Readout Response Tools: QuantumDeviceResponse

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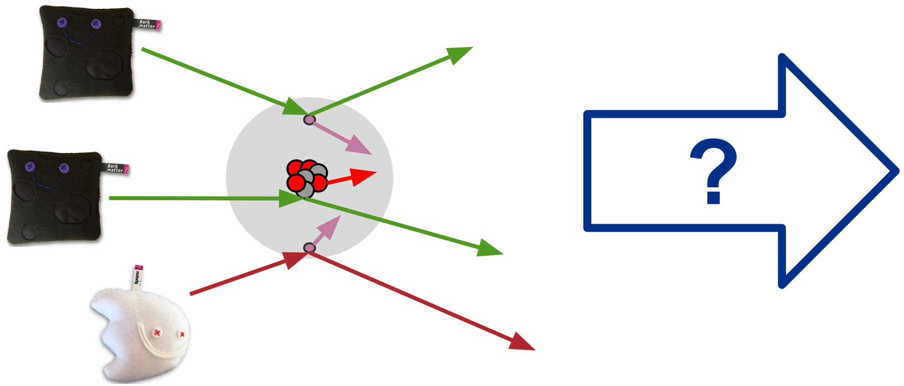
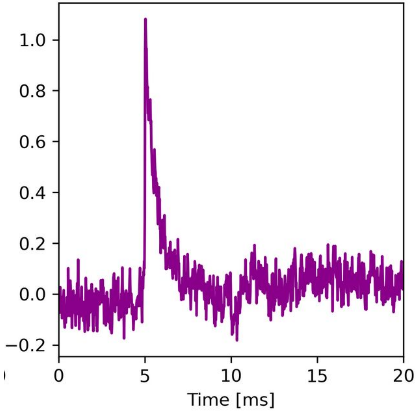
Outline

- Motivation for detector readout simulators
- QDR from 30,000 feet
- Technical details of simulation
- Applications & results
- Conclusions & future work

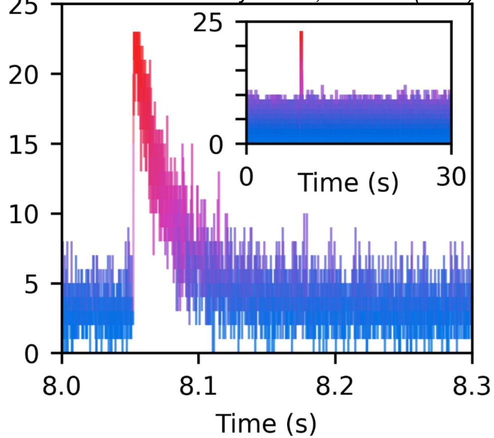
From Interactions to Waveforms

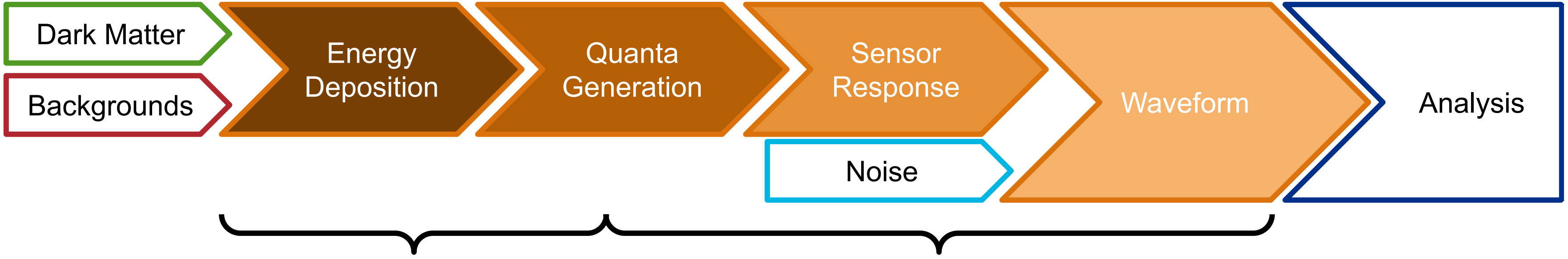


arxiv:2402.04473



Nature Physics **18**, 107–111 (2022)





Dark Matter

Backgrounds

Energy Deposition

Quanta Generation

Sensor Response

Noise

Waveform

Analysis

`Geant4 / G4CMP`

`QuantumDeviceResponse`

QuantumDeviceResponse Simulation Package

C++/ROOT-based simulation tool to bridge the gap between the "particle physics" in Geant4+G4CMP and the physics that governs the response of “quantum” sensors.

- Superconducting (pair-breaking) RF sensors
  - Transmon qubits (gate-based readout, *charge-parity readout**)
  - Kinetic inductance detectors
  - *Quantum capacitance detectors**
  - … and more?!
- Flexible framework allows users to define their own sensor + readout scheme
- Input: G4CMP phonon energy depositions
- Output: Time-domain waveforms for each sensor in a detector

** to be implemented*

Why might **you** use this tool?

QDR from 30,000 feet

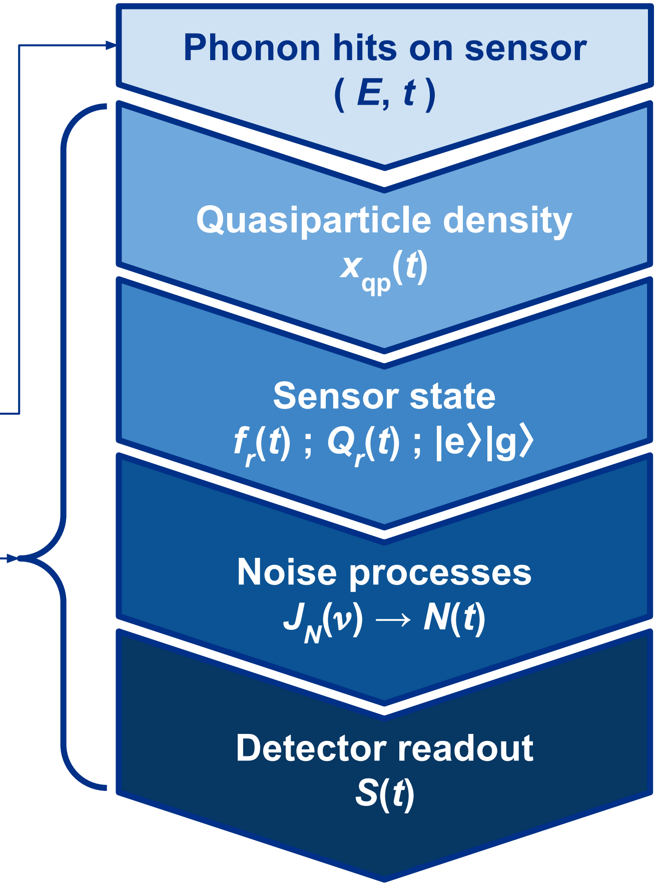
To evaluate the efficacy of a generic “sensor” as a particle detector requires understanding

- Energy deposition from e.g., scattering in detector

  `Geant4` *(+ theory)*
- Propagation of energy (quanta) to sensor

  `G4CMP`
- Response of sensor to phonon absorption

  `QuantumDeviceResponse`
  - Handles QP production from phonon hits
  - Handles QP recombination
  - Handles mapping of QP density to frequency shift, sensor state, etc.
  - Handles noise from external sources



Phonon hits on sensor
(E, t)

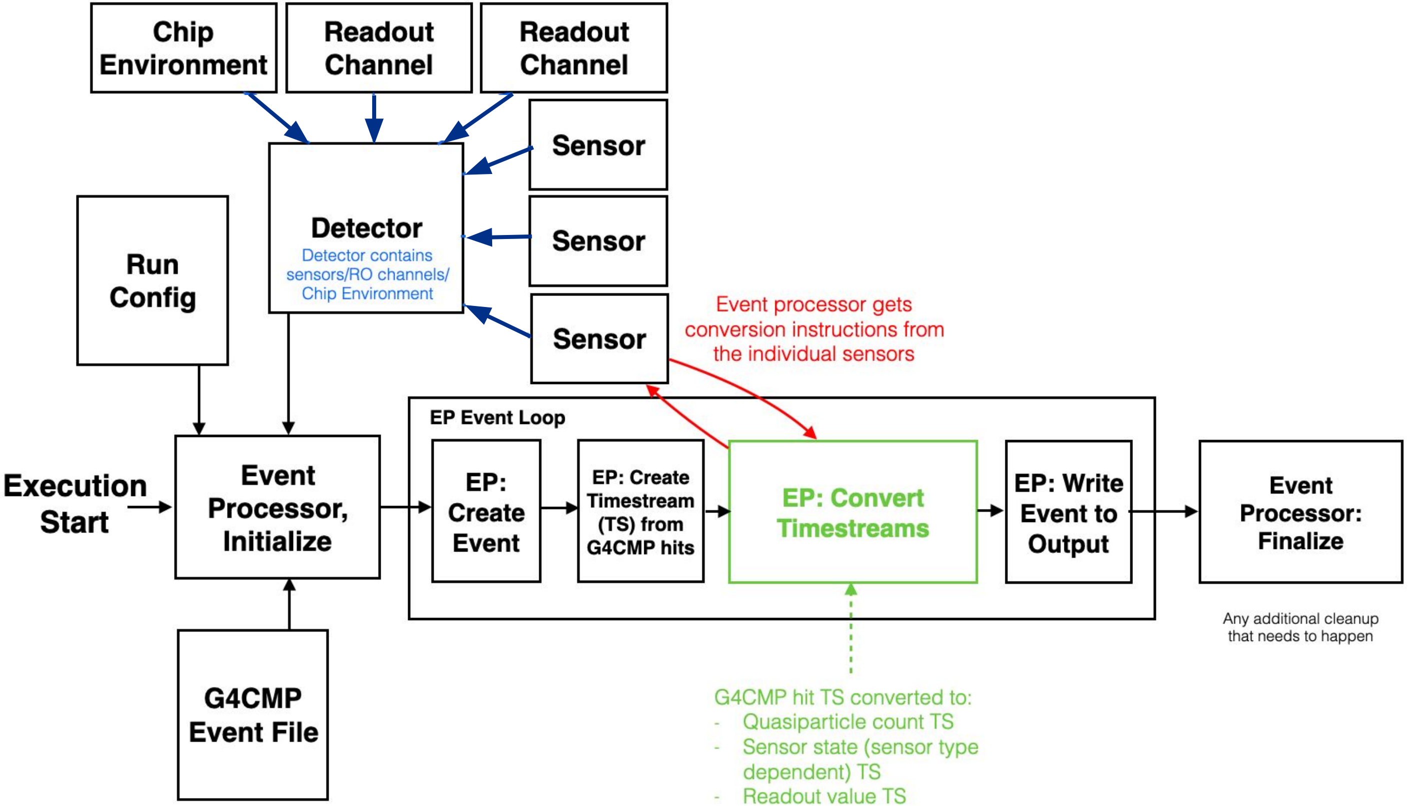
Quasiparticle density
$x_{qp}(t)$

Sensor state
$f_r(t)$; $Q_r(t)$; $|e\rangle|g\rangle$

Noise processes
$J_N(\nu) \rightarrow N(t)$

Detector readout
$S(t)$

Simulation Framework Structure



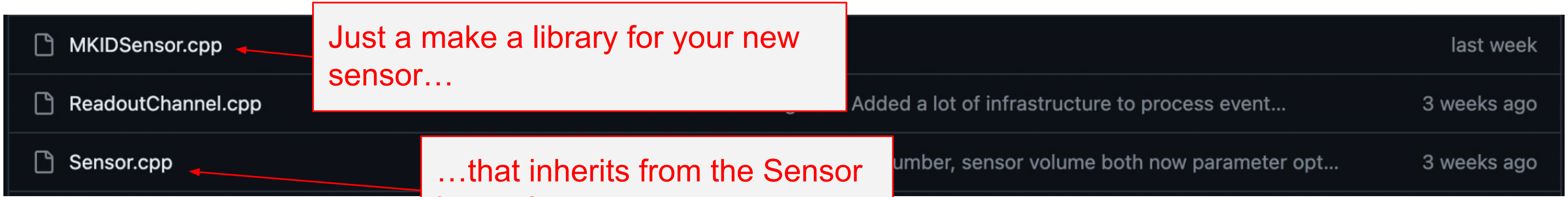
Event processor gets conversion instructions from the individual sensors

Any additional cleanup that needs to happen

G4CMP hit TS converted to:
- Quasiparticle count TS
- Sensor state (sensor type dependent) TS
- Readout value TS

Simulation Framework Structure: Sensor Types

QDR is designed to be flexible and accept new [phonon] detector types



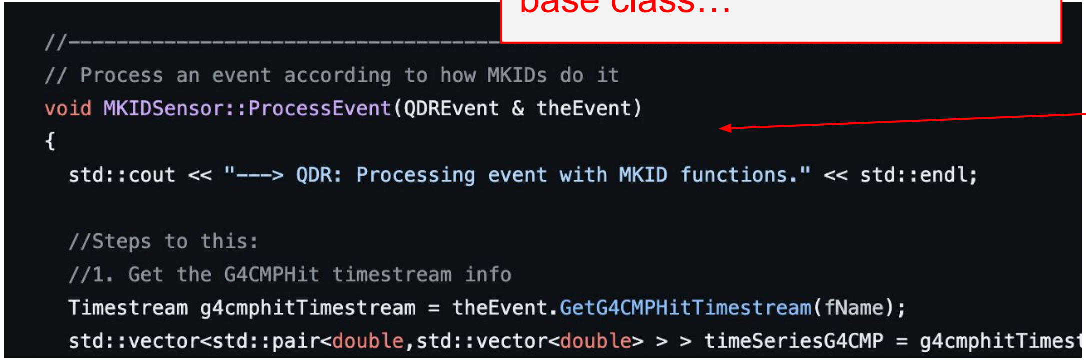
MKIDSensor.cpp last week

ReadoutChannel.cpp Added a lot of infrastructure to process event... 3 weeks ago

Sensor.cpp umber, sensor volume both now parameter opt... 3 weeks ago

Just a make a library for your new sensor…

…that inherits from the Sensor base class…



```
//------------------------------------
// Process an event according to how MKIDs do it
void MKIDSensor::ProcessEvent(QDREvent & theEvent)
{
  std::cout << "---> QDR: Processing event with MKID functions." << std::endl;

  //Steps to this:
  //1. Get the G4CMPHit timestream info
  Timestream g4cmphitTimestream = theEvent.GetG4CMPHitTimestream(fName);
  std::vector<std::pair<double,std::vector<double> > > timeSeriesG4CMP = g4cmphitTimest
```

…and write instructions (within a specific framework) on how that sensor should convert G4CMP hits into a waveform.

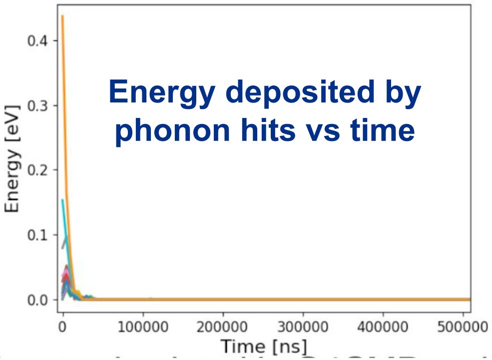
This talk focused on implemented sensor types: phonon-mediated **MKIDs** & **Transmon qubits**

Waveform Generation Step 1: Quasiparticle Density

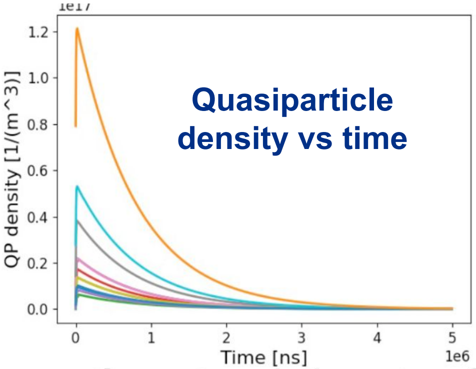
Generation: at each time step, check for phonon hits

- [MKIDs] For a total phonon energy E, create a number of qps ~ E/Δ
- [Transmons] Full recombination diff. eq. $x_{qp} = \left[\frac{E_{\mathrm{dep}}\epsilon}{n_{CP} V \Delta}\right] \frac{1 - r'}{e^{t/\tau_{ss}} - r'} + x_0$

Recombination: Determine number of recombining QPs from exponential with τ_{qp}



Energy deposited by phonon hits vs time



Quasiparticle density vs time

Environment Params
- Temperature (T)

Device Params
- Substrate/SC materials (Δ,τ_{qp})
- Sensor design (V)

Note: In the future this may be handled within G4CMP to account for phonon recycling

Waveform Generation Step 2: Sensor State

Environment Params
- Temperature (T)

Device Params
- Substrate/SC materials (Δ, N_0)
- Sensor design
  - ○ MKID: (α, f_{r0}, Q_{r0}, Q_c)
  - ○ Transmon: (ω_q)

Readout Params
- Stimulus frequency (ω)

Map an instantaneous quasiparticle density in a sensor to a shift in its properties

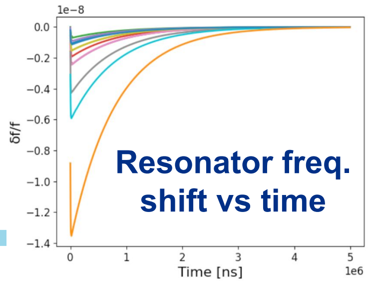
MKIDs

Resonator properties: $f_r(t)$; $Q_r(t)$

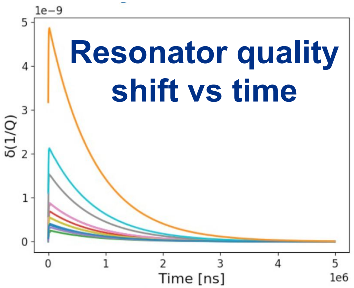
Mattis-Bardeen Theory (complex conductivity):

$$\frac{\delta f_{\text{res}}}{f_{\text{res}}} = -\frac{\alpha}{2}\kappa_2(T,\omega,\Delta_0)n_{\text{qp}}(t)$$

$$\delta\frac{1}{Q_i} = \alpha\kappa_1(T,\omega,\Delta_0)n_{\text{qp}}(t)$$



Resonator freq. shift vs time



Resonator quality shift vs time

Transmons

Model qubit state: $|g\rangle$; $|e\rangle$

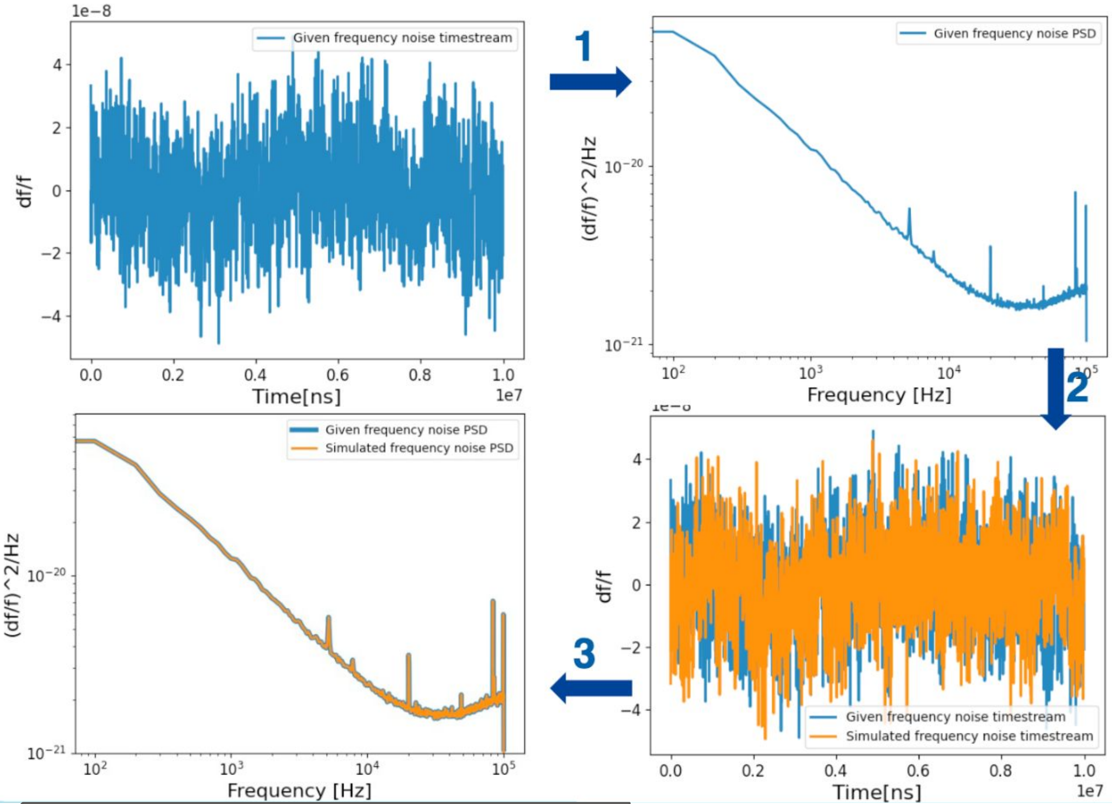
In each time step, determine the rate of qp-induced decoherence and allow for state transitions

$$\Gamma_{qp} = \sqrt{\frac{2\omega_q\Delta}{\pi^2\hbar}}x_{qp},$$

$$x_{qp} = \left[\frac{E_{\text{dep}}\epsilon}{n_{CP}V\Delta}\right]\frac{1-r'}{e^{t/\tau_{ss}}-r'} + x_0$$

Impact of this decoherence arises in **Step 4: Readout**

Waveform Generation Step 3: Noise Processes [MKID Only]



Add noise to signal timestream

- Measured PSD
- Externally-generated PSD
- *Idealized noise* PSD*
  - White, 1/f, etc

Randomly determines phase of each frequency component

PSD Lo f sets max event window

PSD Hi f sets max sampling rate

- *Add white noise above Hi f**

** to be implemented*

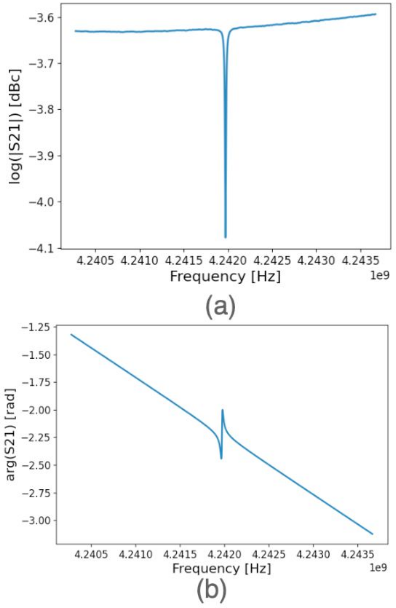
Readout Params

- Freq, Phs Noise PSDs ($J(\nu; f_i, P_i, T)$)

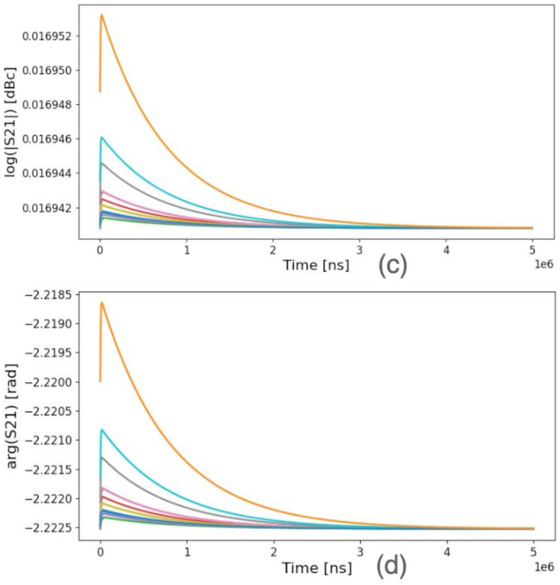
Waveform Generation Step 4: Readout [MKIDs]

Given resonance shape vs time, determine a readout (S_{21}) waveform at a given frequency

Fixed time



On resonance transmission (fixed frequency)



$$S_{21}^{\mathrm{res}}(f) = 1 - \frac{Q/Q_c}{1 + 2jQ\frac{f - f_{\mathrm{res}}}{f_{\mathrm{res}}}},$$

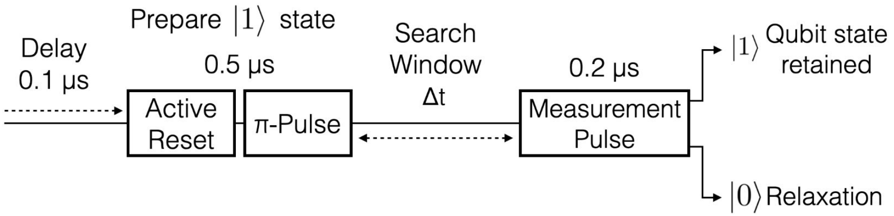
Include contributions to waveform from noise PSD

User-defined line transmission spectrum [$L_{21}(f)$]
- Measured with VNA (resonance removed)
- Externally-generated
- *Idealized (flat at some value)*

Readout Params
- Line Transmission Spectrum ($L_{21}(f)$)
- Readout tones (ω_i, P_i)
- Freq, Phs Noise PSDs ($J(\nu; f_i, P_i, T)$)

Waveform Generation Step 4: Readout [Transmons]

Determine the qubit state (only |g⟩or |e⟩) at the end of a user-defined gate sequence.



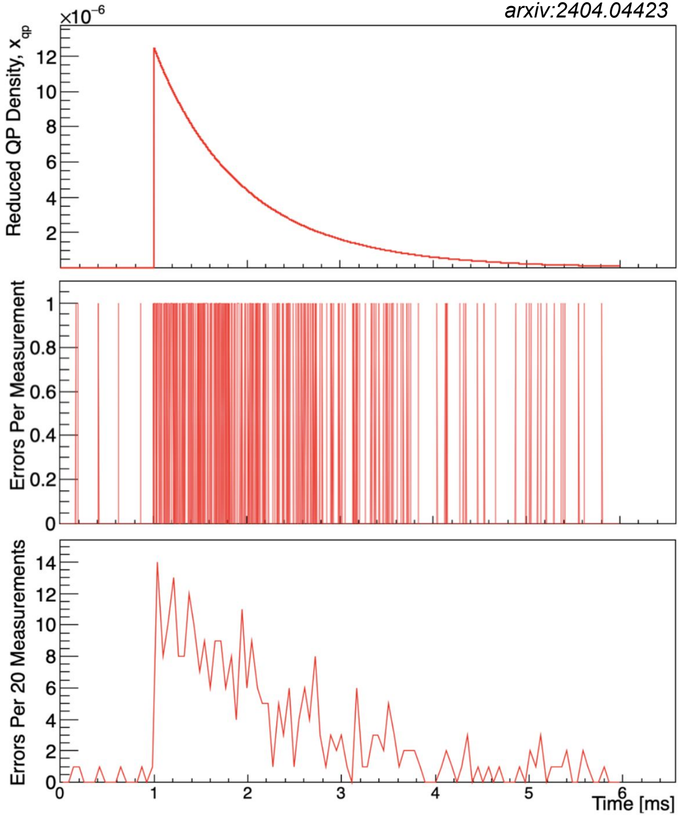
Delay
0.1 μs
Prepare $|1\rangle$ state
0.5 μs
Active Reset
π-Pulse
Search Window Δt
0.2 μs
Measurement Pulse
$|1\rangle$ Qubit state retained
$|0\rangle$ Relaxation

- Allow for non-QP induced decoherence ($T_{1,base}$) and imperfect readout fidelity (SSF)
- Specifics of readout noise are folded into the single-shot fidelity parameter
- Bin measurements in time to get waveform

Device Params
- Qubit design: (ω_q, SSF, T_1)

Readout Params
- Gate sequence
- Measurements per bin

arxiv:2404.04423



Slide courtesy of R. Linehan

Application 1: Estimating energy thresholds of qubit sensors

We can reconstruct an in-chip energy using η_{ph} and reconstructed single-qubit energies:

$$E_{r,\text{chip}} = \frac{\sum_i E_{r,i}}{\eta_{ph,sp}}$$

This helps us understand how to find our in-chip threshold:

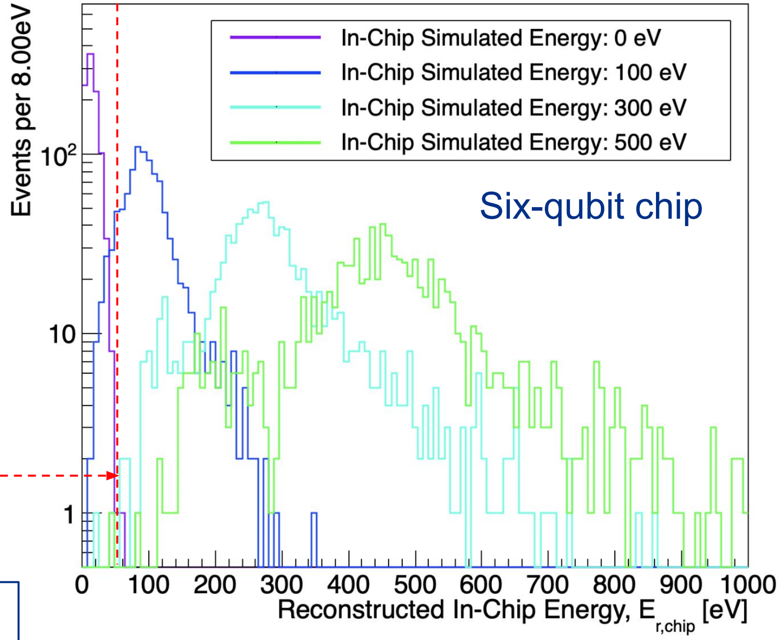
Equivalent to $5\sigma_{E,\text{abs}}$ for a sum of N_q qubits' energies

$$E_{\text{thr,chip}} \simeq \frac{\sigma_{E,\text{abs}}}{\eta_{ph,sp}} \left[\frac{N_q}{\sqrt{2\pi}} + aN_q^b \right]$$

(with a~4.27, b~0.44)

1. For "standard" transmon qubit designs, find **in-chip threshold in range of 40 eV–1200 eV**.
2. With collection fins and QP traps (and no added noise), could reduce to **O(100 meV).**

arxiv:2404.04423



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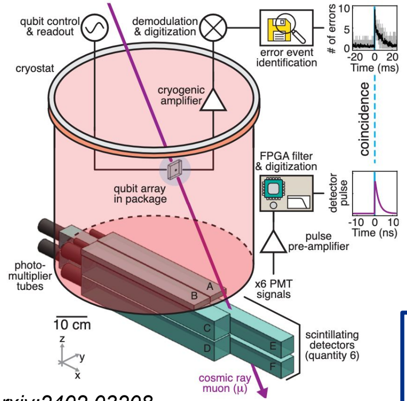
Application 2: Extracting Muon Energy from Qubit Errors

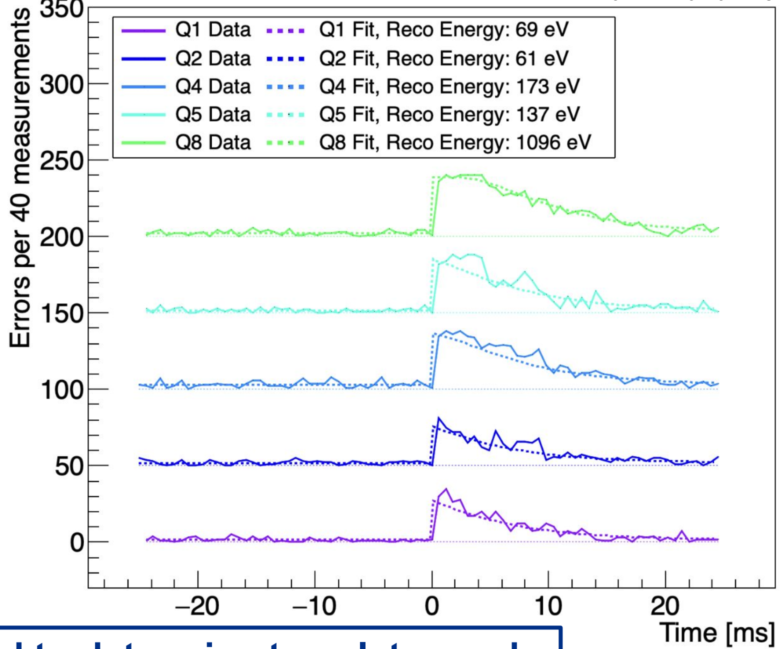
Applying sensor/chip energy reconstruction techniques to literature data gives reasonably self-consistent results!

- Single-qubit ML fits
- Best-guess $\eta_{ph,sp}$ given chip design
- In-chip energy ~ 440 keV
- Builds confidence in energy reconstruction technique



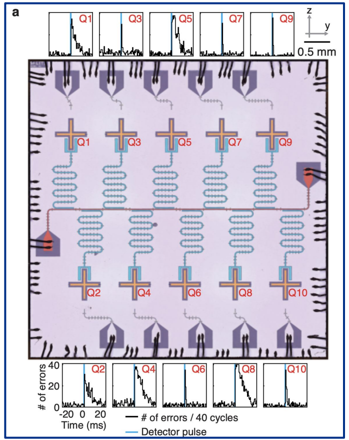
arxiv:2402.03208

arxiv:2404.04423



QDR used to determine templates and anchor to real energy scale

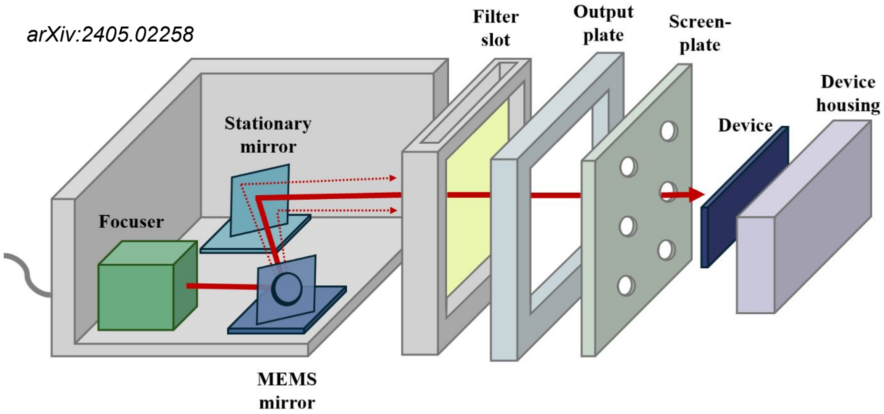
arxiv:2402.03208

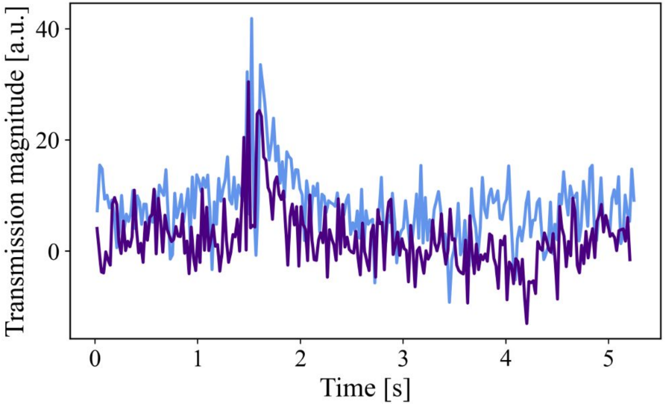


MIT (Harrington) waveforms fit using this technique

Application 3: Simulating an Energy Calibration

arXiv:2405.02258





Position-dependent phonon response:

- Cryo-MEMS mirror delivers targeted photon pulses to device
- Measure MKID response to phonons produced at specific impact sites

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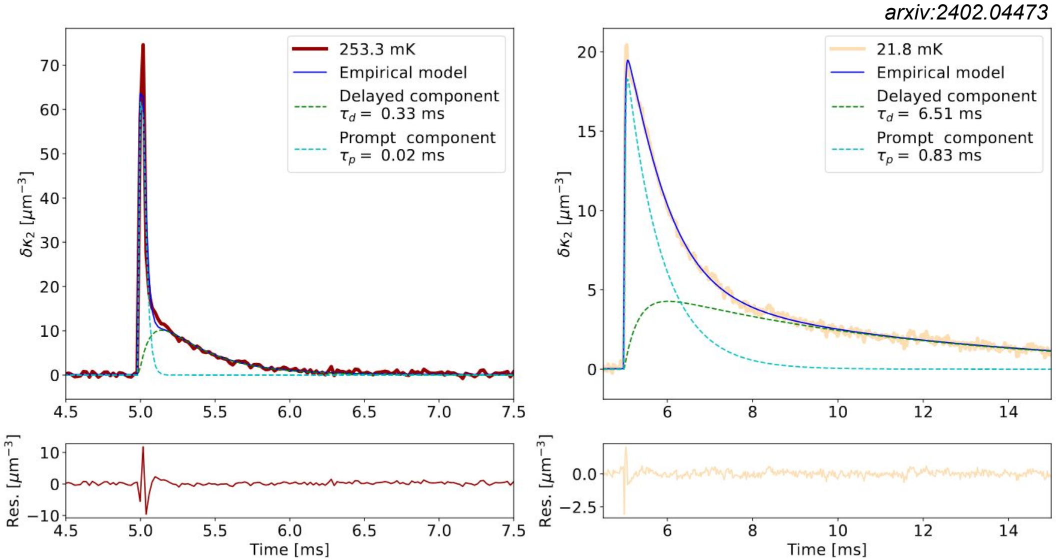
1. Implement calibration in G4CMP
2. Produce waveforms with QDR
3. Collect real waveforms in cal.
4. Compare output of analysis tools

Learn about: phonon partitioning between sensors phonon loss at interfaces, surface mediated downconversion

Application 4: Understanding Pulse Shapes

Separating phonon dynamics from quasiparticle dynamics in MKID sensors


arxiv:2402.04473

Two fall time constants: phonon lifetime & quasiparticle lifetime?

In simulation:

- Known quasiparticle lifetime
- Control over phonon time profile

1. Generate phonon bursts in G4CMP
2. Generate readout waveforms in QDR
3. Pipe through analysis framework to extract the fall time constants as is done with data

Allows us to confirm (or refute) the origin of the two fall-time constants and their dependence on device temperature.

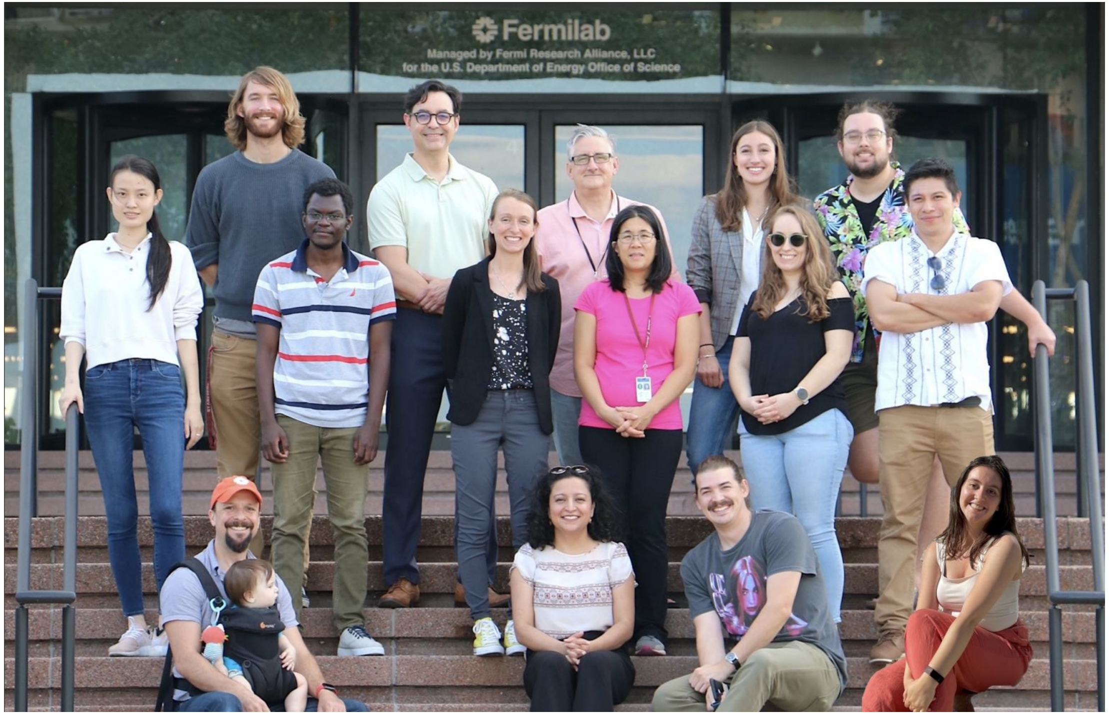
Conclusions

QuantumDeviceResponse provides a framework for generating realistic detector waveforms from simulated phonon impacts

- QDR waveforms can be piped directly into your analysis framework -- looks exactly like your sensor readout!
- Allows for measured or idealized noise & transmission spectra to match your setup
- Use cases:
  - Evaluating DM sensitivity for your detector & analysis chain
  - Estimating threshold/resolution of your detector before fabrication
  - Understanding phonon dynamics and loss mechanisms via direct comparison to data

Room for new features, improved modeling, expanded sensor types!

Interested in contributing? Talk to Ryan or me!



Particle physicists developing qubits and quantum sensors for low-threshold particle detection

QSC@FNAL:
Aaron Chou
Lauren Hsu
Daniel Baxter
Rakshya Khatiwada (IIT)
Daniel Bowring
Gustavo Cancelo
Sho Uemura
Sami Lewis (Wellesley)
Dylan Temples
Sara Sussman
Ryan Linehan
Kester Anyang (IIT)
Israel Hernandez (IIT)
Jialin Yu (IIT)
Stella Dang (Cornell)
Matthew Hollister
Chris James

Northwestern:
Enectali Figueroa
Grace Bartrud
Shilin Ray

Caltech:
Sunil Golwala
Karthik Ramanathan
Osmond Wen
Taylor Aralis
Brandon Sandoval

SLAC/Stanford:
Noah Kurinsky
Kelly Stifter
Hannah Magoon
Sukie Kevane

QSC@Purdue
Alex Ma
Botao Du

UW Madison
Robert McDermott
Sohair Abdullah

Backup

References

[1] R. Linehan et al, “Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Employing Gate-based Operation and Readout,” in preparation.

[2] D. Temples, “Toward a DM Search with Phonon-Mediated MKID Devices at NEXUS.” United States: N. p., 2023. Web. doi:10.2172/1974696.

[3] R. Khatiwada, “Quantum Sensors for Dark Matter searches.” IMFP/CPAN. Santander, Spain: 2023.

[4] Mazin, Benjamin A. (2005) Microwave Kinetic Inductance Detectors. Dissertation (Ph.D.), California Institute of Technology. doi:10.7907/GZ72-V784. https://resolver.caltech.edu/CaltechETD:etd-10042004-120707

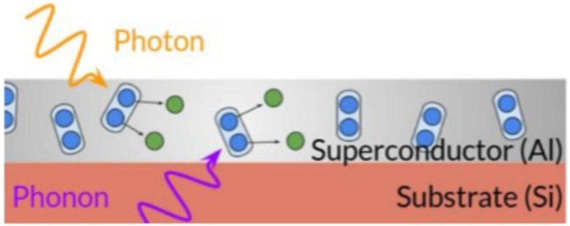
[5] D. Temples, “Performance of a Kinetic Inductance Phonon-Mediated Detector at the NEXUS Cryogenic Facility.” 6 Feb 2024. arXiv:2402.04473v1.

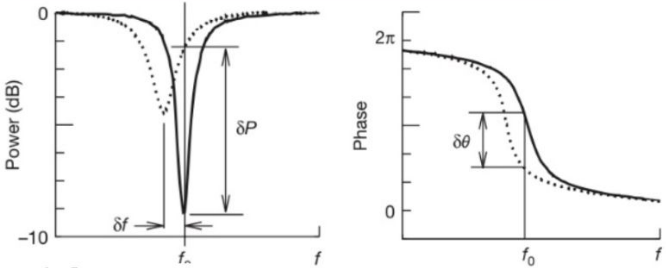
[6] Siegel, Seth Robert (2016) A Multiwavelength Study of the Intracluster Medium and the Characterization of the Multiwavelength Sub/millimeter Inductance Camera. Dissertation (Ph.D.), California Institute of Technology. doi:10.7907/Z9Z31WJ7. https://resolver.caltech.edu/CaltechTHESIS:10212015-211417853

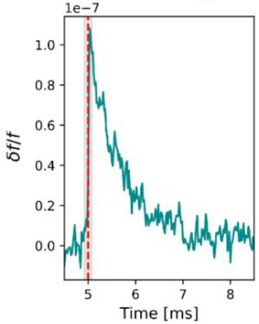
Slide courtesy of S. Dang

Kinetic Inductance Detectors

- MKIDs are superconducting microresonators with potential for phonon detection in DM searches [2]
  - RF stimulus readout enables native frequency-domain multiplexability
- Detection principle
  - Energy depositions in the substrate → athermal phonons
  - Phonons absorbed by superconductor break Cooper pairs → create quasiparticles (QP)
  - Increase in QP density → increase in kinetic inductance in LC resonator → shifts resonant frequency (f_r) and quality factor (Q)
  - Changes the amplitude and phase of the transmitted RF probe signal







Top: Illustration of an MKID device. [2]
Middle: Detection principle. [4]
Bottom: Time-domain δf/f readout on resonance [5]

Slide courtesy of R. Linehan

Simulating Phonon Dynamics

Impact physics
Chip design
Phonon kinematics
SC Response
Qubit Readout
Energy reconstruction
Results

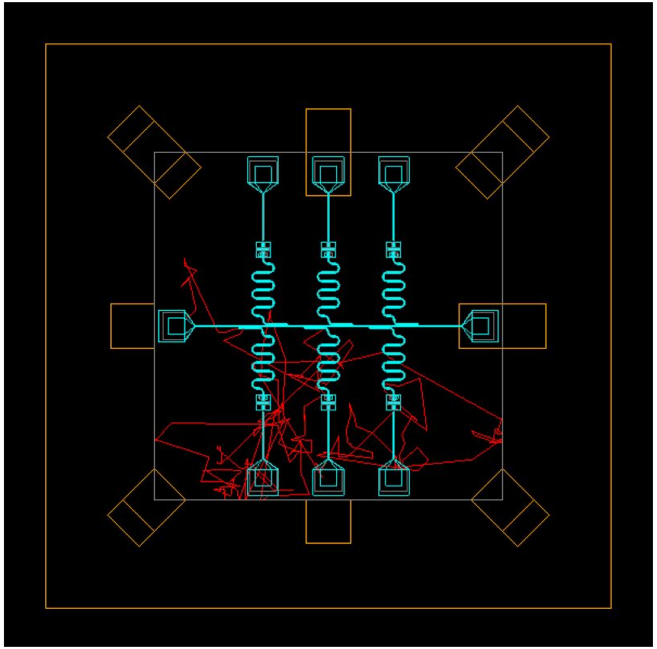
G4CMP (Geant4 Condensed Matter Physics) enables simulation of low-energy phonon processes.

Chip Design:

- Thin SC film with features on substrate
- Ge and Si currently supported for substrate

Phonon kinematics:

- Only acoustic phonons handled
- Anharmonic downconversion ($\Gamma \sim \omega^5$)
- Isotopic scattering ($\Gamma \sim \omega^4$)
- Propagation along phonon caustics
- Parameterized reflection/absorption at surfaces



Phonon energy deposited in chip

5 meV

Slide courtesy of R. Linehan

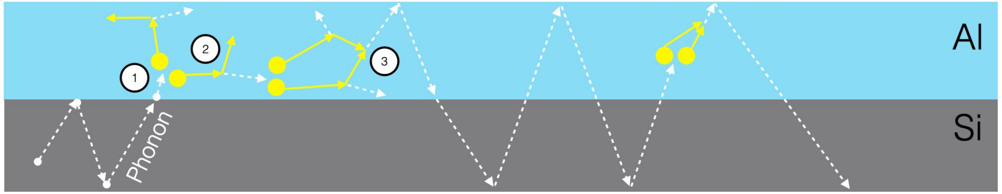
Simulating Phonon Dynamics


Impact physics → Chip design → Phonon kinematics → **SC Response** → Qubit Readout → Energy reconstruction → Results

Superconductor response is complicated, so we use an "effective" phonon-in-SC model here.

What's the full picture? →

1. Phonon breaks CP into QPs
2. QPs radiate phonons (continuing cascade)
3. QPs recombine, producing "recycled" >2Δ phonon



Current strategy: "effective absorption probability" in G4CMP →

- Thin-film dependent
- Phonon energy dependent
- Parameterized energy-to-QP efficiency
- Ignoring recycled phonons for now
- Absorption treated similarly for thermal bath

$$p_{a,s} \simeq 1 - \exp\left[- \frac{2l}{\pi v_s \tau_0^{ph}} \left(\frac{E_{ph}}{\Delta} \right) \right]$$

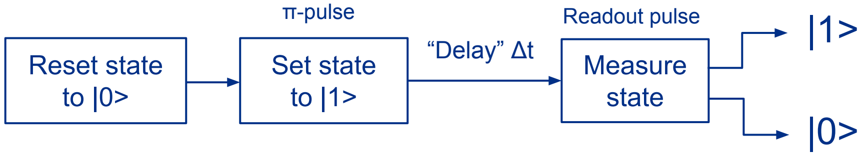
Slide courtesy of R. Linehan

Quantum Device Response

We simulate an event's "waveform" by blending QP evolution with readout response within the Quantum Device Response (QDR) tool.

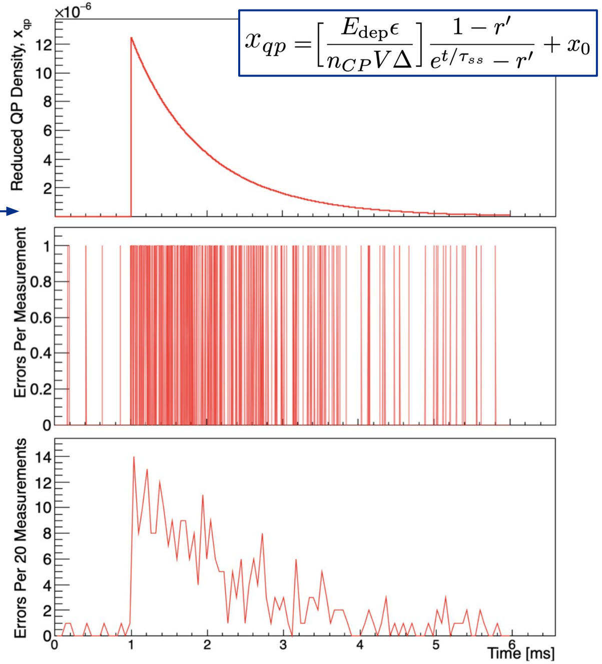
Processes modeled:

- QP evolution: generation, recombination, trapping
- T_1 dependence on QP density and effective non-QP processes
- Gate operations (π-pulse, readout)



Parameterized "dark count" parameters:

- Single-shot fidelity: how faithful is our measured 1 or 0?
- $T_{1,\mathrm{base}}$: how likely is "unrelated" relaxation, given a delay Δt?



$$x_{qp} = \left[\frac{E_{\mathrm{dep}}\epsilon}{n_{CP} V \Delta}\right] \frac{1 - r'}{e^{t/\tau_{ss}} - r'} + x_0$$

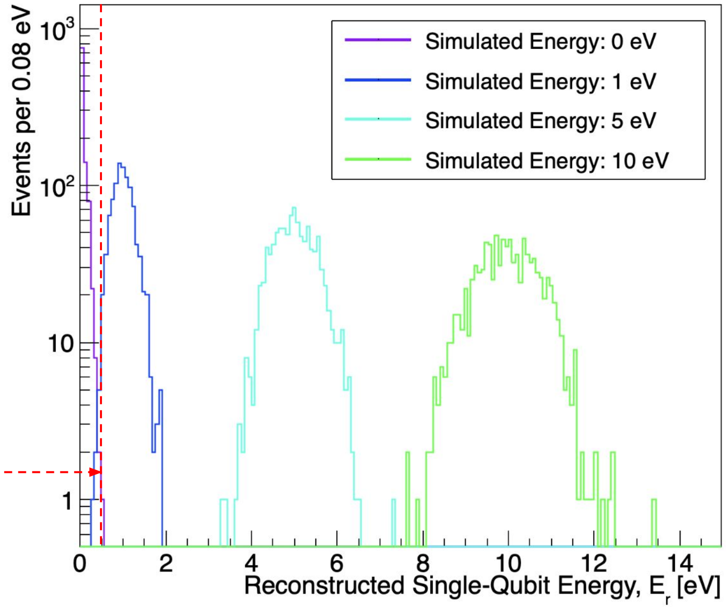
Slide courtesy of R. Linehan

Lessons Learned: Sensor Resolution and Threshold

Impact physics | Chip design | Phonon kinematics | SC Response | Qubit Readout | **Energy reconstruction** | **Results**

Reconstruction of monoenergetic waveforms from QDR helps us understand energy resolution.

- Using $T_{1,\mathrm{base}}$ = 2 ms and 98% single-shot fidelity (challenging but “near term” for field)
- Nonlinear energy resolution vs. input energy – places premium on good calibration!
- Energy resolution/width for “noise-only” 0 eV input, $\sigma_{E,\mathrm{abs}}$ governs threshold: $5\sigma_{E,\mathrm{abs}}$



Estimate sensor resolution $\sigma_{E,\mathrm{abs}}$ of 88 meV, sensor threshold ($5\sigma_{E,\mathrm{abs}}$) of 440 meV.