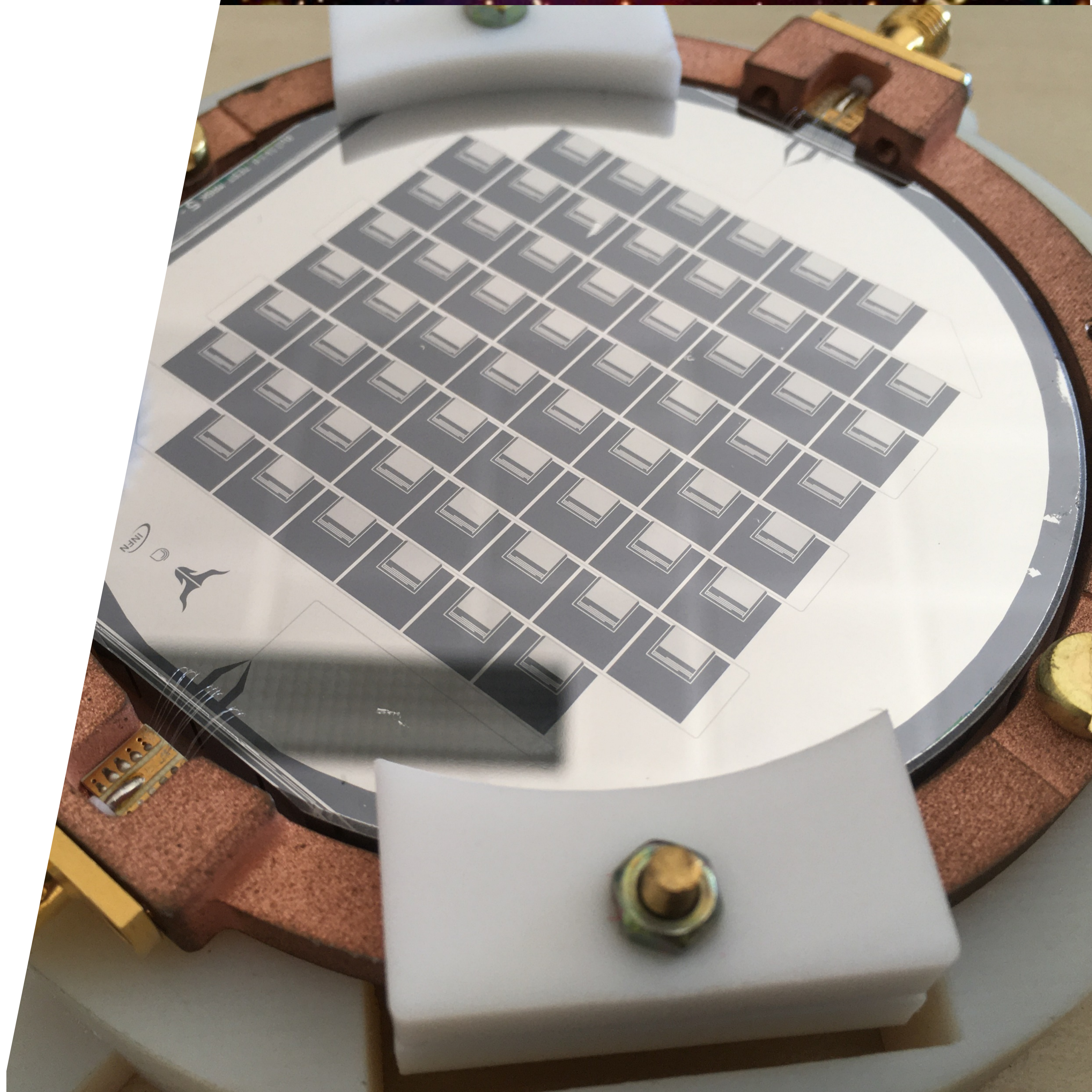
SAPIENZA
UNIVERSITÀ DI ROMA

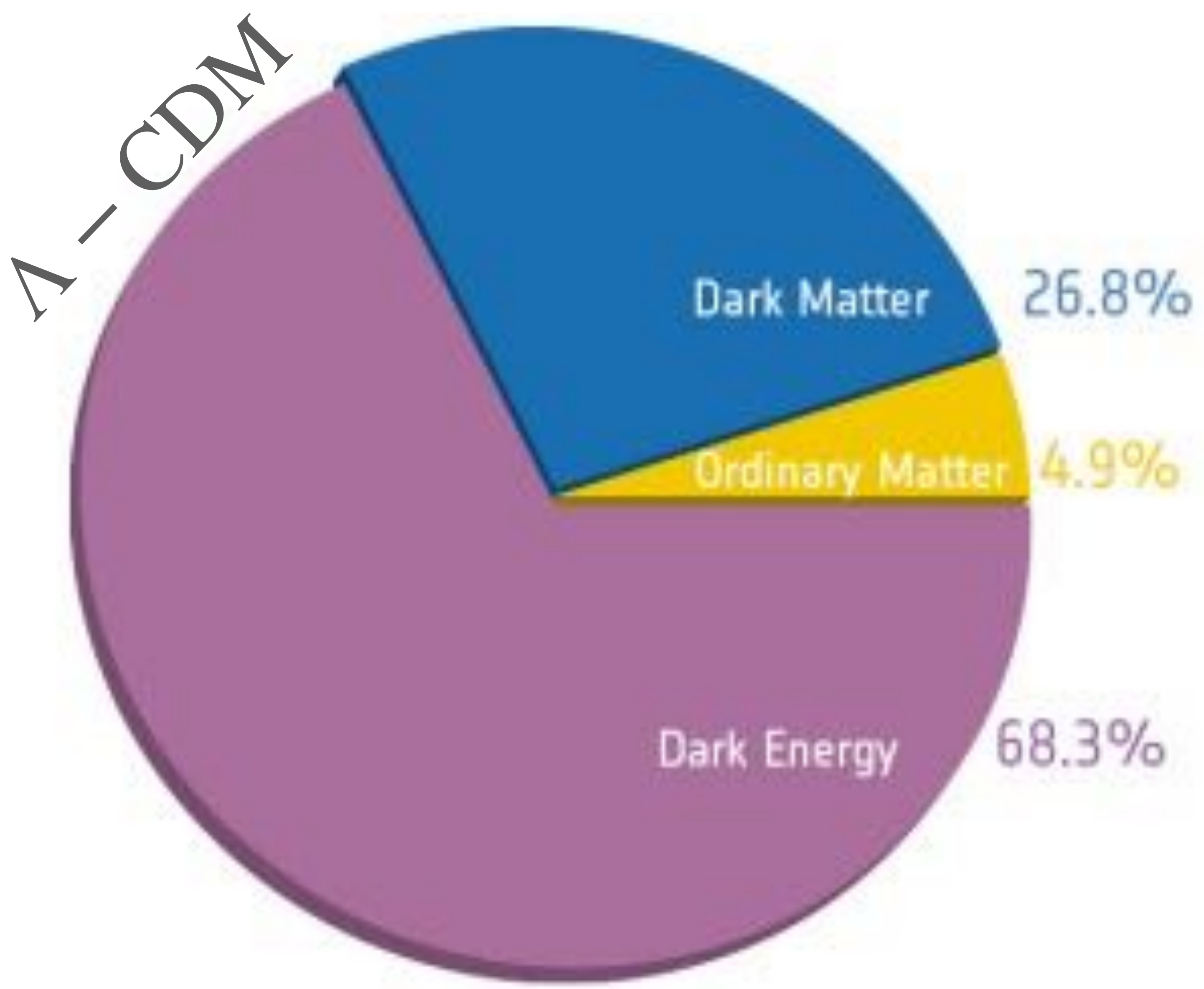
INFN
Istituto Nazionale di Fisica Nucleare

New results from BULLKID

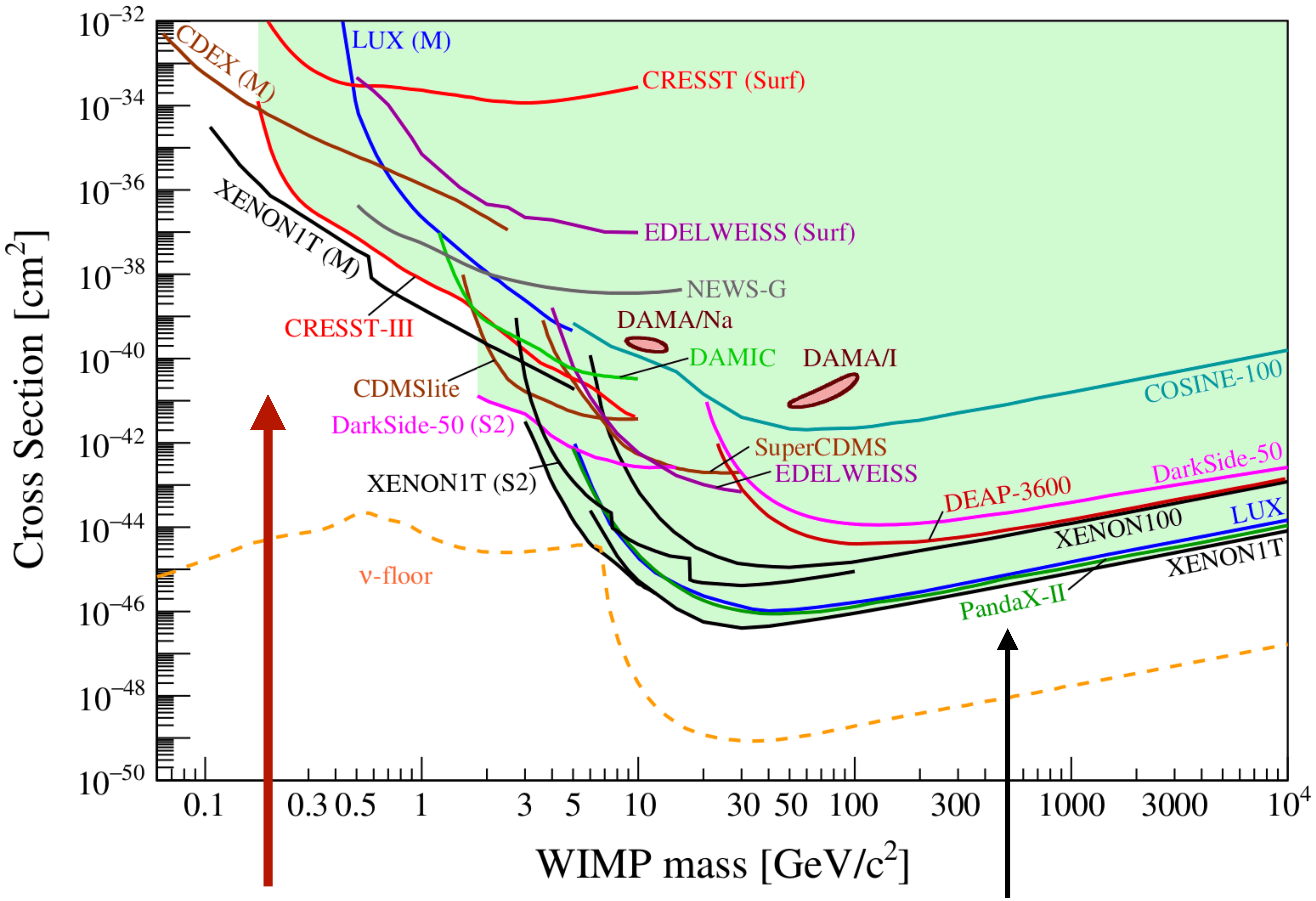


Marco Vignati, on behalf of the BULLKID coll.
Taup, Vienna, 31 August 2023

Dark Matter - direct search



J. Billard, et al, Direct Detection of Dark Matter – APPEC Committee Report, arXiv:2104.07634



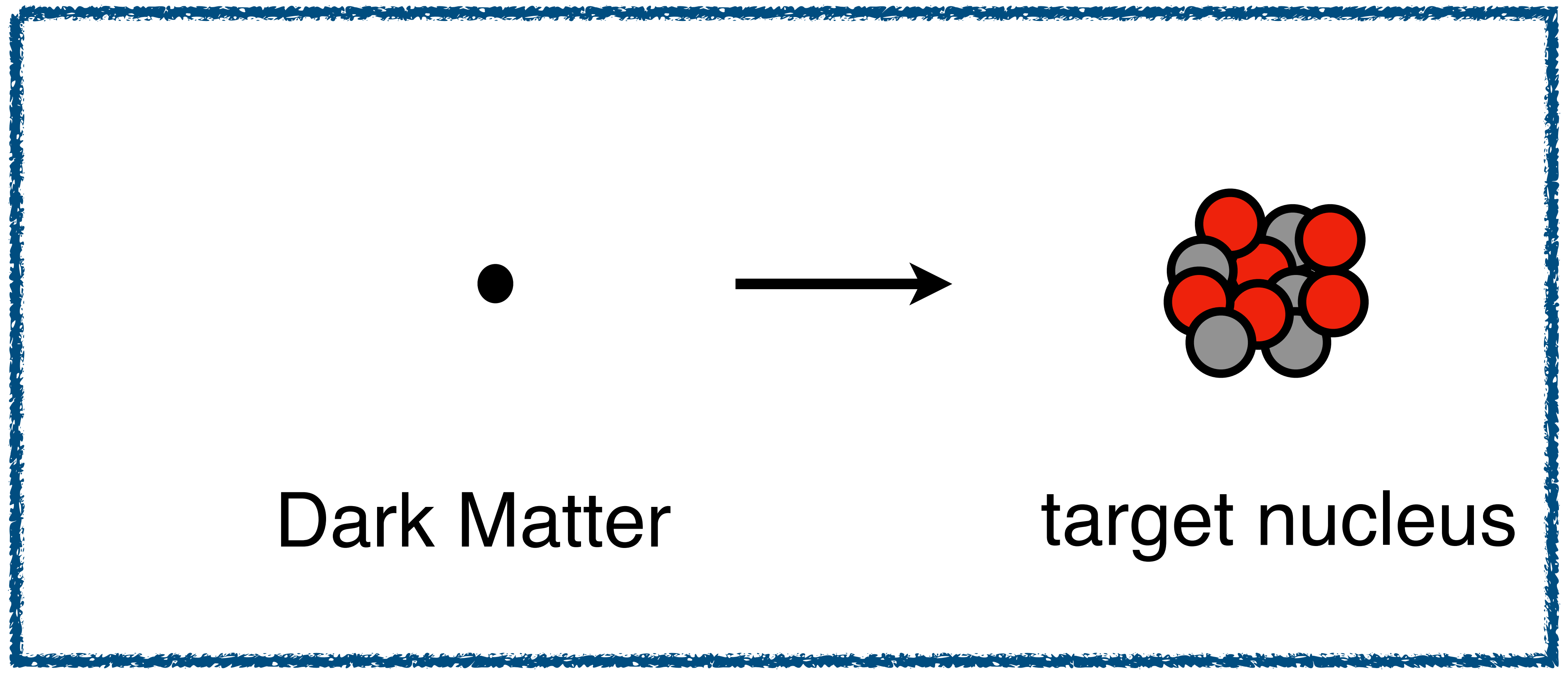
What is the Dark Matter made of?

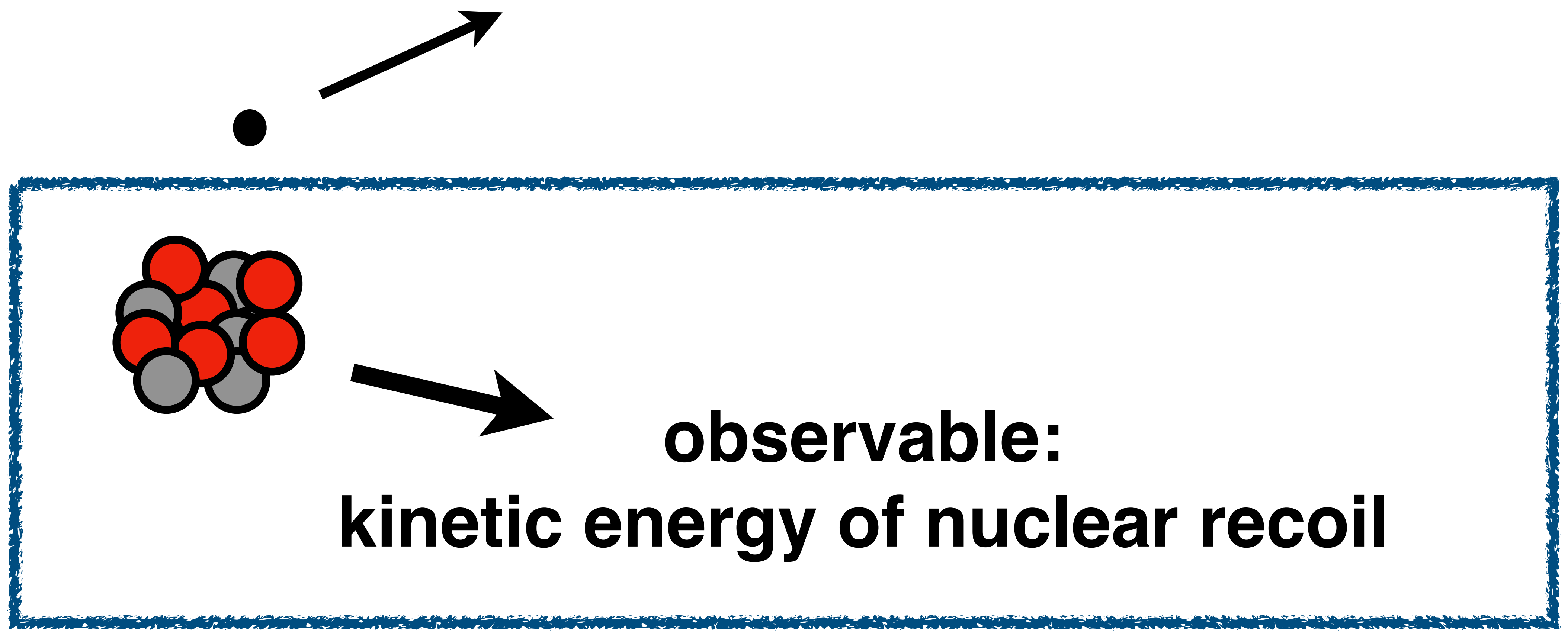
- primordial black holes?
- μeV/c² - eV/c² axion-like waves?
- MeV/c² - TeV/c² WIMP-like particles?

kg-scale solid-state phonon detectors (this talk)

Multi-ton liquid scintillators

Direct dark matter search below 1 GeV/c^2

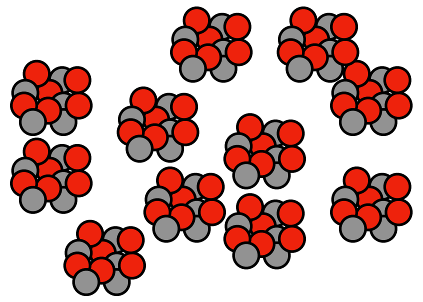


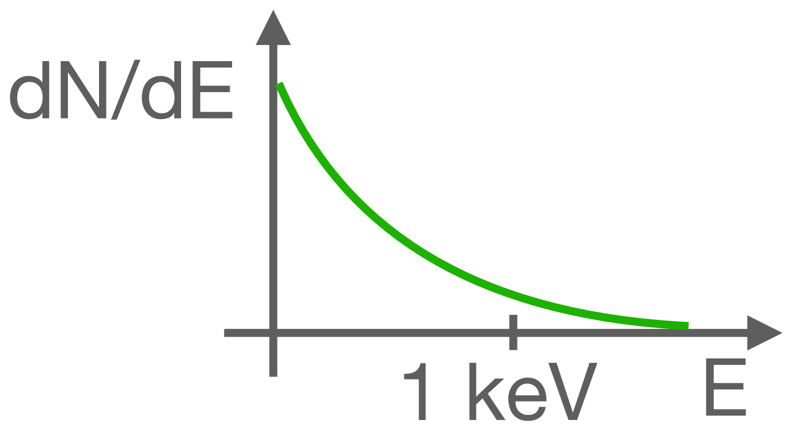


cross section $\sigma < 10^{-40}\ \mathrm{cm}^2$

energy < 1 keV

large number of targets
***O*(1 kg)**





low-energy threshold
***O*(100 eV)**

Difficult with Low-T detectors

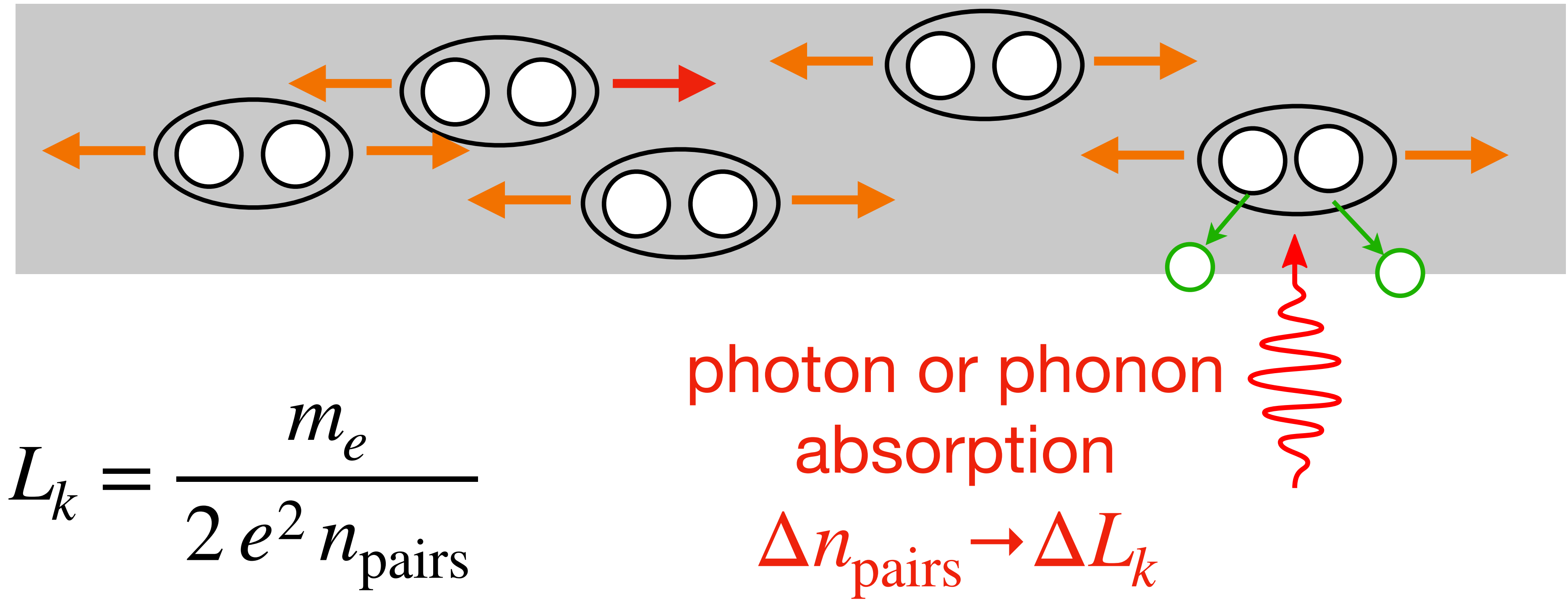
Motivation for Low-T detectors

Kinetic Inductance Detectors

AC superconductivity

- Electrons bound into Cooper pairs (no dissipation)
- High quality factors (Q ~ 10^4 - 10^6)
- Inertia from the mass of pairs (*kinetic inductance, L_k*)

superconductor under AC field $\overrightarrow{E_{AC}}$



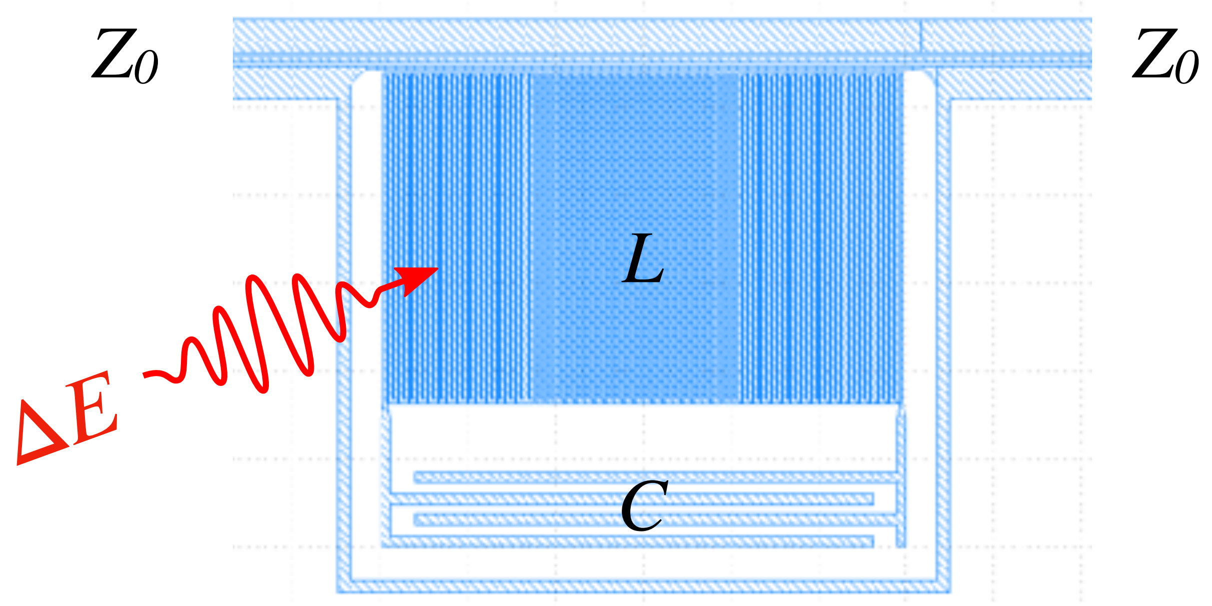
$$L_k = \frac{m_e}{2\, e^2\, n_{\text{pairs}}}$$

Kinetic Inductance Detector (KID)

- Superconductor at T < 200 mK (Al)
- LC resonator

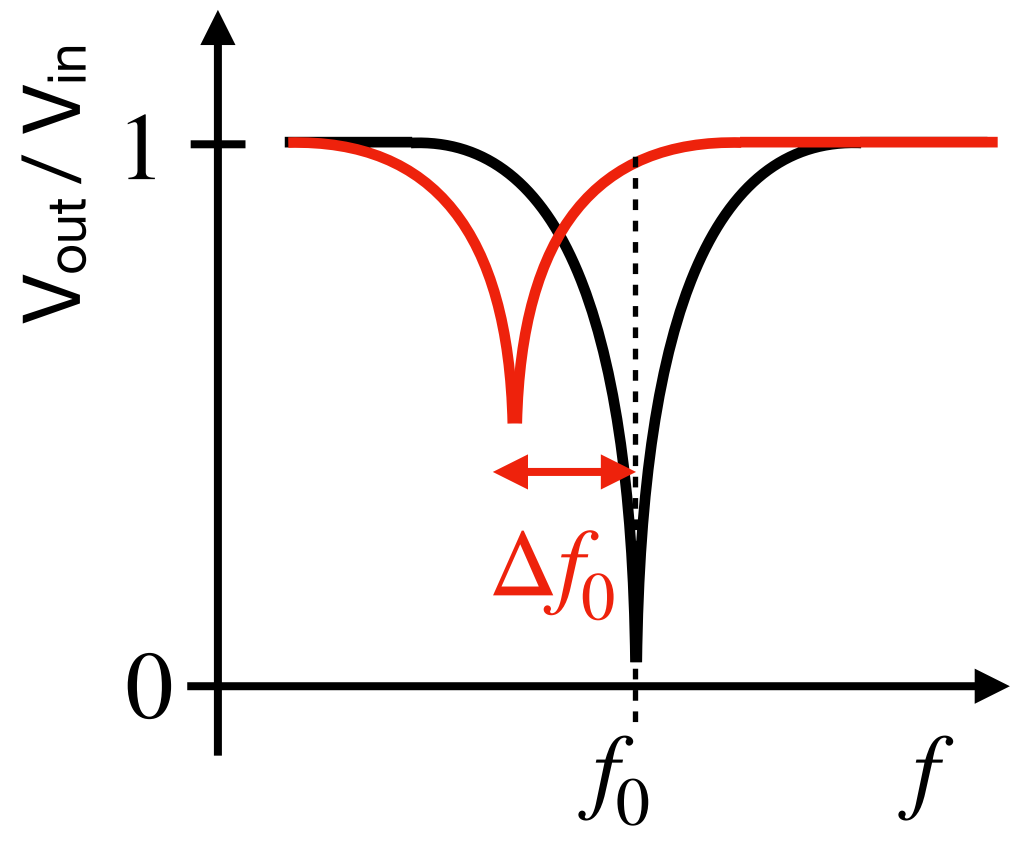
Invented by J. Zmuidzinas and his group at Caltech in 2003 for astrophysical applications

resonator $f_0 = 1/\sqrt{LC}$



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

frequency response



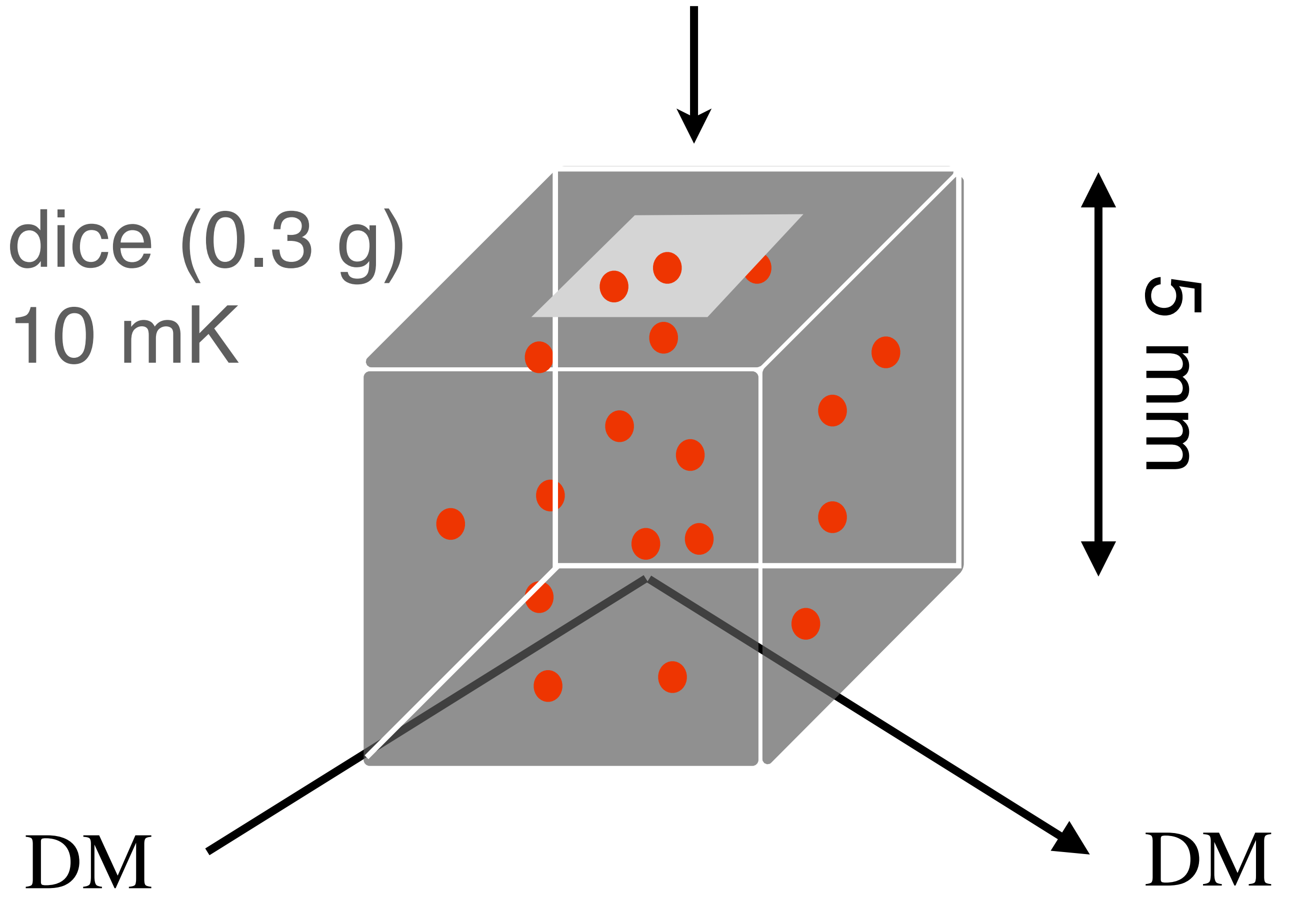
The BULLKID phonon detector array

Phonon mediation

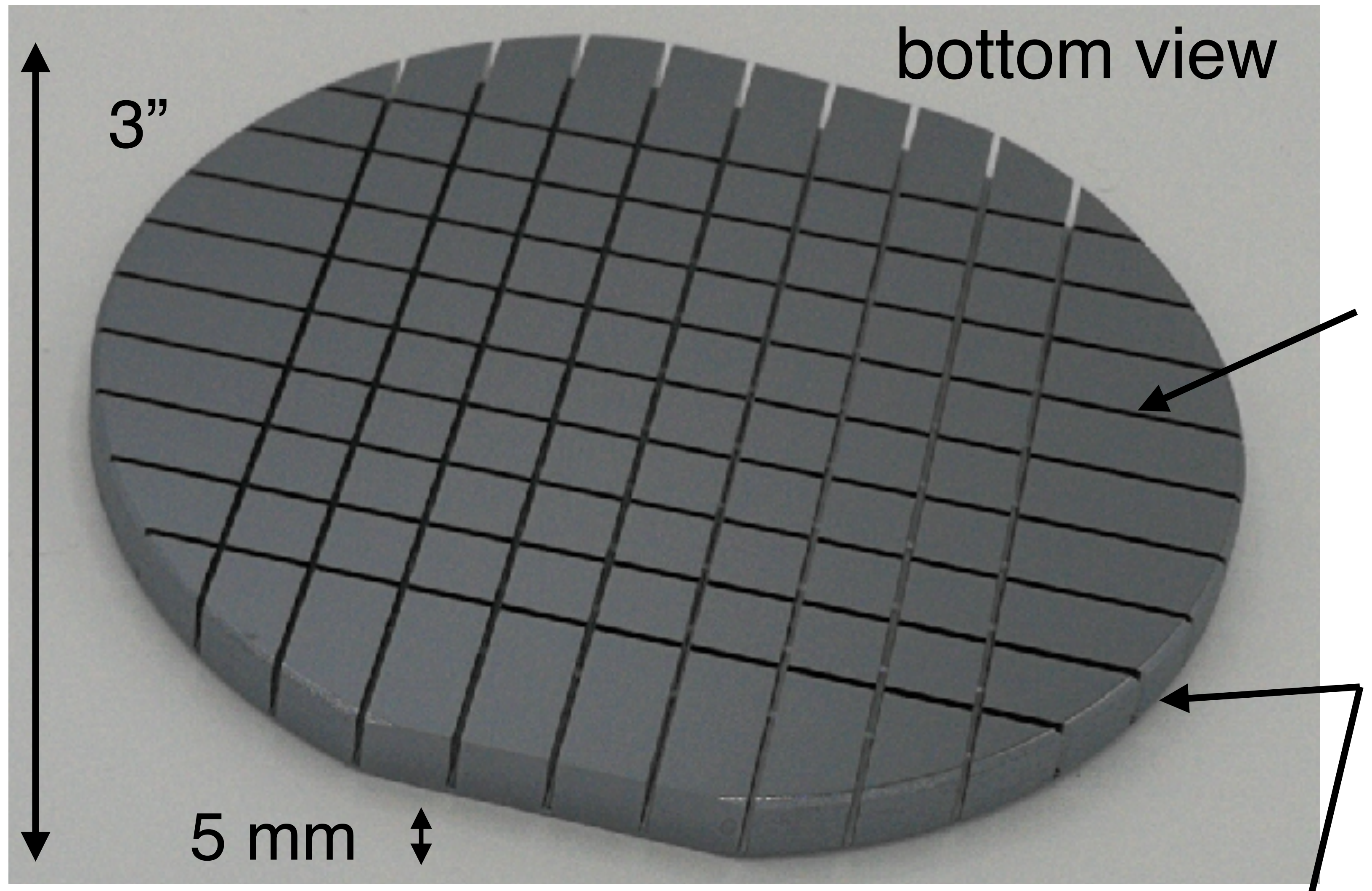
detect phonons created by nuclear recoils in a silicon dice

KID (~ 2x2 mm² x 50 nm, 0.5 µg)

Silicon dice (0.3 g) at 10 mK



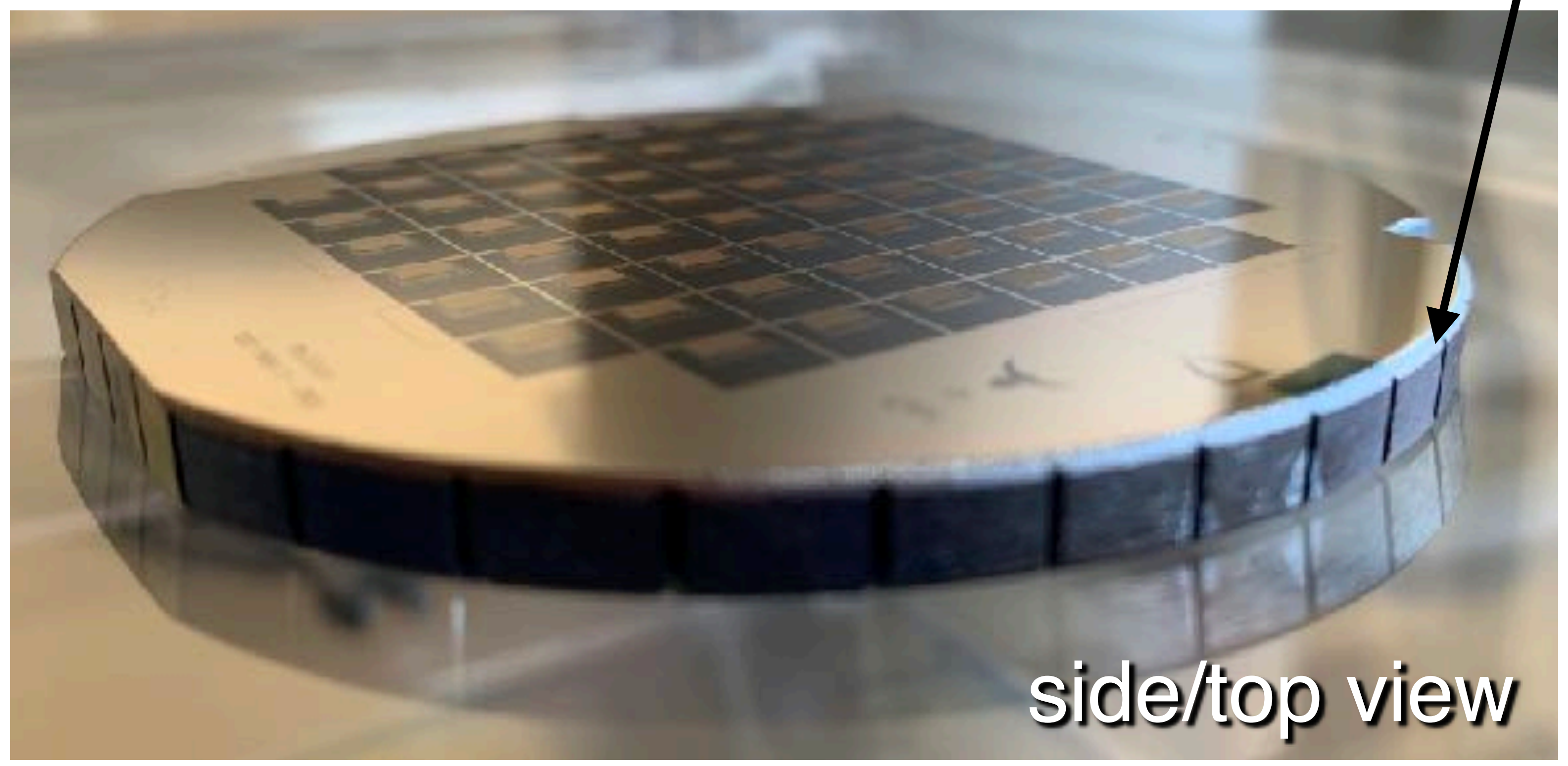
carving of dices in a thick silicon wafer



4.5 mm deep grooves
- 6 mm pitch
- chemical etching

0.5 mm thick common disk:
- holds the structure
- hosts the KIDs

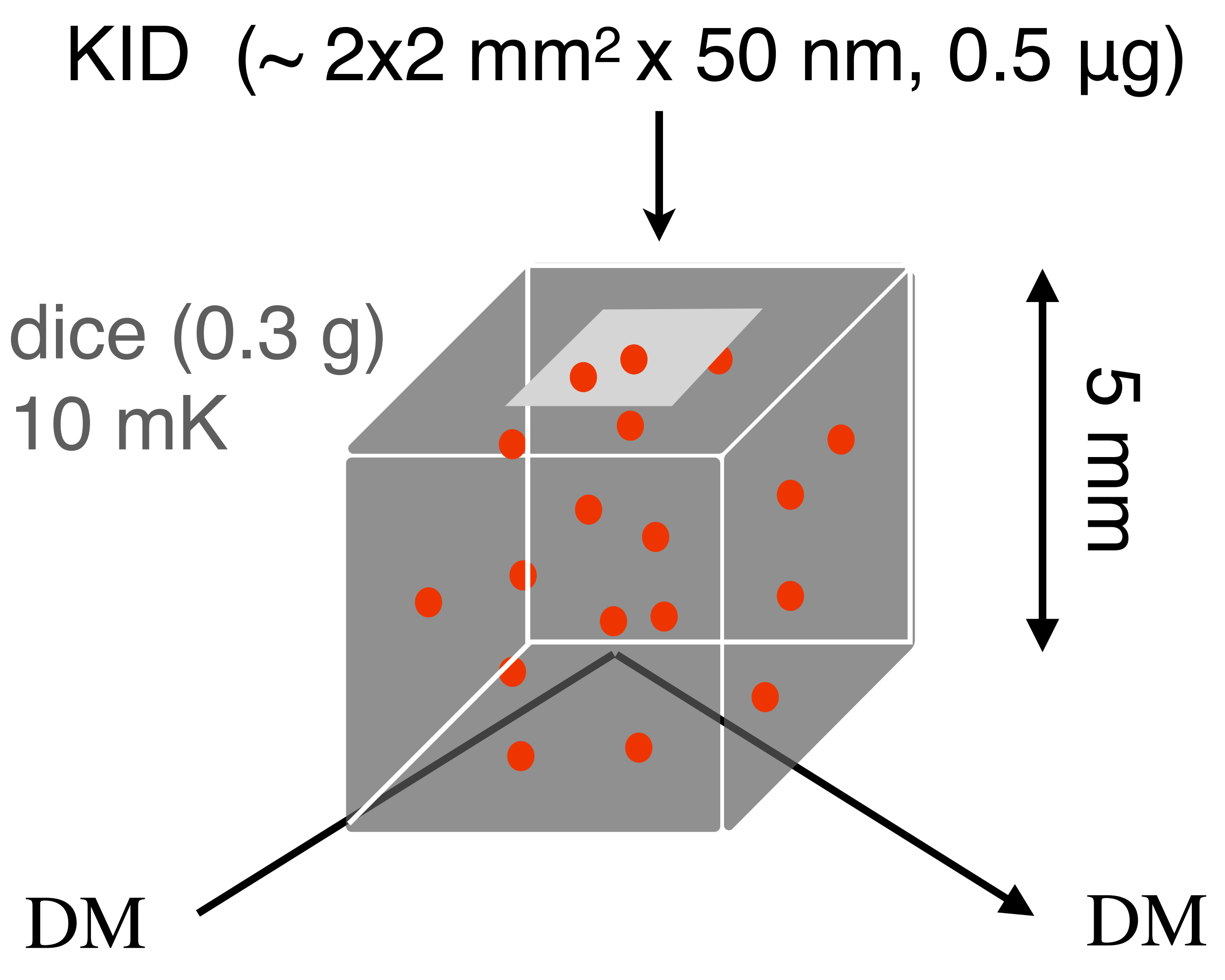
lithography of multiplexed KID array



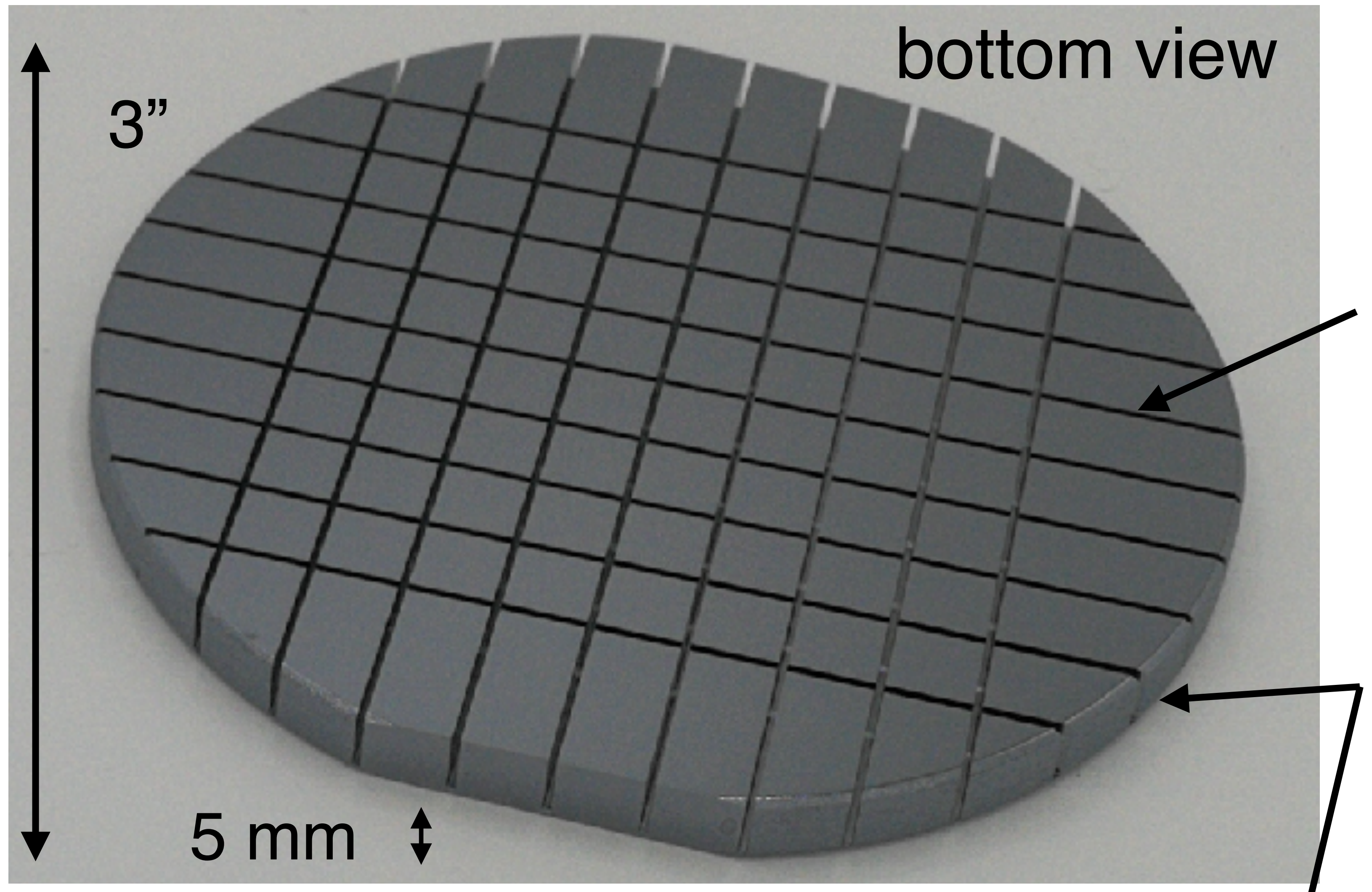
KID array
- 60 nm aluminum film
- 60 KIDs lithography

The BULLKID phonon detector array

Phonon mediation
detect phonons created by nuclear recoils in a silicon dice



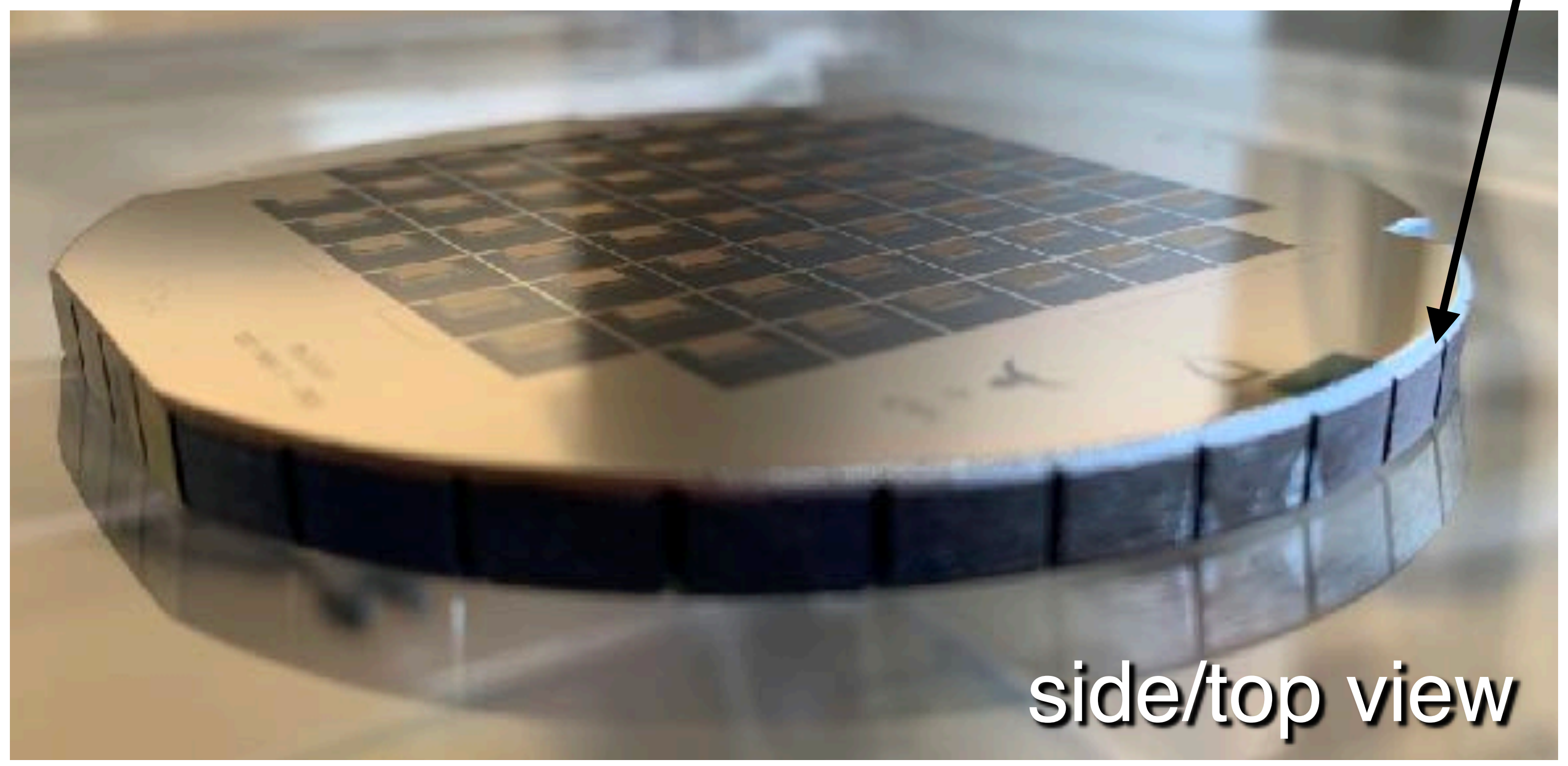
carving of dices in a thick silicon wafer



4.5 mm deep grooves
- 6 mm pitch
- chemical etching

0.5 mm thick common disk:
- holds the structure
- hosts the KIDs

lithography of multiplexed KID array



KID array
- 60 nm aluminum film
- 60 KIDs lithography

✓ 60 detectors in 1

Fully multiplexed
(single readout line)

BULLKID: the team

Sapienza University & INFN Rome

*A. Ahmad, **A. Cruciani,** M. del Gallo Roccagiovine, D. Delicato, G. Del Castello, M. Giammei, D. Maiello, V. Pettinacci, **M. Vignati;***

University & INFN Ferrara

*L. Bandiera, V. Guidi, **A. Mazzolari,** M. Romagnoni, M. Tamisari;*

Institut Néel - CNRS

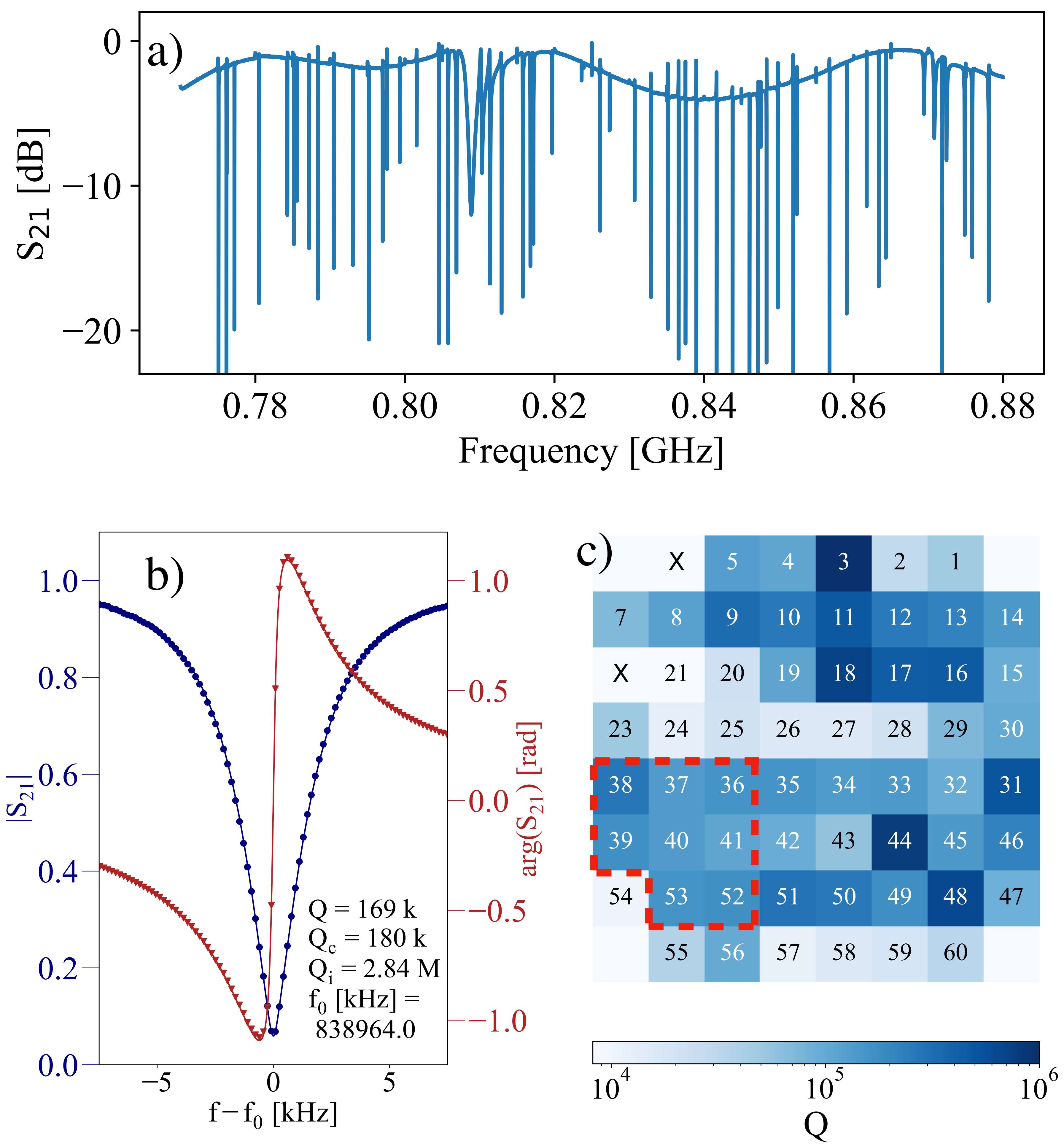
*M. Calvo, D. Delicato, **A. Monfardini;***

BULLKID

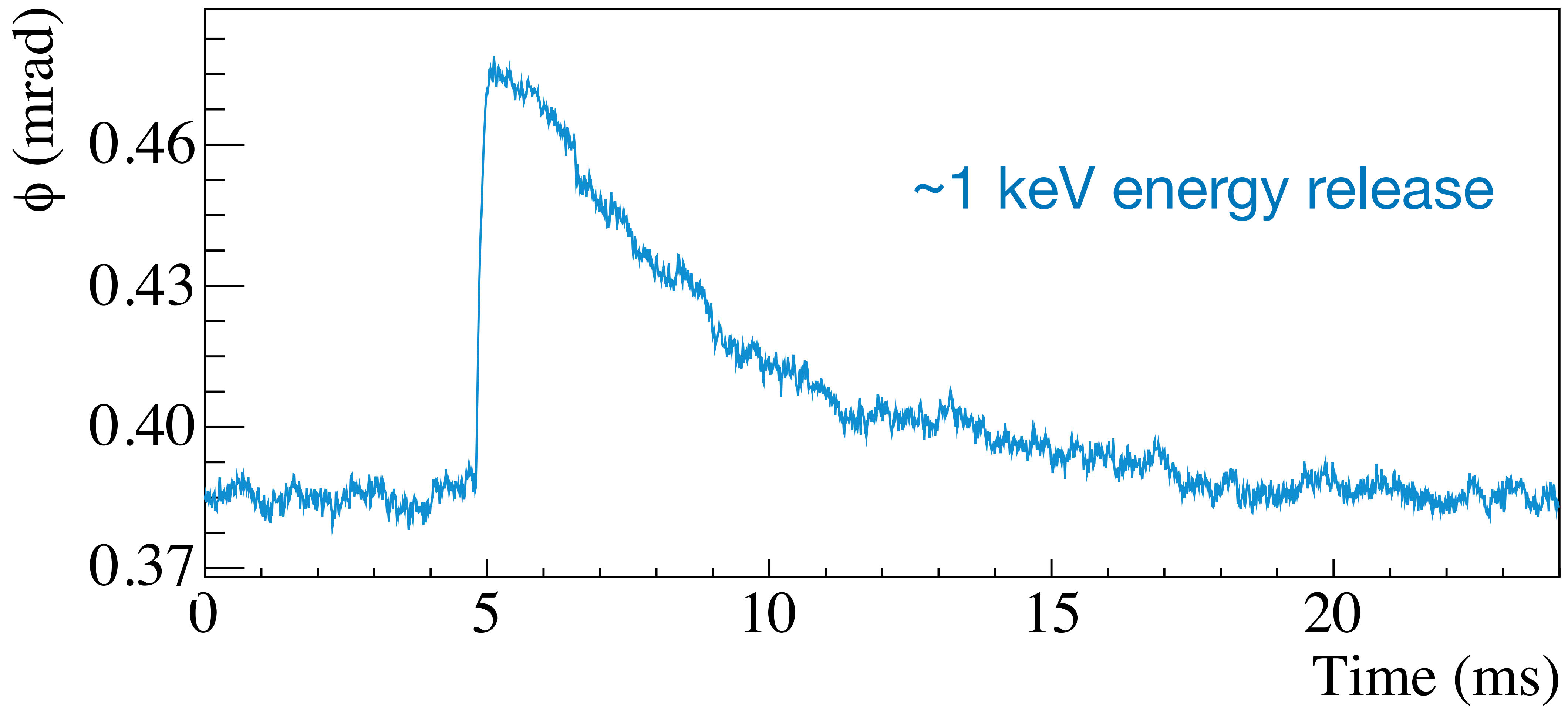
funded by the INFN and by Sapienza U.

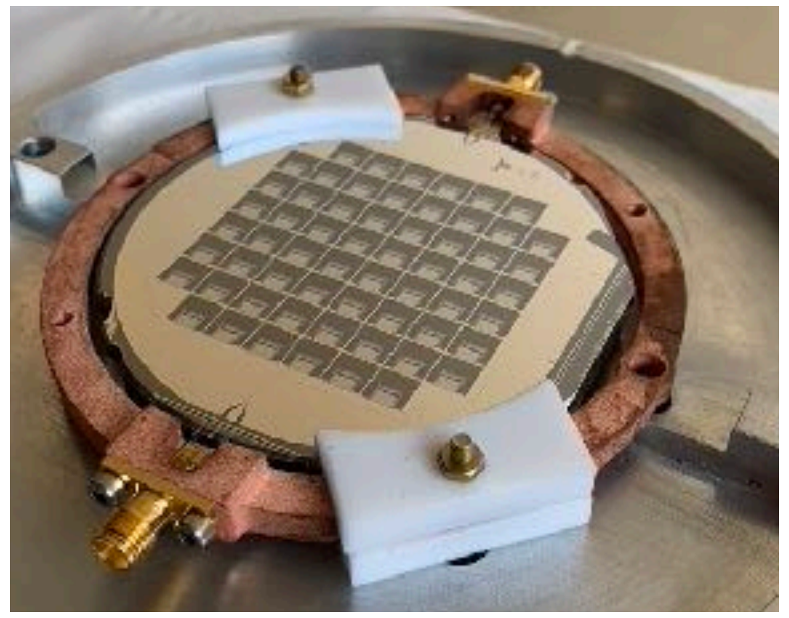
First results (Summer ’22)

Frequency scan of the KID array



Particle interaction in a dice



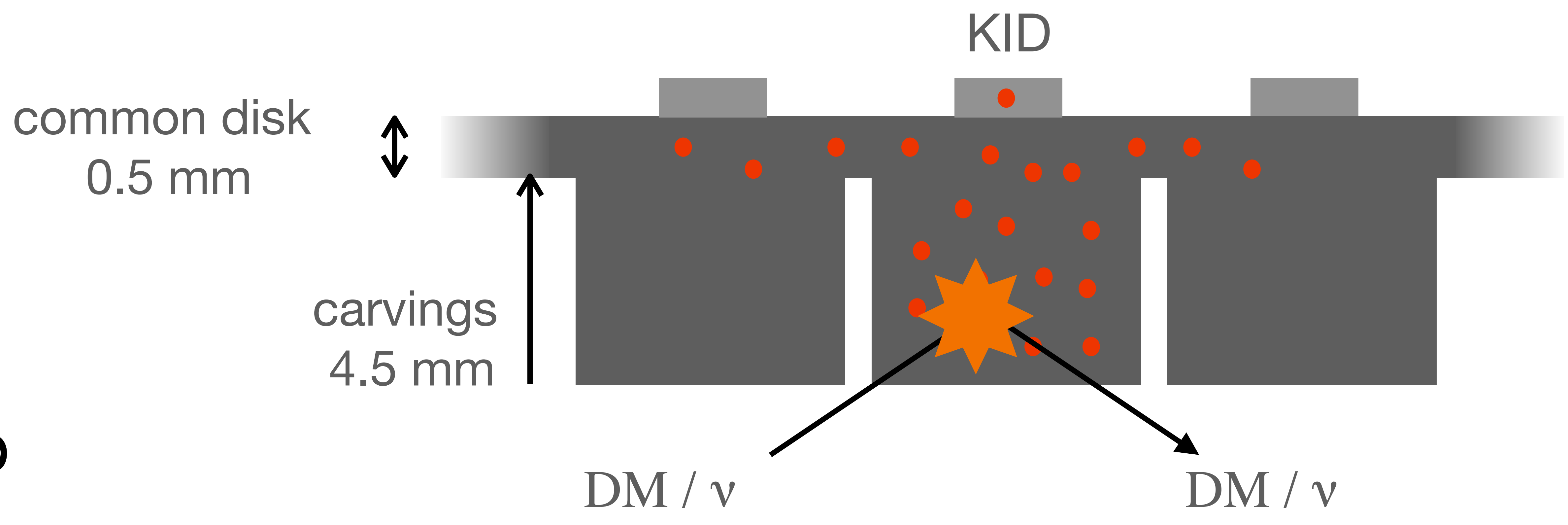


+) 58/60 KIDs alive
+) RMS@0 eV: **26 ± 7 eV**
–) Response not uniform

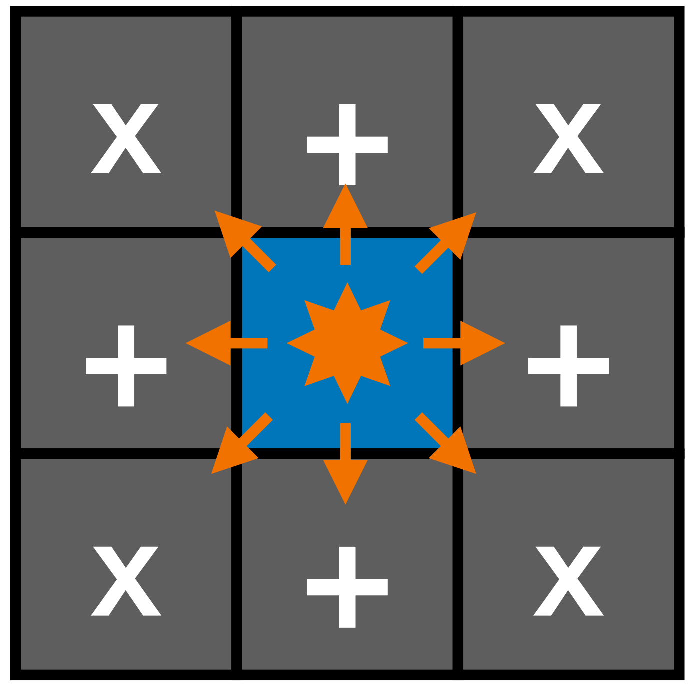
A. Cruciani, et al, Appl. Phys. Lett. 121, 213504 (2022)

Phonon leakage

- Phonons generated by interactions
  - 40% absorbed by the KID
  - the rest leaks in nearby voxels or decays below the KID aluminum gap



- Measured energy leakage relative to central voxel:
  - (14 ± 3) % in each "+" voxel
  - (5 ± 1) % in each "x" voxel

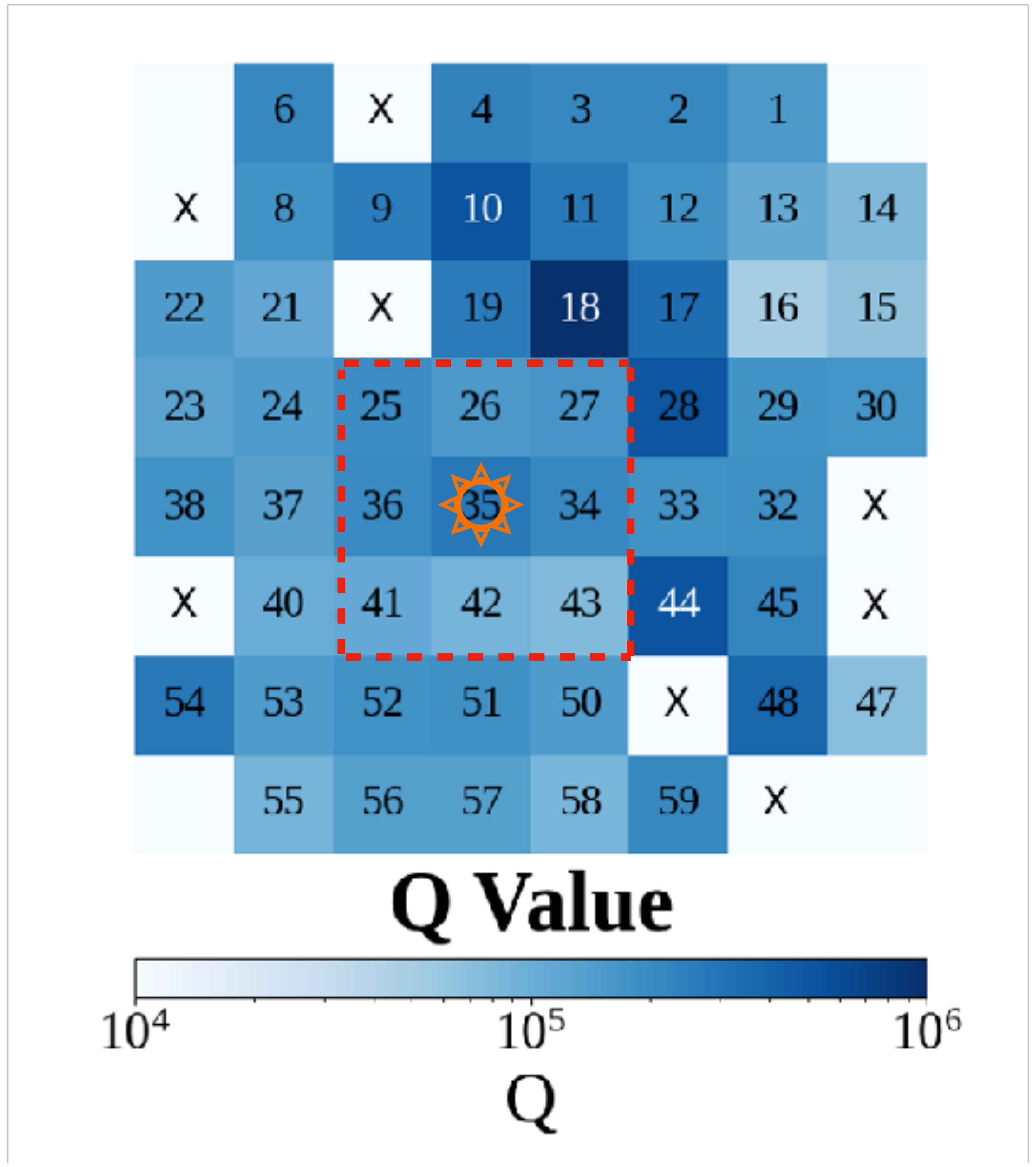


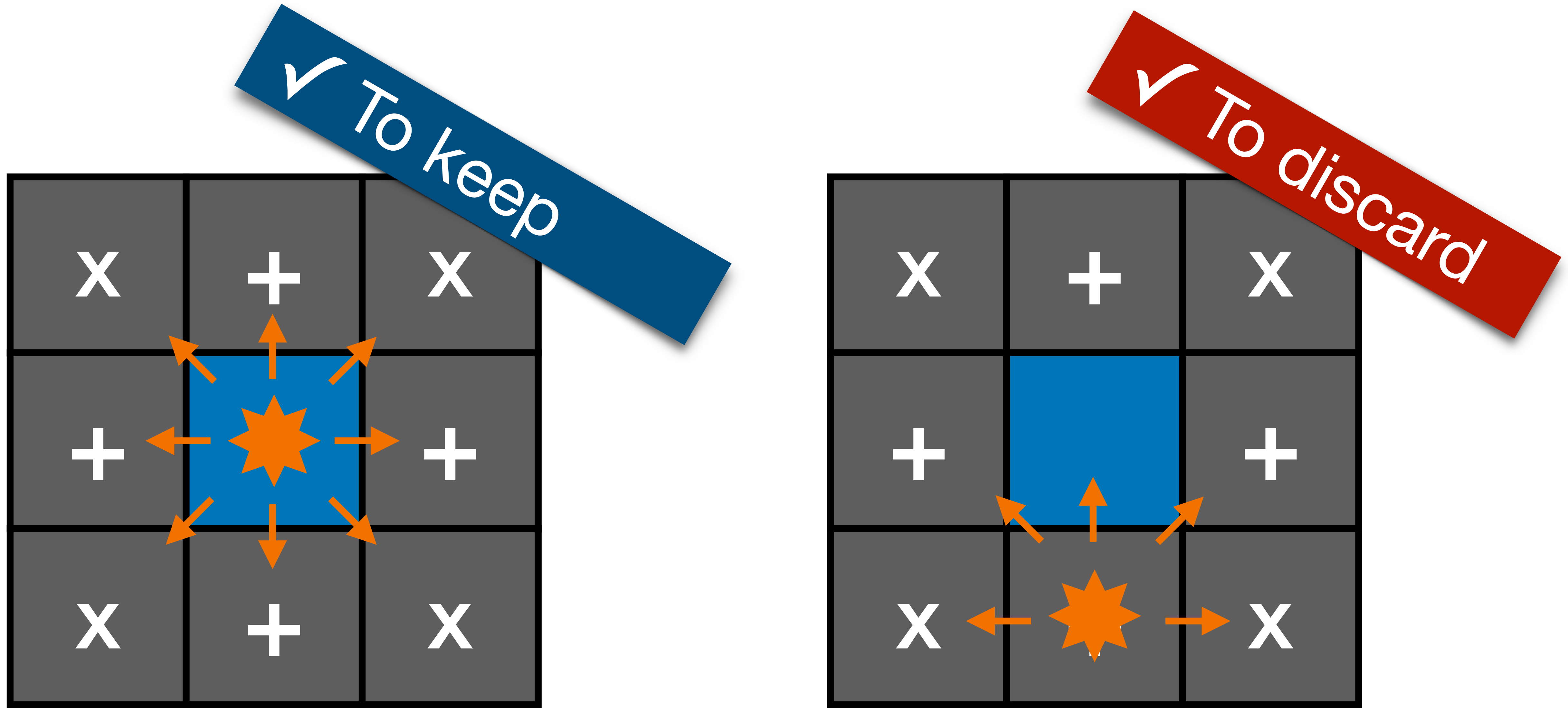
This effect reduces the phonon focusing on the KID but
it can be exploited to reconstruct the interaction voxel

New: combined analysis of a 9-dice cluster

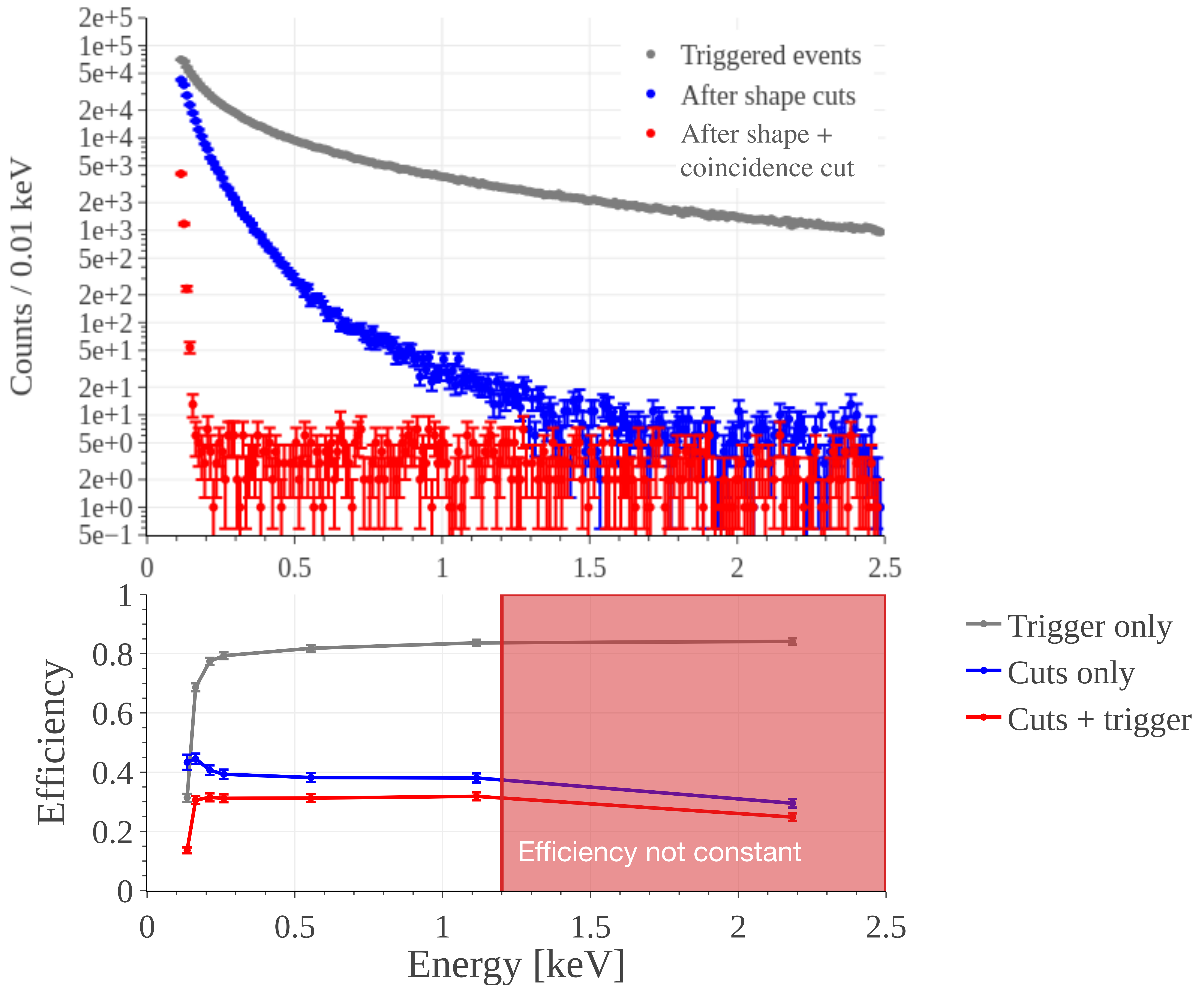
Measurement of the energy spectrum of the central voxel

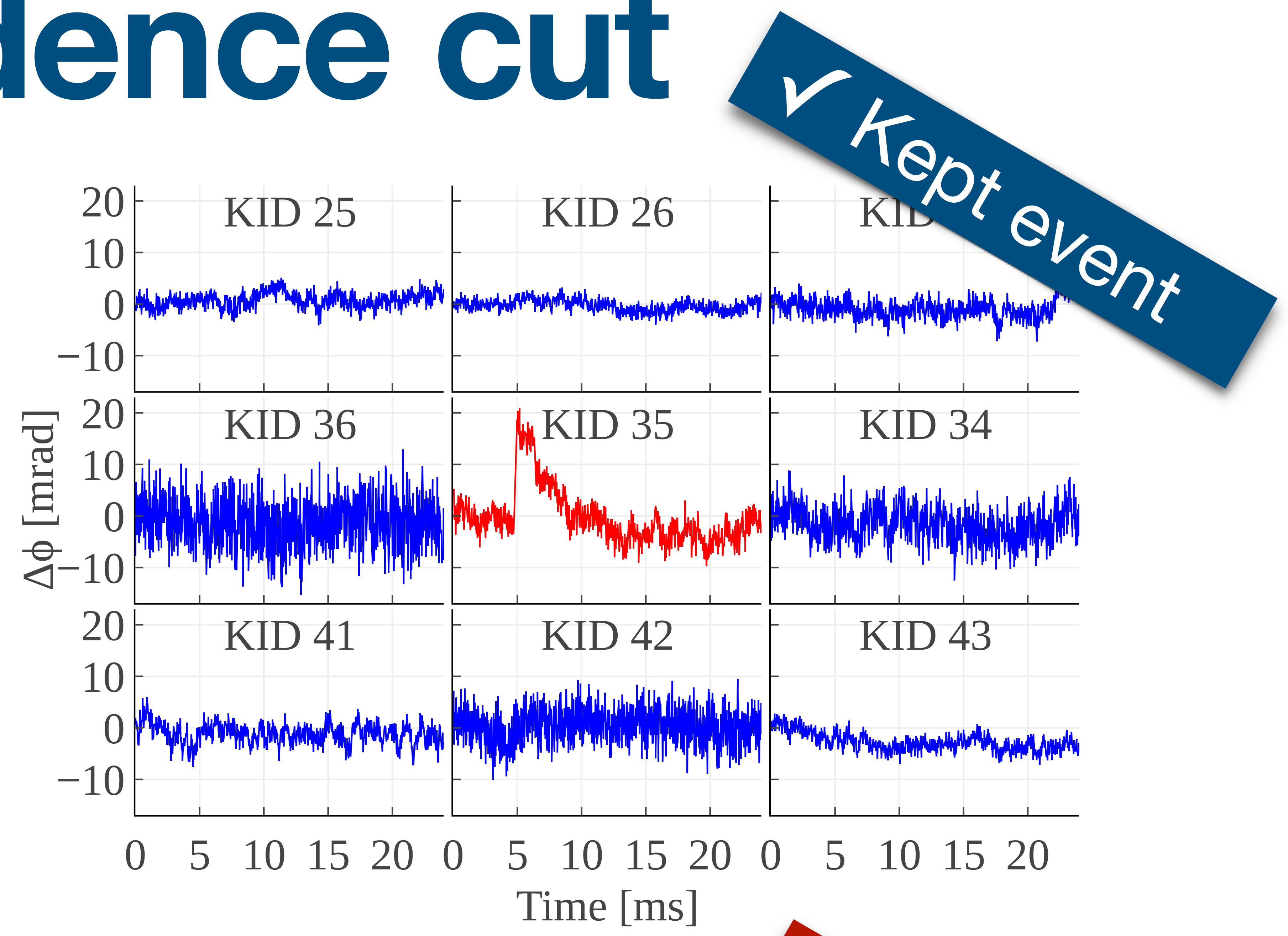
Use the 8 external voxels as “veto” exploiting the phonon leakage

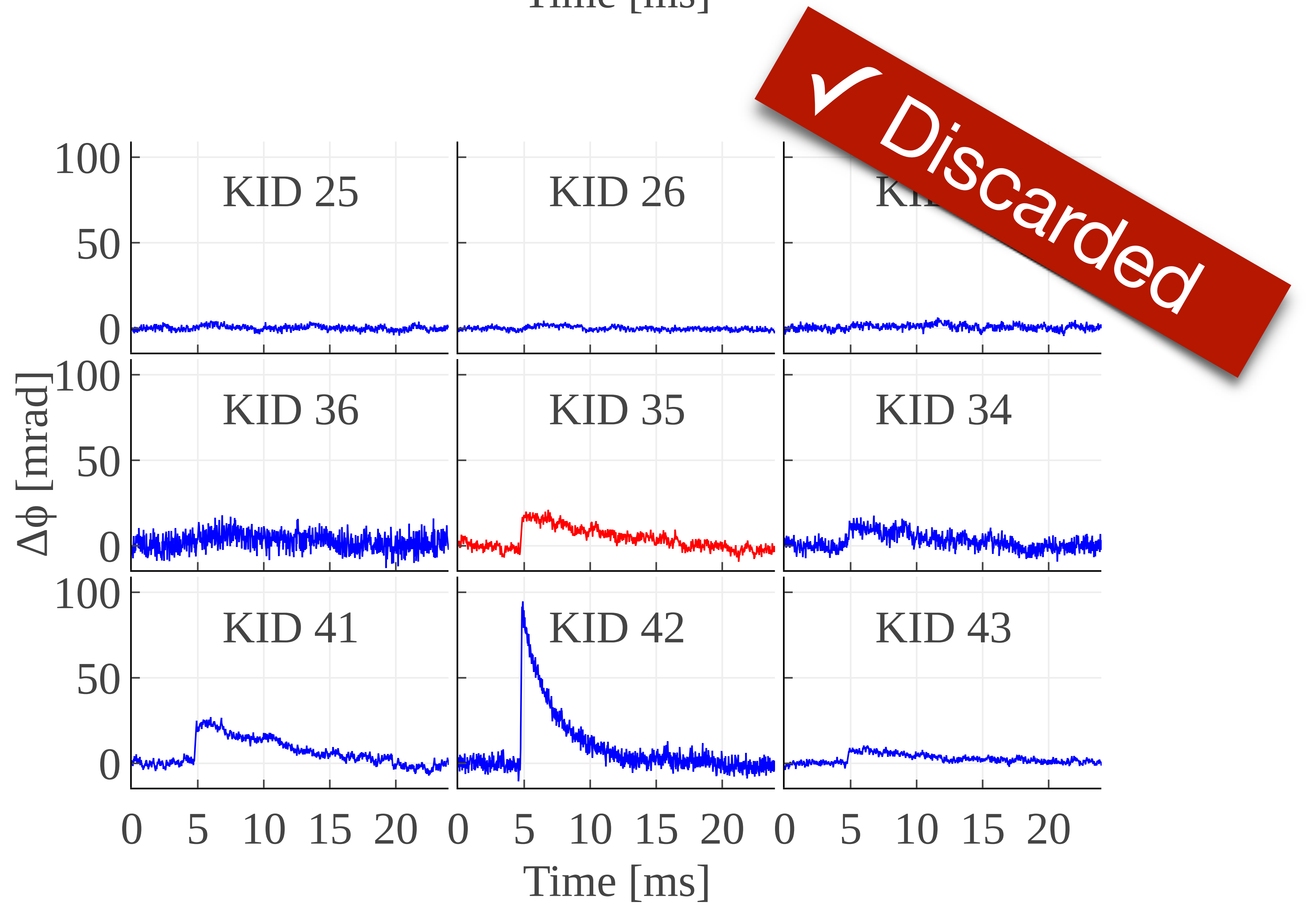




Background: shape + coincidence cut



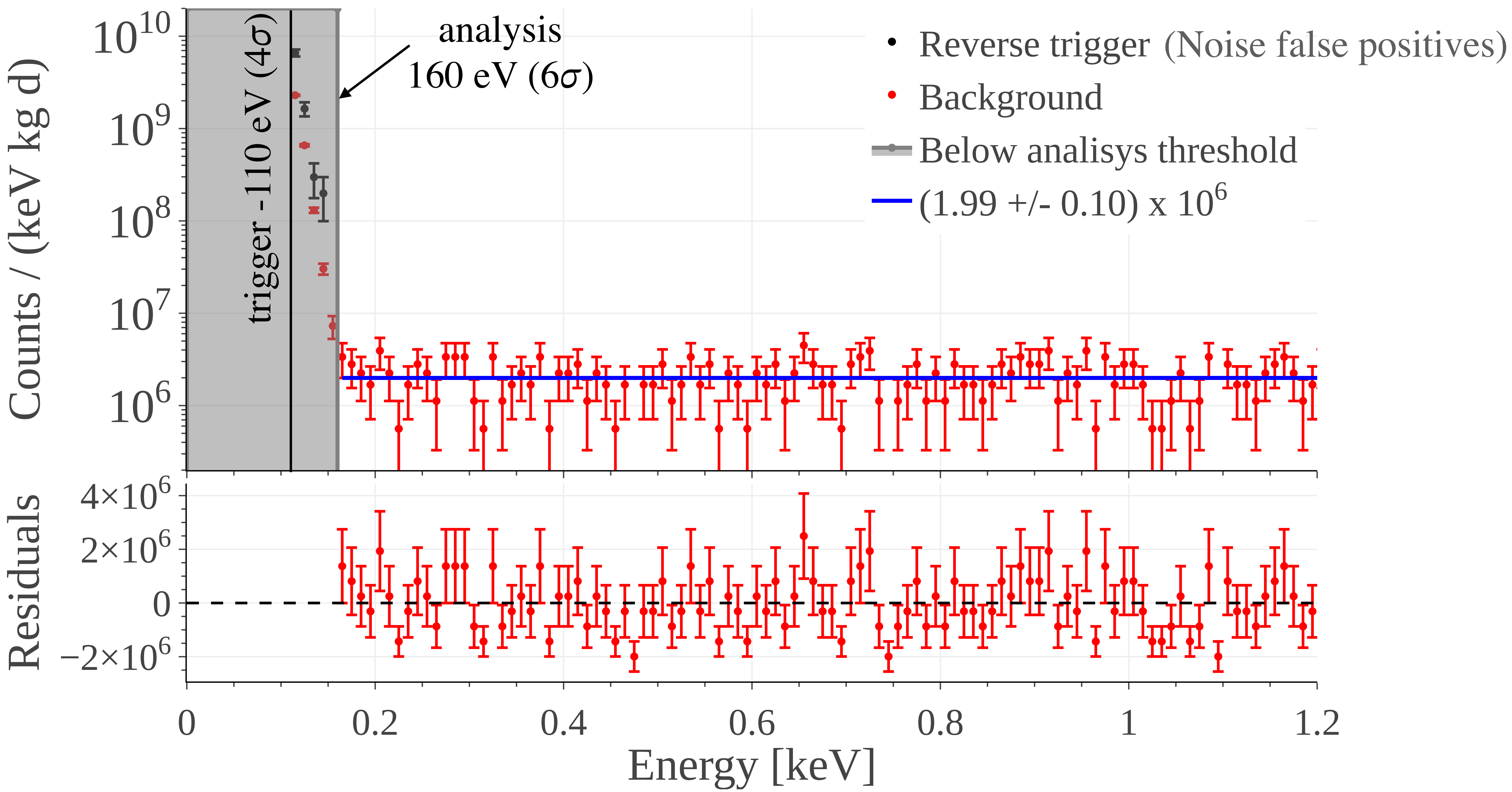




Background: result

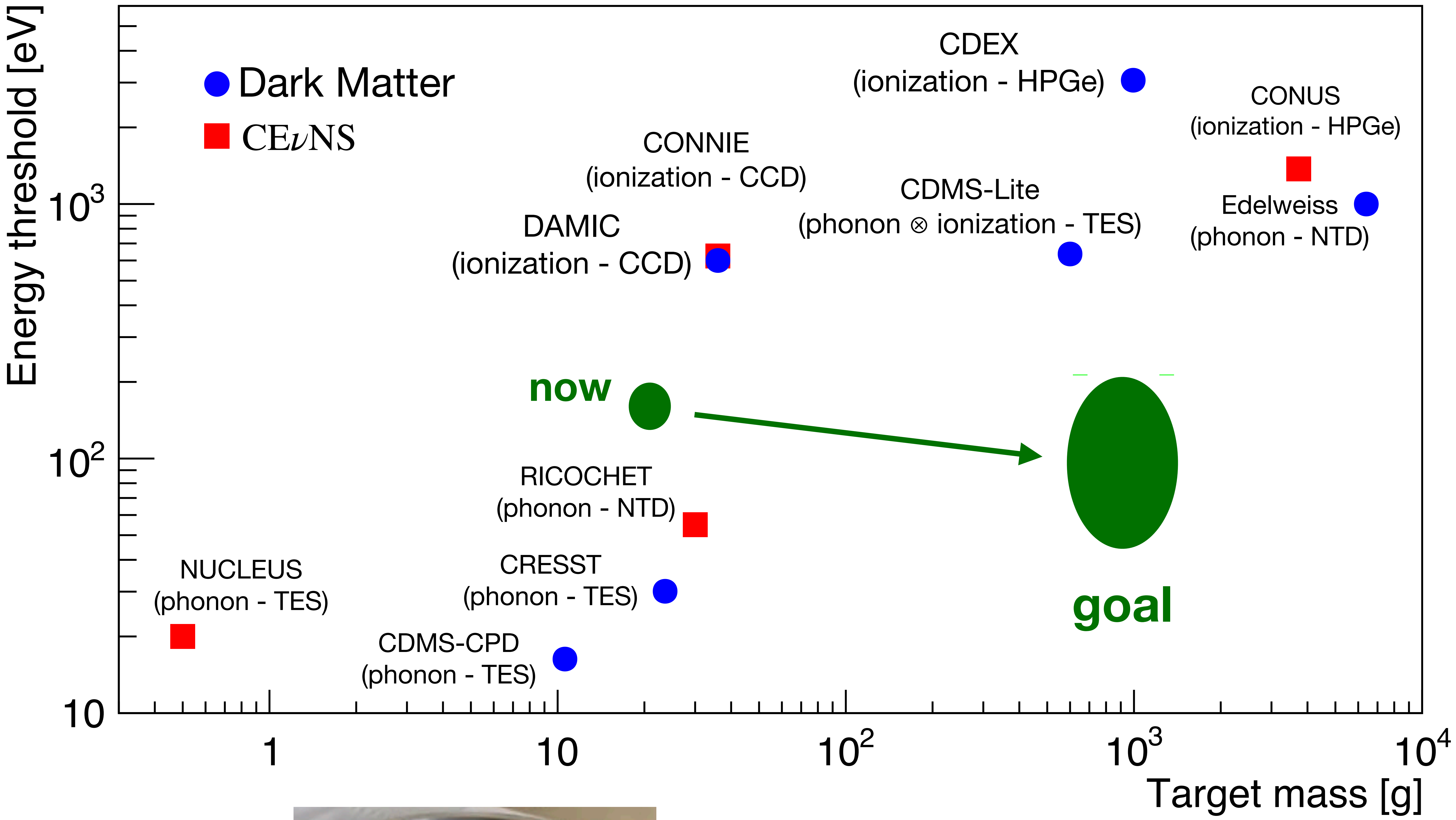
Above ground lab, no shield, 39 live hours

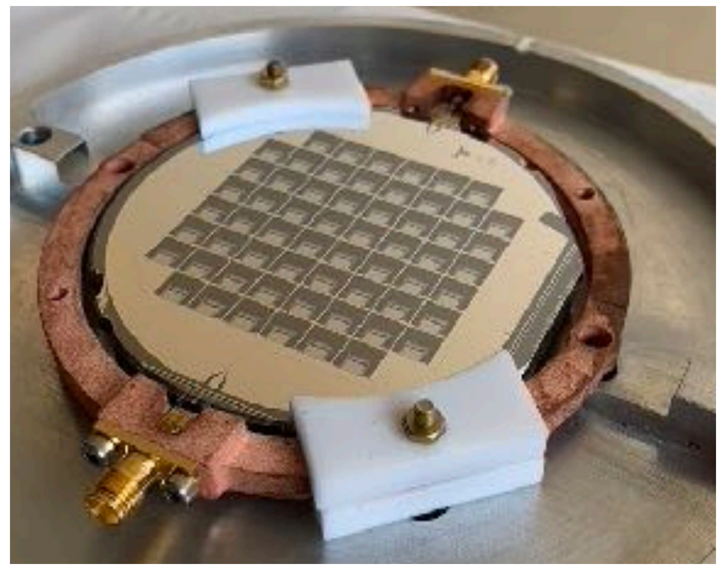
D. Delicato et al, [arXiv:2308.14399](https://arxiv.org/abs/2308.14399)



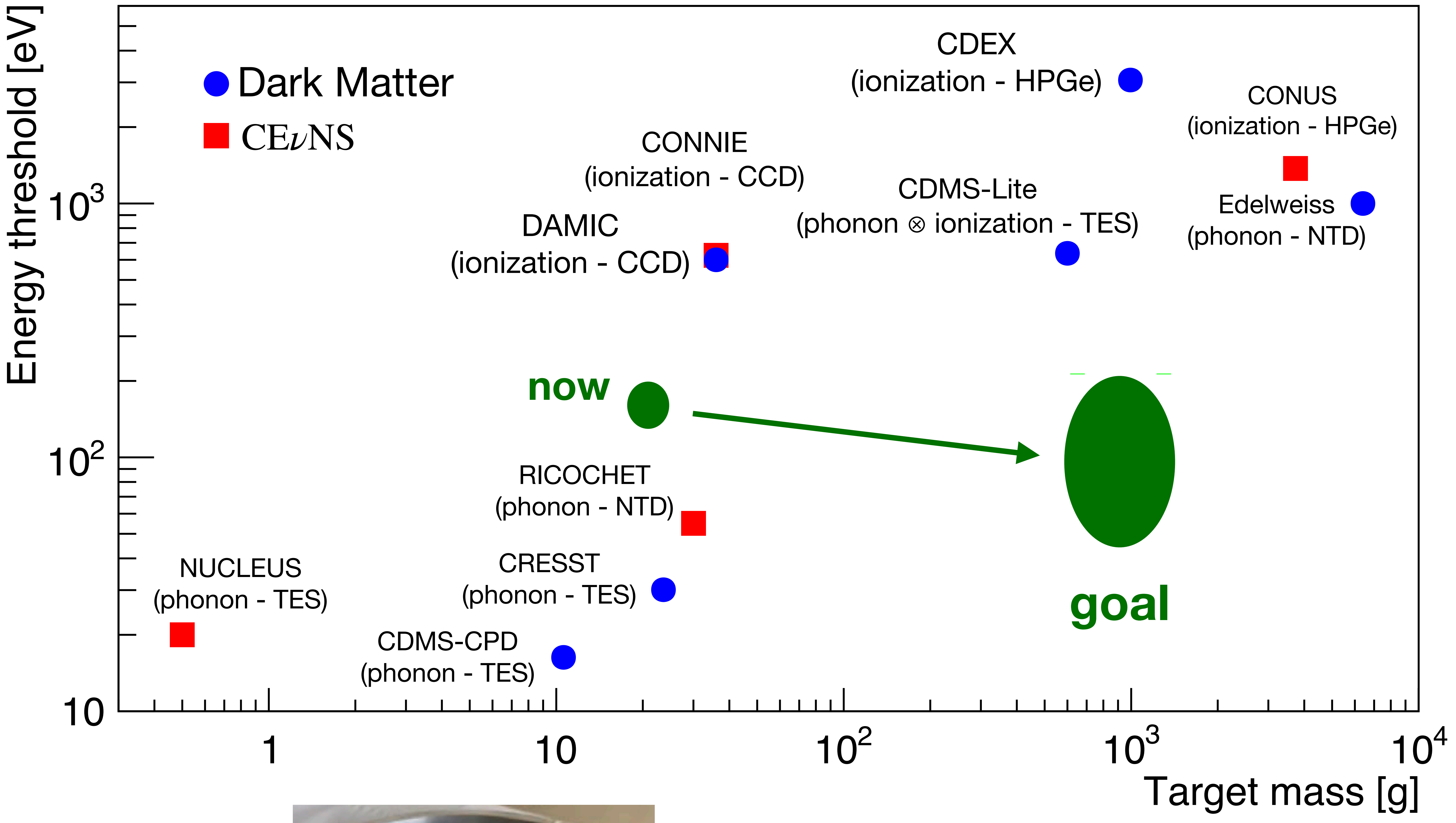
The excess above trigger threshold is compatible with noise false positives.
Background is flat above analysis threshold.

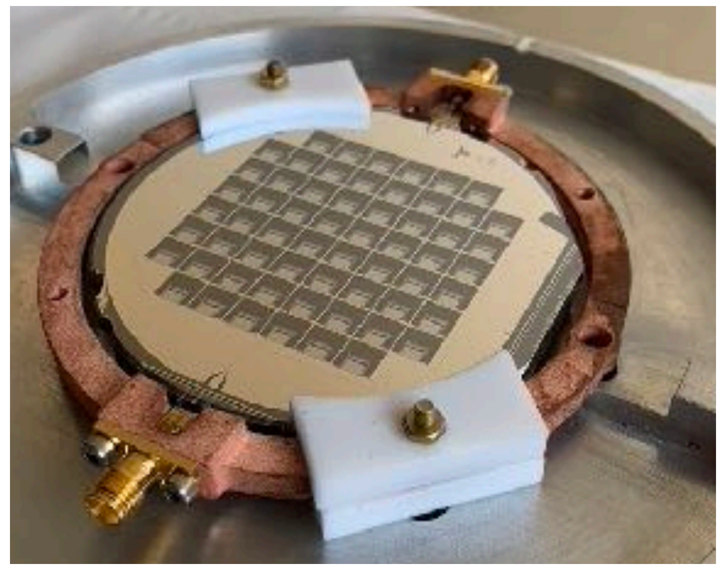
Mass and threshold improvement

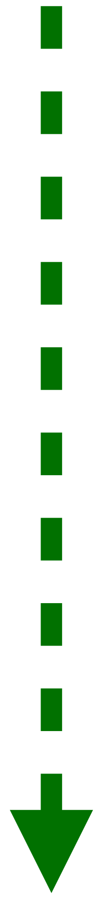




Mass and threshold improvement

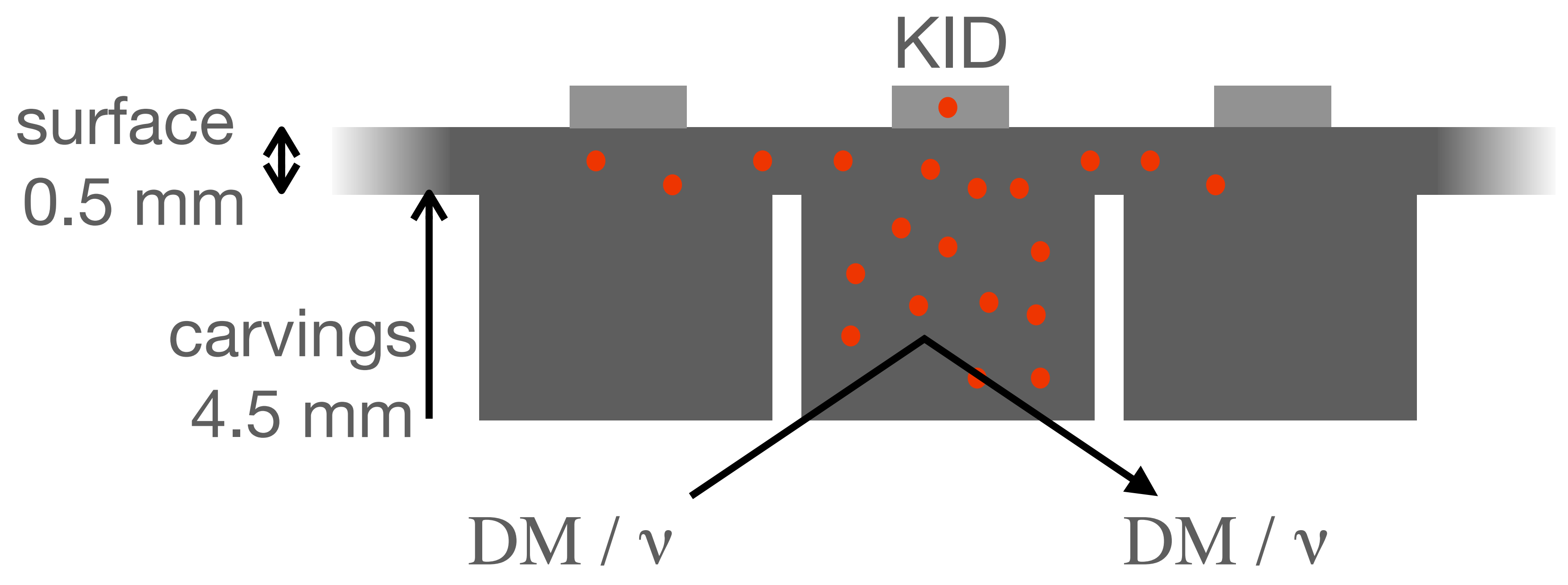






Threshold (ongoing R&D):

1. Replace Al with Al-Ti-Al KIDs - 5x inductance
2. Deeper carvings for higher phonon focussing



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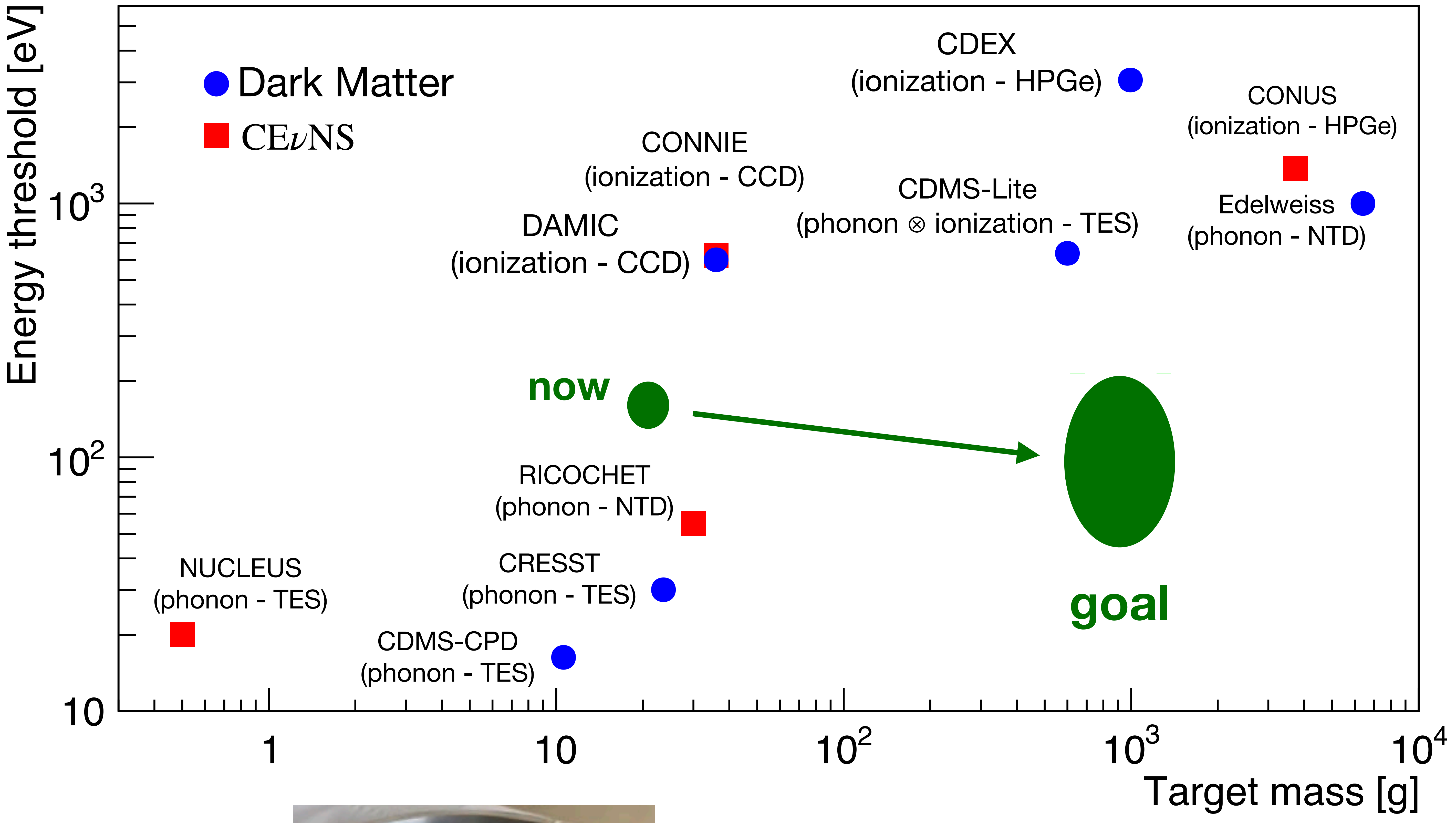

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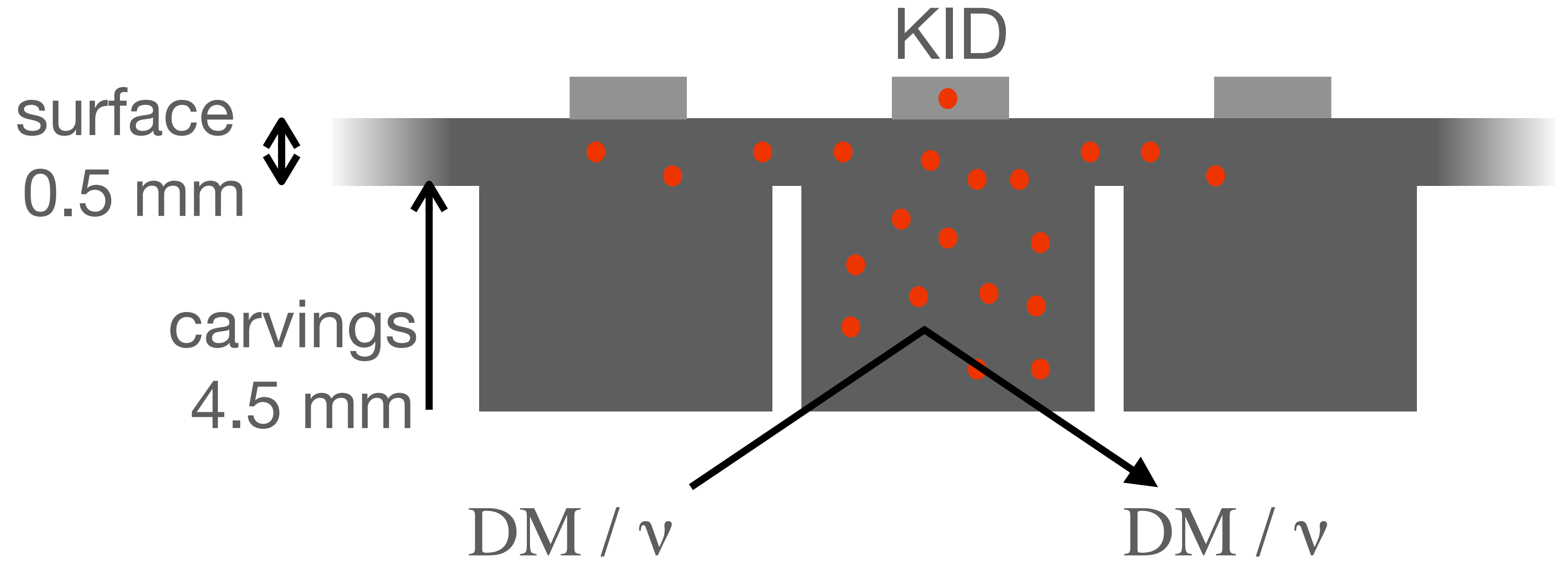
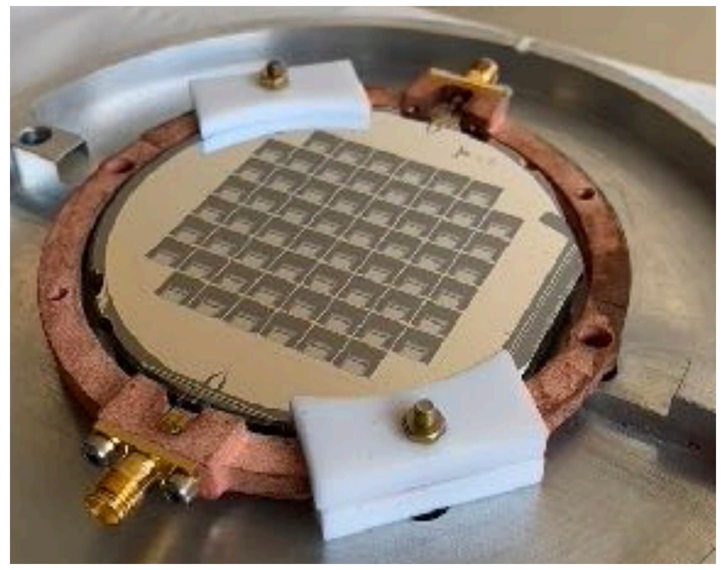
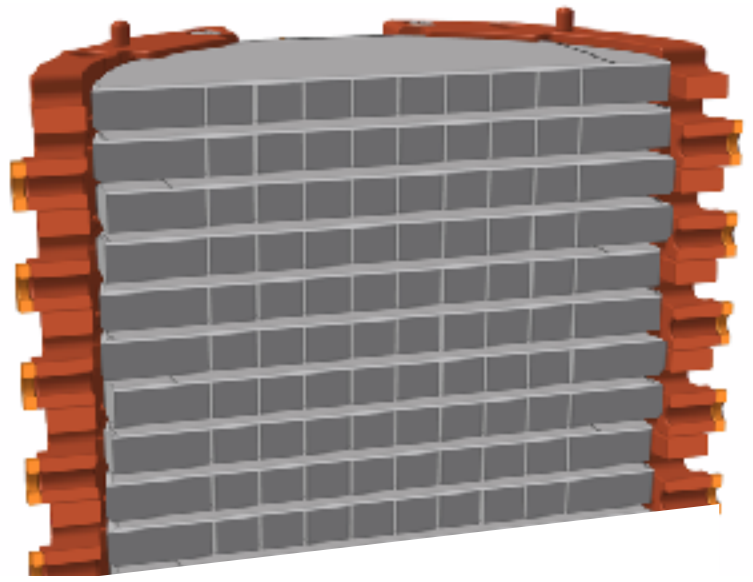


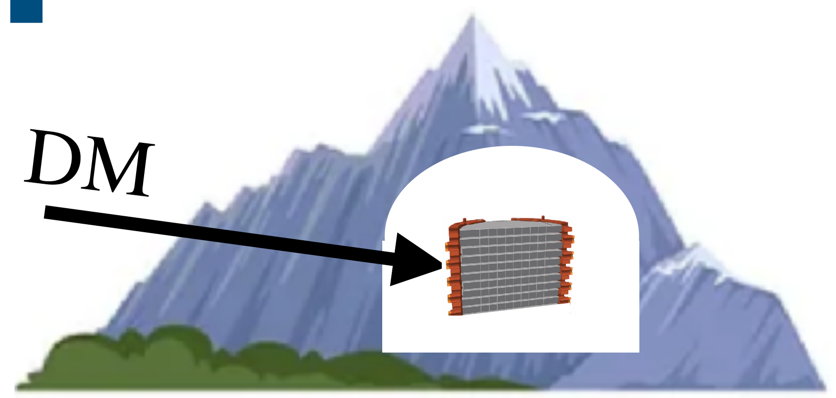


Mass:
from 3” to 4” wafers
stack of wafers



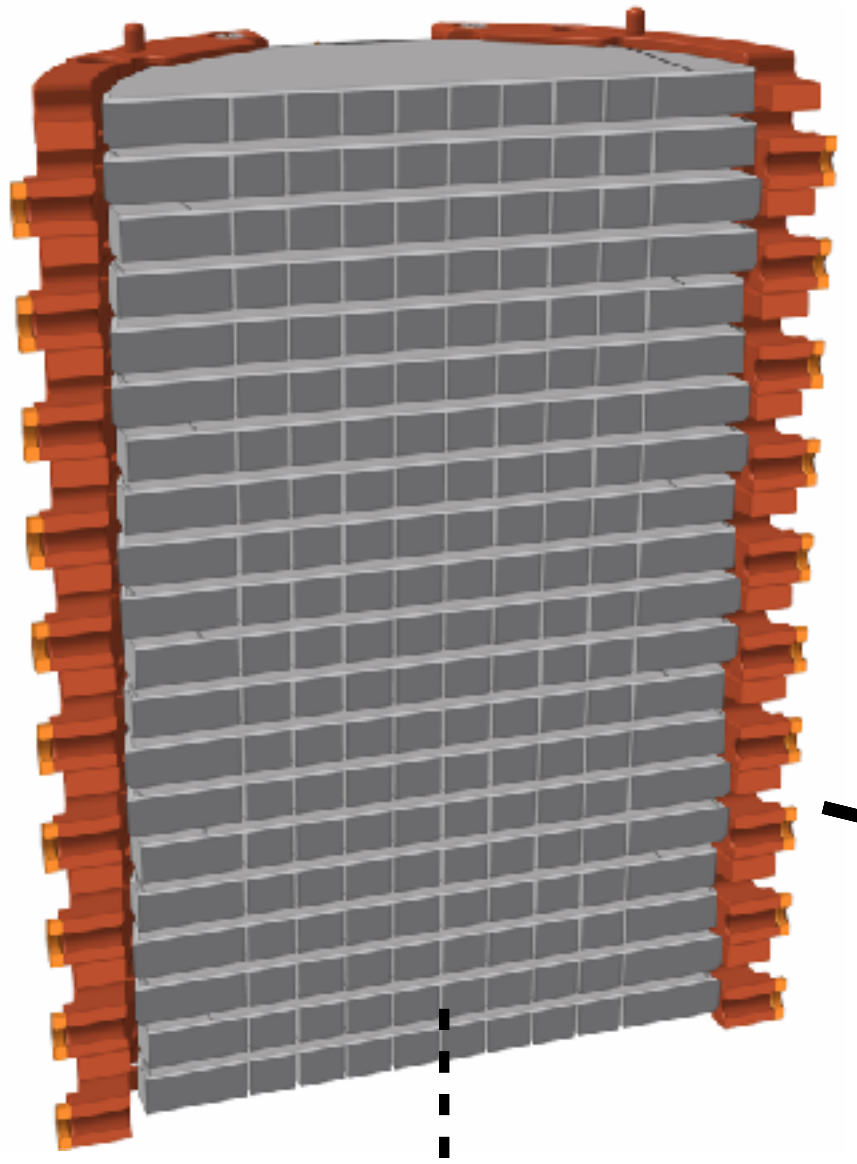
3D copper printing at LNGS
3 wafer holder prototype

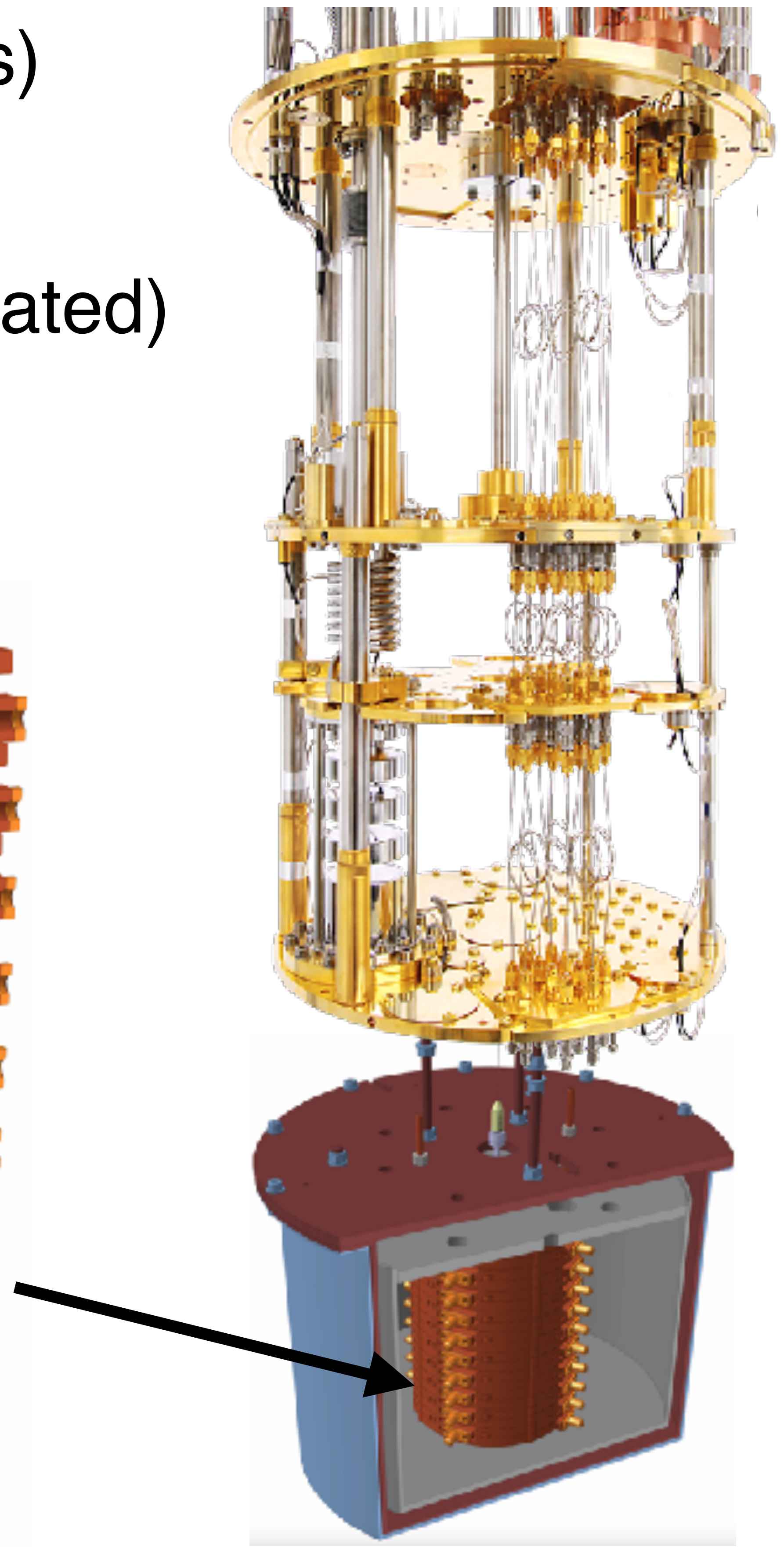
Impact on Dark Matter search

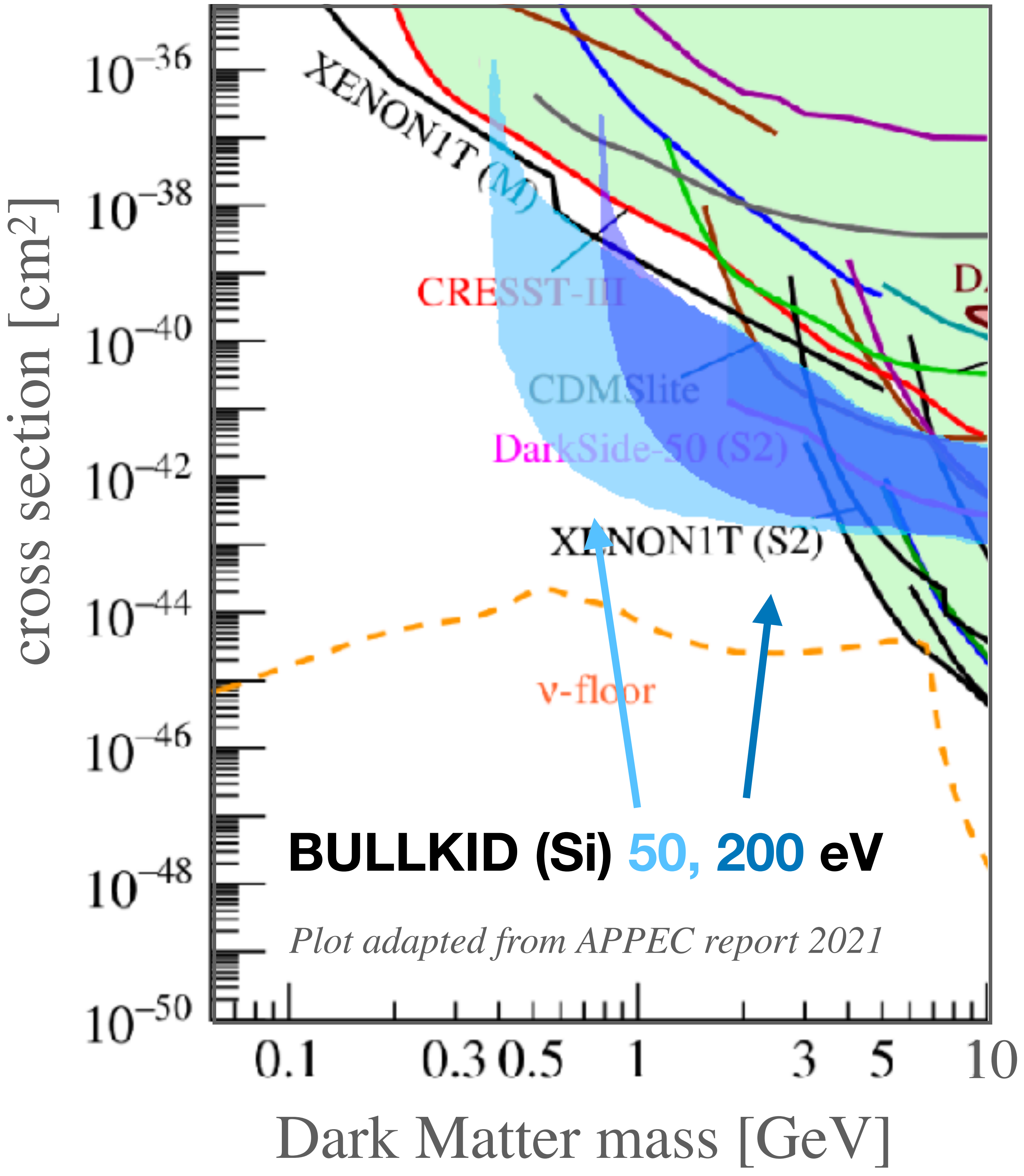


Nuclear recoil detector with:

- ✓ 15 (4”) or 30 (3”) BULLKIDs (2000 voxels)
- ✓ 0.6 kg of silicon target
- ✓ 200 ÷ 50 eV threshold (160 eV demonstrated)







bands range

same background as CRESST

zero background

Unique features for bkg. suppression:

- ✓ No inert material in detector volume
- ✓ fully active
- ✓ fiducialization

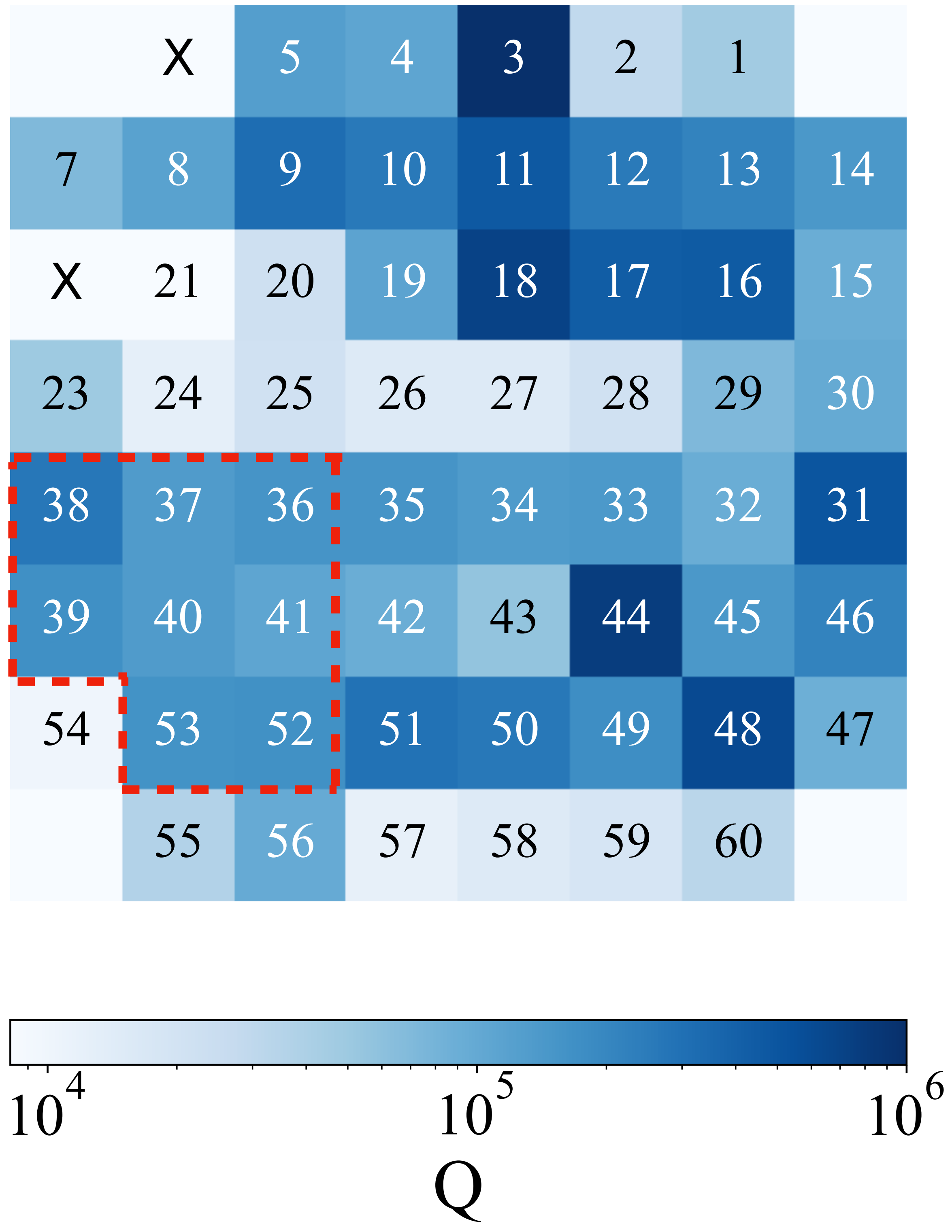
✓ scalable

Collaboration forming now

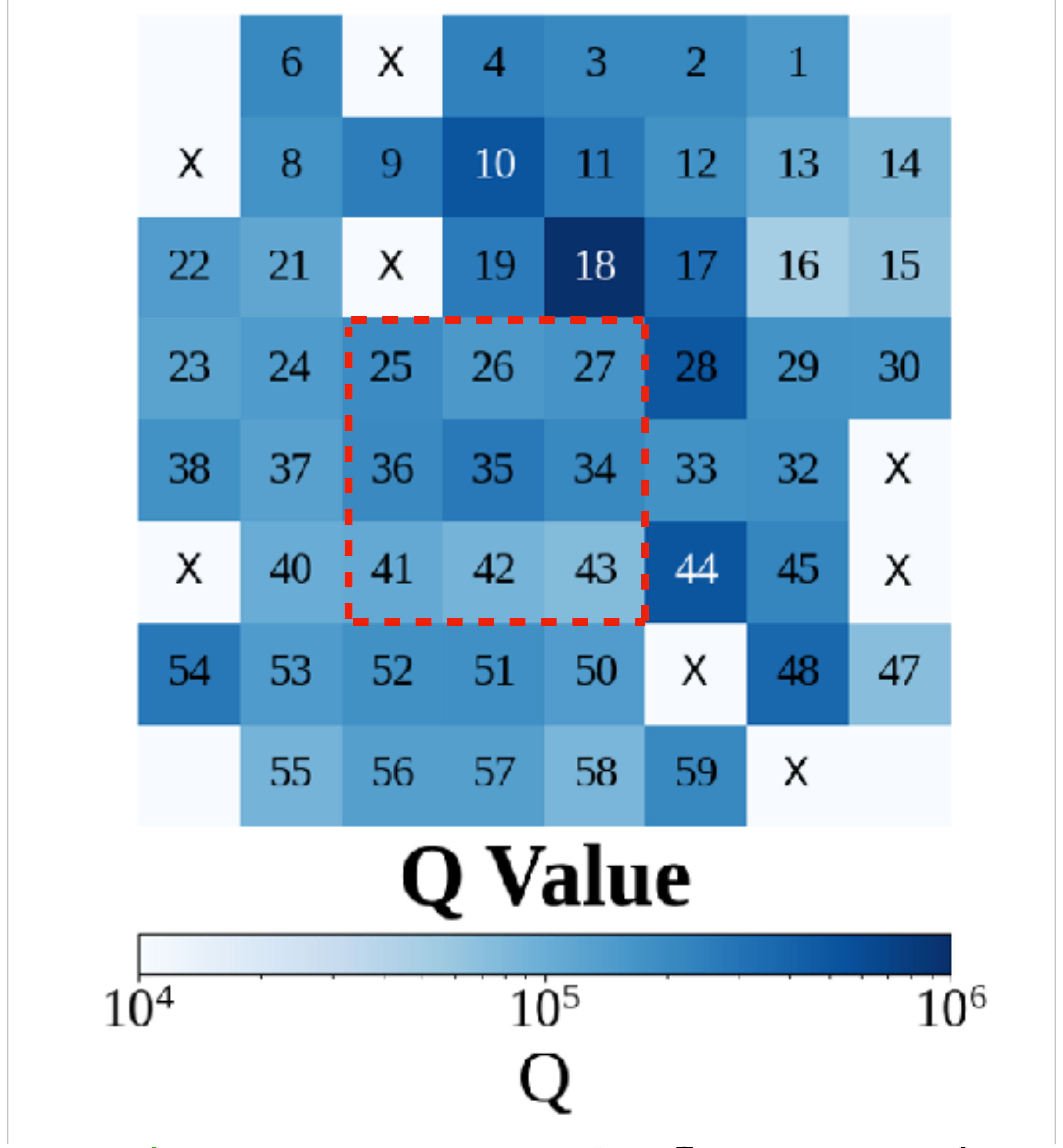
Backup slides

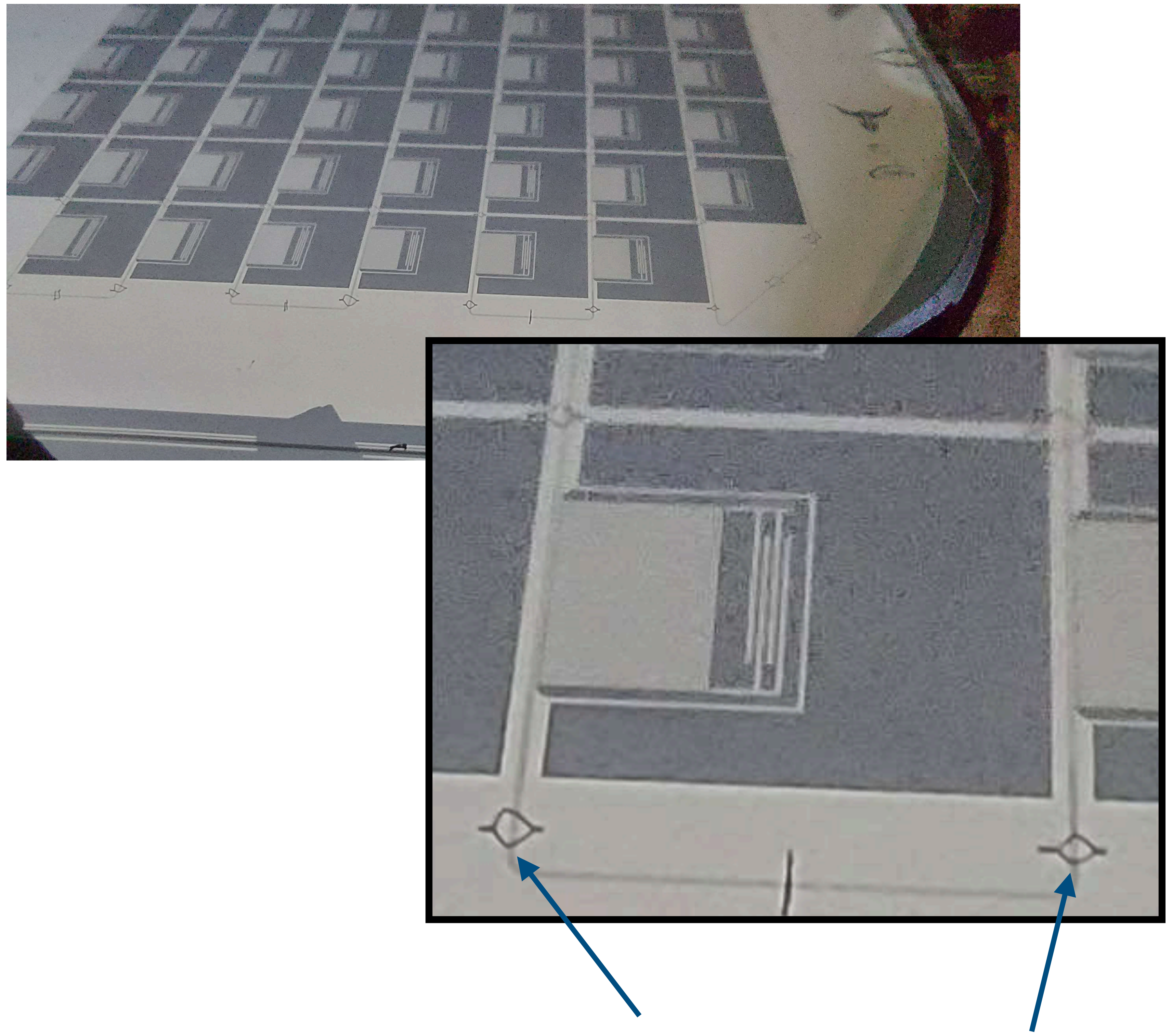
Improvement of uniformity

First version of the array



Same array with improved grounding





Airbridges connecting GND planes

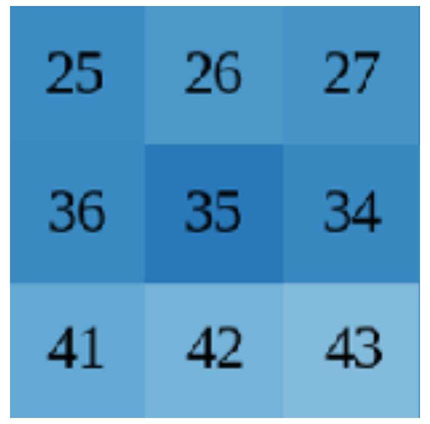
+) 58/60 KIDs alive

–) Response not uniform

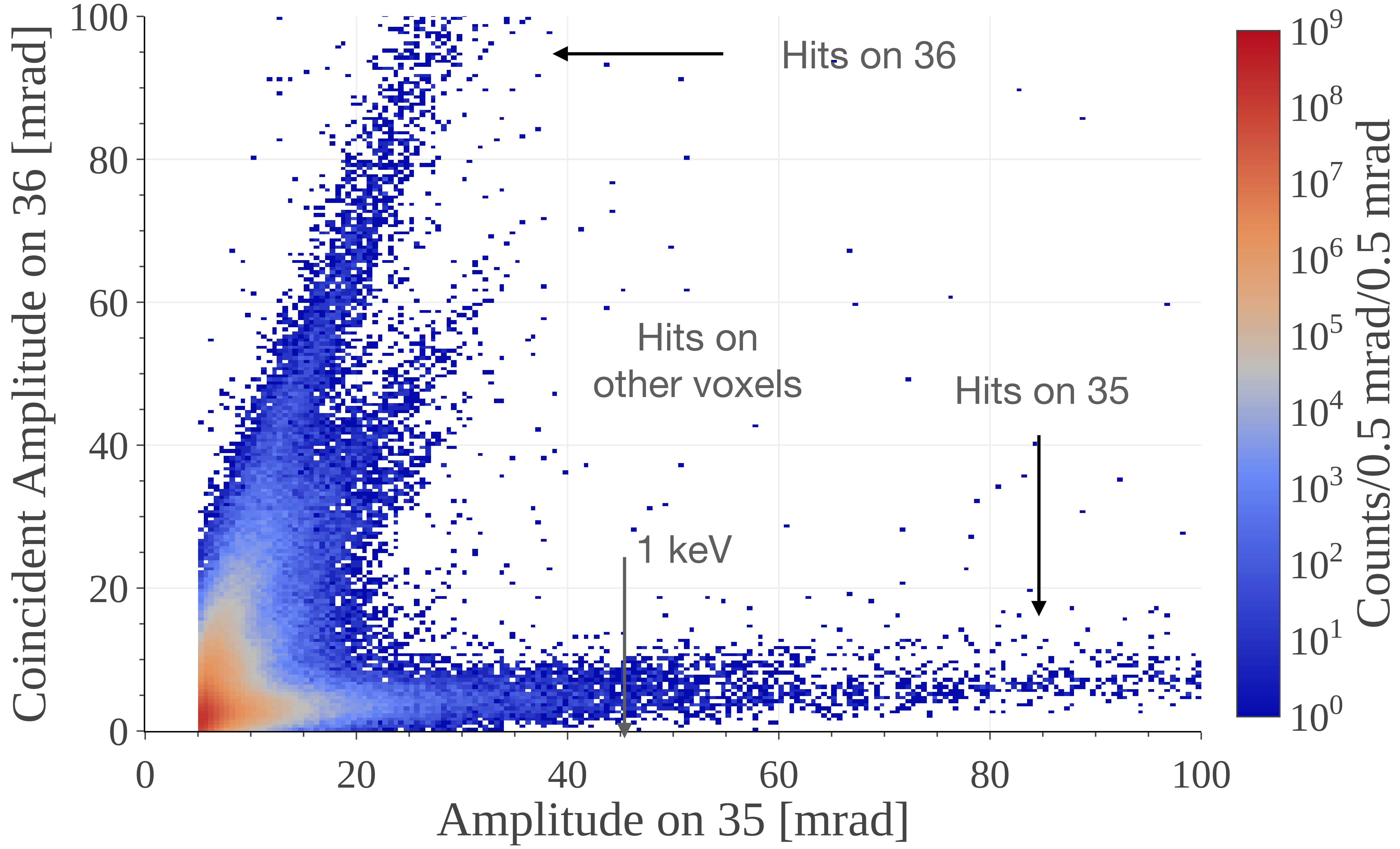
+) All KIDs with Q ~ 10^5 (optimal sensitivity)

–) Some resonator lost during operations

Phonon leakage, selection

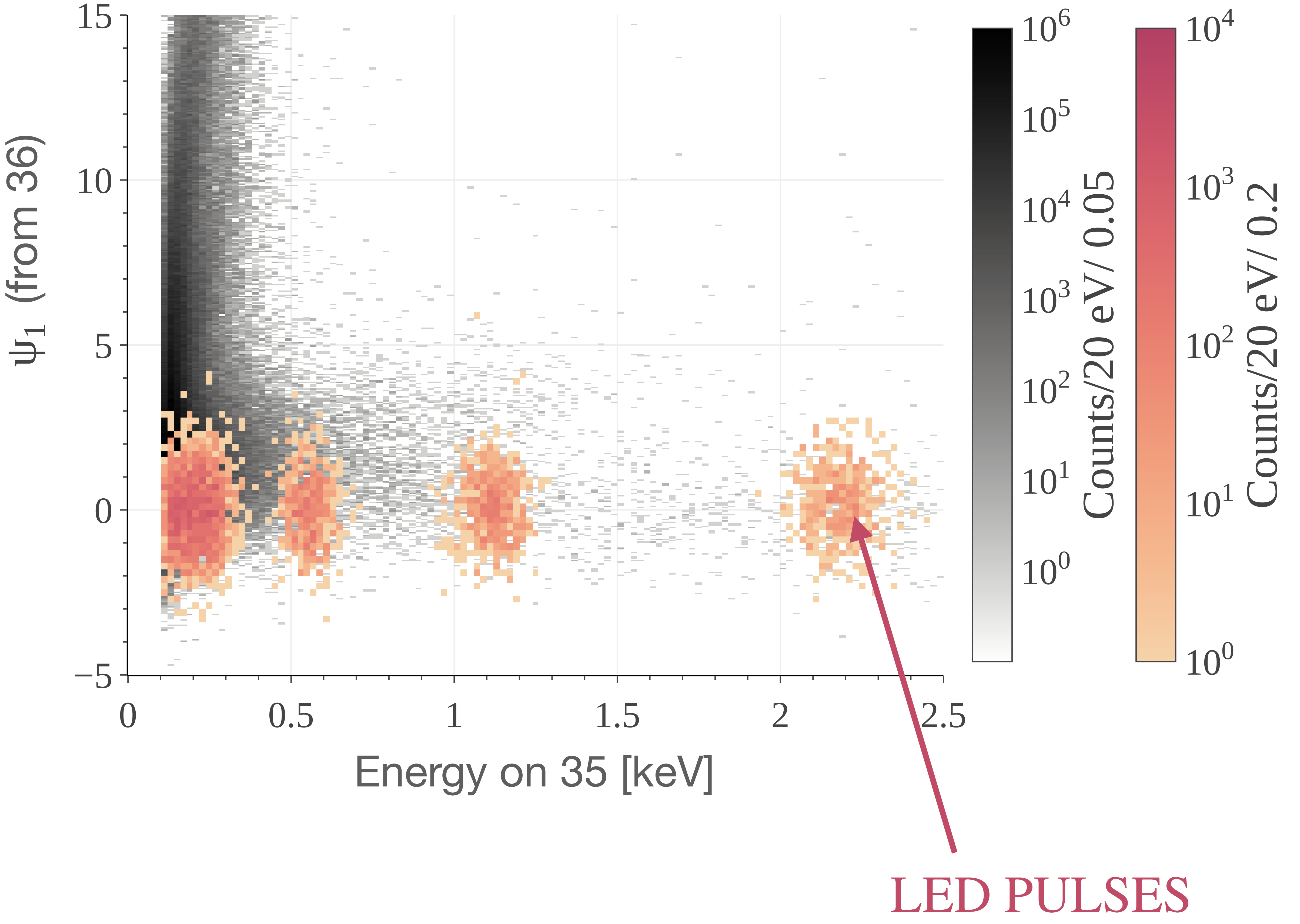


Pulse shape cuts only

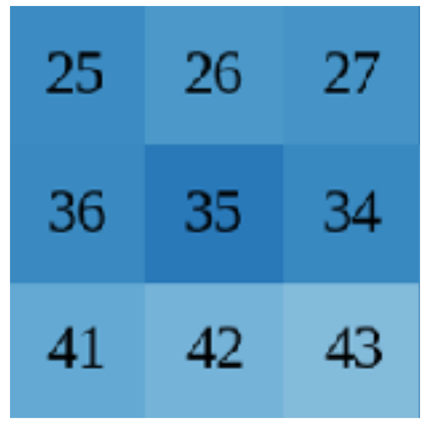


$$\psi_n = \frac{A_n - A \cdot r_n}{\sqrt{\sigma_{0,n}^2 + r_n^2 \cdot \sigma_0^2}}$$

r_n: expected leakage



Phonon leakage, selection



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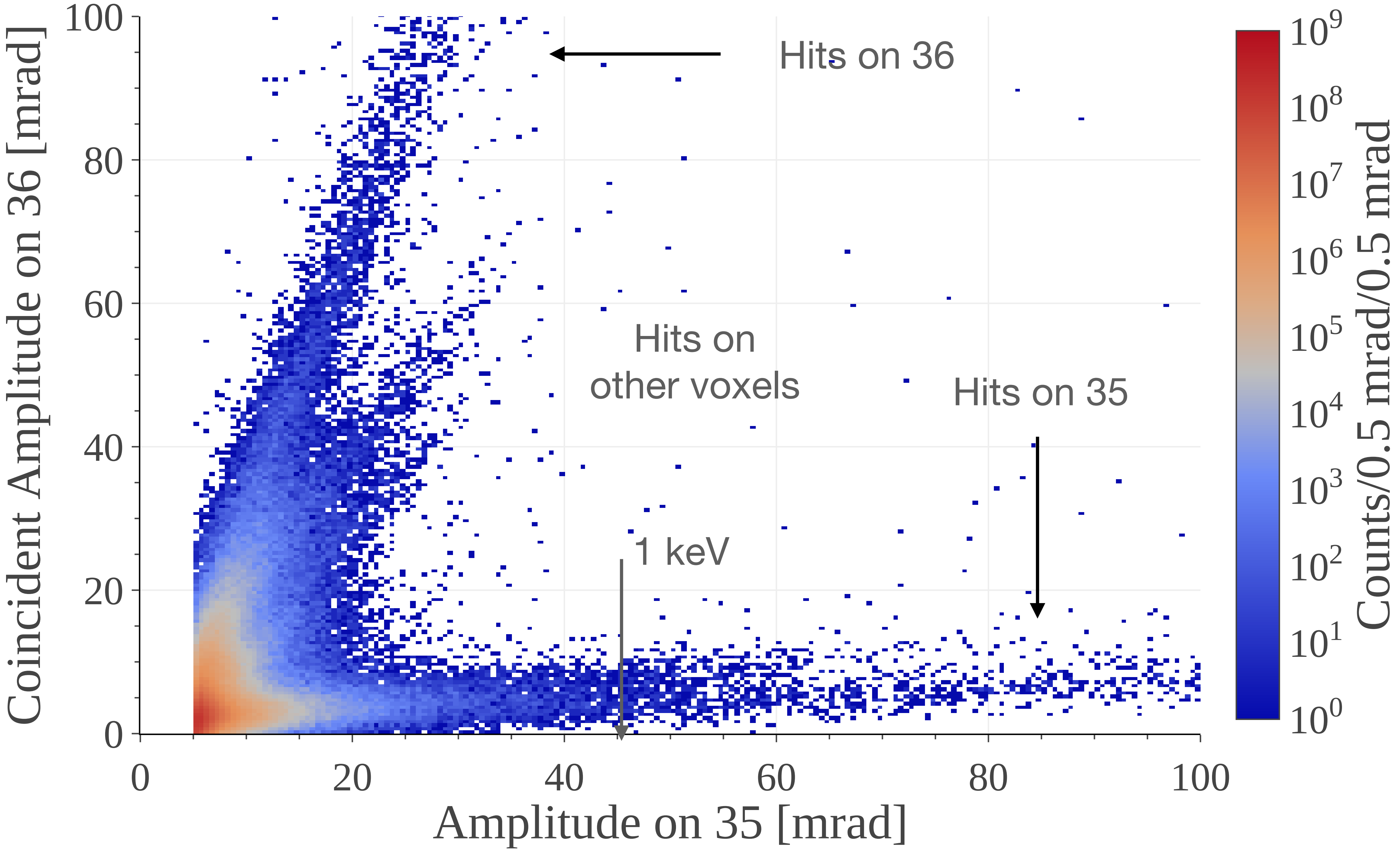

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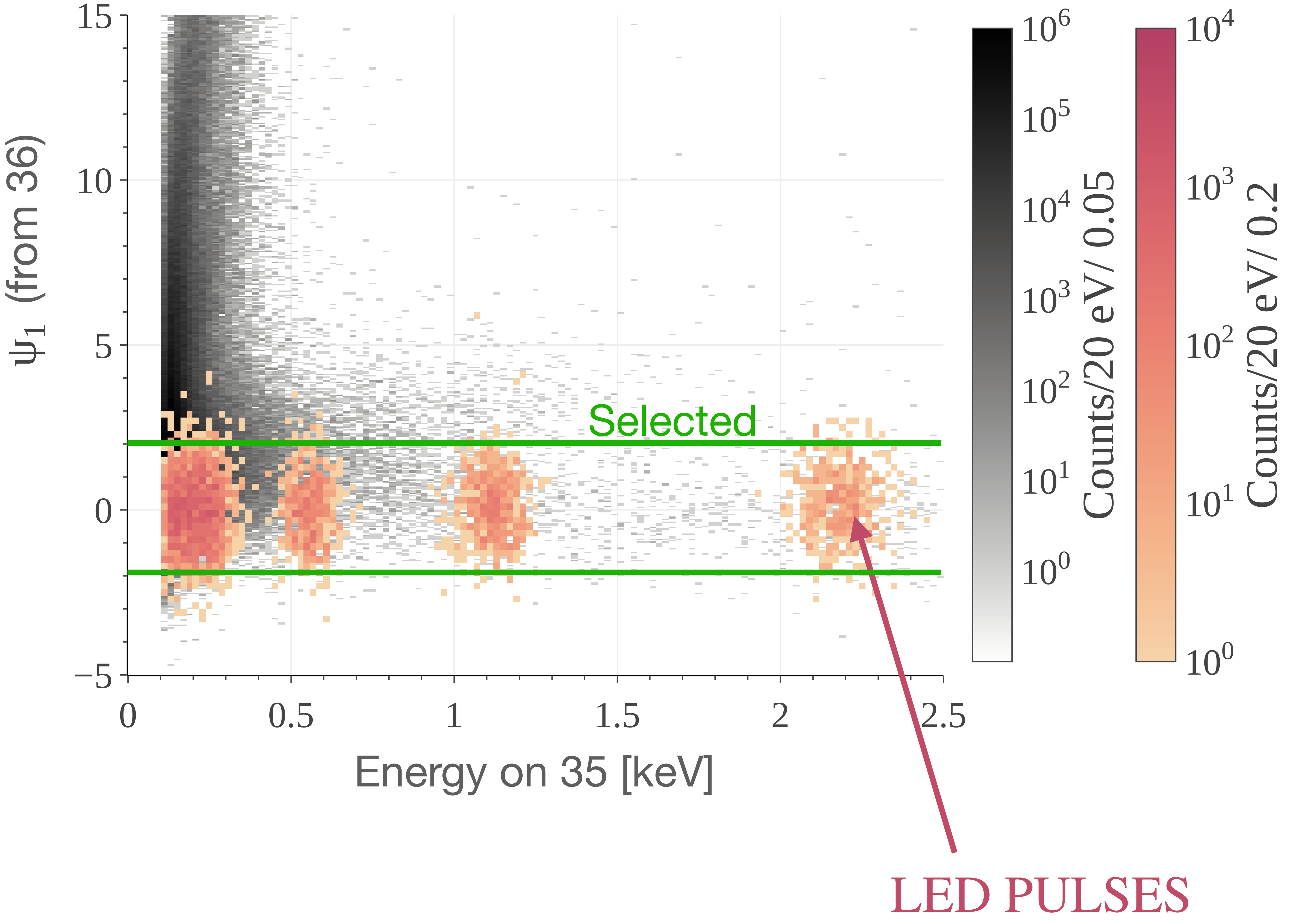
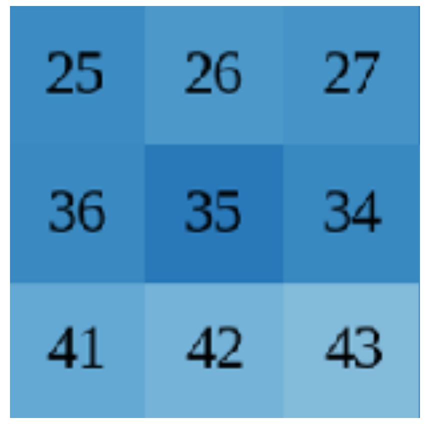
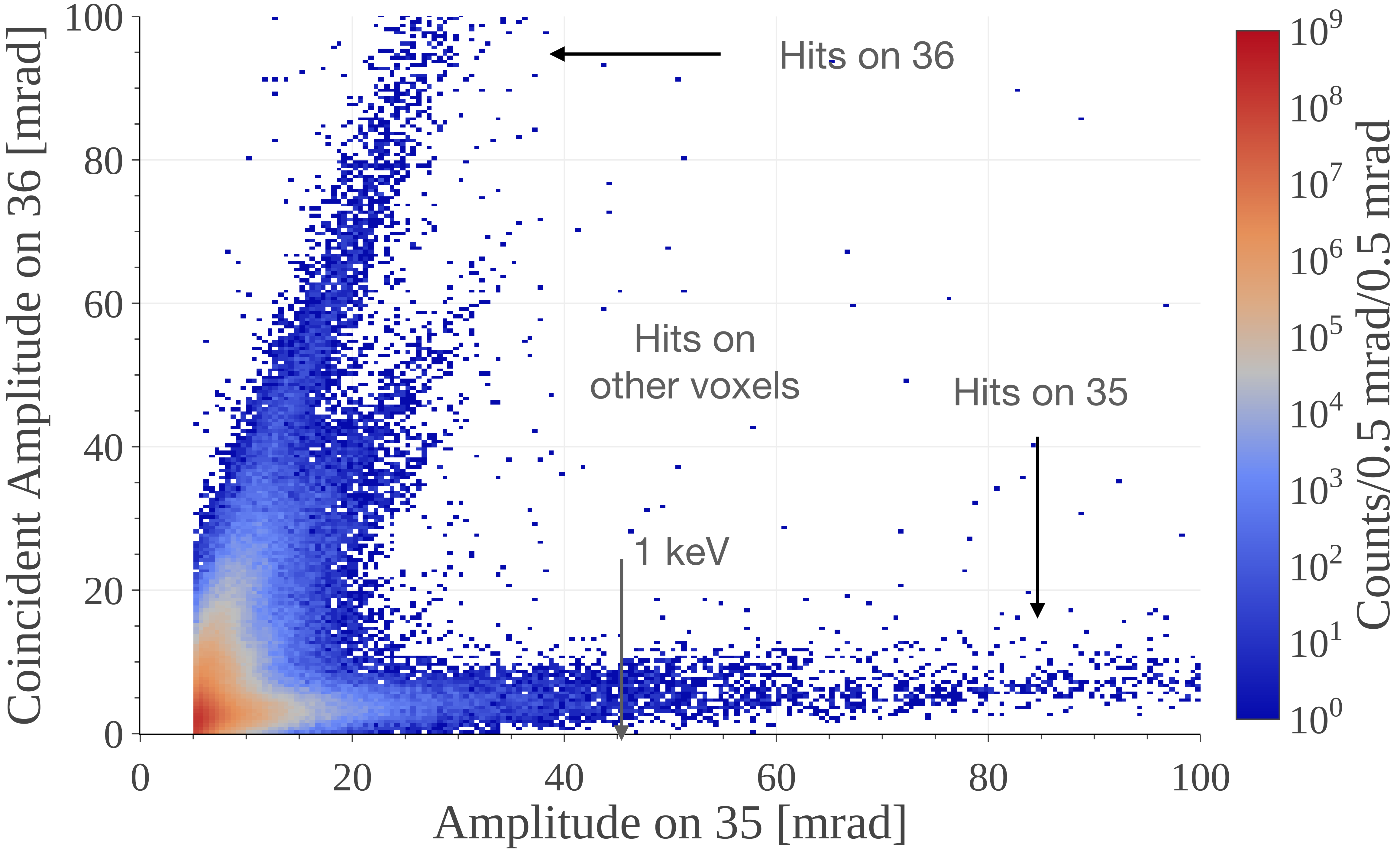


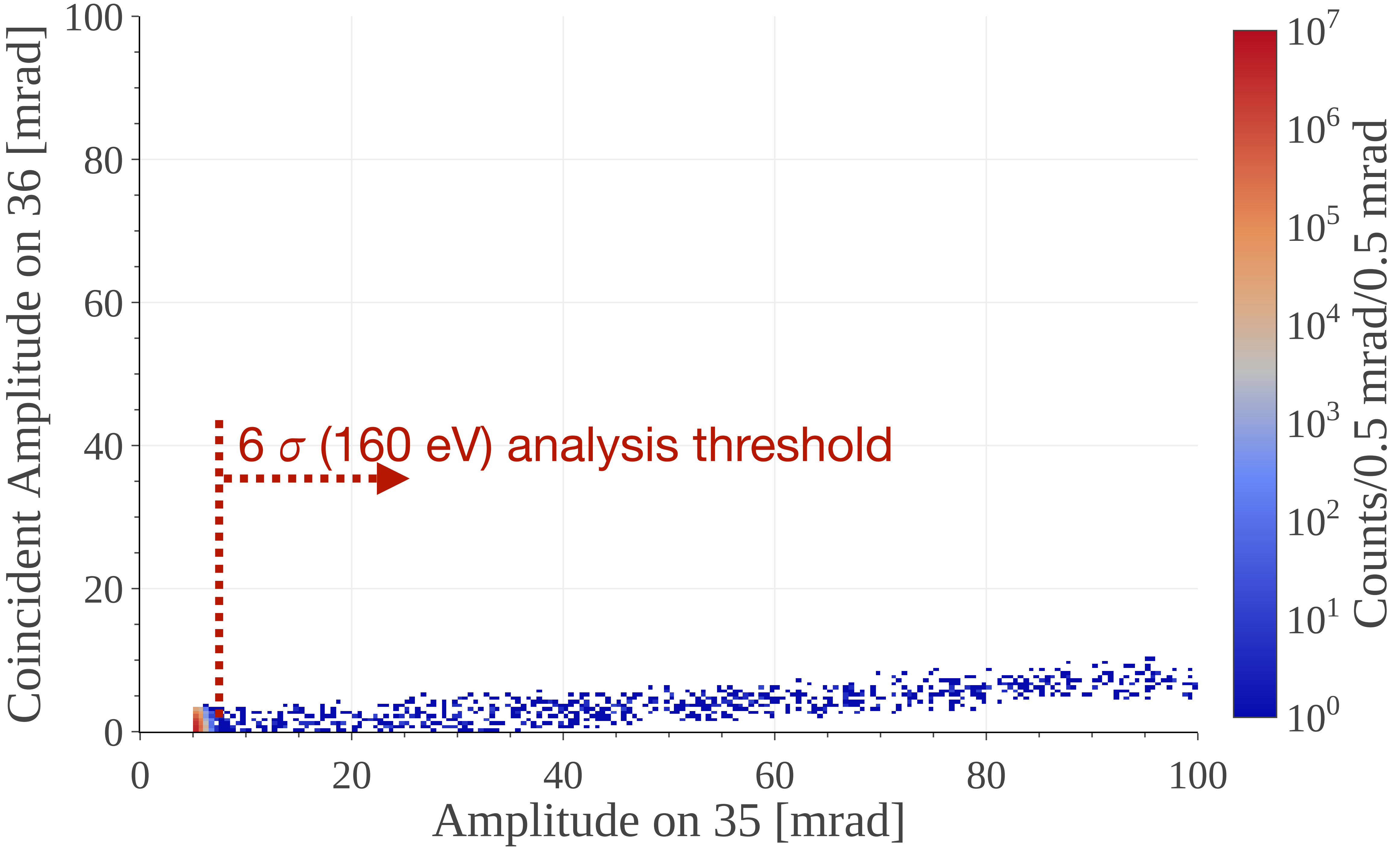
Phonon leakage, selection



Pulse shape cuts only



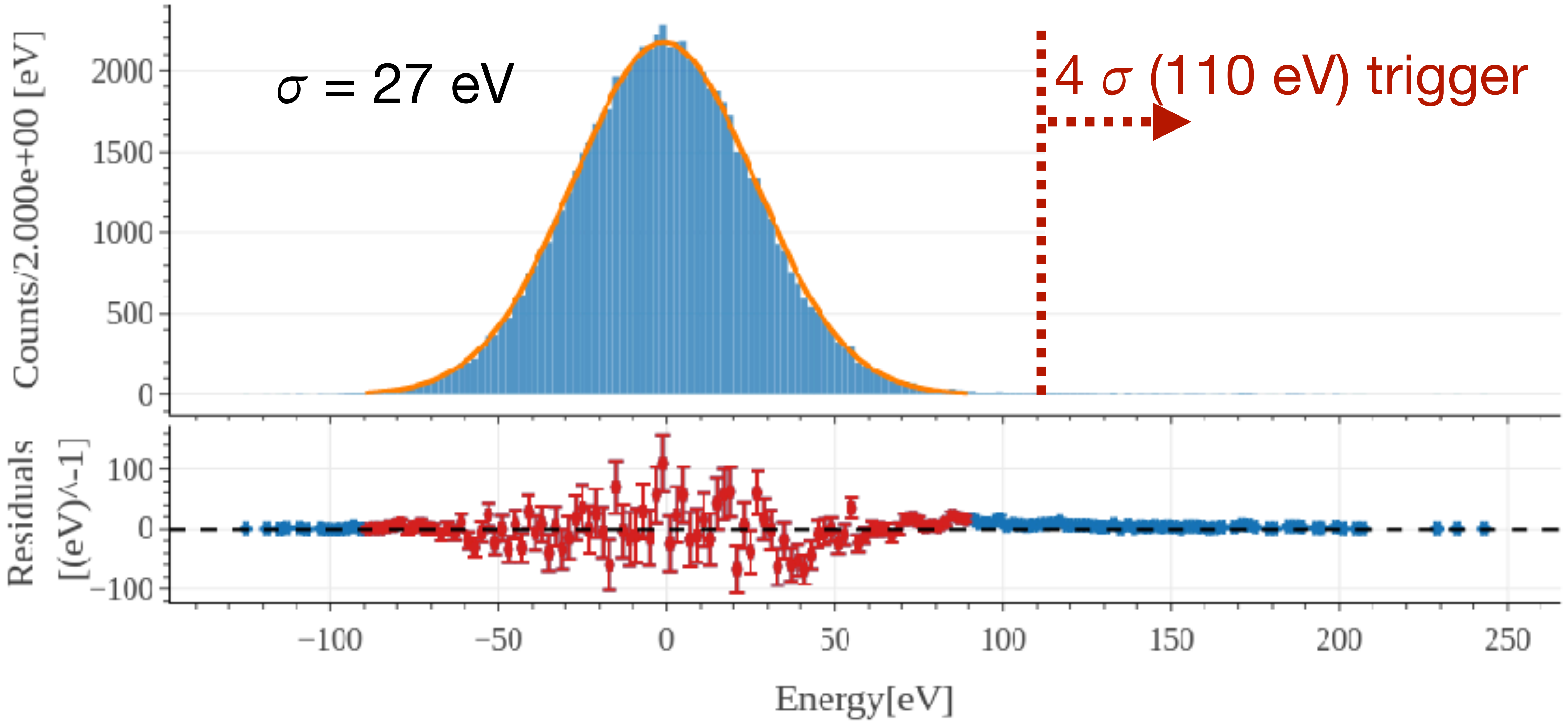
Pulse shape cuts
+ coincident amplitude cut on 8 neighbours



Study of the energy threshold

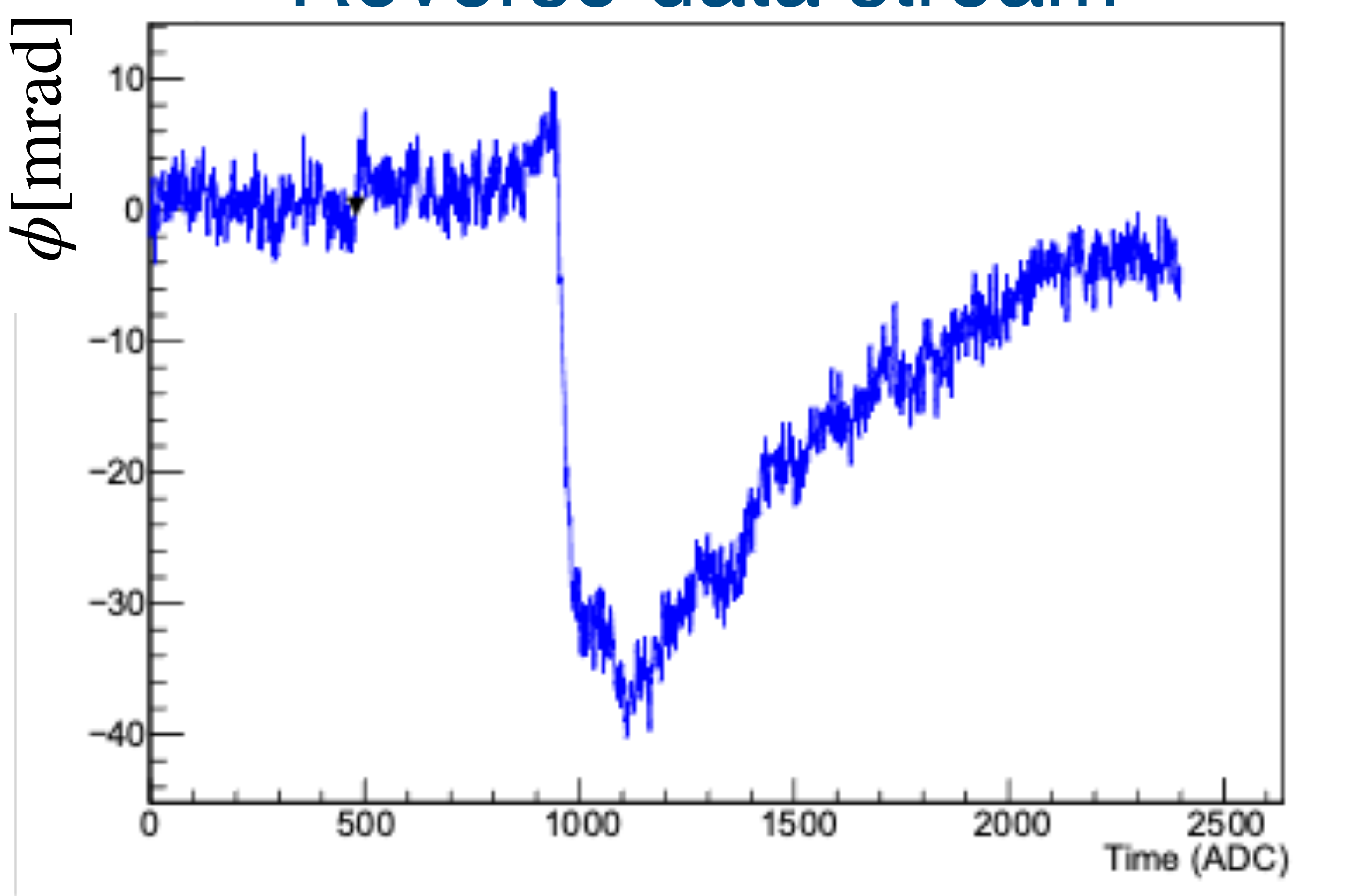
Energy threshold usually set at 5 noise σ

- Reduces the rate of of false triggers
- We choose 4σ for the trigger

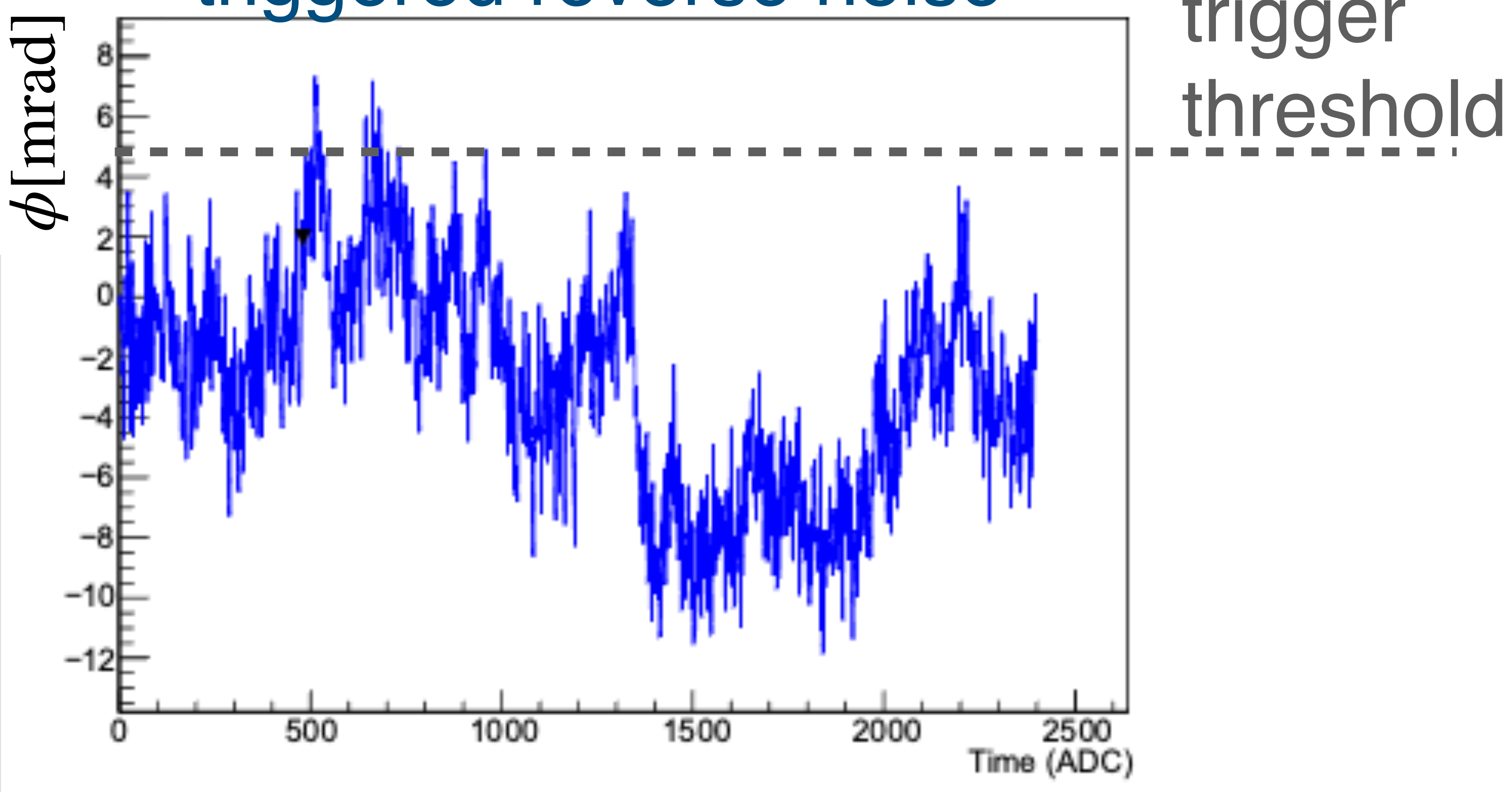


Statistics of false triggers from reverse data stream (minus sign on samples)

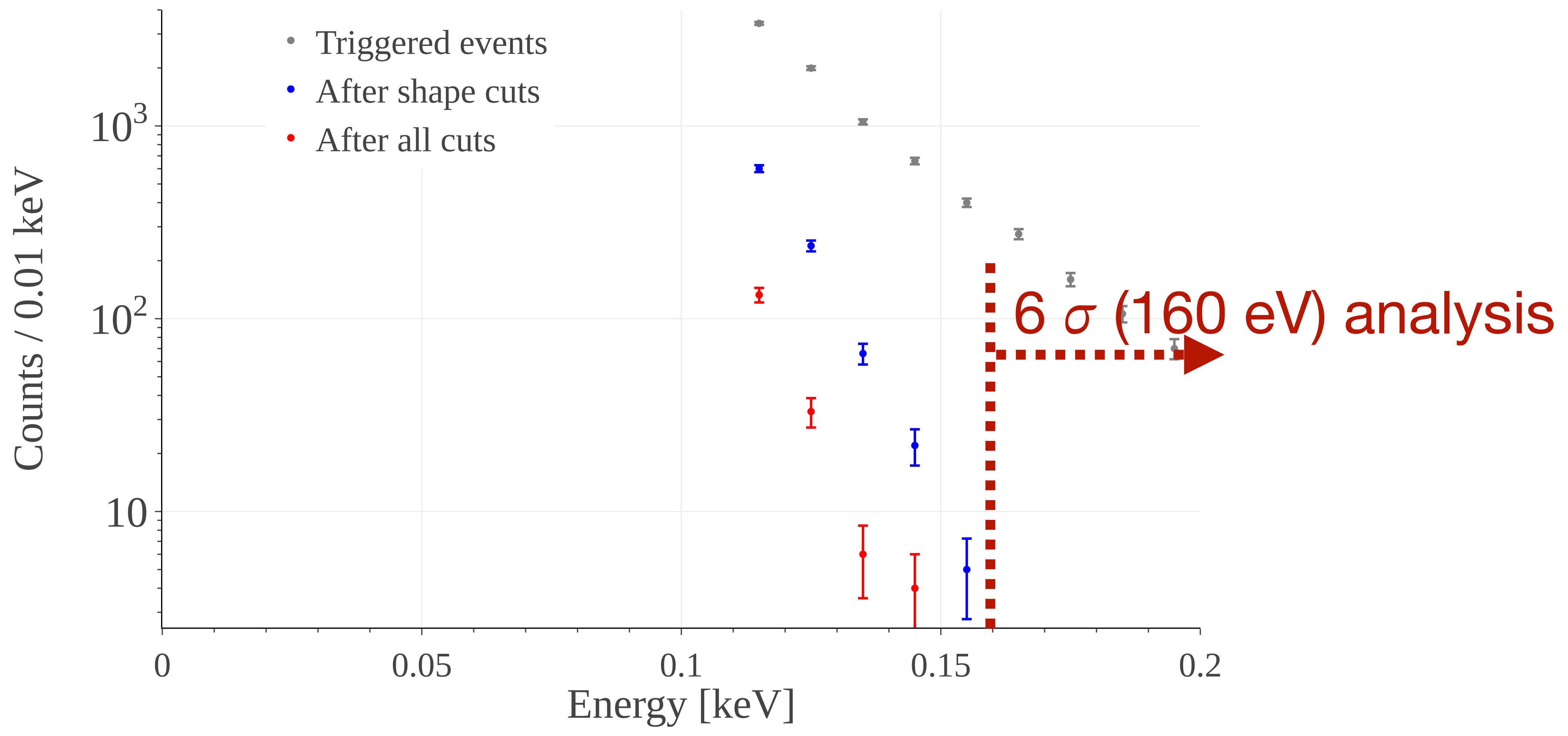
Reverse data stream

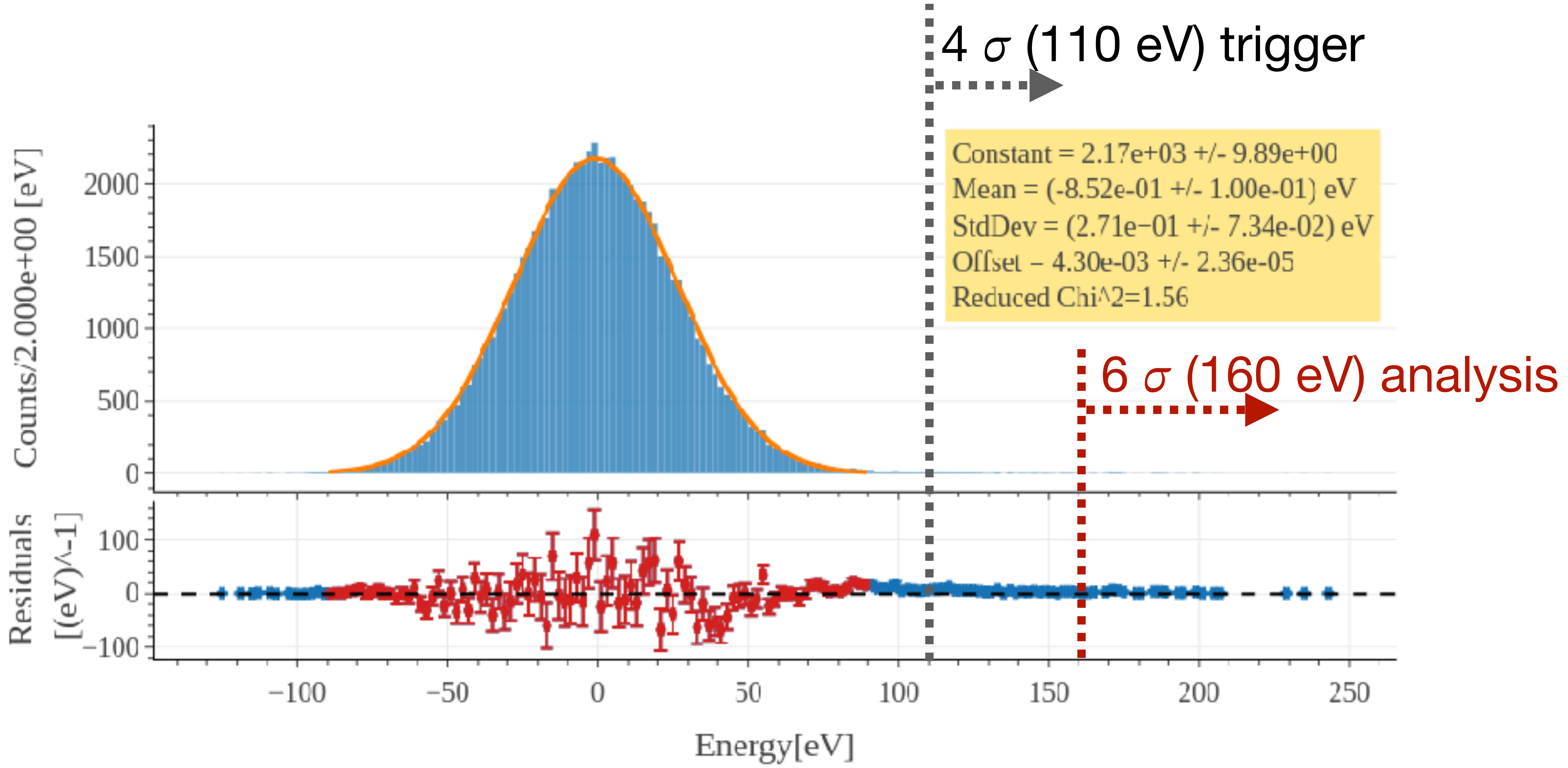


triggered reverse noise



Reverse trigger spectrum (30 mins live time)





From the spectrum of false positive reverse triggers surviving the cuts

we set the analysis threshold to 6σ

Towards the experiment

MC Simulations

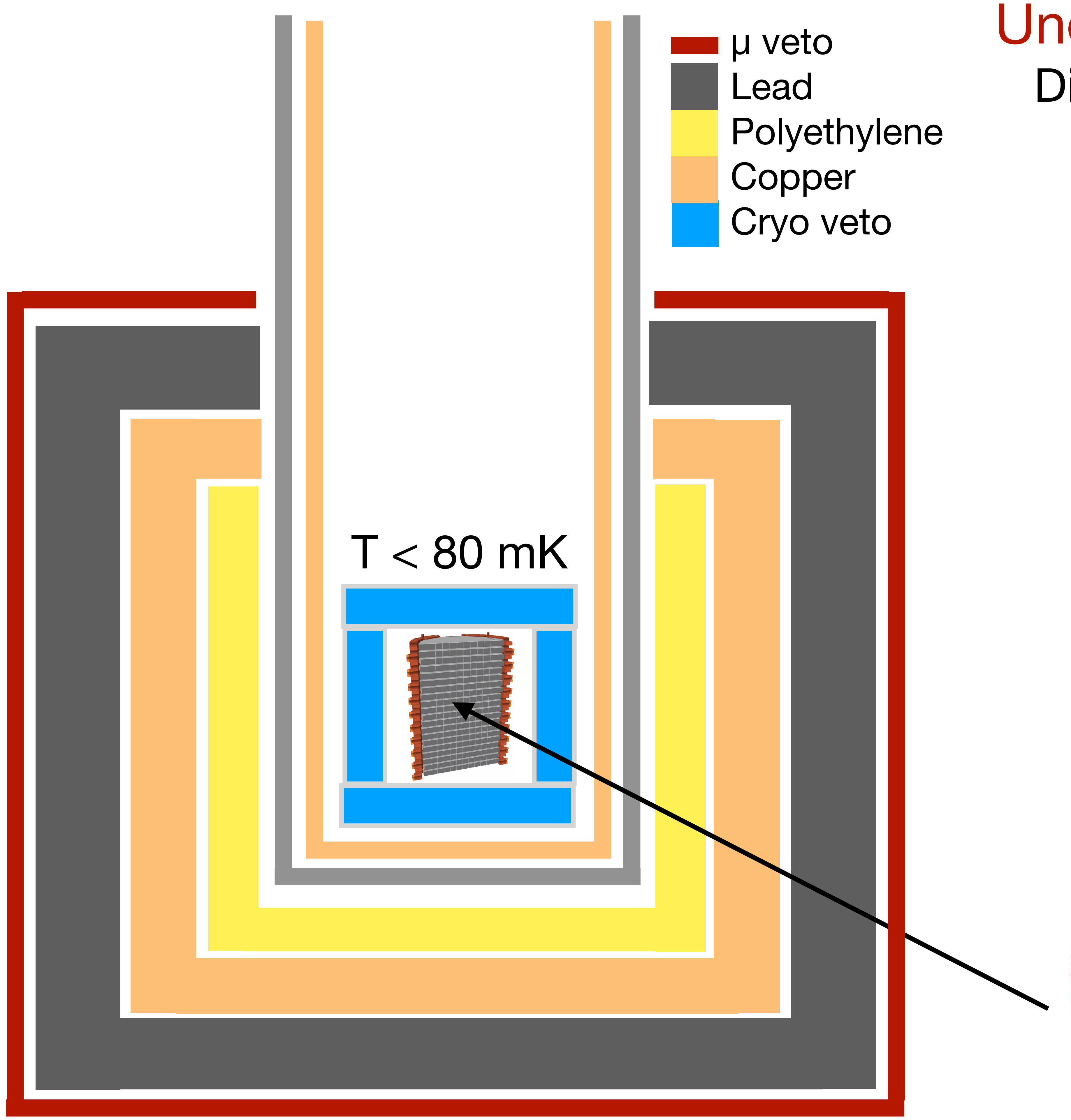
Design of the apparatus
Definition of required radiopurity

Apparatus

Cryostat outer shielding (PE, Pb, …)
Inner shielding
Outer muon veto (scint. panels)?
Cryo-veto around the BULLKIDs?
(BGO + Light detector?)

Energy calibration

Not possible with fibers:
neutron recoils (a là CRAB)?
Cs or Co Compton ?



Underground cryo-infrastructure

Dilution refrigerator with T < 80 mK

RF Readout

~20 RF lines,
SDR boards with sync,
trigger logic (clusters)

DAQ

Data handling
Data storage

Data analysis

2k pixel,
cluster analysis

erc DANAE
stack of wafers

Collaboration is forming and is open to contributions