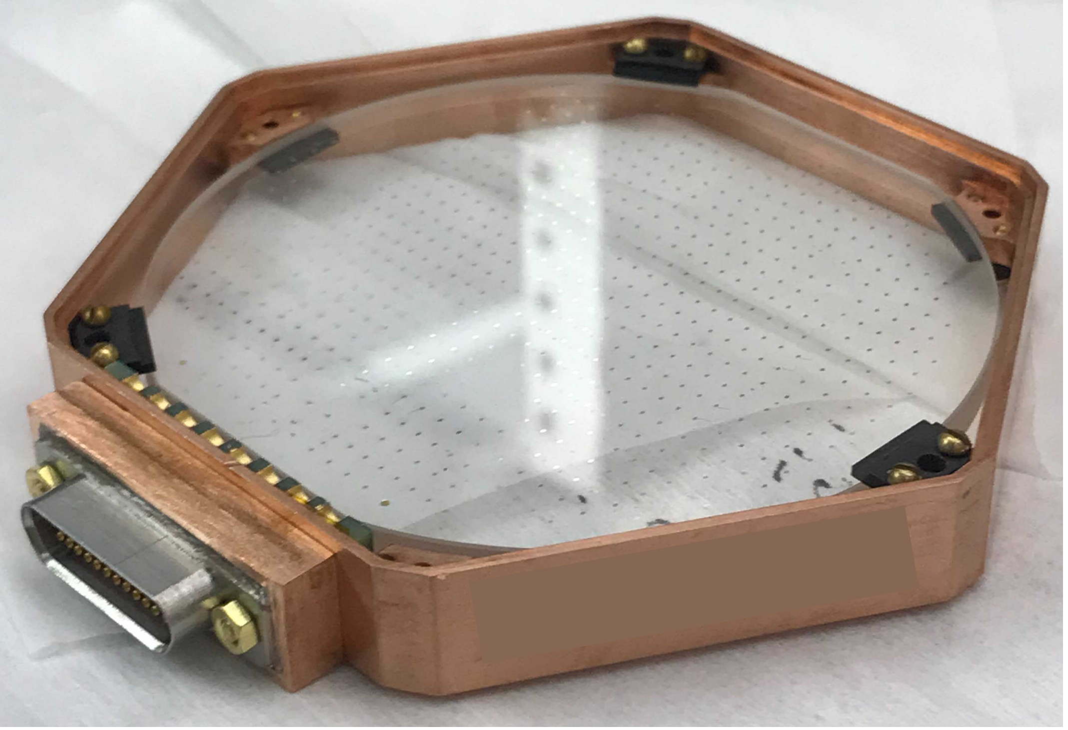
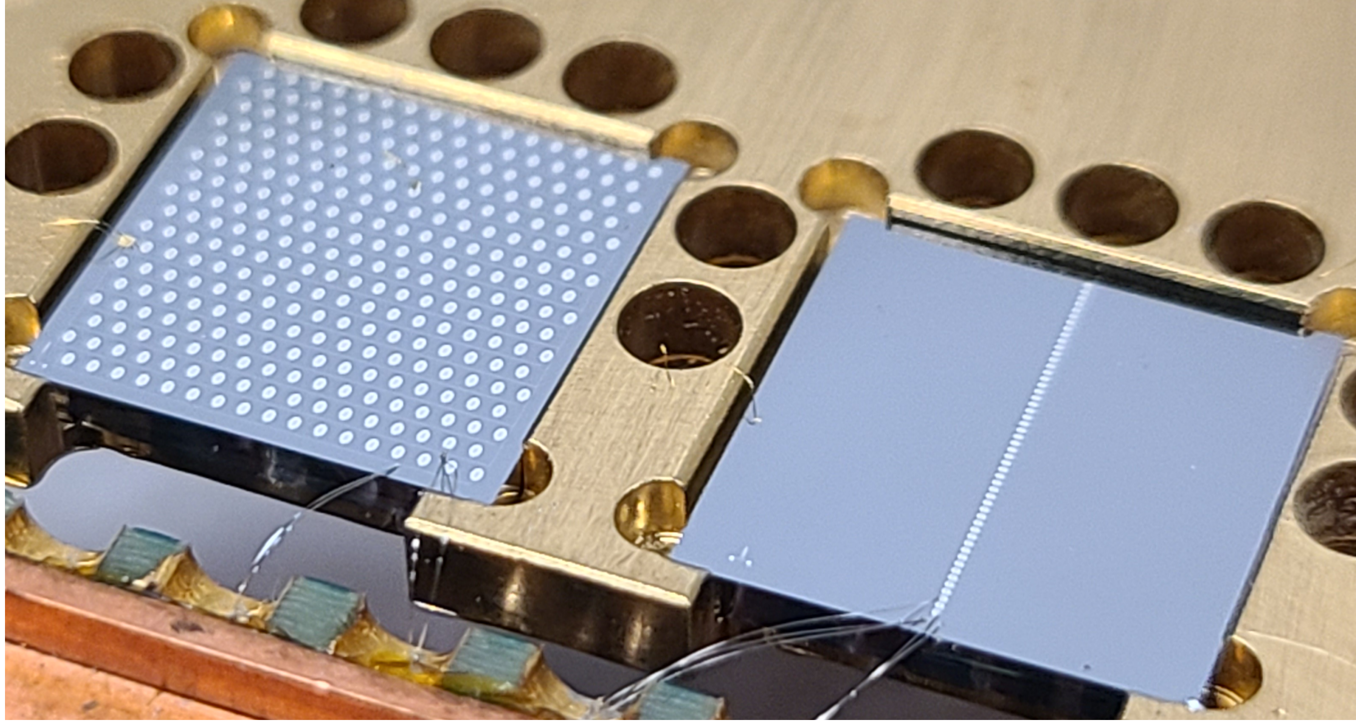


Low Energy Event Excess in Calorimeters

Matt Pyle

EXCESS 22

2/15/21

SuperCDMS Cryogenic Dark Matter Search

SPICE | HeRALD

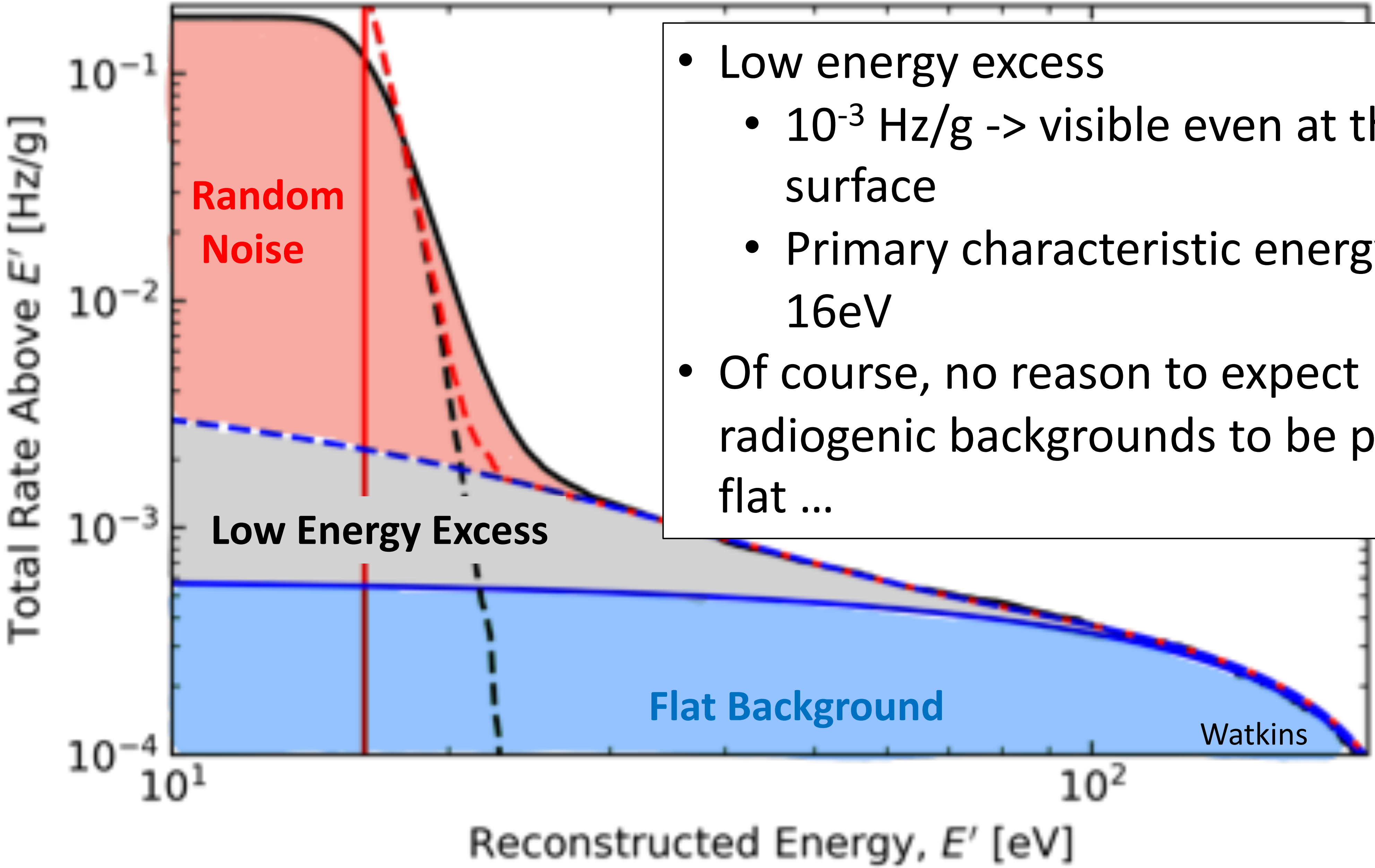
Outline

1. Summary of low energy excess measurements and testing this information vs various hypotheses.
2. Solutions to the low energy excess problem
   A. Direct mitigation
   B. Discrimination using multiple channels
   C. Separation in Energy

Cryogenic Photon Detector (CPD)

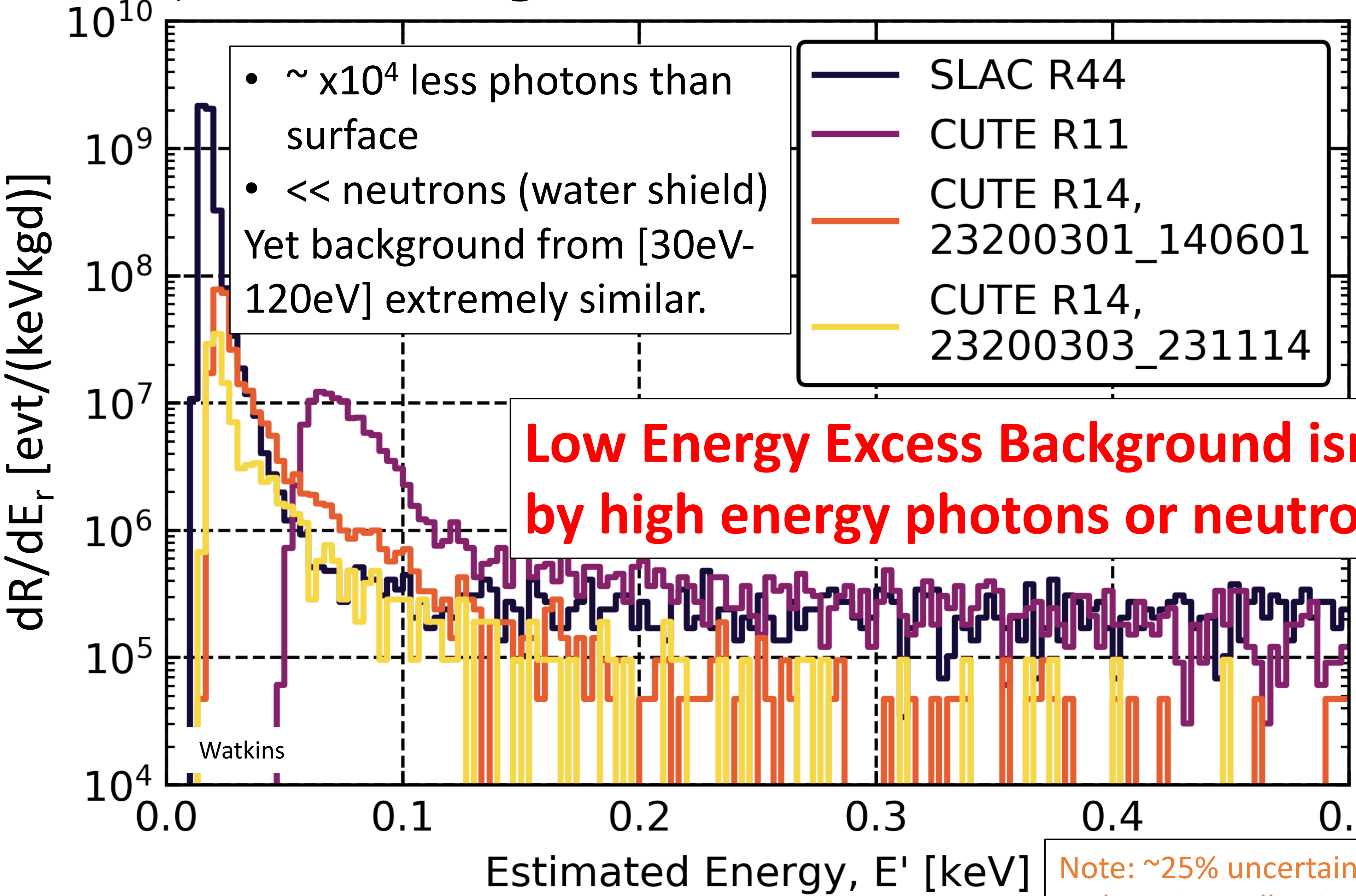
- CPD: 10g 45cm^{2}x1mm Si Athermal Phonon Detector Designed for Light Collection
- σ_{pt} =3.9eVt
- Run both above (SLAC) and below ground (CUTE @ SNOLAB) jointly by the SuperCDMS and CPD collaborations
- Technical Paper: 2009.14302 (APL)
- SLAC DM Search: 2007.14289 (PRL)

Low Energy Excess Event Rate: CPD



- Low energy excess
  - 10^{-3} Hz/g -> visible even at the surface
  - Primary characteristic energy Scale: 16eV
- Of course, no reason to expect radiogenic backgrounds to be perfectly flat …

1) Go Underground and Shield: Excess Still There



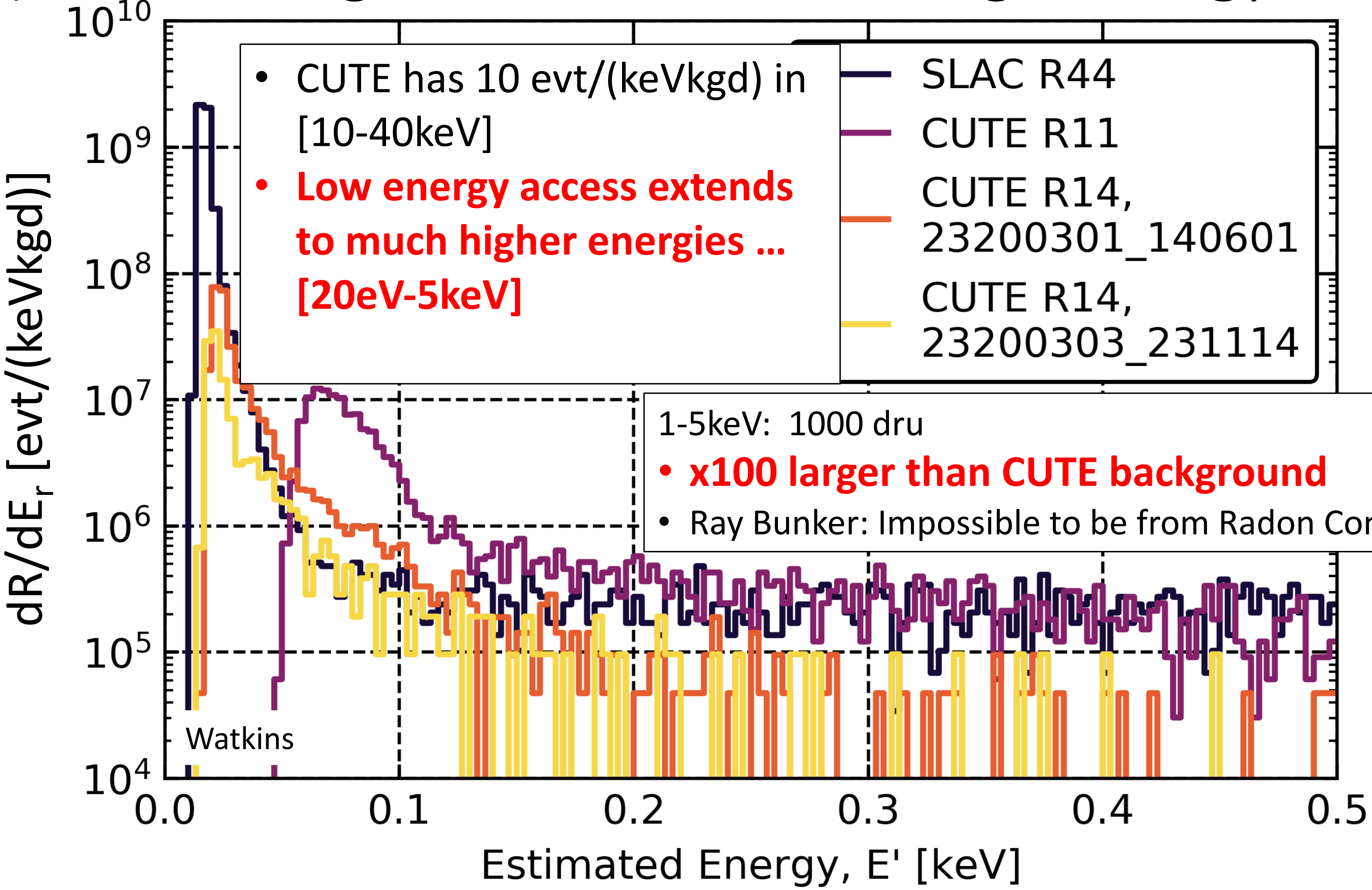
- ~ x10^4 less photons than surface
- << neutrons (water shield)

Yet background from [30eV-120eV] extremely similar.

Low Energy Excess Background isn't sourced by high energy photons or neutrons

Note: ~25% uncertainty in Run 11 and 14 energy scale. Using collection effiency from SLAC

2) Go Underground and Shield: High Energy Excess

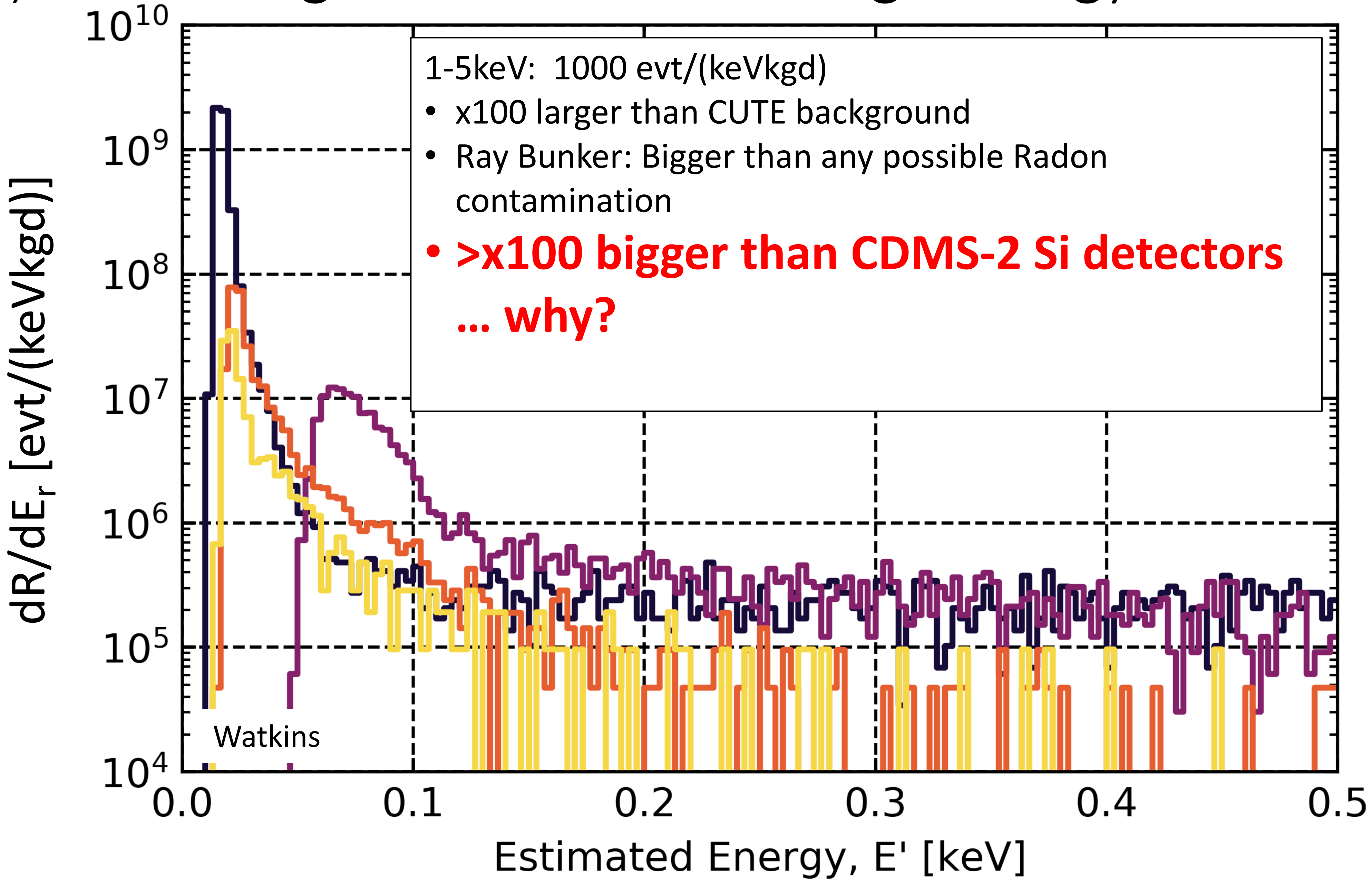


- CUTE has 10 evt/(keVkgd) in [10-40keV]
- **Low energy access extends to much higher energies … [20eV-5keV]**

1-5keV: 1000 dru

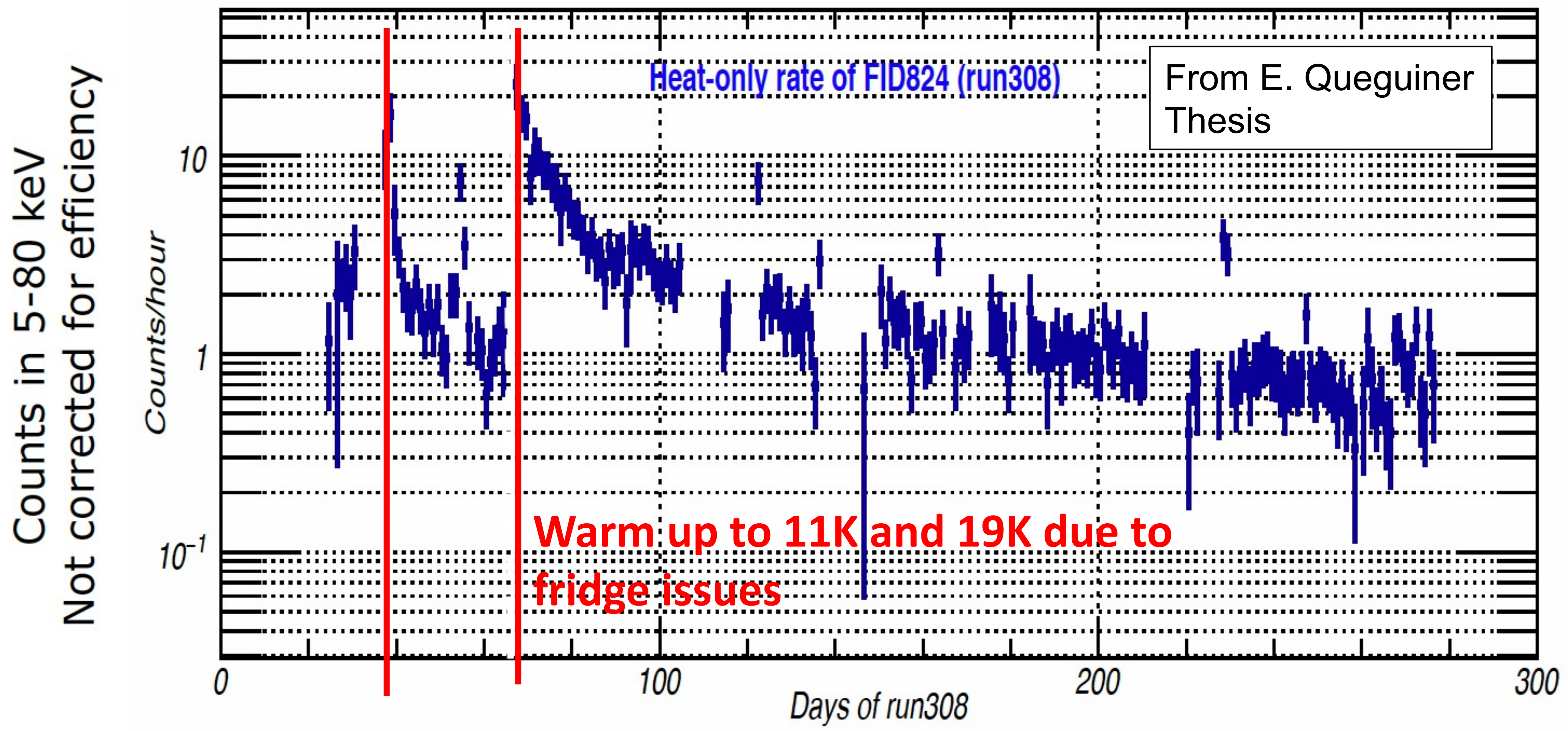
- **x100 larger than CUTE background**
- Ray Bunker: Impossible to be from Radon Contamination

3) Go Underground and Shield: High Energy Rate >> CDMS2



4) Variation with Time Since Cooldown

EDELWEISS Low Energy Excess (FID 824)

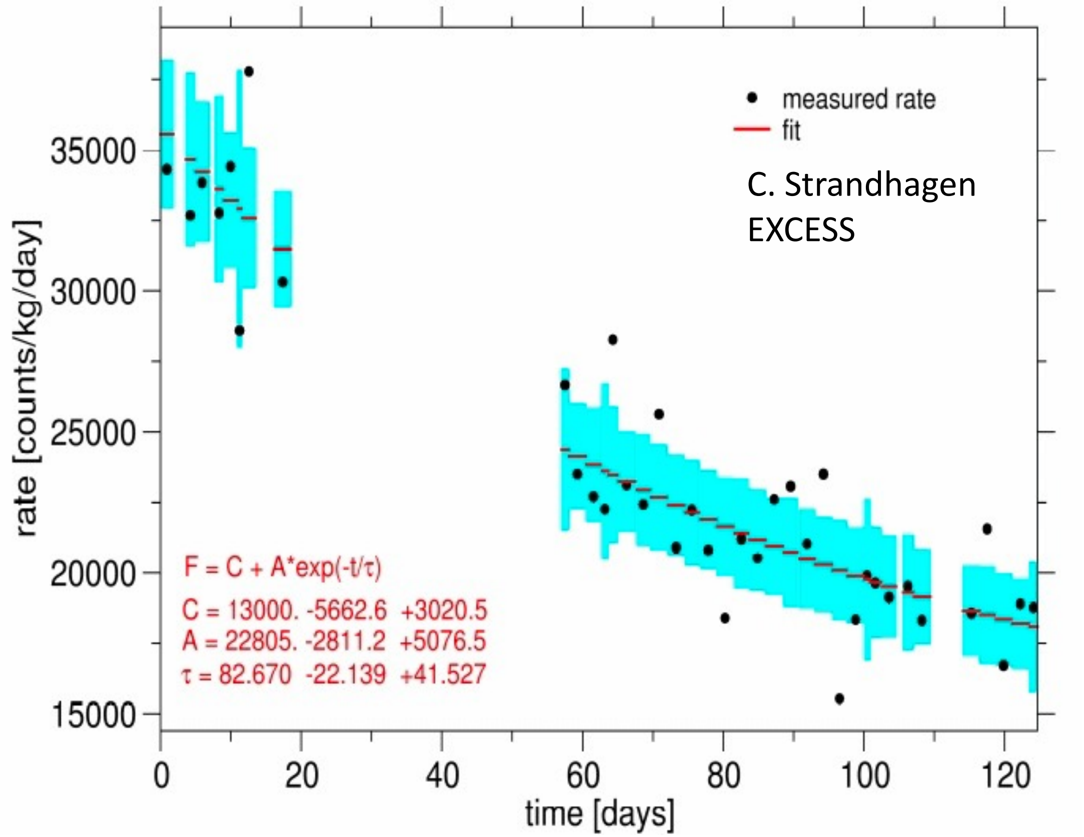


Most Important Question:

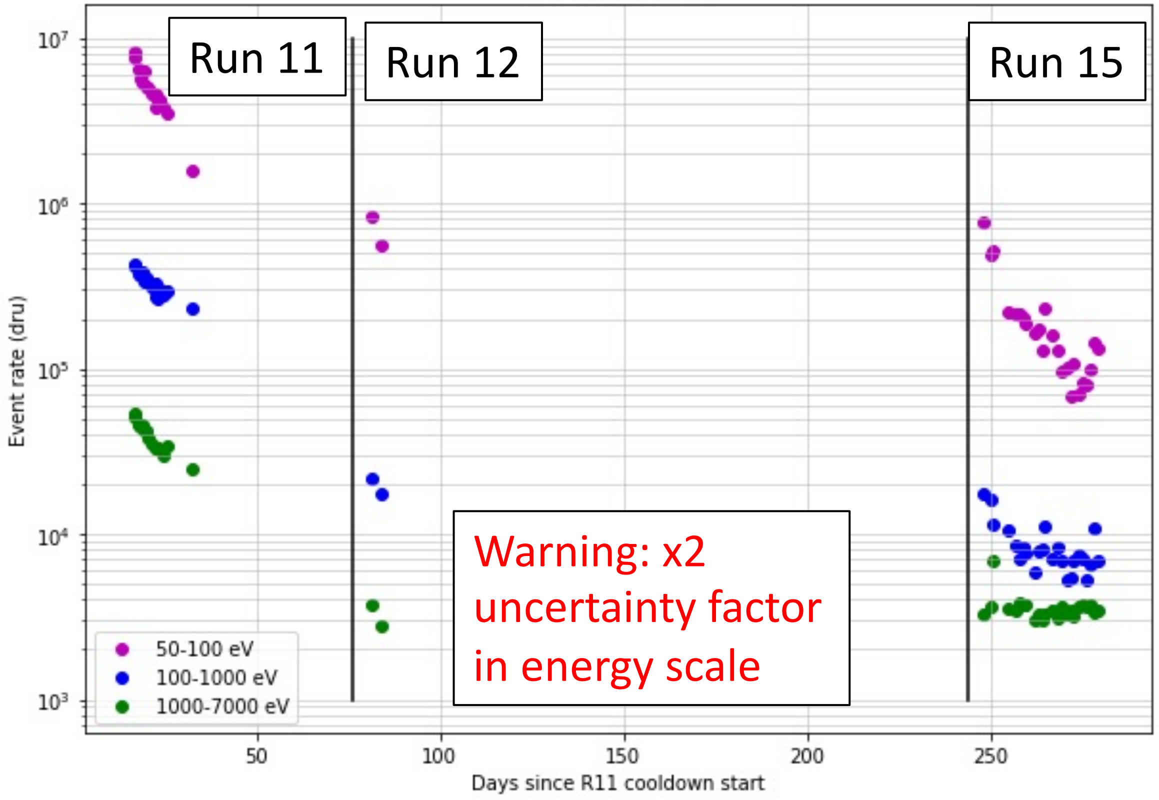
What background sources can vary with time since cooldown?

4) Variation with Time Since Cooldown

CRESST Sapphire



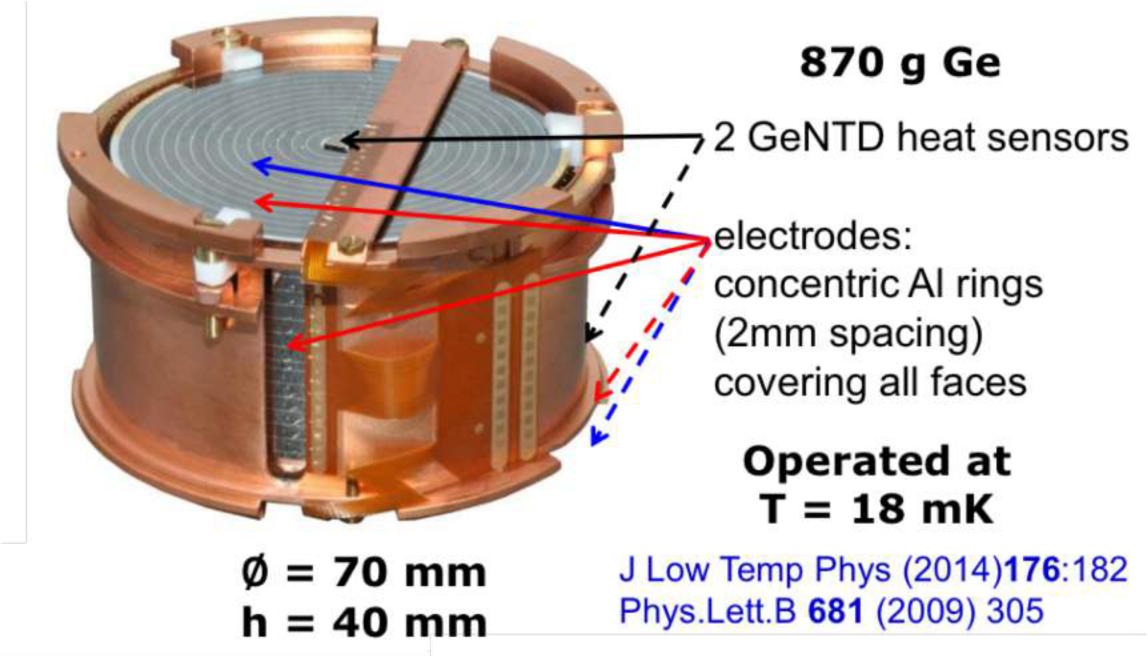
CPD@CUTE

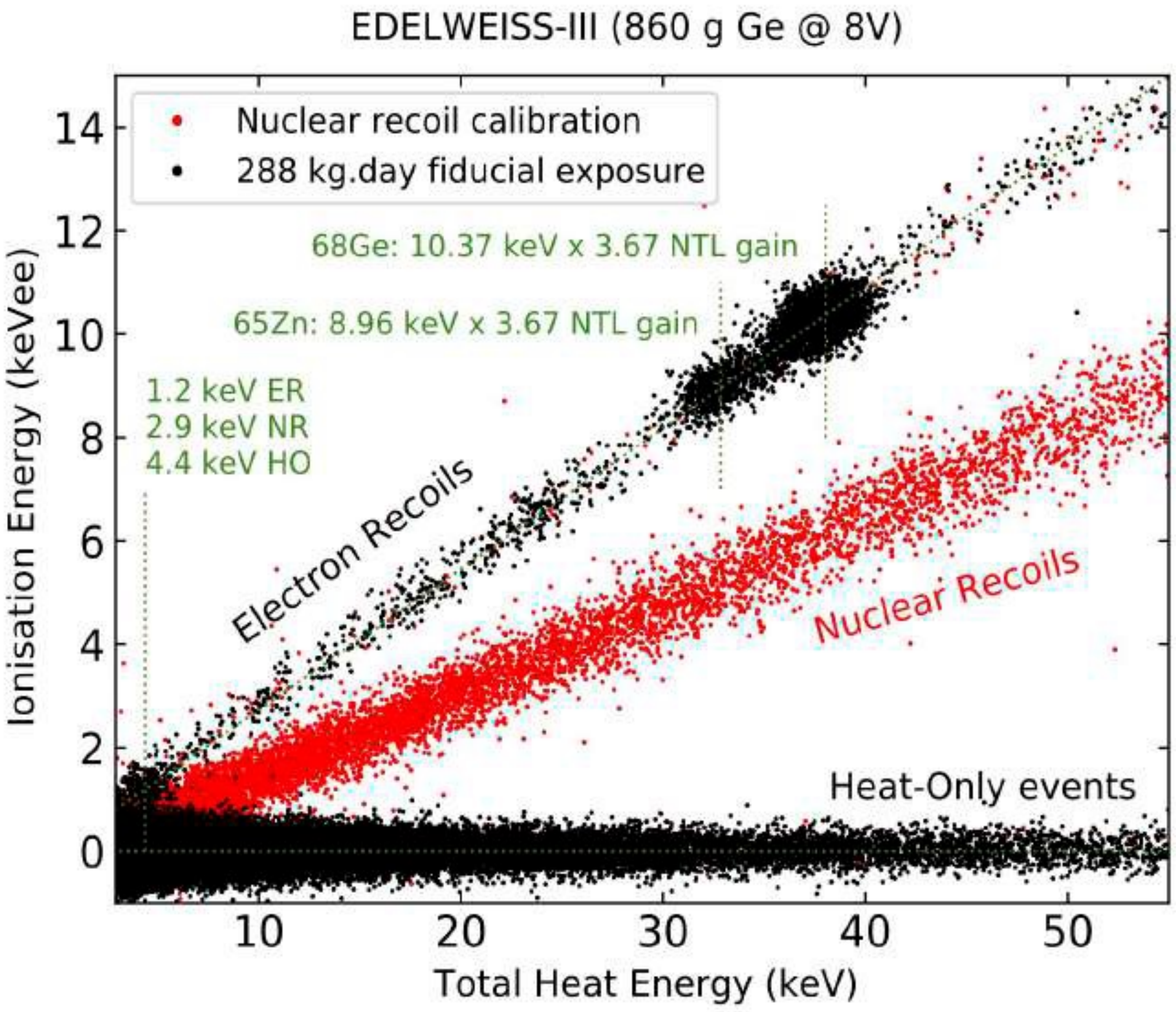


Both CRESST and CPD have low energy excess that vary with time

- Interestingly: decrease seems to be additive with cold time for CPD, but not for EDELWEISS … werid

5) Low Energy Excess is Non-Ionizing



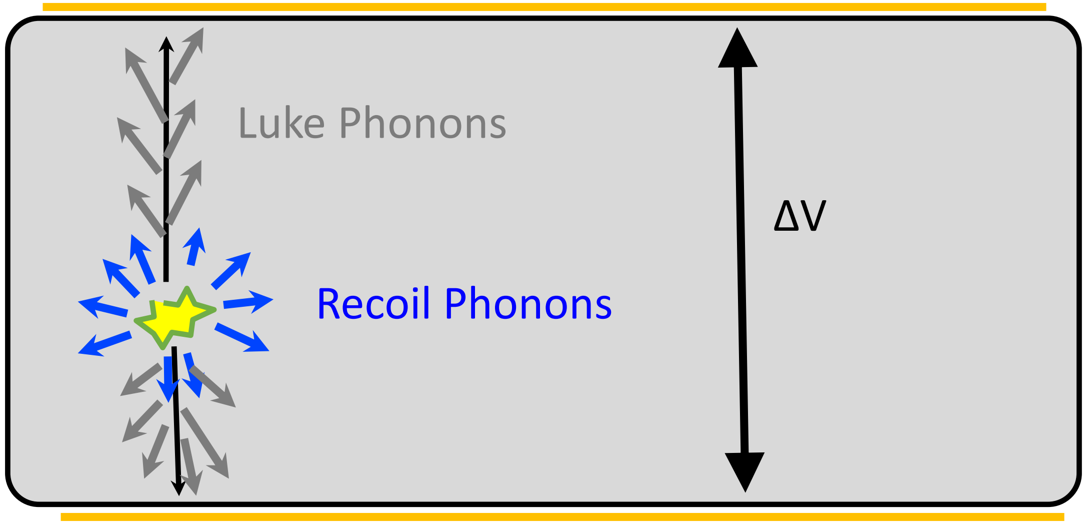


- EDELWEISS interleaved detectors measure both phonons (NTD) and ionization production
- Large no ionization background of unknown origin out to pretty high energies

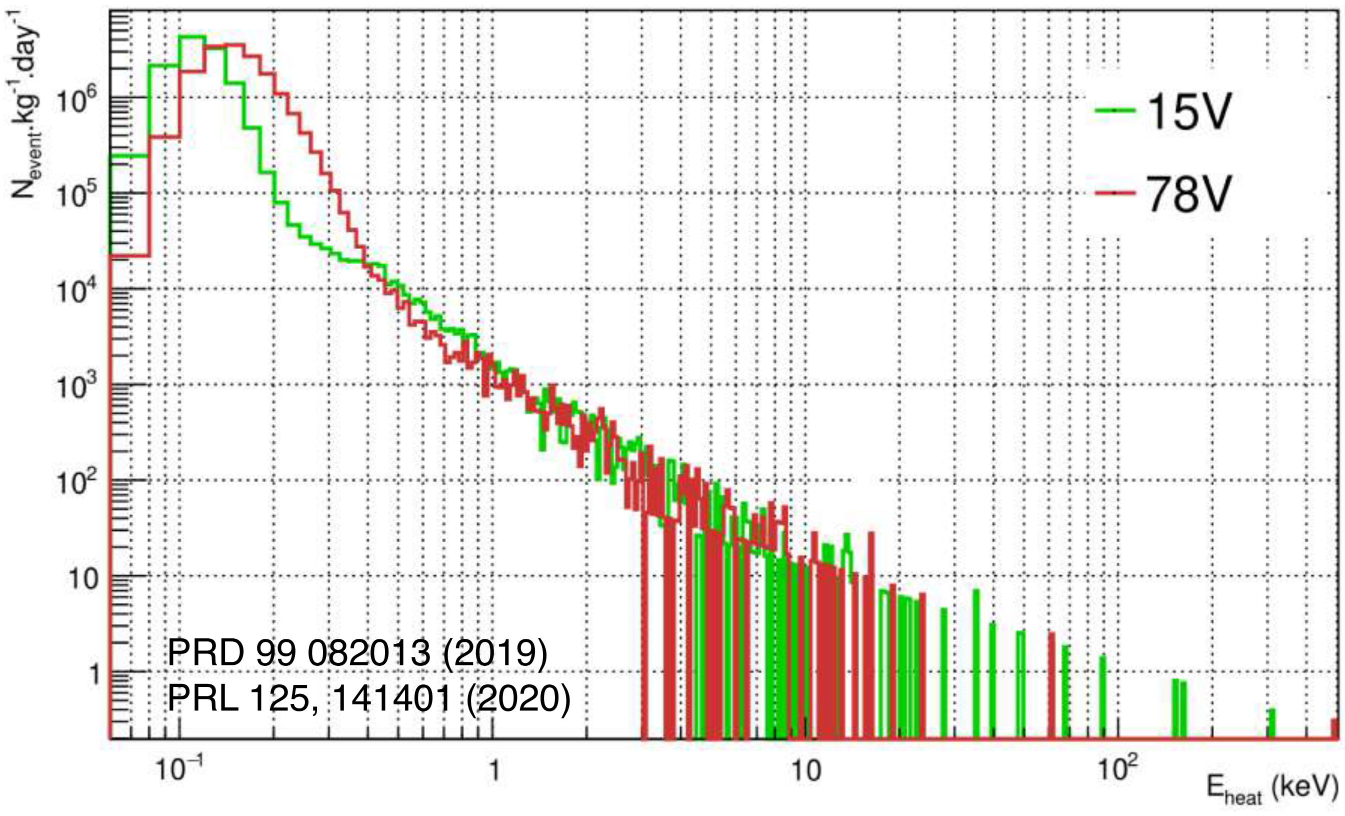
From J. Gascon /EDELWEISS

5) Low Energy Excess is Non-Ionizing

- Drifting **charges** release kinetic energy via Neganov Tiramov Luke (NTL) Phonon Production
- $$E_{total} = E_{recoil} + E_{NTL}$$
  $$= E_{recoil} + n_{eh} e \Delta V$$



EDELWEISS RED30



Lack of stretching means there is very little ionization in these events.

Probably same conclusion for SuperCDMS except more sketchy (not same detector)

Low Energy Excess Fact Summary:

	CPD / CDMS	EDELWEISS	CRESST
1) Same above and below ground	mostly	mostly	
2) Broad Energy Scale	Yes	Yes	
3) Rate varies significantly between detectors	Yes	Yes	Yes
4)Time variation with time since cooldown	Yes (since run 11?)	Yes	Yes (partial)
5) Low Energy Excess is Non-Ionizing	Probably?	Yes	?

- ~~Daughters from high energy photons/ neutrons~~
  1)~same rate above ground and at CUTE
  2) Time since cooldown variation
  3) Zero ionization
- ~~Radon or any surface contamination~~
  3) Time since cooldown variation
  2) Energy spectrum/shape (radon)
  5) Rate … just too big (radon)
- ~~EMI Noise~~
  6) Phonon pulse shape
- ~~Metastable electronic states:~~

  2) Energy Scale: the scale of condensed matter is eV scale 100eV excess event must be multiple particles rearranging

- **Stress Induced Microfractures: matches all facts**
  3)Time since cooldown variation
  2) Energy Scale

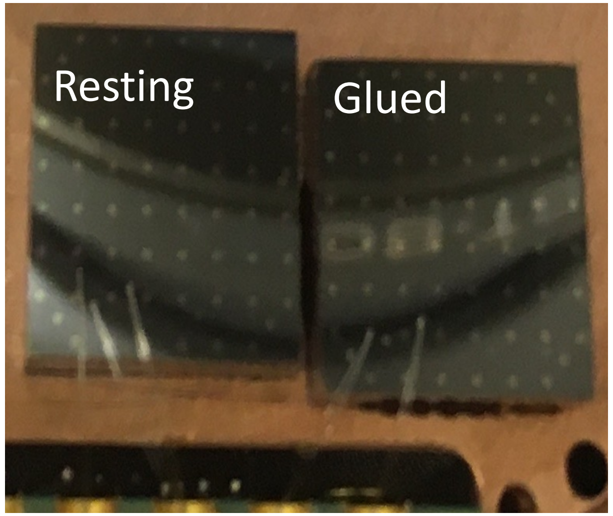
Warning: Hypothesis Testing

- Low energy excess could have subdominant sources that don't meet all of these facts:
  - Example: Only a portion of their low energy excess displays time since cooldown dependence (CRESST).
- Low energy excess at different energy scales could have different sources
  - Perhaps the 20-120eV excess rate is EMI while the 120eV-5keV background is something else.
- (I will talk a bit about mitigating some of these other potential sources later)

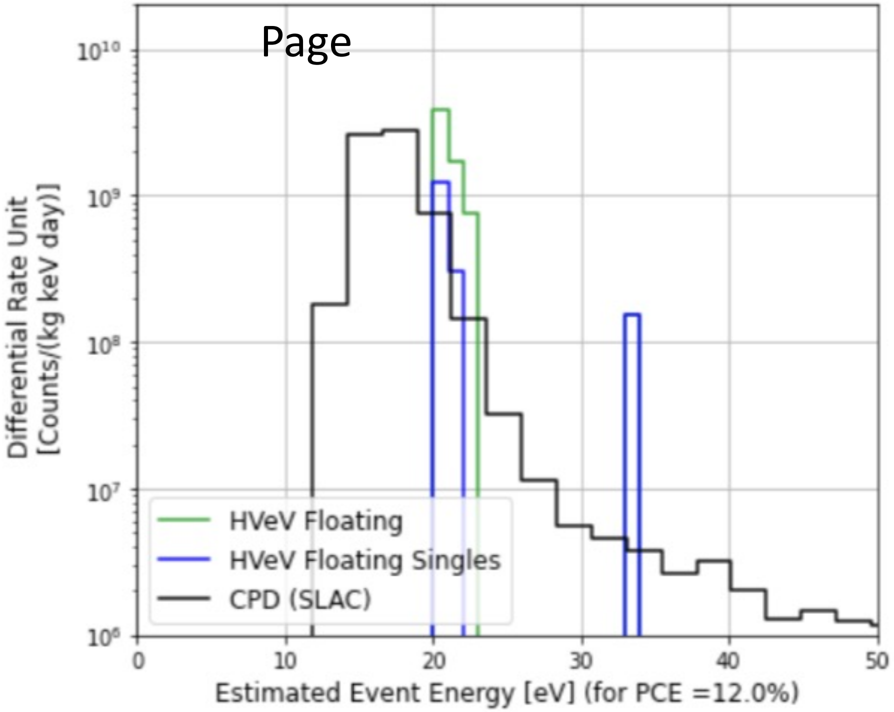
Additional Evidence: CDMS-2 vs CPD

- CPD has ~ x500 higher backgrounds in the 1-5keV range than CDMS2-Si
- Differences:
  - Radon control
  - 1cm vs 1mm thick
  - CPD clamping placed enough stress on the 1mm Si wafer to visibly distort the surface.
- Consistent with the hypothesis of stress induced microfractures

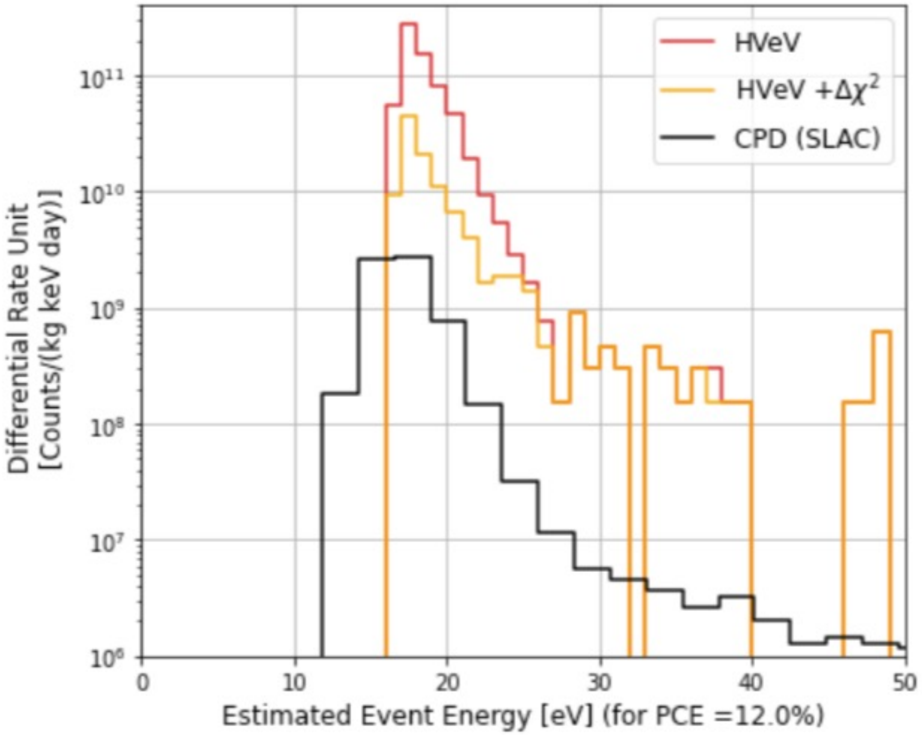
Additional Evidence: GE Varnish Studies



Resting Chip



Glued Chip



Thermal stress in GE varnish produce 5Hz/cm^2 of low energy microfractures

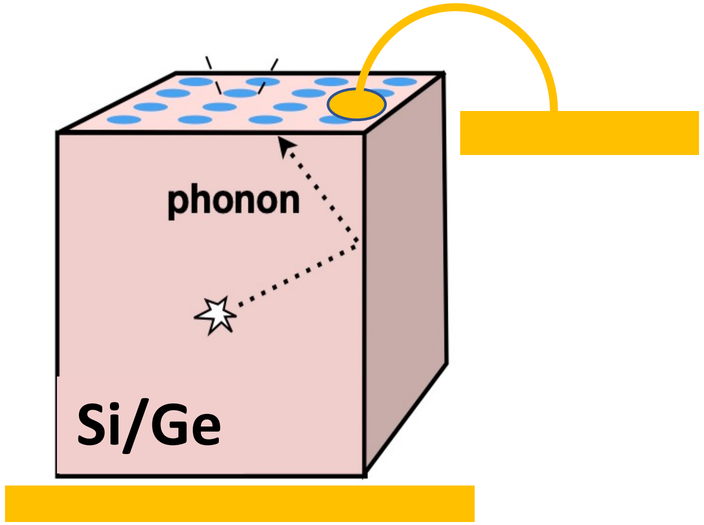
Mitigation for Stress Induced Microfracture Events

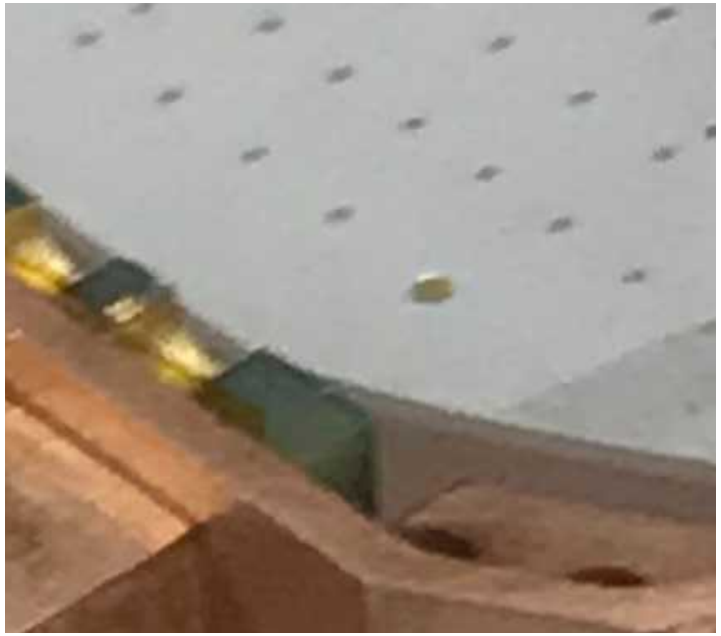
Mitigation

- Remove/Lower all possible sources of stress in your detector!
- Problem: This is hard work with lots of ancillary side effects

Example: Complications with removing stress

- Thermal conductance to bath scales with clamp normal force
  - TES bias power is dissipated through clamps … if not removed our high bandwidth athermal phonon sensors become low bandwidth thermal calorimeters.
- Solution: add gold pad + wirebond thermal link to athermal phonon sensor design

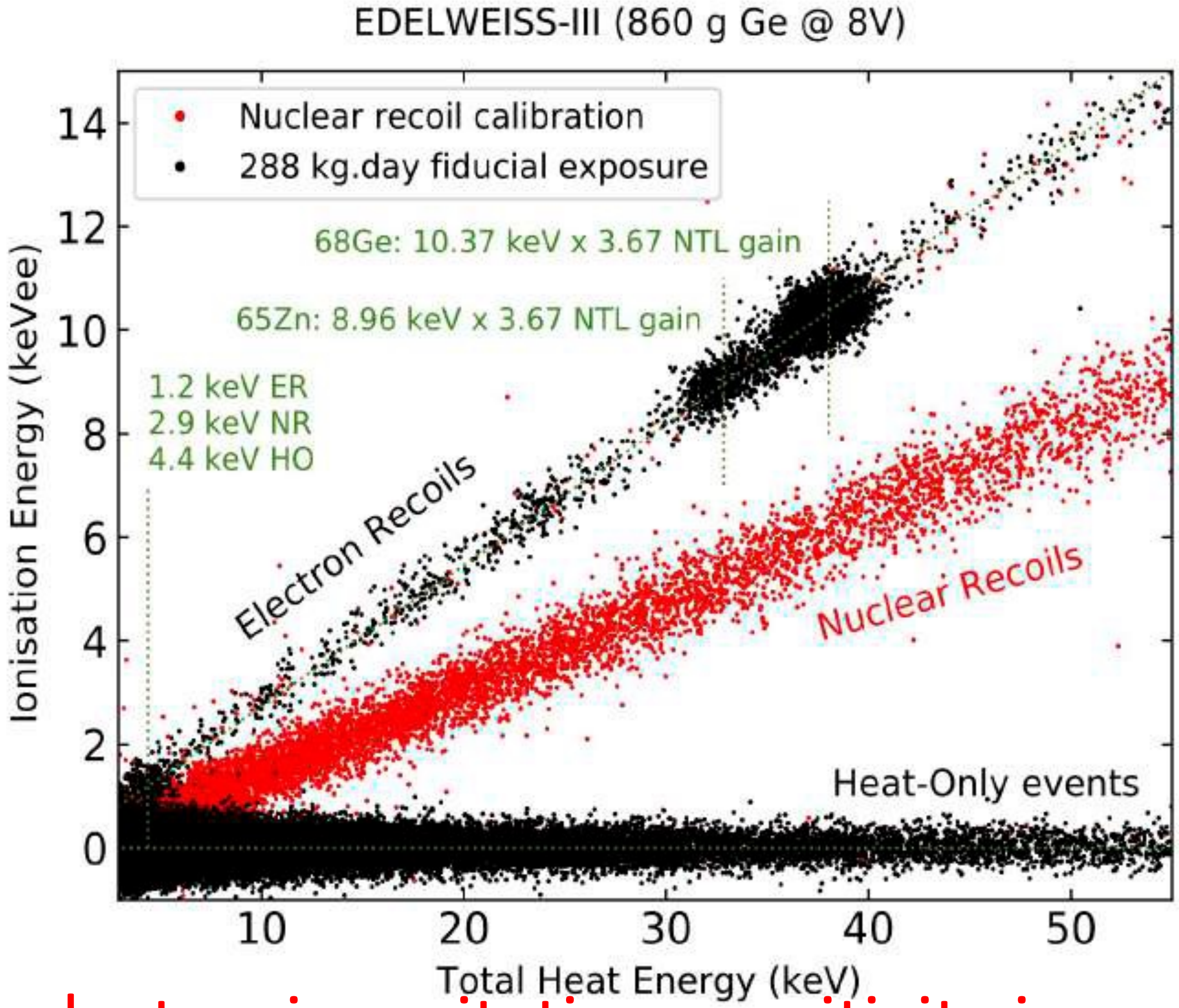




Discrimination of Ionizing Events vs Non-Ionizing Events (like microfractures)

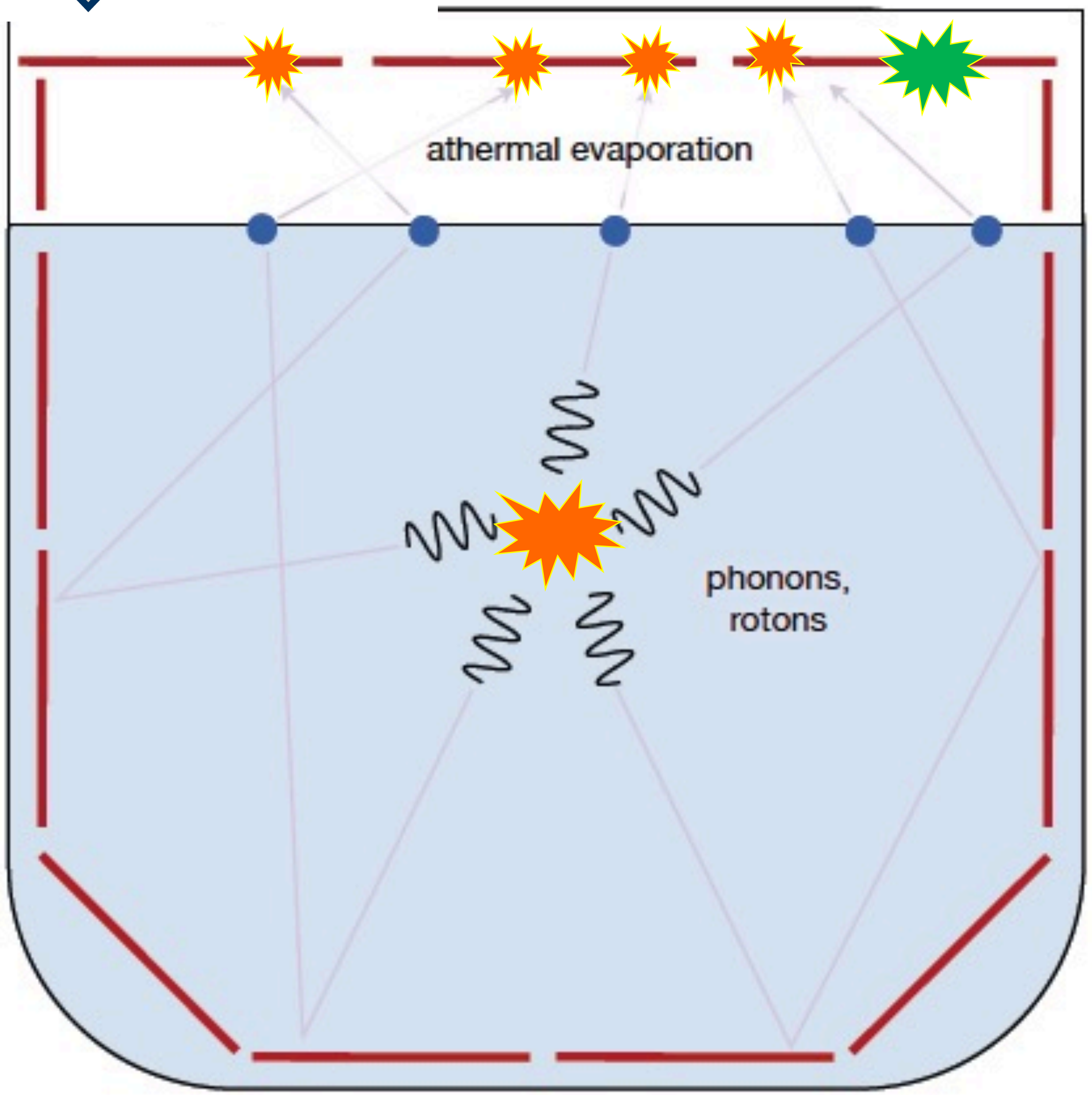
Discrimination: Real Recoils vs Microfracture Events

- Electronic Recoils and Nuclear Recoils for DM with M_{DM} > O(200MeV) produce ionization
- Design an experiment that independently measures phonons and electronic excitations



Problem: single photon / few electronic excitation sensitivity is challenging

HeRALD Helium Roton Apparatus for Light Dark matter



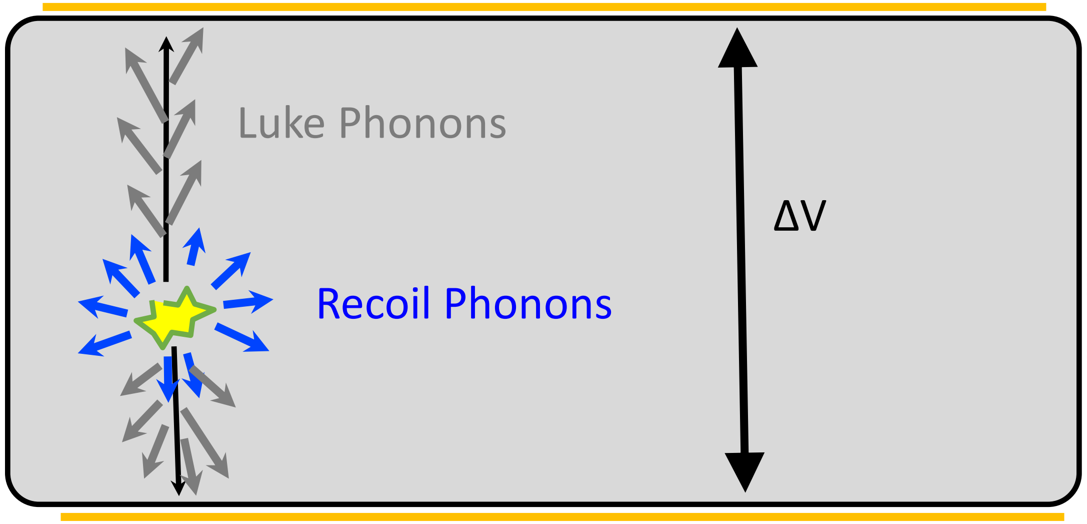
- Superfluid Helium: it's a liquid … no stress microfractures
- Multiple Pixel Coincidence for He DM events
  - microfractures (low energy excess) uncorrelated between detectors
  - DM recoiling off of He: produces signals in multiple roton detectors -> require multiple pixel coincidence for He events
- Pulse Shape: Helium is slow!

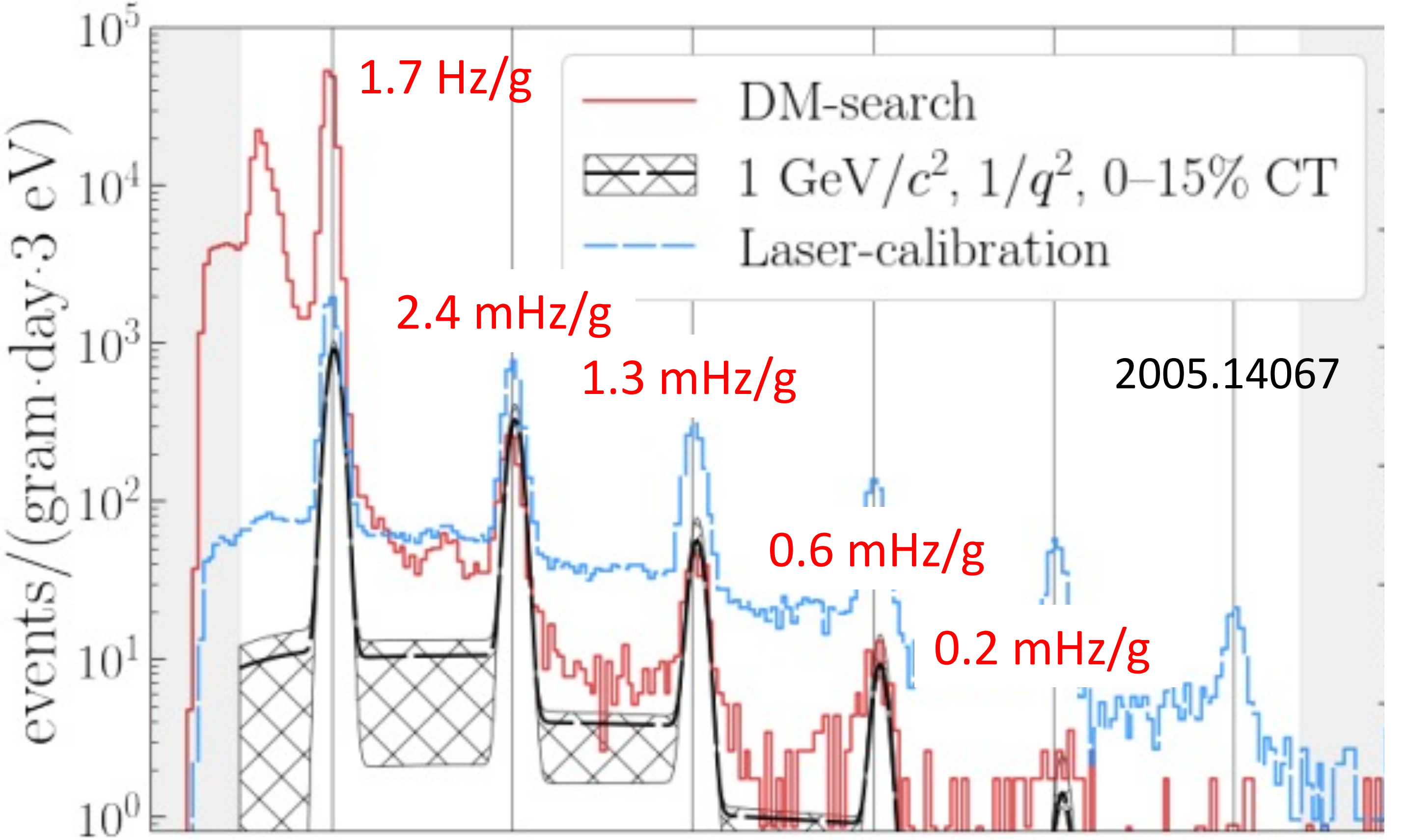
HeRALD is a hard experiment … but it has multiple background rejection techniques that crystals don't have

Separating Signal from Low Energy Excess Backgrounds

Separation in Energy: NTL Amplification

$$E_{total} = E_{recoil} + E_{NTL}$$
$$= E_{recoil} + n_{eh} e \Delta V$$



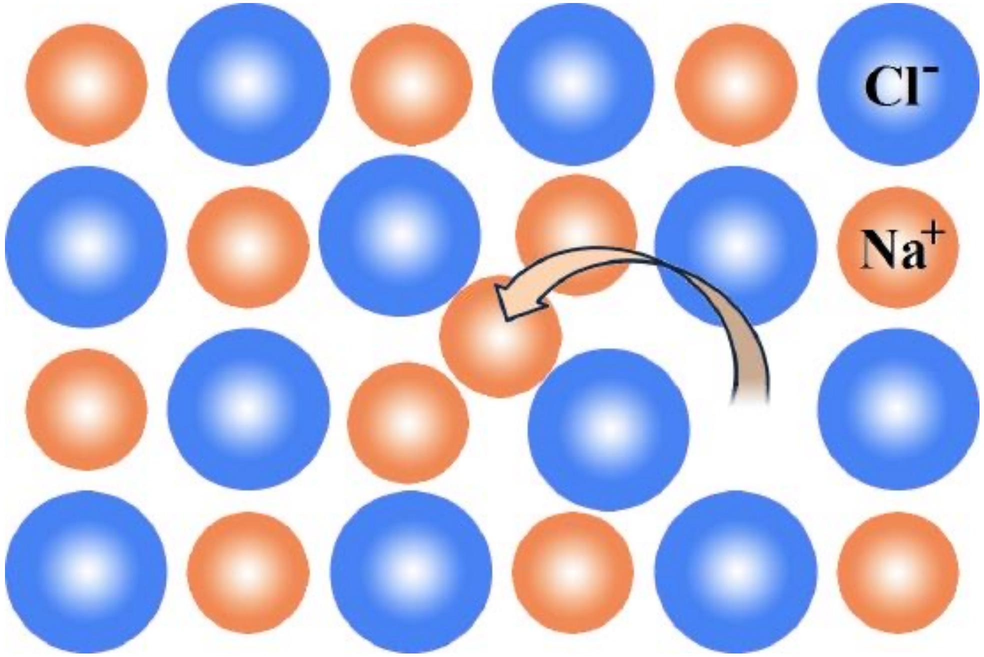


Just boost the ionizing signal above the low energy excess with TNL Gain

Problem: You become sensitive to charge leakage tunneling ☹

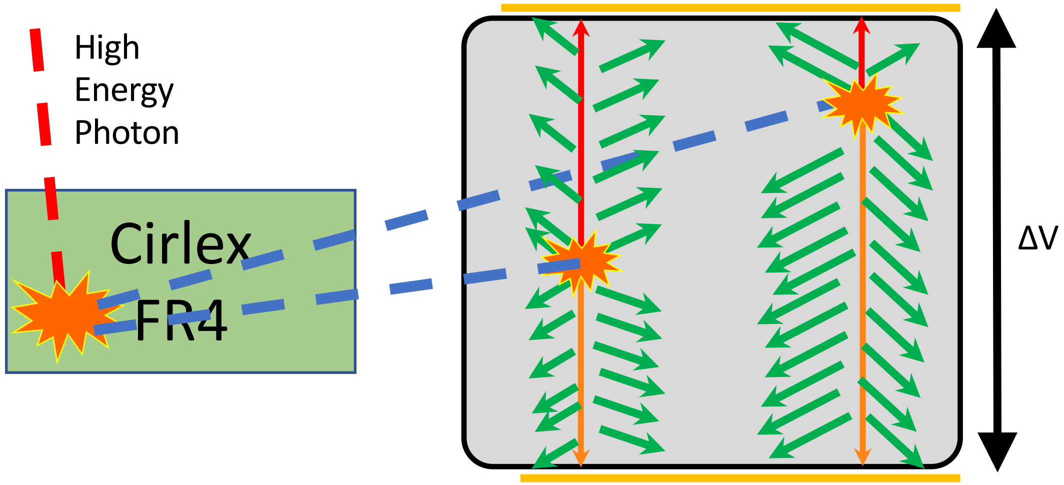
Separation in Energy: What happens below O(eV)?

- No low energy excess measurements below 20eV currently
- BIG QUESTION: Is there a lower energy threshold to the low energy excess? If yes, just look below this threshold
- Why would we expect a low energy threshold? Crystal stuff happens at the eV scale
  - Frenkel Pair Crystal Defect has O(4eV) in Si
  - Electronic excitatations O(eV)
- Problem: Designing detectors with 100meV thresholds



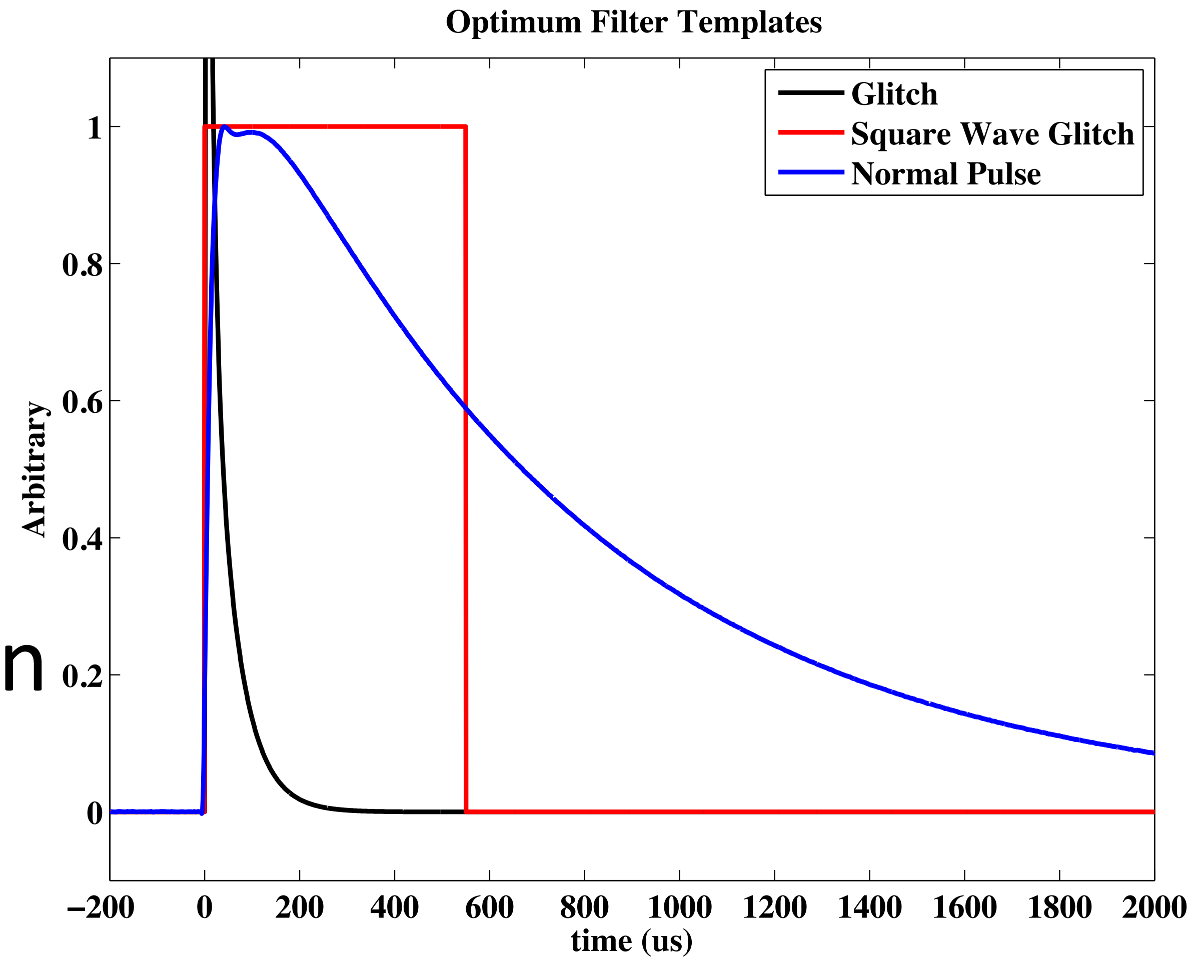
Other Possible Background Sources: Photon Sourced

- Events sourced by high energy photons
  - SuperCDMS HVeV, SENSEI (2011.13939)
  - Single Phonon Backgrounds (2112.09702)
- Solution:
  - Get rid of non-active insulating materials in optical cavity -> x10^3 reduction
  - Get rid of photon backgrounds 10^4 dru -> 1dru -> x10^4 reduction
  - 4pi Active Veto -> ~x10^2 reduction
- I think this is a solveable problem! Note: more challenging for CCDs because of the lack of timing information



Other Possible Backgrounds: EMI

- Near Threshold "Events" could be non-stationary EMI
- Unlikely, EMI is usually correlated …
- Solutions:
  1. Pulse shape Discrimination: make dirac-delta EMI pulses look different from phonon signals (you can control phonon pulse shapes via fractional sensor coverage)
  2. Faraday Cages!



Other Possible Backgrounds: ?

Conclusions

1. A substantial component (but potentially not all) of the low energy background is:
   - Independent of photon/neutron backgrounds
   - Non-ionizing
   - Varies with time since cooldown
   - Energy scales >> condensed matter scales

   This feels like stress induced microfractures

2. Solutions to microfractures
   - Mitigation
   - Discrimination
   - **Separation in Energy**