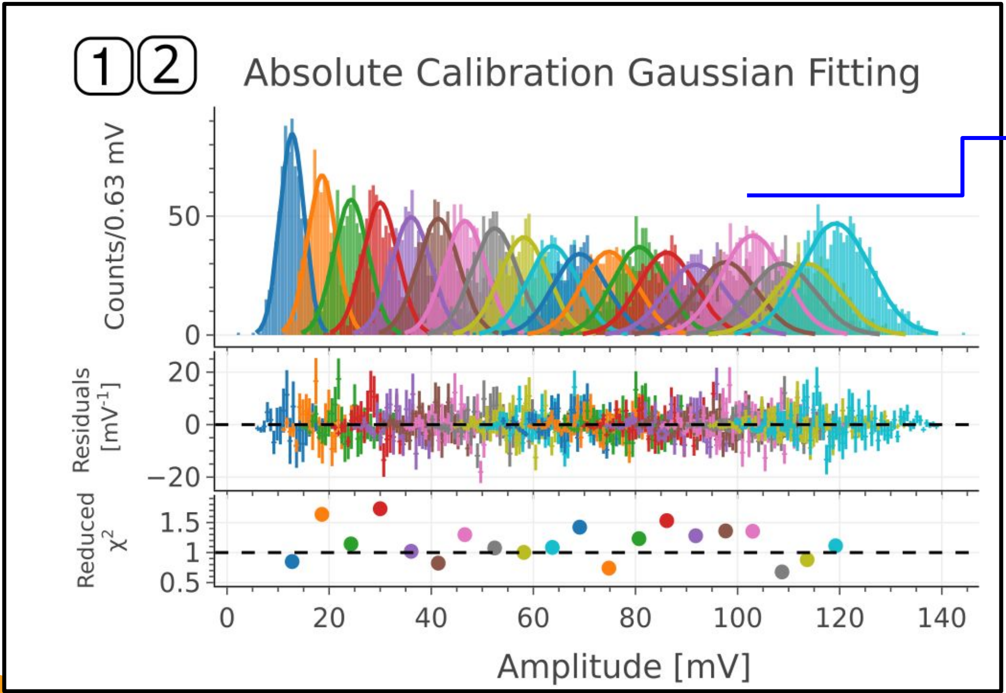
Energy calibration with X-rays

Matteo Folcarelli
BULLKID-DM - Collaboration meeting in Ferrara
01/07/2025

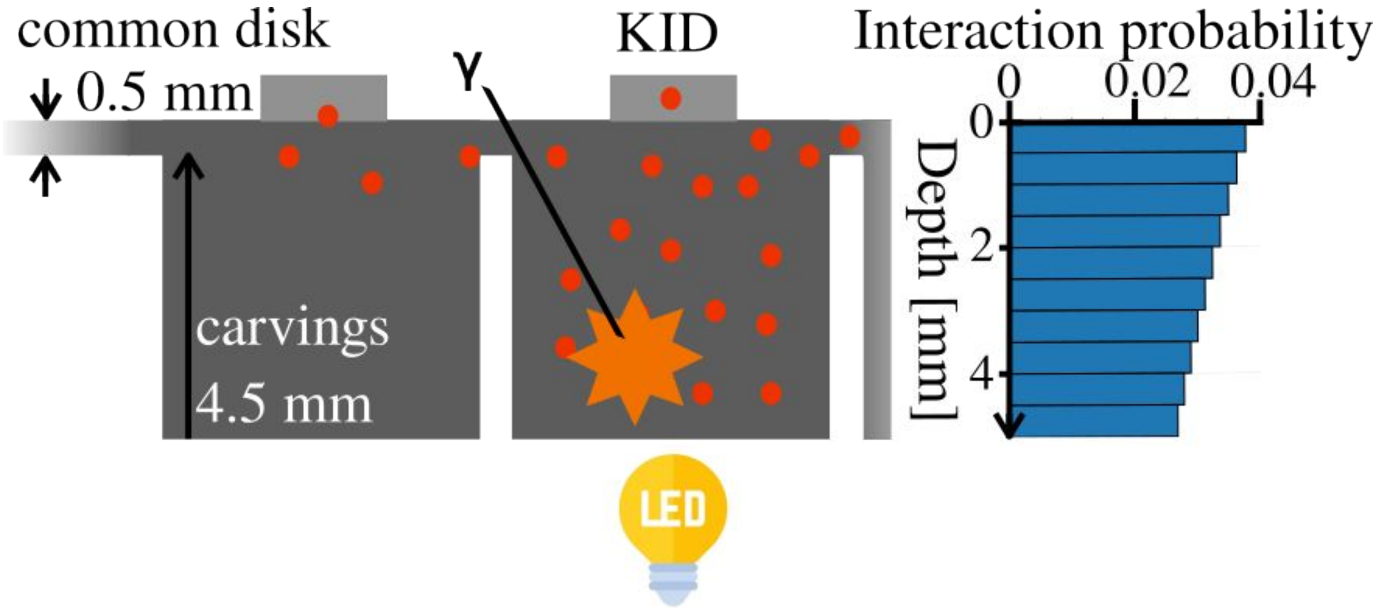
Outline of the presentation



During this year we have performed different times the **validation** of
the standard optical calibration
with particles peaks

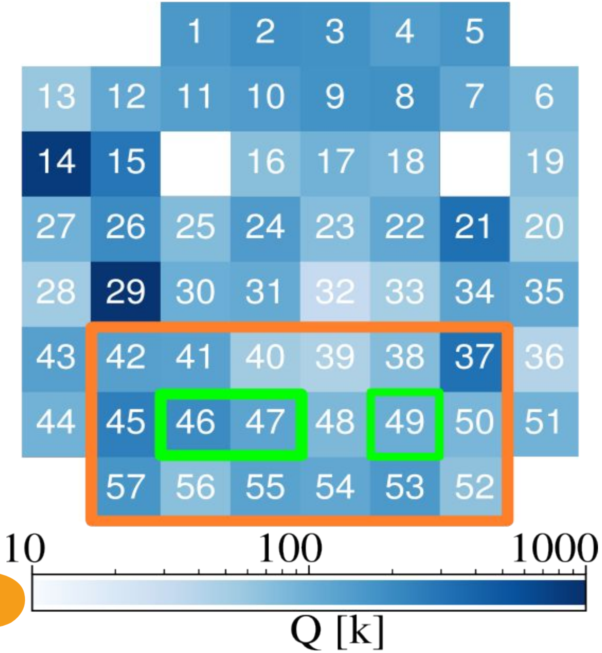
- Through the 59.5 keV gammas of ^{241}Am (energy calibration with bulk events)
  - paper drafted
- Through the X-ray peaks of Pb (surface background with mild shield)

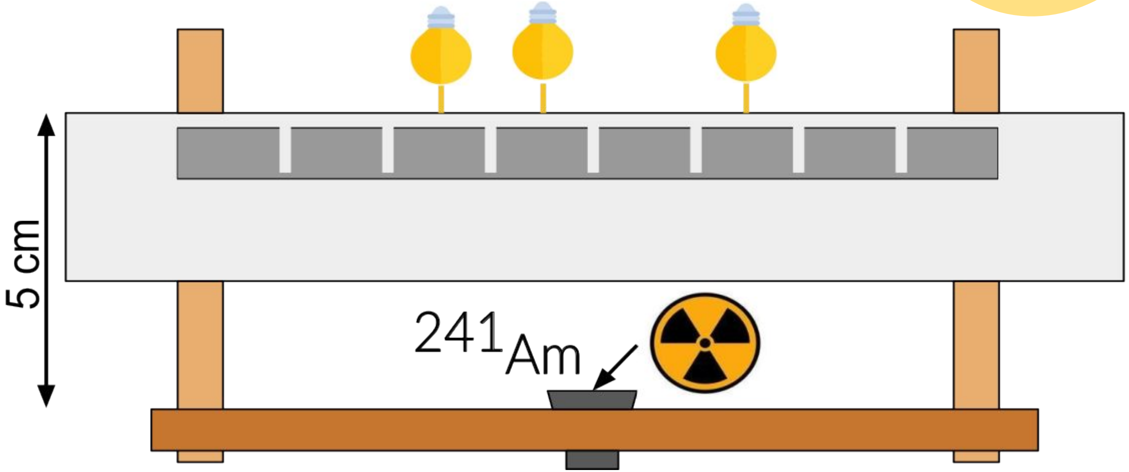
Energy calibration of bulk events with ^{241}Am



The 59.5 keV of ^{241}Am are enough energetic to penetrate the entire crystal volume (λ= 13 mm), in contrast to optical photons, which are fully absorbed at the surface (λ=82 nm)

Data Acquisition



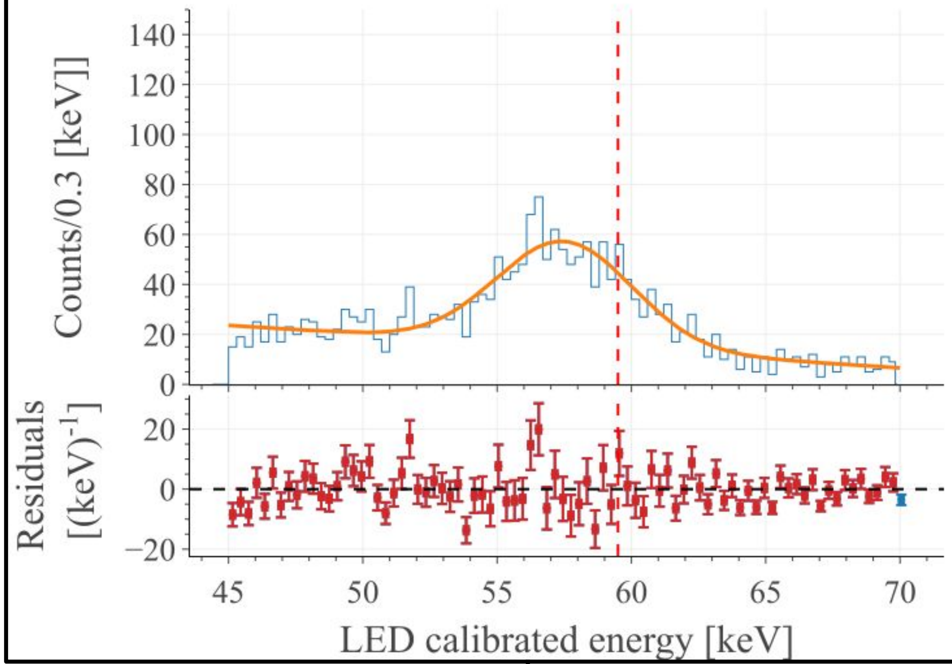


Acquisition of three main KIDs (46,47,49) in coincidence with their neighbours for a total of 28 h. The americium source is located inside the cryostat outside the aluminum pot

Energy spectra

KID	Mean [keV]	σ [keV]	Mean - nominal
46	56.2 ± 0.1	2.2 ± 0.1	-6 %
47	55.5 ± 0.2	2.4 ± 0.2	-7 %
49	57.2 ± 0.2	2.9 ± 0.2	-4 %

Energy spectrum of KID 49 in the energy range [45 , 70] keV calibrated with optical calibration. The americium peak is fitted with a gaussian model and the red-dashed vertical line represent the 59.5 keV nominal energy



Neighbour analysis for bulk events

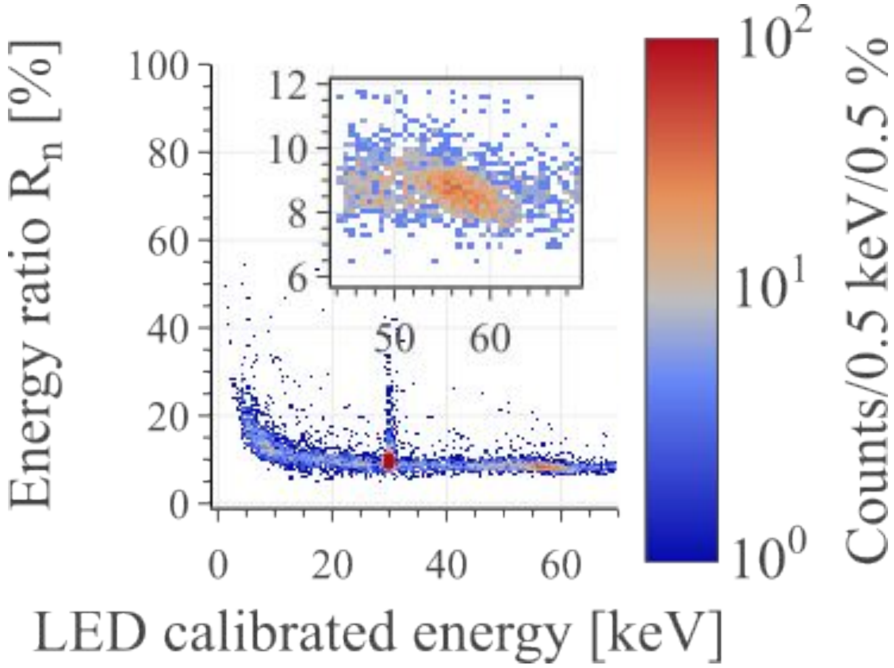
Effects related to interactions in the bulk position of americium can be investigated by studying the partition energy between main and neighbouring dice

Calibrated phase:

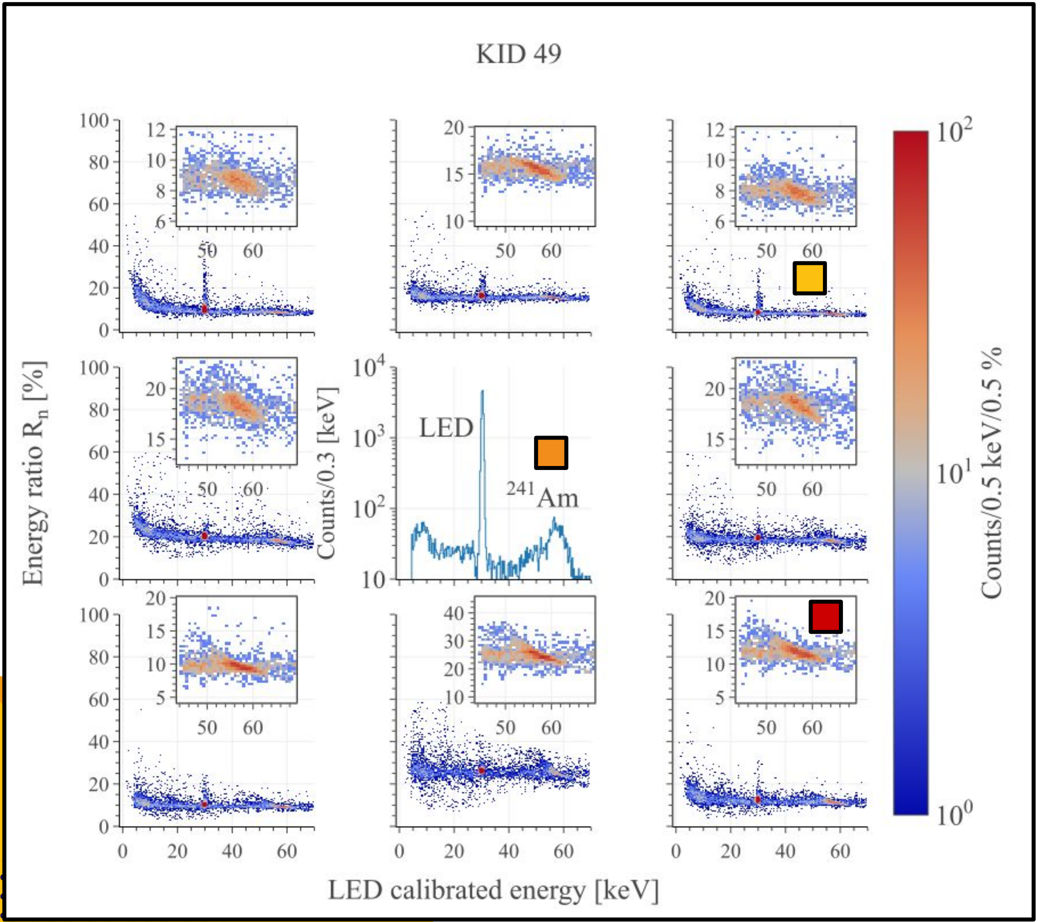
$$\Delta\Phi \propto Q \cdot \Delta E$$

Energy ratio:

$$R_n = \frac{A_n}{A} \cdot \frac{Q}{Q_n}$$



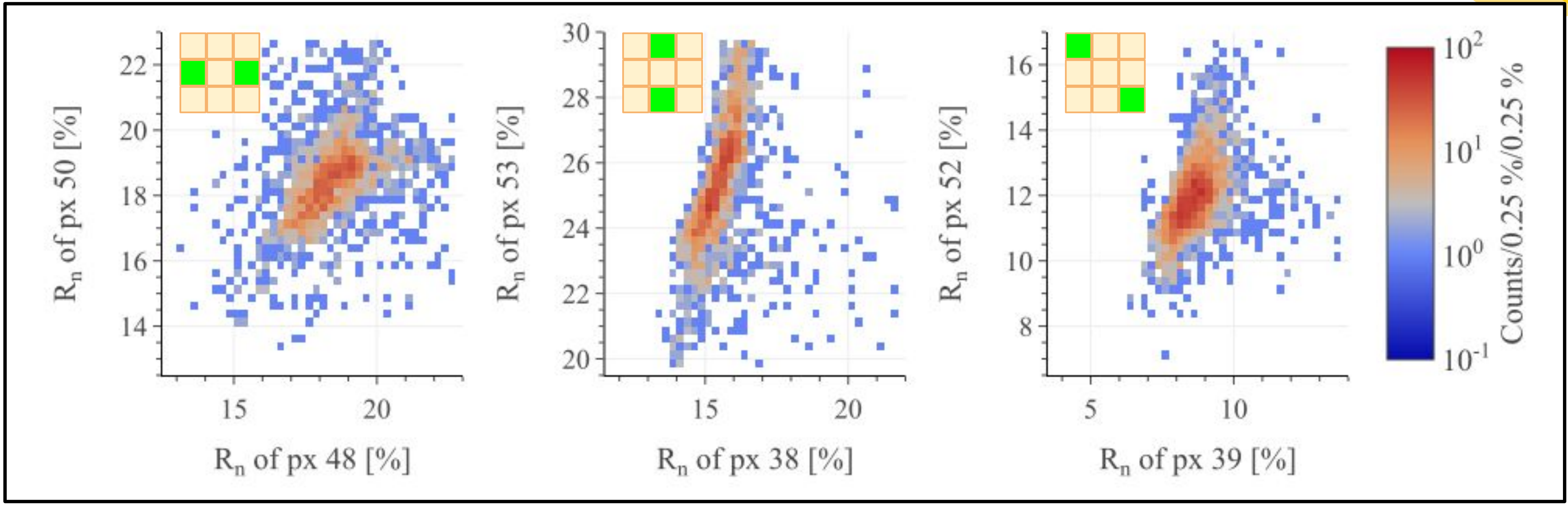
Neighbour analysis for bulk events



- Energy ratio for the neighboring dice of KID 49 as a function of the LED calibration energy in the main die.
- Energy spectrum of KID 49. Both the peaks of control LED and americium are clearly visible
- The insets are a zoom in the americium energy range [45,70] keV

Same energy ratio between LED and bulk events

Neighbour analysis for bulk events



Energy ratio between three couples of neighbors of KID 49: left/right, top/bottom, up-right/down-left corners. Only americium events are considered. We observe a positive correlation in all the three cases

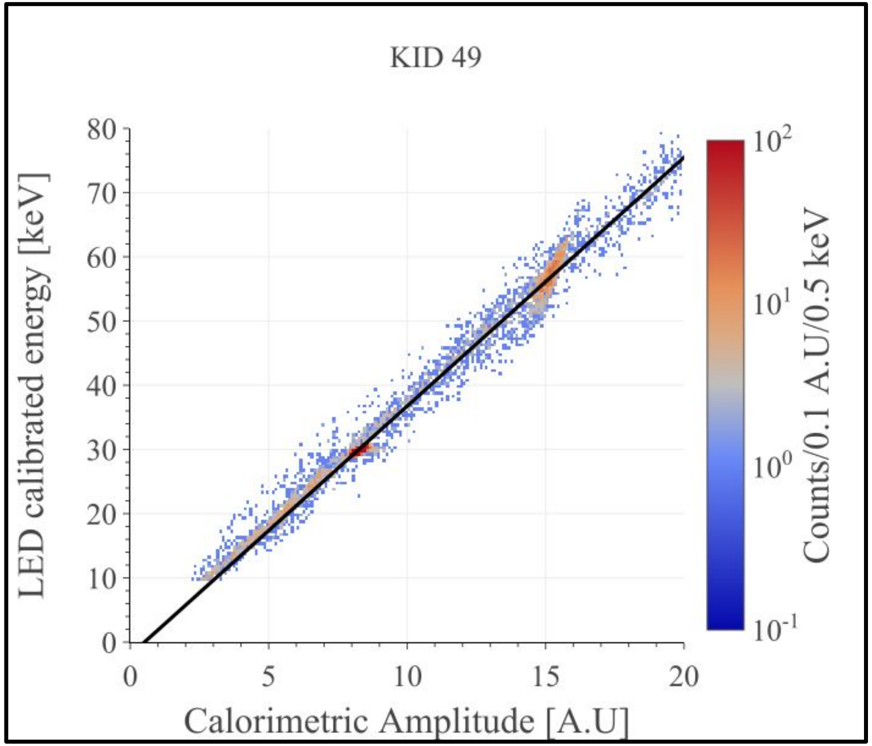
Calorimetric amplitude

Following the results just exposed, **the sum of the amplitudes of all the KIDs**, corrected for the quality factor, should be able to compensate the anti-correlation and **improve the resolution of ^{241}Am events**

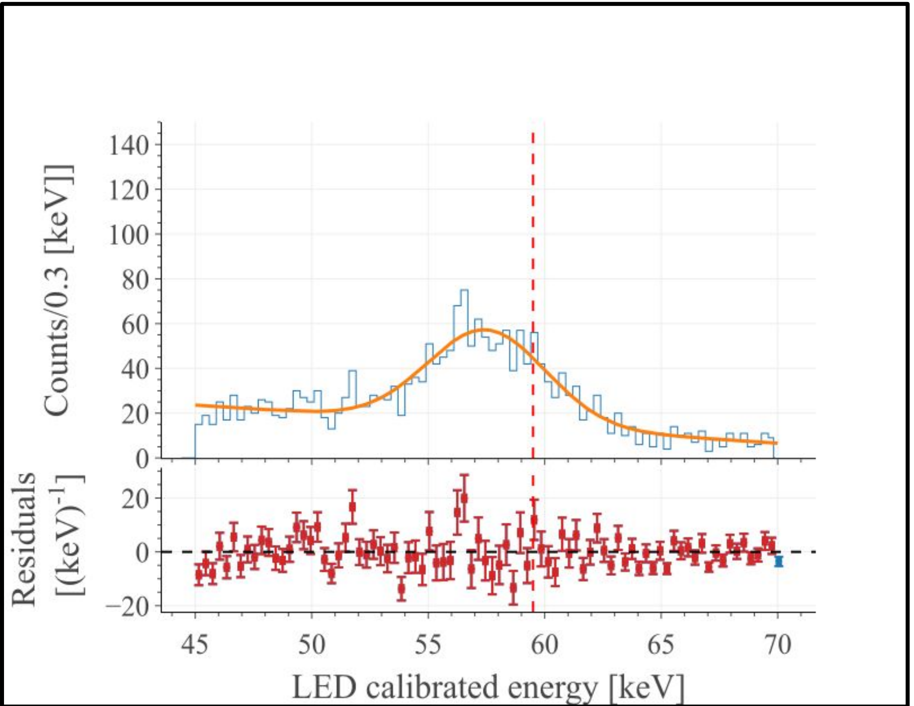
Calorimetric amplitude:

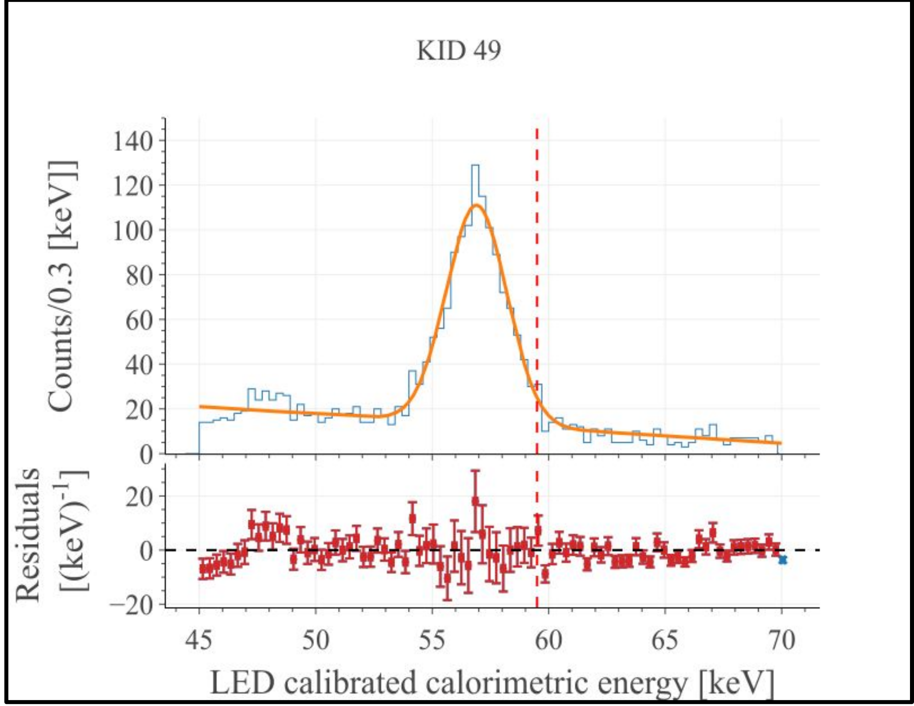
$$A_{cal} = A_c/Q_c + \sum_{neigh} A_n/Q_n$$

The calorimetric amplitude is calibrated assuming a linear relation with the LED calibrated amplitude of the main die



Calorimetric energy spectra

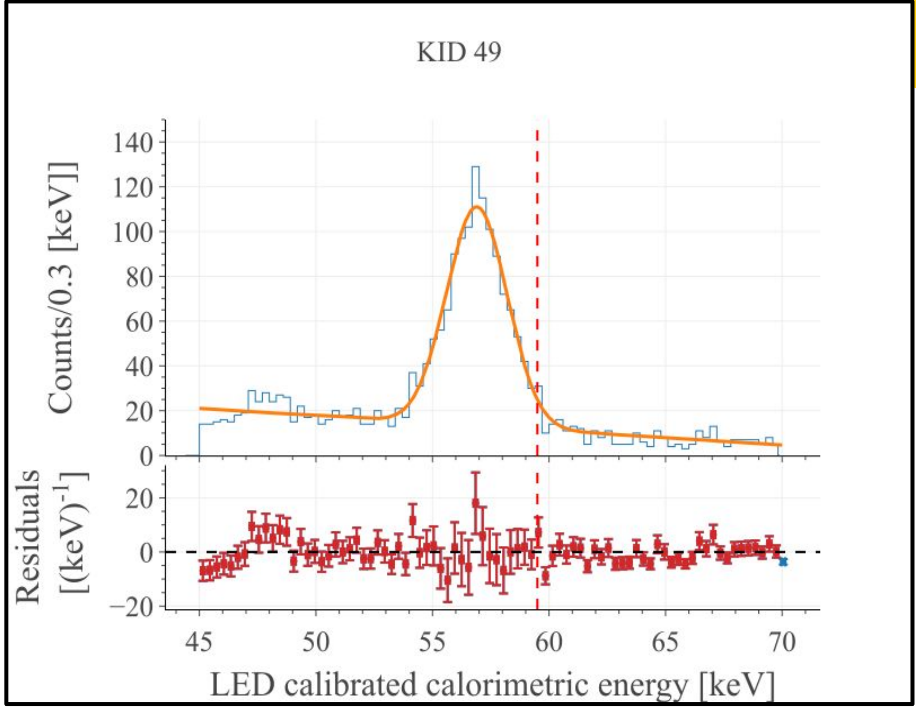




Comparison between the energy spectrum of KID 49 using the standard and the calorimetric LED calibrated energy

Calorimetric energy spectra

KID	Mean [keV]	σ [keV]	σ_{Cal} [keV]
46	56.2 ± 0.1	2.2 ± 0.1	1.06 ± 0.05
47	55.5 ± 0.2	2.4 ± 0.2	1.07 ± 0.05
49	57.2 ± 0.2	2.9 ± 0.2	1.34 ± 0.05



Comparison between the energy spectrum of KID 49 using the standard and the calorimetric LED calibrated energy

Conclusions and status of the paper

- Calibration of the bulk events induced by the 59.5 keV gamma rays of ^{241}Am
- Standard optical calibration validated with a deficit below 10%
- Energy resolution improved from 5 to 2% (σ) by summing the energies of neighbouring dice

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Energy calibration of bulk events in the BULLKID detector

A. Acevedo-Rentería[5], L. E. Ardila-Perez[9], P. Azzurri[4], L. Bandiera[6], M. Calvo[7], M. Cappelli[1,2], R. Caravita[10], F. Carillo[4], U. Chowdhury[7], A. Cruciani[2], A. D'Addabbo[8], M. De Luci[3,4], G. Del Castello[2], M. del Gallo Roccagiovine[1,2], D. Delicato[1,2,7], F. Ferraro[8], Matteo Folcarelli[a,1,2], S. Fu[8], R. Gartmann[9], M. Grassi[4], V. Guidi[6,11], T. Lari[3,4], L. Malagutti[6], A. Mazzolari[6,11], A. Monfardini[7], T. Muscheid[9], D. Nicolò[3,4], F. Paolucci[3,4], D. Pasciuto[2], L. Pesce[1,2], C. Puglia[4], D. Quaranta[1,2], C. M. A. Roda[3,4], S. Roddaro[3,4], M. Romagnoni[6], G. Signorelli[3,4], F. Simon[9], M. Tamisari[6,12], A. Tartari[4], E. Vázquez-Jáuregui[5], M. Vignati[1,2]

[1] Dipartimento di Fisica, Sapienza Università di Roma, P. le A. Moro 2, 00185 Roma, Italy
[2] INFN Sezione di Roma, P.le A. Moro 2, 00185 Roma, Italy
[3] Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[4] INFN Sezione di Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[5] Instituto de Física, Universidad Nacional Autónoma de México, A.P. 20-364, Ciudad de México 01000, México
[6] INFN Sezione di Ferrara, Via Saragat 1, 44122 Ferrara, Italy
[7] University Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France
[8] INFN Laboratori Nazionali del Gran Sasso, 67100 Assergi (AQ) - Italy
[9] Institute for Data Processing and Electronics, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1 76344, Eggenstein-Leopoldshafen - Germany
[10] INFN - TIFPA, Via Sommarive 14, 38123 Povo (Trento) Italy
[11] Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Via Saragat 1, 44100 Ferrara - Italy
[12] Dipartimento di Neuroscienze e Riabilitazione, Università di Ferrara, Via Luigi Borsari 46, 44121 Ferrara - Italy

June 15, 2025

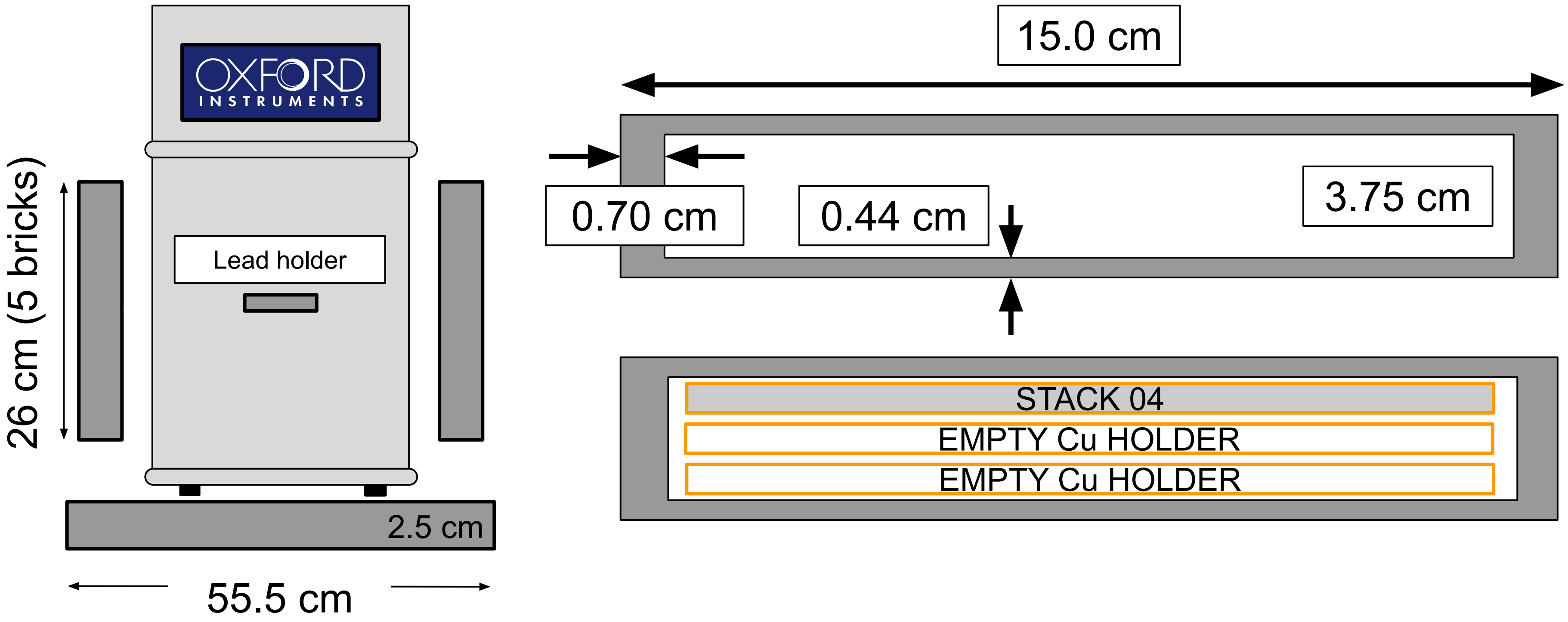
Abstract BULLKID is a cryogenic, solid-state detector designed for direct searches of particle Dark Matter candidates, with mass ≤ 1 GeV/c^2, and coherent neutrino-nucleus scattering. It is based on an array of dice carved in 5 mm thick crystals, sensed by phonon mediated Kinetic Inductance Detectors. In previous works, the array was calibrated with bursts of optical photons, which are absorbed in the first micrometer of the dice and behave as surface events. In this work, we present the reconstruction of bulk events through the 59.5 keV X-ray generated by an ^{241}Am source, which emulates more closely the interaction of Dark Matter and neutrinos. The peak resolution is 4.5% and its mean is shifted by less than −10 % with respect to the optical calibration. The resolution is further improved by a factor ~ 2 combining the signal from neighbors dice. These results confirm the performance of the detector in view of the physics goals of the BULLKID-DM experiment.

1 Introduction

BULLKID [2, 5, 7] is a monolithic array of dice of $5.4 \times 5.4 \times 5.0$ mm^3 carved in crystal (silicon or germanium) and sensed by phonon-mediated cryogenic Kinetic Inductance Detectors (KIDs). It is designed for the detection of sub-keV energy depositions from particle interactions within the crystal, making it suitable for direct Dark-Matter (DM) searches and coherent elastic neutrino-nucleus scattering (CEνNS) experiments. One of the main challenges in this low-energy regime is the energy calibration and, so far, the BULLKID-DM collaboration has adopted a method based on bursts of 400 nm optical photons [3, 8]. These photons produce electron recoils near the surface of the crystal, unlike DM or CEνNS interactions which produce nuclear recoils uniformly throughout the crystal volume (bulk events). Validating this optical calibration method, using particle interactions, is thus of critical importance to confirm the detector's performance under realistic conditions. In this work, we present such a validation by reconstructing the 59.5 keV X-ray peak from a radioactive ^{241}Am source using a silicon BULLKID. These X-rays, see (Fig. 1), are sufficiently energetic to penetrate the entire crystal volume (λ_{abs} = 13 mm) [9], in contrast to optical photons, which are fully absorbed at the surface (λ_{abs} ~ 82 nm) [6]. This measurement both confirms the reliability of the optical calibration technique and allows the investigation for different responses between bulk and surface events.

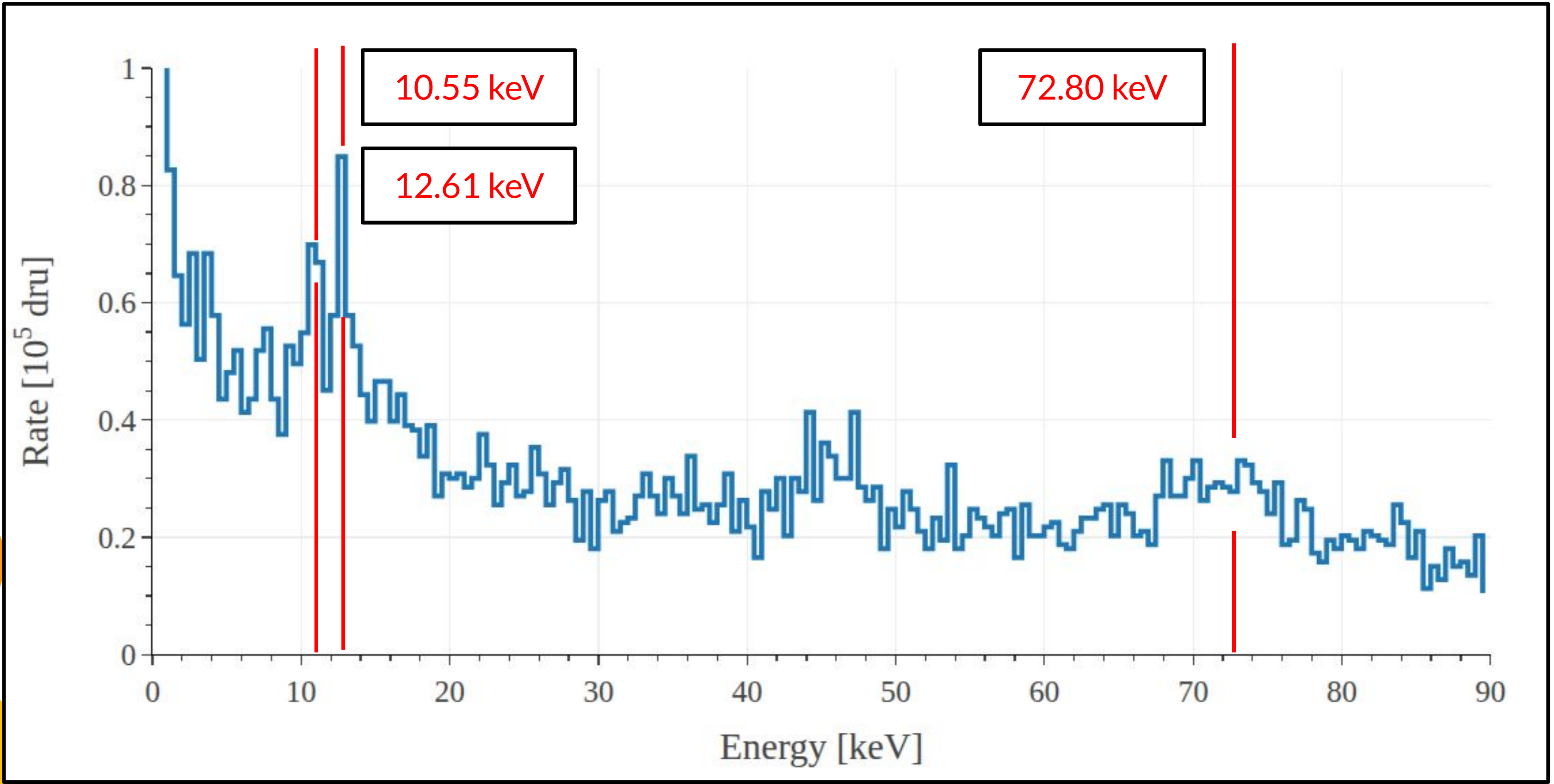
[a] e-mail: matteo.folcarelli@uniroma1.it (corresponding author)

Background with mild shield



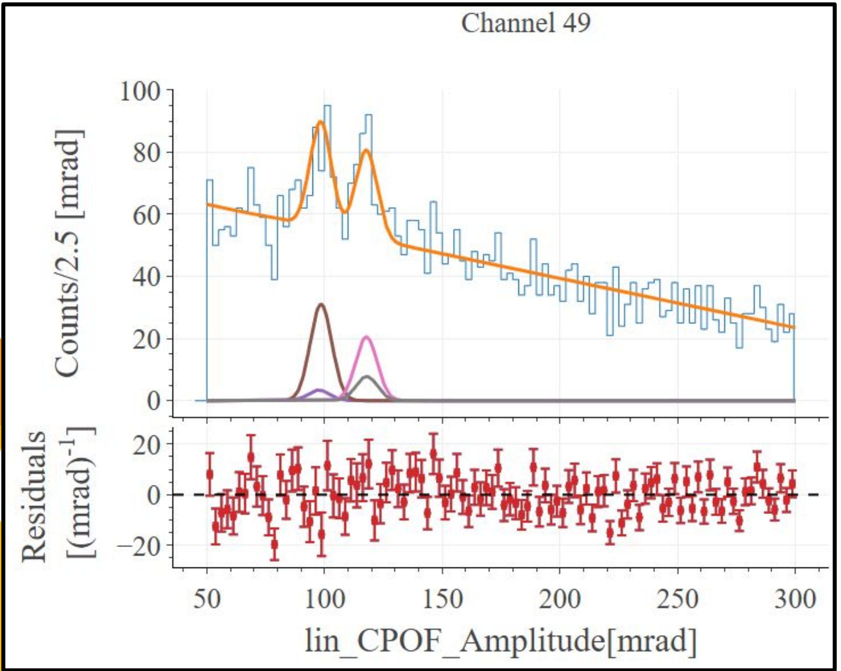
The setup is based on a single wafer (STACK-04) in a lead holder for the suppression of natural radioactivity

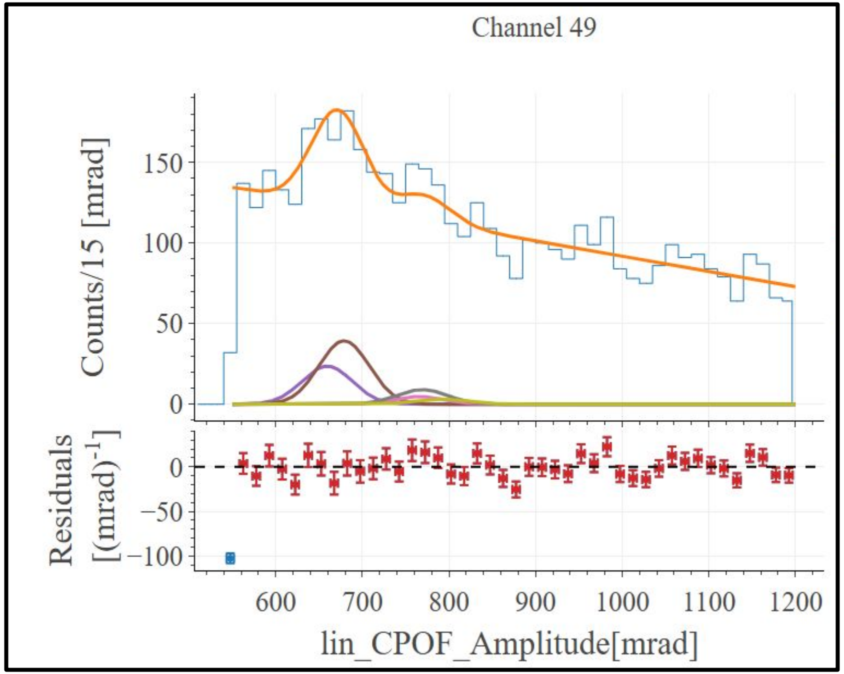
Energy calibration with Pb X-ray peaks



Fitting strategy

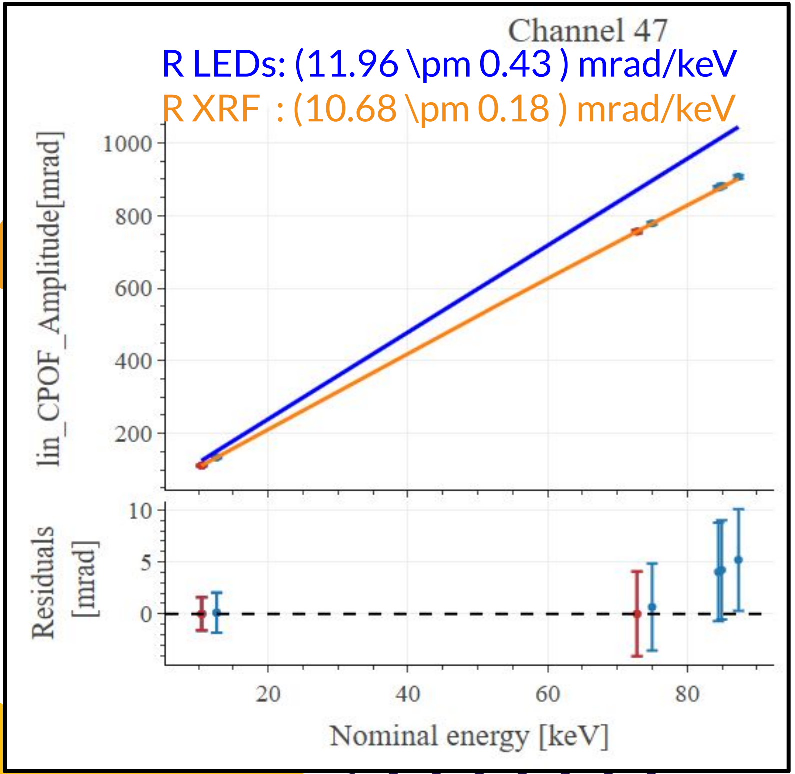
Fitted the peaks in two intervals in the uncalibrated [mrad] amplitude. Assumed a **linearly decreasing** background and **fixed the relative position and intensity of the peaks**.
In each interval, assumed **the same sigma** for all the peaks.

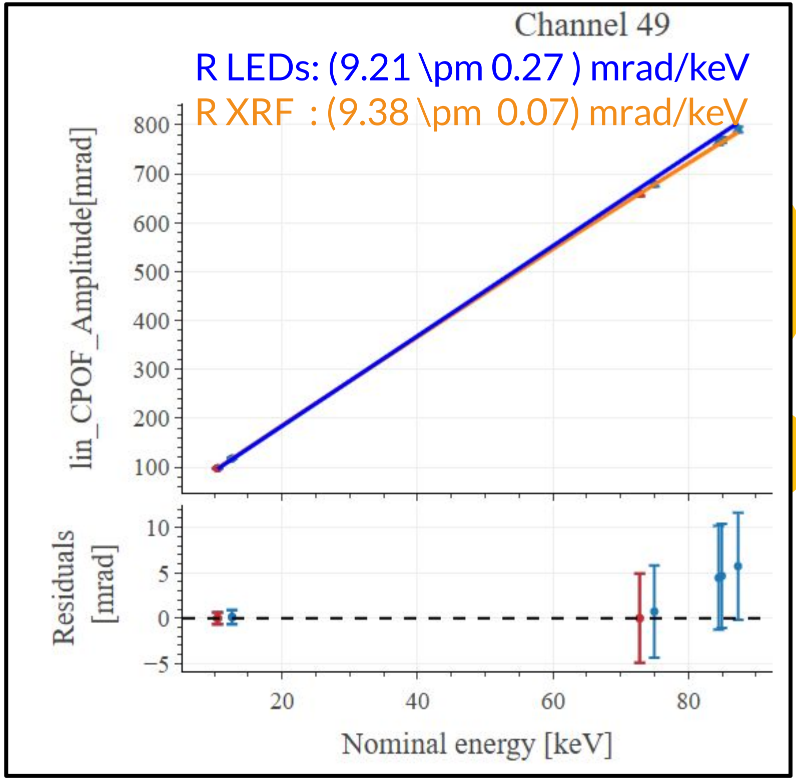




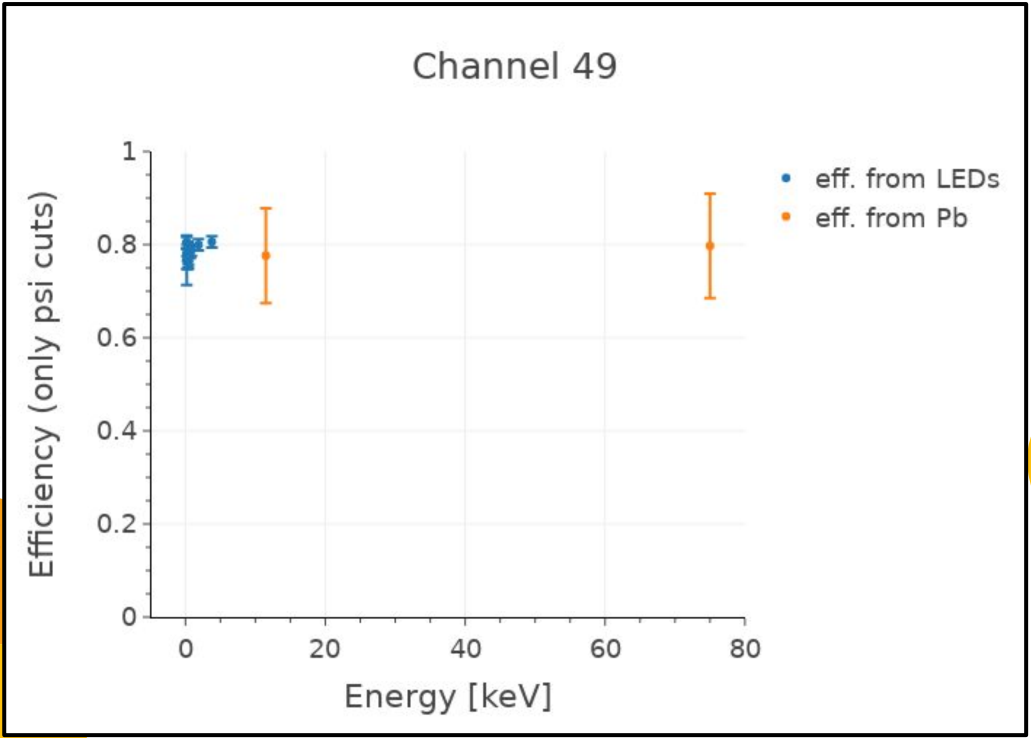
Calibration function

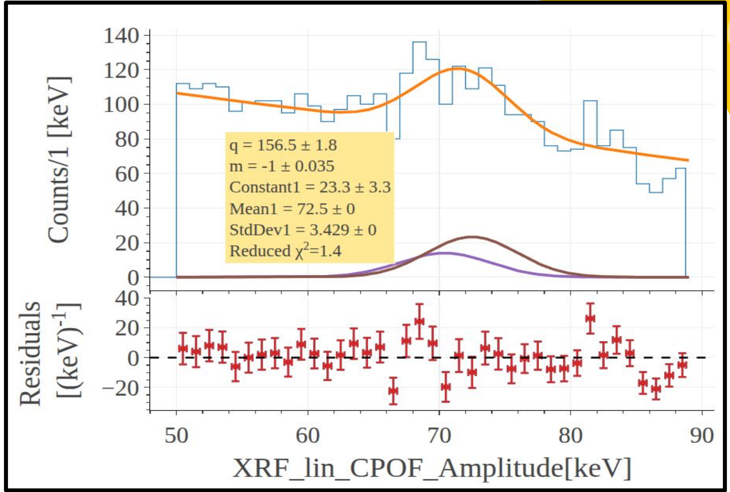
From the fits we can evaluate the **responsivity** and the non-linearity coefficient

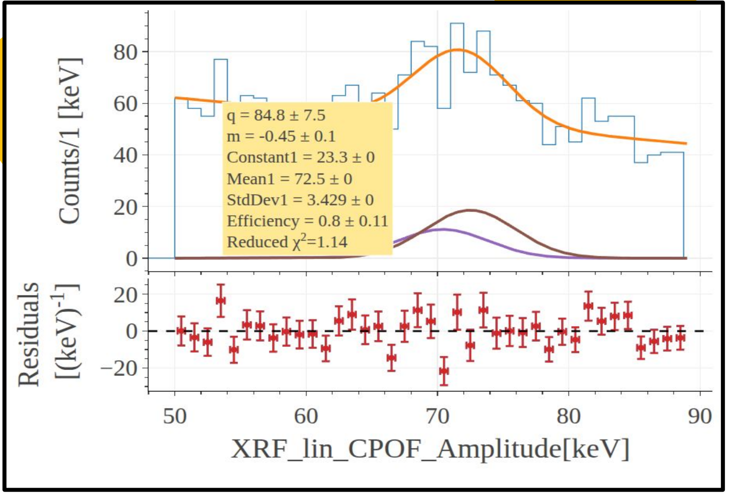




Cut's efficiency evaluation

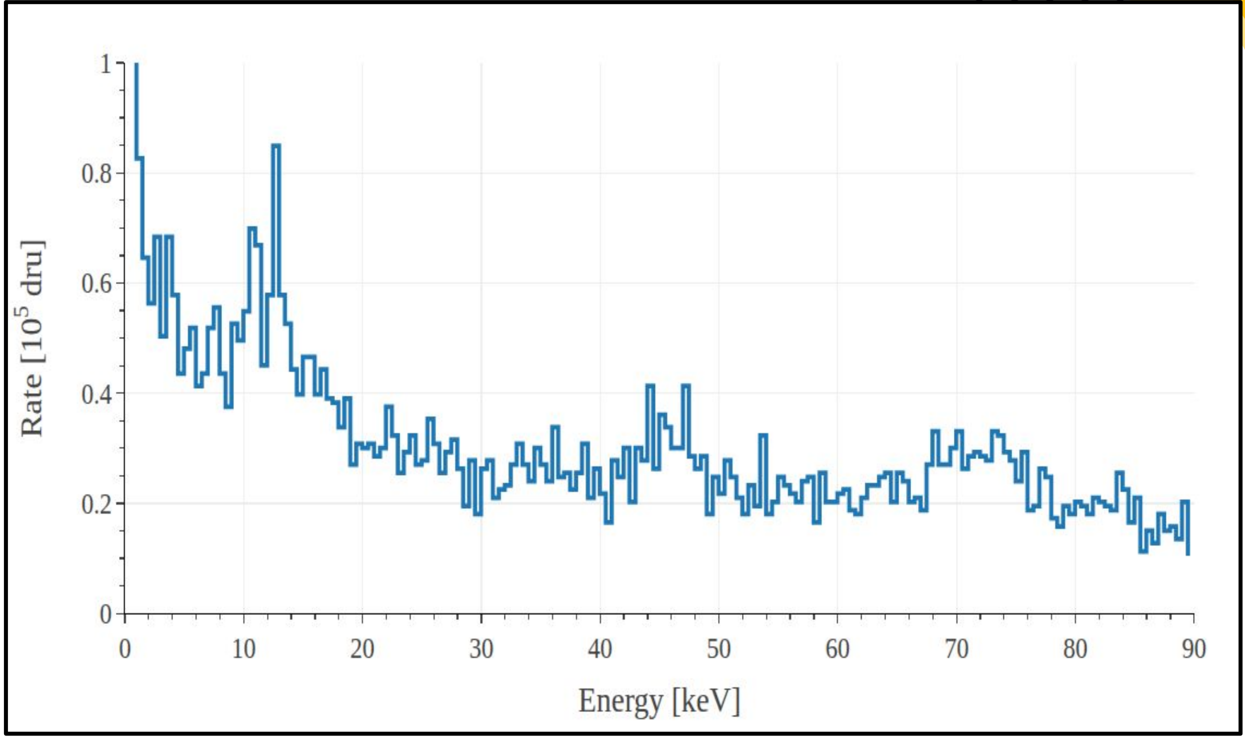






Conclusions

- The presence of the X-ray peaks of Pb allowed the energy calibration during the last acquisition with mild shield.
- Discrepancy with optical calibration of -10%, confirming the results of americium analysis
- Evaluation of the cut’s efficiency at high energy



Thank you for the attention

Matteo Folcarelli
BULLKID-DM - Collaboration meeting in Ferrara
01/07/2025