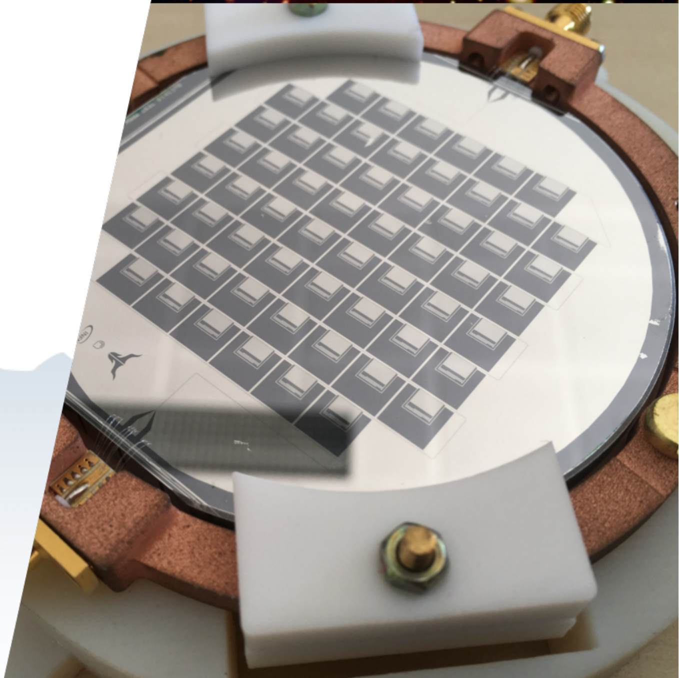
BULLKID-DM

searching for light WIMP with monolithic arrays of detectors

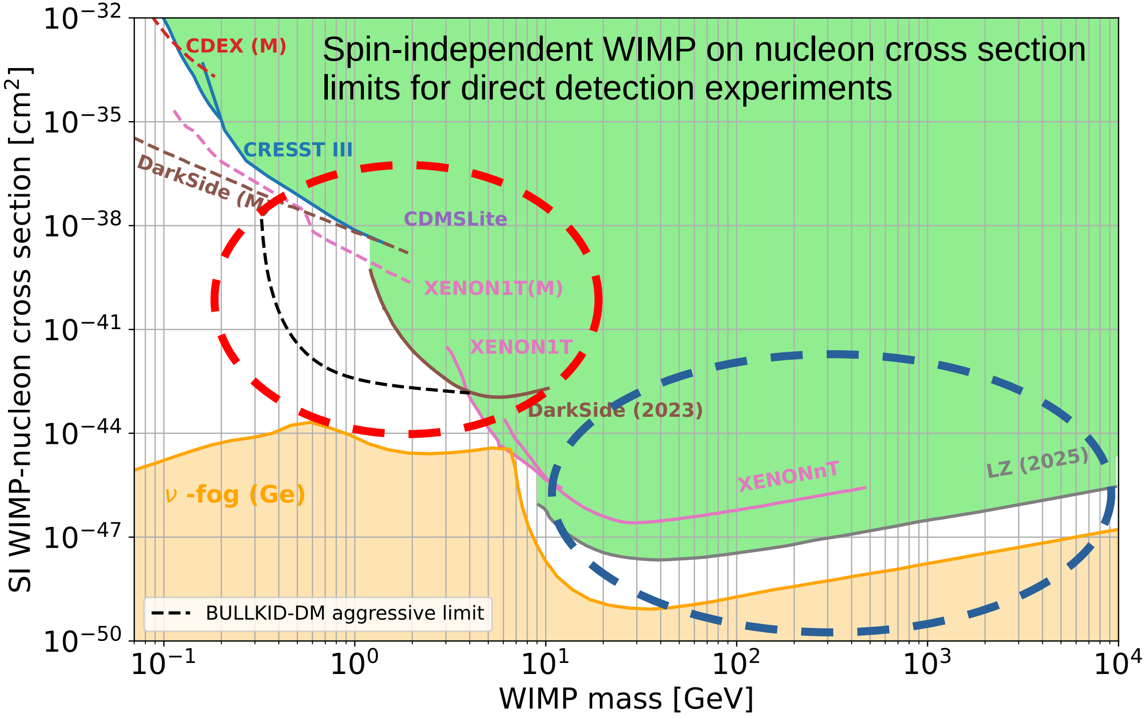


Matteo Folcarelli on behalf of the collaboration
Università La Sapienza di Roma, INFN - Roma 1

August 26, 2025

TAUP XICHANG

BULLKID-DM: A WIMP-like Dark Matter experiment



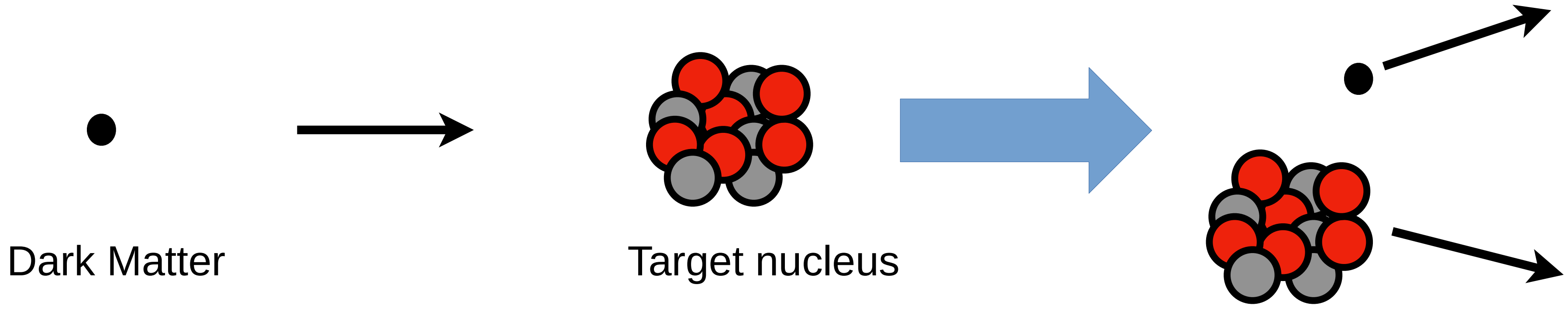
Kg-scale solid state phonon detectors

Multi-ton liquid scintillators

Detection principle: nuclear recoils

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

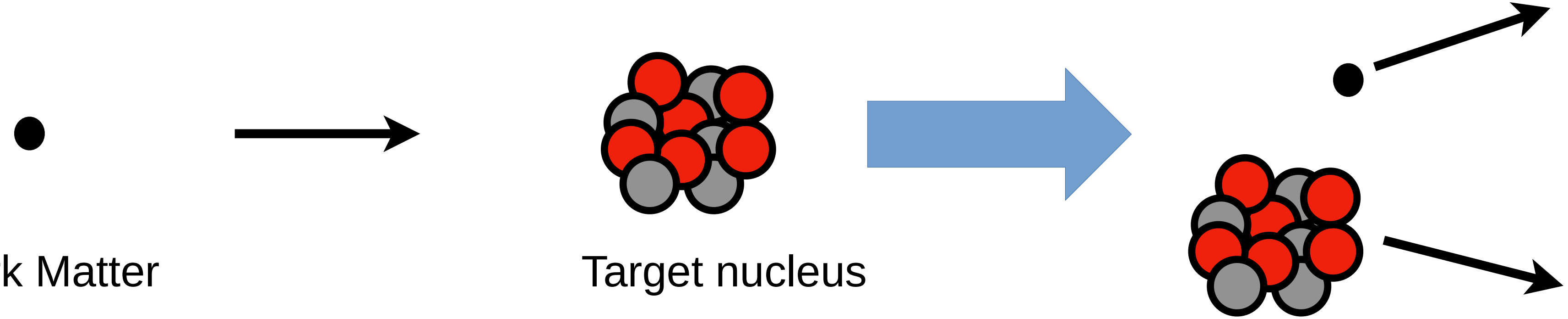
Si: A. Cruciani et al, Appl. Phys. Lett. 121, 213504 (2022)   Ge: D. Delicato et al, Appl. Phys. Lett. 126, 153502 (2025)



Detection principle: nuclear recoils

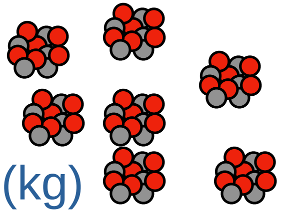
Target: Silicon (Si) + ongoing effort to port technology on Germanium

Si: A. Cruciani et al, Appl. Phys. Lett. 121, 213504 (2022)   Ge: D. Delicato et al, Appl. Phys. Lett. 126, 153502 (2025)



Cross section $\sigma < 10^{-40}$ cm^2

Large number of targets O(kg)

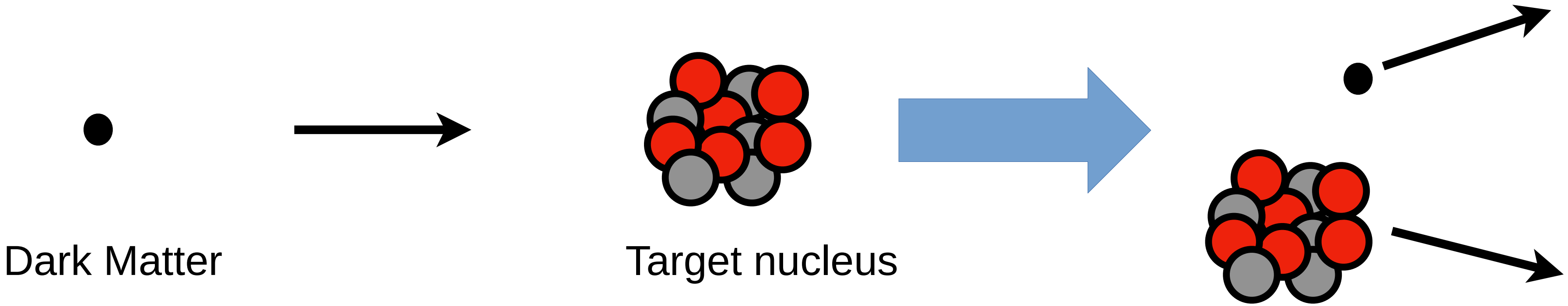


Difficult with low temperature detectors

Detection principle: nuclear recoils

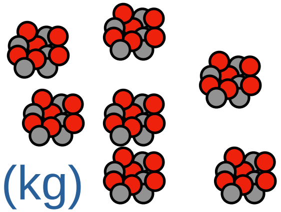
Target: Silicon (Si) + ongoing effort to port technology on Germanium

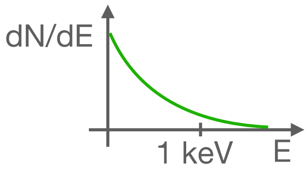
Si: A. Cruciani et al, Appl. Phys. Lett. 121, 213504 (2022) Ge: D. Delicato et al, Appl. Phys. Lett. 126, 153502 (2025)



Cross section $\sigma < 10^{-40}$ cm^2

Energy < 1 keV





Large number of targets O(kg)

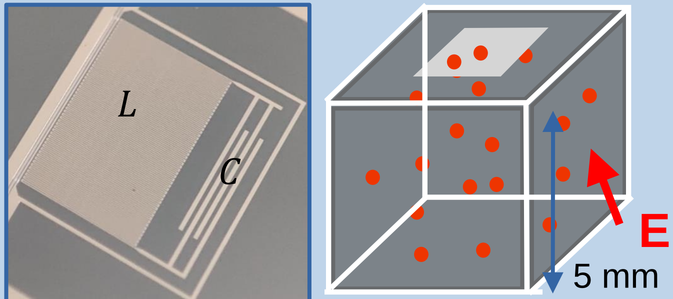
Difficult with low temperature detectors

Low energy threshold O(100 eV)

Motivation for low temperature detectors

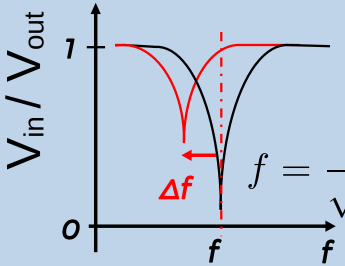
Detector: Fully active structure of cryogenic calorimeters

Al KID (~ 2 x 2 mm^2 x 60 nm), 0.5 ug



Athermal phonons

Silicon die (0.34 g) at < 80 mK



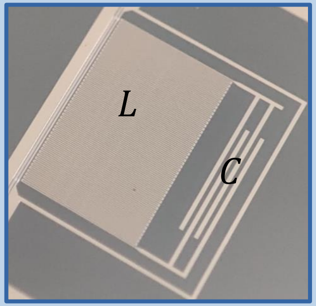
$$f = \frac{1}{\sqrt{LC}}$$

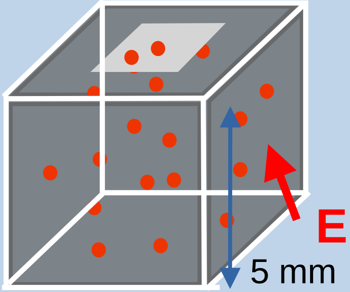
$$E \propto \Delta f$$

Phonon mediated cryogenic aluminum KIDs

Detector: Fully active structure of cryogenic calorimeters

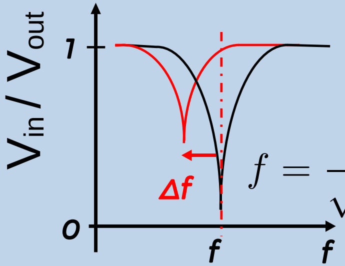
Al KID (~ 2 x 2 mm² x 60 nm), 0.5 ug





Athermal phonons

Silicon die (0.34 g) at < 80 mK

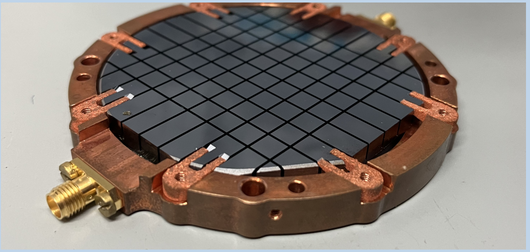


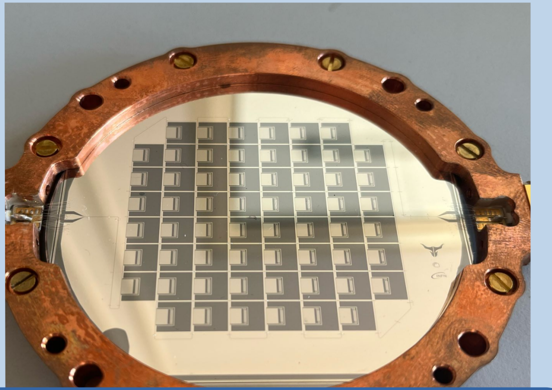
$$f = \frac{1}{\sqrt{LC}}$$

$$E \propto \Delta f$$

Phonon mediated cryogenic aluminum KIDs

Diced silicon wafers instrumented with **aluminum KIDs**

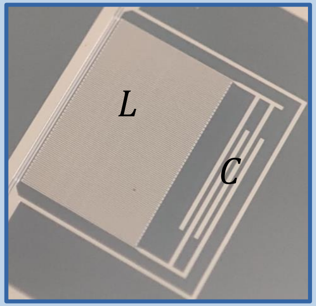


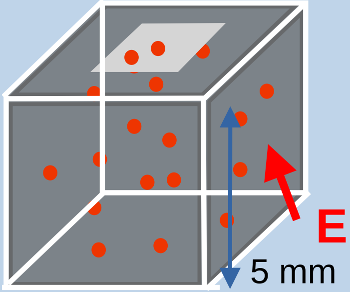


Monolithic and **fully active** structure with 60 detectors fully multiplexed

Detector: Fully active structure of cryogenic calorimeters

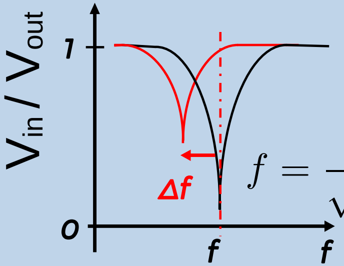
Al KID (~ 2 x 2 mm² x 60 nm), 0.5 ug





Athermal phonons

Silicon die (0.34 g) at < 80 mK

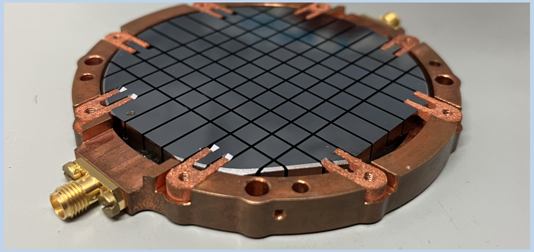


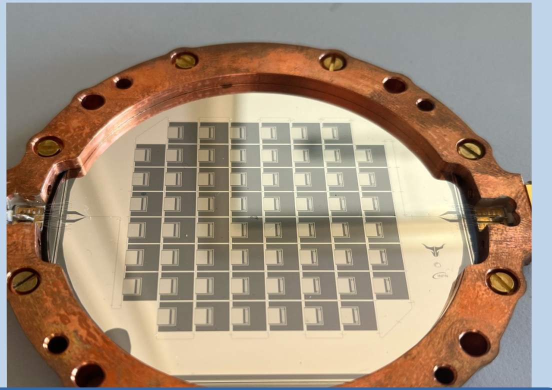
$$f = \frac{1}{\sqrt{LC}}$$

$$E \propto \Delta f$$

Phonon mediated cryogenic aluminum KIDs

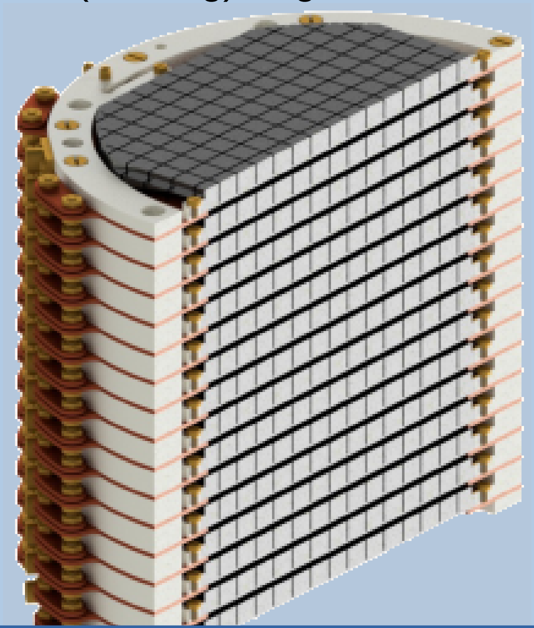
Diced silicon wafers instrumented with **aluminum KIDs**





Monolithic and **fully active** structure with 60 detectors fully multiplexed

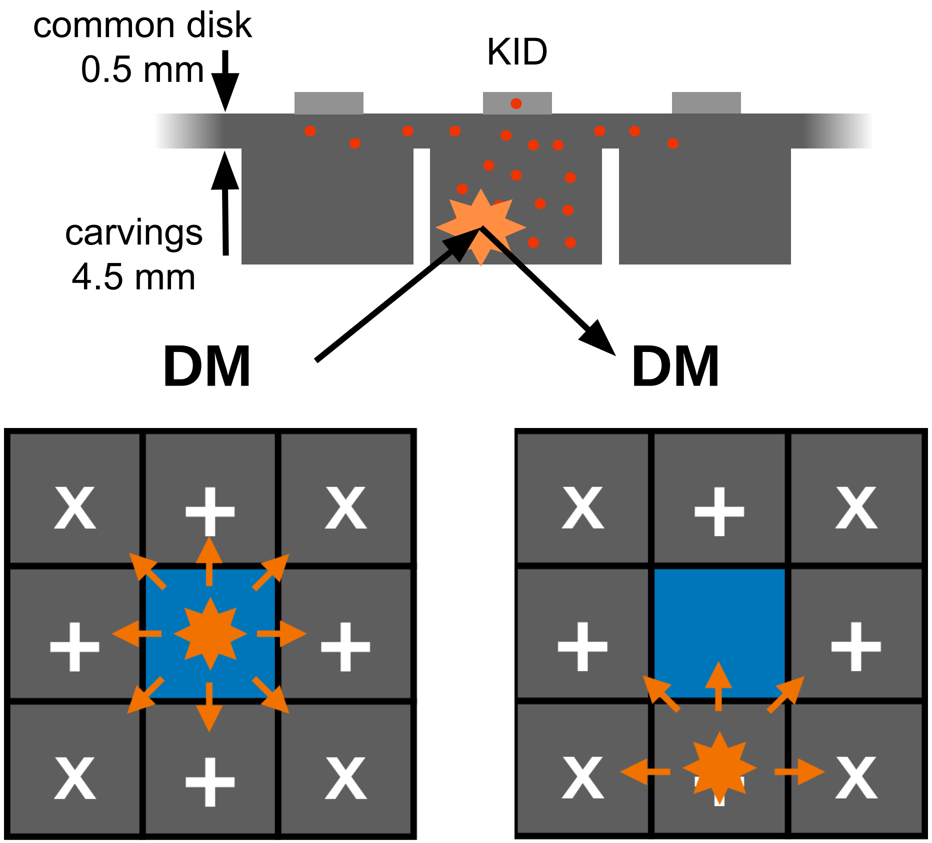
Final detector design
Stack of 16 x 100 mm Si wafers (~ 800 g) target mass



Mass scalability

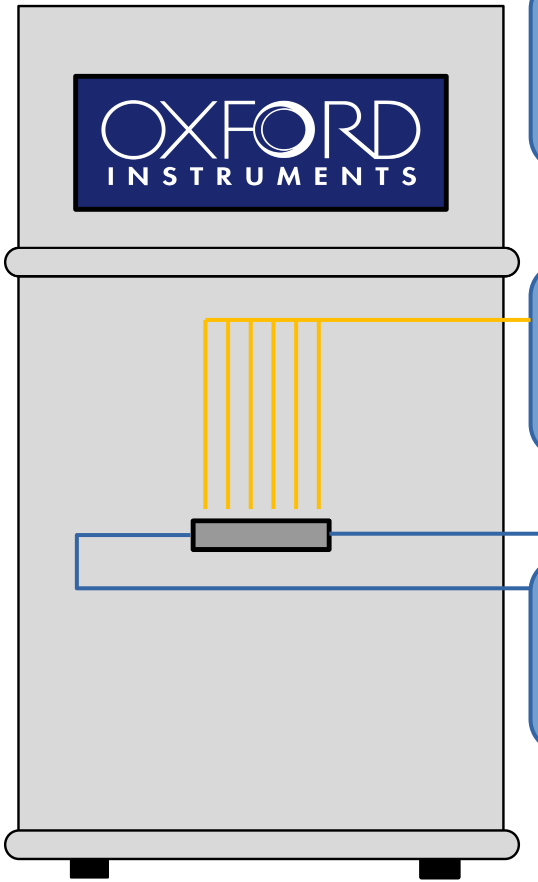
Phonon leakage and mapping

- Only part of the phonons are absorbed by the KID
- The rest leaks in nearby dice:
  - ~20% in each “+” die
  - ~10% in each “x” die
  - the rest in outer dice



This effect reduces the phonon focusing on the KID but is exploited to identify the interaction voxel

Experimental setup of BULLKID detectors



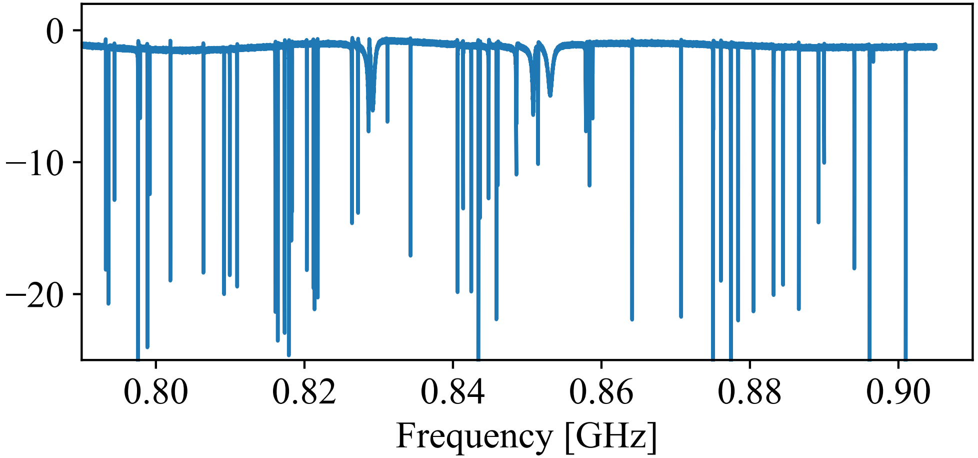
Mechanical mounting

BULLKID detectors are anchored to the coldest point of a dry ^{3}He/^{4}He dilution refrigerator with base temperature of 20 mK.

Optical fibers

Optical fibers injects optical photons produced by LEDs at room temperature directly to the single dice. **Optical calibration of the KIDs**

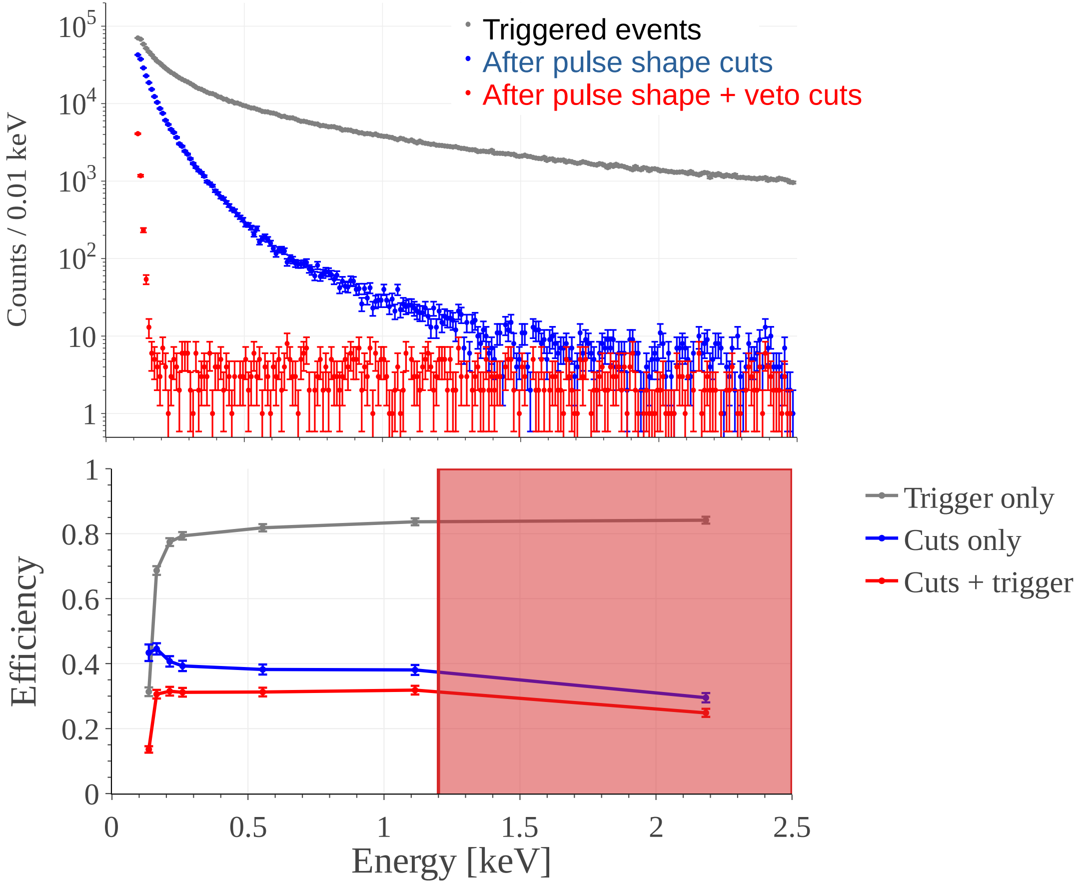
RF electronics

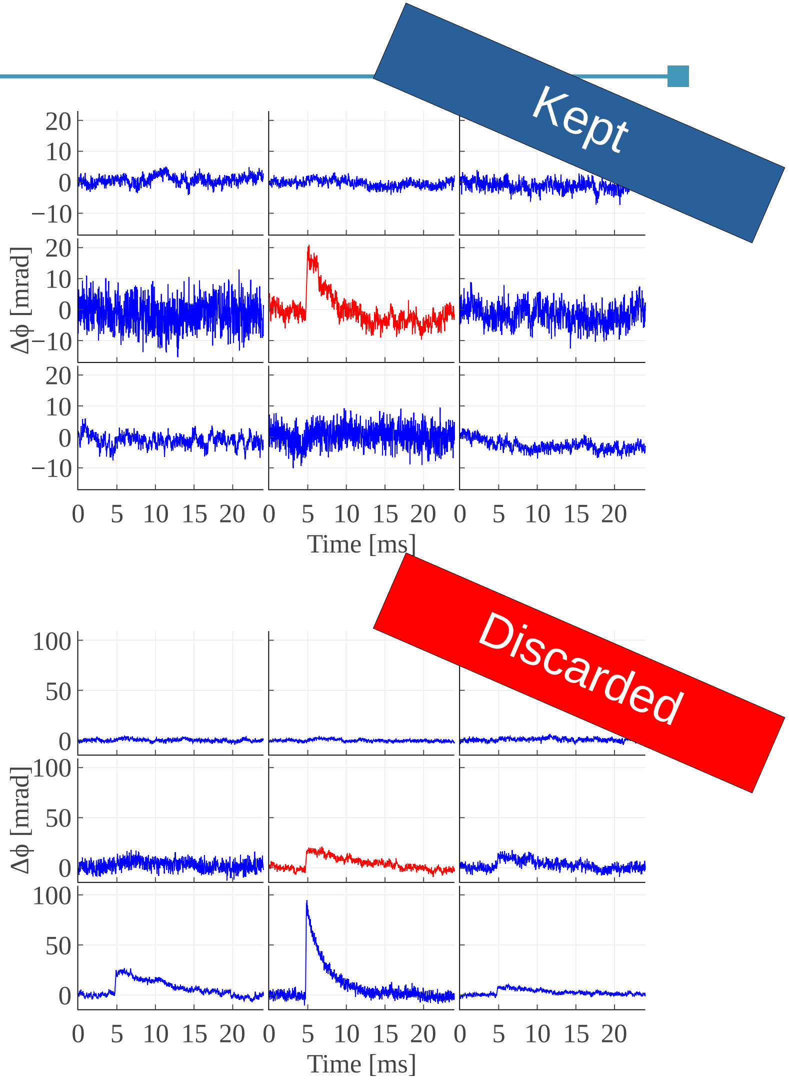


Pulse shape & veto cuts

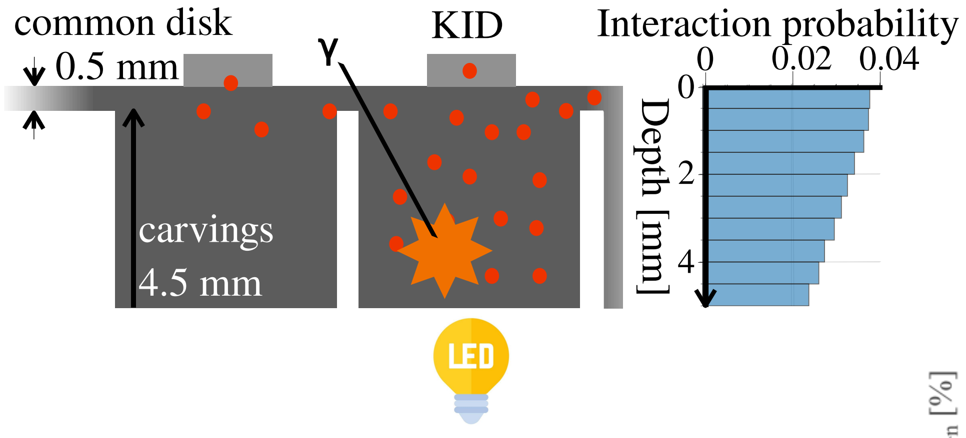
- Cuts and efficiencies built on LED events

D. Delicato, et al., The European Physical Journal C84(4) (2024)



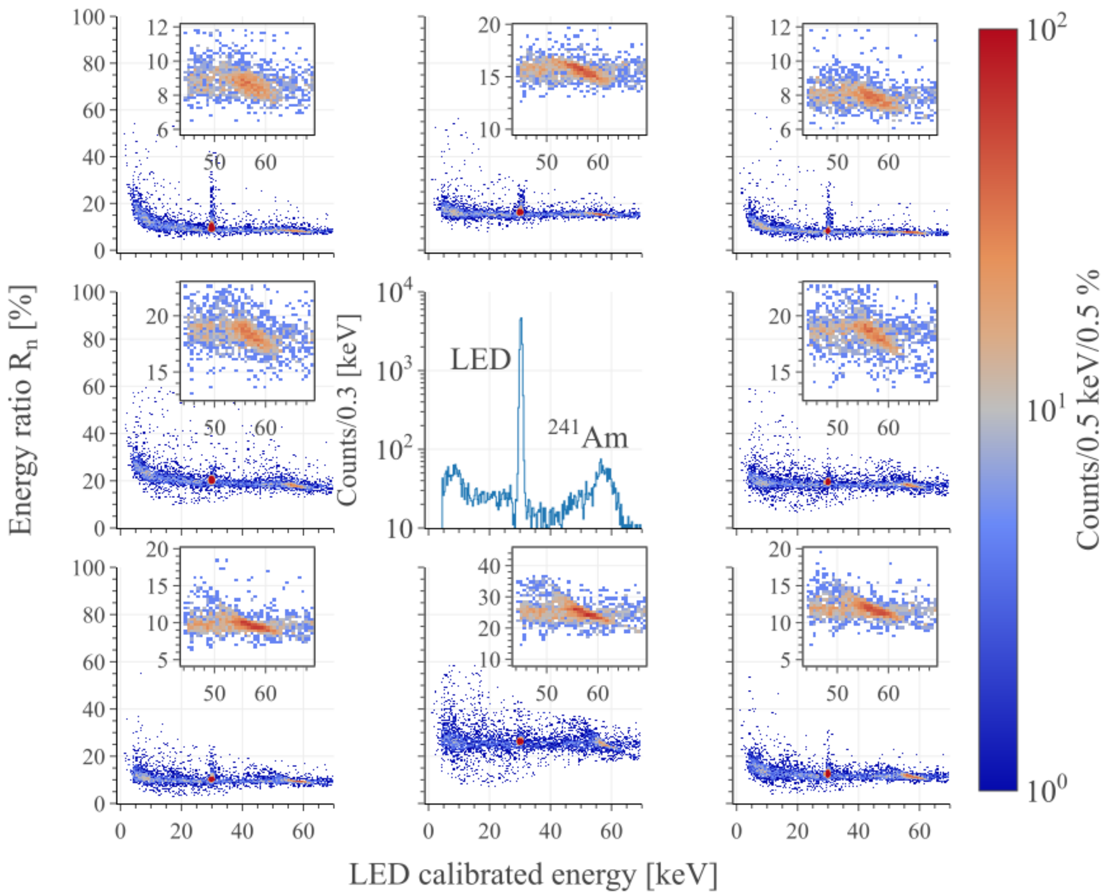


Energy calibration of bulk events (^{241}Am)



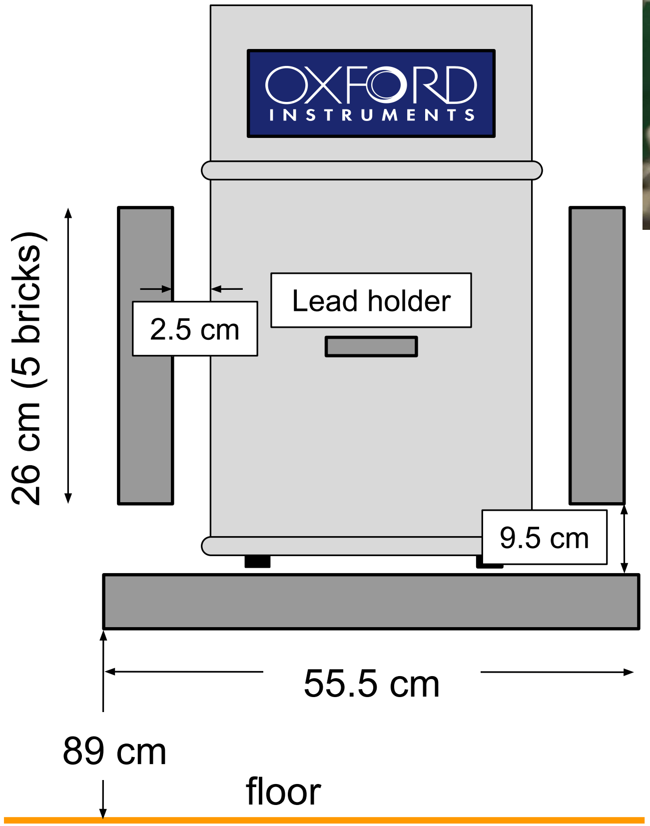
- Dedicated cooldown with ^{241}Am source (59.5 keV γ ray)
- Less than 10% deficit between LED (surface) and Americium (bulk) calibration
- Same phonon leakage between bulk and LEDs

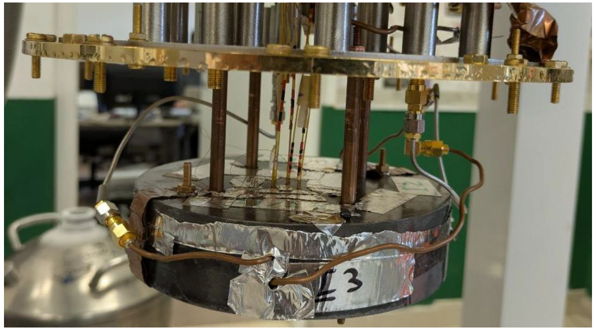
Upcoming paper (Preliminary)



Background measurement with mild shield

- Location: Surface laboratory (Sapienza, 1st floor)
- Midly shielded environment with lead (internal and external)
- Optical fibers for detector calibration and monitoring
- Run time:
  19th Apr 22:00 → 5th May 08:00
  (290 live hours)
- Acquisition of 15 KIDs: 2 triggering + 13 as veto



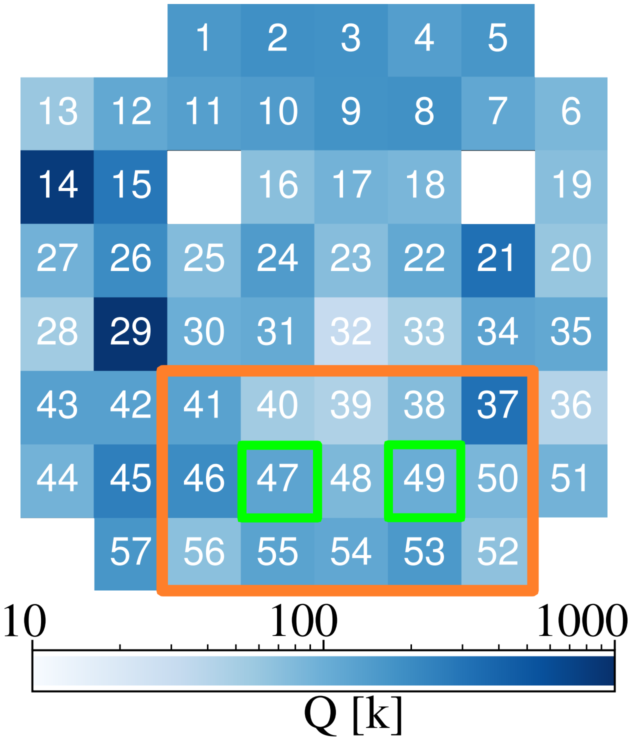


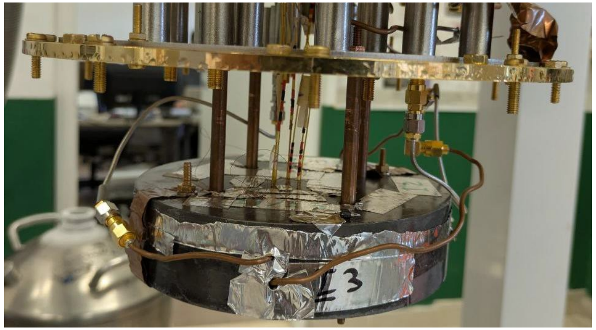
Background measurement with mild shield

- Location: Surface laboratory (Sapienza, 1st floor)
- Midly shielded environment with lead (internal and external)
- Optical fibers for detector calibration and monitoring
- Run time: 19th Apr 22:00 → 5th May 08:00 (290 live hours)
- Acquisition of 15 KIDs: 2 triggering + 13 as veto

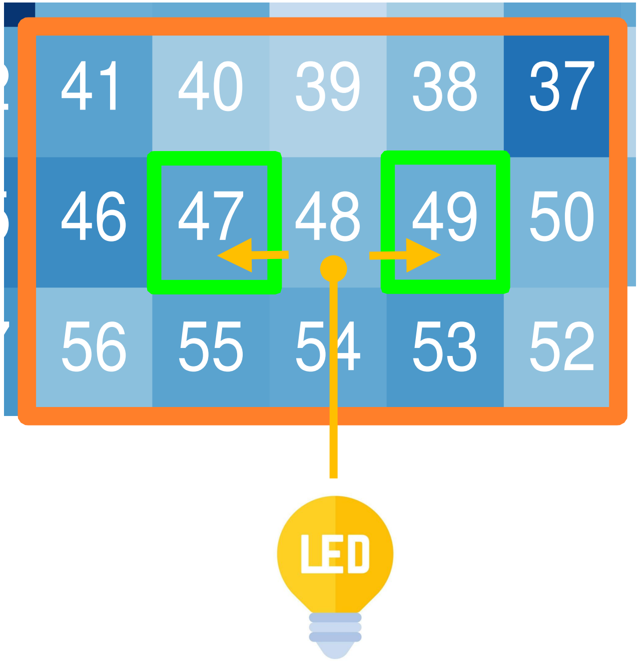
Triggering KIDs

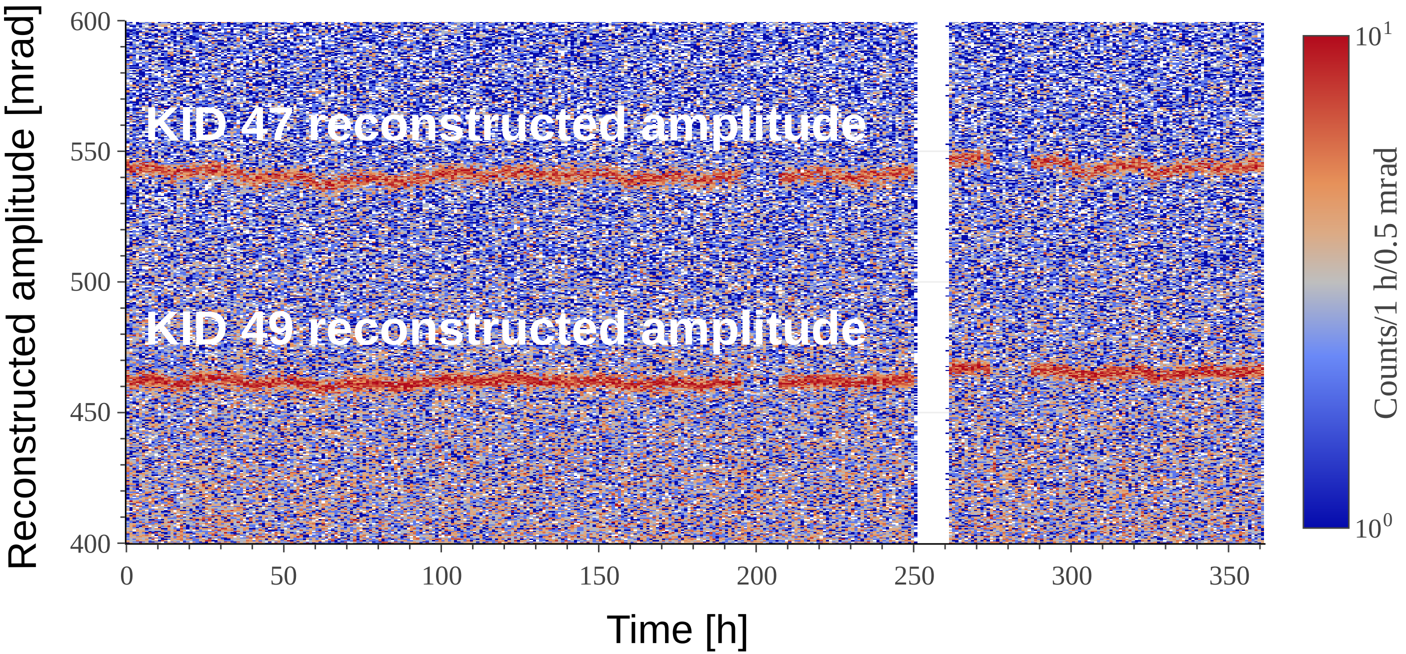
KIDs acquired in coincidence as veto





Stability evaluation with controlled LED pulses

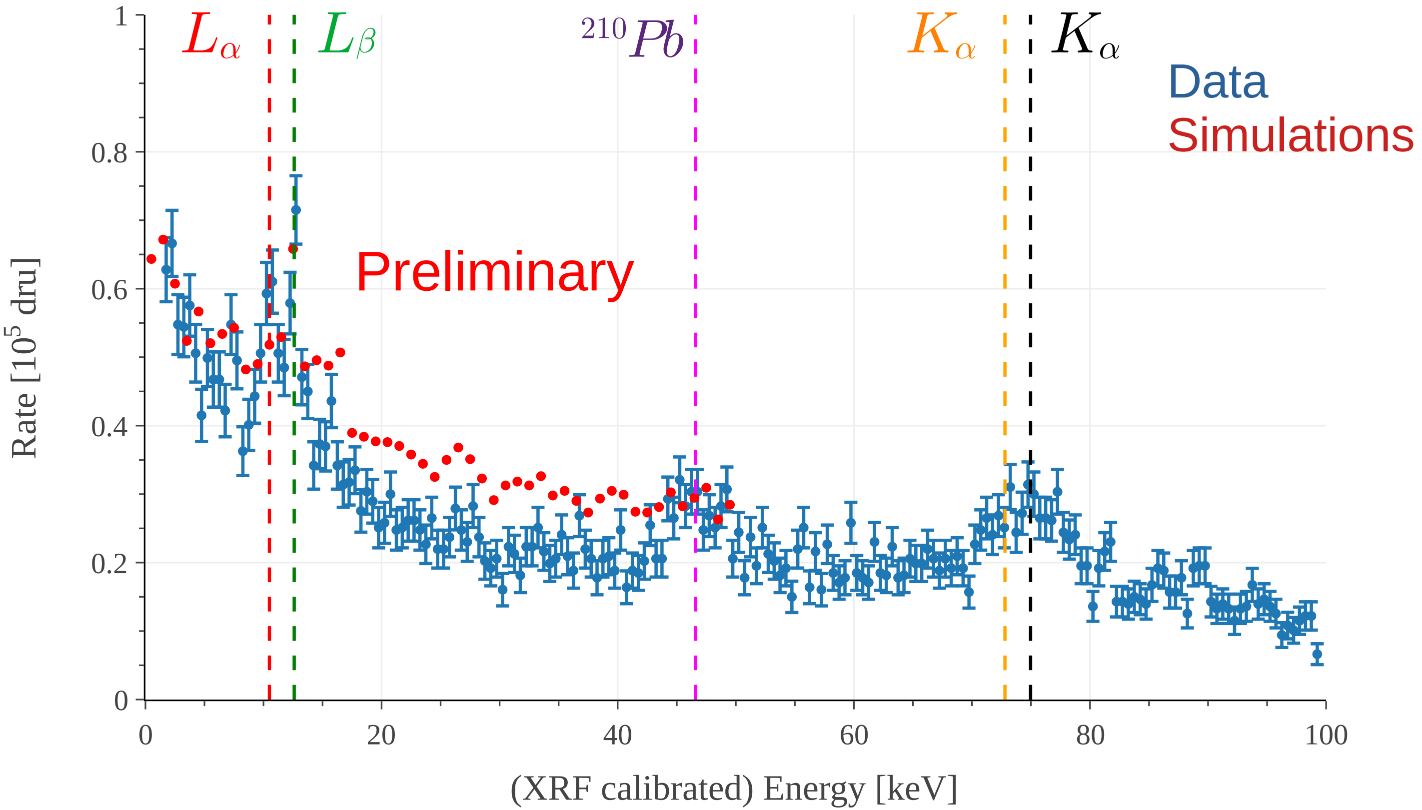




KID **47** : Noise RMS **35 eV**
KID **49** : Noise RMS **30 eV**

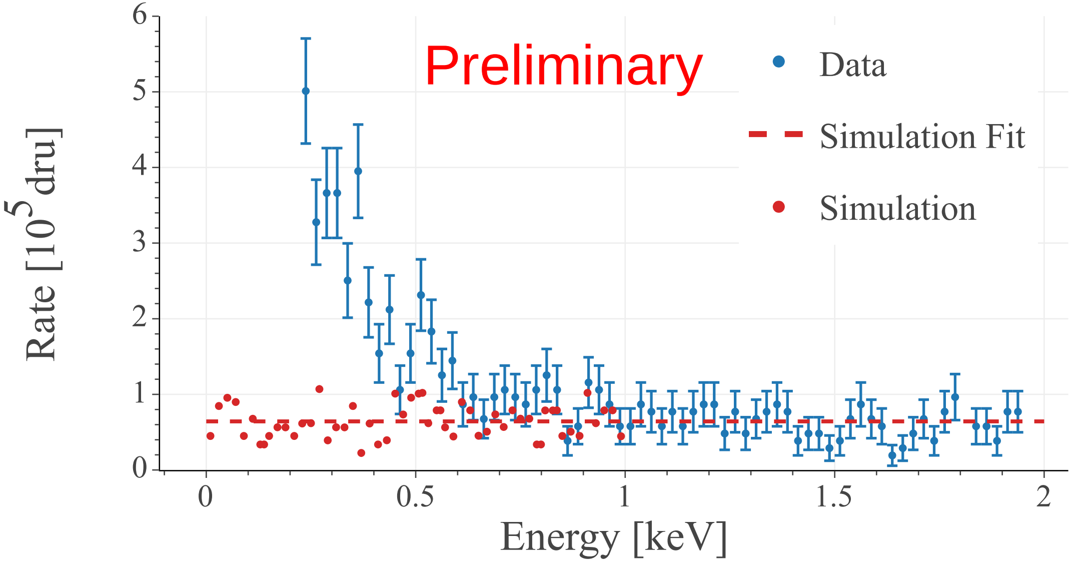
- Stability of the triggering KIDs evaluated with leakage signal from KID 48 via controlled LED pulses
- Detector stable over the entire data acquisition

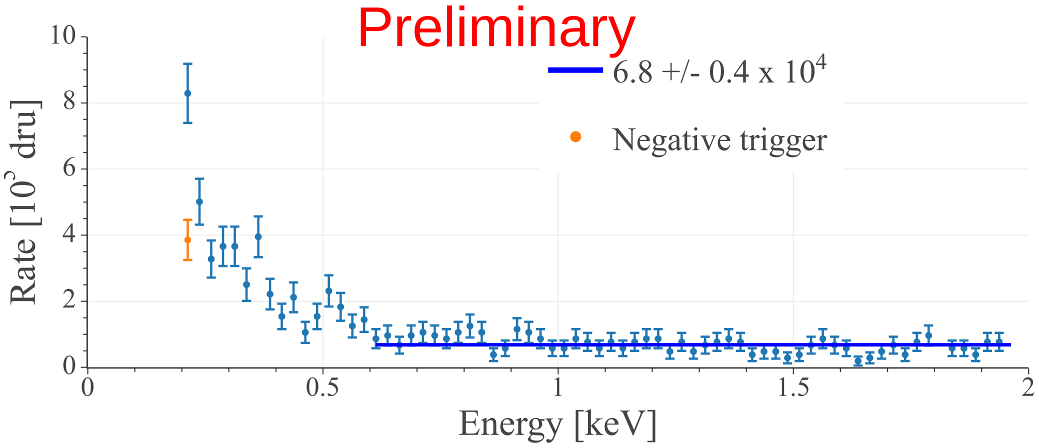
High energy spectrum and simulation comparison



- Visible Pb X-rays well reconstructed (under 10% discrepancy) with LED calibration
- Overall fairly well matching with simulations but Pb rays not well reproduced

Low energy spectrum



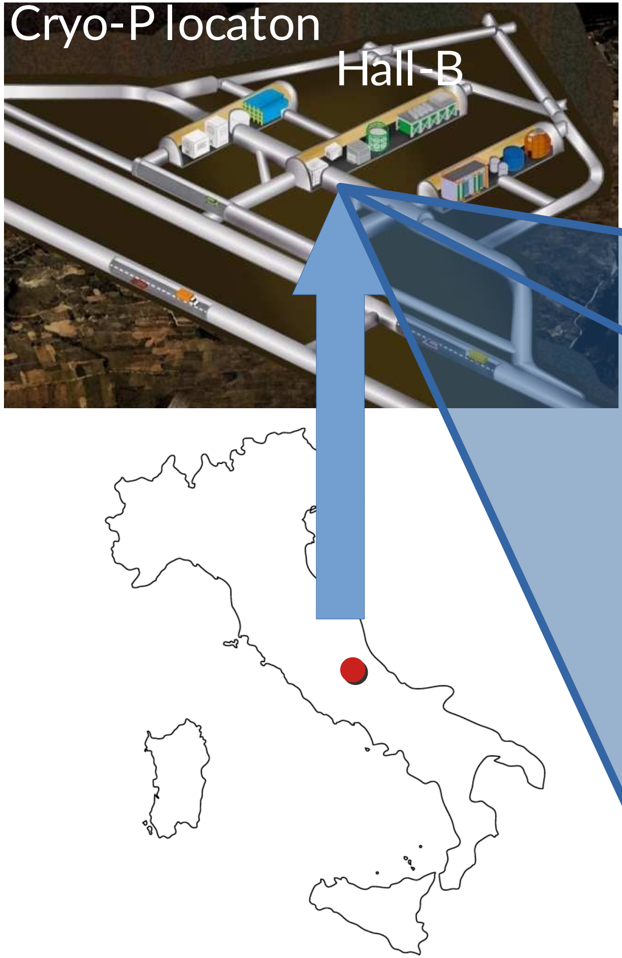


- Flat background: $(68 \pm 4) \cdot 10^3$ d.r.u (simulated $(61 \pm 3) \cdot 10^3$ d.r.u)
- In < 600 eV measured a rise up to a factor ~ 5
- Spectra compatible between the two triggering KIDs
- Rise not compatible with negative triggers (noise false positives)

Background measurement underground (LNGS)

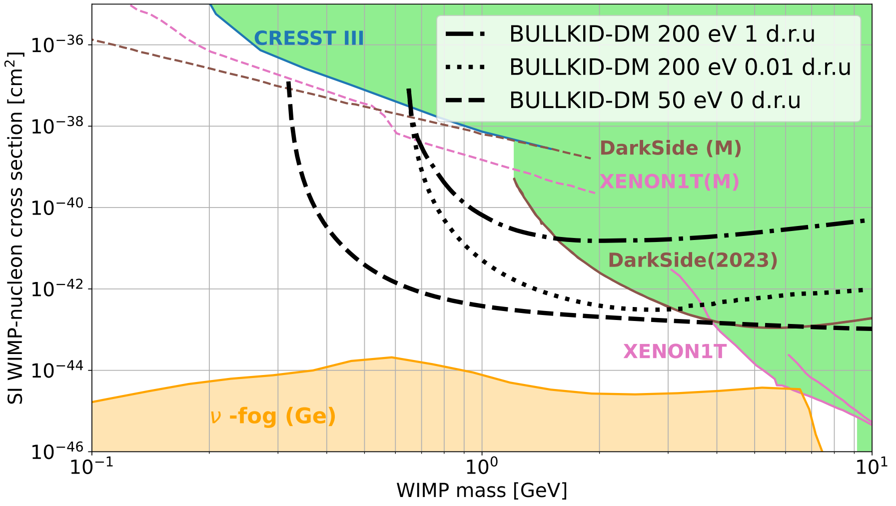
The cryo-platform is a cryogenic underground hub for mK applications:

- Oxford Proteox Cryostat successfully commissioned in July (base temperature < 10 mK)
- Overall facility ready in next few months



BULLKID-DM roadmap

	BULLKID prototype	BULLKID-DM Demonstrator		BULLKID-DM
mass	20 g	60 g		800 g
# of sensors	60	180		2300
Threshold	160 eV	200 eV		< 200 eV
Bkg (c / keV Kg d)	2 x 10^6	< 10^5		1 – 0.01
laboratory	Sapienza U.	Sapienza U.	LNGS	LNGS
installation	2023	2025	2026	2027



We are now in the **Demonstrator phase!**

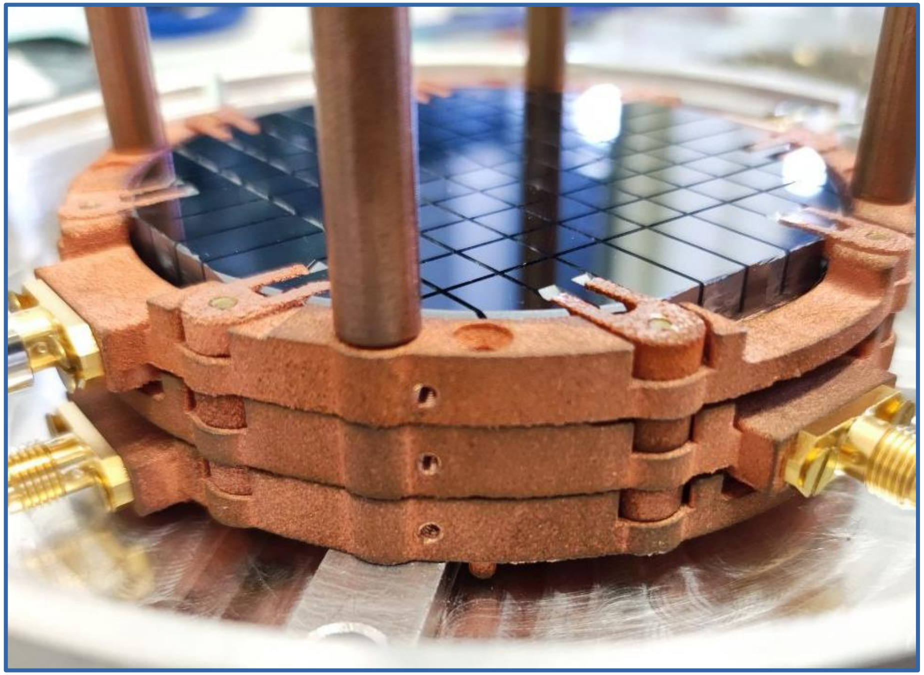
Status of the demonstrator:

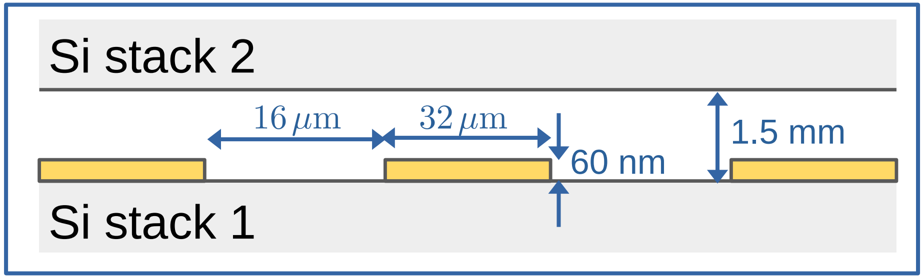
- stack of 3 wafers
- RF electronics

Working in view of the experiment:

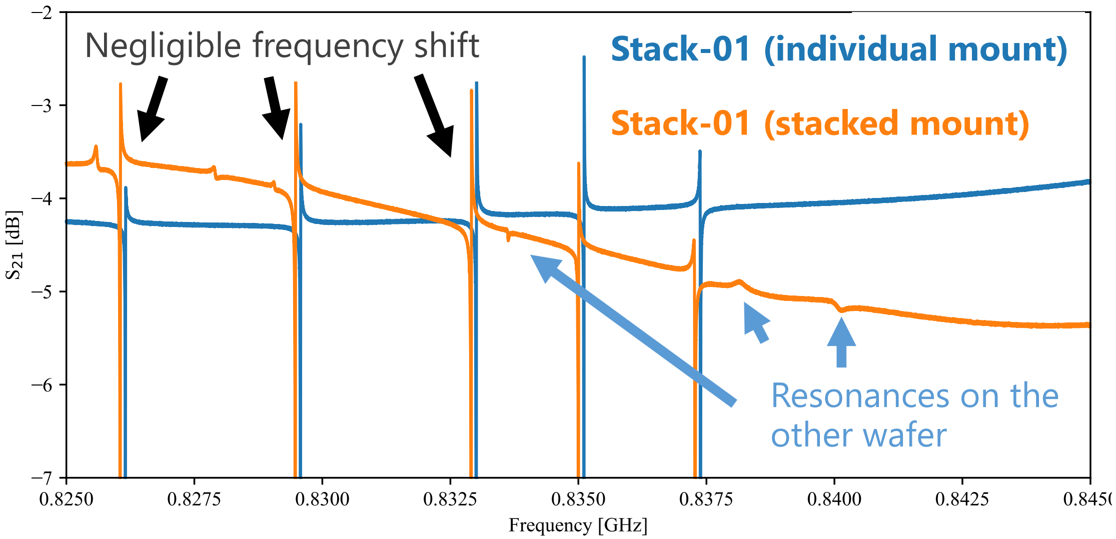
- 100 mm arrays: tests, assembly and serial production
- Shielding and veto

Status of the 3-wafer stack





- Holding structure: **thermalization** and **mounting**
- Reproducibility of **electrical coupling**
- Reproduction of the results of the unstacked wafers



RF electronics

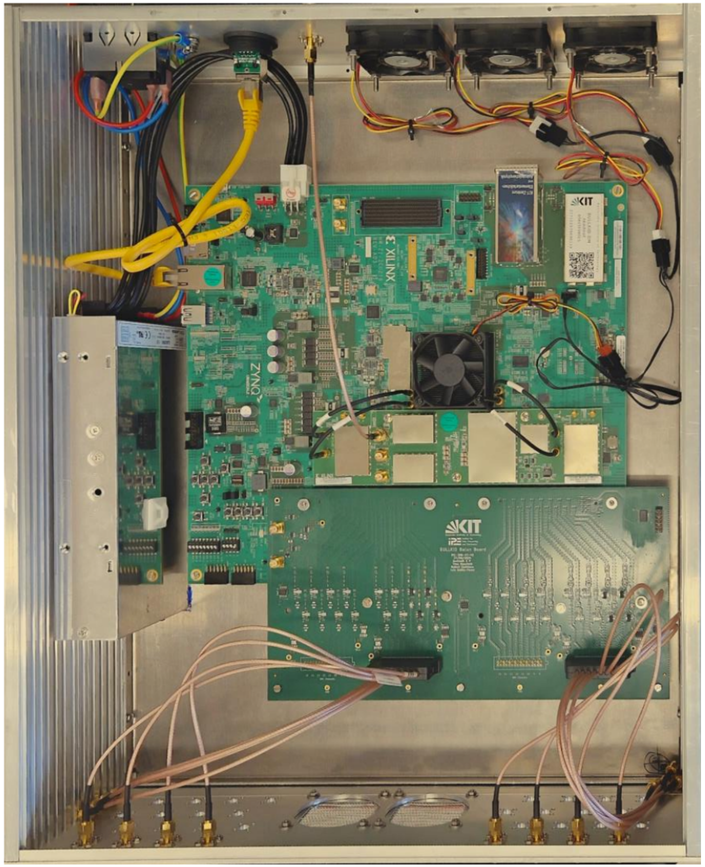
Current electronics:

- Ettus Research USRP X310:
  30 KIDs / board

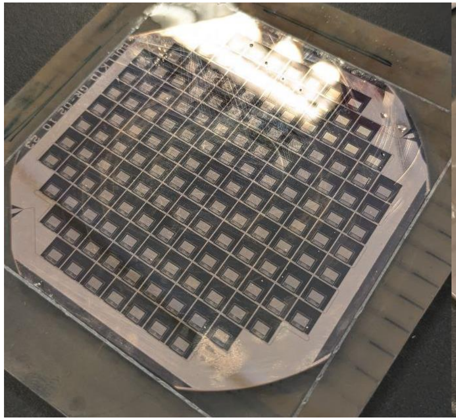
New electronics:

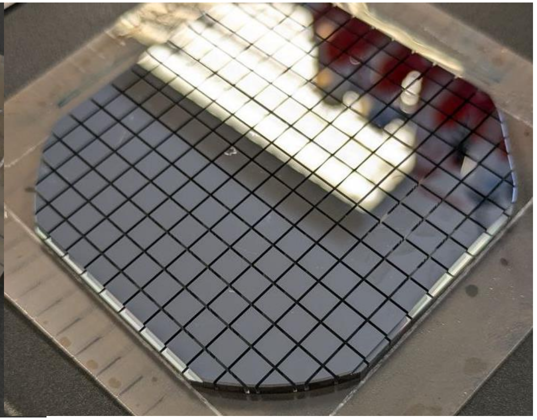
- ZCU215 Evaluation Board with 16 lines):
  Goal >= 150 KIDs / line
  2300 KIDs / board
  - Custom analog Front-End
  - Control firmware by KIT group
  - **Status:** First tests on BULLKID prototype ongoing

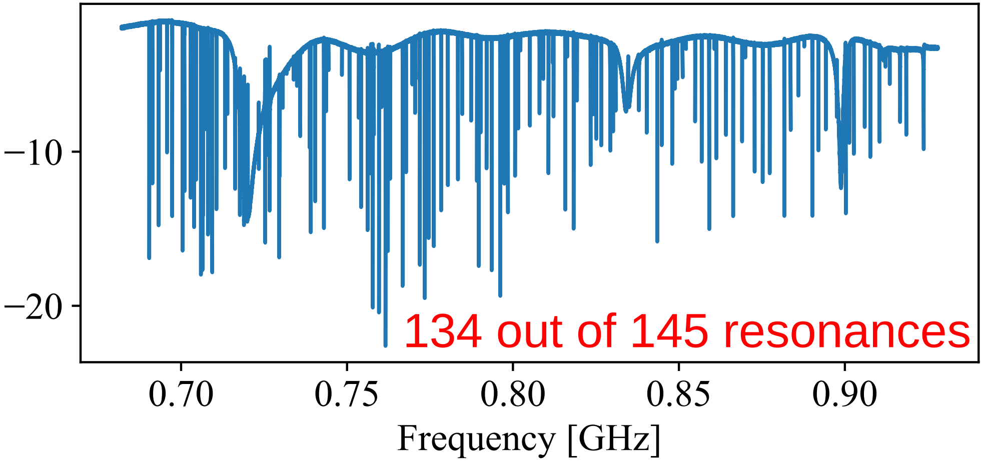
Upcoming paper

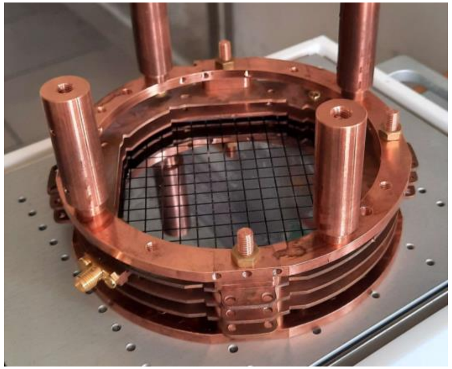


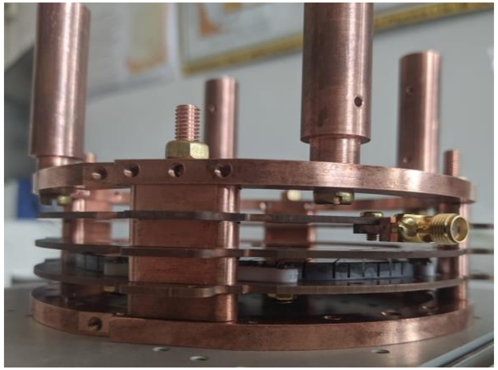
Scalability for the 100 mm mask







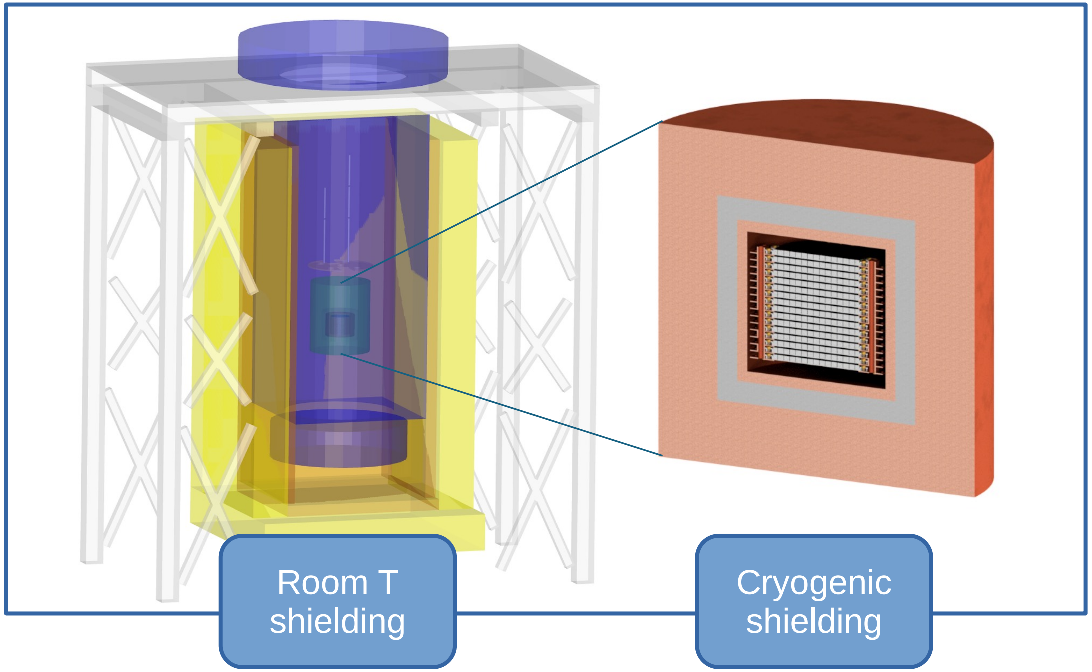




Next steps:

- Series wafer production
- Improvement of the lithography

Simulations: shields and veto

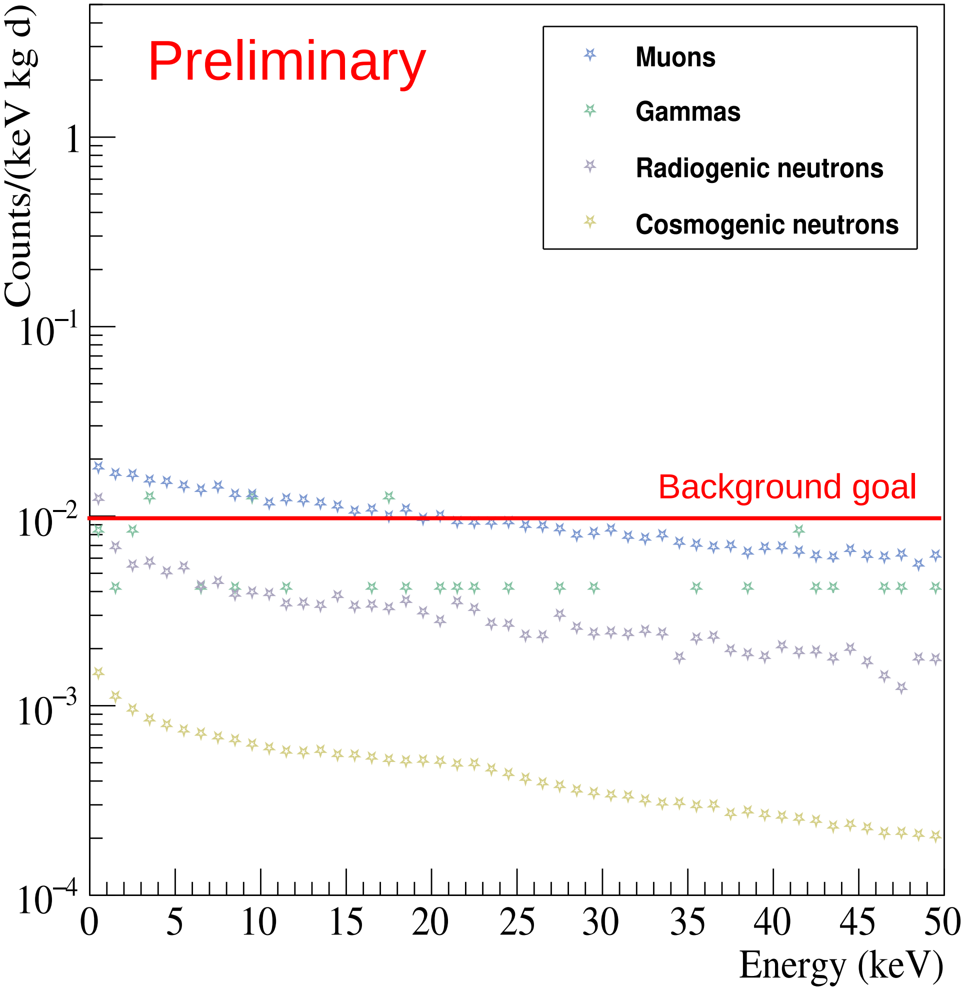


Room T shielding:

- Lead
- Copper
- Polyethylene

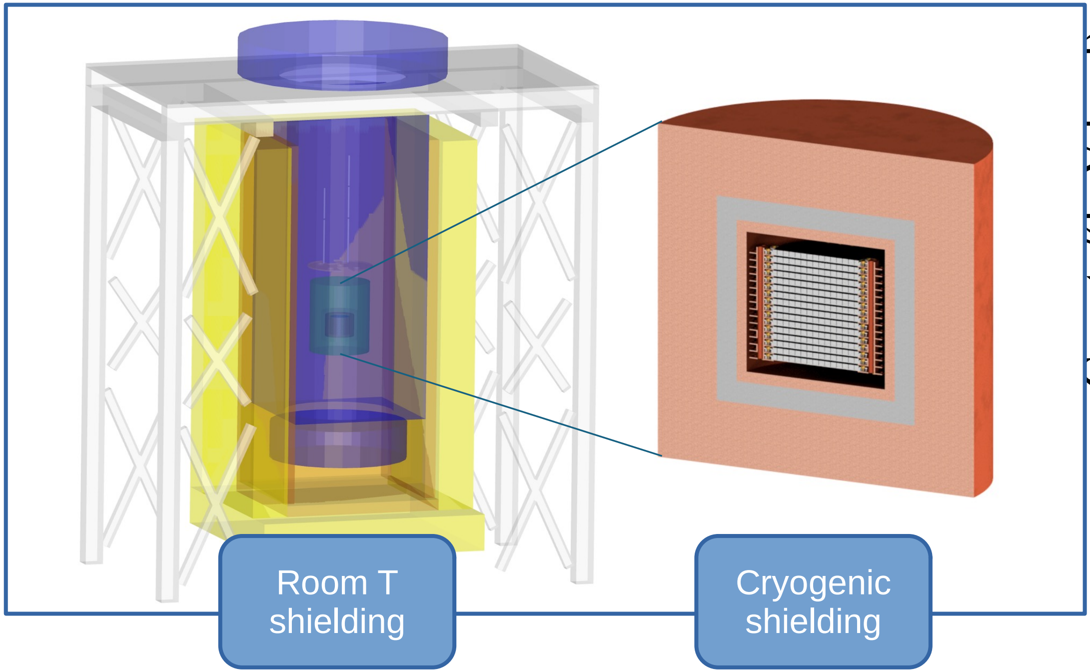
Cryogenic shielding:

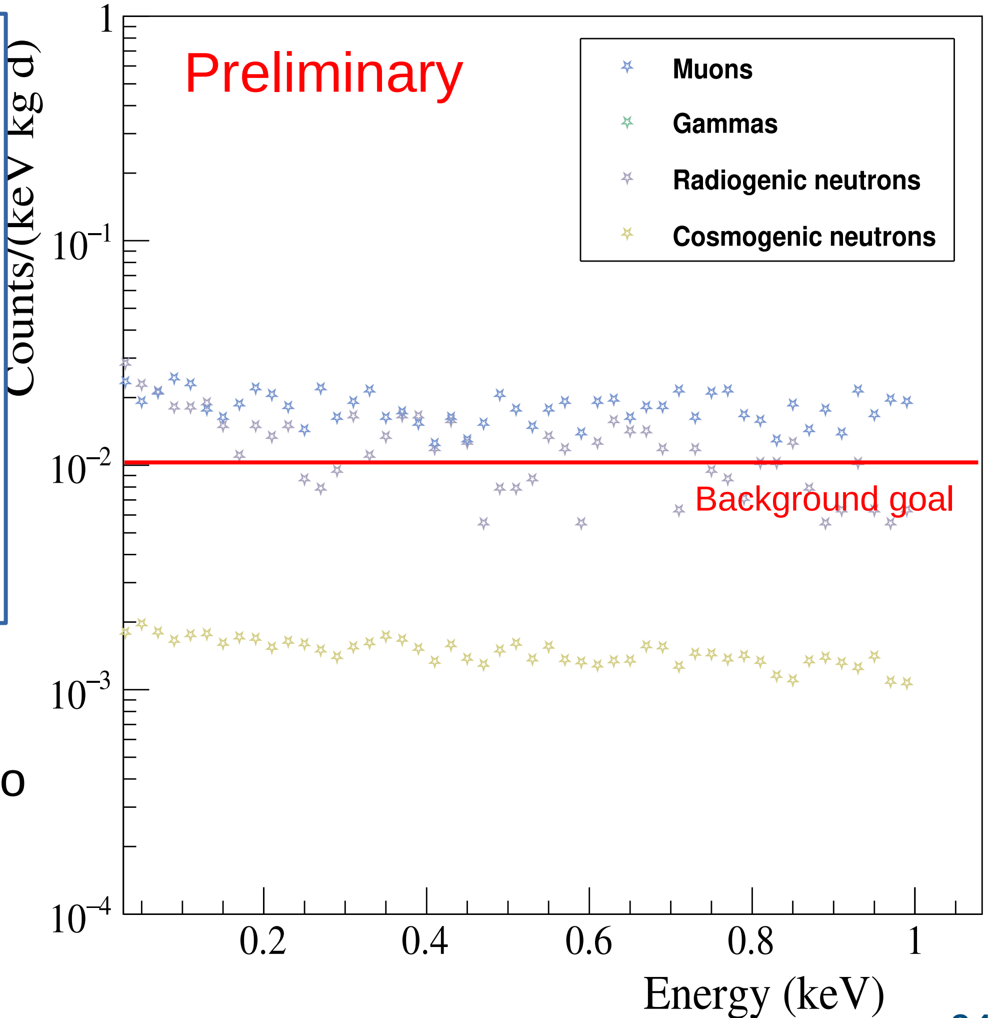
- Copper
- B_4C or PE or veto
- Copper



Currently working on lead and veto contamination

Simulations: shields and veto



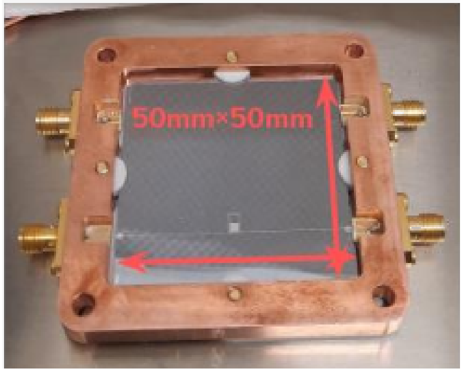


Room T shielding:
- Lead
- Copper
- Polyethylene

Cryogenic shielding:
- Copper
- B_4C or PE or veto
- Copper

Currently working on lead and veto contamination

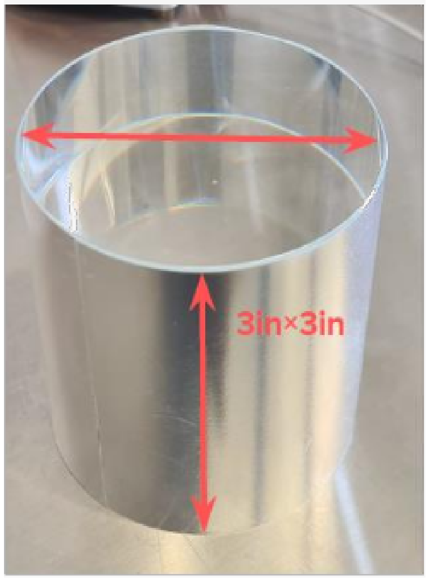
Cryogenic veto

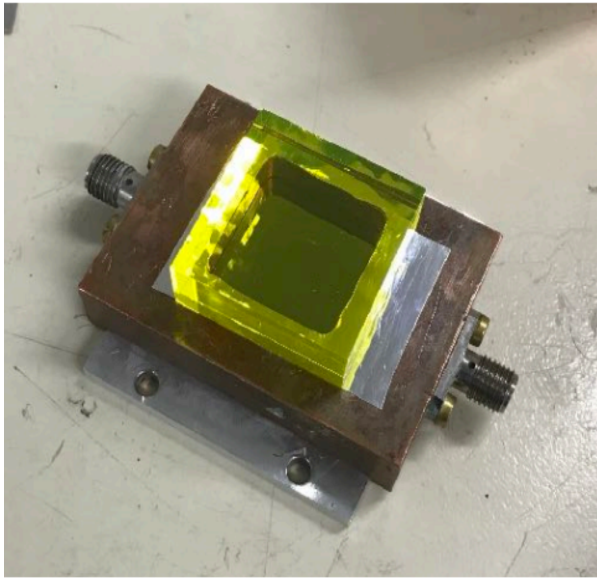


Idea: Use scintillating crystals (BGO, GSO or GAGG) read by KID light detectors as cryogenic veto

Pros:
- Dense materials
- Same readout of the central experiment
- Mass produced in industry

Cons:
- Low radio-purity
- Materials not well tested at cryogenic temperatures
- KID readout to be optimized

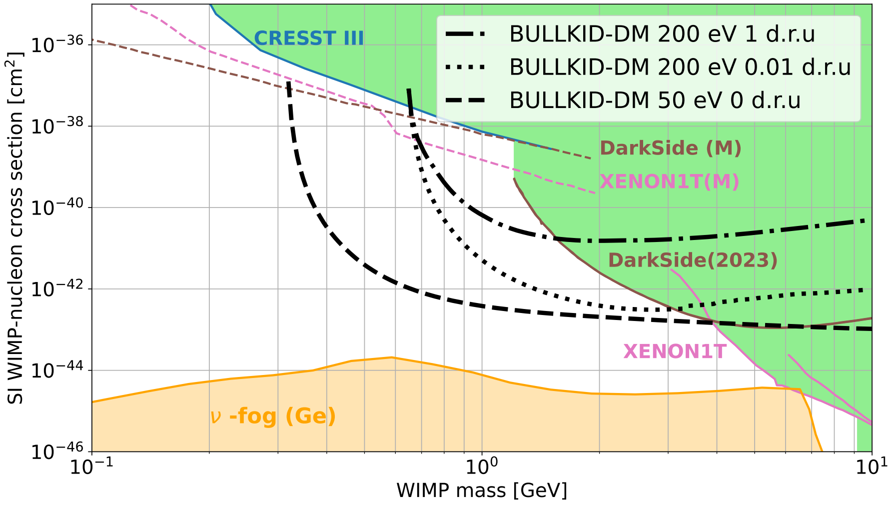




Goal: energy threshold < 50 keV

BULLKID-DM roadmap

	BULLKID prototype	BULLKID-DM Demonstrator		BULLKID-DM
mass	20 g	60 g		800 g
# of sensors	60	180		2300
Threshold	160 eV	200 eV		< 200 eV
Bkg (c / keV Kg d)	2 x 10^6	< 10^5		1 – 0.01
laboratory	Sapienza U.	Sapienza U.	LNGS	LNGS
installation	2023	2025	2026	2027



- 800 g of silicon target
- 2300 detector units (dice)
- Unique features for background suppression:
  - No inert material in the detector volume
  - Fully active
  - Fiducialization (600 g)
- Will it help with the unknown backgrounds?

BULLKID-DM

Thank you for the attention!

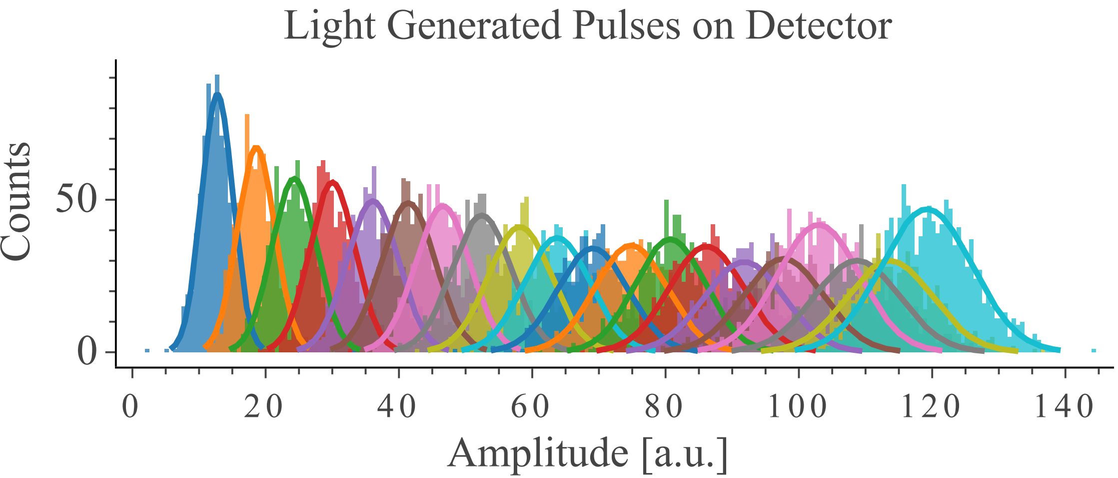
Matteo Folcarelli on behalf of the collaboration
Università La Sapienza di Roma, INFN - Roma 1

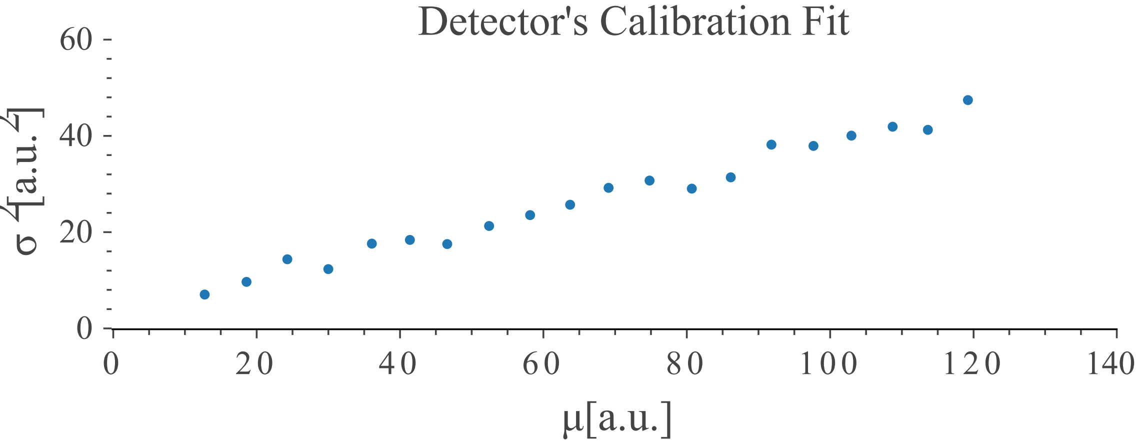
Other contribution to TAUP2025:
POSTER: Energy calibration of the BULLIKID-DM experiment (speaker Matteo Folcarelli)

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

Backup Slides

Optical calibration





The amplitude of the LED induced pulse is a Poisson distributed variable.

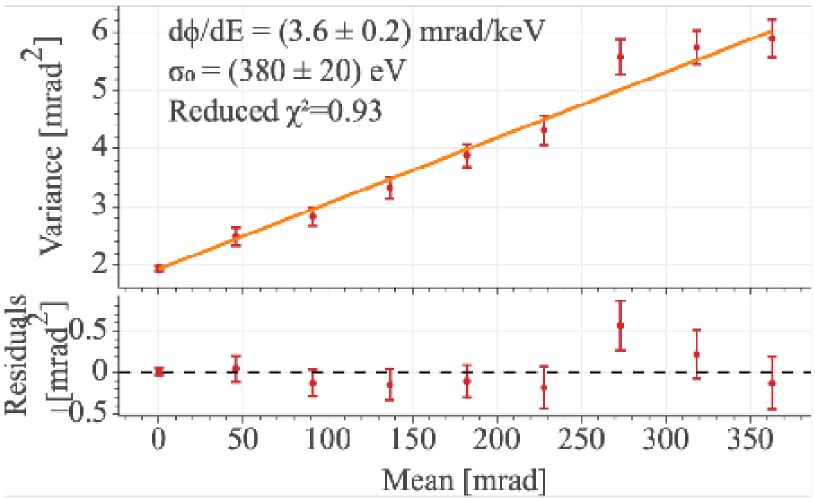
Then the mean and the variance of the distributions can be expressed as follows:

$$\sigma^2_{LED} = \sigma^2_0 + r \cdot \epsilon \cdot \mu$$

Where ϵ is the photon energy,

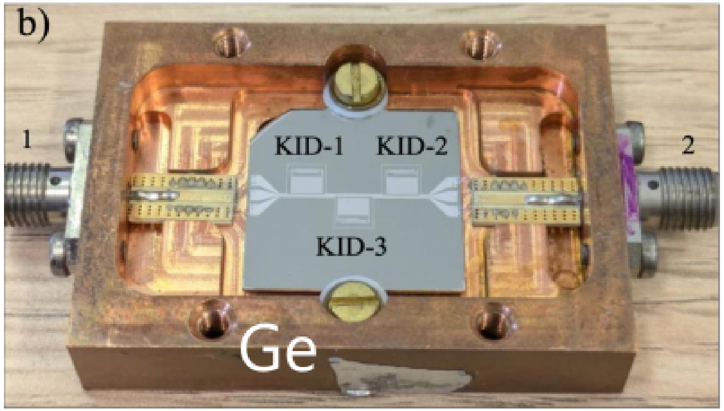
r is the responsivity of the KID

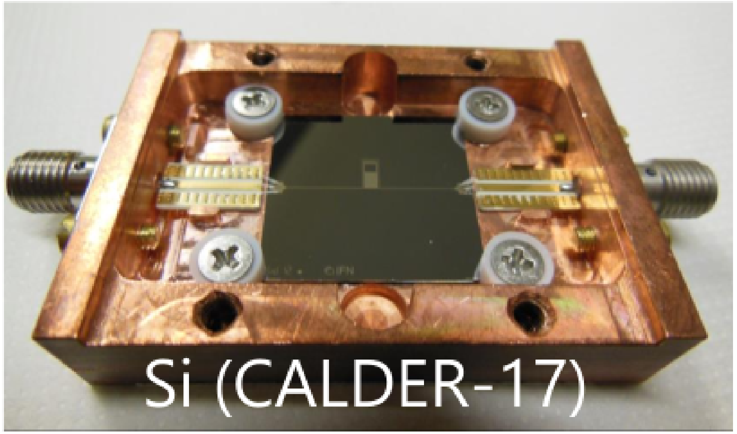
KIDs on Germanium fro neutrino detection



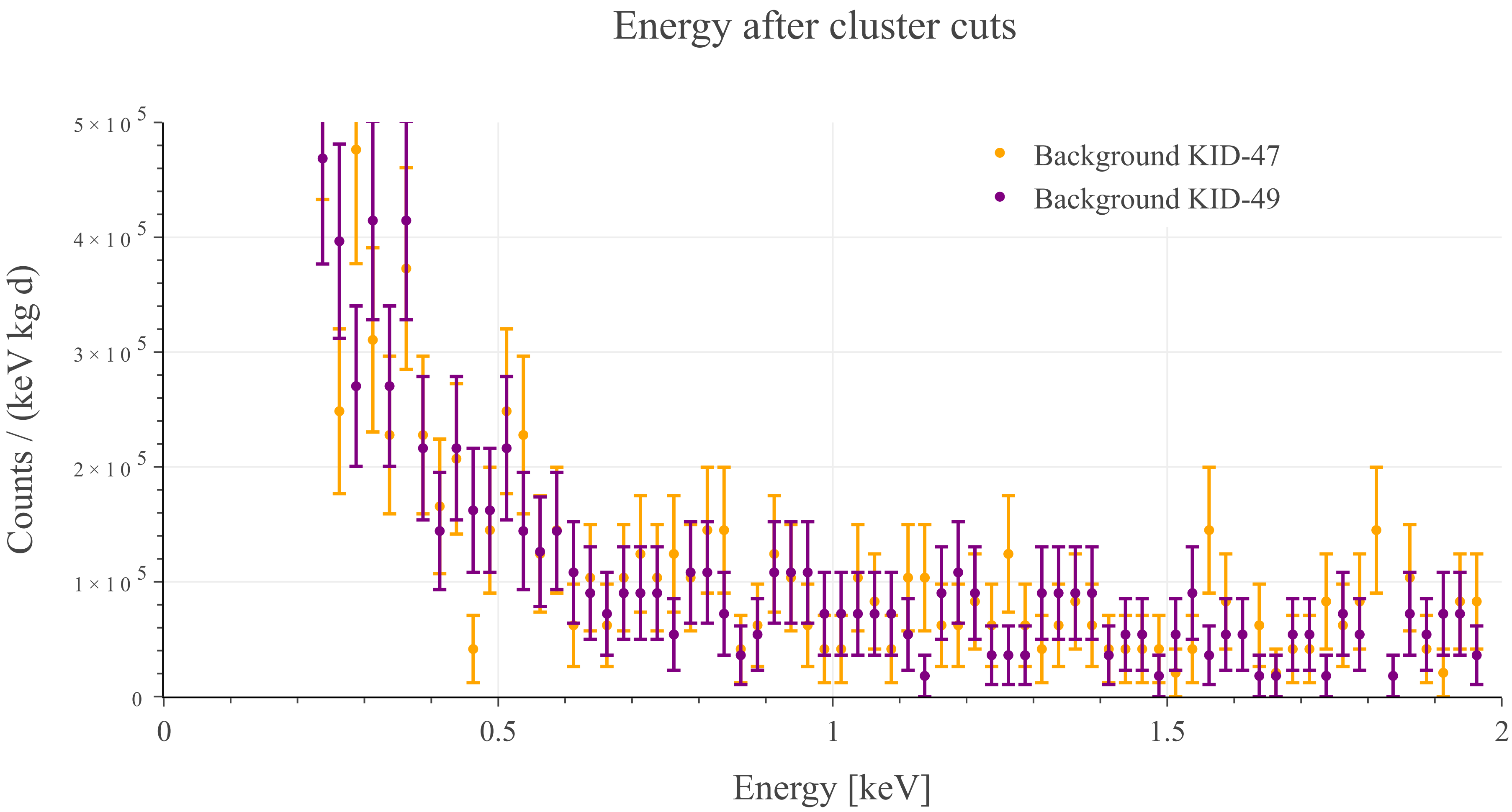
	$d\phi/dE$ [mrad/keV]	σ_0 [eV]	η [%]	$\frac{A_{KID}}{A_{TOT}}$
KID-1	3.6 ± 0.2	380 ± 20	2.0 ± 0.2	0.12
KID-2	2.5 ± 0.1	450 ± 22	2.0 ± 0.2	"
KID-3	2.2 ± 0.2	540 ± 31	1.6 ± 0.2	"
CALDER-17	5.8	115 ± 6	$7.4 - 9.4$	0.42

D.Delicato et al, Appl. Phys. Lett. 126, 153502 (2025)

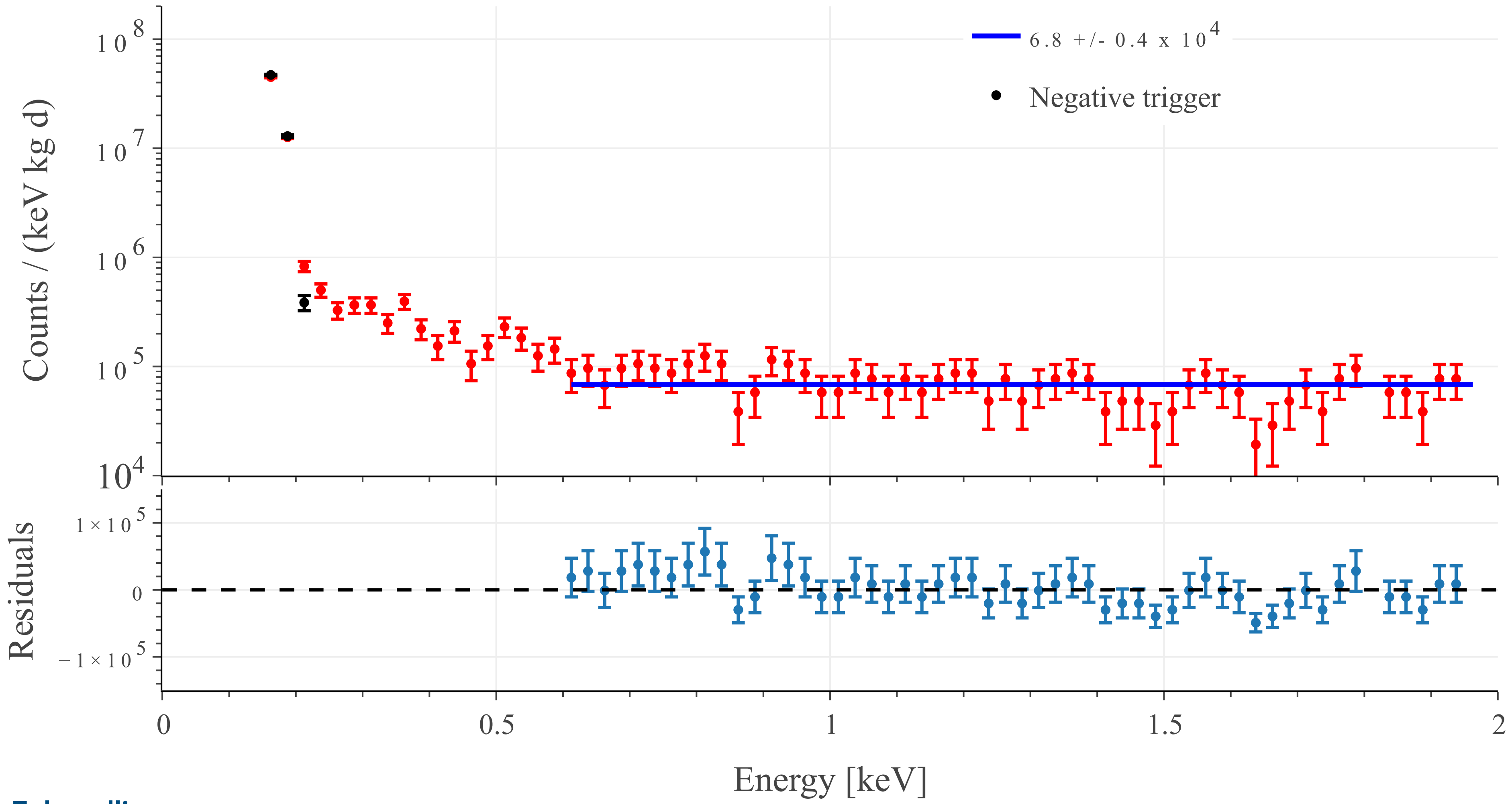




Comparison between px 47 and 49



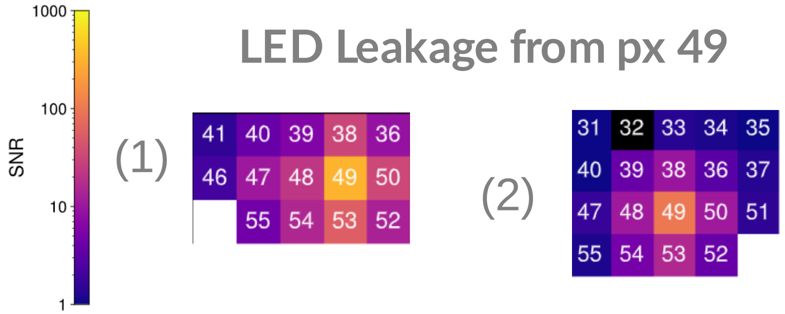
Spectrum in logscale for Negative Triggers

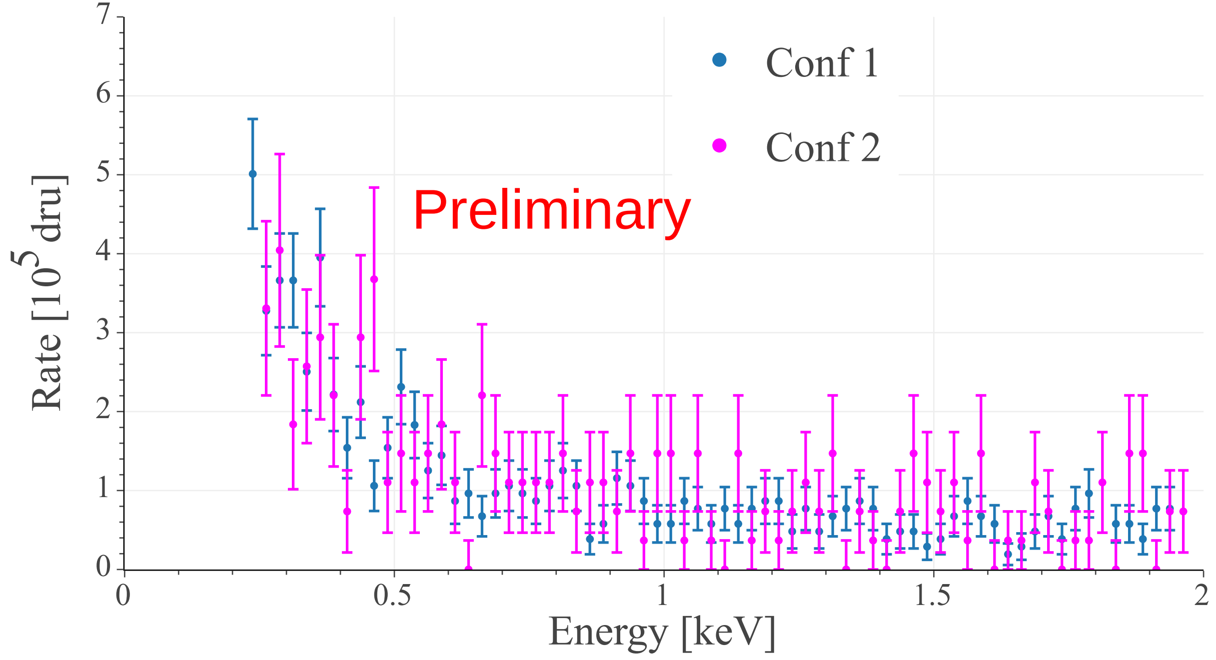


Repeated data taking

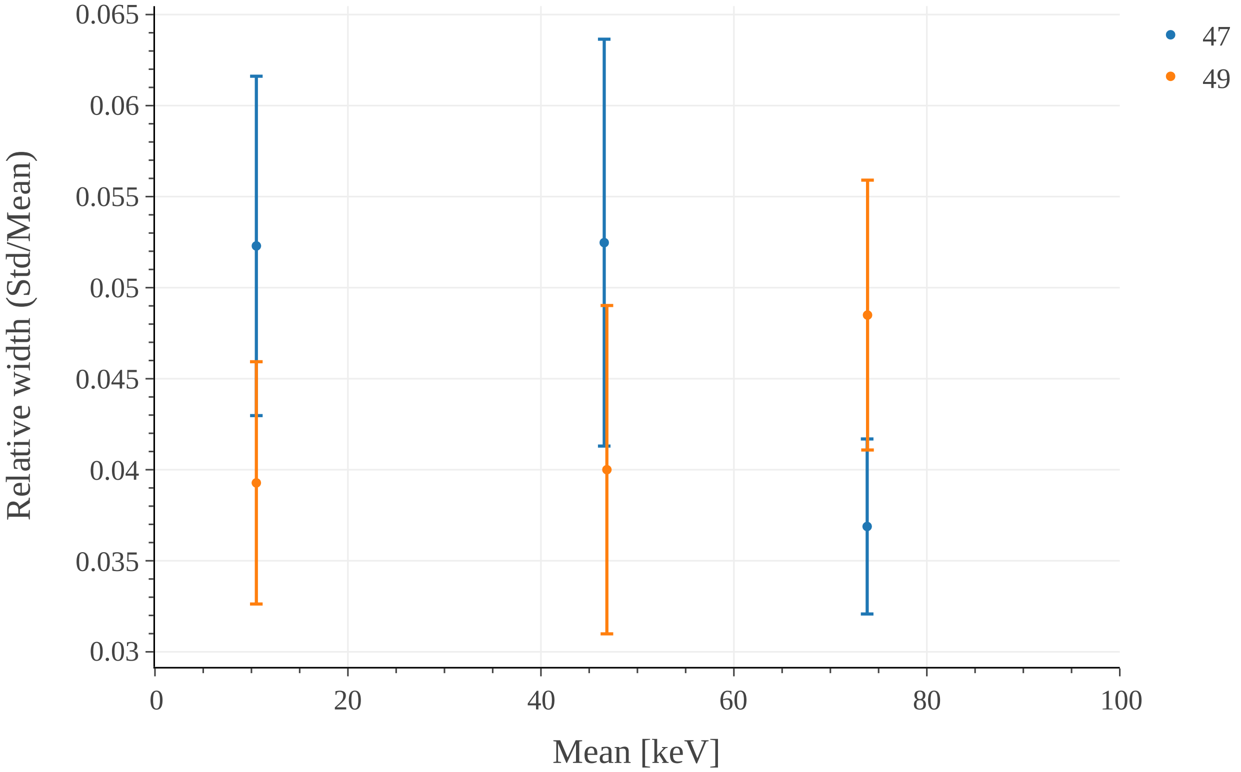
- Different working conditions tried:
  1) Optimizing the resolution of the triggering pixels
  2) Uniform leakage SNR in between pixels
- Data taking period in the same cooldown:
  1) 19/04 → 05/05 (~ 15 days)
  2) 19/05 → 26/05 (~ 7 days)

Observed no difference in between the energy spectra in the two configurations





Resolution as function of the energy



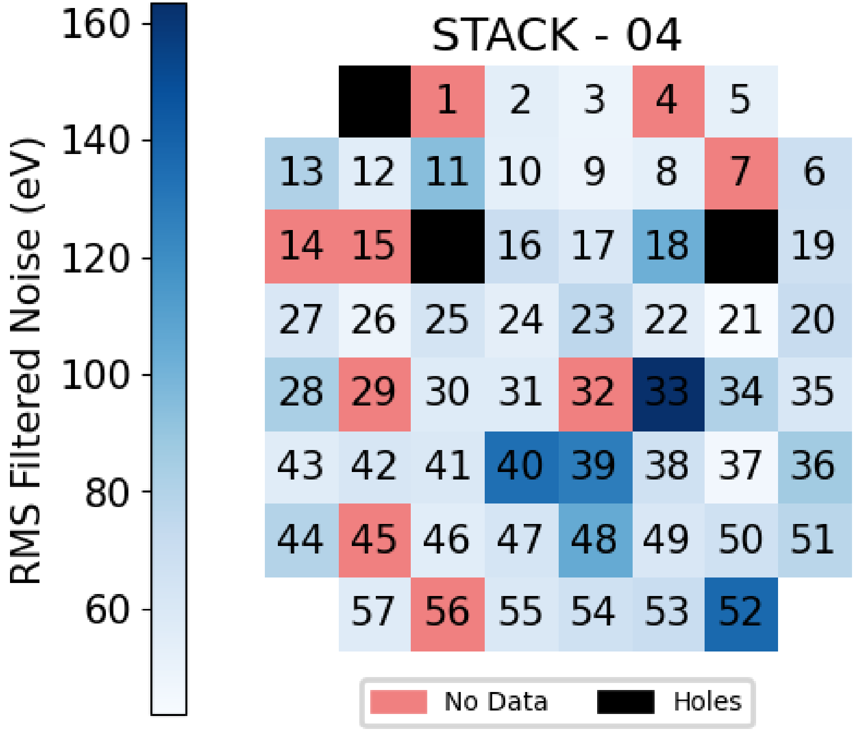
- Pb peaks allows the evaluation of the energy resolution of a BULLKID detector

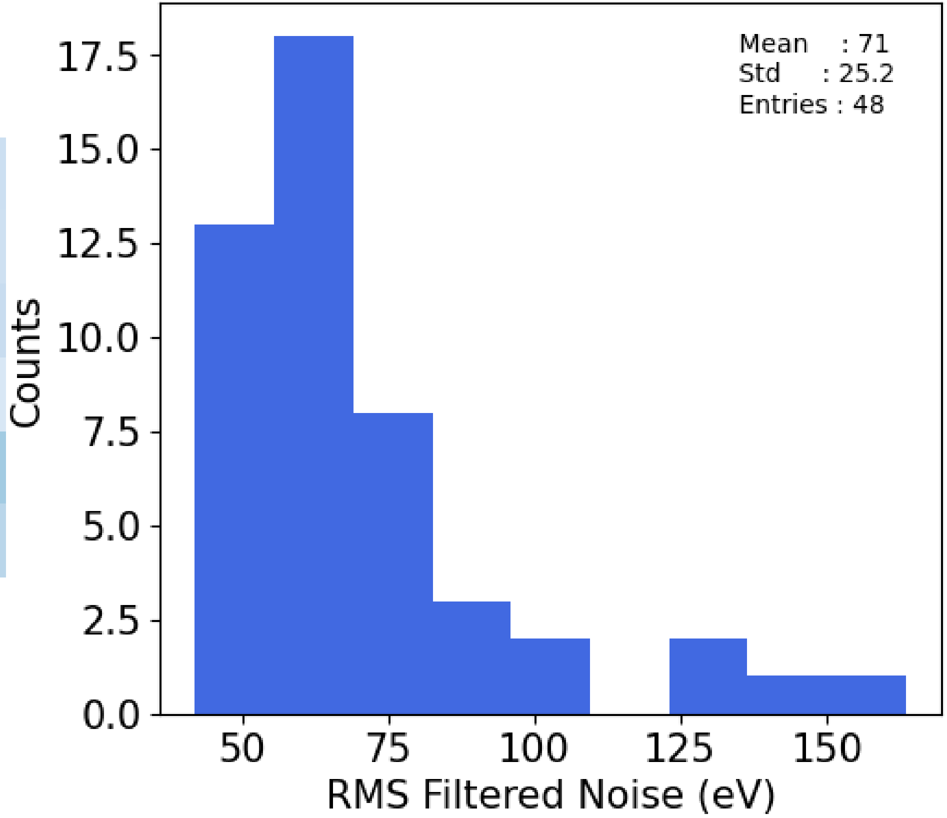
- Each peak is fitted with a Gaussian over a linearly decreasing background

A resolution around 5% is found for energies above 10 keV

Uniformity of the wafer response

Noise after calibration (FS) @ low bias power

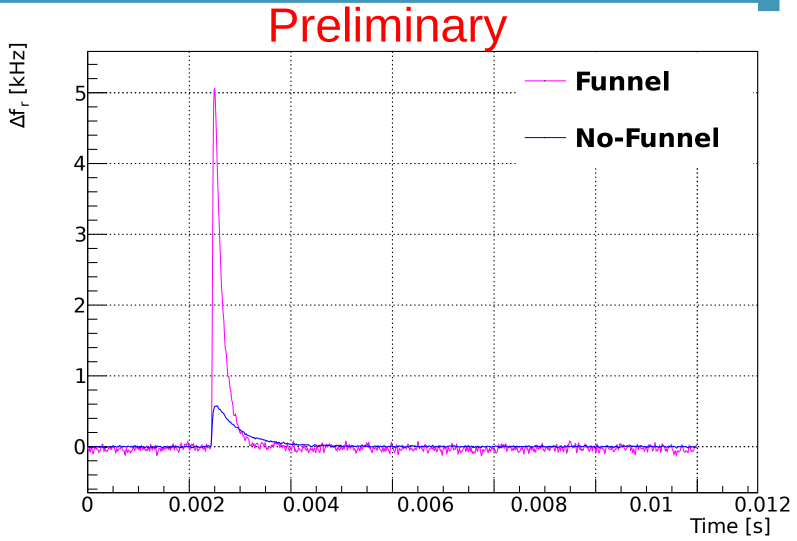


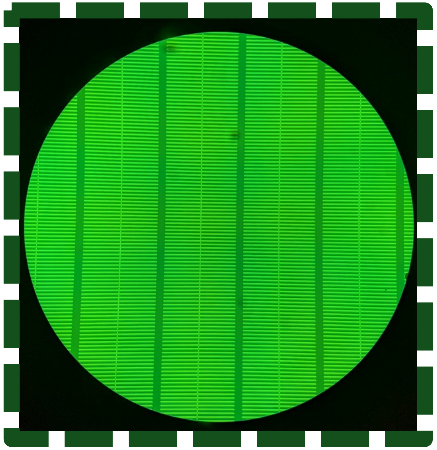


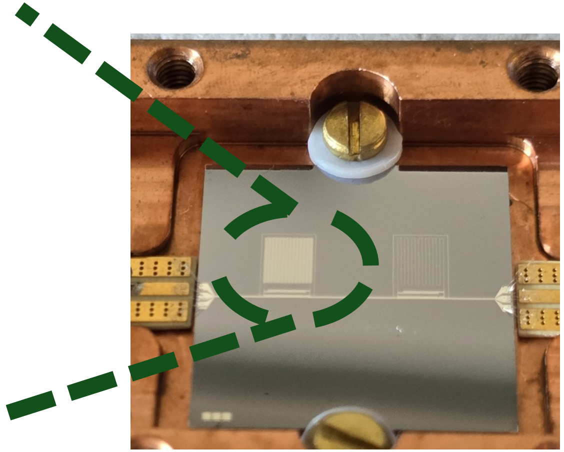
R&D efforts: phonon funnels

Upcoming paper

- Development of KIDs with dedicated phonon collection structures (funnels)
- Improvement in collection efficiency and resolution
- Trilayer KID (77 nm Al/Ti/Al) + funnel volume at higher gap (Al) for phonon funneling effect

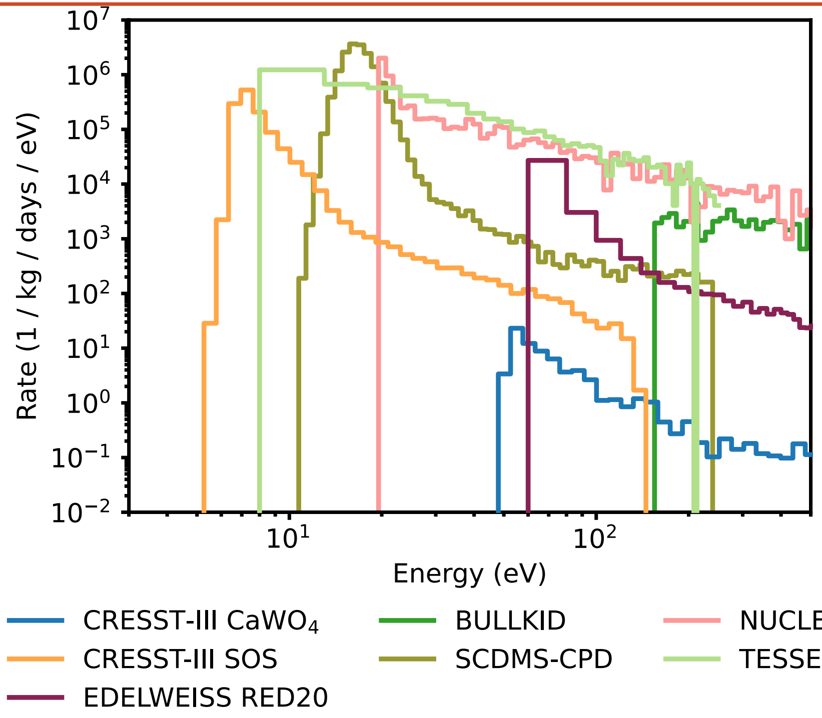




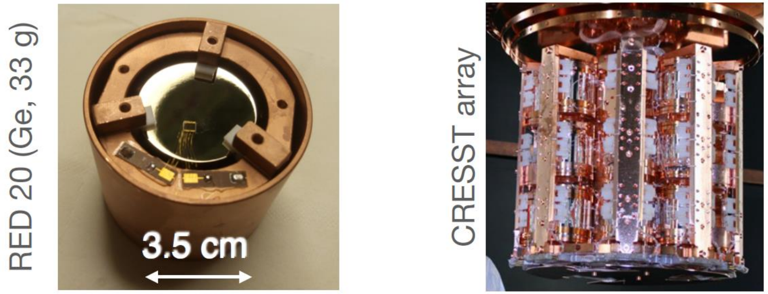


Background issue in low-T experiments

Not understood excess background rising at low energies



- Phonon bursts (crystal-support friction) ?
- Lattice relaxations after cool down?
- Phonon leakage from interactions in the supports?



Excess workshop 2025
Santa Fe, 31 May
https://indico.cern.ch/event/1502420/

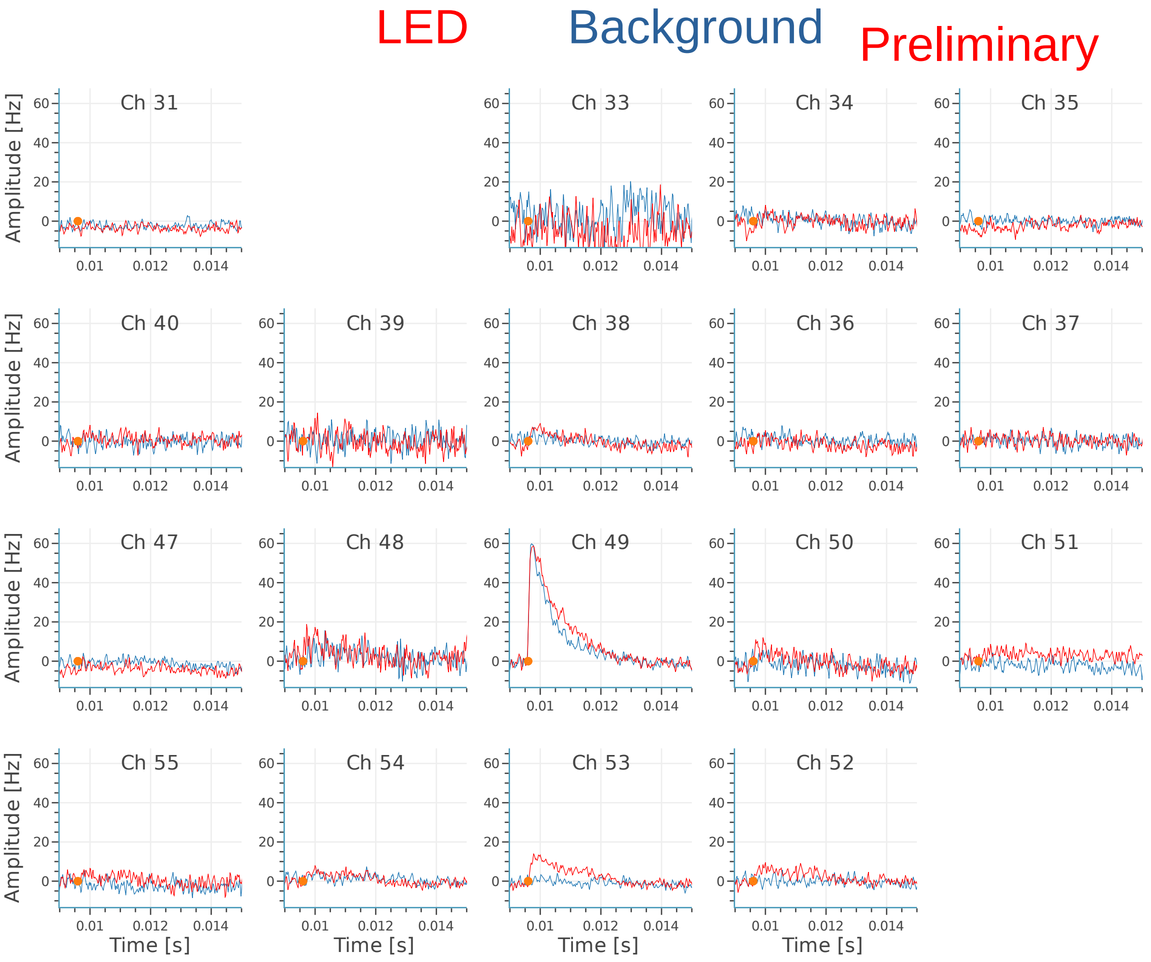
This background limits the sensitivity of present experiments

Singles observed in BULLKID

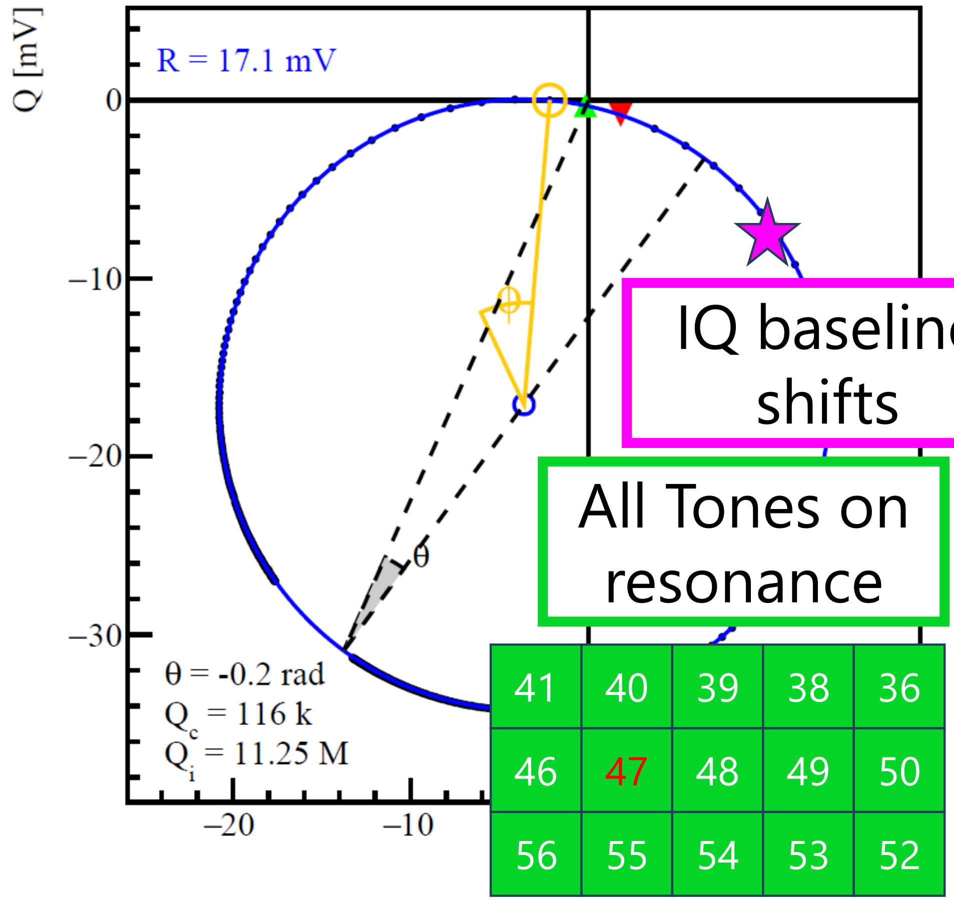
BULLKID architecture cannot distinguish Shared/Singles at threshold (small phonon leakage)

At higher energies:

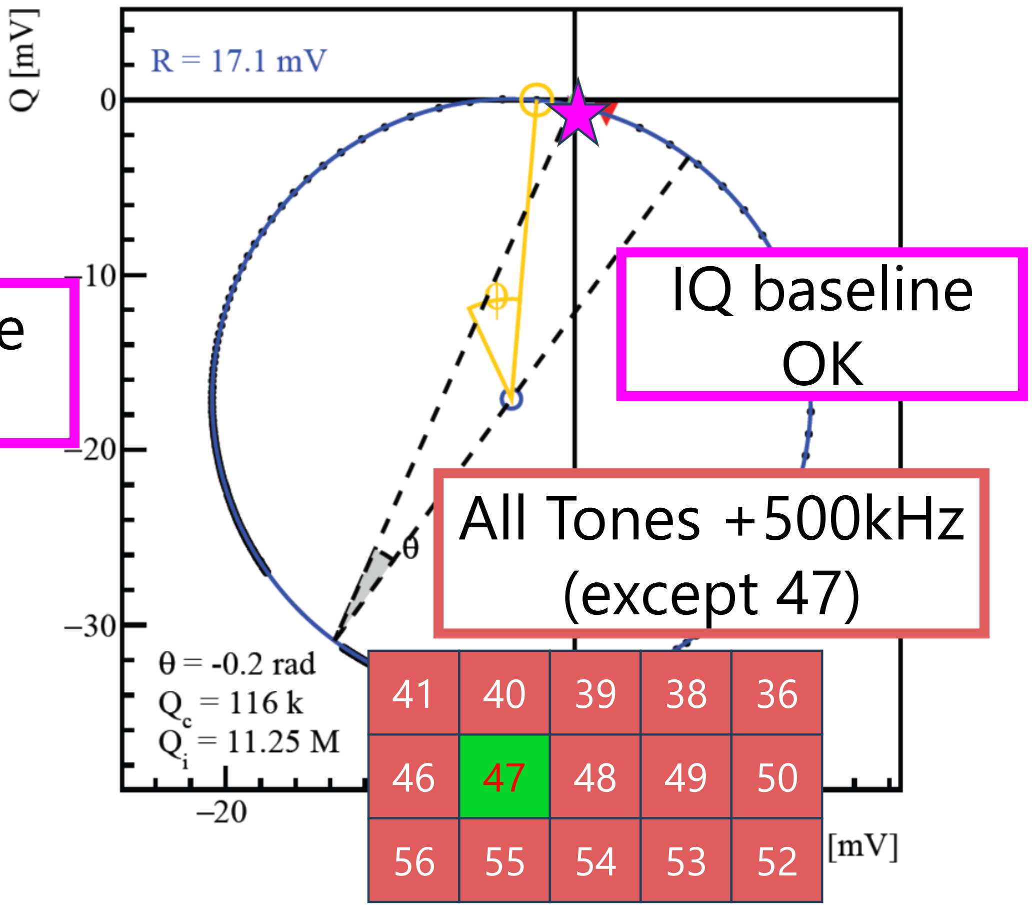
- Singles visible at ~2 keV and above
- Could be direct KID hits due to high metalized area (Al absorbs well 100 eV photons)
- Could it be that the rise is due to Singles?



Electronic x-talk



41	40	39	38	36
46	47	48	49	50
56	55	54	53	52



41	40	39	38	36
46	47	48	49	50
56	55	54	53	52