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From signal to noise athermal phonon mitigation in quantum devices

Xinran Li
Physics department, Lawrence Berkeley Laboratory

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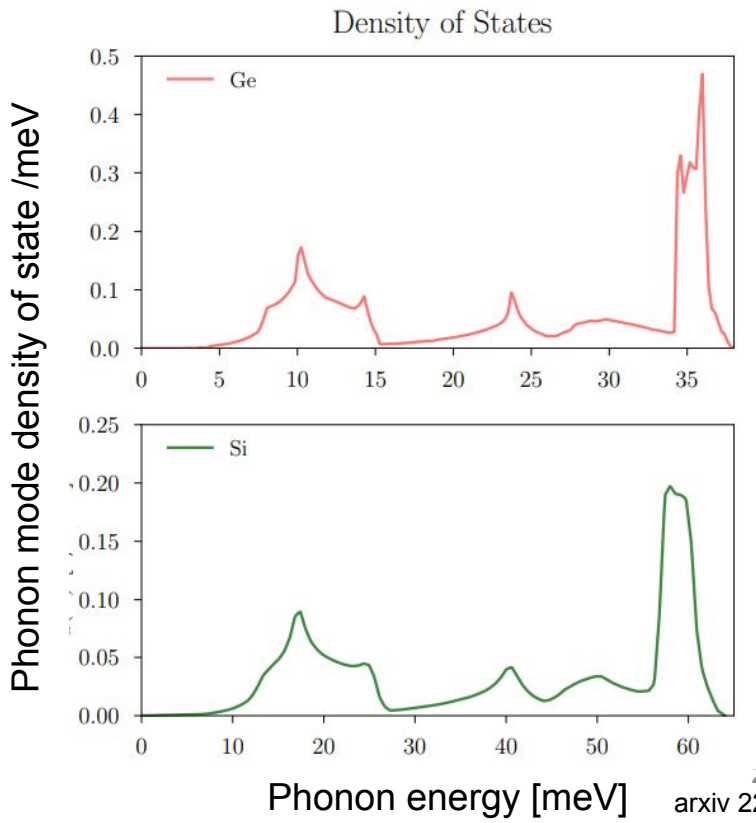
Low Radioactivity Techniques 2022, Rapid City

Athermal phonon as signal in dark matter search

Athermal phonon and its propagation

- Phonons are collective movements of atoms in solid state substrates.
- **Energy impulse from radiation and dark matter particles creates high energy phonons well above the thermal energy level → Athermal phonons**
- O(10)meV
- Detector with single phonon sensitivity targets 0.1~1000 MeV dark matter.



arxiv 2205.02250

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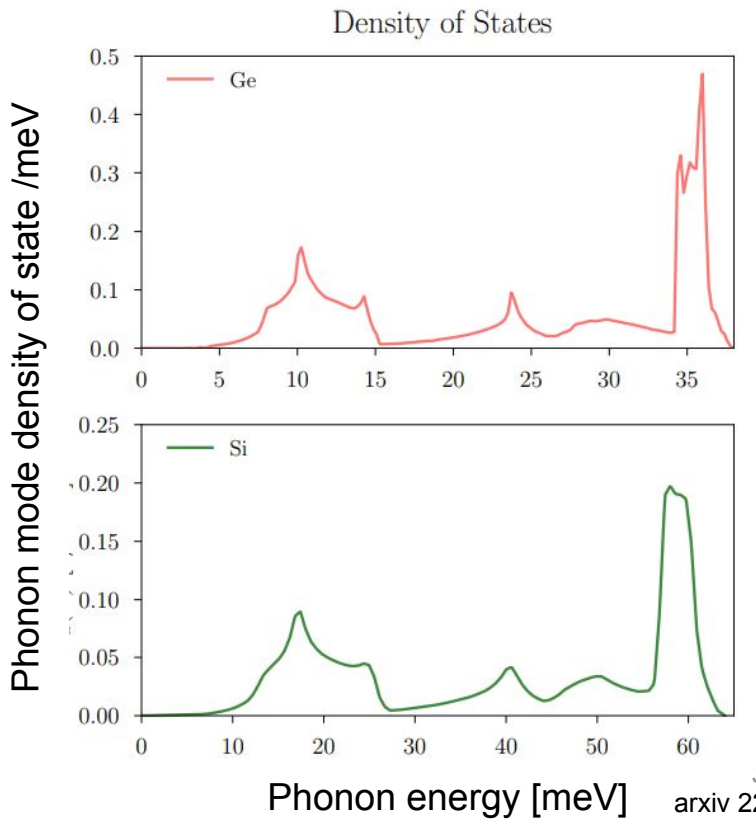
- **Energy impulse from radiation and dark matter particles creates high energy phonons well above the thermal energy level → Athermal phonons**
- O(10)meV
- Detector with single phonon sensitivity targets 0.1~1000 MeV dark matter.
- 1 muon will deposit O(100) keV energy over ~1mm silicon. 10^7 athermal phonons from one muon event!
- 1 muon /min/cm^2
- Underground labs + Low radioactivity materials



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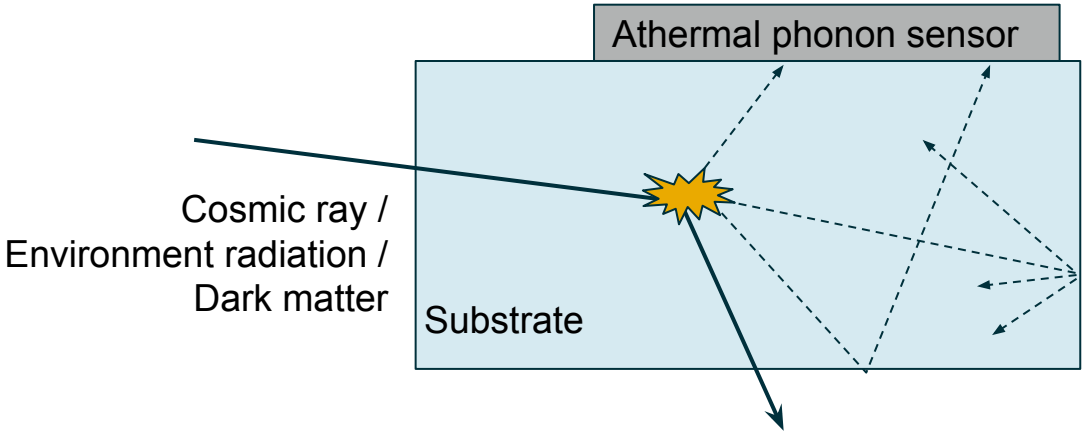
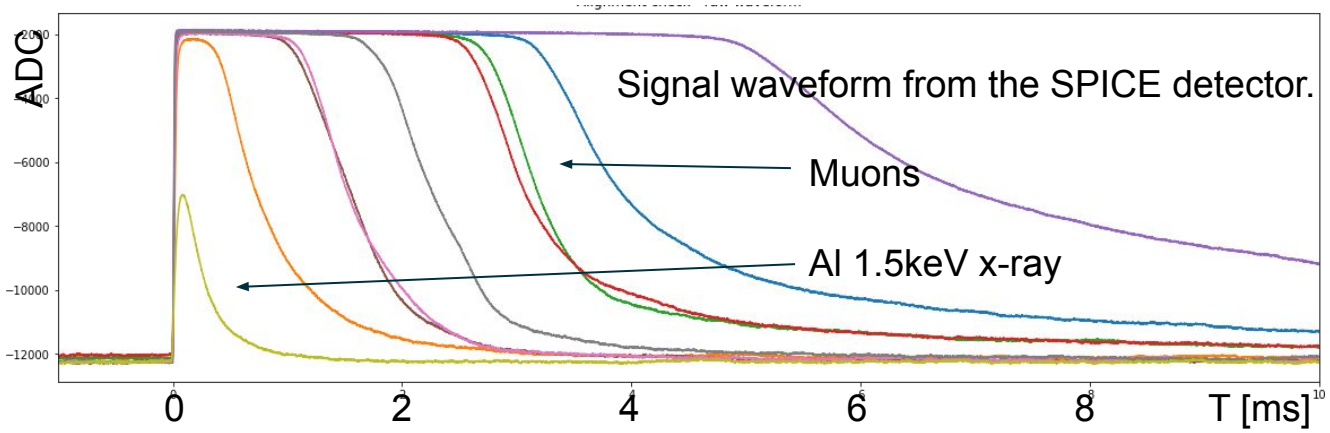
- **Energy impulse from radiation and dark matter particles creates high energy phonons well above the thermal energy level → Athermal phonons**
- Ballistically propagate
- Down convert on impurities, defacts, and surfaces
- Lifetime as long as 100 us in surface-polished crystals

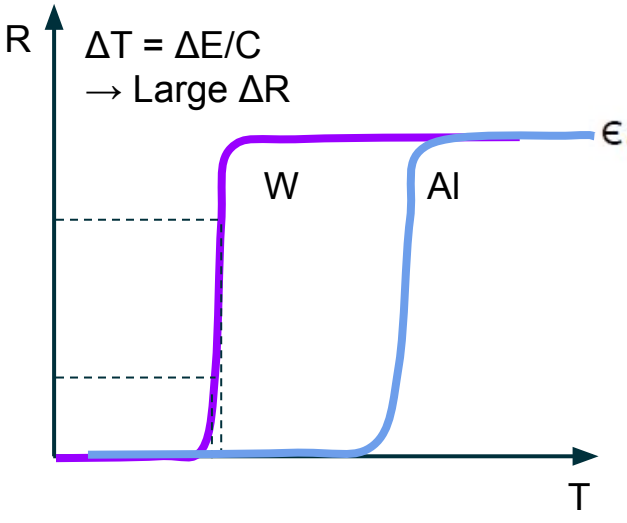


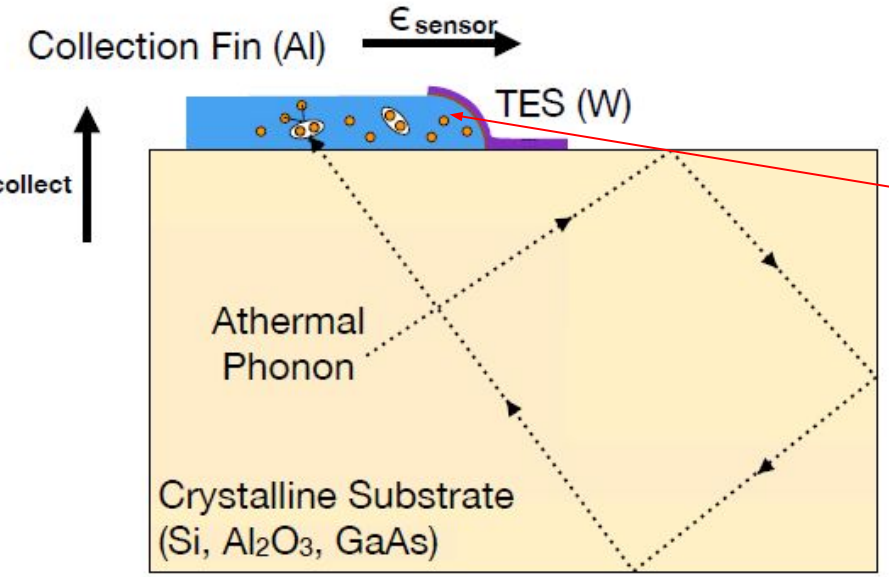


Athermal phonon as signal in dark matter search

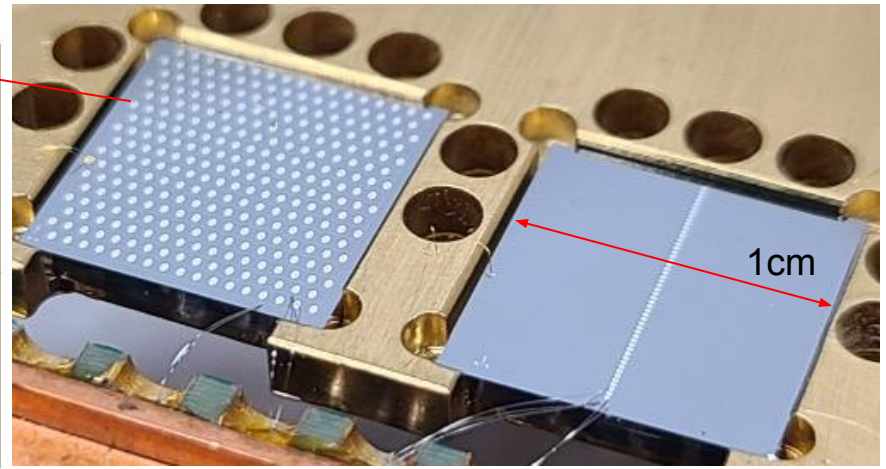
Athermal phonon detection

- Detectable by cryogenic particle sensors, for example, **transition edge sensor (TES)** and microwave kinetic inductance device (MKID).
- **Cooper pair breaking in superconductors**





The **TESSERACT** experiment



1cm Si detectors with 4% and 0.25% sensor coverage
Tuning phonon collection time

Athermal phonon as signal in dark matter search

Athermal phonon detection

- Detectable by cryogenic particle sensors, for example, transition edge sensor (TES) and **microwave kinetic inductance device (MKID)**.
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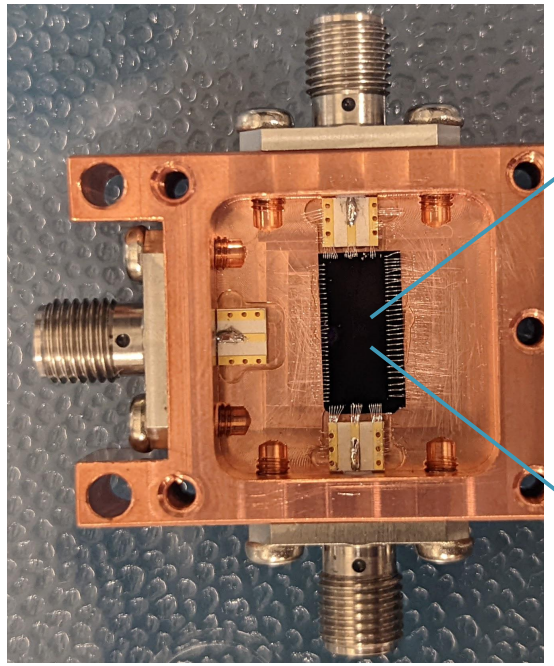
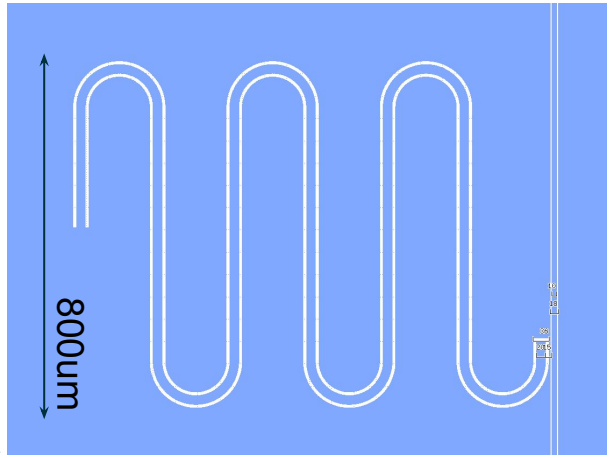
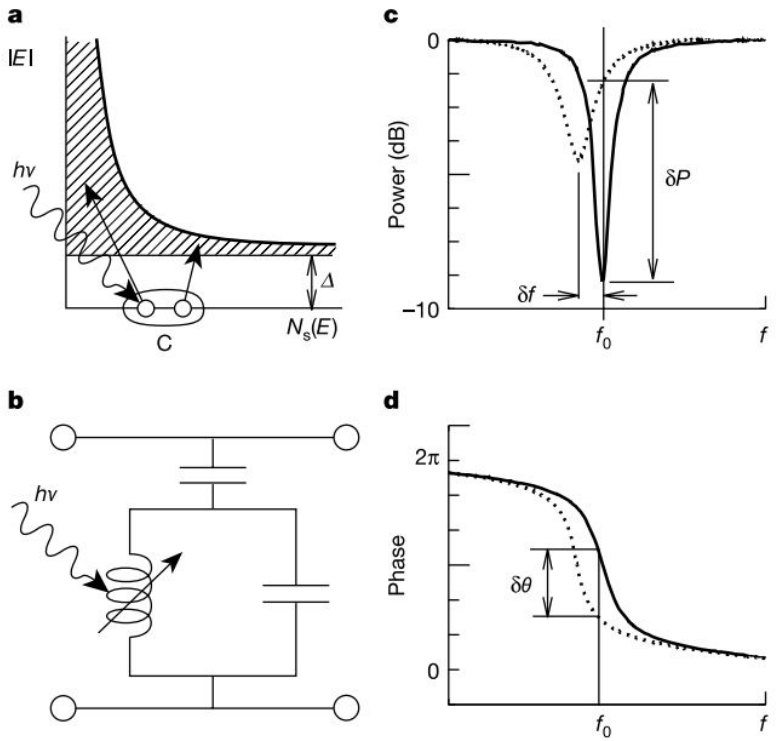




Example of a MKID, Nb on Si coplanar waveguide (CPW) resonator.
6GHz.



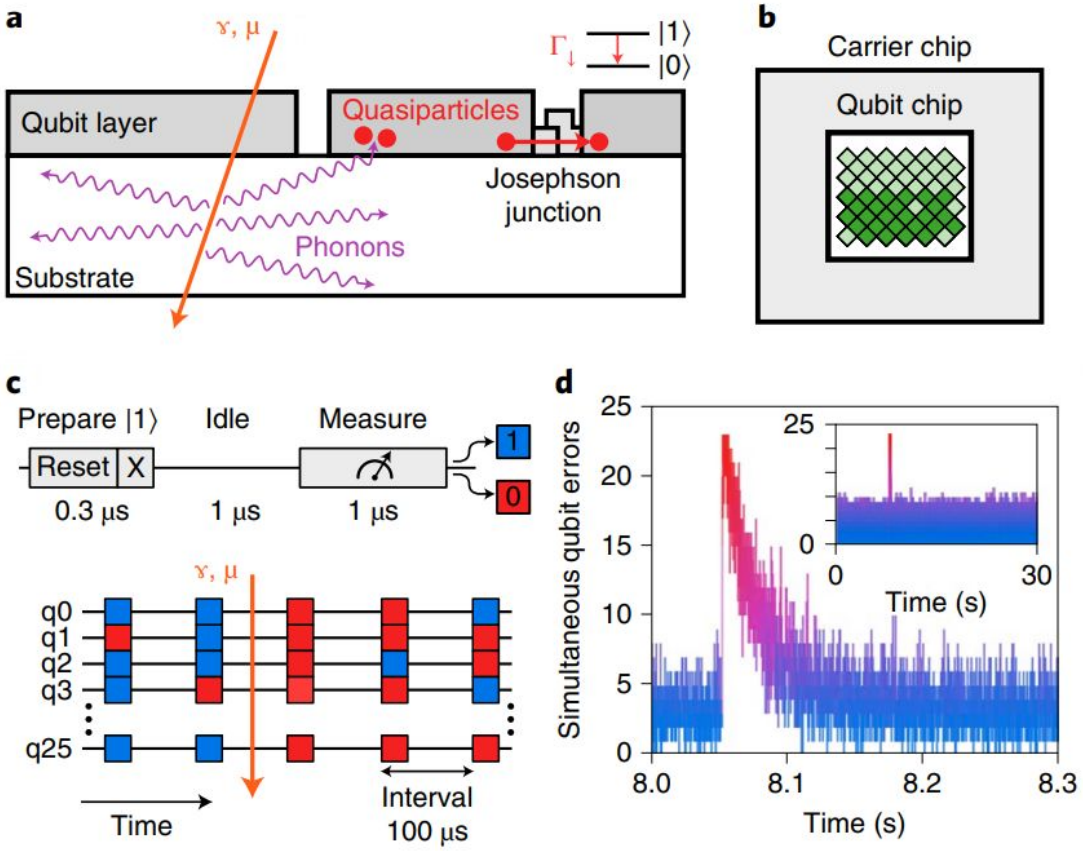
Nature 425.6960 (2003): 817-821.

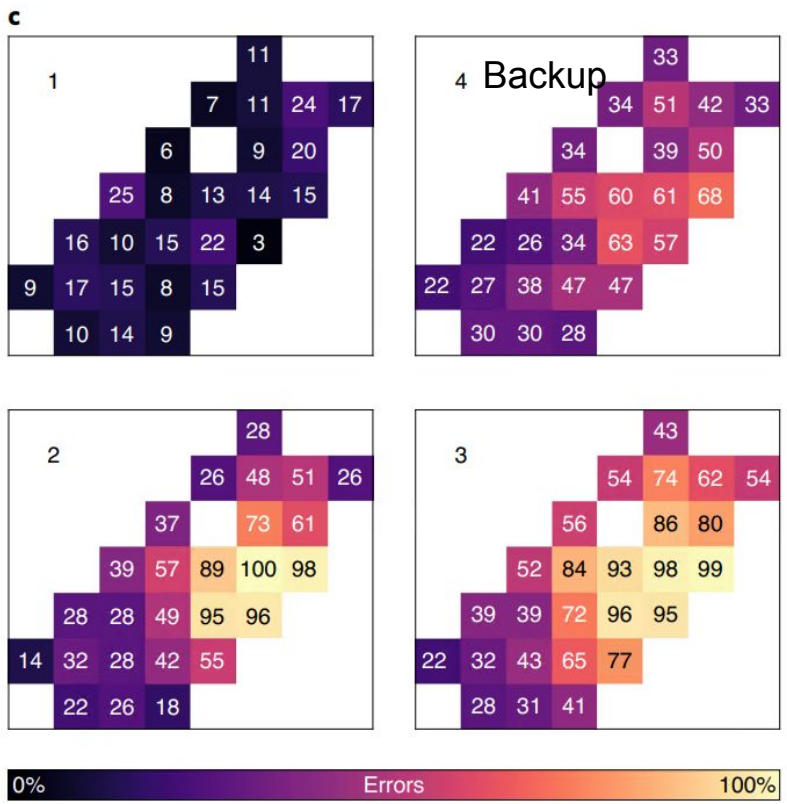
Athermal phonon as noise in quantum devices

Effect of phonons on qbits

- “Catastrophic” whole chip error bursts caused by cosmic rays

The Google Sycamore processor
Nature Physics volume 18, 107–111 (2022)





Spatial distribution of error rates in time frames before during and after the impact.

Athermal phonon as noise in quantum devices

Effect of phonons on qubits

- “Catastrophic” whole chip error bursts caused by cosmic rays
- Phonons above the superconductor bandgap will **create quasiparticles**, disturb the qubit.
- **Phonons below the bandgap also introduces decoherence**.
  - Spin-orbit coupling sensitive to lattice deformation.
  - Electric field - phonon field coupling due to “two-level systems” in amorphous surfaces.

It is important to **protect Qubits from all athermal phonons** generated by radioactive backgrounds.

Athermal phonon mitigation

Lessons from the particle physics and cosmology

- Isolation

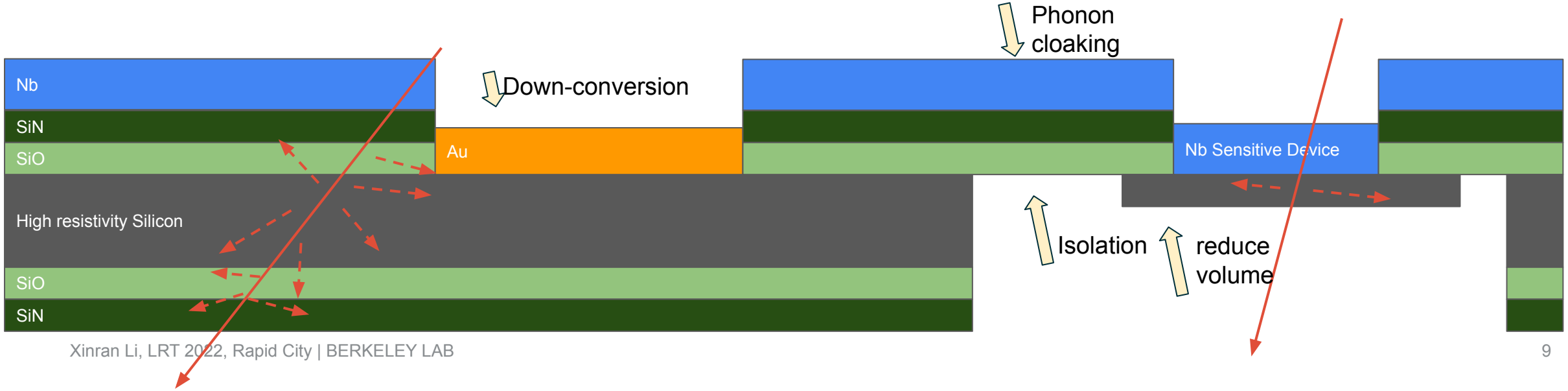
Reduce the volume subject to radioactivity.

- Down-conversion

Shorten the life-time of athermal phonons and down-convert them to less problematic low energy phonons.

- Phonon cloaking

Manipulate the substrate material property and cloak sensitive qubits from athermal phonons.



Isolation

- Reduce the volume of substrate directly in contact with the qbit.
- **Reduce the rate and energy deposition per hit** directly in the sensitive volume by cosmic rays.

Figures:

Top: CMB measurement contaminated by cosmic rays.

Bottom: A TES sensor hanging in the middle of a SiN spider web. Designed for ballon based CMB measurement.

Challenges:

Fabrication

Quality of the qubit.

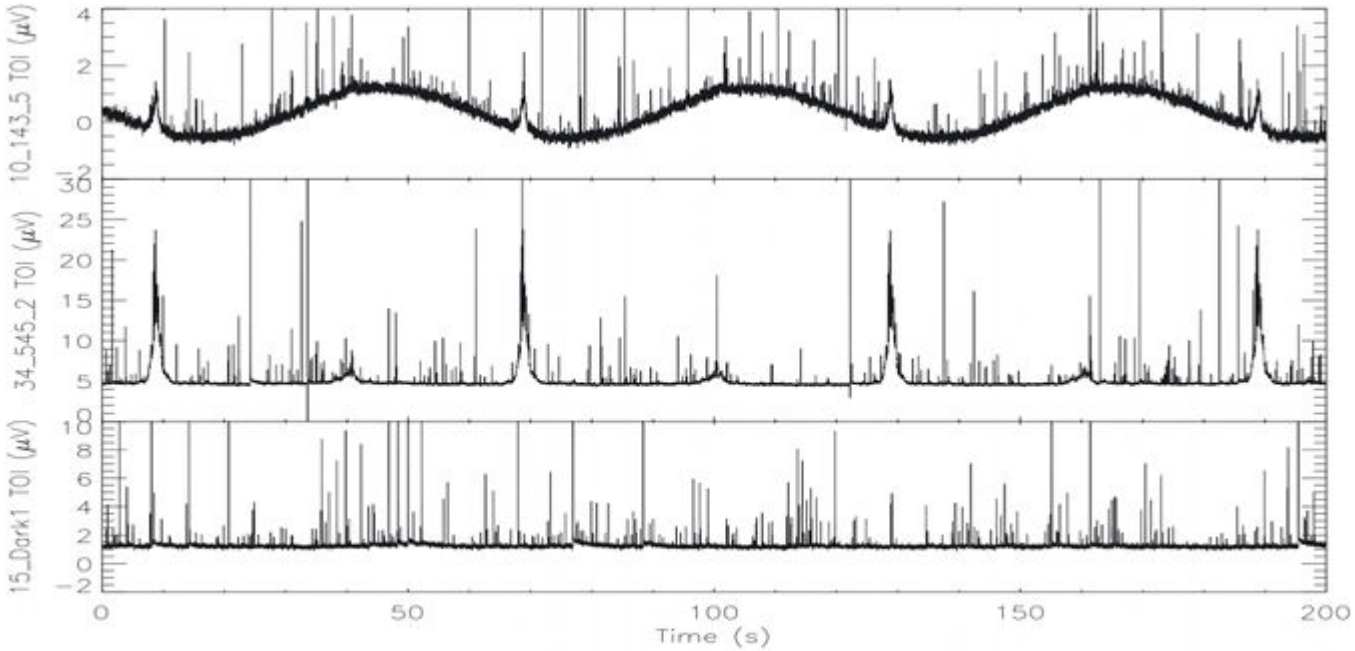


Fig. 4. Raw TOIs for three bolometers, the "143-5" (*top*), "545-2" (*middle*), and "Dark1" (*bottom*) illustrating the typical behaviour of a detector at 143 GHz, 545 GHz, and a blind detector over the course of three rotations of the spacecraft at 1 rpm. At 143 GHz, one clearly sees the CMB dipole with a 60 s period. The 143 and 545 GHz bolometers show vividly the two Galactic Plane crossings, also with 60 s periodicity. The dark bolometer exhibits a nearly constant baseline together with a population of glitches from cosmic rays similar to those seen in the *two upper panels*.

Raw signal traces from Planck
[HFI performance summary - Planck Legacy Archive Wiki (esa.int)]

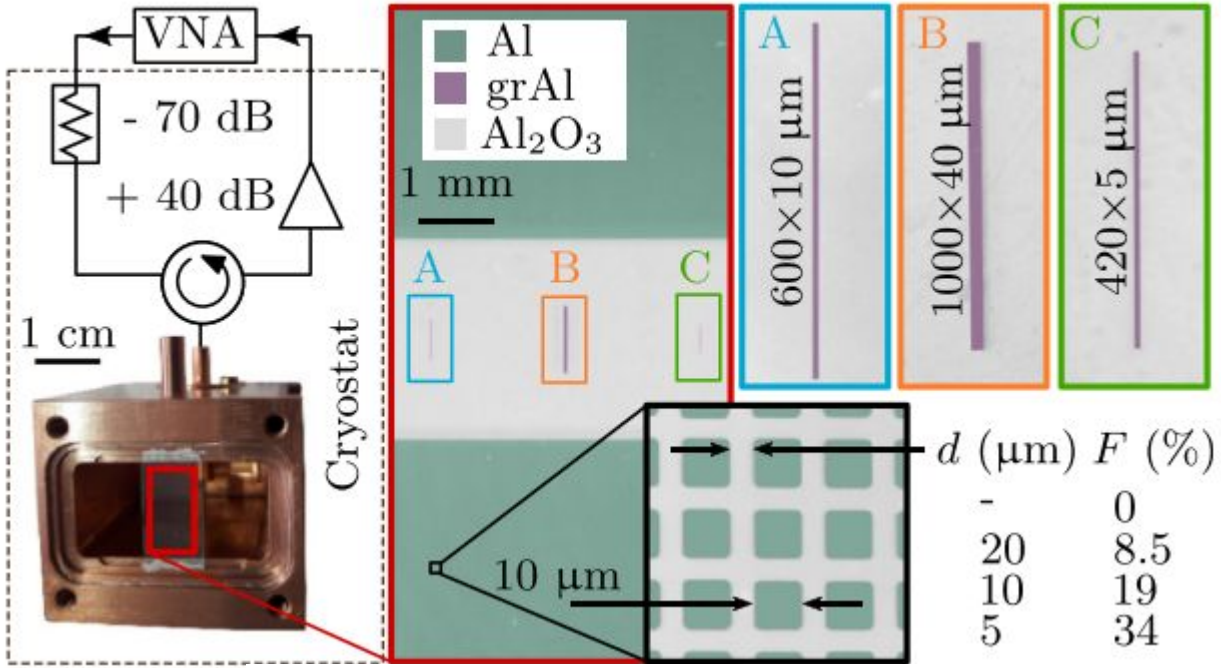
Spider web TES detector for ballon based CMB measurement
arxiv 1007.3672

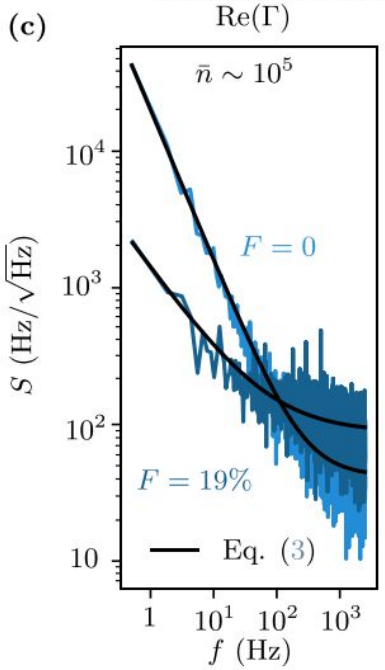
Down-conversion

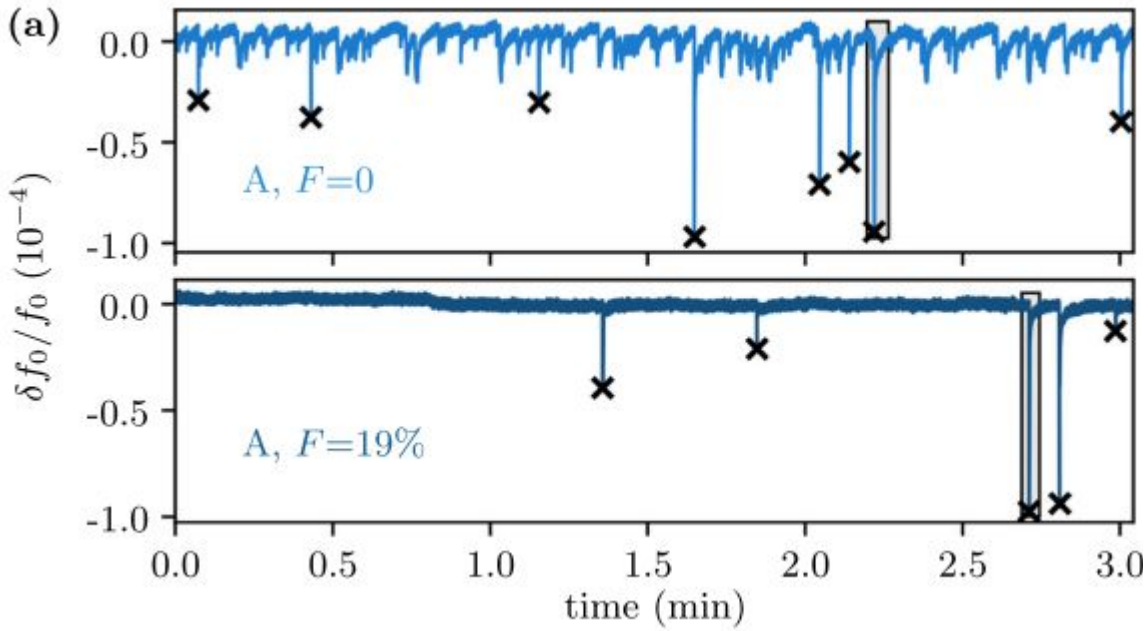
- Increase surface roughness
- Use amorphous material for the suspending structure on the phonon path.
- Coat surfaces with **low transition temperature** superconducting films (figurs) or **normal metal** as **phonon sponge** (PRB 96, 220501(R) (2017)).

Figures:

Granular Al resonator (high Tc) protected by Al coating (low Tc). Reduces both phonon burst rate and readout noise. Appl. Phys. Lett. 115, 212601 (2019)







Phonon cloaking

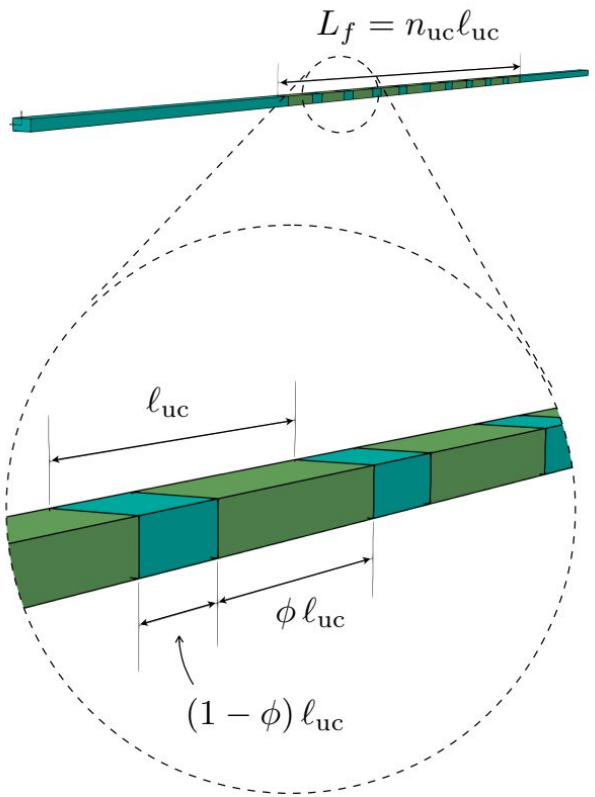
"Meta material"

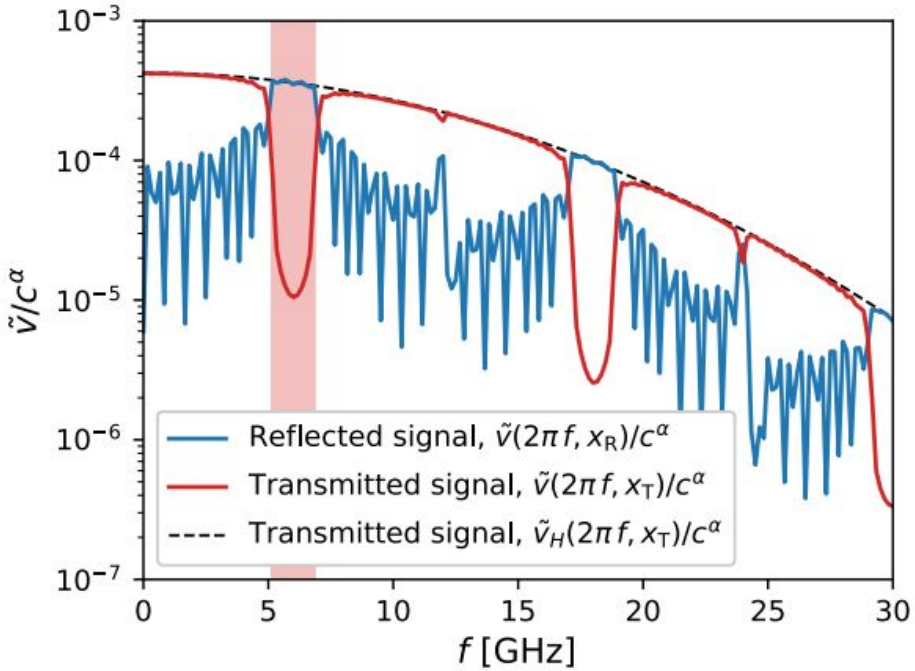
Opening phonon energy gap on a 1D suspending beam with **helium ion implantation**.

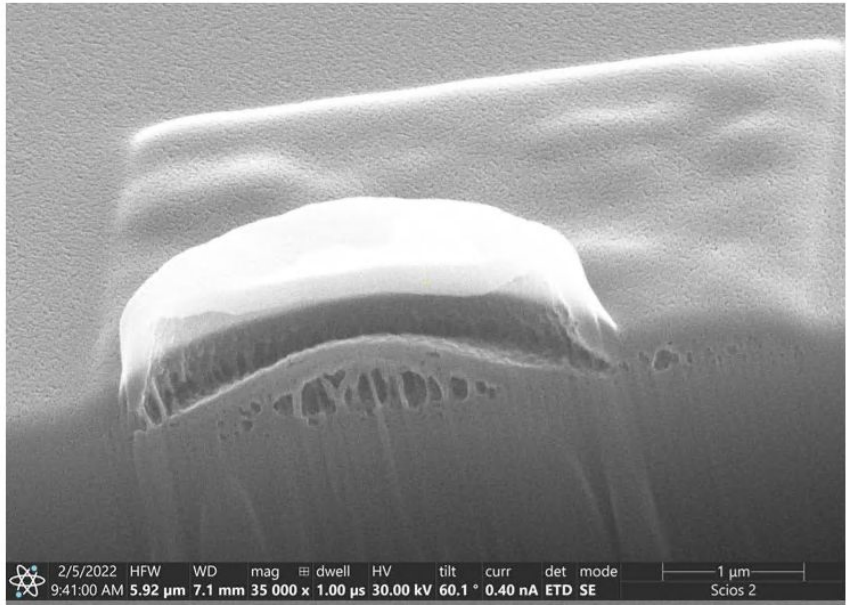
Most effective for **low energy phonons**. 6GHz, 0.025meV, ~2 um wavelength.

Top: simulation of a photonic waveguide with periodically implanted SiN beam.

Bottom: He forms babbles in SiN under high does of implantation.



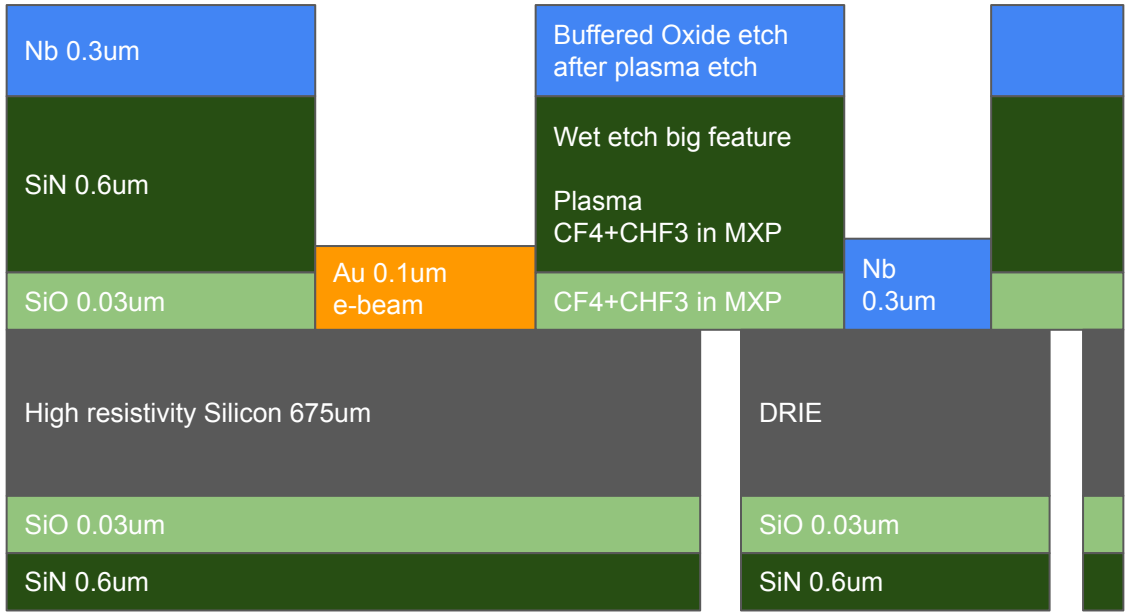


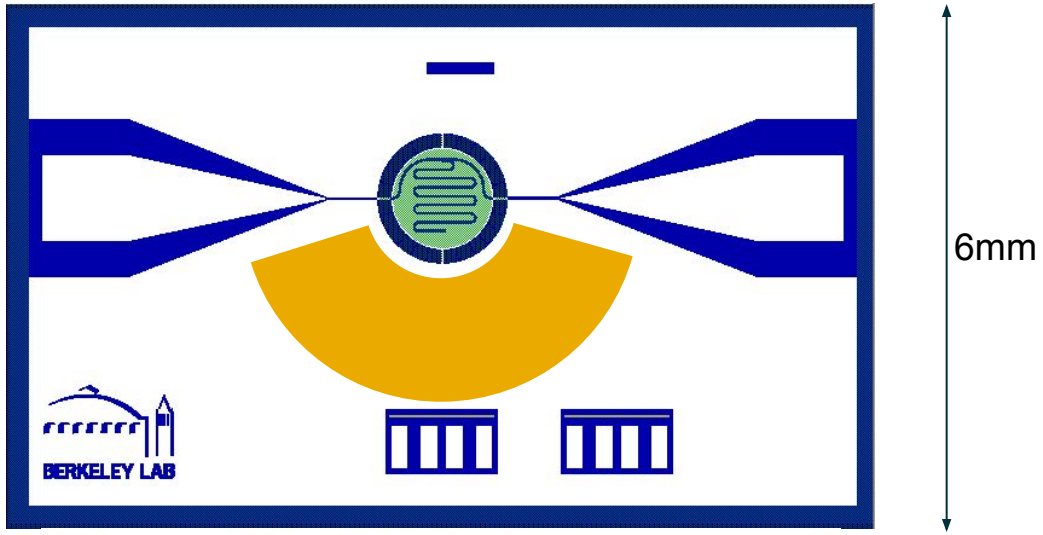


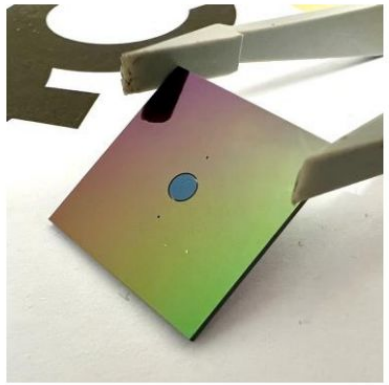
Contribution from
Vincenzo Gulizzi (LBL)
Mehdi Balooch (UCB)

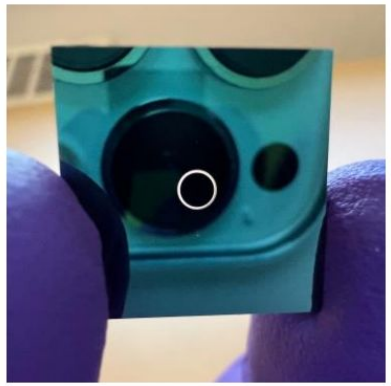
Current R&D effort at LBL

Use superconducting resonators to test the effectiveness of the phonon mitigation methods.
Fabrication of high quality factor resonators on the suspended island.



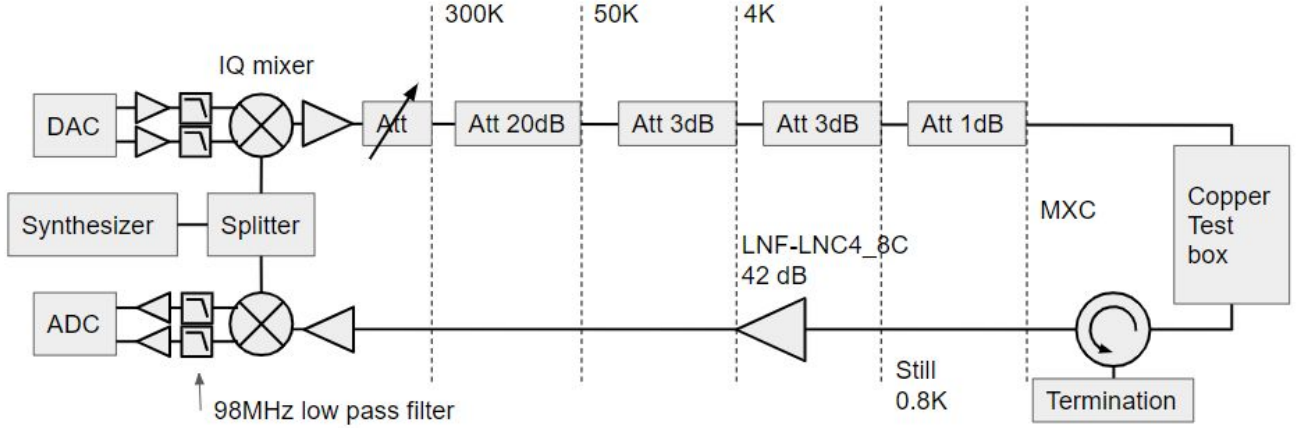




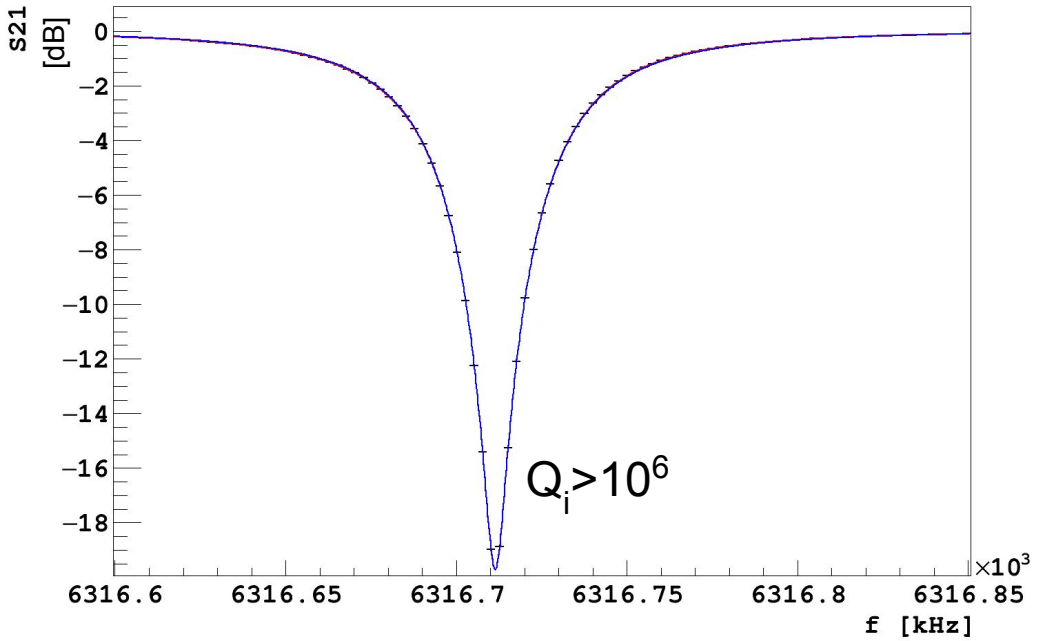


Current R&D effort at LBL

RF readout system is ready and tested.



First result from a simple resonator.
High Q achieved with Nb oxide removal.
PRX Quantum, *3*(2), 020312.



Conclusions

Superconducting devices are sensitive to athermal phonons generated by radiation.

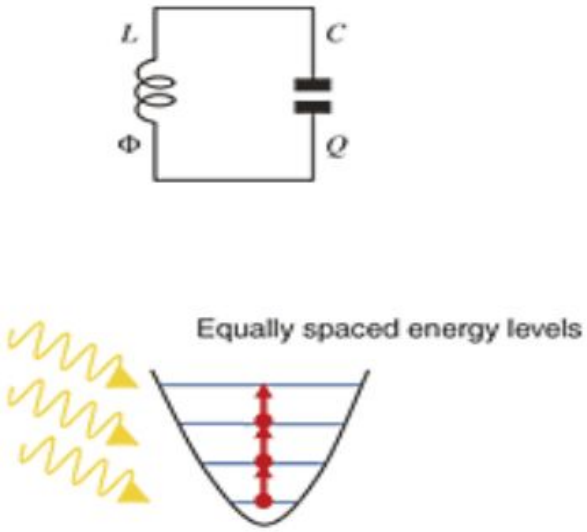
Particle detectors are engineered to be effective at collecting them.

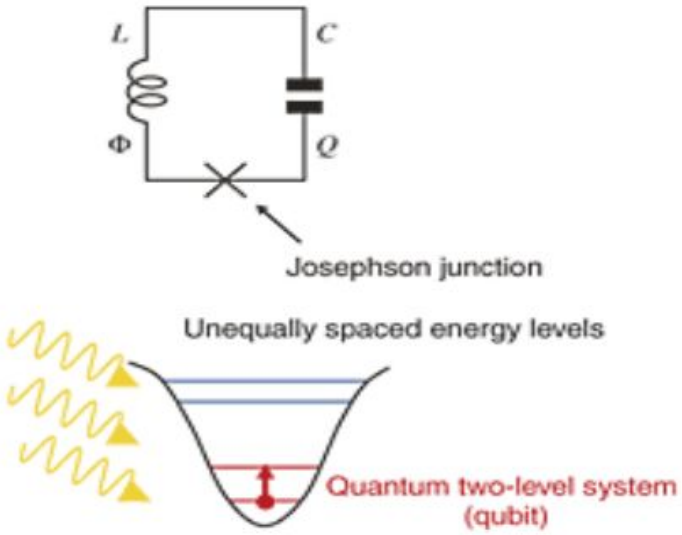
Quantum information sensors should reverse the design.

- Isolation
- Down-conversion
- Phonon cloaking

R&D at LBL is currently on-going to prove that the techniques are compatible with quantum information sensors.

Thank You





KID (kinetic inductance detector).

This is plainly a High Q superconducting resonator. Commonly the resonance F0 is designed at 2 or 3 GHz, but the actual value is only of practical importance (like component cost).

L (and therefore F0) has one value in the superconducting phase, and a different value in the normal conducting phase. Therefore, if something breaks Cooper pairs in L (eg phonons), F0 will shift. The higher the Q the smaller the detectable shift. (The qubit's vice is the KID's virtue).

Other than the Q value, the sensitivity of a KID is determined by the noise of the amplifier used to read it. The lower the noise the smaller an F0 shift that can be detected. Parametric amplifiers and squeezing can be used to reduce amplifier noise.

Superconducting qubit

This is the same High Q superconducting resonator with one added element: the Josephson junction. The JJ nonlinearity modifies the energy levels forming a pair with unique spacing, far from others, which gives a nice "atomic" 2-level system.

Commonly the resonance F0 is designed at 7 or 8 GHz. The resonance Q value determines the sharpness of the energy levels and the phase decoherence time T2. Random breaking of Cooper pairs (eg by phonon noise) is bad as they cause F0 jitter and effectively broaden the resonance.

Amplifier noise determines the fidelity of the readout so need the lowest possible noise just as for KIDs. Parametric amplifiers and squeezing can be used to reduce amplifier noise.