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The low energy excess in dark matter and neutrino experiments

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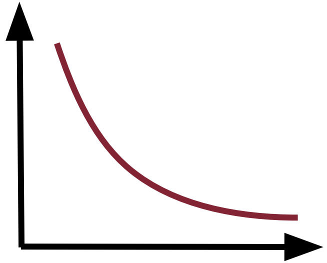
PhD Seminar Season 12 Episode 5
02/04/2024

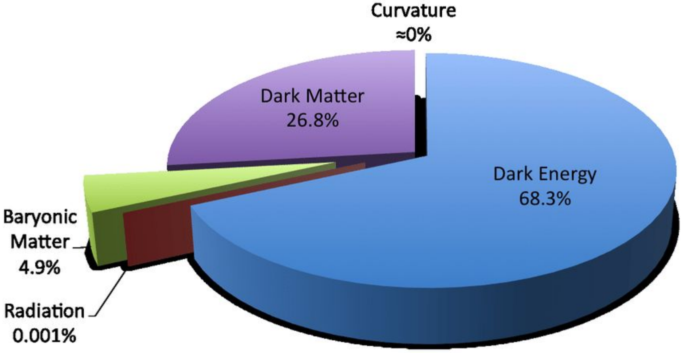


Outline

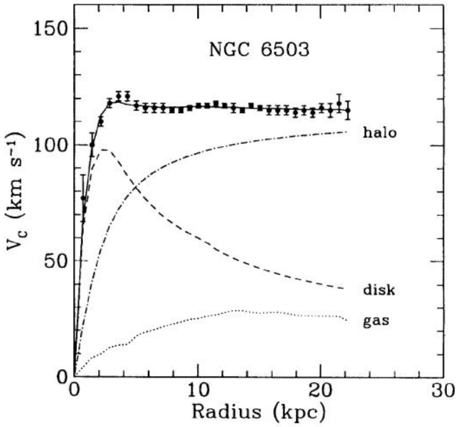
- Motivation: Dark Matter and CEνNS experiments
- The “Low Energy Excess” from the beginning
- The nature of the problem
- Studies, observations and possible explanations
- Conclusions and further developments

Motivation: dark matter particles

Several cosmological observations suggest that ~25% of the energy content of the universe is made of non baryonic matter, namely **dark matter**.



The measured galaxy rotational speed requires additional non visible mass



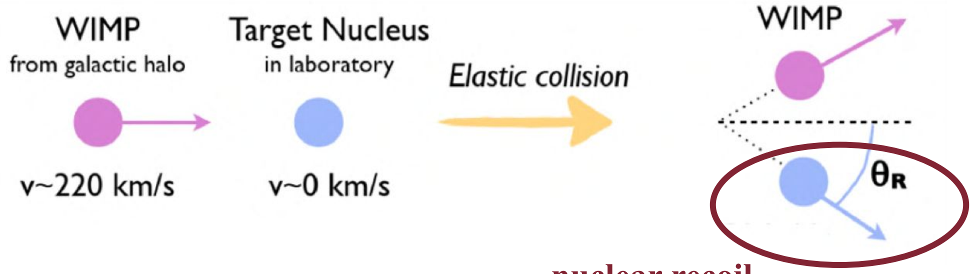
Dark matter inferred from gravitational lensing and cluster collisions

Many **different candidates** for dark matter (WIMPs, axions, MACHOs…) and experimental programs.

WIMPs are particles in the GeV-TeV mass range interacting at the weak scale with ordinary matter.
Valuable option since they predict the correct **dark matter abundance**.

Direct detection WIMPs experiments

Measure the **direct interaction** of a dark matter particle with **target nuclei** of the detector.



nuclear recoil

The observable is the **nuclear recoil** of the target. Its energy can go into:

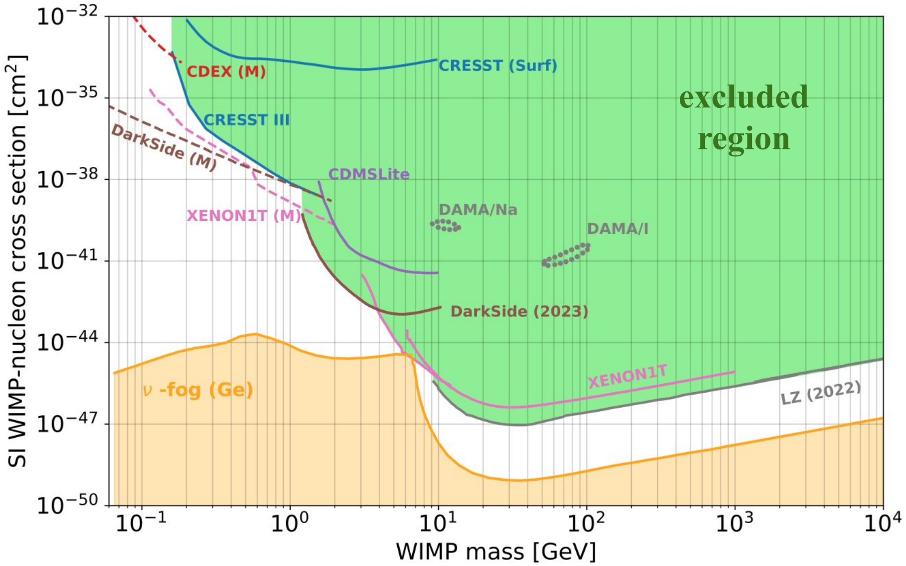
- **Electrons** (charge readout)
- **Photons** (light readout)
- **Phonons** (temperature readout)

The dark matter **interaction rate** depends on:

- **Cross section** with ordinary matter
- Dark matter **mass**

⇓

Measuring the rate, we measure these two parameters.
Or we **put a limit** if **no signal** is observed.
Up to now, only **upper limits** in the parameter space.

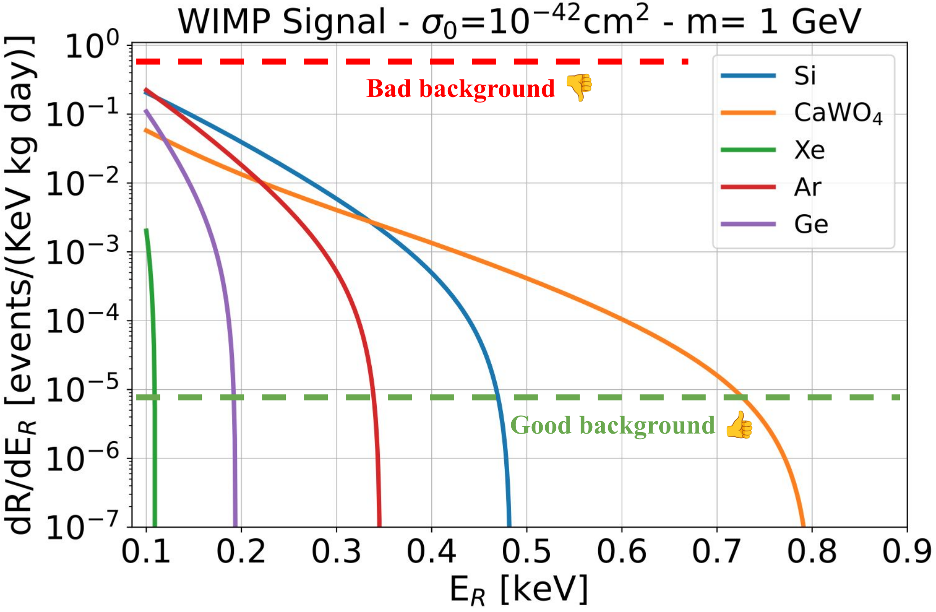


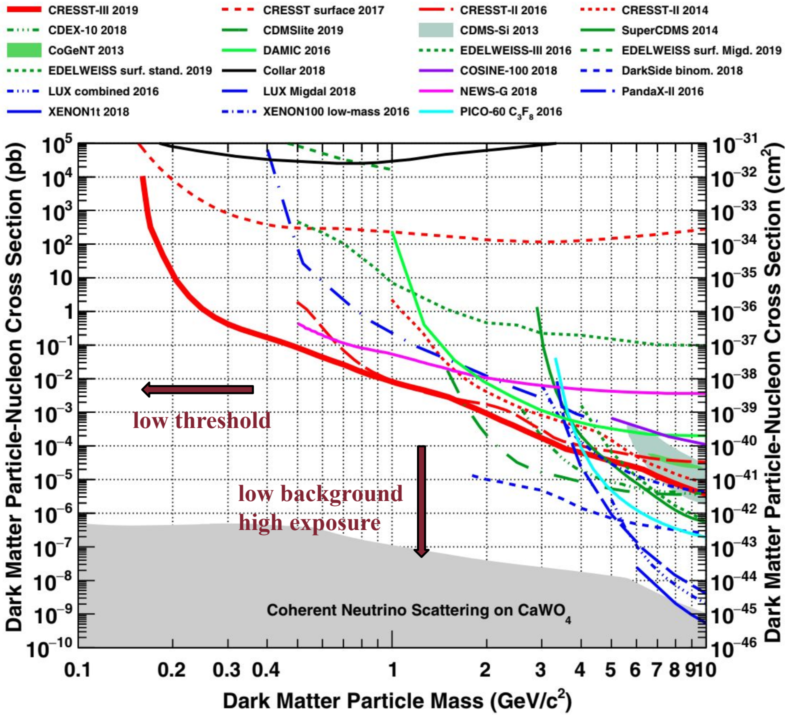
The recipe for a dark matter experiment

Every dark matter experiment needs:

- **Large target mass** to enhance the interaction probability
- **Low background** to detect the dark matter signal (few counts per year)

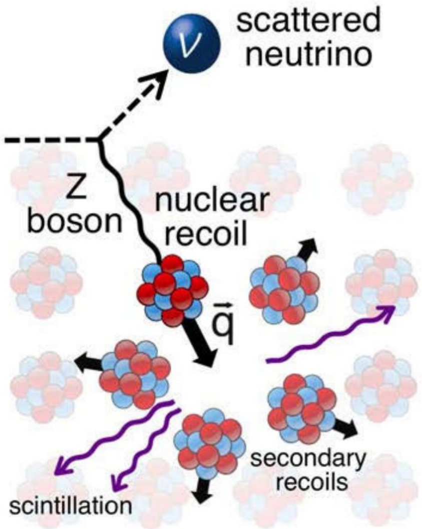
In recent years the interest moved to the unexplored region of **low mass dark matter** (0.1-1 GeV).
Need for **low energy threshold** O(100 eV), use solid state **phonon detectors**.





Another motivation: CEνNS

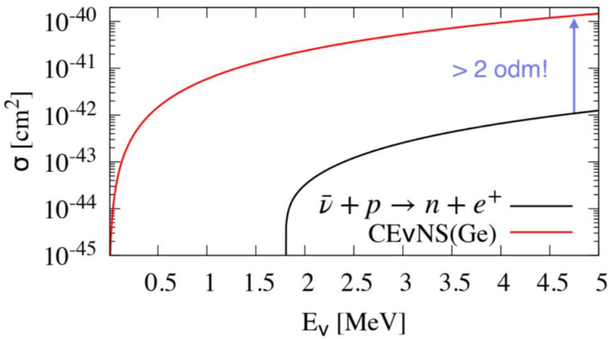
Coherent elastic neutrino-nucleus scattering (CEνNS) is a standard model process in which a low energy neutrino scatters neutrally with the whole atomic nucleus.



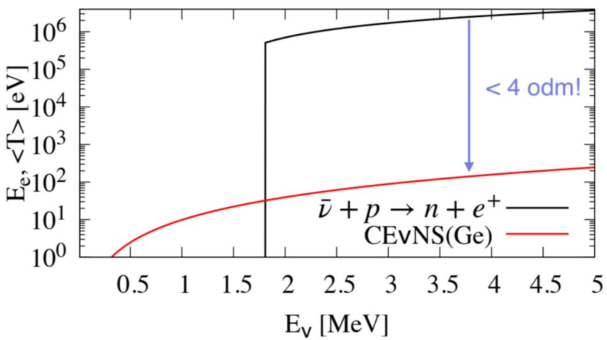
$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} E_\nu^2 Q_W^2 \left(1 - \frac{2E_\nu}{M_A}\right) F^2(q^2)$$

Enhanced at small momentum transfer q because of the nuclear form factor $F(q^2) \to 1$.

No energy threshold, large cross section compared to IBD



Very small recoil energies, up to few hundreds of eV



Same signal as dark matter, **same detector technology**.

Predicted in 1974, but firstly observed only in 2017 due to low recoil signals (doi.org/10.1126/science.aao0990).

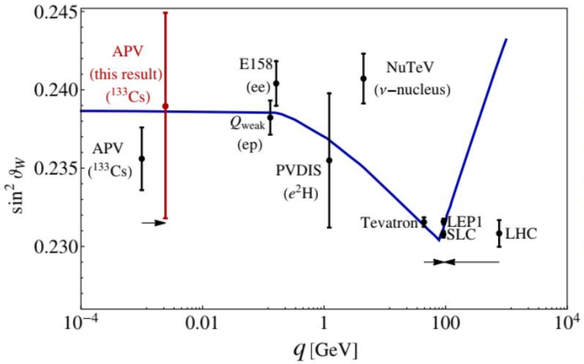
CEνNS applications

A **precise measurement** of the CEνNS cross section requires low energy neutrinos produced from reactors and has a broad range of applications, from **physics BSM** to **civil applications**.

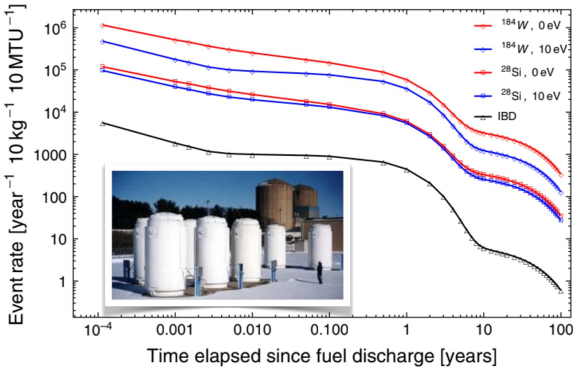
- Neutrino magnetic dipole moment
- Non standard neutrino interactions
- Weinberg angle at low q
- Nuclear form factors measurements

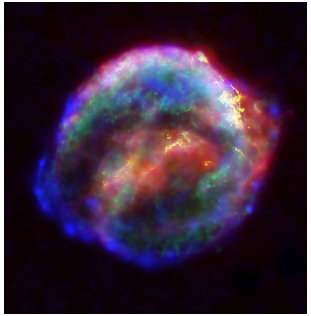
- Monitor reactor content for nuclear non-proliferation
- Monitor nuclear waste activity

- Supernova detection with neutrinos
- Measurement of the ultimate background in dark-matter experiments (neutrino floor)



Cadeddu, M and Dordei, F, Phys. Rev. D 99 (2019) 033010

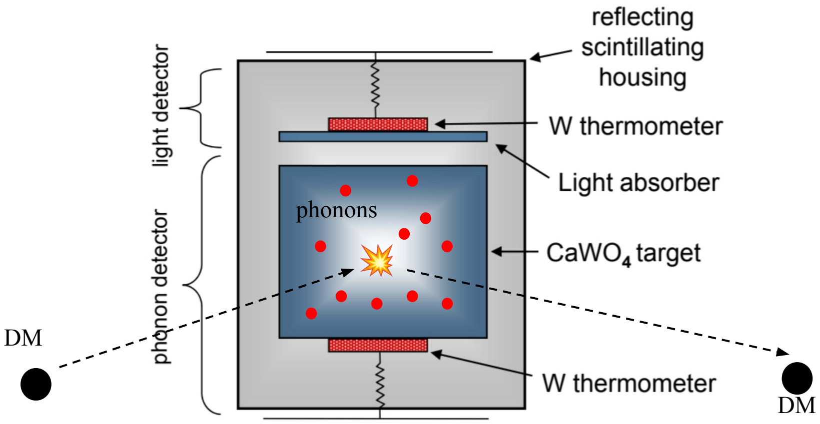


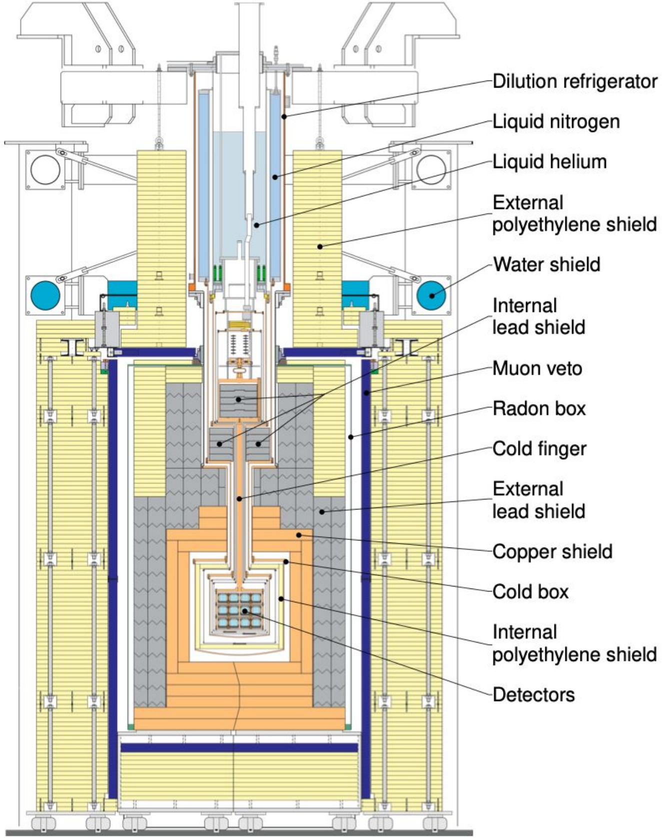


Also in this case, a low energy threshold and a low background level are **mandatory**.

The beginning: 2019 with CRESST experiment

CRESST probes the low mass region of DM parameter space with **phonon detectors**.



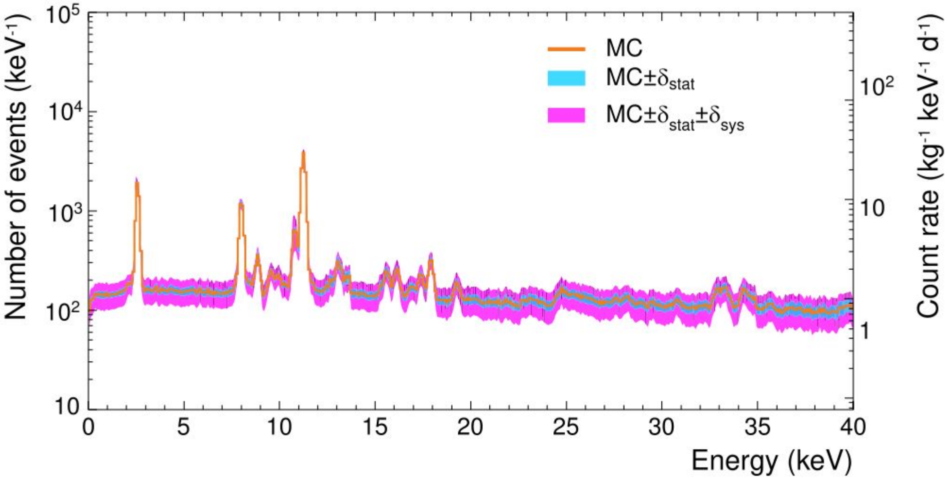


Phonons provide an extremely low **energy threshold of ~30 eV**.
Go underground at LNGS to reduce the cosmic background.
Use **passive and active shieldings** to further mitigate the background.

The beginning: 2019 with CRESST experiment

What CRESST expected to measure in absence of dark matter.

Background (simulated)



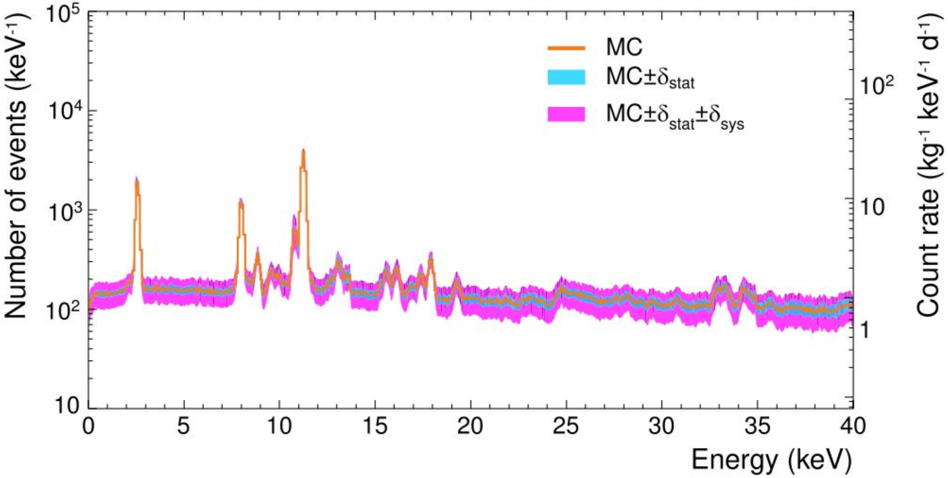
In DM and neutrino experiments the rate is expressed in **dark rate units** (dru): 1 dru = 1 count / (kg · keV · day). Expected CRESST background is flat at 1 dru.

The beginning: 2019 with CRESST experiment

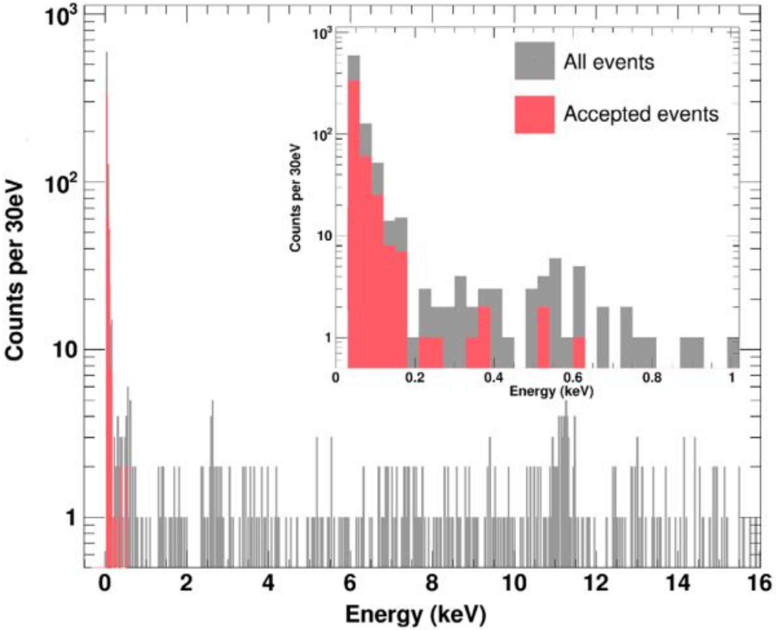
What CRESST expected to measure in absence of dark matter.

What CRESST measured.

Background (simulated)



Data

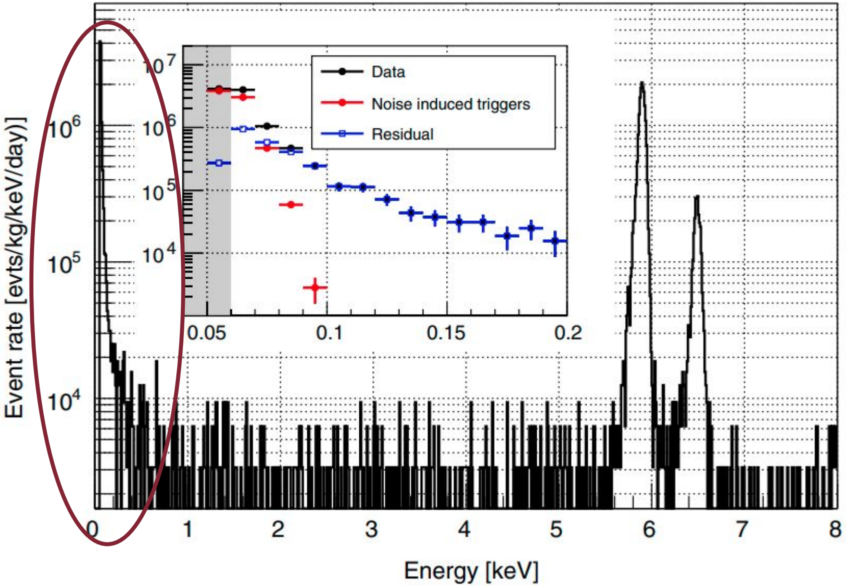


In DM and neutrino experiments the rate is expressed in **dark rate units** (dru): 1 dru = 1 count / (kg · keV · day).
Expected CRESST background is flat at 1 dru.
In data there is an additional **non-flat contribution**, rising at low energies. **Is it the dark matter signal????**

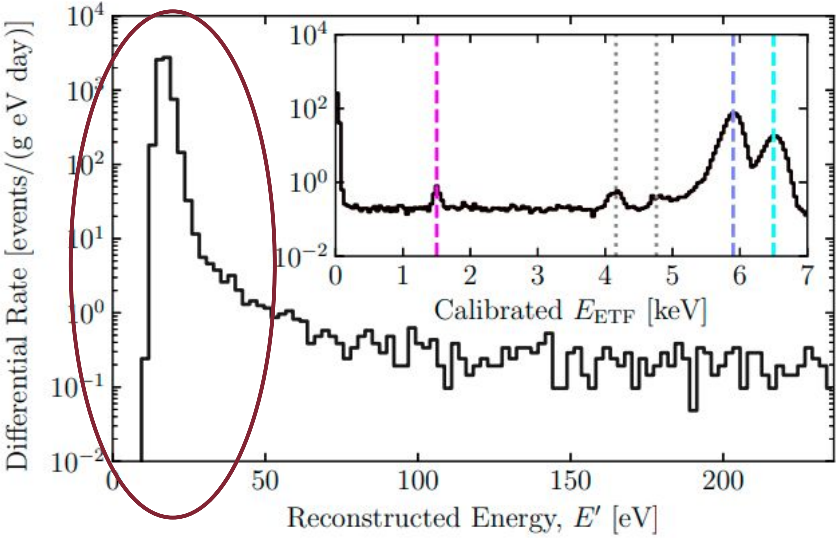
Not only CRESST

Soon other low threshold phonon experiments started to observe the same rising of events at low energies.

EDELWEISS (2019)



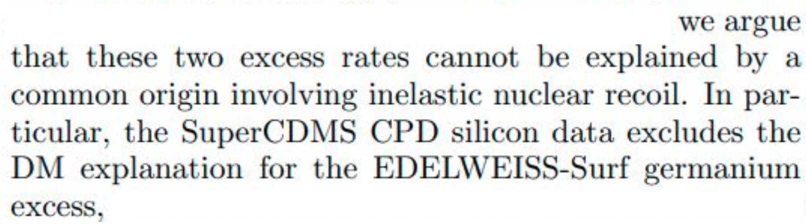
SuperCDMS (2020)



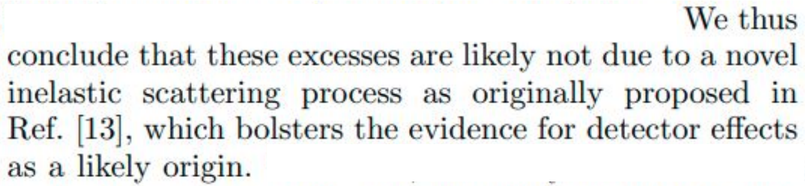
Never compatible with known backgrounds. **Is it the dark matter signal????**

LEE: a new terrible source of background

A common **dark matter explanation** has been quickly **discarded**. The rate and the shape are not compatible between different experiments.



we argue that these two excess rates cannot be explained by a common origin involving inelastic nuclear recoil. In particular, the SuperCDMS CPD silicon data excludes the DM explanation for the EDELWEISS-Surf germanium excess,



We thus conclude that these excesses are likely not due to a novel inelastic scattering process as originally proposed in Ref. [13], which bolsters the evidence for detector effects as a likely origin.

doi.org/10.1103/PhysRevD.105.123002

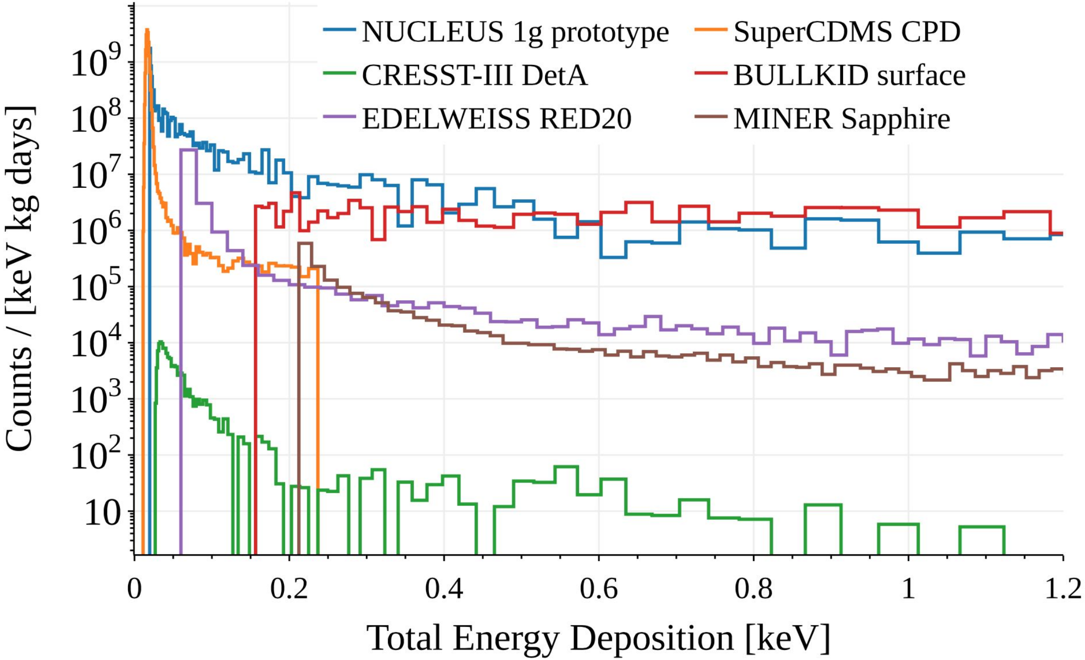
This excess of events is a background!
Now it is known as the **“Low Energy Excess”** (LEE).

- Rising at low energy, in the signal region
- Orders of magnitude higher than known backgrounds and signals, but with ~ the signal shape
- Unknown origin, so unknown mitigation strategies

The **worst possible background** that can happen to a rare events experiment!

Current status of the LEE

Present in ~ all experiment using phonons, with different energy thresholds and different background levels.



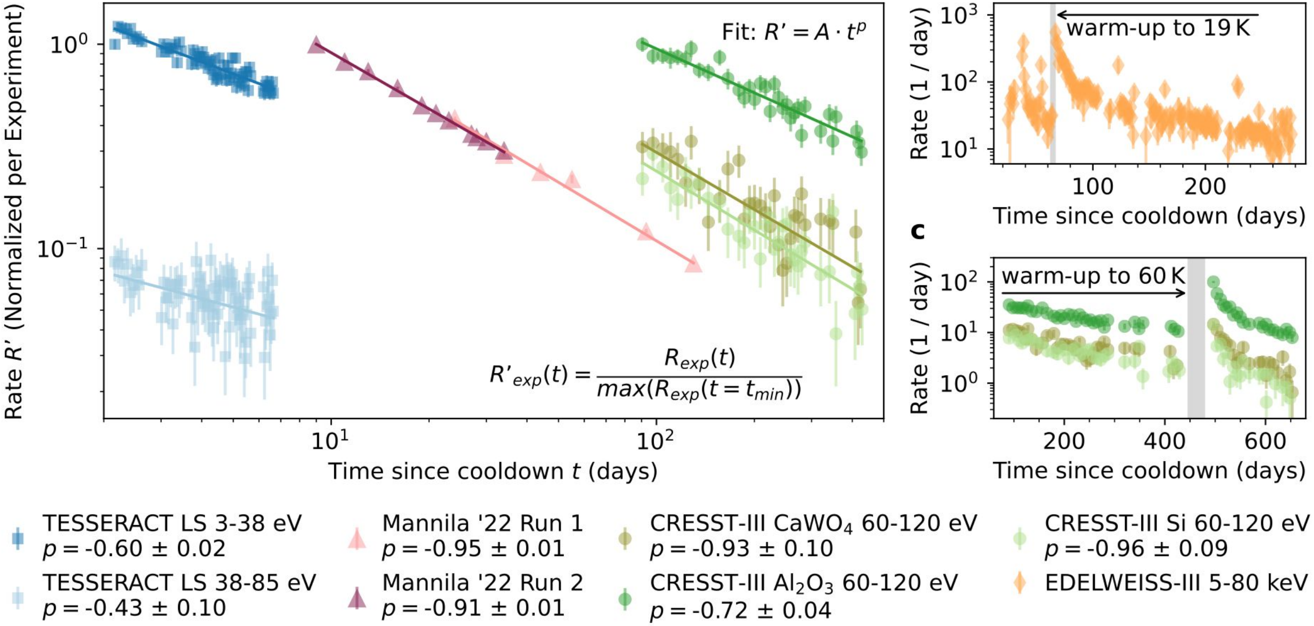
The experiment joined their force and they are collaborating to understand the LEE, with a series of dedicated measurements. Here I will show some results of those studies.

Decreases with time after cooldown

These detectors have to be cooled to **O(10 mK) temperatures**.

LEE rate **decreases** with time **after the cooldown**, and is **re-enhance after warm-up**.

Fitted with a power law, but the data are also well described by exponentials. **Time constants ranging from days to months**.

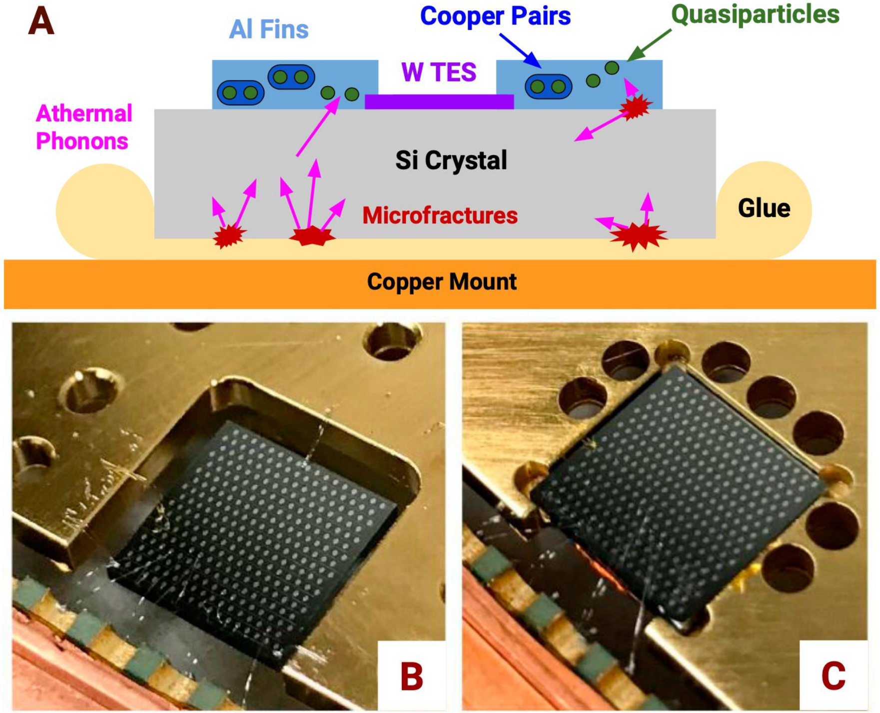


This observation is incompatible with LEE being mainly induced by particle interactions. It points towards **solid state effects**:

- Stress from detector holders
- Stress from sensors
- Energy stored in crystal defects

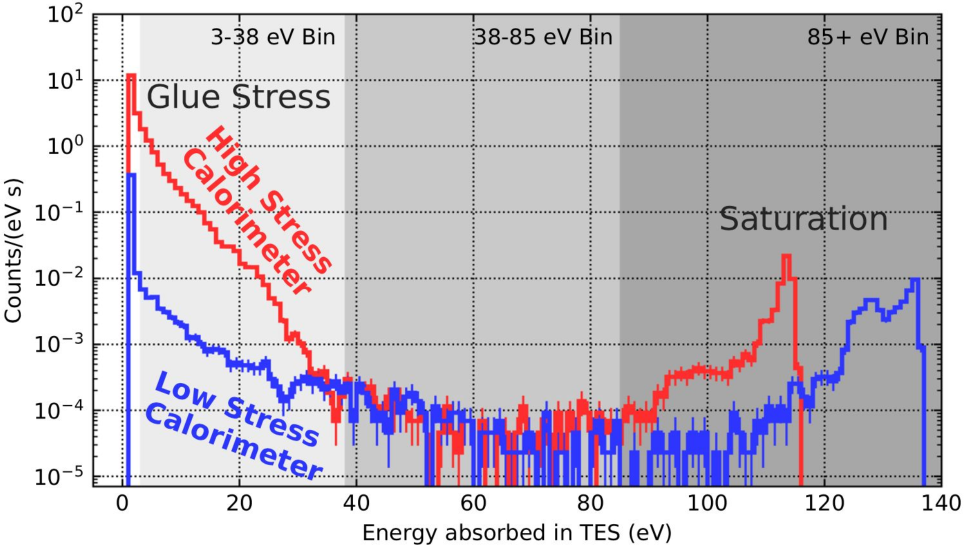
Stress from holder structure

Different thermal contractions between holder and crystal can create stress on the surface that release energy gradually.



Low stress, suspended crystal.
Does not touch the holder.

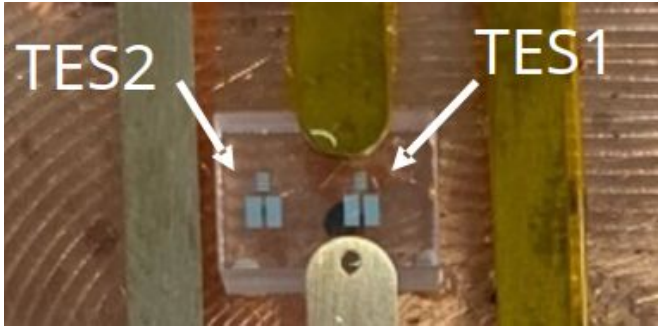
High stress, glued crystal.
Does touch the holder.



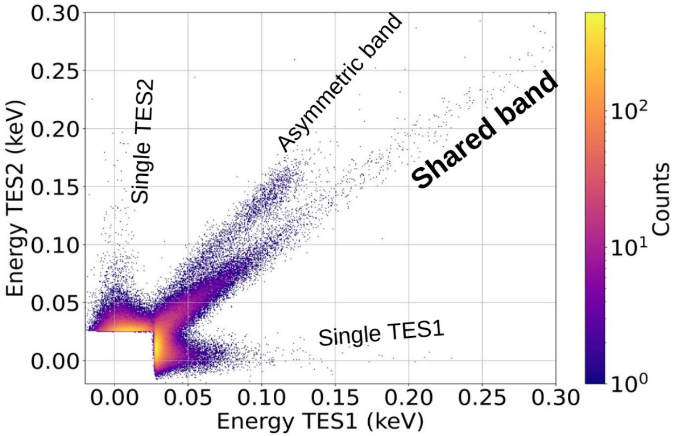
Clearly holder related events have an impact on LEE.
Maybe not the dominant component.

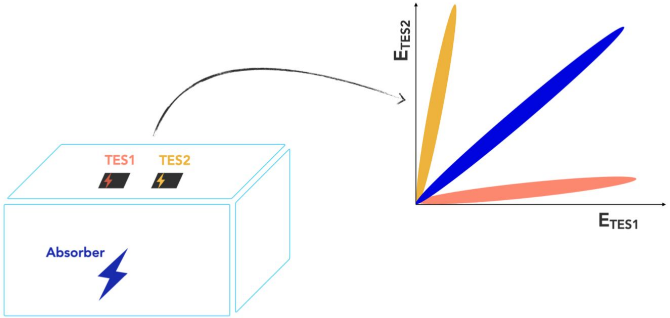
Stress from sensors

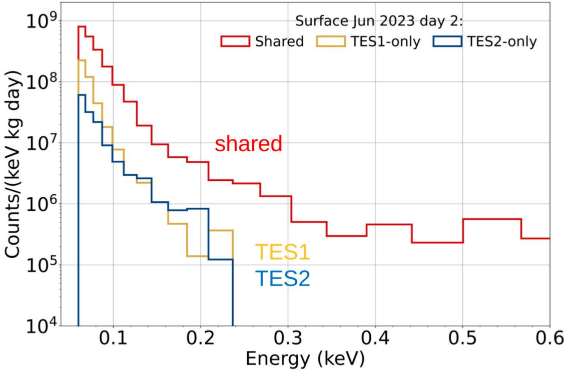
Stress events can also be originated in the interface between the absorber (crystal) and the sensor (metal). By putting **two sensors on the same absorber** we can discriminate between sensor events (singles) and absorber events (shared).



Events in the absorber are seen by both sensors, “**Shared band**”. Events created in a sensor are seen only by that sensor, “**Singles**”.







These sensor events **contribute to the LEE**. Here they are **subdominant**, but their impact can depend on the experiment or on the setup.

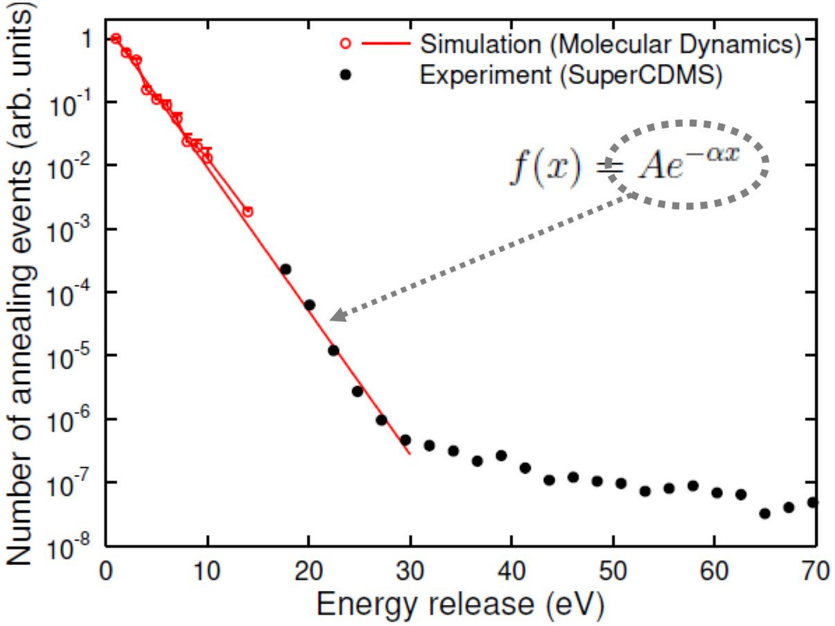
Crystal defects

Defects in the crystal lattice can store energy, which can be released after relaxation.

Energy released in the crystal (from radiation or impurities decays) → Damage in the crystal → Recombination and energy release

Simulation of low temperature solid state dynamics.
Only the slope must be compared.

Good agreement between data and simulation.



To understand the LEE the **collaboration with solid state physicists** is needed!

Current status of the LEE

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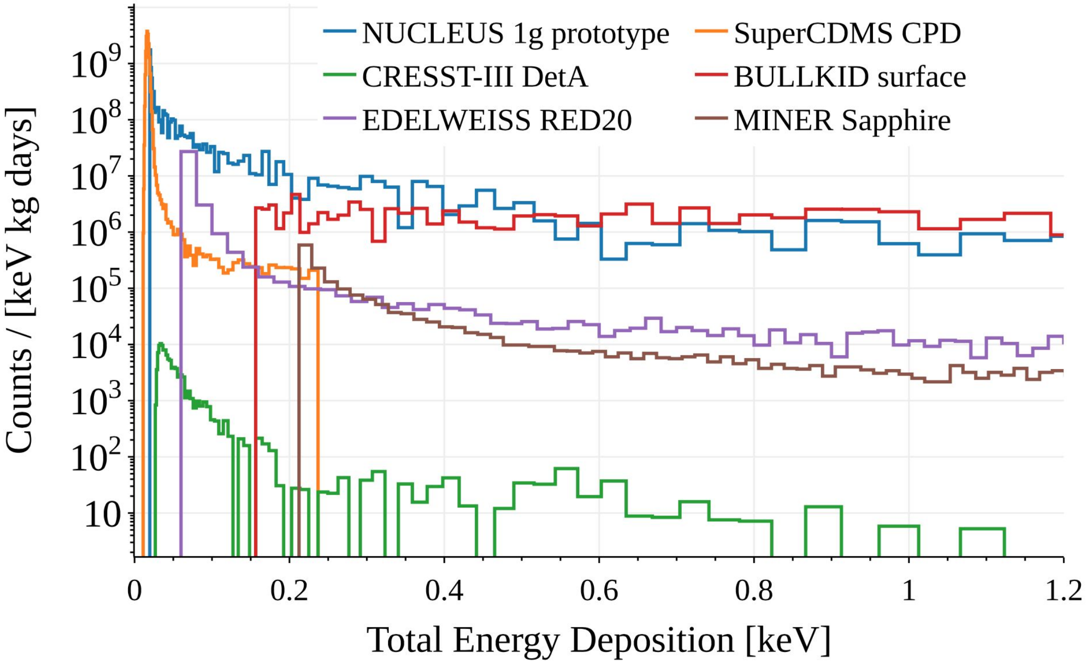

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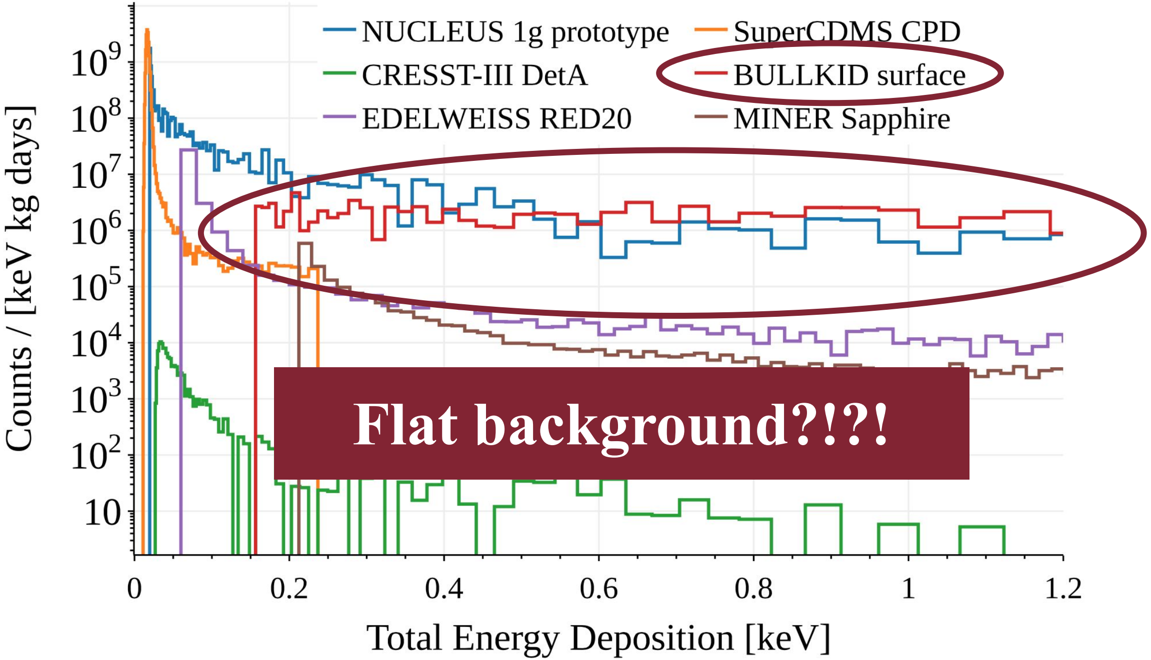

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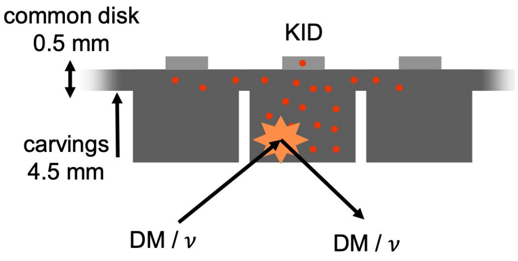
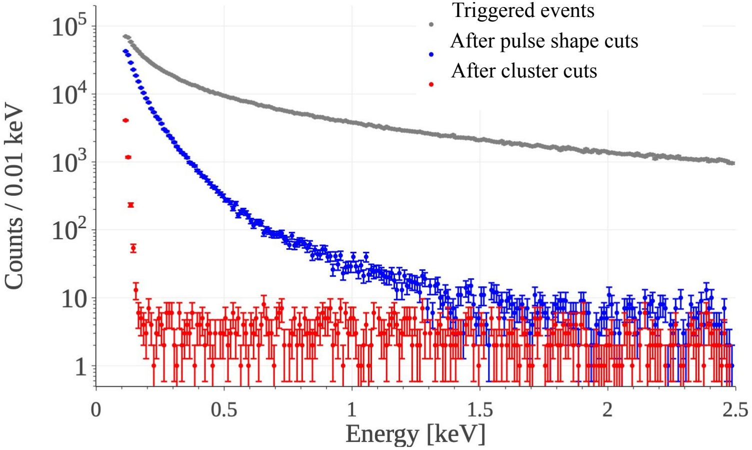
BULLKID and its background @Sapienza

DM detector using a Si absorber and Kinetic Inductance Detector as sensors. Phonons in an absorber can leak towards other pixels.



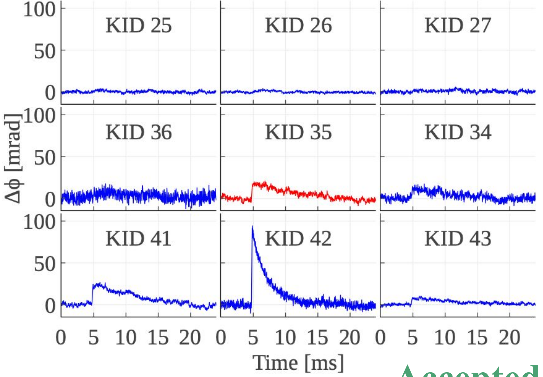


We can identify if the interaction happened in the pixel under analysis or if it is a phonon leakage from nearby pixels.

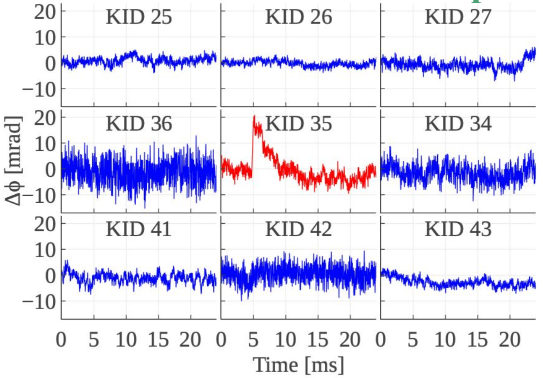
With this “**cluster cut**” the rise at low energy is discarded and **the final spectrum is flat**.

This result must be confirmed with a lower background and a lower threshold (here was 160 eV).

Discarded



Accepted



Conclusions

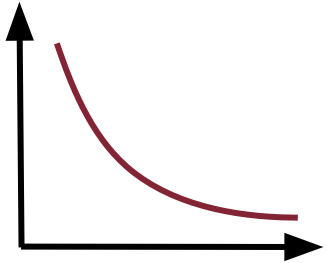
- The “Low Energy Excess” is a rise of background events at low energies, affecting low threshold detectors used in dark matter and neutrino searches

- A complete understanding of the causes is still unknown, and this is seriously limiting the sensitivity of these experiments

- Several hypotheses have been made, supported by observations (stress from holders/sensors, crystal defects, leakage from nearby interactions…)

- LEE seems to have many causes, and experiments are preparing combined mitigation strategies (instrumented holders, double readout, vetoing…), in combination with measurement used to address the problem

thanks for your attention!



EXCESS Workshop

From 2022, there is a dedicated workshop on this topic, the **EXCESS Workshop**, with many collaborations involved.

[EXCESS 2024 in Rome]

References (some)

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- BULLKID flat background doi.org/10.1140/epjc/s10052-024-12714-9

List of acronyms

- DM: Dark Matter
- WIMPs: Weakly Interacting Massive Particles
- MACHOs: MAssive Compact Halo Objects
- CEνNS: Coherent Elastic Neutrino Nucleus Scattering
- IBD: Inverse Beta Decay
- BSM: Beyond Standard Model
- LNGS: Laboratori Nazionali del Gran Sasso
- dru: dark rate units (counts/(kg · keV · day))
- LEE: Low Energy Excess
- TES: Transition Edge Sensor
- KID: Kinetic Inductance Detector