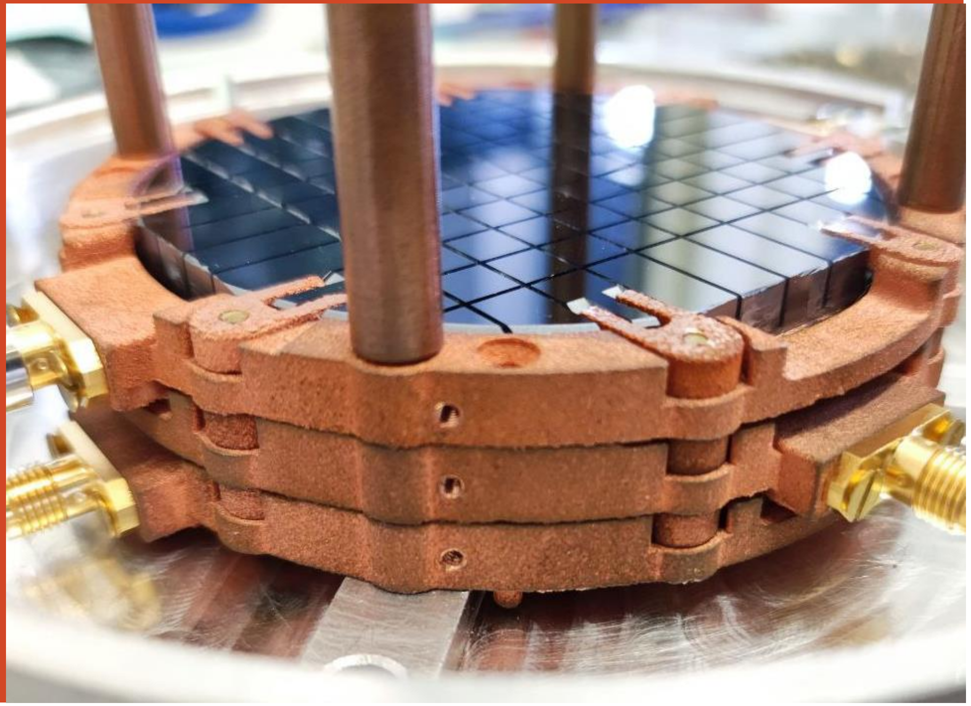
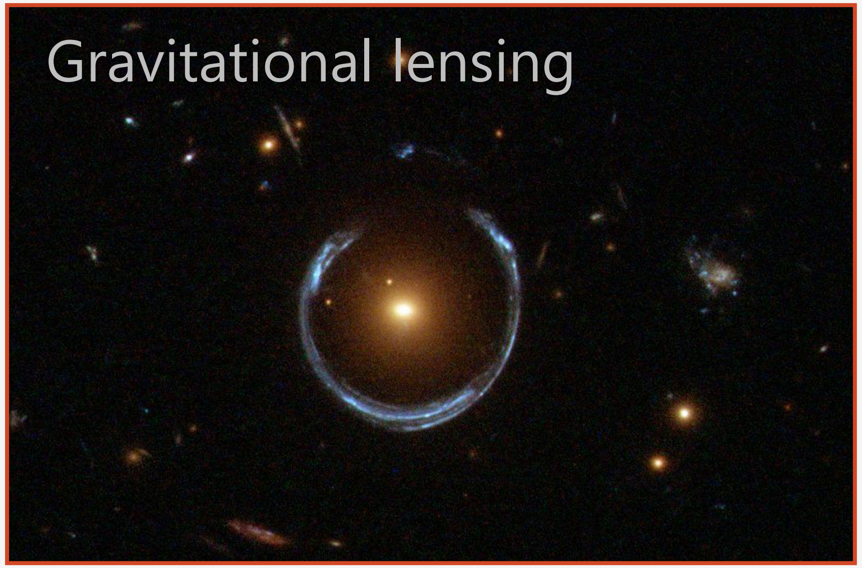
BULLKID-DM: searching for light WIMP with monolithic arrays of detectors

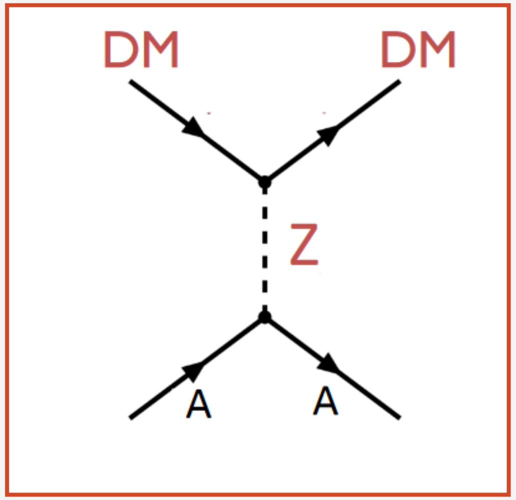
RICAP – Rome, 24/09/2024

Daniele Delicato on behalf of the collaboration



Motivation: Dark Matter direct search

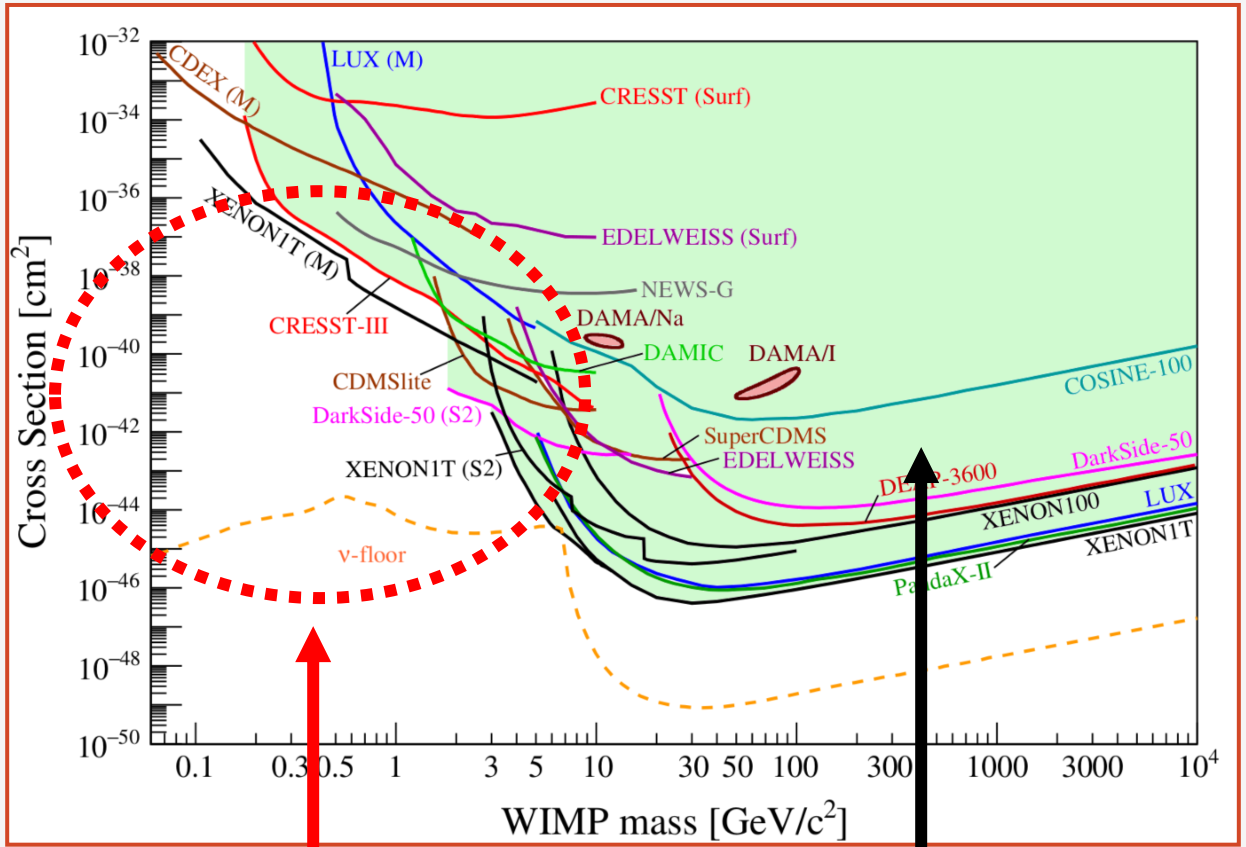




Dark Matter:

MeV/c^2 - TeV/c^2
WIMP-like particles?

Spin-independent WIMP on nucleon scattering cross section limits for direct detection experiments

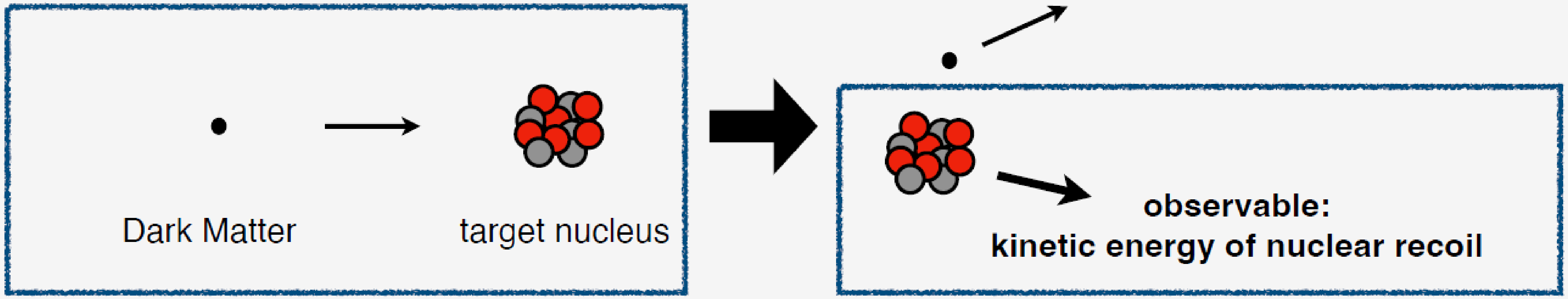


Kg-scale solid state phonon detectors

Multi-ton liquid scintillators

APPEC committee report (April 22)

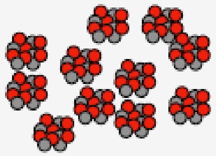
Detection Principle

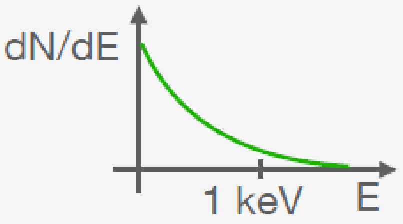


cross section $\sigma < 10^{-40}\ \mathrm{cm}^2$

energy < 1 keV

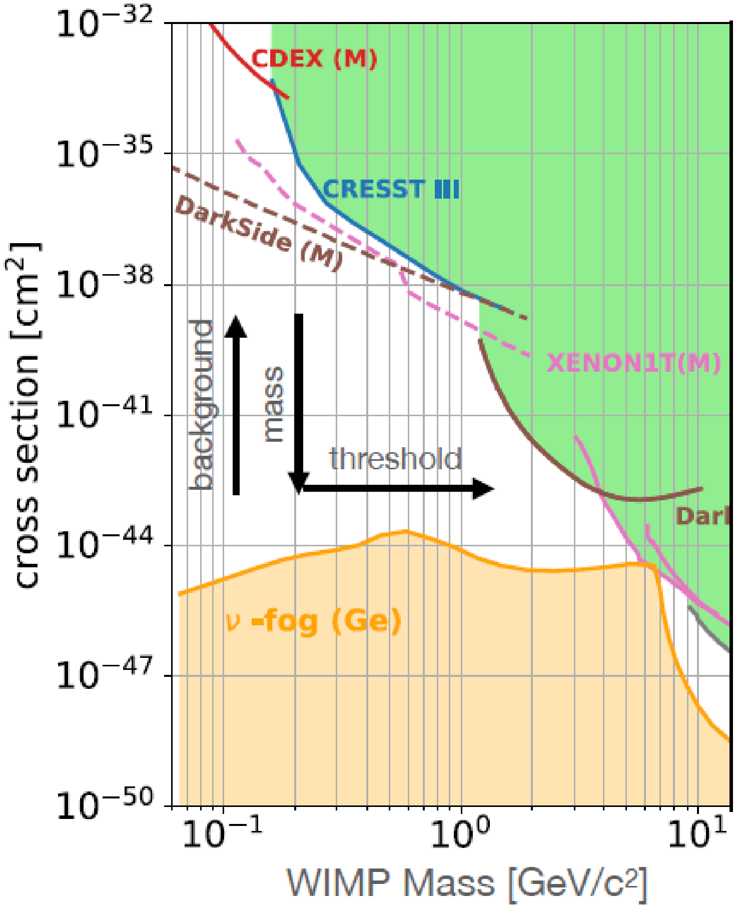
large number of targets
***O*(1 kg)**

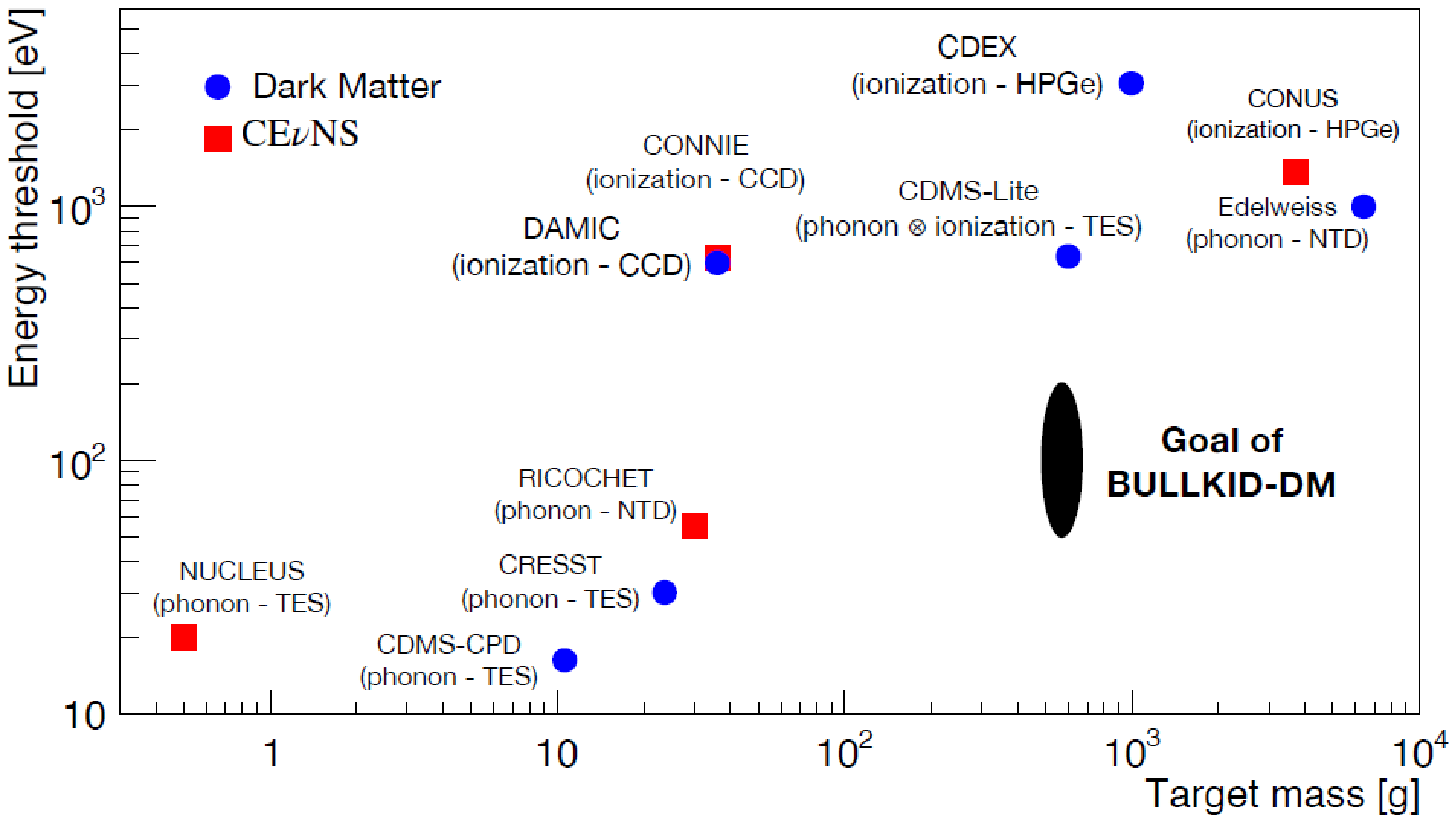




low-energy threshold
***O*(100 eV)**

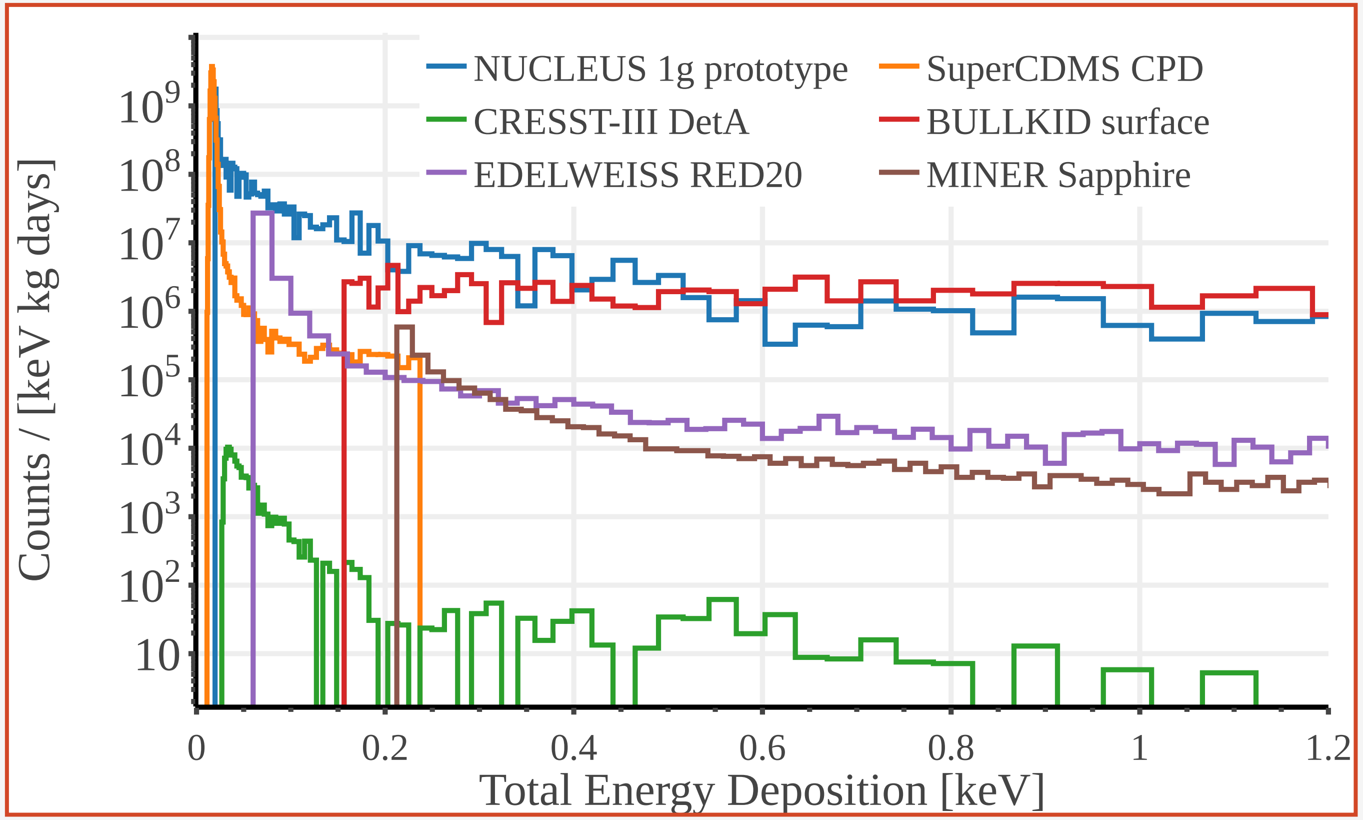
State of the art



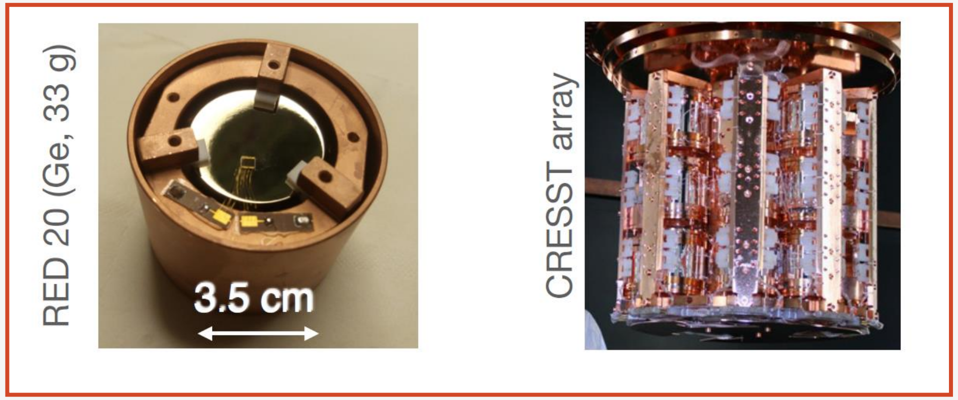


Background issue in low-T experiments

Not understood excess background rising at low energies



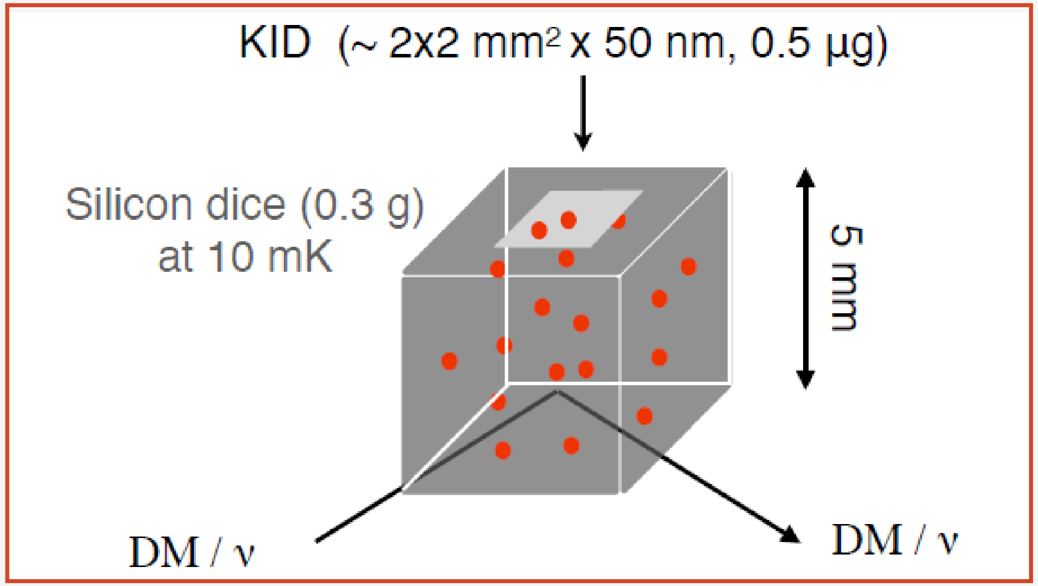
- Phonon bursts (crystal-support friction) ?
- Lattice relaxations after cool down?
- Phonon leakage from interactions in the supports?



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

This background limits the sensitivity of present experiments

Large mass: phonons and multiplexing



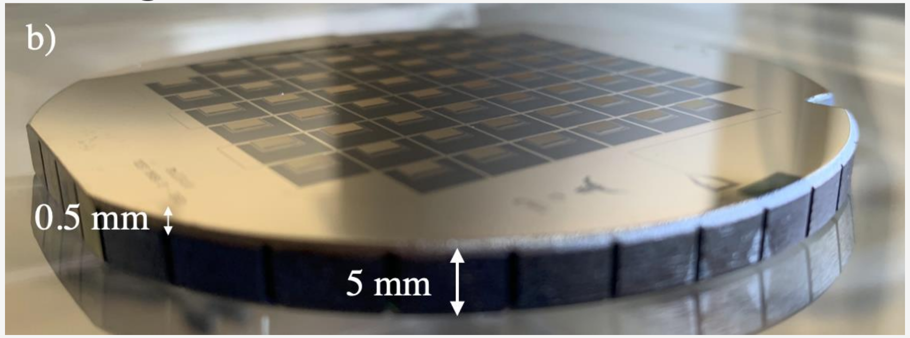
Phonon mediation

Detect phonons created by nuclear recoils in a silicon die

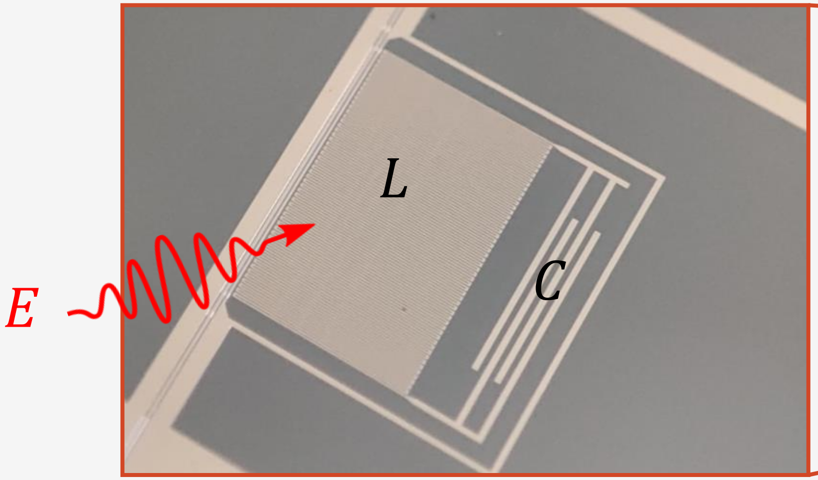
Total active mass is 20g

Diced silicon absorber

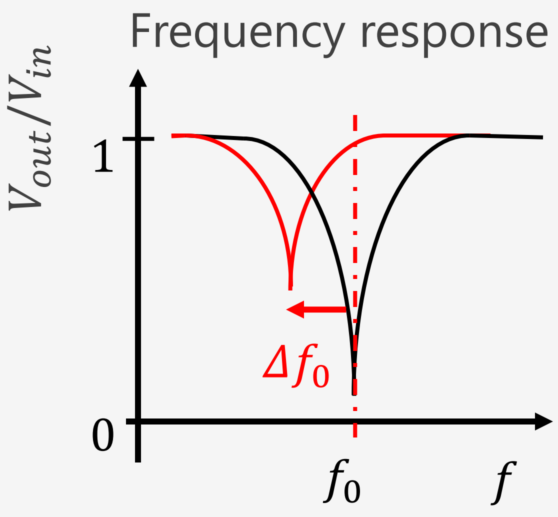
KID array on the other side of the wafer hosting 60 resonators (60 nm Al)

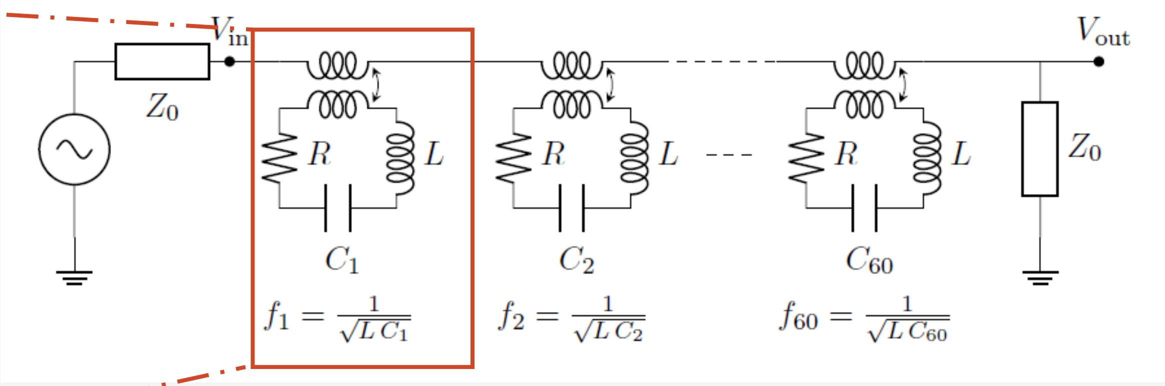


Kinetic Inductance Detectors (KIDs)



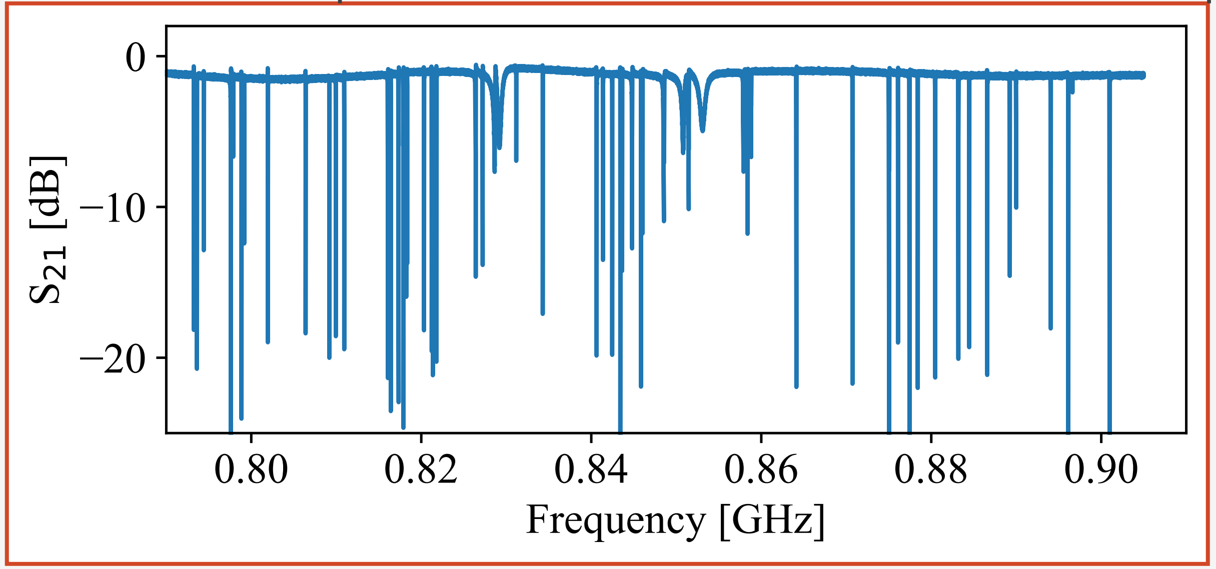
$E \rightarrow \Delta n_{\text{pairs}} \rightarrow \Delta L \rightarrow \Delta f_0$





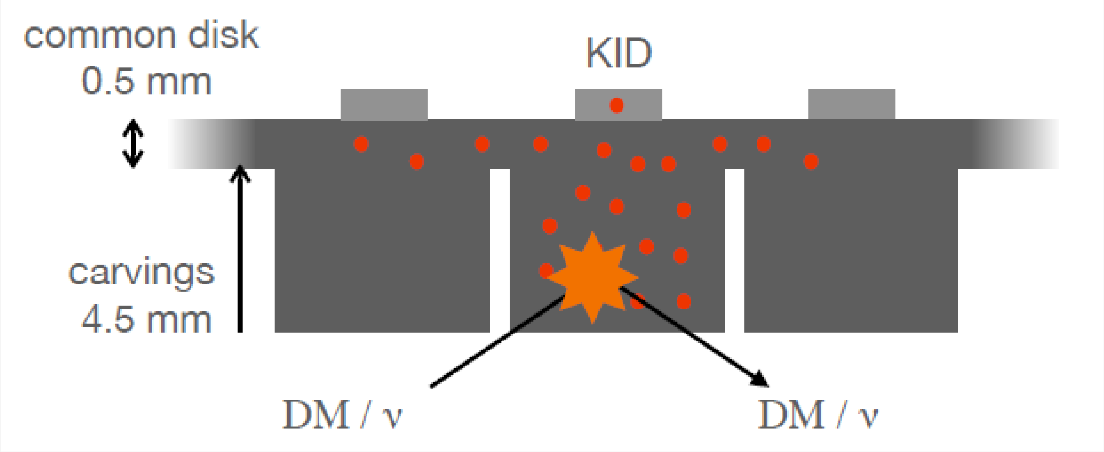
Unique feature of KIDs: multiplexed readout

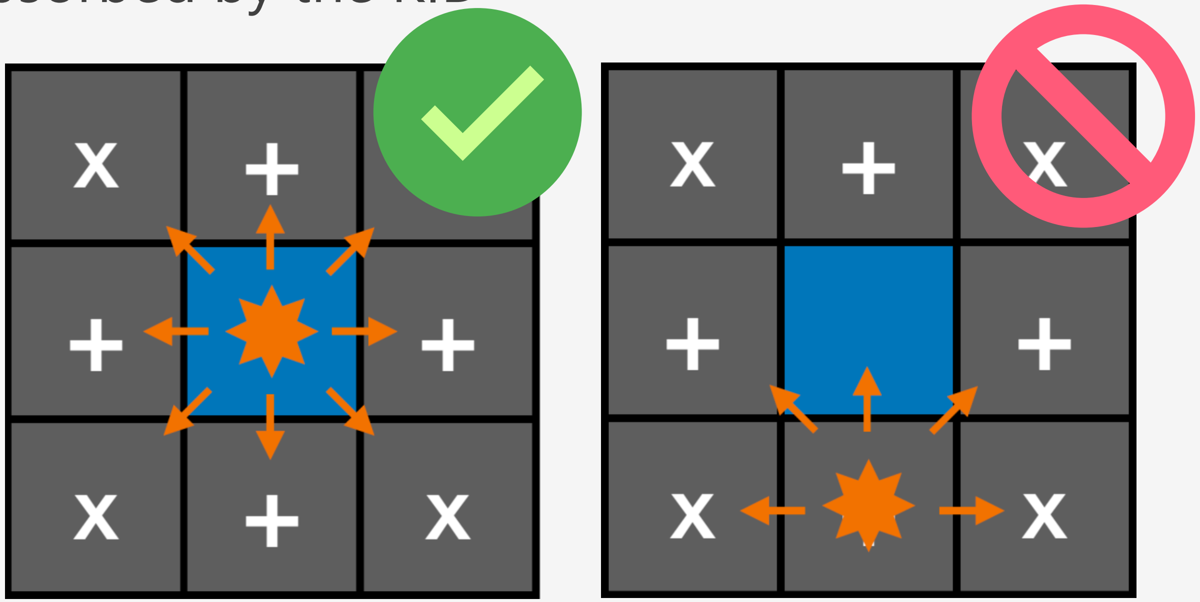
Several KIDs coupled to the same feedline at different frequencies



Data analysis: phonon leakage

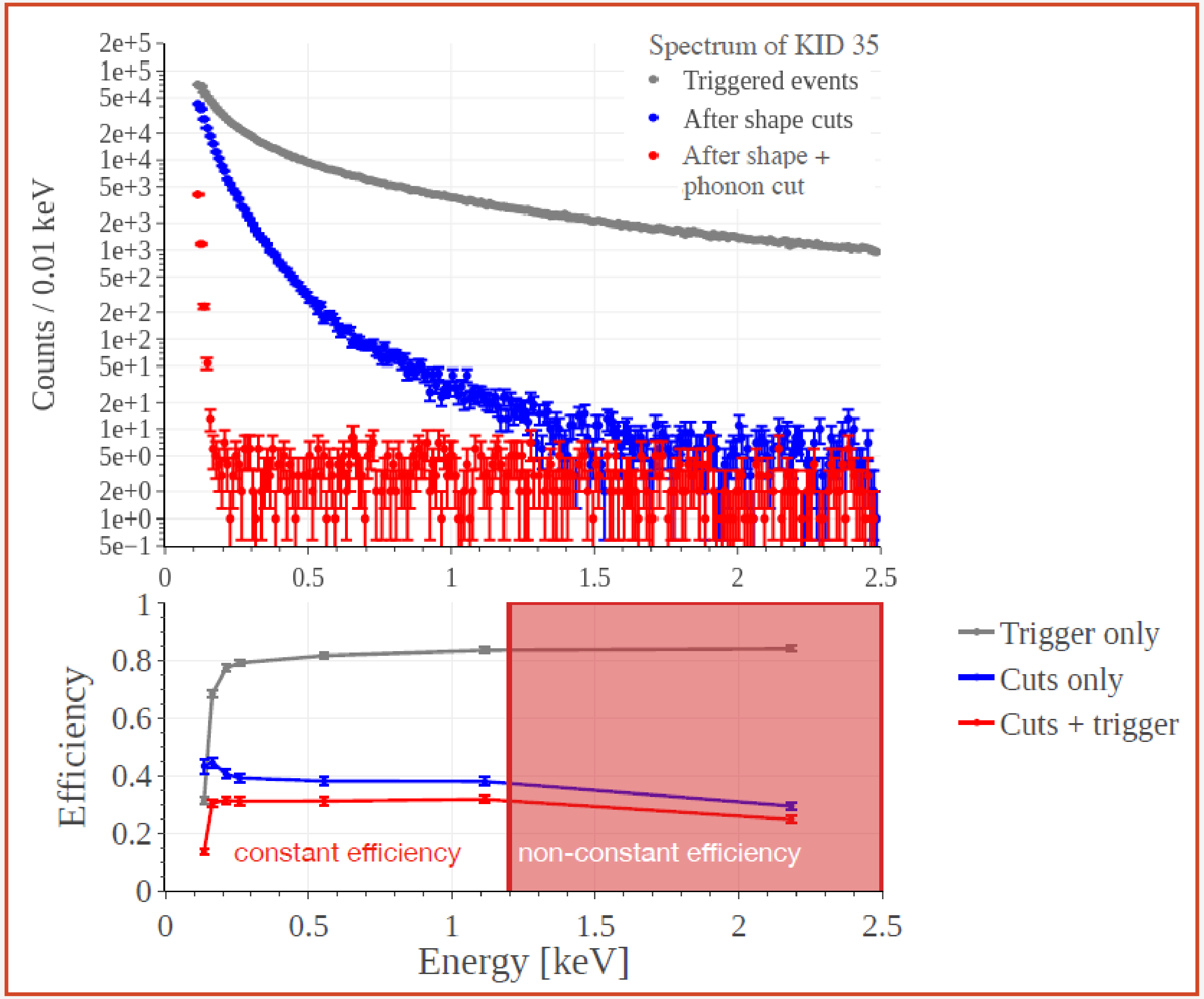
- Only 50% of the phonons generated are absorbed by the KID
- The rest leaks in nearby voxels
  - (8 ± 2) % in each "+" die
  - (3 ± 1) % in each "x" die
  - the rest in outer dice

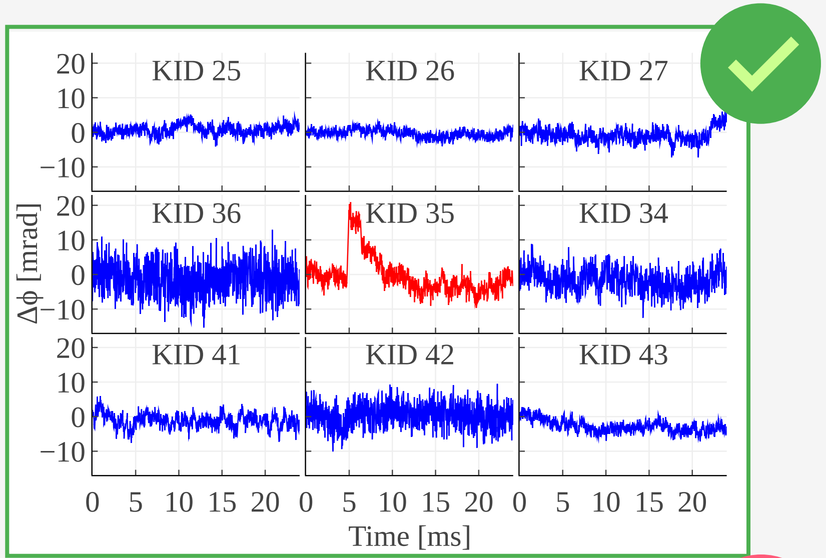


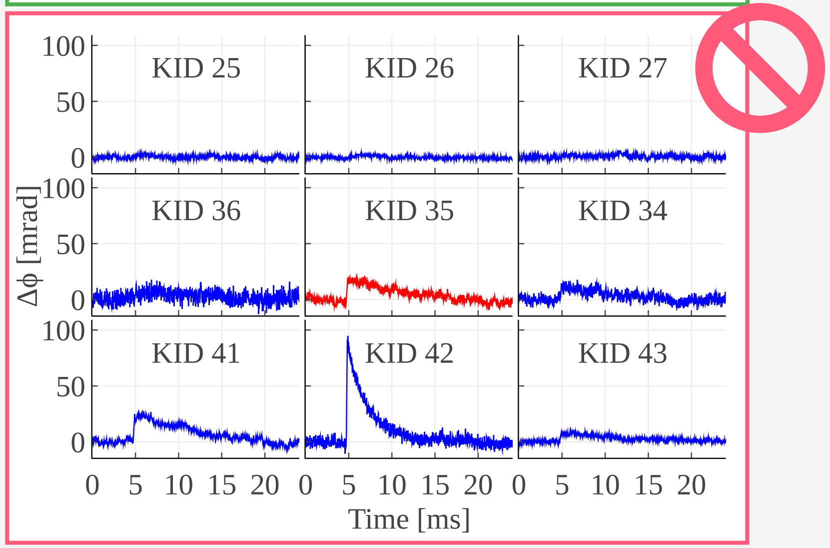


This effect reduces the phonon focusing on the KID but is **exploited to identify the interaction voxel**

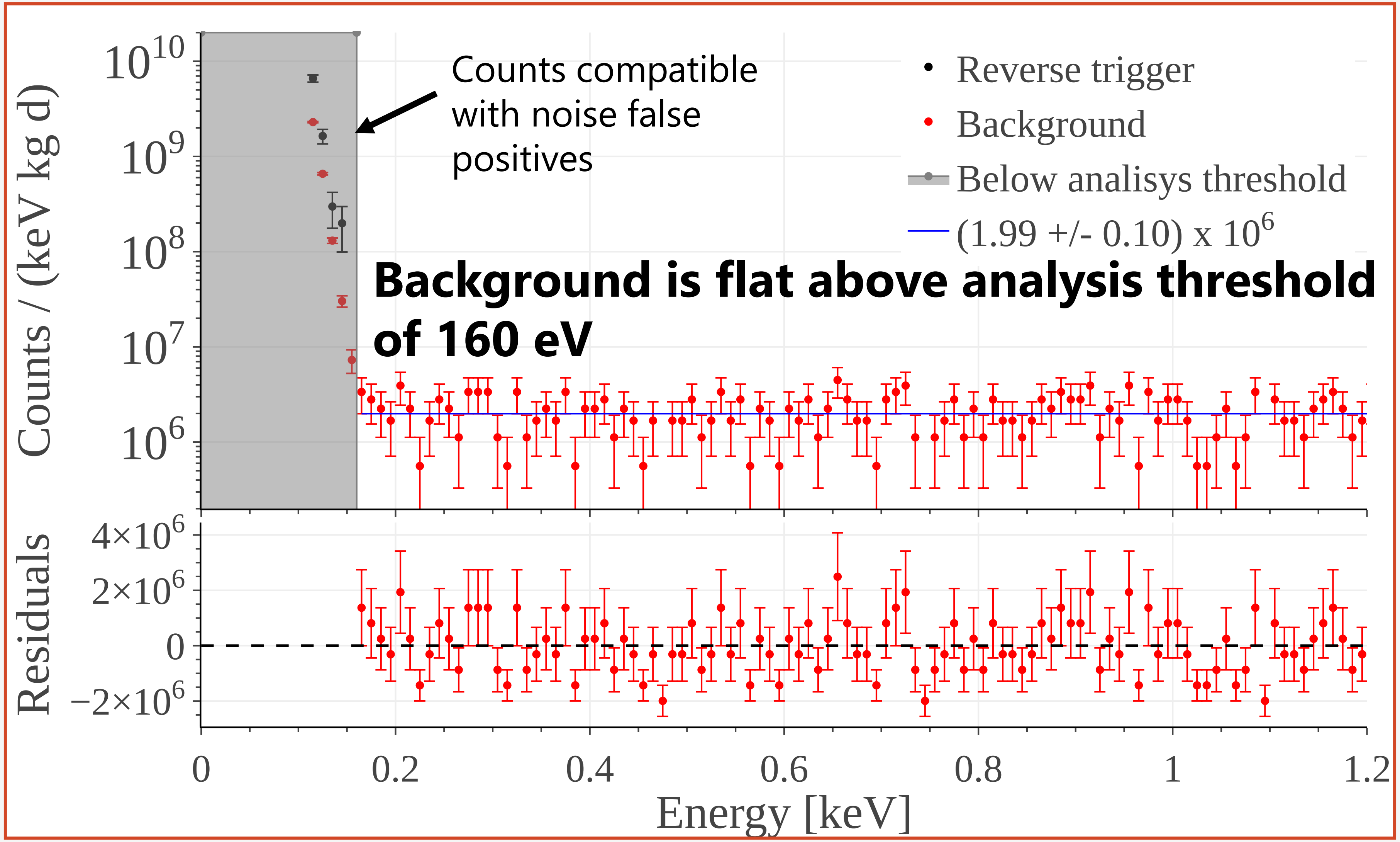
Background: pulse shape + phonon cuts





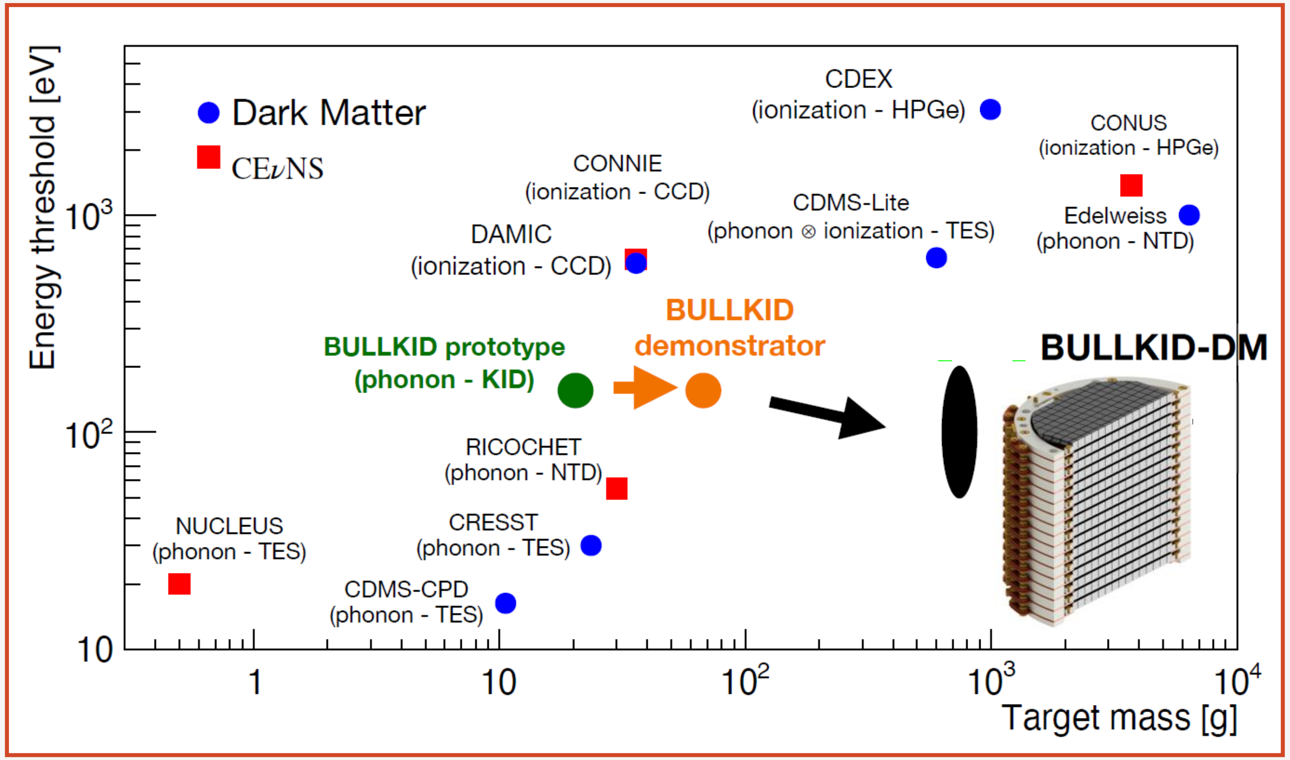


Background: result on surface @Sapienza U., no shield, 39 live hours



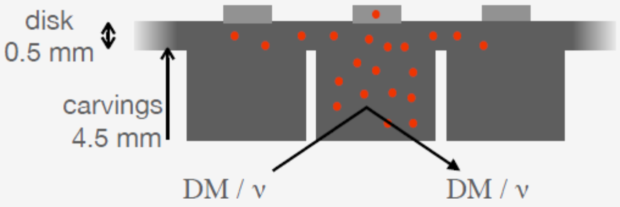
D. Delicato et al, Eur. Phys. J. C 84 (2024) 353

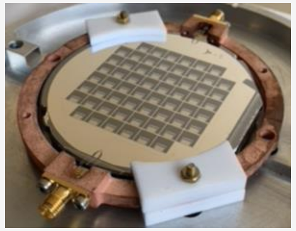
Threshold and mass



Threshold (ongoing R&Ds):

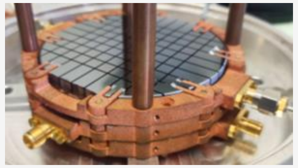
1. Replace Al with Al-Ti-Al KIDs: 5x inductance
2. Deeper carvings for higher phonon focussing





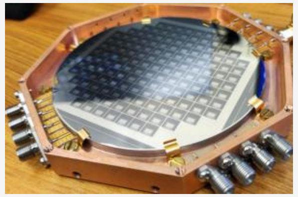
Prototype - 20 g / 60 dice

single 3″ wafer
concluded in 2023



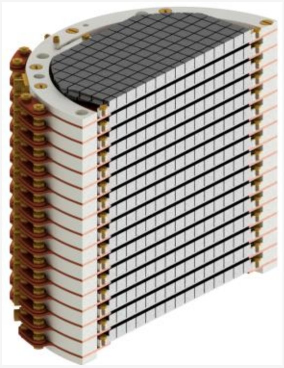
Demonstrator - 60 g / 180 dice

3-layer stack of 3″ wafers
operations ongoing



R&D on large wafer 50 g / 145 dice

single 100 mm wafer first operations fall 2024



BULLKID-DM - 800 g / 2300 dice

16-layer stack of 100 mm wafers
commissioning in 2026 at Sapienza U.
Fiducial mass: 600g

BULLKID-DM Collaboration

Istituto Nazionale di Fisica Nucleare

Roma
Ferrara
LNGS
Pisa

Karlsruher Institut für Technologie

BULLKID-DM
Conceptual Design Report (CDR)

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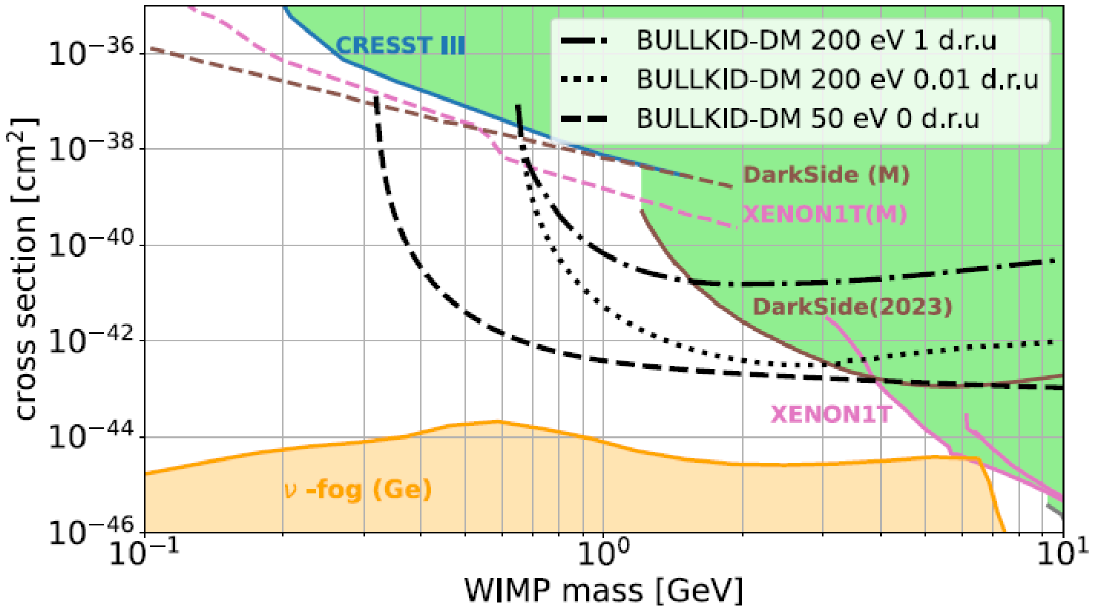
June 28, 2024

Dark Matter - direct search with BULLKID-DM

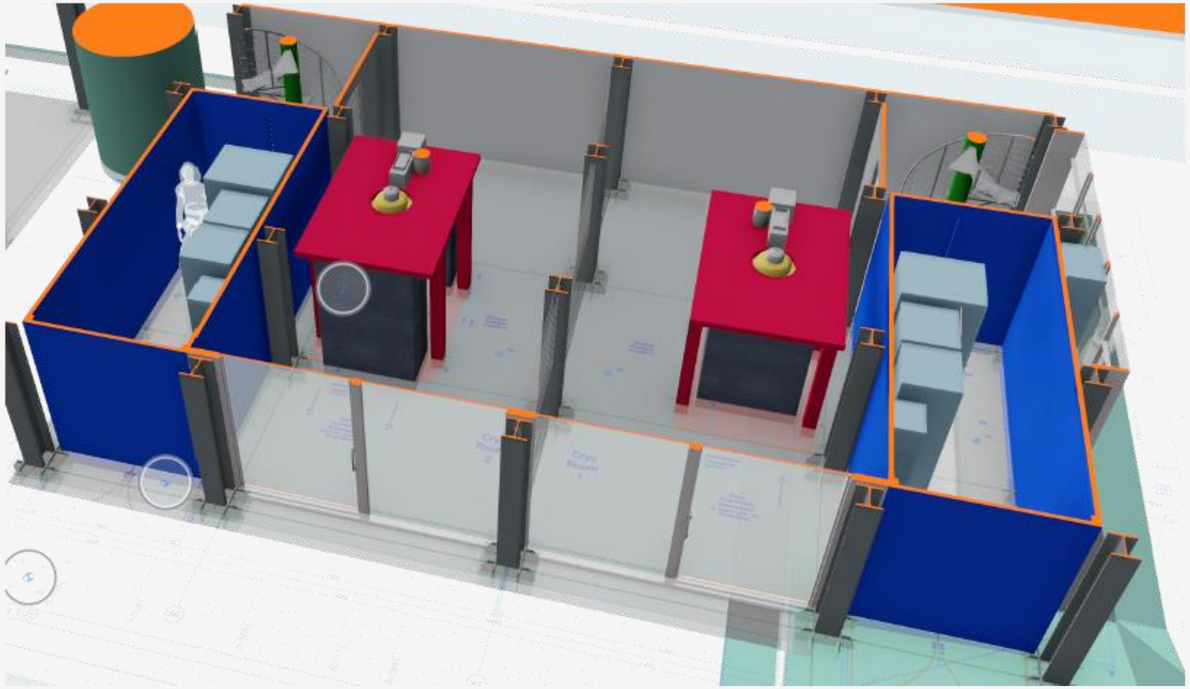
	BULLKID prototype	BULLKID-DM demonstrator		BULLKID-DM
mass	20 g	60 g		800 g
# of sensors	60	180		2300
threshold	160 eV	200 eV		≤ 200 eV
bkg (c/keV kg d)	2×10^6	$< 10^5$		1 - 0.01
laboratory	Sapienza U.	Sapienza	LNGS	LNGS
installation	2023	2024	2026	2027



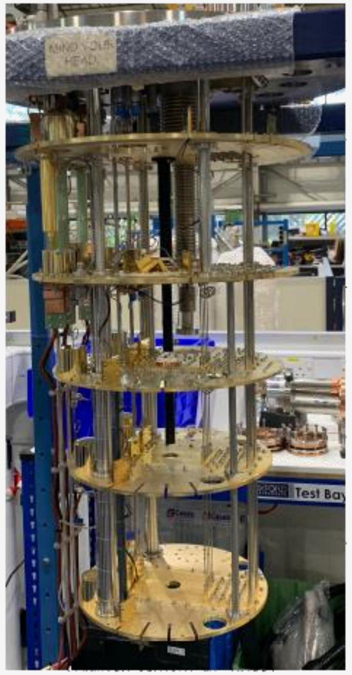
Exposure:
1Yr x 600g of fiducial mass

LNGS Cryogenic facility

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



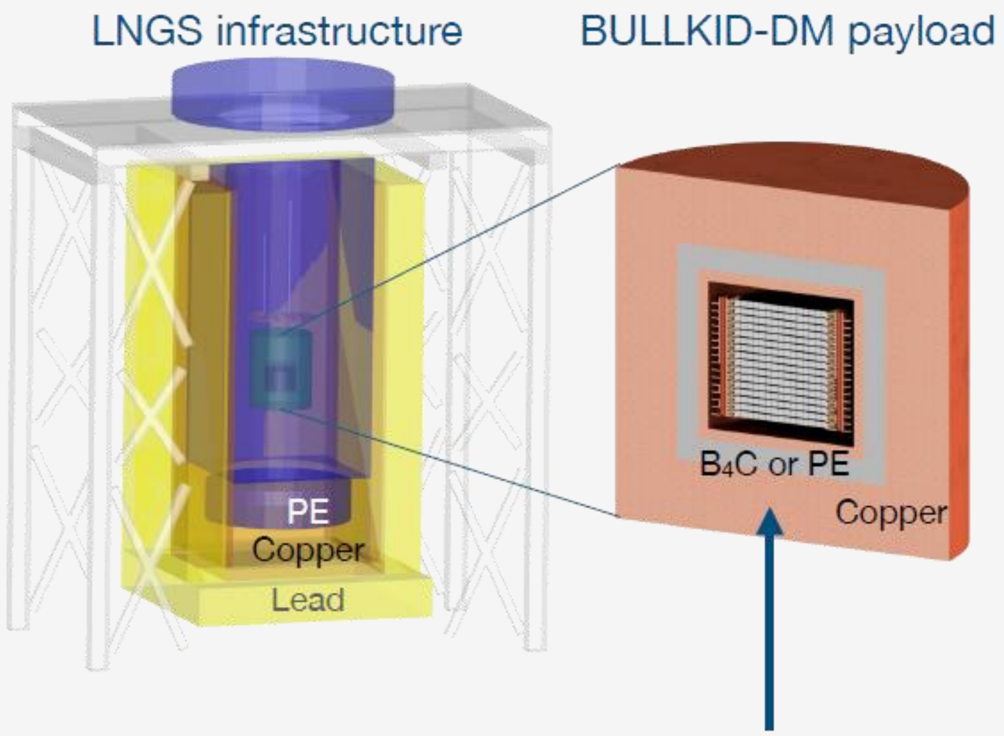
Ordered Oxford Proteox fits the needs



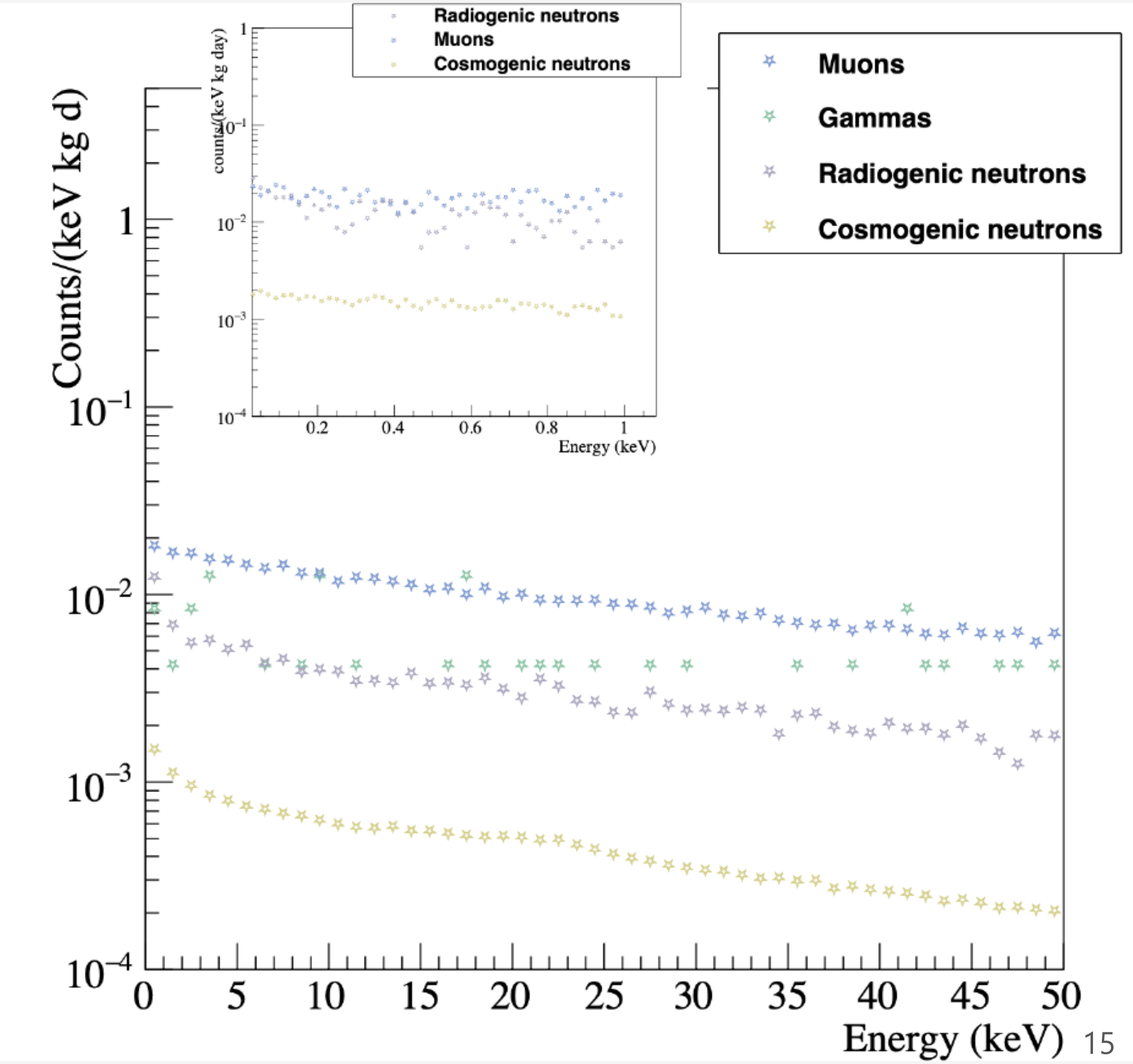
Replaceable insert to be instrumented with RF lines

Simulations: shields and veto

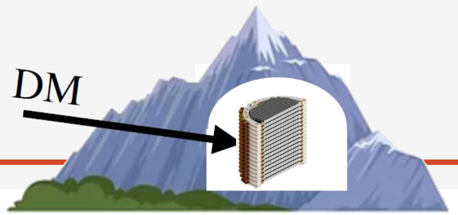
muons, gammas and neutrons from:
Astropart. Phys. 33 (2010) 169,
Phys. Rev. D 73 (2006) 053004,
Eur. Phys. J. A 41 (2009) 155,
Astropart. Phys. 22 (2004) 313.



Replacing this with an active veto of BGO or GSO:
Background ~ 10^{-3} counts/(keV kg y)



Wrap up

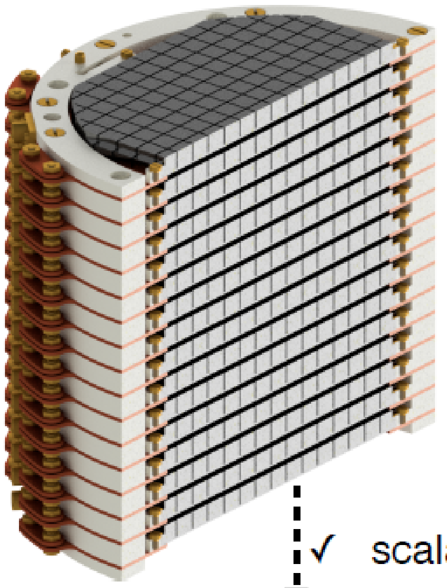


- ✓ 800 g of silicon target
- ✓ 2300 detector units (dice)

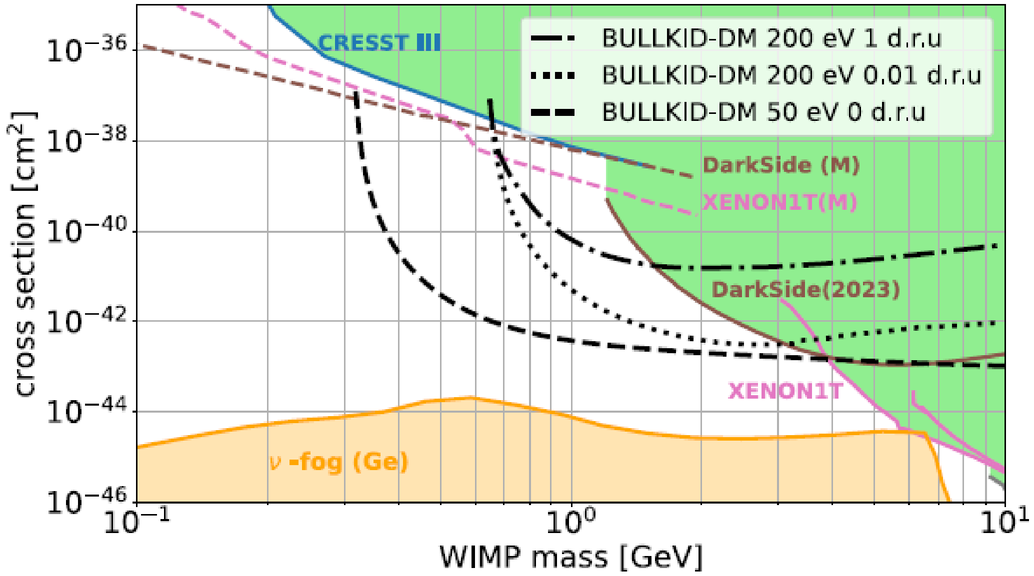
Unique features for bkg. suppression:

- ✓ No inert material in detector volume
- ✓ fully active
- ✓ fiducialization (600 g)

Will it help with the unknown backgrounds?



✓ scalable



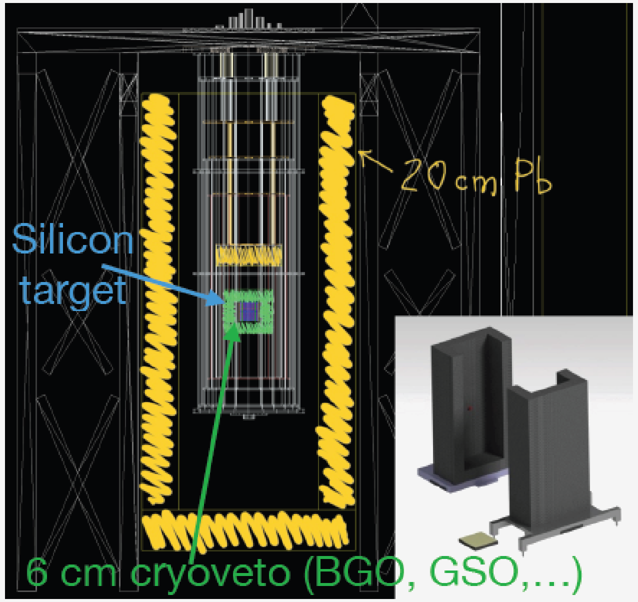
2023	2024	2025	2026		2027
Prototype works	demonstrator (3 wafer)		demonstrator at LNGS	full detector at Sapienza	installation at LNGS
LoI to INFN and LNGS	CDR submitted to INFN		TDR		

BACKUP SLIDES

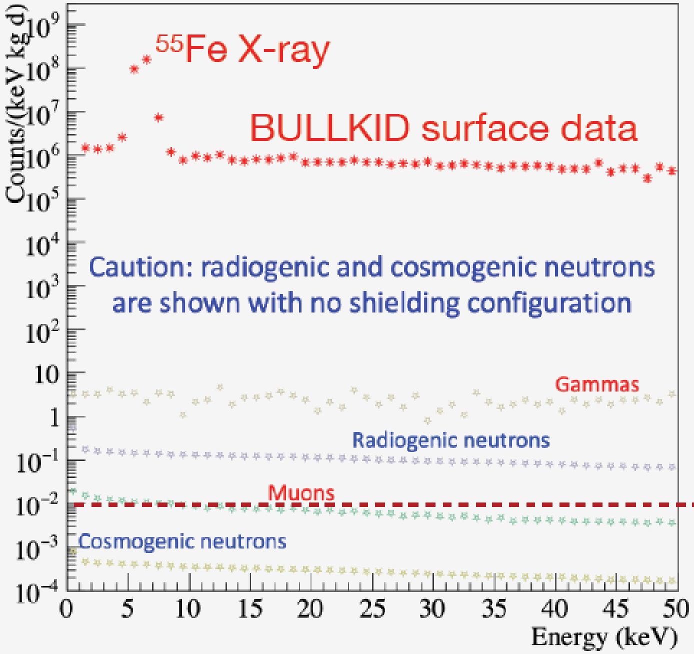
Simulations: shields and veto

✓ preliminary

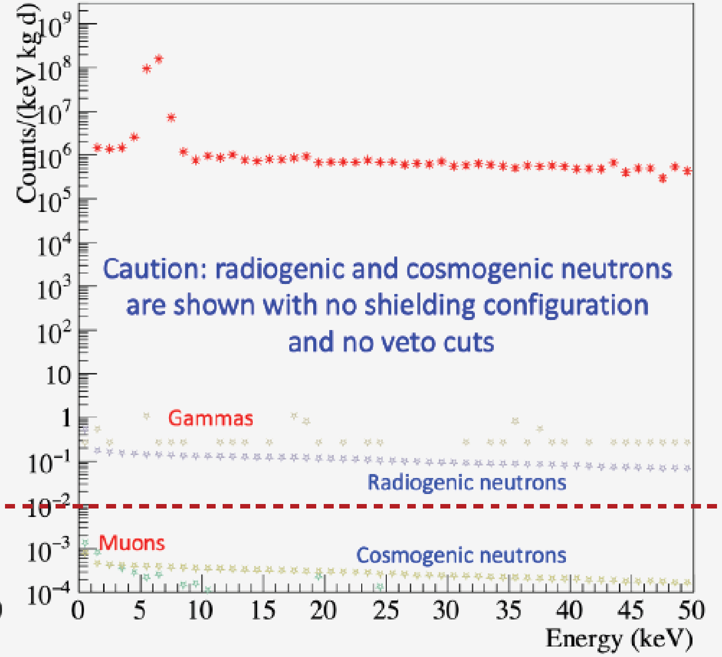
No polyethylene, copper and top lead yet



"passive" veto



"active" veto E_{th} = 50 keV



"zero" bkg.

Currently working on internal contaminations in lead and veto

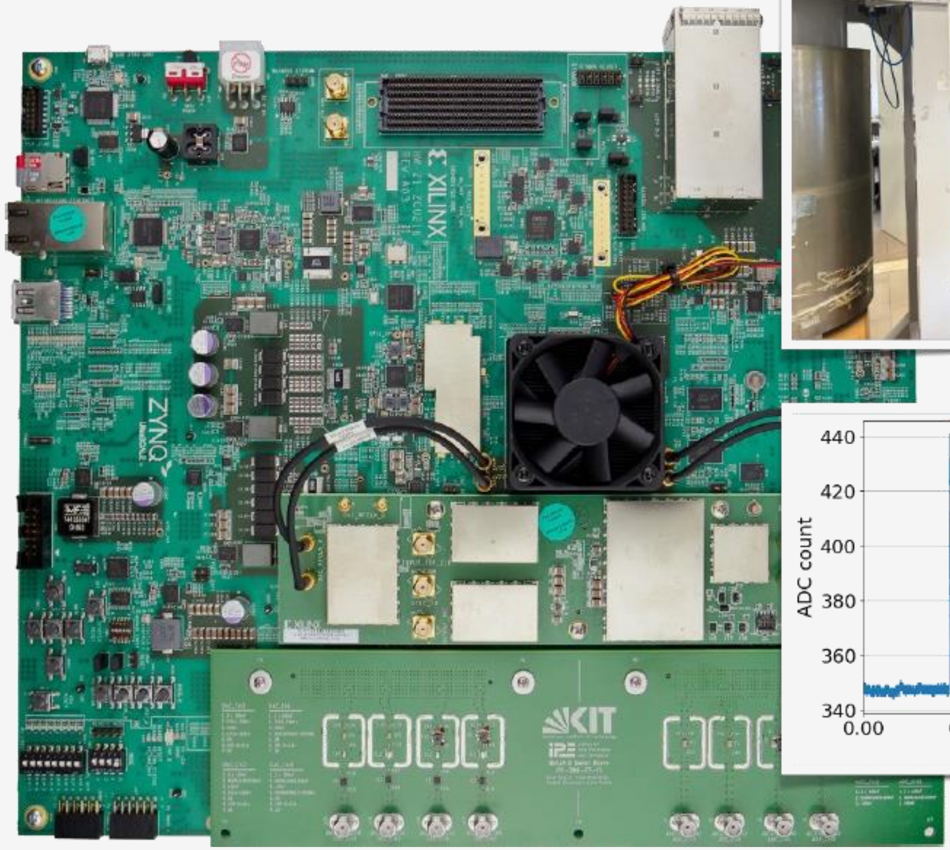
muons, gammas and neutrons from:
Astropart. Phys. 33 (2010) 169,
Phys. Rev. D 73 (2006) 053004,
Eur. Phys. J. A 41 (2009) 155,
Astropart. Phys. 22 (2004) 313.

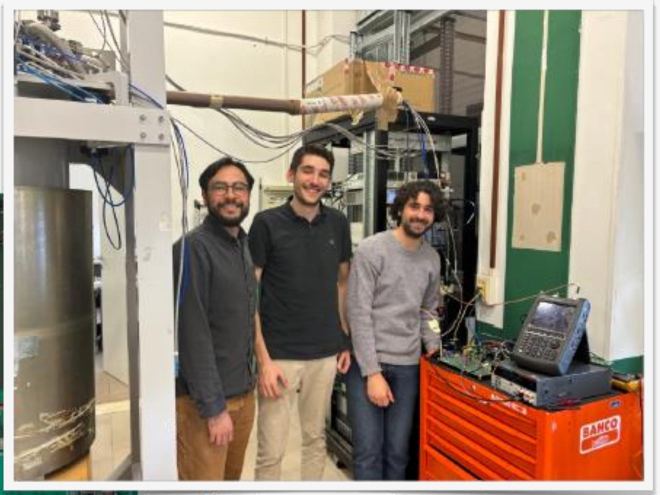
RF Electronics

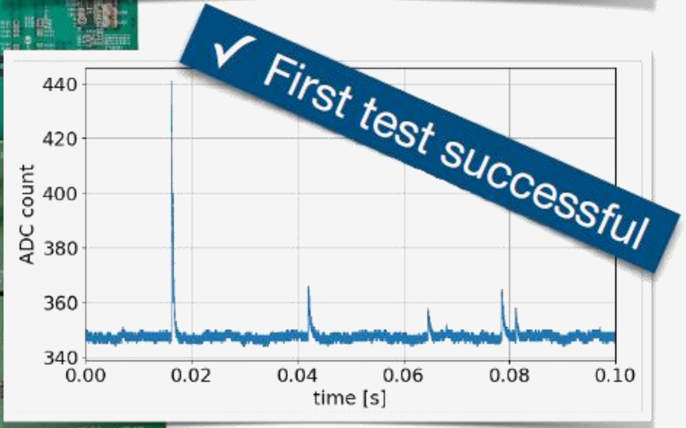
Current electronics (Ettus x310):
30 KIDs / board

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**





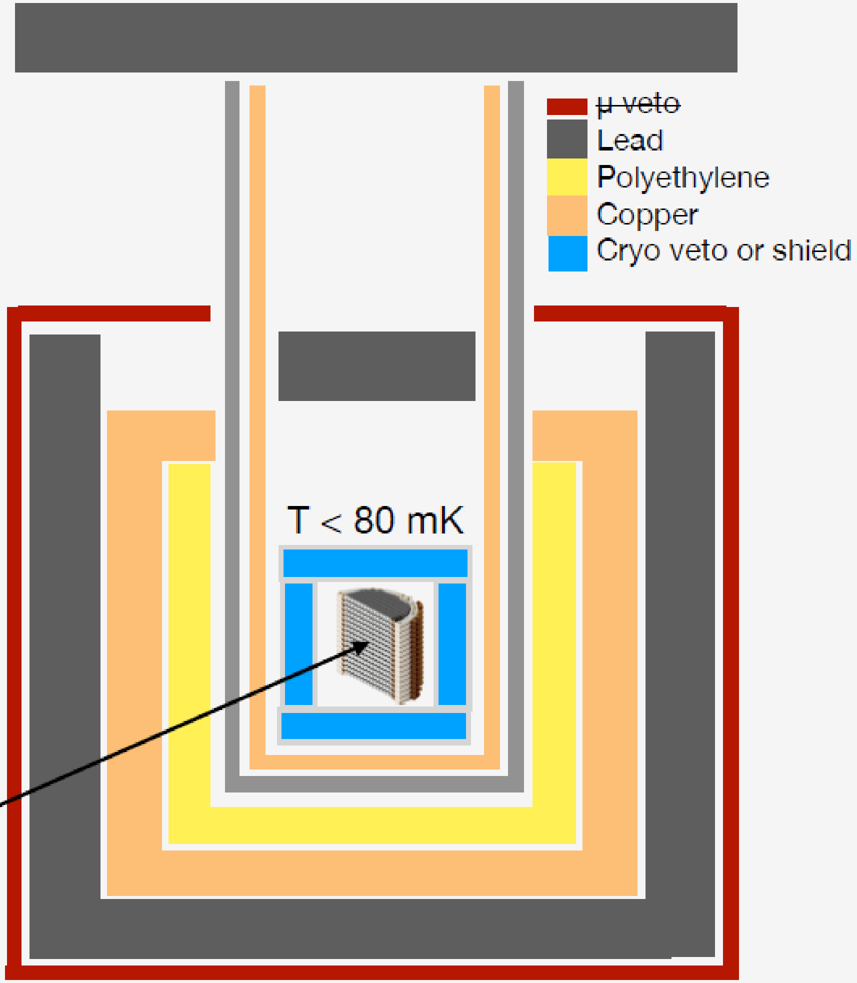


Towards the experiment

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?

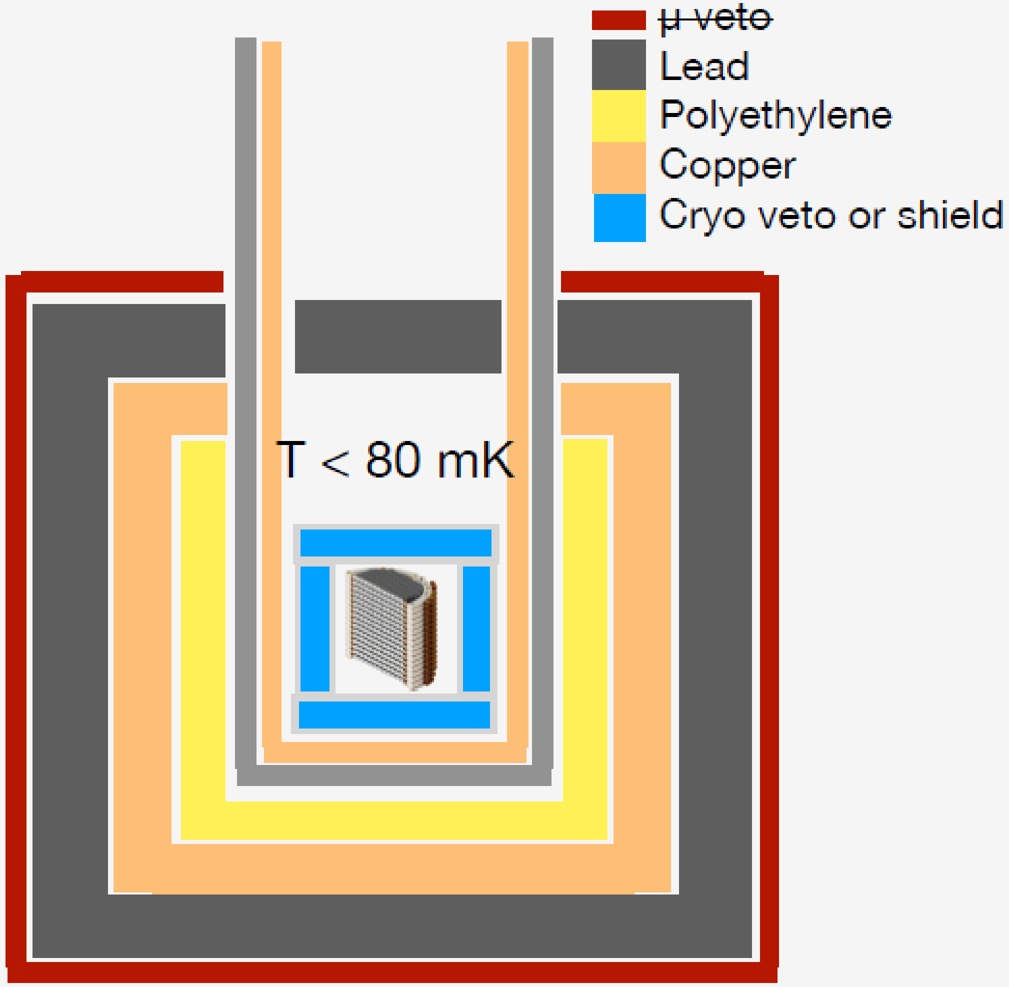
Energy calibration options?
- IR light
- neutron recoils (a là CRAB)
- ^{137}Cs or ^{60}Co Compton
- asynchronous

RF Readout and DAQ
SDR boards
onboard trigger

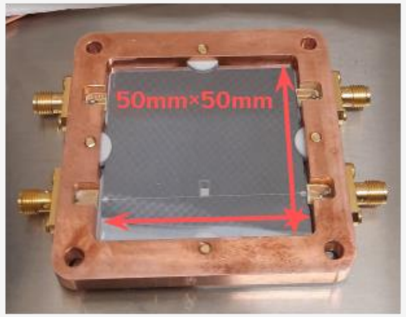
Computing
Data transfer
Data storage

Data analysis
2000+ channels,
cluster analysis

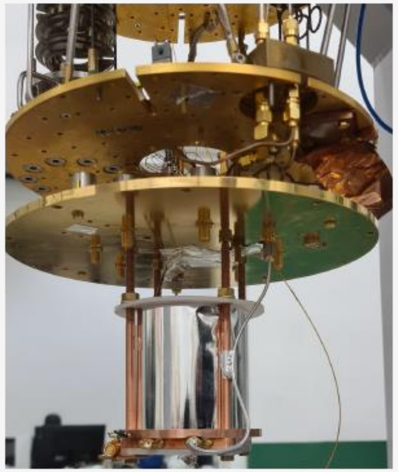
Cryogenic veto: BGO prototype



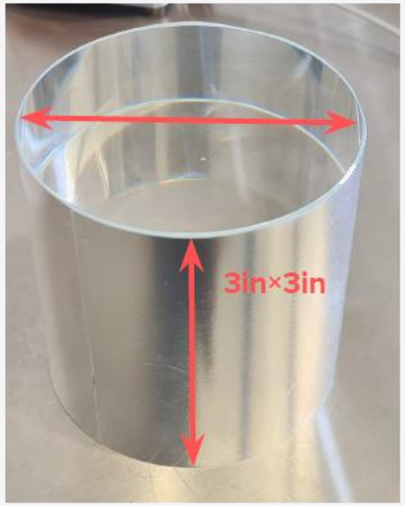
CALDER KID Light detector

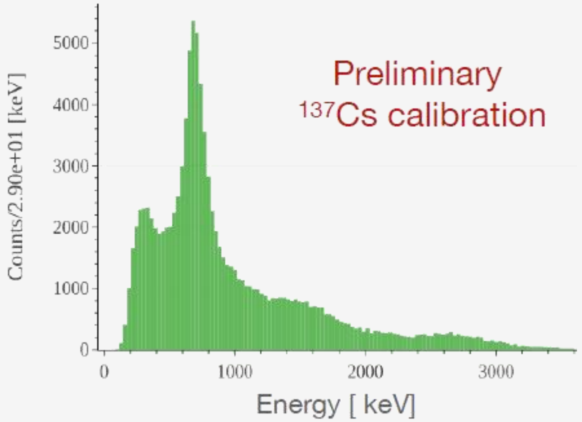


Assembly with reflector



BGO Crystal

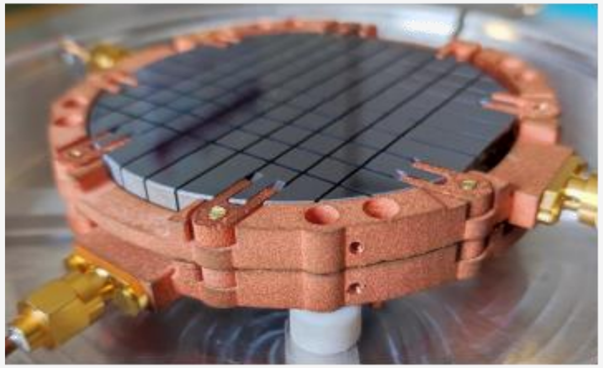


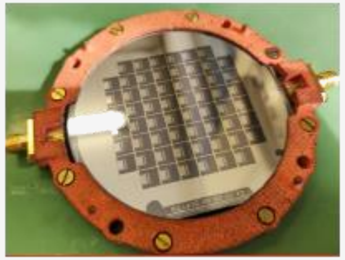


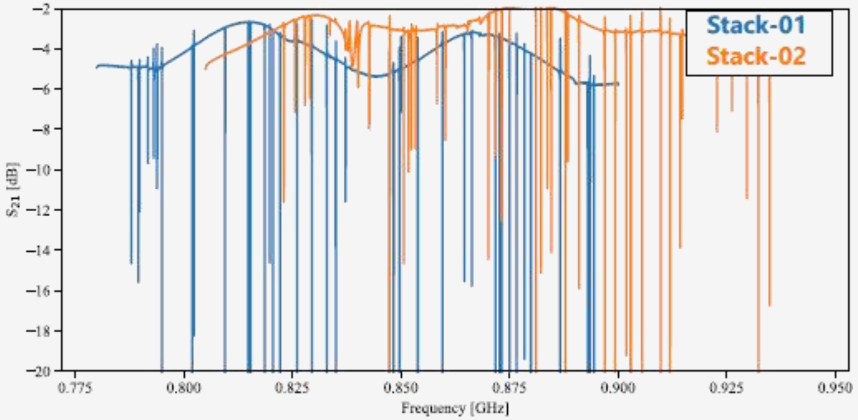
Goal: energy threshold < 50 keV

Status of the 3-wafer stack

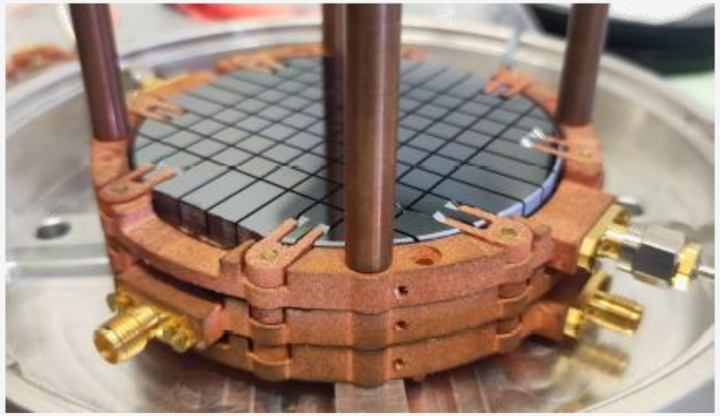
2-wafer stack operated. No issues observed

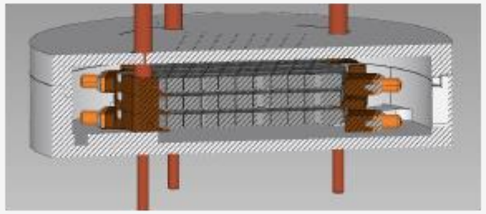






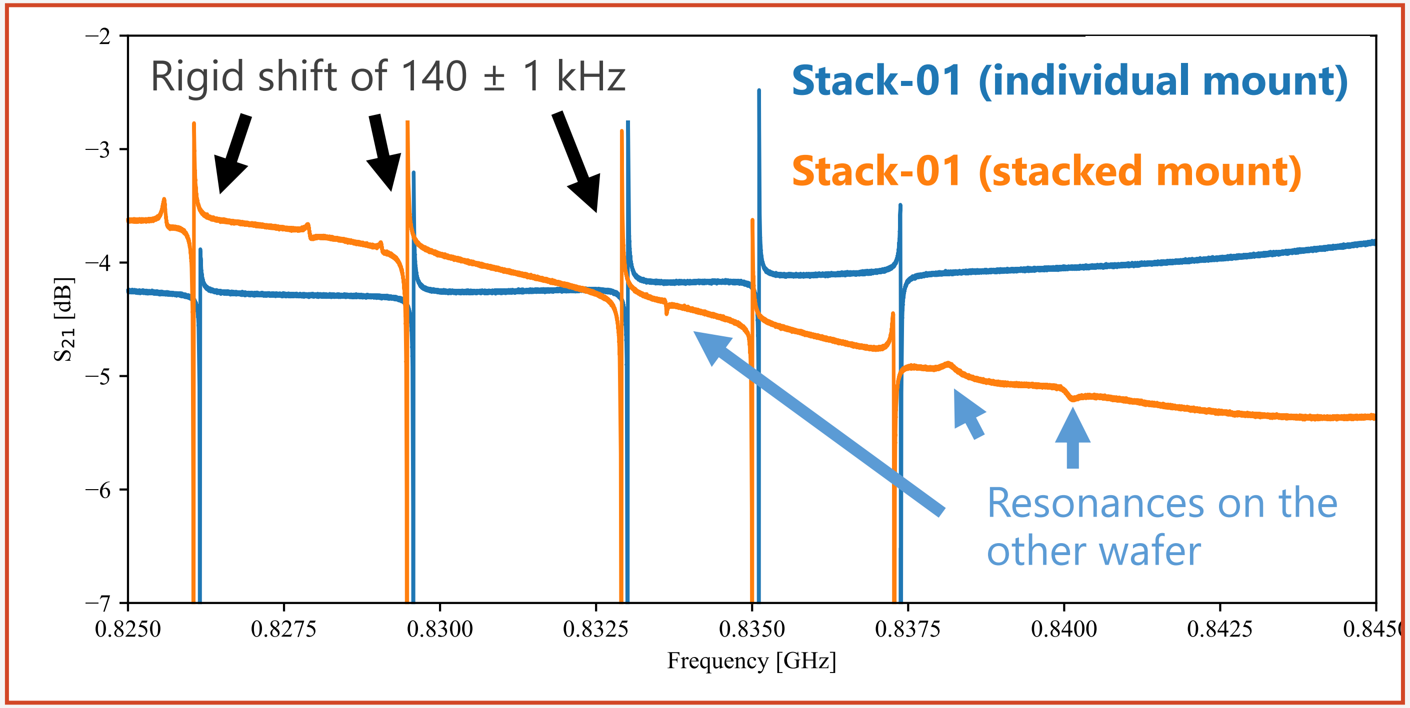
3-wafer stack assembled

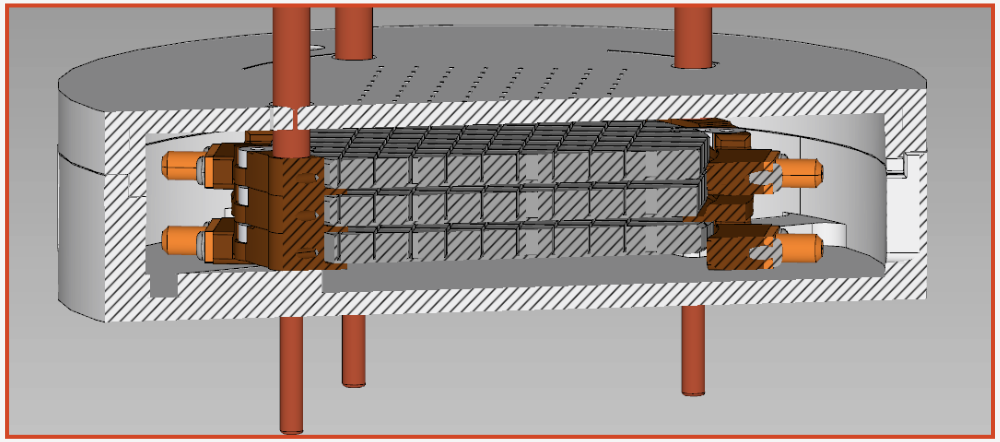


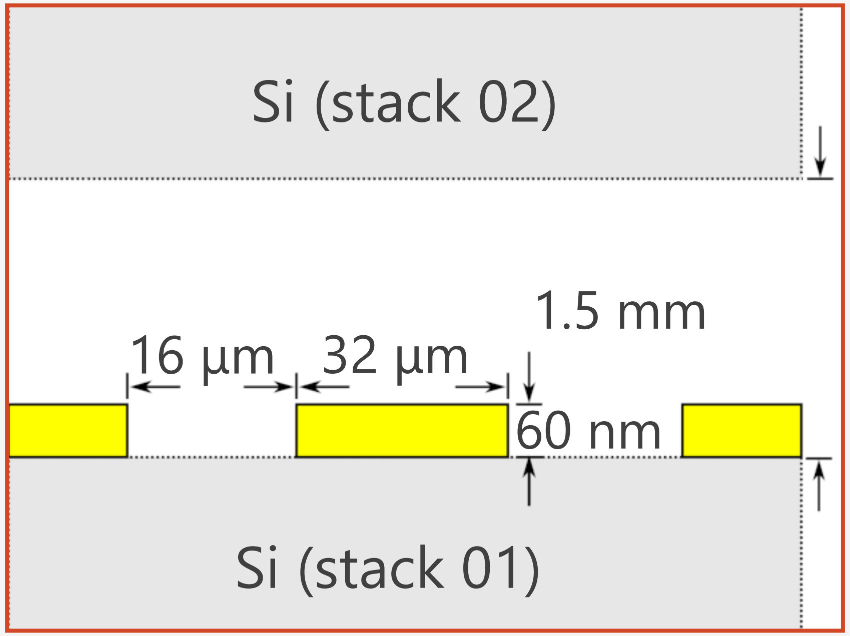


Status of the 3-wafer stack

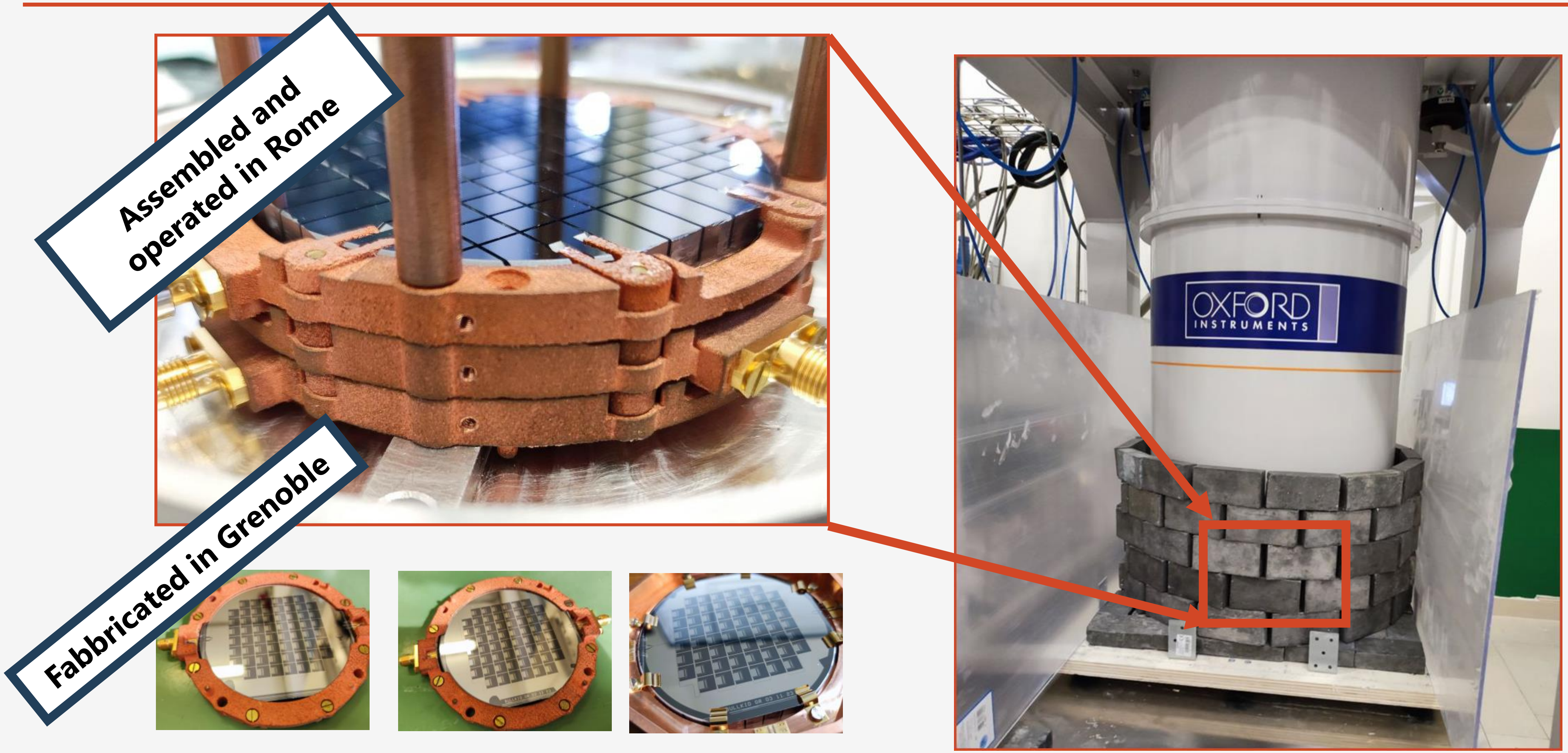
- Holding structure: **thermalization** and mounting
- Reproducibility of the **electrical coupling**
- Reproduce the results of the unstacked wafers





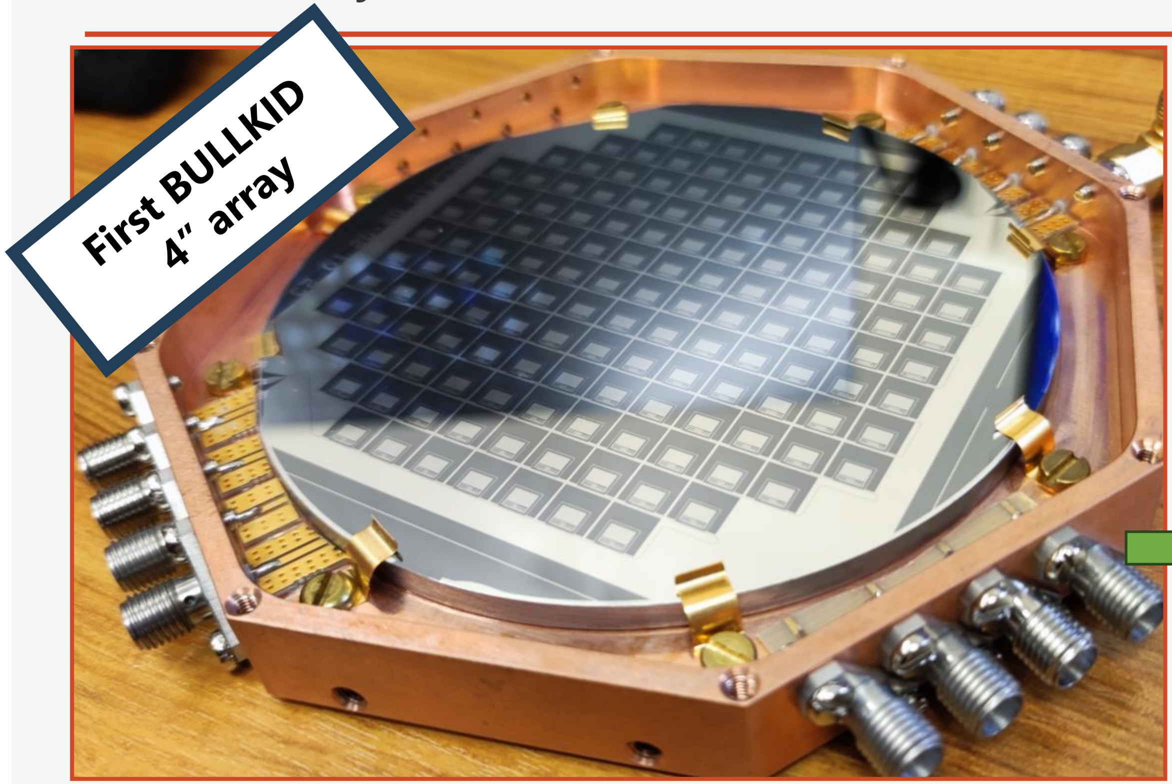


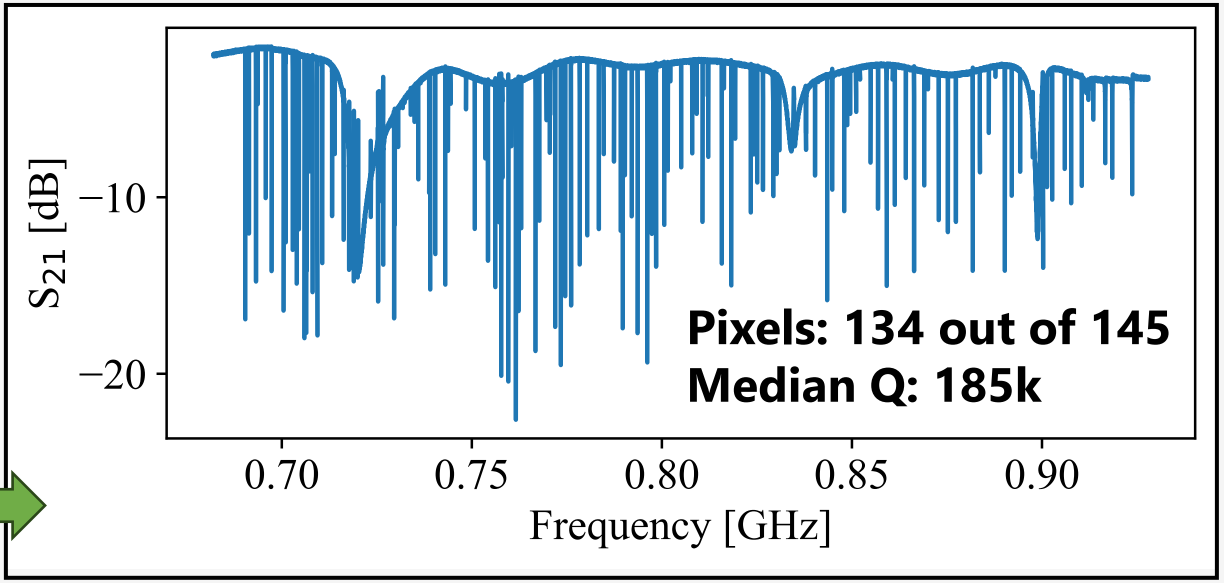
Status of the 3-wafer stack



Stacked configuration with the **250 Kg lead castle shielding**

Scalability for the 100mm mask: thick wafer

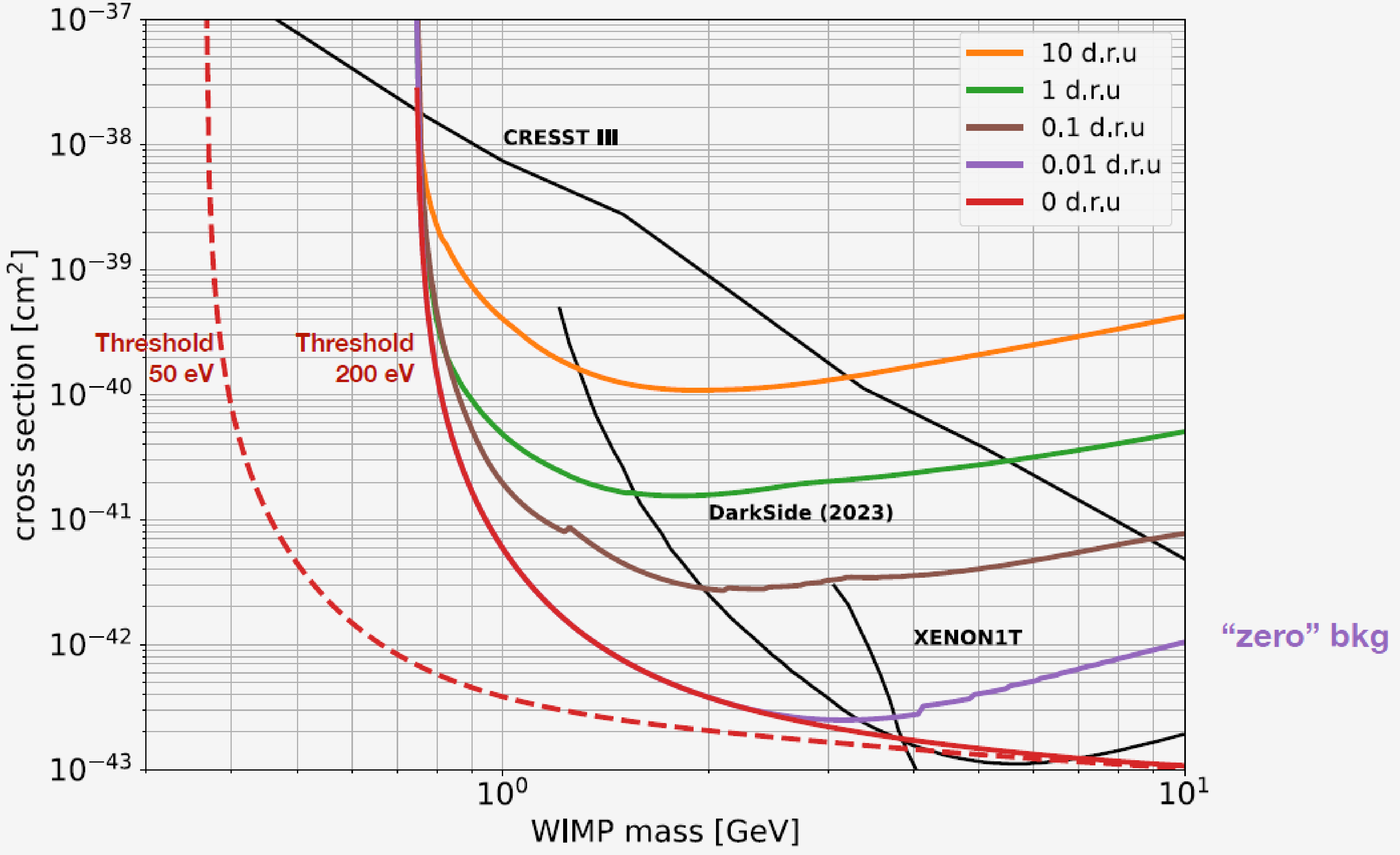




From 3″ to 4″:

- **145 pixels**
- **49.3g of active silicon per wafer**
- *Diced prototype will be tested soon*

Sensitivity plots



Motivation: Coherent elastic neutrino nucleus scattering (CEνNS)

$$\sigma_{CE\upsilon NS} = \frac{G_F}{4\pi} E_\nu^2 Q_W^2 F(q^2)$$

$$\sigma_{CE\upsilon NS} \leq 10^{-40}\text{cm}^2$$

Neutrino Energy

$$E_\nu \approx O(\text{few MeVs})$$

Weak Force Charge

$$Q_W = N - P(1 - 4\sin^2\theta_W) \approx N$$

Nuclear Form Factor

$$F(q) = \frac{1}{Q_W}\int_0^{R_N} \rho_W(r)\frac{\sin(qr)}{qr}dr$$

$$\rho_W(r) = \rho_N(r) - (1 - 4\sin^2(\theta_W))\rho_P(r)$$

Fourier transform of the nucleon distribution

Coherency

Neutrino does not see the internal structure of the nucleus

$$\text{Coherent:} F(q^2) \approx 1$$

↓

$$q \cdot R_N \ll 1$$

↓

$$E_\nu^{max} \approx 20\text{MeV [He]} \div 70\text{MeV [U]}$$

Same detection principle as WIMPs!

Observed in 2017 by COHERENT

- Precision **tests of the standard model** (es $\sin^2\theta_W$)
- **Nuclear waste monitoring**

But needs a precision < a few %

Currently 15% precision on $\sigma_{CE\nu NS}$