Fermilab

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Understanding Cryogenic Microphysics for Novel Low-Threshold Dark Matter Detectors

Ryan Linehan
on behalf of the Fermilab CosmiQuantum Group

U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

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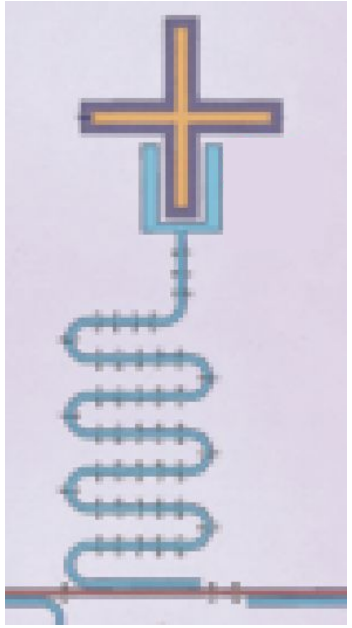
Phonon Sensing: Enter Quantum Sensors

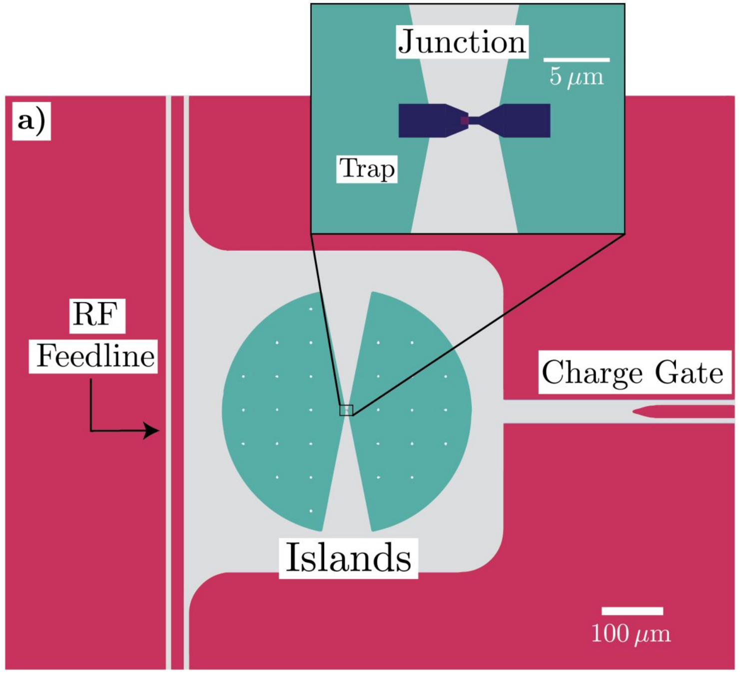
In the last five years, the field of dark matter direct detection has explored using superconducting quantum computing architectures for phonon detection.

“Standard” Transmon Qubit



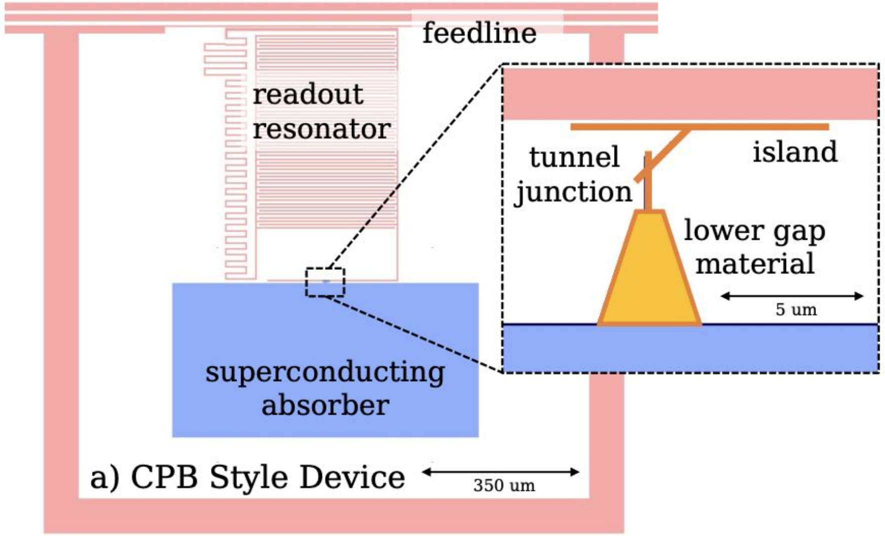
https://arxiv.org/pdf/2402.03208

SQuAT Sensor Design



https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.22.054009

QPD Sensor Design



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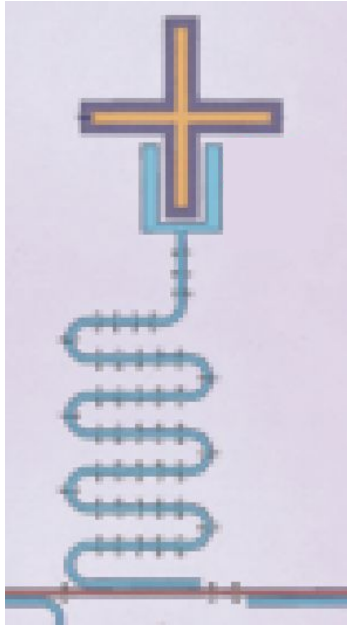

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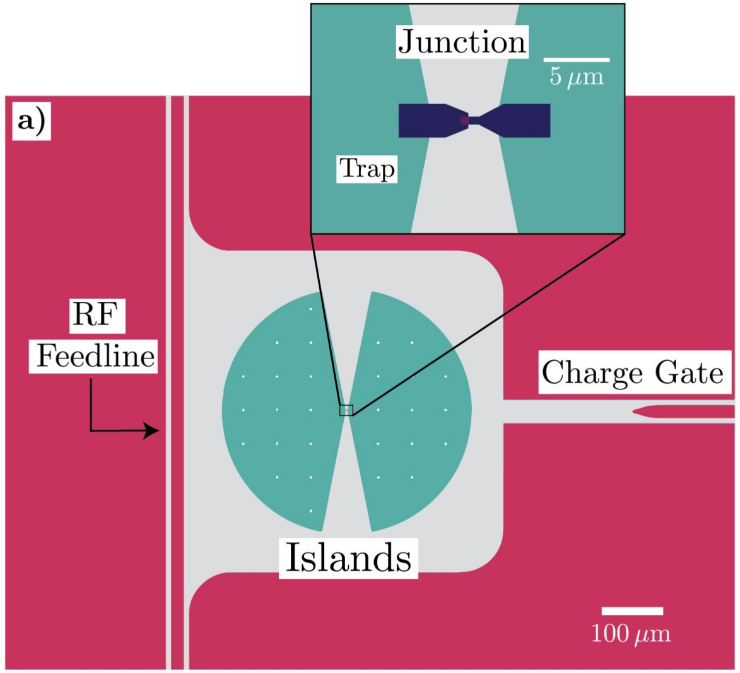
This talk’s focus

SQuAT Sensor Design



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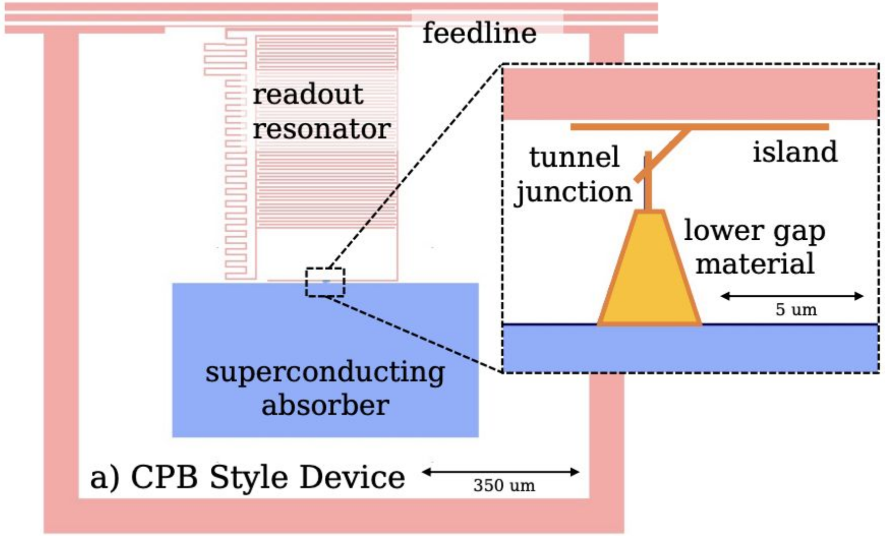

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Sensing Weak Signals with Quantum Devices: What Matters?

Two tenets for novel detector development:

- Is a new signal real? → Need to understand your detector's microphysics.

- Understand that microphysics? → May unearth new sensing strategies.

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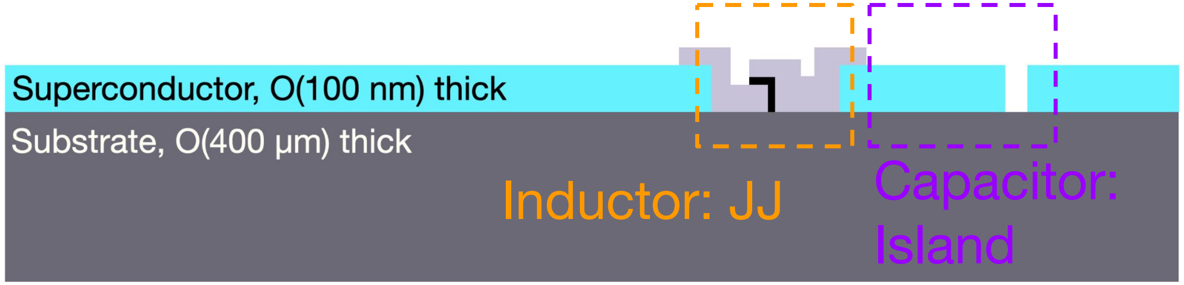
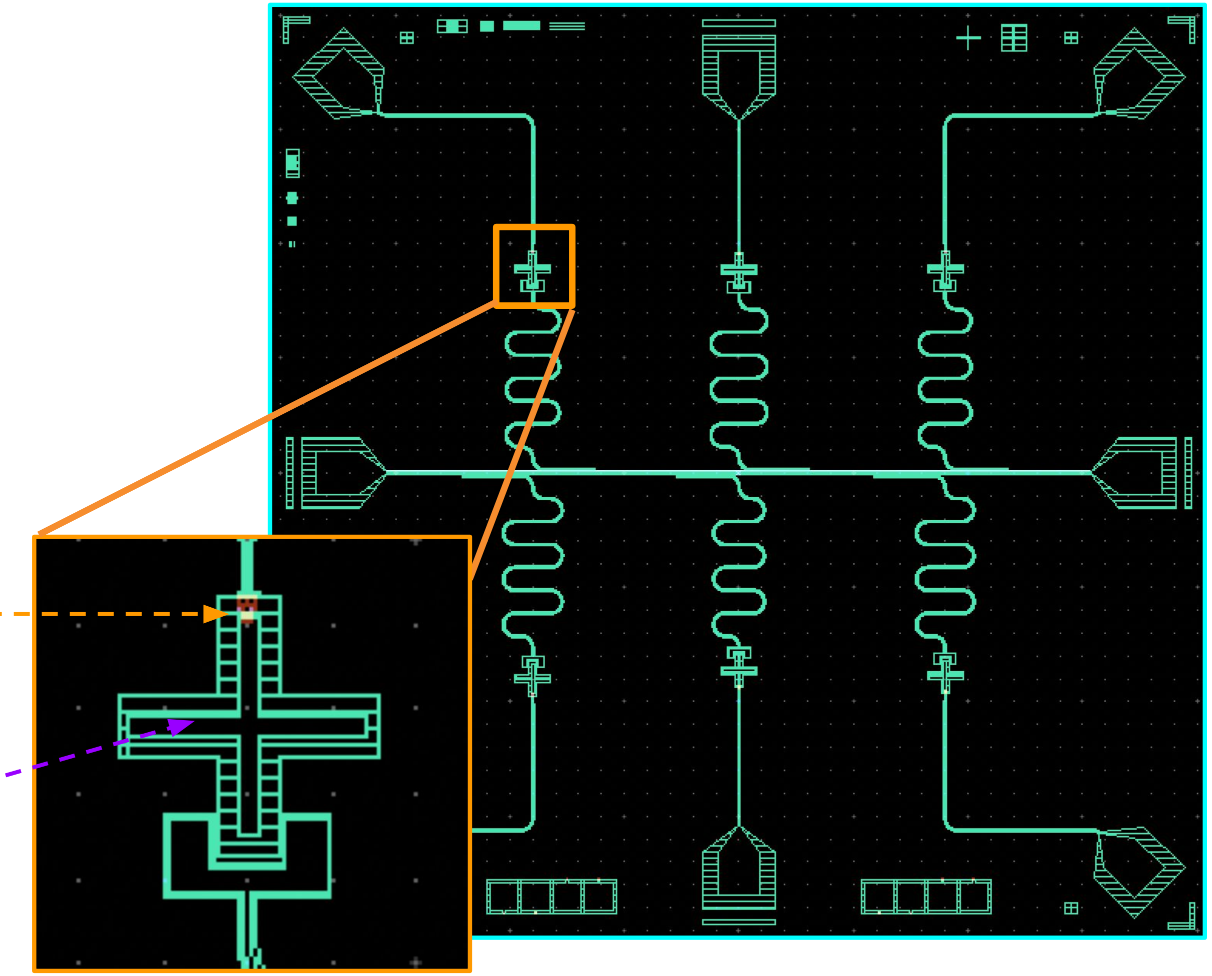
Superconducting Qubits

To understand detector microphysics, let’s first understand our detector: a **superconducting qubit.**

Physical form: Thin-film superconducting capacitor + inductor plated on thicker substrate.



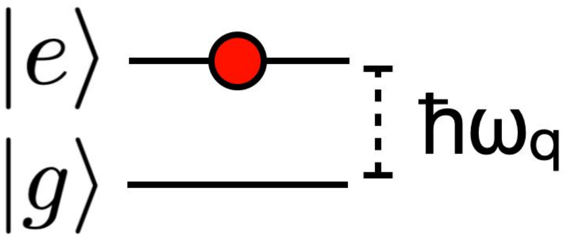


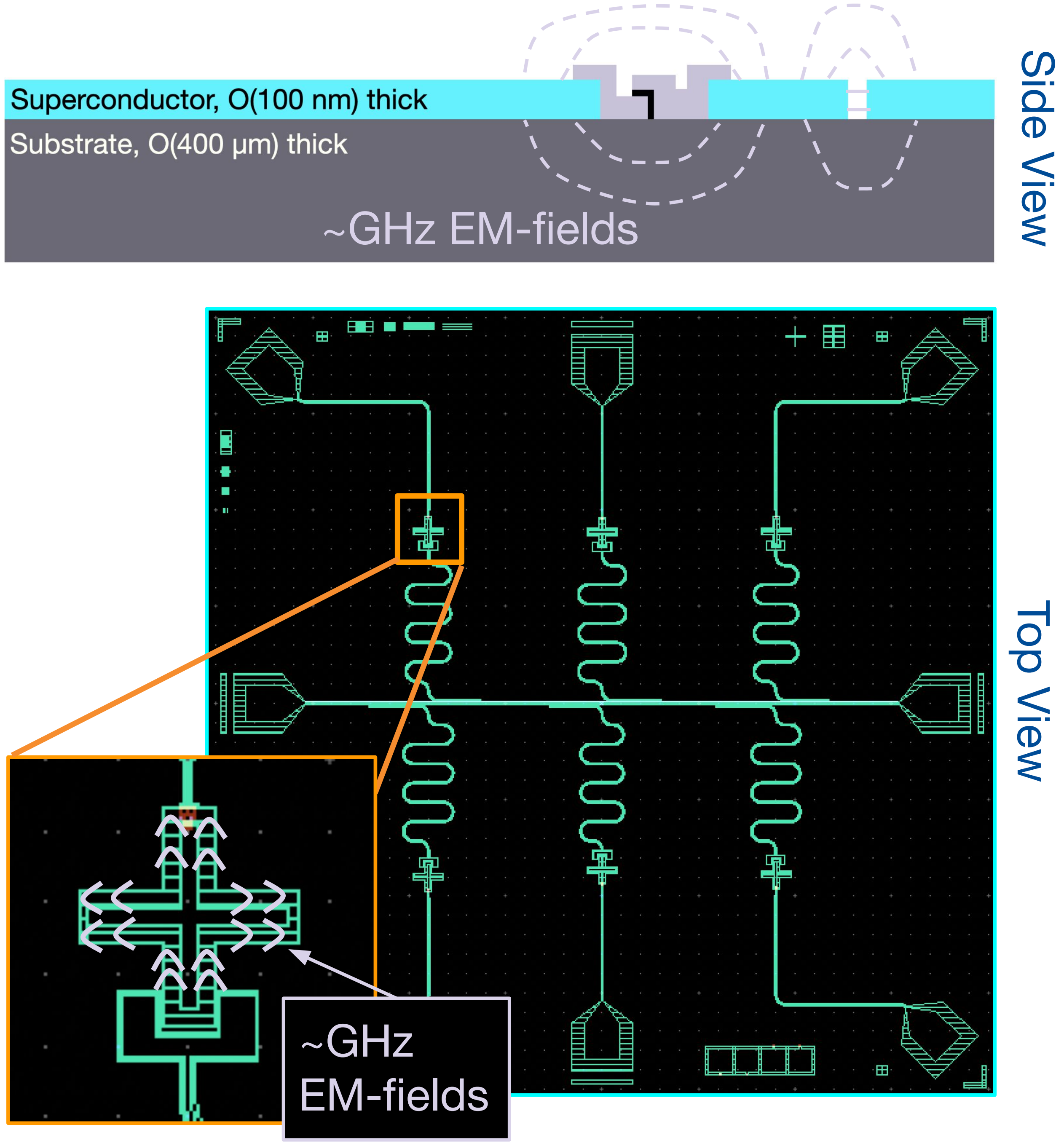
Superconducting Qubits

To understand detector microphysics, let's first understand our detector: a **superconducting qubit.**

Physical form: Thin-film superconducting capacitor + inductor plated on thicker substrate.

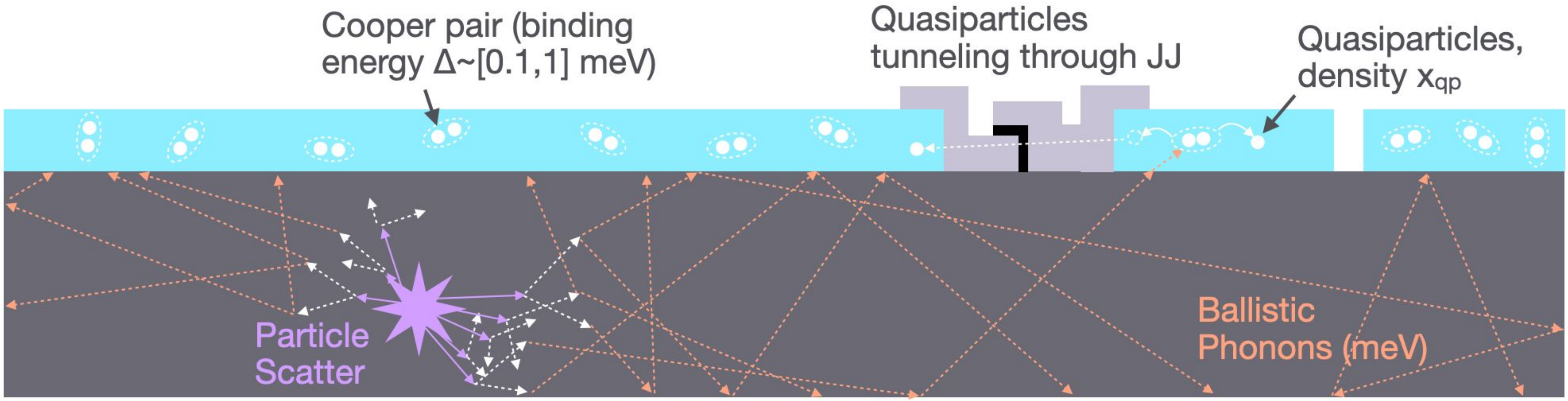
Functional form: container for individual microwave photons of a specific, "qubit" frequency ~5GHz / 10μeV

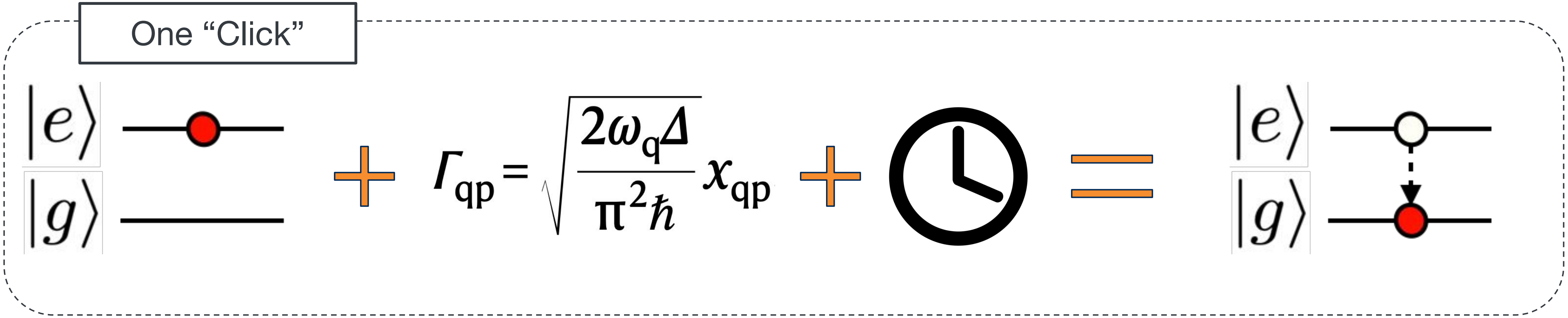




Qubits as "Click" Detectors

Superconducting qubits can act as "click" detectors for quasiparticles (QPs), which can cause the qubit to relax as they tunnel through the JJ.





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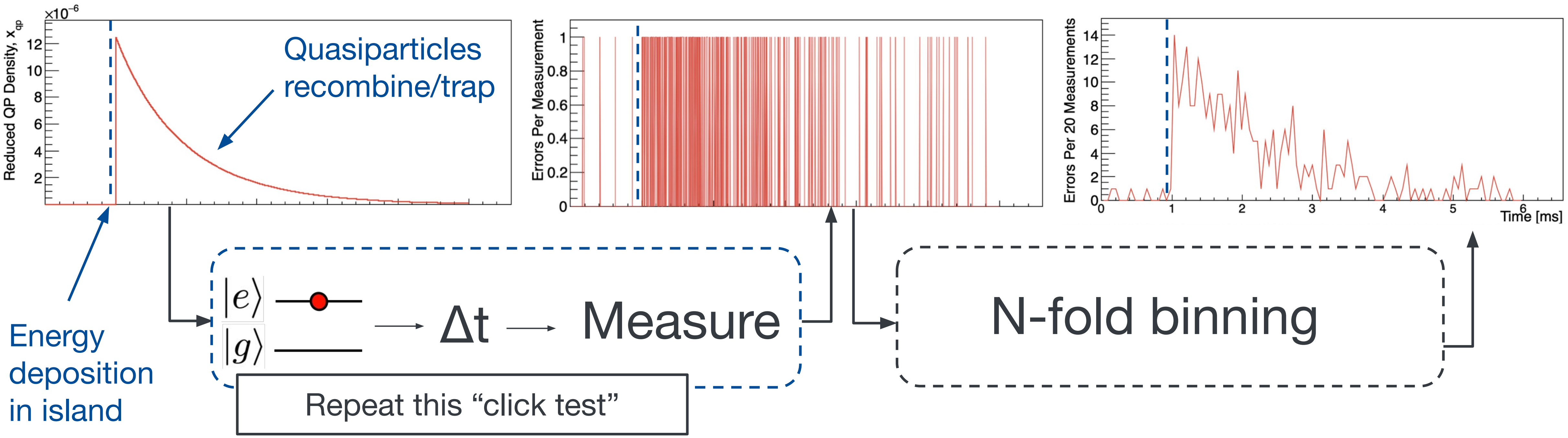
Qubits, Beyond Click Detection

By stringing together several subsequent clicks, we can build a "click" (or relaxation) waveform.*

Simulated quasiparticle density x_{qp} | Series of individual click results | "Waveform" of click *probabilities*



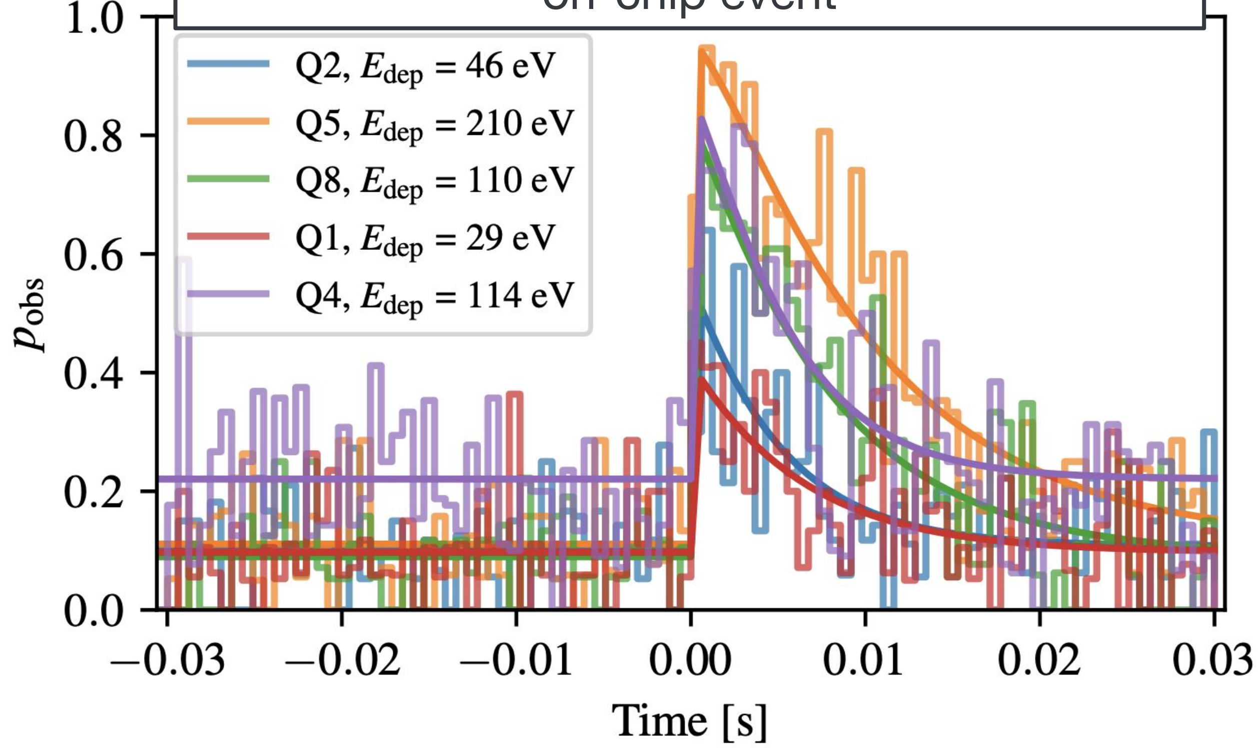
https://link.aps.org/doi/10.1103/PhysRevD.111.063047

*interestingly, a waveform governed by *binomial* statistics, not gaussian statistics.

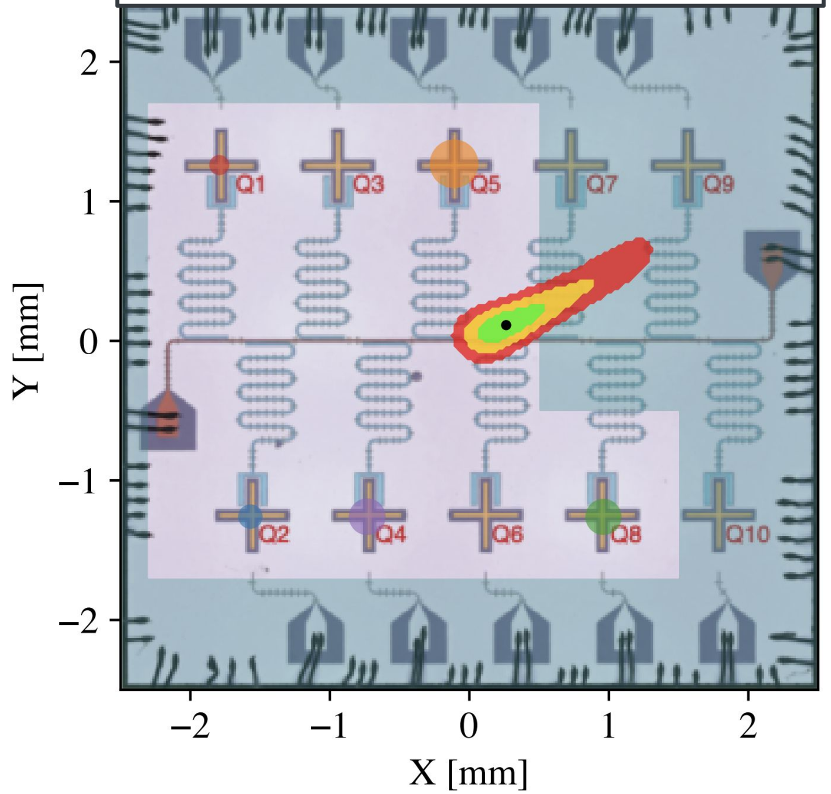
Qubits as Energy-Resolving Detectors

Single-qubit click probability waveforms ("relaxation waveforms") allow for traditional in-chip energy reconstruction…

Reconstructed in-qubit energies, single on-chip event



Scatter XY Reconstruction



(Celi et al, https://arxiv.org/pdf/2604.13176)

…assuming you have a model for how phonons disperse throughout the chip.

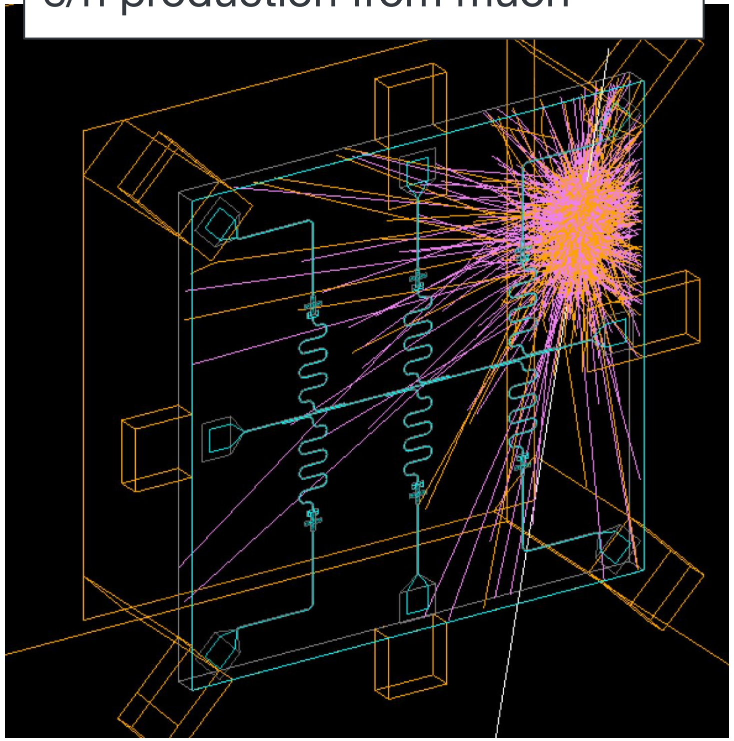
Phonon Modeling in G4CMP

Fundamentally, **most phonon physics is fairly well-established**, allowing us to use phonon propagation models to understand detector response.

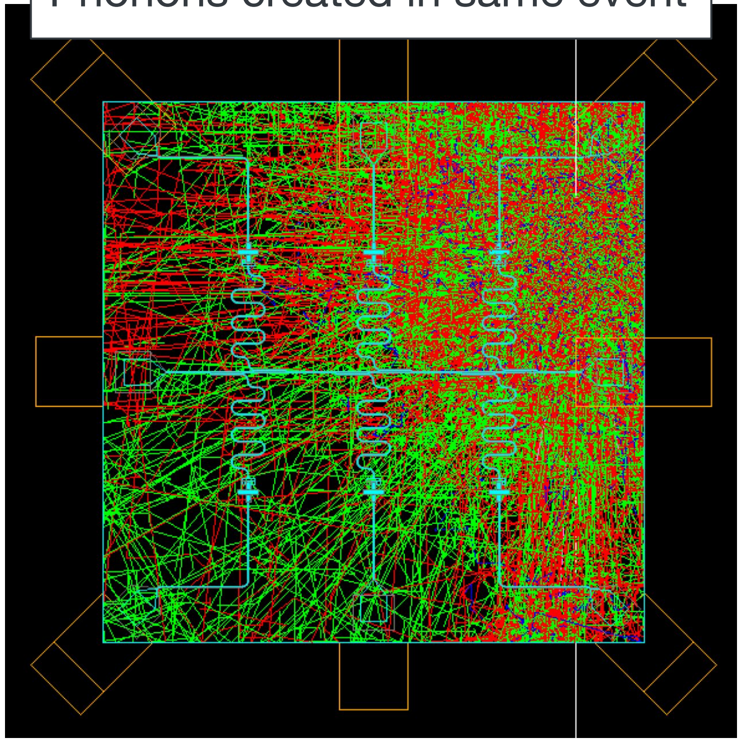
G4CMP*: Geant4 Condensed Matter Physics
- Low-energy (meV-scale) Geant4 extension
- e/h production/transport
- Phonon production/transport
- Like Geant4, open source*!

The catch: while phonon physics is well-established, individual device *parameters* are still idiosyncratic
- Problem for field!
- For now, need calibration!

e/h production from muon



Phonons created in same event

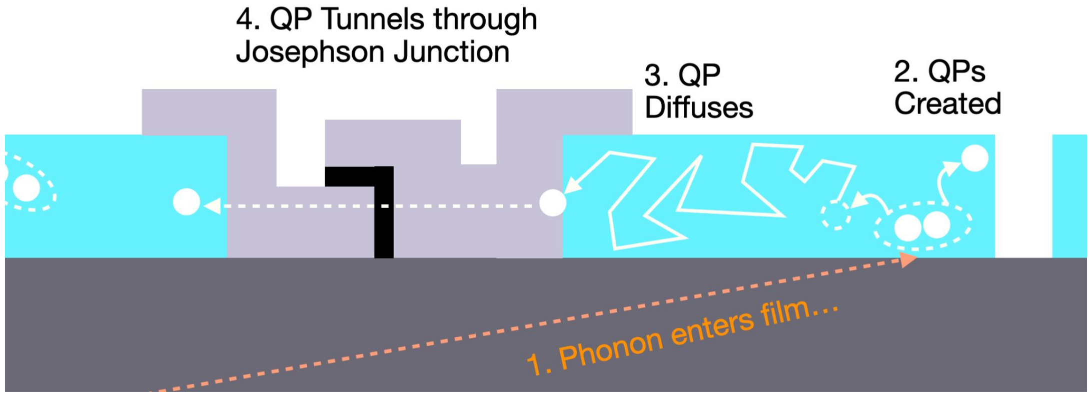


*Link: https://www.sciencedirect.com/science/article/pii/S0168900223004631
*Github: https://github.com/G4CMP/G4CMP/tree/master

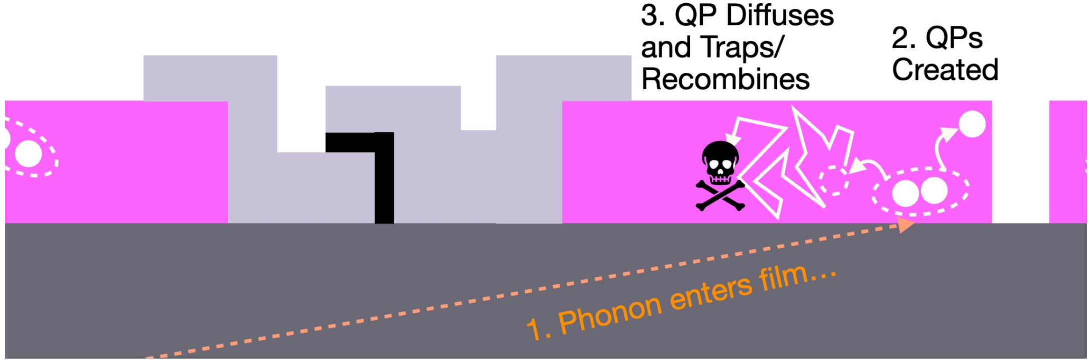
Refining Detector Response: QP Transport

To understand (and optimize) detector response, the devil is in the details of *QP* response as well.

Understanding Impact of Materials Selection

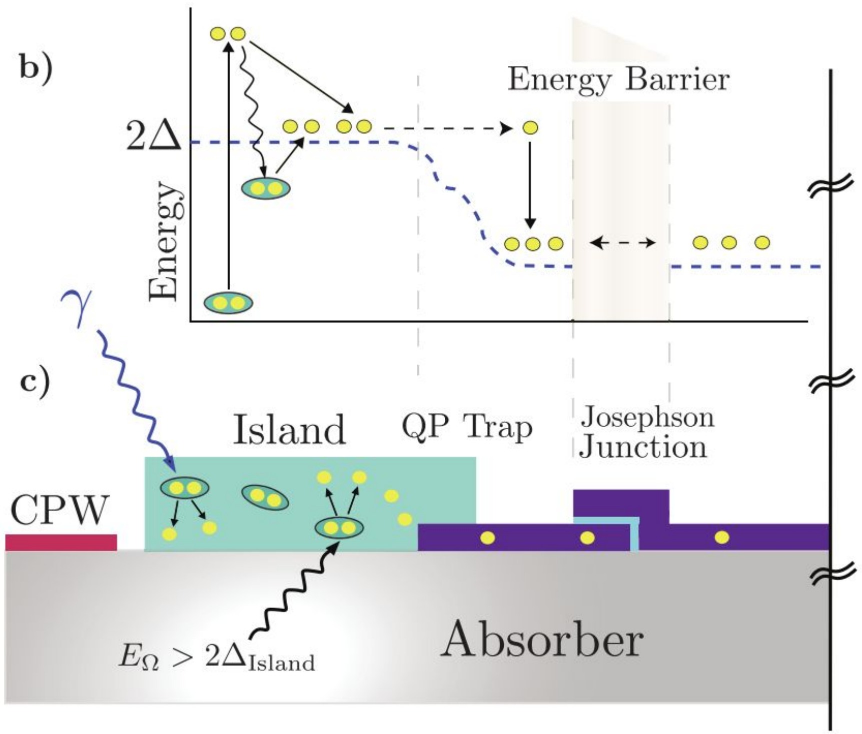


Al: more QPs/phonon energy, longer QP lifetimes



Nb: fewer QPs/phonon energy, shorter QP lifetimes

Quasiparticle Signal Amplification via Gap Engineering



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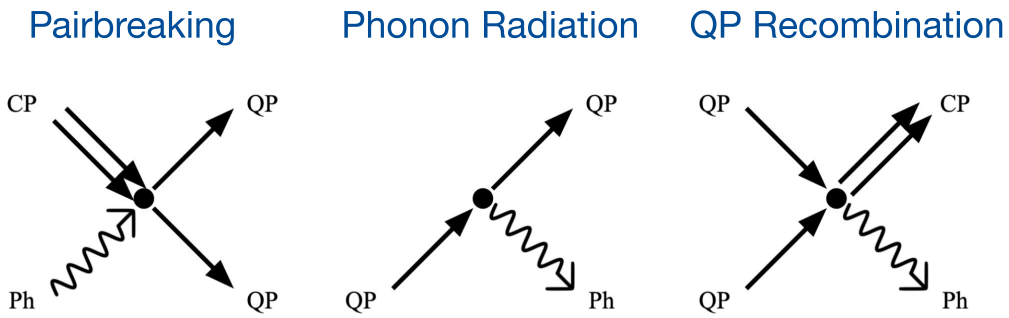
Quasiparticle Modeling in G4CMP

We've also recently refined G4CMP's response of QPs created once phonons enter a superconducting volume, adding:

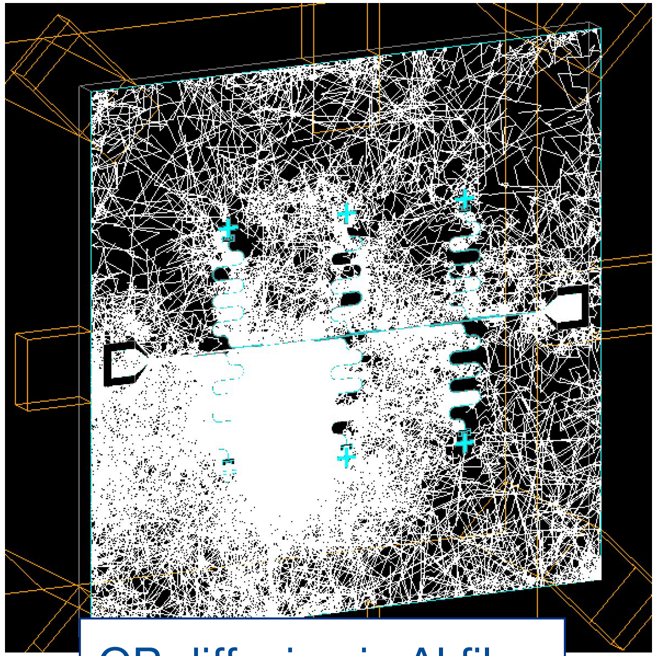
- New physics list handling phonon-QP inelastic processes:



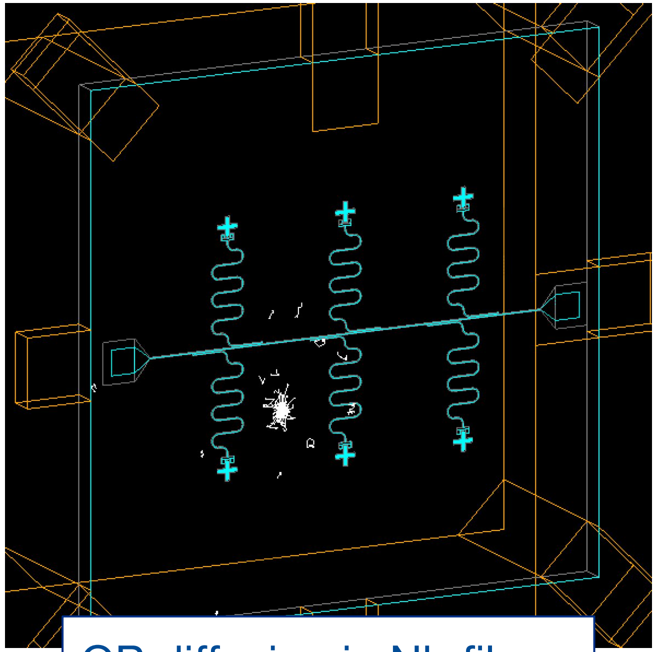
- QP 2D transport
- Multiple materials (Al, Nb)
- QP trapping on localized sites

The catch:

- Params still fab-dependent!
- No n^2 recombination in G4-based code!



QP diffusion in Al film



QP diffusion in Nb film

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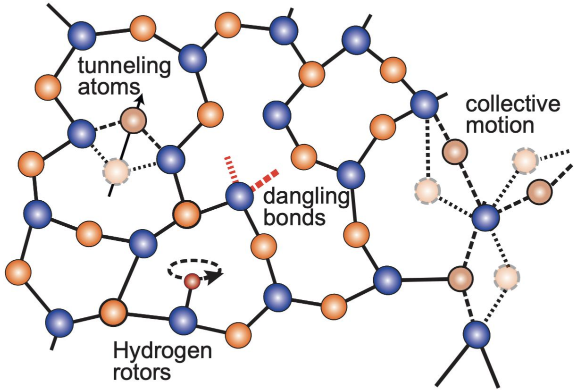
Knowing our Noise: Two-level systems (TLS)

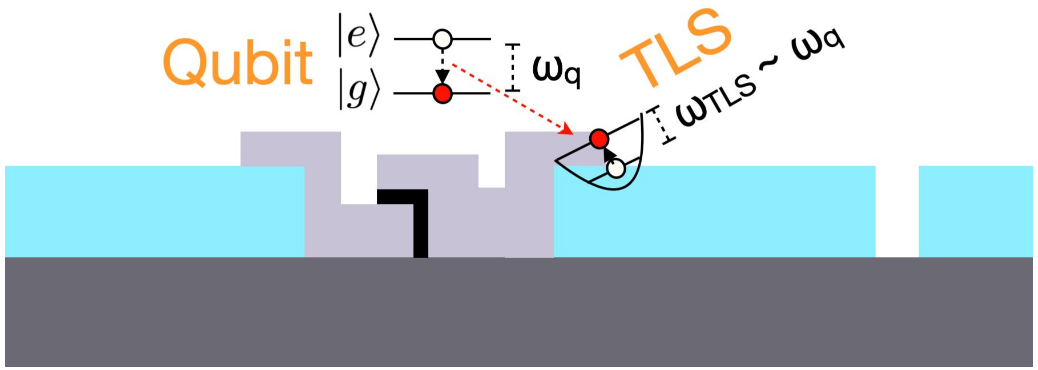
Qubits interact electromagnetically with ambient quantum two-level systems (TLS), giving stochastic qubit frequency shifts and spurious “clicks” (relaxations).

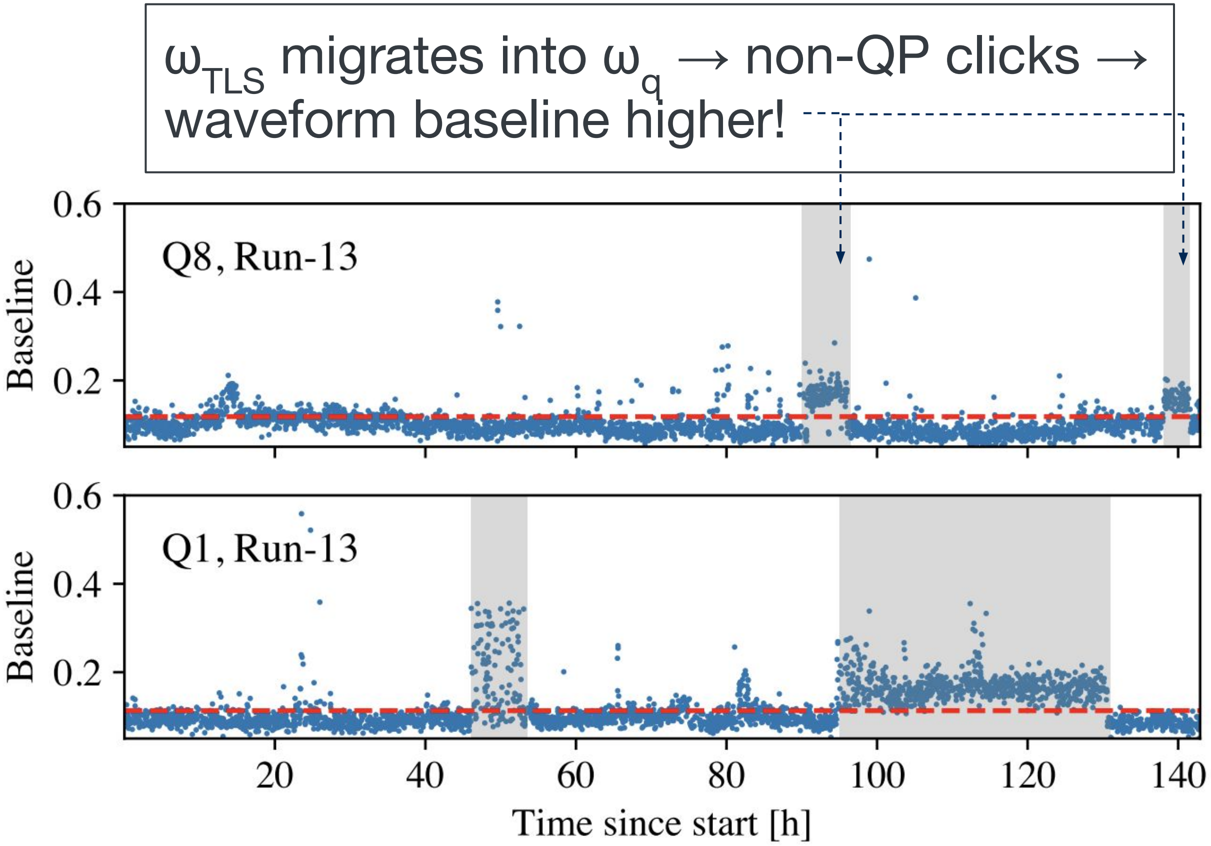
Physical picture: unknown, tied to disorder.

https://arxiv.org/pdf/1705.01108



Conceptual picture: two-level system near qubit with frequency ω_{TLS}, that can jitter.





(Celi et al, https://arxiv.org/pdf/2604.13176)

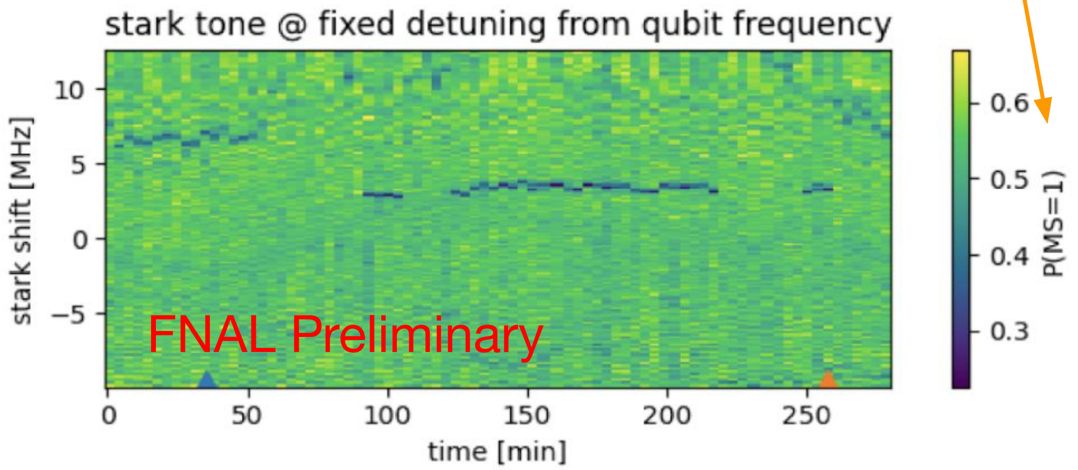
Two-level systems: An *annoying* noise source

TLSs are driven stochastically by other underlying microphysical systems (two-level *fluctuators*), and are a bane of high-precision, repeatable measurements.

TLS spectroscopy “unveils” locations of TLSs in frequency, and shows their hard-to-predict frequency jitter:

Proxy for qubit frequency

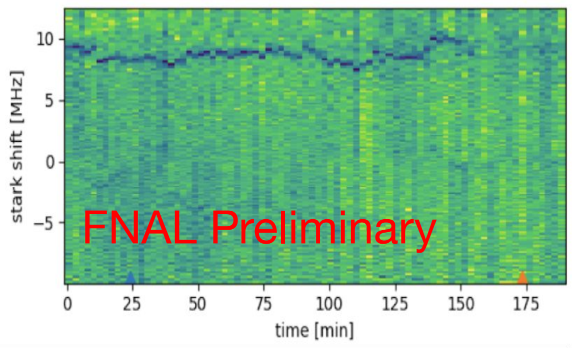
Qubit relaxation probability



ω_{TLS} is E-field and strain-dependent – hard to longitudinally study or predict individual TLSs across fridge thermal cycles…

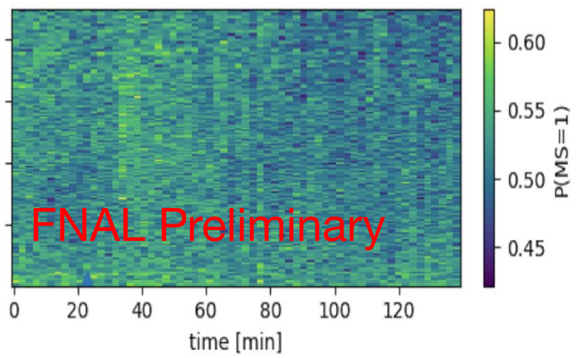
Cooldown 1:

$\delta\omega_{TLS}$~10 MHz



Cooldown 2:

TLS no longer in range!



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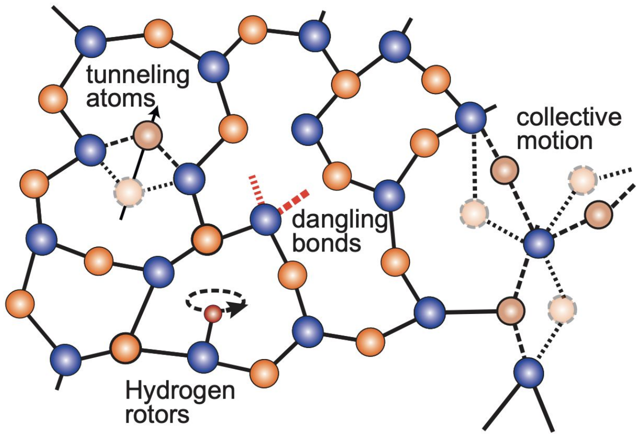
TLSs: What we love and (love to) hate

TLS are unintentional and frustratingly inconsistent, but underscore a sensitivity of qubits to 10μeV systems that we could maybe exploit for detectors.



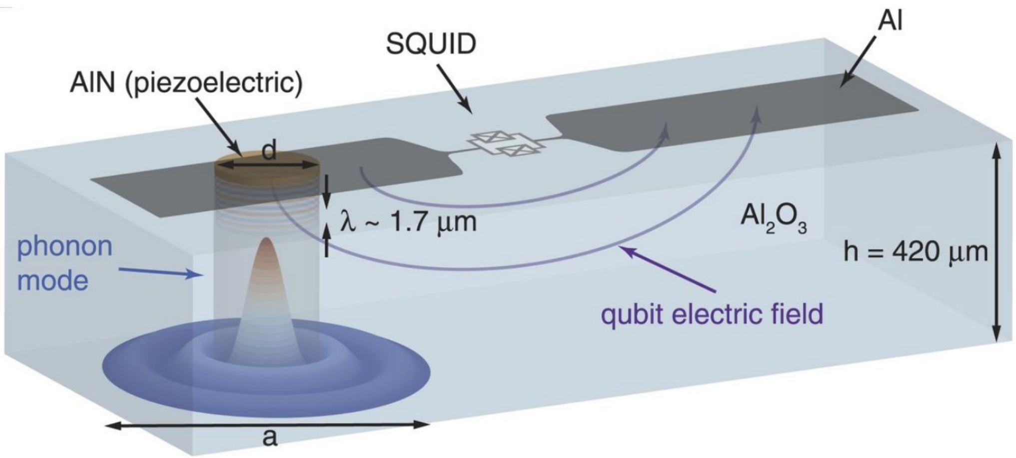
What we (love to) hate	What we love
Unintentional!	Small, ~10μeV energy splitting
Unpredictable sensitivity to electric fields	State can be probed **directly** with qubit
Unpredictable sensitivity to strain fields	
Stochastic frequency shifts linked to underlying two-level fluctuators	
Disappears (or appears) from cooldown to cooldown	

Are there any systems that have fewer disadvantages but keep the advantages?

A Potential Path Forward: Quantum Acoustics

With quantum acoustics, we get the reliability of phonons with the energy scale of TLSs.

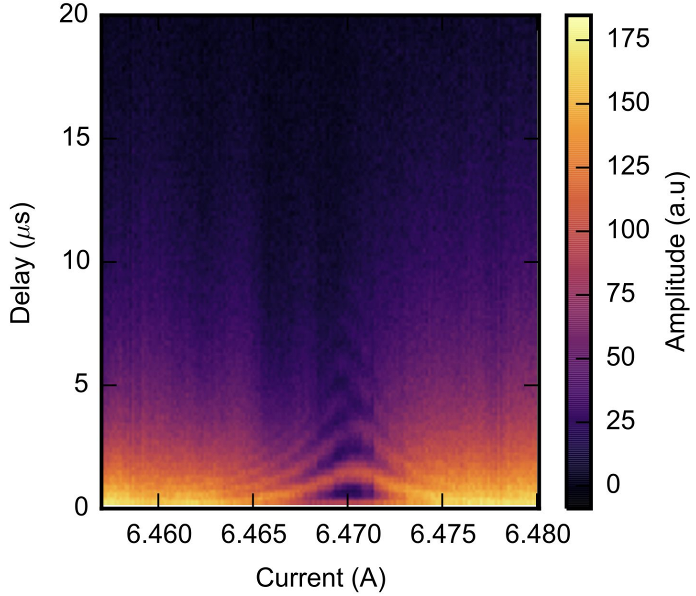
Quantum acoustics: piezoelectric coupling between high-overtone bulk acoustic resonator (hBAR) and superconducting qubit.



$$H = \omega_q a^\dagger a + \omega_n b^\dagger b + g(a^\dagger b + a b^\dagger)$$

SC Qubit — Acoustic cavity (hBAR) — Piezoelectric coupling term

Single-quanta energy exchange demonstrated between a qubit mode and an hBAR ~GHz frequencies (~10μeV)



If you can **inject** phonons, you can also **detect** ambient phonons.

Quantum acoustics with superconducting qubits

YIWEN CHU, PRASHANTA KHAREL, WILLIAM H. RENNINGER, LUKE D. BURKHART, LUIGI FRUNZIO, PETER T. RAKICH, AND ROBERT J. SCHOELKOPF

Quantum Acoustics: Novel Technique for Low Threshold Sensing?

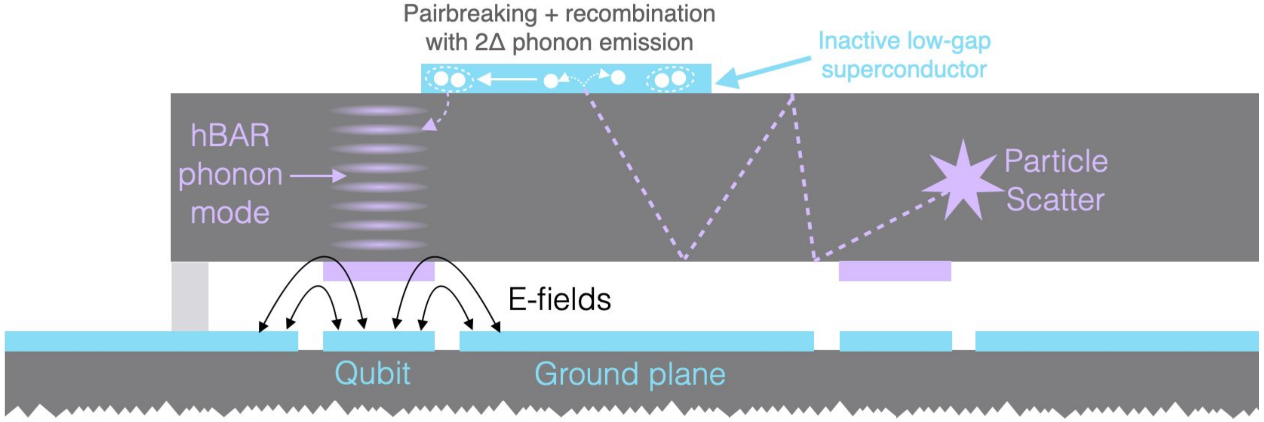
Qubit-coupled hBARs may enable low-threshold probes of particle impacts.

Good news: plenty of phonons produced in particle impacts!

Bad news: phonons produced have *too much* energy to be sensed by the hBAR.
- Particle scatters → meV-scale
- hBAR → 10 μeV-scale

Need a way to *downconvert* phonons.
- Bulk downconversion too slow!
- Normal metal downconversion:
- Superconductor gap-edge downconversion + recombination at 2Δ

Exploration of this underway at FNAL/Chicagoland!



Phonon downconversion to suppress correlated errors in superconducting qubits

V. Iaia, J. Ku, A. Ballard, C. P. Larson, E. Yelton, C. H. Liu, S. Patel, R. McDermott & B. L. T. Plourde

Material	Hf	α-W	α-W + β-W	AlMn
Gap, 2Δ	30 μeV	3 μeV	O(10μeV), tunable	Tunable

Summary

- Superconducting qubits: recently entered low-mass dark matter direct detection field

- **Need to better understand detector microphysics to have faith in new physics detection**

- By understanding this microphysics, we explore new, complementary detection techniques

Thanks for Listening!

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Toback Lab @ TAMU
Golwala Lab @ Caltech
DMQIS Lab @ SLAC
DM/QIS Lab @ SNOLab
McDermott Lab @ UW-Madison
Plourde Lab @ UW-Madison

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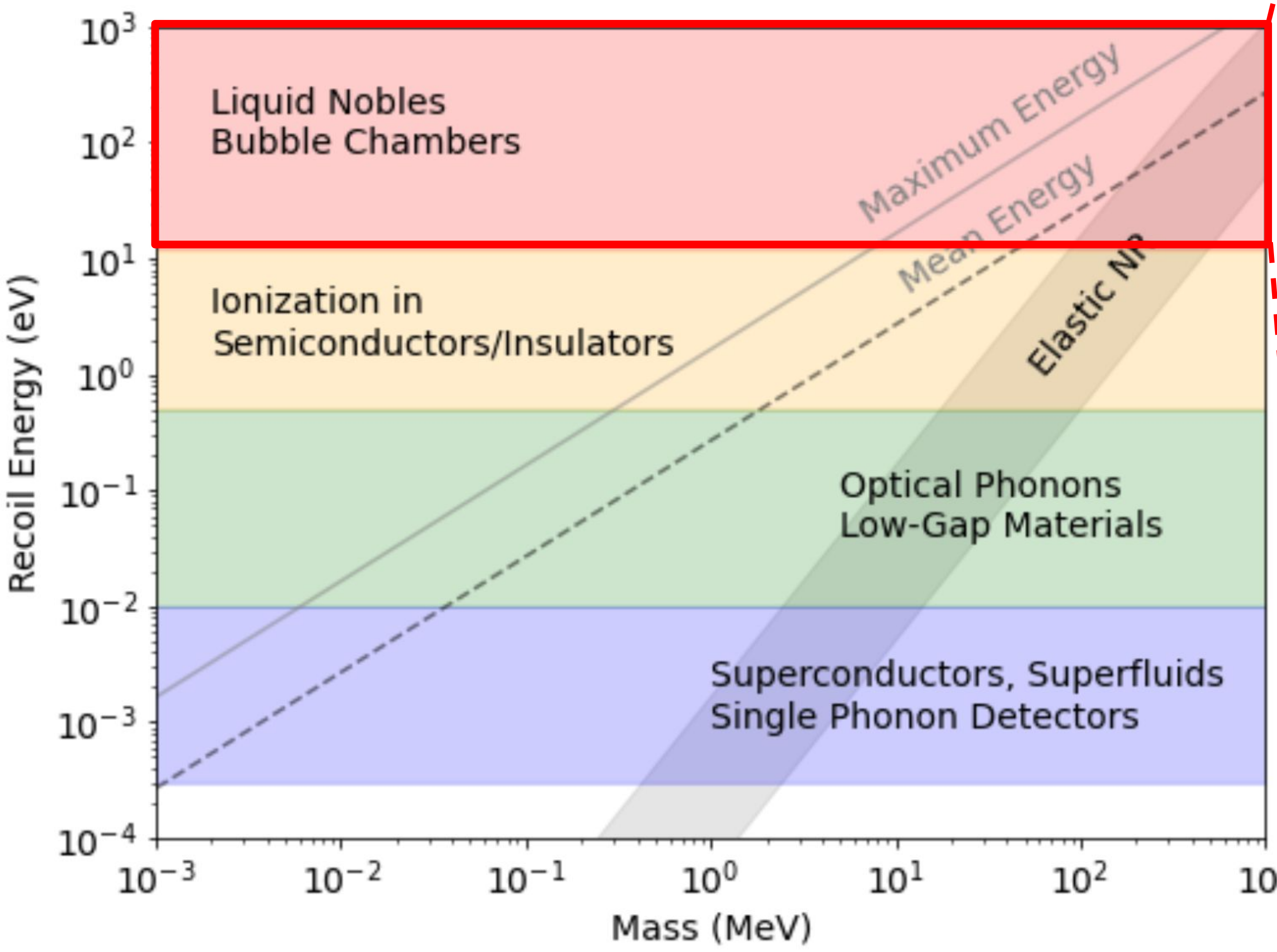
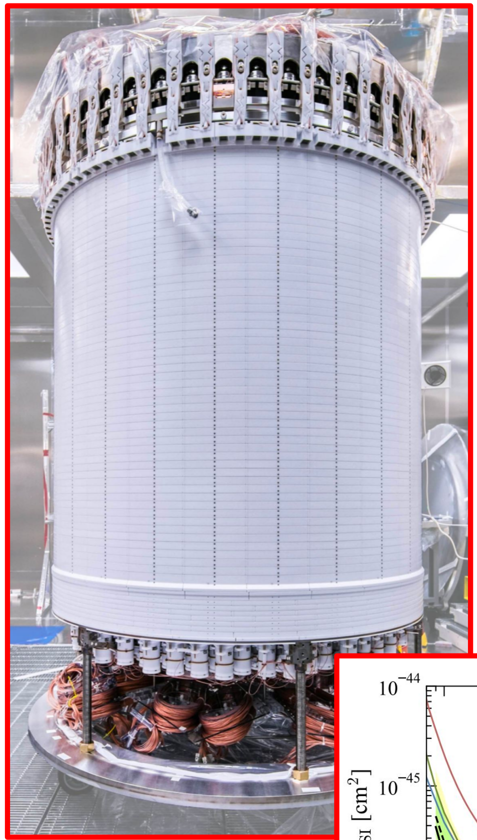
Backup

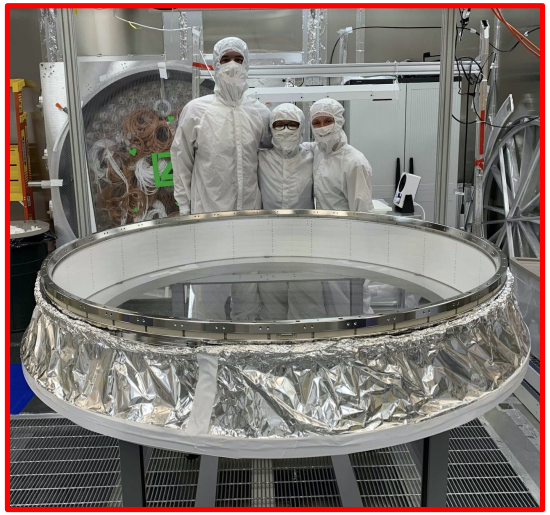
Motivation

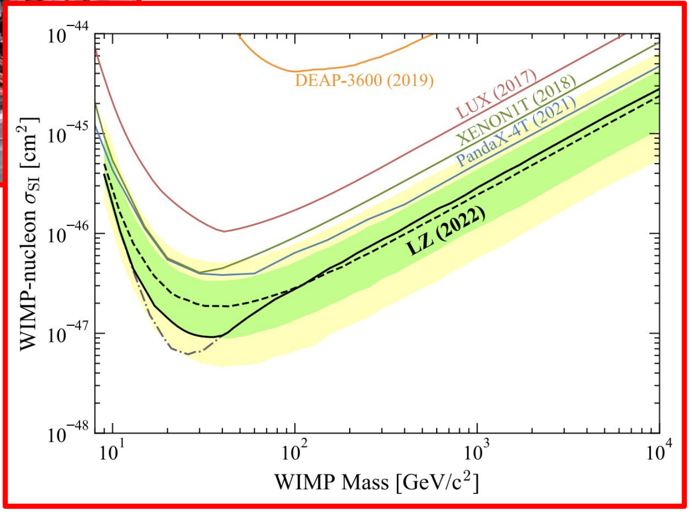
For low-mass dark matter detection, we need technologies with low energy thresholds.



The LZ Experiment







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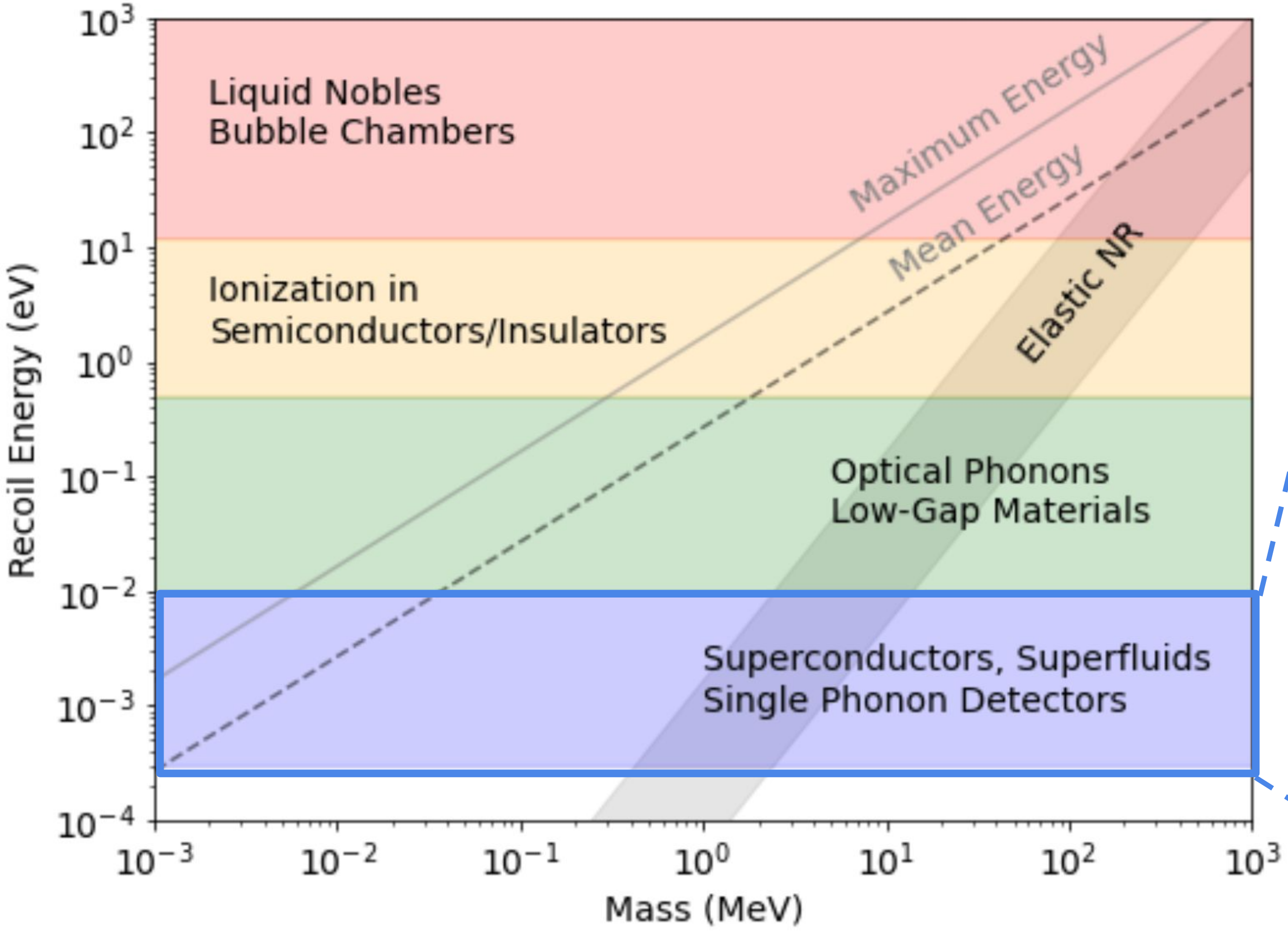
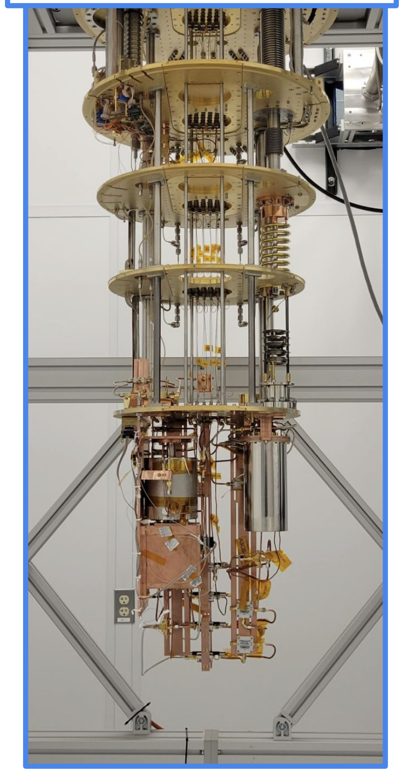
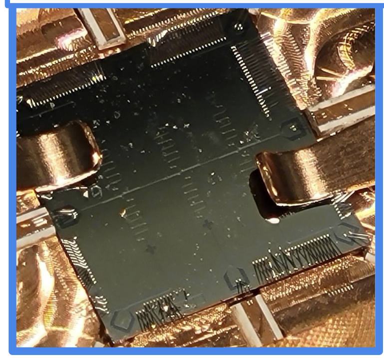


Primary strategy: phonon sensing

Cryogenic Platforms



Superconductors



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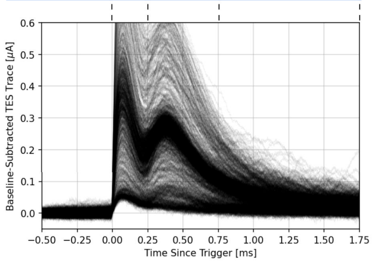
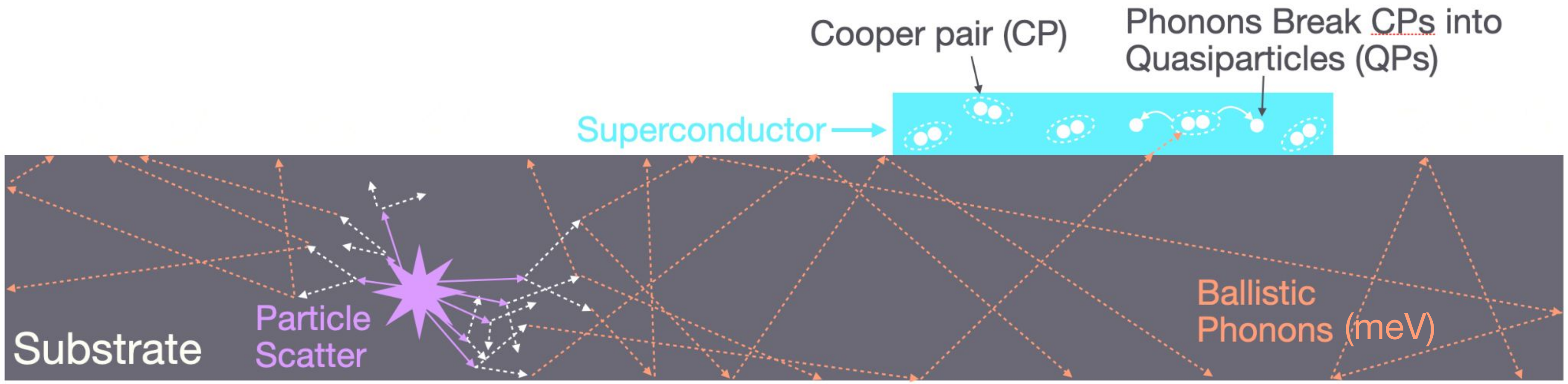


Phonon Sensing: The Pairbreaking Paradigm

Devices that sense athermal phonons via breaking Cooper pairs into quasiparticles are ubiquitous in low-threshold detection.



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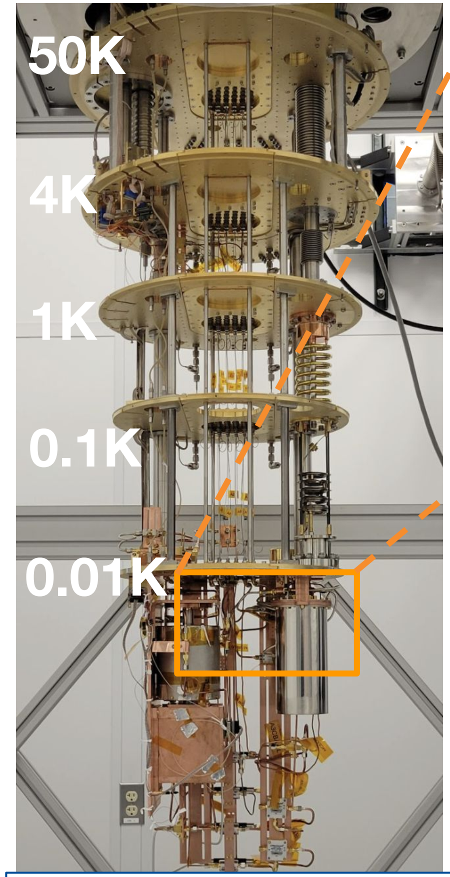
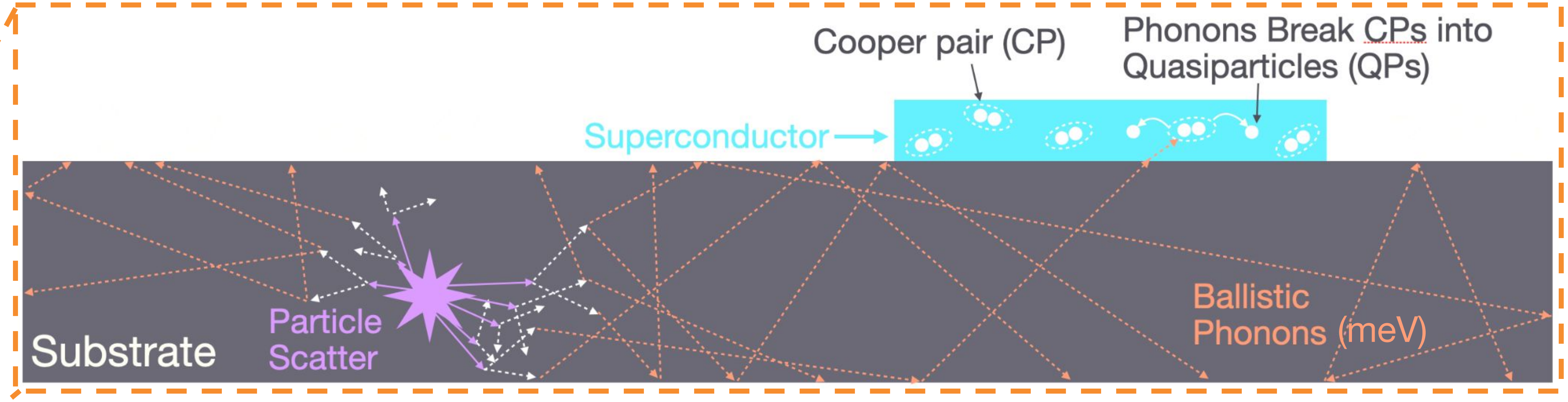


Dilution Fridge Facility, FNAL



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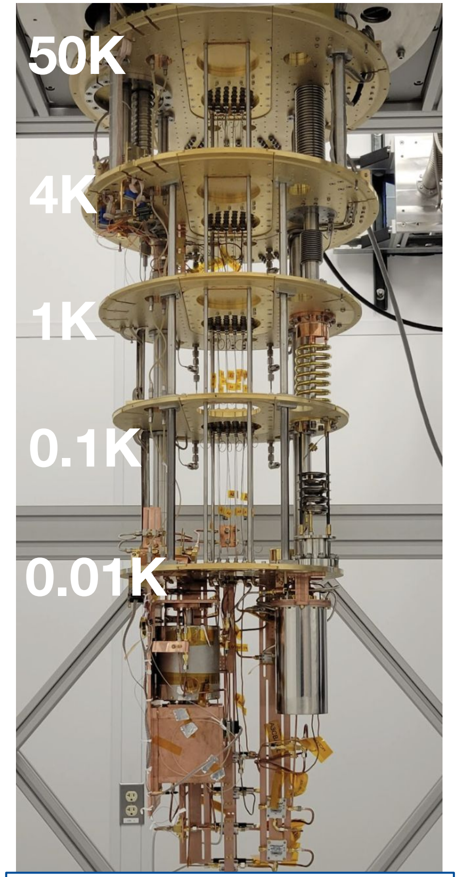

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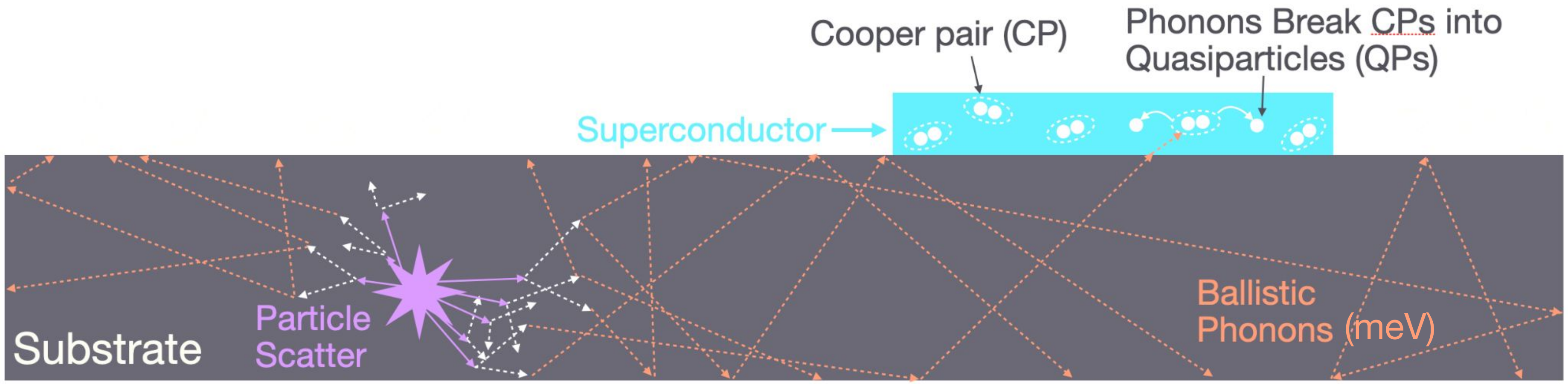
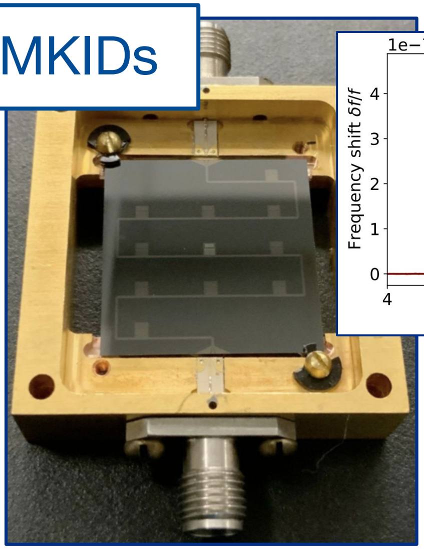
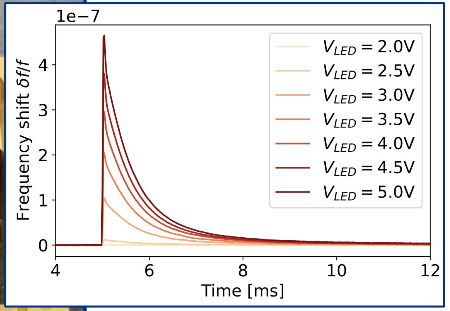


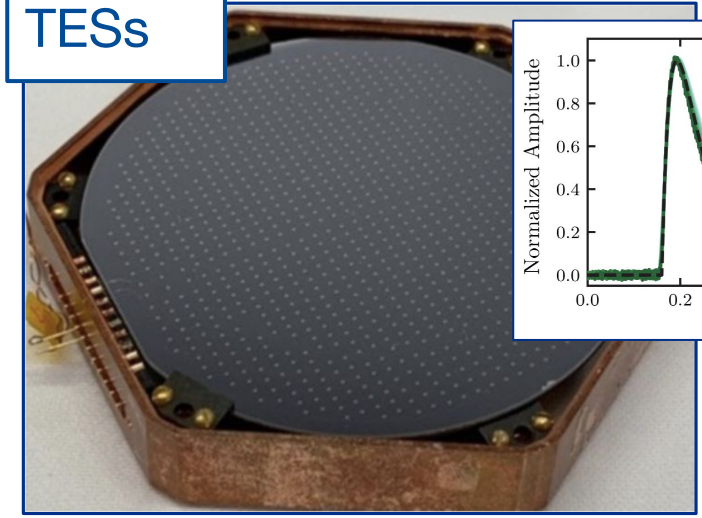
MKIDs

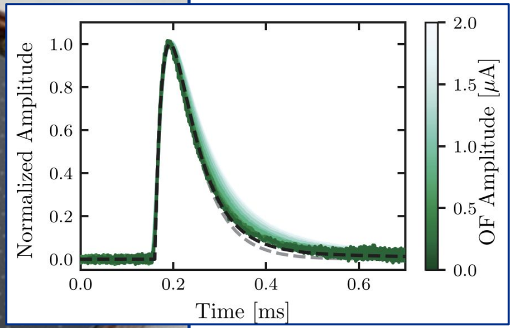




https://doi.org/10.1103/PhysRevApplied.22.044045

TESs





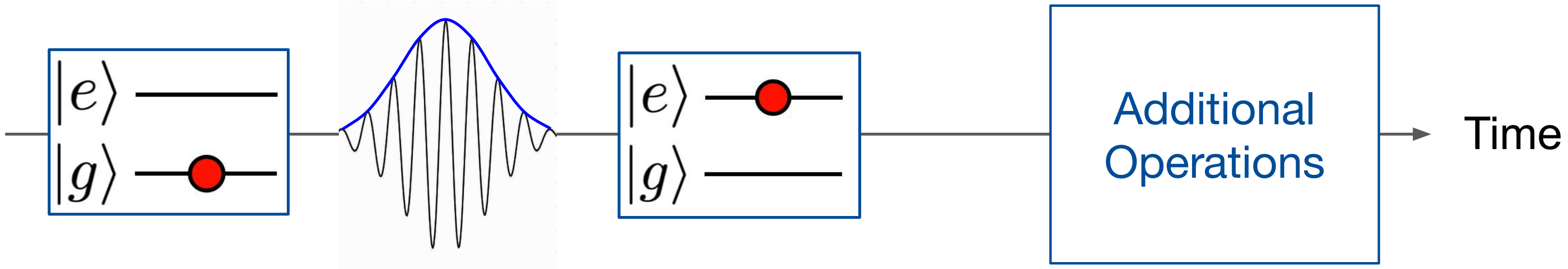
https://doi.org/10.1063/5.0032372

Qubit Operation: What matters?

For useful operation of superconducting qubits, we need good **control over qubit frequencies** and good **retention of excitations**.

Example: exciting a qubit:

RF "π"-pulse
(@ qubit frequency, ω_q)



Failure modes:

- π-pulse is not resonant with ω_q, → failed excitation!
- Qubit excited, but wait too long → excitation decays!

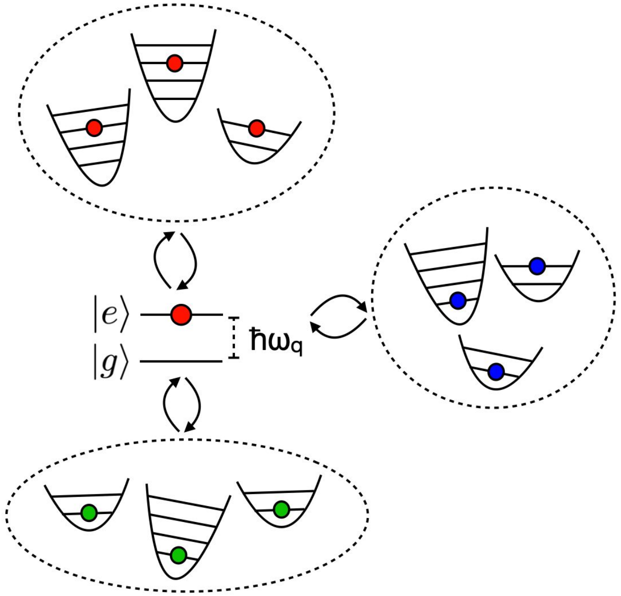
These failure modes harm later operations that assume an excited qubit!

Environment-induced Noise in SC Qubits

…which are both caused by underlying fundamental microphysics...

Relaxation: excitations lost to environmental baths.

- Characteristic time T_1



Underlying microphysical systems

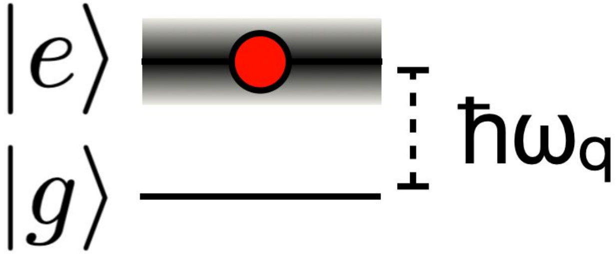
Phonons/ Quasiparticles

Two-level systems (TLSs)

...and much more

Dephasing: time variation/jitter in the qubit frequency

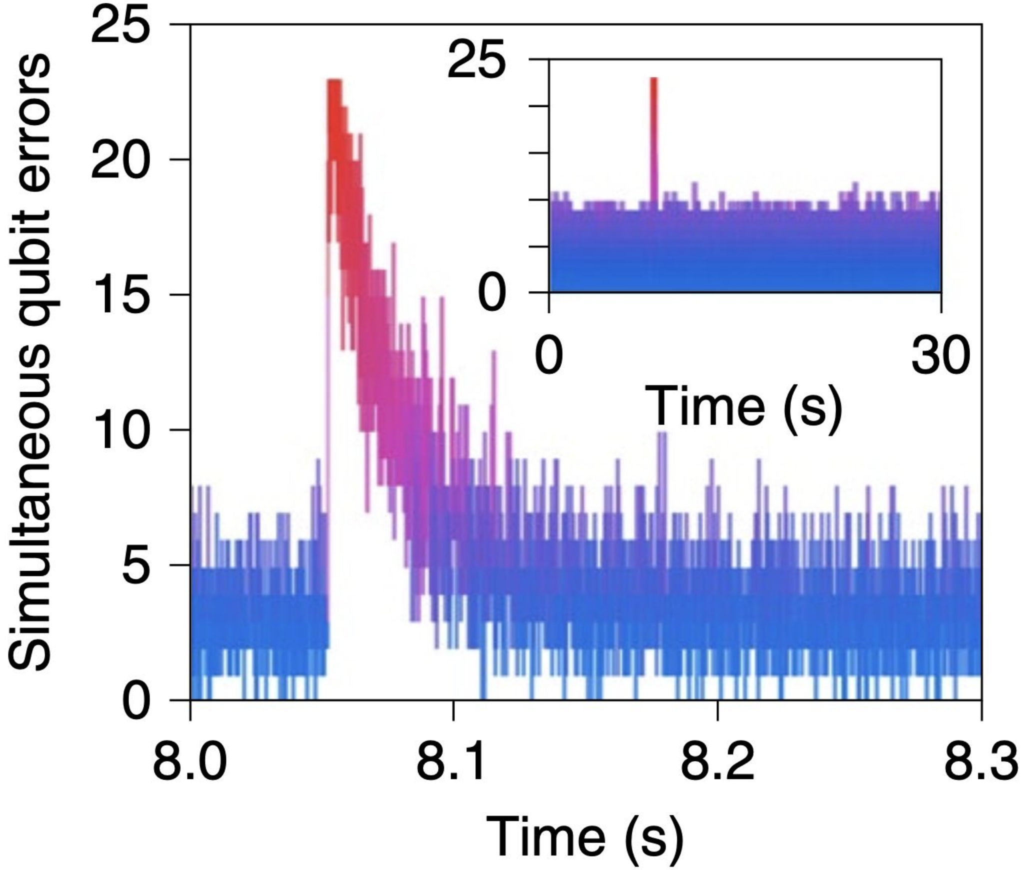
- Characteristic time T_2



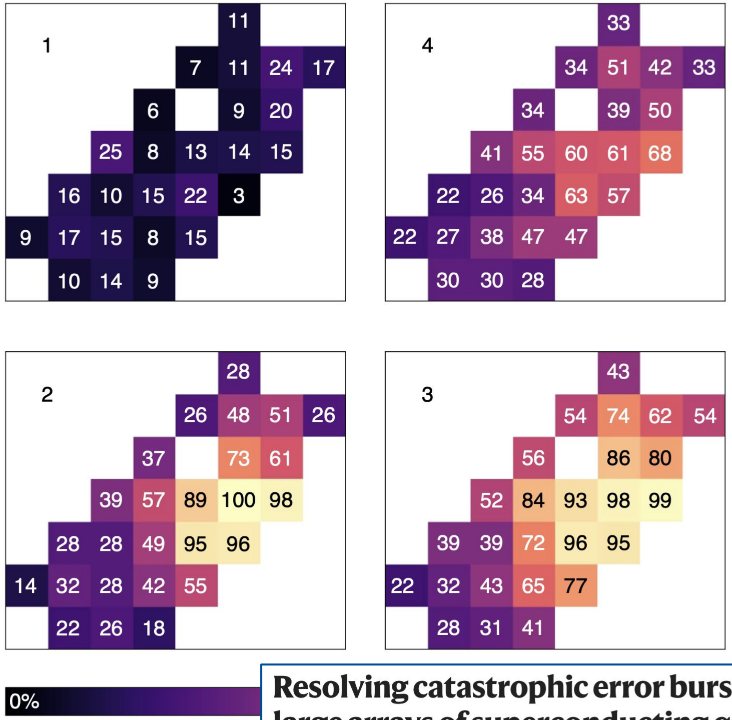
Phonon Environment: What's Observed?

Quantum computing groups have observed excess bit-flip errors that are correlated in time and space, and thought to be from ionizing radiation.

Time correlation of errors in Google's Sycamore Chip, 2022



Spatial correlation of errors in Sycamore Chip, 2022

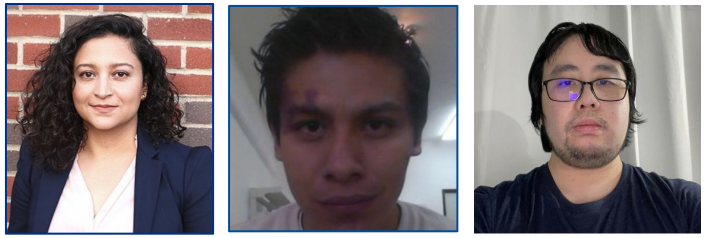


Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

Matt McEwen, Lara Faoro, Kunal Arya, Andrew Dunsworth, Trent Huang, Seon Kim, Brian Burkett, Austin Fowler, Frank Arute, Joseph C. Bardin, Andreas Bengtsson, Alexander Bilmes, Bob B. Buckley, Nicholas Bushnell, Zijun Chen, Roberto Collins, Sean Demura, Alan R. Derk, Catherine Erickson, Marissa Giustina, Sean D. Harrington, Sabrina Hong, Evan Jeffrey, Julian Kelly, ... Rami Barends + Show authors

Phonon Modeling in G4CMP

At FNAL, we also **develop** G4CMP, and have recently been adding capability for phonon propagation in new materials.

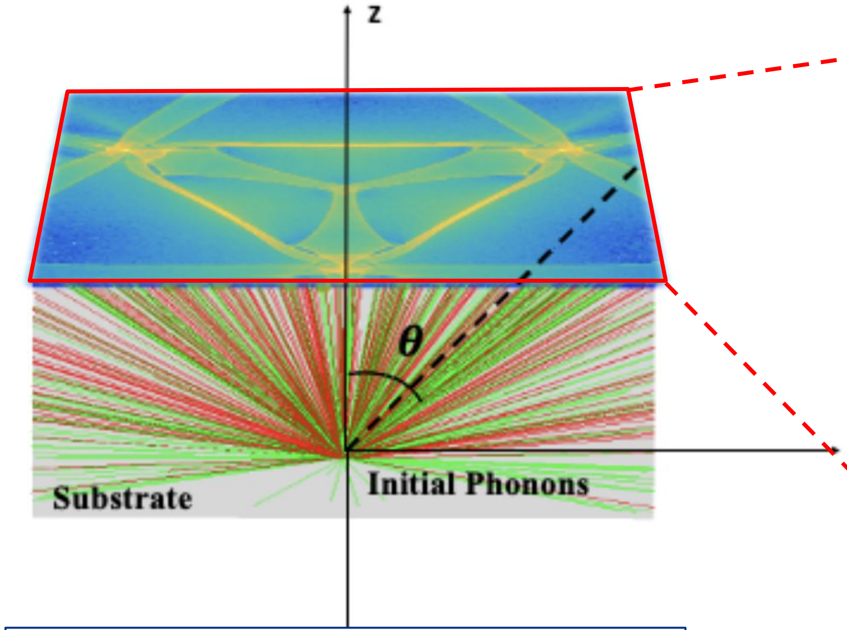


R. Khatiwada, IIT

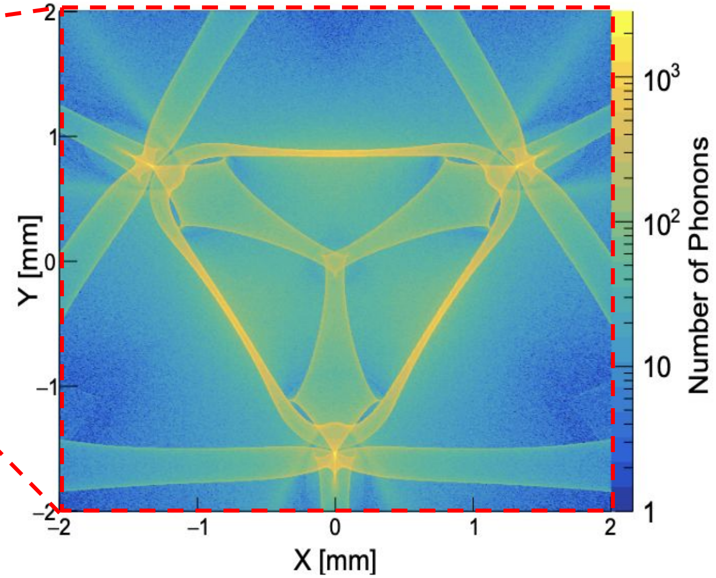
I. Hernandez, IIT

Z. Cai, IIT

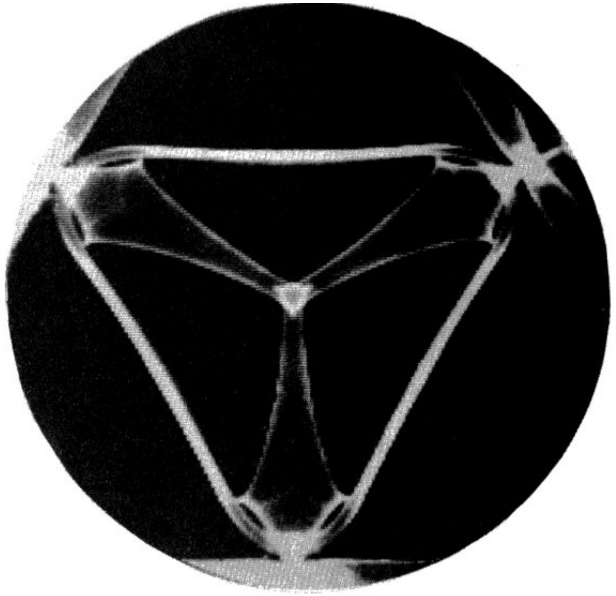
Example: phonon transport along *caustics*, preferred directions of phonon group velocity in a crystal.



Visualization of chip/phonons

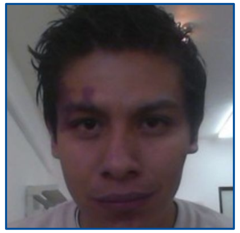


Simulated caustic pattern on chip surface (Al_2O_3)



Al_2O_3 Experimental data [https://journals.aps.org/prb/abstract/10.1103/PhysRevB.29.2190]

Phonon Modeling in G4CMP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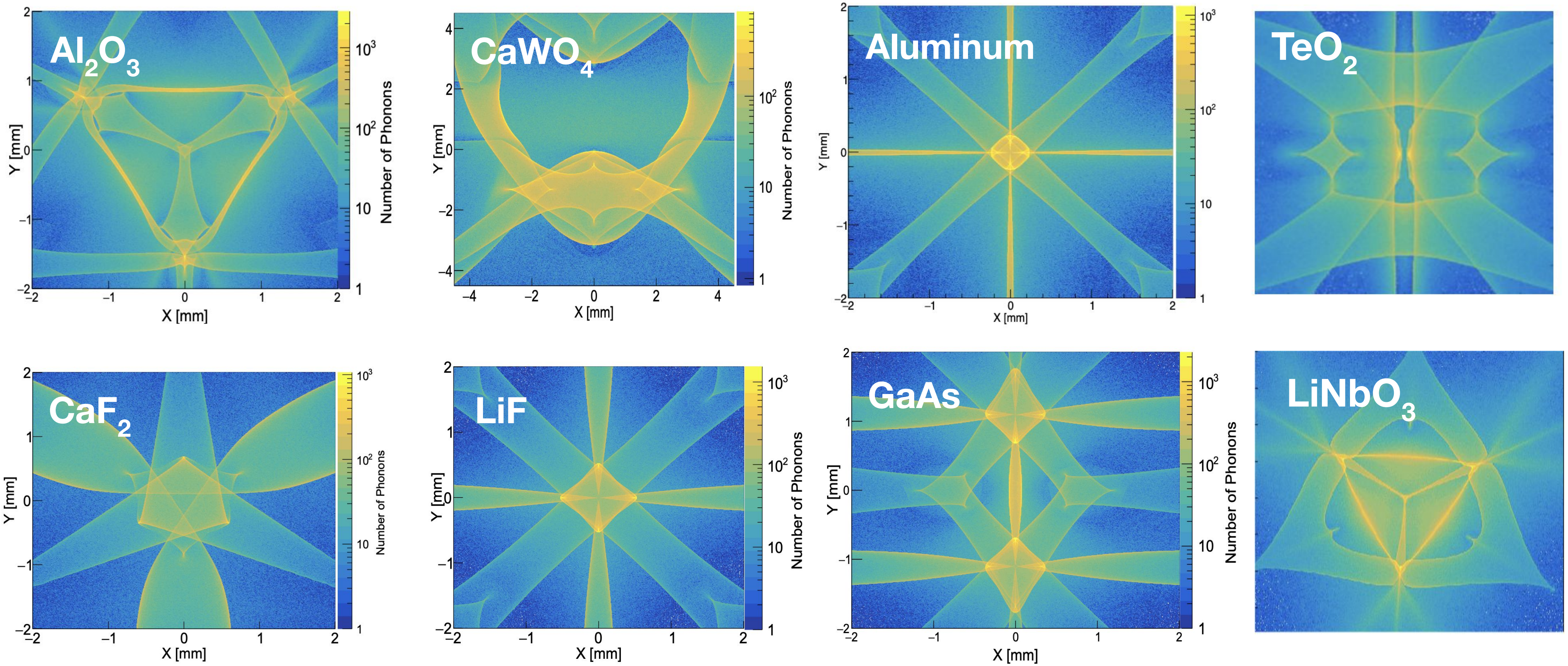
I. Hernandez, IIT

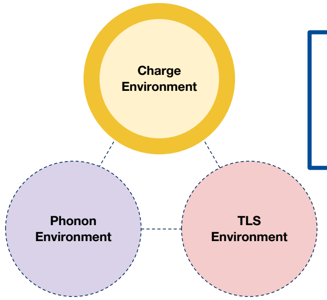
Z. Cai, IIT

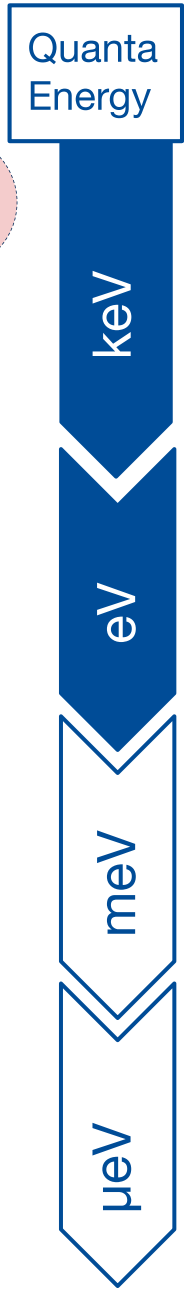
We've been building and validating a *library* of available materials for use in both HEP and QIS applications.



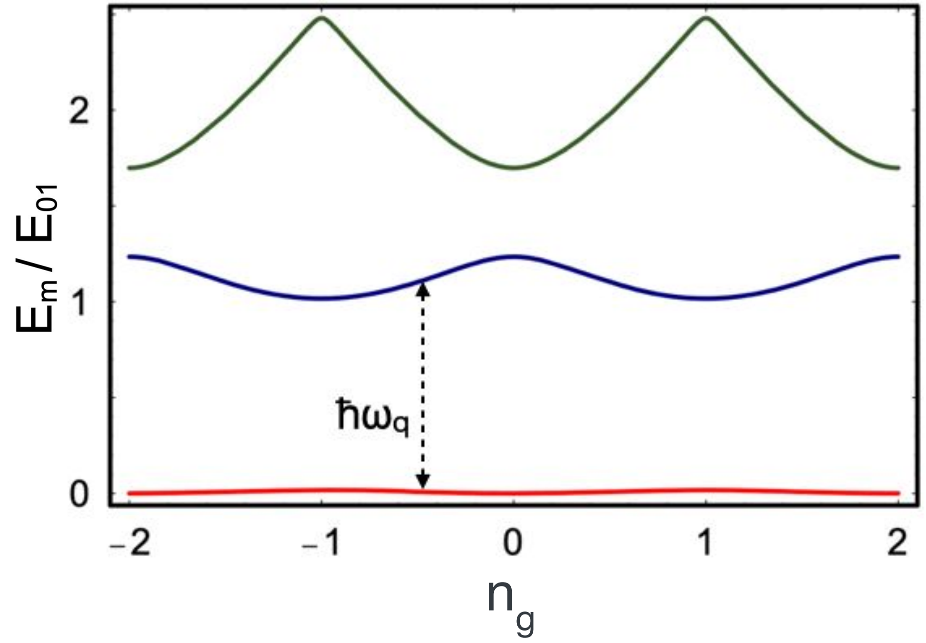
(plus more: Ta, Nb)

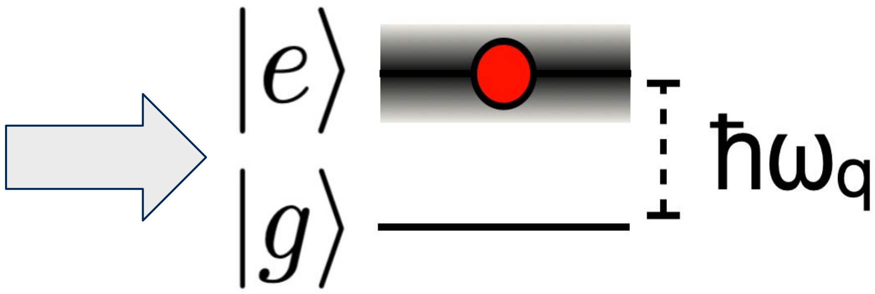
Charge Noise





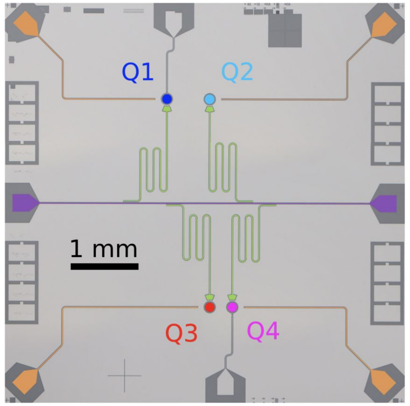
Ionizing radiation can create dephasing noise in qubits whose energy levels are sensitive to the local electrostatic field.





Radiation-induced Charge Noise

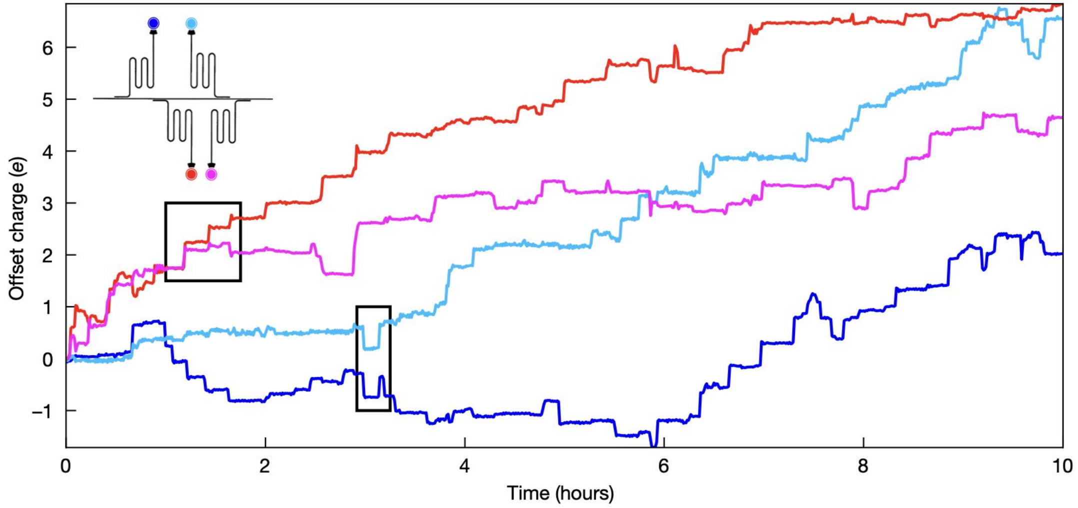
Experiments have taken advantage of this charge sensitivity to confirm the radiation dependence and its correlated impacts on neighboring qubits.



Correlated charge noise and relaxation errors in superconducting qubits

https://doi.org/10.1038/s41586-021-03557-5
Received: 14 December 2020

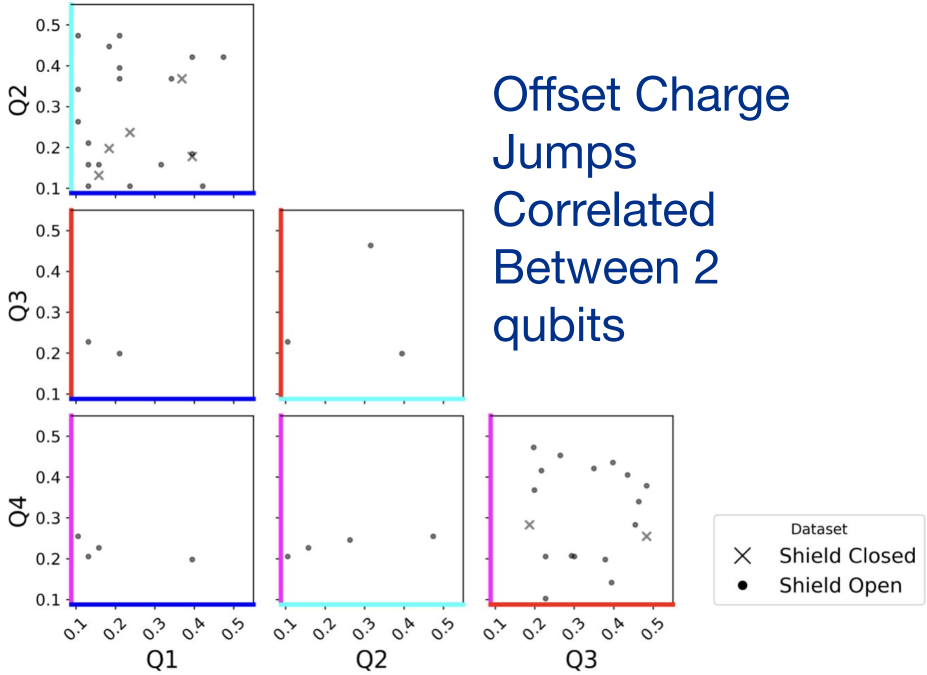
C. D. Wilen[1✉], S. Abdullah[1], N. A. Kurinsky[2,3], C. Stanford[4], L. Cardani[5], G. D'Imperio[5], C. Tomei[5], L. Faoro[1,6], L. B. Ioffe[7], C. H. Liu[1], A. Opremcak[1], B. G. Christensen[1], J. L. DuBois[8] & R. McDermott[1✉]



Article | Open access | Published: 11 November 2025

Measurement of correlated charge noise in superconducting qubits at an underground facility

G. Bratrud, S. Lewis, K. Anyang, A. Colón Cesaní, T. Dyson, H. Magoon, D. Sabhari, G. Spahn, G.



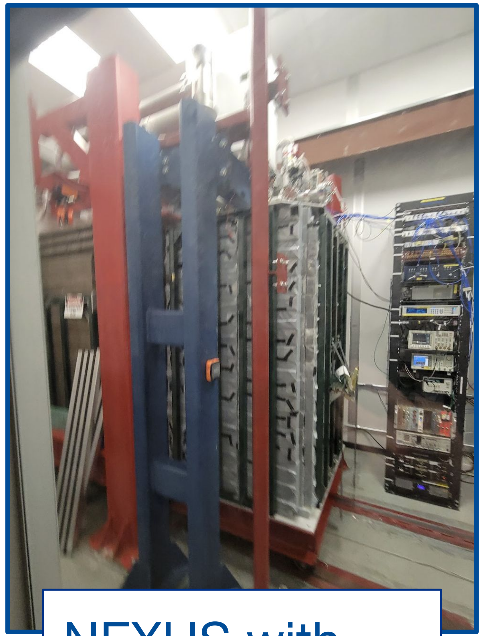
Offset Charge Jumps Correlated Between 2 qubits

Is charge noise a solved problem?

There are multiple strategies to mitigating this charge noise, and at leading order it is largely manageable.

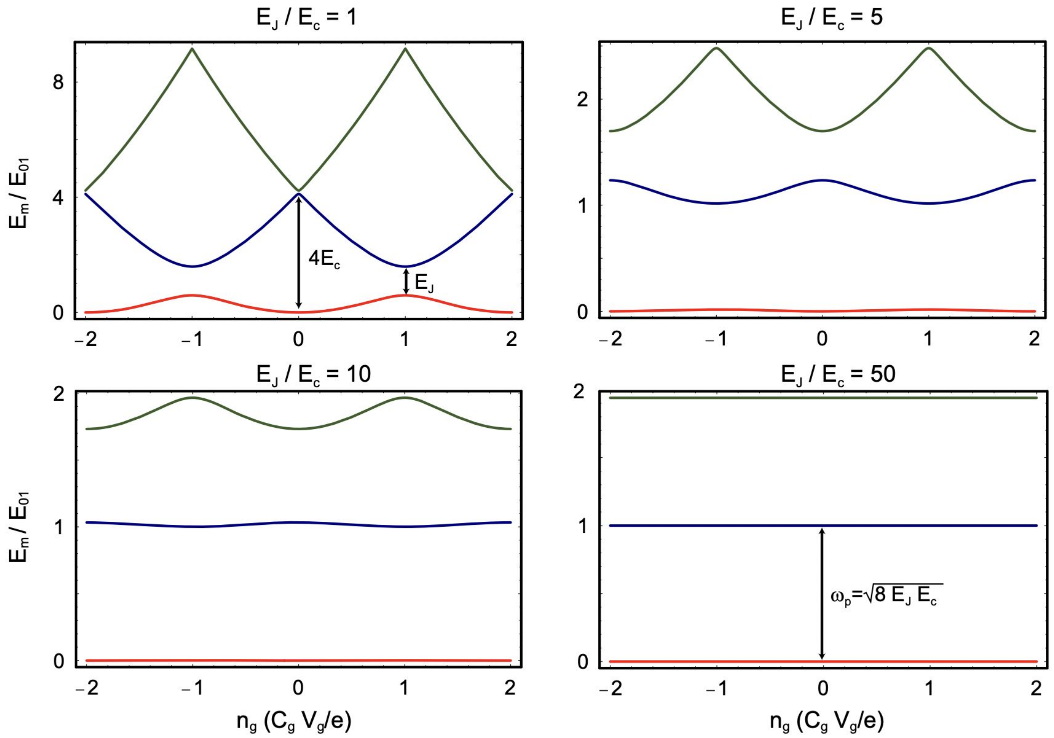
Naive strategy: shielding!

Unshielded NEXUS fridge



NEXUS with lead shielding

More convenient strategy: qubit design

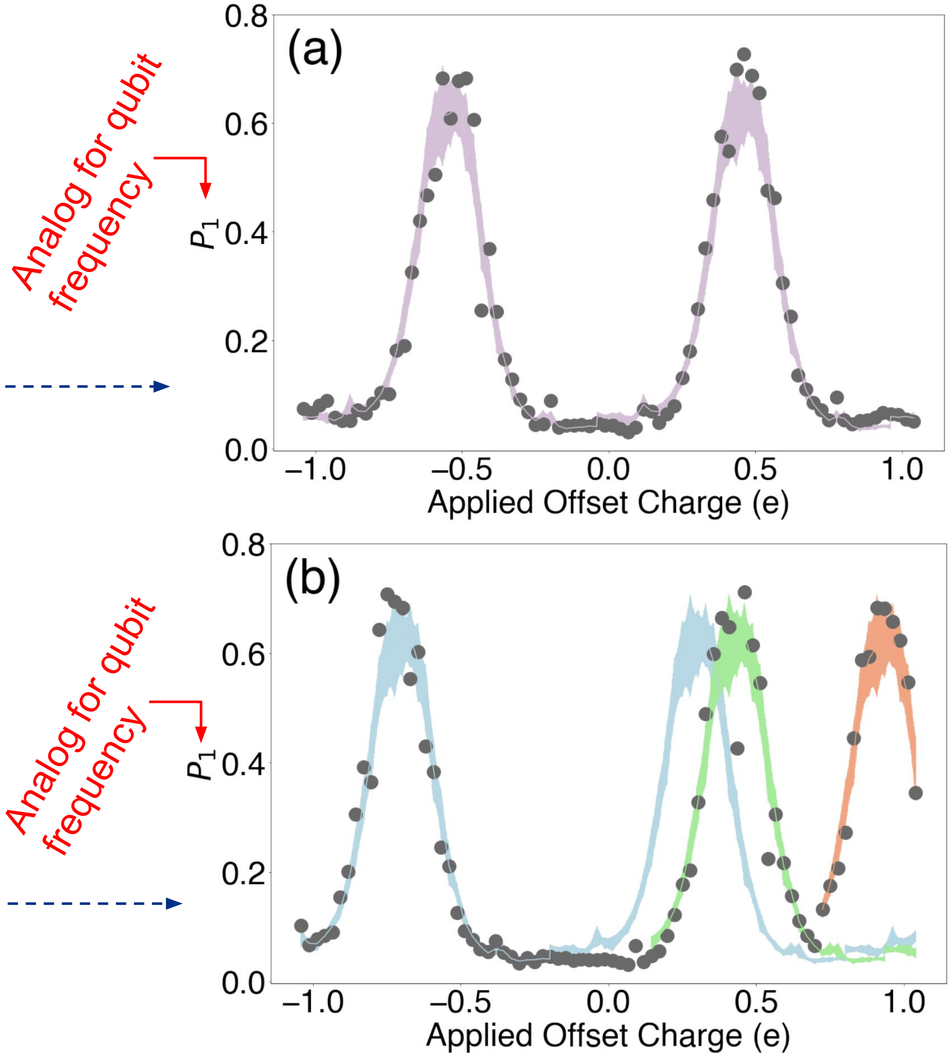


Qubit energy levels, various island/junction geometries.

Charge Bursts from Ionizing Radiation

At NEXUS, we have begun to disentangle different sources of charge bursts in a Nb-on-Si qubit chip.

- Ramsey tomography scan:
  - Qubit frequency dependent on environmental "offset" charge
  - Sweep in applied voltage bias → periodic sweep in qubit frequency
- Ionizing radiation rearranges charge environment, presents as jump in phase of sweep ("charge jump")
- **Measured rates:**
  - Shield open (SO): 0.51 mHz
  - Shield closed (SC): 0.19 mHz
  - *Naive expected SO/SC ratio (ambient γ's): 20:1*



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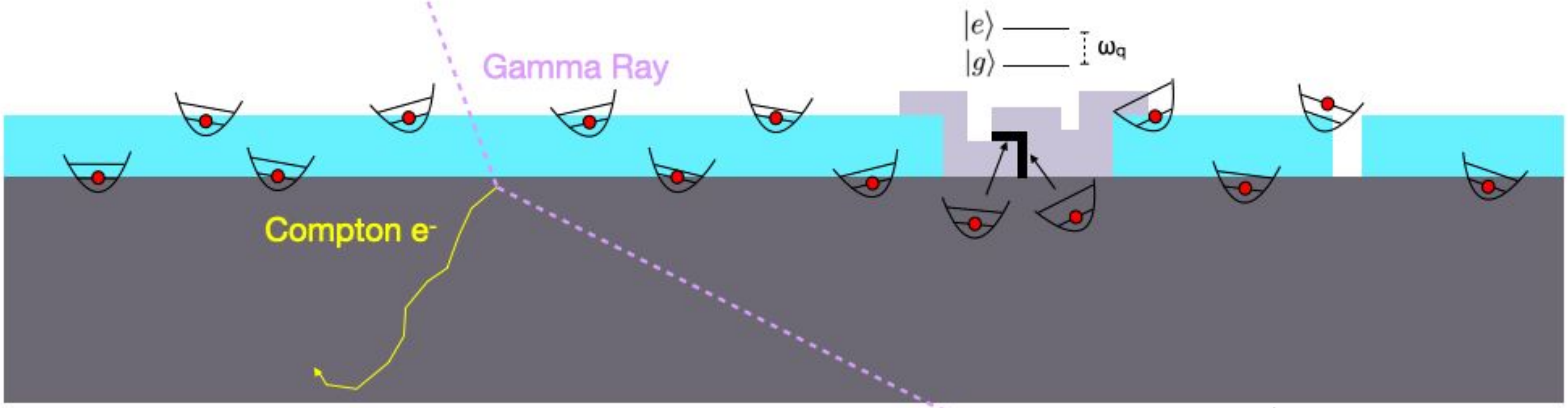
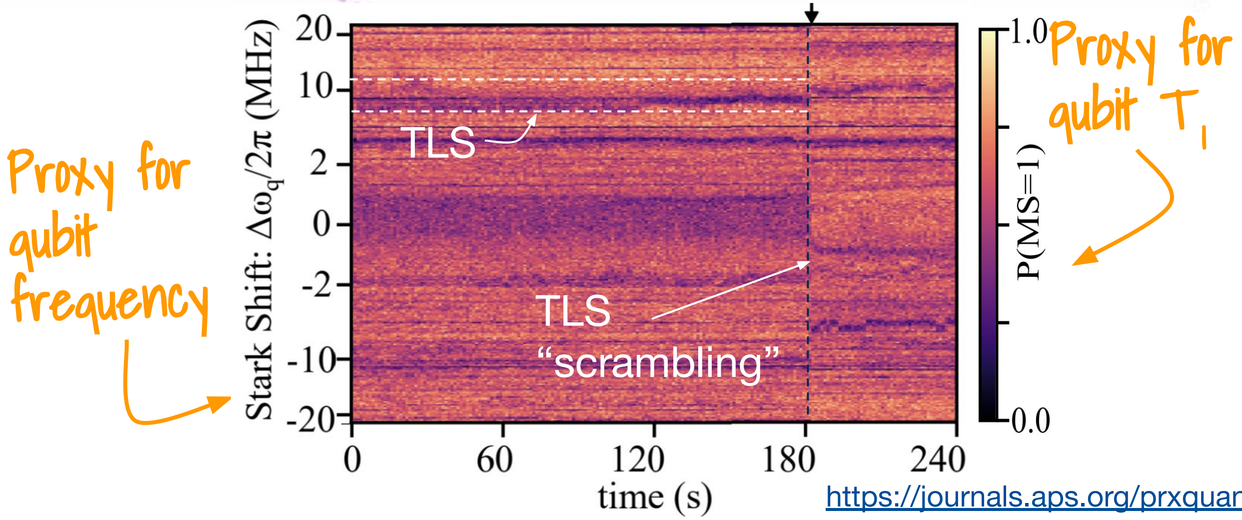
Radiation-amplified TLS noise

Ionizing radiation can change TLSs' frequencies via charge rearrangement.



Studies have confirmed this effect, but are few and far between…

Notably, **radiation impacts are not 1-to-1 with TLS scrambling** in a given qubit.



https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.4.020356

Quanta Energy
keV
eV
meV
μeV

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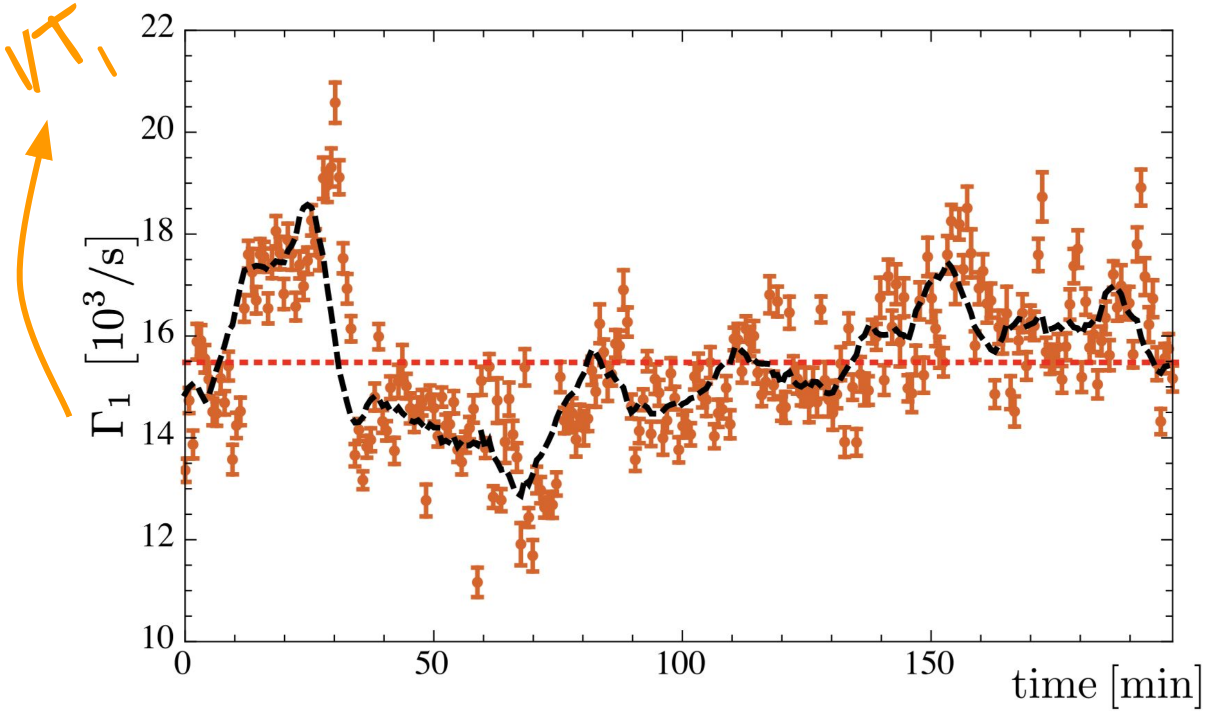
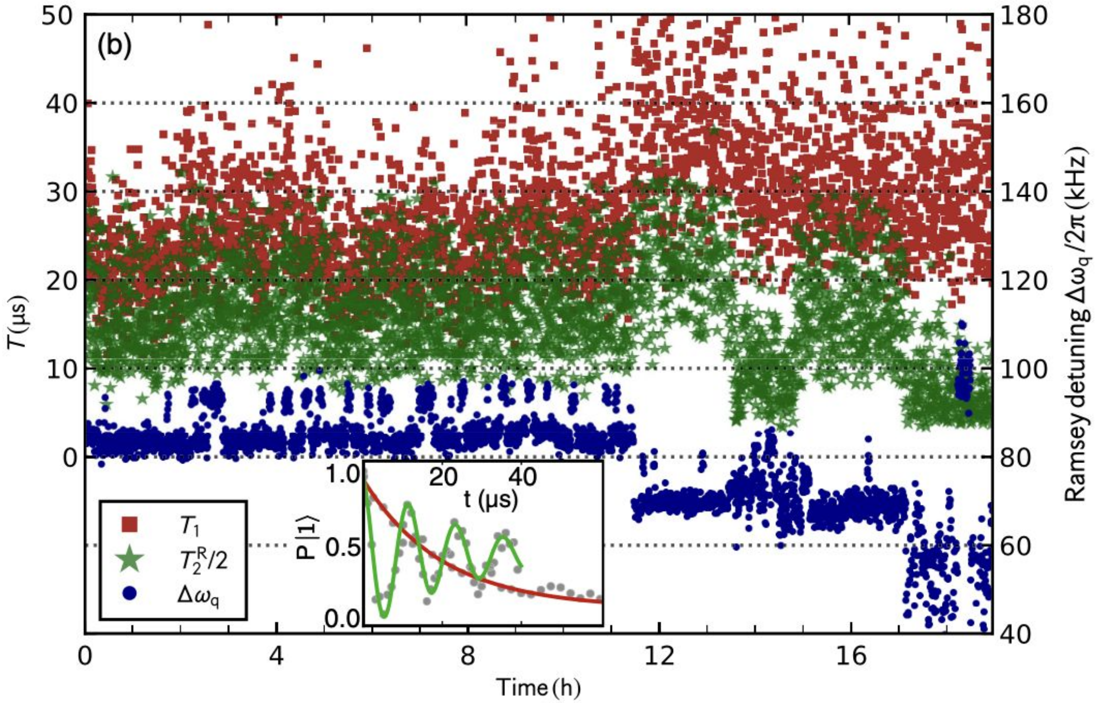
TLS Environment: What's Observed?

Superconducting qubit frequencies and coherence times have been observed to fluctuate nontrivially with time.



Interacting two-level defects as sources of fluctuating high-frequency noise in superconducting circuits

Clemens Müller,[1,2] Jürgen Lisenfeld,[3] Alexander Shnirman,[4,5] and Stefano Poletto[6,*]

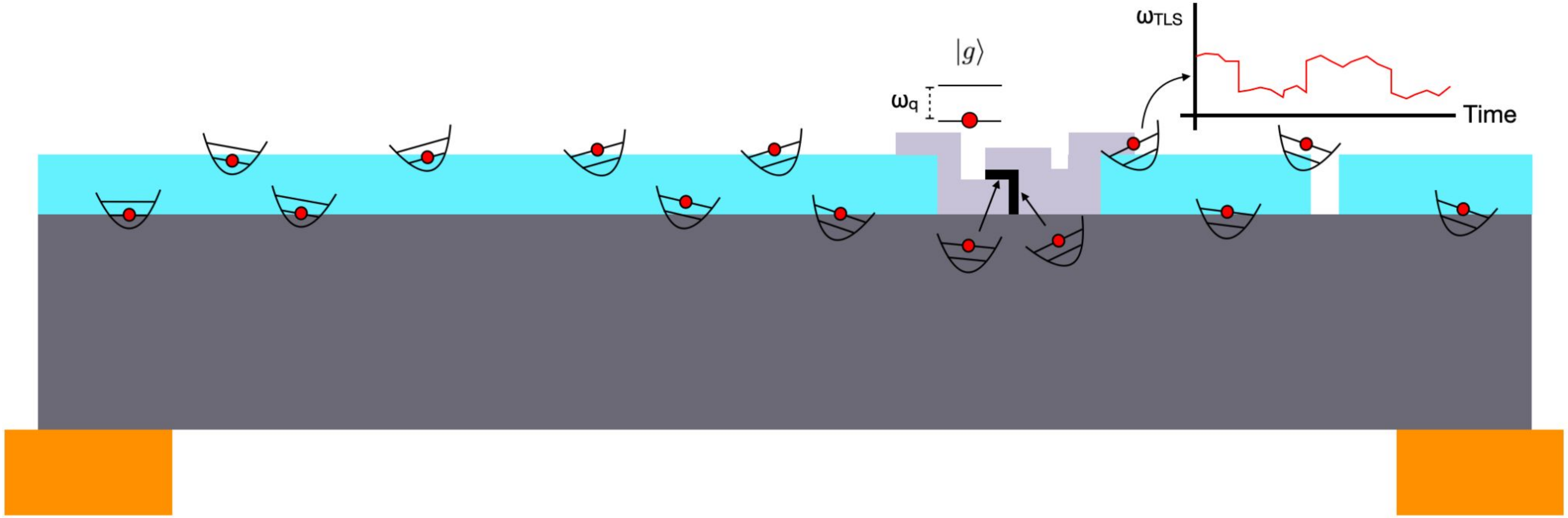


Correlating Decoherence in Transmon Qubits: Low Frequency Noise by Single Fluctuators

Steffen Schlör,[1,*] Jürgen Lisenfeld,[1] Clemens Müller,[2,3] Alexander Bilmes,[1] Andre Schneider,[1] David P. Pappas,[4] Alexey V. Ustinov,[1,5] and Martin Weides[1,6,†]

TLS Environment: What's the Picture?

This qubit misbehavior has been ascribed to the presence of quantum "two-level-systems" (TLSs) nearby in physical and frequency space to the qubit



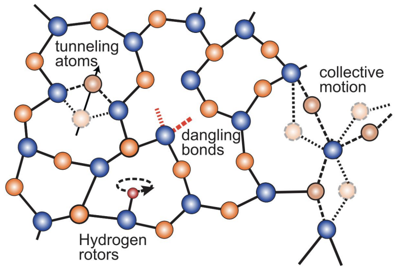
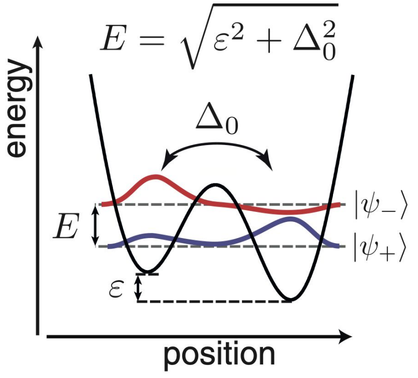
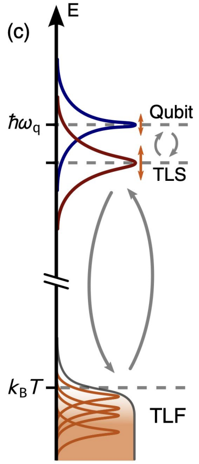


Figure 3. Illustration of some example mechanisms of TLS formation in an amorphous material: tunneling of single atoms and collective motion of small atomic groups, dangling bonds, and hydrogen defects.





1. Fundamental origin not well known, but tied to disorder
2. Effective model: "double potential well"
3. TLS frequency $\omega_{TLS} = E/\hbar$ at many scales, including ~GHz, near ω_q
4. Can accept excitations from the qubit if near-resonant (causing T_1 drop)
5. ω_{TLS} jitters due to coupling with thermal fluctuators (TLSs with ω_{TLS} ~ kT)
6. **Result:** diffusive and telegraphic jitter in qubit T_1, ω_q.

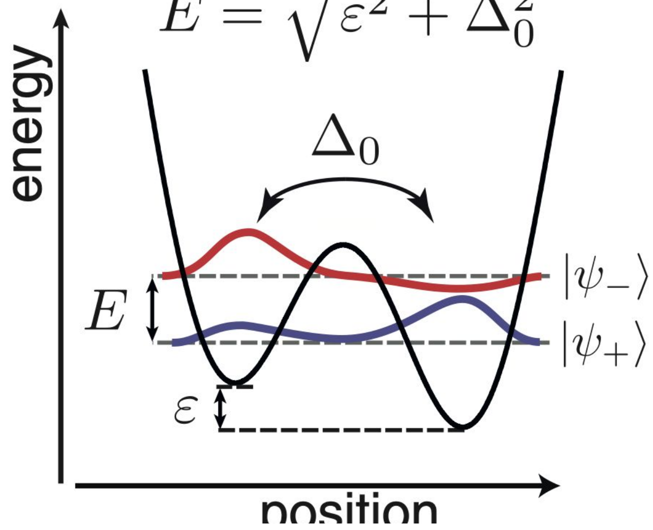
TLS Environment: What's the Picture?

While the fundamental origin of TLSs is still not well known (or even singular), they do share common properties.

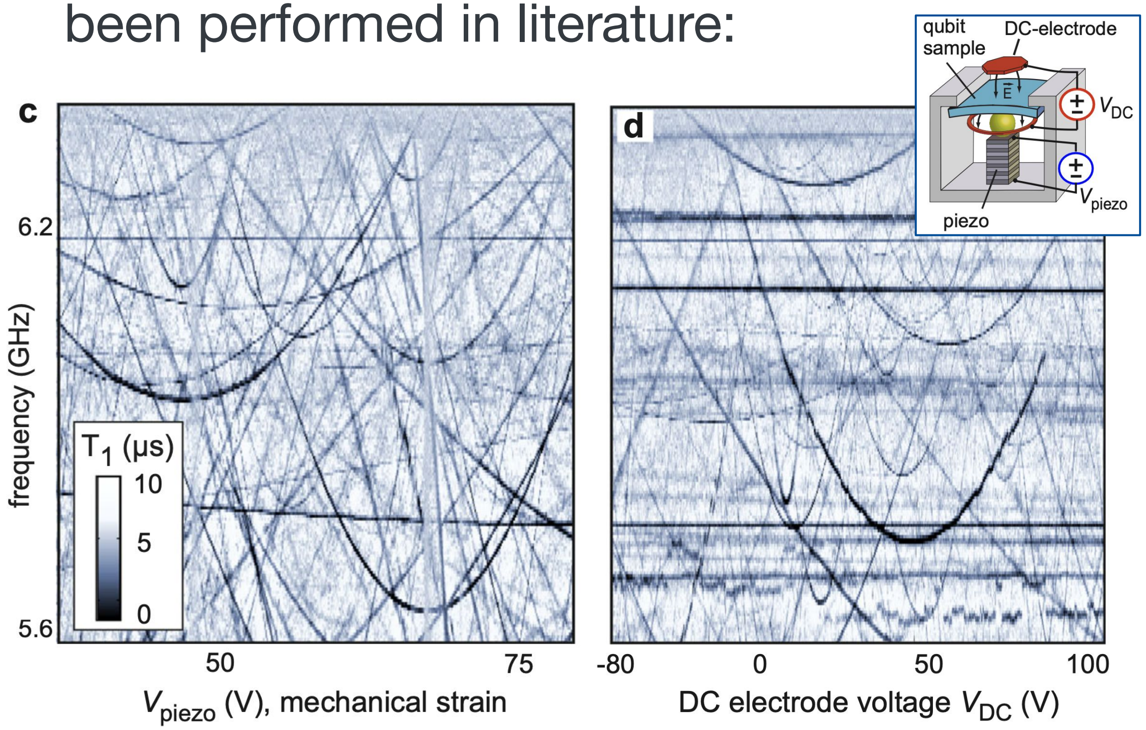
TLS frequency depends on local strain and local E-field: $\varepsilon = 2\boldsymbol{\gamma}\cdot\mathbf{S} + 2\,\mathbf{p}\cdot\mathbf{E} + \varepsilon_0.$

- $\boldsymbol{\gamma}$: TLS strain coupling
- $\mathbf{S}$: Local strain
- $\mathbf{p}$: TLS dipole moment
- $\mathbf{E}$: Local E-field

$$E = \sqrt{\varepsilon^2 + \Delta_0^2}$$



Strain- and E-field-tuning of TLSs has been performed in literature:



Electric field spectroscopy of material defects in transmon qubits

Jürgen Lisenfeld[1*], Alexander Bilmes[1], Anthony Megrant[2], Rami Barends[2], Julian Kelly[2], Paul Klimov[2], Georg Weiss[1], John M. Martinis[2] and Alexey V. Ustinov[1,3]

Quanta Energy

MeV

keV

eV

meV

μeV

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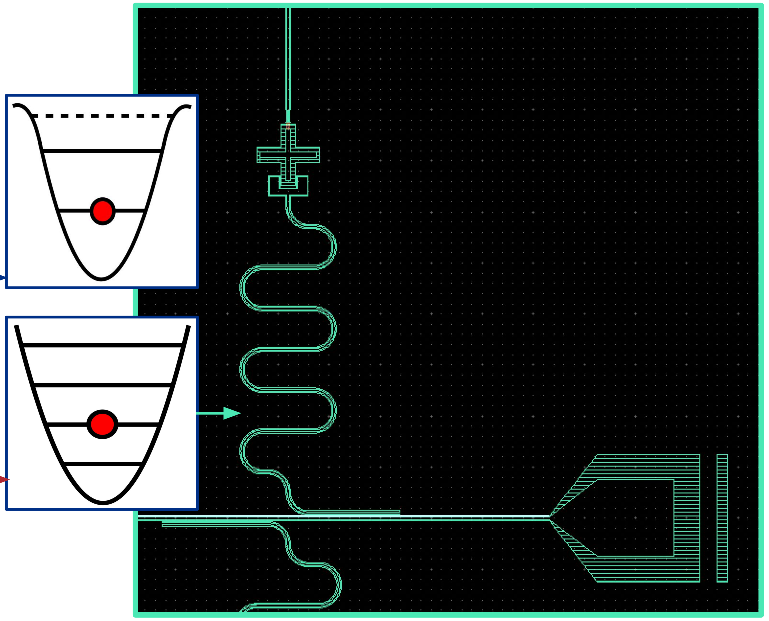
Resonant Energy Exchange

Useful tool for QIS devices: resonant energy exchange (Rabi Oscillations) between coupled oscillators.

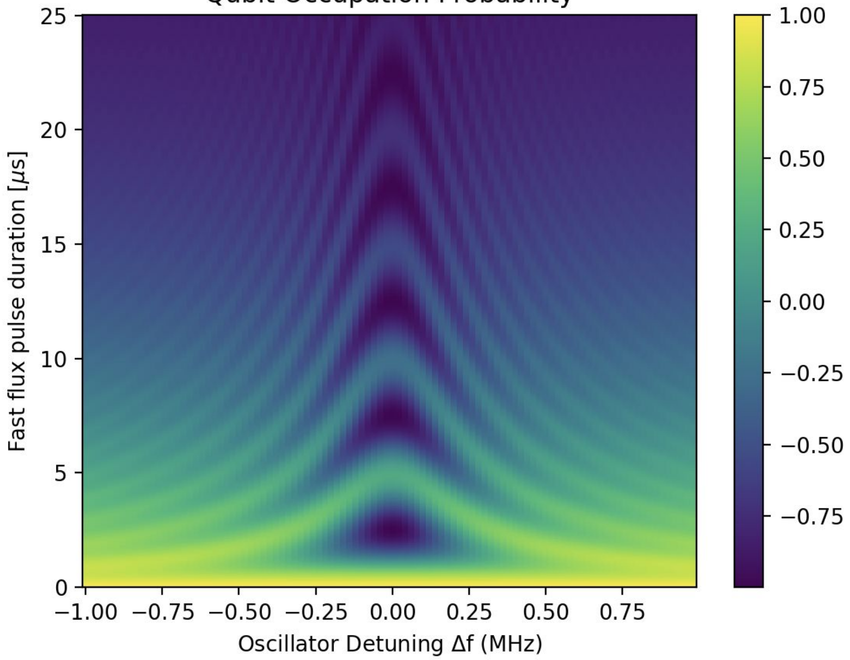
Hamiltonian of two quantum oscillators "a" and "b" coupled with strength g:



$$H = \omega_q a^\dagger a + \omega_n b^\dagger b + g\,(a^\dagger b + a b^\dagger)$$

- $\omega_q a^\dagger a$: Oscillator "a" energy
- $\omega_n b^\dagger b$: Oscillator "b" energy
- $a^\dagger b$: Transfer excitation: b→a
- $a b^\dagger$: Transfer excitation: a→b

When the oscillators' frequencies are brought on resonance, the total system evolves by swapping an excitation from one oscillator to the other.



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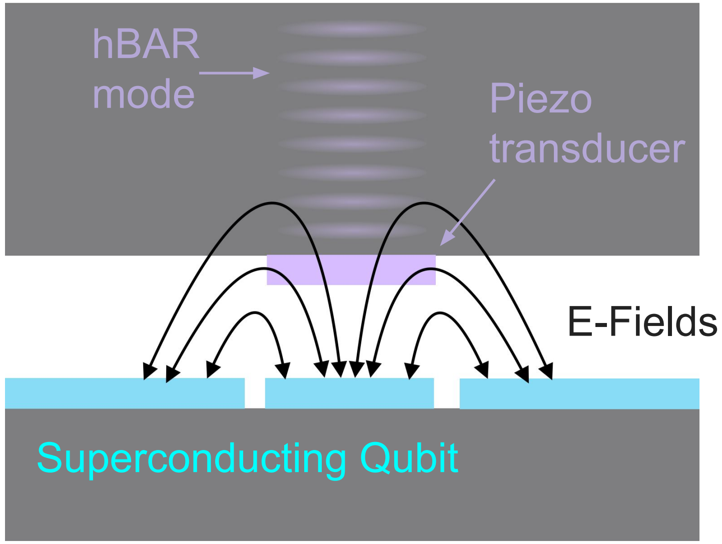
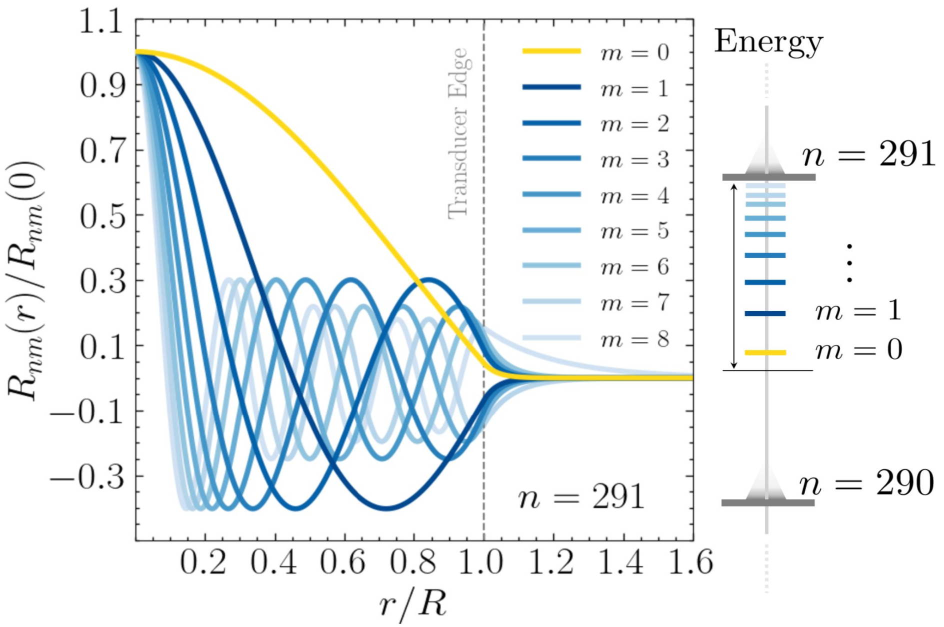
qc-hBAR Swap Efficiency

For detection sensitivity, need swap efficiency, which is driven by the qubit-hBAR coupling and time evolution.

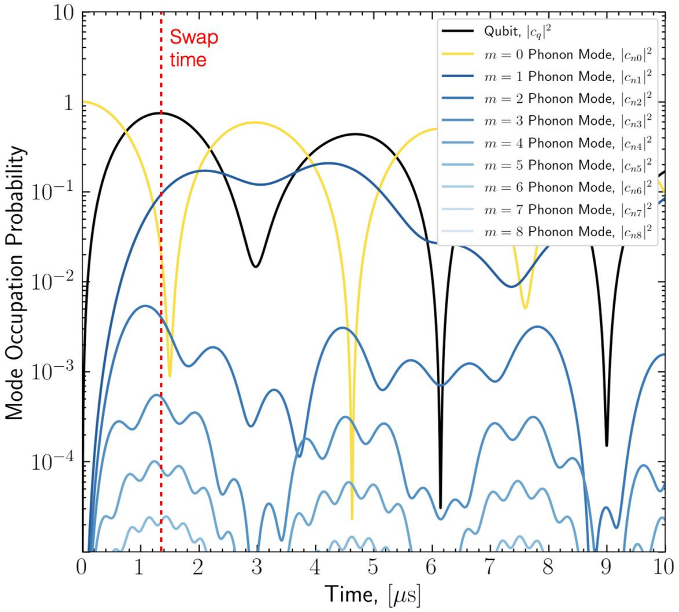


How well spatially-matched are the EM modes to the phonon mode?

$$U_{nm}(r,z) = \cos\left(\frac{n\pi z}{L+h(r)}\right) R_{nm}(r)$$



Qubit can couple to rich set of modes with different radial "m" structure (with different coupling strengths).



Mode set evolves together with qubit, giving first swap efficiencies ~ 70%.

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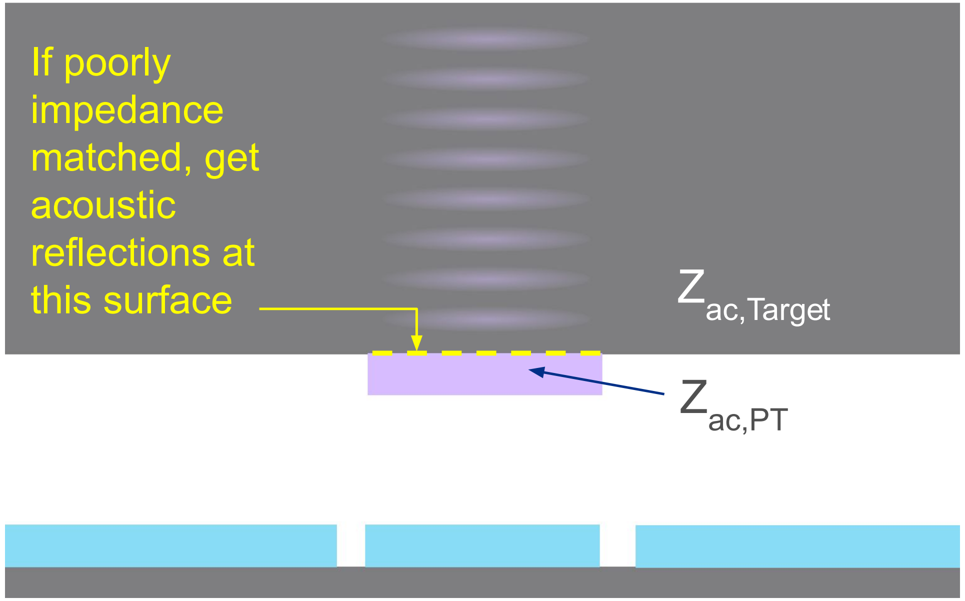
Acoustic Matching

Good acoustic impedance matching between the target chip and the piezoelectric is a “hidden” requirement in achieving good swap efficiency.



Acoustic impedance: density x sound speed

$$Z_{ac} = \rho c$$

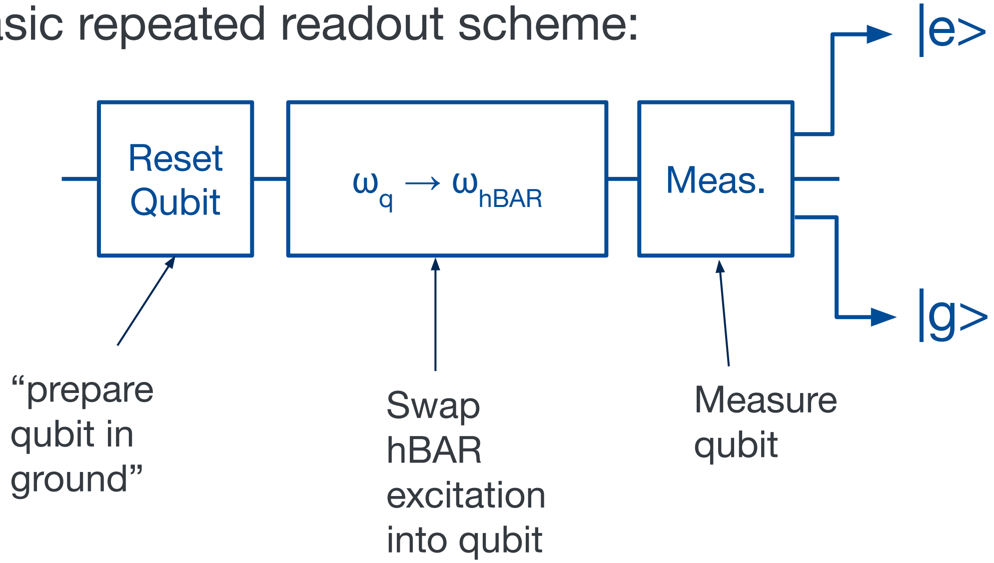
Goal: match these parameters between the piezo and the substrate

Material	AIN	$LiNbO_3$	GaN	Al2O3	SiC	Si
ρ (kg/m^3)	3260	4600	6100	3.98	3210	2330
C (km/s)	11.3	6.5-7.3	3.96-8.0 (link)	11.25 (c-plane)	13.0	8.433
Z_{ac} (kg/m^2s)	37e3	29.3e3 – 33.6e3	24.0e4 – 48.8e3	44.7e3	41.7e3	19.6e3

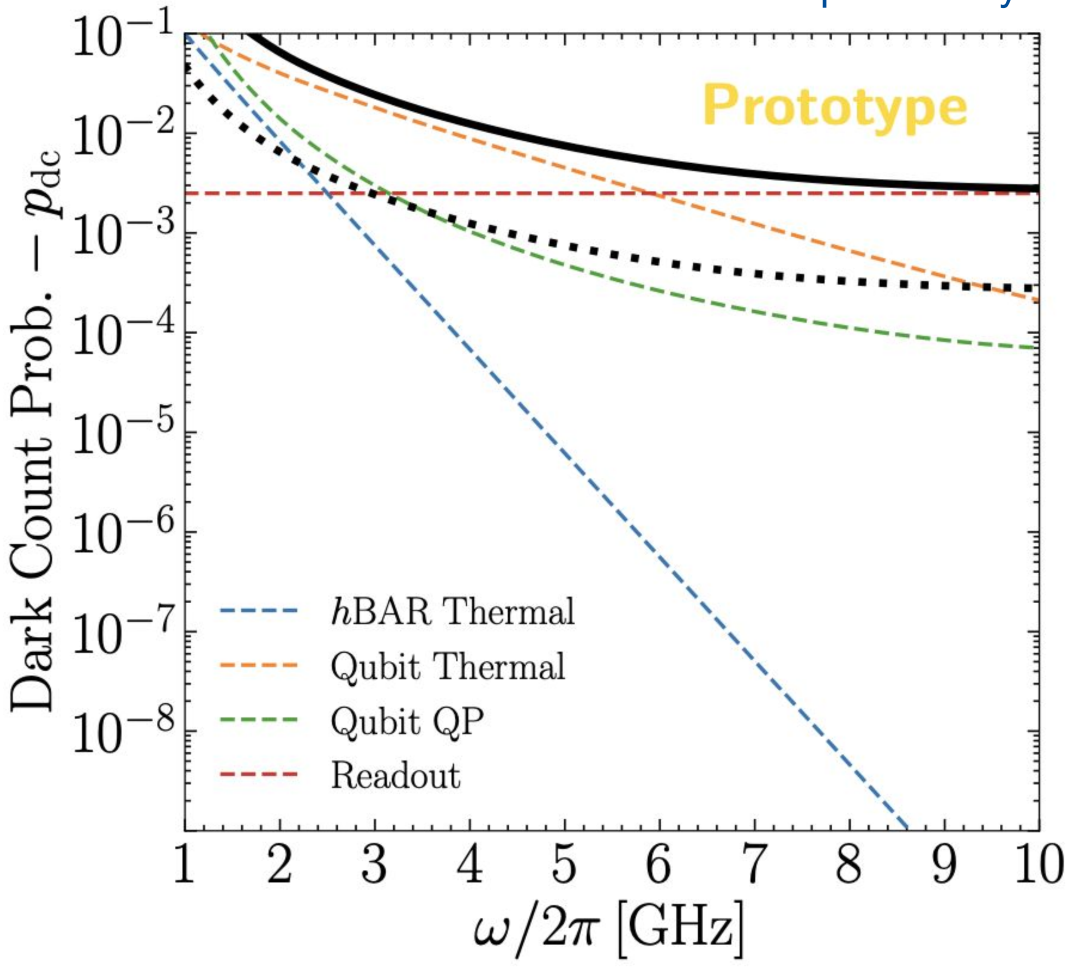
Backgrounds for Quantum Acoustics Detectors

For a “simple” quanta-swap detection scheme, the dark count backgrounds feature the microphysics we’ve discussed!

Basic repeated readout scheme:



Estimated near-term dark count probability



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Backgrounds for Quantum Acoustics Detectors

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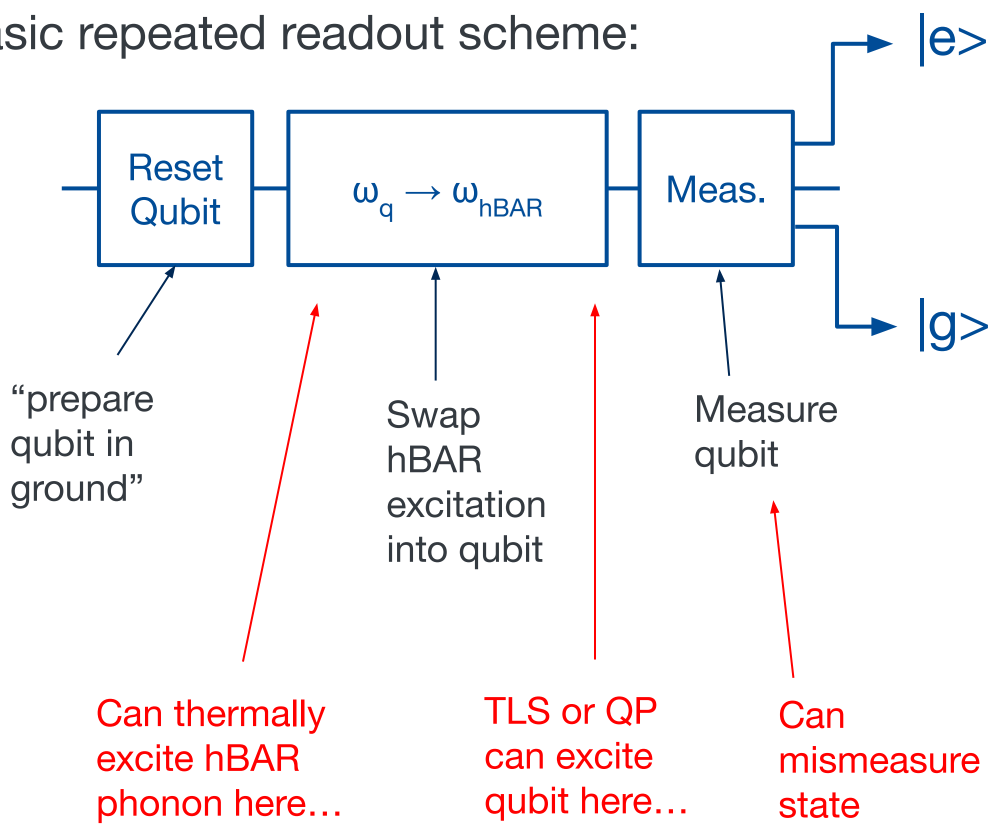

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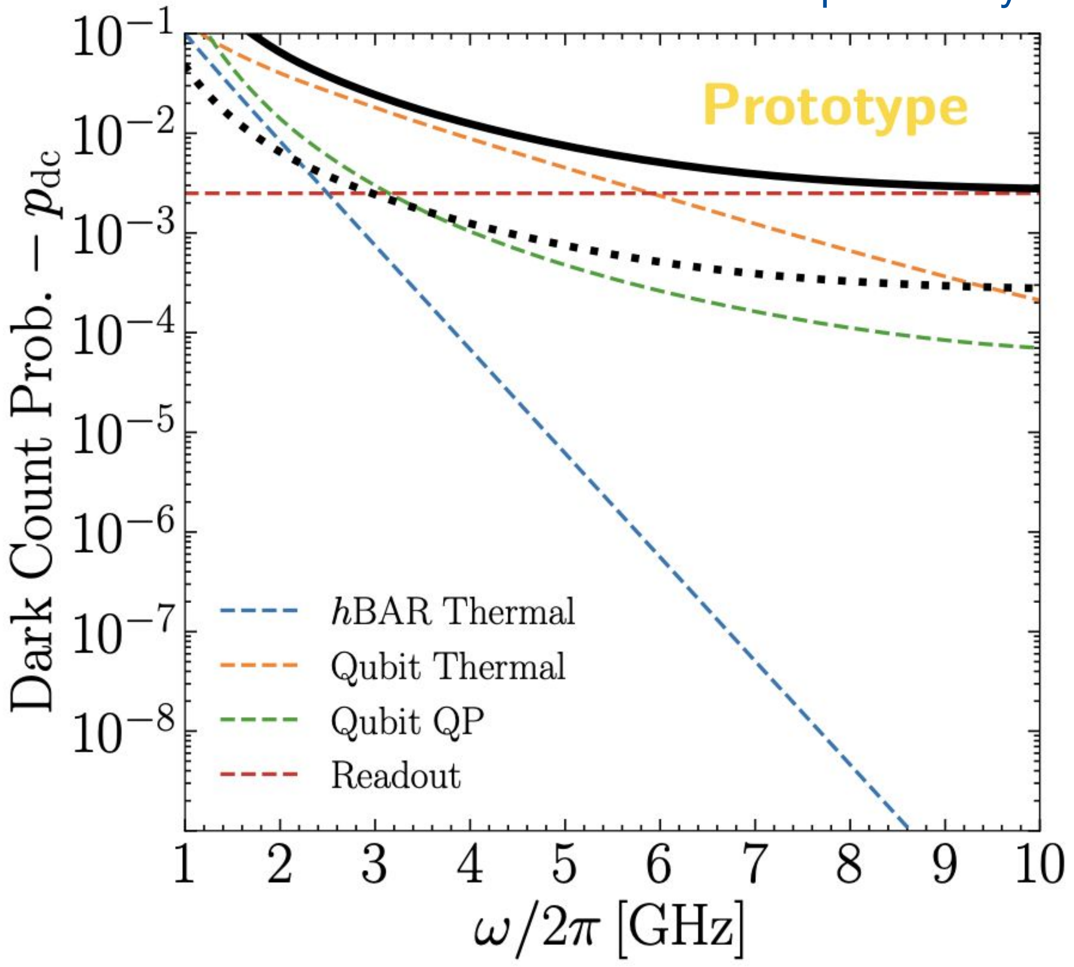


Quantum Acoustics for Wavelike DM

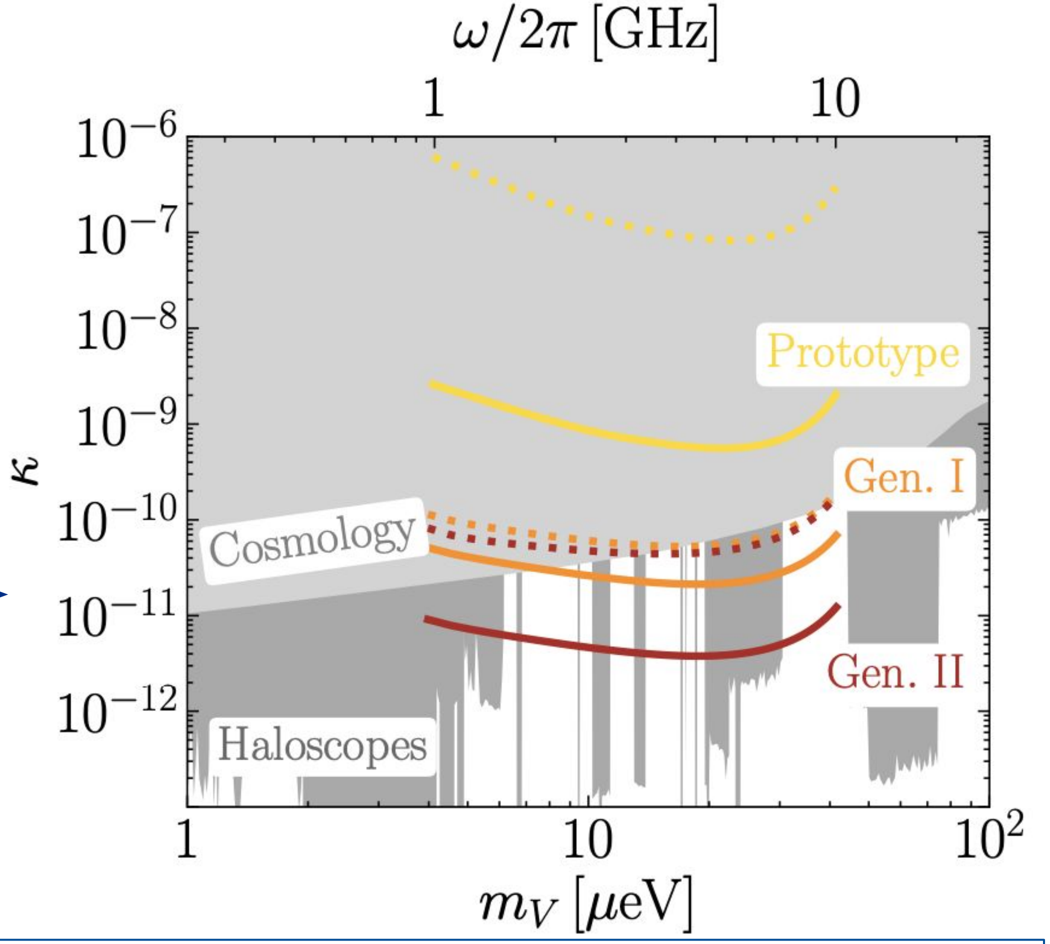
Qubit-coupled hBAR detectors give potential for wavelike DM and BSM probes.

Searches for "effective force" BSM physics:

$$|\langle nm|\delta H_0|0\rangle|^2 = \left(\frac{f_0}{\rho_h}\right)^2 \frac{2}{\omega_{nm}} \frac{M_\lambda^2}{M_h} \mathcal{C}_{nm}^2$$

Dark photon:
- Couples to and drives piezo transducer
- Potential daily modulation from preferred polarization

High-frequency gravitational waves
- Couples to entire hBAR



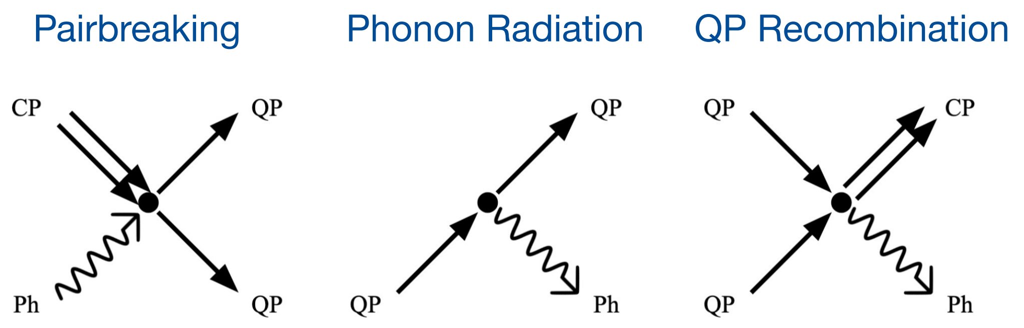
Listening For New Physics With Quantum Acoustics

Ryan Linehan,[1,*] Tanner Trickle,[2] Christopher R. Conner,[3] Sohitri Ghosh,[2] Tongyan Lin,[4] Mukul Sholapurkar,[4,5] and Andrew N. Cleland[3,6]

Wait, but how do we *produce* 10μeV phonons?

To efficiently produce 10μeV phonons for sensing with quantum acoustics architectures, we may be able to exploit emergent superconductor physics…

Returning to the inelastic processes now in G4CMP…



Material	Hf	α-W	α-W + β-W	AlMn
Gap, 2Δ	30 μeV	3 μeV	O(10μeV), tunable	Broadly tunable