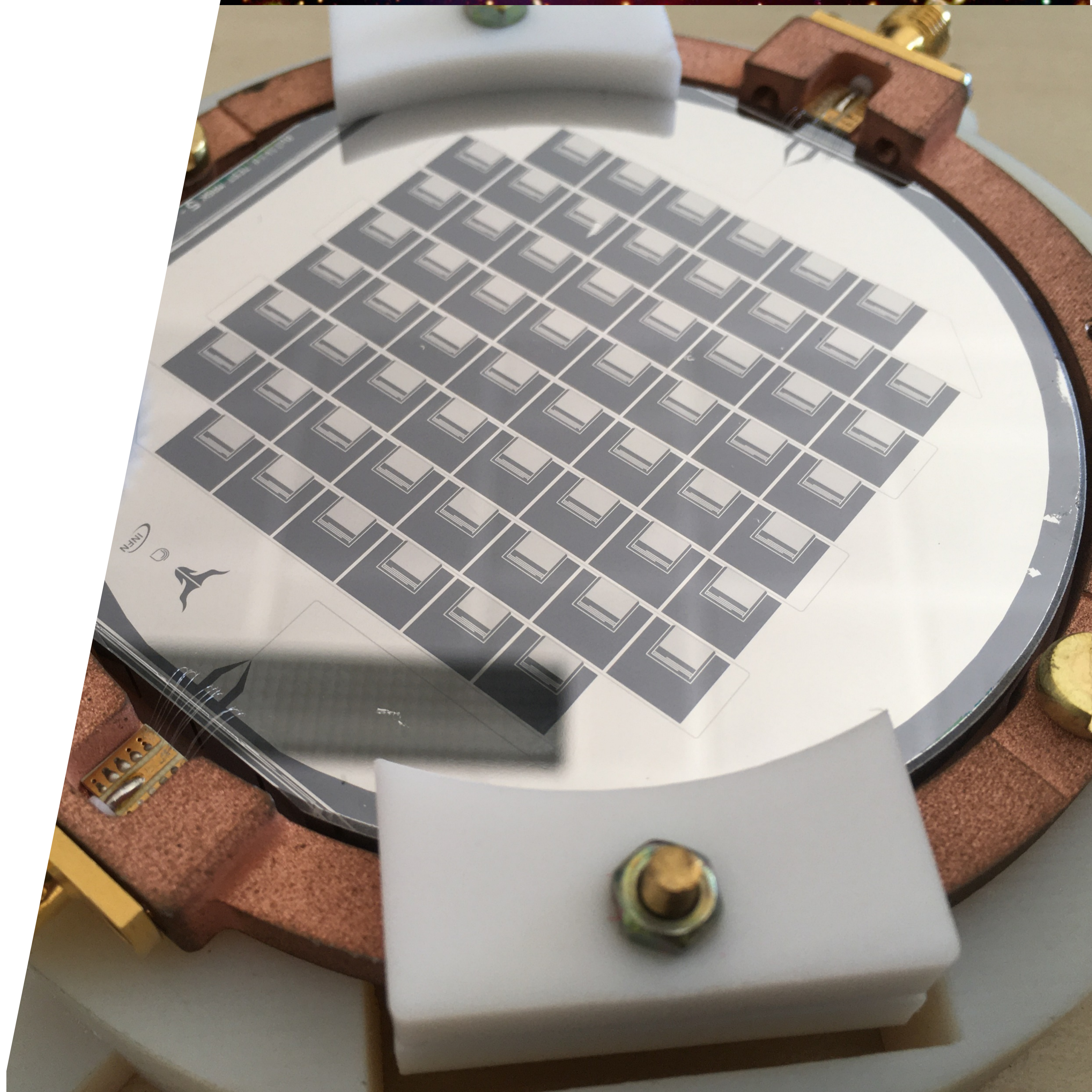
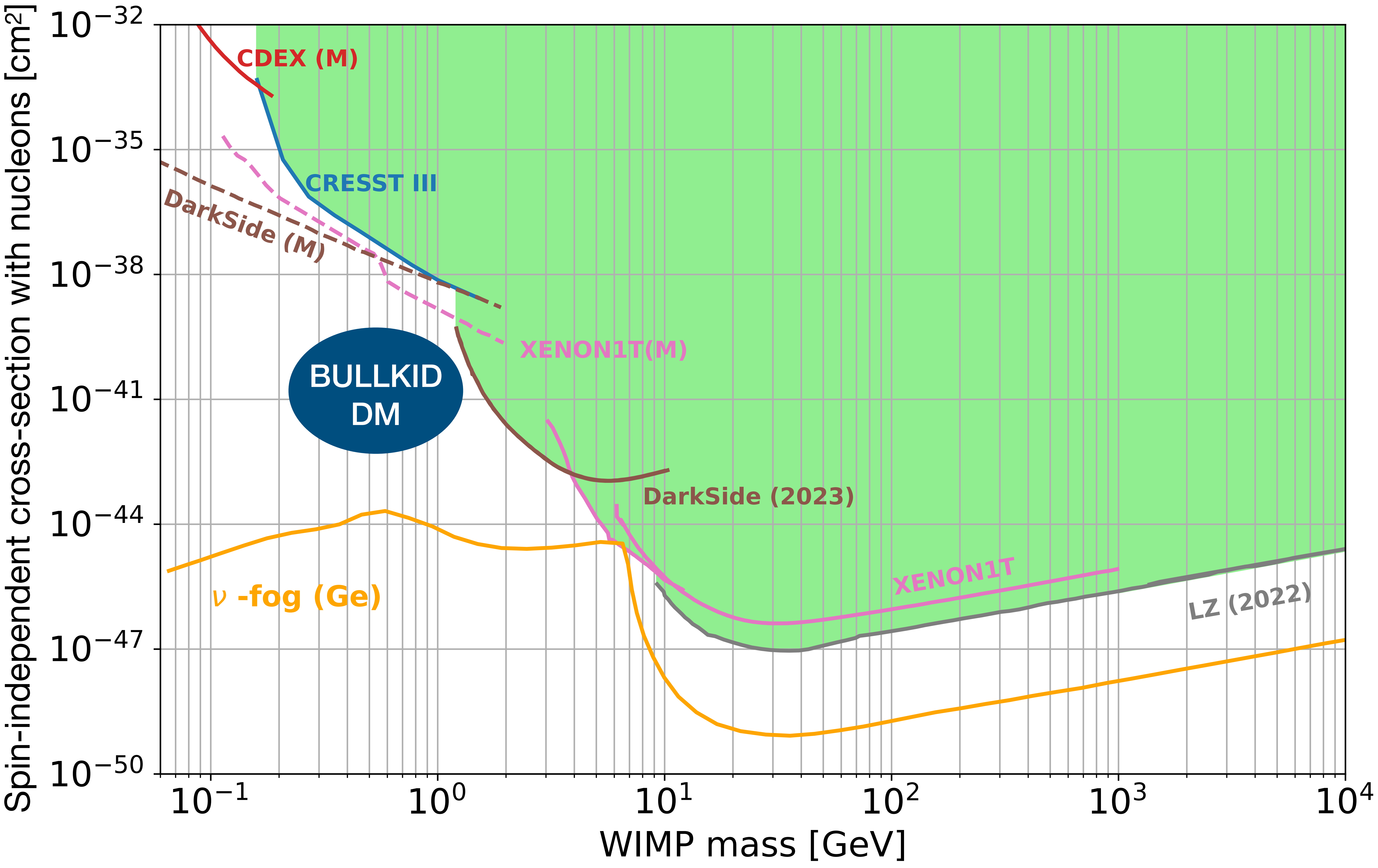
BULLKID-DM

Marco Vignati on behalf of the coll., LNGS, 22 April 2024

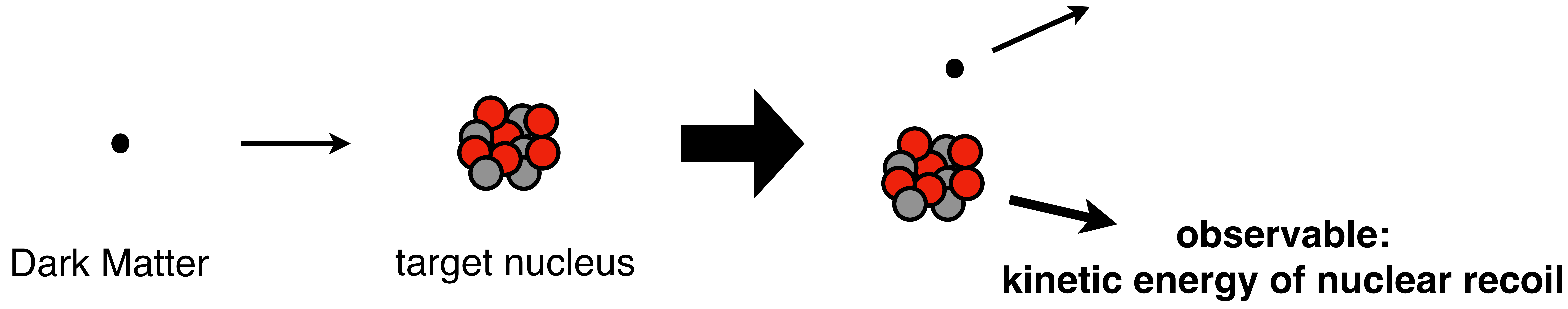


Objective

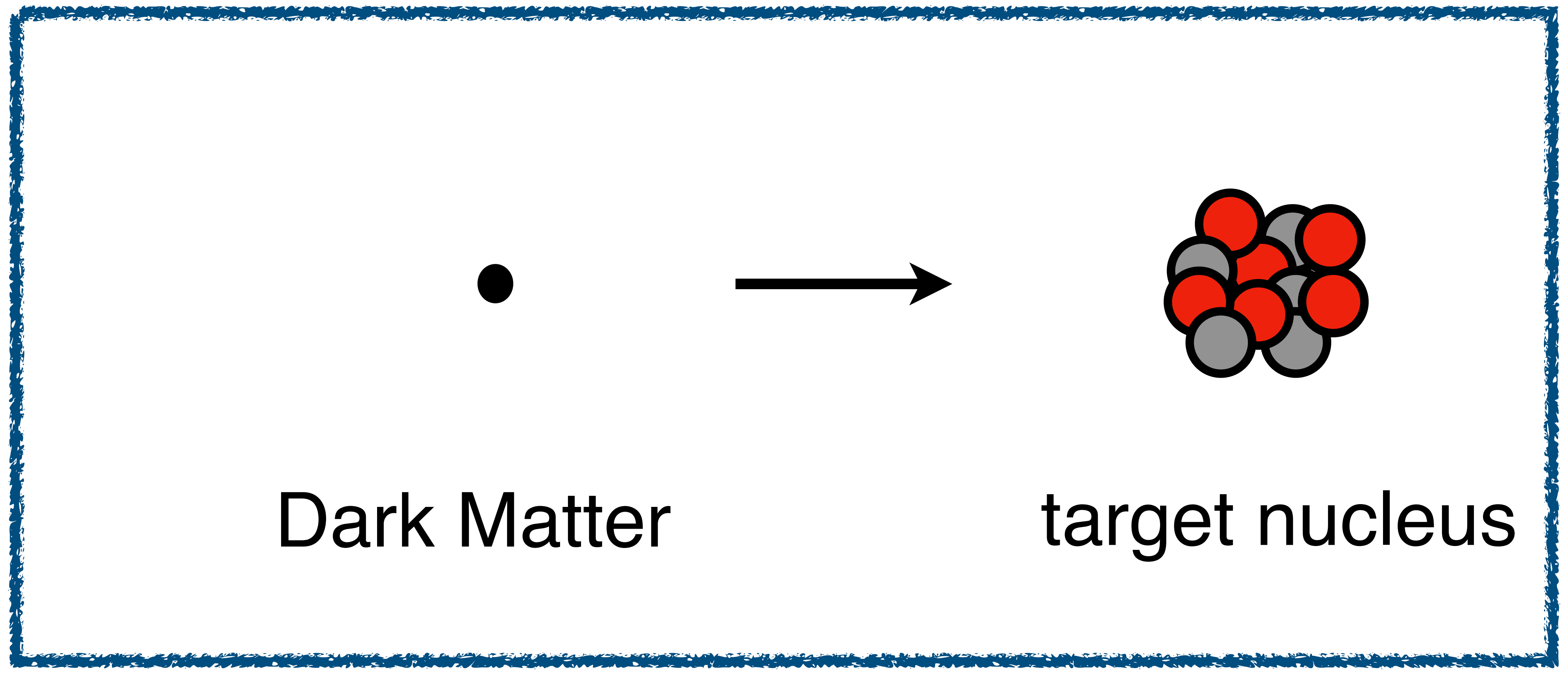


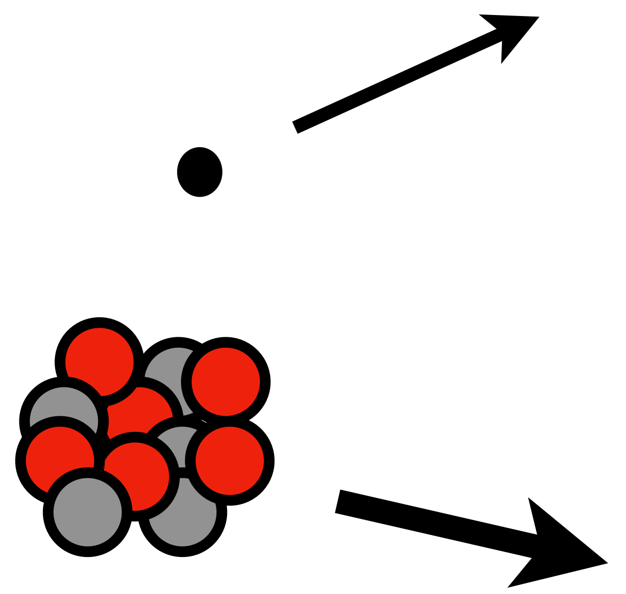
Spin-independent cross-section with nucleons [cm^2]
10^{-32}
10^{-35}
10^{-38}
10^{-41}
10^{-44}
10^{-47}
10^{-50}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
WIMP mass [GeV]
CDEX (M)
CRESST III
DarkSide (M)
XENON1T(M)
BULLKID DM
DarkSide (2023)
XENON1T
LZ (2022)
ν -fog (Ge)

Direct dark matter search below 1 GeV/c^2



Direct dark matter search below 1 GeV/c^2

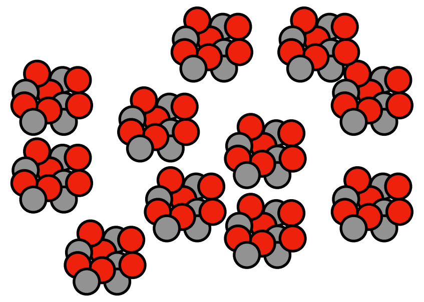




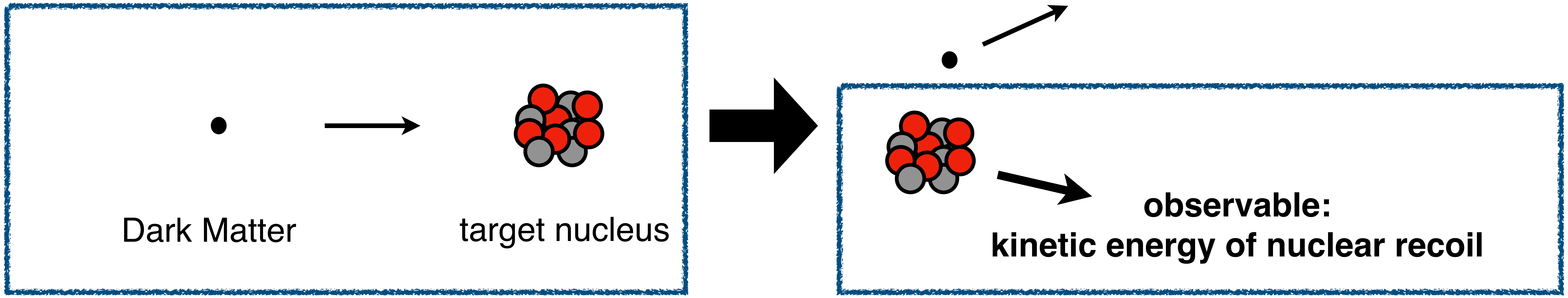
observable:
kinetic energy of nuclear recoil

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

zero-background
large number of targets *O*(1 kg)



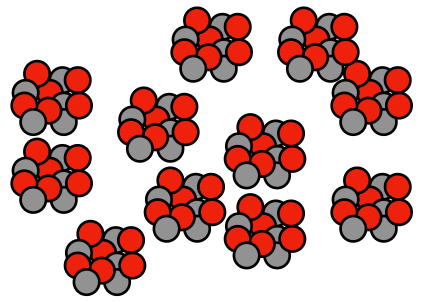
Direct dark matter search below 1 GeV/c^2

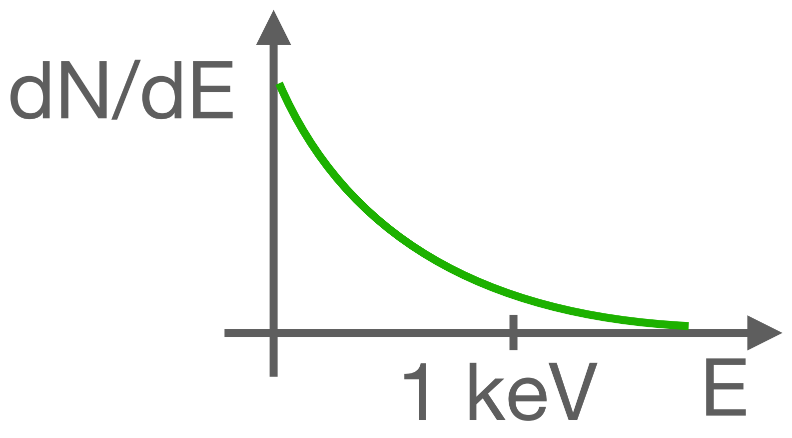


cross section $\sigma < 10^{-40}\ \mathrm{cm}^2$

energy < 1 keV

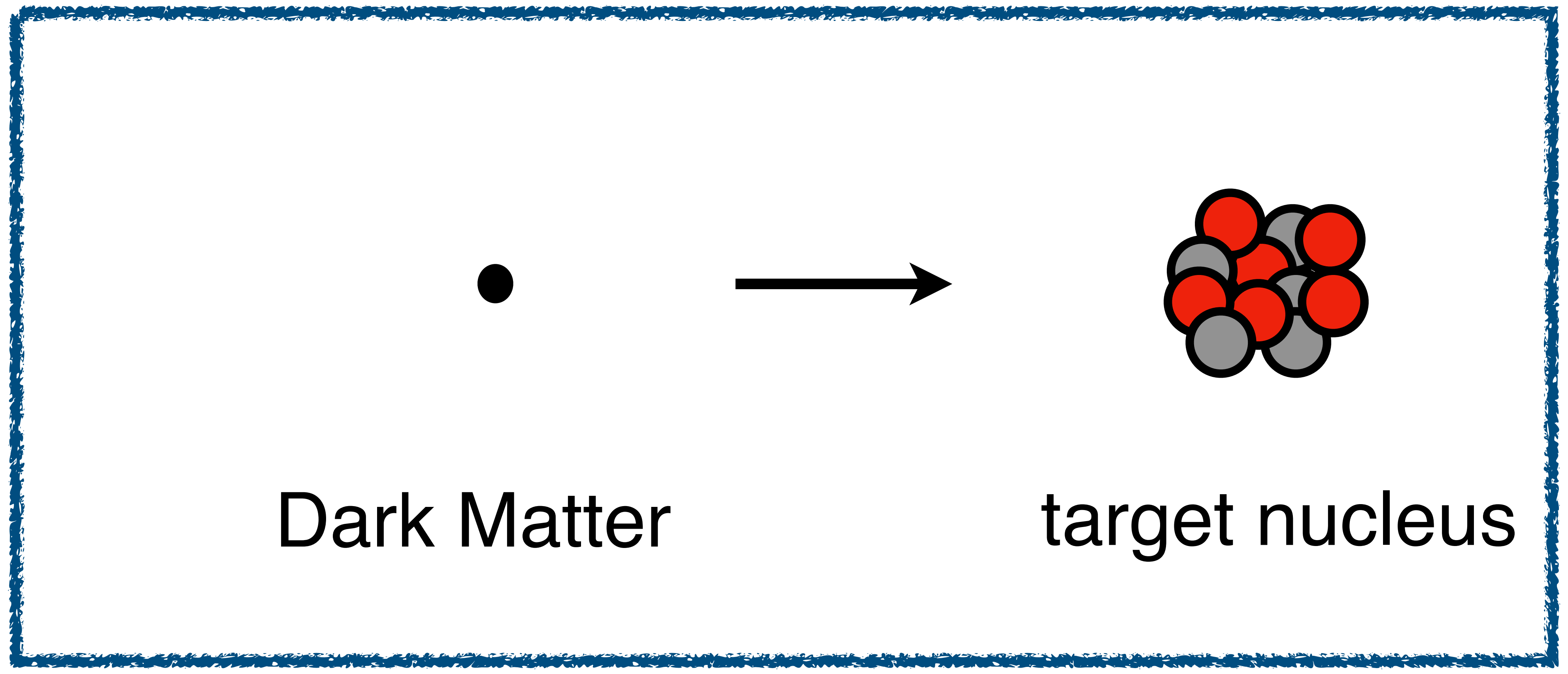
zero-background
large number of targets *O*(1 kg)

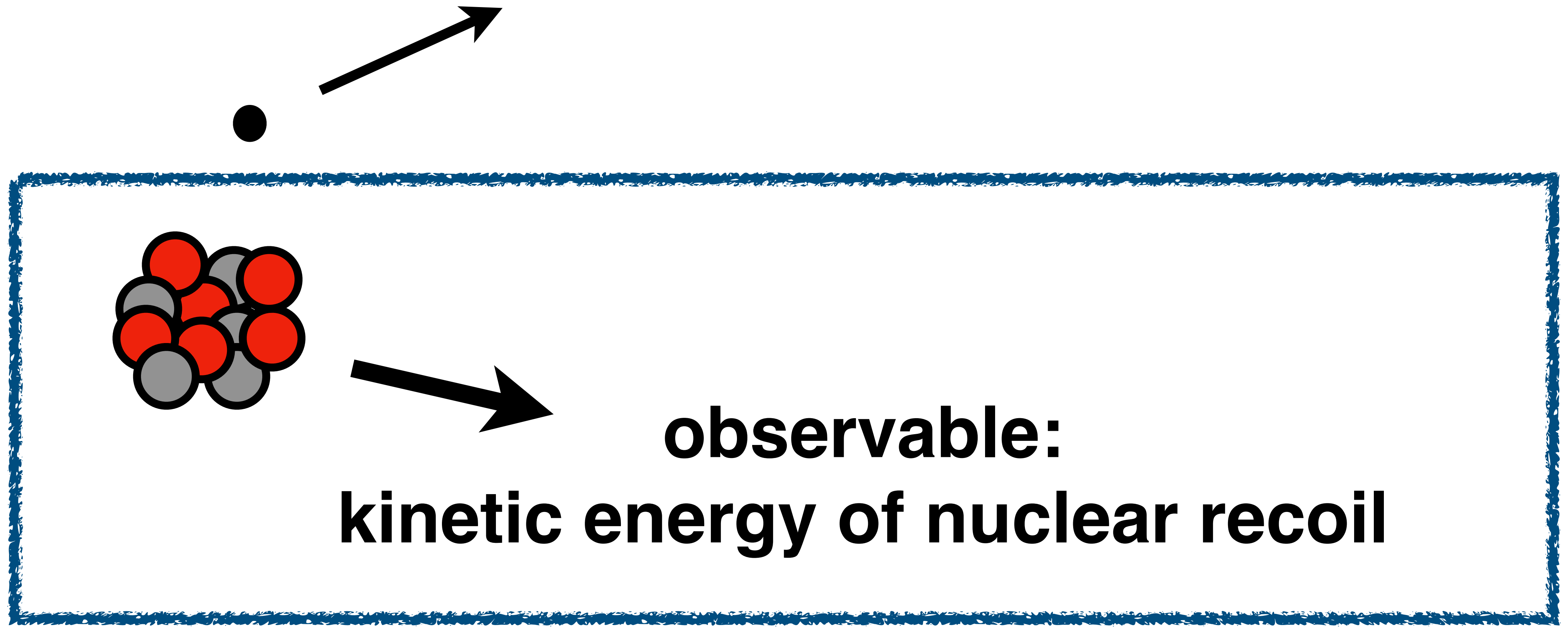




low-energy threshold
***O*(100 eV)**

Direct dark matter search below 1 GeV/c^2

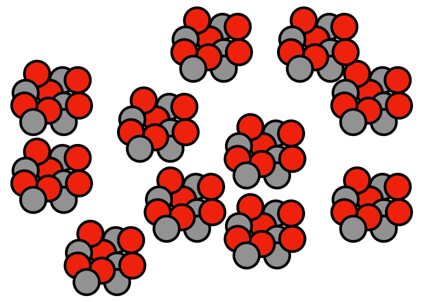


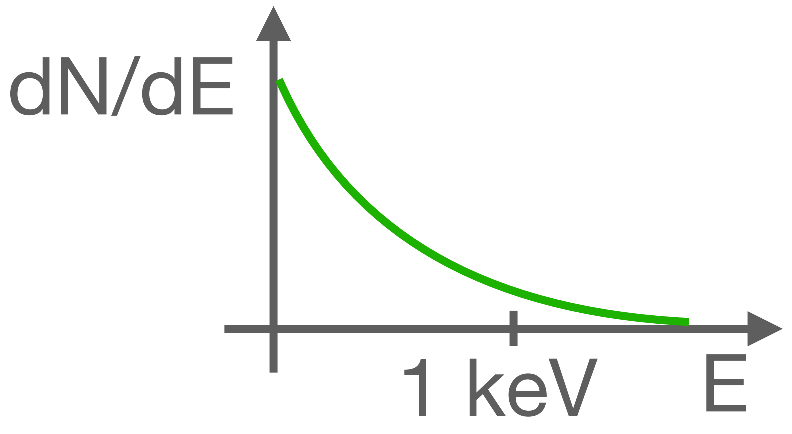


cross section $\sigma < 10^{-40}\ \mathrm{cm}^2$

energy < 1 keV

zero-background
large number of targets *O*(1 kg)



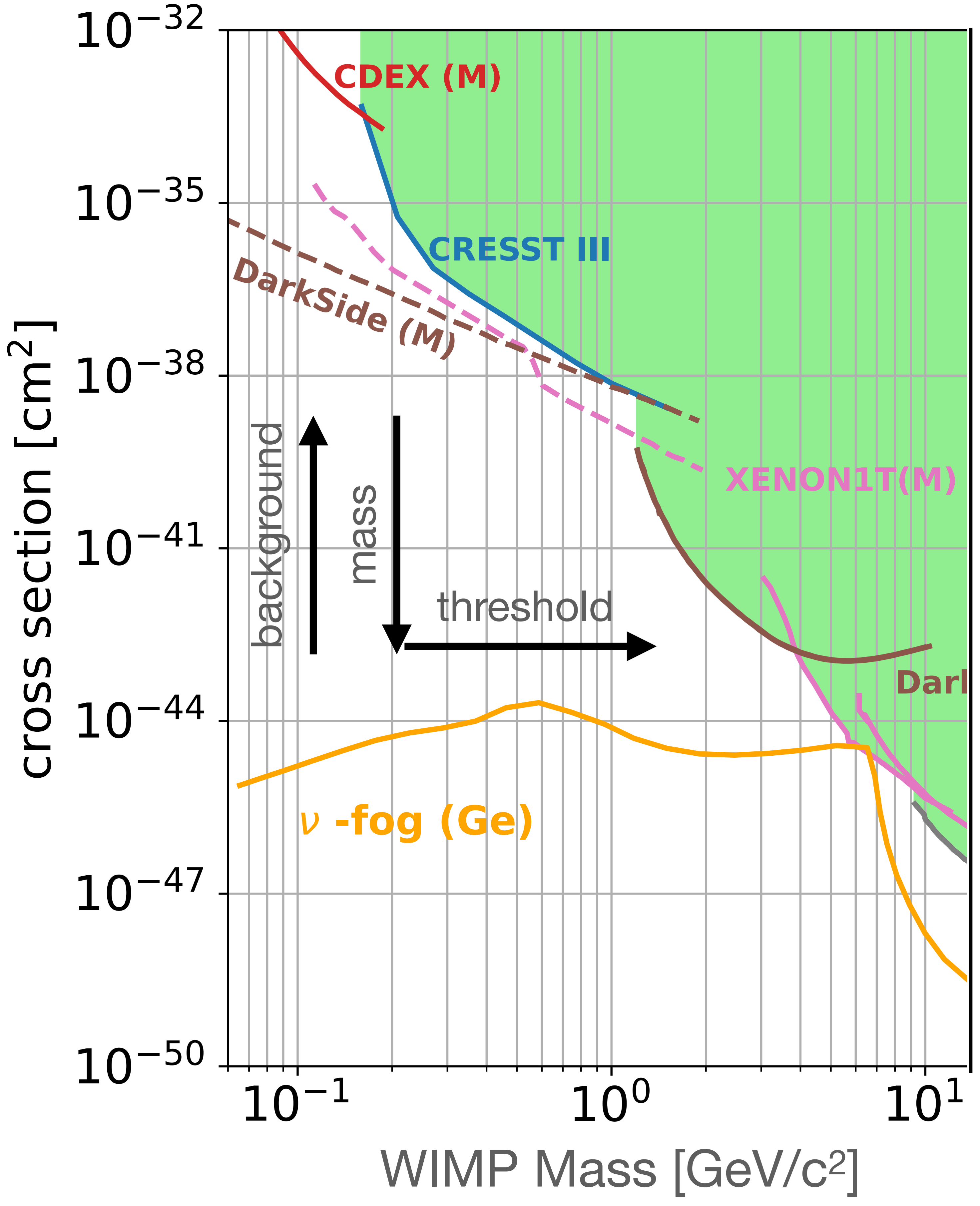


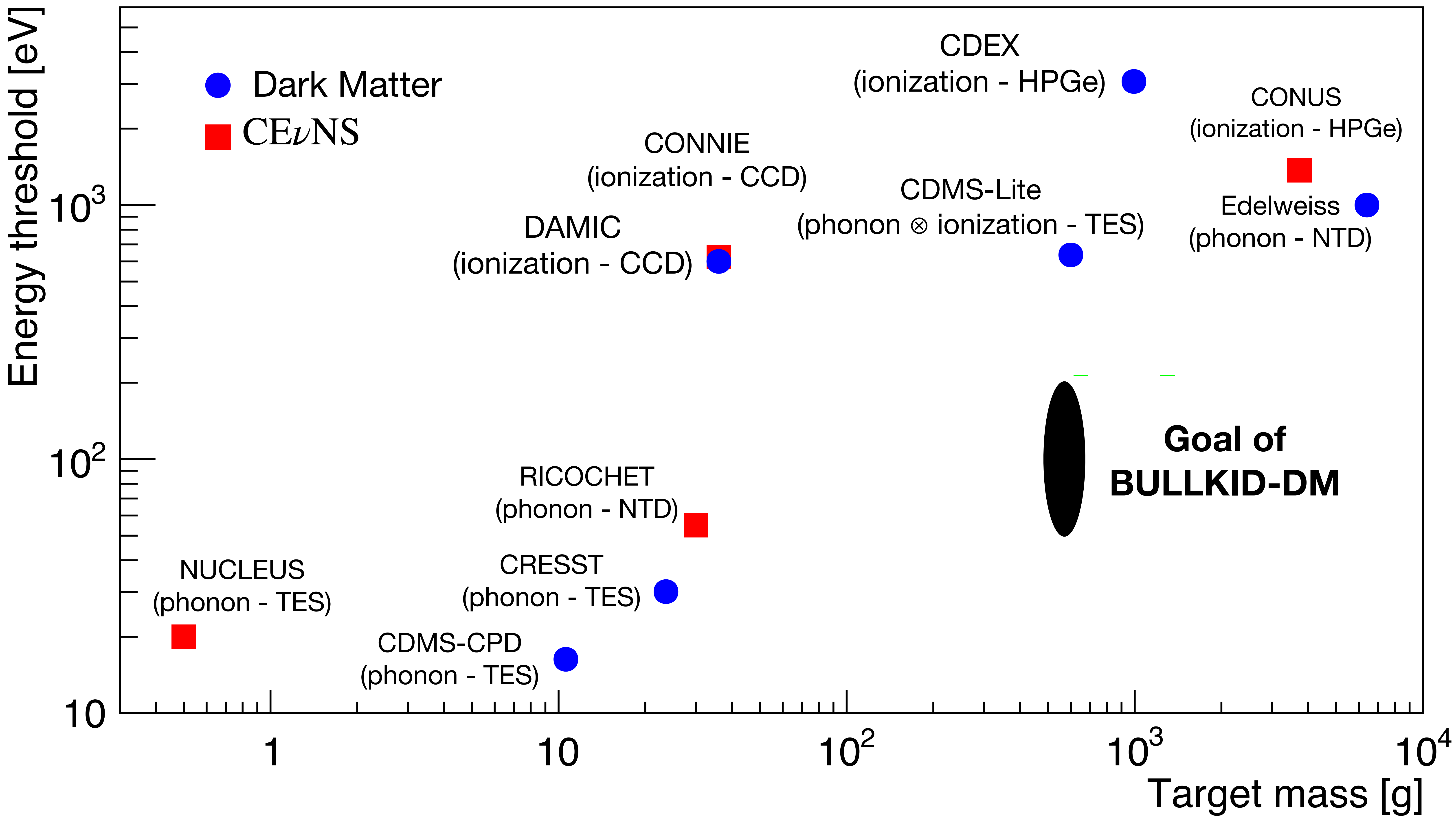
low-energy threshold
***O*(100 eV)**

Difficult with Low-T detectors

Motivation for Low-T detectors

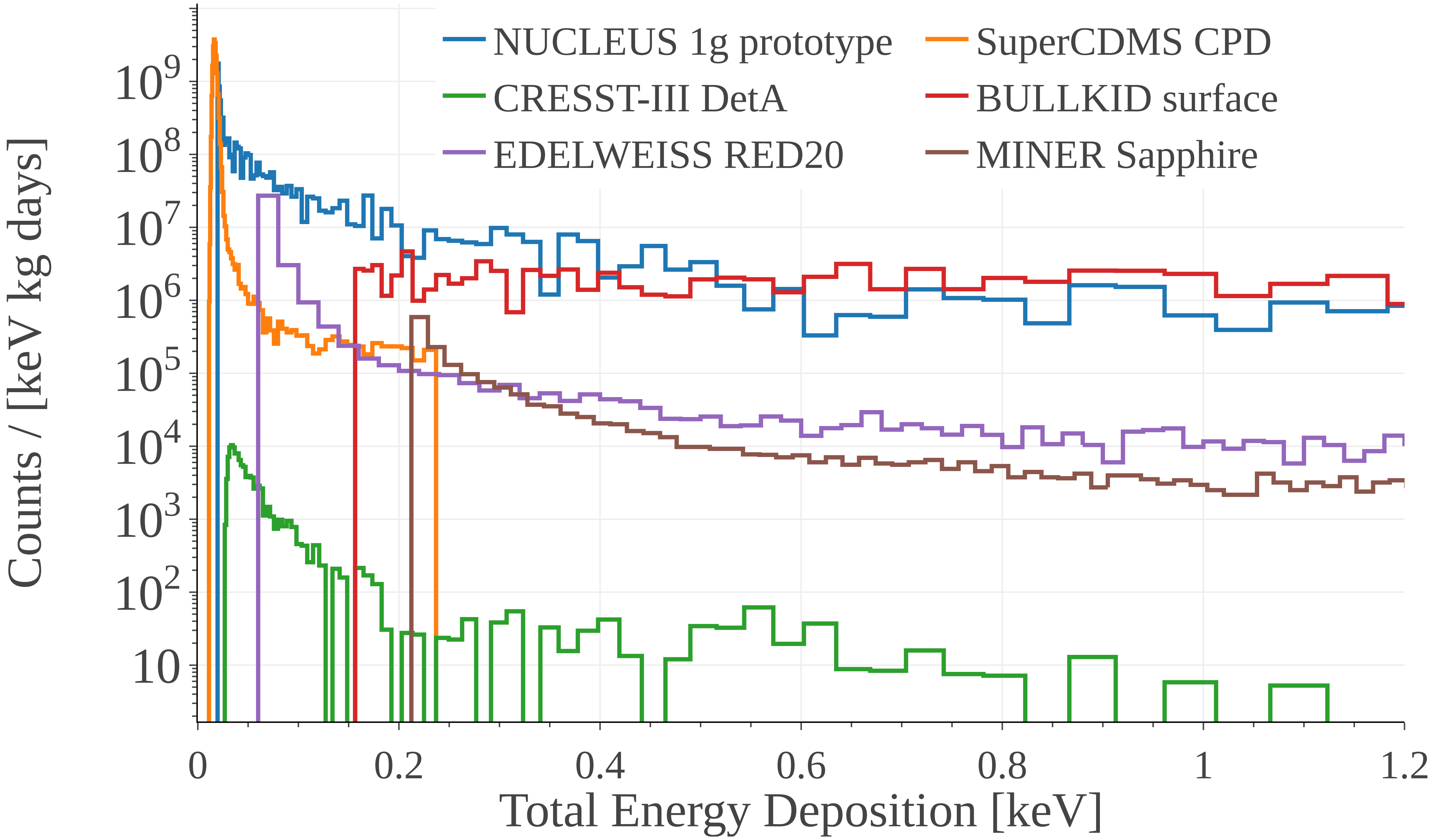
State of the art (solid-state detectors)





Background issue in low-T experiments

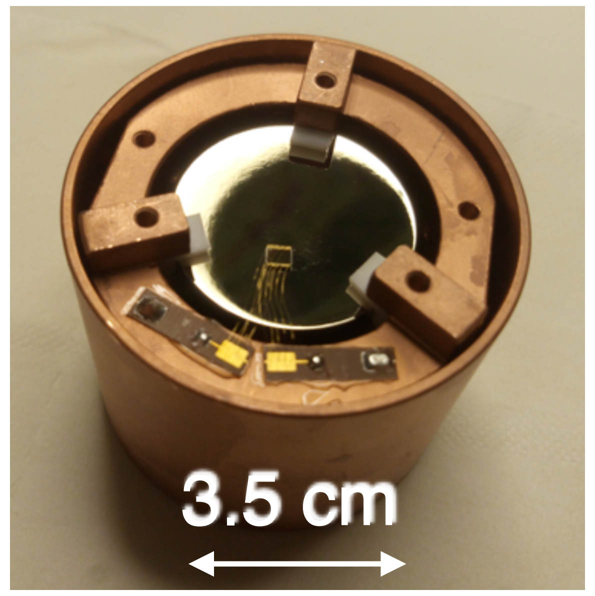
Not understood *excess* background rising at low energies



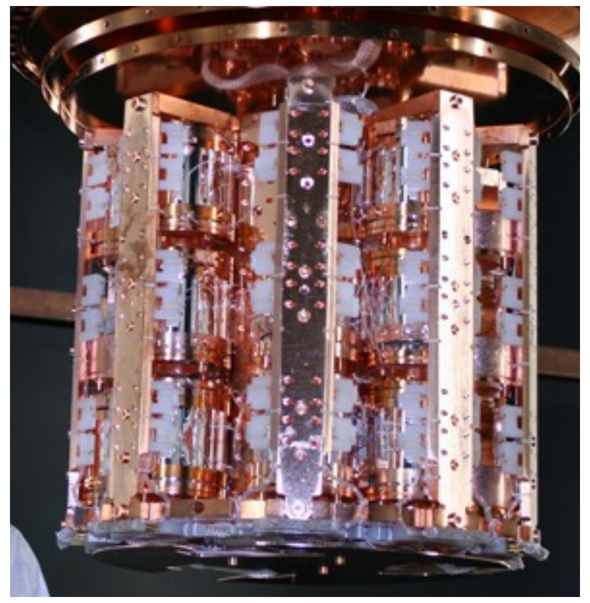
P. Adari, et al.: EXCESS workshop: Descriptions of rising low-energy spectra
SciPost Phys. Proc. 9 (2022) 001 + D. Delicato et al EPJ C 84 (2024) 353

- Phonon bursts (crystal-support friction) ?
- Lattice relaxations after cool down?
- Phonon leakage from interactions in the supports?
- ~~Neutrons (cosmic ray induced, radioactivity) ?~~

RED 20 (Ge, 33 g)



CRESST array

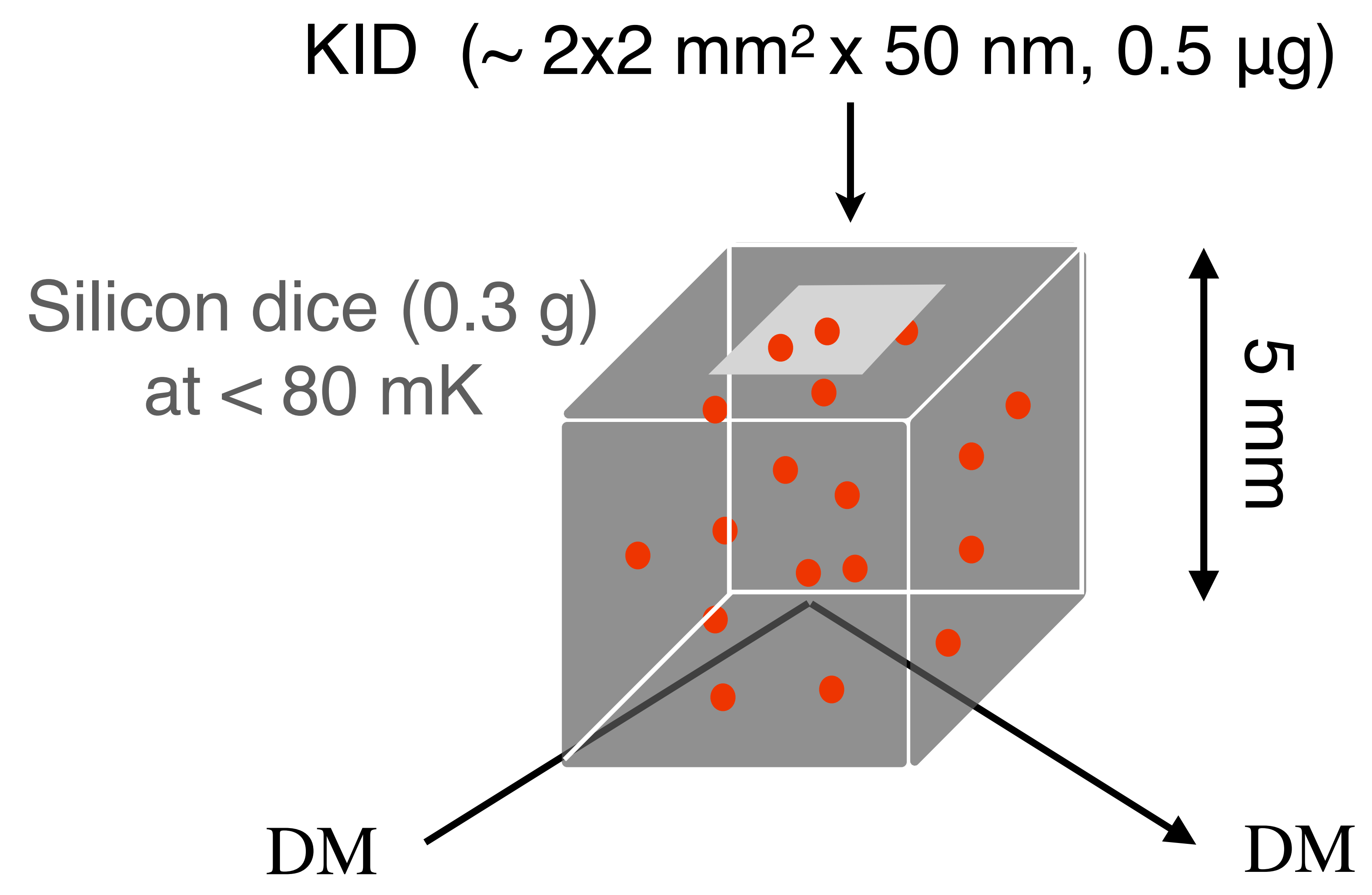


Excess workshop 2024
Roma, 6 July
https://agenda.infn.it/event/39007/

This background limits the sensitivity of present experiments

The BULLKID phonon-detector array

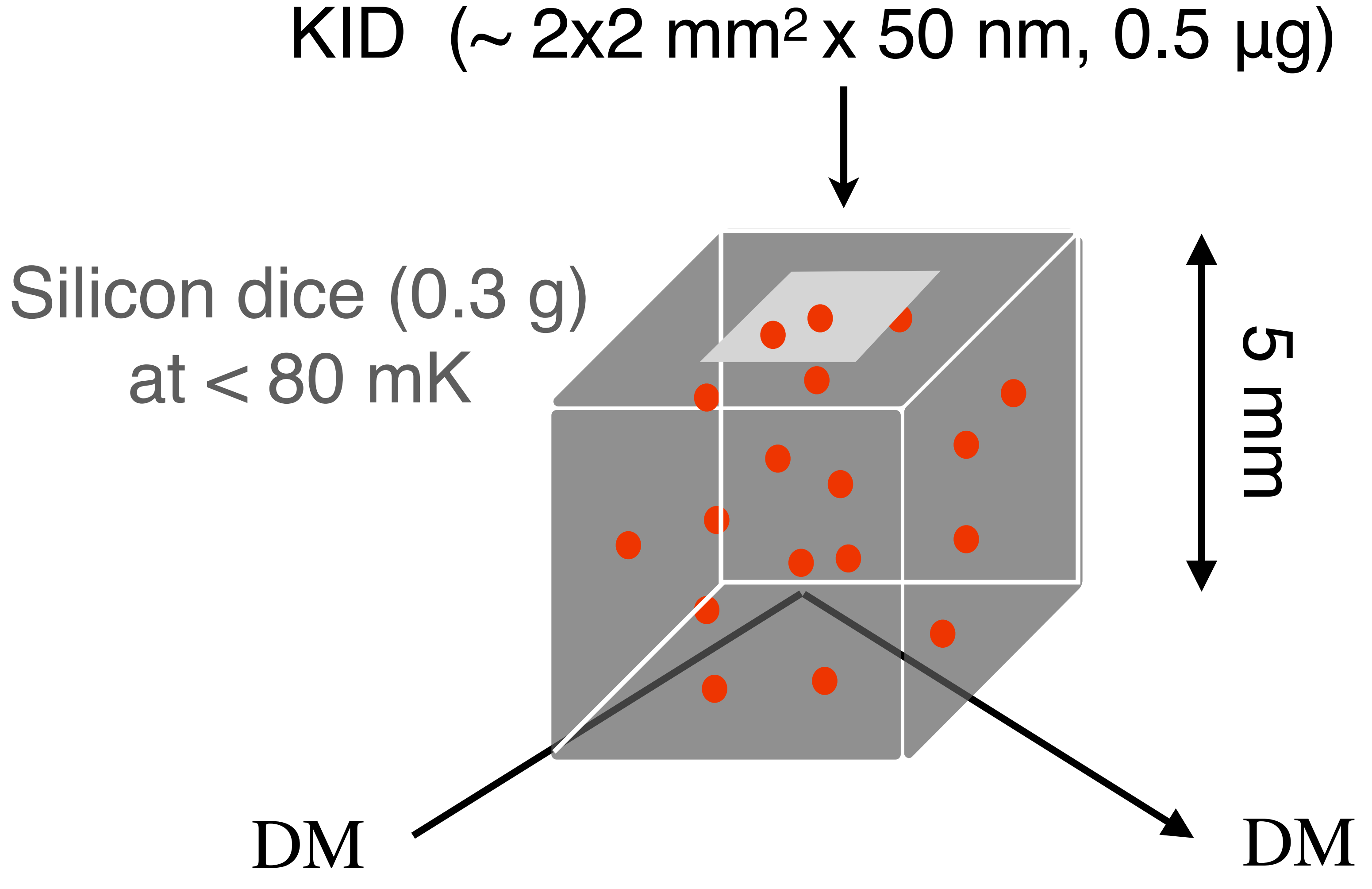
Phonon mediation
detect phonons created by nuclear recoils
in a silicon die



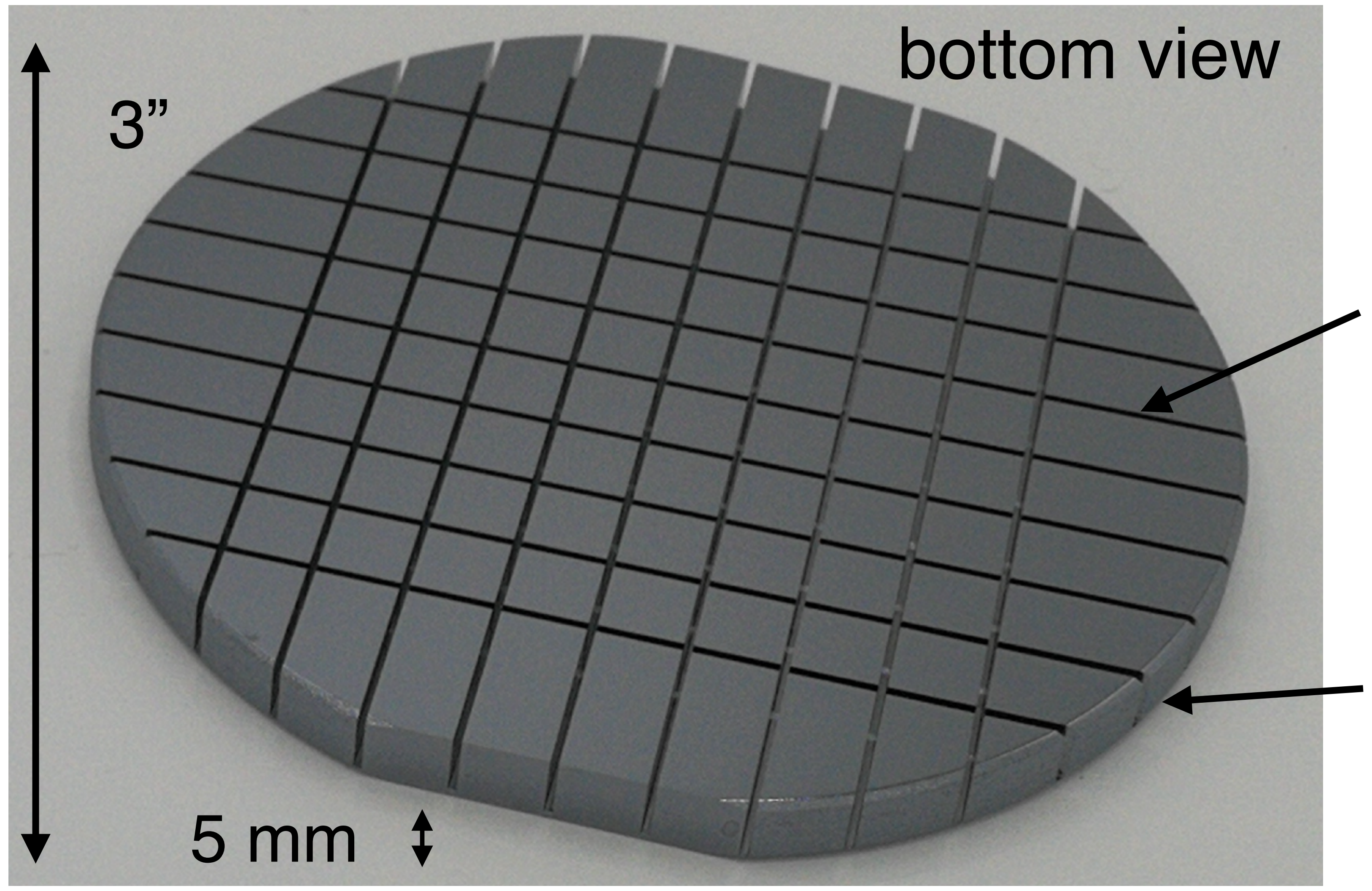
A. Cruciani, et al, Appl. Phys. Lett. 121, 213504 (2022)

The BULLKID phonon-detector array

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



carving of dice in a thick silicon wafer



✓ monolithic

4.5 mm deep grooves
- 6 mm pitch
- chemical etching

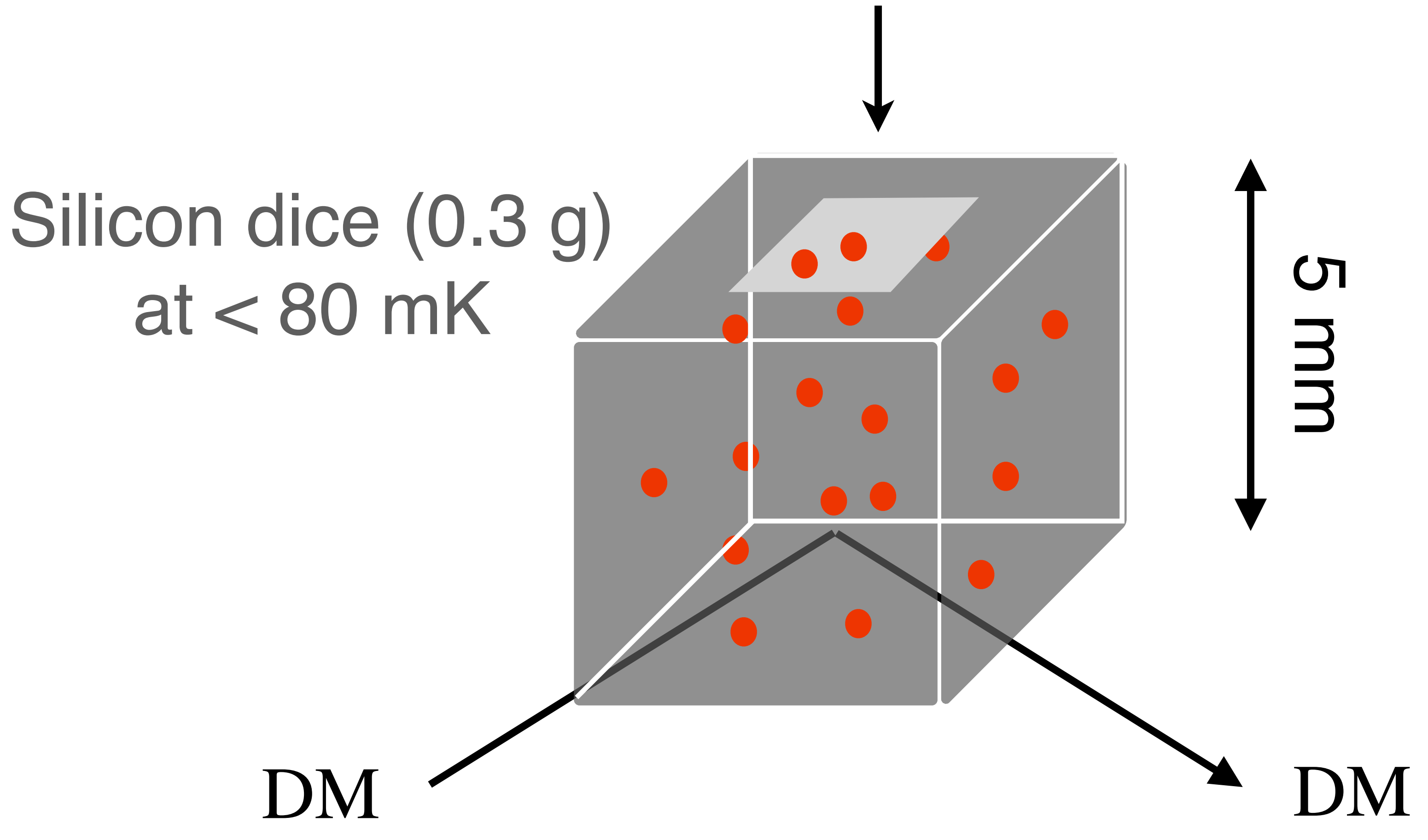
0.5 mm thick common disk:
- holds the structure
- hosts the sensors

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

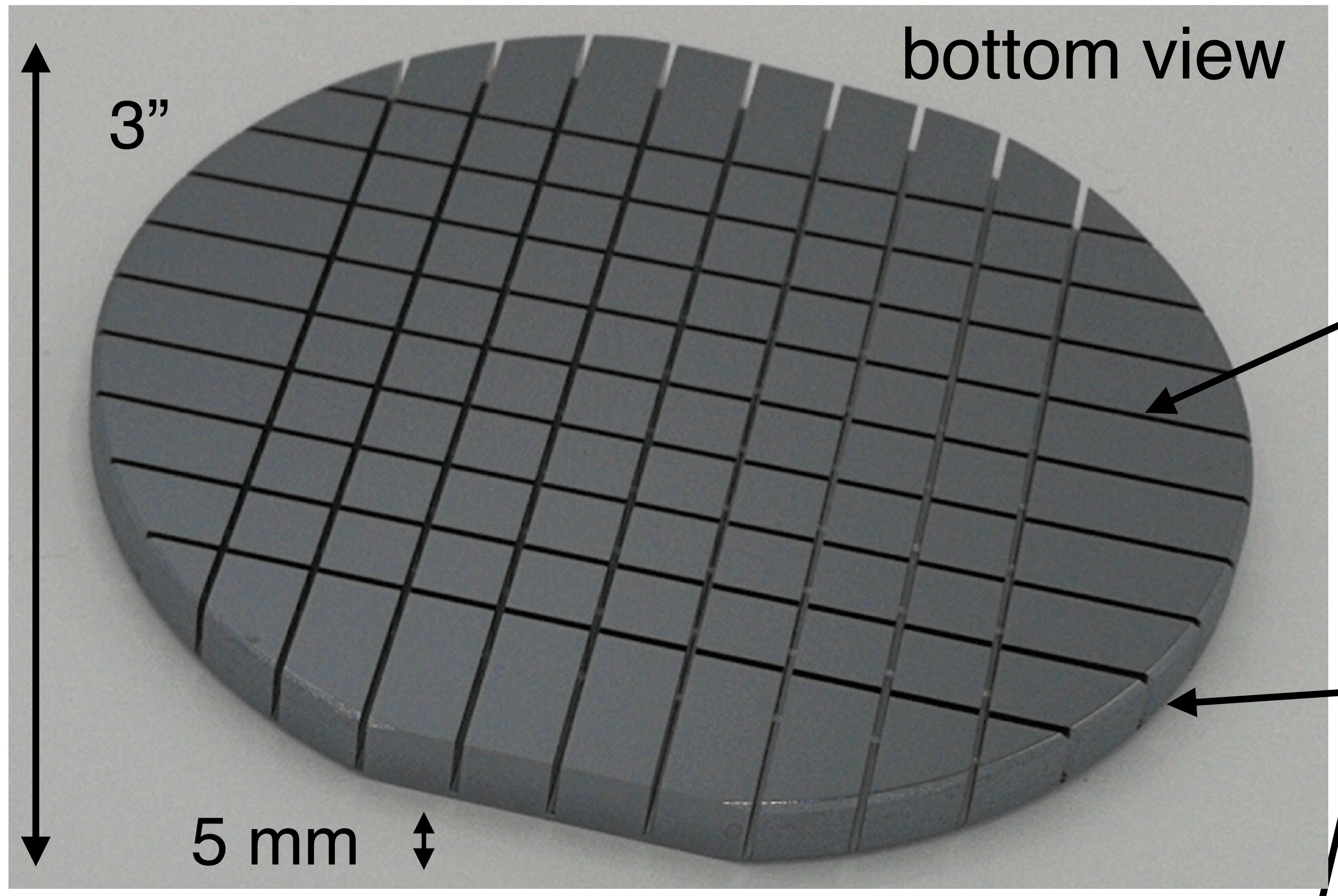
The BULLKID phonon-detector array

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

KID (~ 2x2 mm² x 50 nm, 0.5 µg)



carving of dice in a thick silicon wafer

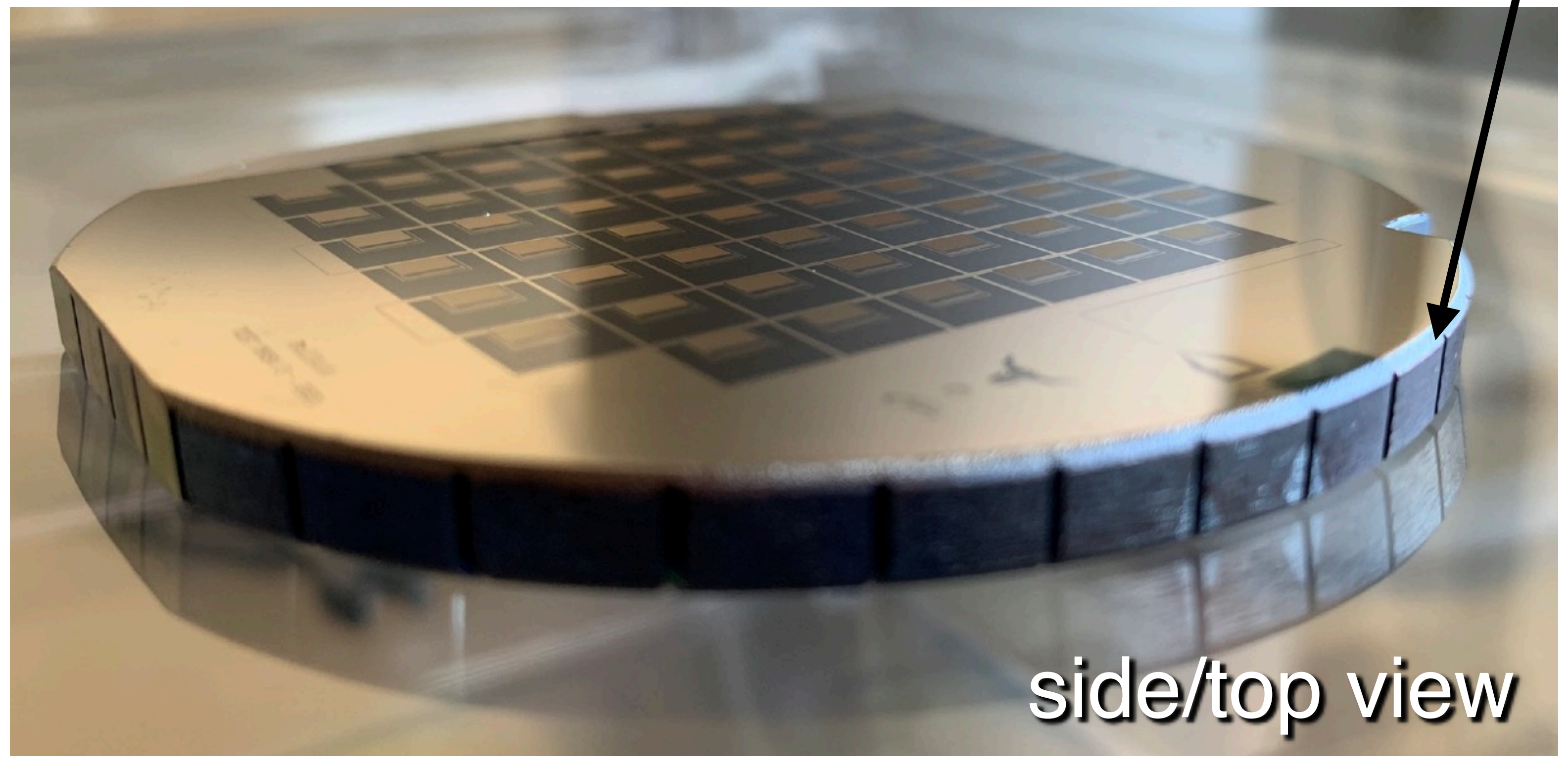


✓ monolithic

4.5 mm deep grooves
- 6 mm pitch
- chemical etching

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

lithography of KID sensors



KID sensor array:
- 60 nm thick aluminum film
- 60 elements (1 per die)

✓ 60 detectors in 1

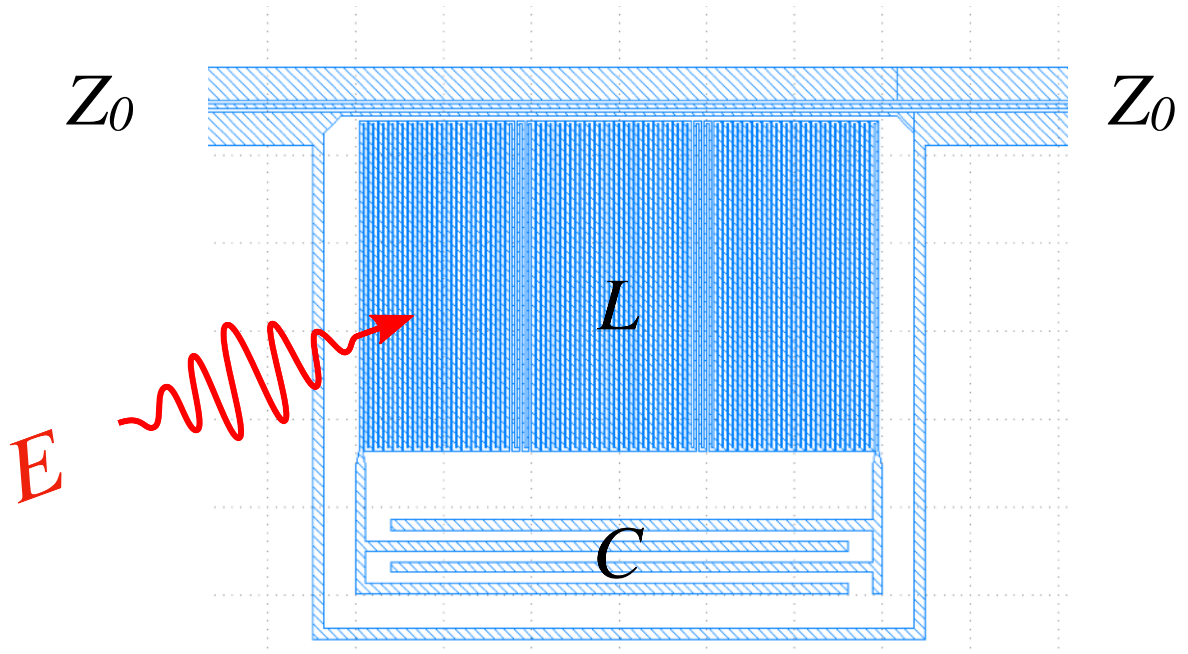
Fully multiplexed
(single readout line)

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

Kinetic Inductance Detectors (KIDs)

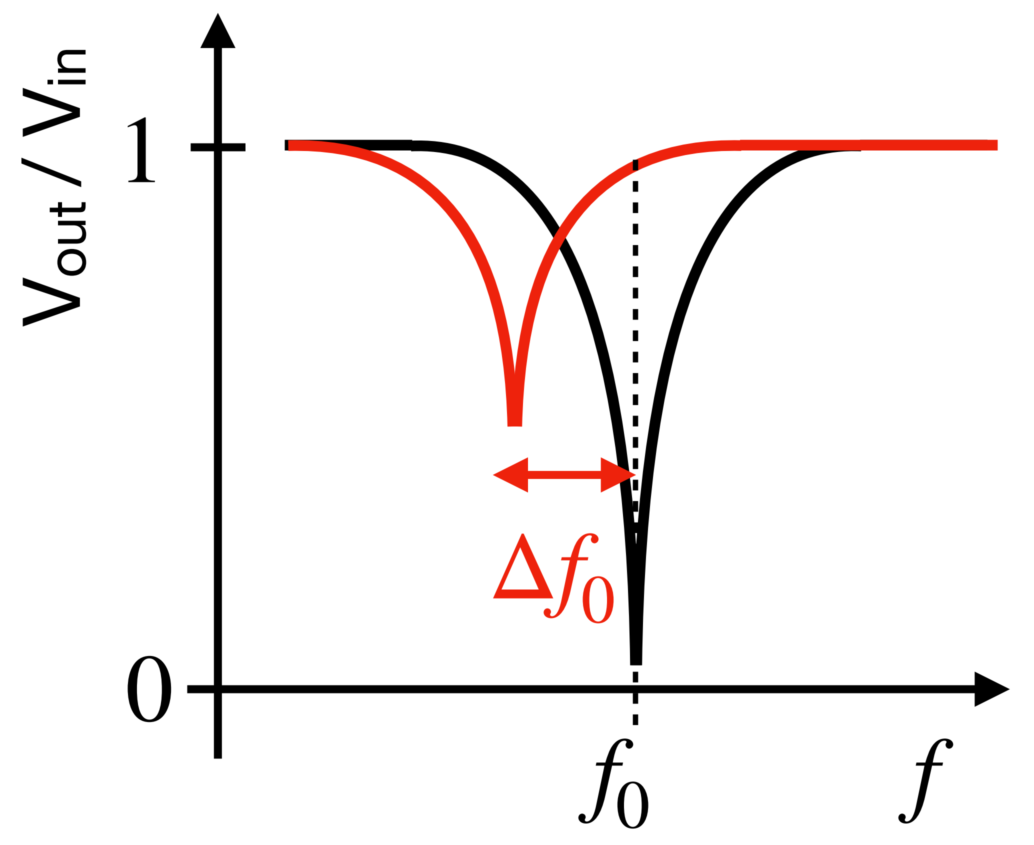
- Superconductor at T < 200 mK (Al)
- LC resonator
- Cooper pairs inductance $L_k = \dfrac{m_e}{2\,e^2\,n_{\text{pairs}}}$
- Absorbed energy breaks Cooper pairs

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



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

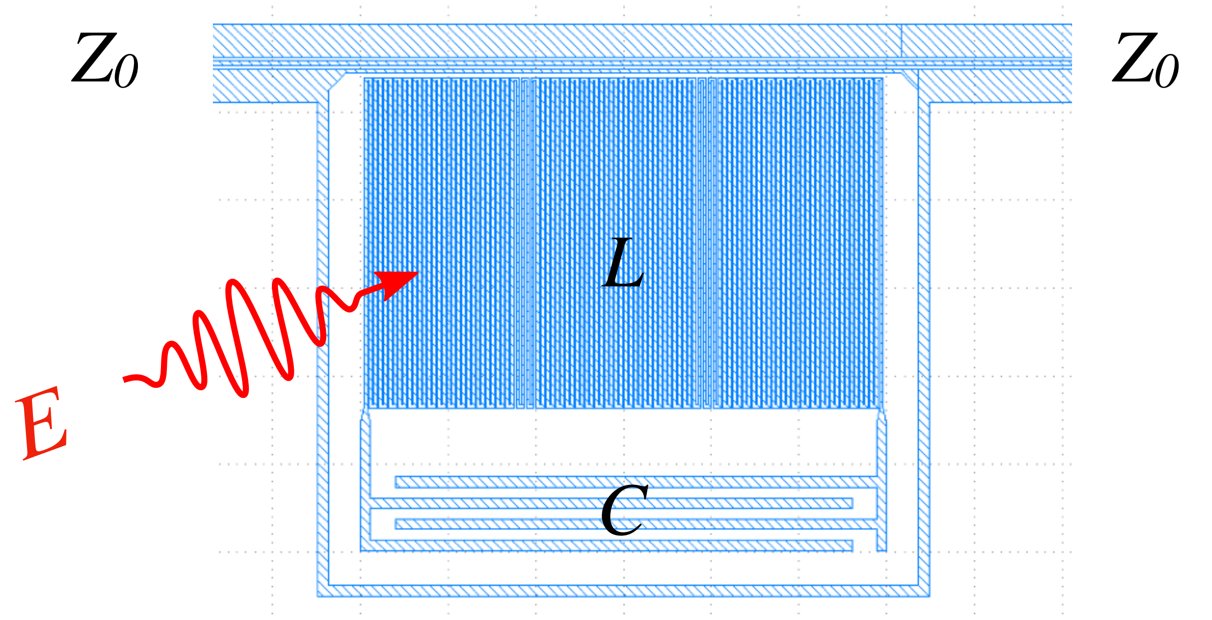
frequency response



Kinetic Inductance Detectors (KIDs)

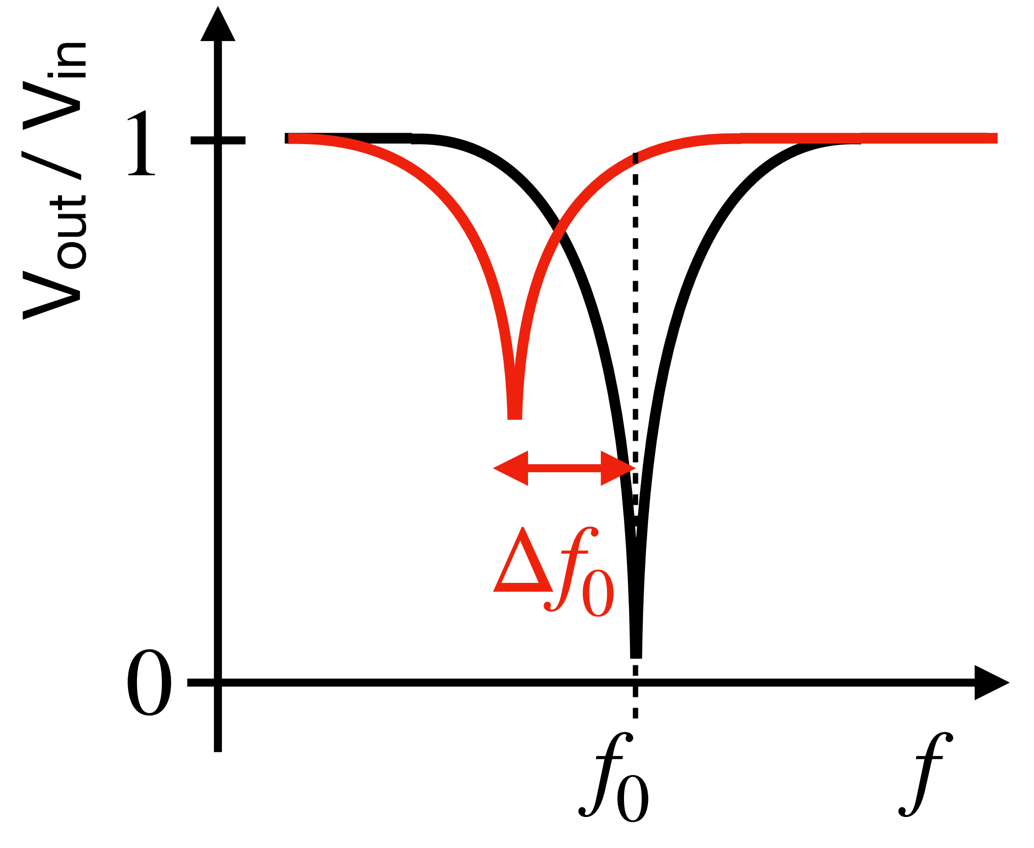
- Superconductor at T < 200 mK (Al)
- LC resonator
- Cooper pairs inductance $L_k = \dfrac{m_e}{2\,e^2\,n_{pairs}}$
- Absorbed energy breaks Cooper pairs

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

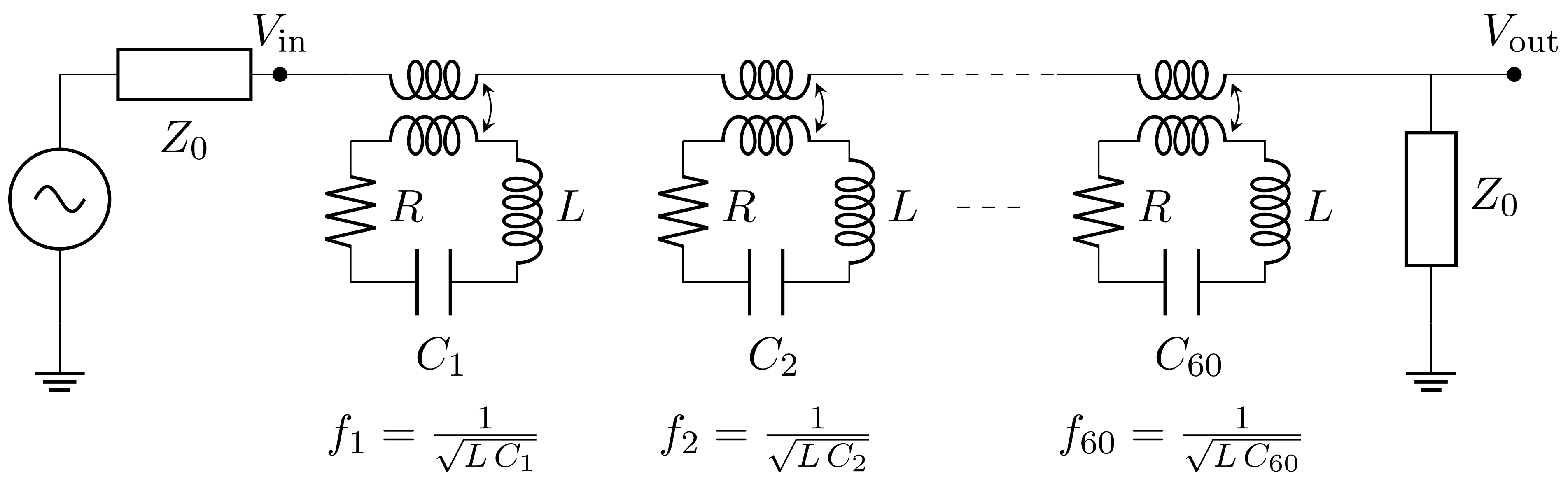


$E \rightarrow \Delta n_{pairs} \rightarrow \Delta L \rightarrow \Delta f_0$

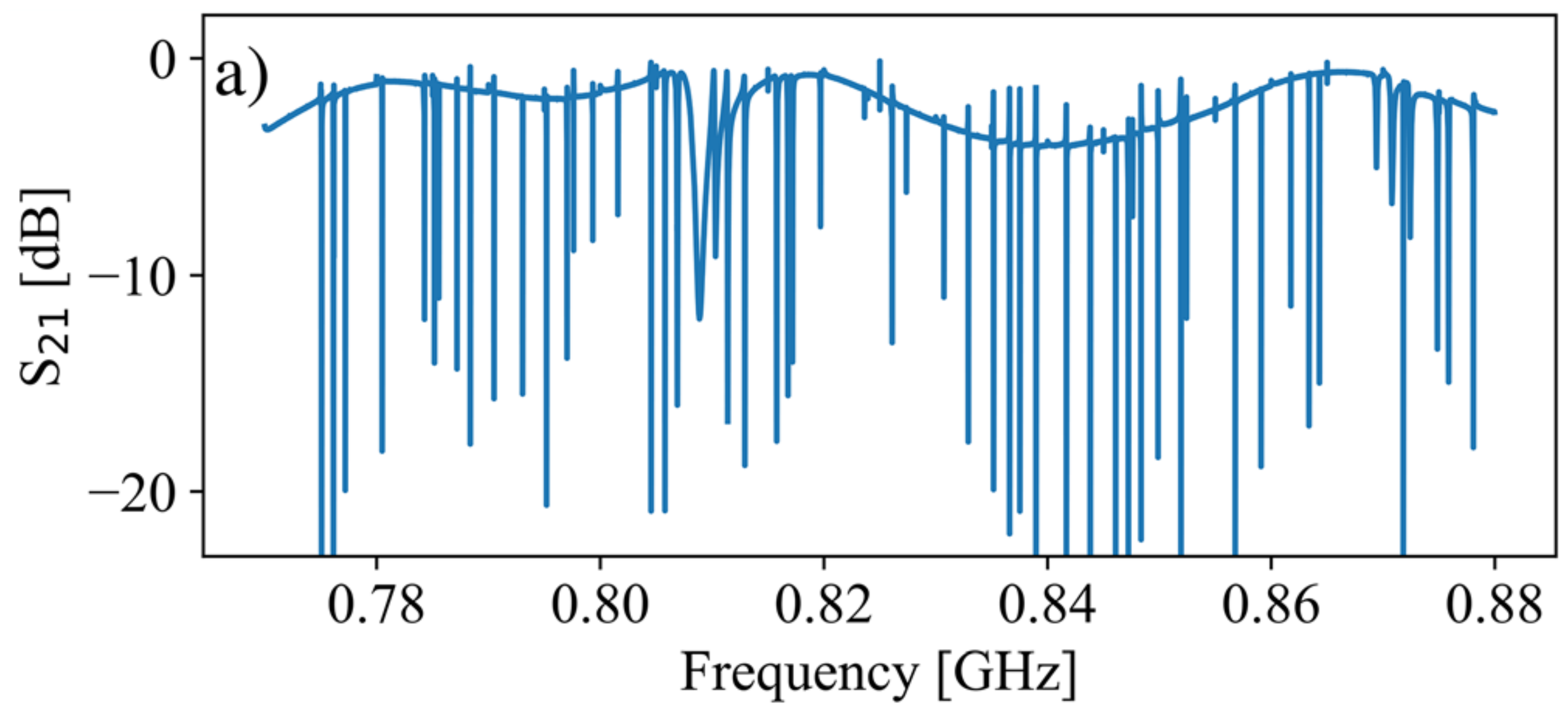
frequency response



Readout: different KIDs coupled to a the same line

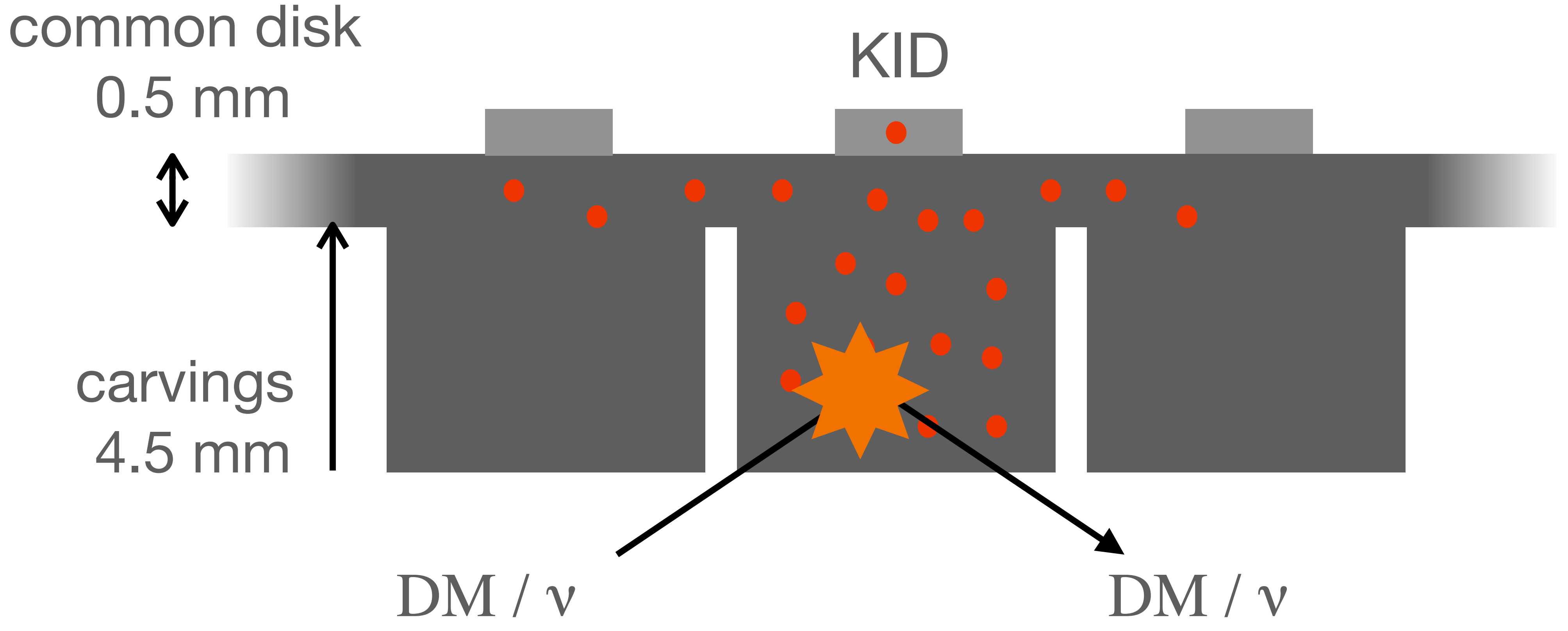


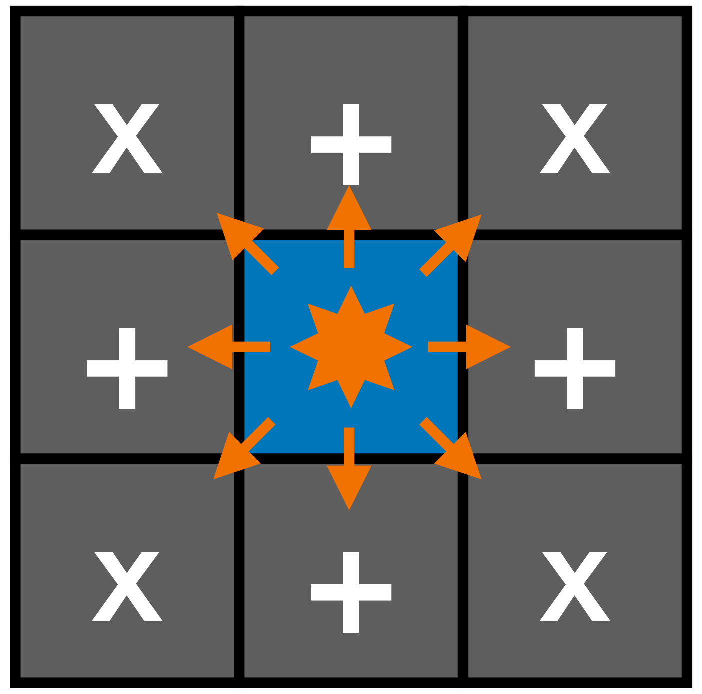
frequency scan of the 60 KIDs of BULLKID

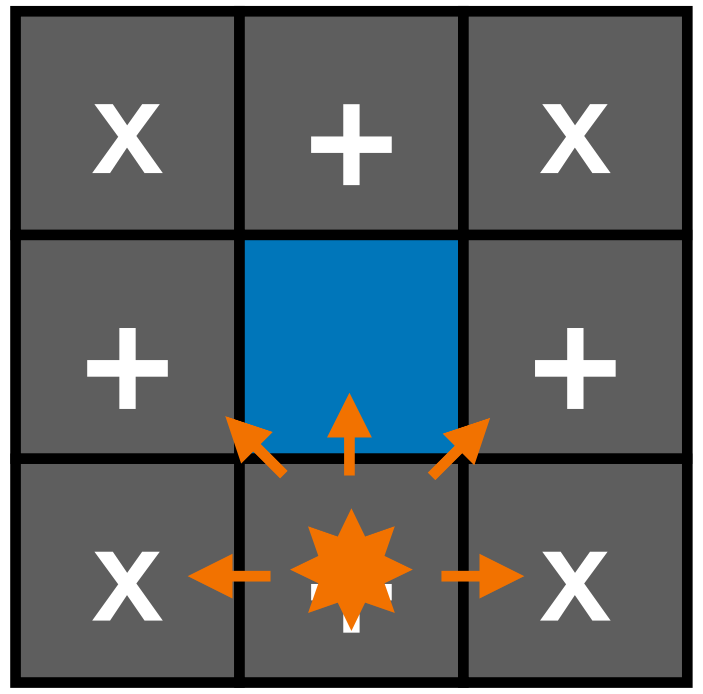


Phonon leakage and mapping

- 50% of phonons is detected in the interaction die
- 50% leaks out and is detected in nearby dice
  - (8 ± 2) % in each "+" die
  - (3 ± 1) % in each "x" die
  - the rest in outer dice

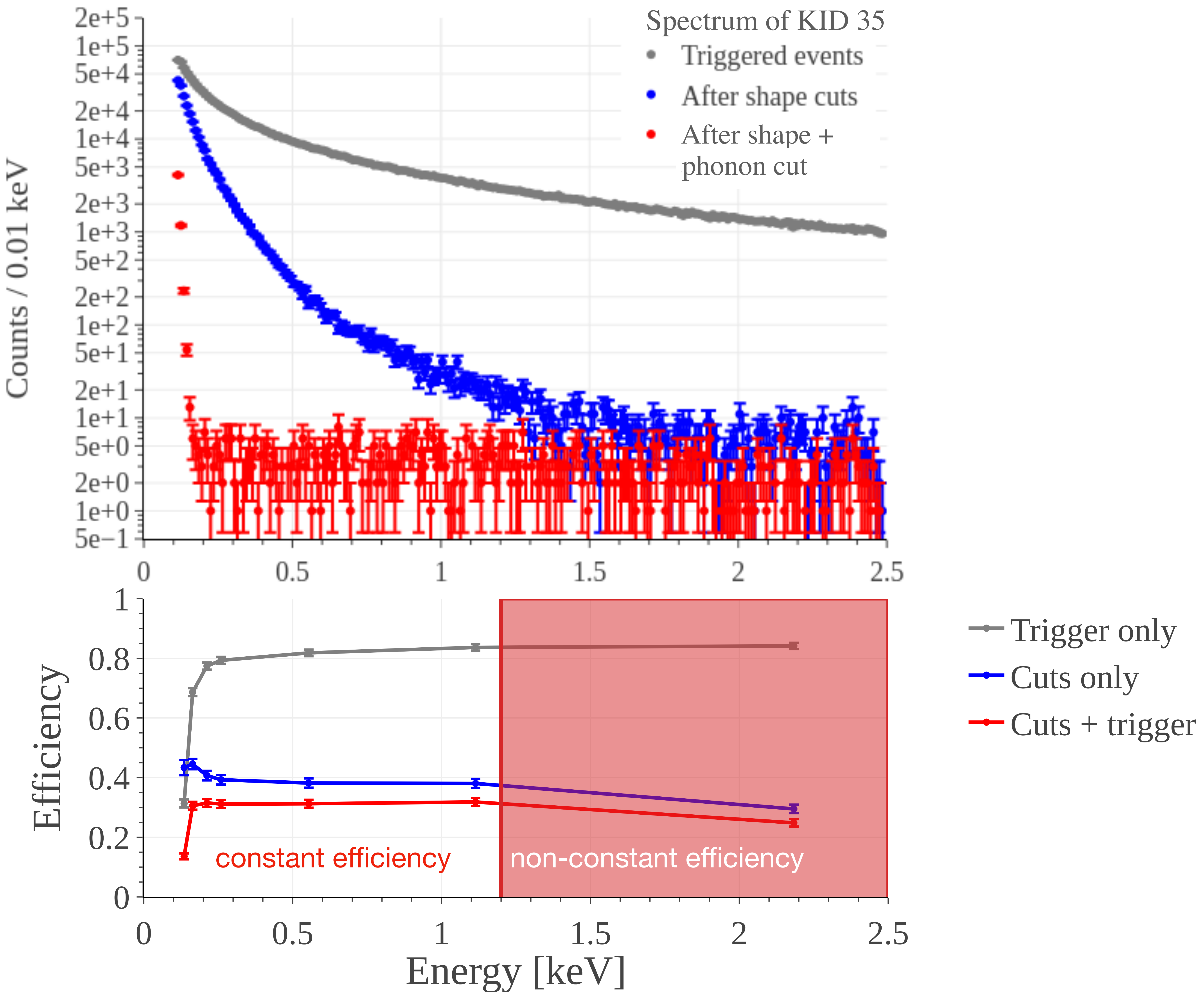


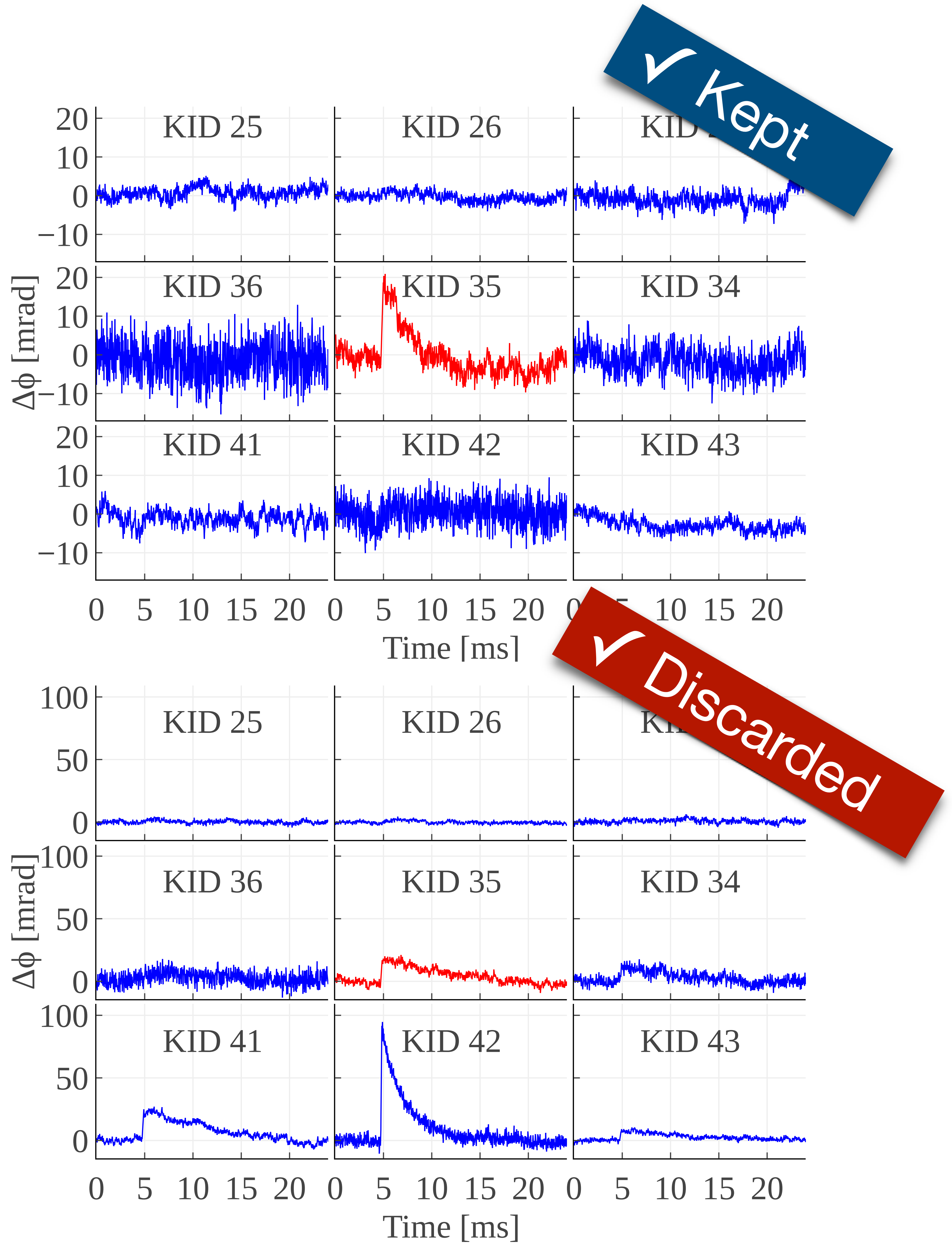




This effect reduces the phonon focusing on the KID but is **exploited to identify the interaction voxel**

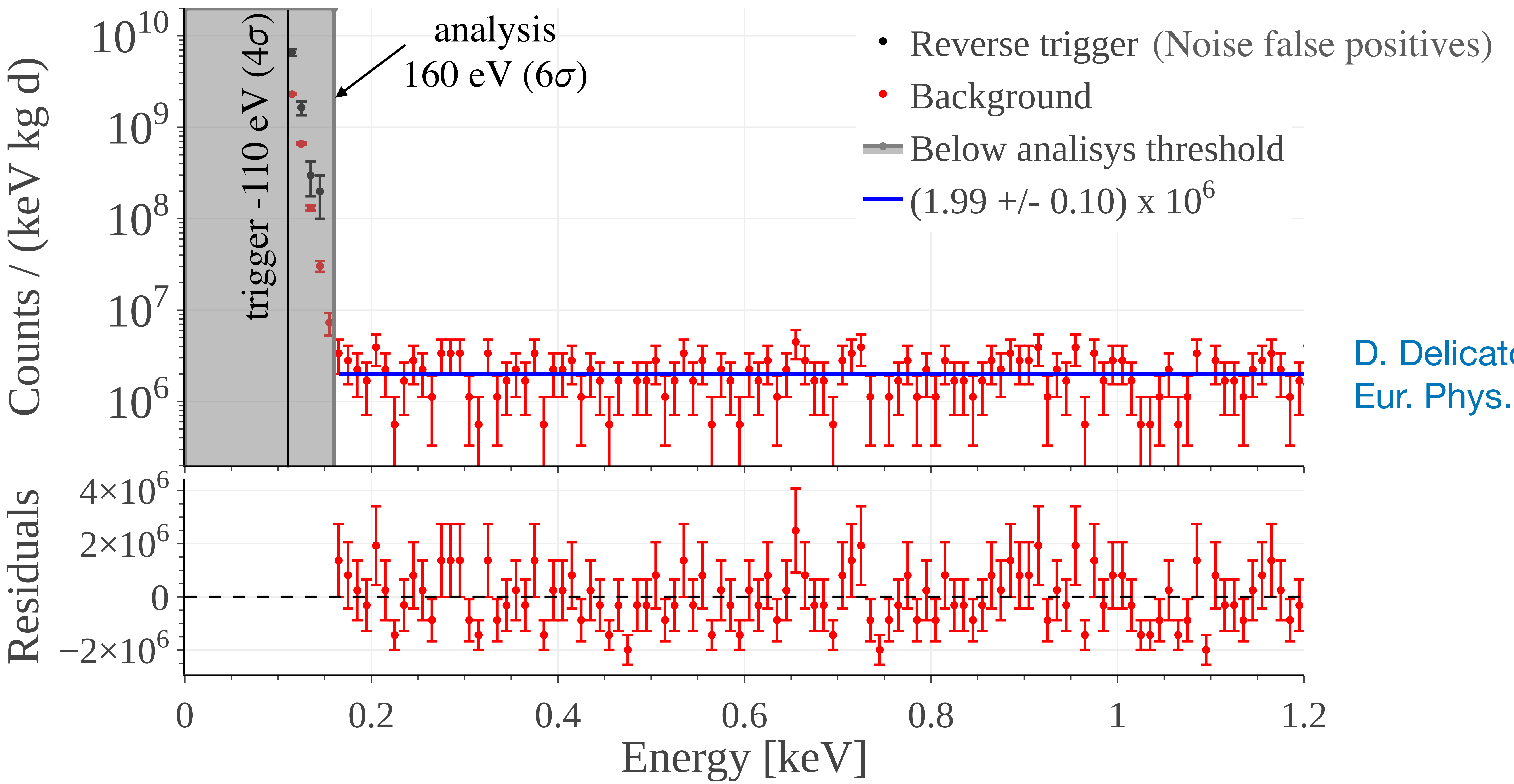
Background: pulse shape + phonon cuts





Background: result on surface

Above ground lab @Sapienza U., no shield, 39 live hours



D. Delicato et al,
Eur. Phys. J. C 84 (2024) 353

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

BULLKID-DM Collaboration

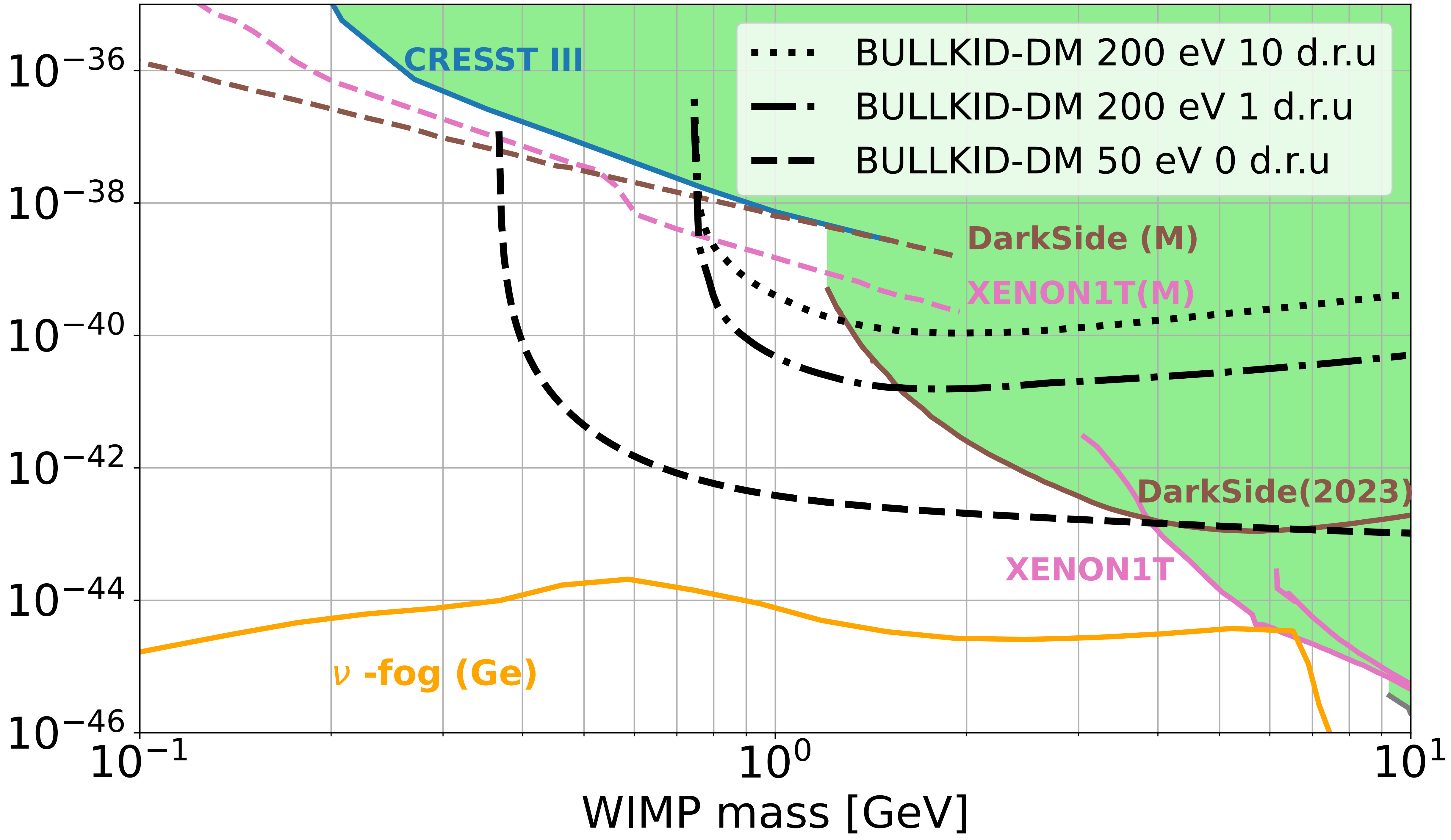
INFN
Istituto Nazionale di Fisica Nucleare

Roma
Ferrara
LNGS
Pisa

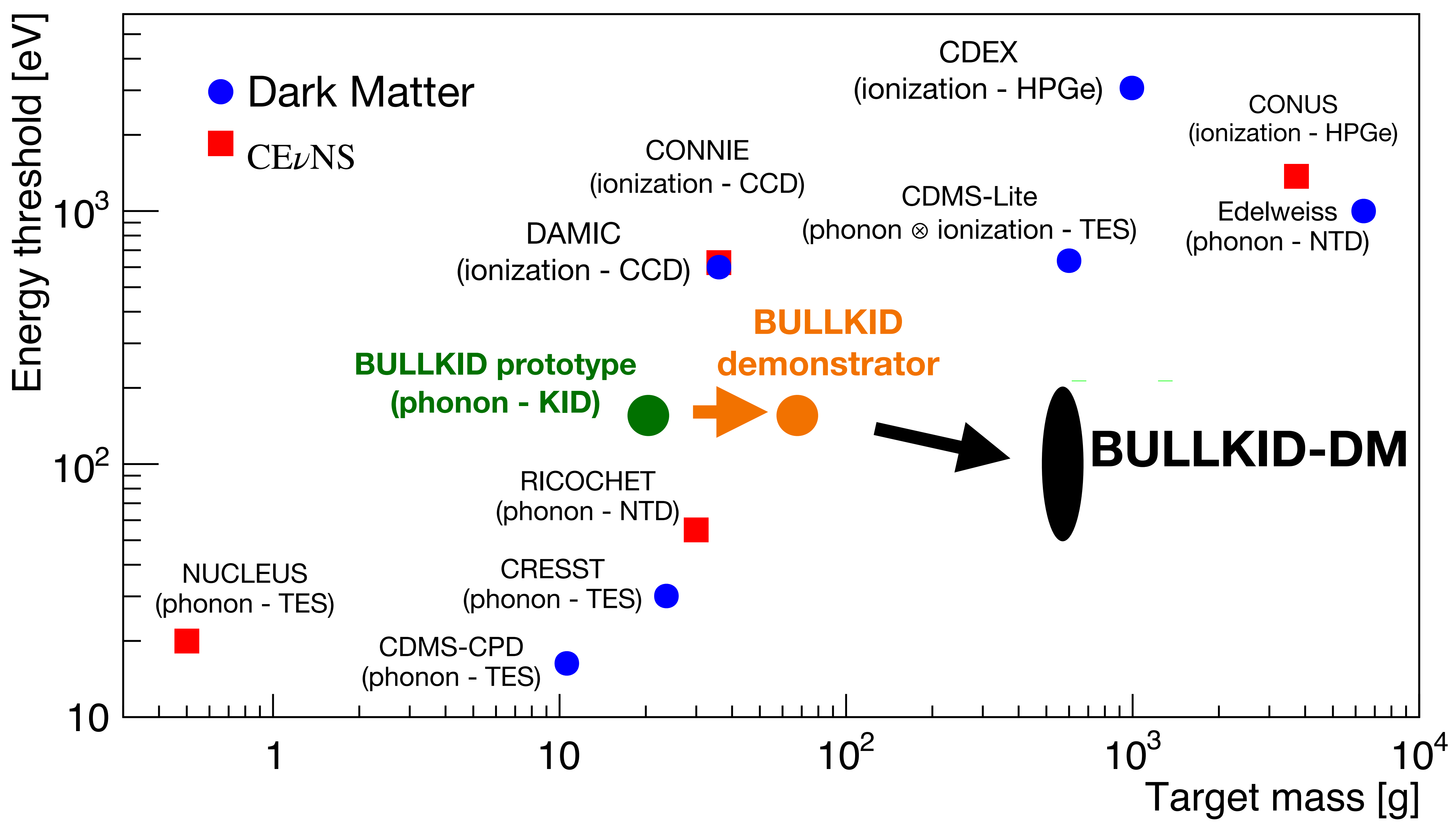
KIT
Karlsruher Institut für Technologie

Dark Matter - direct search with BULLKID-DM

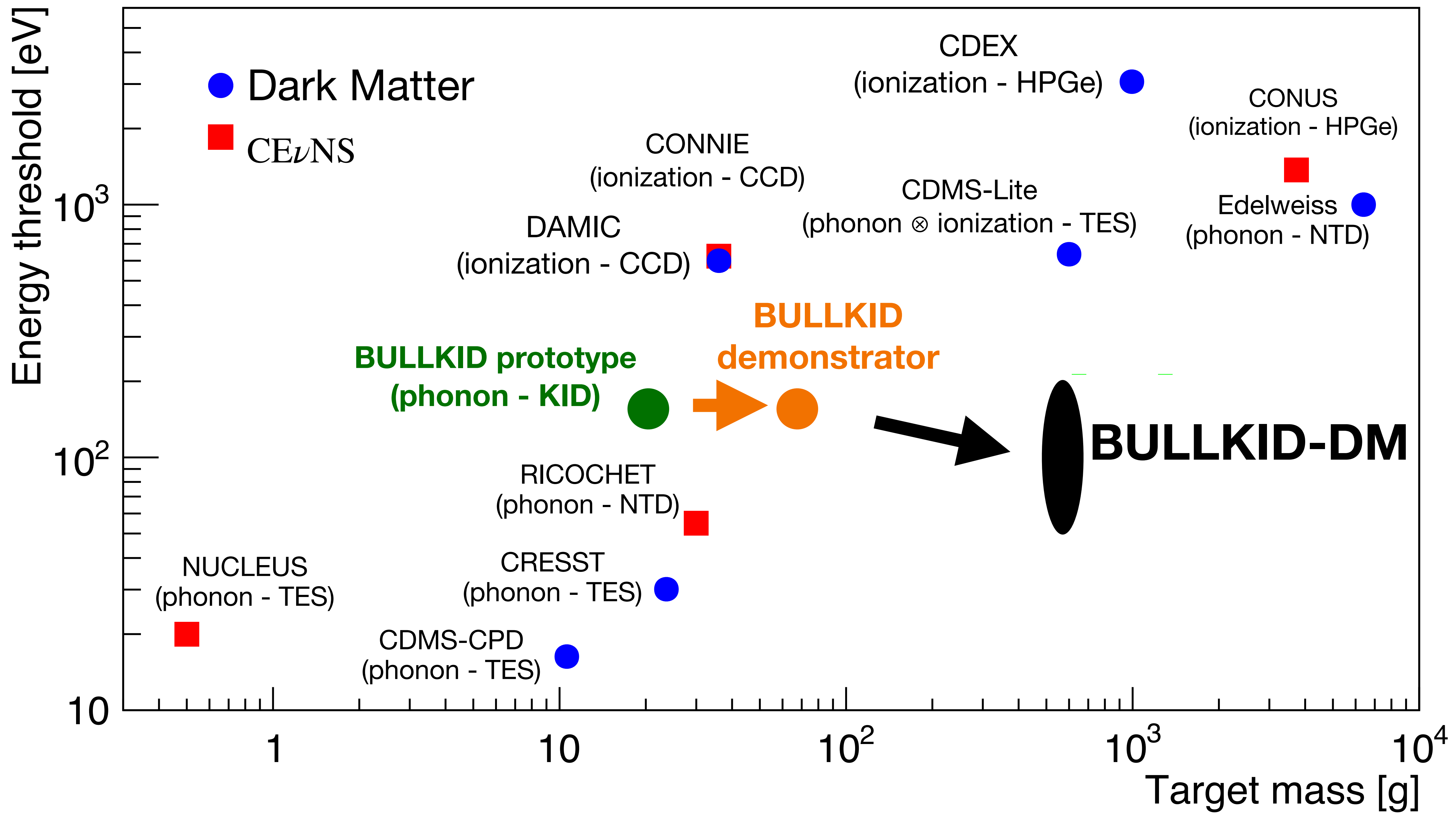
	BULLKID prototype	BULLKID-DM demonstrator		BULLKID-DM
mass	20 g	60 g		600 g
# of sensors	60	180		~2500
threshold	160 eV	200 eV		200 eV or lower
bkg (c/keV kg d)	2×10^6	$\sim 10^4$		10 - 0.01
laboratory	Sapienza U.	Sapienza	LNGS?	LNGS
installation	2023	2024	2025	2027?



Threshold and mass

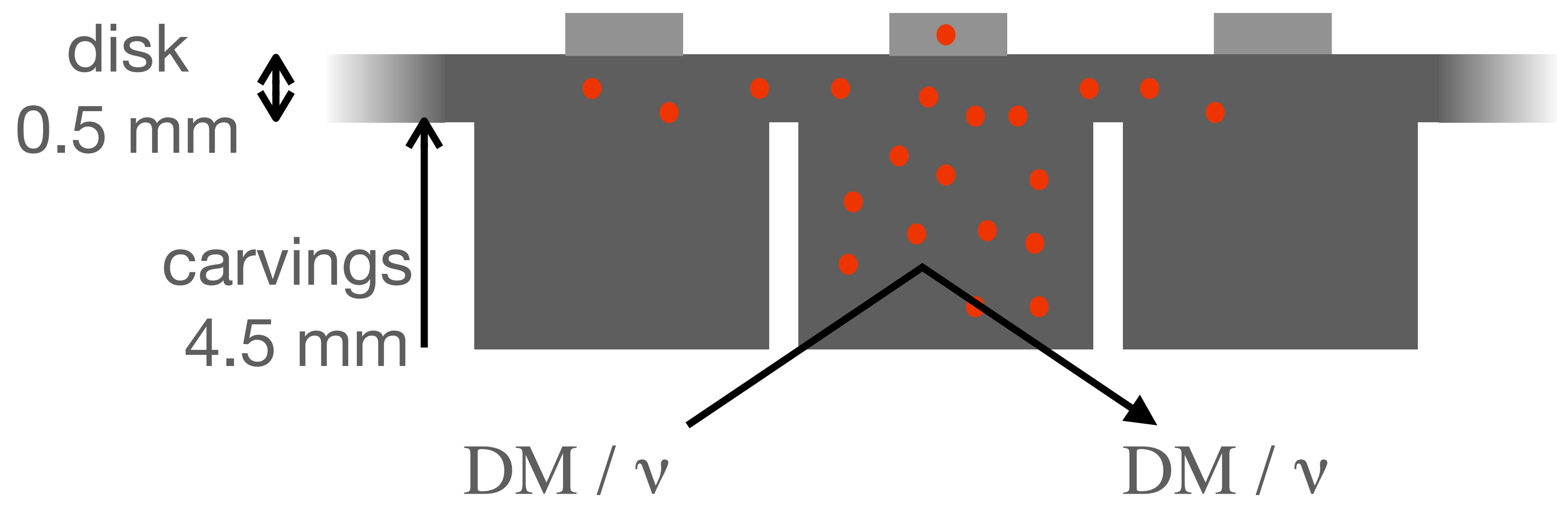


Threshold and mass

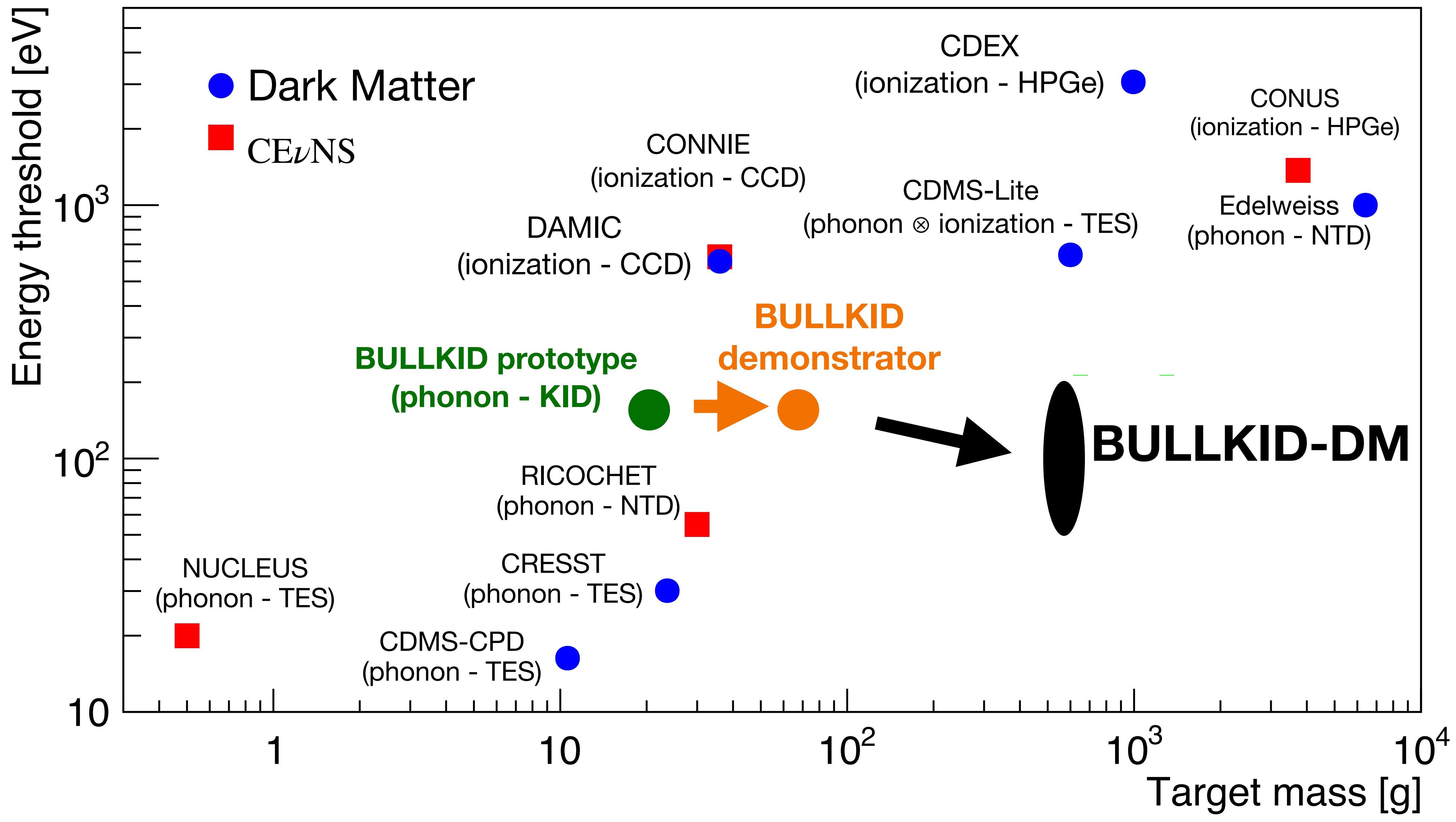


Threshold (ongoing R&Ds):

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

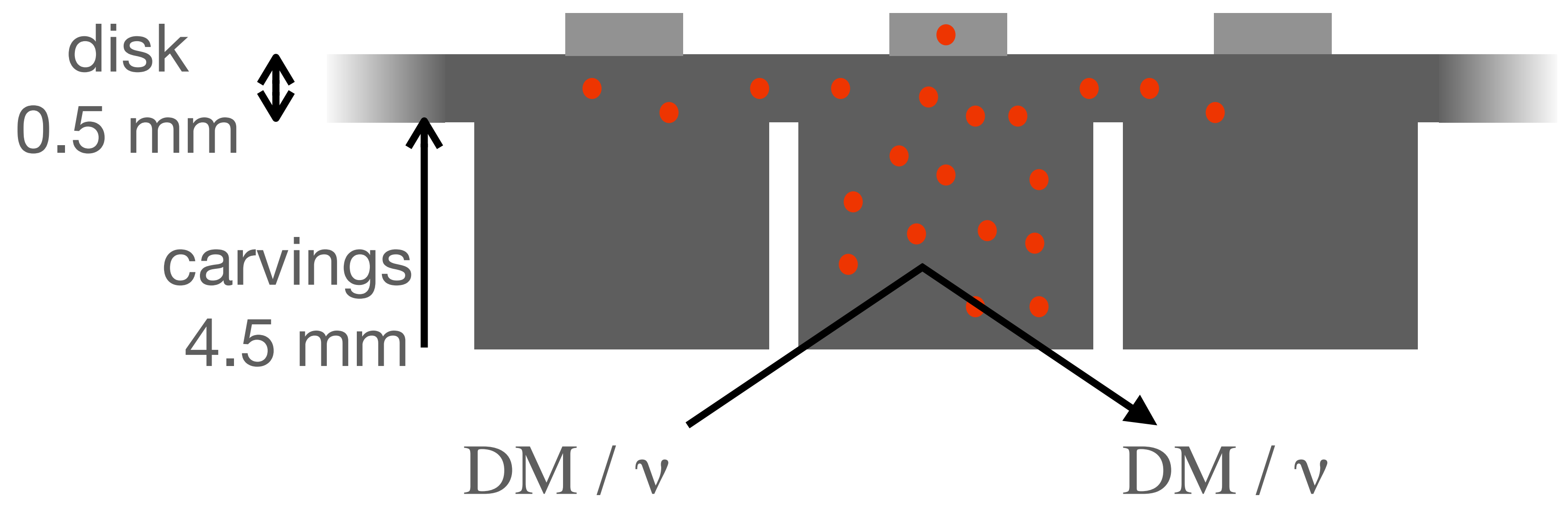


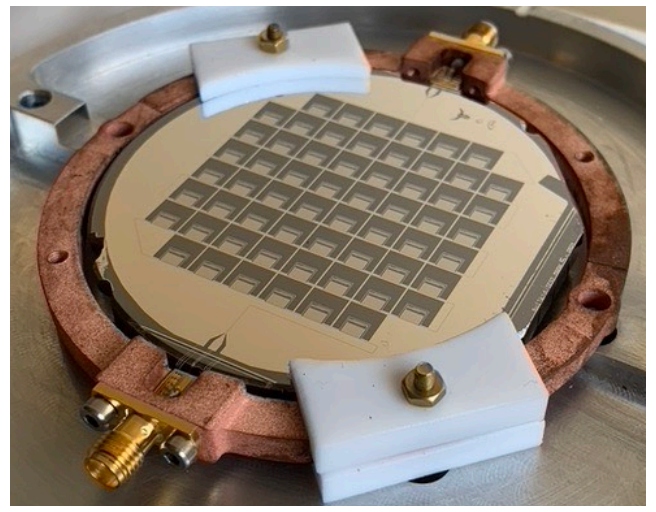
Threshold and mass



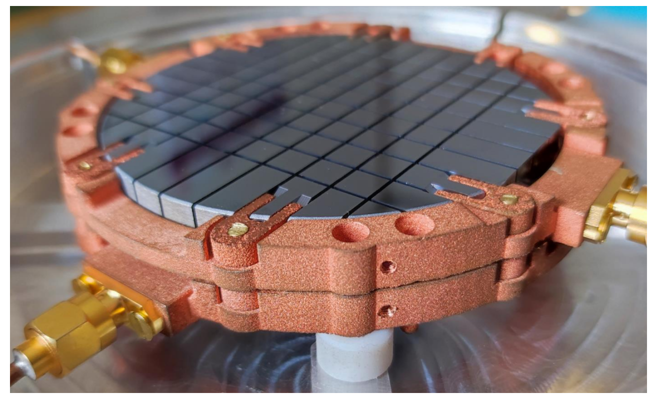
Threshold (ongoing R&Ds):

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

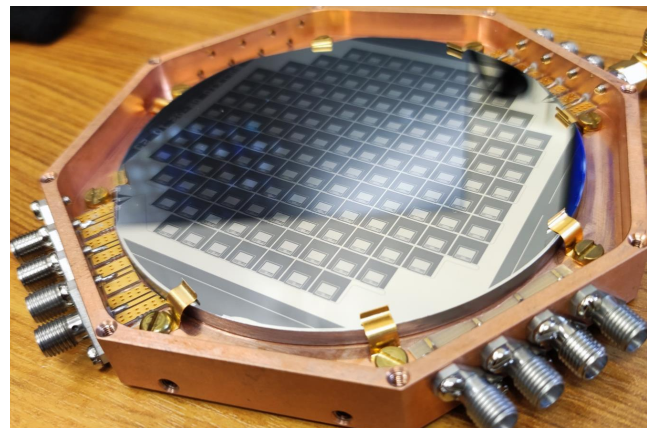




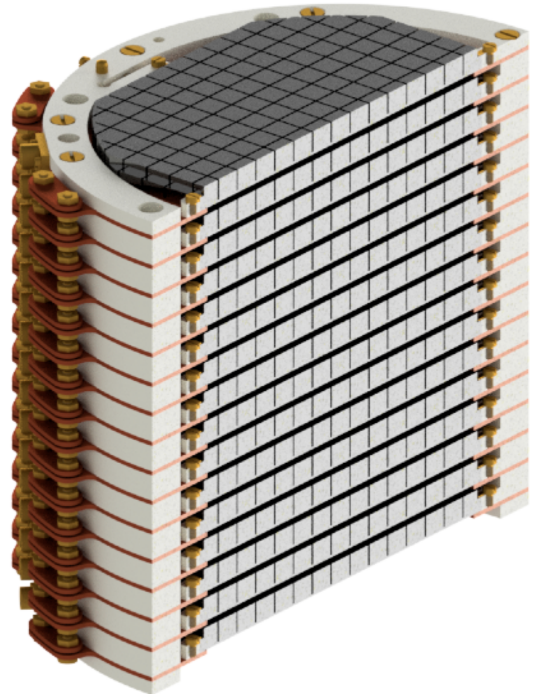
Prototype - 20 g / 60 dice
single 3” wafer
concluded in 2023



Demonstrator - 60 g / 180 dice
3-layer stack of 3” wafers
first operations before summer



R&D on large wafer 50 g / 145 dice
single 100 mm wafer
first operations fall 2024



BULLKID-DM - 600 g / ~2500 dice
16-layer stack of 100 mm wafers
commissioning in 2026 at Sapienza U.

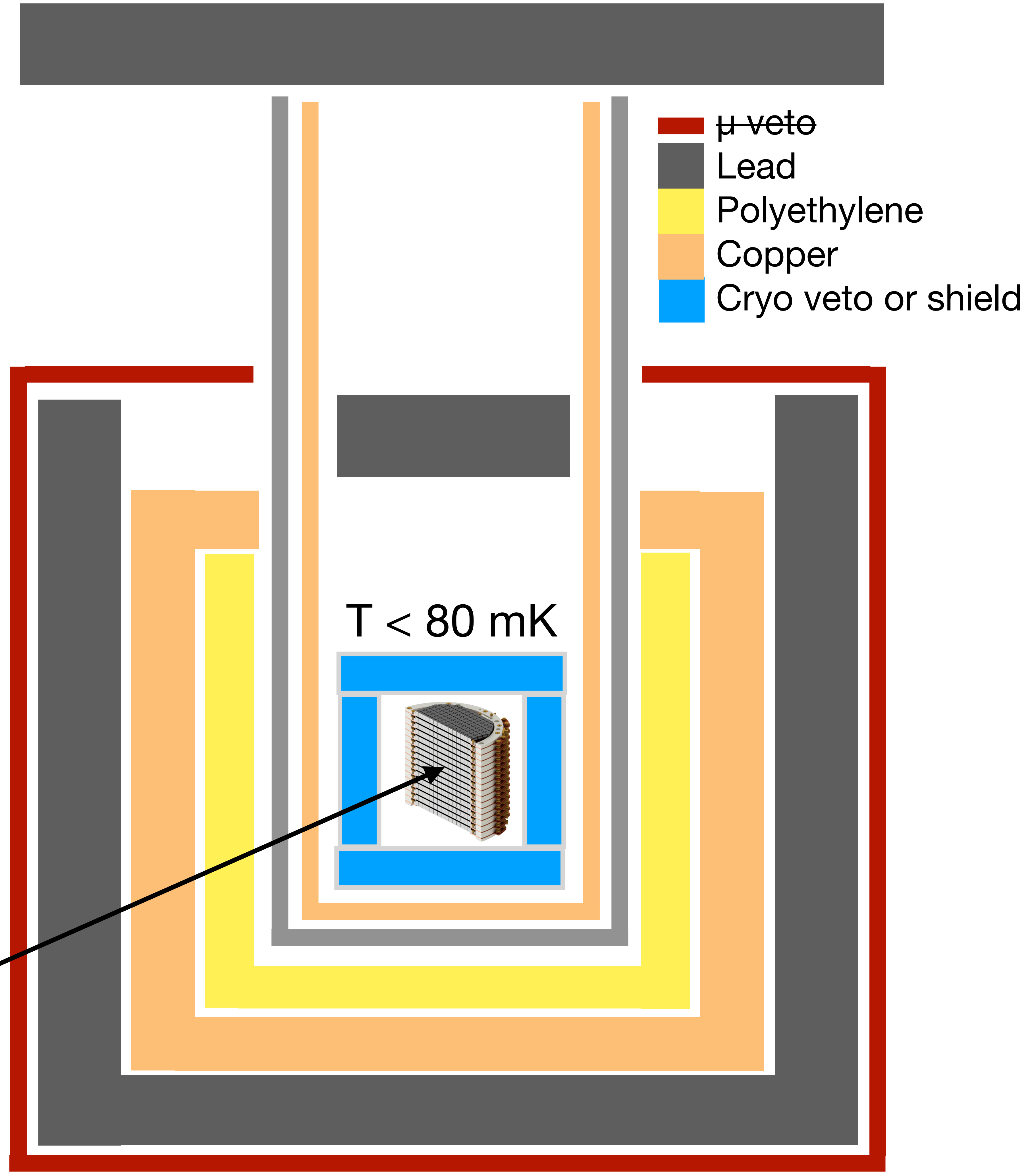
Towards the experiment

Underground cryo-infrastructure
Dilution refrigerator with T < 80 mK
Cryostat outer shielding (PE, Pb, …)
Inner shielding
~~Outer muon veto~~
~20 RF lines

MC Simulations
Design of the apparatus
Definition of required radiopurity

Inner veto or shield
Cryo-veto around the BULLKIDs
(BGO/GSO + Light detector)
or lead passive shield?

erc DANAE
stack of wafers



✓ Ideas?

Energy calibration options:
- IR light
- neutron recoils (a là CRAB)
- ^{137}Cs or ^{60}Co Compton
- asynchronous

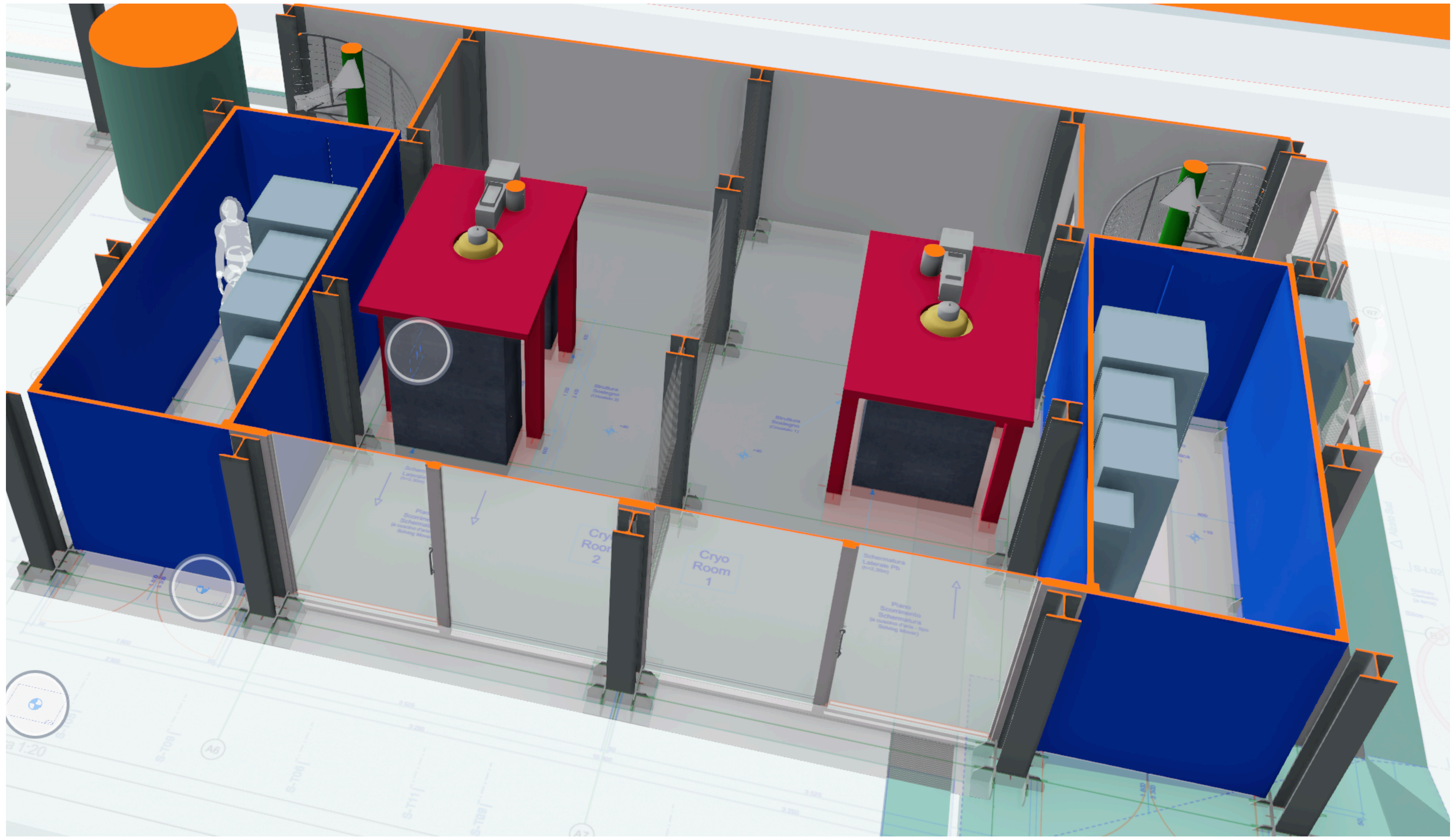
RF Readout and DAQ
SDR boards
onboard trigger

Computing
Data transfer
Data storage

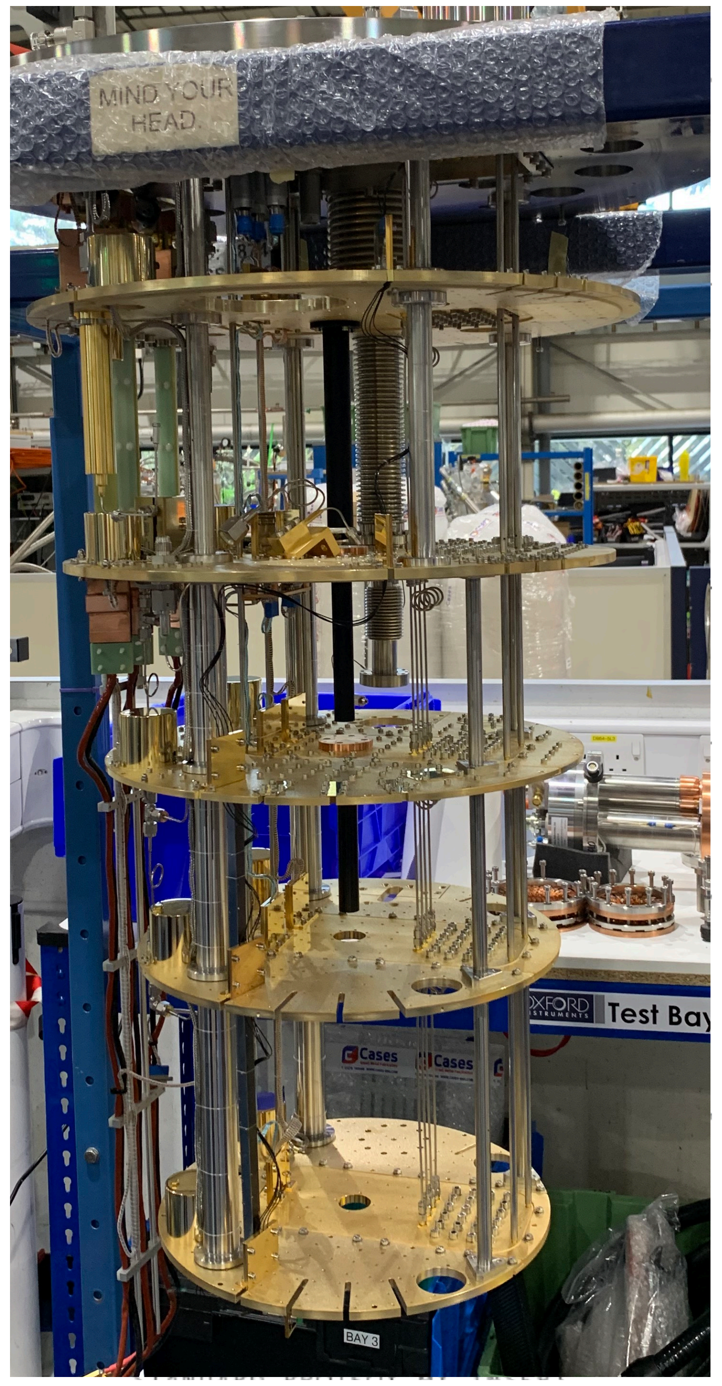
Data analysis
2000+ channels,
cluster analysis

LNGS Cryogenic facility

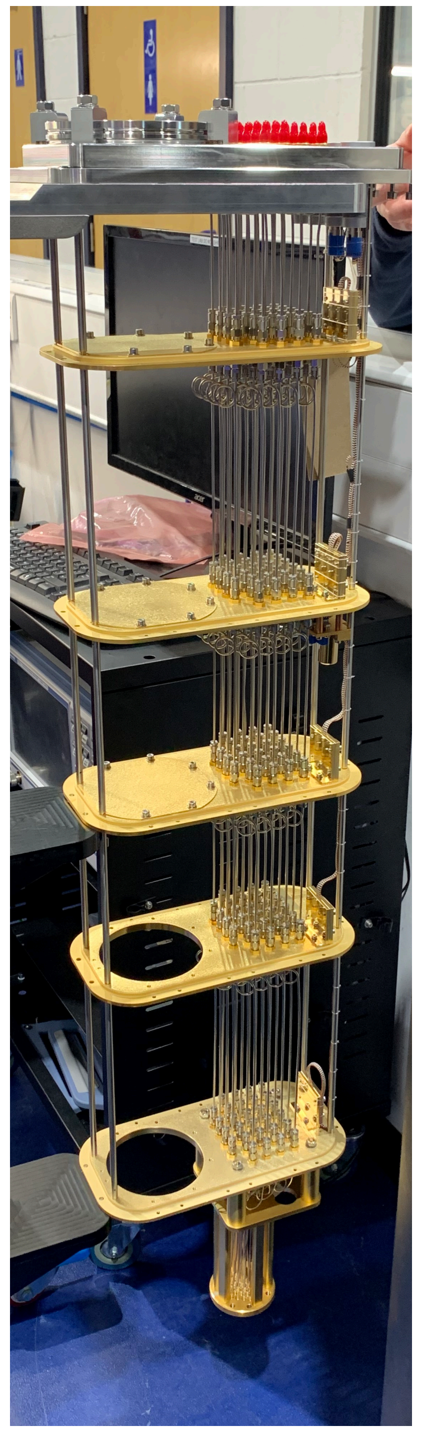
BULLKID-DM intends to be a user of the new facility in Hall B
Additional shielding might be required



Ordered Oxford Proteox fits the needs



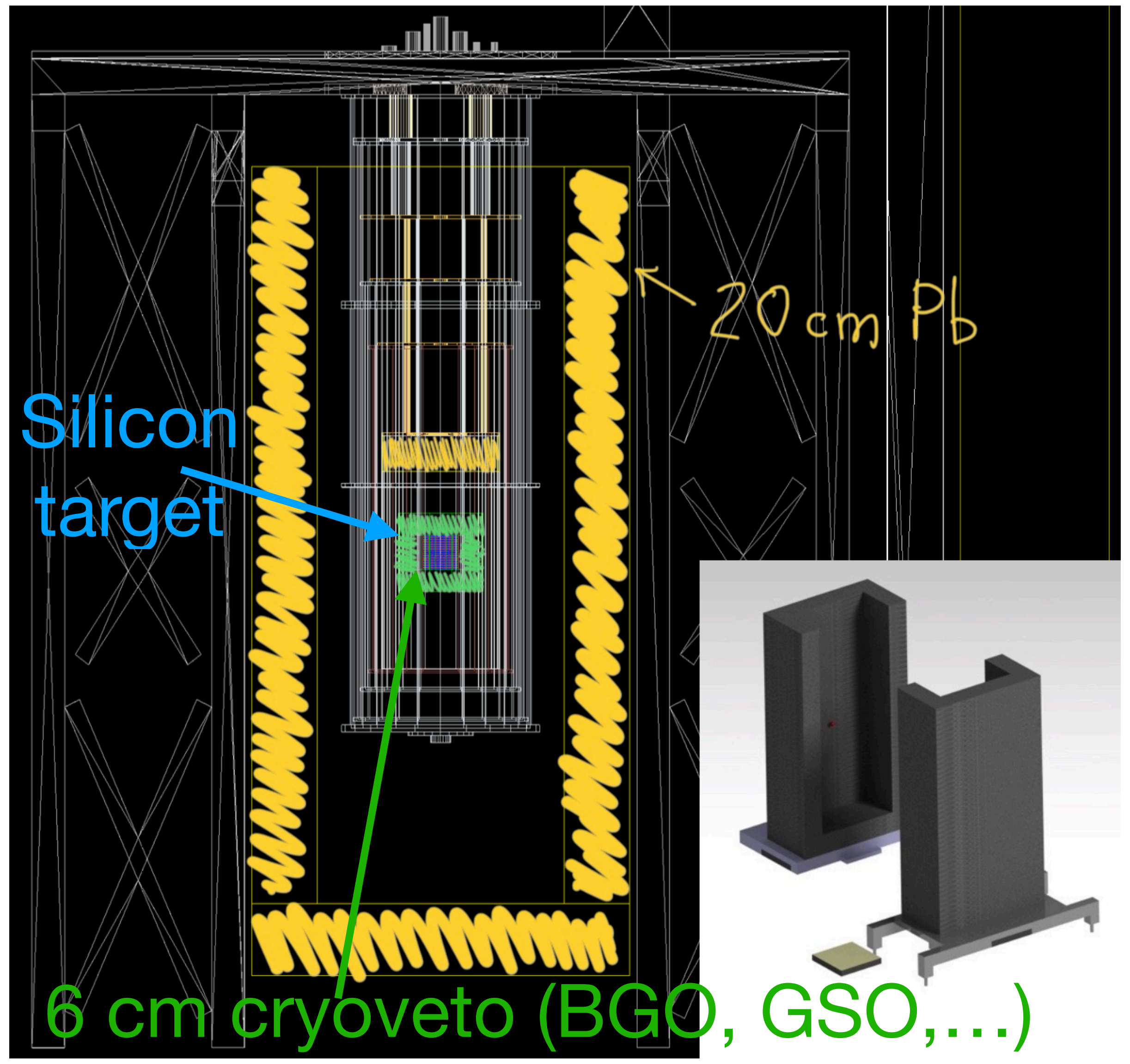
Replaceable insert to be instrumented with RF lines



Simulations: shields and veto

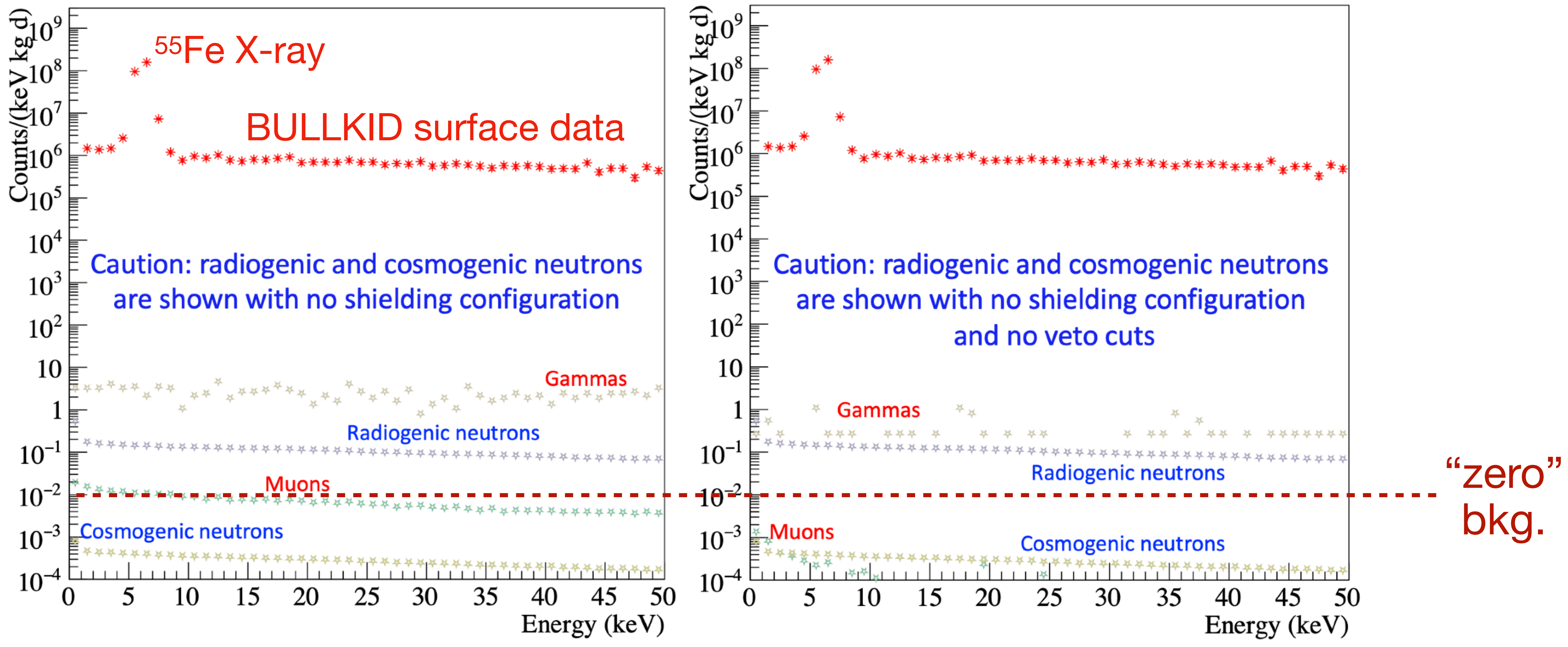
✓ preliminary

No polyethylene, copper and top lead yet



“passive” veto

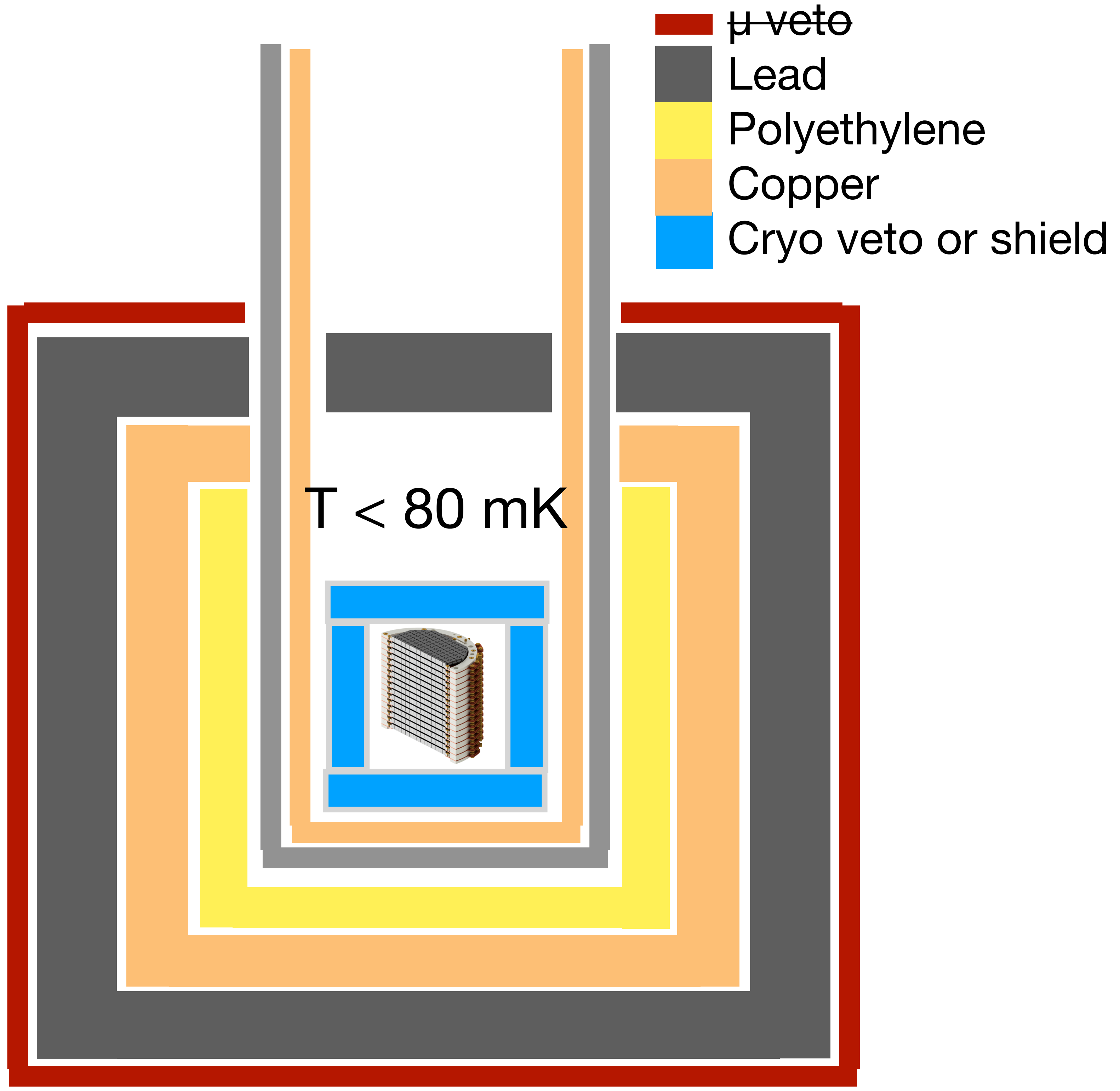
“active” veto E_{th} = 50 keV



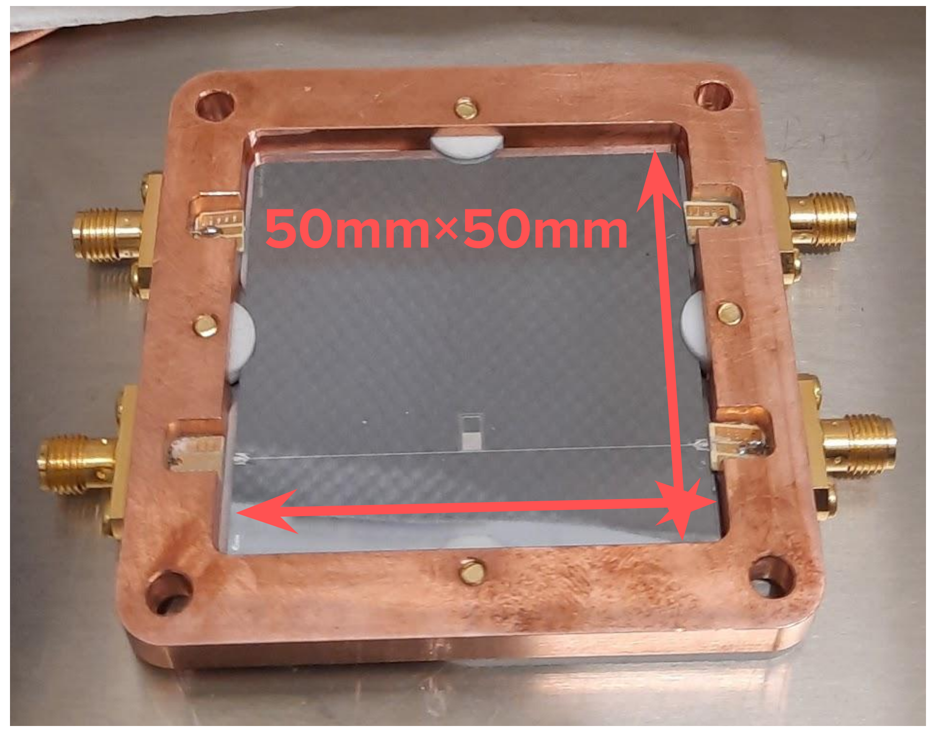
Currently working on internal contaminations in lead and veto

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.

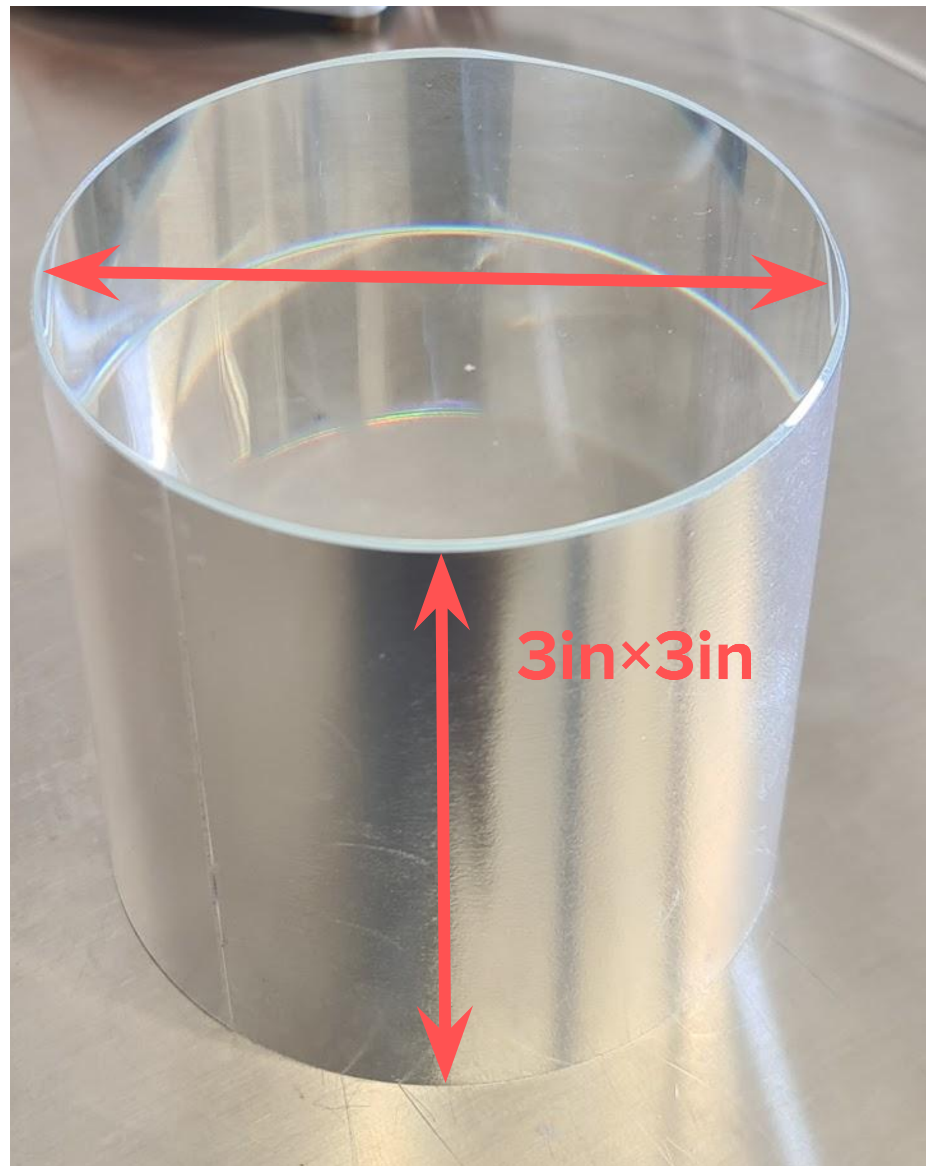
Cryogenic veto: BGO prototype



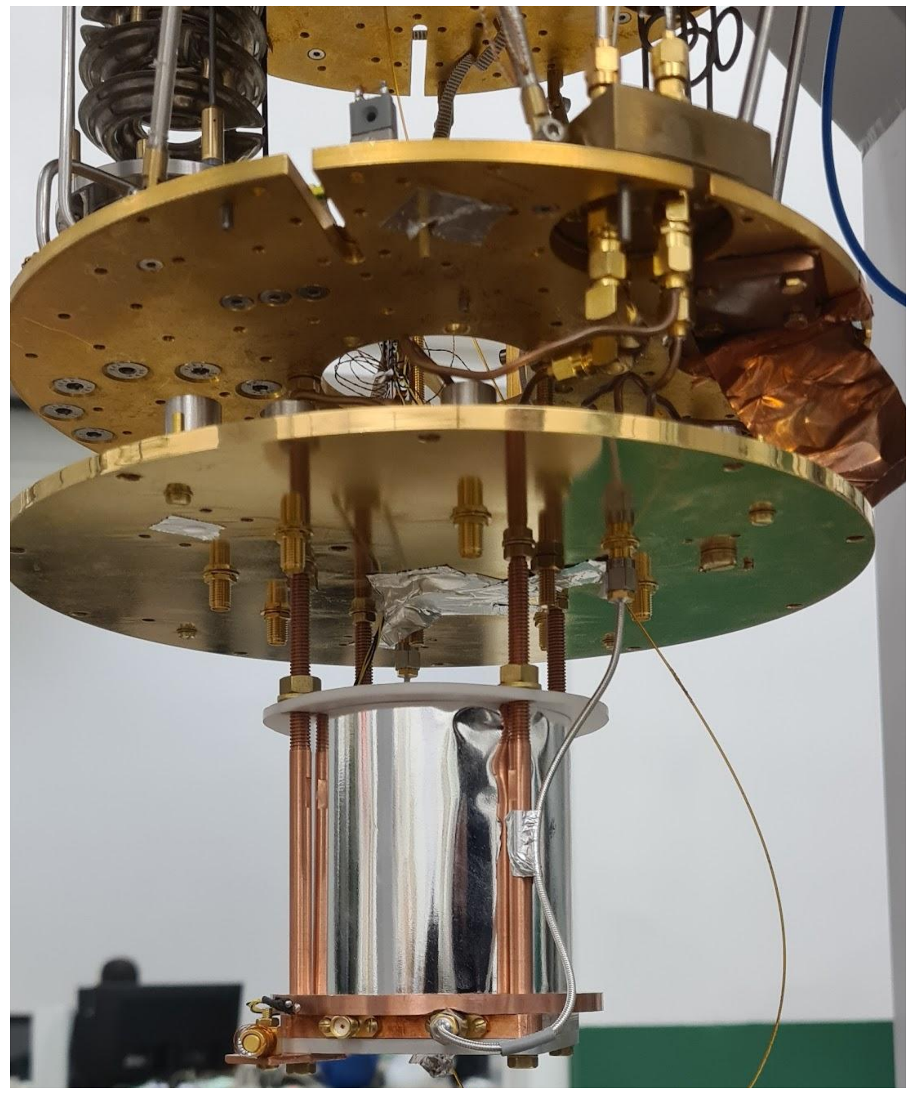
CALDER KID Light detector

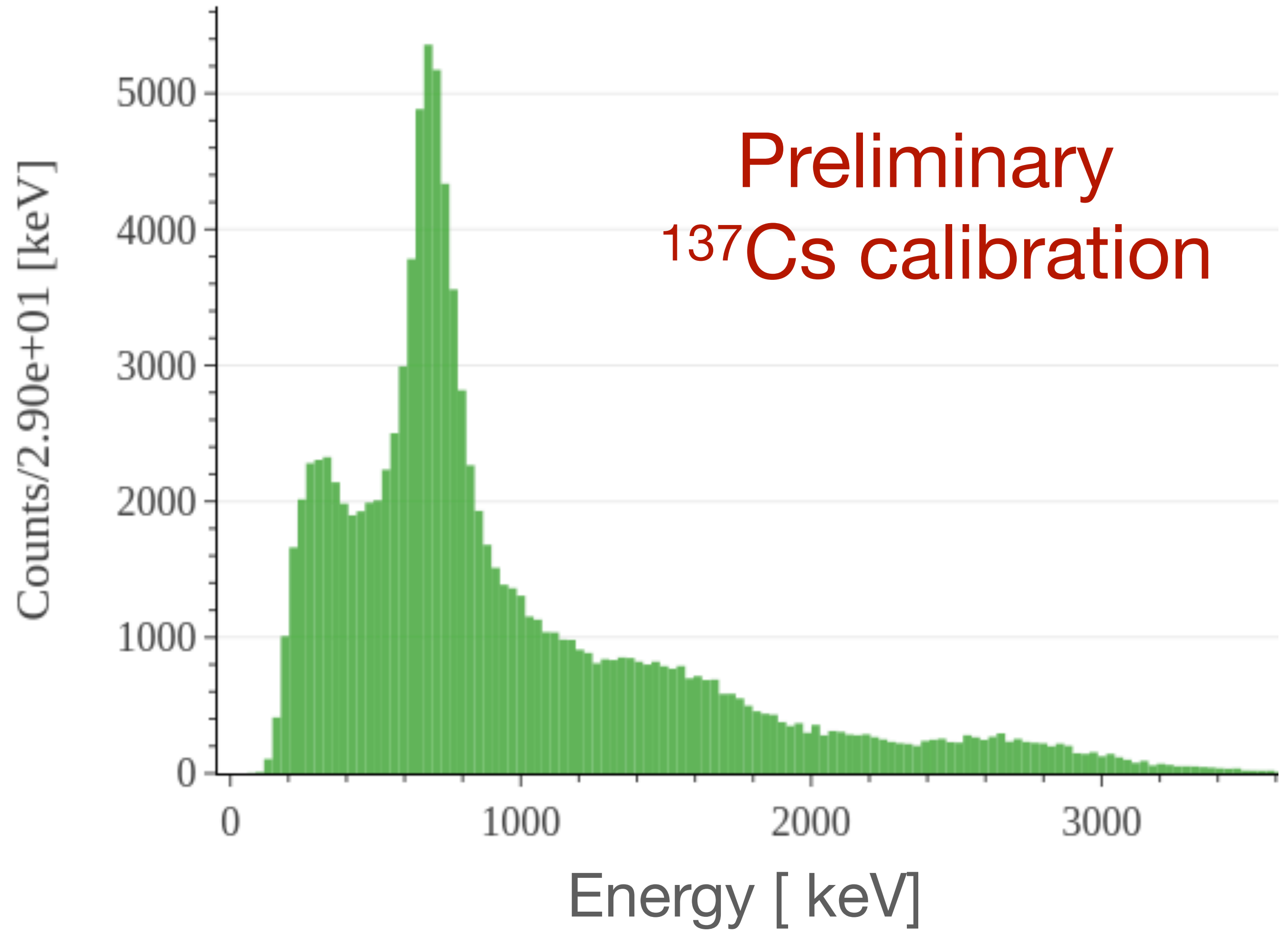


BGO Crystal



Assembly with reflector





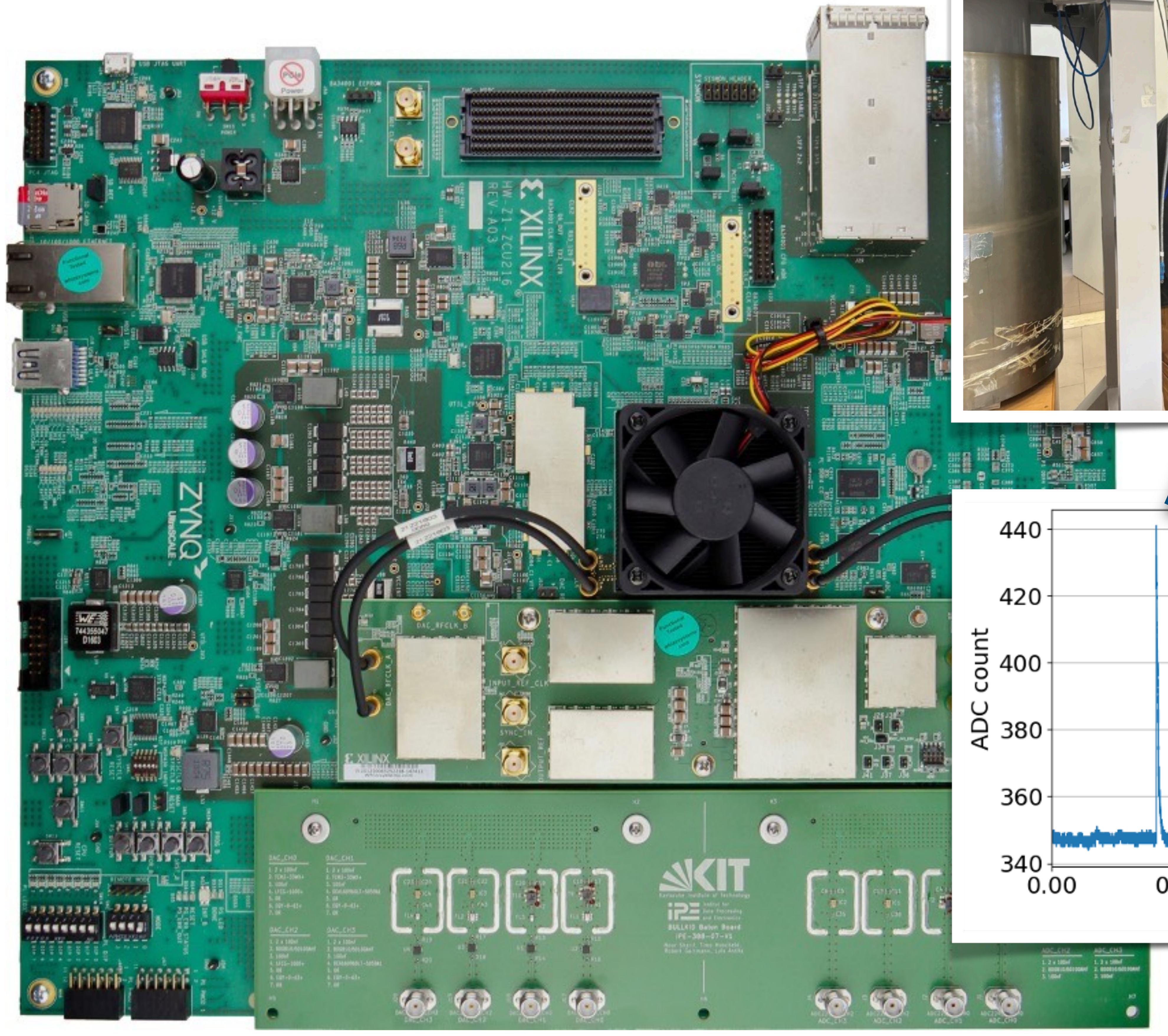
Goal: energy threshold < 50 keV

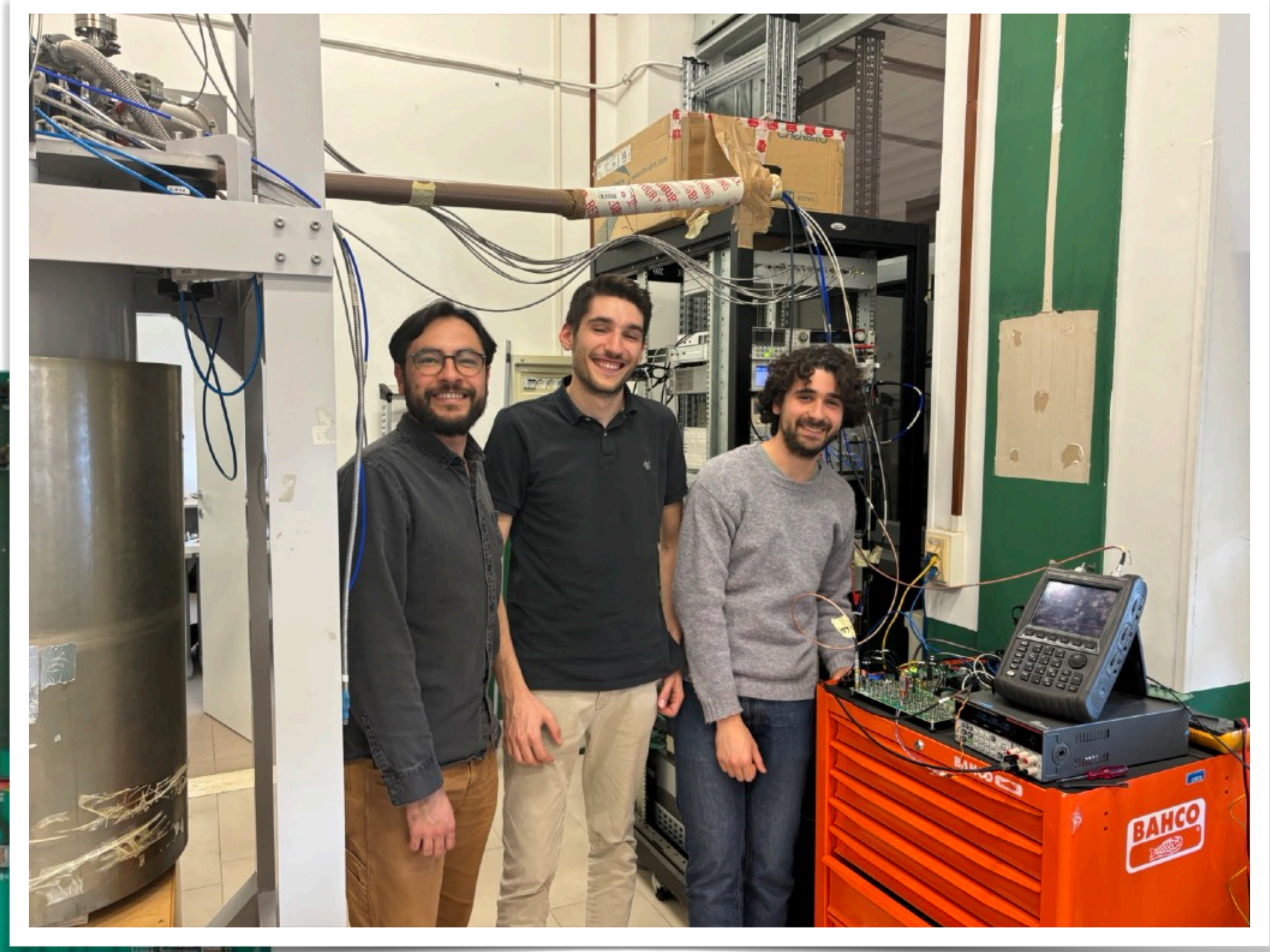
RF Electronics

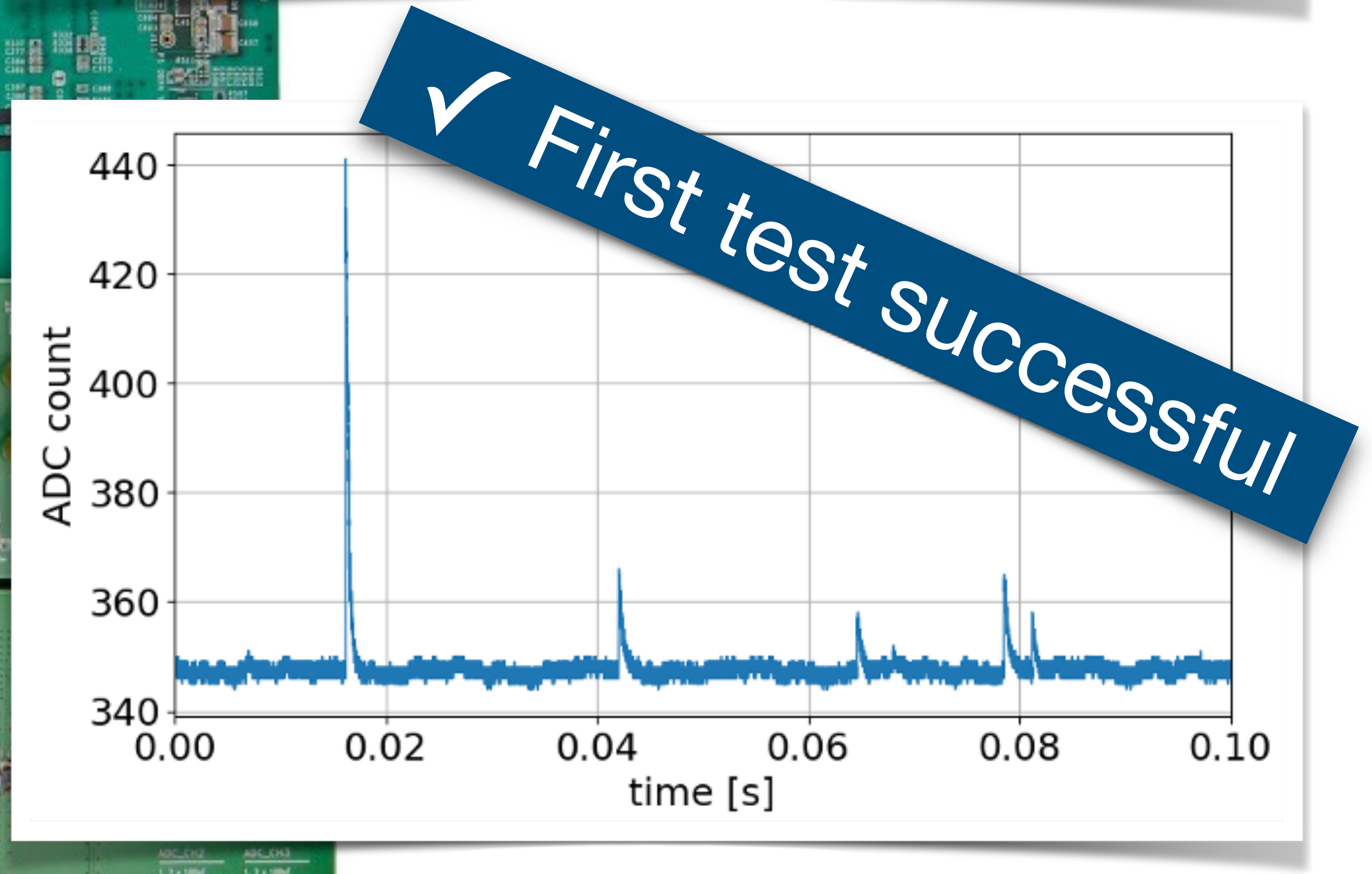
Current electronics (Ettus x310):
30 KIDs / board

New electronics (ZCU216 Evaluation Board with 16 lines):
Goal >= 150 KIDs / line

- Custom Analog Front-End and
- Control Firmware by the KIT group
- **Status: first tests on BULLKID-prototype**







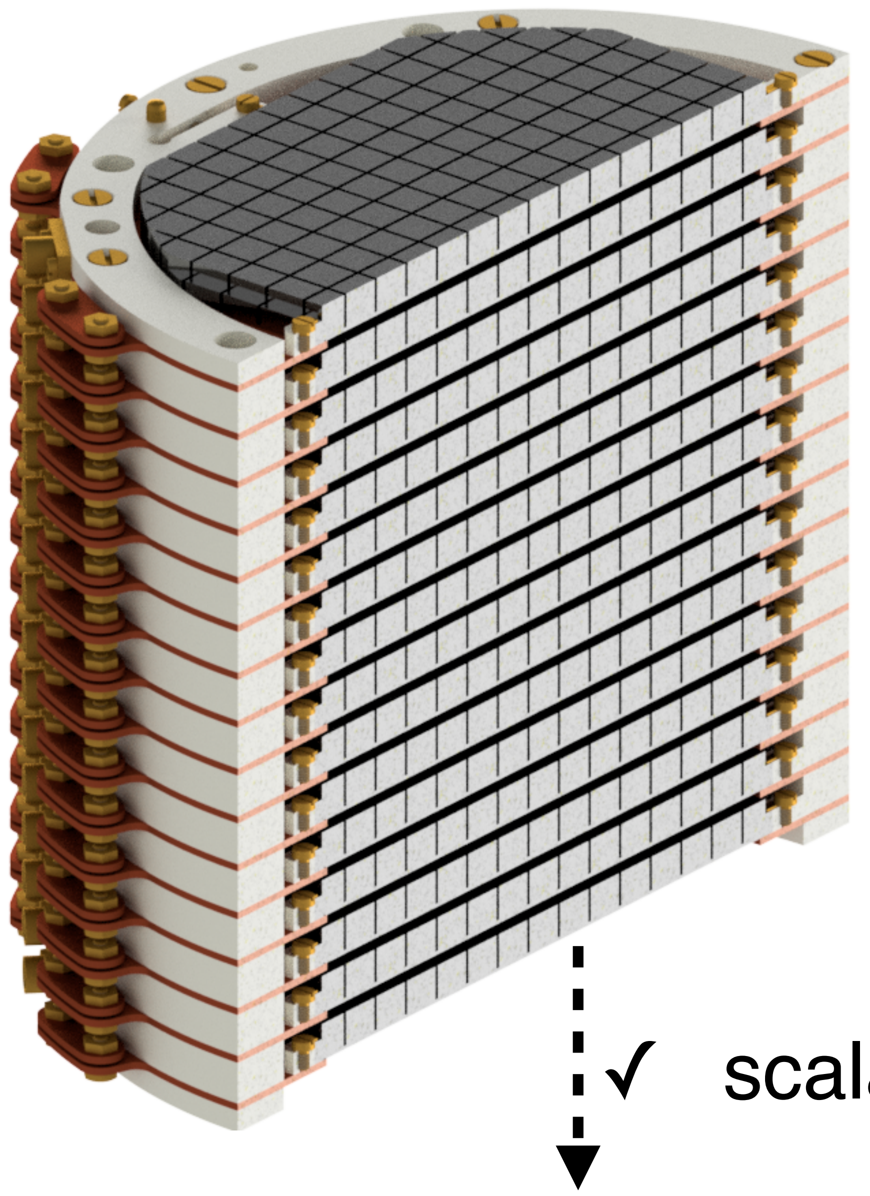
Wrap-up

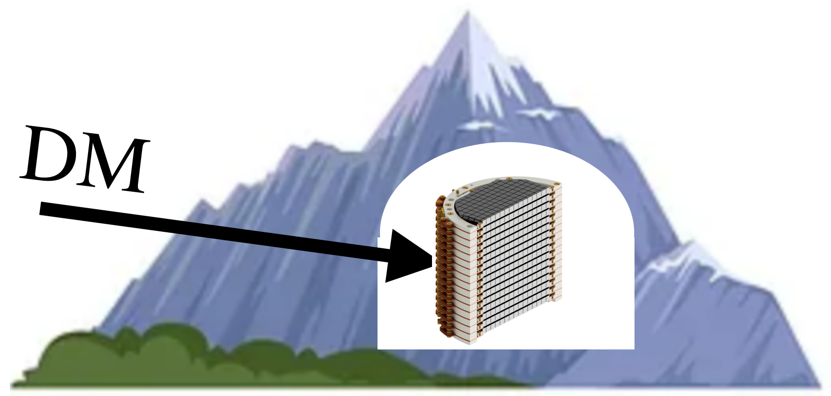
- ✓ 0.6 kg of silicon target
- ✓ 2500 detector units (dice)

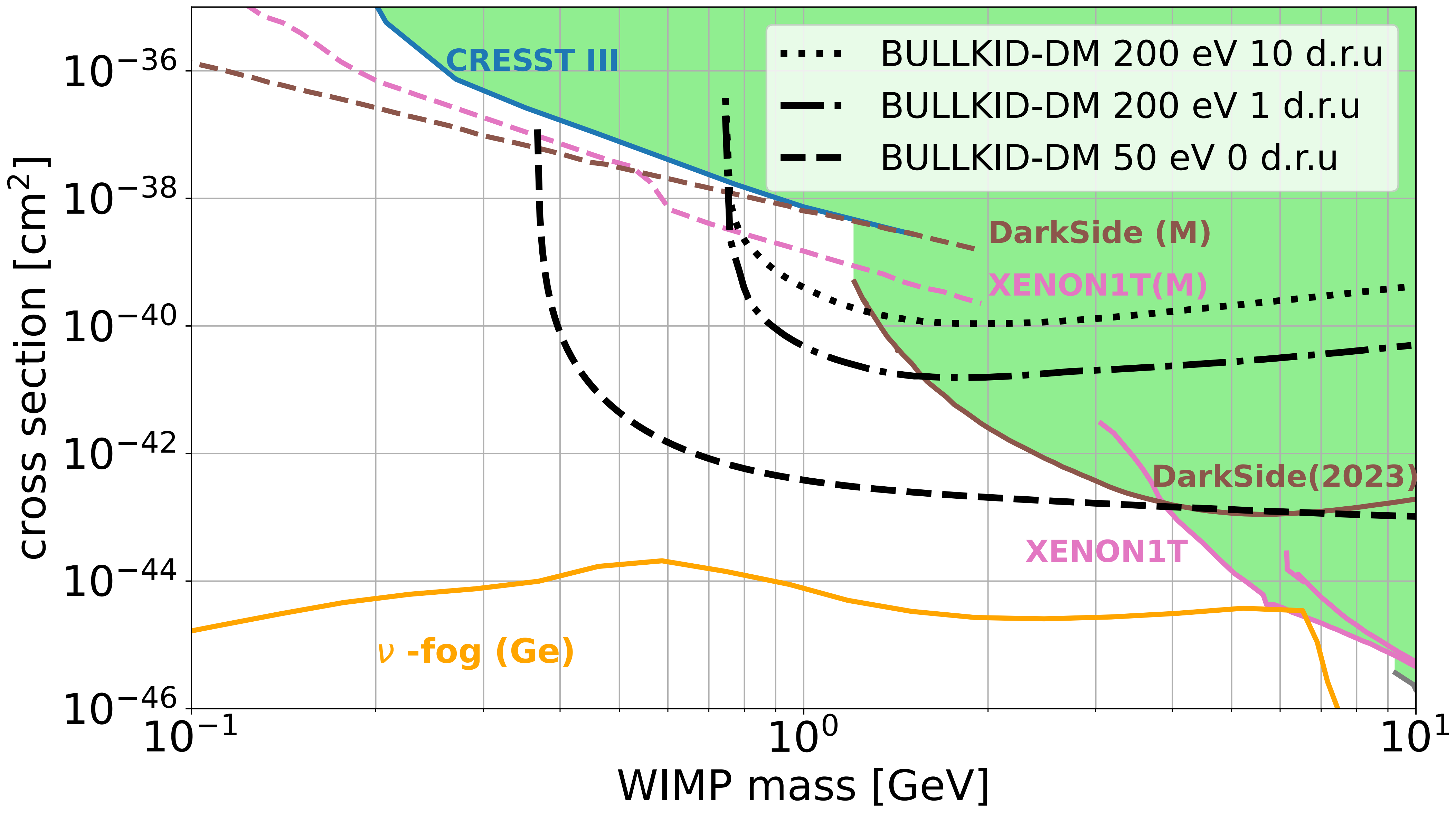
Unique features for bkg. suppression:

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

Will it help with the unknown backgrounds?







Prototype works | demonstrator (3 wafer) | 60 KID electronics | 150 KID electronics and prototype veto | full stack commissioned in Roma, full veto and electronics

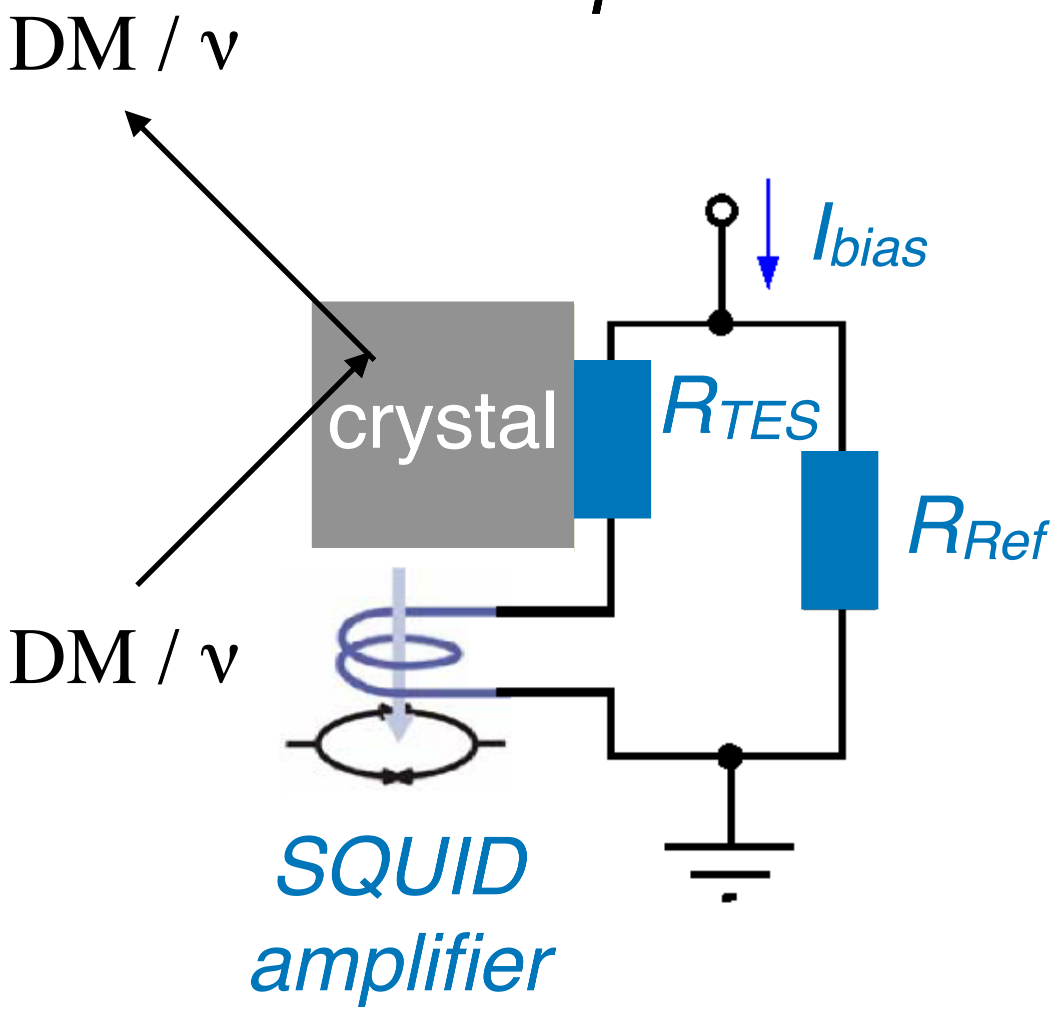
2023 — 2024 — 2025 — 2026 — 2027

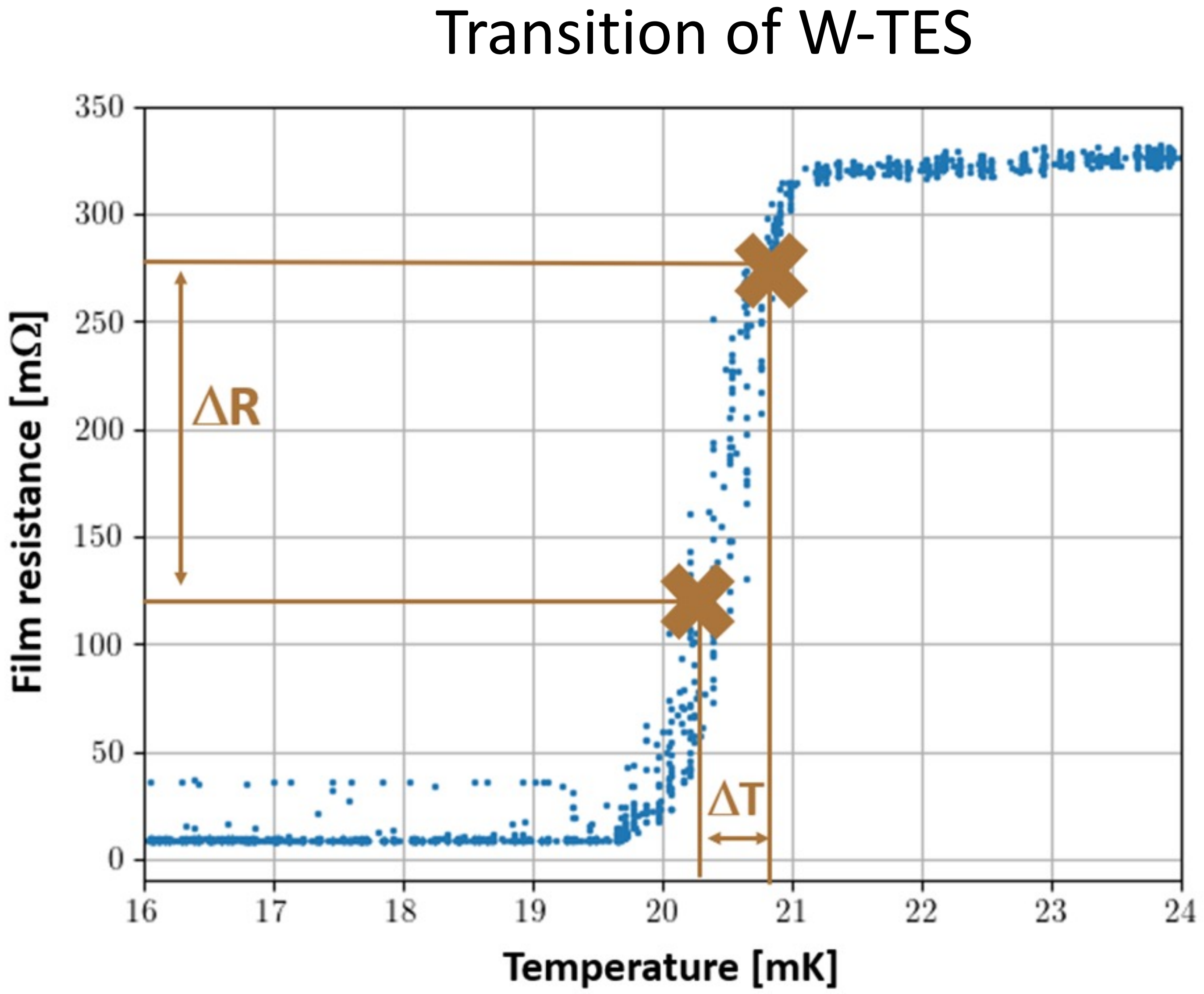
tentative schedule for LNGS: demonstrator (technical run) | additional shielding installation | detector installation | data taking

Backup slides

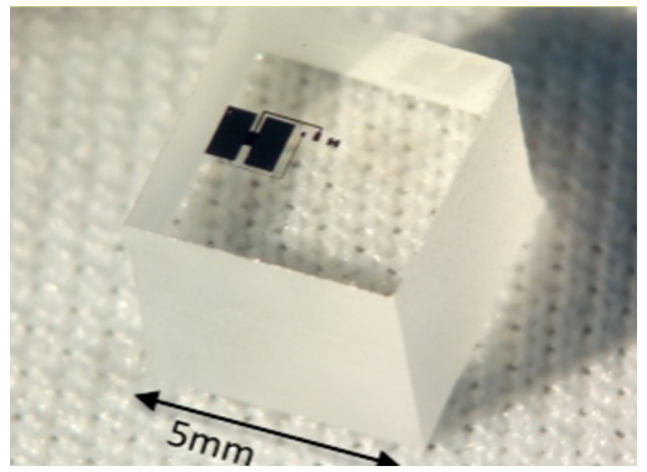
State of the art of phonon detection
(CRESST/NUCLEUS experiments)

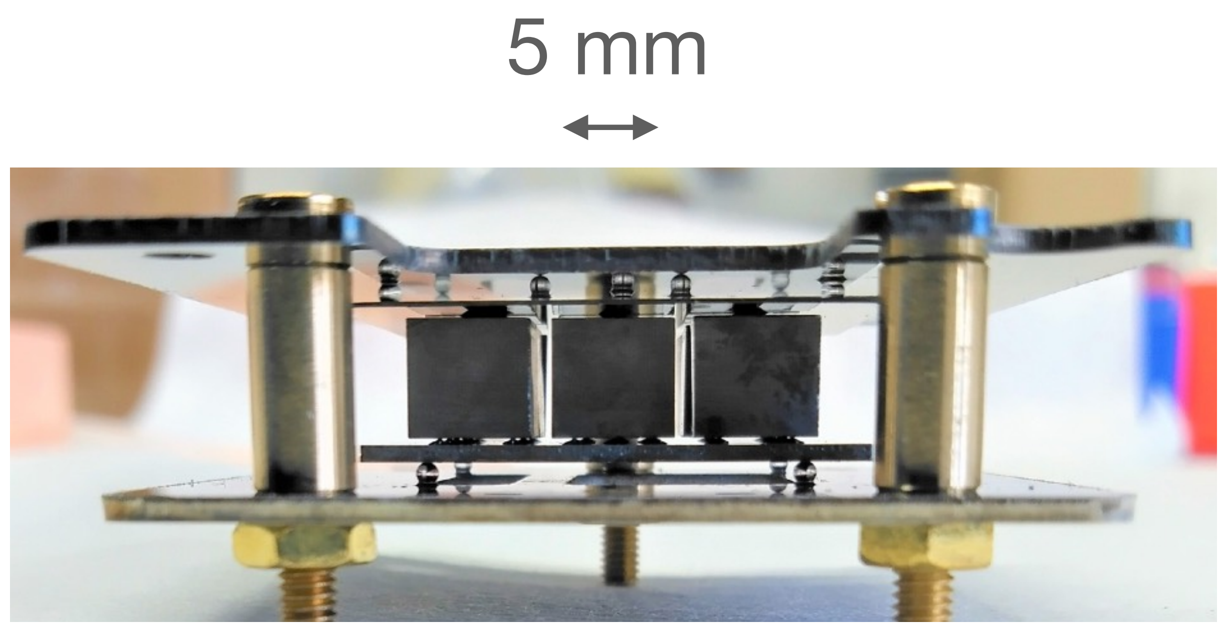
Superconducting thermometers (TES)

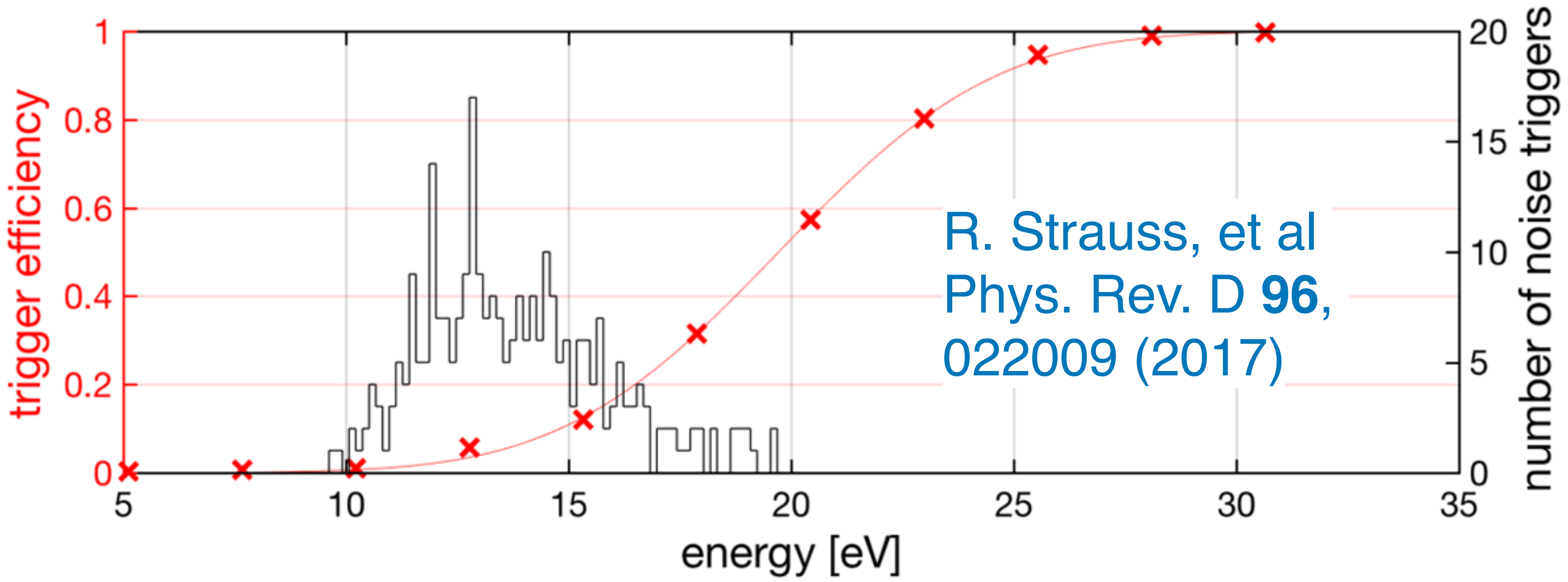




Limitation: individual readout







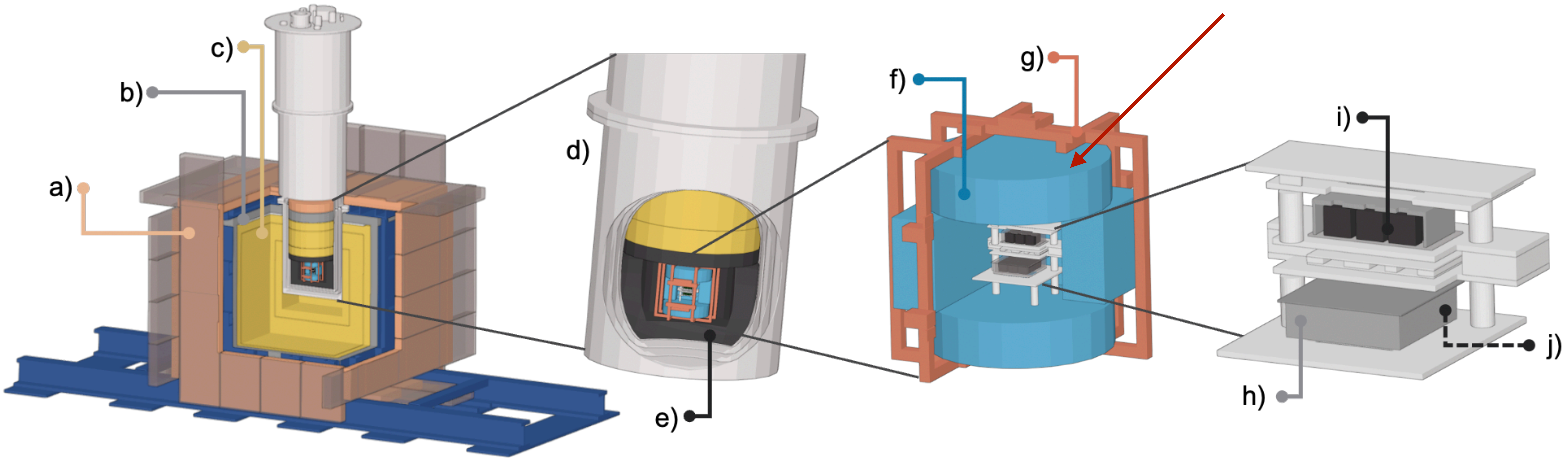
Pro: record-low energy threshold ~ 20 eV

Future experiments point to kg targets (100÷1000 crystals) challenging with this technology

NUCLEUS: experimental apparatus

above ground experiment (3 m.w.e)

In BULLKID: BGO/GSO crystals read by the KID light detectors of CALDER?

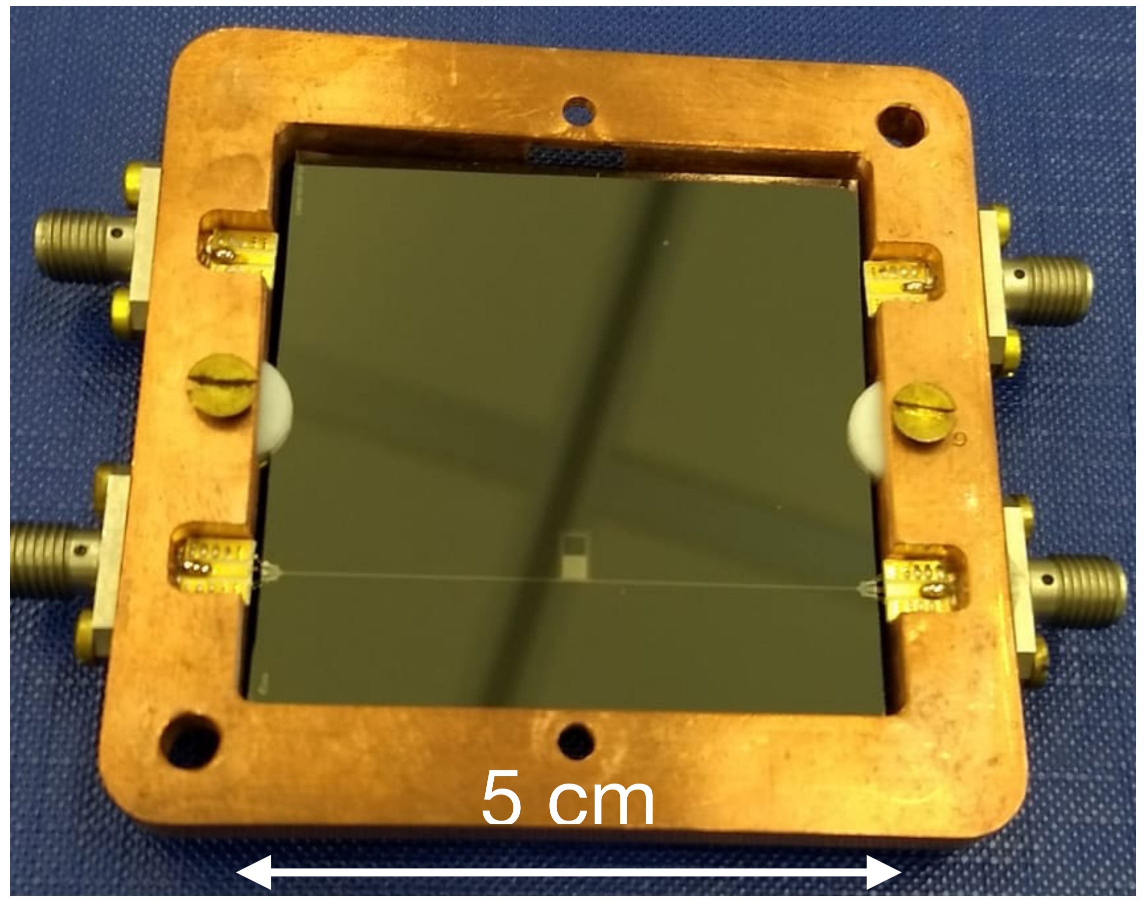


C. Goupy et al [NUCLEUS Coll.], arXiv:2211.04189

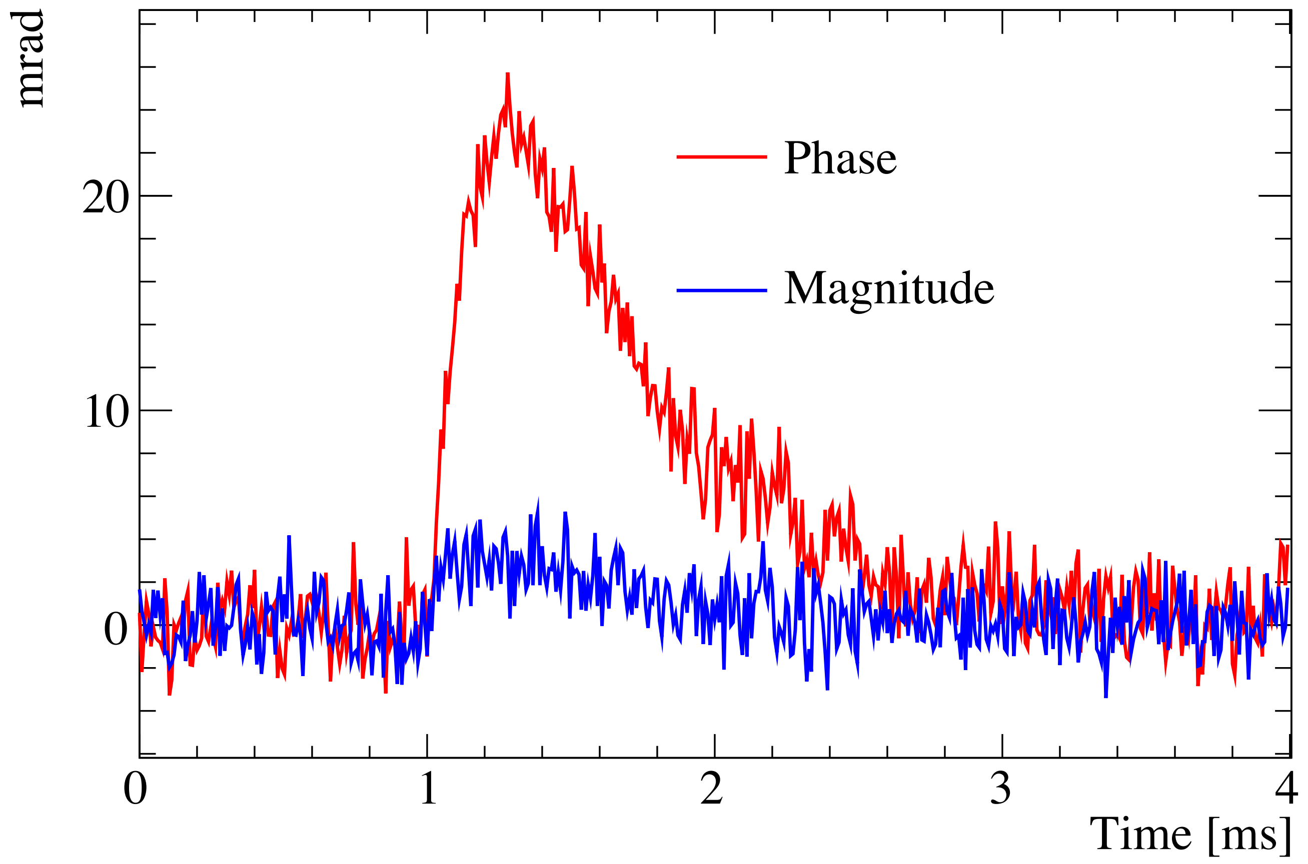
a) 28 5-cm thick Muon Veto panels, **b)** a 5-cm thick lead layer, and **c)** a 20-cm thick borated polyethylene. **d)** A dilution refrigerator is inserted inside the shielding and contains **e)** a 4-cm thick boron carbide layer and **f)** a Cryogenic Outer Veto made of six high purity germanium crystals held by **g)** a copper cage. Finally the cryogenic detectors are organised in two arrays of nine cubes of **i)** $CaWO_4$ and **j)** Al_2O_3, held by **h)** the silicon inner veto.

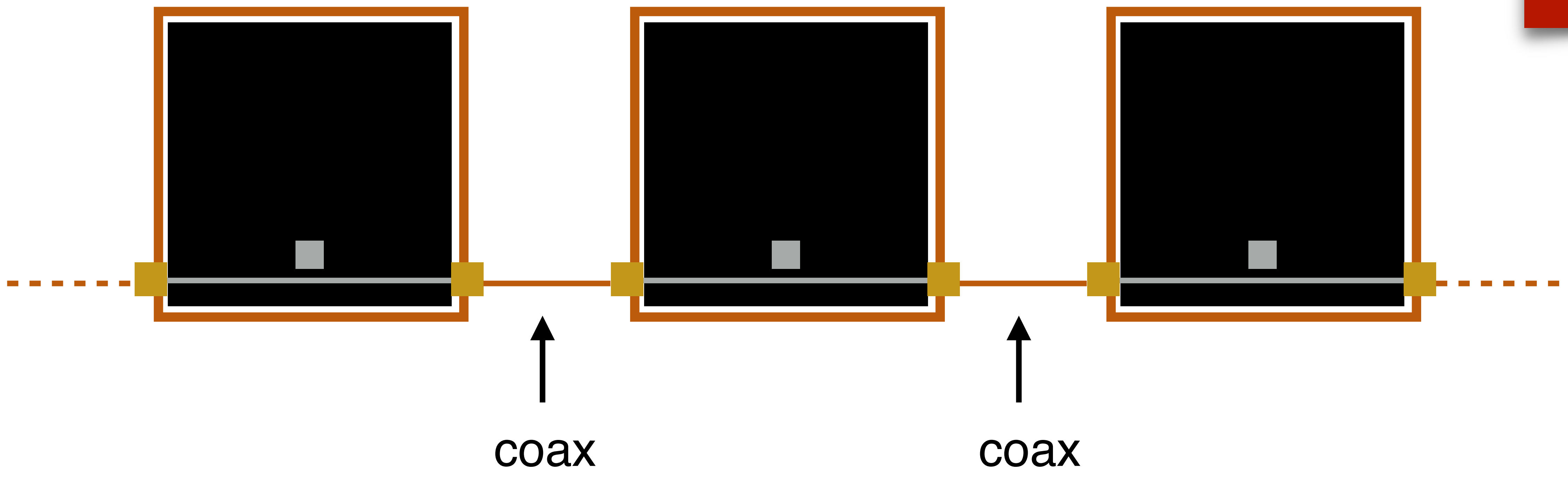
CALDER: light detectors w KIDs

L. Cardani et al, EPJC 81 (2021) 636



Area [cm²]	25
ΔE [eV RMS]	34 90 w/o vibration decoupling
Response time [ms]	**0.12**
Temperature [mK]	8-120
# detectors	Multiplexing

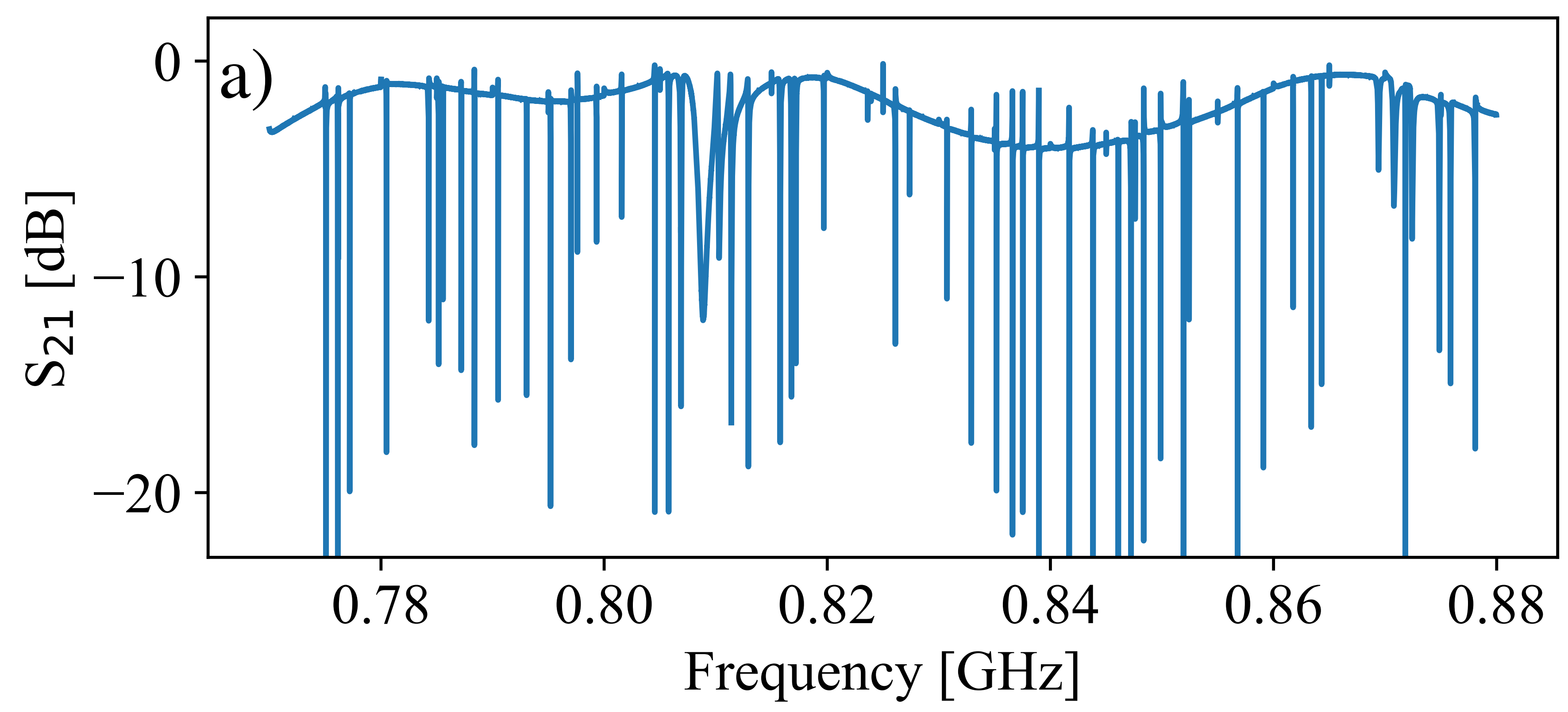


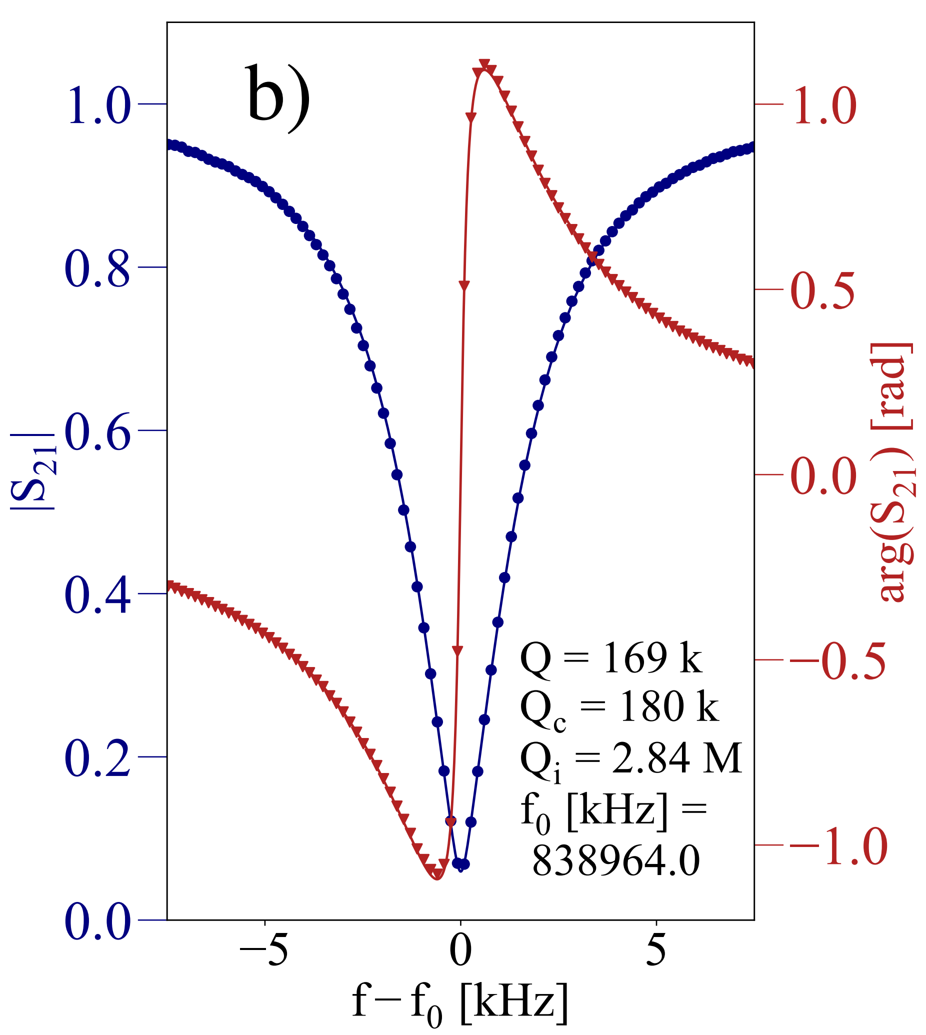


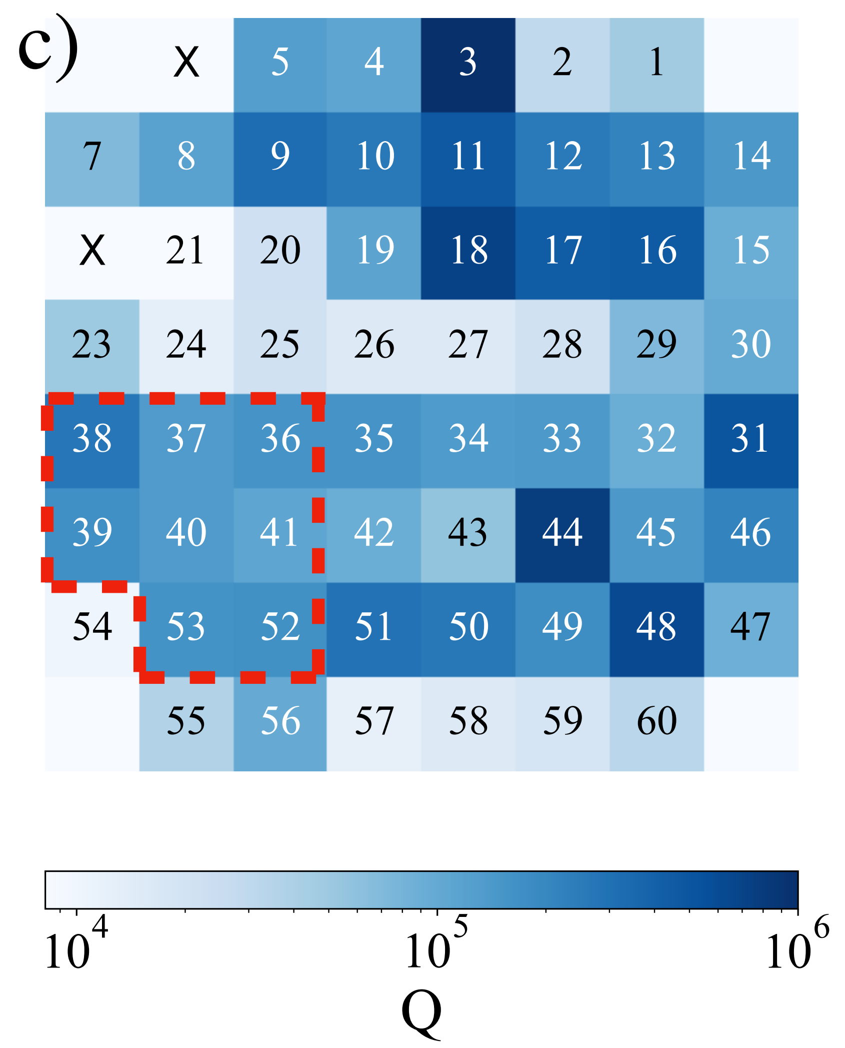
Could be coupled to scintillating crystals for the BULLKID veto

First results (Summer ’22)

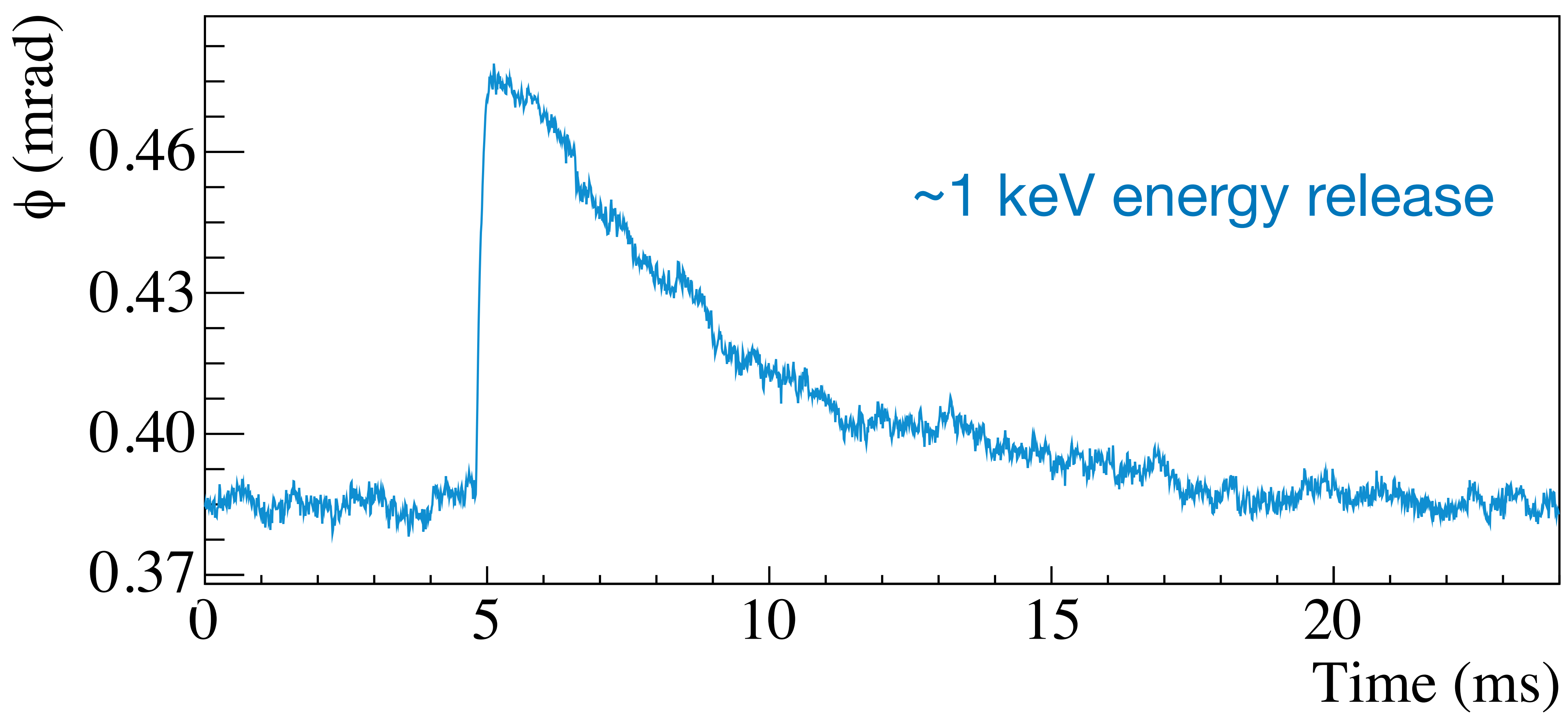
Frequency scan of the KID array

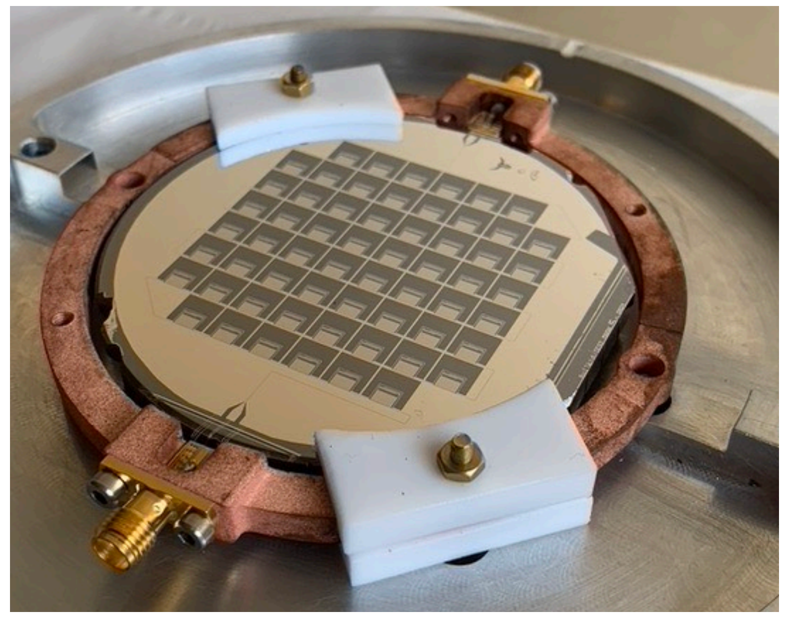






Particle interaction in a dice





+) 58/60 KIDs alive

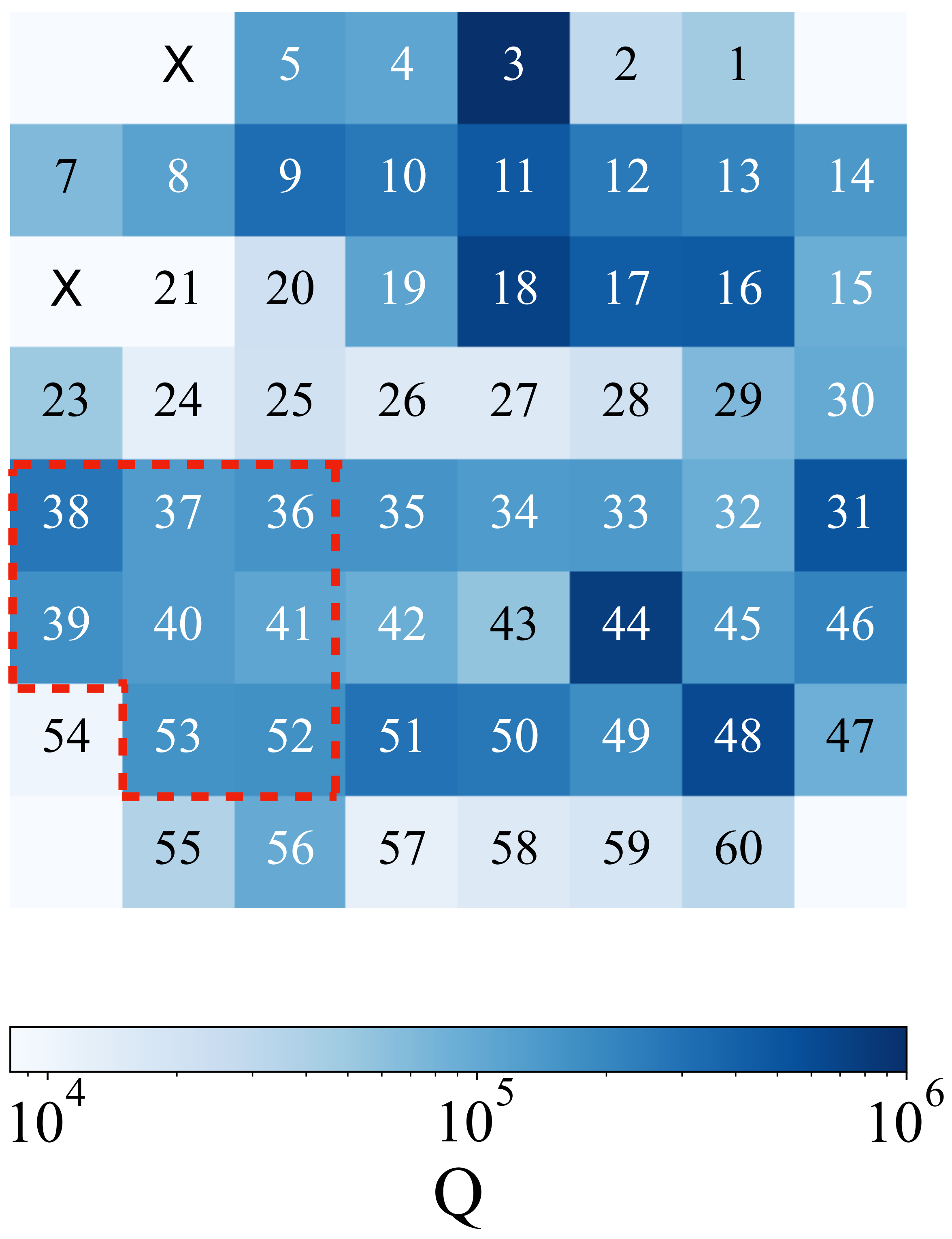
+) RMS@0 eV: **26 ± 7 eV**

–) Response not uniform

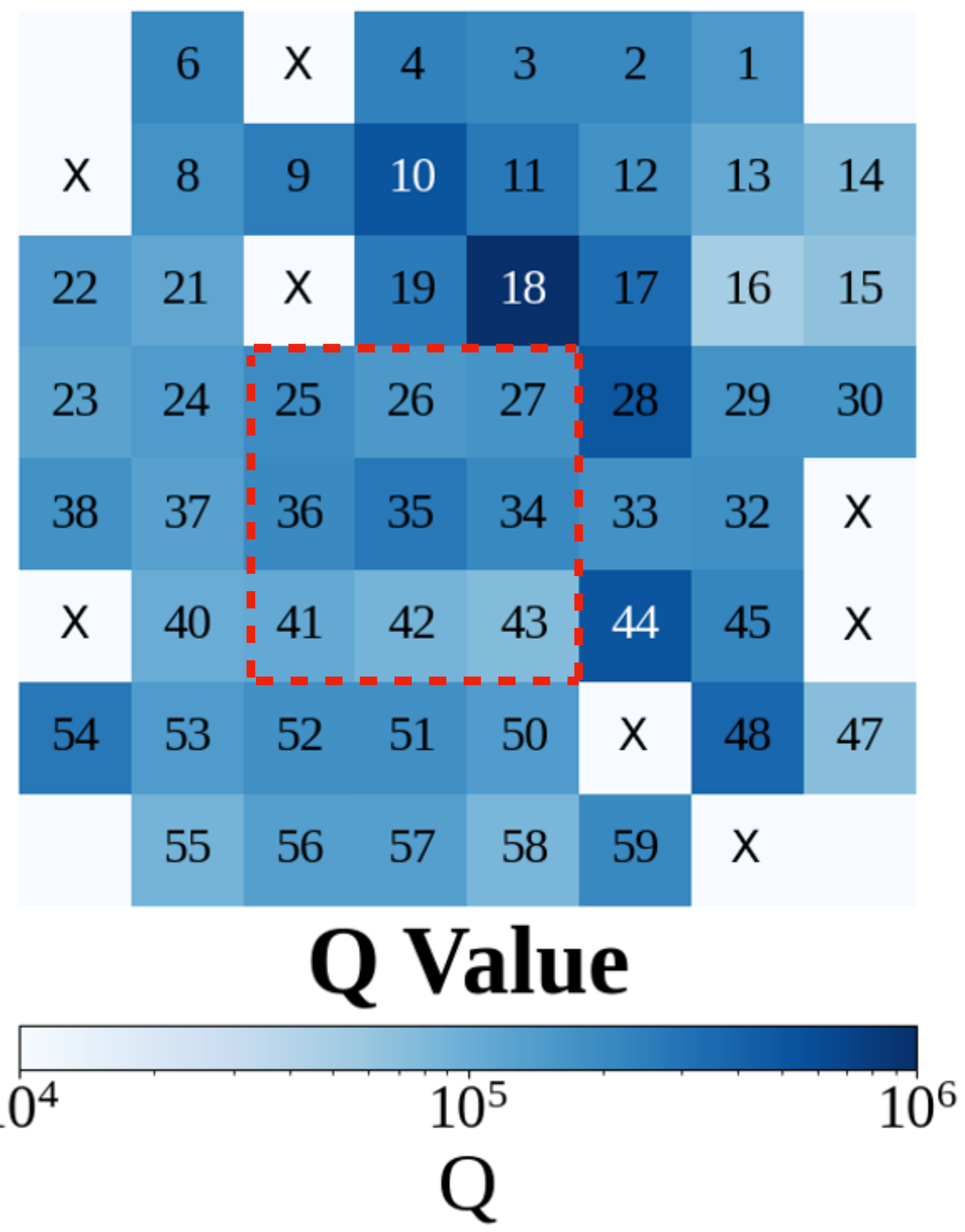
A. Cruciani, et al, Appl. Phys. Lett. 121, 213504 (2022)

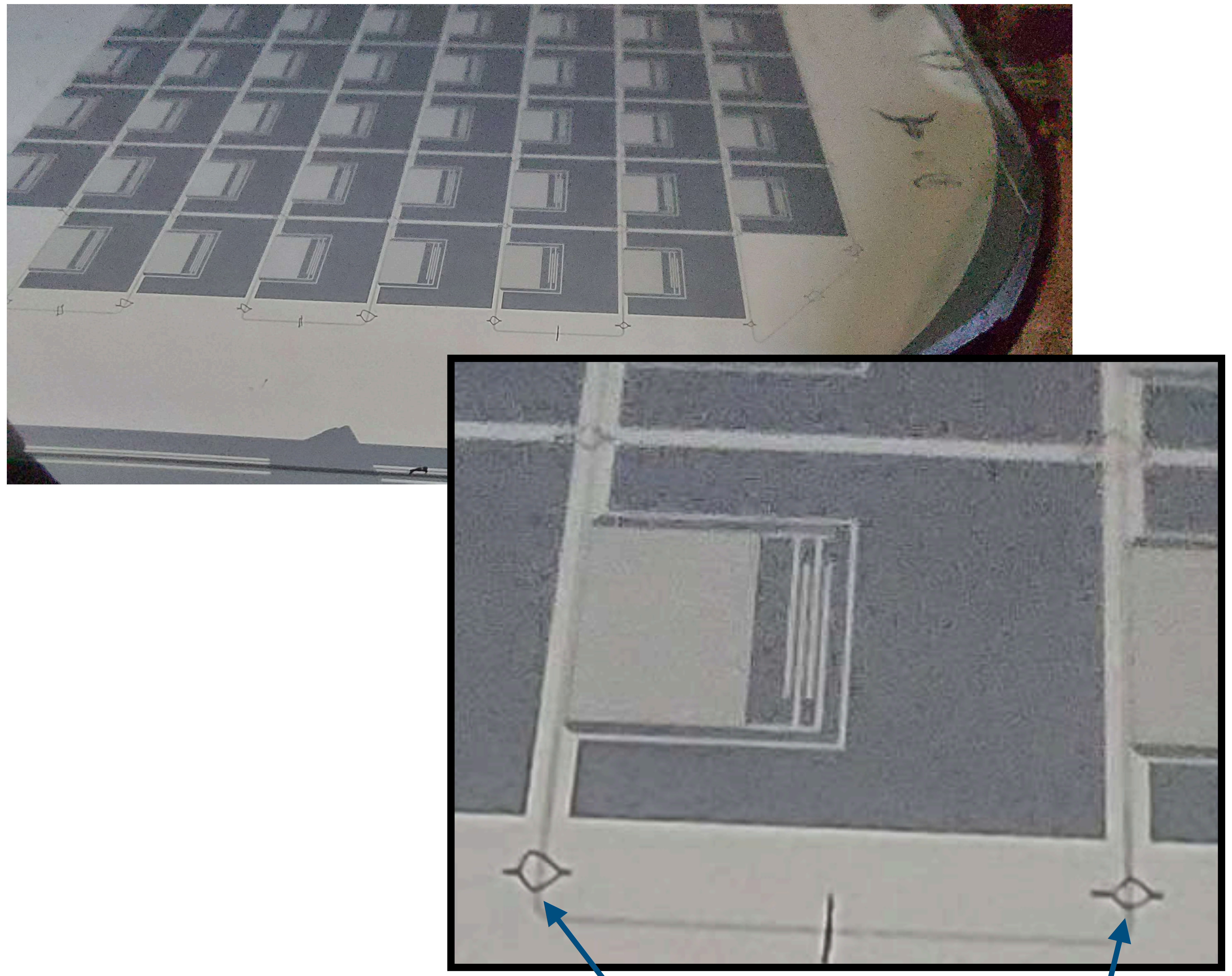
Improvement of uniformity ('23)

First version of the array



Same array with improved grounding





Airbridges connecting GND planes

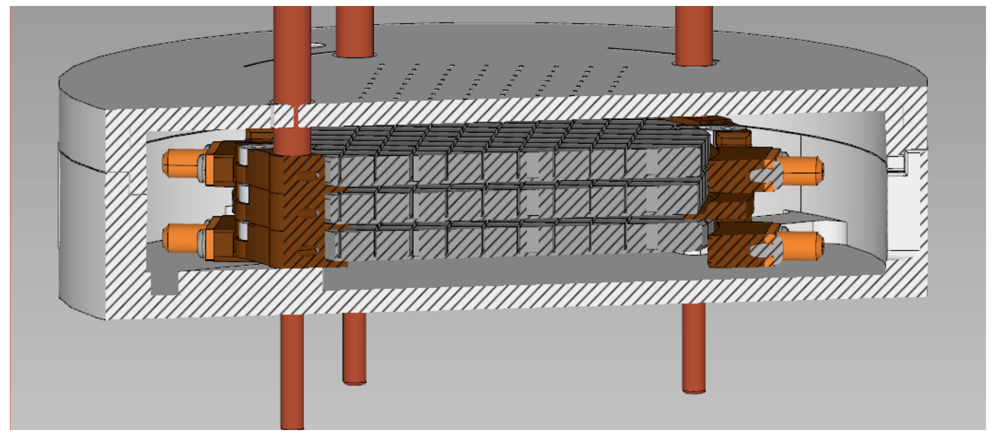
+) 58/60 KIDs alive

–) Response not uniform

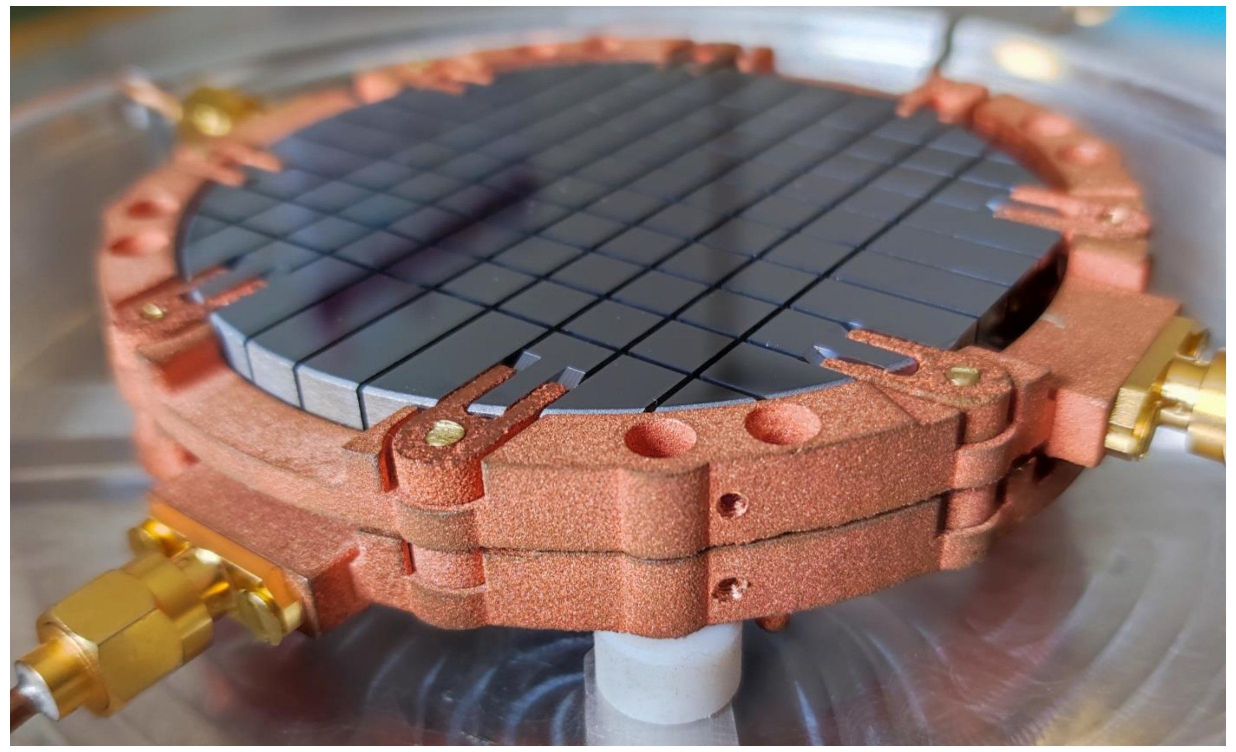
+) All KIDs with Q ~ 10^5 (optimal sensitivity)

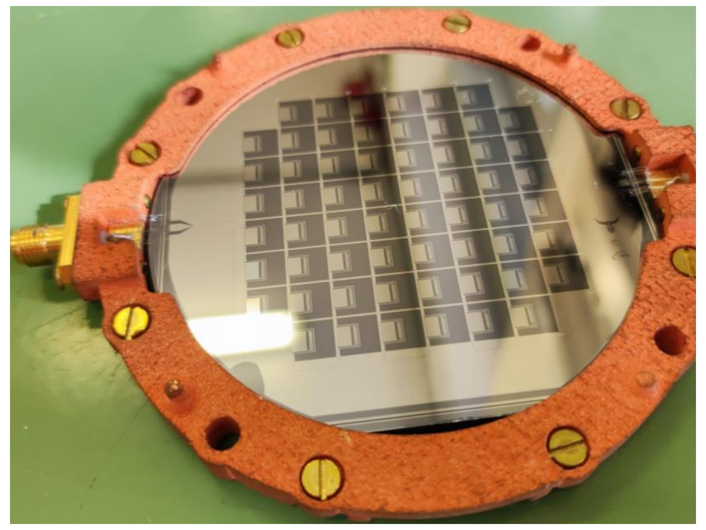
–) Some resonator lost during operations

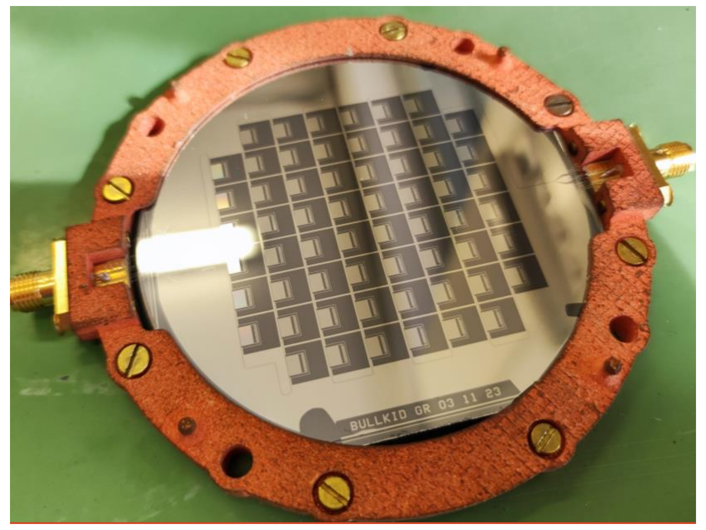
Status of the 3-wafer demonstrator

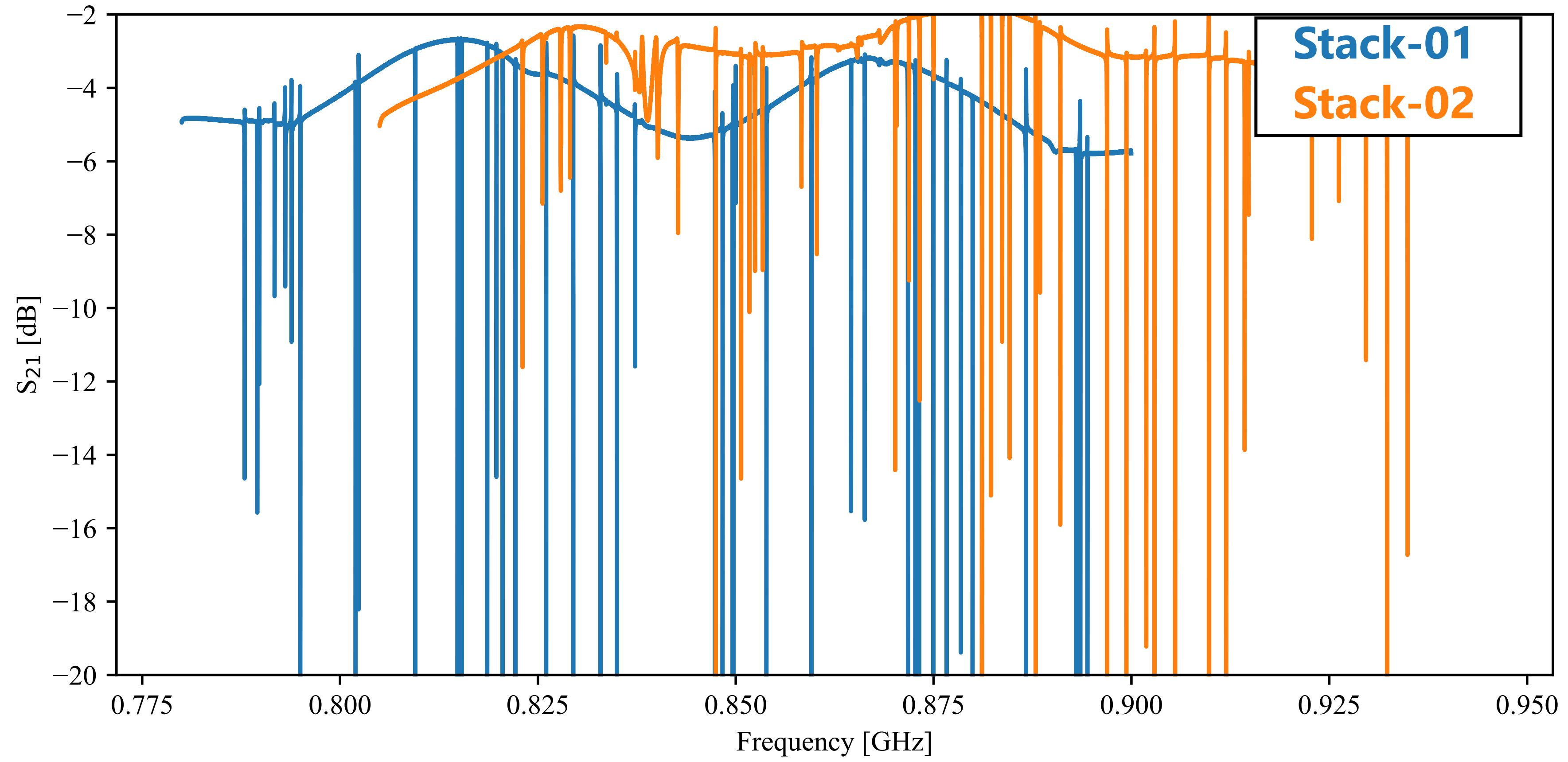


2-wafer stack operated. No issues observed

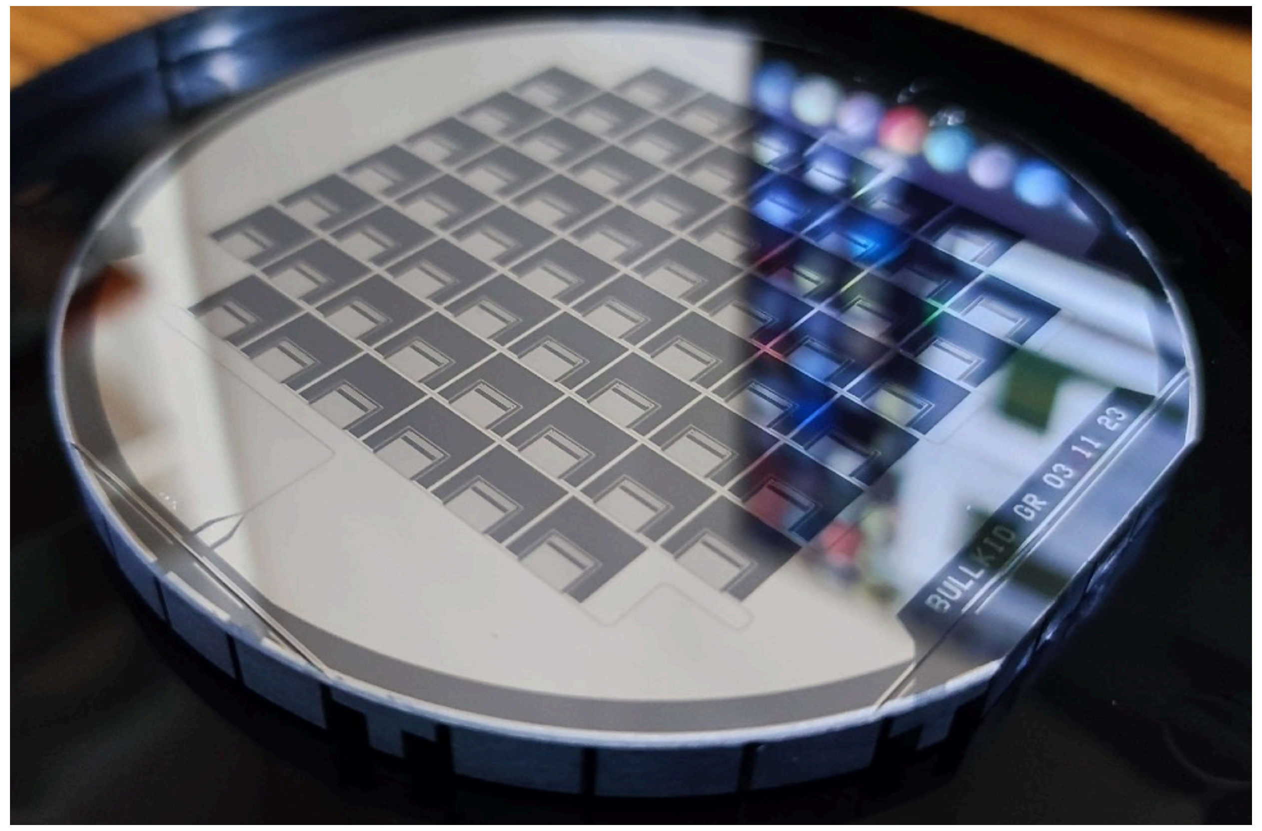


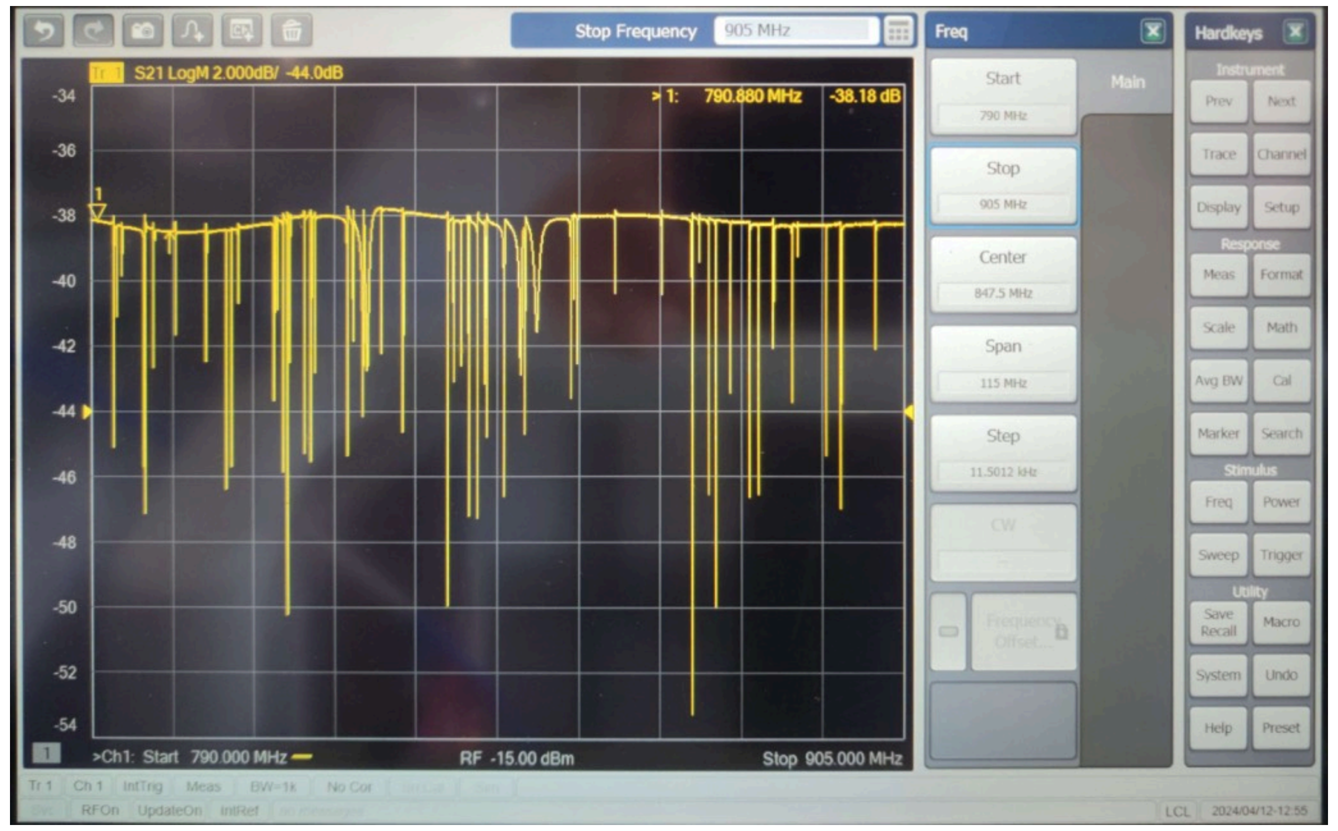






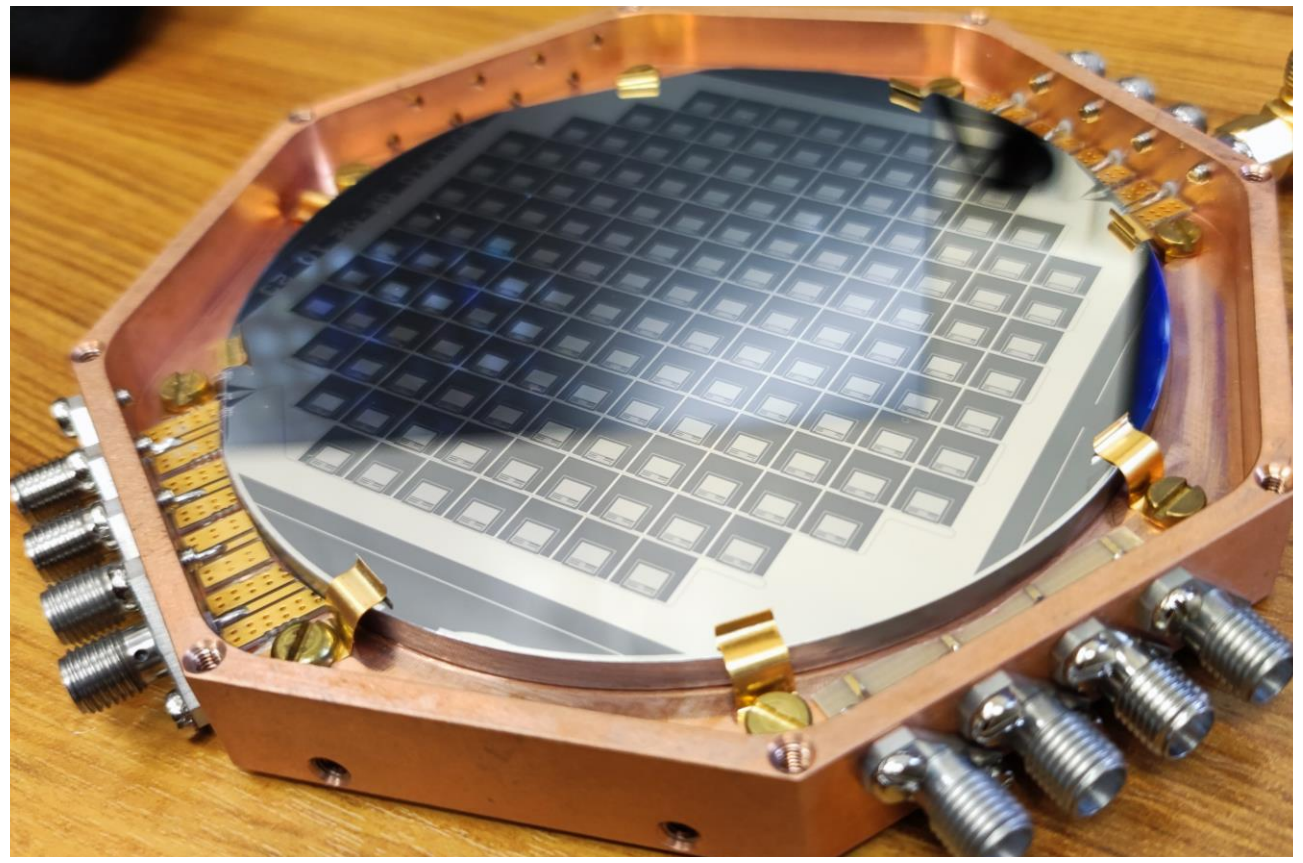
3rd wafer produced and tested. Assembly in the stack in May '24

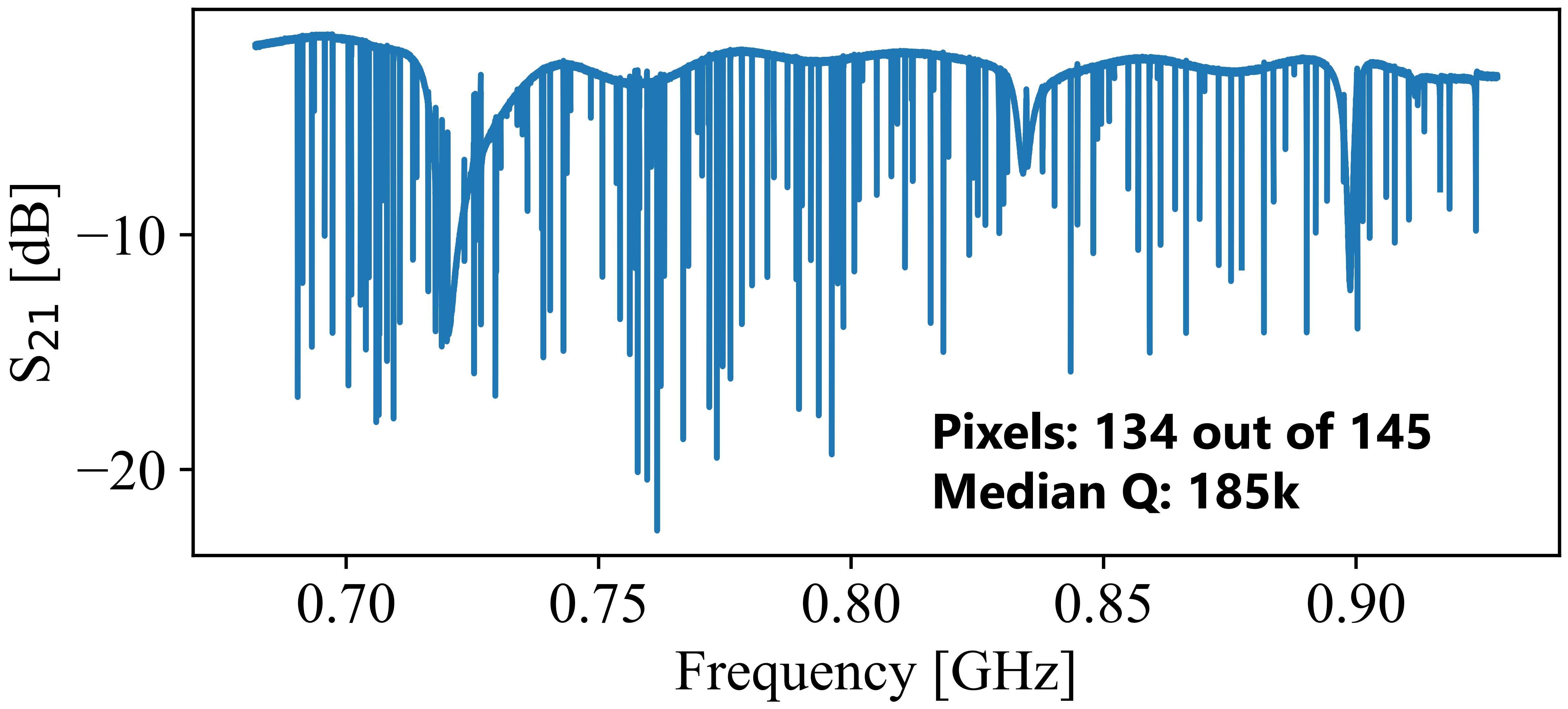




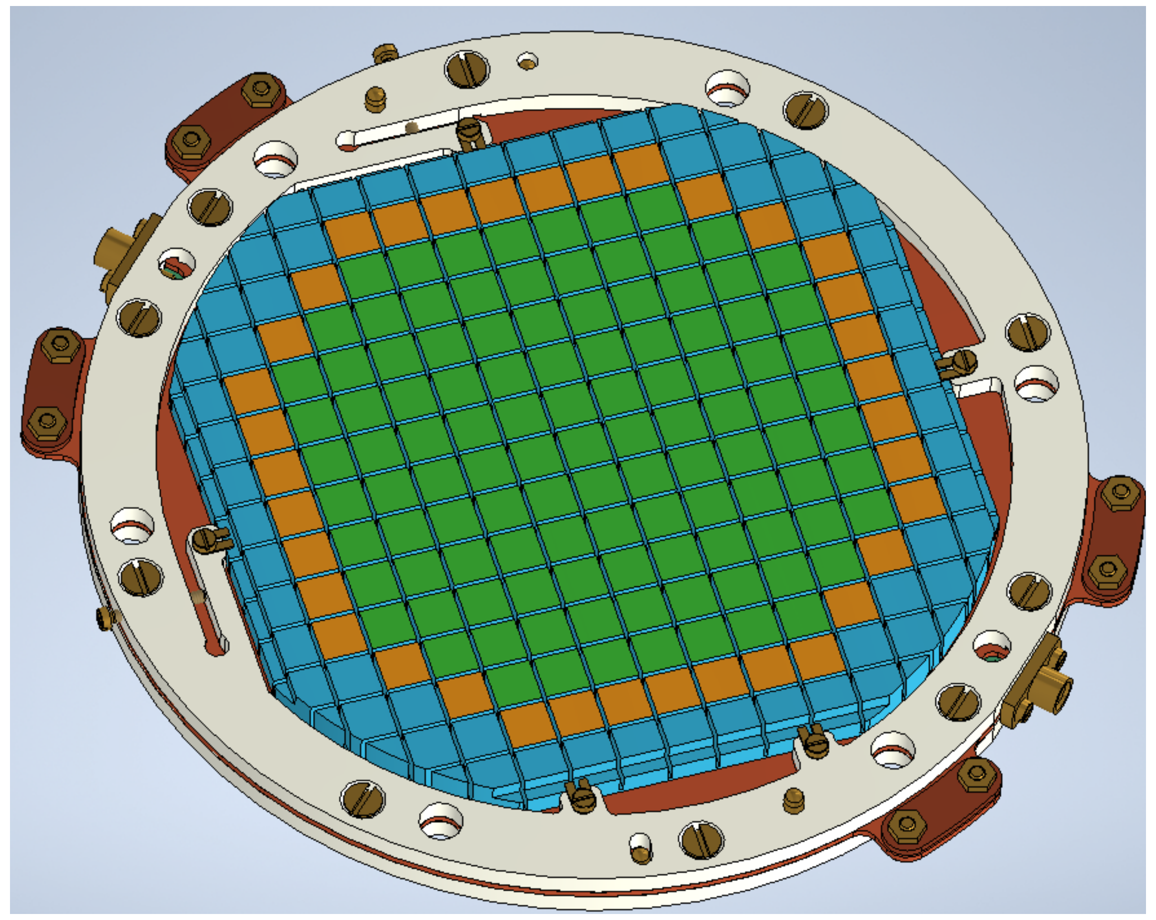
Status of 100 mm wafers

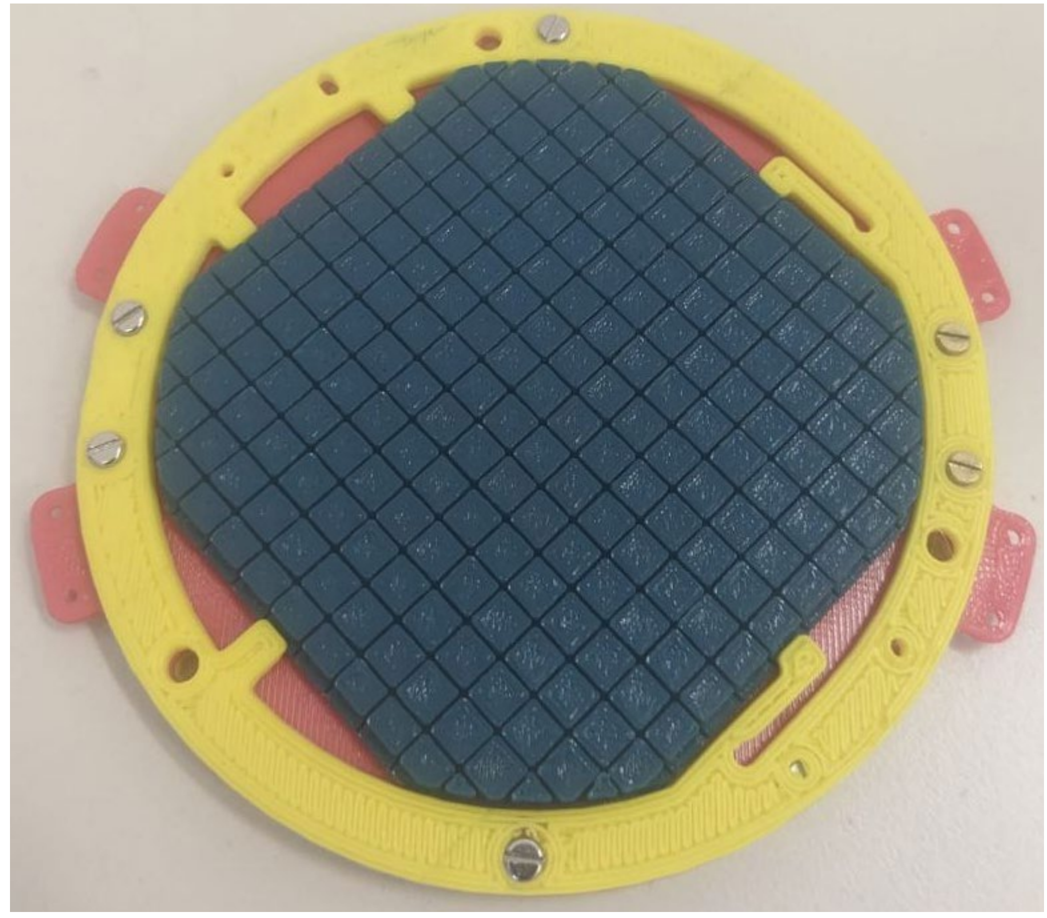
145 KID array test on thin (0.3 mm) wafer successful





Assembly under development



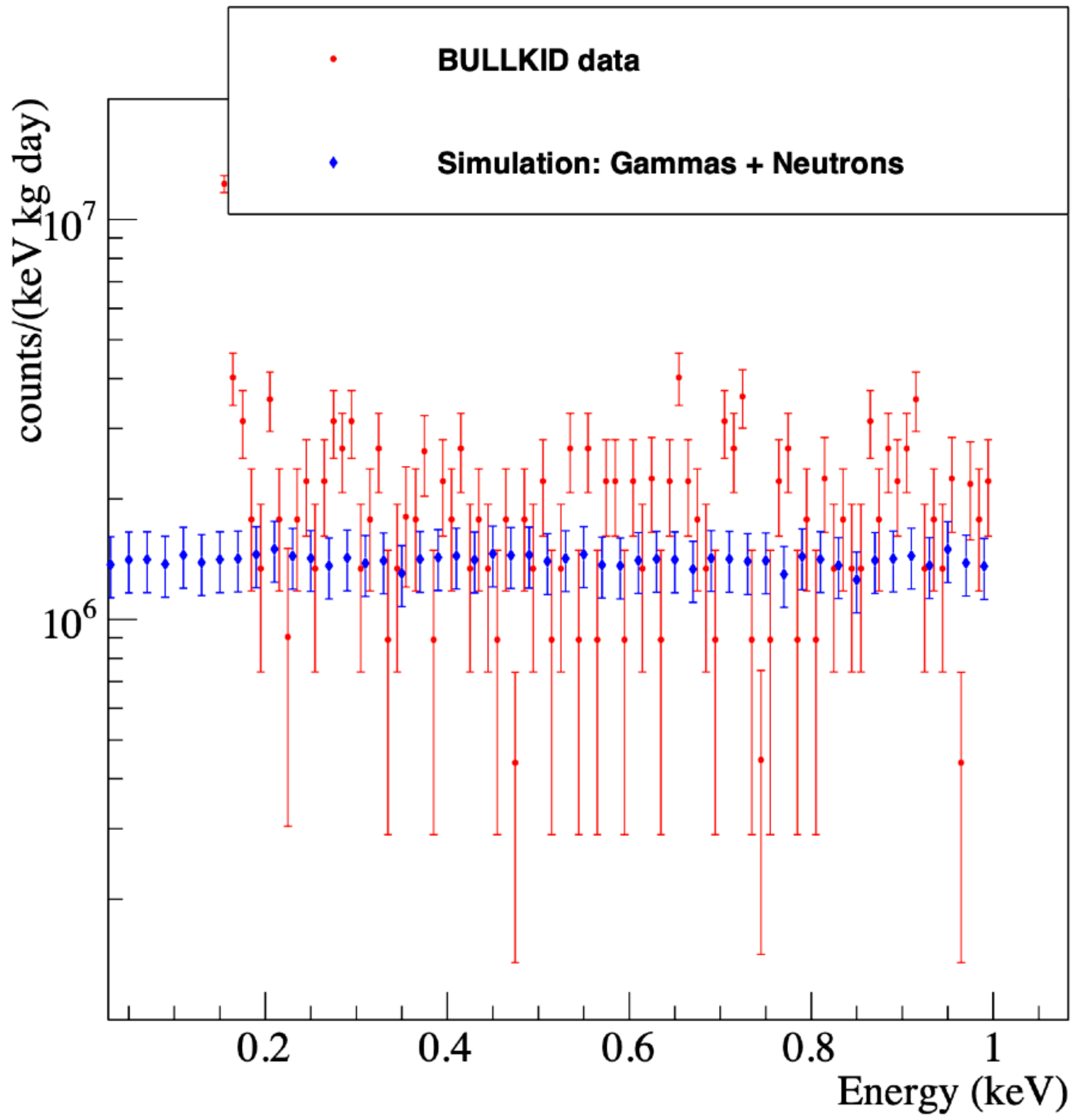


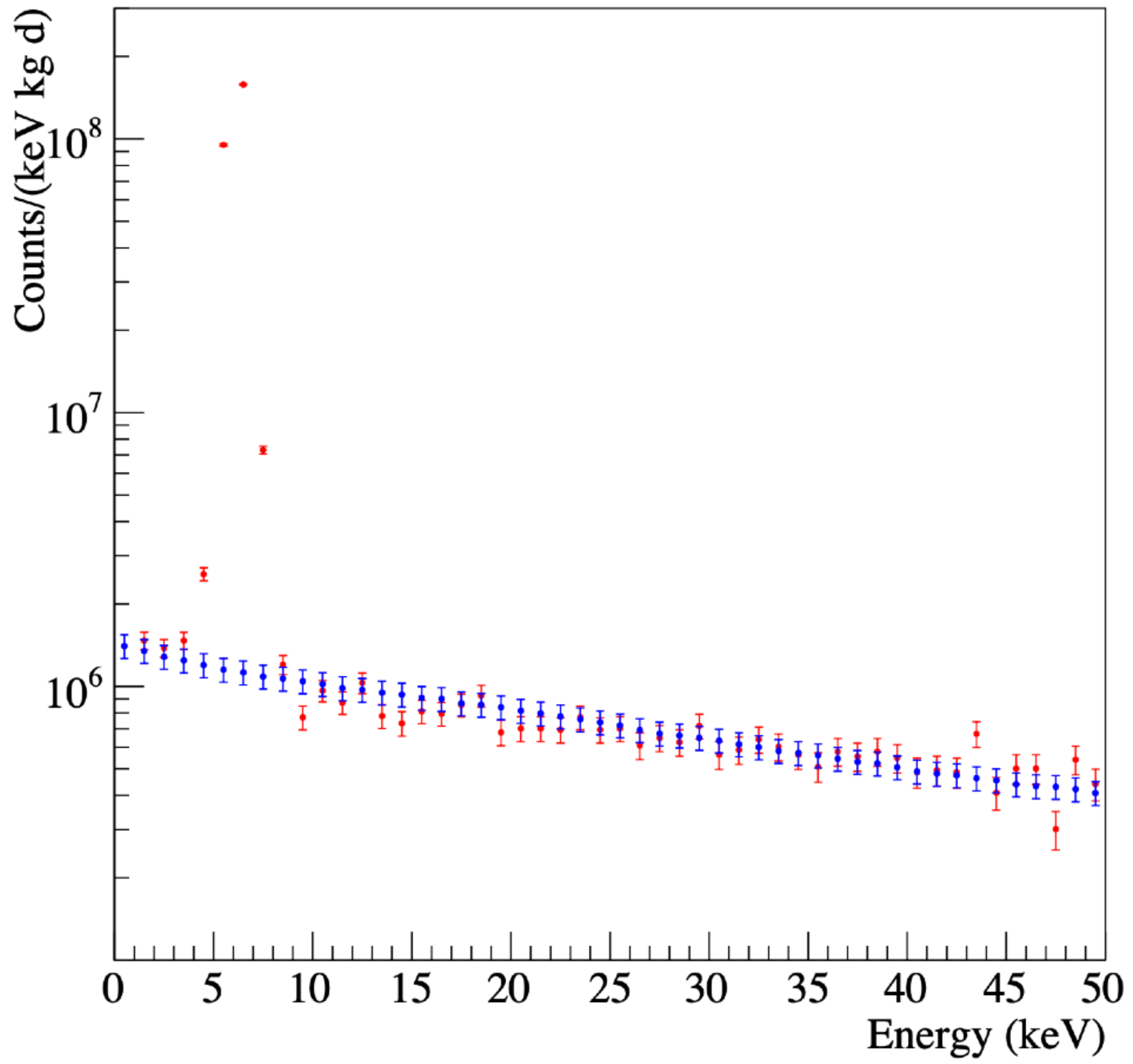
5 mm wafer grooved succesfull

Simulations: validation on Sapienza setup

Gammas (99%) and neutrons (1%) measured and used as input for the simulation

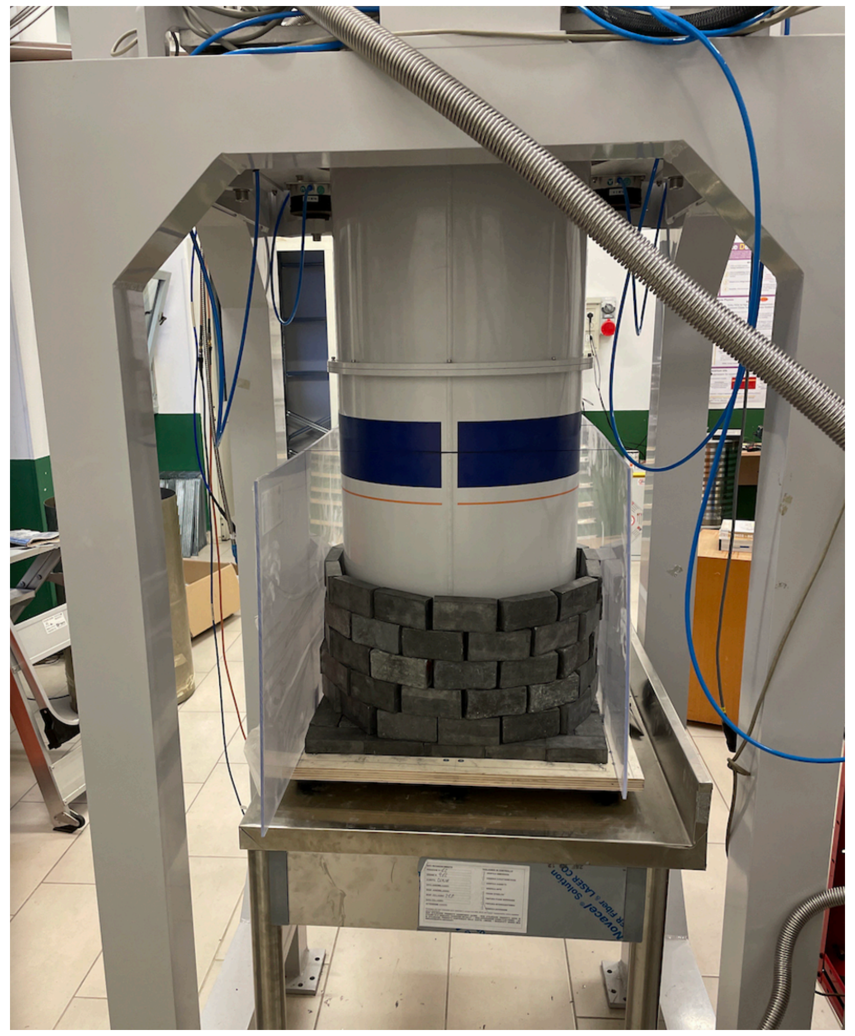
Agreement over wide energy range observed

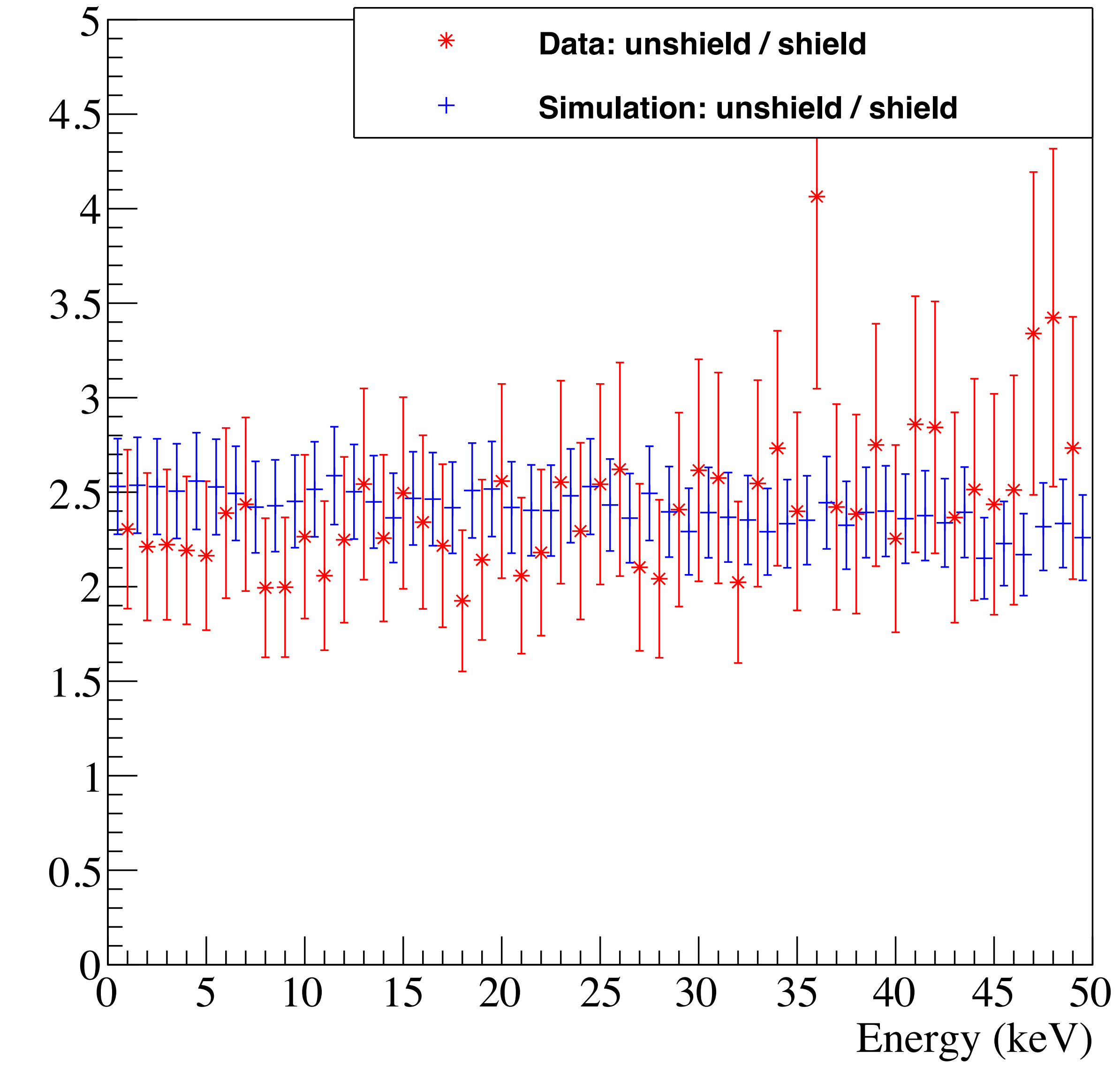




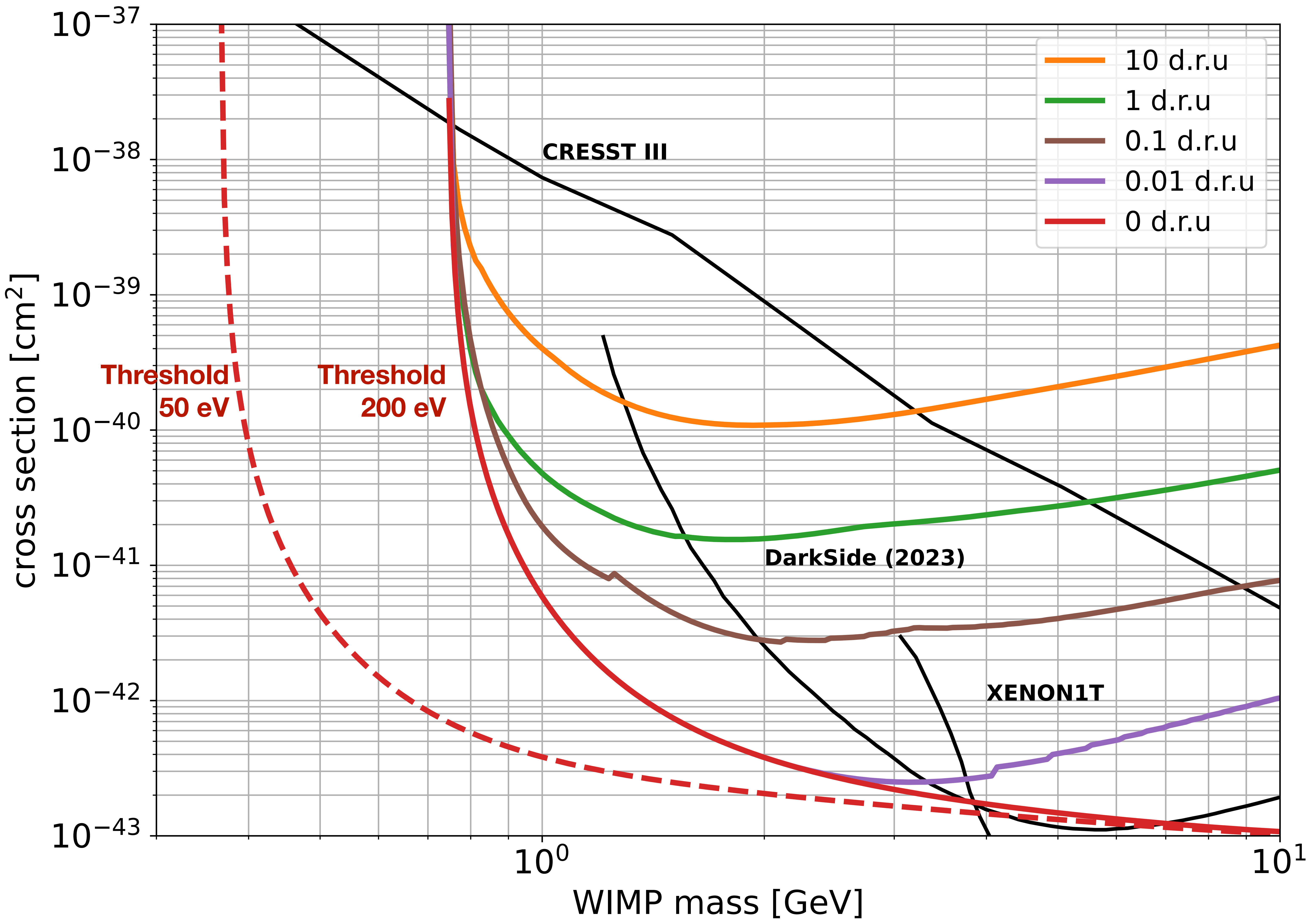
Mild lead shield added

Reduction of the background agrees with simulations





Sensitivity



"zero" bkg