Bulk Acoustic Wave devices for HFGW [and axions]

Informal meeting with FLASH

- **Outline**
  - BAUSCIA (funded by MUR under “progetto Dipartimenti di Eccellenza 2023-2027”)
  - A few details on BAWs

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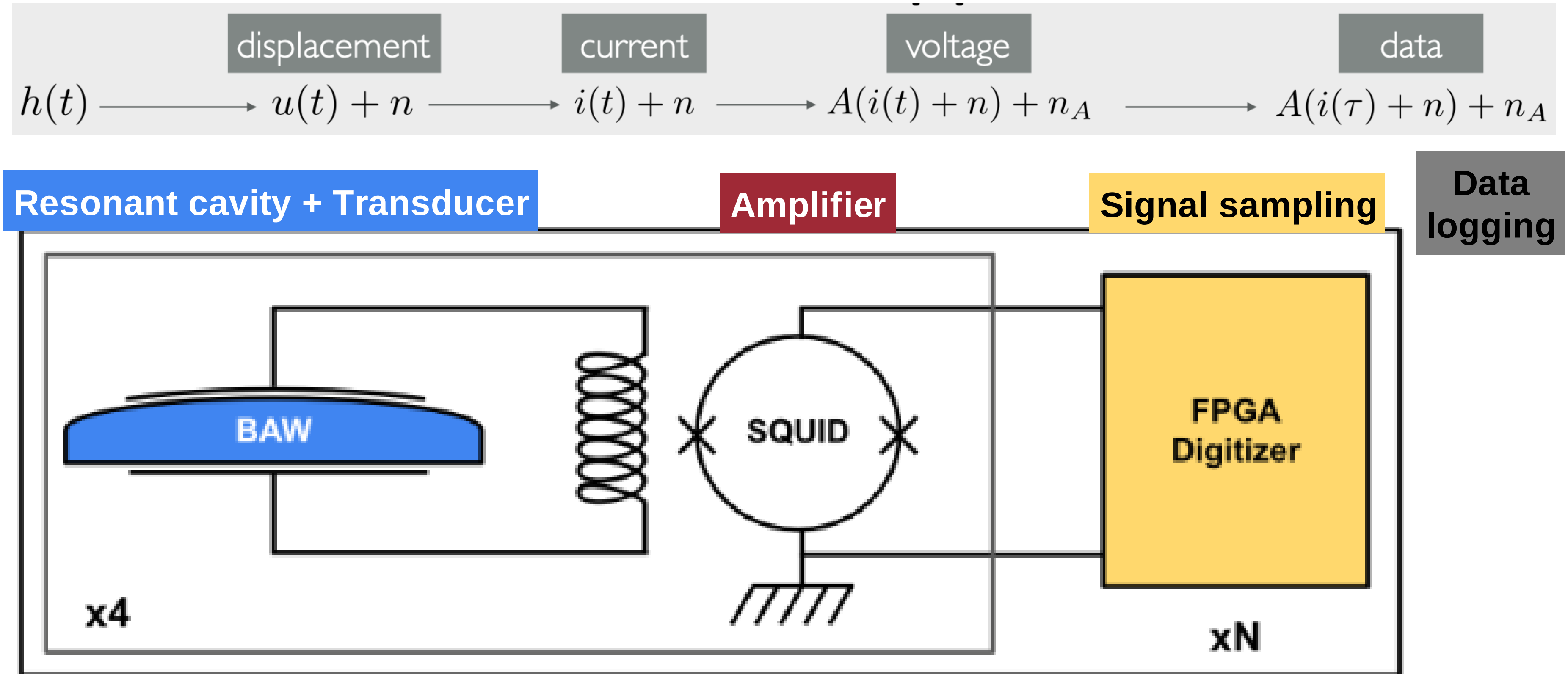
- W. Campbell, M. Goryachev, and M. Tobar (University of Western Australia)

Progetto BAUSCIA

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



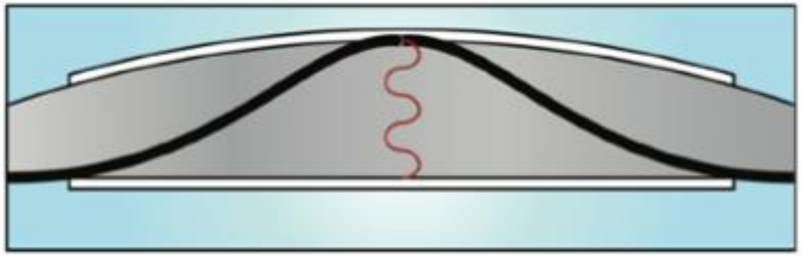
  - Seminal proposal by M. Goryachev and M. Tobar, PRD 90,102005 (2014)
- **Resonant mass detector with sensitivity at multiple frequencies provided by**
  - Multiple overtones sensing per BAW
  - Array of many BAWs tuned to different frequencies → requires specific R&D on BAWs

BAUSCIA: two-stage plan

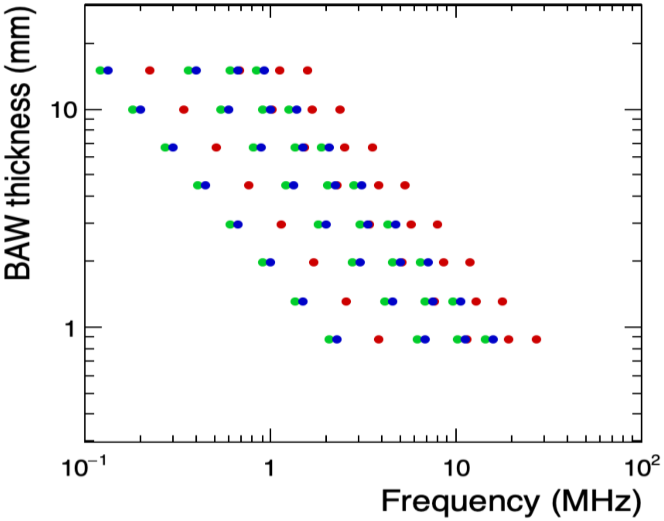
1. **Multimode antenna w/ commercially available BAWs (multi-site detection with MAGE)**
2. **Array of customized BAWs to cover a broad spectrum of frequencies**
   - Multiple overtones from three families of standing waves with different velocities

- **(Primary) target: GW sources including DM candidates and "standard" signals:**
  - PBH binary mergers optimal [Franciolini, Maharana, Muia Phys. Rev. D 106, 103520]
  - Black hole superradiance (QCD axion annihilations to gravitons in cloud around black holes) [A. Arvanitaki et. al PRD 83, 044026 (2011)]
  - QCD phase transition in binary neutron stars post-merger (in coincidence with LVK) at *f ~ 0.6 MHz*
    - Casalderrey-Solana, Mateos, Sanchez-Garitaonandia, arXiv:2210.03171
- **Sinergies with axion / dark photons to explore**
  - E.g., T.Trickle, arXiv:2501.05504 (sensitivity depends in the same BAW parameters)

Plano-convex BAW



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

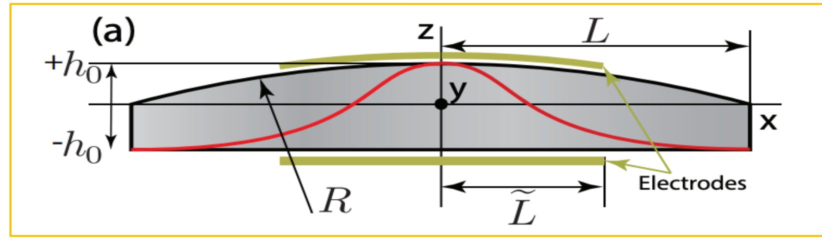


SiO_2 n=1,3,5,7
- A mode
- B mode
- C mode

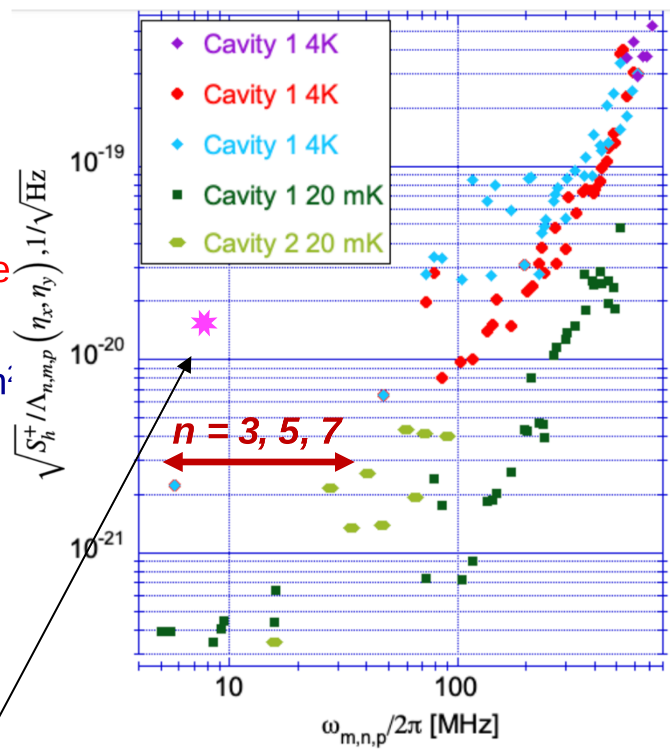
Detection limit and strain sensitivity

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

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



PRD 90, 102005 (2014); Erratum PRD 108, 129901 (2023)



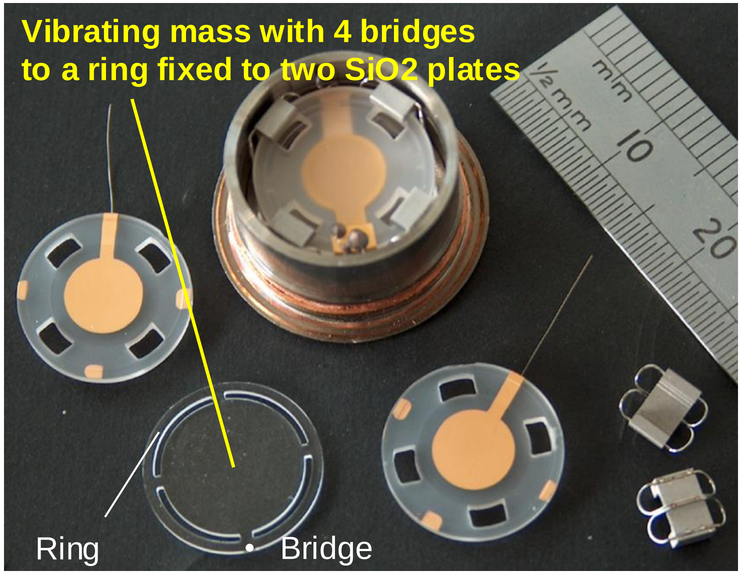
- λ = (X, n,m,p)
  - X = mode,
  - n = overtone number
  - m and p = transverse mode indices
- w(ω): phonon statistic distribution weight (not critical)
- m_λ: effective (vibrating) mass [shown for n,0,0 in the picture
- Q_λ: cavity quality factor
- ξ: dimensionless coupling coefficient to GW: scales with 1/n
  [has also a mild dependence on phonon trapping]

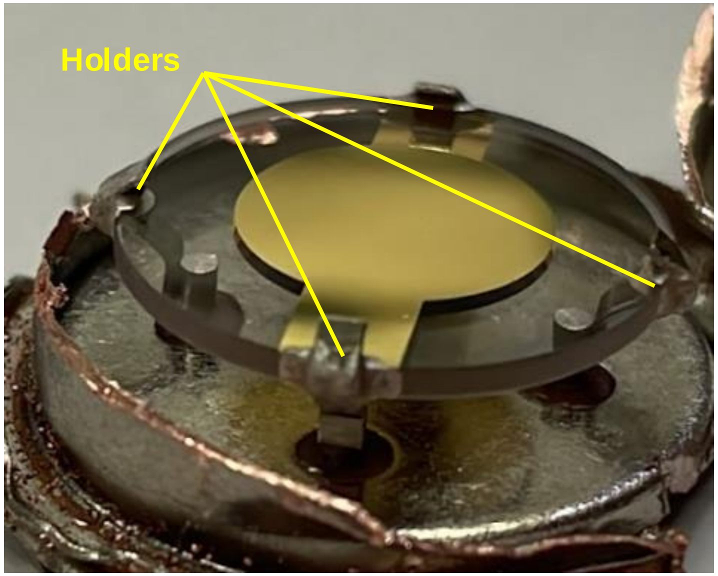
- **Projected single-sided spectral density around $10^{-21}/\sqrt{Hz}$ at T = 20 mK (Q ~ 10^9) for n = 3, 5, 7**
  - Optimal sensitivity limited to ~ 5 – 50 MHz
  - ✳ Current MAGE experiment at 4K
    [W. Campbell et al. ArXiv: 2307.00715]

Existing BAWs

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

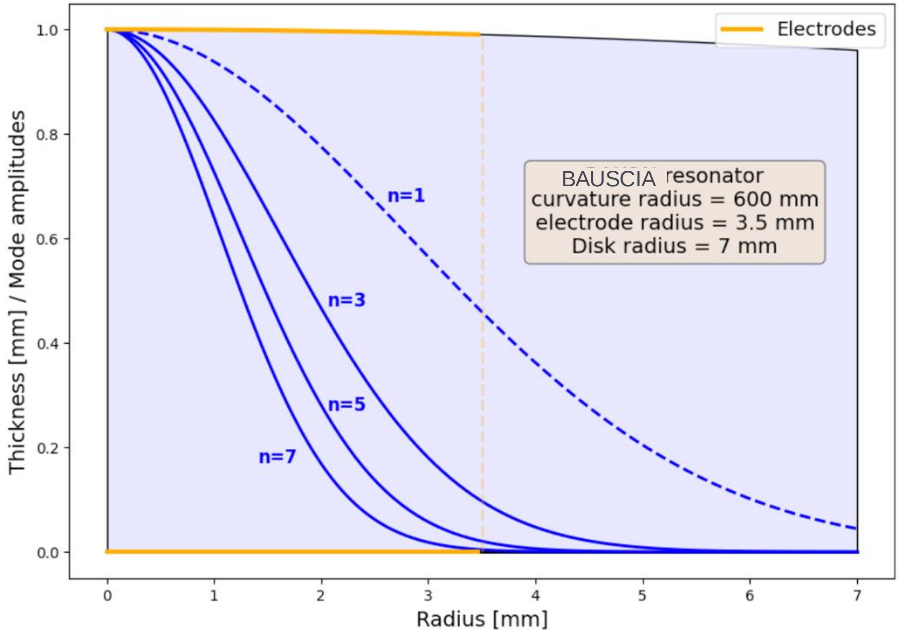
- **BAUSCIA (Milano Bicocca)**
  - <u>Off-the-shelf</u> quartz cavities (Rakon XO)
  - SiO_2 crystal with four rigid mounts: d~1 mm
  - *Electrodes deposited on BAW (suboptimal?)*

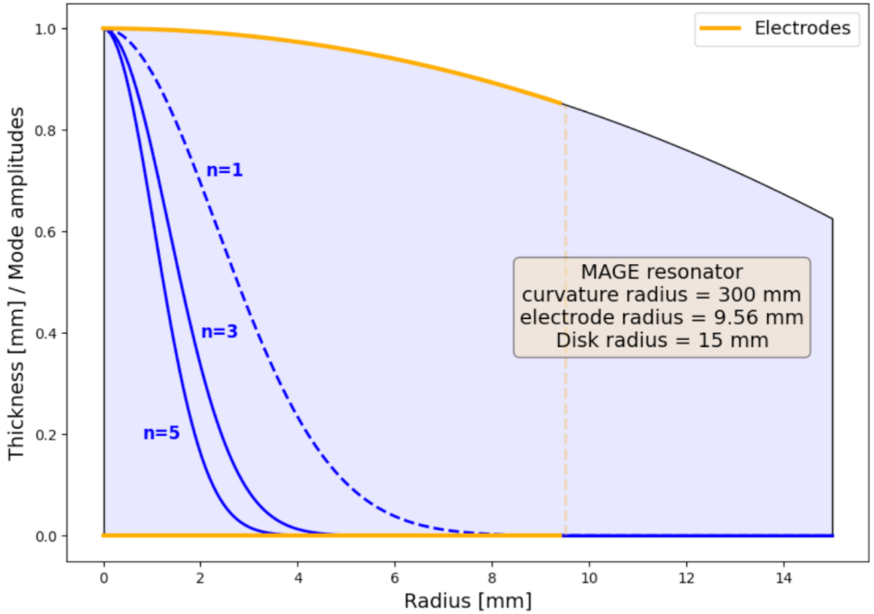




- **Room temperature: Q ~ 10^6**
  - Optimized for the 3rd overtone of the C-mode (slow shear) at ~5 MHz (clock standard)
  - Low Q at n=1 (lwhere the coupling to GW is largest)
- **Cryogenic temperatures: Q > 10^7 (low overtones)**
  - [up to 10^9 at high frequencies but reduced coupling to GW signals]

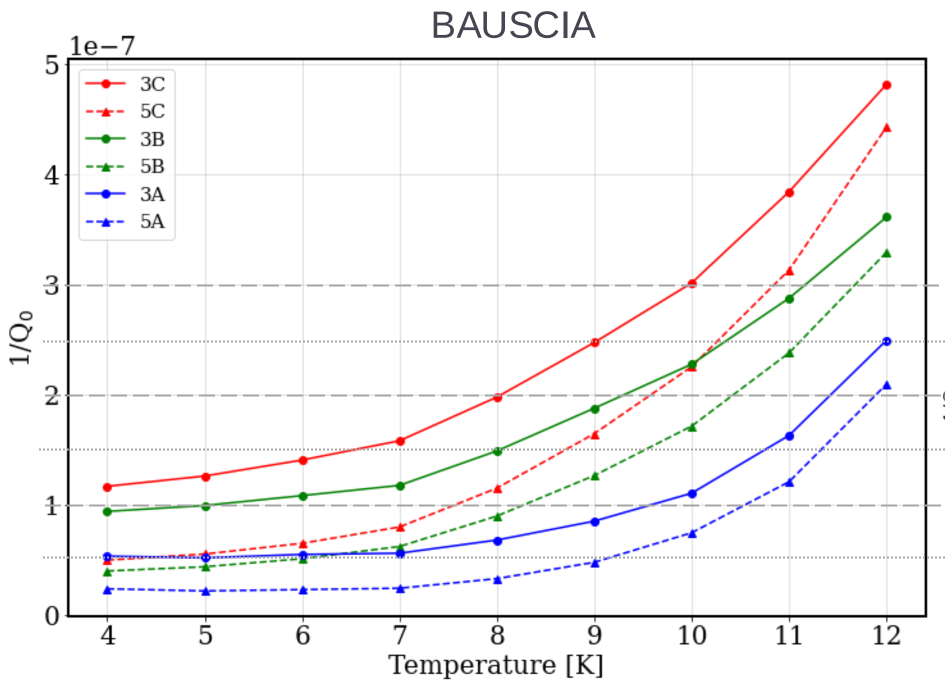
Cavity losses



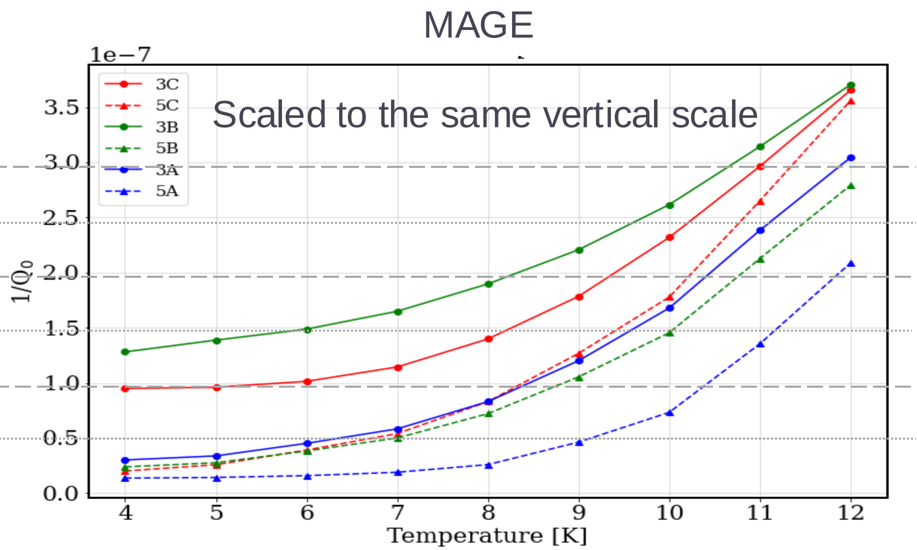


- **Plano-convex shapes minimize mechanical losses through supports**
  - Admits standing waves (phonon modes) with Gaussian profile in the transverse direction [Stevens-Tiersten model and axial symmetry]
  - *Same effective (vibrating) mass in BAUSCIA and MAGE sensors, despite different size*
    - *Resonances at n = 1 are not observed (Q factor too low) in both cavities*
  - *Same Q factor at room temperature (no need to over-confine the vibration)*

Low T behaviour



See for T dependencies:
- M. Goryachev *et al*, Sci. Rep. Vol.3, 2132 (2013)
- M. Goryaachev *et al*, PRL, III, 085502 (2013)



- **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
  - Indication of further (mild) improvement at T<4 K for MAGE not observed for BAUSCIA devices
    - Tentatively ascribed to manufacturing differences (electrode deposition on quartz)

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Status

- **Stage 1:**
  - **Devices are good enough to setup an antenna with sensitivity comparable to MAGE**
  - Two devices available and ready to go (working on SQUIDs and DAQ, awaiting for dedicated criostat)
    - One device sacrified to measure BAW parameters (undisclosed by the vendor)

- **Stage 2:**
  - Optimization of BAWs and R&D in progress
    - Inquired several manufatcurers of oscillators and bare crystals with limited success
      - BAWs are becoming an obsolete technology for clock and telecommunications
      - Vendors requires huge productions to become interested

  - Procuring blanks of SiO_2 crystals (24 blanks in production with thickness between 1 mm and 30 mm)
    - Require post-processing and optimization of the setup (though copying the Rakon setup might be OK)
      - Create plano-convex geometry providing confinement
      - Electrode depostion / external pickup
      - Support stiffness

  - Investigating alternatives cuts of the crystals (cost impact and size impact);
    - SC cut (φ=35°, θ=21°54′ +/- 0.1’)
      - high stablity of the frequency vs temp., tight tolerances, complex processing, limited crystal size
    - AT cut (φ=35°)
      - Lower stability ves temp. (not a tight requirement for us), relaxed tolerances
  - Investigating alternative crystals ($LiNbO_3$) and geometries (“mesa”) to achieve confinement