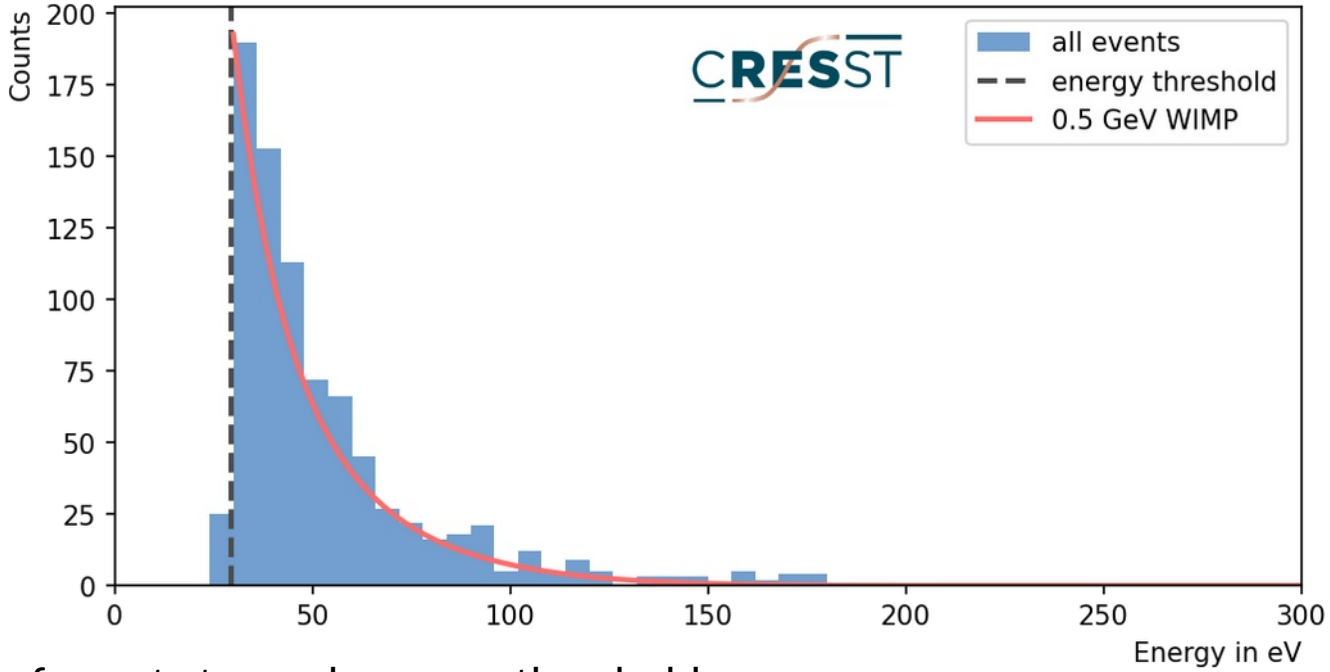
EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Low Energy Excess(es) in Cryogenic Detectors

Christian Strandhagen
University Tübingen

The Low Energy Excess



Phys. Rev. D 100, 102002 (2019)

- **steep rise** of events towards energy threshold
- shape similar to light DM or CEvNS signal → severely **impacts sensitivity**

EXCESS Workshop Series

- workshop series started in 2021 bringing together experiments & experts from other communities
- 5th iteration took place on Saturday in Rome

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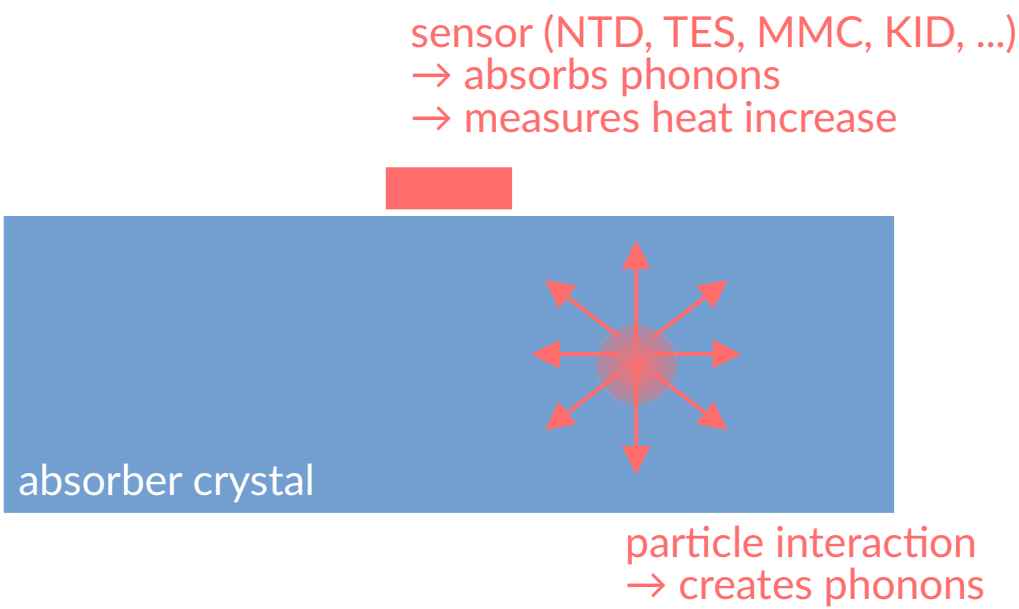
Slides from previous EXCESS workshops

- https://indico.cern.ch/event/1013203/
- https://indico.scc.kit.edu/event/2575/
- https://indico.cern.ch/event/1117540/
- https://indico.cern.ch/event/1213348/
- https://agenda.infn.it/event/39007/

- Basics of **Cryogenic Detectors**
- **Observations** of the Low Energy Excess
- **Ideas** about its Origin
- Experimental **Strategies**

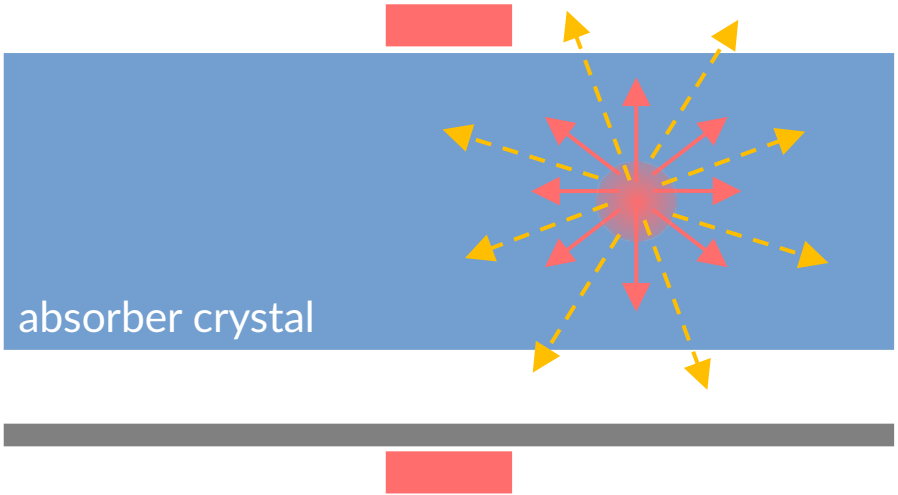
Cryogenic Detectors



- phonon signal gives very precise measure of total deposited energy
- demonstrated energy thresholds of few eV for gram-scale detectors

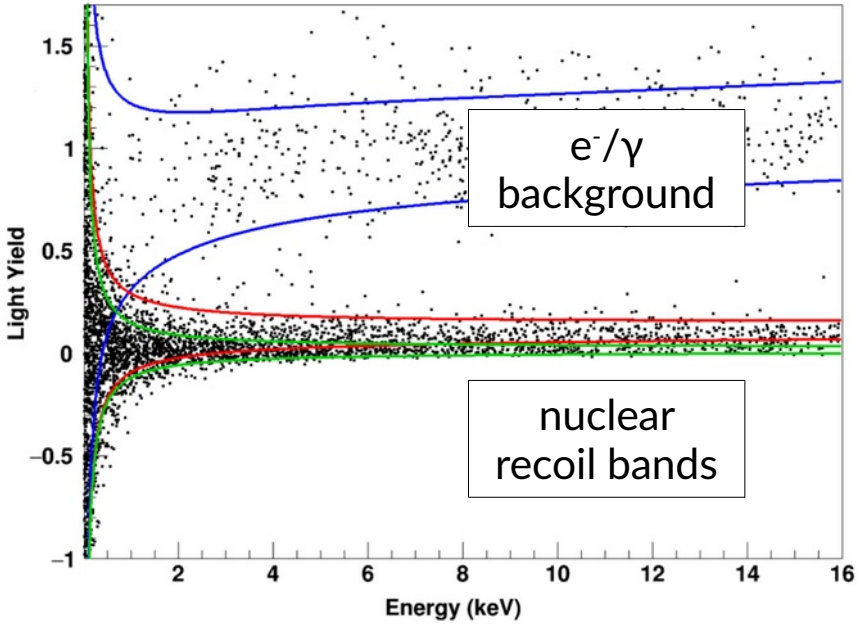
Cryogenic Detectors

sensor (NTD, TES, MMC, KID, ...)
→ absorbs phonons
→ measures heat increase



scintillating absorbers create photons
→ detected in secondary detector

- enables particle identification



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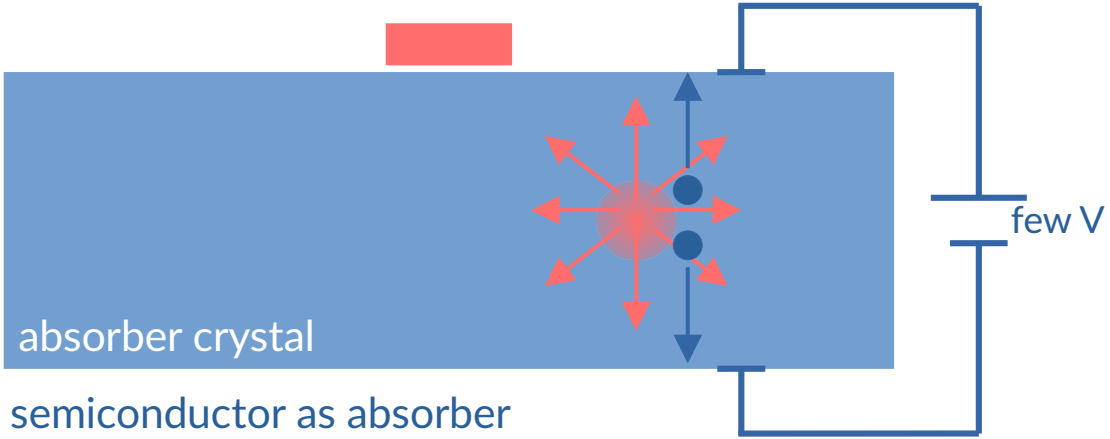
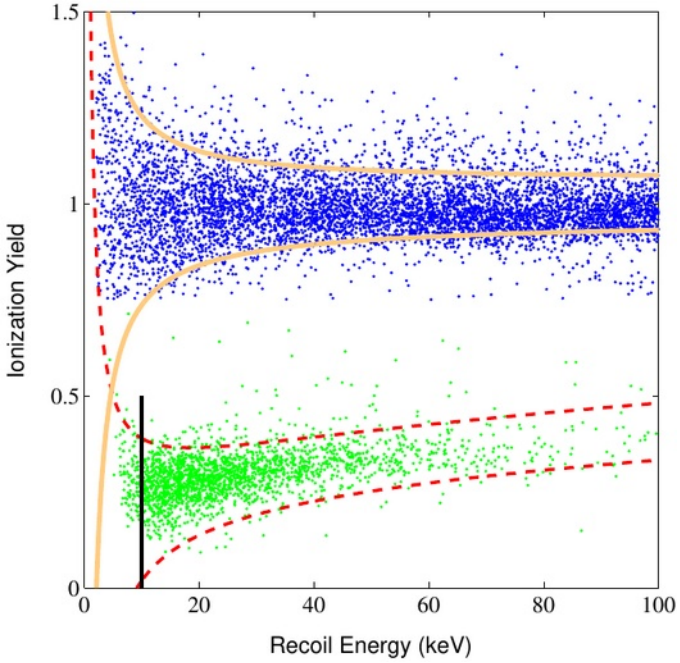


semiconductor as absorber
→ interaction creates charges
→ measure ionization

- enables particle identification



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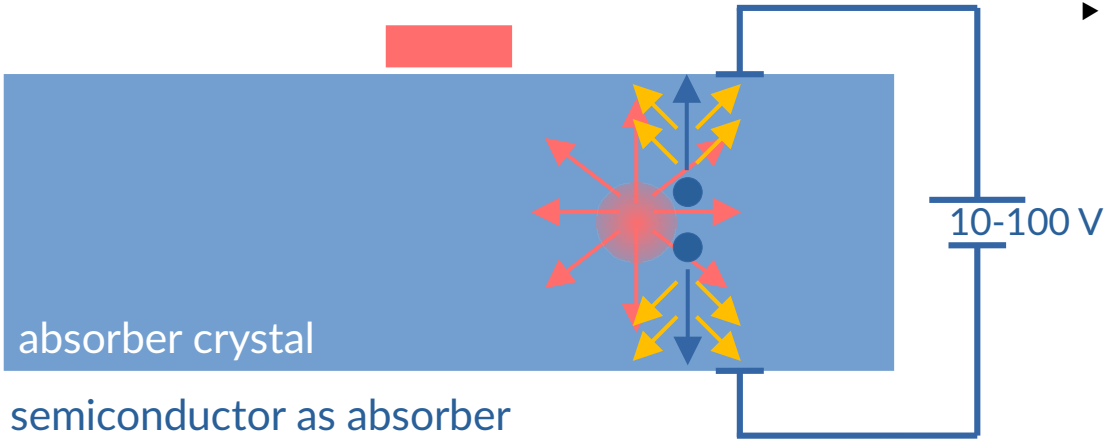
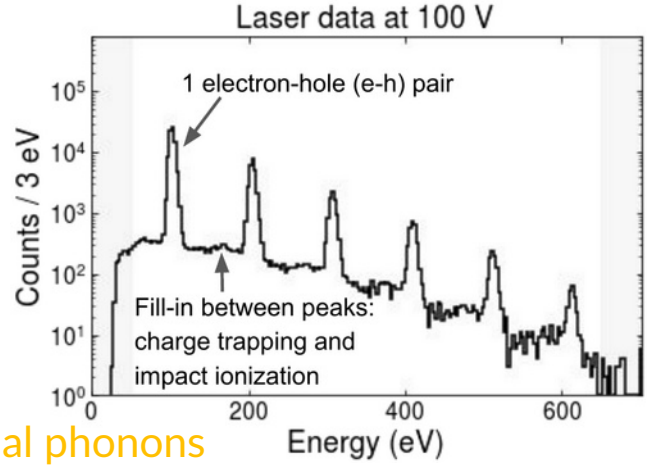


semiconductor as absorber
→ interaction creates charges
→ measure ionization

moving charges create additional phonons
→ amplification of signals with ionization
("Neganov-Trofimov-Luke effect")

- high voltage mode foregoes particle identifications
- sensitivity to single e^- signals



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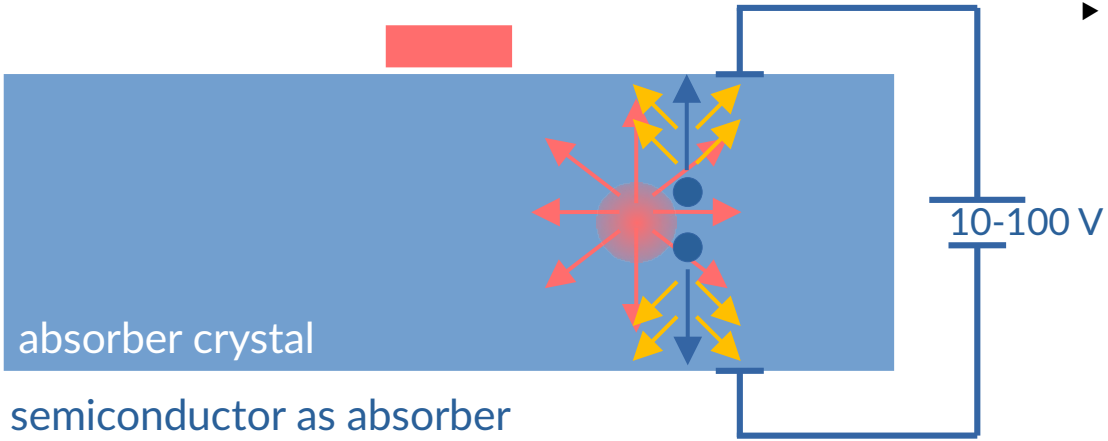

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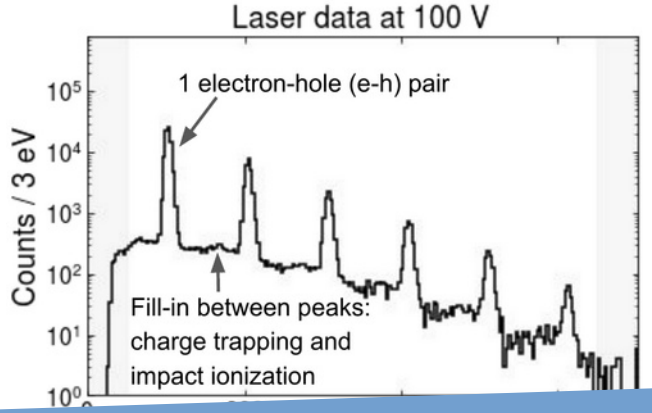
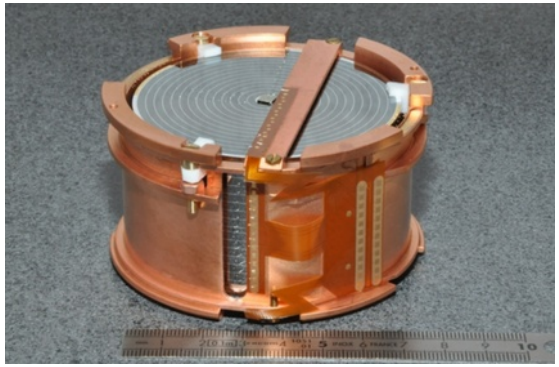


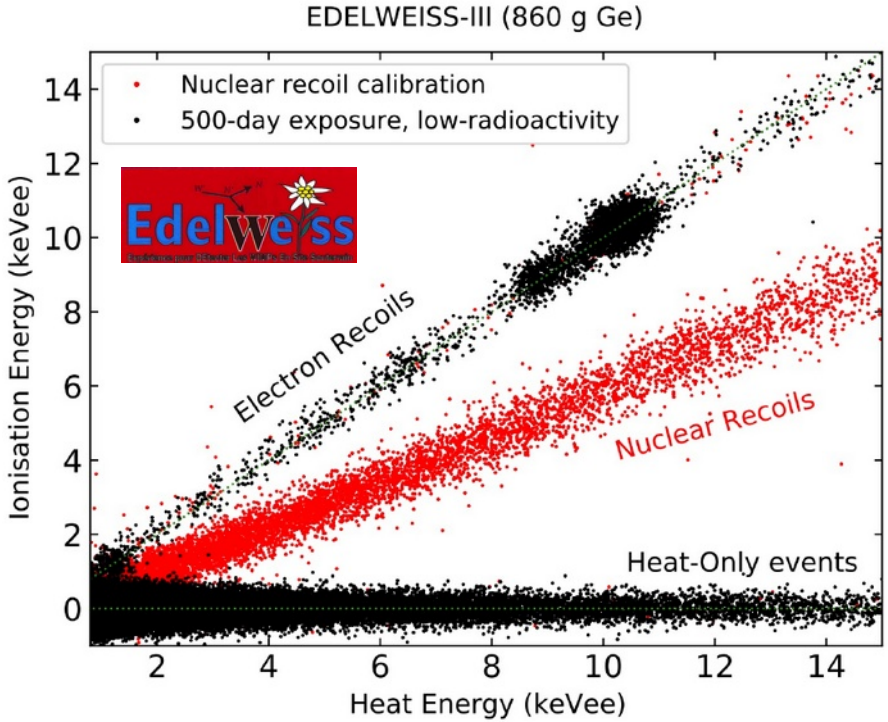
see talk by Matthew Wilson (Tue 15.00)

and poster by Kyle Kennard

LEE is not ionizing

- EDELWEISS reads out heat/phonons (via NTD) and ionization
- background population **without charge** signal extending to high energies





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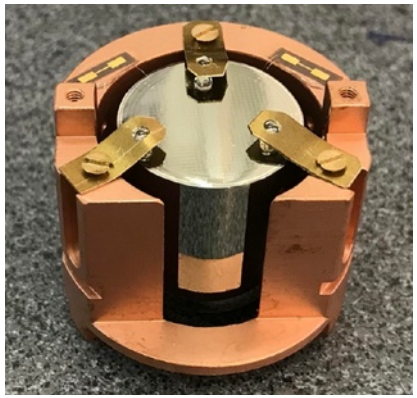
- NTL amplification does not affect LEE



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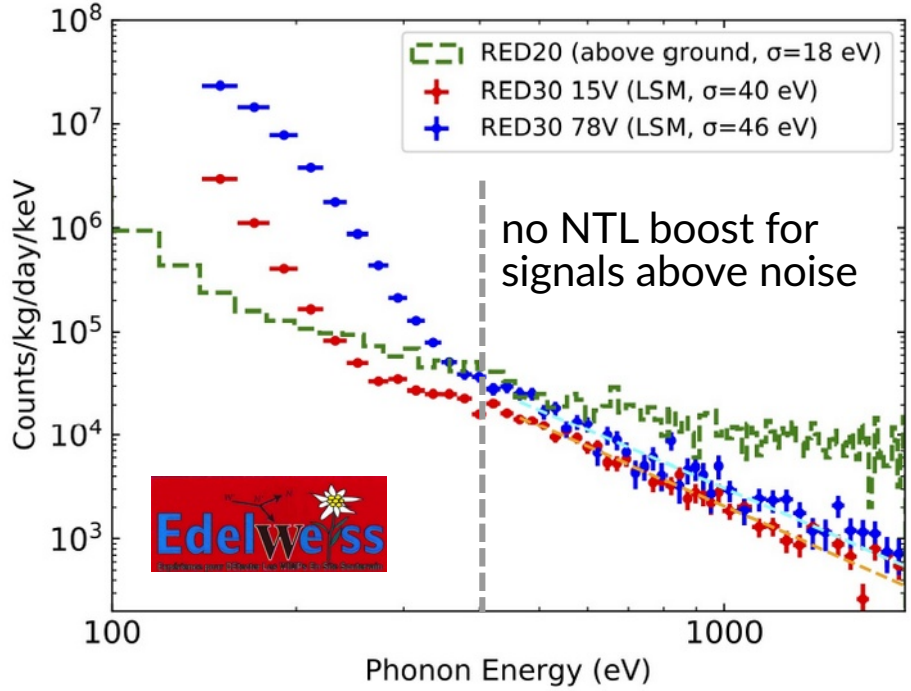
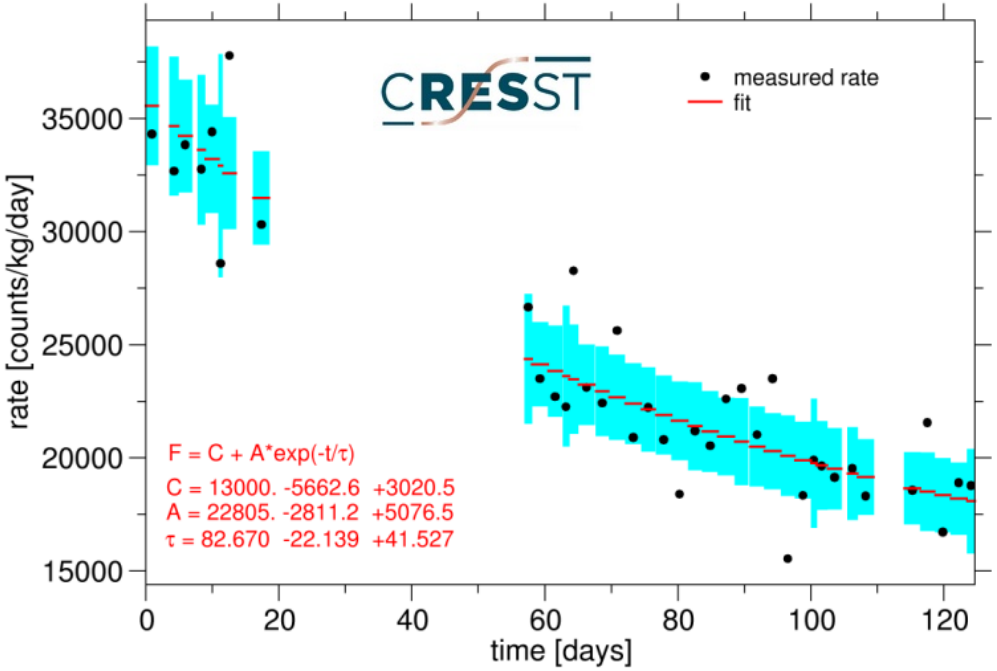
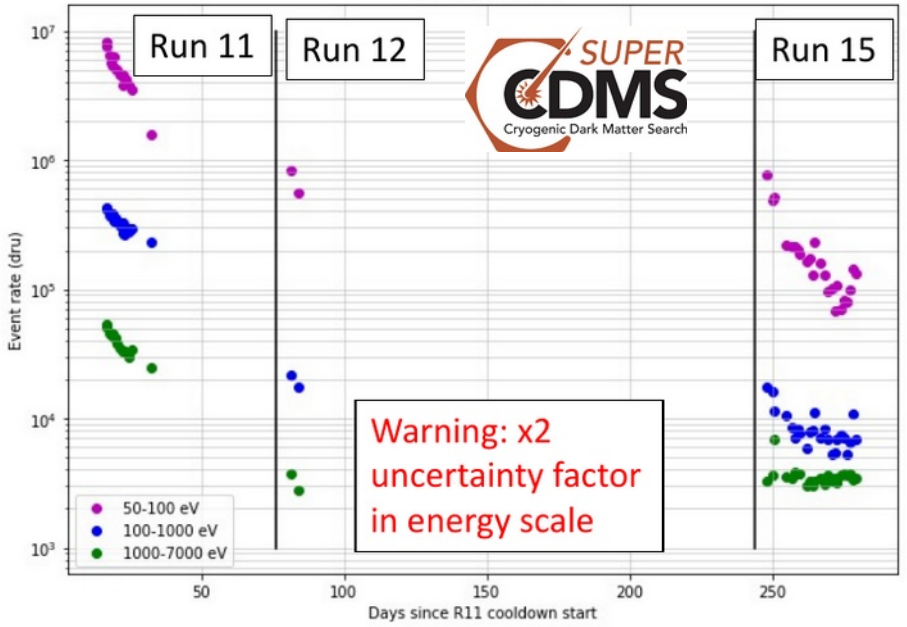


LEE decreases over time

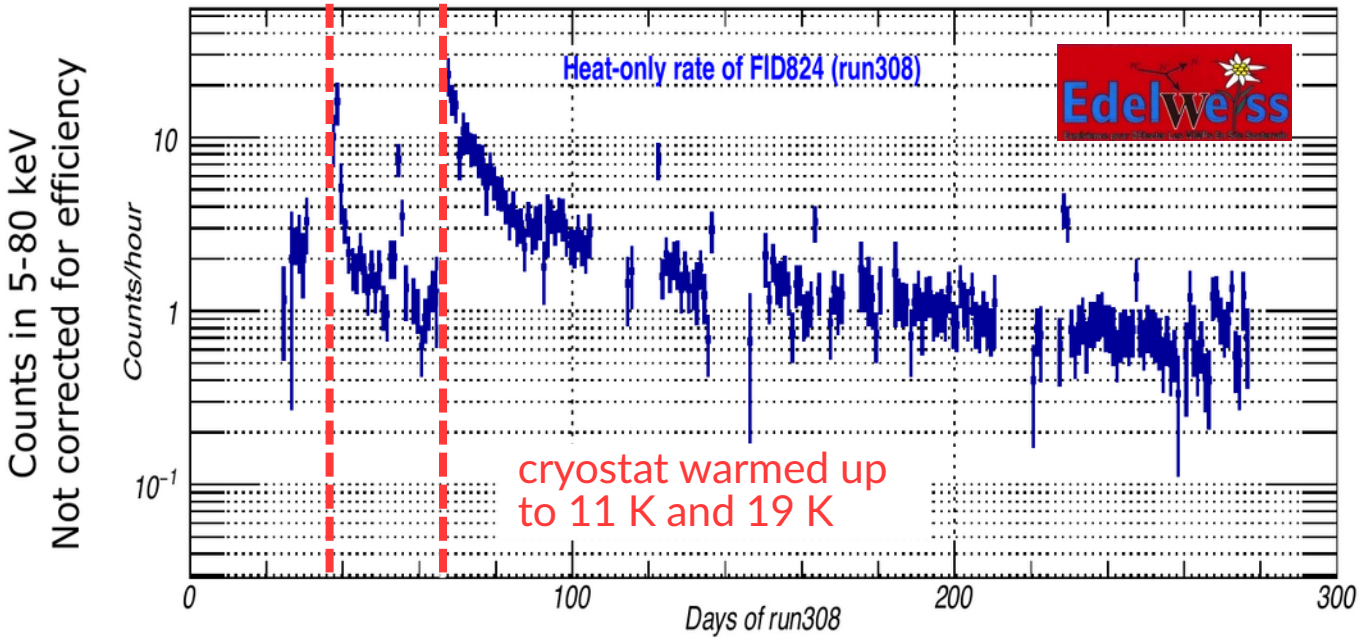




- several observations across different experiments that **LEE rate decreases over time**

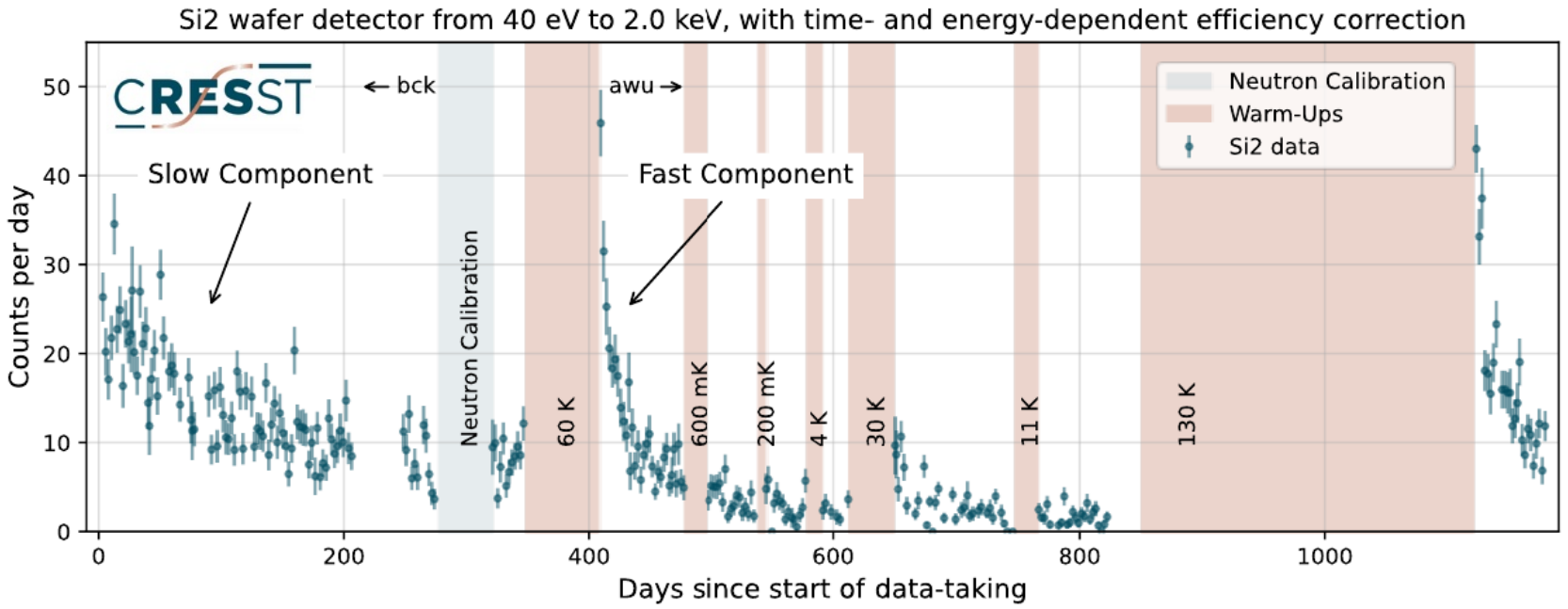
LEE can be reactivated with thermal cycles

- after temporary **warm-ups** of the cryostat, the **LEE rate increases sharply**
- induced rate decreases again rather quickly



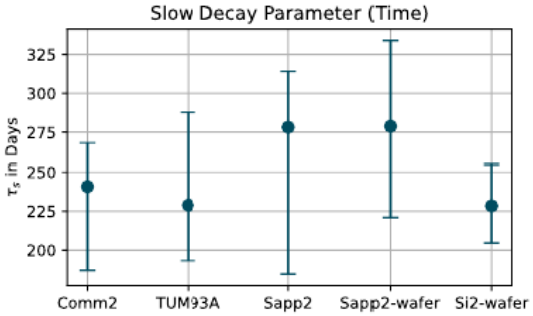
LEE can be reactivated with thermal cycles

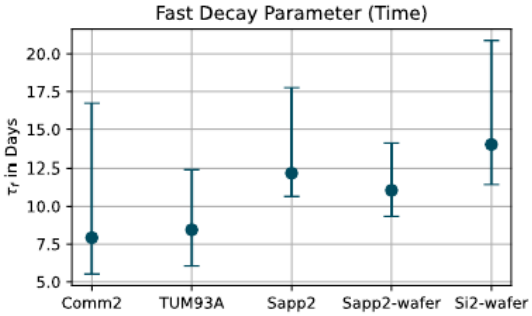
- studied in detail by CRESST over the past three years
- **several thermal cycles** to different temperatures with varying length

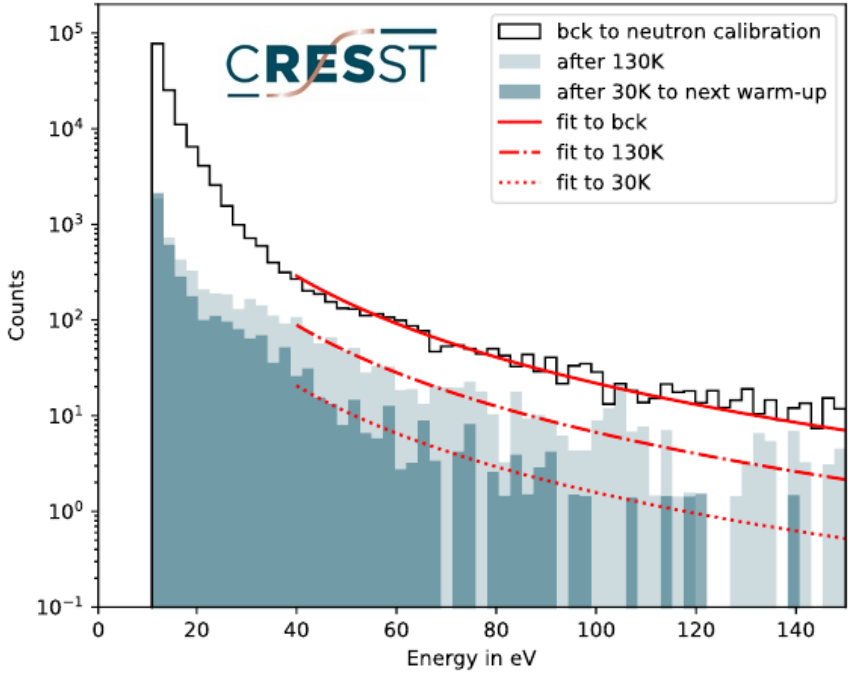


LEE can be reactivated with thermal cycles

- consistent model above ~ 40 eV:
  - LEE has **fast (~ 10 days)** and **slow (~ 250 days)** component
  - both can be modeled in energy by the same **power law**
  - decay times are similar between detectors with different materials and geometries







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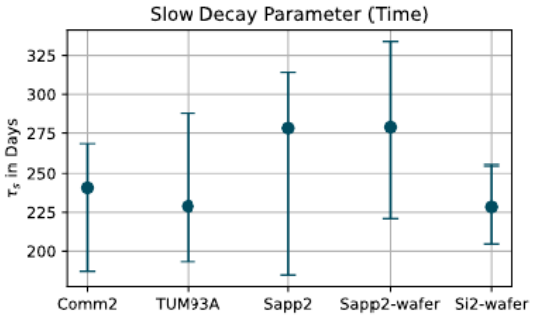
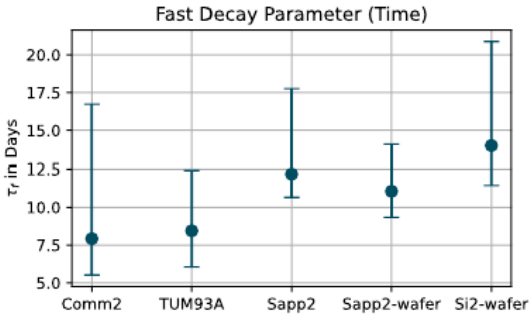
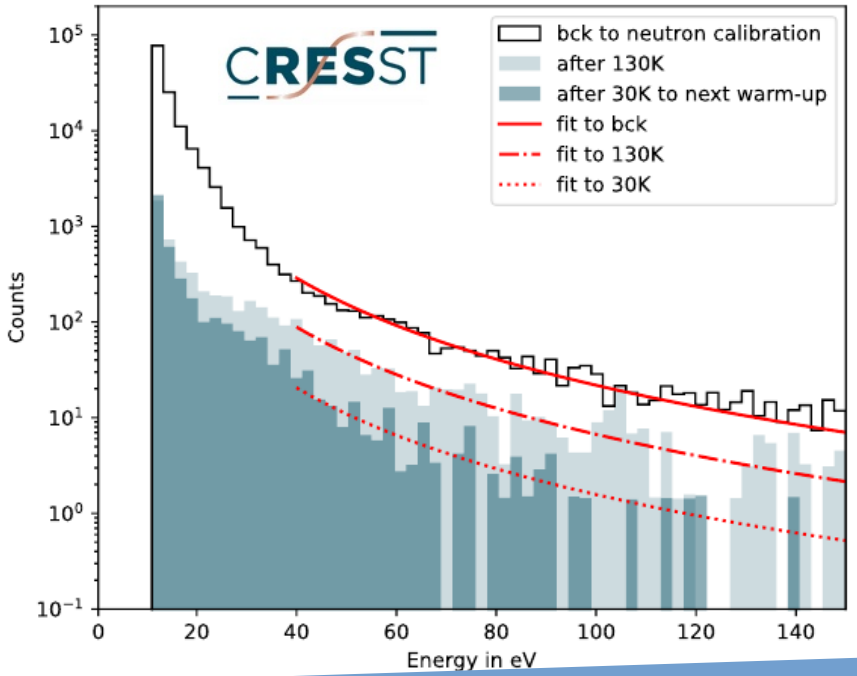






see poster by Sarah Kuckuk

Ideas about the origin of the LEE

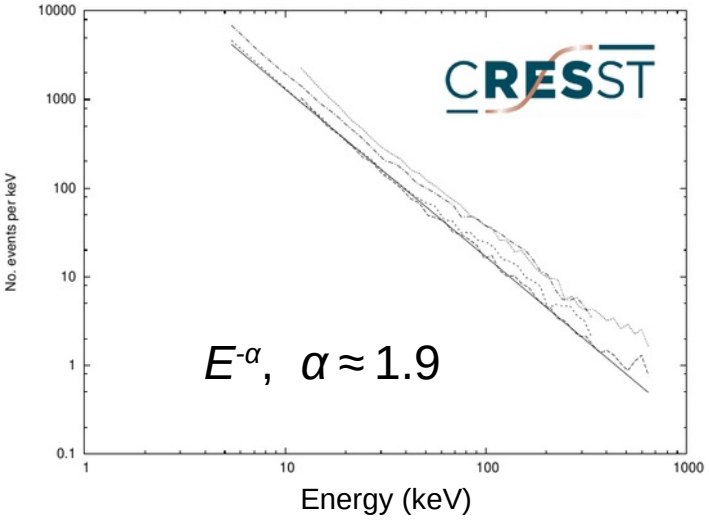
- lack of ionization and time behavior strongly **disfavors particle origin**
- favored explanation by the community – energy release through relaxation processes

Three main categories:

- Stress induced by the **holding structure**
- **Intrinsic stress** from the bulk material
- Stress in the **sensors** or the **interface to the sensors**

External stress can cause LEE

- CRESST-I observed a large rate of events following the **pattern of earthquakes** (bursts)
- could be attributed to **macroscopic cracks** caused by the clamps holding the sapphire crystals
  → visible under microscope

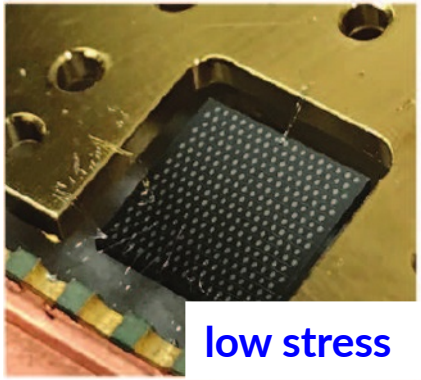


- energies extend to MeV and follow **power law**
- reducing clamp pressure eliminated the events

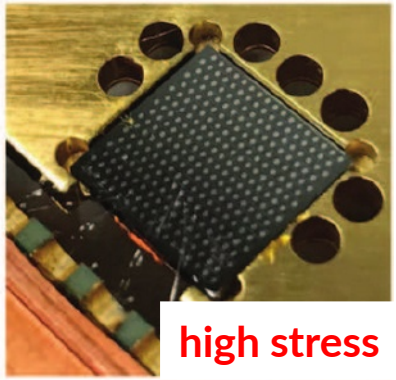
Phys.Lett. A356 (2006) 262-266

External stress can cause LEE

- SPICE performed a dedicated test with two identical detectors
  - one was **glued** to the copper holding
    → **high stress**
  - the other was **hanging from bond wires**
    → **low stress**
- significantly higher LEE for glued detector

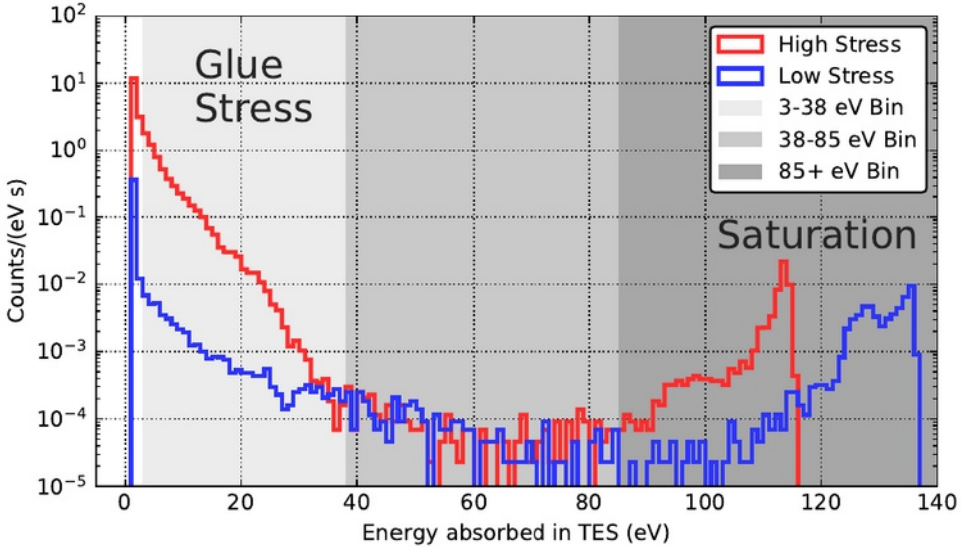


low stress



high stress

arXiv:2208.02790



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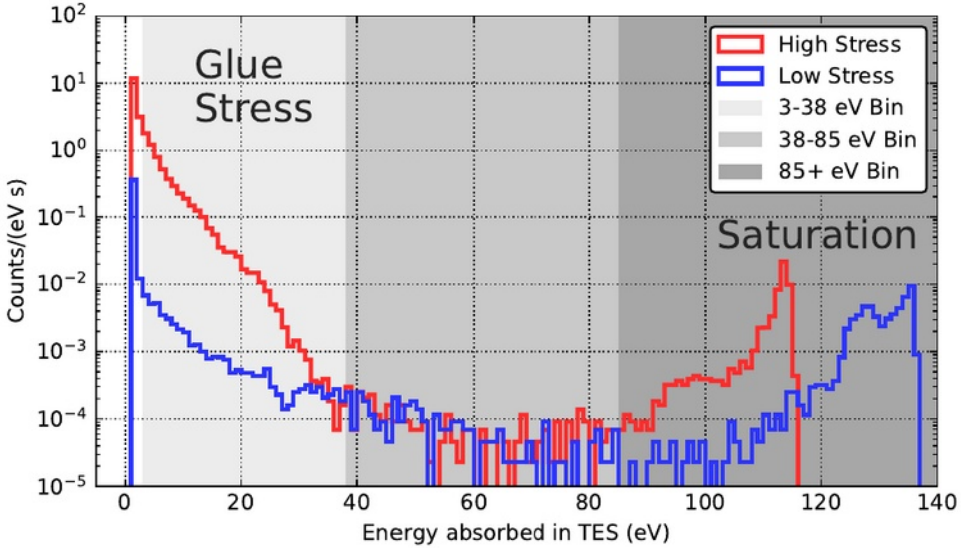
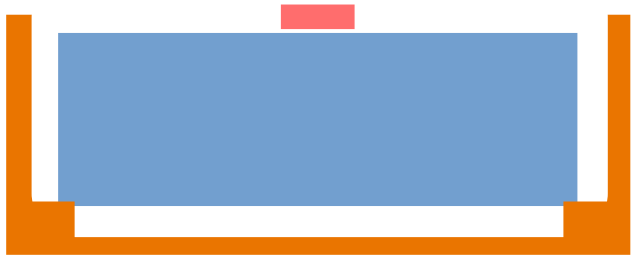


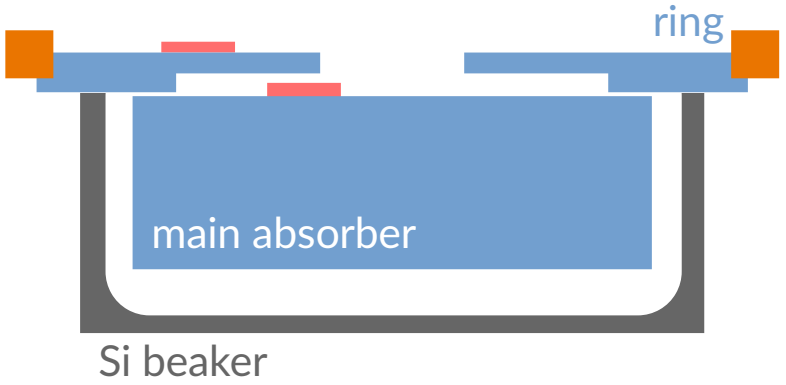
see talk by Roger Romani (Thu 15.00)

Mitigation of holder stress in CRESST

- let **absorbers rest** on minimal amount of copper (“gravity-assisted holding”)
  → **no clamp pressure**

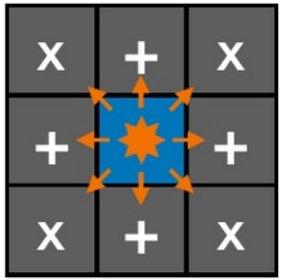


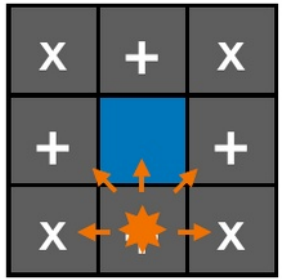
- **identify holder events**
  → “mini-beaker module”
  - holder events happen only in ring
  - veto with different signal distribution in ring and absorber

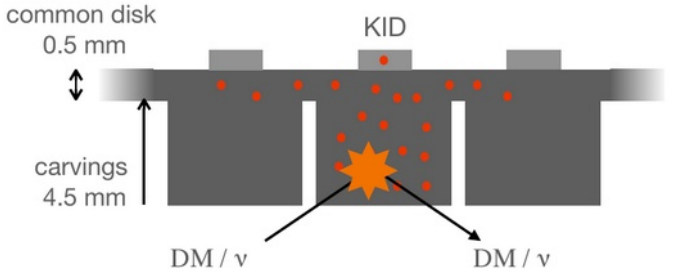


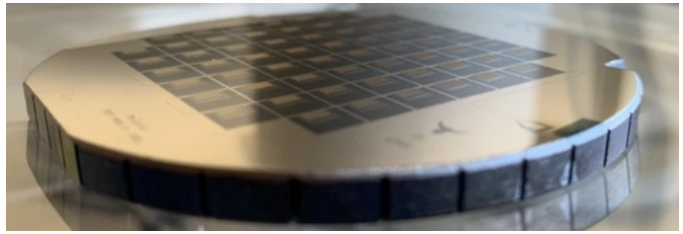
BULLKID

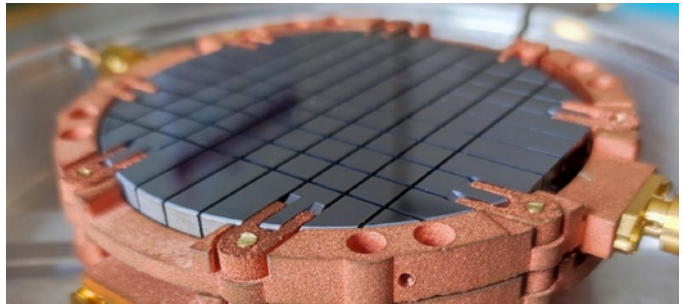
- 60 voxels created by cutting grooves in 5 mm thick 3” silicon wafer
  → “no holder” for individual voxels
- read out by kinetic inductance (KID) sensors
  → can be easily multiplexed
- identify interaction voxel by looking at signal leakage in neighboring voxels





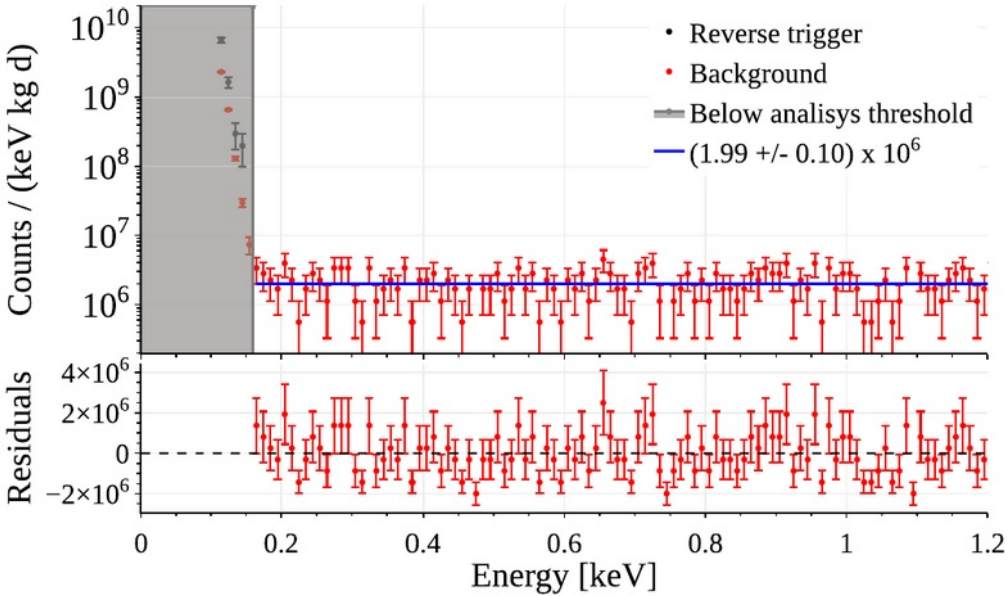






BULLKID

Eur. Phys. J. C 84 (2024) 353



- first prototype measurement above ground shows **no LEE above** analysis threshold of **160 eV**
- events below are compatible with noise

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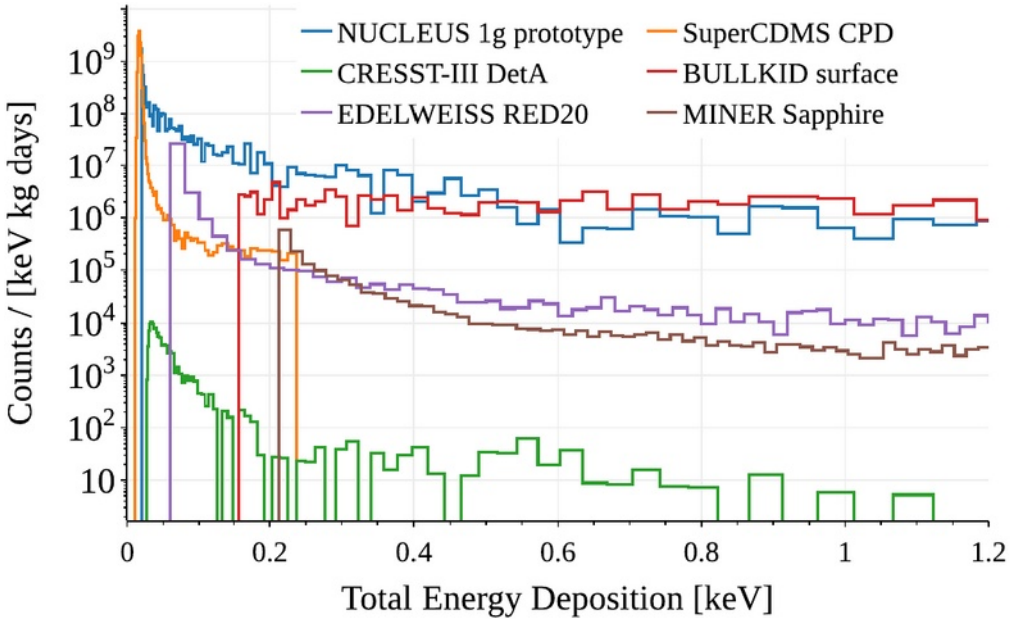

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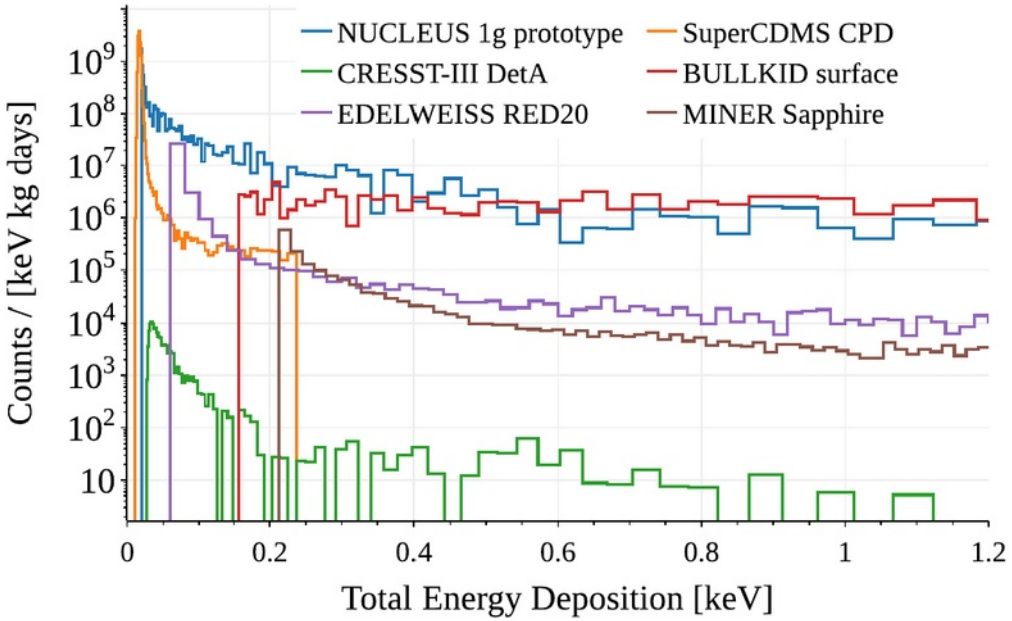

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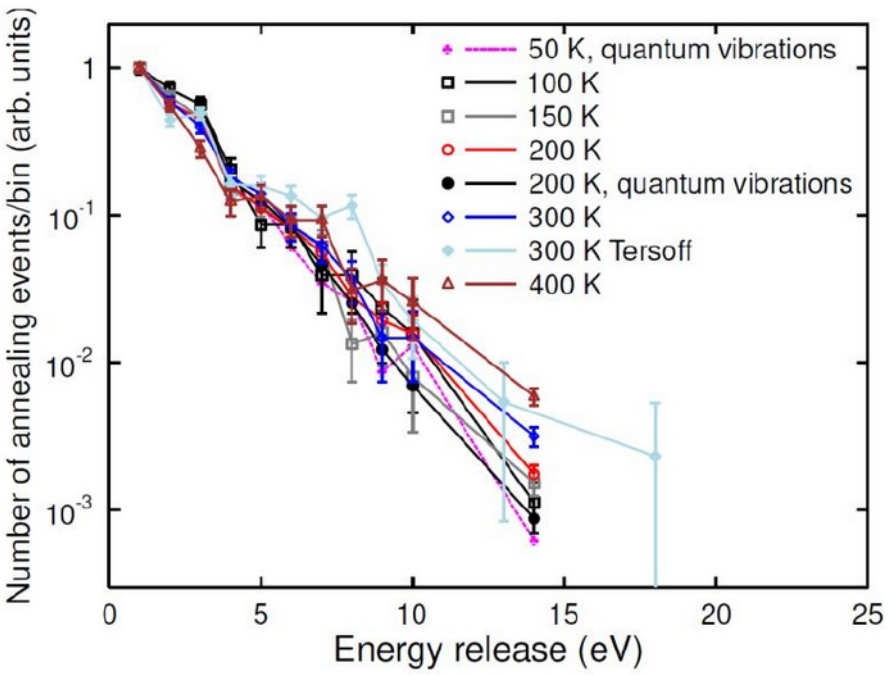
see talk by Marco Vignati (Tue 18.10)

and poster by Daniele Delicato

Relaxation of defects/stress in crystals

- all crystals have defects and impurities
  - can be caused by particle interactions
  - can already be there from production
- molecular dynamics simulations show that **defects can anneal even at low temperatures** → energy release
- predicts **power law** extending to few 10 eV
- rate within one order of magnitude for wide range of temperatures

EXCESS24: talk by Flyura Djurabekova



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- matches experimental results!

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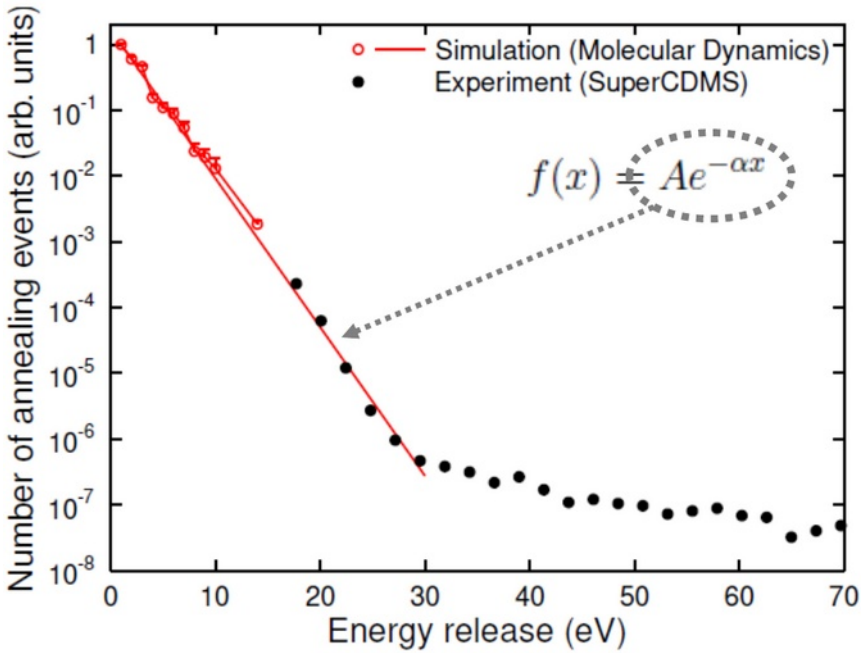
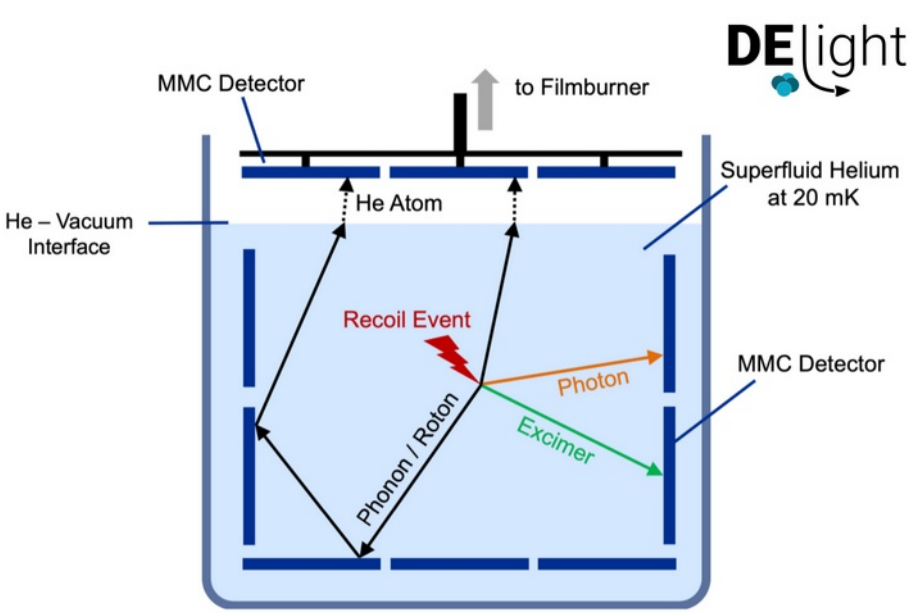
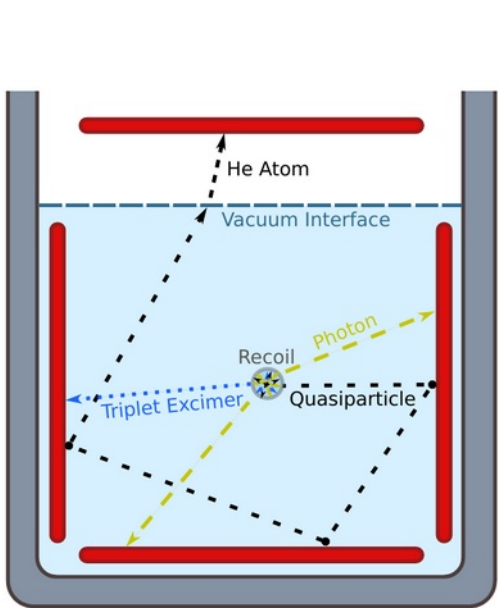


Mitigation of crystal stress

- can one accelerate the annealing of crystal defects?
- move to **liquid absorbers** → *DELight* and *HeRALD*





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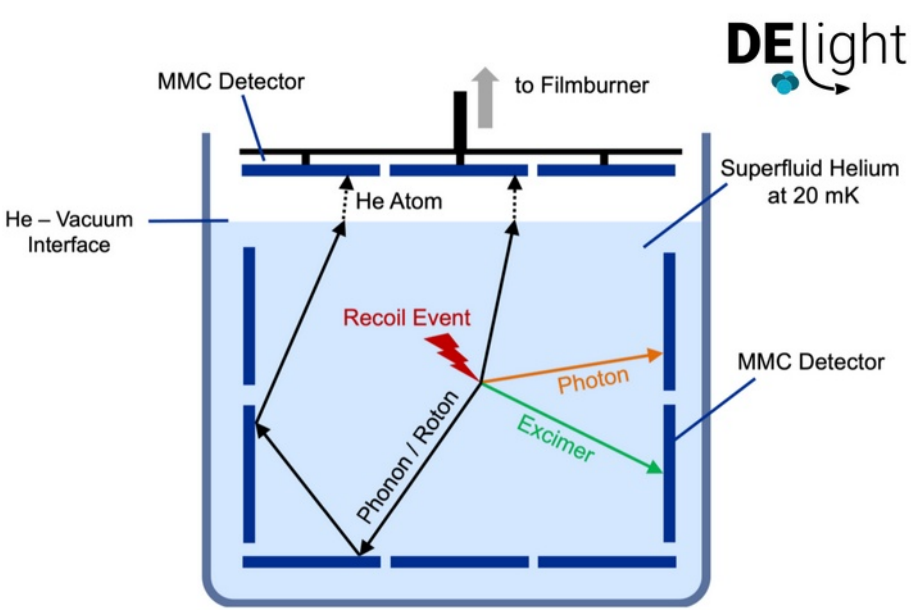
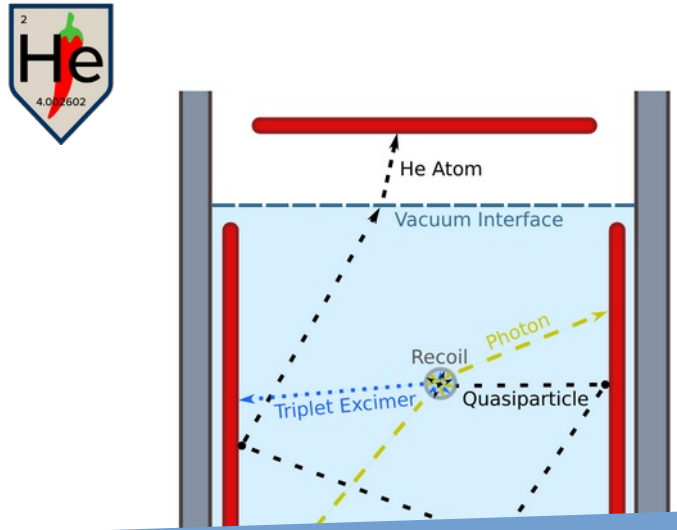


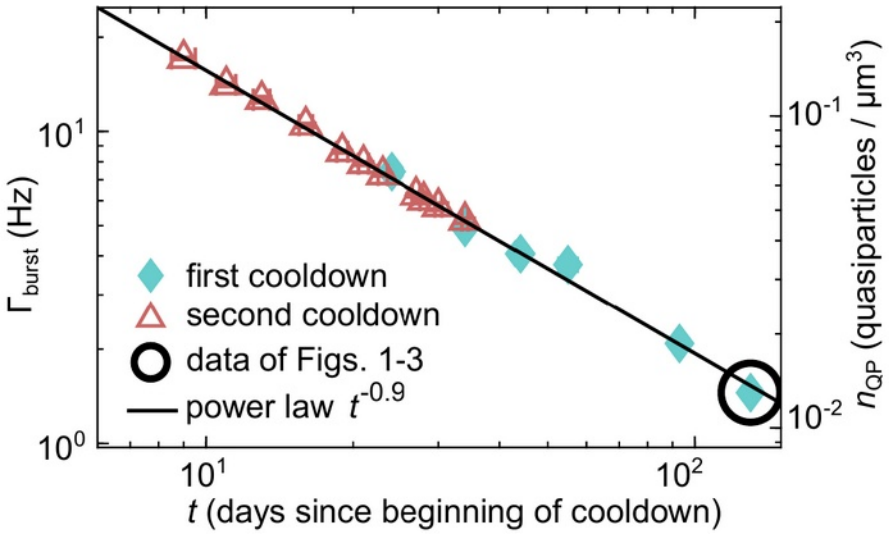


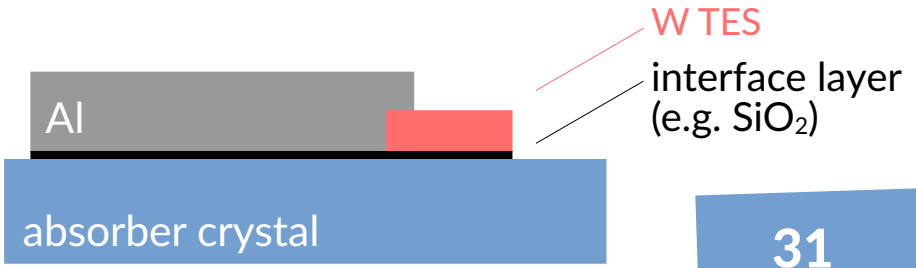
see talk by Scott Haselschwardt (Thu 15.20)

Relaxation processes in sensors

- spurious **quasi-particles** (broken Cooper pairs) degrade performance of superconducting qubits and sensors
- dedicated study of quasi-particles in Al shows **decrease in time** after cool-down → similar to LEE
- proposed model (arXiv:2406.15425) predicts similar behavior in Al films used in TES based detectors
- **differential thermal expansion** in the various layers of a sensor could introduce stress during thermal cycles

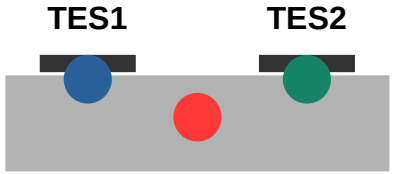
Mannilla *et al.*, Nature Physics 18, 145-148 (2022)

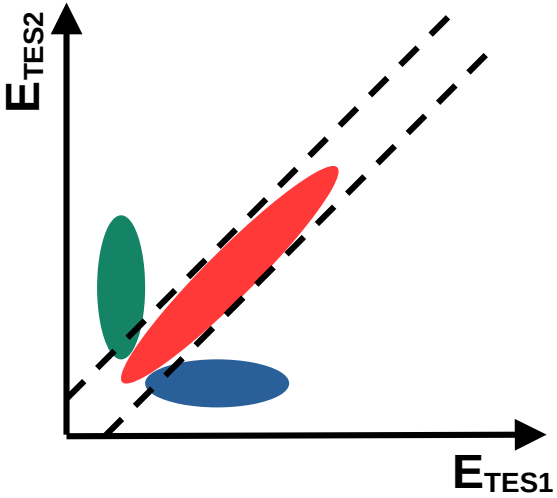


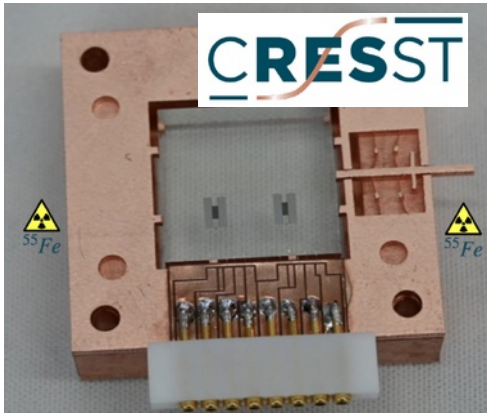


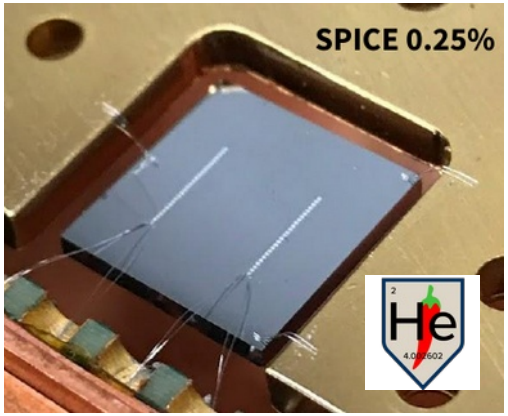
Use Multiple Sensors to Identify Sensor Events

- events from sensor itself should only show up in that sensor
- bulk events should be seen by all sensors
- first prototypes tested by CRESST, Nucleus and SPICE

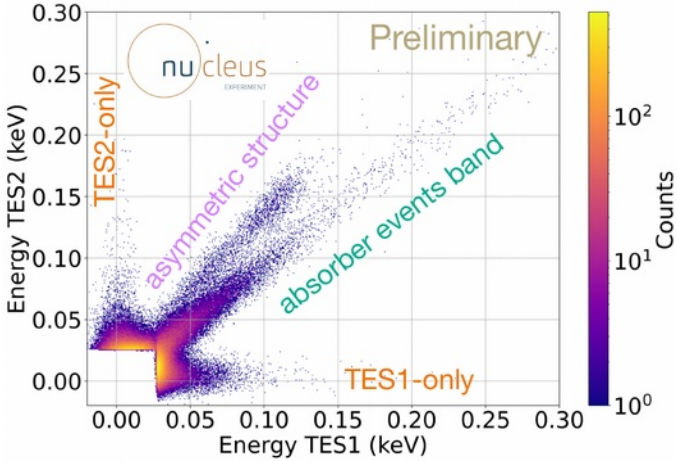


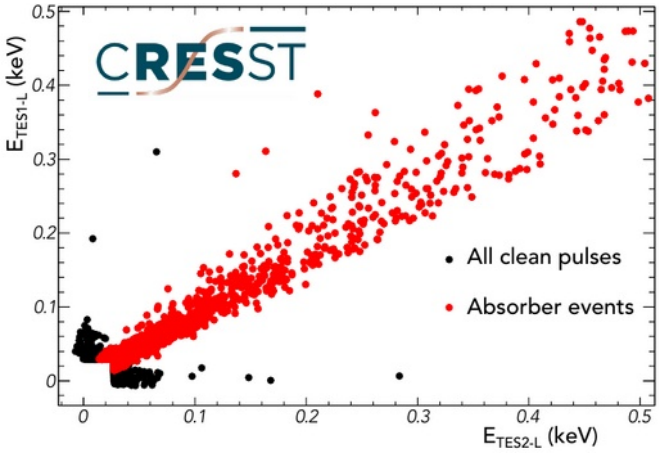


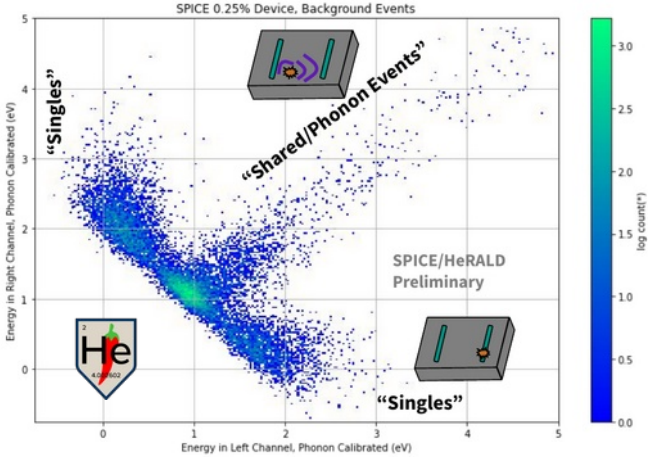




Use Multiple Sensors to Identify Sensor Events

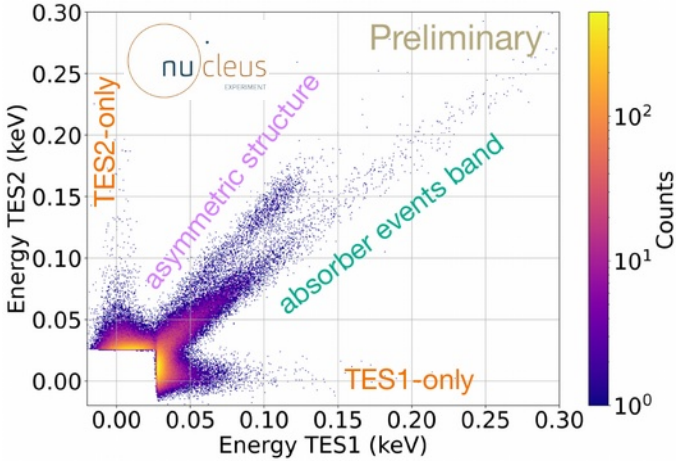


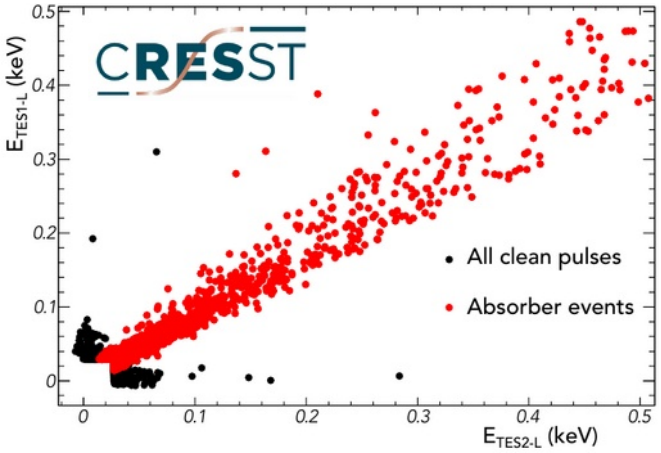


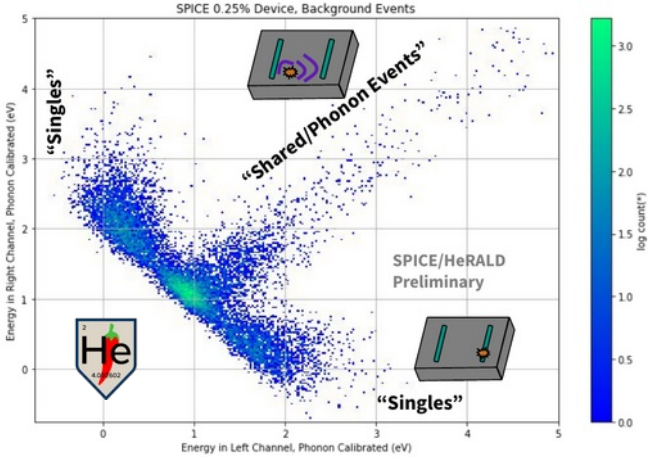


- prototypes can **identify single TES events** down to low energies
- remaining **LEE component in shared band**
- behavior of the two components needs to be studied further

Use Multiple Sensors to Identify Sensor Events







- prototypes can **identify single TES events** down to low energies
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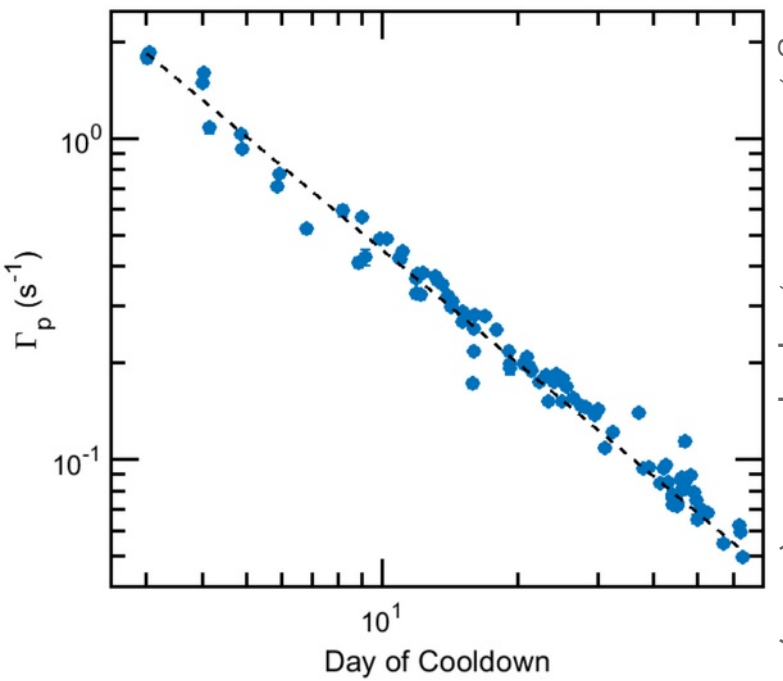
see poster by Francesca Pucci

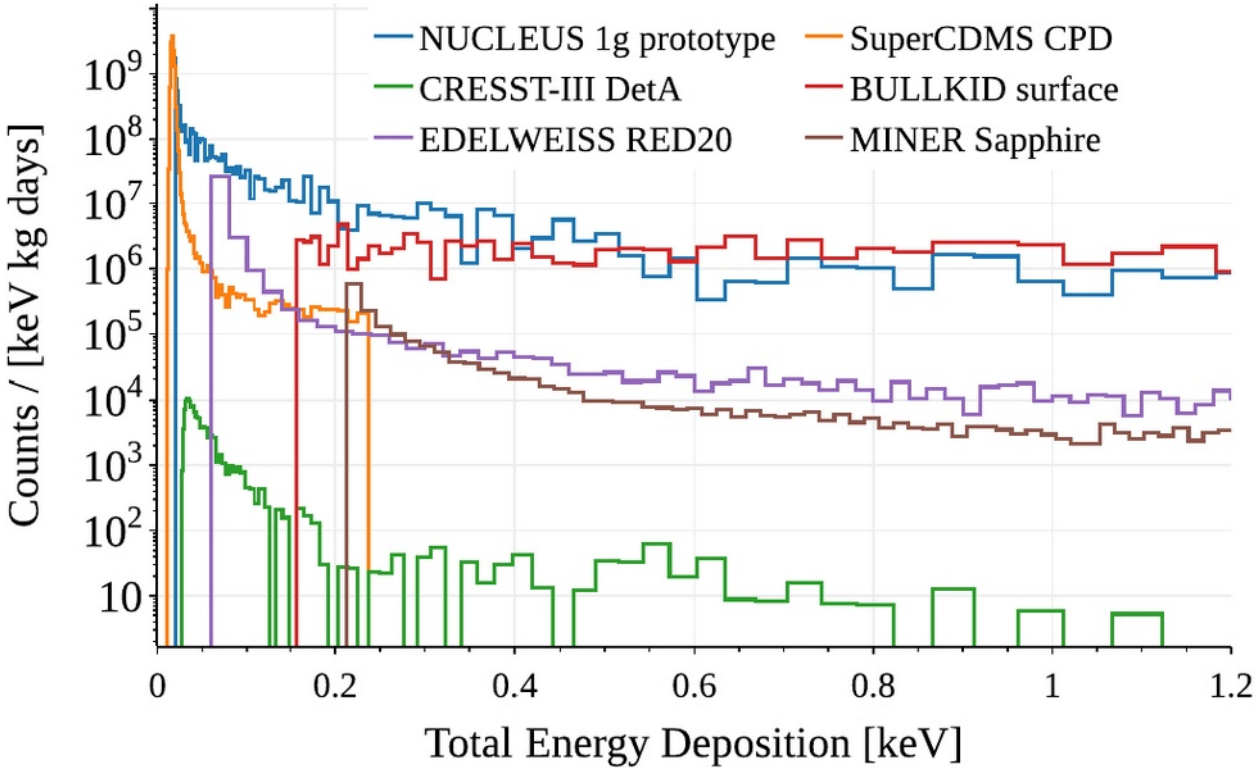
More Input from Quantum Computing

- superconducting qubits share some similarities to cryogenic detectors
- energy deposition can break cooper pairs and destroy coherence of qubit (“quasi-particle poisoning”)
- phonons in the substrate are causing disturbances (“parity switching events”) in qubits
  → rate decreases with time (power law)
- **IR radiation** from slowly cooling components was shown to affect qubits
  → can this cause events with ~ 100 eV ?



Dodge, Yelton *et al.*; in preparation (2024)

What's next ?



- huge difference in rate between above ground and underground measurements
- CRESST observes by far the lowest LEE rate
- more underground measurements needed to identify the nature of the residual LEE

https://github.com/fewagner/excess

What's next ?

- many experiments have started or are preparing new measurements at undeground laboratories
  - new CRESST campaign at LNGS started in April
  - SuperCDMS HVeV taking data in CUTE at SNOLAB
  - SuperCDMS SNOLAB is in installation phase

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see talks by

- Anna Bertolini – CRESST (Wed 14.00)
- Sukeerthi Dharani – SuperCDMS (Wed 15.20)

Summary

- LEE is seen by (almost) all low threshold cryogenic experiments
- very likely **not caused by particles** → solid state effects
- probably **multiple origins**
  - stress from **holding**
  - events in sensors or **sensor interface**
  - relaxation in **crystal bulk**
- interesting connections to **quantum computing**
- **new measurements** at underground facilities are coming up