TES Based Light Detectors for CUPID using an IrPt bi-layer transition edge sensor

15th Pisa Meeting on Advanced Detectors
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2022-05-26

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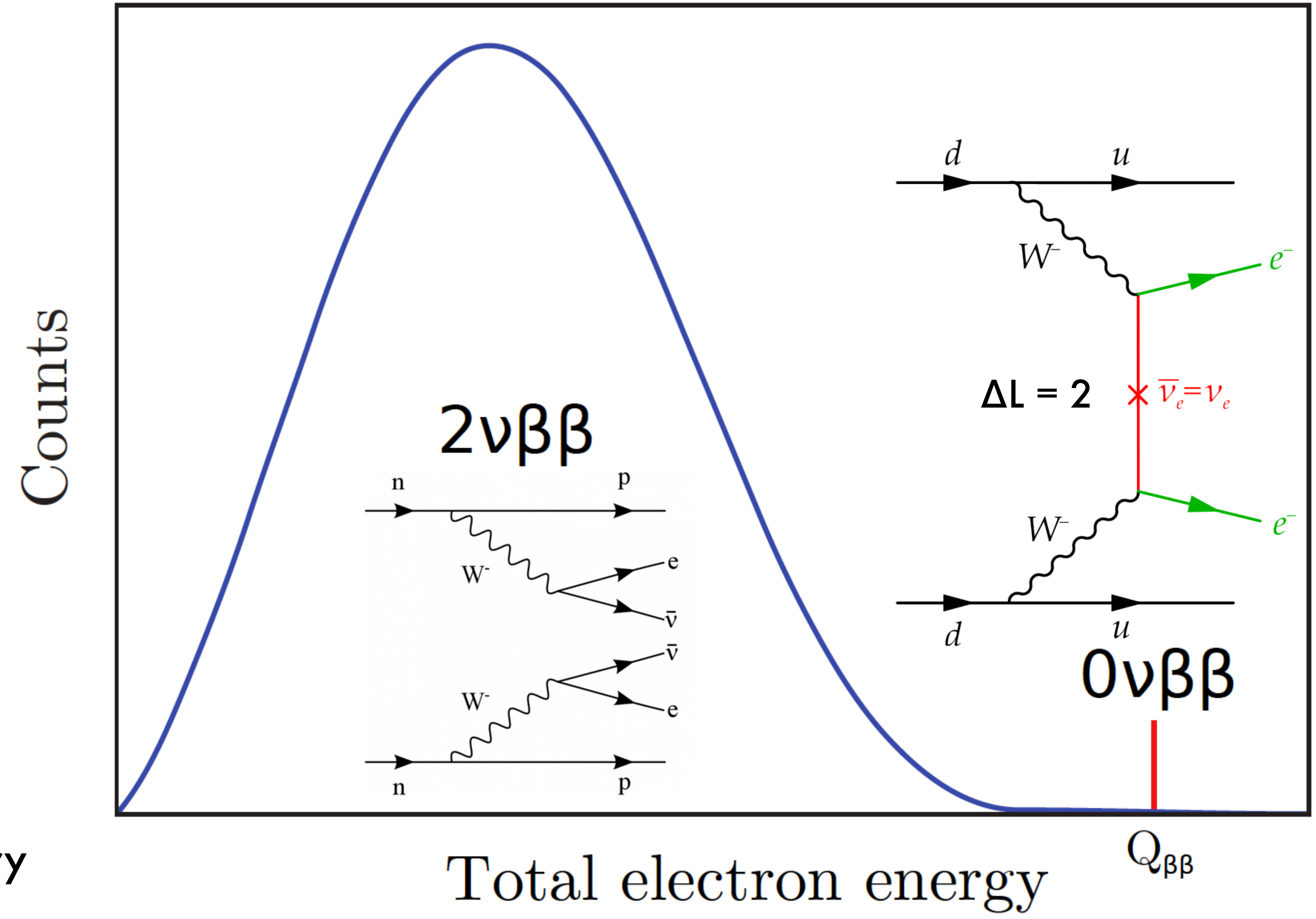
UNIVERSITY OF CALIFORNIA

Motivation: Double Beta Decay

- $2\nu\beta\beta$ is a rare standard model process
- Broad energy distribution
- Observed half-lives $\tau > 10^{19}$ years
- $0\nu\beta\beta$ is a hypothetical, unobserved process
- Immediate implication of $\Delta L \neq 0$
  - Lepton number violation = new physics!
  - Can imply Majorana mass of ν
  - Possible connection to baryon asymmetry



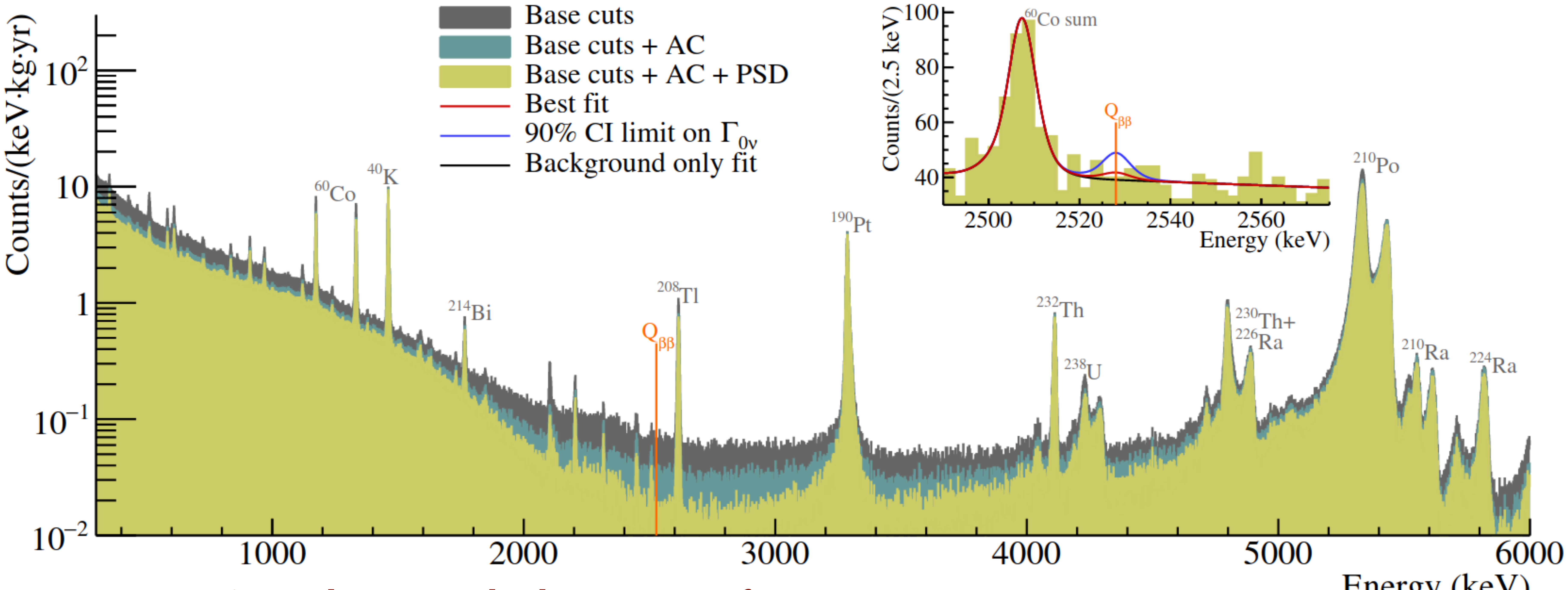
Motivation: CUORE

- Brand new analysis results on 1038.4 kg-yr of exposure
- Pulse shape discrimination via single component PCA
- Bayesian analysis via BAT with various nuisance parameters (<0.8% impact on limit due to systematics)
- Publication: Nature 604, 53–58 (2022)

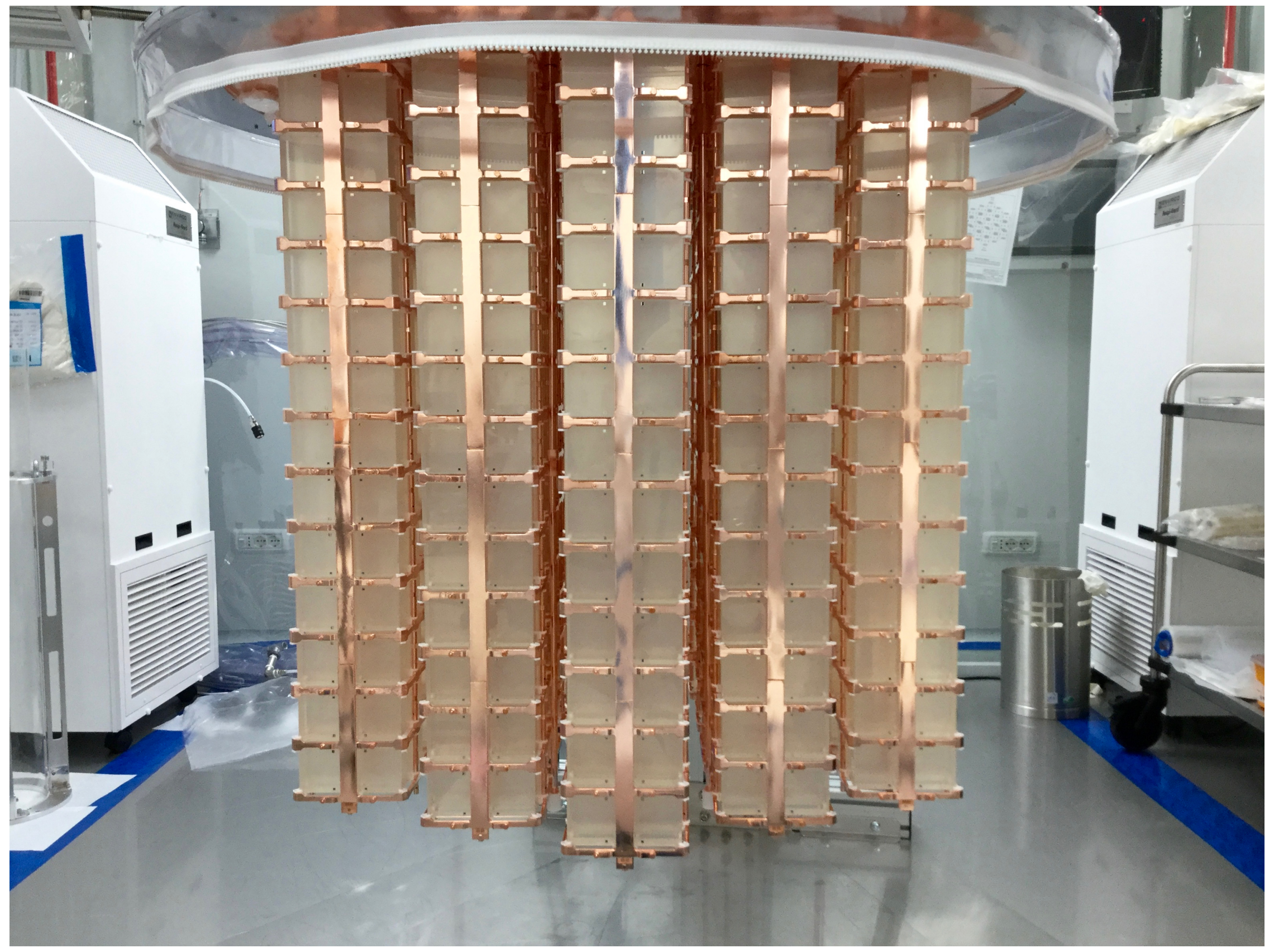
CUORE Result

$$T_{1/2}^{0\nu} > 2.2 \times 10^{25}\ \mathrm{yr}\ (90\ \%\ \mathrm{C.I.})$$

$$m_{\beta\beta} < (90 - 305)\ \mathrm{meV}\ (90\ \%\ \mathrm{C.I.})$$



Cryogenic Underground Observatory for Rare Events



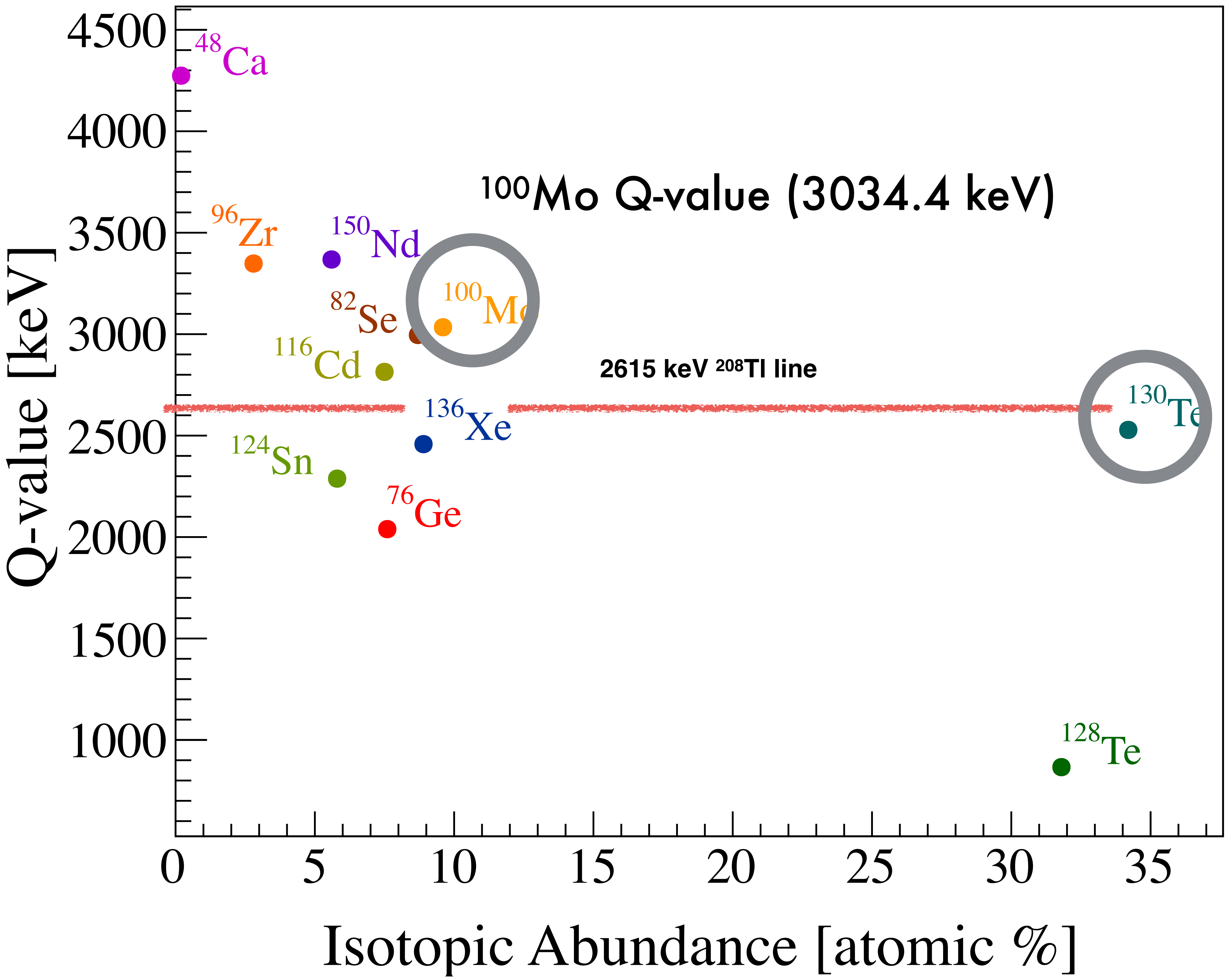
- Array of 988 5x5x5 cm^3 $^{nat}TeO_2$ crystals (742 kg, 206 kg active isotope)
- $Q_{\beta\beta}$ ~ 2527.52 keV
- Source = detector (0νββ containment ε ~ 88%)
- Cryogenic calorimeters read-out with NTD-thermistors

Motivation: Beyond CUORE

- CUORE uses ^{130}Te (Q-value 2527.515 keV)

Phys. Rev. Lett. 120, 132501
Phys. Rev. Lett. 124, 122501
Nature 604, 53–58 (2022) (1 Ton-yr)

- Degraded α's pose problem
- **C**UORE **U**pgrade with **P**article **ID** (CUPID)
- Use scintillating calorimeters => $Li_2{}^{100}MoO_4$ (LMO)



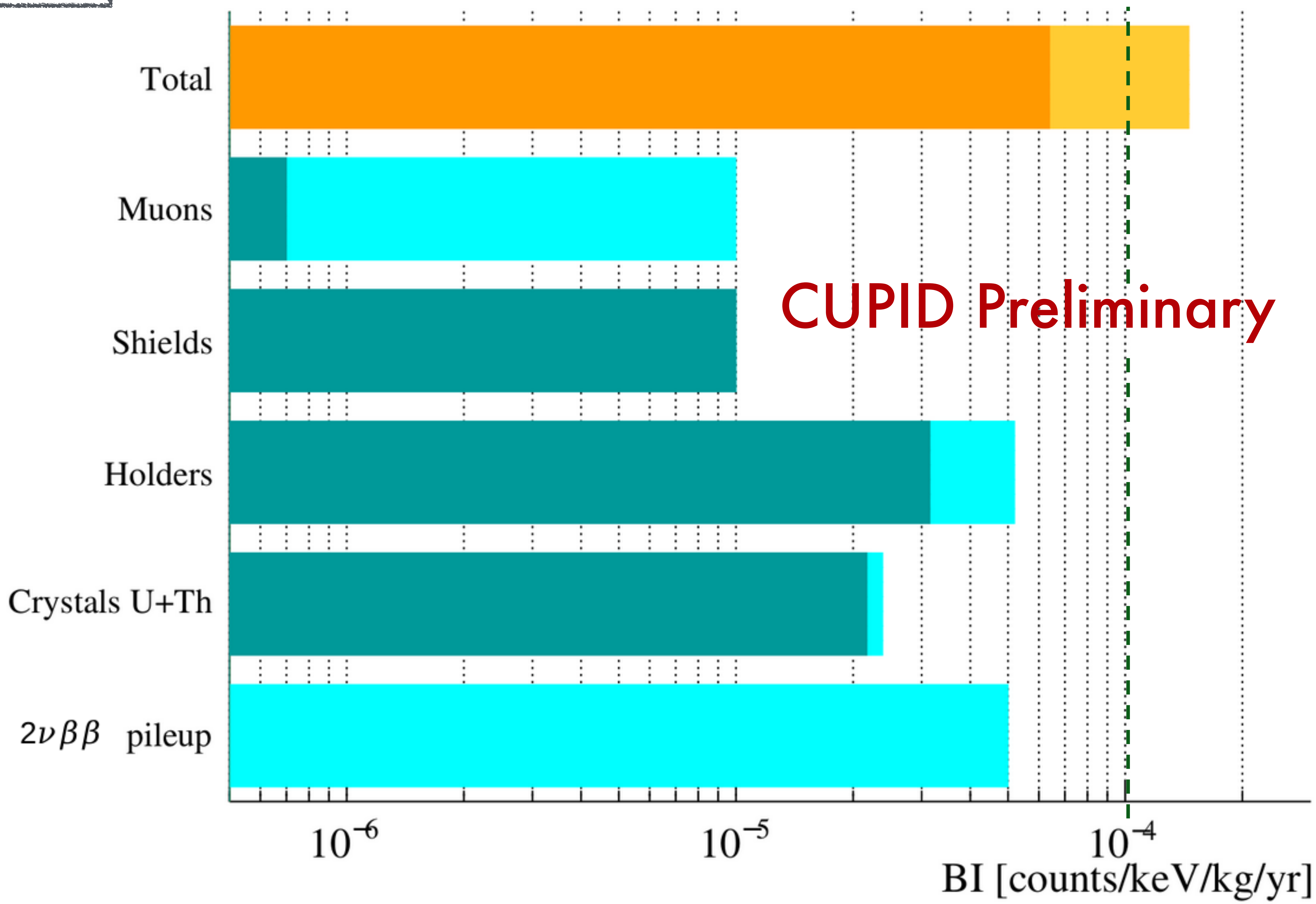
Background Limited

$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} \sqrt{\frac{MT}{b\Delta E}}$$

Background Free

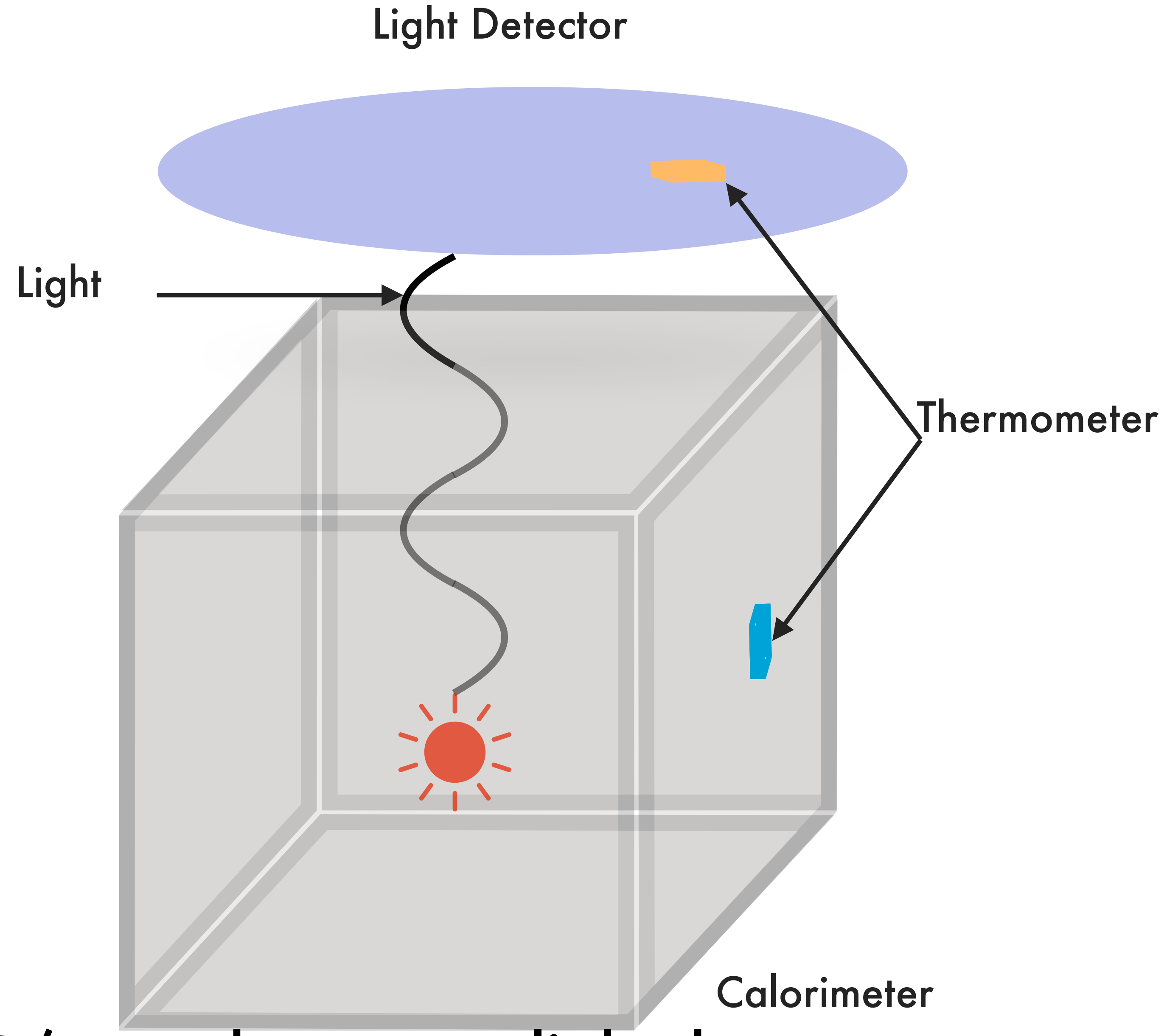
$$S \propto \frac{N_A a \eta \epsilon}{M_{mol}} MT$$

CUPID (baseline) goal



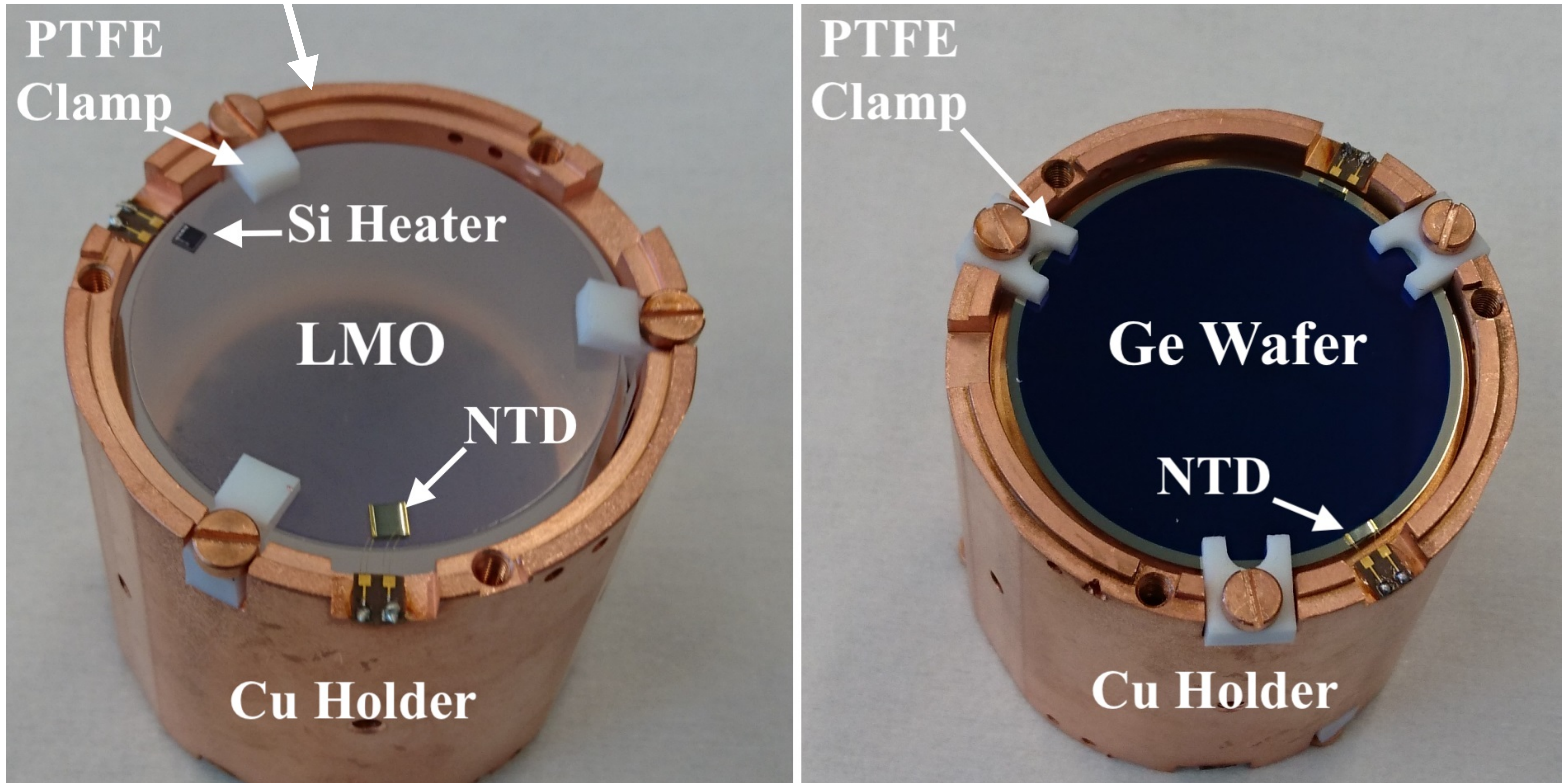
Scintillating Calorimeters

- Low heat capacity => very temperature sensitive
- Neutron transmutation doped (NTD) Ge sensor
- Method has good energy resolution
- NTD meet technical needs for CUPID bolometers
- Additional energy from scintillating light
- 2νββ pileup poses a problem – TES well suited to address especially for CUPID-1T

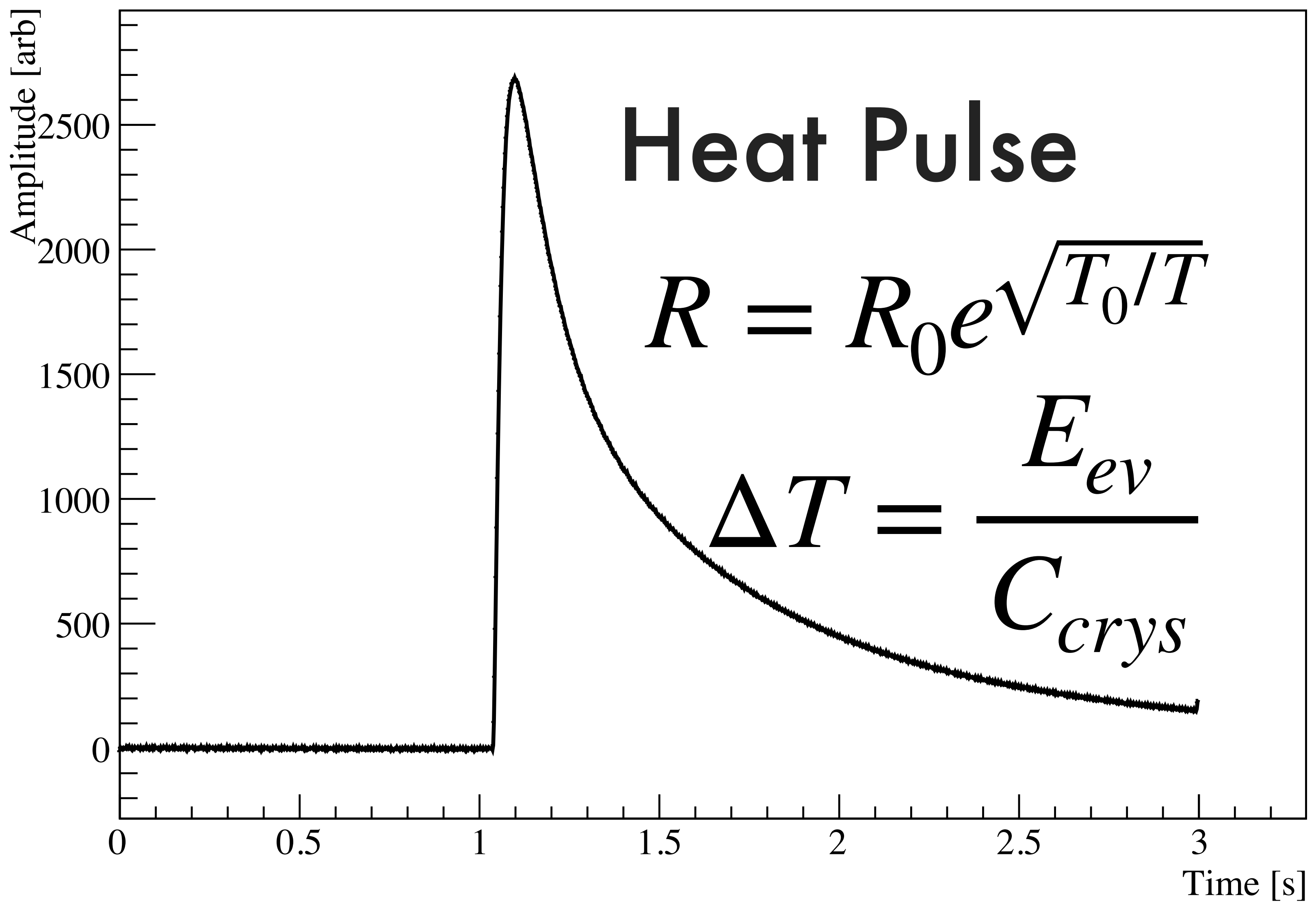


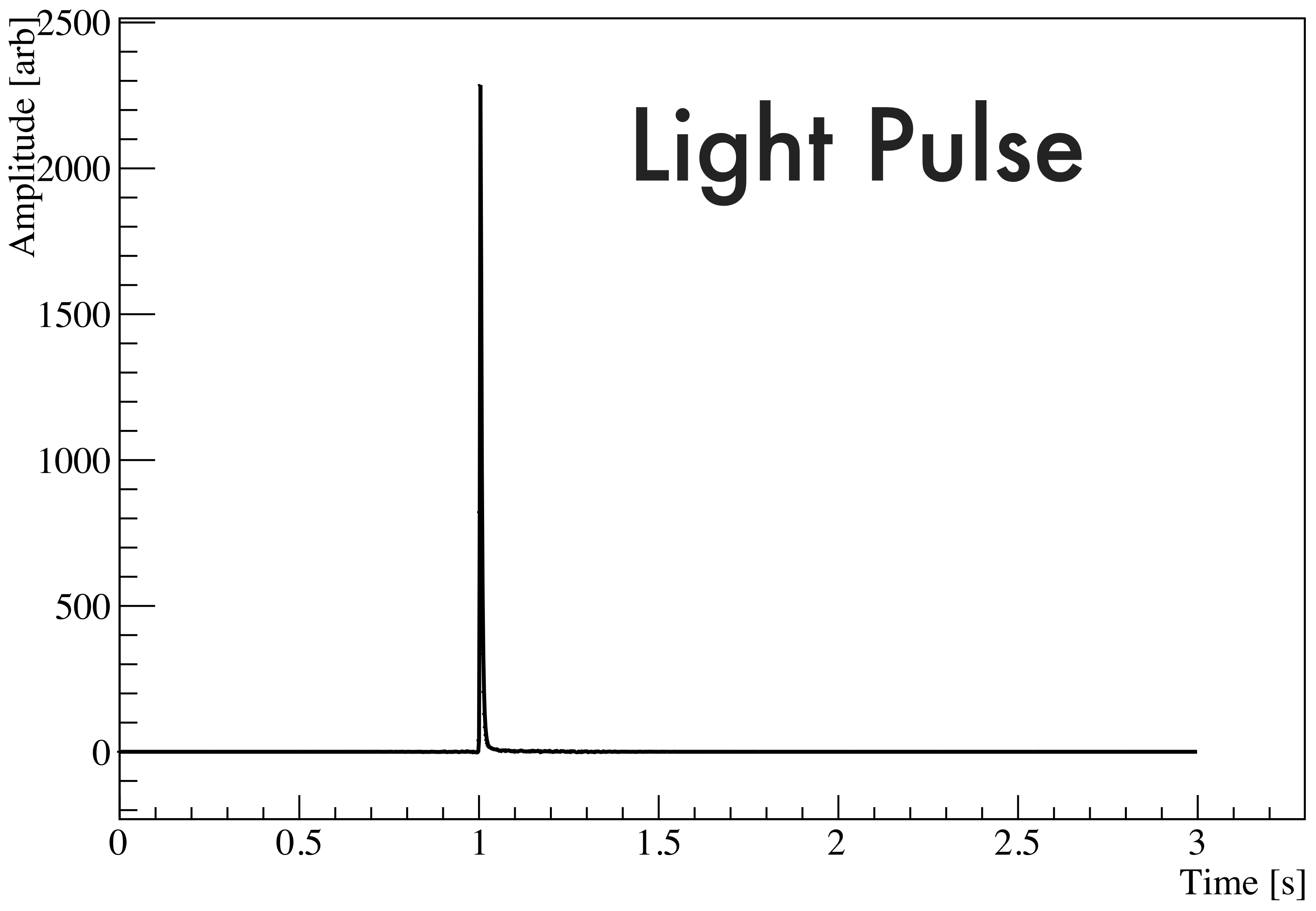
β/γ produce more light than α

Example: CUPID-Mo LMO and LD



European Physical Journal C 80, 44 (2020)





Transition Edge Sensor

$$C \approx C_{bolo}\left(T^3\right) + C_{TES}(T) + C_{impur.}$$

TES heat capacity is small and thin Si wafer C ~ 20 pJ/K

TES response to temperature and current changes can be parameterized

$$\alpha = \frac{T_0}{R_0}\frac{\partial R}{\partial T}\bigg|_I \qquad \beta = \frac{I_0}{R_0}\frac{\partial R}{\partial I}\bigg|_T \qquad \mathscr{L}_0 = \frac{I_0^2 R_0 \alpha}{G T_0}$$

TES operated at I_0, R_0, T_0, and with thermal conductivity G from TES to bath

$$\tau = \frac{C}{G} \xrightarrow{\text{ETF}} \tau_{eff} = \frac{C}{G\left(1 + \mathscr{L}_0\right)}$$

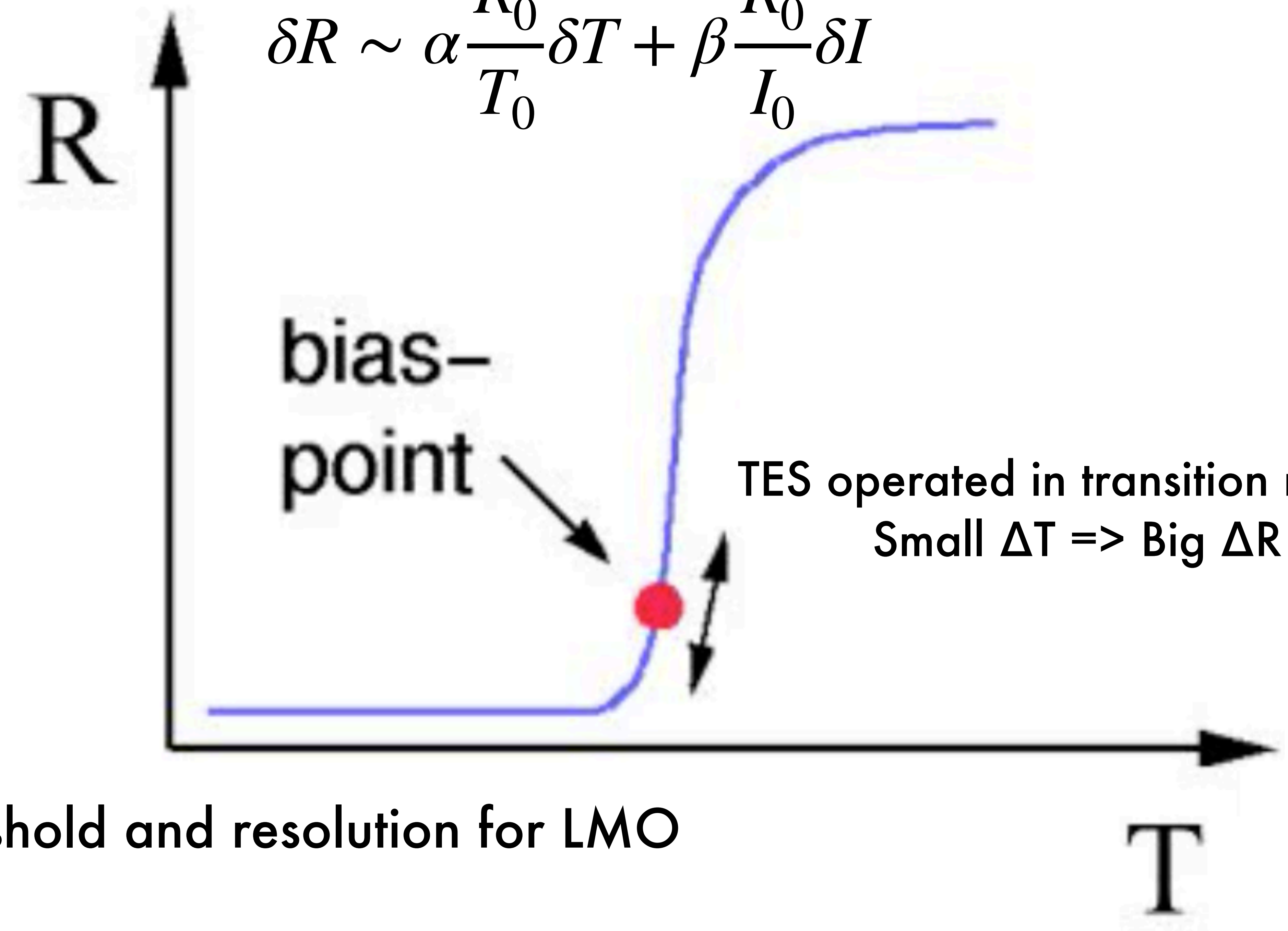
Electrothermal feedback enhances thermal decay constant

$$\Delta E_{FWHM} \sim \sqrt{\frac{4 k_B T_0^2 C}{\alpha}\sqrt{\frac{n}{2}}}$$

Very high intrinsic resolution ~ 10 eV at typical operating values
(T ~ 40 mK, C ~ 20 pJ/K, a ~ 50, n = 5)

K. D. Irwin and G. C. Hilton, Topics Appl. Phys. 99, 63-149 (2005)

$$\delta R \sim \alpha \frac{R_0}{T_0}\delta T + \beta \frac{R_0}{I_0}\delta I$$



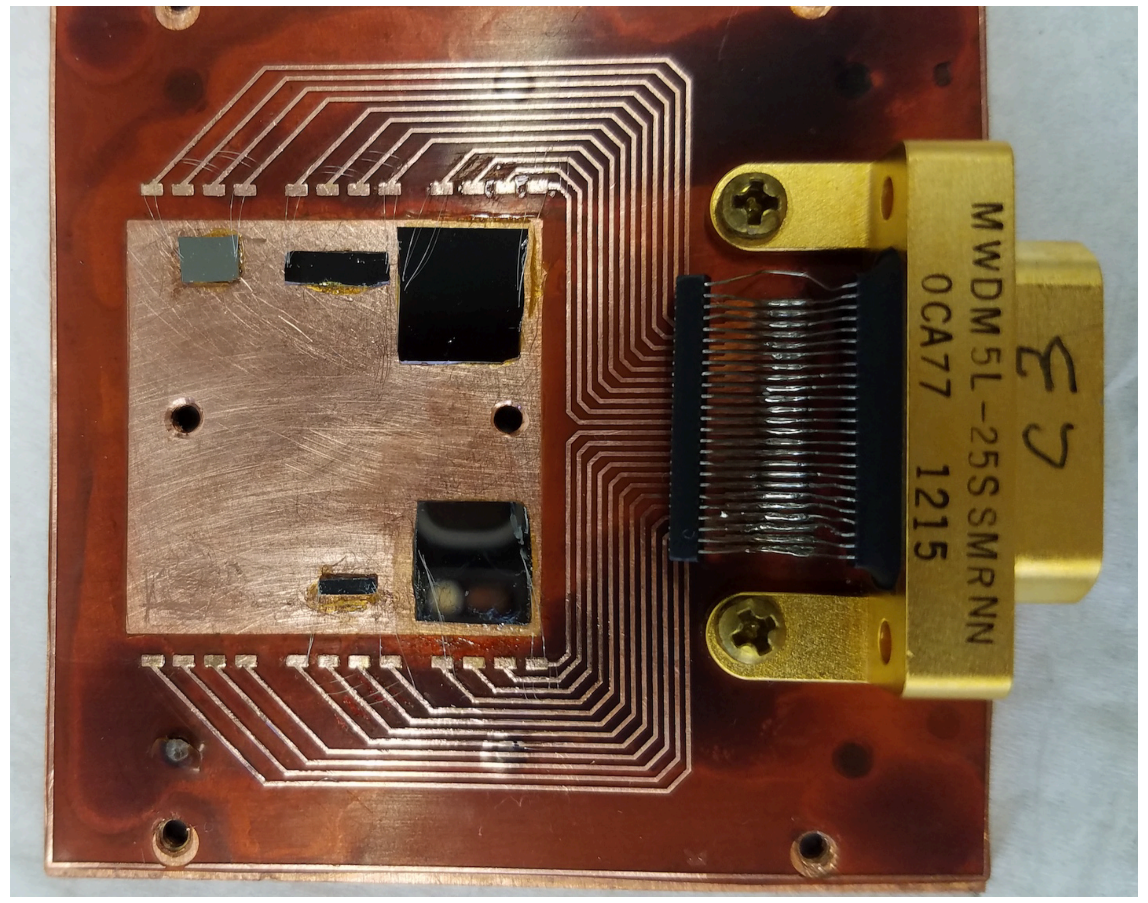
TES operated in transition region
Small ΔT => Big ΔR

- Energy threshold and resolution for LMO
  - O(keV) detection at Q-value due to scintillation
  - ~100 eV (FWHM) threshold for light sensor
- **Timing resolution is important**
  - 2νββ decays in ^{100}Mo ($T_{1/2}$ = 7.1 x 10^{18} y)
  - Pileup from 2νββ decays become a background
  - Requires rise times ~ 150μs or better Chernyak, D.M. et. al, Eur. Phys. J. C (2012) 72:1989
- Negative Electrothermal feedback keeps TES stable and decreases sensor time constant => faster pulses

TES: Initial Development

- Investigate control of Tc via proximity effect
  - Normal metal on superconducting layer suppresses Tc
  - Device: IrPt bilayer
- Collaboration between UCB + LBNL + ANL
  - Sputtering fabrication at Argonne
  - Test facility at UCB and ANL

IrPt chips (100nm/80 nm) in a sample holder

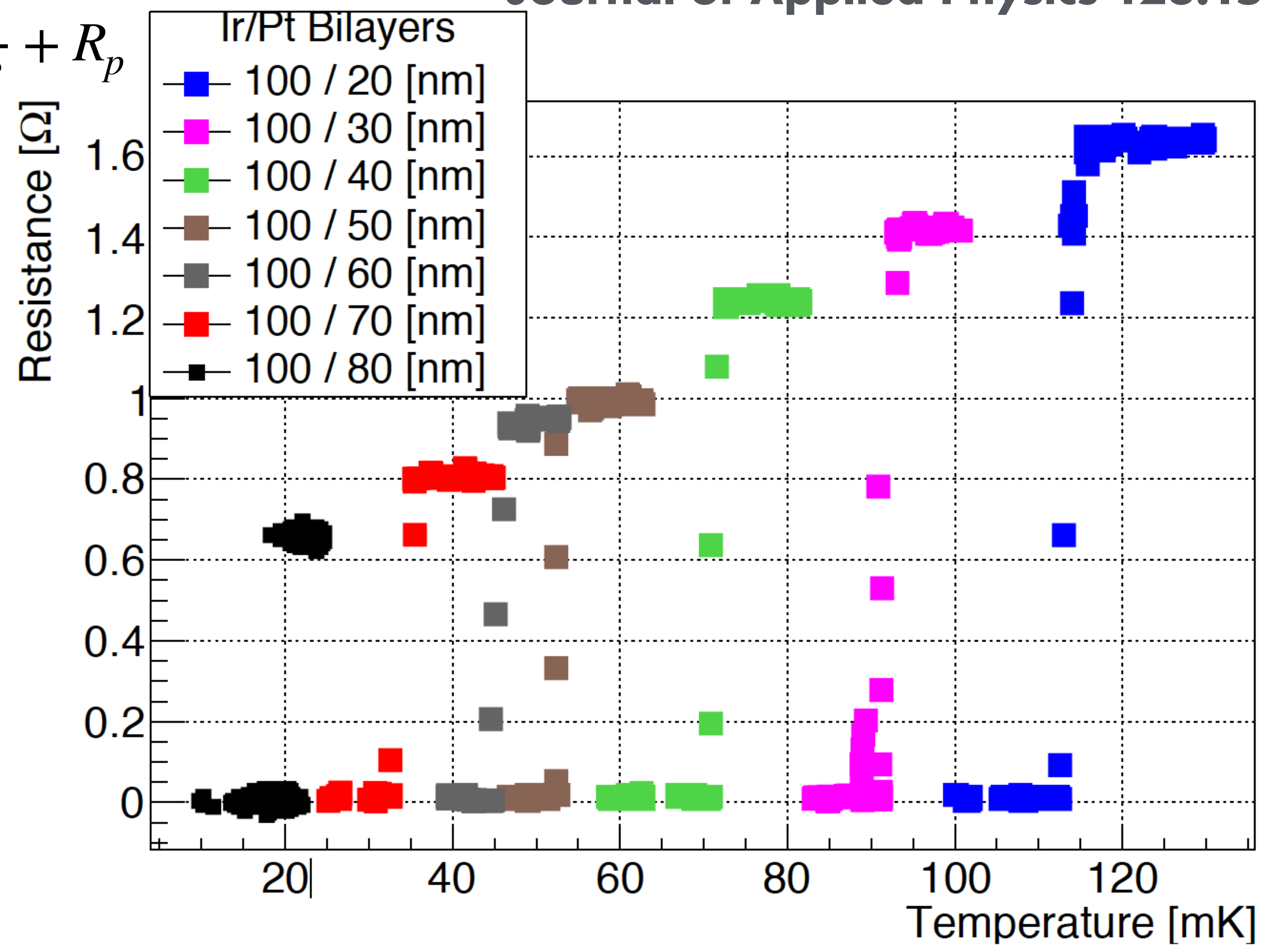


- T_c: 20mK - 110 mK demonstrated with IrPt chips
- T_c stable over time - repeated measurement of chips gives consistent T_c

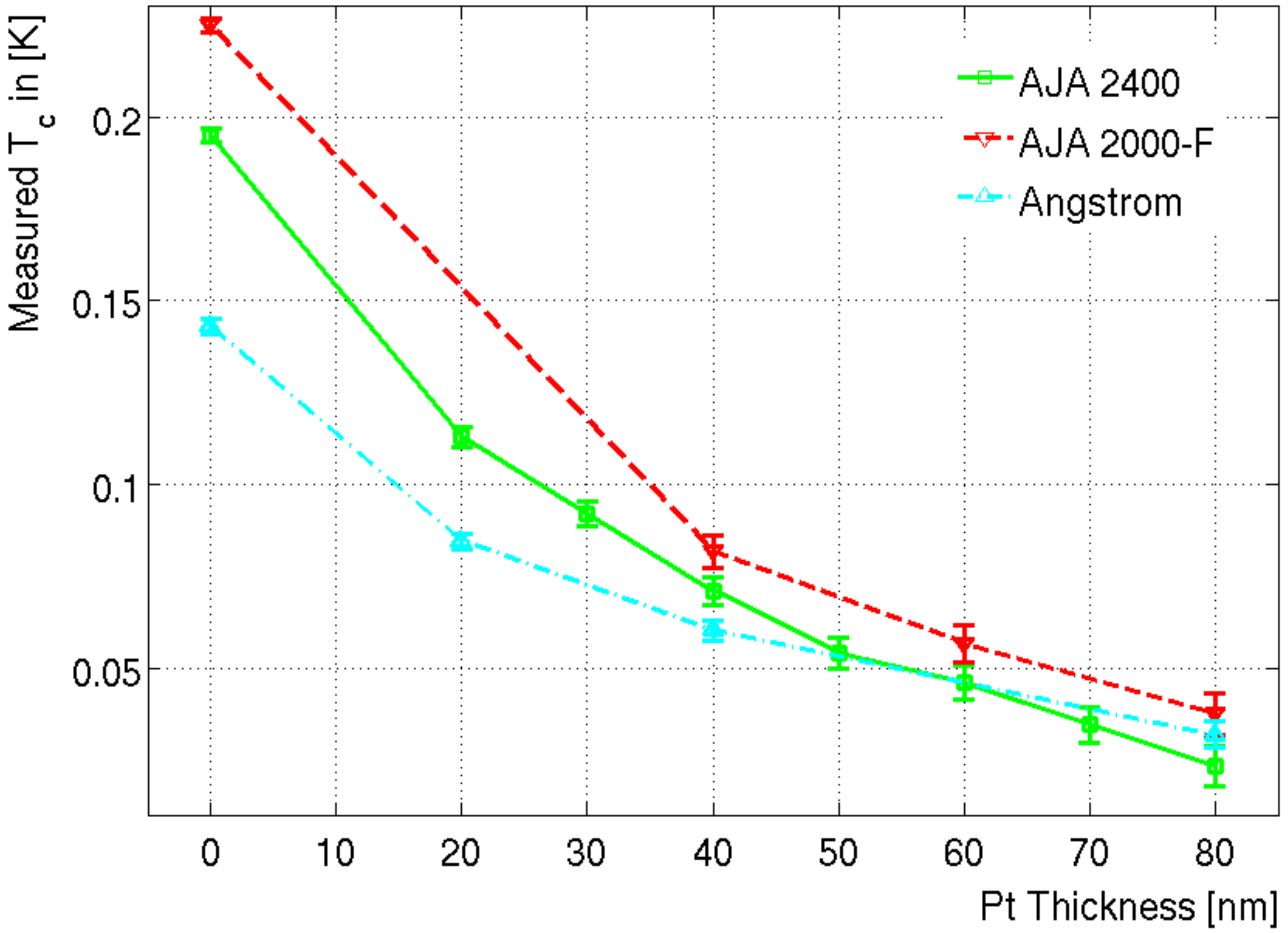
$$R = R_N \frac{e^{AT+B}}{1+e^{AT+B}} + R_p$$

$$T_c = -\frac{B}{A}$$

Journal of Applied Physics 128:15

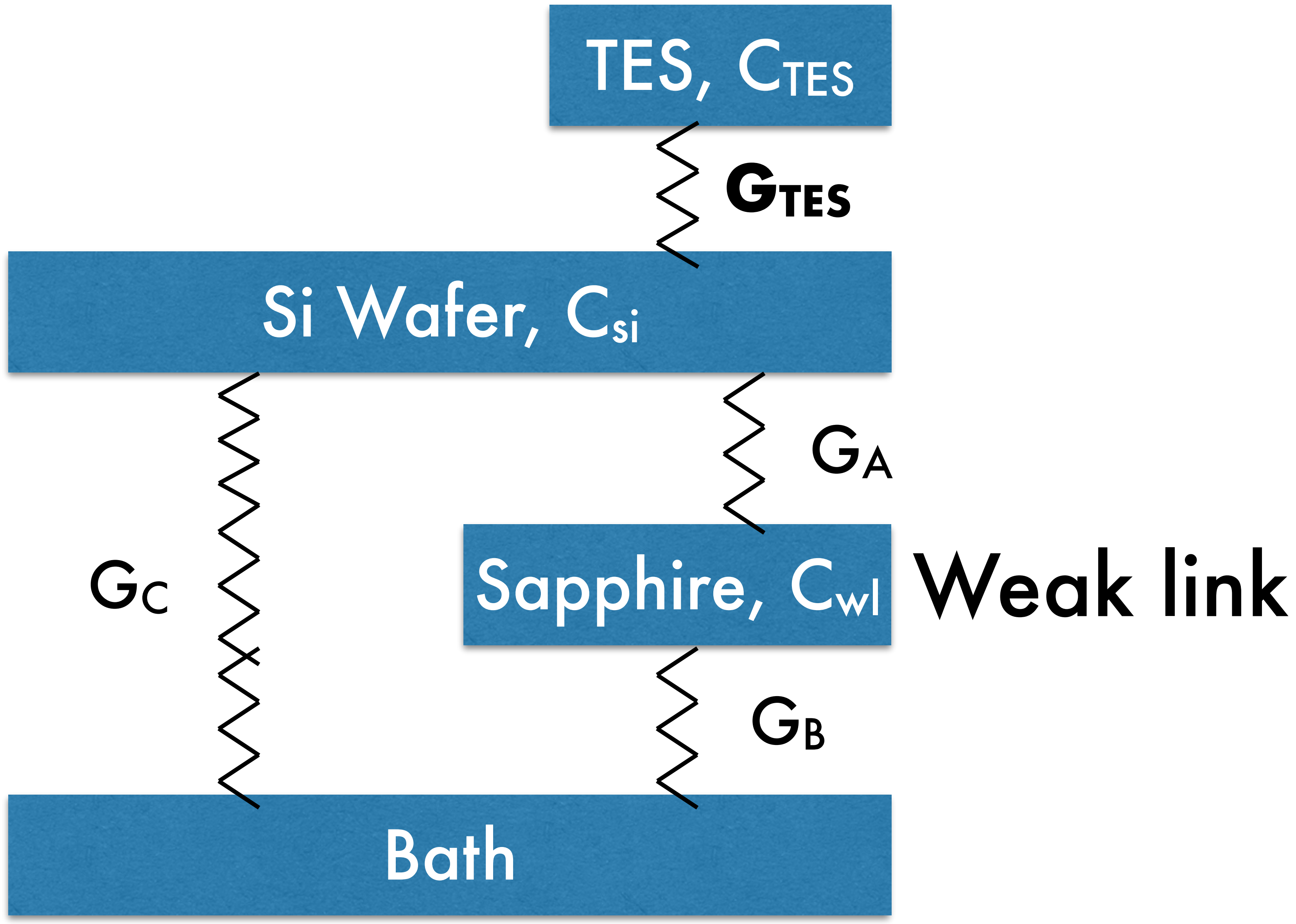


Note: Measurements taken with 3.16 μA excitation



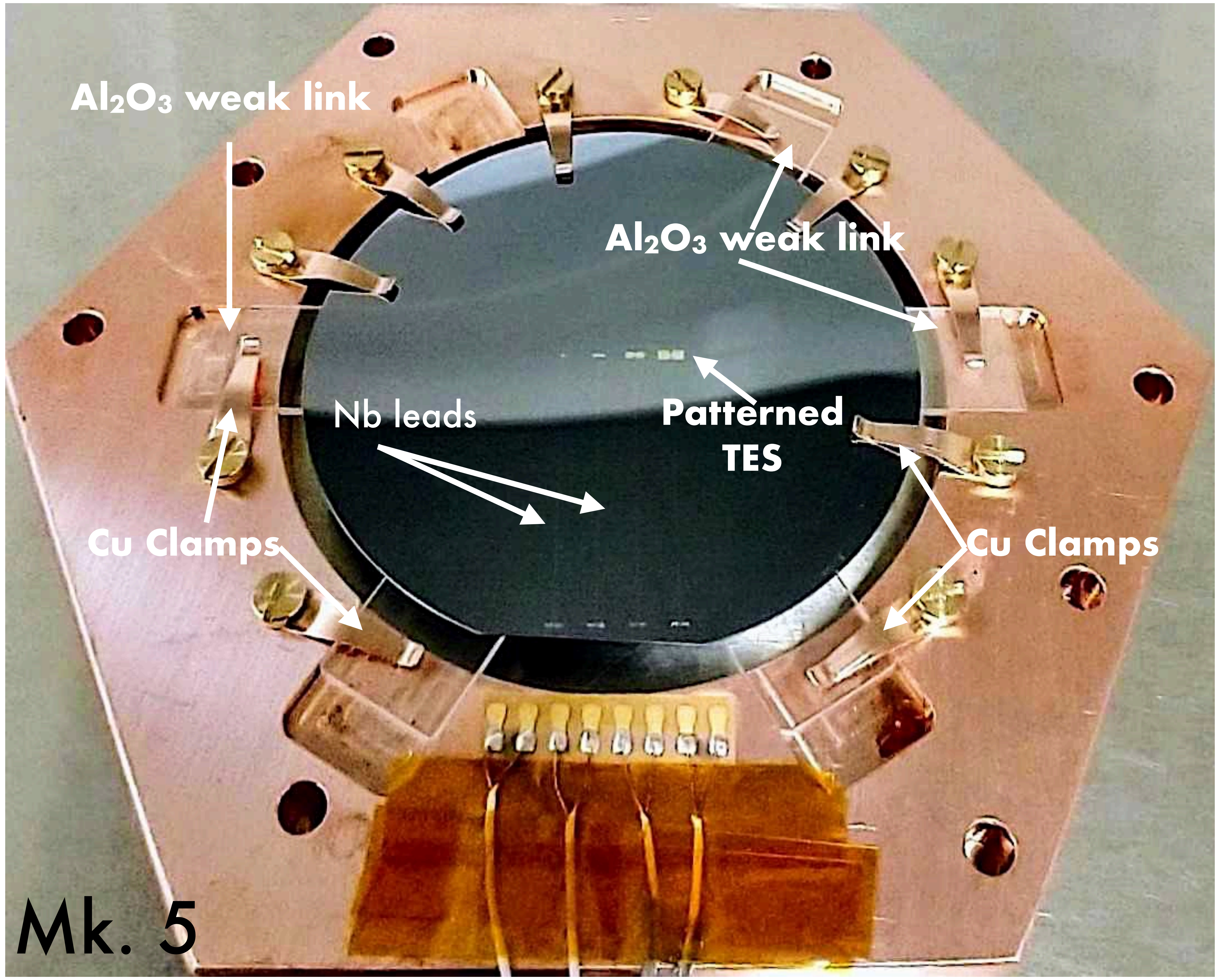
TES: Light Detectors

Schematic thermal model for TES light detector



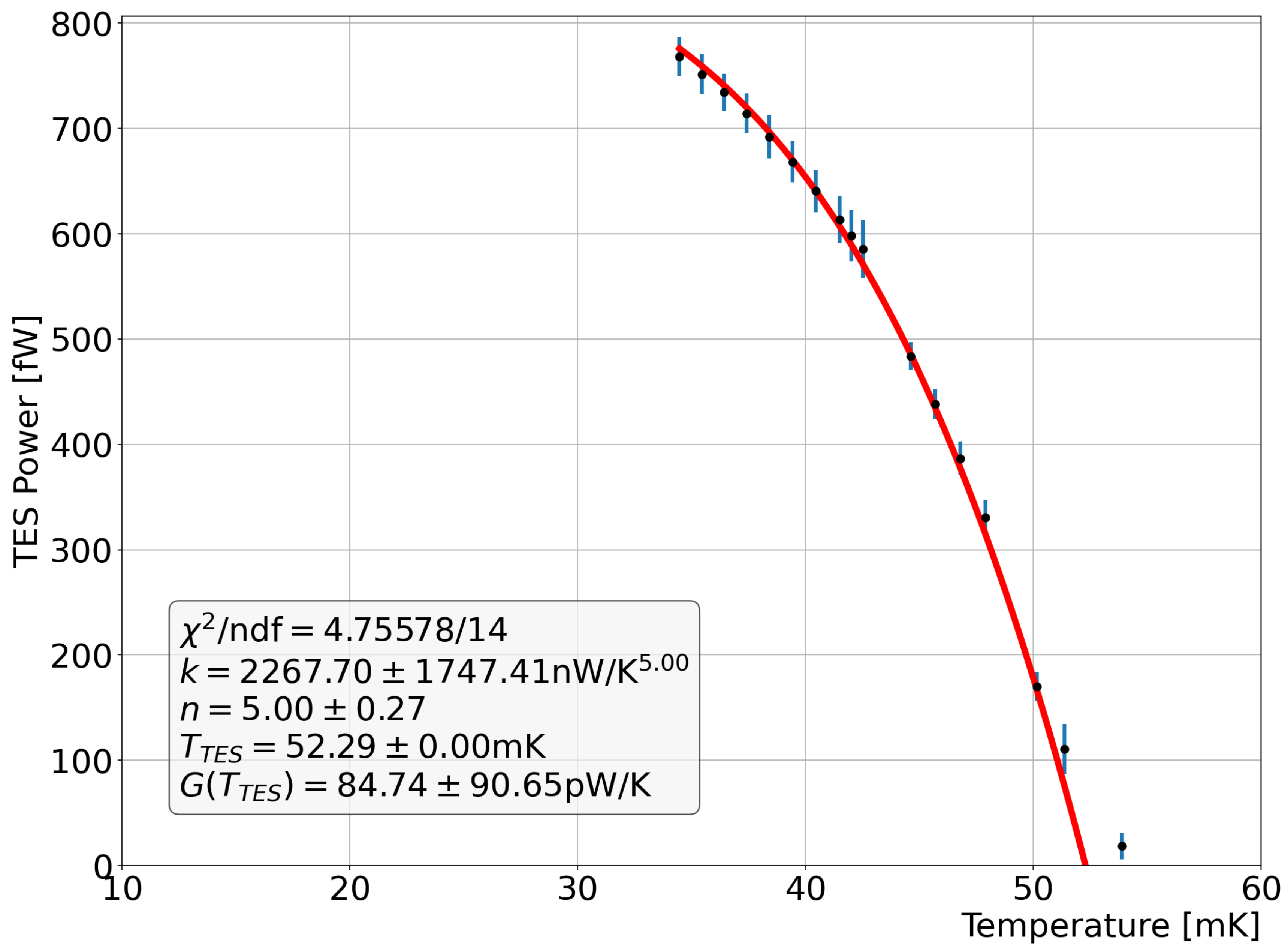
- Tuning TES coupling to Si wafer and wafer coupling to bath is important for optimal operation
- Sapphire used for weak link
  - wafer glued to sapphire, sapphire clamped to holder
- Adjustable Cu clamps can allow adjustment for link to bath
- Clamps are coated in Ge varnish to provide electrical isolation

- IrPt bilayer deposited on Si wafer (5.08 cm dia., 275 µm width)
- Variable TES sizes: 300-500 µm x 300-500 µm
- Nb leads to Al wire bonding pads

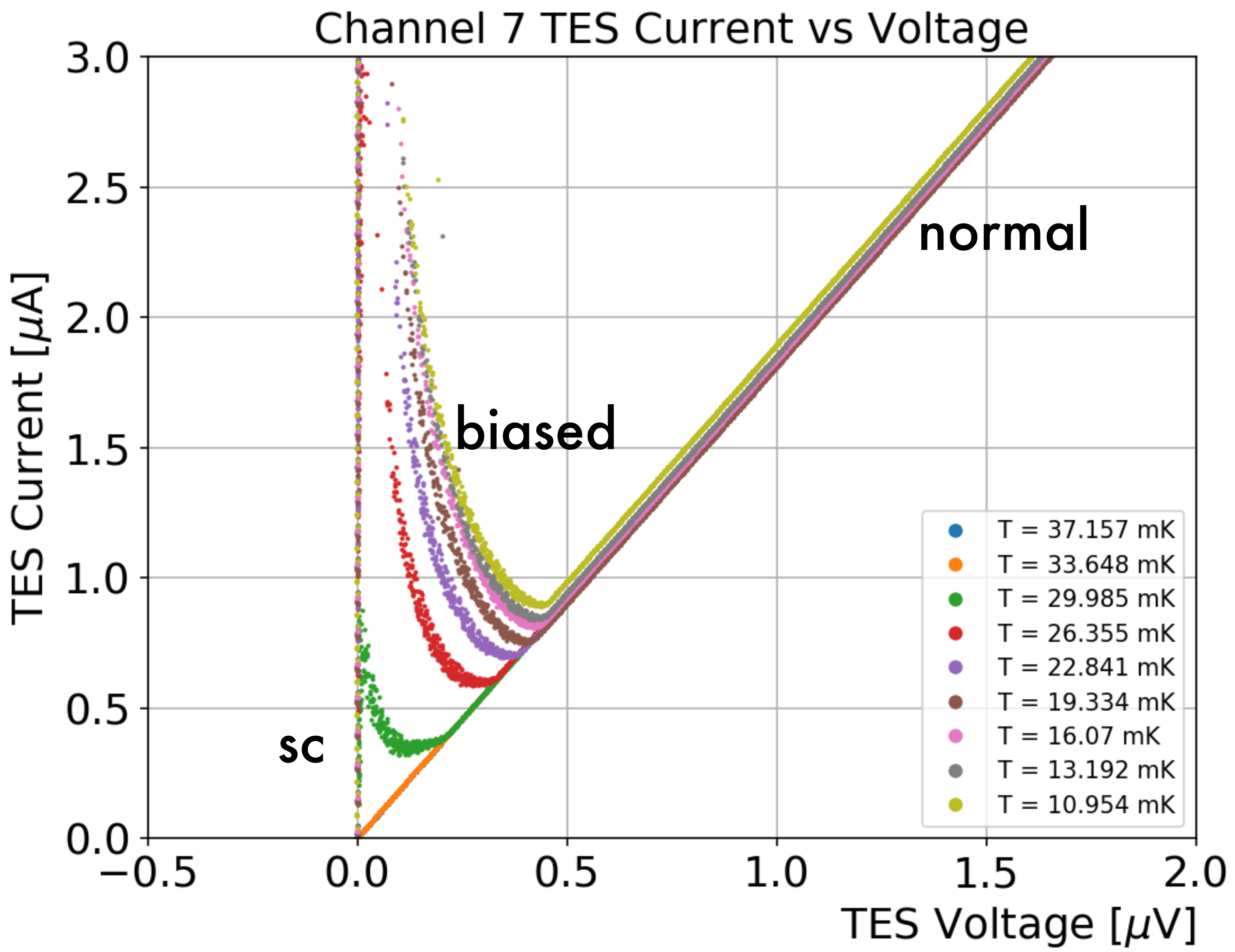


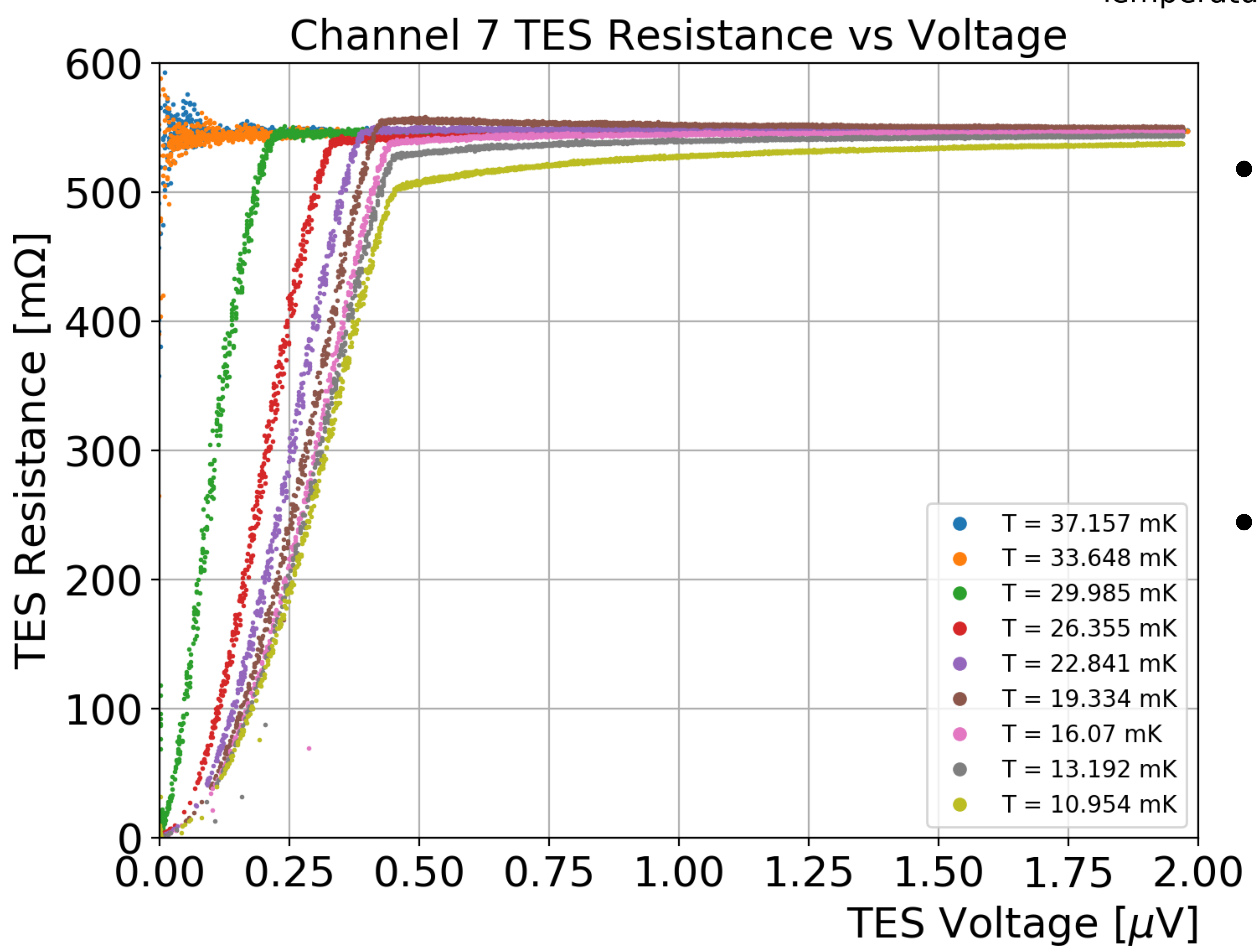
TES LD IV Characterization

- UCB test facility Oxford Triton 400 dry dilution fridge
- 4 Magnicon SQUIDs + 1 noise thermometer



- TES power in biased region is constant but varies depending on temperature
- Would like to increase G to improve sensor operation



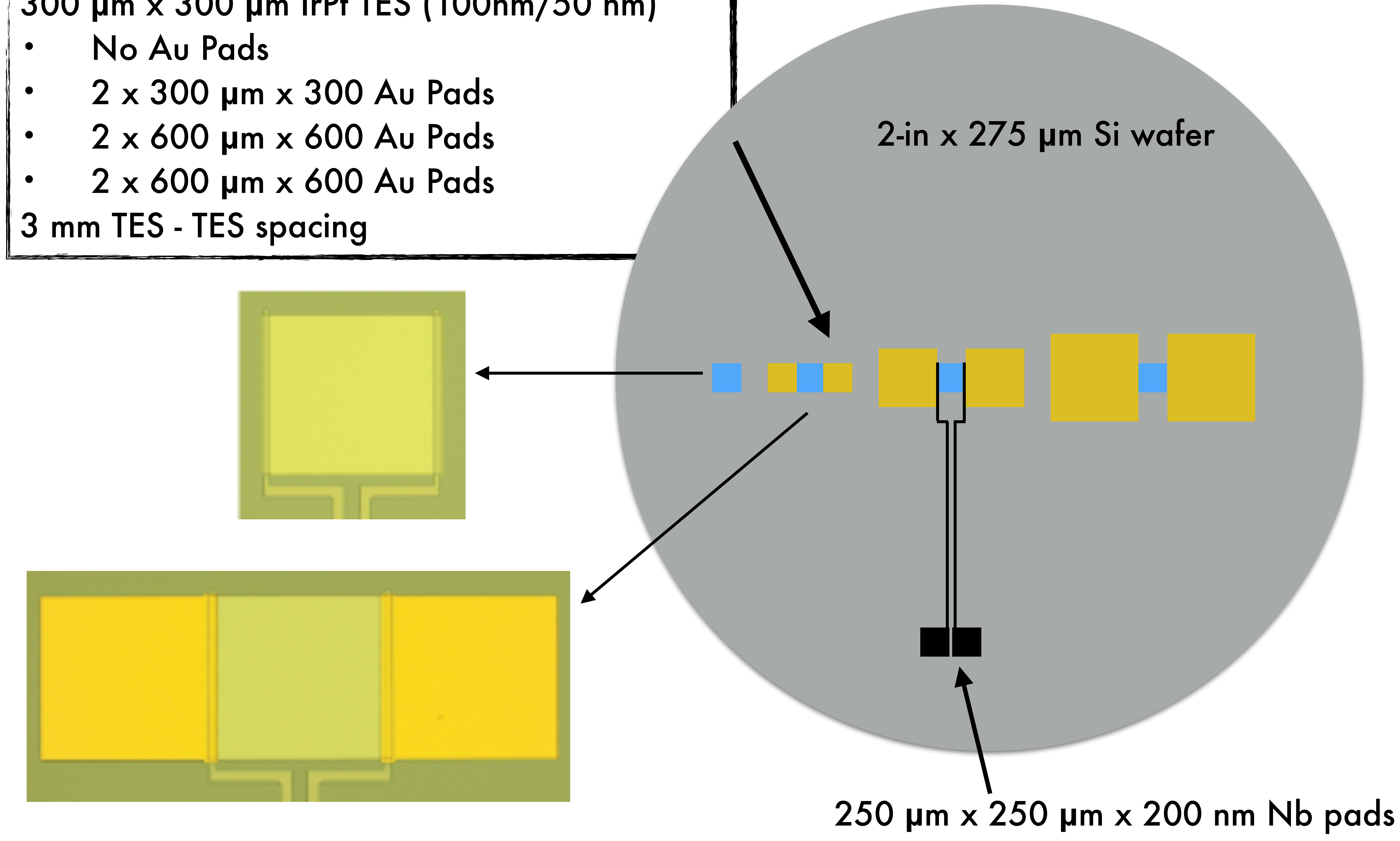


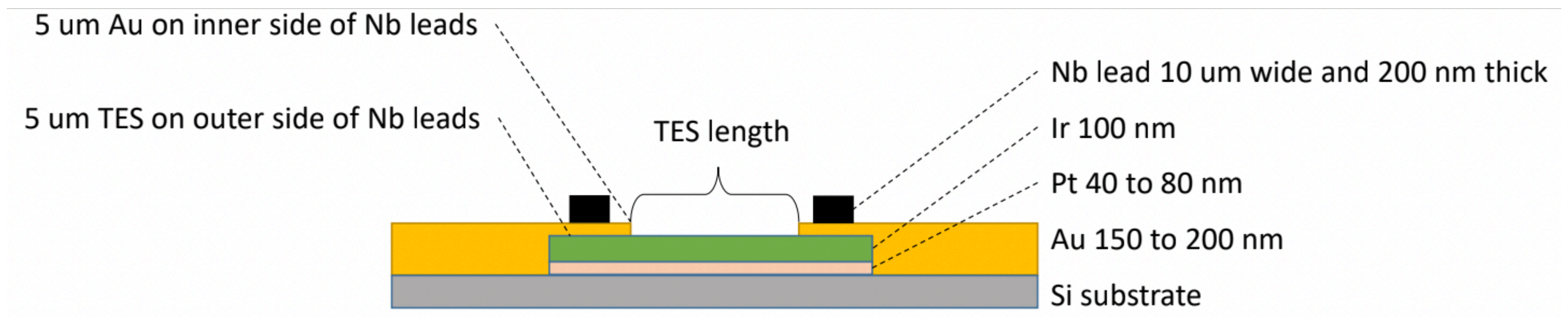
- Sweep bias voltage to produce output response (IV measurement)
- Provide information on load resistance, TES normal resistance, Tc, and thermal conductivity

Campaign to Improve G_{TES}

300 µm x 300 µm IrPt TES (100nm/50 nm)
- No Au Pads
- 2 x 300 µm x 300 Au Pads
- 2 x 600 µm x 600 Au Pads
- 2 x 600 µm x 600 Au Pads

3 mm TES - TES spacing



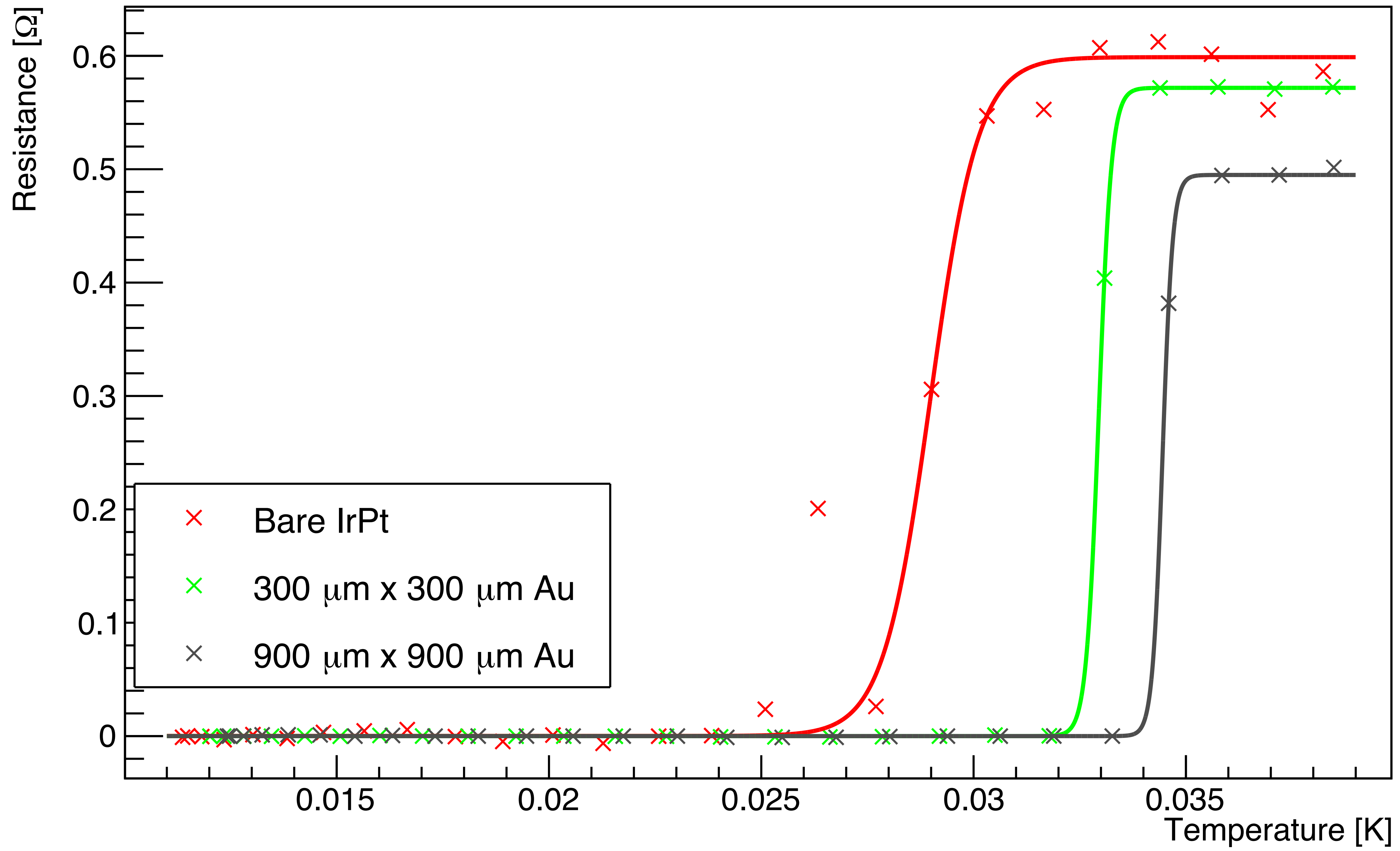


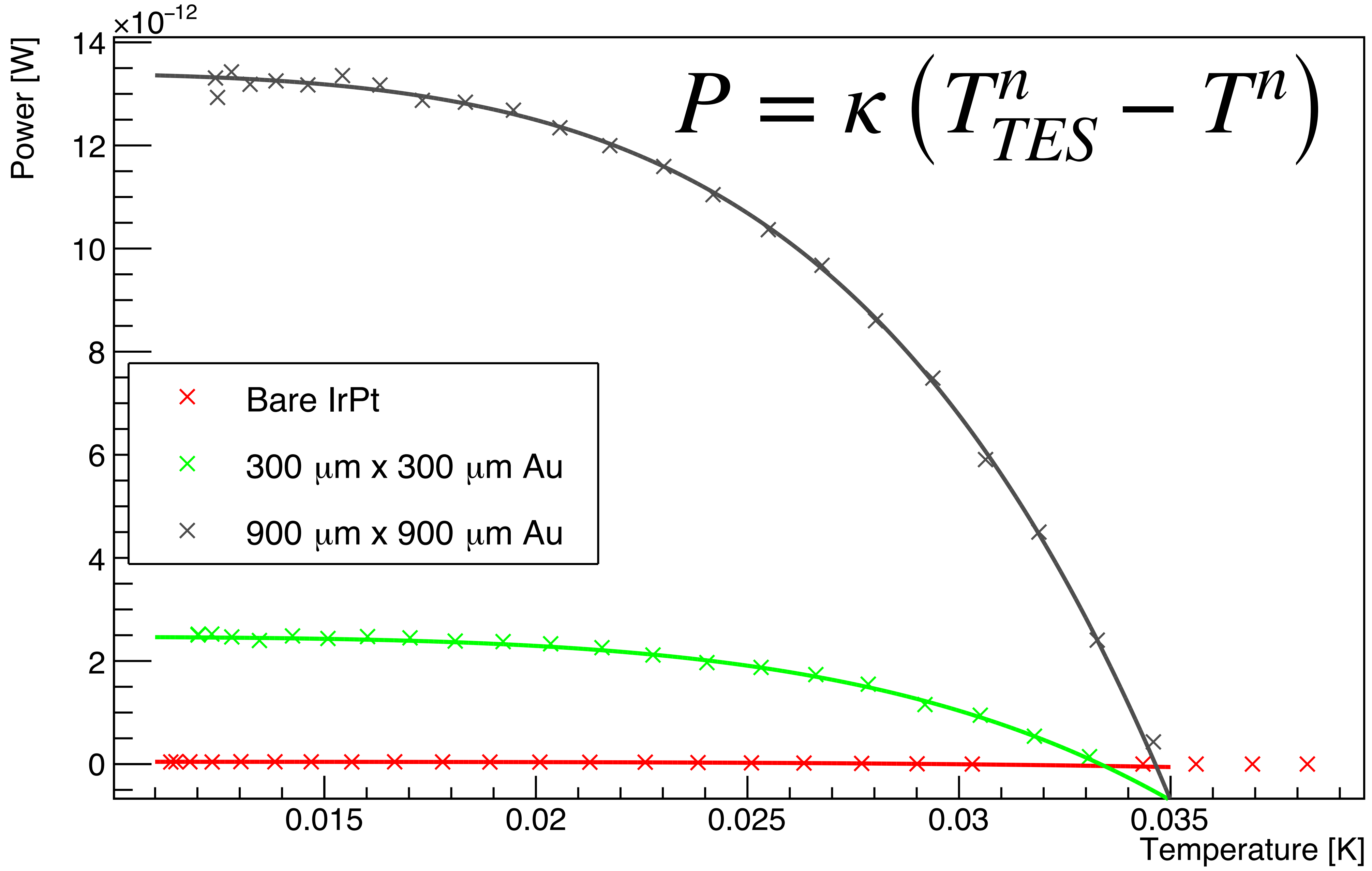
Cross-section view of TES

- Small pulses seen with plain IrPt TES
- Relatively weak coupling of TES to absorber improved by adding Au surfaces near the TES
- 4 TES with various Au pad sizes deposited onto single wafer for study

Campaign to Improve G_{TES}

- Clear improvement in thermal conductivity with addition of Au pads
- For the devices n is between 4 and 5
  - n = 4: Kapitza-boundary resistance
  - n = 5: electron-phonon decoupling

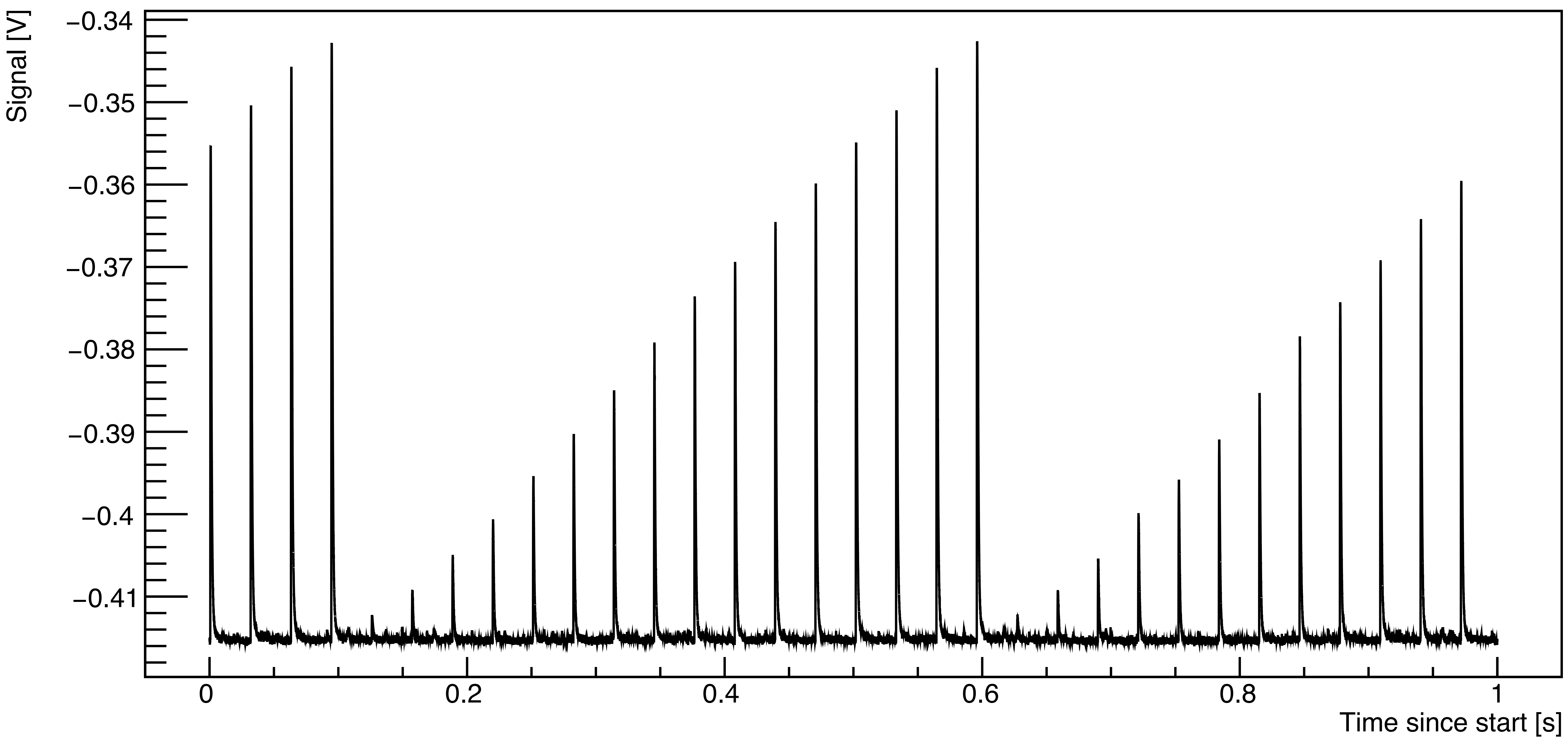




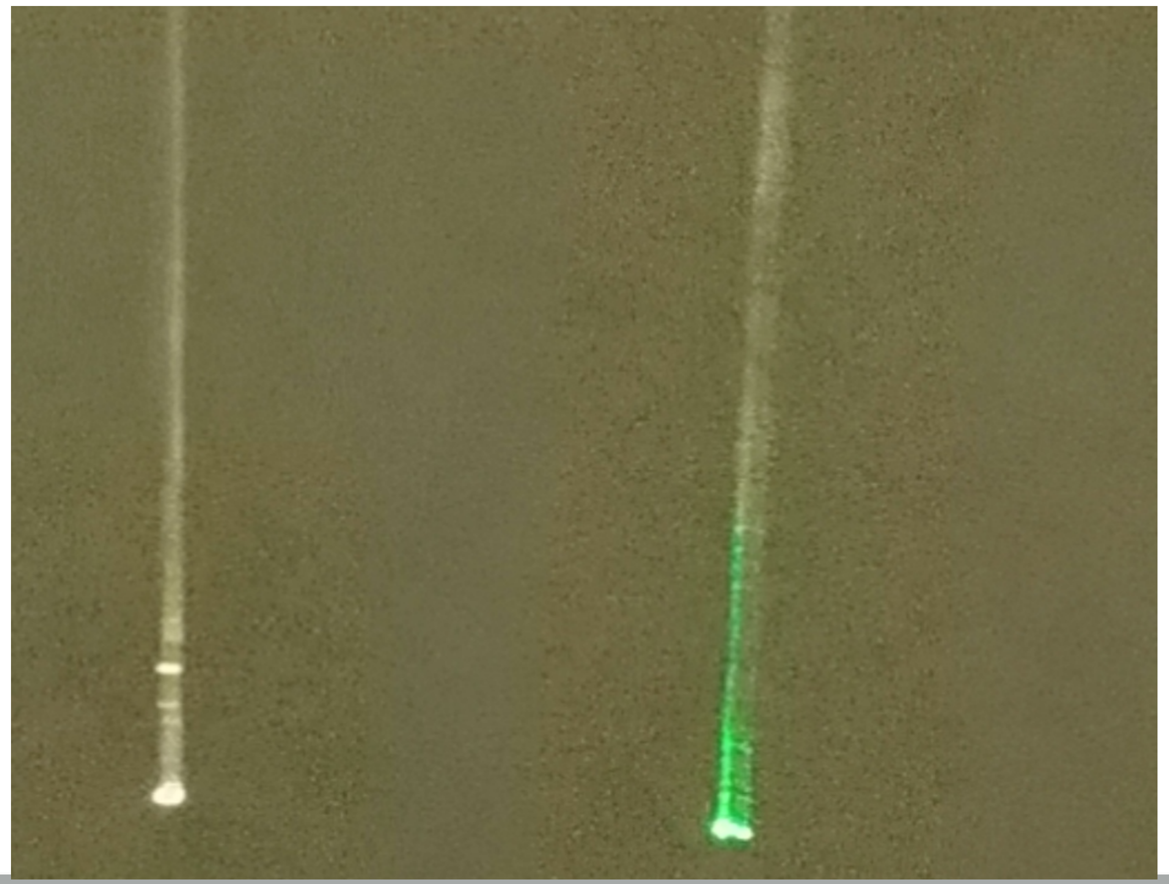
$$P = \kappa\left(T_{TES}^{n} - T^{n}\right)$$

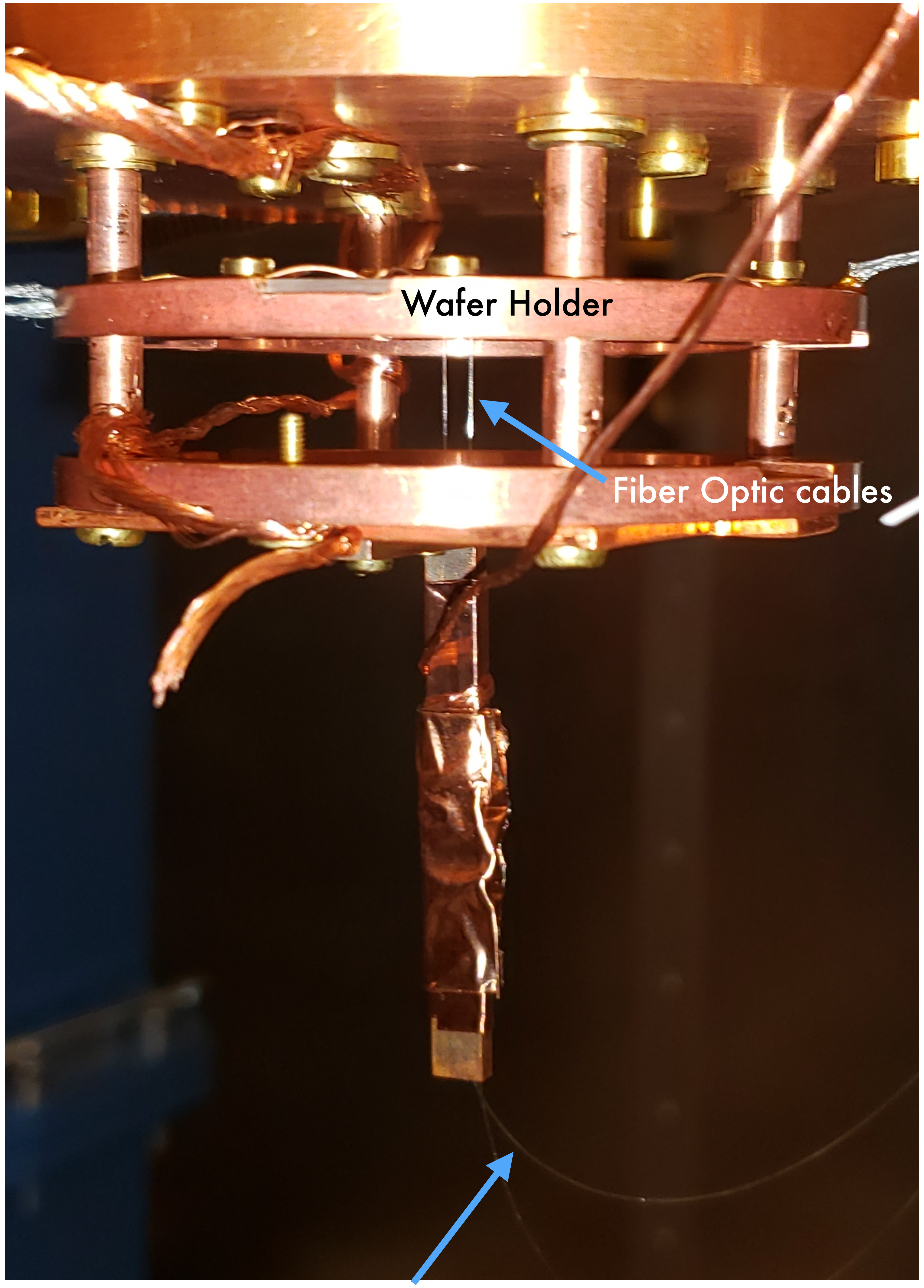
- TES normal resistance has slight suppression with more Au
- Tc slightly lower with smaller Au
- Bare IrPt shows lowest Tc => excess noise with less strong coupling to absorber
- Current designs under test are 300 μm x 300 μm IrPt (100/60 nm or 45/20 nm) with Au pads
- T_c ~ 30-40 mK, R_n ~ 0.5 - 1 Ω

Pulse Characterization



- Installed several fiber optic cables in cryostat
- Inject LED light pulses (λ = 600 nm) to study device timing and energy resolution

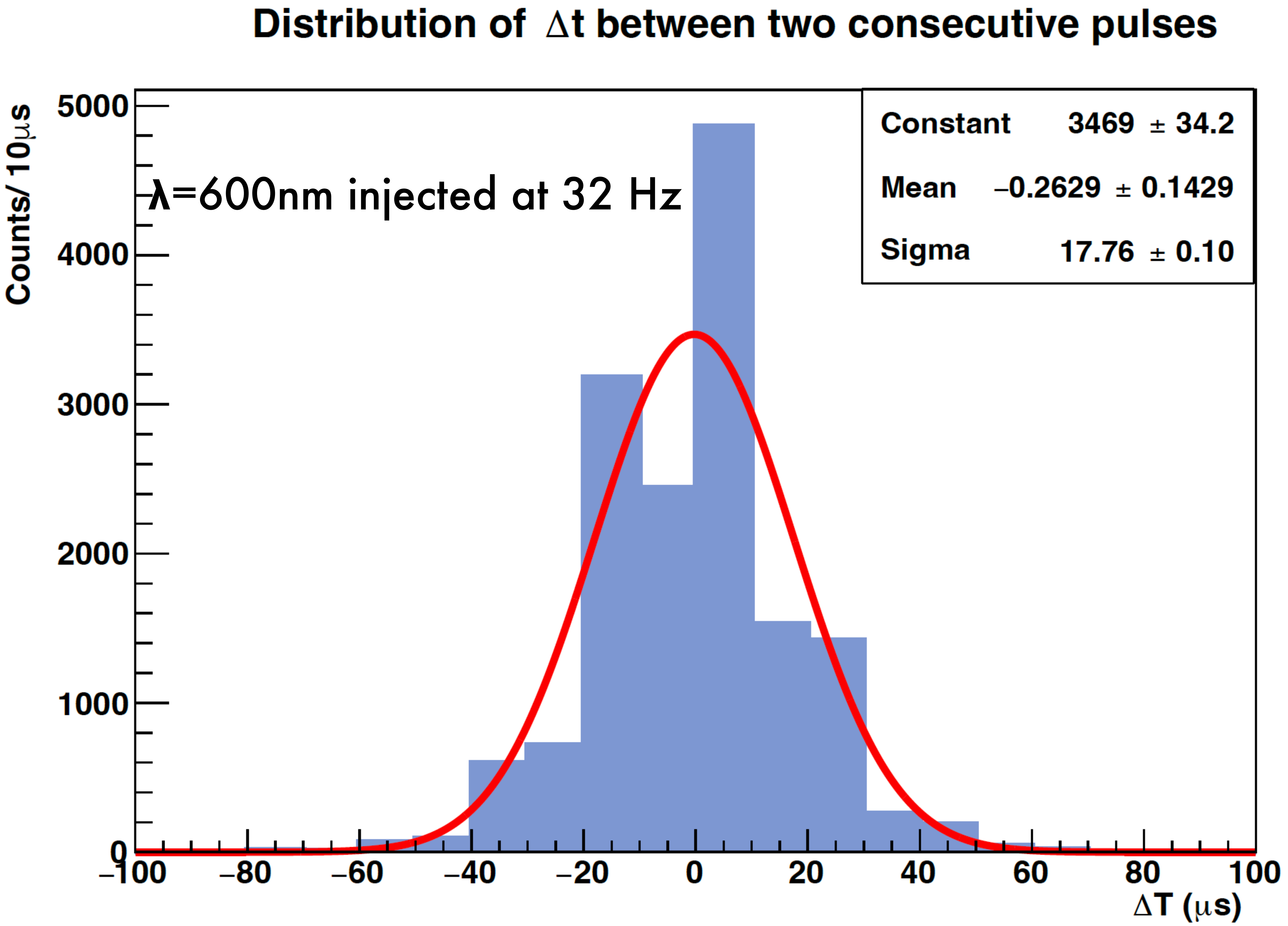


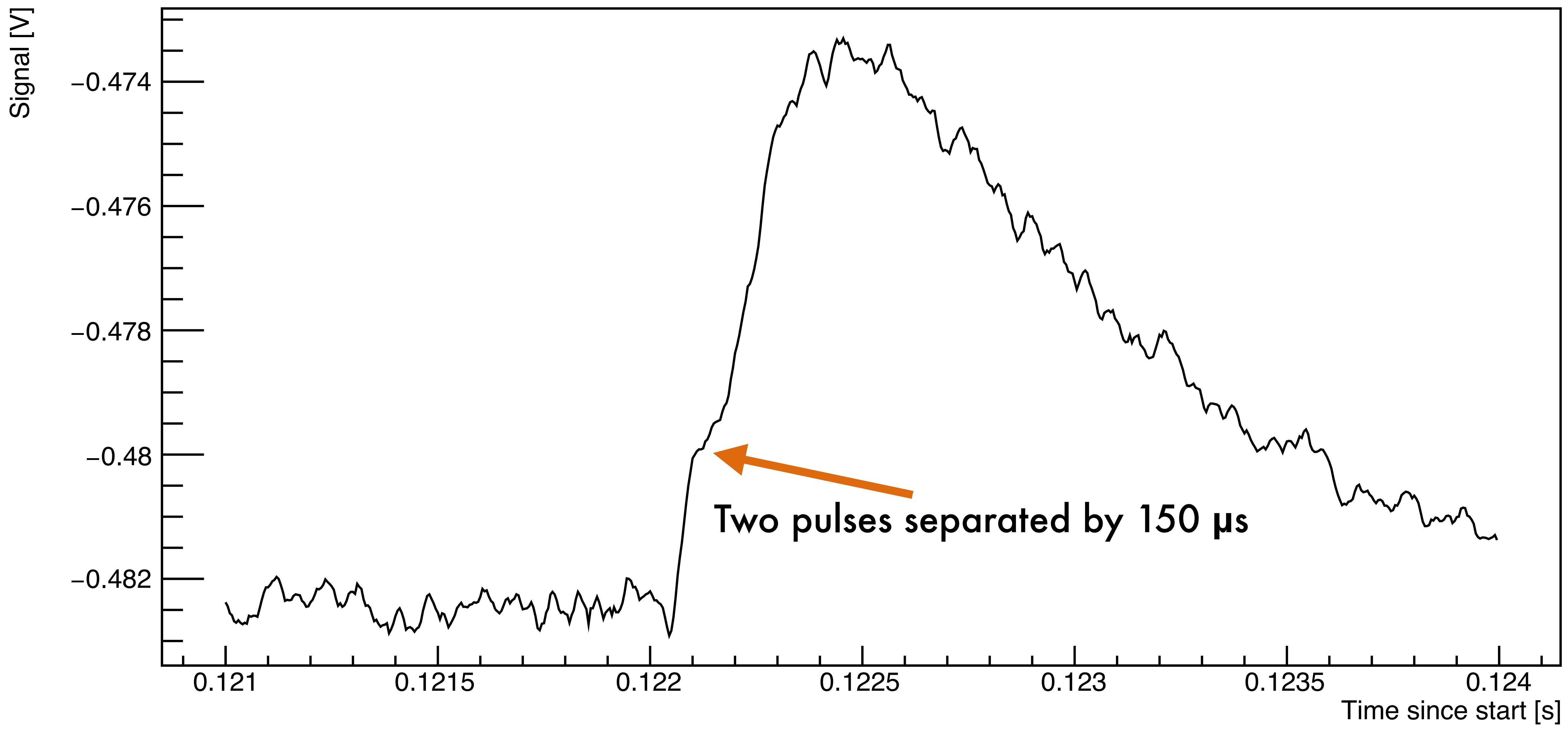


Fiber Optic cables

Timing Resolution

- Inject pulses with fixed rate
- Characterize timing resolution by examination of typical time between pulses in LD
- Timing resolution ~ 20μs
- Well within CUPID baseline requirement (<100μs) for 2νββ pileup rejection

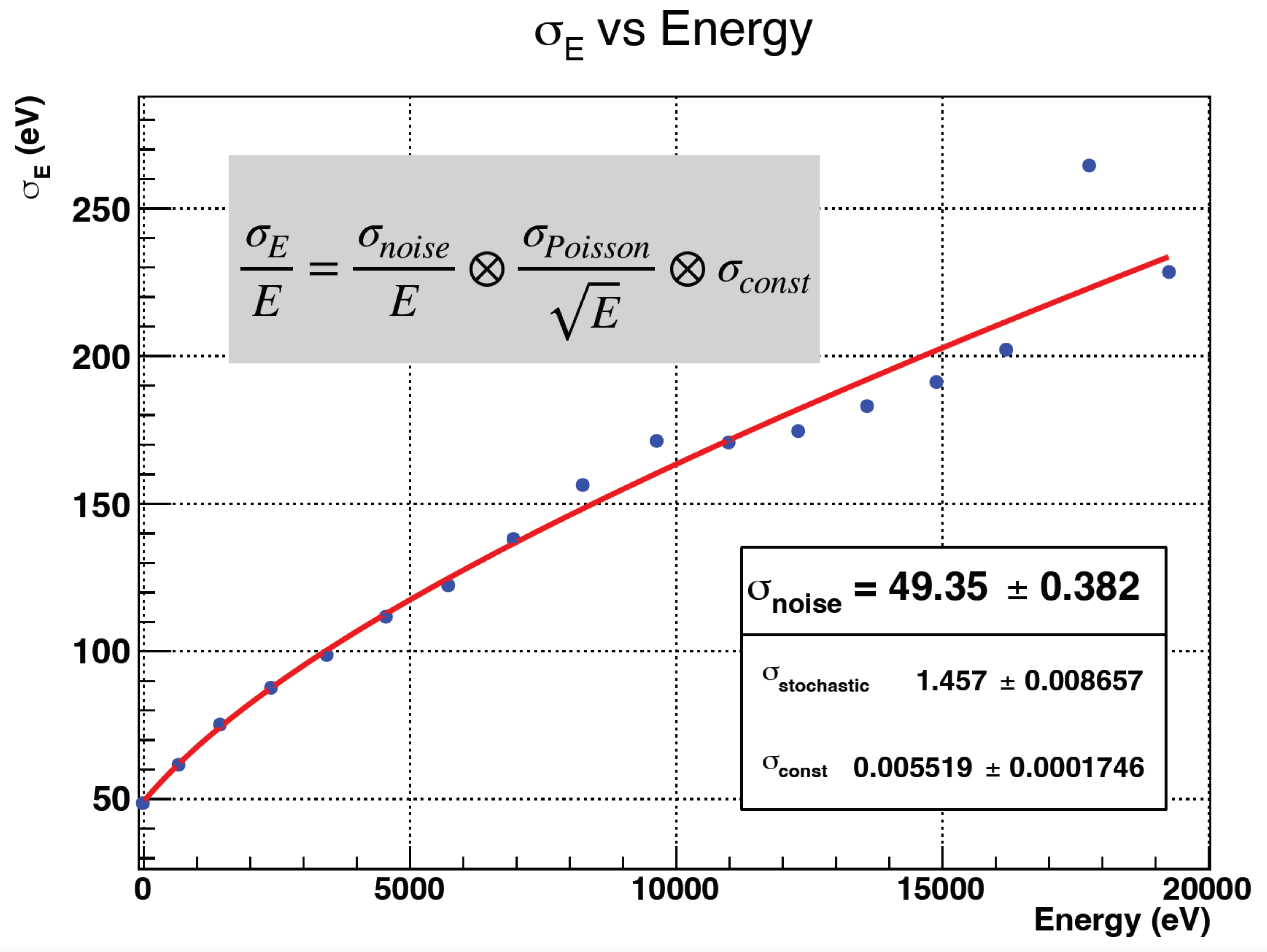




- Able to distinguish pulses 150 μs apart
- Allows for pulse shape discrimination for pileup events

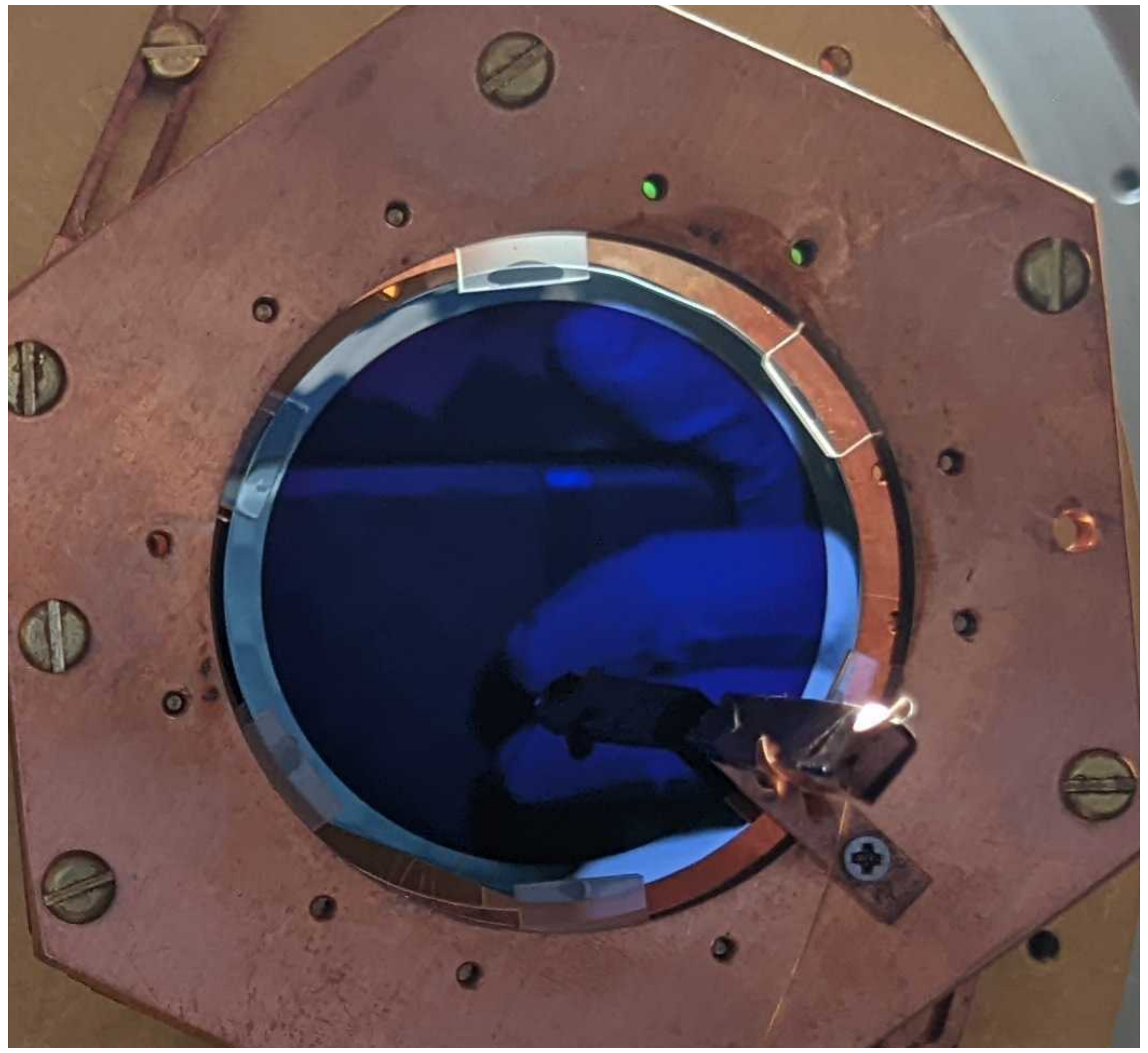
Energy Resolution

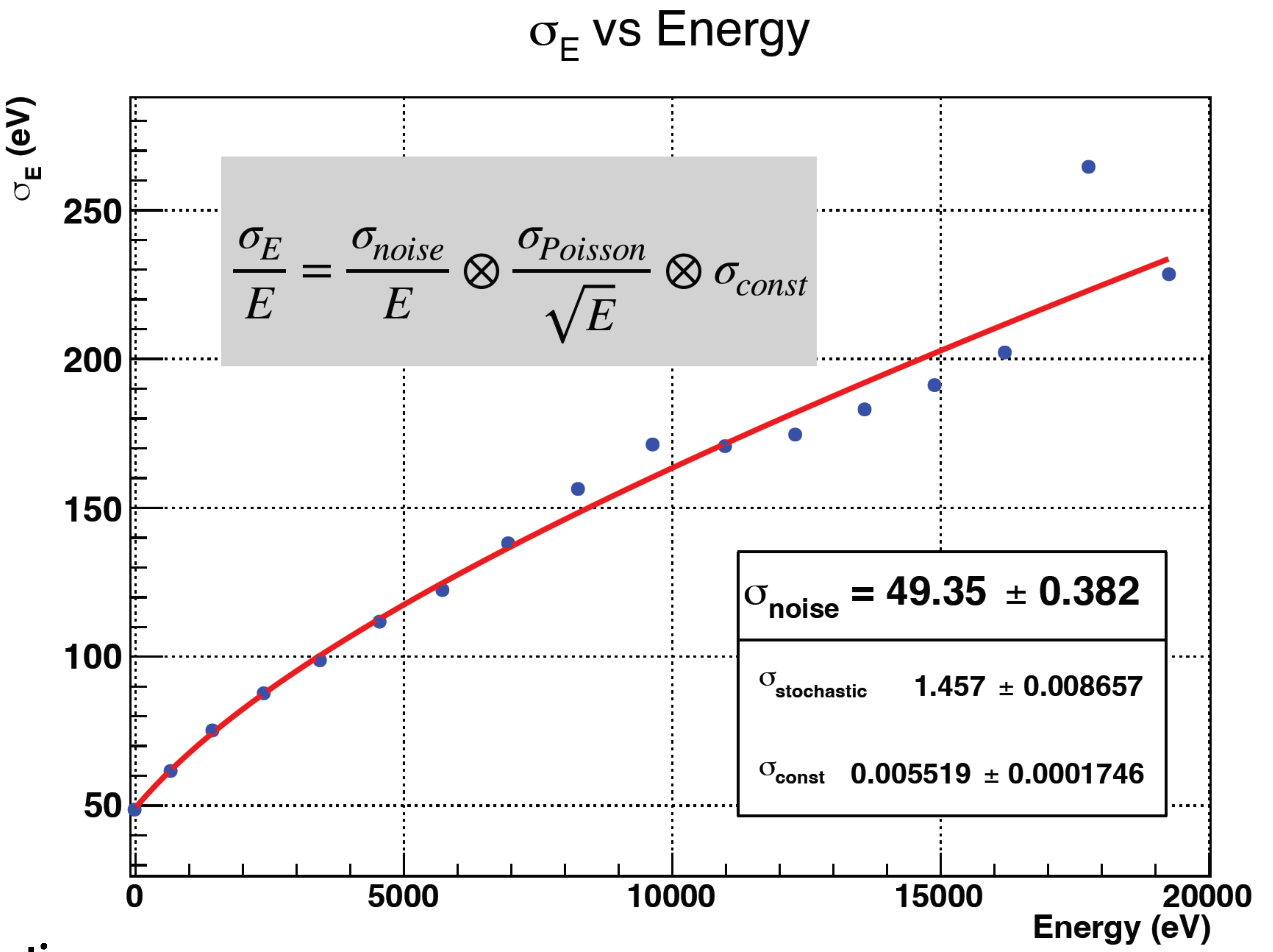
- Use LED pulses again
- Characterize resolution as function of energy with photon statistics
- Baseline noise at ~50 eV



Energy Resolution & AR Coating

- Use LED pulses again
- Characterize resolution as function of energy with photon statistics
- Baseline noise at ~50 eV



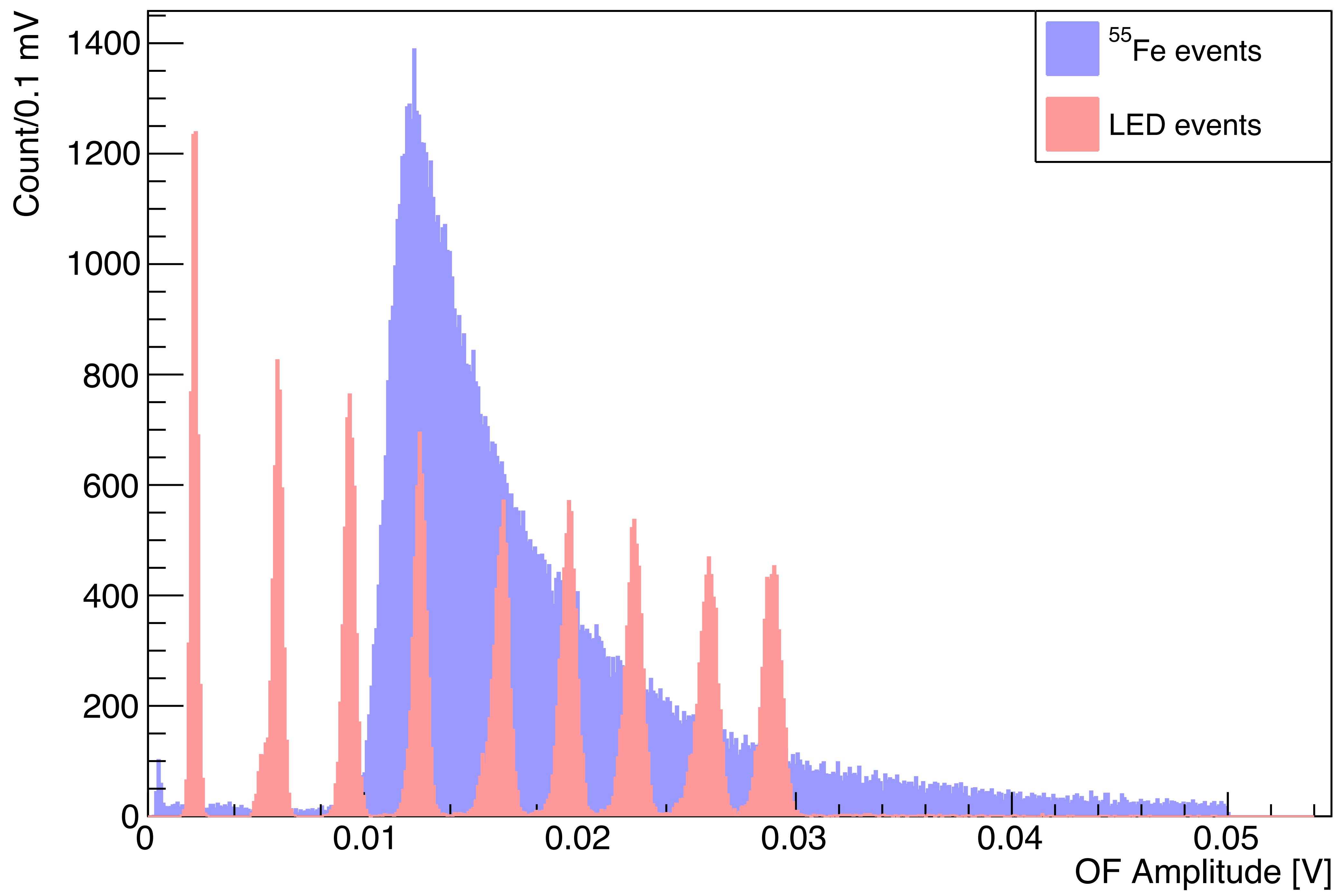


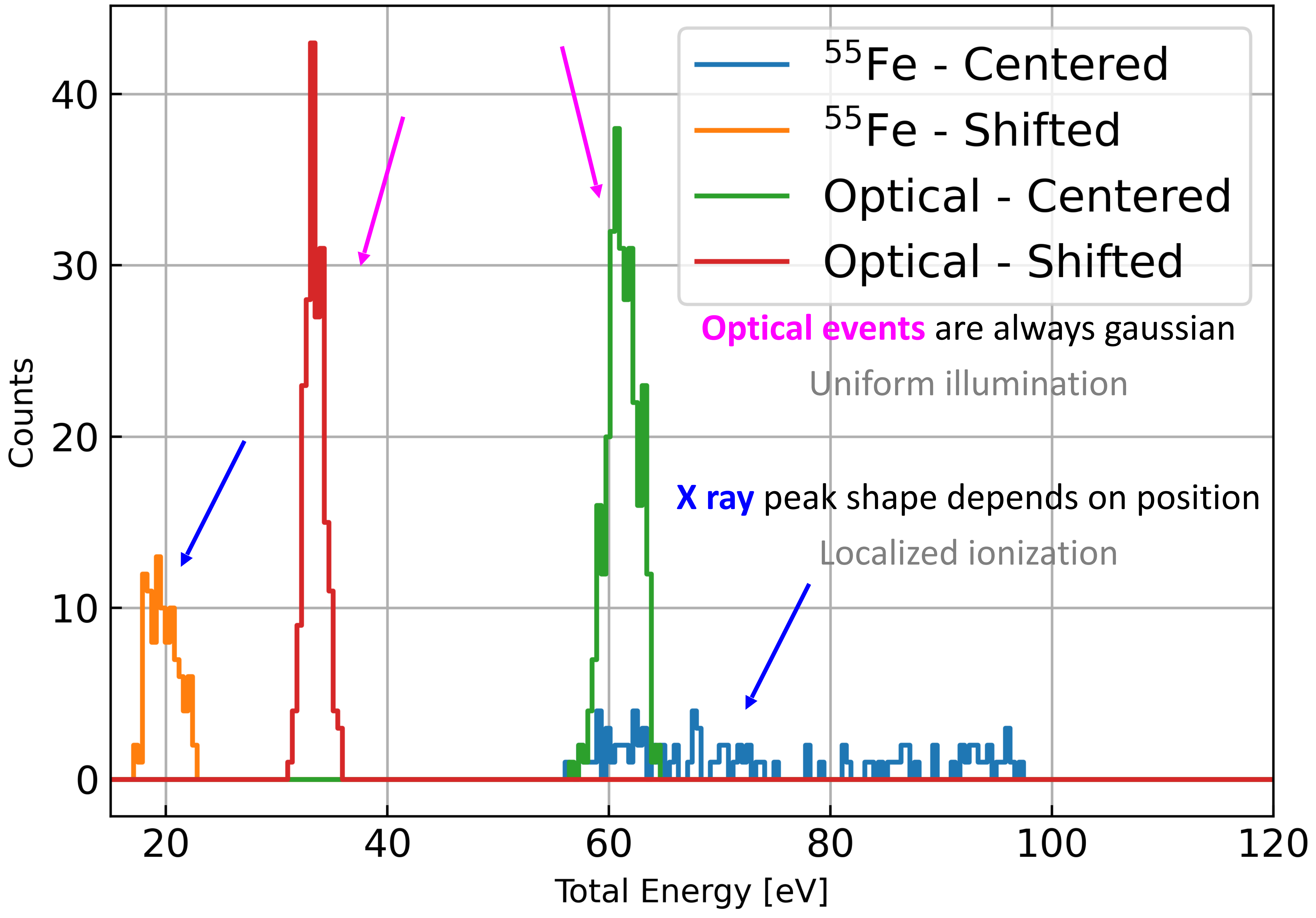
- Also testing anti-reflective coating:
  - ~68nm of Si_3N_4 backside only
- Expected Reflectance: < 3% (λ: 400-700 nm) and < 0.5% (λ: 550-600 nm)
- Observe no significant change to TES performance with presence of AR coating

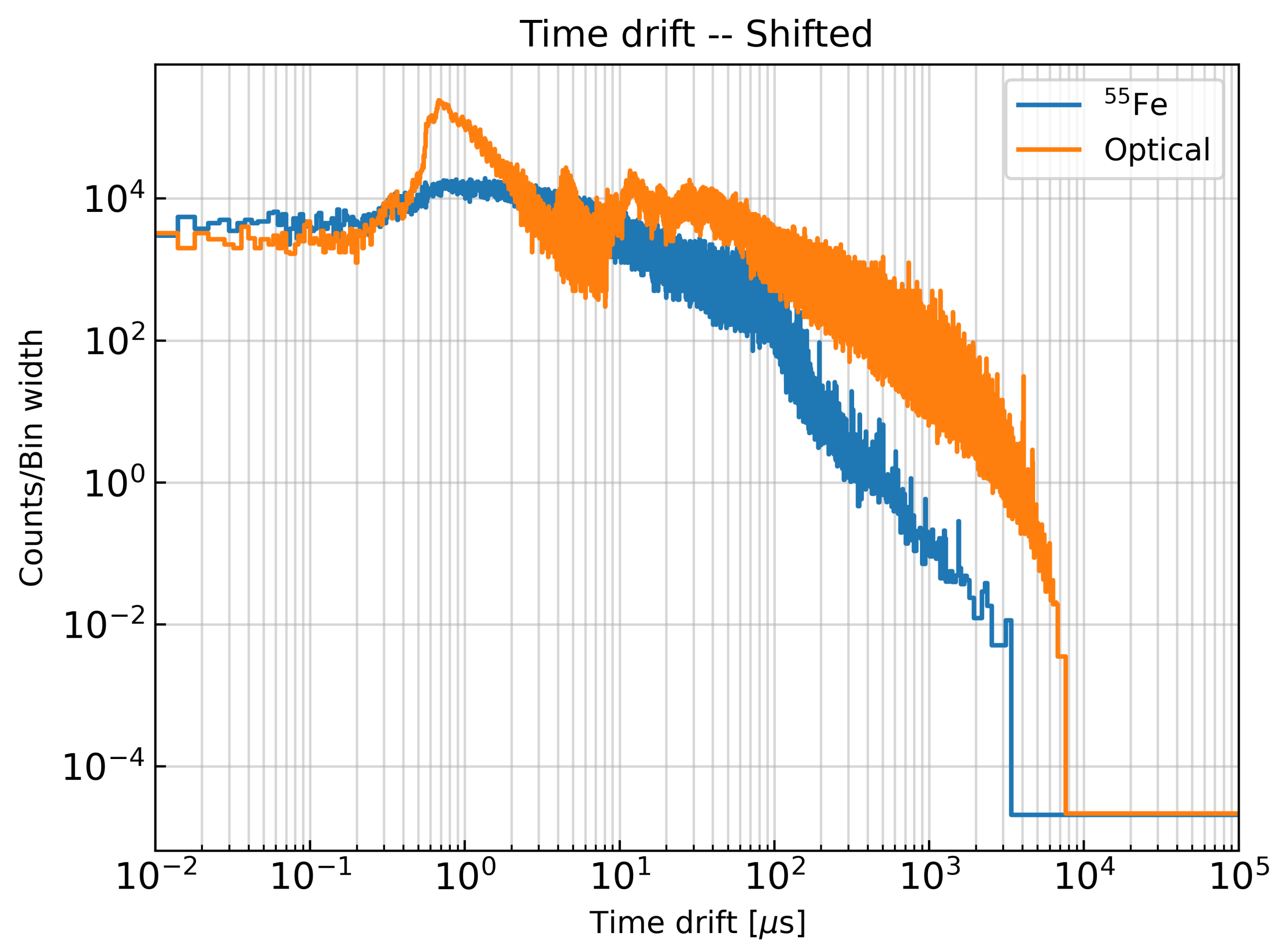
	Risetime (μs)	Decaytime (μs)	Energy Resolution (eV)
AR Coating	200	770	50
No AR Coating	200	880	82

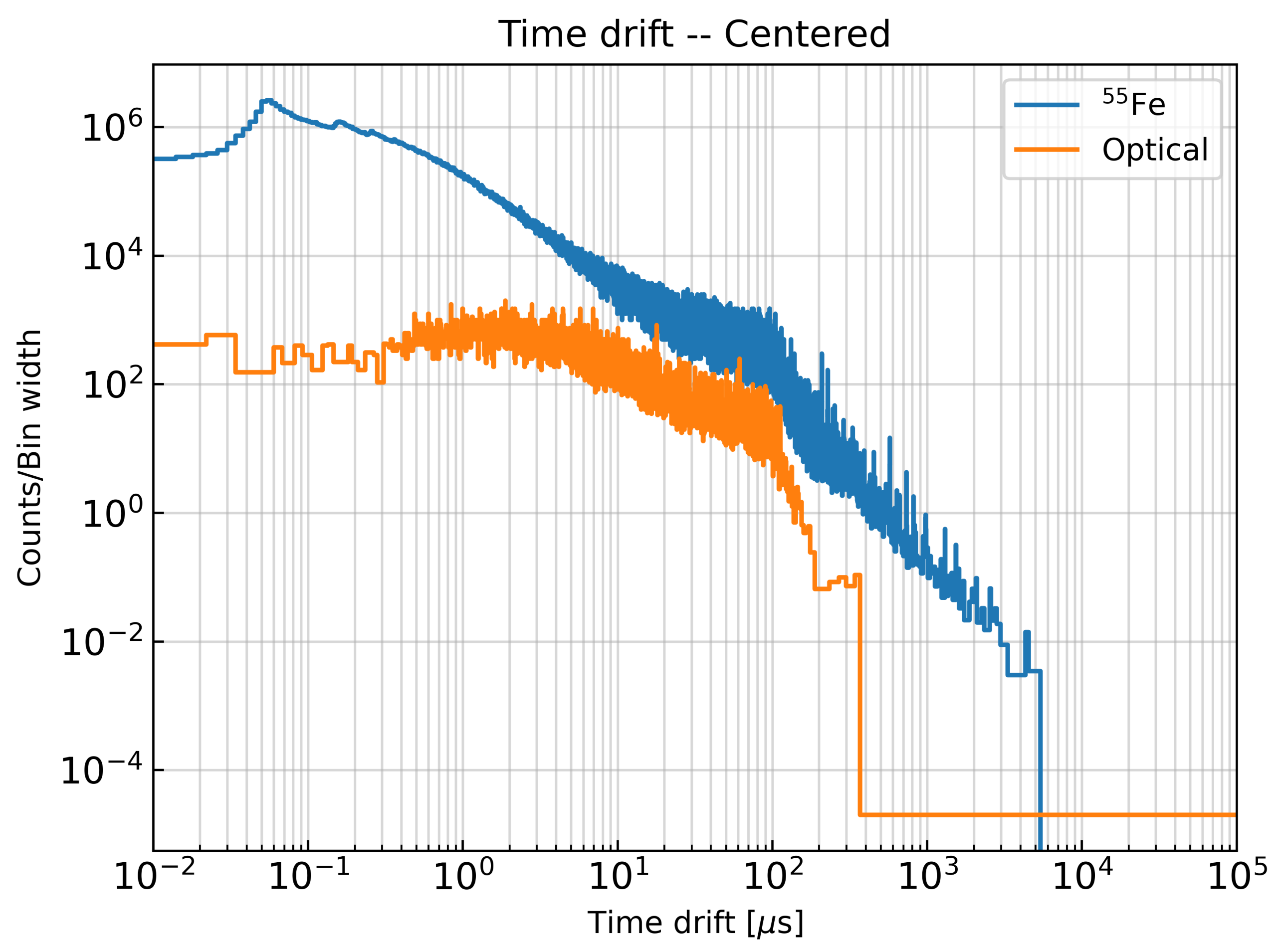
Pulse shape and detector energy resolution

^{55}Fe & Phonon Simulation





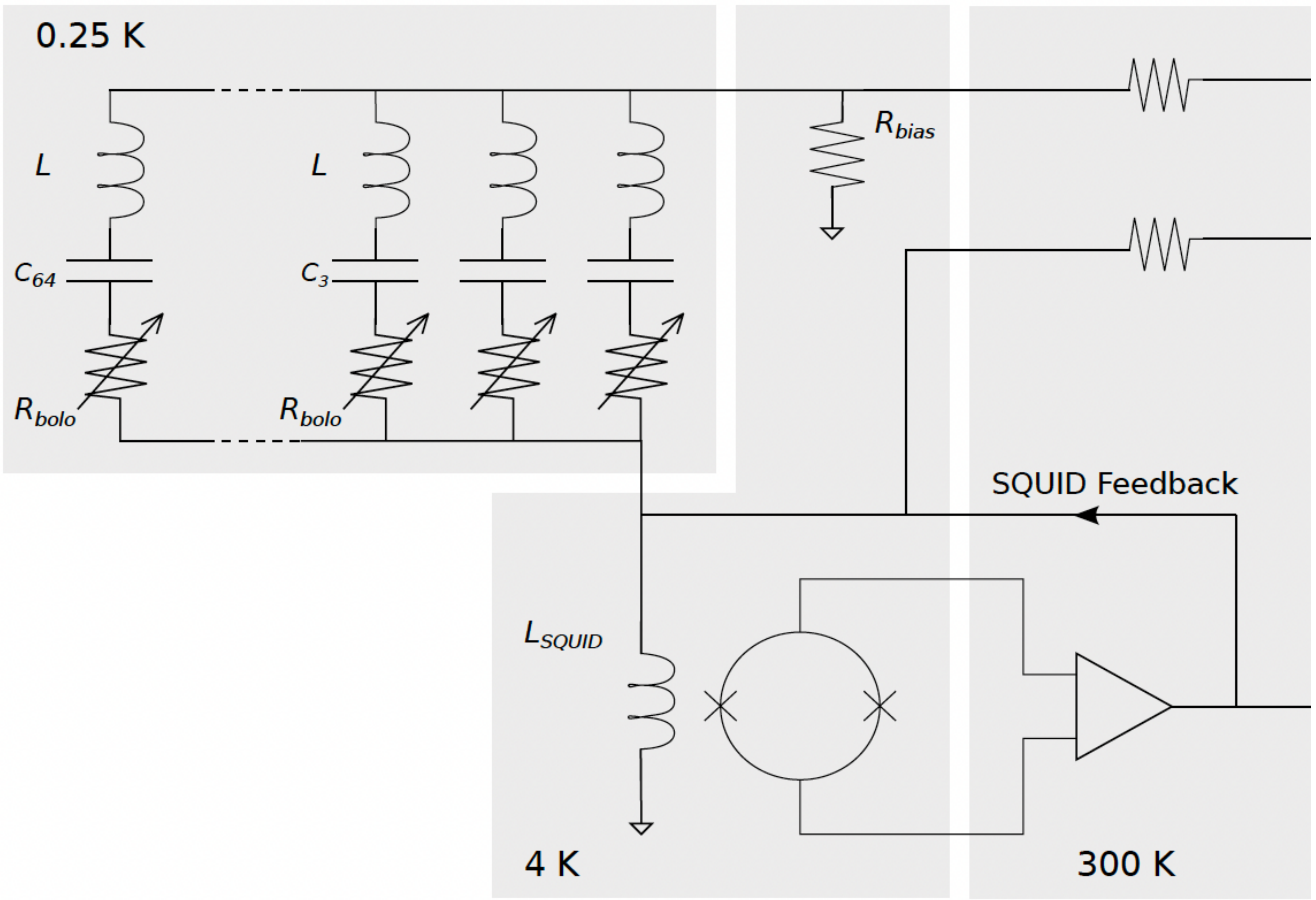




- We also expose LD to a ^{55}Fe source for absolute calibratio
- Disagreement with LED calibration
- Highly non-Gaussian shape
- Simulation work on phonon propagation to attempt to understand this and position dependence

Scaling up for CUPID & Beyond

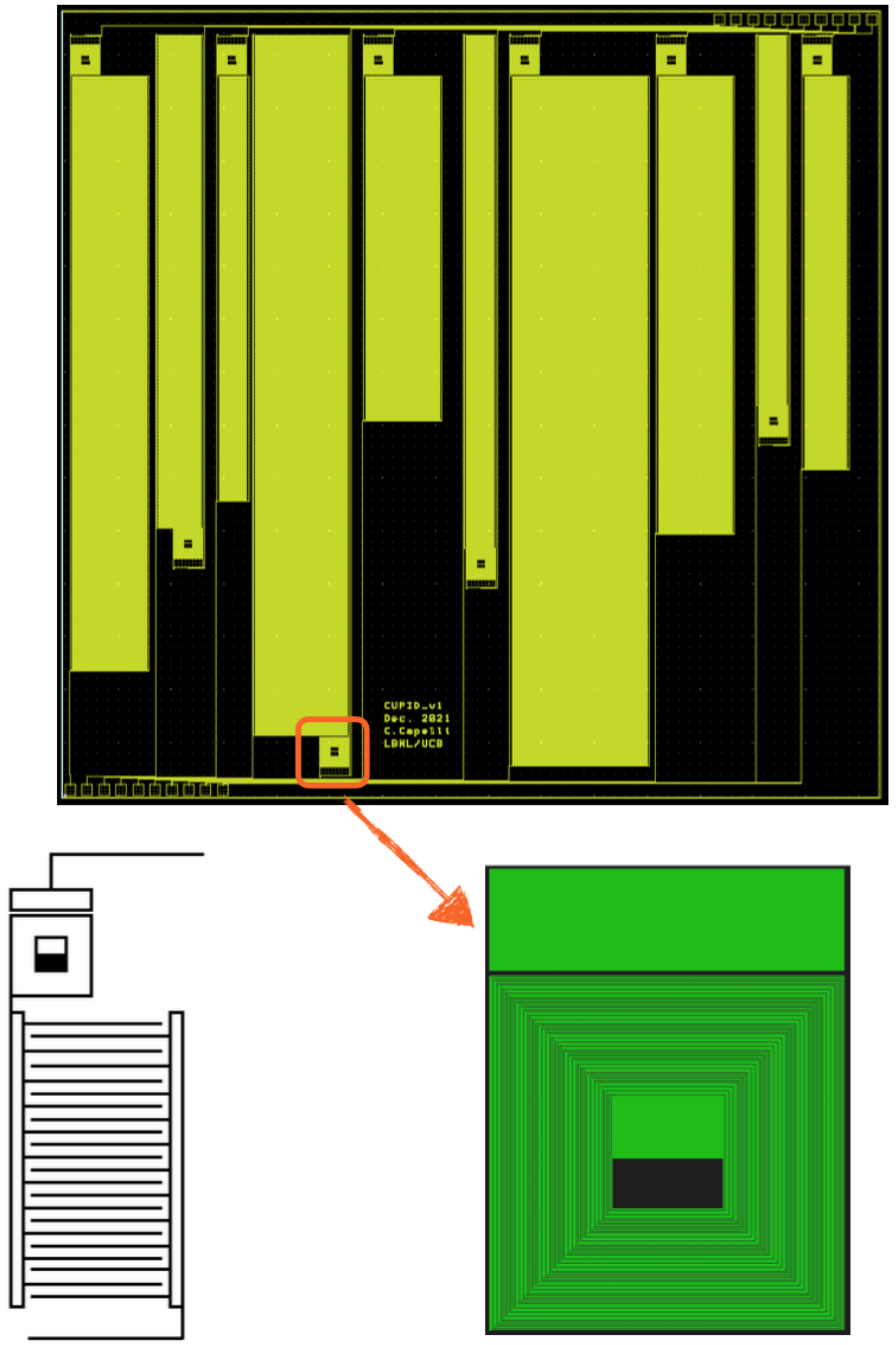
- CUPID: ~3000 TES sensors for both light detectors + crystal readout
- CUPID-1T: O(10k) channels
- Minimize heat load from SQUIDs + cabling
- Frequency domain multiplexing
- Small multiplexing factors on the order of 10

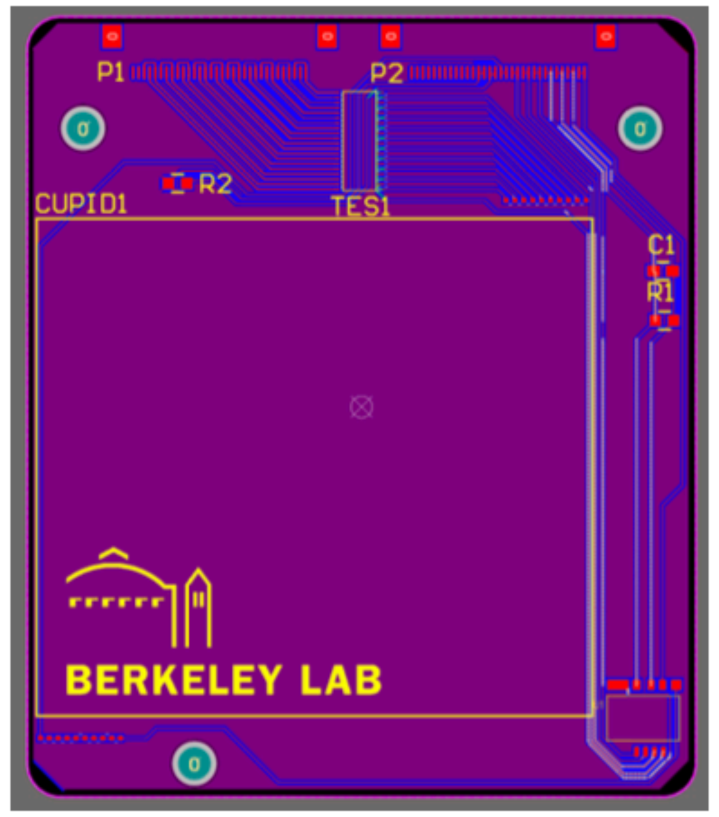


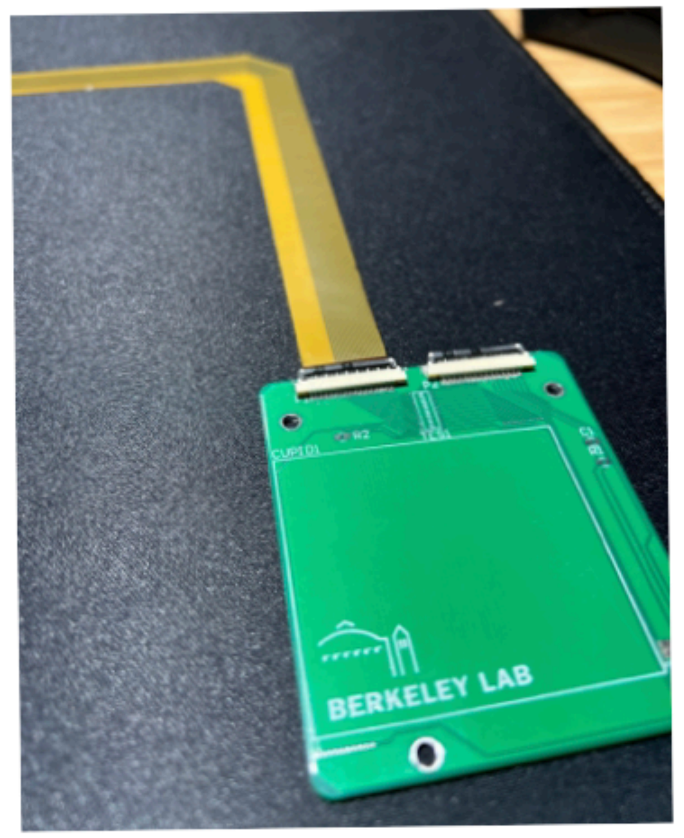
Proc. of SPIE Vol. 9914 99141D-1

Multiplexing

- 10 resonators with L ~4 μH and variable C
- Lithographic spiral inductors with interdigitated capacitors on Si substrate
- Cross talk expected < 0.4%
- Resonance Q-factor ~ 100kHz
- PCB with resonator at 700 mK in magnetic shield
- Superconducting Al traces on Kapton to connect TES to MUX chip

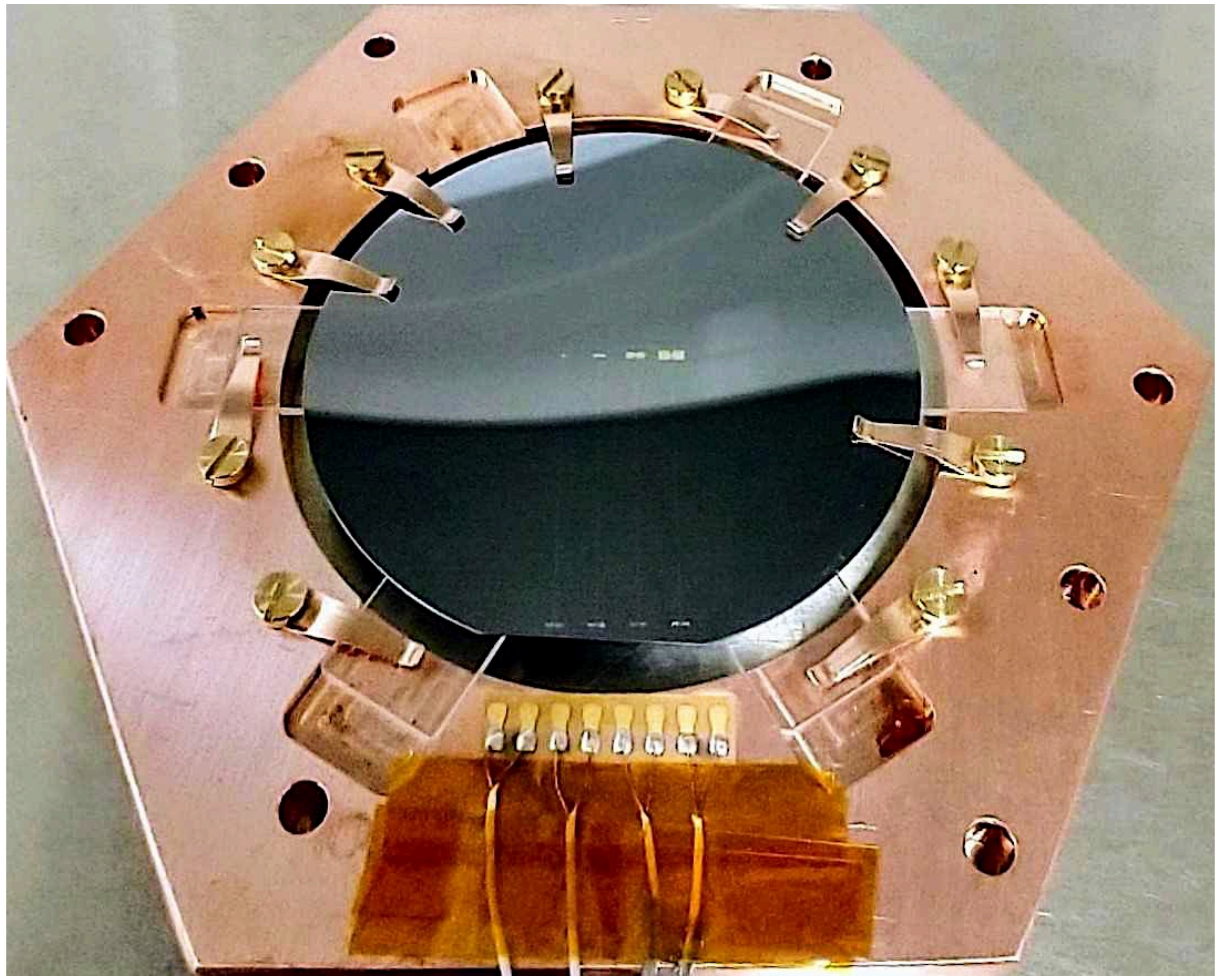


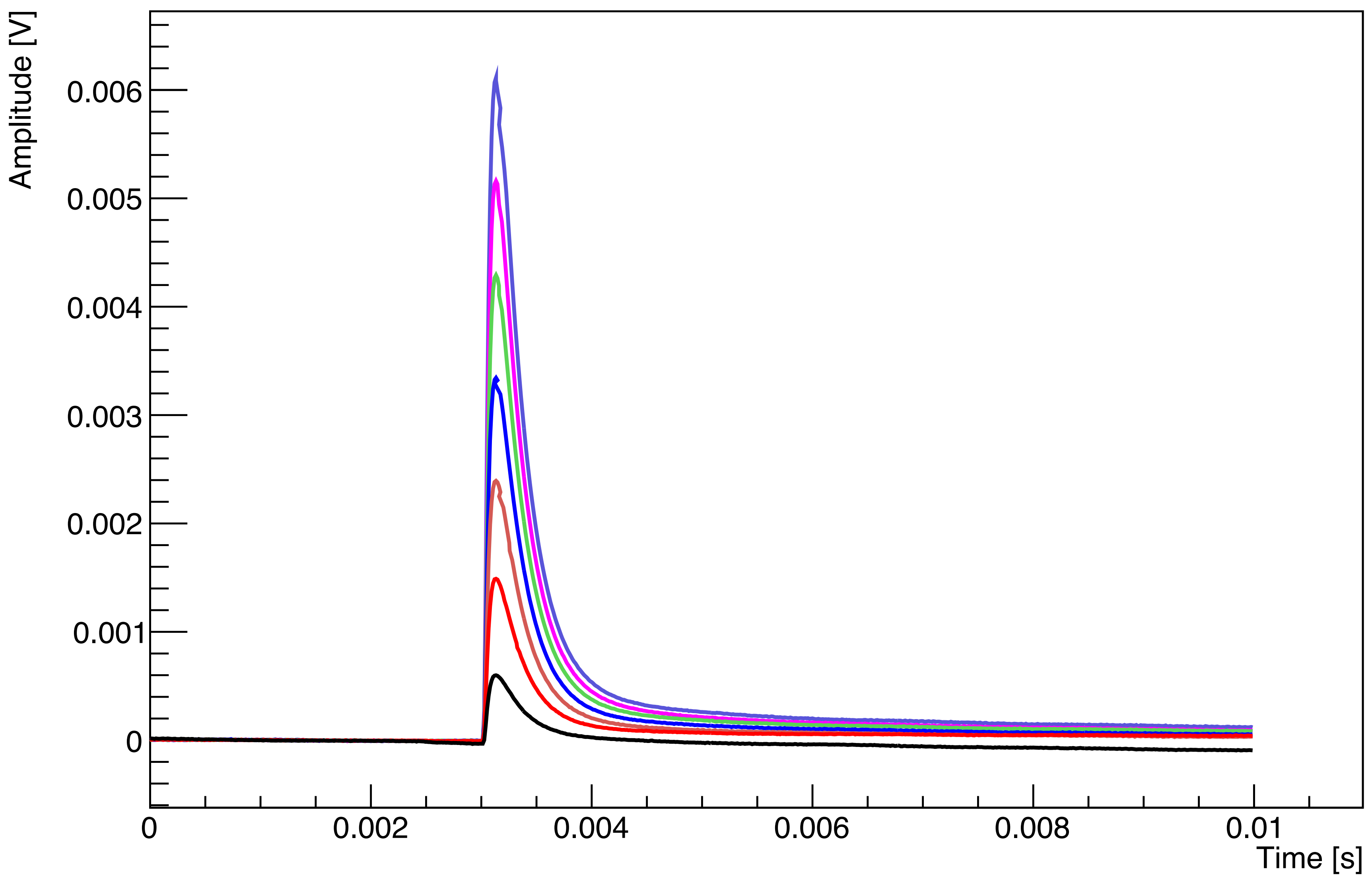




Conclusions

- TES R&D progress from ANL, UCB, LBL collaboration
- Successful campaign to improve G via Au pads
- Energy scale calibration with ^{55}Fe + photon statistics (LED pulses)
- ~50 eV baseline resolution would meet CUPID energy threshold requirement
- Timing resolution ~20 μs & fast rise times satisfy CUPID requirements for 2νββ pileup rejection
- Further tests underway to optimize TES design, improve in situ. noise, study position dependence, and implement multiplexing



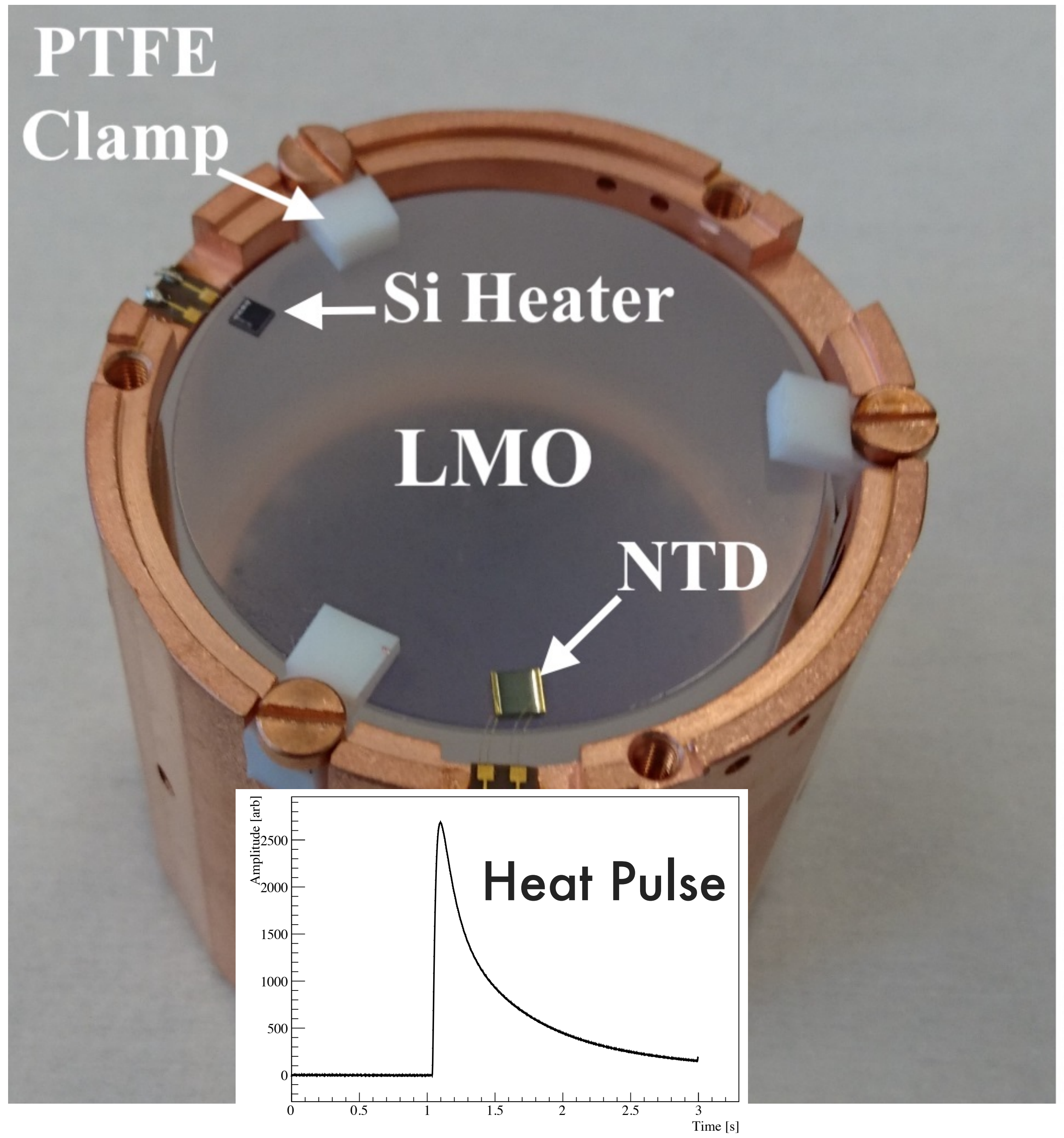



Thank You

CUPID-Mo

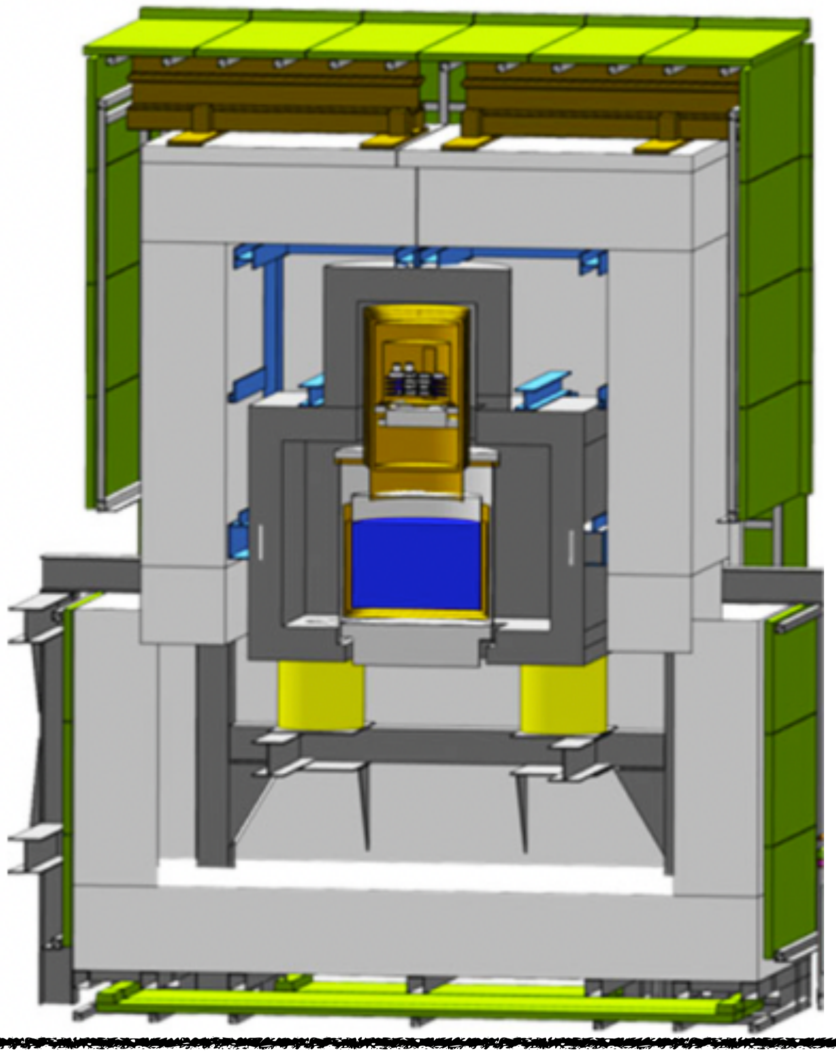
C. Capelli (E14.10): Transition-edge sensor multiplexing multiplexing readout for CUPID-1T

V. Singh (G12.2): Low-temperature optical photon detectors for the CUPID experiment

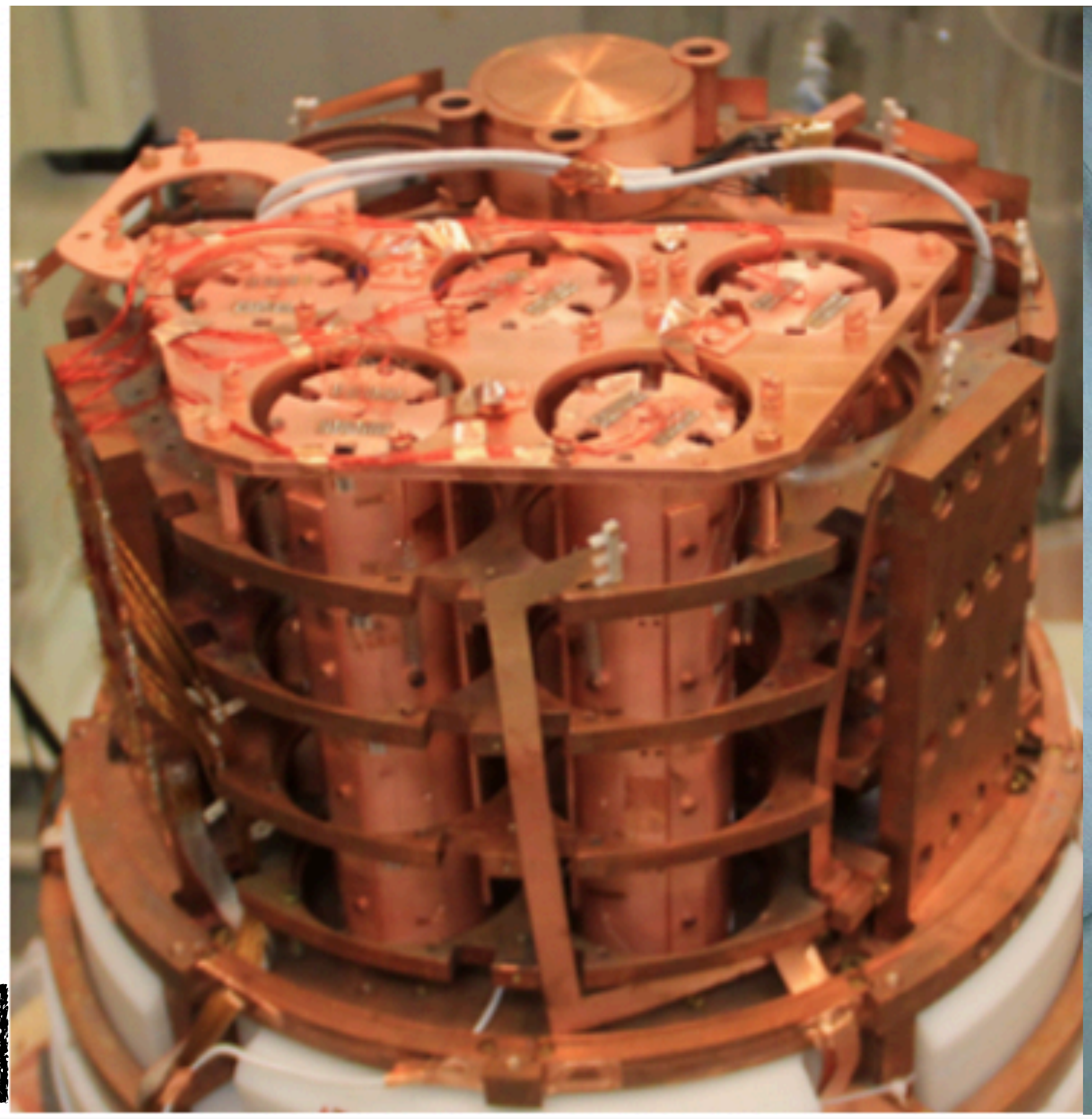


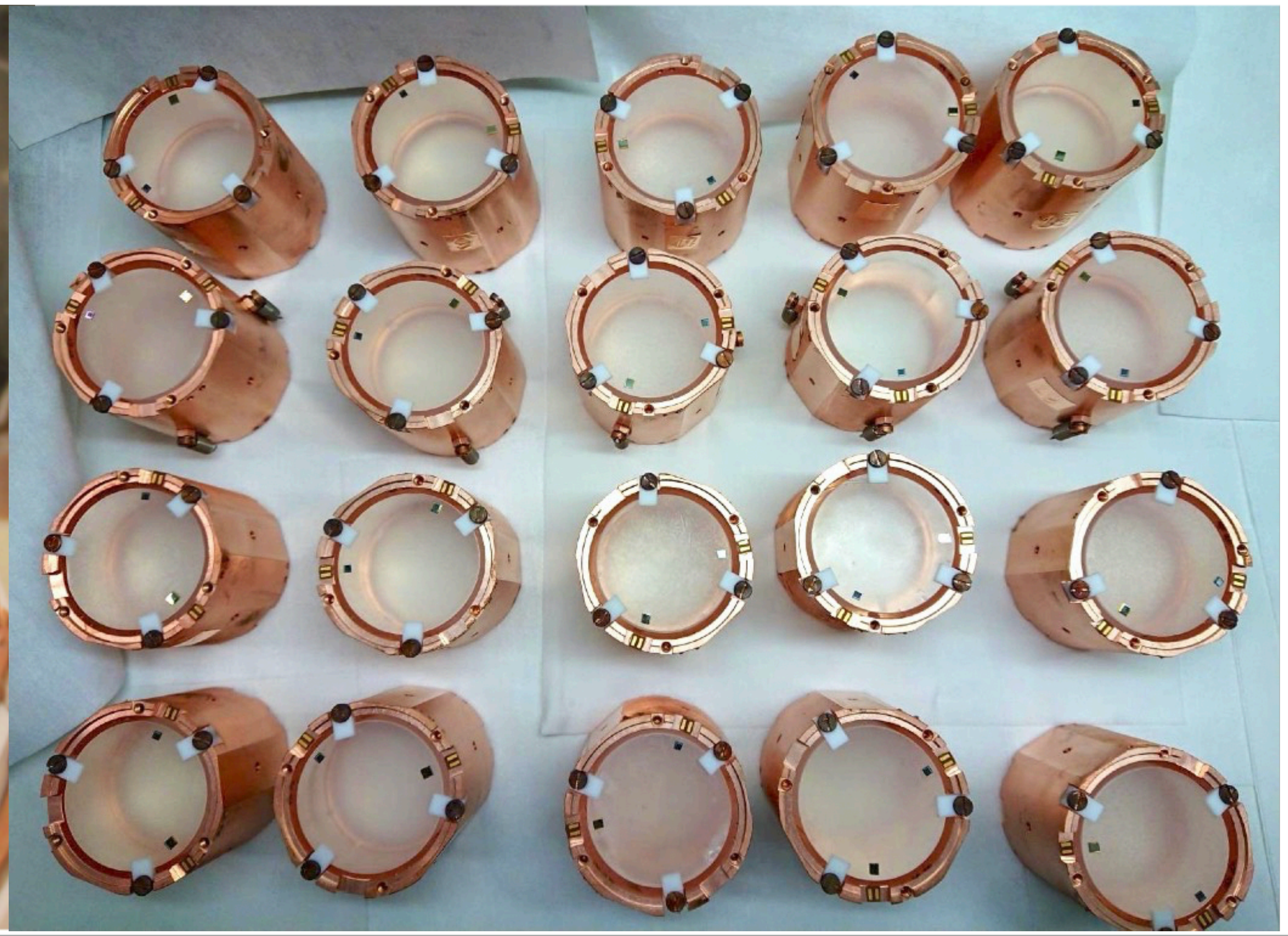
- Operated at Laboratoire Souterrain de Modane (LSM) in the EDELWEISS cryostat
- 20x ~210 g cylindrical $Li_2{}^{100}MoO_4$ (LMO) crystals (ø44 mm x 45mm) with ^{100}Mo enriched to ~97%
- Operated as scintillating calorimeters with neutron transmutation doped (NTD) thermistors for readout
- ~20 mK operation March 2019 – July 2020
- Ge wafer with SiO anti-reflective coating for light detectors (LD)

Parameter	LMO	LD
R_{NTD} (MΩ)	1.4	0.8
Rise time (ms)	24	4
Decay time (ms)	300	9
Baseline Resolution (keV FWHM)	2.0	0.15

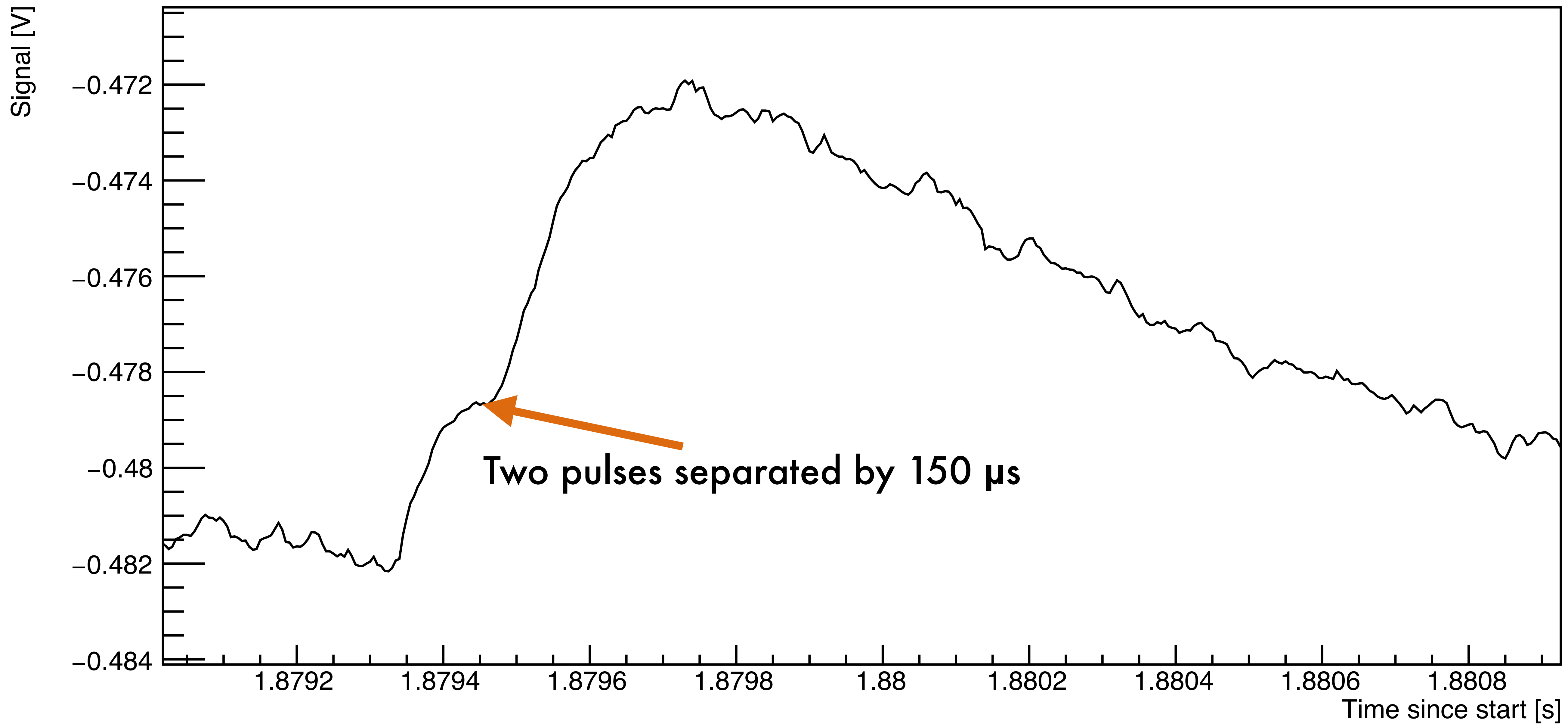


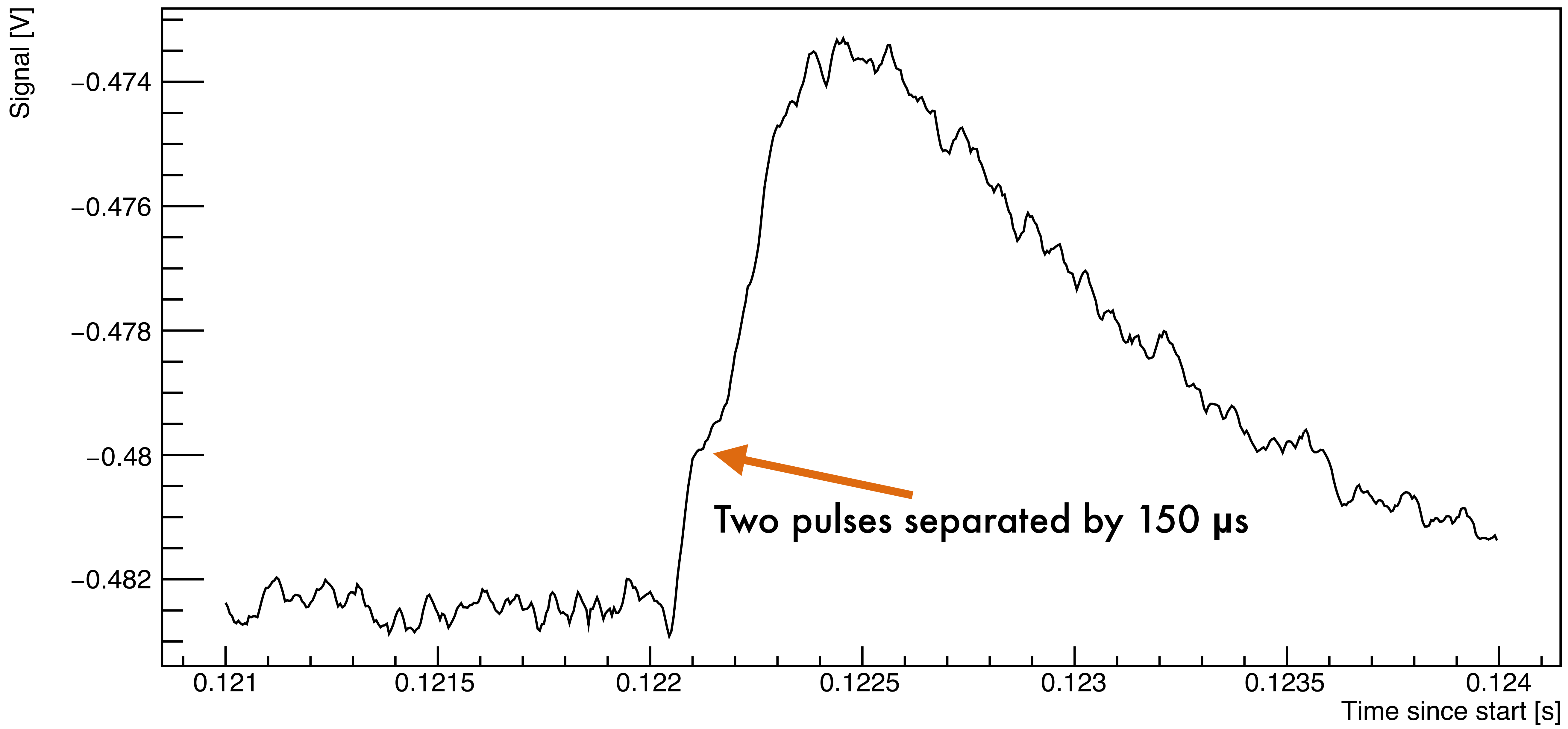
European Physical Journal C 80, 44 (2020)





Timing Resolution

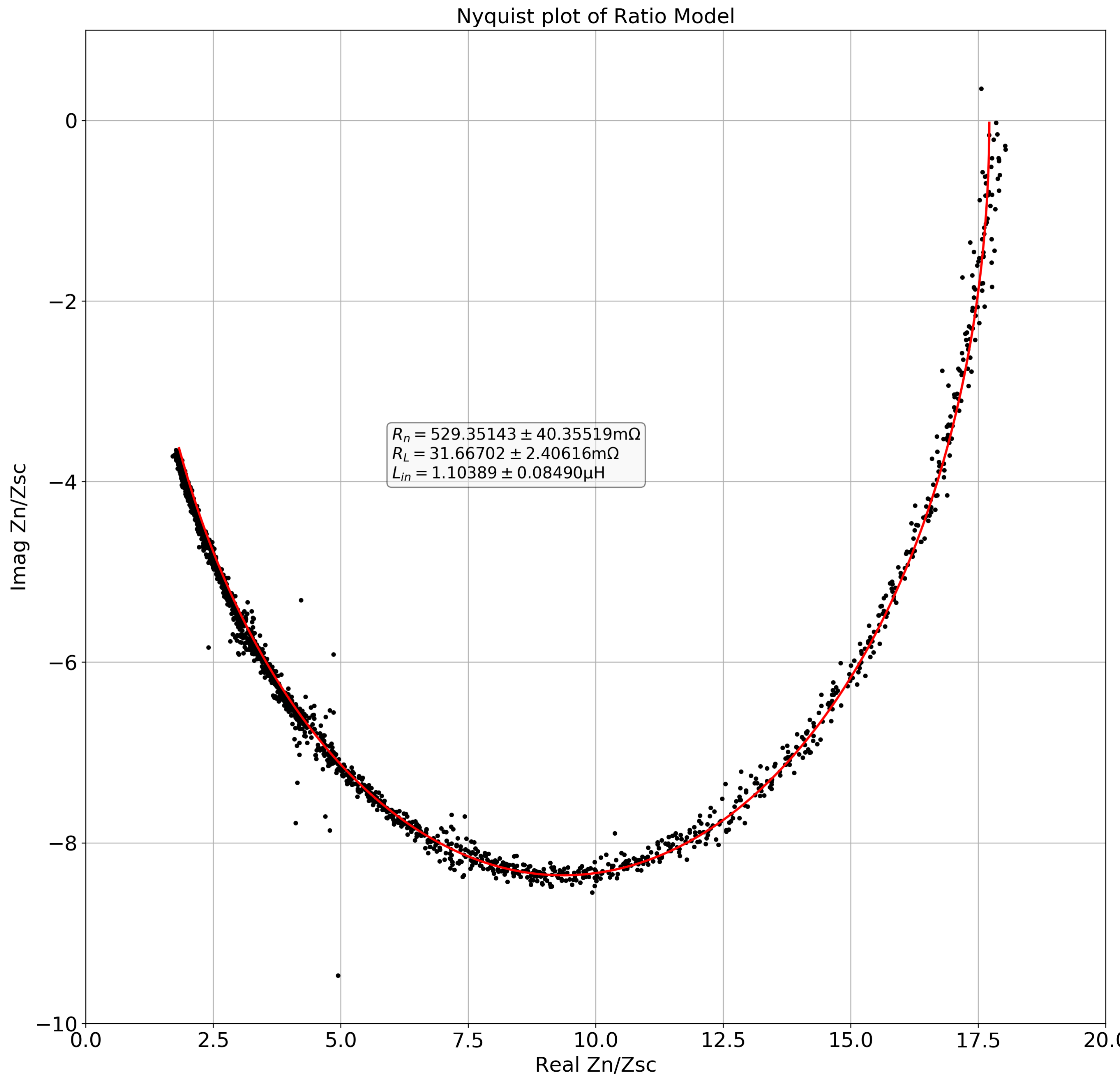


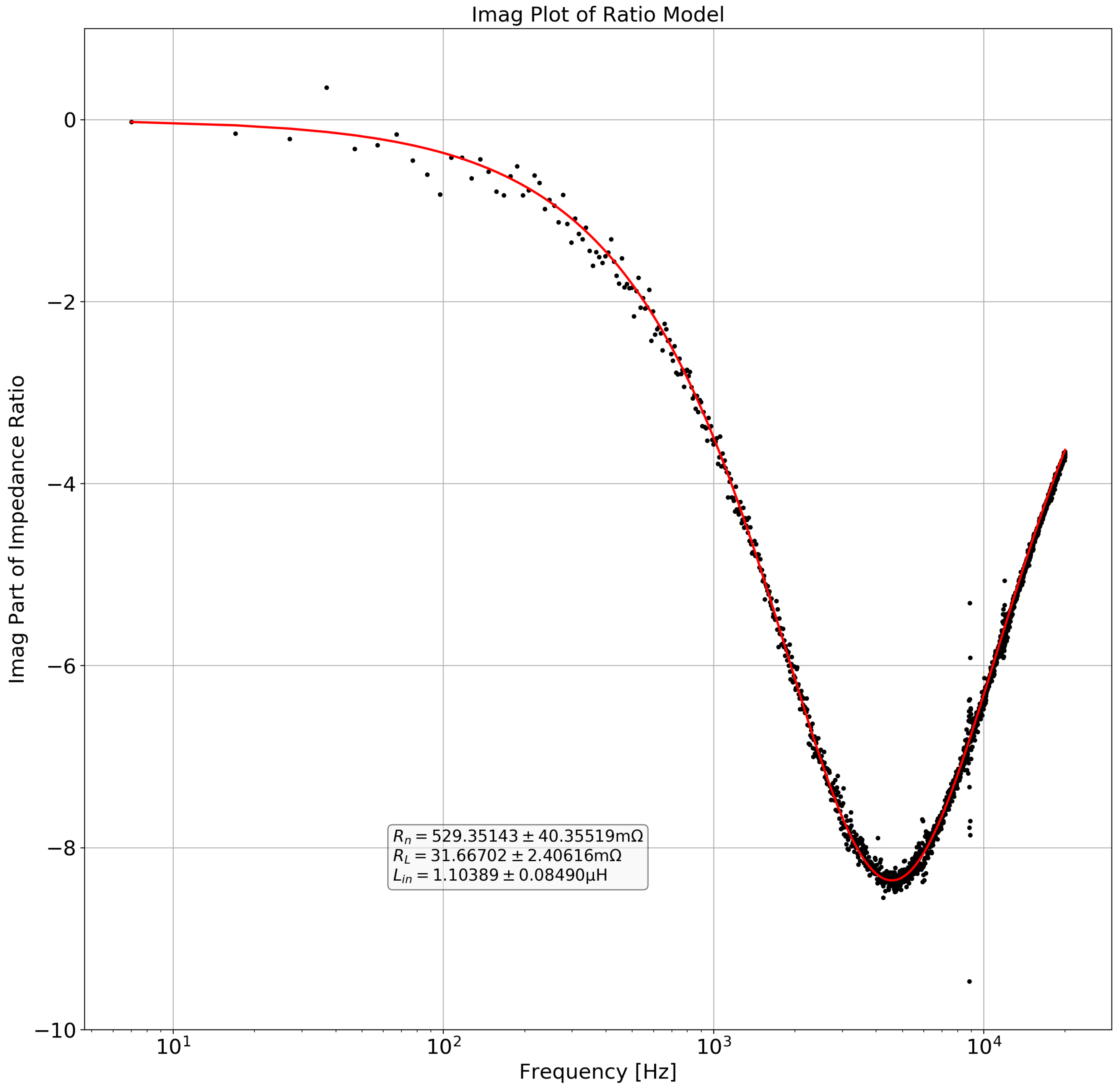


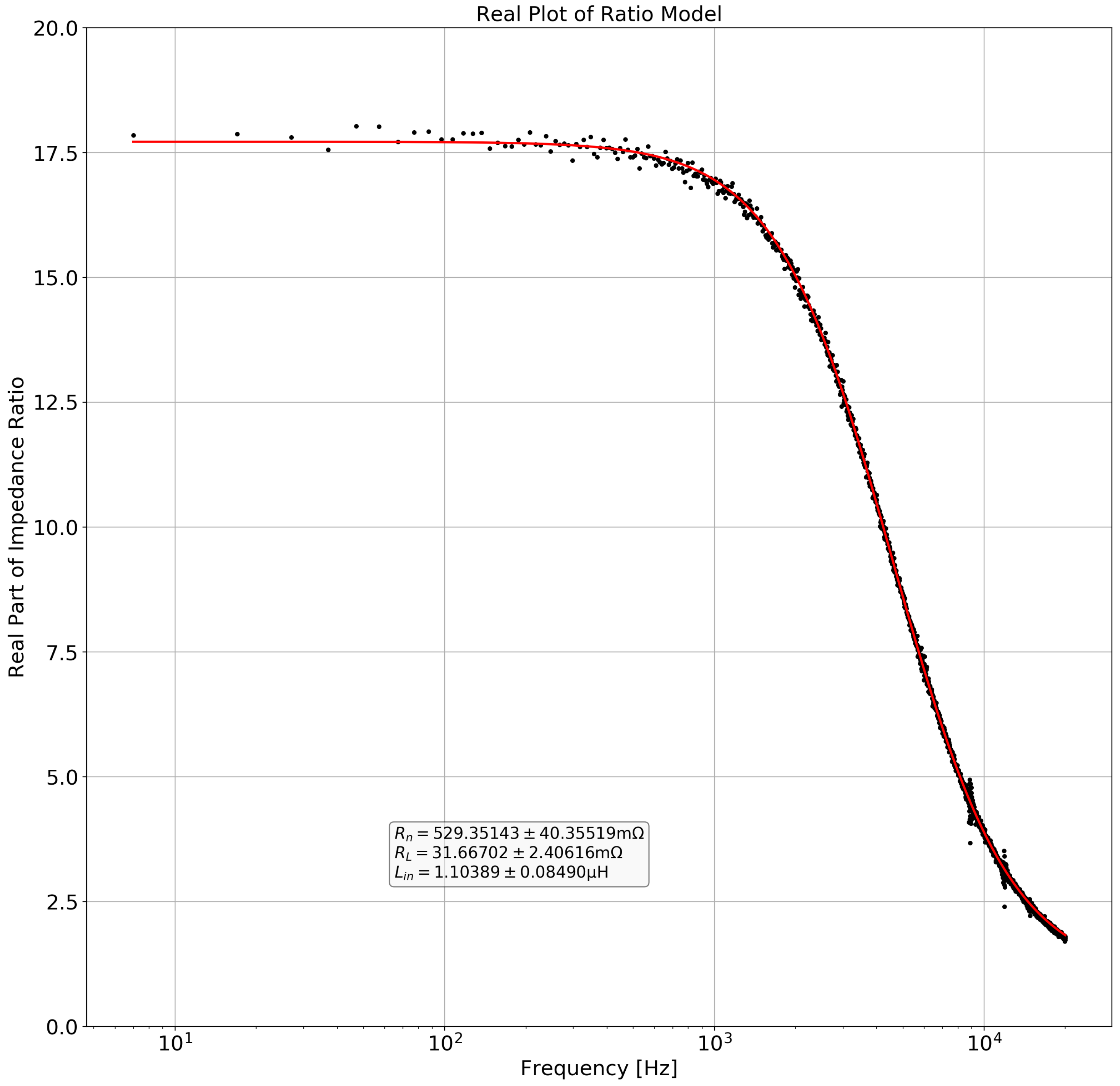
- Able to distinguish pulses 150 µs apart
- Allows for pulse shape discrimination for pileup events

Complex Impedance Transfer function

- Suggests we have about 1 uH of parasitic input line inductance
  - This needs to be improved
- Normal and load resistances agree very nicely with IV data
- Obtaining actual Z_{tes} requires a few improvements to DAQ process and noise environment
- Required for full electrothermal characterization

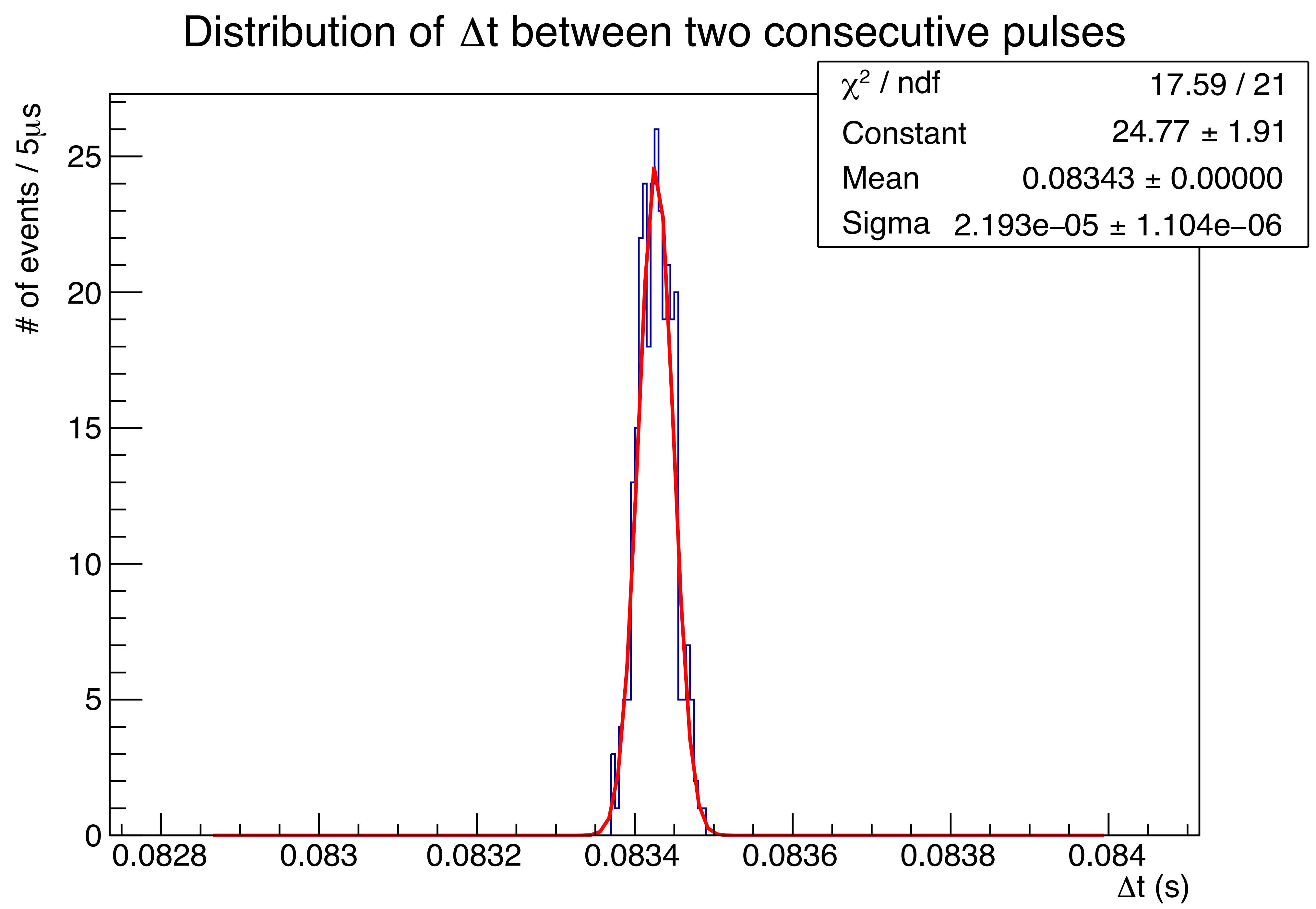


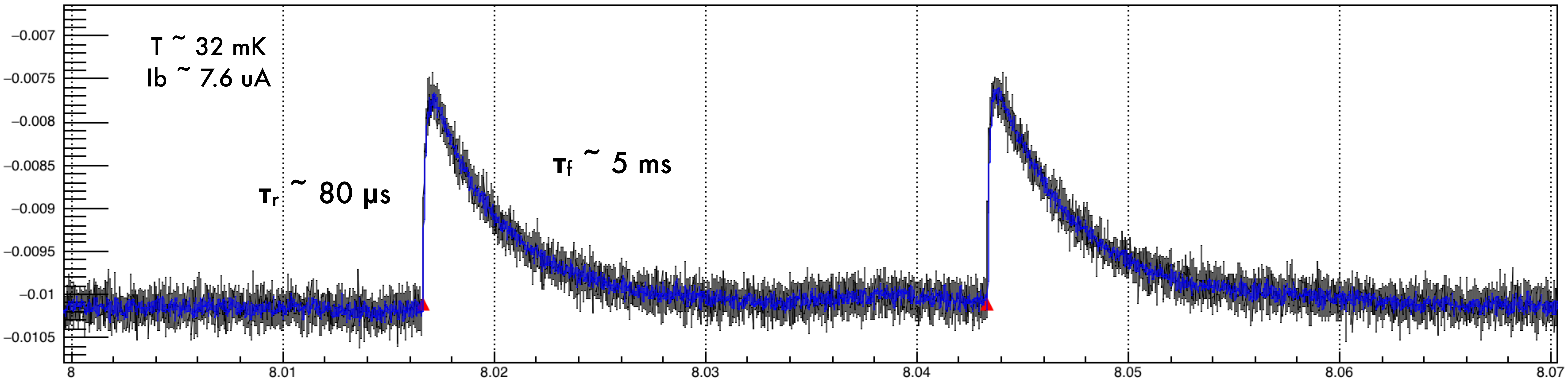




TES LD Timing

- Send heater pulses with variable time separation
- Examine timing resolution and pileup
- Pulses for a given train have fixed time separation
  - Can be used to give approximation of time resolution



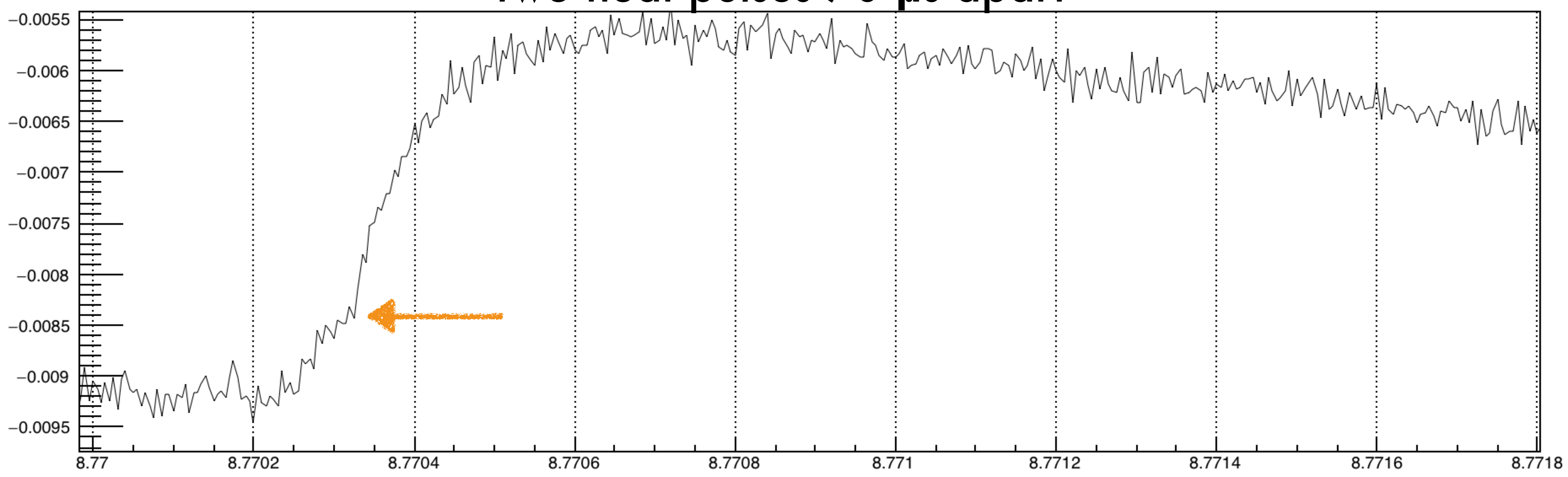


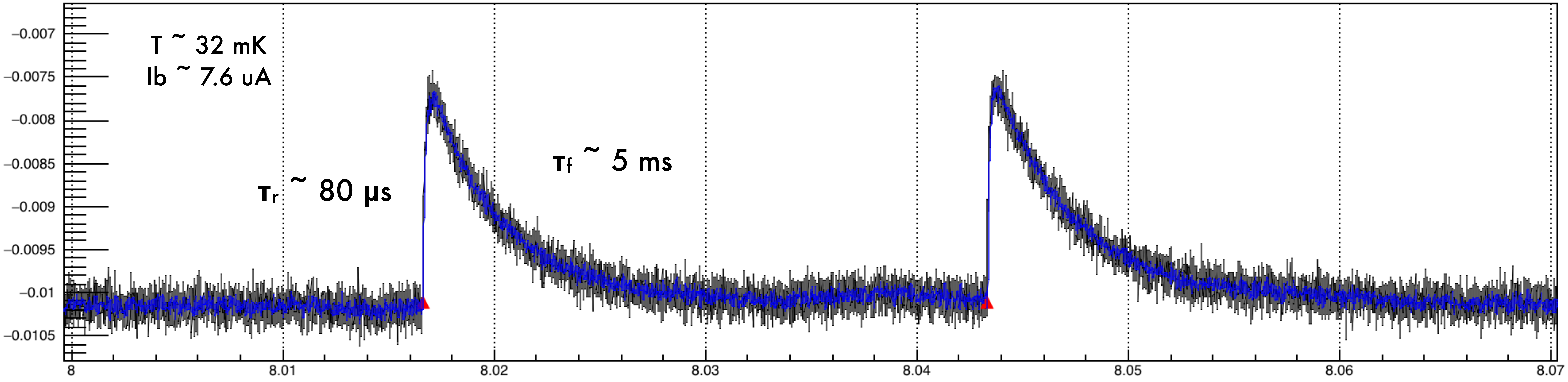
- Timing resolution σ_t ~ 20 μs

TES LD Timing

- Pileup discrimination needs to be quantified beyond simple 'by-eye' examination
- Timing only examined in 32 mK data
  - This is very close to device T_c
  - Studies at lower temperature underway

Two heat pulses 70 µs apart

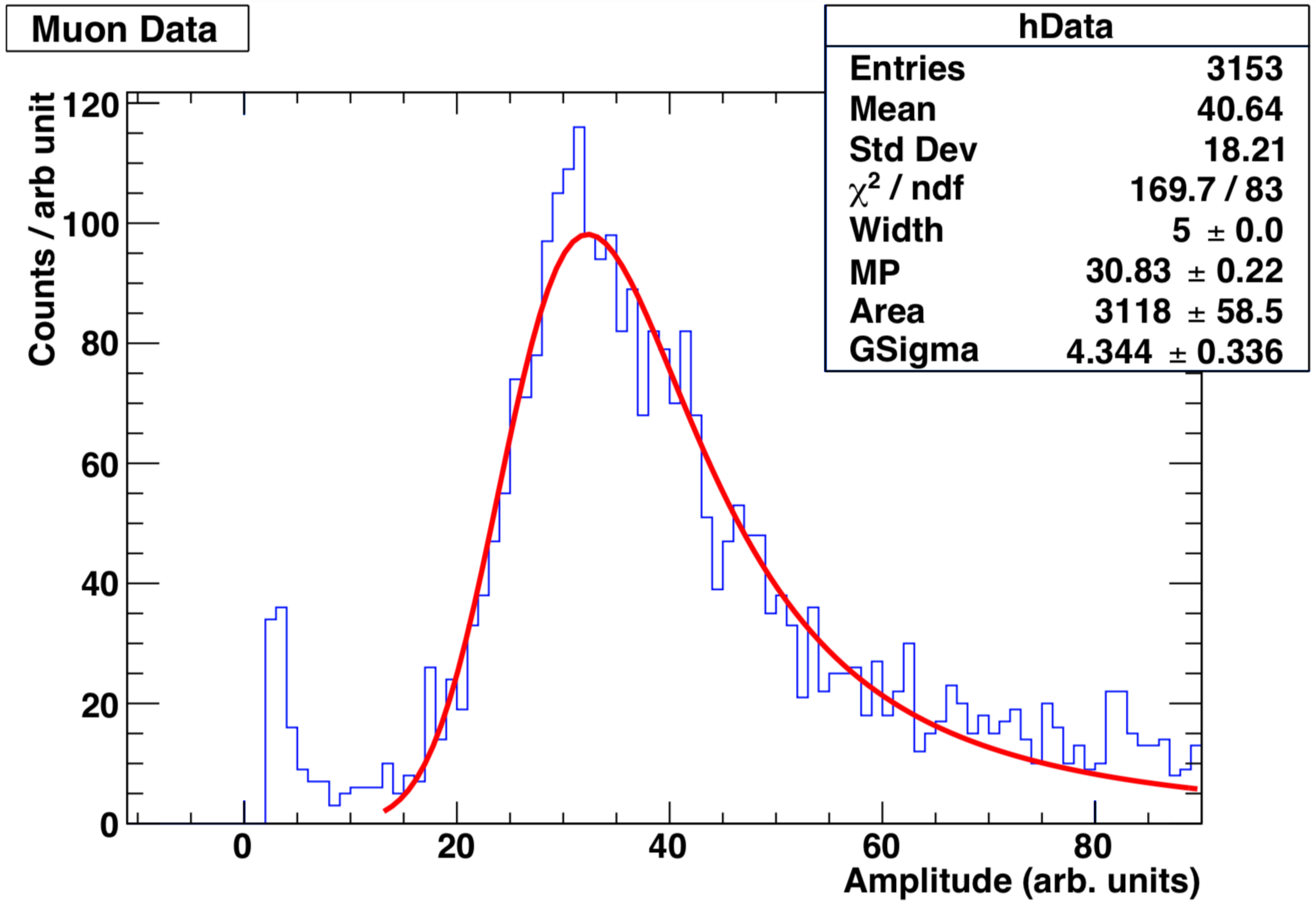


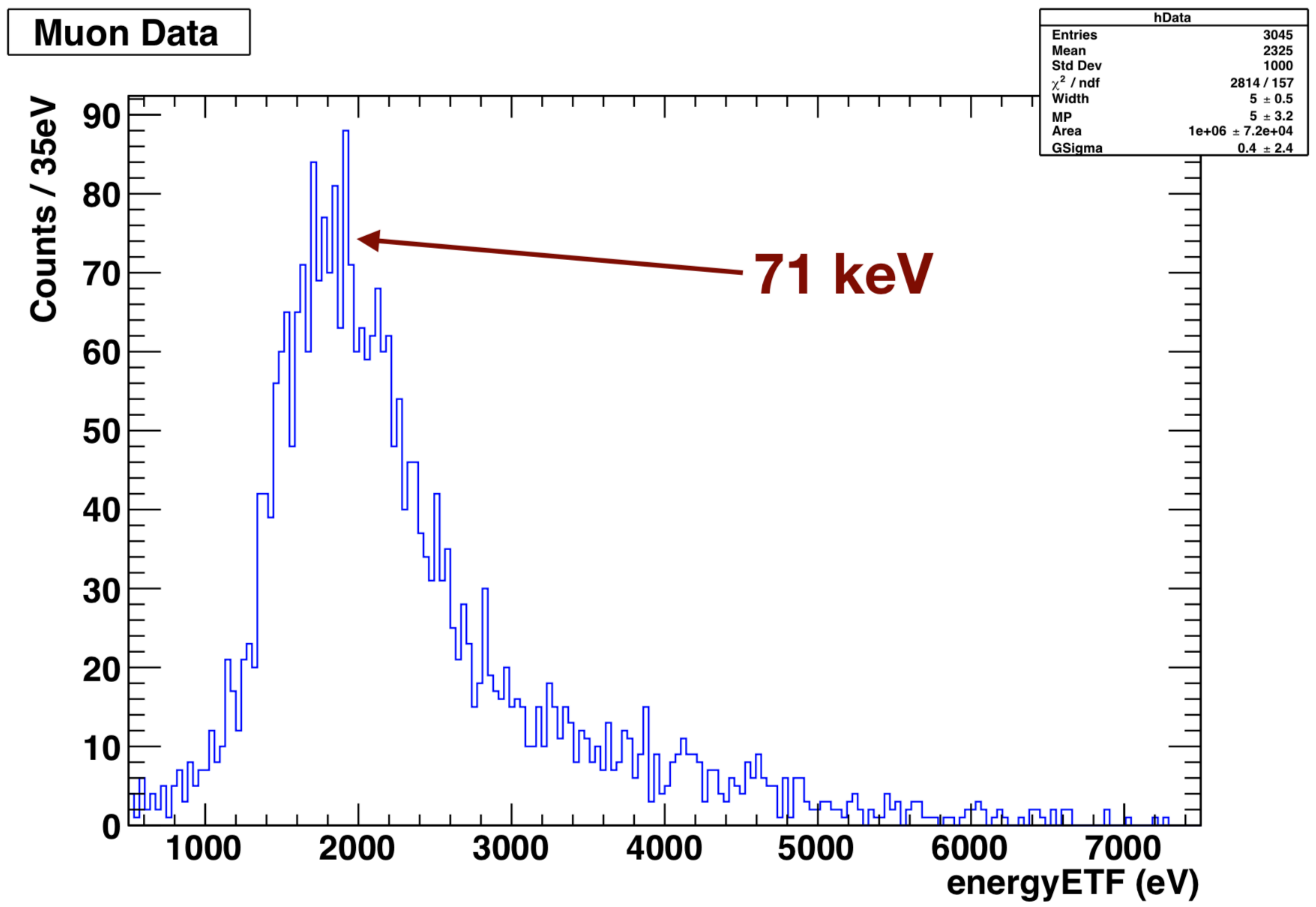


TES Energy Measurements

- Attempt to get idea of phonon collection efficiency by using cosmic ray muons

- 2 days of data taken with scintillating muon paddle placed ~1.5 m below TES





- Vertically traveling muons will deposit ~ 71 keV in 275 μm of Si

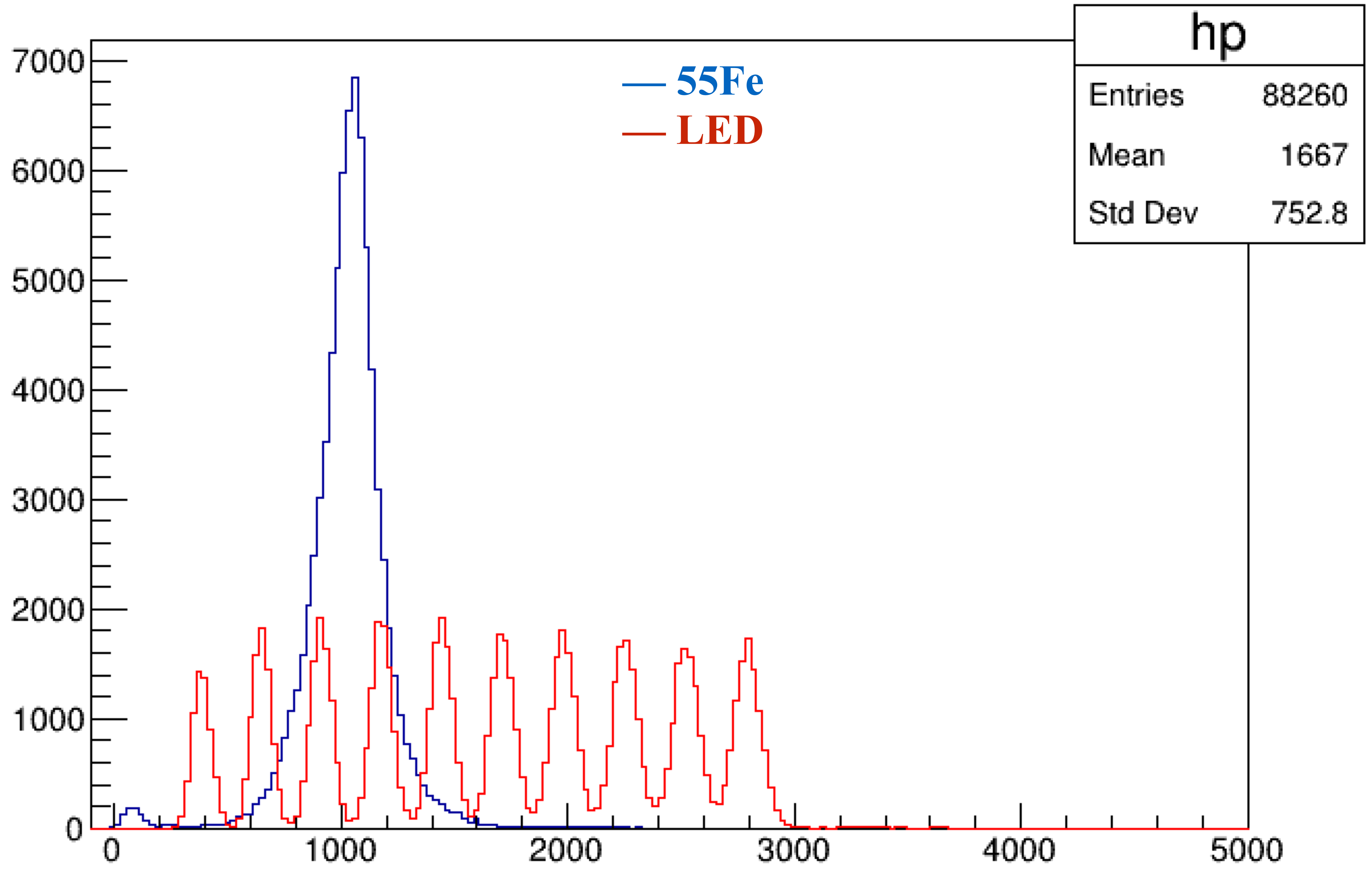
- Integrate total power through the TES pulse => Gives a rough estimate of energy through the TES

- $E_{ETF} = (i_0 R_L - V) \int \delta i(t) dt + R_L \int \delta i(t)^2 dt$

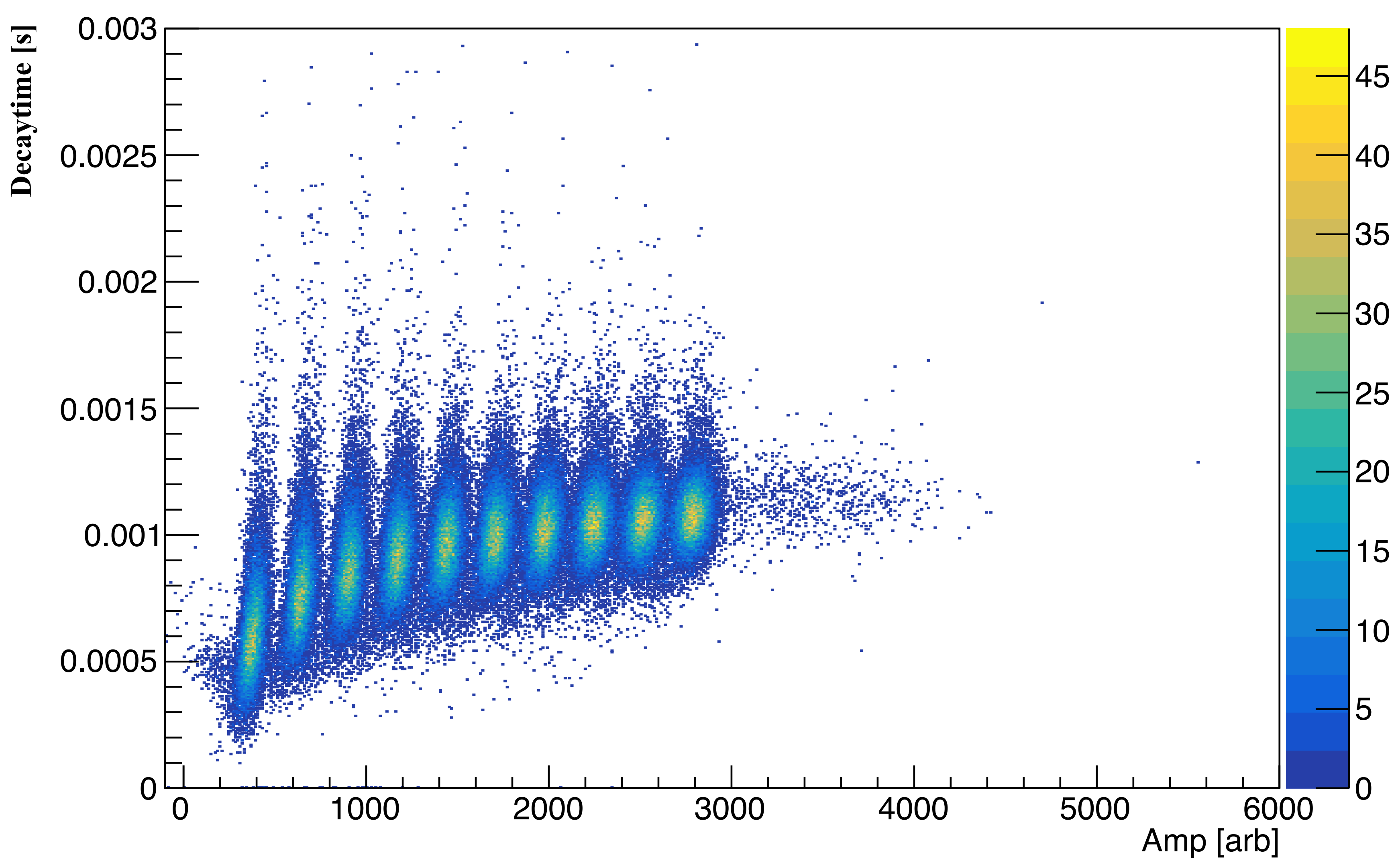
- Using ETF integral muon peak located around 2 keV

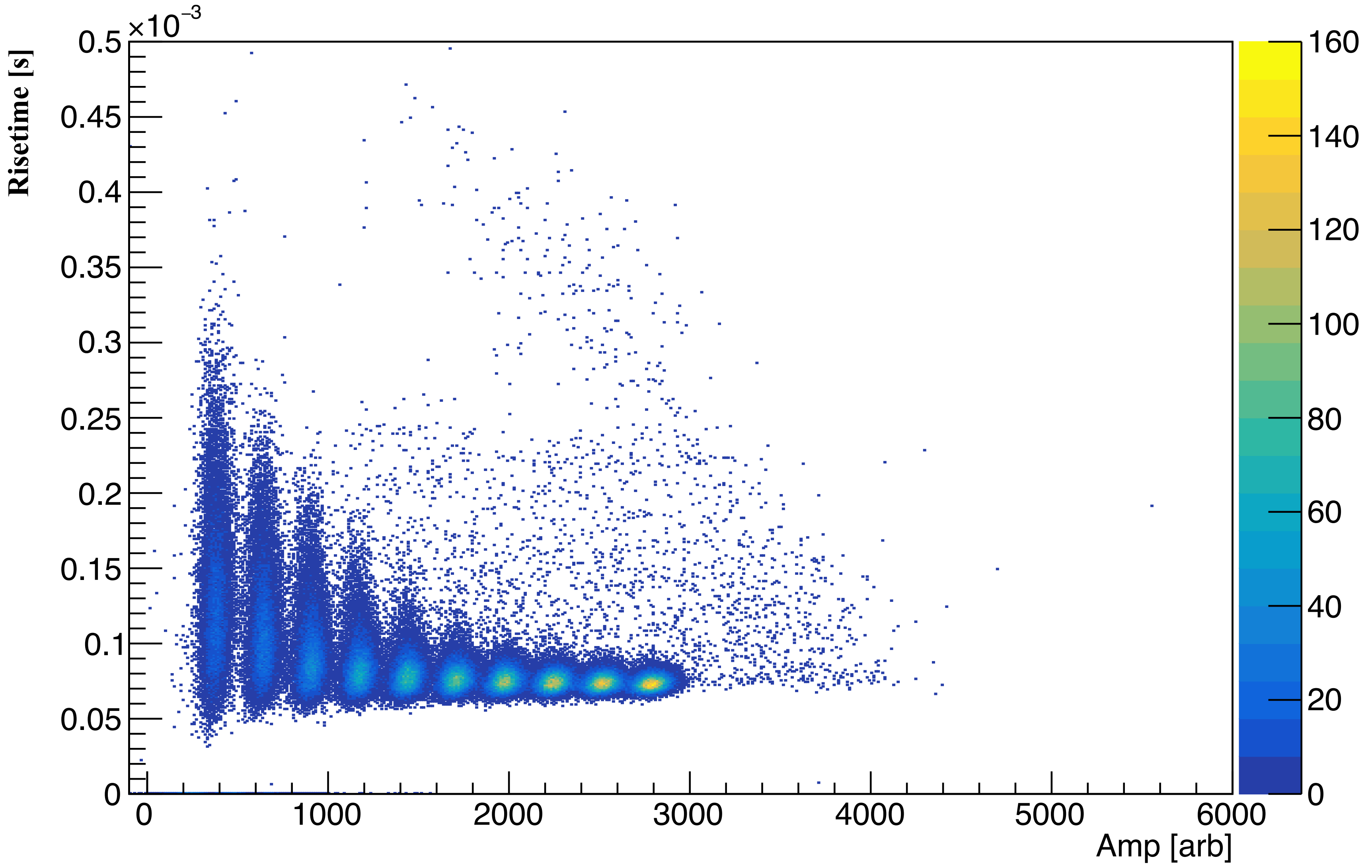
Pulse Measurements

- Run LED pulses alongside 55Fe calibration
- Allows rough calibration of LED energy scale based on a linear calibration from the 5.9 keV 55Fe peak

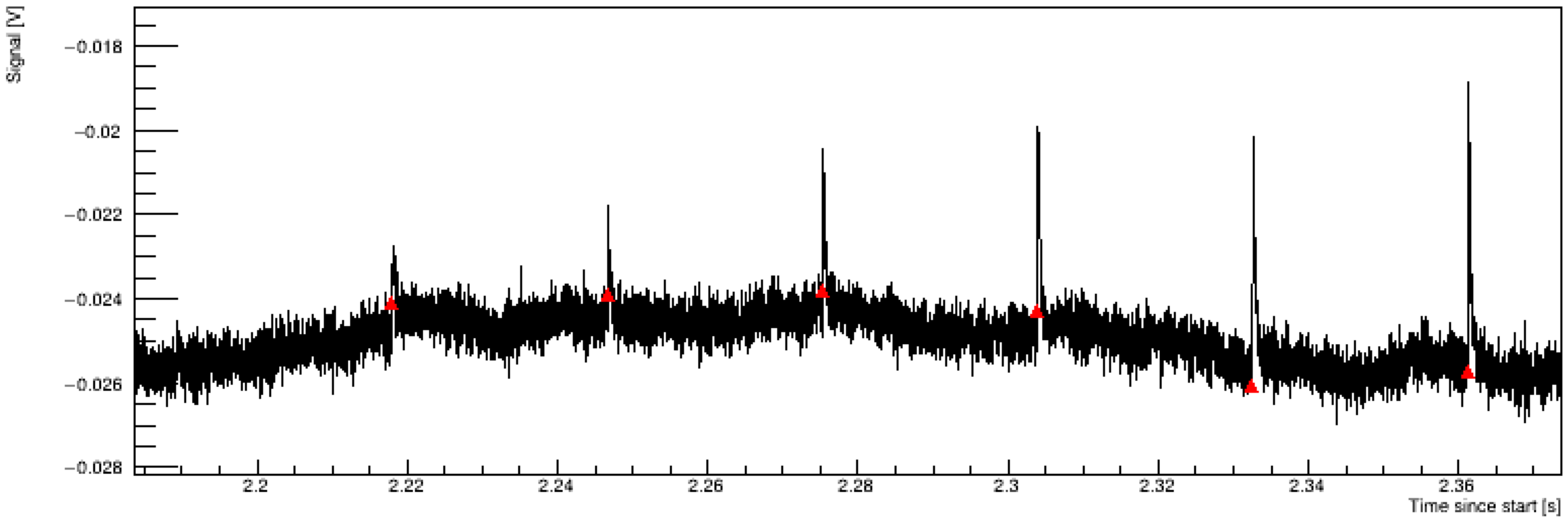


- Risetime ~ 75 µs
- Decaytime ~ 1ms

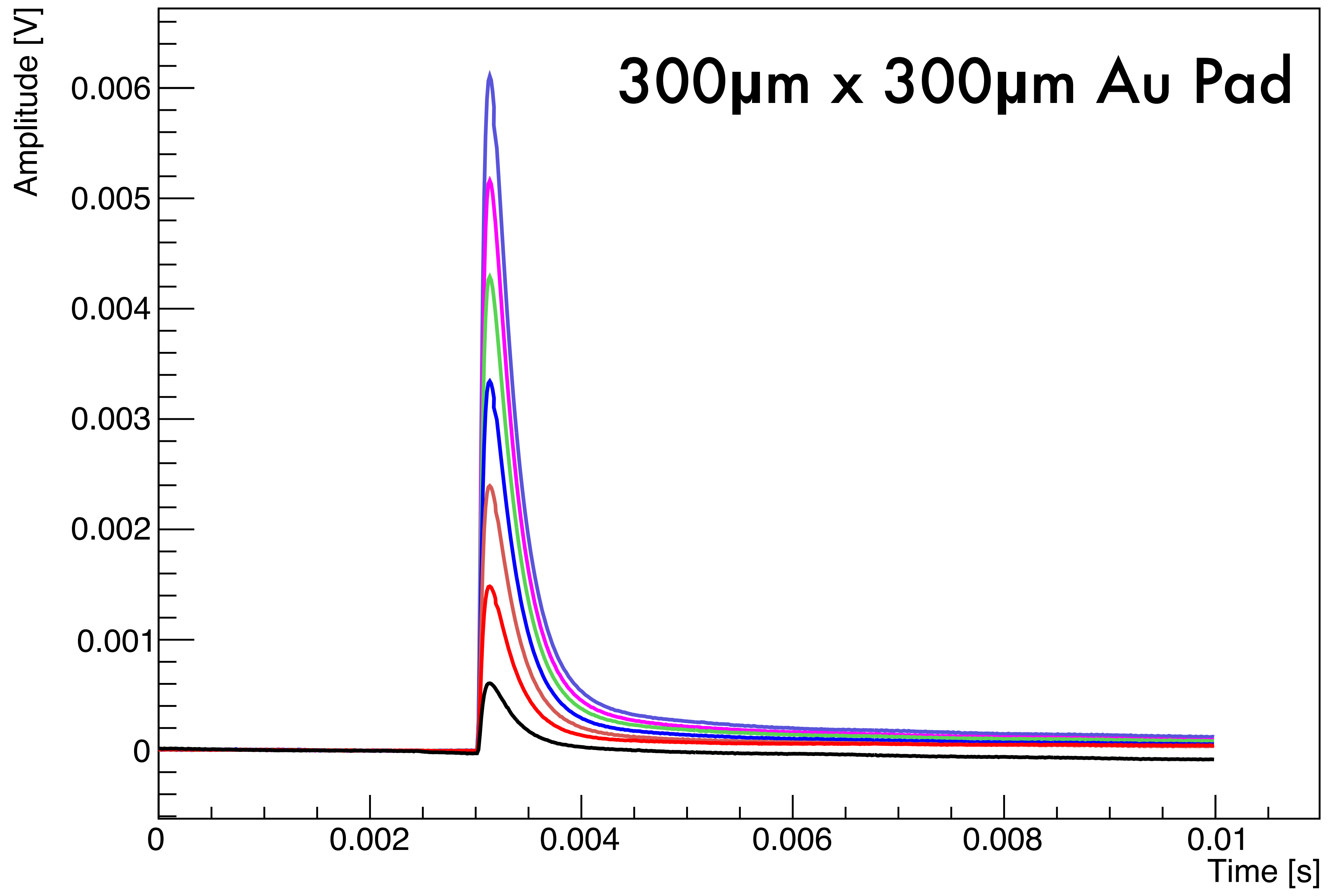


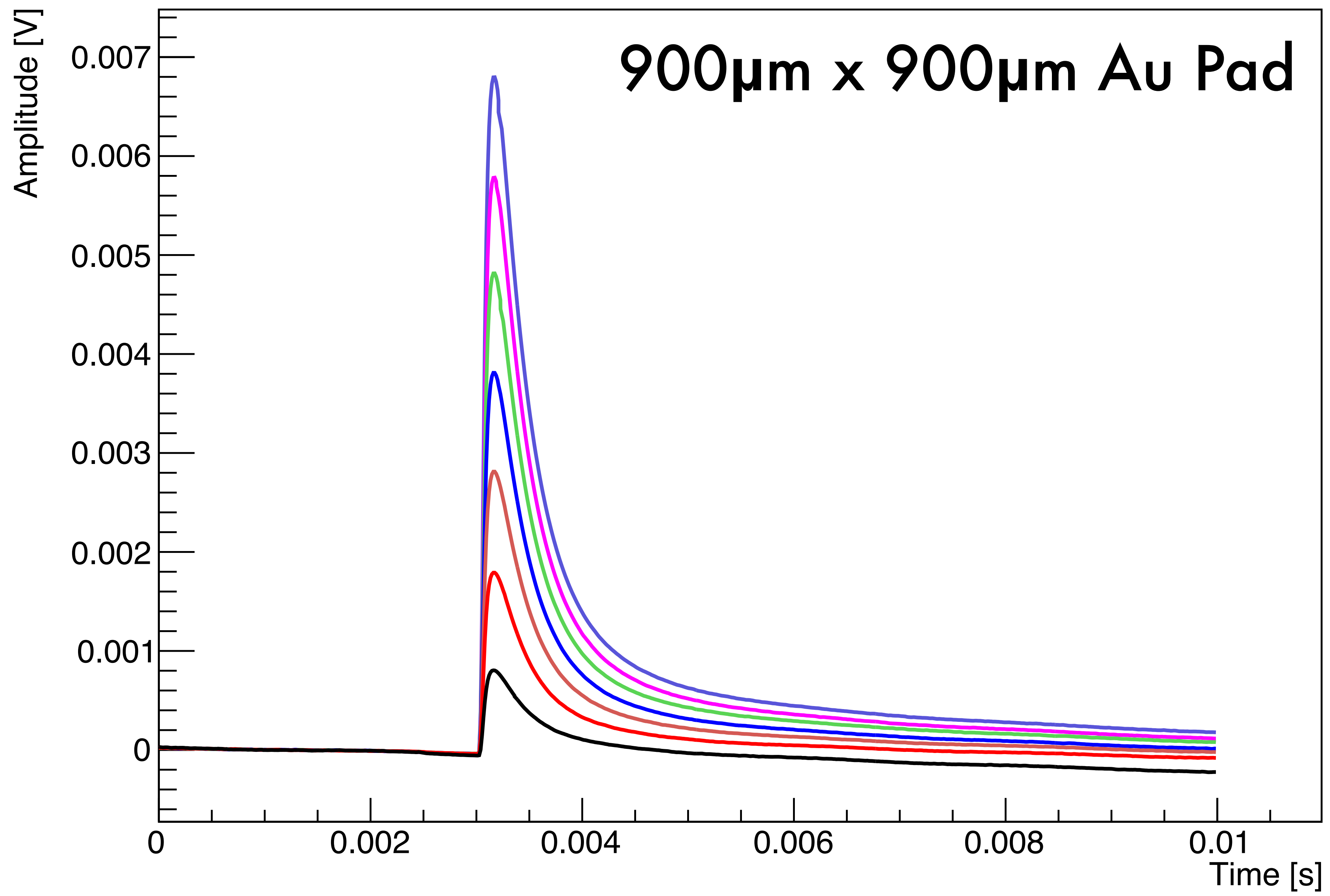


Pulse Measurements



- Remove 55Fe source and examine LED only
- Retrofit new active vibration dampening system between measurements
- Lower incident energy of LED pulses
- 7 LED pulses of duration 250 – 2750 ns
    - ~ 500 eV – 3500 eV





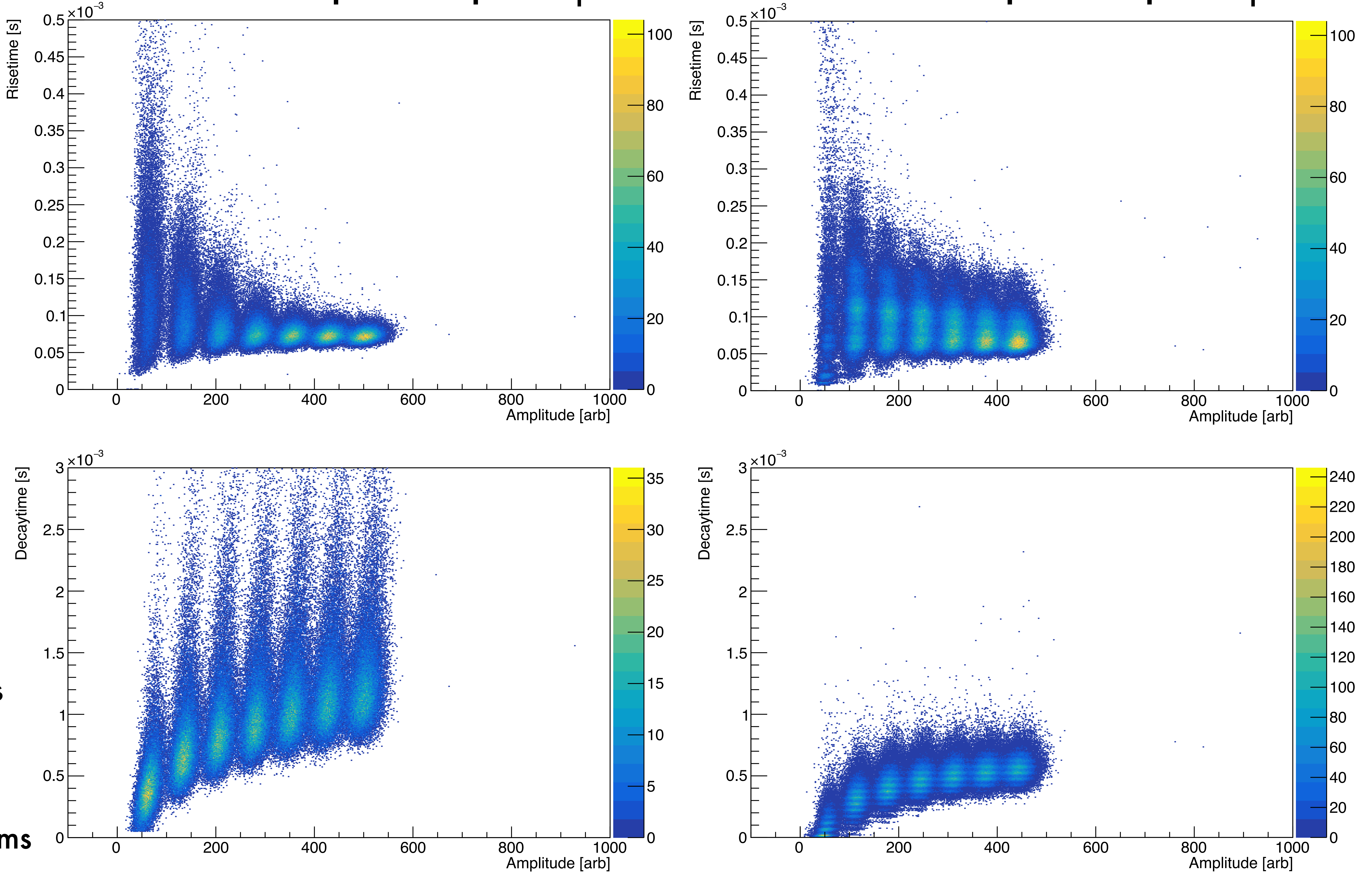
Average TES Pulses

Pulse Shape

- LED pulses on TES at 15.4 mK, TES resistanc 200 mΩ
- Risetimes are fast (<100 µs)
- Decaytimes ~ 1ms
  - Amplitude dependence possibly due to noise
- Walking average pulses:
  - No more amplitude dependence
  - Large Au Pad:
    - Risetime ~71 µs, decaytime ~1.5 ms
  - Small Au Pad:
    - Risetime ~61 µs, decaytime ~ 0.73 ms

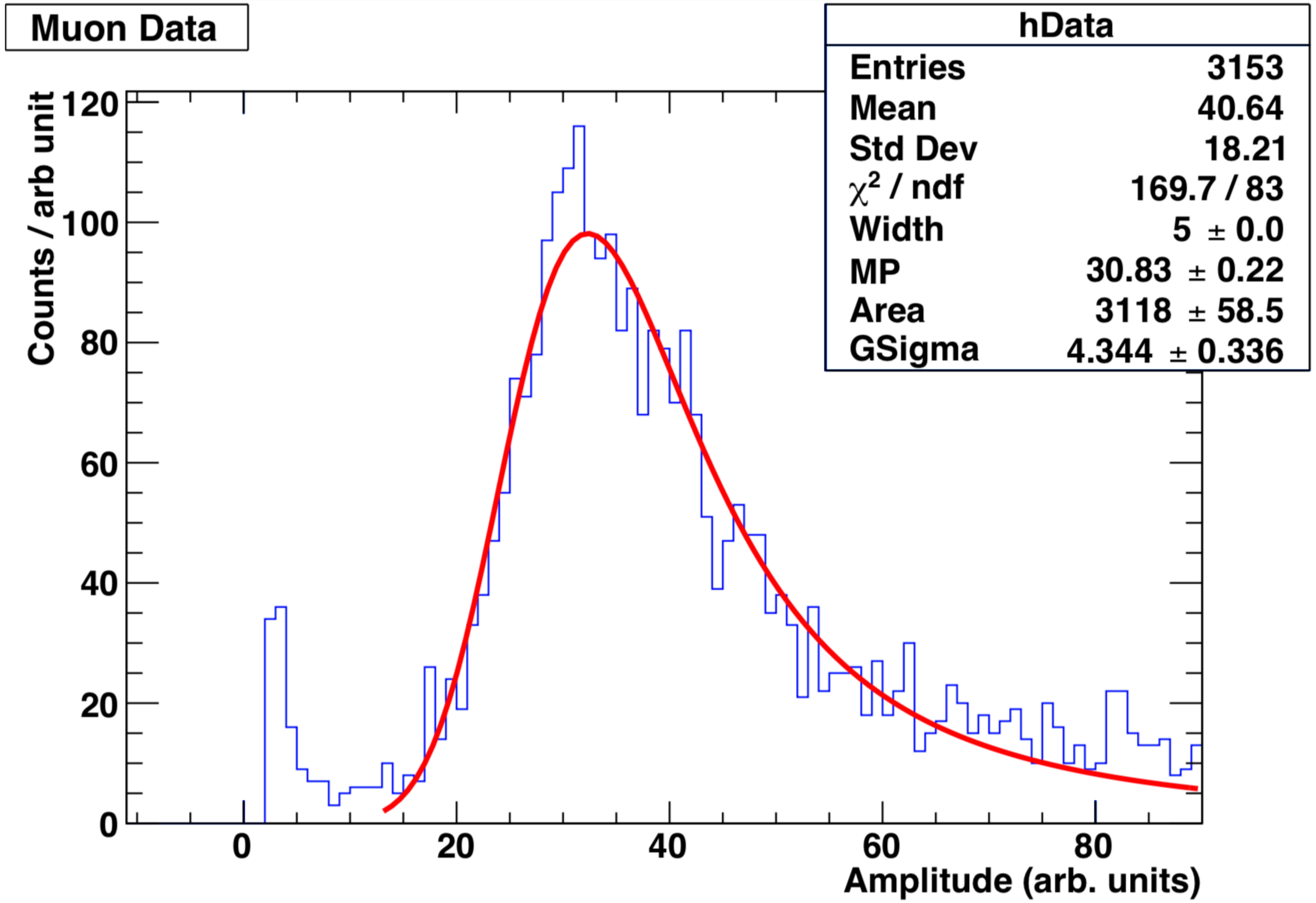
900µm x 900µm Au pad IrPt

300µm x 300µm Au pad IrPt



TES Energy Measurements

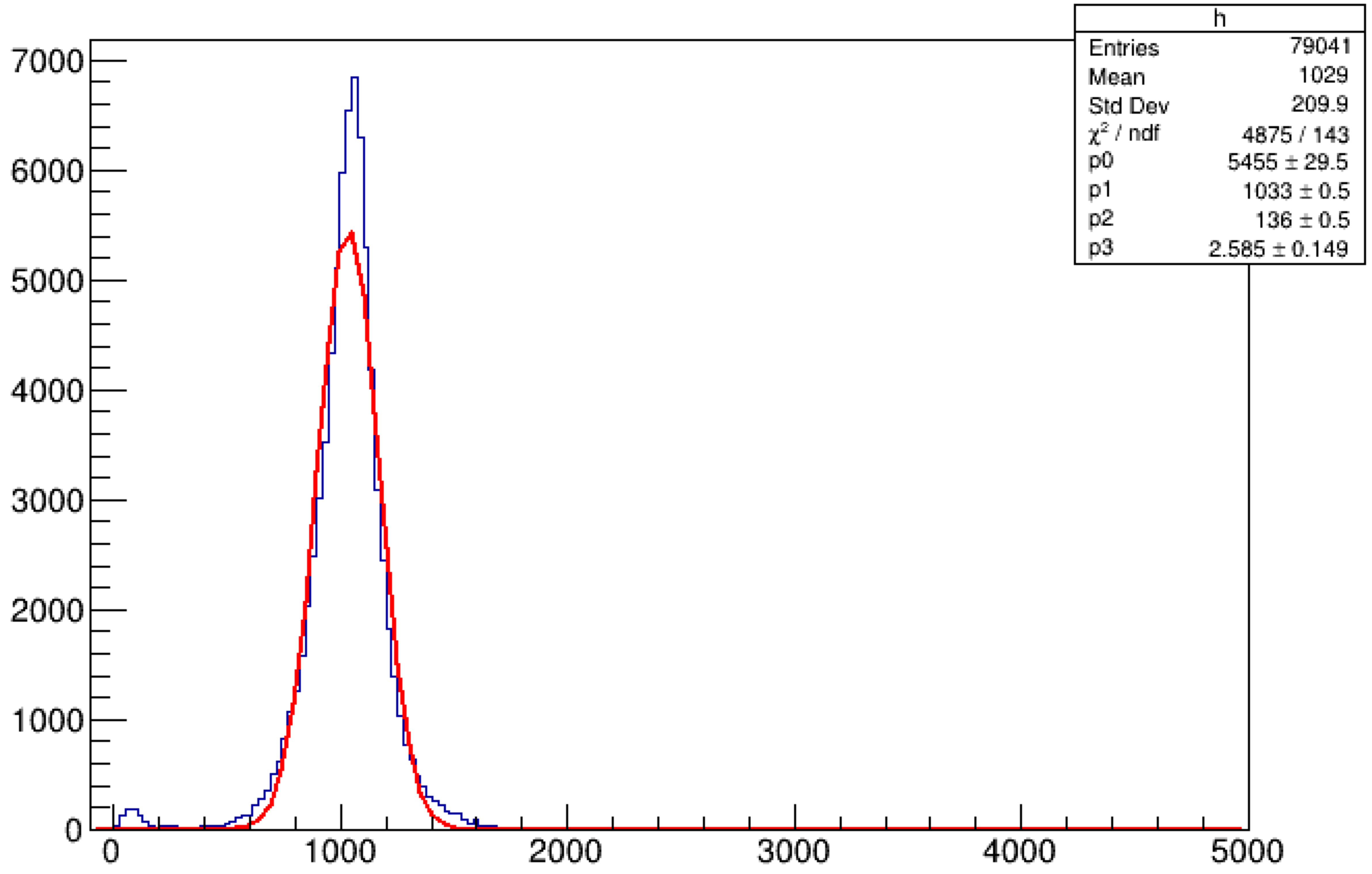
- Examine cosmogenic muons
- Scintillating muon paddle placed ~1.5 m below TES => 2 days of operation
- Amplitude spectrum shows broad cosmogenic muon peak
- Fit with convolution of Gaussian + Landau function
  - Gaussian for detector resolution
  - Landau for muon interactions with Si wafer



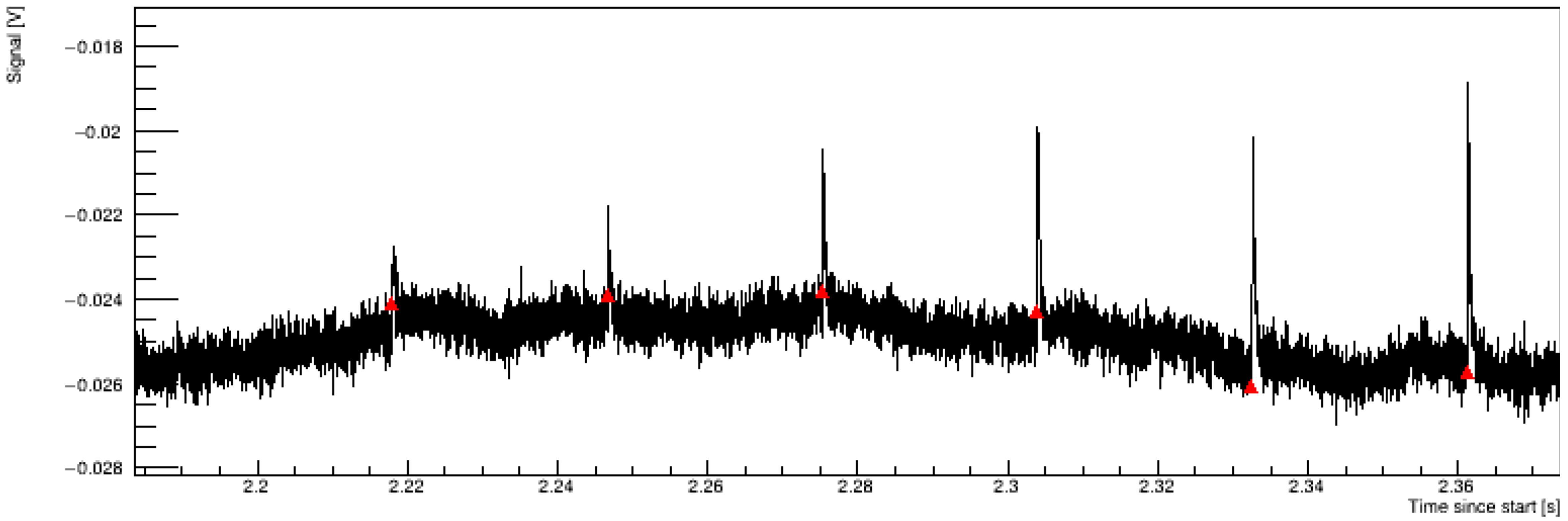
$\Delta E_{FWHM}/E \sim 0.3$

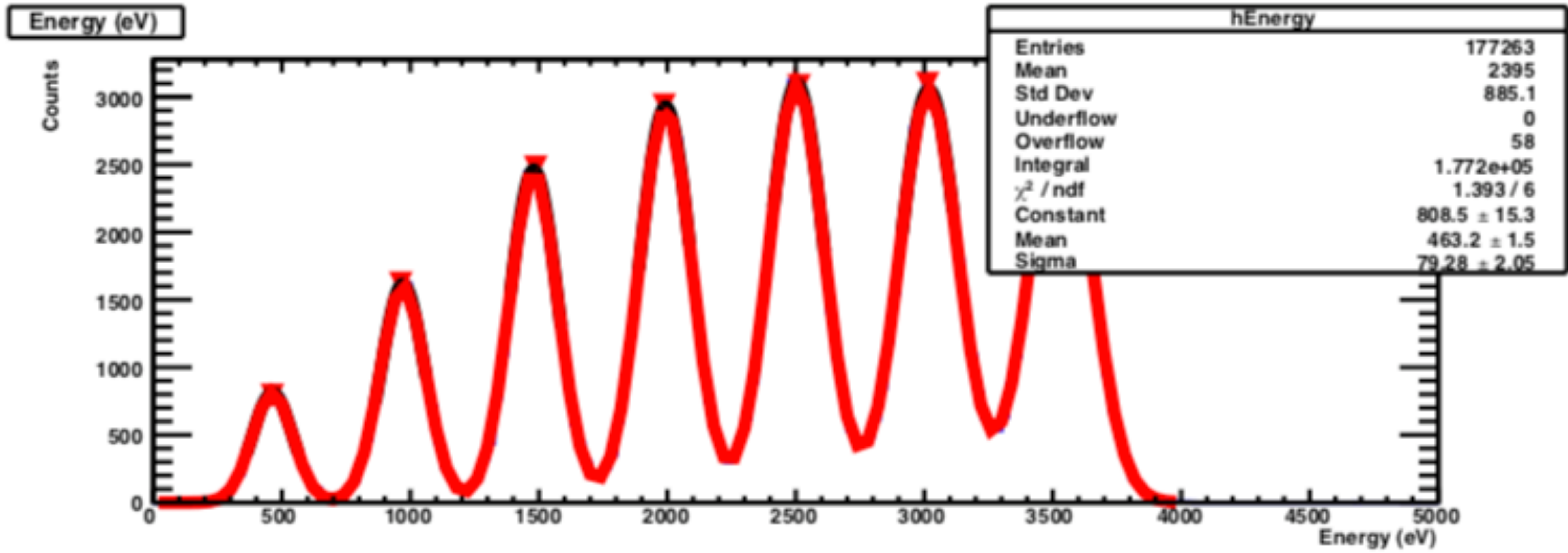
55Fe Calibration

- 55Fe source installed below wafer
- Resolution 35% (FWHM) at 5.9 keV
  - Pileup – high intensity source
  - Vibrations

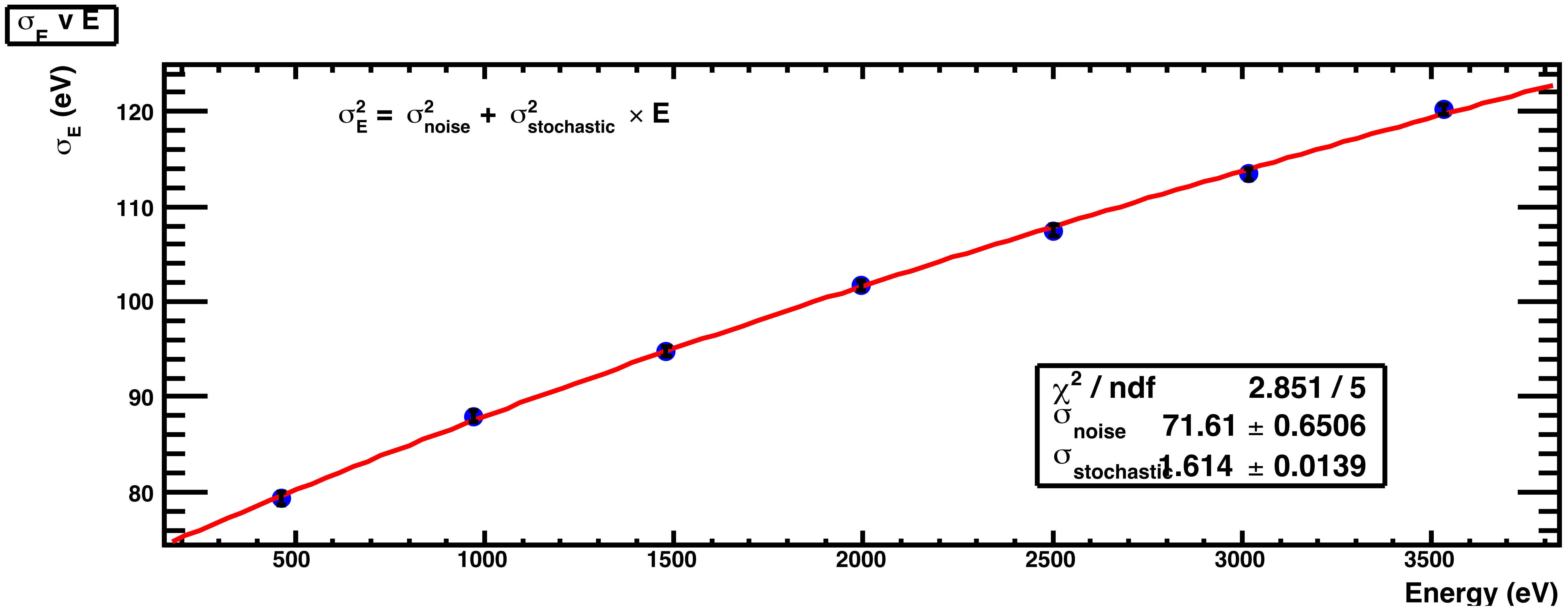


Pulse Measurements



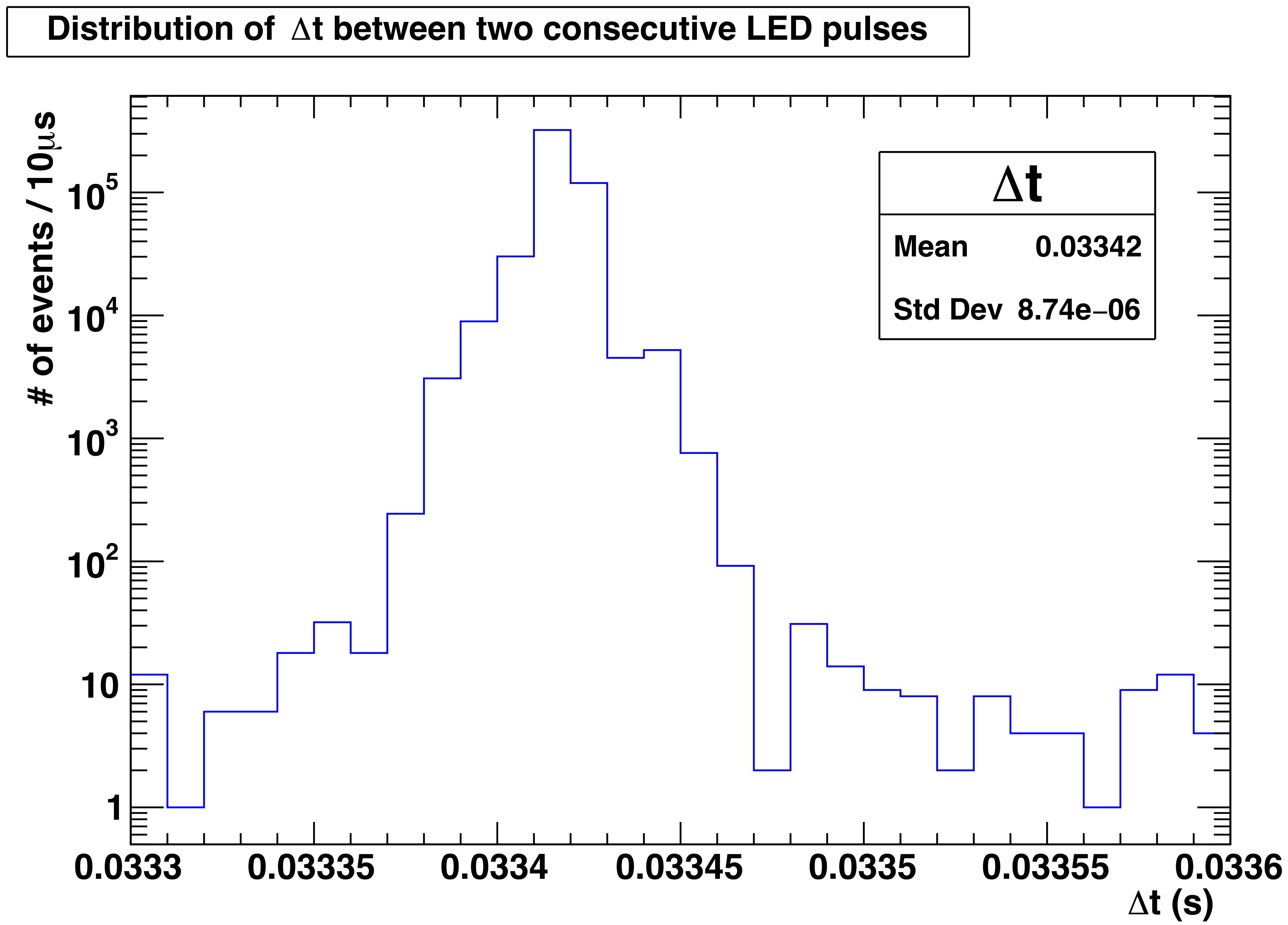


- Fit LED pulser peaks and extract baseline energy resolution (using photon statistics)



- $\sigma_E^2 = \sigma_{noise}^2 + \sigma_{stoch.}^2 E$
  - ~72 eV baseline

TES LD Timing



- Timing resolution σ_t ~ 9 μs

- Generate a train of LED pulses with some separation time >> decay time
- Examine distribution of times between some set of subsequent pulses in TES response
- Here LED pulses injected with frequency of 30 Hz
- Distribution is peaked at 33 ms with width 8.7 μs
- Pileup studies still needed but previous iterations of slower TES showed < 70 μs

TES Requirements

- Change in TES current response is relatively large...
  - ...but absolutely small
- Use SQUIDs to amplify signal
  - Default operation is 1 SQUID per TES
- Requires magnetic shielding
- Minimize noise by moving SQUIDs closer to TES
- Power dissipation
  - Magnicon SQUID: **1 nW**
  - Shunt Resistor: 20 pW
- Scaling up to CUORE sized electronics would require O(μW) cooling power!