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

Speakers: Roger Romani

Series: Particle Physics

Date: November 08, 2022 - 1:00 PM

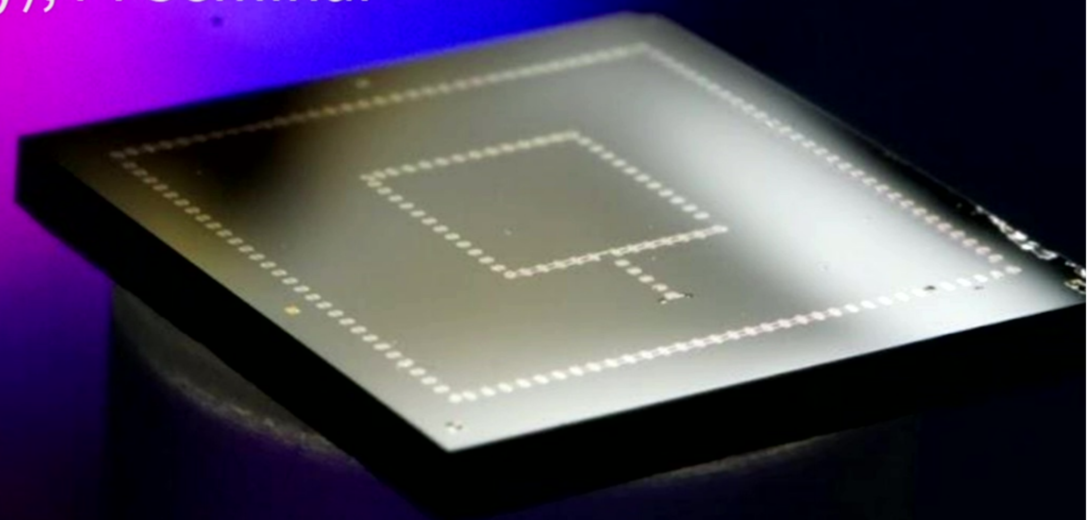
URL: https://pirsa.org/22110031

Abstract: With no hints of dark matter in the "classical WIMP" region of parameter space, experimentalists have begun searching in earnest for low mass (MeV-GeV scale) dark matter. However, efforts to probe this region of parameter space have been hindered by an unexpected and mysterious source of background events, dubbed the "low energy excess." Recently, mechanical stress has been shown to create a "low energy excess"-like source of events, and a microphysical picture of how stress creates this background is emerging. In addition to providing a path forward for low mass dark matter searches, these results may address several outstanding problems limiting the performance of superconducting quantum computers.

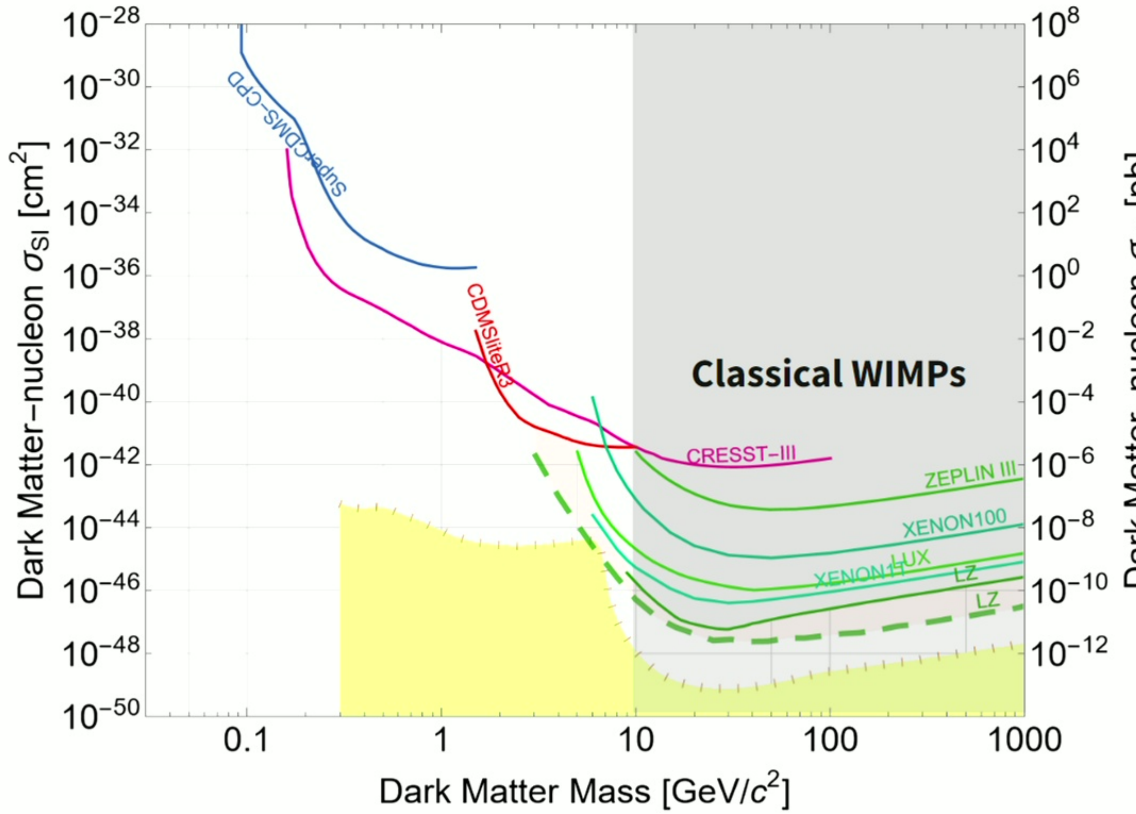
Zoom Link: https://pitp.zoom.us/j/92147233613?pwd=RW5PaUNUZlE3SUNnTlZHaVFrdnV3dz09

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

Roger K. Romani (UC Berkeley), PI Seminar



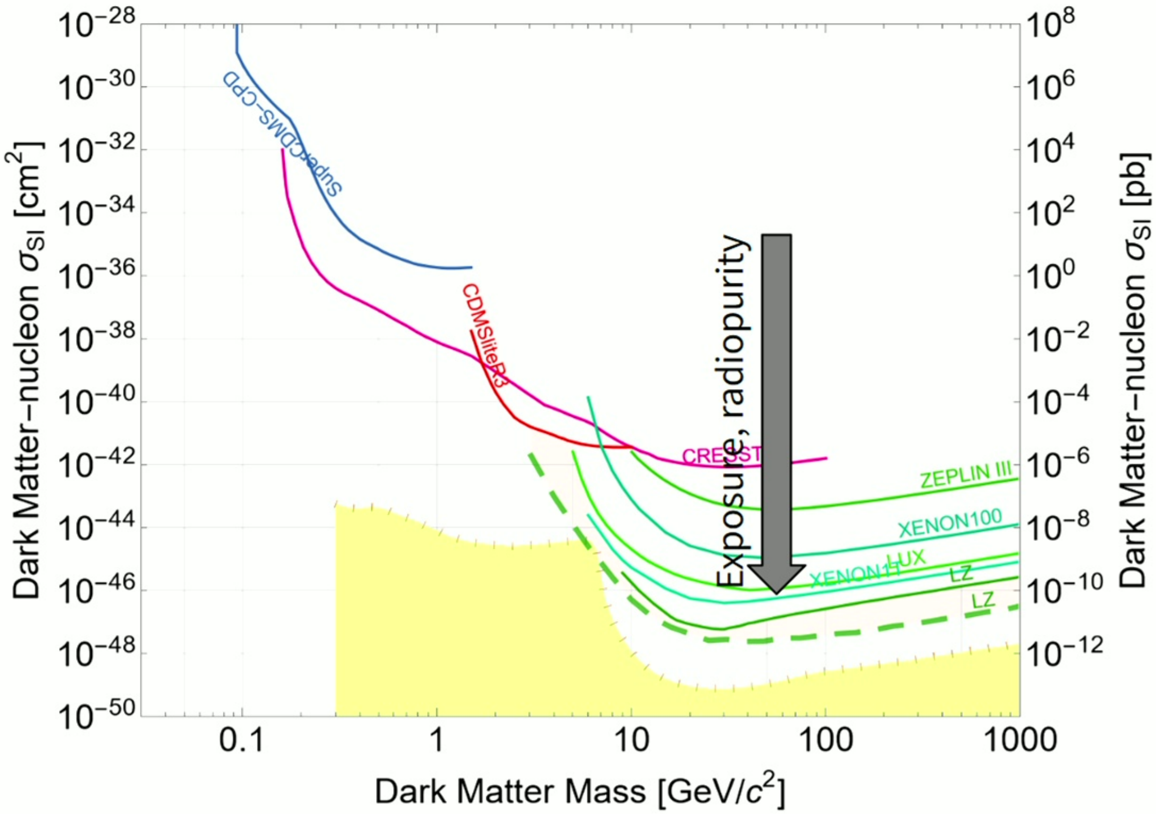
Two Ways to Look for Dark Matter*



* "WIMP-like" DM, won't talk about axions etc. here

Two Ways to Look for Dark Matter*

1. Lower cross sections
   - Bigger, cleaner detectors
   - Fundamentally, more $ and time



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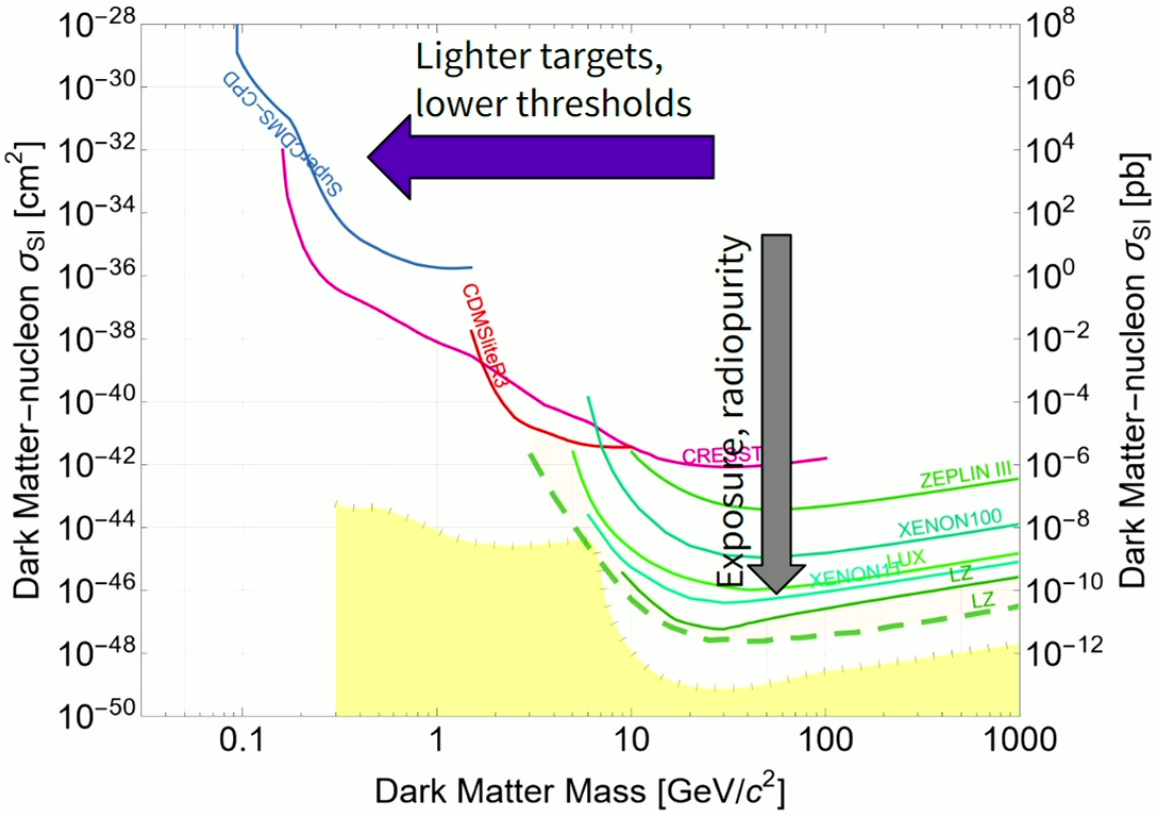
Two Ways to Look for Dark Matter*

1. Lower cross sections
   - Bigger, cleaner detectors
   - Fundamentally, more $ and time
2. Lighter DM particles
   - Better energy resolution detectors
   - Lighter target nuclei



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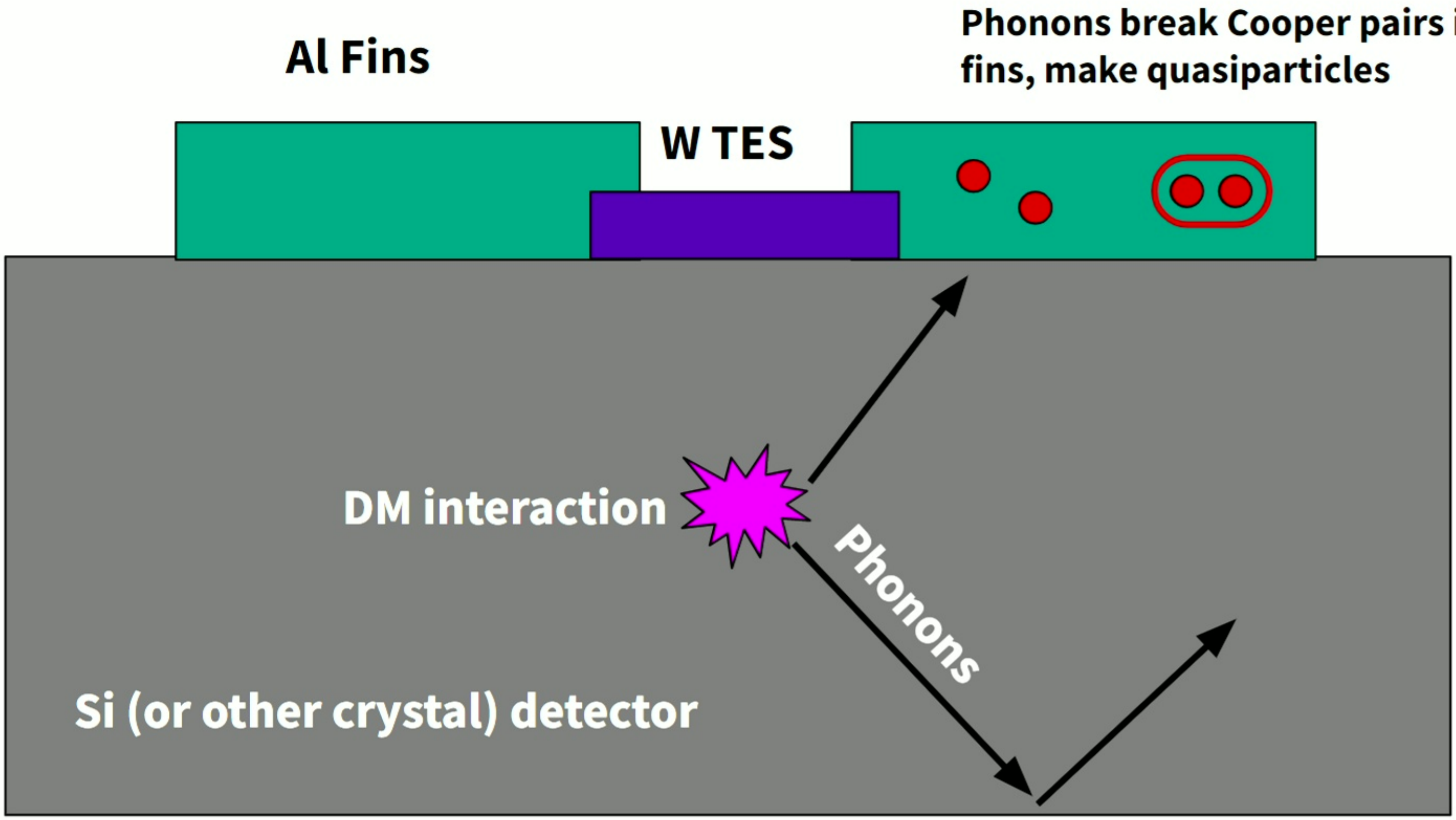
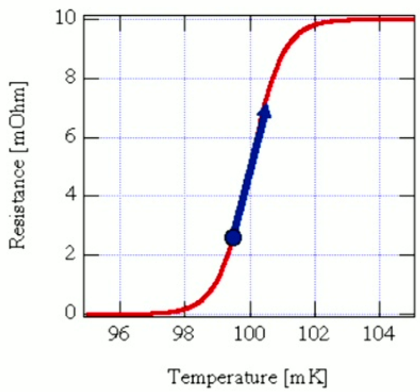
Our Approach: Calorimetry

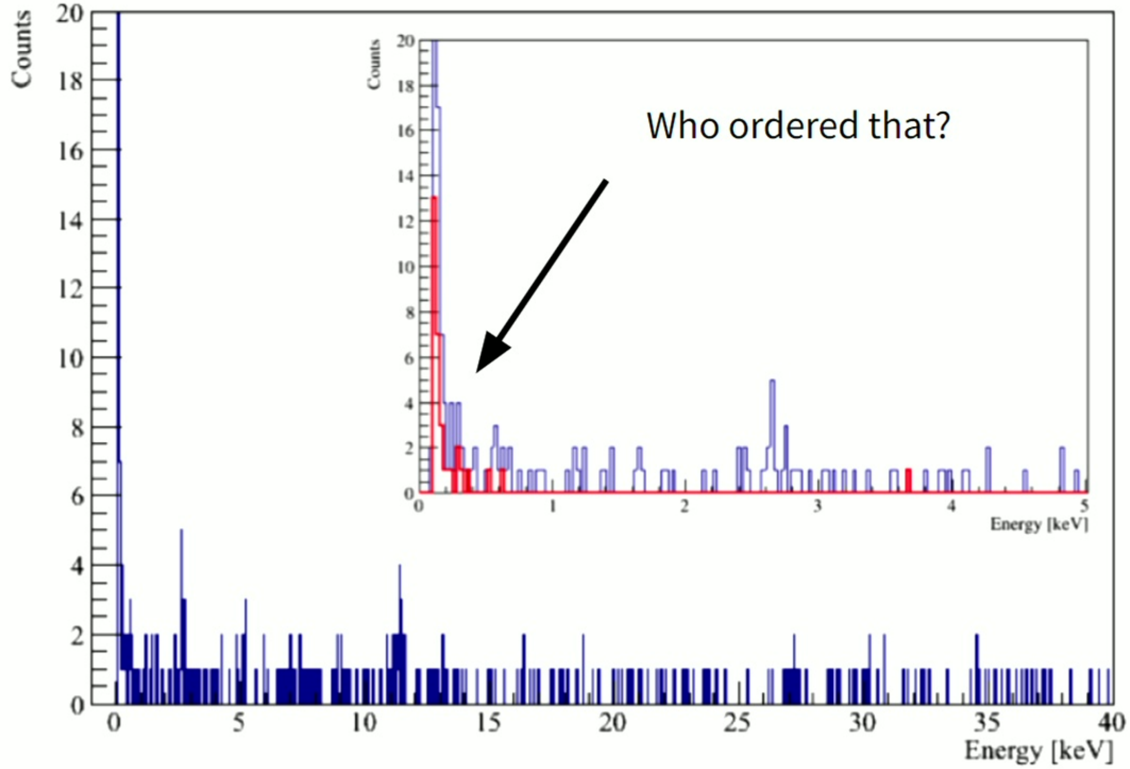




*all at ~10 mK in dilution refrigerator

First Hints of a Problem: CRESST 2017

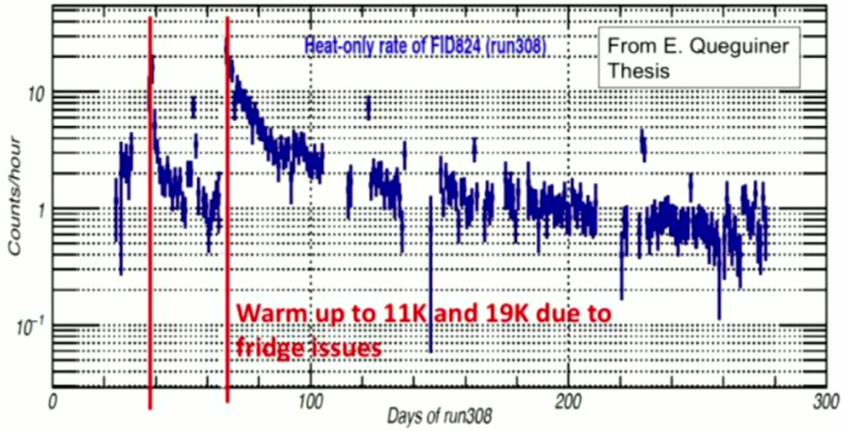
- Lots of low energy events (below ~300 eV)
- Completely unexpected!
- Not:
  - Known radioactive backgrounds
  - Instrumental noise (events look like particle events)



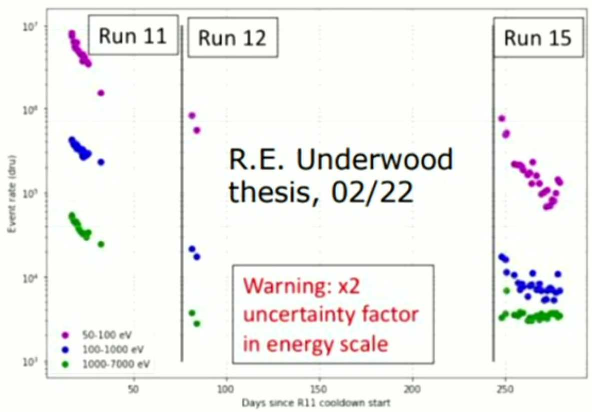
CDMS-CPD, EDELWEISS: Same Problem

- Similar detector styles
- Seen with no + low overburden (CPD), deep underground (CRESST)
- Rate variations with time!
  - Plus (possibly) temperature history of fridge
  - Later seen in CRESST detectors too
- EDELWEISS: non-ionizing
- Definitely not radiogenics (or DM)
- Looks like "real" event in each experiment

EDELWEISS Low Energy Excess (FID 824)

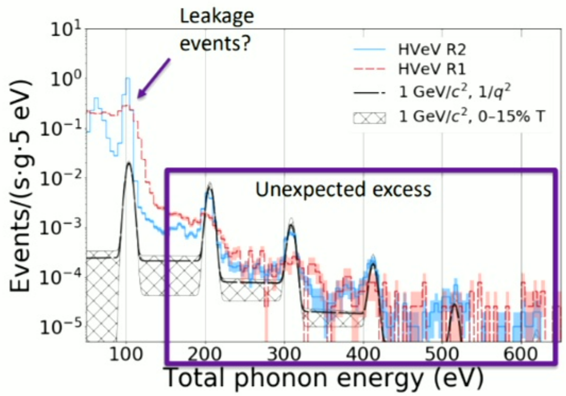


CPD@CUTE

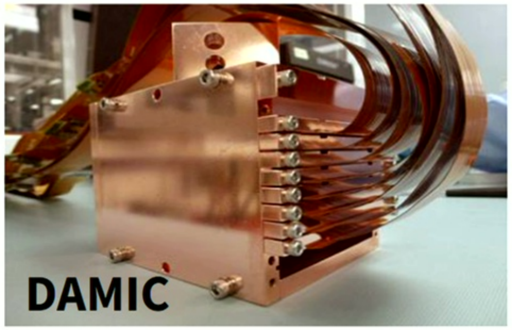


Ionization Based Experiments See Excess Too

- Look at semiconductor
- Count ionized e-
- See more multi e- events than expected
  - Expect single e- “leakage” events
- Different experiments, techniques all see excess



D. W. Amaral *et al.*, Phys. Rev. D 102, 091101(R), 2020



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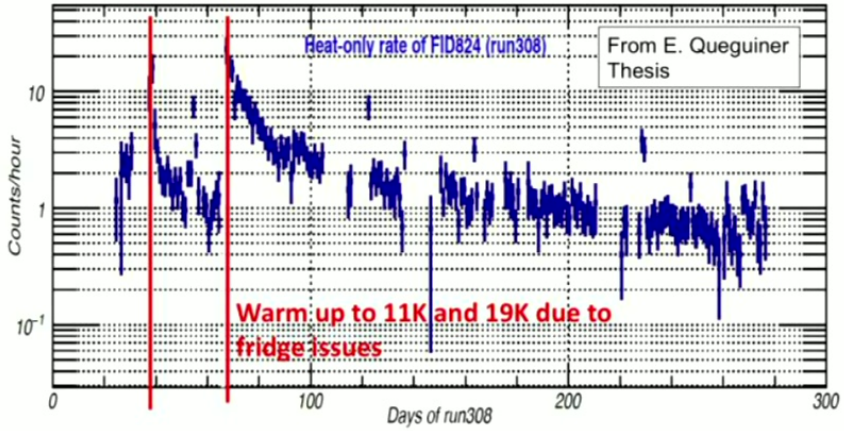

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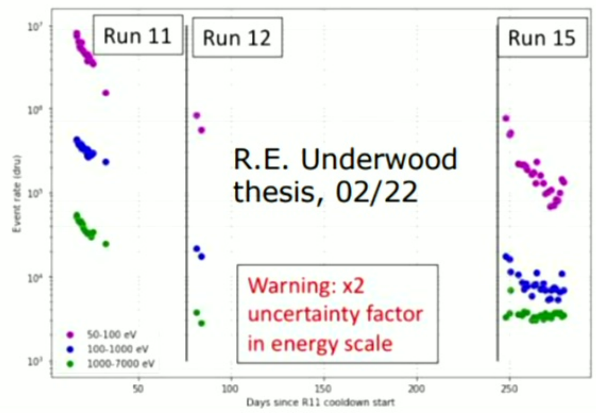
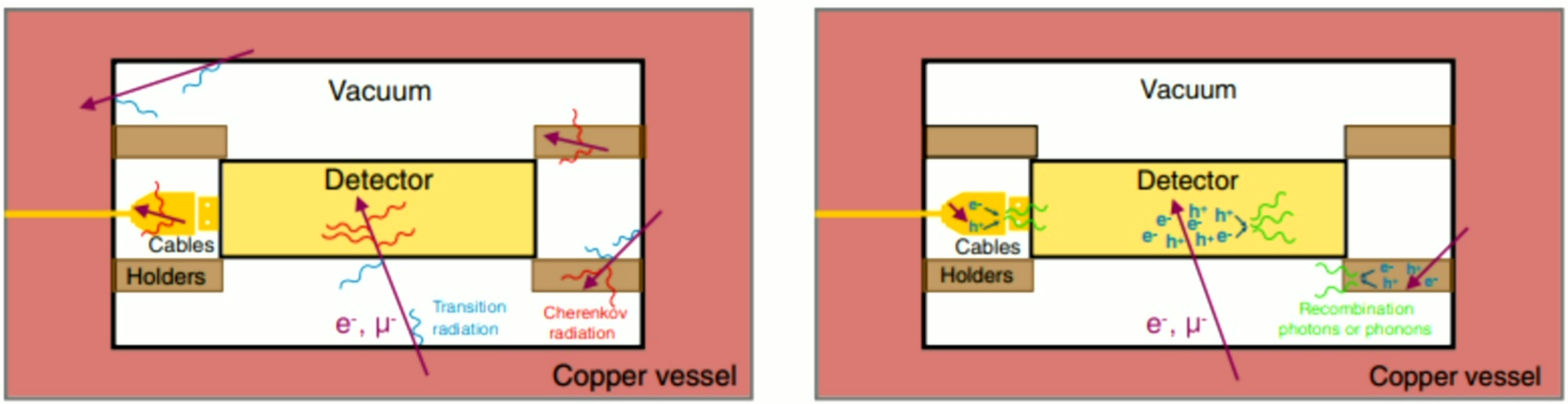


First Big Breakthrough: Cosmics -> Low Energy

Sources of Low-Energy Events in Low-Threshold Dark-Matter and Neutrino Detectors

Peizhi Du,[1] Daniel Egana-Ugrinovic,[2] Rouven Essig,[1] and Mukul Sholapurkar[1]
[1]*C. N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

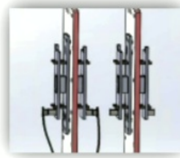
(Received 18 December 2020; revised 12 November 2021; accepted 15 November 2021; published 13 January 2022)

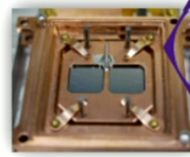


Time dependence?

Zero ionization?

Improvements Made, Part of Excess Remains



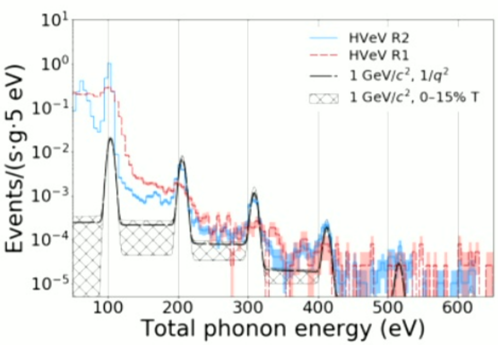


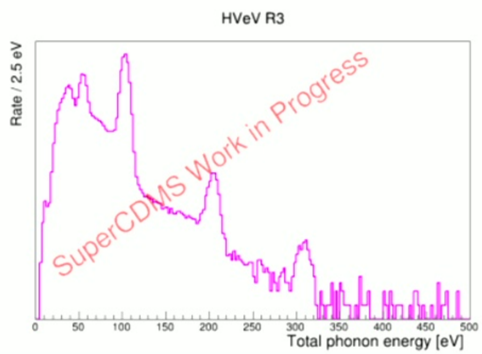
- Burst events detection and study
- Hypothesis: originated by SiO_2 in the detector holder (PCB)

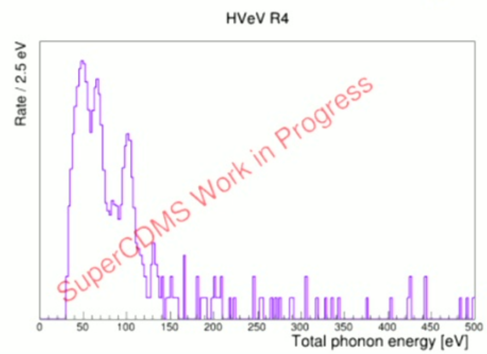
- Coincidence measurement
- Confirmed external origin of this background and its reduction with coincidence cut

- Removed PCB from the detector holder
- Elimination of the quantized background above 1 eh peak

HVeV R2 HVeV R3 HVeV R4







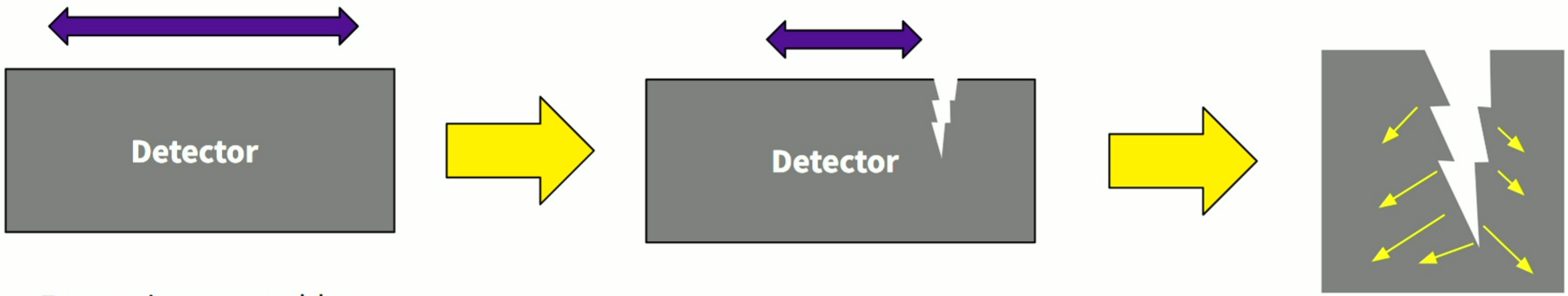
V. Novati, EXCESS 2022 Slides

What is a Stress Background?

Stress (thermal contraction, manufacturing, previous events…)

Relaxation event (partially) reduces energy of system

Athermal phonons created



Energetic, metastable state

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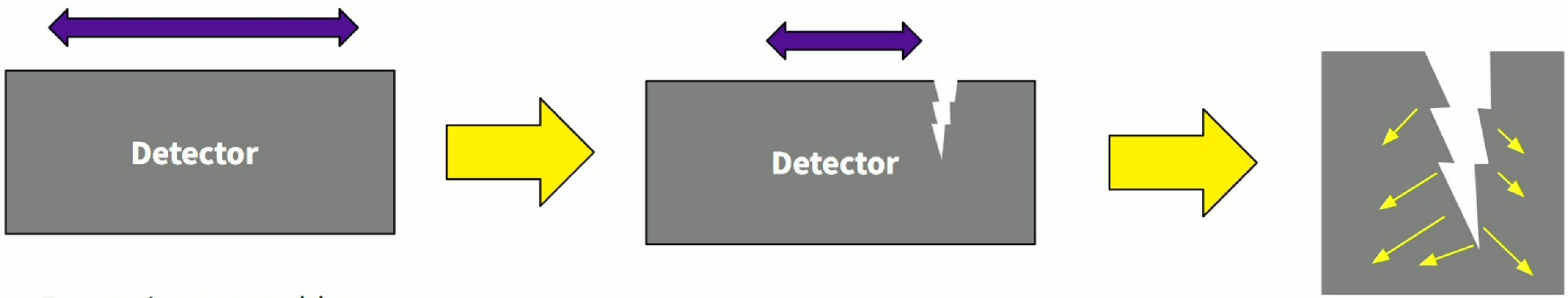
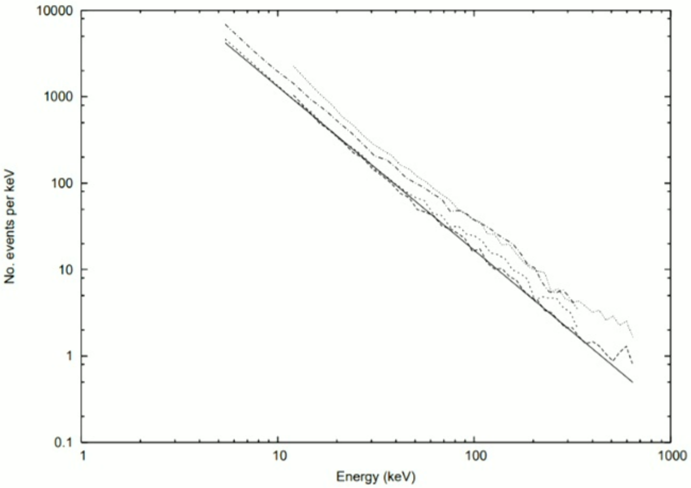


Energetic, metastable state

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“

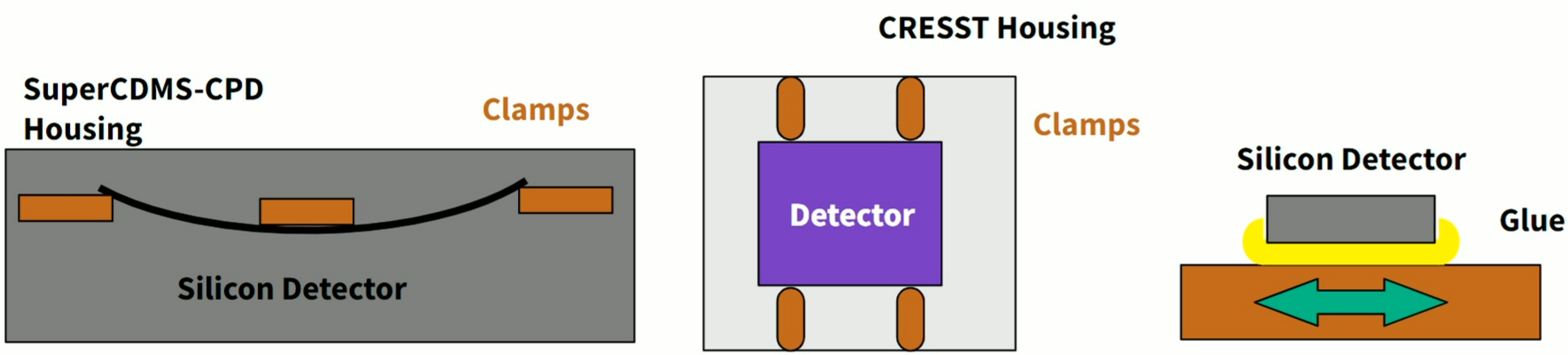


An extensive search for the origin of the pulses was finally successful when it was noticed that there appeared to be markings or scratches on the crystal at the contact points with the sapphire balls. When the sapphire balls were replaced by plastic stubs, which are evidently much softer, the event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

Stress as a Source of the Low Energy Excess?

Matt Pyle: events from stress can explain remaining excess!

- Time variation with cooldown (stress relaxes over time)
- Zero yield (each event subgap, many events essentially simultaneously)
- How to eliminate? Reduce stress in detector holding



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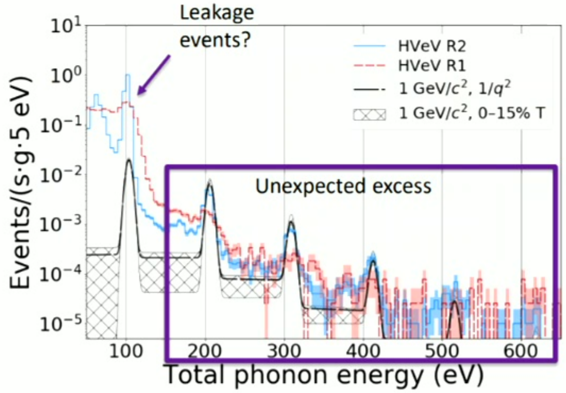
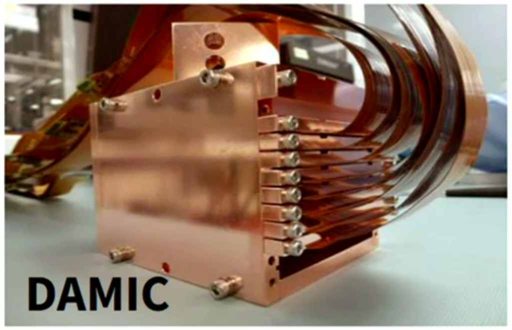


D. W. Amaral *et al.*, Phys. Rev. D 102, 091101(R), 2020



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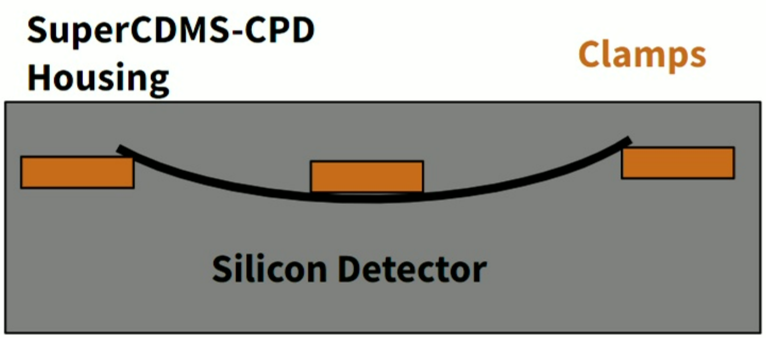
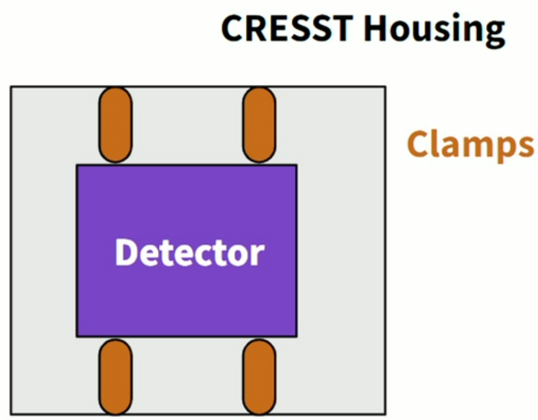
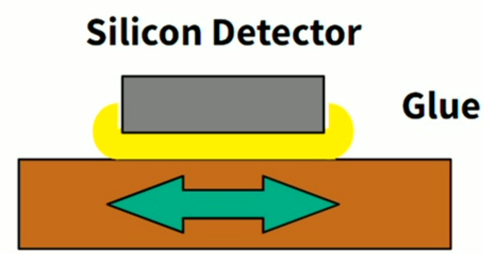
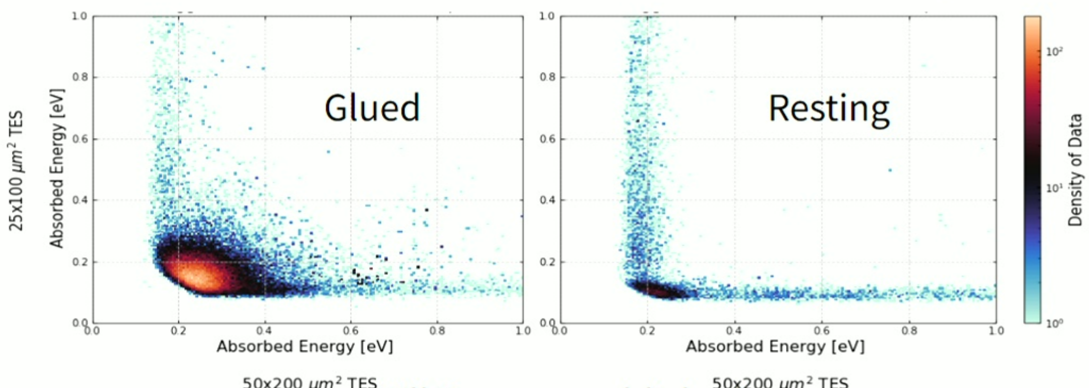




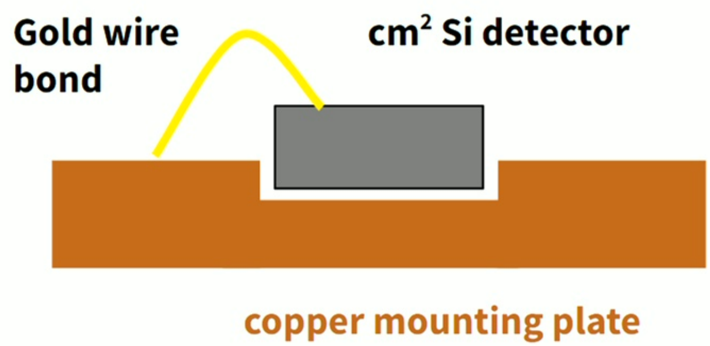


Game Plan: Reduce Stress in Detectors

- Initial concept: “resting” detectors
  - Si detector free to move (no thermal contraction), only mg force on surface
- Problem: how do you cool down detector?
  - Solution: gold wire bond from detector to fridge pulls out
- Problem: how do you keep detector from sliding around?
  - Fridge vibrates when running, motion causes noise/events in detector
  - Solution: run for short times (15 mins) with pulse tube off



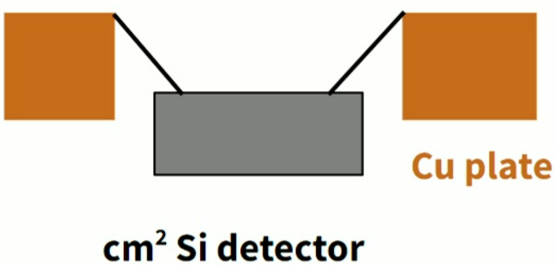
Bill Page, unpublished

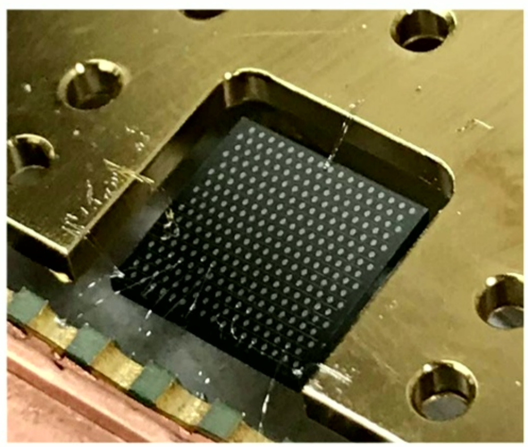


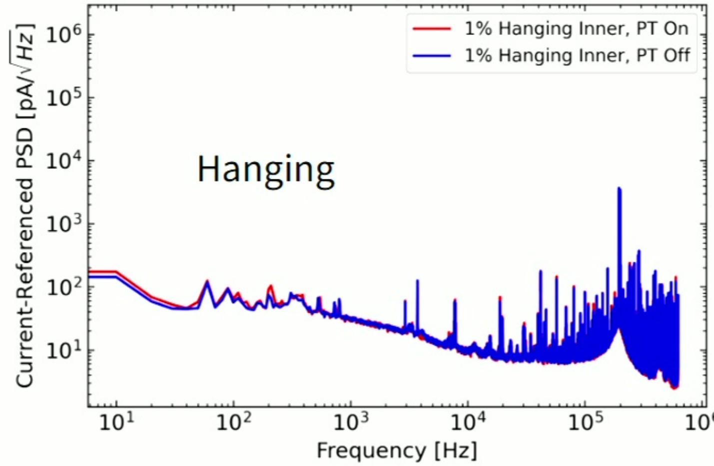
Hanging Detectors

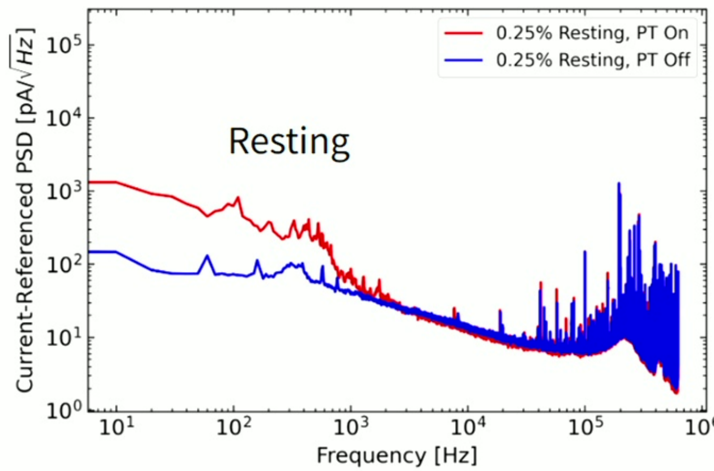
Basic concept: suspend detector from wire bonds

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





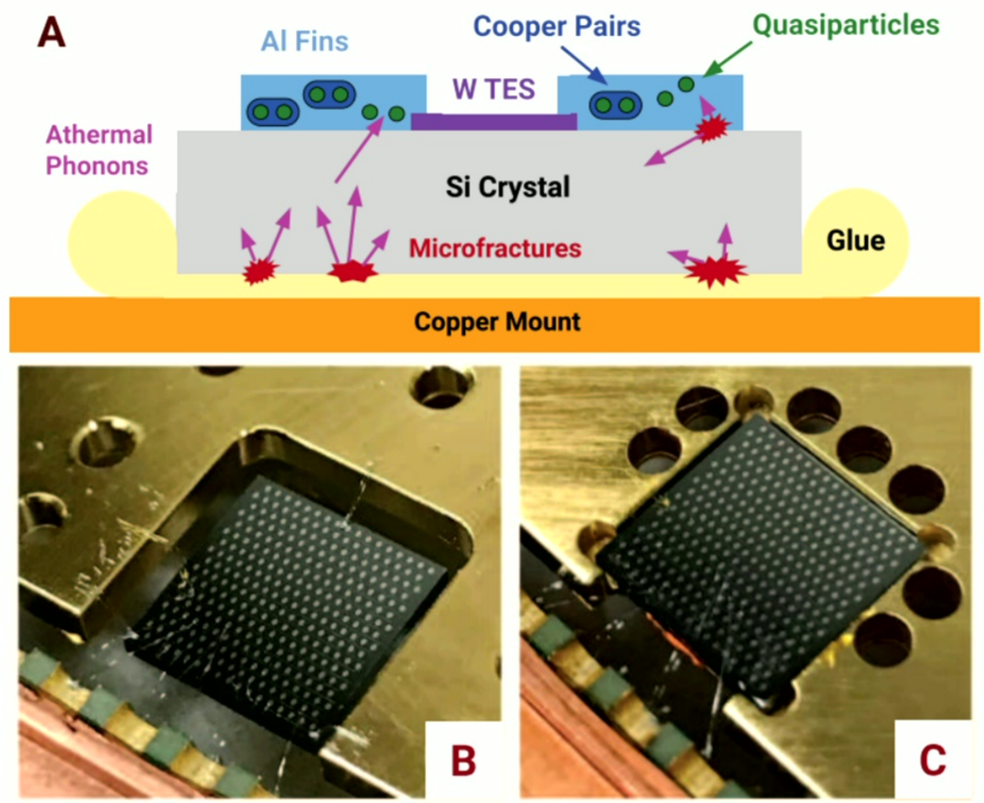




Fink, Watkins theses, 2021

Compare High Stress and Low Stress Detectors

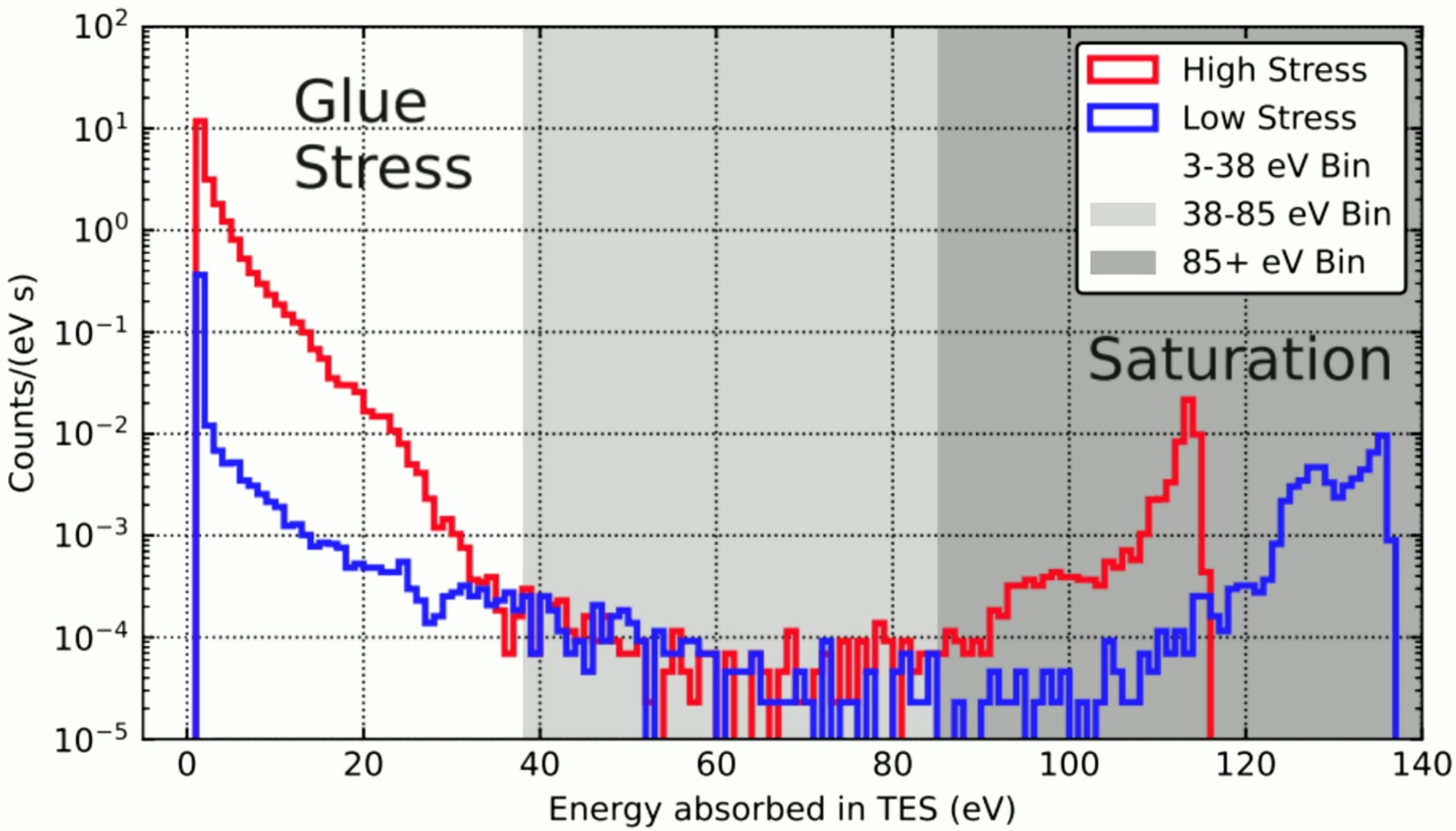
- Two identical as possible* detectors
  - One glued down
  - One hanging from wire bonds
- TES based readout measures athermal phonon pulses in substrate
  - Just as a "real" low mass DM detector would



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



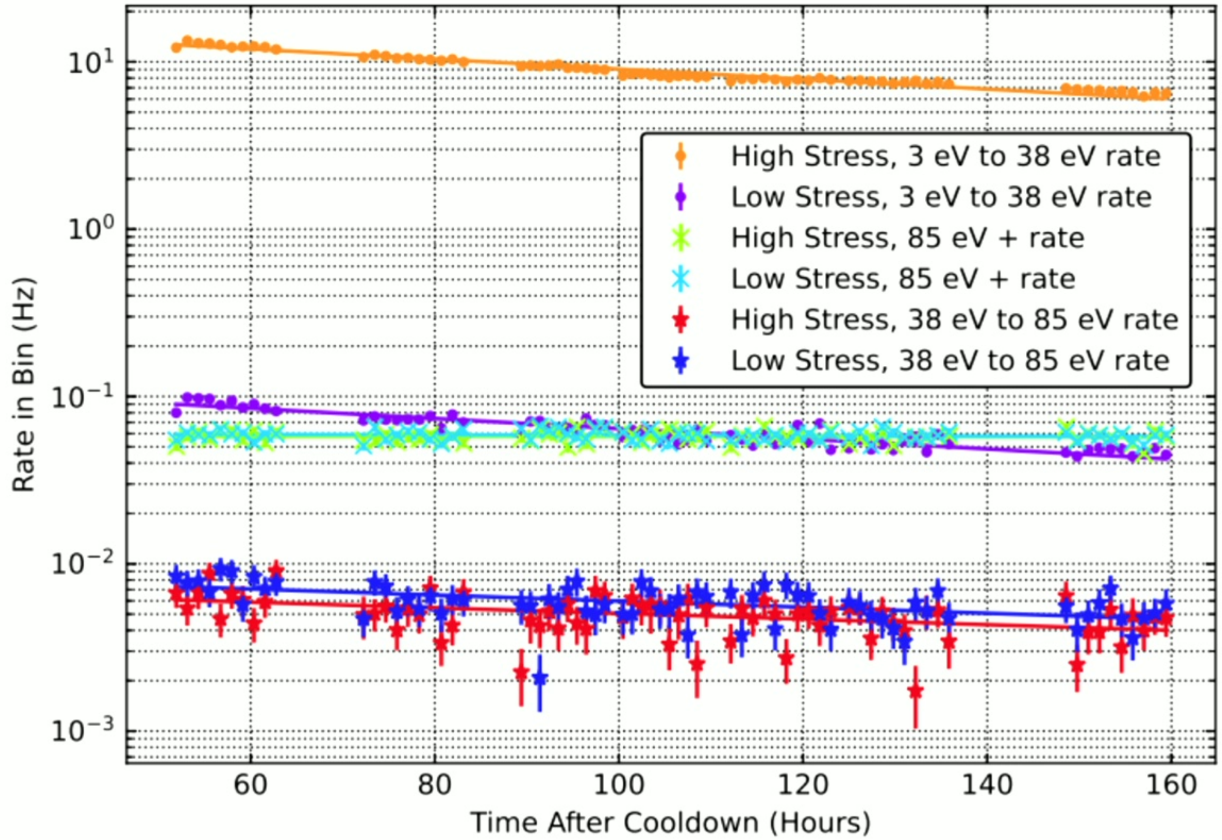
Stress Causes LEE like Events: Results

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

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

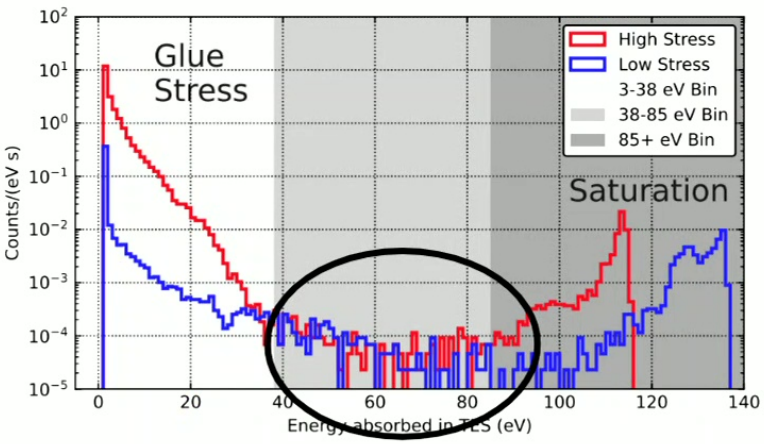
In medium energy range, see essentially identical LEE in both detectors

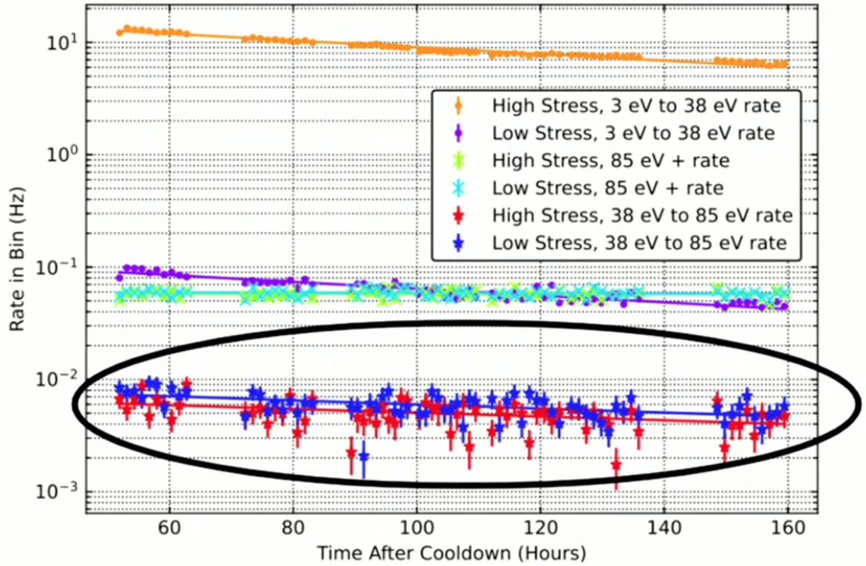
What's going on?



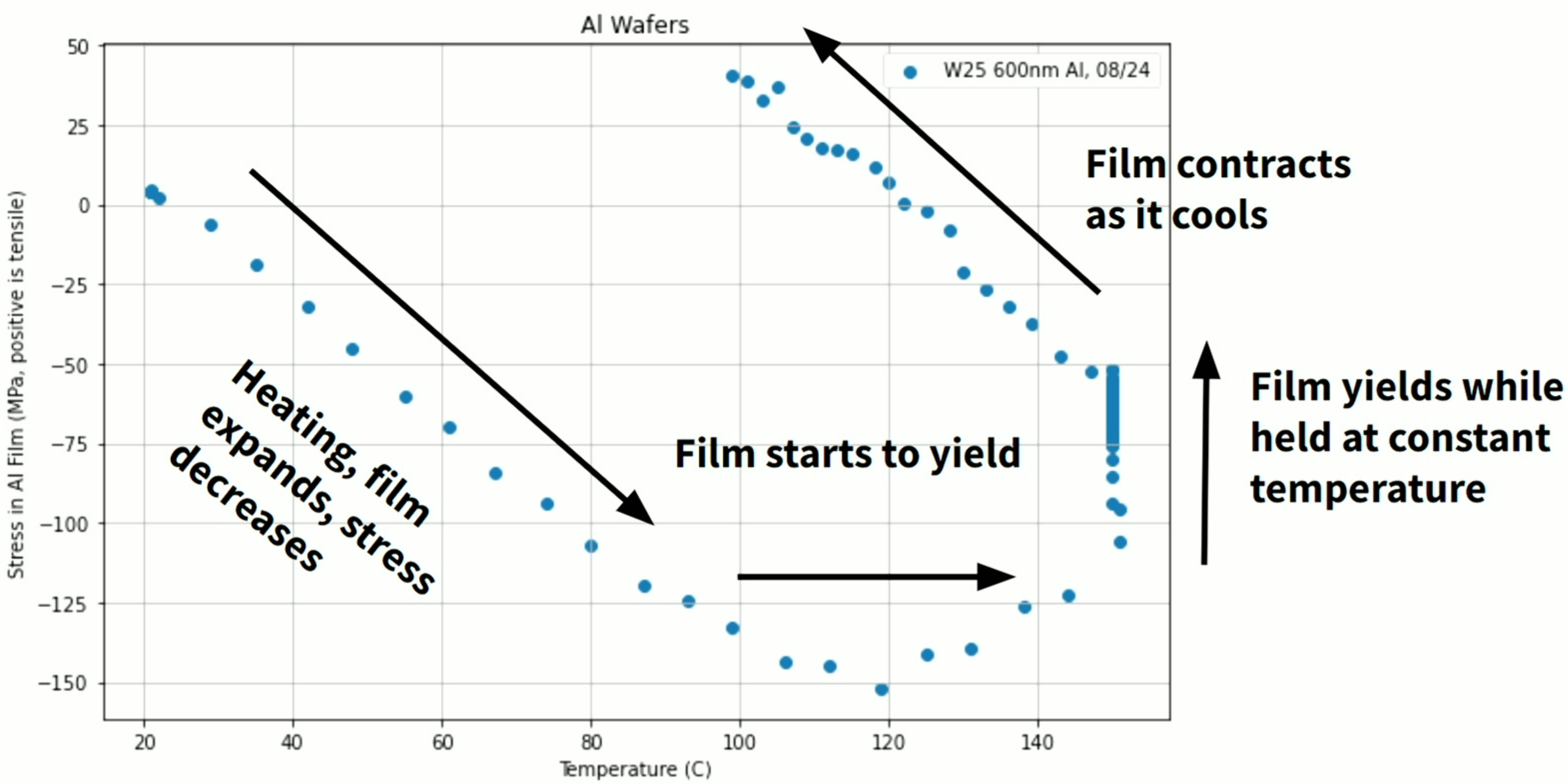
Source needs to be:

- 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



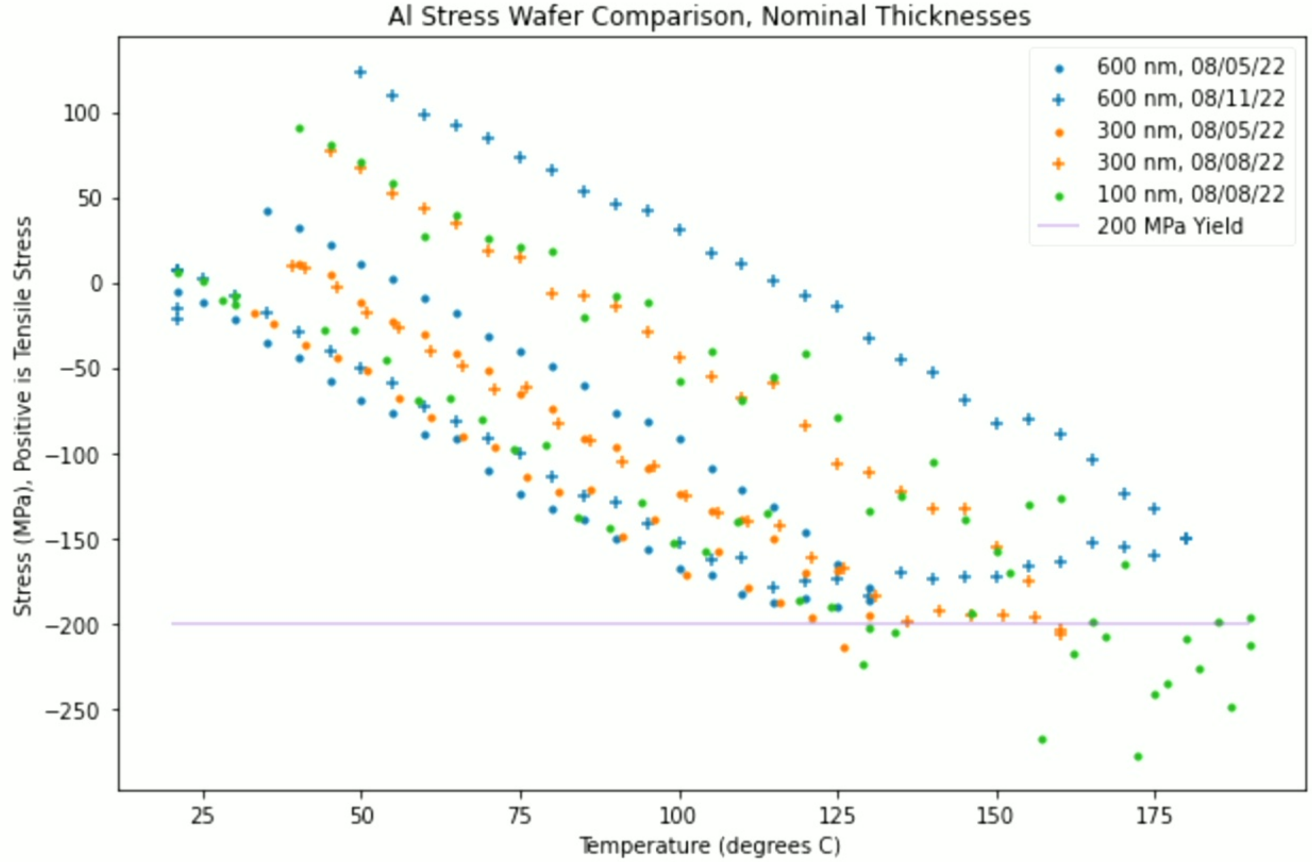


Al films can yield on Si!



Different Al Thicknesses Yield at Same Bulk Stress

- Measured with different thicknesses
  - If interface yielding: 100 nm should yield at 6x film stress of 600 nm
  - If film bulk yielding, stress independent of film thickness
- What is pure Al yield?
  - Depends on grain size, temp, dislocation density… ~100s of MPa reasonable



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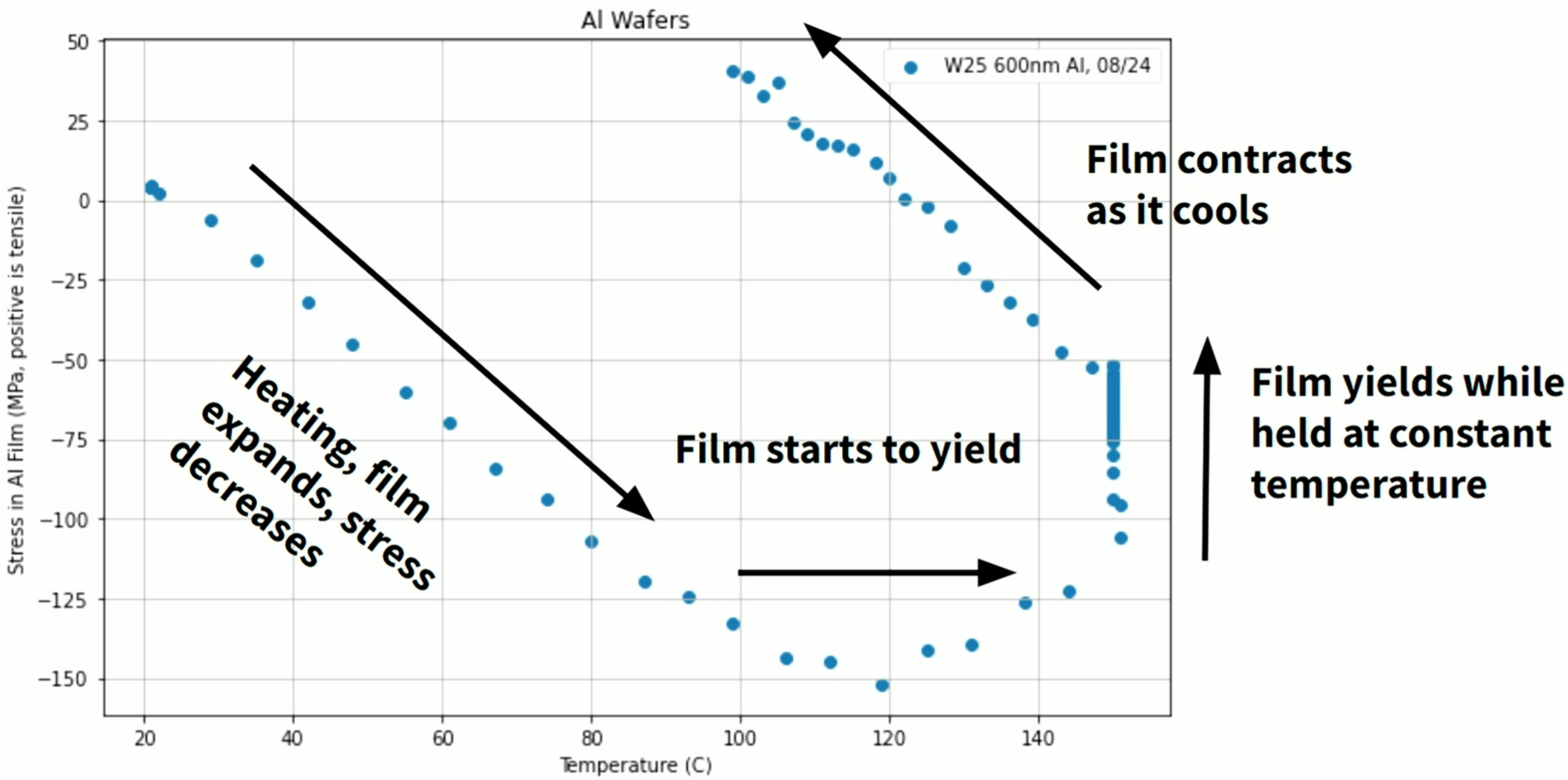
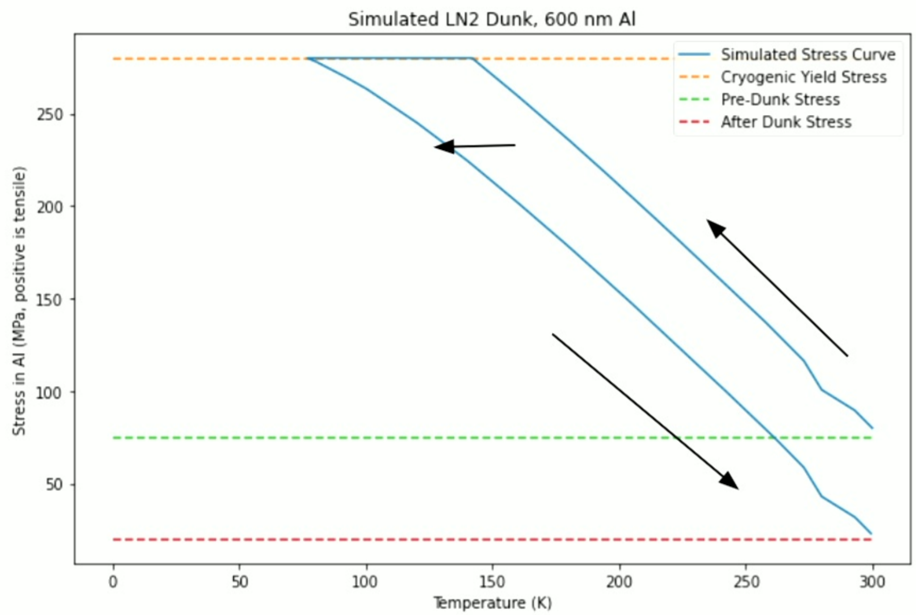
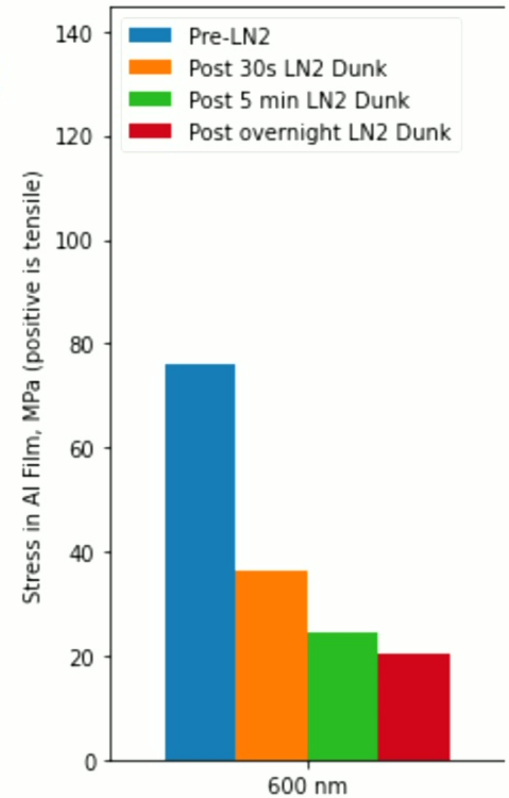


Deformation at 77K

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

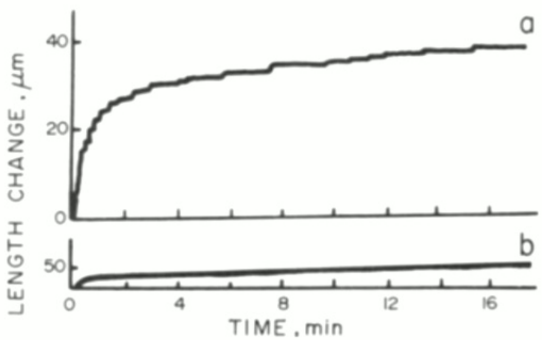
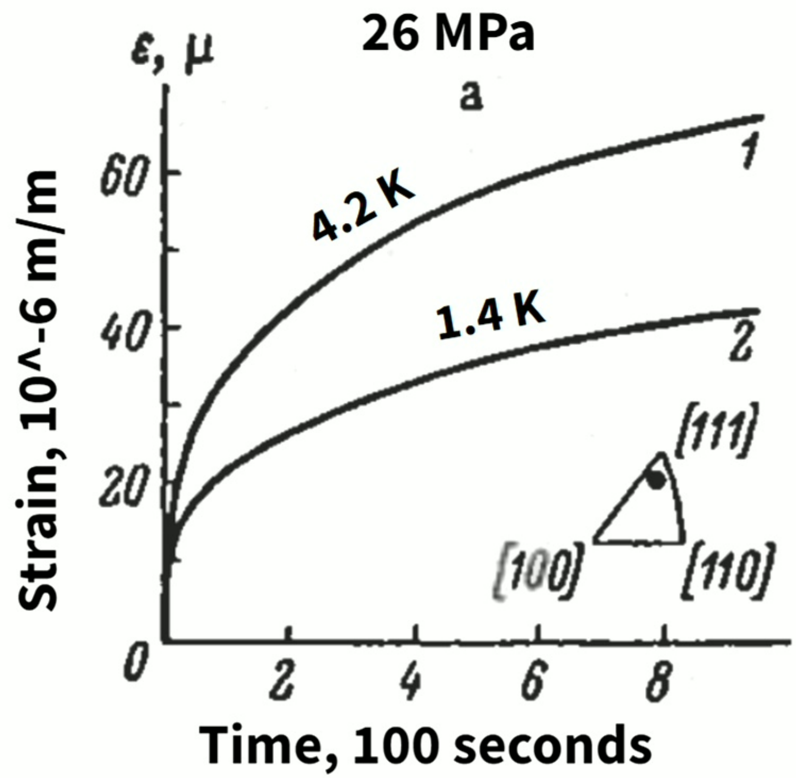
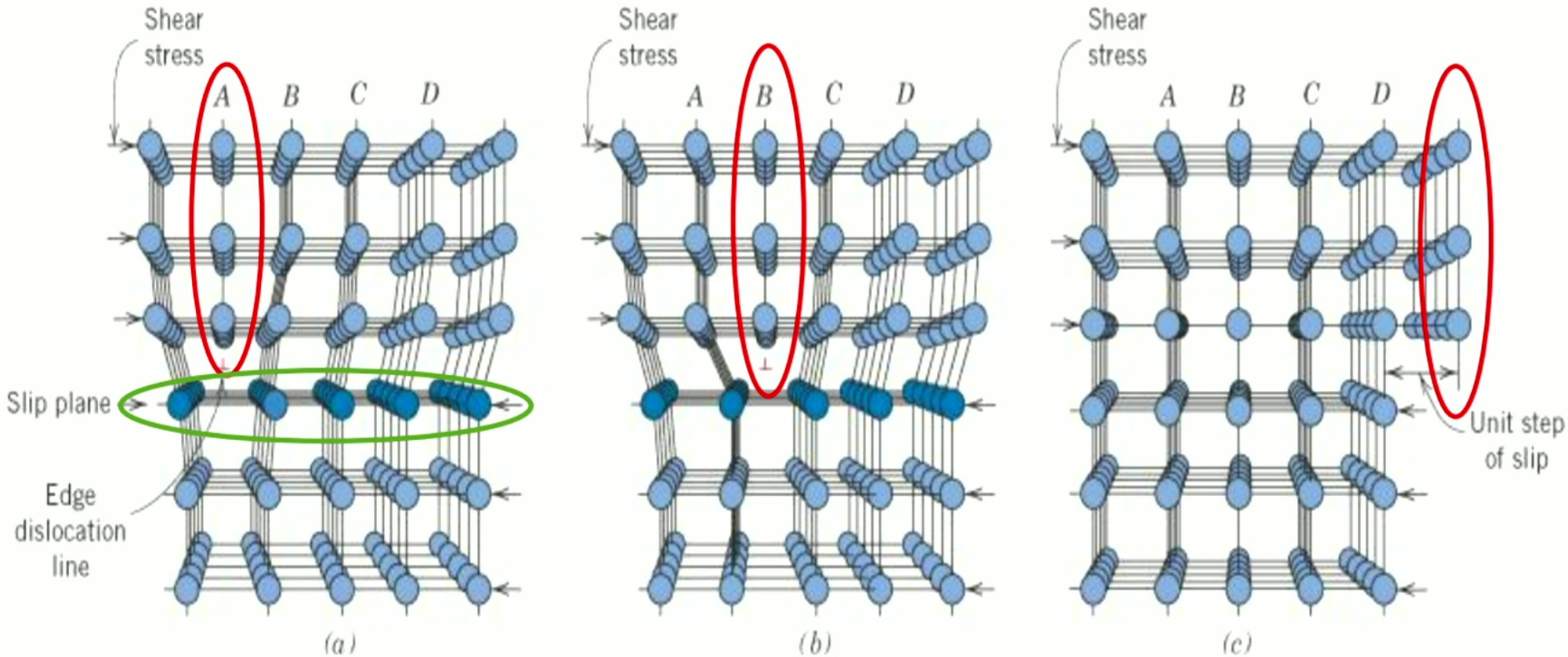


Fig. 1. Machine creep curve for 99.99% Al recorded on (1) the 5000:1 scale and (2) 500:1 scale; shear stress, $\tau = 300\ \mathrm{g/mm^2}$; $T = 3$ K.



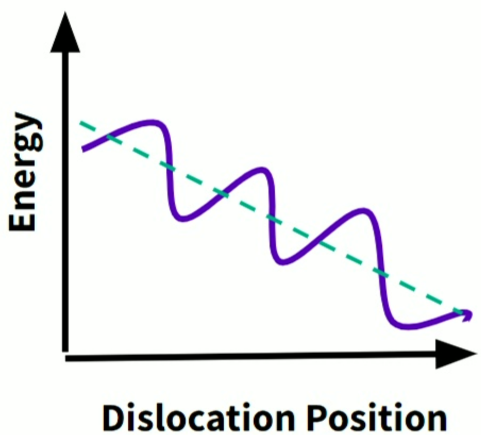
Basics of crystal deformation

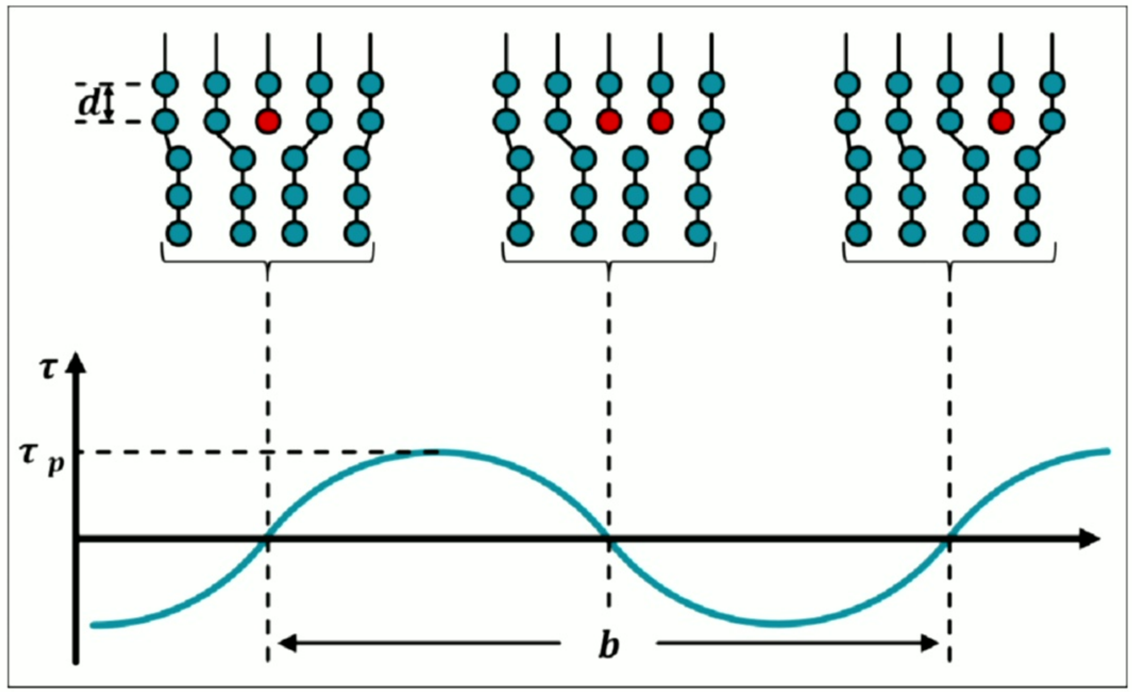


Peierls Stress and Deformation Motion

Peierls stress/potential: energy associated with moving dislocation forward one row of atoms

Modified in stress field





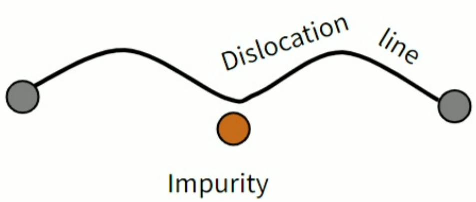
A Sketch of a Theory in Four Parts

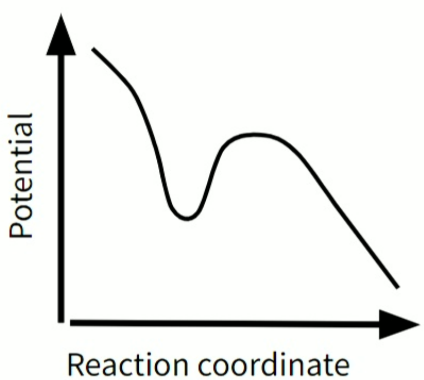
0) The setup (how the stress gets into the film)
1) How dislocations start moving
2) What happens when dislocations move (phonon emission)
3) Why the dislocations stop (energy scale)

Step One: Initial Motion of Dislocation

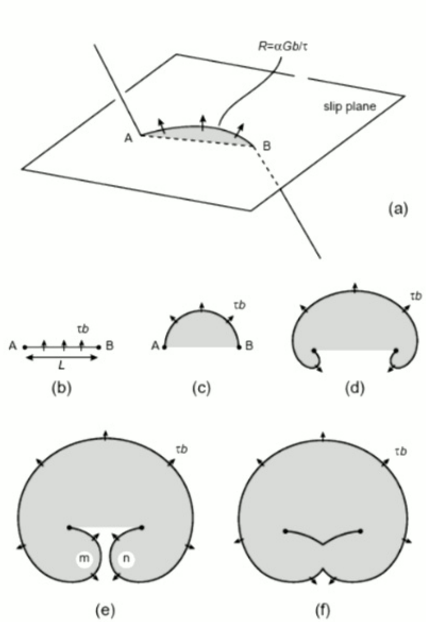
Two potential mechanisms:

Impurity pinning

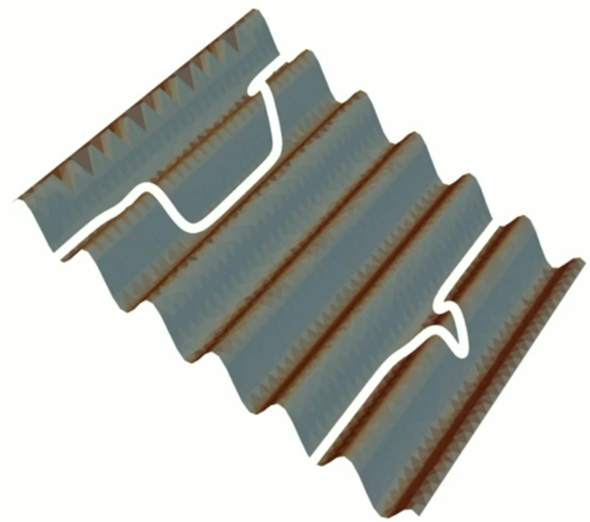




Tunneled Frank Reed Source Activation



"Introduction to Dislocations", D. Hull , and D. J. Bacon

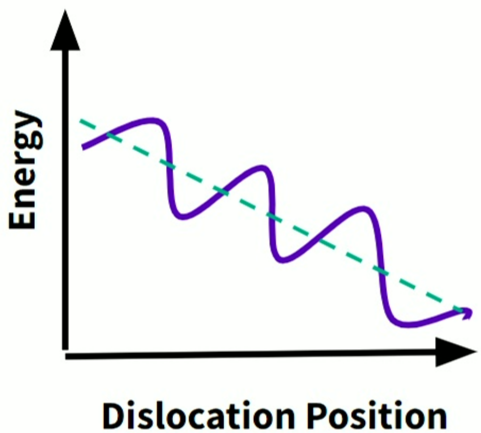


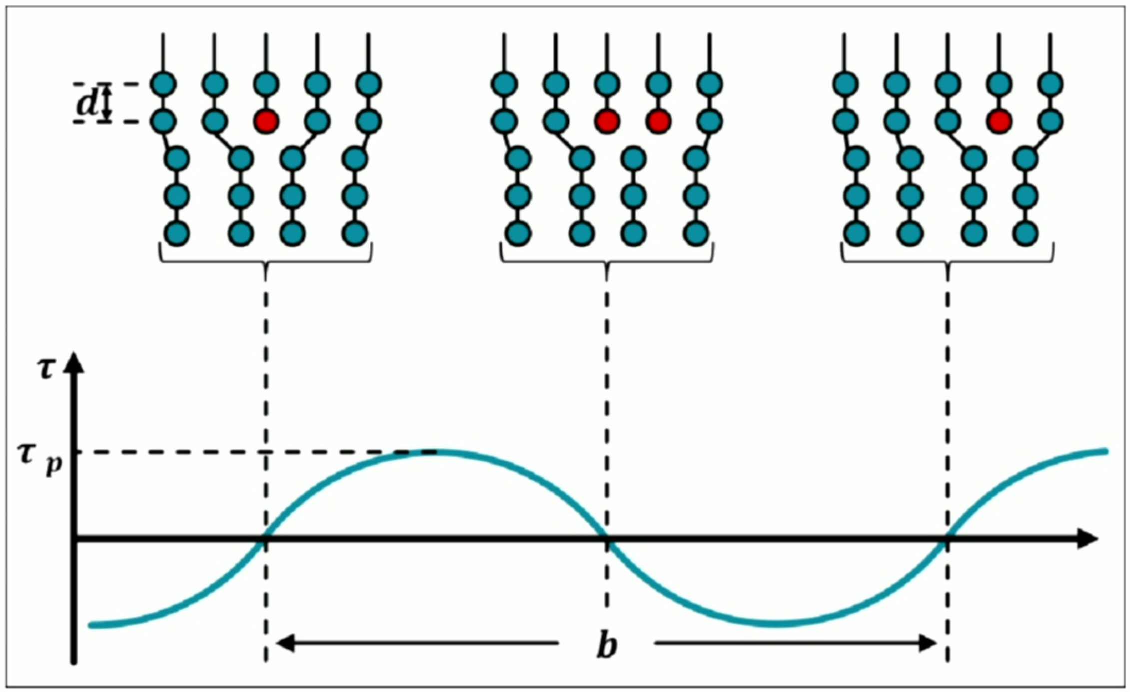
"Kink pair production and dislocation motion" Fitzgerald 2016

Peierls Stress and Deformation Motion

Peierls stress/potential: energy associated with moving dislocation forward one row of atoms

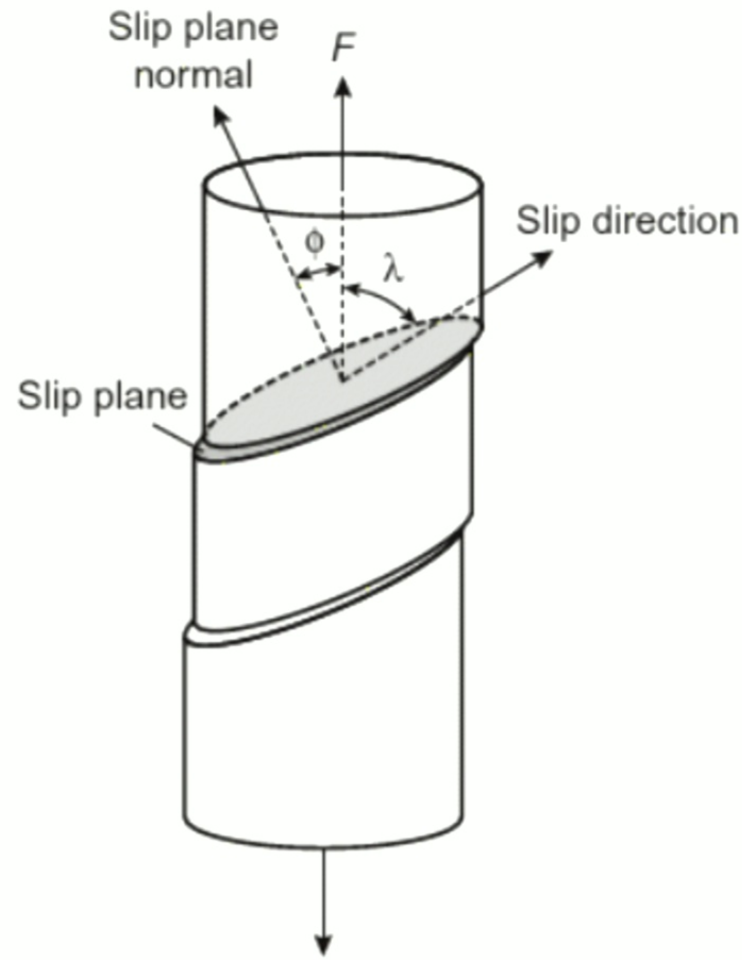
Modified in stress field





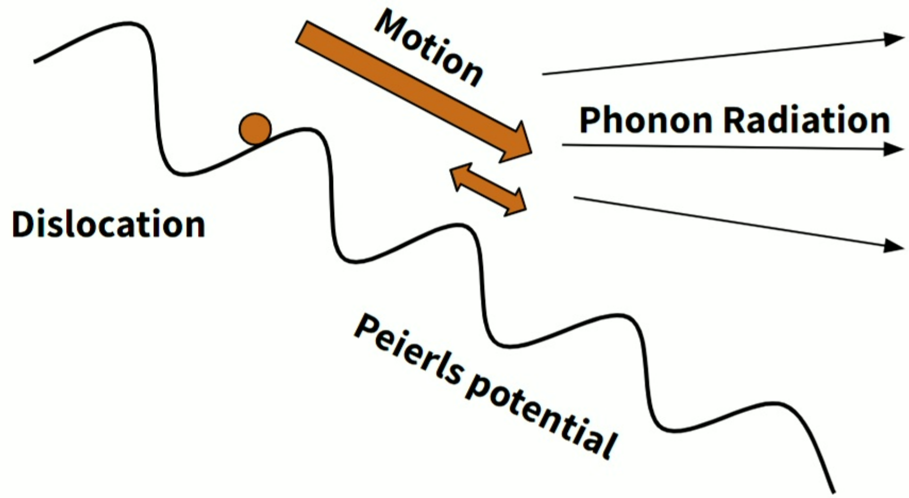
Step One: Stress Dependence

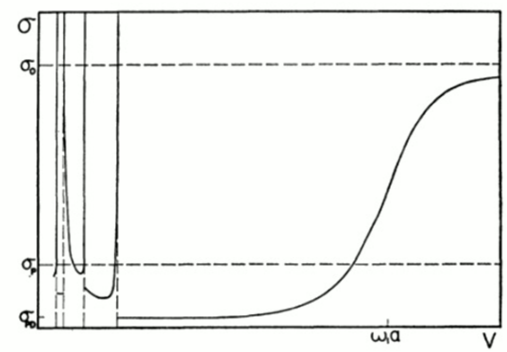
- Generically, tunneling from some kind of metastable state through a potential set by the stress experienced by the dislocation
  - From WKB, tunneling rate ~ exp(f(σ cos(ϕ)cos(λ)))
- Importantly, this is the resolved stress, i.e. stress in the direction dislocation can move set by crystallography
- Tunneling rate also varies site to site
  - Dislocation to impurity separation
  - Frank Reed source size
- In some ways, this makes more sense than a single exponential time constant… experiments don't see single time constant



Step Two: Dislocation Motion

- Forces acting on dislocation: stress field, “line tension,” drag
- Most drag terms (phonon wind interactions, electron interactions) frozen out
- One remaining: phonon radiation
- Dislocation accelerates backwards and forwards as it experiences Peierls potential
- Radiates phonons, main mode at ~ v/d, beamed forward, creates drag

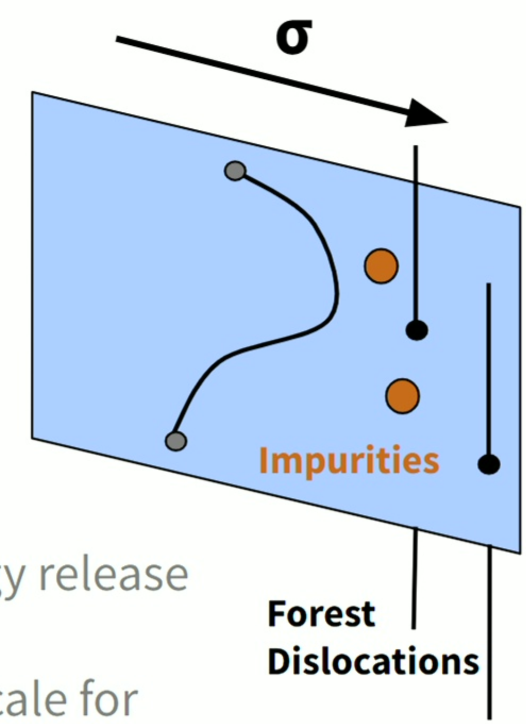




“Motion of a Frenkel-Kontorowa Dislocation in a One-Dimensional Crystal”, Atkinson and Cabrera 1964

Step Three: Dislocation Stops

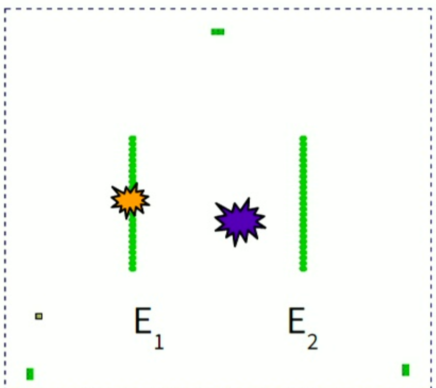
- Motion stops when dislocation hits:
  - Grain boundary (~200-600 nm)
  - "Forest Dislocation," i.e. dislocations in other planes
  - Strong impurity pinning site
  - FR source completes rotation
- Total energy release: σ b A
  - Forest dislocation density: $\sim 10^{14}$ m^{-2}, A = $\sim(100\ nm)^2$
  - Grain boundaries: ~ $(600\ nm)^2$
  - Impuries: ~ 10 ppm, range of ~ 10b, A = $\sim(24\ nm)^2$
- For σ = 10 MPa = $\sim 10\sigma_p$, A = $(100\ nm)^2$ 150 eV of energy release
  - Right around what we expect!
- Dislocation travels at $\sim c_s$ ~ 1000 m/s, gives ns timescale for phonon emission
  - Fast compared to detector response!

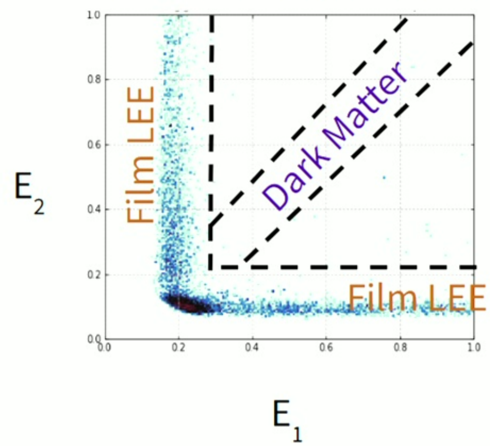


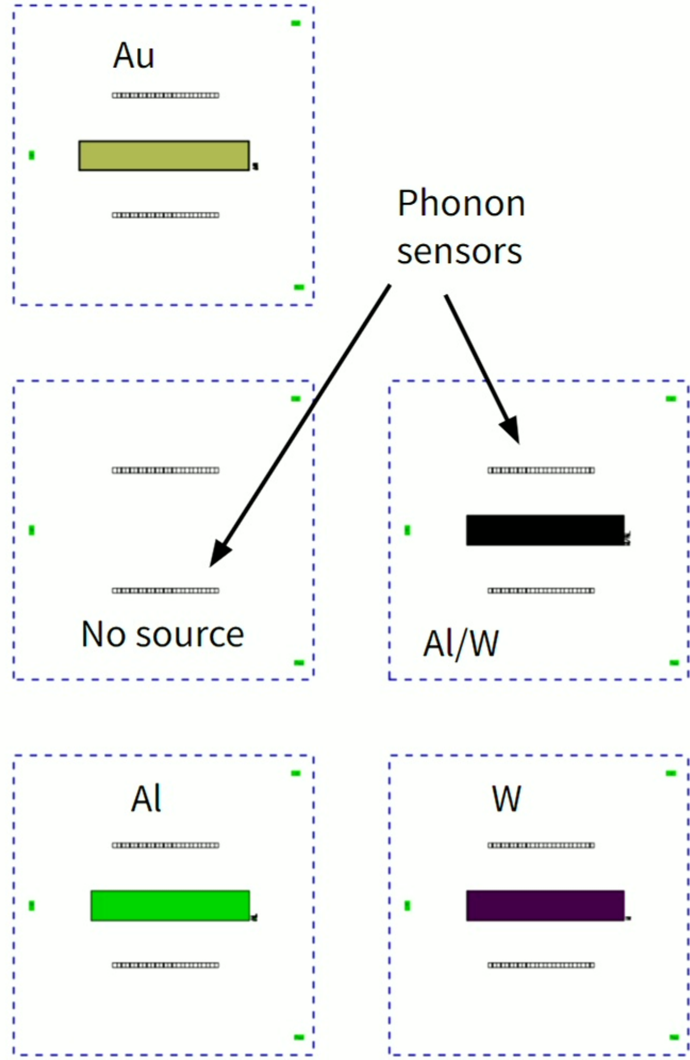
What do we do about it?

First, confirm story!

- More Al on a detector should make more LEE
- Fraction of LEE should be absorbed locally vs. globally
  - Use two channels to distinguish between film singles (LEE) and substrate events (DM)

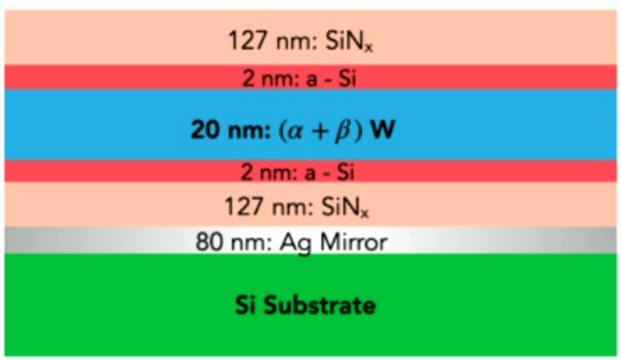




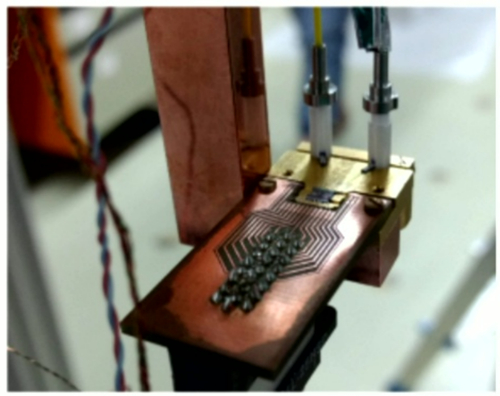


TESs in Optical Haloscopes?

- TESs with sub-eV resolution can detect photons in optical haloscope
  - Advantages: energy resolution(muon vs. haloscope), pulse shape discrimination (substrate/TES)
- Current standard in dark counts ALPS II: ~$6*10^{-6}$ s^{-1}, including PSD/energy discrimination techniques
- SNSPDs have similar performance, ~$6*10^{-6}$ in LAMPOST, s^{-1}



(a)

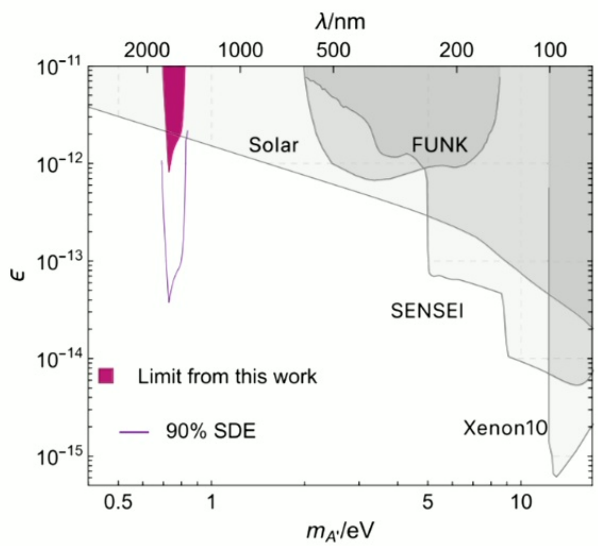


(b)

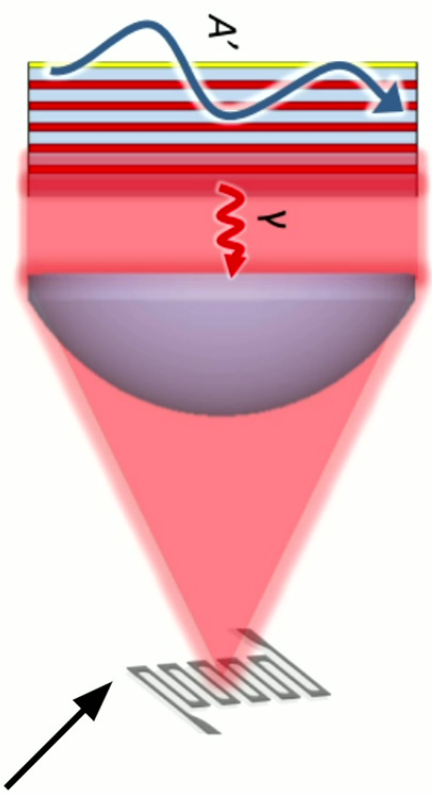
"Characterising a Single-Photon Detector for ALPS II", Shah et. al. 2022

Aside: Dark Counts in Optical Haloscopes

- Haloscope: DM converts to photons in dielectric stack
- Detect photons with low dark rate counter
  - Photons at the ~eV energy range
  - LAMPOST uses SNSPDs currently as “single click” photon counter



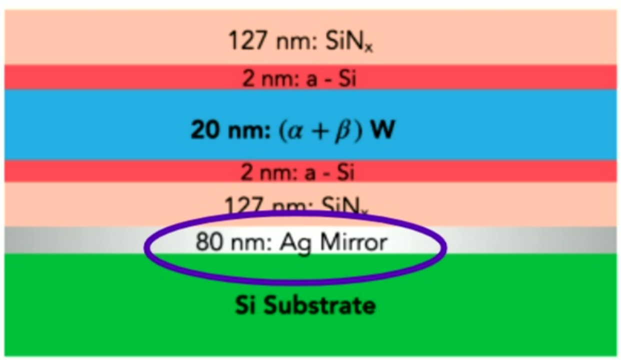
“New Constraints on Dark Photon Dark Matter with Superconducting Nanowire Detectors in an Optical Haloscope” Chiles et. al. 2022



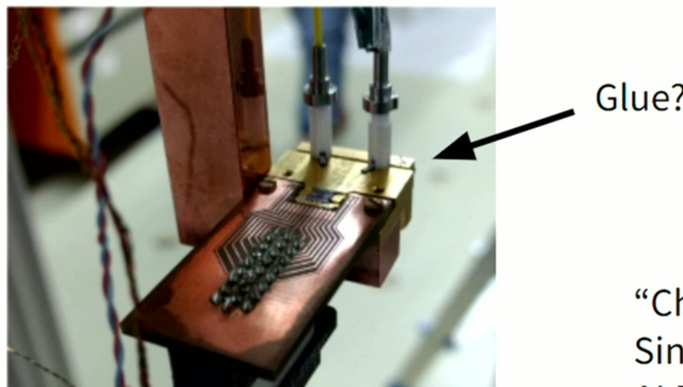
SNSPD (could be replaced by TES)

Dark Counts in TESs for Optical Haloscopes: Stress Backgrounds?

- TES dark counts may be stress backgrounds!
  - Glue holding TES chips down? (Potential for 200x worse performance!)
  - FCC metals in chip (Al readout wiring, Ag mirror plane)
- Reduce stress backgrounds, reduce dark counts
- Benefit from TES PSD and energy resolution, better haloscope search



(a)



(b)

"Characterising a Single-Photon Detector for ALPS II", Shah et. al. 2022

Decoherence in Superconducting Qubits

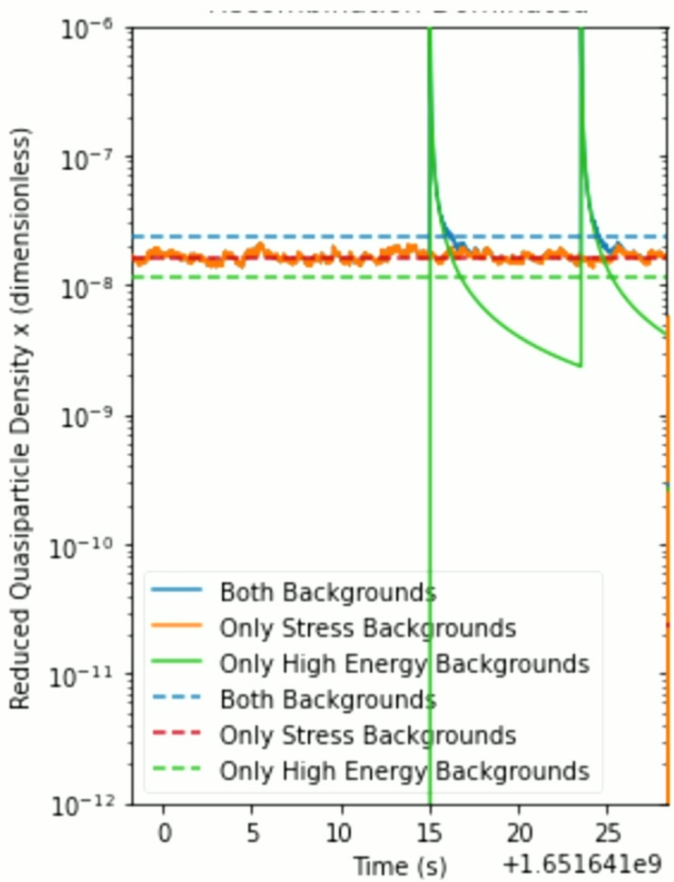
Two Key Problems in SC Qubit Performance

- Key figure of merit: Gate Fidelity = 1 - (Gate Time)/(Coherence Time)
- Coherence time limited by:
- Quasiparticle poisoning:
    - QPs appear in superconducting qubit near JJ, decohere qubit
    - Density of QPs falls off with time
- Two Level Systems (TLSs):
    - Qubit becomes entangled with TLS, decoheres
    - Caused by impurities introduced in fab… but some other source seems likely as well
    - Stressing qubit materials changes energy splitting of TLS

Stress can play a role in both!

Quasiparticle Poisoning: Stress Worse than Cosmics

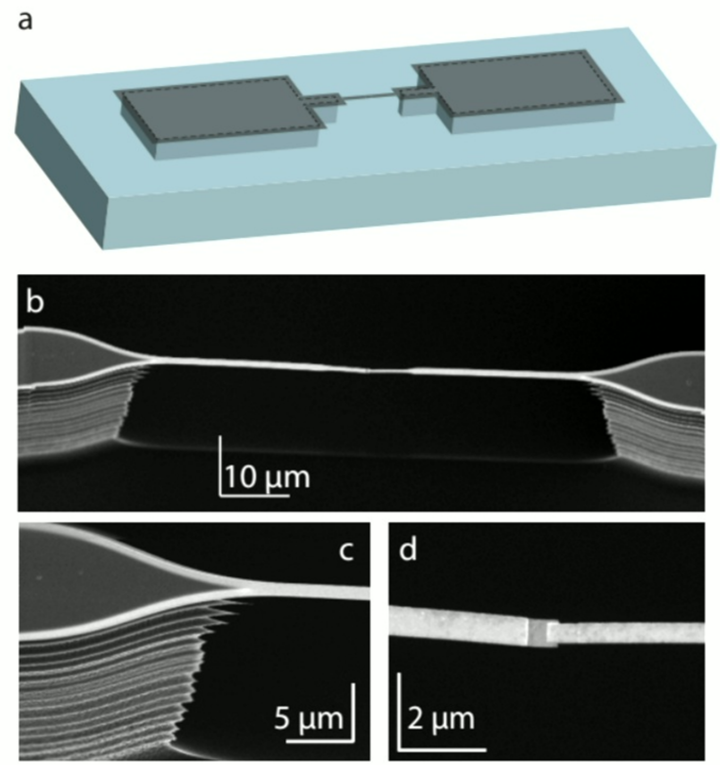
- QP dynamics in many qubits recombination dominate:
  - QPs die away quickly at high densities, stick around at low densities
- Cosmic rays, radiobackgrounds, etc.: infrequent big bursts
- Stress events: very frequent, small bursts
- Simulation based on actual events seen in high stress device from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



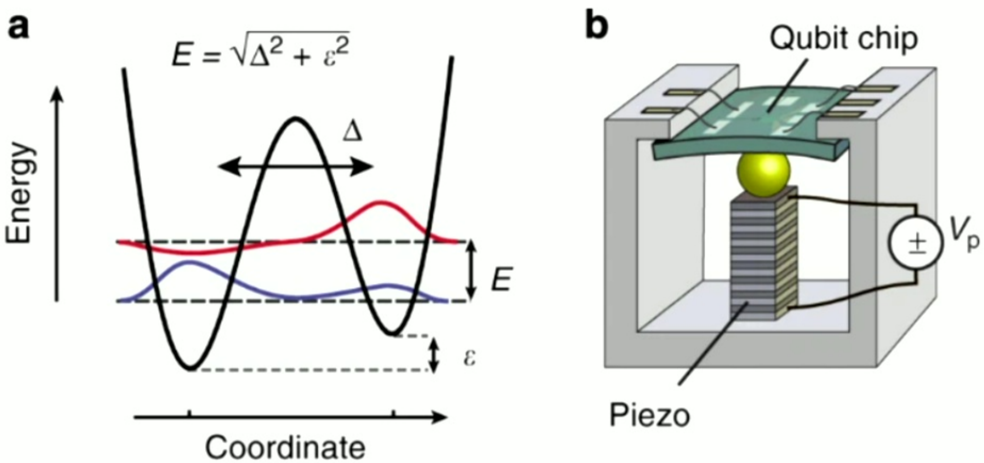
QP Poisoning: Stress From Detector Materials?

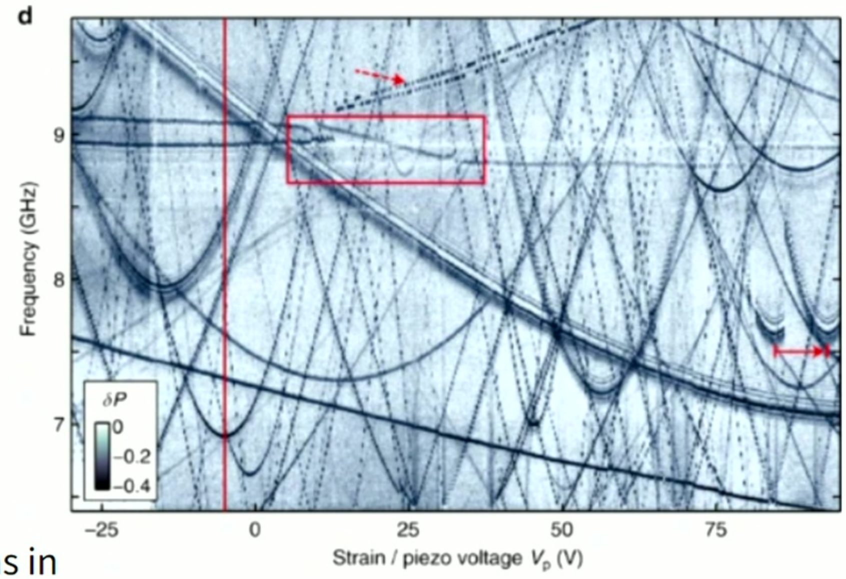
- Evidence from DM experiments: stress from films on detector surfaces creates phonons
- Naturally get very high yields of phonons -> QPs
- Ways to solve:
    - Different materials (BCC metals, like Nb) with less thermal contraction, higher yields
    - Different grain structures with higher yields
    - Unsupported qubits: no contraction relative to Si underlayer, no stress!
    - Can't do this in DM experiments
    - Has been tried in qubits, but wrong geometry

"Suspending superconducting qubits by silicon micromachining" Chu et. al. 2015



Two Level Systems: Stress/Strain Coupling

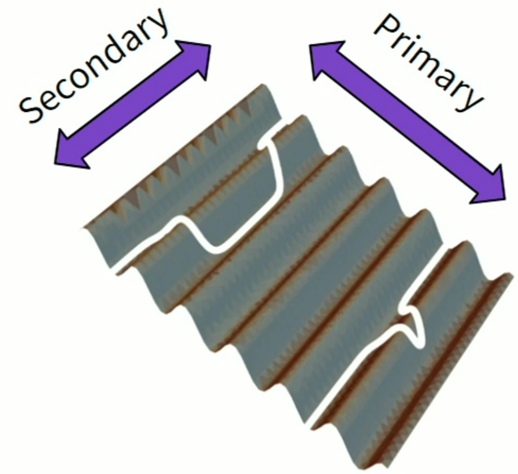




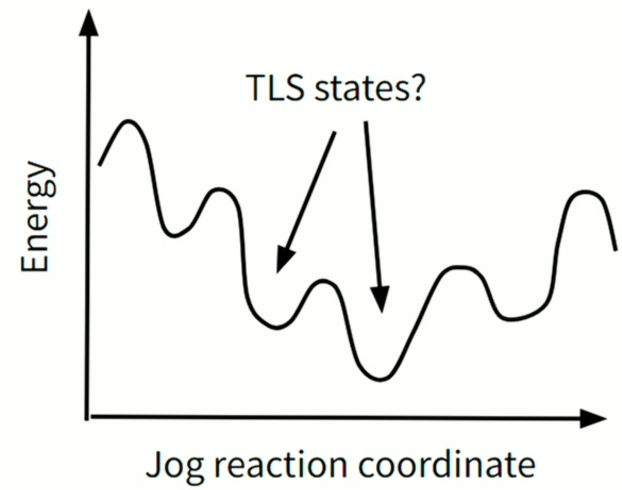
"Observation of directly interacting coherent two-level systems in an amorphous material" Lisenfeld et. al., 2015

TLSs move with warmup too

Strain in Aluminum Could be Source!



- Clearly not only source… (others include impurities left over from fab)
- Tunneling dislocations
  - Obvious coupling to stress/strain
  - Motion of atoms: dipole moment?
- In copper (FCC metal similar to aluminum), dislocations have shown to easily tunnel between minima in the *secondary* Peierls potential
  - "Calculation of quantum tunneling for a spatially extended defect: The dislocation kink in copper has a low effective mass", Vegge et. al. 2001
- Perhaps worth further thought

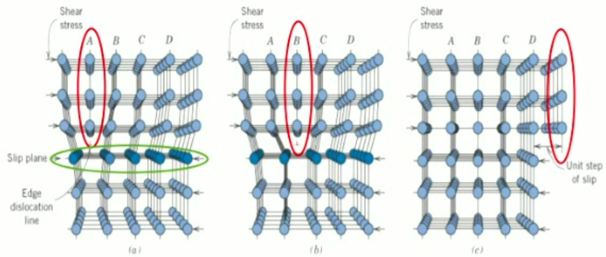


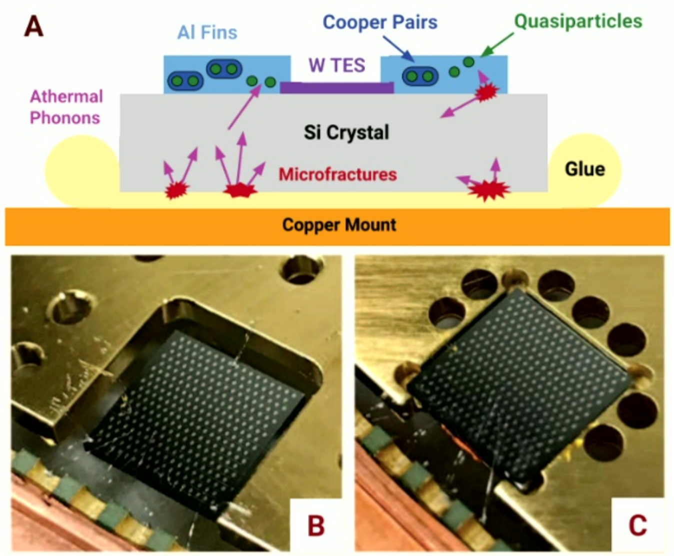
Summary: Stress in Superconducting Qubits

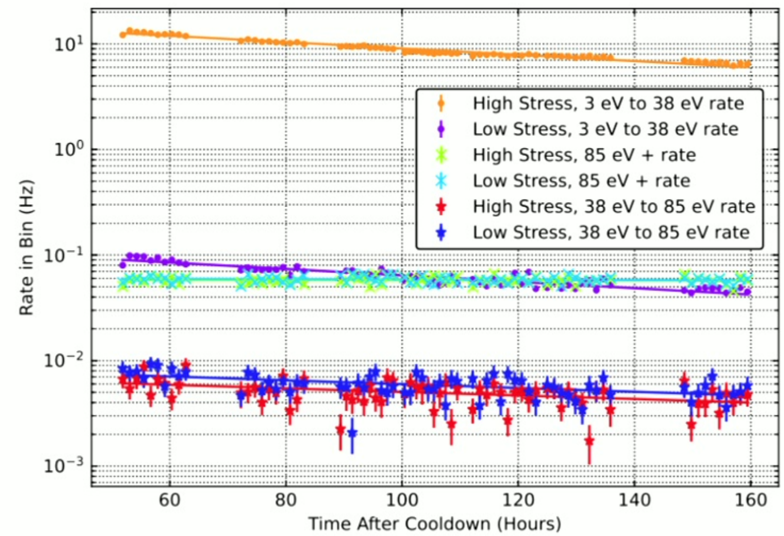
Two big problems: Quasiparticle Poisoning and TLSs

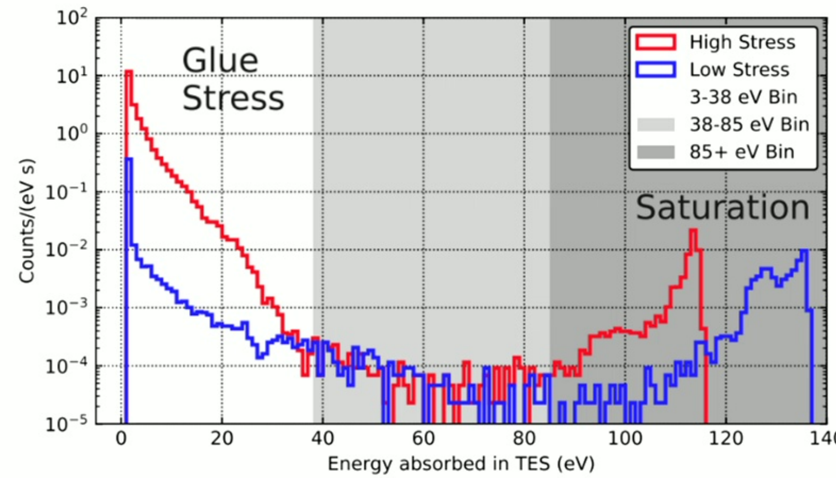
- Stress can be the dominant phonon and therefore QP background (depending on the exact experimental setup and QP dynamics in qubit superconductors)
  - Stress in mounting scheme (don't use glue/grease!) is important
  - Stress in qubit materials (especially Al near junction) is also likely important
  - Lots of interesting tricks to think about, suspending junctions, different materials…
- Dislocation tunneling may be part of the TLS population qubits see
  - Key question: does the system have electronic coupling?
  - Natural strain coupling, changes to system after warm up…

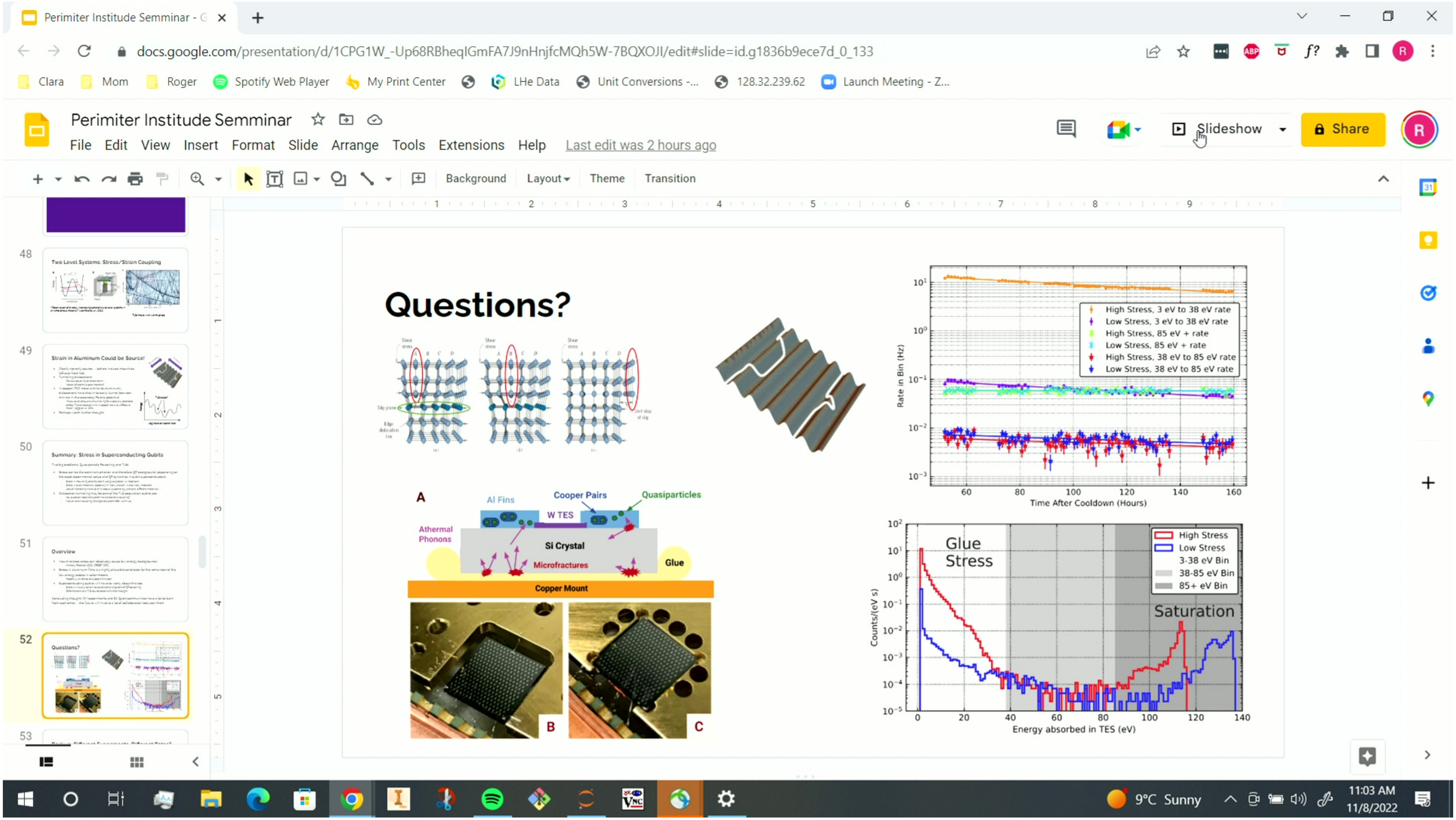
Questions?


Shear stress
Slip plane
Edge dislocation line
Unit step of slip


A
Al Fins
Cooper Pairs
Quasiparticles
W TES
Athermal Phonons
Si Crystal
Microfractures
Glue
Copper Mount
B
C


High Stress, 3 eV to 38 eV rate
Low Stress, 3 eV to 38 eV rate
High Stress, 85 eV + rate
Low Stress, 85 eV + rate
High Stress, 38 eV to 85 eV rate
Low Stress, 38 eV to 85 eV rate
Rate in Bin (Hz)
Time After Cooldown (Hours)


Glue Stress
Saturation
High Stress
Low Stress
3-38 eV Bin
38-85 eV Bin
85+ eV Bin
Counts/(eV s)
Energy absorbed in TES (eV)



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File Edit View Insert Format Slide Arrange Tools Extensions Help
Last edit was 2 hours ago
Slideshow
Share
Background Layout Theme Transition
Questions?
A
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High Stress, 3 eV to 38 eV rate
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Rate in Bin (Hz)
Time After Cooldown (Hours)
Glue Stress
Saturation
High Stress
Low Stress
3-38 eV Bin
38-85 eV Bin
85+ eV Bin
Counts/(eV s)
Energy absorbed in TES (eV)
9°C Sunny
11:03 AM
11/8/2022