EXCESS workshop: a community effort towards understanding low energy excesses

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1 Fermi National Accelerator Laboratory
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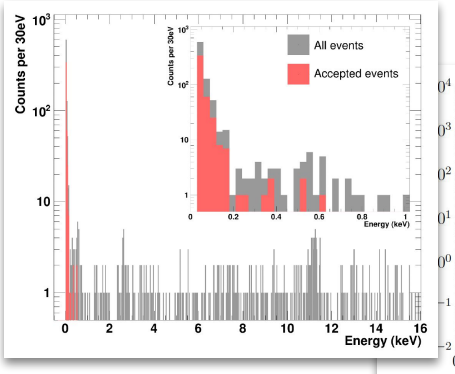
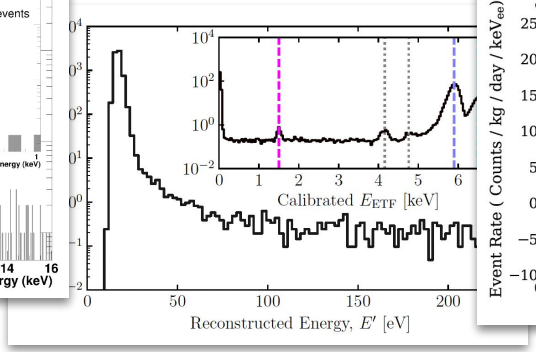
on behalf of the EXCESS workshop team
XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP 2023), August 31, 2023

Low energy excesses

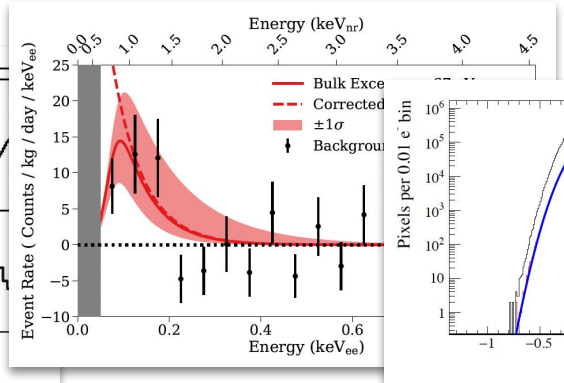
Phys. Rev. D 100, 102002



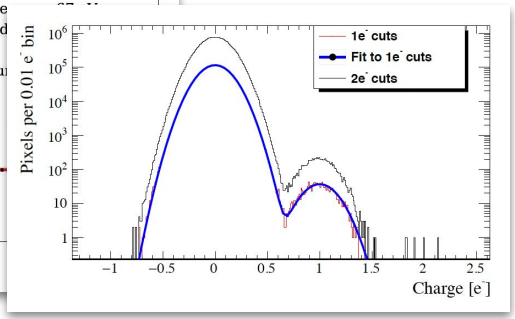
Phys. Rev. Lett. 127, 061801



Phys. Rev. Lett. 125, 241803

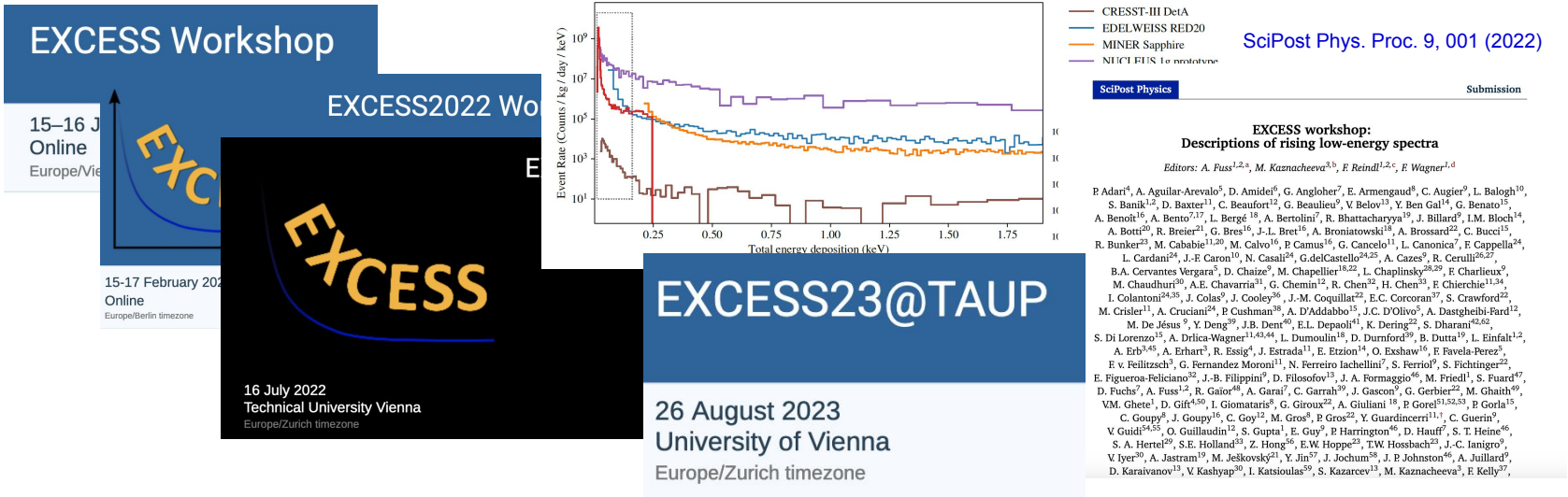


Phys. Rev. Lett. 125, 171802



Status 2020: experiments have successfully lowered their recoil energy thresholds, down to ~10 eV. On these energy scales, they observe excesses above known backgrounds, with steeply rising rate towards lower energies in **cryogenic**, **CCD-like** and **gaseous ionization detectors**.

The EXCESS workshop series



SciPost Phys. Proc. 9, 001 (2022)

SciPost Physics Submission

EXCESS workshop: Descriptions of rising low-energy spectra

Editors: A. Fuss[1,2,a], M. Kaznacheeva[3,b], F. Reindl[1,2,c], F. Wagner[1,d]

P. Adari[4], A. Aguilar-Arevalo[5], D. Amidei[6], G. Angloher[7], E. Armengaud[8], C. Augier[9], L. Balogh[10], S. Banik[1,2], D. Baxter[11], C. Beaufort[12], G. Beaulieu[9], V. Belov[13], Y. Ben Gal[14], G. Benato[15], A. Benoît[16], A. Bento[7,17], L. Bergé[18], A. Bertolini[7], R. Bhattacharyya[19], J. Billard[9], I.M. Bloch[14], A. Botti[20], R. Breier[21], G. Bres[16], J.-L. Bret[16], A. Broniatowski[18], A. Brossard[22], C. Bucci[15], R. Bunker[23], M. Cababie[11,20], M. Calvo[16], P. Camus[16], G. Cancelo[11], L. Canonica[7], F. Cappella[24], L. Cardani[24], J.-F. Caron[10], N. Casali[24], G.delCastello[24,25], A. Cazes[9], R. Cerulli[26,27], B.A. Cervantes Vergara[5], D. Chaize[9], M. Chapellier[18,22], L. Chaplinsky[28,29], F. Charlieux[9], M. Chaudhuri[30], A.E. Chavarria[31], G. Chemin[12], R. Chen[32], H. Chen[33], F. Chierchie[11,34], I. Colantoni[24,35], J. Colas[9], J. Cooley[36], J.-M. Coquillat[22], E.C. Corcoran[37], S. Crawford[22], M. Crisler[11], A. Cruciani[24], P. Cushman[38], A. D'Addabbo[15], J.C. D'Olivo[5], A. Dastgheibi-Fard[12], M. De Jésus[9], Y. Deng[39], J.B. Dent[40], E.L. Depaoli[41], K. Dering[22], S. Dharani[42,62], S. Di Lorenzo[15], A. Drlica-Wagner[11,43,44], L. Dumoulin[18], D. Durnford[39], B. Dutta[19], L. Einfalt[1,2], A. Erb[3,45], A. Erhart[3], R. Essig[4], J. Estrada[11], E. Etzion[14], O. Exshaw[16], F. Favela-Perez[5], F. v. Feilitzsch[3], G. Fernandez Moroni[11], N. Ferreiro Iachellini[7], S. Ferriol[9], S. Fichtinger[22], E. Figueroa-Feliciano[32], J.-B. Filippini[9], D. Filosofov[13], J. A. Formaggio[46], M. Friedl[1], S. Fuard[47], D. Fuchs[7], A. Fuss[1,2], R. Gaïor[48], A. Garai[7], C. Garrah[39], J. Gascon[9], G. Gerbier[22], M. Ghaith[49], VM. Ghete[1], D. Gift[4,50], I. Giomataris[8], G. Giroux[22], A. Giuliani[18], P. Gorel[51,52,53], P. Gorla[15], C. Goupy[8], J. Goupy[16], C. Goy[12], M. Gros[8], P. Gros[22], Y. Guardincerri[11,†], C. Guerin[9], V. Guidi[54,55], O. Guillaudin[12], S. Gupta[1], E. Guy[9], P. Harrington[46], D. Hauff[7], S. T. Heine[46], S. A. Hertel[29], S.E. Holland[33], Z. Hong[56], E.W. Hoppe[23], T.W. Hossbach[23], J.-C. Ianigro[9], V. Iyer[30], A. Jastram[19], M. Ješkovský[21], Y. Jin[57], J. Jochum[58], J. P. Johnston[46], A. Juillard[9], D. Karaivanov[13], V. Kashyap[30], I. Katsioulas[59], S. Kazarcev[13], M. Kaznacheeva[3], F. Kelly[37],

We started a community effort to study the observations & learn more about the new backgrounds.

“New physics” origin of excesses mostly excluded - but possibly **“previously not directly observed physics phenomena”** at (partially) low temperatures and energies.

Status 2023: Fourth workshop iteration attached to TAUP23.

EXCESS23@TAUP

talks: 15+10

CCDs

08:00

Registration
University of Vienna 08:30 - 09:00

09:00

Welcome and Introduction *Felix Wagner*
University of Vienna 09:00 - 09:15

SENSEI: Origin and characterization of single-electron events *Mariano Cababie*
University of Vienna 09:15 - 09:40

CONNIE first results with Skipper-CCDs *Dr Alexis Aguilar-Arevalo*
University of Vienna 09:40 - 10:05

10:00

DAMIC-M: Background and Dark Current Studies with Low Background Chamber *Radomir Smida*
University of Vienna 10:05 - 10:30

Questions & Discussion
University of Vienna 10:30 - 10:35

CCDs

11:00

Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs *Dr Michelangelo Traina*
University of Vienna 11:00 - 11:25

Questions & Discussion
University of Vienna 11:25 - 11:30

Improved Modeling of Charge Trapping and Impact Ionization in SuperCDMS HVeV detectors *Alexander Zaytsev*
University of Vienna 11:30 - 11:55

Cryogenic detectors

12:00

Heat-Only background discrimination in EDELWEISS and RICOCHET cryogenic germanium detectors
Prof. Jules GASCON

Low energy excess in a diamond-MMC (MAGNETO) and a STJ (BeEST) detectors *Geon-Bo Kim*
University of Vienna 12:20 - 12:45

Questions & Discussion
University of Vienna 12:45 - 12:50

13:00

Cryogenic detectors

14:00

Observations of the LEE in a Two Channel SPICE Athermal Phonon Detector *Roger Romani*
University of Vienna 13:50 - 14:15

The low energy excess in CRESST-III *Dominik Fuchs*
University of Vienna 14:15 - 14:40

CRESST/NUCLEUS: Results of doubleTES detectors *Francesca Pucci*
University of Vienna 14:40 - 15:05

15:00

The low energy spectrum of BULLKID *Marco Vignati*
University of Vienna 15:05 - 15:30

Questions & Discussion
University of Vienna 15:30 - 15:35

Panel discussion

16:00

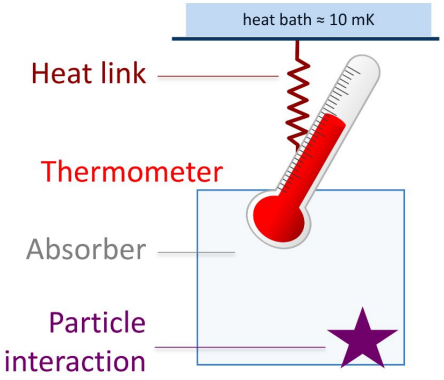
Panel Discussion *Christian Enss et al.*
University of Vienna 16:00 - 17:30

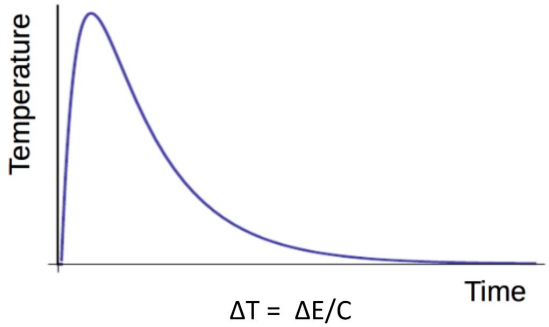
17:00

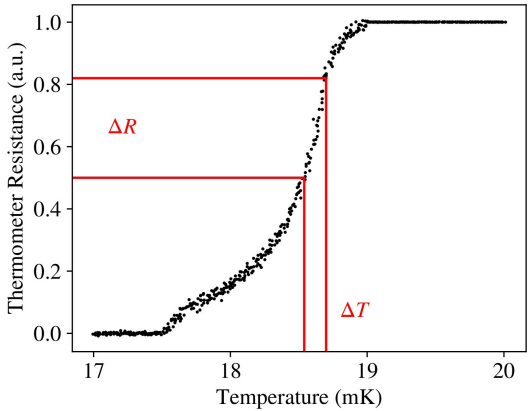
Closing remarks
University of Vienna 17:30 - 17:35

Christian Enss, Heidelberg University
Daniel Egana-Ugrinovic, Perimeter Institute
Jürgen Stockburger, Ulm University
Radomir Smida, University of Chicago
Vanessa Zema, Max Planck Institute for Physics

Cryogenic thermometers







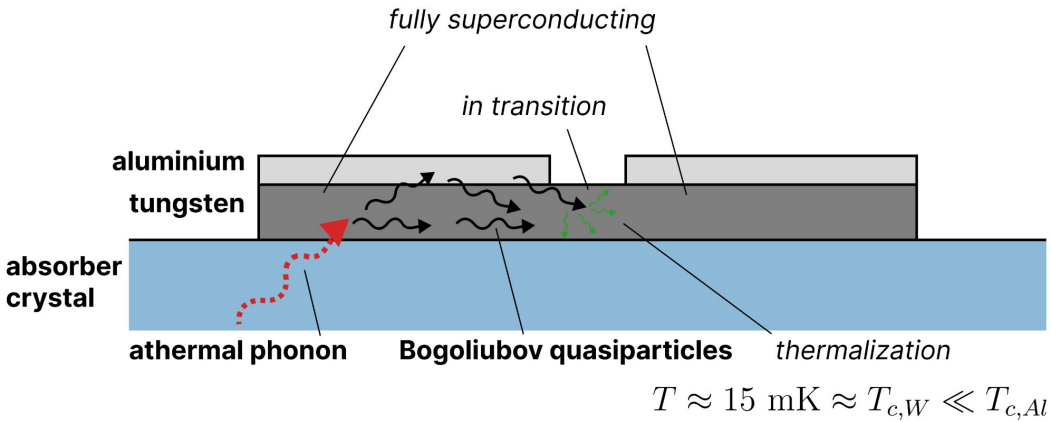
TES transition curve

Detection principle: measure the temperature rise in a sensor, induced by phonons from particle interaction. Operation at lowest temperatures (~10 mK).

Possible sensor types: TES, NTD, MMC, …

thermistor magnetic flux

Athermal phonon detection

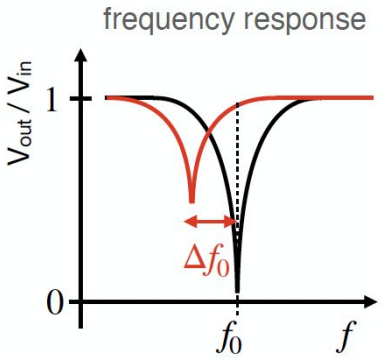


Modern, most sensitive detectors collect the **initial high-energy ("athermal") phonons** before they down-convert in the target crystal.

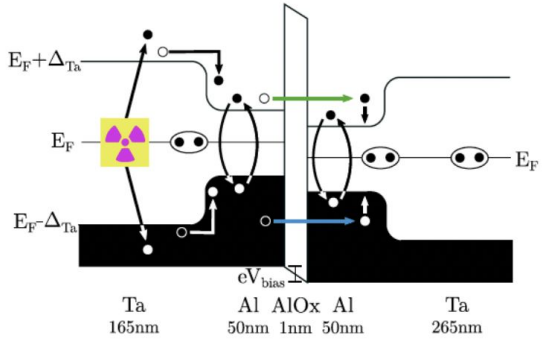
Detection principle: high energy phonon impact cause quasiparticles in superconducting film. They scatter with the thermometer, increasing its temperature.

Non-thermometer phonon detectors

KID Operating Principle



STJ Operating Principle

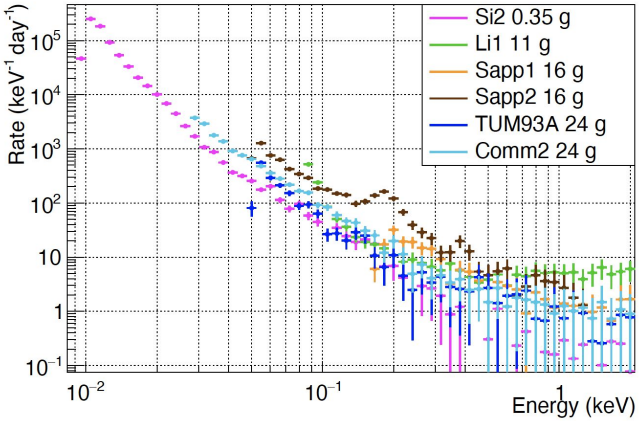


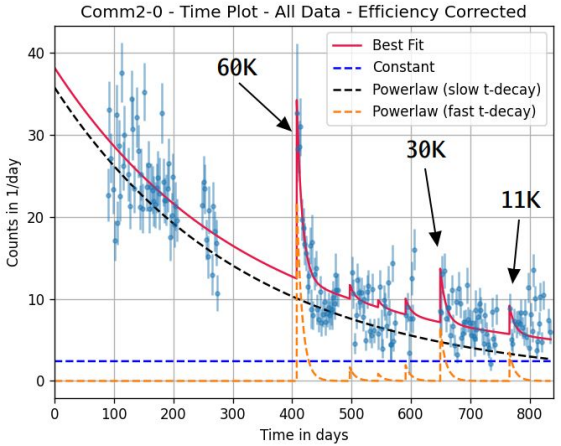
Detection principle: high energy phonon impact cause quasiparticles in superconducting film. Their movement induce measurable signal, e.g. frequency shift, tunneling current.

Possible sensor types: KID, STJ, …

Figs. by Marco Vignati, Geon-Bo Kim @EXCESS23TAUP

Excesses in cryogenic detectors





Dominik Fuchs @EXCESS23TAUP

CRESST (using TES) observes vastly different excess rates in detector modules, with **no obvious dependence on material and target size**.

Spectral shape can be described with a **two-component power law** fit.

The event rate decays after the cooldown of the experiment, on **two time scales of days and weeks**.

Similar observations by SuperCDMS, SPICE, EDELWEISS!

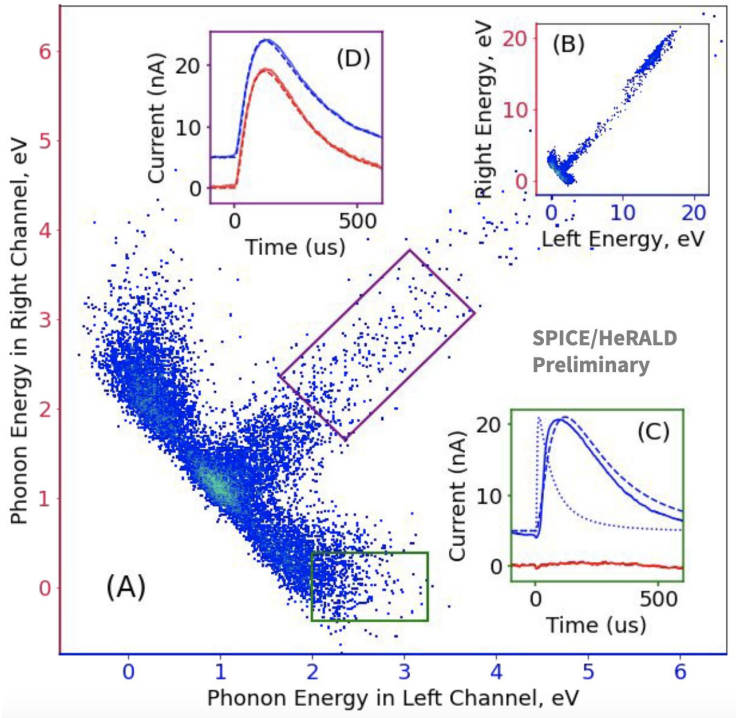
Excesses in cryogenic detectors

SPICE (also using TES): identification of sensor and crystal by simultaneous operation of **two sensors**.

Hints towards two processes: excess in **film and crystal**.

Sub-threshold excess contributes to sensor noise.

Relevant beyond astroparticles! Similarities with **quasiparticle poisoning** in superconducting qubits.



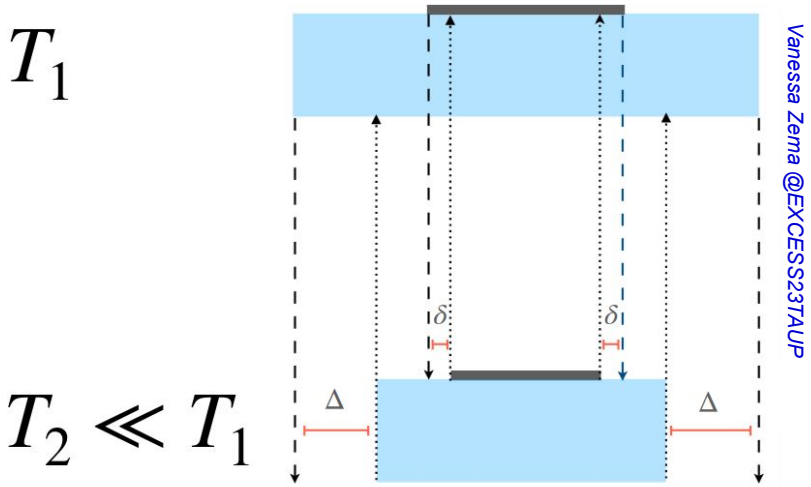
Roger Romani @EXCESS23TAUP

Similar observations by CRESST/NUCLEUS (see *Francesca Pucci @EXCESS23TAUP*)!

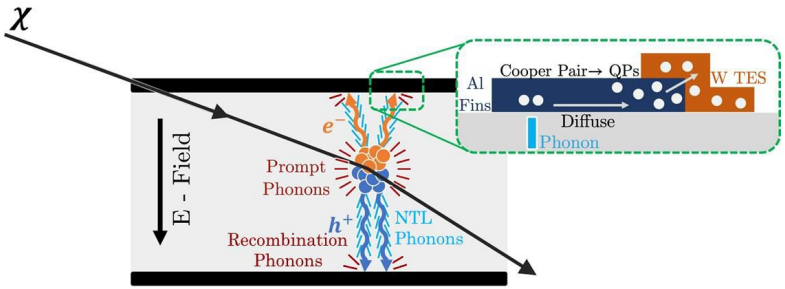
Thermal expansion coefficients

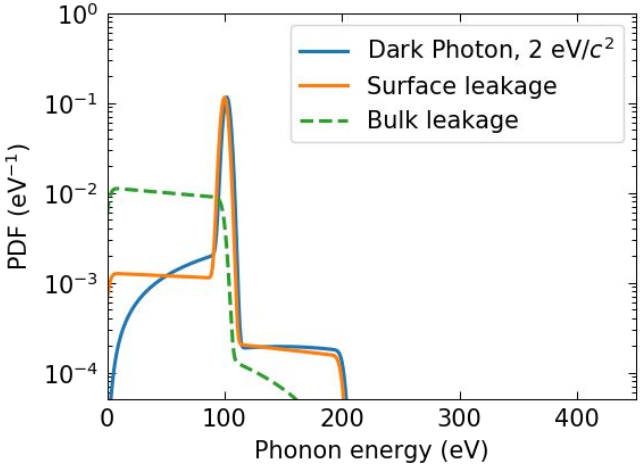
Mismatch between thermal expansion coefficients as a suspect for **crystal defect creation**?

Interesting observation: integrated energy released by excess events has same order of magnitude as elastic energy that should be released during the cooldown!



Mitigation strategies?





Alexander Zaytsev @EXCESS23TAUP

SuperCDMS: HVeV detector design boosts electron-hole pairs created in particle impact through **NTL effect**.

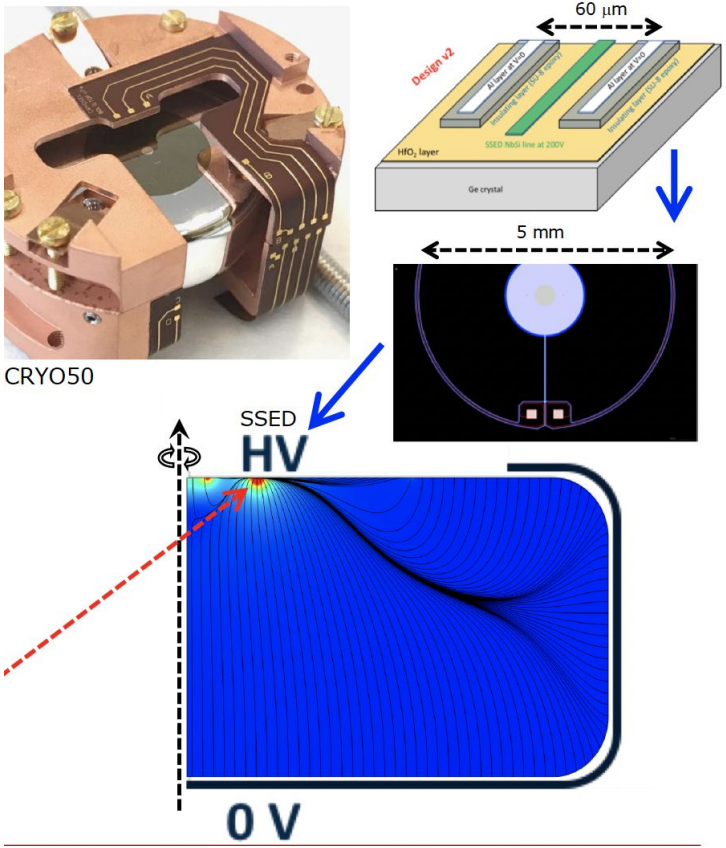
Can boost above (non-ionizing) low energy excess.

Much progress, e.g. **improved models of charge trapping and impact ionization**.

Mitigation strategies?

EDELWEISS has a history of observing (relatively) high energy **heat-only background** with NTDs.

EDELWEISS/RICOCHET/CRYOCUBE develops a new detector design (CRYOSEL) with **strong discrimination power for non-ionizing events**.

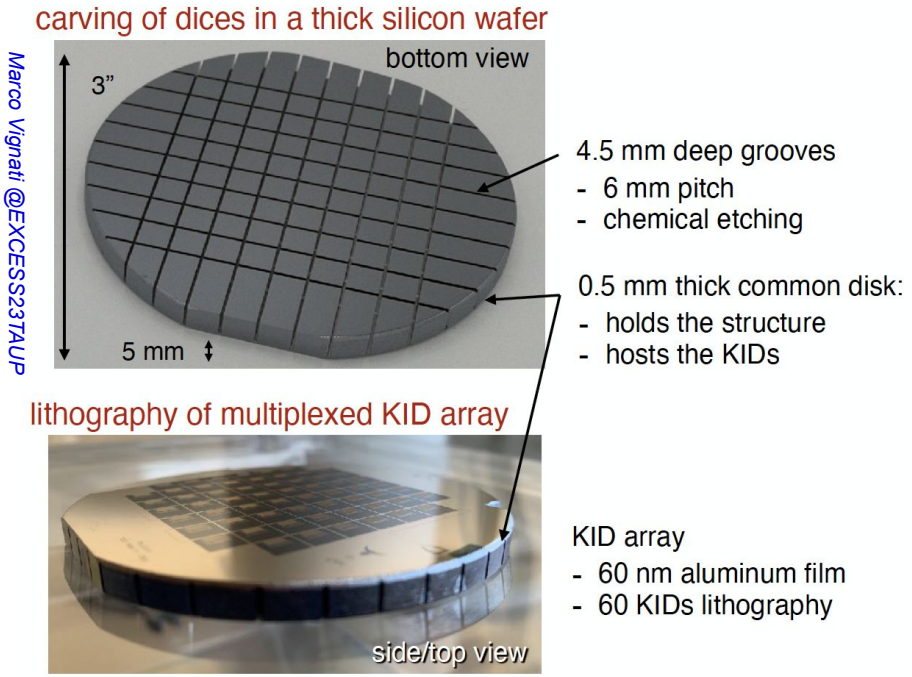


Mitigation strategies?

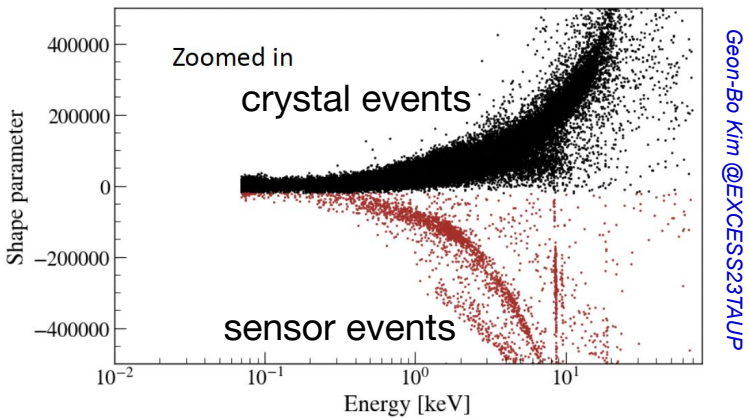
BULLKID operates an **array of KIDs** on joint wafer, separated by notches.

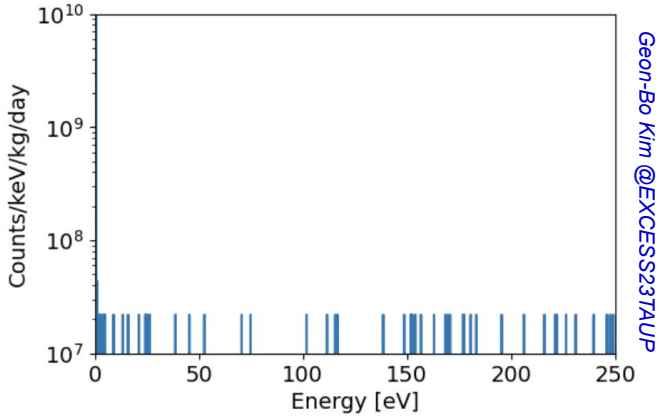
Allows for coincidence cuts between the notched cubes.

Results from first measurement: **no rise towards energy threshold of 160 eV** after data selection cuts.



First excess measurements with MMCs and STJs





MMC on remote pad, PSD of **crystal and sensor events** possible.

Largest share of LE events **in crystal**!

STJ: **no rise in event rate** towards threshold!

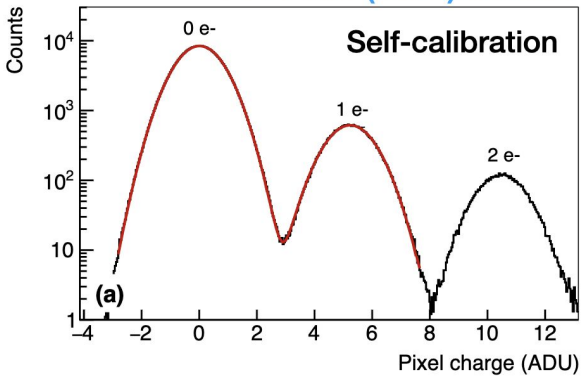
However, phonon collection efficiency unknown - energy scale might be off.

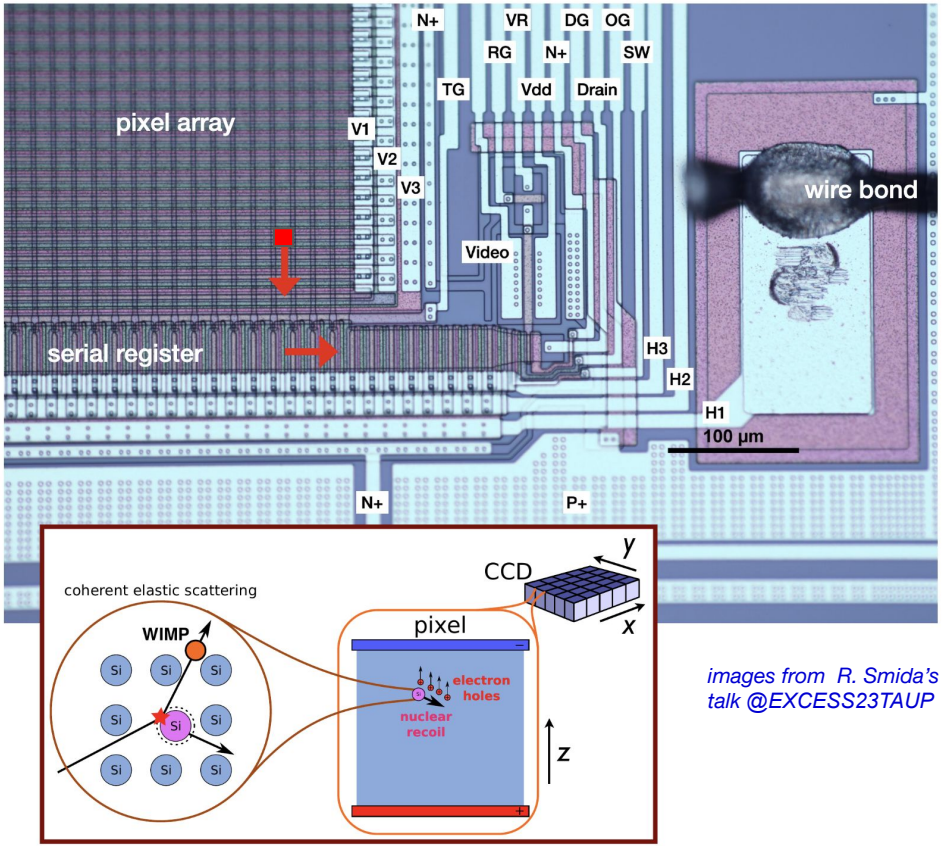
CCDs

Charge produced in a bulk silicon substrate is drifted to and collected in 15x15 micron^2 pixels over long (8-24hr) time exposures at 100-140K

- Incredible position resolution
- Quantized e^- sensitivity

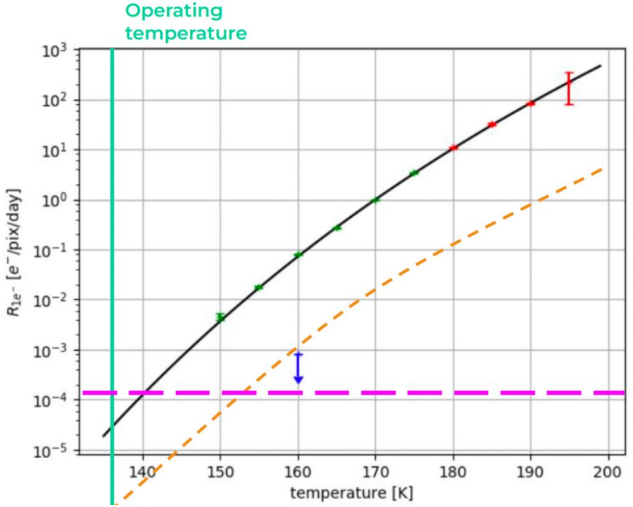
PRD 106 (2022) 092001



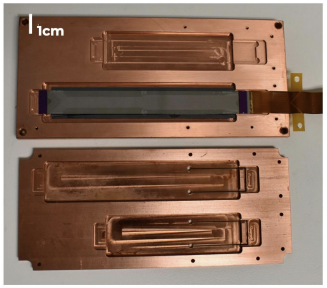


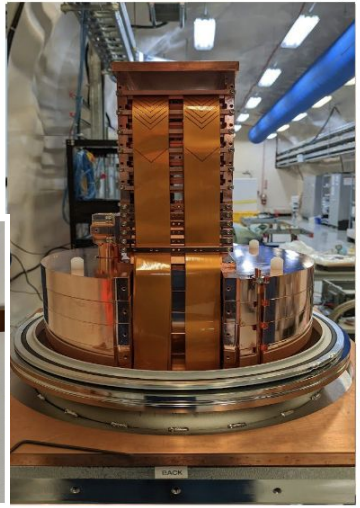
images from R. Smida's talk @EXCESS23TAUP

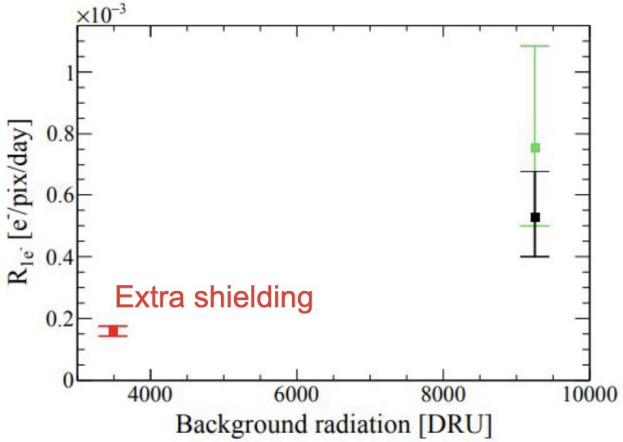
CCDs - SENSEI



images from M. Cababie's talk at workshop







-Skipper CCDs have achieved world-leading dark rates for single-electron sensing (SENSEI: ~1e-4 cts/pix/day)

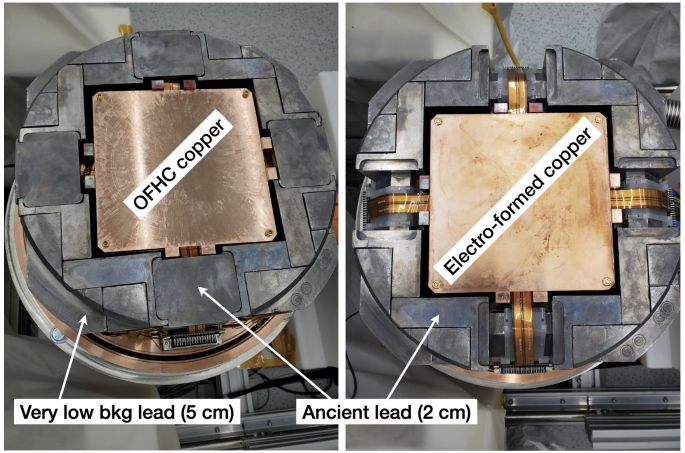
-Still some apparent radiation-dependence at this level

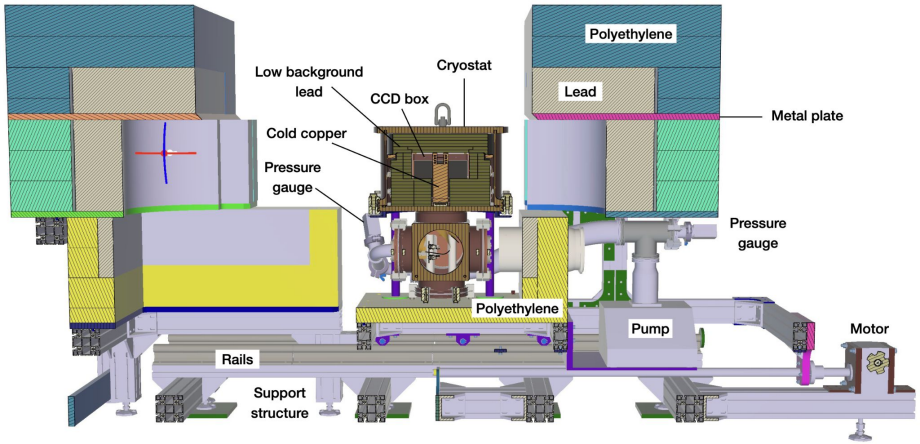
-Orders of magnitude above bulk expectation

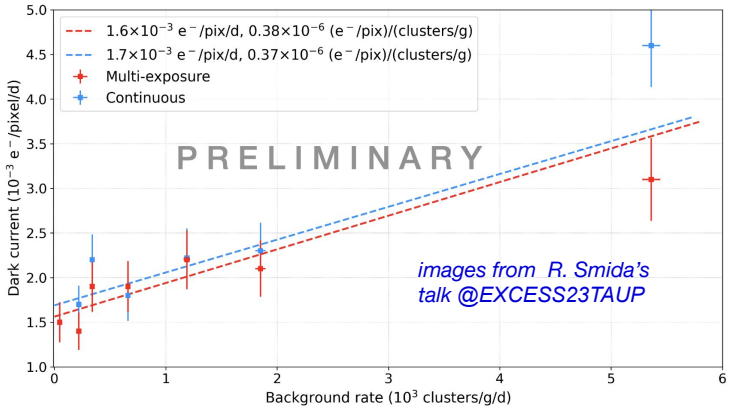
CCDs - DAMIC-M LBC

-Radiation-dependence also clear in DAMIC-M (LBC: ~1e-3 cts/pix/day)

-But the dark rate clearly also includes a non-radiogenic component (bot-right plot)

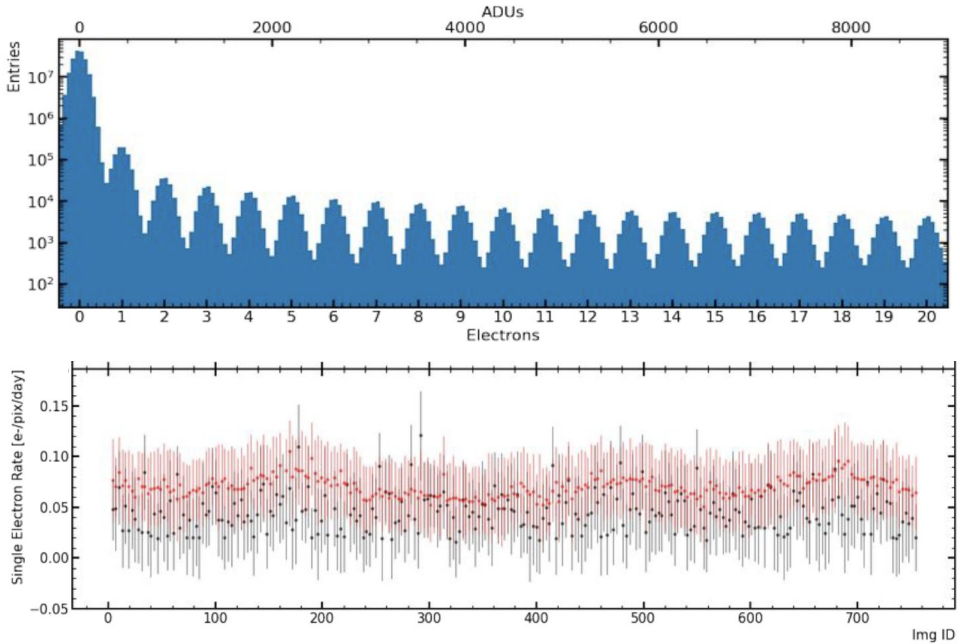


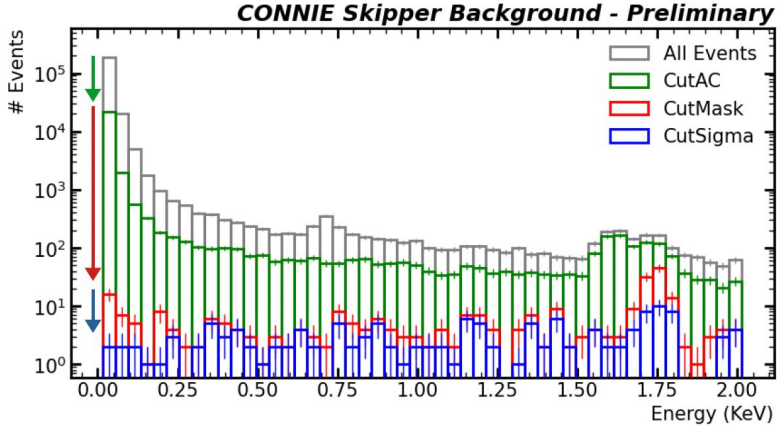




CCDs - CONNIE

-Can ***increase*** radiation-induced DC by going to a reactor (CE*v*NS detection)



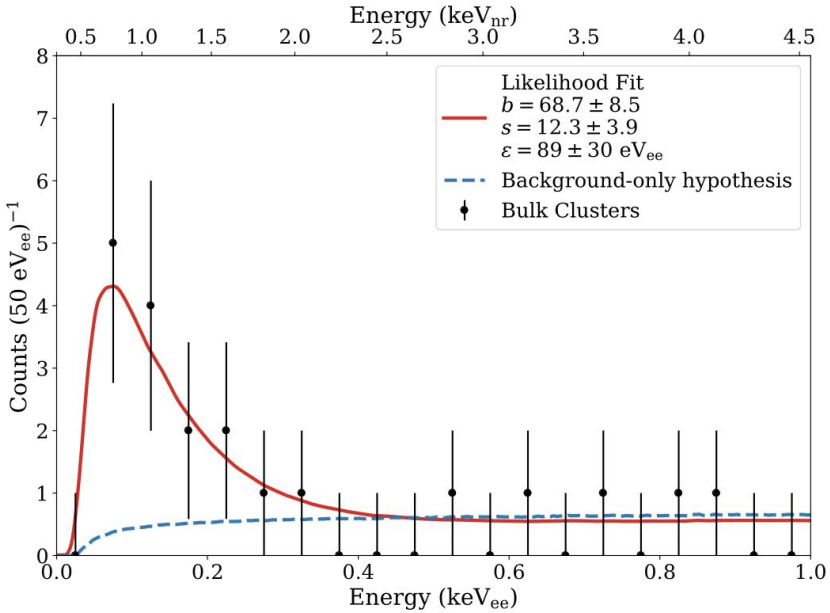


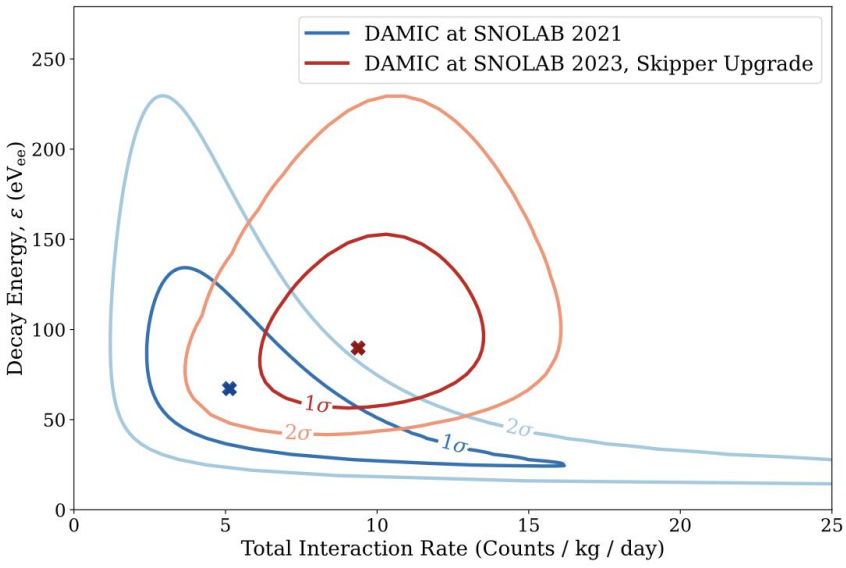
-CONNIE reduced their low energy background with quality cuts, masking, and fiducialization

-DC appears stable over time (CONNIE: ~5e-2 cts/pix/day)

images from A. Aguilar-Arevalo's talk @EXCESS23TAUP

CCDs - DAMIC at SNOLAB





Now verified with Skipper CCDs at >5σ, a bulk, spatially-uniform, temporally-constant excess of ~8 cts/kg-day below 200 eV$_{ee}$ (<1.5 keV$_{nr}$).

see M. Traina's talk @EXCESS23TAUP or in Parallel 7B earlier today

Panel of Experts

Vanessa Zema
CRESST, COSINUS

Radomir Smida
DAMIC, DAMIC-M

Christian Enss
DELight, HERON

Jürgen Stockburger
QSolid (theory)

Daniel Egaña-Ugrinovic
Skipper CCDs (theory)

Panel of Experts

We appear to be observing different manifestations of long-lived metastable states releasing energy in our systems

- Self-organized criticality
- Long-lived states can store massive amounts of energy >MeV that gets released in small bursts

- How do you remove long-lived stored energy in a system?
- **Analogy: How do you prevent an avalanche?**

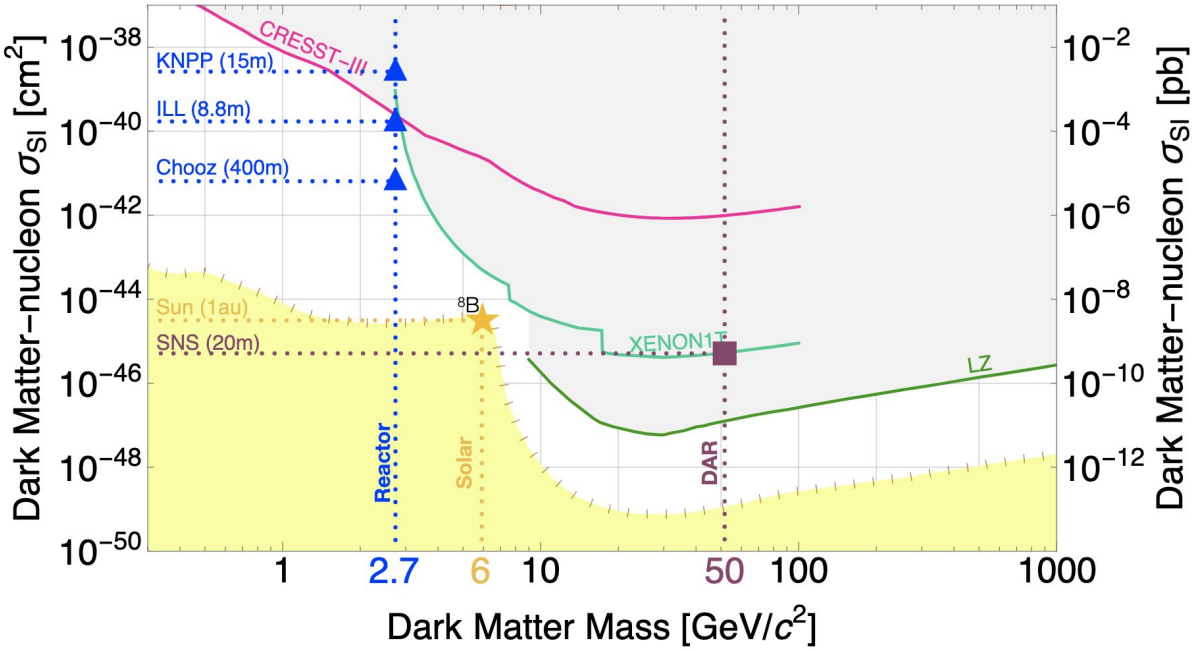
Panel of Experts

We appear to be observing different manifestations of long-lived metastable states releasing energy in our system

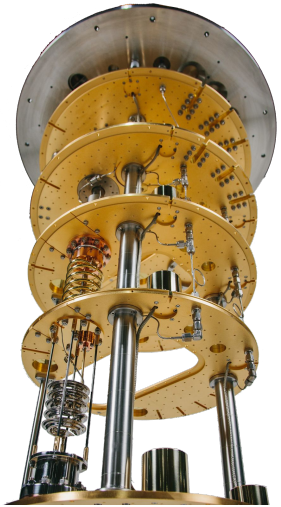
- Self-organized criticality
- Long-lived states can store massive amounts of energy >MeV that gets released in small bursts

- How do you remove long-lived stored energy in a system?
- **Analogy: How do you prevent an avalanche?**
- **Answer: Cause an avalanche! (remove the stored energy)**

Challenges ahead!



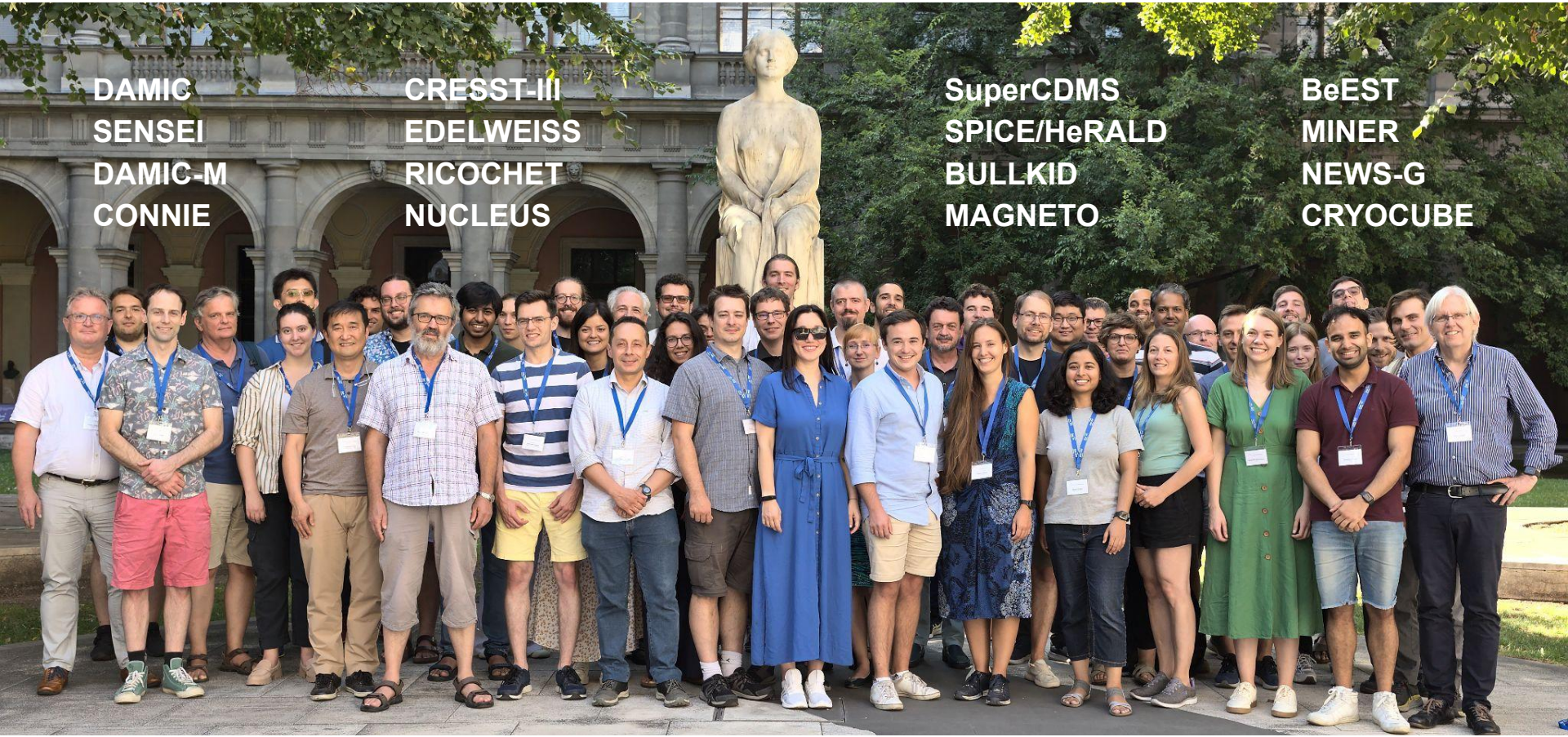
Major background for DM and CEvNS!



Industrial impact?
(errors in qubits, …)

Fig. by
Enectali Figueroa-Feliciano @ Magnificent CEvNS 2023

Fig. adapted from
Nature Physics volume 18, pages 107–111 (2022)


DAMIC
SENSEI
DAMIC-M
CONNIE
CRESST-III
EDELWEISS
RICOCHET
NUCLEUS
SuperCDMS
SPICE/HeRALD
BULLKID
MAGNETO
BeEST
MINER
NEWS-G
CRYOCUBE

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Summary and outlook

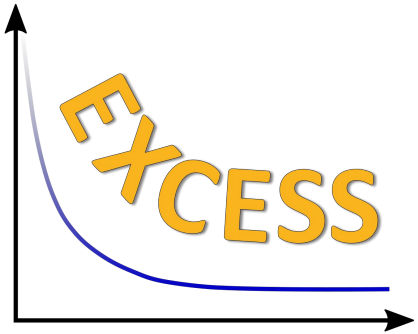
Three unique types of excesses identified!

- Excesses in **cryo-detectors** (non-ionizing, decaying, …) have possibly one common origin! Hot suspect: interface and bulk stress. Currently focused research topic, transferable impact expected (qubits, …).
- Excesses in **CCDs** (single electron production) can be explained by dark current and detector effects, but further reduction is required or future experiments (e.g. OSCURA).
- The **DAMIC excess** remains a riddle.

The workshop continues as a platform for focussed discussions. We are currently scouting a location for the next iteration, planned for summer 2024.

- Contact us at excessworkshop@gmail.com

Reasons for optimism! Lot's of progress so far! We will figure this out!



SCAN ME

Slack channel to stay in touch!

App.

The EXCESS workshop series

symbolic image

Goal: platform to collect the knowledge to navigate this energy region (**“roadmap”**).

Wish: map observations to phenomena as easy as a hitchhikers map (left).

Reality: a lot is going on close to energy thresholds, with many paths leading apart and some leading back together (right).