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Development of Superconducting Qubit-Based Sensors for meV Scale Detectors

Caleb Fink
Directors Postdoc Fellow - LANL

LA-UR-23-32579

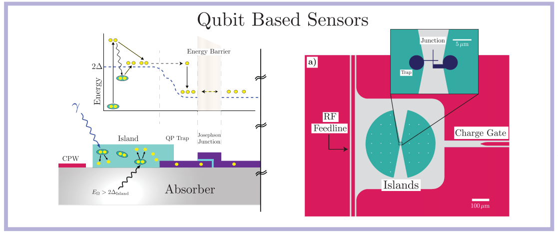
New Physics at the meV Scale

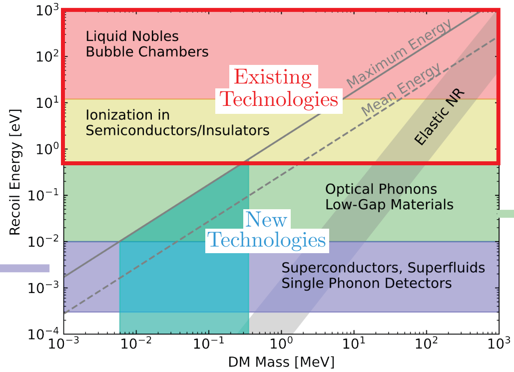
- New Physics beyond the standard model at low energies
  - Light dark
  - BSM deviations of the CEVNS spectrum
  - THz photons from Axions
- Low kinetic energy of these particles impart very little energy into detector

  → Requires new detector technology with meV sensitivity

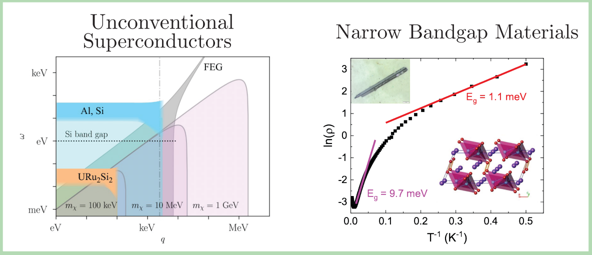
Two paths forward:

Novel Superconducting Sensors





novel topological materials



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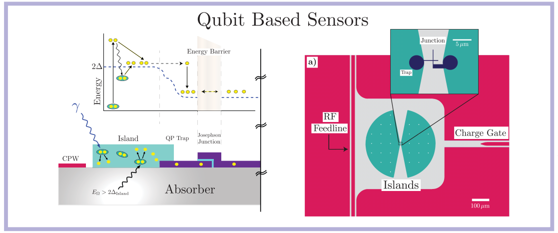
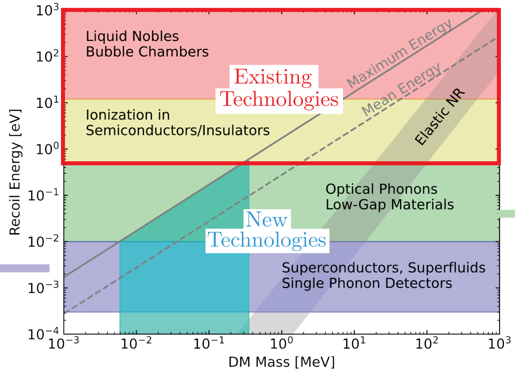
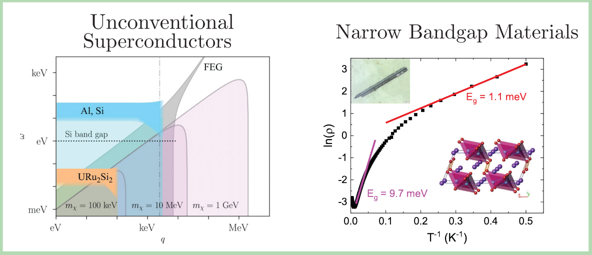




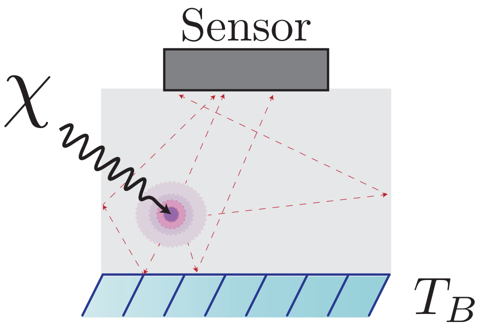
Early career plenary 8:30am (tomorrow)

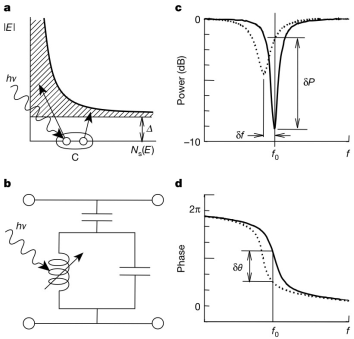
novel topological materials

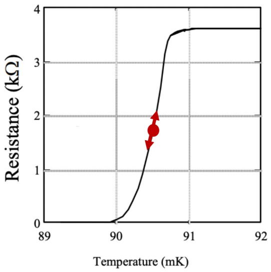


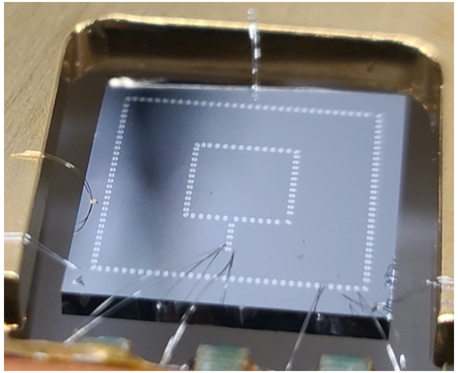
Calorimetry with Superconducting Sensors

- Rare event searches require large exposure
  - SC Sensors typically coupled to much larger absorbers
- Many detectors use sensors patterned on absorber as phonon sensors
- Sensors are typically TESs, MKIDs, or NTDs
  - Use fluctuations in phonon or quasiparticle *densities* to measure energy depositions
- State of the art detectors have achieved O(100 meV) resolutions









Microcalorimetry beyond the TES

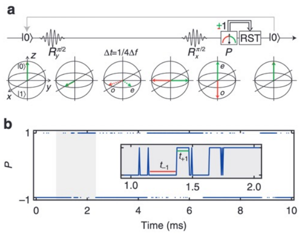
- Multiple experiments have observed correlated errors across qubits originating from phonons in the device substrate
- Groups have demonstrated that single quasiparticle tunneling events can be resolved in transmon qubits via parity flips

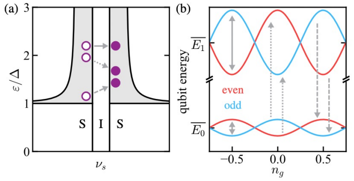
Goal: exploit single QP sensitivity of qubits to make meV scale phonon sensors

Millisecond charge-parity fluctuations and induced decoherence in a superconducting transmon qubit

D. Ristè, C. C. Bultink, M. J. Tiggelman, R. N. Schouten, K. W. Lehnert & L. DiCarlo

Nature Communications **4**, Article number: 1913 (2013) | Cite this article

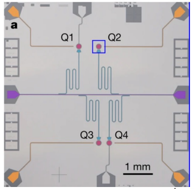




Hot Nonequilibrium Quasiparticles in Transmon Qubits

K. Serniak, M. Hays, G. de Lange, S. Diamond, S. Shankar, L. D. Burkhart, L. Frunzio, M. Houzet, and M. H. Devoret

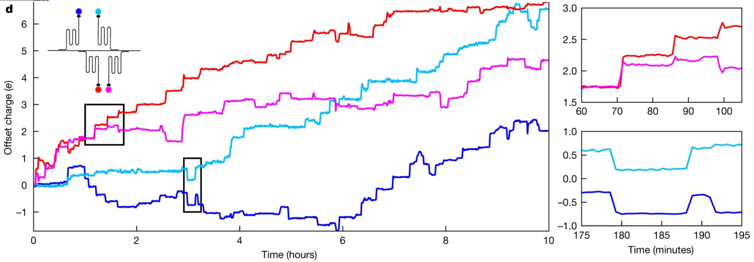
Phys. Rev. Lett. **121**, 157701 – Published 10 October 2018



Correlated charge noise and relaxation errors in superconducting qubits

C. D. Wilen, S. Abdullah, N. A. Kurinsky, C. Stanford, L. Cardani, G. D'Imperio, C. Tomei, L. Faoro, L. B. Ioffe, C. H. Liu, A. Opremcak, B. G. Christensen, J. L. DuBois & R. McDermott

Nature **594**, 369–373 (2021) | Cite this article



The Superconducting Quasiparticle-Amplifying Transmon

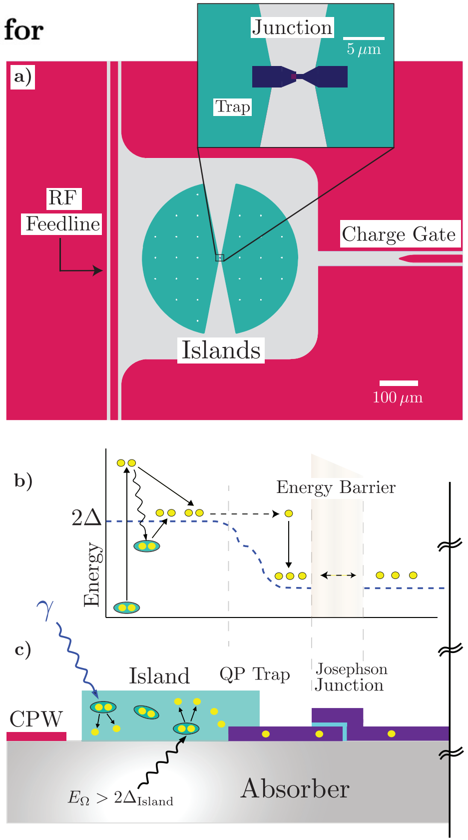
The Superconducting Quasiparticle-Amplifying Transmon: A Qubit-Based Sensor for meV Scale Phonons and Single THz Photons

C.W. Fink,[1,*] C. Salemi,[2,3,†] B.A. Young,[4] D.I. Schuster,[5] and N.A. Kurinsky[2,3,‡]

arXiv:2310.01345 [physics.ins-det]

- A sensor based on the weakly charge-coupled transmon architecture
- Charge dispersion allows for sensitivity to parity flip from single quasiparticle tunneling event
- Leverages quasiparticle trapping and amplifying techniques pioneered by SuperCDMS
- Will be sensitive single meV phonons in substrate with measurement times of $1\mu s$

** Work funded by DOE HEP Early Career Award, KA25, and Los Alamos National Lab LDRD*



Quasiparticle Trapping

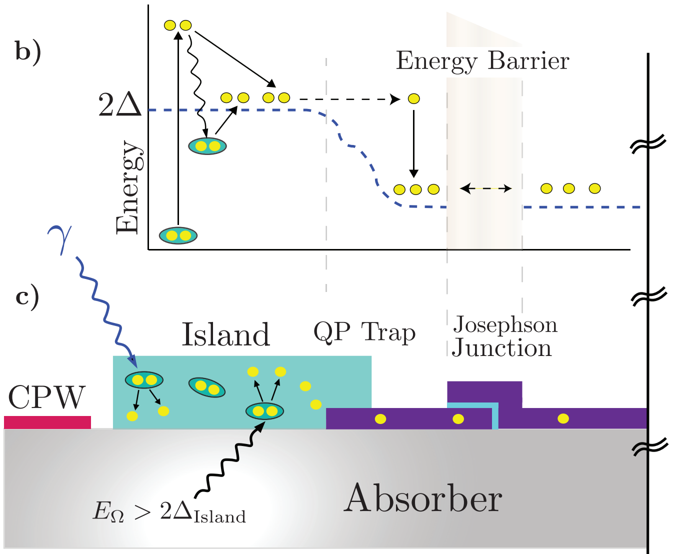
Qubit fabricated from two materials such that

- Islands: Al
- Junctions: AlMn

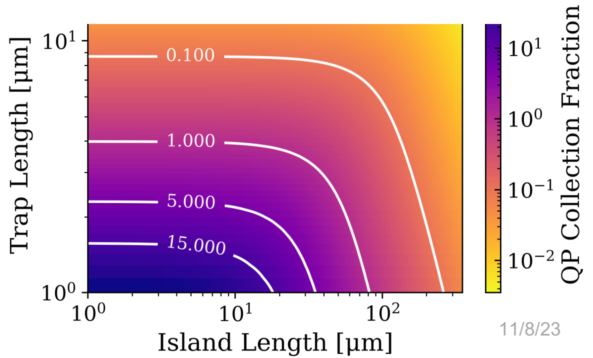
$$\Delta_{junction} \ll \Delta_{island}$$

1. Phonons (photons) with energy greater than $2\Delta_{island}$ break Cooper-pairs in islands
2. Quasiparticles diffuse in island until becoming trapped in lower gap material
3. QP's undergo multiplication process in lower gap material
4. QP's tunnel across junction in low gap material until recombination

Steps 2 & 3 can result in collection efficiencies of greater than unity

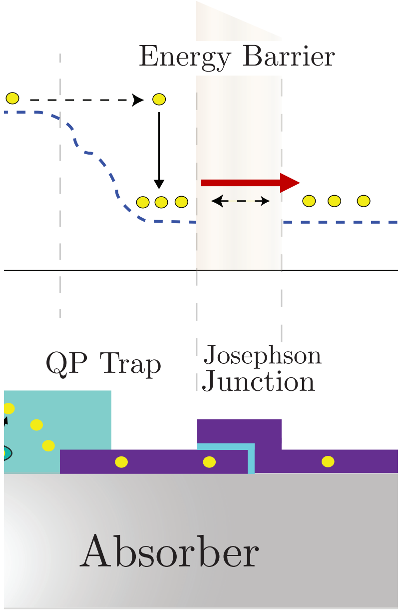


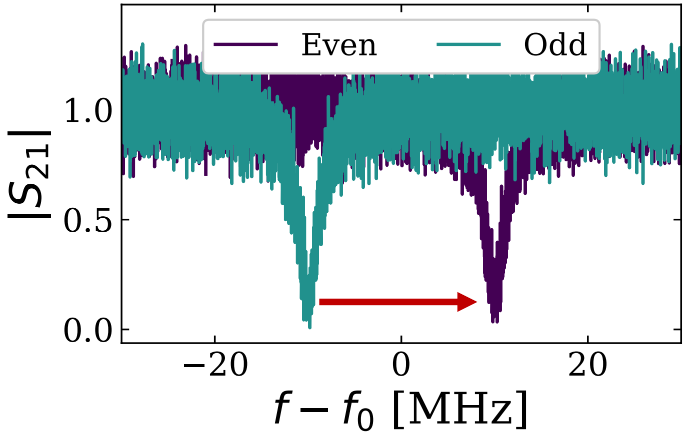
$$\frac{\partial}{\partial t} n(\mathbf{x}, t) = D_{\text{island}} \nabla^2 n(\mathbf{x}, t) - \frac{n(\mathbf{x}, t)}{\tau_{\text{island}}} + s$$

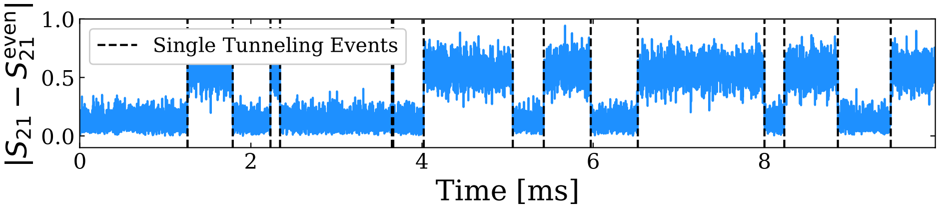


Signal Pathway

- Quasiparticles in the trapped region of sensor will diffuse until tunneling across junction
- Each tunneling event changes parity state – observable as small frequency shift



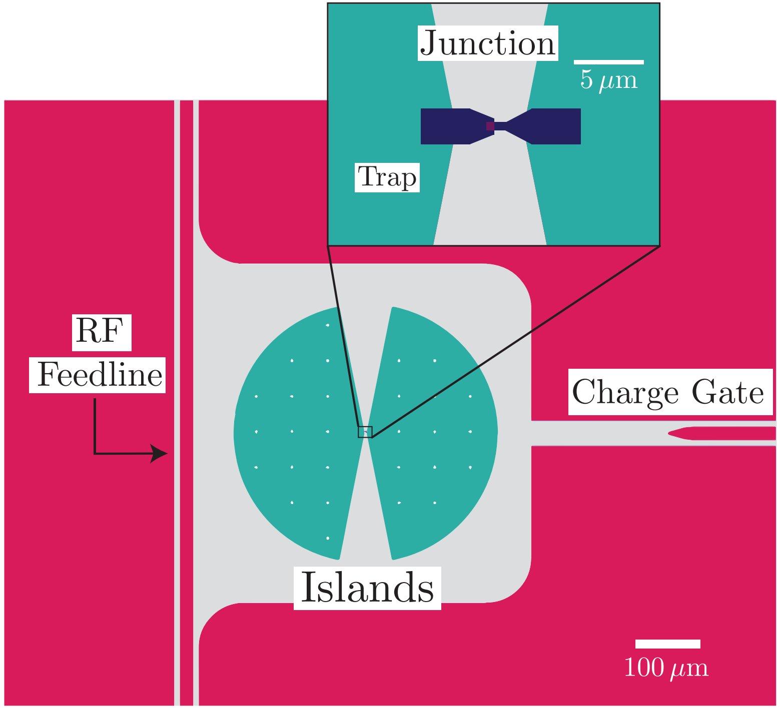




Sensor Readout

- Unlike traditional qubit readout, readout resonator is removed
- Resonance determined by qubit transition directly, not by coupled resonator
- Removing resonator couples the qubit much stronger to the environment

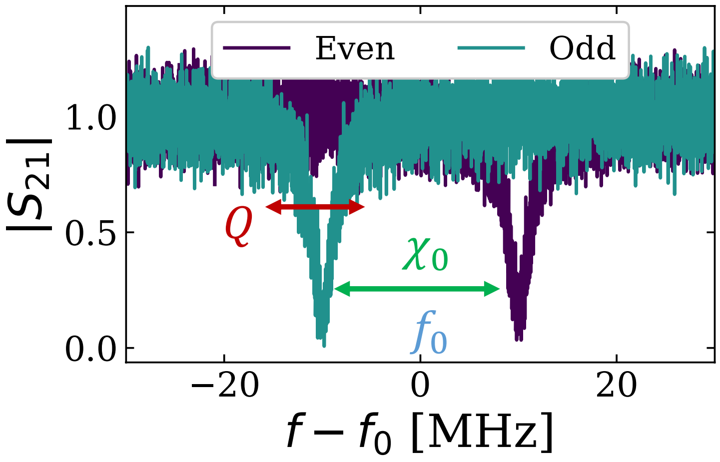
- This change allows unit cell to be decreased
  - Increased pixel density
  - Reduction of two-level system noise
  - Increased detection efficiency



Qubit Tuning

Three parameters to tune:

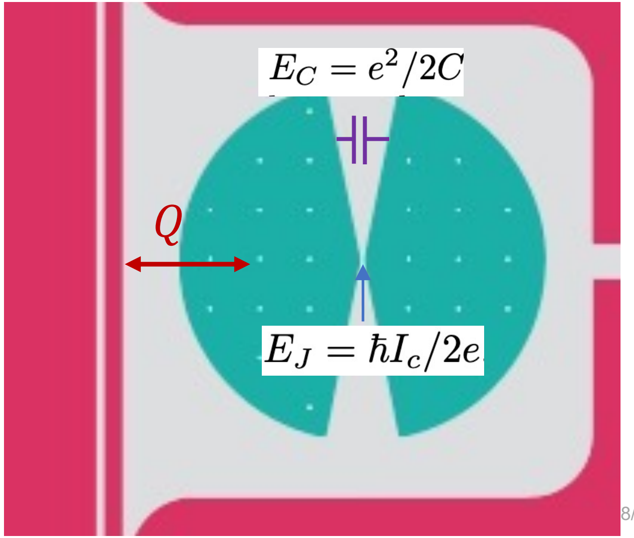
1. Undressed resonance frequency, f_0
2. Frequency separation of parity states, χ_0
3. Total quality factor, Q



f_0 and χ_0 are determined by the charging energy E_C and the Josephson energy E_J

- Determined by Island capacitance and junction parameters

Q is determined by capacitance between qubit and RF feedline



$$\hbar\omega_0 \approx \sqrt{8E_C E_J} - E_C \qquad \frac{2\chi_0}{\omega_0} \approx e^{-\sqrt{8\xi}}\left[A\xi^{3/4} + B\xi^{1/4}\right]$$

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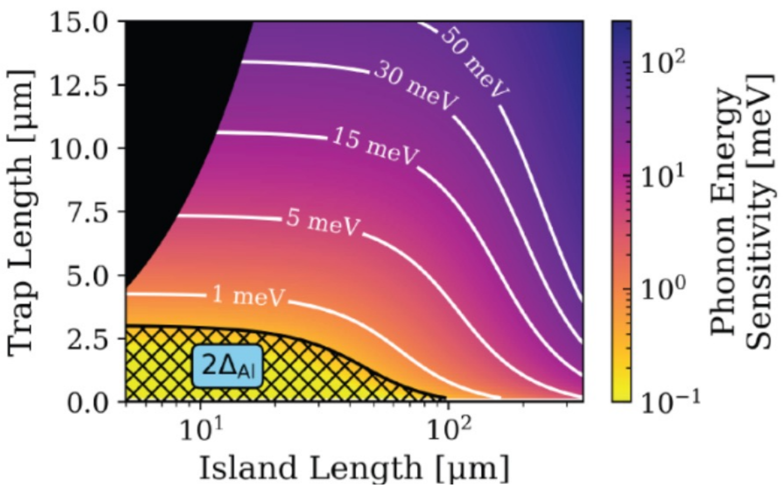
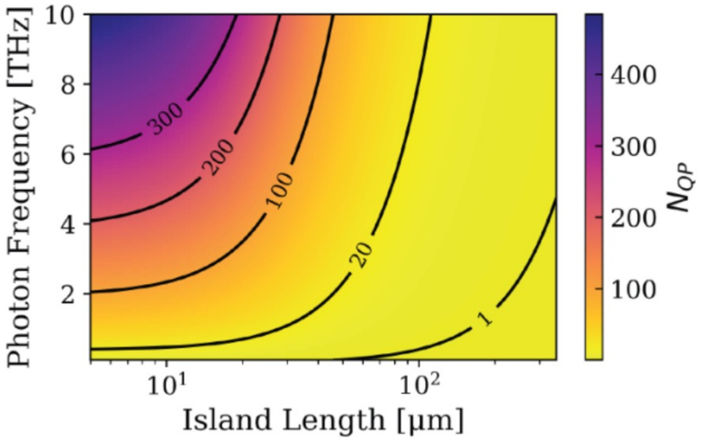
Energy Sensitivity

- Sensor is measuring quasiparticle number
  - Signal enhancement of ratio of energy in QP system to island gap!

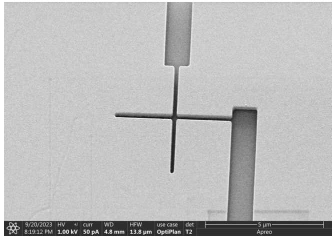
$$N_{QP} \approx \frac{\eta_{QP}}{\Delta_{island}}$$

- Readout scheme with sensitivity of parity flip from single QP events allows for sensor geometries sensitive to single meV phonons and photons

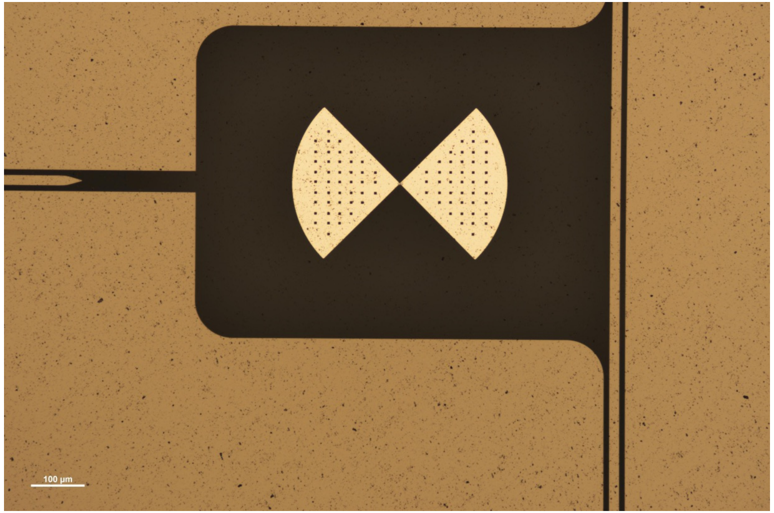


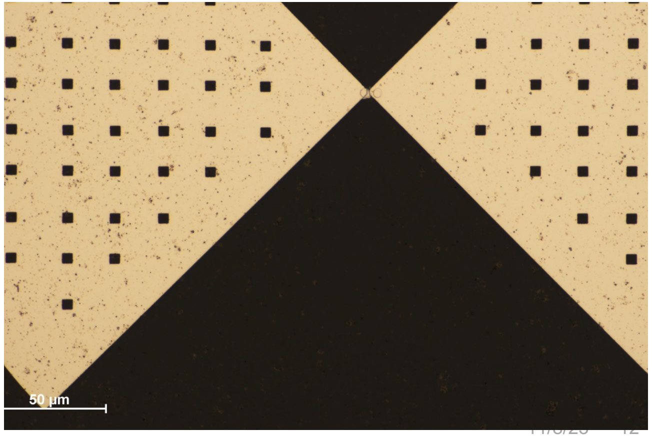


First R&D Prototype Devices



- First prototype devices have been fabricated at SLAC
- Initial device have Al islands and Al junctions (no QP trapping)
- Devices meant to test understanding of qubit parameters and test single QP readout
- Using Manhattan style junctions, next iteration will move to Dolan junctions





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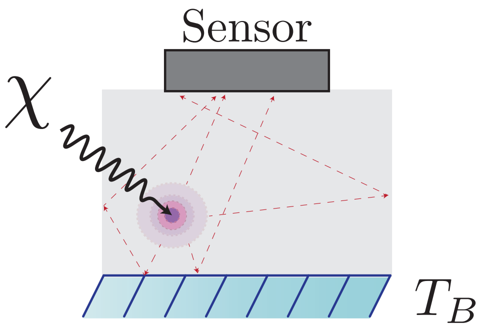
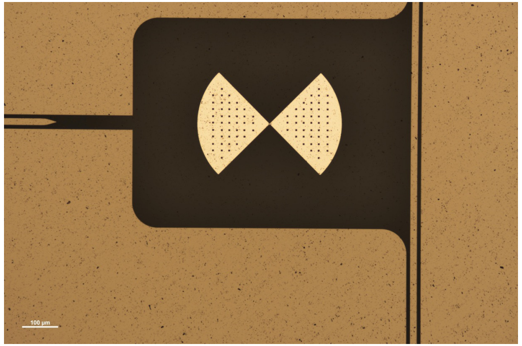
Conclusions

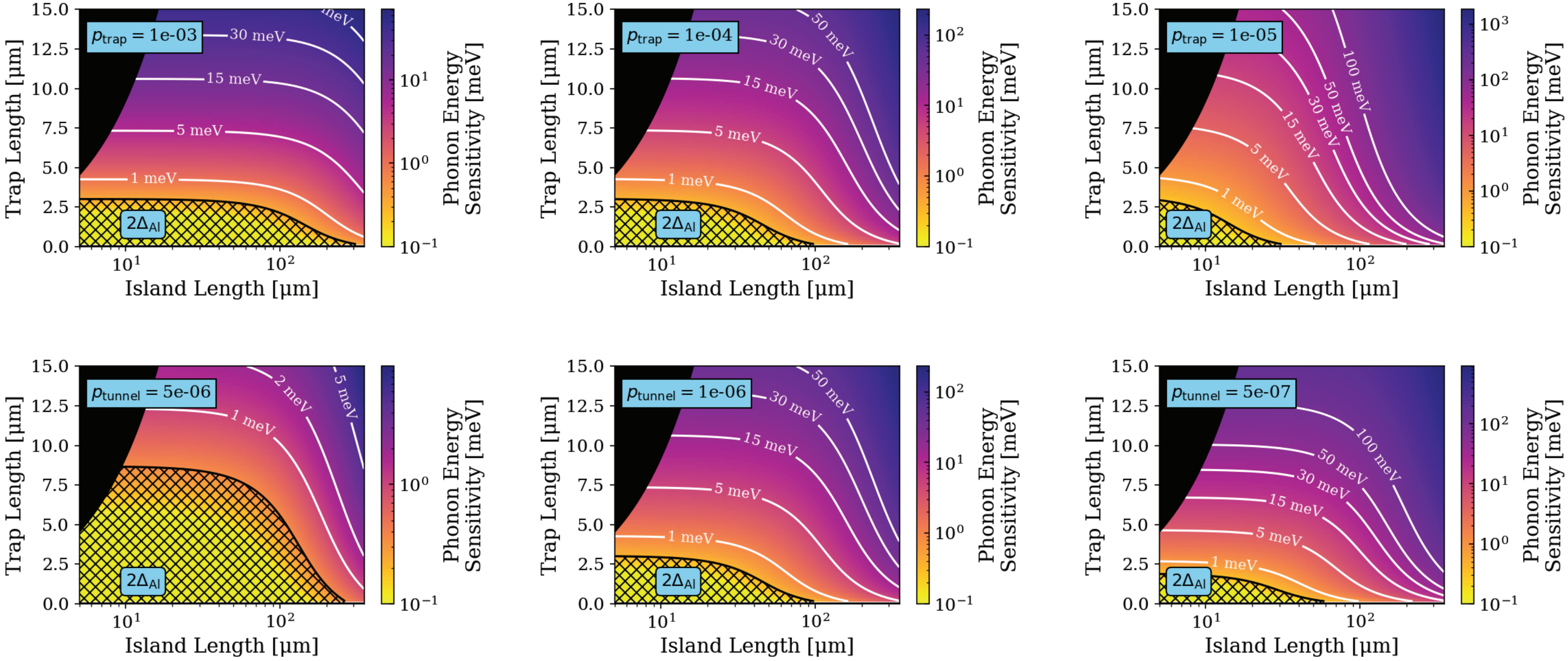
- Lots of new physics beyond the standard model to explore with sensors at the meV scale
- Superconducting qubit-based sensors are a promising route to probing this energy range
- The SQUAT design provides a clear path to single meV phonon sensitive detectors, without relying on long coherence times necessary in other qubit-based sensors





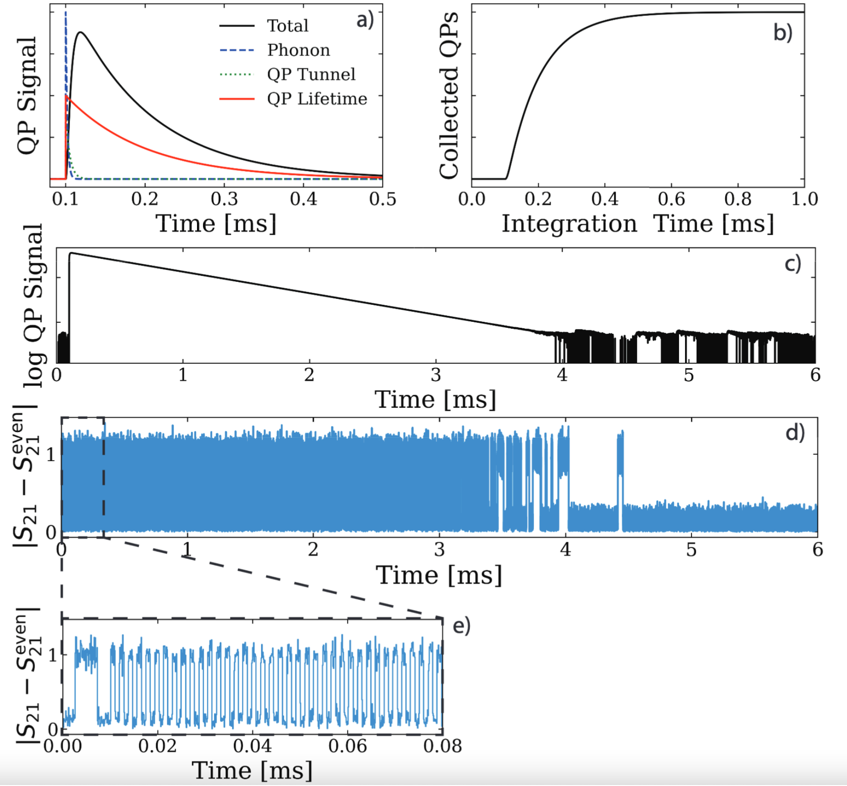
Backup Slides

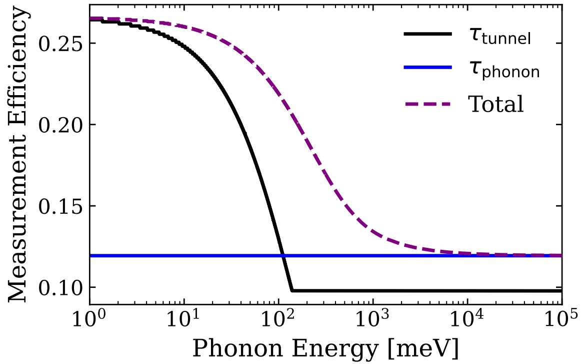
Effect of Tunneling and Trapping



Sensor Bandwidth

- Expected signal pulse is convolution of phonon signal, QP tunneling rate, and QP lifetime
- Finite readout bandwidth of 1MHz sets limit on observable parity switching rate
- Bandwidth decreases energy efficiency for events eV and above





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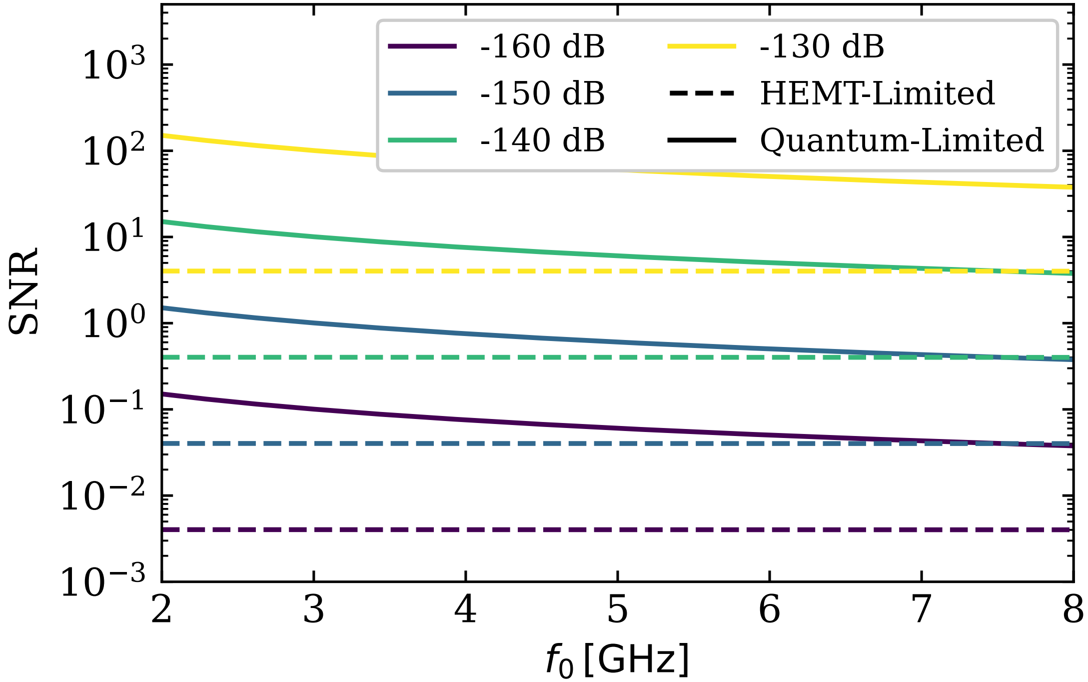
Signal to Noise



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Qubit Simulations