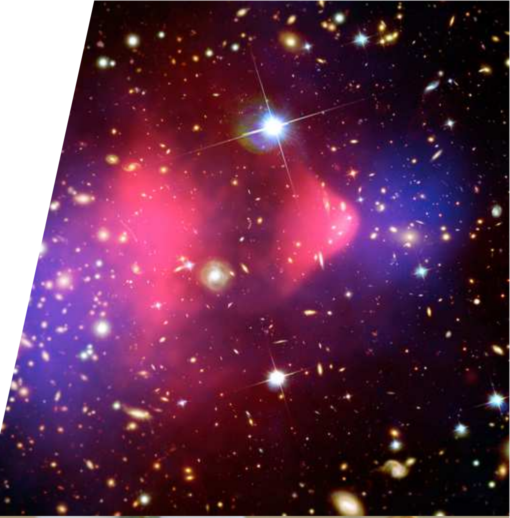
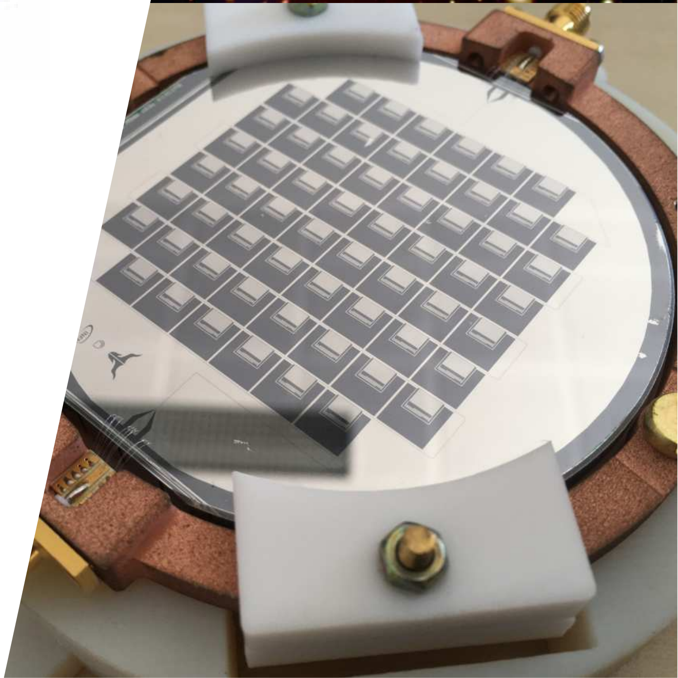


BULLKID-DM

WIMP direct detection with a monolithic arrays of cryogenic detectors



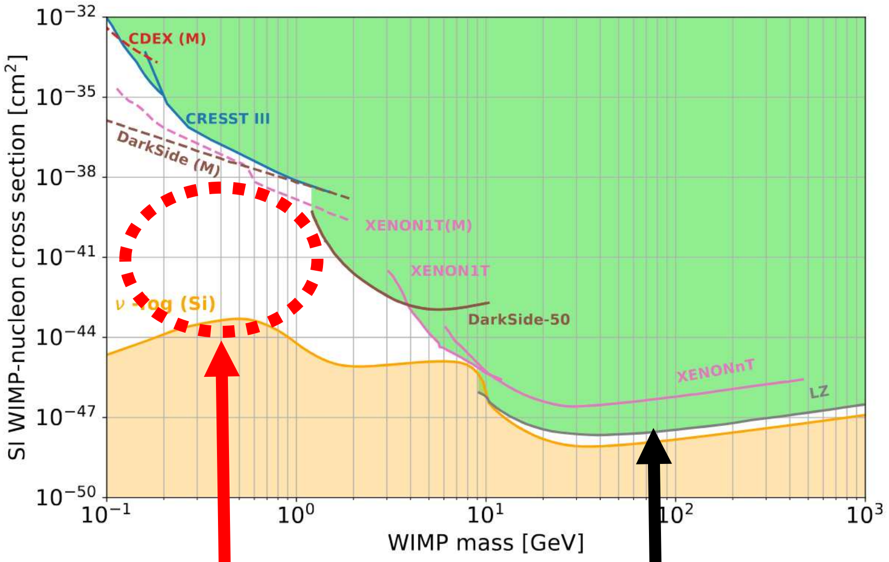
Giorgio Del Castello on behalf of the collaboration
INFN - Roma 1

June 4, 2026

BULLKID-DM: A WIMP-like dark matter experiment

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

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



kg-scale solid state phonon detectors

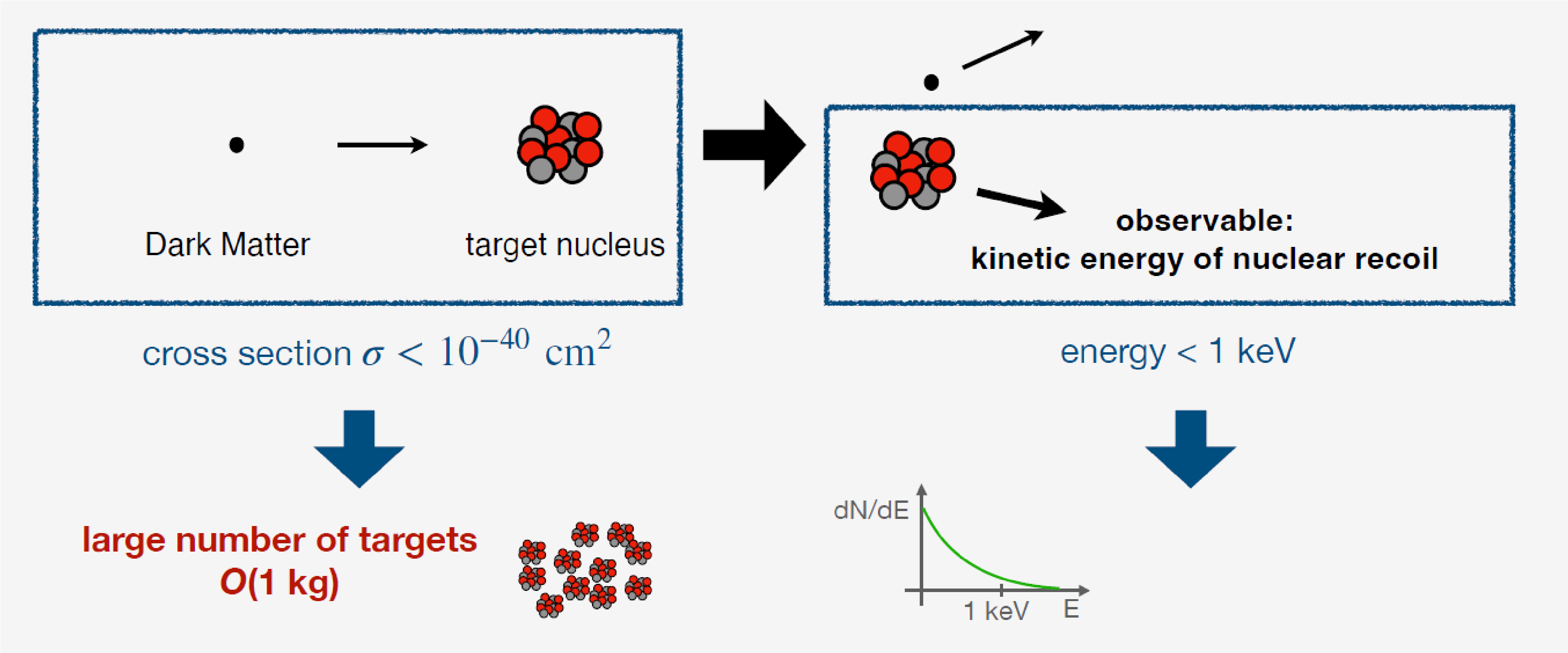
Multi-ton liquid scintillators

[S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)] updated to late 2025 by M. Folcarelli

Detection Principle: Nuclear Recoils

Target: Silicon (Si) sensed with ~200 eVnr threshold

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



Experimental Site: Cryoplatform @ LNGS

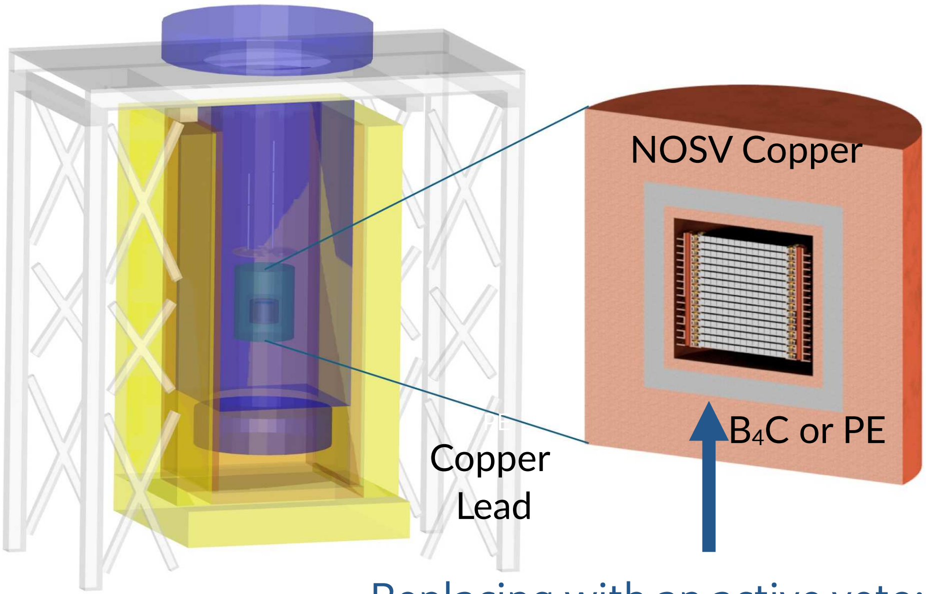
BULLKID-DM @ LNGS cryoplatform
(Hall B)

Oxford Proteox cryostat delivered in 2025

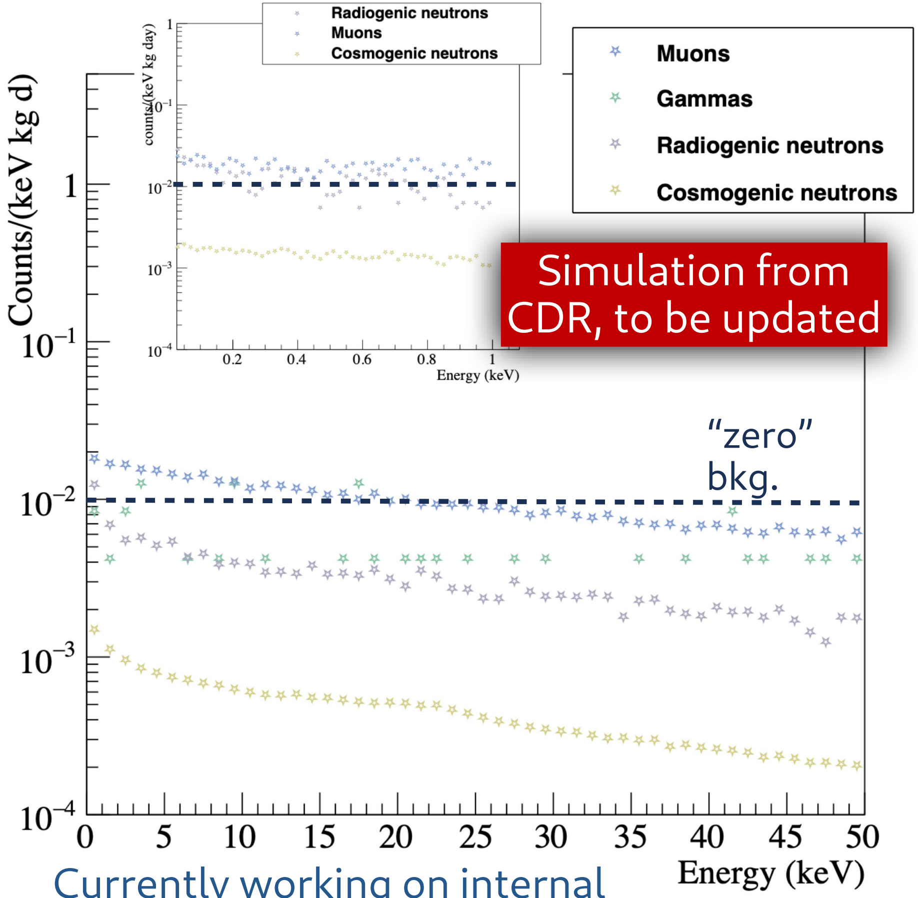
Equipped with removable RF lines for quick installation

Expected Background and Shields

Muons, Gammas and Neutrons from:
Astropart. Phys. 33 (2010) 169,
Phys. Rev. D 73 (2006) 053004,
Eur. Phys. J. A 41 (2009) 155,
Astropart. Phys. 22 (2004) 313.



Replacing with an active veto:
5-10x less background



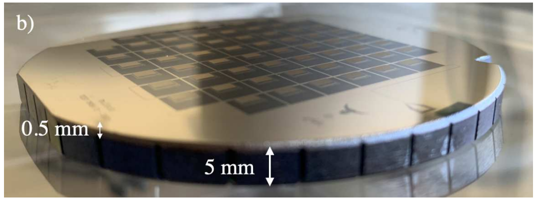
Currently working on internal contaminations in lead and veto

Core Detector: Fully active structure of cryogenic calorimeters

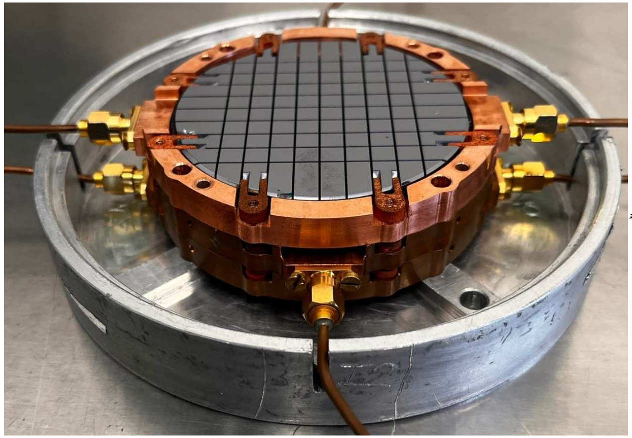
No passive structures near detectors!
Monolithic and compact design for background reduction!
kg scale detector with 2320 sensors!

Prototype

Instrumented with Al-based MKIDs

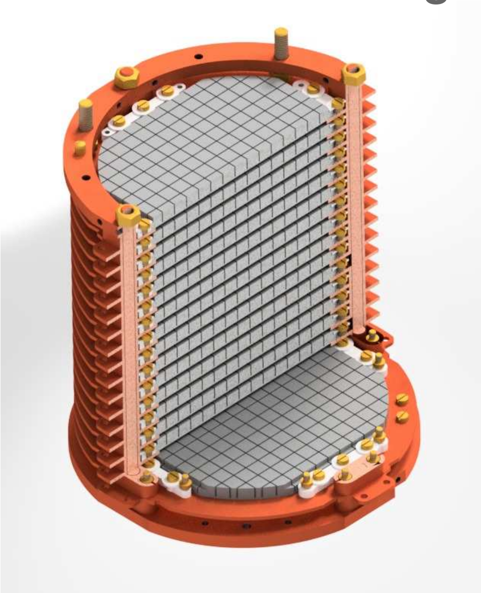


Demonstrator



3x prototypes stacked

Final Detector Design

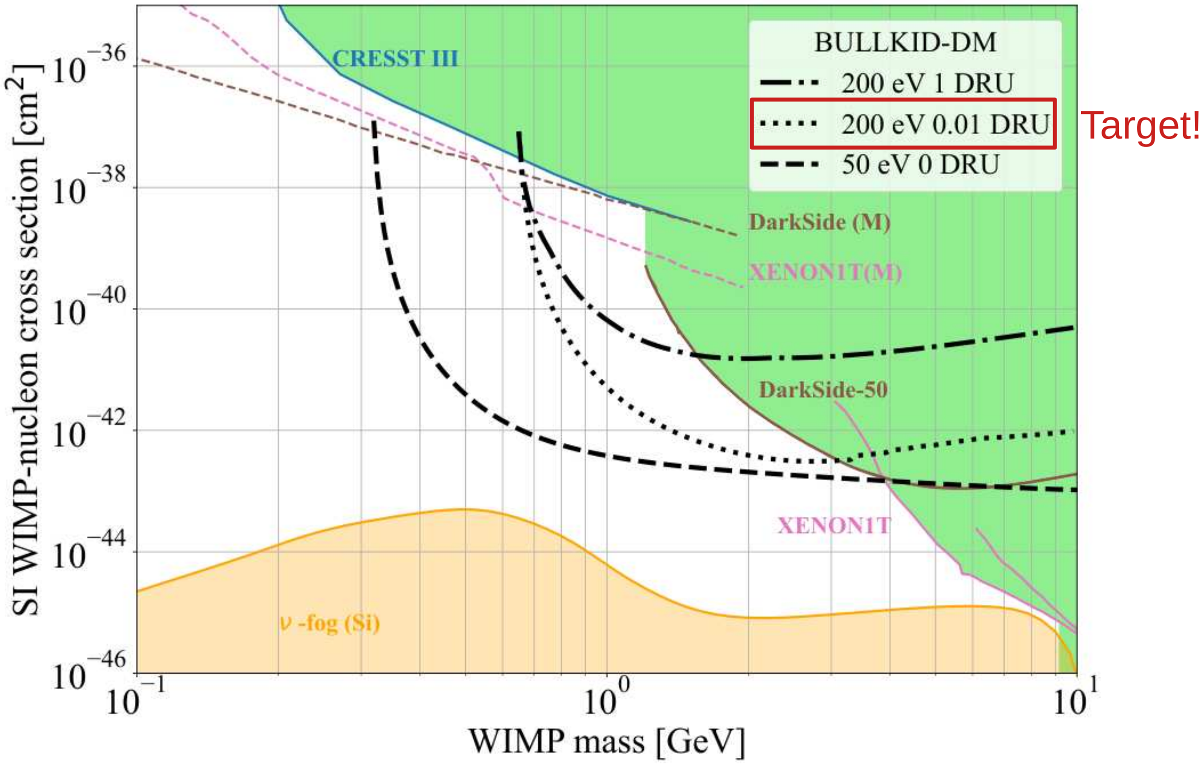


Stack of 16x100 mm instrumented Si wafers (~800 g target mass)

Sensitivity to WIMP-like Dark Matter

Green Region: Excluded
Orange Region: Neutrino Fog
Lines: BULLKID-DM projections

M. Folcarelli, et al., Projected sensitivity to light WIMP-like particles of the BULLKID-DM experiment, arXiv 2601.13766



Sensitivity to Sub-GeV WIMP masses

O(0.01 DRU): background goal (“zero background” environment)

200 eV Analysis Threshold: already achieved

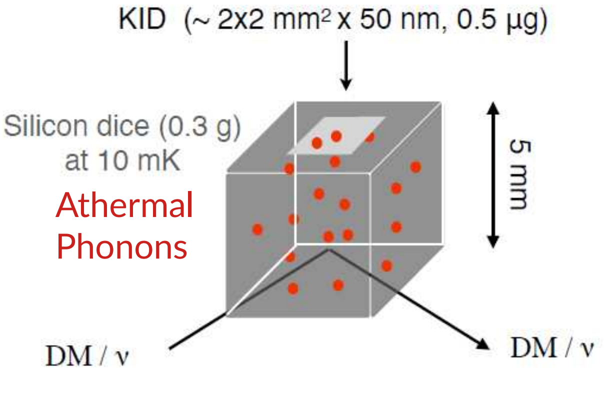
Limits set using Yellin method for unknown background model

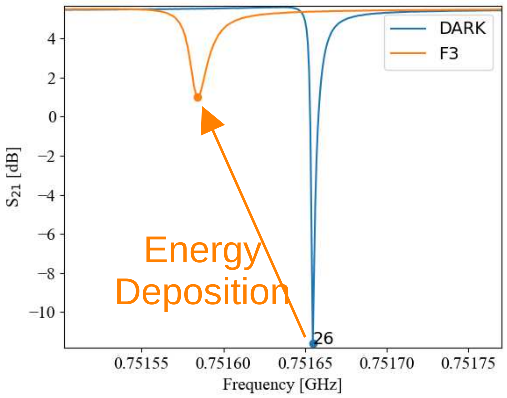
KID-based calorimetry

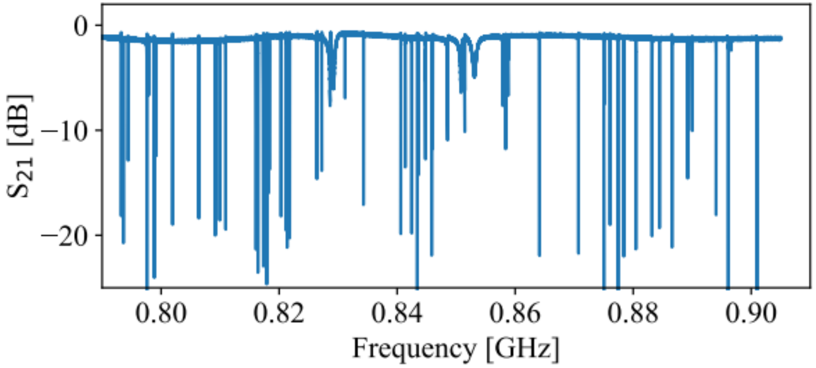
- MKIDS are superconductive LC resonators (sensitive only to athermal phonons)
- Allow for frequency multiplexing.
- Target energy threshold: 200 eV

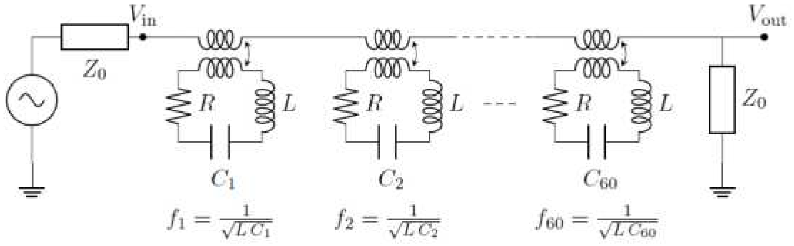
Natural Frequency Multiplexing!

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







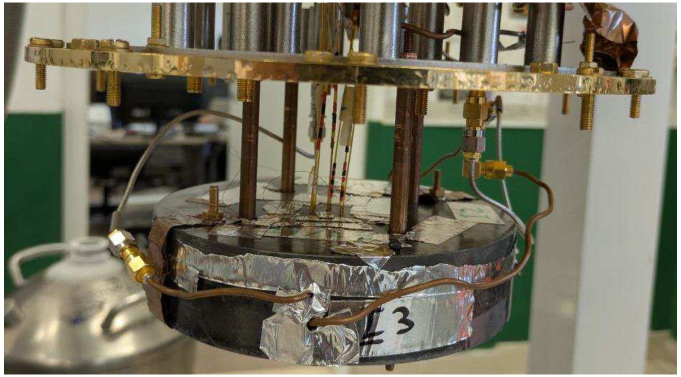


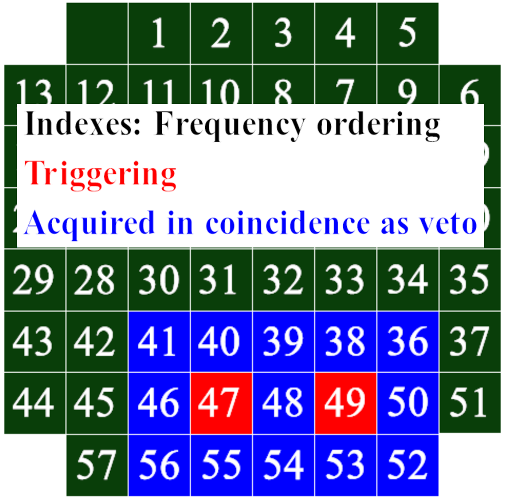
$$E \rightarrow \Delta n_{\text{pairs}} \rightarrow \Delta L \rightarrow \Delta f_0$$

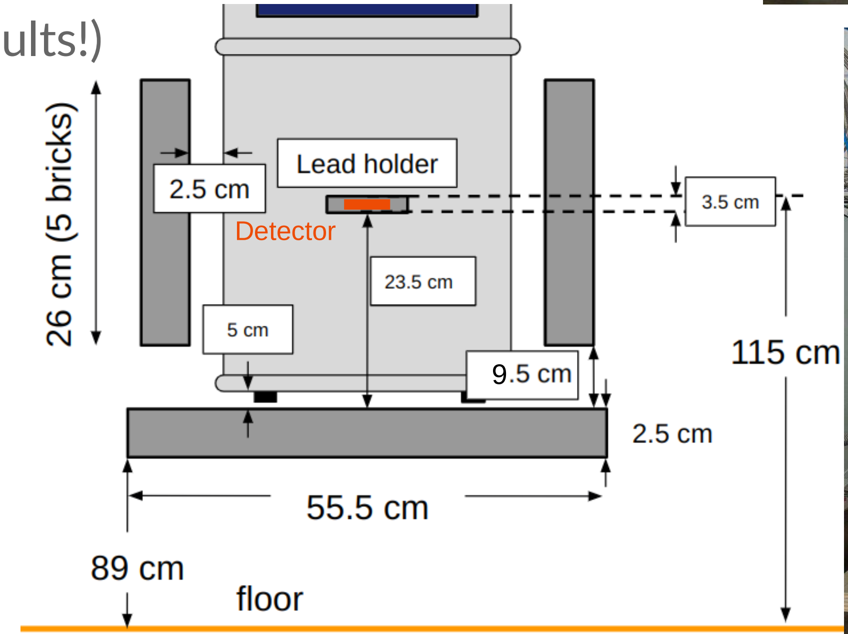
Background at Sapienza with Mild Shield

- 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!)

D. Delicato, et al., Background of the BULLKID detector array operated with moderate shield on surface, arXiv 2605.02468



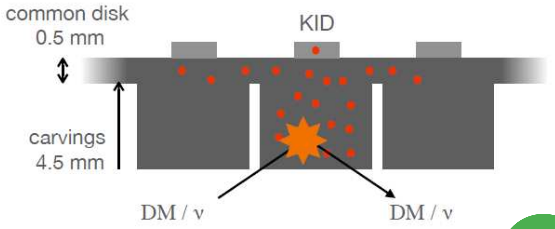


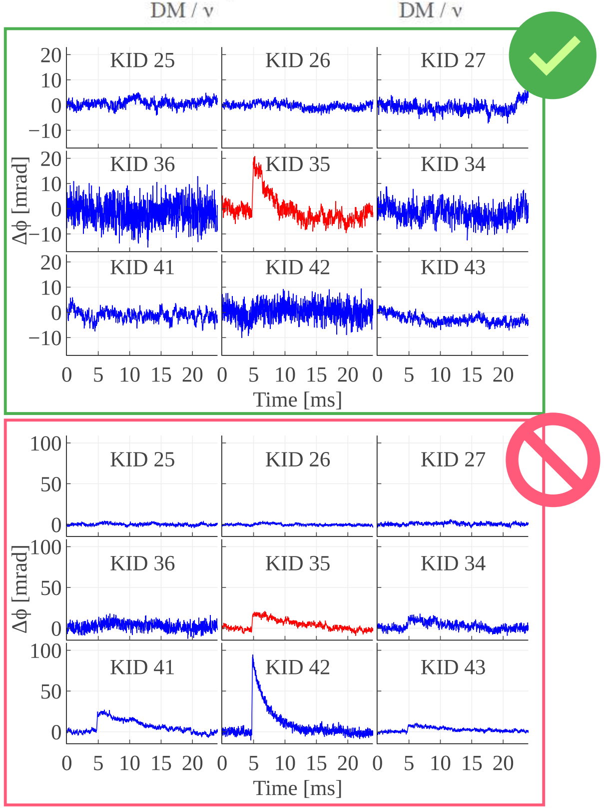


Analysis and Results

- Fiducialization on phonon leakage → interaction location discrimination
- Lead induced radioactive peaks → used for cross-calibration
- In line with simulations
- Demonstrated:
  - Calibration
  - Detector stability over ~1 month
  - Energy spectrum compatibility between different KIDs

D. Delicato, et al., Background of the BULLKID detector array operated with moderate shield on surface, arXiv 2605.02468





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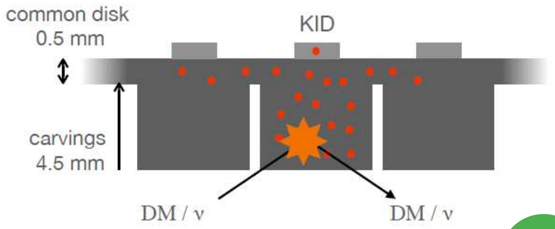
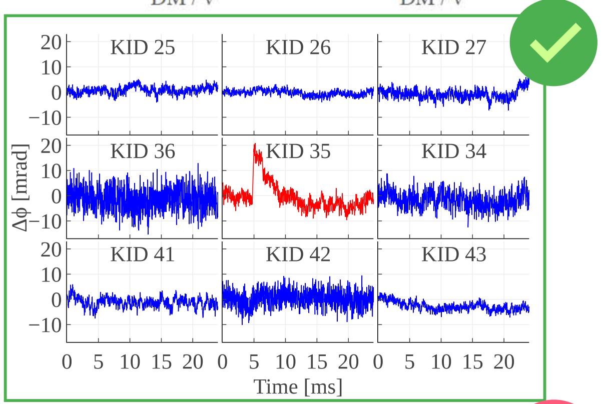
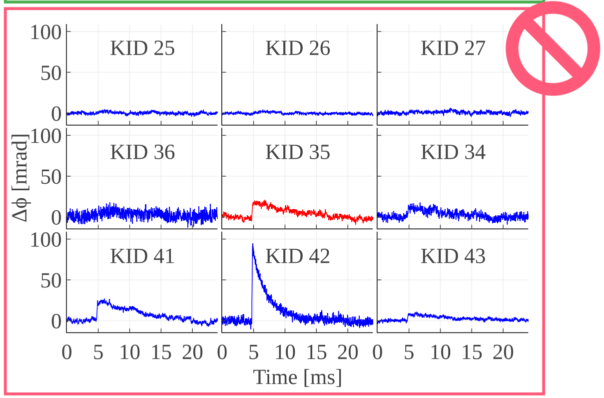
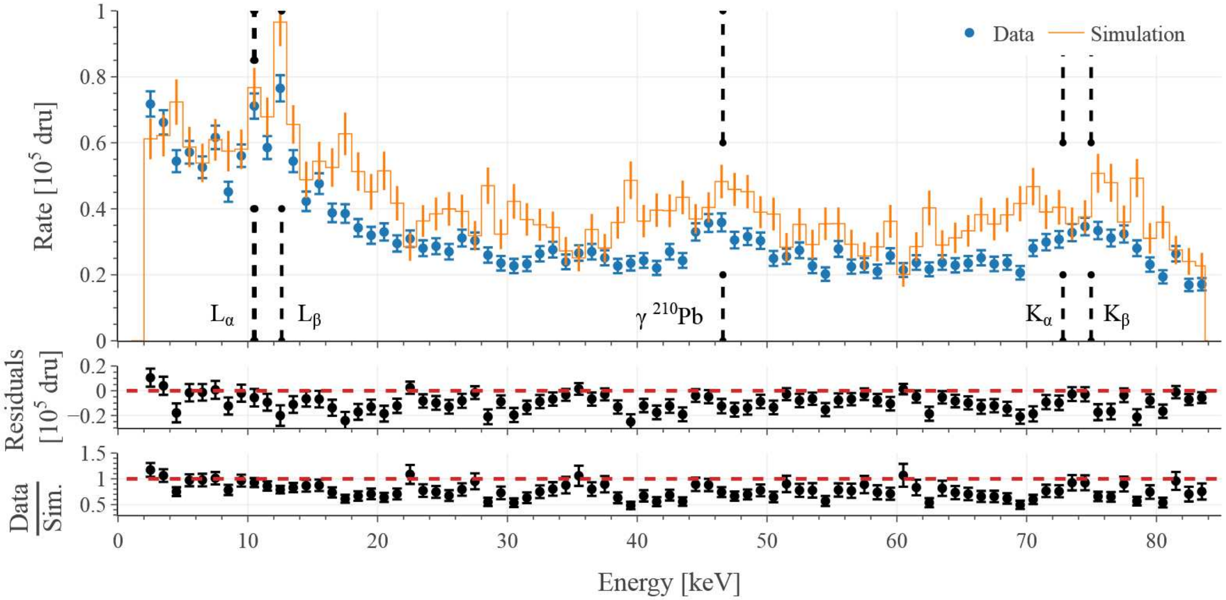
D. Delicato, et al., Background of the BULLKID detector array operated with moderate shield on surface, arXiv 2605.02468

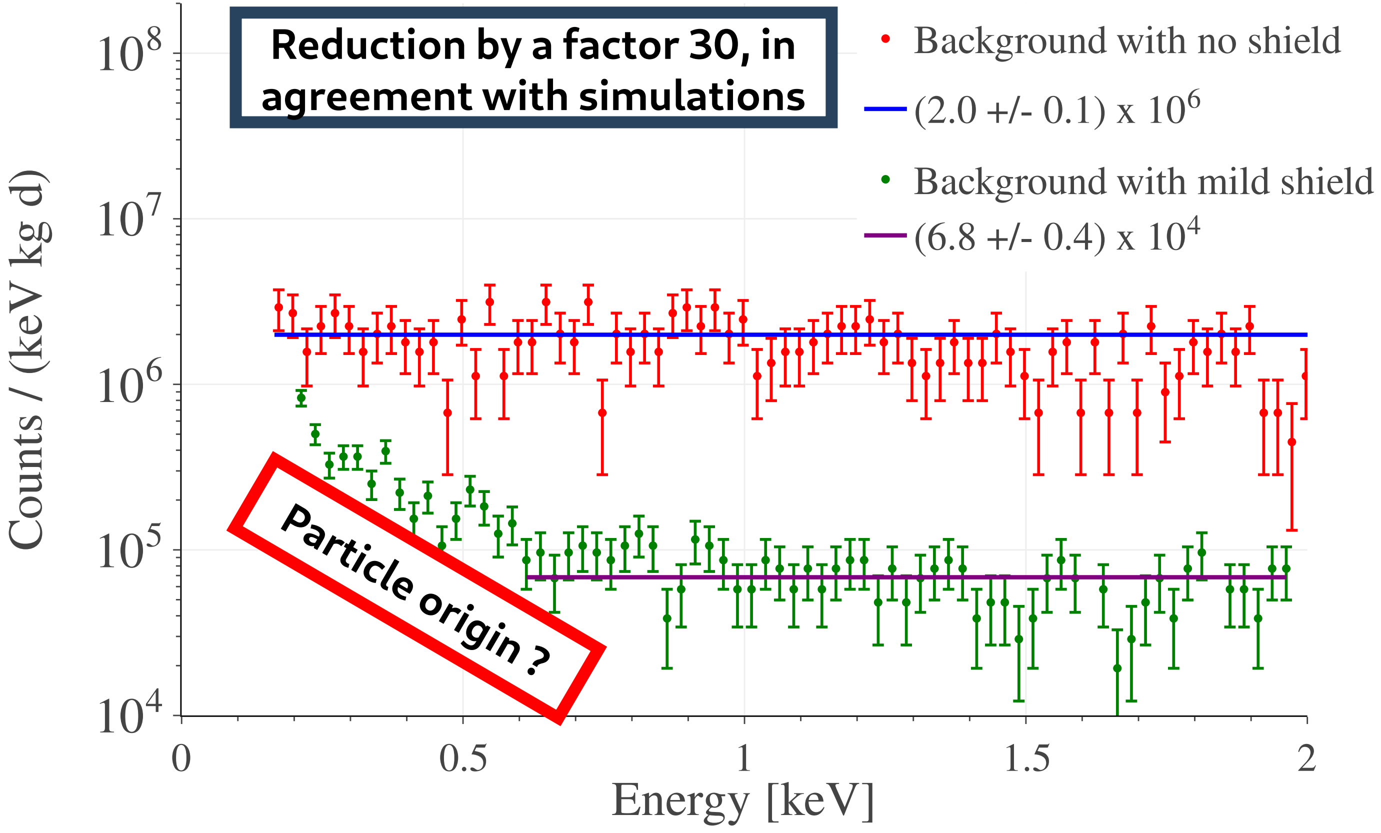








Low energy background



Check out M. Folcarelli's talk at EXCESS workshop!

Factor x30 lower background thanks to shielding

Low Energy Rise (Low Energy Excess?)

Probably Not:

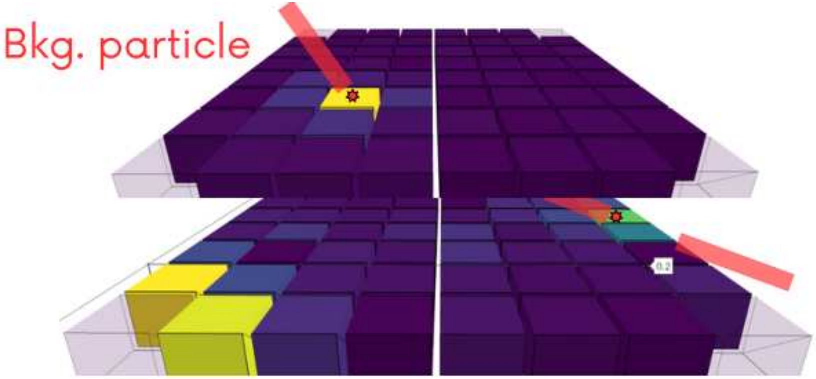
- No Time Decay
- Compatibility between detectors

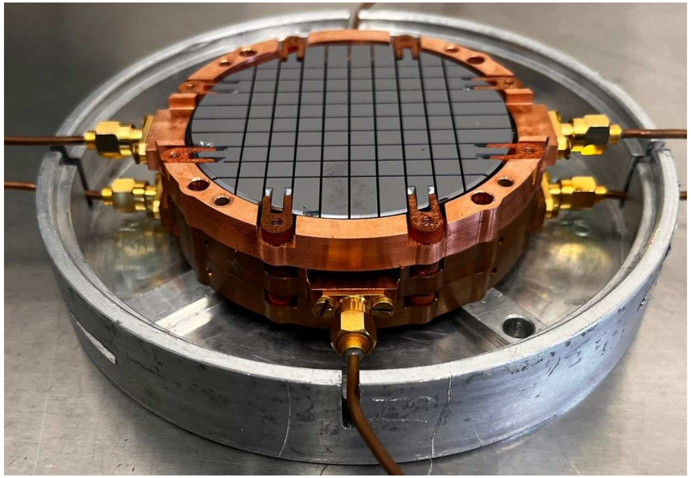
Next step: Check scaling with background

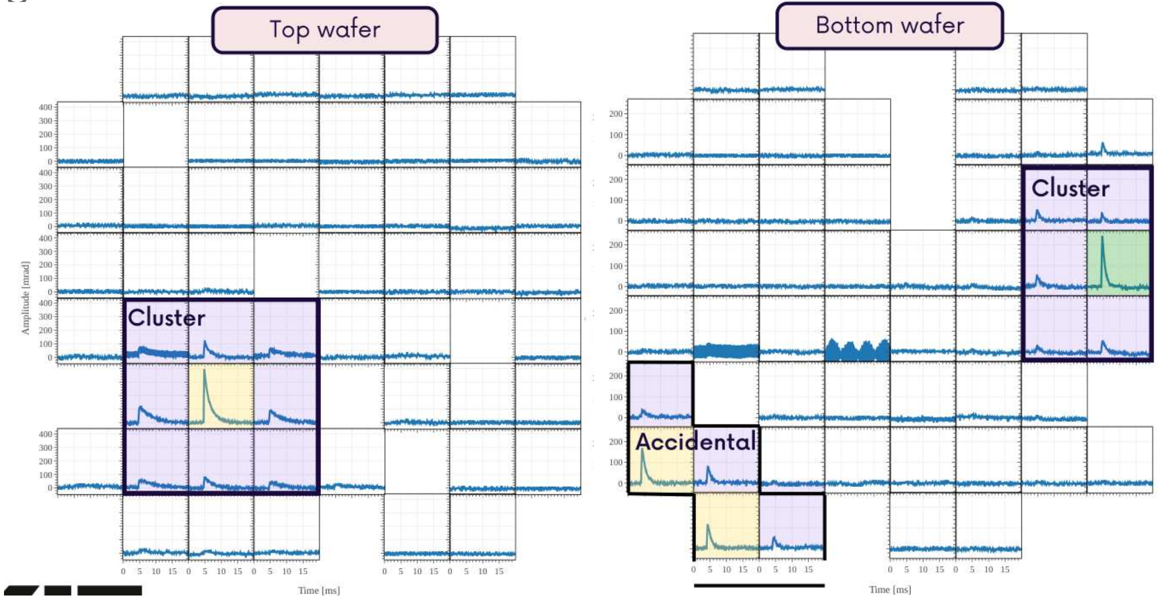
Demonstrator Deployment at Sapienza

Preliminary Run of Demonstrator Detector in Sapienza

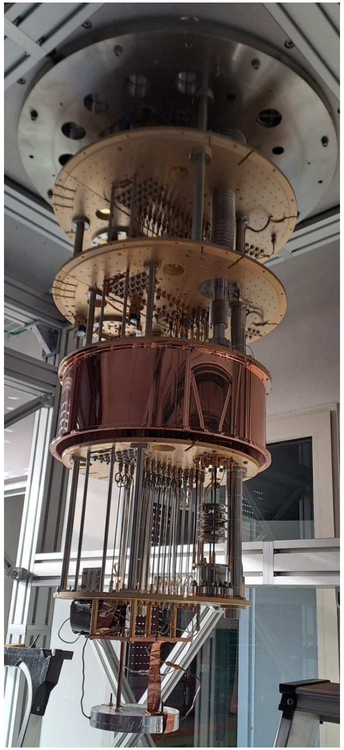
- Validated detectors (158/180 working resonators)
- Acquired in coincidence with new electronics
- Results compatible with old electronics
- Currently finalizing DAQ T. Muscheid, et al., Real-Time Readout System Design for the BULLKID-DM Experiment: Enhancing Dark Matter Search Capabilities, IEEE Trans. Appl. Supercond. 36 (2026)
- Waiting for copper shield for next low(er) background run!







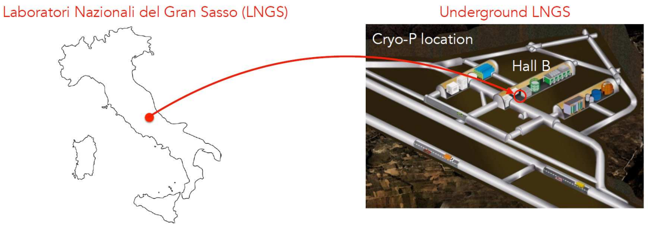
Upcoming measurements



Twin Oxford Proteox @ Sapienza

@ Sapienza in summer 2026

~250 kg of NOSV copper to be deployed at mK stage!



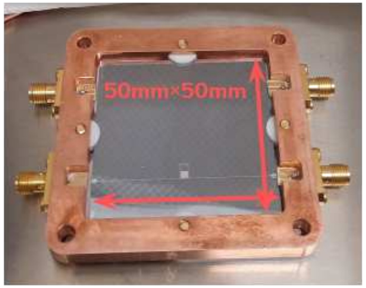
@ LNGS in late 2026

STAY TUNED!

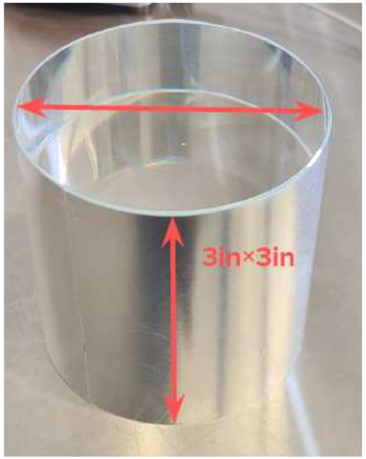
R&D Efforts

Cryogenic Outer Veto (BGO or GSO based)

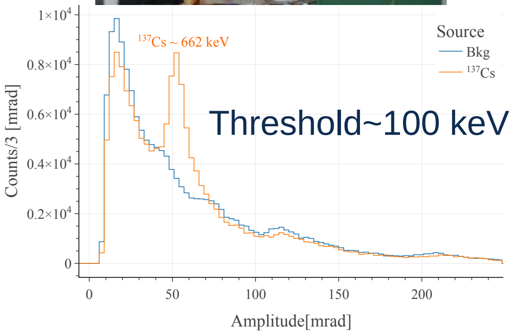
CALDER KID Light detector



BGO Crystal

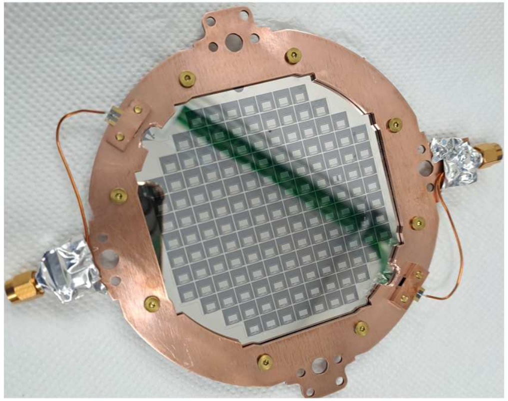


Assembly with reflector



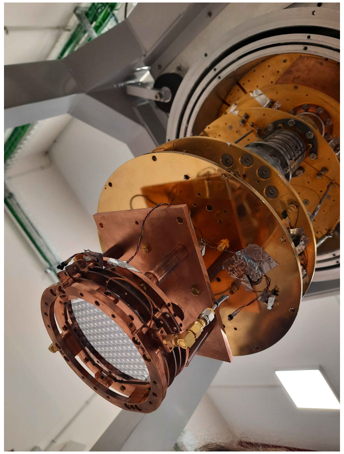
T. Lari, et al., Developing the Cryogenic Veto for BULLKID-DM Experiment, IEEE Transactions on Applied Superconductivity (Volume: 36, Issue: 6, September 2026)

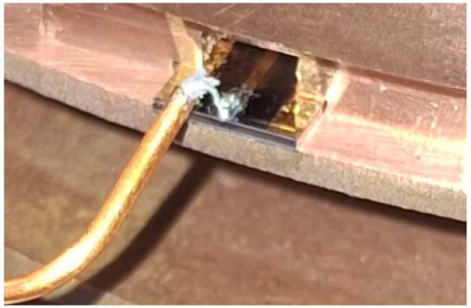
Low Radioactivity RF Mounting

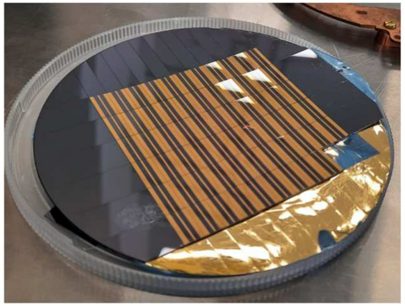


Wafer mounting and bonding

2-wafer test stack







Silicon PCB and clean solder: remove close-to-detector radioactivity

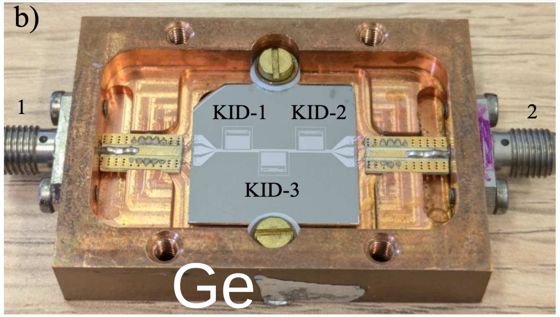
R&D Efforts

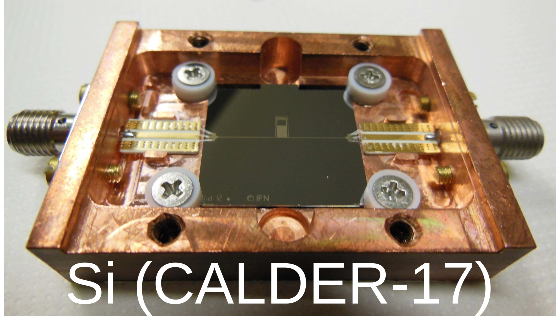
Germanium Target

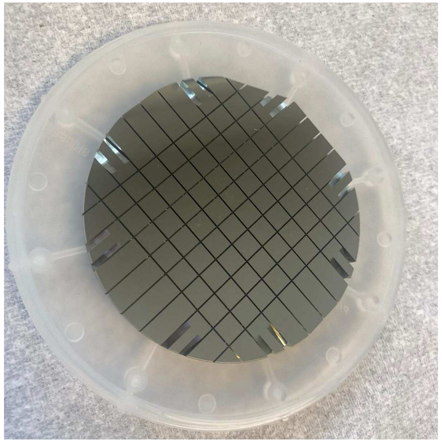
D. Delicato, et al., Germanium target sensed by phonon-mediated kinetic inductance detectors, Appl. Phys. Lett. 126, 153502 (2025)

$$\sigma_{WIMP} \propto A^2$$

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

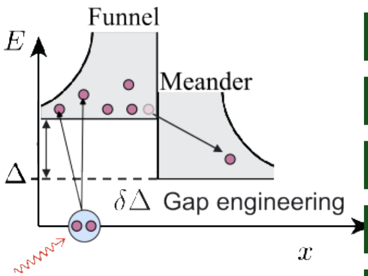


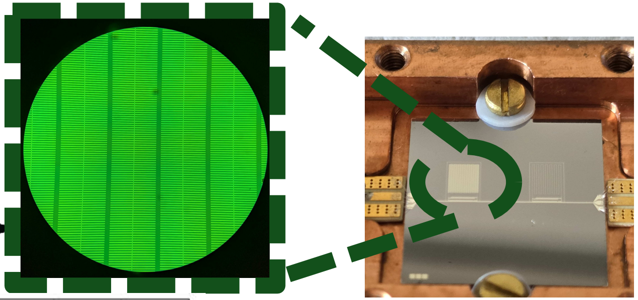


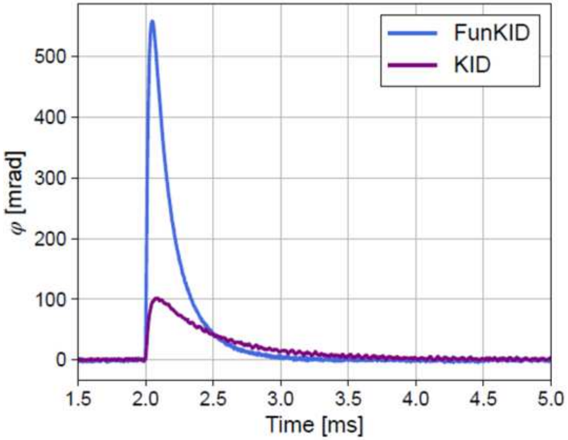


Energy resolution agrees with detector model. Same phonon transport properties of KIDs on Si.

Phonon "Funneling" in KIDs





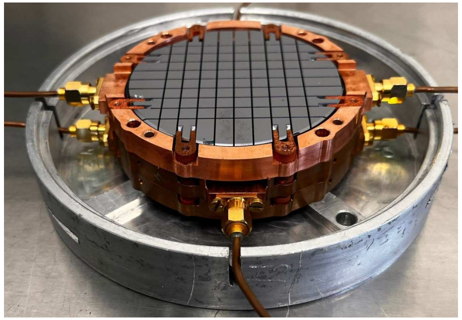


L. Pesce, et al., Enhanced athermal phonon responsivity in a kinetic inductance detector with integrated phonon collectors, Appl. Phys. Lett. 128, 163504 (2026)

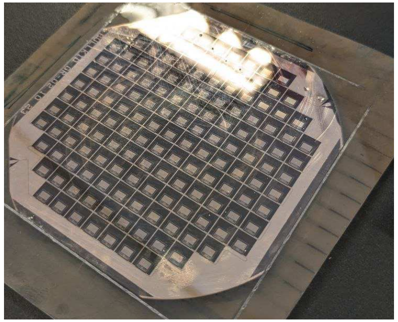
Exploit "gap engineering" for enhancing KID responsivity (~factor 7 improvement).

BULLKID-DM

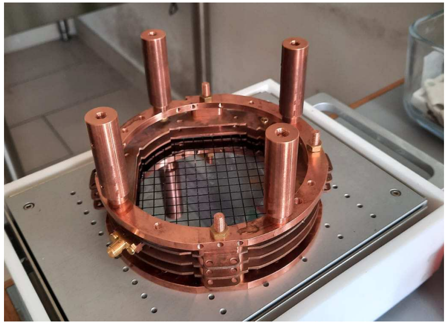
Thank you for the attention!



Demonstrator 3x3'' wafer



100mm prototype



100mm assembly

We are here!

Working Prototype

2023

First Demonstrator Operation

2024

Operation of Demonstrator with shield

2025

2026

First simultaneous acquisition of full Demonstrator!

Demonstrator +Shield @Sapienza

Demonstrator +Shield @LNGS

Full Detector at Sapienza

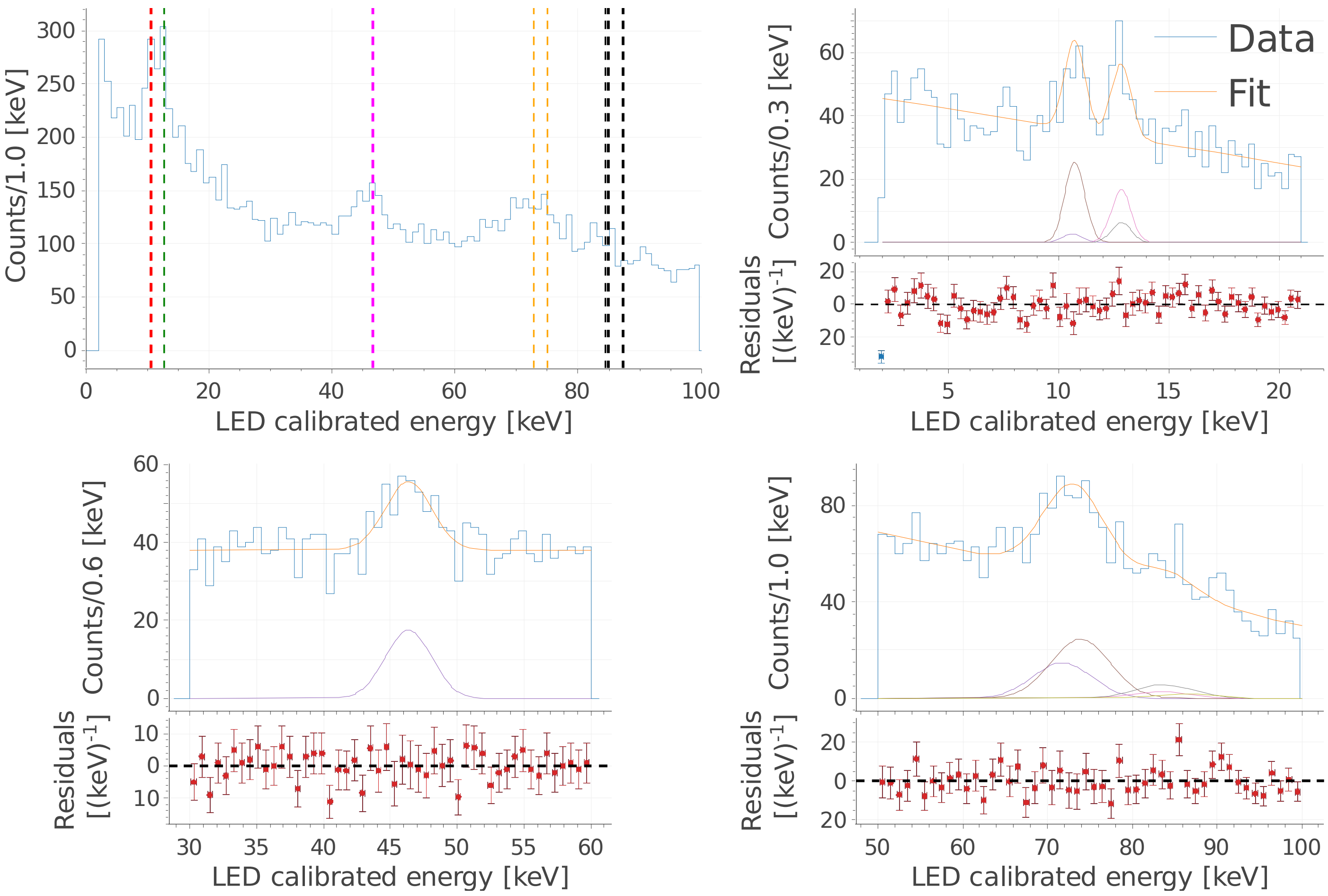
2027

Full installation @LNGS

This work was partially supported through the European Research Council through the Consolidator Grant DANAE number 101087663

Backup Slides

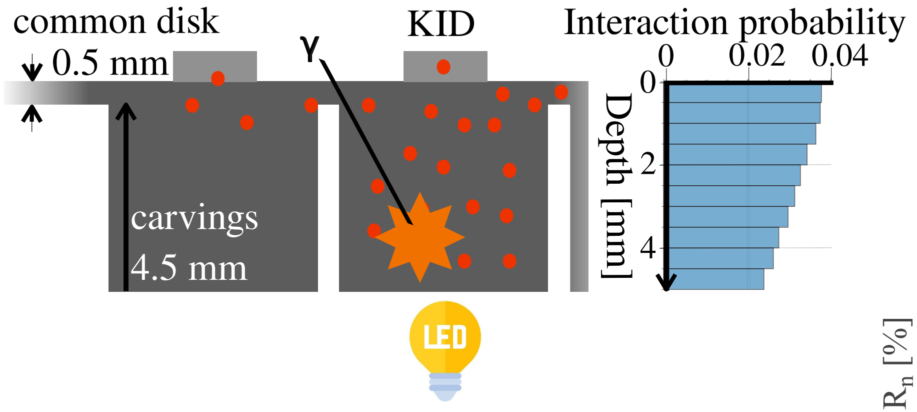
Calibration: Lead



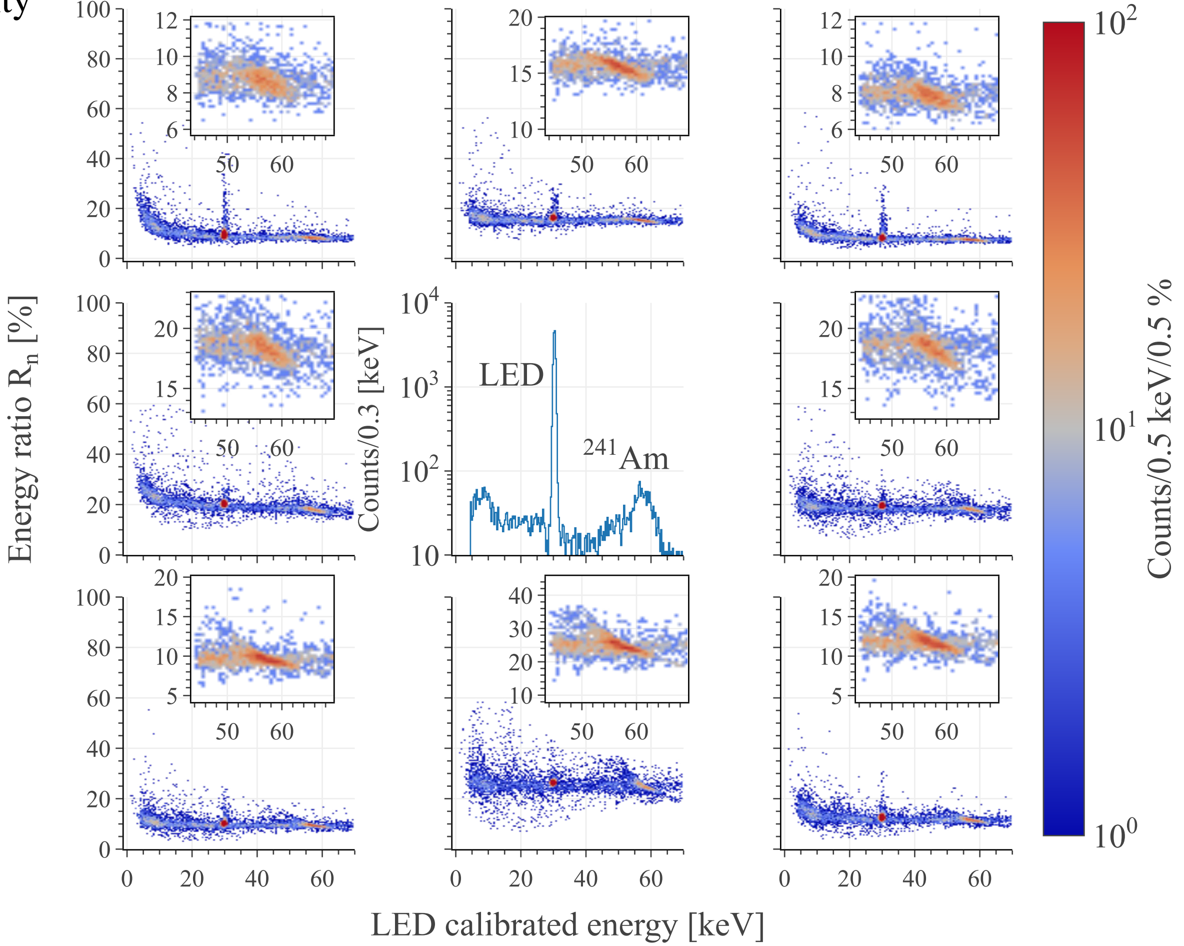
Lead fluorescence and gamma peaks allows the energy calibration of the triggering KIDs

[D. Delicato et al: arXiv:2605.02468v1 [hep-ex] 04 May 2026]

Calibration: Americium



- Dedicated cooldown with ^{241}Am source
- -10% discrepancy between calibrations
- Same leakage between surface and bulk events

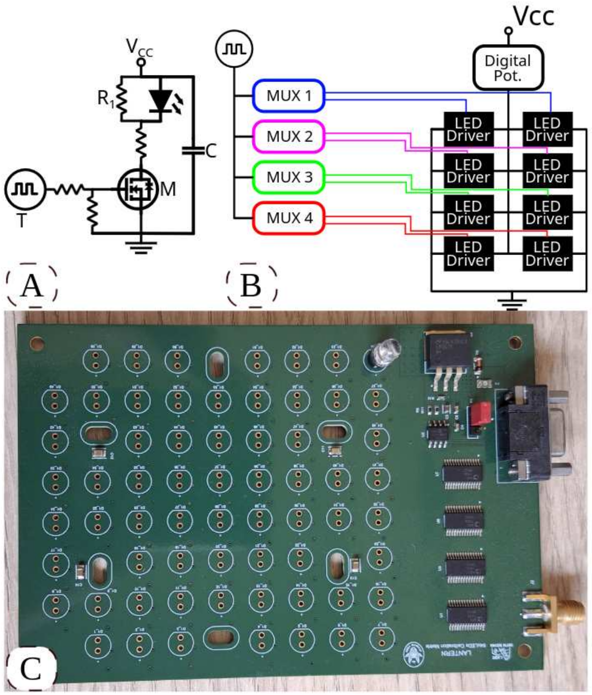


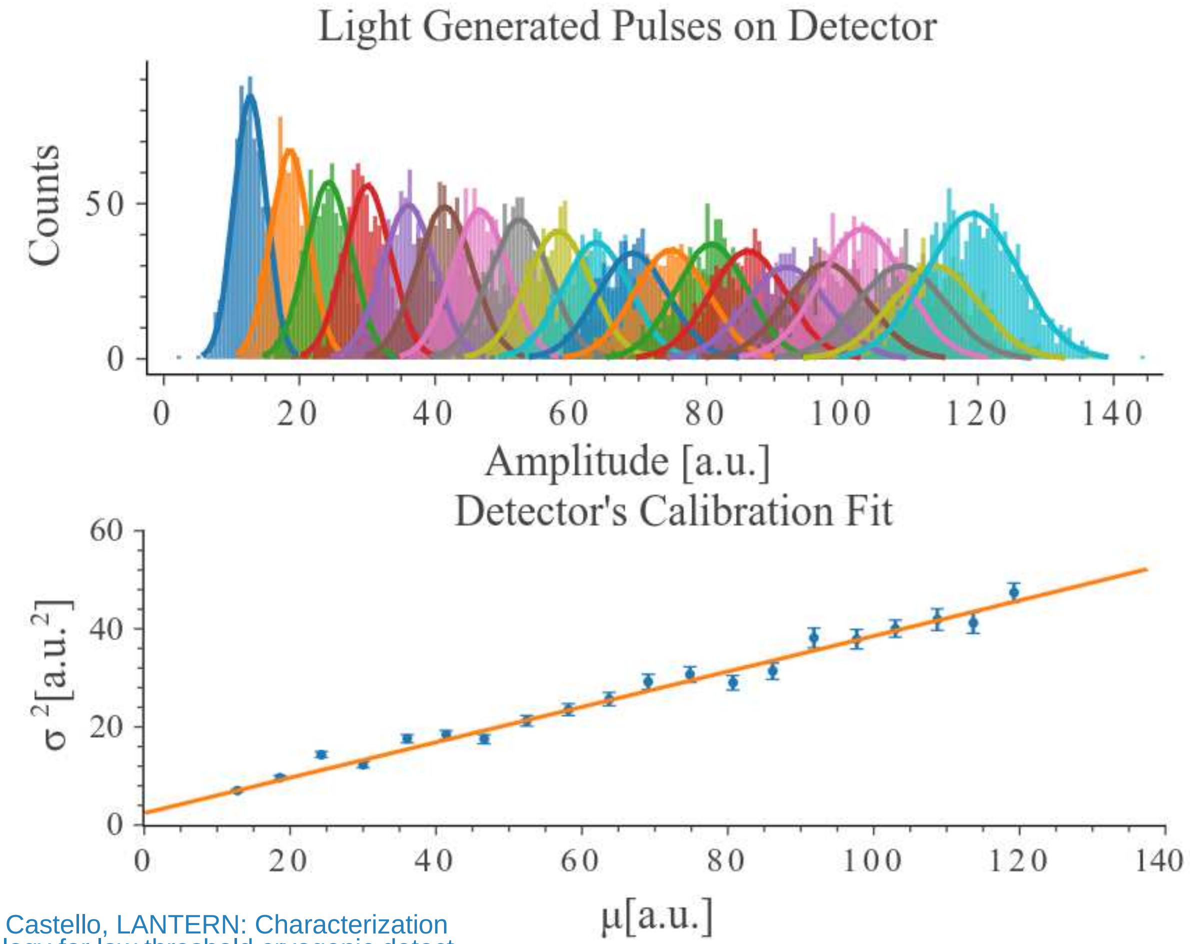
[Folcarelli, M. et al. Eur. Phys. J. C 86, 301 (2026).https://doi.org/10.1140/epjc/s10052-026-15523-4](https://doi.org/10.1140/epjc/s10052-026-15523-4)

Calibration: LED

$$\mu_\gamma = r\epsilon_\gamma \langle N_\gamma \rangle \qquad \sigma_\gamma^2 = (r\epsilon_\gamma)^2 \langle N_\gamma \rangle = r\epsilon_\gamma \mu_\gamma$$

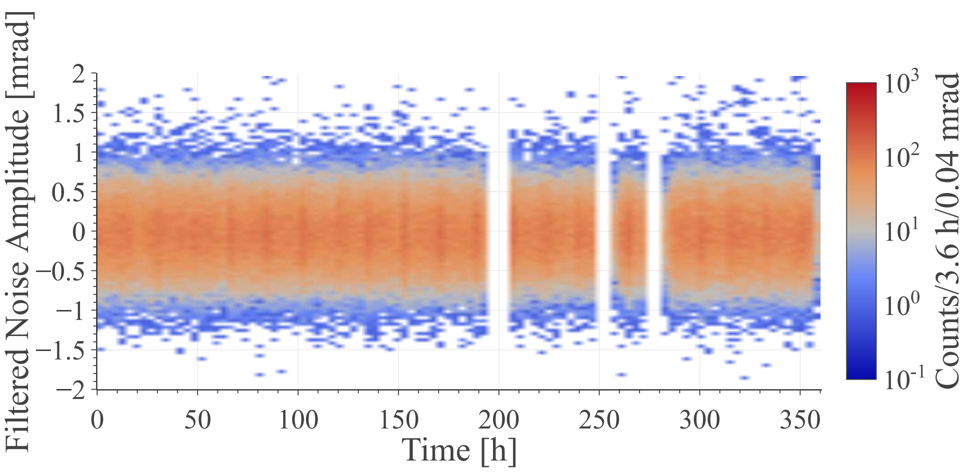
$$\sigma_{LED}^2 = \sigma_0^2 + \sigma_\gamma^2 = r\epsilon_\gamma \mu_\gamma + \sigma_0^2$$

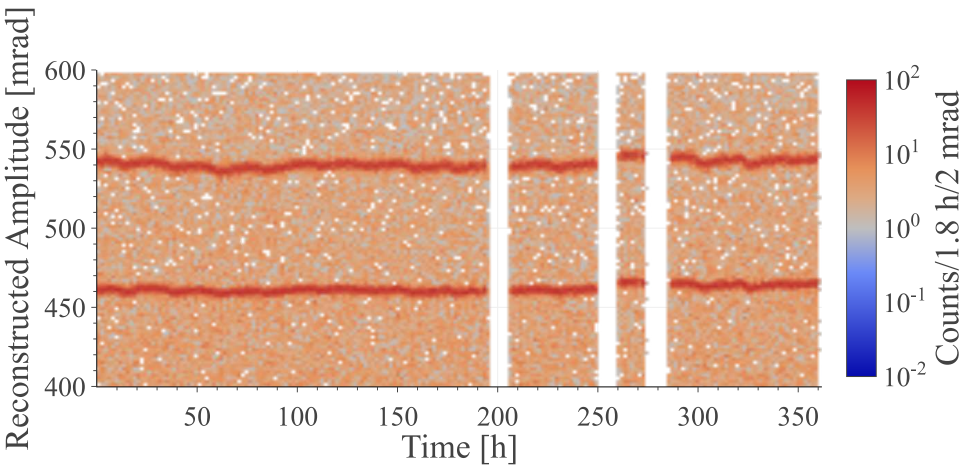




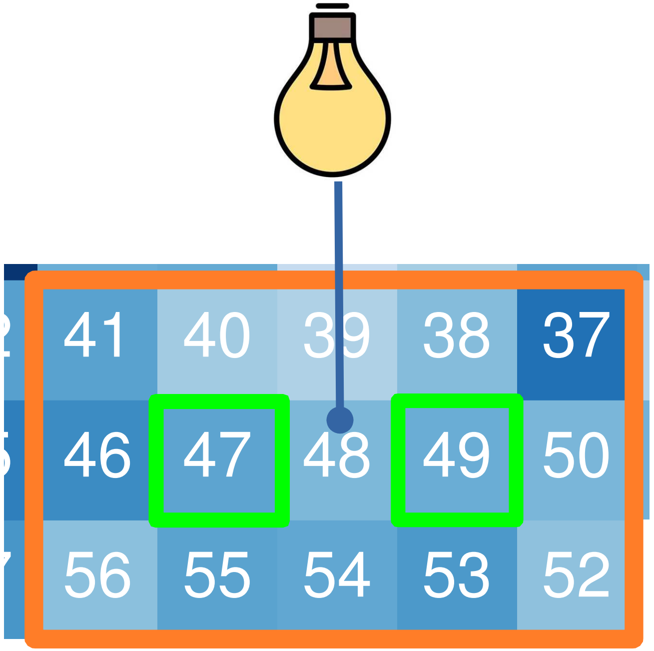
G. Del Castello, LANTERN: Characterization technology for low threshold cryogenic detect ors, arXiv: 2602.20369

Stability



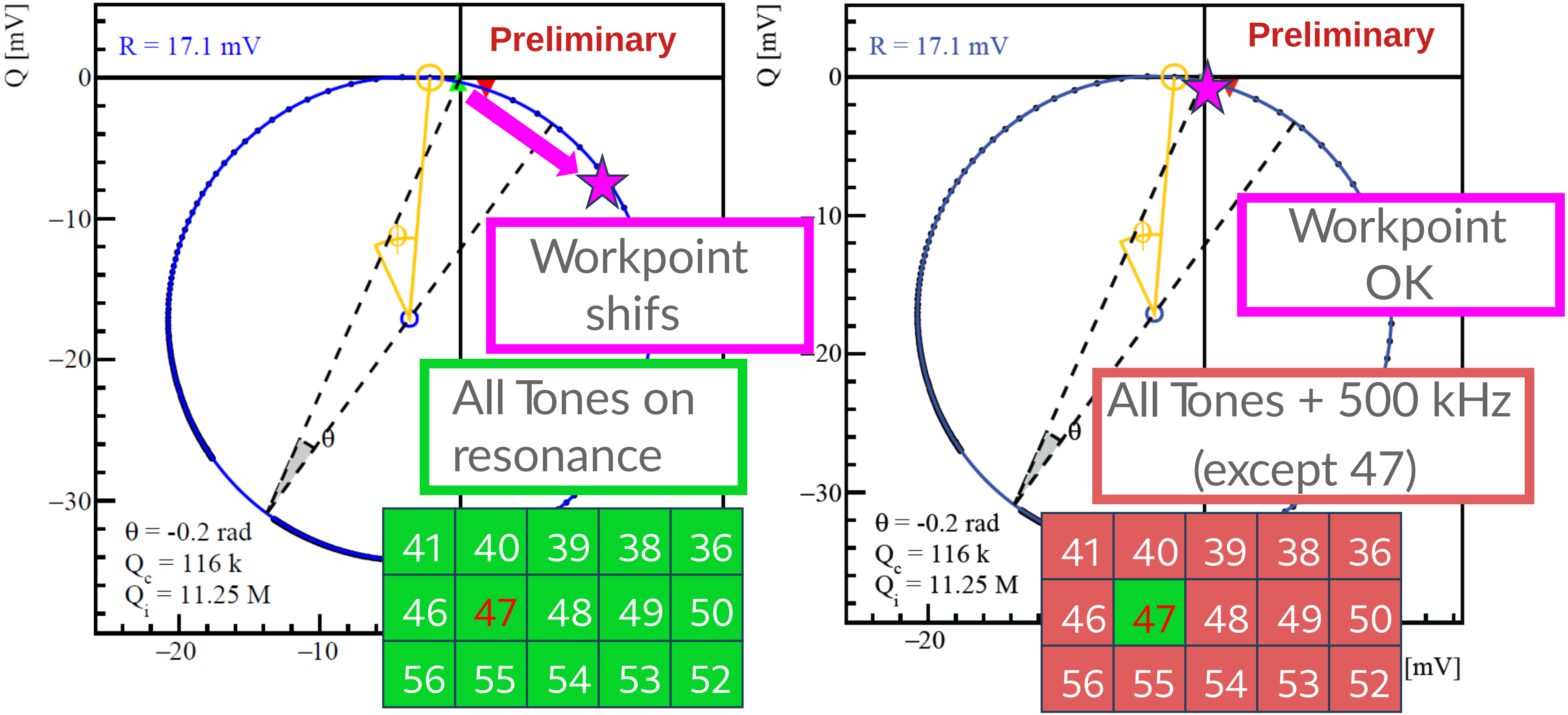


Fire on KID 48
Evaluated stability on triggering KIDs
with leakage signal



Power bias issue

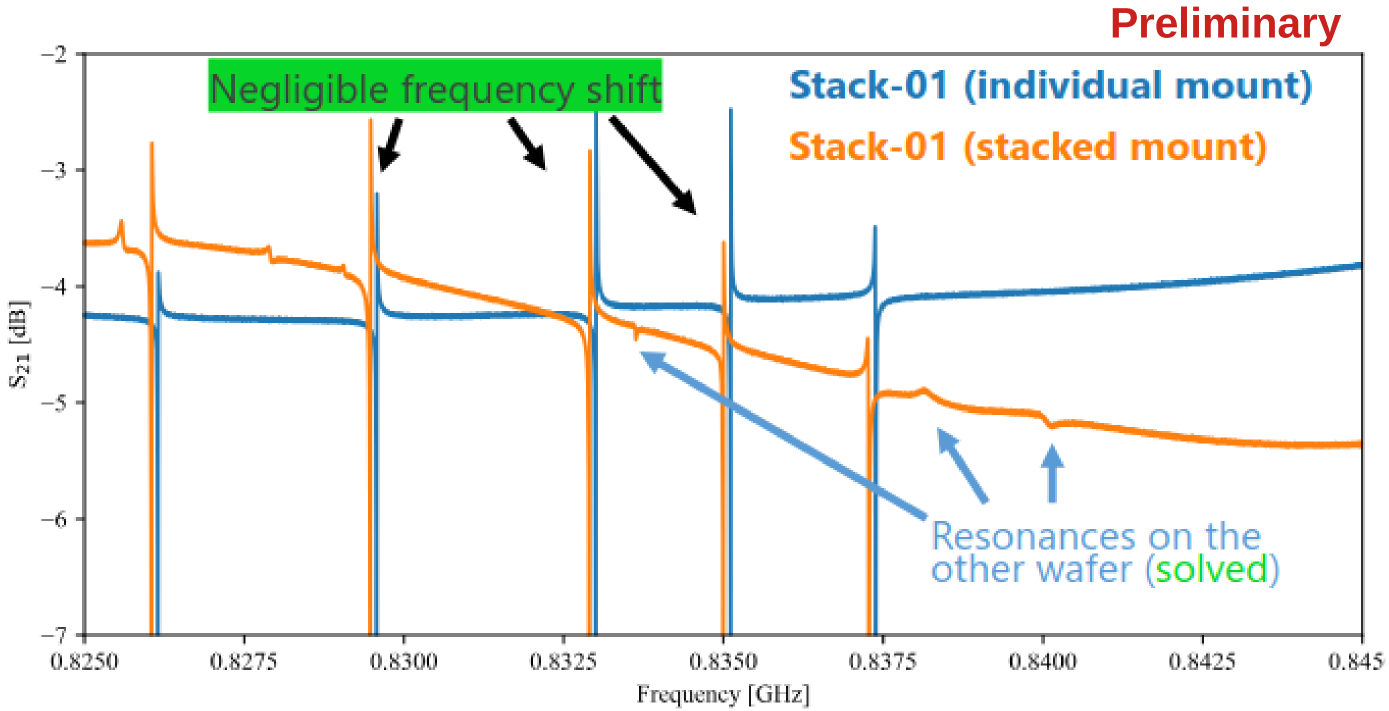
When MKID absorbs power there is X-talk to nearby pixels and influences working conditions. Known issue in MKID community, countermeasures are being implemented.



Demonstrator Deployment

Operating 2 nearby wafers:

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

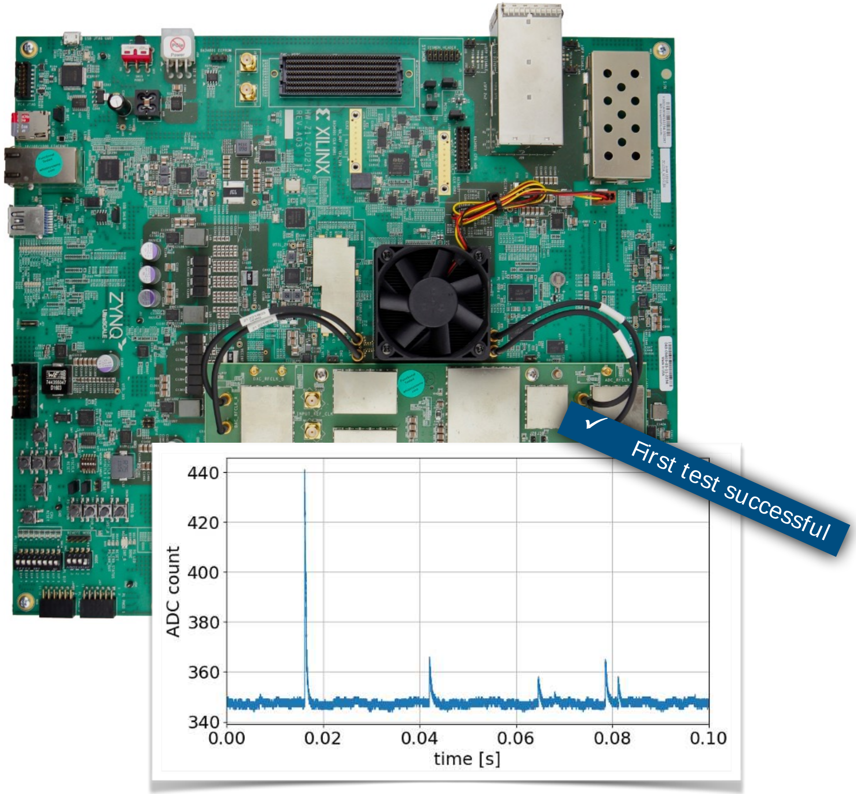


Electronics

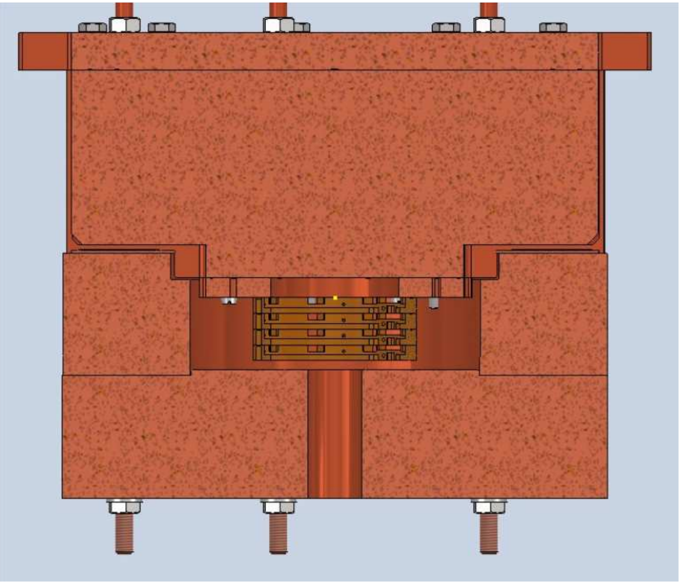
Current electronics (Ettus x310):
30 KIDs / line

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**



Demonstrator Cryogenic Shielding



Starting Material:

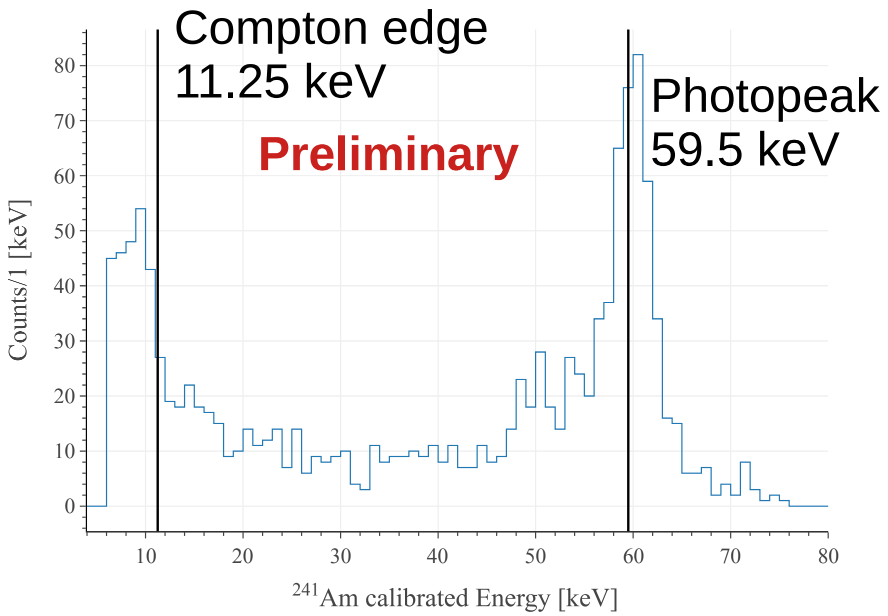
B410 x 1.440mm Billet NOSV Copper

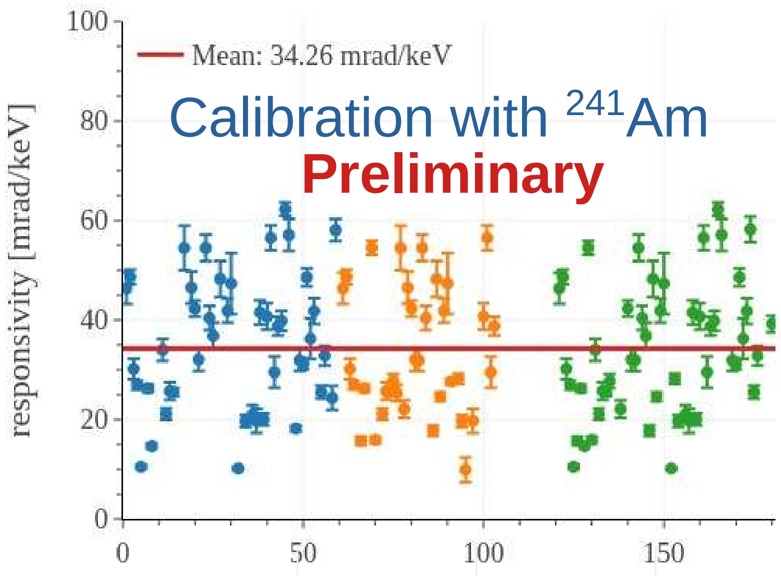
Sizes:

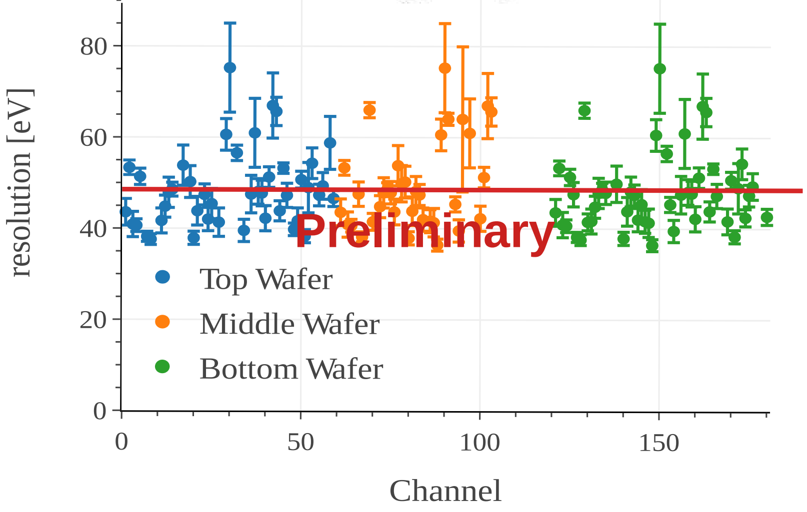
- Interface plate: D 350 mm, h 20 mm
- Lid: D 300 mm, h 100 mm
- Pot: D 300 mm, d 158, h 66 mm
- Bottom: D 300mm, h 60 mm

Detector Resolution

Preliminary performances of the demonstrator evaluated from the energy spectrum a ^{241}Am source







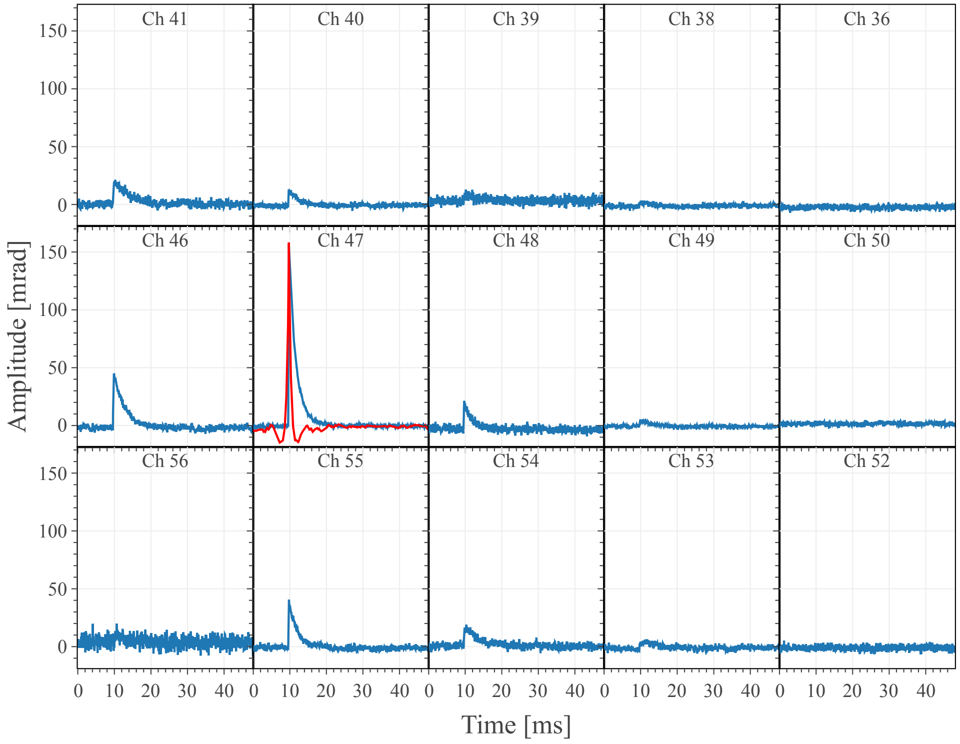
Multidimensional Matched Filtering

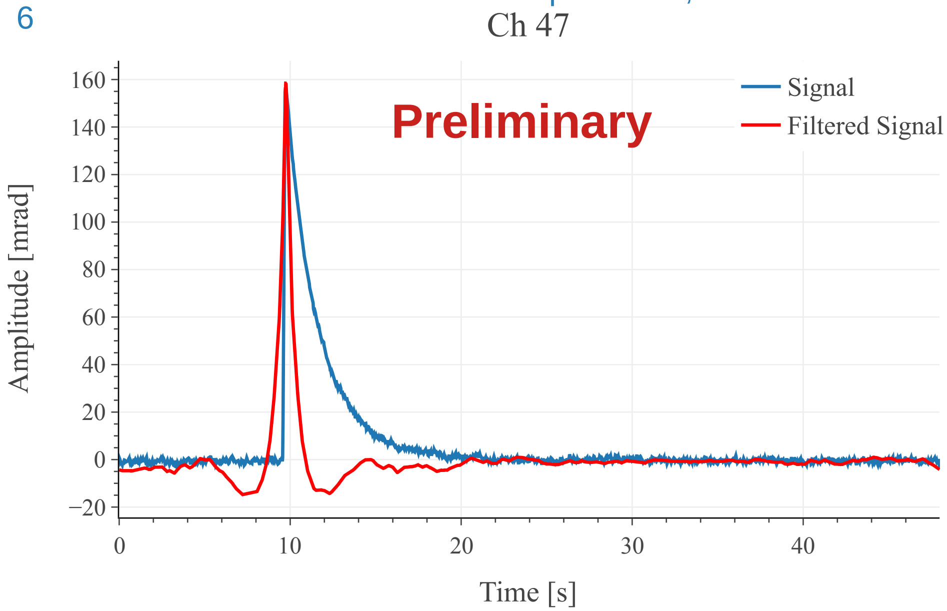
- **Combines the template** of different dice
- **Lowers the baseline resolution** exploiting the noise correlation

$$\tilde{v}_{\text{filtered}}(f) = \sum_{i,j=1}^{N_{\text{channels}}} \tilde{s}_i^*(f)\,\hat{N}_{ij}^{-1}(f)\,\tilde{v}_j(f)\,,\ \text{being}$$

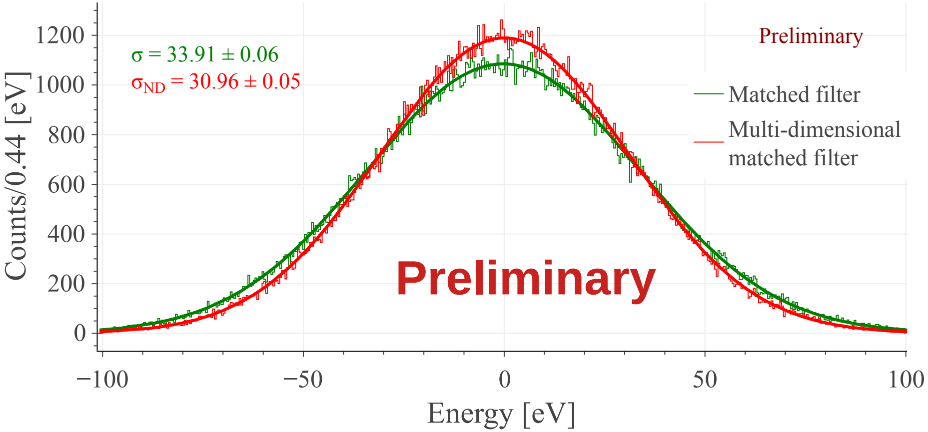
- $\tilde{v}_i(f)$ the waveform on channel i
- $\hat{N}_{ij}(f)$ the noise covariance between channels i and j
- $\tilde{s}_i(f)$ the expected signal on channel i

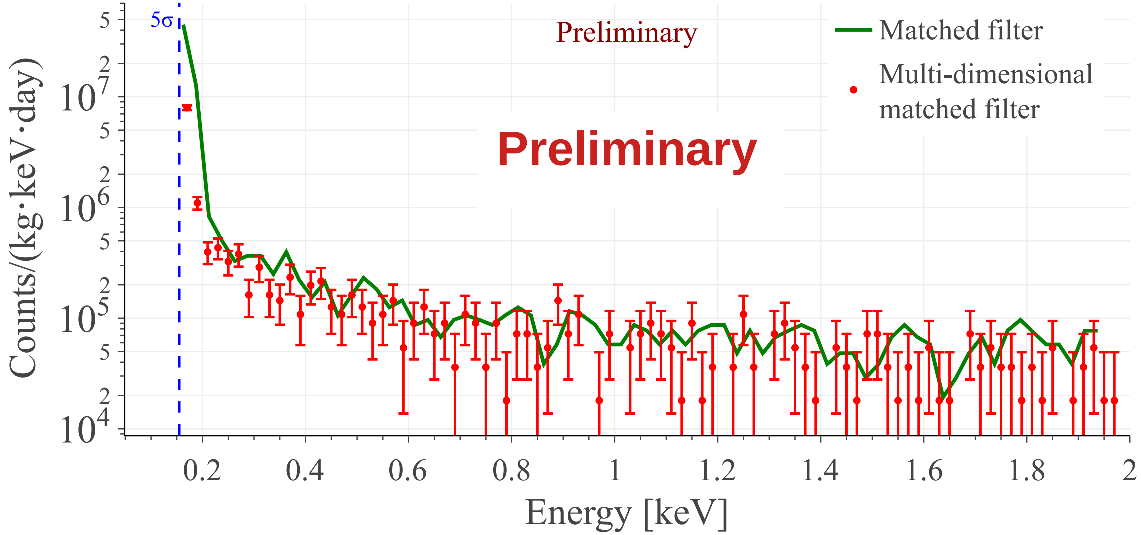
M. Cappelli, et al. "Sensitivity enhancement techniques for cryogenic calorimeters in the NUCLEUS experiment", arXiv 2603.28276





Improved analysis: spectra comparison



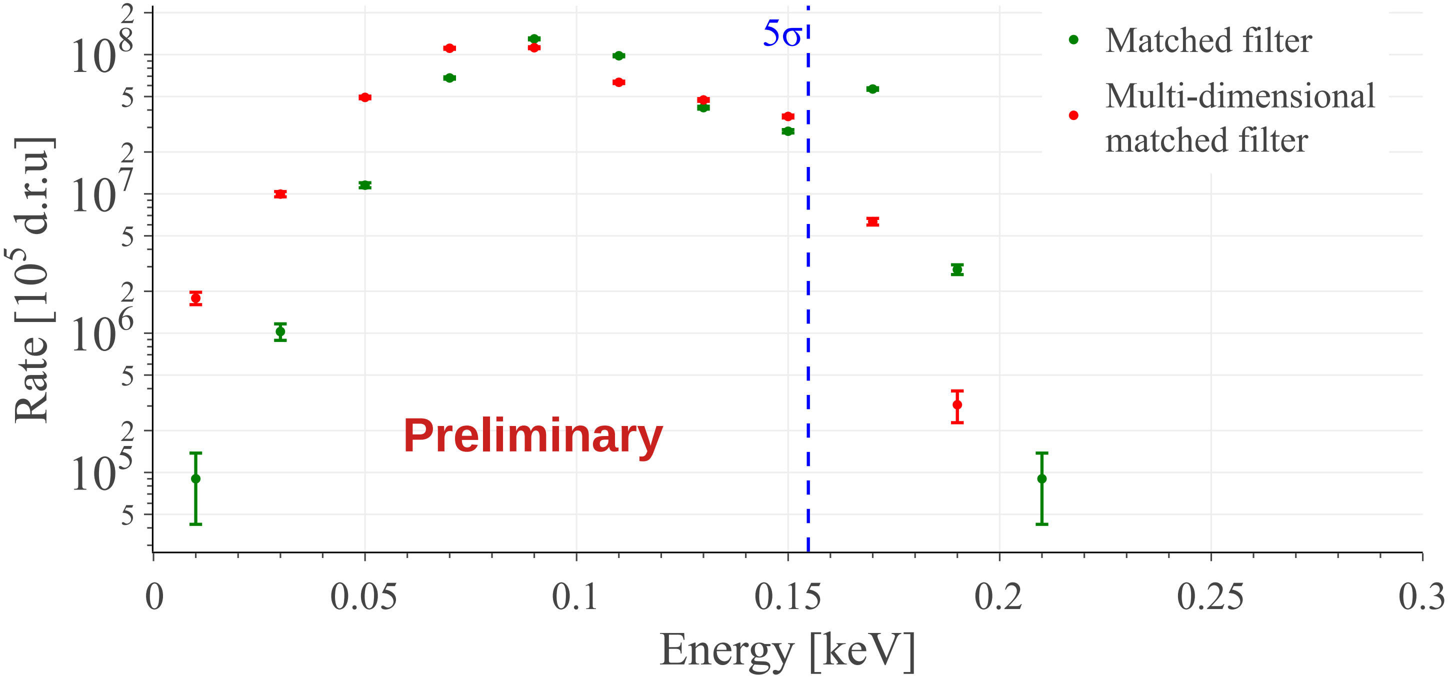


- Improved analysis allows

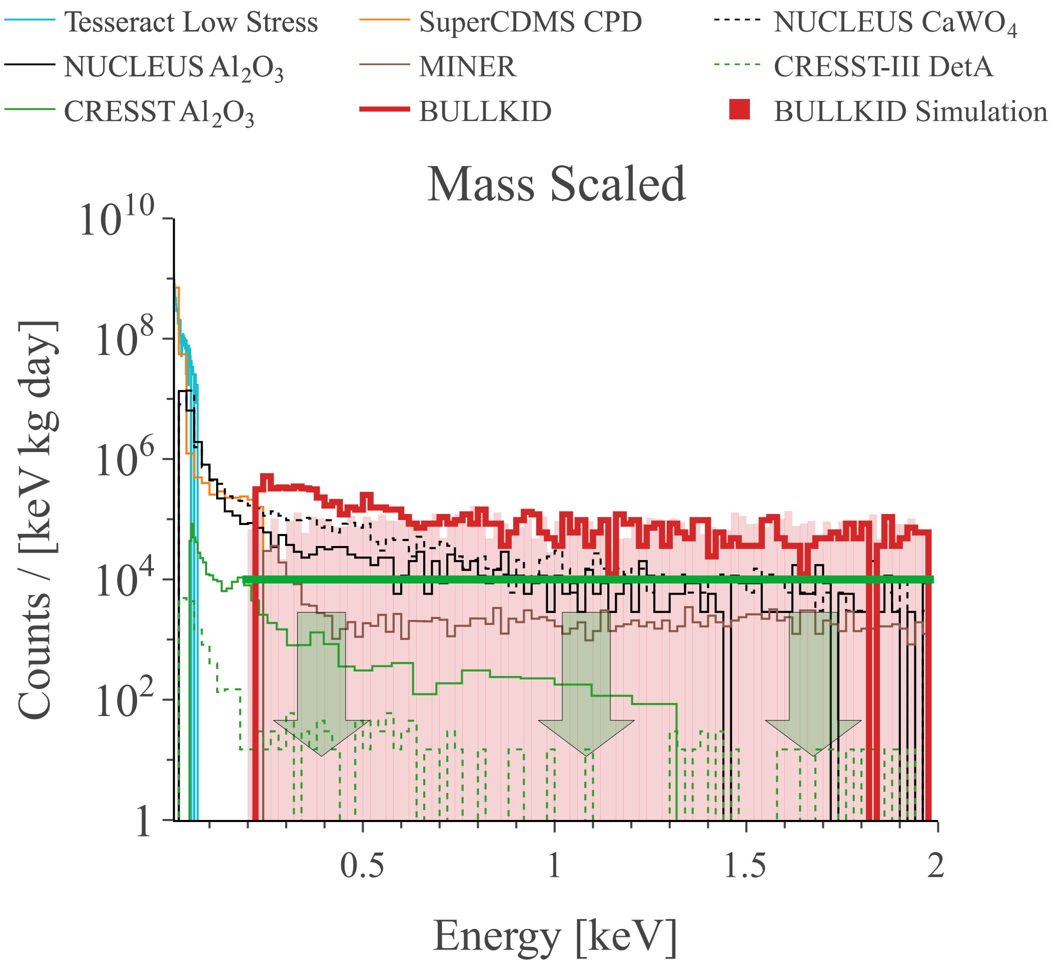
  better discrimination of noise false positives
- Resolution improved about 10%
- **Same rise below 600 eV**

Noise False Positives

N-dim matched filter allows a better noise false positive discrimination



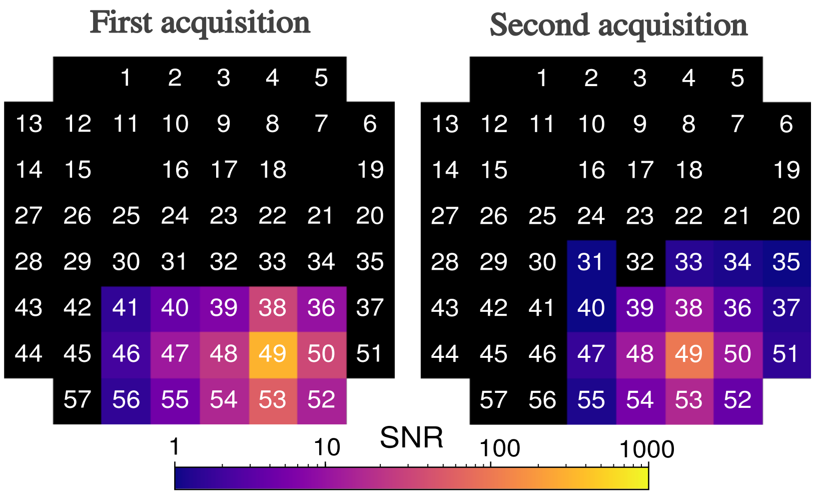
Low Energy Excess and Demonstrator Run

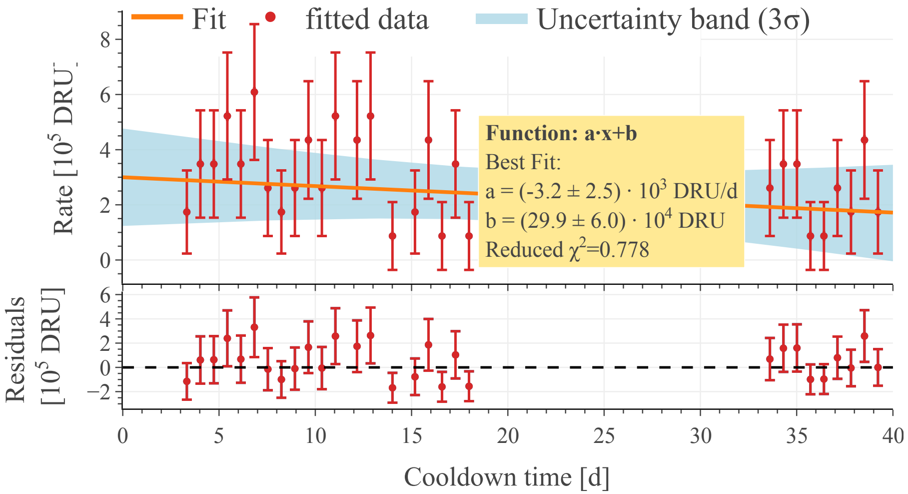


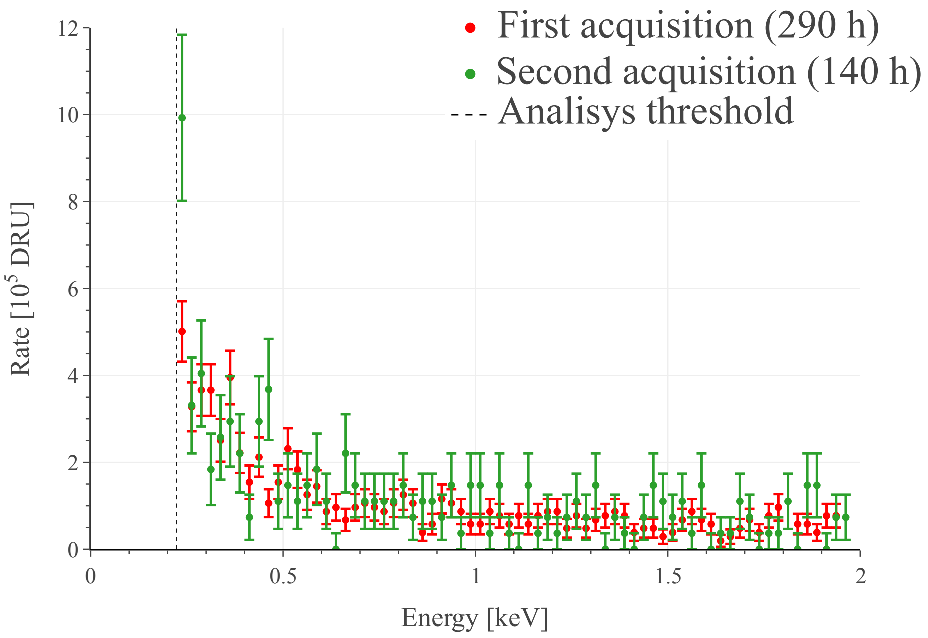
Investigate the presence of the LEE

- Below 10^4 DRU background
- Full 3D veto capability
- Threshold ~ 200 eV

Rise Time Dependence







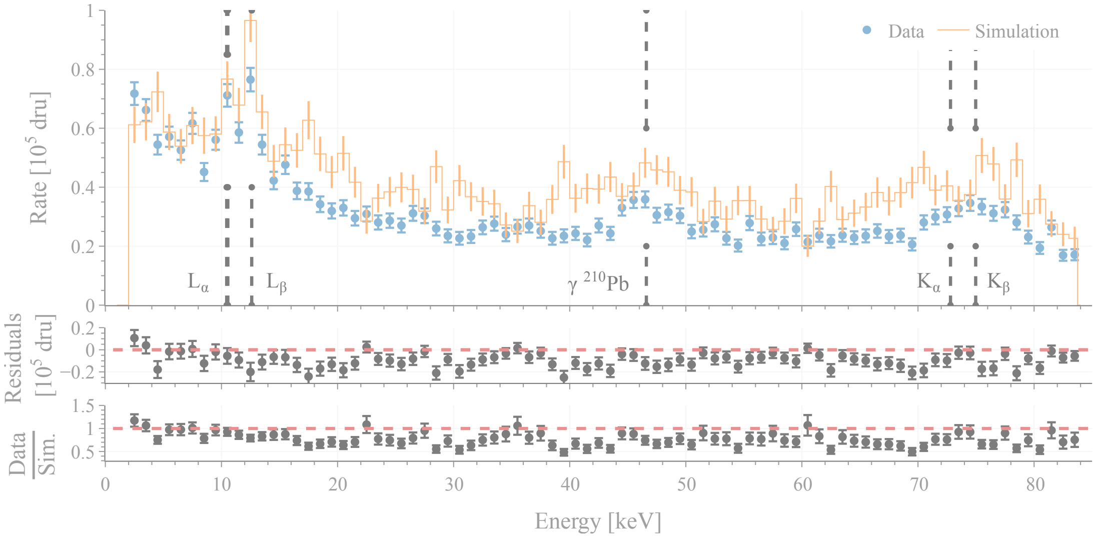
Repeated the acquisition with improved vetoes capabilities

Spectra compatible after + 30 days

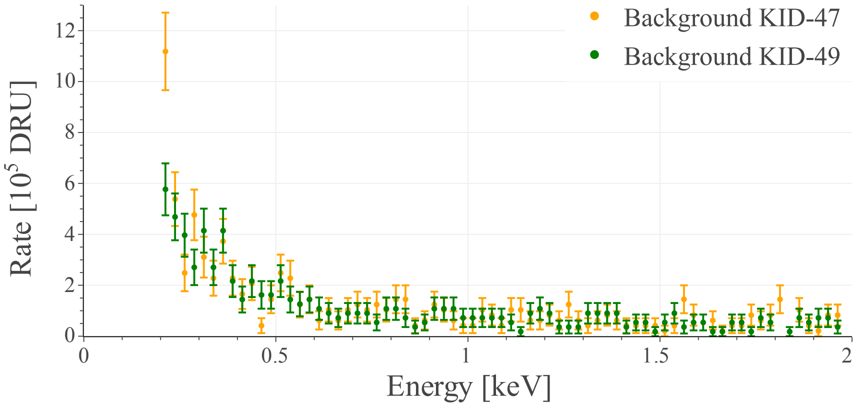
Energy spectra

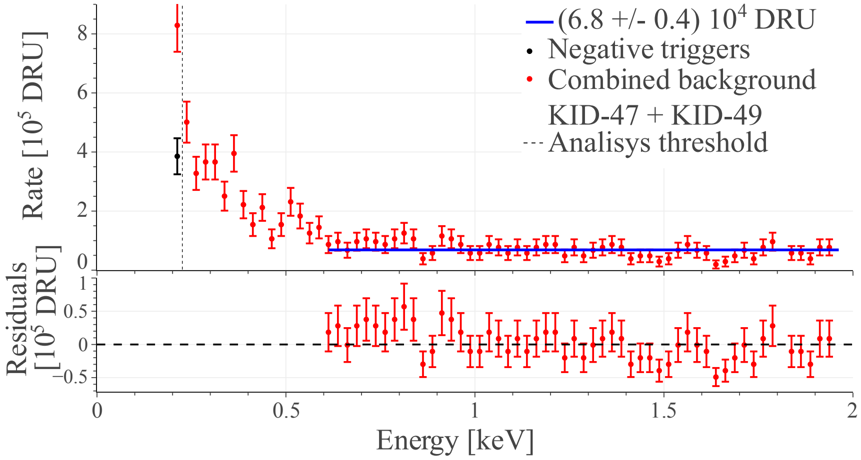
D. Delicato et al: arXiv:2605.02468v1 [hep-ex] 04 May 2026

High energy spectrum



Low energy spectrum





- Spectra compatible between the 2 triggering pixels
- Rise below 600 eV not compatible with negative triggers

Singles observed in BULLKID

BULLKID architecture
cannot distinguish Shared/Singles
at threshold

At higher energies:

- Singles observed
- Ongoing evaluation of the energy spectrum
  - Efficiencies hard to evaluate
  - **ASPECT filter** for low SNR discrimination?

Matteo Cappelli et al, 10.1088/1748-0221/19/06/P06034 JINST 19 (2024) 06, P06034, Journal of Instrumentation, Volume 19, June 2024, P06034