Modeling Phonon-mediated Quasiparticle Poisoning and Particle Impacts using G4CMP

Eric Yelton

RISQ G4CMP Workshop Lightning Talk

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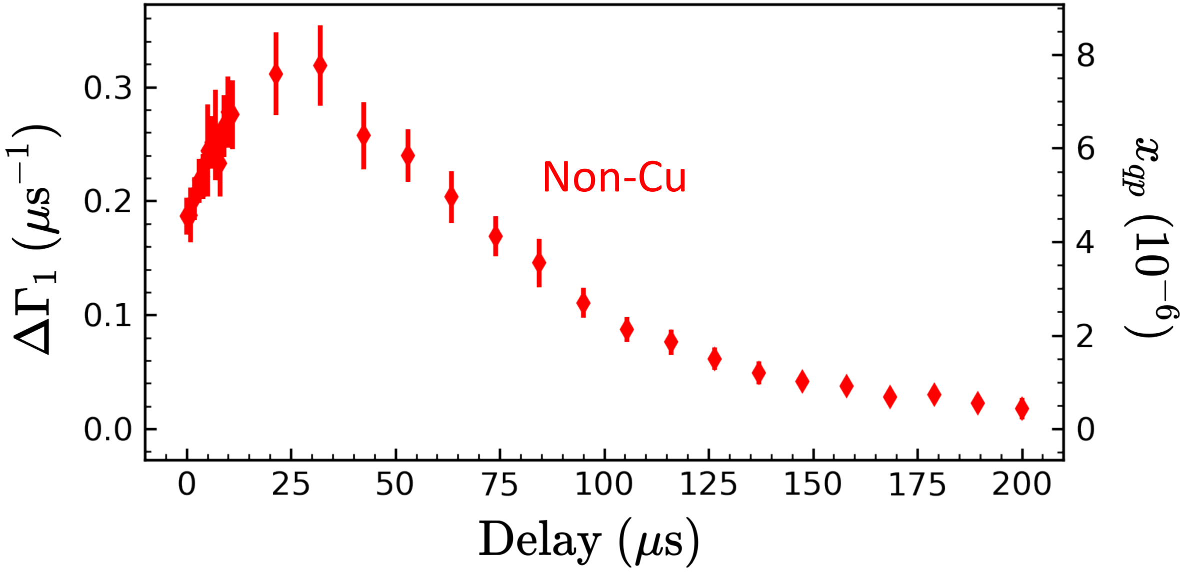
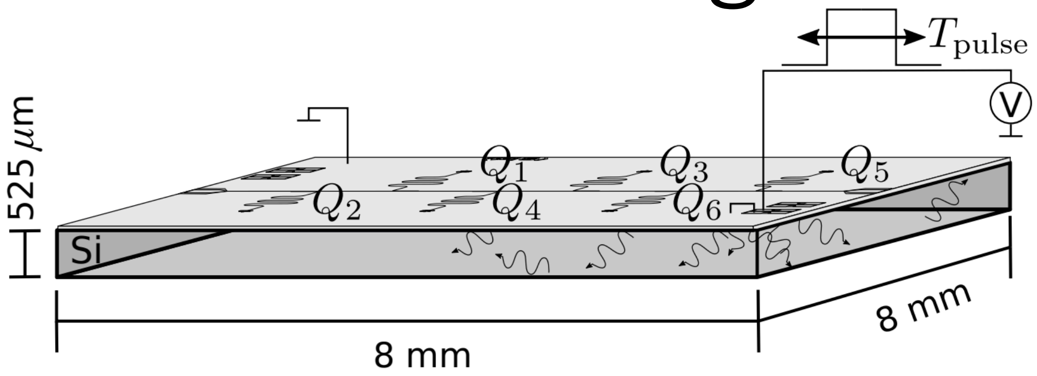
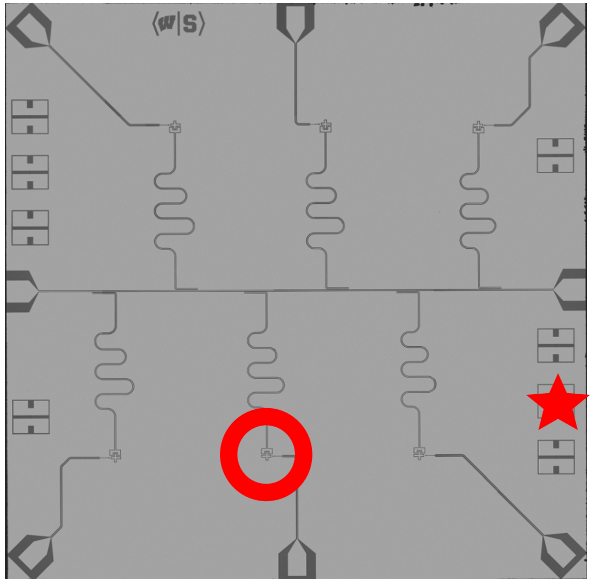
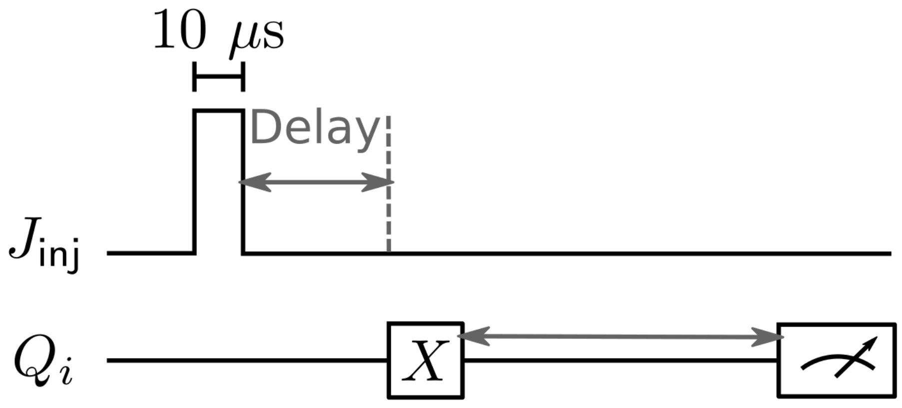
Controlled Phonon-mediated Poisoning







- Nb Ground plane device
- Array of six charge-sensitive Transmons

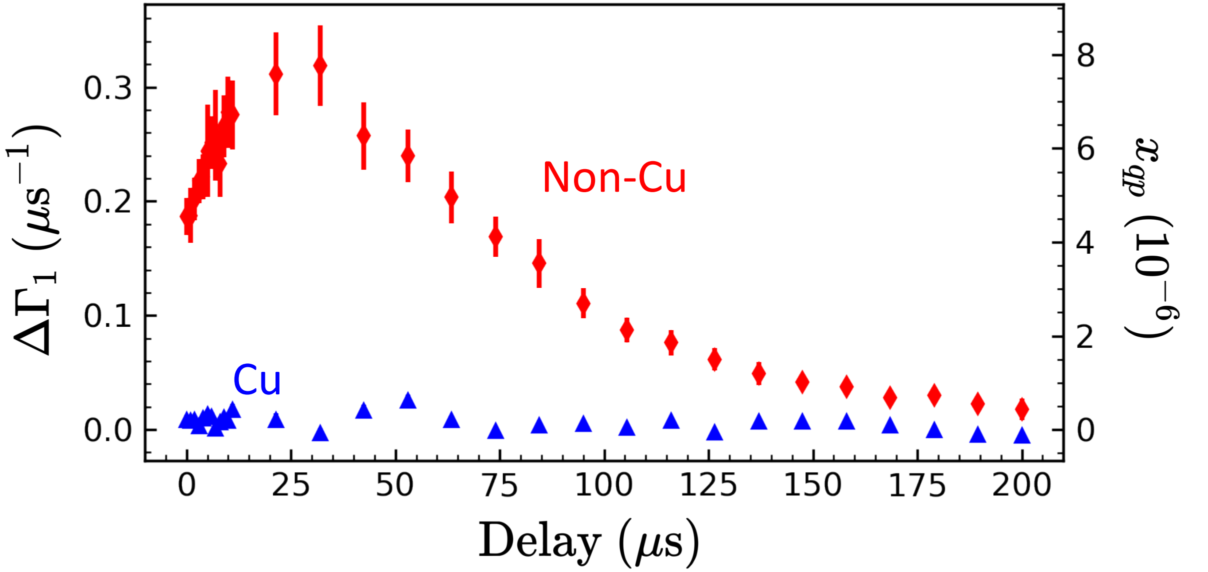


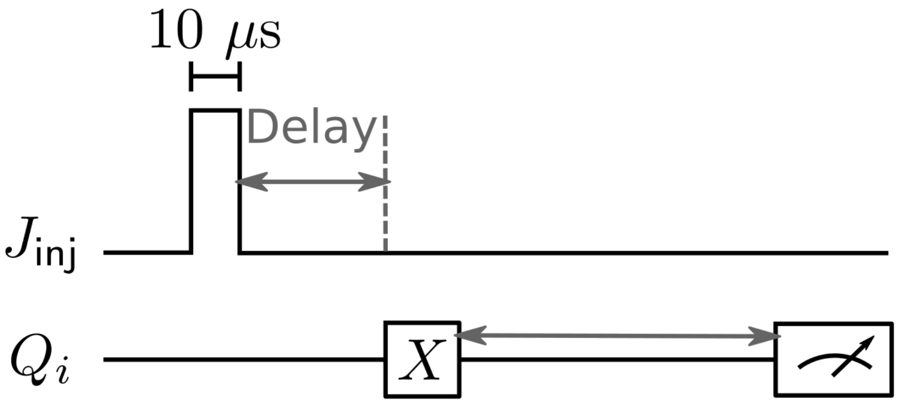
$$\Delta\Gamma_1 = \frac{1}{T_1} - \frac{1}{T_1^b} \qquad x_{qp} = \frac{\pi}{\sqrt{\omega_{01} 2\Delta/\hbar}}\Delta\Gamma_1$$

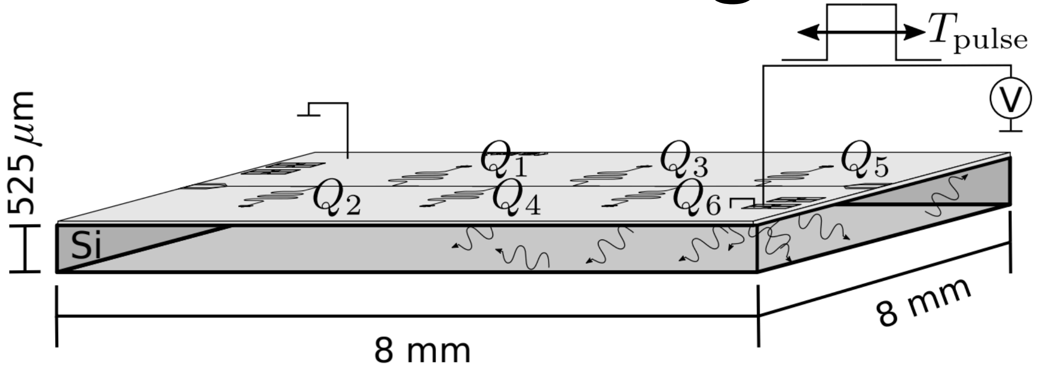
Iaia, Ku *et al.*, Nature Comm. 13, 6425 (2022)

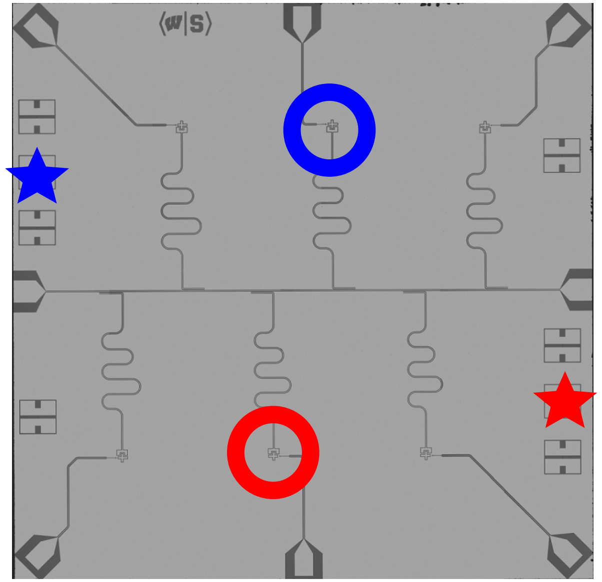
Controlled Phonon-mediated Poisoning

10 μm Cu islands relax pair-breaking phonons

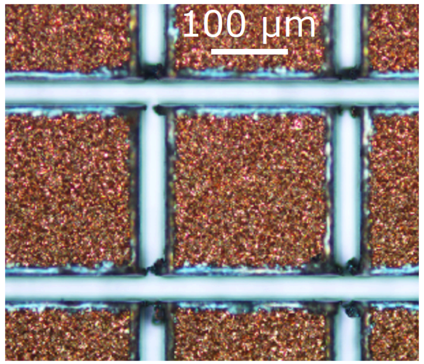








Cornell NanoScale Science and Technology Facility



$$\Delta\Gamma_1 = \frac{1}{T_1} - \frac{1}{T_1^b}$$

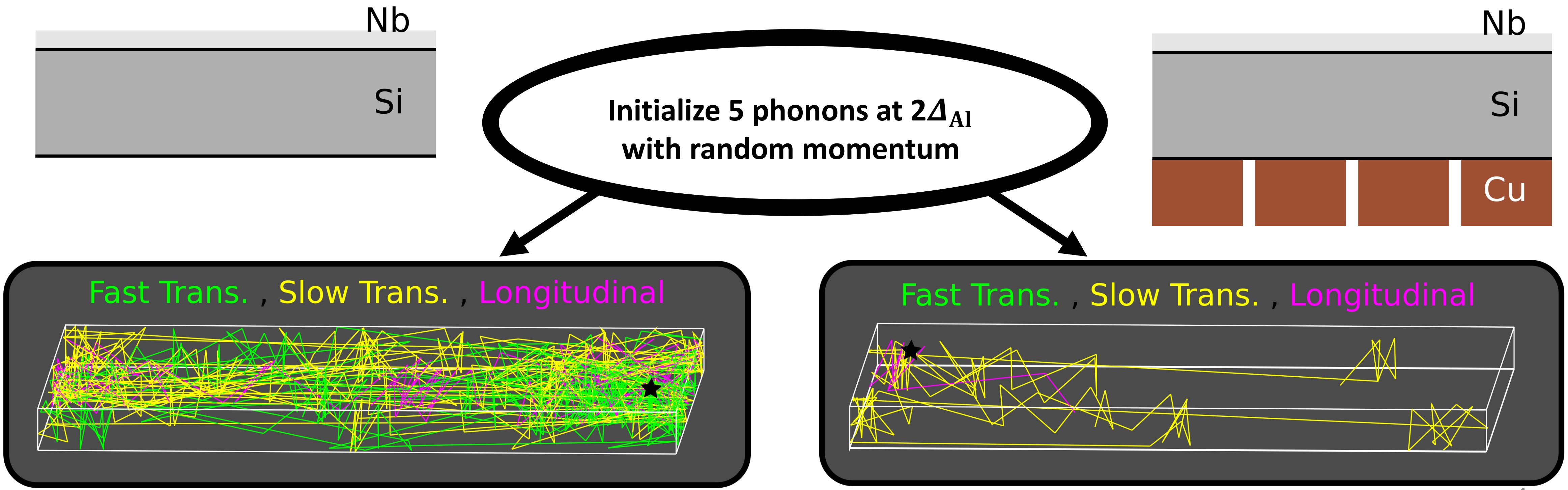
$$x_{qp} = \frac{\pi}{\sqrt{\omega_{01} 2\Delta/\hbar}}\Delta\Gamma_1$$

Iaia, Ku *et al.*, Nature Comm. 13, 6425 (2022)

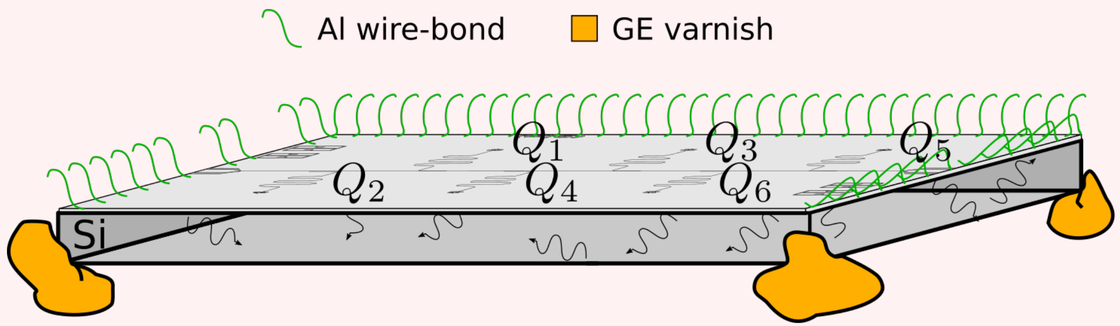
Numerical Model of Phonon Injection

Geant4 Condensed Matter Physics (**G4CMP**)– Monte Carlo simulation toolkit to simulate particle transport in various materials

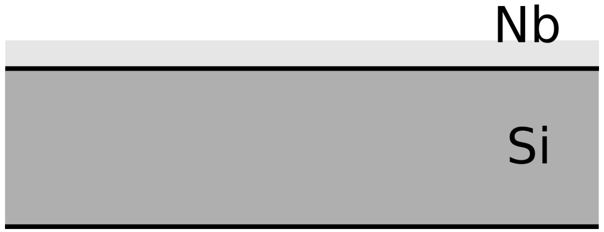
- Simulates production and transport of e^{-}/h^{+} pairs and phonons in crystals
- Simulates quasiparticle (QP) production in superconducting films



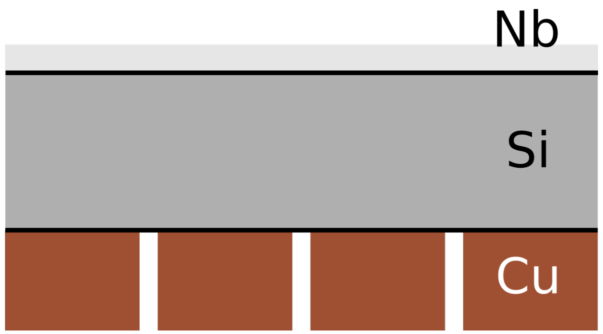
Numerical Model of Phonon Injection

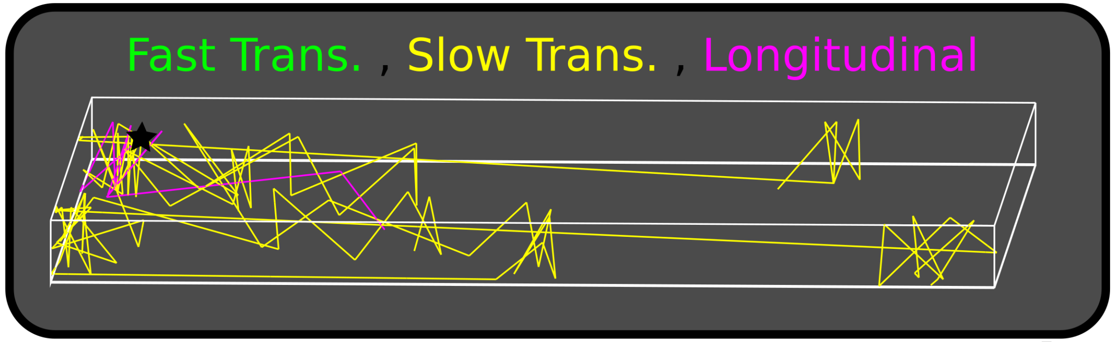


Model phonon loss via wire bonds and GE varnish as a uniform probability on the vertical wall boundaries

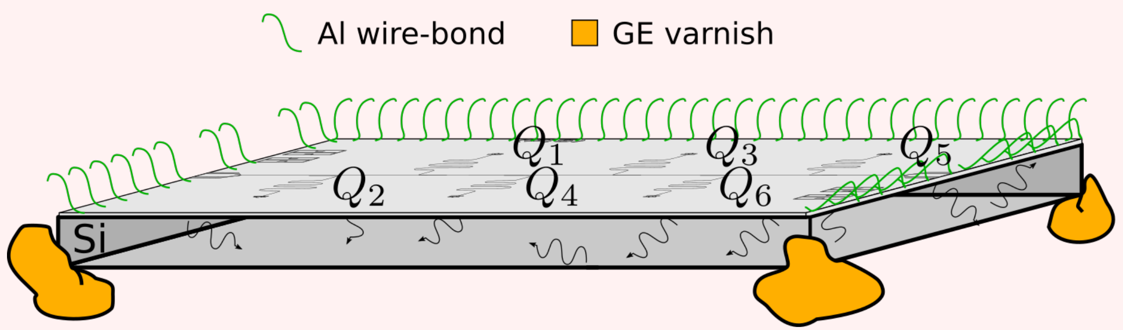


Initialize 5 phonons at $2\Delta_{Al}$ with random momentum

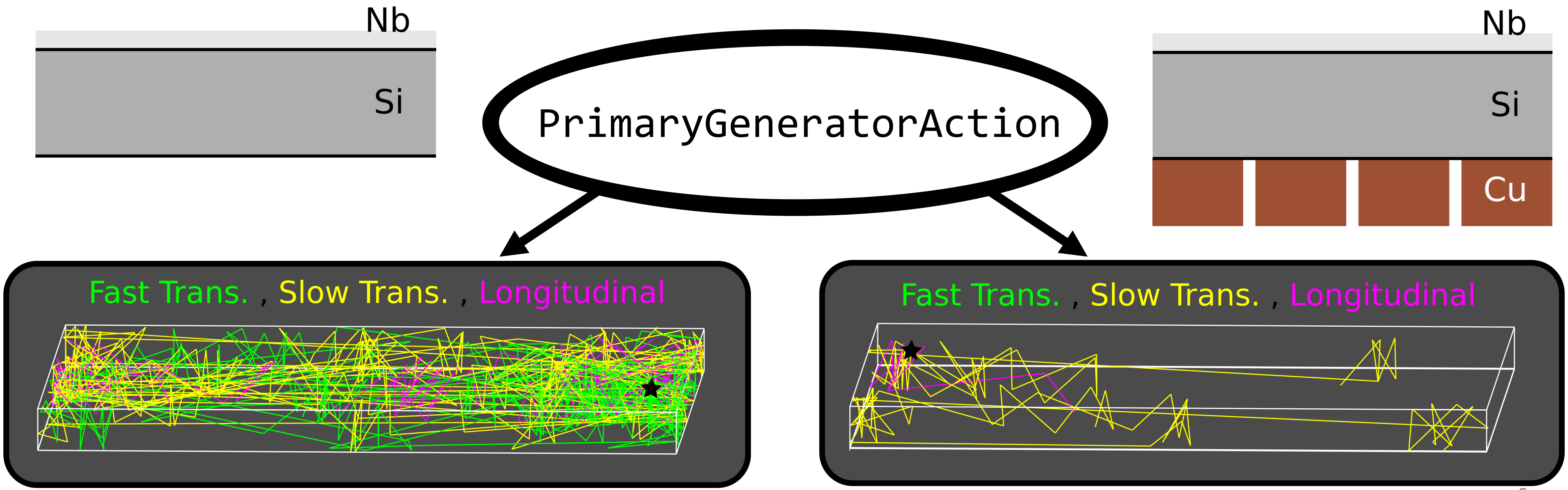




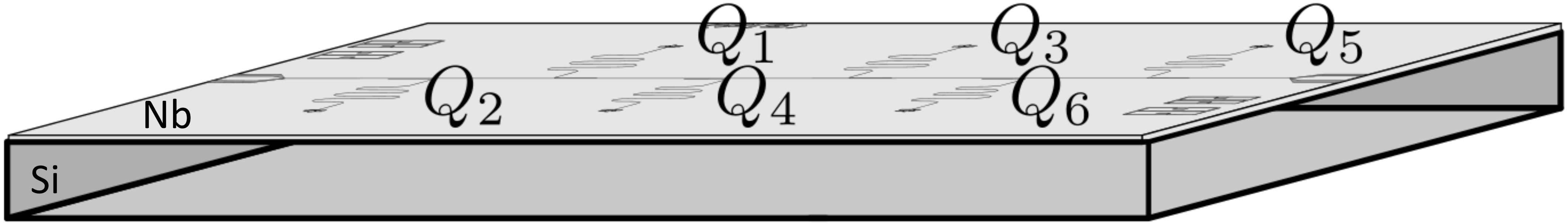
Numerical Model of Phonon Injection

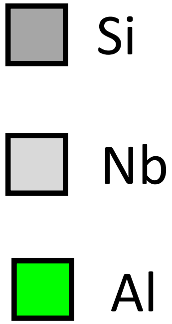


G4CMPSurfaceProperty

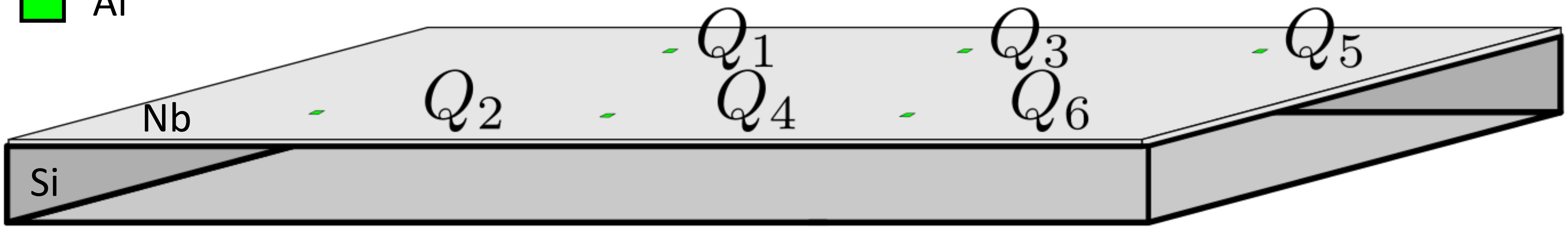


Model of Qubit Electrodes





Model Qubit Electrodes as 10 x 10 μm^2 patches of Al

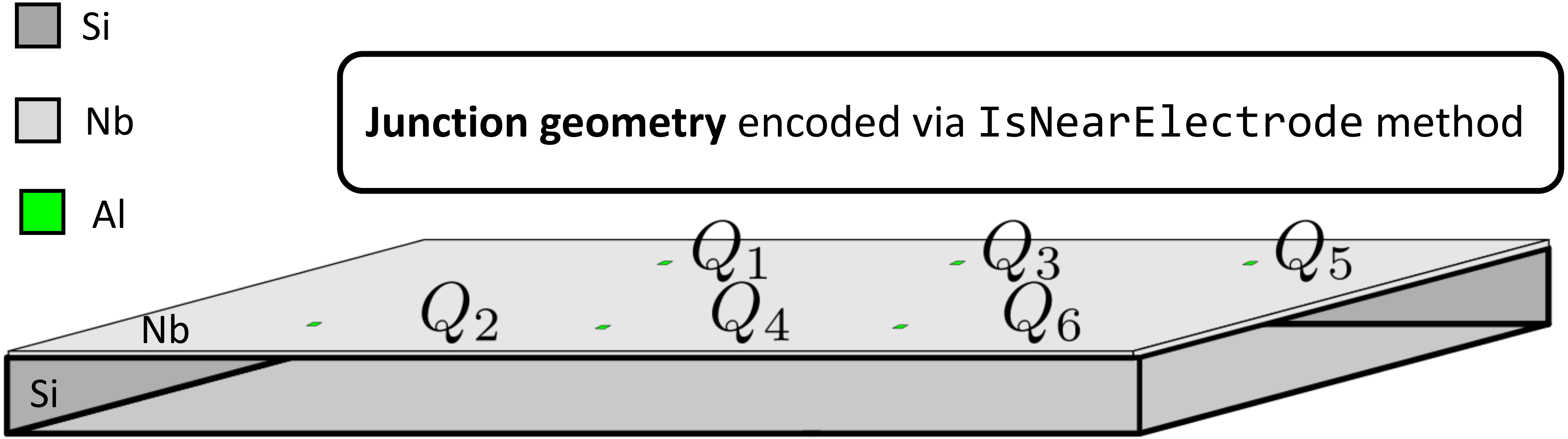


Model of Qubit Electrodes

Custom `PhononElectrode` class

Materials handled via custom child class of `G4CMPSurfaceProperty`

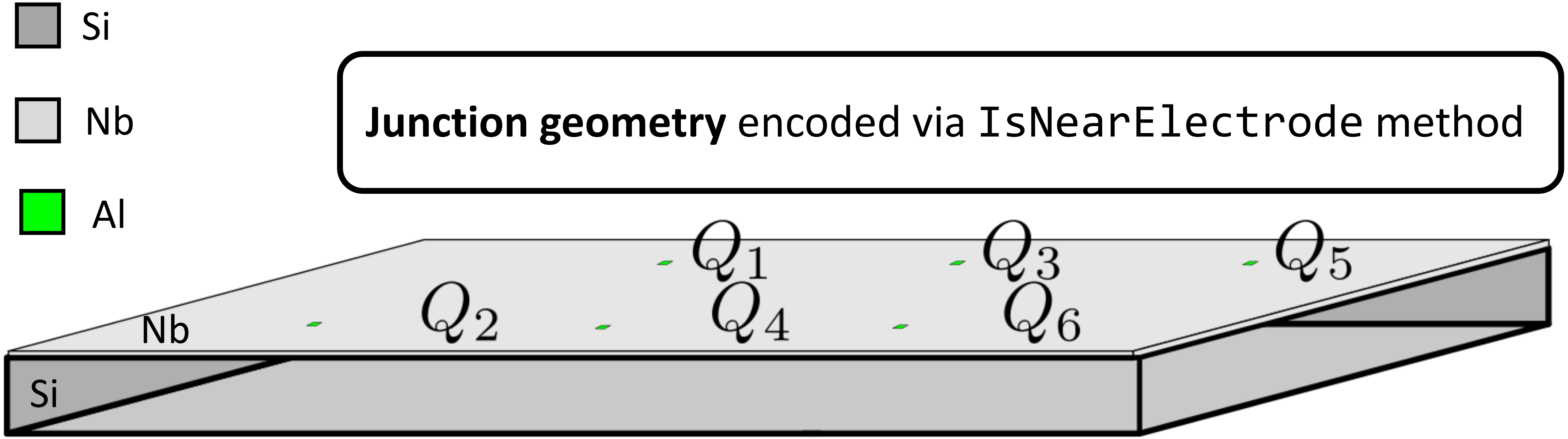
Junction geometry encoded via `IsNearElectrode` method



Model of Qubit Electrodes and Backside Films

Custom `PhononElectrode` class

Materials handled via custom child class of `G4CMPSurfaceProperty`

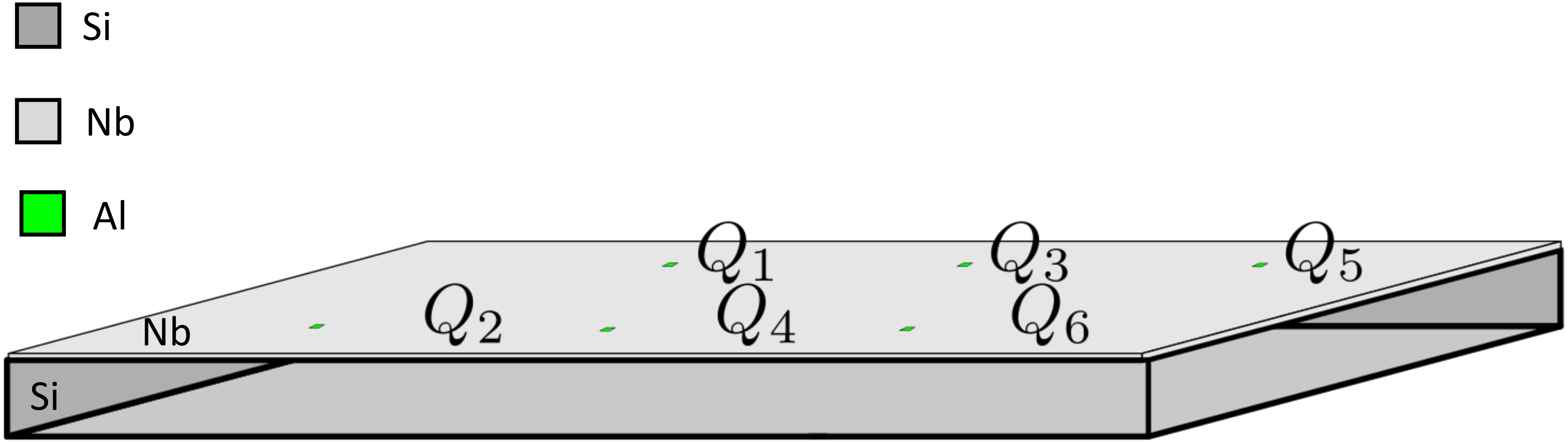


Junction geometry encoded via `IsNearElectrode` method

Similar scheme for backside metallization

Modeling Quasiparticle Dynamics

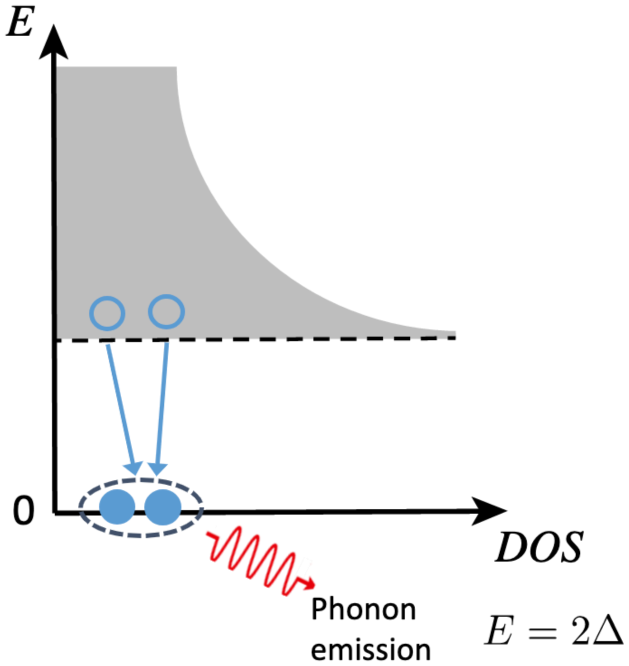
$$\frac{\mathrm{d}x_{qp}}{\mathrm{d}t} = -rx_{qp}^2 - sx_{qp} + g(t)$$



Modeling Quasiparticle Dynamics

$$\frac{\mathrm{d}x_{qp}}{\mathrm{d}t} = -\underbrace{rx_{qp}^2}_{} - sx_{qp} + g(t)$$

Quasiparticle Recombination

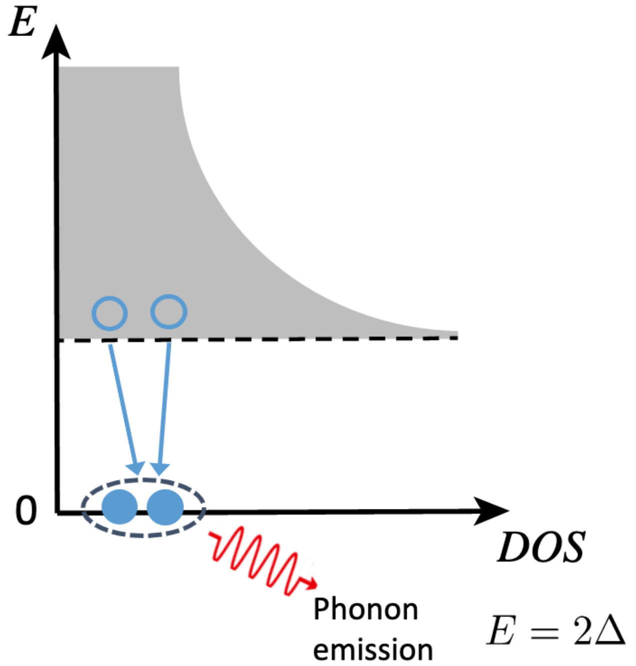


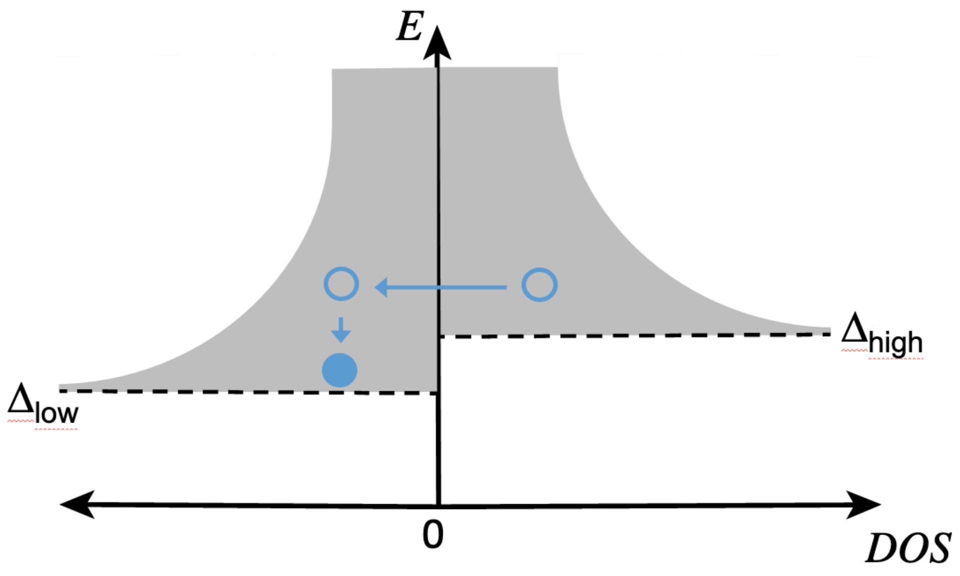
Modeling Quasiparticle Dynamics

$$\frac{\mathrm{d}x_{qp}}{\mathrm{d}t} = -rx_{qp}^2 - sx_{qp} + g(t)$$

Quasiparticle Recombination

Quasiparticle Trapping



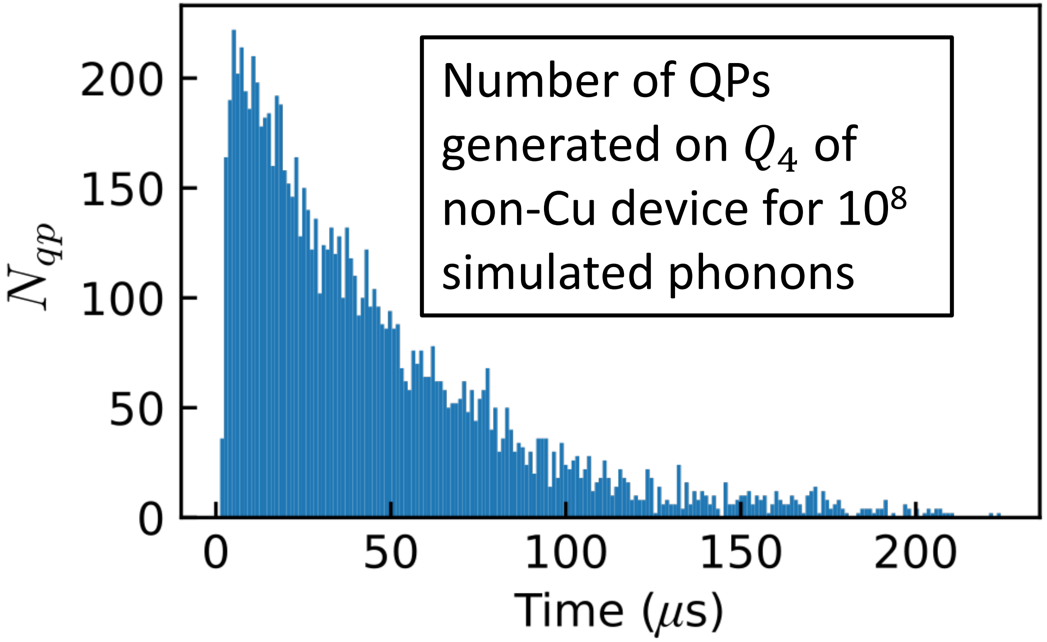


Modeling Quasiparticle Dynamics

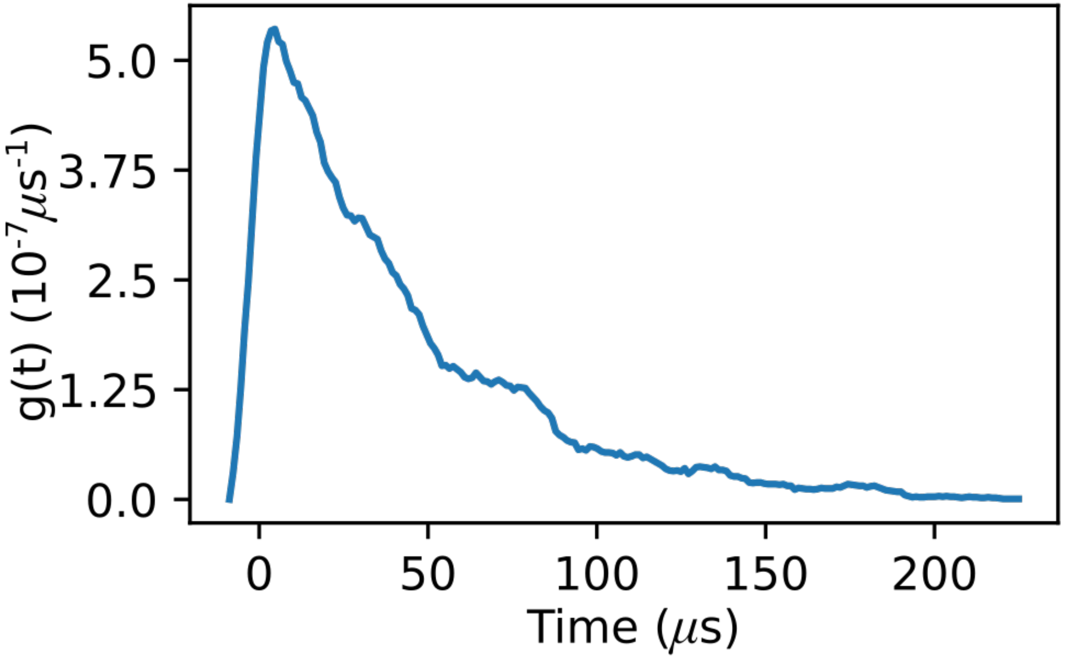
$$\frac{\mathrm{d}x_{qp}}{\mathrm{d}t} = -rx_{qp}^2 - sx_{qp} + g(t)$$

From G4CMP Simulation

`G4CMPElectrodeHit->GetEnergyDeposit()` from phonon energy deposition result from `G4CMPKaplanQP`

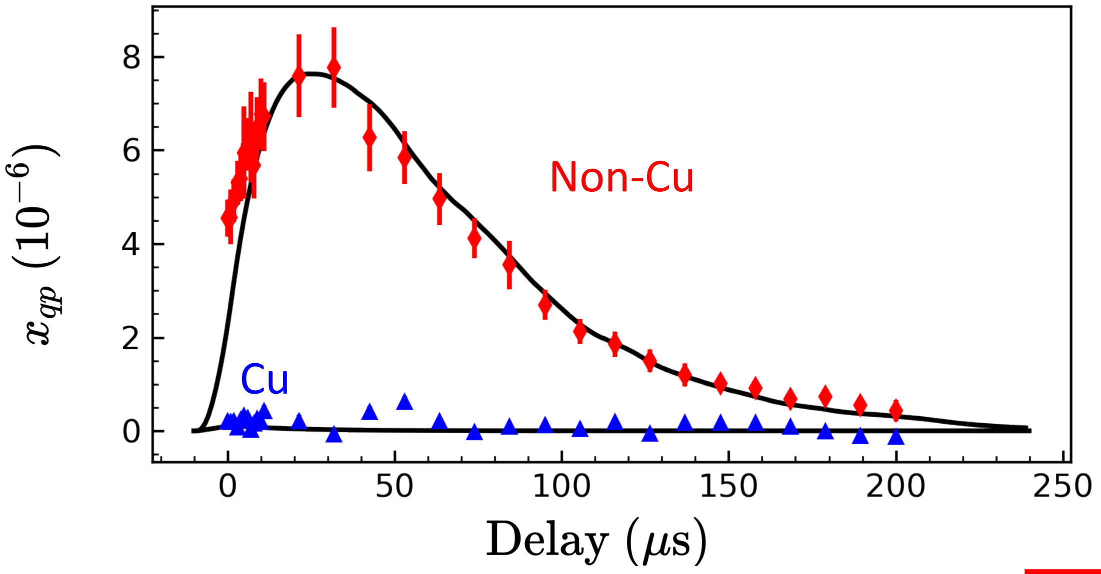


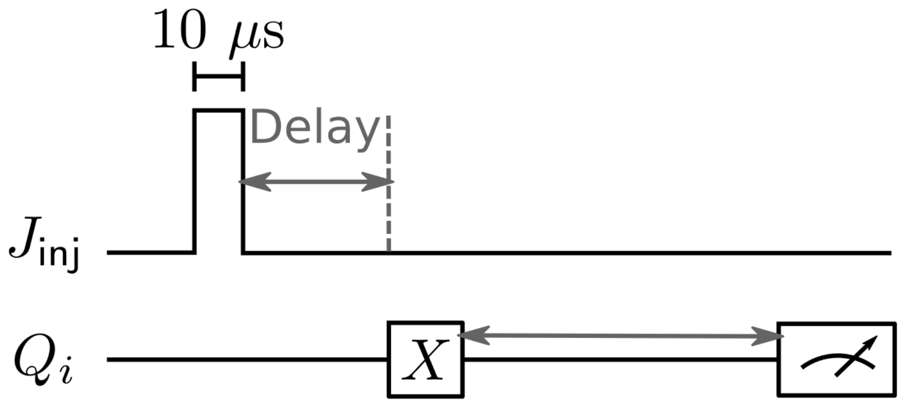
Account for injection pulse width



Yelton *et al.*, arXiv:2402.15471 (2024)

Injection Modeling Results





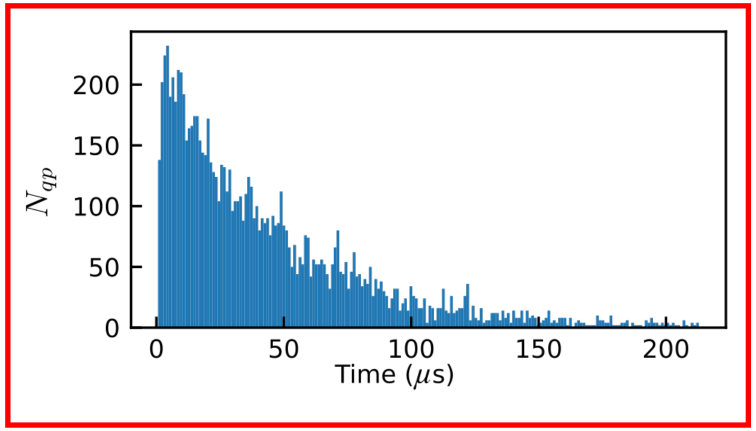
Solve the ODE with the time dependent ODE from the G4CMP modeling of the experiment

$$\text{Wall Abs. Prob.} = 2.5\% \qquad r = 1/(10\ \text{ns})$$

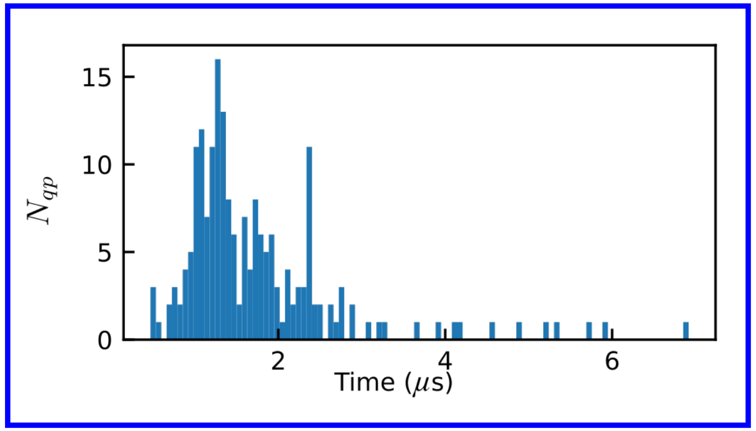
from fit to data:

$$s = 4.5(2) \times 10^{-2}\ \mu s^{-1} \qquad s = 5 \times 10^{-2}\ \mu s^{-1}$$

non-Cu



10μm-Cu



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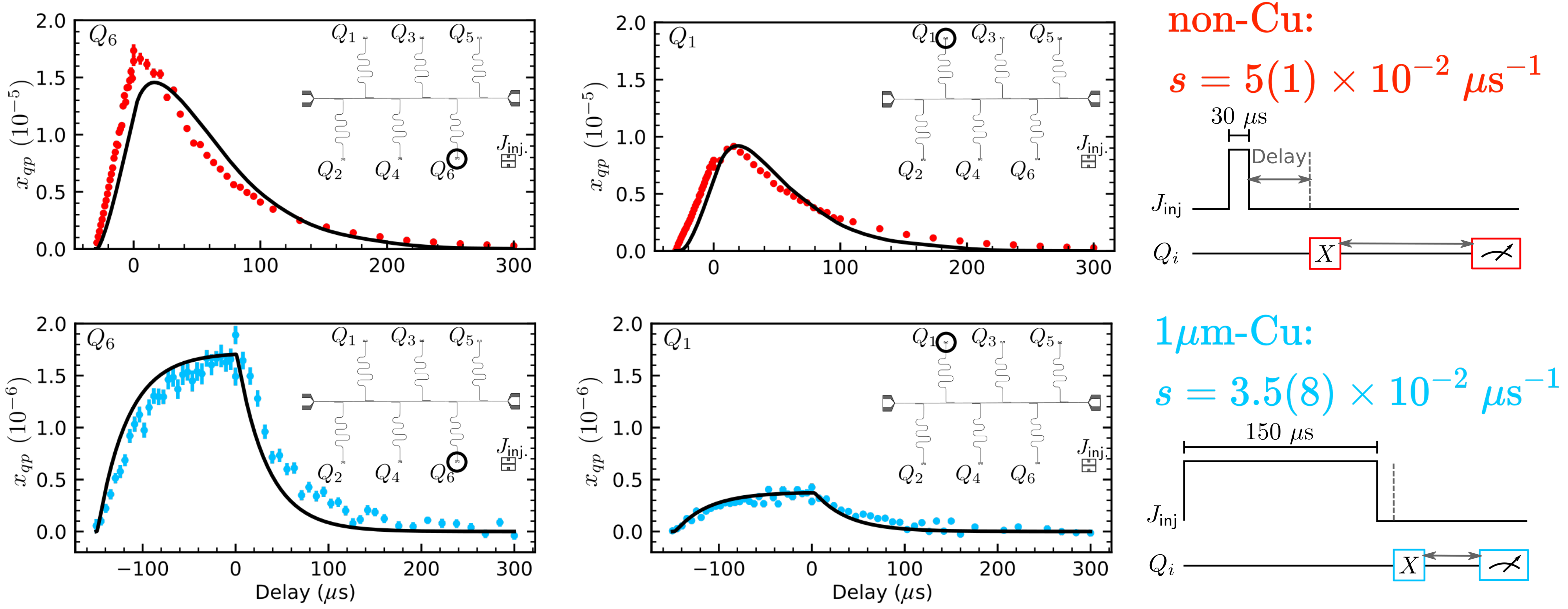

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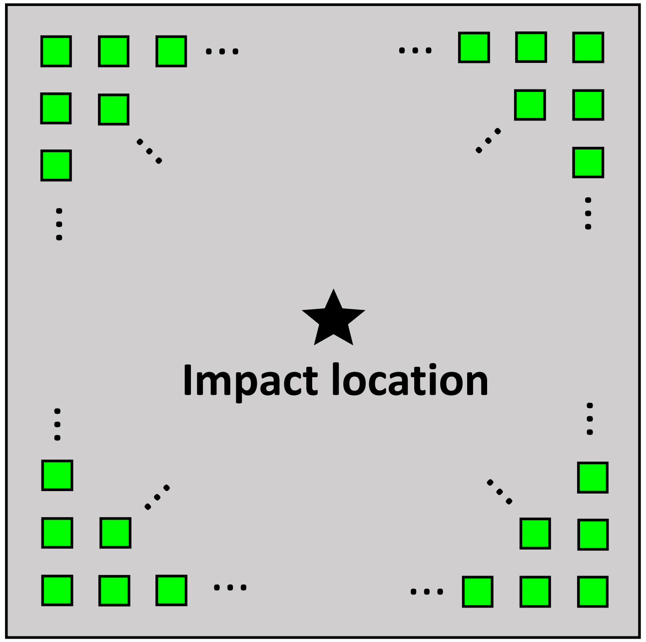
Modeling a Dense Qubit Array

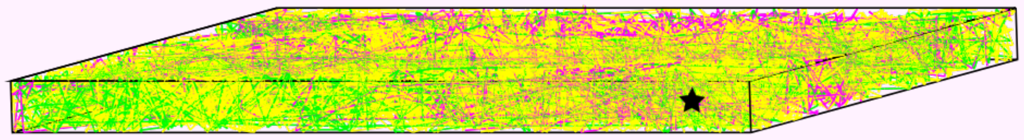
$x_{qp}(x, y, t)$



- The Al patches that model the qubit electrodes are arranged in a on the ground plane
- We make use of the G4CMP toolkit to model the phonon burst from a typical gamma impact

Typical background γ creates ~30,000 e^-/h^+ pairs

★ e^-/h^+ pair initialization



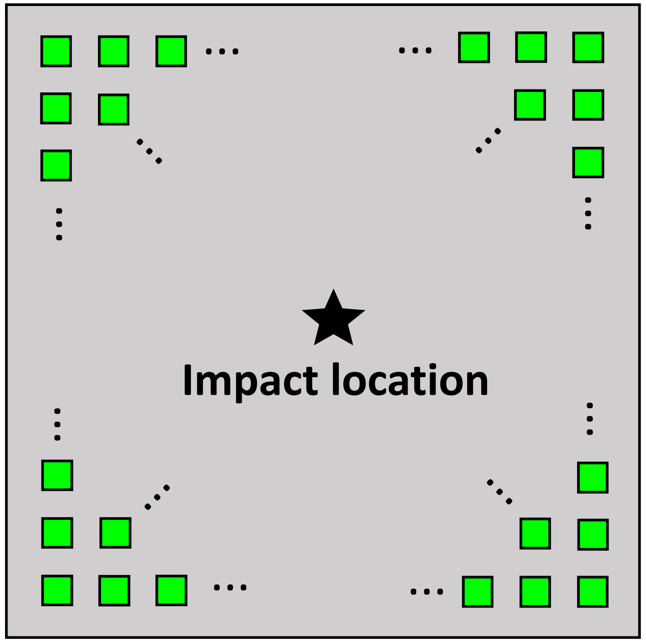
Only ~5% of generated phonons shown

Phonon burst from a single e^-/h^+ pair of energy 3.6 eV

Yelton *et al.*, arXiv:2402.15471 (2024)

Modeling a Dense Qubit Array

Custom PhononElectrode



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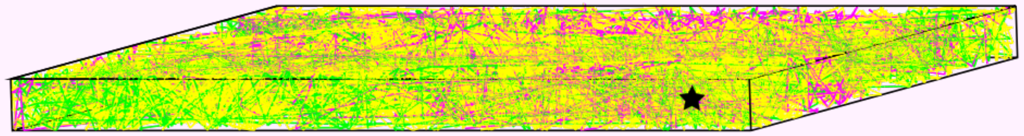
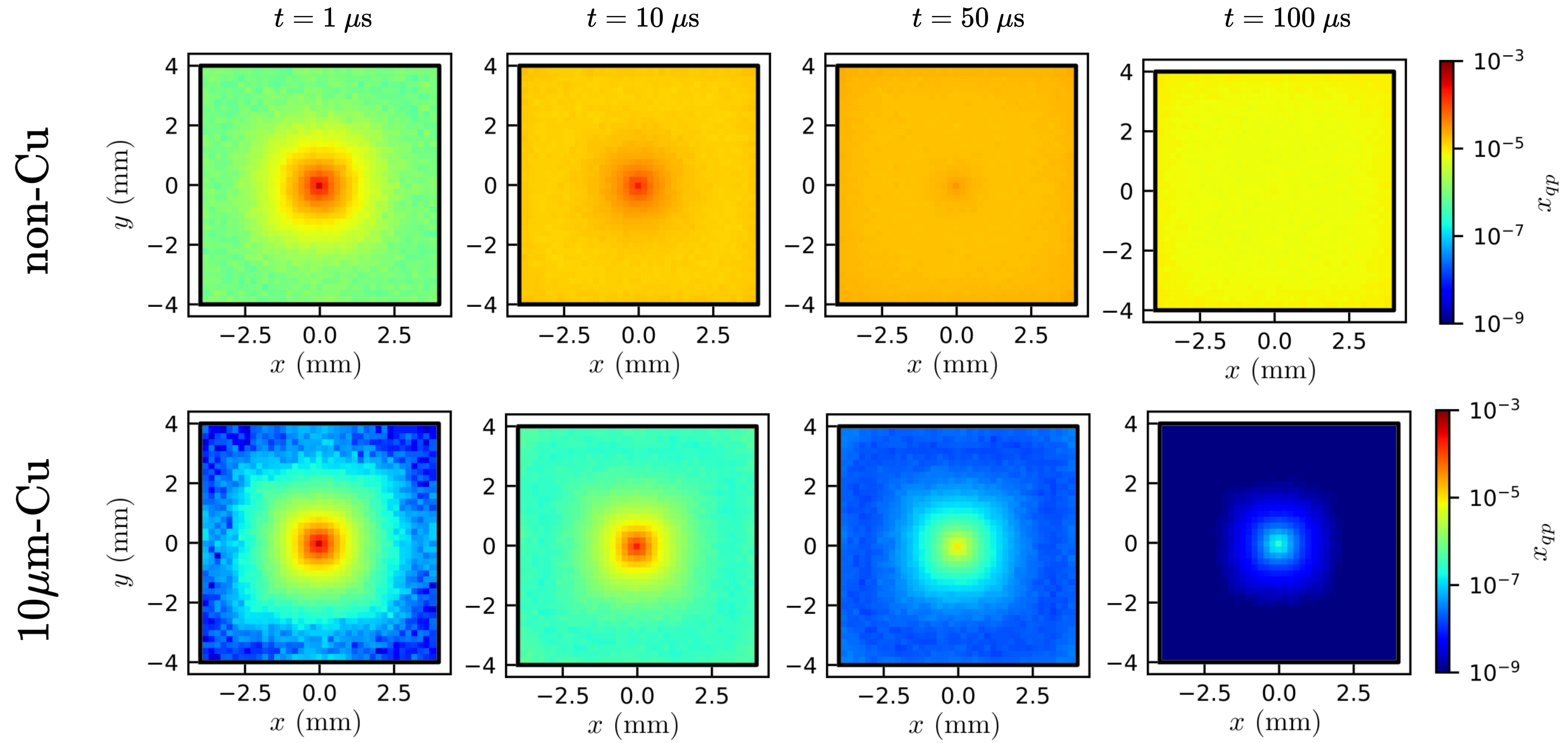


Only ~5% of generated phonons shown

PrimaryGeneratorAction

Yelton *et al.*, arXiv:2402.15471 (2024)

QP poisoning from a gamma-ray impact



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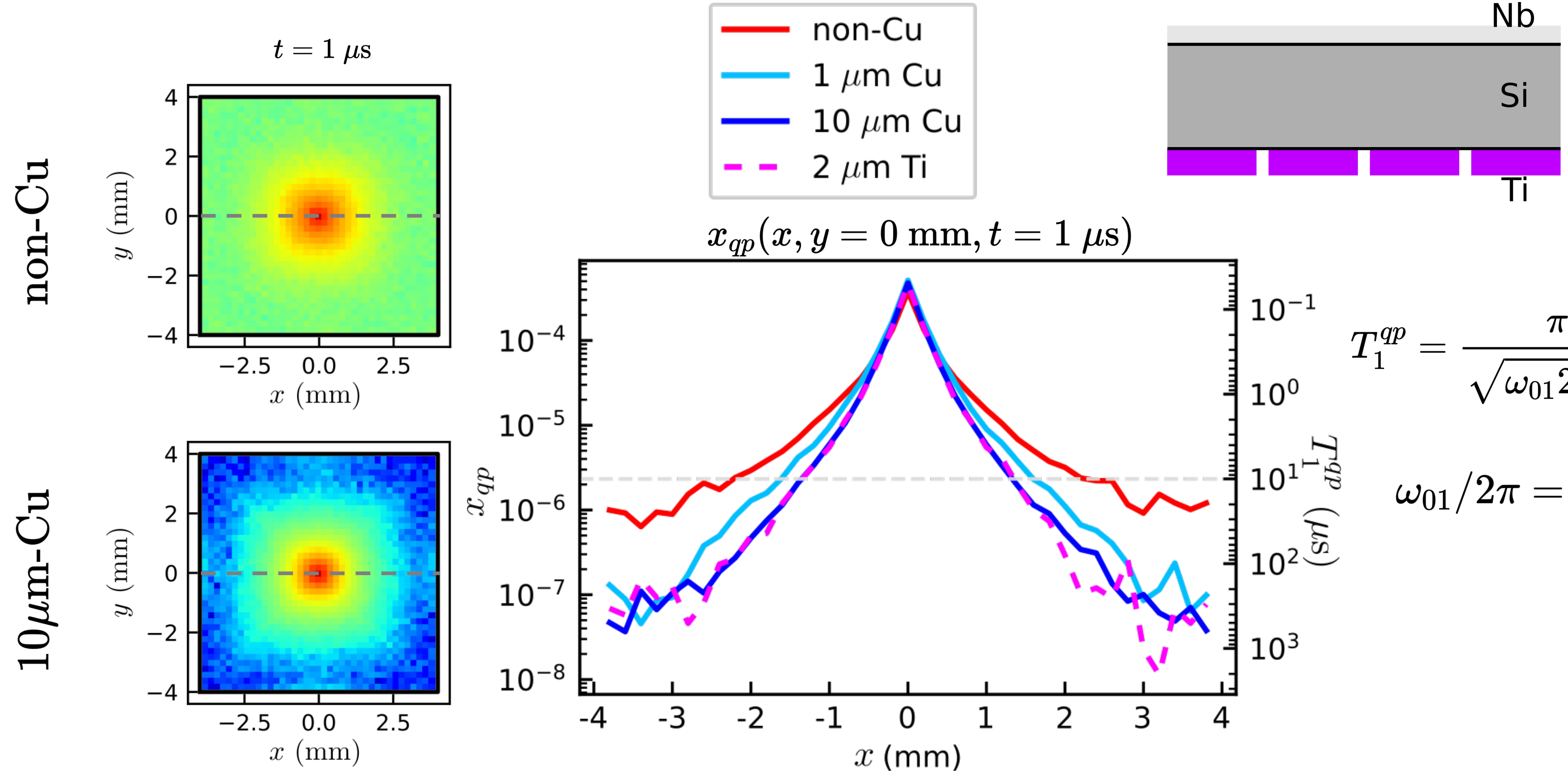
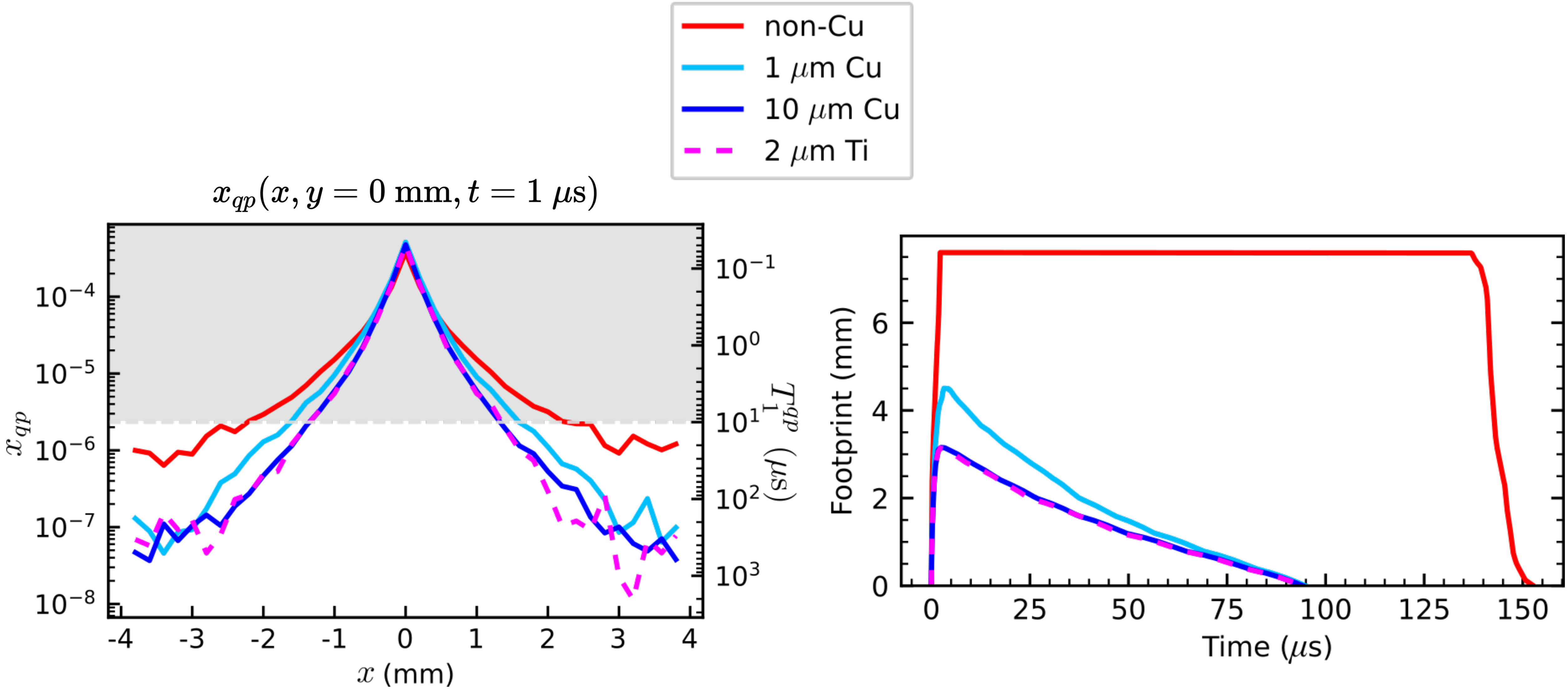


$$T_1^{qp} = \frac{\pi}{\sqrt{\omega_{01} 2\Delta/\hbar}} \frac{1}{x_{qp}}$$

$$\omega_{01}/2\pi = 5\ \mathrm{GHz}$$

Yelton *et al.*, arXiv:2402.15471 (2024)

QP poisoning from a gamma-ray impact



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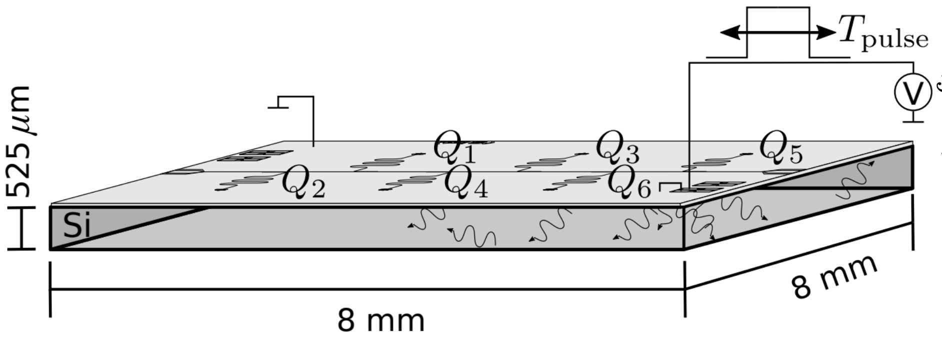
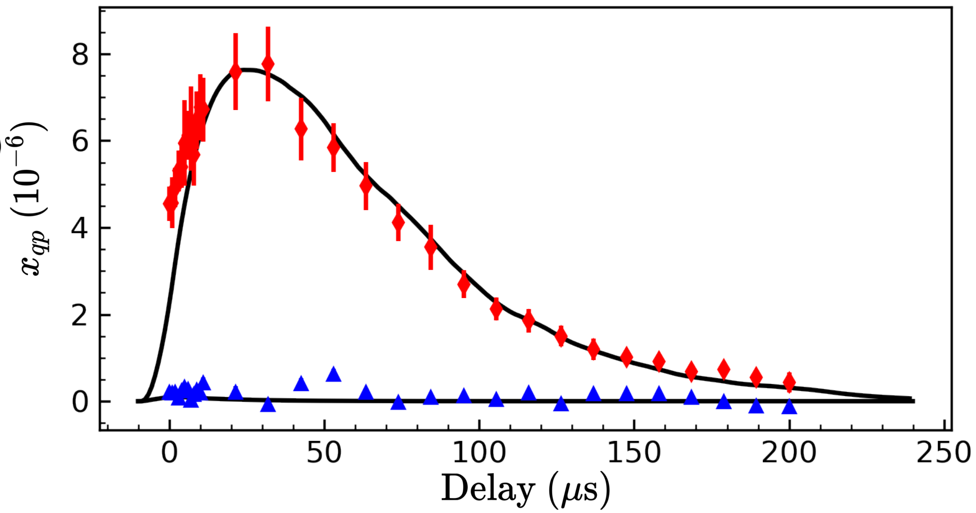
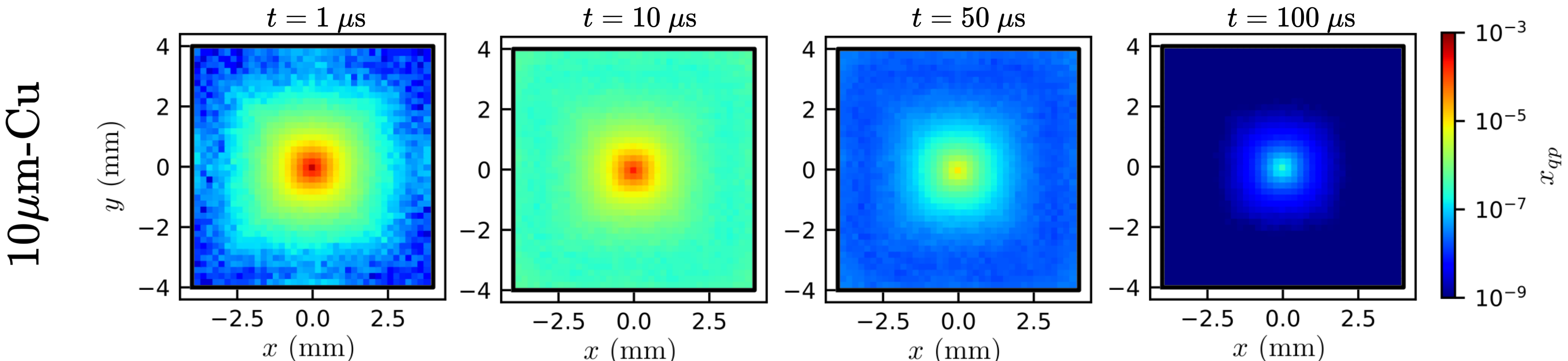
Conclusion

- Shown a realistic model of QP poisoning in superconducting qubit devices
- Modeled dense qubit arrays while exposed to a background gamma-ray impact

arXiv:2402.15471

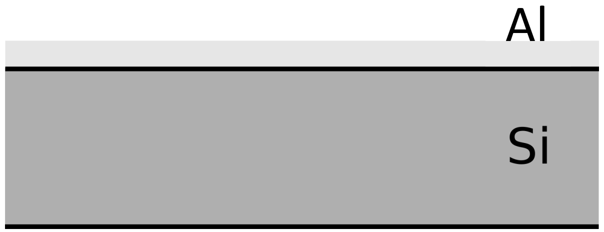


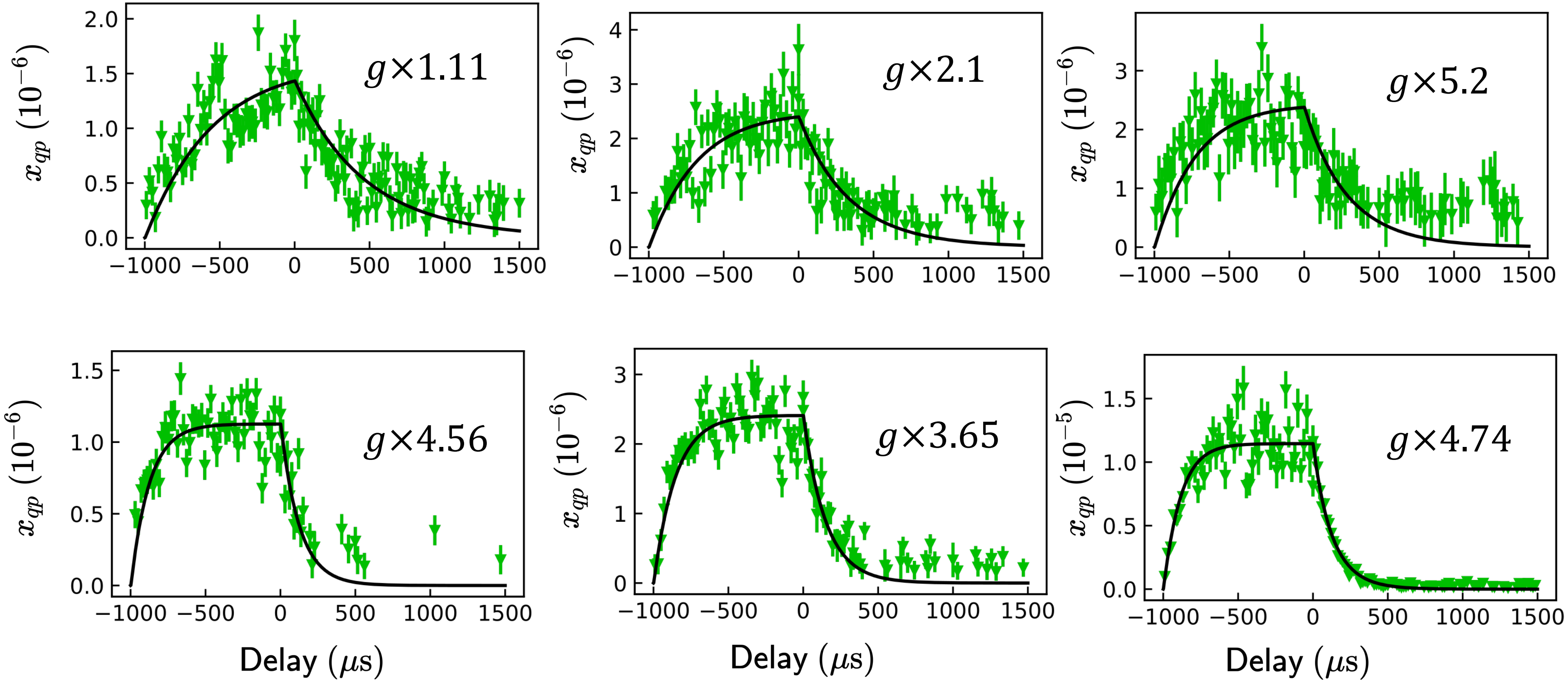




Back-up Slides

Injection on an Al GND plane device



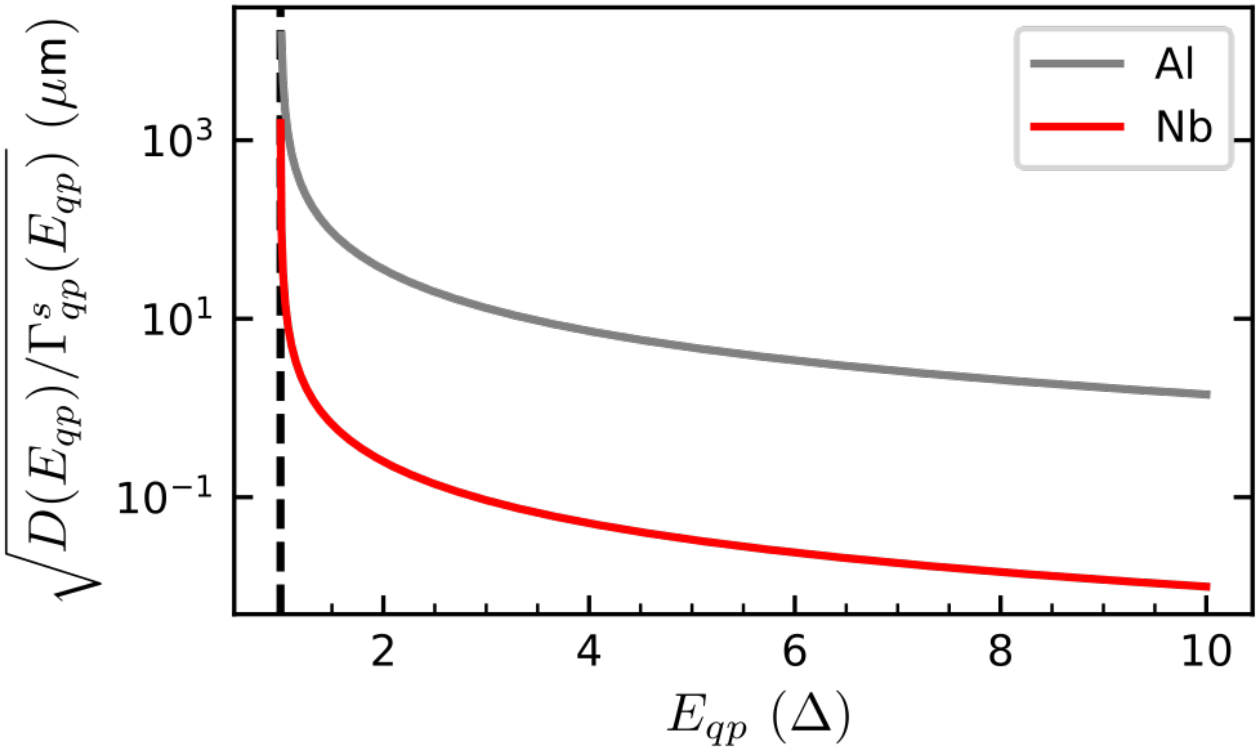


We only saw agreement between modeling and data when scaling generation term in post

QP Diffusion

$$D(E_{qp}) = D_n\sqrt{1-\left(\frac{\Delta}{E_{qp}}\right)^2}$$

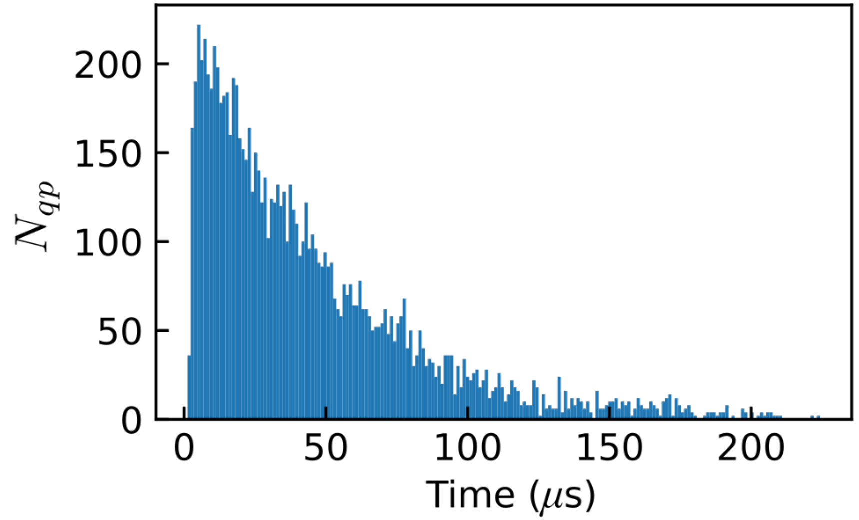
$$\Gamma^s_{qp}(E_{qp}) \approx \frac{1.8}{\tau_0^{qp}}\left[\left(\frac{E_{qp}}{\Delta}\right)-1\right]^3$$



$$D_n = 6\ \mu m^2 ns^{-1}$$
$$\tau_0^{qp} = 440\ ns$$

$$D_n = 0.88\ \mu m^2 ns^{-1}$$
$$\tau_0^{qp} = 0.15\ ns$$

Formulating the generation term



g(t) is the convolution of a response function to an injection rate pulse

$$g(t) = \int^{t} h(t-\tau) I_{ph}(\tau) \mathrm{d}\tau$$

In the simulation the routine all phonons are injected at t=0. Thus,

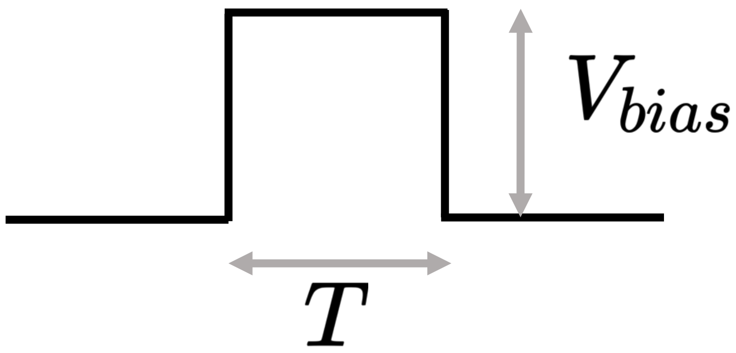
$$I_{ph}(t) = N_{ph}^{s} \delta(t) \rightarrow h(t) = \frac{N_{qp}(t)}{V \Delta t N_{ph}^{s}}$$

Discretizing the first equation with the above response function gives the following:

$$\boxed{g(t_i) = \sum_{j<i} \frac{N_{qp}(t_i - t_j)}{V N_{ph}^{s}} I_{ph}(t_j)}$$

Phonon injection rate $I_{ph}(t)$

In solving the QP density equation the time dependent phonon injection rate should match our experimental parameters

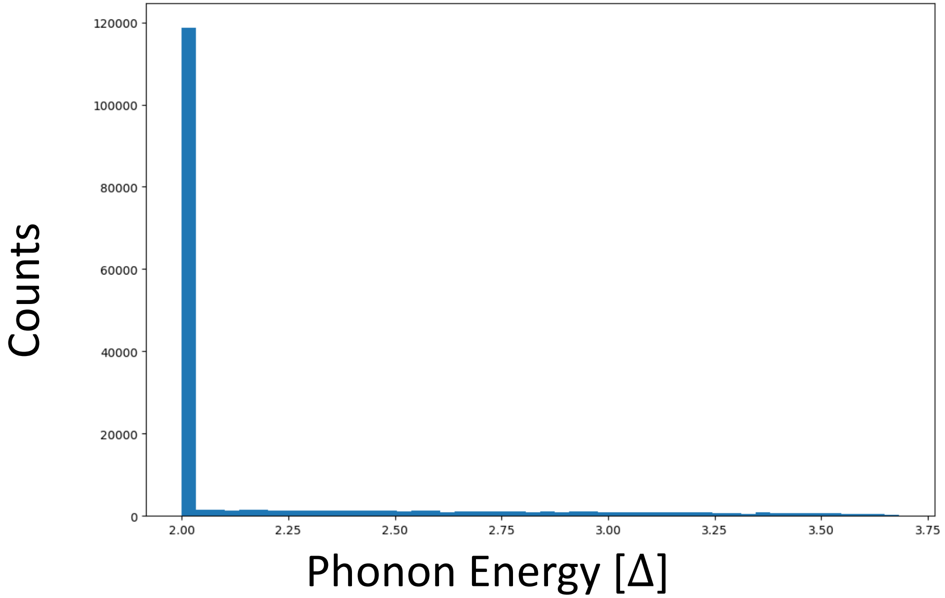


$$I_{pair} = \frac{V_{bias}}{2eR_n} \quad eV_{bias} \approx 5.5\Delta_{\mathrm{Al}} > 4\Delta_{\mathrm{Al}}$$

Monte Carlo simulation:

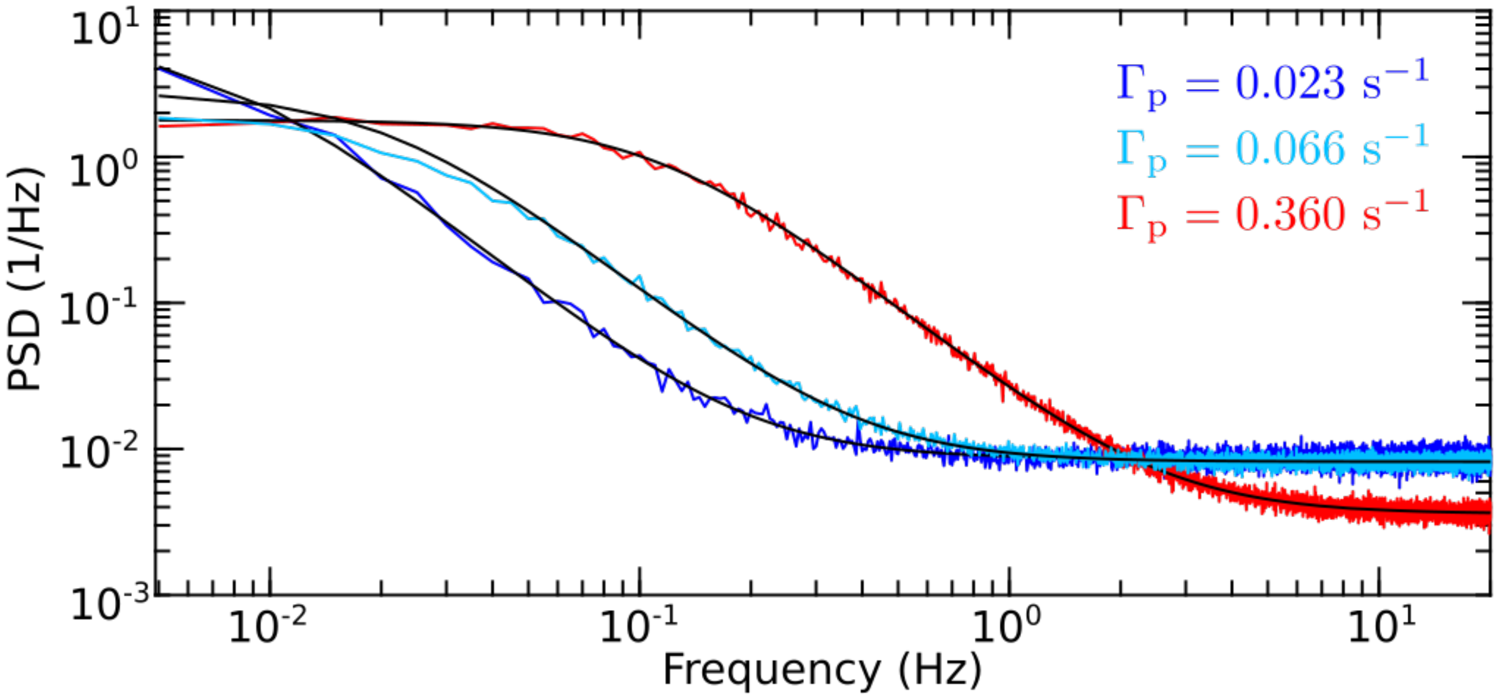
Simulate 100,000 broken pairs of energy 1 meV

Generates 167259 pair breaking phonons



$$I_{ph}(t) = \begin{cases} 1.673 I_{pair}, & \text{if } t \leq T \\ 0, & \text{otherwise} \end{cases}$$

Parity Switching data



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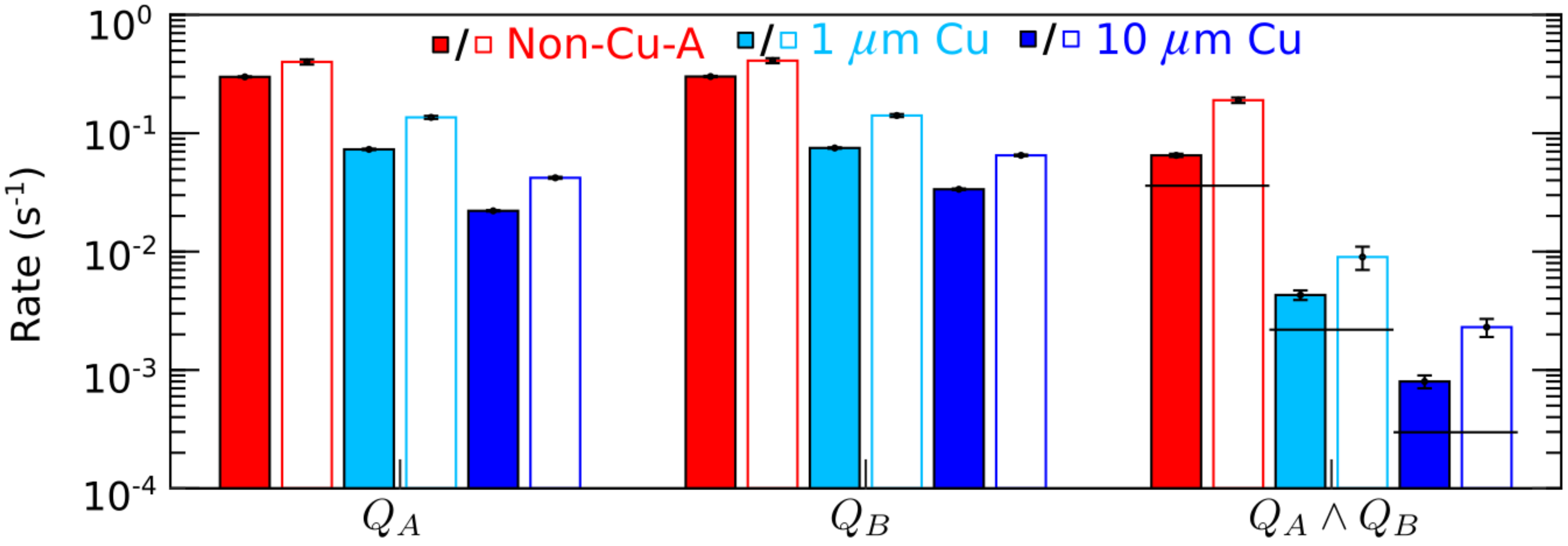
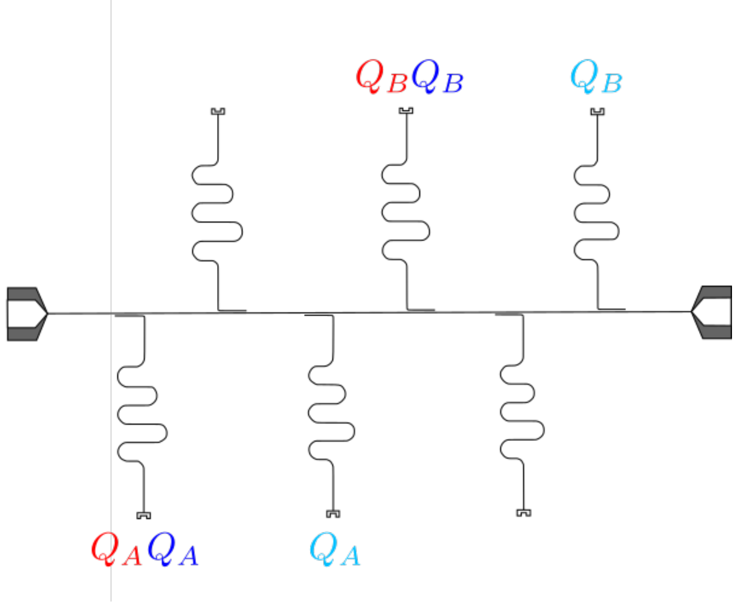
Parity Switching data





$$p_A^{obs} = \frac{1}{2}(p_{AB} + p_A)$$

$$p_B^{obs} = \frac{1}{2}(p_{AB} + p_B)$$

$$p_{AB}^{obs} = \frac{1}{4}(p_{AB} + p_A p_B)$$

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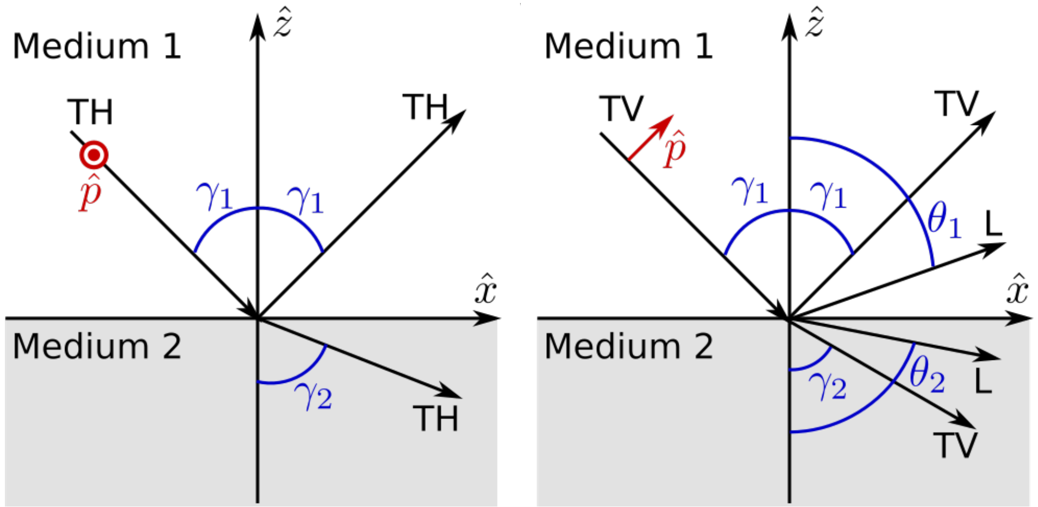
Phonon Absorption

In general, the absorption probability of elastic plane wave at the interface of two semi-infinite media depends on material properties, the angle of incidence and the polarization of the waves



$$\eta_T \;\&\; \eta_L \text{ are angle averaged transmission coefficients}$$

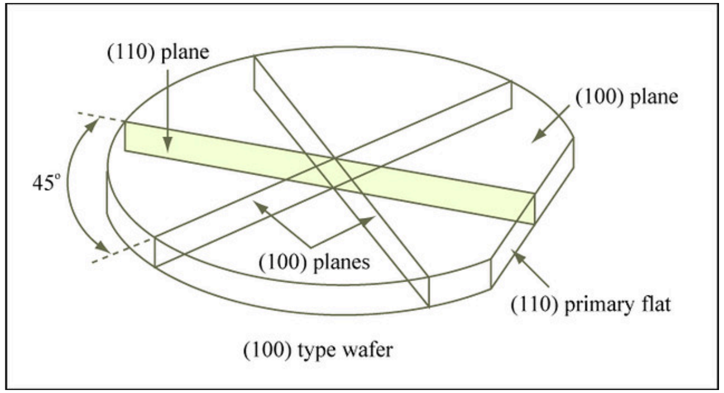
We take the probability for a phonon in the Si substrate to be absorbed into a superconducting film to be the sum of the angle averaged transmissions coefficients for each mode weighted by the density of states in Si.

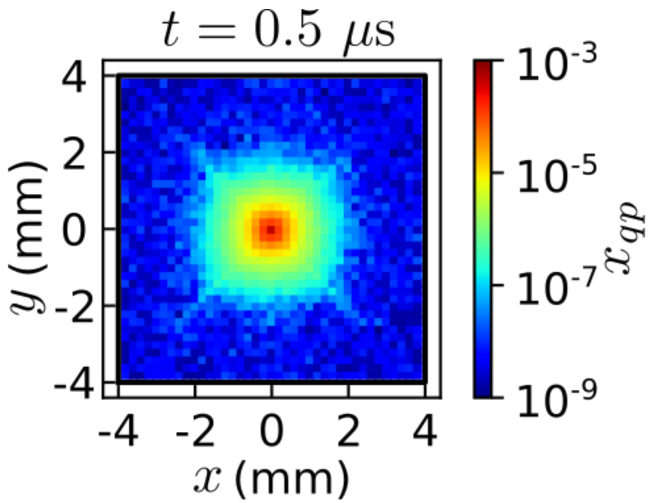
$$p_{abs} = 0.907\eta_T + 0.093\eta_L$$

Phonon Caustics

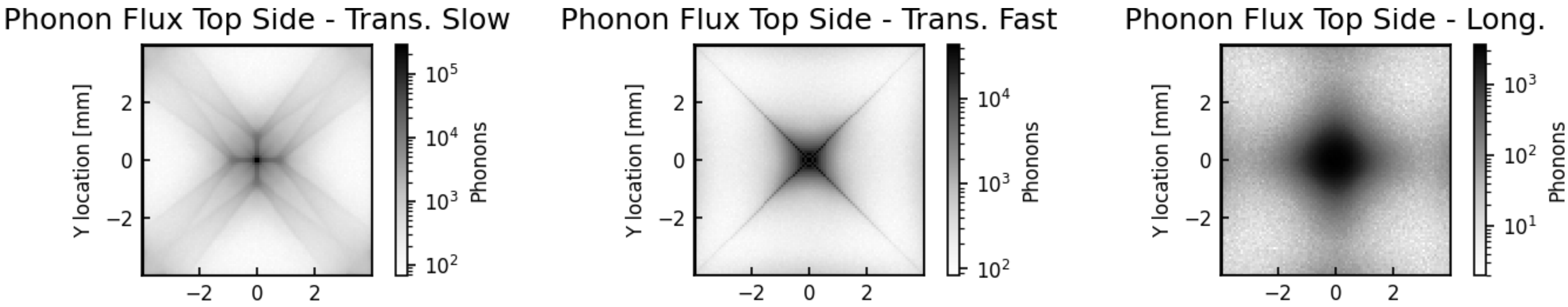
$$\vec{v}_g = \nabla_k \omega(\vec{k})$$

$$\rho\omega^2 e_i = C_{ijml} k_j k_m e_l$$

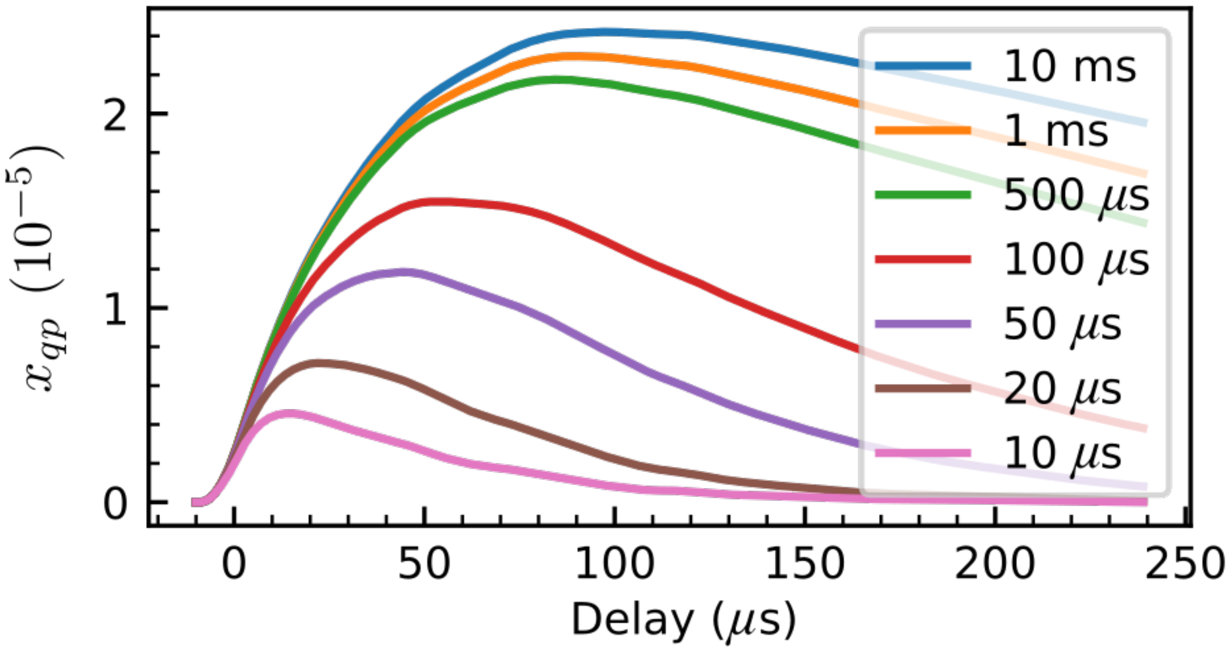


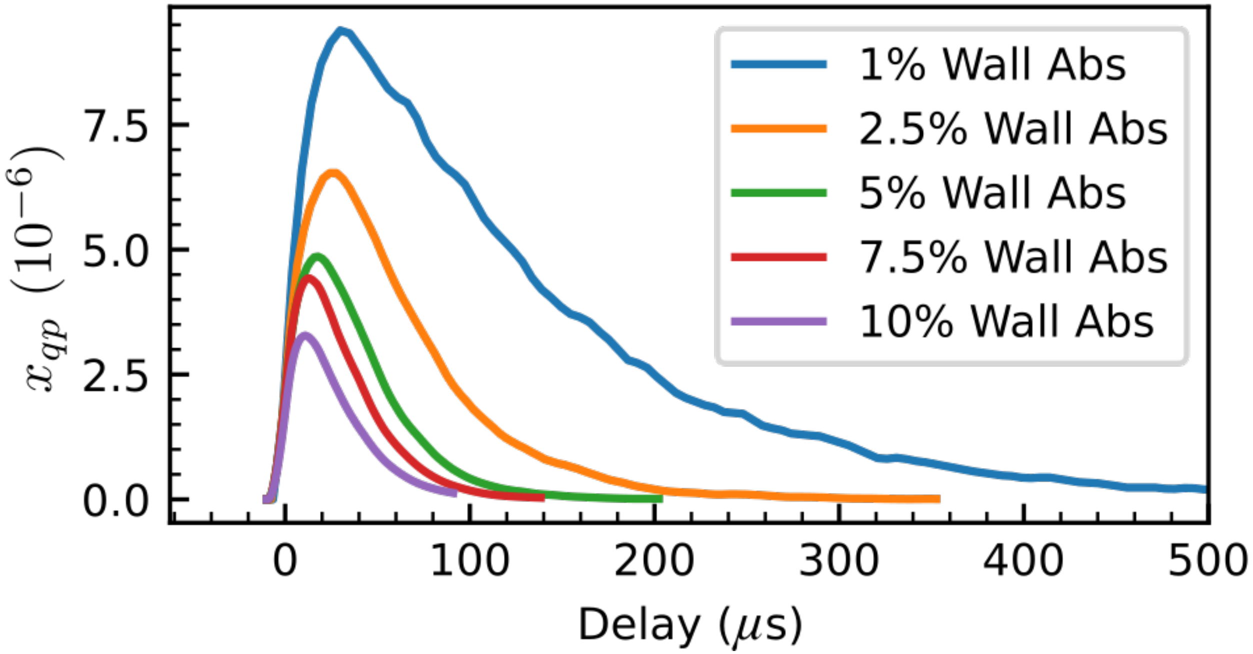


Due to anisotropies in the elasticity tensor the group velocity is generally not in the same direction as the wavevector



QP density Wall Abs. and Trapping rate





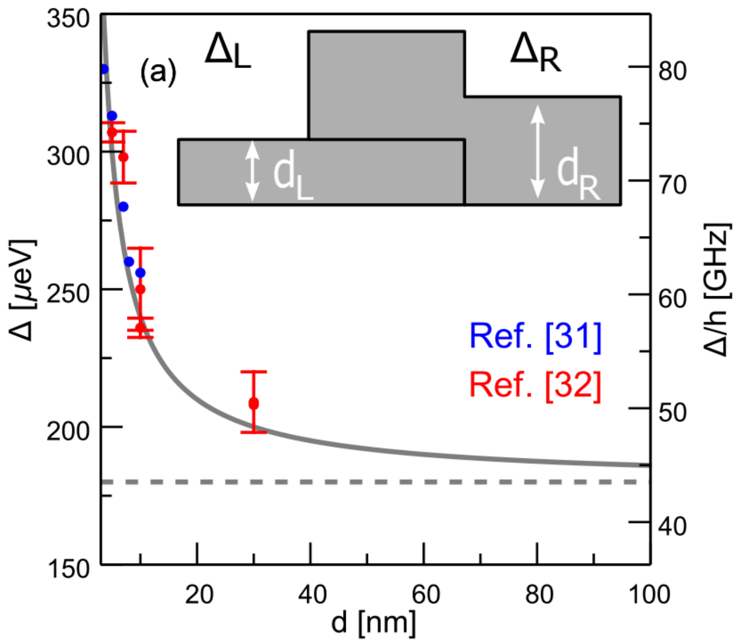
Wall Abs. set to be 2.5%

Inverse trapping rate of 20 us

Gap of the electrodes

$$\Delta(d) = \Delta_{\text{bulk}} + \frac{600\ \mu\text{eVnm}}{d}$$

$$\Delta(40\ \text{nm}) = 195\ \mu\text{eV} \qquad \Delta(80\ \text{nm}) = 187.5\ \mu\text{eV}$$



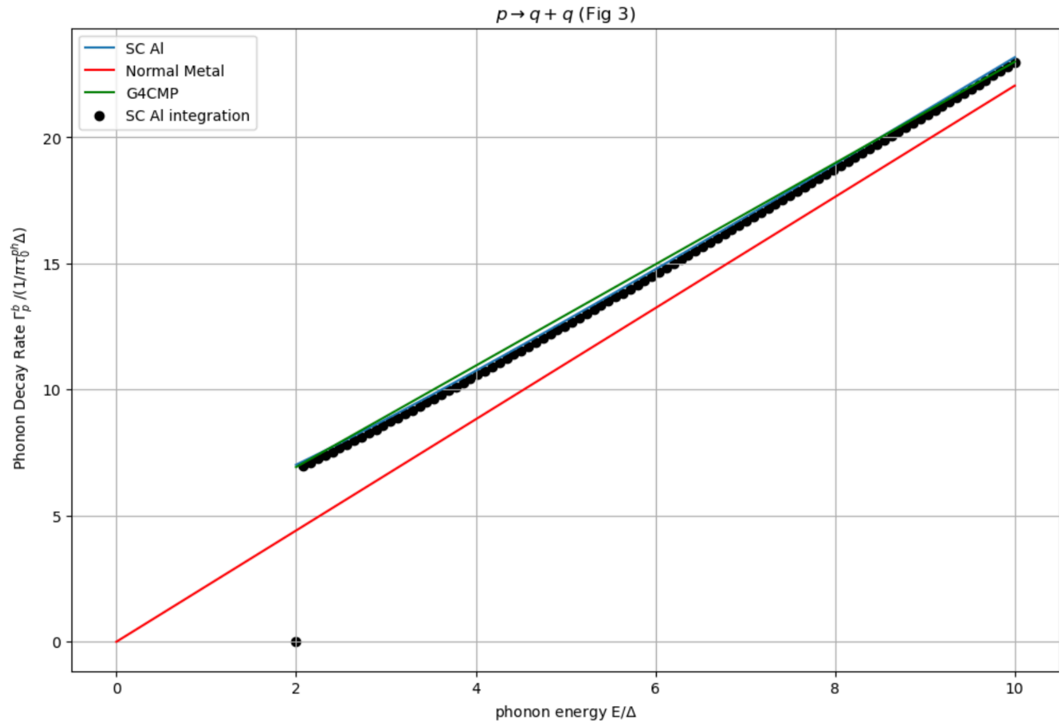
- We have 40 nm / 80 nm dolan bridge style junctions
- **Assume the simulated junction patches have a gap of the average of the two films ~ 191 ueV and a total thickness of 120 nm**

Other film parameters

- Gap Energy Table IV from this source
- Phonon Lifetime slope $\delta\tau^{ph}$ is 0.29
- vSound – long. and trans. modes are weighed by the DOS of phonons in Si. The sound speeds are from this source.

$$\nu_{\text{sound}} = \text{DOS}_{\text{Si}}^{\text{trans.}} \nu_{\text{trans.}} + \text{DOS}_{\text{Si}}^{\text{long.}} \nu_{\text{long.}}$$

$$\nu_{\text{sound}} = 0.907\nu_{\text{trans.}} + 0.093\nu_{\text{long.}}$$

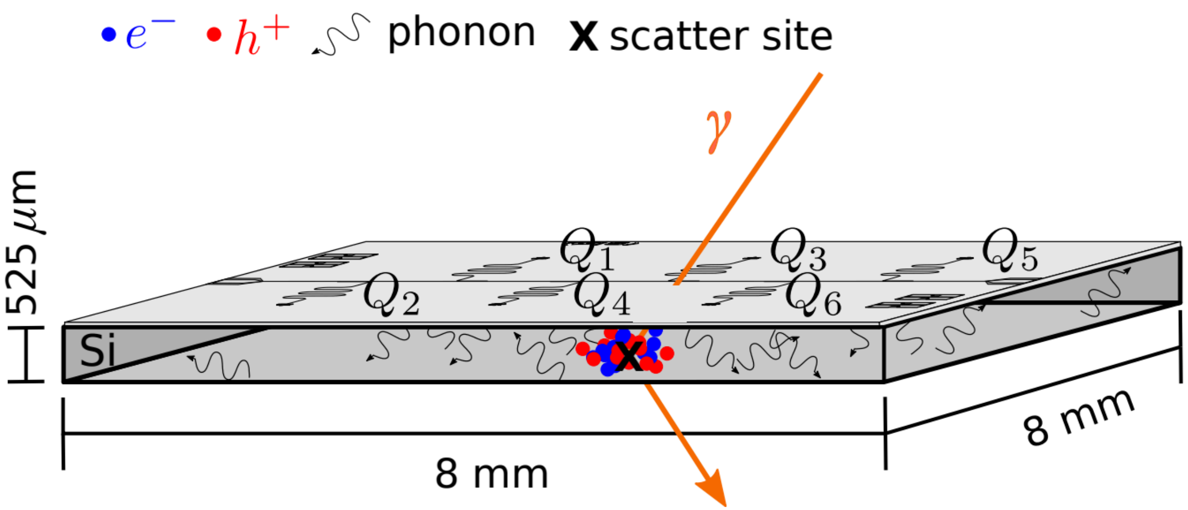


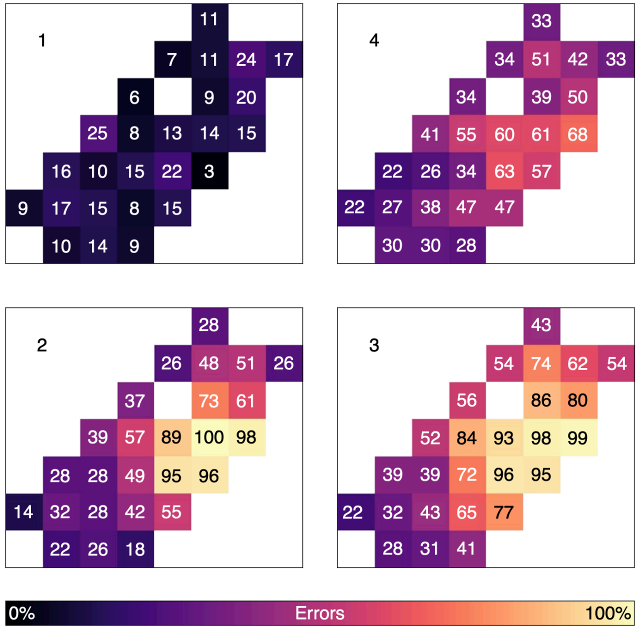
$$\Gamma_b^p(E_{ph}) \approx \frac{1}{\tau_0^{ph}}\left(1 + \delta\tau^{ph}\left(E_{ph}/\Delta - 2\right)\right)$$

$$\Gamma_b^p \approx \frac{1.4}{\pi\tau_0^{ph}\Delta}E_{ph} \approx \frac{1}{0.64\ \text{ns}}\left(E_{ph}/\text{K}\right)\ \text{Ti}$$

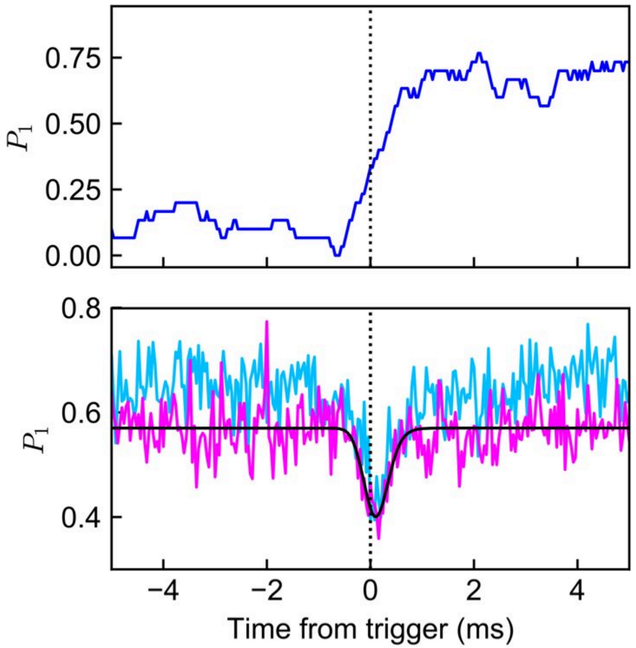
Motivation

- Background γ-rays and cosmic ray muons create a burst of charge and phonons in Si
- Energetic phonons break cooper pairs creating QPs which cause correlated errors
- Correlated errors break QEC





McEwen et al., *Nature Physics* 18, 107 (2021)



Wilen et al., *Nature* 594, 7863 (2021)

Charge Transport

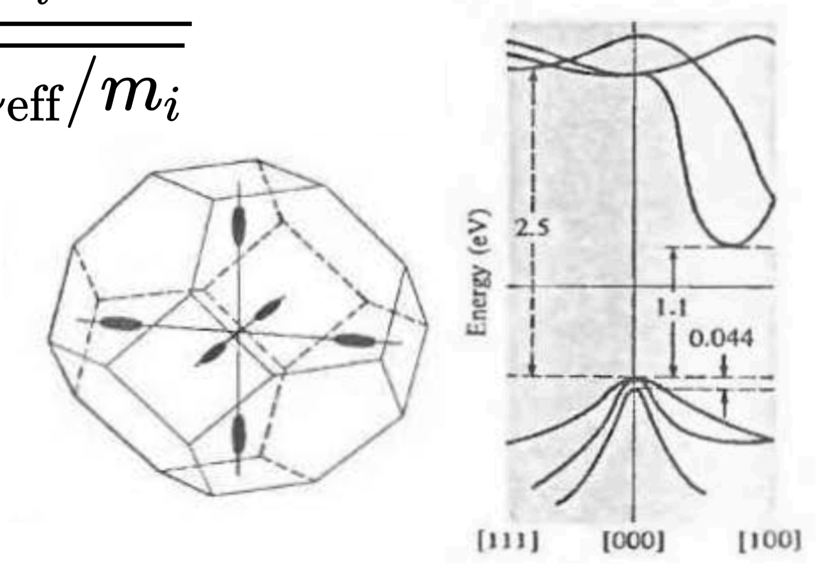
$$\text{E.O.M.}: \frac{eE_i}{m_i} = \frac{dv_i}{dt} \rightarrow \frac{eE_i^*}{m_{\text{eff}}} = \frac{dv_i^*}{dt} \text{ where } v_i^* = \frac{v_i}{\sqrt{m_{\text{eff}}/m_i}}$$

Electron mass tensor

- Mass of holes is scalar

$$T_{\text{HV}} = \begin{pmatrix} \sqrt{\frac{m_{\text{eff}}}{m_x}} & 0 & 0 \\ 0 & \sqrt{\frac{m_{\text{eff}}}{m_y}} & 0 \\ 0 & 0 & \sqrt{\frac{m_{\text{eff}}}{m_z}} \end{pmatrix}$$

$$3/m_{\text{eff}} = 1/m_x + 1/m_y + 1/m_z$$



N. W. Ashcroft, N. D. Mermin, Solid State Physics, College Edition, Saunders College Publishing, 1976

Charge Trapping

$$e^- D^0 \rightarrow D^-$$
$$h^+ D^- \rightarrow D^0$$
$$e^- A^+ \rightarrow A^0$$
$$h^+ A^0 \rightarrow A^+$$

Impact Ionization

$$e^- D^- \rightarrow e^- e^- D^0$$
$$h^+ D^- \rightarrow h^+ e^- D^0$$
$$e^- A^+ \rightarrow e^- h^+ A^0$$
$$h^+ A^+ \rightarrow h^+ h^+ A^0$$

- Intervalley Scattering : Electrons are scattered from absorption of thermal phonons-> momentum transfer from one valley to another
- Charges recombine and emit half of band gap energy as phonons at Debye freq (62.03 meV)

Phonon Transport

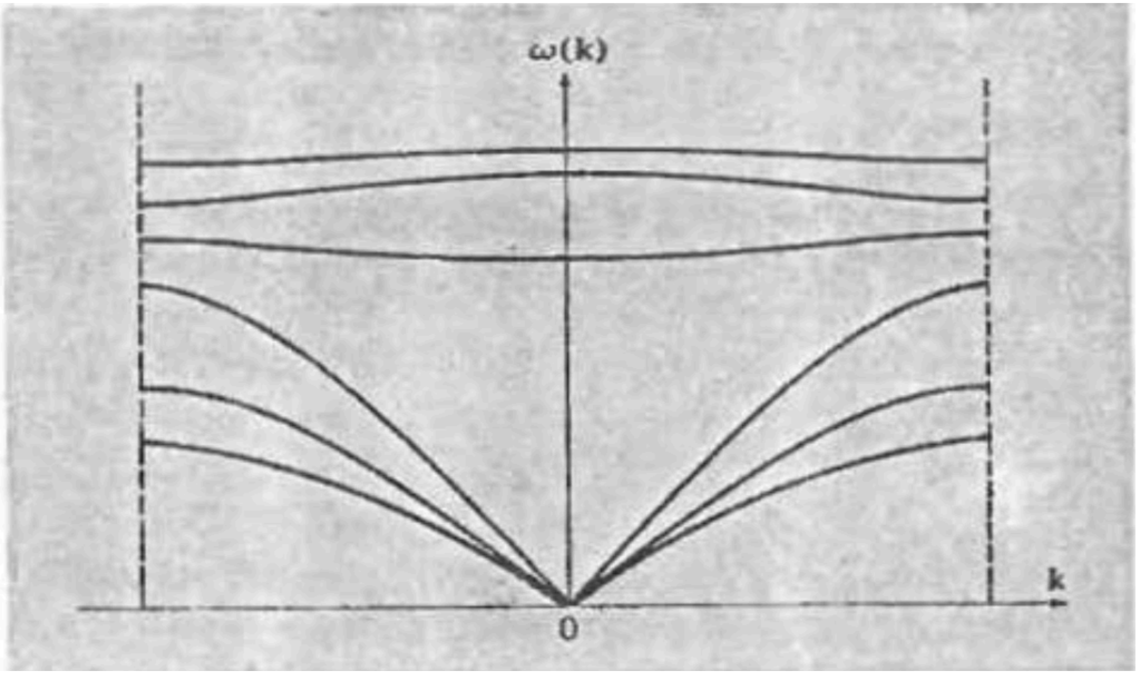
$$\rho\omega^2 e_i = C_{ijlm} k_j k_m e_l \qquad \mathbf{v_g} = \nabla_k \omega(\mathbf{k})$$

$$\Gamma_{\text{anh.}} \propto \omega^5$$

$$L \to L'T$$
$$L \to TT$$

$$\Gamma_{\text{scatter}} \propto \omega^4$$

53.1% Slow Trans.
37.6% Fast Trans.
9.3% Longitudinal



N. W. Ashcroft, N. D. Mermin, Solid State Physics, College Edition, Saunders College Publishing, 1976

- Wave equation is not solved in real-time but by using a look-up table
- Only Acoustic phonons are modeled
- Optical phonons immediately decay into acoustic modes in mK limit -> drawback photon-phonon scattering is not modeled

Superconducting Film Boundaries

QP downconversion $q \rightarrow q + p$

$$\Gamma_q^s(\epsilon) = \frac{1}{\tau_0} \int_\Delta^\epsilon \mathrm{d}\epsilon' \, \frac{(\epsilon - \epsilon')^2}{(kT_C)^3} \rho(\epsilon') \Big(1 - \frac{\Delta^2}{\epsilon \epsilon'}\Big)$$

$$P_{ph}(E_q) = \frac{(E_q - E_q')^2}{(kT_C)^3} \rho(E_q') \big(1 - \frac{\Delta^2}{E_q E_q'}\big)$$

Pair breaking $p \rightarrow q + q$

$$\Gamma_p^b(E_p) = \frac{1}{\pi \tau_0^{ph} \Delta} \int_{E_p - \Delta}^{\Delta} \mathrm{d}\epsilon \rho(\epsilon) \rho(E_p - \epsilon) \Big(1 + \frac{\Delta^2}{\epsilon(E_p - \epsilon)}\Big)$$

$$P_{QP}(E_q) = \rho(E_q) \rho(E_{\text{phonon}} - E_q) \big(1 + \frac{\Delta^2}{E_q(E_{\text{phonon}} - E_q)}\big)$$

$$P_{\text{escape}} = \exp\left(\frac{-2 * 2d}{\lambda(E_{\text{phonon}})}\right)$$

$$\lambda(E_{ph}) = \frac{v_{\text{sound}} \, \tau}{1 + \delta\tau \cdot (E_{ph}/\Delta - 2)}$$

Normal Metal Film Boundaries

QP downconversion / Electron Relaxation

$$P_{ph}(E_q) = \frac{(E_q - E_q')^2}{(kT_C)^3}\rho(E_q')\big(1 - \frac{\Delta^2}{E_q E_q'}\big)$$

$\Delta \to 0$

$$P_{ph}(E_q) \propto (E_q - E_q')^2$$

Pair breaking / Electron excitation

$$P_{QP}(E_q) = \rho(E_q)\rho(E_{\text{phonon}} - E_q)\big(1 + \frac{\Delta^2}{E_q(E_{\text{phonon}} - E_q)}\big)$$

$$P_{QP}(E_q) = 1$$

$$P_{\text{escape}} = \exp\left(\frac{-2 * 2d}{\lambda(E_{\text{phonon}})}\right) \qquad \lambda = \frac{v_L}{\Gamma} \qquad \Gamma^{\text{Cu}}_{\text{p}\to\text{e+e}} = \frac{1}{8.2\text{ns}}\Big(\frac{T_{\text{p}}}{\text{K}}\Big)$$