Comparison of G4CMP-Based Simulation to Experimental Data

for HVeV Dark Matter Sensors

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for the SuperCDMS Collaboration

GEANT4/G4CMP Satellite Workshop, RISQ
29 May 2024

Motivation for Using G4CMP with High Voltage eV-Resolution (HVeV) Detectors

Purpose of HVeV detectors

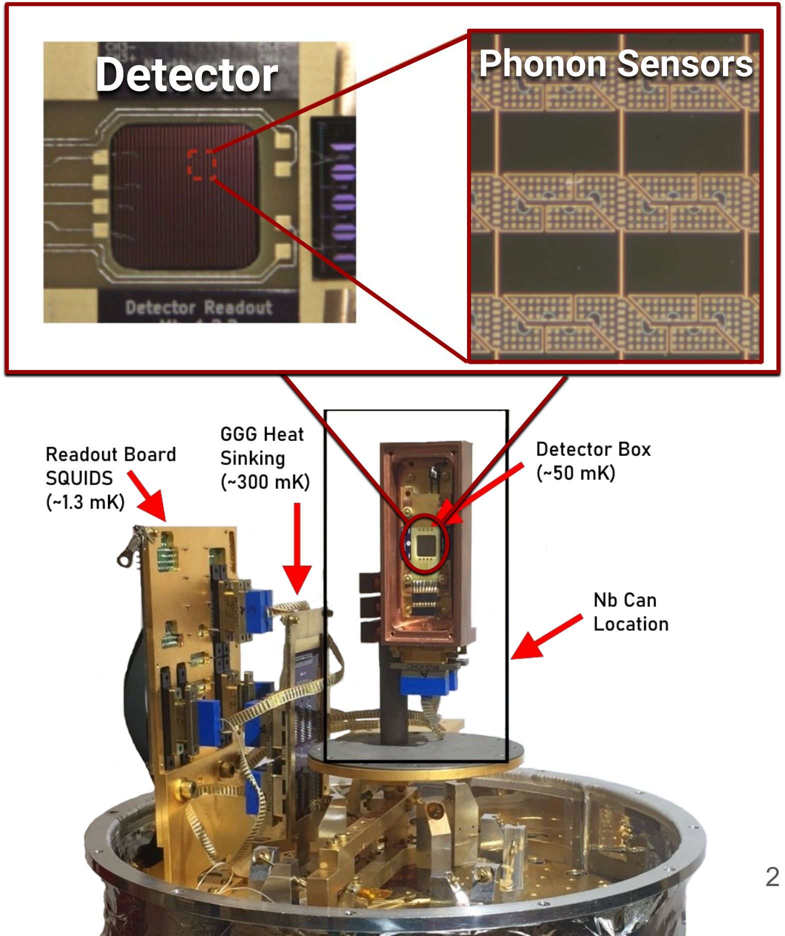
- Prototype to prepare for SuperCDMS SNOLAB experiment
- Low-mass (≲ few GeV/c^2)* dark matter searches

Fully-validated G4CMP-based simulation is essential to

- Enhance understanding of HVeV detector
  - What physical properties or effects are responsible for experimental observations?
- Use detector response information which is not experimentally probed for data analysis

In this talk, we check to see if our simulation reproduces HVeV experimental observations

E. Azadbakht, Ph.D. Thesis (2022)



E. Azadbakht, Ph.D. Thesis (2022)

* PRD 102, 091101 (2020)

Energy Deposit Results in Phonon Production

Incoming particle deposits energy

→ **electrons + holes**

→ **prompt phonons**

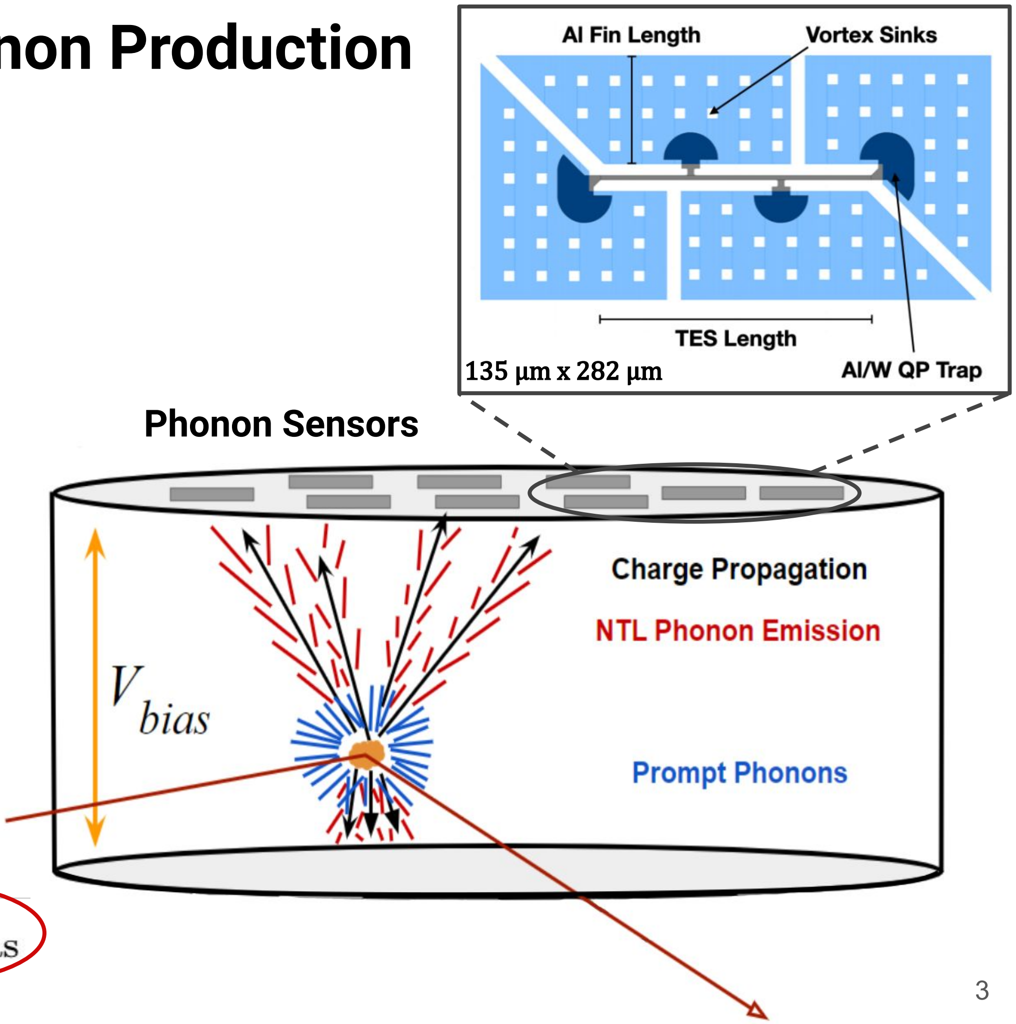
Under V_{bias}

→ **electrons + holes accelerate**

→ **NTL phonon emission**

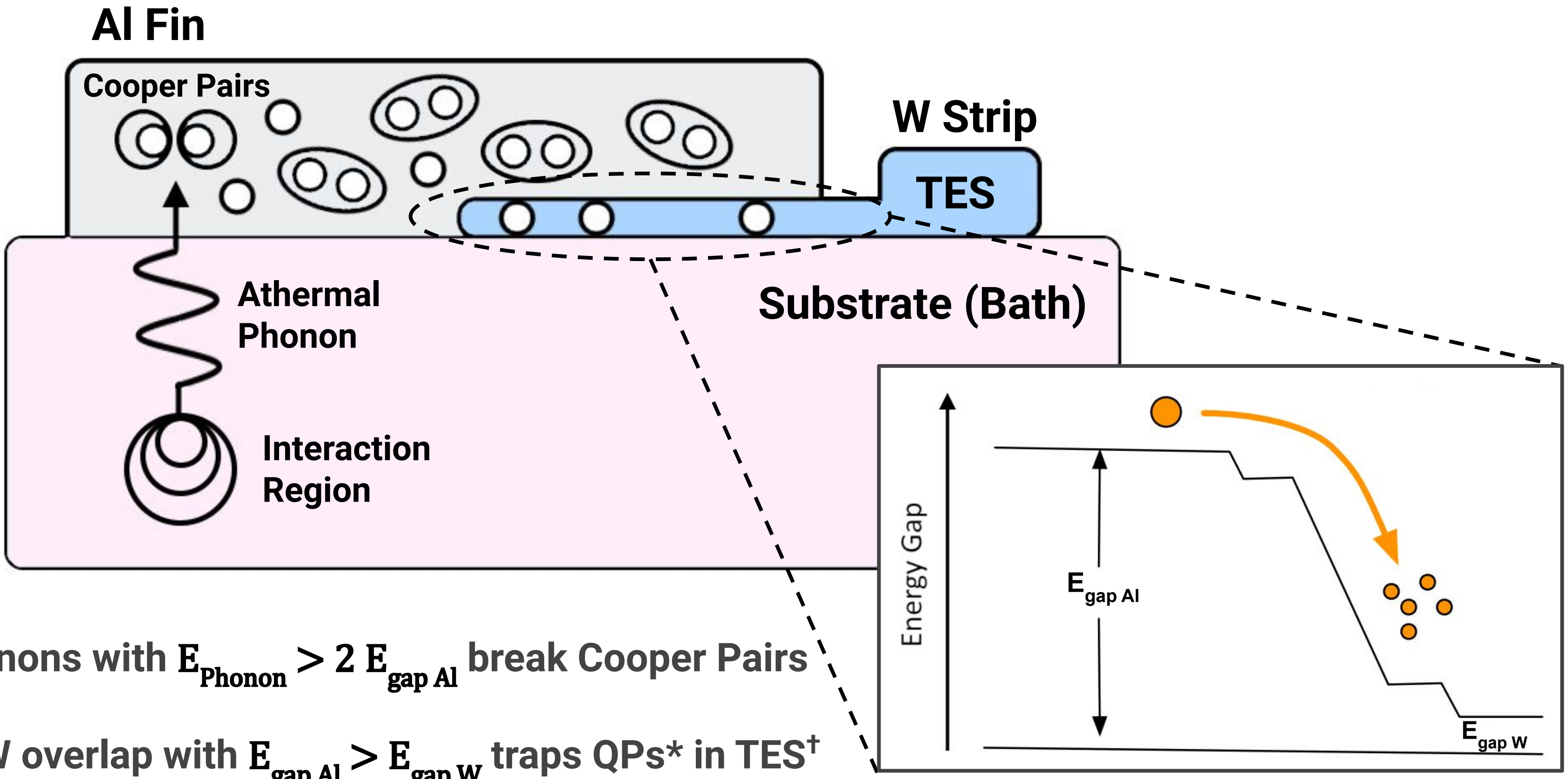
Neganov-Trofimov-Luke (NTL) Effect:

$$E_{\text{Phonon, Generated}} = E_{\text{recoil}} + N_{\text{eh}} e V_{\text{bias}}$$


PRD 104, 032010, 2021

Note: the above geometry and processes are modeled in G4CMP

Quasiparticles are Created and Trapped in TES



Phonons with $E_{Phonon} > 2\,E_{gap\,Al}$ break Cooper Pairs

Al/W overlap with $E_{gap\,Al} > E_{gap\,W}$ traps QPs* in TES†

M. C. Pyle, Ph.D. Thesis (2012)

Note: Modeled with G4CMPKaplanQP

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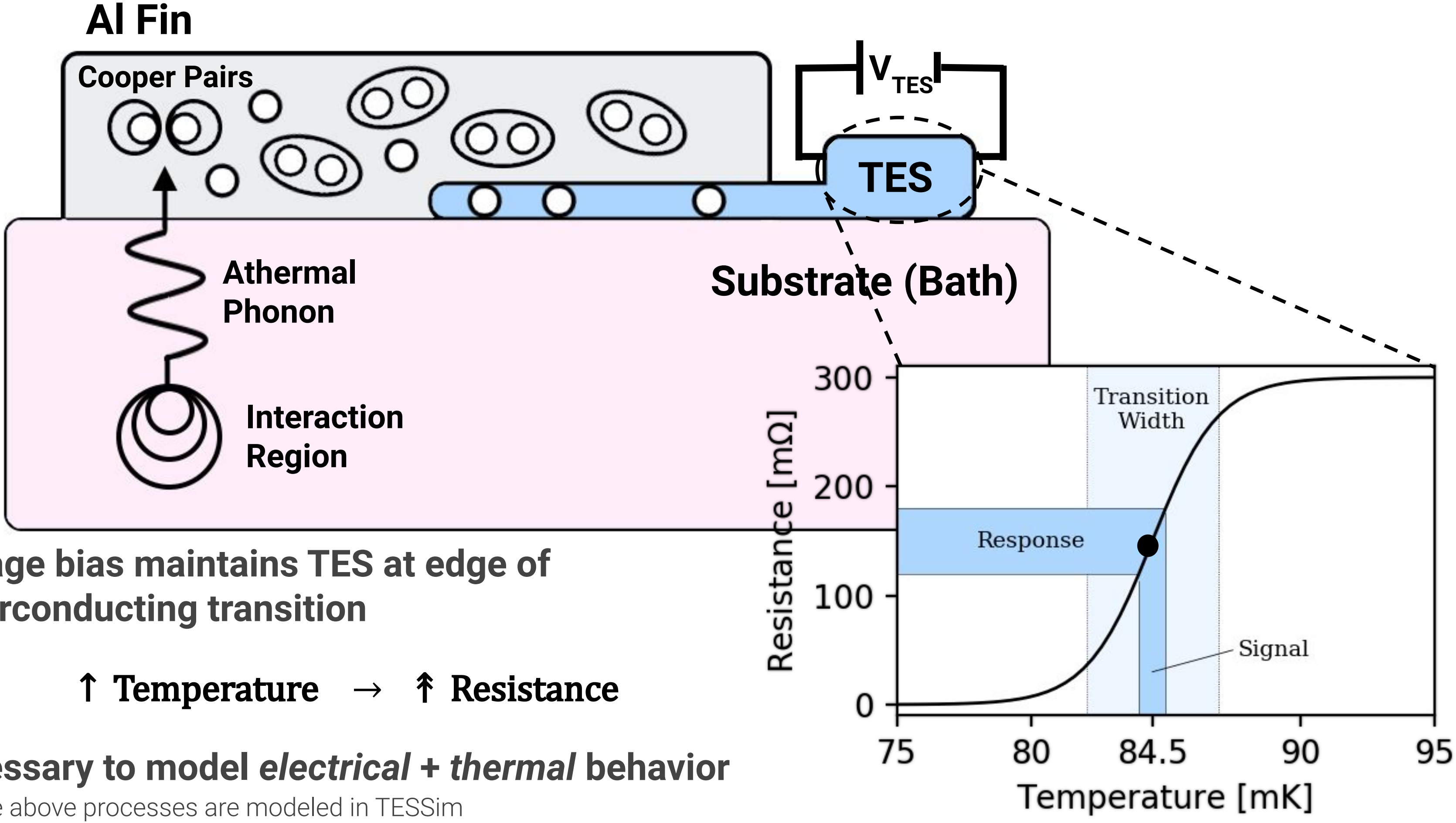
*Quasiparticles

†Transition Edge Sensor

TES Exploits Resistance–Temperature Transition Curve



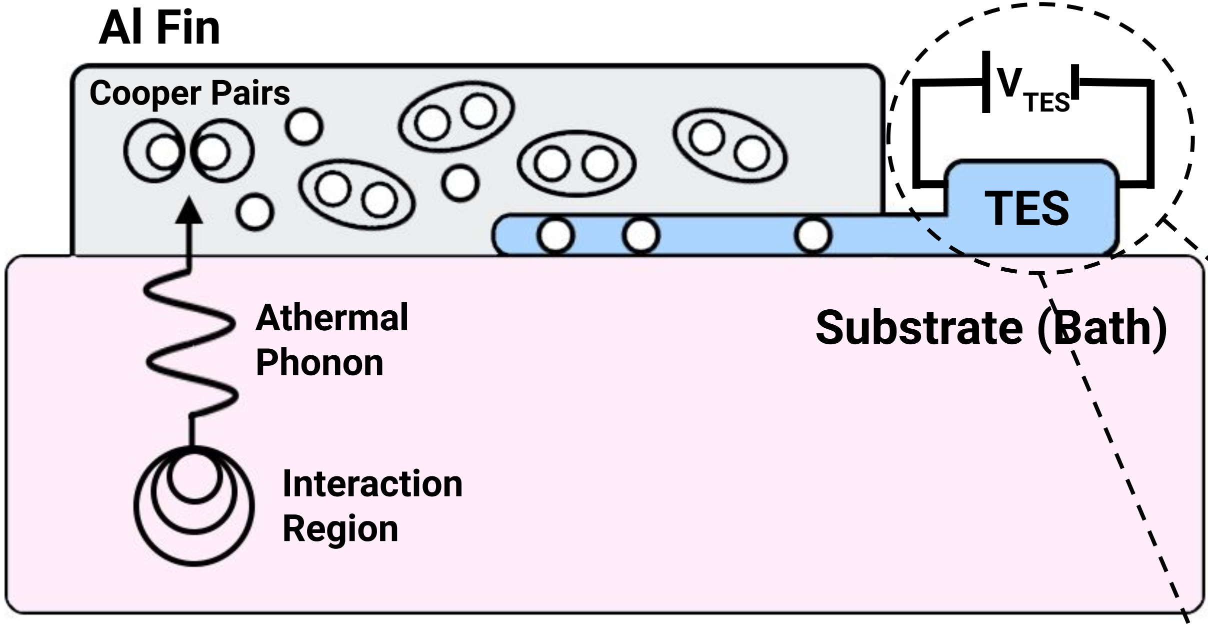
Voltage bias maintains TES at edge of superconducting transition

↑ Temperature → ↑ Resistance

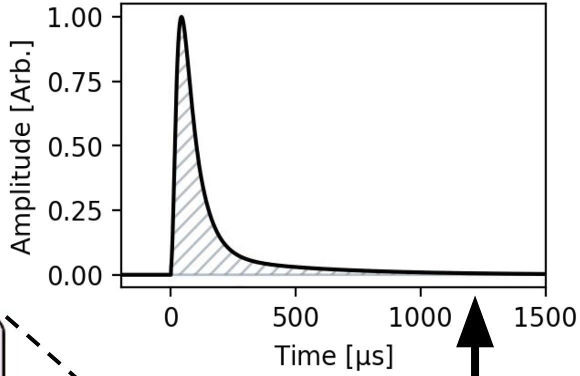
Necessary to model *electrical* + *thermal* behavior

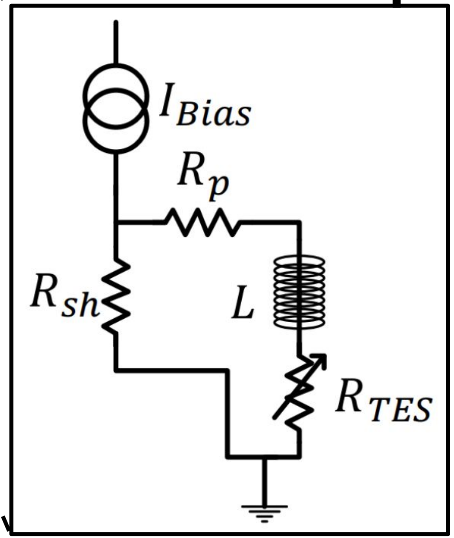
Note: the above processes are modeled in TESSim

Readout Circuit Produces Current Signal



Kelsey et al., NIM A 1055 (2023) 168473.





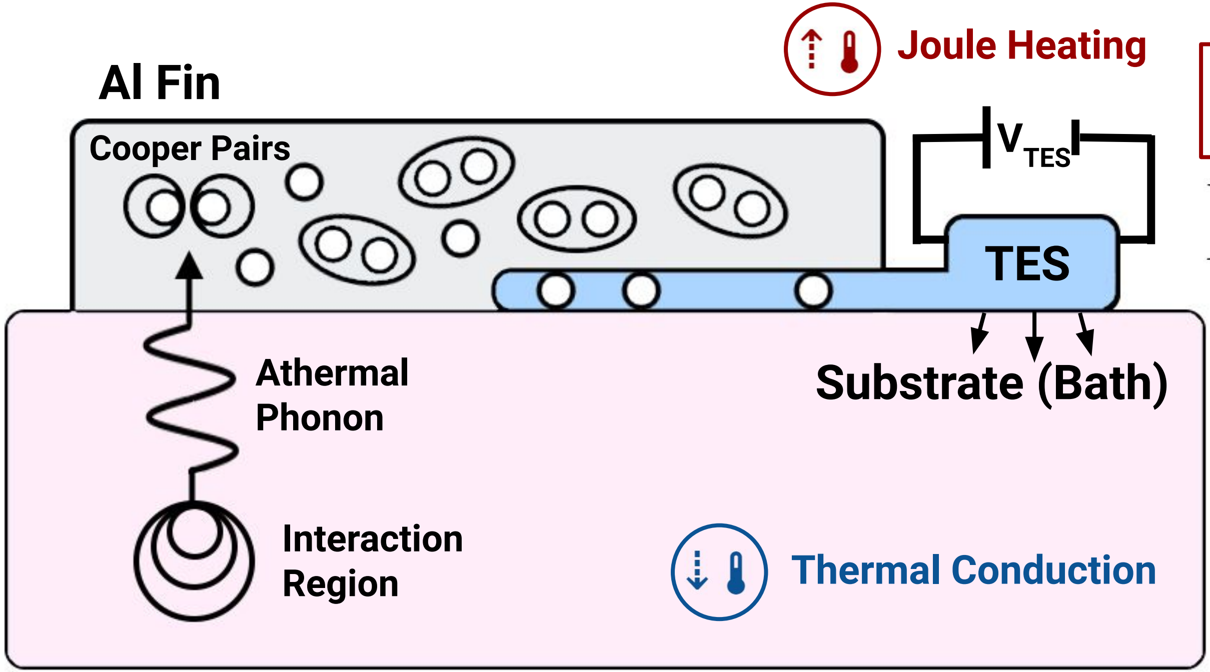
M. C. Pyle, Ph.D. Thesis (2012)

TES serves as variable resistor in readout circuit

thermal signature → current signal

Note: the above processes are modeled in TESSim

Other Physical Processes Change the TES Temperature



$$\boxed{P_{\text{Joule}} = V_{\text{TES}}^2 / R_{\text{TES}}}$$

V_{TES} - voltage drop across TES
R_{TES} - resistance of TES

$$\boxed{P_{\text{Bath}} = \kappa (T^5 - T_{\text{Bath}}^5)}$$

κ - thermal conductivity constant
T - TES electron temperature
T_{Bath} - substrate (bath) temperature

Note: the above processes are modeled in TESSim

Comparison of G4CMP-Based Simulation to Experimental Data

1. ***Parameter tuning***
    1.1. What set of simulation parameter values give the expected pulse shape?
    1.2. Do tuned parameters match theoretical expectations?
2. ***Estimating phonon measurement efficiency***
    2.1. Does simulation predict the HVeV detector's ability to collect and convert phonons to a detectable signal?
    2.2. Are energy loss mechanisms present and used appropriately?

Parameter Choices are Motivated by Absorption Processes

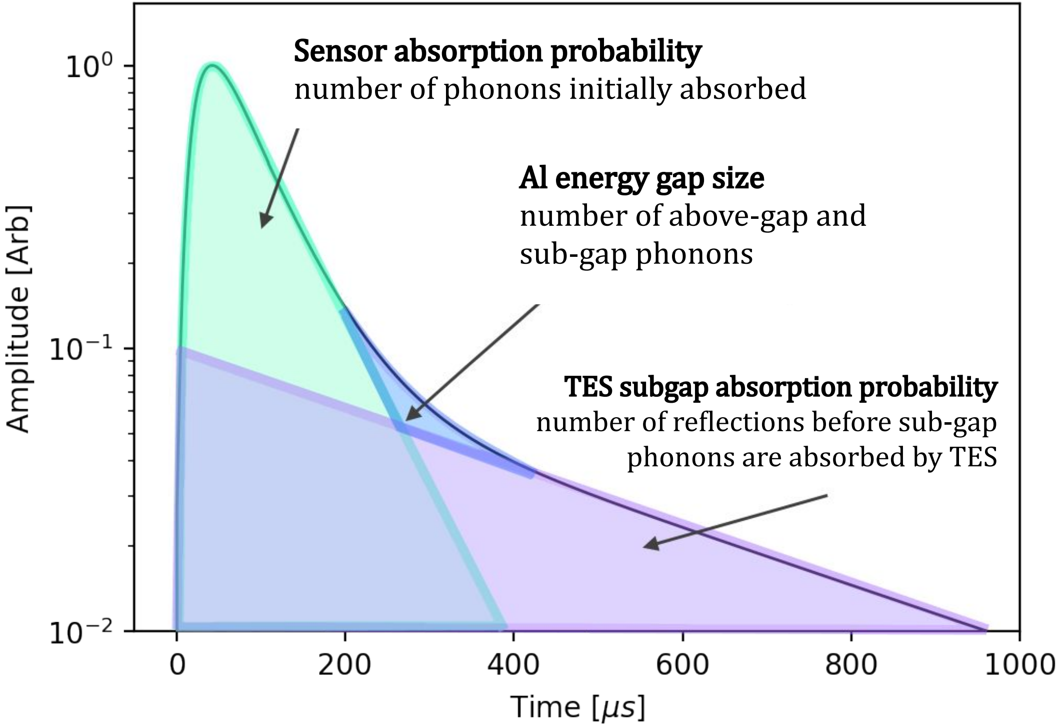
Chosen Parameters

Sensor absorption
Al energy gap
TES subgap absorption
Critical Temperature
Transition Width
Substrate Temperature
Volumetric Heat Capacity Coefficient
Inductance

🟦 **Absorption (G4CMP) Parameters**

⬜ **TESSim Parameters**

Kelsey et al., NIM A 1055 (2023) 168473.



Sensor absorption probability
number of phonons initially absorbed

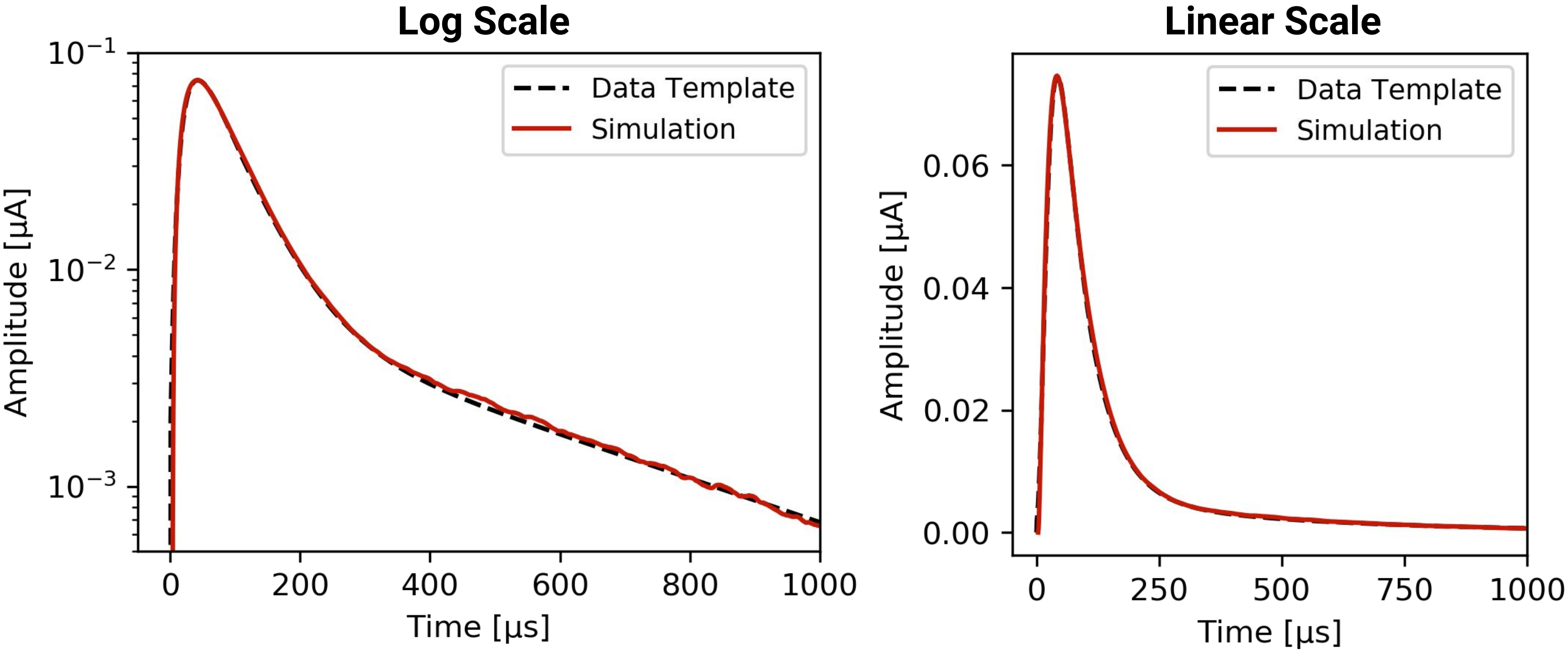
Al energy gap size
number of above-gap and sub-gap phonons

TES subgap absorption probability
number of reflections before sub-gap phonons are absorbed by TES

Corresponding G4CMP parameters are identified for the absorption processes

Note: similar procedure followed for TESSim parameters

TES Simulation Can Be Tuned to Match Data



Tuned 3 Absorption (G4CMP) + 5 TESSim parameters with a χ^2 fit to expected pulse shape

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Matching Simulation Output to Data Requires Unphysical Parameter Values

Phonon Collection Parameter	**Literature Value**	**Tuned Parameterization**
Al energy gap [μeV]	173.715	1075

⬅ **Unphysical**

TESSim Parameter	**HVeV Measurement**	**Tuned Parameterization**
Critical Temperature [mK]	64 - 66	84.5
Transition Width [mK]	0.3 - 0.8	2.45
Inductance [nH]	650 - 800	1250

} **Inconsistent**

Full table of parameter values in backup slides

Al energy gap – Mocking up a mechanism that increases subgap phonon population

Critical Temperature, Transition width, & Inductance – Not fully understood

Simulation Internals are Used to Estimate Phonon Measurement Efficiency

Using internal state equations of simulation

- temperature
- resistance

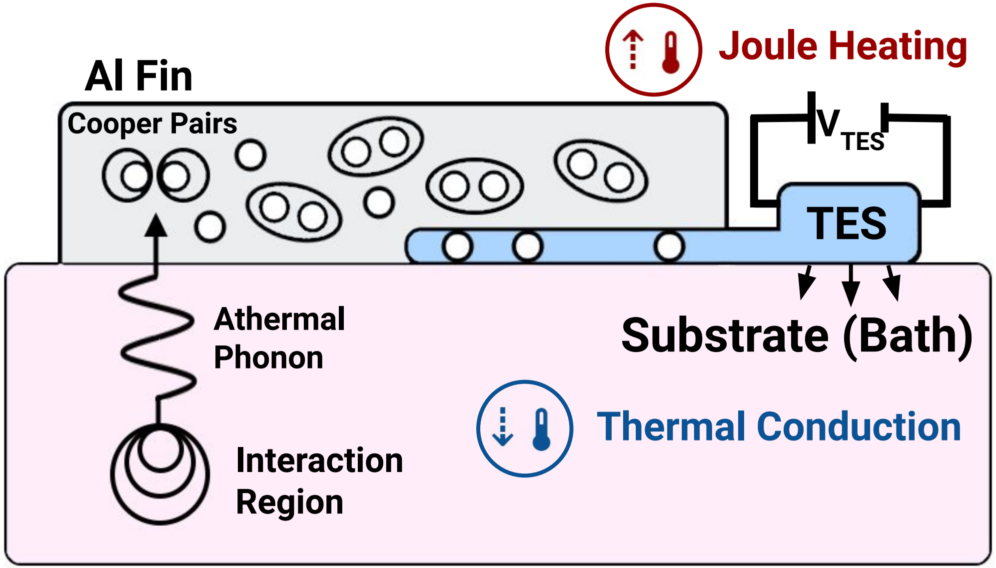
we can calculate

$$P_{\text{Joule}} = V_{\text{TES}}^2 / R_{\text{TES}}$$

$$P_{\text{Bath}} = \kappa(T^5 - T_{\text{Bath}}^5)$$

1st order estimate of phonon energy is given by

$$E_{\text{Phonon, Measured}} = -\int \Delta P_{\text{Joule}} dt$$



Measurement efficiency

ratio of $E_{\text{Phonon, Measured}}$ to the generated phonon energy

$$E_{\text{Phonon, Generated}} = E_{\text{recoil}} + N_{\text{eh}} e V_{\text{bias}}$$

Comparing to Experiment Reveals Deficits in Phonon Collection Model

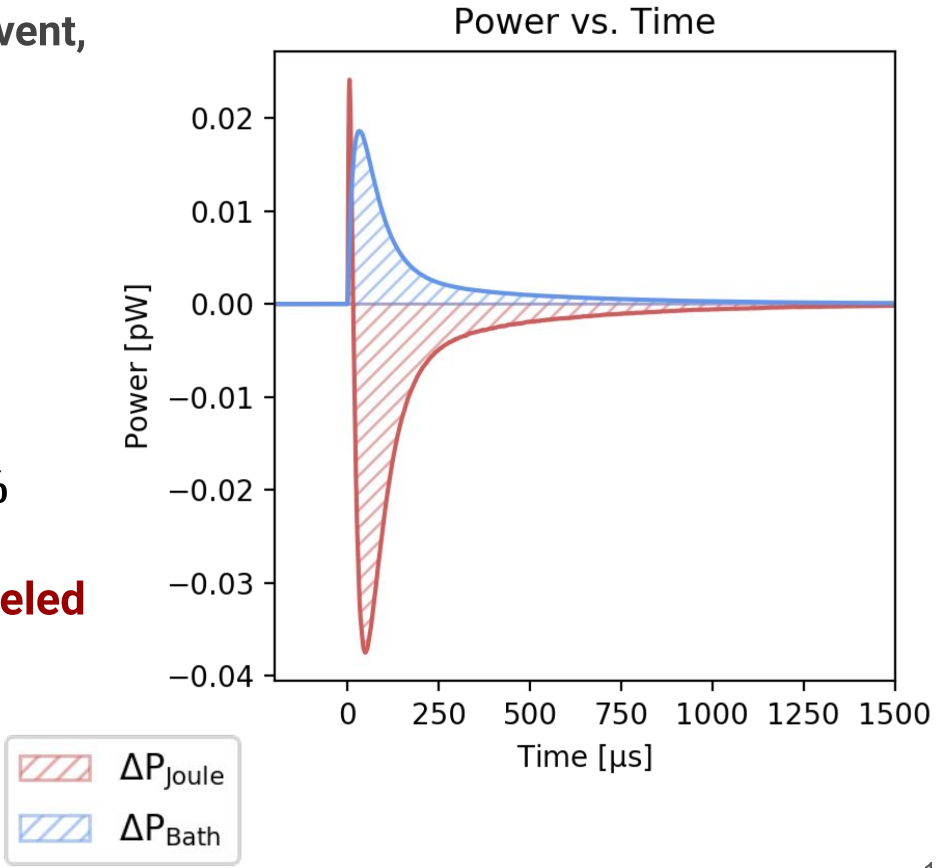
Of the phonon energy that is collected in an event,

- **~⅓** is dissipated to the bath
- **~⅔** goes to a decrease in Joule heating

The reported measurement of HVeV phonon measurement efficiency is ≳29%*

The simulation predicts this value to be ~66%

No other energy loss mechanisms are modeled



*PRD 104, 032010, 2021

Summary & Outlook

Comparing our simulation to experimental data reveals

- We can match simulated pulse shape to data if we use unphysical parameter values to mock up a missing mechanism that increases the sub-gap phonon population*
- Simulation does not correctly predict the detector's phonon measurement efficiency due to missing phonon energy loss mechanisms†

We are working on implementing more physics processes to make the simulation more realistic

* Check if latest G4CMP developments (*e.g.* surface anharmonic decay) eliminate this issue

† Model other mechanisms of energy loss in the crystal (*e.g.* energy escape through clamps)

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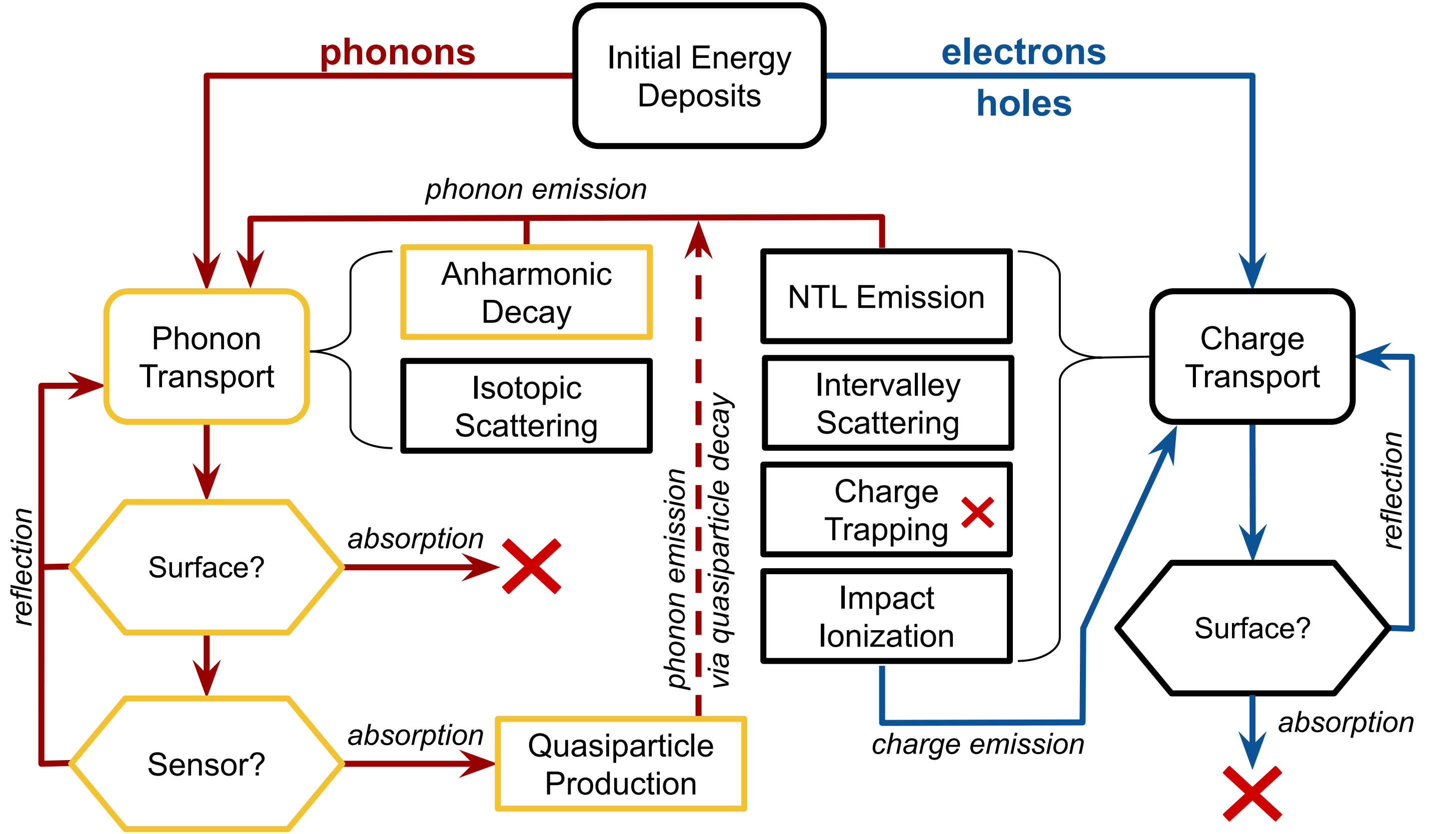
Backup Slides

G4CMP Models Detector Response Using Known Physics



Are these processes used appropriately in the simulation?
Do they give results consistent with the experiment?

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Optimized Parameter Values

⬜ **Tuned Values which cannot be compared to a real measurement**
🟨 **Tuned Values which are *inconsistent* with HVeV measurements**
🟥 **Tuned Values which are *unphysical***

CrystalSim Parameter	**HVeV Measurement / Literature**	**Tuned Value**
Sensor Absorption	N/A	0.54
TES subgap absorption	N/A	0.0365
Energy gap [μeV]	173.715	1075

TESSim Parameter	**HVeV Measurement / Literature**	**Tuned Value**
Critical Temperature [mK]	64 - 66	84.5
Transition Width [mK]	0.3 - 0.8	2.45
Substrate Temperature [mK]	N/A	67.25
Volumetric Heat Capacity Coefficient [J/(m^{3}K^2)]	N/A	100
Inductance [nH]	650 - 800	1250

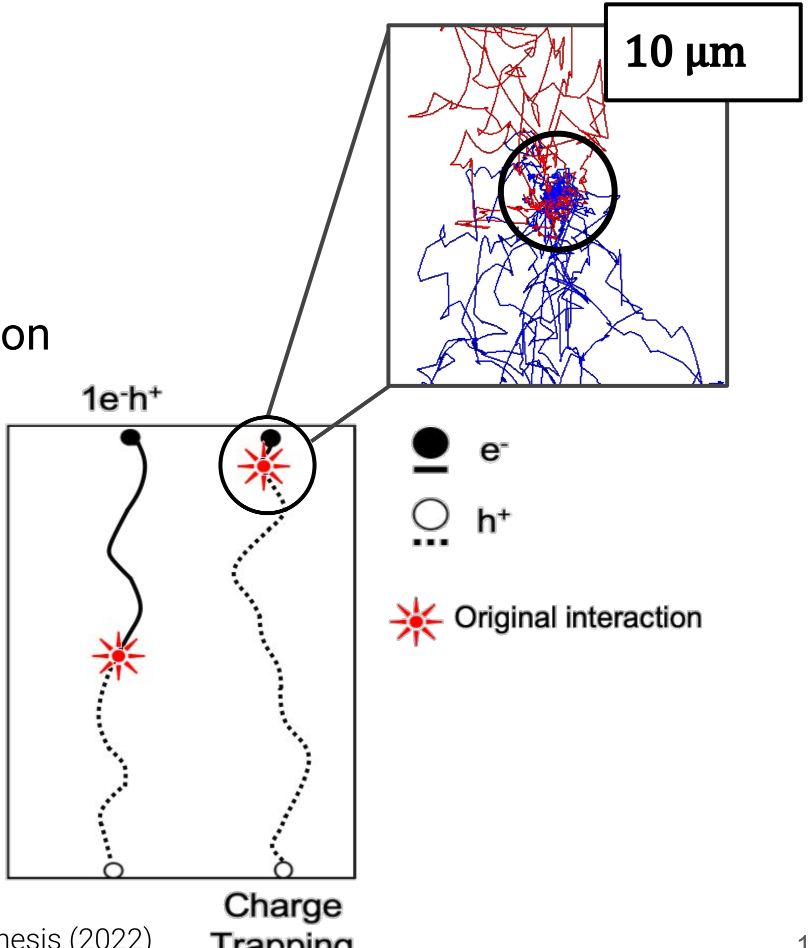
Near-Surface Photon Interactions Affect NTL Amplification

e^-/h^+ pairs are made with ~1 eV kinetic energy split between them

- Lose most energy fast, radiating phonons
- Particles 'random walk' in ~10 μm in any direction

1.95 eV photons penetrate ~5 μm in silicon

- Charges can hit surface during random walk
- NTL amplification is reduced



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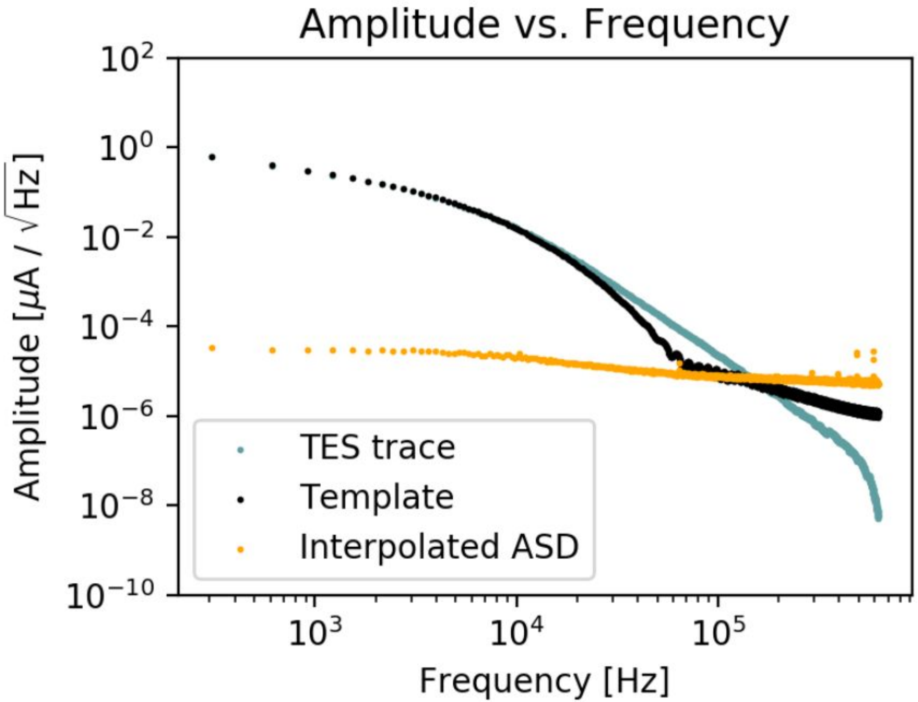
Tuning Process: χ^2 Measurement

Perform frequency-domain χ^2 fit with TESSim trace, template and noise

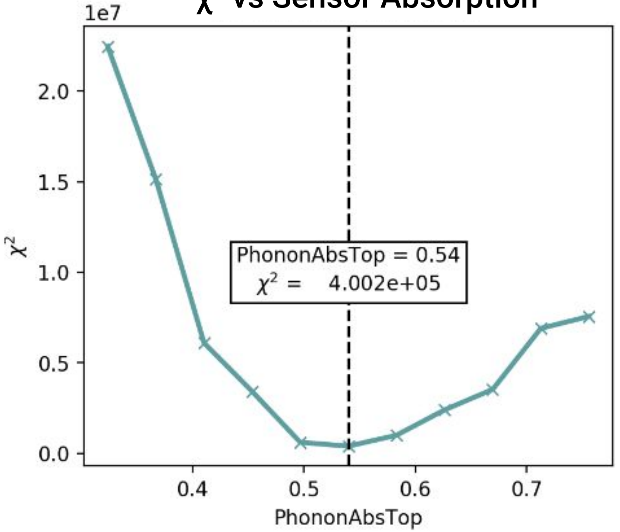
$$\chi^2(A,t) = \int_{-\infty}^{\infty} df \, \frac{|\tilde{v}(f) - Ae^{-i2\pi ft}\tilde{s}(f)|^2}{J(f)}$$

$\boldsymbol{A}$ – amplitude (use experiment calibrations)
$\boldsymbol{\tilde{v}}$ – Signal (TESSim trace)
$\boldsymbol{\tilde{s}}$ – average pulse shape (Template)
$\boldsymbol{J = \langle n^2 \rangle}$ – square of noise trace (ASD)
$\boldsymbol{t}$ – time shift between trace and template (floats)

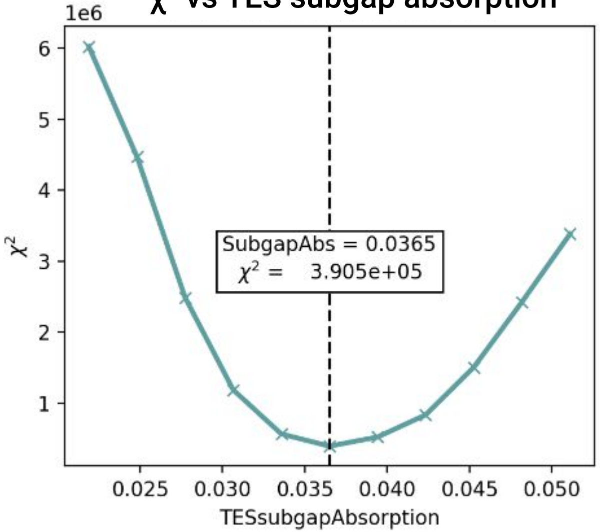


Tuning Process: Parameter Scanning

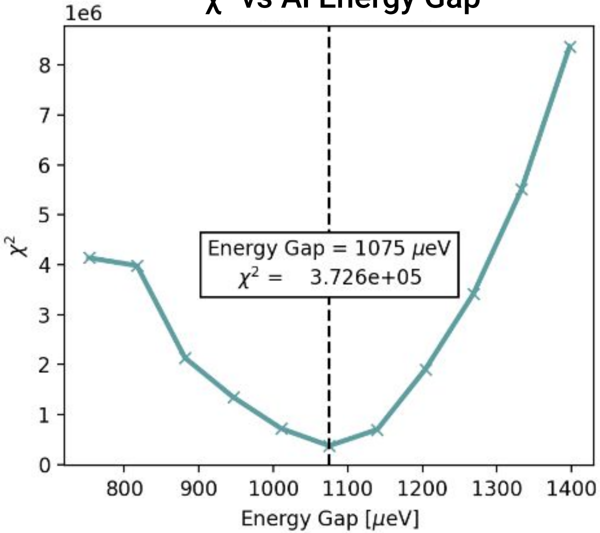
χ^2 vs Sensor Absorption



χ^2 vs TES subgap absorption



χ^2 vs Al Energy Gap



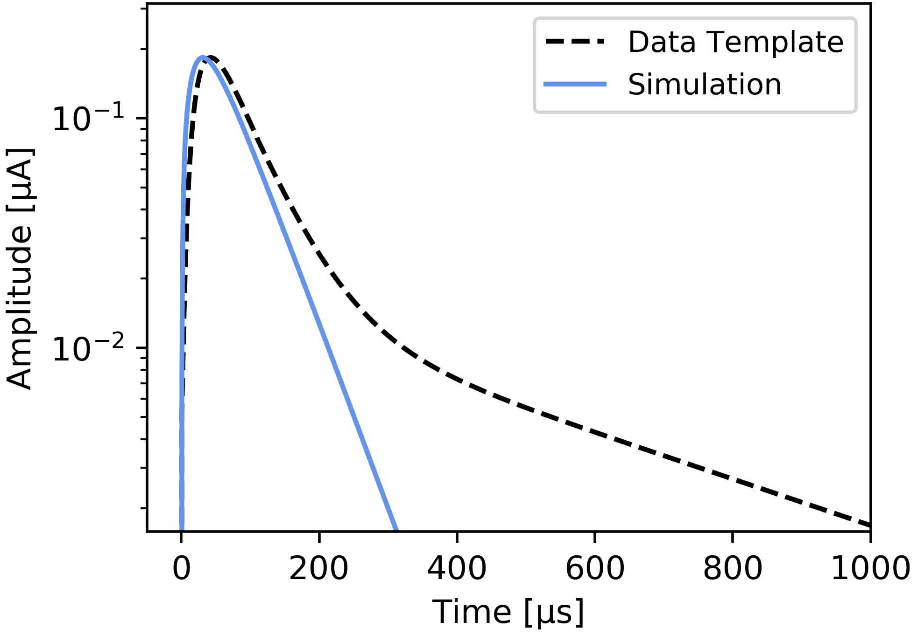
Each parameter is scanned to identify an ‘optimal’ value for data-simulation matching

Scan each parameter until all converge

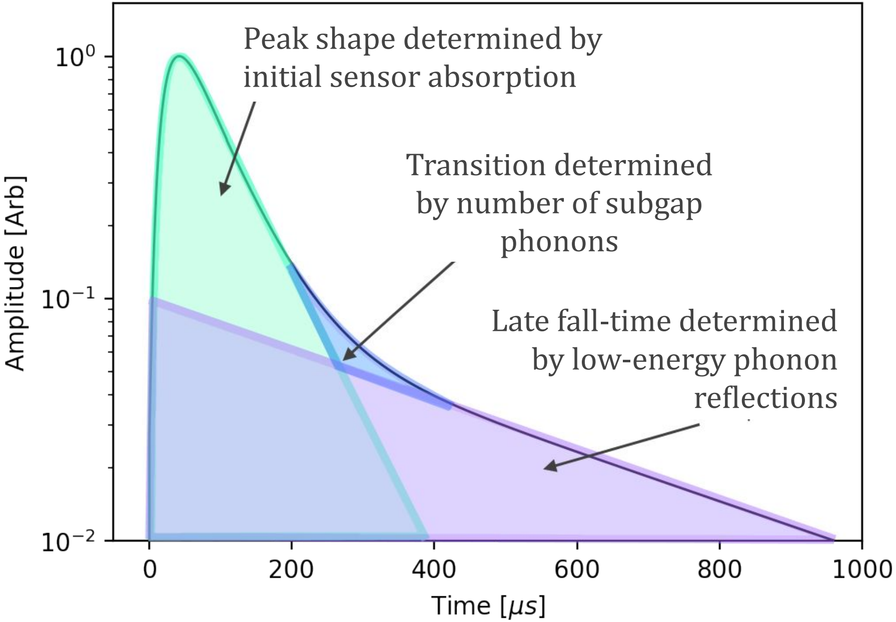
DOF = 4097

Absorption Processes Affect the Pulse Shape

Nominal Pulse Shape



Effects of Absorption Processes



Peak shape determined by initial sensor absorption

Transition determined by number of subgap phonons

Late fall-time determined by low-energy phonon reflections

Nominal set of simulation parameter values gives poor fit to data

Use understanding of absorption processes to select parameters for tuning

Kelsey et al., NIM A 1055 (2023) 168473.