



SAPIENZA
UNIVERSITÀ DI ROMA



BULLKID-DM:

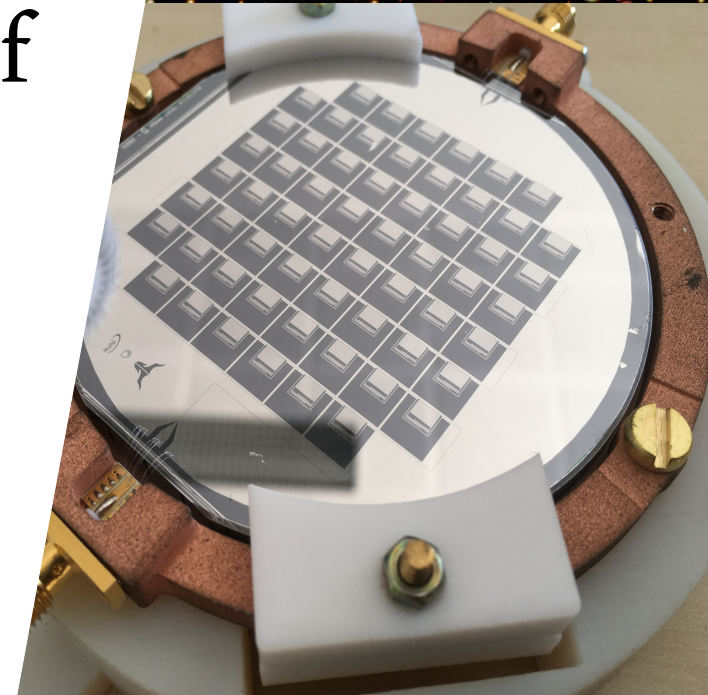
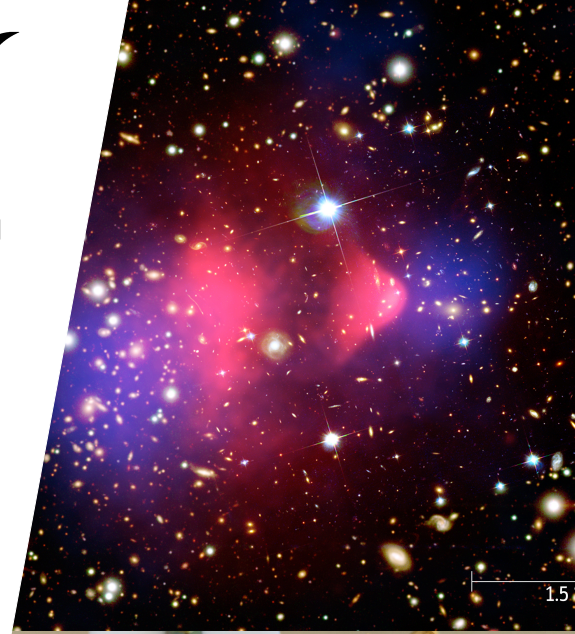
direct detection of light WIMP dark matter with monolithic arrays of cryogenic detectors

Camilla Bonomo on behalf of BULLKID-DM collaboration

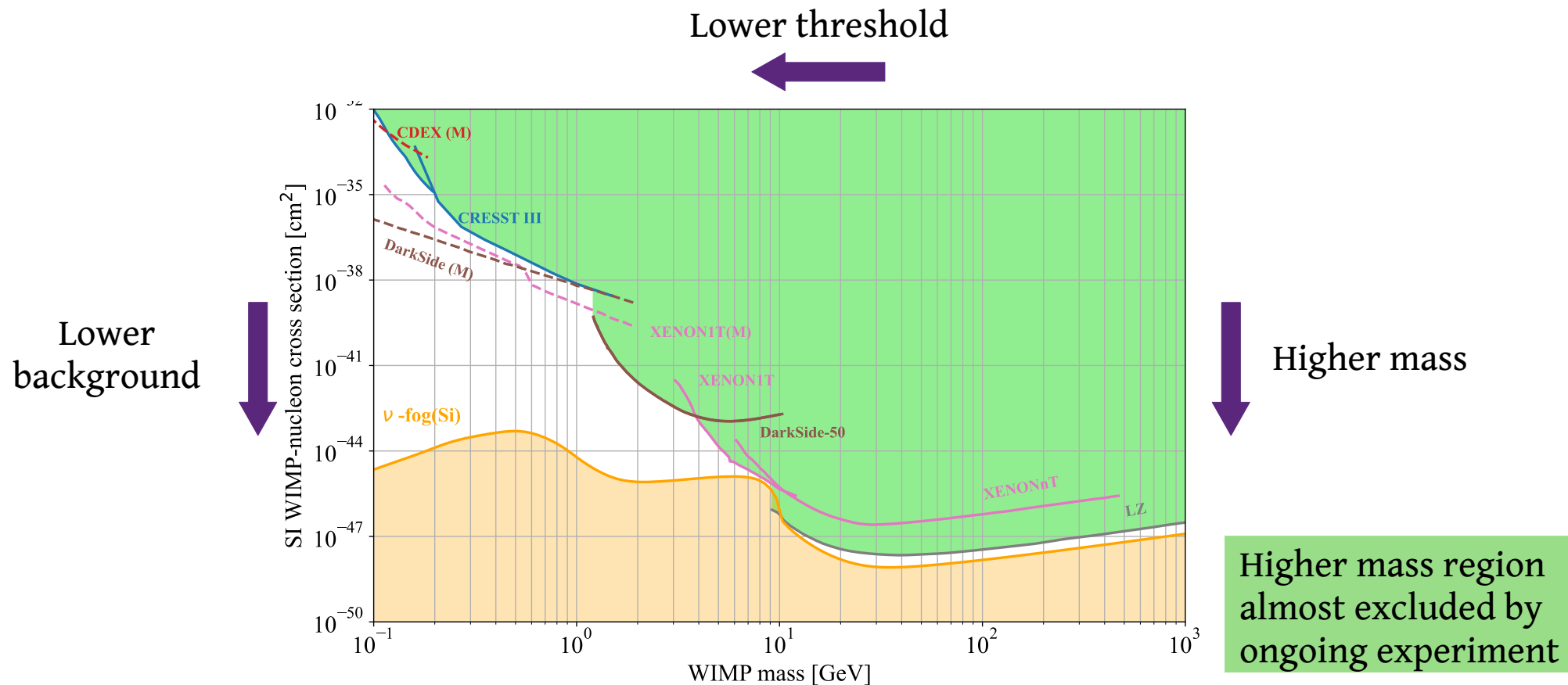
1st BiCoQ Conference: from particles to gravity

ercDANAE

Camilla.bonomo@uniroma1.it



WIMP search: where are we?



[Folcarelli M. et al., arXiv:2601.13766]

BULLKID-DM

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WIMP search: BULLKID-DM?

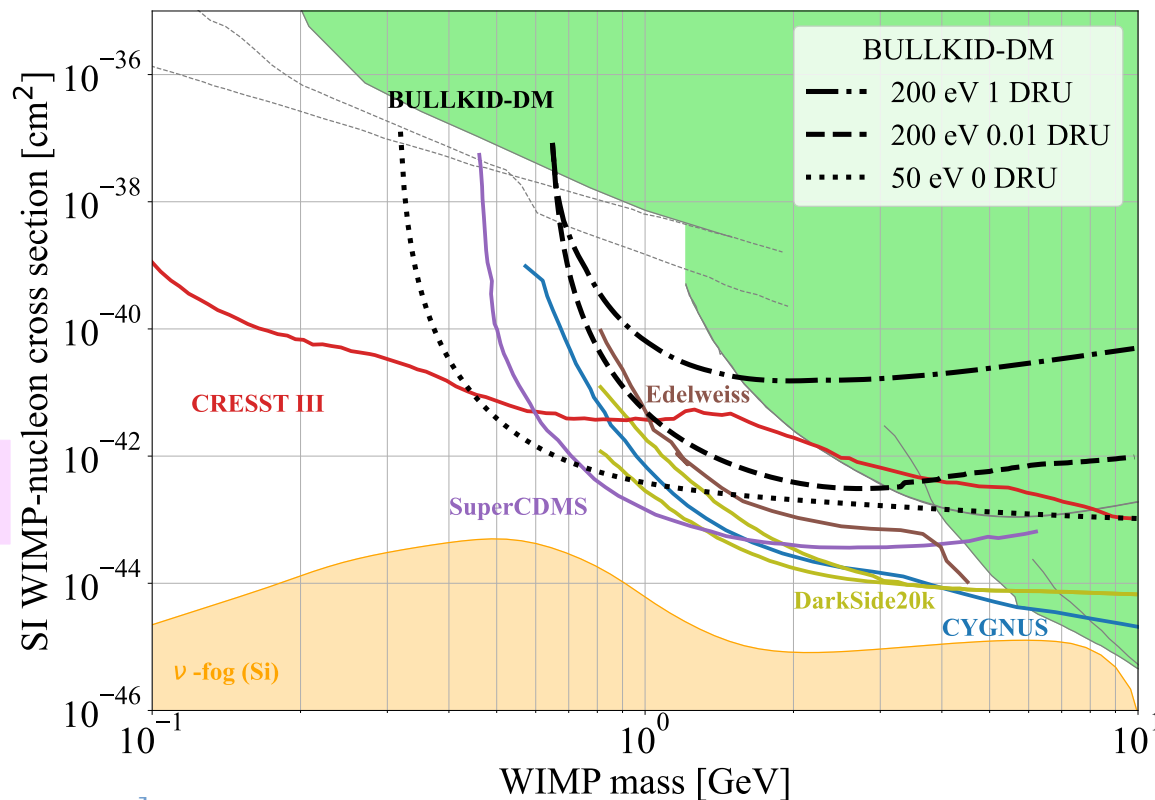
O(eV) → Phonons
Lower threshold



Lower background



Fiducialization
No inert material



Higher mass



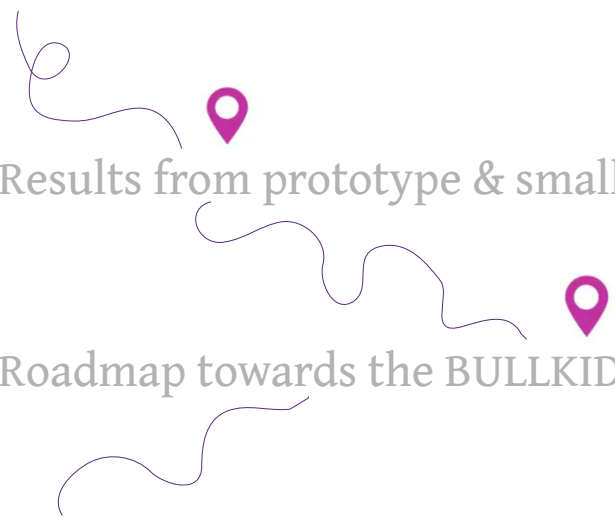
Solid-state detector
800 g of active mass

[Folcarelli M. et al., arXiv:2601.13766]

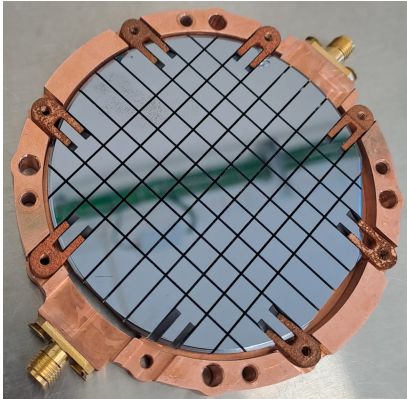
BULLKID-DM

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Outline

- 1 The BULLKID detector
 - 2 Results from prototype & small-scale demonstrator
 - 3 Roadmap towards the BULLKID-DM experiment
 - 4 R&D activities
- 
- A decorative graphic consisting of wavy lines and location pin icons. A wavy line starts from the right side of item 1, loops around, and ends with a location pin icon above item 2. Another wavy line starts from the right side of item 2, loops around, and ends with a location pin icon above item 3. A third wavy line starts from the right side of item 3, loops around, and ends with a location pin icon above item 4.

The BULky Low-threshold Kinetic Inductance Detector



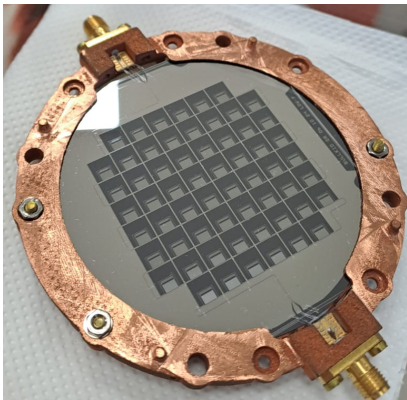
Bottom view

- 5 mm-thick carved Silicon wafer
- 60 dice held by 0.5 mm common disk

Monolithic



No passive holders



Top view

- Each die instrumented with Aluminum Kinetic Inductance Detector (KID)
- 60 detectors per wafer

Multiplexed readout



Mass scalability

How does a KID work?

KID ↔ LC resonator:

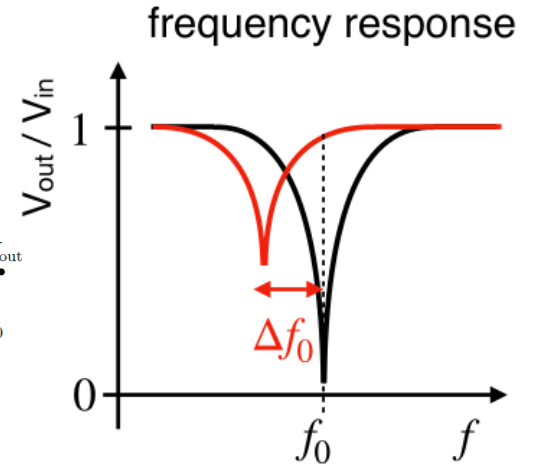
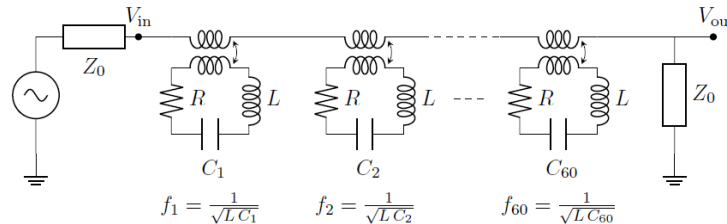
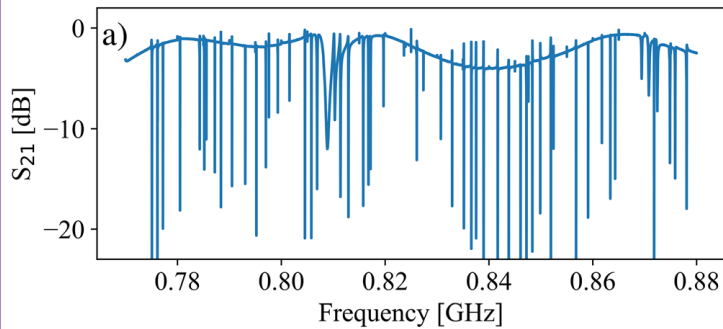
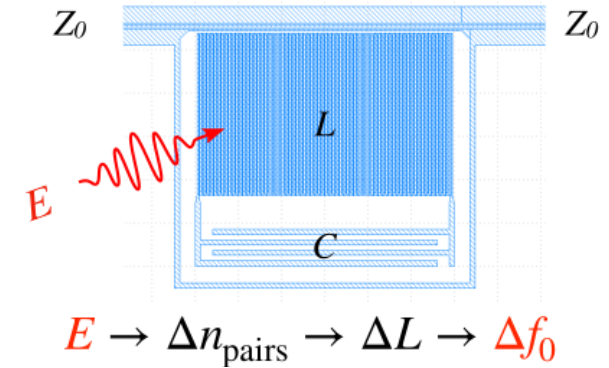
$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Aluminum is a **superconductor** below critical temperature:
electrons coupled in Cooper Pairs (CPs)

Kinetic inductance + Magnetic Inductance

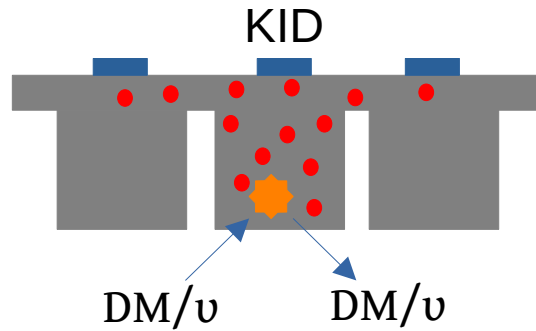
$$L = L_{kin} + L_M$$

Multiplexing: 60 RF tones centered in each f_0



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

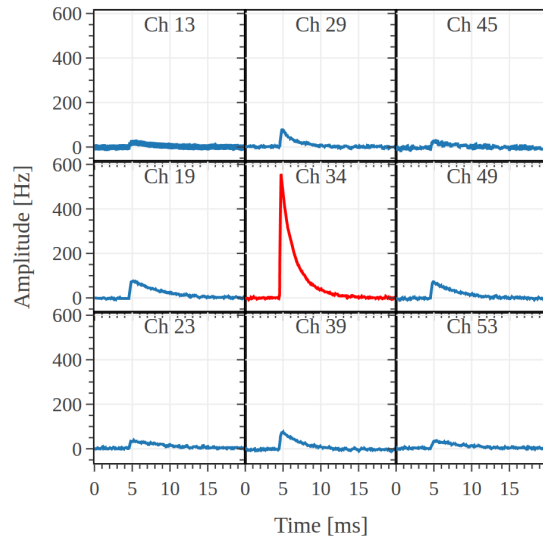
How to detect a signal?




DM-nucleus interaction \longrightarrow athermal **phonons**

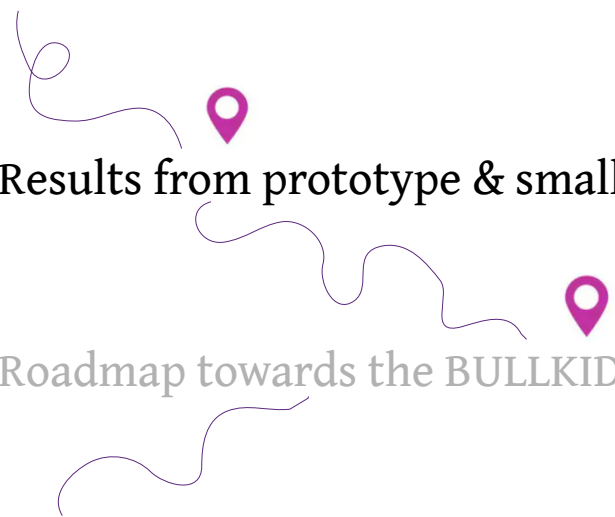
Phonons in **KID** break Cooper Pairs \longrightarrow frequency shift \longrightarrow signal

Phonons leak in neighbouring dice \longrightarrow cluster accepted for analysis

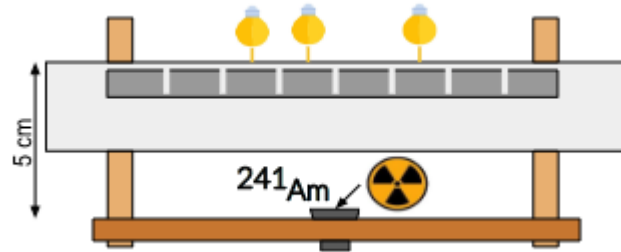


3%	8%	3%
8%		8%
3%	8%	3%

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- 

Bulk events calibration with americium source



- Calibration (bulk events) with ^{241}Am photopeak @ 59.5 keV
- Calibration (surface events) with pulsed optical pulses



Compatible within less than 10% discrepancy

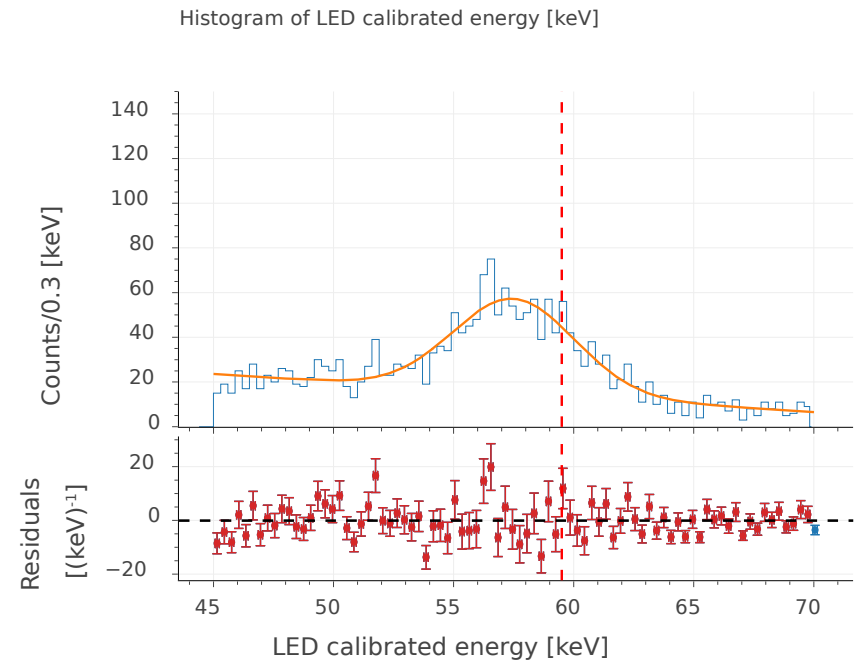


[Folcarelli, M., et al. Eur. Phys. J. C 86, 301 (2026)]

[Del Castello G., arXiv:2602.20369s]

BULLKID-DM

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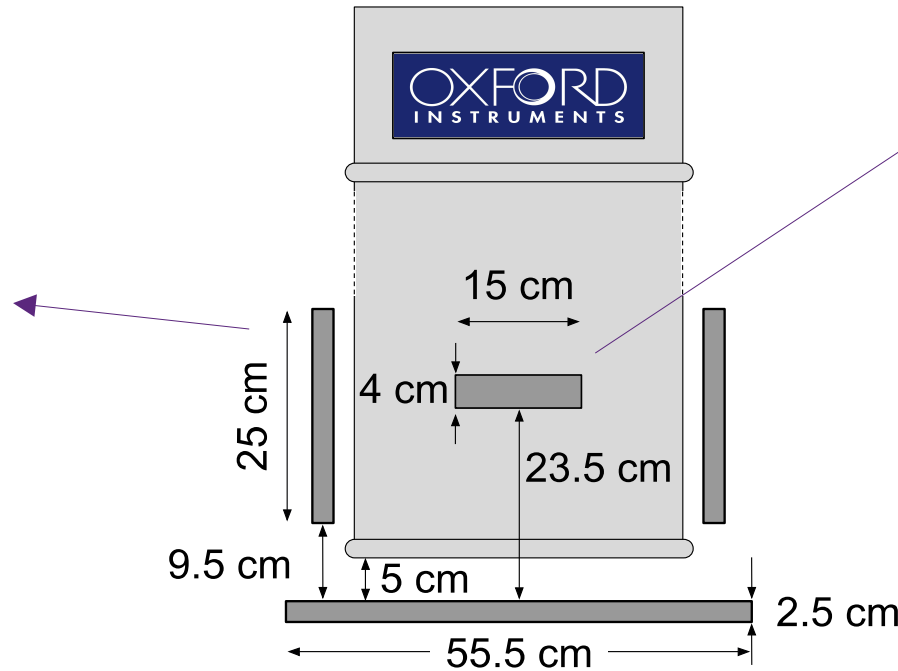
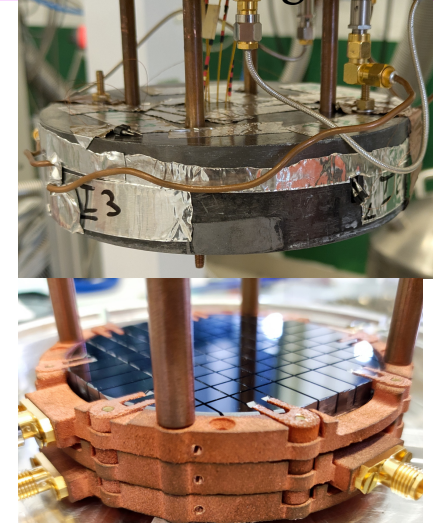


On surface background with moderate shield

External lead bricks



Lead case hosting the wafer

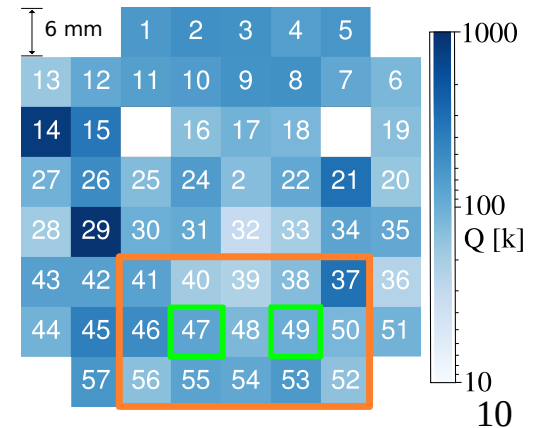


- 15 KIDs acquired
- **2 triggering channels** and the **13 veto channels**
- 290 hrs exposure

[Delicato D. et al., arXiv:2605.02468.]

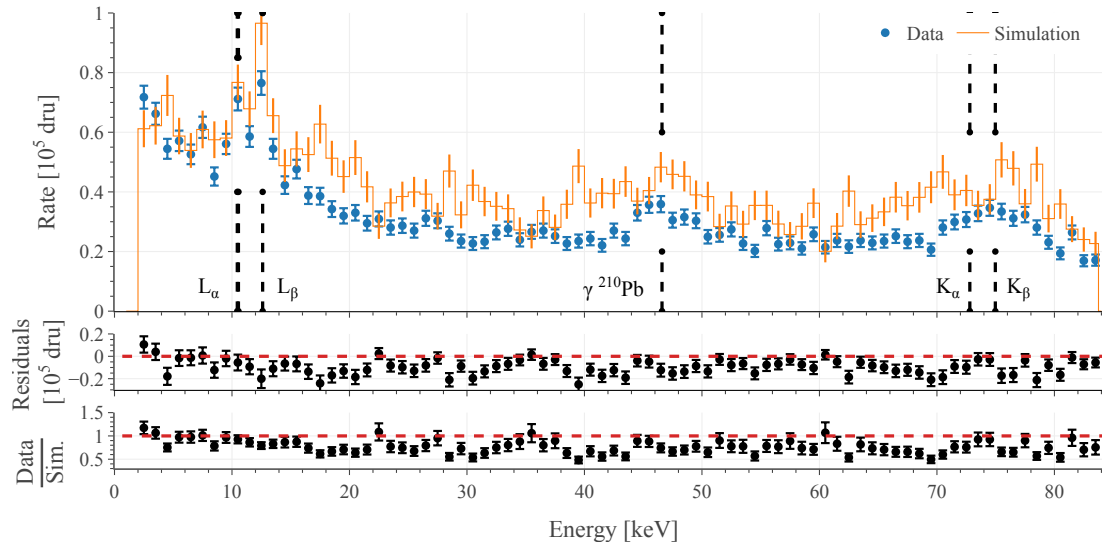
BULLKID-DM

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Moderate shield above-ground operations

Energy spectrum



Simulation in agreement with data up to a factor 1.3

Slight discrepancy possibly due to:

- Systematics in gamma flux estimation;
- Systematics in implemented setup geometry

Lead γ and fluorescence lines used for calibration + efficiency evaluation

[Delicato D. et al., arXiv:2605.02468.]

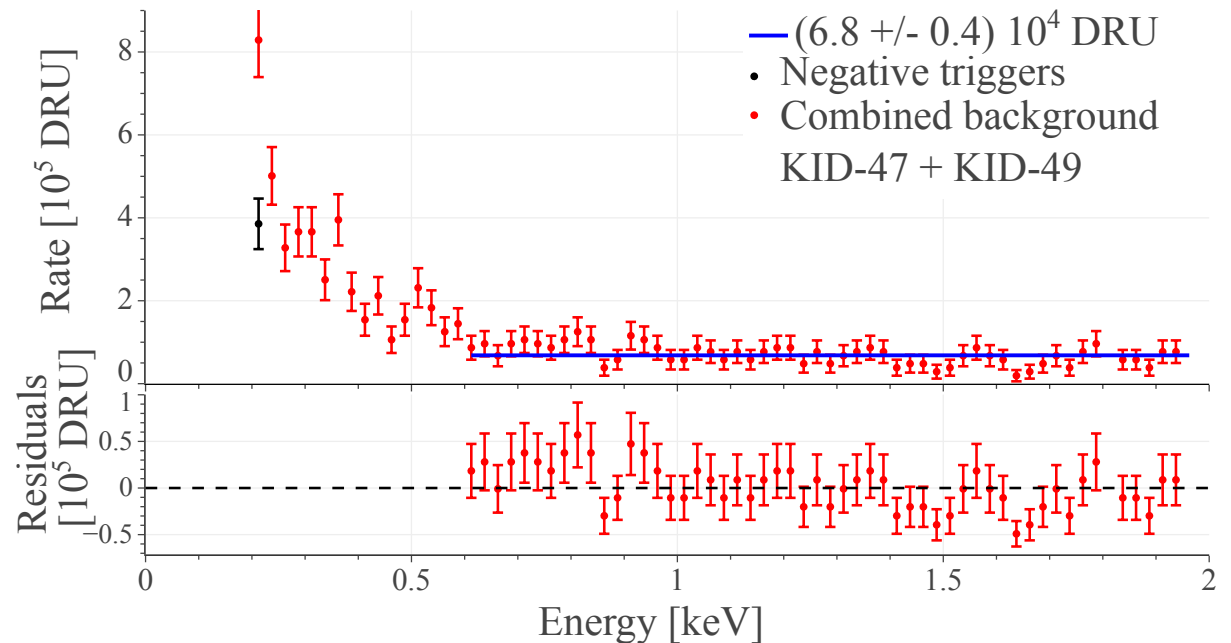
Moderate shield above-ground operations

Energy spectrum

Is it Low Energy Excess?

LEE: excess in counting rate possibly due to solid state effects – still unexplained

Low energy rise



[Delicato D. et al., arXiv:2605.02468.]

Moderate shield above-ground operations

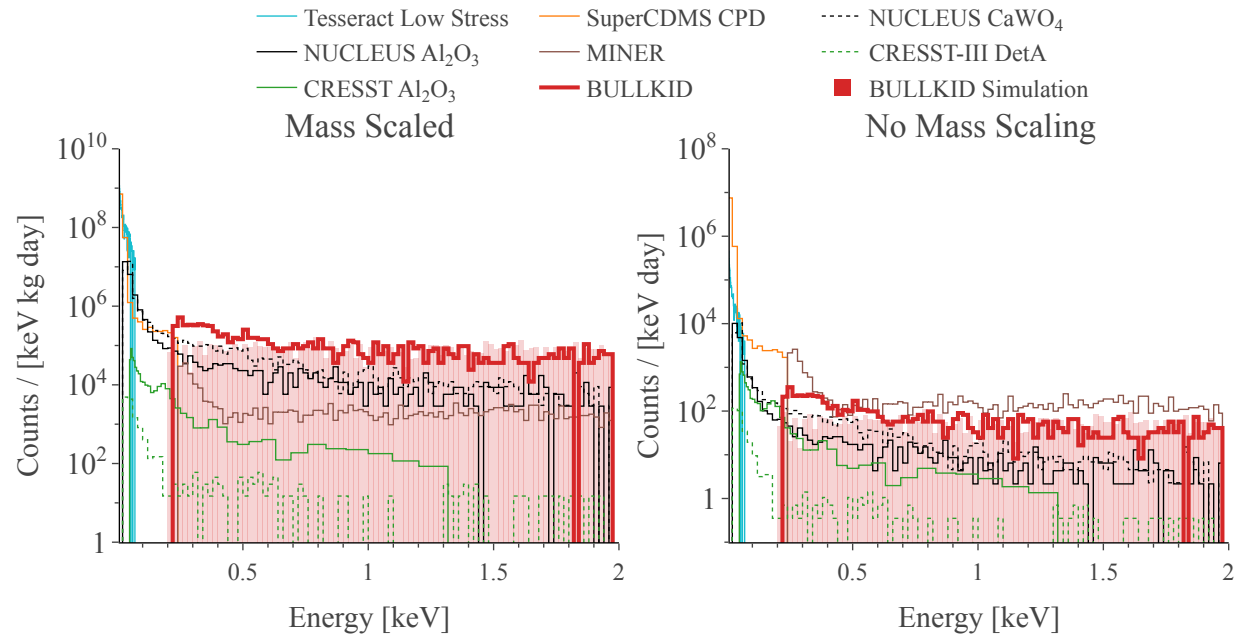
Energy spectrum

Is it Low Energy Excess?

LEE: excess in counting rate possibly due to solid state effects – still unexplained

Typical features:

- Not ionizing
- Decrease over time
- Reactivated with thermal cycles;
- Not reproducible amongst different detectors

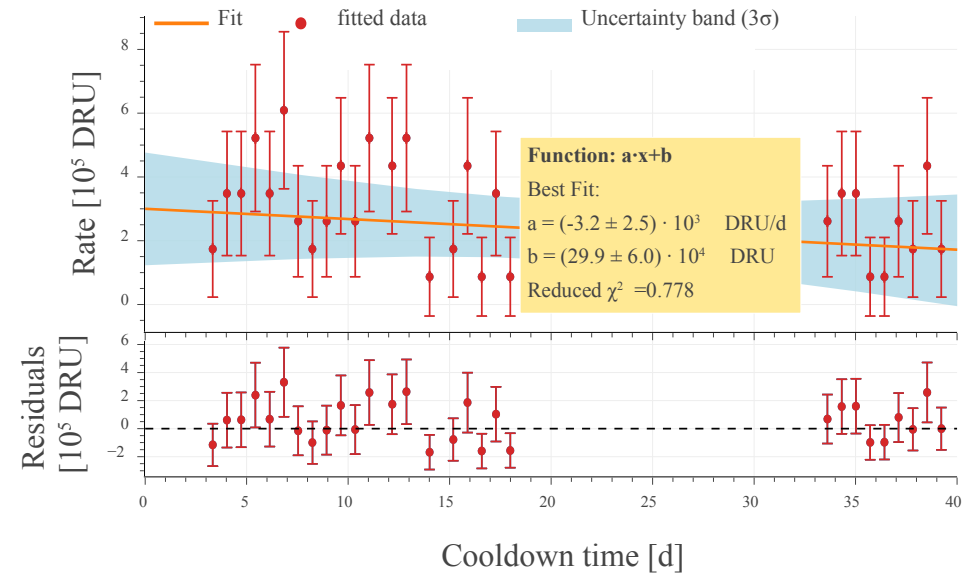


Moderate shield above-ground operations

Low Energy Excess?



No exponential decay of counting rate during cooldown



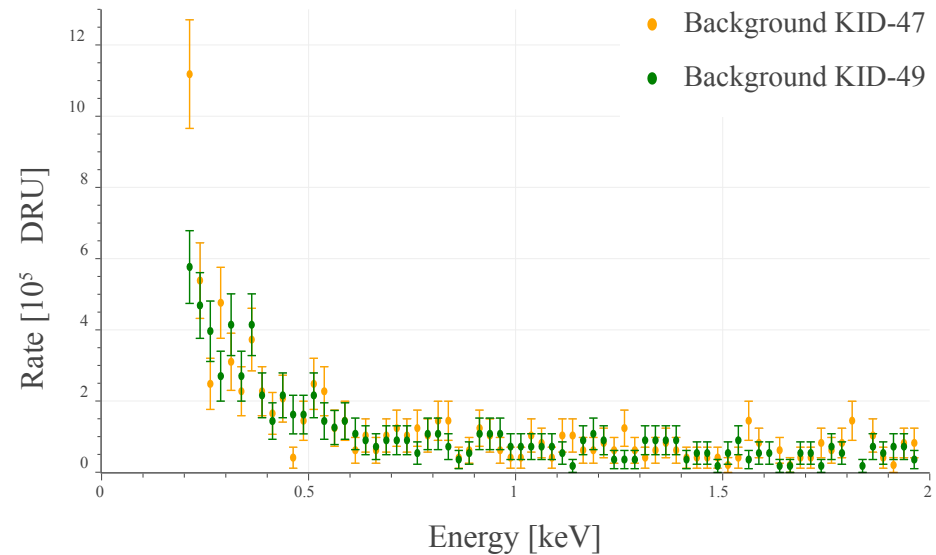
[Delicato D. et al., arXiv:2605.02468.]

Moderate shield above-ground operations

Low Energy Excess?



Counting rate compatibility between channels

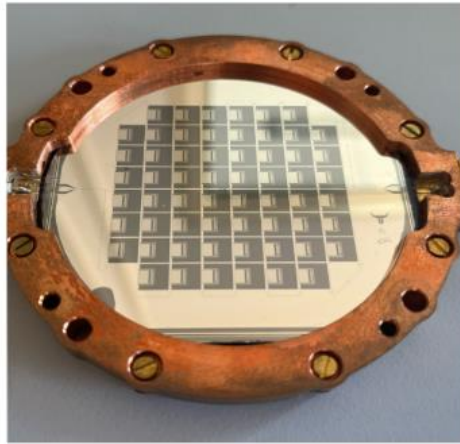


Possible particle origin?

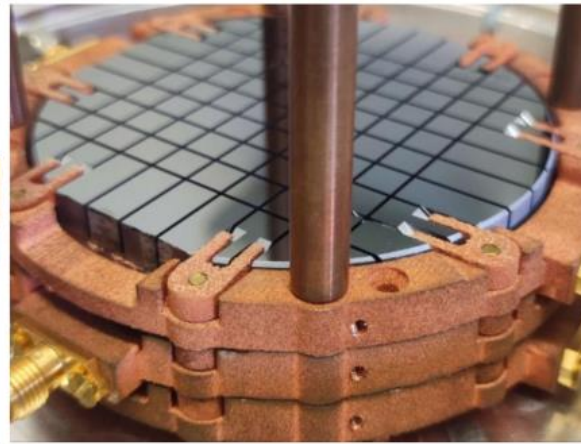
[Delicato D. et al., arXiv:2605.02468.]

BULLKID-DM: what needs to be done

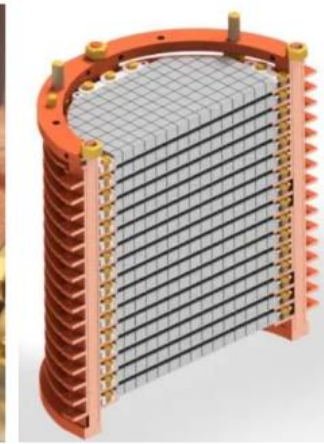
Prototype



Demonstrator



Experiment



	1. Prototype	2. Demonstrator		3. Experiment
mass	20 g	60 g		800 g
# sensors	60	180		2300
Threshold	160 eV	≤ 200 eV		≤ 200 eV
Bkg rate (DRU)	$2 \cdot 10^6$	$< 10^5$	$\sim 10^4$	$1 \div 0.01$
Laboratory	Sapienza U.	Sapienza U.	LNGS	LNGS
Period	2023	2024 - 2026	2026	2027 -

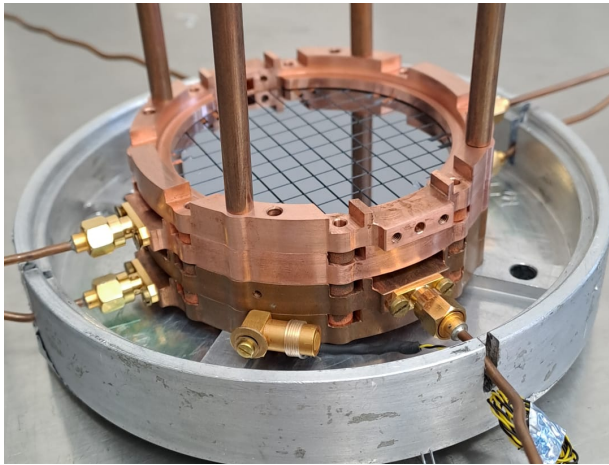
We are here

[Folcarelli M. et al., arXiv:2601.13766]

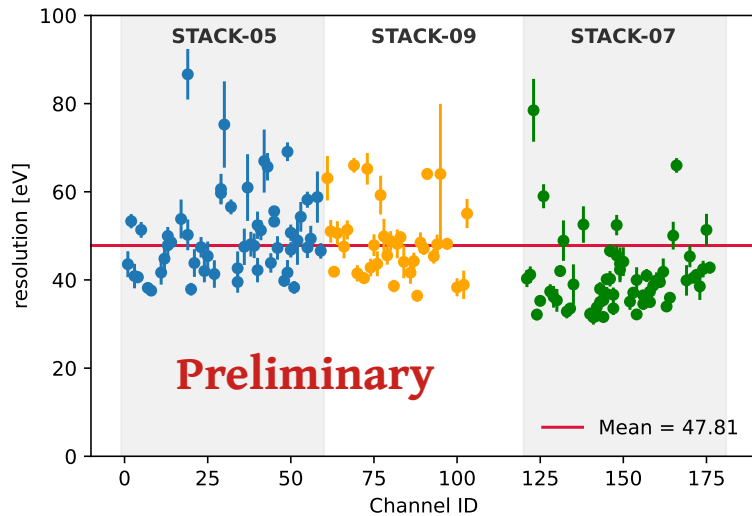
BULLKID-DM

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First operation of the demonstrator

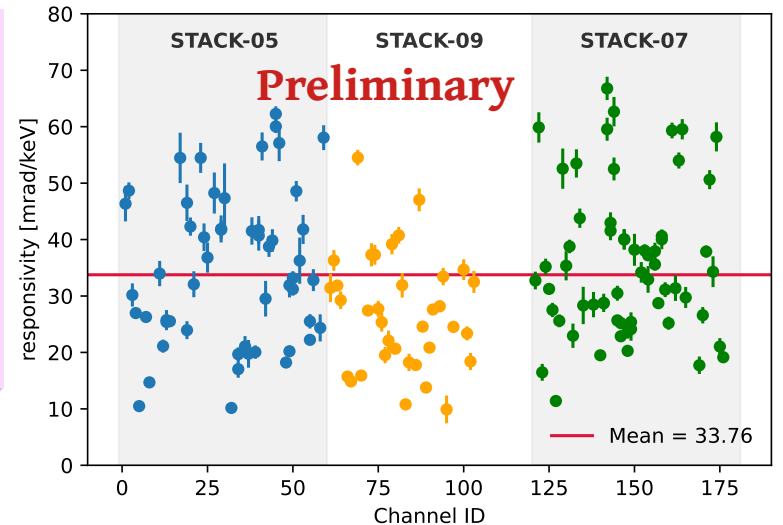


- 3-wafers stack
- 60 g of total active mass
- ^{241}Am calibration (photo-peak + Compton Edge)
- New DAQ electronics \rightarrow multiple array read at once
- Cryogenic copper shield
- First run above-ground @ Sapienza: July
- Second run underground @ LNGS: end of summer

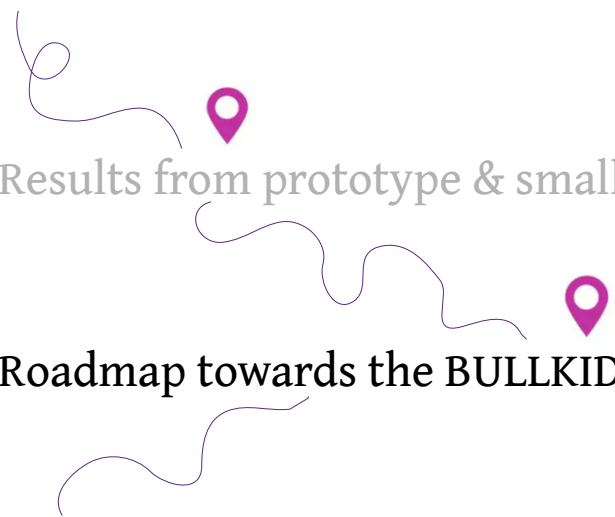


Mean resolution
@ 48 eV

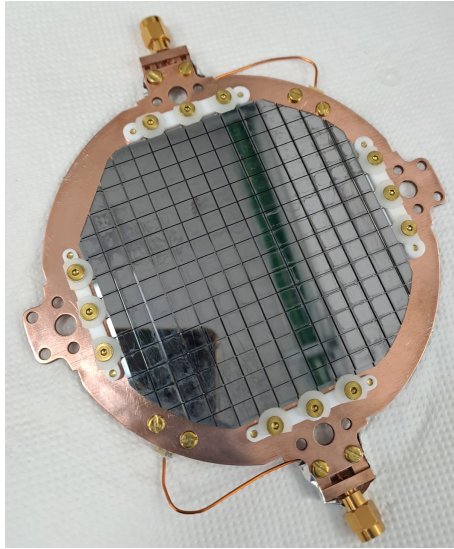
Mean responsivity
@ 34 mrad/keV



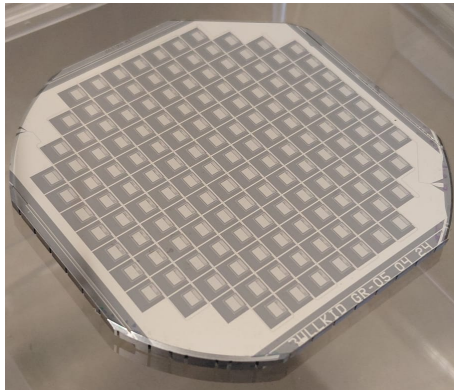
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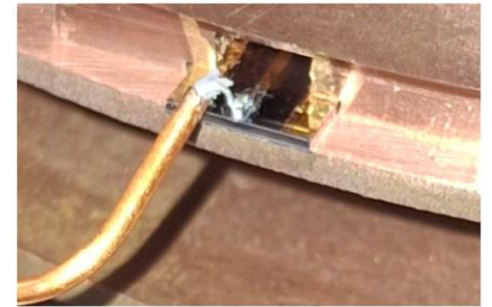
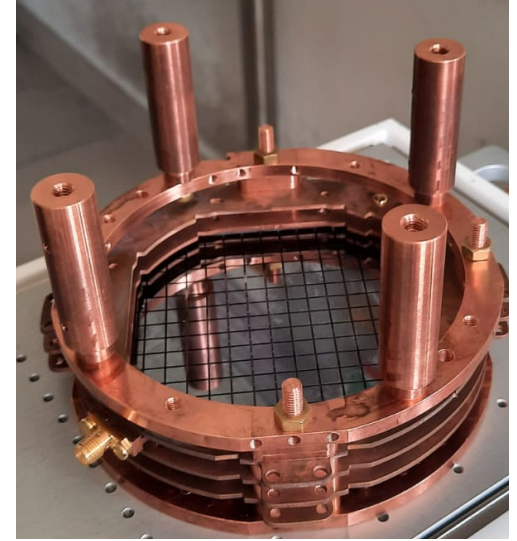
BULLKID-DM: make it larger



- 100 mm silicon wafer
- 50 g of active mass
- 145 dice with KIDs
- Copper holders

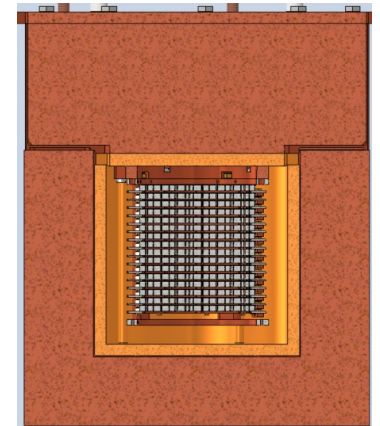
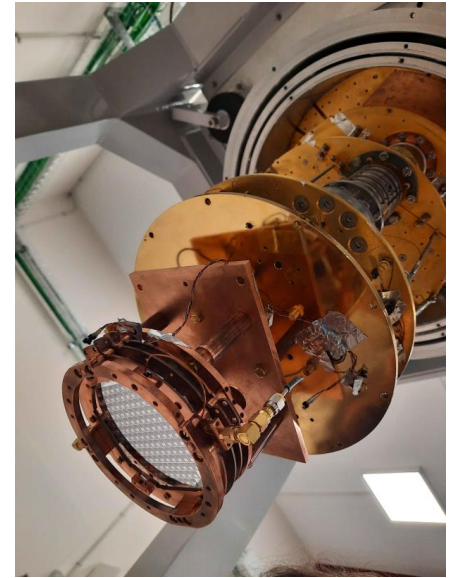
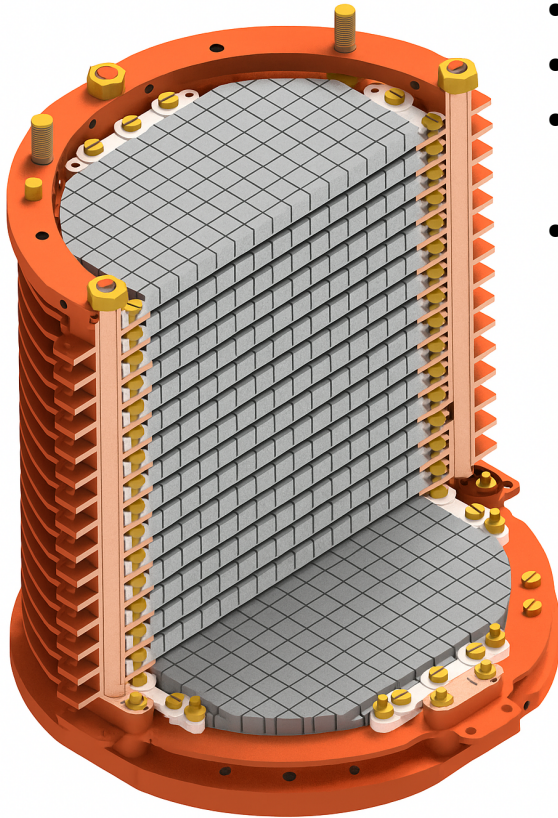


- New low-radioactivity launchers to replace PCB



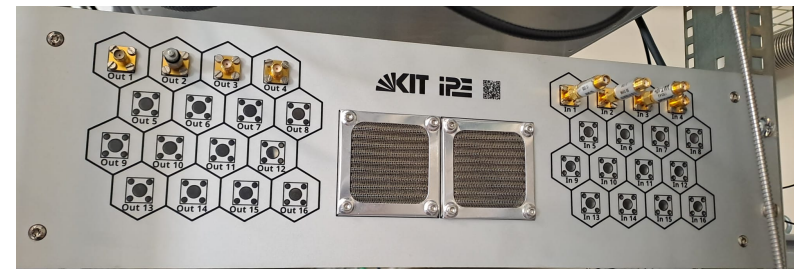
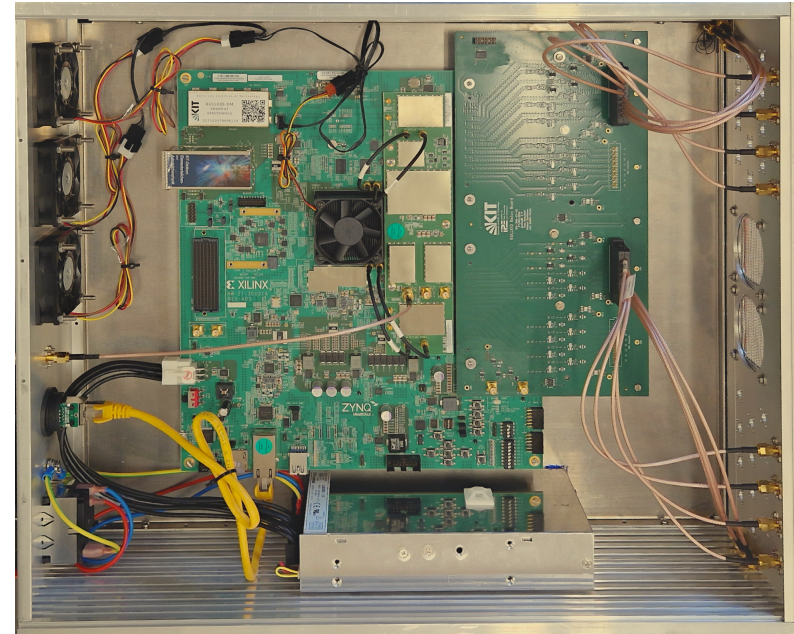
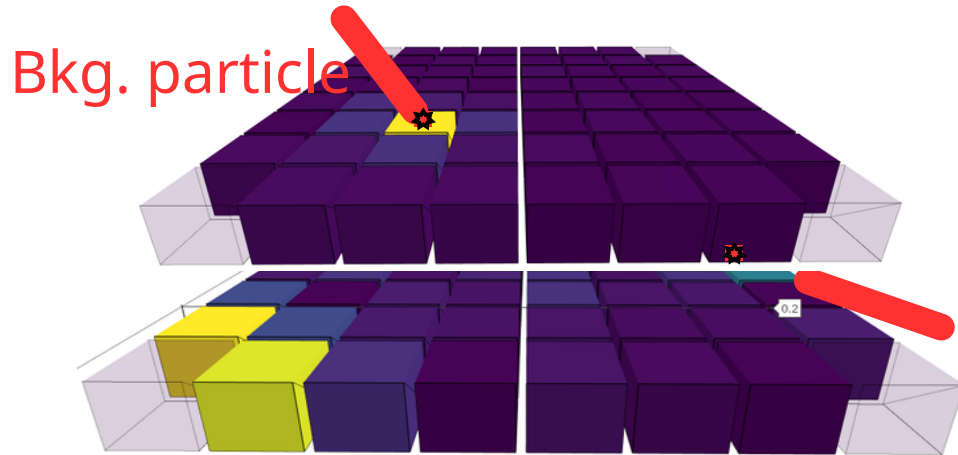
BULLKID-DM: make it taller

- 16 Si wafers
- 2320 channels
- 800 g of active target mass
- Cryogenic NOSV copper shield high-purity, oxygen-bearing copper alloy
- Movable Americium source for calibration



BULLKID-DM: the new electronics

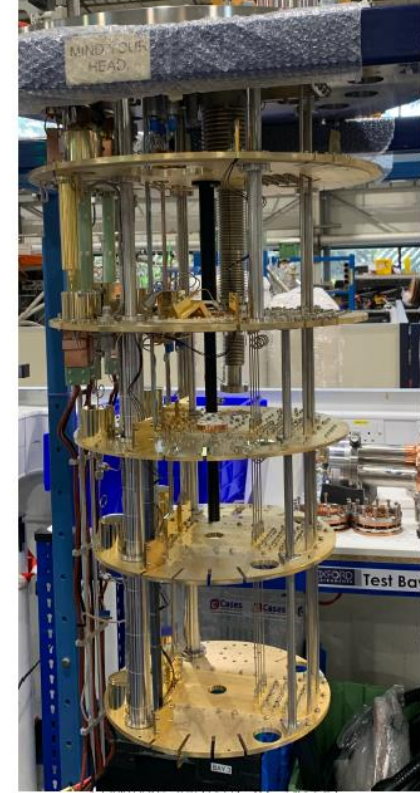
- AMD ZCU216 evaluation board
- Custom front-end & firmware
- 16 lines, each handling up to 145 channels
- First test done during test run



BULLKID-DM: where will it be operated?

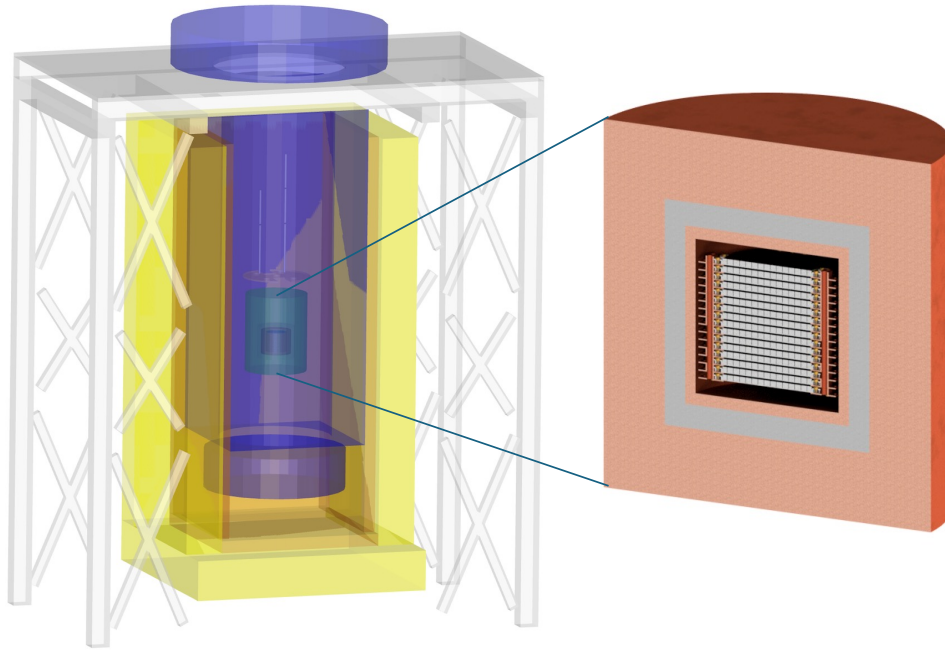


Cryoplatfrom, Hall B, LNGS – under construction



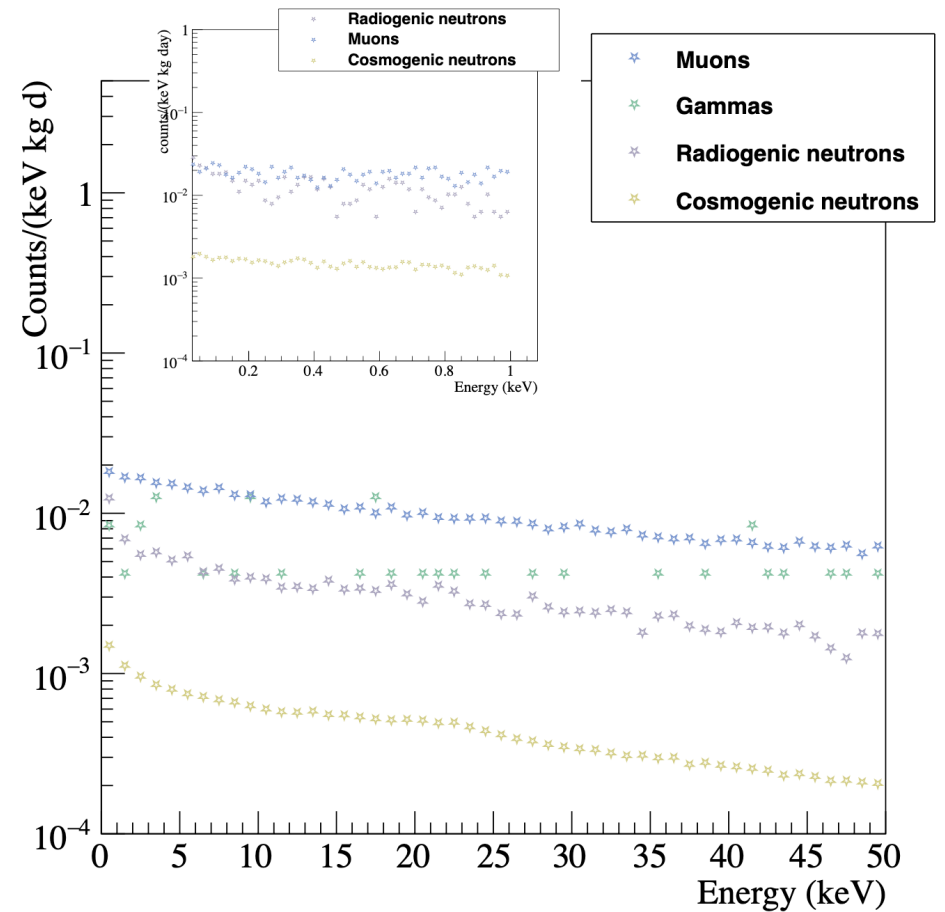
PROTEO-MX Oxford Cryostat

BULLKID-DM: shielding



Room temperature external shields: **lead**, **copper**, and **polyethylene**

Cryogenic shields: **copper**, B_4C and inner **copper**



BULLKID-DM: our collaboration



BULLKID-DM

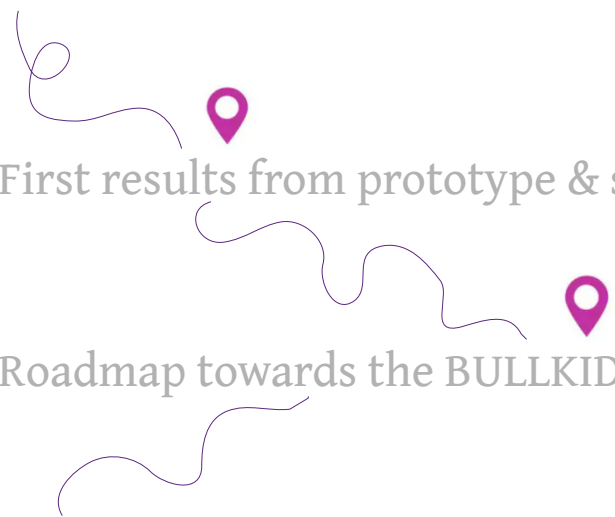
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Roma
Ferrara
LNGS
Pisa
Trento

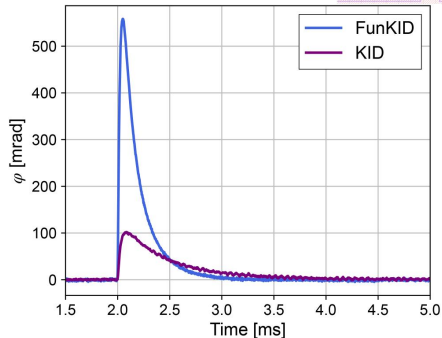
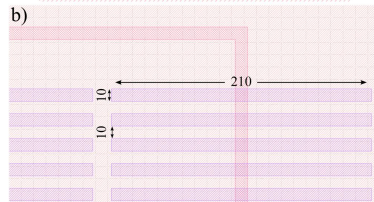
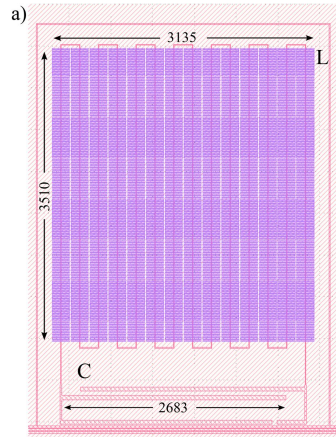
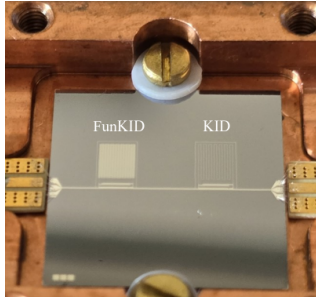


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- 

Improving sensor performances

[Pesce L. et al., Appl. Phys. Lett. 128, 163504 (2026)]



BULLKID-DM

$$\frac{d\Phi}{dE} \propto \frac{\eta}{V} \frac{\alpha Q}{\Delta_0^2}$$

Optimize phonon collection

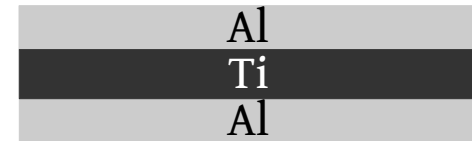
Increase kinetic inductance



FunKID: KID with phonon collectors (funnels)

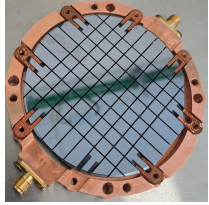
Al-Ti-Al: trilayer structure – higher responsivity

Challenge: increase phonon to quasi-particle conversion efficiency keeping volume small

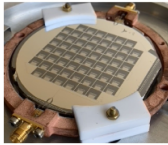


[Cardani L. et al., Supercond.Sci.Technol. 31 (2018) 7, 075002]

Conclusions



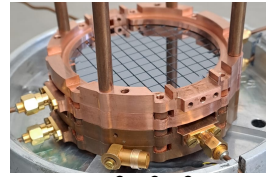
Working prototype



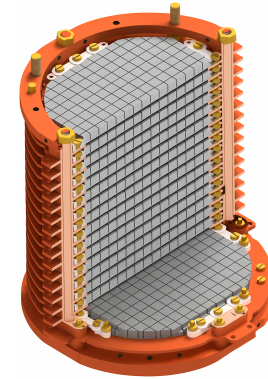
First demonstrator operation



Operation of demonstrator with shield



Acquisition of full demonstrator @ Sapienza, LNGS



BULLKID-DM

2023

2024

2025

2026

2027

**THANKS FOR YOUR
ATTENTION!**

*This work was partially supported by the European Research Council, through the Consolidator Grant DANAe, no. 101087663

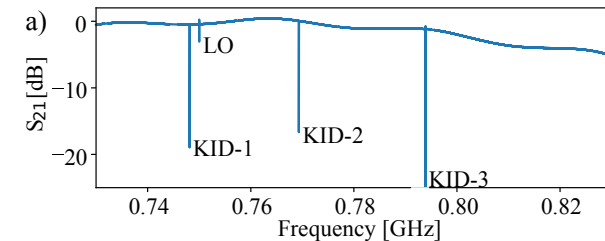
BACKUP

KIDs on Germanium substrate

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

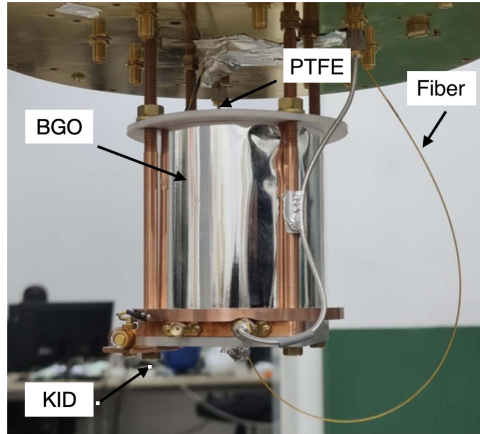
$$\sigma_{CE\nu NS} \propto G_F^2 [N - Z \cdot (1 - 4\sin^2\theta_\omega)]^2 E_\nu^2$$

- $(N_{Ge}/N_{Si})^2 \simeq 9 \rightarrow$ Ge better suited for CEvNS detection
- Phonon-sensing performance similar to Si
- BULLKID-like germanium wafer in preparation



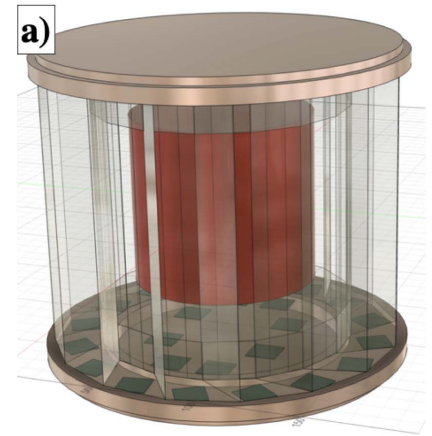
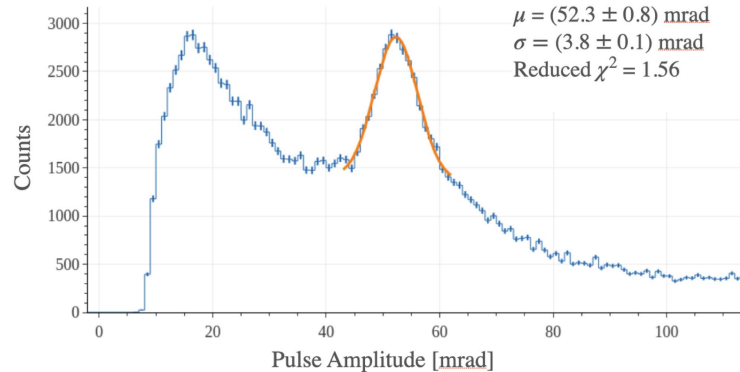
[Delicato D. et al, Appl. Phys. Lett. 126, 153502 (2025)]

Development of cryogenic veto



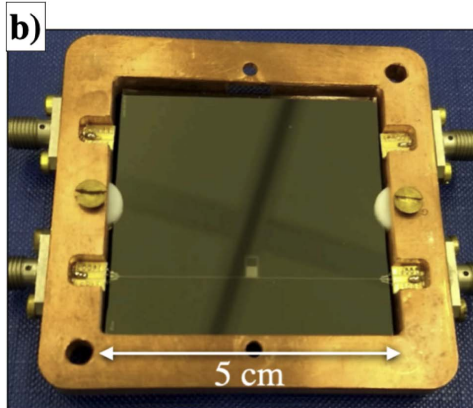
Goal: reduce neutron and γ background

Energy spectrum of ^{137}Cs source with Bismuth-Germanate (BGO) crystal



In BULLKID-DM: scintillating crystal tiles surrounding the stack

Gadolinium-Aluminum-Gallium-Garnet (GAGG) and Gadolinium-Oxyorthosilicate (GSO) under investigation



KID-based light detector coupled to crystal

[Lari T. et al., IEEE Transactions on Applied Superconductivity, vol. 36, no. 6, pp. 1-7, Sept. 2026]

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KID responsivity

$$\alpha = \frac{L_k}{L_{tot}}$$

Quality factor

$$\frac{d\Phi}{dE} = \eta \frac{\alpha S_2(\omega, T) Q}{N_0 V \Delta_0^2}$$

Energy \rightarrow quasi-particle
conversion efficiency

Single spin
density of states
@ Fermi level

Superconducting gap

Resonator volume

KID readout

Complex readout
signal

Quality factor

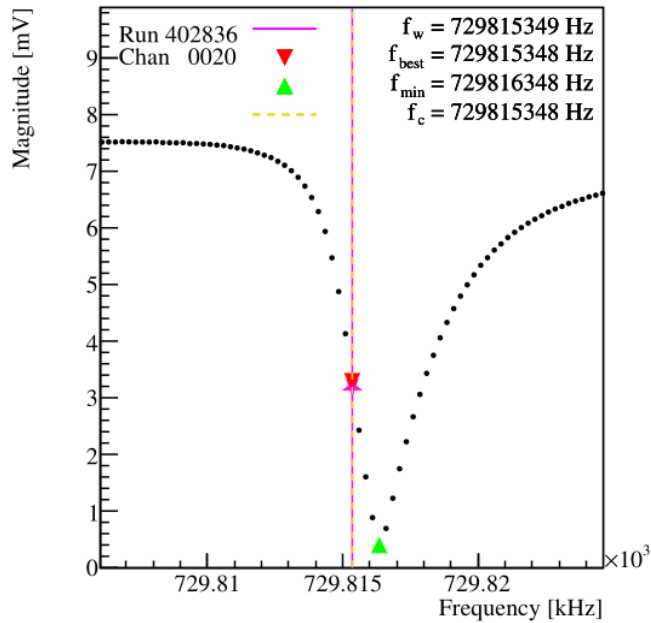
$$Q^{-1} = (Q_c^{-1} + Q_i^{-1})^{-1}$$

$$S_{21}(f) = 1 - \frac{Q}{Q_c} \frac{1}{1 + 2jQx}$$

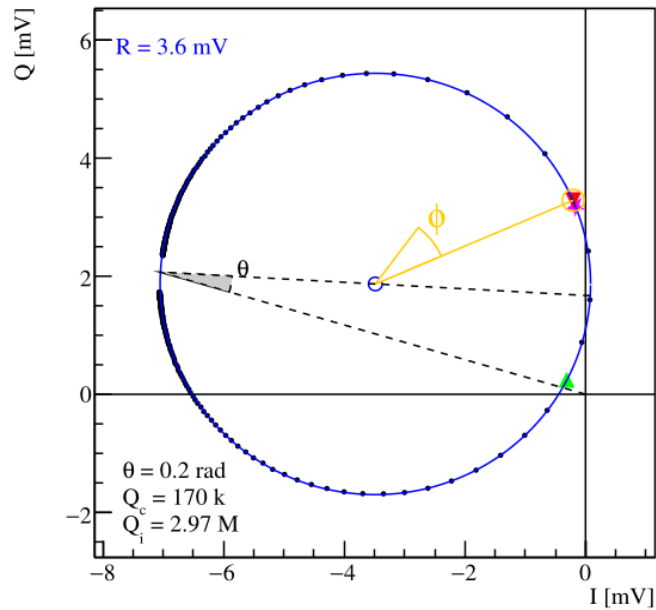
Detuning

$$x = \frac{f - f_0}{f_0}$$

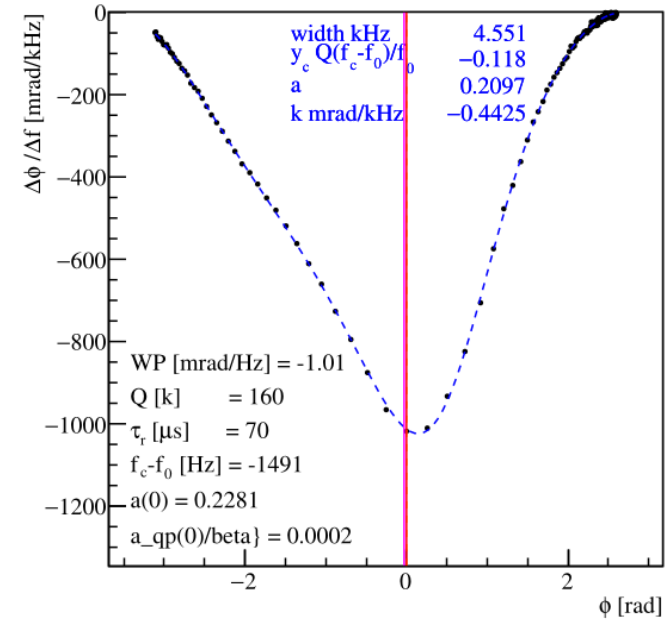
KID readout



Amplitude @ resonant frequency

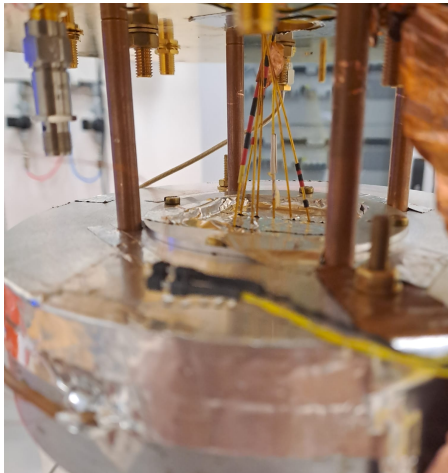
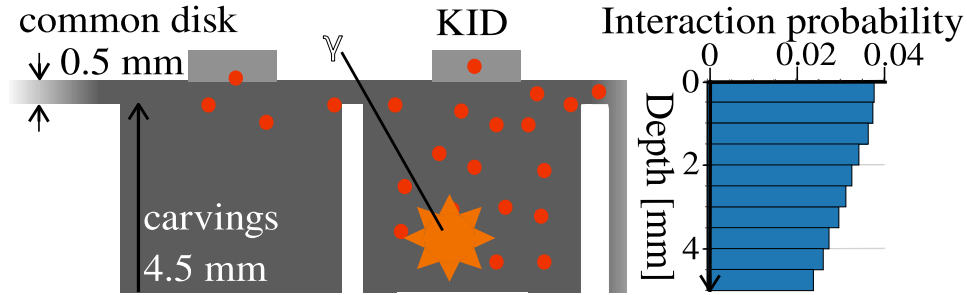


Resonant circle in the IQ plane



Fractional phase shift in frequency

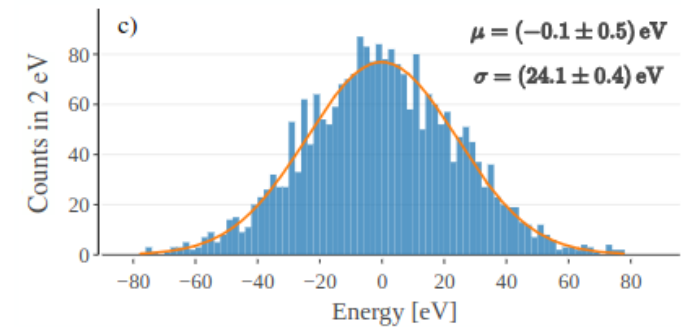
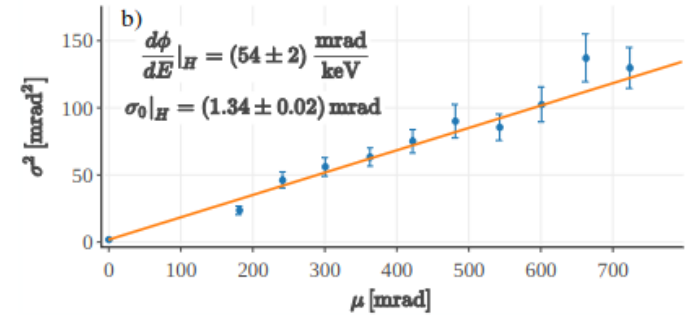
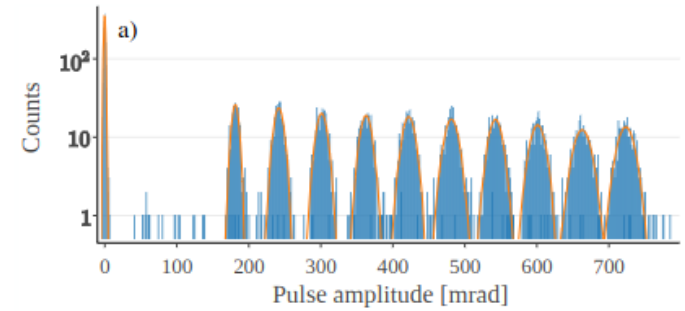
LED calibration



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

resolution

responsivity



Kinetic Inductance

Superconductor below critical temperature \longrightarrow Unpaired electrons (quasi-particles) +
Cooper pairs (binding energy ~ 0.4 meV in Al)

Surface resistance

Surface reactance

$$Z_s = R_s + j\omega L_s$$

$$Z_s = \frac{\omega^2 L_k^2}{R_{qp}} + j\omega(L_k + L_M)$$

Kinetic inductance depends on the number of Cooper pairs n_s

$$L_k = \frac{m_e^2}{tn_s e^2}$$

Americium calibration

