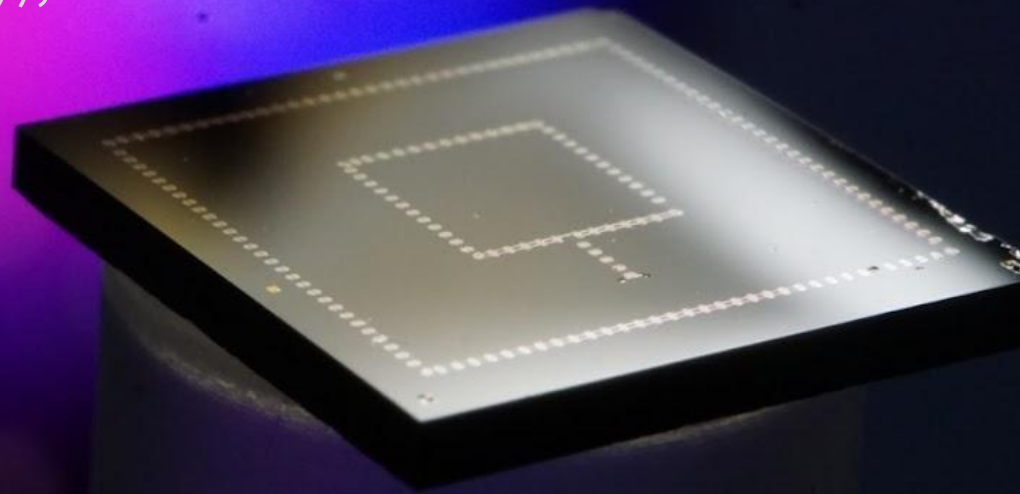
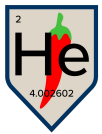
Stress as a Background in Dark Matter Direct Detection Experiments and Source of Decoherence in Superconducting Qubits

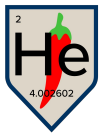
Roger K. Romani (UC Berkeley), CPAD 2022



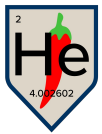
- **Dark Matter: the biggest prize in particle physics?**



- **Dark Matter: the biggest prize in particle physics?**
- Virtually 100% sure that DM exists, not known SM particle
- 30 years of focused searching, no credible discovery claim

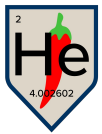


- **Dark Matter: the biggest prize in particle physics?**
- Virtually 100% sure that DM exists, not known SM particle
- 30 years of focused searching, no credible discovery claim
- Two of the Really Great Ideas™ turned out to be wrong
    - MACHOs searched for, not found
    - Traditional weak scale ~300 GeV WIMPs definitely ruled out (weaker couplings always possible)



- **Dark Matter: the biggest prize in particle physics?**
- Virtually 100% sure that DM exists, not known SM particle
- 30 years of focused searching, no credible discovery claim
- Two of the Really Great Ideas™ turned out to be wrong
    - MACHOs searched for, not found
    - Traditional weak scale ~300 GeV WIMPs definitely ruled out (weaker couplings always possible)

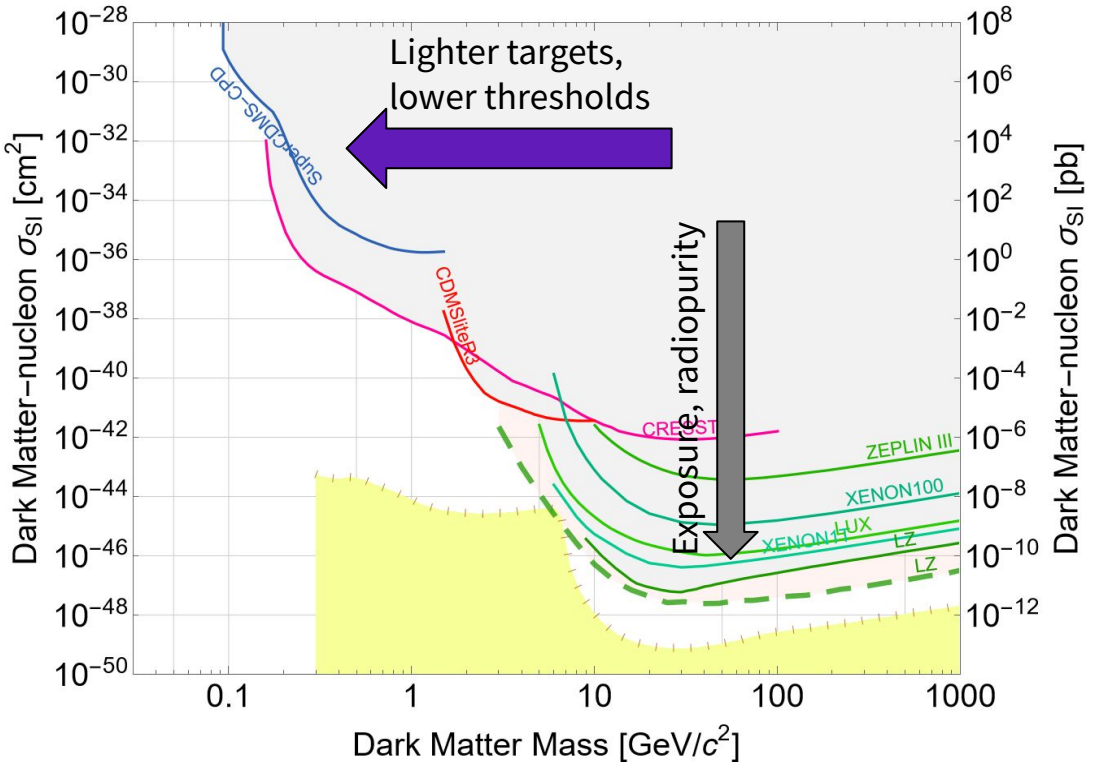
Where do we go from here?



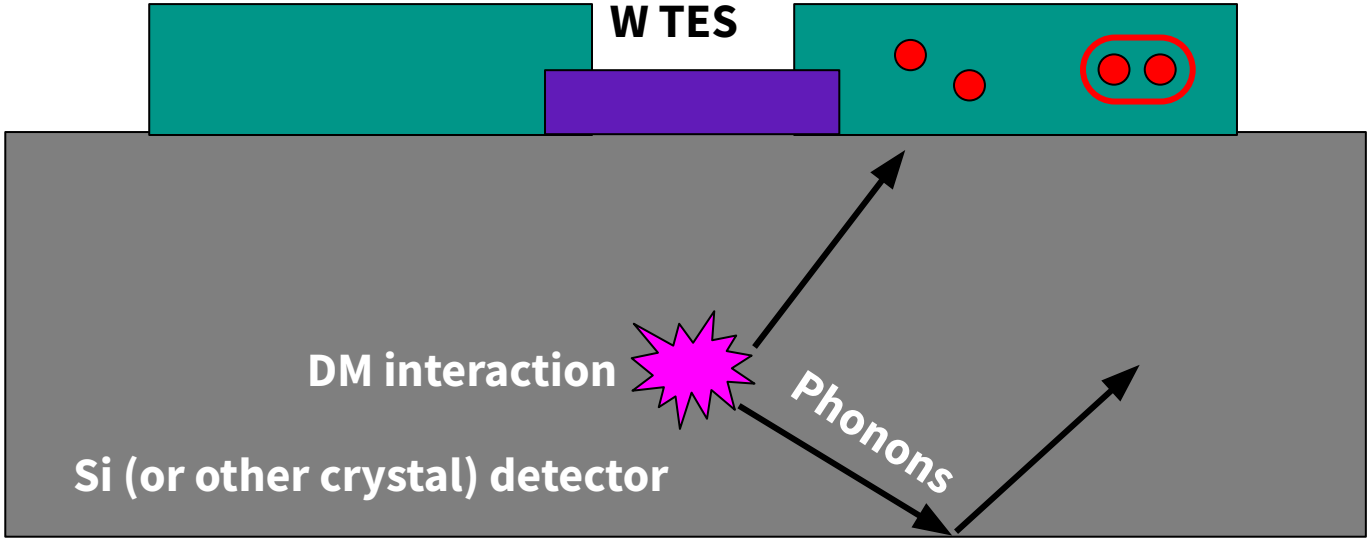
Three Ways to Look for Dark Matter

1. Axions or ALPs (see BREAD, LAMPOST, DM-Radio…)
2. Lower WIMP cross sections
   - Bigger, cleaner detectors
   - Fundamentally, more $ and time
3. Lighter DM particles
   - Better energy resolution detectors
   - Lighter target nuclei

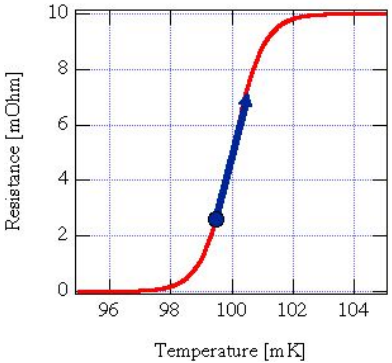
I'll be talking about the third approach today



Our Approach: Calorimetry



Phonons break Cooper pairs in fins, make quasiparticles

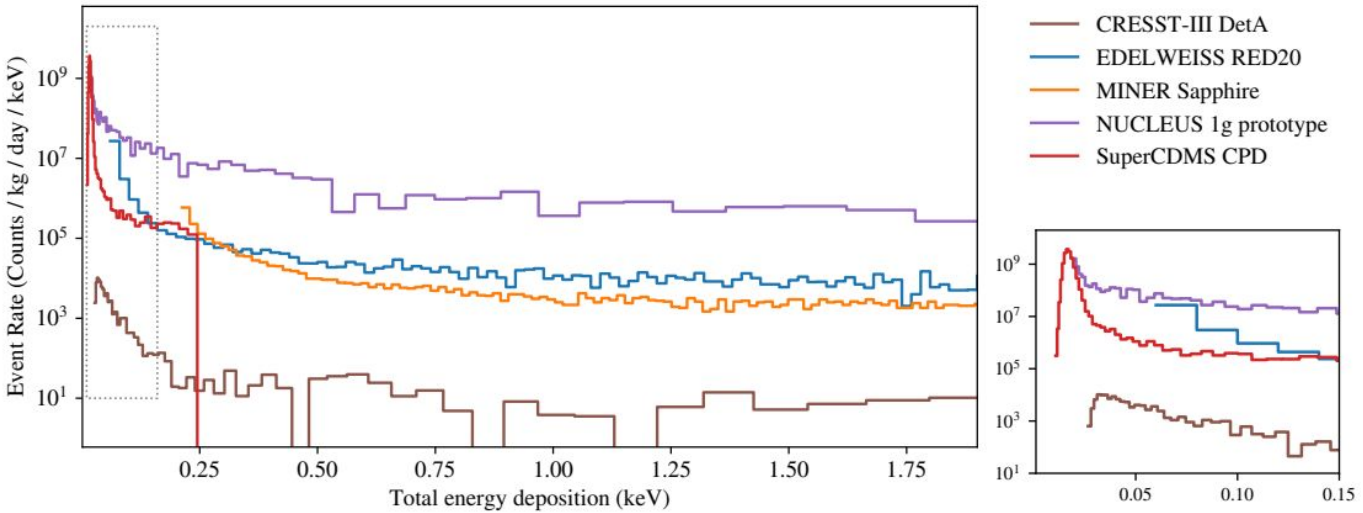


***all at ~10 mK in dilution refrigerator**

The Problem: The Low Energy Excess

Need low thresholds, low backgrounds to search for sub-GeV DM

Completely unexpected: backgrounds grow enormously at low energies!



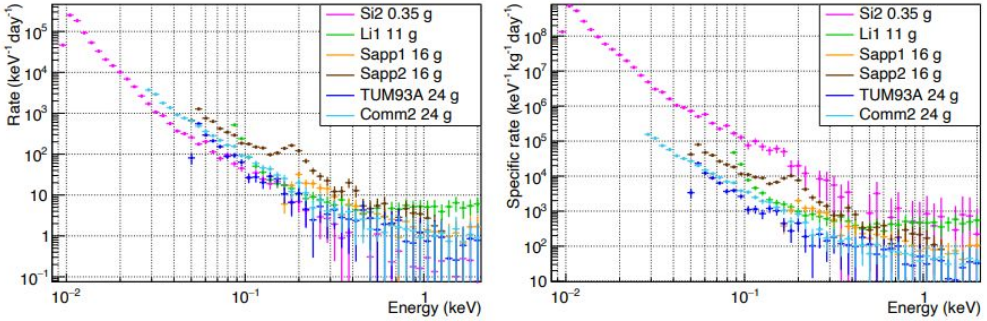
*part of LEE understood to be track induced photon backgrounds, see Du et. al. 2022, but only really helps with ionizing component

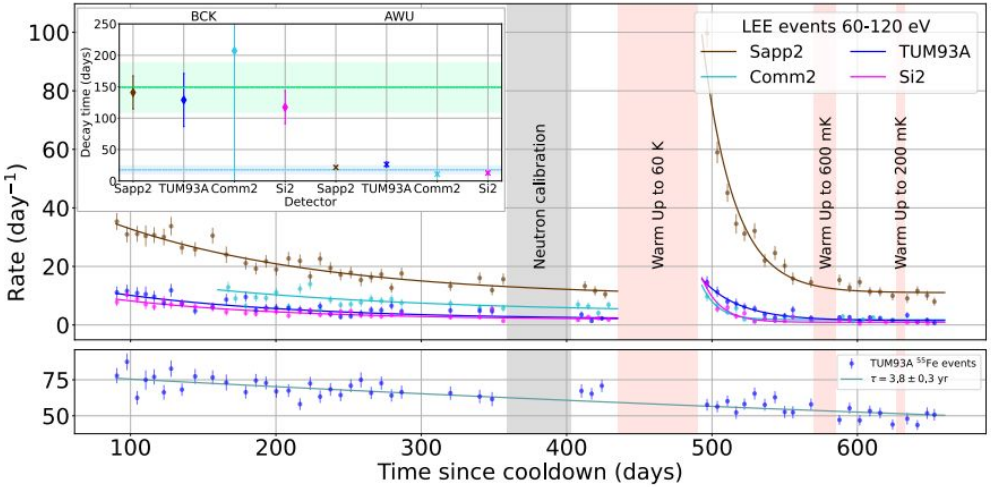
EXCESS workshop, 2022

Weird LEE properties

- ~same underground and at surface (SuperCDMS-CPD)
- Doesn't seem to scale with detector mass (CRESST 2022)
- Decreases in rate with time after cooldown (CRESST 2022)
  - Warm up: increase background!
- No ionization (EDELWEISS), "heat only"

Not radiobackgrounds, what is this??



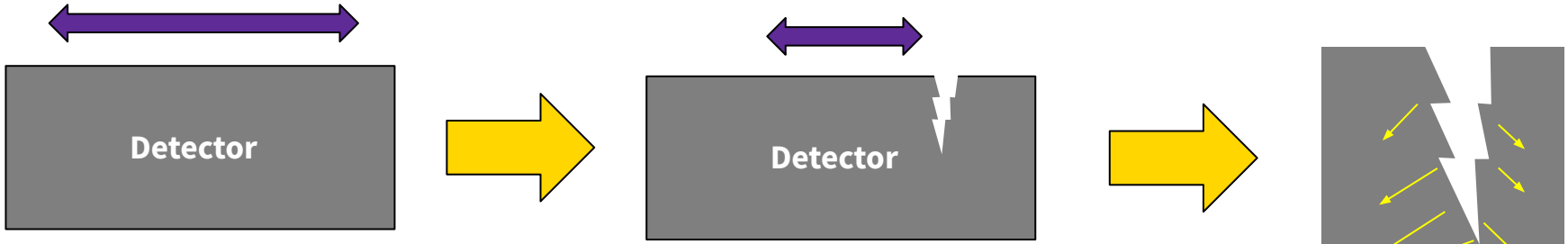


What is a Stress Background?

Stress (thermal contraction, manufacturing, previous events…)

Relaxation event (partially) reduces energy of system

Athermal phonons created

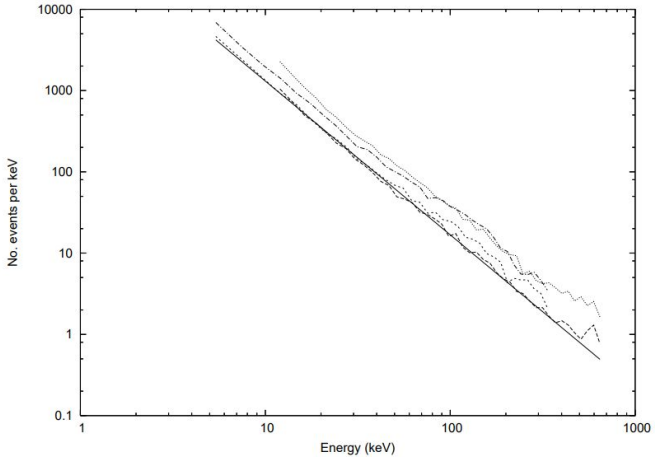


Energetic, metastable state

Pre-history: CRESST 2005

- 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“

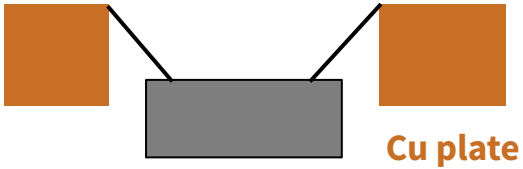


An extensive search for the origin of the pulses was finally successful when it was noticed that there appeared to be markings or scratches on the crystal at the contact points with the sapphire balls. When the sapphire balls were replaced by plastic stubs, which are evidently much softer, the event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

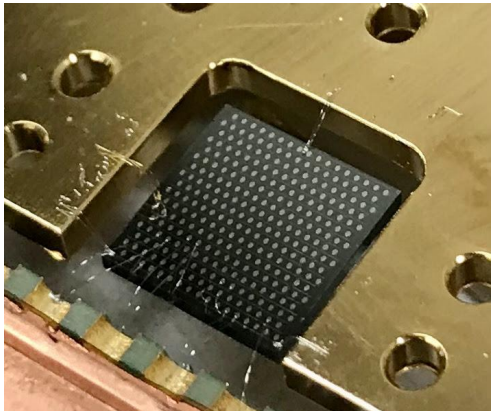
Hanging Detectors

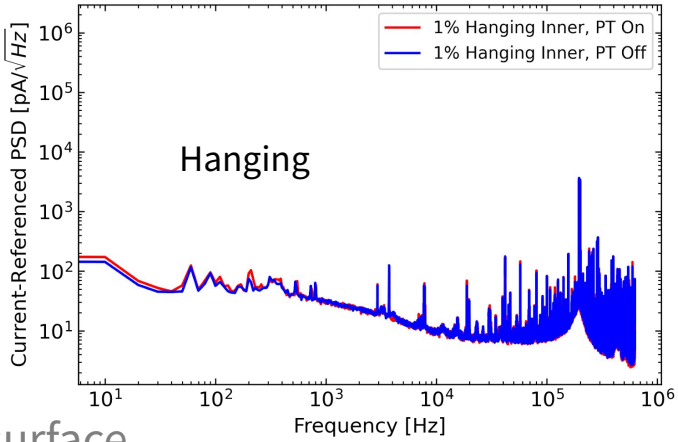
Basic concept: suspend detector from wire bonds

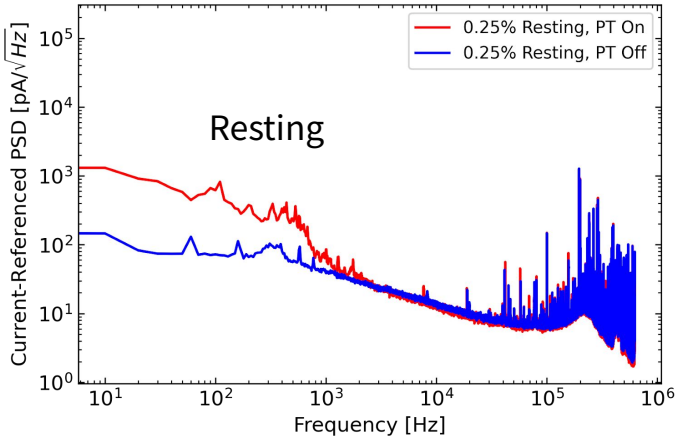
- Low stress (no clamping)
- No relative motion between detector and holding surface
- Bonus: low pass filter for vibrations



cm² Si detector



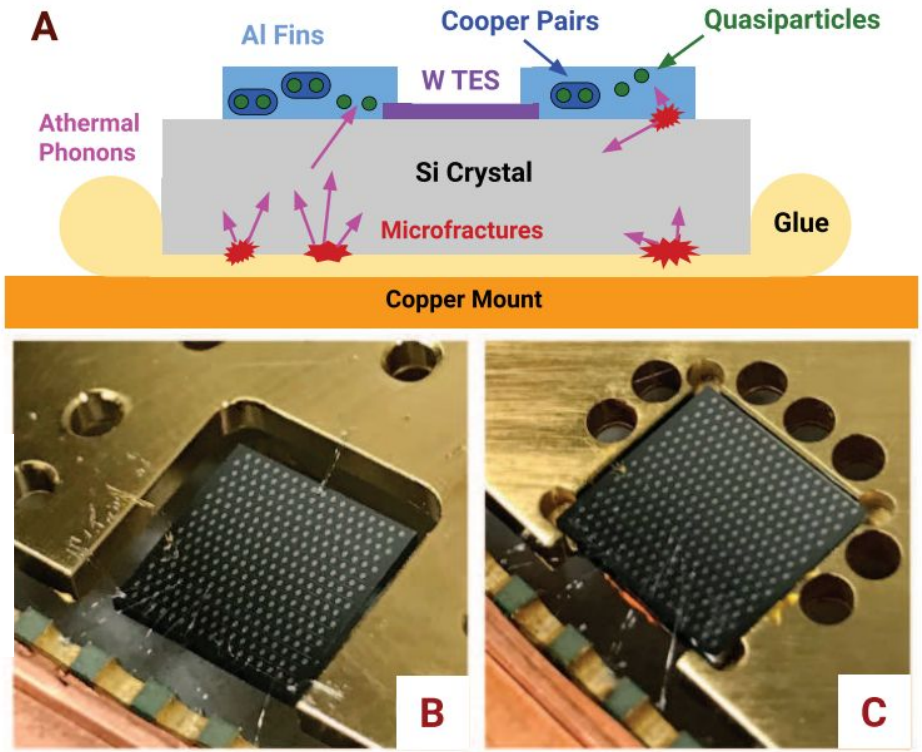




Fink, Watkins theses, 2021

Compare High Stress and Low Stress Detectors

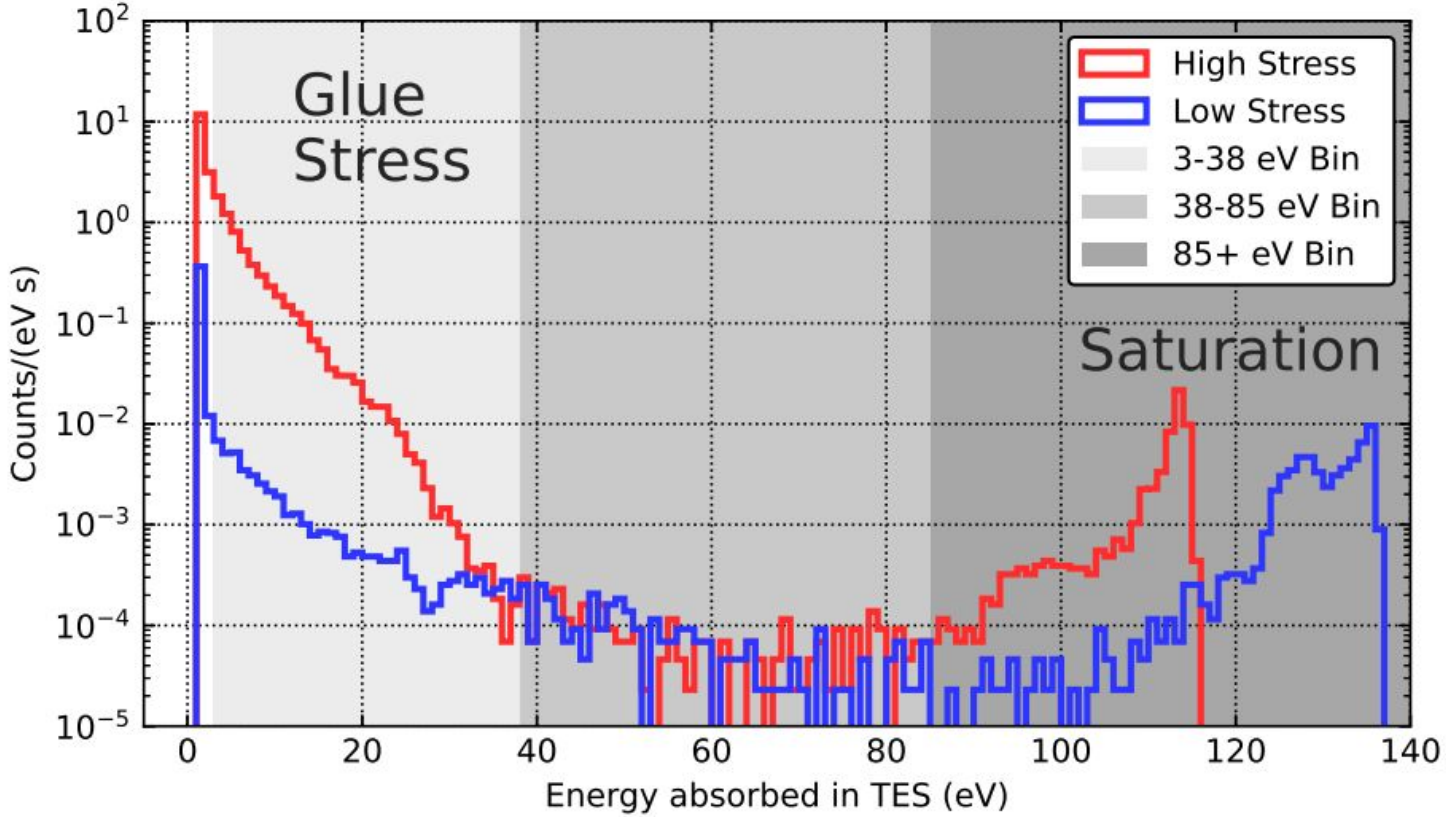
- Two identical as possible* detectors
  - One glued down
  - One hanging from wire bonds
- TES based readout measures athermal phonon pulses in substrate



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]

Stress Causes LEE like Events: Results



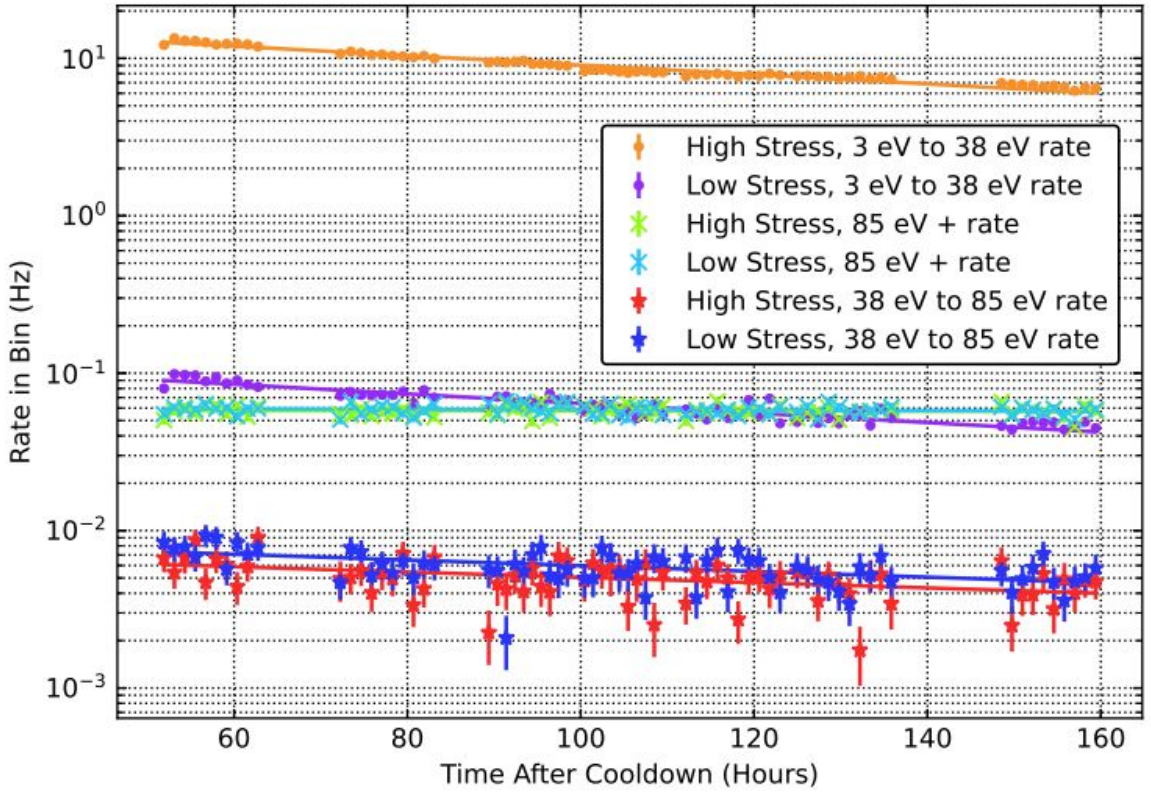
Stress Causes LEE like Events: Results

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

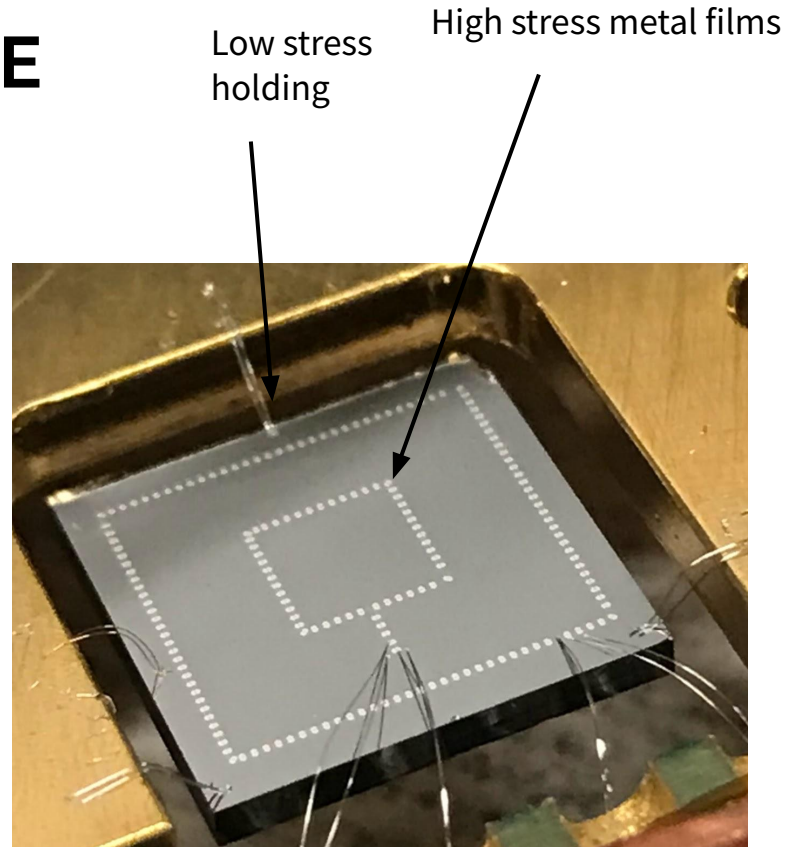
What's going on?



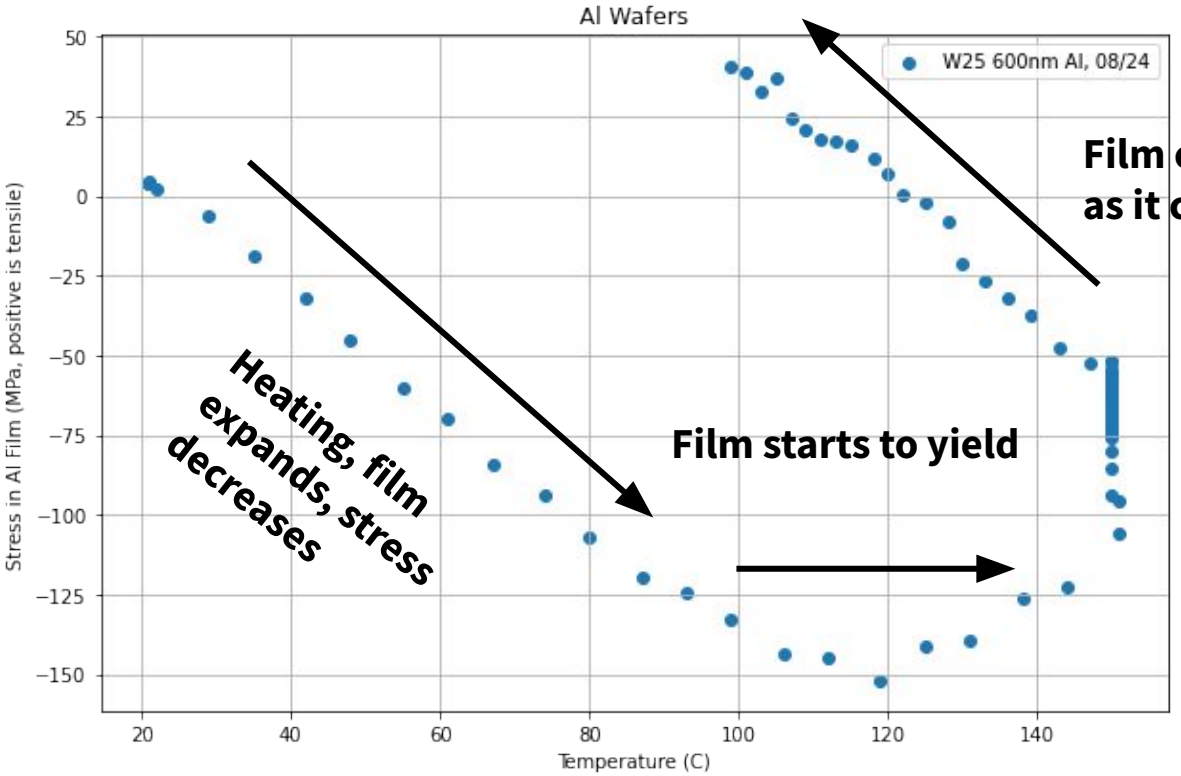
Metal Films as a Source of LEE

- Well known: metal films can have stress in them too
  - Thermal contraction, “as fabed”
- Idea: this relaxing stress could create LEE too
- Would be identical in “identical” detectors, like LS/HS calorimeters

Metal films deforming → LEE

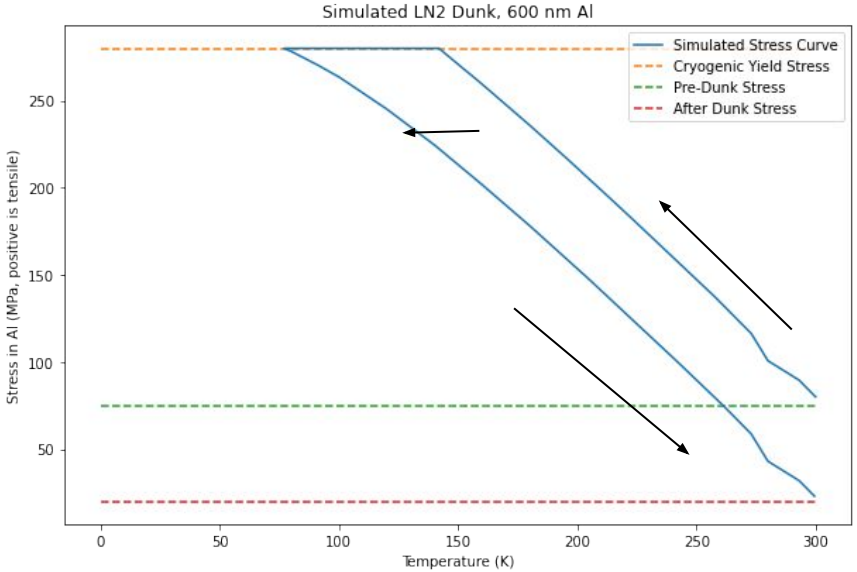


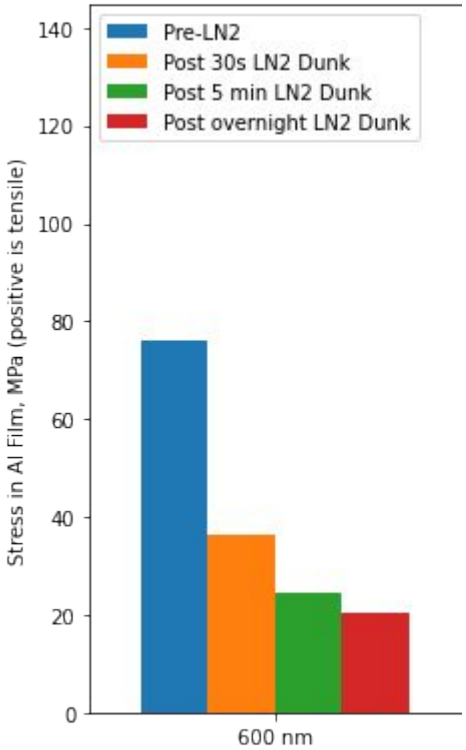
Al films can yield on Si!



Deformation at 77K

Basic idea: measure stress in film before and after dunking in LN2





Deformation at Much Colder Temps

Soviet groups studied deformation in bulk single crystal aluminum, saw deformation all the way down to 1.4K

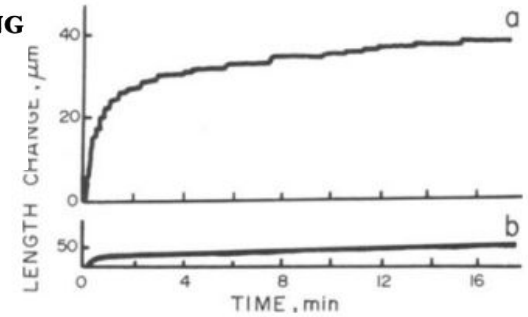
Evidence for jumplike deformation?

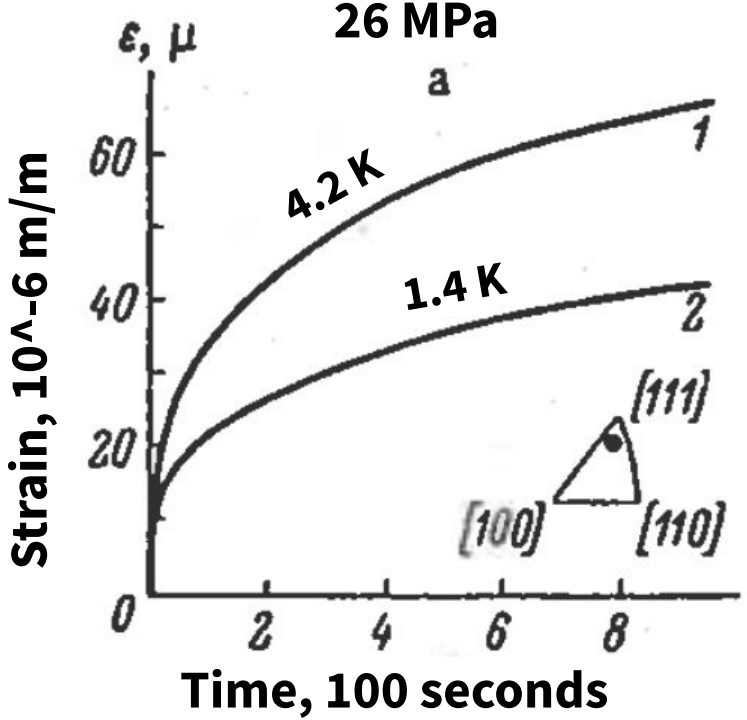
JUMPLIKE DEFORMATION OF COPPER AND ALUMINUM DURING LOW-TEMPERATURE CREEP

V. A. Koval and V. P. Soldatov

Physico-Technical Institute of Low Temperatures UkrSSR Academy of Sciences, Kharkov, USSR

Fig. 1. Machine creep curve for 99.99% Al recorded on (1) the 5000:1 scale and (2) 500:1 scale; shear stress, $\tau = 300\ g/mm^2$; $T = 3\ K$.





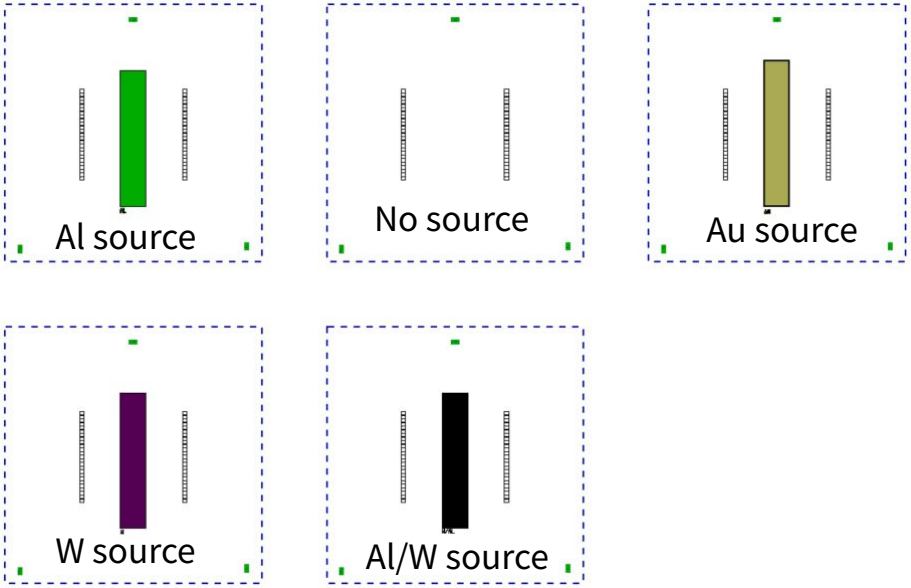
Our Theory: Metal Film Deformation → LEE

- Tungsten and/or aluminum films put under stress at low temperatures, relax
- Relaxation while cold naturally “zero yield,” rate decreases over time
- Energy → athermal phonons → signal in DM detectors

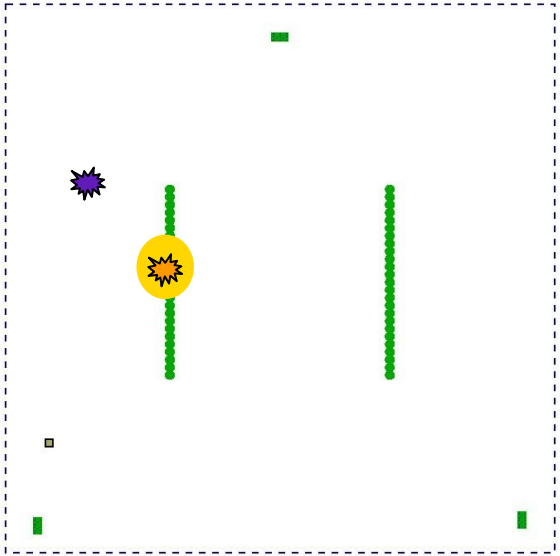
Stay tuned, paper forthcoming!

What Can We Do (Briefly…)

Microfracture “sources”

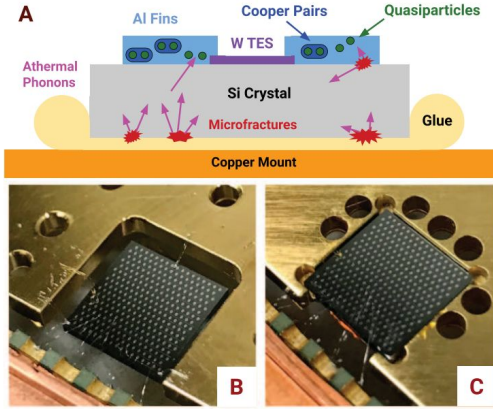


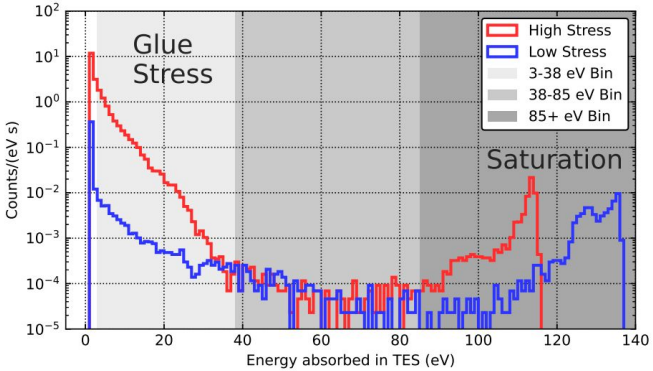
Relaxation events preferentially partition into one channel over other?

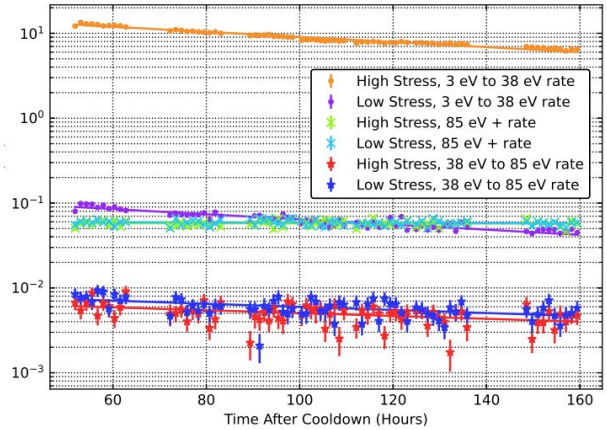


Conclusions

- Mount stress (glue on crystals) can create LEE
  - Probably what's going on in EDELWEISS… they glue down NTDs on their crystals
- Growing evidence stress in metal films can make LEE
  - Stay tuned, paper coming soon!
- Superconducting qubits need to worry about these backgrounds too
  - Depending on the system, stress events may be the dominant source of quasiparticle poisoning







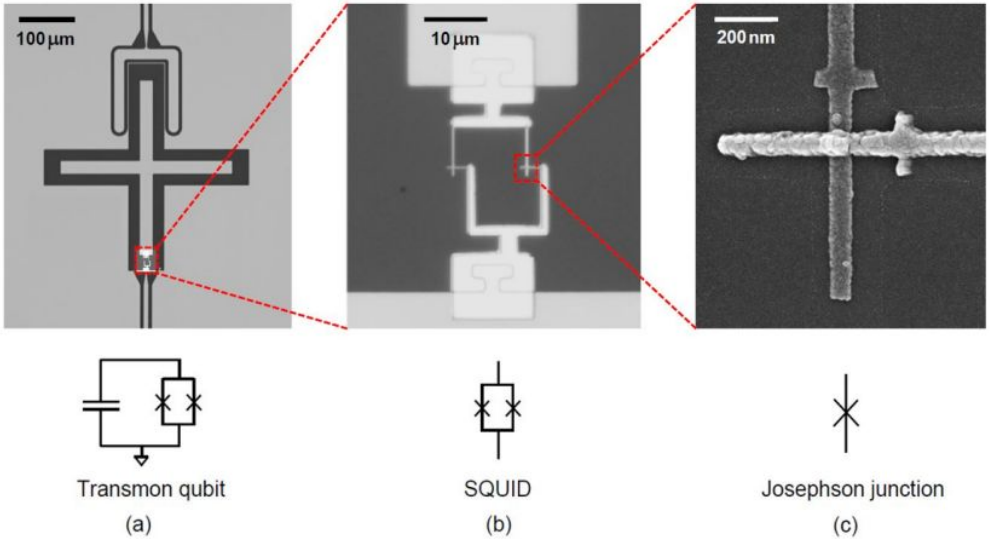
Quantum Computing

Quasiparticle Poisoning: Hurting SC Qubits

- SC qubit performance limited by decoherence
- Major decoherence mechanism: quasiparticles at Josephson Junction
    - “Quasiparticle Poisoning”

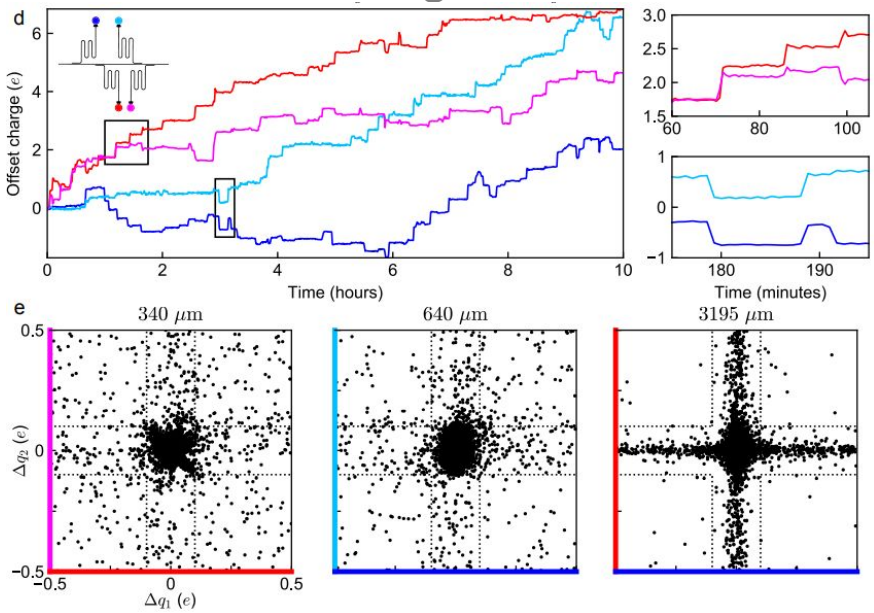
This prevents SC qubits, quantum computers from progressing!

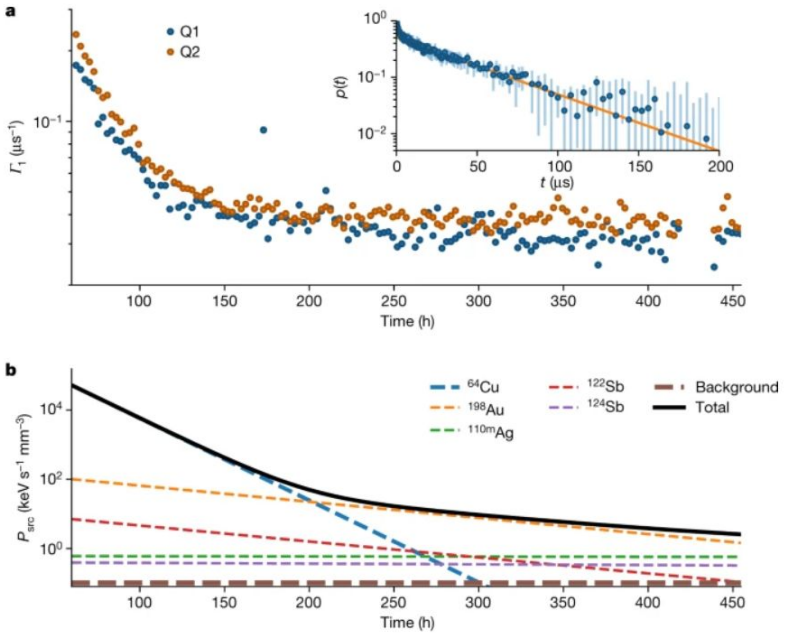
“An Introduction to the Transmon Qubit for Electromagnetic Engineers” Roth et. al. 2021



Quasiparticle Poisoning: Radiation Induced QPs

Traditional DM backgrounds as source of QP poisoning





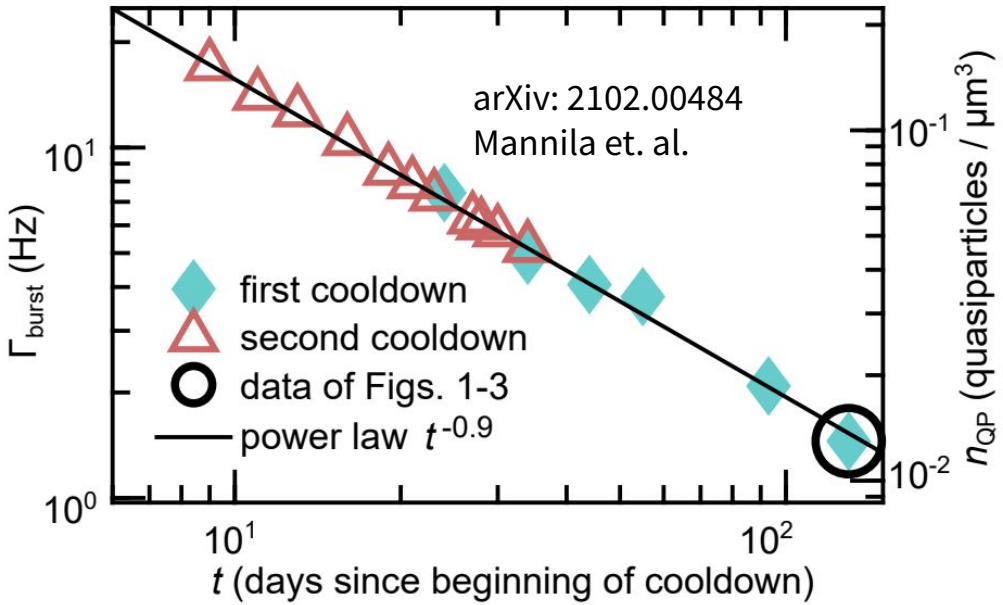
"Correlated Charge Noise and Relaxation Errors in Superconducting Qubits" Wilen et. al. 2020

Issues: no fall off with time, doesn't explain all decoherence or QP poisoning

"Impact of ionizing radiation on superconducting qubit coherence", Vepsäläinen et. al. 2020

Quasiparticle Poisoning: Mounting Stress

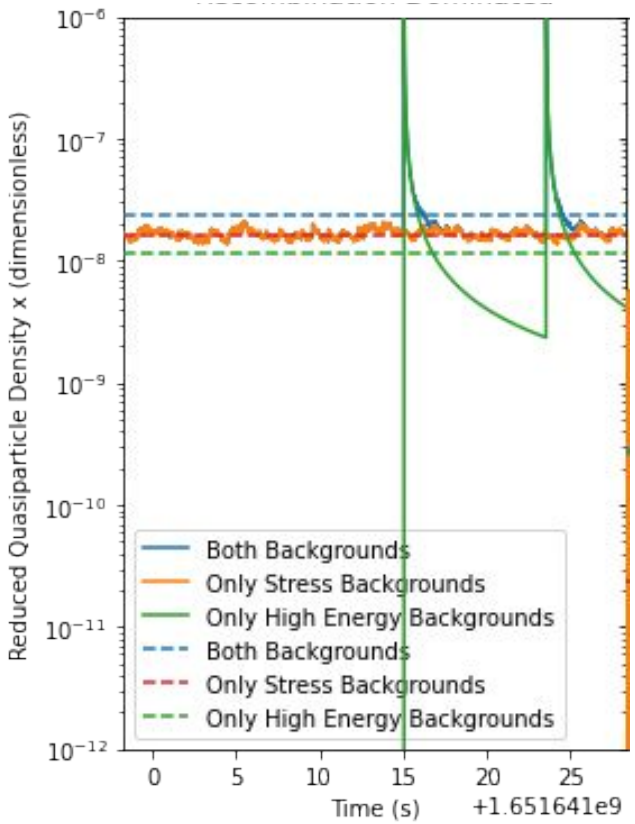
- QP density falls off over time… just like LEE



Quasiparticle Poisoning: Stress Worse than Cosmics

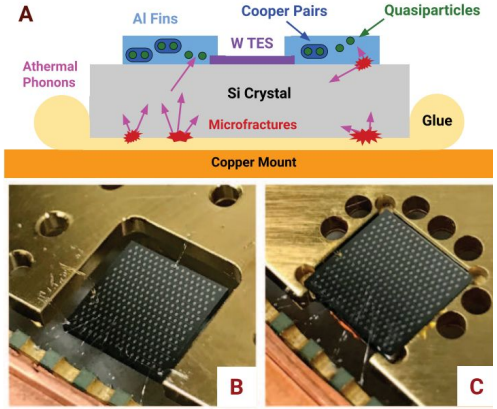
- QP dynamics in many qubits recombination dominate:
  - QPs die away quickly at high densities, stick around at low densities
- Cosmic rays, radiobackgrounds, etc.: infrequent big bursts
- Stress events: very frequent, small bursts
- Simulation based on actual events seen in high stress device from 2022 stress backgrounds paper

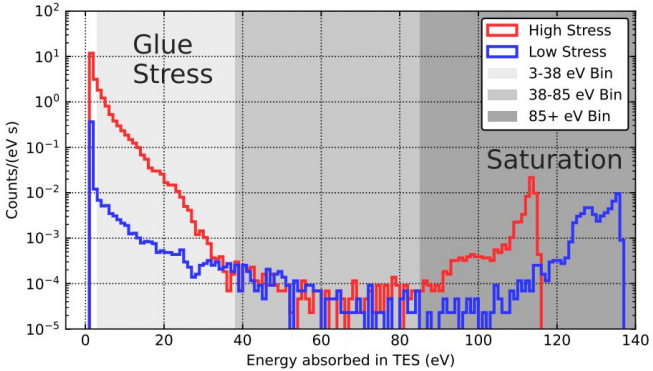
Don’t glue/vacuum grease your qubits down!

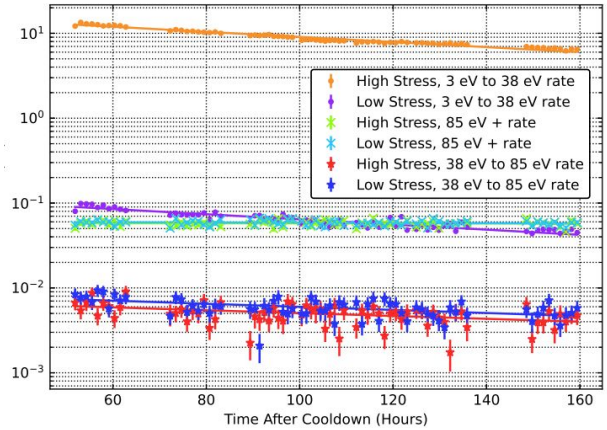


Conclusions

- Mount stress (glue on crystals) can create LEE
  - Probably what's going on in EDELWEISS… they glue down NTDs on their crystals
- Growing evidence stress in metal films can make LEE
  - Stay tuned, paper coming soon!
- Superconducting qubits need to worry about these backgrounds too
  - Depending on the system, stress events may be the dominant source of quasiparticle poisoning

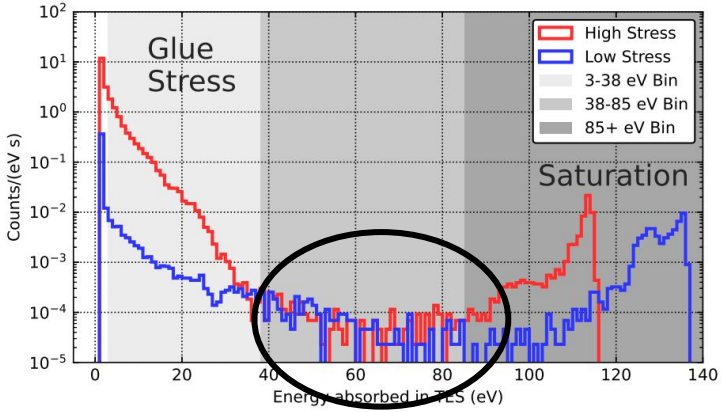


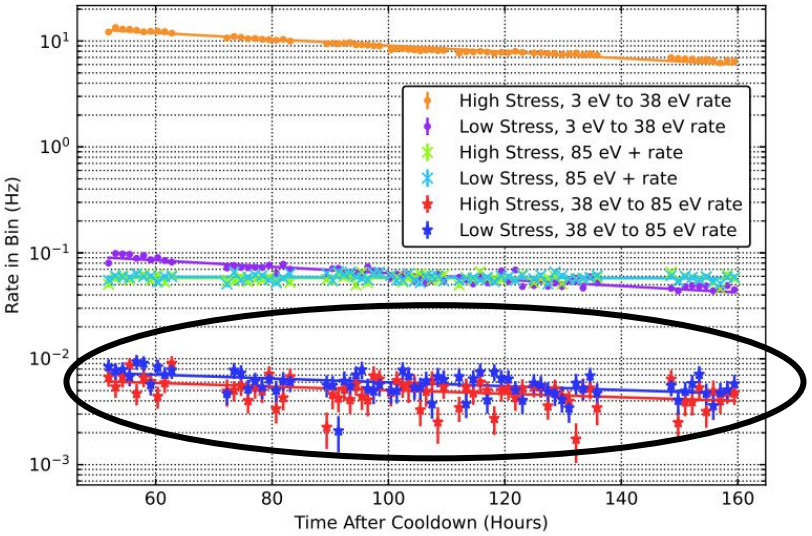




Source needs to be:

- Virtually identical between two HS/LS detectors
  - Not mounting stress related
- But… spectral shape and time dependence of events looks like stress events
- Look for stress elsewhere in system

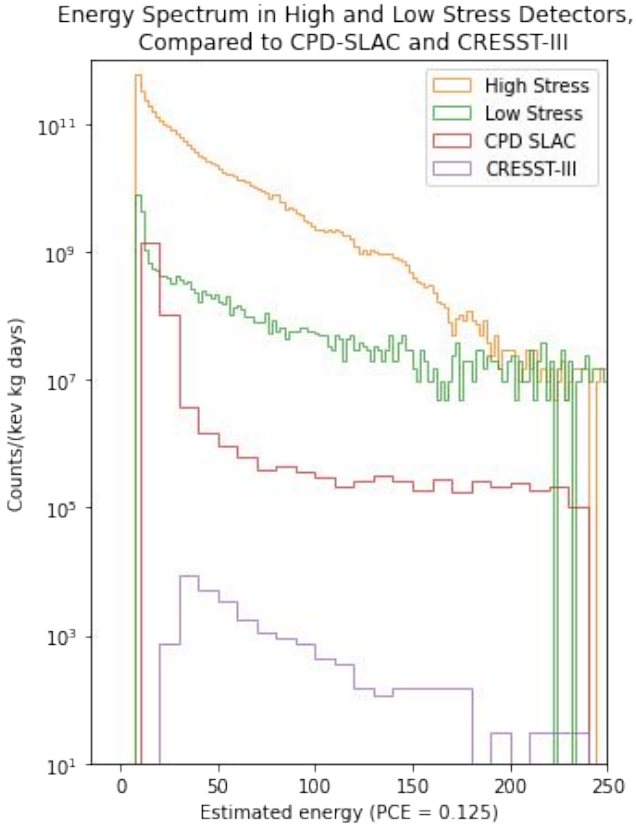




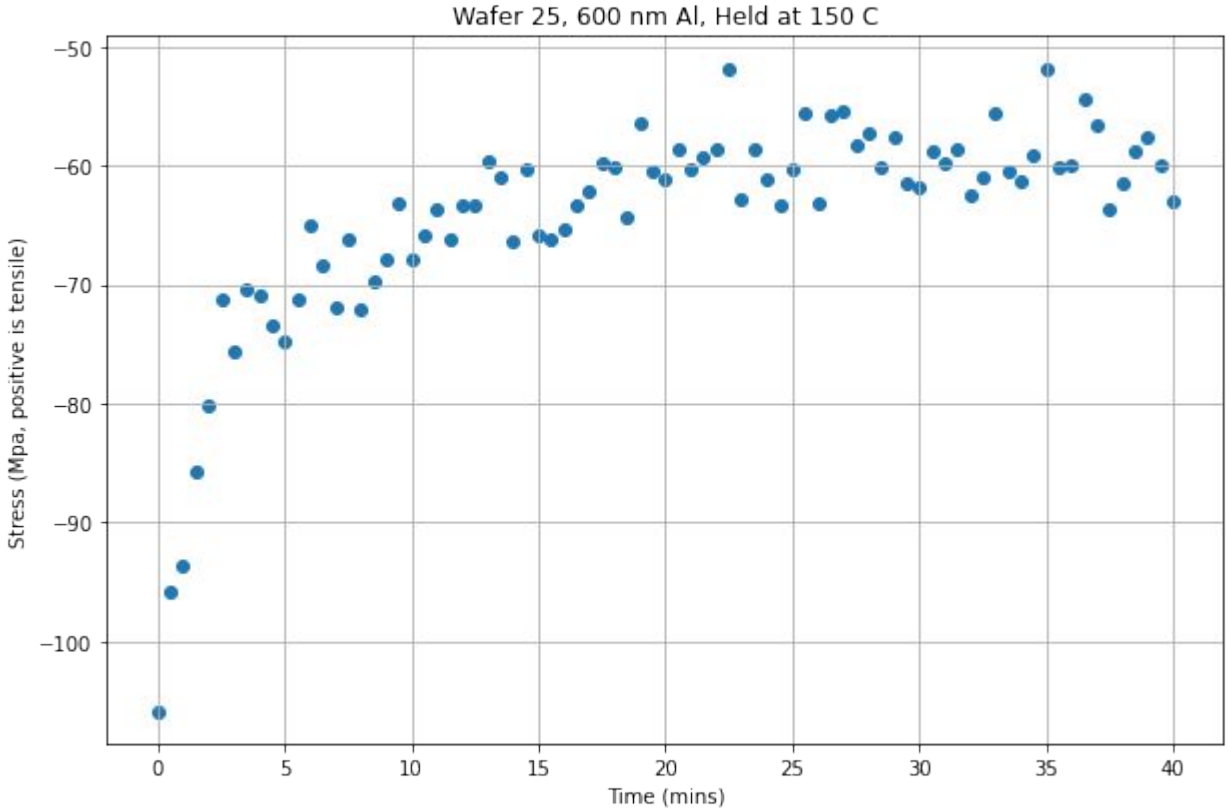
Backup: Different Experiments, Different Rates?

Probably multiple culprits

- Different detector mass to film mass ratios
  - E.g. ~100x more Al on CPD vs. CRESST detectors
- Cold for different lengths of time
  - CRESST cold for ~year, CPD cold for ~weeks
- Different films between experiments



Backup: Warm Creep of Aluminum



Constant temperature portion of slide on stress vs temperature