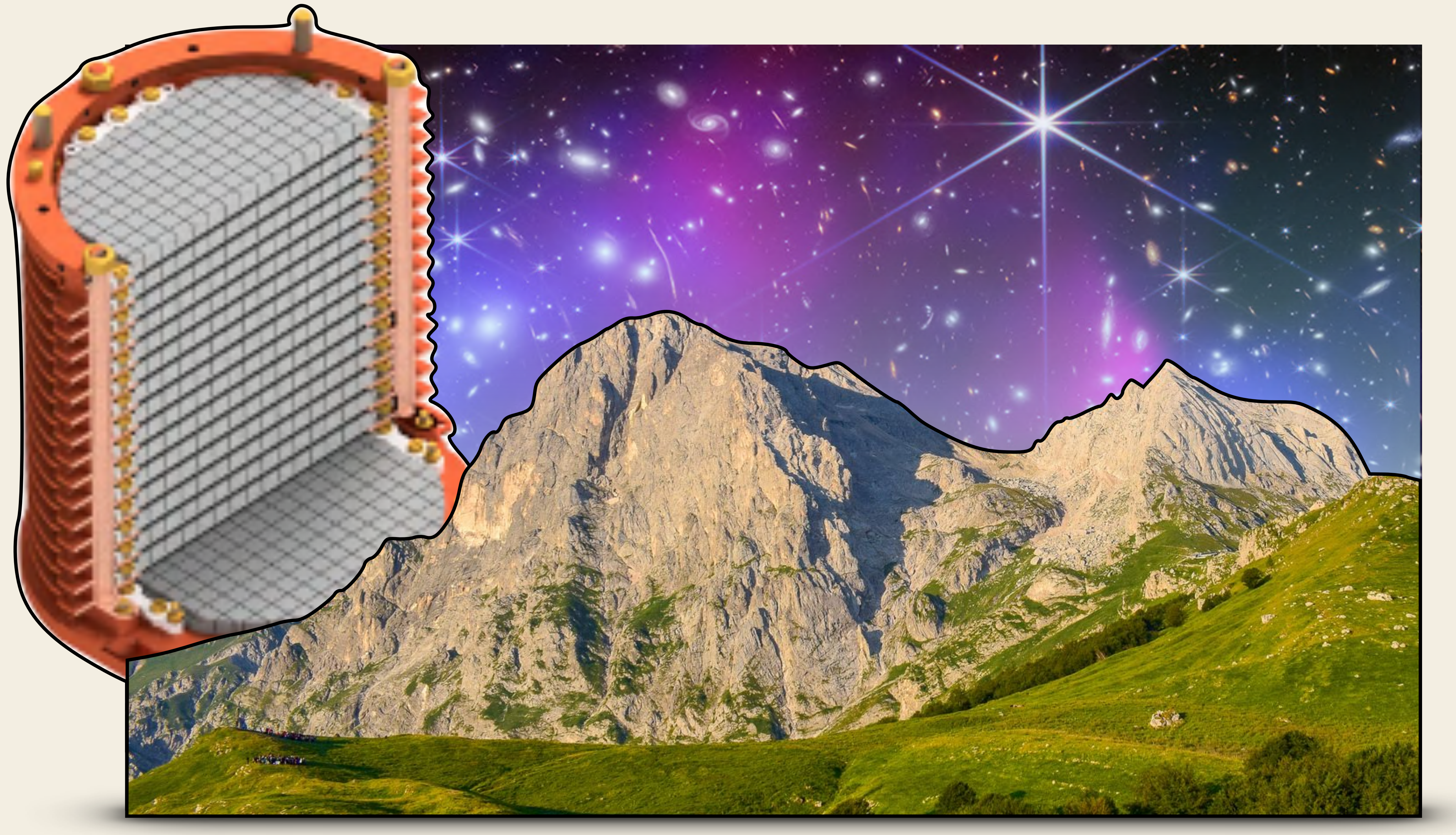
Axion2026, Qingdao, China, 09-13 August, 2026

Search for light WIMPs with BULLKID-DM experiment using monolithic arrays of detectors

Kangkang Zhao （赵康康）

On behalf of BULLKID-DM Collaboration

12nd August, 2026



The 5th International Conference on Axion Physics and Experiment，Qingdao, China

BULLKID-DM Collaboration

BULky and **L**ow-threshold **K**inetic **I**nductance **D**etectors (**BULLKID**)

Istituto Nazionale di Fisica Nucleare

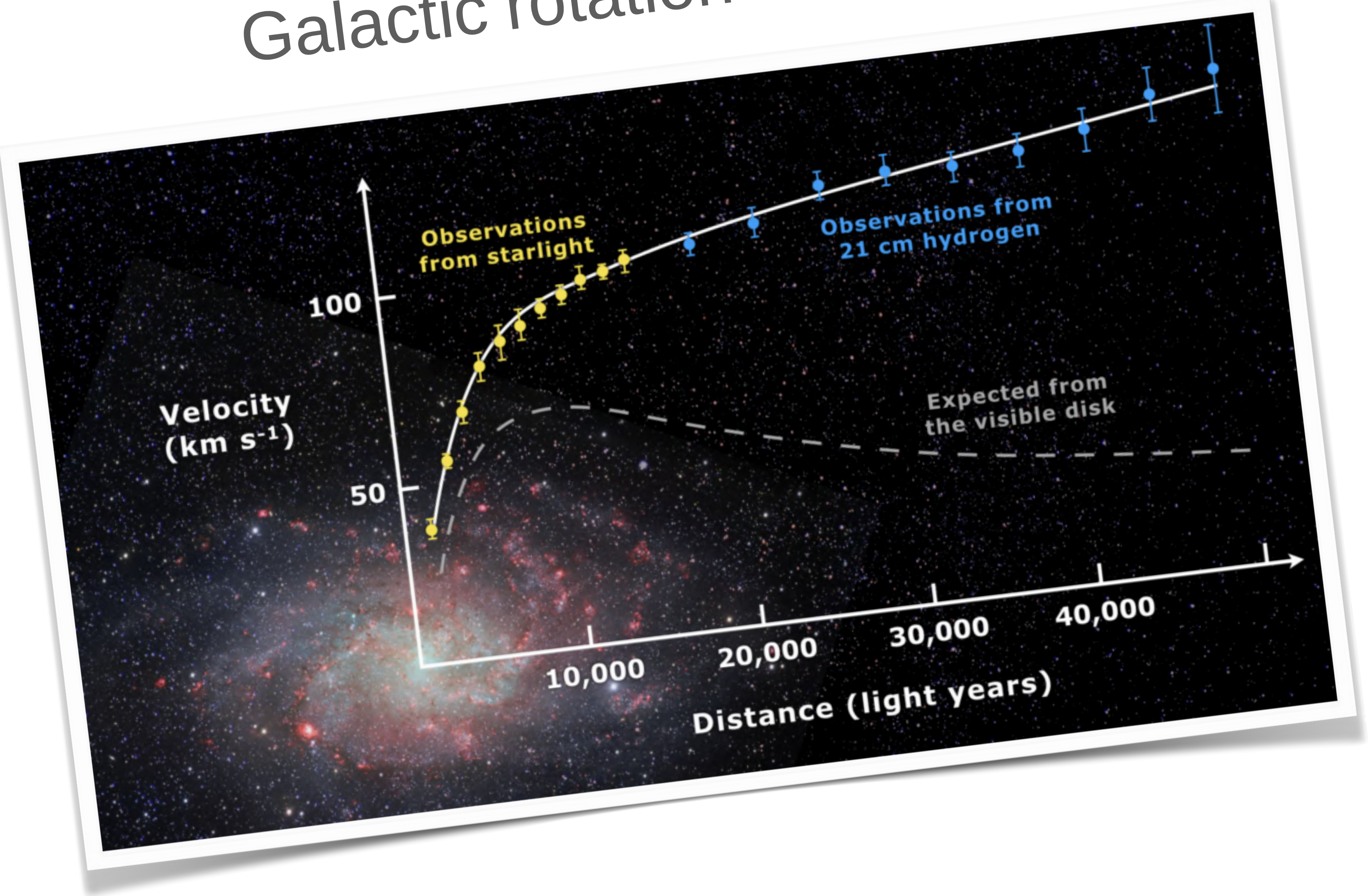
ROMA
FERRARA
PISA
LNGS
TRENTO

Karlsruher Institut für Technologie

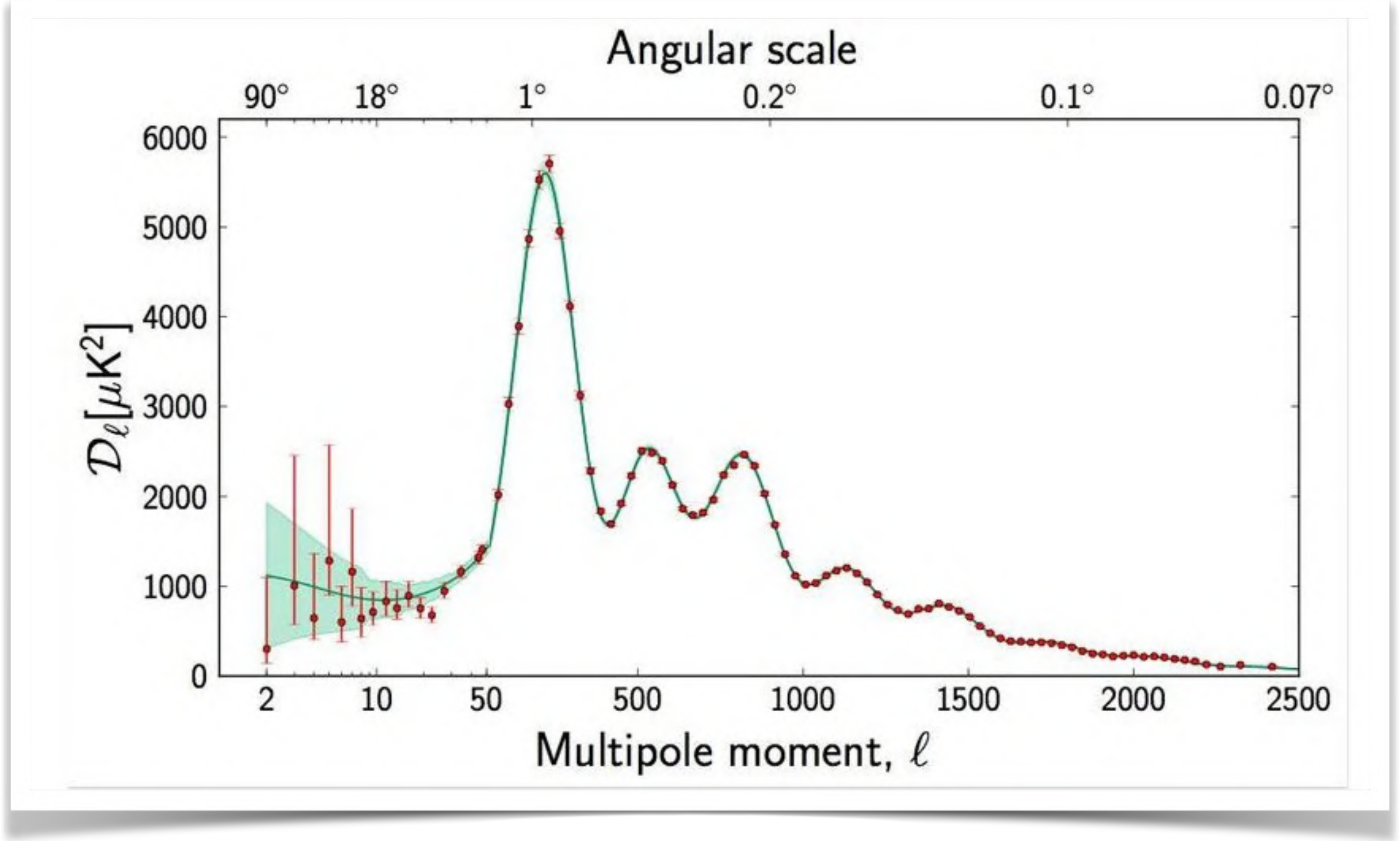
Formed in 2024 and accounts for > 40 members over 10 institutions and 4 countries

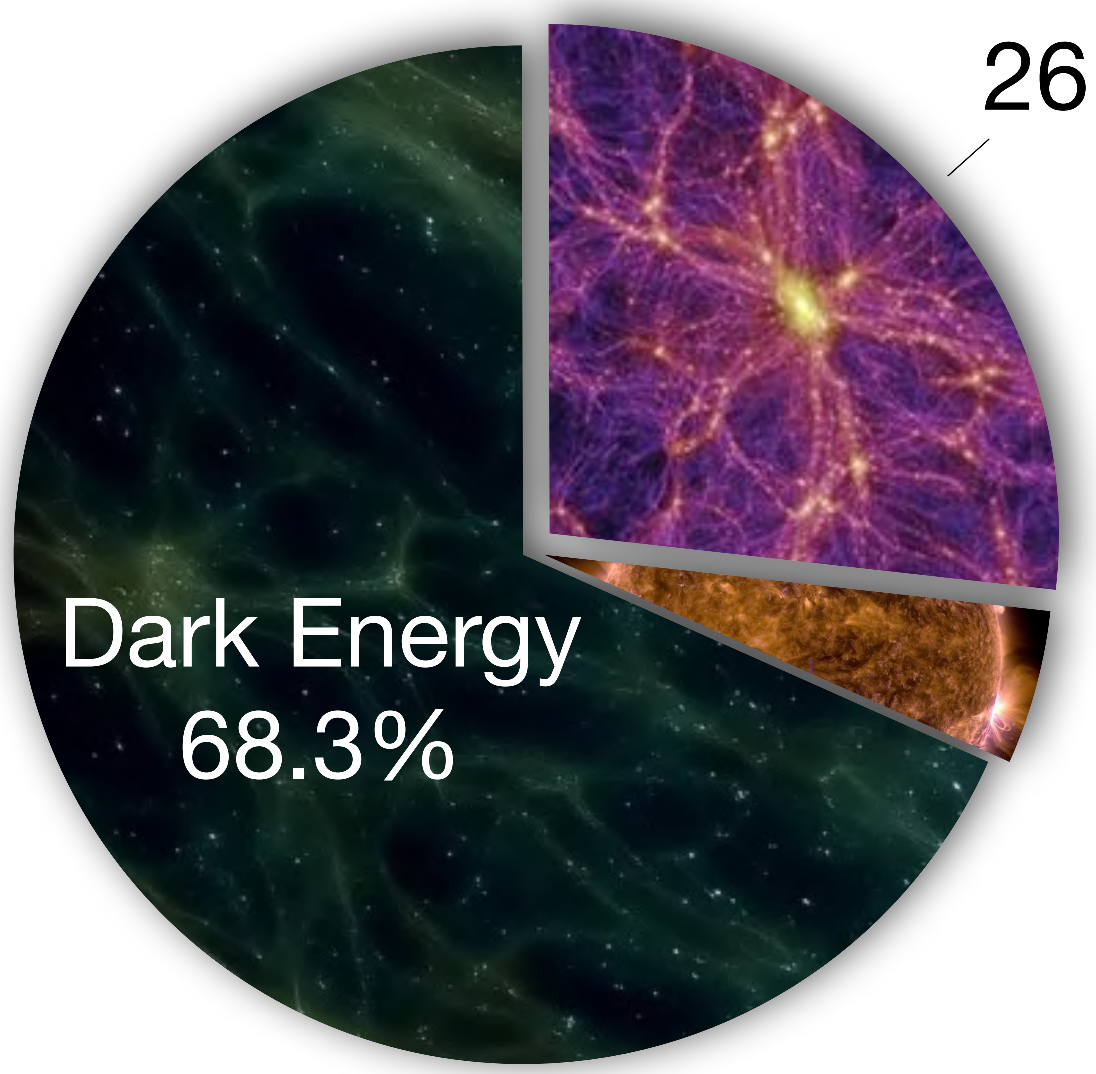
Dark Matter paradigm

Galactic rotation curves



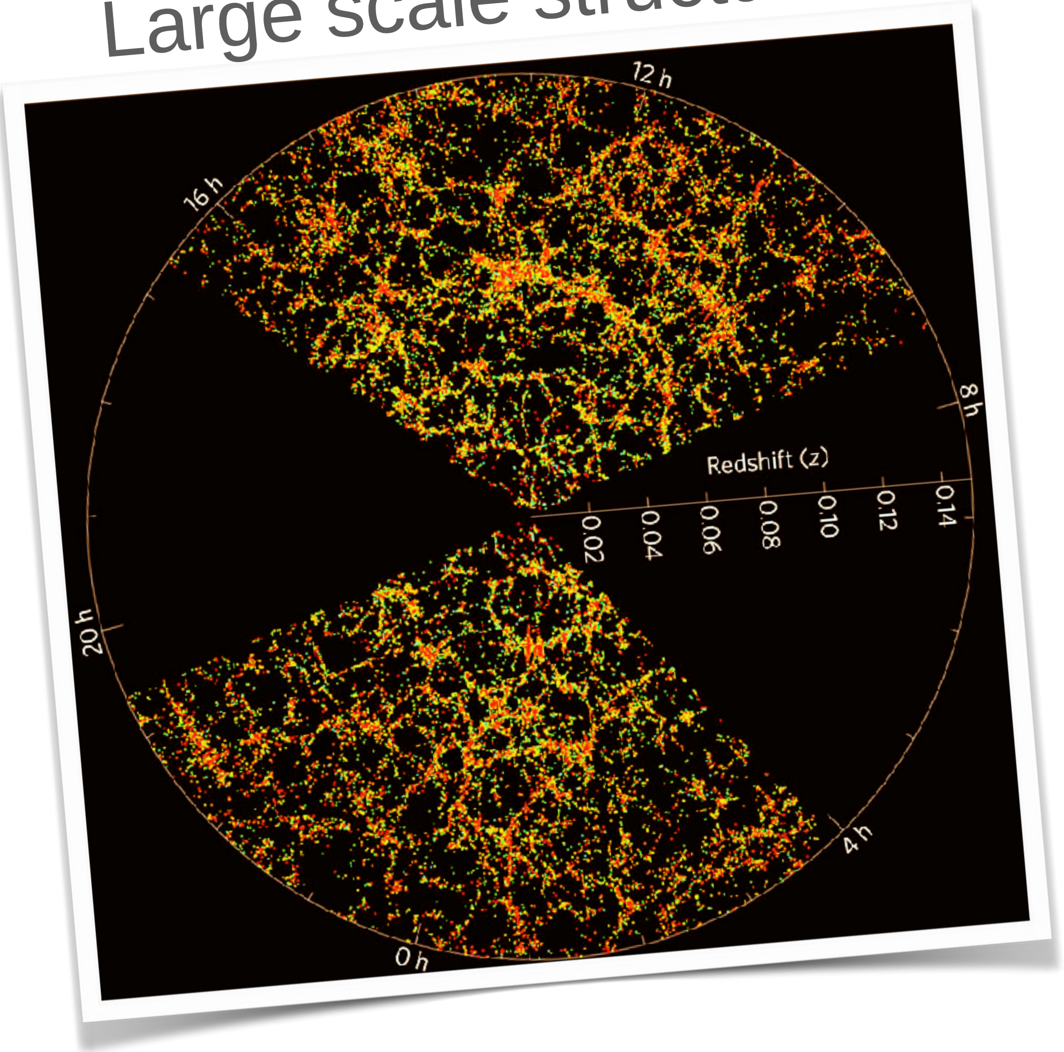
Cosmic Microwave Background (CMB)





Gravitational lensing and "Bullet" cluster

Large scale structure



Properties of DM

- Interacts via gravity (and a weak force?)
- Stable, relics from the big bang
- Neutral and weakly interacting
- Non-relativistic (cold)

DM candidates

- WIMPs (Weakly Interacting Massive Particles)
  - weak-scale cross-sections can yield the observed DM density via thermal freeze-out
- Axion, sterile neutrinos, others…

WIMP miracle!

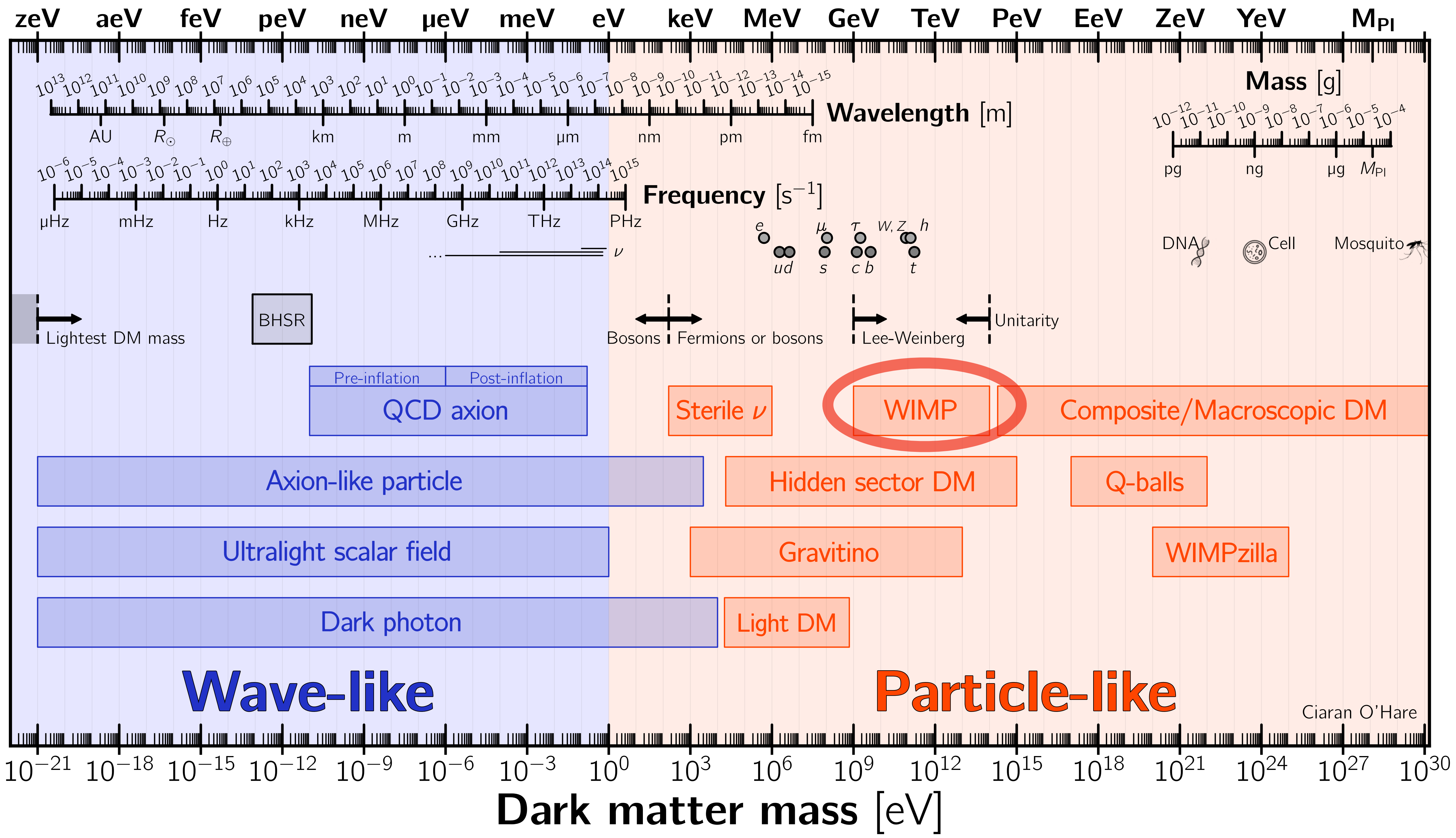
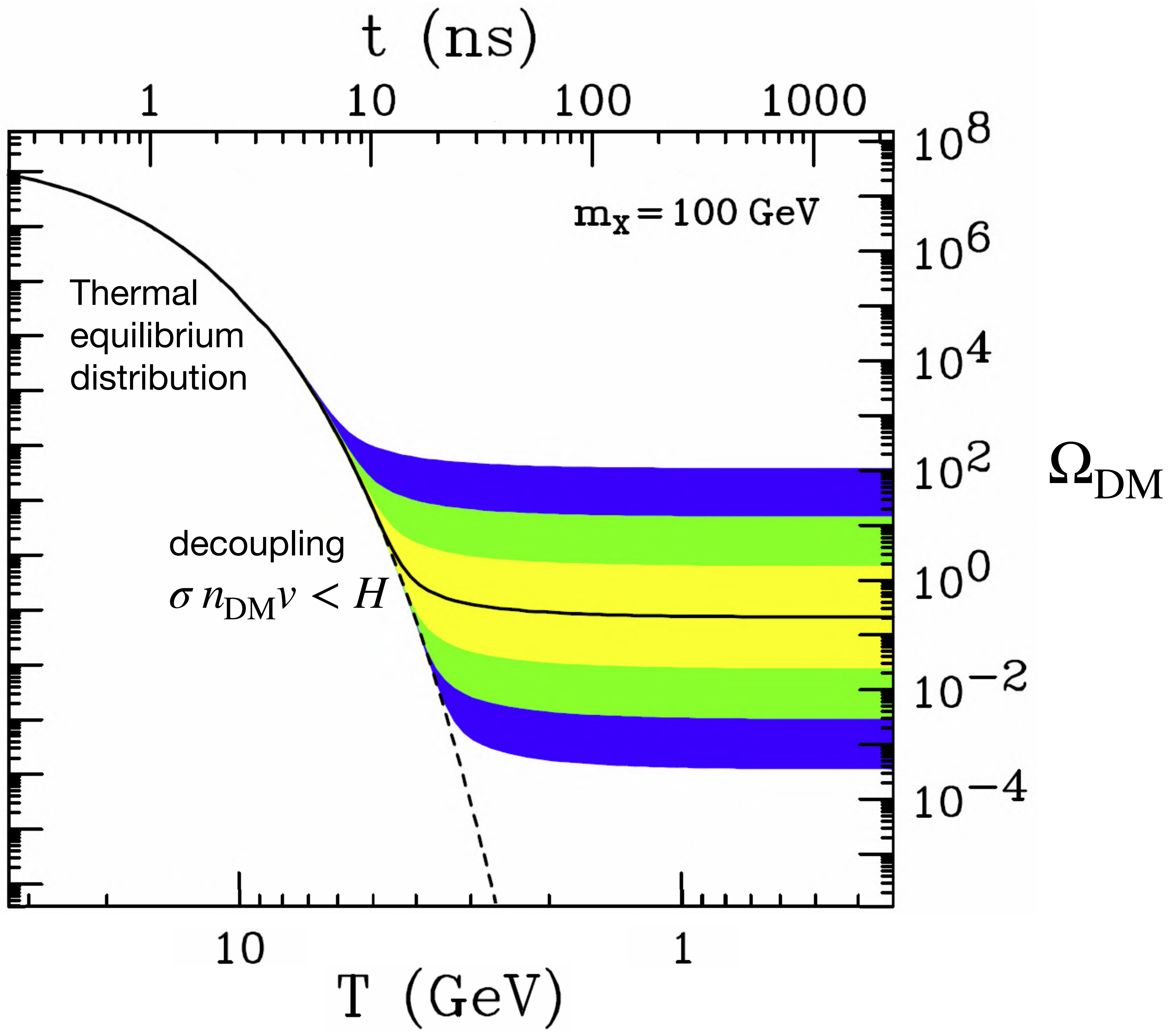


Figure from: *Wikipedia*, https://en.wikipedia.org/wiki/Dark_matter

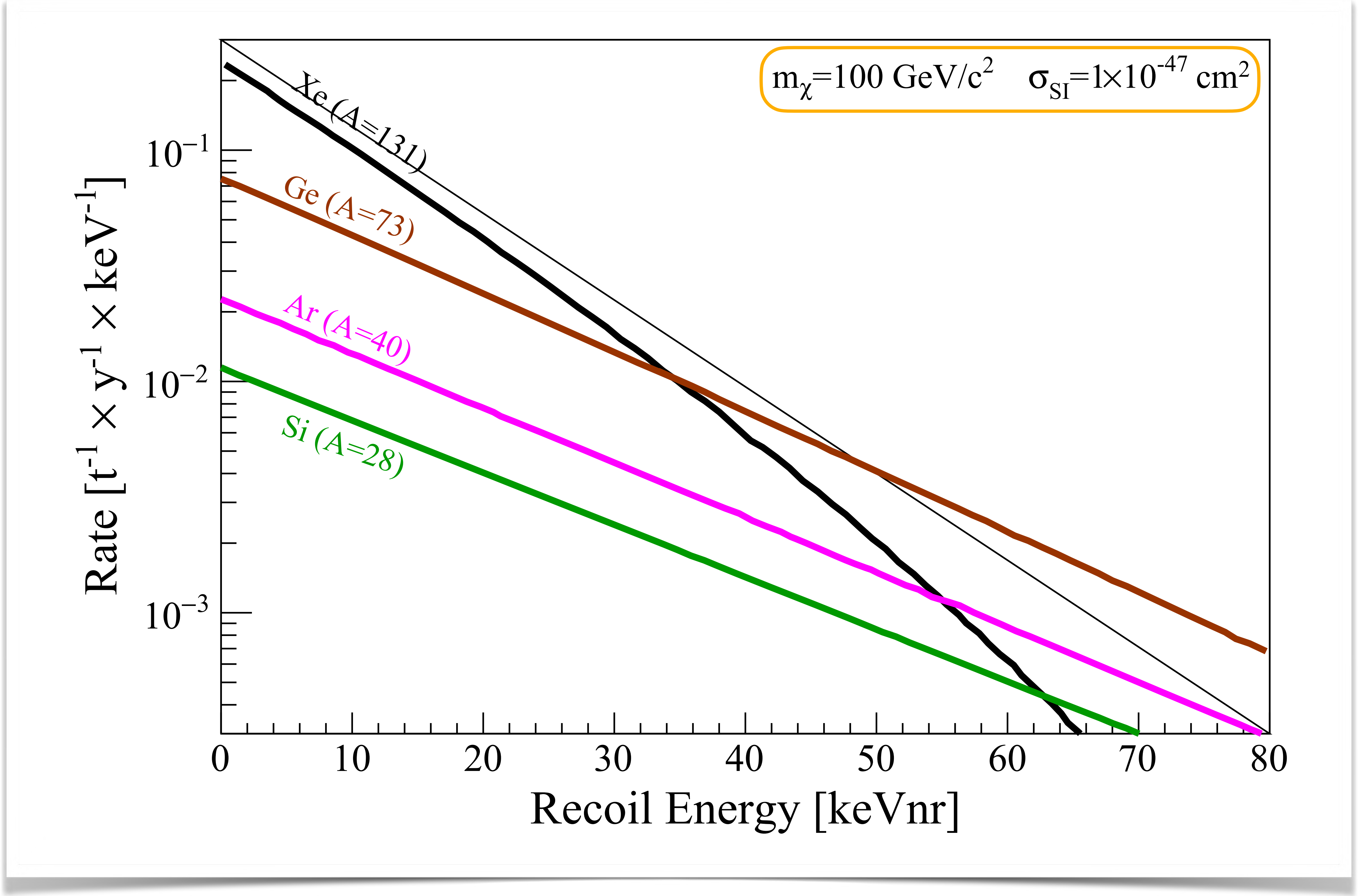


$$\Omega_{DM,0} \simeq 0.26 \times \left(\frac{10^{-36}\mathrm{cm}^2 \cdot 0.1 \cdot c}{\sigma \cdot v_{DM}}\right)$$

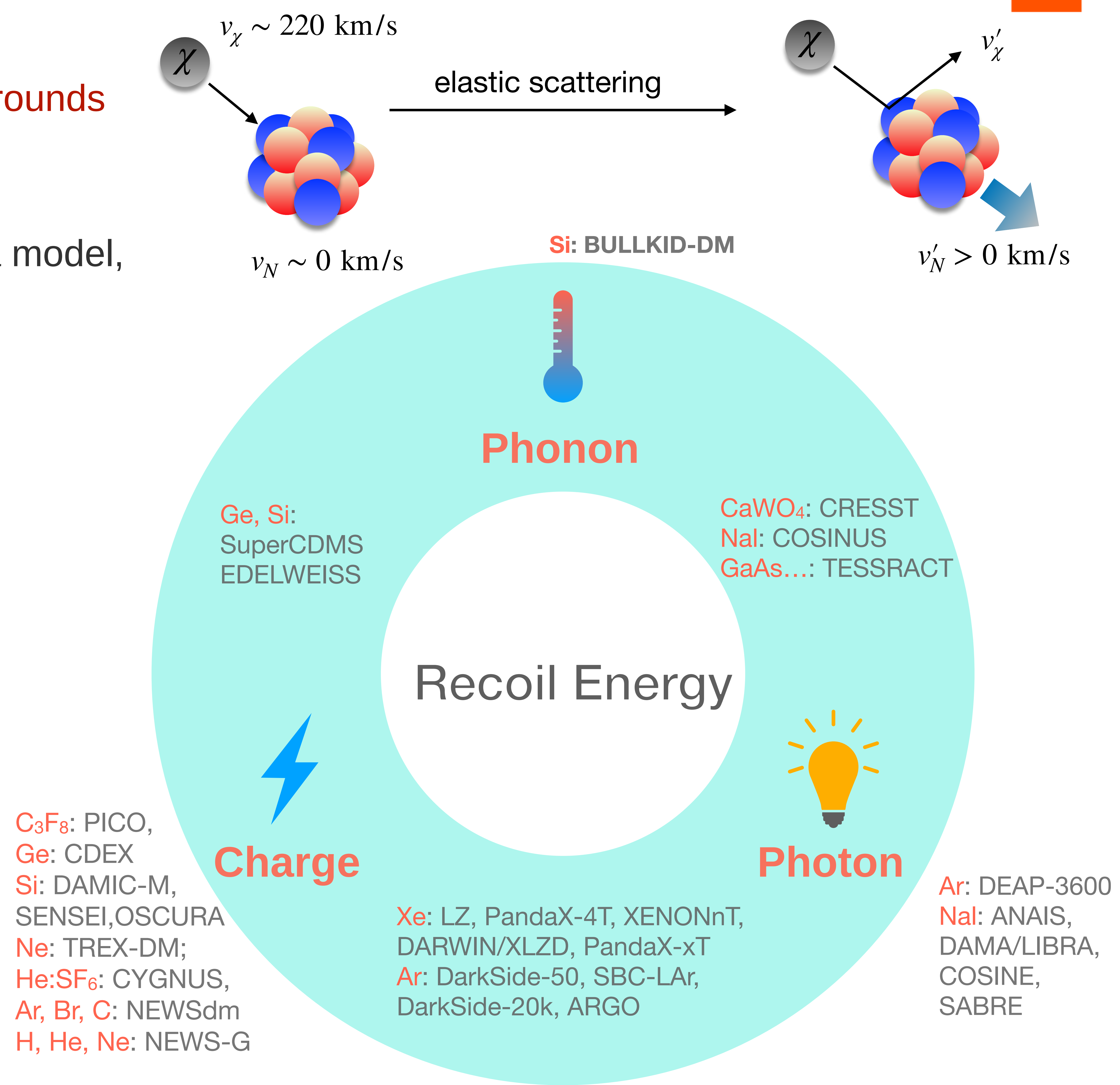
Direct detection of WIMP-like DM

- Expected Signal: exponential-like, increasing at low E
  - Demands keV or lower thresholds, large target mass and backgrounds close to zero
  - A single experiment can place a limit
  - Discovery requires confirmation by multiple experiments under a model, or ancillary confirmation (e.g. annual modulation)

Energy spectrum of recoiling nucleus



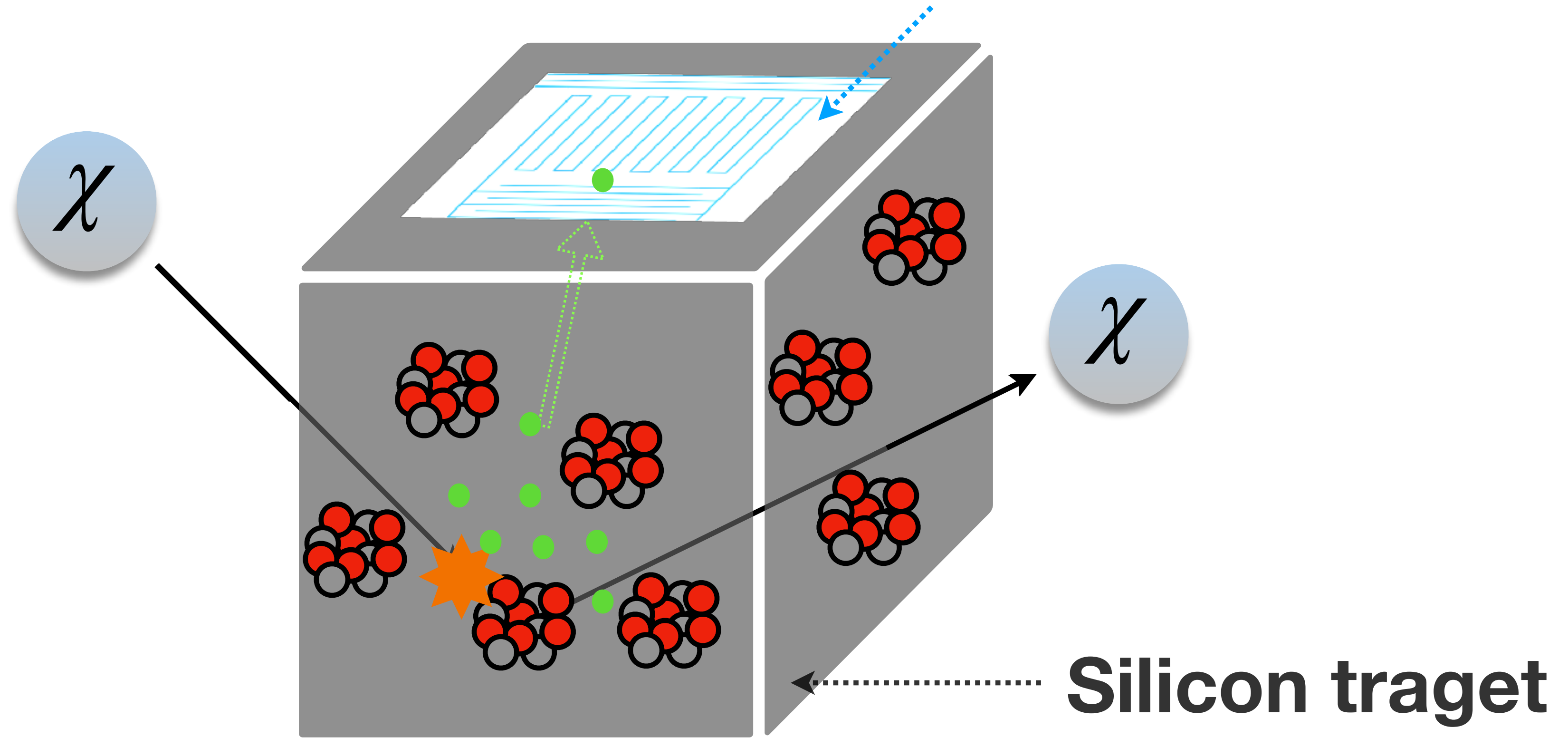
Marc Schumann 2019 J. *Phys. G: Nucl. Part. Phys.* 46 103003



BULLKID-DM detection method

GSSI

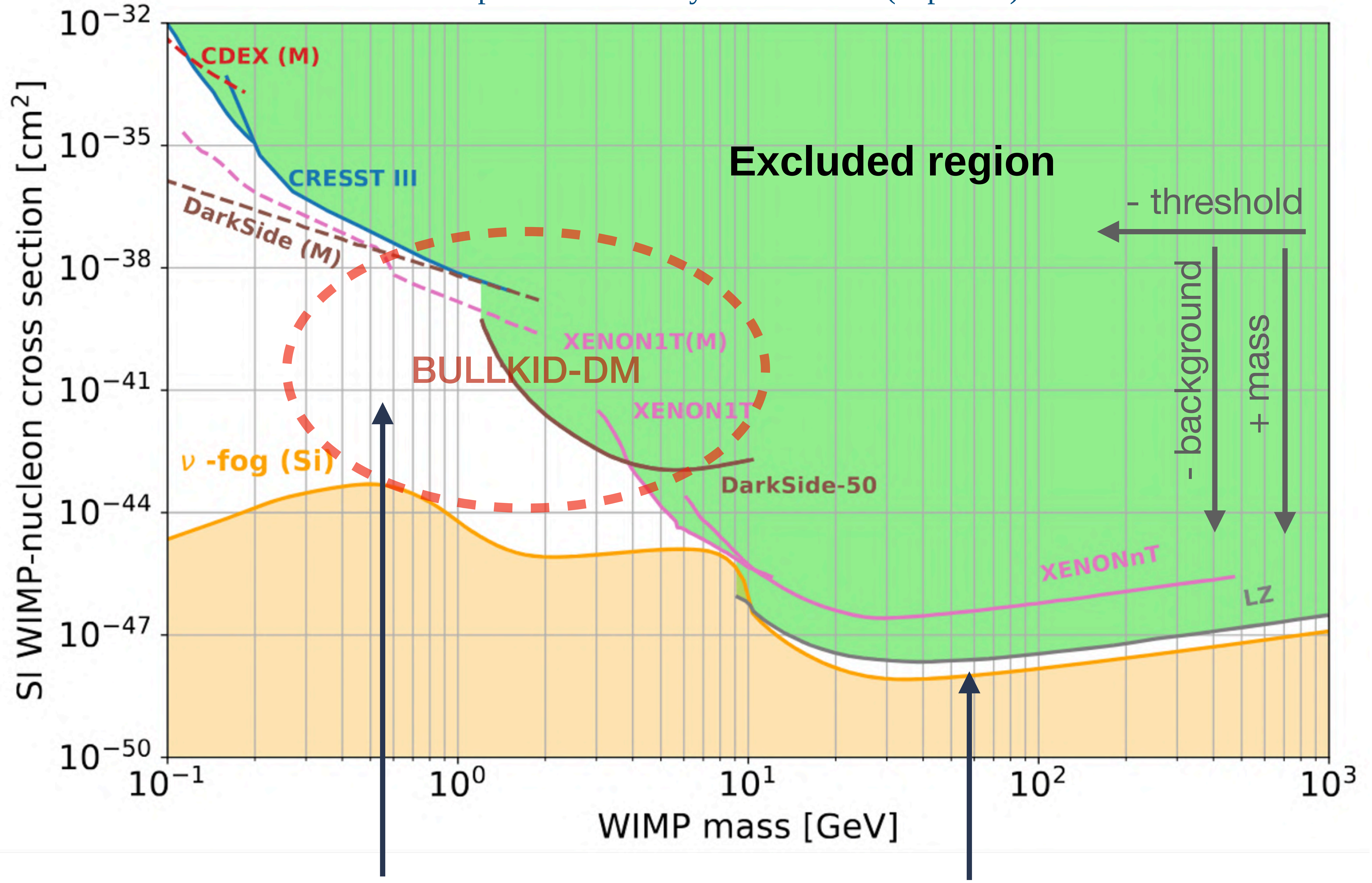
- Solid-state cryogenic (mK) **phonon** detectors
  (The nucleus recoil **generate phonons** that propagates in the silicon can be transmitted and **absorbed by the KID** and **induce a signal**)



  - Sub-keV low energy threshold $\lesssim$ **200 eV**
  - High energy resolution **~ 5% (σ)**
  - Mass scalable to **$\mathcal{O}$(1 kg)**

- Kinetic Inductance Detectors (KIDs)
  - Athermal phonon sensitive only
  - multiplexed readout

[S. Navas et al. (Particle Data Group), *Phys. Rev. D* 110, 030001 (2024)], updated to 2025 by M. Folcarelli (Sapienza)



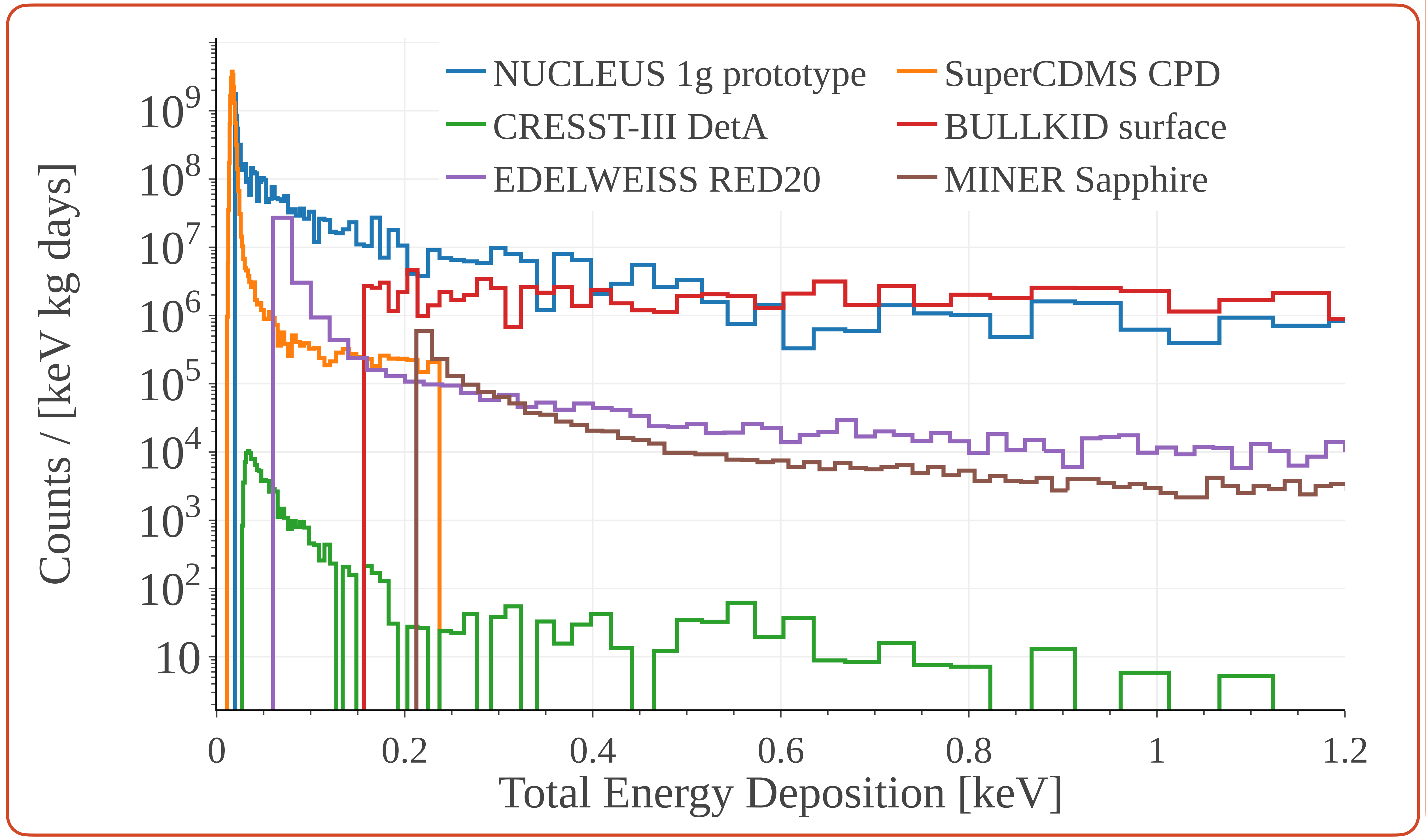
kg-scale solid-state phonon detectors **multi-ton liquid scintillators**

Background issue in low-T experiments

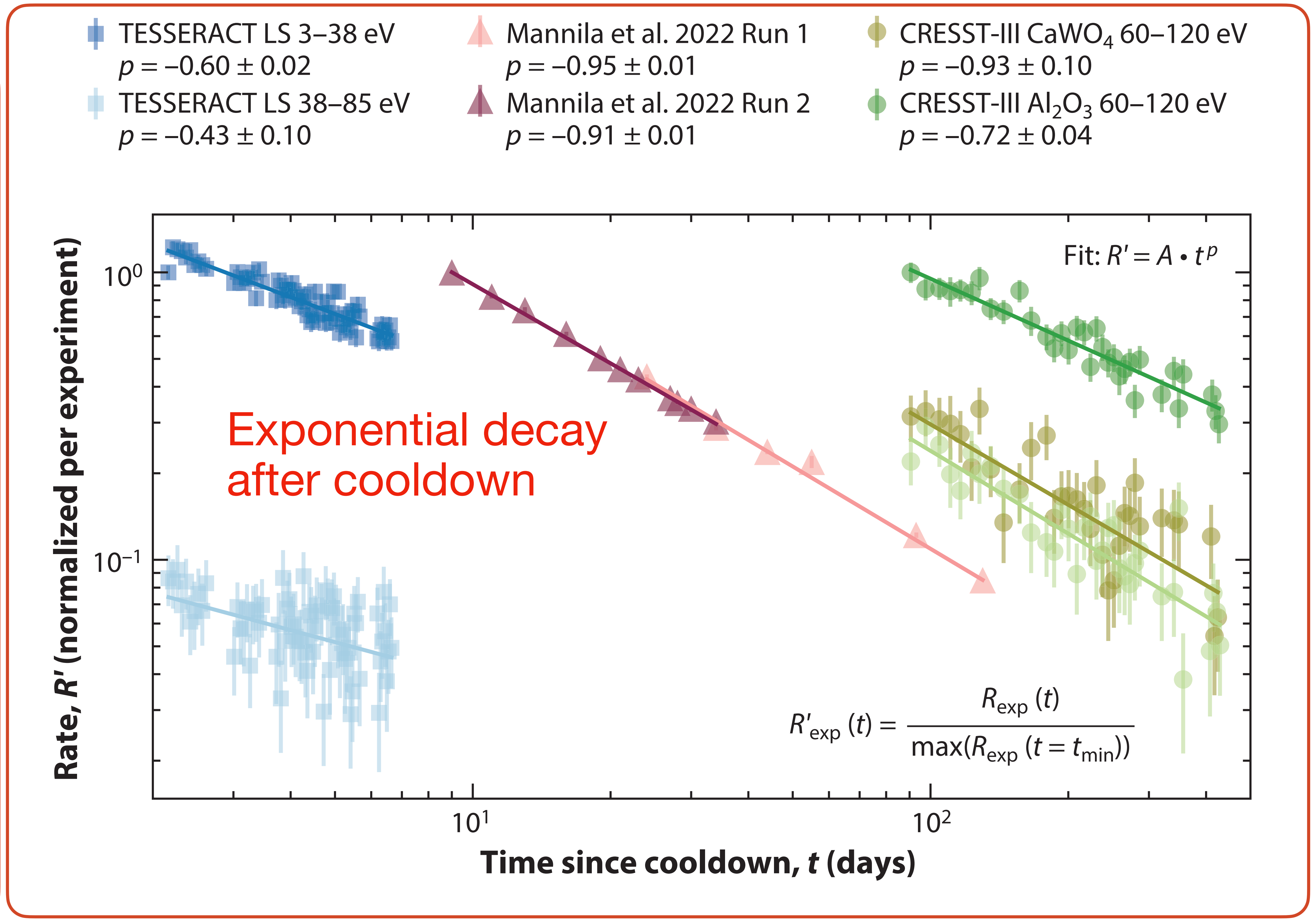
- Excess background rising at low energies observed but not understood yet
  - **Phonon bursts** (crystal-support friction) ?
  - Lattice **relaxations** after cool down?
  - Phonon leakage from the supports?

Low Energy Excess

EXCESS26@IDM
Zaragoza on May 30, 2026.
https://indico.cern.ch/event/1644935/



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



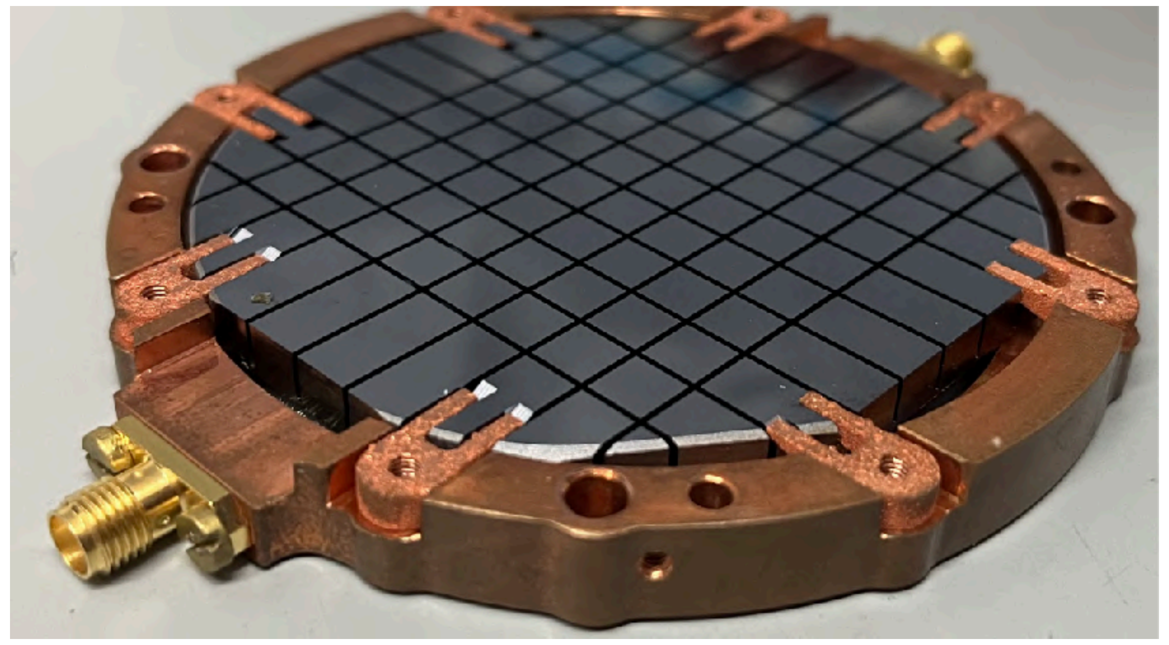
D.Baxter et al, *Annu. Rev. Nucl. Part. Sci.* 2025. 75:301–26

This background limits the sensitivity of present experiments

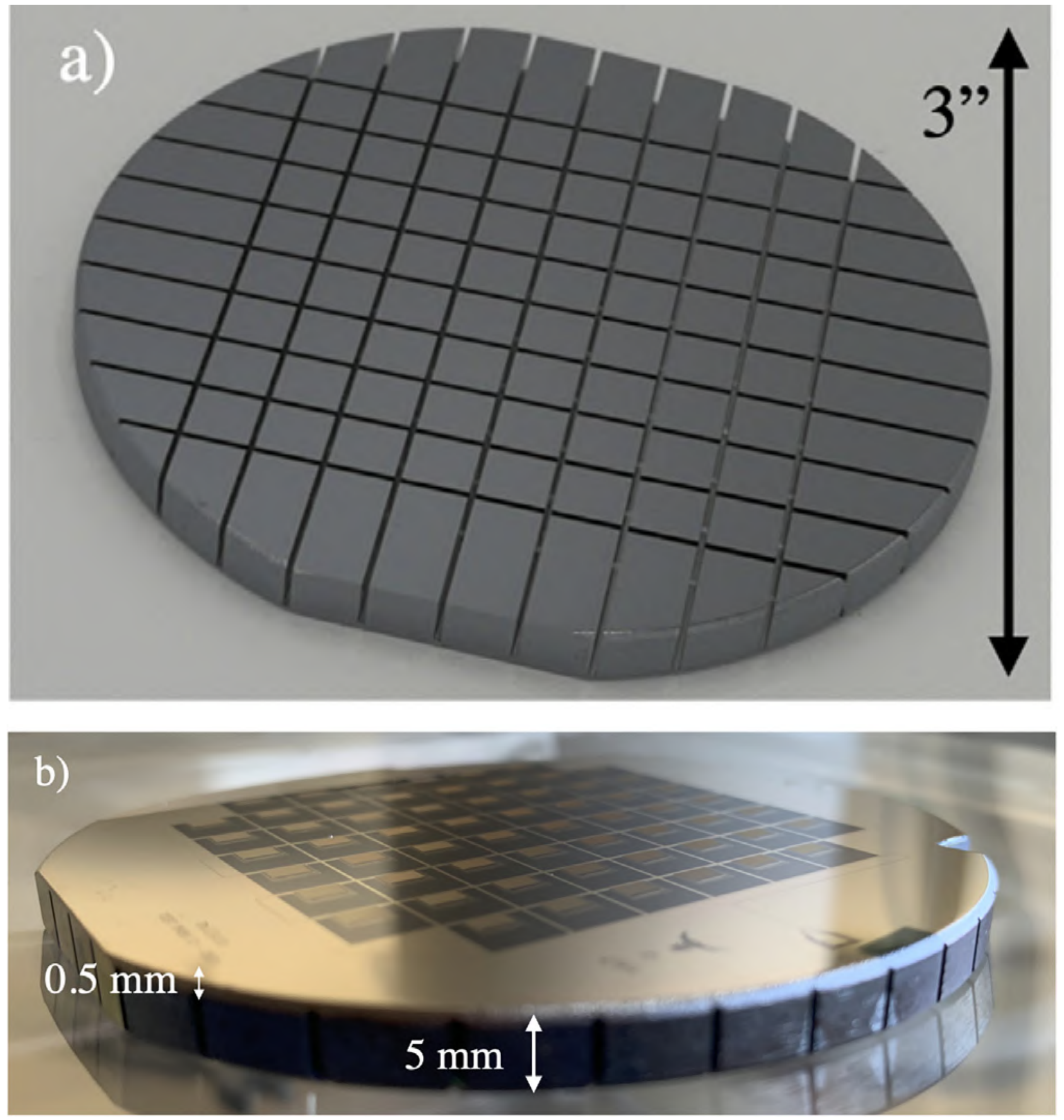
BULLKID-DM Architecture

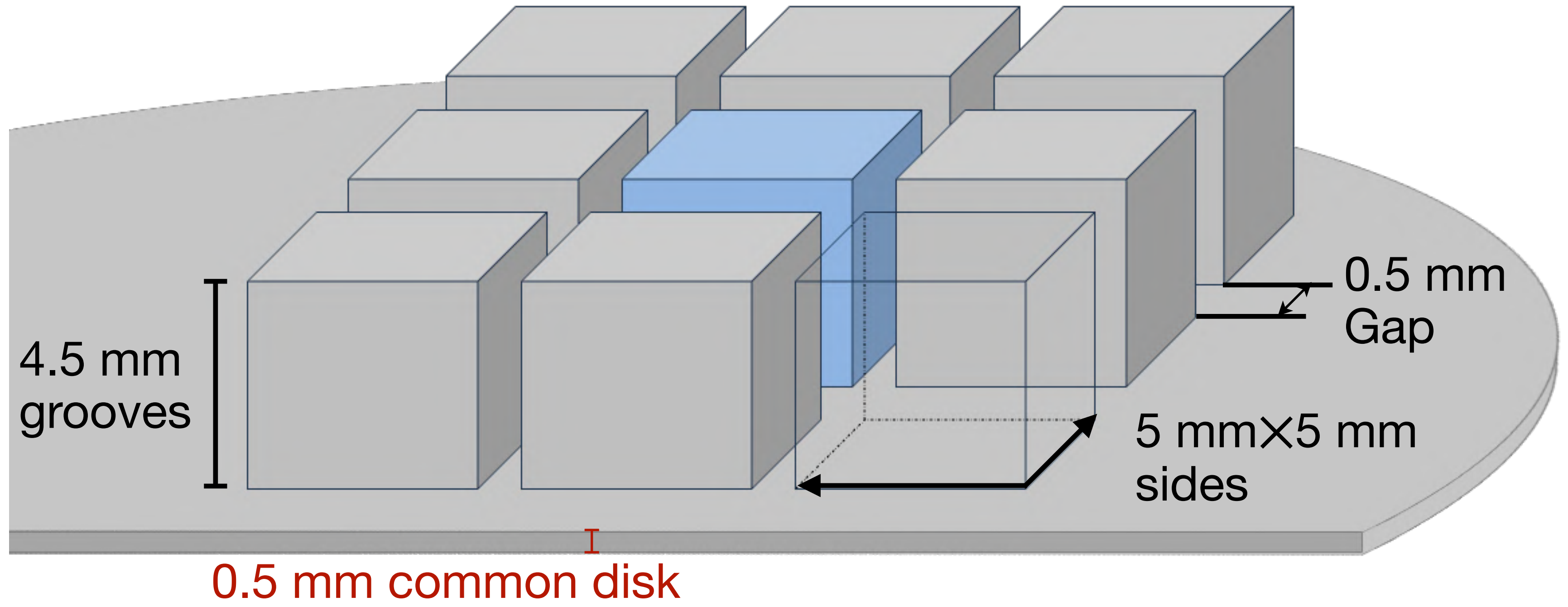
- **Monolithic** and **fully active** structure with 145 detectors (4" wafer)
  - Silicon die 0.34 g each, 5×5 mm^2 - 4.5 mm deep grooves - 5.5 mm pitch
  - **Aluminum** KIDs arrays ~ 2×2 mm^2 × 60 nm, 0.5 µg
- **Fully multiplexed**, single readout line per wafer
- Stack of 16×100 mm Si wafers (~ 800 g target mass) with **2320 sensors**

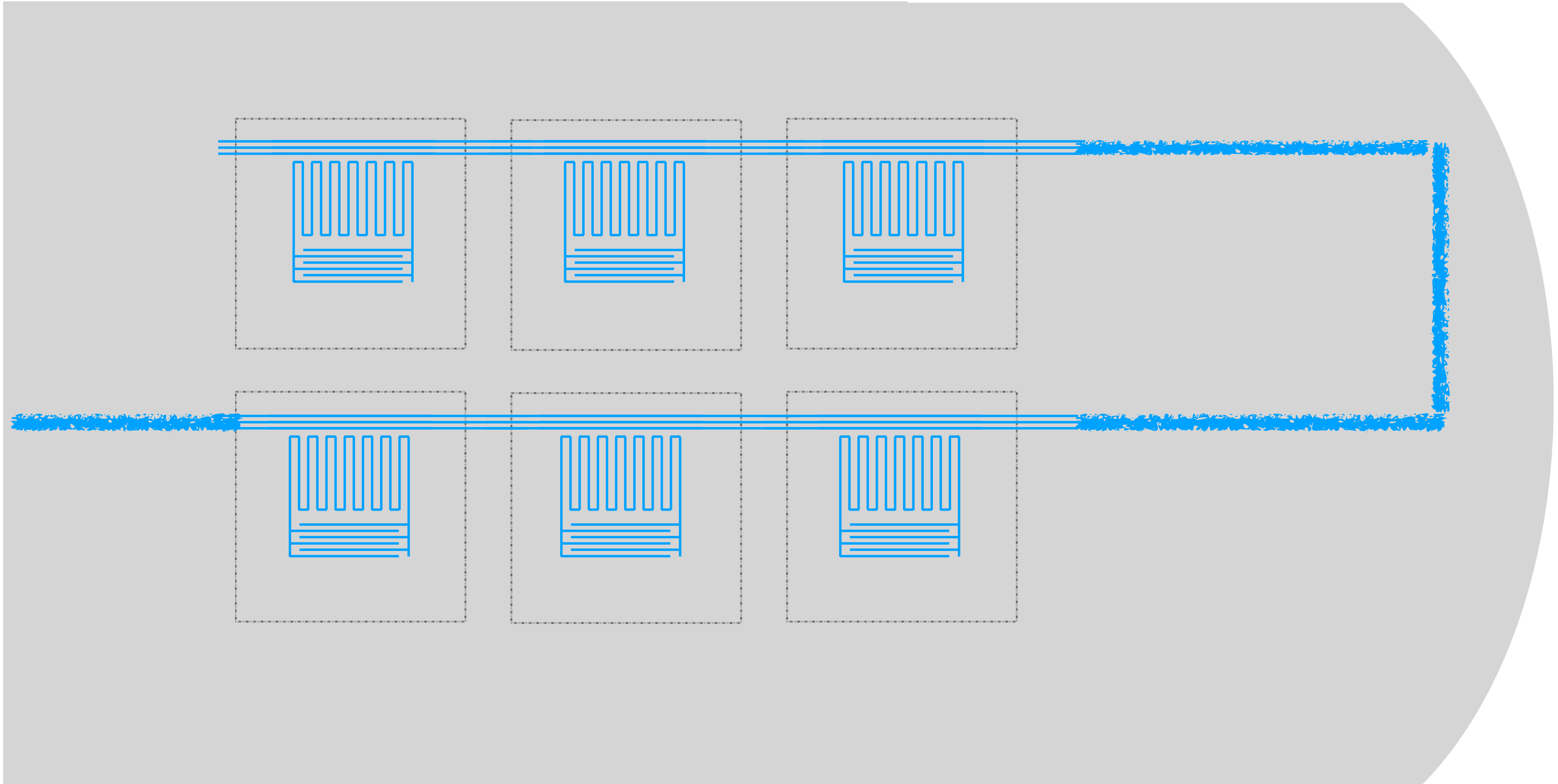
Demonstrator

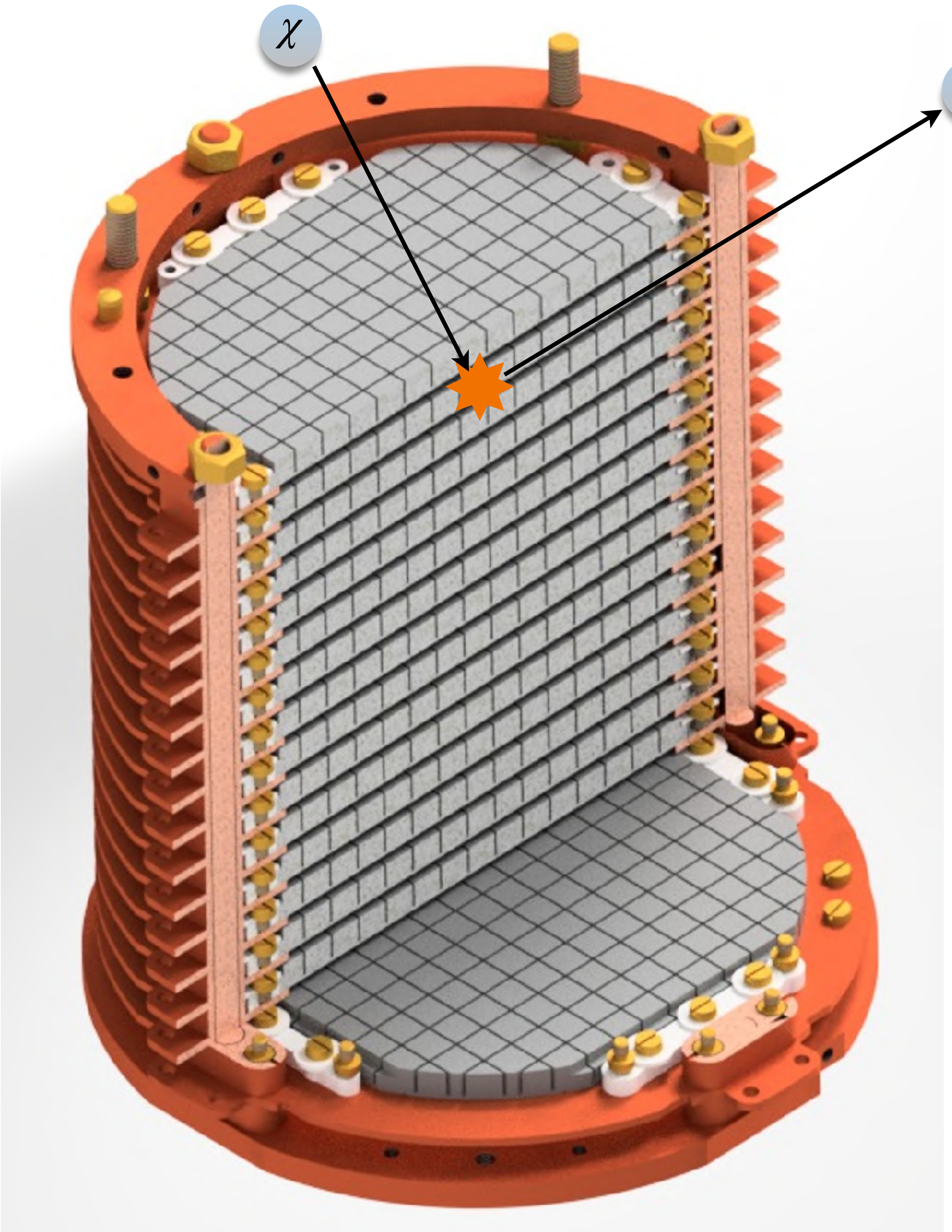


Demonstrator: 60 detectors (KIDs) for 3" wafer



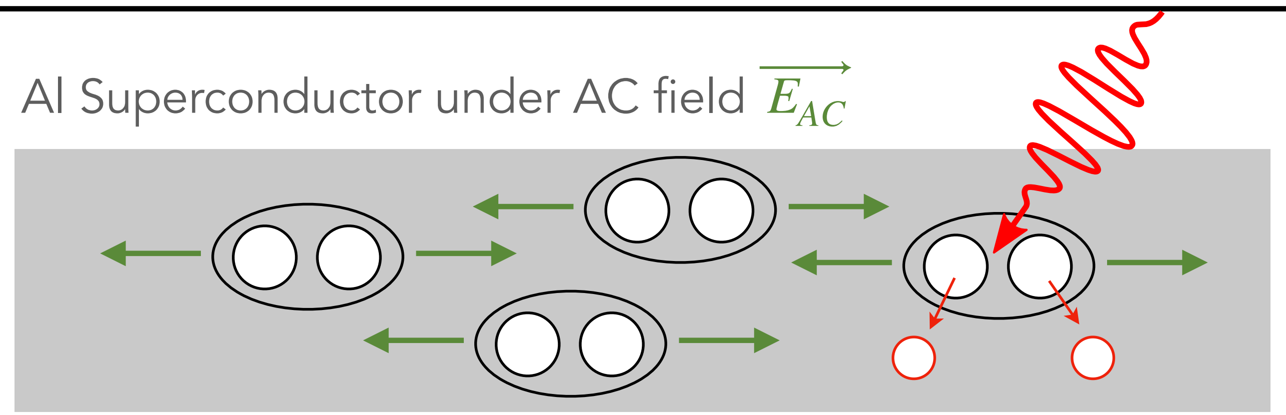






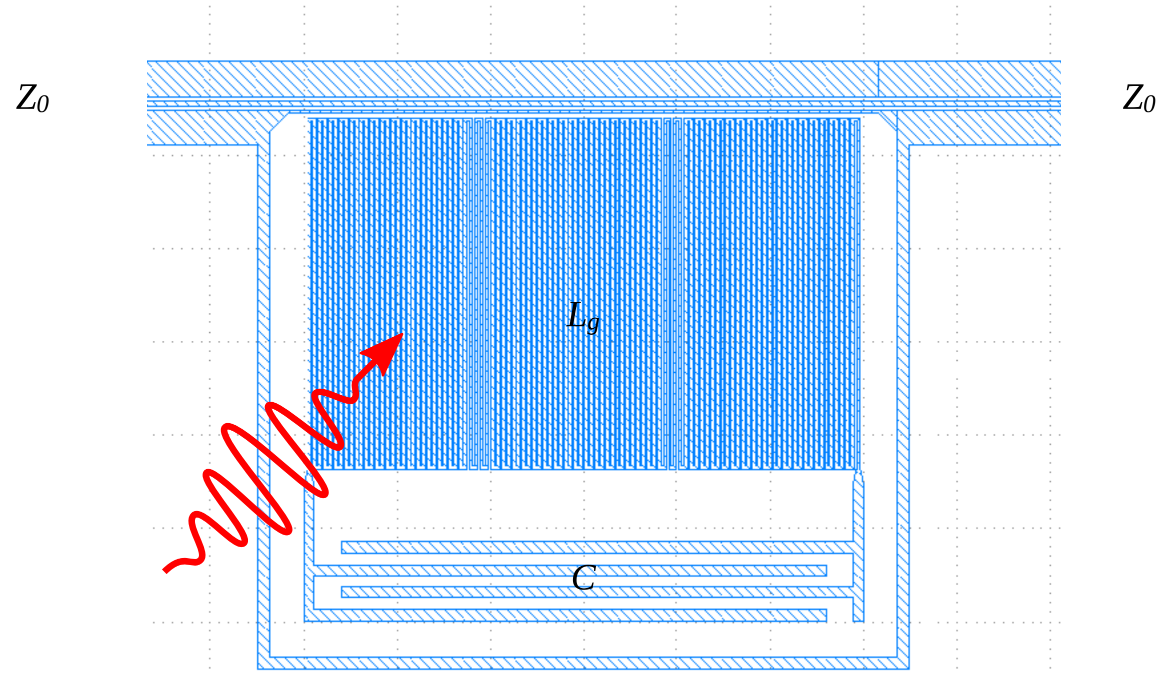
Kinetic Inductance Detectors (KIDs)

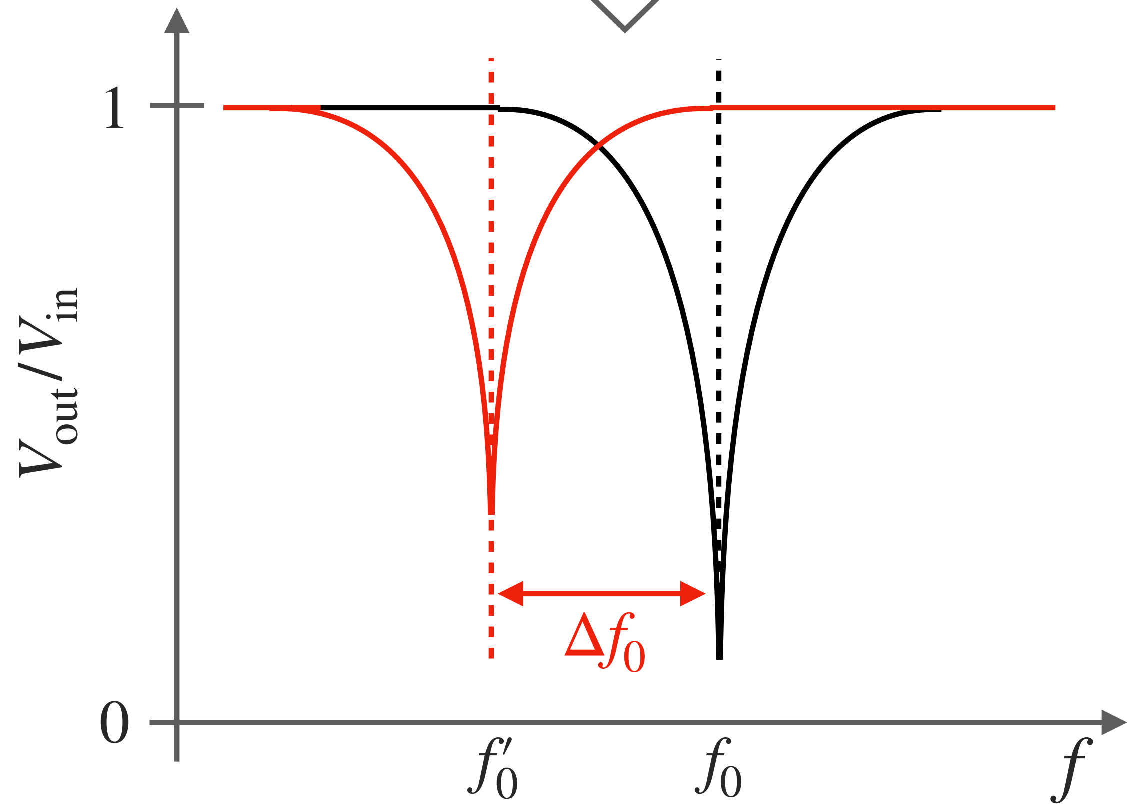
- Superconductor at $T \ll T_C$, electrons are bounded in Cooper pairs, bounding energy $2\Delta_{\text{pairs}} = 3.5 \cdot k_B T_C$
- The inertia given by the Cooper pairs mass acts as an electric inductance, named kinetic inductance L_k
- Building an **electric resonator of LC circuit** with a thin superconducting deposition (~10 nm)
  - Electric capacity C
  - Total inductance $L_{\text{tot}} = L_k + L_g$
- Frequency Domain Multiplexing: assign different resonance frequencies for **Aluminum** KIDs in parallel by tuning the electric capacity

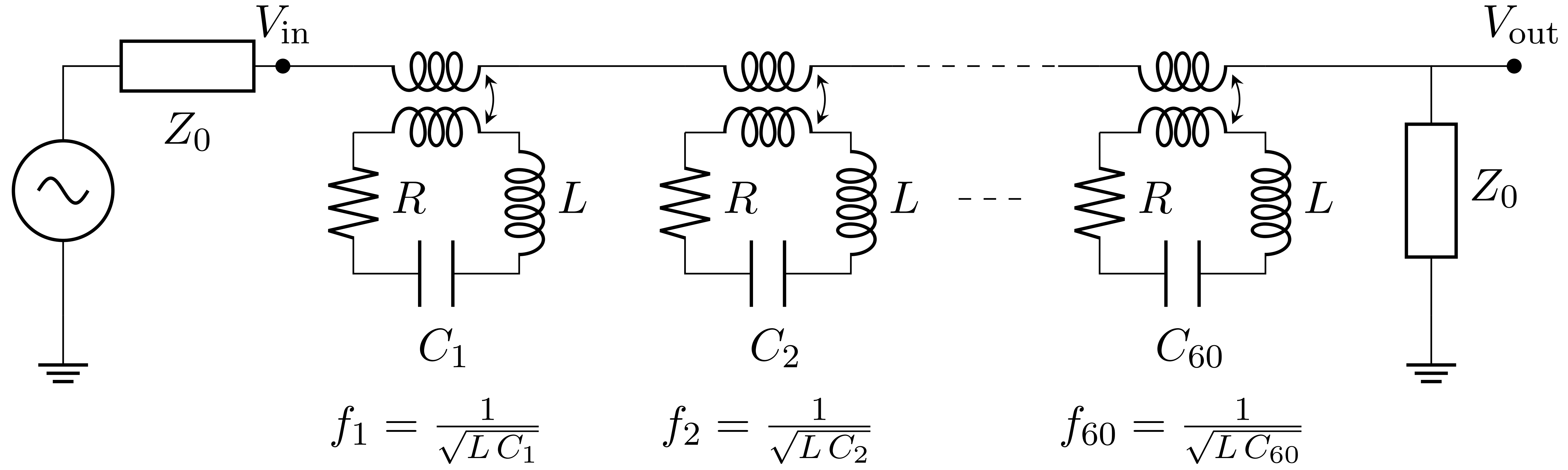


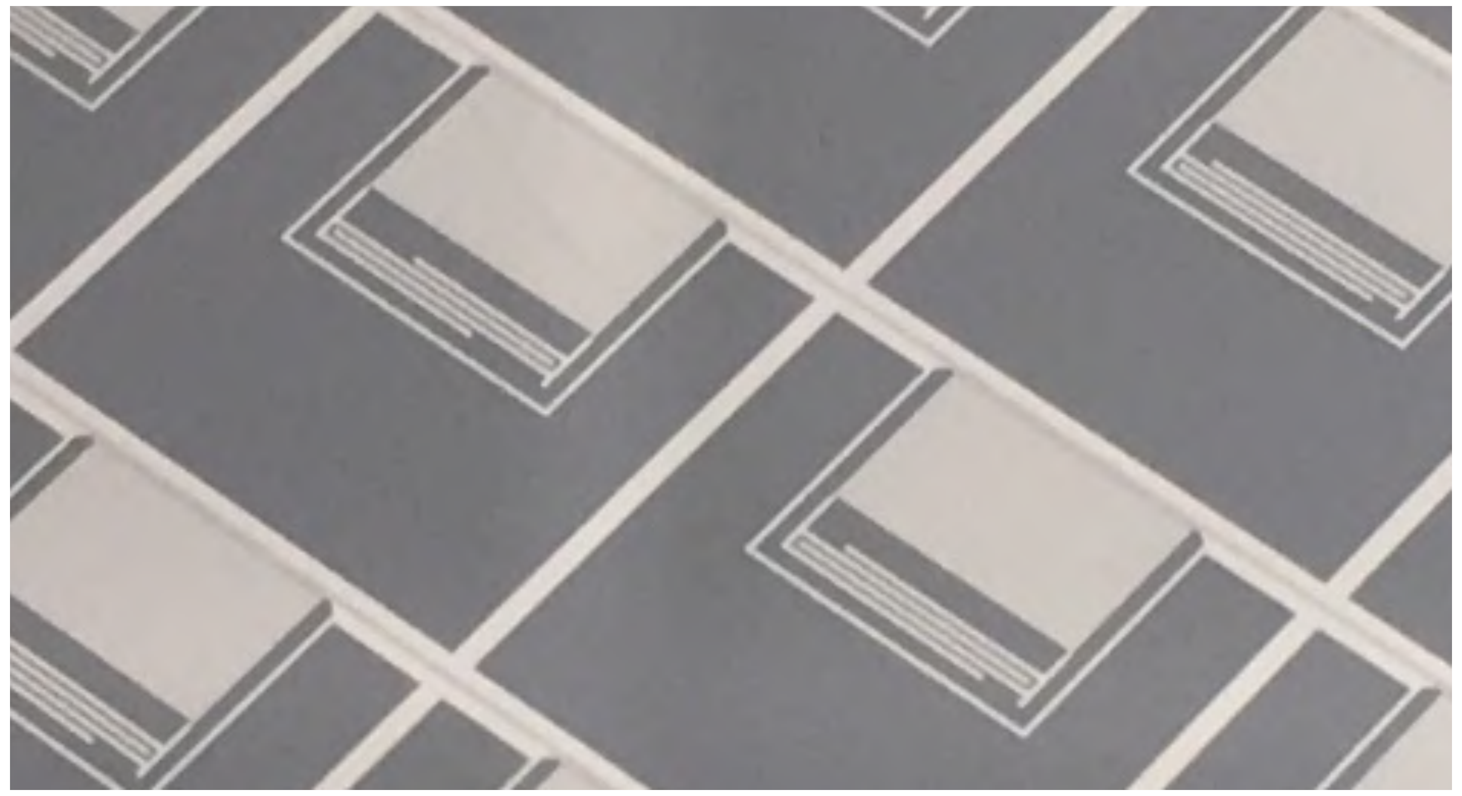
Phonon absorption
$E > 2\Delta_{\text{pairs}}$
$\Delta n_{\text{pairs}} \rightarrow \Delta L_k$

$$L_k = \frac{m_e}{2\, e^2\, n_{\text{pairs}}} \qquad f_0 \sim 1/\sqrt{LC}$$



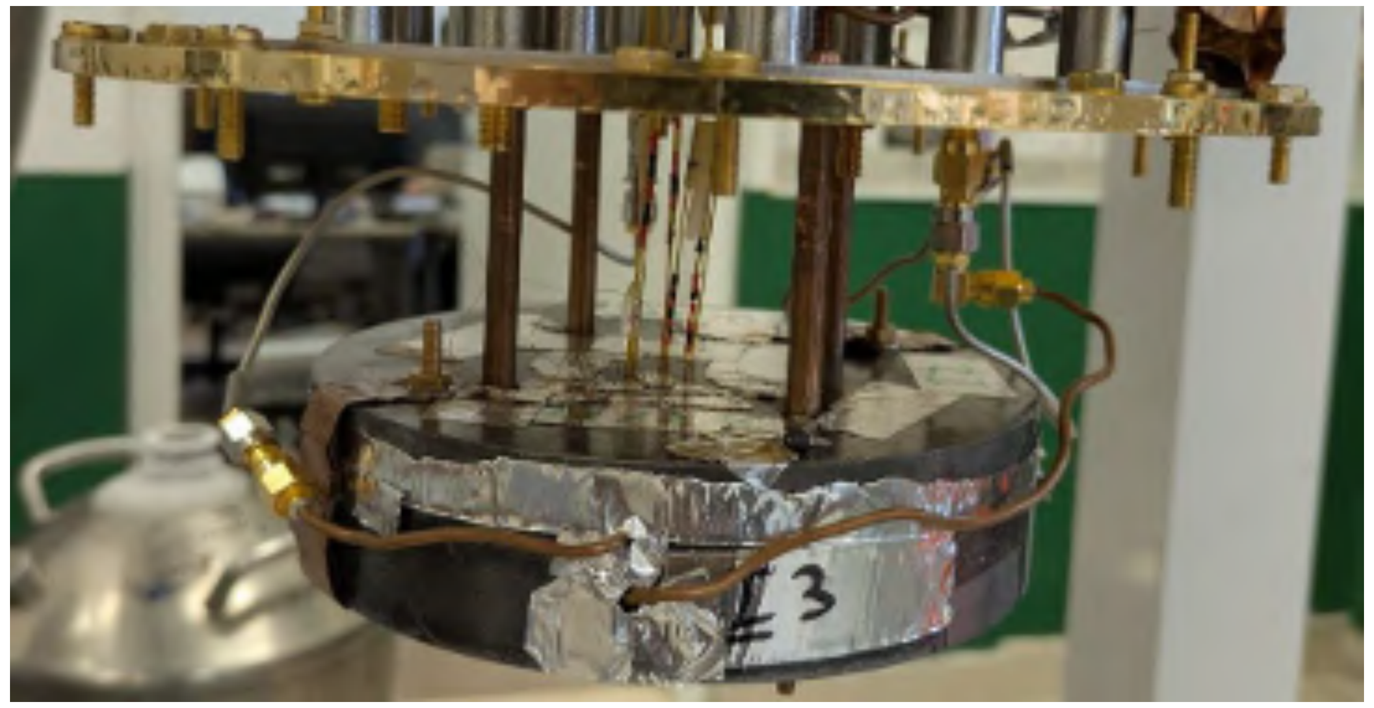


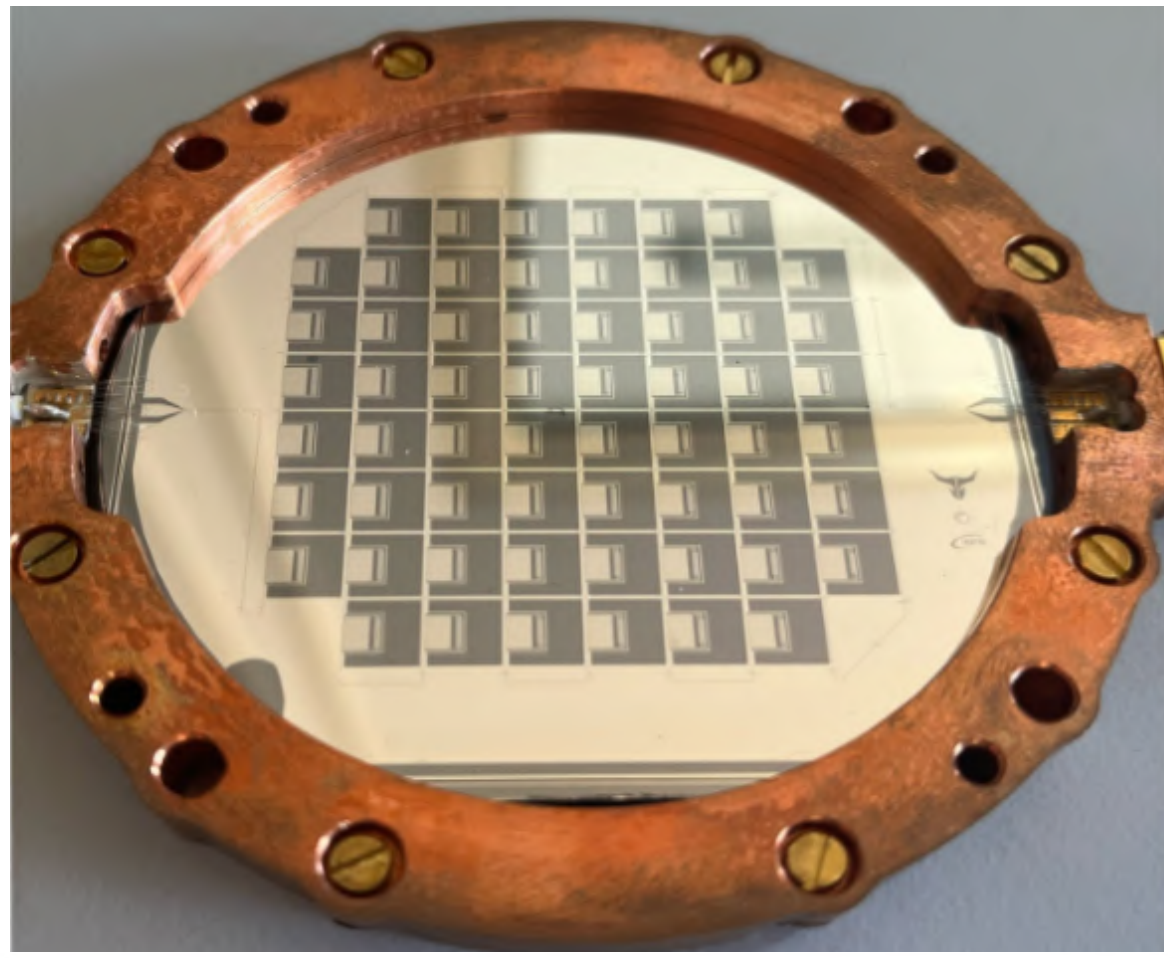


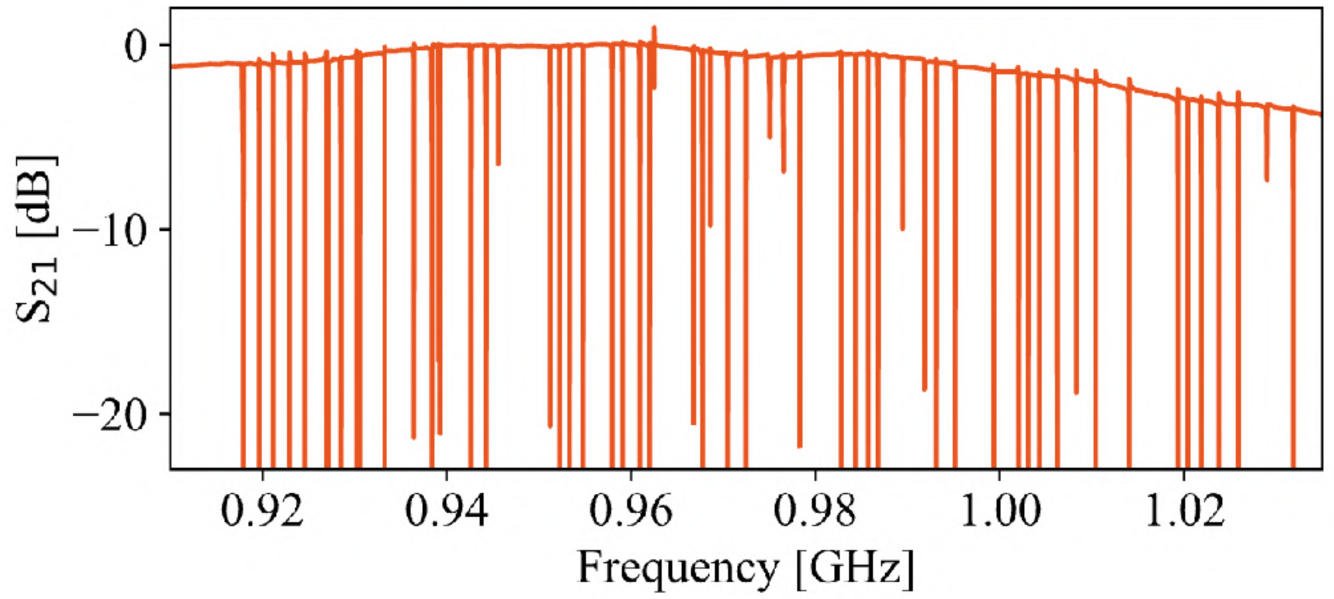


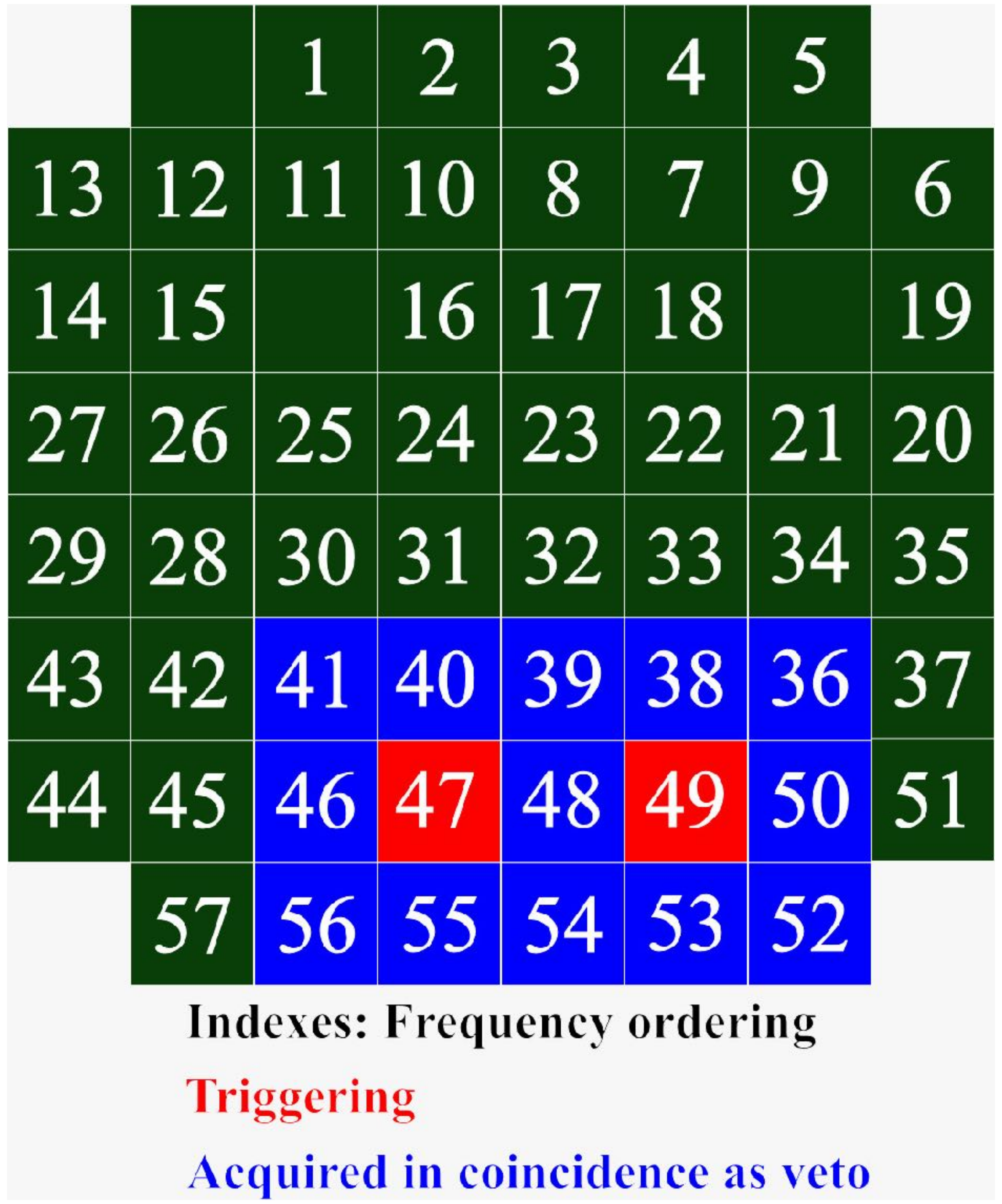
Prototype

- Deployed 1x3'' wafer, 57/60 working KIDs
- Surface laboratory in Rome D. Delicato, et al., *Background of the BULLKID detector array operated with moderate shield on surface*, arXiv 2605.02468
- Mildly shielded environment with LEAD (internal and external)
- Optical fibers for detector calibration and monitoring
- >1 month of data taking with detector stability (April-May 2025)



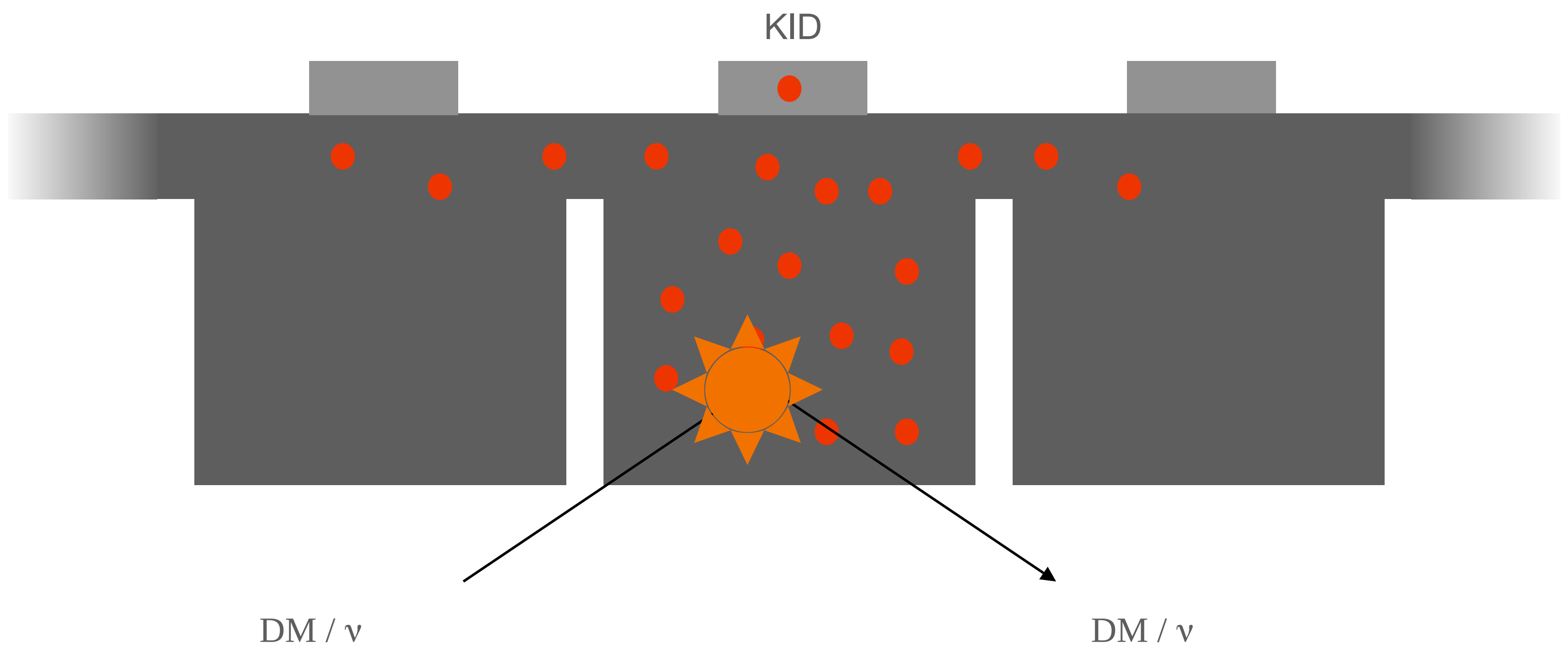




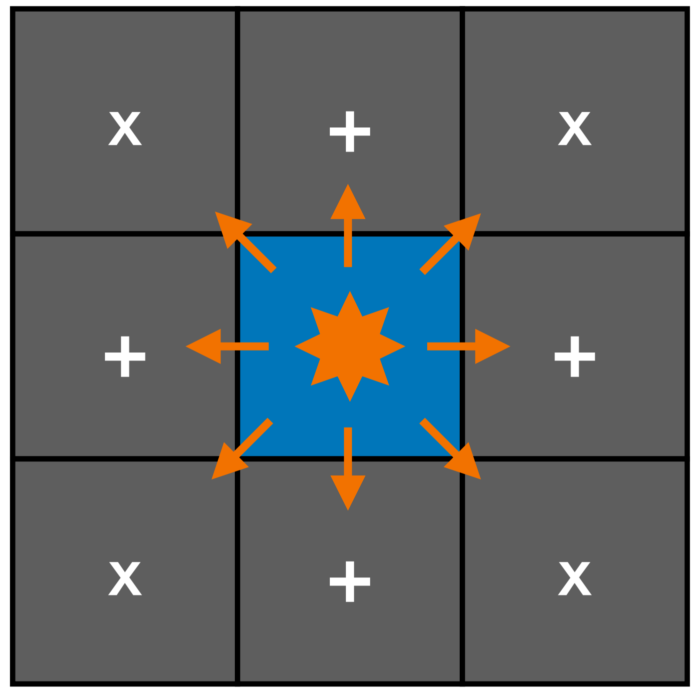


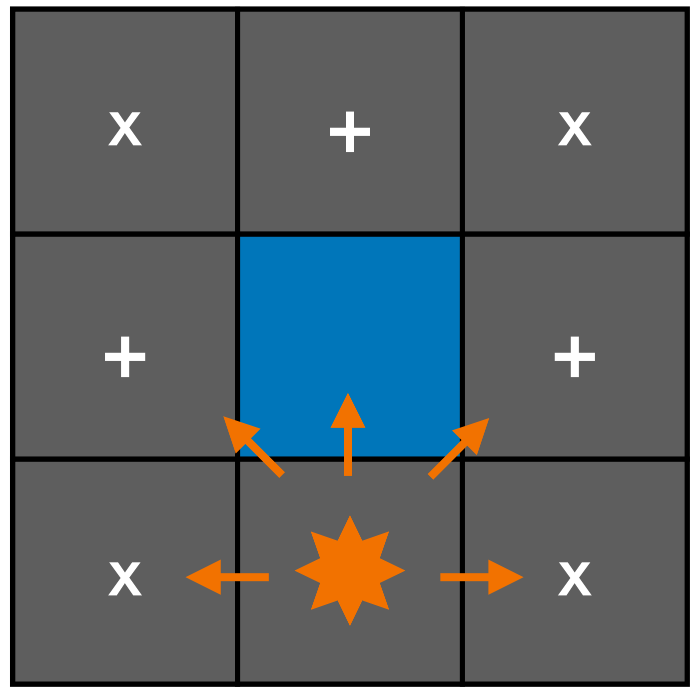
Analysis: phonon leakage

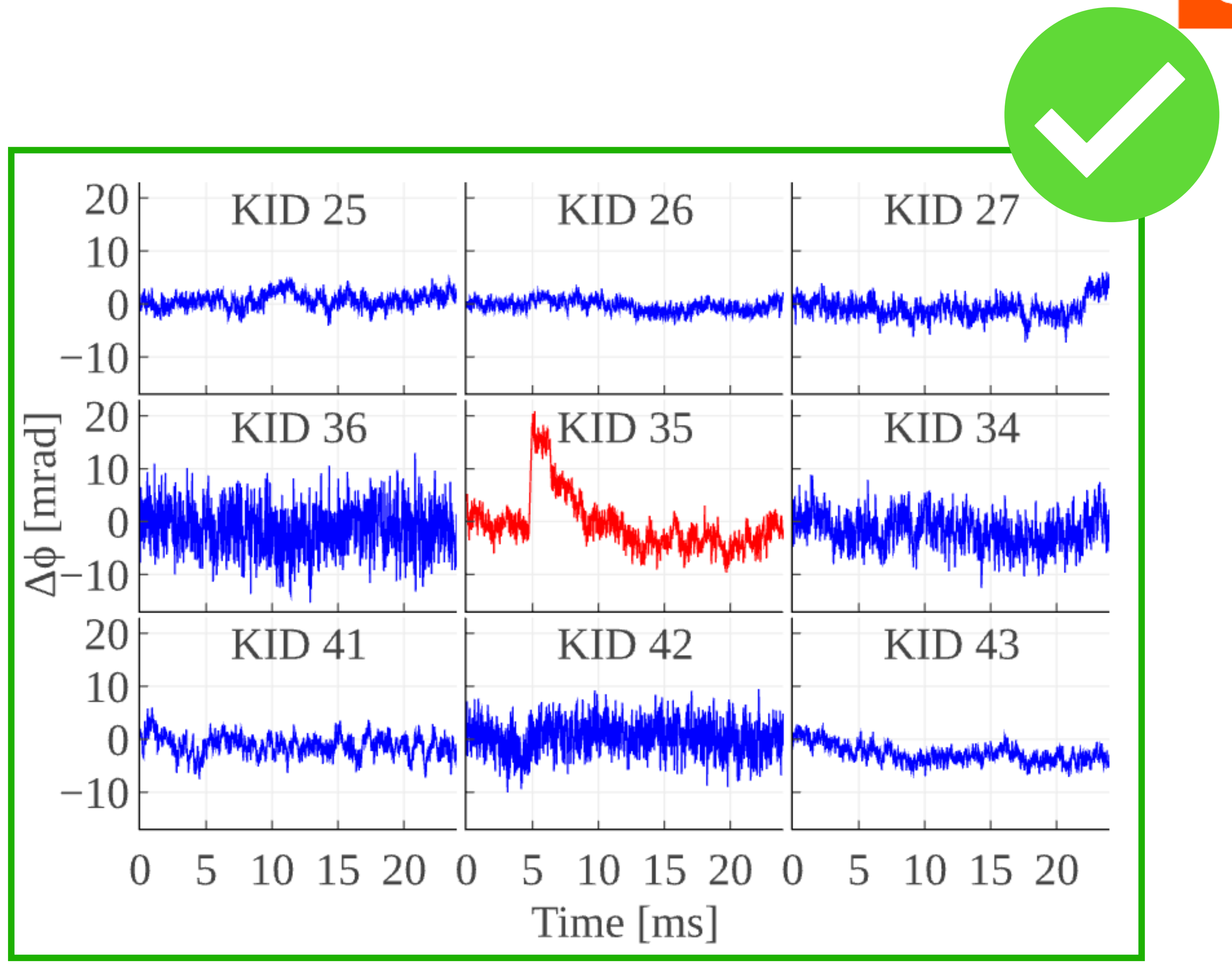
- Only 40% of the phonons generated are absorbed by the KID
- The rest leaks in nearby voxels:
  - 10% in each “+” die
  - 5% in each “x” die
  - the rest in outer dice

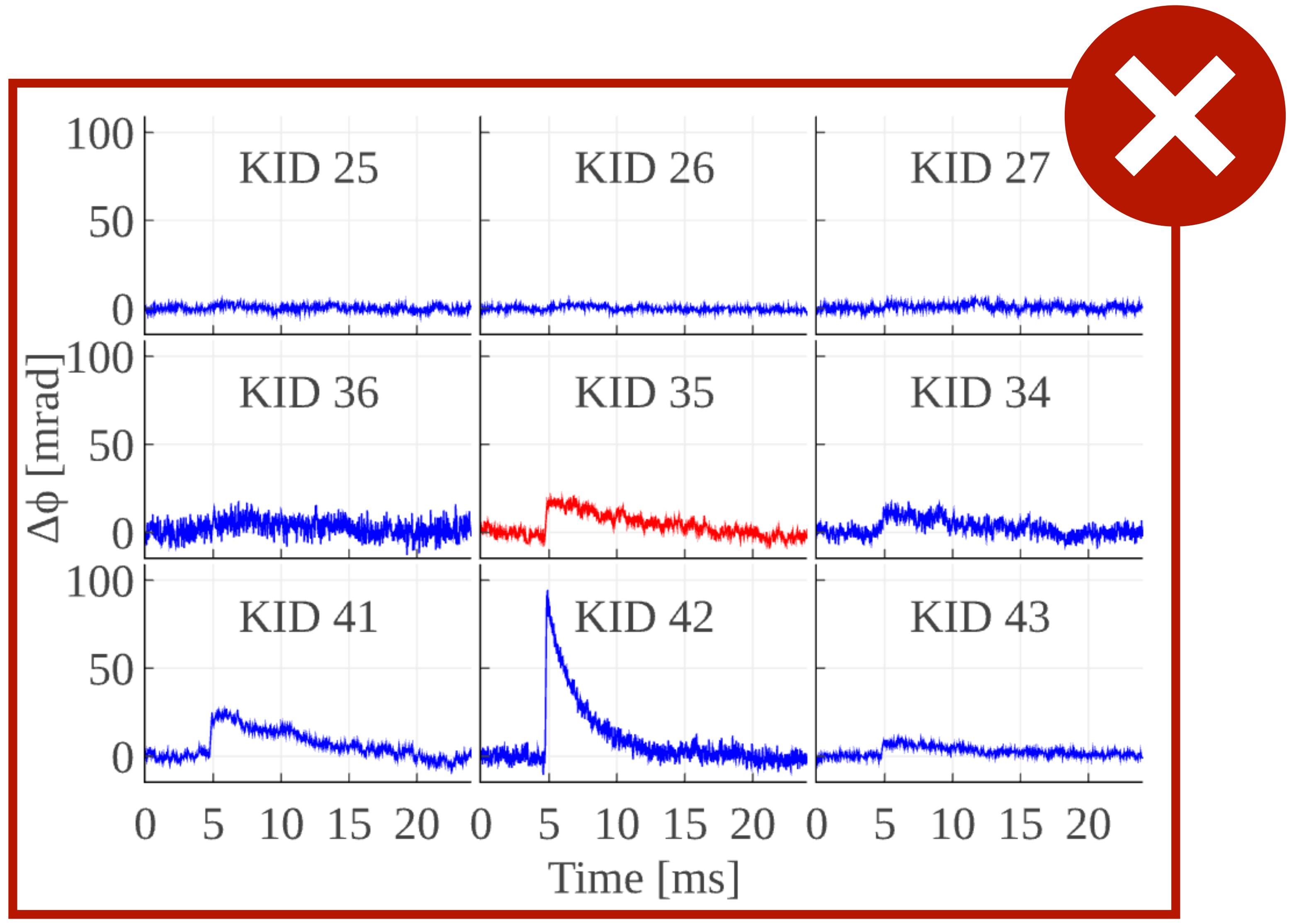


A. Cruciani, et al, *Appl. Phys. Lett.* 121, 213504 (2022)





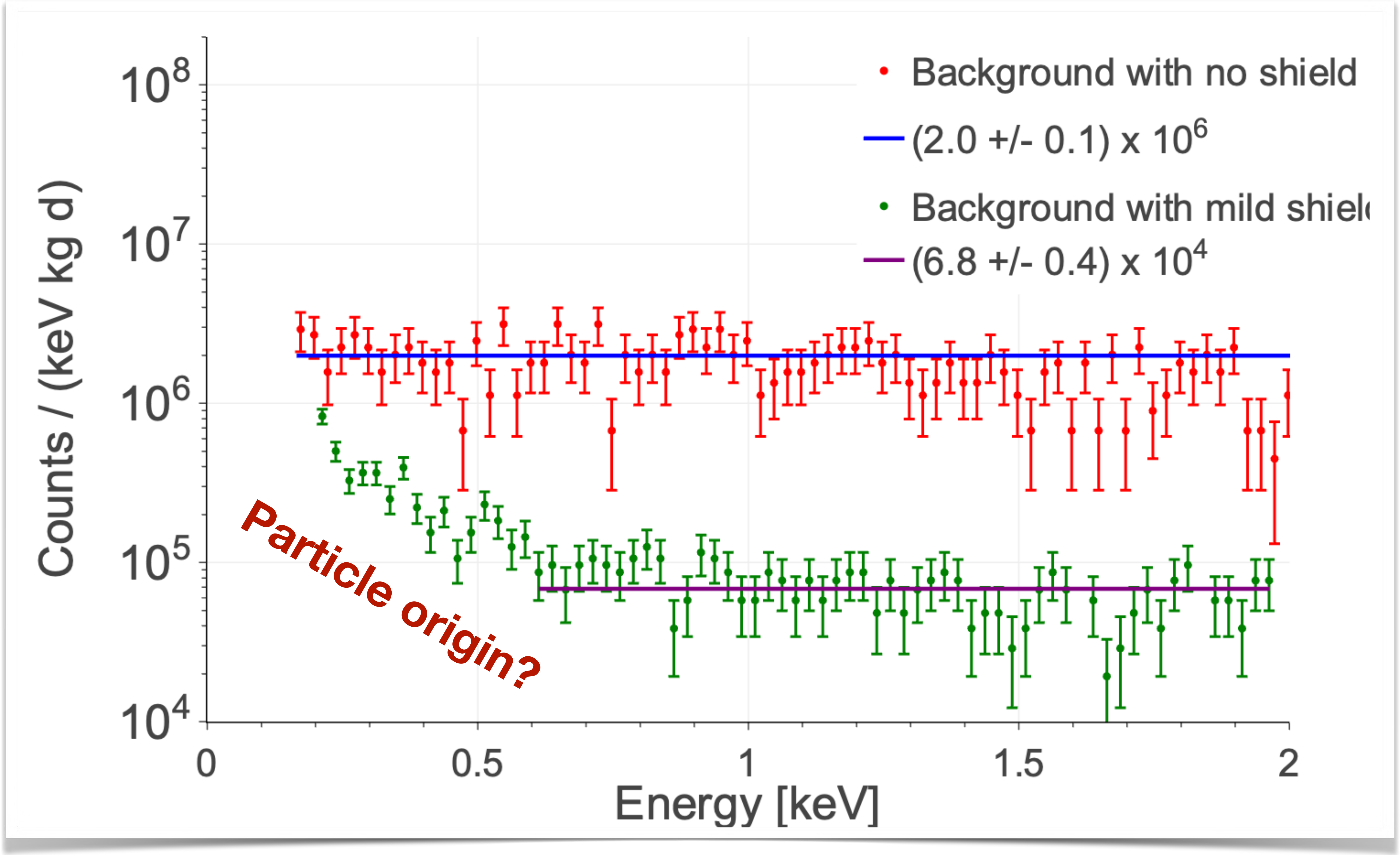


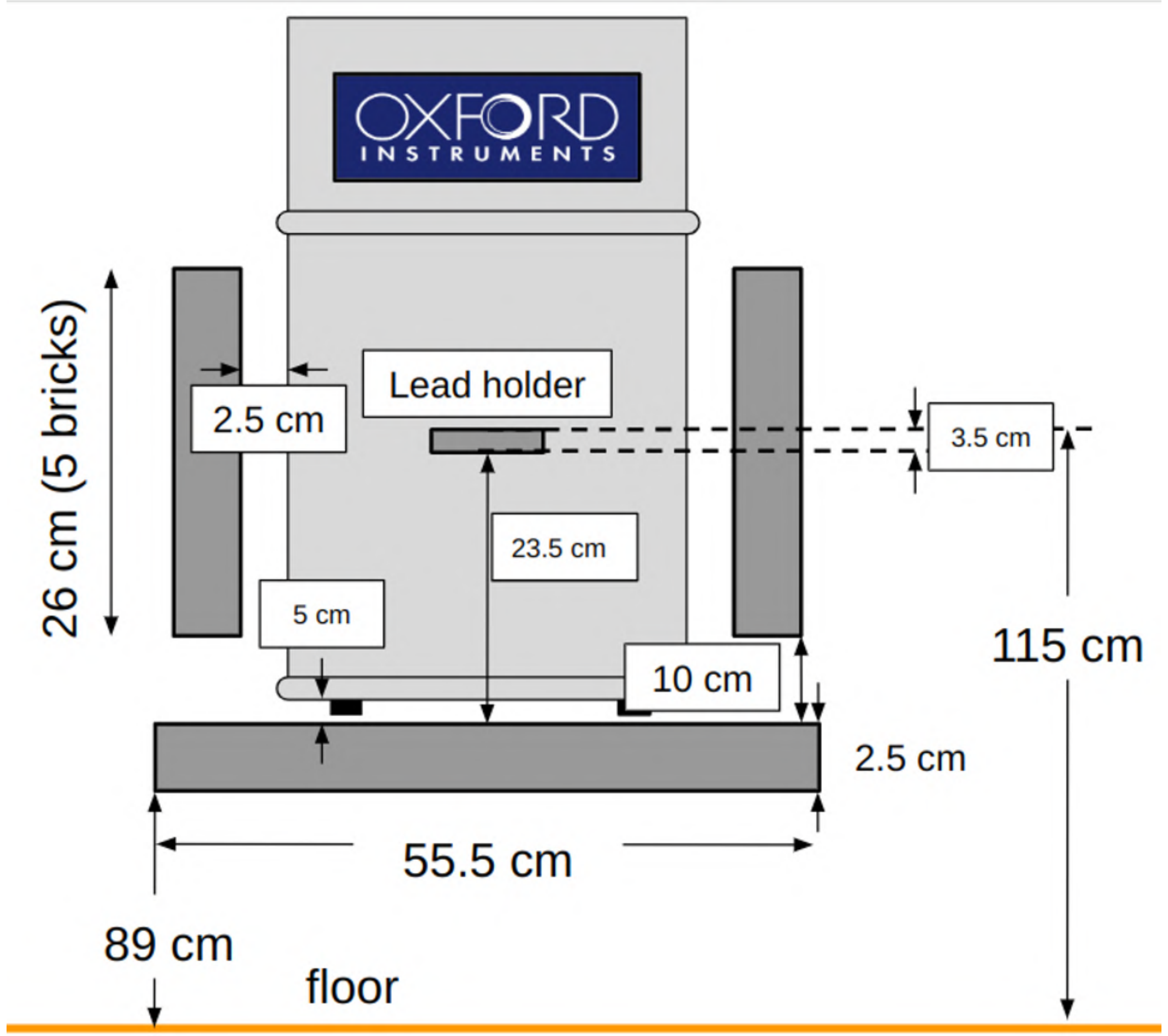


- Fiducialization on phonon leakage → interaction voxel discrimination

Background with mild shields

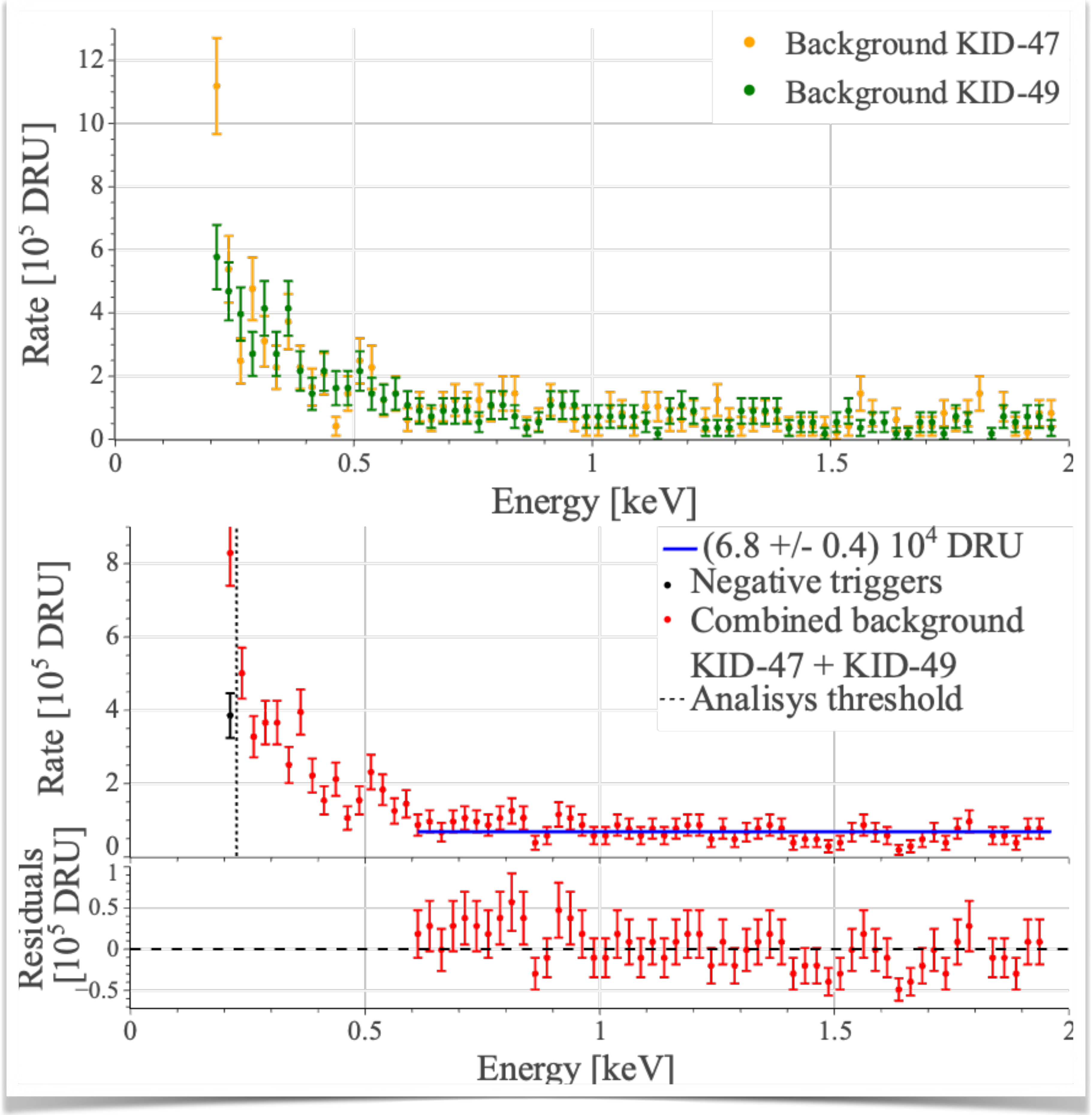
- Aboveground, lead shield, 290 live hours
- Background reduction by factor ~30, in agreement with simulations
- Low energy rise observed, is Low Energy Excess?



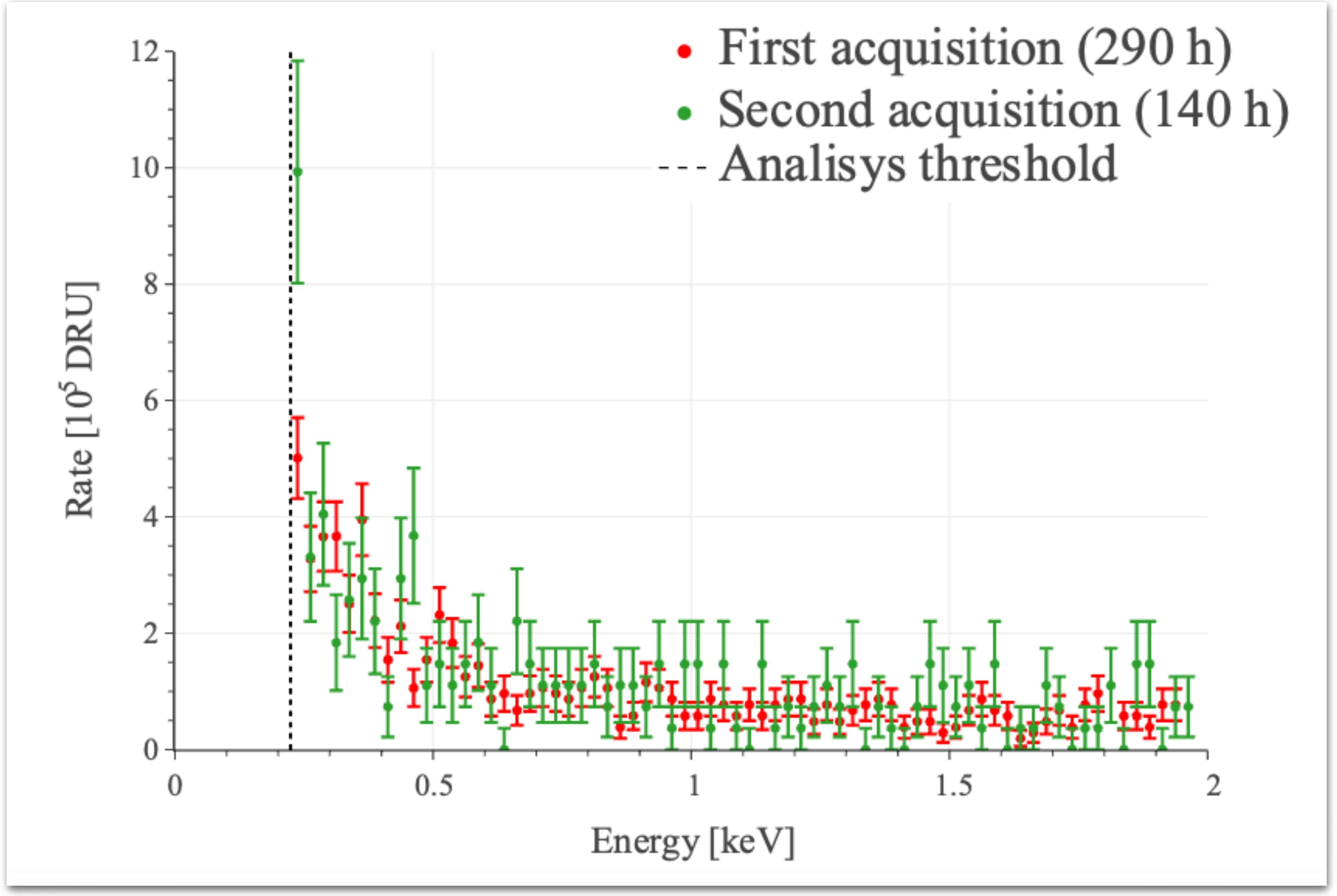


Low energy background

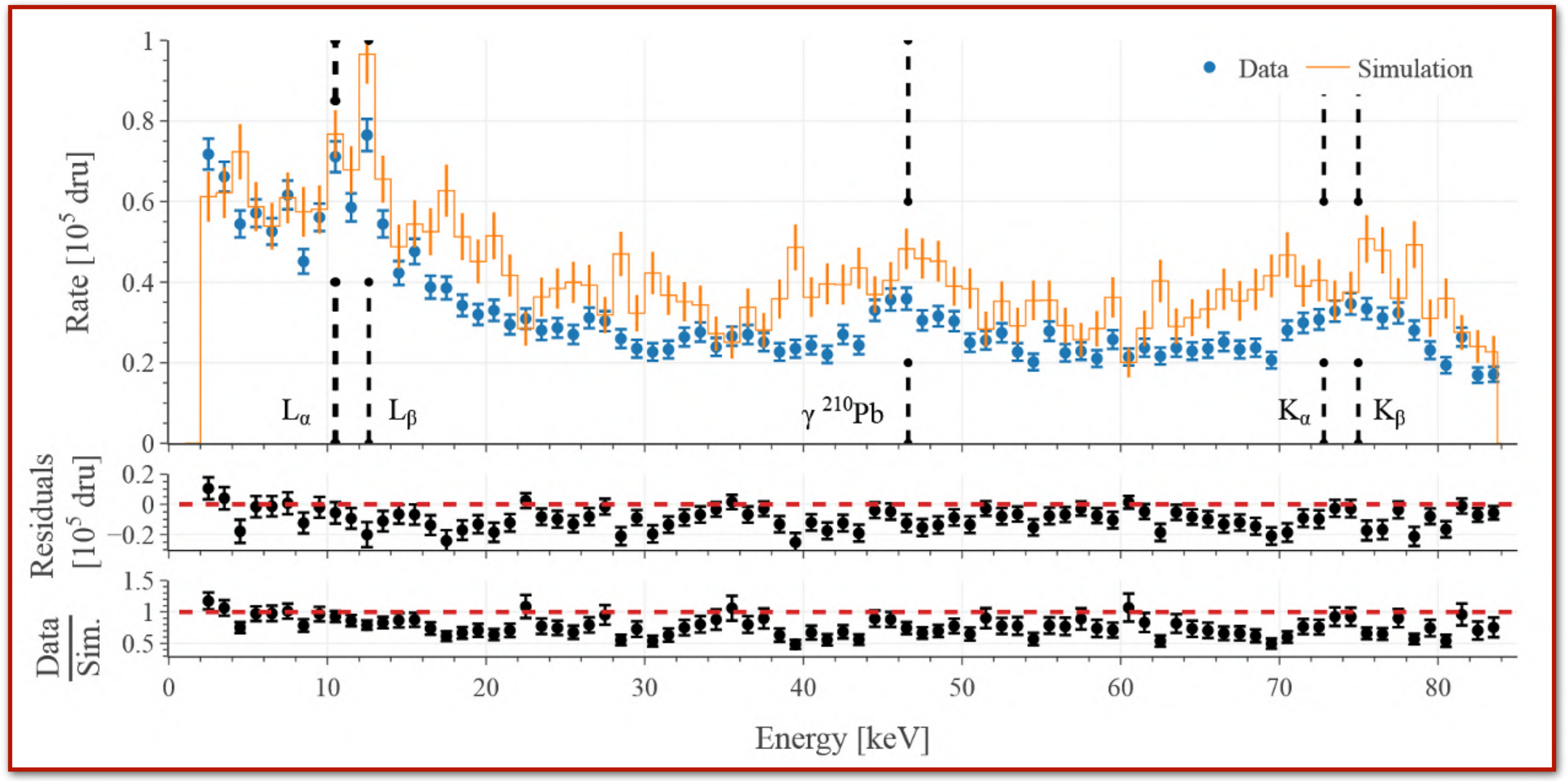
- Consistent spectra among different triggering clusters
- Rise below 600 eV not compatible with negative triggers
- No time decay (LEE symptom) of low energy rise



- Is it LEE?
- Needs new measurements!



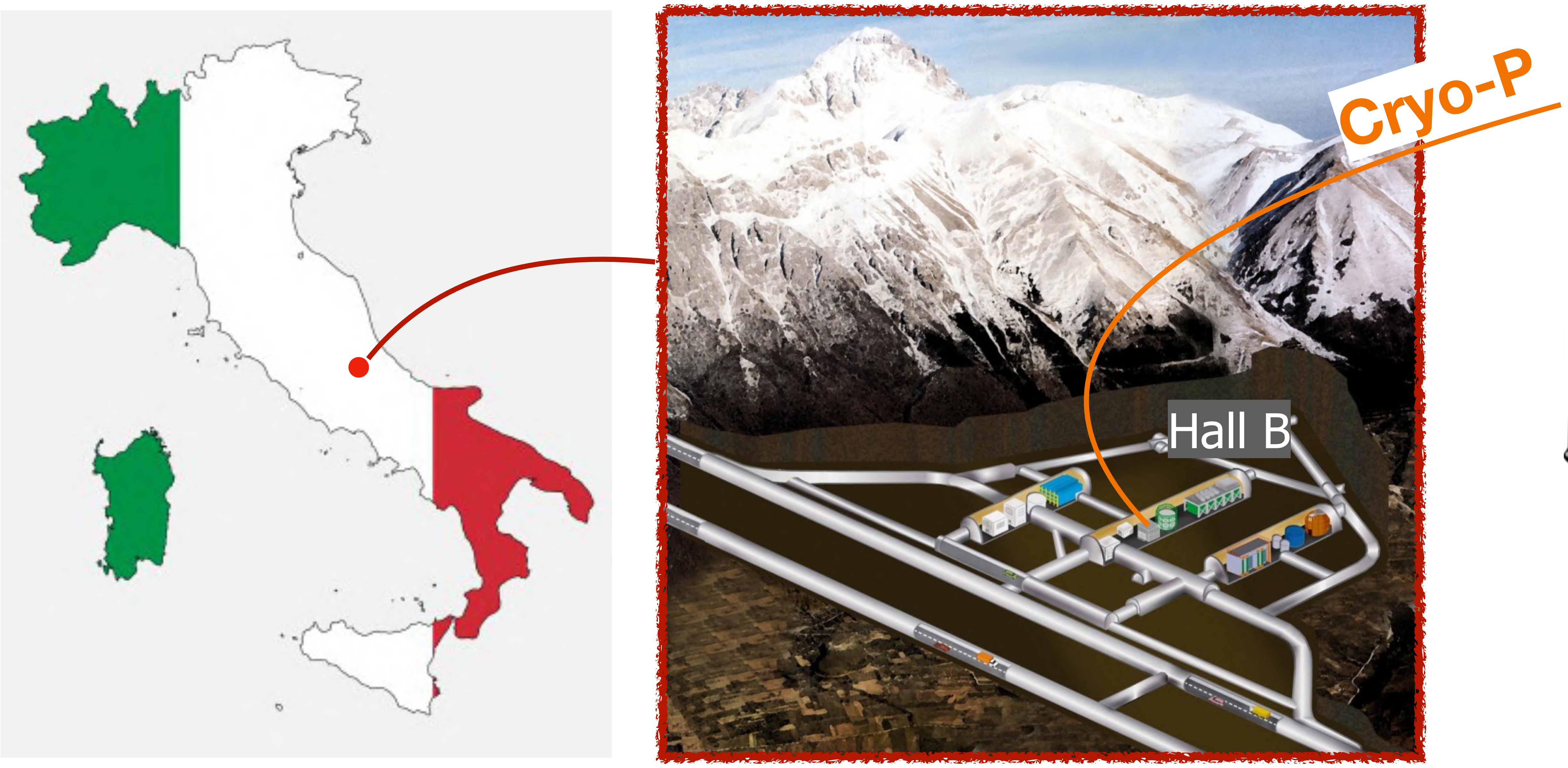
High energy spectrum



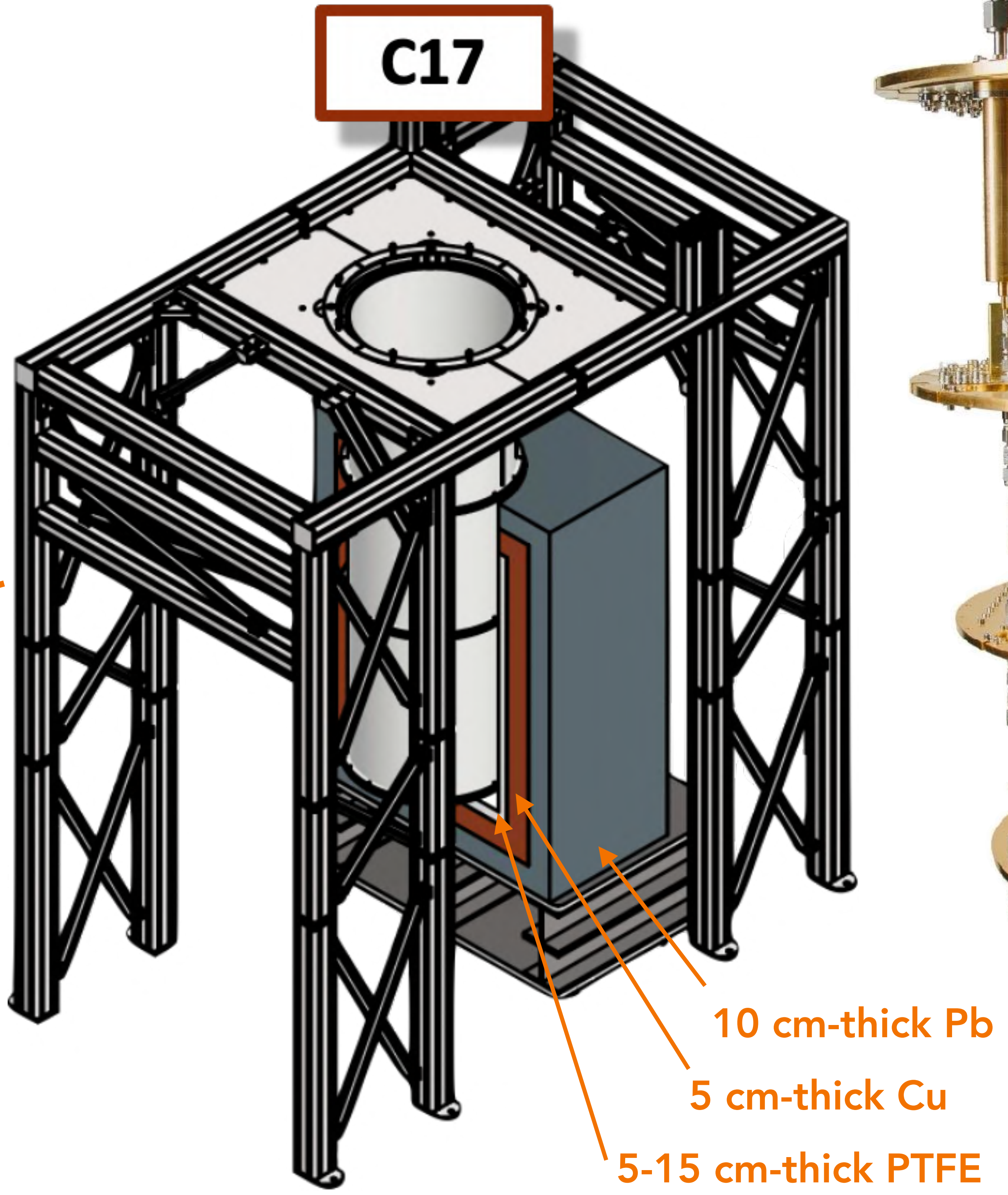
Experimental Site: Cryo-Platform @ LNGS

- LNGS, 1400 m of rocks overburden, radioactive background:
  - μ: $3 \times 10^{-8}\ \mathrm{s}^{-1} \cdot \mathrm{cm}^{-2}$, 1 million less w.r.t. surface
- **Cryo-Platform**: a large underground milli-Kelvin infrastructure for astro-particle searches and low-temperature applications
- **External shields** from environmental radioactivity

Laboratori Nazionali del Gran Sasso (LNGS)



BULLKID-DM will use C17
Oxford Proteox-MX cryostat!



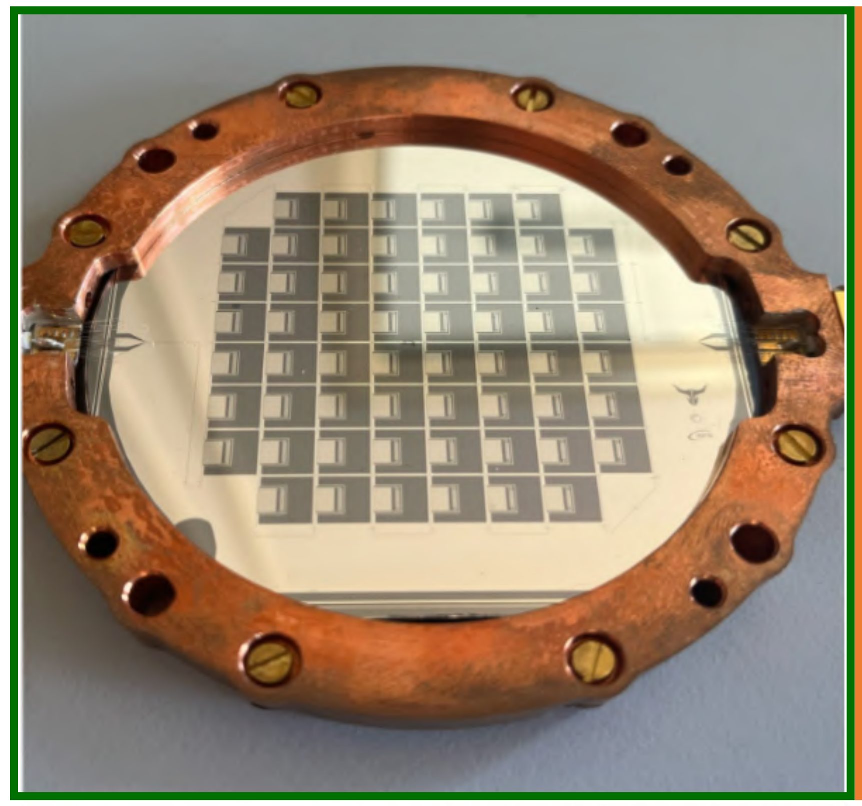
Commissioned in July 2025
Base temperature 9.8 mK!

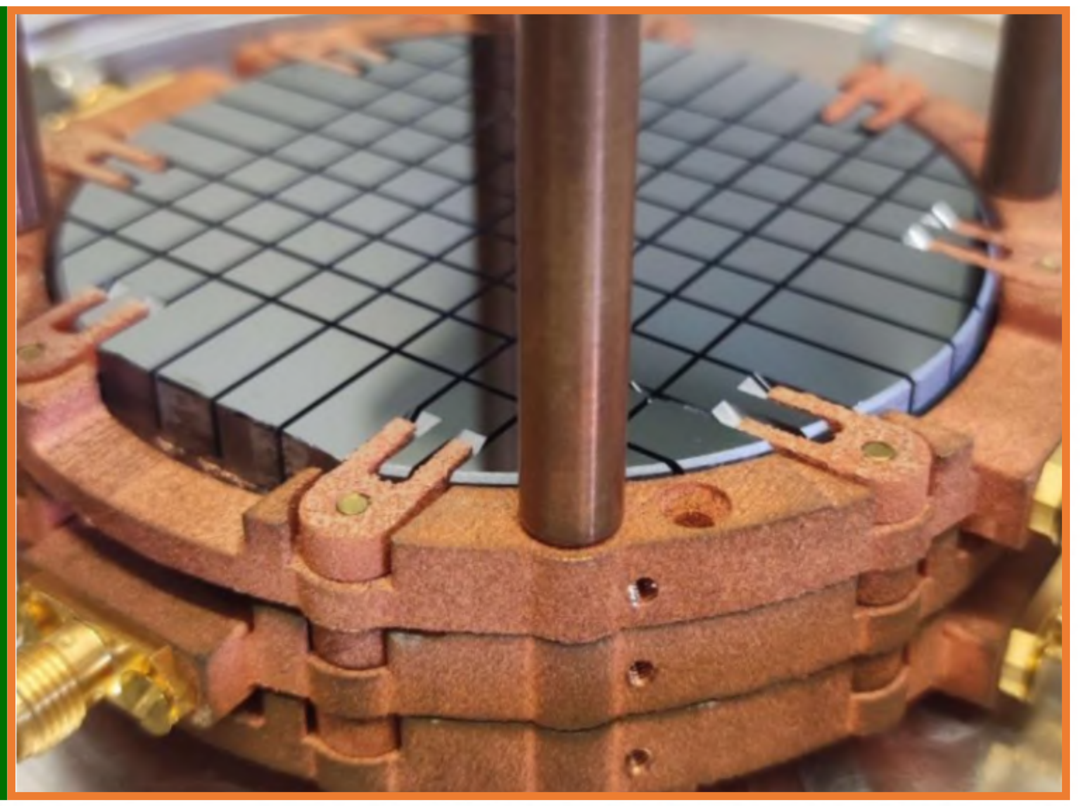
BULLKID-DM roadmap

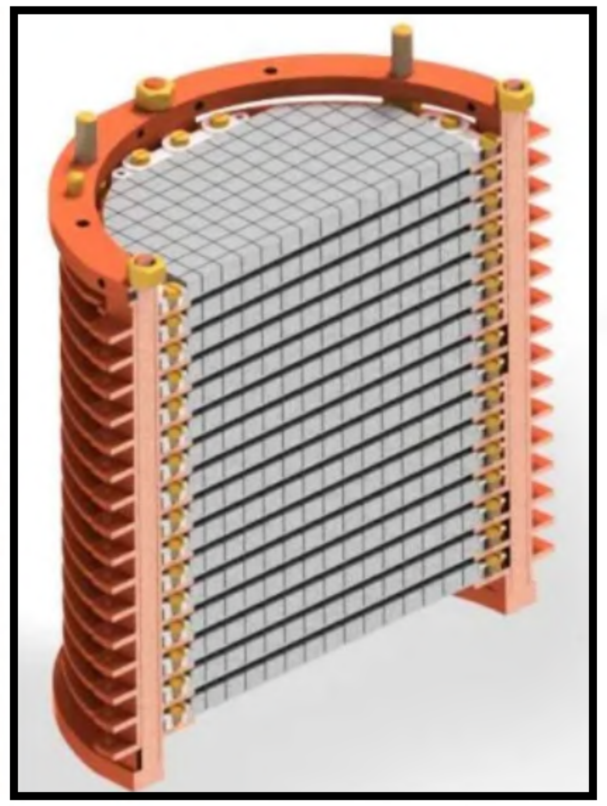
- Robust validations from prototype, demonstrator for final experiment

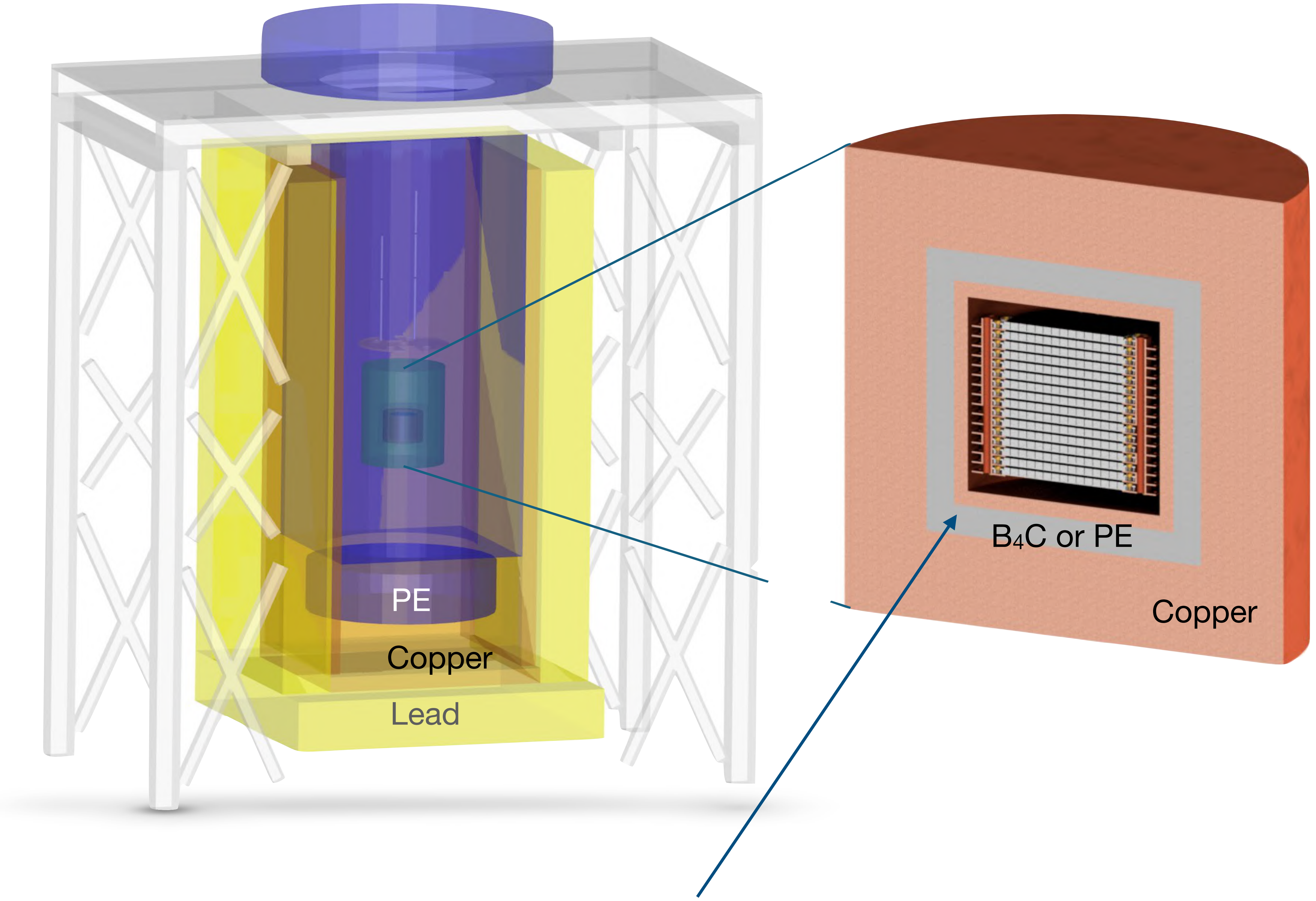
	BULLKID prototype	BULLKID-DM demonstrator		BULLKID-DM experiment
mass	20 g	60 g		800 g
# of KIDs	60	180		2300
threshold	160 eV	200 eV		≤ 200 eV
laboratory	Sapienza	Sapienza	LNGS	LNGS
installation	2023	2024-26	2026	2027
bkg [d.r.u]	2×10^6	7×10^4	$\sim 10^4$	1 - 0.01

We are here now!





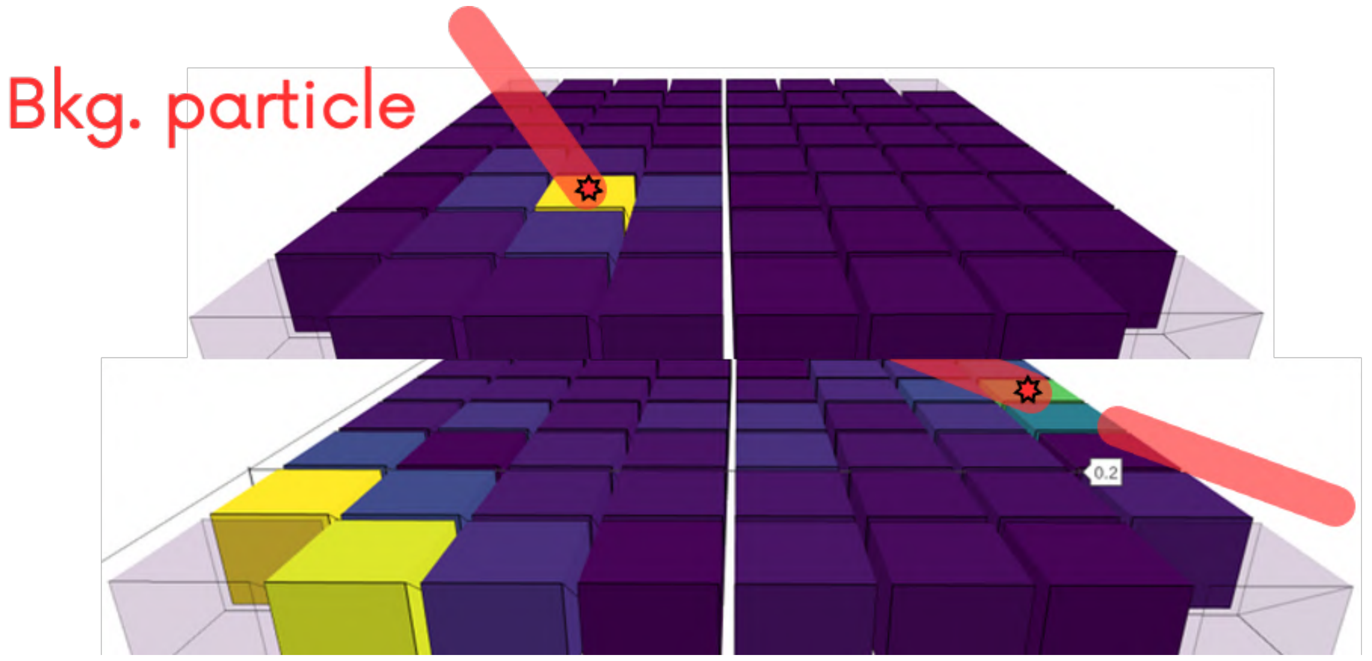


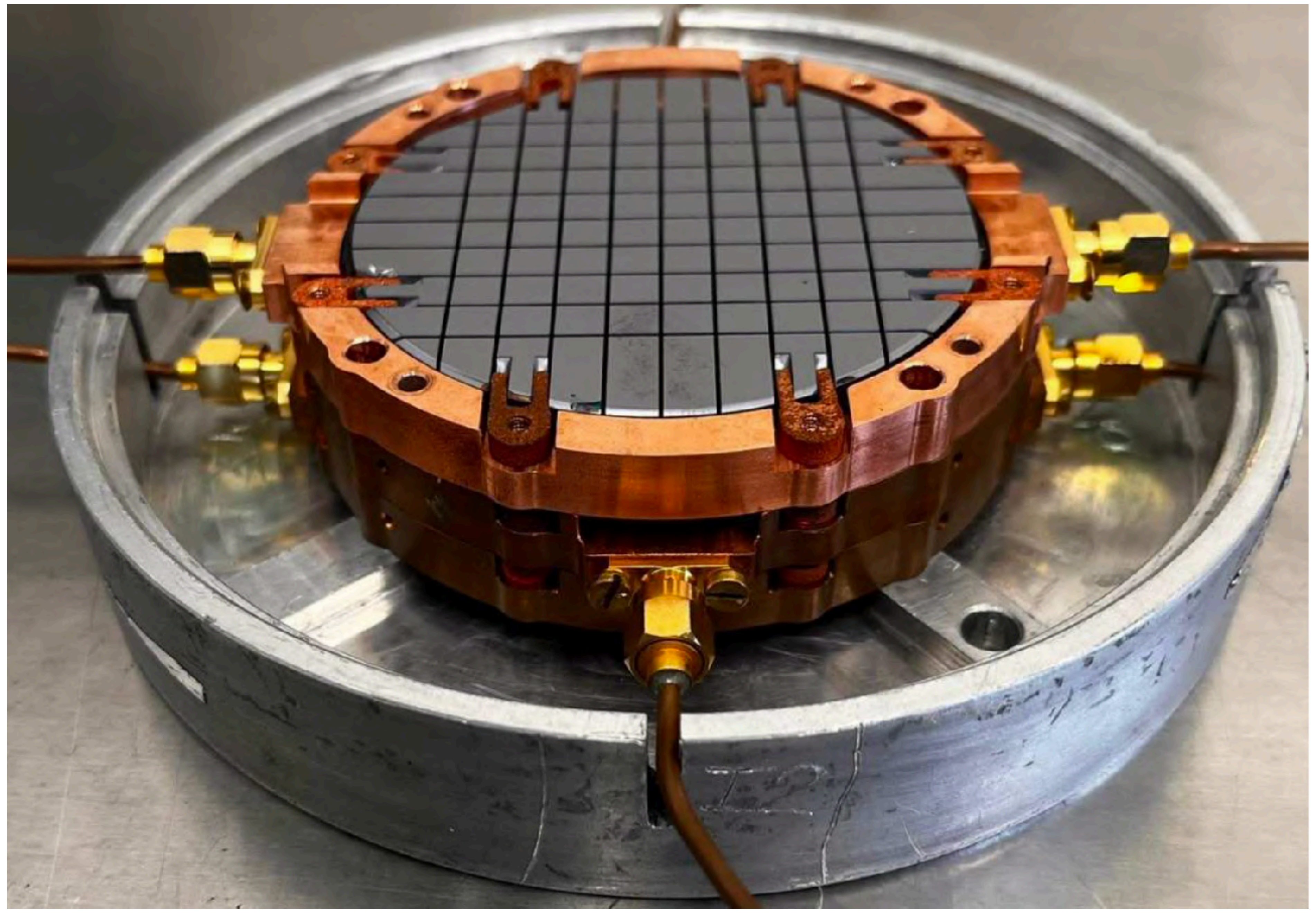


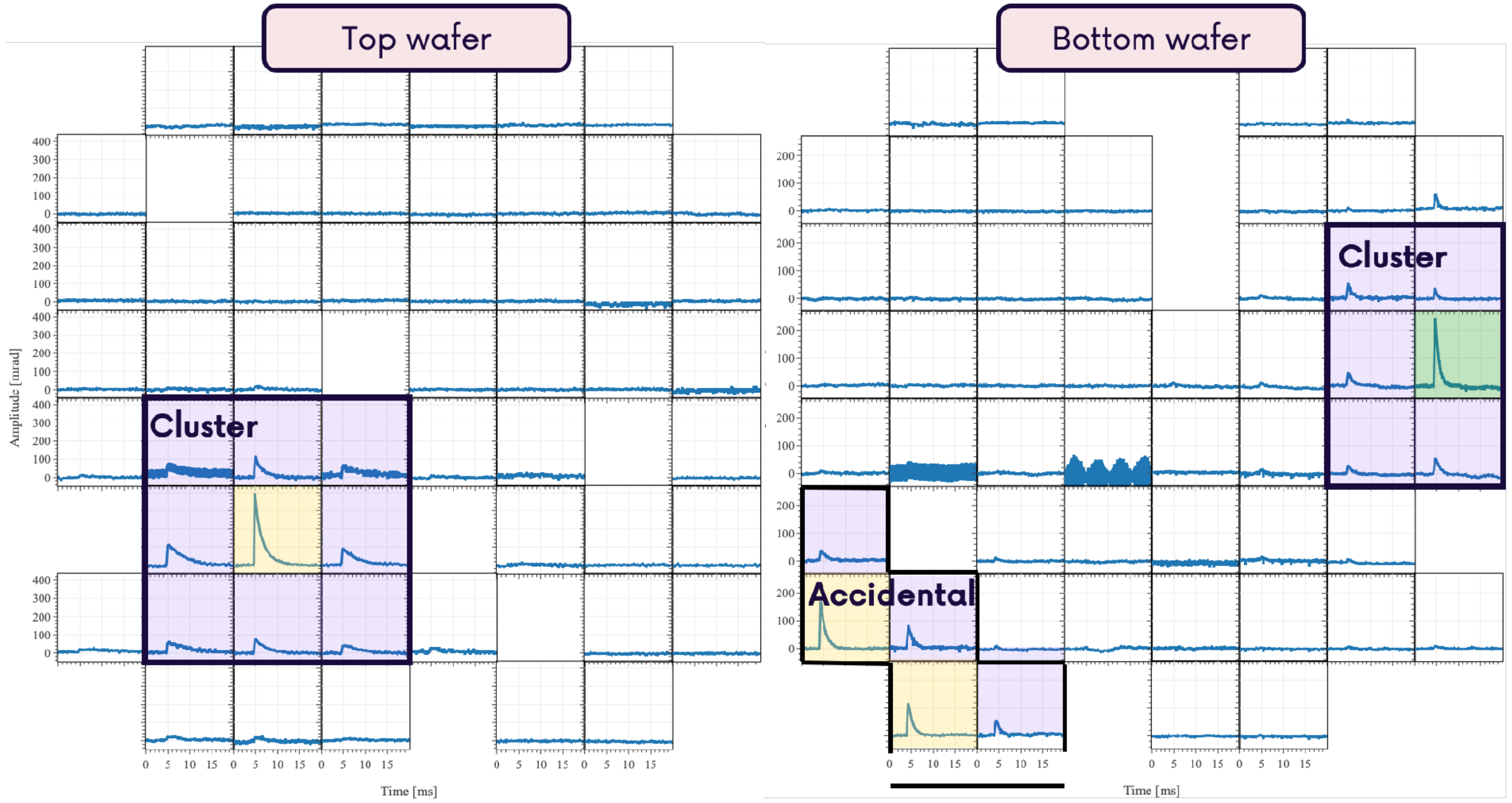
5-10x less background improvement in Simulation
If replaced B_4C with an active veto of BGO or GSO

Demonstrator with multiple wafers

- Validated detectors (158/180 working resonators)
- New electronics validated for acquisition in coincidence, finalizing DAQ
- Simultaneous readout of multiple arrays proved, with full characterization of electrical properties and energy calibration of more than 100 KIDs at once





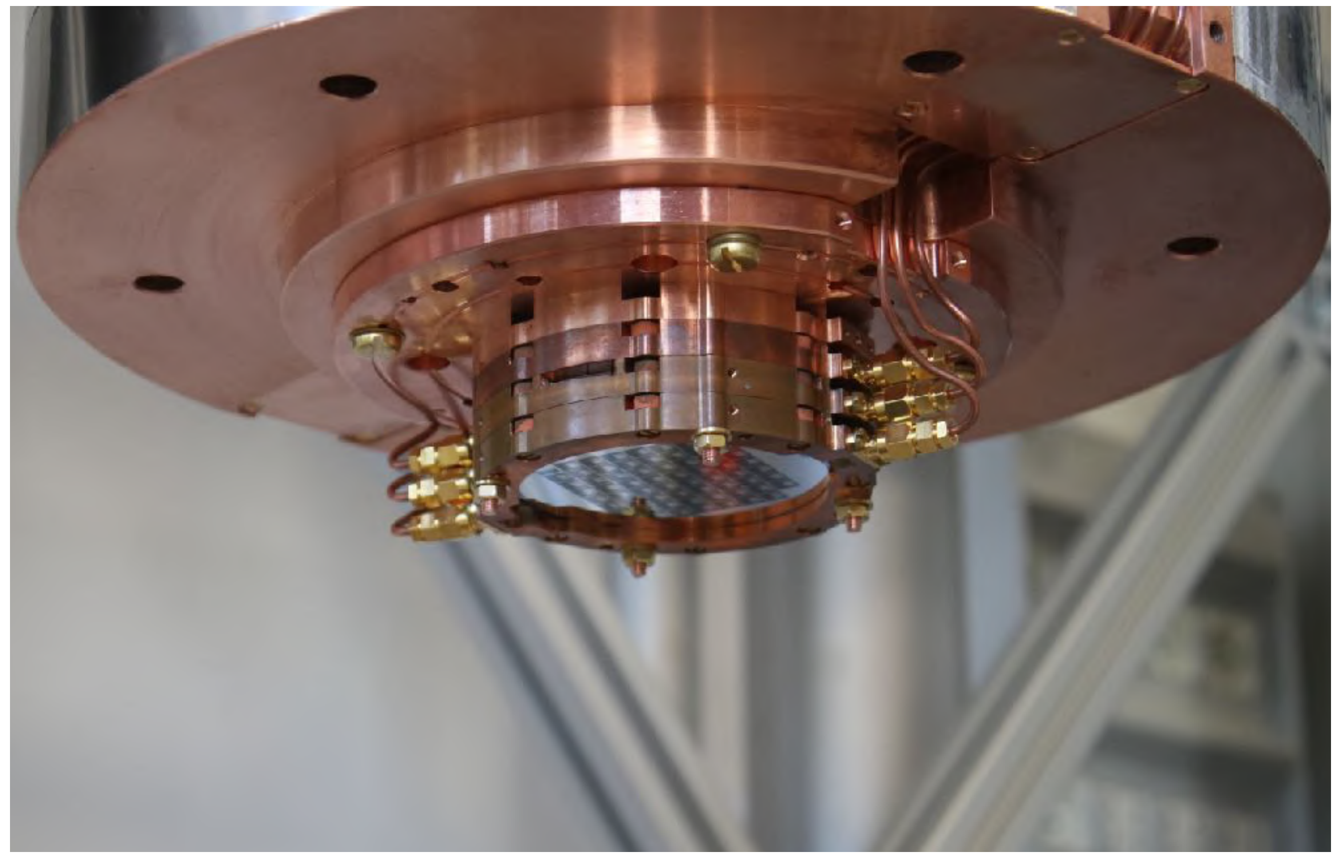


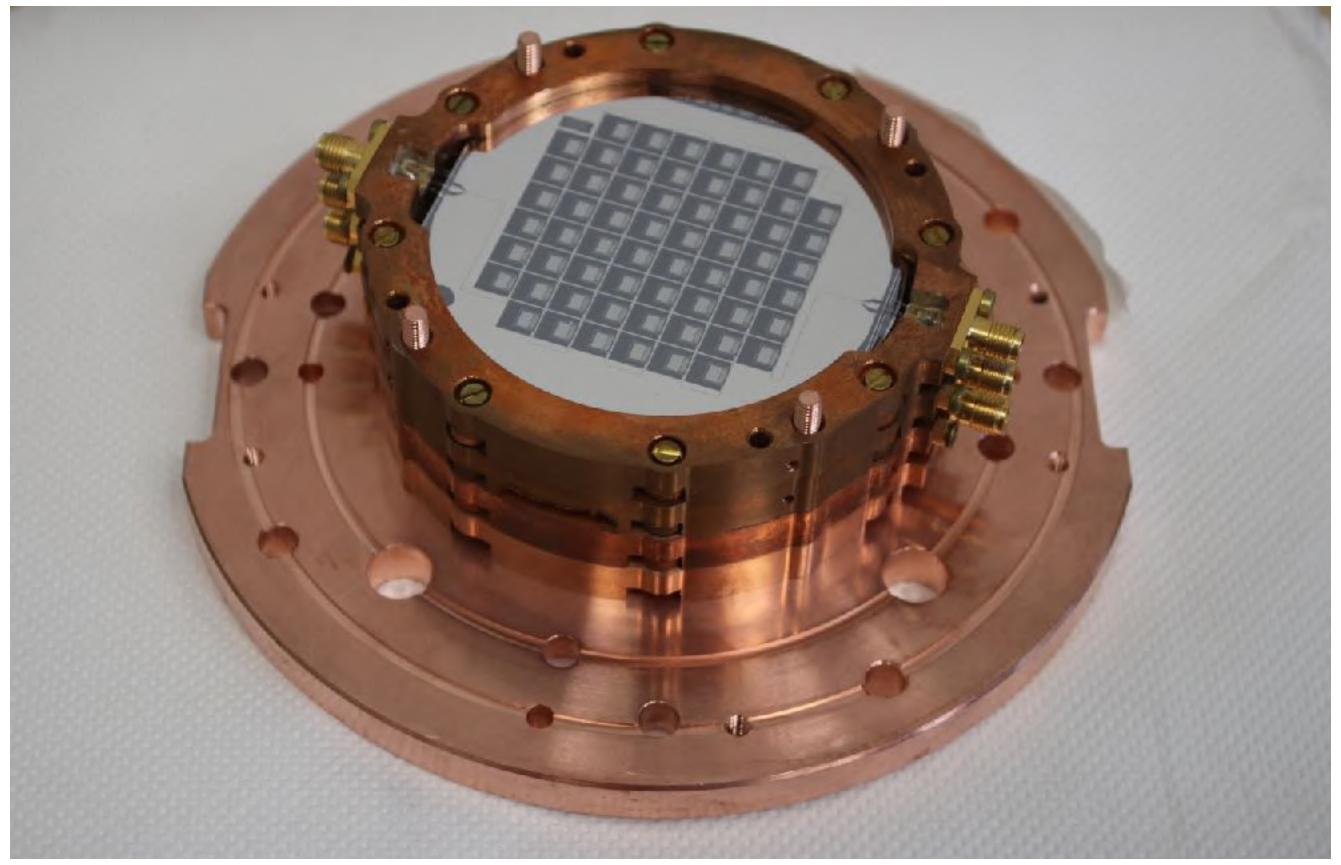
T. Muscheid, et al., *Real-Time Readout System Design for the BULLKID-DM Experiment: Enhancing Dark Matter Search Capabilities*, IEEE Trans. Appl. Supercond. 36 (2026)

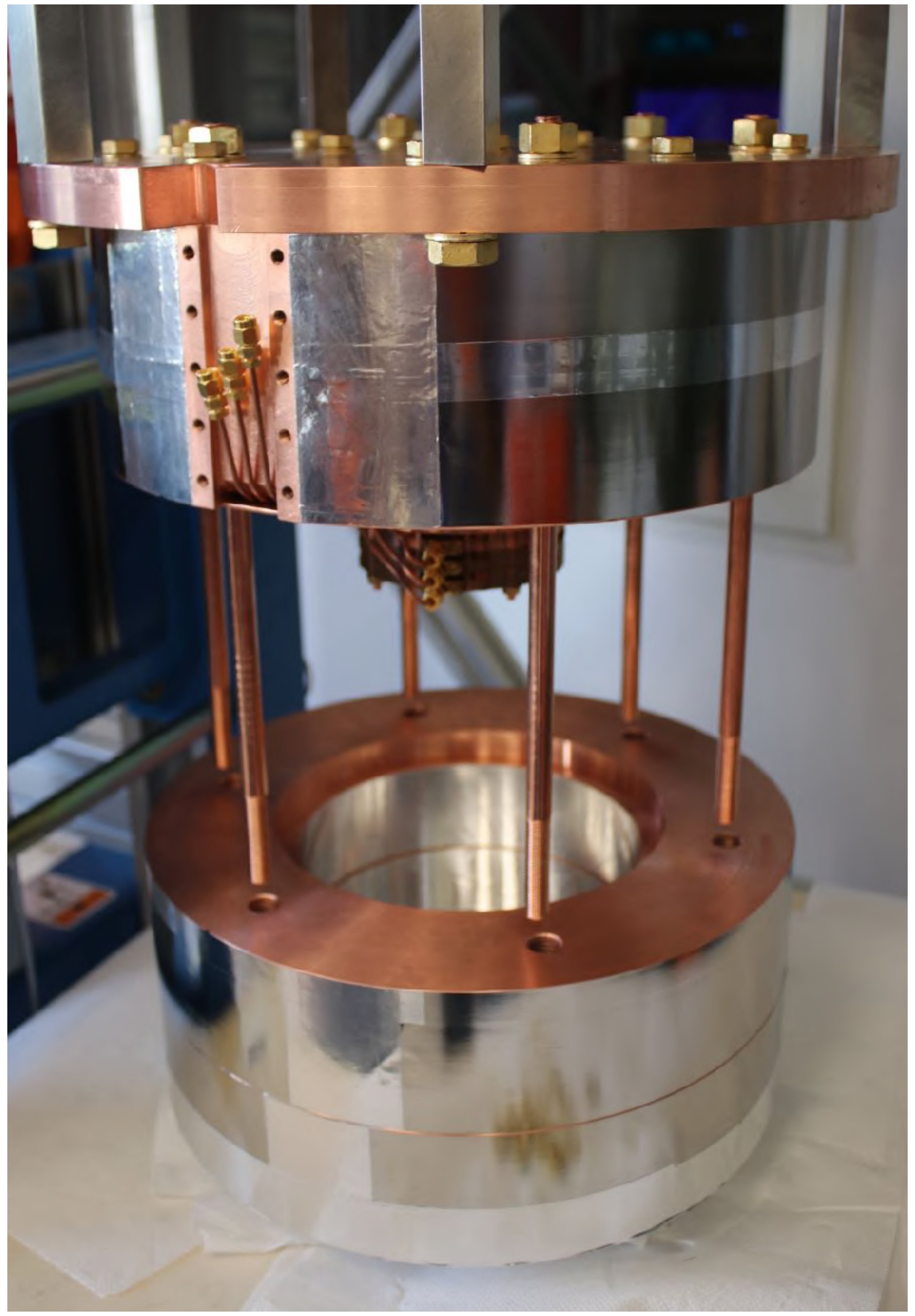
Demonstrator with inner copper shield

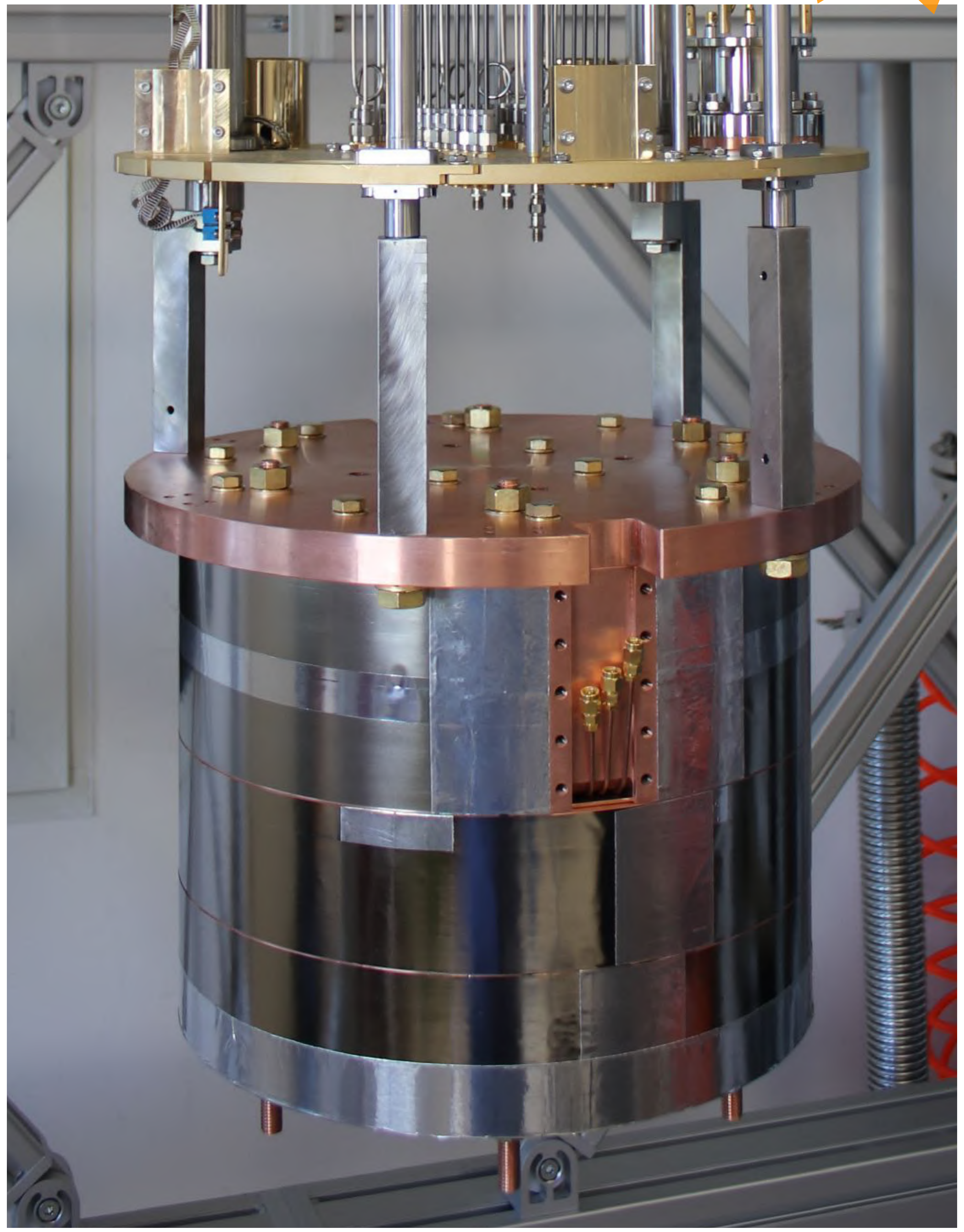
- Inner copper shield mounted in the twin cryostat in surface laboratory @Roma.Sapienza
- Waiting for cooling down to base temperature

Stay Tuned!





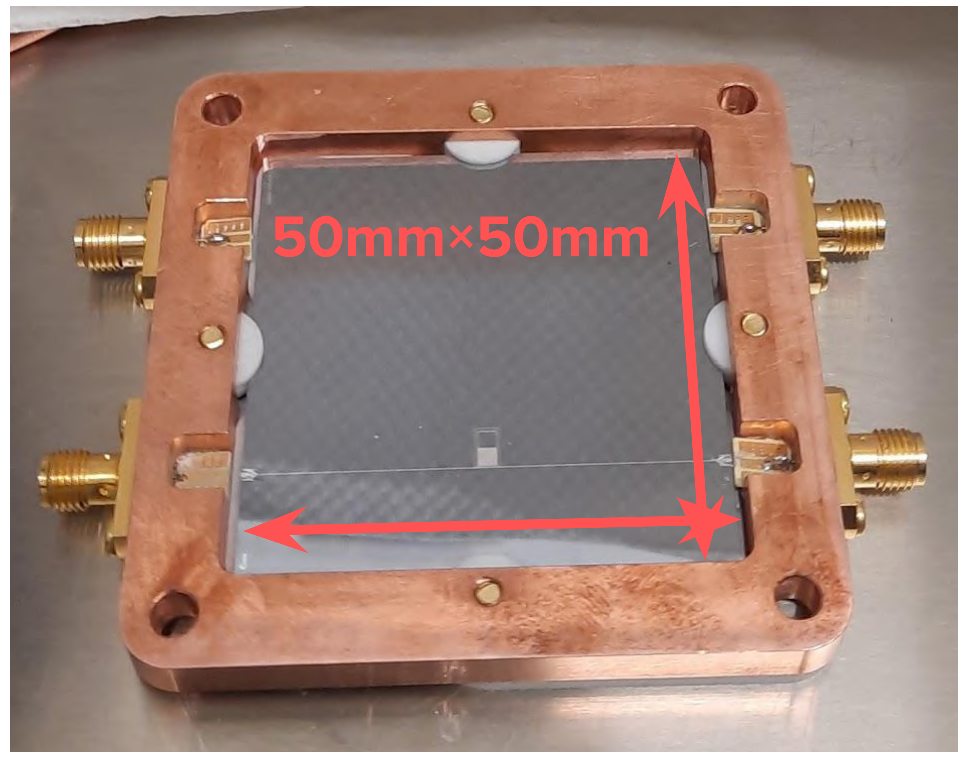




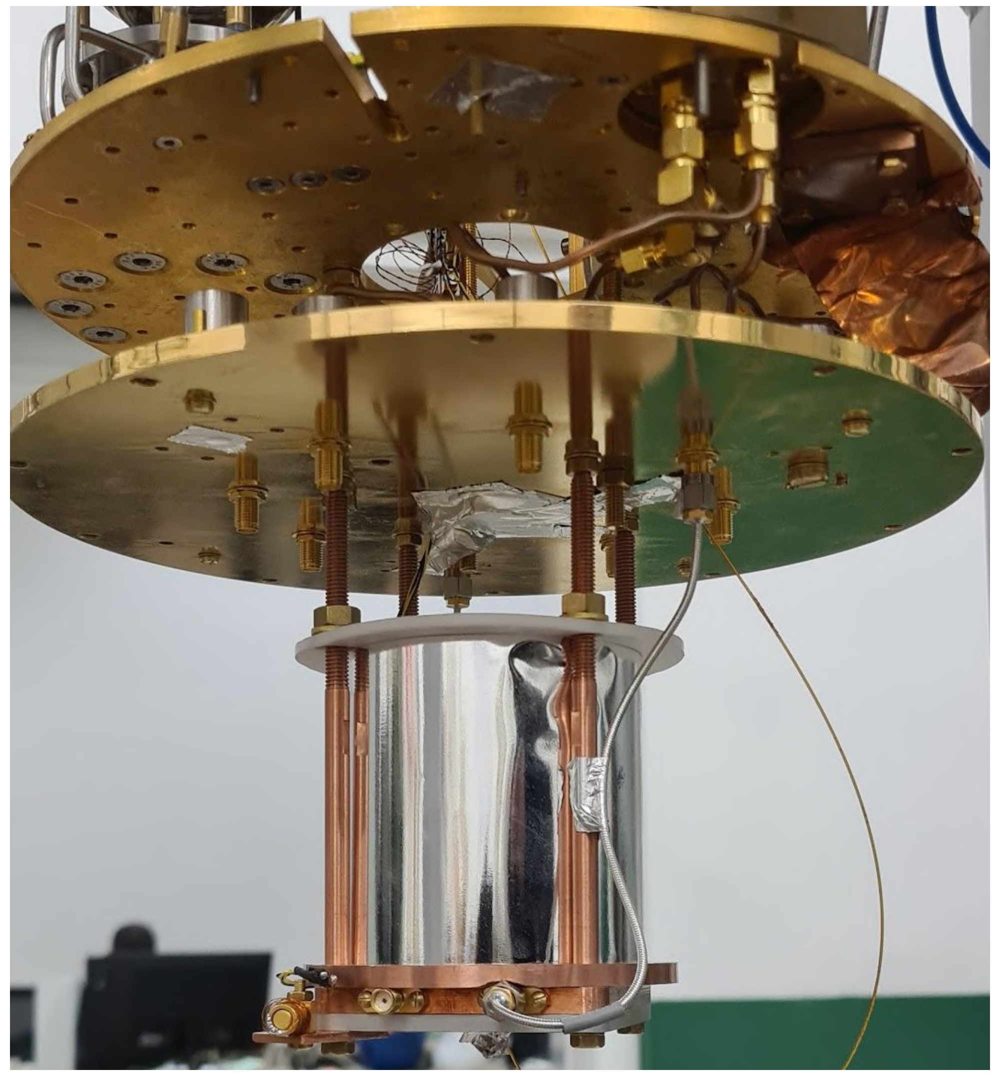
R&D Efforts

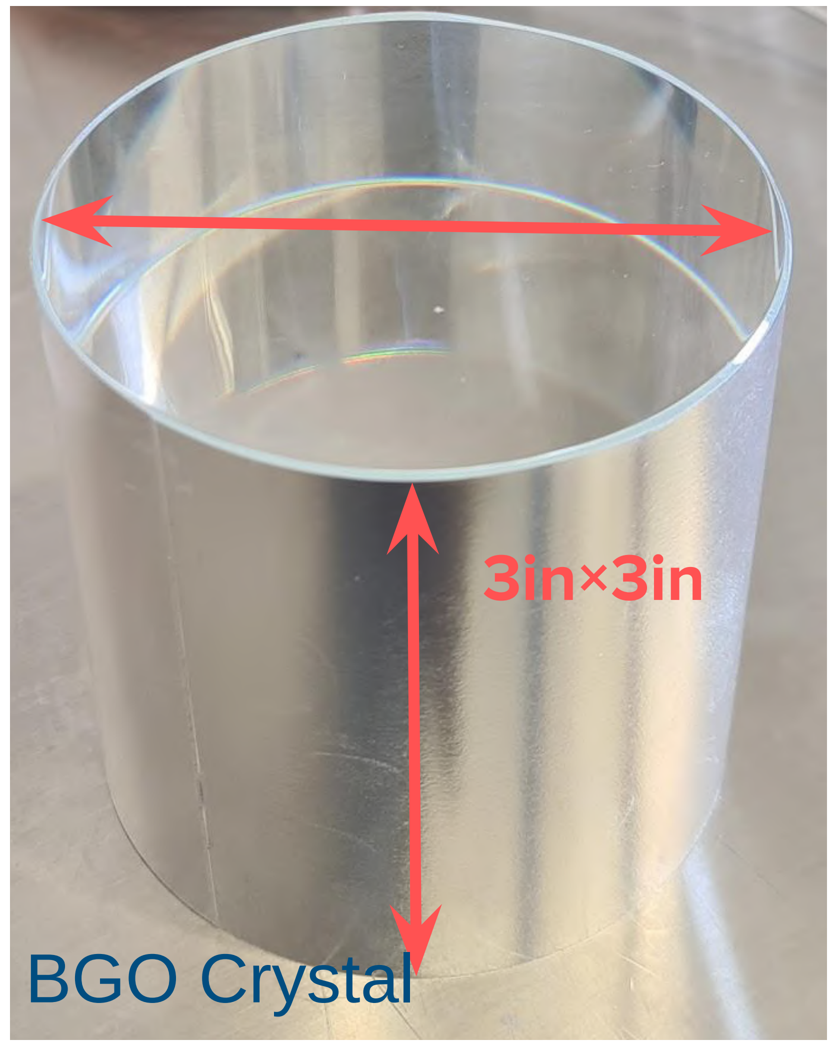
Cryogenic active veto

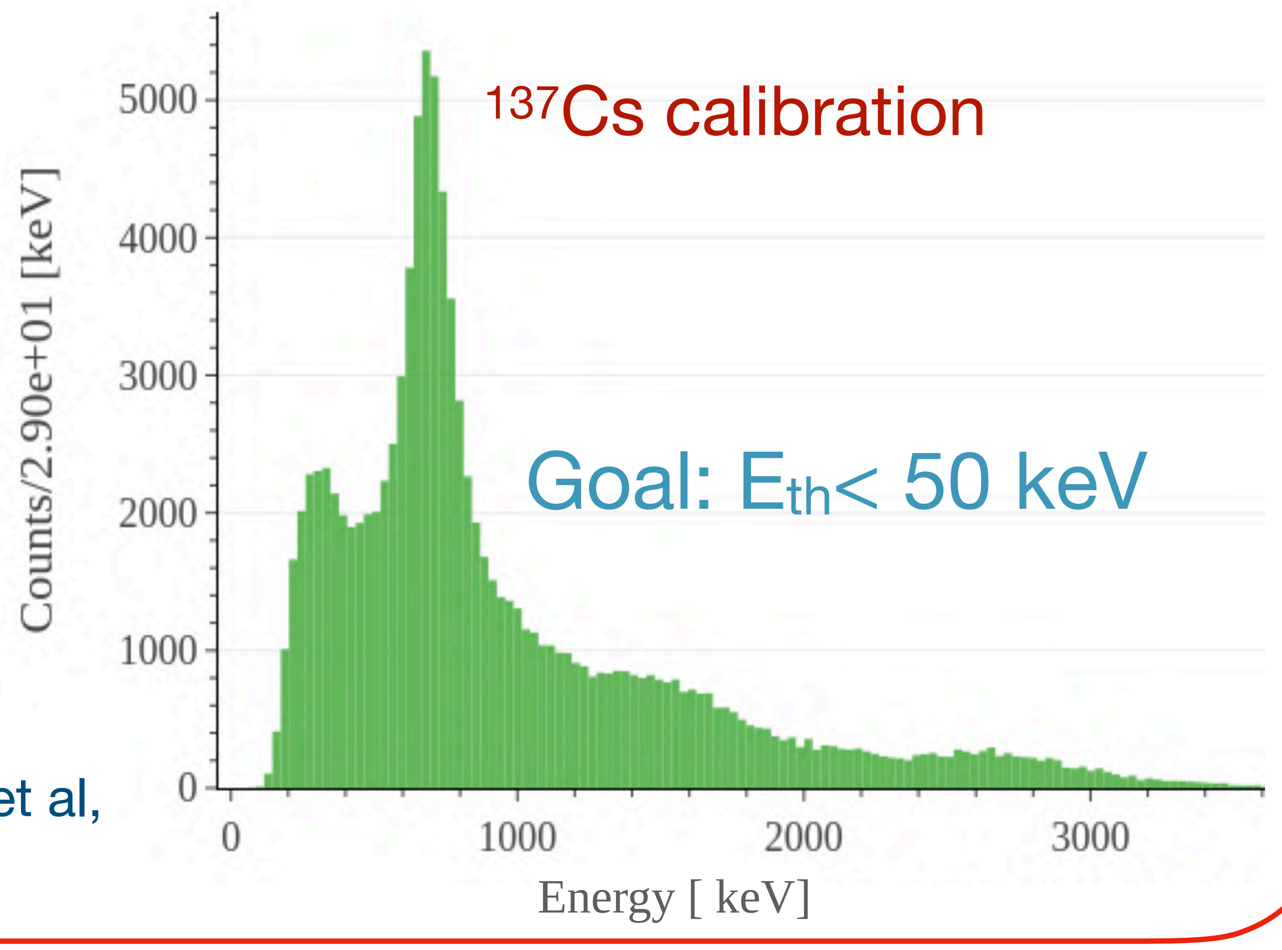
CALDER KID Light detector



Assembly with reflector

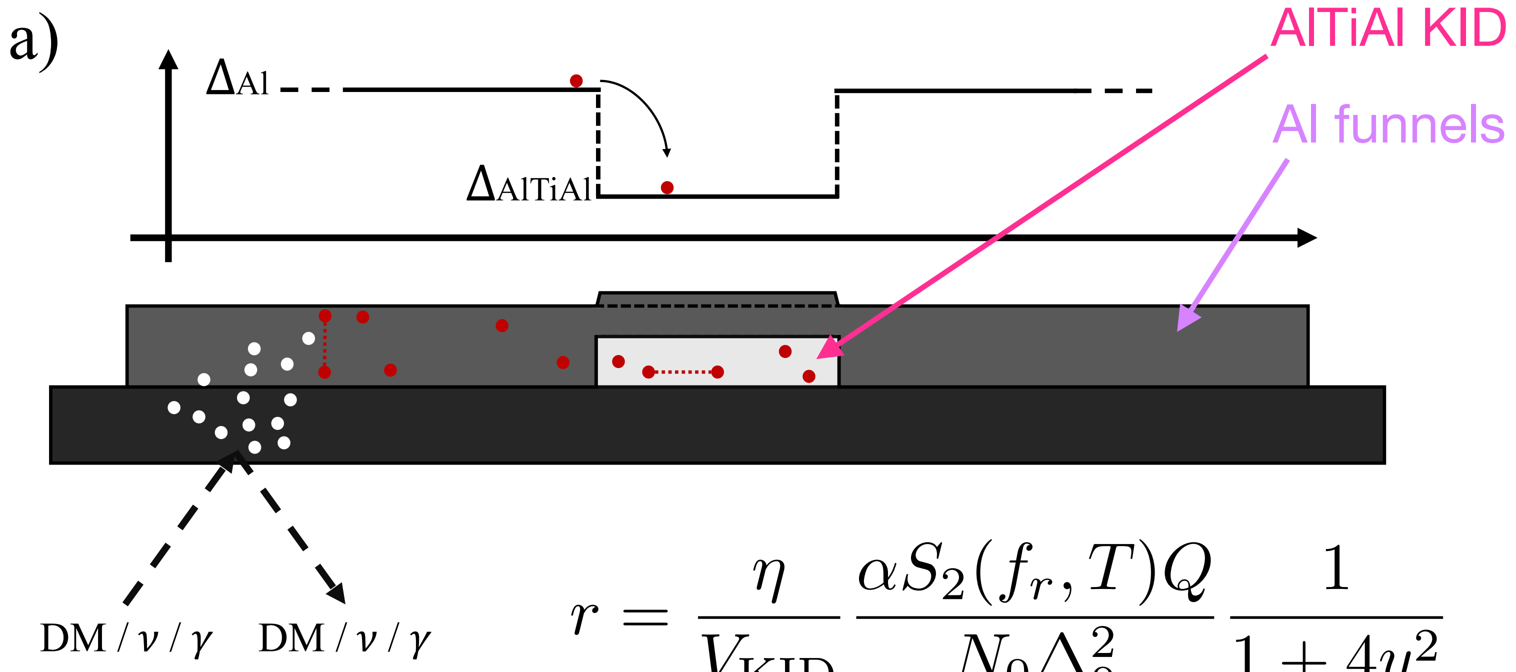




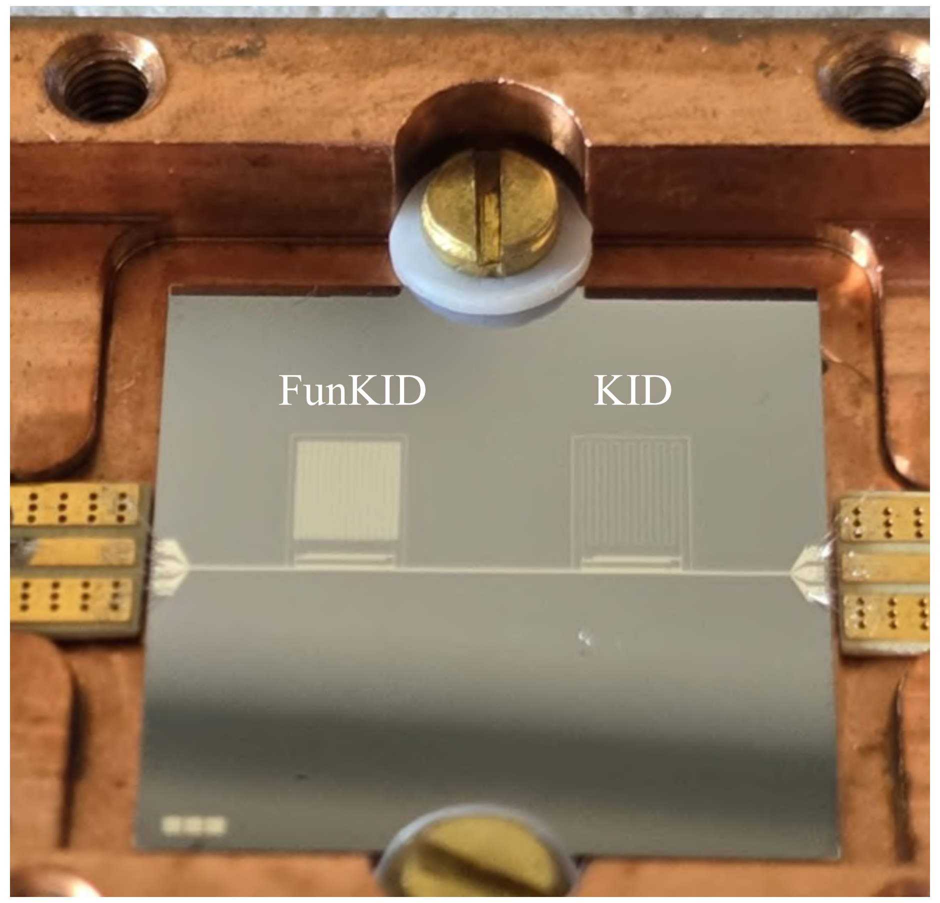


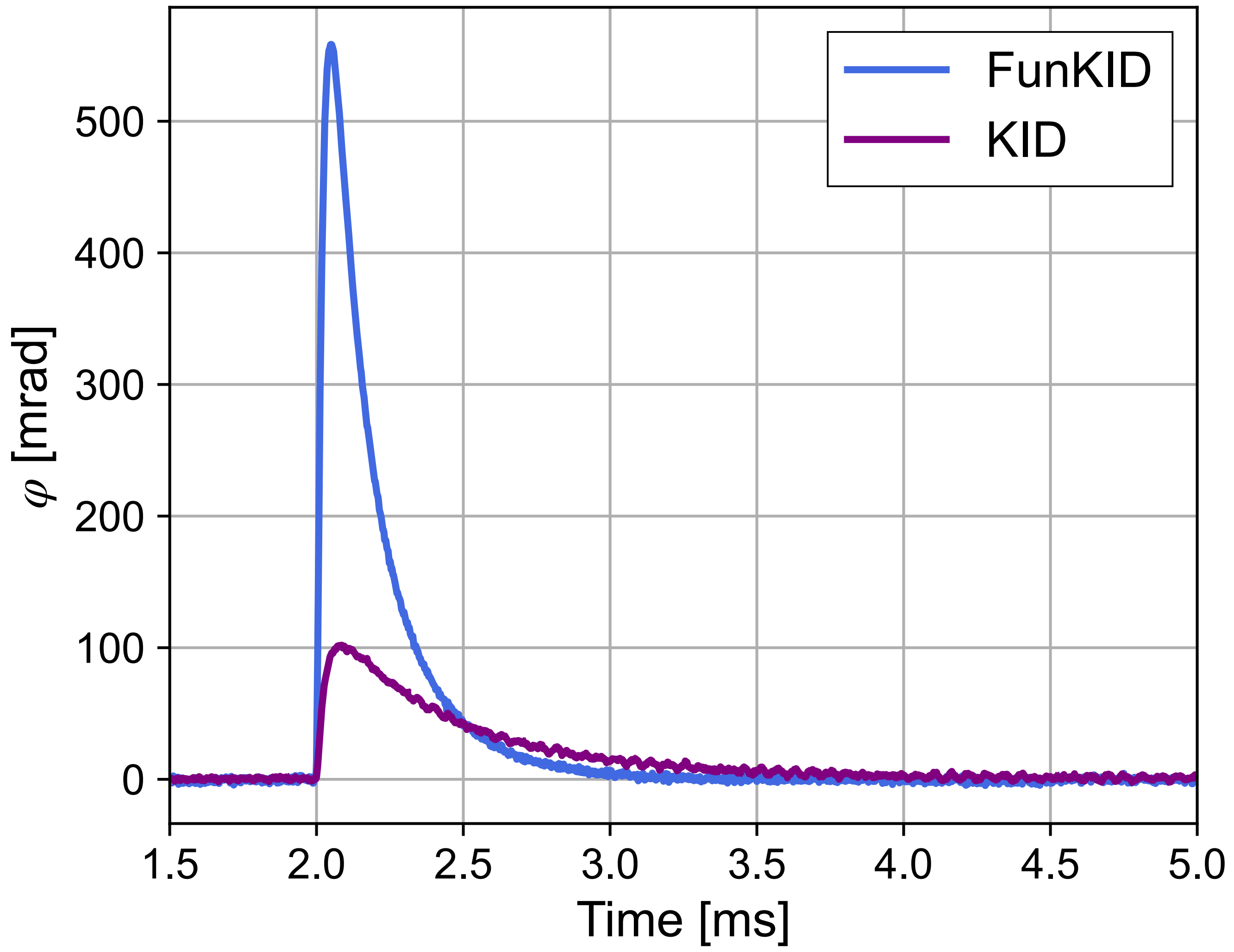
T. Lari, M. del Gallo Roccagiovine, et al, DOI 10.1109/TASC.2026.3665727

Responsivity enhanced KID



$$r = \frac{\eta}{V_{\mathrm{KID}}} \frac{\alpha S_2(f_r, T) Q}{N_0 \Delta_0^2} \frac{1}{1+4y^2}$$





	f_r [MHz]	Q_c [k]	Q_i [k]	Q [k]	τ_{ring} [μs]
FunKID	968.6	19	20	10	3
KID	1029.0	20	410	19	6

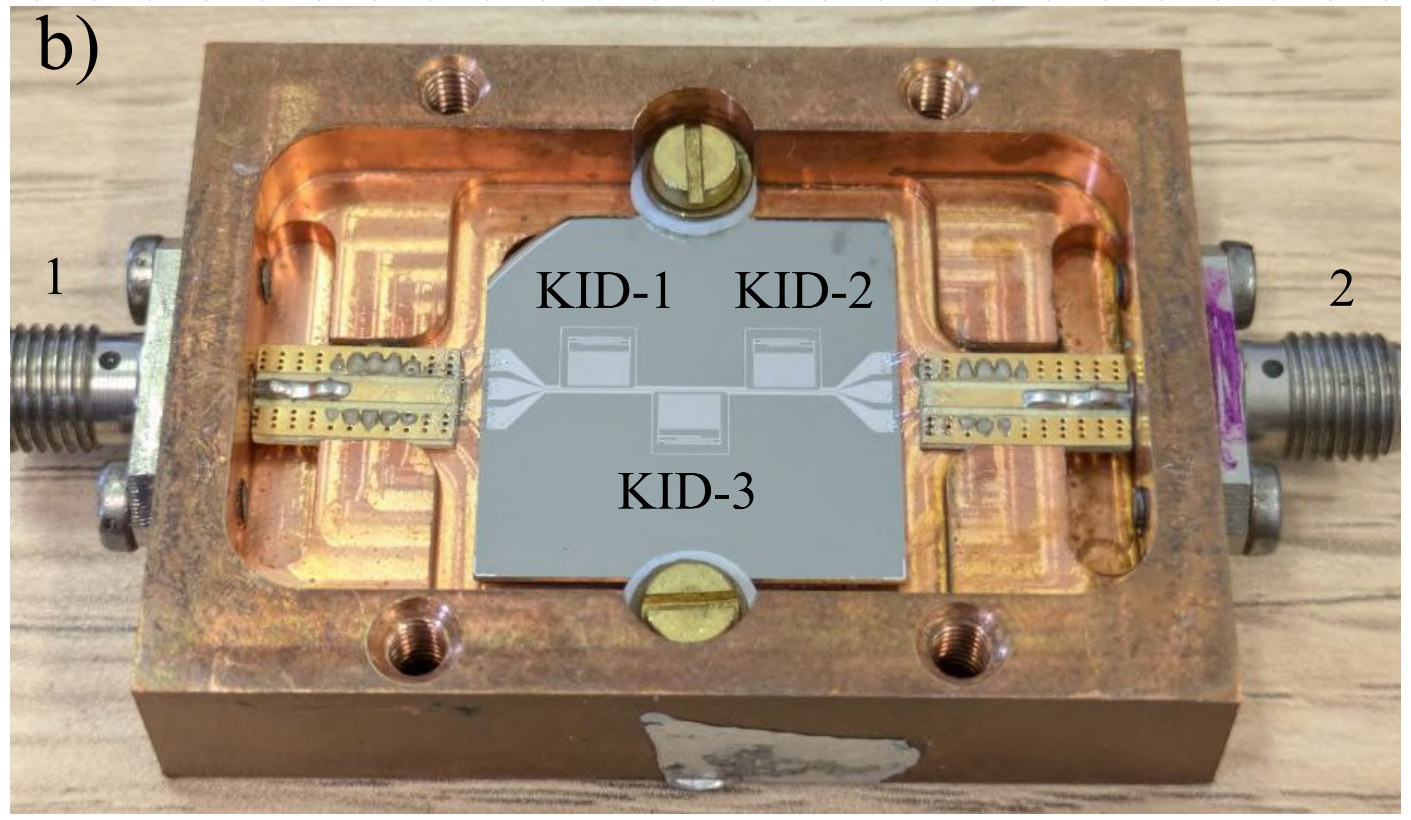
	FunKID	**KID**
P_{cal} [dBm]	-68	-62
r [mrad/keV]	5.85 ± 0.14	1.11 ± 0.04
σ_N [mrad]	0.386 ± 0.009	0.173 ± 0.005

Further work on Q and noise needed

L. Pesce et al, Appl. Phys. Lett. 128, 163504 (2026)

R&D Efforts

KIDs on Germanium

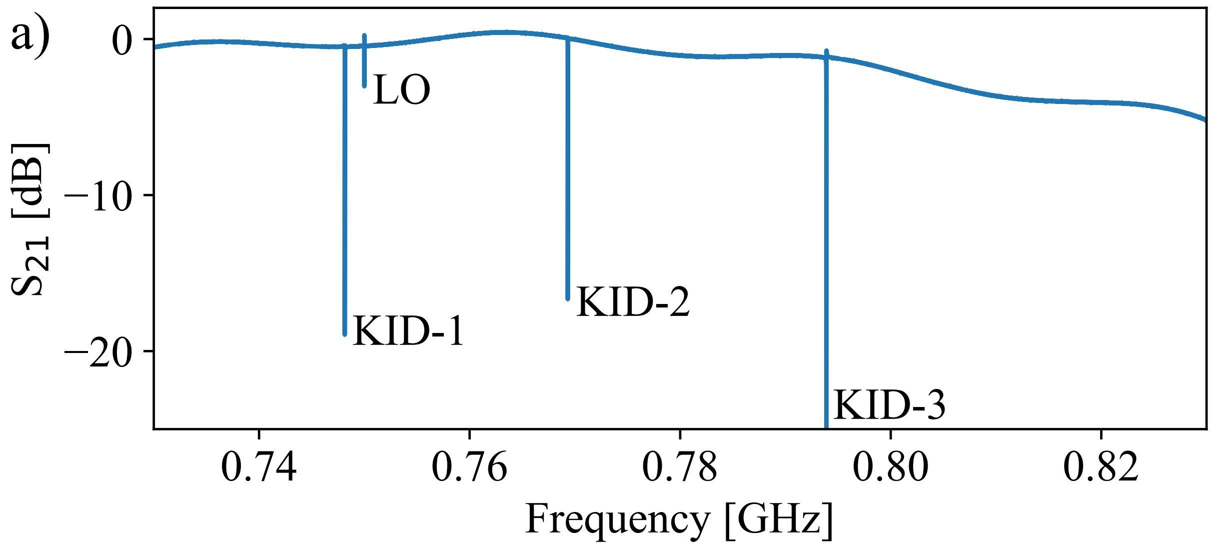


$$\sigma_{\mathrm{WIMP}} \propto A^2$$

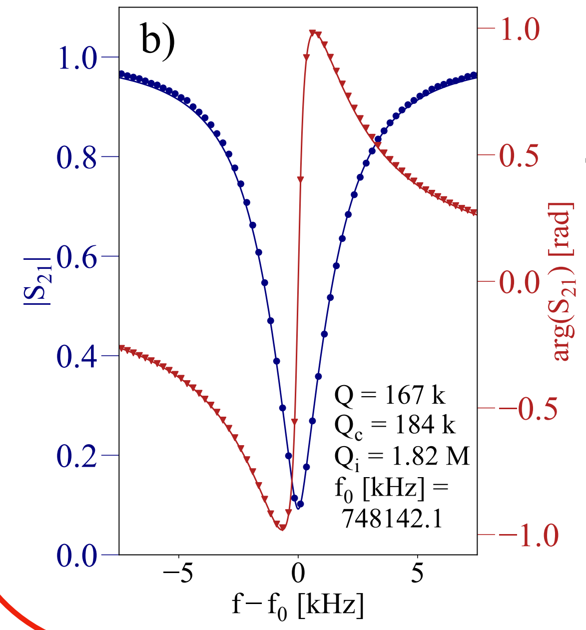
$$\sigma_{\mathrm{Ge}} \simeq 9 \cdot \sigma_{\mathrm{Si}}$$

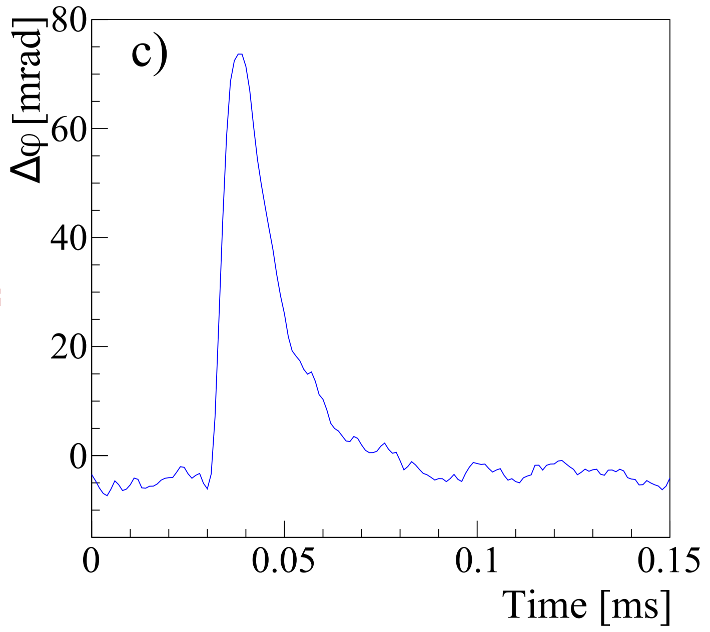
D. Delicato et al, *Appl.Phys.Lett.* 126 (2025) 153502

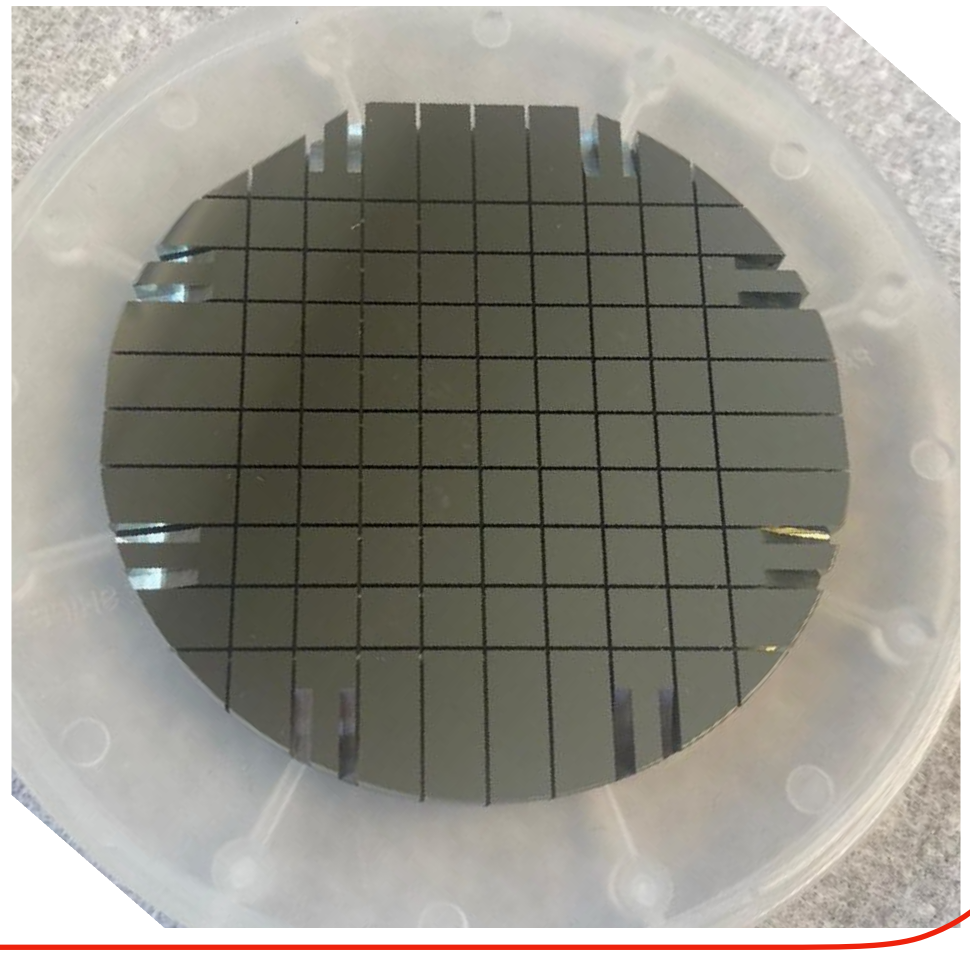
First proof of KIDs deposited on Ge substrates



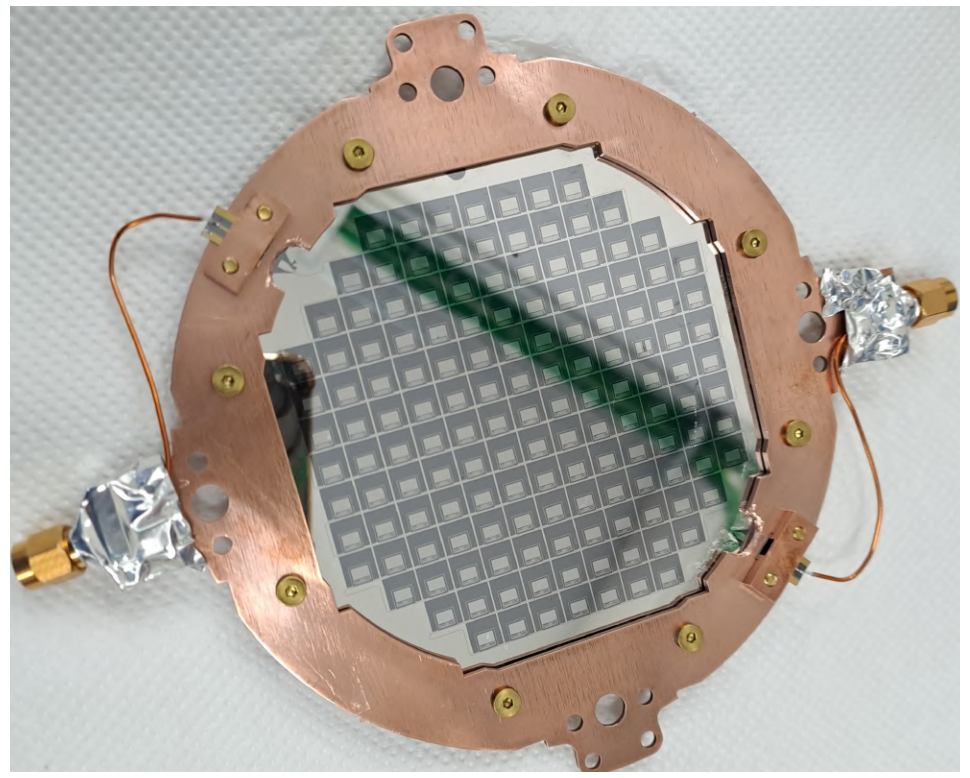
	f_0 [MHz]	Q [k]	Q_c [k]	Q_i [M]
KID-1	748.1	167	184	1.82
KID-2	769.3	114	120	2.24
KID-3	793.9	127	132	3.03
CALDER-17	2644	147	156	> 2



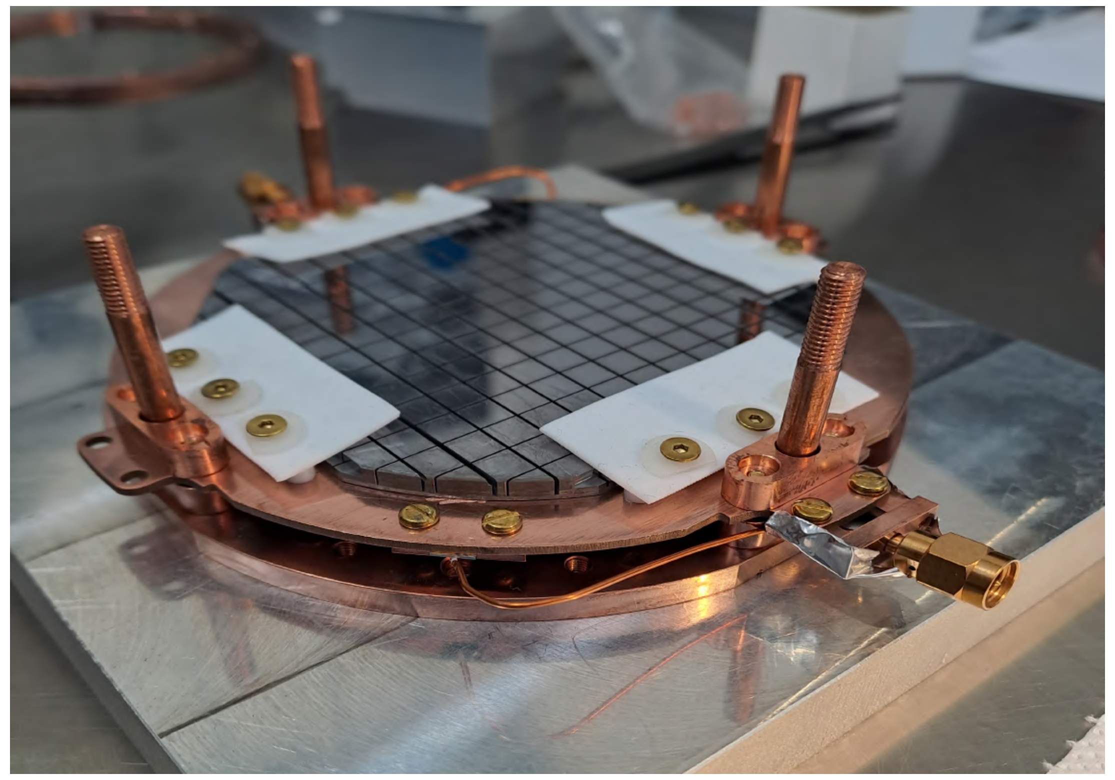




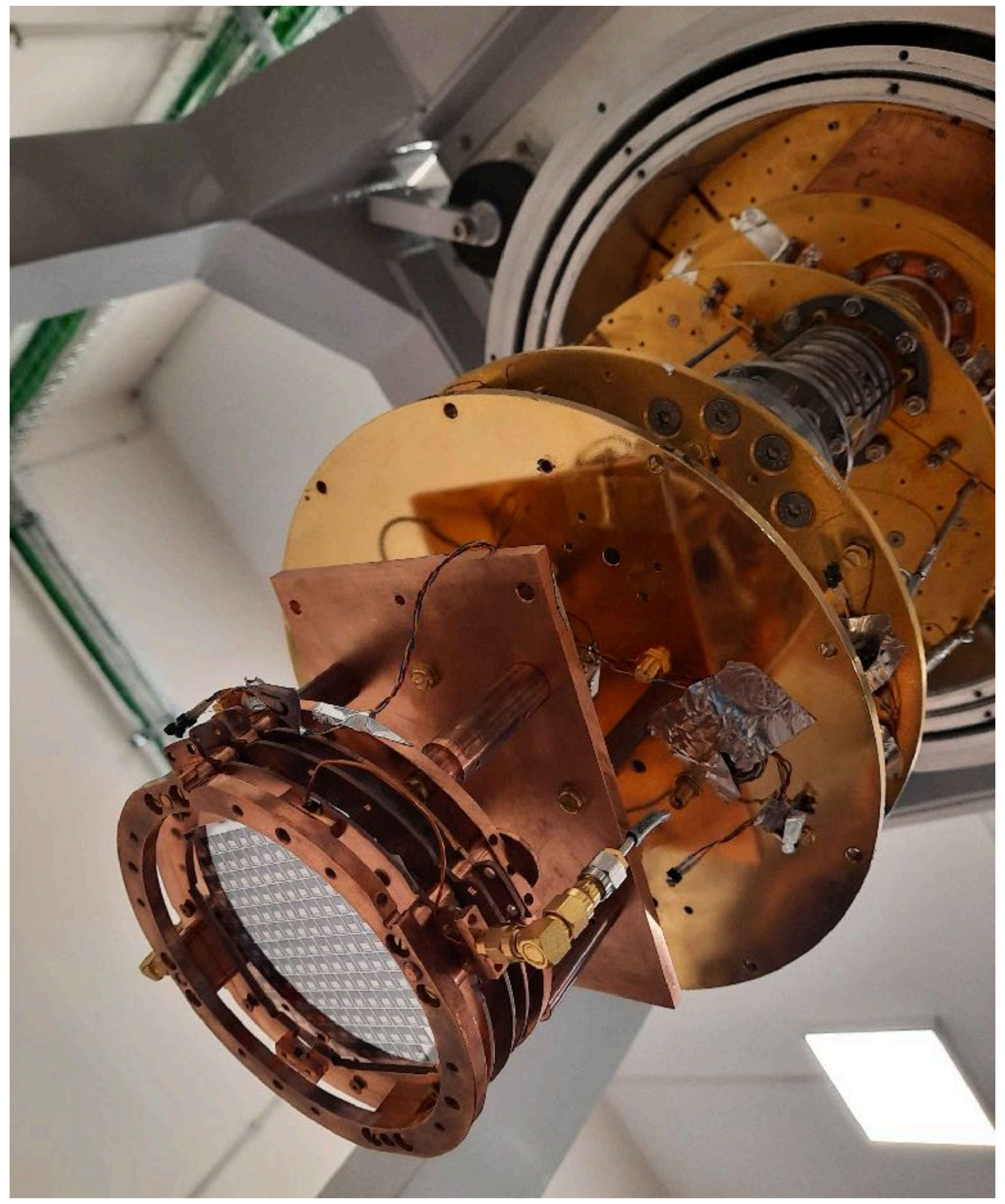
100-mm wafer exploring

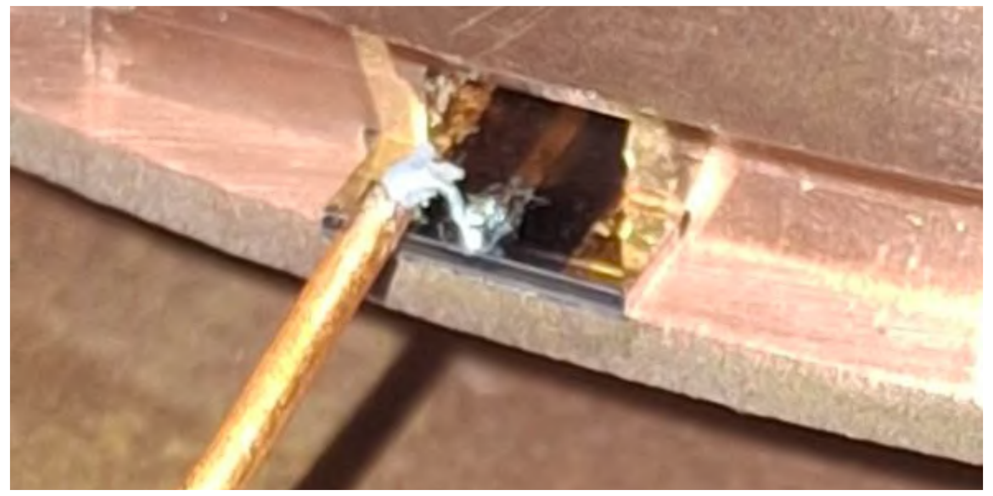


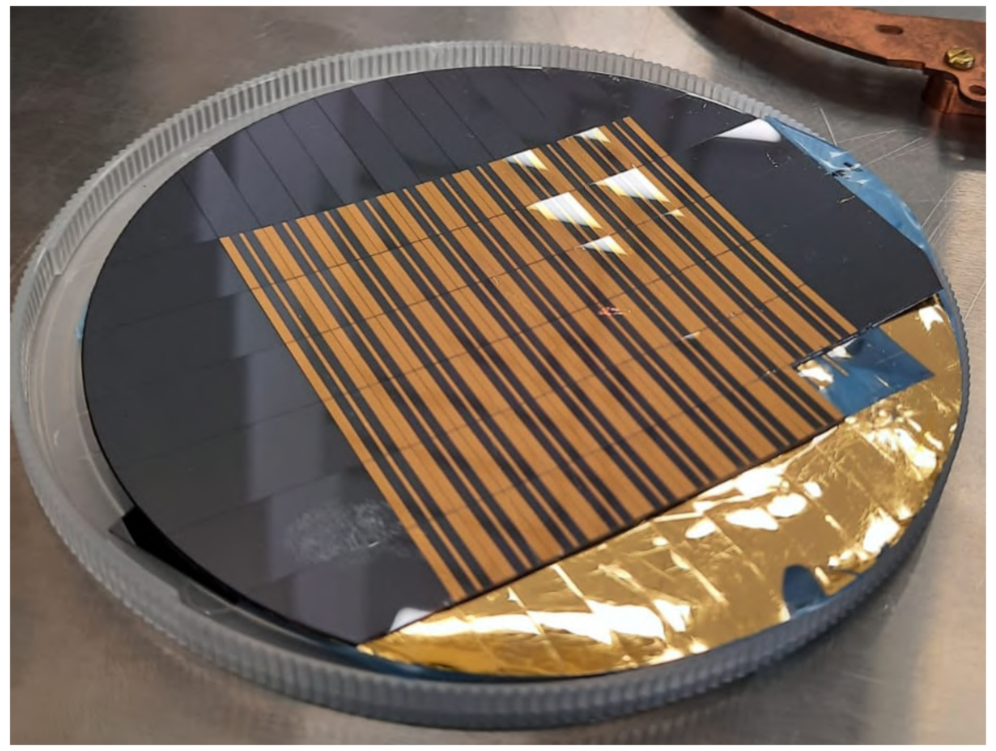
mounting/bonding



stacking



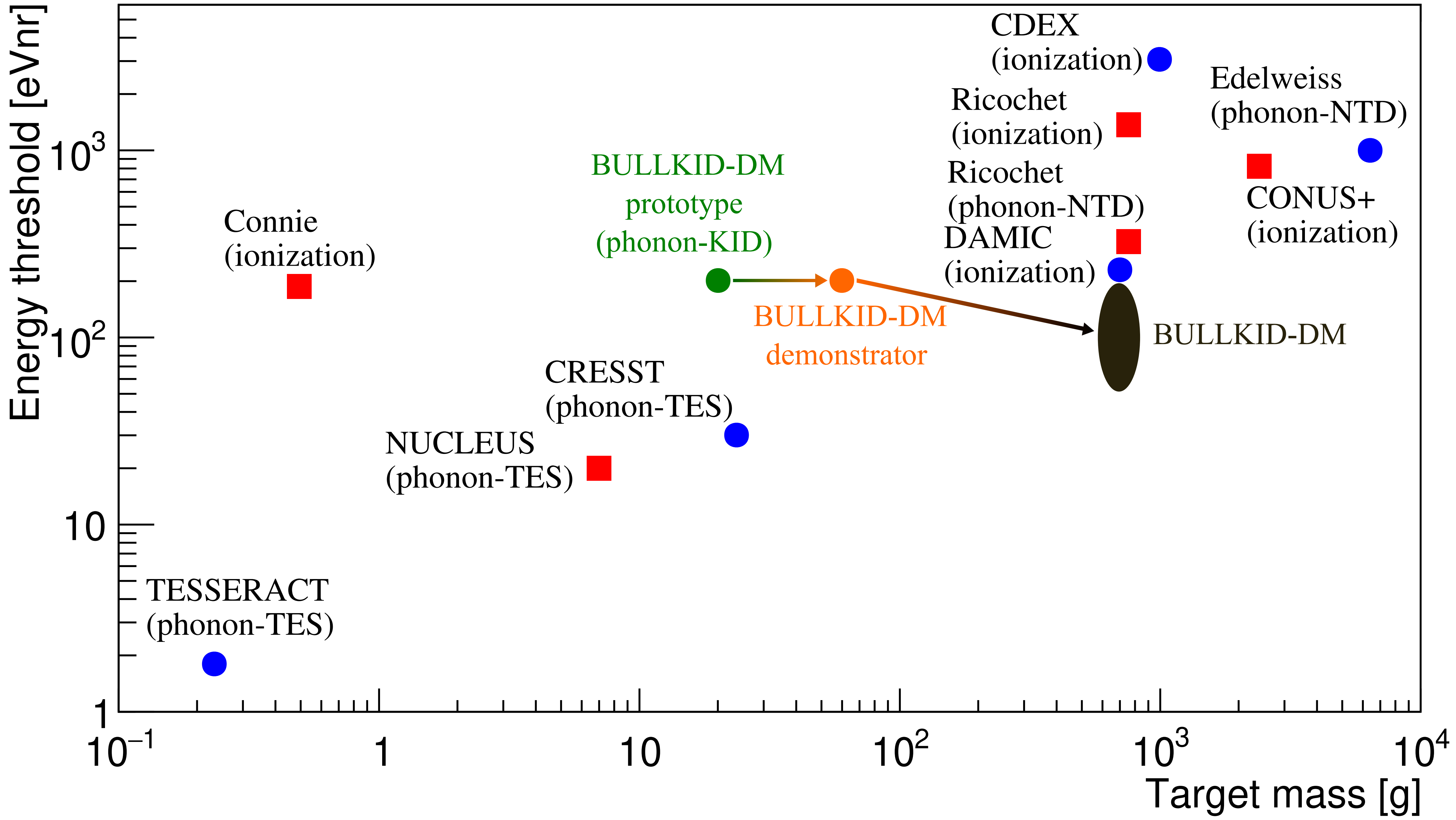




Silicon PCB: R&D to remove close-to-detector radioactivity

Conclusion

- A new promising experiment exploring Sub-GeV DM using monolithic cryogenic detector arrays
  - Fully active and multiplexed, fiducialization
- Operation of demonstrator on surface laboratory
  - Compatible observation with simulation for single-wafer with/without moderate shields
  - Multi-wafers operation validated, further measurement with cryogenic inner copper shields mounted
- Multiple efforts are ongoing for the deployment of final experiment
  - Detector upgrades, active cryogenic scintillating veto,
  - Radioactivity control, Background simulation



Thanks for your attention!

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European Research Council
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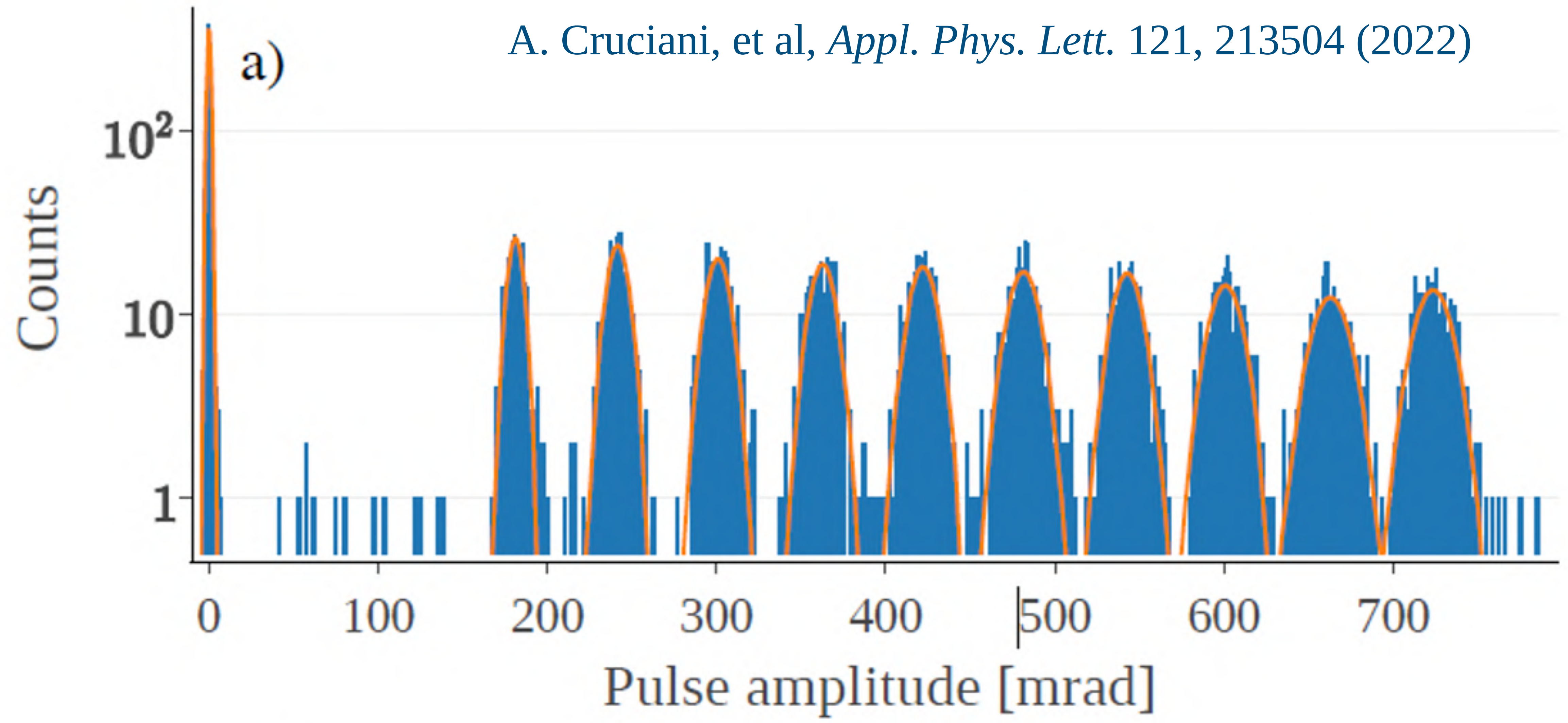
This work was partially supported through the European Research Council through the Consolidator Grant DANAE number 101087663

Backup slides

- Energy calibration using LED photons

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



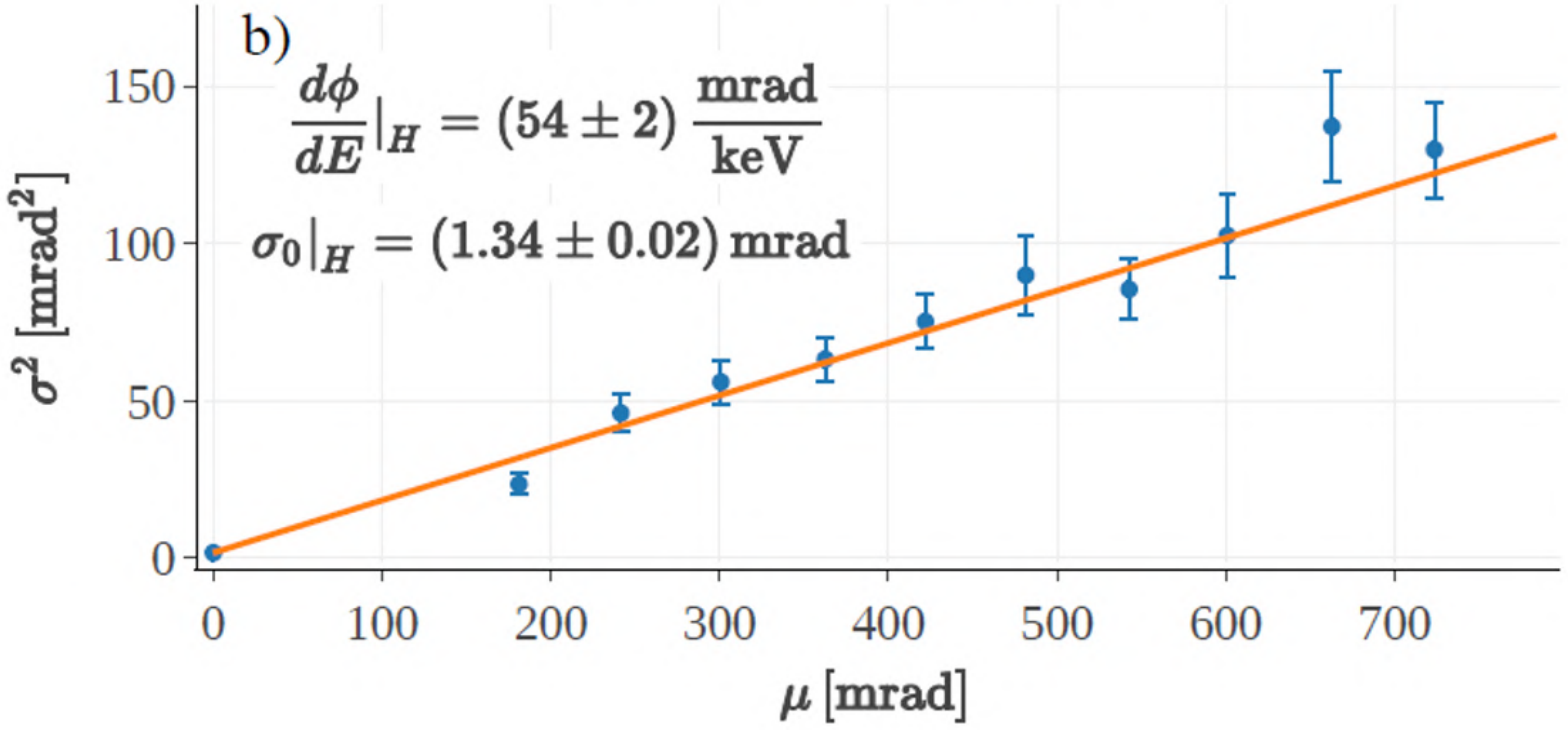
$$\sigma = \sqrt{\sigma_0^2 + \epsilon_{\text{photon}} \cdot \frac{\mathrm{d}\phi}{\mathrm{d}E} \cdot \mu}$$

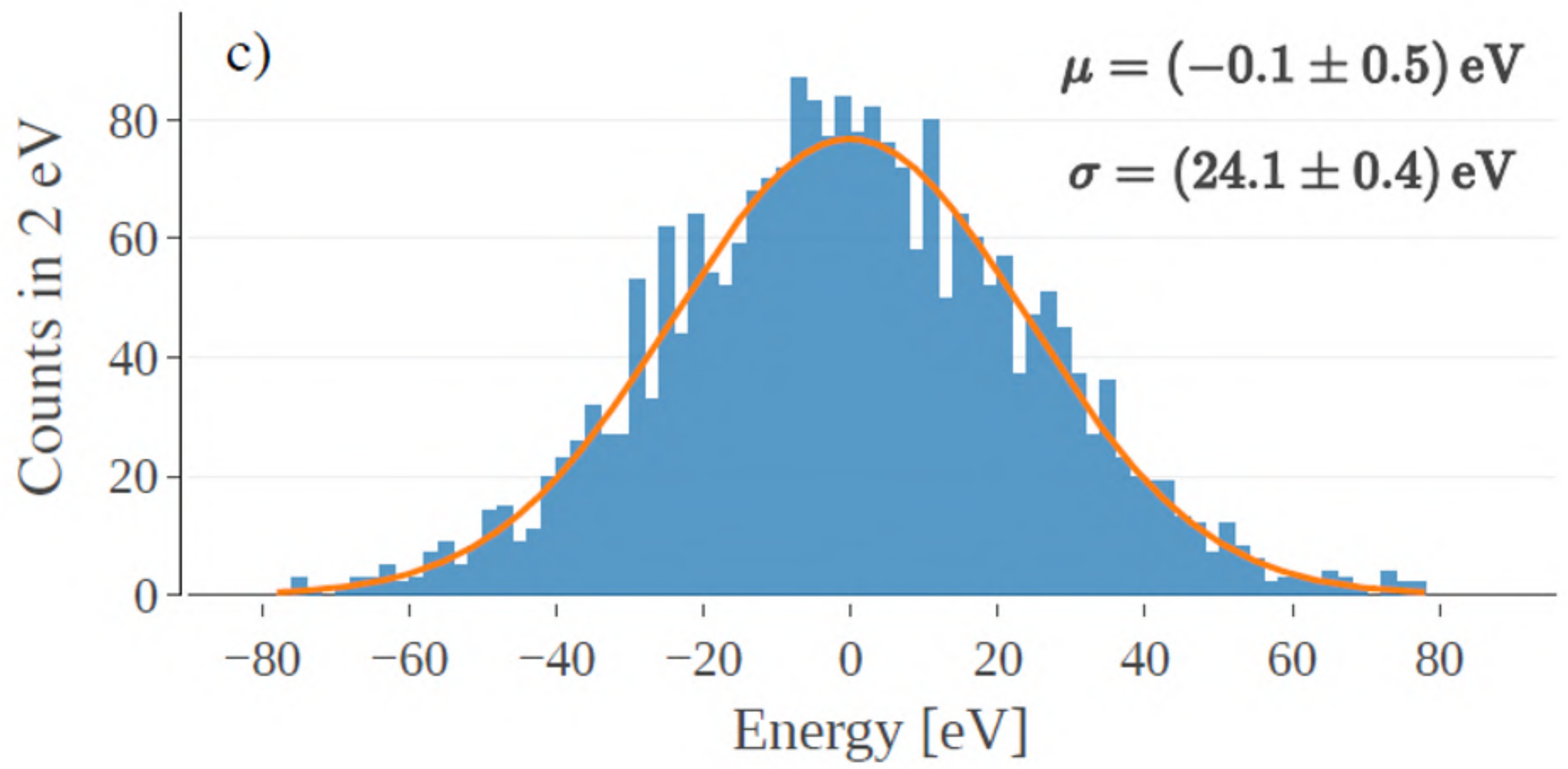
- σ_0 → Baseline resolution (phonon)
- $\frac{\mathrm{d}\phi}{\mathrm{d}E}$ → KID responsivity

Average resolution across 8 pixels:

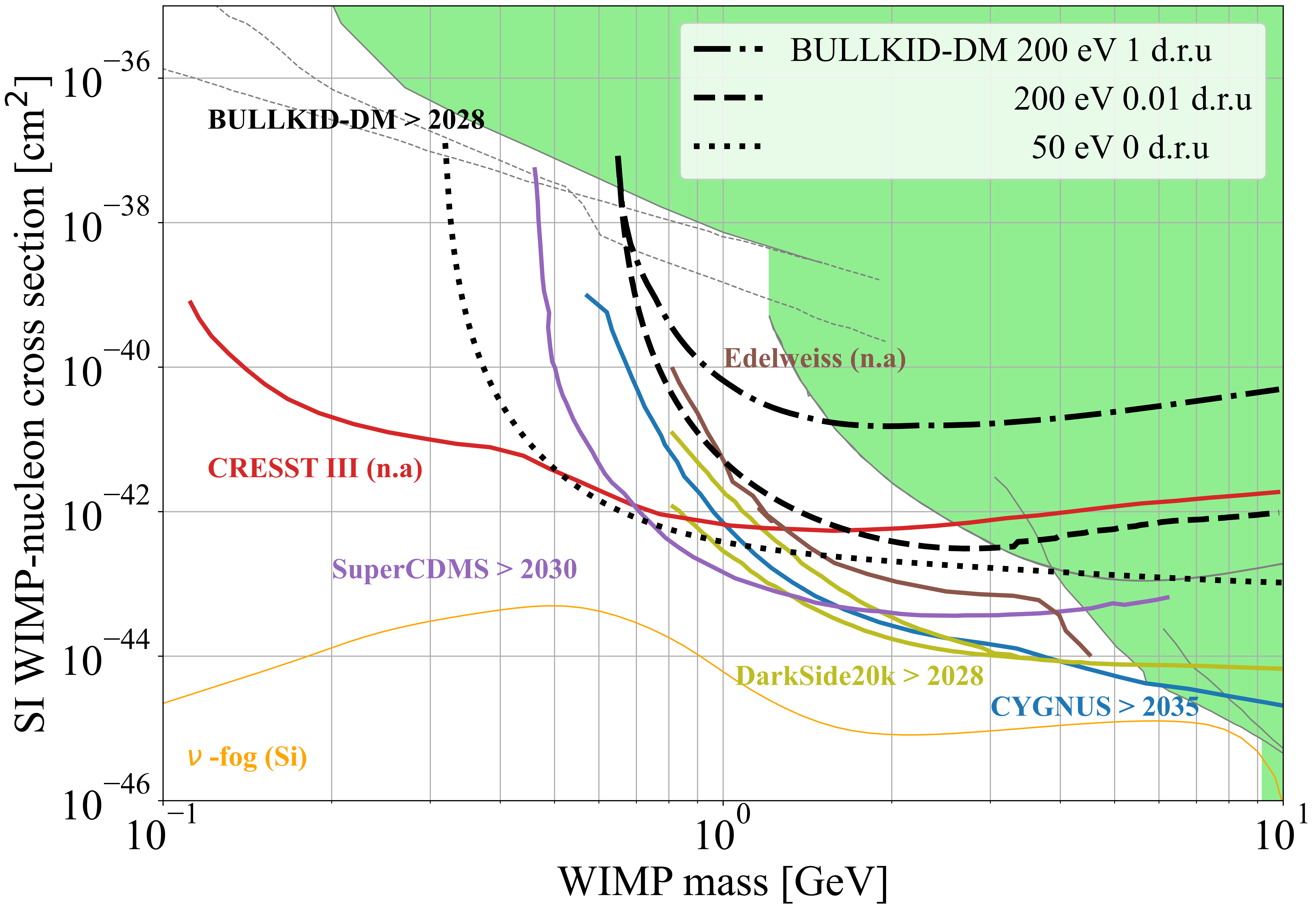
$$\sigma_0|_H = 26 \pm 7$$

Allowing for a threshold ≈ 150 eV





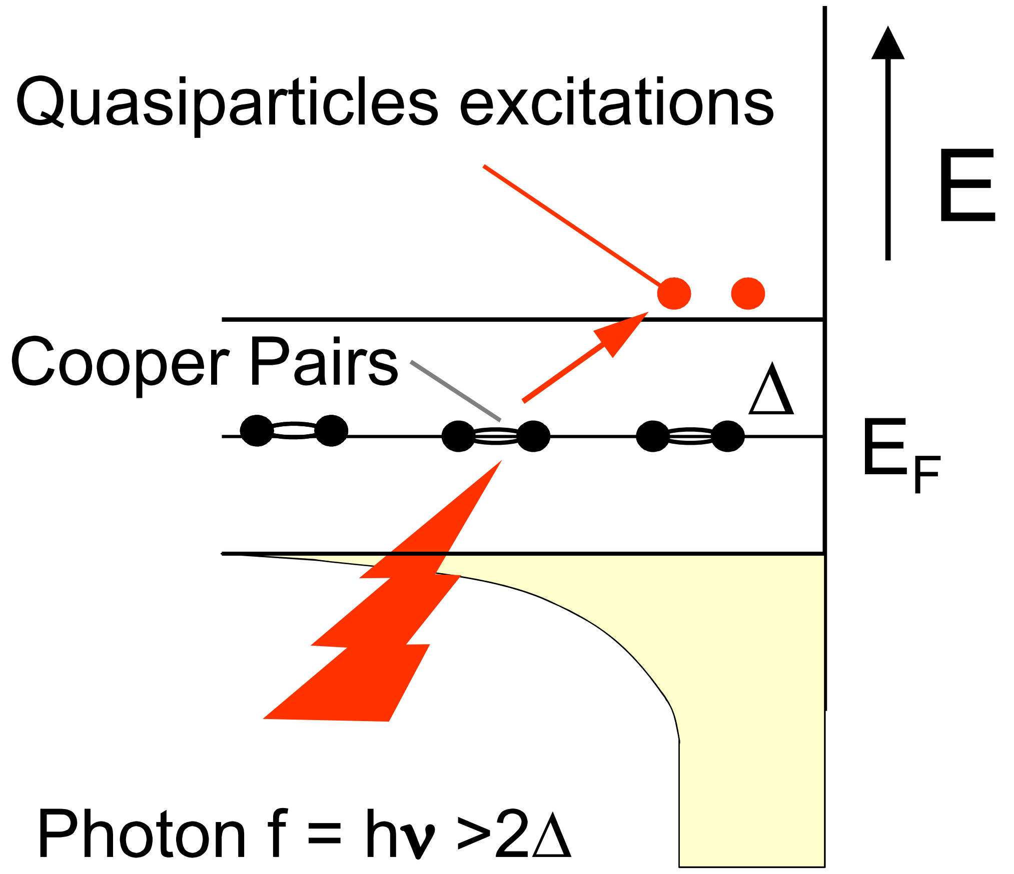
Projected sensitivity

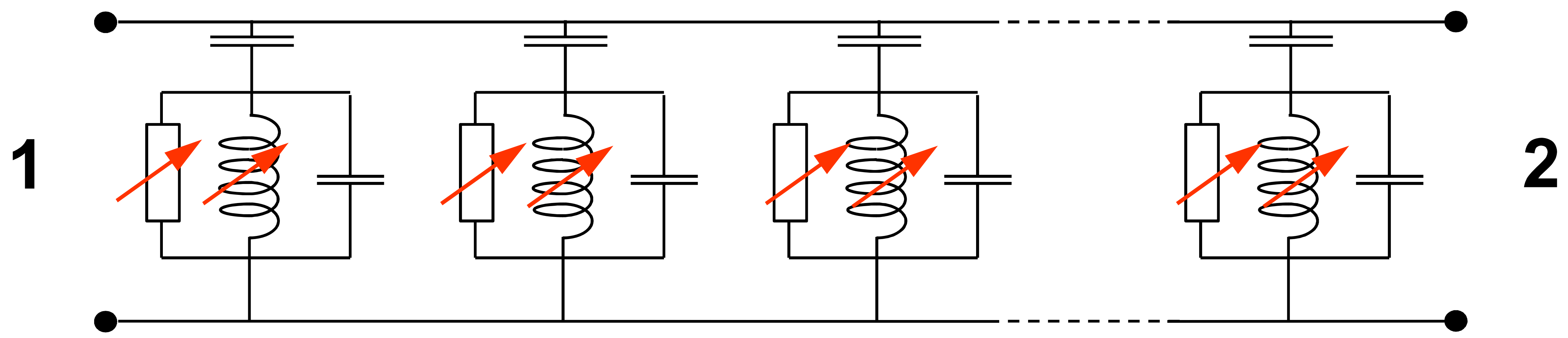


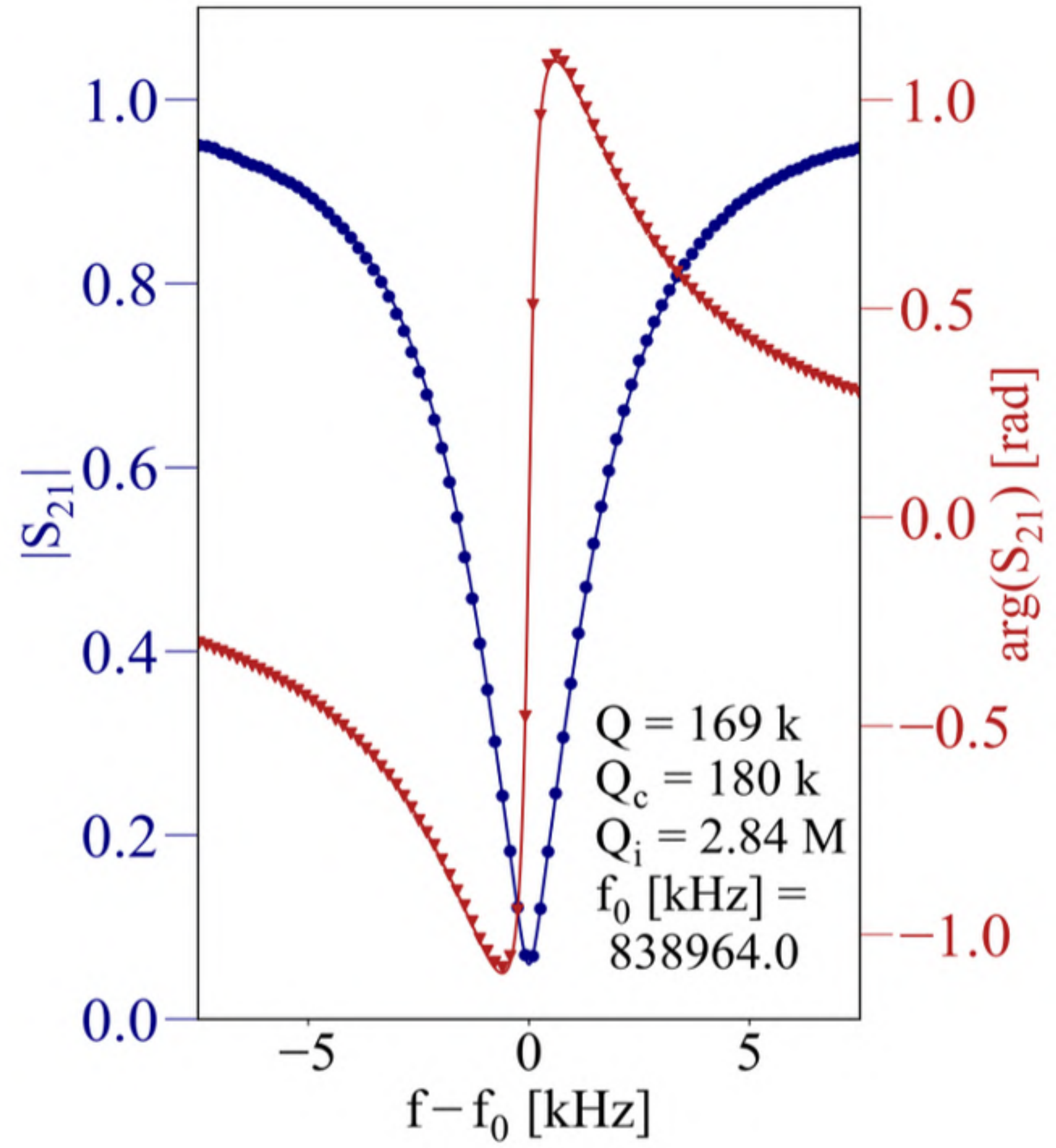
KID principle

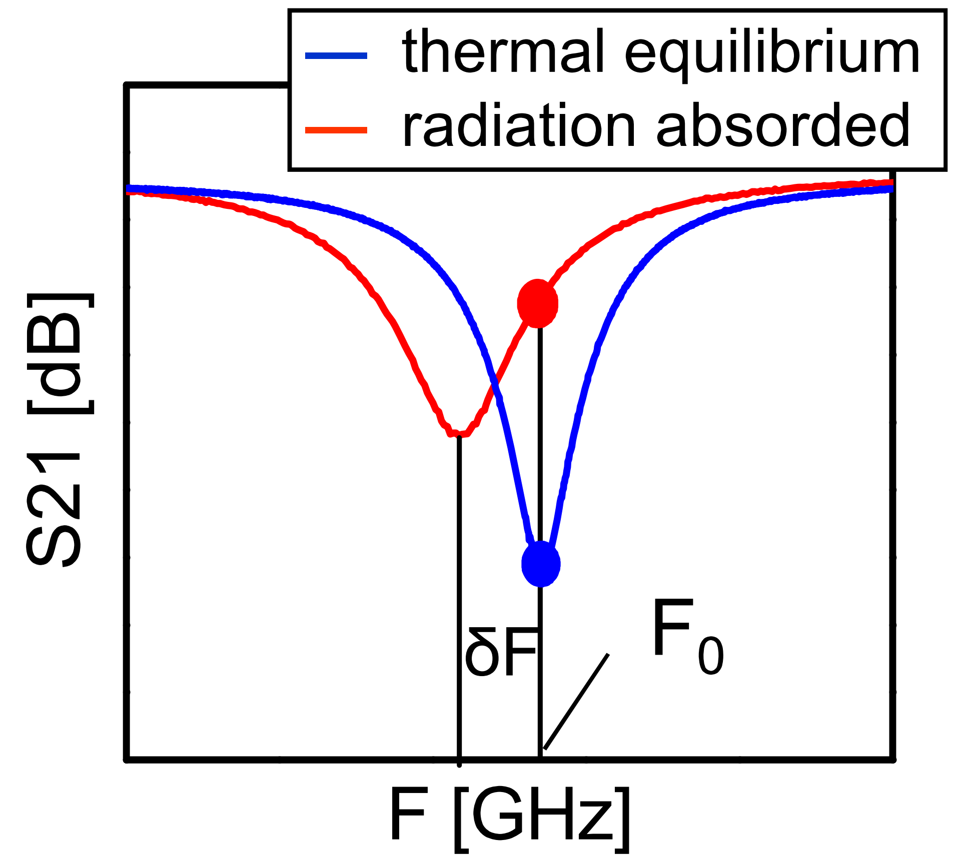
$$S21 = \frac{2}{2+\frac{Z_{\mathrm{eff}}}{Z_0}} = \frac{1}{1+\frac{\omega^2 M^2}{2Z_{\mathrm{res}}Z_0}}$$

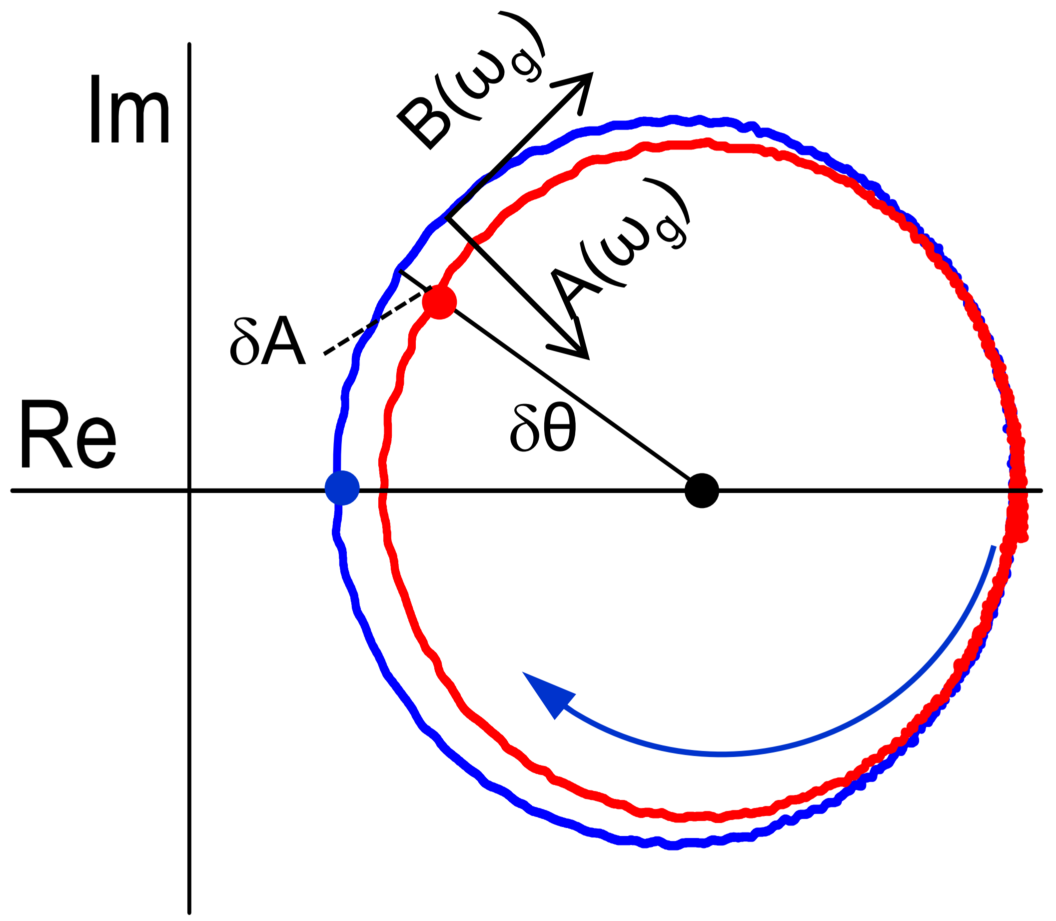
$$Z_{\mathrm{res}} = j\omega L + \frac{1}{j\omega C} + R$$

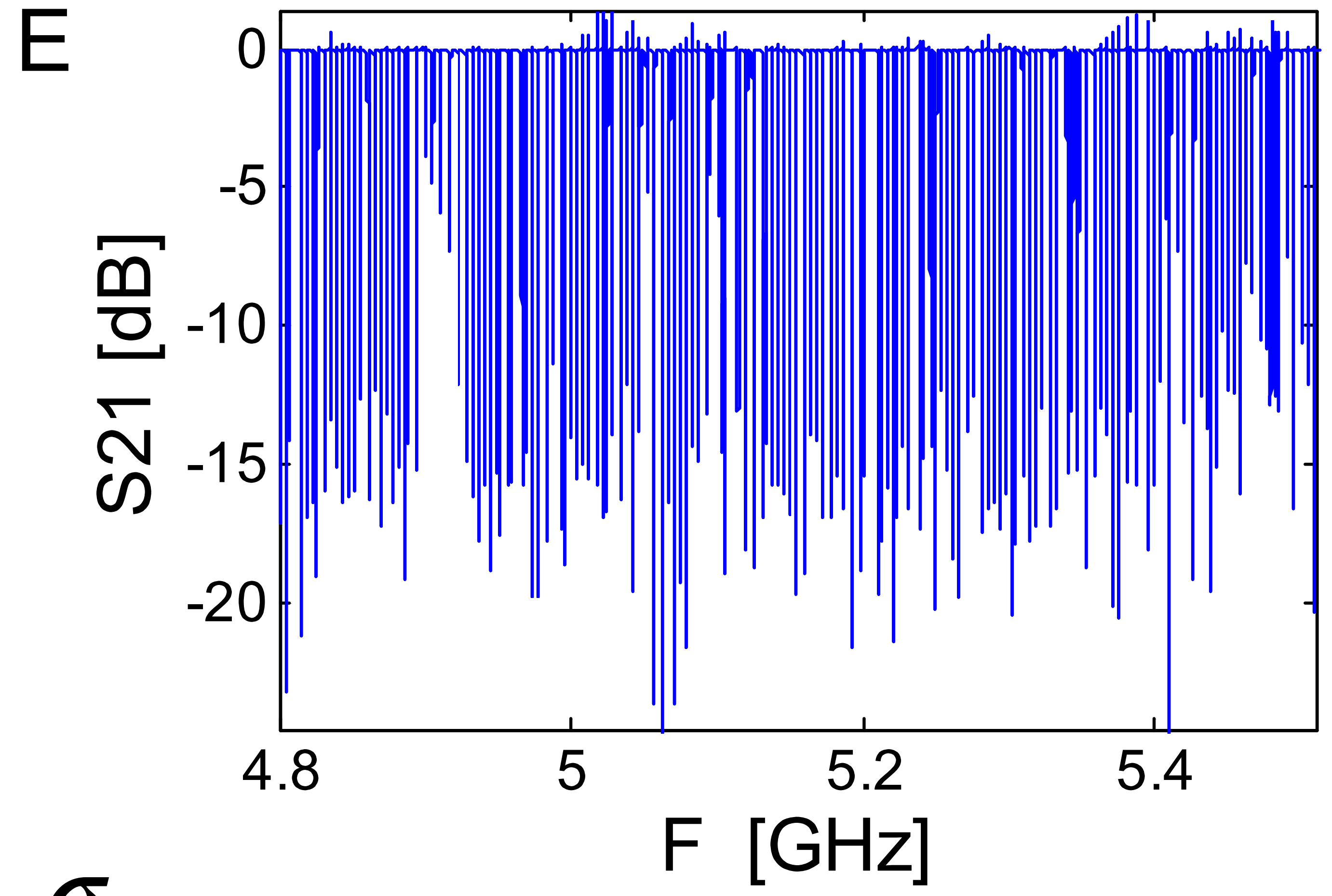












$$Q \sim \frac{f_n}{\Delta f_{n,FWHM}}$$

$$R = L_k \omega \frac{\sigma_1}{\sigma_2}$$

$$L_{\mathrm{int}} = L_k + L_m = \frac{\mu_0 \lambda_L}{2} \coth\left(\frac{t}{2\lambda_L}\right)$$

Fabrication of detector wafers