BAUSCIA

An antenna for high frequency gravitational waves

Matteo Borghesi

Contributors (Milano-Bicocca):
G. Albani, M.Borghesi, M. Benaglia, G. Conenna, T. Tabarelli de Fatis, F. De Guio,
M. Faverzani, E. Ferri, A. Ghezzi, R. Gerosa, B. Giacomazzo, A. Giachero,
M. Malberti, A. Nucciotti, G. Pessina.

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Istituto Nazionale di Fisica Nucleare

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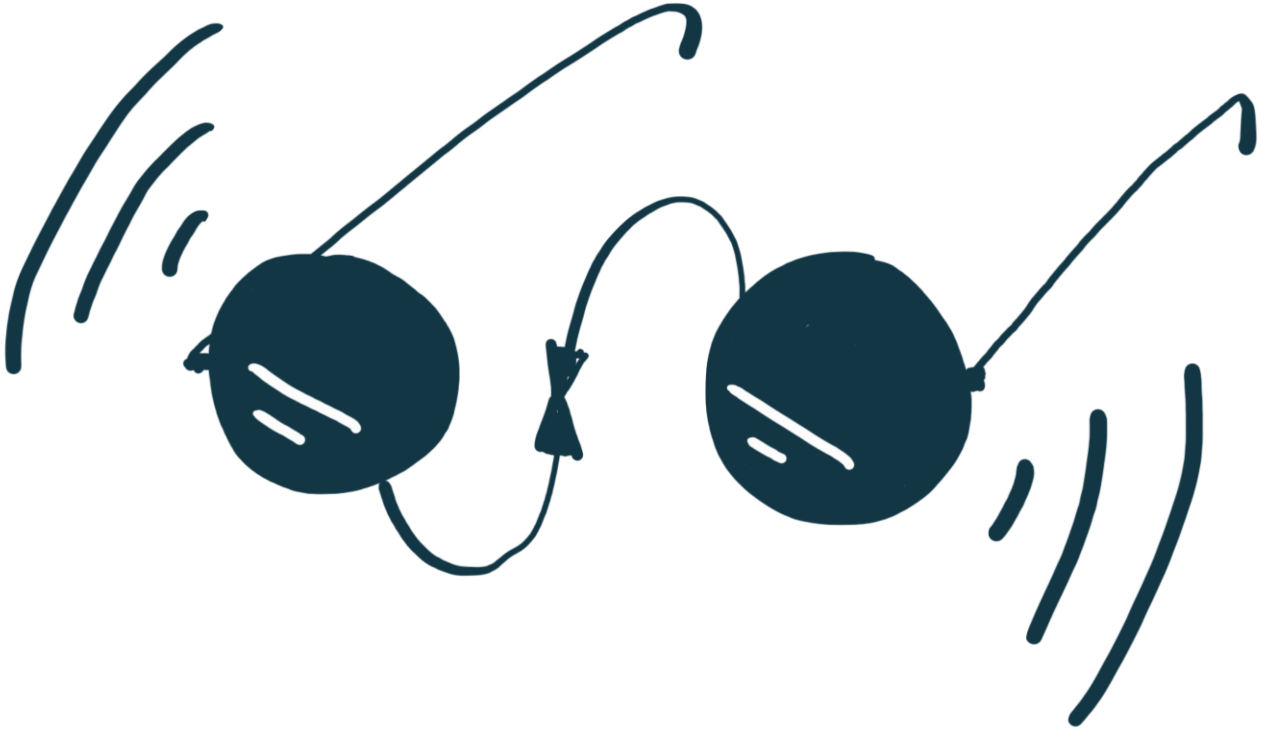
Centro Bicocca di Cosmologia Quantitativa

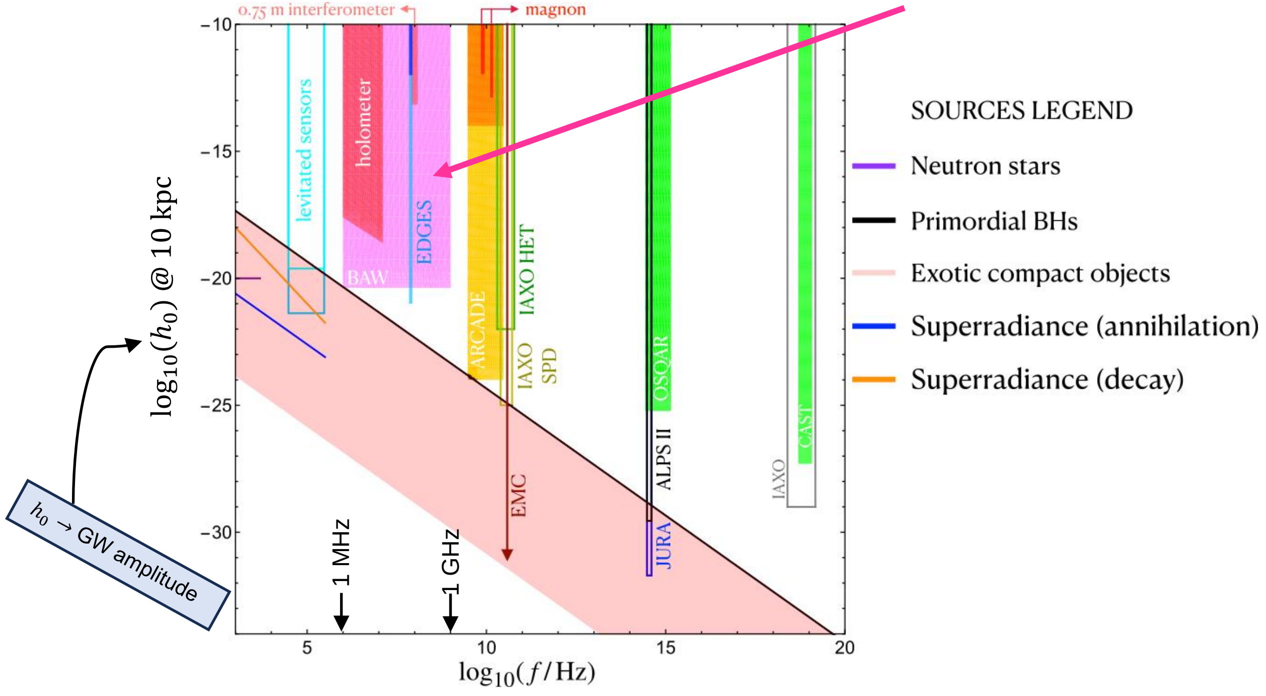


Why high frequency gravitational waves?

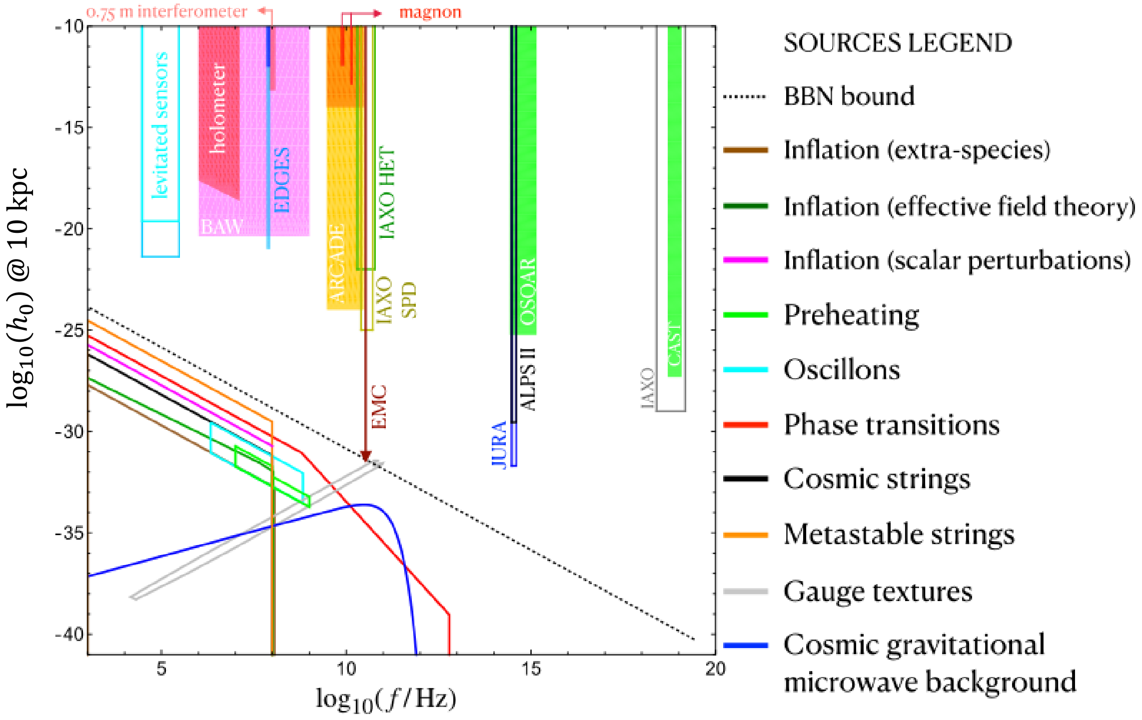
- There are **many potential GW sources** at frequency higher than those covered by interferometers.

Aggarwal, N., Aguiar, O.D., Bauswein, A. *et al.* Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies. *Living Rev Relativ* **24**, 4 (2021).
https://doi.org/10.1007/s41114-021-00032-5

Example of coherent HF-GW sources



Example of stochastic HF-GW sources

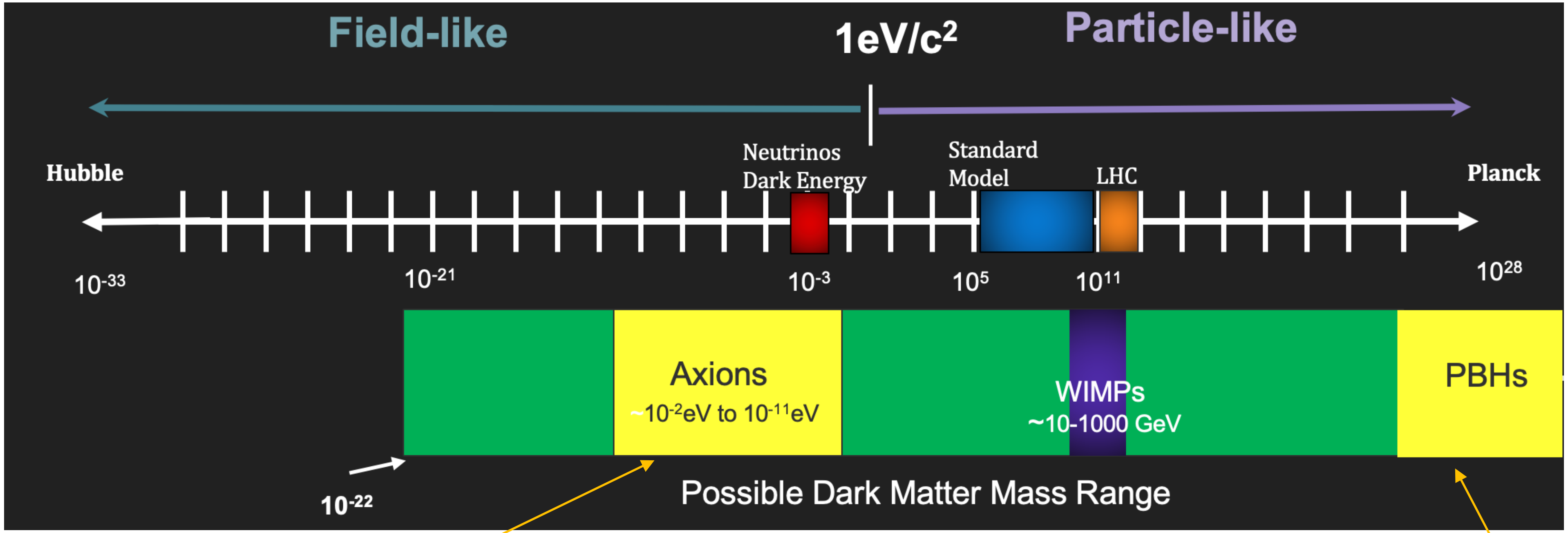


- The **identity of dark matter** is still unknown. It may hide in HF-GW?

A glimpse of HF-GW DM sources (I)

- With **HF-GW** we can **probe very different mass range of DM**!

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



Black hole superradiance

- ➢ QCD **axion** annihilations to gravitons in cloud around black holes.
- ➢ Requires detection sensitivity around 10-100 kHz

  Coverable with customized BAW

Light **Primordial Black Holes** (PBH)

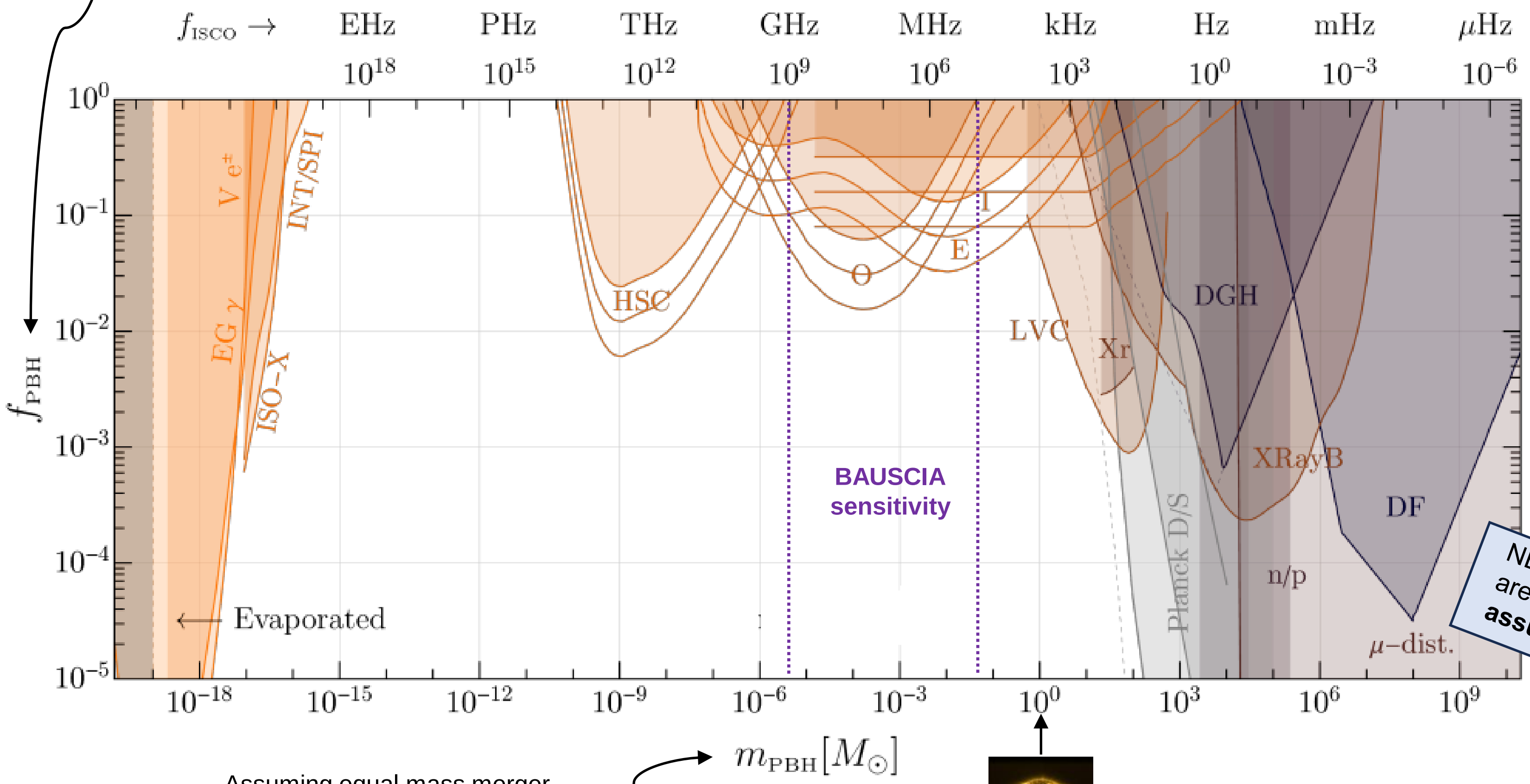
- ➢ Primordial black holes (**PBH**) can contribute up to about 10% of the dark matter at planetary masses (see next slide).

  GW emission coverable by existing BAW

A glimpse of HF-GW DM sources (II)

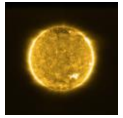
Fraction of dark matter composed of PBH

Most stringent constraints on the PBH abundance

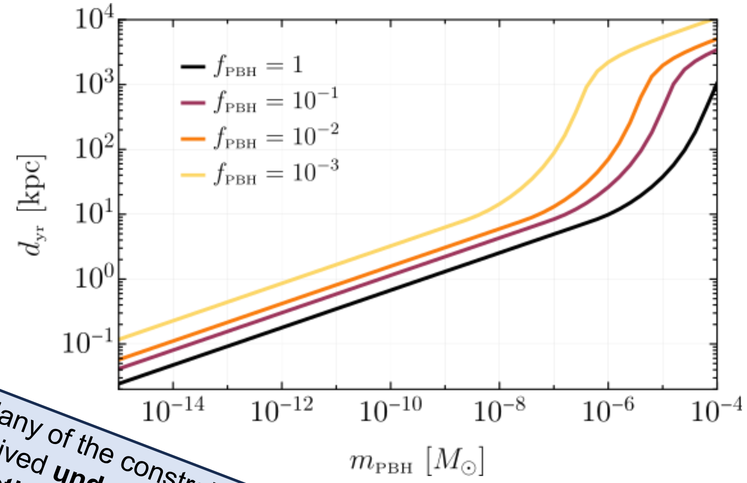


BAUSCIA sensitivity

Assuming equal mass merger and narrow mass distribution



Size of the region containing *O*(1) merger event per year



NB: Many of the constraints are derived **under specific assumptions**

Hunt for light primordial black hole dark matter with ultrahigh-frequency gravitational waves
Gabriele Franciolini, Anshuman Maharana, and Francesco Muia
Phys. Rev. D **106**, 103520 – Published 17 November 2022

Few things to keep in mind

Amplitudes of the “plus” and “cross” polarization of the wave

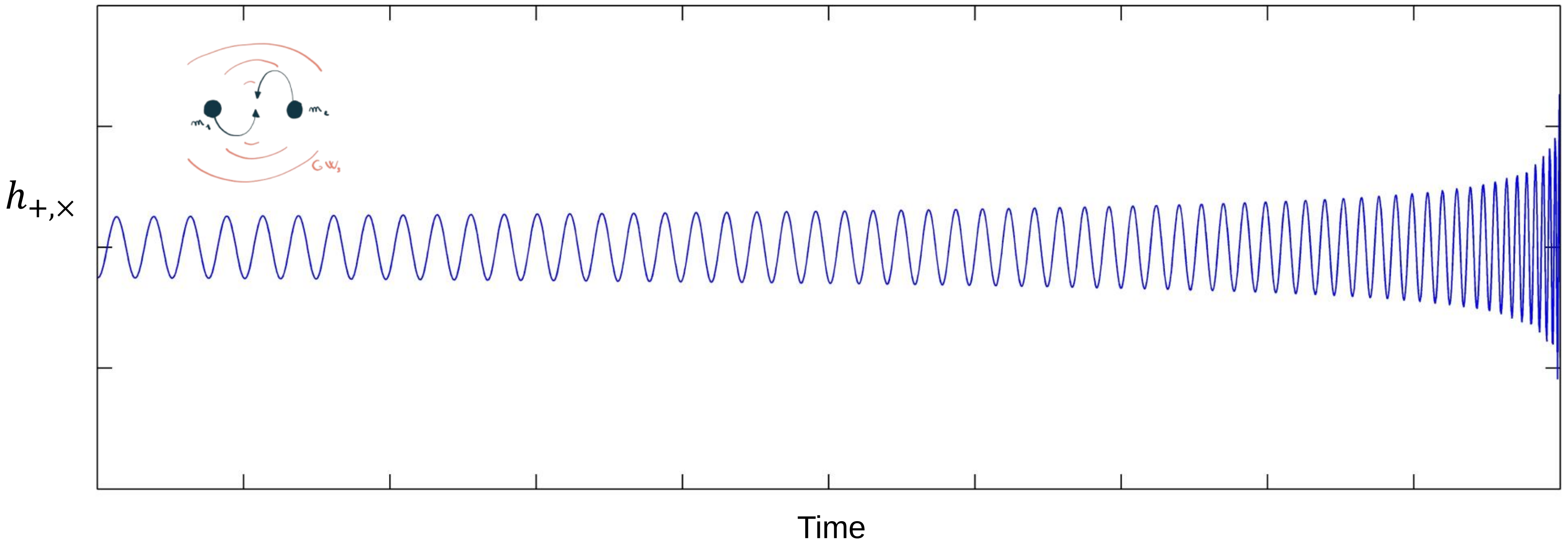
$$h_{+,\times}(t) \propto \frac{1}{\boldsymbol{d_L}}\left(\frac{G\boldsymbol{M_c}}{c^2}\right)^{\frac{5}{3}}\left(\frac{\pi \boldsymbol{f_{gw}}}{c}\right)^{\frac{2}{3}}\cos(2\pi \boldsymbol{f_{gw}} t+\phi)$$

Distance from the observer

$$M_c = M_c(m_1, m_2)$$

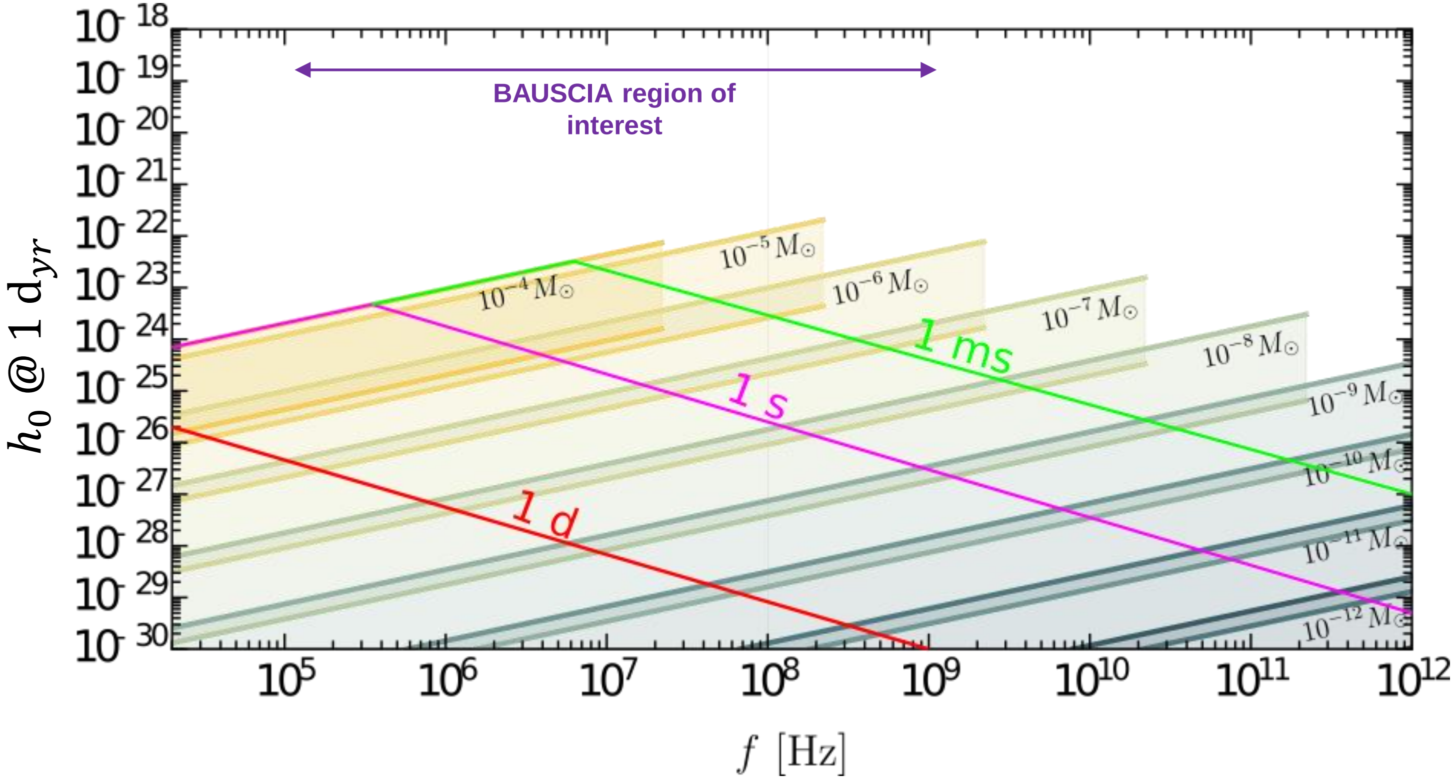
$$f_{gw}(t) \propto \left(\frac{1}{t_{coal}-t}\right)^{3/8}\left(\frac{GM_c}{c^3}\right)^{-5/8}$$

Time evolution of the GW amplitude (inspiral phase of a binary system)

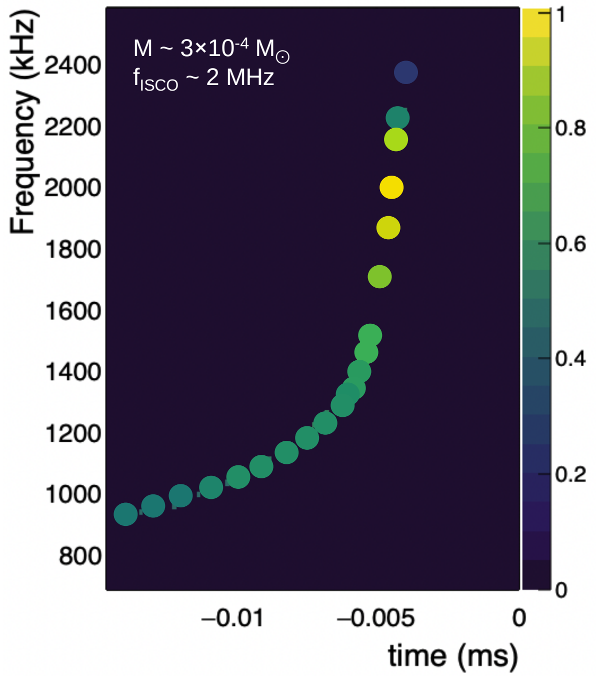


A glimpse of HF-GW DM sources (III)

PBH merger, expected signal



Example of a merger event near f_{ISCO} frequency



A glimpse of HF-GW DM sources (III)

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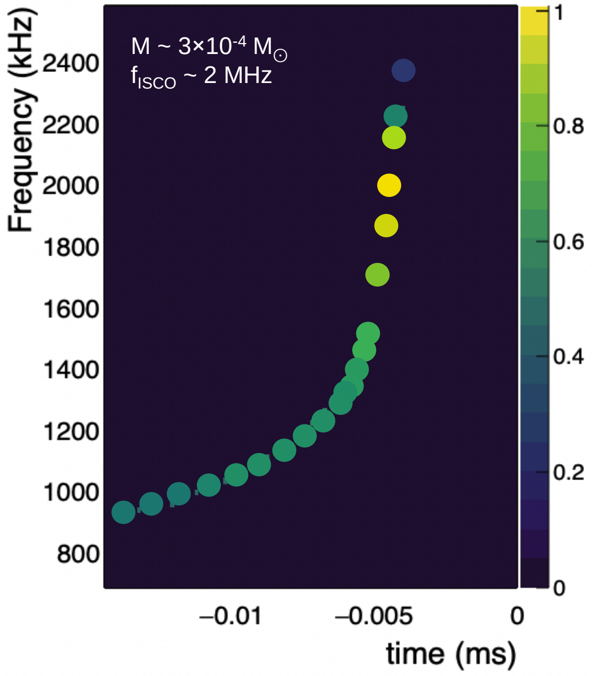
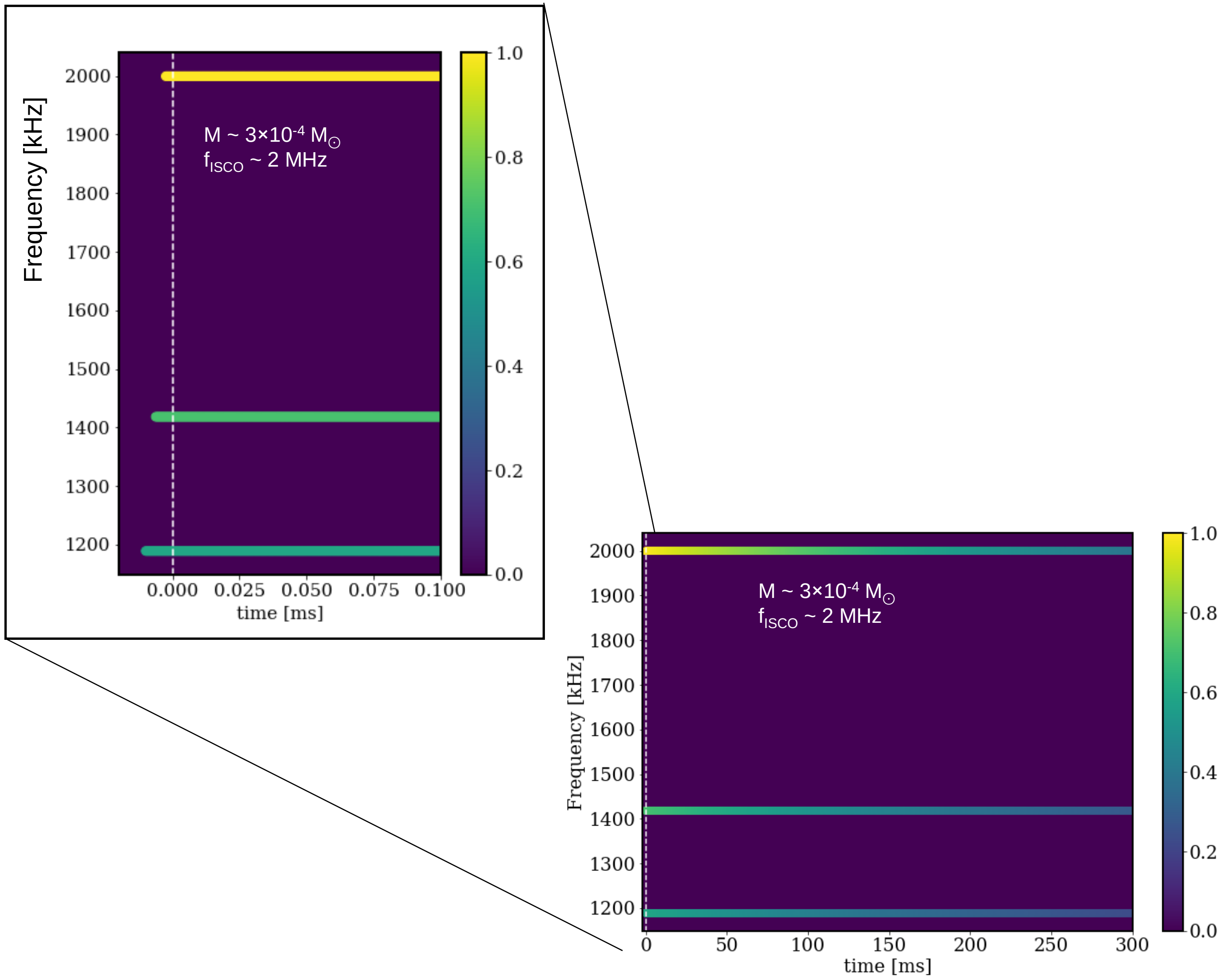
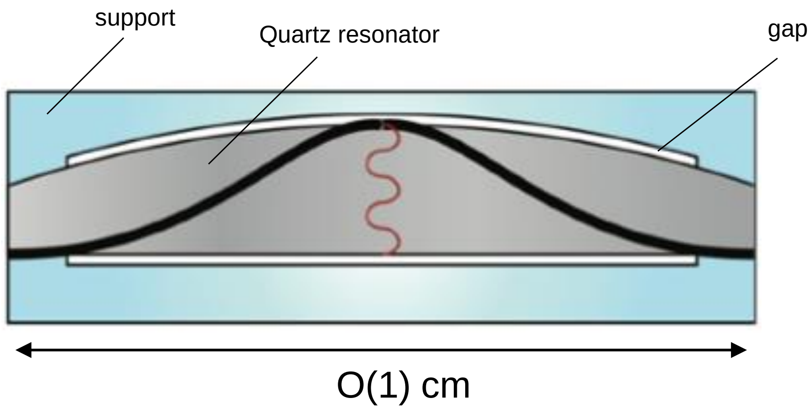


1 Resonant mass BAUSCIA-like detector



Bulk Acoustic Wave (BAW) Device

- **B**ulk **A**coustic **W**ave **S**ensors for a **H**igh Frequency **A**ntenna (BAUSCIA, in Milan's dialect)
- GW tidal forces stretches and squeeze the mass: **resonance mass detector**
- Length variation only **detectable at the resonant frequency** of the vibration mode(s)

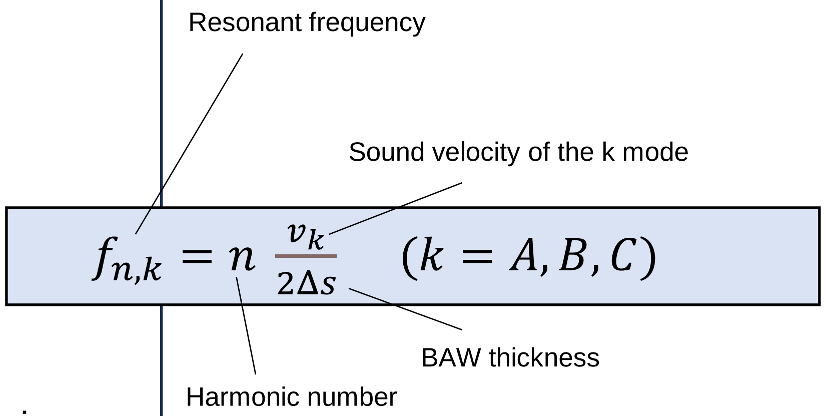


- **MAGE**: existing experiment. In 2021 it detected two signals of uncertain origin

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

PRO:

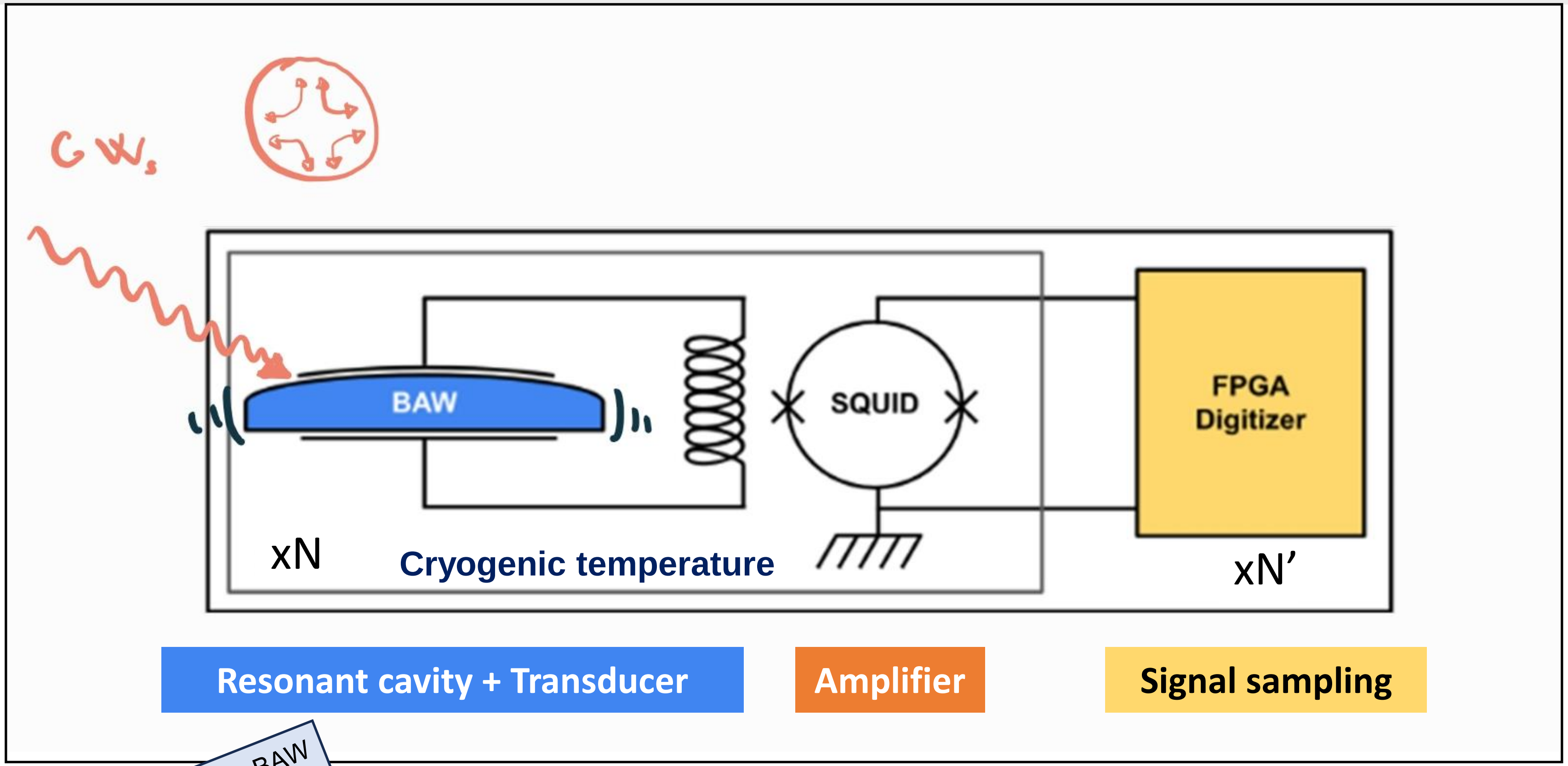
- ➢ High narrow band sensitivity through **high quality factor (Q)**
- ➢ Internal transducer: **piezoelectric**
  - Only odd overtones audible
- ➢ **Wide frequency range** of high Q **modes**
  - Three family types with different velocities
  - 2 transverse (B,C) and 1 longitudinal (A)
  - multiple overtones and vibration modes
- ➢ **Scalable** technology, established > 70 years for precision clock applications



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

BAW Detection concept

$$h(t) \longrightarrow \overset{\text{displacement}}{u(t)+n} \longrightarrow \overset{\text{current}}{i(t)+n} \longrightarrow \overset{\text{voltage}}{A(i(t)+n)+n_A} \longrightarrow \overset{\text{data}}{A(i(\tau)+n)+n_A}$$



Noise is dominated by BAW thermal noise.

BAUSCIA idea

“**Broadband**” **sensitivity** provided by:

- Multiple **overtones** sensing per BAW
- **Array** of many **BAWs** tuned to different frequency

  Requires specific R&D on BAWs

BAW HF-GW sensitivity

- The time component of the displacement (ξ_λ) follow the forced harmonic oscillator equation

$$\ddot{\xi}_\lambda + \gamma_\lambda \dot{\xi}_\lambda + \omega_\lambda^2 \xi_\lambda = -c^2 \times \left(R_{i0j0}\right) \times \frac{\Delta s}{2} \times \Xi_\lambda$$

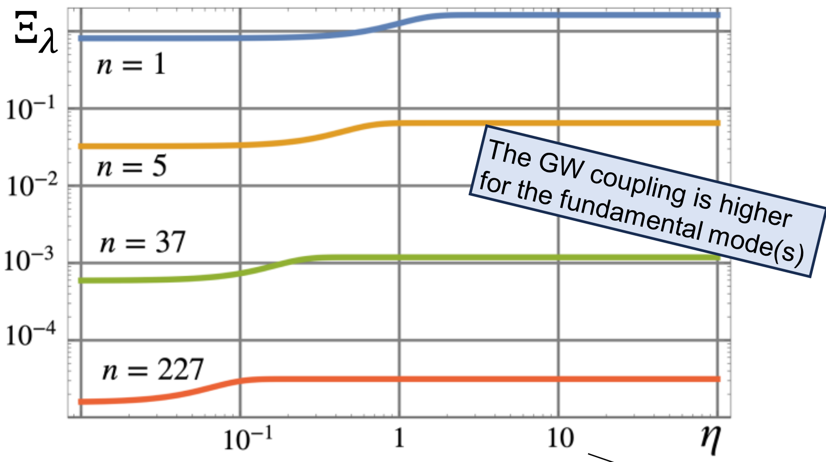
displacement

Mode numbers ($\lambda = X, n, m, p$)

GW

BAW thickness

GW-cavity coupling



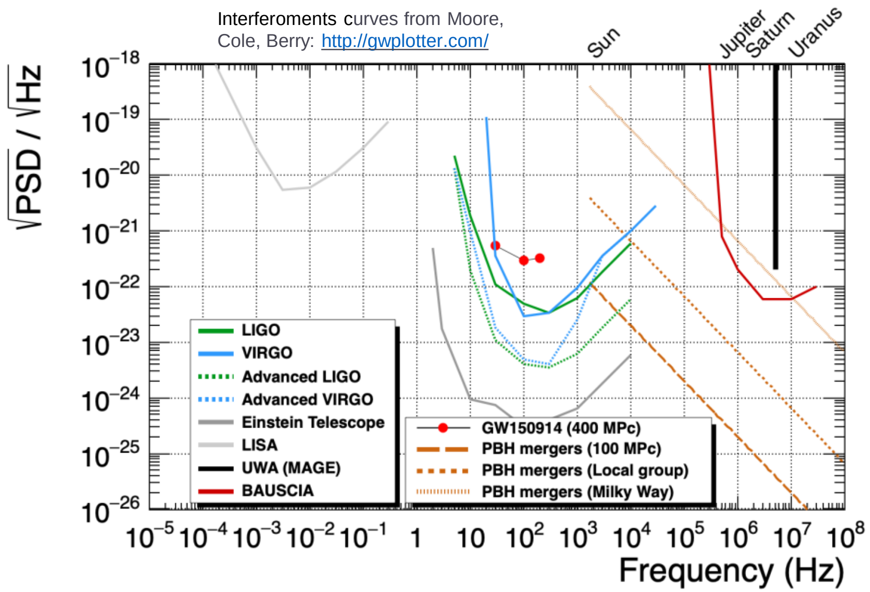
The GW coupling is higher for the fundamental mode(s)

Typical value for a BAW sensor

- Expected sensitivity (PRELIMINARY) scaling from the MAGE antenna to an array of multiple BAW cavities of comparable quality.

$$S_h^+(\omega = \omega_\lambda) = \sqrt{\frac{4\, k_b T_\lambda \omega_\lambda}{Q_\lambda M_\lambda}}\left(\frac{1}{\omega_\lambda^2 (\Delta s/2)\Xi_\lambda}\right)$$

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

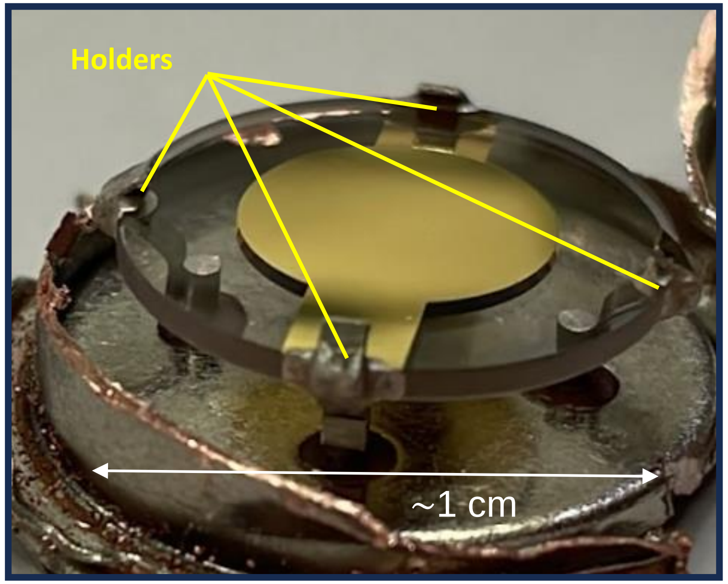


- ➢ Complementary to large interferometers
- ➢ Supplementary to MAGE

BAW samples @ MiB

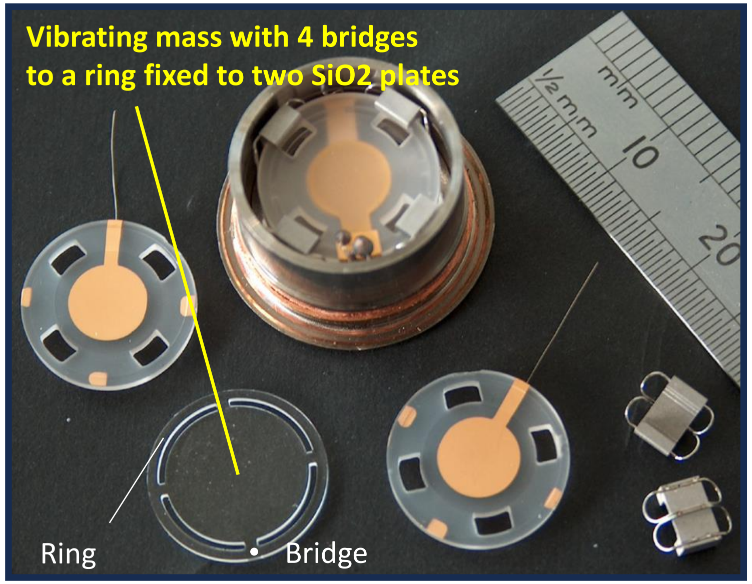
Off-the-shelf quartz cavities (Rakon XO)

- $\mathrm{SiO_2}$ crystal with 4 rigid mounts
- Electrodes deposited on BAW (**suboptimal**)
- Optimized at room temperature for the 3rd Overtone of the C-mode (~5 MHz)
- Low Q at n = 1



MAGE-like BAW

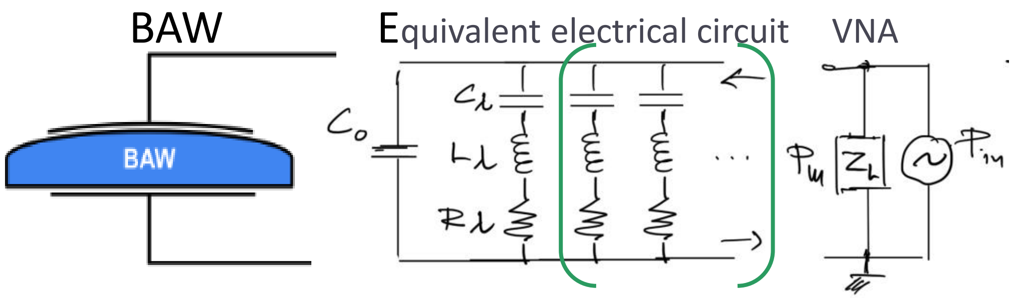
- Piano convex $\mathrm{SiO_2}$crystal
- Electrodes deposited on separated support plates (**low loss design**)



Both exhibit **Q factor > 10^6** at cryogenic temperature (4K)

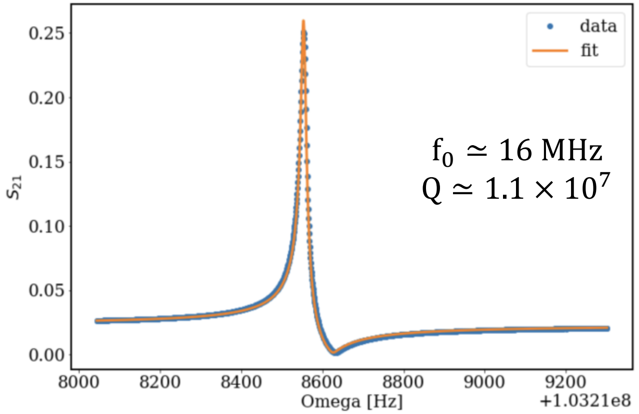
Current activities @ MiB

- Study of low temperature BAW behaviour



only one mode at resonance

Example of a BAW Resonance fit



Laboratorio di Microonde Milano-Bicocca

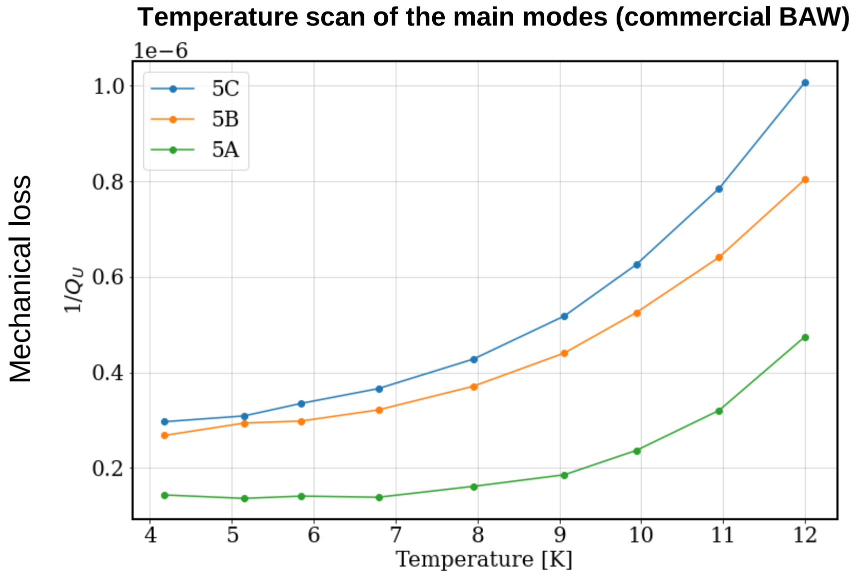
BAUSCIA will have its own cryostat in the new cryogenic lab

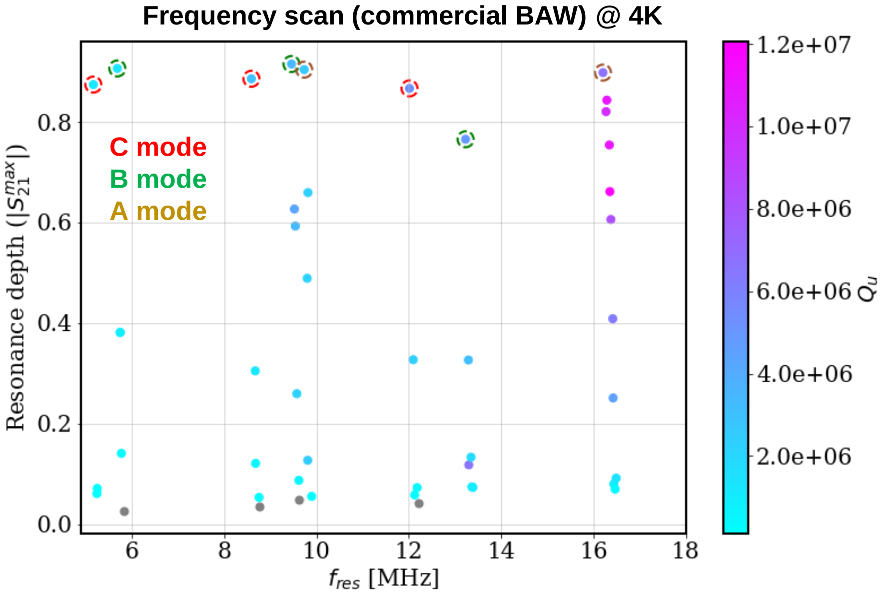
BAW on cold plate of a dilution refrigerator

Laboratorio Criogenia INFN Milano-Bicocca

Current activities @ MiB

- Study of low temperature BAW behaviour





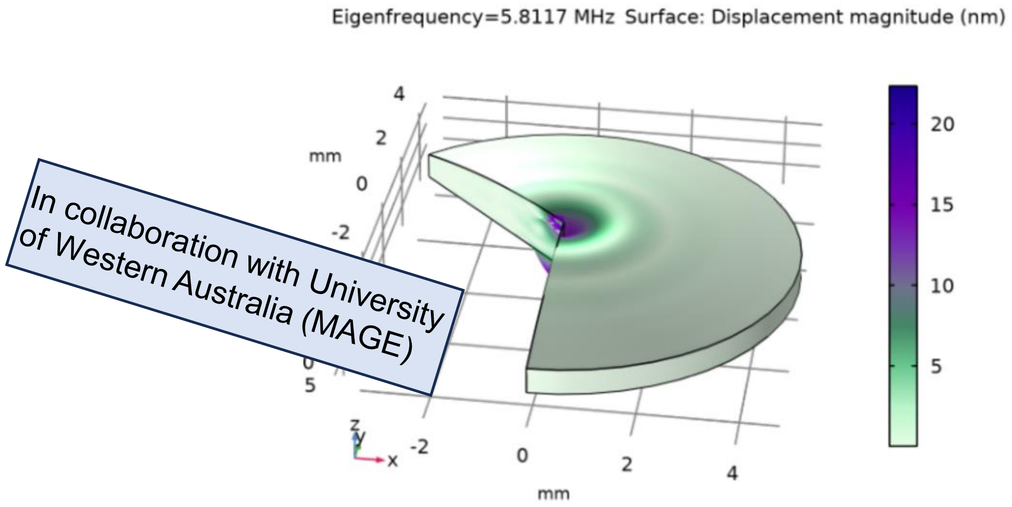
- **Mechanical loss comparable to device in use at MAGE**

- Ready to **setup a GW detector** to supplement MAGE measurement
  - ➢ Readout SQUIDs expected by late spring 2024
  - ➢ Expected sensitivity sufficient to compare measurements

NEXT steps: BAWs optimization

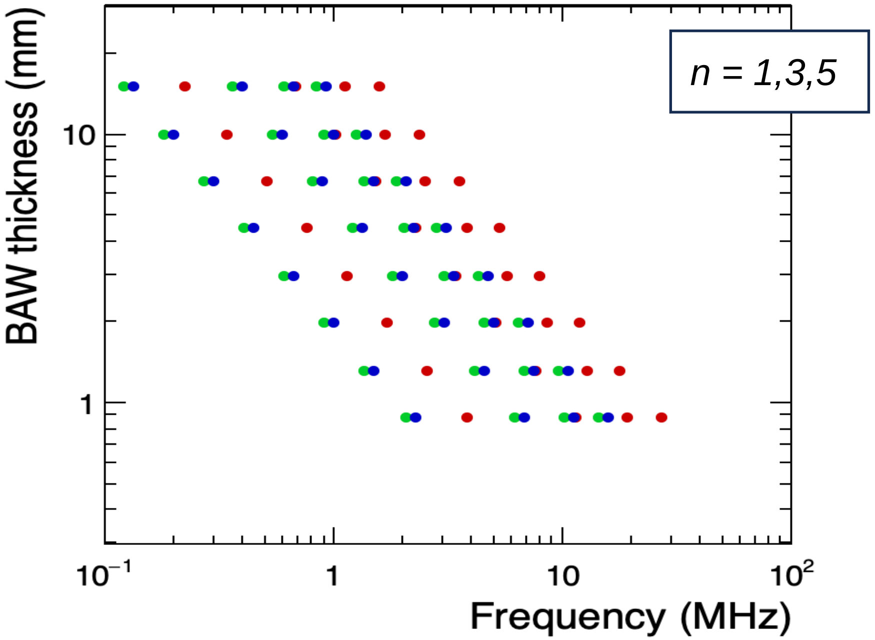
- **BAW** with **customized** shape (curvature) and thickness
  - Design to minimize mechanical losses for n=1

Comsol simulation of a BAW



In collaboration with University of Western Australia (MAGE)

Frequency map of an array of eight BAWs



- **Material** type and quality
  - $\mathrm{SiO_2}, \mathrm{LiNbO_3}$ $(*)$, etc. in discussion with crystal manufactures

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

Summary

- **High Frequency Gravitational Waves** can provide sensitivity to **dark matter searches** complementary to other research lines

- **Broad range sensitivity** requires many BAWs of different thickness
  - Sensitivity scales as $\sim 1/n$ (n = overtone)
  - Optimal sensitivity as n=1

- (Easy) We are setting up a **HF-GW detection site at Milano-Bicocca** with off-the-shelf BAWs
  - Expected sensitivity comparable to MAGE

Further details:
- "Bulk Acoustic Wave Devices", talk at the Ultrahigh Frequency Gravitational Waves workshop: where to next?

- (Hard) We will design (and measure) **custom BAWs cavities** optimized for GW detection.

BACKUP

- GWs act on resonant mass (**BAW**) as a driving force, resulting in a **driven harmonic oscillator**.

Displacement

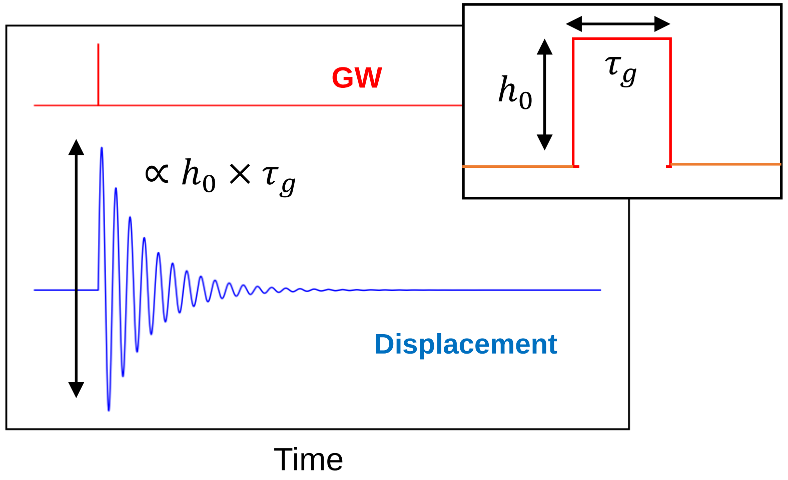
The effect of GW can me described in terms of a **Newtonian force** (If the linear size of the detector is less than the reduce wavelength of the GW)

$$\ddot{\xi}_n + \gamma_n \dot{\xi}_n + \omega_n^2 \xi_n = C_n \times \frac{2L}{\pi^2} \boldsymbol{\ddot{h}_{yy}^{TT}}$$

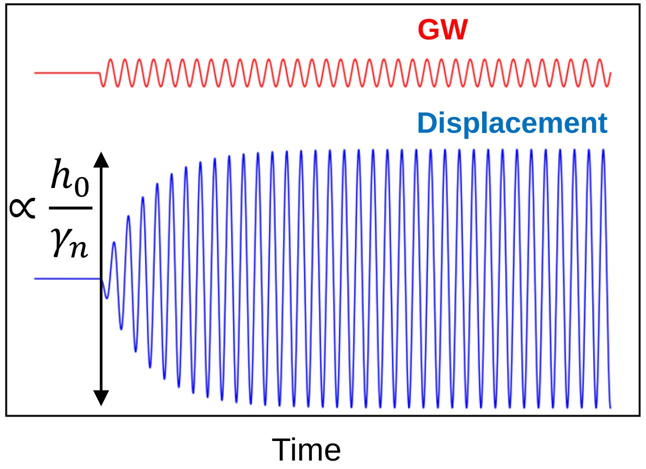
Dissipation factor of the mode *n*

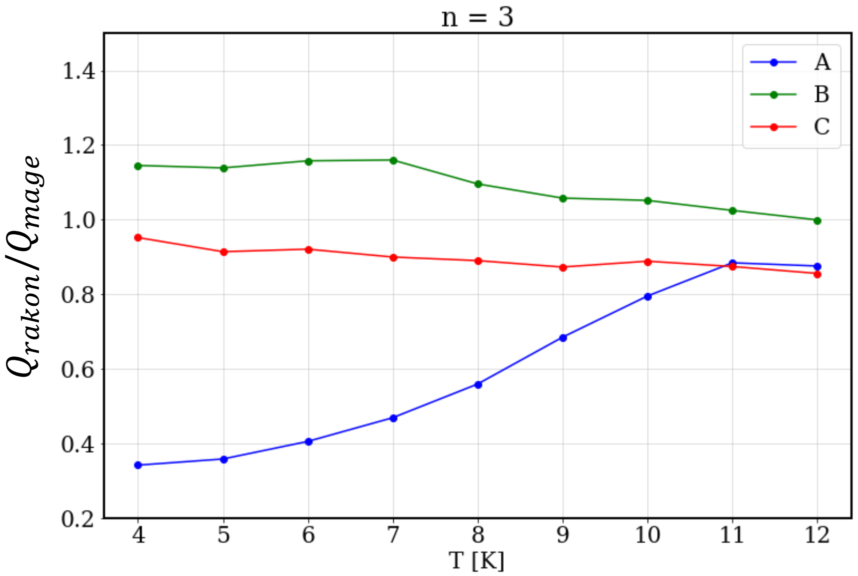
Resonance frequency of the mode *n*

Resonant mass: response to a burst like signal

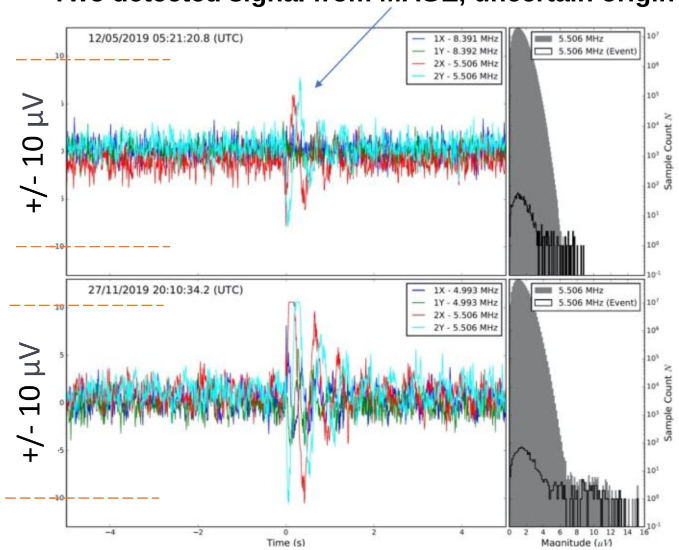


Resonant mass: response to periodic like signal





Two detected signal from MAGE, uncertain origin


+/- 10 µV

+/- 10 µV