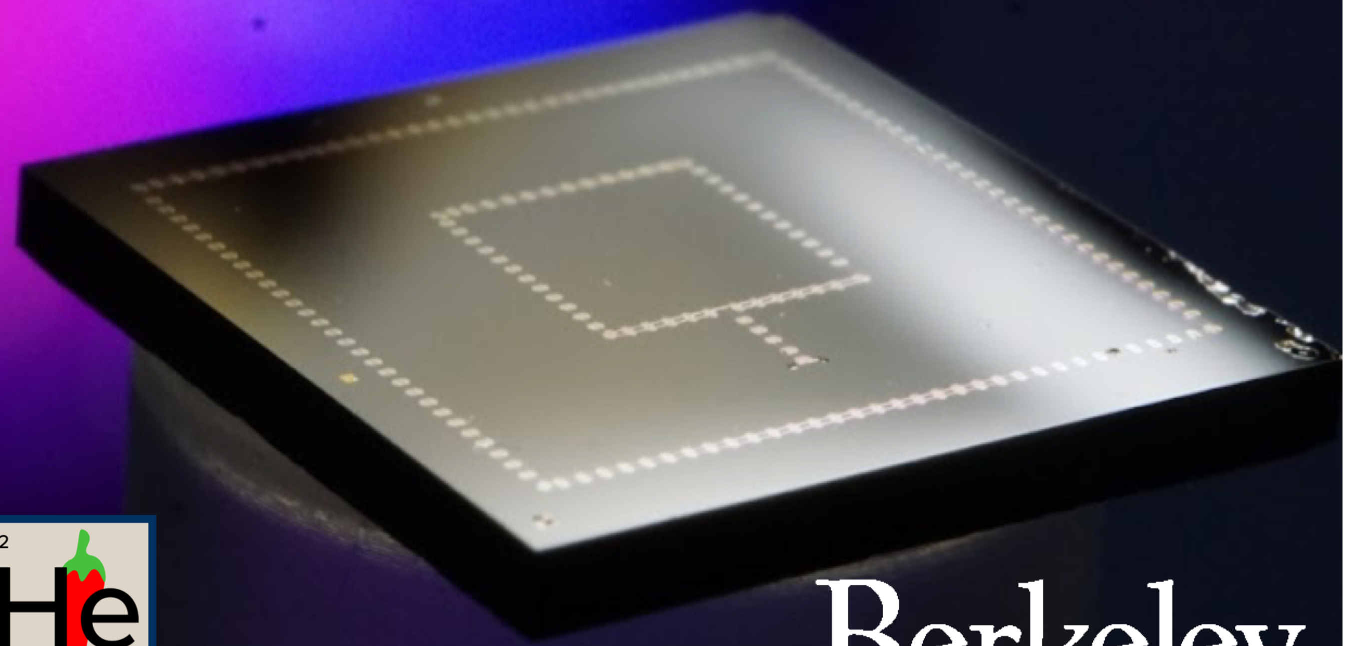
Stress Induced Background in Cryogenic Crystal Calorimeters



Roger K. Romani for the
SPICE/HeRALD Collaboration
(Presented by Dan McKinsey)

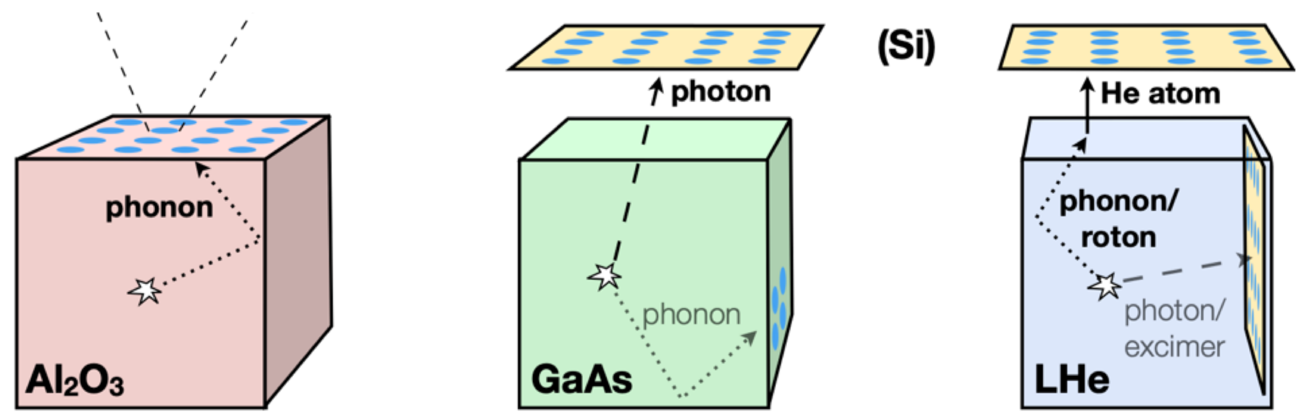
Berkeley
UNIVERSITY OF CALIFORNIA

The SPICE/HeRALD Collaboration

(unified under TESSERACT Project, currently in an R&D phase)

A new and growing collaboration searching for low mass Dark Matter!

- 50 + collaborators, 8 institutions
- 3 DM target materials, unified by state of the art TES readout
- Emphasis on discrimination techniques, reduction/elimination of heat-only backgrounds
- Want to learn more about TESSERACT? Read our Snowmass LOI, see D. McKinsey talk at IDM

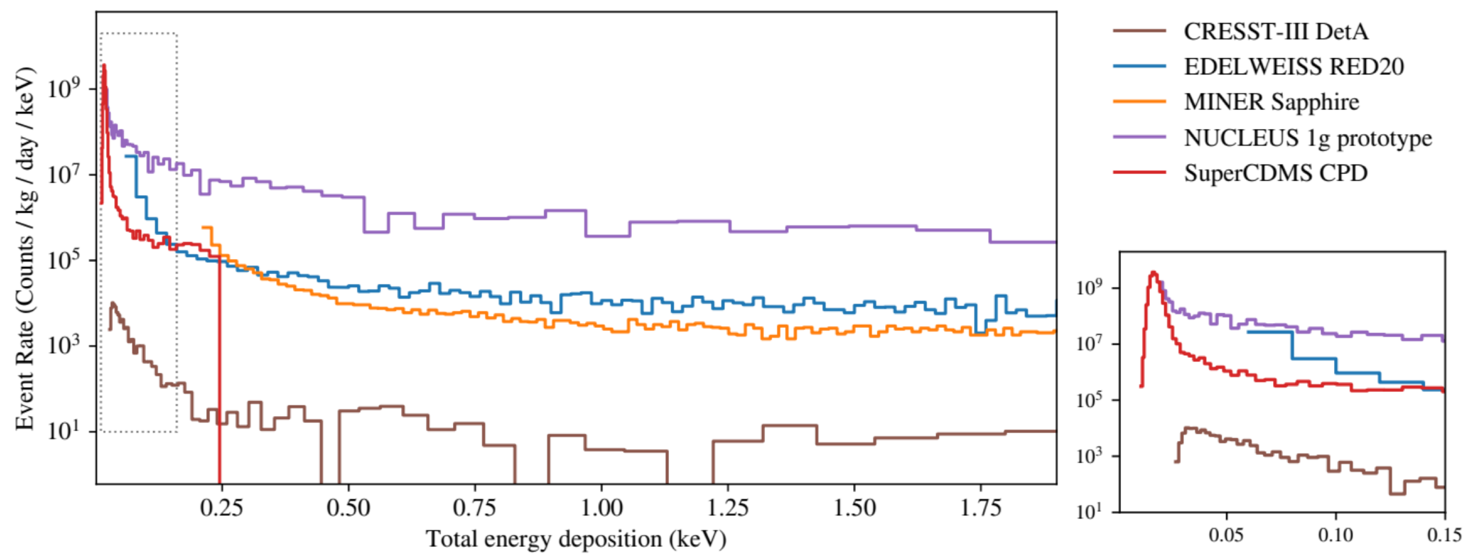


Prob 1 – DM Direct Detection: Low Energy Excess

The summary of the problem as we see it:

- Unknown source of low energy (below ~100 eV) events in many experiments
  - **Rate varies with time since cooldown** (can't be radiogenic)
  - Non-ionizing (i.e. "Heat Only") for EDELWEISS/RICOCHET
  - Track induced backgrounds (as in SENSEI) can account for some, not all
- Reduce the low energy excess and you can look for low mass (MeV - GeV) DM

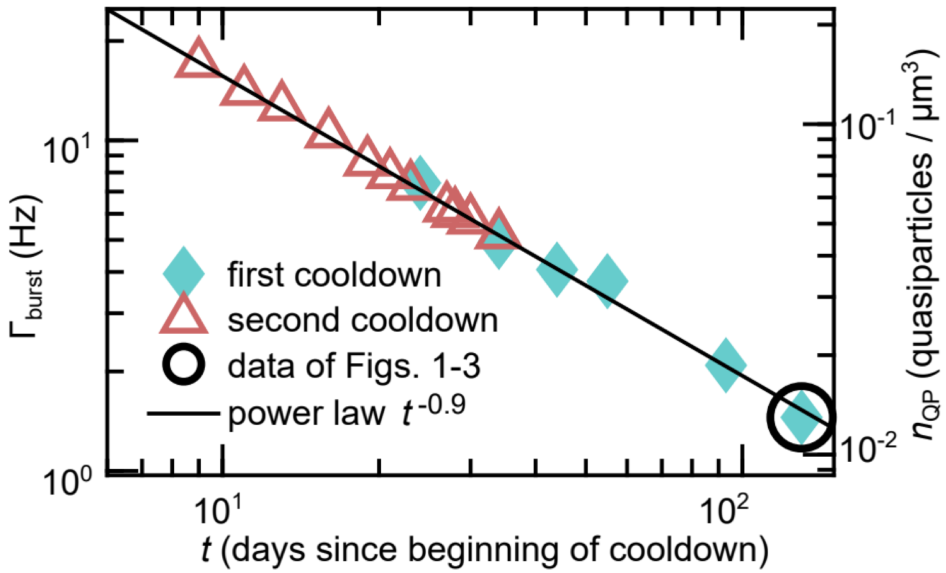
From arXiv: 2202.05097 EXCESS Workshop



Prob 2 – Quantum Computing: Quasiparticle Poisoning

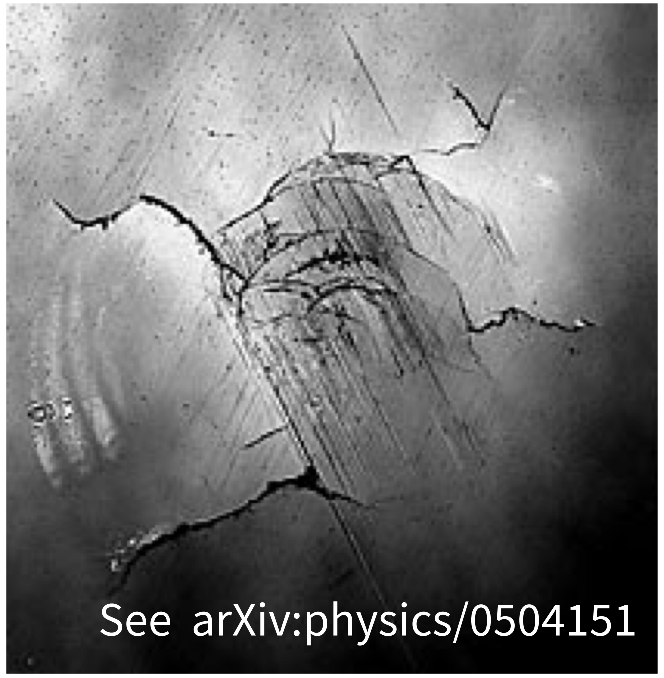
- Superconducting quantum circuits (qubits) see anomalously short decoherence times due to high density of quasiparticles (QP, broken Cooper pairs)
  - Problem has been holding back superconducting qubits for at least a decade
  - With excess quasiparticles, you need to error correct: complexity penalty
  - Lots of sources of excess QPs: radioactivity, muons, IR…
  - **In 2102.00484, excess quasiparticle density decreased as a function of time**
  - Solve excess QP problem, allow quantum computers to make big step forward

arXiv: 2102.00484
Mannila et. al.



Origin? Stress Induced Backgrounds

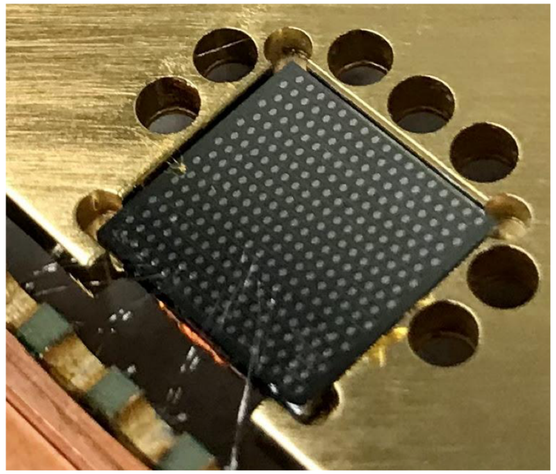
- We propose that one effect causes both problems!
- Differential contraction-induced strain
- Strained crystal slowly relaxes over time, releasing energy as athermal phonons
- Where are these stressed sites? Lots of places!
  - Glued down crystals/Neutron-Doped Transistors/samples coupled by vacuum grease (2102.00484)
  - Clamped crystals
  - Metal films on crystal surface
- Not unprecedented, CRESST saw stress-induced microfractures in mid 2000s
  - Clamped sapphire balls cracked crystal substrate
  - Up to 100s of keV/event, ~0.1 Hz event rate



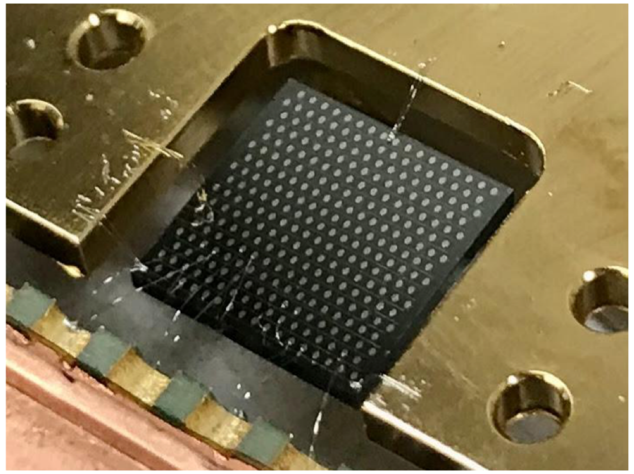
See arXiv:physics/0504151

An Apples-to-Apples Demonstration

- Two essentially identical TES/QET based athermal phonon detectors
  - 1 cm^2 by 1 mm thick silicon absorber
  - Same run, same optical cavity, very similar readout electronics…
- One glued down to copper substrate (high stress)
- One suspended from wire bonds (low stress)
- No calibrations, but can directly measure energy absorbed in TES

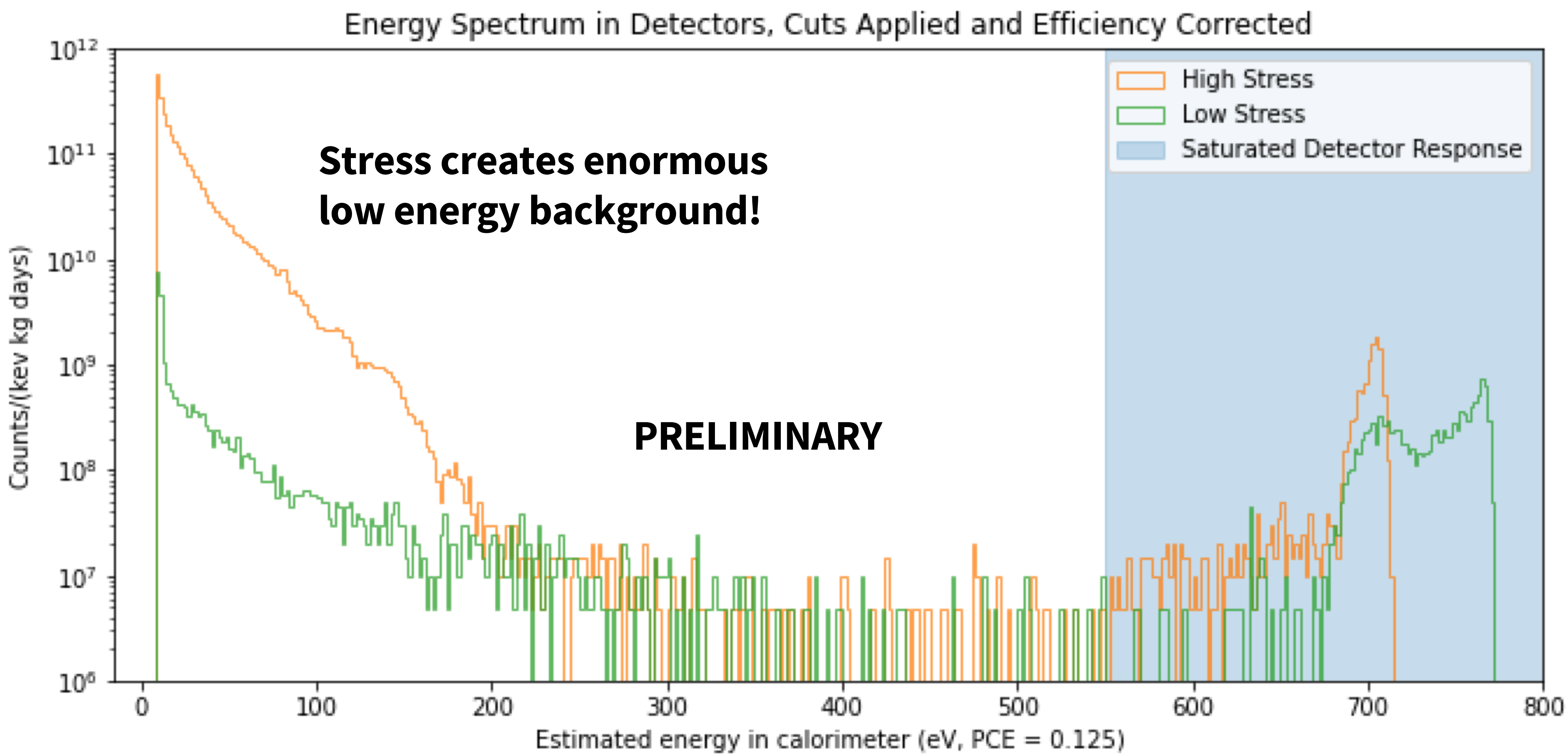


High stress



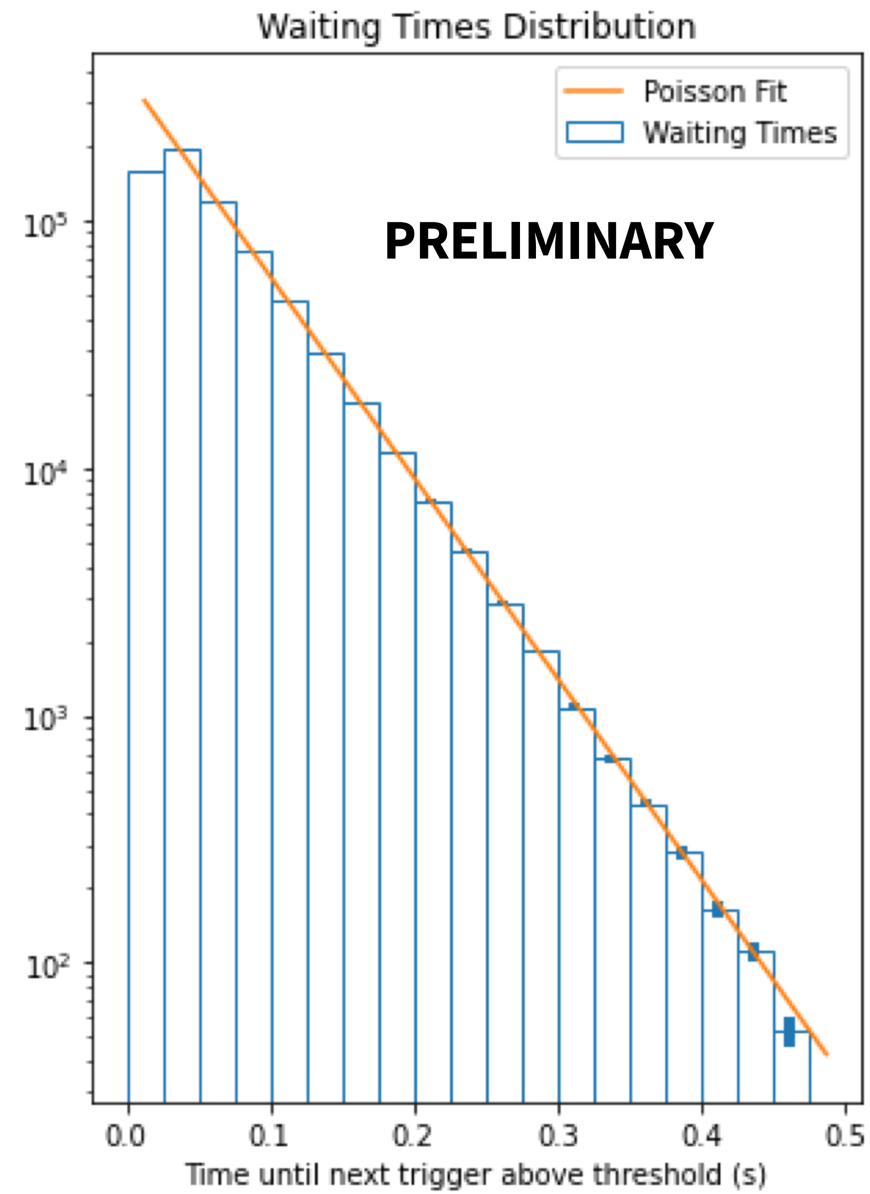
Low stress

Energy Spectra

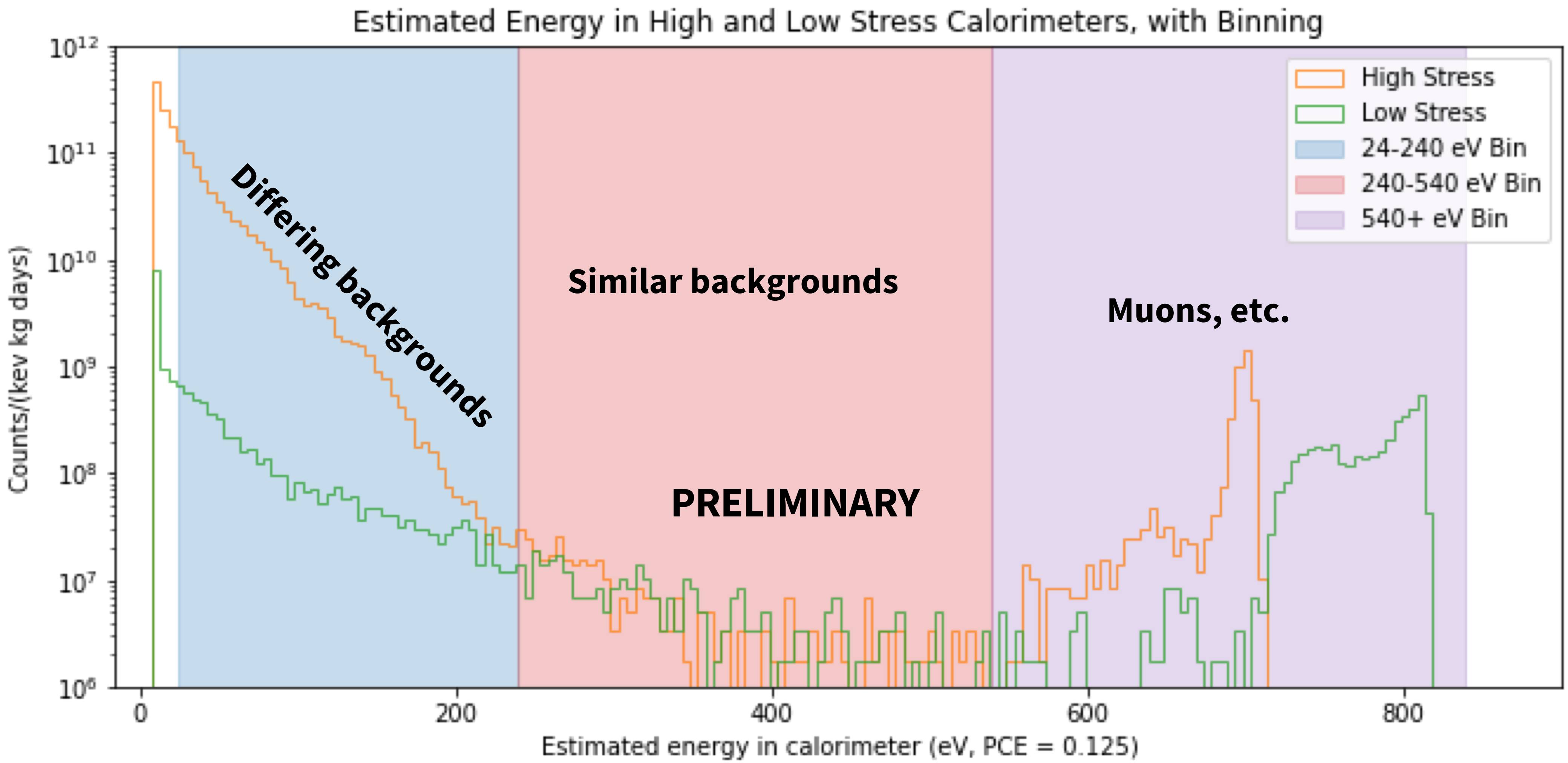


Time Distribution of Events

- Measured “waiting time” between events above a given energy threshold
- Waiting times longer than trace length are Poisson distributed
    - CRESST saw slightly different waiting times distribution… they were 1000 times higher energy



Time Dependence of Excess

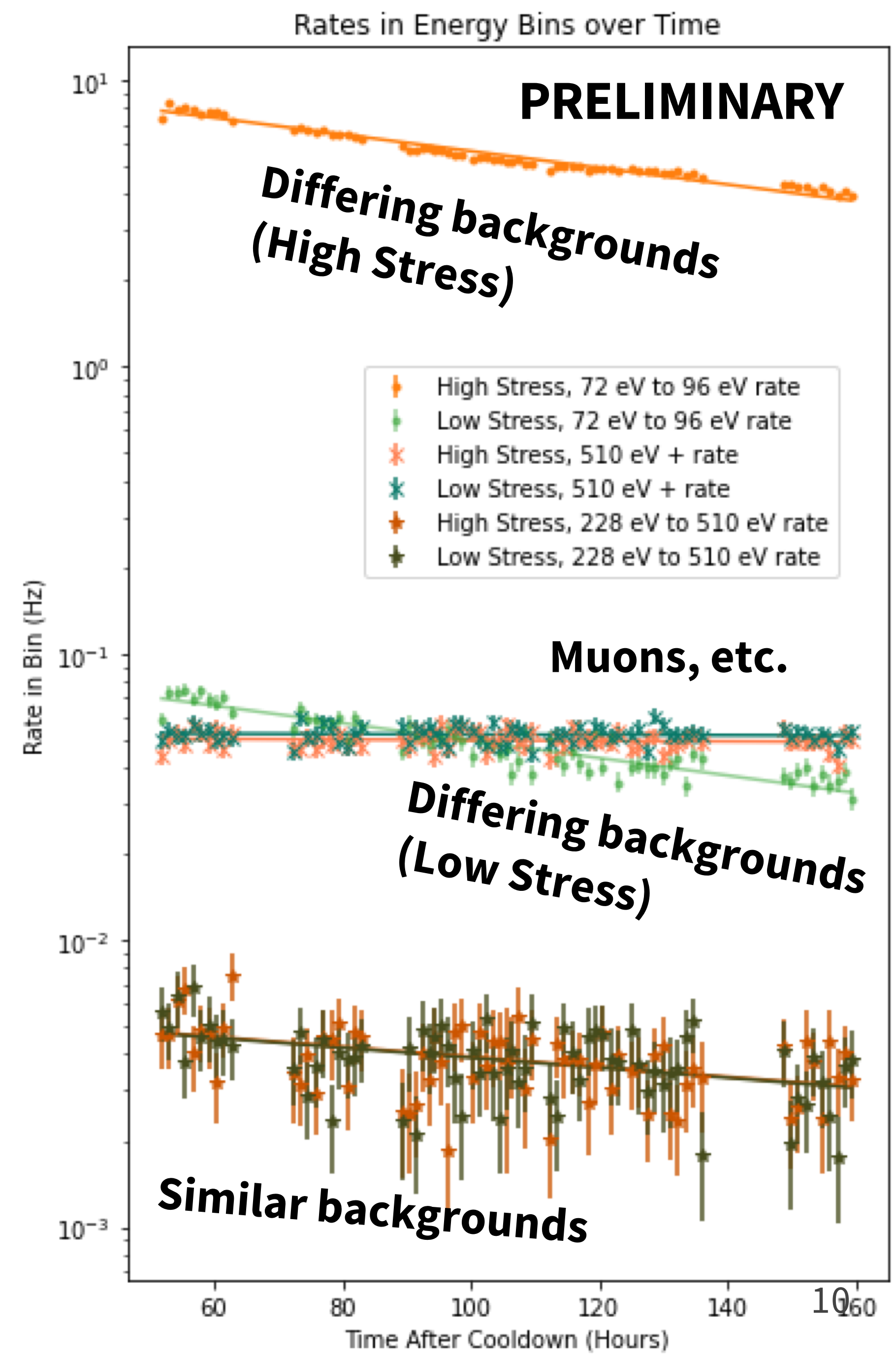


Time Dependence of Excess

- See both lower energy and moderate energy background bins rates decrease over time
  - τ ~ 6-10 days
  - Both exponential and 1/t reasonable fits to data
  - Factor ~2 rate decrease during ~5 day experiment
- Saturated (high energy) events (muons etc.) don't vary with time (as expected!)
- <15% of low energy events cut – cuts can't cause 2x rate changes

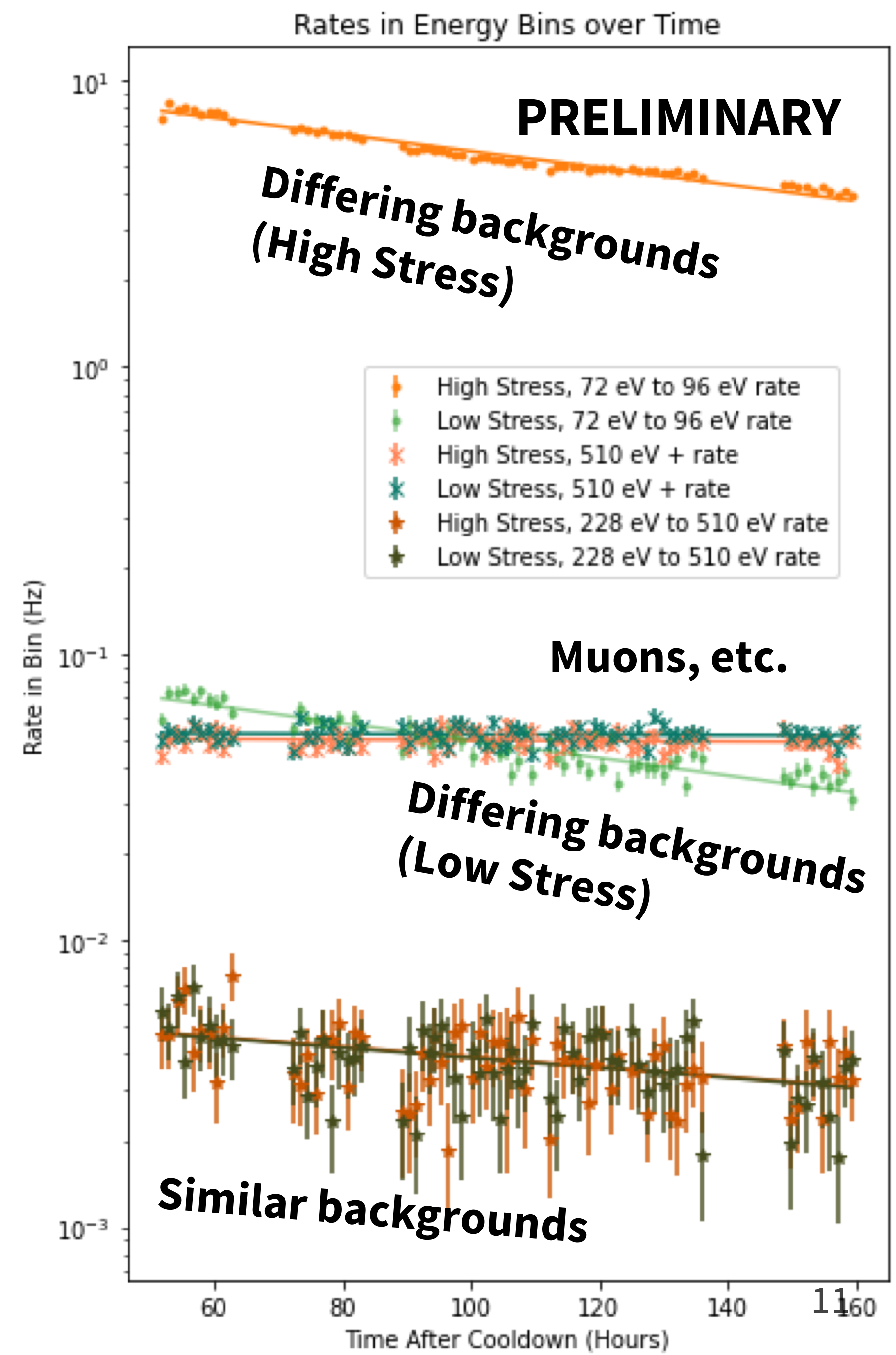
High Stress

Low Stress



Source of Rates

- Saturated rate makes sense: muons, radioactive backgrounds…
- Differing background region (lower energies):
  - Varies with time: not radioactivity, track backgrounds
  - Glue causes stress, relaxation causes events
  - Much less stress in hanging calorimeter, less stress to relax = fewer events
- Similar background region (higher energies):
  - Still varies with time, similar τ to glued stress events
  - Circumstantial evidence: caused by similar mechanism in both calorimeters
  - Look for source of time varying events present in both calorimeters…



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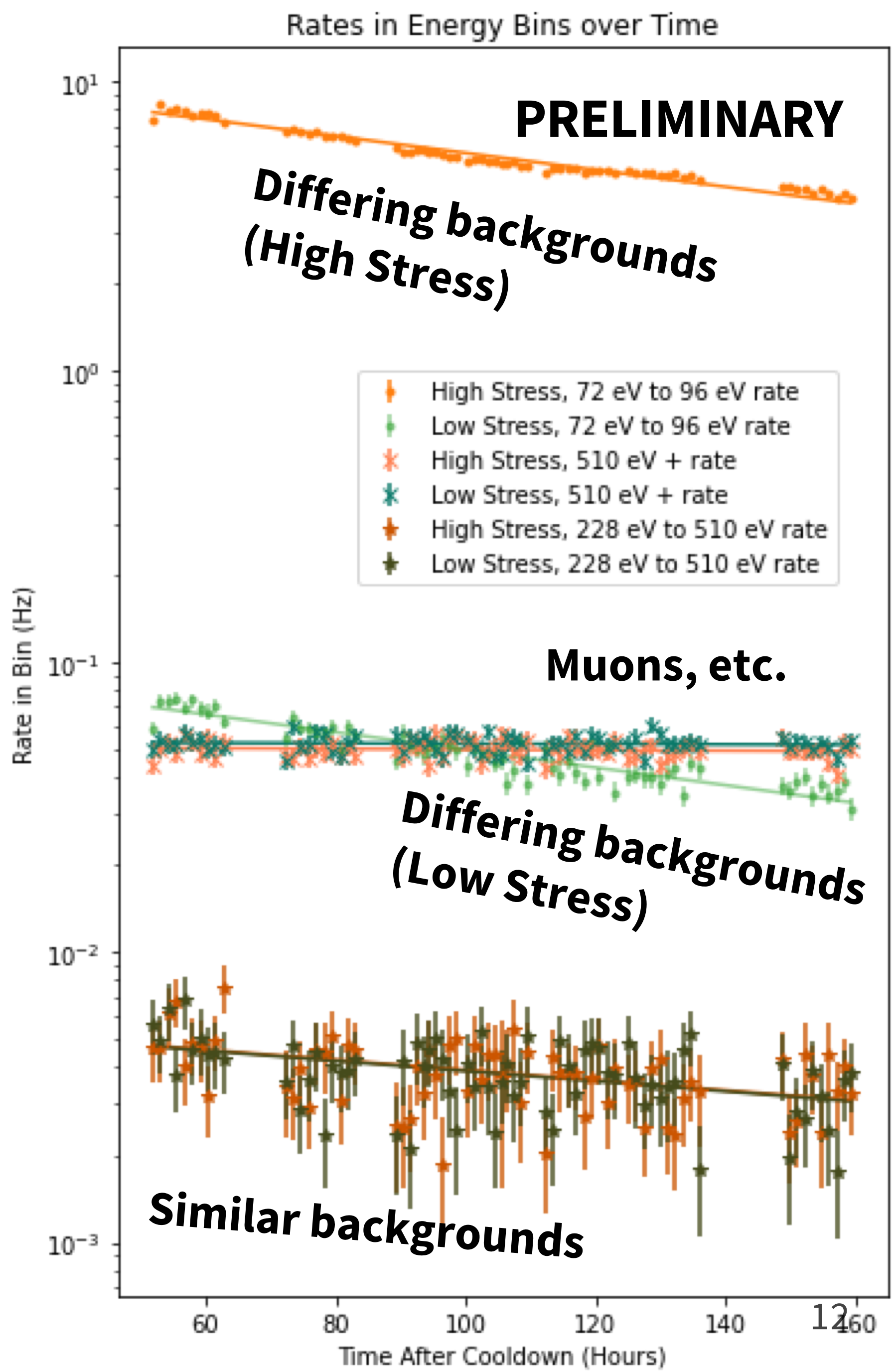
  - **Stress between TES films and crystal?**

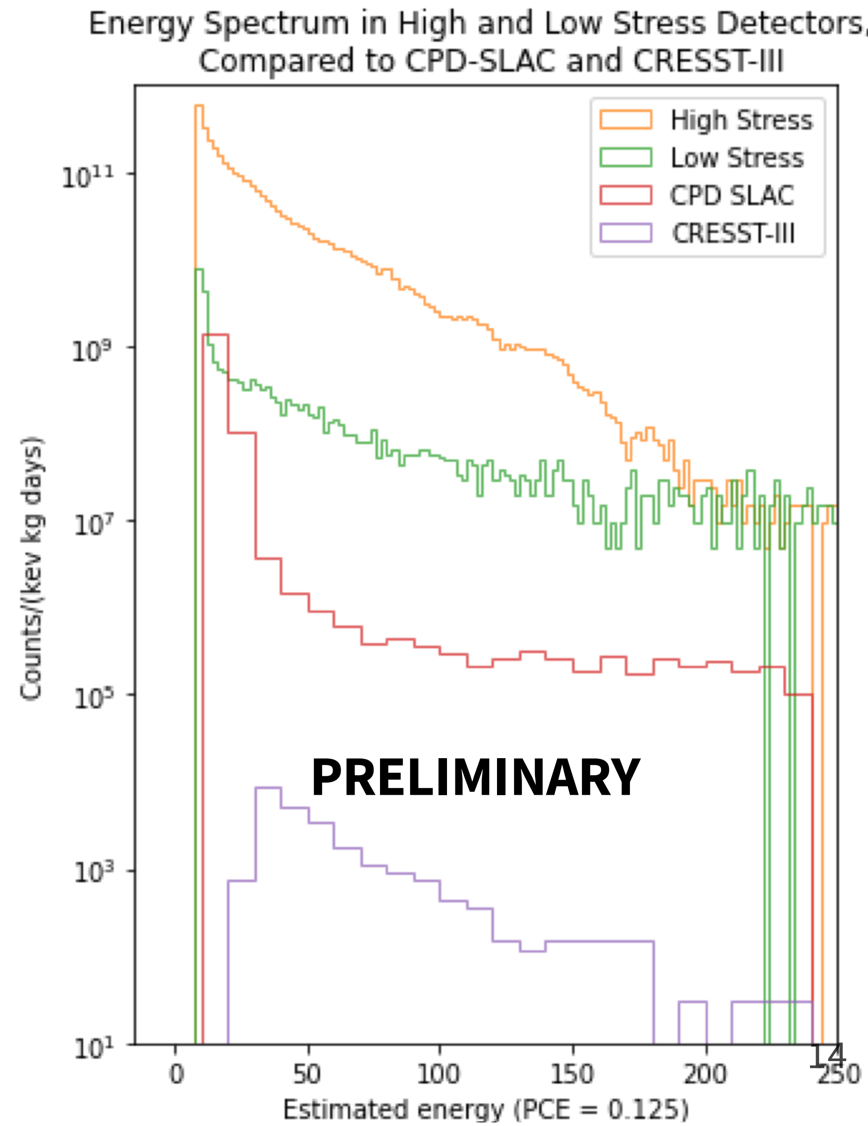


Looking for TES stress events

- Look in multiple channels
  - Presumably a stress event only happens in one TES channel at a time, more energy will end up there
  - Veto TES events, hopefully get more background free region
- Look at pulse shape
  - If TES fall times are much shorter than phonon collection times (not true for these calorimeters), energy that goes directly into TES should have different pulse shape vs. collected phonons
- Tag as a TES stress event/substrate event, see what the remaining excess is made of in low stress calorimeters

Comparison to Other Low Mass DM Experiments

- Note: our low stress detector rate is still ~200x CPD, ~10^5x CRESST
- Why are we so much worse?
  - Not fridge or shielding specific, ran CPD in this fridge, saw background that agreed with published measurement within factor of ~2



Comparison to Other Low Mass DM Experiments

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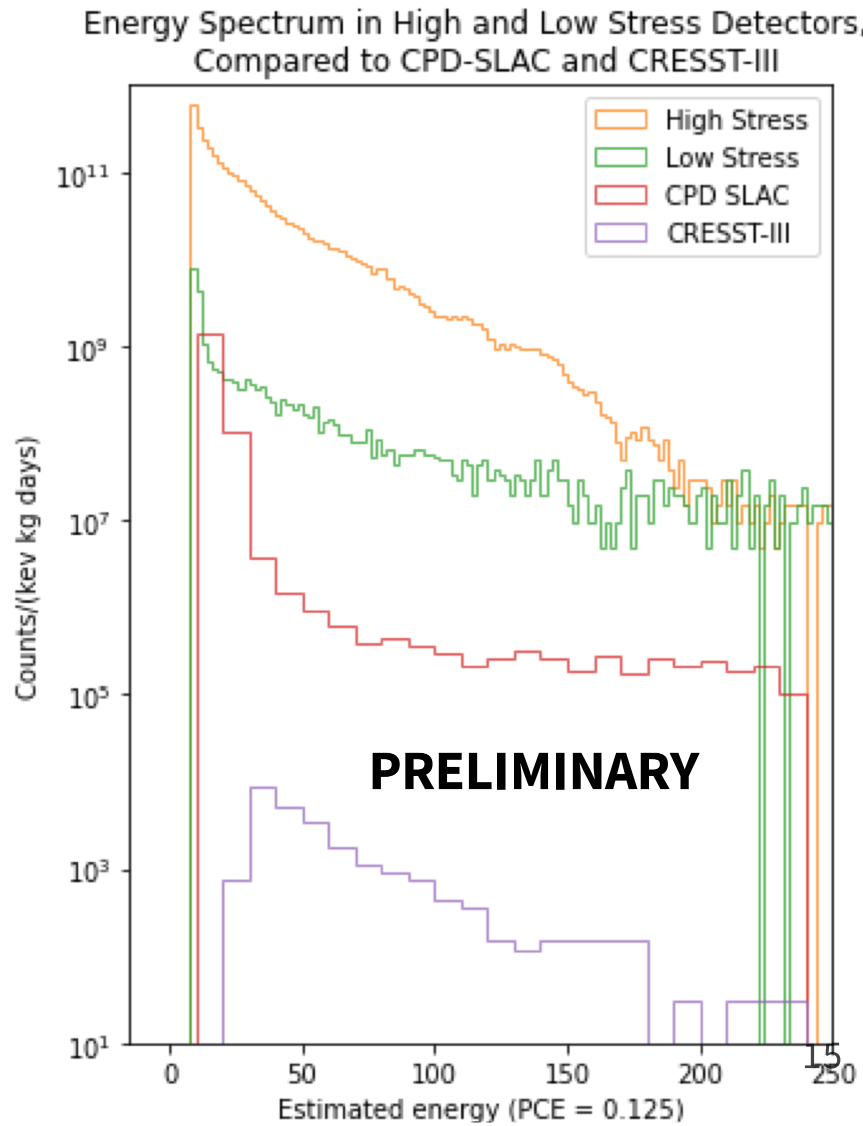
- Why are we so much worse?
  - Not fridge or shielding specific, ran CPD in this fridge, saw background that agreed with published measurement within factor of ~2
- Hypothesis: fabrication-induced strain at TES interface varies greatly between detectors
- Stress event rate decreases while cold, may anneal out while warm too
- **Mitigation Plan: Fanatically minimize stress everywhere in our detectors**



Implications for Low Mass DM Direct Detection

- Mount-associated stress release is a new background we have to worry about
  - Pretty much unimportant for high threshold detectors
  - Extremely important for low threshold (low mass) direct detection
- Don't use glue on your detectors!
- More generically, look for stress everywhere, try to eliminate it
  - Clamping schemes
  - Films on crystals
- Time variation is a powerful tool for understanding these backgrounds

Implications for Quantum Computing

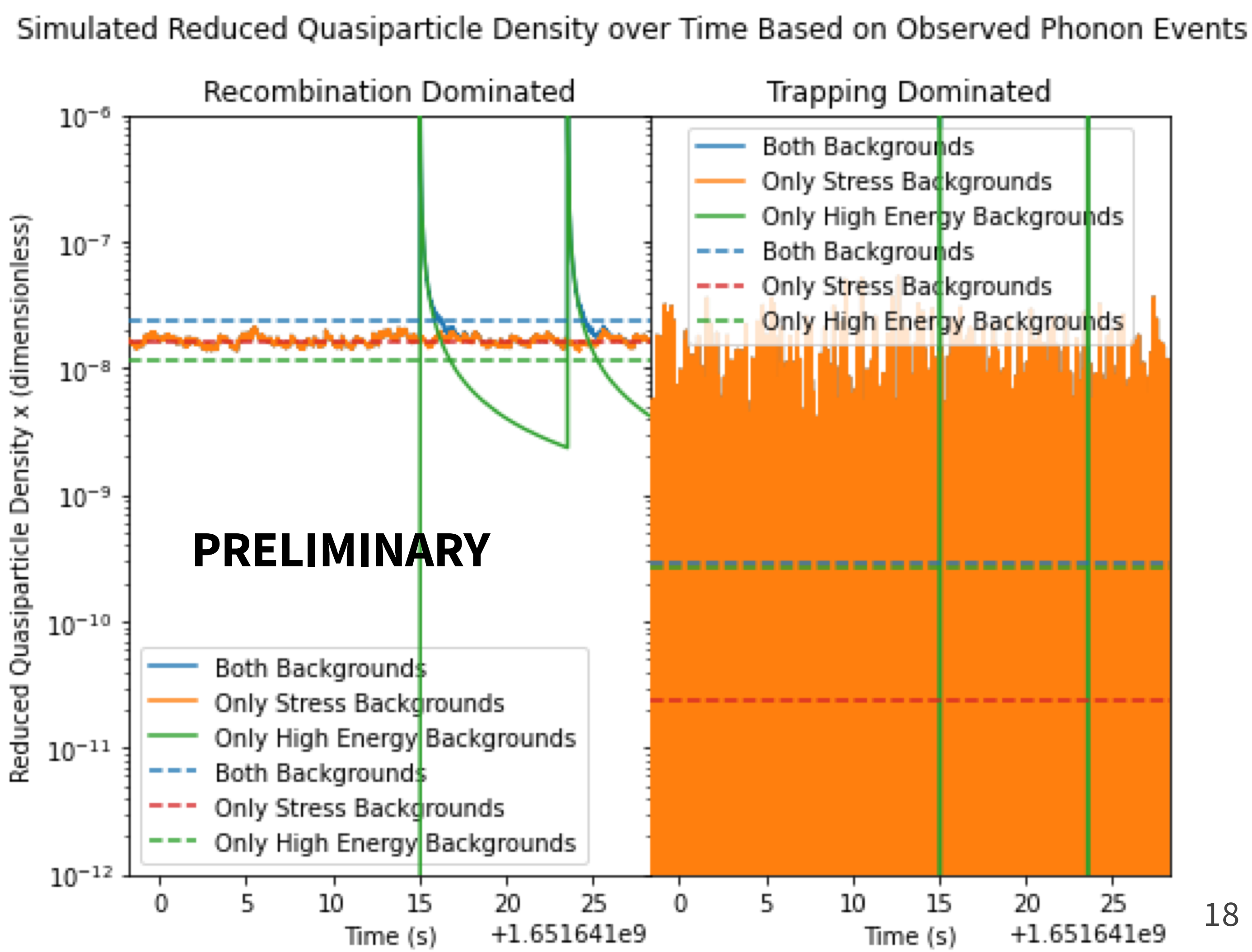
Our model for quasiparticle poisoning:

- Stress-release radiates athermal phonons in quantum computer Si substrates, these phonons when absorbed in quantum circuits create quasiparticles
    - Higher rate than muons + other high energy backgrounds (for setups that have high stress)
- We may have identified a source of quasiparticle poisoning
    - This has plagued superconducting quantum computers for more than a decade
    - Long coherence times are of course important
    - Even more critical: stress-release “burst events” could decohere all qubits on a chip at once, make error correction difficult/impossible

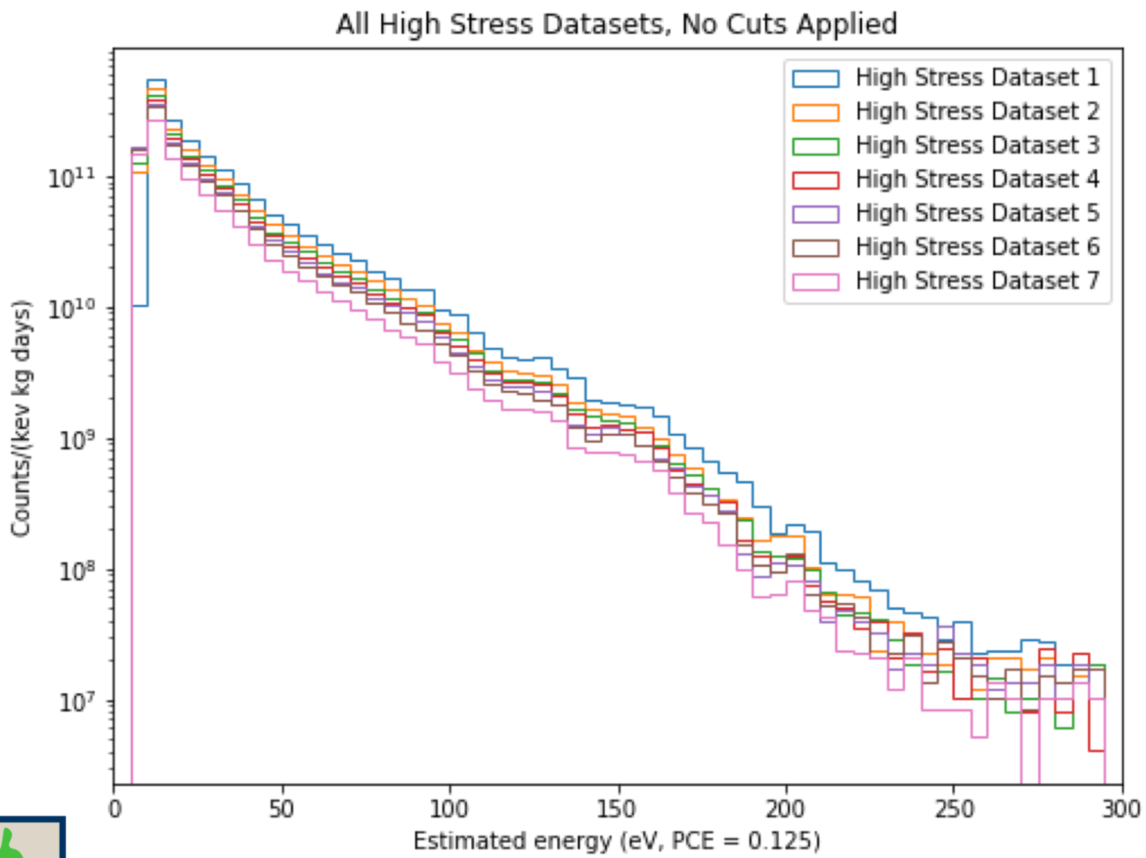
Implications for Quantum Computing

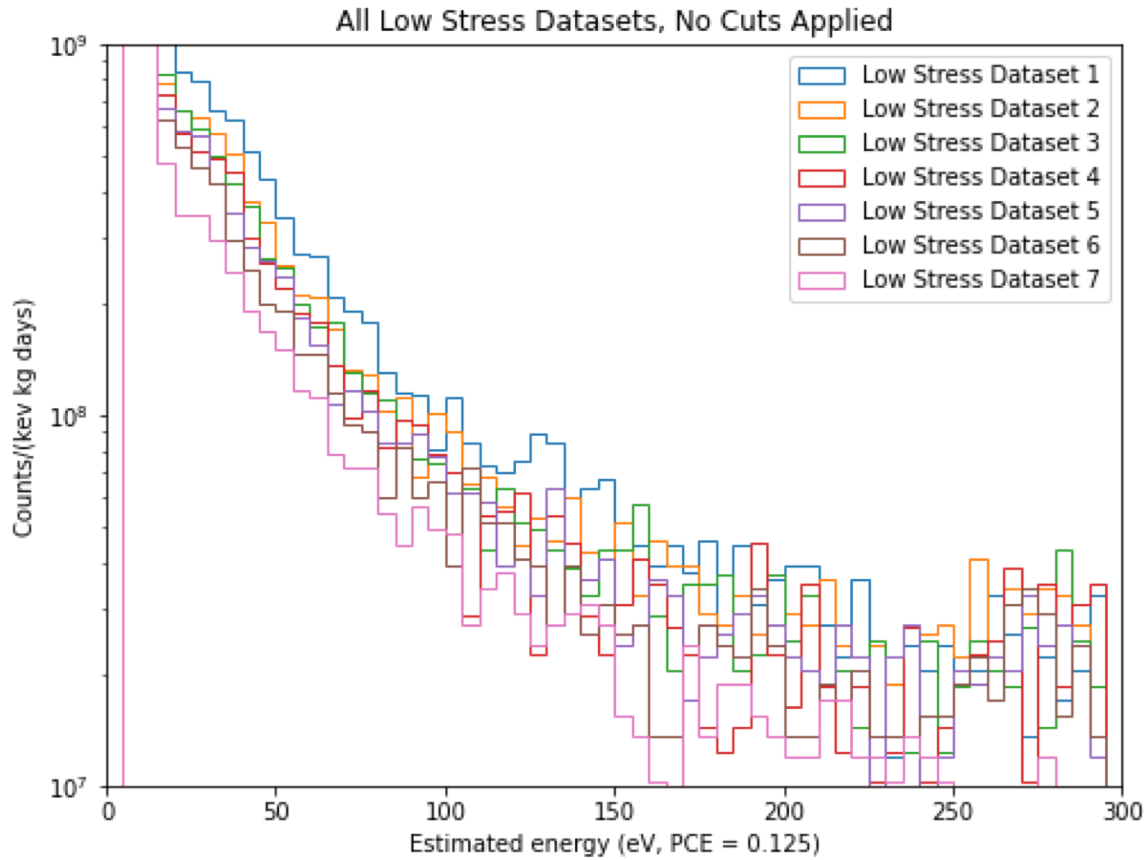
Backgrounds and SC qubits:

- Most qubits don't have quasiparticle traps
  - In that limit, frequent low energy backgrounds are way more important than infrequent high energy backgrounds
  - Stress at the level we see will totally dominate radiogenic backgrounds with UG qubits

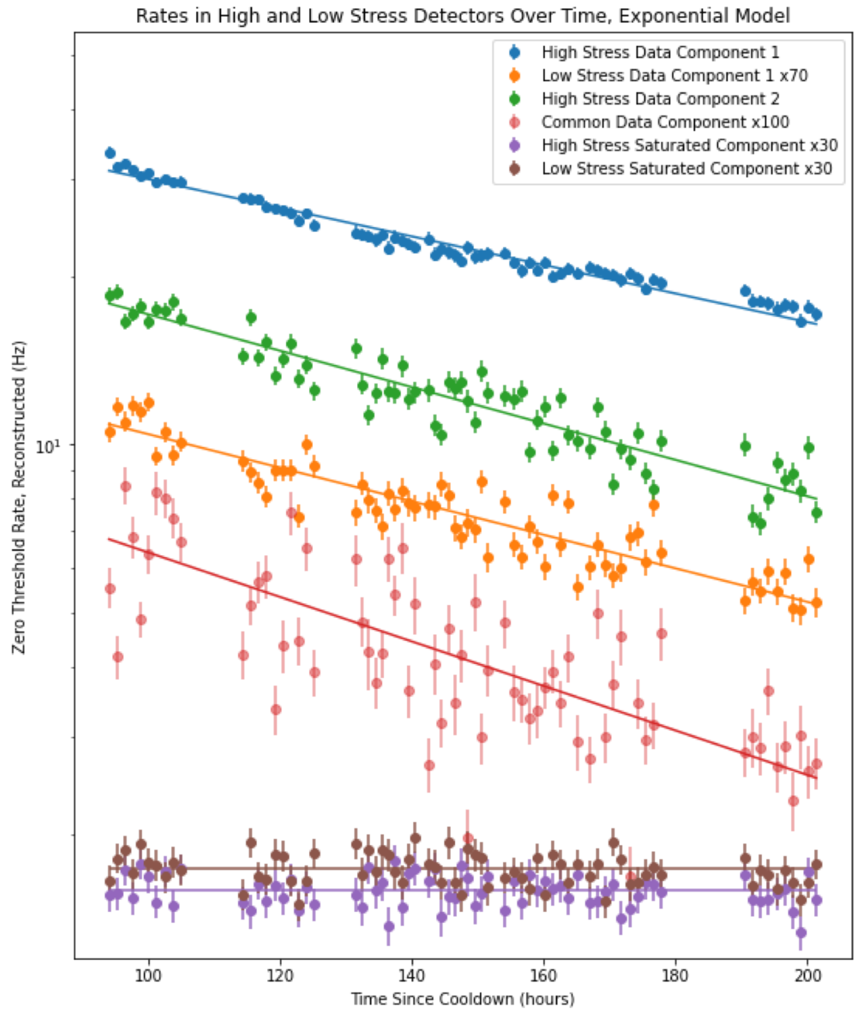


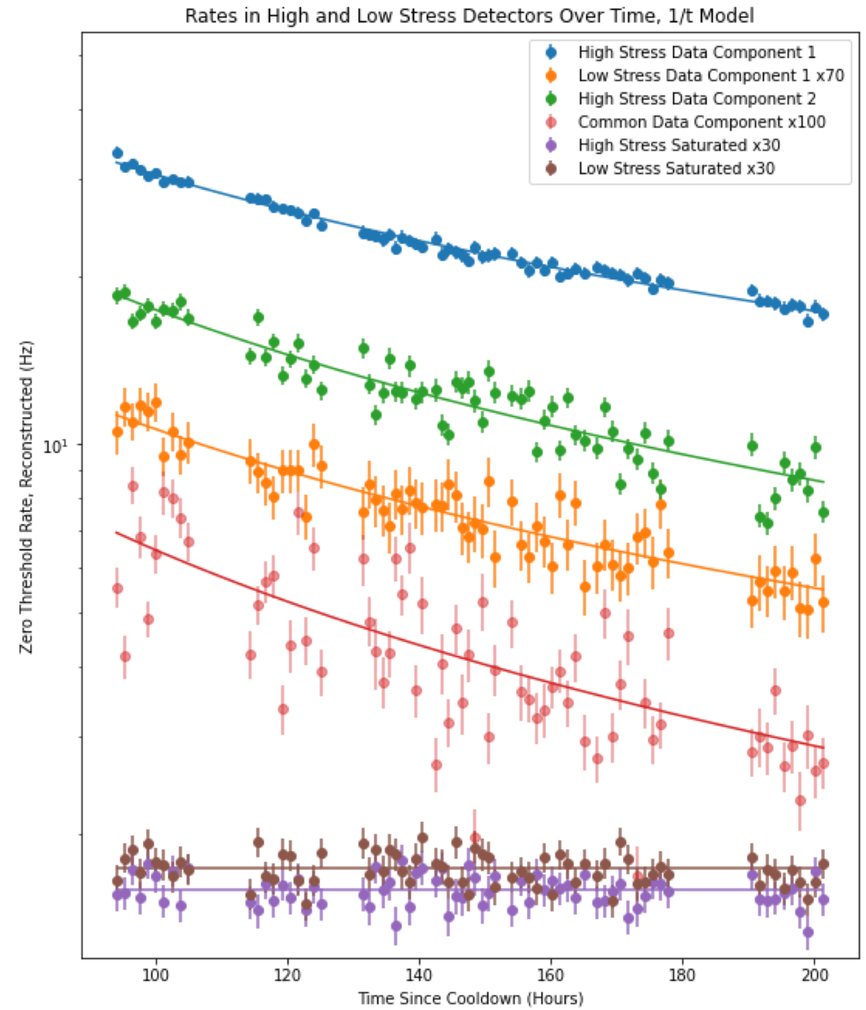
Backup: Spectra Over Time Without Cuts





Backup: 1/t vs. Exponential Fits to Rates





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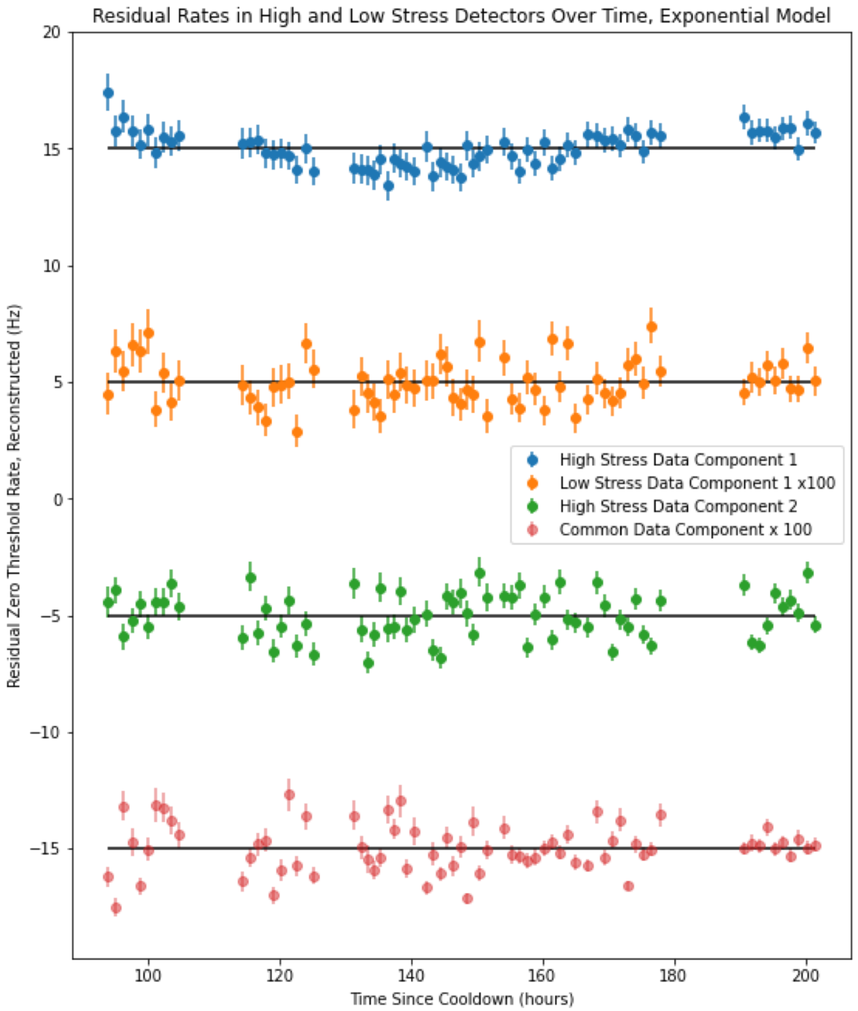
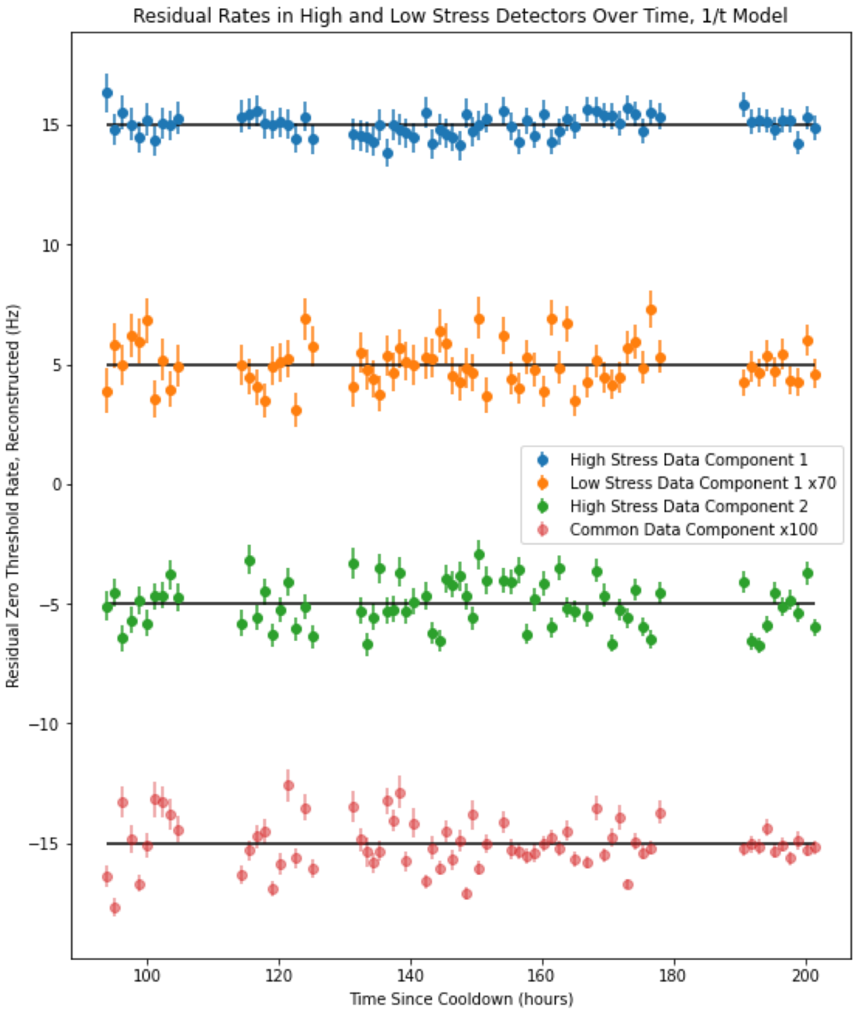
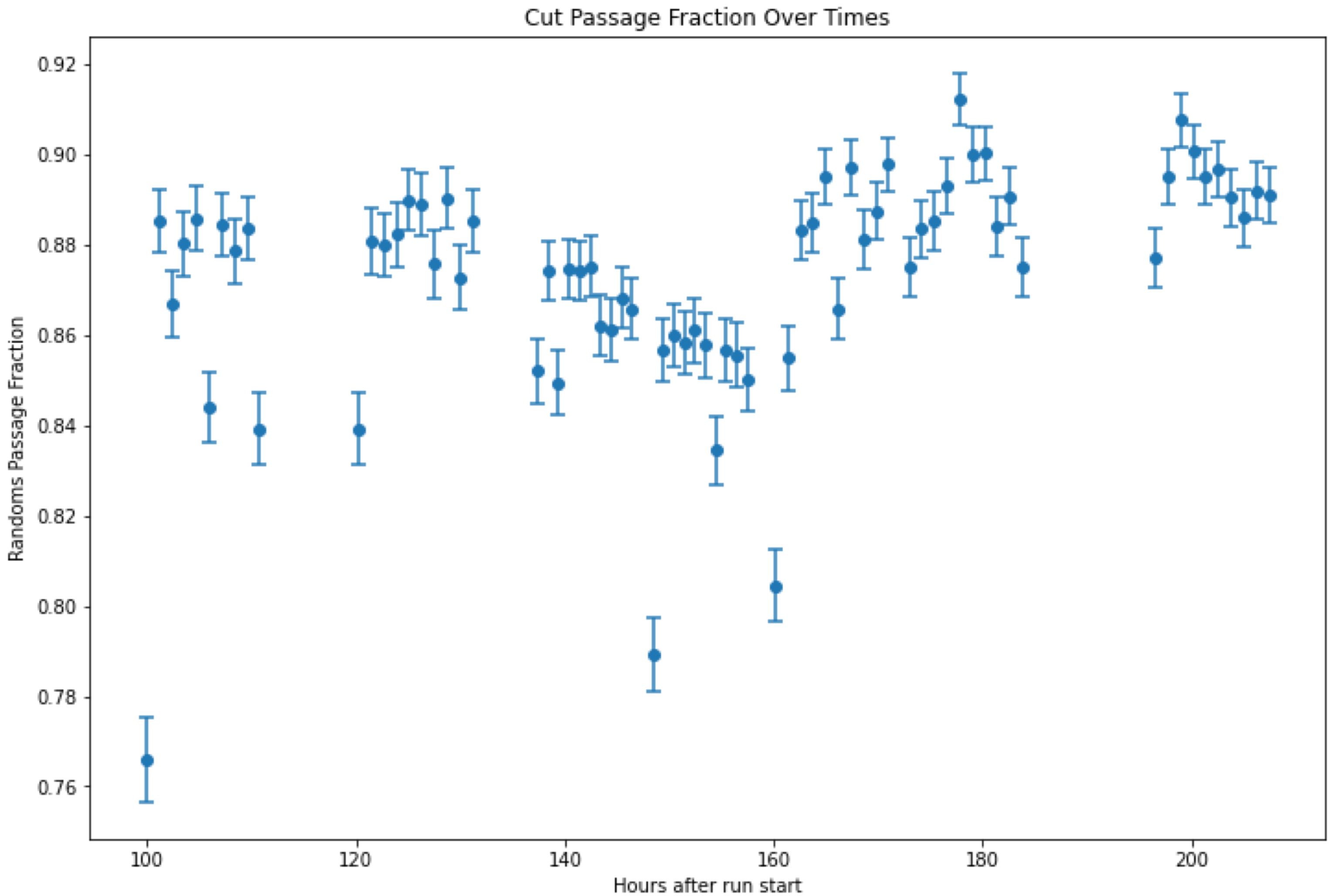
Backup: Residuals for Rate Fits

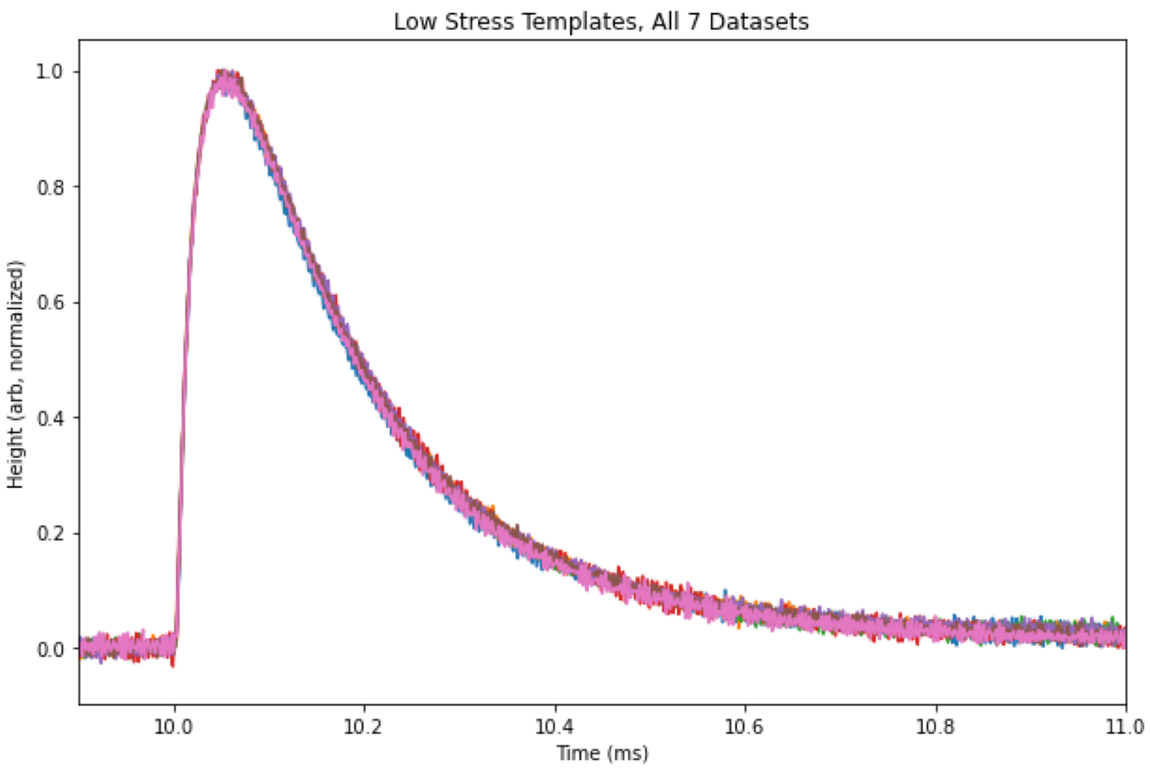


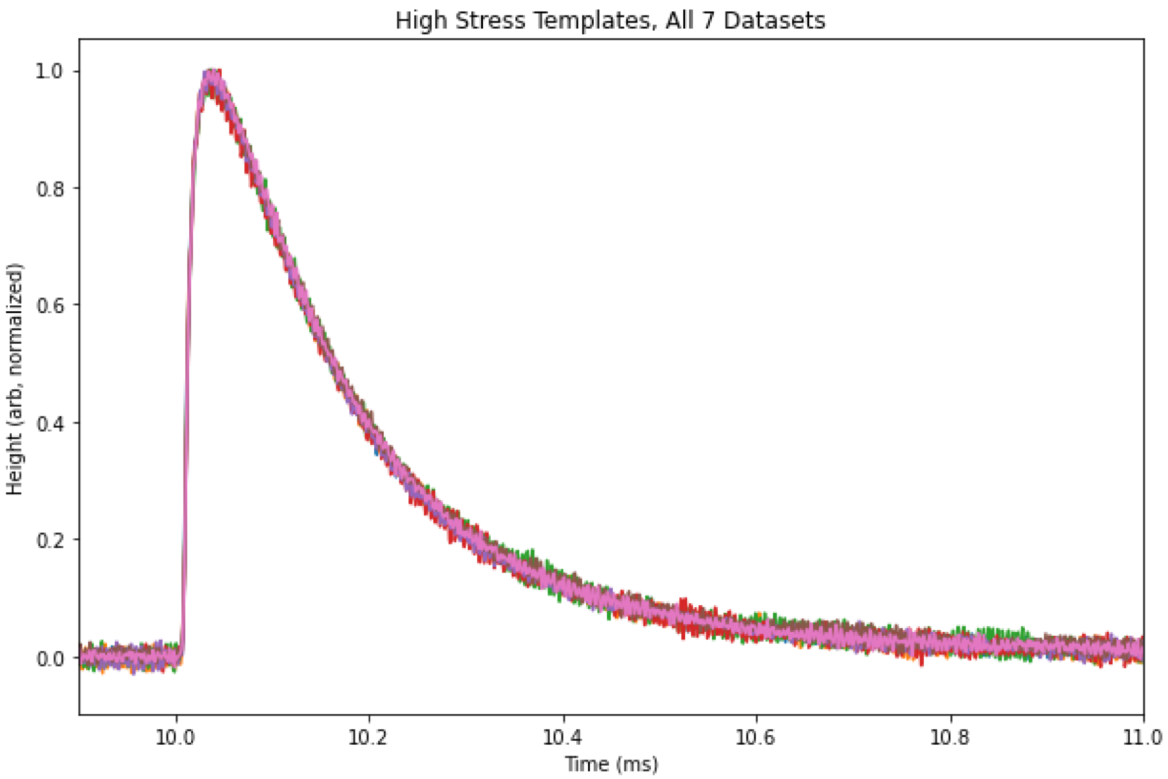


Backup: Cut Passage Fraction over Time



Backup: Pulse Shape Over Time



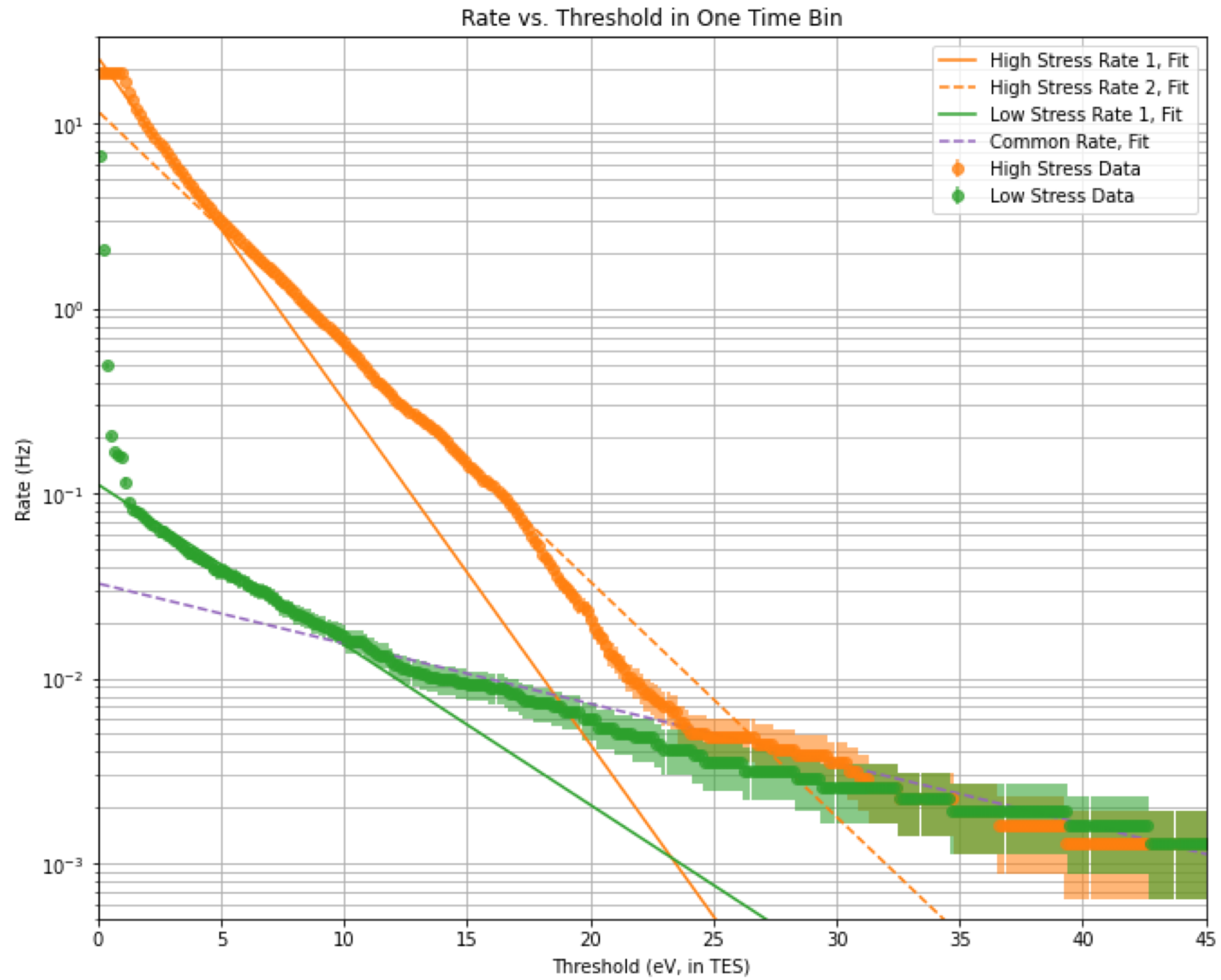


Backup: Observed Rates Time Constants

- Differing backgrounds region (low energy):
  - High stress: 6.2 +/- 0.15 days
  - Low stress: 5.9 +/- 0.30 days
- Similar backgrounds region (higher energies):
  - High stress: 10.3 +/- 2.5 days
  - Low stress: 10.3 +/- 2.4 days
- Saturated region:
  - High and low stress statistically consistent with constant w.r.t. time model

Threshold Rate Dependence

- Very large background seen in high stress detector, not seen in low stress detector
  - This is our key finding
  - As detectors are otherwise identical, we attribute this to stress events caused by glue joint
- High threshold background present in both detectors
  - 10+ eV in low stress, 25+ eV in high stress
  - But events not coincident!
- Can fit rate vs. threshold data to find extrapolated rate at zero threshold



Time Dependence in Rate

- See both common (high threshold) and unique (lower threshold) background rates decrease over time with τ ~ 6 days
  - Both exponential and 1/t reasonable fits to data
  - Factor ~2 rate decrease during experiment
- Saturated (high energy) events (muons etc.) don't vary with time (as expected!)
- <15% of low energy events cut – cuts can't cause 2x rate changes