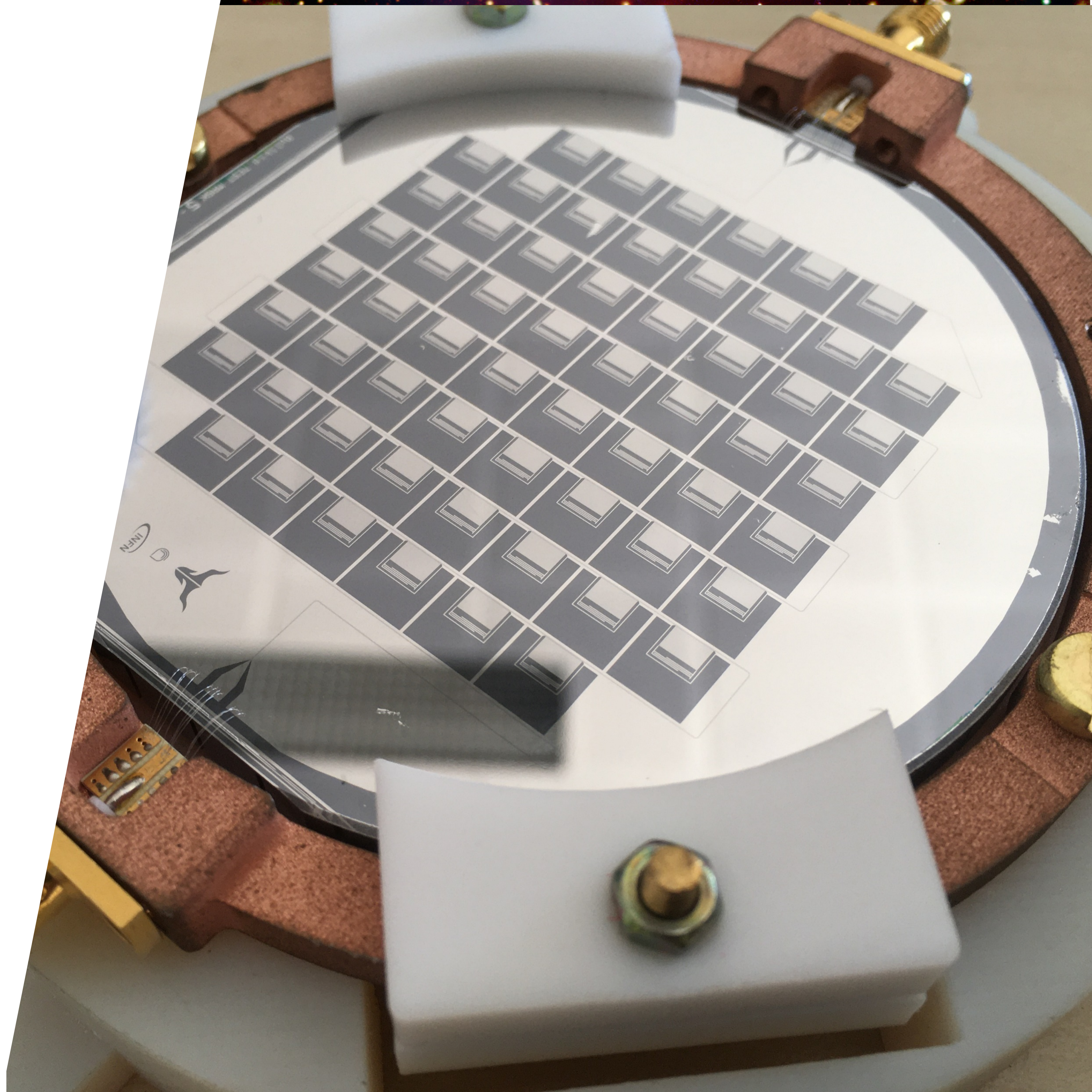
SAPIENZA
UNIVERSITÀ DI ROMA

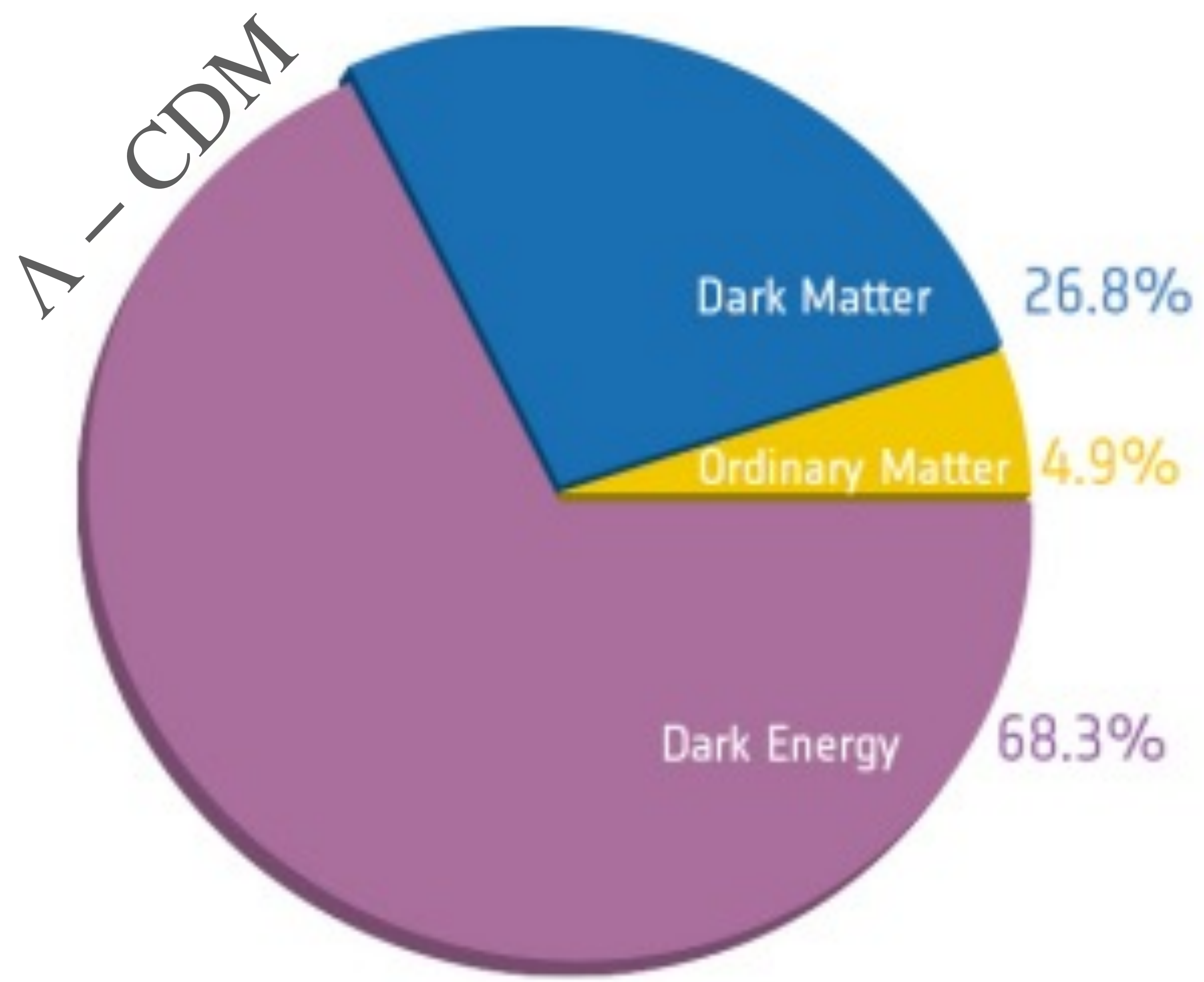
INFN
Istituto Nazionale di Fisica Nucleare

BULLKID-DM introduction

Marco Vignati, LNGS, 19 March 2024



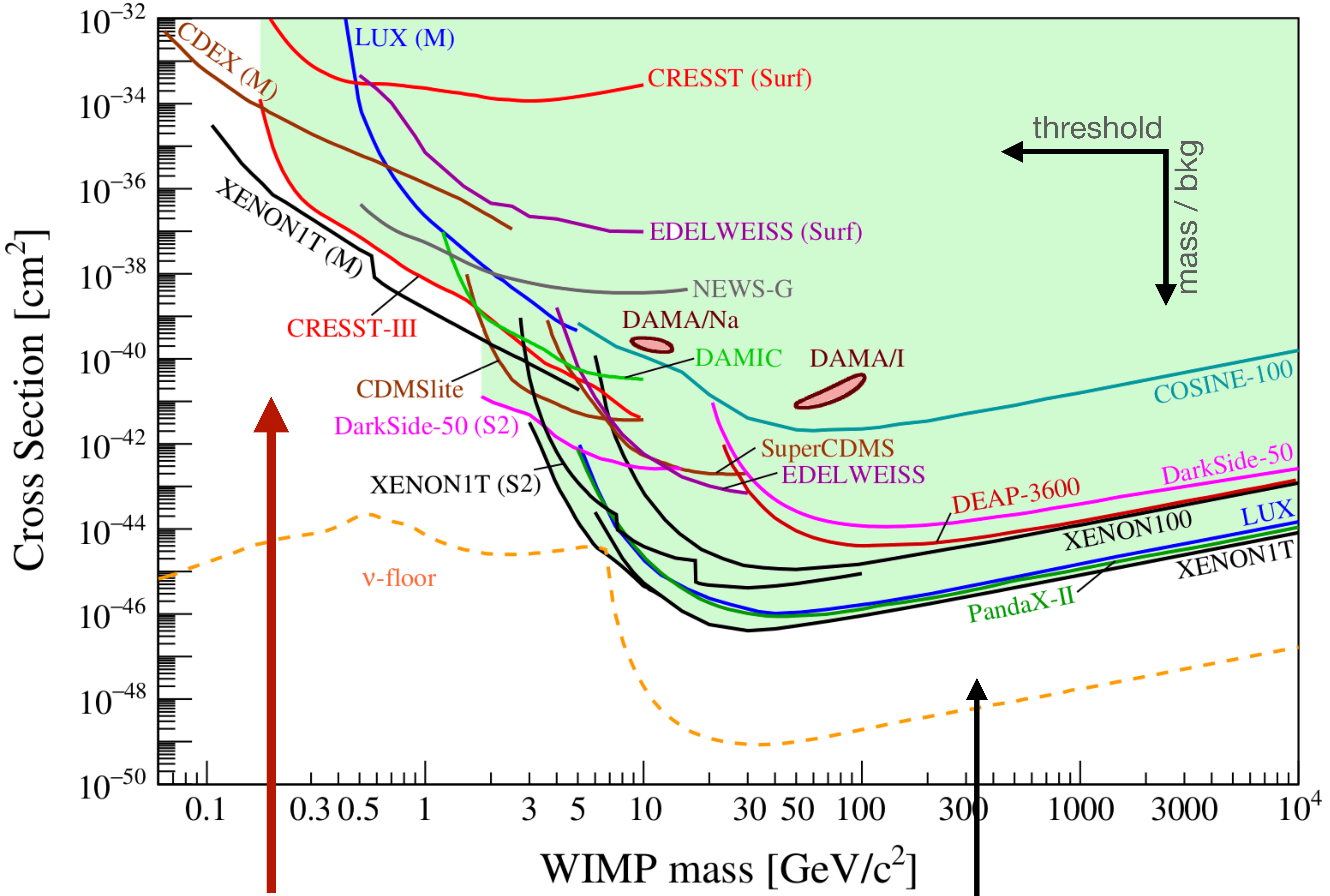
Dark Matter - direct search



What is the Dark Matter made of?

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

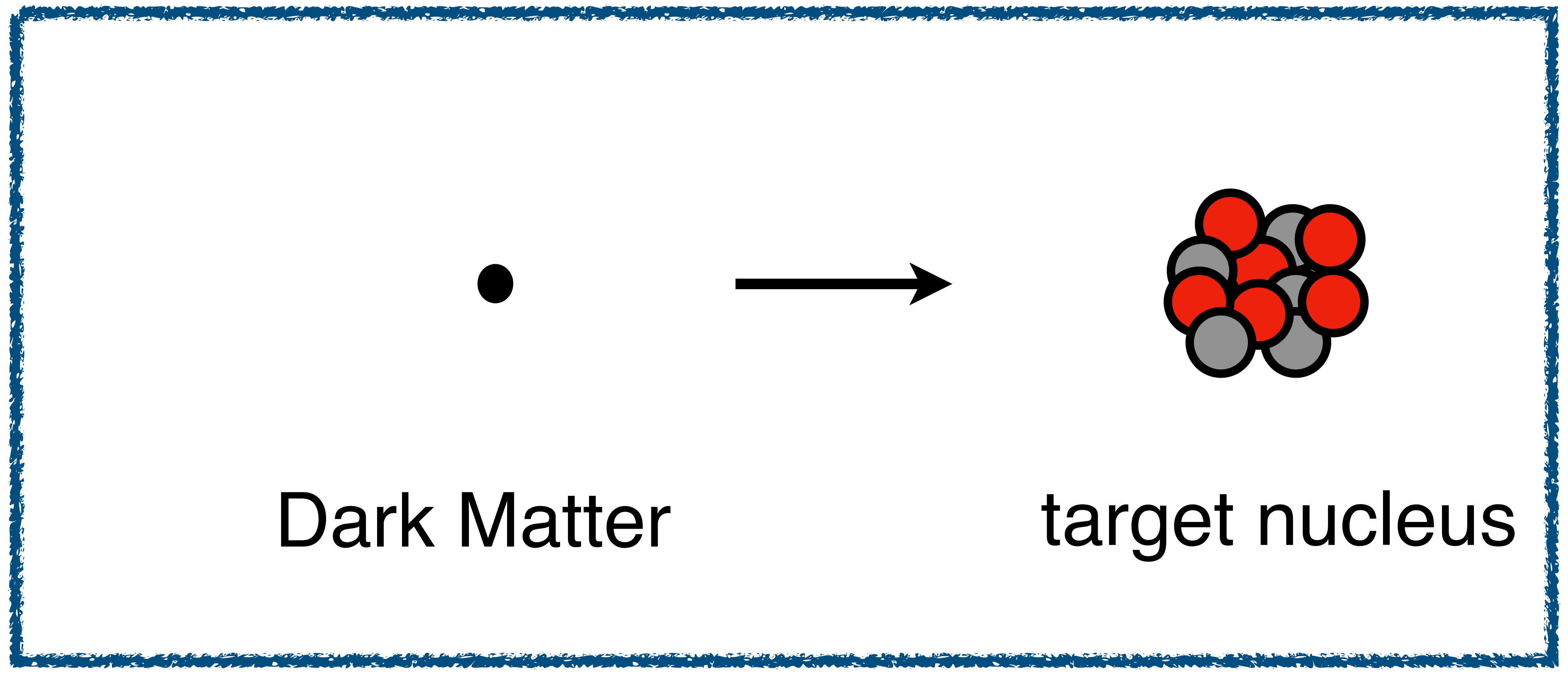
J. Billard, et al, Direct Detection of Dark Matter – APPEC Committee Report, arXiv:2104.07634

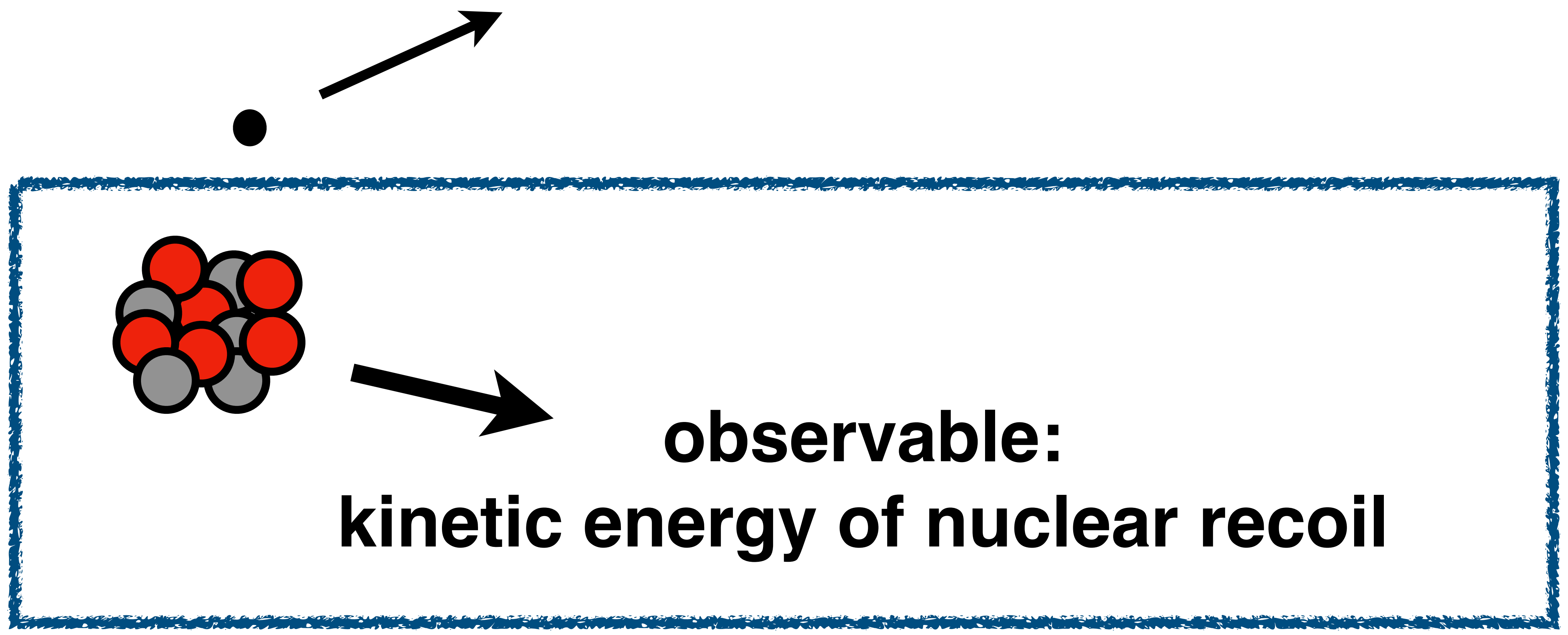


solid-state phonon detectors with:
- **zero background**
- **kg target**
- **threshold < 200 eV**

Multi-ton liquid scintillators

Direct dark matter search below 1 GeV/c^2

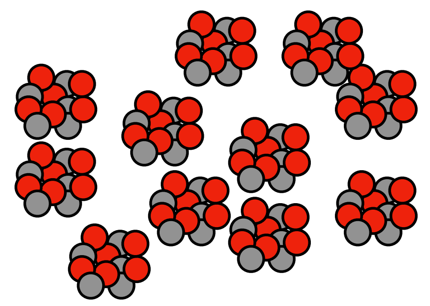




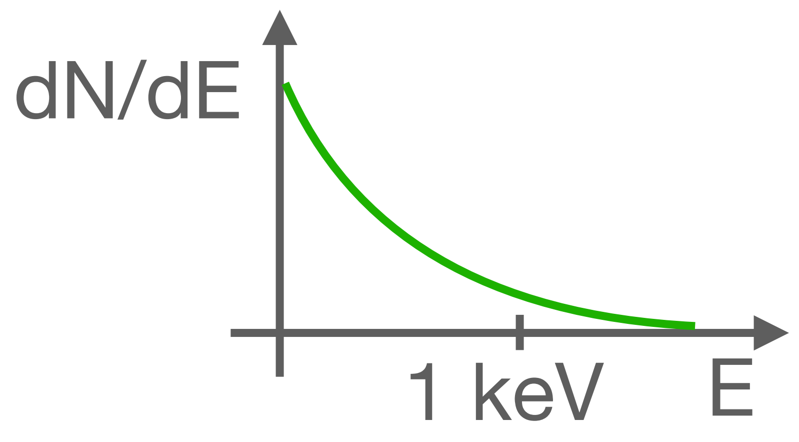
cross section $\sigma < 10^{-40}\ \mathrm{cm}^2$

energy < 1 keV

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



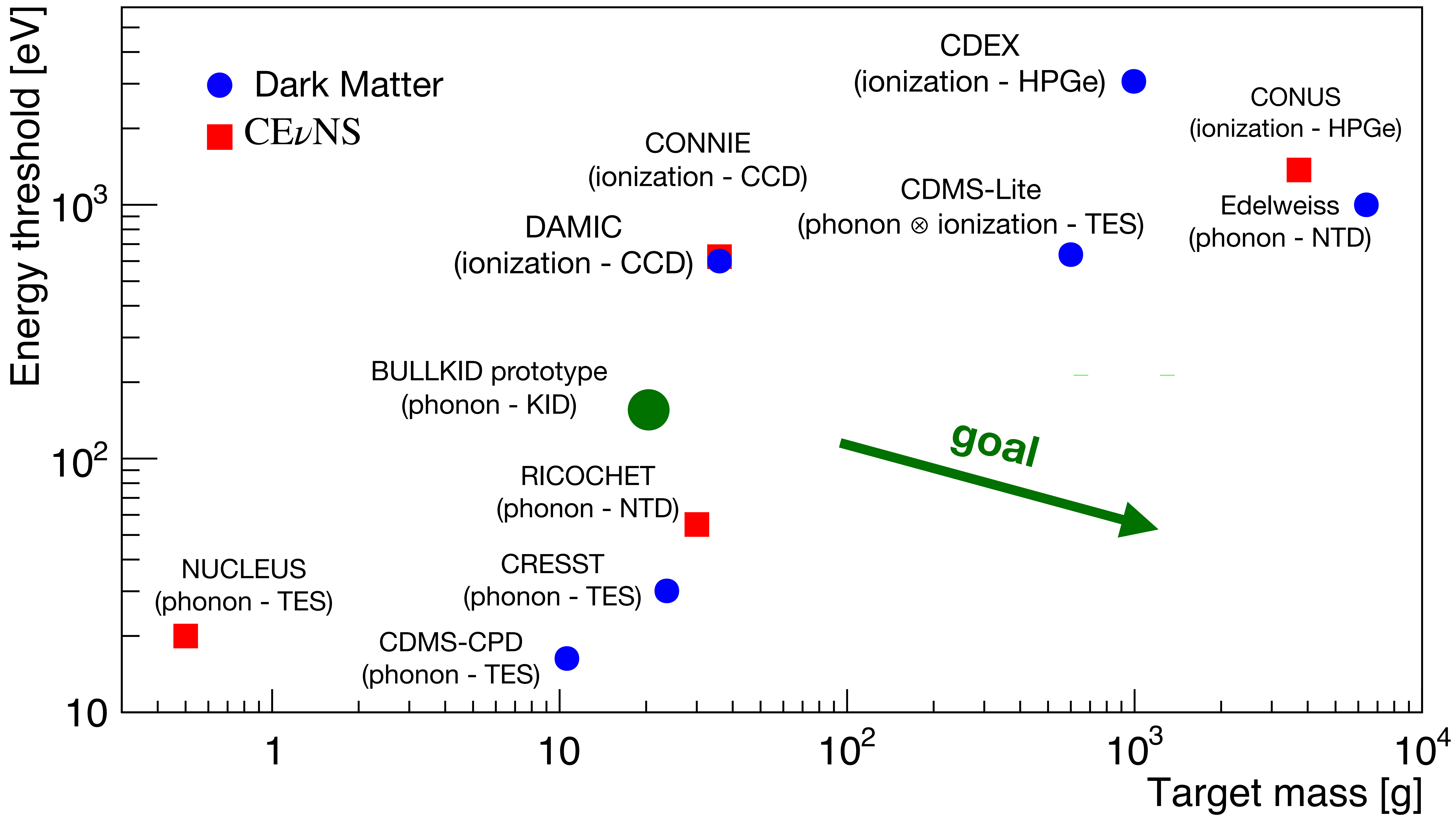
Difficult with Low-T detectors

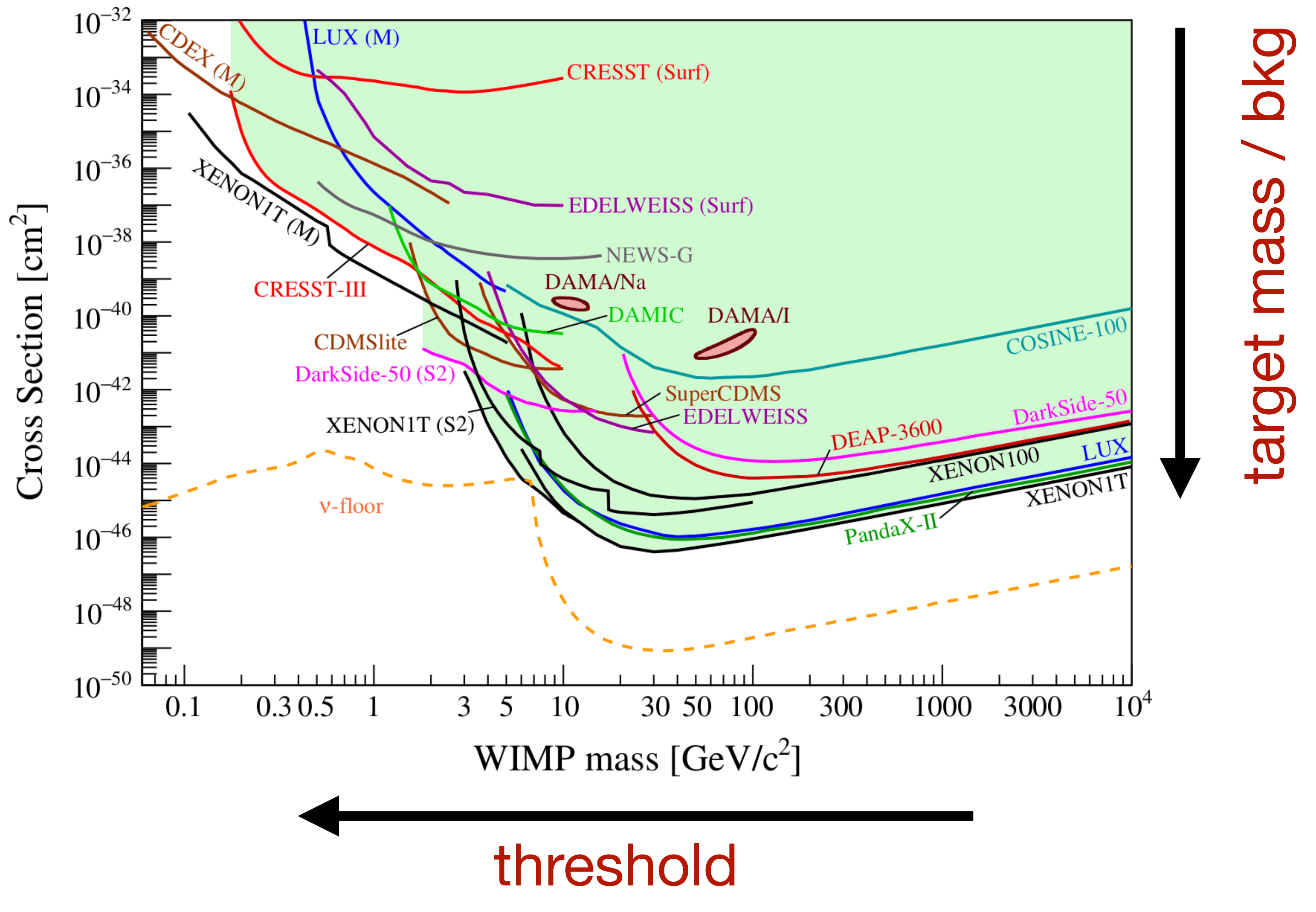


low-energy threshold
***O*(100 eV)**

Motivation for Low-T detectors

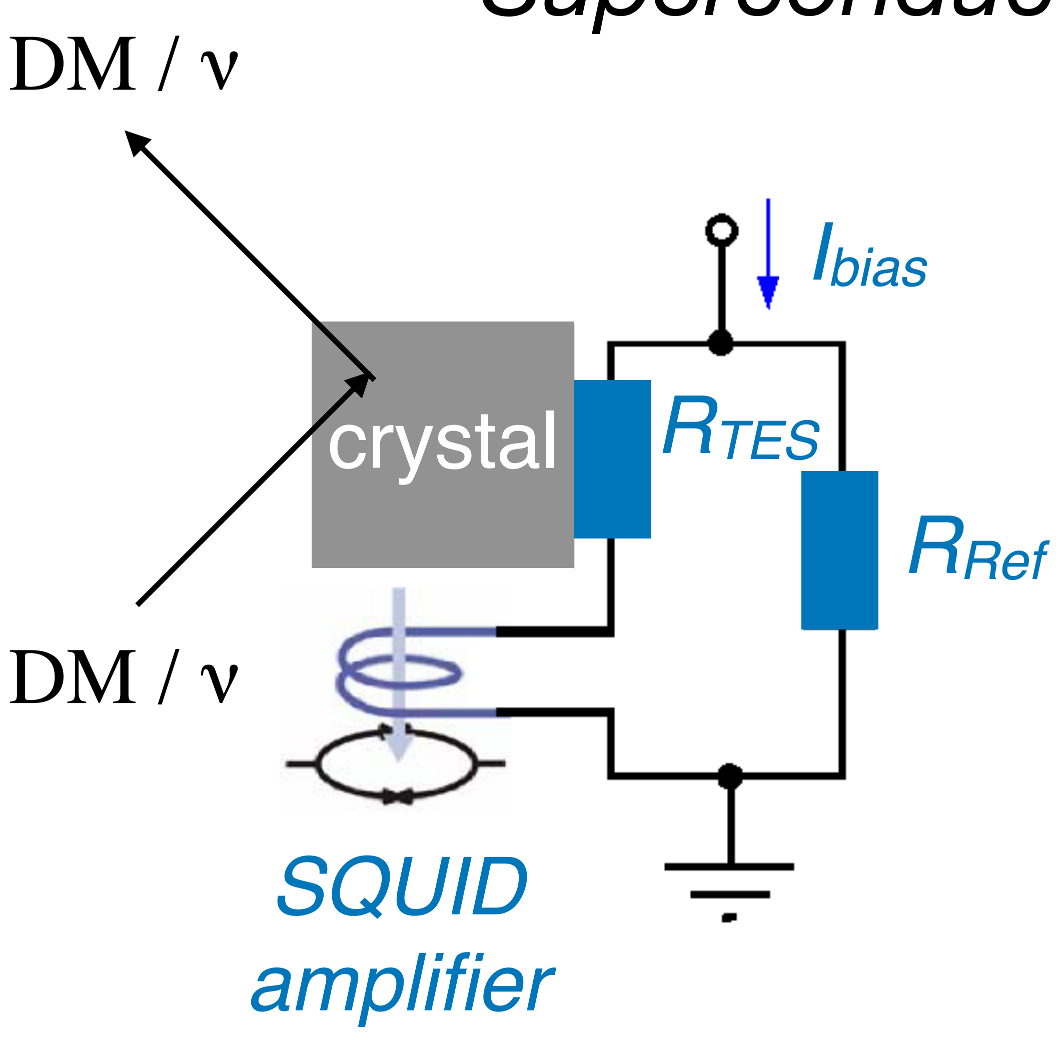
State of the art (solid-state detectors)

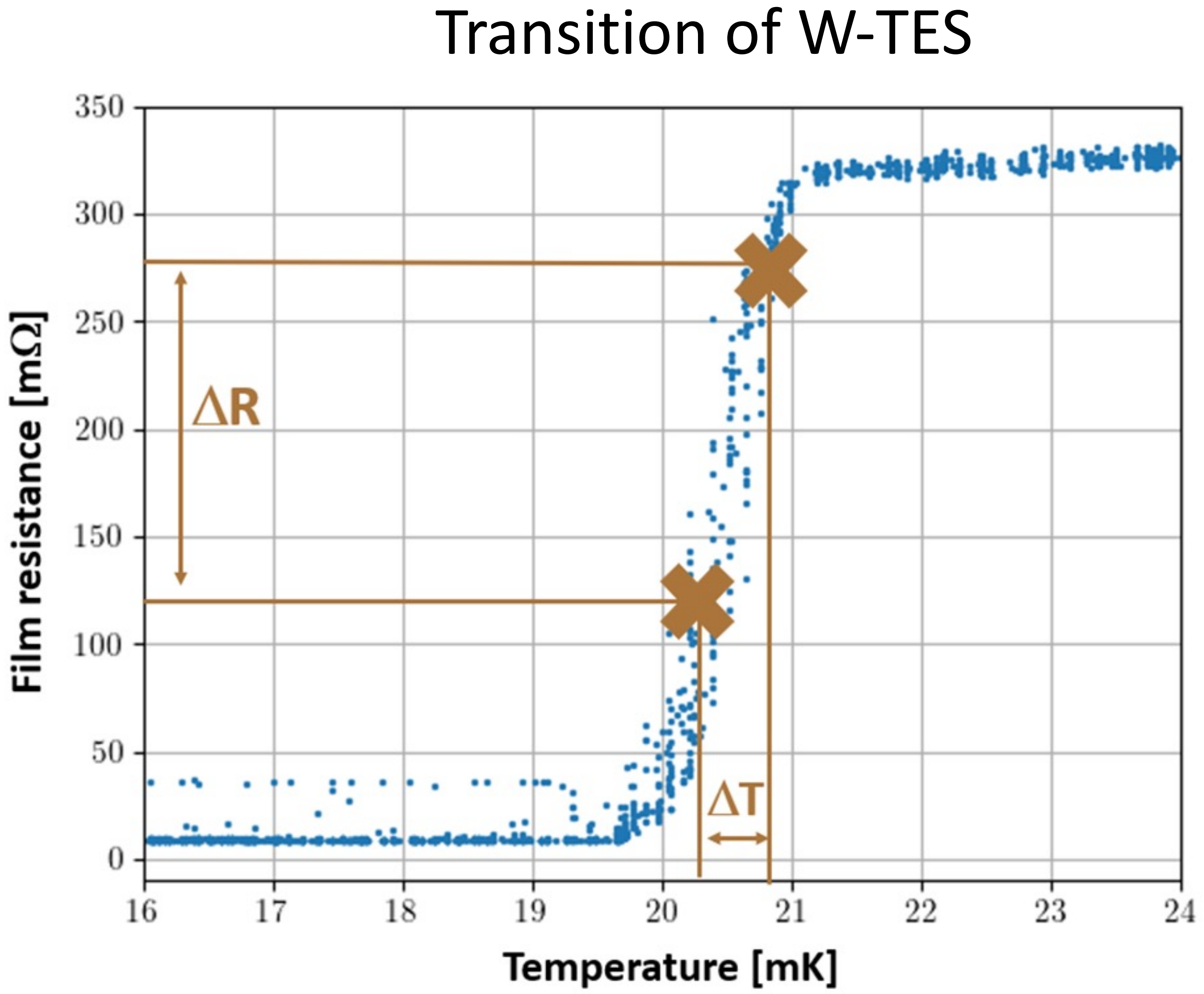


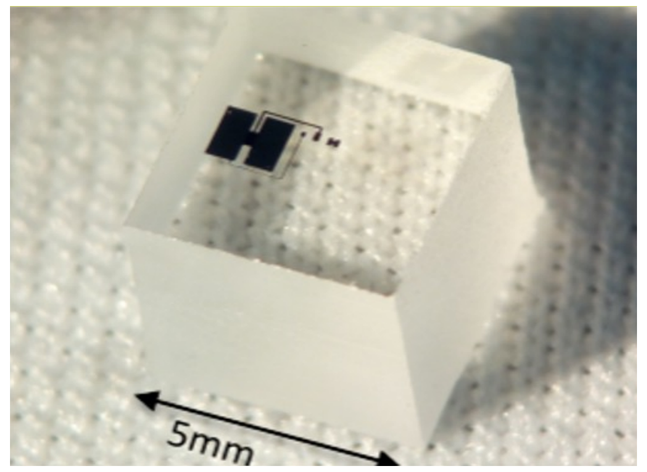


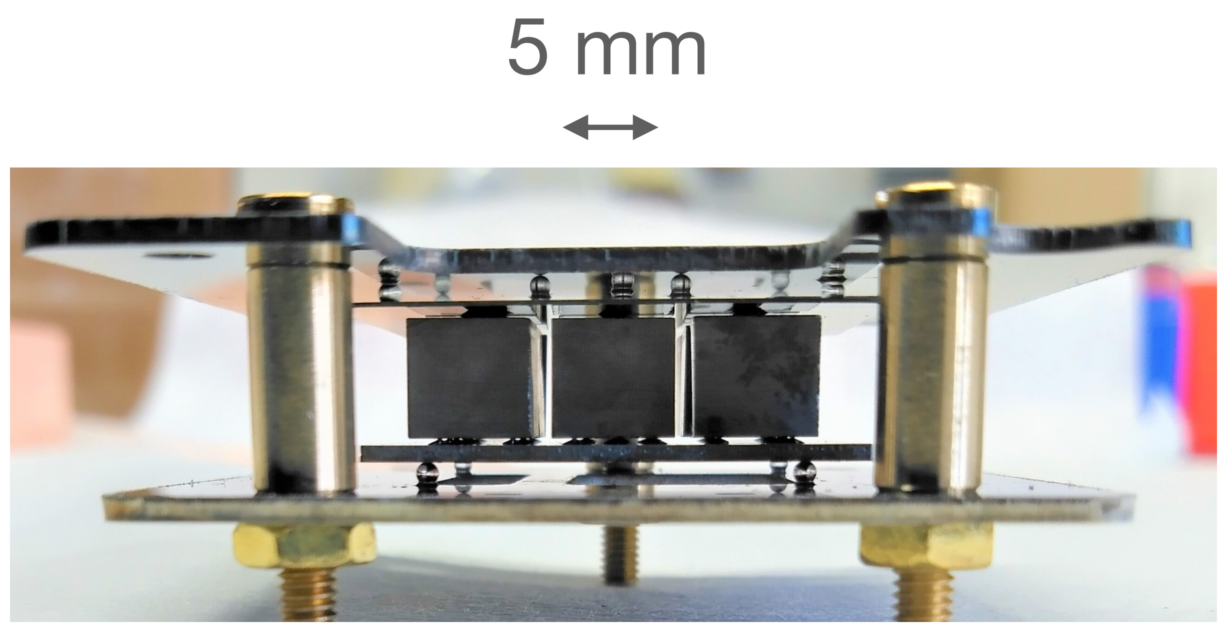
State of the art of phonon detection
(CRESST/NUCLEUS experiments)

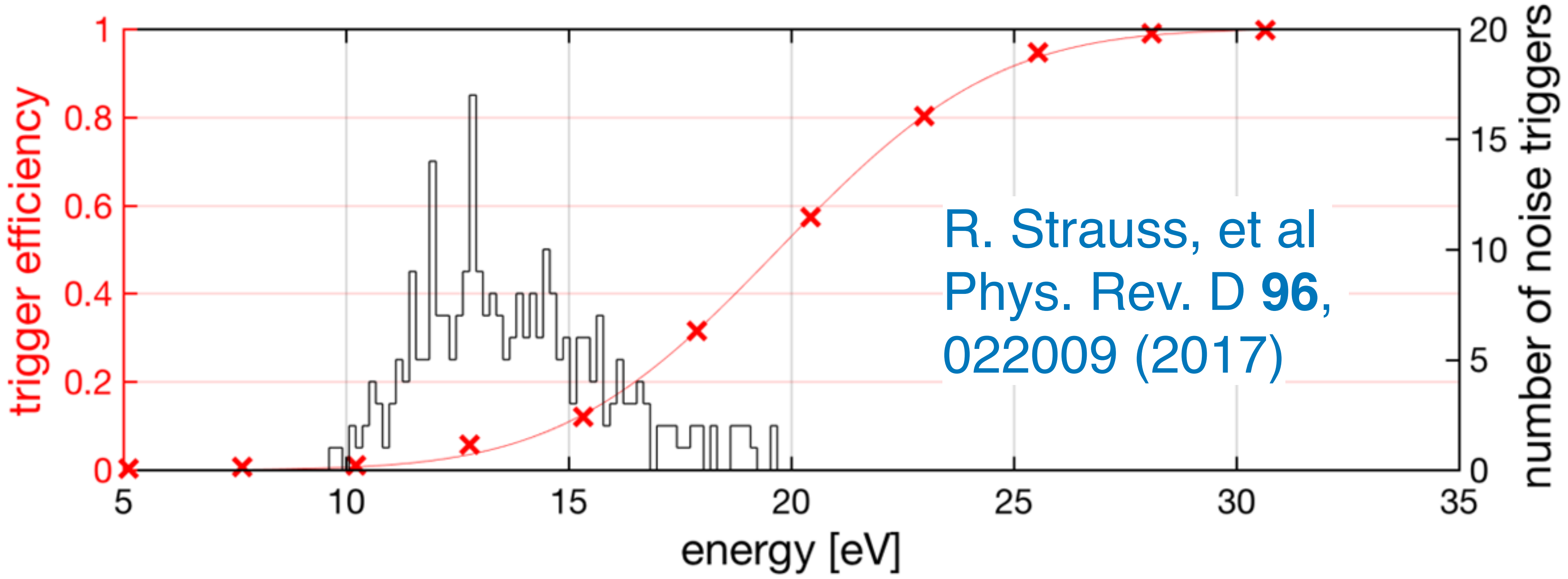
Superconducting thermometers (TES)









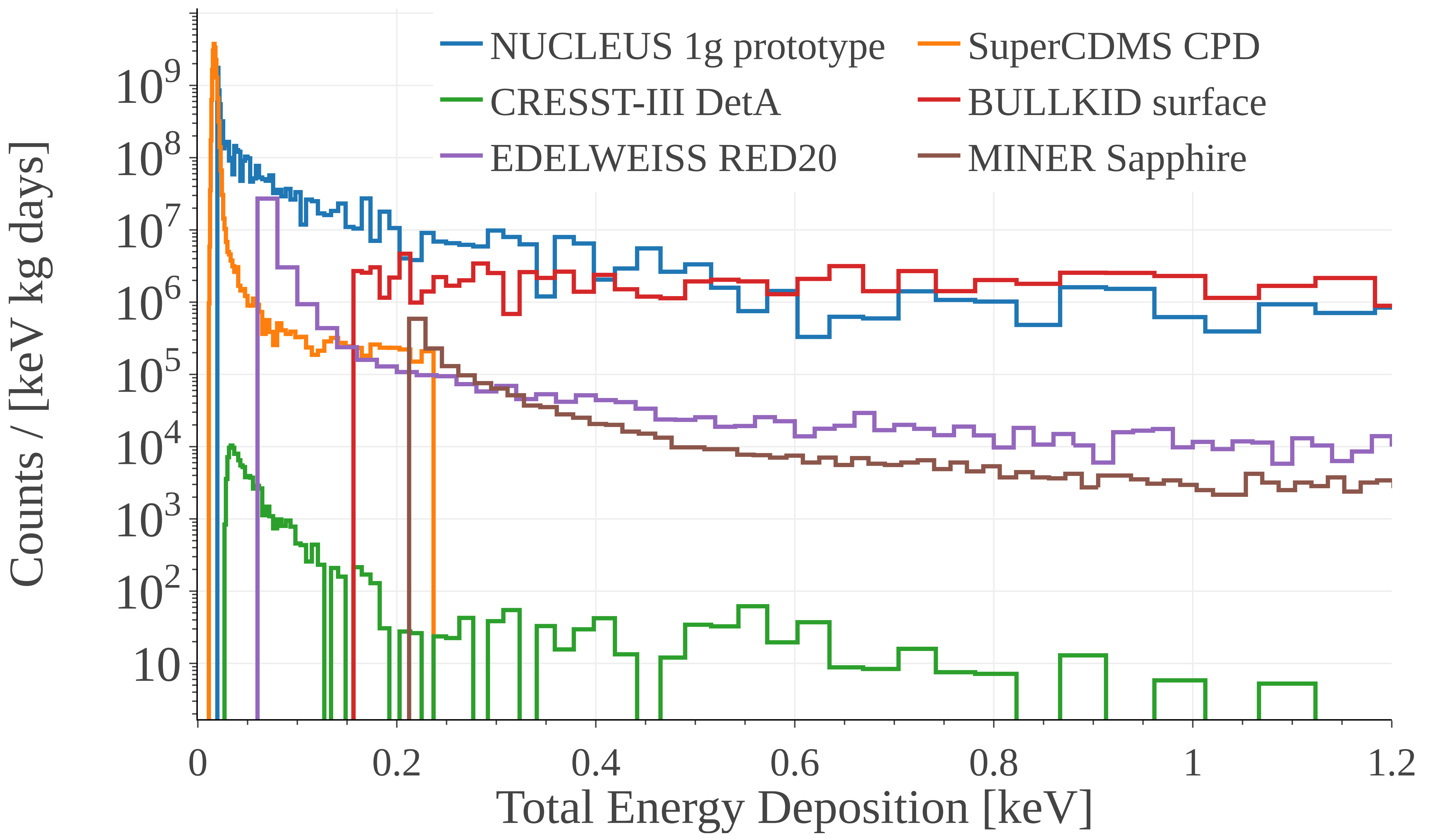


Limitation: individual readout

Pro: record-low energy threshold ~ 20 eV

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

Background issue in phonon experiments

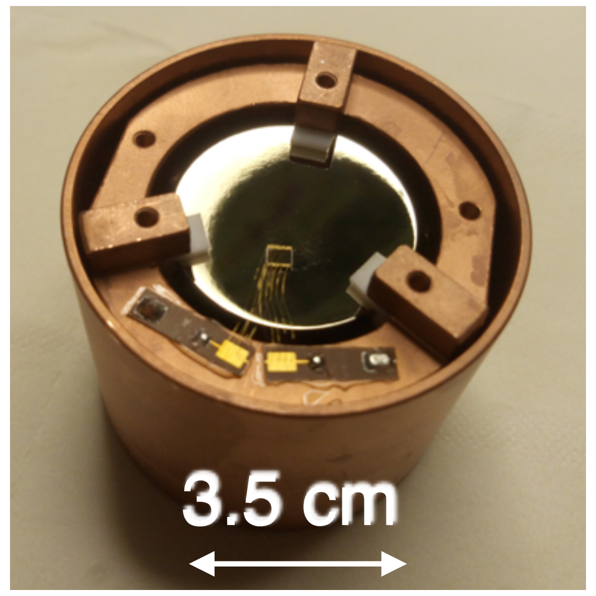


P. Adari, et al.: EXCESS workshop: Descriptions of rising low-energy spectra SciPost Phys. Proc. 9 (2022) 001 + BULLKID 2023

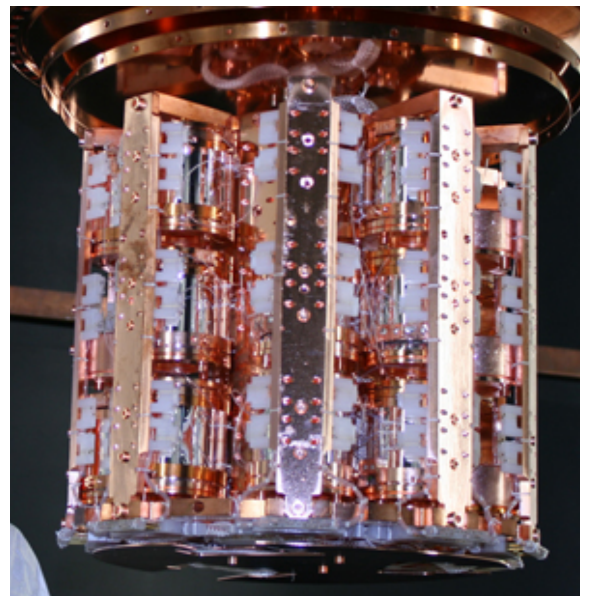
Not understood *excess* background rising at low energies:

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

RED 20 (Ge, 33 g)



CRESST array



This background limits the sensitivity of present experiments

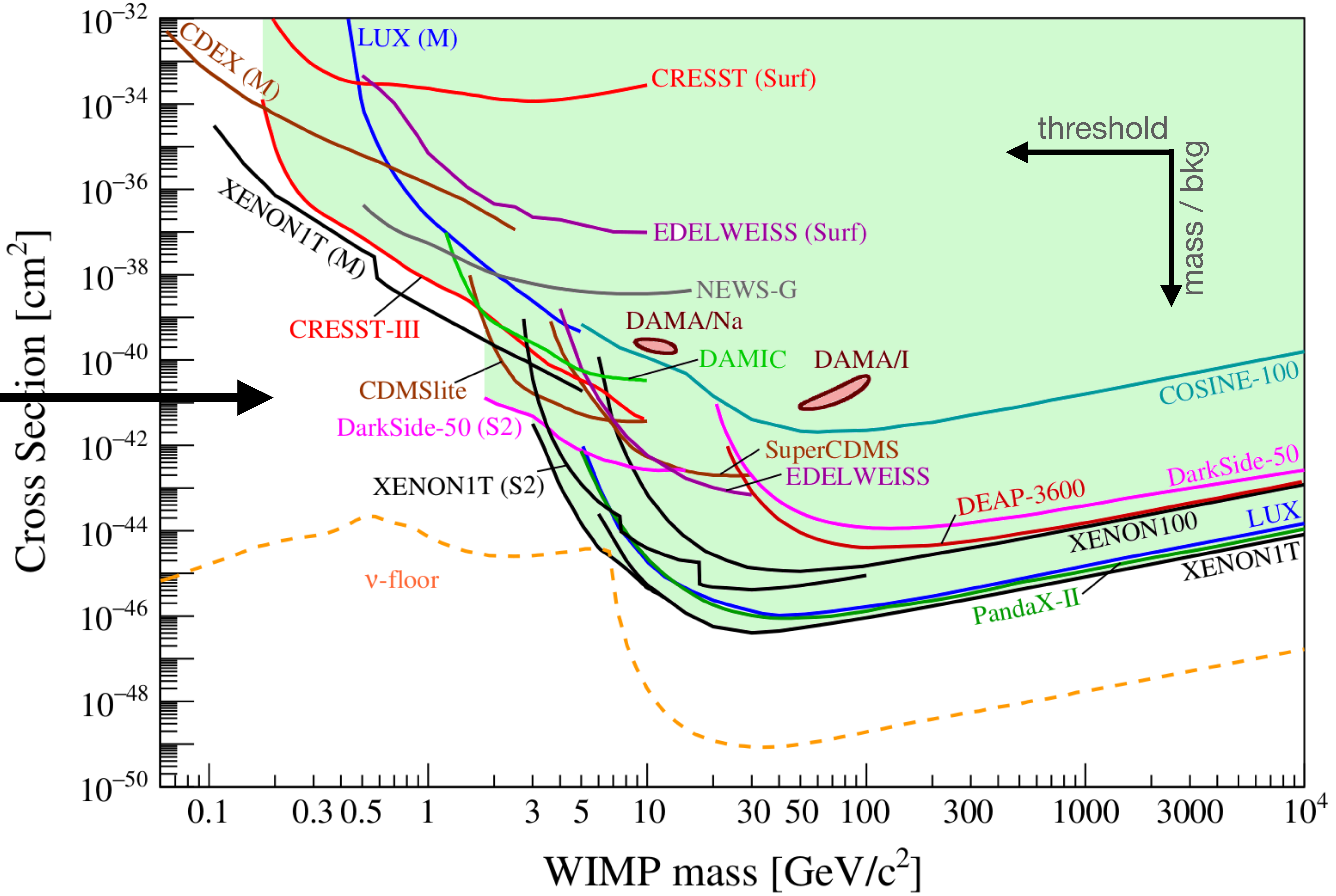
Dark Matter - direct search with BULLKID

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

solid-state phonon detectors with:

- **zero background**
- **kg target**
- **threshold < 200 eV**

With BULLKID-DM we can achieve these goals. How?

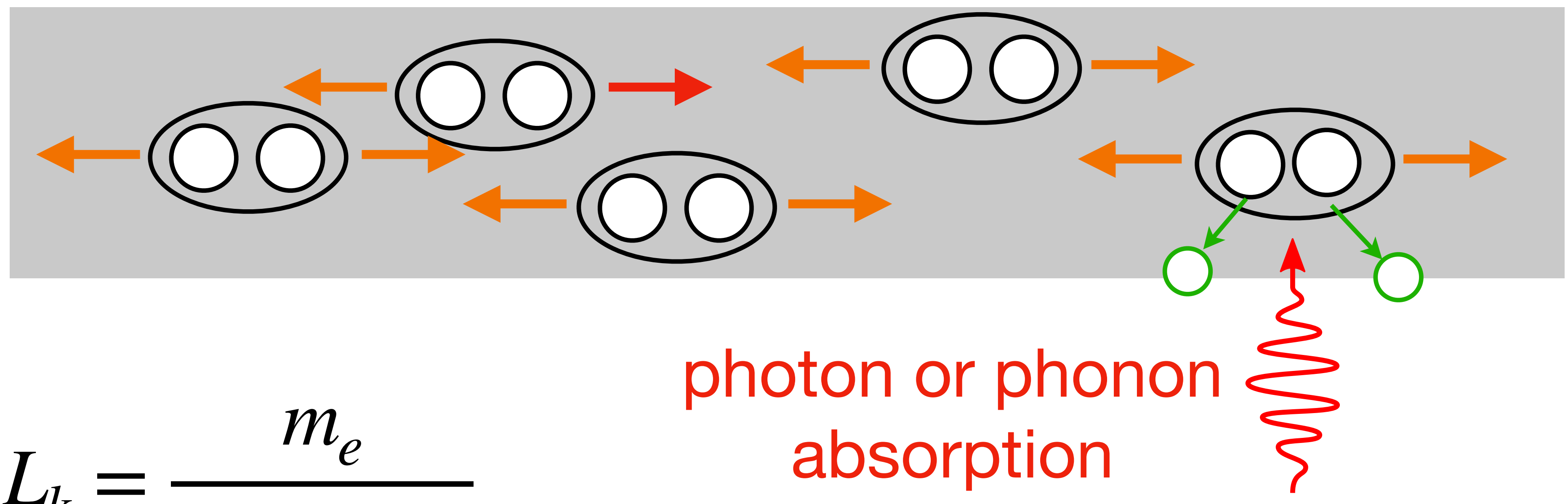


Kinetic Inductance Detectors

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 $\overrightarrow{E_{AC}}$



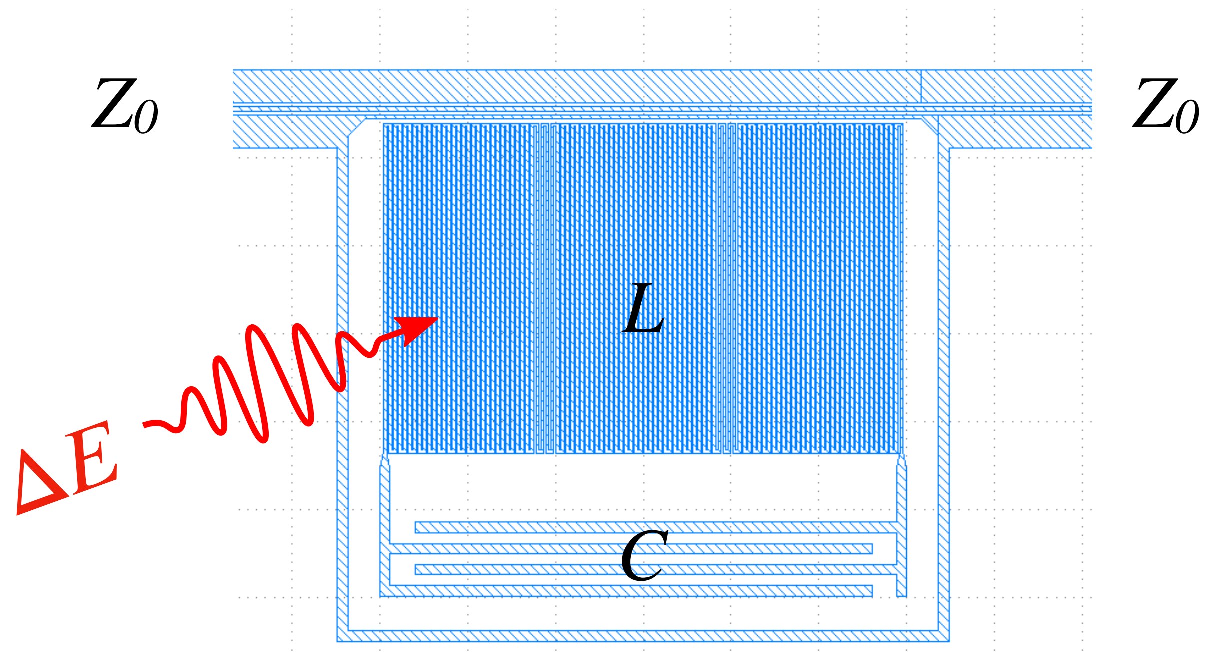
$$L_k = \frac{m_e}{2\,e^2\,n_{\text{pairs}}}$$

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

Kinetic Inductance Detector (KID)

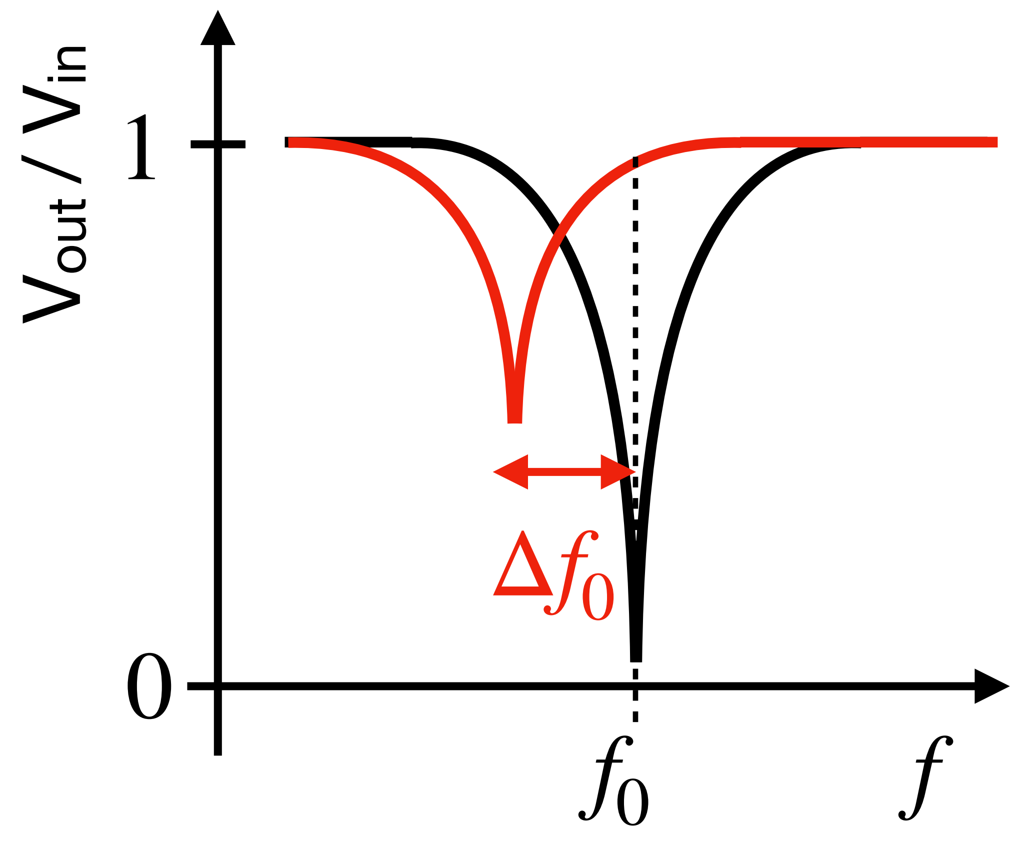
- Superconductor at T < 200 mK (Al)
- LC resonator

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



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

frequency response



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

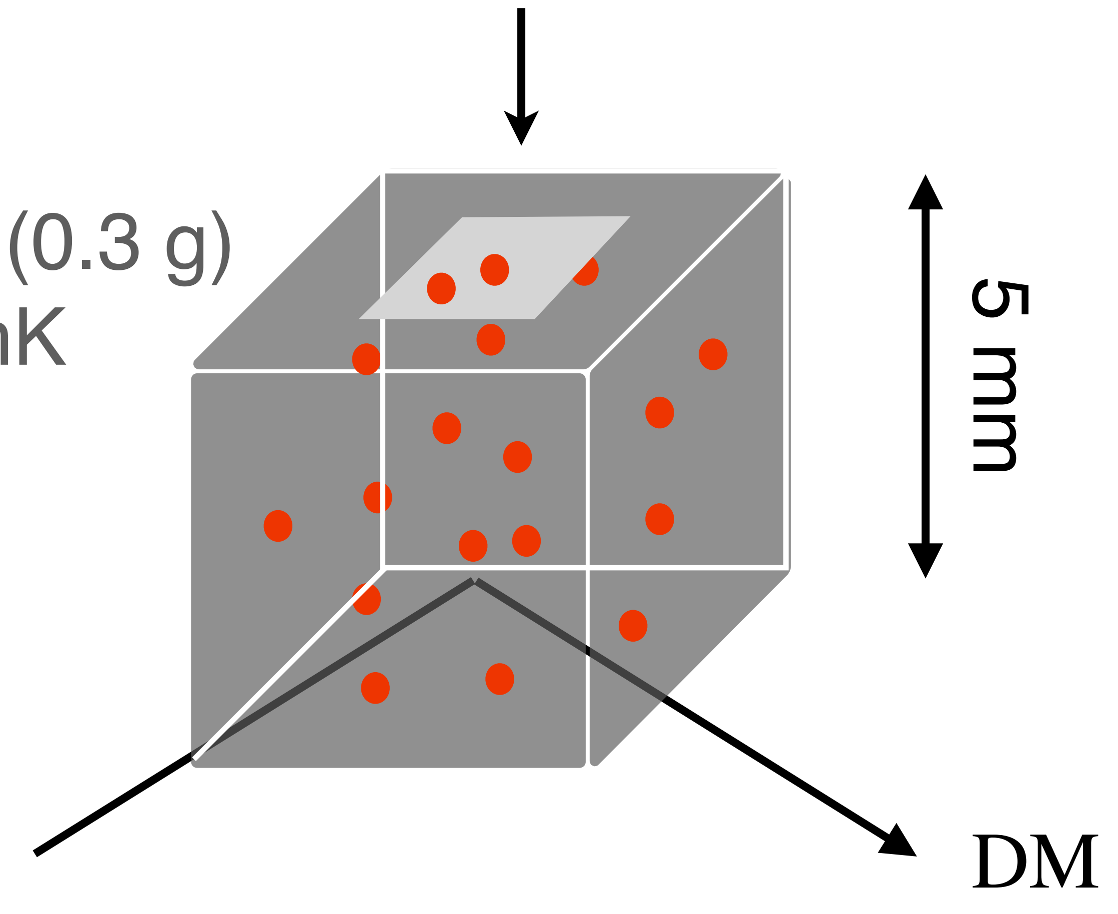
The BULLKID phonon detector array

Phonon mediation

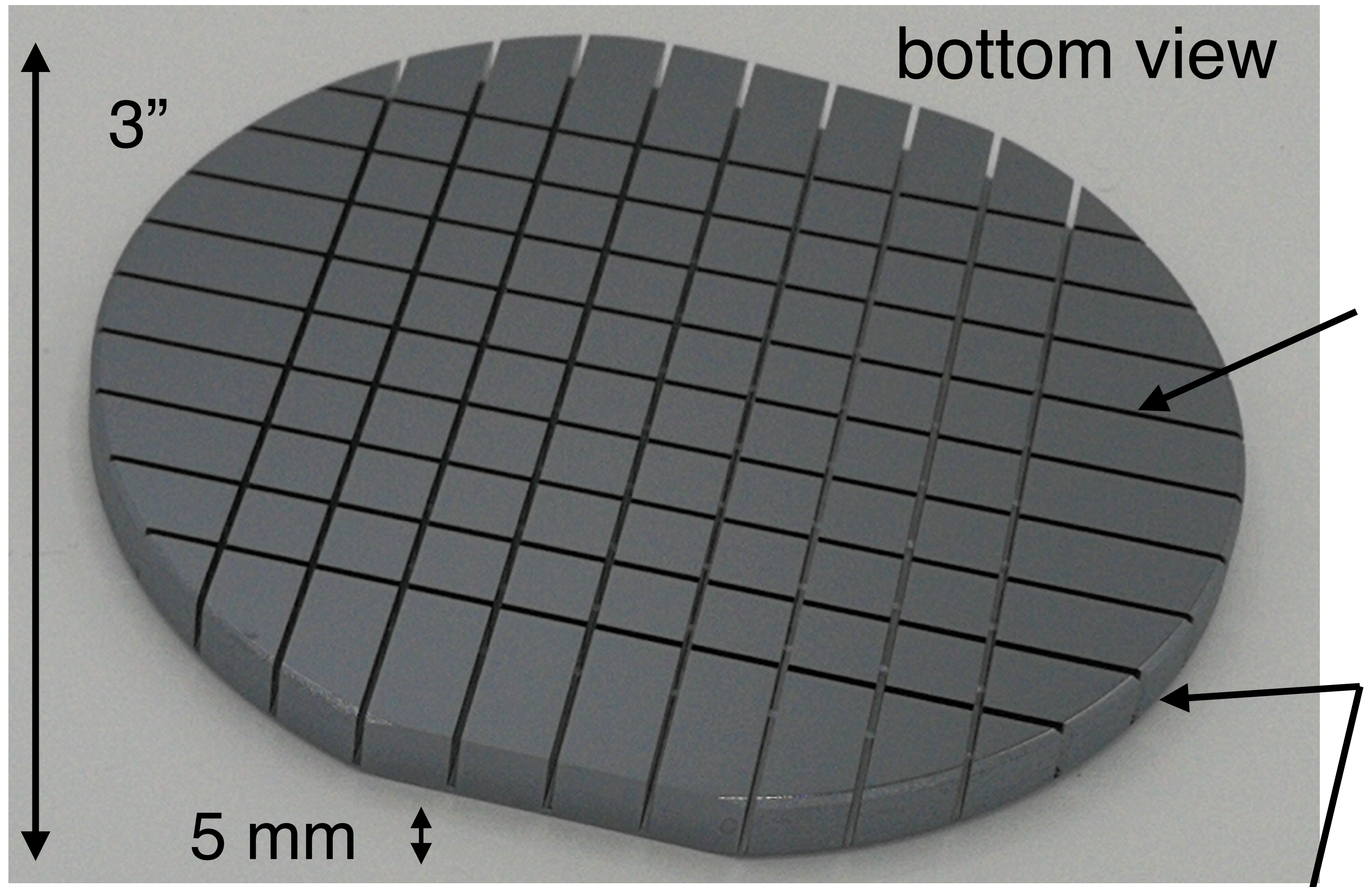
detect phonons created by nuclear recoils
in a silicon dice

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



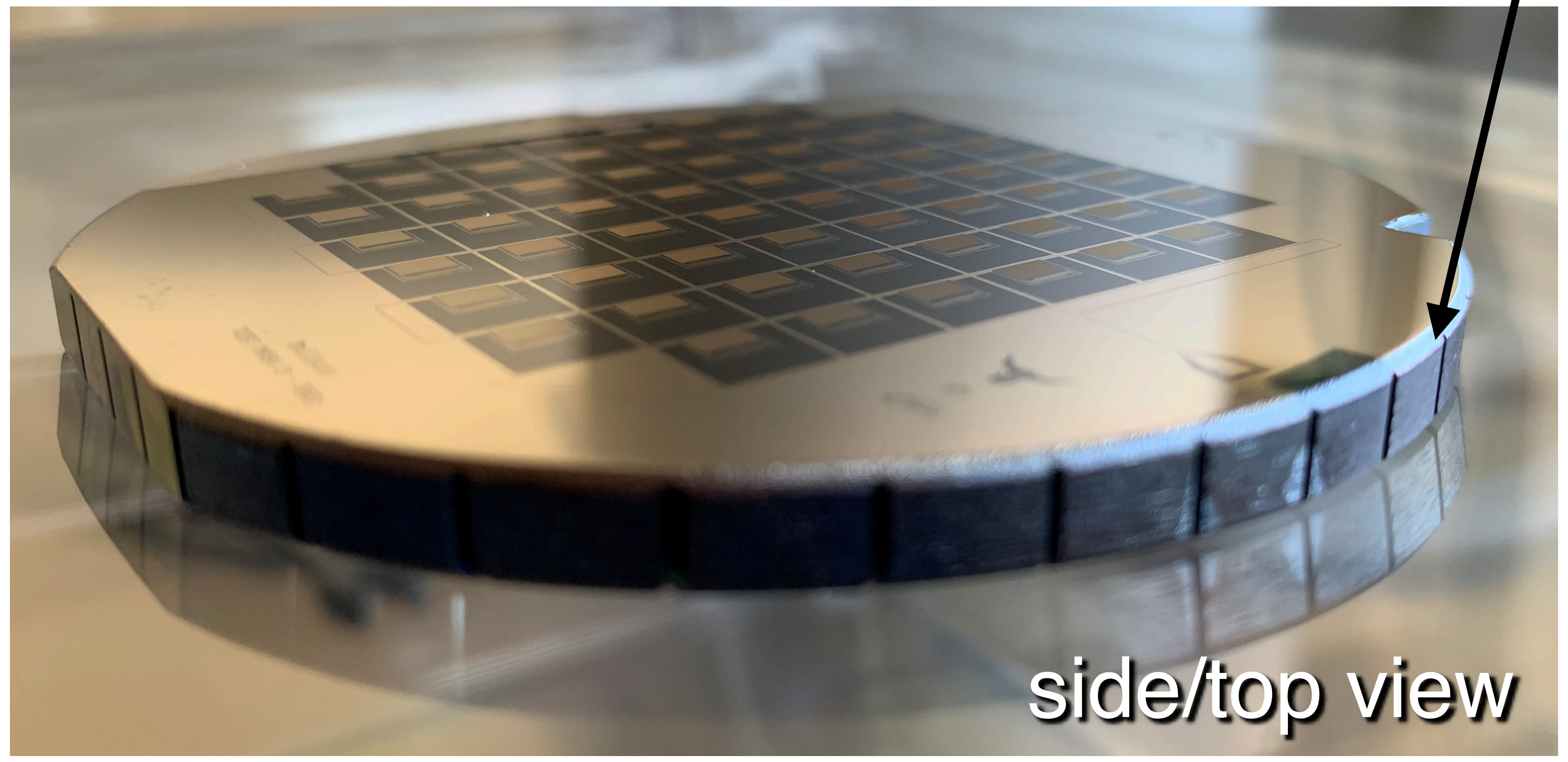
4.5 mm deep grooves

- 6 mm pitch
- chemical etching

0.5 mm thick common disk:

- holds the structure
- hosts the KIDs

lithography of multiplexed KID array



KID array

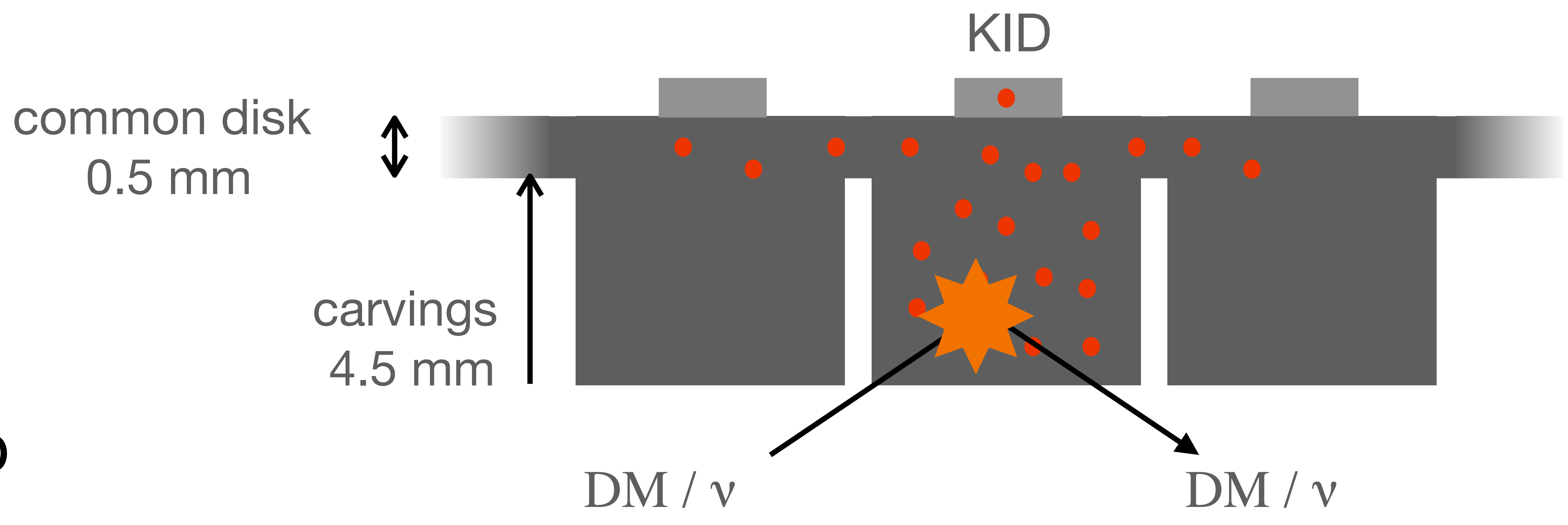
- 60 nm aluminum film
- 60 KIDs lithography

✓ 60 detectors in 1

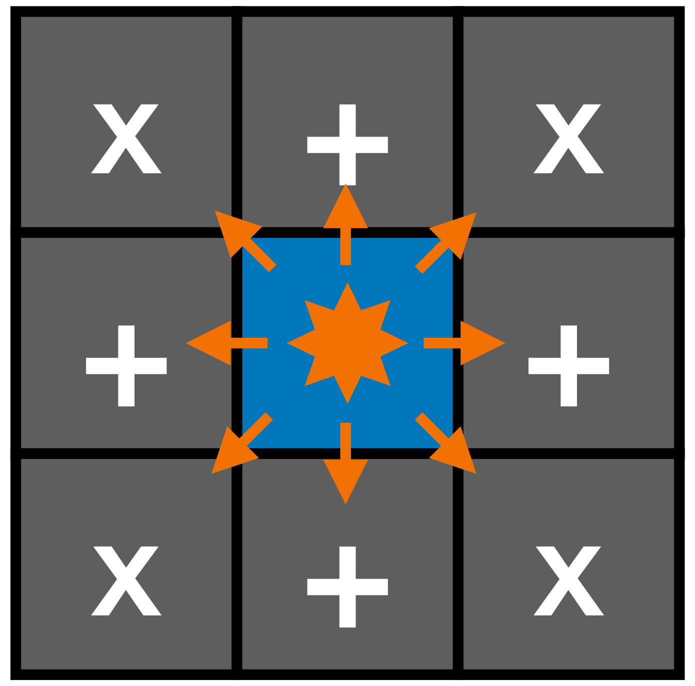
Fully multiplexed
(single readout line)

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

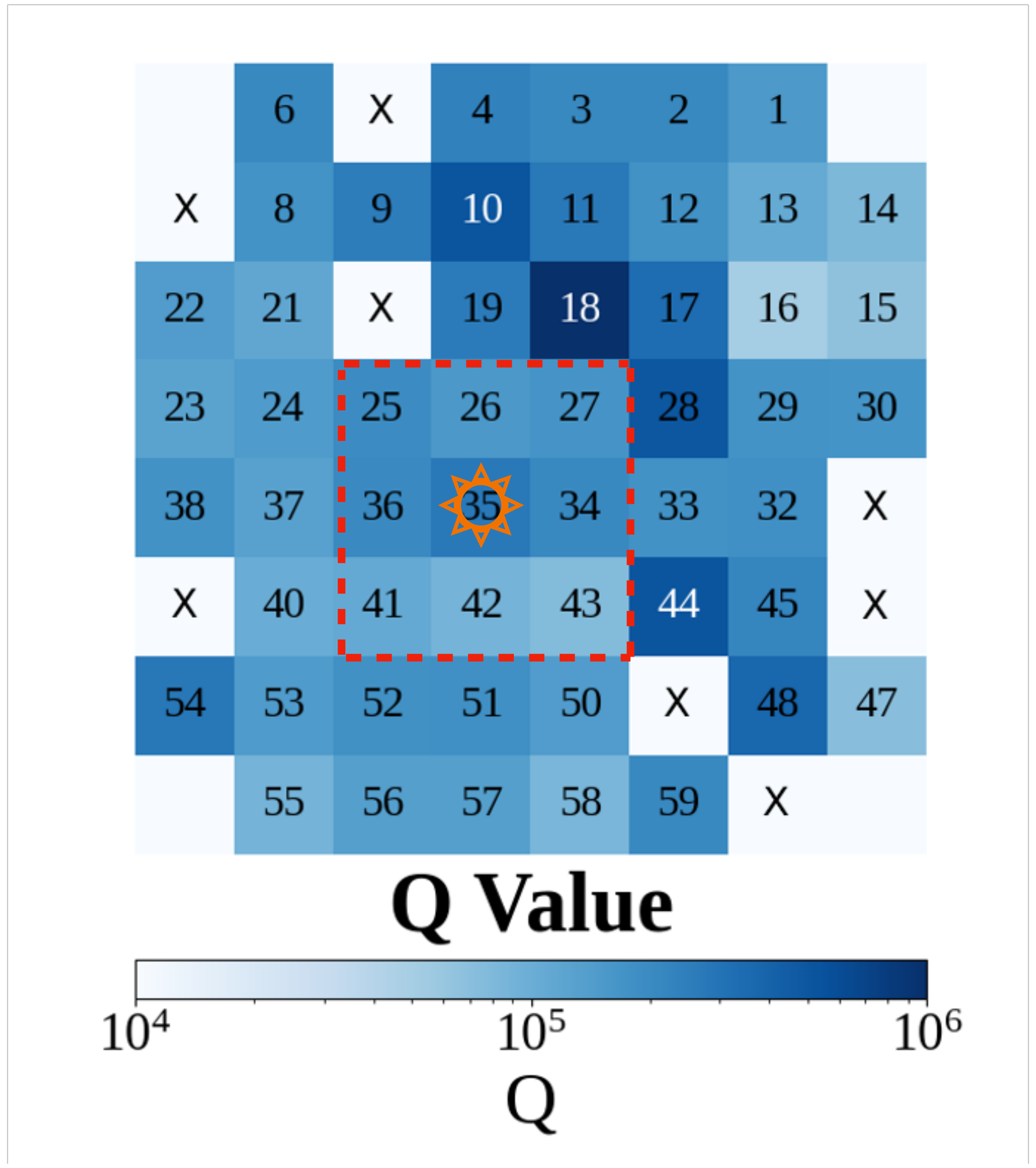


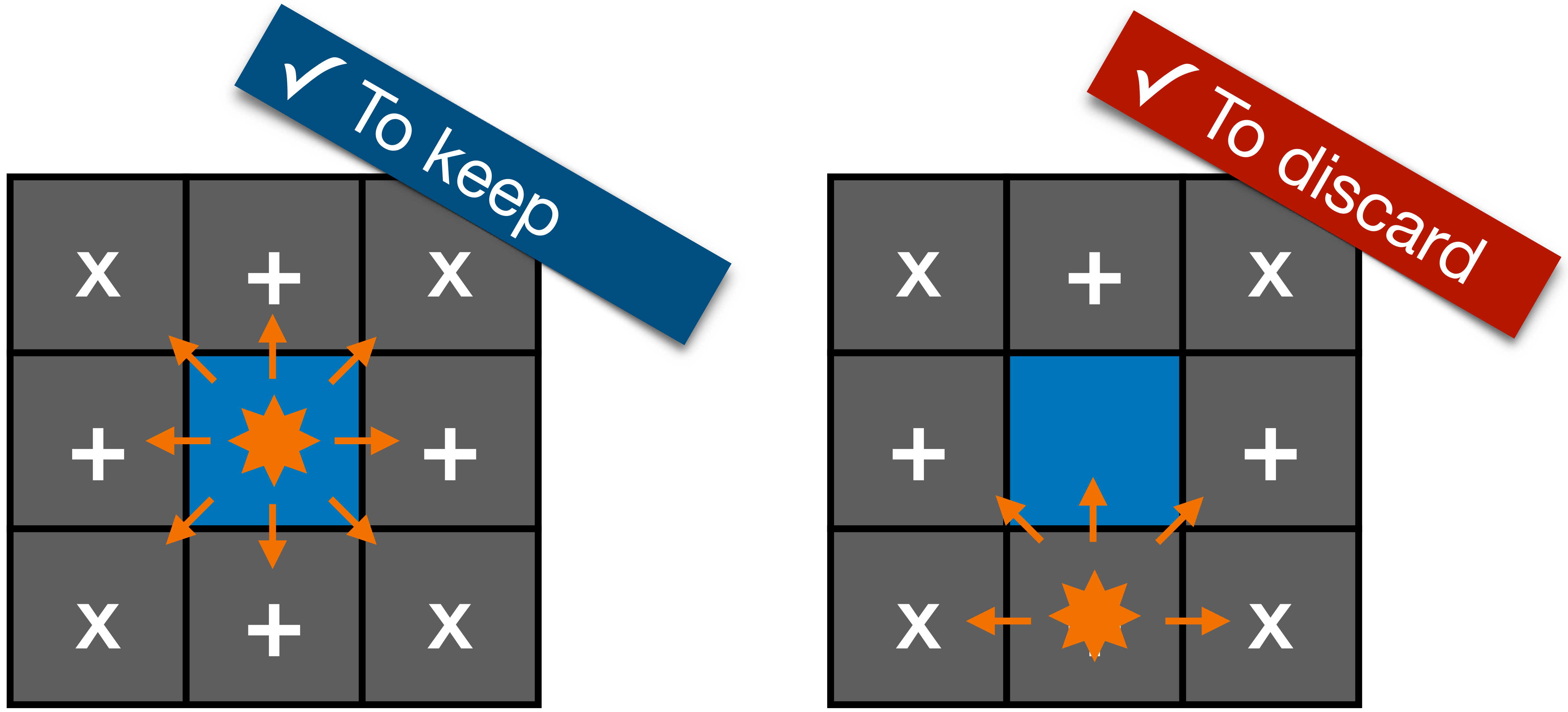
This effect reduces the phonon focusing on the KID but
it can be exploited to reconstruct the interaction voxel

Combined analysis of a 9-dice cluster

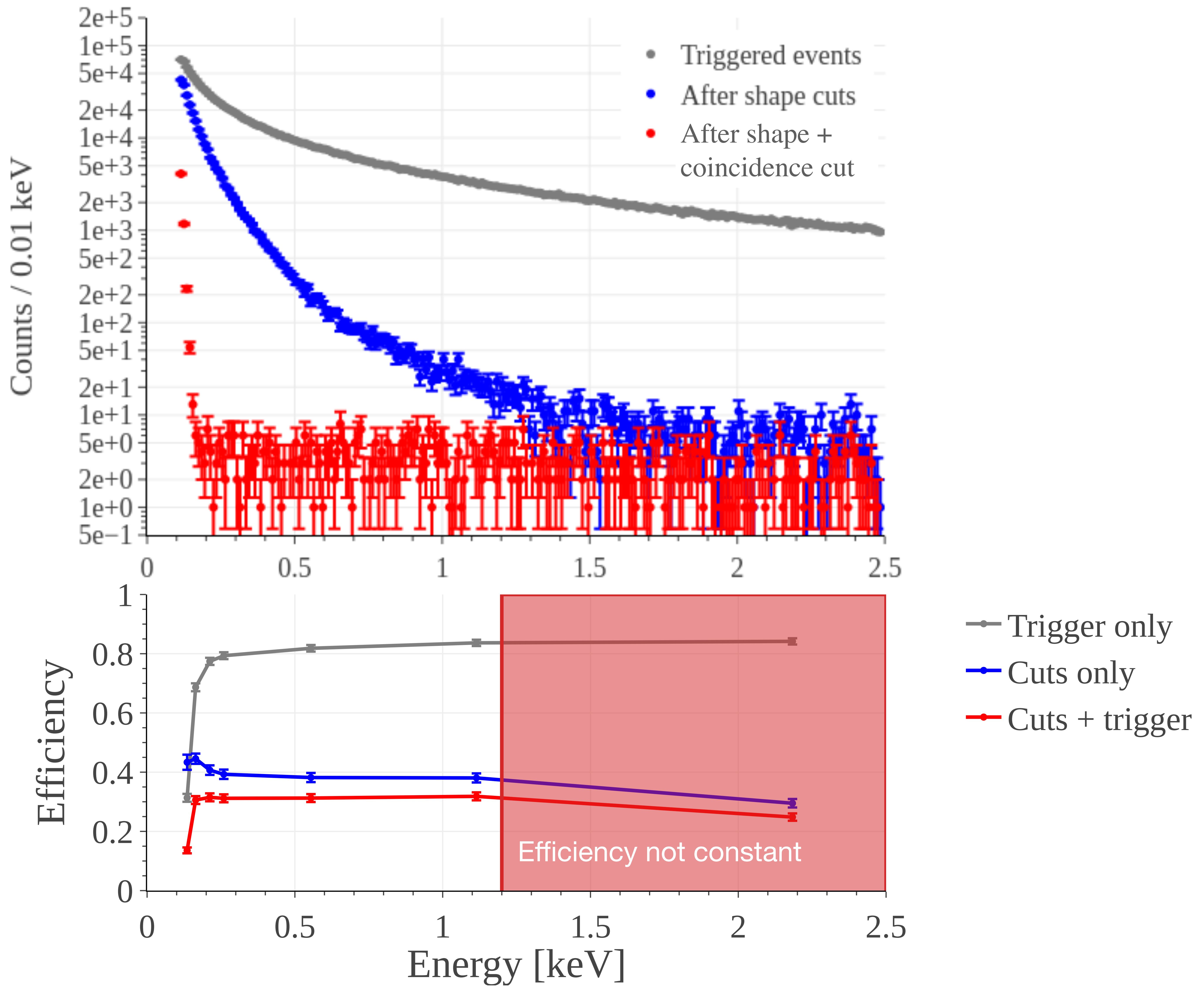
Measurement of the energy spectrum of the central voxel

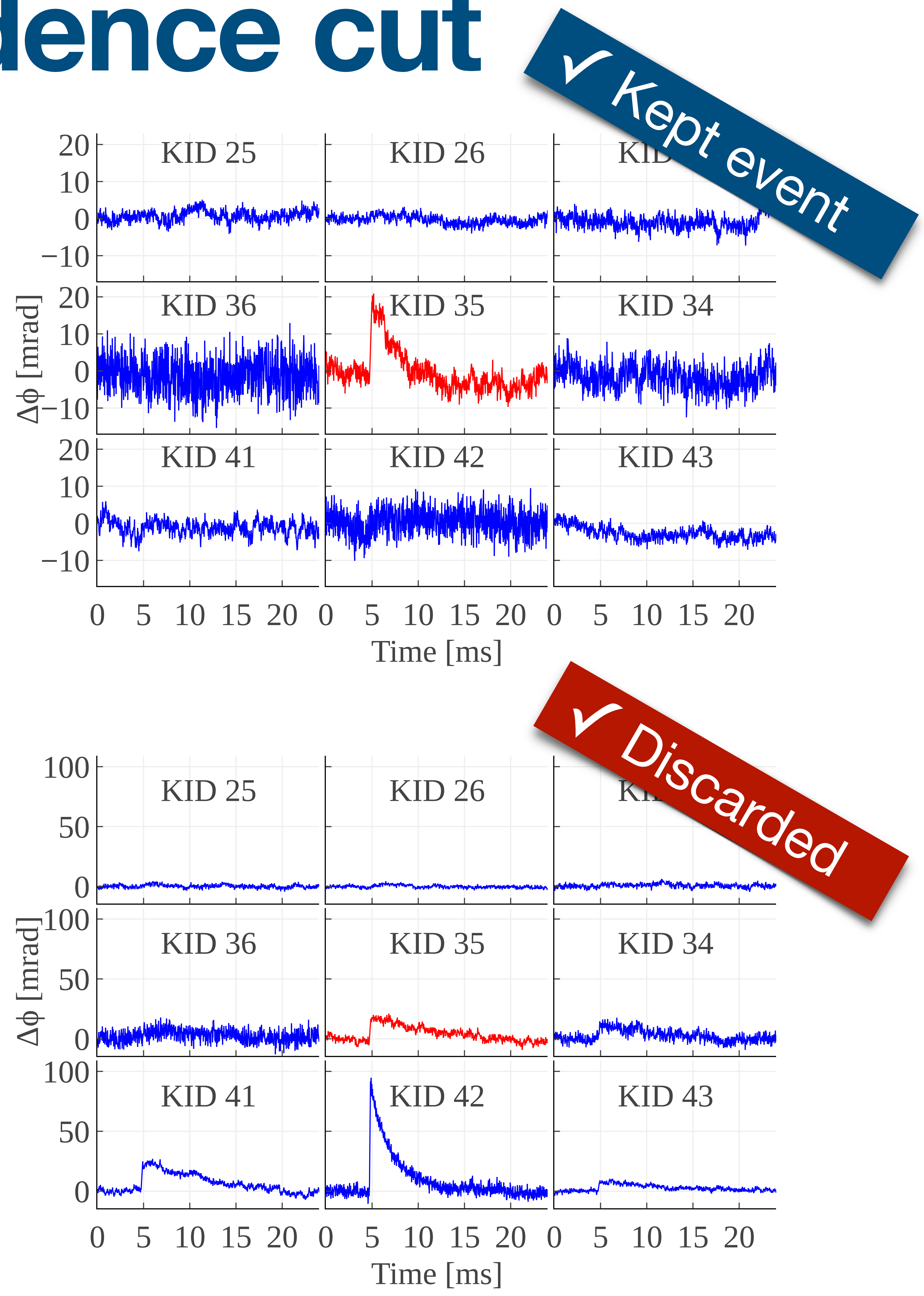
Use the 8 external voxels as “veto” exploiting the phonon leakage





Background: shape + coincidence cut

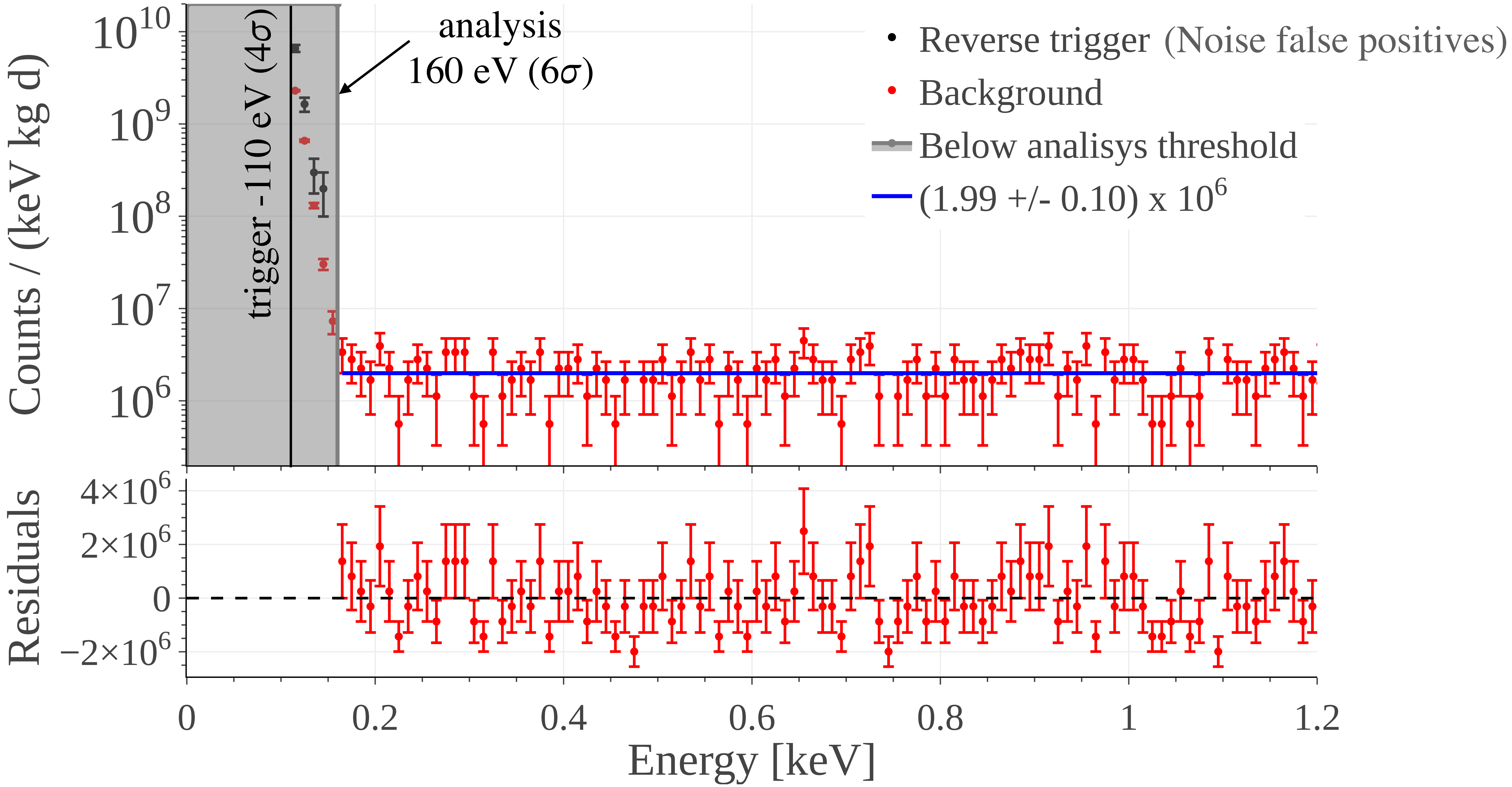




Background: surface result

Above ground lab, no shield, 39 live hours

D. Delicato et al, arXiv:2308.14399



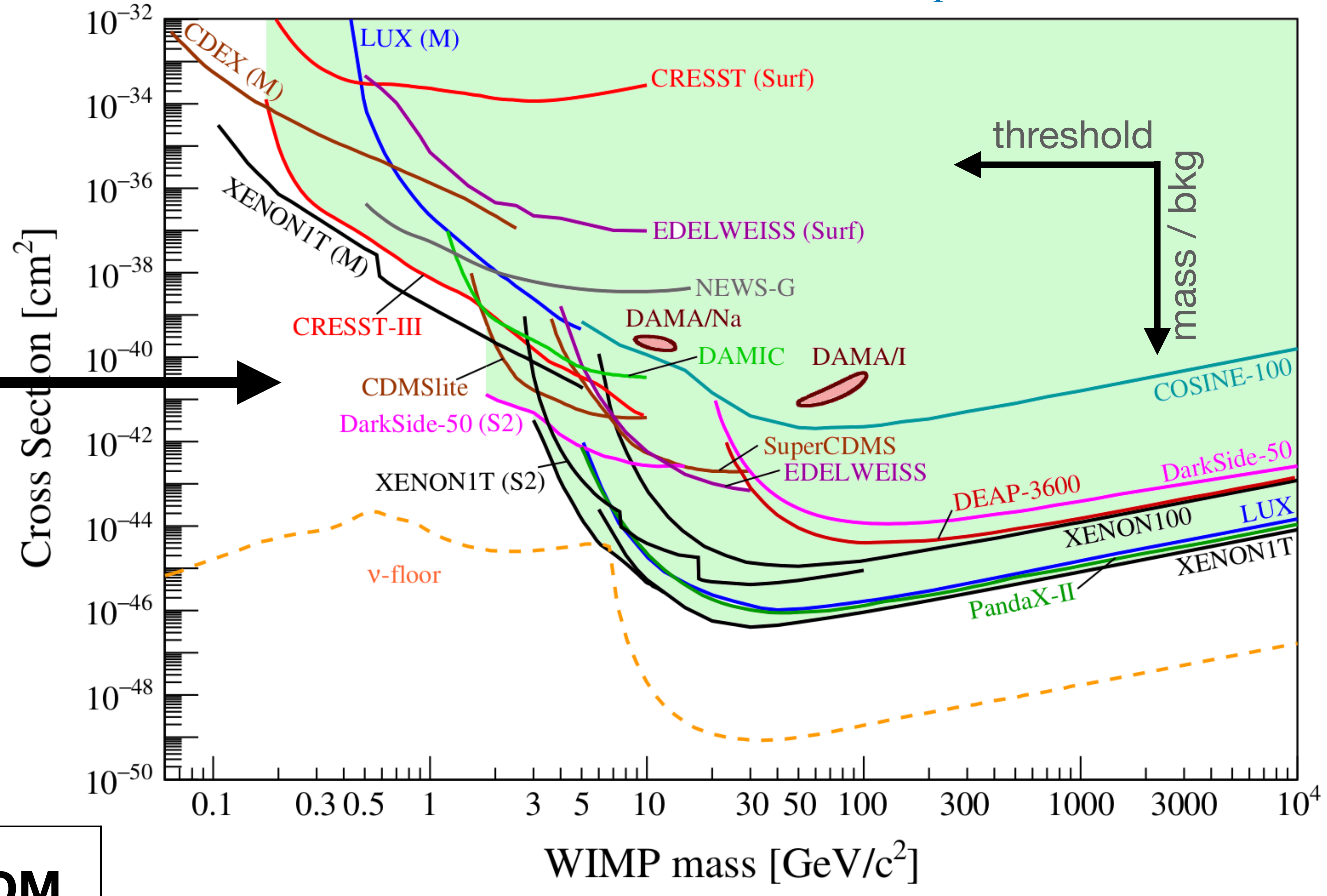
The excess above trigger threshold is compatible with noise false positives.
Background is flat above analysis threshold.

Dark Matter - direct search with BULLKID-DM

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

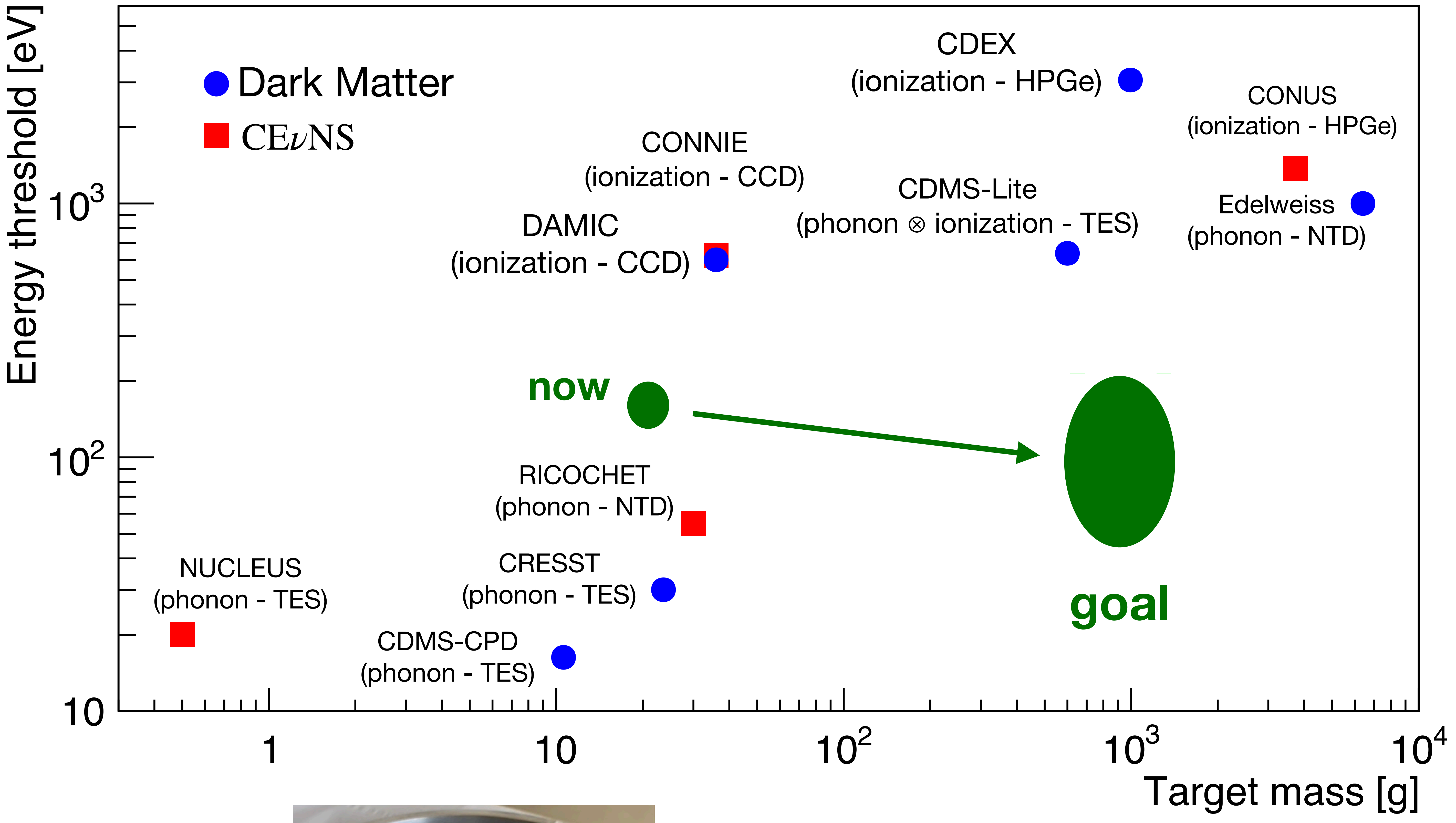
solid-state phonon detectors with:
- **zero background**
- **kg target**
- **threshold < 200 eV**

With BULLKID-DM we can achieve these goals. How?



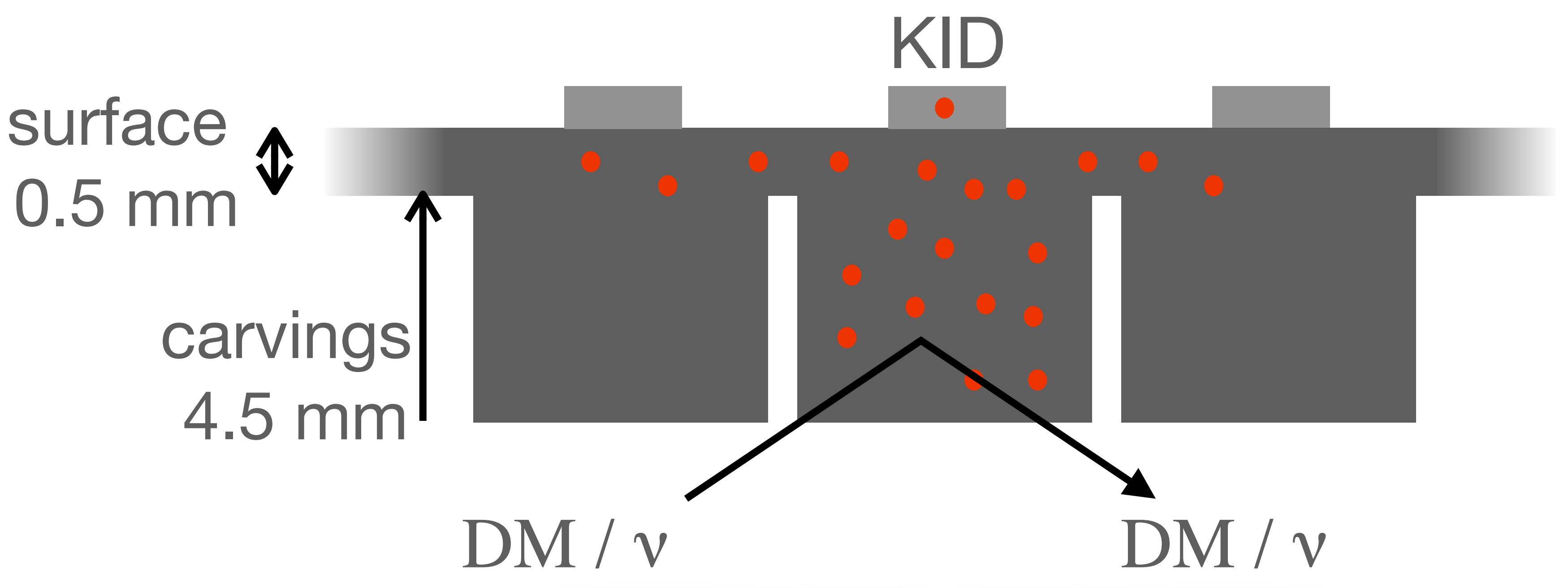
	BULLKID-Surface	BULLKID-DM-Demo	BULLKID-DM
bkg (c/keV kg y)	2,000,000	10,000-1,000	0.1-0.01
threshold (eV)	160	similar	similar or better
mass	0.35-20 g	20-60 g	600 g

Mass and threshold improvement

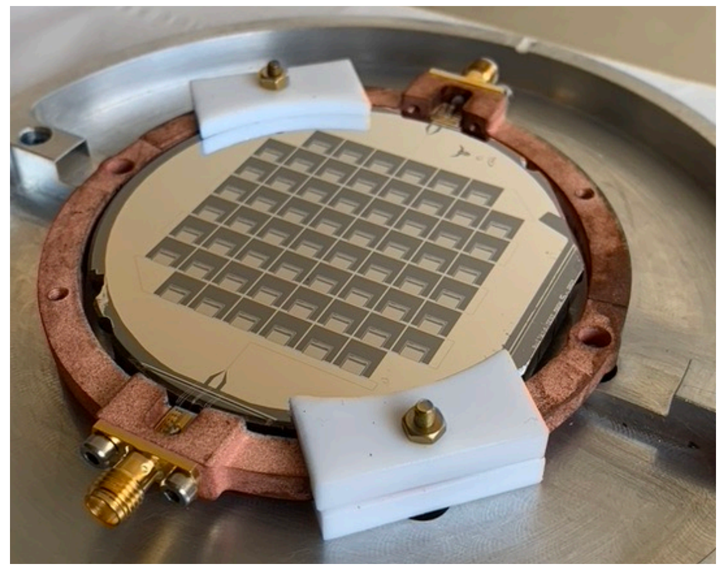


Threshold (ongoing R&D):

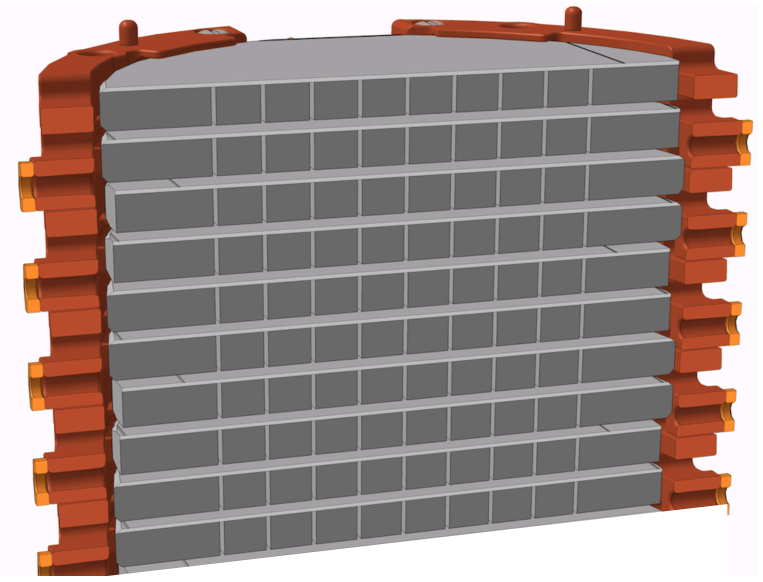
1. Replace Al with Al-Ti-Al KIDs - 5x inductance
2. Deeper carvings for higher phonon focussing



lower priority

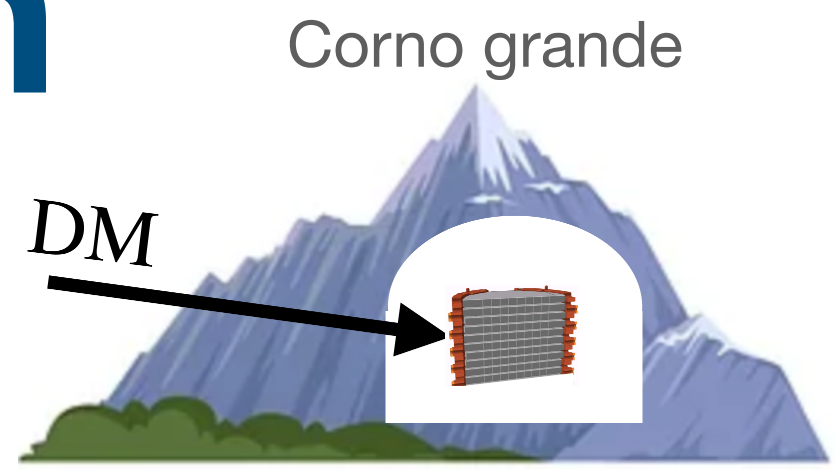


Mass:
from 3” to 4” wafers
stack of wafers



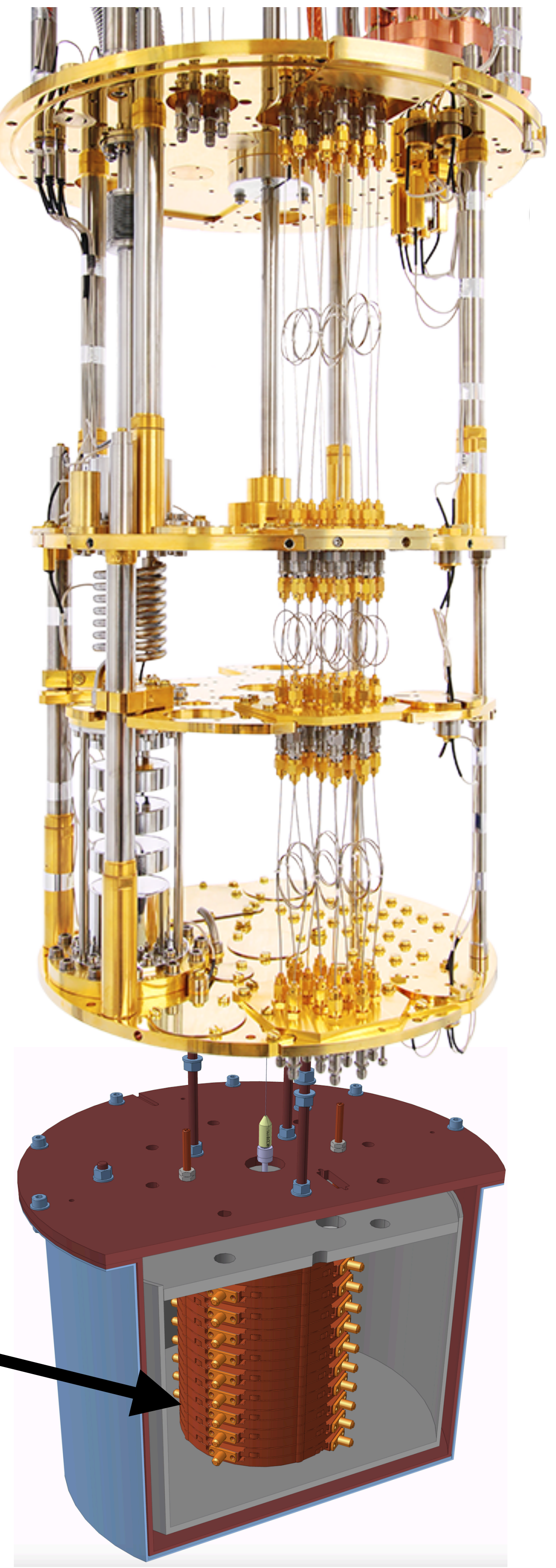
higher priority

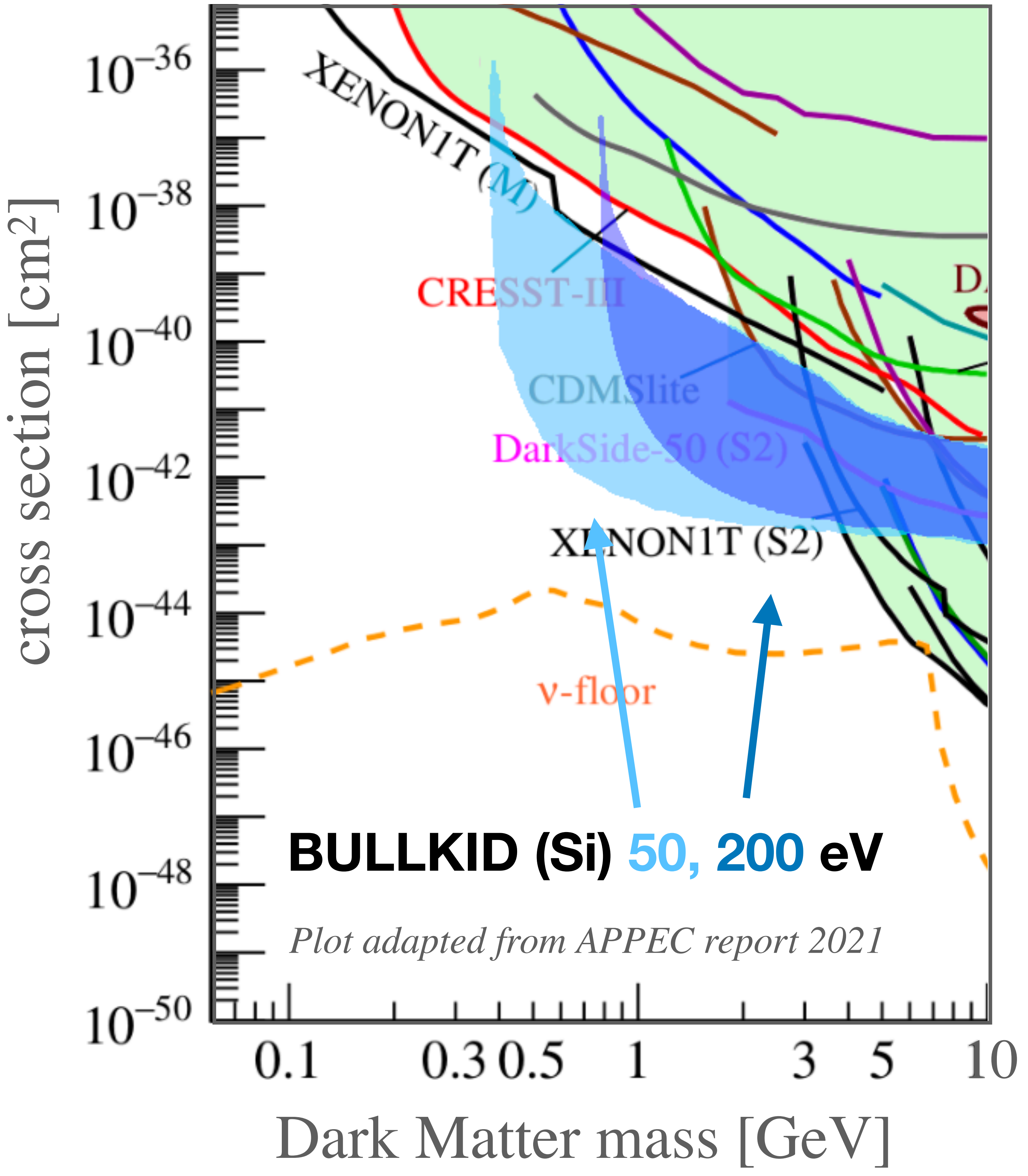
Impact on Dark Matter search



Nuclear recoil detector with:

- ✓ 16 (4”) or 30 (3”) BULLKIDs (2000 voxels)
- ✓ 0.6 kg of silicon target
- ✓ 200 ÷ 50 eV threshold (160 eV demonstrated)





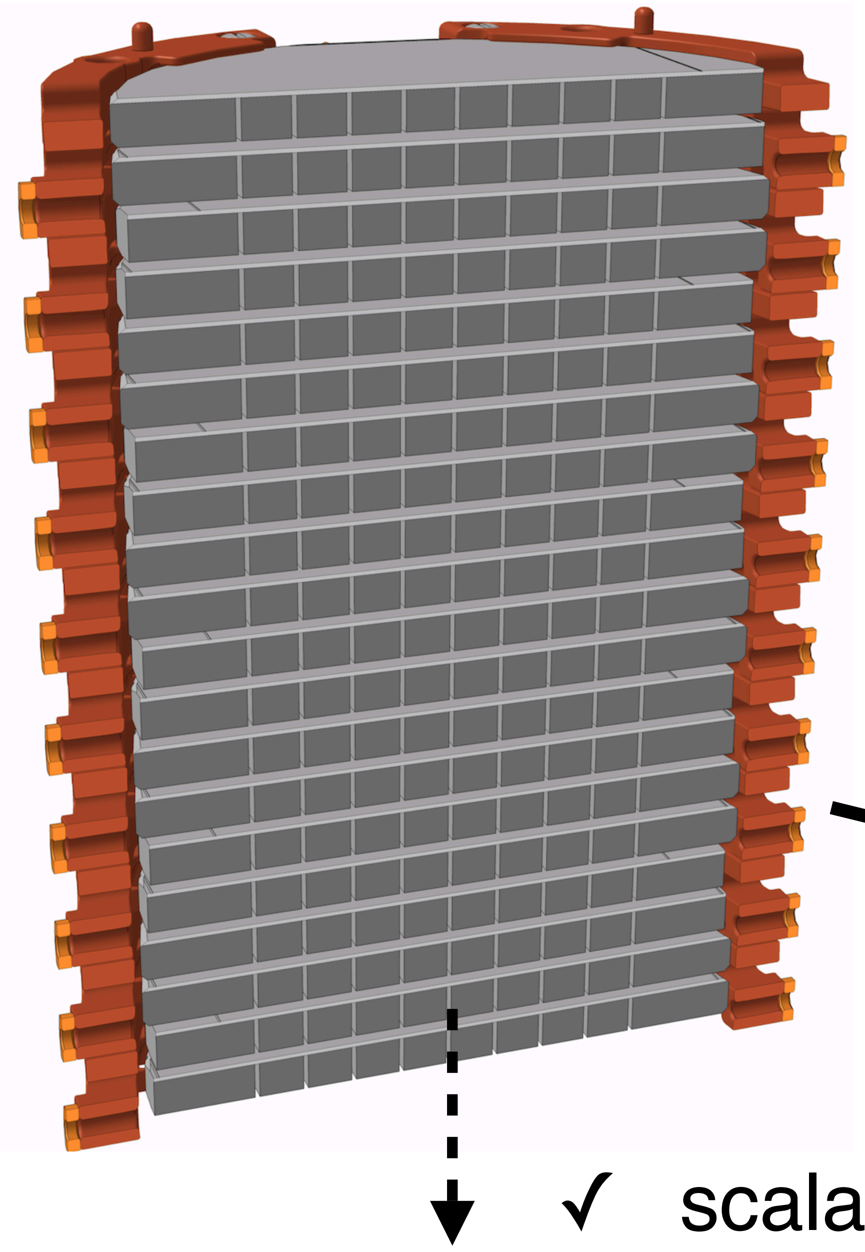
bands range

same background as CRESST

zero background

Unique features for bkg. suppression:

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



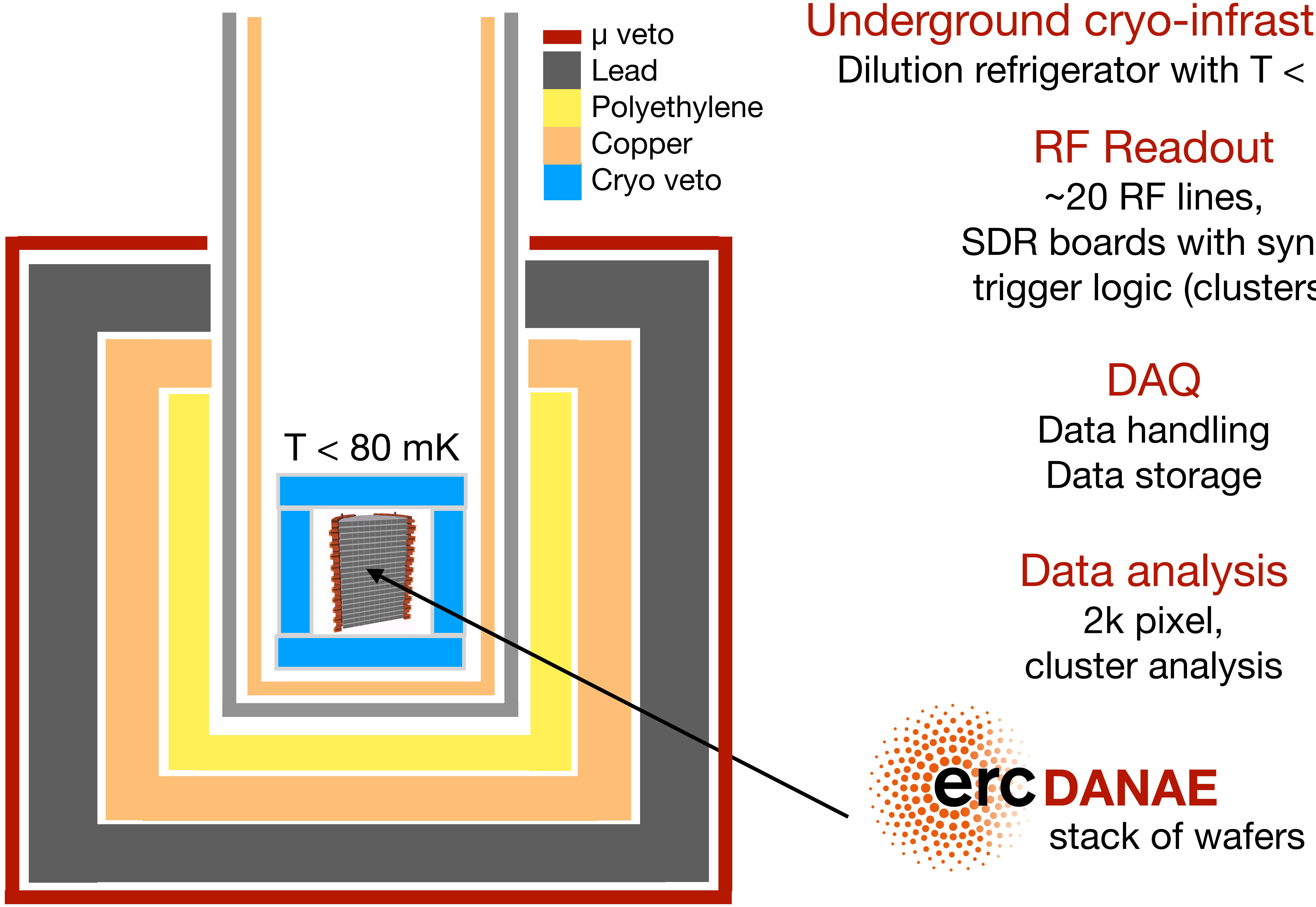
✓ scalable

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/GSO + 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)

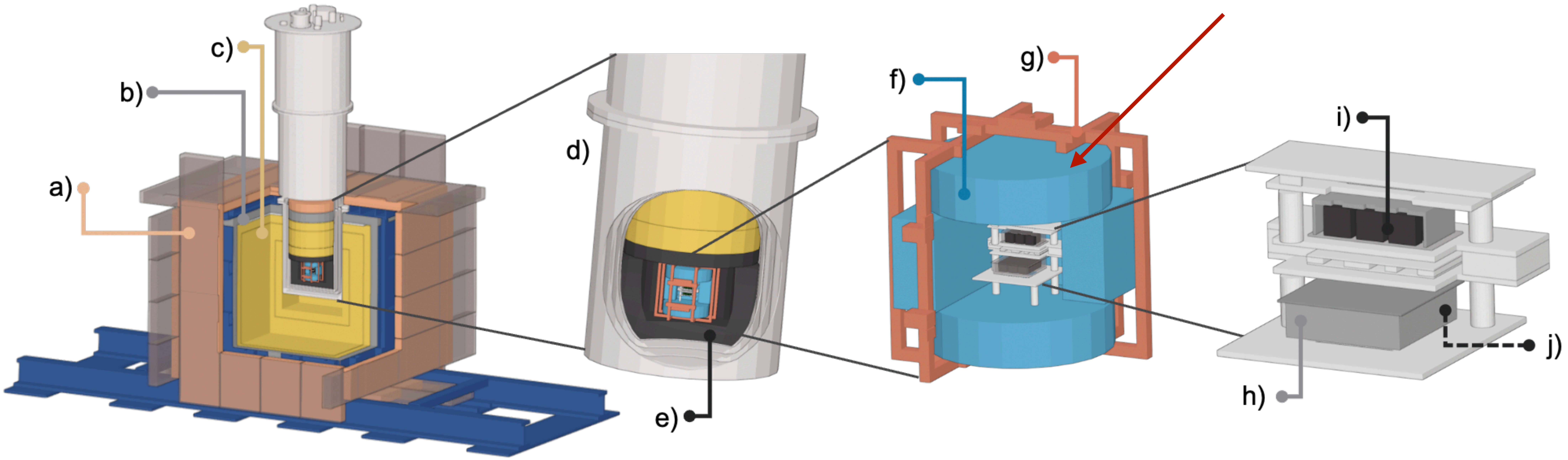
DAQ
Data handling
Data storage

Data analysis
2k pixel,
cluster analysis

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.

Goals of this meeting

- Agree on WPs, assignements
- Delineate timescale and milestones

  ➡ Macro milestone TBD: Demonstrator in early 2025

- Set Working Group on the CDR
- Next deadlines:

  1. June 2024: CDR for INFN
  2. Oct 2024: Presentation/Requests at LNGS committee
  3. Fundings in DE and MX?

#	WP	$	Resp.Unit	2024		2025		2026		2027	
				I	II	I	II	I	II	I	II
1	Collaboration	-	All	Meeting	CDR		TDR				
2	Stack	ERC	RM-Fe-Neel	Prototype assembly	4” test		Stack start				
3	Demonstrator	ERC	RM-Fe-Neel	Lead RM1 10^4 DRU		Final assembly < 10^4 DRU ? at LNGS?					
4	Simulations	?	MX	Surface Sci. Impact	Under-ground						
5	Electronics	?	KIT-Pi	60 px	150 px						
6	RM1 Cryo	ERC	RM	Tender		Delivery/ Shielding					
7	LNGS Cryo	LNGS	LNGS		Delivery?	Shielding					
8	Cryo veto	CSN2	Pi-RM	PoC	Project	Delivery	Tests				
9	Calibration	CSN2	Pi-RM?			PoC					
10	KID R&D	ERC	RM-Neel								
11	DAQ	CSN2	Pi		Project	Delivery	Tests				
12	Computing	CSN2	Pi?								
13	Germanium	ERC	Rm-Fe-Neel								

Letter of interest for BULLKID-DM:
Search for Dark Matter with arrays of Kinetic Inductance Detectors at LNGS

L. Ardila-Perez,[1] P. Azzurri,[2] L. Bandiera,[3] M. Calvo,[4] R. Caravita,[5] A. Cruciani,[6] A. D’Addabbo,[7] D. Delicato,[4,8,6] G. Del Castello,[8,6] M. del Gallo Roccagiovine,[8,6] M. de Lucia,[9,2] F. Ferraro,[7] R. Gartmann,[1] V. Guidi,[10,3] L. Malagutti,[3] A. Mazzolari,[10,3] A. Monfardini,[4] T. Muscheid,[1] D. Nicolò,[9,2] F. Paolucci,[2] D. Pasciuto,[6] E. Pedreschi,[2] V. Pettinacci,[6] C. Roda,[9,2] S. Roddaro,[2] M. Romagnoni,[3] O. Sander,[1] G. Signorelli,[2] F. Simon,[1] F. Spinella,[2] M. Tamisari,[11,3] A. Tartari,[2] E. Vazquez-Jauregui,[12] and M. Vignati[8,6]

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

(Dated: September 29, 2023)

BULLKID-DM aims to conduct an experiment for the search of WIMP-like Dark Matter particles with GeV / sub-GeV mass and cross section down to 10^{-42} cm^2. The detector consists of a highly segmented array of thousands silicon targets sensed by Kinetic Inductance Detectors, with total target mass exceeding 0.5 kg and energy threshold below 200 eV. The proposed array structure avoids the use of inert material between the single sensitive units and enables fiducialization techniques for background reduction, not yet exploited in solid-state detectors searching for WIMPs. With this Letter We manifest our interest in operating the experiment at LNGS, possibly exploiting one of the planned cryogenic facilities.

Structure of this meeting

Tuesday, 19 March

		Speaker			
09:30 → 09:40	Welcome	Antonio D'Addabbo (Istituto Nazionale di Fisica Nucleare)	10m	Room "E. Majorana"	Welcome.p...
09:40 → 10:20	Overview of BULLKID-DM	Marco Vignati (Istituto Nazionale di Fisica Nucleare)	40m	Room "E. Majorana"	
10:20 → 10:30	Presentation of the Rome group	Marco Vignati (Istituto Nazionale di Fisica Nucleare)	10m	Room "E. Majorana"	
10:30 → 10:45	Presentation of the KIT group	Luis Ardila Perez (Karlsruhe Institute of Techonology)	15m	Room "E. Majorana"	2024-03-19...
10:45 → 11:00	Presentation of the Ferrara Group	Andrea Mazzolari (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
11:00 → 11:30	Coffee		30m	Room "E. Majorana"	
11:30 → 11:45	Presentation of the UNAM group	Eric Vazquez Jauregui (Instituto de Física, UNAM)	15m	Room "E. Majorana"	
11:45 → 12:00	Presentation of the Grenoble group	Alessandro Monfardini (CNRS Grenoble)	15m	Room "E. Majorana"	
12:00 → 12:15	Presentation of the Pisa group	Donato Nicolo' (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
12:15 → 12:30	Sensitivity to WIMP-like Dark Matter	Matteo Folcarelli (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	Minutes; Sensitivity ...
12:30 → 12:50	Review of competitors	Marco Vignati (Istituto Nazionale di Fisica Nucleare)	20m	Room "E. Majorana"	
12:50 → 13:10	CEvNS application	Giorgio Del Castello (Istituto Nazionale di Fisica Nucleare)	20m	Room "E. Majorana"	Bulkid4Ce...
13:30 → 14:45	Lunch		1h 15m	Room "E. Majorana"	

		Speaker			
14:45 → 15:00	The DANAE Detector: Roadmap	Angelo Cruciani (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
15:00 → 15:15	Electronics study	Mario De Lucia	15m	Room "E. Majorana"	electronics...
15:15 → 15:45	Prototype electronics system	Mr Timo Muscheid (KIT)	30m	Room "E. Majorana"	BULLKID_D...
15:45 → 16:00	3"x3 Demonstrator	Daniele Delicato (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
16:00 → 16:15	4" Stack	Daniele Pasciuto (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
16:15 → 16:30	Wafer dicing	Marco Romagnoni (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
16:30 → 16:50	Simulations: DANAE setup in Rome	Eric Vazquez Jauregui (Instituto de Física, UNAM)	20m	Room "E. Majorana"	
16:50 → 17:10	Simulations: BULLKID-DM setup at Gran Sasso	Eric Vazquez Jauregui (Instituto de Física, UNAM)	20m	Room "E. Majorana"	
17:10 → 17:40	Coffee		30m	Room "E. Majorana"	
17:40 → 19:00	PI council			Room "E. Majorana"	
20:00 → 22:30	Social dinner		2h 30m		

Wednesday, 20 March

		Speaker			
09:30 → 09:50	Tests on BGO	Matteo del Gallo Roccagiovine	20m	Room "E. Majorana"	BGO-LNGS...
09:50 → 10:10	KID R&D	Daniele Delicato (Istituto Nazionale di Fisica Nucleare)	20m	Room "E. Majorana"	
10:10 → 10:25	LNGS Cryo facility	Antonio D'Addabbo (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
10:25 → 10:40	Rome Cryolab	Angelo Cruciani (Istituto Nazionale di Fisica Nucleare)	15m	Room "E. Majorana"	
10:40 → 10:55	Cryogenics in Pisa	Giovanni Signorelli	15m	Room "E. Majorana"	
11:00 → 11:30	Coffee		30m	Room "E. Majorana"	
11:30 → 12:00	CDR	Angelo Cruciani (Istituto Nazionale di Fisica Nucleare)	30m	Room "E. Majorana"	
12:00 → 13:00	Round table: Workpackages and milestones definition	Angelo Cruciani (Istituto Nazionale di Fisica Nucleare), Marco Vignati (Istituto Nazionale di Fisica Nucleare)	1h	Room "E. Majorana"	
13:00 → 13:20	Concluding remarks		20m	Room "E. Majorana"	
13:30 → 14:30	Lunch break		1h	Room "E. Majorana"	
14:30 → 17:30	Visit to underground labs		3h	Room "E. Majorana"	

Backup slides