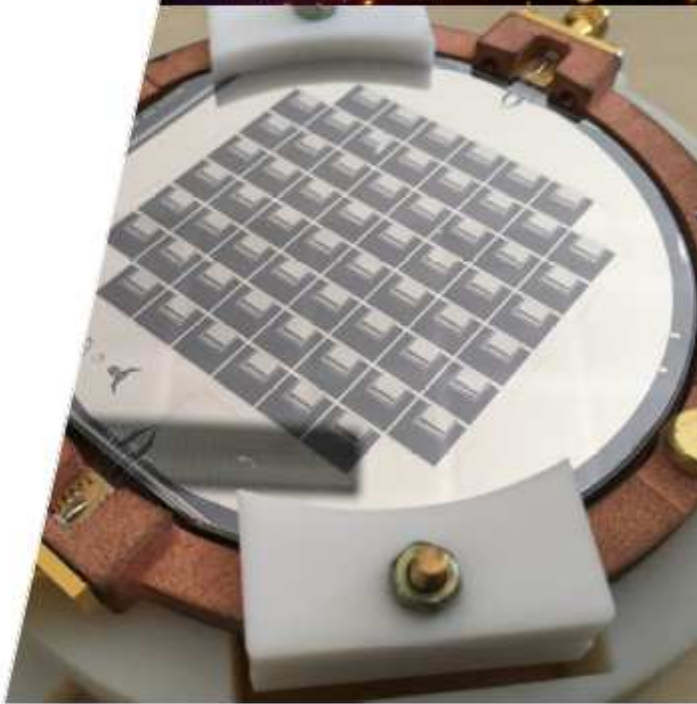
BULLKID-DM

Phonon mediated Kinetic Inductance Detectors for light WIMP direct detection

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

19/11/2025



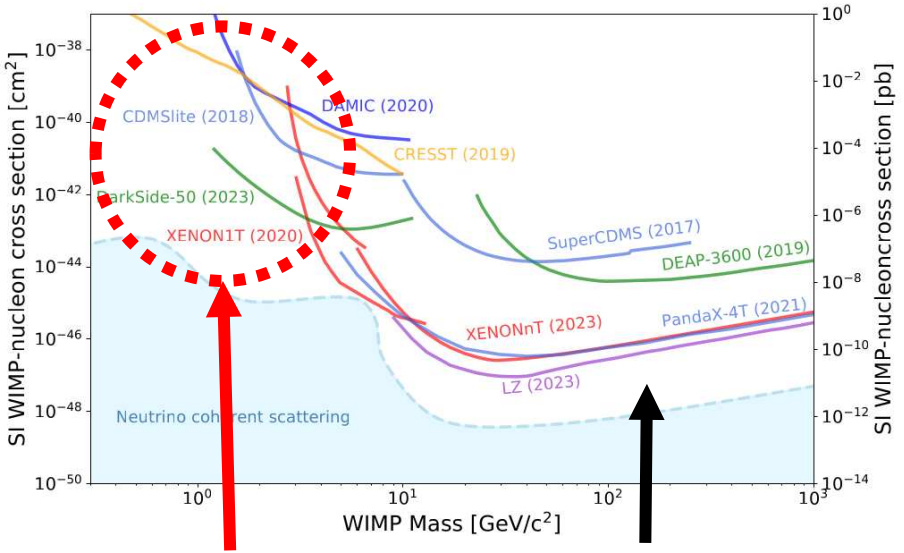
BULLKID-DM: A WIMP-like dark matter experiment

Roma
Ferrara
LNGS
Pisa
Trento

Karlsruher Institut für Technologie

Spin-independent WIMP on nucleon scattering cross section limits for direct detection experiments

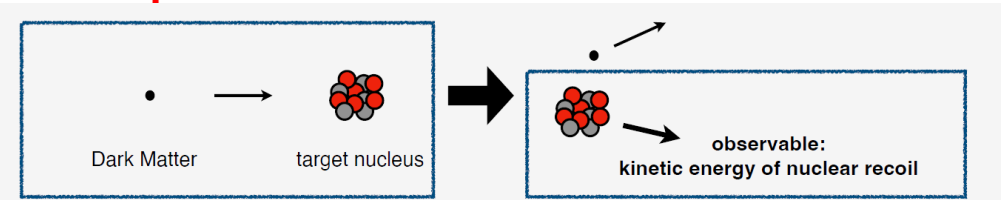
[S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)]



Kg-scale solid state phonon detectors

Multi-ton liquid scintillators

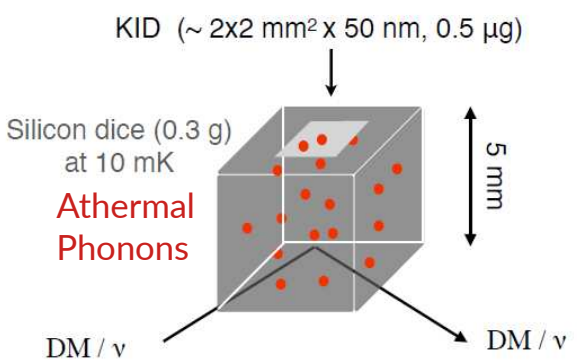
- ~ 40 members
- Formed in 2024
- 12 Institutions in 4 countries

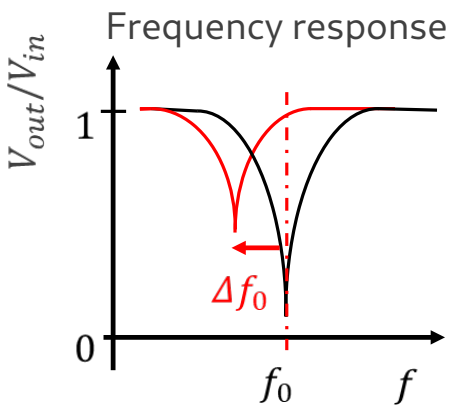


KID based calorimetry

- MKIDS are superconductive LC resonators (sensitive only to athermal phonons)
- Allow for frequency multiplexing.
- Target energy threshold <200 eV

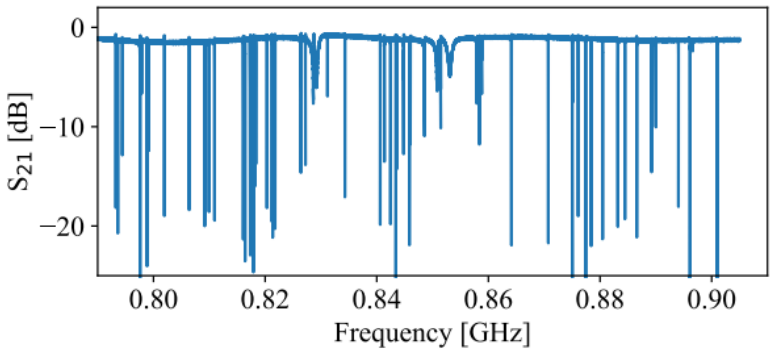
Phonons from particle interaction → Phonon absorption in **sensor** → Kinetic Inductance Change → Signal

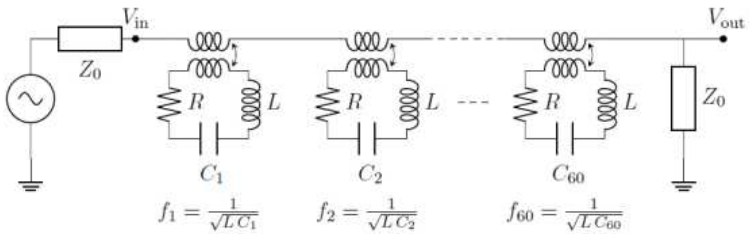




$$E \rightarrow \Delta n_{\text{pairs}} \rightarrow \Delta L \rightarrow \Delta f_0$$

Natural Frequency Multiplexing!



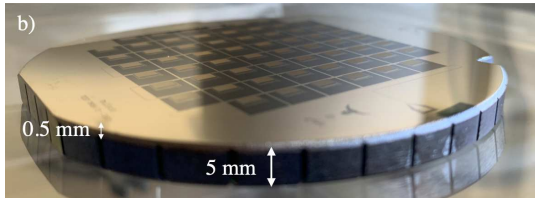


Detector: Fully active structure of cryogenic calorimeters

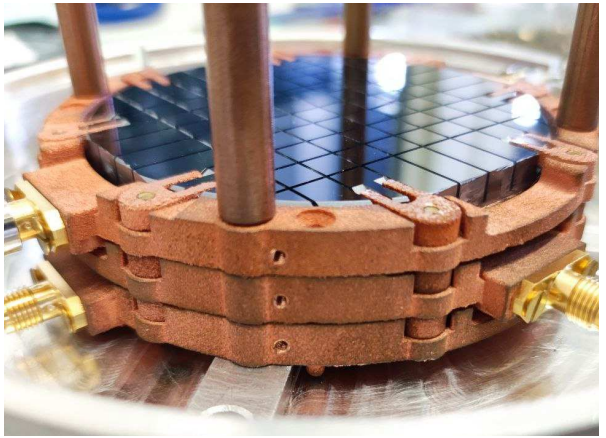
No passive structures near detectors!
Monolithic and compact design for background reduction!
kg scale detector with ~2000 sensors!

Prototype

Instrumented with Al-based MKIDs

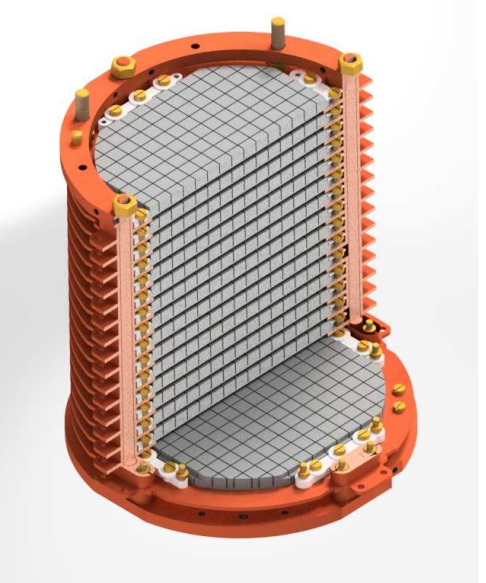


Demonstrator



3x prototypes stacked

Final Detector Design

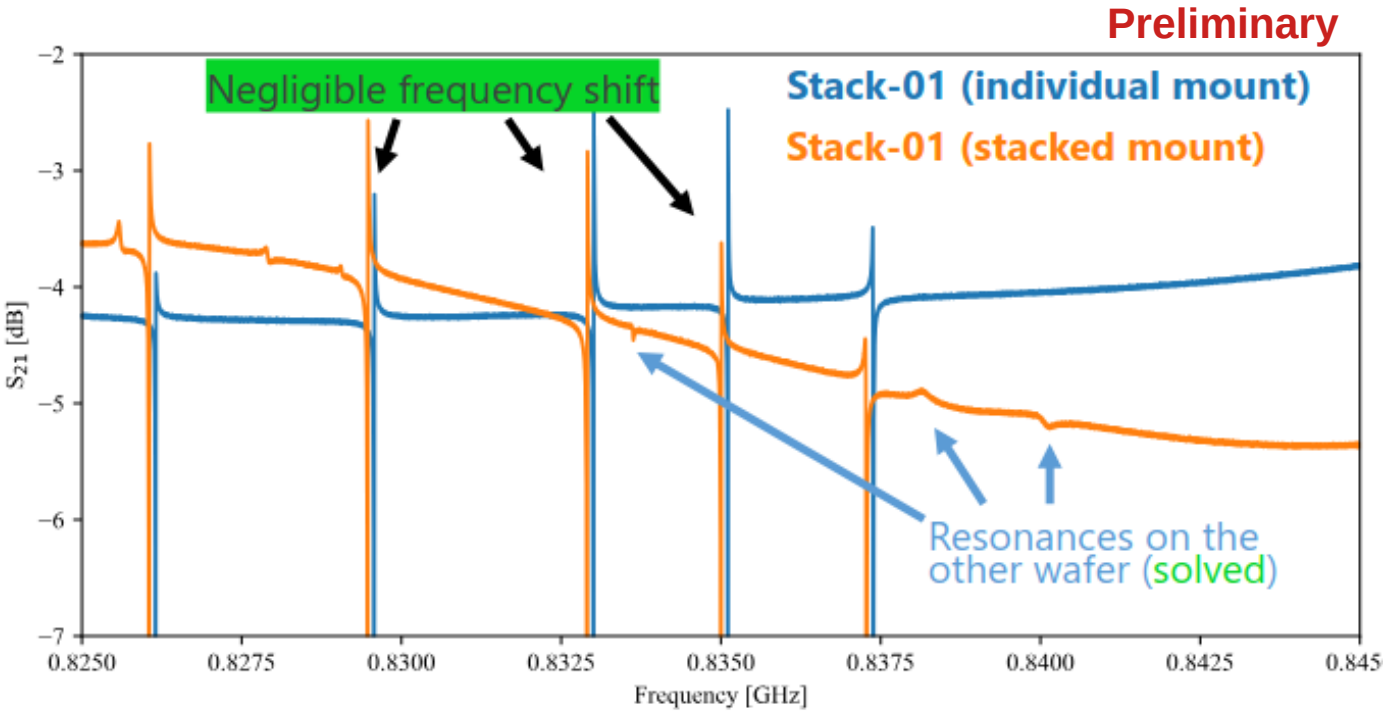


Stack of 16x100 mm instrumented Si wafers (~800 g target mass)

Stacked deployment

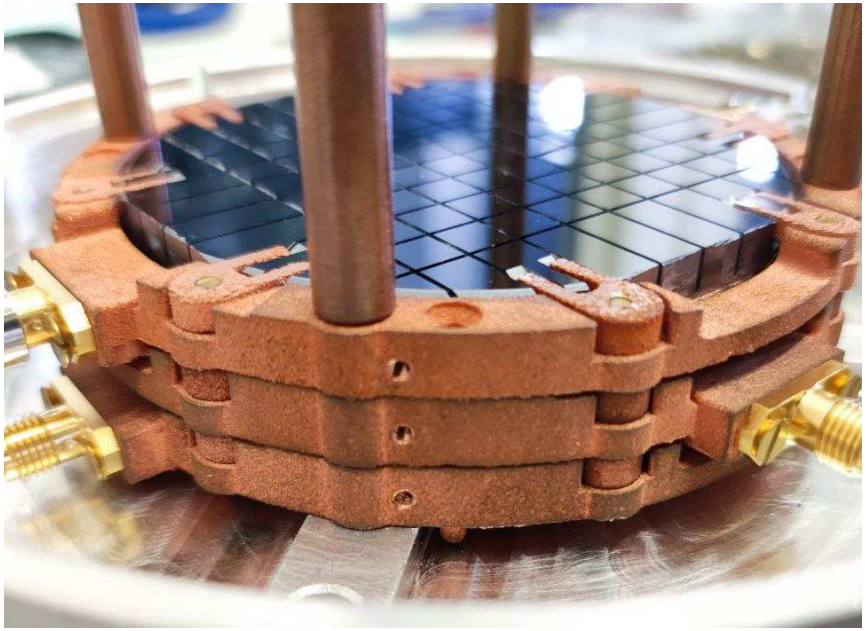
Operating 2 nearby wafers:

- Small frequency shifts (marginal)
- minor features coming from the other wafer (marginal)



Current Efforts

- DAQ system finalization for full 16 wafer stack
- Mass up-scaling to 100 mm wafers
- LNGS Shield Design
- Geant 4 background simulations
- R&D: Ge-based BULLKID, Phonon Collectors on MKIDs, Cryogenic Outer Veto
- Calibration (X-rays and LEDs)
- Deployment at Sapienza of a 3x3'' wafer stack (demonstrator)
- Background measurement at Sapienza in mildly shielded environment



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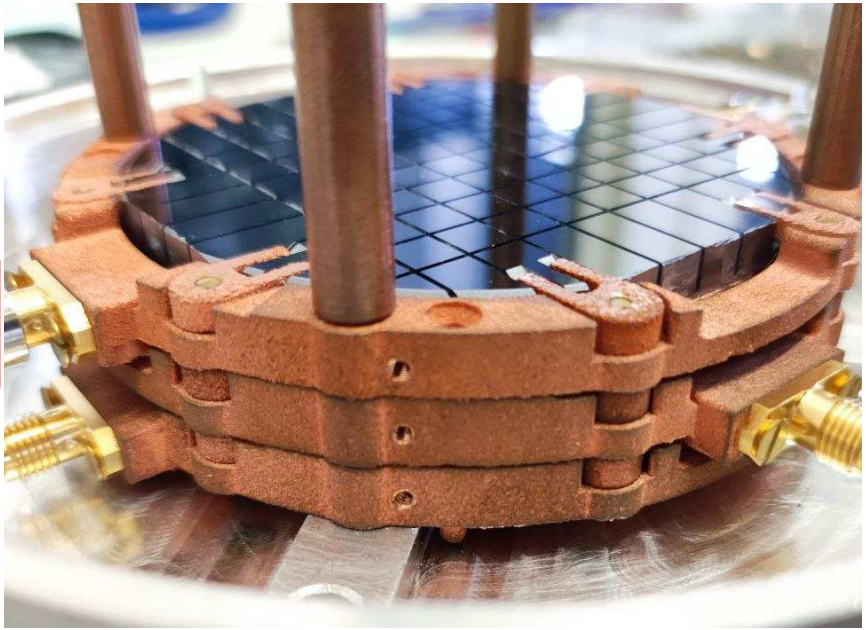
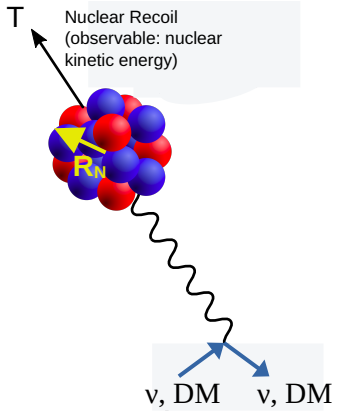


Multitarget BULLKID: Germanium based

CEvNS, DM

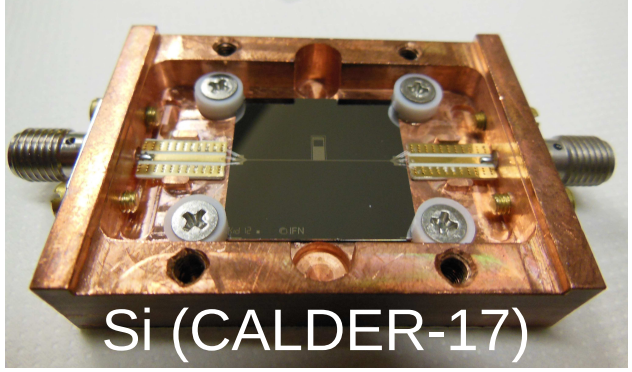


Higher nuclear mass
=
Higher cross-section

$$\sigma_{CE\nu NS} \propto N^2 \quad \sigma_{WIMP} \propto A^2$$

$$\boxed{\sigma_{Ge} \approx 9 \cdot \sigma_{Si}}$$

D. Delicato, et al., Germanium target sensed by phonon-mediated kinetic i nductance detectors, Appl. Phys. Lett . 126, 153502 (2025)



	$d\phi/dE$ [mrad/keV]	σ_0 [eV]	η [%]	$\frac{A_{\mathrm{KID}}}{A_{\mathrm{TOT}}}$
KID-1	3.6 ± 0.2	380 ± 20	2.0 ± 0.2	0.12
KID-2	2.5 ± 0.1	450 ± 22	2.0 ± 0.2	"
KID-3	2.2 ± 0.2	540 ± 31	1.6 ± 0.2	"
CALDER-17	5.8	115 ± 6	$7.4 - 9.4$	0.42

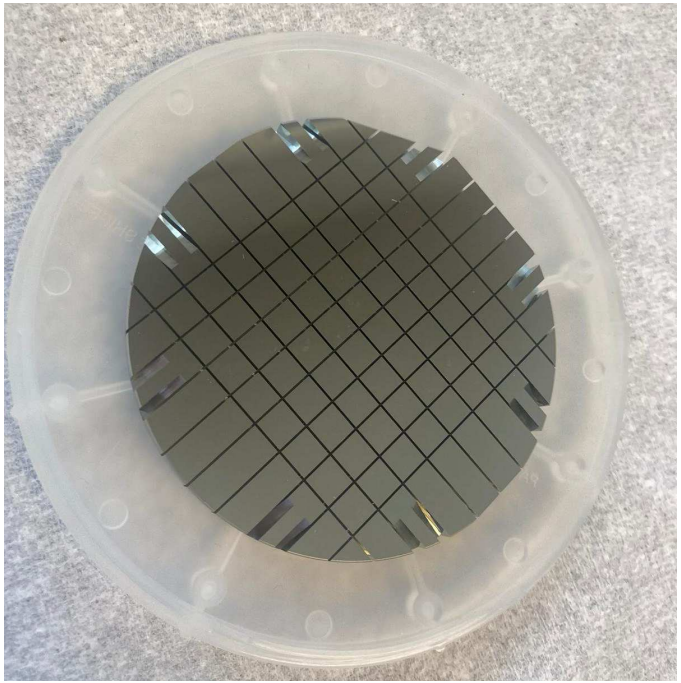
Energy resolution agrees with detector model
Same phonon transport properties of KIDs on Si.

Multitarget BULLKID: Germanium based

INFN Ferrara

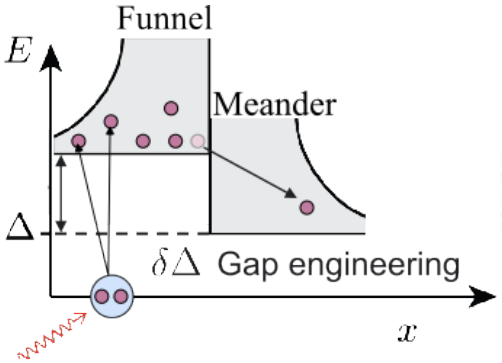
MAX-PLANCK-INSTITUT FÜR PHYSIK

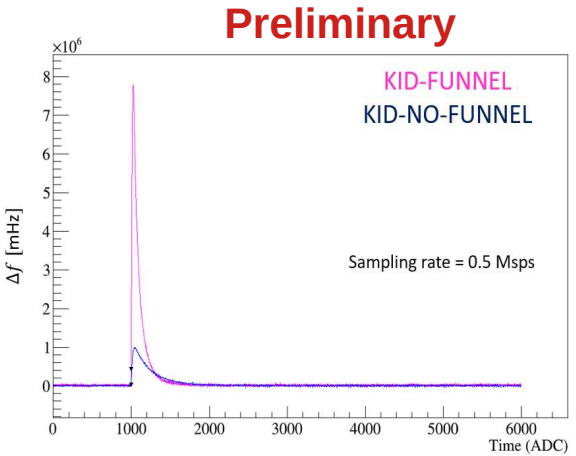
- New annealing procedure to develop
- 9 wafers 3”x 5 mm available in Ferrara: 2 are being diced now!
- TBD: Baking in an oven (T ~ 1200 °C, Diameter > 3”, Ultra High Vacuum) -> Kindly offered by Max Planck für Physik
- TBD: Lithography and test in the standard BULLKID setup.

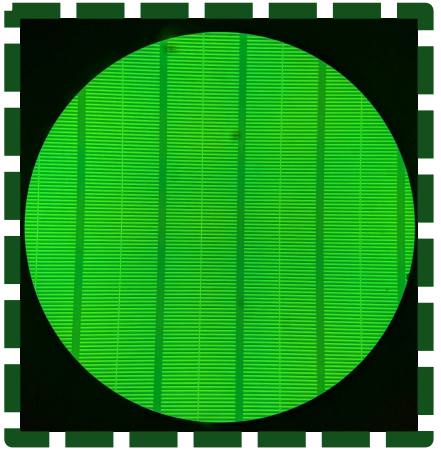


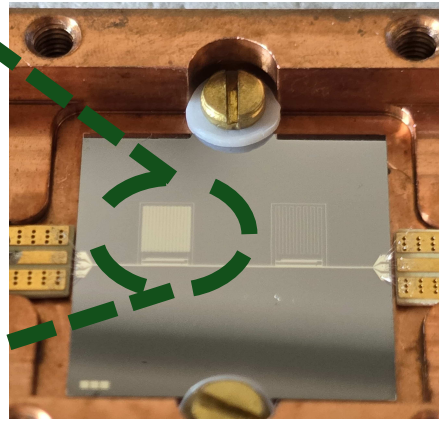
BULLKID: Improving energy threshold

- Development of KIDs with dedicated phonon collection structure (Funnels)
- Improvement in collection efficiency and resolution
- Trilayer KID (77nm Al/Ti/Al)+funnel volume at higher gap (Al) for phonon funneling effect
- Funnel Resolution: ~70 eV
- No Funnel Resolution: ~165 eV



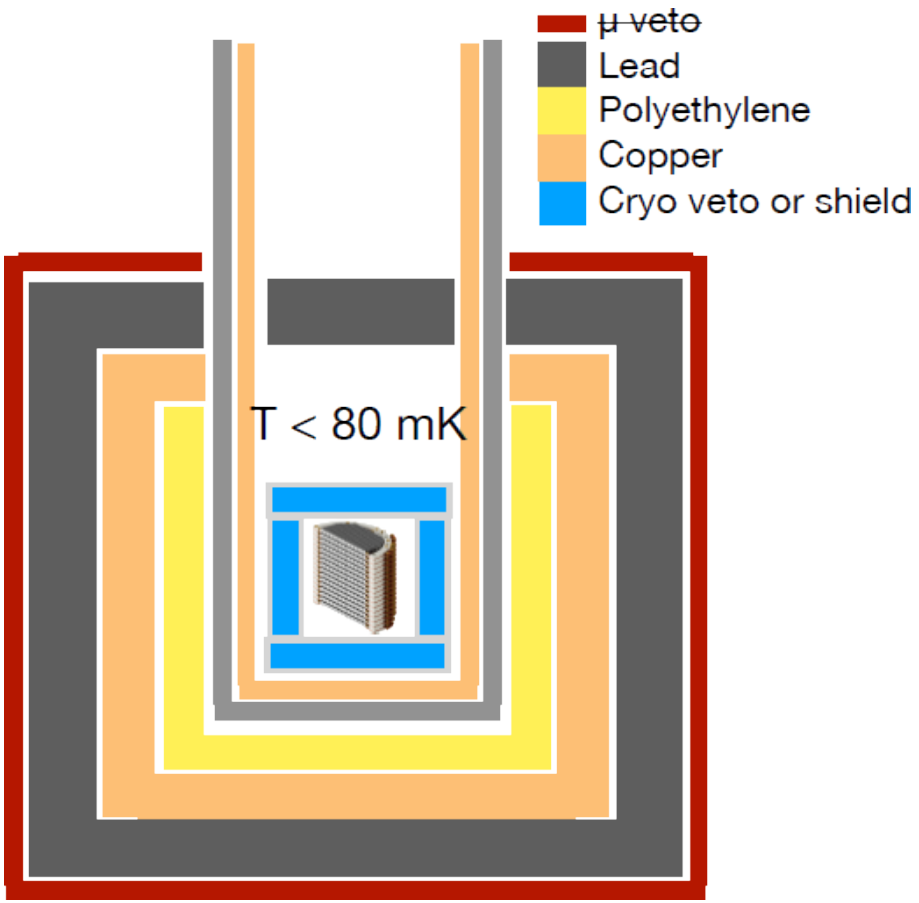






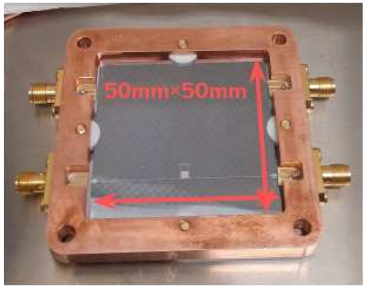
UPCOMING PAPER

BULLKID: BGO cryogenic veto prototype



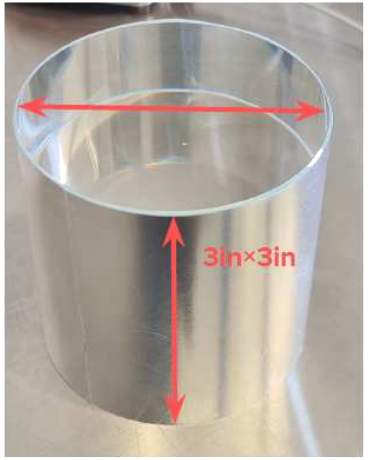
Preliminary shield layout

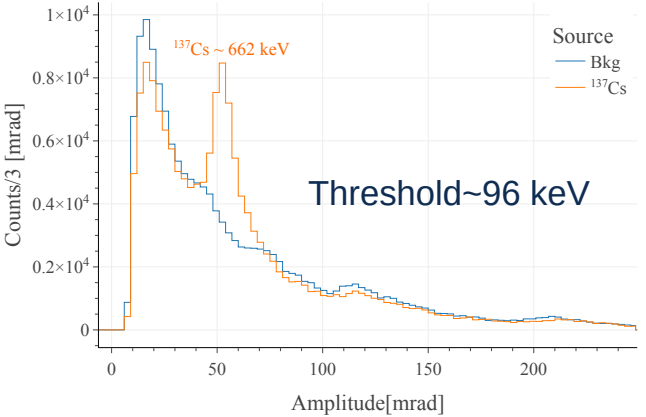
CALDER KID Light detector



Assembly with reflector

BGO Crystal





Goal: energy threshold < 50 keV

Current Efforts

- DAQ system finalization for full 16 wafer stack
- Mass up-scaling to 100mm wafers
- LNGS Shield Definition
- Simulation tuning for accurate background prediction
- R&D: Ge-based BULLKID, Phonon Collectors on MKIDs, Cryogenic Outer Veto
- Calibration (X-rays and LEDs)
- Deployment at Sapienza of a 3x3" wafer stack (demonstrator)
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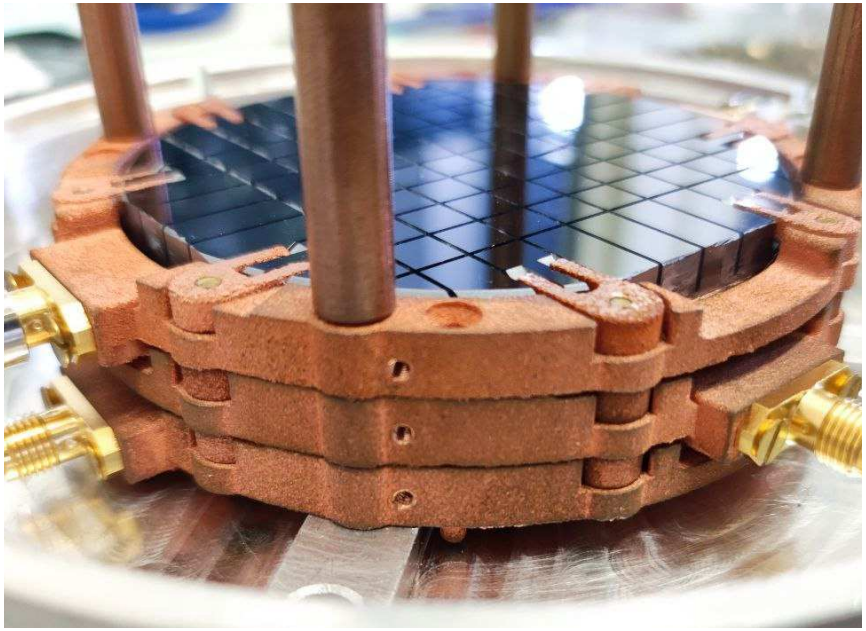
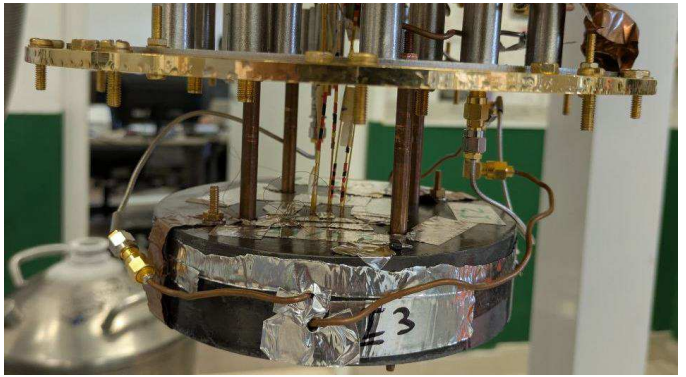
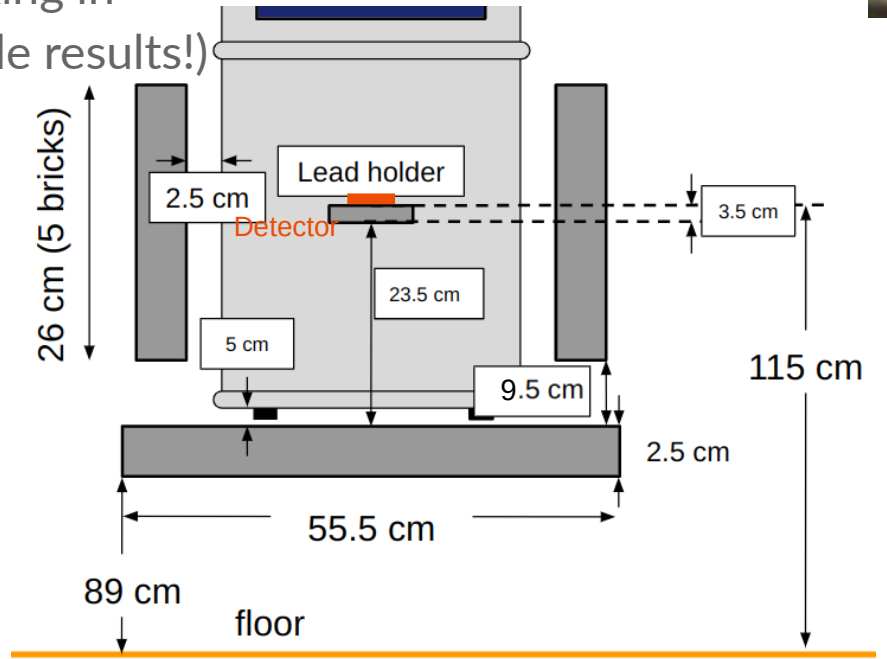
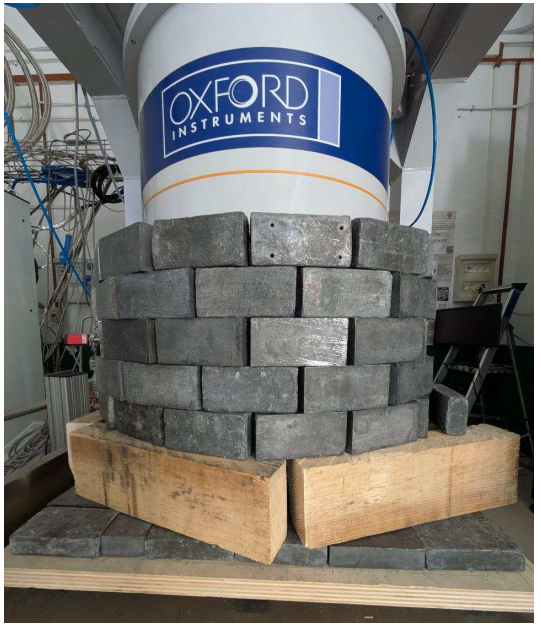


Background Measurement @ Sapienza

- Location: Surface laboratory (~5 m above sea level, ~1 m.w.e.)
- Mildly shielded environment with LEAD (internal and external)
- LEAD Pot ~4 mm thickness
- Optical fibers for detector calibration and monitoring
- Deployed 1x3" wafer
- >1 month of data taking in 2 datasets (compatible results!)







Datataking and Analysis Description

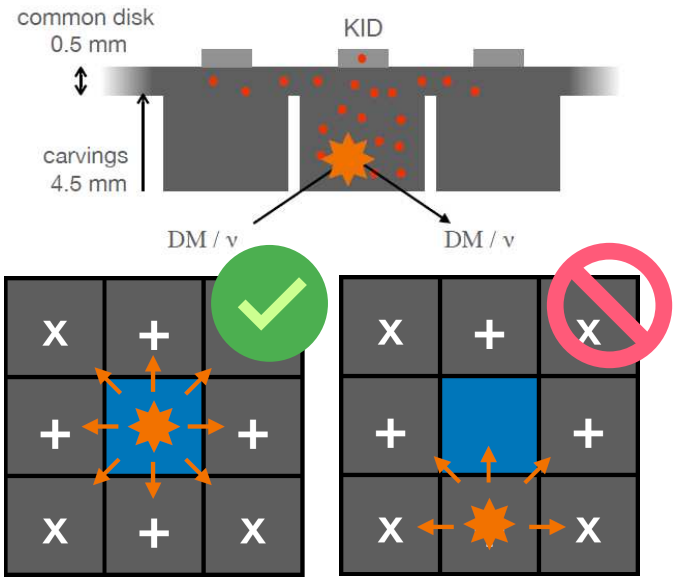
- **15 KIDs** (2 triggering + 13 as veto)
- Run time: **19 Apr 22:00 → 5 May 8:00**
- Live hours per cluster: 290

		1	2	3	4	5	
13	12	11	10	8	7	9	6
14	15		16	17	18		19
27	26	25	24	23	22	21	20
29	28	30	31	32	33	34	35
43	42	41	40	39	38	36	37
44	45	46	47	48	49	50	51
	57	56	55	54	53	52	

Indexes: Frequency ordering

Triggering

Acquired in coincidence as veto

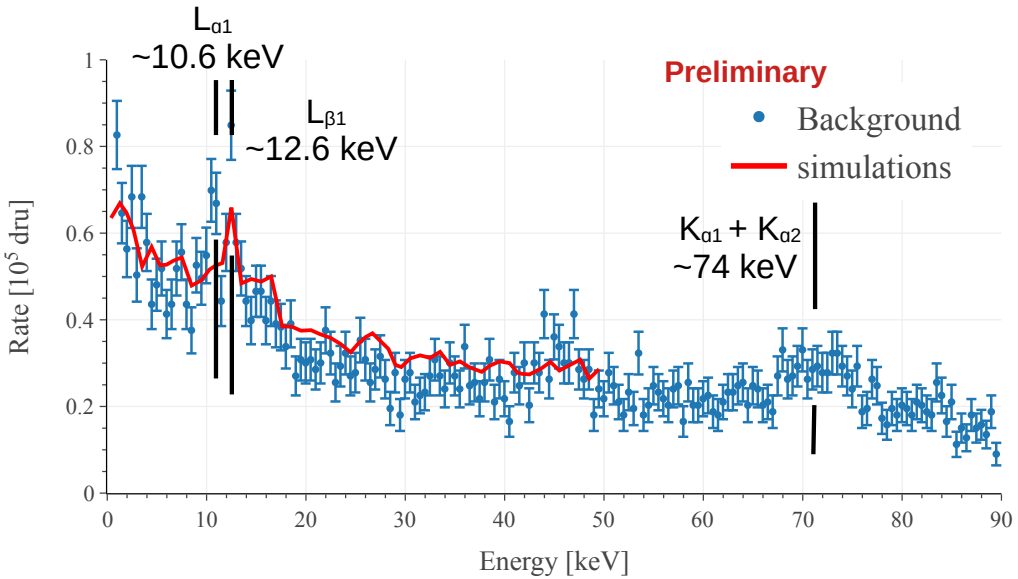


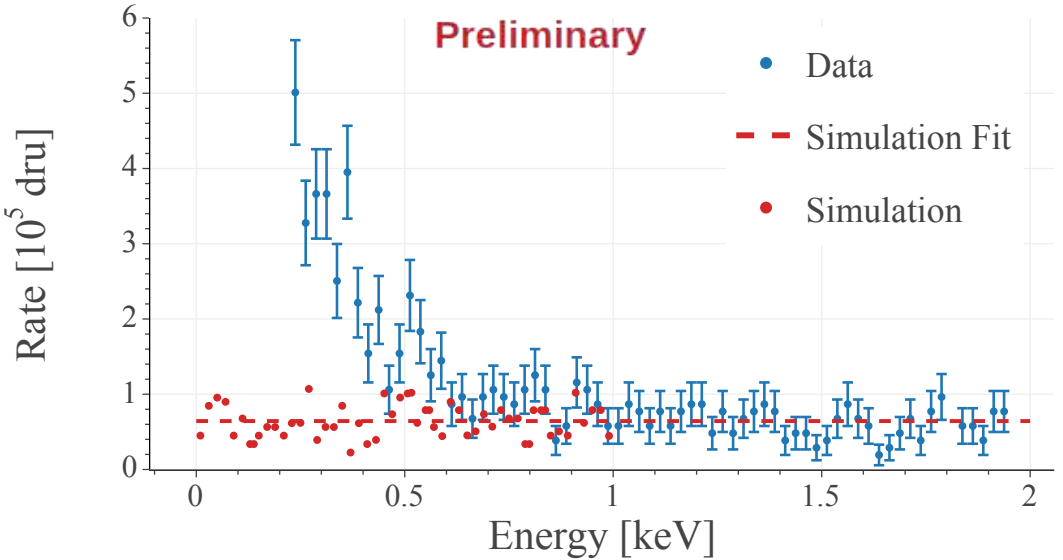
50% of the phonons are absorbed by the KID.

The rest leaks in nearby voxels:

- ~10% in each "+" die
- ~5% in each "x" die
- the rest in outer dice

Energy Spectrum and Simulation Comparison

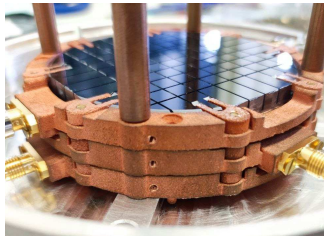


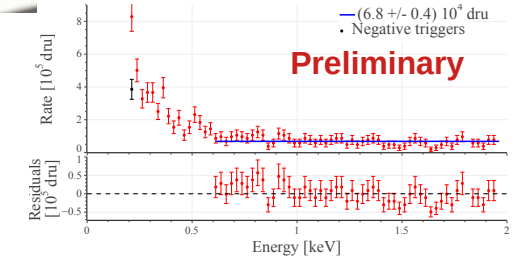


- Pb X-rays well reconstructed with LED calibration
- Pb X-rays at 10 keV not well reproduced by simulations
- Overall background well reproduced

- Flat background: (68±4) kdru (simulated 61±3 kdru)
- In <600 eV measured rise up to a factor ~5
- **Spectra compatible between the two triggering pixels!**
- Rise not compatible with noise false positives
- Rise DOES NOT decay with time!

Conclusion

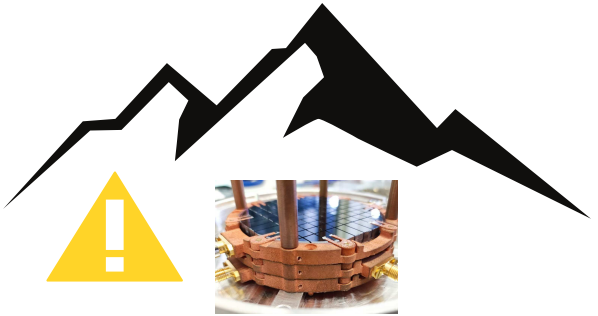




General Achievements

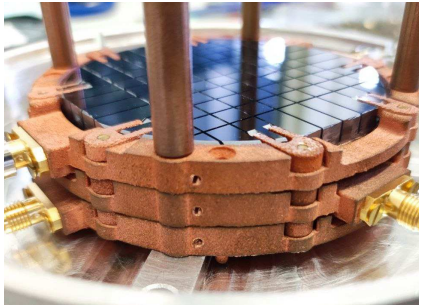
- **MultiKID acquisition**
- **Stable over one month**
- **Lower background** in keV region to ~60 kdru (compatible with simulation)
- Geant4 **simulations do not reproduce the Pb** induced structures (could also affect lower energies)
- **Cross-calibration between LED and X-Rays compatible within 10%**

- **Priority: deploy demonstrator @LNGS to study background in a heavy shielded environment (muon free)**
- Continue R&D for Germanium absorber
- Lower the threshold with funnels
- Prepare BGO veto for lower background

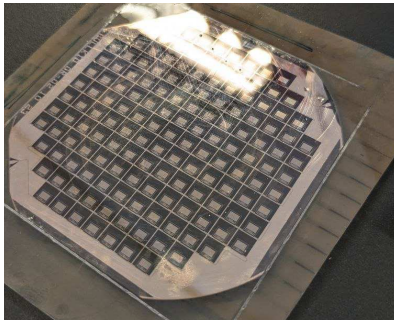


BULLKID-DM

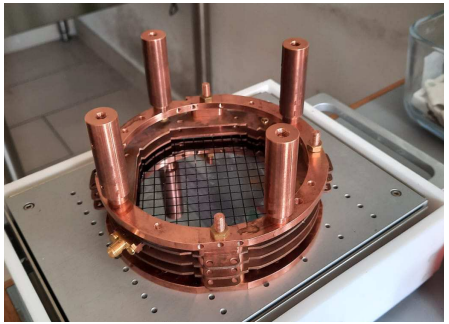
Thank you for the attention!



Demonstrator
3x3'' wafer



100mm prototype

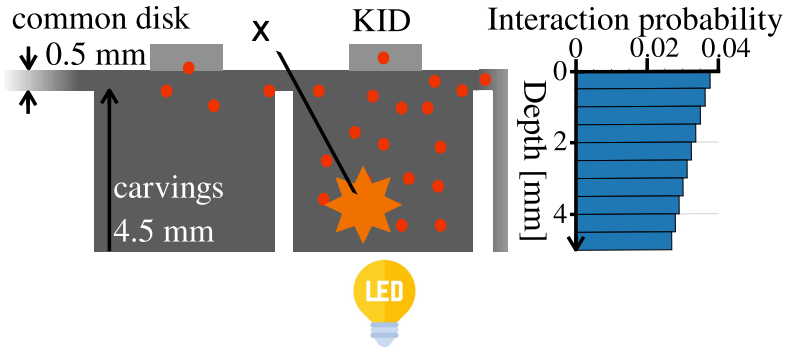


100mm assembly

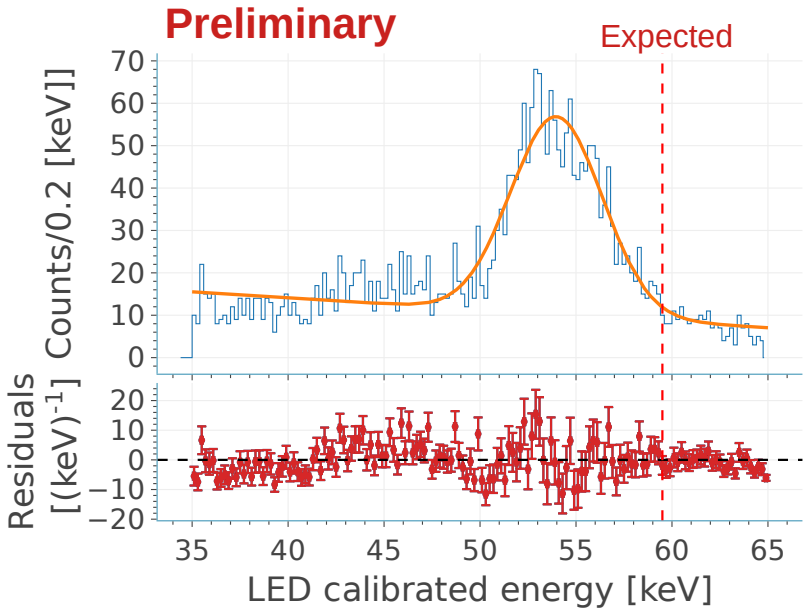
This work was partially supported through the European Research Council through the Consolidator Grant DANAE number 101077663

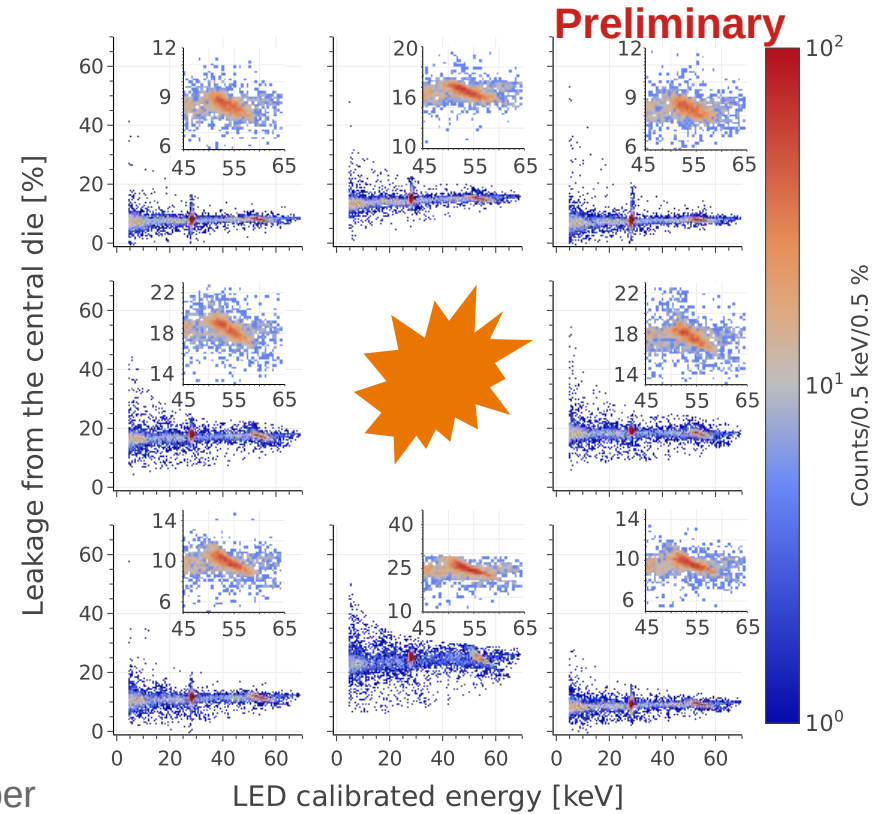
Backup Slides

Bulk (Am) vs Surface (LED) events



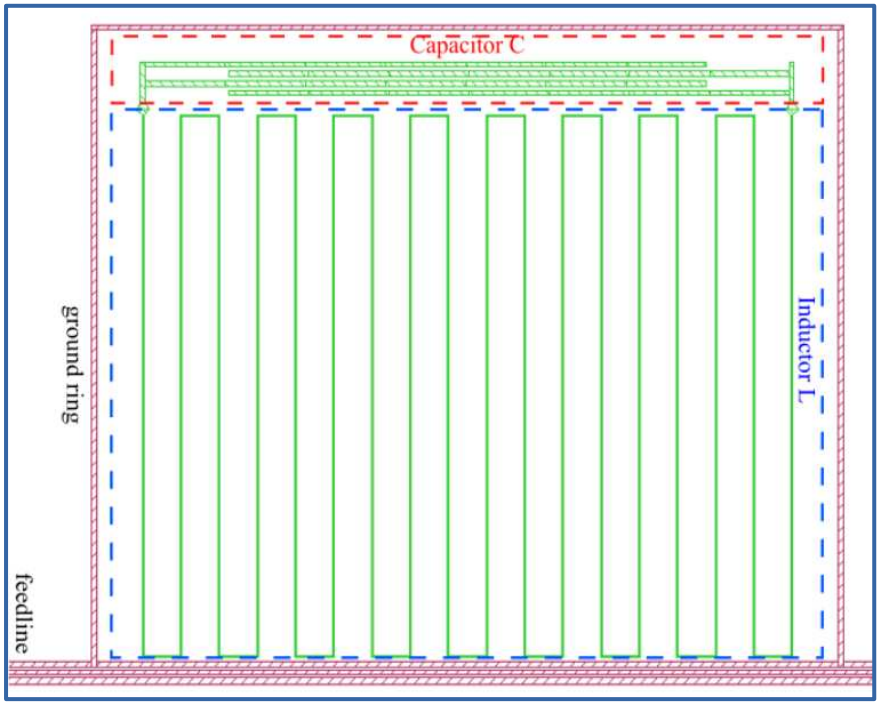
- Dedicated cooldown with Am source (59.5 keV X-Ray)
- -10% discrepancy between calibrations
- Same leakage between bulk and LED

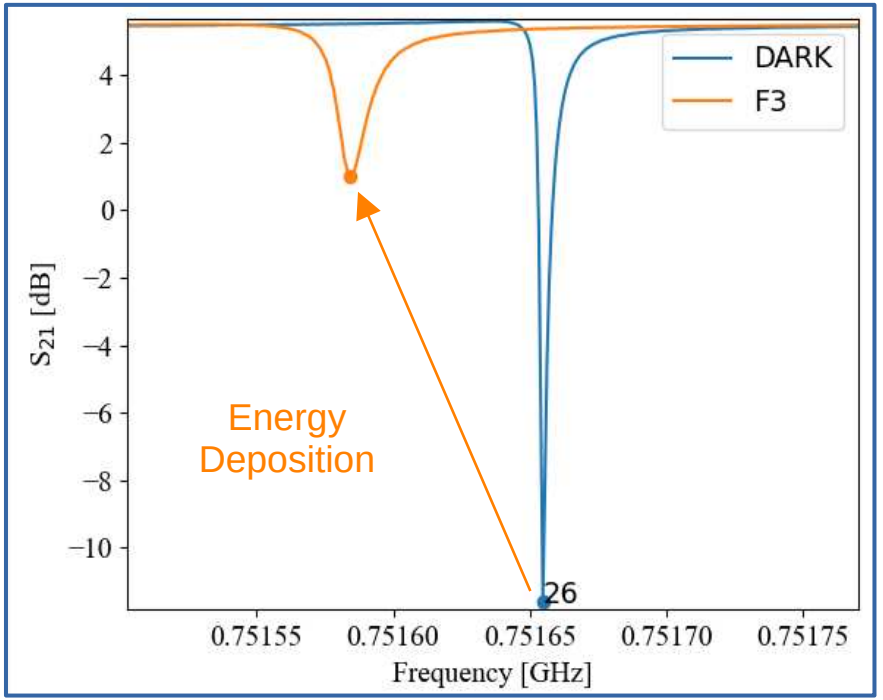




Upcoming Paper

KID Response





KID: Kinetic Inductance Detectors

Superconductive LC resonators $\longrightarrow L = L_{\mathrm{G}} + L_{\mathrm{K}}$

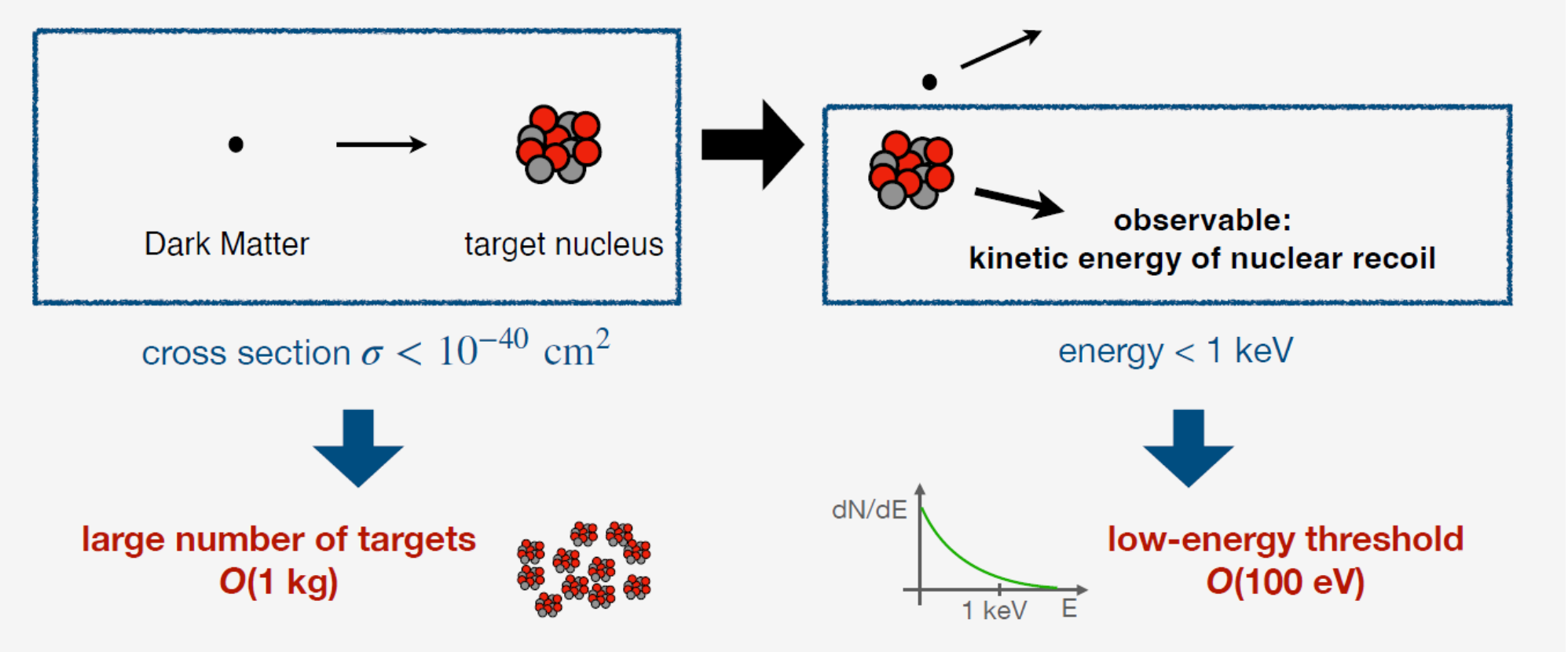
L_K: Kinetic Inductance (changes when Cooper Pairs are broken)

Detection Principle: Nuclear Recoils

Target: Silicon (Si) + ongoing effort to port technology on Germanium

A. Cruciani, et al., BULLKID: Monolithic array of particle absorbers sensed by kinetic inductance detectors. Appl. Phys. Lett. 21 November 2022; 121 (21): 213504.

D. Delicato, et al., Germanium target sensed by phonon-mediated kinetic inductance detectors, Appl. Phys. Lett. 126, 153502 (2025)

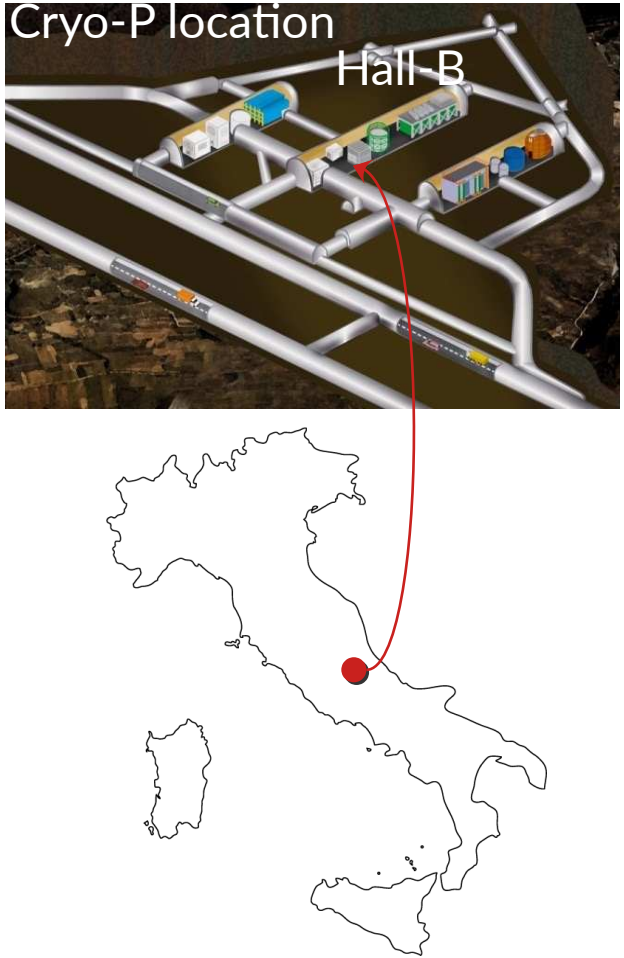


Site: LNGS Cryo Platform

The Cryo-Platform (or Cryo-P) is a cryogenic underground hub for mK applications in the field of astro-particle physics

- Equipped with Oxford Proteox Cryostat (base temperature ≤10 mK)
- Background shielding design being finalized/procured

Facility under construction. Ready in the next few months!

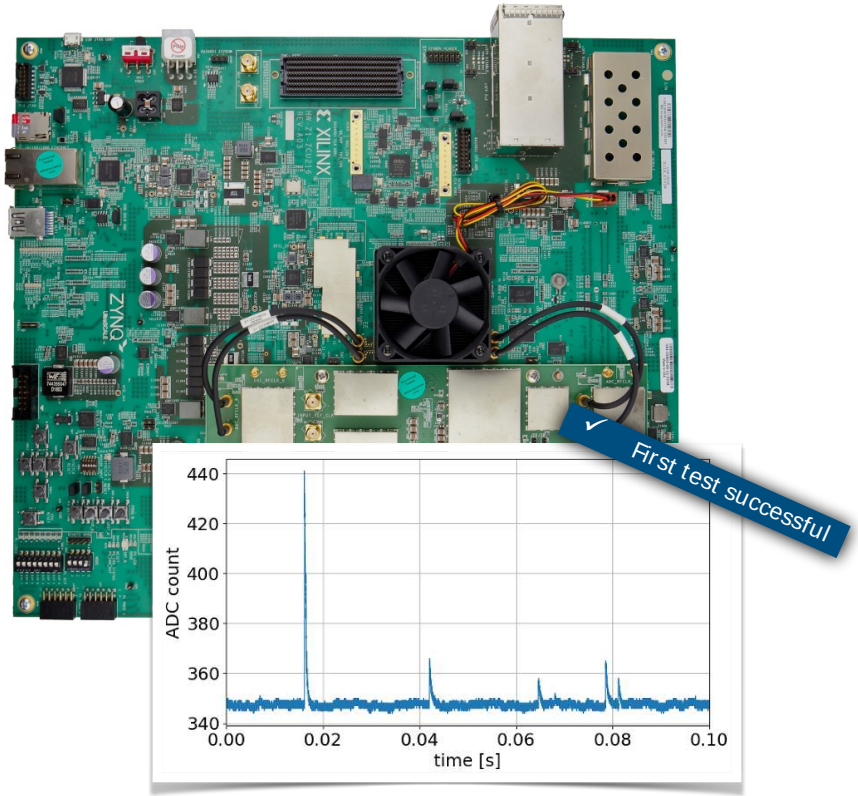


RF Electronics

Current electronics (Ettus x310):
30 KIDs / line

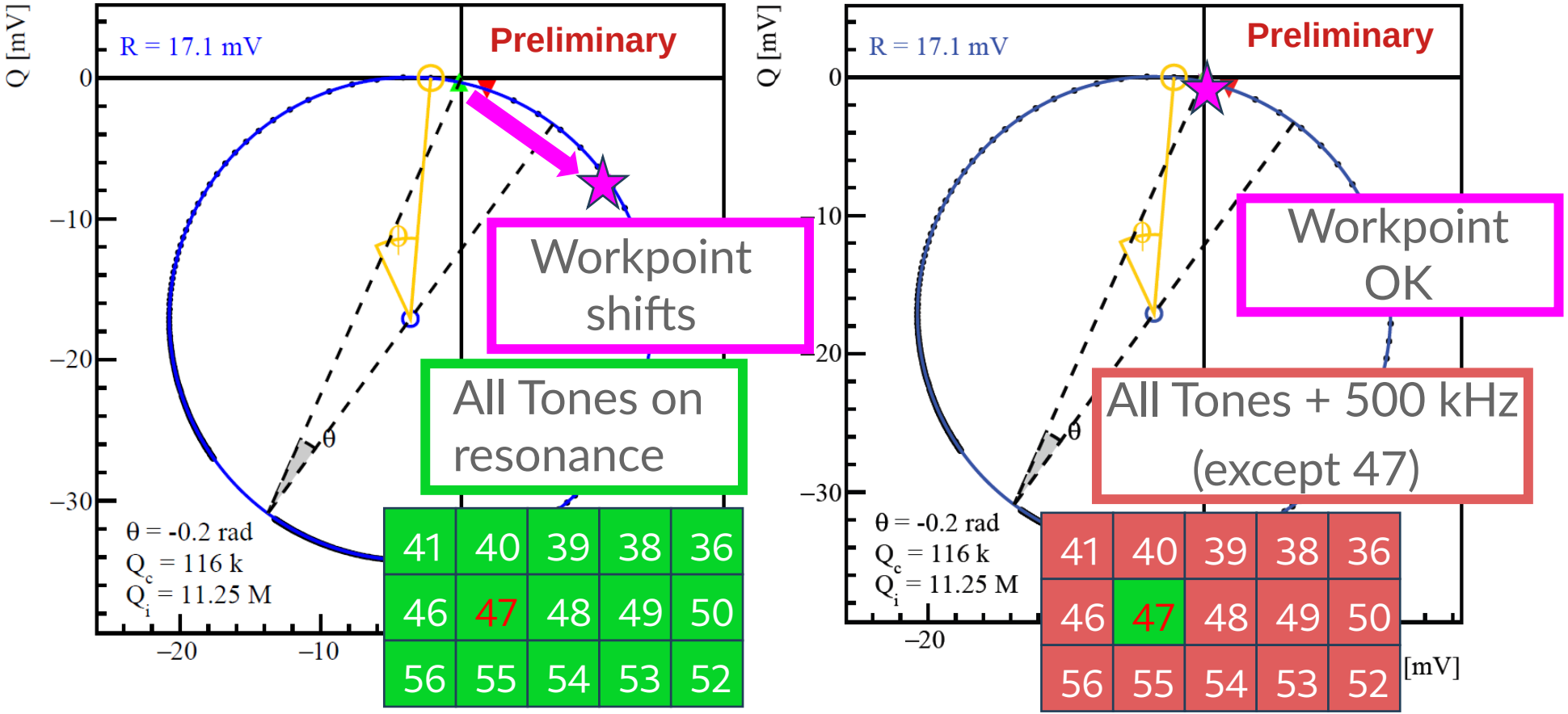
New electronics (ZCU216 Evaluation Board with 16 lines):
Goal >= 150 KIDs / line

- Custom Analog Front-End and
- Control Firmware by the KIT group
- **Status: prototyping on the BULLKID-DM demonstrator**



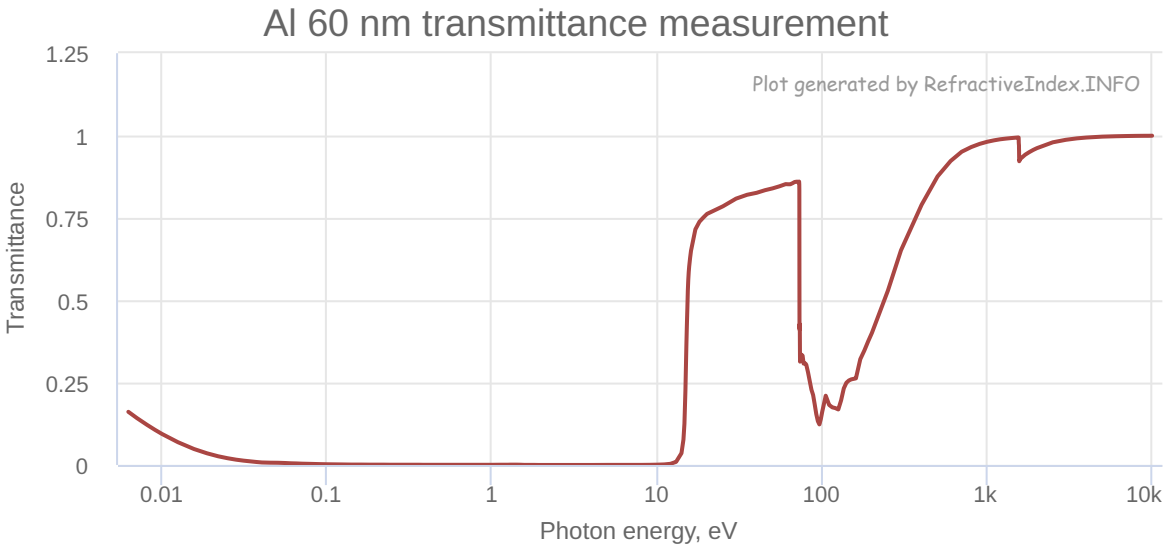
Power Biasing Issue

When MKID absorbs power there is X-talk to nearby pixels and influences working conditions. Known issue in MKID community, countermeasures are being implemented.

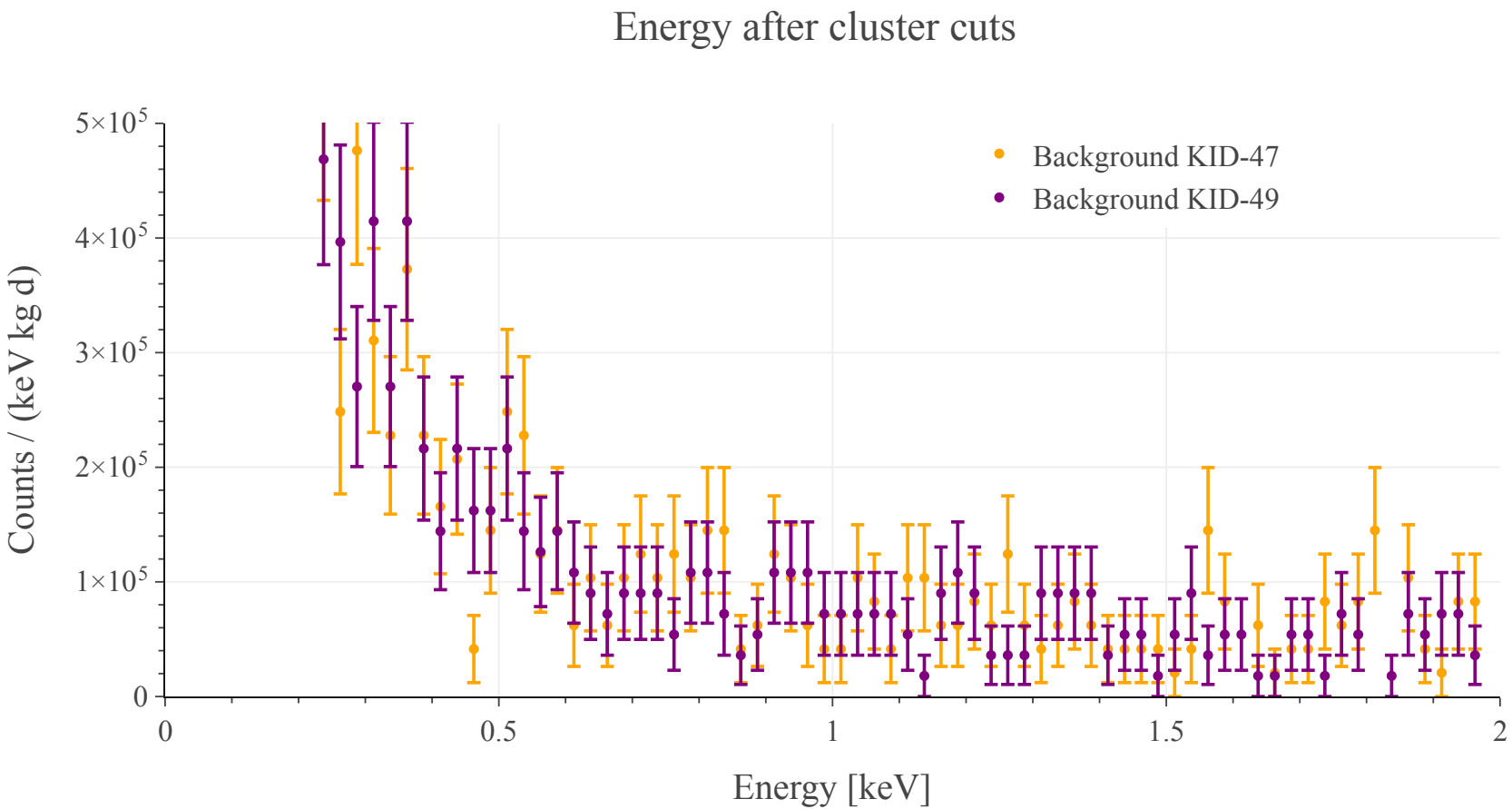


Al Photon transparency

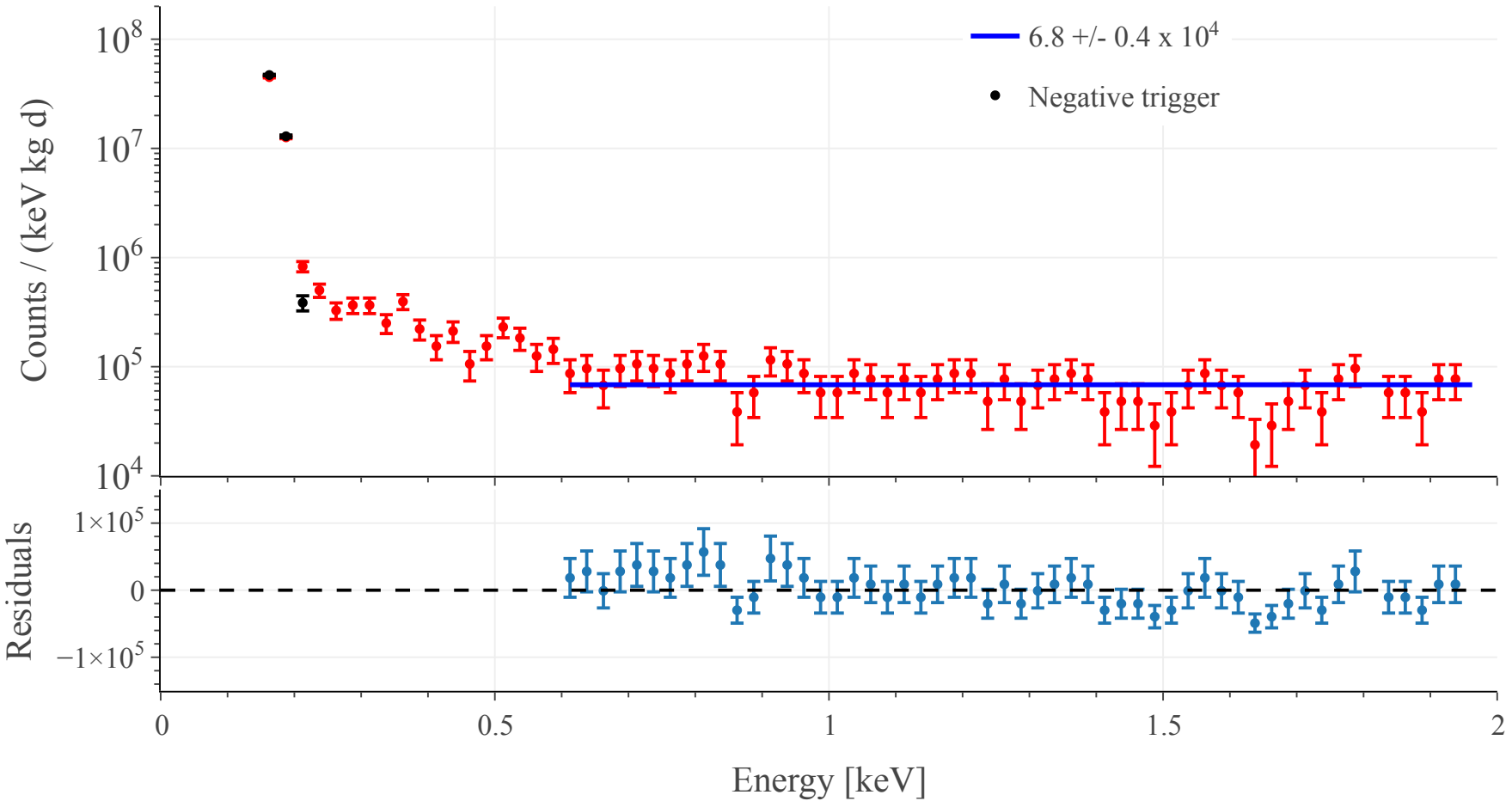
- 60 nm Al easily absorbs photons under 1 keV
- Generated following Rakic, A.D. (1995) Algorithm for the Determination of Intrinsic Optical Constants of Metal Films: Application to Aluminum. Applied Optics, 34, 4755-4767



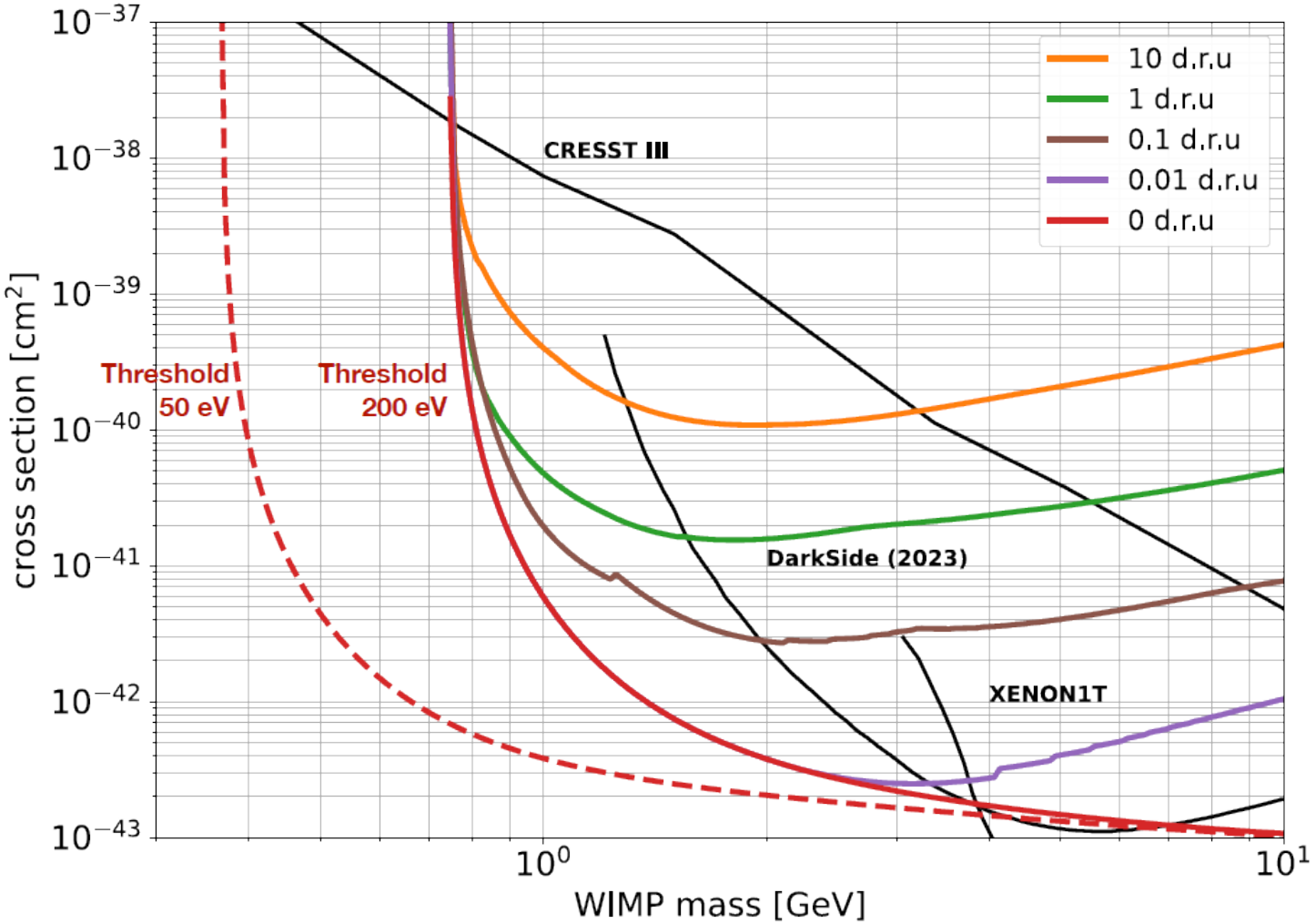
Background recorded in different pixels



Spectrum in logscale for Negative Triggers



Sensitivity



"zero" bkg

Repeated Data-taking

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

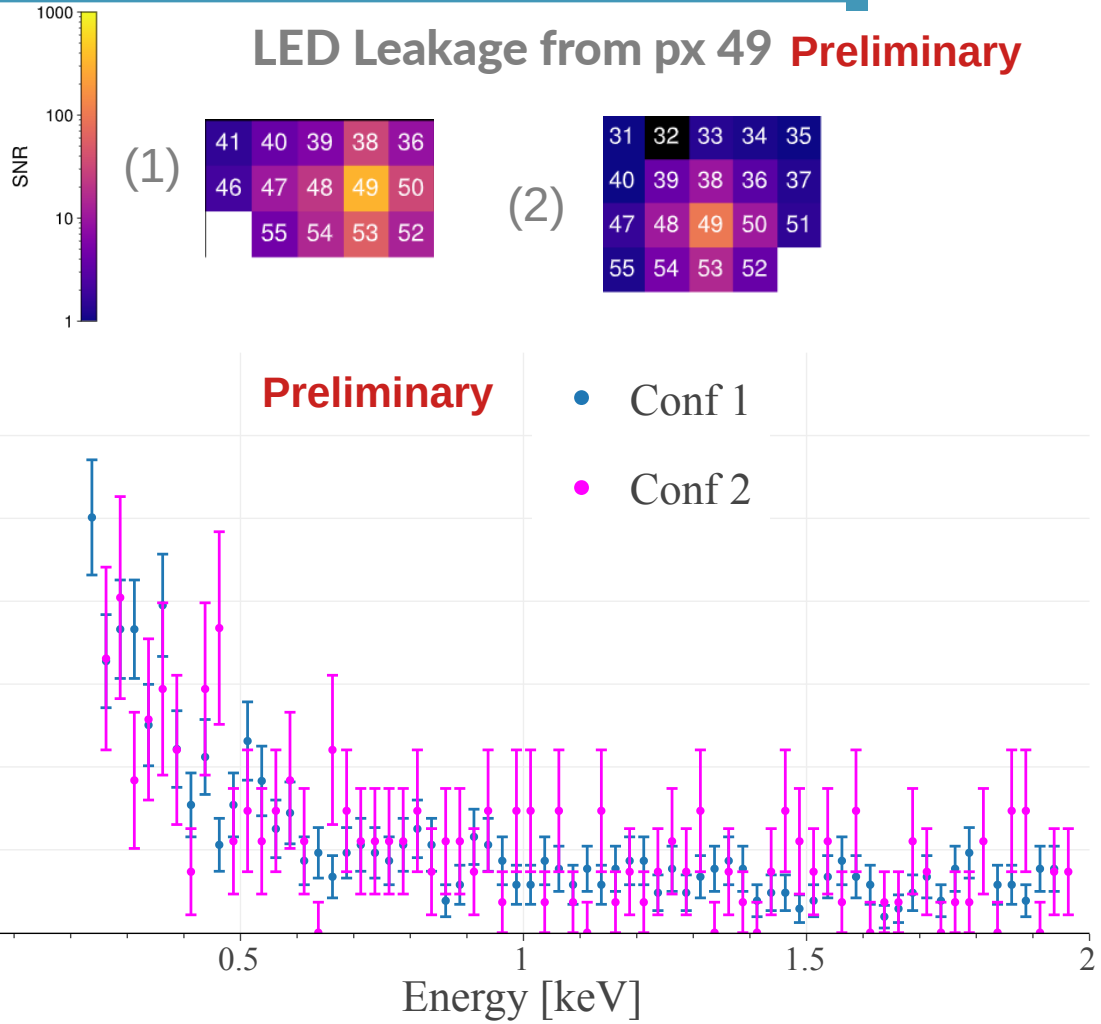
1) Optimizing resolution of triggering pixels (best reached 28 eV, during data taking 30 eV)

   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!)

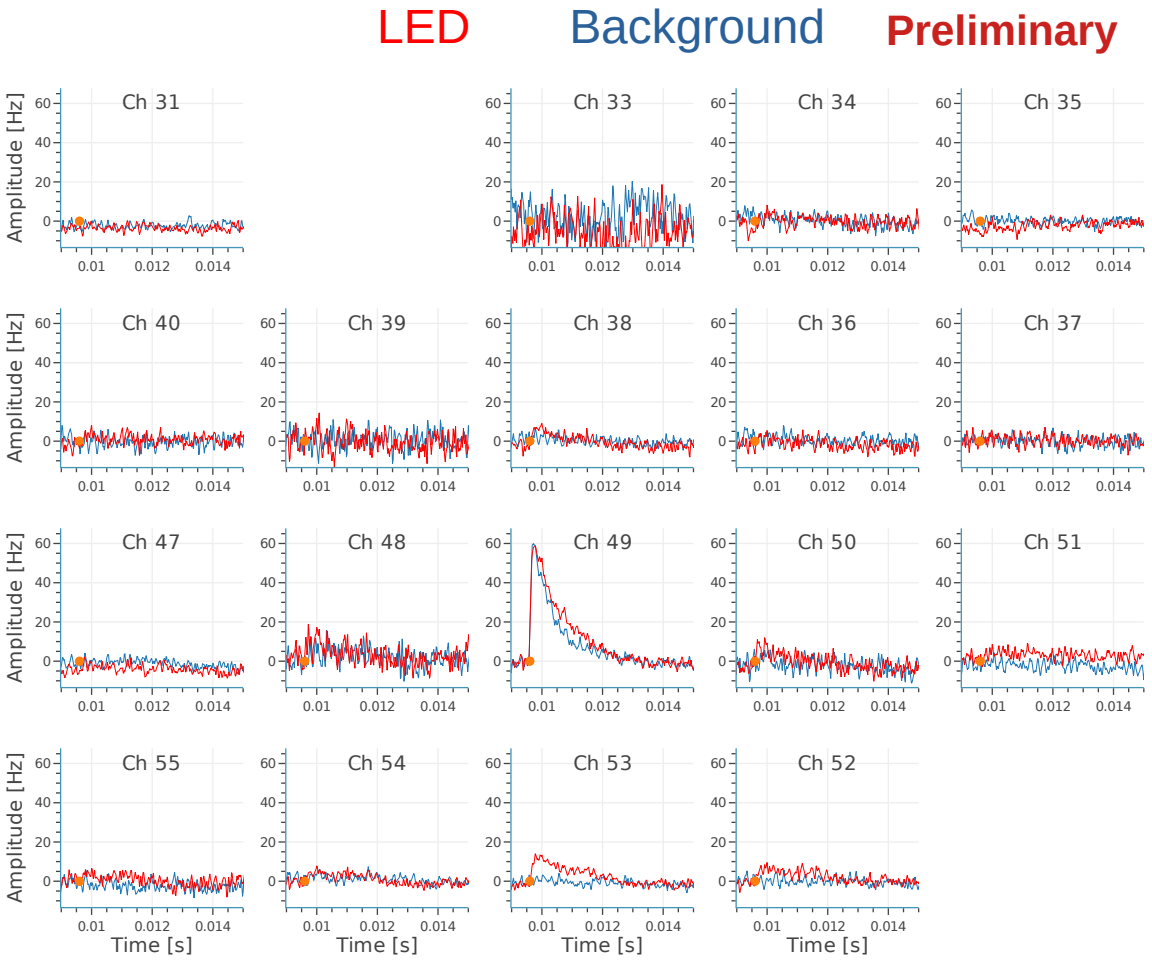


Singles observed in BULLKID

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

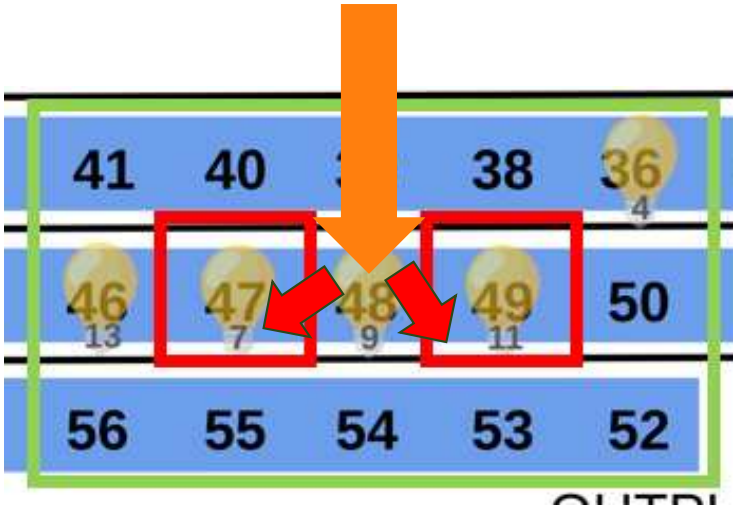
At higher energies:

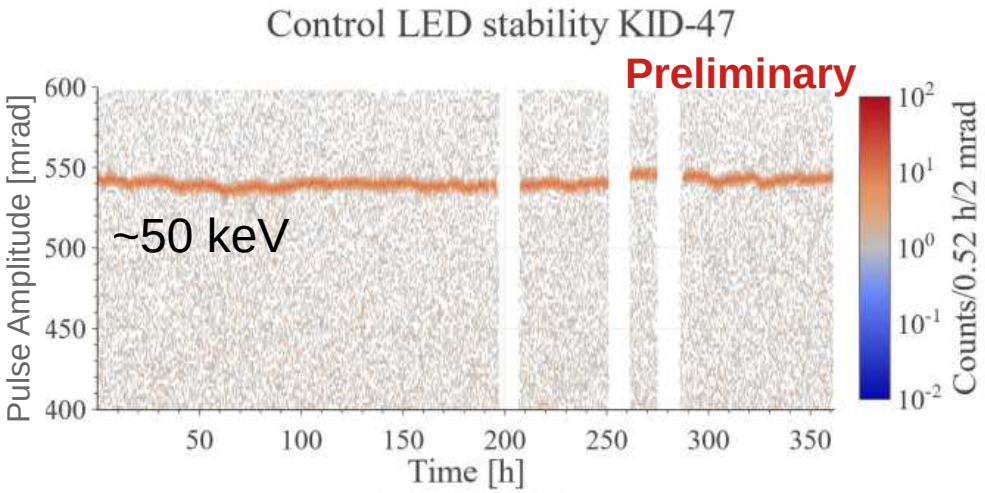
- Singles visible at ~2keV and above
- Could be direct KID hits due to high metalized area (Al absorbs well 100 eV photons)
- Could it be that the rise is due to Singles (under investigation)?

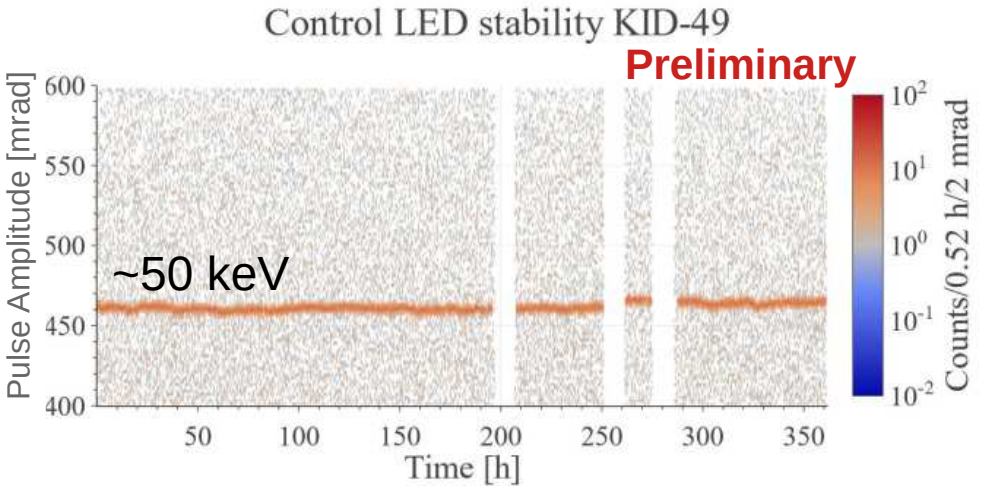


Background Measurement Stability

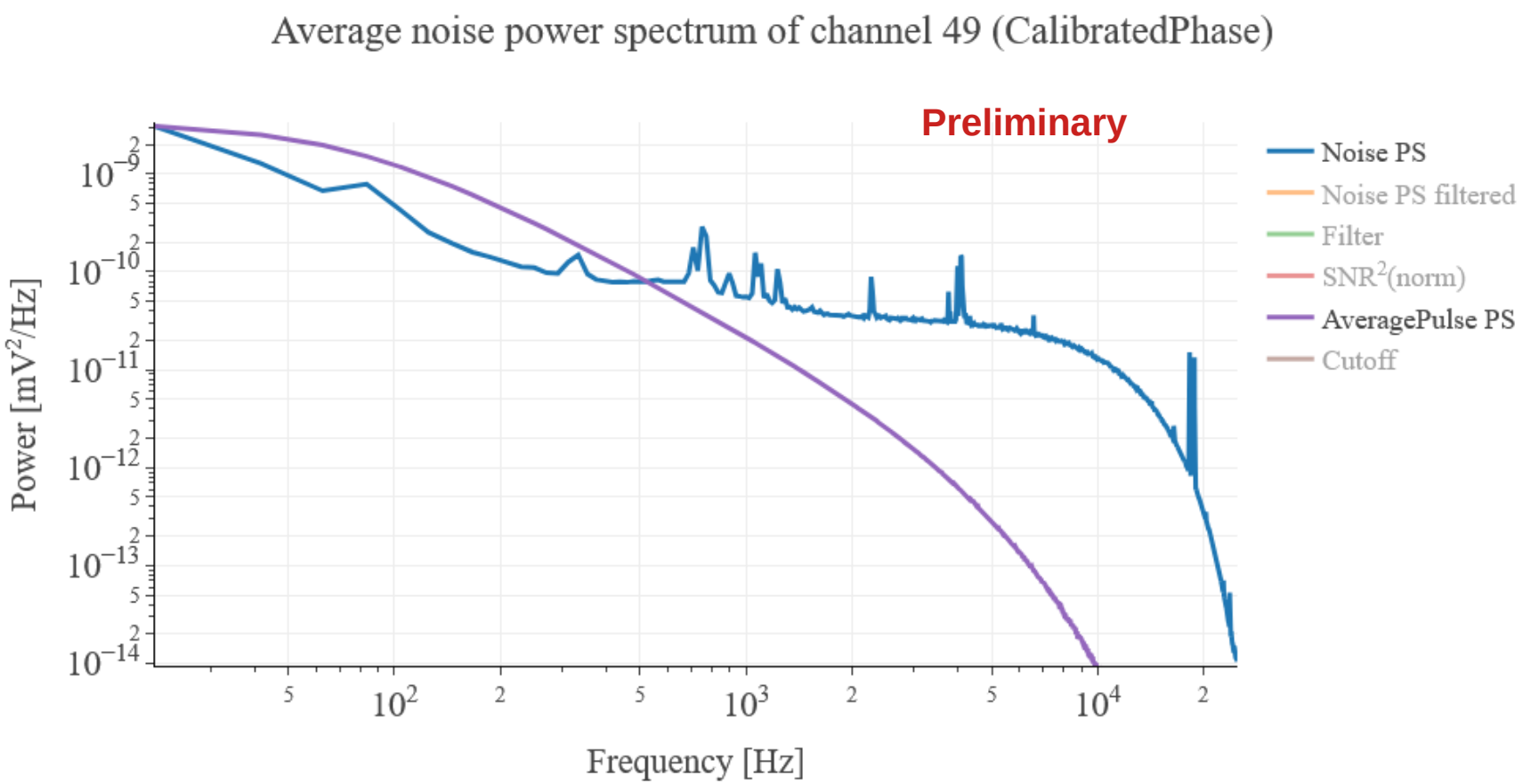
Fire on KID-48, evaluate stability of masters with leakage signal



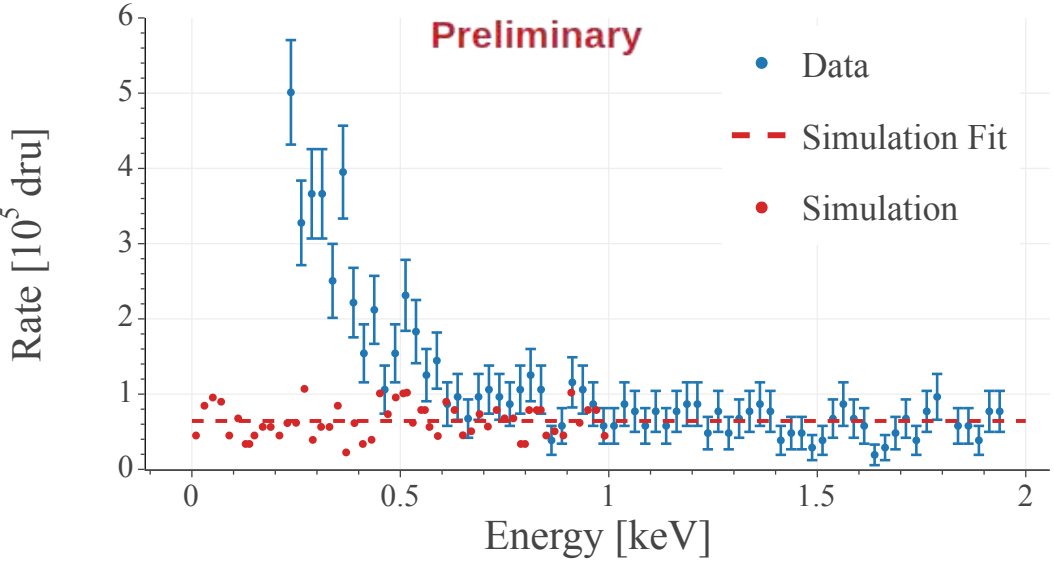


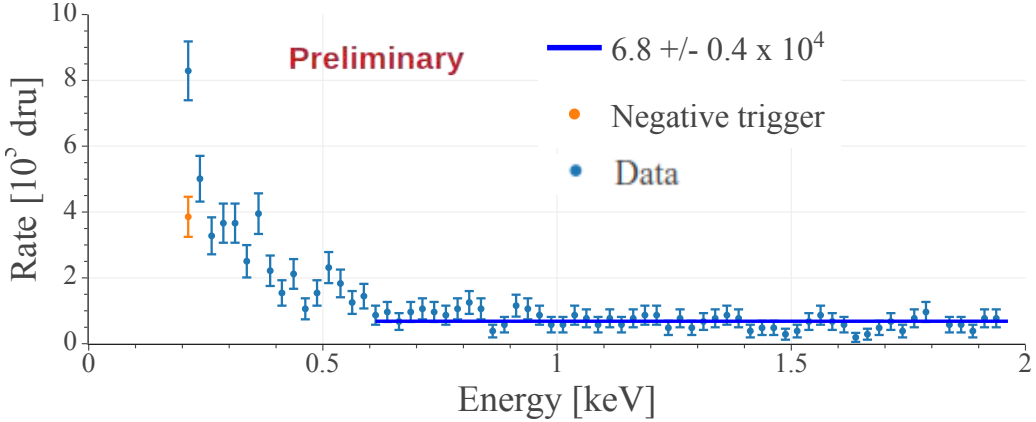


NPSD


Average noise power spectrum of channel 49 (CalibratedPhase)
Preliminary
Noise PS
Noise PS filtered
Filter
SNR²(norm)
AveragePulse PS
Cutoff
Power [mV²/Hz]
Frequency [Hz]

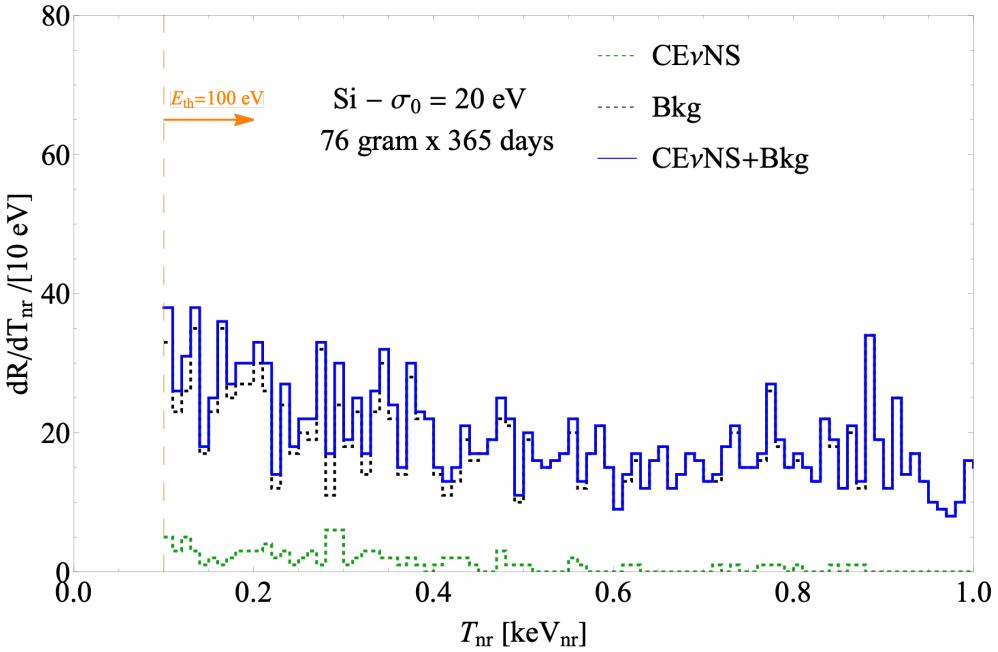
Energy Spectrum

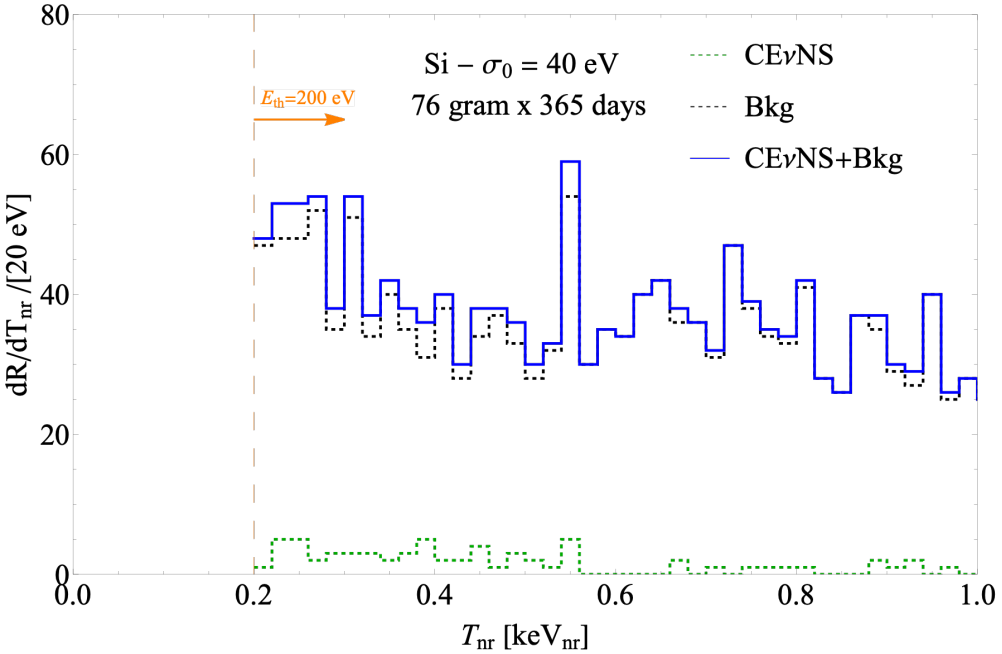




- Flat background: (68±4) kdru (simulated 61±3 kdru)
- In <600 eV measured rise up to a factor ~5
- Spectra compatible between the two triggering pixels!
- Rise not compatible with negative triggers (noise false positives)
- Has the basic symptoms of the LEE

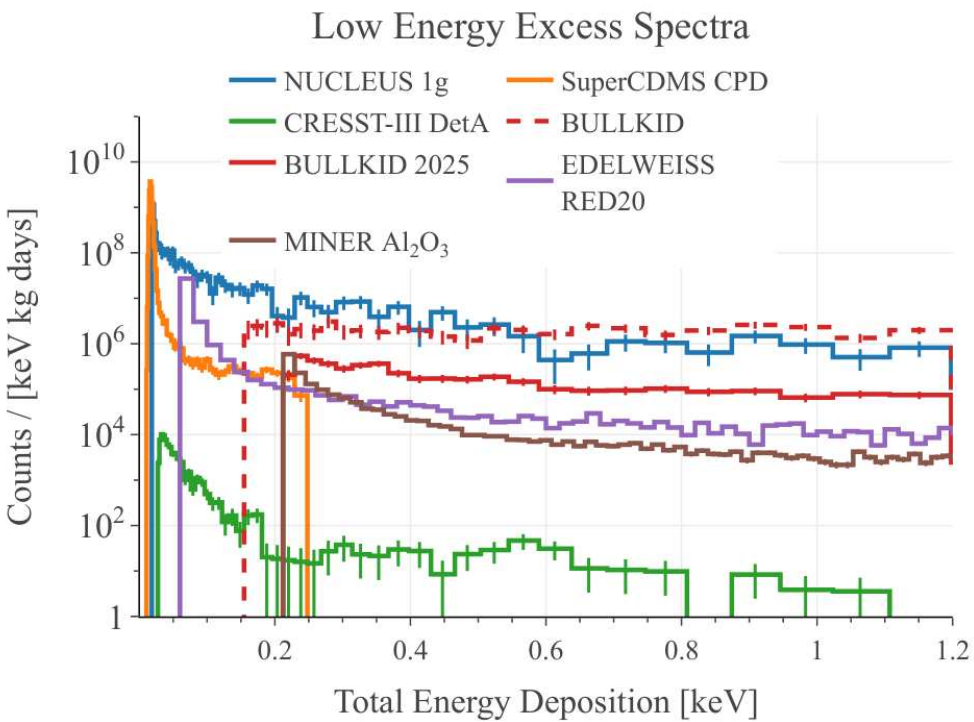
Expected Spectrum from Simulations (Si target)





Low Energy Excess

- Unexplained exponential rise of events at low energies
- Most low energy experiments are TES based
- **BULLKID: KID based experiment shows no evidence of LEE so far**

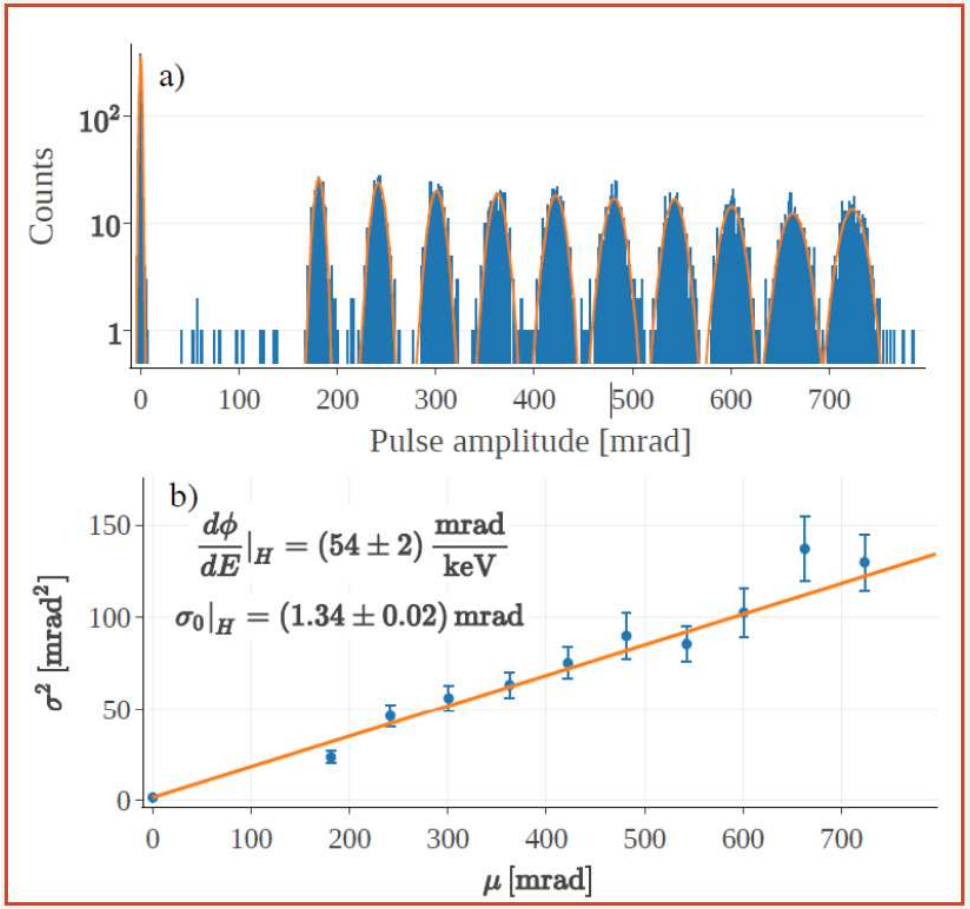


KIDs resilience is currently unexplained, the hypotheses are:

- KIDs are **simpler sensors** (evaporated lithography)
- KIDs are purely **athermal phonon** detectors
- Detector geometry

LOWER BACKGROUND IS NECESSARY FOR COMPETITIVE STATEMENT

LED Calibration



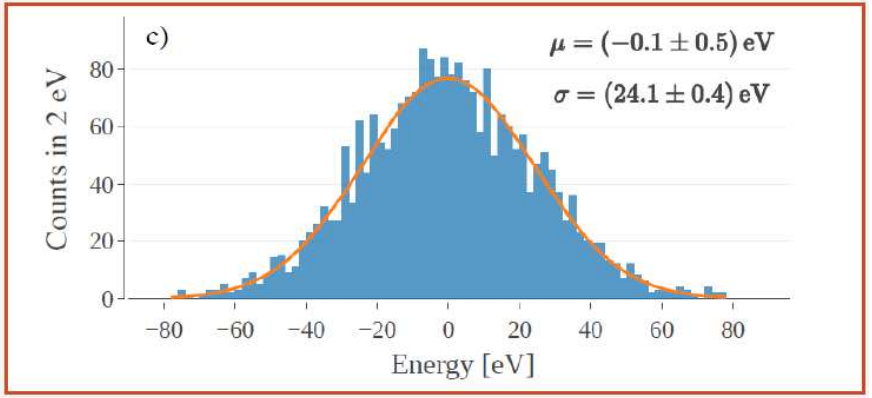
$$\sigma = \sqrt{\sigma_0^2 + \epsilon_{ph} \cdot \frac{d\phi}{dE} \cdot \mu}$$

- σ_0 (resolution)
- $\frac{d\phi}{dE}$ (responsivity)

Average resolution across 8 pixels:

$$\sigma_0|_H = 26 \pm 7 \text{ eV.}$$

Allowing for a **threshold** ≈ **150 eV**



A. Cruciani, et al, Appl. Phys. Lett. 121, 213504 (2022)

Coherent Elastic Neutrino Nucleus Scattering

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

$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} \leq 10^{-40}\mathrm{cm}^2$$

Neutrino Energy (see later)

$$E_\nu \approx O(\text{few MeVs})$$

Weak Force Charge

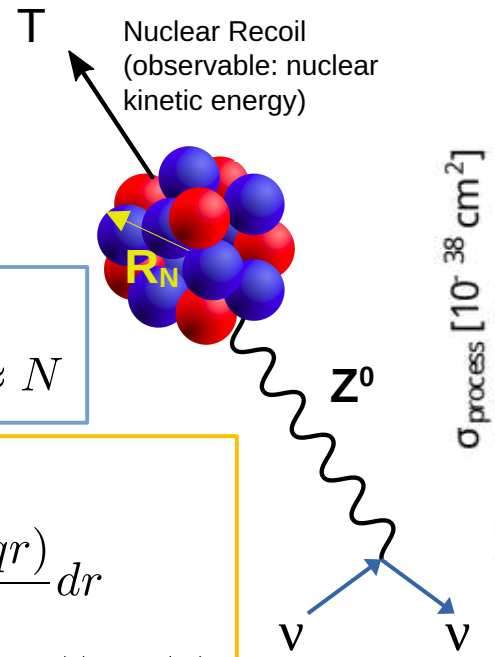
$$Q_W = N - P(1 - 4\sin^2\theta_W) \approx N$$

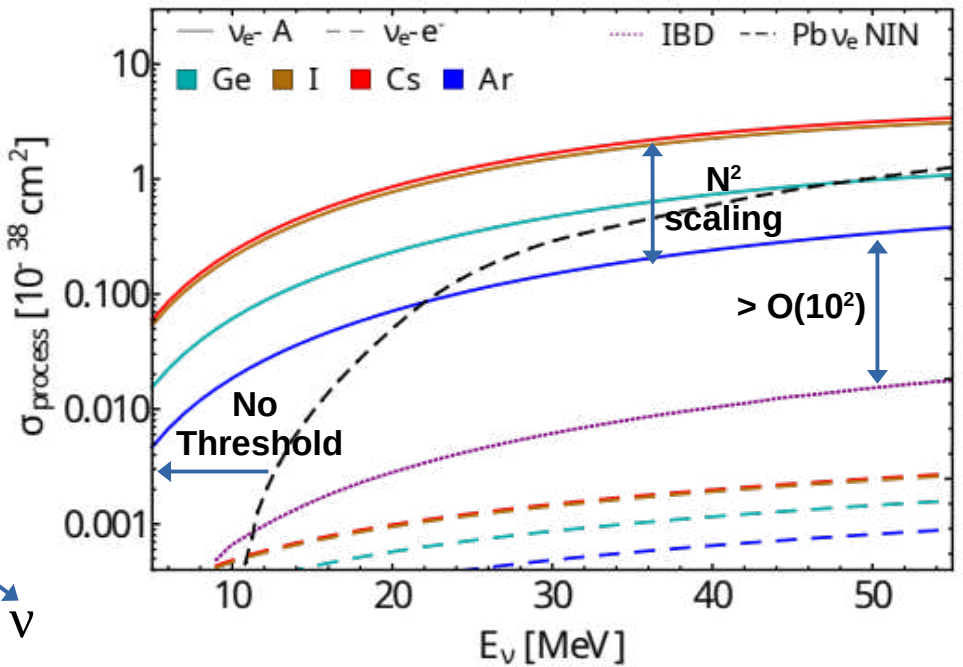
Nuclear Form Factor

$$F(q) = \frac{1}{Q_W}\int_0^{R_N} \rho_W(r)\frac{\sin(qr)}{qr}dr$$

$$\rho_W(r) = \rho_N(r) - (1 - 4\sin^2(\theta_W))\rho_P(r)$$

Fourier transform of the nucleon distribution





$$E_\nu^{max} \approx 20\mathrm{MeV}\ [\mathrm{He}] \div 70\mathrm{MeV}\ [\mathrm{U}]$$