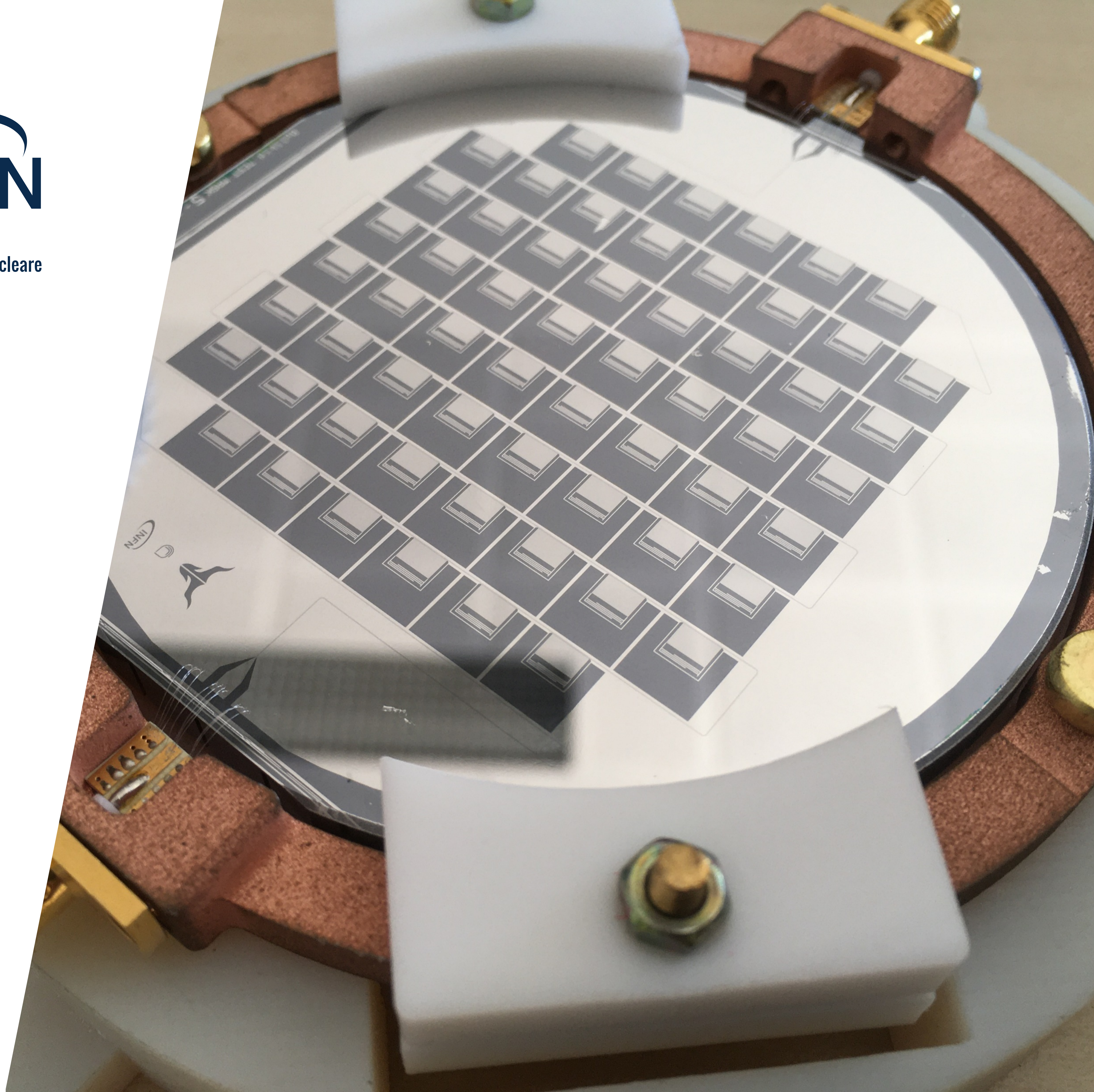
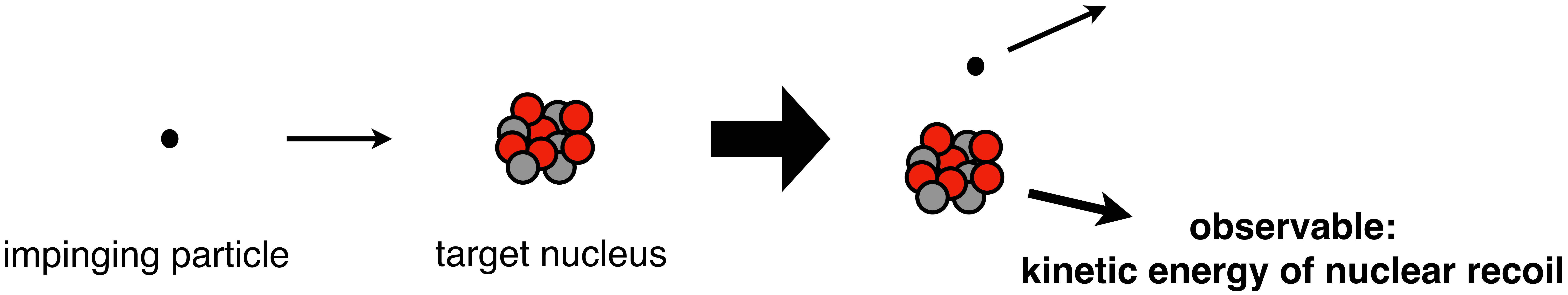
BULLKID

Marco Vignati - 9 July 2022
ICHEP, Bologna (Italy)



Particle detection via nuclear recoils



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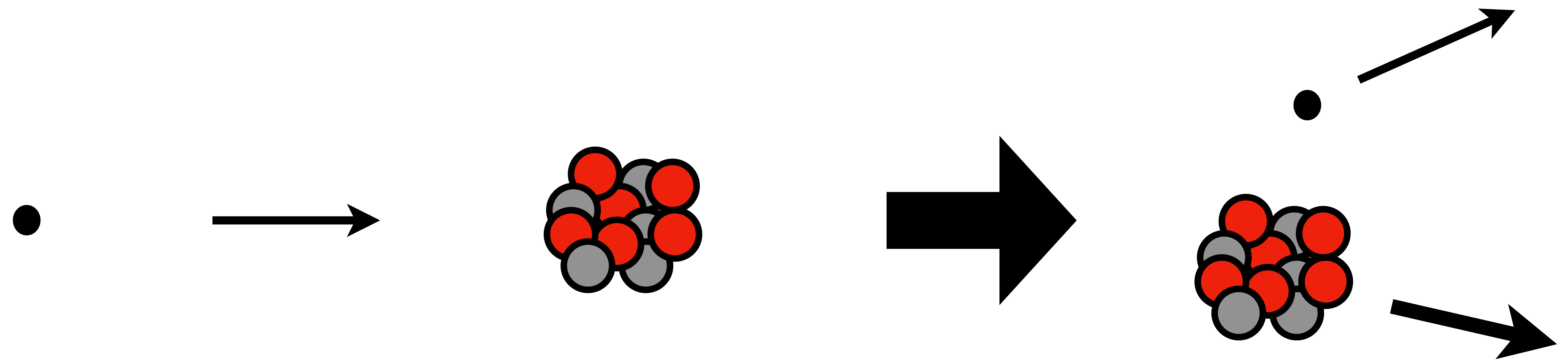
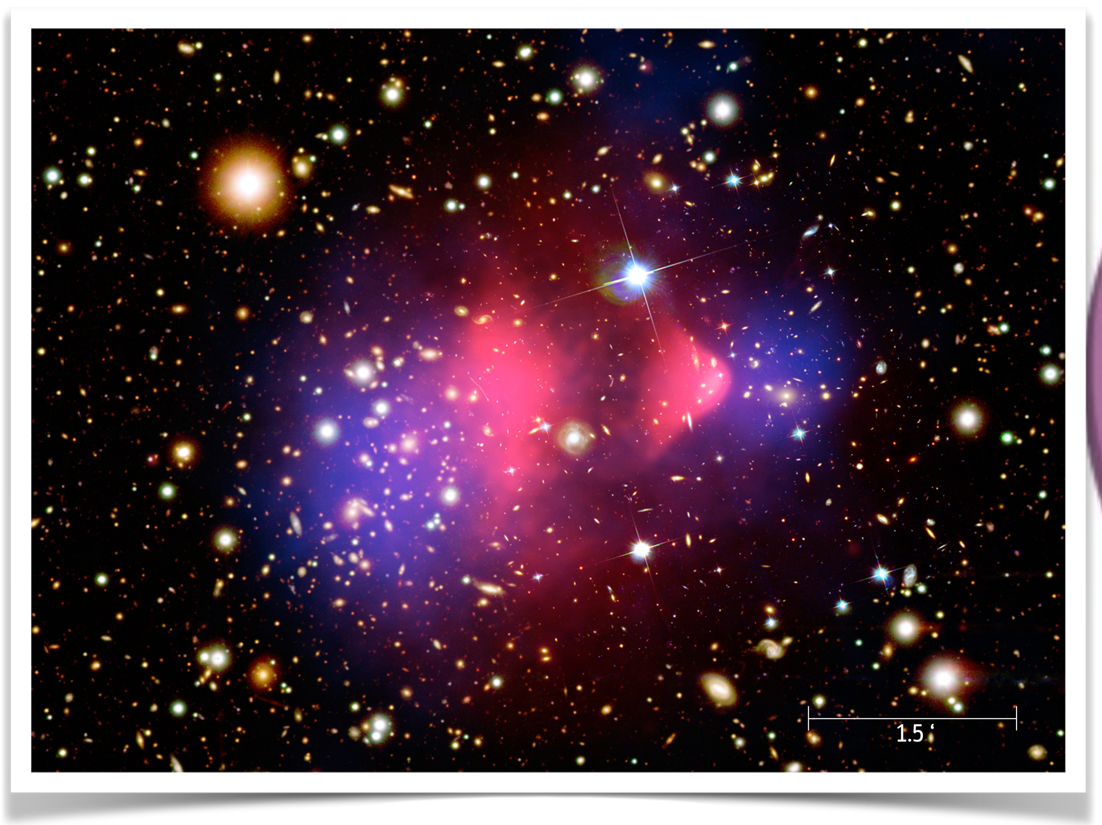
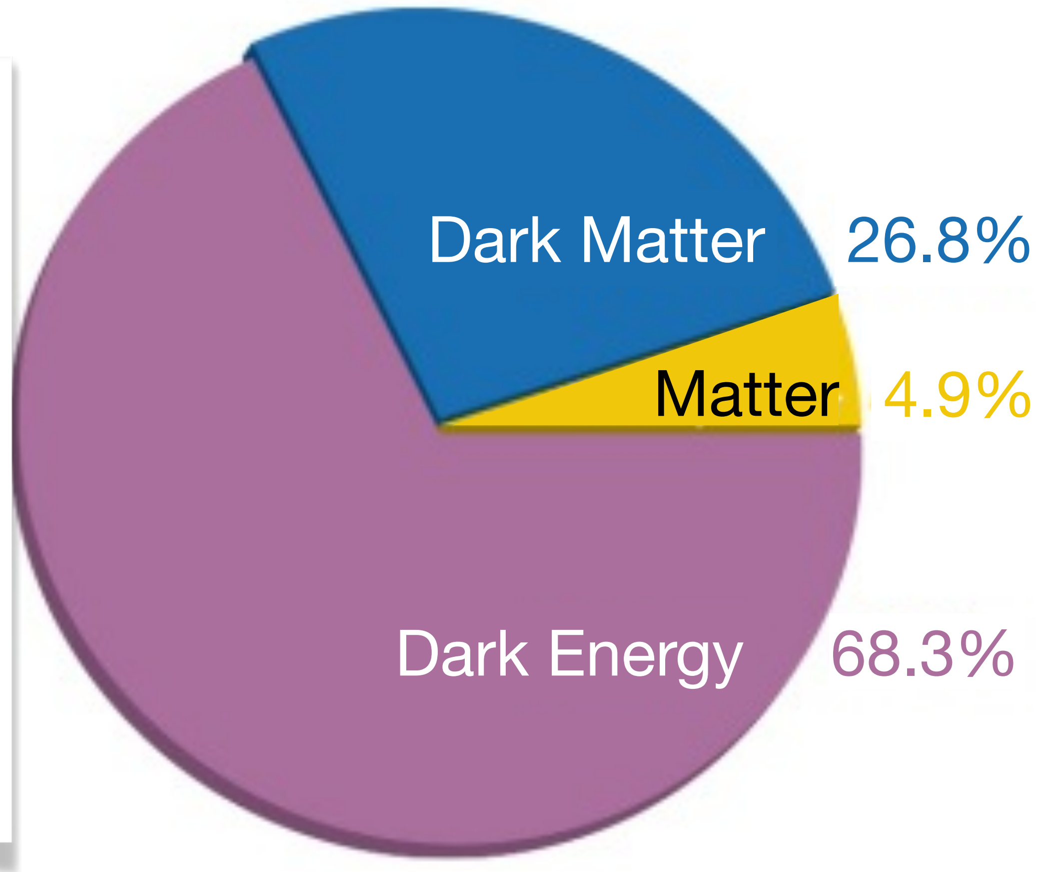


impinging particle target nucleus

observable:
kinetic energy of nuclear recoil

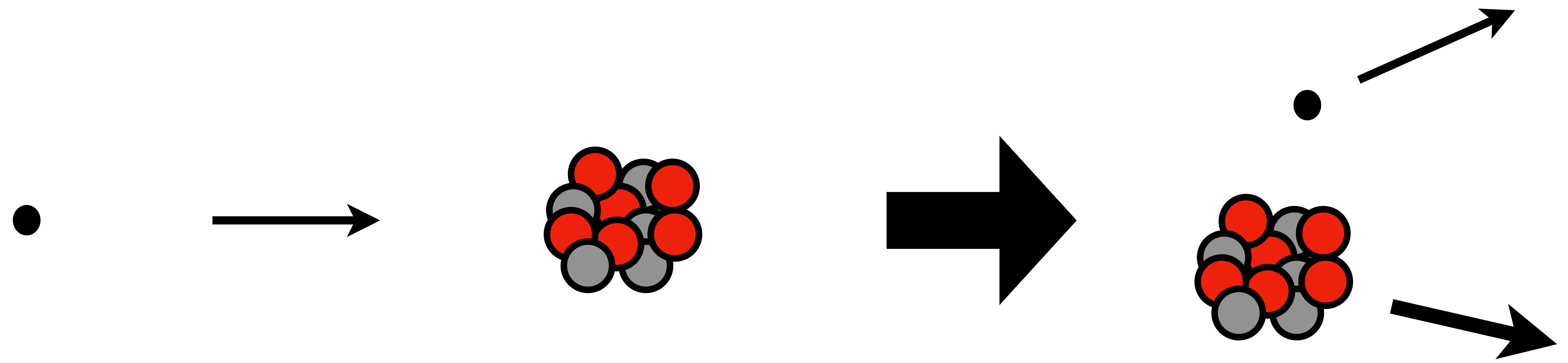
Dark Matter





next frontier: particles with mass < 1 GeV/c^2

Particle detection via nuclear recoils



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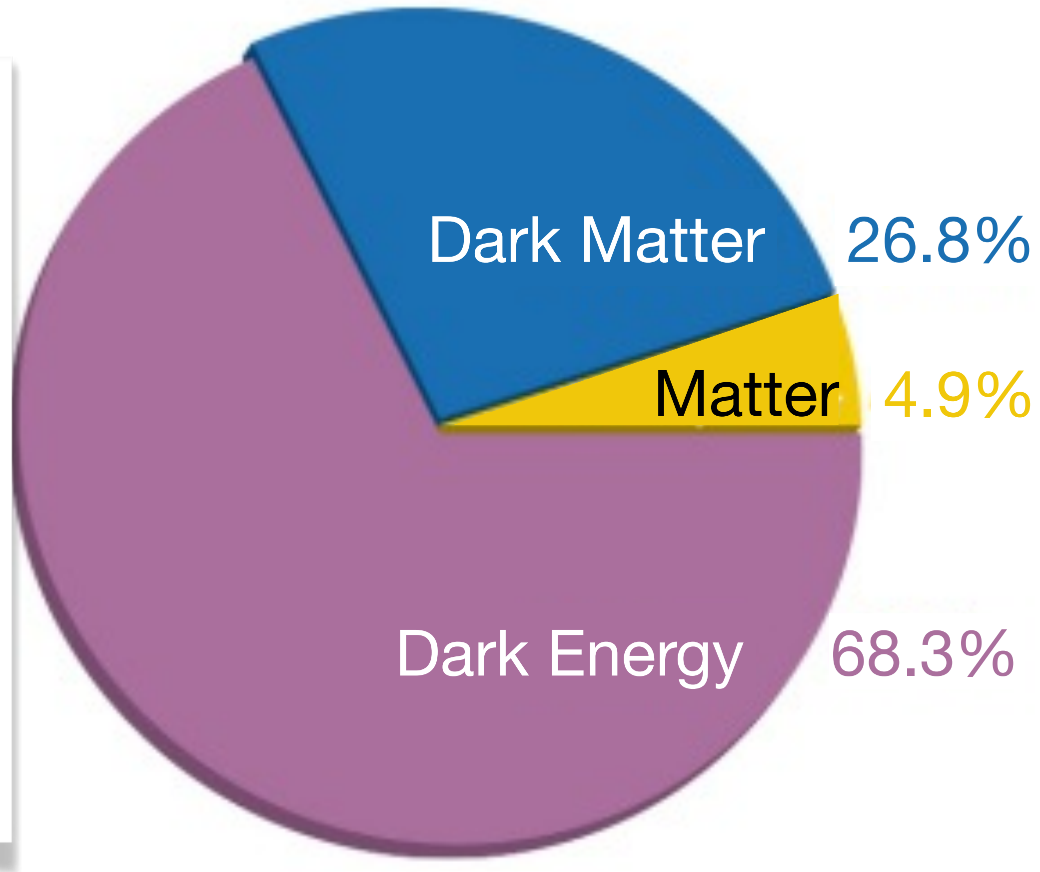
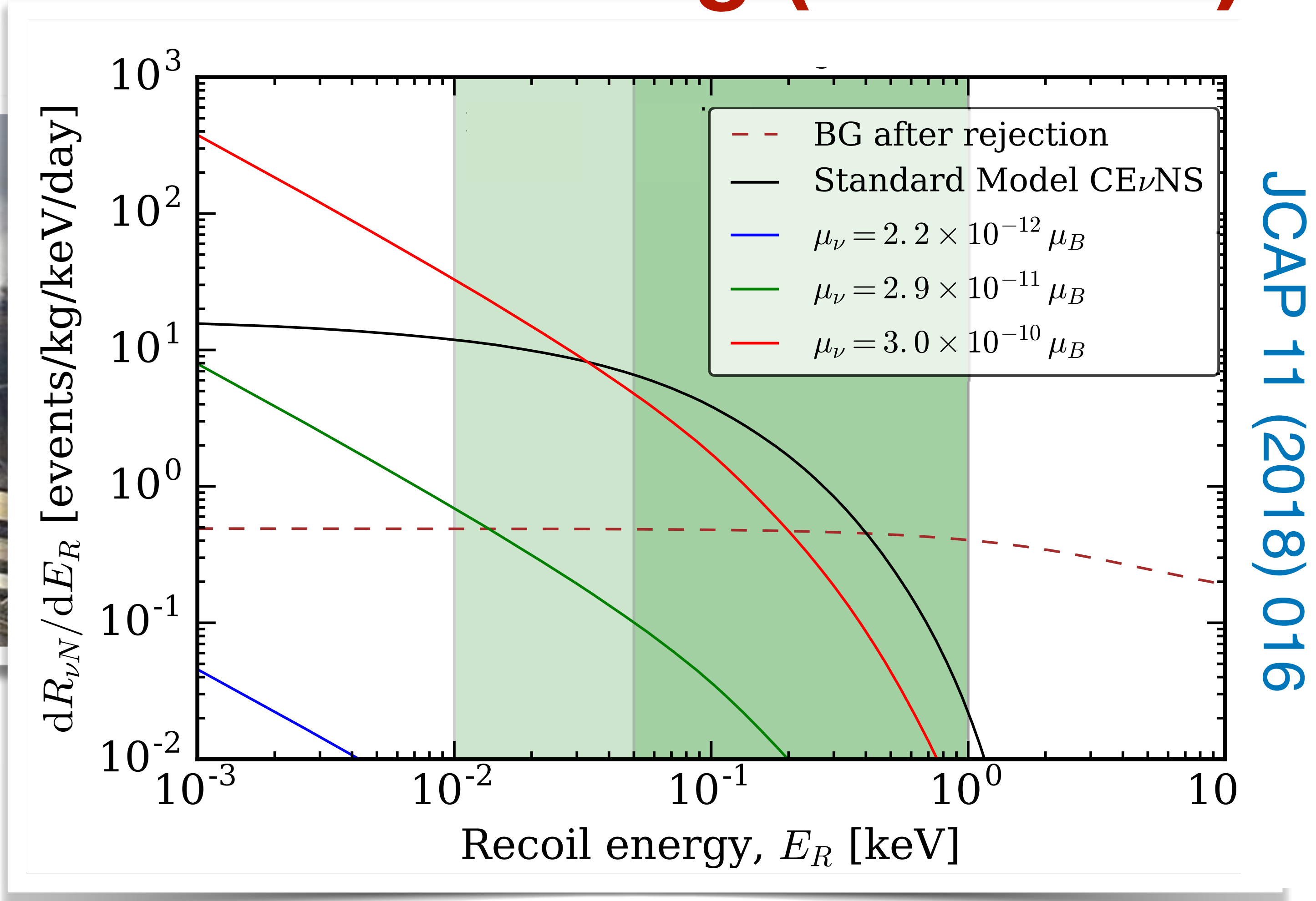


next frontier: particles with mass < 1 GeV/c²

Neutrino coherent scattering (CEνNS)

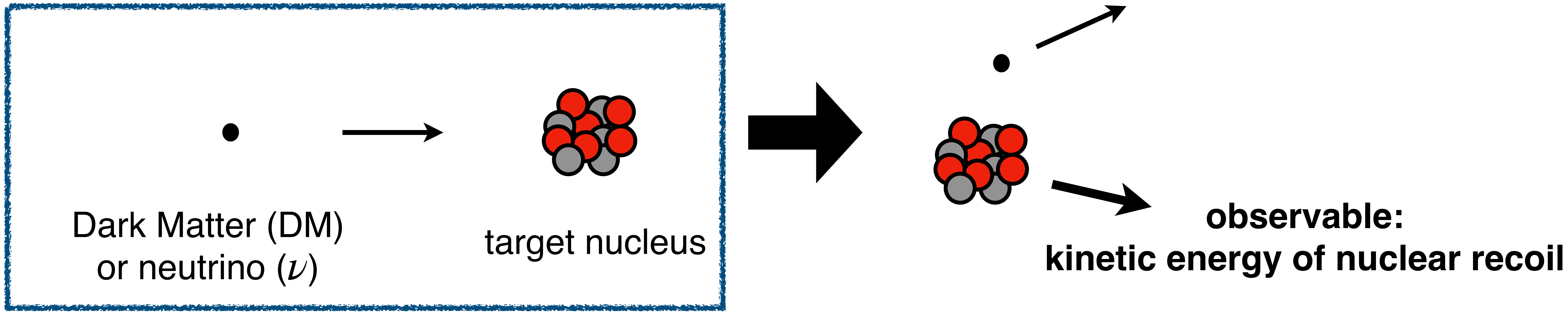
reactor monitoring
from safe distances



Billard, Johnston and Kannavagh, JCAP 11 (2018) 016

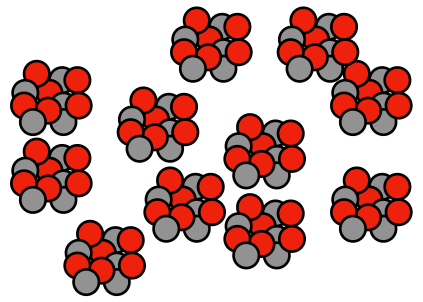
precision tests of the
Standard Model (NSI, μ_ν, …)

Requirements

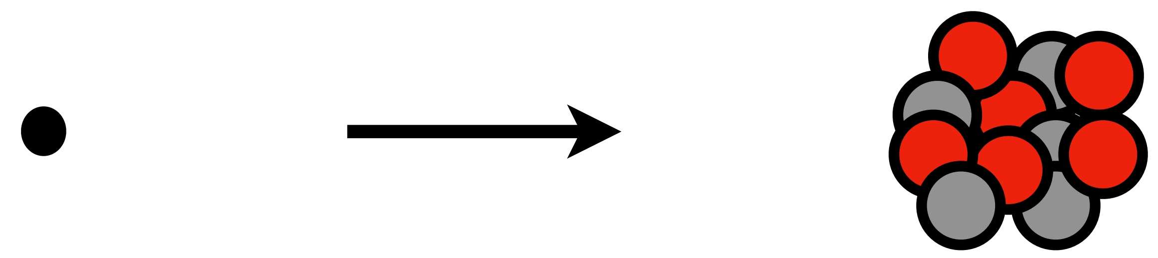


cross section $\sigma < 10^{-40}\ \mathrm{cm}^2$

large number of targets
(large target mass)

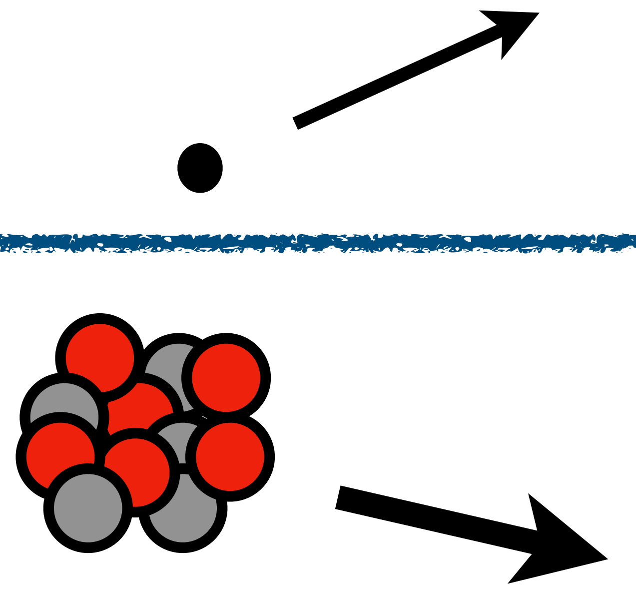


Requirements



Dark Matter (DM)
or neutrino (ν)

target nucleus

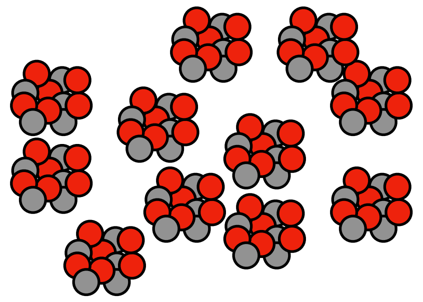


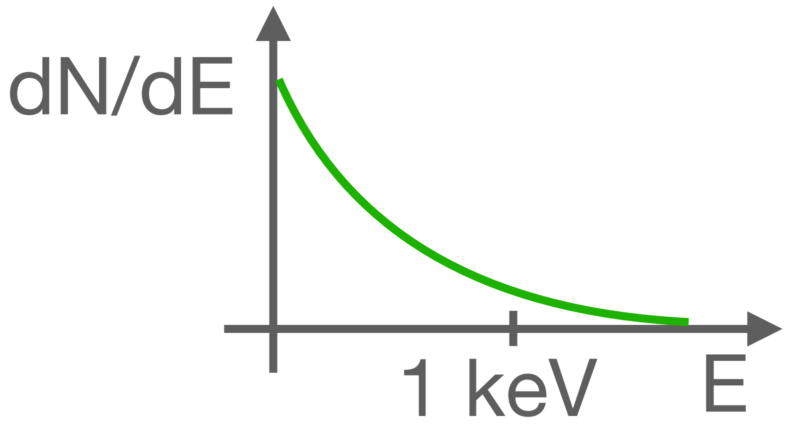
observable:
kinetic energy of nuclear recoil

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

energy < 1 keV

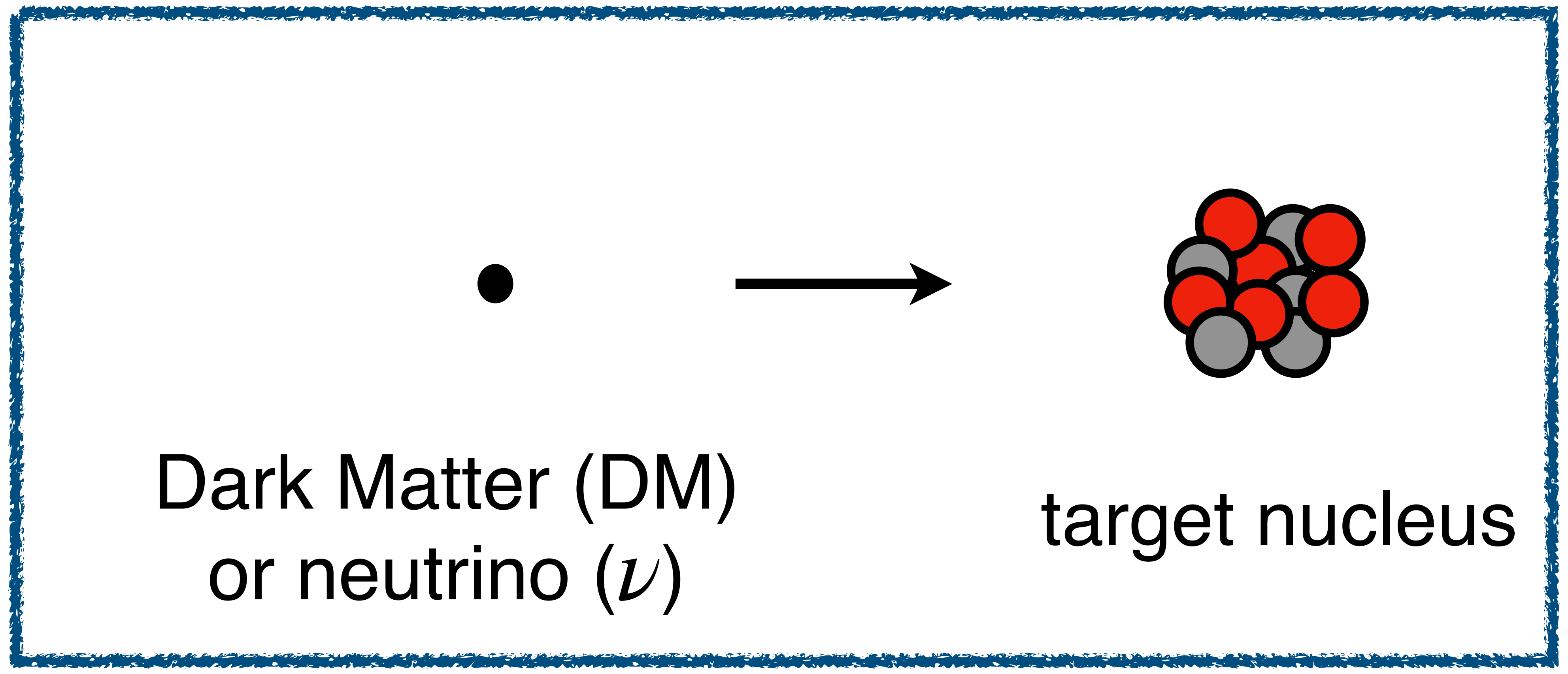
large number of targets
(large target mass)

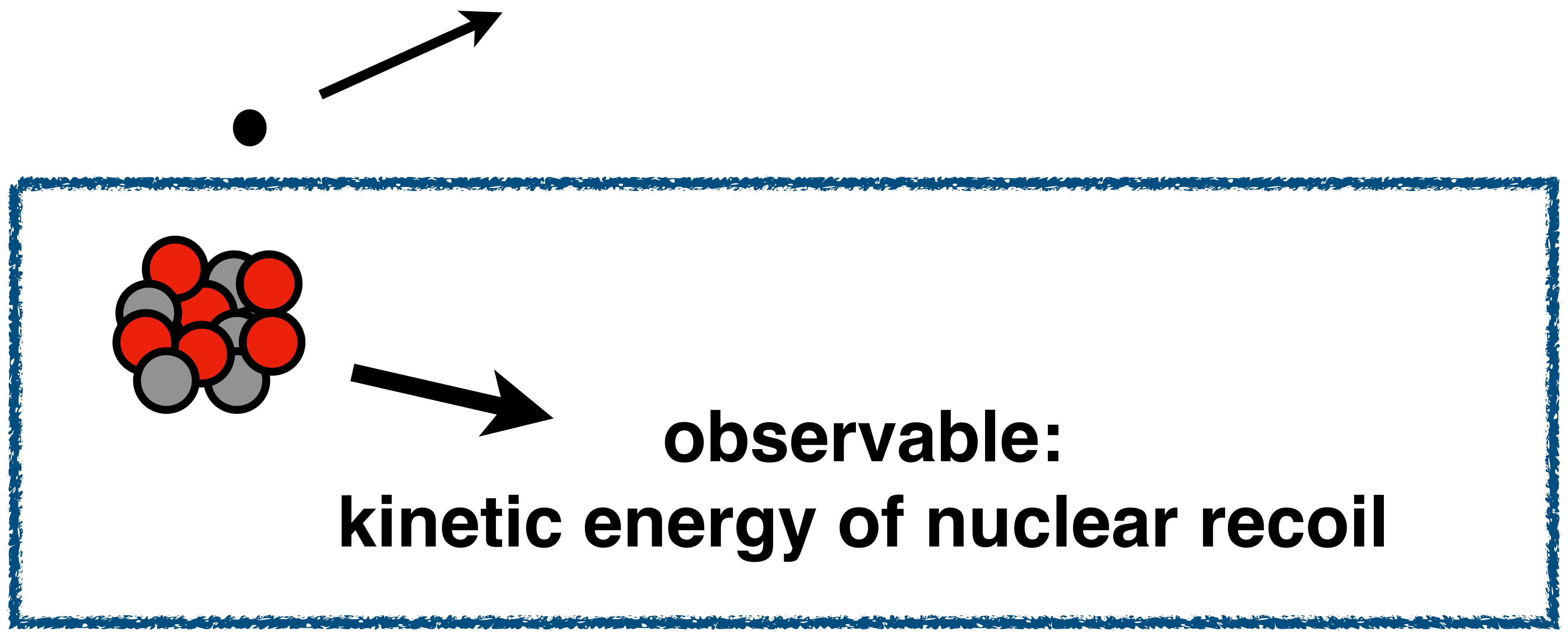




low-energy
detection threshold

Requirements





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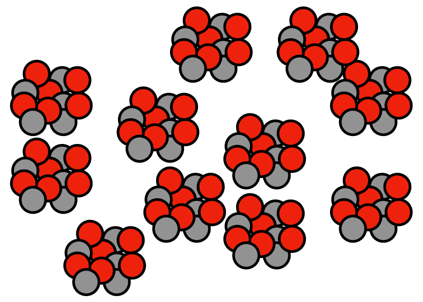
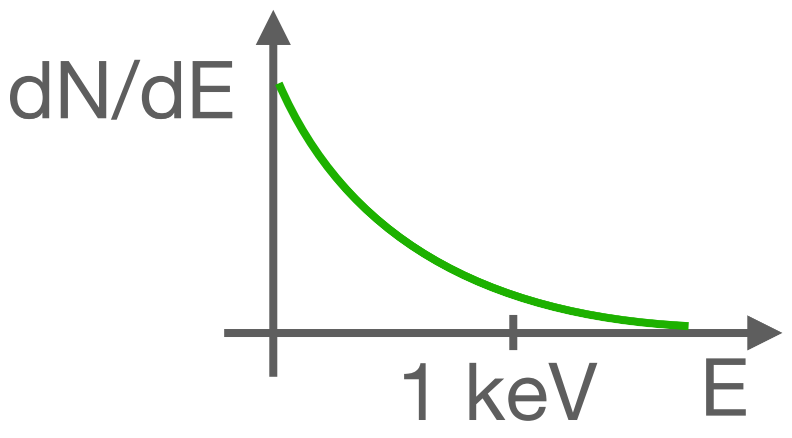
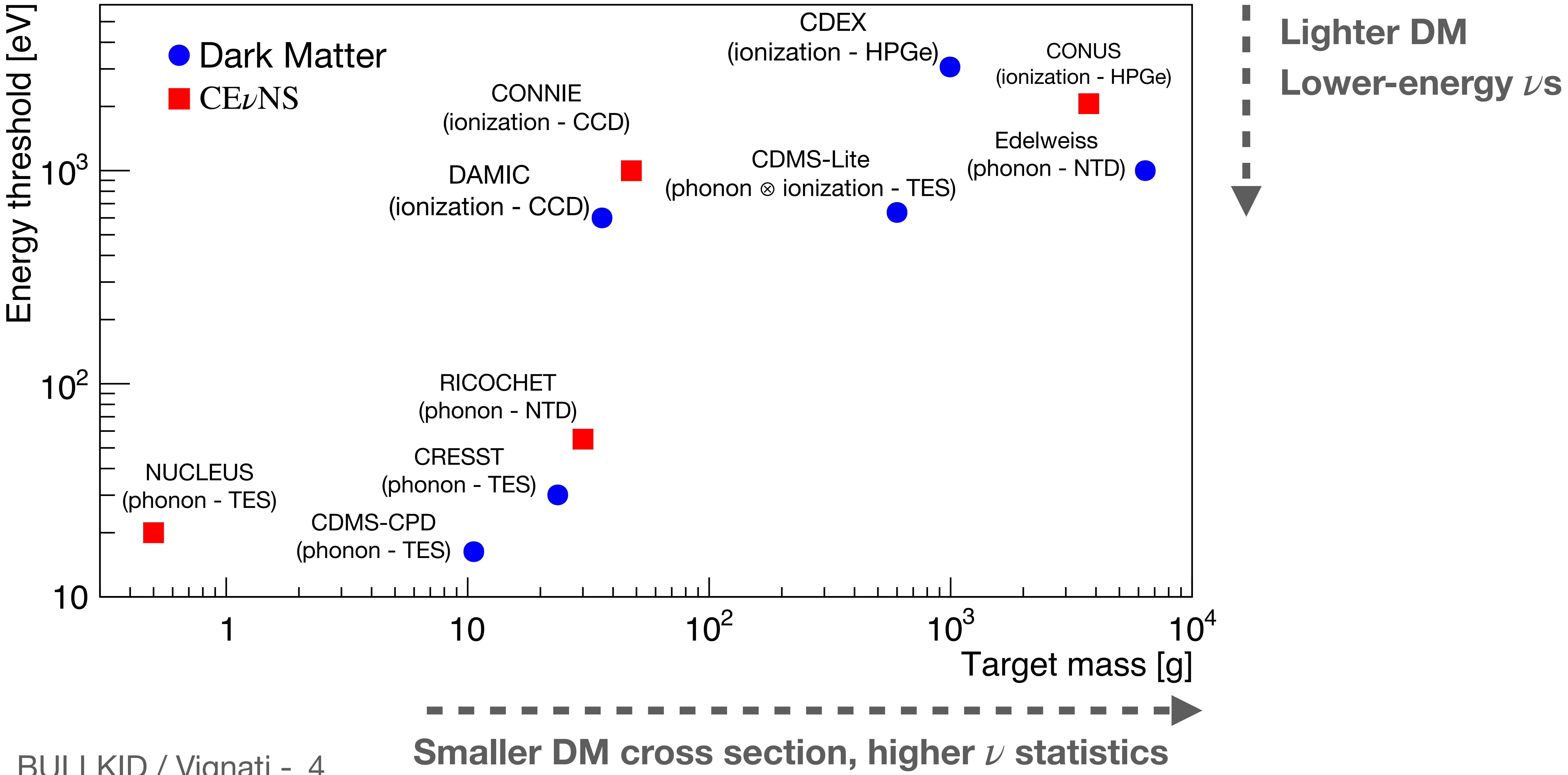




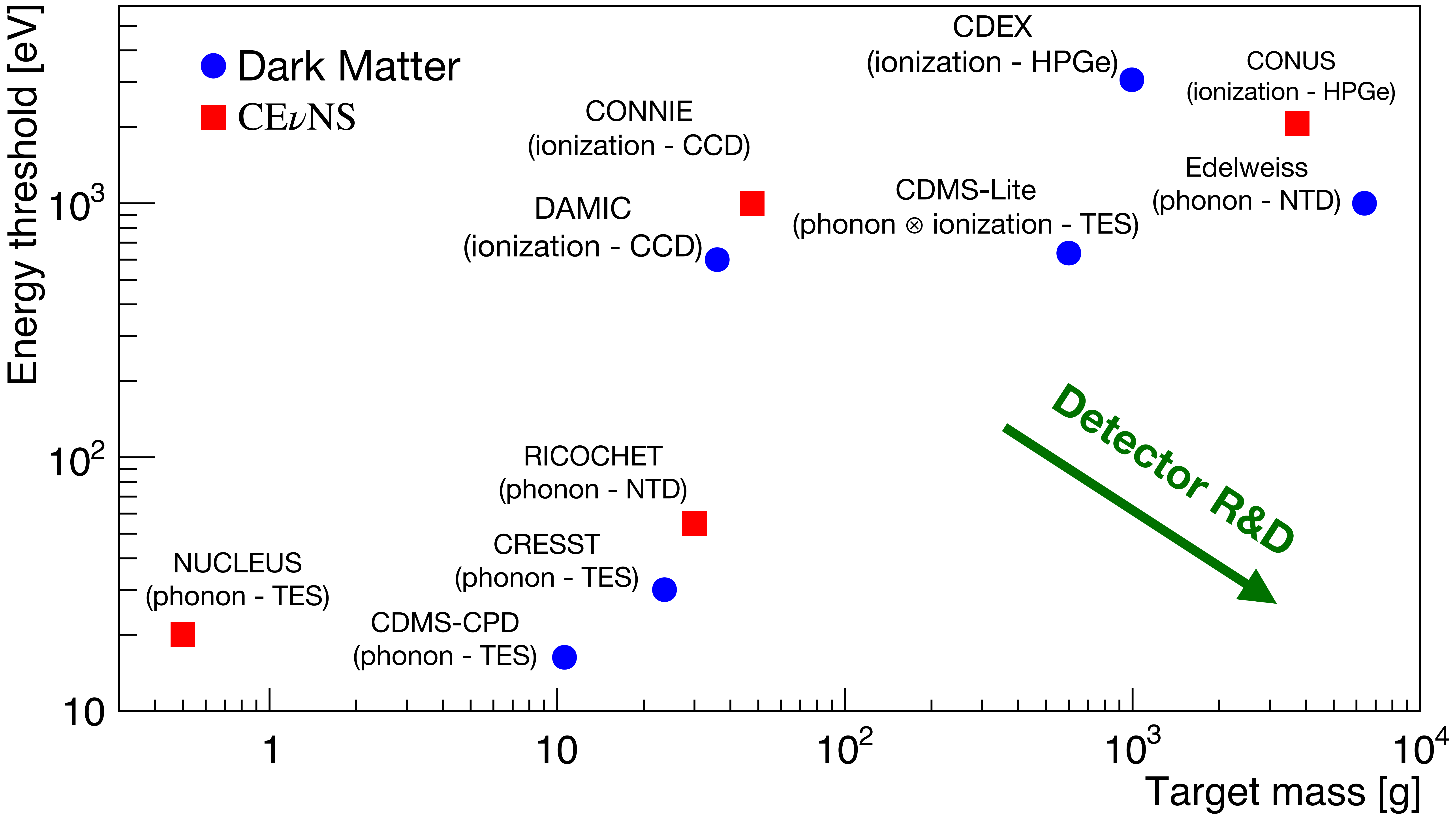
low-energy
detection threshold

Difficult to have both in the same experiment!

State of the art (solid-state detectors)



State of the art (solid-state detectors)



Lighter DM

Lower-energy νs

BULLKID:
(phonon - KIDs)

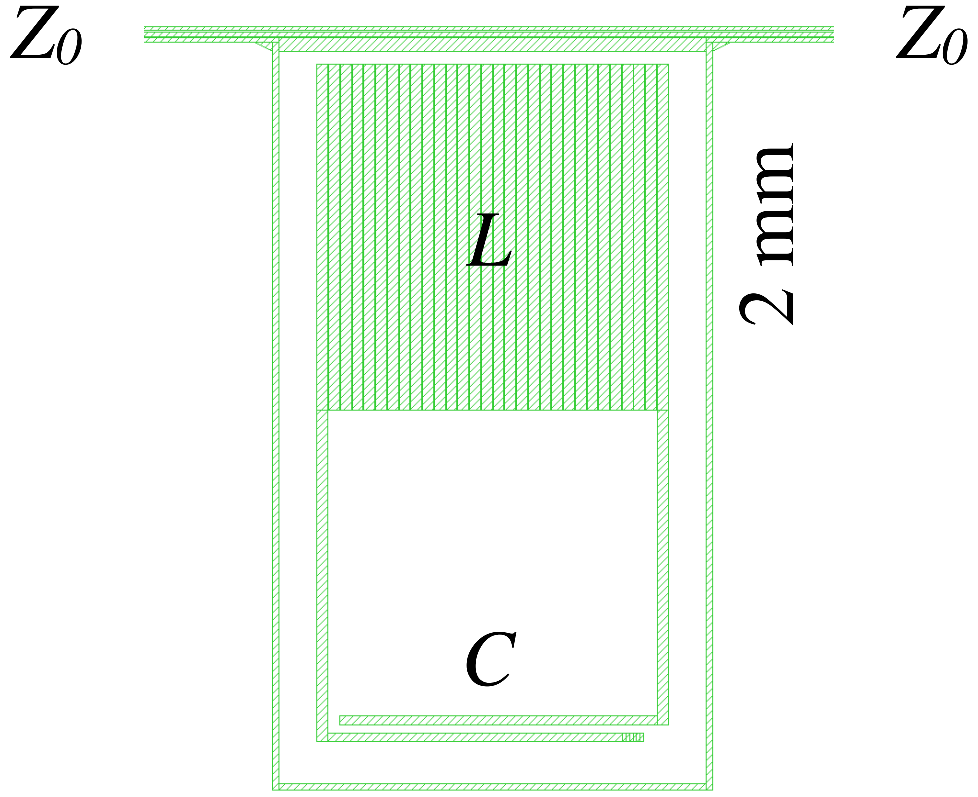
Smaller DM cross section, higher ν statistics

Low energy threshold with KIDs

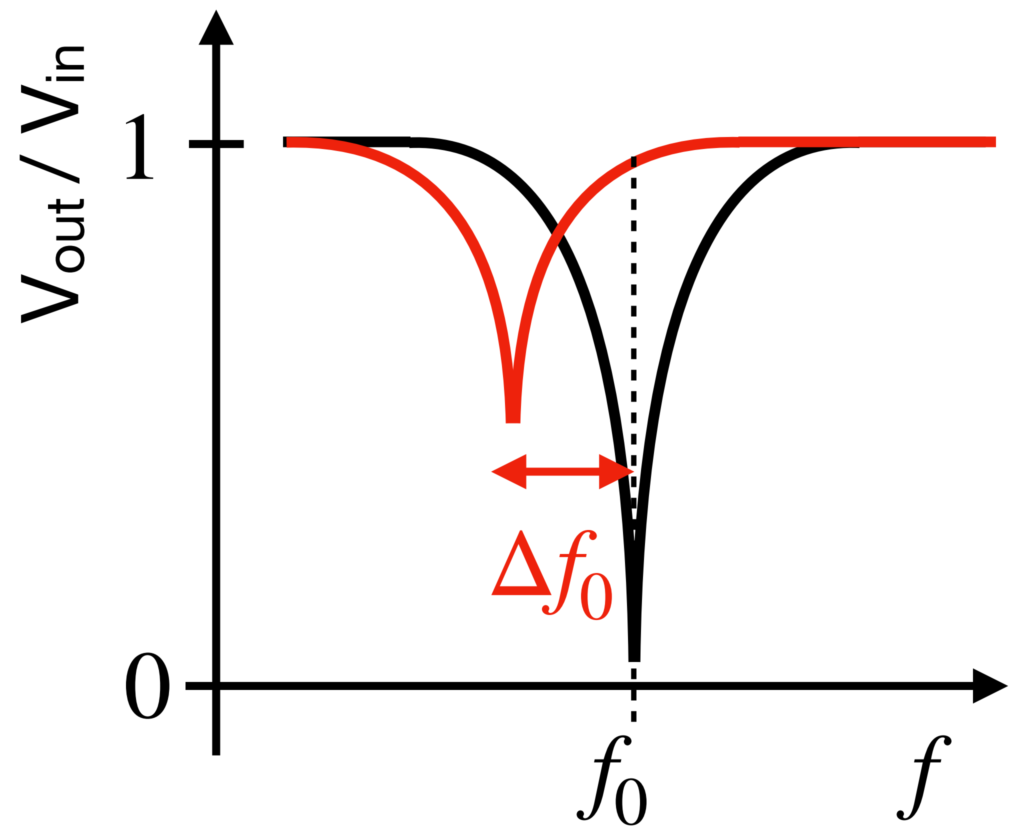
Kinetic Inductance Detector (KID):

- Thin film (~50 nm) superconductor at T < 200 mK
- Energy release → Cooper-pair breaking (ΔL)
- Resonant circuit ($f_0 = 1/\sqrt{LC}$), $\Delta L \rightarrow \Delta f_0$

superconducting resonator



frequency response



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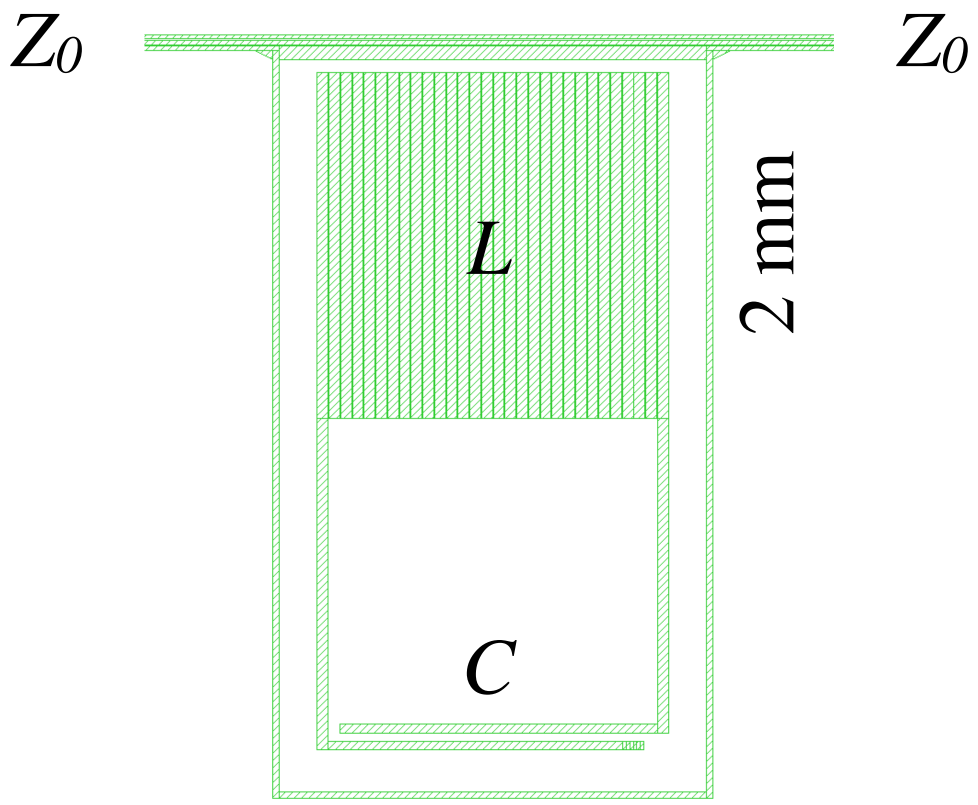

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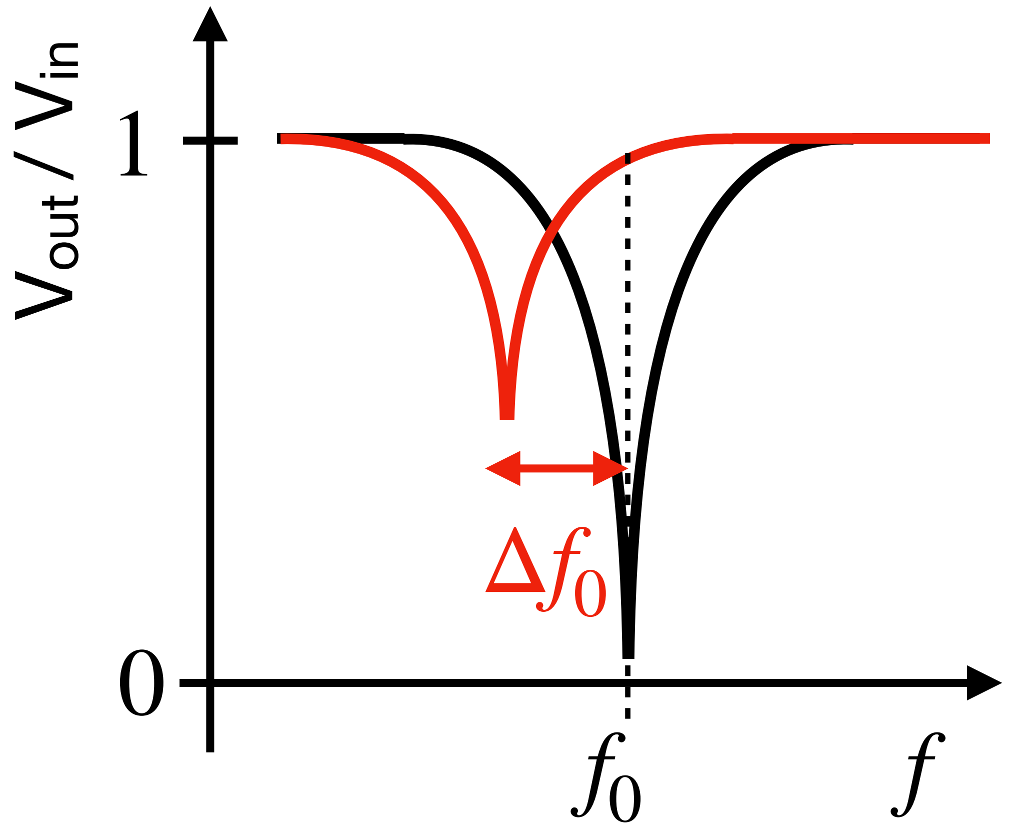
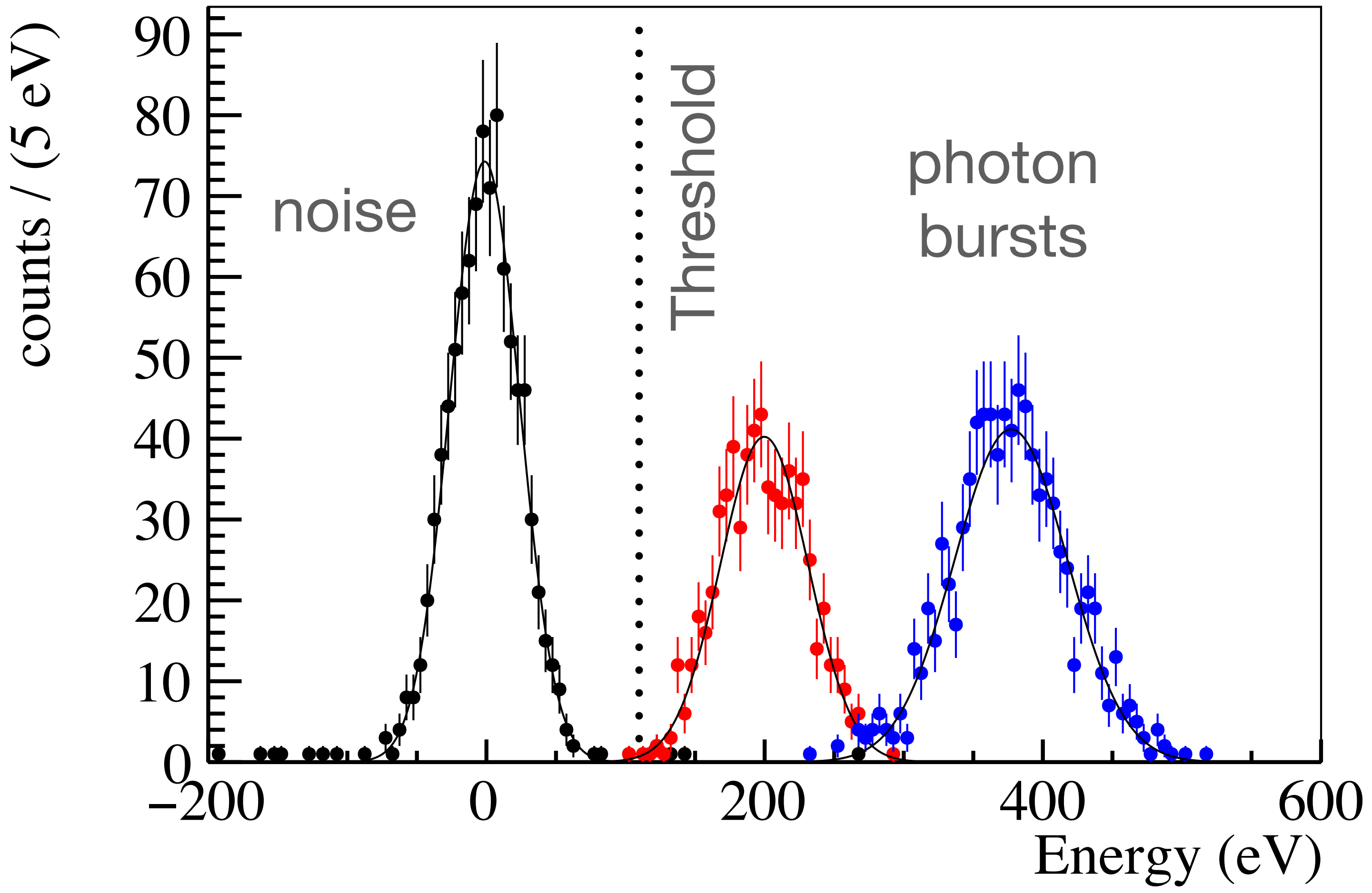
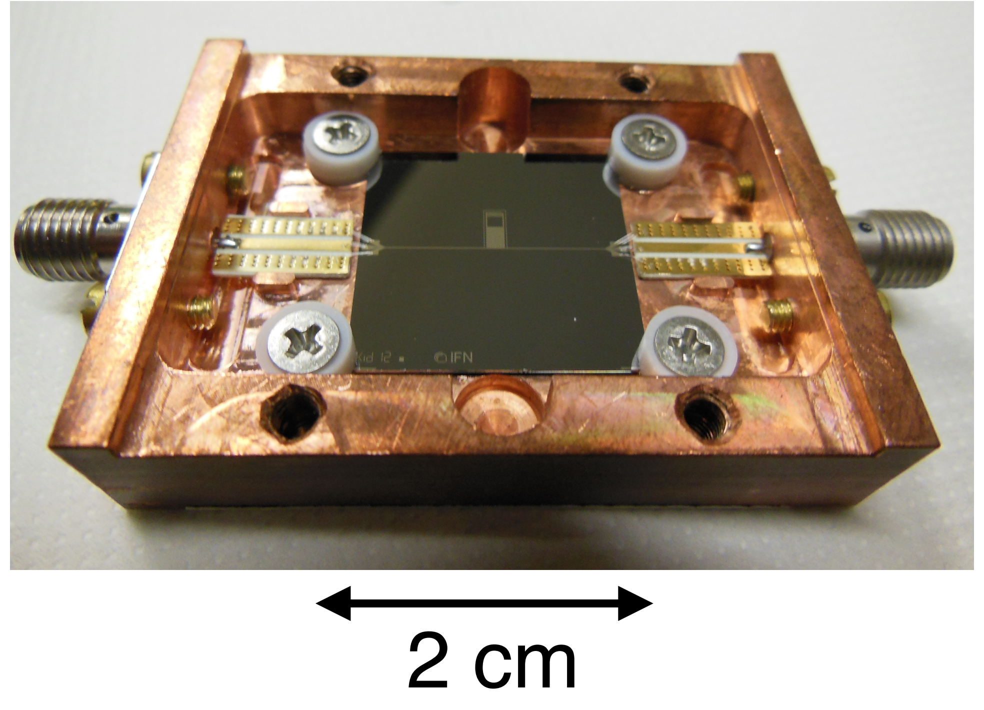


KID-based **photon sensors:**

✓ Energy threshold = 125 eV





L. Cardani, et al. [CALDER], SUST 31 (2018) 075002

BULLKID team

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Consiglio Nazionale delle Ricerche
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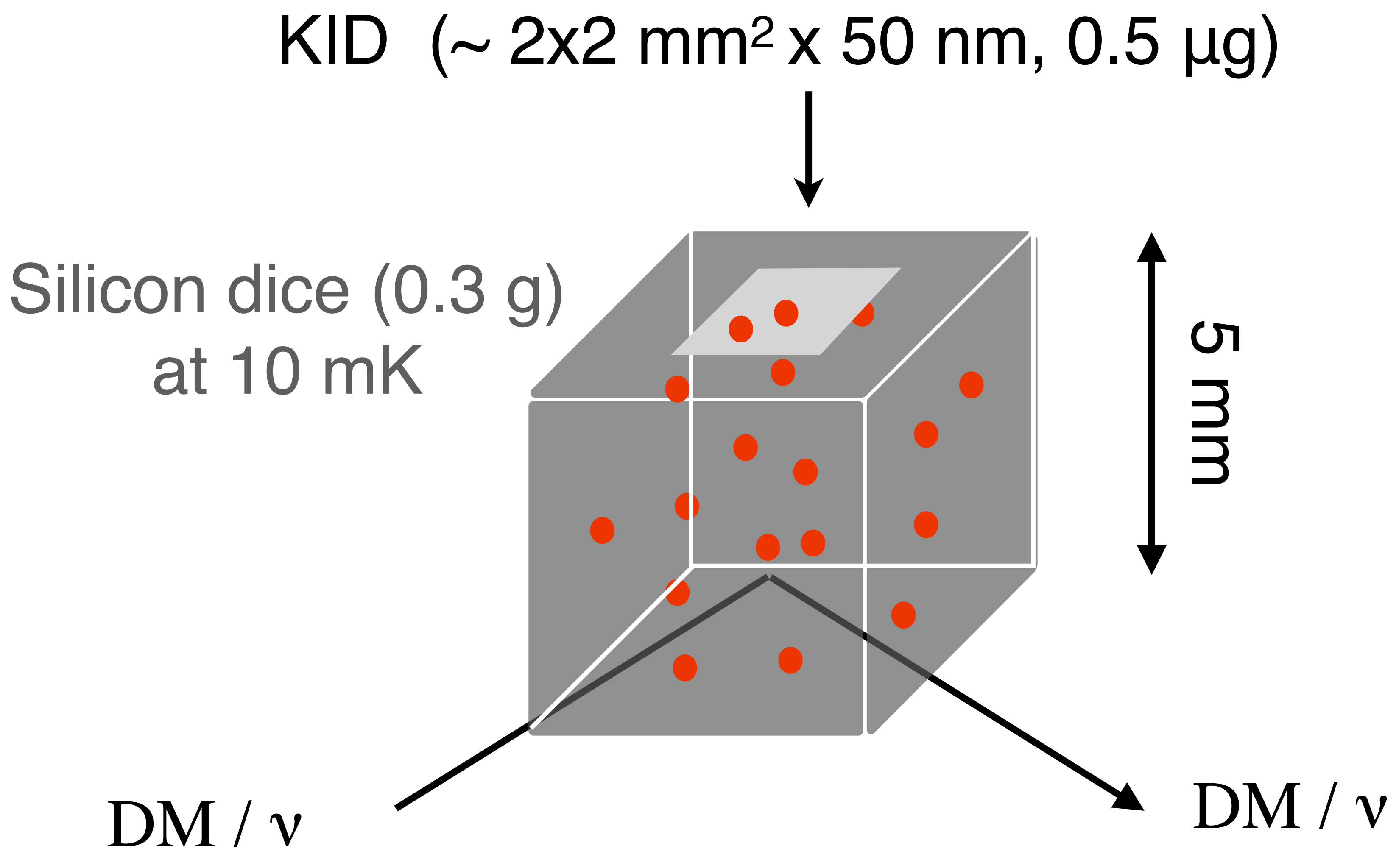
Ferrara University:
M. Romagnoni, V Guidi;

Genova University
S. Di Domizio.

BULLKID
funded by the INFN

Large targets: phonons and multiplexing

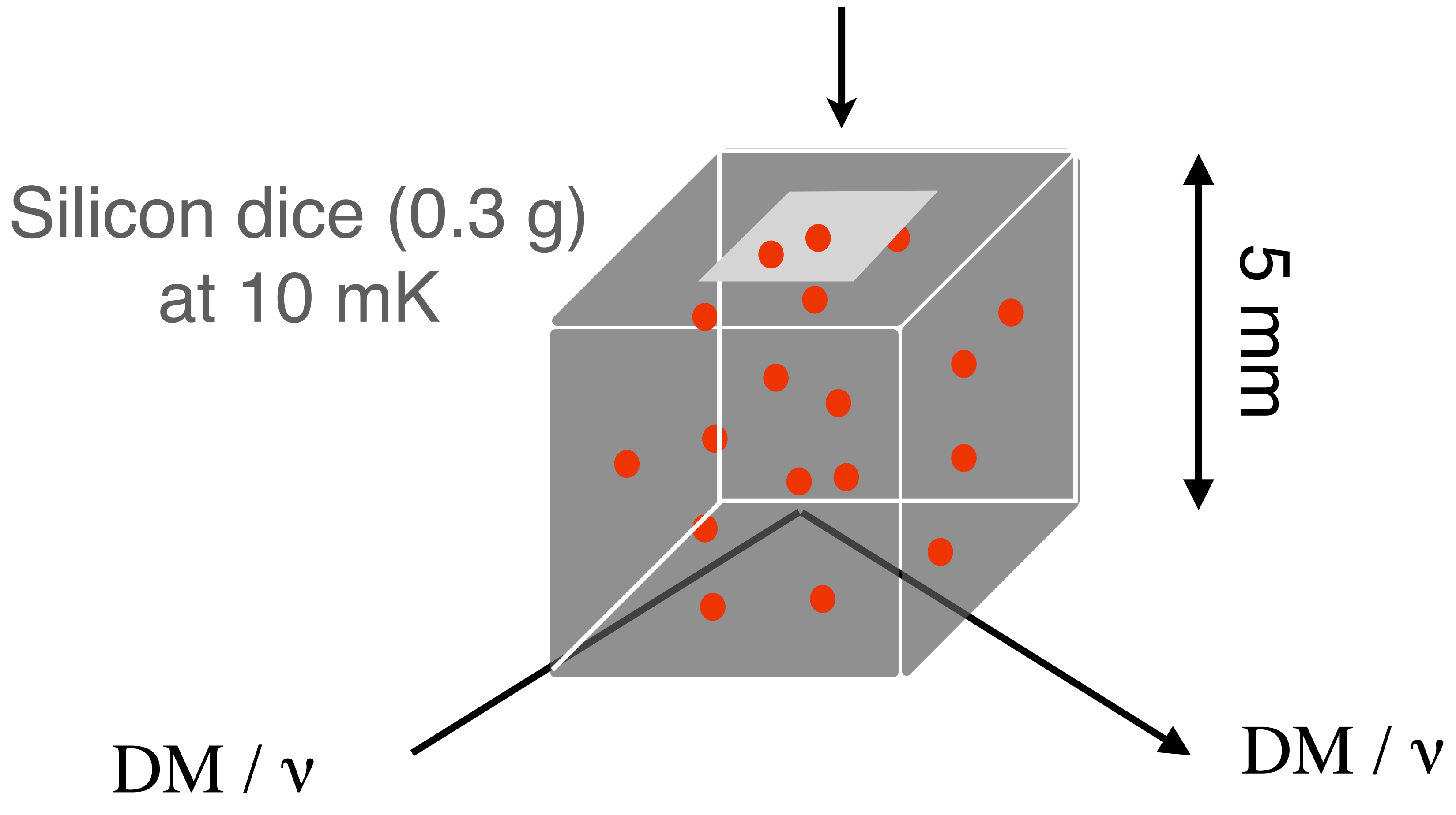
Phonon mediation
detect phonons created by nuclear recoils in a silicon dice



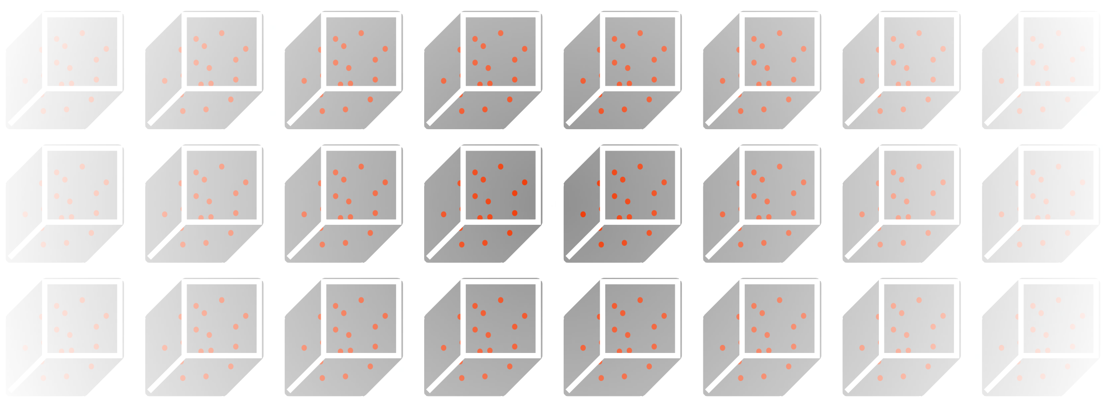
Large targets: phonons and multiplexing

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

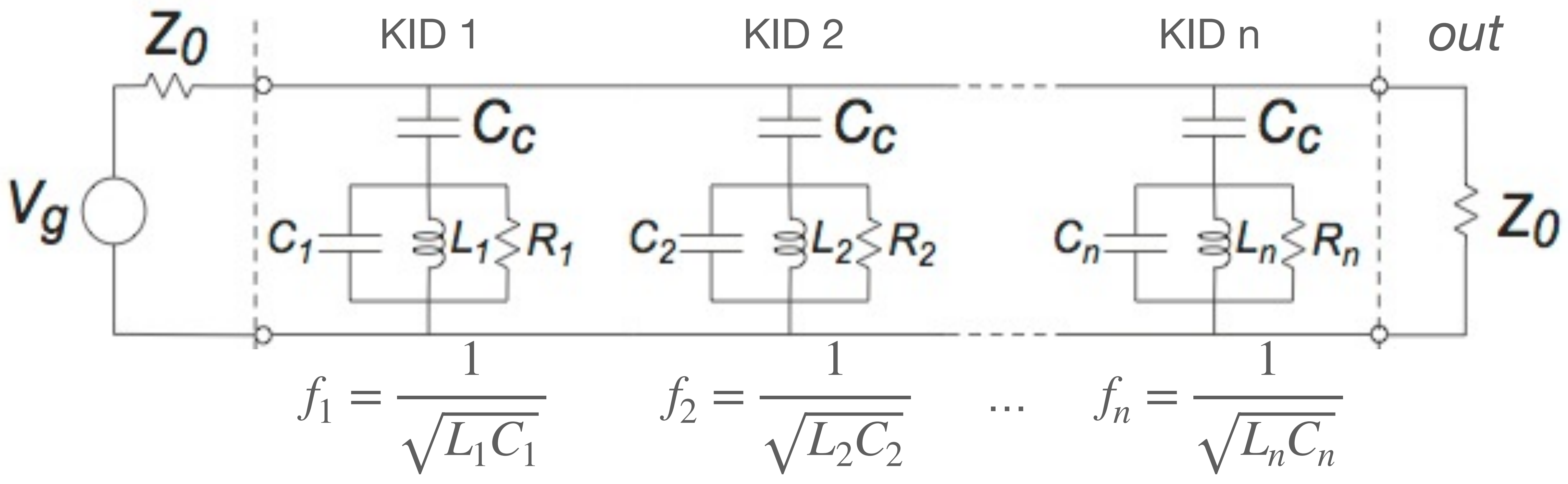
KID (~ 2x2 mm² x 50 nm, 0.5 μg)



kg mass: array of 3000 Si-dices / KIDs

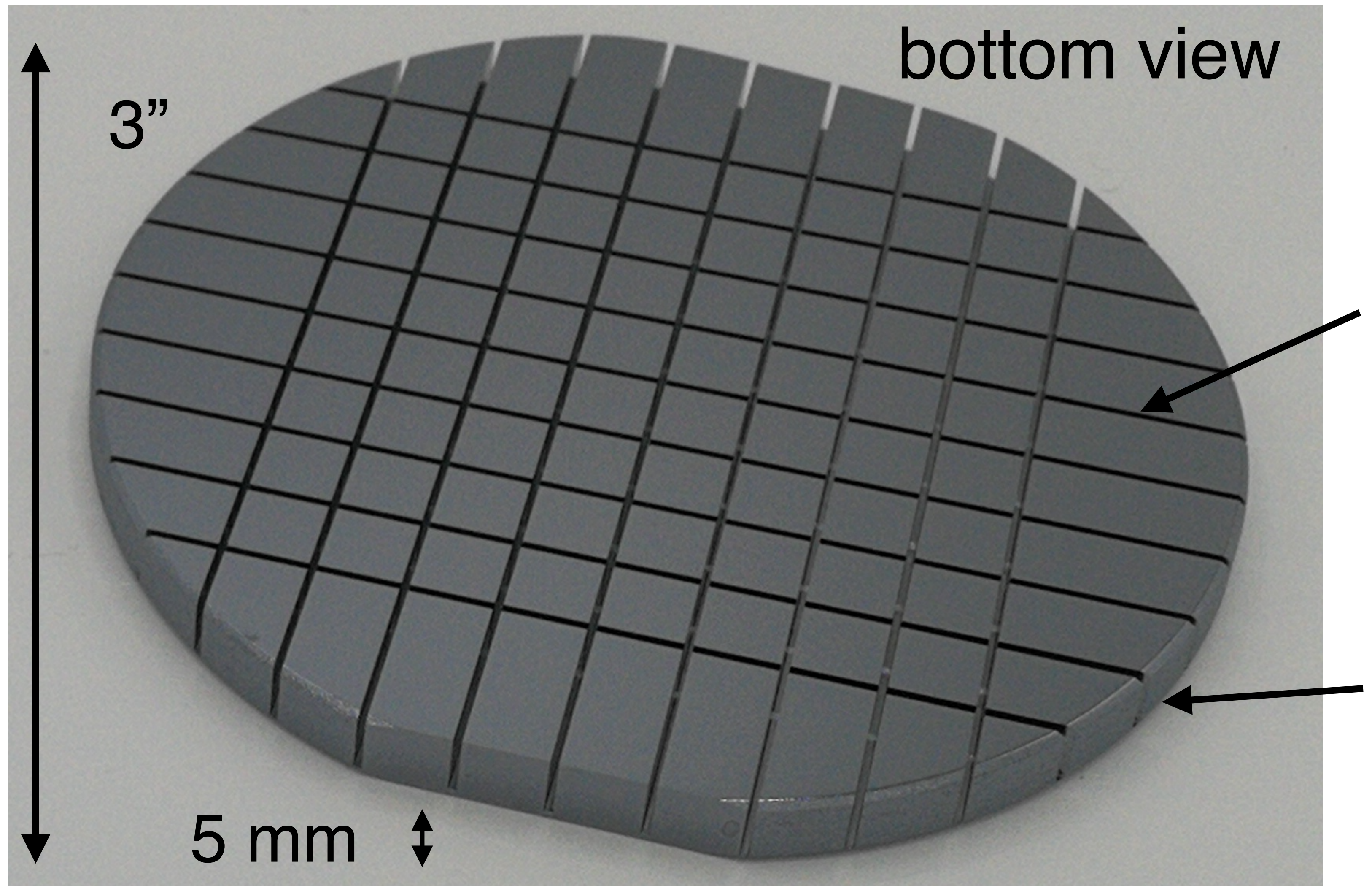


unique feature of KIDs: multiplexed readout
several KIDs coupled to the same feedline at different frequencies



Large number of targets: BULLKID

1. carving of dices in a thick silicon wafer



4.5 mm deep grooves

- 5.5 mm pitch
- chemical etching

0.5 mm thick surface:

- holds the structure
- hosts the KIDs

Large number of targets: BULLKID

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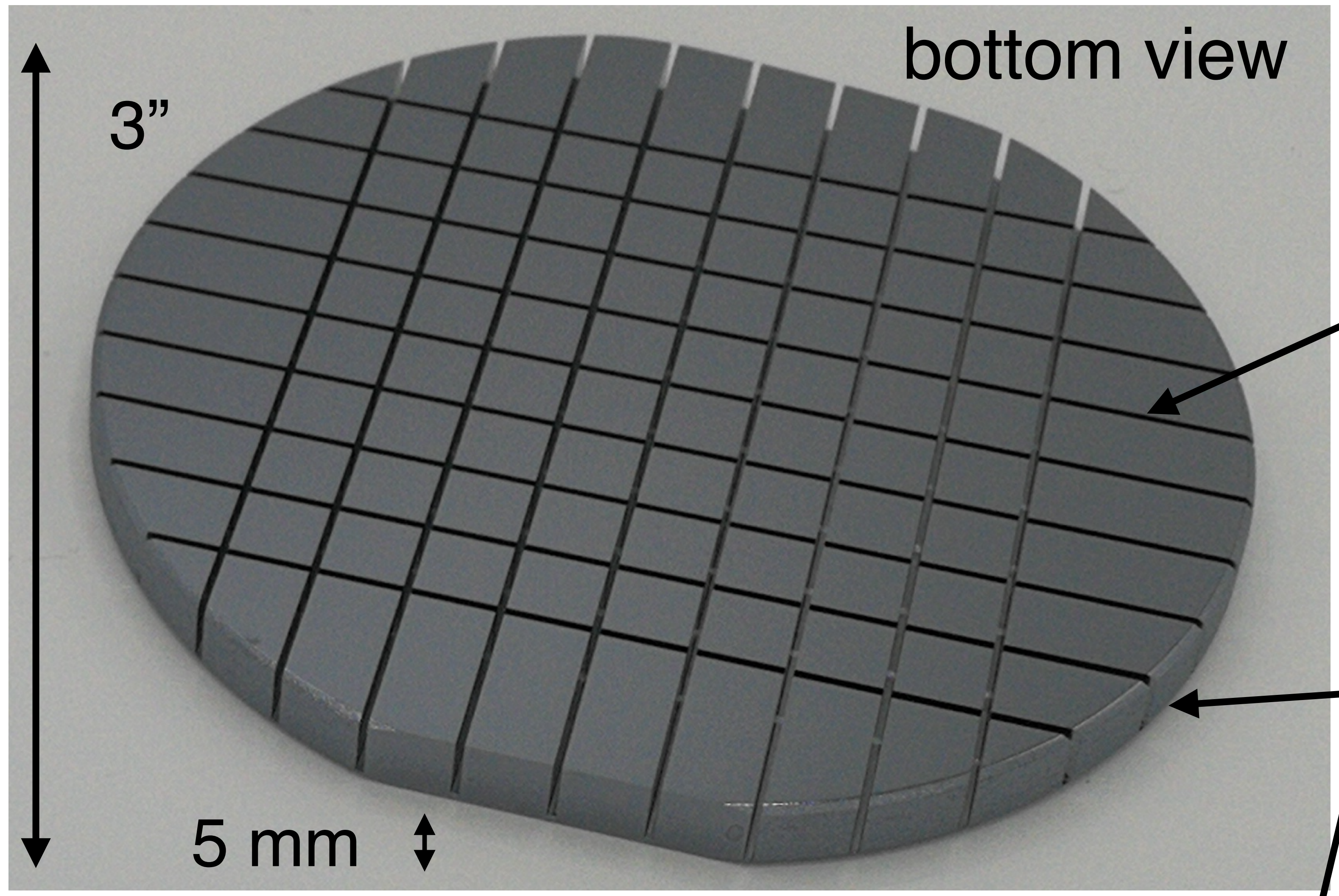


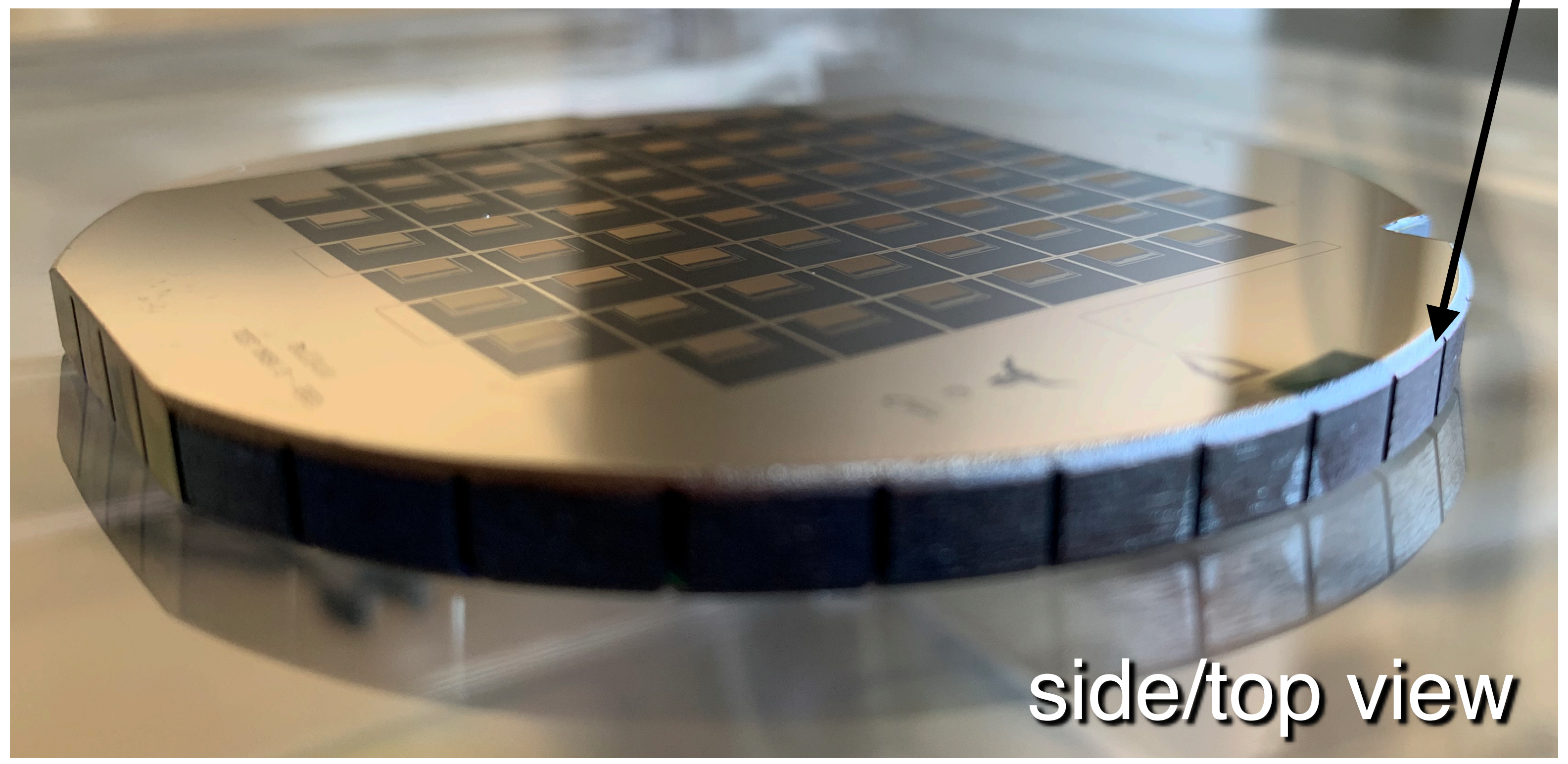
4.5 mm deep grooves

- 5.5 mm pitch
- chemical etching

0.5 mm thick surface:

- holds the structure
- hosts the KIDs

2. lithography of multiplexed KID array



KID array

- 60 nm aluminum film
- 60 KIDs lithography

Large number of targets: BULLKID

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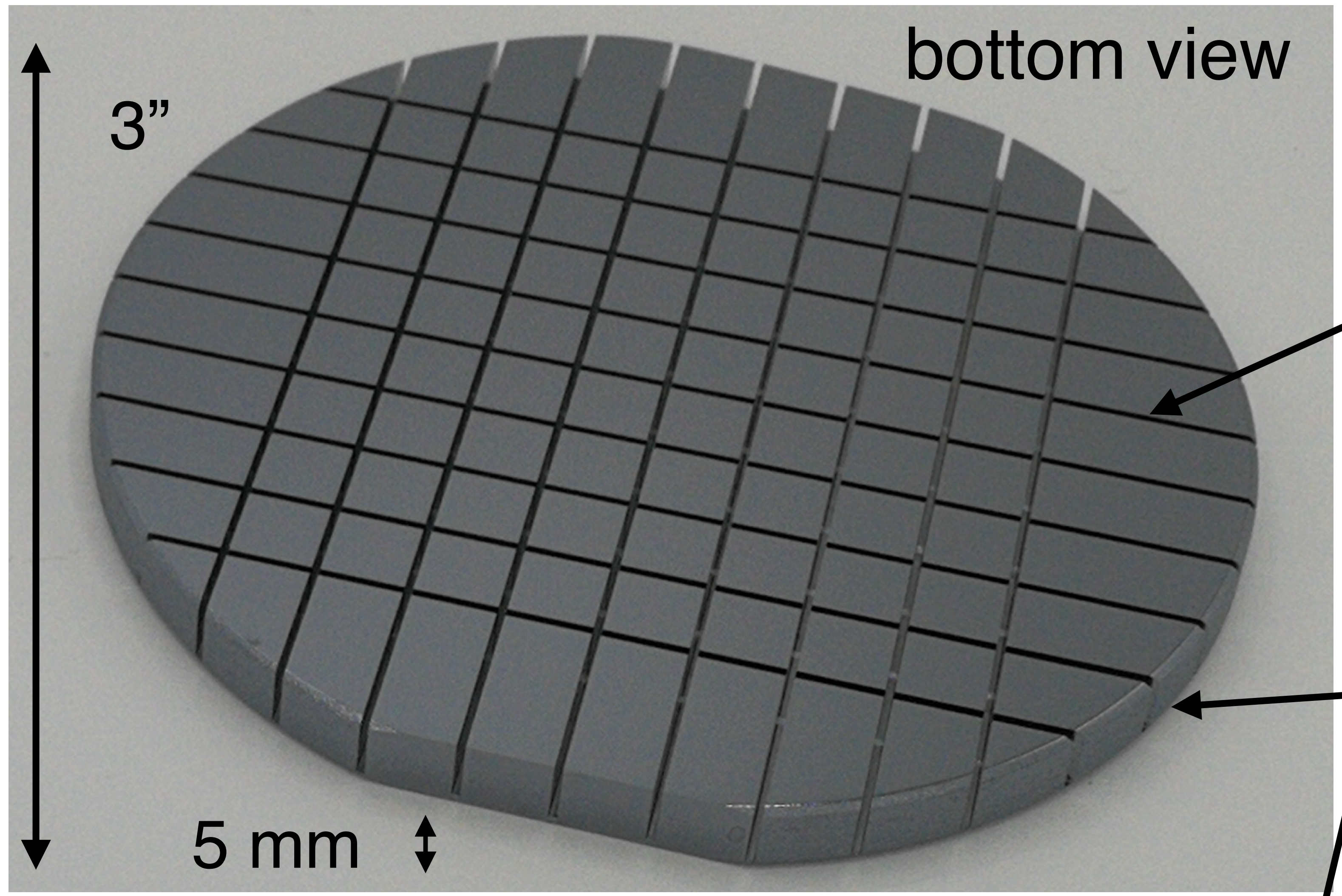

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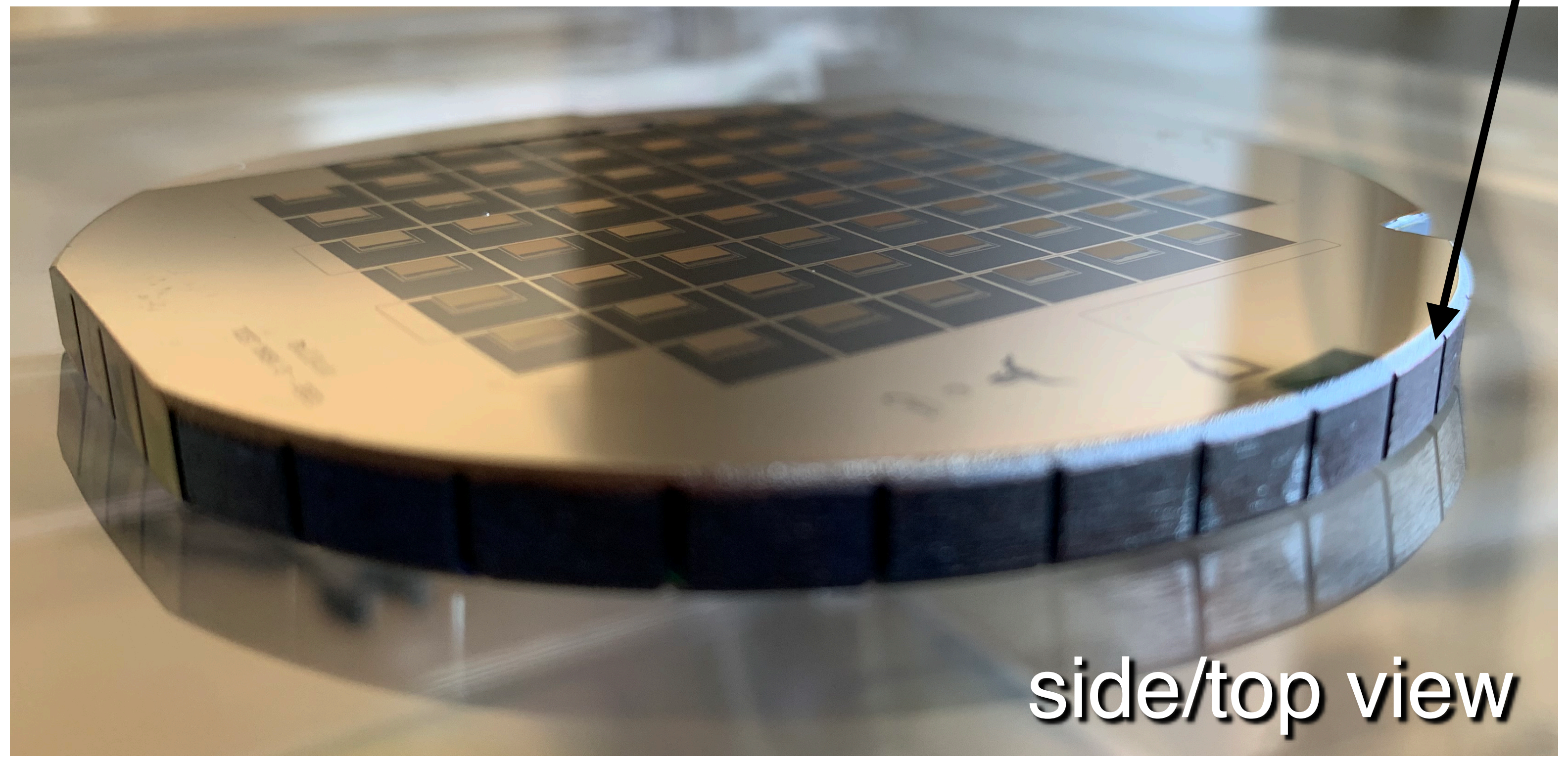
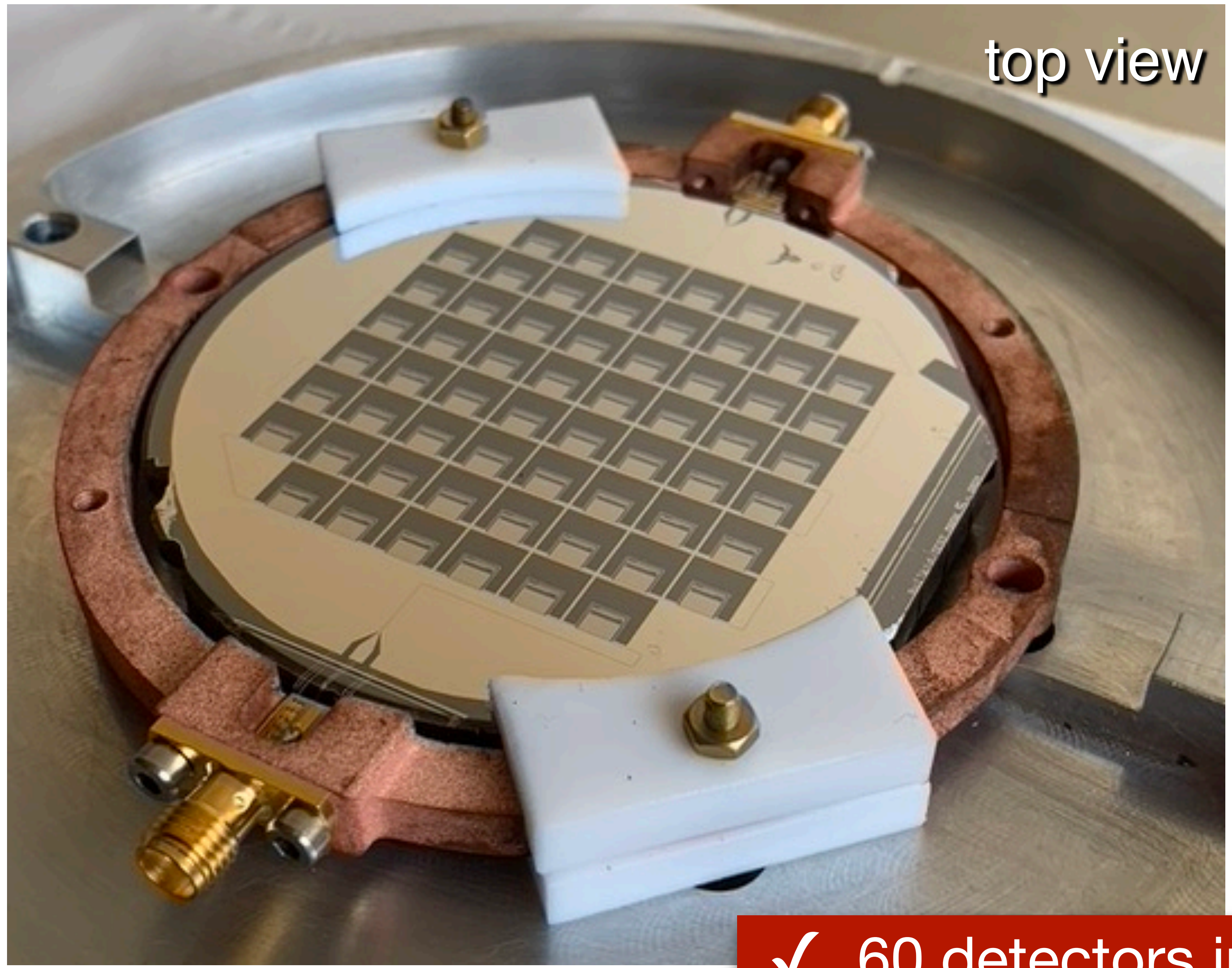


KID array

- 60 nm aluminum film
- 60 KIDs lithography

3. assembly



✓ 60 detectors in 1

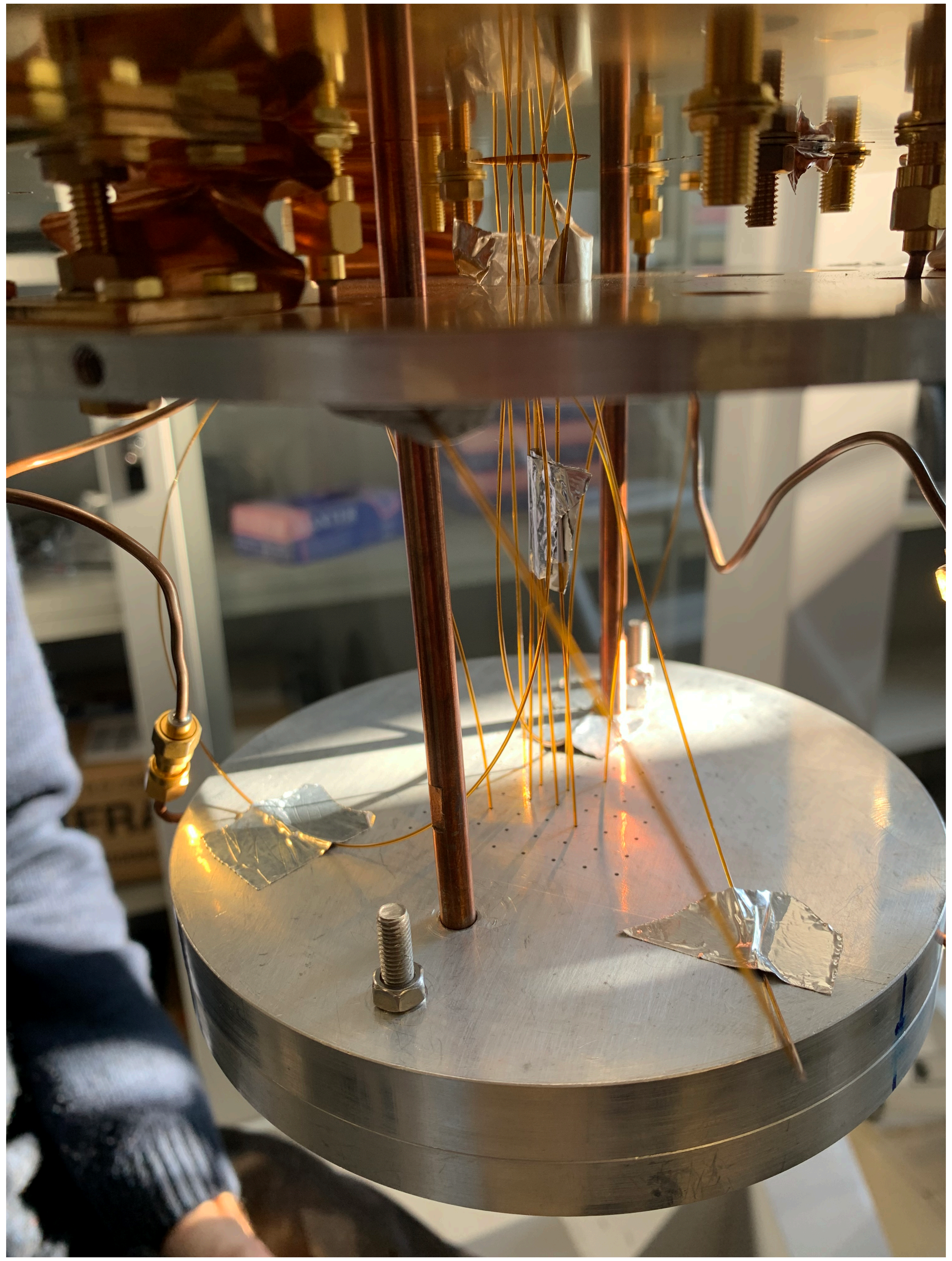
60 dices 0.3 g each

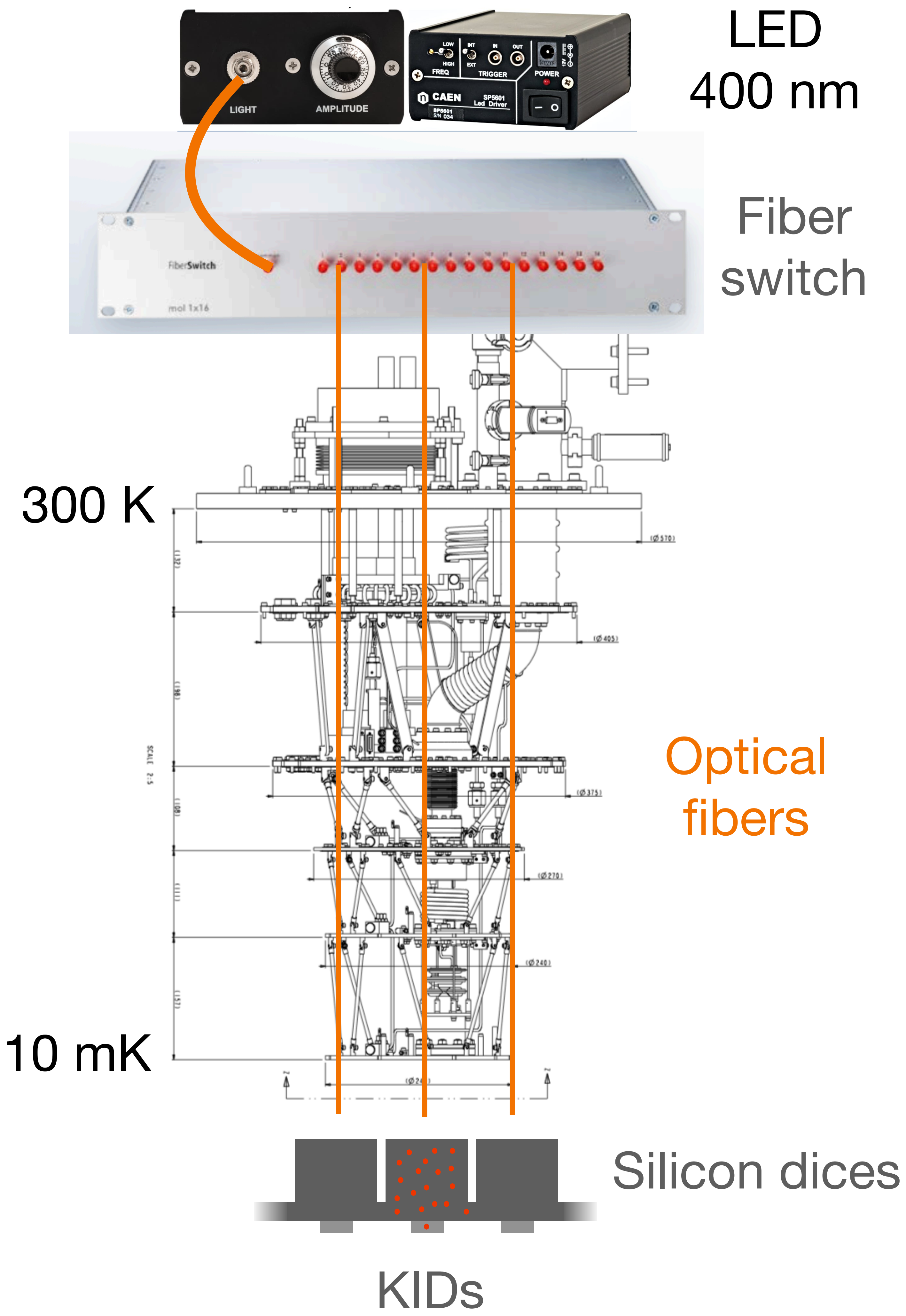
1 readout line

Design and assembly

- 3D-printed Cu holder
- Aluminum case

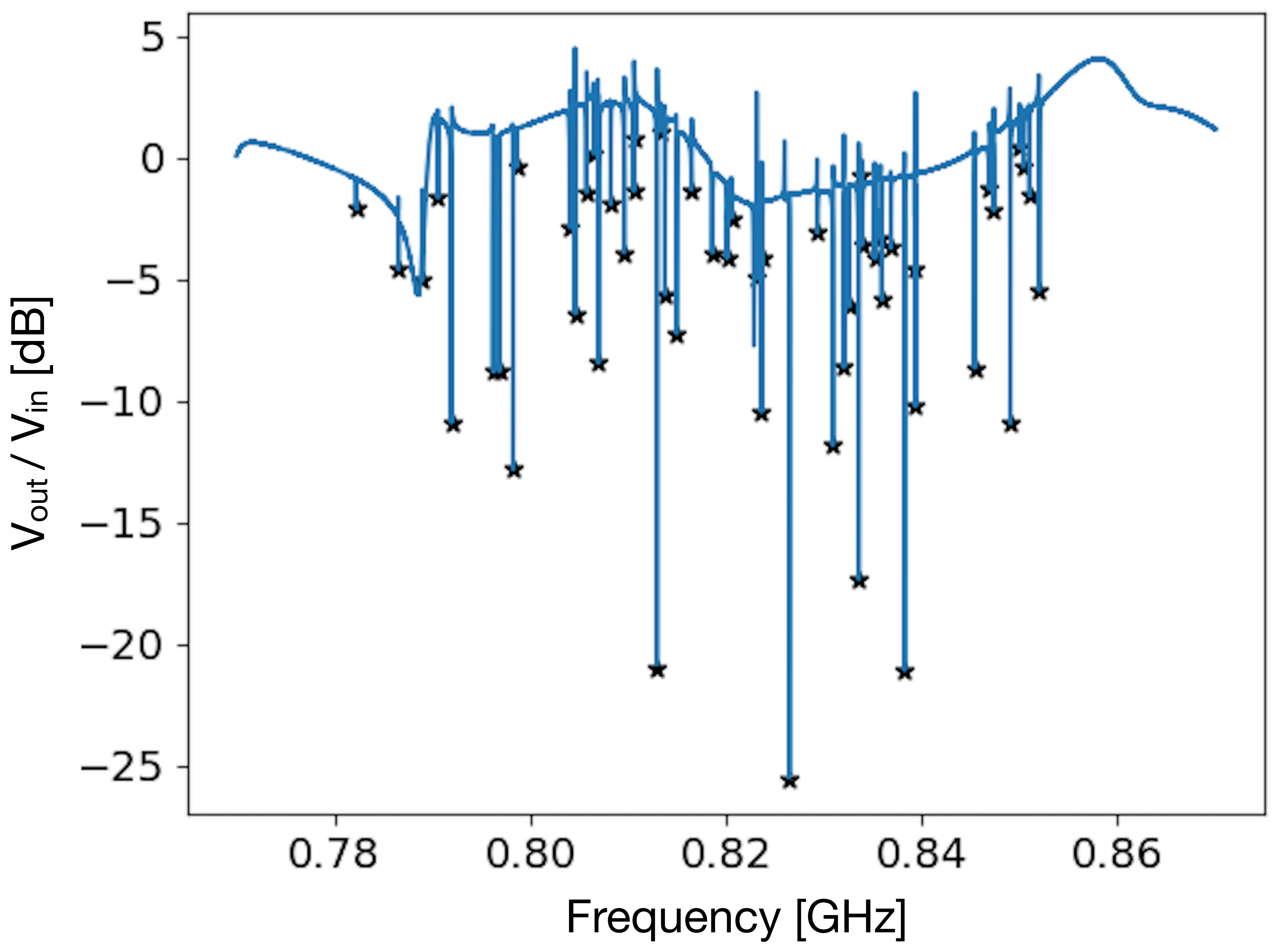
Operation in refrigerator



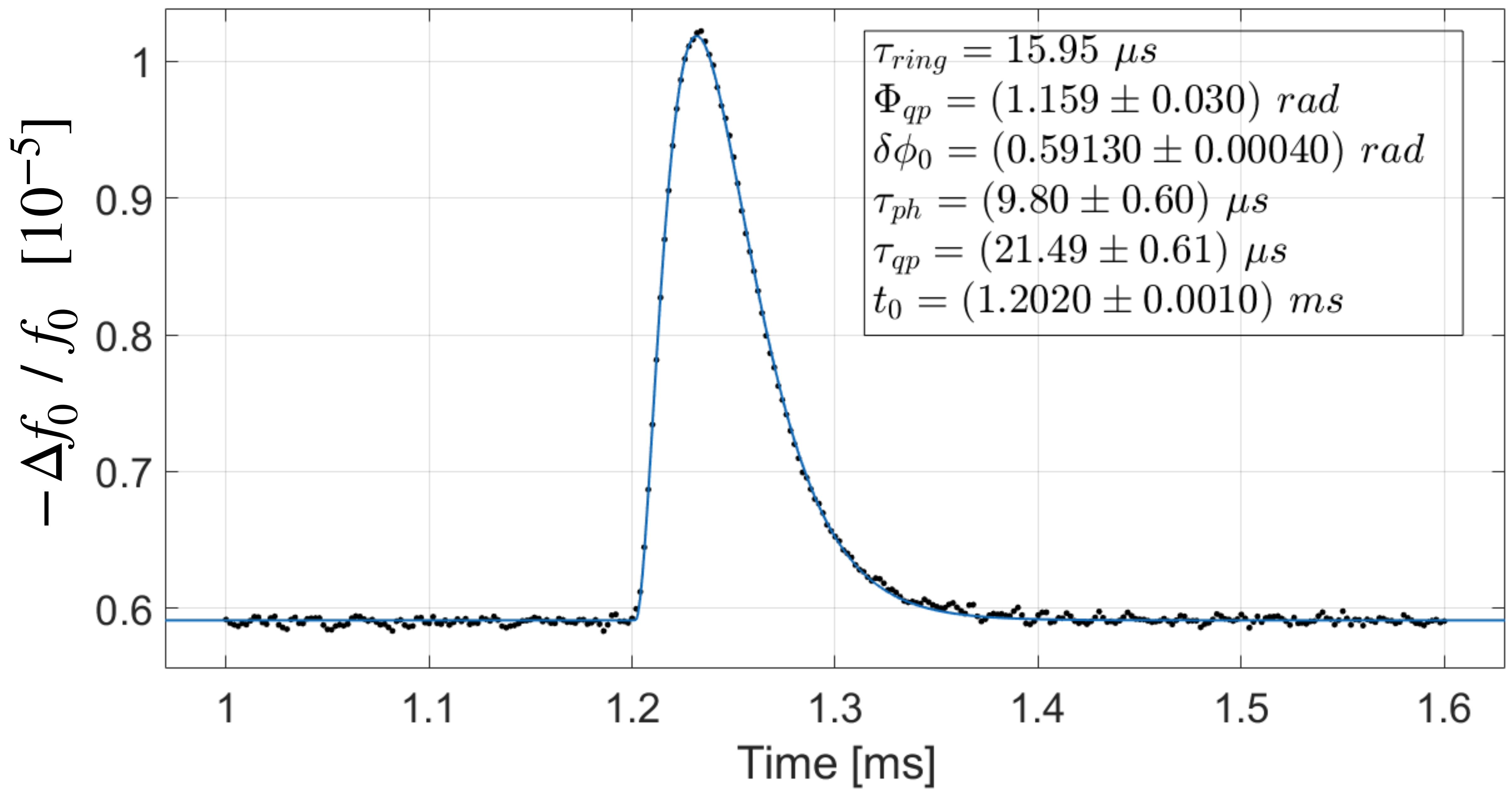


First prototype (Fall 2021)

Frequency scan of the KID array

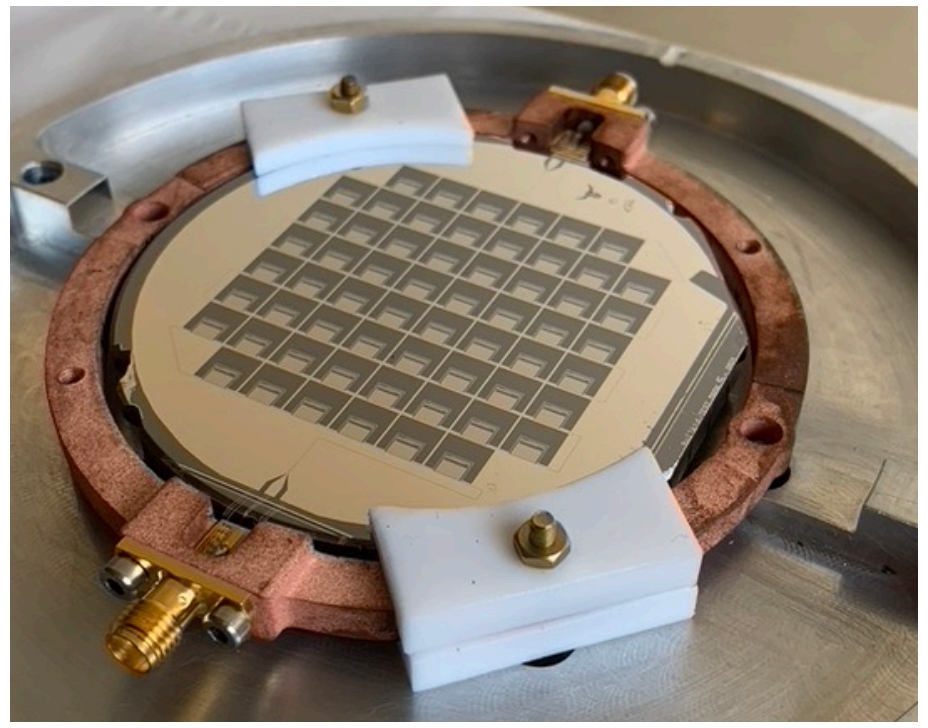


Signal from a dice

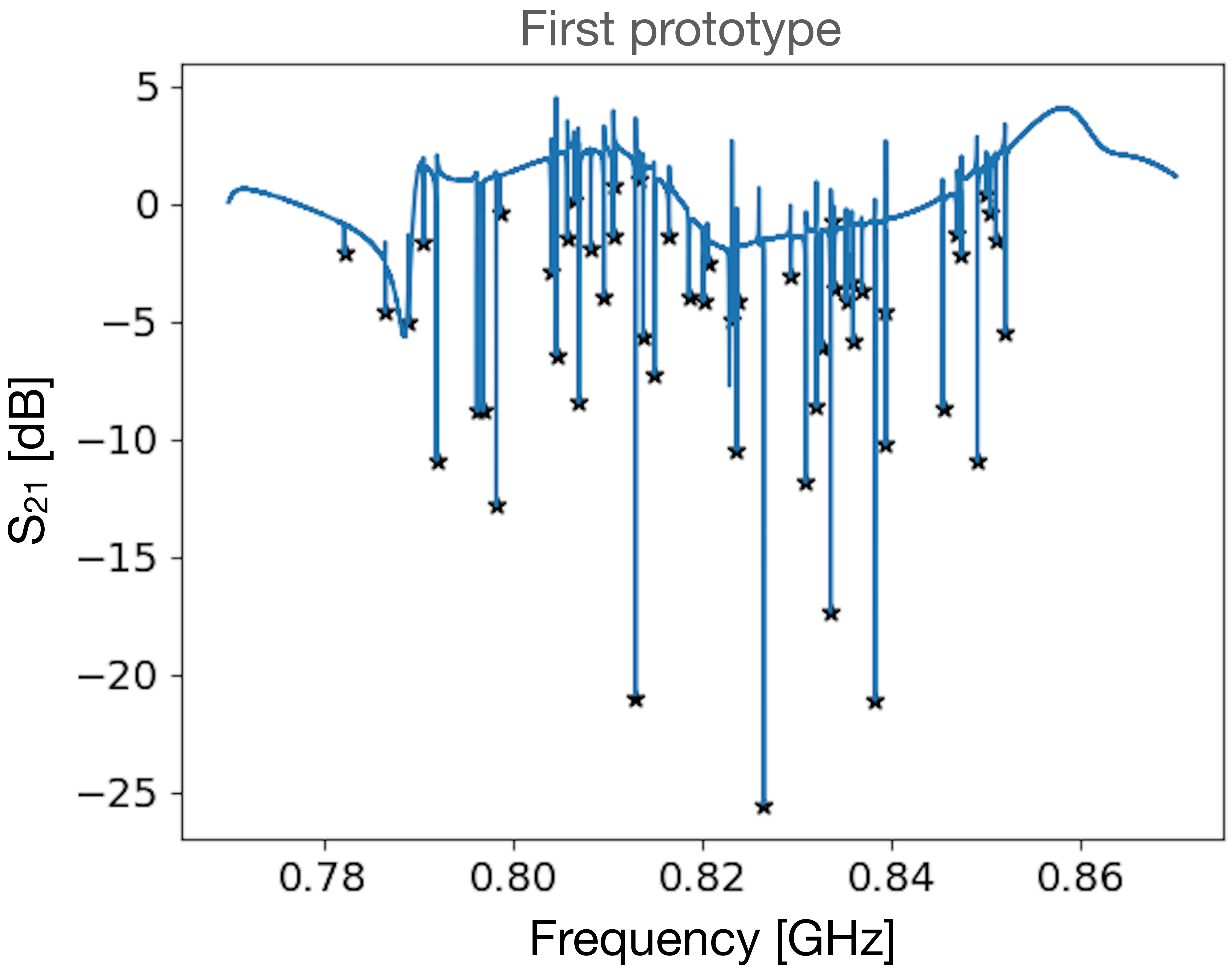


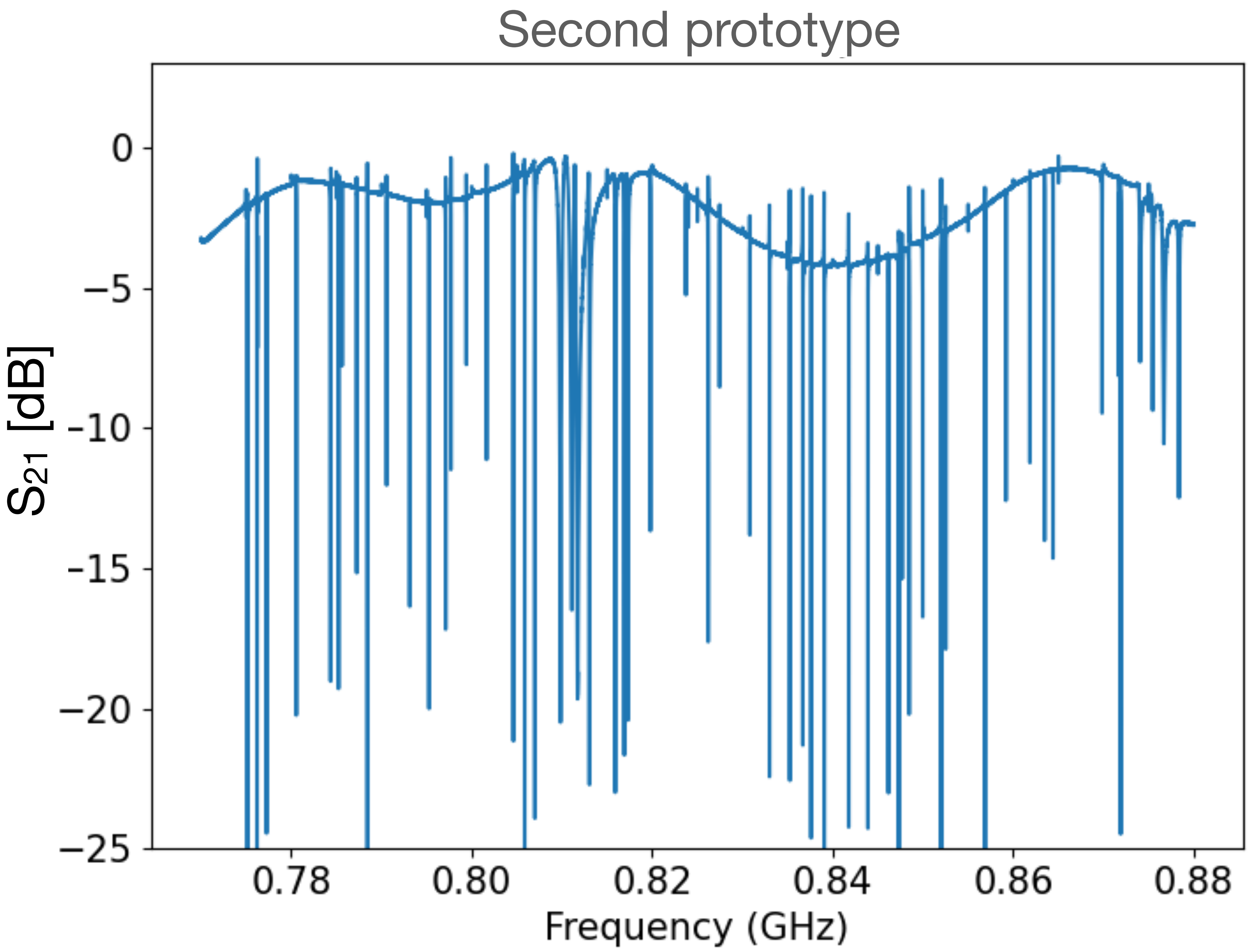
- 👍 **Proved that detector concept works**
- 👎 Poor uniformity across the array
- 👎 Low quality factor of the resonators (0.2×10^5, aiming at $> 10^5$)

Second prototype (Summer 2022)

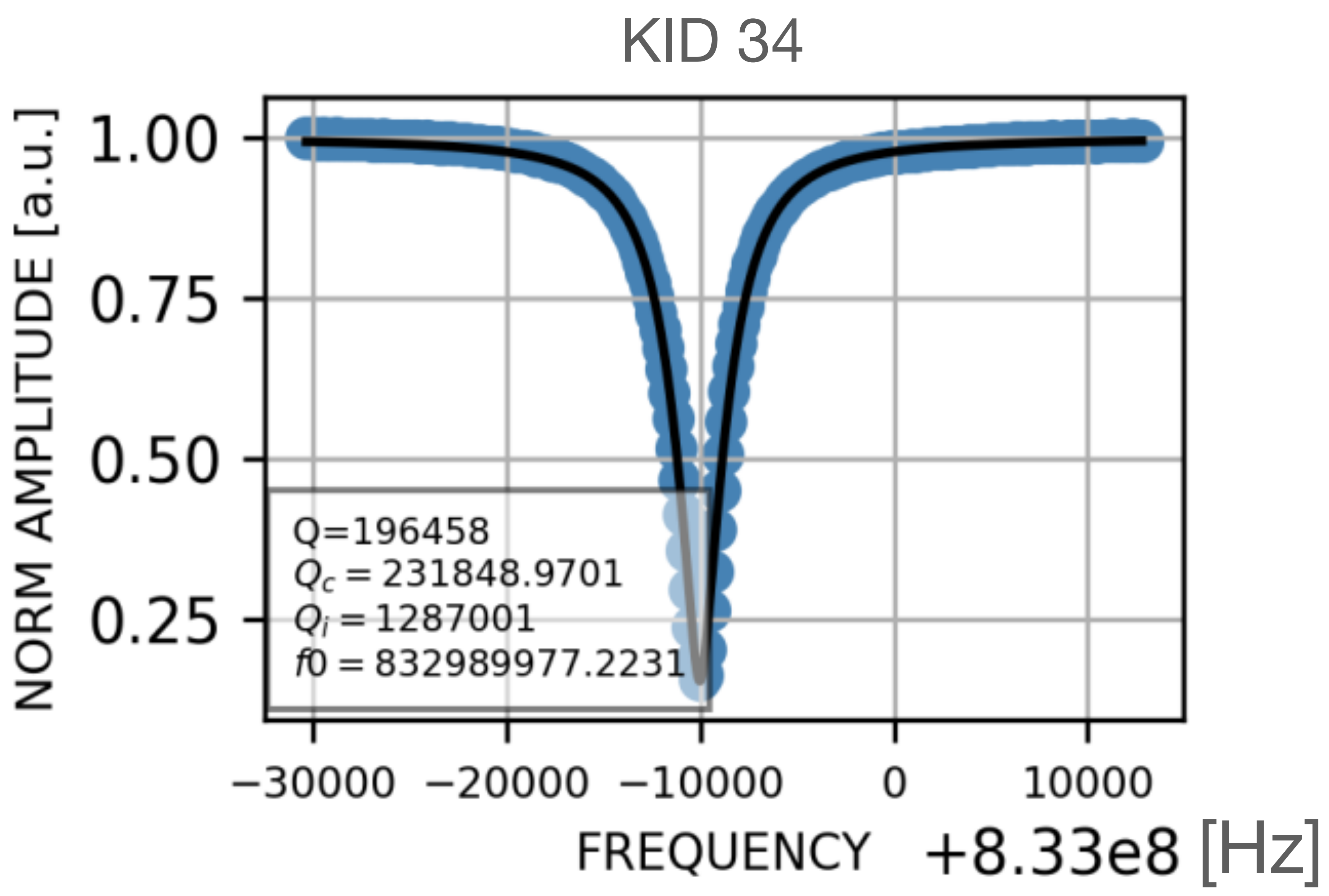


- Reduced electrical x-talk (frequency spacing from 1 to 2 MHz)
- Improved film quality of the KIDs (uniform etching of the wafer surface)

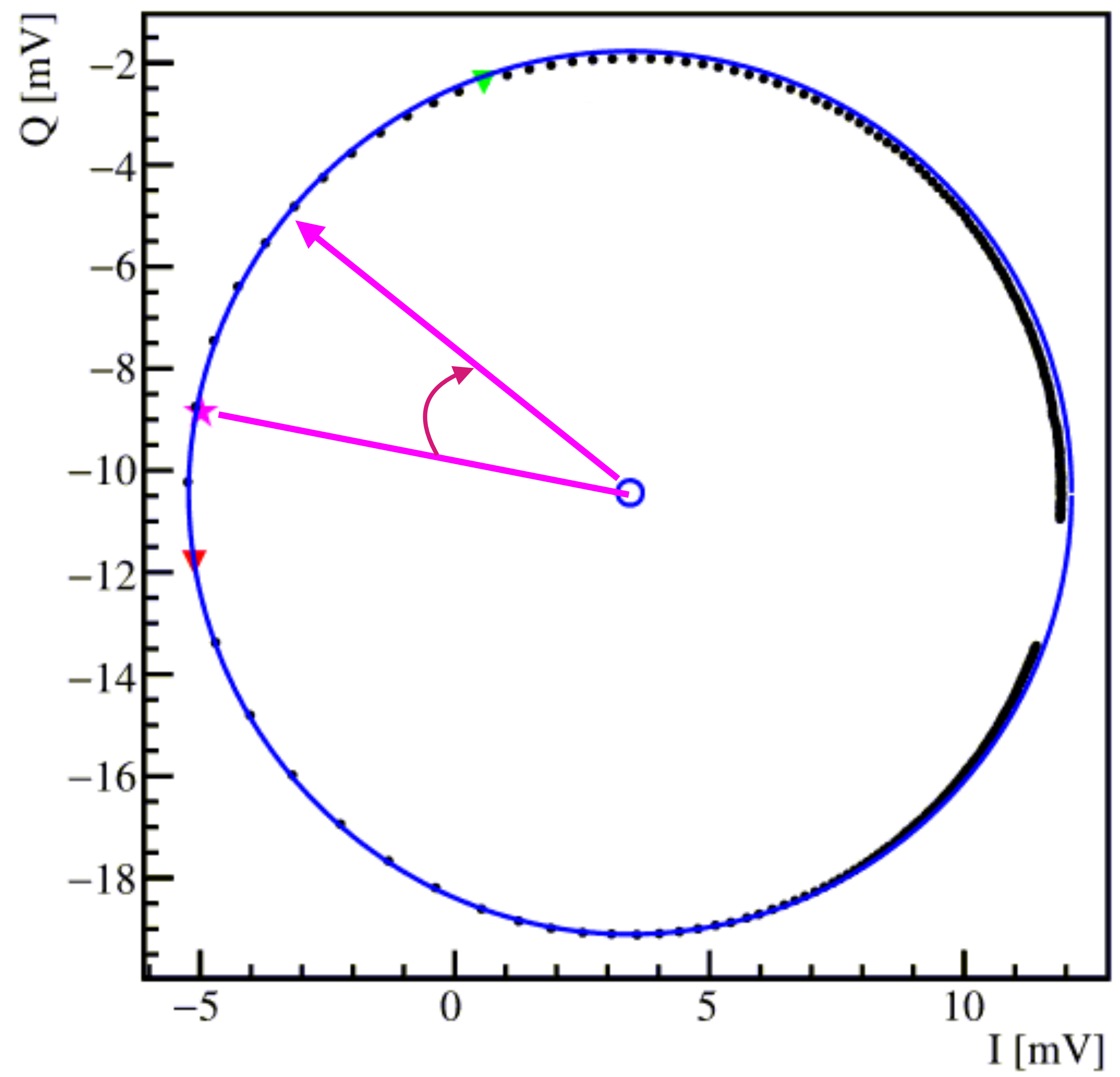


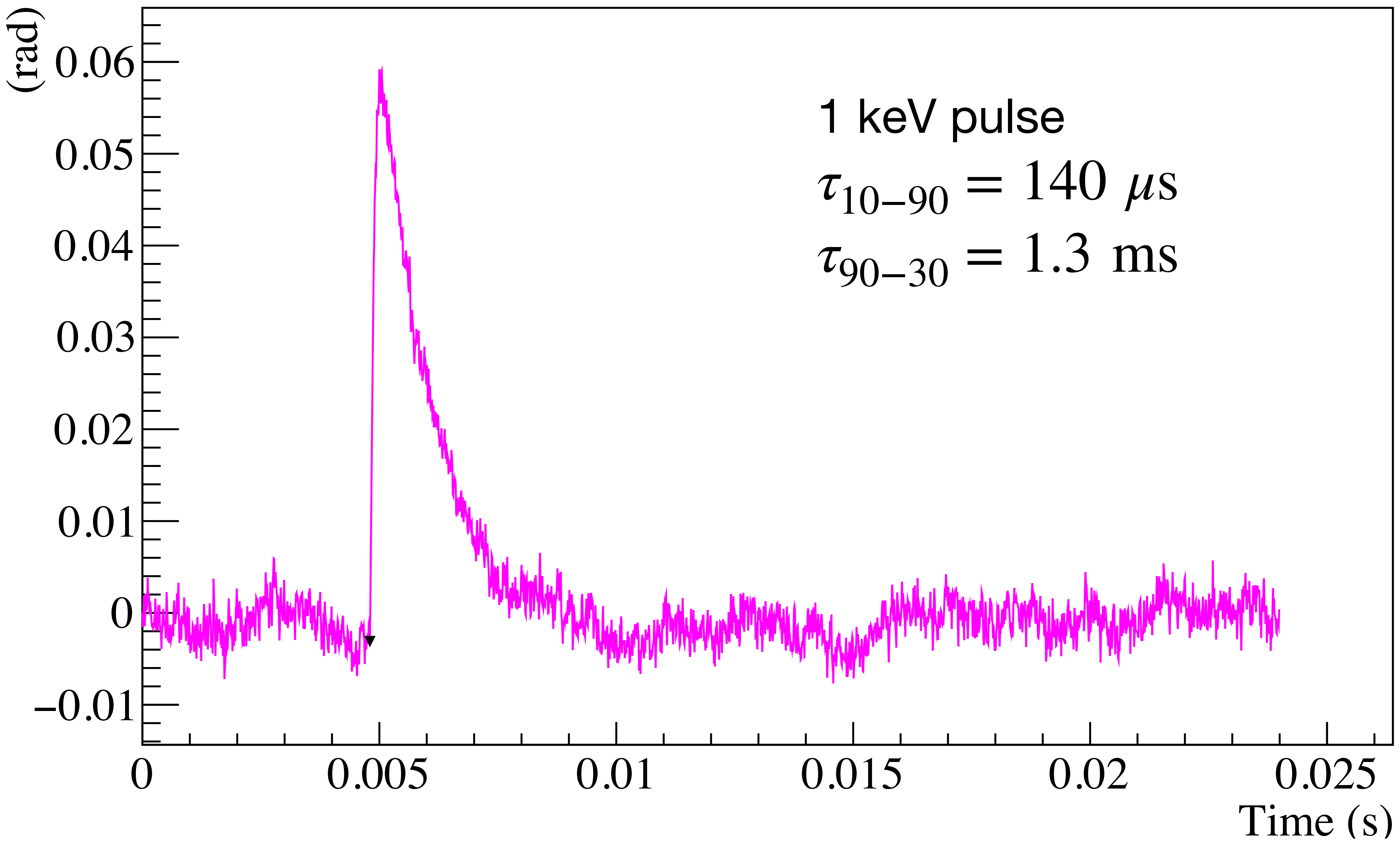


Readout

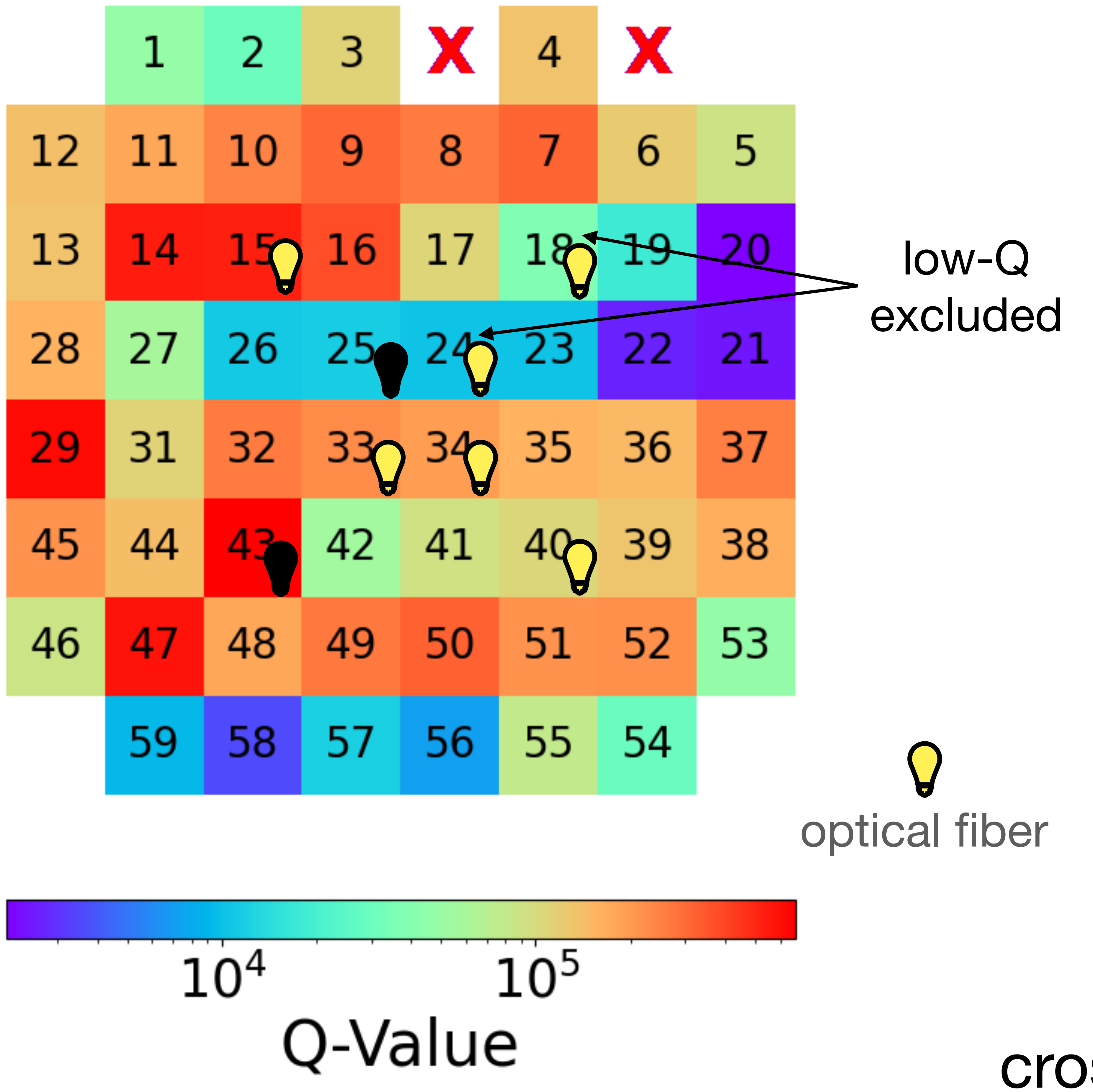


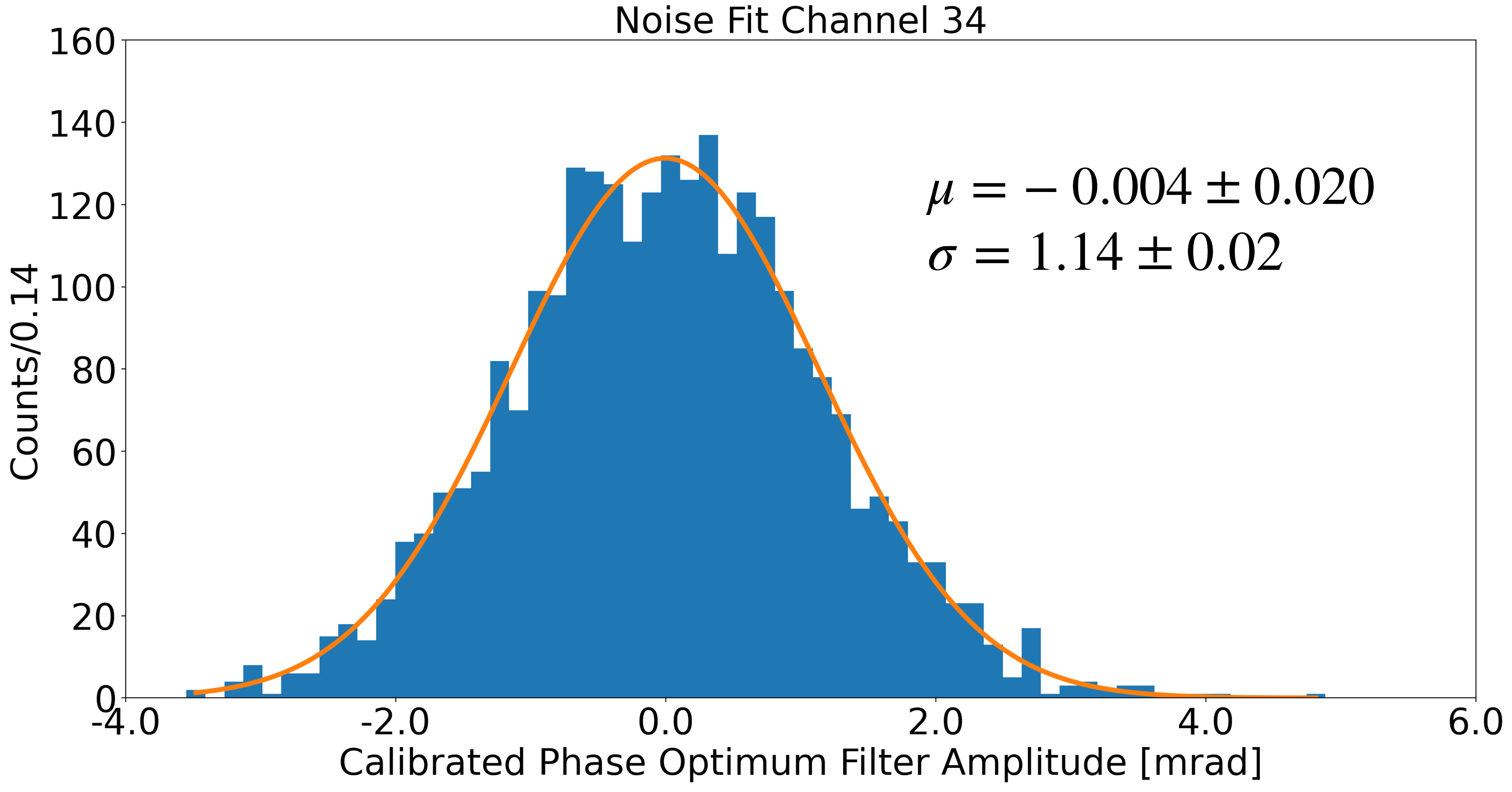
Ettus X310
can MUX the entire array





Preliminary results





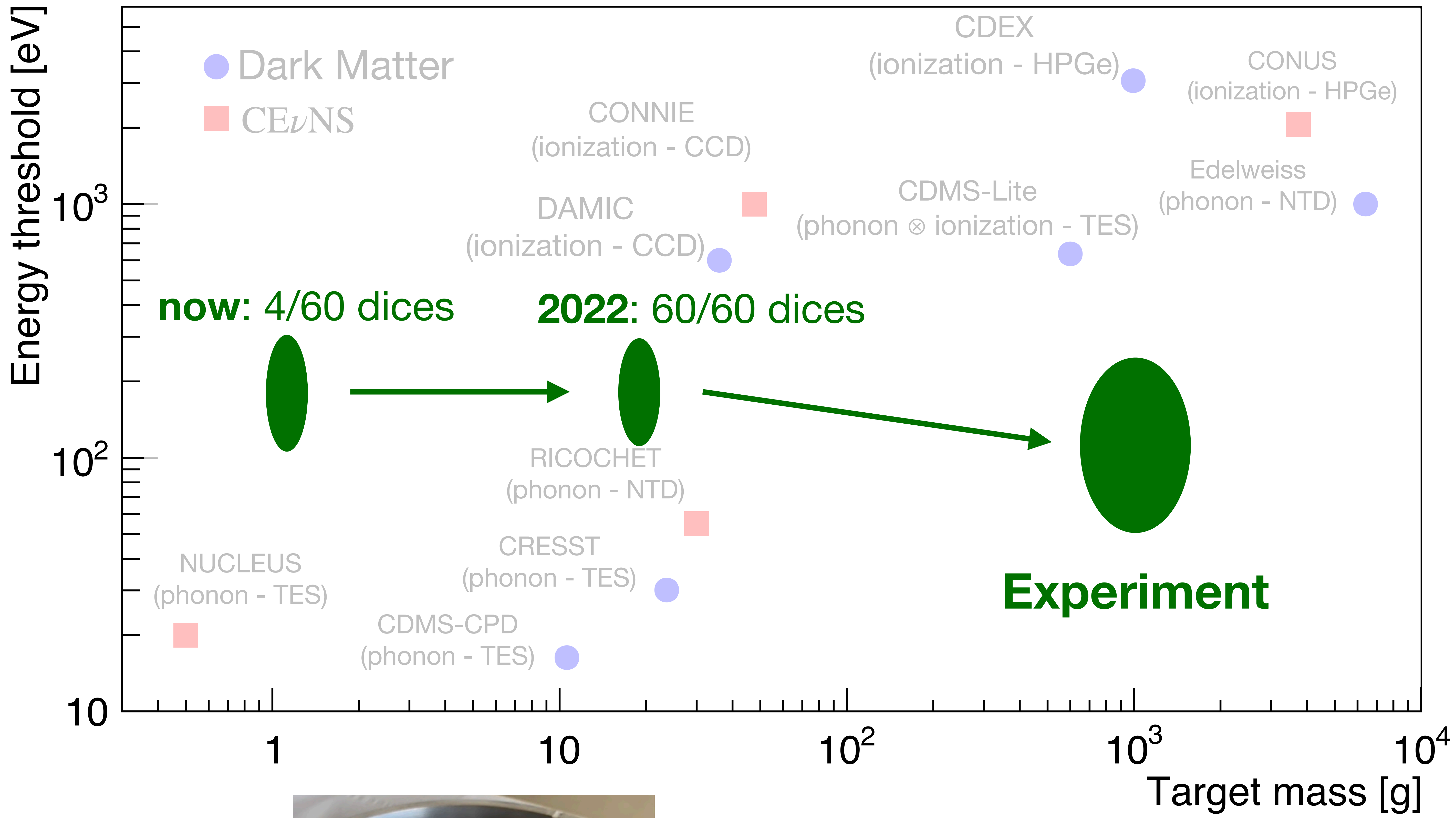
KID	σ_0 [mrad]	σ_0 [eV]
15	3.4±0.1	*25.0±1.2*
33	1.78±0.03	*22.9±0.8*
34	1.14±0.02	*25.4±0.5*
40	0.73±0.01	*20.6±0.9*

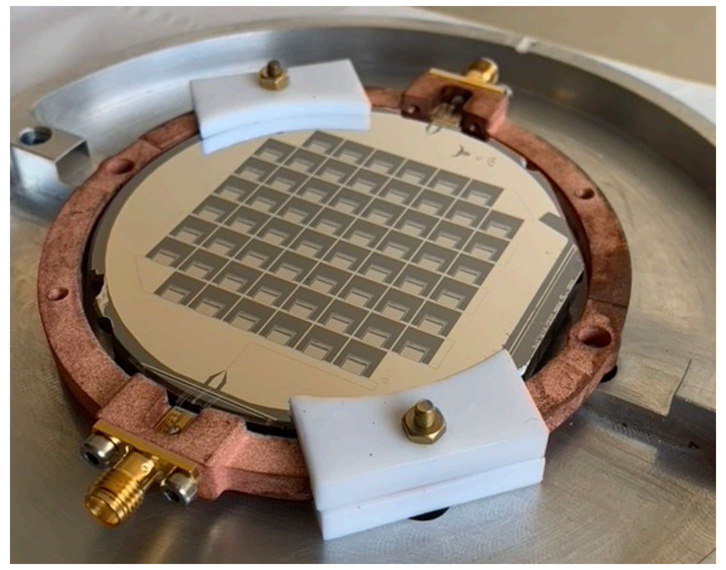
⬅ optical cal

➡ threshold ~120 *eV*

Next cool-down:
cross-check with x-ray calibration, light on other channels

Towards the experiment





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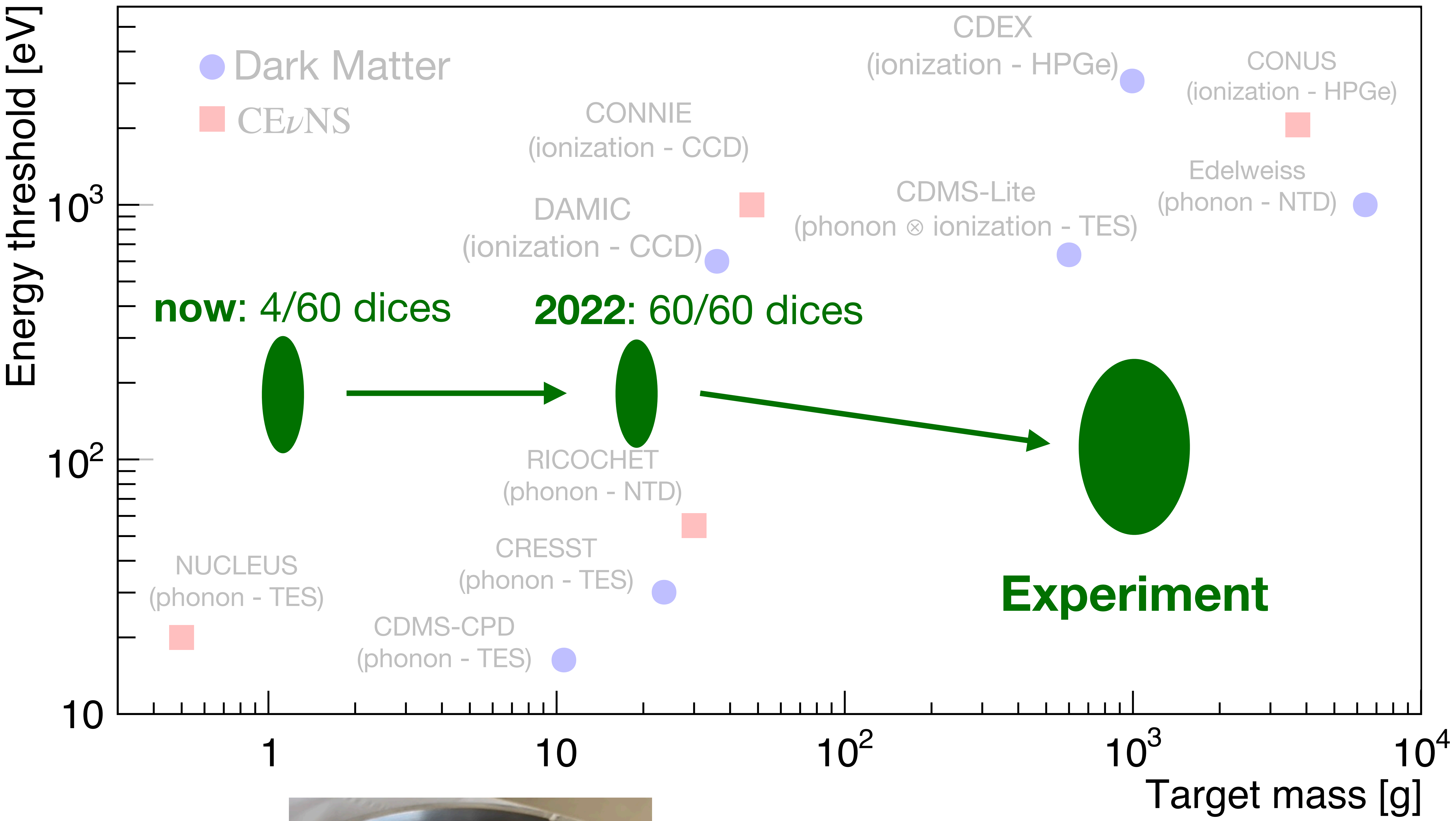
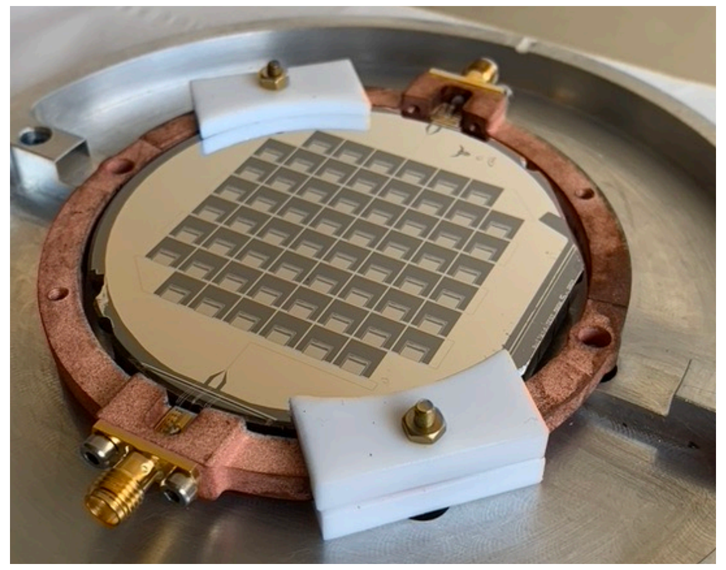
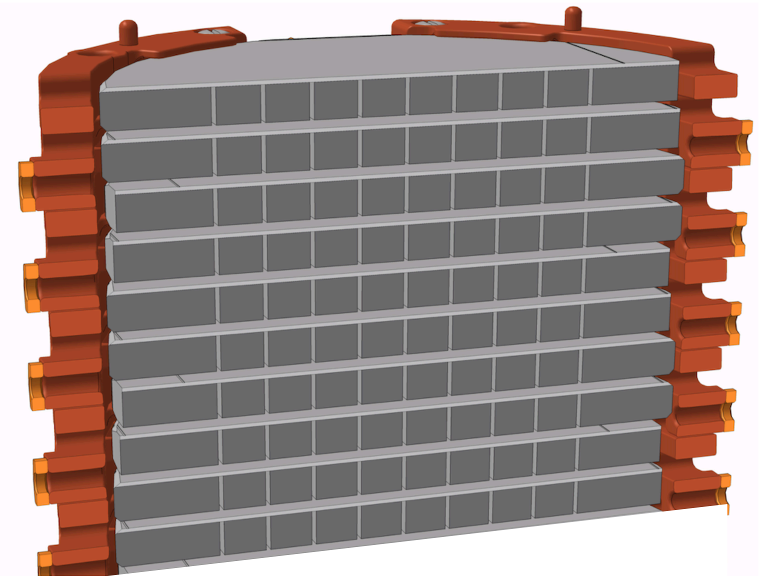


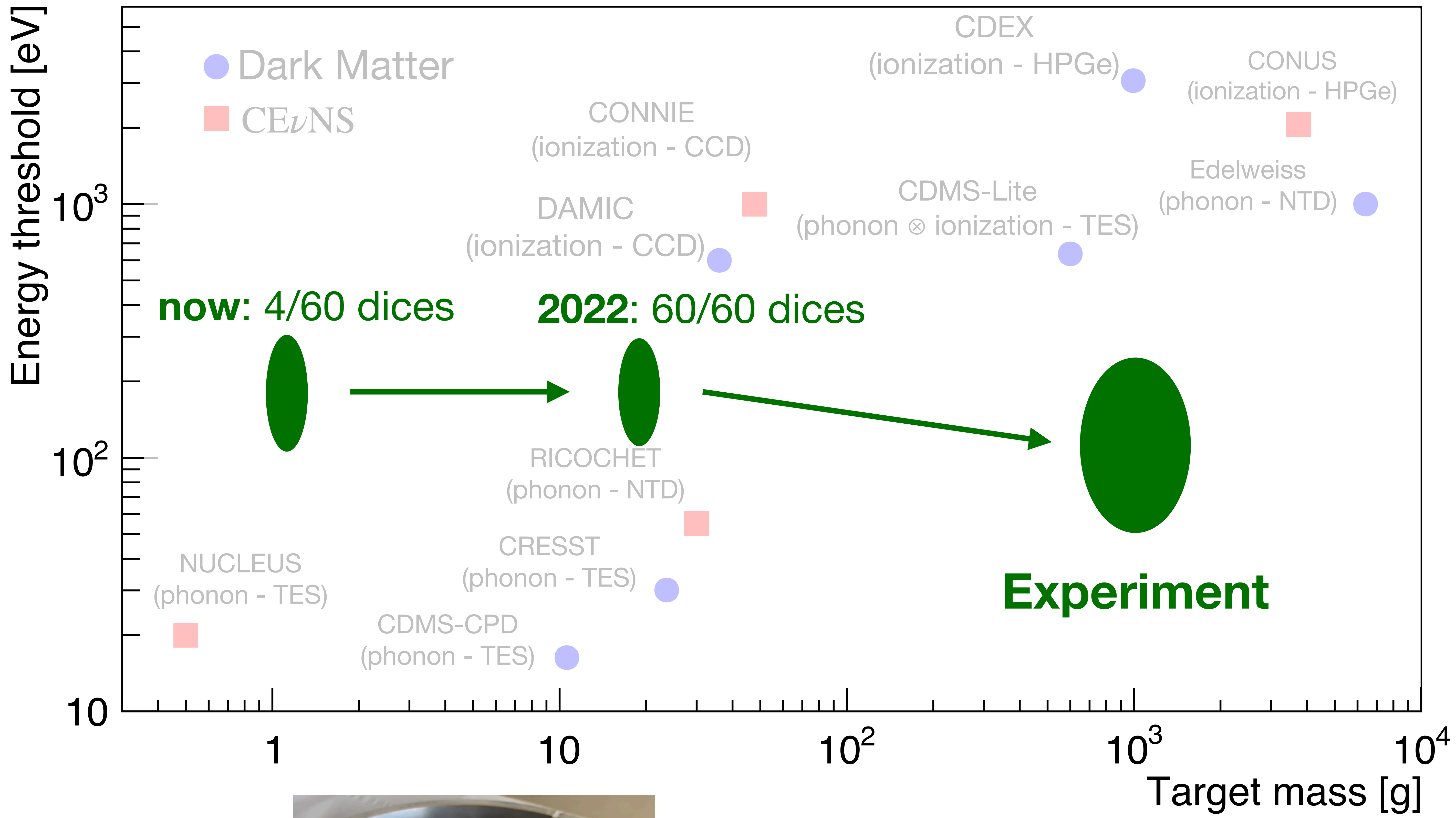


Mass:
from 3” to 4” wafers
stack of wafers



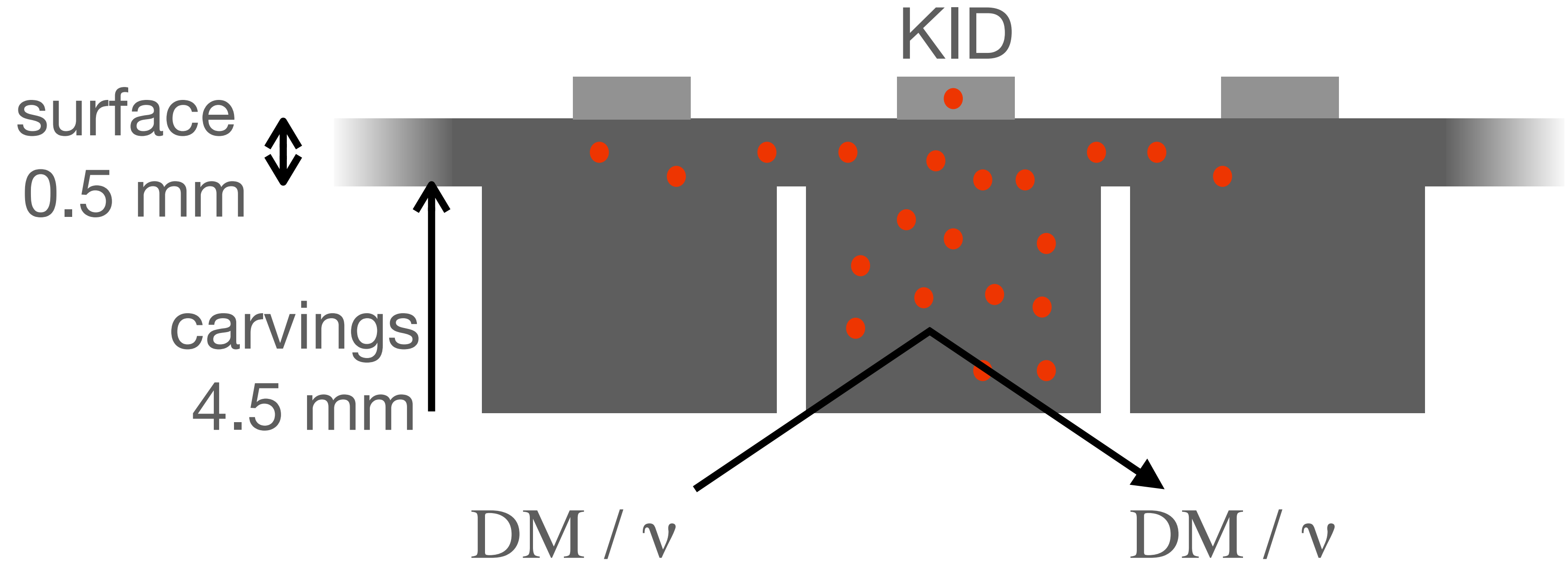
3D-printed Cu stacking prototype

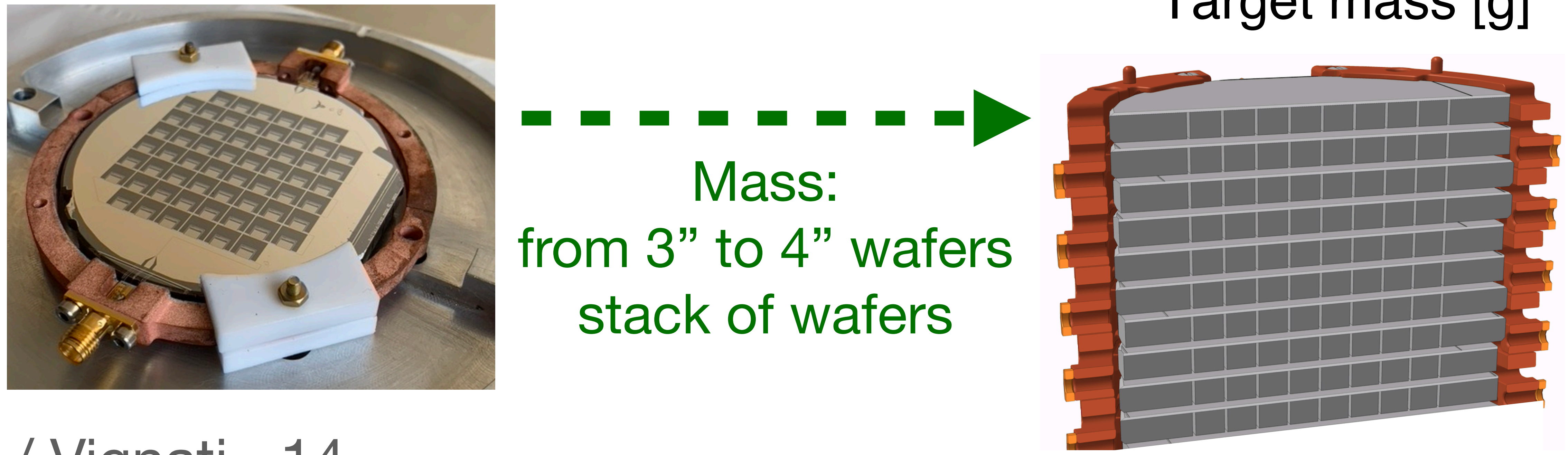
Towards the experiment



Threshold (ongoing R&D):

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





3D-printed Cu stacking prototype

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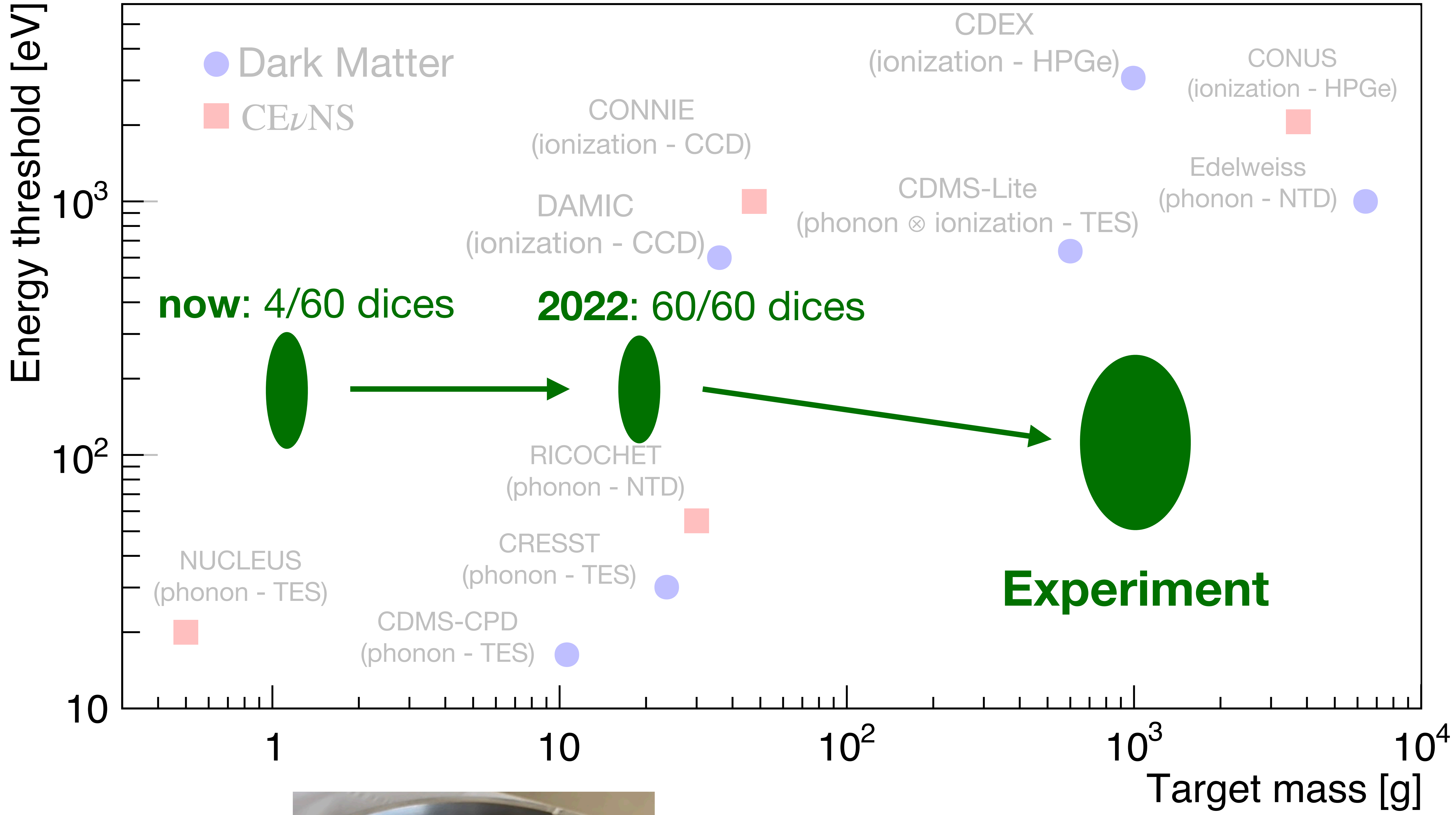

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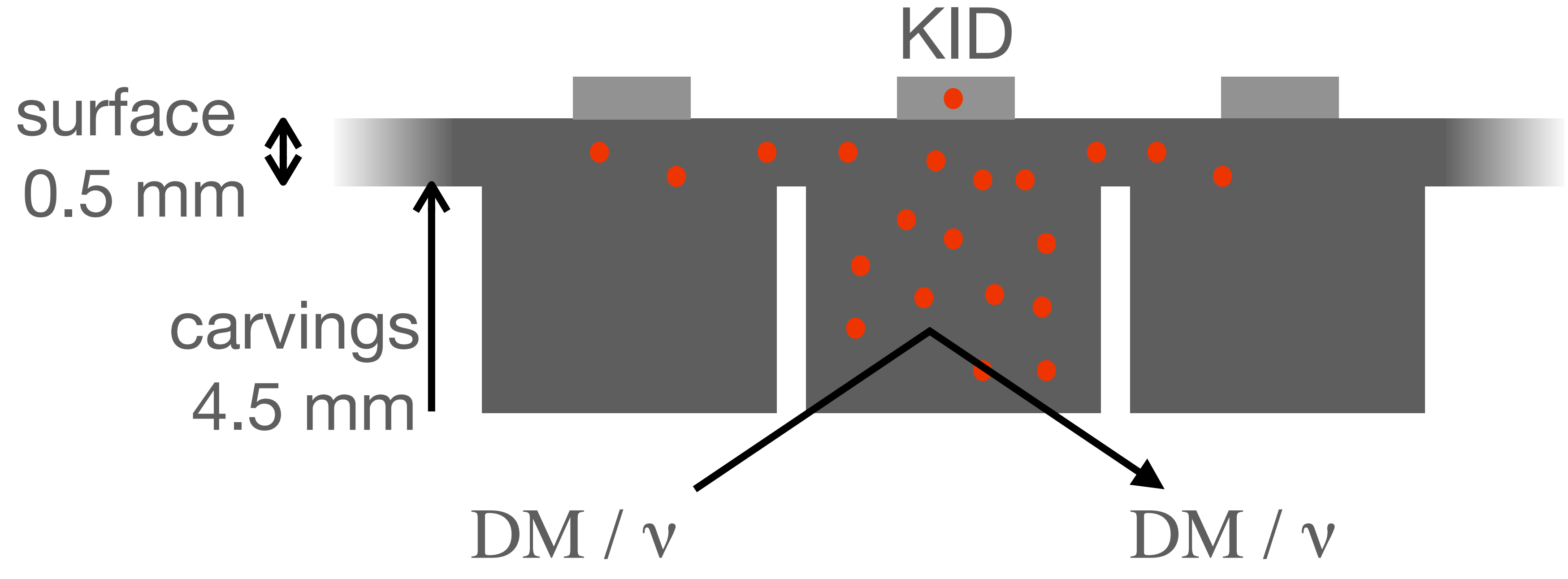
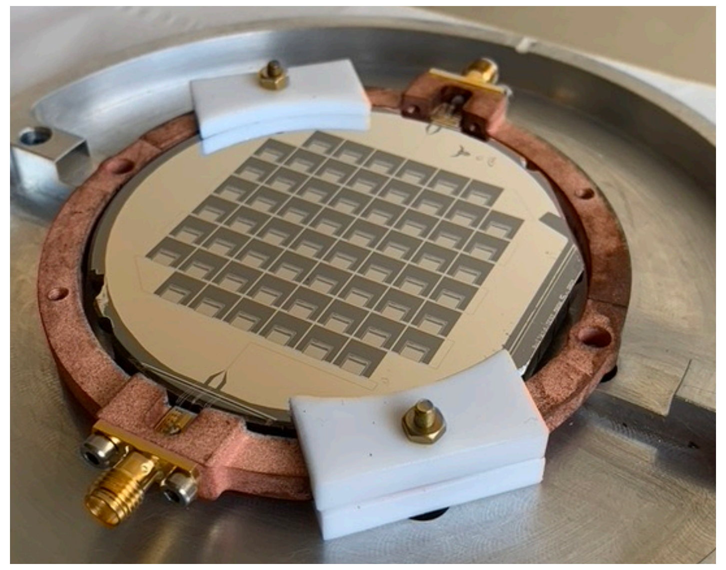


+ port the technology to Germanium wafers
(10x neutrino x-sec, does not apply to Dark Matter)



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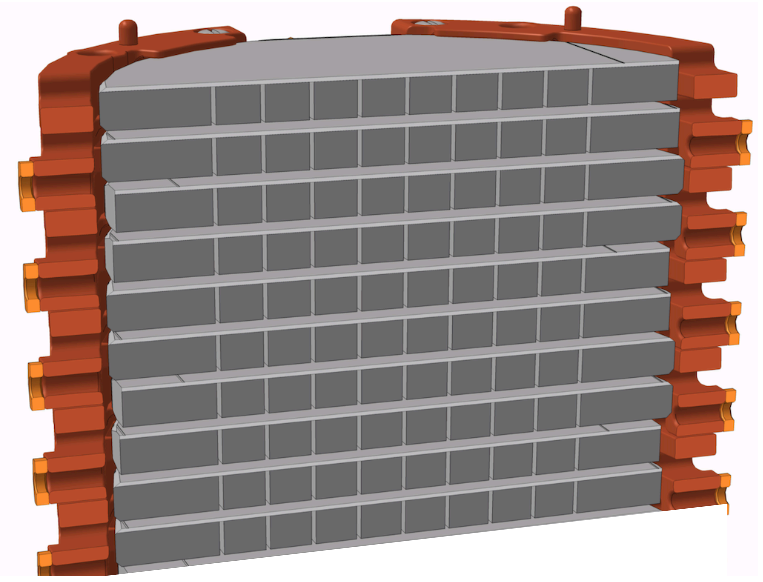
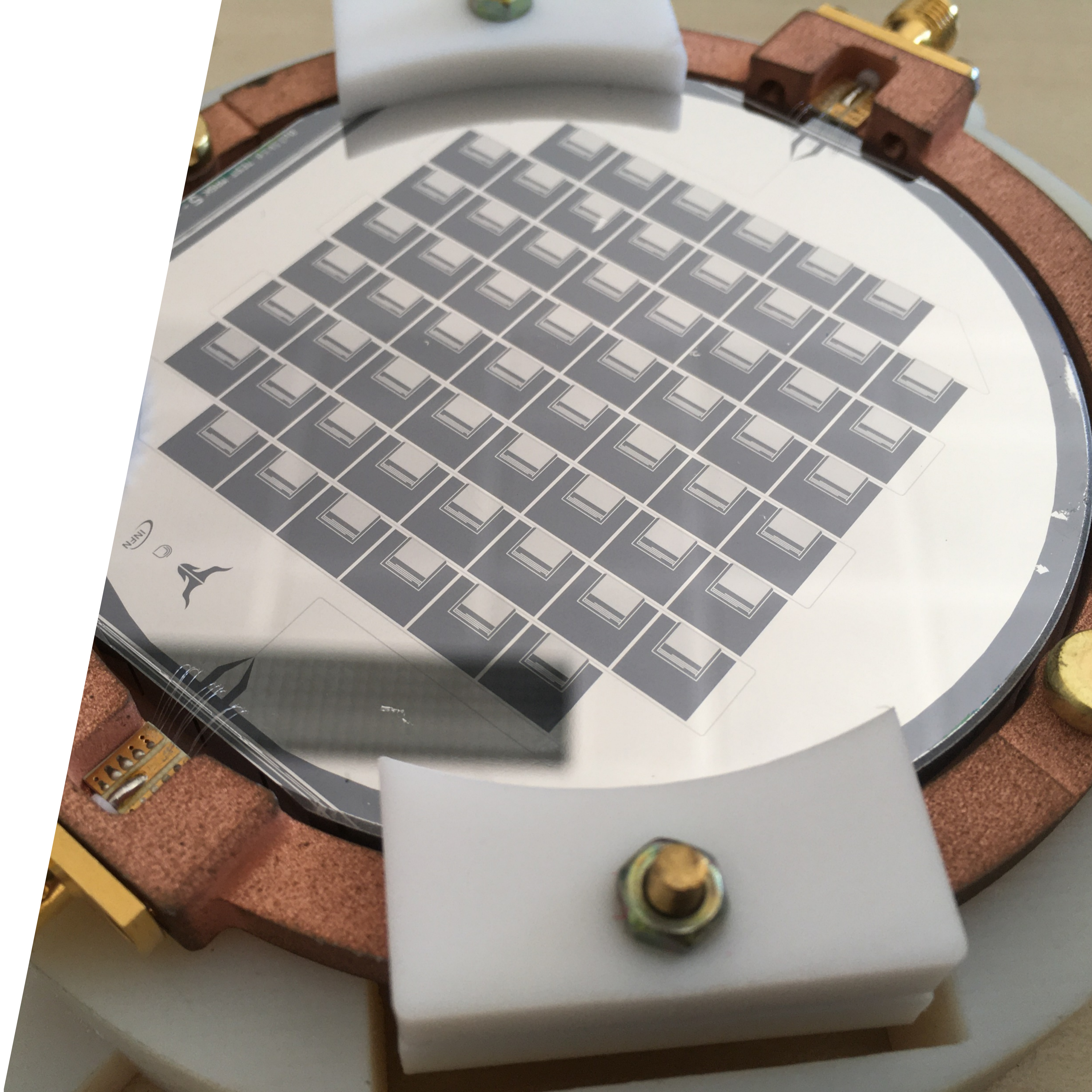


3D-printed Cu stacking prototype

BACKUP



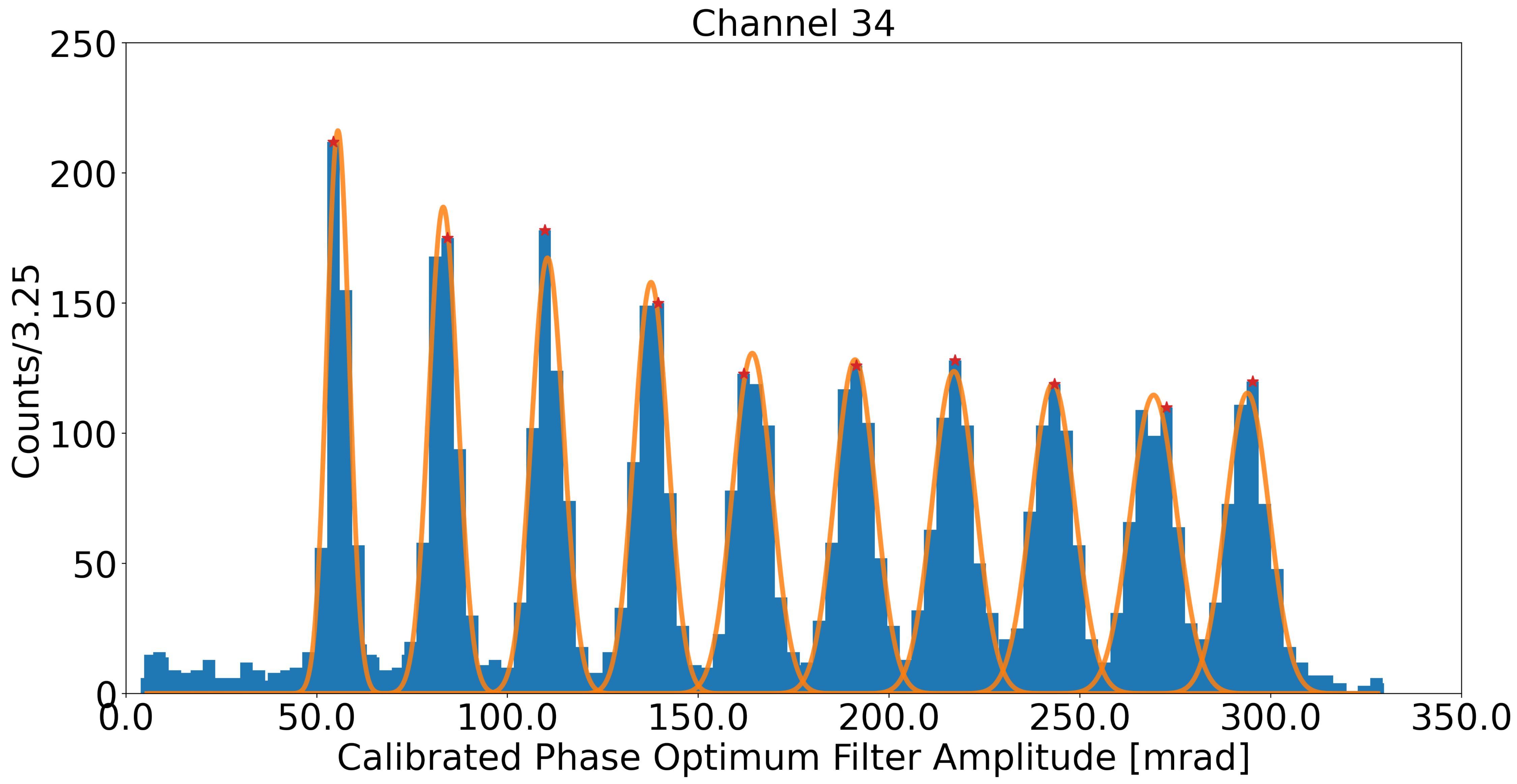
Energy calibration

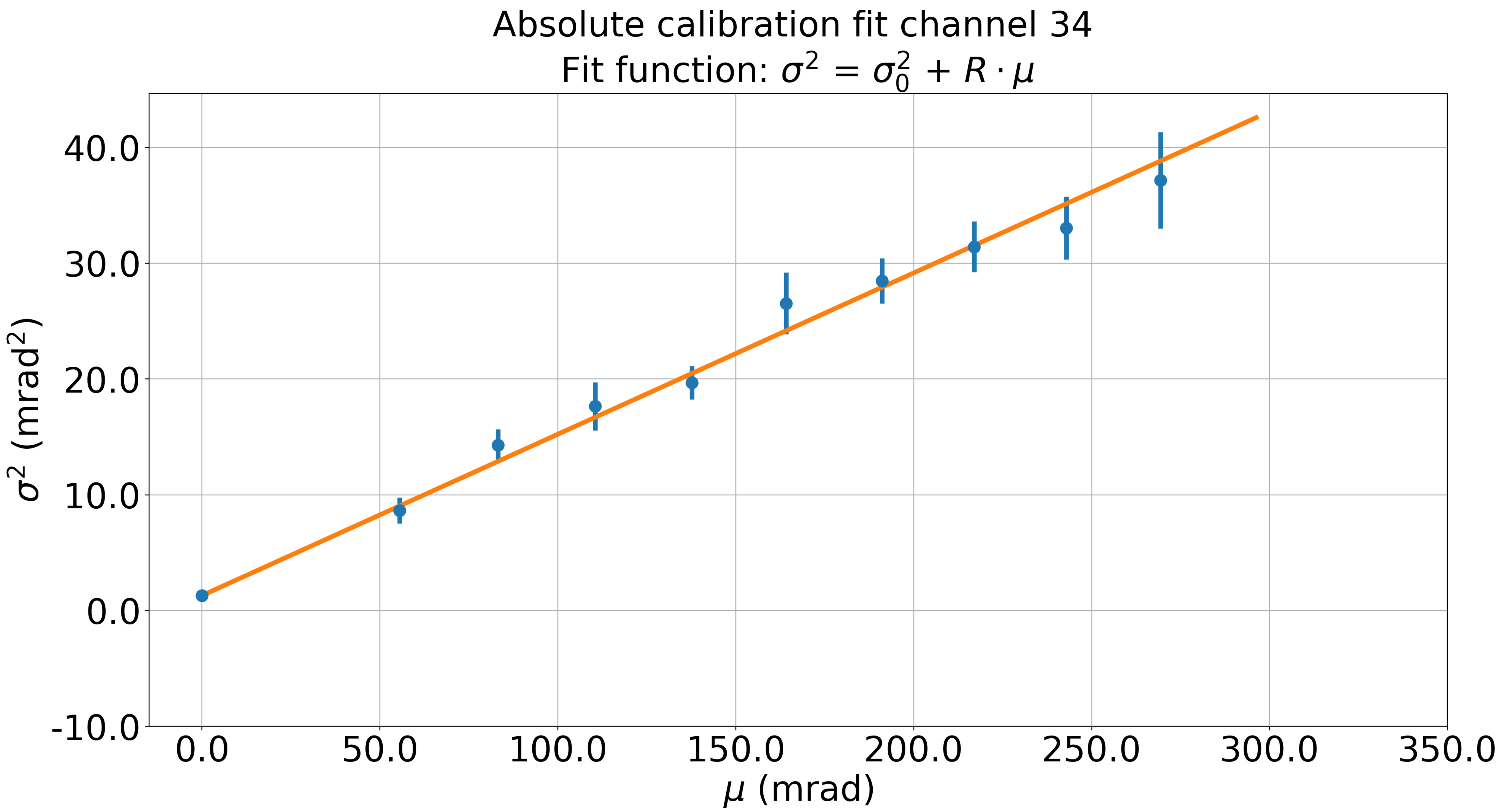
Exploit the Poisson's statistics of bursts of N optical photons of known energy ϵ to extract the calibration constant k:

- $\mu = k\,N\,\epsilon$
- $\sigma^2 = \sigma_0^2 + k^2 N \epsilon^2 = \sigma_0^2 + k\epsilon \cdot \mu$

Linear fit for σ_0^2 and $R = k\epsilon$:

- $k = \dfrac{R}{\epsilon}\ , \quad \epsilon(400\ \mathrm{nm}) = 3.1\ \mathrm{eV}$



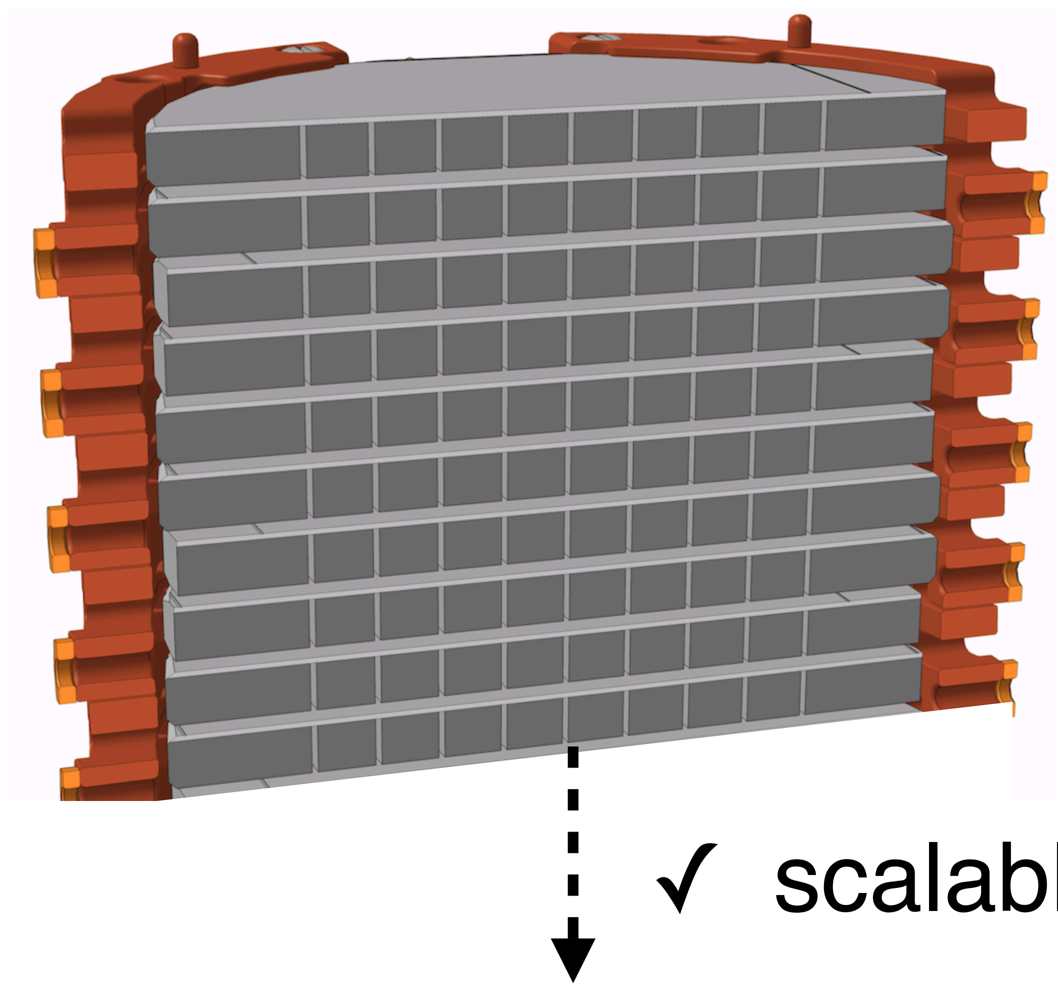


Impact

Nuclear recoil detector with:

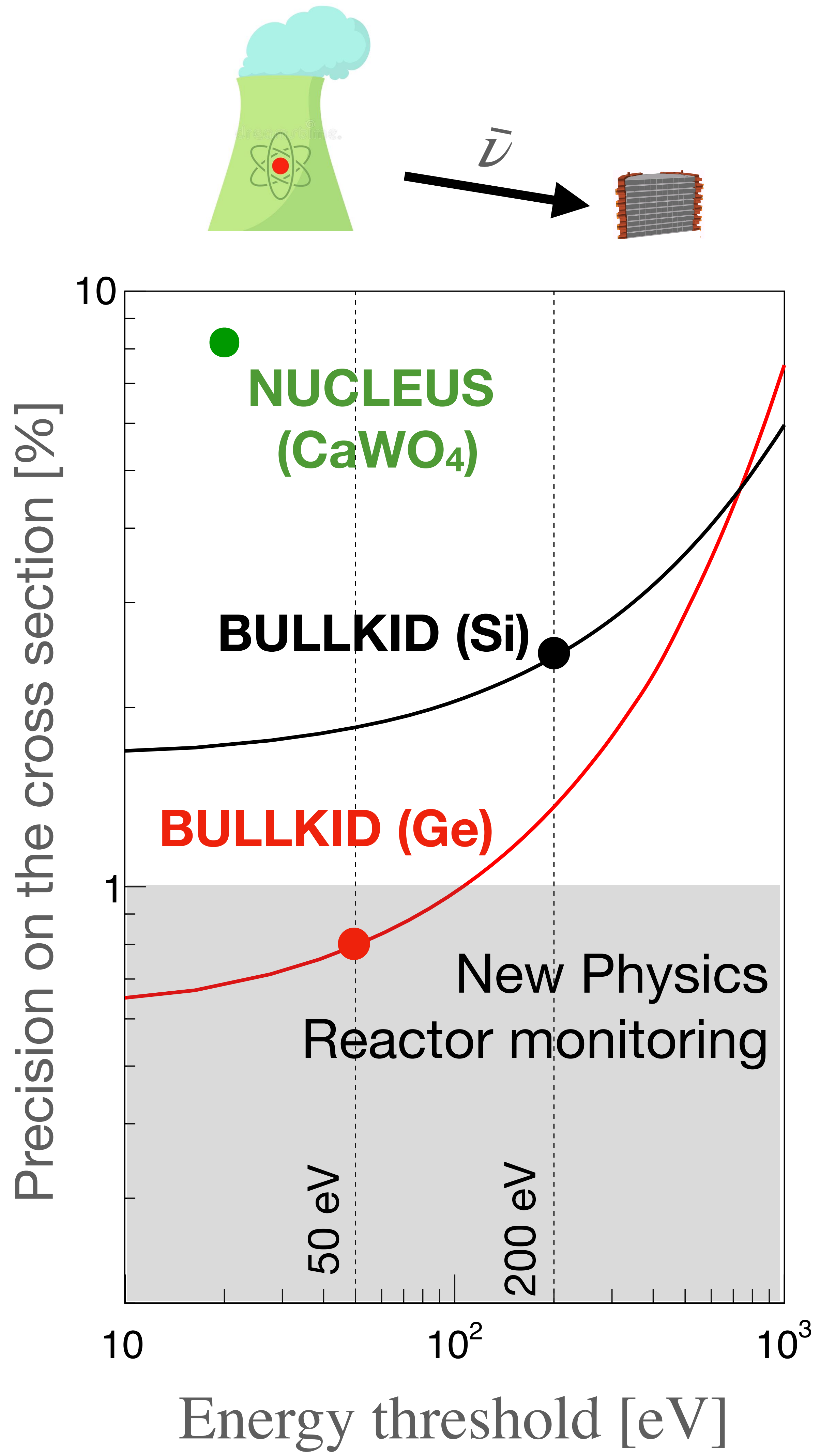
✓ 0.6 kg (Si) / 1.3 kg (Ge) target

✓ 200 ÷ 50 eV threshold



✓ scalable

Neutrino scattering experiment



Dark Matter experiment