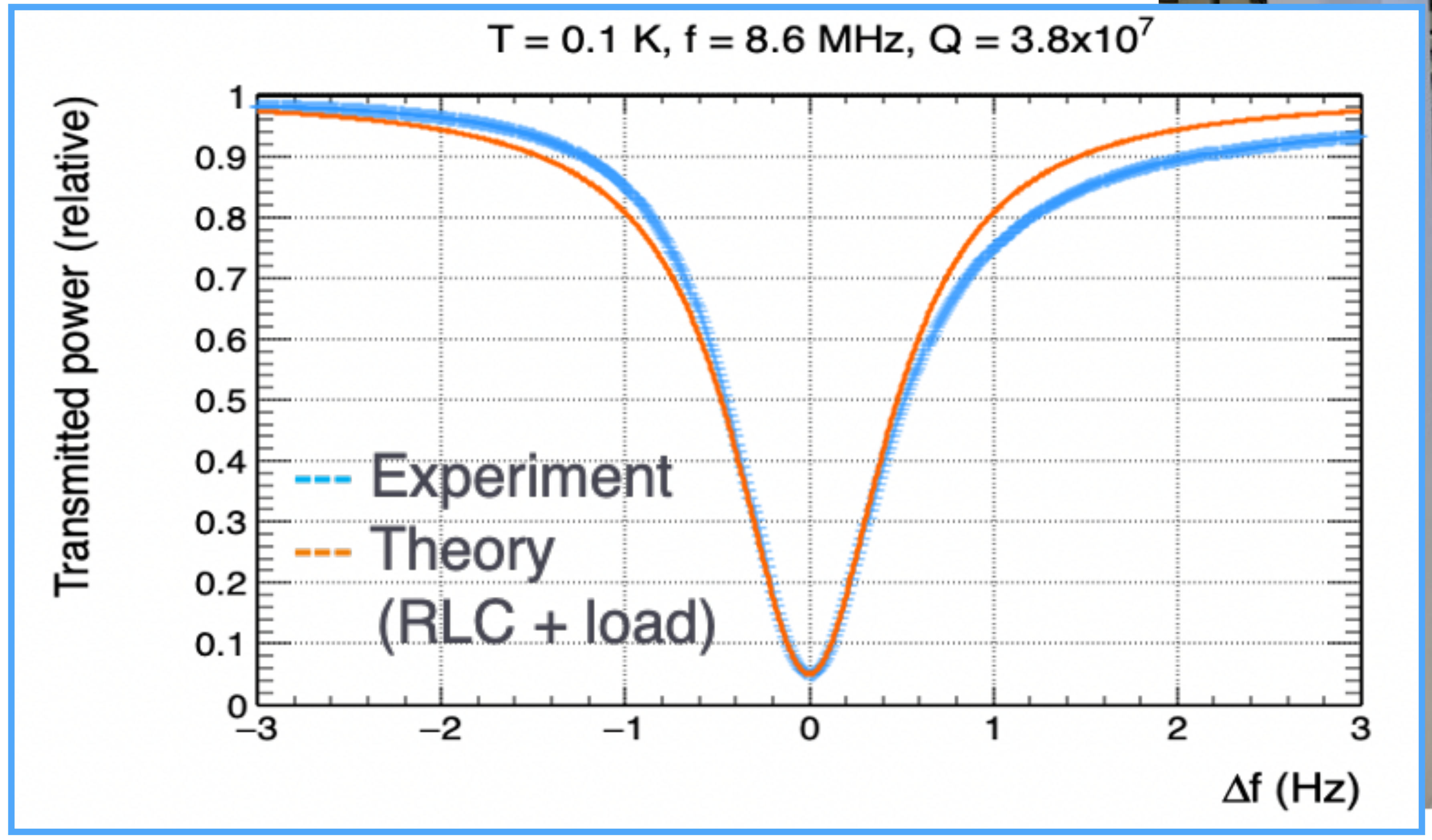
- *Method: excite* the BAW via an *electrical signal* to produce *vibrations*
- *Instrumentation:* use a *Vector Network Analyser (VNA)* as a source of electrical signal with different ω_s
- *Measurement: power* on the *VNA output* modified w.r.t. power in input by the *mechanical vibrations*

Electrical BAW model

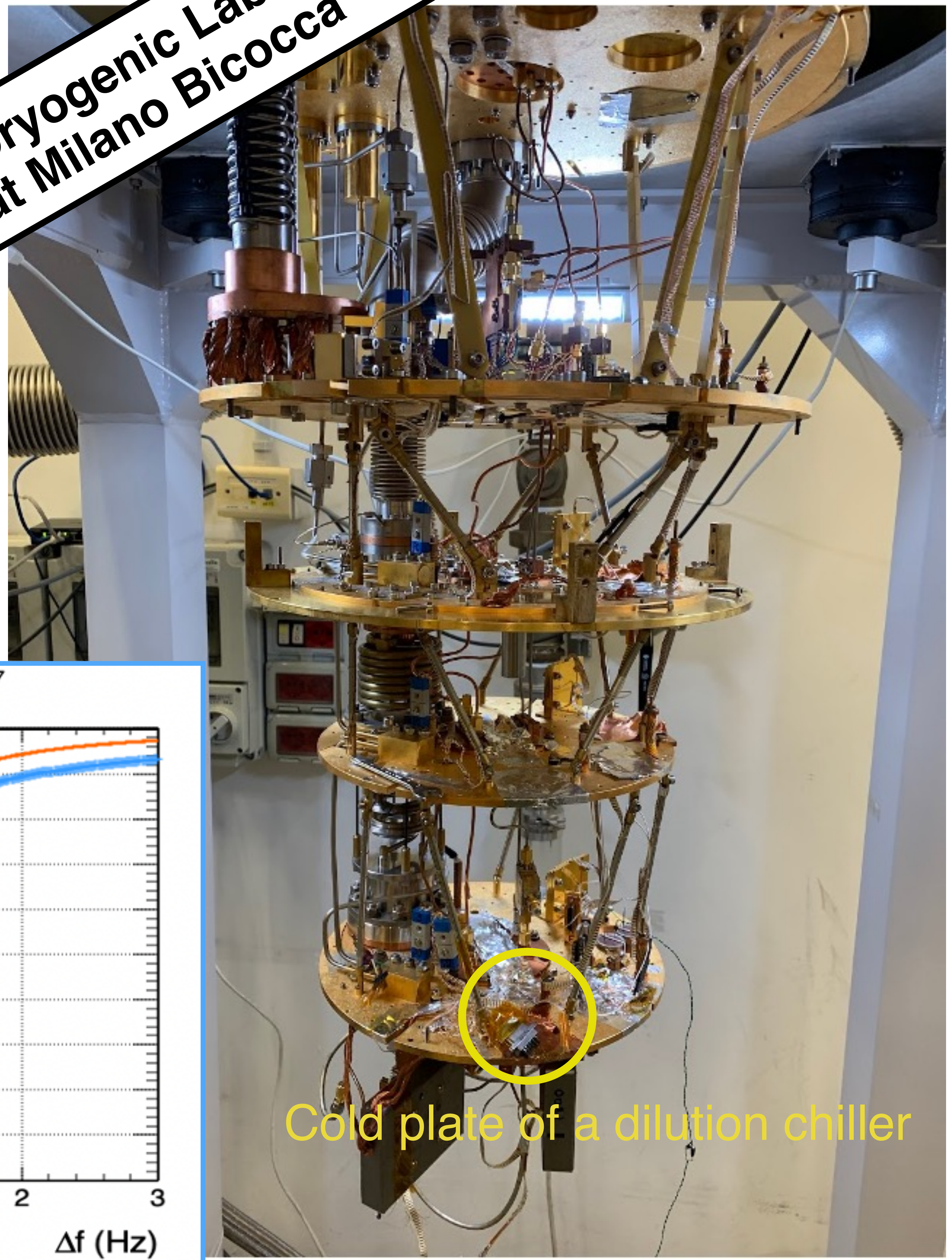


- Data fitted with an *analytical model* to extract the Q-factor of the resonator

$$P_{out} = P_{in} \times \left| \frac{Z_B}{Z_B + R_L} \right|^2$$



INFN Cryogenic Laboratory at Milano Bicocca

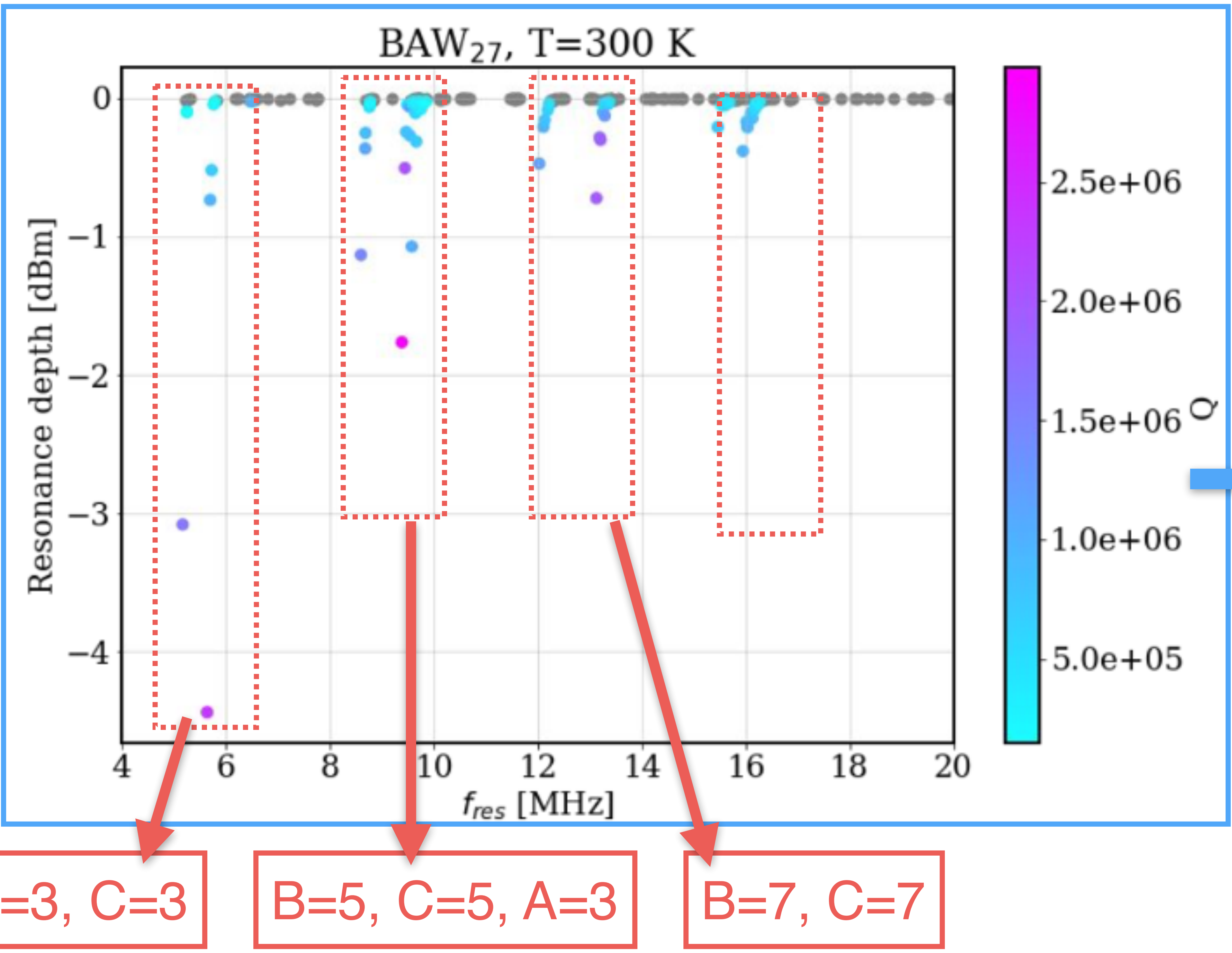


Commercial BAWs @ T = 300 K

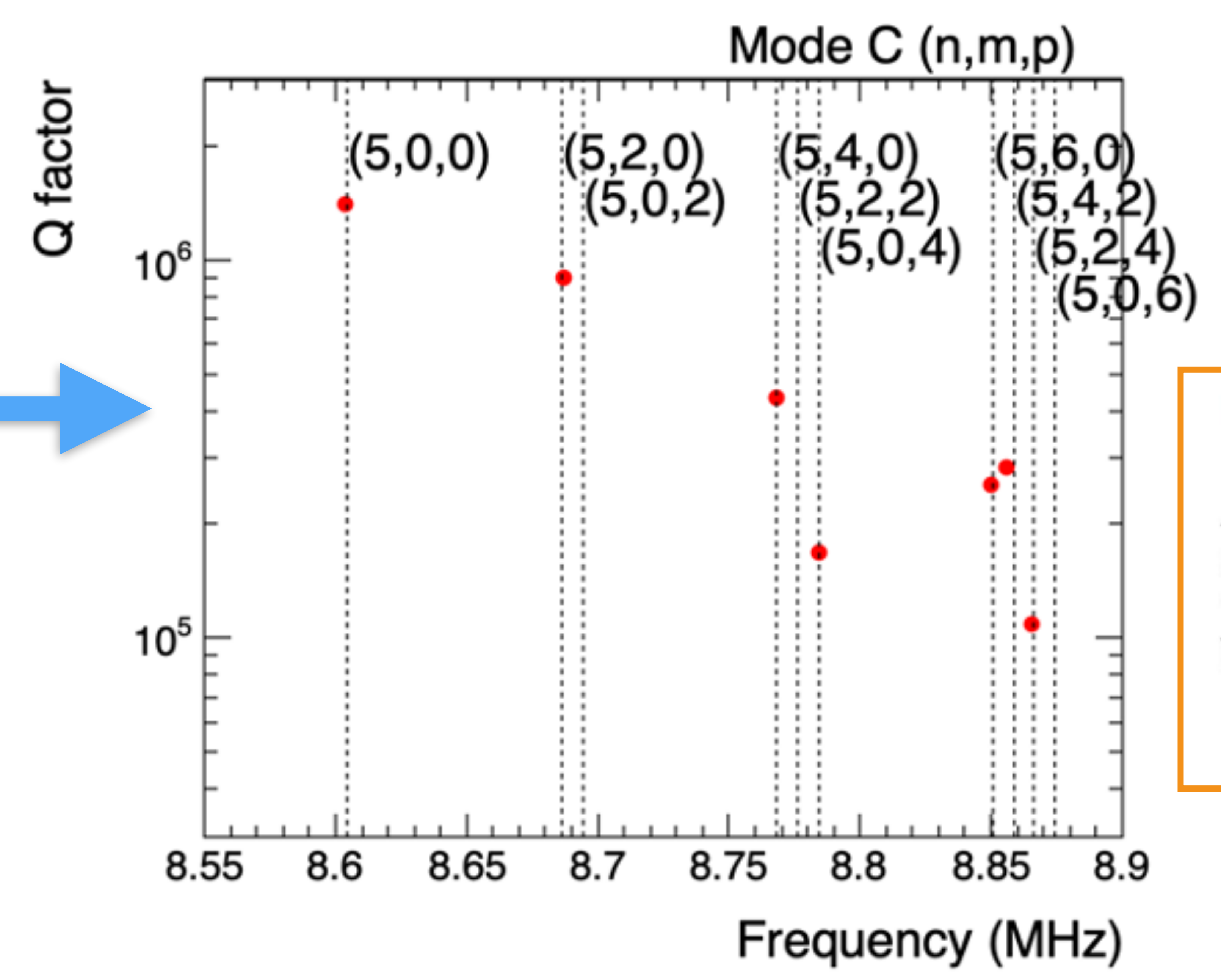
- *Frequency scan at T = 300 K* in the *[4,20] MHz range* injecting -35 dBm of power, span window 100 Hz, bandwidth of 10 Hz
- *Q-factors* and *frequency* extracted for each mode and overtone from an analytical fit as described in **slide**

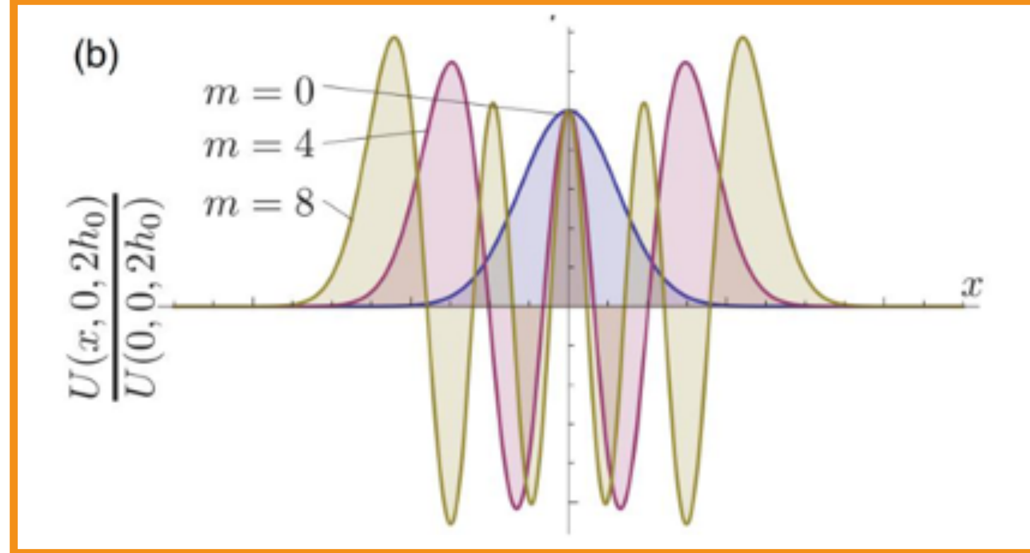
Mode resonant frequency vs (n,m,p)

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



Q-factors for mode C, n = 5





Wave distribution in transverse plane

** A-mode is longitudinal, B-mode fast shear, C is slow shear

What limits the Q-factor of a BAW?

- A BAW is the acoustic equivalent of an optical Fabry-Perot cavity → *BAW as a phonon cavity*
- The *Q-factor* value is determined by *losses* in the BAW given by *material* or *design* effects

  - *Design losses* → energy leakage due to electrodes, substrates, clamping → *don't scale with Temp.*

  - *Material losses* can be reduced with temperature but limited by type of crystal, impurities, geometry, etc.

- If the phonon-tunnelling loss towards the environment is minimised, *total loss* of an acoustic resonator is

$$\frac{1}{Q_{total}} = \frac{1}{Q_{ph-ph}} + \frac{1}{Q_{TLS}} + \frac{1}{Q_{scat}} + \frac{1}{Q_{thermo}} + etc\,.$$

Scientific Reports Vol 3, 2132 (2013)

Q_{ph-ph}: *Scattering* of acoustic *phonons* with thermal ones over the crystal *(Landau-Rumer)*

Q_{TLS}: *TLS absorption* ascribed to *impurity ions* in the lattice (Al^{3+},Na^{+},Li^{+},etc)

Q_{scat}: *Scattering* of acoustic phonons on *surfaces* or on *impurities* in the bulk *(Rayleigh scattering)*

Q_{thermo}: *Thermal* currents induced by *lattice compression*

Q-factor vs Temperature

Theory world

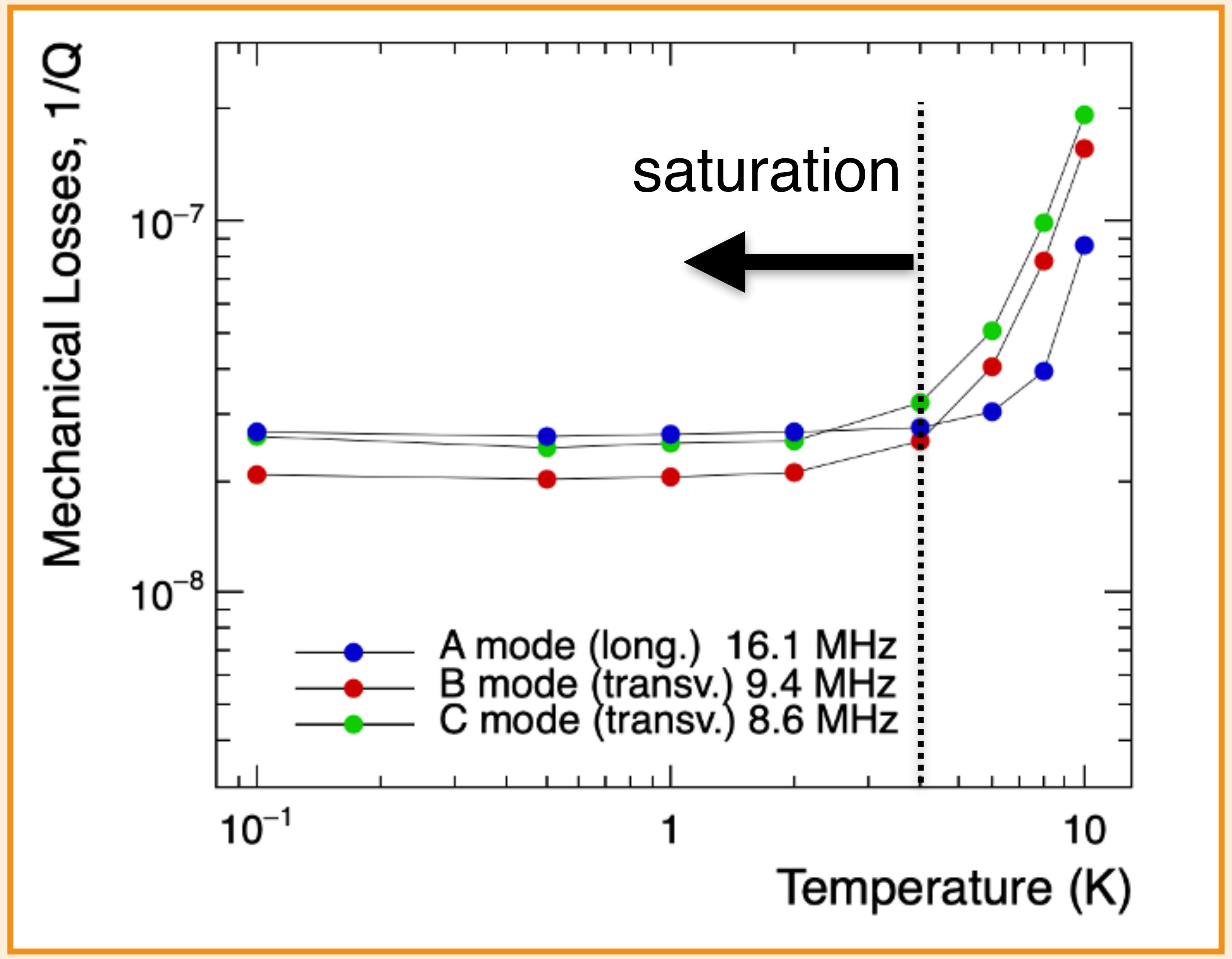
$$\frac{1}{Q_{total}} = \frac{1}{Q_{ph-ph}} + \frac{1}{Q_{TLS}} + \frac{1}{Q_{scat}} + \frac{1}{Q_{thermo}} + etc\,.$$

- *Phonon-phonon* ~ $T^{-6.5}$ → negligible at small T
- *TLS* ~ $T^{-0.3}$ → requires small impurities but can be minimised at small T
- *Rayleigh scattering* depends on impurities and surface properties. *T independent* and dominates at *low T*
- *Thermal effects* generated by longitudinal vibrations can estimated by solving thermal propagation. *Contribution difficult to estimate at cryogenic T*

Scientific Reports Vol 3, 2132 (2013)

Experimental world

- Tested in Milano-Bicocca down to *10 mK*
- Results shown for the 5th overtone → similar for other (n)



- *Gain ~10-20* w.r.t T = 300 K *saturating* below 3-5 K
- *Reasons:* most-likely mechanical losses due to electrodes, followed by impurities, etc.

Summary and future plans

Today's summary

- BAW resonators are promising devices that can be used for high-frequency GWs searches
- Group of researcher at UWA are pioneers in this technology and its application
- A second detection site + group of researchers is setting up at Milano Bicocca

Future activities at Milano-Bicocca

Easier

- *Improvements in measurement of the unloaded Q-factor*
  - Using another VNA that measures the full scattering-matrix to fully characterise the transmission line
  - Important at low temperatures where impedance mismatch (line vs BAW) is larger
- *Purchase of SQUIDs and off-detector readout boards (digitiser, FPGAs, etc.)*
  - Tests of the full readout chain, evaluation of electronic noise, develop signal processing, etc
- *Increase number of channels with different physical dimensions*

Harder

- *Design dedicated BAWs simulating Q-factor vs geometry, crystal type, electrodes deposition, heat transport, …*