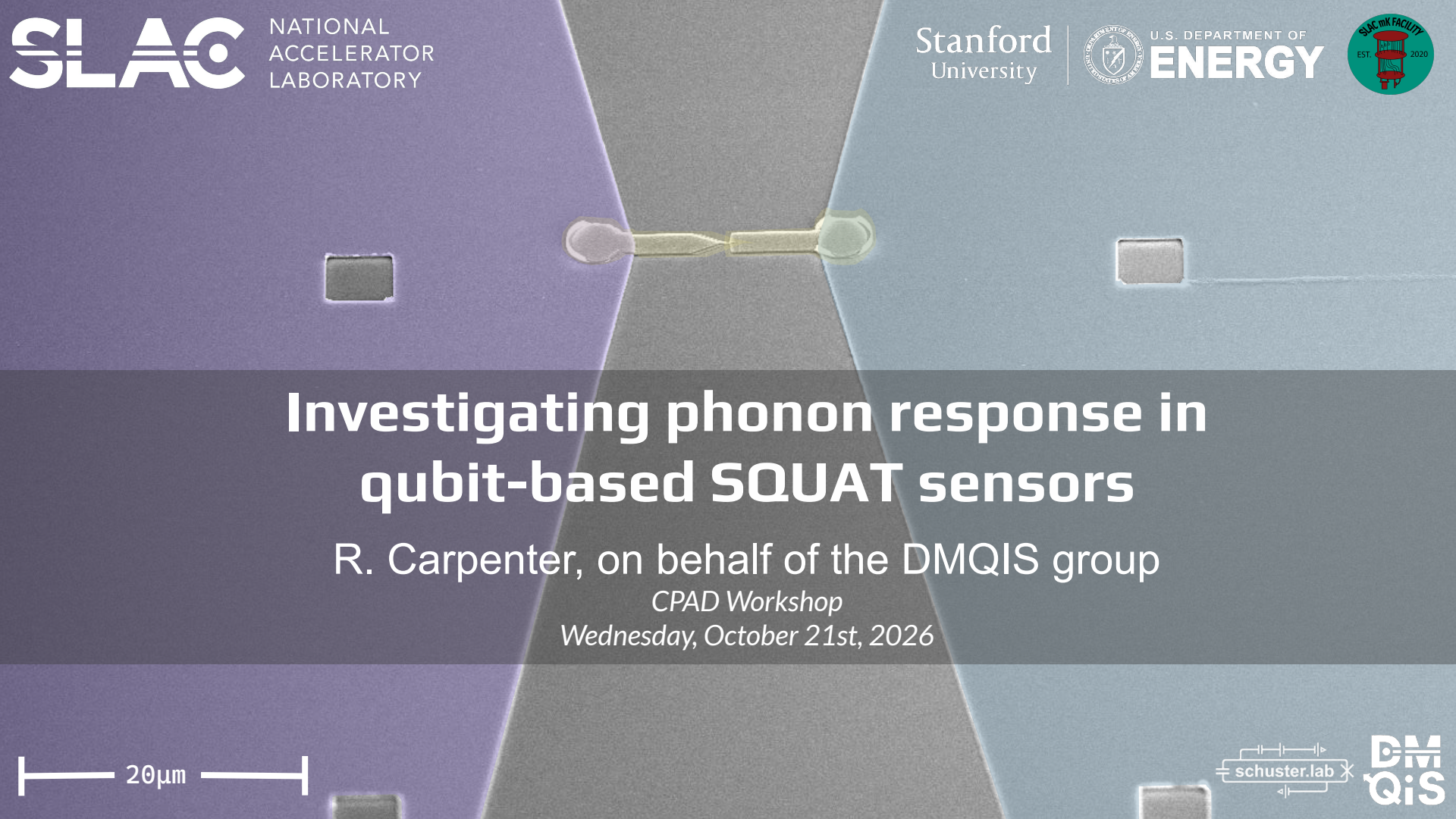


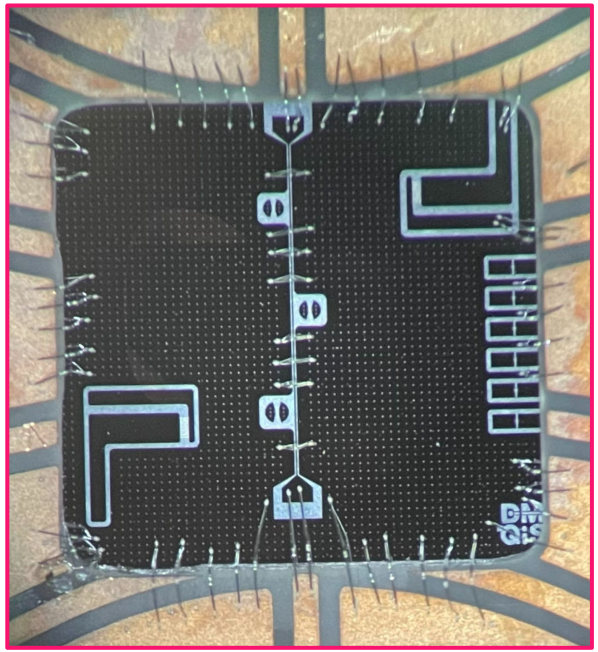
Investigating phonon response in qubit-based SQUAT sensors

R. Carpenter, on behalf of the DMQIS group

CPAD Workshop

Wednesday, October 21st, 2026

Superconducting **Qu**asiparticle-**A**mplifying **T**ransmon (SQUAT)



Design Paper

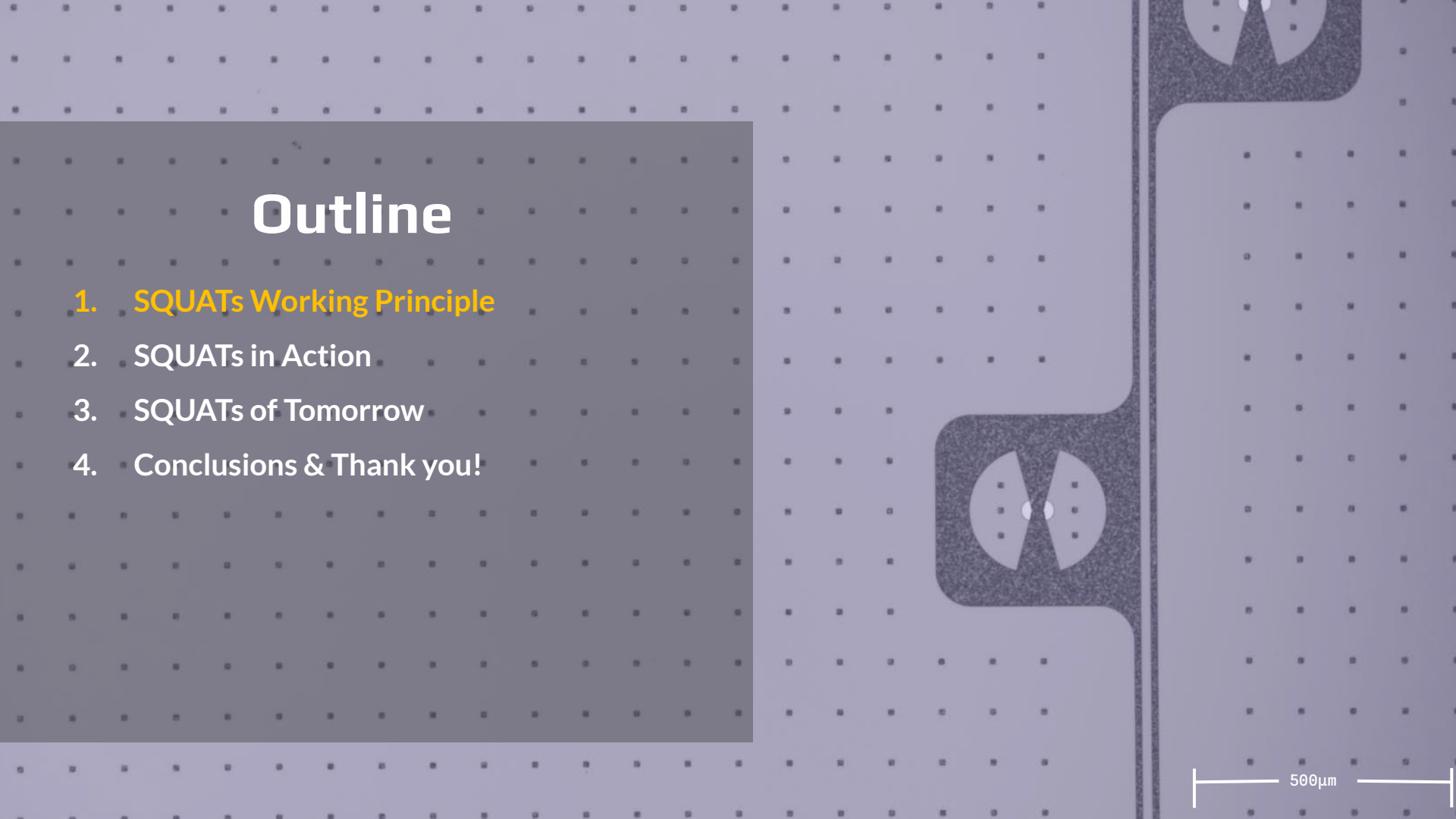
“The Superconducting Quasiparticle-Amplifying Transmon: A Qubit-Based Sensor for meV Scale Phonons and Single THz Photons”, C.W. Fink, C.P. Salemi et al., [arXiv:2310.01345v2]

Characterization Paper

“A First Demonstration of the SQUAT Detector Architecture: Direct Measurement of Resonator-Free Charge-Sensitive Transmons”, H.Magoon, T.Aralis et al., [arXiv:2601.16261]

Outline

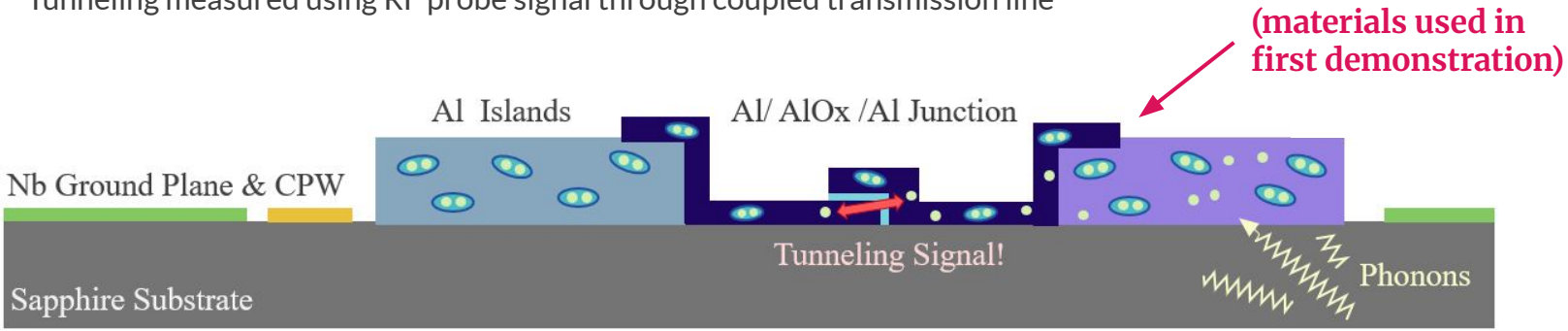
1. SQUATs Working Principle
2. SQUATs in Action
3. SQUATs of Tomorrow
4. Conclusions & Thank you!



SQUAT Overview

Basic sensing principal:

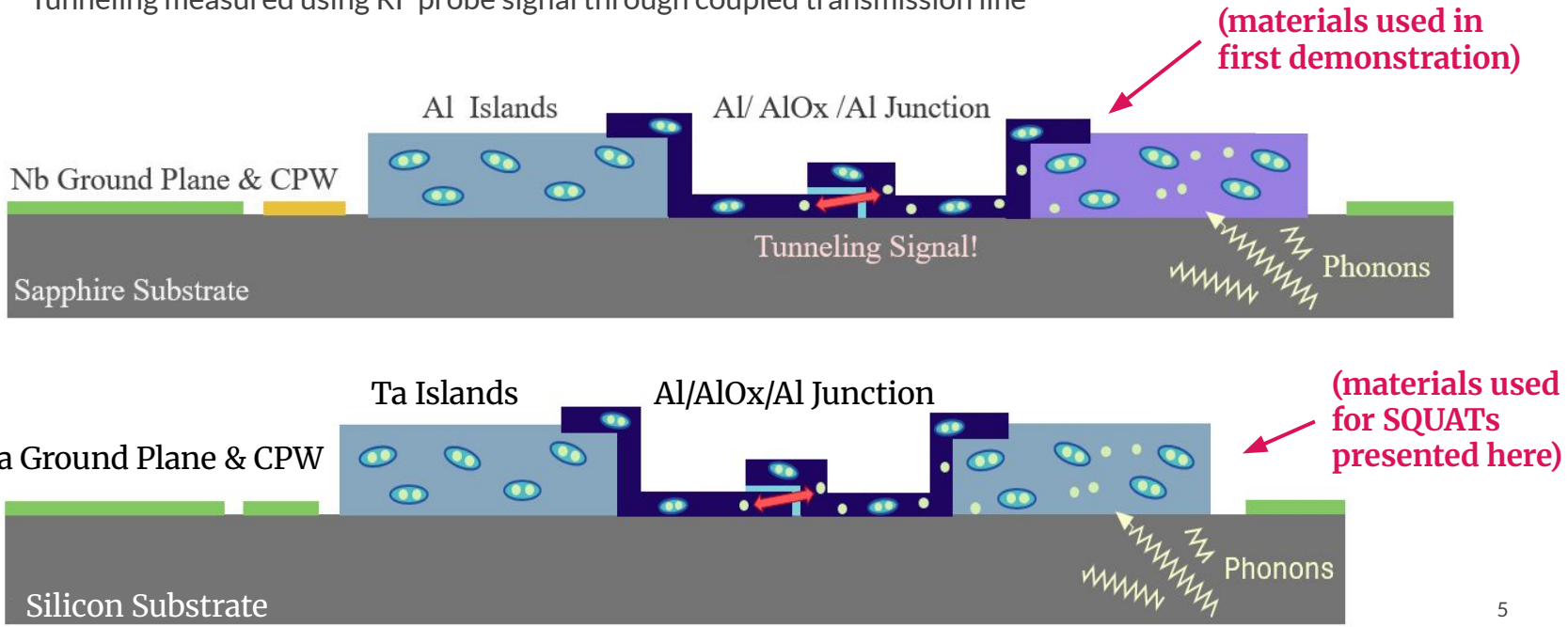
- Phonons produced in the substrate are absorbed by capacitive “islands/fins”
- Absorbed energy breaks Cooper-pairs in the superconductor ($\Delta \approx 0.2$ meV)
- Quasiparticles tunnel across the Josephson junction
- Tunneling measured using RF probe signal through coupled transmission line



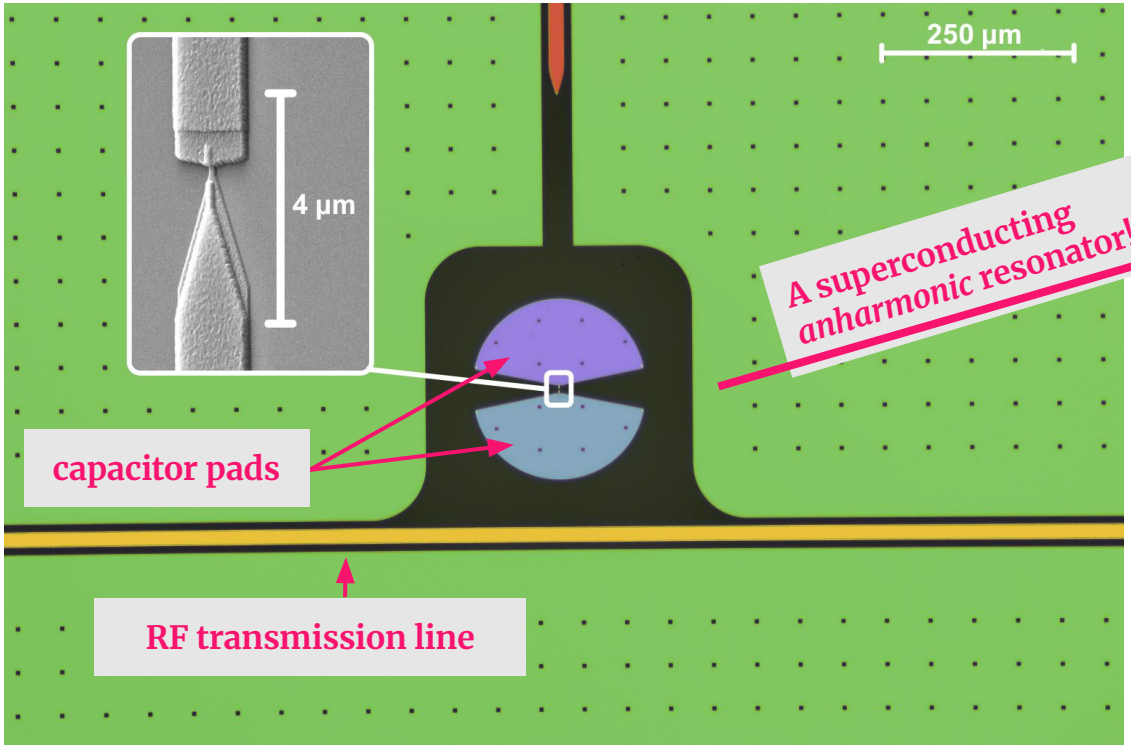
SQUAT Overview

Basic sensing principal:

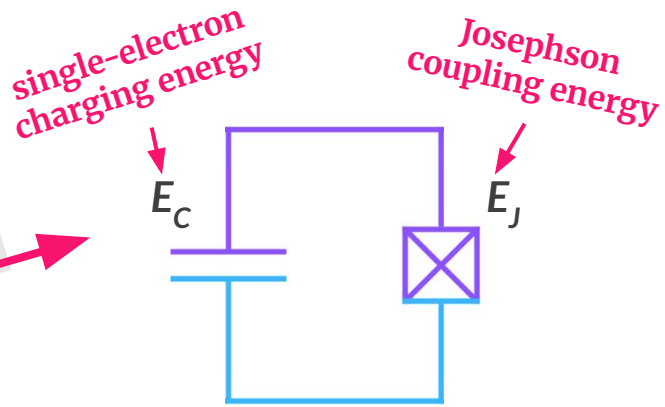
- Phonons produced in the substrate are absorbed by capacitive “islands/fins”
- Absorbed energy breaks Cooper-pairs in the superconductor ($\Delta \approx 0.2$ meV)
- Quasiparticles tunnel across the Josephson junction
- Tunneling measured using RF probe signal through coupled transmission line



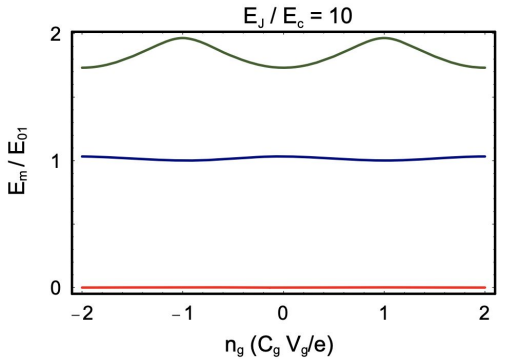
Qubit-based Sensing (e.g. SQUATs)



A superconducting anharmonic resonator!

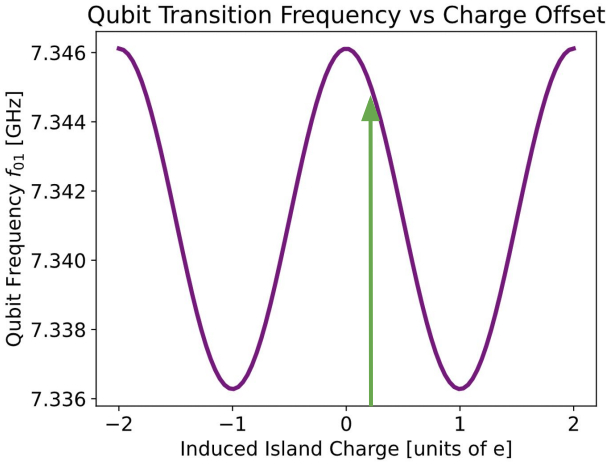


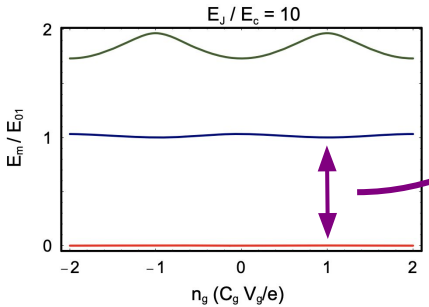
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\delta})$$



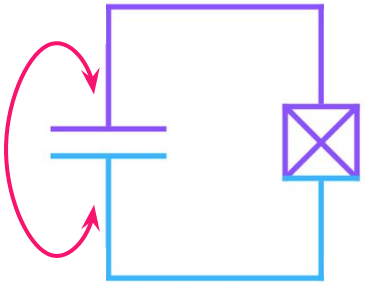
Qubit-based Sensing (e.g. SQUATs)

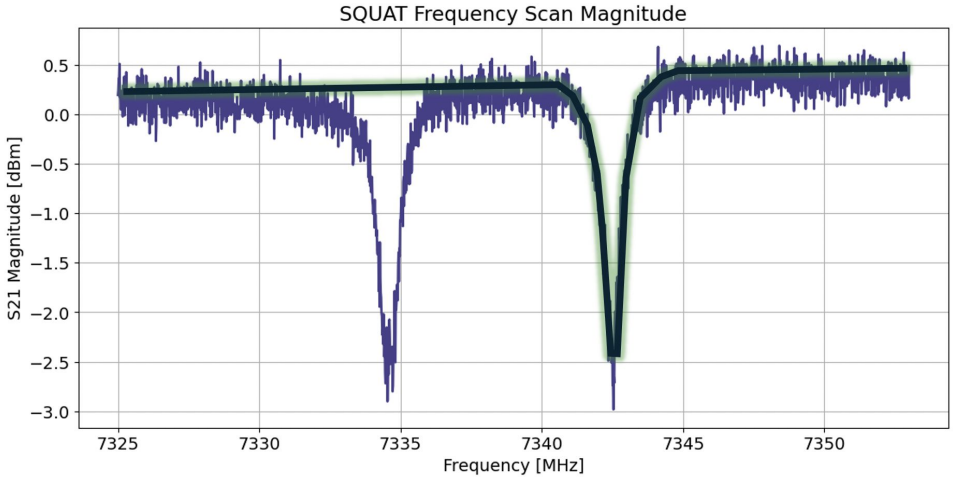
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\delta})$$





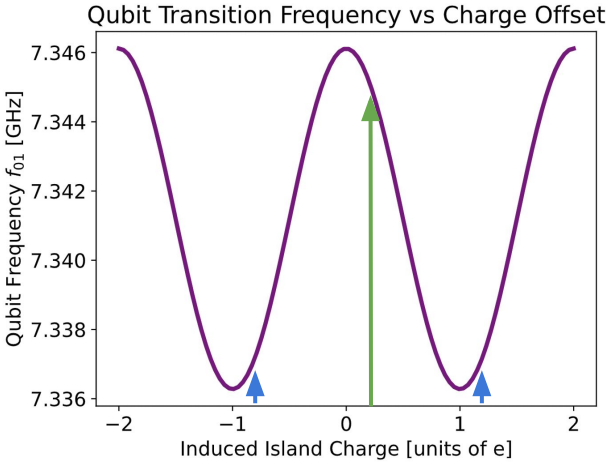
A single quasiparticle tunneling across the junction: $\Delta n_g = 1$

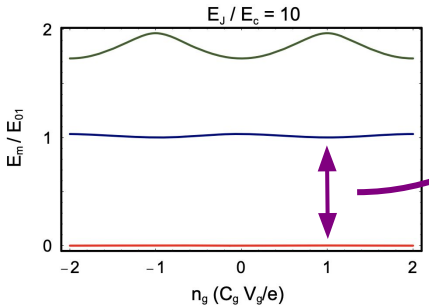




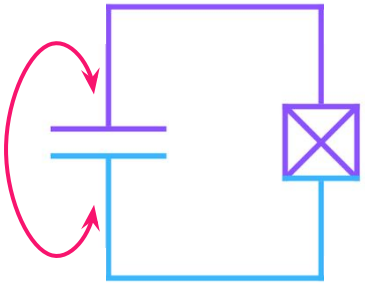
Qubit-based Sensing (e.g. SQUATs)

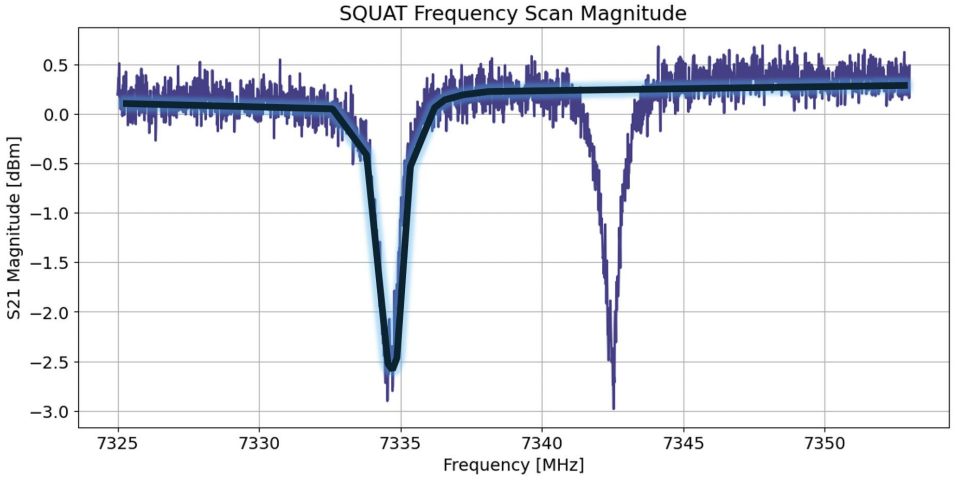
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\delta})$$





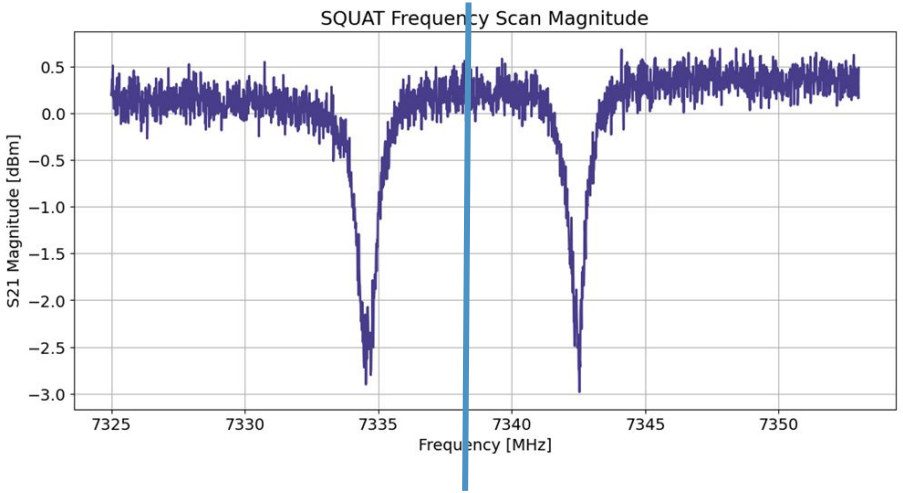
A single quasiparticle tunneling across the junction: $\Delta n_g = 1$





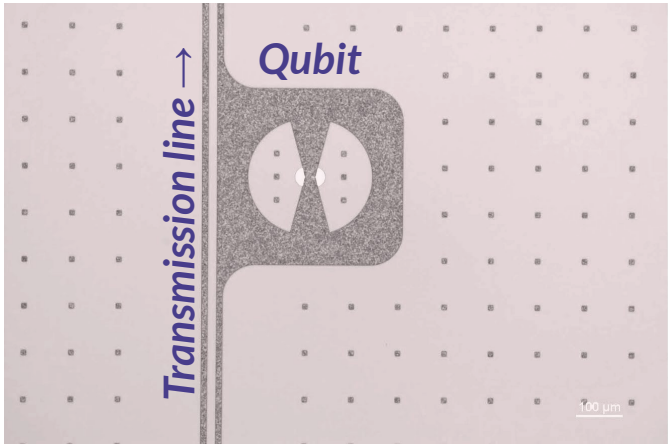
Parity Measurement Procedure

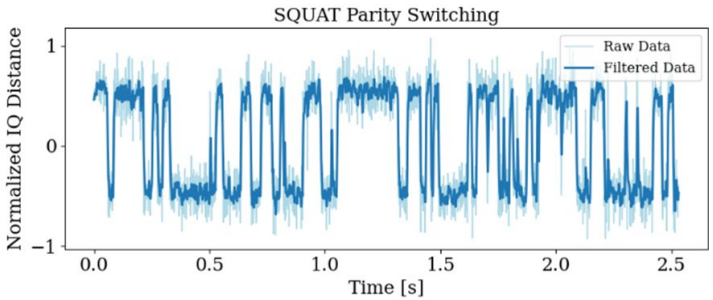
The SQUAT is a charge sensitive transmon directly coupled to a feedline, allowing for parity state tracking with a single CW readout tone



Readout tone

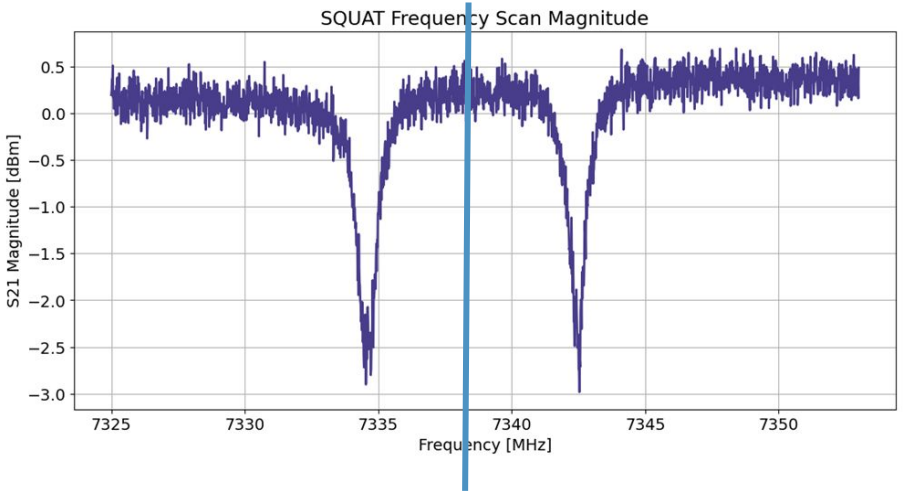
Plotting transmission of readout tone as a function of time shows tunneling events between parity states





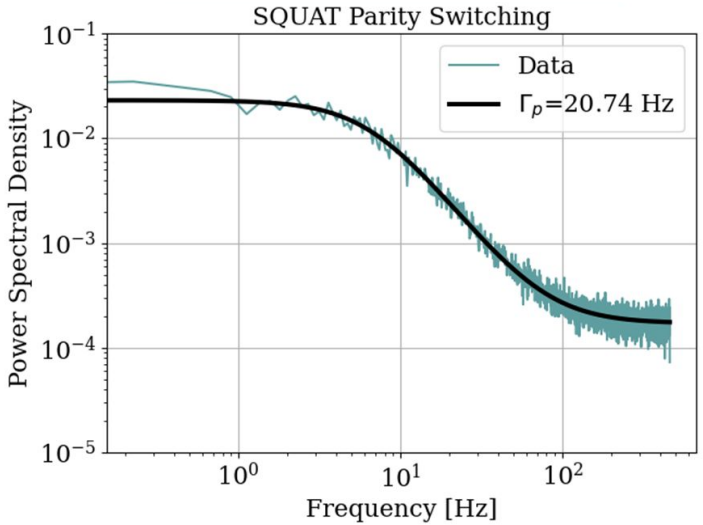
Parity Measurement Procedure

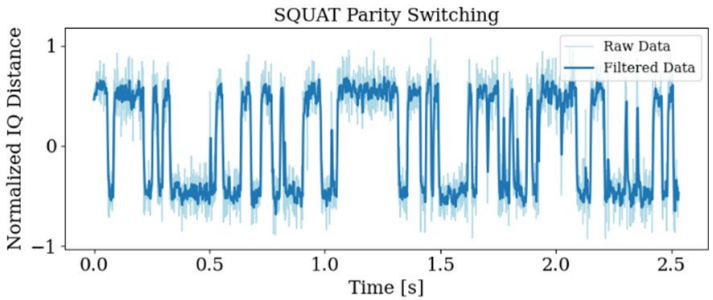
The SQUAT is a charge sensitive transmon directly coupled to a feedline, allowing for parity state tracking with a single CW readout tone



Readout tone

Plotting transmission of readout tone as a function of time shows tunneling events between parity states

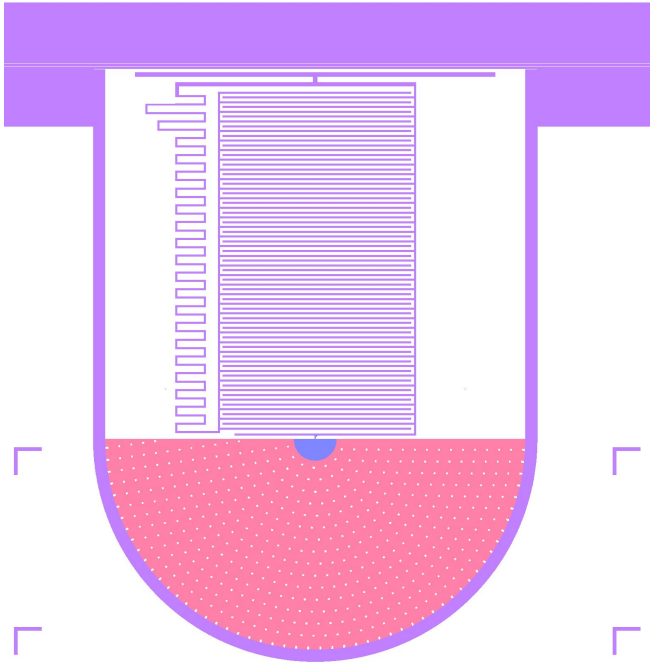




Two Quick Asides

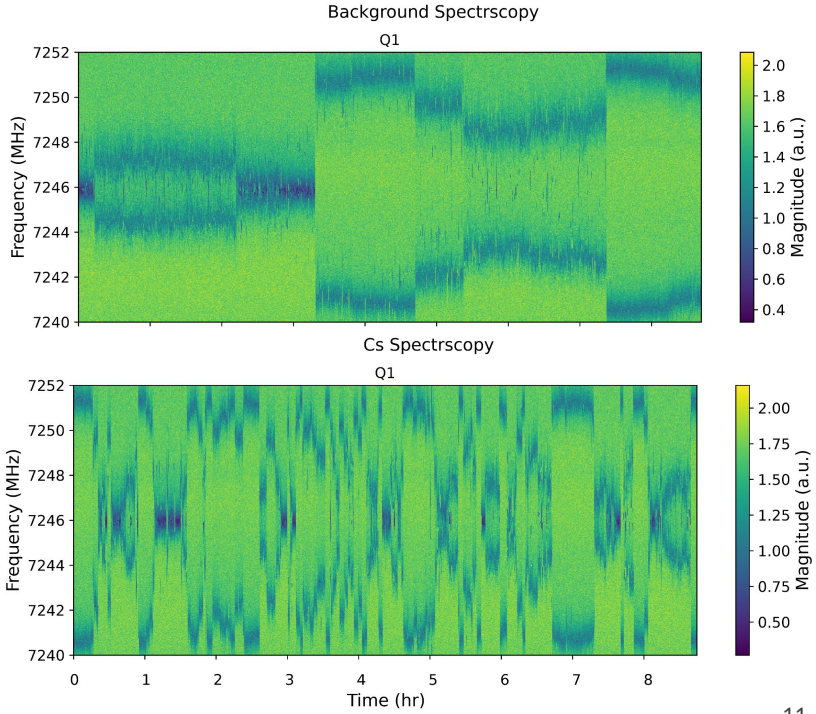
Alternative Architecture: Quantum Parity Detectors (QPDs) → See Brandon's Talk!

Resonator-coupled qubits with asymmetric tunnelling



Investigating Charge Events in SQUATs

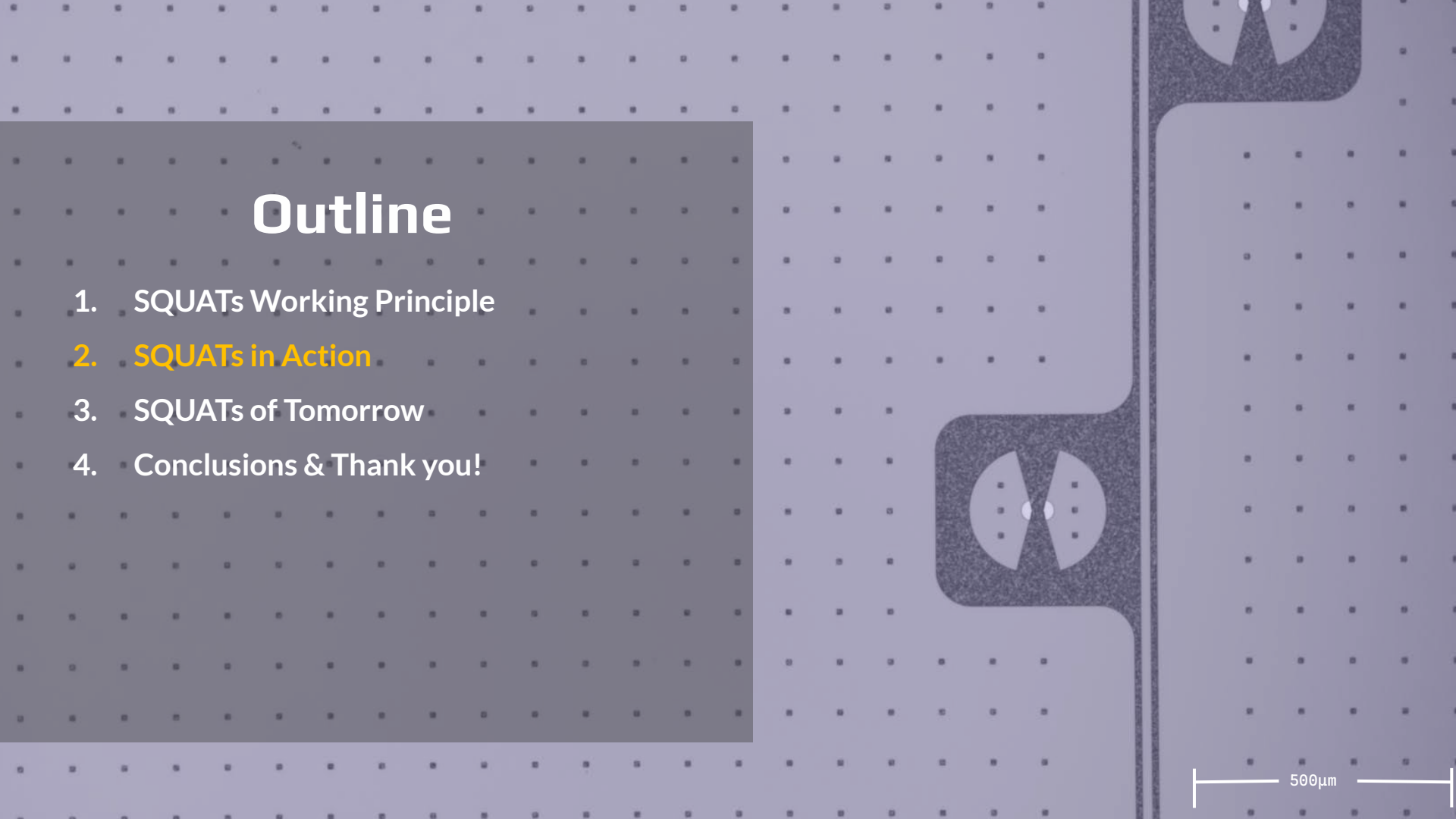
SLAC/FNAL: SQUAT charge dynamics in Si and sapphire



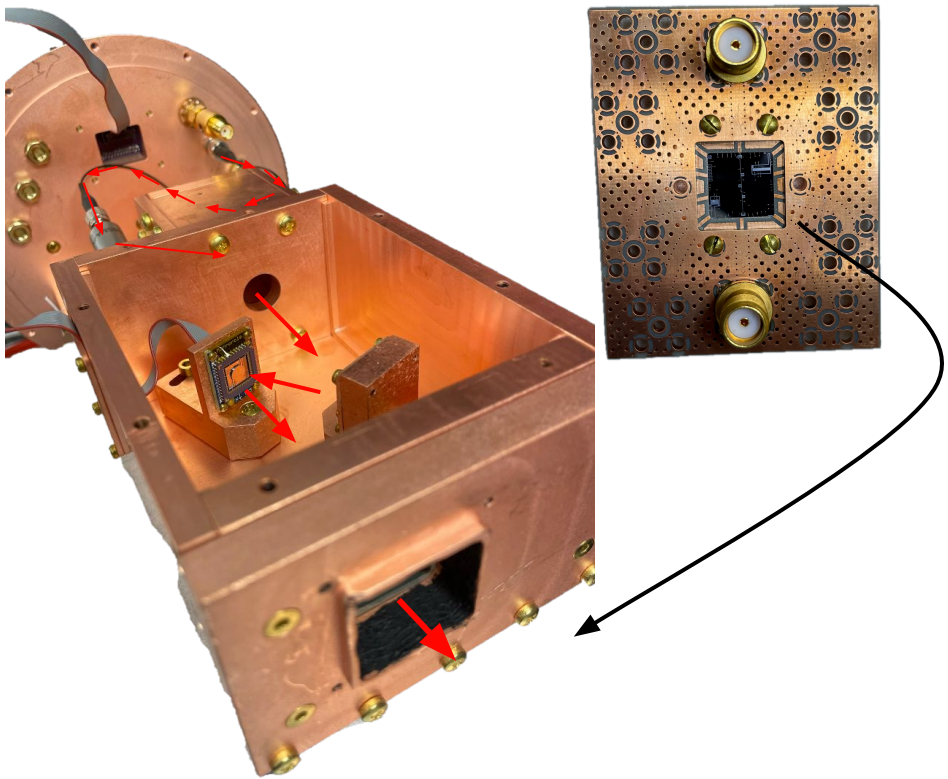
Plots courtesy of G. Bratrud (FNAL/Northwestern)

Outline

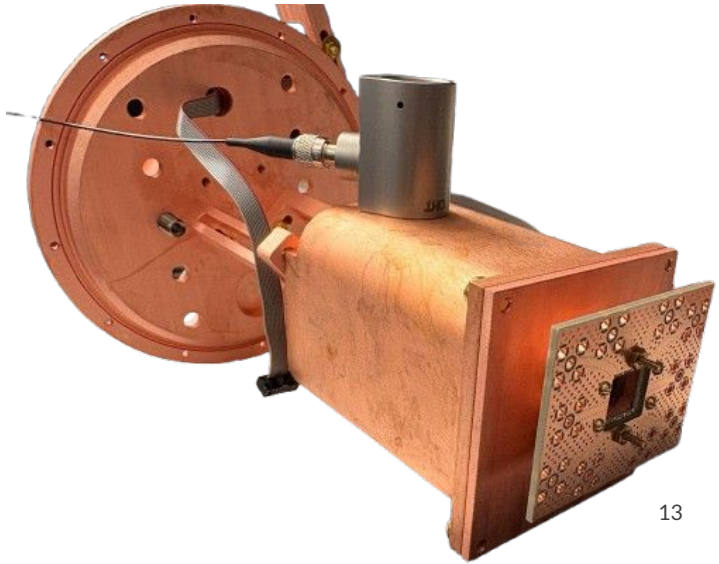
1. SQUATs Working Principle
2. SQUATs in Action
3. SQUATs of Tomorrow
4. Conclusions & Thank you!



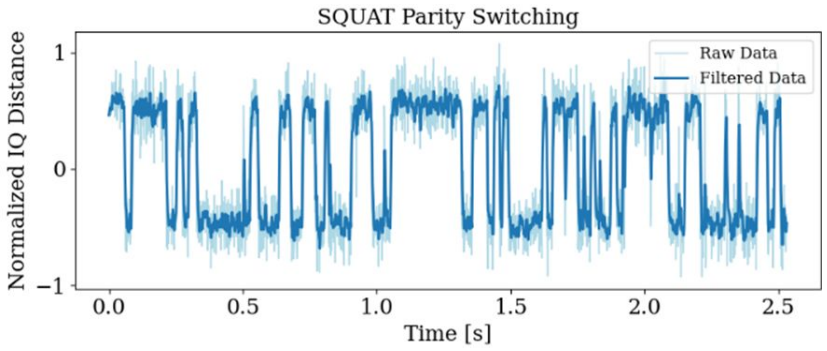
SQUAT Characterization *with MEMS Mirrors*



- Micro-ElectroMechanical System (MEMS) mirror optical steering assembly
  - XY position control (voltage-steered)
  - 80 um FWHM optical spot
  - 625 nm LED photon source
- Operates at mK temperatures, right above chip
- Backside chip illumination →phonon generation in Si



Continuous-wave MEMS Scans

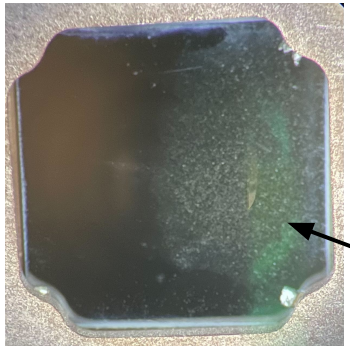


Measurement Pipeline

Data Collection

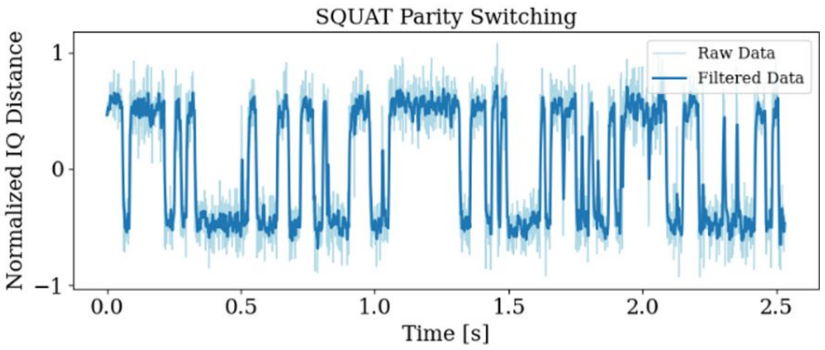
1. Direct MEMS beam at target location
2. Record N timestreams monitoring parity of target SQUAT
3. Repeat for all MEMS positions

Chip backplane: (target for MEMS light)



Silica dust *(debris from laser dicing)*

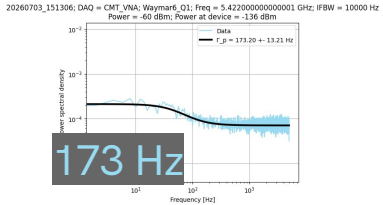
Continuous-wave MEMS Scans

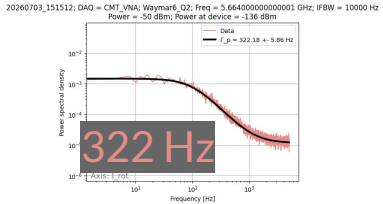


Measurement Pipeline

Data Collection

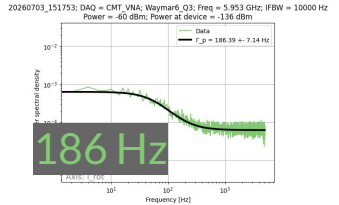
1. Direct MEMS beam at target location
2. Record N timestreams monitoring parity of target SQUAT
3. Repeat for all MEMS positions



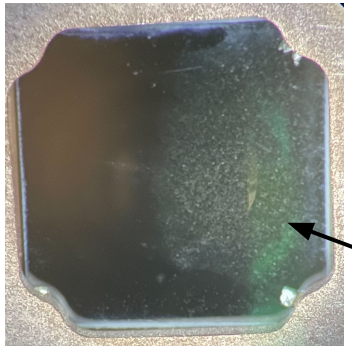


Data Processing

1. Take the PSD of all N timestreams at each location
2. Average the N PSDs and fit for the tunnelling rate, Γ_p
3. (optional) For combined imaging, normalize tunnelling rate for each SQUAT and add signals pixel-by-pixel

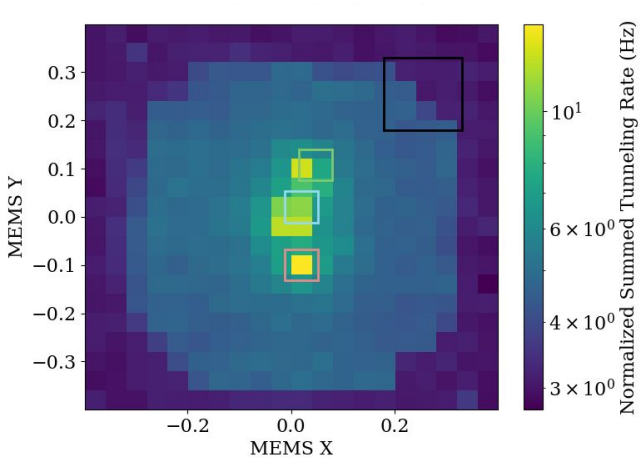


Chip backplane: (target for MEMS light)

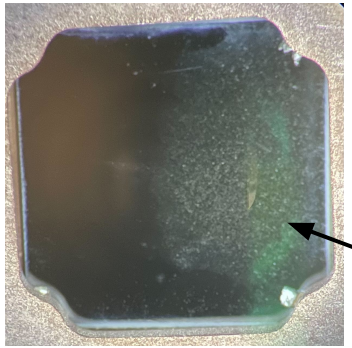


Silica dust *(debris from laser dicing)*

Continuous-wave MEMS Scans



Chip backplane: (target for MEMS light)



Silica dust *(debris from laser dicing)*

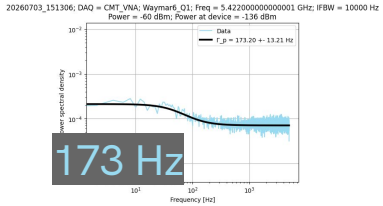
Measurement Pipeline

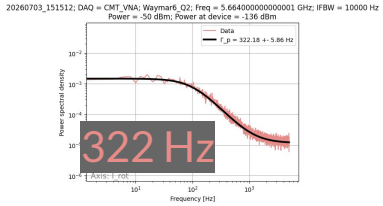
Data Collection

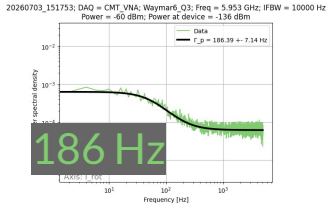
1. Direct MEMS beam at target location
2. Record N timestreams monitoring parity of target SQUAT
3. Repeat for all MEMS positions

Data Processing

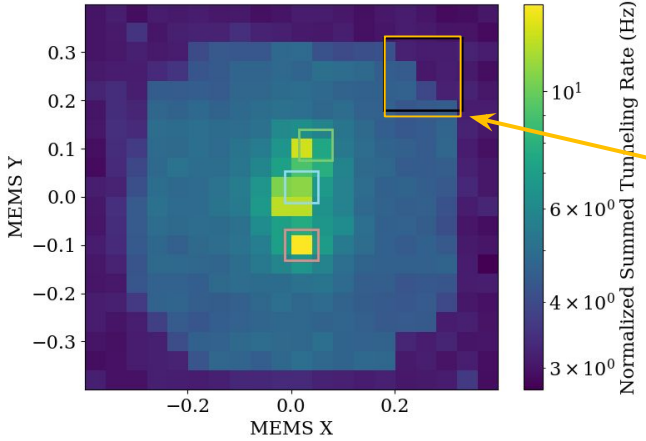
1. Take the PSD of all N timestreams at each location
2. Average the N PSDs and fit for the tunnelling rate, Γ_p
3. (optional) For combined imaging, normalize tunnelling rate for each SQUAT and add signals pixel-by-pixel

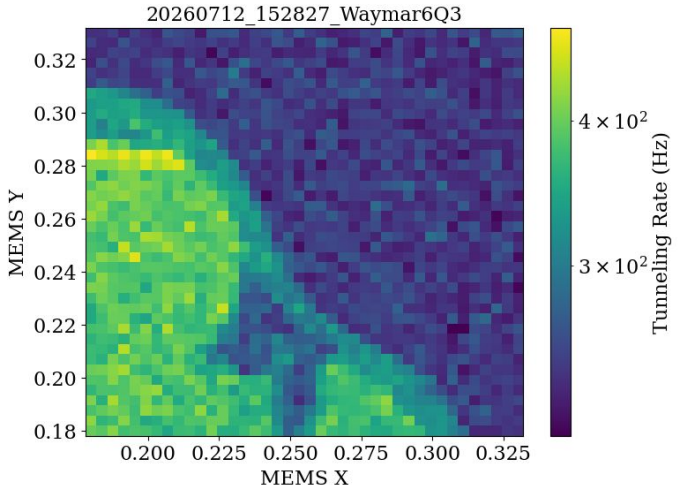




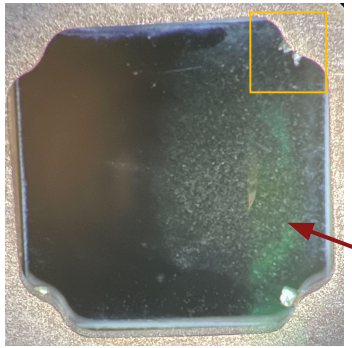


CW MEMS: Chip-scale Imaging

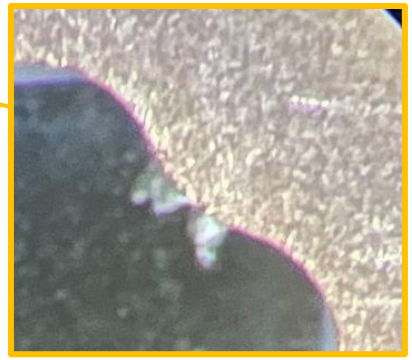




Chip backplane: (target for MEMS light)



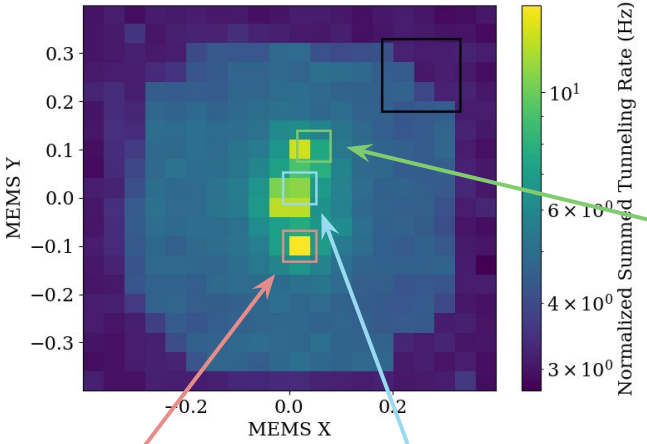
Silica dust *(debris from laser dicing)*

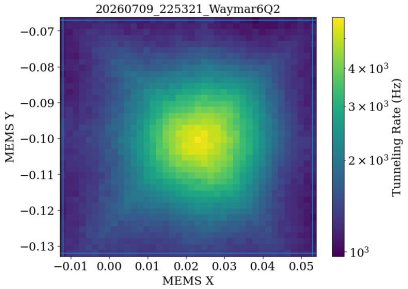


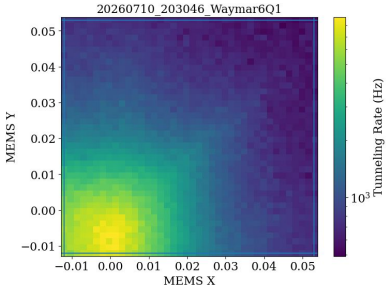
Indium wire *(used for mounting)*

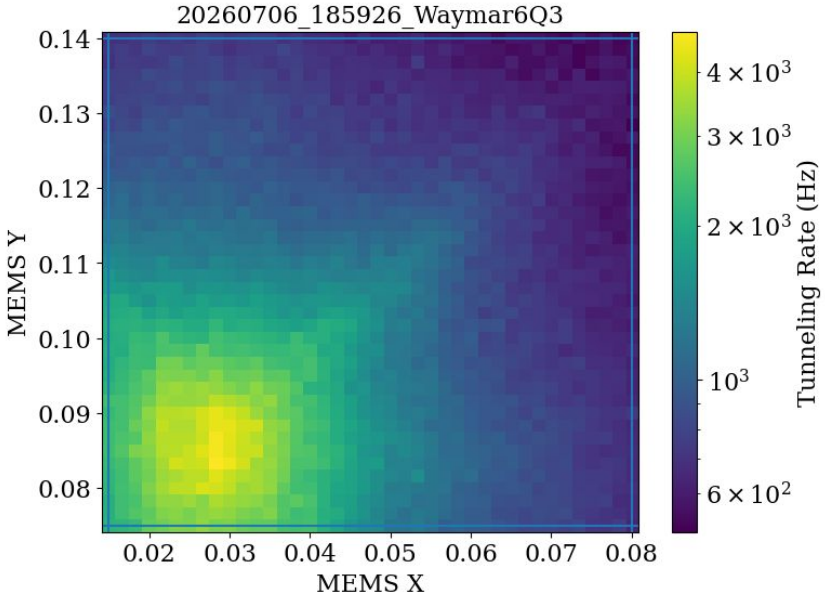
CW MEMS: SQUAT Zoom-in

Higher resolution MEMS scans in close proximity to each SQUAT



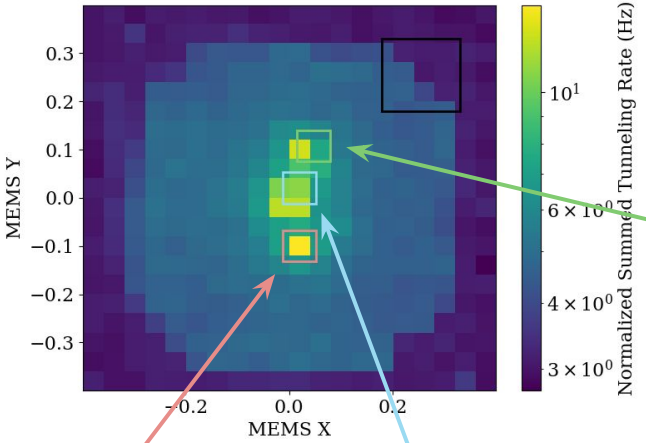


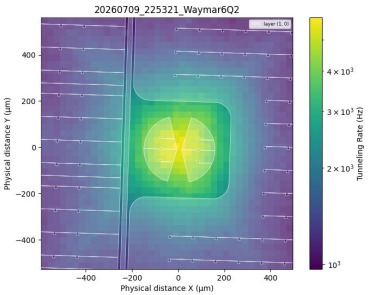


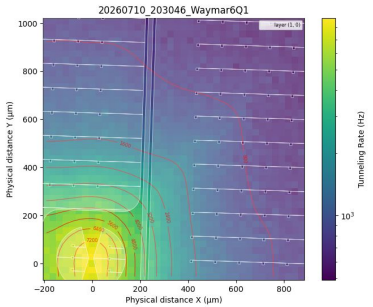


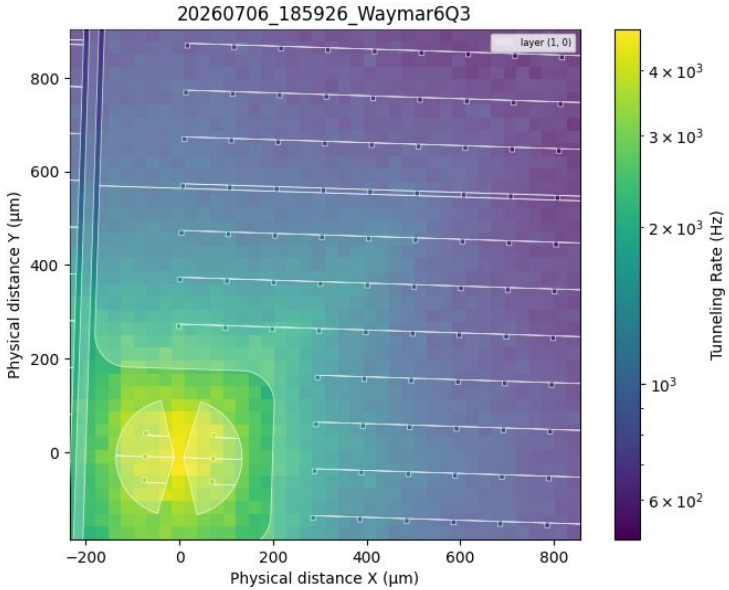
CW MEMS: SQUAT Zoom-in

Higher resolution MEMS scans in close proximity to each SQUAT





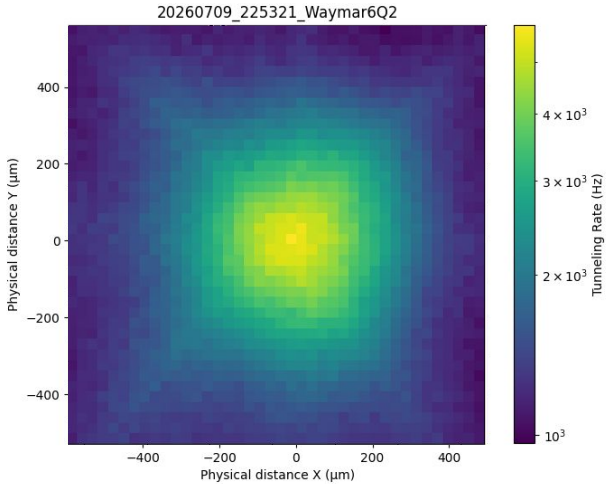




CW MEMS: Phonon Caustics

- Phonon propagation in silicon known to be anisotropic
- Preferential propagation along Si crystal axes produces a star-shaped pattern for the initial arrival position at the surface of a (100) Si substrate subject to backside phonon generation point source

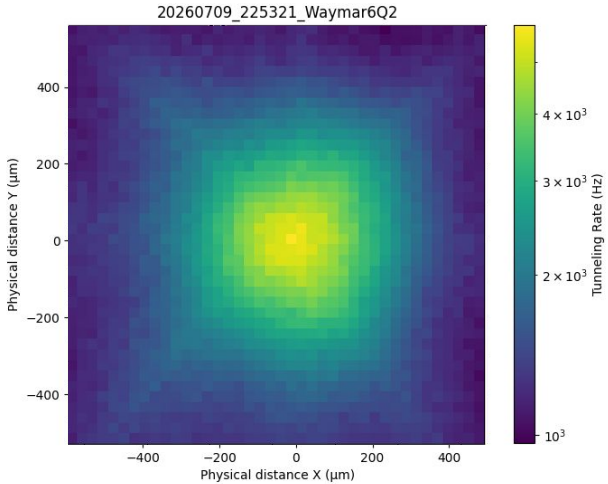
Data



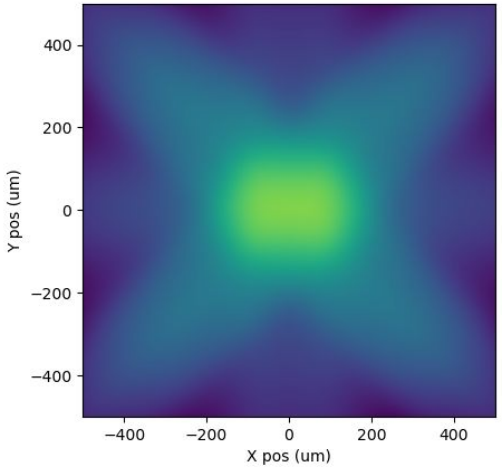
CW MEMS: Phonon Caustics

- Phonon propagation in silicon known to be anisotropic
- Preferential propagation along Si crystal axes produces a star-shaped pattern for the initial arrival position at the surface of a (100) Si substrate subject to backside phonon generation point source

Data



Monte-Carlo Simulation of
Phonon Trajectories in (100) Si*

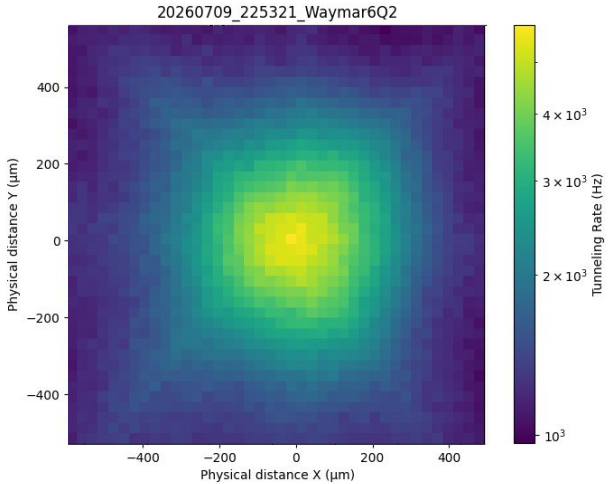


*Based on methods of B. Cabrera et al. *J Low Temp Phys 93*, 1993

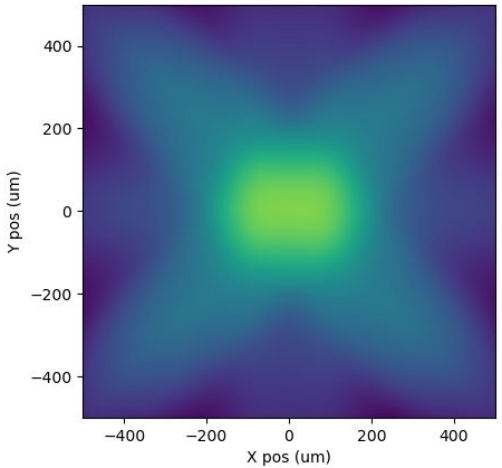
CW MEMS: Phonon Caustics

- Phonon propagation in silicon known to be anisotropic
- Preferential propagation along Si crystal axes produces a star-shaped pattern for the initial arrival position at the surface of a (100) Si substrate subject to backside phonon generation point source

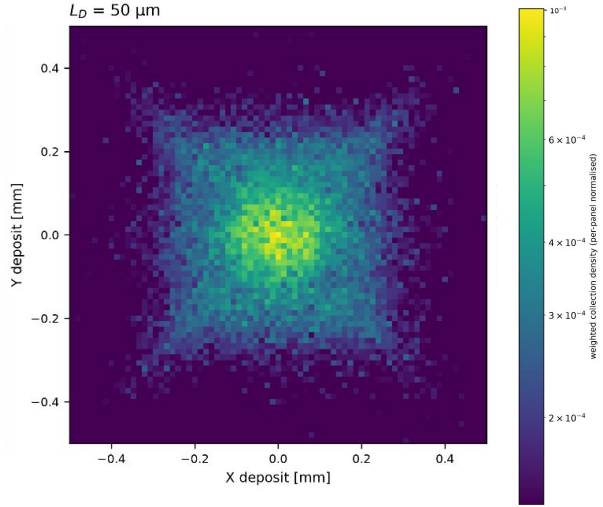
Data



Monte-Carlo Simulation of Phonon Trajectories in (100) Si*



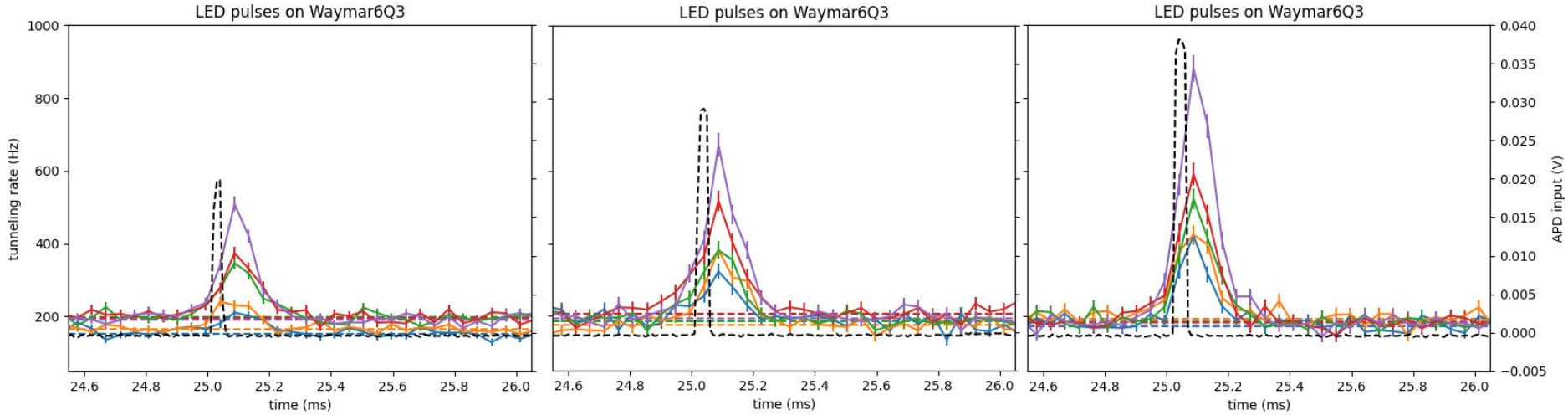
G4CMP Simulation of Phonon Trajectories and Absorption



*Based on methods of B. Cabrera et al. *J Low Temp Phys 93*, 1993

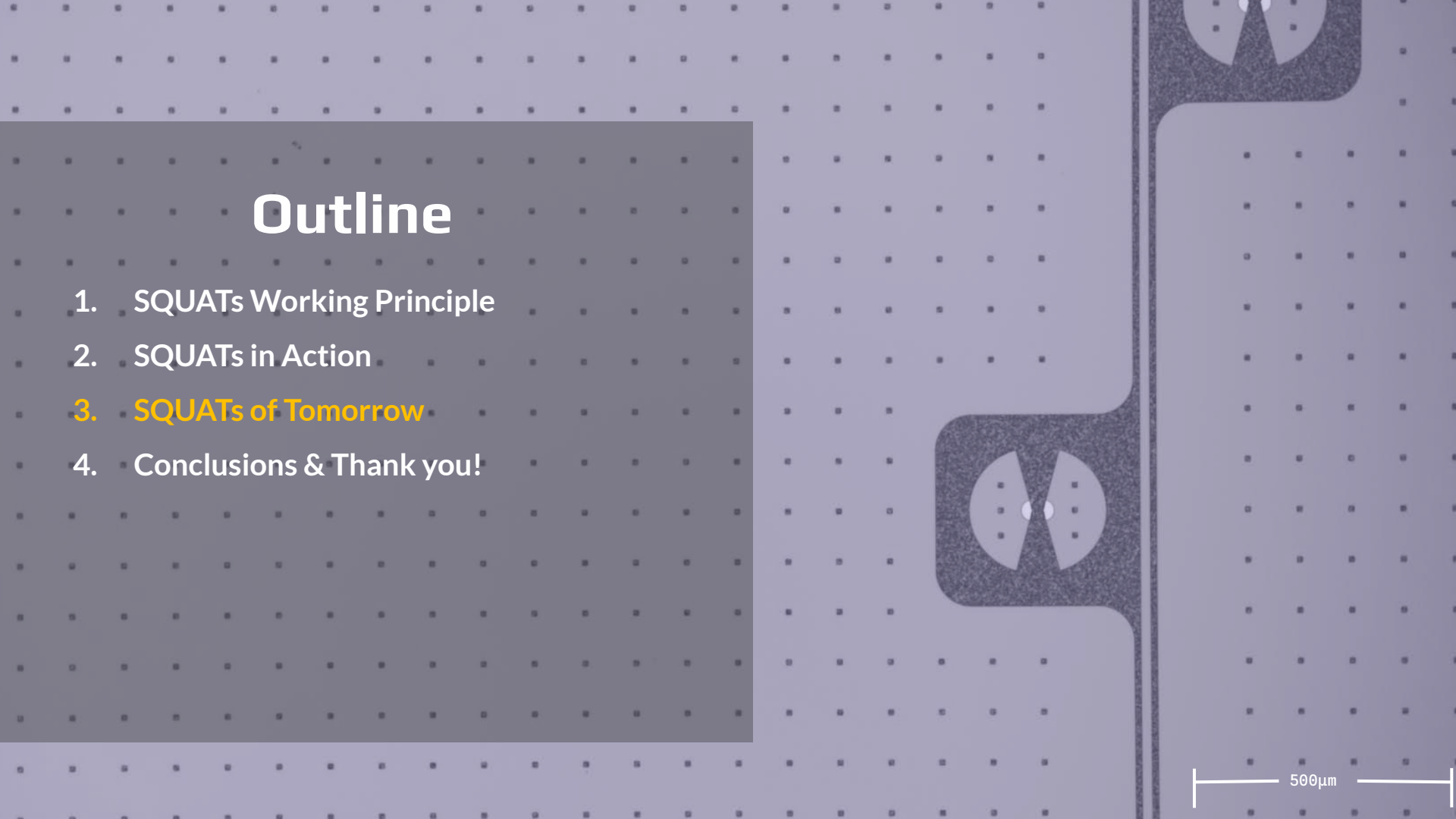
Preliminary MEMS Pulse Response

- 50 us pulse length shown here; some response observed down to 5 us pulse length
- Low intensity regime required to mitigate charge events
- Tunnelling rate, averaged over many identical pulses aimed at particular chip locations
  - Response peaks directly behind the SQUAT
  - Peak height roughly proportional to LED pulse intensity

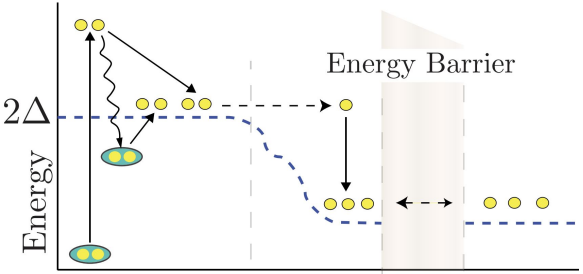


Outline

1. SQUATs Working Principle
2. SQUATs in Action
3. SQUATs of Tomorrow
4. Conclusions & Thank you!



Quasiparticle Trapping

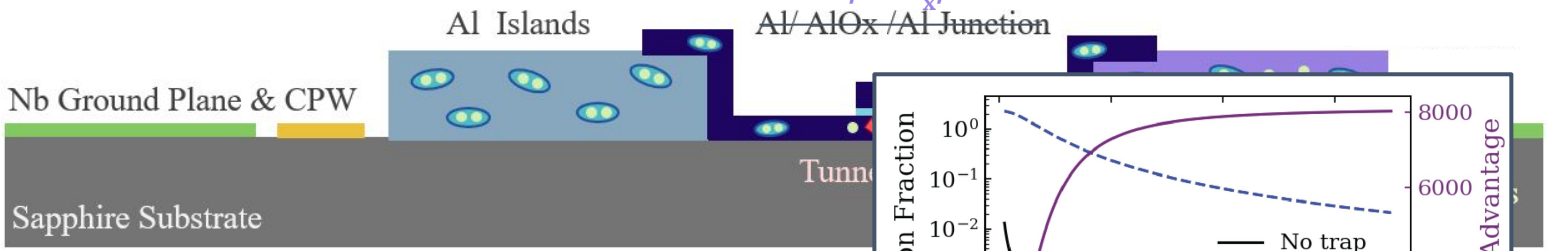


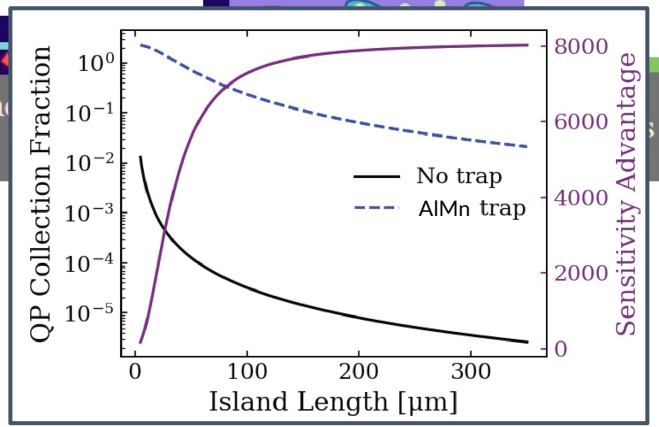
Basic sensing principal **w/trapping!**

- Phonons produced in the substrate are absorbed by capacitor "fins"
- Absorbed energy breaks Cooper-pairs in the superconductor (Δ≈0.2 meV)
- **Quasiparticles diffuse into lower gap junction (e.g. AlMn, Hf) → downconvert → trapped**
- Quasiparticles tunnel across the Josephson junction
  - **More often, with quasiparticles trapped near the junction**
  - **Possible for single quasiparticles to tunnel multiple times**
- Tunneling measured using RF probe signal through coupled transmission line

Like QETs

AlMn/AlOx/AlMn
Hf/HfO_x/Hf
~~Al/ AlOx /Al Junction~~

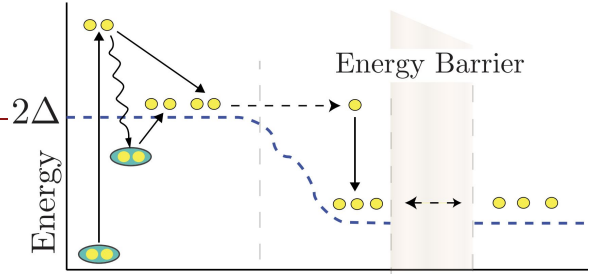




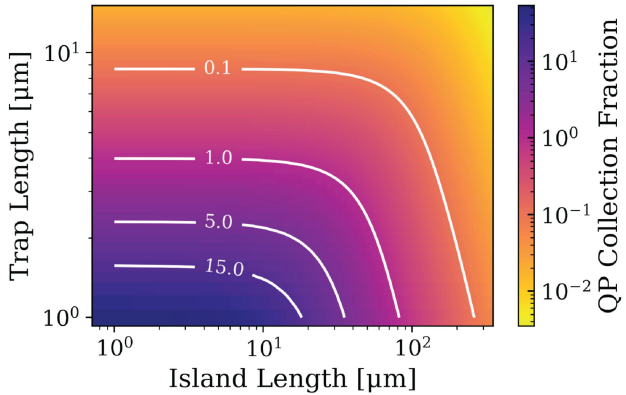
~~(materials are those used in first demonstration)~~

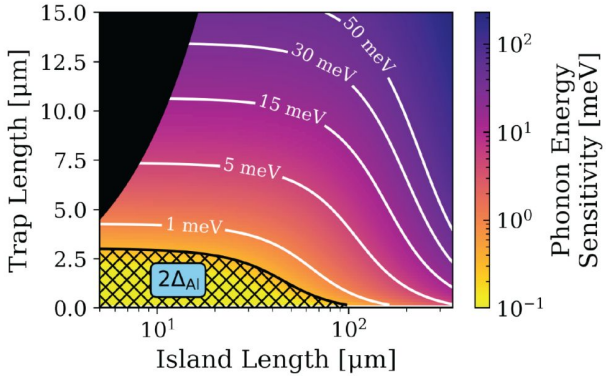
Superconducting Quasiparticle Amplifying Transmon (SQUAT)

Quasiparticle Trapping



Simulated sensitivity advantage (assuming Al fins and Tc~100mK junctions):



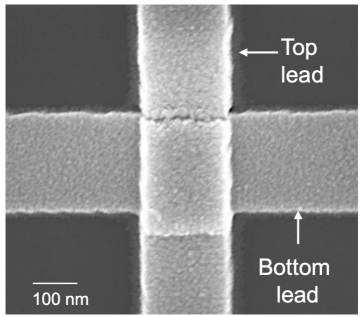


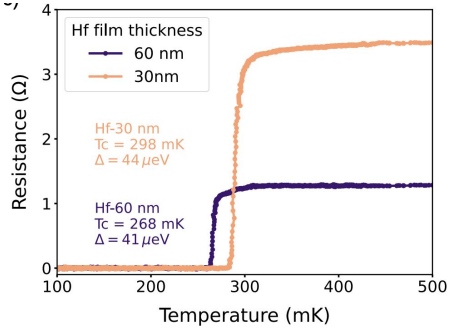
Low-Tc Junction Development

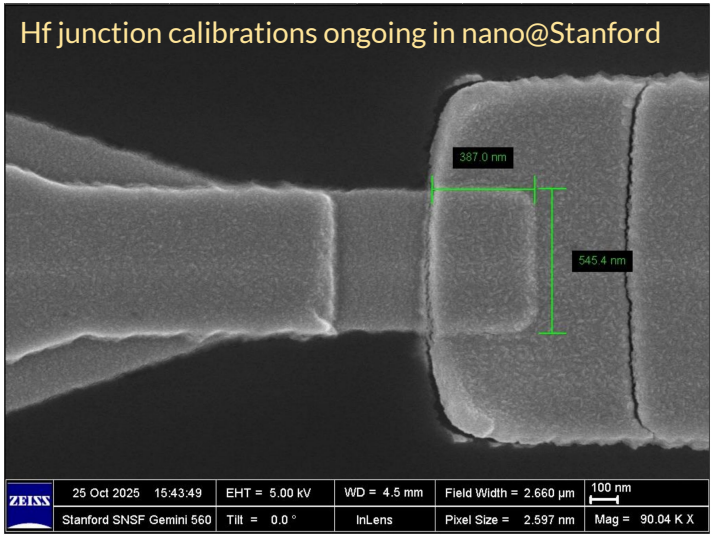
- Low Tc junctions allow gap-engineered QP trapping, improving device sensitivity
- Hf (Δ≈0.017 meV) junctions shown viable

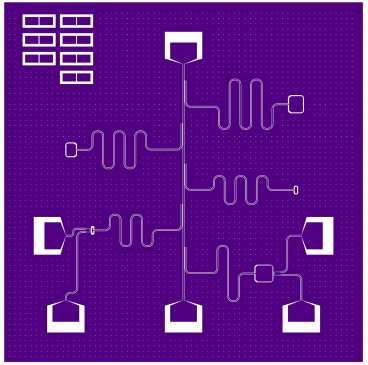
Low-Gap Hf–HfO$_x$–Hf Josephson Junctions for meV-Scale Particle Detection

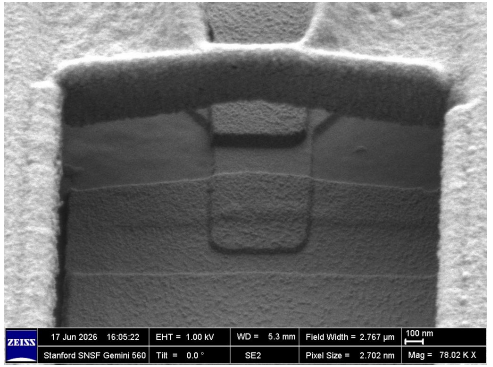
Y. Balaji[1], M. Surendran[1], X. Li[2], A. Kemelbay[1], A. Gashi[1], C. Salemi[2,3], A. Suzuki[2], S. Aloni[1], A. Tynes Hammack[1], and A. Schwartzberg[1]
[1]*Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA*
[2]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA and*
[3]*Department of Physics, University of California Berkeley, Berkeley, CA-94720, USA*
(Dated: November 11, 2025)











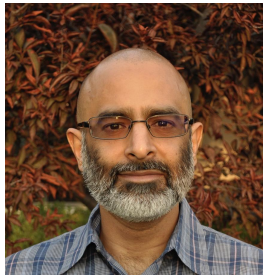
Transmon qubit designed to benchmark coherence & critical current density

SoniQ Collaboration *(Sensing of Neutrinos In Qubits)*

WashU Caltech DMQiS SLAC The University of Wisconsin Madison The University of California Berkeley JPL Jet Propulsion Laboratory California Institute of Technology



Karthik Ramanathan



Sunil Golwala



Noah Kurinsky



Britton Plourde



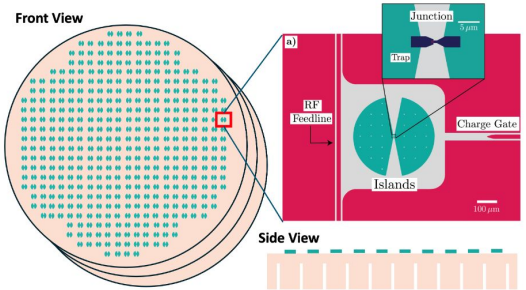
Chiara Salemi

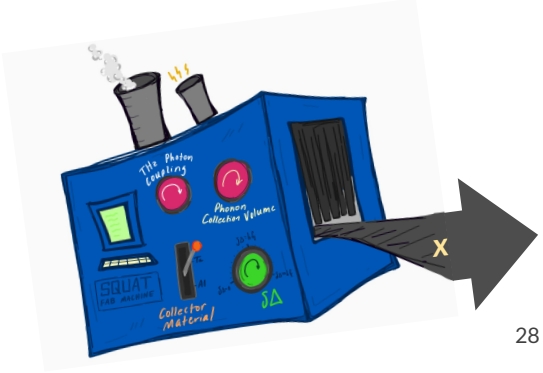


Pierre Echternach

Final Deliverable

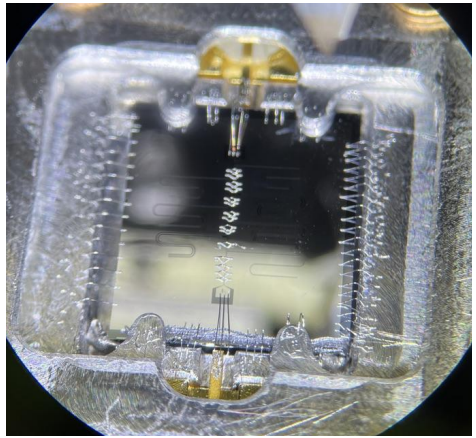
- 14x Ge wafers
- 4” by 2 mm thick
- Voxelized into 1x1 mm smaller segments
- ~6400 qubits per wafer

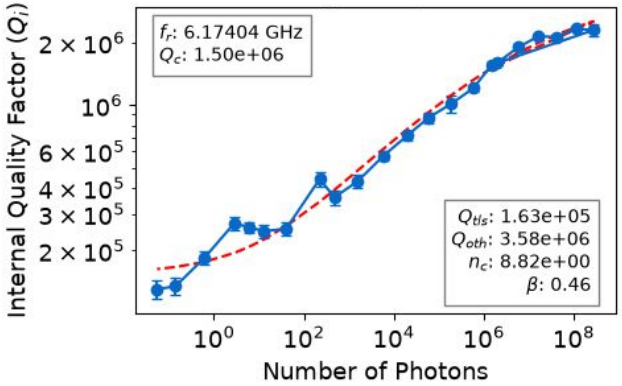


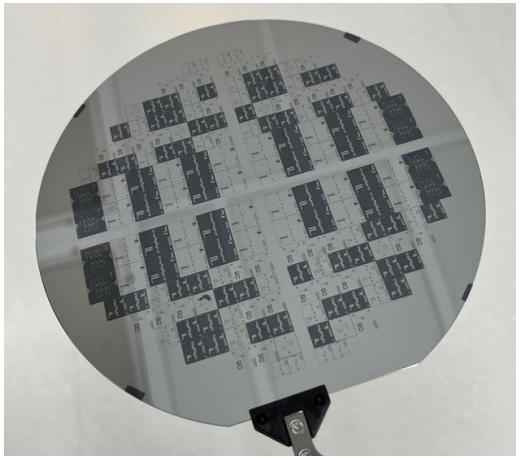


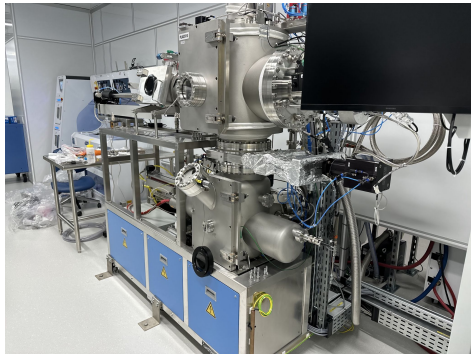
The SLAC Detector Microfabrication Facility (DMF)

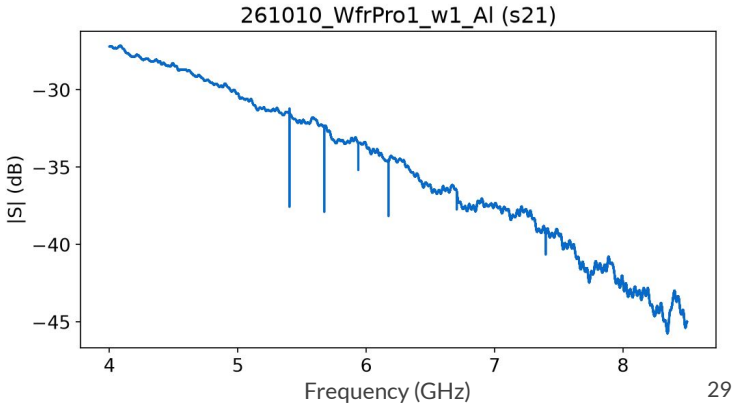
- Ge substrates and Hf source material undergoing approval for use in a Plassys MEB700S2-I UHV evaporator
- First cryogenic measurements of Al CPW resonators fabricated entirely in the DMF





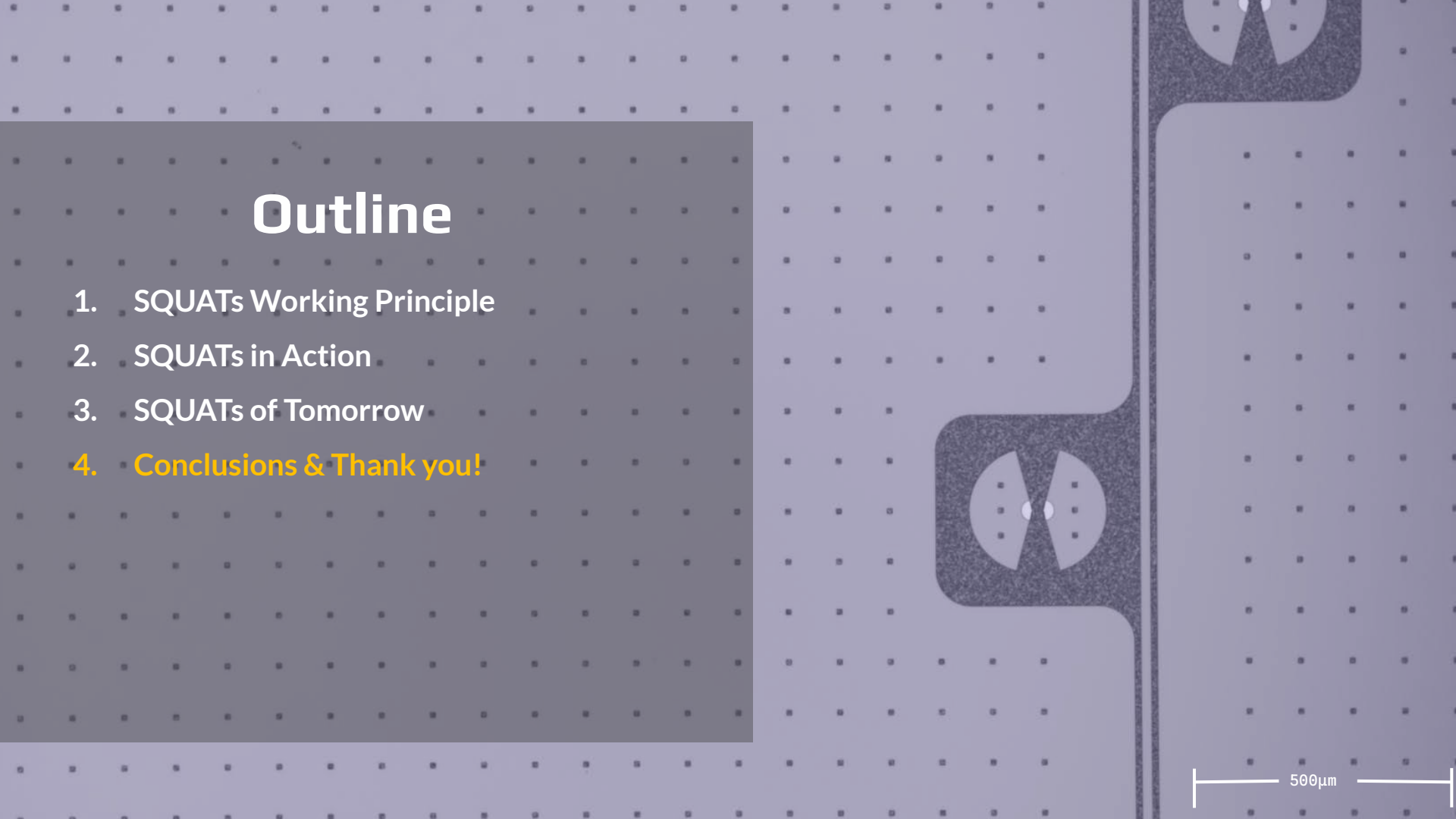




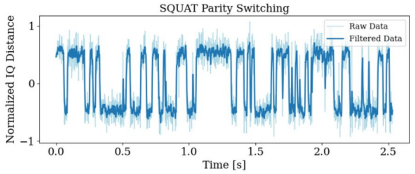


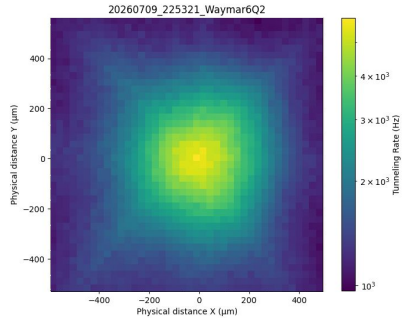
Outline

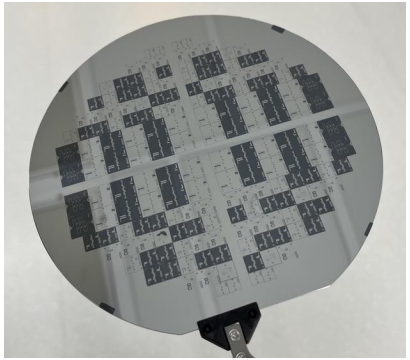
1. SQUATs Working Principle
2. SQUATs in Action
3. SQUATs of Tomorrow
4. Conclusions & Thank you!



Conclusions





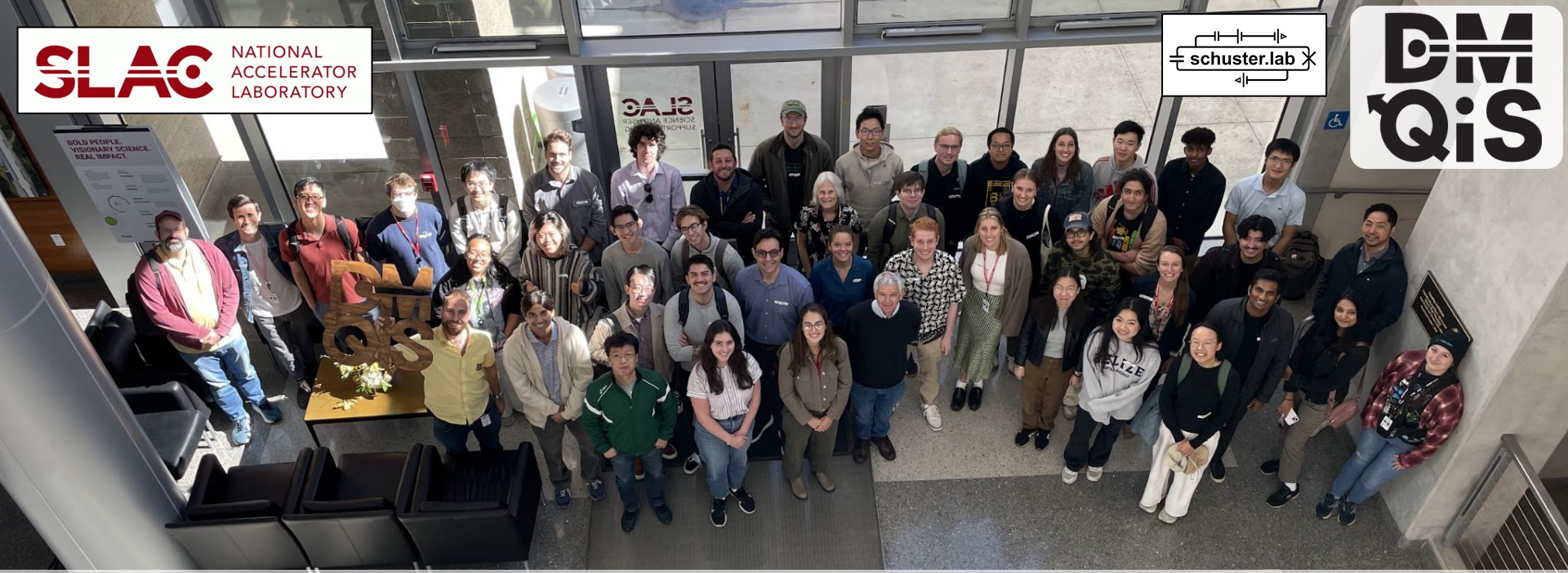


The SQUAT architecture enables straightforward measurement of QP tunneling, enabling measurement of photon and/or phonon events

Continuous-wave MEMS scans demonstrate phonon sensitivity, evidenced by characteristic (100) Si phonon caustics

Pulsed MEMS measurements ongoing to develop an energy calibration

Fabrication of next-gen SQUATs in development at the SLAC Detector Microfabrication Facility



Faculty/Staff

Noah Kurinsky (SLAC)
Shannon Harvey (SLAC)
David Schuster (Stanford)
Kelly Stifter (SLAC)
Shawn Henderson (SLAC)
Jenny Smith (SLAC Engineer)
Sidney Stevens (SLAC Engineer)
Betty Young (SCU)

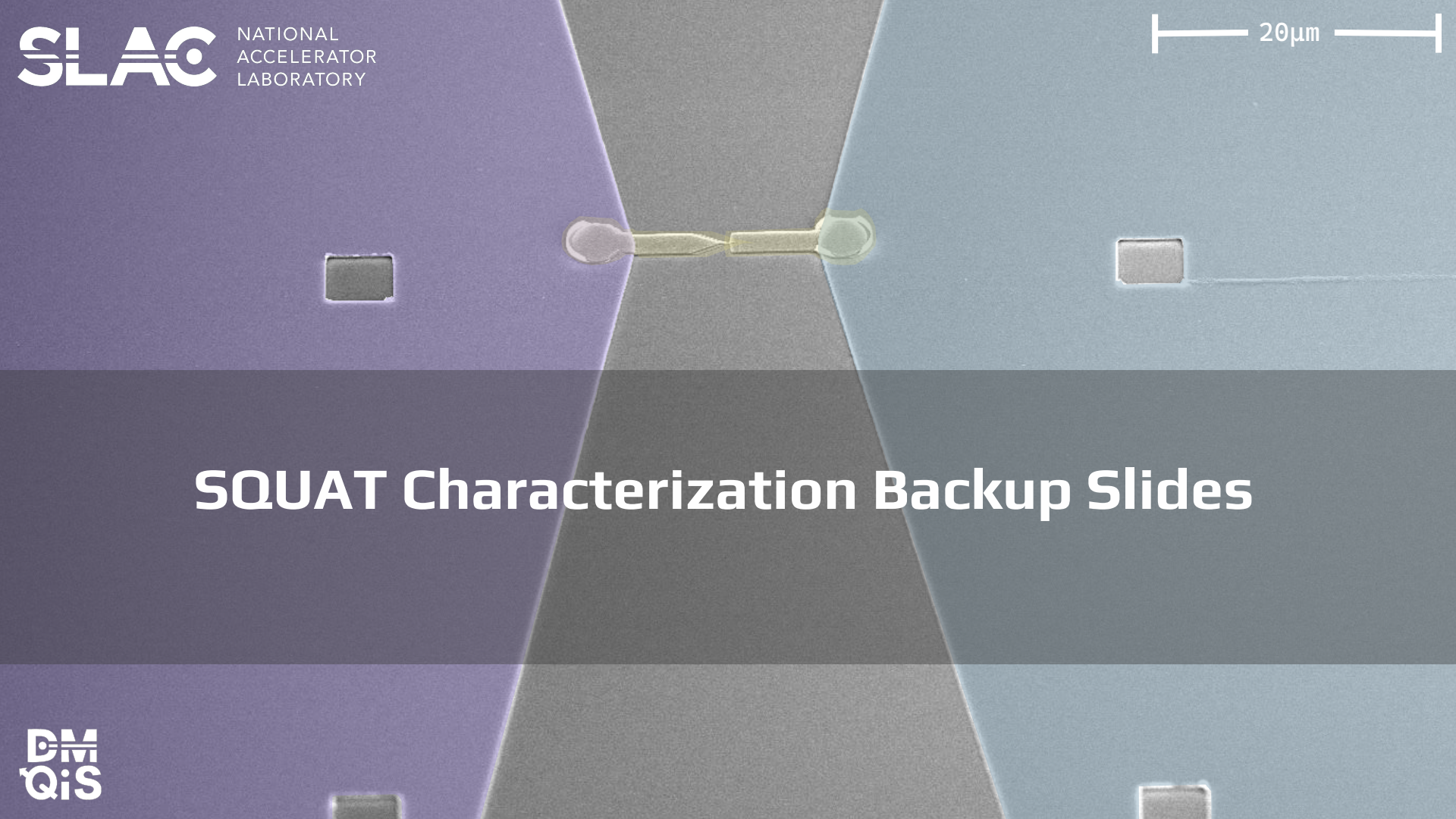
Postdocs

Taylor Aralis (SLAC)
Alex Droster (SLAC)
Aditi Pradeep (SLAC)

Students

Hannah Magoon (SLAC/Stanford)
Riley Carpenter (SLAC/Stanford)
Zach Gillis (SLAC/Stanford)
Taj Dyson (SLAC/Stanford)
Aviv Simchony (SLAC/Stanford)
Holden Kowitt (undergrad)
Emily Scott (undergrad)

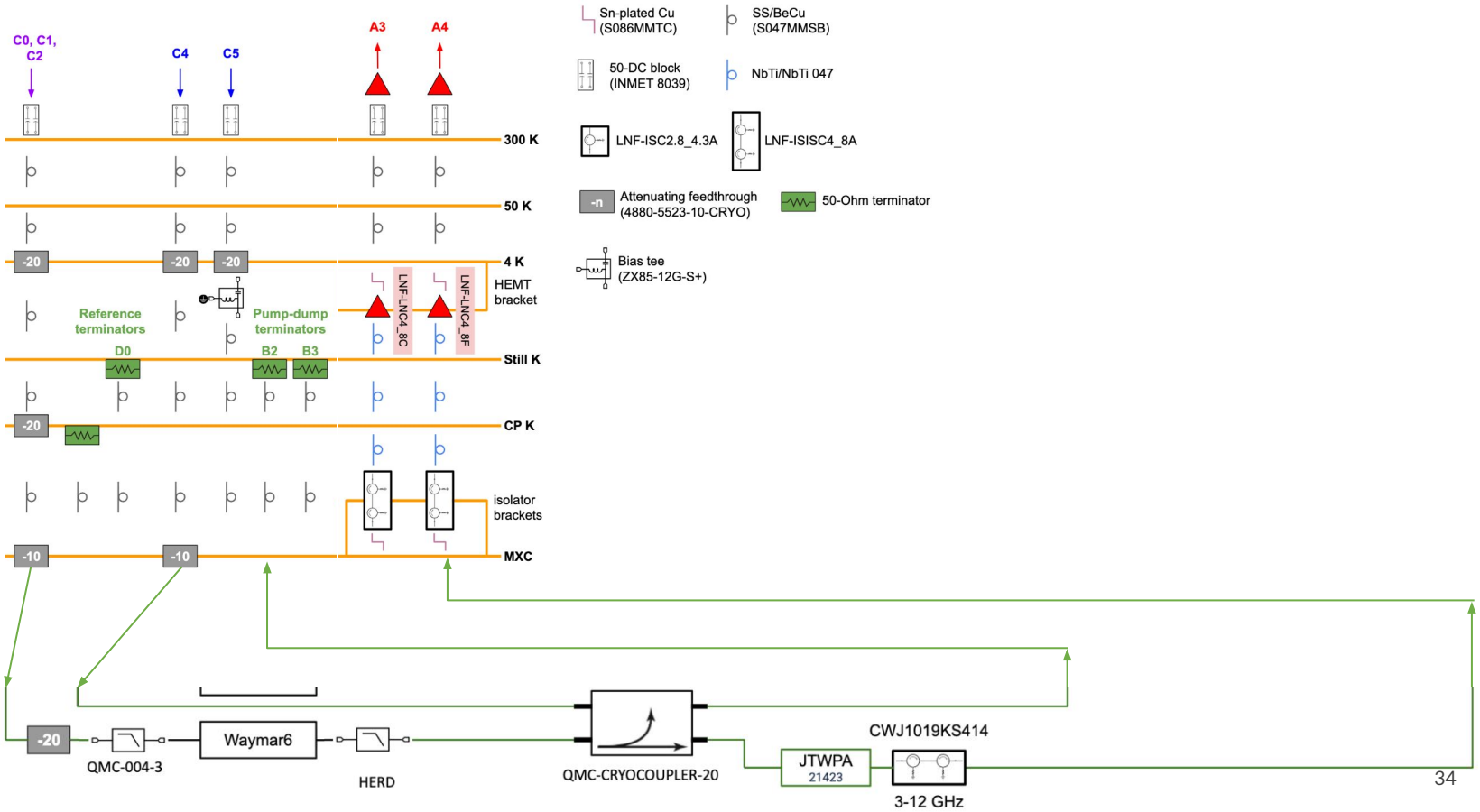
SLAC NATIONAL ACCELERATOR LABORATORY



SQUAT Characterization Backup Slides

DMQiS

Dilution Refrigerator RF Wiring Diagram

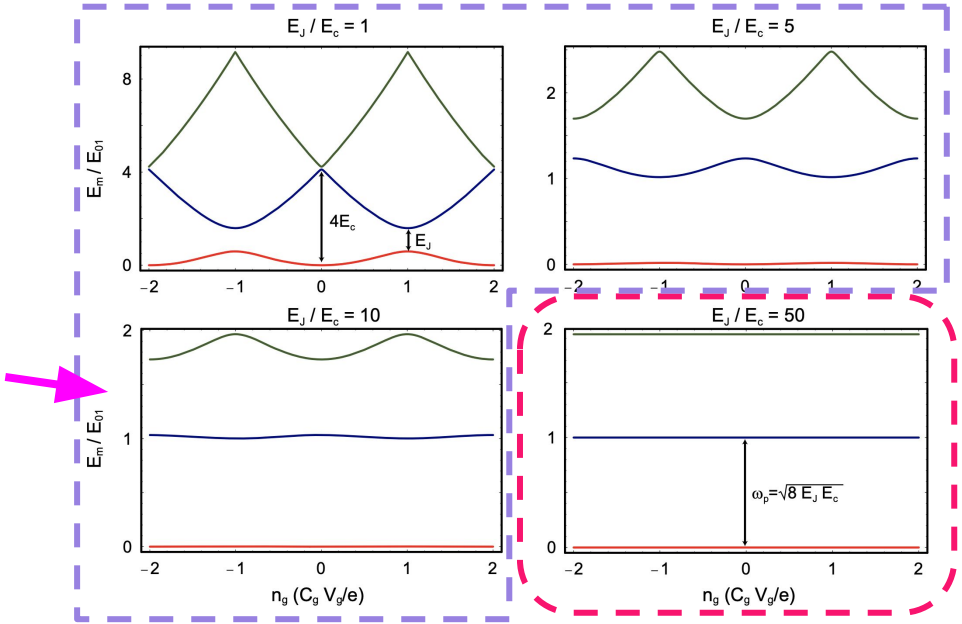


Qubit-based Sensing (e.g. SQUATs)

Transmon qubits are designed in this regime:

- Nearly insensitive to charge noise
- Sufficient anharmonicity to be an effective TLS

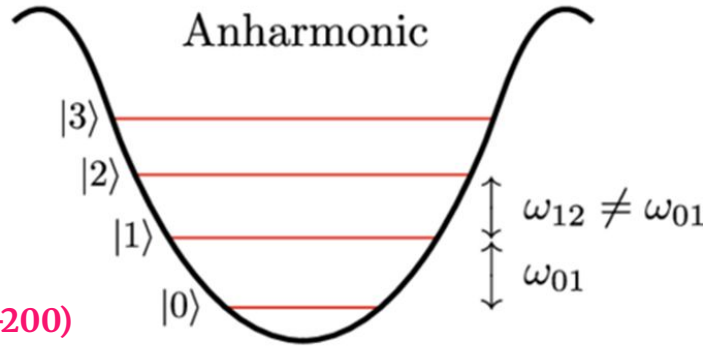
But if we retain charge sensitivity, we have a **detector** sensitive to offset charge



good detectors

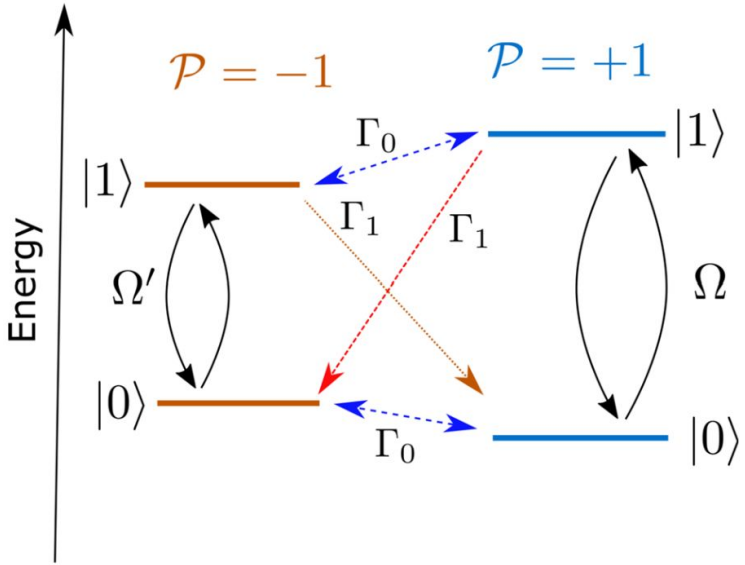
good qubits
(E_J / E_C ≈ 50-200)

SQUATs *specifically* are designed to be weakly charge sensitive ($E_J/E_C \gtrsim 10$)

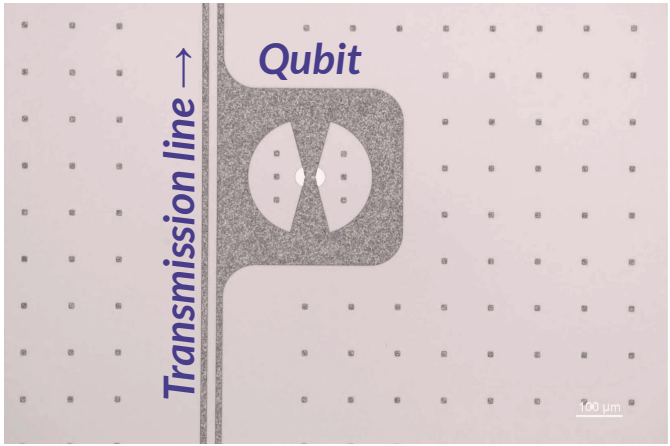


Parity Measurement Procedure

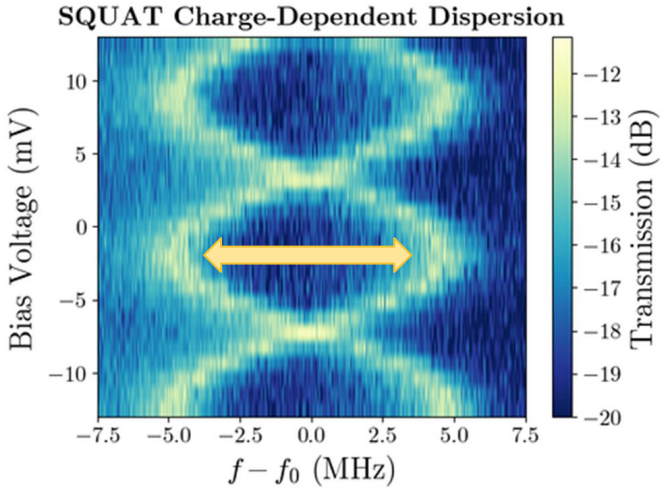
The SQUAT is a charge sensitive transmon directly coupled to a feedline, allowing for parity state tracking with a single CW readout tone

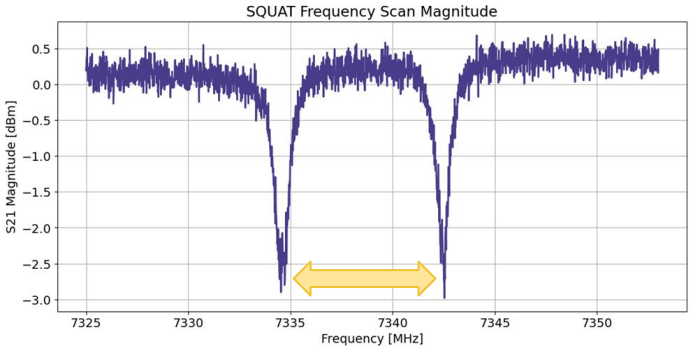


[Amin 2024, arxiv:2404.01277]



Weak Charge Sensitivity





Weakly charge sensitive transmon:

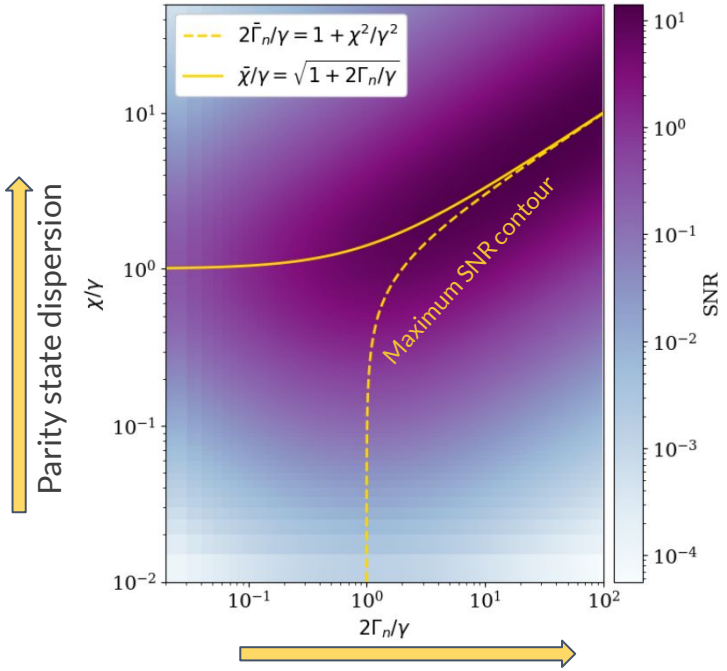
$$\hat{H}_{\mathrm{CPB}} = 4E_C\left(\hat{n} - n_g + \frac{P-1}{4}\right)^2 - E_J\cos\hat{\varphi}$$

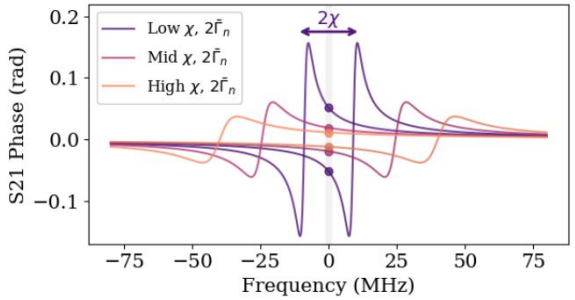
First transition energy varies with capacitor offset charge. Single QP tunneling events change the charge parity (P), causing a measurable shift in qubit resonance frequency.

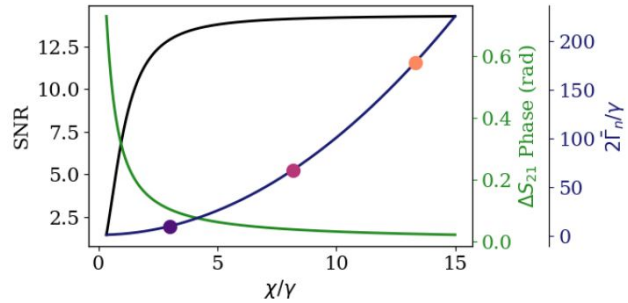
We typically aim for typically Ej/Ec ~15-20, with a maximum parity state dispersion of ~10MHz

Parity Measurement Fidelity Optimization

Direct feedline coupling makes it is easy to measure tunneling rate of devices with a wide range of dispersions, with the understanding that higher dispersions require higher readout tone power



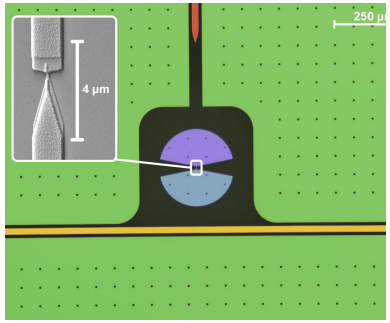




Plots show expected relations, not actual data

SQUAT Readout Dynamics

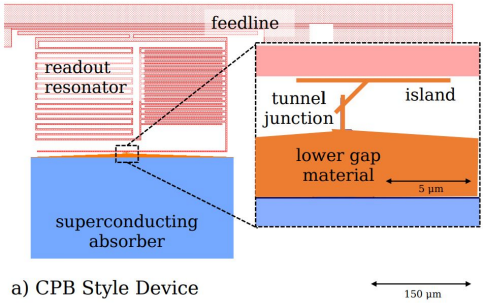
SQUATs are directly coupled to the feedline… why??



SQUATs

Advantages of direct coupling

- Enables single-tone readout of qubit parity state (no Ramsey sequences needed!)
- Simplified design
- Less dead metal per detector pixel
- Overcoupling to feedline reduces impacts of TLSs (useful for novel low-Tc junctions)



a) CPB Style Device

arXiv: 2405.17192

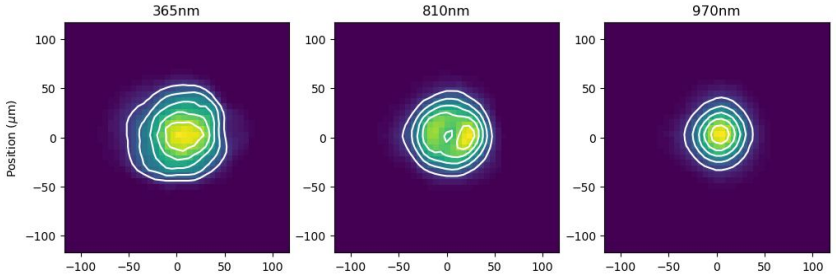
QPDs + OCS Transmons:

Advantages of dispersive coupling:

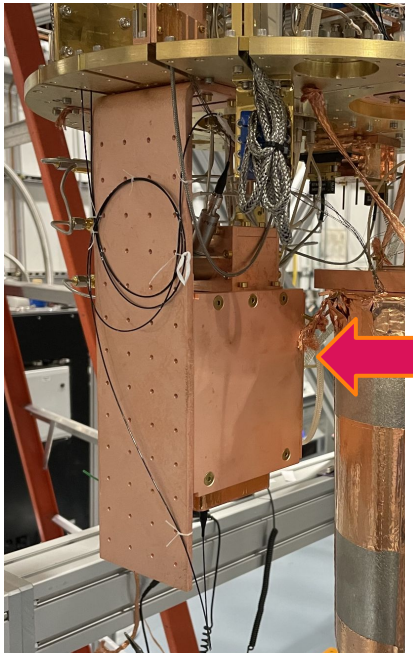
- Single-tone CW readout if your coupling is clever
- Easier to tightly pack devices with predictable frequencies when multiplexing
- Can enable higher readout powers

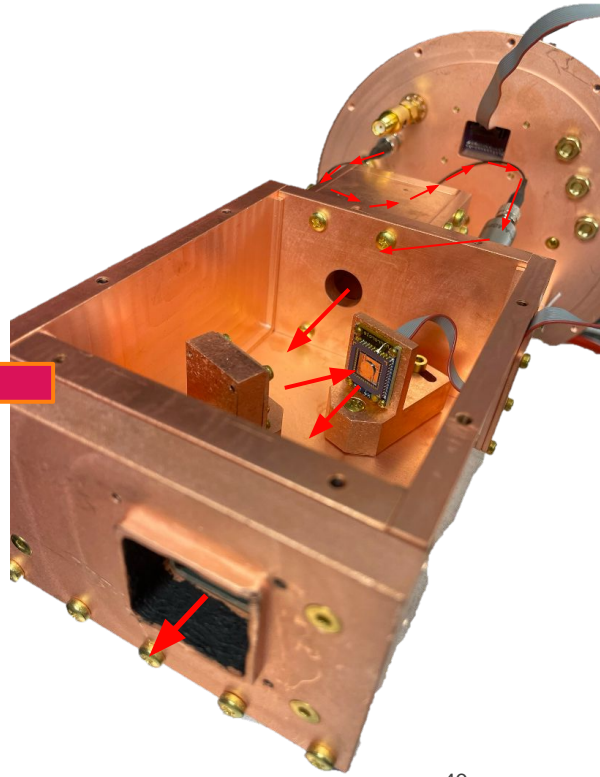
MEMS-based Optical Beam Steering

Characterized warm and cold



Wavelength (nm)	Spot Size [μm] CCD 300K	Fiber 300K	Fiber 10 mK	Pulse Width [μs] 300K	Pulse Width [μs] 10 mK
365	98.6			7.86	4.58
385	95.1			8.36	4.45
530	92.9			7.01	4.39
625	90.9	115.7		7.71	4.29
660	89.8	99.7	96.9	6.67	4.53
740	84.2			7.16	4.41
810	86.2			5.23	4.27
940	-			5.41	-
970	73.5			6.14	-





spot size < 100 μm **scan speed > 20 m/s**