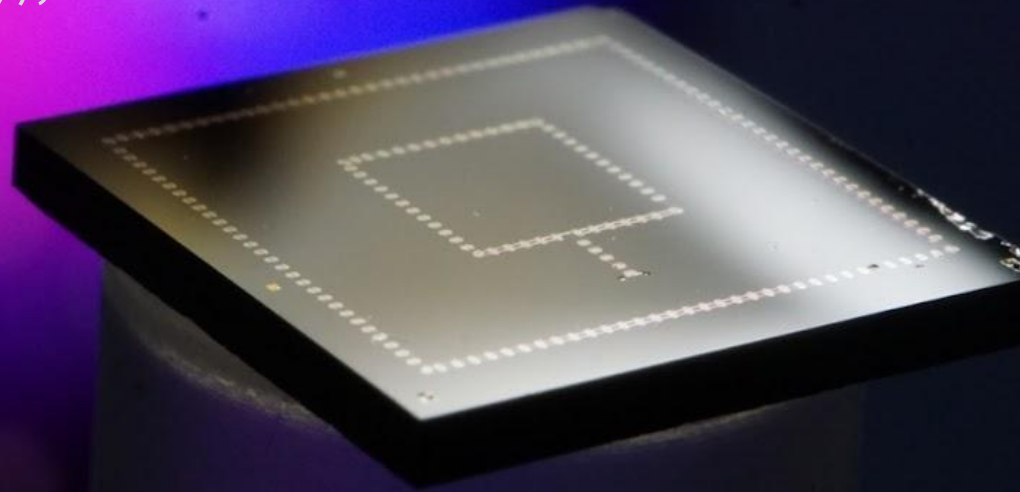
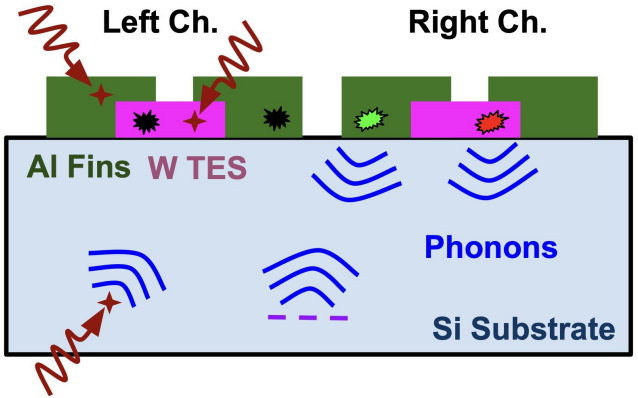
Observations of the LEE in a Two Channel SPICE Athermal Phonon Detector

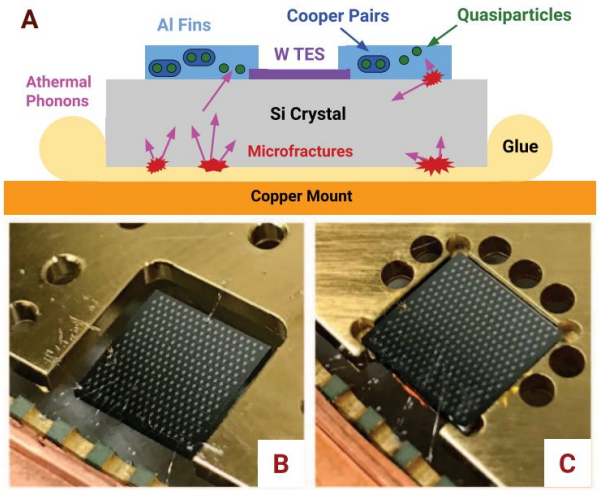
Roger K. Romani (UC Berkeley), EXCESS 2023

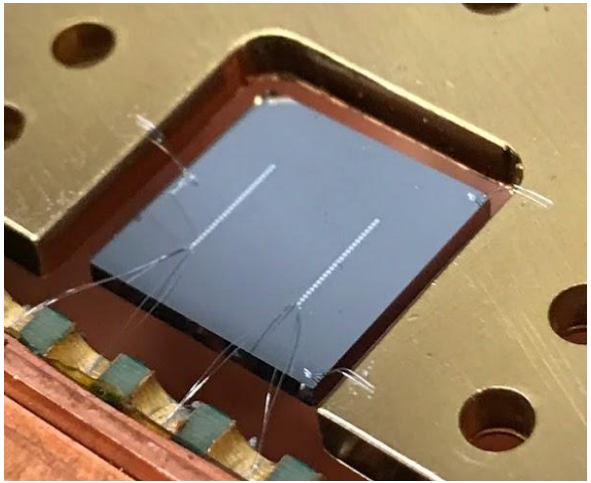


Outline

- Who we are
- Last year: stress causes LEE like events
- This year: Two channel detectors for discrimination/investigation of LEE
  - Noise is part of the LEE story too!
- Next year: Films cause LEE?



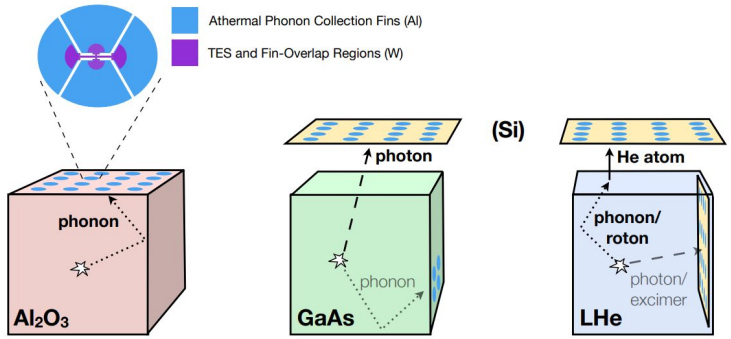


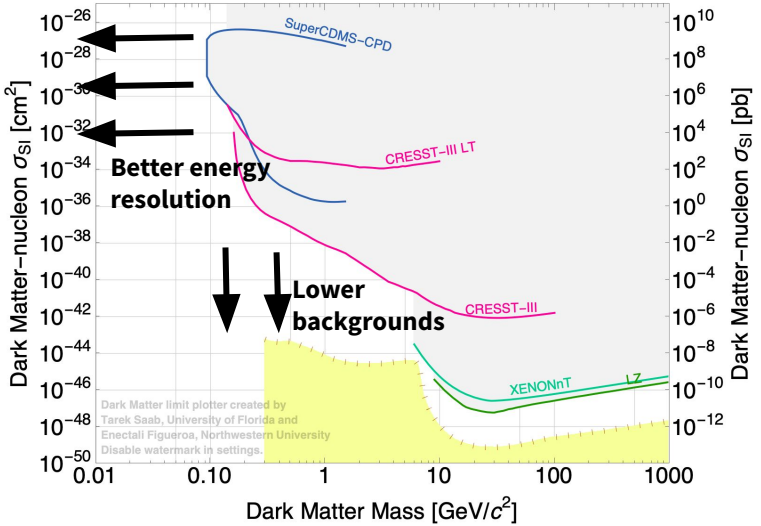


SPICE/HeRALD Collaboration

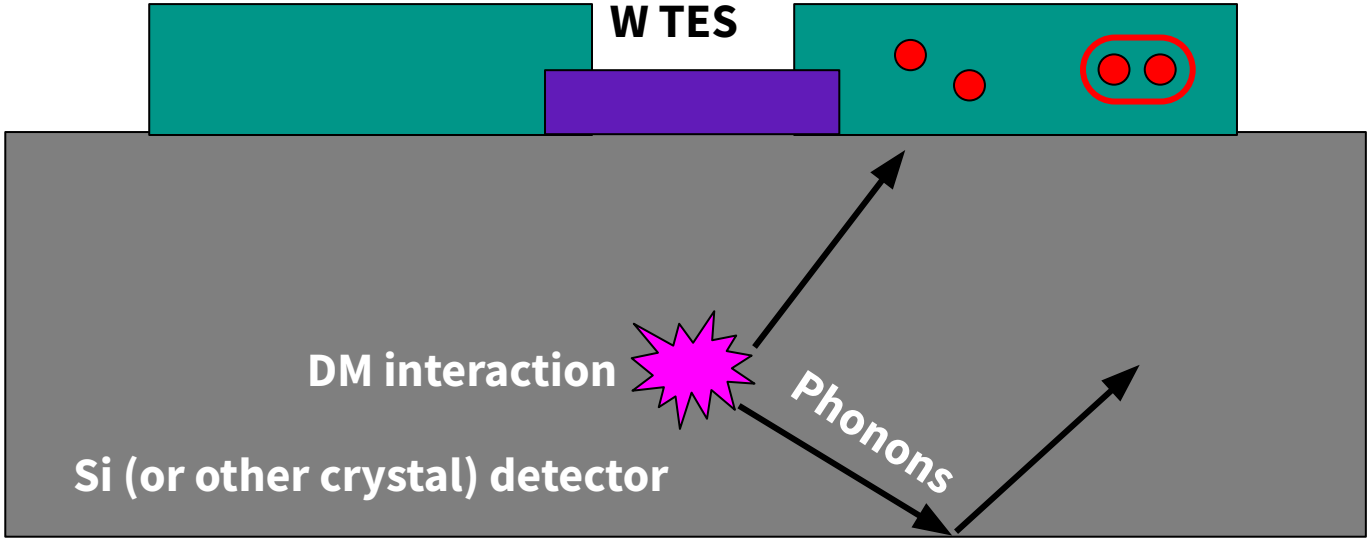
(also known as TESSERACT)

- A new US based collaboration searching for Light (MeV-GeV) Dark Matter
- SPICE: high energy resolution calorimeters for polar crystals

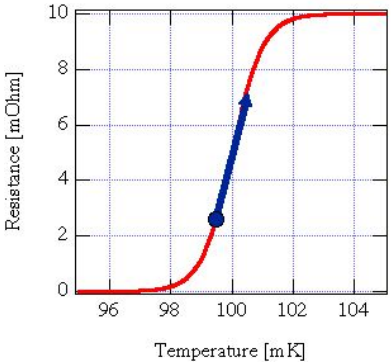




Our Approach: Calorimetry



Phonons break Cooper pairs in fins, make quasiparticles



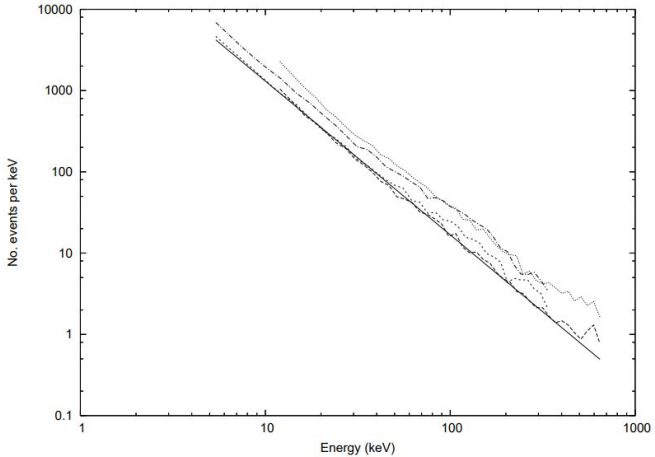
***all at ~10 mK in dilution refrigerator**

Last Year: Stress Creates LEE-like Events

Last Year: Why Investigate Holding?

- CRESST saw excess of “low energy” events (10-100 keV)
- Found that clamps were causing cracking at contact point
- When they reduced this clamp stress, events went away

Astrom et. al. 2005, “Fracture Processes Observed with A Cryogenic Detector“

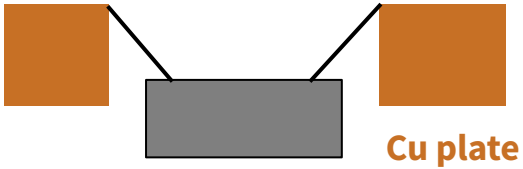


An extensive search for the origin of the pulses was finally successful when it was noticed that there appeared to be markings or scratches on the crystal at the contact points with the sapphire balls. When the sapphire balls were replaced by plastic stubs, which are evidently much softer, the event rate immediately dropped from some thousands per hour to the expected few per hour.

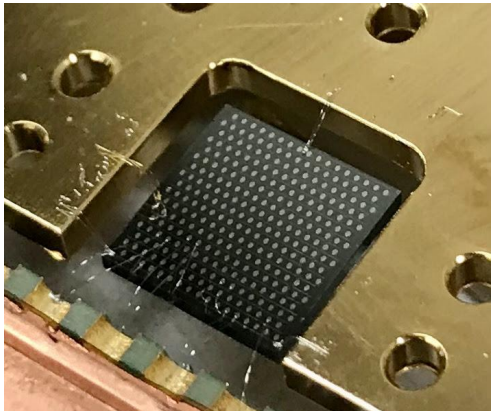
Last Year: Hanging Detectors

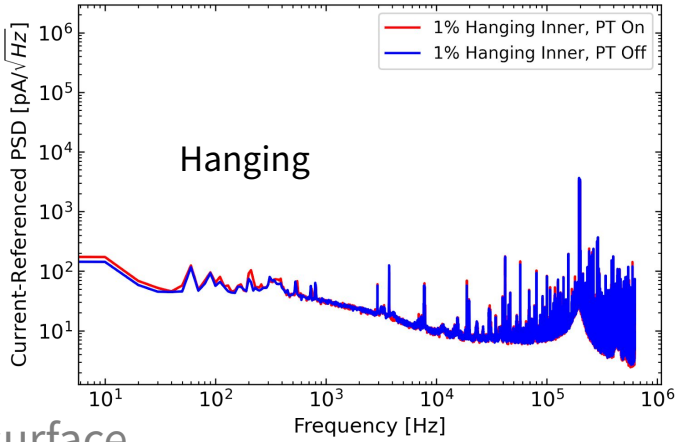
Basic concept: suspend detector from wire bonds

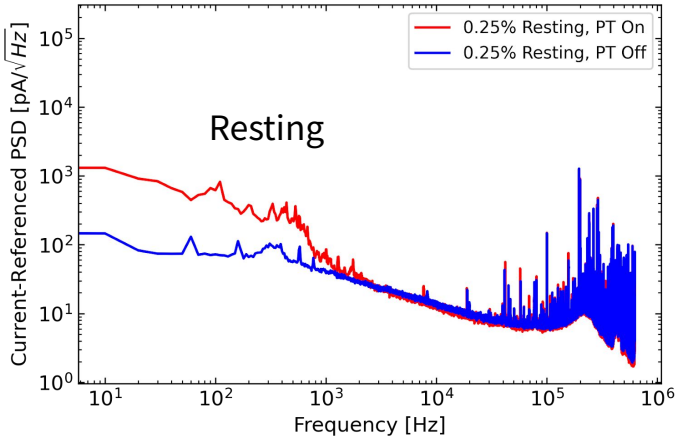
- Low stress (no clamping)
- No relative motion between detector and holding surface
- Bonus: low pass filter for vibrations



cm² Si detector



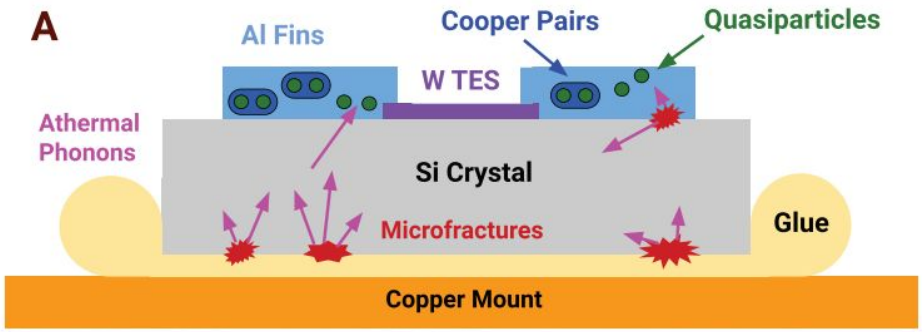


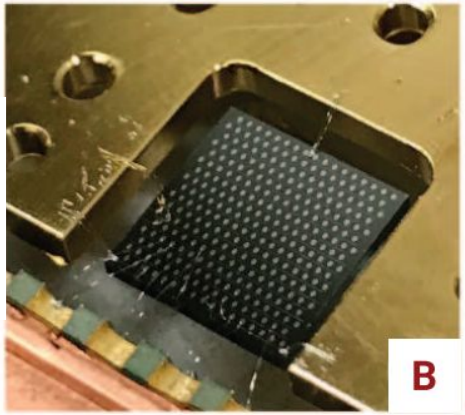


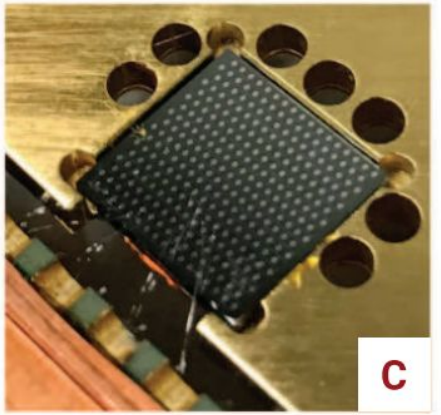
Fink, Watkins theses, 2021

Last Year: Compare Hanging/Glued Detectors

- Two identical as possible* detectors
  - One glued down
  - One hanging from wire bonds
- TES based readout measures athermal phonon pulses in substrate



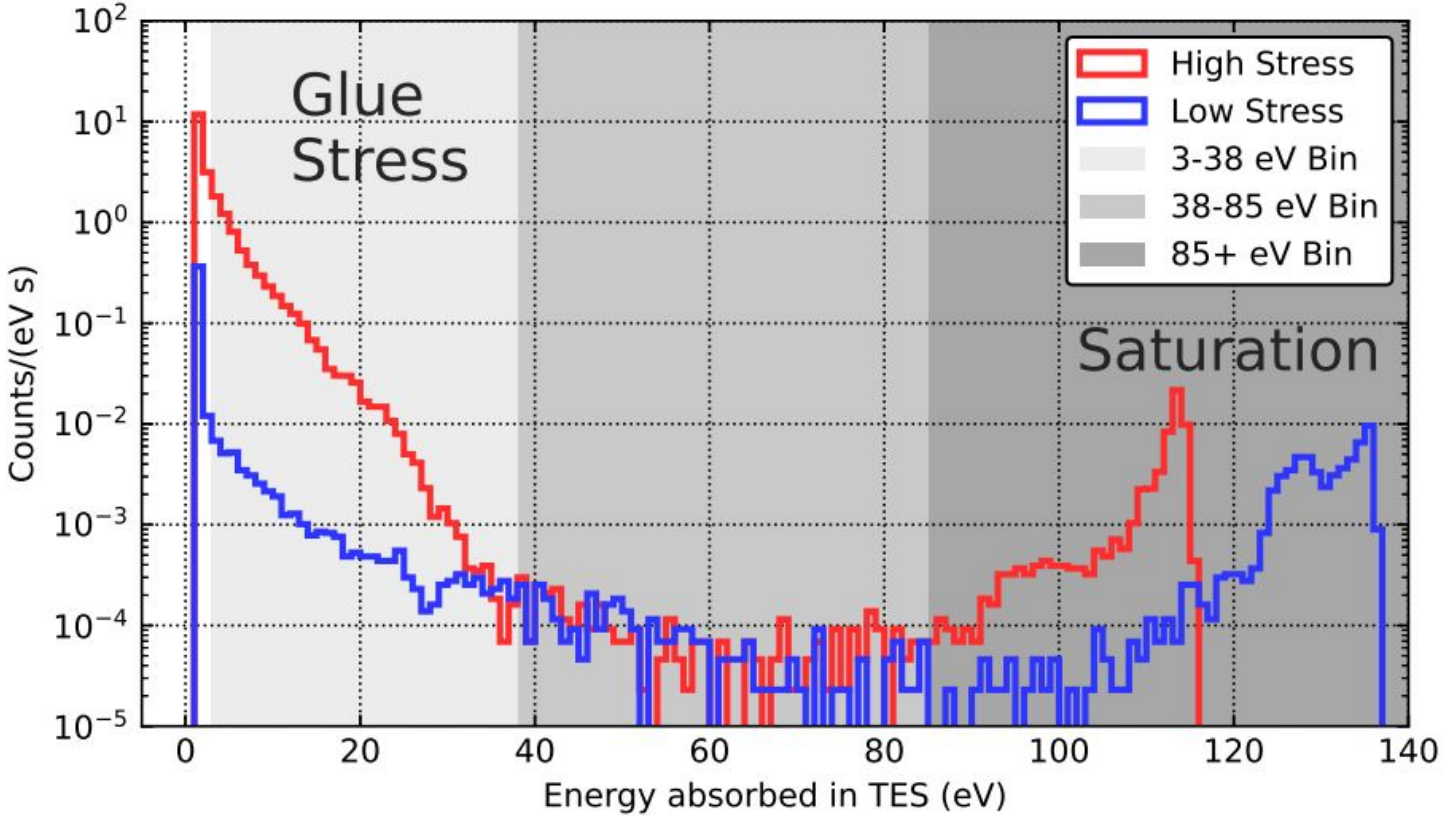




A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning

R. Anthony-Petersen,[1] A. Biekert,[1,2] R. Bunker,[3] C.L. Chang,[4,5,6] Y.-Y. Chang,[1] L. Chaplinsky,[7] E. Fascione,[8,9] C.W. Fink,[1] M. Garcia-Sciveres,[2] R. Germond,[8,9] W. Guo,[10,11] S.A. Hertel,[7] Z. Hong,[12] N.A. Kurinsky,[13] X. Li,[2] J. Lin,[1,2] M. Lisovenko,[4] R. Mahapatra,[14] A.J. Mayer,[9] D.N. McKinsey,[1,2] S. Mehrotra,[1] N. Mirabolfathi,[14] B. Neblosky,[15] W.A. Page,[1,*] P.K. Patel,[7] B. Penning,[16] H.D. Pinckney,[7] M. Platt,[14] M. Pyle,[1] M. Reed,[1] R.K. Romani,[1,*] H. Santana Queiroz,[1] B. Sadoulet,[1] B. Serfass,[1] R. Smith,[1,2] P. Sorensen,[2] B. Suerfu,[1,2] A. Suzuki,[2] R. Underwood,[8] V. Velan,[1,2] G. Wang,[4] Y. Wang,[1,2] S.L. Watkins,[1] M.R. Williams,[16] V. Yefremenko,[4] and J. Zhang[4]

Last Year: Stress Causes LEE like Events



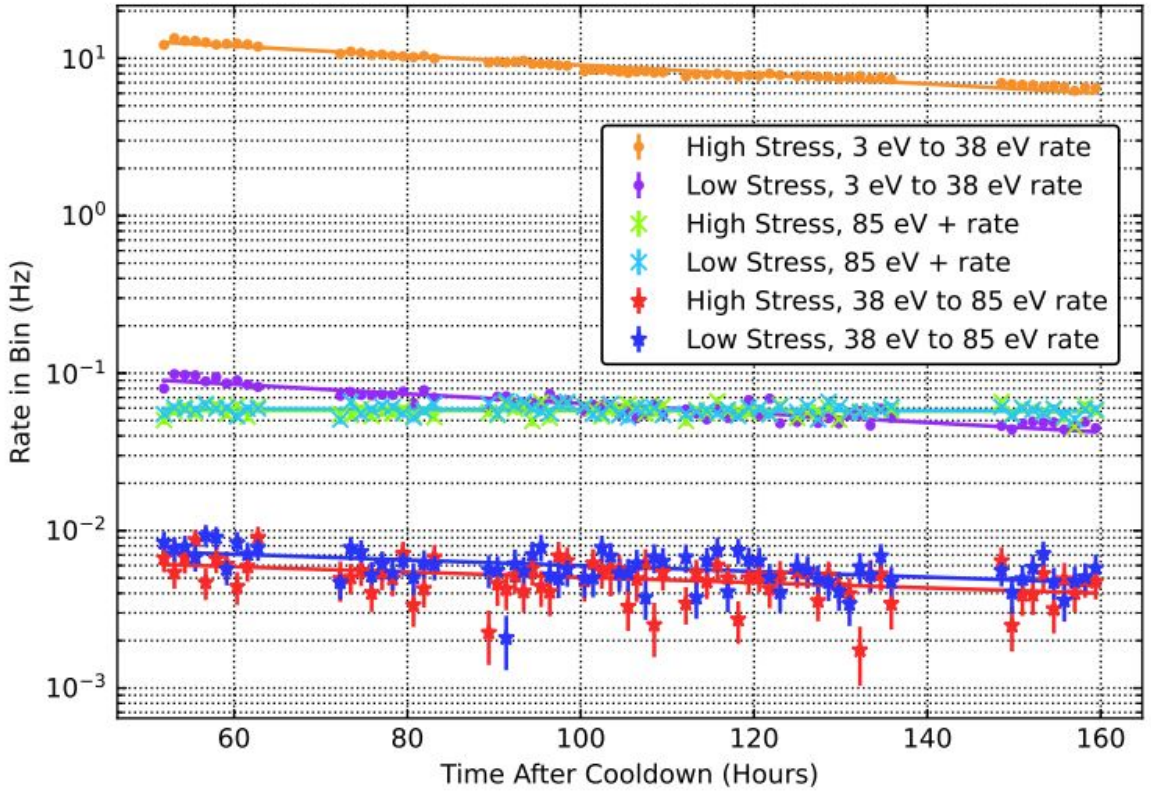
Last Year: Stress Causes LEE like Events

Glue-like excess falls off with time, as LEE does

High energy: muons etc. remain constant, nice cross check

In medium energy range, see essentially identical LEE in both detectors

Stress creates LEE like events, but holding stress isn't whole story



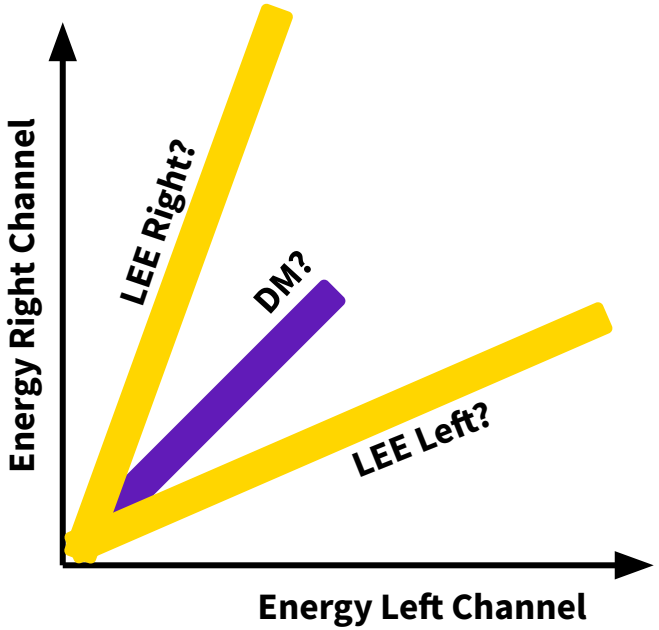
Look in films!

This Year: Two Channel Detectors and LEE

Basic idea: LEE comes from films, might deposit some of energy locally

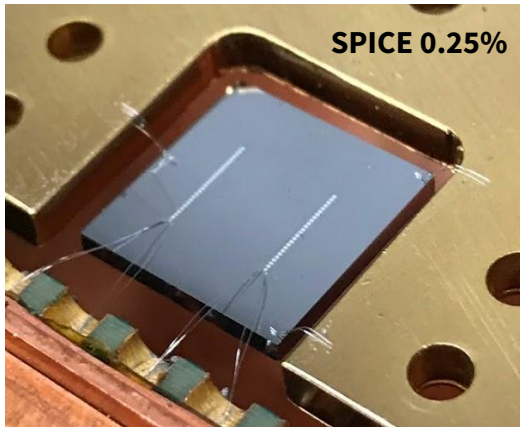
- Tungsten: ~60% of photon energy absorbed locally, known from optical TESs, etc.
- Aluminum: mean free path of phonons shorter than film for phonons above ~2 meV

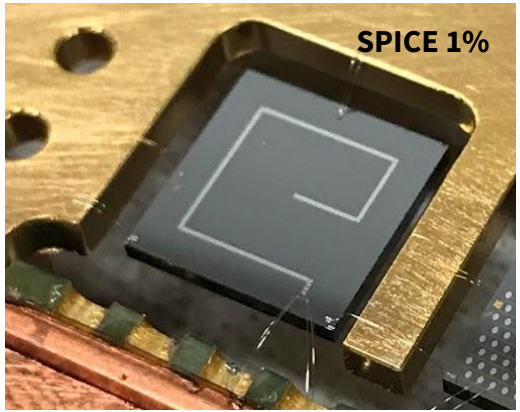
Two channels: discriminate events in one channel from the other



2 Prototype Detectors: SPICE 0.25% and SPICE 1%

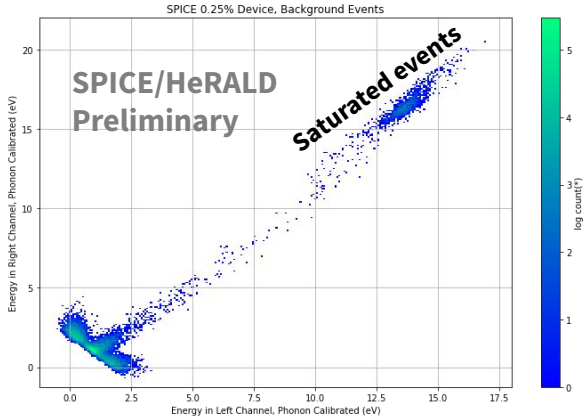
- Both athermal phonon detectors:
  - TES coupled to aluminum fins (QET, CDMS style readout)
  - ~48 mK Tc
  - Suspended from wirebonds rather than glued or clamped, suppresses “low energy excess” background events
  - Silicon, 1^2 cm by 1 mm thick
- SPICE 0.25%:
  - Two identical channels, 25 TESs/QETs per channel
  - Nominal 0.25% surface coverage
- SPICE 1%:
  - Single channel, 177 TESs/QETs
  - Nominal 1% surface coverage

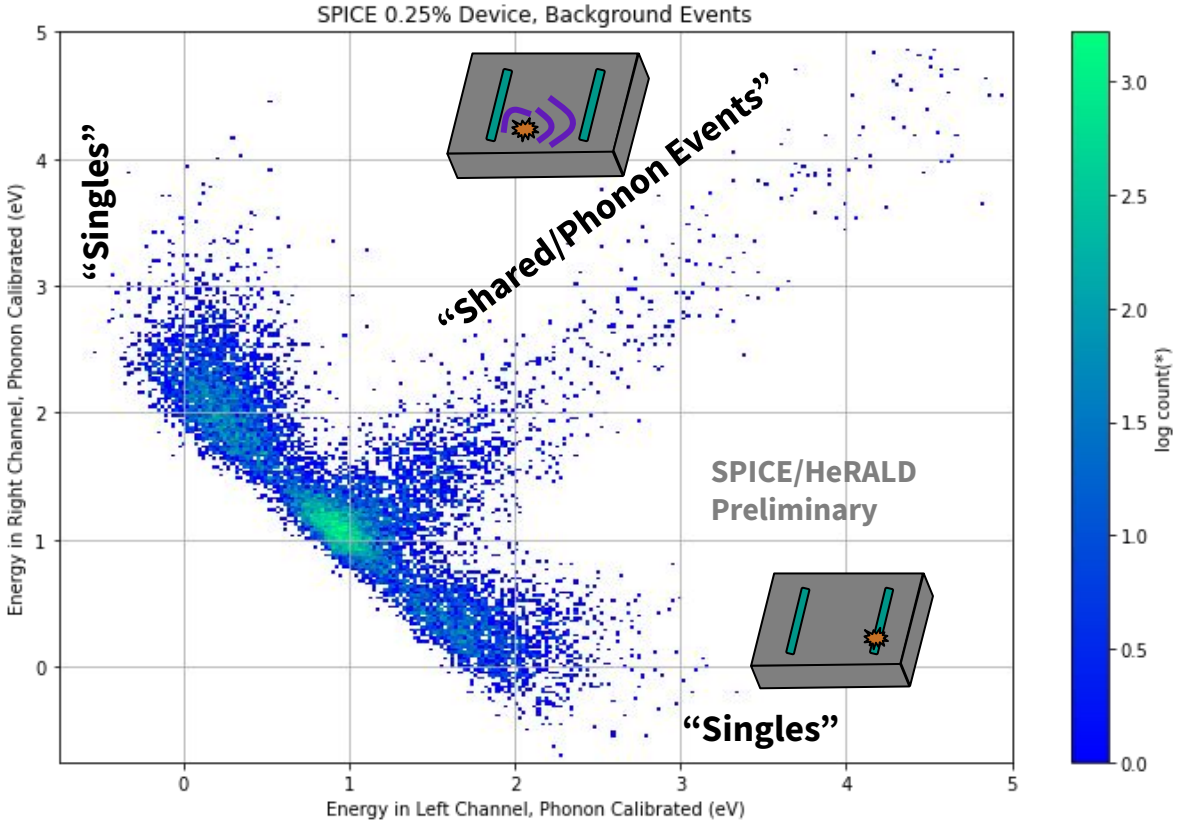




Observed Two Channel Device Backgrounds

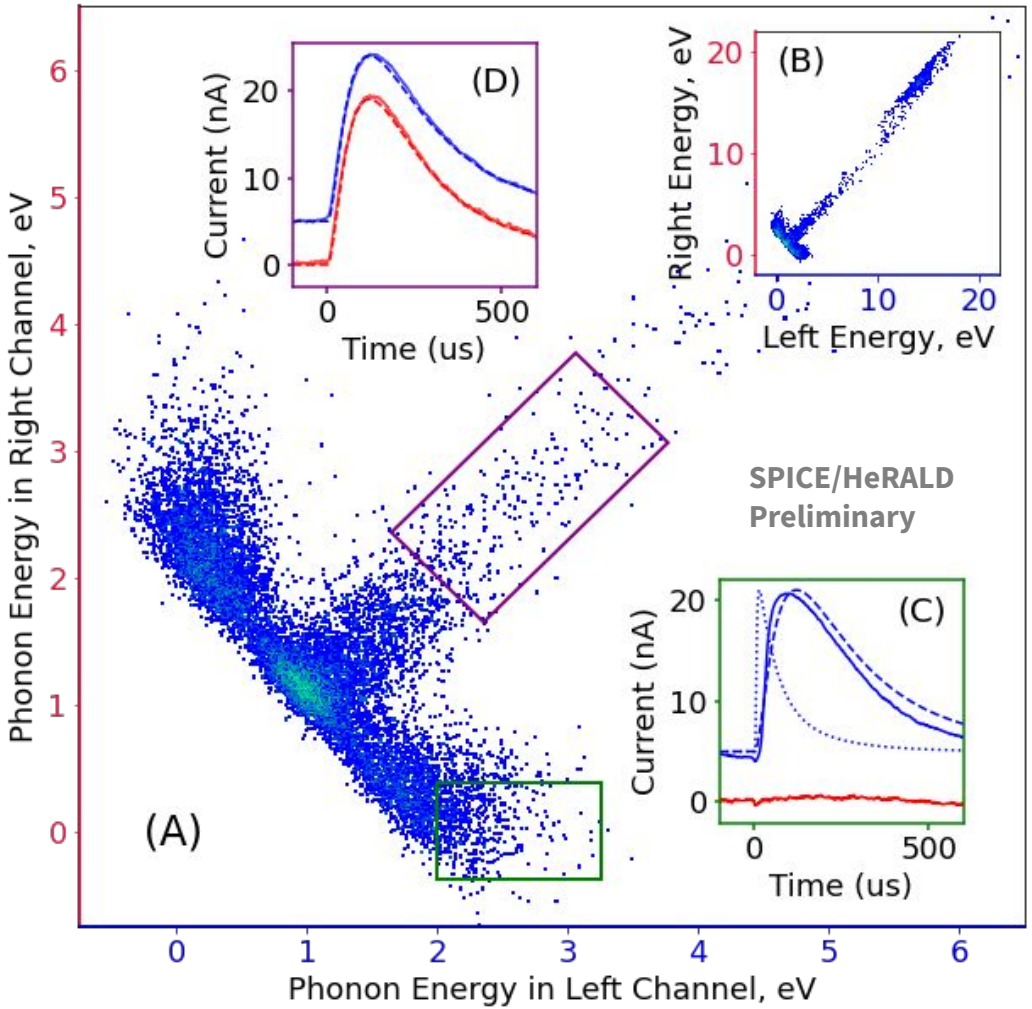
Two components: phonon mediated events in both channels, fast events in just one or other





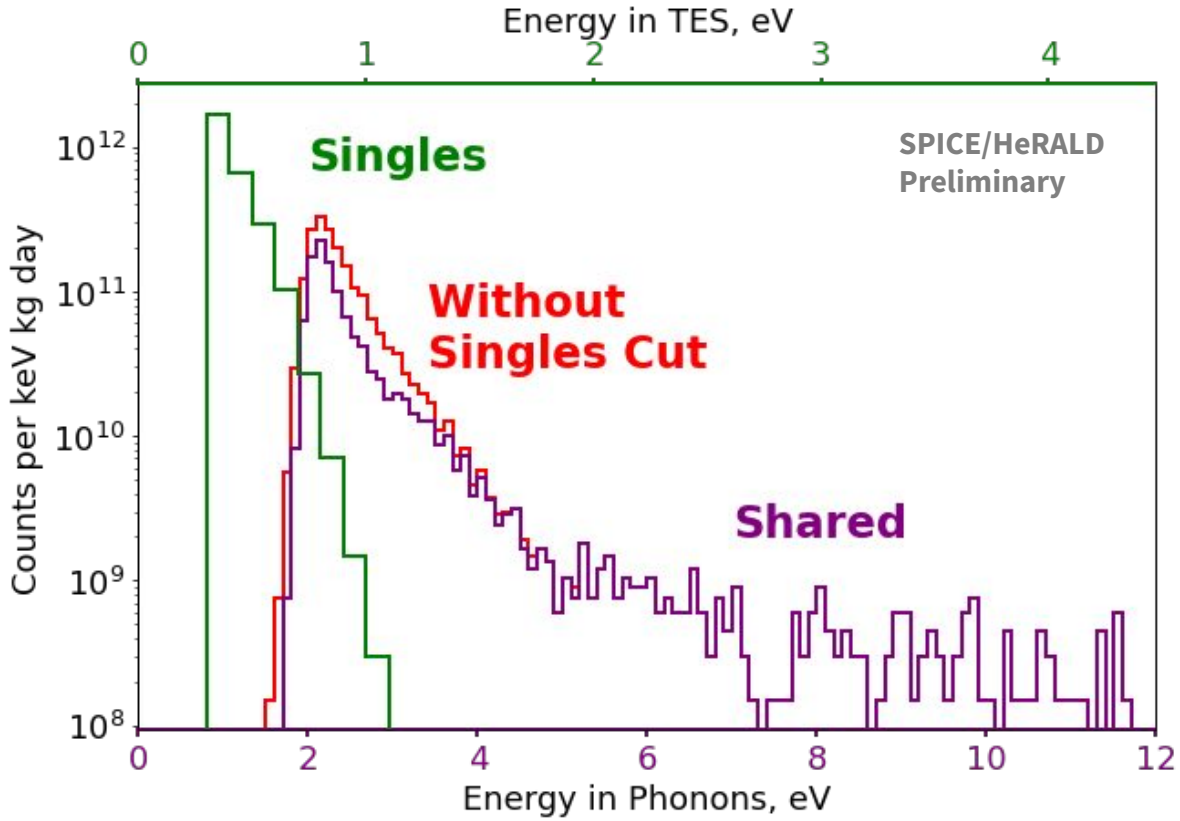
Pulse Shapes

- Shared: 100% consistent with phonon mediation
  - Exact pulse shape match
  - Equal partitioning
- Singles: energy deposition directly in TES
  - Slower than delta function like power impulse response
  - Very small phonon component in other channel



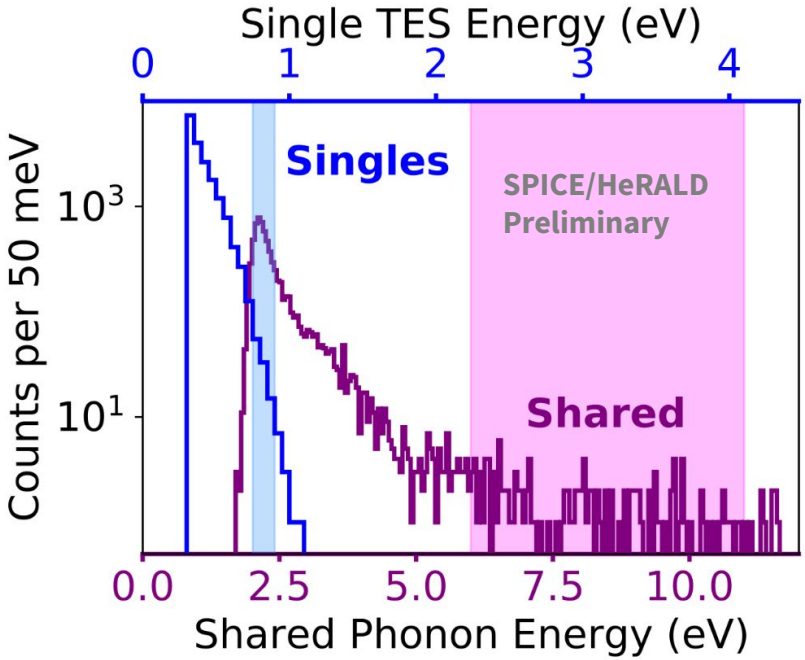
Singles vs. Shared Rates

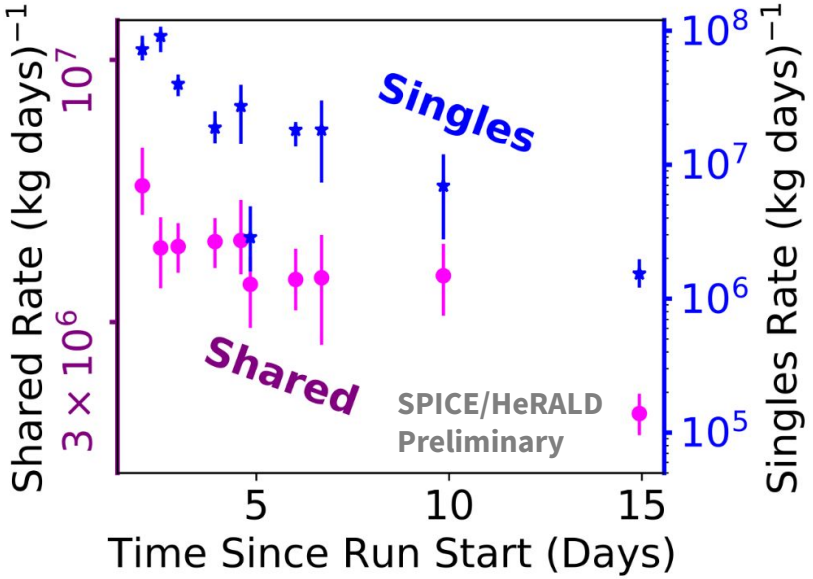
- Delta-χ^2 pulse shape based cut to discriminate singles vs. shared events
  - Doesn't help much with reducing super low energy rate
- Curious: singles and shared low energy rate turns on at approximately same energy, similar rate…



Event Rate over Time

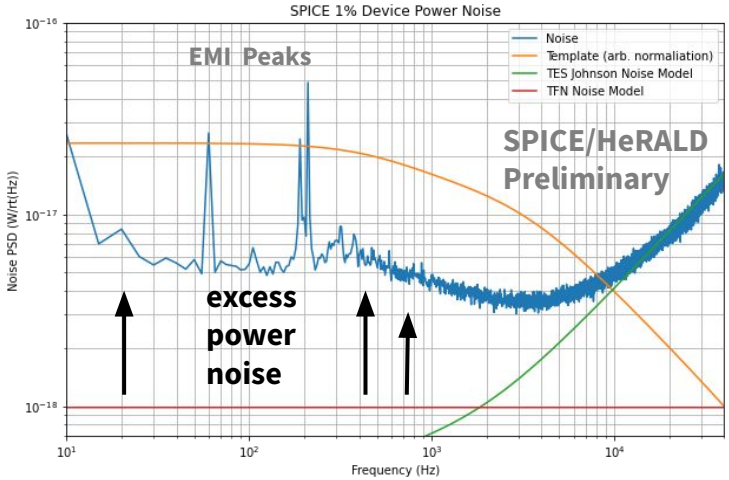
Singles and shared events both go down over time, singles go down way faster

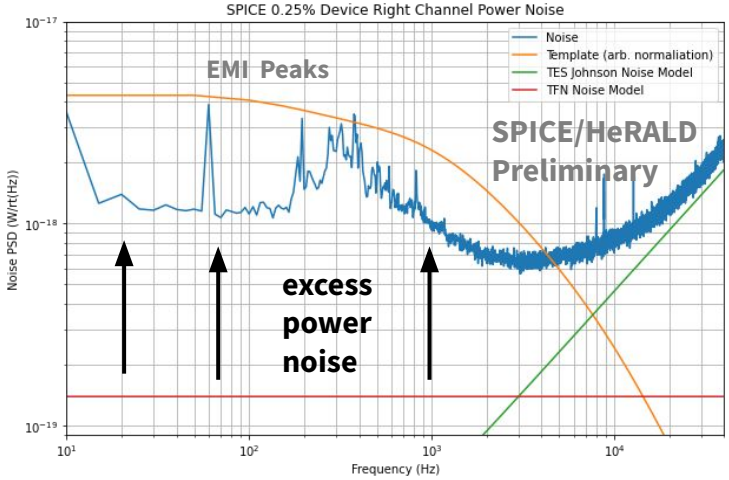




Excess Backgrounds, Excess Noise…

- Completely dominated in signal band by an unknown broadband power noise source
  - Not upstream noise, only appears in transition
- Achieving design noise performance would allow huge gains in energy resolution



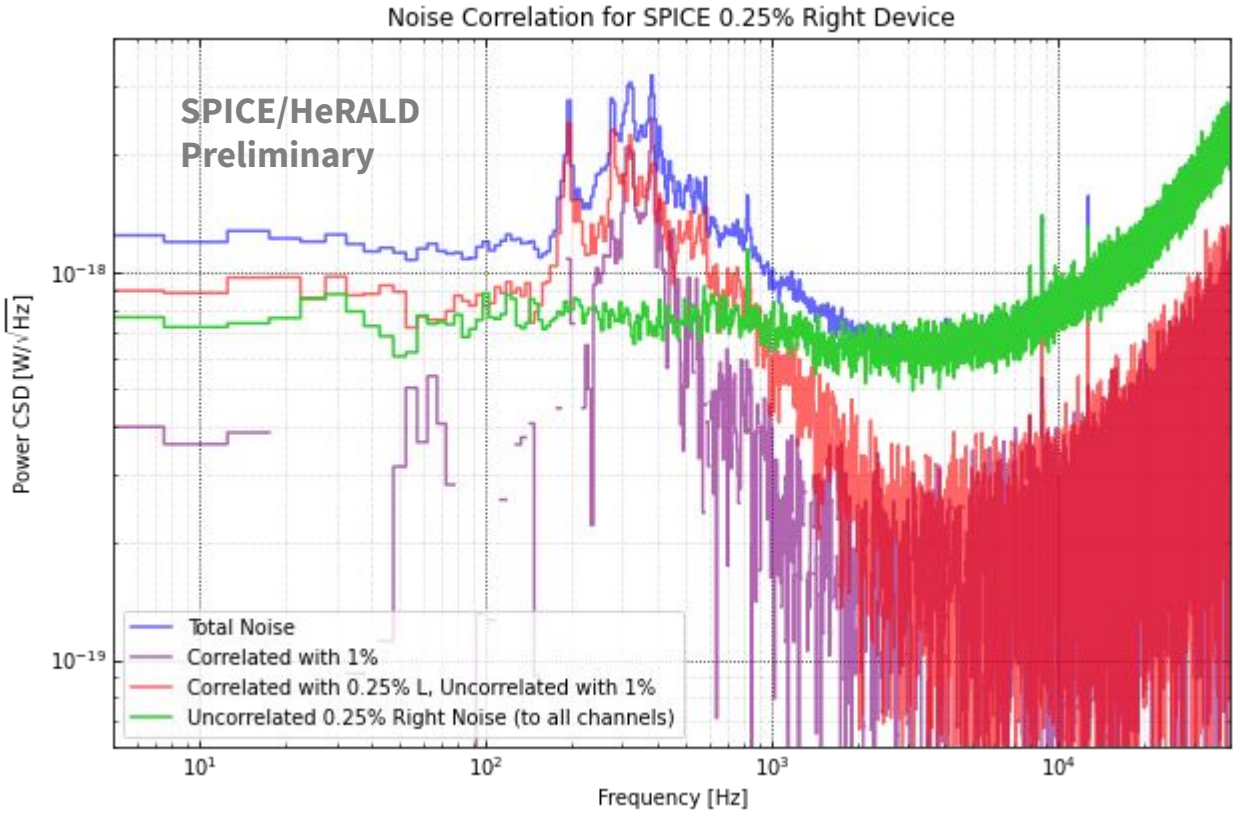


Noise in 2 Channel SPICE 0.25% Device

Can separate noise into two* components:

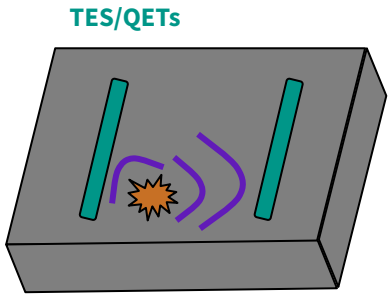
- Correlated with other 0.25% channel
- Uncorrelated with other 0.25% channel

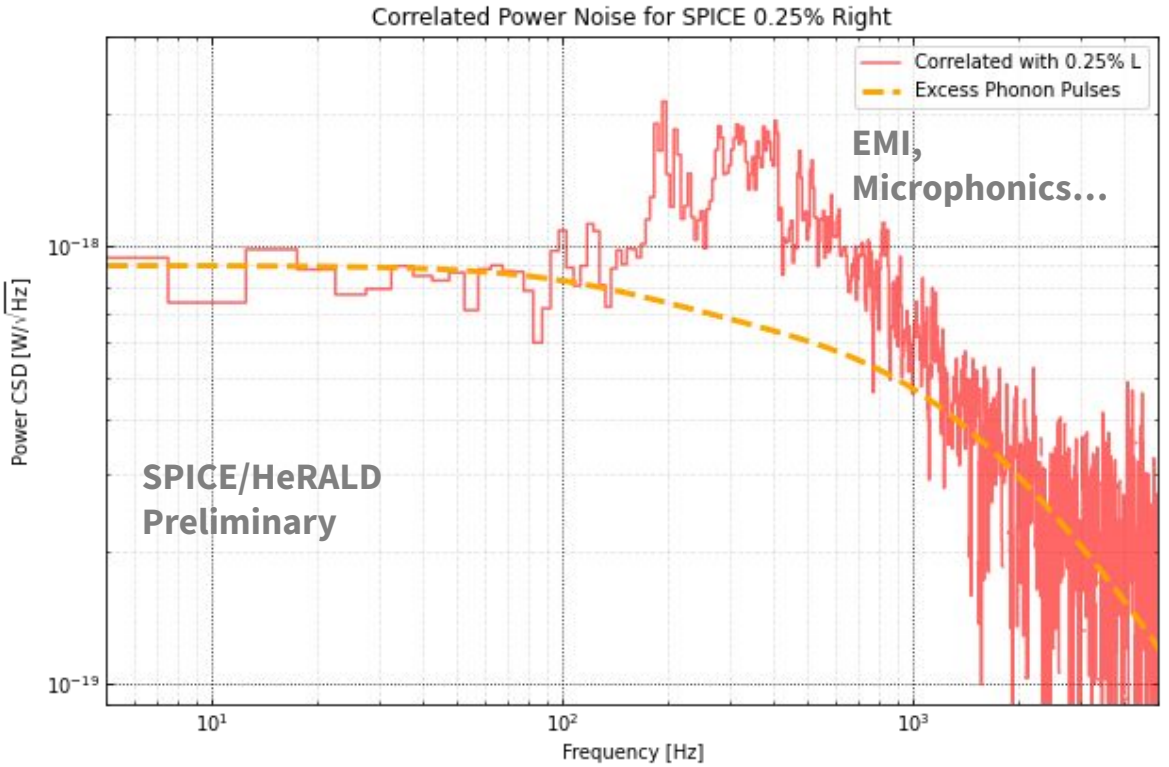
*plus noise correlated with other channels, downstream, EMI…



Correlated Noise: Phonon Driven

- Excess noise fits phonon pulse template
  - Model: phonons hitting both channels
- Peaks: EMI, microphonics…

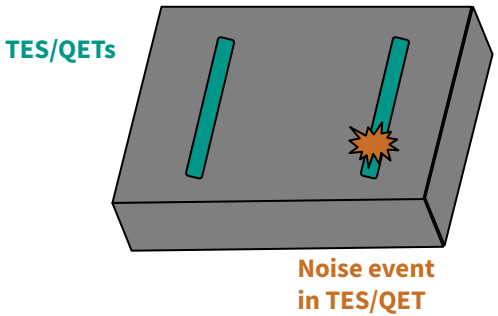


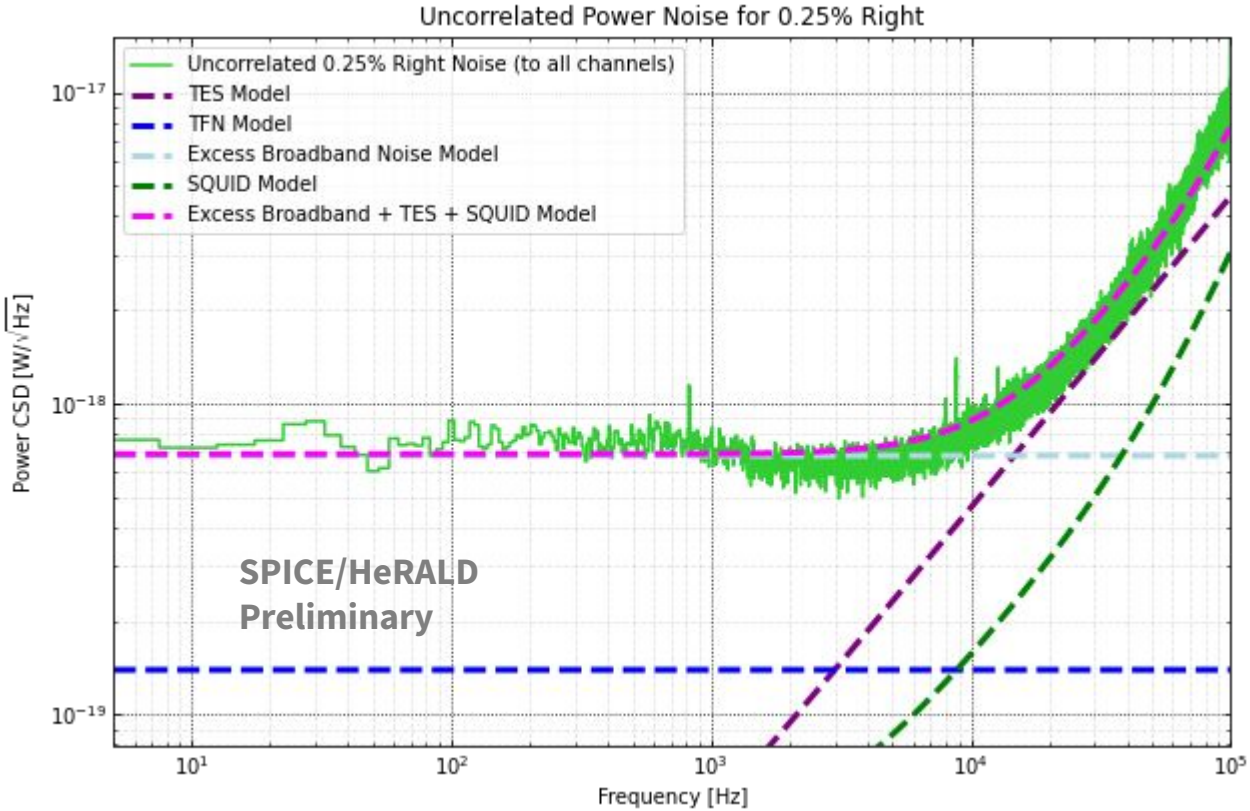


Uncorrelated Noise: Broadband

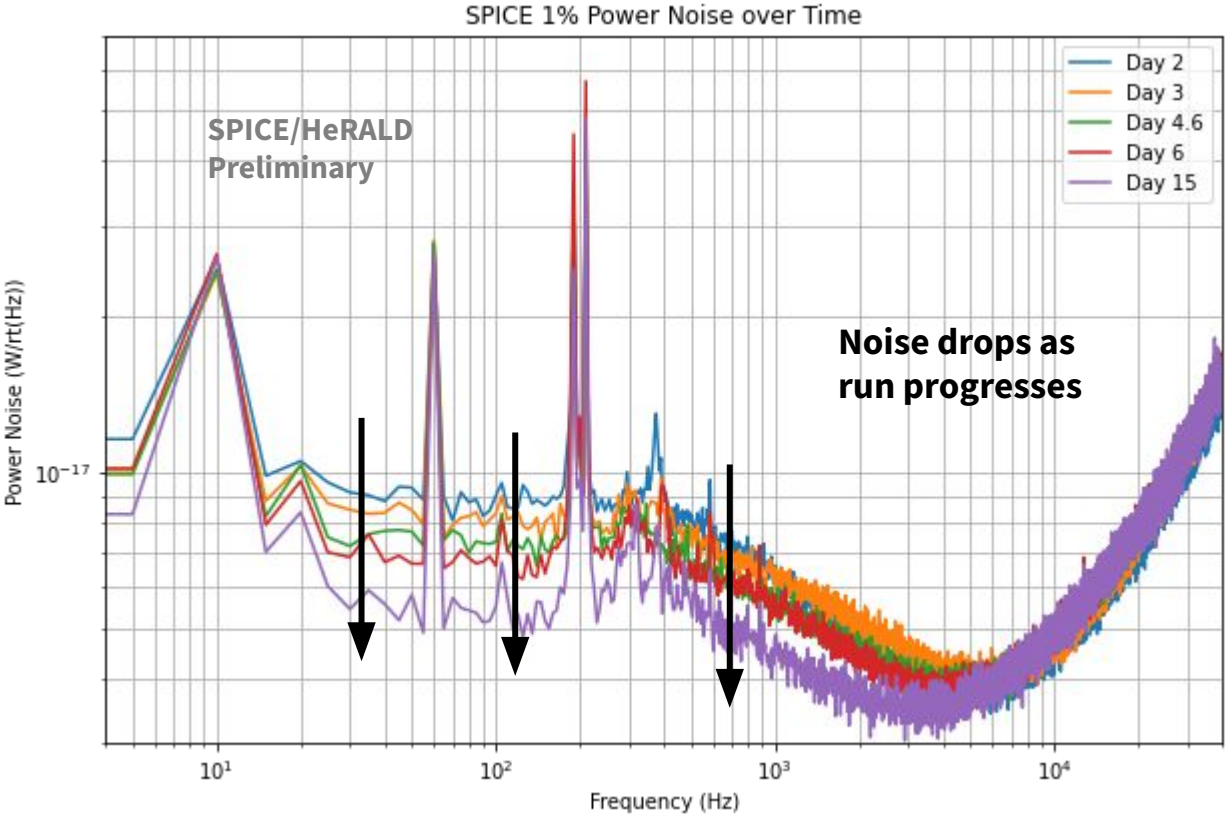
Uncorrelated noise: excess broadband noise term

Shot noise?

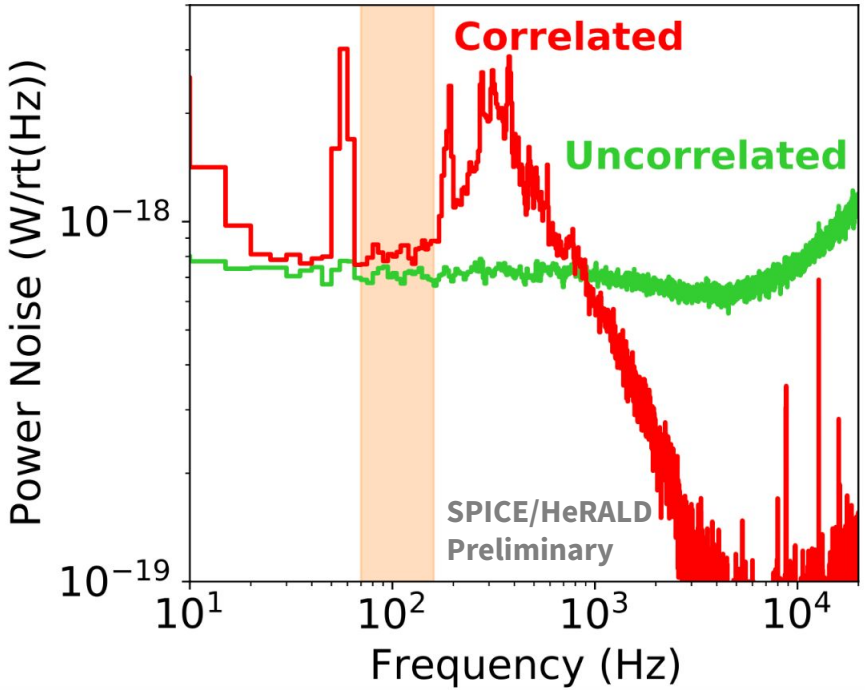


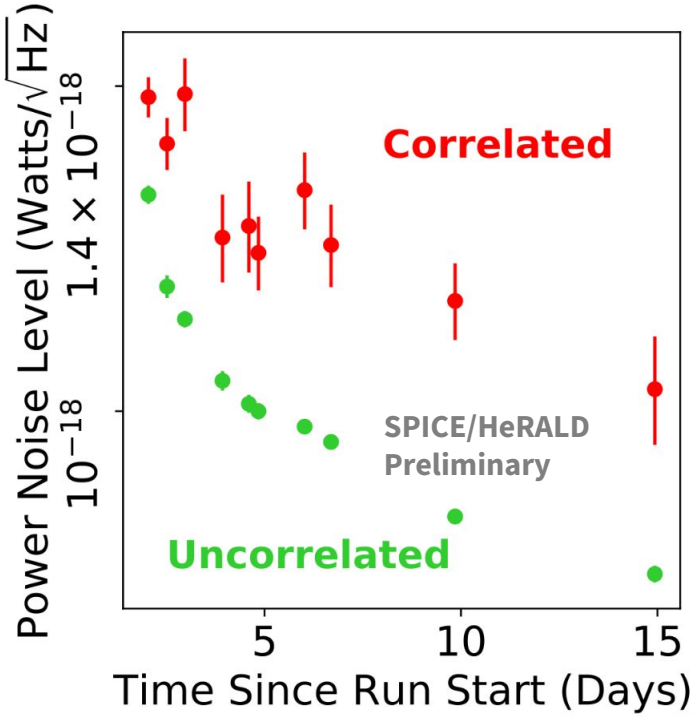


SPICE 1% Power Noise over Time



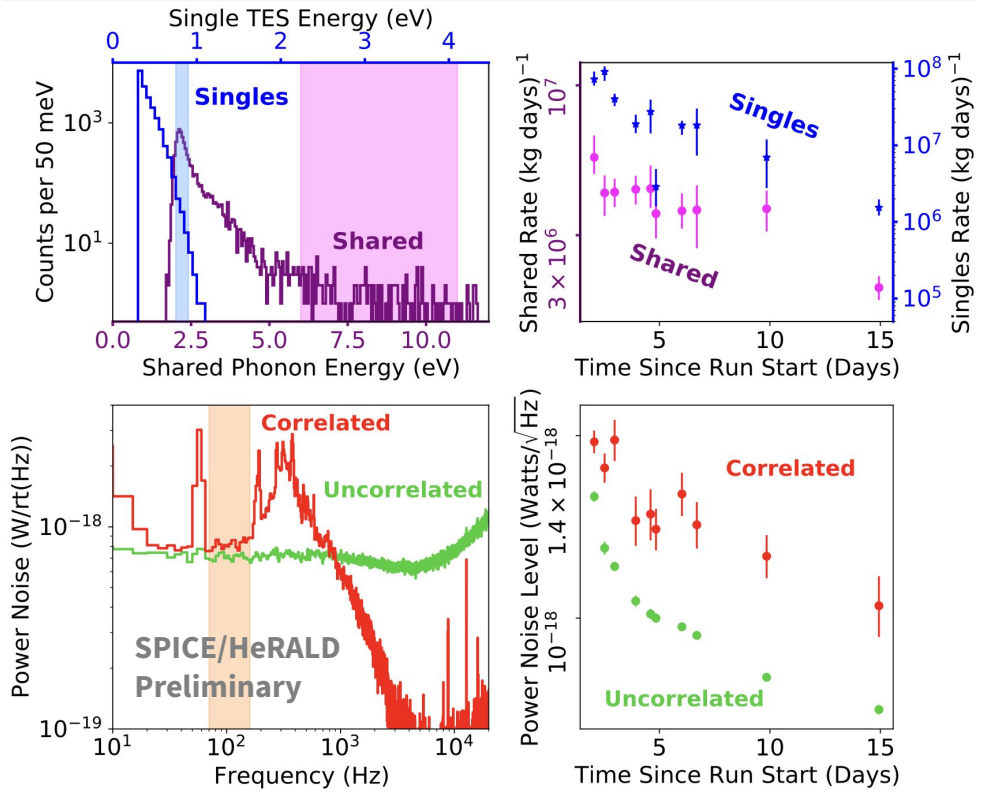
Correlated and Uncorrelated Noise Drops with Time





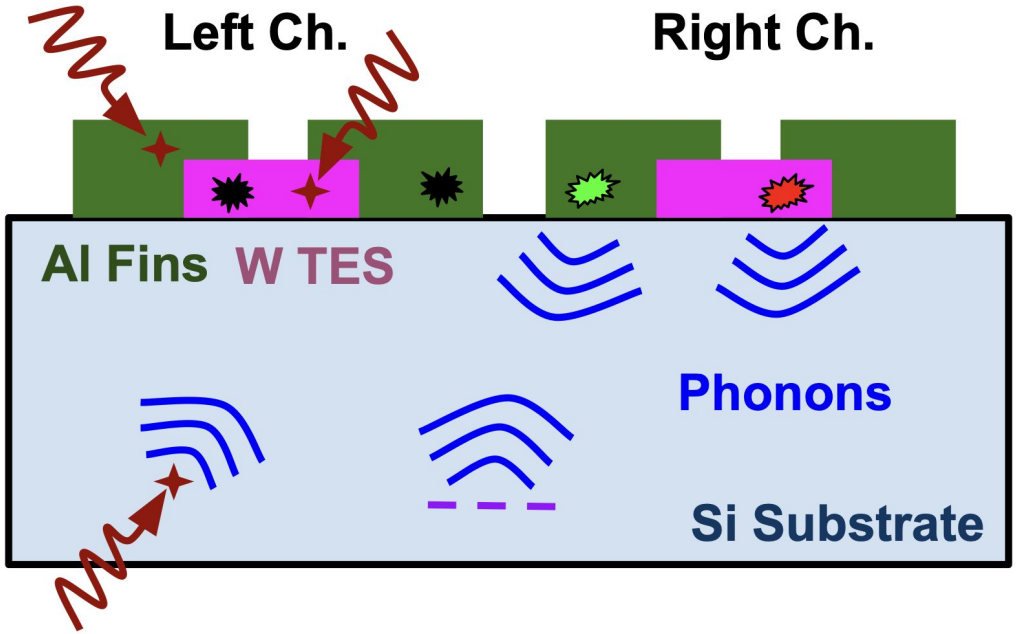
Everything Drops Over Time: Relaxation Process

- Why should LEE stop at threshold?
  - See LEE-like events in analogy to shared (correlated) / single (uncorrelated) events below threshold
  - Same/similar mechanism?
- Below threshold noise: shot noise like, very small singles/shared events
- Drop of with time implies something is relaxing
- No detailed warm up studies yet, but indications that noise resets too



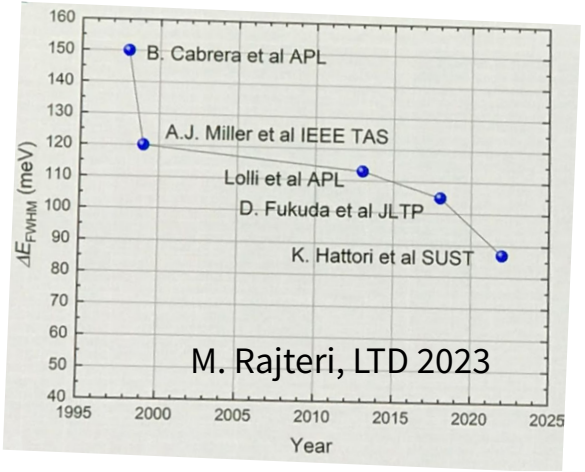
Our Case for Film Stress => LEE

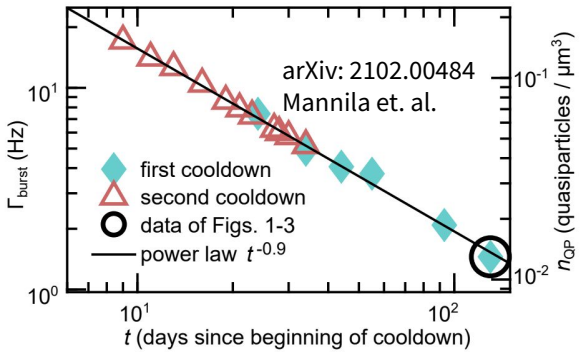
- Know stress can make events that look just like LEE
  - Glued/hanging detector study
- LEE needs to be associated with relaxation
  - Everyone sees LEE go down with time
- LEE-like events clearly happening in films
  - See singles in our two channel detector
  - Biggest problem still with bulk events



We Should Be Thinking Bigger than DM and CEvNS

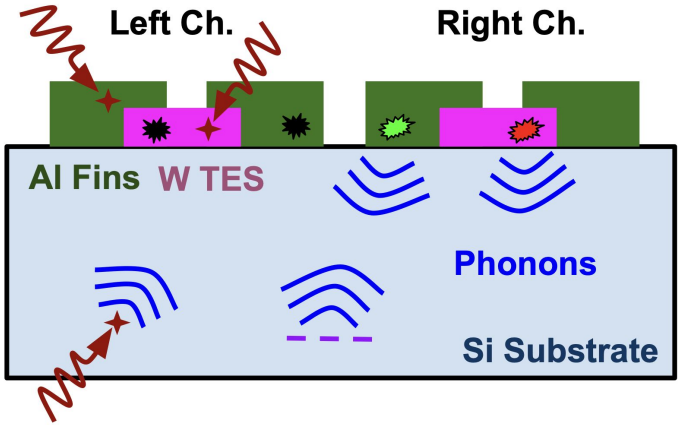
- Light dark matter and CEvNS are great science! But the LEE could show up in many more places…
- We see LEE-like excess noise in our TESs dominating us by 10x… why not other groups too?
  - Optical TESs have only improved by ~2x in ~25 years
  - KIDs could also see issues depending on LEE details
  - Lots of great science to do with high energy resolution TESs, etc.
- Superconducting quantum computers
  - Very long standing issue: excess quasparticles in superconductors cause decoherence, “quasiparticle poisoning”
  - QP densities decline with time, reset with thermal cycling…
  - One or multiple LEE-like processes involved? In film, in phonon events…

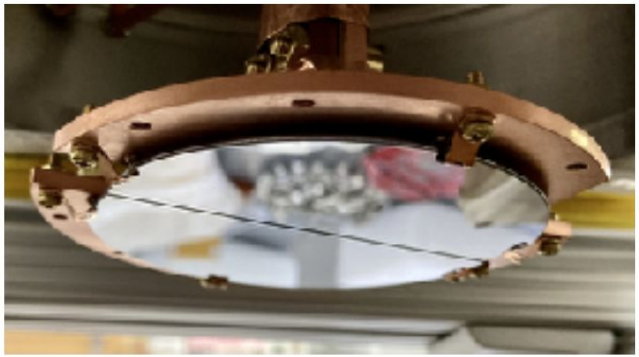




Where Do We Go From Here?

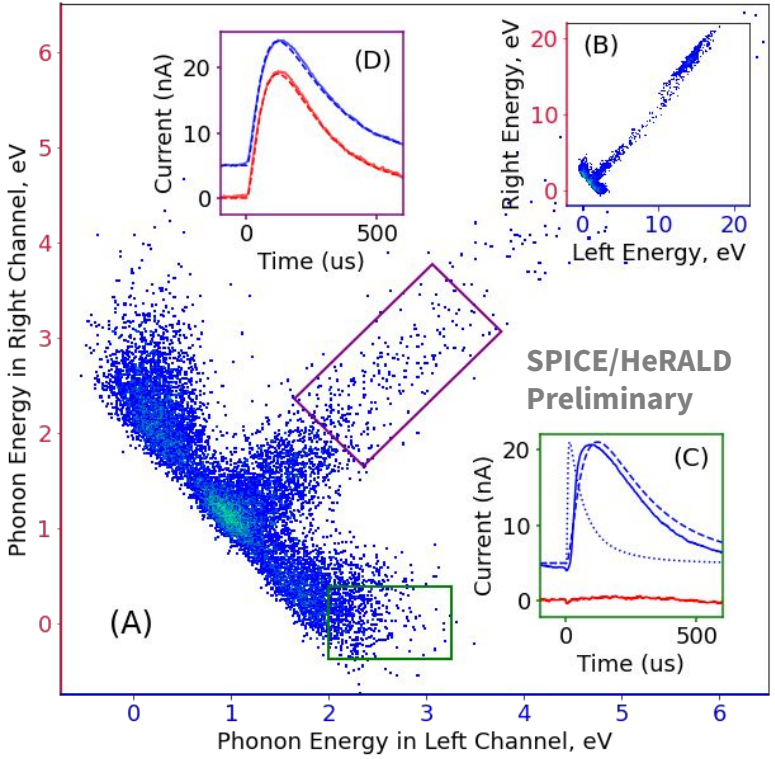
- Films remain THE prime candidate for LEE
  - Scale up/down areas of metal films
  - Which film?
- Discrimination is a somewhat dead end, but 2 channel detectors are an extremely powerful tool
  - Two channels lets you cut fraction of events but far from solves
  - Majority of LEE is indistinguishable from DM phonon events
- Reduce stress in films?
- Maybe LEE can't be solved in solid state… look for coincidence in Helium evaporation detectors

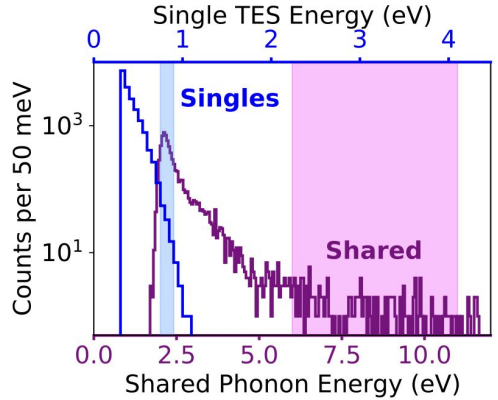


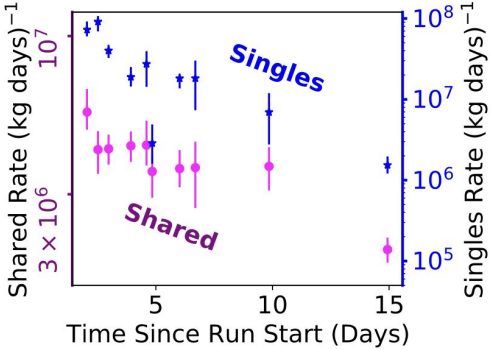


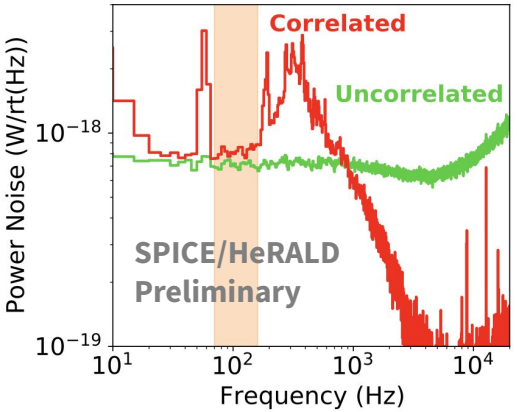
HeRALD 2 channel

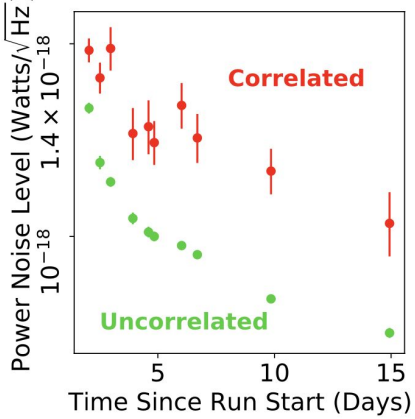
Questions?


Phonon Energy in Right Channel, eV
Phonon Energy in Left Channel, eV
(A)
(B)
Right Energy, eV
Left Energy, eV
(C)
Current (nA)
Time (us)
(D)
SPICE/HeRALD
Preliminary

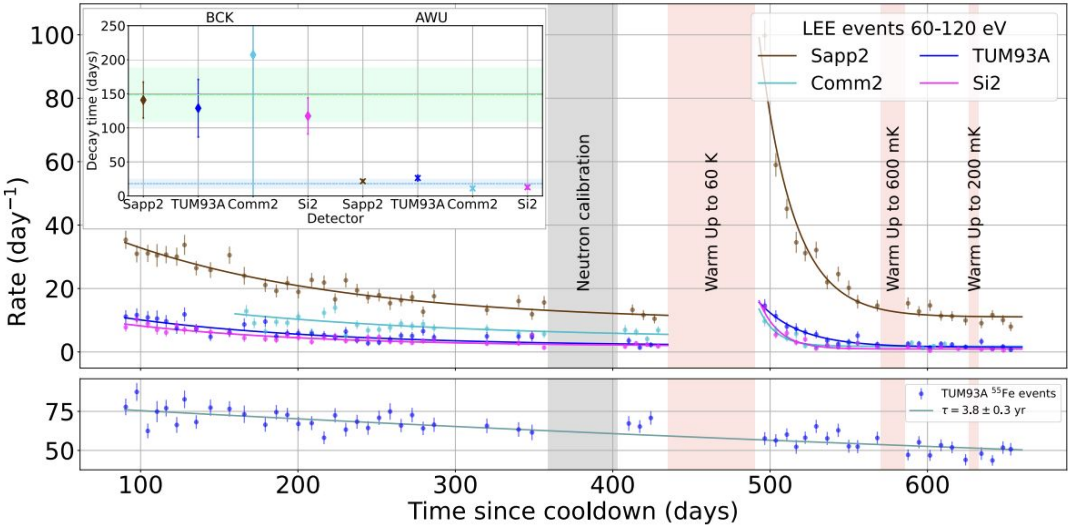

Single TES Energy (eV)
Counts per 50 meV
Singles
Shared
Shared Phonon Energy (eV)


Shared Rate (kg days)$^{-1}$
Singles Rate (kg days)$^{-1}$
Singles
Shared
Time Since Run Start (Days)

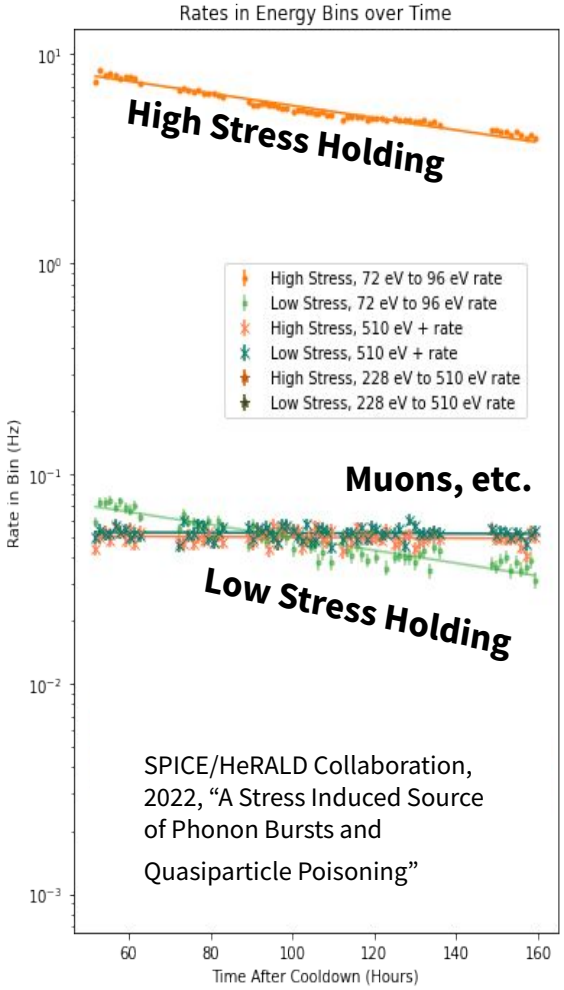

Power Noise (W/rt(Hz))
Correlated
Uncorrelated
SPICE/HeRALD
Preliminary
Frequency (Hz)


Power Noise Level (Watts/√Hz)
Correlated
Uncorrelated
Time Since Run Start (Days)

Backup: Relaxation Processes Linked to Low Energy Excess



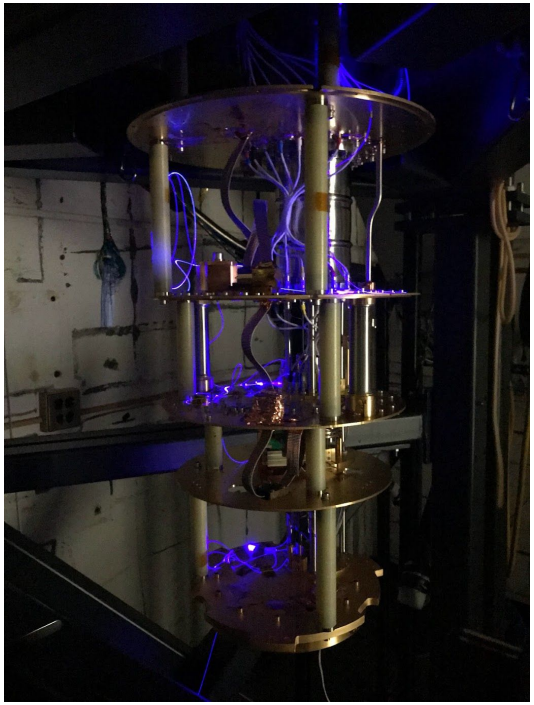
CRESST Collaboration, 2022, “Latest observations on the low energy excess in CRESST-III”

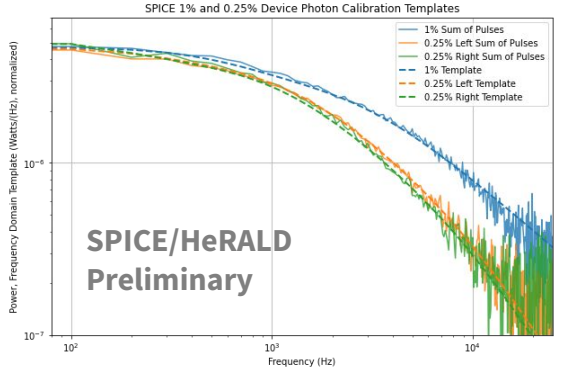


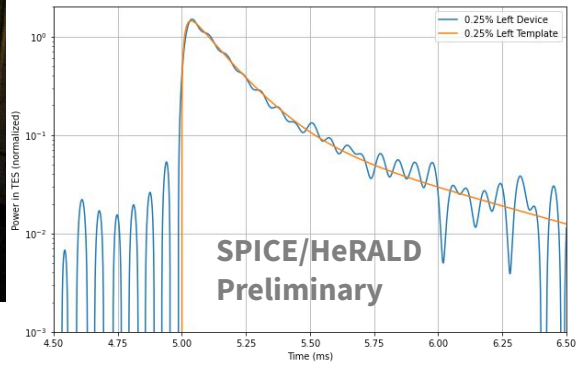
SPICE/HeRALD Collaboration, 2022, “A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning”

Backup: Photon Calibrations: Phonon Response

- Laser + optical fiber: photons on detector
- Put short (~100s of ns) photon bursts on detector
- Study response down to very low energies with good statistics
- Known trigger time, precision pulse shape measurements

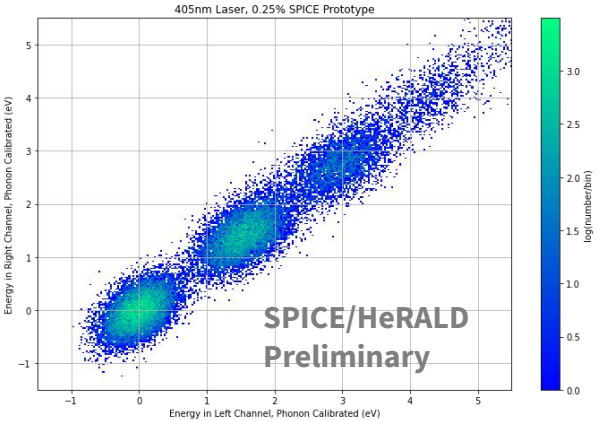


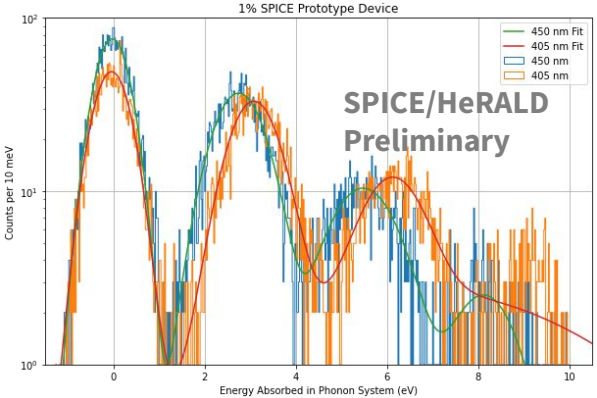




Backup: Photon Calibrations: Calibrate Energy

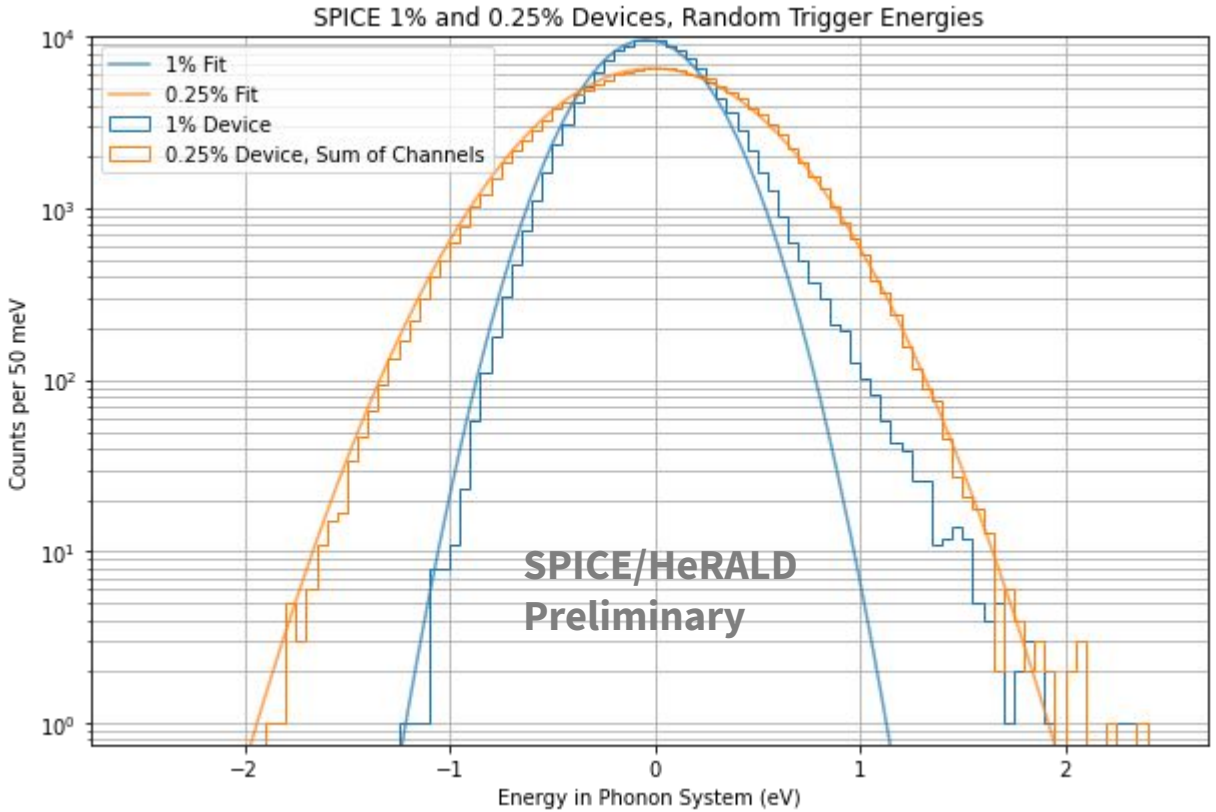
- Shine ~3 eV photons onto detector from optical fiber
- See peaks: zero, one, two… photons absorbed
- Calibrate energy response to absorption of n photons





Backup: World Leading Energy Resolution

- SPICE 1%: 273 meV (sigma) energy resolution in phonon system
- SPICE 0.25%: 460 meV (sigma) energy resolution in phonon system



Backup: Single vs. Shared Pulse Shapes