CHARACTERIZING NTD EVENTS IN CUORE-0

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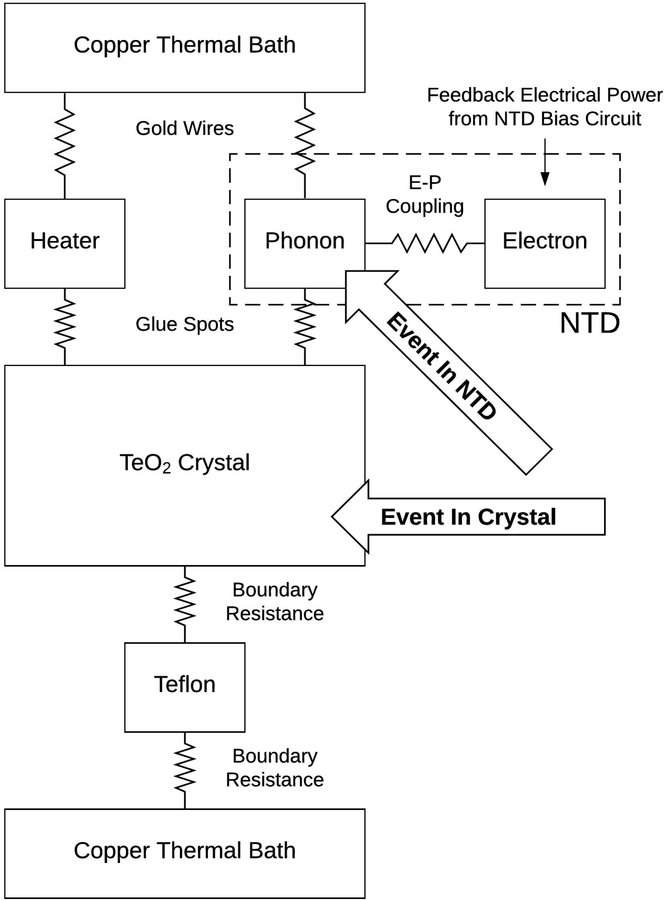
PURPOSE

- Develop thermal model for NTD events
- Characterize events that occur in NTDs in terms of pulse shape features
- Identify events with appropriate cuts and analyses in CUORE-0 data
- Understand energy spectrum and establish rates for NTD events

- Possible background reduction/analysis use in CUORE?

PART 1: THERMAL MODELING

THERMAL MODEL



- Built on top of existing thermal model (Alexey 2016)
- Split NTD into two components: electron gas and phonon lattice
- NTD event characterized by applied power in phonon lattice
- Heater, NTD Phonon and Electron, Crystal, and Teflon have heat capacitance. Connections have conductance values.
- Copper Thermal Bath is "ground" → base temperature

TEMP INDEPENDENT EQs

Phonon: $C_{\text{Phonon}} \frac{dT_{\text{Phonon}}}{dt} + K_{\text{NTD Gold Wire}}(T_{\text{Phonon}} - T_{\text{Sink}}) - K_{\text{NTD Glue}}(T_{\text{TeO}_2} - T_{\text{Phonon}}) - K_{\text{E-P Coupling}}(T_{\text{Electron}} - T_{\text{Phonon}}) = P_{\text{NTD Event}}$

Electron: $C_{\text{Electron}} \frac{dT_{\text{Electron}}}{dt} - P_{\text{Electrical Power}} + K_{\text{E-P Coupling}}(T_{\text{Electron}} - T_{\text{Phonon}}) = 0$

Heater: $C_{\text{Heater}} \frac{dT_{\text{Heater}}}{dt} + K_{\text{Heater Gold Wire}}(T_{\text{Heater}} - T_{\text{Sink}}) - K_{\text{Heater Glue}}(T_{\text{TeO}_2} - T_{\text{Heater}}) = 0$

Crystal: $C_{\text{Crystal}} \frac{dT_{\text{Crystal}}}{dt} + K_{\text{Heater Glue}}(T_{\text{TeO}_2} - T_{\text{Heater}}) + K_{\text{NTD Glue}}(T_{\text{TeO}_2} - T_{\text{NTD Phonon}}) + K_{\text{TeO}_2 \leftrightarrow \text{Teflon}}(T_{\text{TeO}_2} - T_{\text{Teflon}}) = 0$

Teflon: $C_{\text{Teflon}} \frac{dT_{\text{Teflon}}}{dt} + K_{\text{Teflon} \leftrightarrow \text{Sink}}(T_{\text{Teflon}} - T_{\text{Sink}}) - K_{\text{TeO}_2 \leftrightarrow \text{Teflon}}(T_{\text{TeO}_2} - T_{\text{Teflon}}) = 0$

- Simplistic version of thermal model for NTD event at const. temperature
- Need to add temperature dependence and tune parameters

ADDING TEMP DEPENDENCE

Conductance

Conductance (K) is related to temperature by a power law relation:

$$K(T) = K_0 T^{\beta}$$

It can also be written as the time derivative of power, such that we can express power as

$$P(T) = \int_{T_1}^{T_2} K(T')dT'$$

Using this, we can integrate the equation to get:

$$({T_2}^{\beta+1} - {T_1}^{\beta+1}) = \frac{\beta+1}{K_0} P(T)$$

Capacitance

Additionally, various heat capacitances also have temperature dependence based on the material. They are as follows:

$$\begin{aligned} C_{\text{Phonon}} &= \alpha T^3 \\ C_{\text{Electron}} &= \alpha T \\ C_{\text{Heater}} &= \alpha T \\ C_{\text{Crystal}} &= \alpha T^3 \\ C_{\text{Teflon}} &= \alpha_1 T + \alpha_2 T^3 \end{aligned}$$

Initial Parameters

Initial values for conductance and capacitance are taken from Marisa’s thesis. Tuning parameters will be discussed later

ADDING TEMP DEPENDENCE

Electronic Feedback

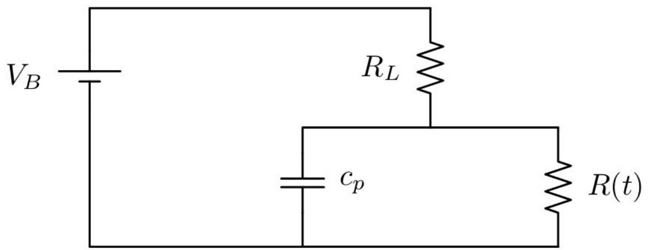


Figure 3.2. Biasing circuit of the thermistor. The thermistor resistance $R(t)$ is in series with a load resistance R_L. The couple of wires used to read the voltage across $R(t)$ has a non negligible capacitance c_p.

- Solving this equation, we obtain (Vignati): $$\left[\frac{R_L + R(T)}{R(T)}\right] V(T) - V_B + R_L c_p \frac{dV(T)}{dt} = 0$$
- The resistance of the NTD is given by: $$R(T) = R_0 \exp\left(\frac{T_0}{T}\right)^{\gamma}$$
- Differential equation for feedback voltage added to calculation

TEMP DEPENDENT EQs

$$\text{Phonon (a)} : P_{\text{NTD Event}} = \alpha_a {T_a}^3 \frac{dT_a}{dt} - \frac{K_{0,\text{ NTD Glue}}}{\beta_1+1}({T_d}^{\beta_1+1} - {T_a}^{\beta_1+1}) - \frac{K_{0,\text{ E-P Coupling}}}{\beta_2+1}({T_b}^{\beta_2+1} - {T_a}^{\beta_2+1}) + \frac{K_{0,\text{ NTD Gold Wire}}}{\beta_3+1}({T_a}^{\beta_3+1} - {T_s}^{\beta_3+1})$$

$$\text{Electron (b)} : 0 = \alpha_b T_b \frac{dT_b}{dt} - \frac{V(T)^2 - V_0(T)^2}{R_0 \exp\left(\frac{T_0}{T}\right)^{\gamma}} + \frac{K_{0,\text{ E-P Coupling}}}{\beta_2+1}({T_b}^{\beta_2+1} - {T_a}^{\beta_2+1})$$

$$\text{Heater (c)} : 0 = \alpha_c T_c \frac{dT_c}{dt} - \frac{K_{0,\text{ Heater Glue}}}{\beta_4+1}({T_d}^{\beta_4+1} - {T_c}^{\beta_4+1}) + \frac{K_{0,\text{ Heater Gold Wire}}}{\beta_5+1}({T_c}^{\beta_5+1} - {T_s}^{\beta_5+1})$$

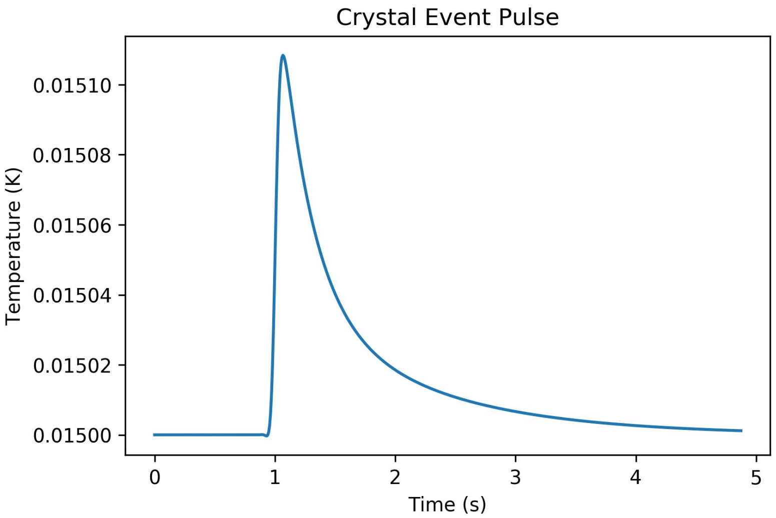
$$\text{Crystal (d)} : P_{\text{Crystal}} = \alpha_d {T_d}^3 \frac{dT_d}{dt} + \frac{K_{0,\text{ NTD Glue}}}{\beta_1+1}({T_d}^{\beta_1+1} - {T_a}^{\beta_1+1}) + \frac{K_{0,\text{ Heater Glue}}}{\beta_4+1}({T_d}^{\beta_4+1} - {T_c}^{\beta_4+1}) + \frac{K_{0,\text{ TeO}_2\leftrightarrow\text{Teflon}}}{\beta_6+1}({T_d}^{\beta_6+1} - {T_e}^{\beta_6+1})$$

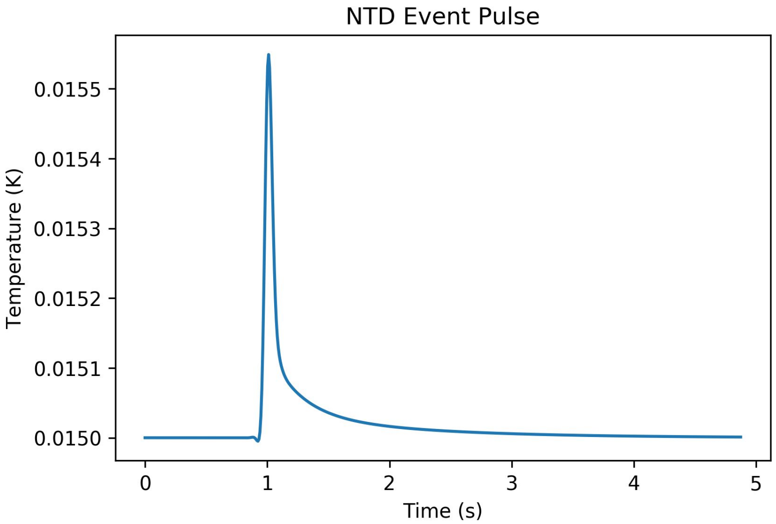
$$\text{Teflon (e)} : 0 = (\alpha_{e1} T_e + \alpha_{e2} {T_e}^3) \frac{dT_e}{dt} - \frac{K_{0,\text{ TeO}_2\leftrightarrow\text{Teflon}}}{\beta_6+1}({T_d}^{\beta_6+1} - {T_e}^{\beta_6+1}) + \frac{K_{0,\text{ Teflon}\leftrightarrow\text{Sink}}}{\beta_7+1}({T_e}^{\beta_7+1} - {T_s}^{\beta_7+1})$$

$$\text{Feedback V (f)} : 0 = \left[\frac{R_L + R_0 \exp\left(\frac{T_0}{T}\right)^{\gamma}}{R_0 \exp\left(\frac{T_0}{T}\right)^{\gamma}}\right] V(T) - V_B + R_L c_p \frac{dV(T)}{dt}$$

- Equations solved using 4th Order Runge-Kutta numerical solver (Python)

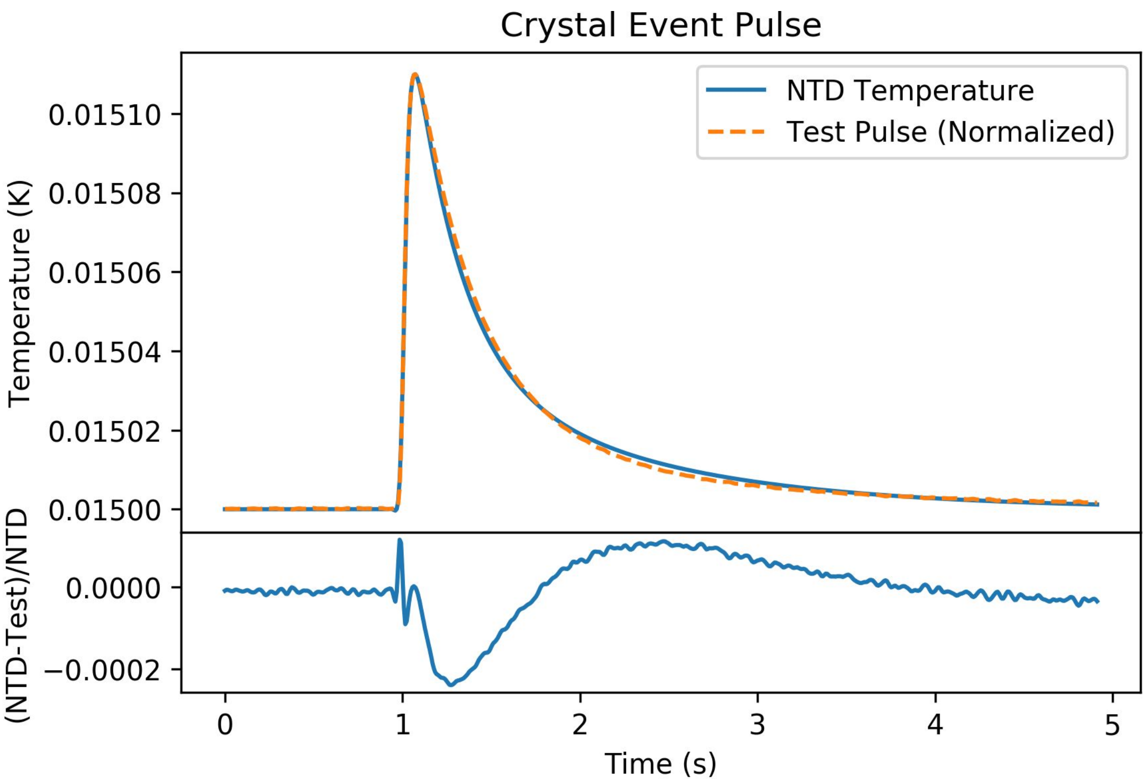
CRYSTAL vs NTD EVENTS





- Solved for 2615 KeV energy deposition over 1 ms, 15 mK base temperature
- 12 Hz bessel filter added to replicate CUORE-0 parameters

PARAMETER TUNING



- Compared to test pulses from CUORE-0 data (pulse shape remains roughly same for various energies)
- Test pulse normalized by amplitude, code matches rise of pulses to ± 4 ms
- Parameters tuned by eye. Most changes to PTFE boundary conductance values.

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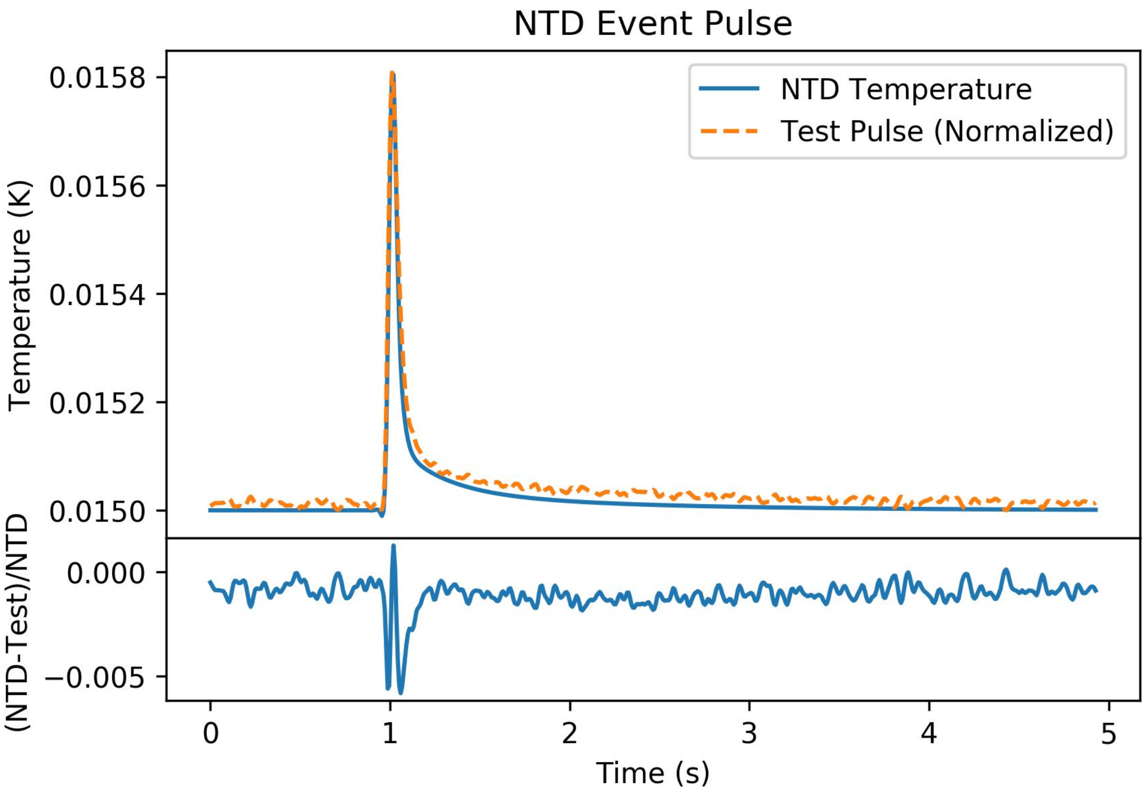

- Compared to test pulses from CUORE-0 data (pulse shape remains roughly same for various energies)
- Test pulse normalized by amplitude, code matches rise of pulses to ± 4 ms
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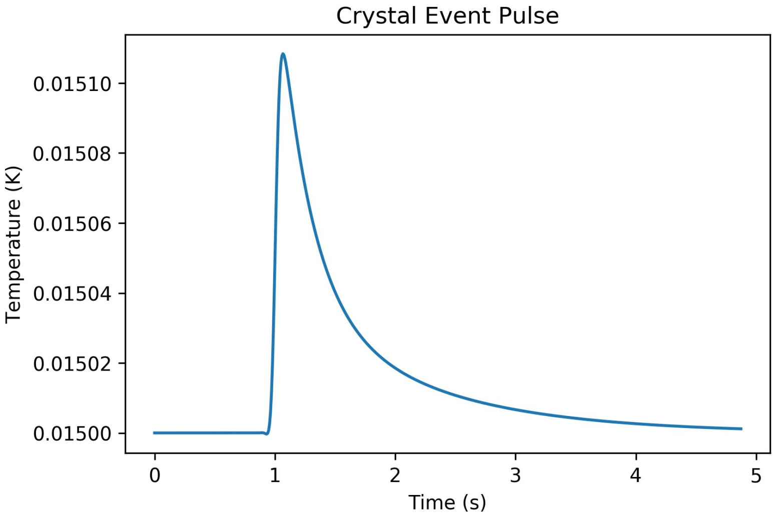
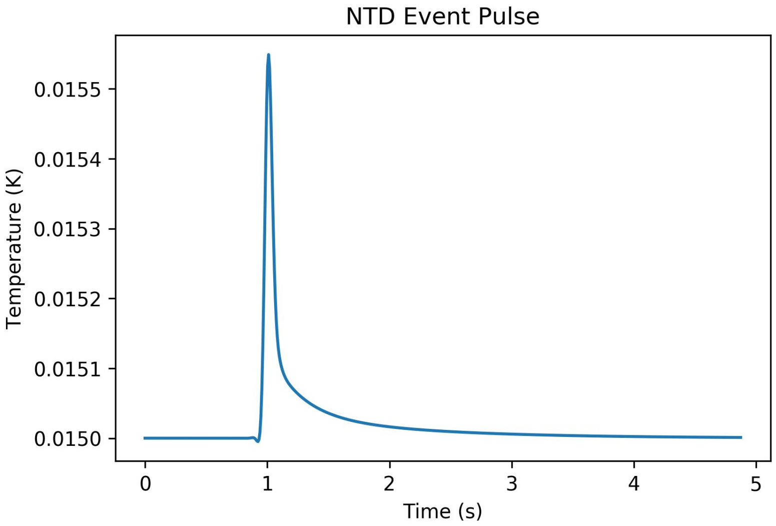
DISCUSSION

- Issues with parameter values, particularly for PTFE boundary conductances.
- Possible Monte-Carlo to explore parameter space
  - Use chi2 values to determine “closest fit”
  - Advanced methods like machine learning can also be implemented
- No reliable method to measure uncertainty of these values…yet!

PART 2: CUORE-0 ANALYSIS

DECAY vs RISE TIME
(THERMAL MODEL PULSES)

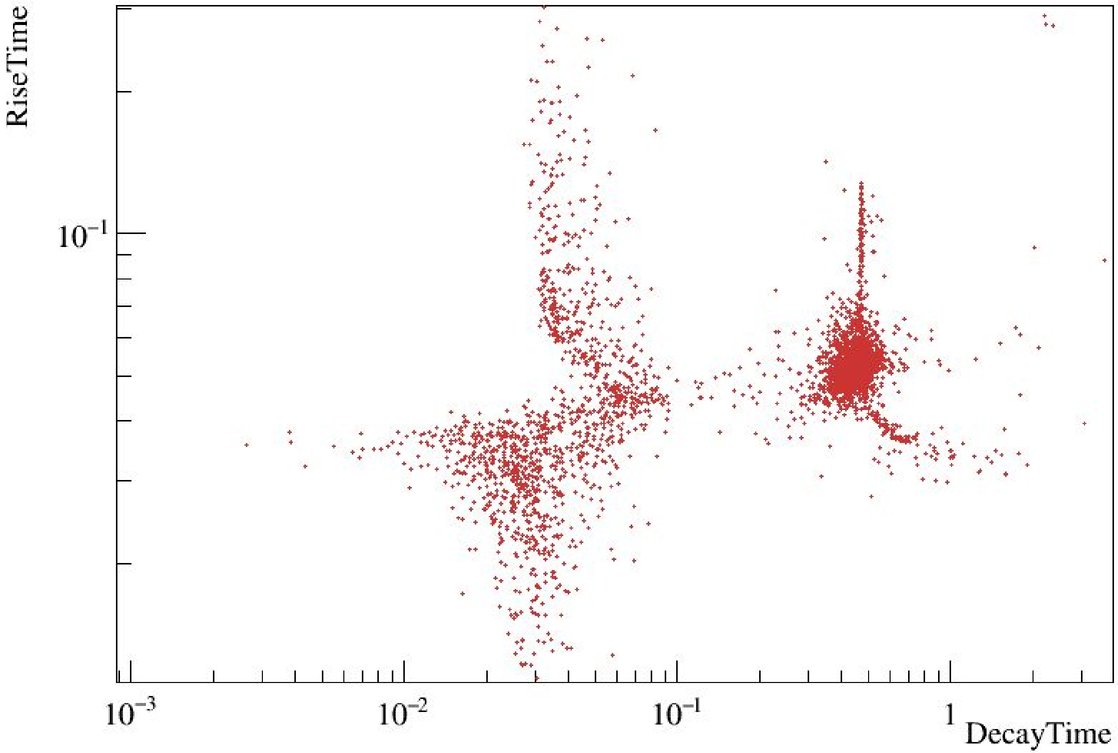




- Rise Time: 0.048 ± 0.004 s
- Decay Time: 0.488 ± 0.004 s
- Decay Time / Rise Time: **10.17 ± 0.85**

- Rise Time: 0.032 ± 0.004 s
- Decay Time: 0.040 ± 0.004 s
- Decay Time / Rise Time : **1.25 ± 0.20**

DECAY vs RISE TIME
(CUORE-0 DATA)

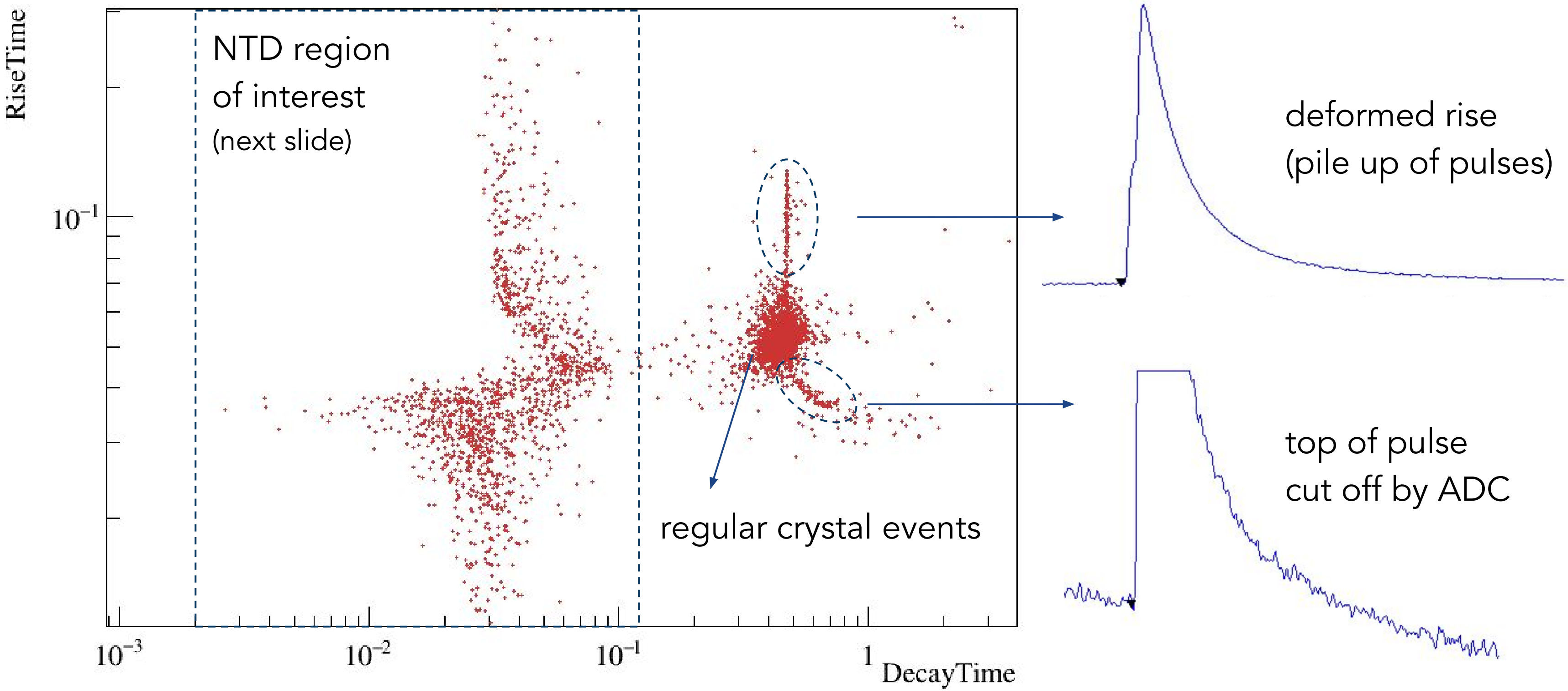


Run: ds2139 [unblinded]

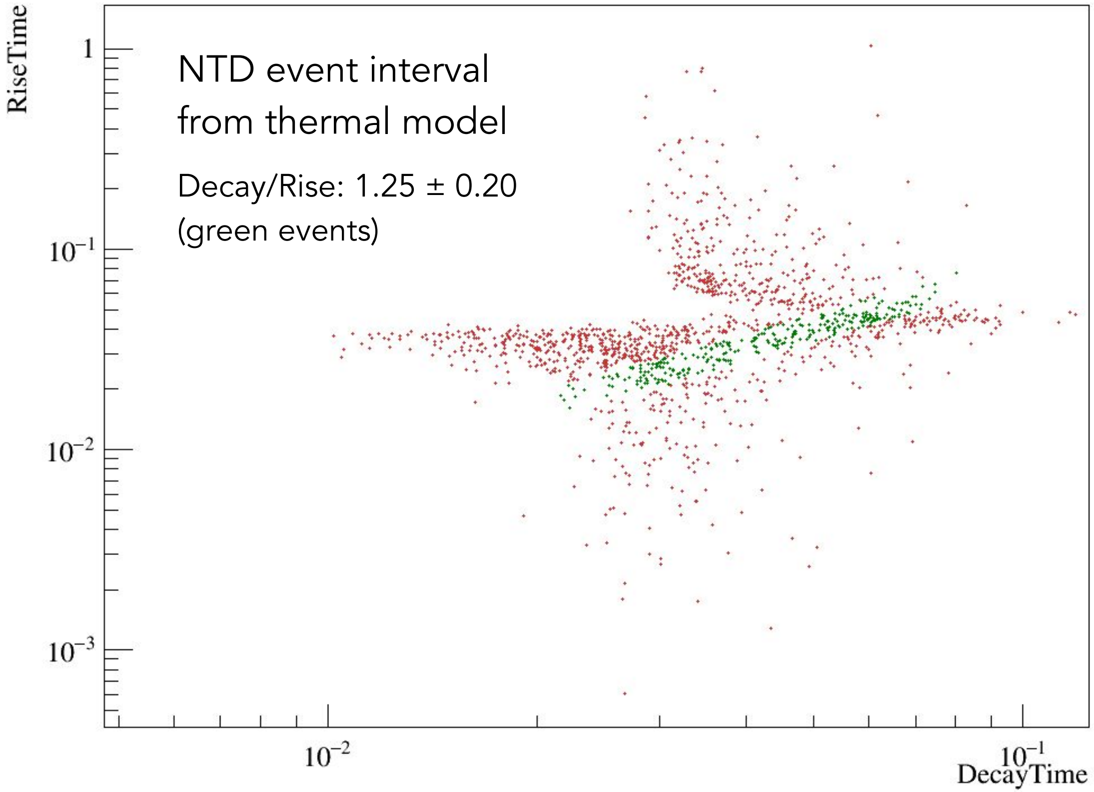
Cuts Applied:

- IsSignal
- NumberOfPulses==1
- Channel==6
- |BaselineSlope|<0.1
- BaselineRMS<2

DECAY vs RISE TIME
(CUORE-0 DATA)



DECAY vs RISE TIME
(CUORE-0 DATA)

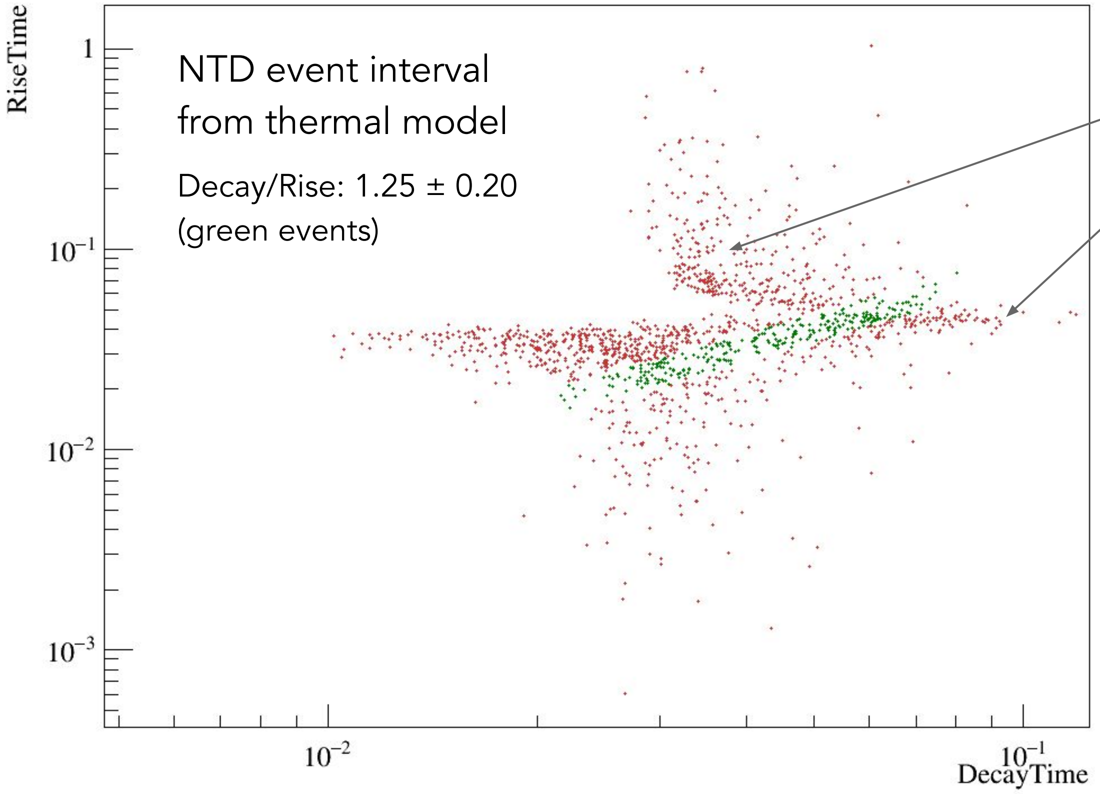


Run: ds2139 [unblinded]

Cuts Applied:

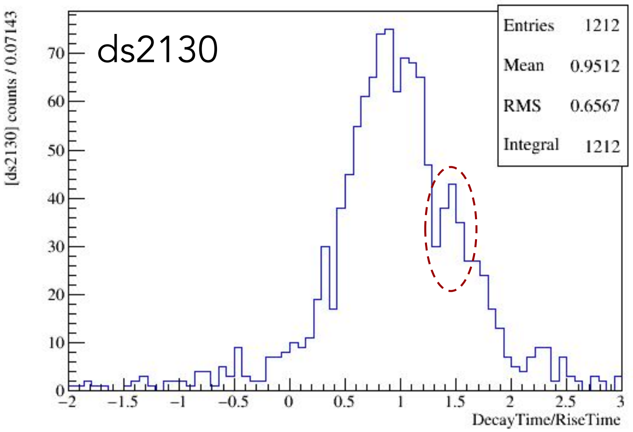
- IsSignal
- NumberOfPulses==1
- Channel==6
- |BaselineSlope|<0.1
- BaselineRMS<2
- **DecayTime < 0.12**

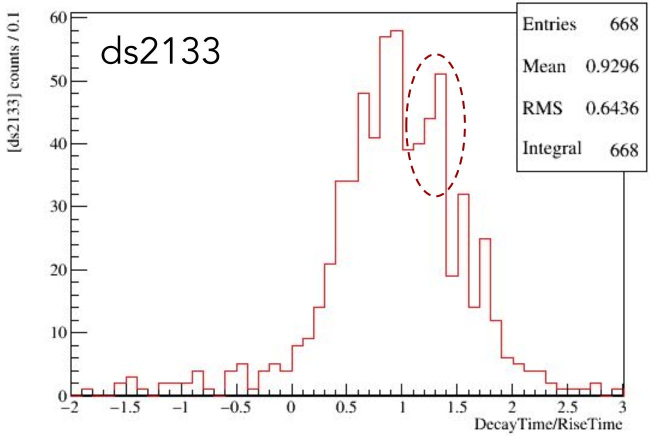
DECAY vs RISE TIME
(CUORE-0 DATA)

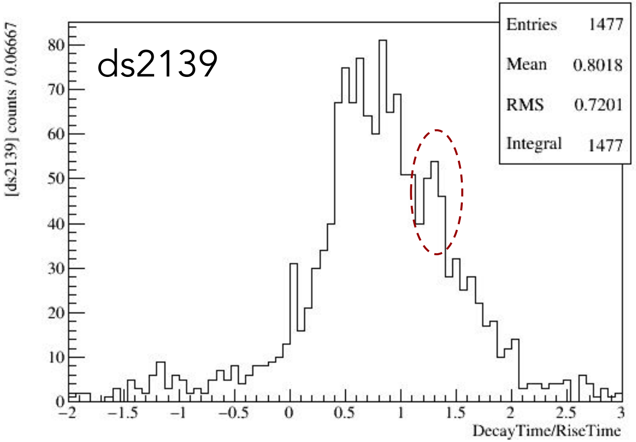


- No visible difference between pulses in bands (mostly due to background noise)
- Green events do not seem to align to particular bands or patterns in data
- 3 possible culprits: problematic rise time calculation in DAQ, high background noise, and uncertainties in thermal model parameters

BIMODAL DISTRIBUTION







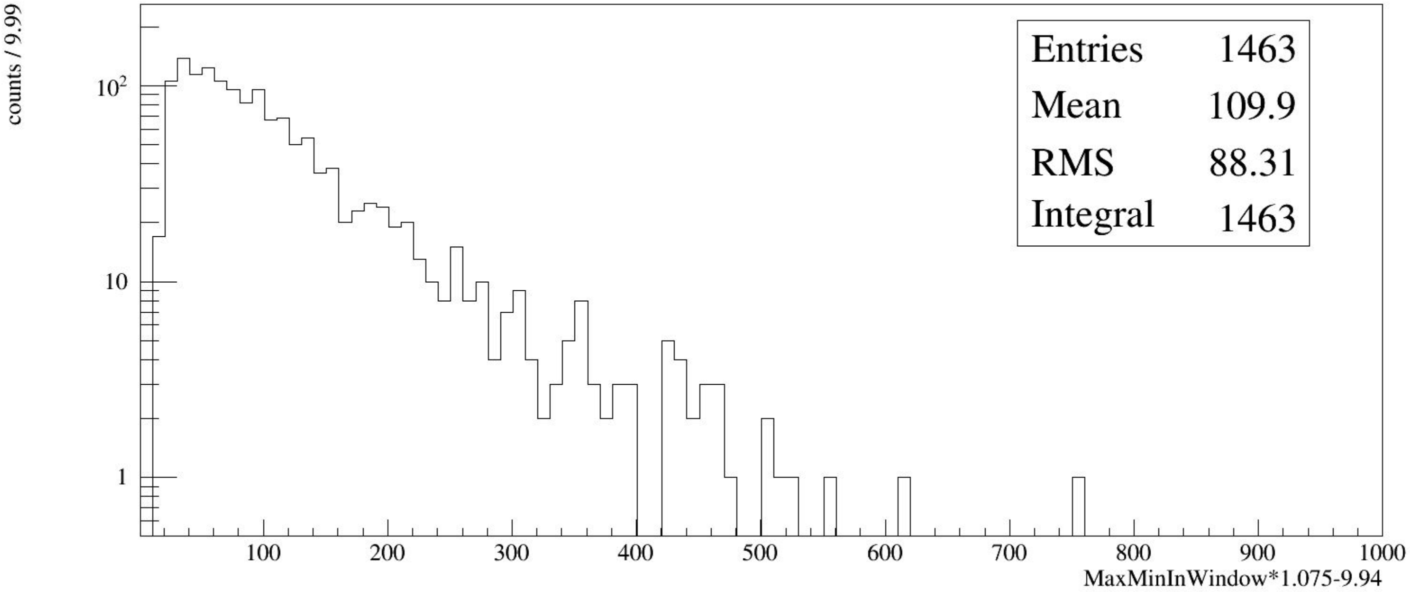
- Hints of 2nd peak around Decay/Rise ratio of 1.25 (NTD ratio)
- Possible combination of NTD events + spurious pulses/noise
- Unsure how to discriminate events - need better method

DISCUSSION

- Need to figure out if all events in interesting region are NTD events, or if there are spurious/noisy pulses involved
- If spurious/noisy pulses, how to discriminate?
  - Possible use of TVR and filters to extract parameters of decay
- Determine better energy calculation of NTD pulses (rough procedure described in next section)

PART 3: ENERGY DEPOSITION SPECTRUM

CUORE-0 SPECTRUM

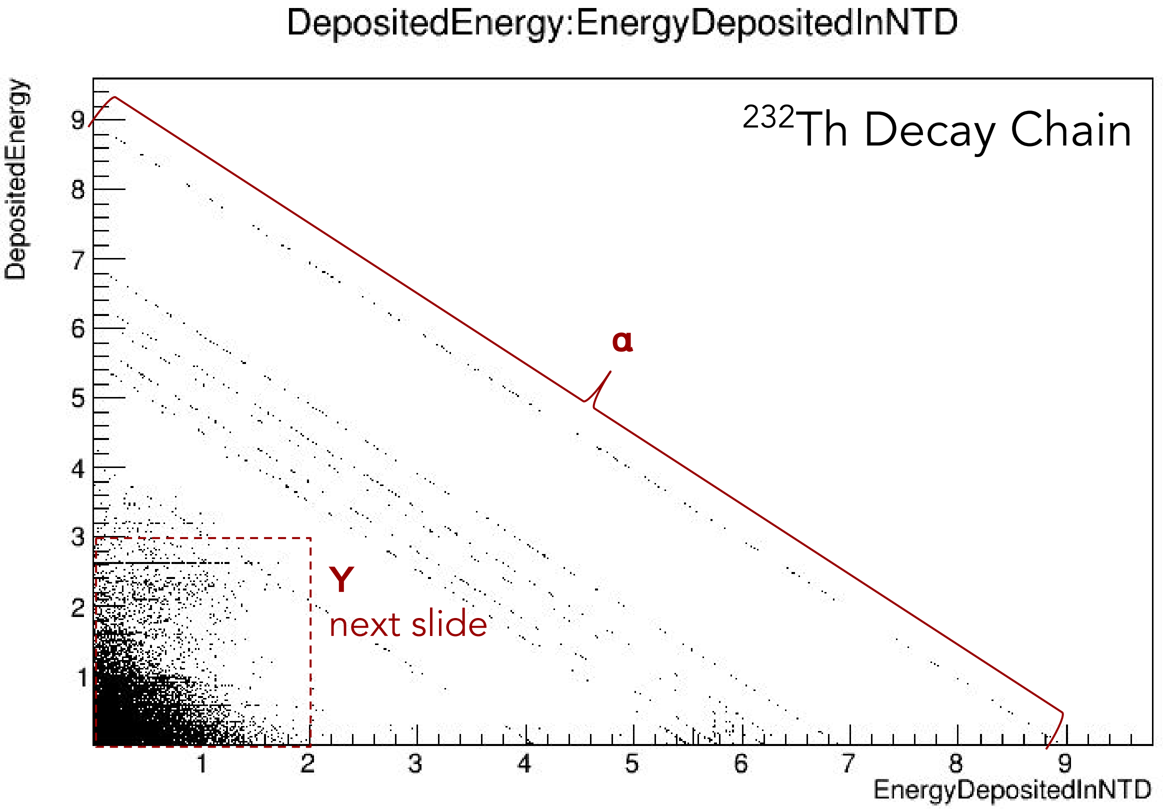


- Calculated from 95% interval of rise-decay normal distribution (NTD region of interest)
- Energy calculated from amplitude, using amplitude-energy linear fit of crystal pulses

GEANT4 MC SIMULATIONS

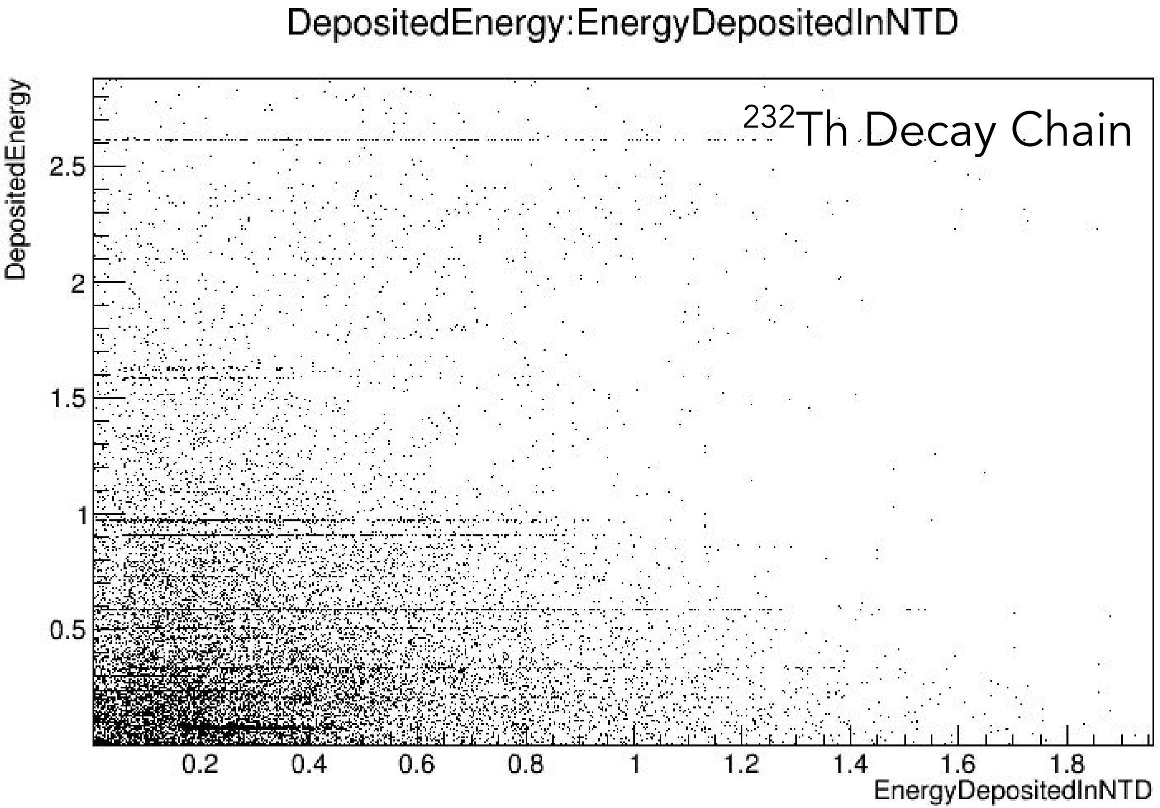
- MCuoreZ - simulated CUORE-0 events
- 100k events uniformly distributed throughout NTD volumes
- ^{232}Th, ^{238}U, and ^{60}Co decay chains

GEANT4 MC SIMULATIONS



- Similar scatter pattern for all decay chains
- Diagonal bands → Alpha events
- Total energy deposition split evenly between NTD and crystal
- Events near bottom shown in more detail in next slides

GEANT4 MC SIMULATIONS



- Horizontal bands
  → Gamma events
- All corresponding energy deposited in crystal - peaks from ^{232}Th visible
- Energy deposited in NTD through scattering processes
- Still investigating cause of bands

NEXT STEPS

- Determine how to discriminate NTD events and other noise events, if they exist
- Understand energy deposition in NTD and crystal, particularly for gamma events
- Spectrum comparison: various decay chains vs CUORE-0 NTD events
- Get NTD event rate estimate from CUORE-0 data
- Propagate uncertainties from thermal model and CUORE-0 data cuts
- Get better estimates for thermal model parameters