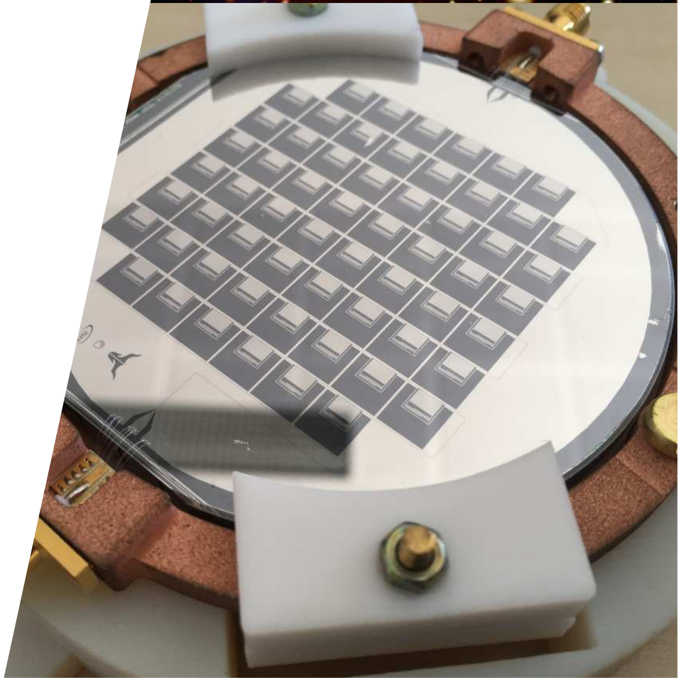
BULLKID-DM

EXCESS and rare event searches (a phonon-based POV)



Giorgio Del Castello on behalf of the collaboration
INFN - Roma 1

09/06/2025

What is the Low Energy Excess?

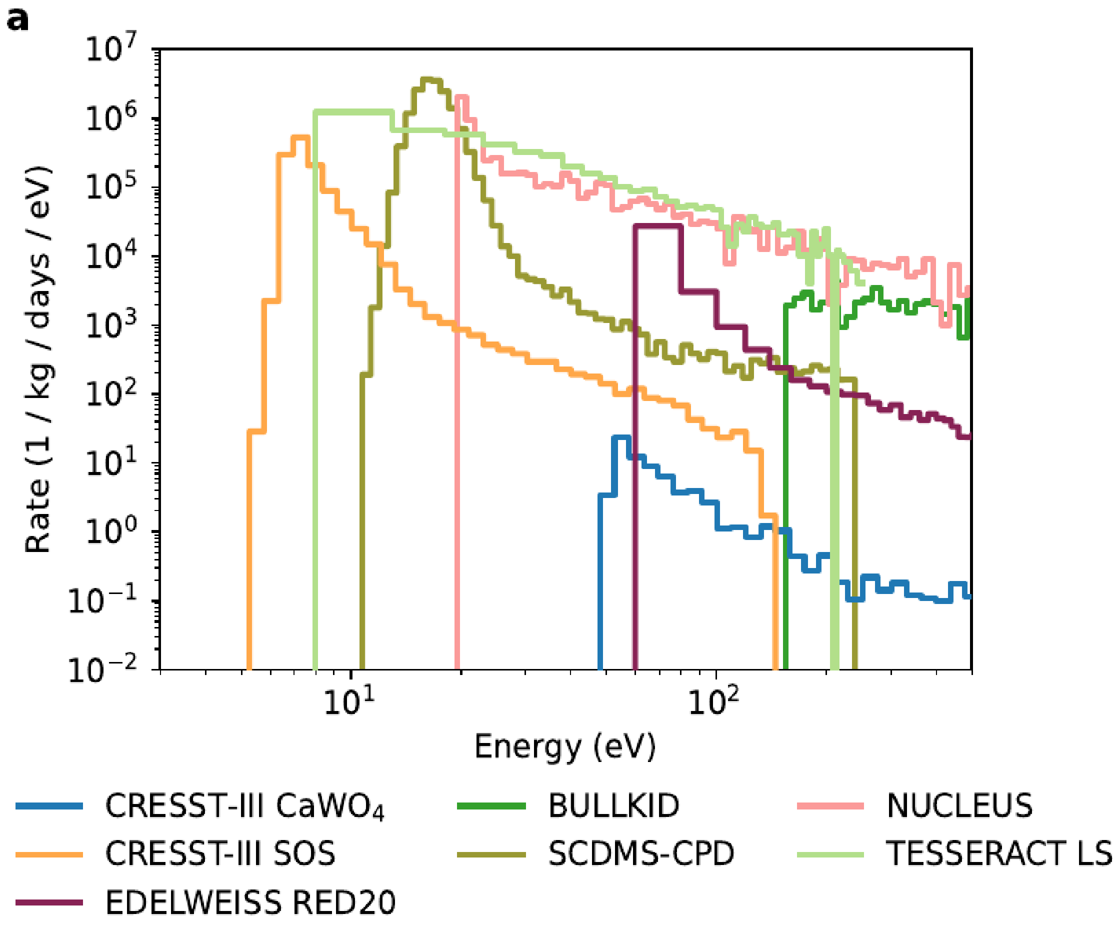
Exponential decrease in the spectrum under 500 eV.

Common to most low threshold experiments.

Unexpected and not reproducible background between experimental runs.

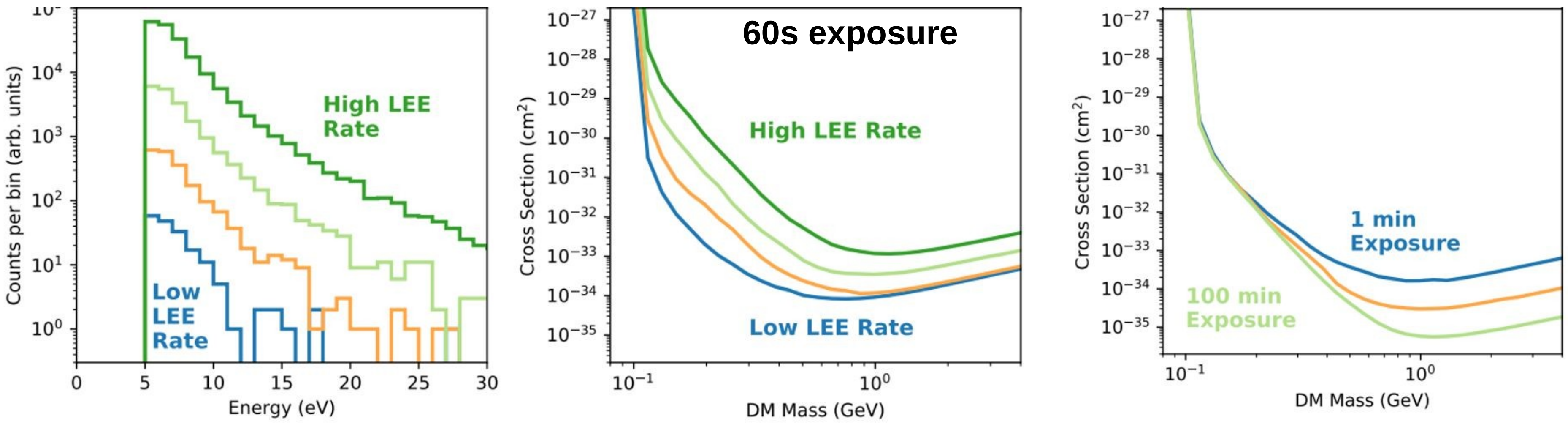
Not reproduced by simulations (GEANT).

Heavily reduces sensitivity of experiments.



Sensitivity to WIMPs and LEE

Spin-independent DM limit for 1g of Si (1 eV resolution)



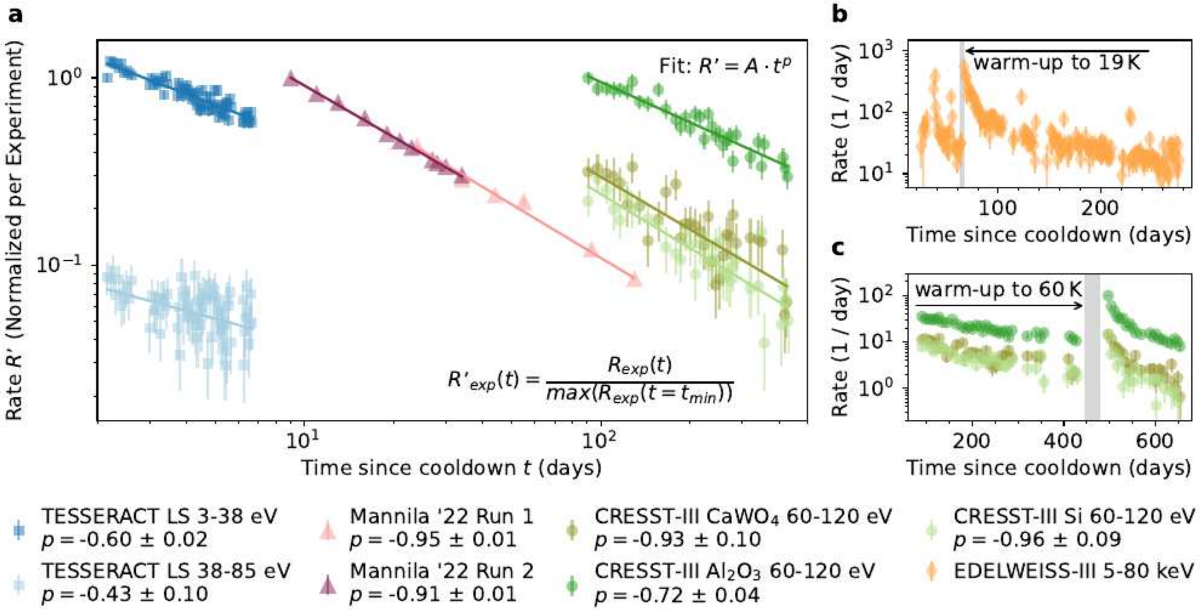
In the presence of LEE the DM sensitivity is worsened by orders of magnitude!

Exposure increase does not help in the sub-GeV DM regime

What do we know?

AGREED

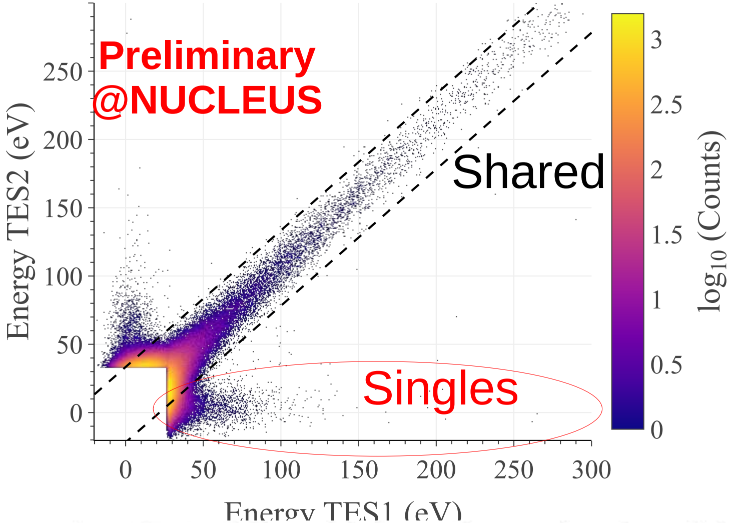
- Heat-only / Non-ionizing
- ~O(100 eV) Energies
- Decreases with energy
- Rate decays in time after cooldown
- Rate recharges upon a warm-up of setup (> 10 K)
- Likely multiple processes contribute to the LEE

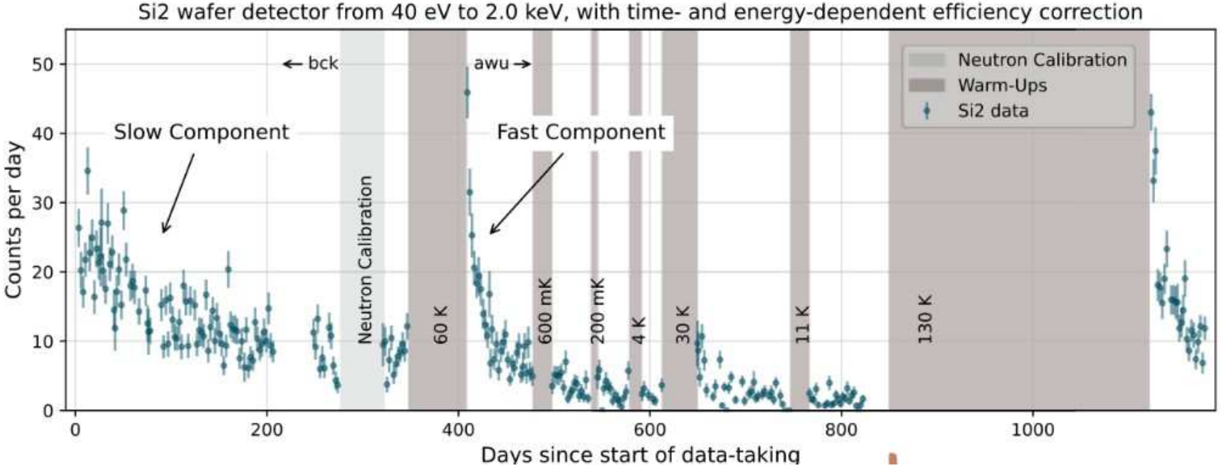


What do we know?

MOSTLY AGREED:

- One or multiple power laws in energy (or exponentials?)
- At least two components: crystal-mediated (Shared) and sensor-related events (Singles)
- Double time-decaying component
- Substantial mounting/holder stress increases the rate of the LEE at lowest energies.





Honorable Mentions

Low Energy EXCESS in different technologies

QBits

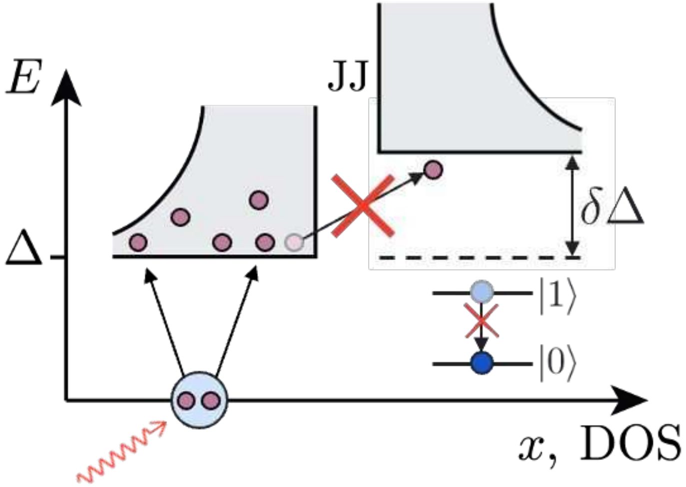
LEE manifests as an increase in the Qbit errors related to quasi-particle tunneling rate

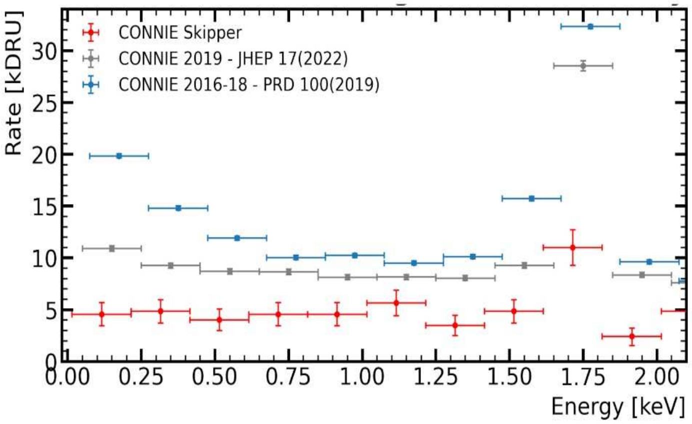
Correlated tunneling observed in multiple Qbits on joint chip

QuDev Lab (ETH Zurich)

Google Quantum AI

Gap engineering, radiation and IR reduction





CCDs

Skipper CCD technology (below the Shot noise readout): no timing resolution but spatial resolution

Increase in the dark counting rate and point-like events

Different LEE than phonon based!

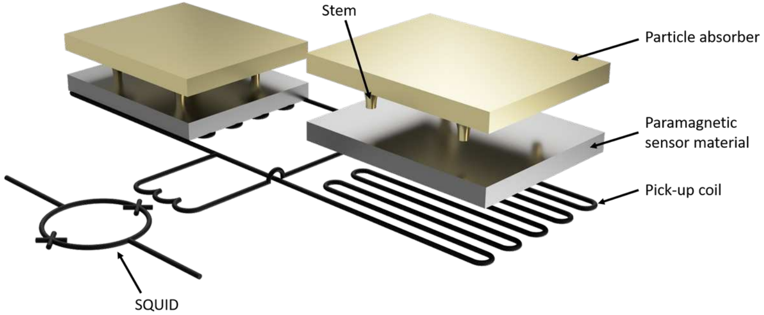
Connie: CEvNS experiment (EXCESS free after careful fiducialization)

Damic: Improve temperature and electronics induced IR

Sensei: Reduced background from 1 to 10^{-5} e^{-}/pixel/day

Other Technologies

MMCs

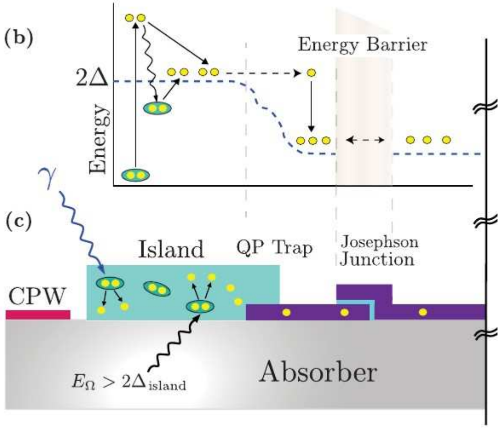


Very fast detectors (few us rise): powerful pulse shape discrimination

Superconducting Nanowires

Increased dark count rate:

- Thermal Fluctuations
- Electrical
- Vortices

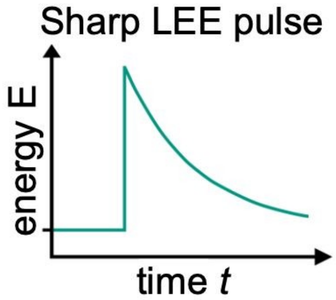


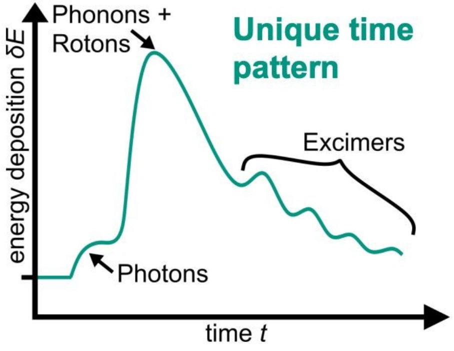
SQUATs

Extremely low threshold detectors. Hybrid between KID and Qbit

DELight (LHe, MMC)

Superfluid He has high pulse shape potential for discriminating LEE and DM events

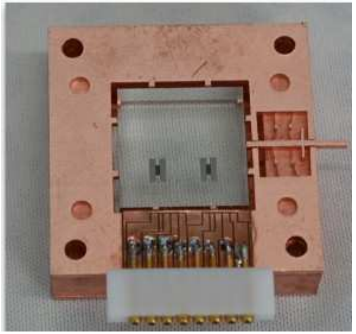




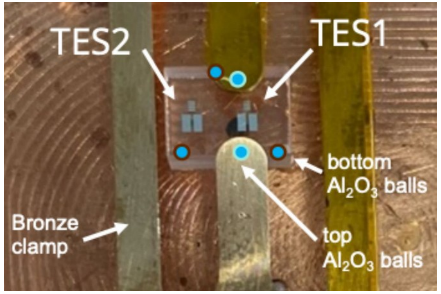
Phonons!

Experimental Overview (only phonon based calorimetry)

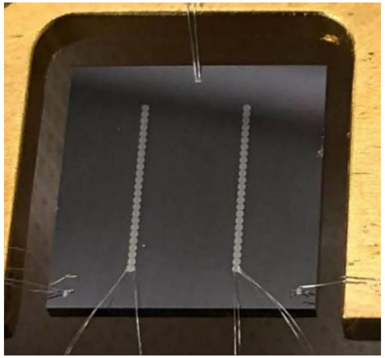
CRESST: TES @ LNGS with double TES and low stress mounting



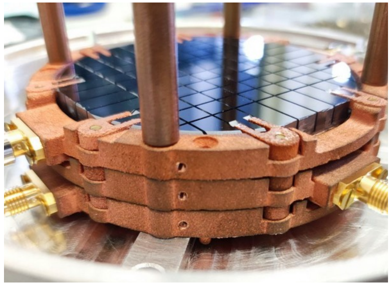
NUCLEUS: TES-based; instrumented holder and double readout



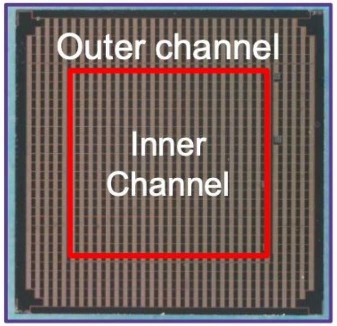
TESSERACT: TES (QET) <0.3 eV resolution (double TES and low stress mounting)



BULLKID: KID based with signal fiducialization



SuperCDMS: Particle ID via ionization channel (TES-QET)



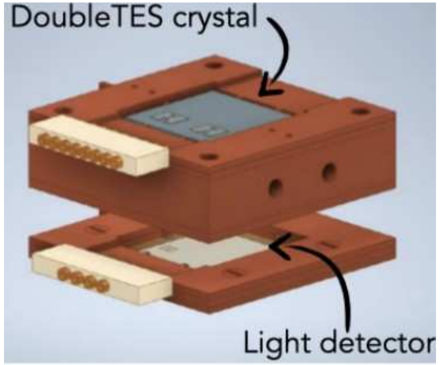
RICOCHET (EDELWEISS): Fiducialization and particle ID via ionization channel (NTD)

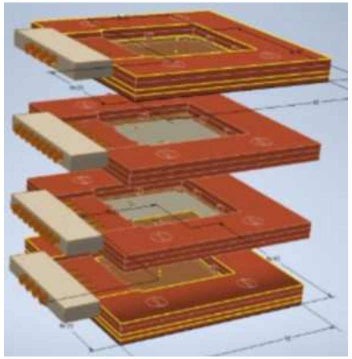
CRESST @ EXCESS Workshop 2025

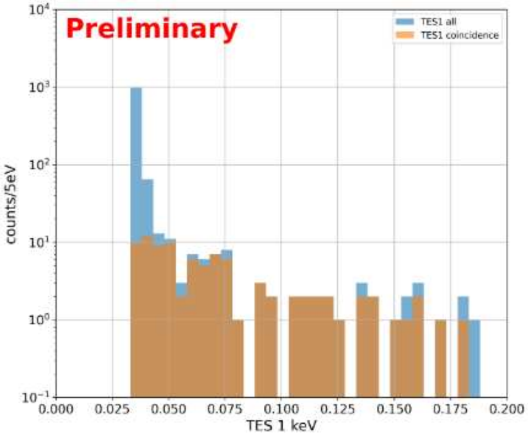
- Attempted Studies with negative results:
  - Mounting
  - Low Stress crystals (slowly grown)
  - Detector Geometry
  - Active Mounting not improving

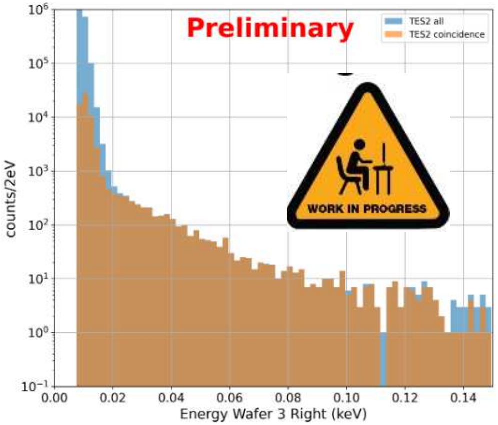
- Double TES (24g $CaWO_4$) with threshold <35 eV

- Stack of Si double TESs (4x0.6 g) with threshold <10 eV



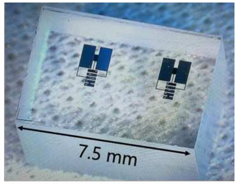






Below 30 eV a new rise is visible! Seems to be made of pulses

NUCLEUS @ EXCESS Workshop 2025

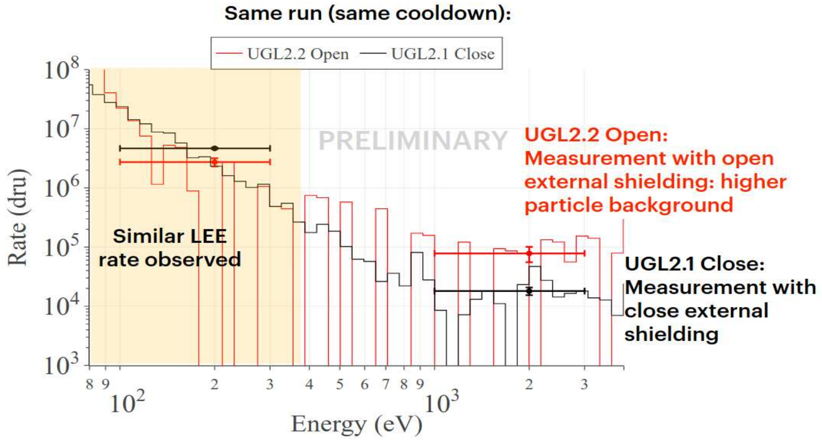


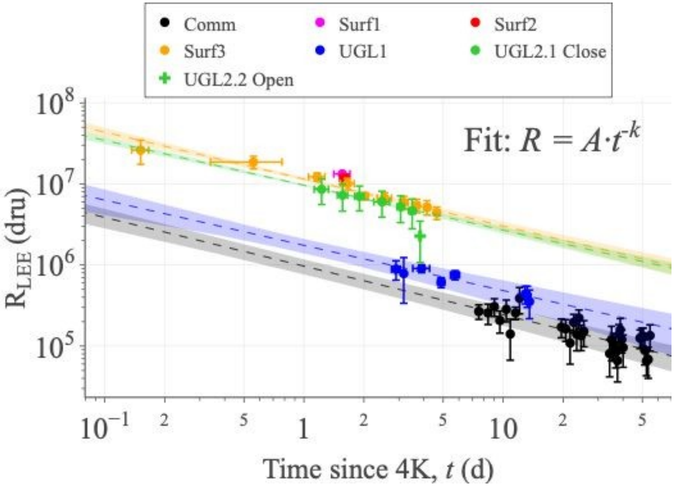
Al_2O_3 crystal | 0.75 g
Best achieved σ_{BL}=5.5 eV

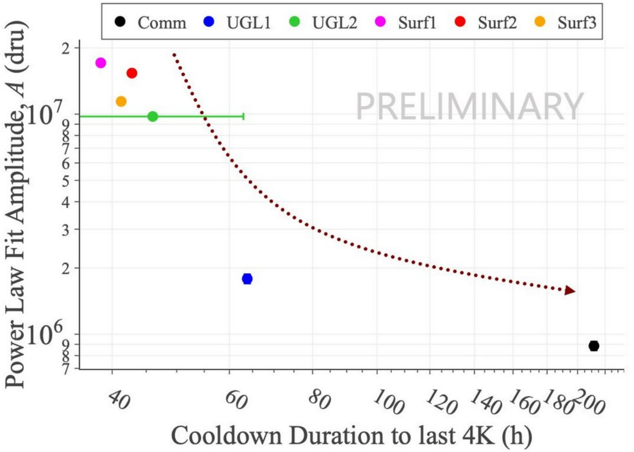
- LEE rate does not correlate with:
  - Muons/Particles
  - Thermal Cycles
  - Time at cold
  - Time since mounting

- Power law R=$A \cdot t^{-0.57}$ describes well the LEE rate evolution with time

- Lower initial LEE rate for slower cooldowns

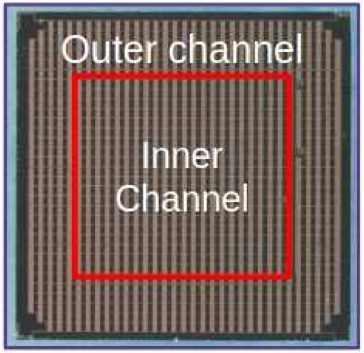


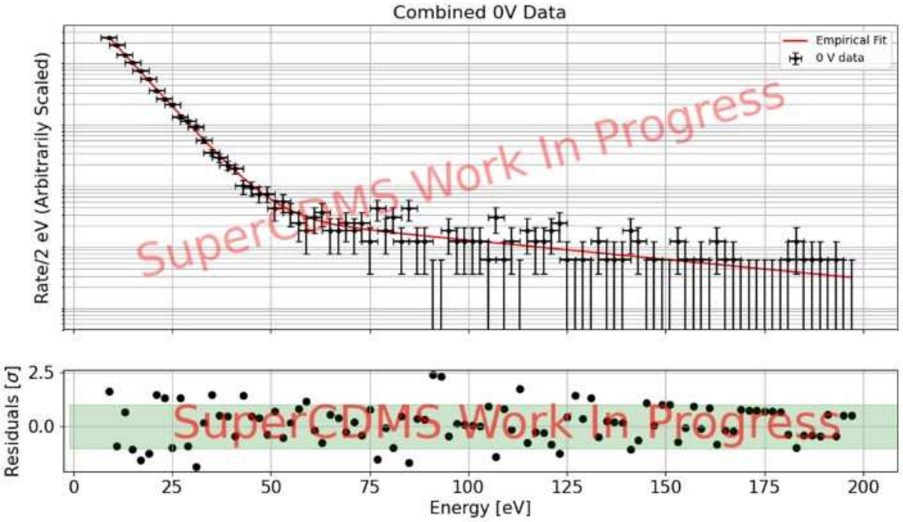


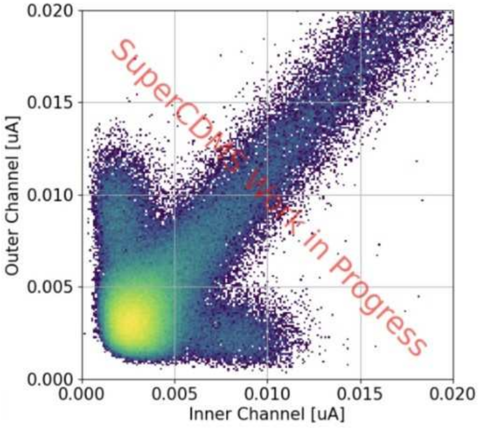


SuperCDMS @ EXCESS Workshop 2025

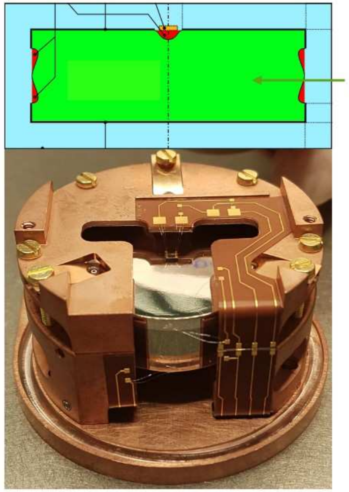
- Shape of 0V spectrum is constant over the run
- Same shape, different rate
- Present without NTL or ionization effects (0V)!
- Hints of excess noise also in the NPSD (analysis ongoing)

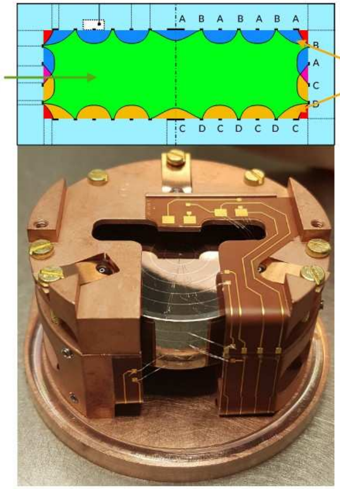


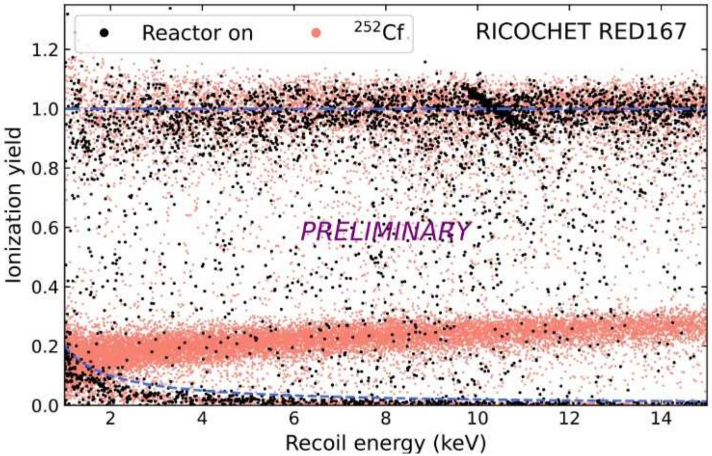




RICOCHET @ Magnificent CEvNS!







NO LOW ENERGY SPECTRUM HAS BEEN SHOWN

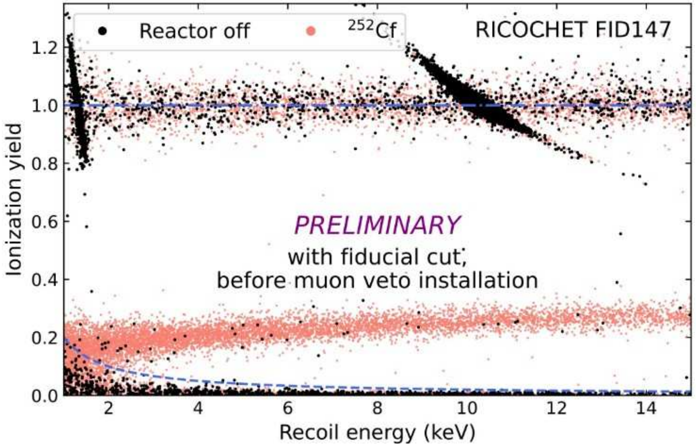
RUNS @ ILL

- RUN013 from February 19th to April 4th, 2024
- RUN014 from May 7th to October 14th, 2024
- RUN015 from January 22th to June 4th, 2025

commissioning runs

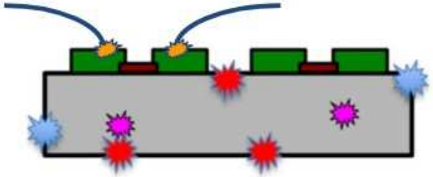
- RUN016 from July 2025 to end of 2026 → 18 detectors (planar + FID)

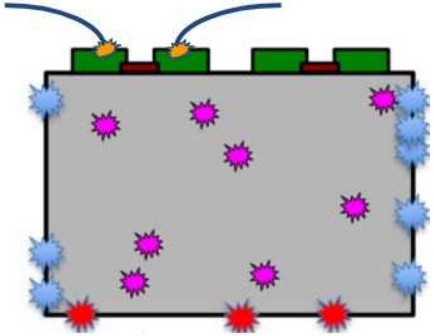
science run starting this Summer!

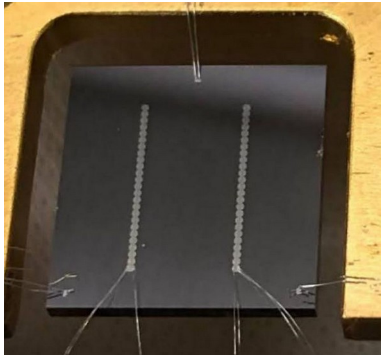


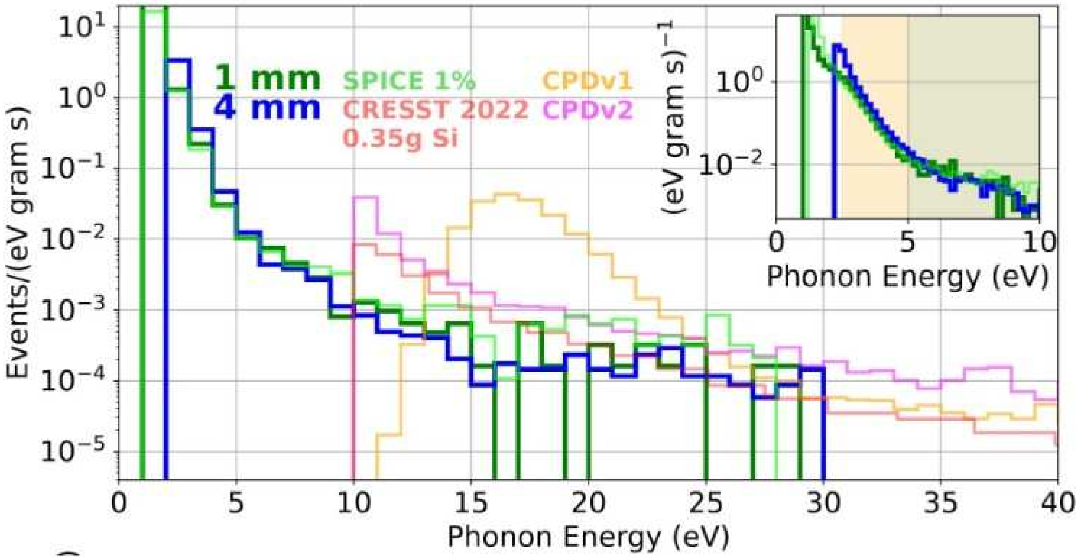
TESSERACT @ EXCESS Workshop 2025

- 2 Identical detectors are produced: only difference is the height (i.e. the mass)
- This test excludes:
  - Surface origin (Polished and unpolished)
  - Transmission through wire bonds
- LEE scales with detector mass! (tension with CRESST)



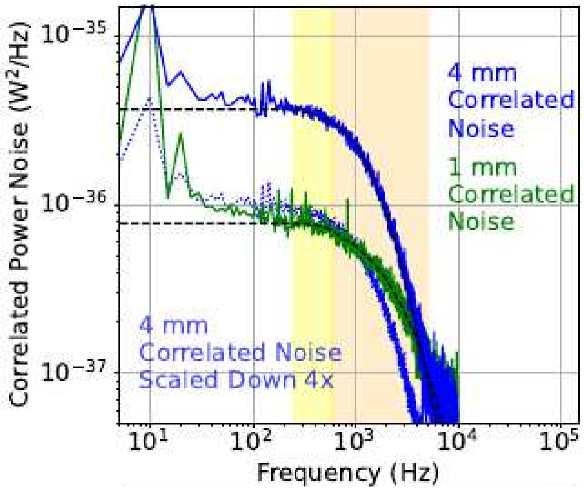


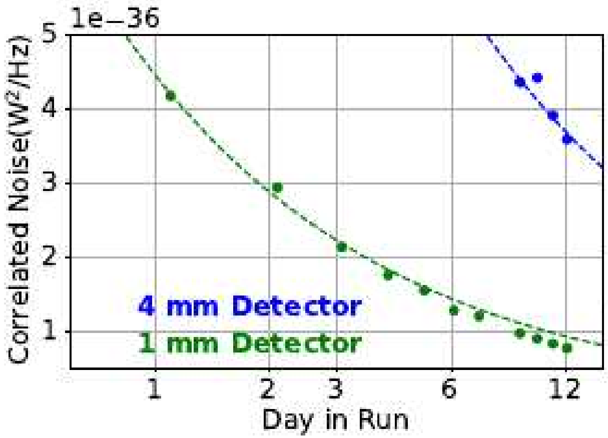


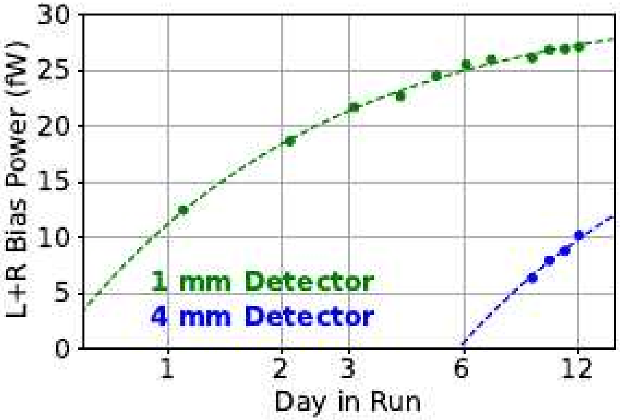


TESSERACT Below threshold EXCESS

- Factor 4 increase in the correlated NPSD (mass scaling)
- EXCESS uncorrelated noise present at low frequencies
- Decrease of the NPSD with time is measured
- Increase of bias power with time is measured

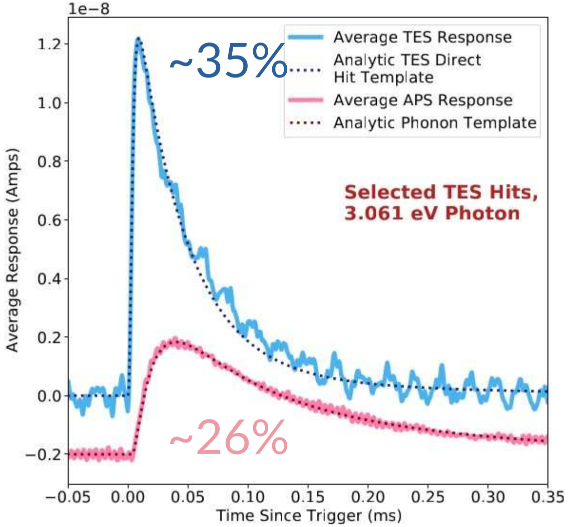


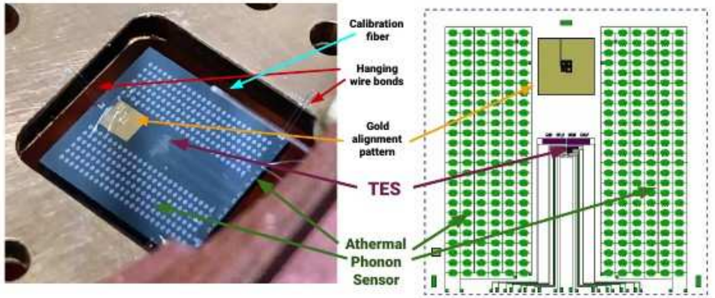


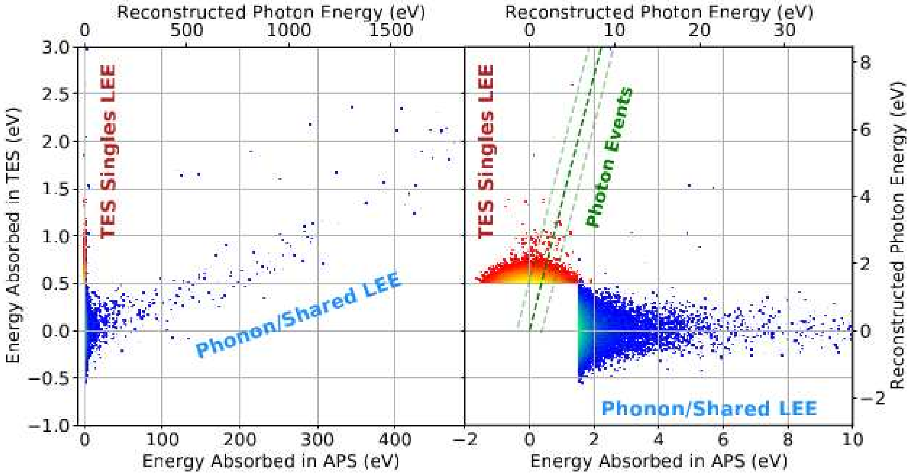


TESSERACT Singles

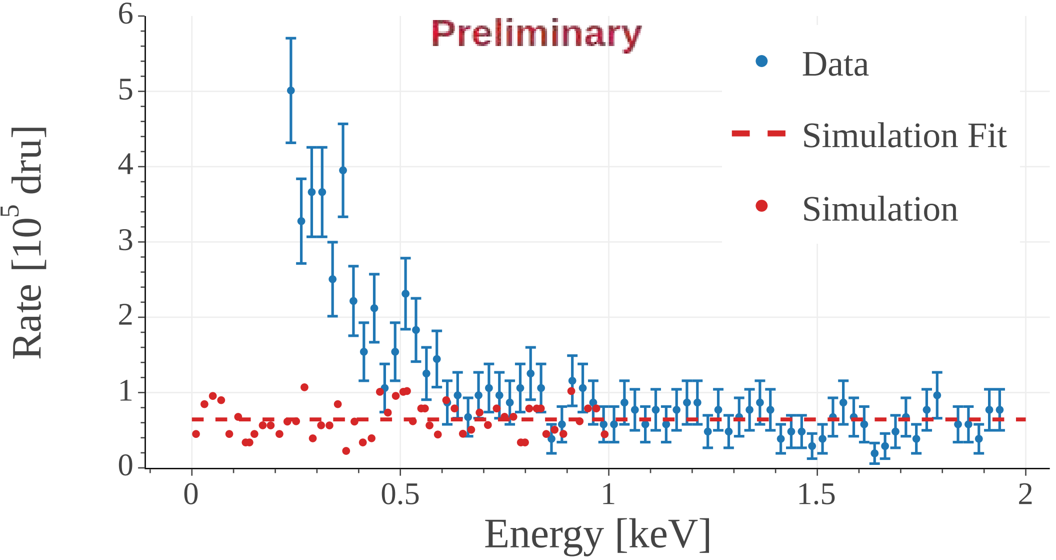
- Detector with TES (for direct hits) and QET for phonon sensing (APS)
- **Bulk Events: ~50% in APS and <1% in TES**
- TES direct hits: are not singles due to phonon leakage to substrate!
- **Singles: NOT ENOUGH PHONONS IN APS!**
- In APS the usual LEE is seen
- No significant decrease of the Singles rate

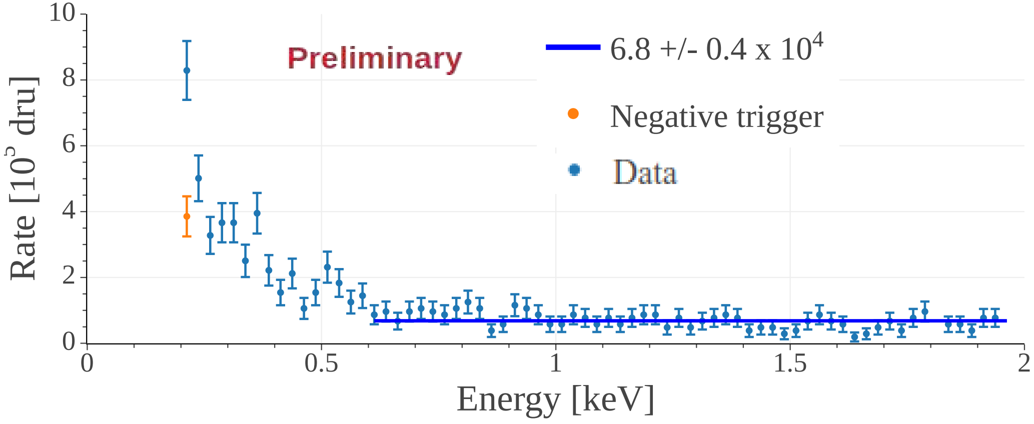






How does BULLKID compare?





- In <600 eV measured rise up to a factor ~5
- Spectra compatible between the two triggering pixels!
- Rise not compatible with negative triggers (noise false positives)
- Has the basic symptoms of the LEE

How does BULLKID compare?

Different working conditions tried **in same cooldown**:

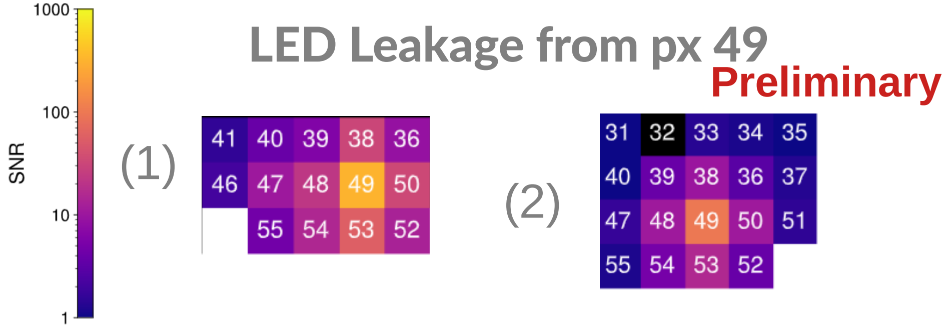
1) Optimizing resolution of triggering pixels (best reached 28 eV, during data taking 30 eV)

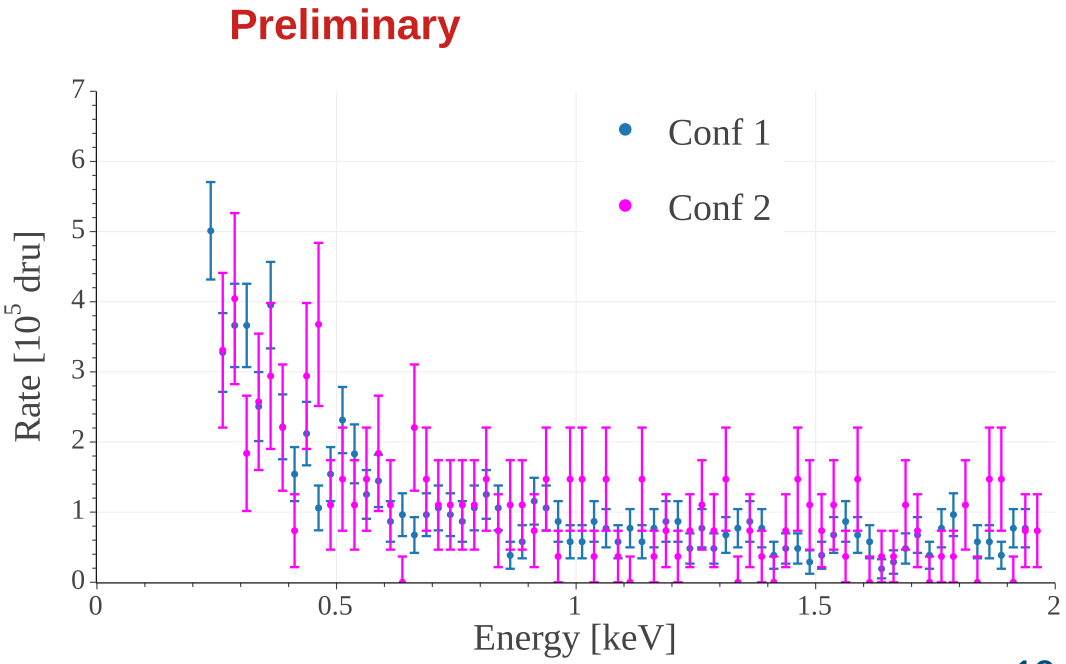
   19/04 - 5/05 (~15 solar days)

2) Uniform leakage SNR in between pixels

   19/05 -26/05 (~7 solar days)

Observed no difference in between spectra 1 and 2 (not even a time decay!)



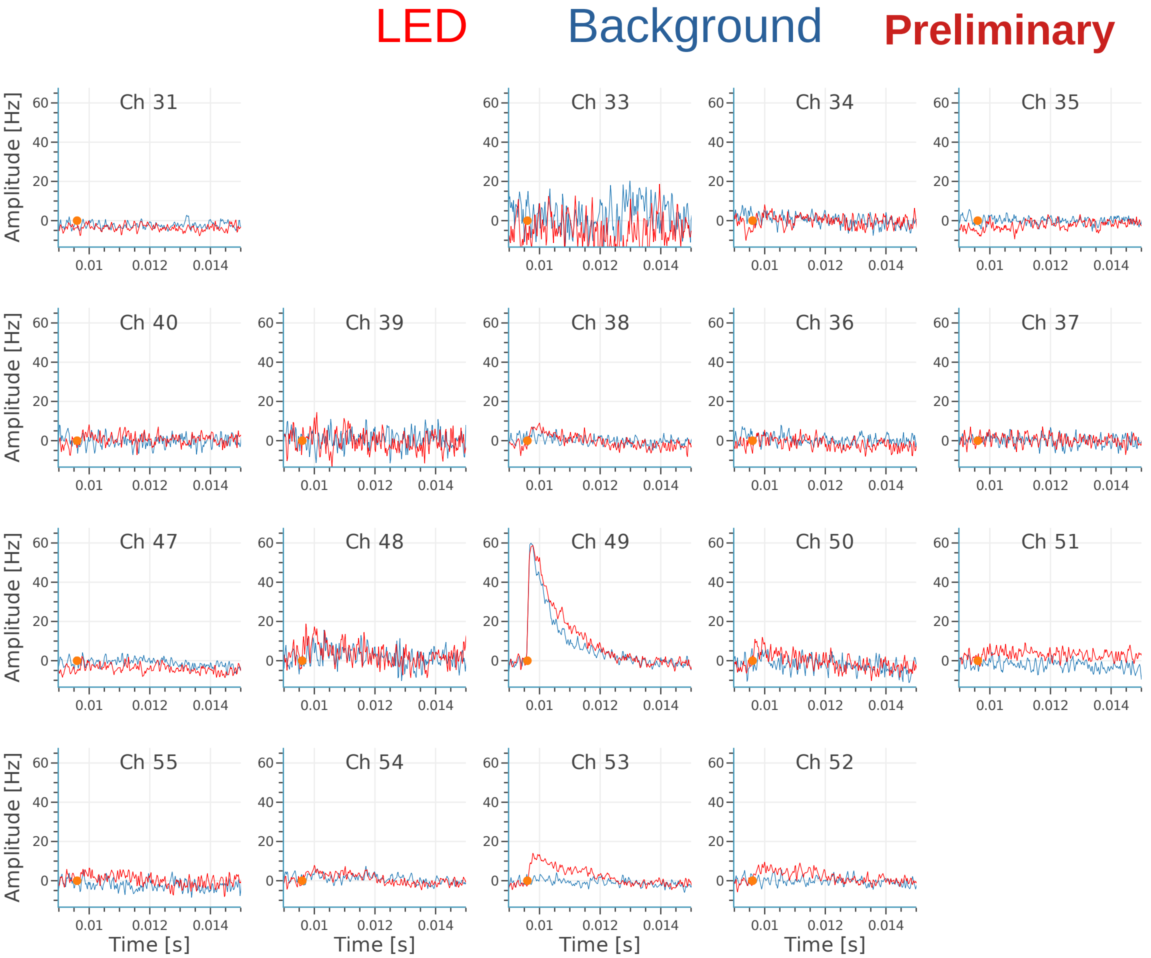


How does BULLKID compare?

BULLKID architecture cannot distinguish Shared/Singles at threshold (small phonon leakage).

At higher energies:

- Singles visible at ~2keV and above
- Could be direct KID hits due to high metalized area (Al absorbs well 100 eV photons)
- Could it be that the rise is due to Singles (under investigation)?

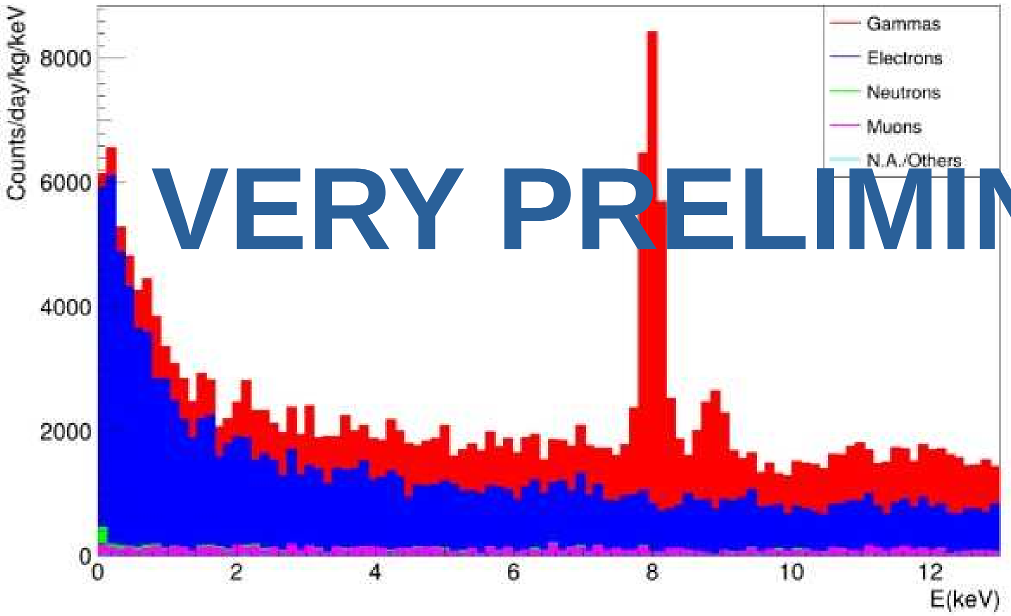


Keeping in mind NUCLEUS simulations…

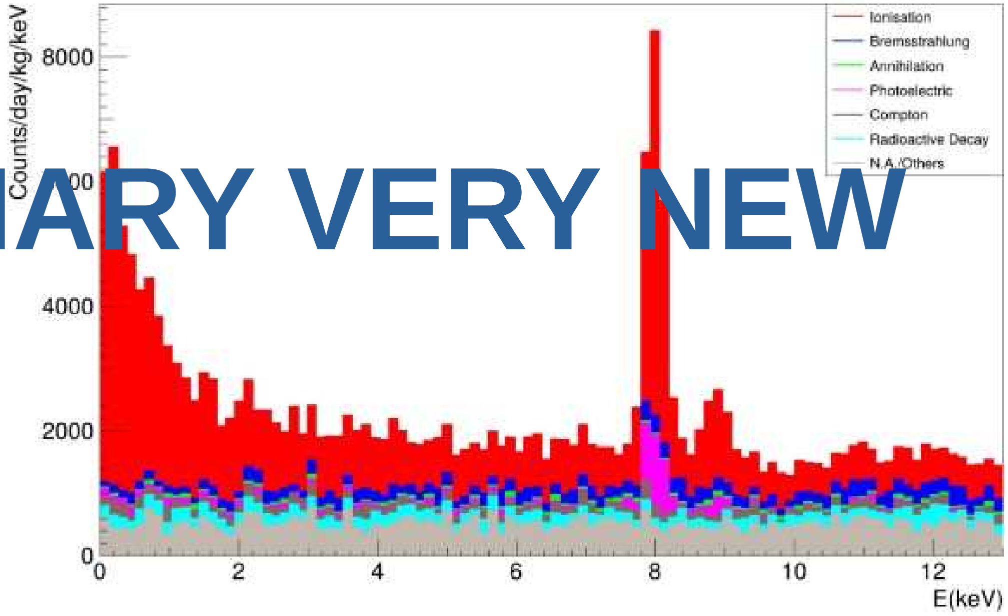
Simulation in $CaWO_4$ in UGL (15 m.w.e.) with LEAD shield (~few 10^3 dru)

Credit @Fabio Cappella

VERY PRELIMINARY VERY NEW

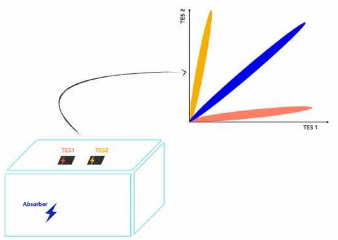


Particles interacting with $CaWO_4$ target



Creator processes of the particles

Findings overview



Shared

- Phonon mediated
- Scales with detector mass? TESSERACT ↔ CRESST tension
- Does not scale with particle background
- Recharges when a (partial) warm-up happens
- Can be related to mounting stress (not entirely)
- Appears to decrease with a slower cooldown
- Avalanche recombination of crystal damages could play a role (in contrast with no recharge due to neutron calibration)

Singles

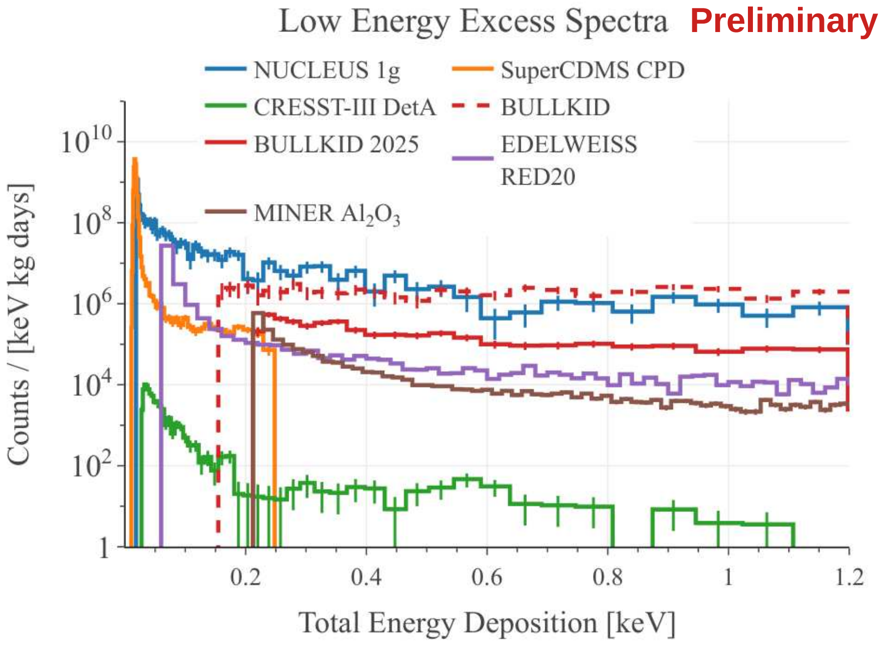
- **Unclear origin…**
- Possible direct sensor hits or film to crystal stress
  - TESSERACT excludes this due to lack of phonon signal
- Appears to not decay with time
- Fluctuates in various runs with an unclear cause
- A crazy origin (TESSERACT): bursts of sub-aluminum bandgap photons that couple to the TES via its antenna-like bias lines (~ GHz)
- **Easy to remove with double readout**

Conclusion

- Most low threshold experiments see the LEE
- Also different technologies such as QBits and CCDs see a version of the LEE
  - But CCDs appear to be on their way to solve it (probably not the same LEE as cryodets)
- In phonon based detection:
  - Decays with time
  - Appears to have power law decay in both energy and time

BULLKID

- Rise below 500 eV
- Rise compatible between voxels and does not decay with time!
- Could be that simulations are missing something ? Since Pu related peaks are not well reproduced…
- Further tests are needed … especially at LNGS with full demonstrator!!



References

Papers:

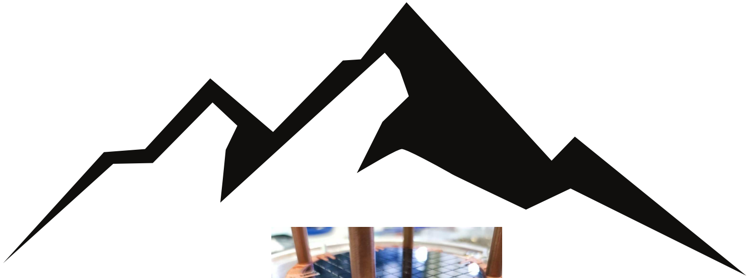
- Low-Energy Backgrounds in Solid-State Phonon and Charge Detectors, D. Baxter, et al., Annual Review of Nuclear and Particle Science 0163-8998 2025
- EXCESS workshop: Descriptions of rising low-energy spectra, P. Adari, et al., SciPost Phys. Proc. 9, 001 (2022)
- A transition edge sensor operated in coincidence with a high sensitivity athermal phonon sensor for photon coupled rare event searches, R. K. Romani, et al, Appl. Phys. Lett. 125, 232601 (2024)
- Spontaneous generation of athermal phonon bursts within bulk silicon causing excess noise, low energy background events and quasiparticle poisoning in superconducting sensors, C.L. Chang, et al., https://doi.org/10.48550/arXiv.2505.16092
- First results from the CRESST-III low-mass dark matter program, A. H. Abdelhameed, et al., Phys. Rev. D 100, 102002 (2019)

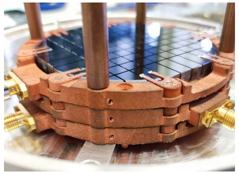
Conferences:

- EXCESS Workshop 2025
- Magnificent CEvNS workshop 2025
- LTD 2025
- Dark Matter 2025
- EXCESS Workshop 2024
- IDM 2024

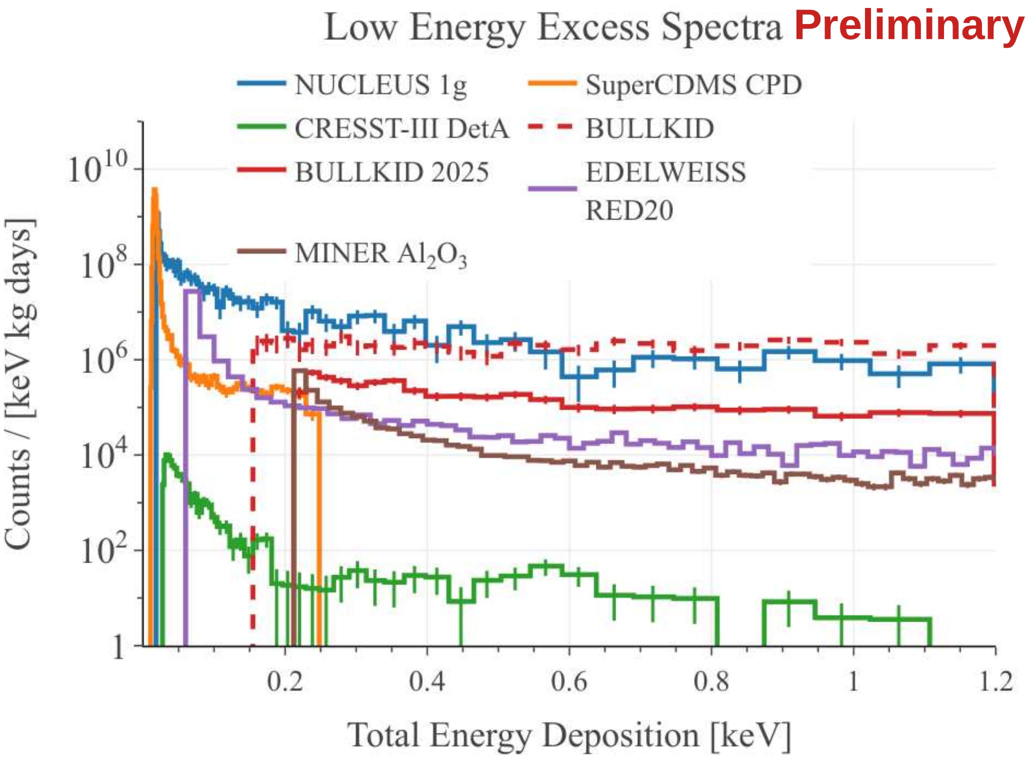
BULLKID-DM

Thank you for the attention!





WE NEED DEMONSTRATOR@LNGS !

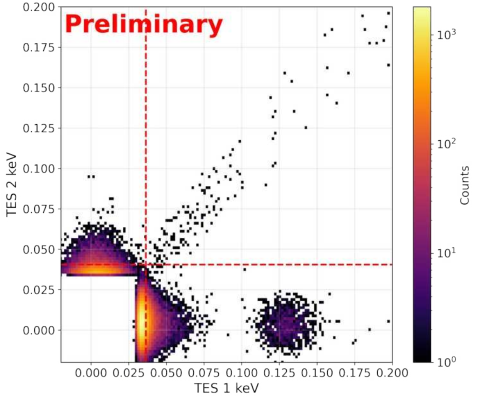


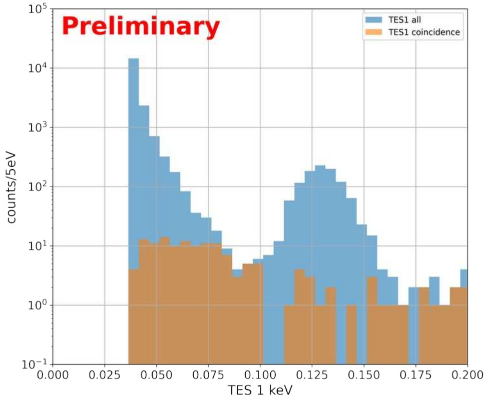
This work was partially supported through the European Research Council through the Consolidator Grant DANAE number 101077663

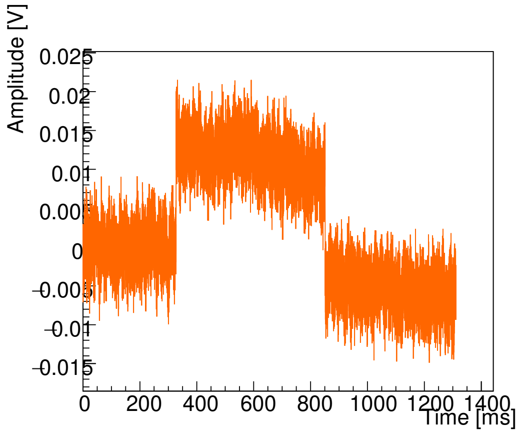
Backup Slides

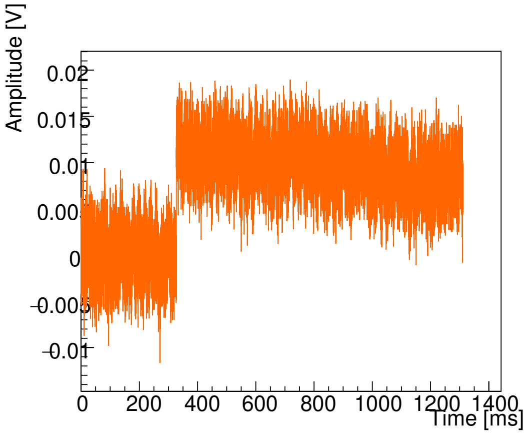
CRESST

$CaWO_4$ Double TES

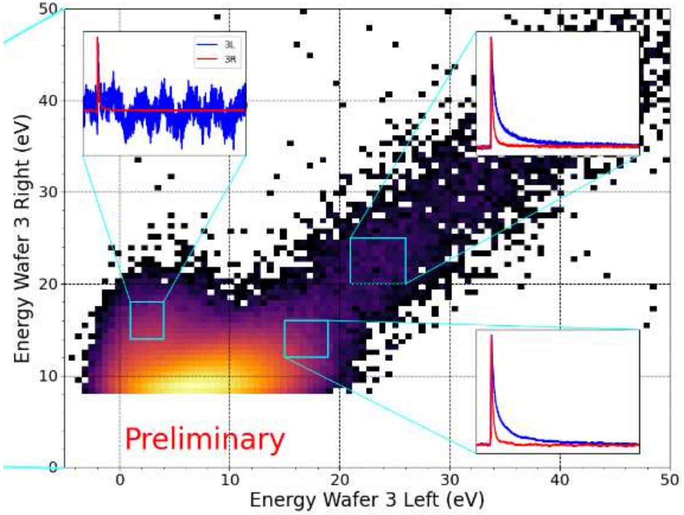




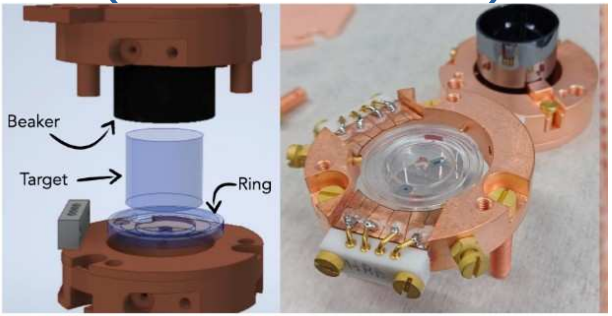


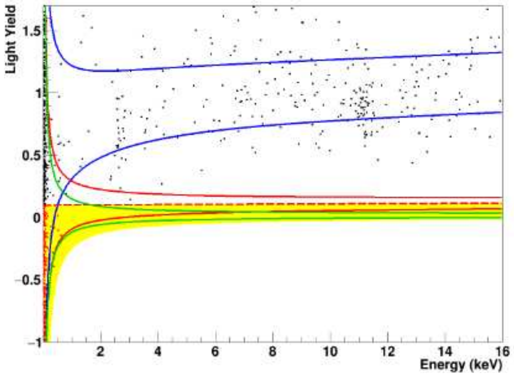


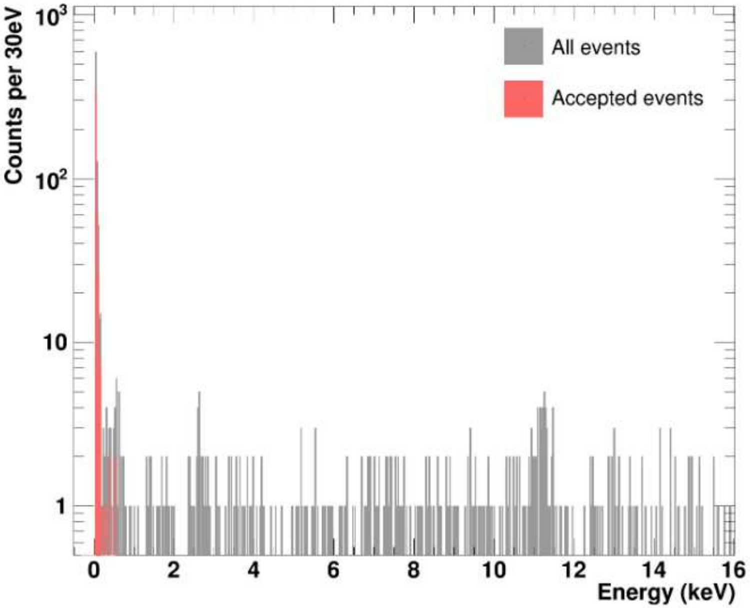
Si Stack

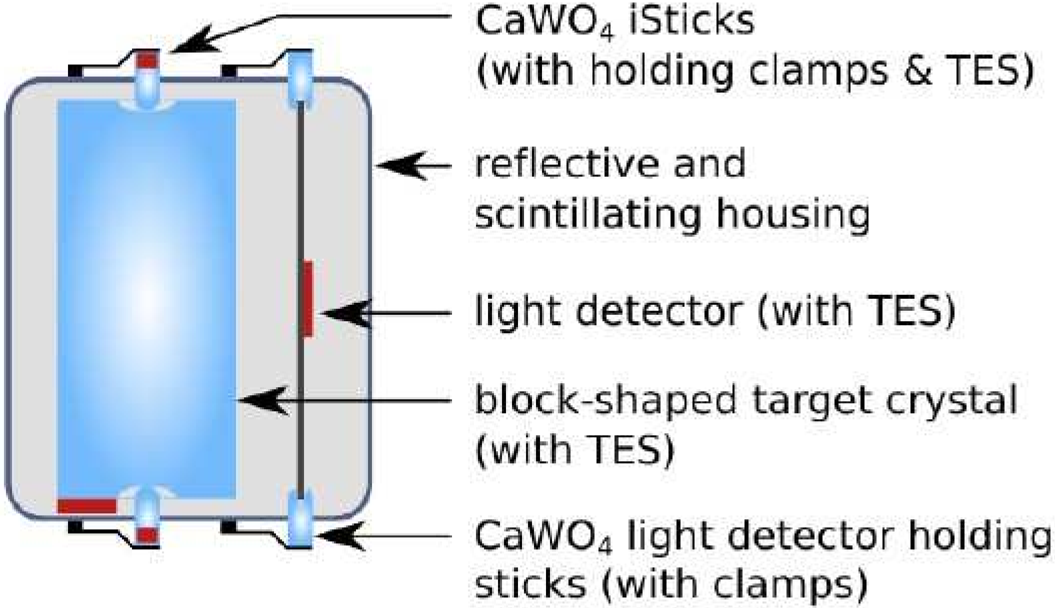


Al_2O_3 + Si Beaker (instrumented)









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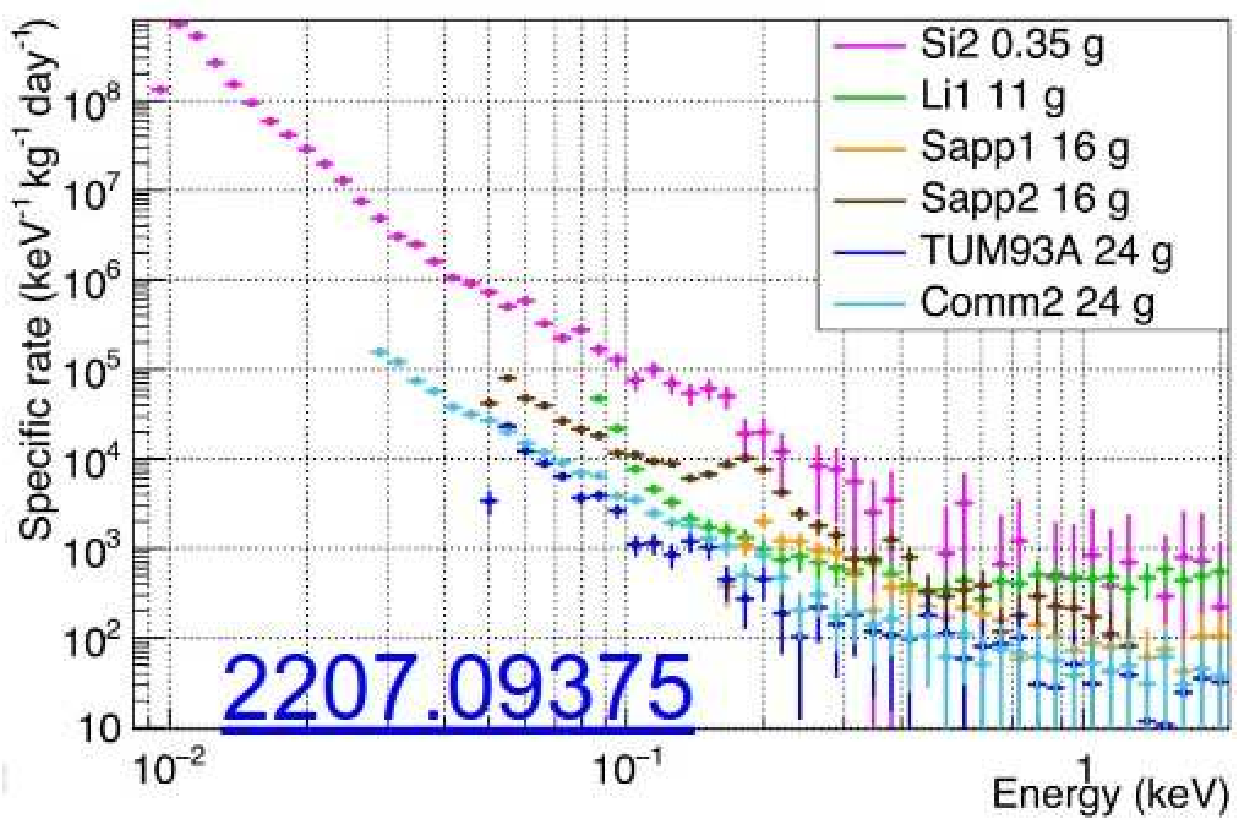
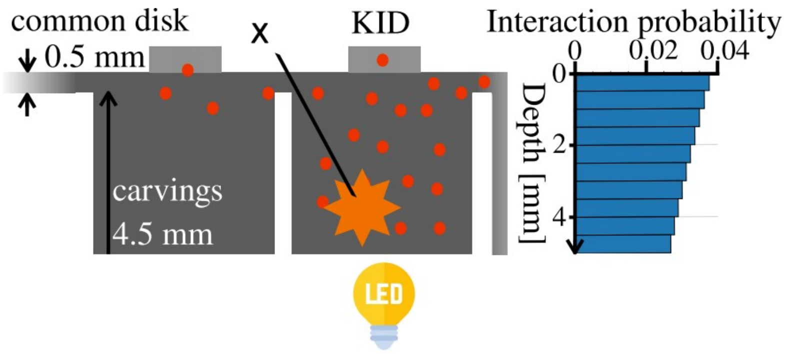
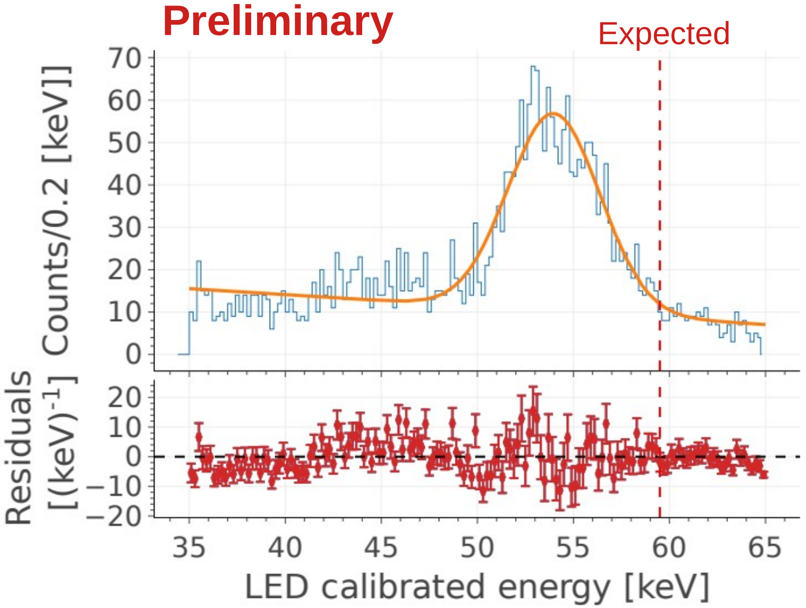


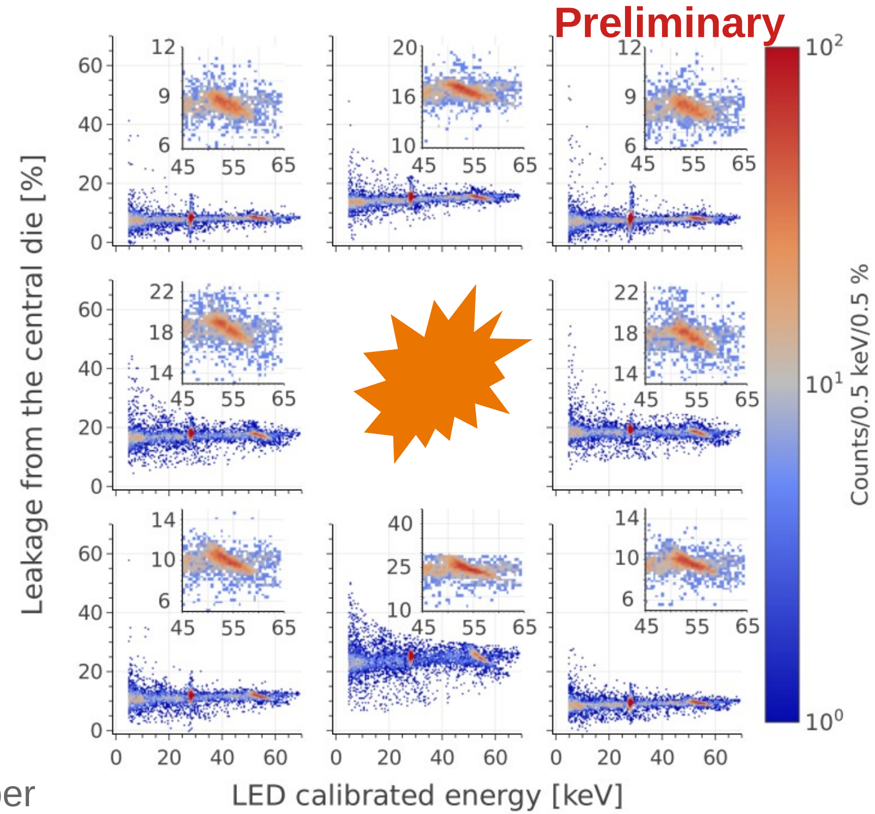
Specific rate (keV^{-1} kg^{-1} day^{-1})
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^{-2}
10^{-1}
1
Energy (keV)
Si2 0.35 g
Li1 11 g
Sapp1 16 g
Sapp2 16 g
TUM93A 24 g
Comm2 24 g
2207.09375

Bulk (Am) vs Surface (LED) events



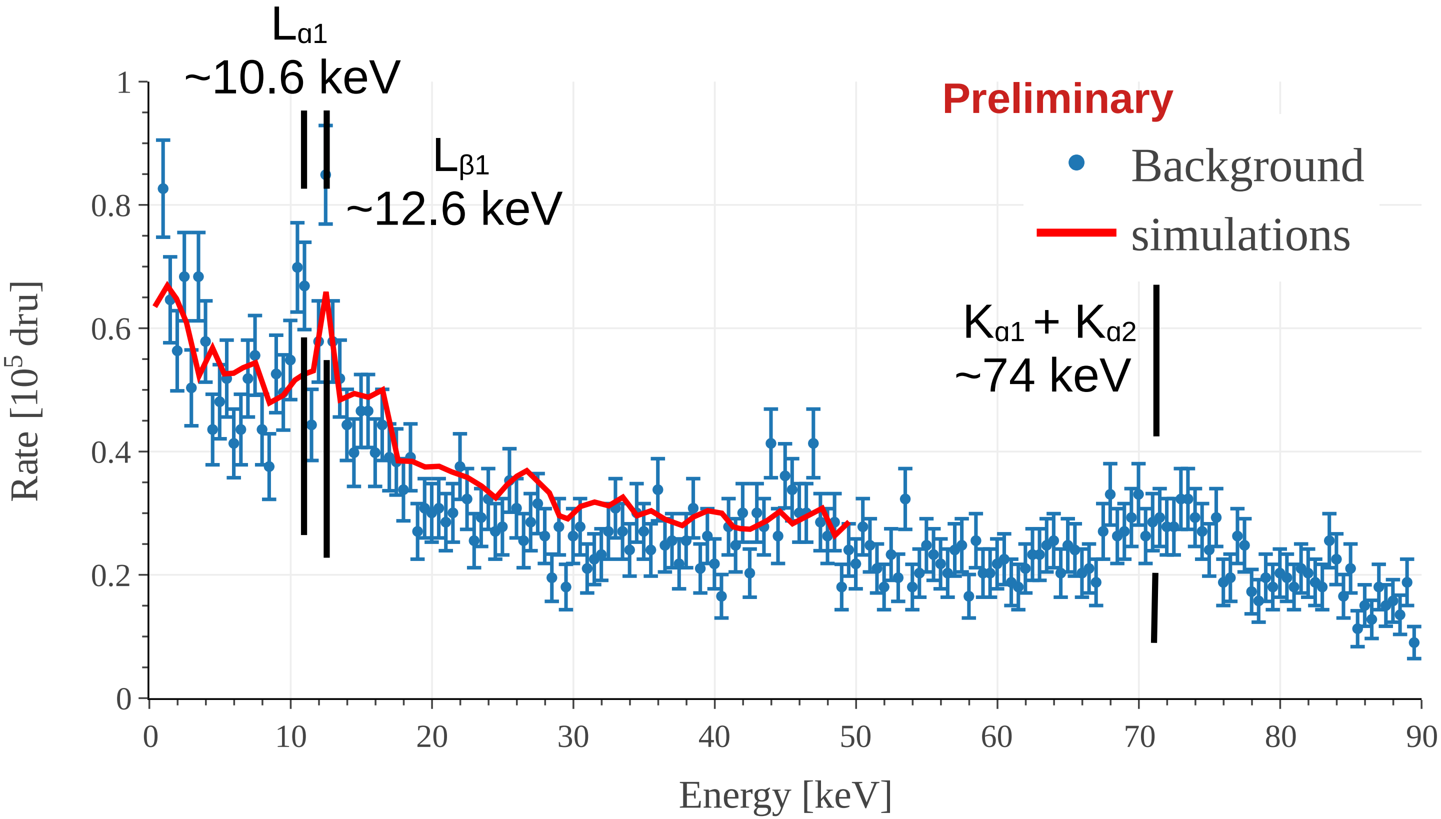
- Dedicated cooldown with Am source (59.5 keV X-Ray)
- -10% discrepancy between calibrations
- Same leakage between bulk and LED





Upcoming Paper

High Energy Spectrum and Simulation Comparison



- Visible Pb X-rays well reconstructed (under 10% discrepancy) with LED calibration
- Pb X-rays at 10 keV not well reproduced by simulations (resolution not applied)
- Overall behavior of background fairly well reproduced (analysis being perfected above 20 keV)

Al Photon transparency

- 60 nm Al easily absorbs photons under 1 keV
- Generated following Rakic, A.D. (1995) Algorithm for the Determination of Intrinsic Optical Constants of Metal Films: Application to Aluminum. Applied Optics, 34, 4755-4767