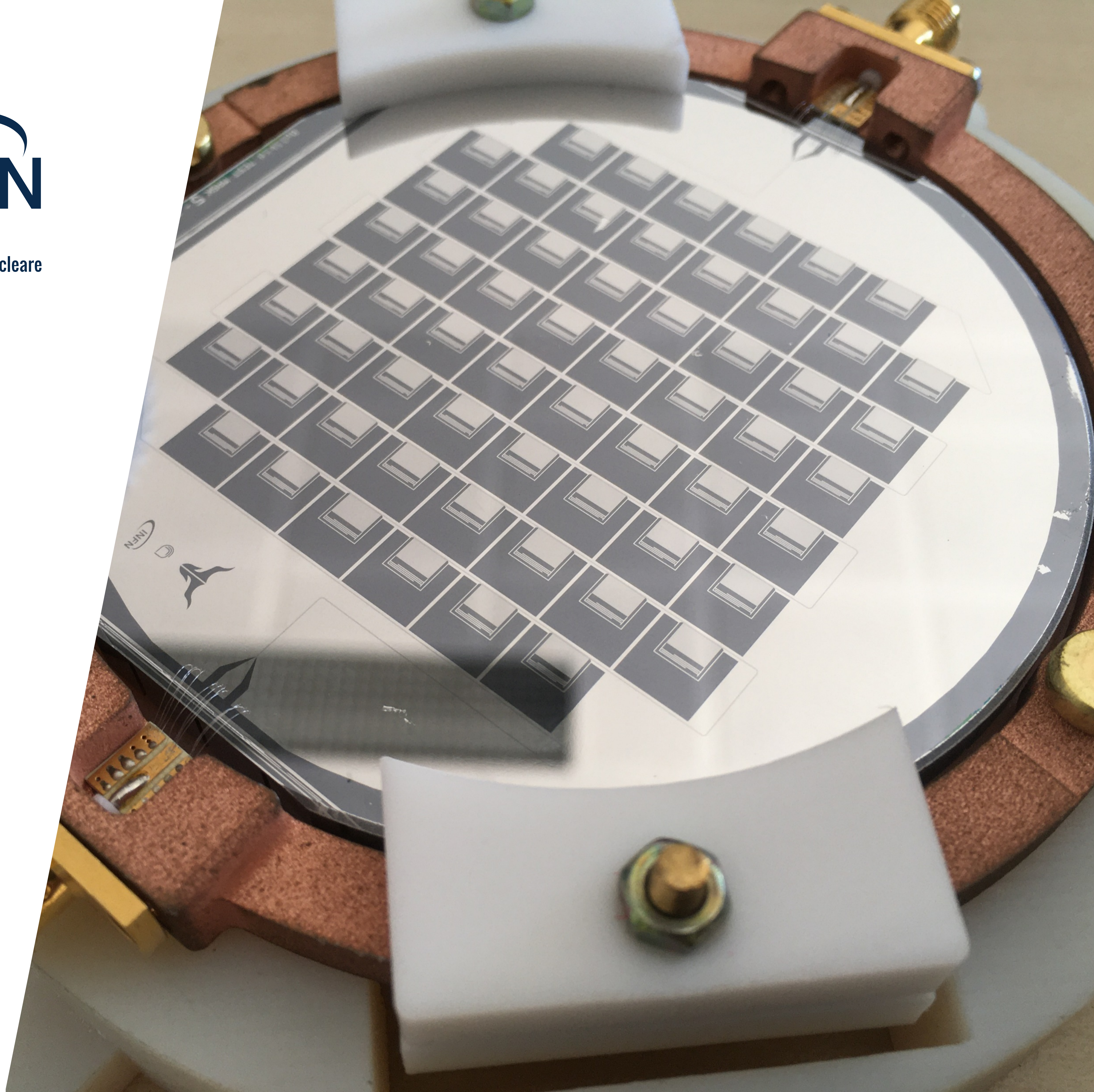
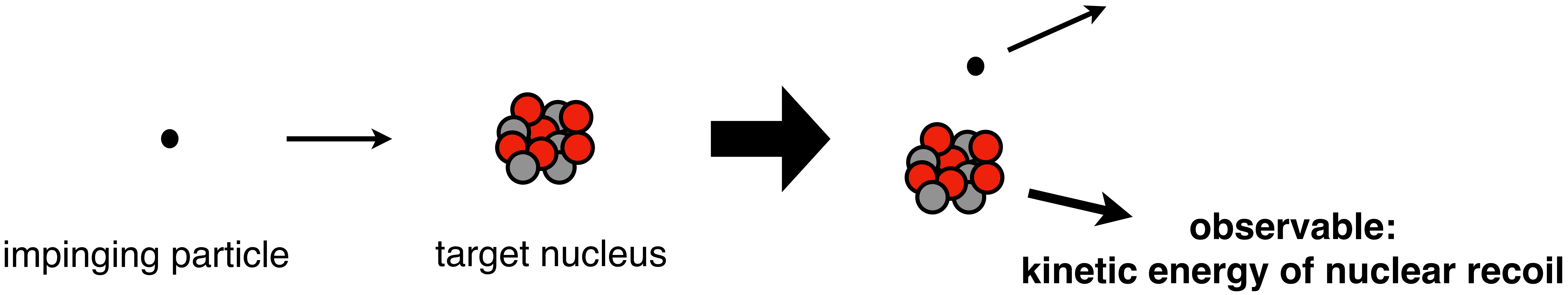
BULLKID

Marco Vignati - 26 May 2022
Pisa Meeting on Advanced Detectors



Particle detection via nuclear recoils



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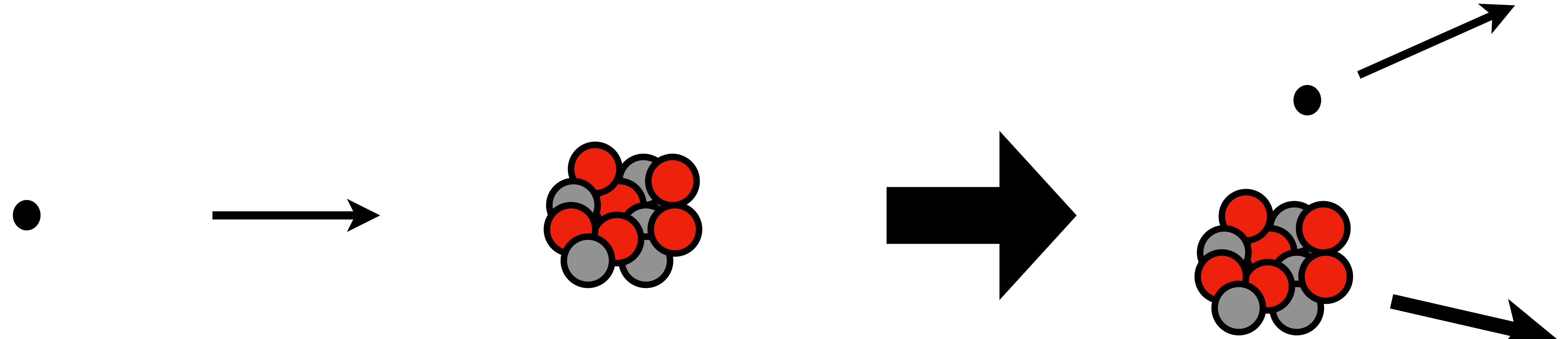
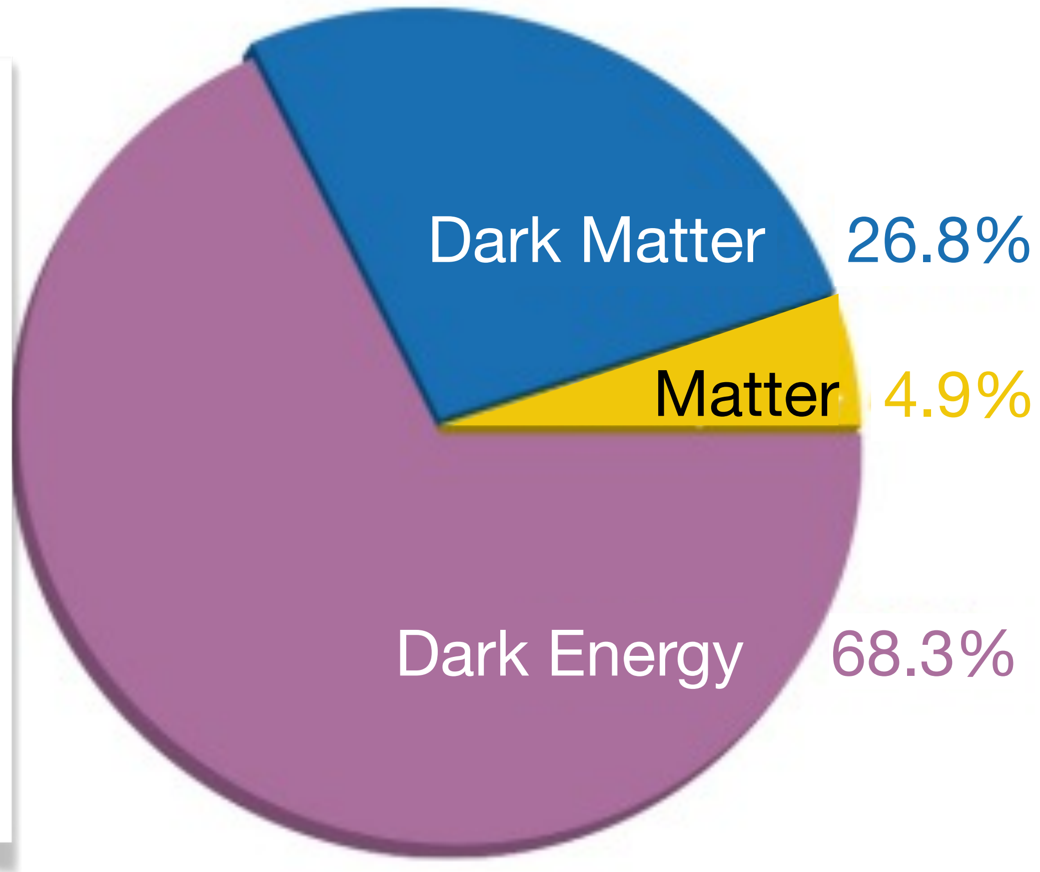


impinging particle

target nucleus

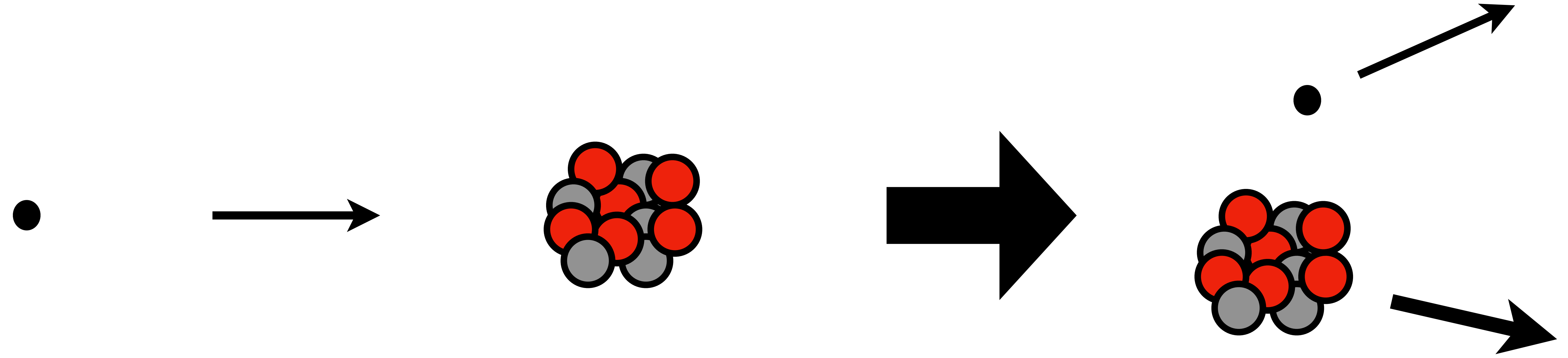
observable:
kinetic energy of nuclear recoil

Dark Matter



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

Particle detection via nuclear recoils



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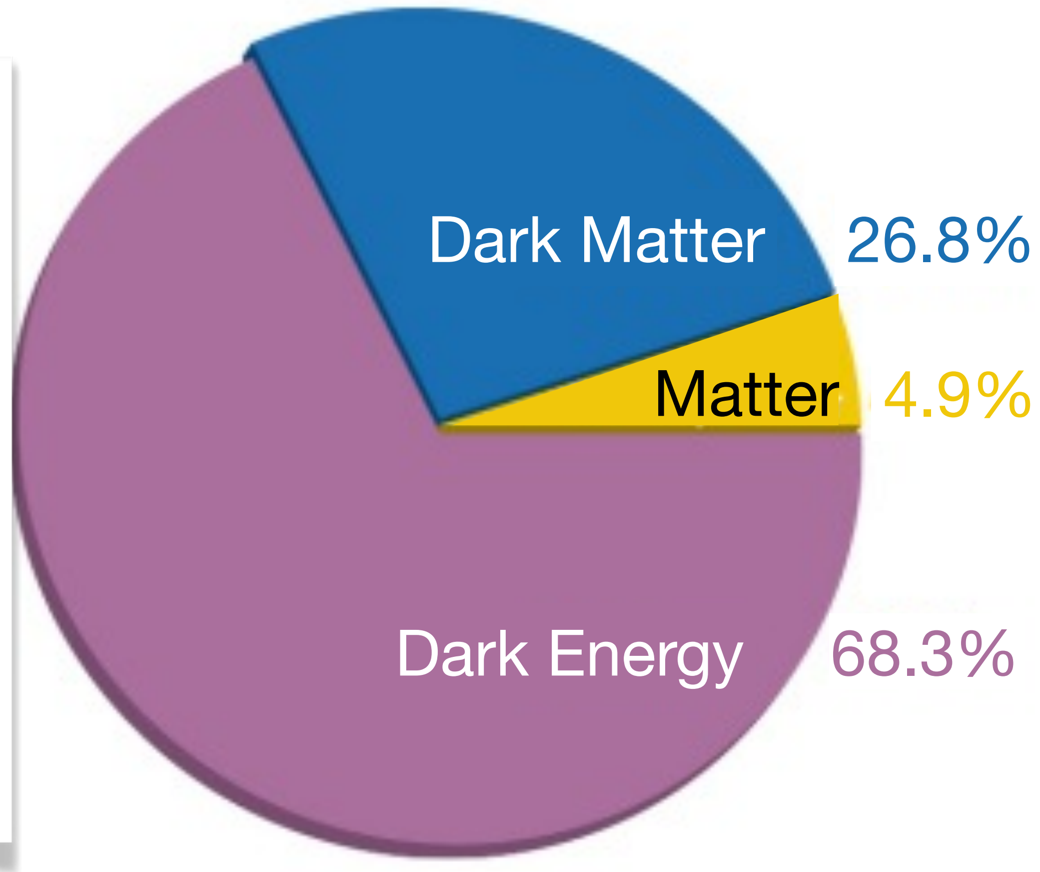
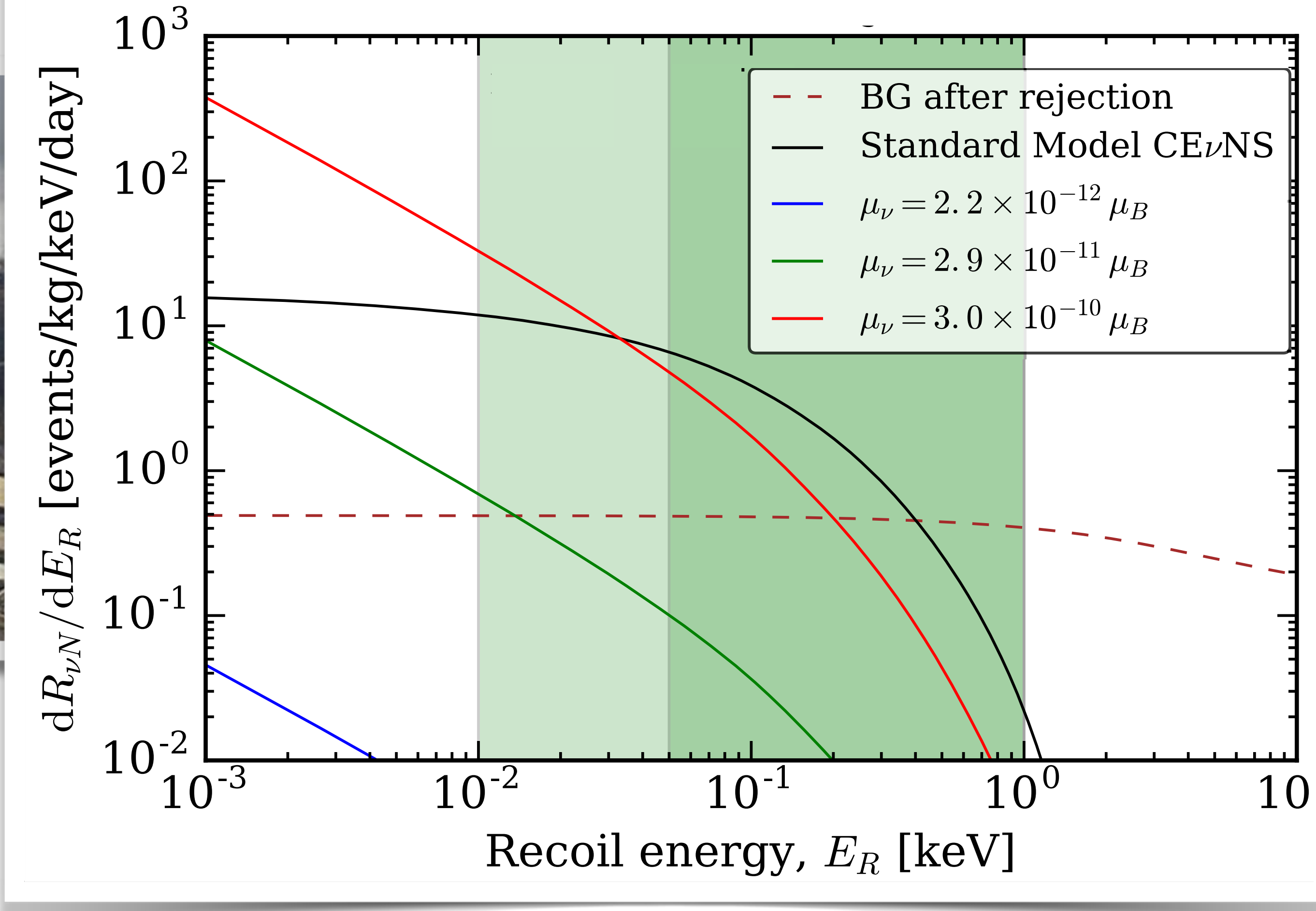


next frontier: particles with mass < 1 GeV/c²

Neutrino coherent scattering (CEνNS)

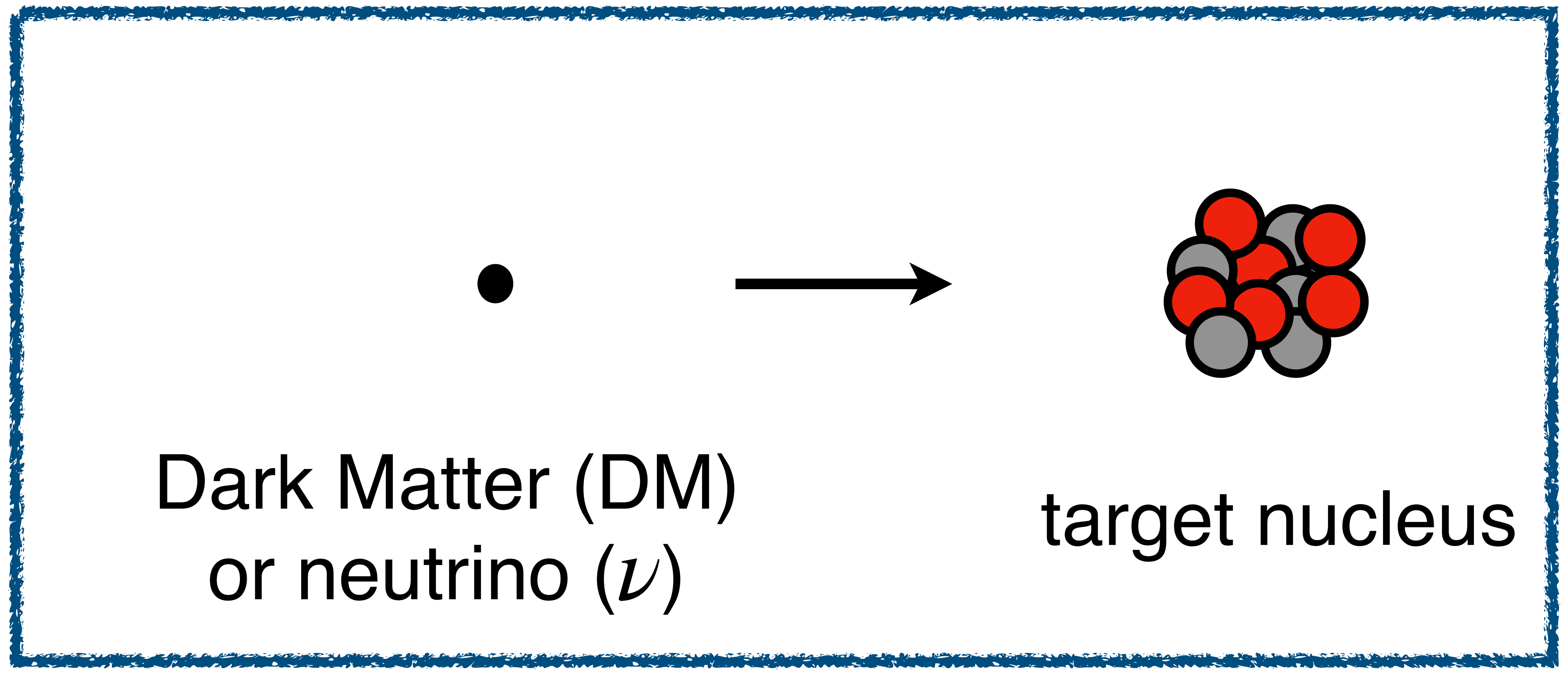
reactor monitoring
from safe distances

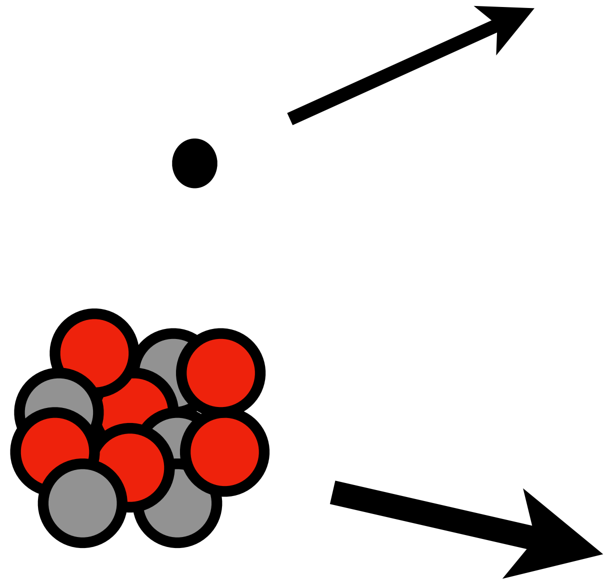


Billard, Johnston and Kannavagh, JCAP 11 (2018) 016

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

Requirements

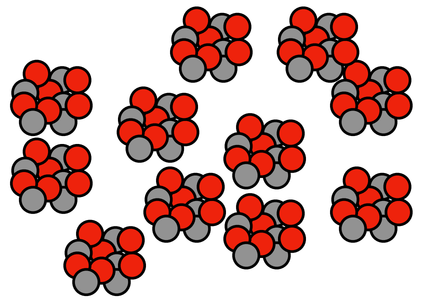




observable:
kinetic energy of nuclear recoil

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

large number of targets
(large target mass)



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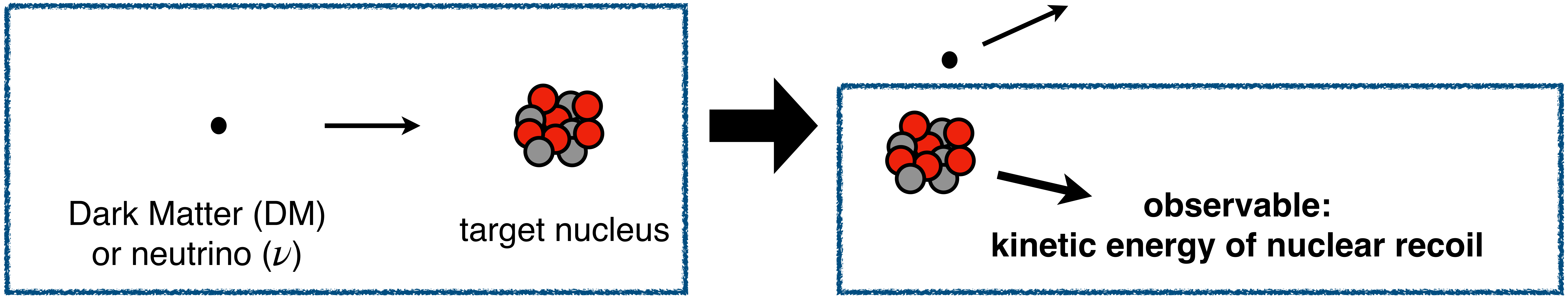
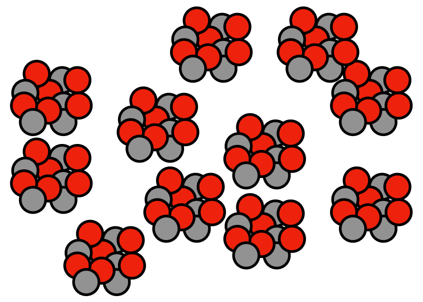
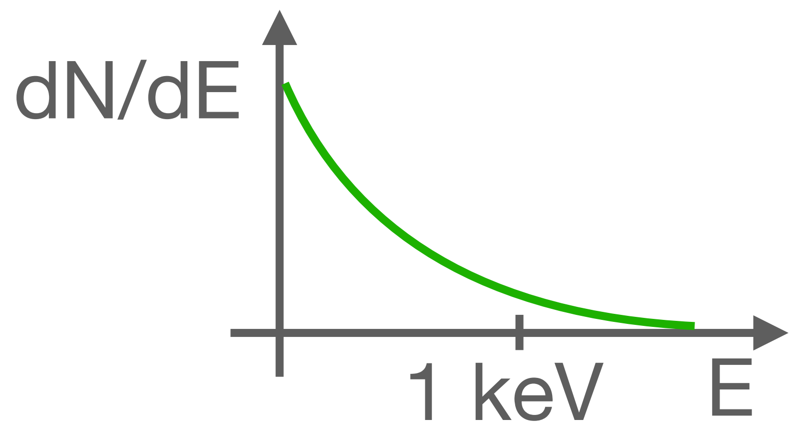


cross section $\sigma < 10^{-40}\ \mathrm{cm}^2$

energy < 1 keV

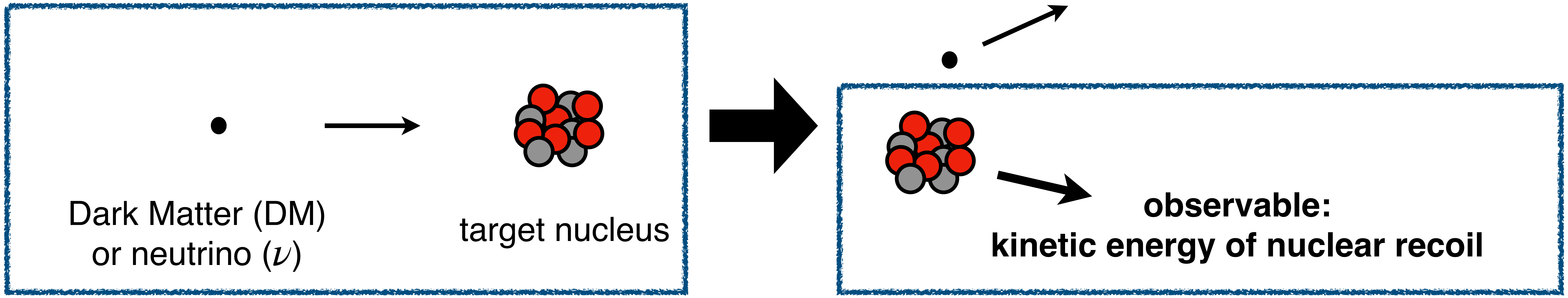
large number of targets
(large target mass)





low-energy
detection threshold

Requirements



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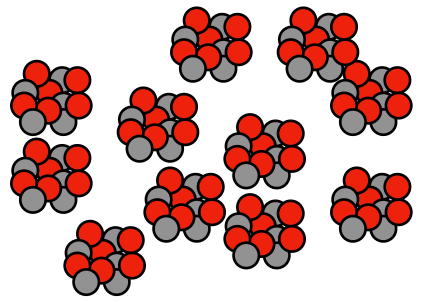
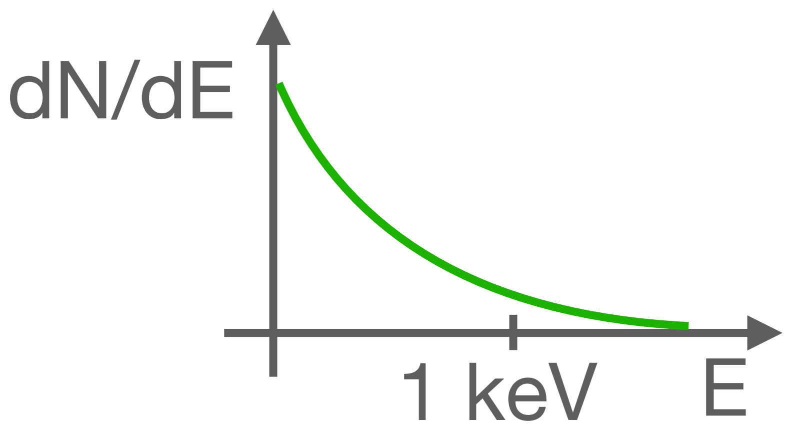
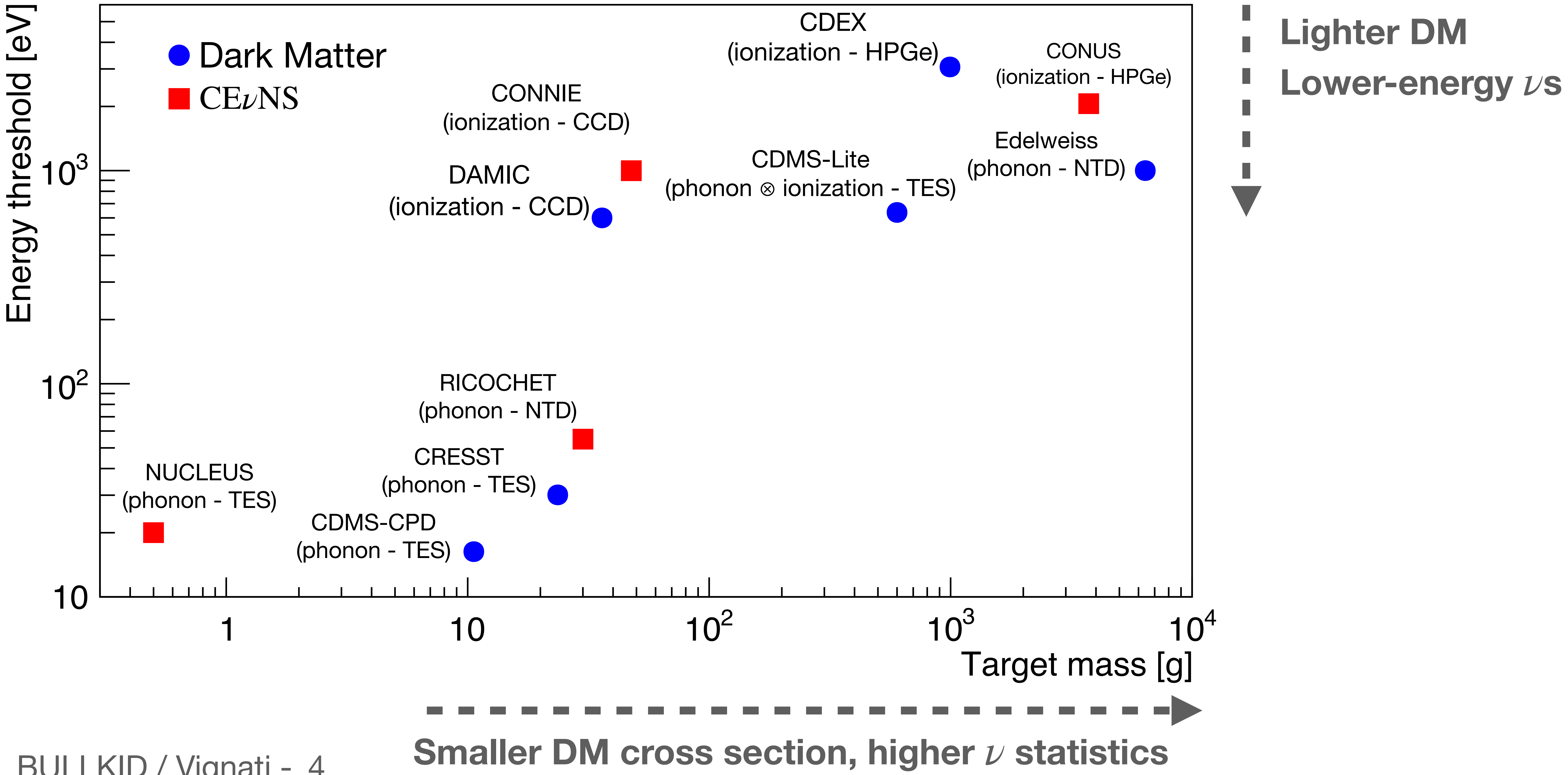




low-energy
detection threshold

Difficult to have both in the same experiment!

State of the art (solid-state detectors)



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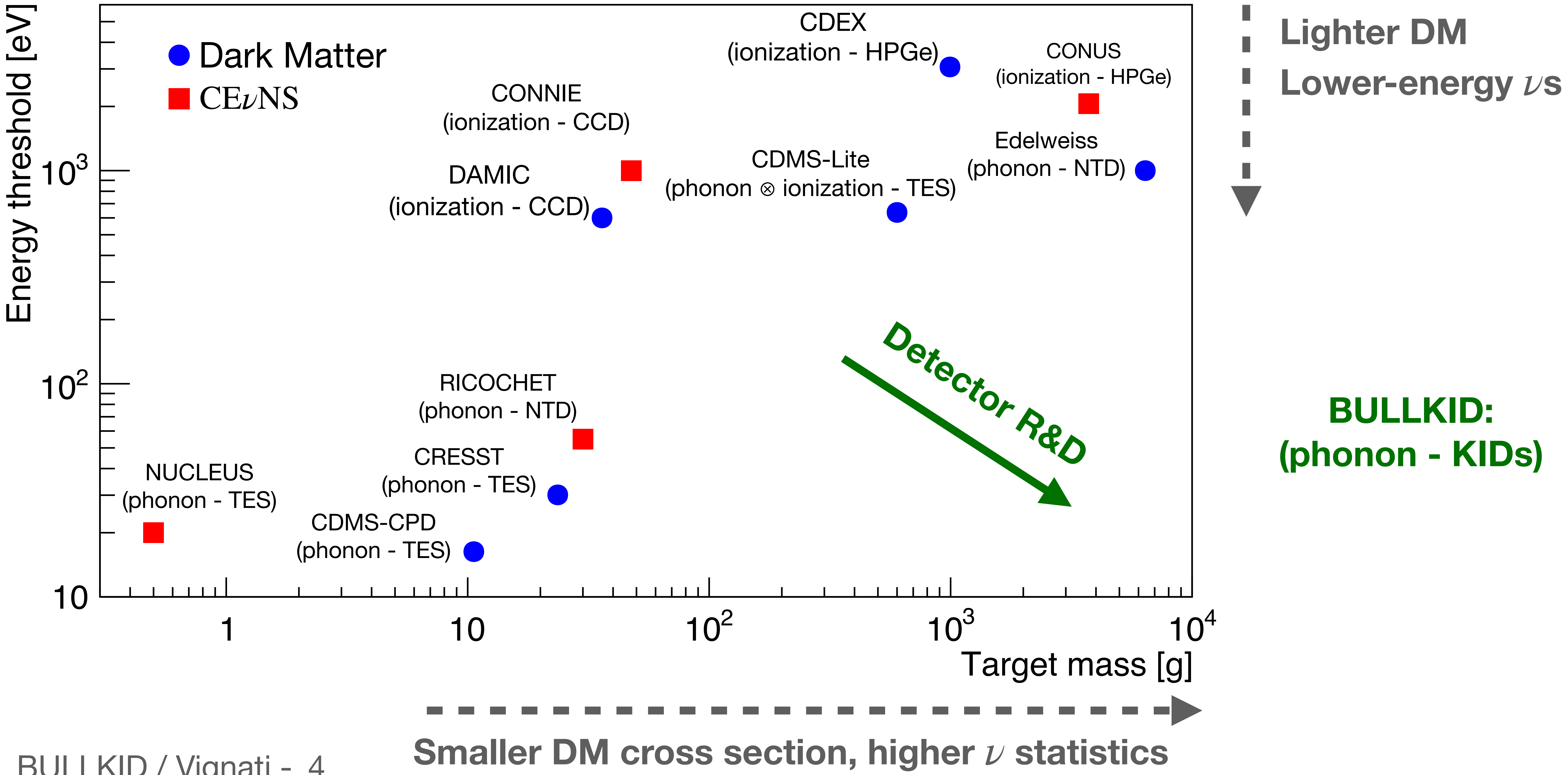


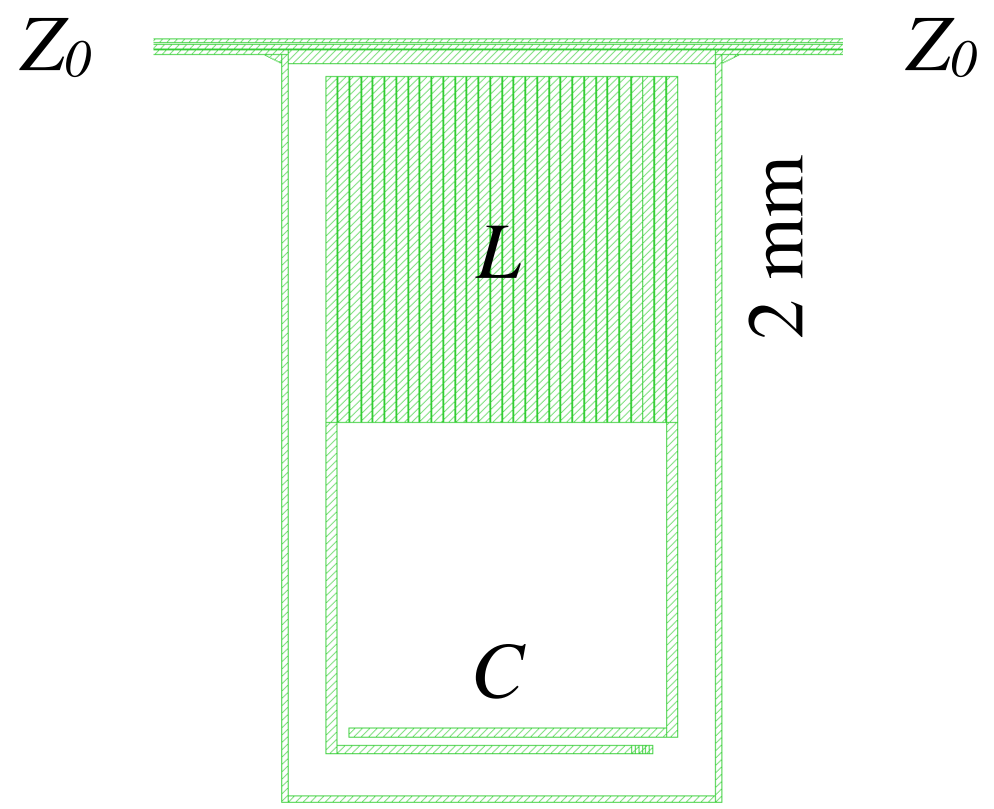
BULLKID:
(phonon - KIDs)

Low energy threshold with KIDs

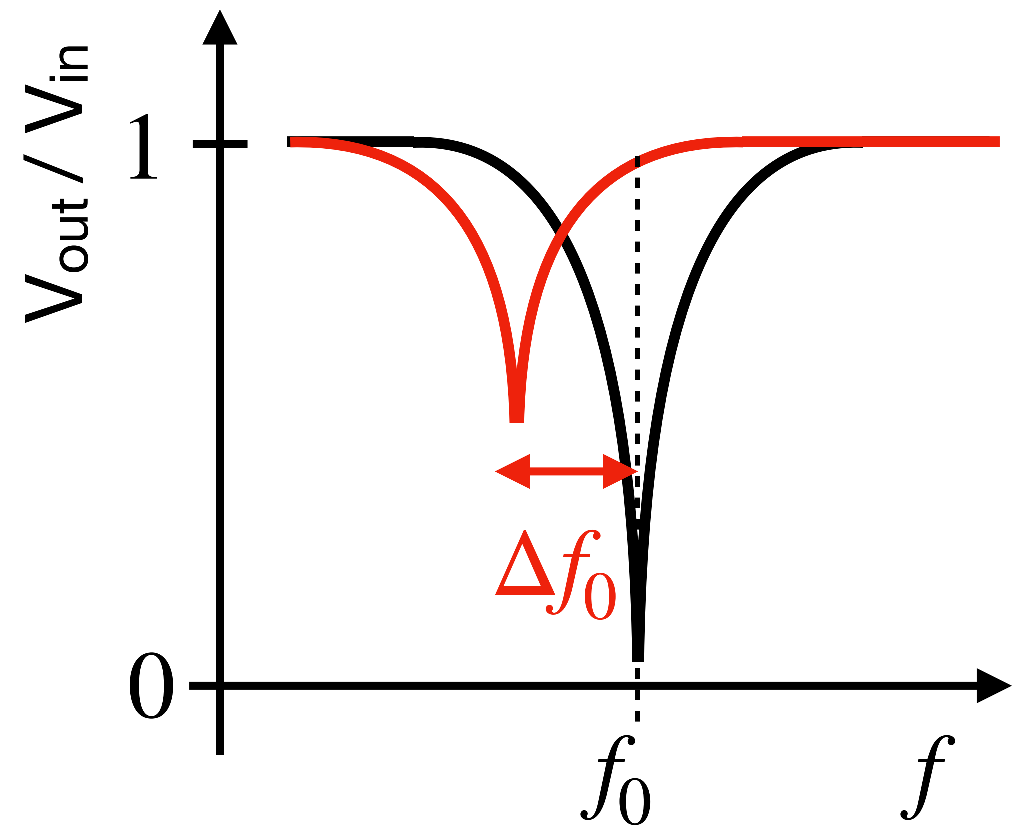
Kinetic Inductance Detector (KID):

- 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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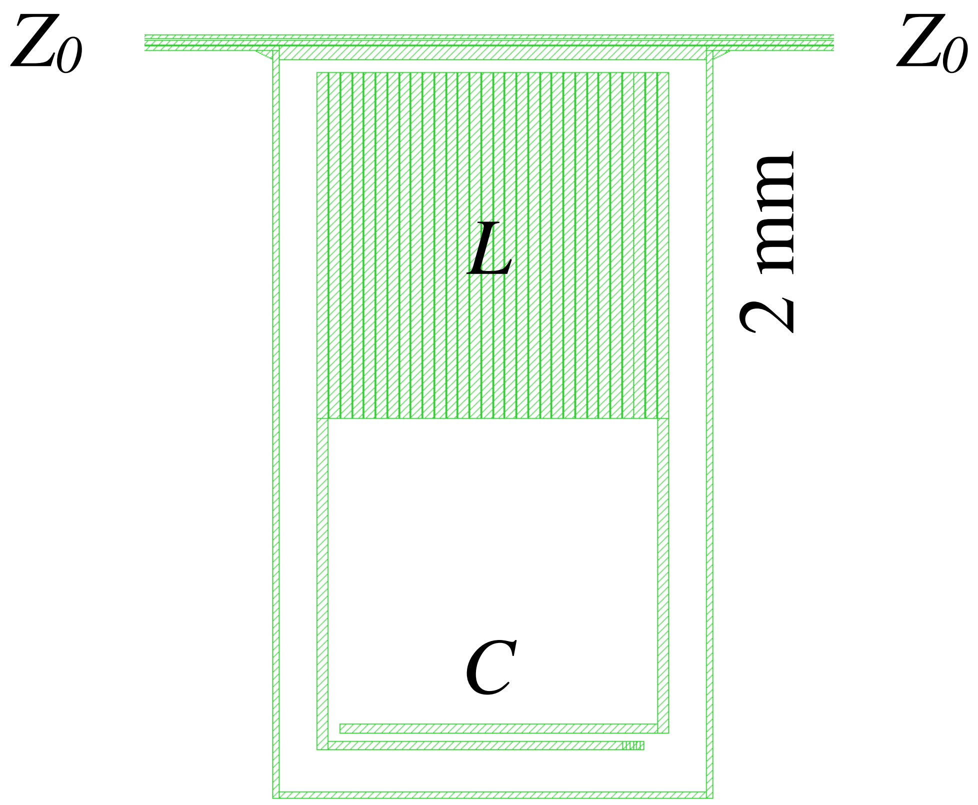

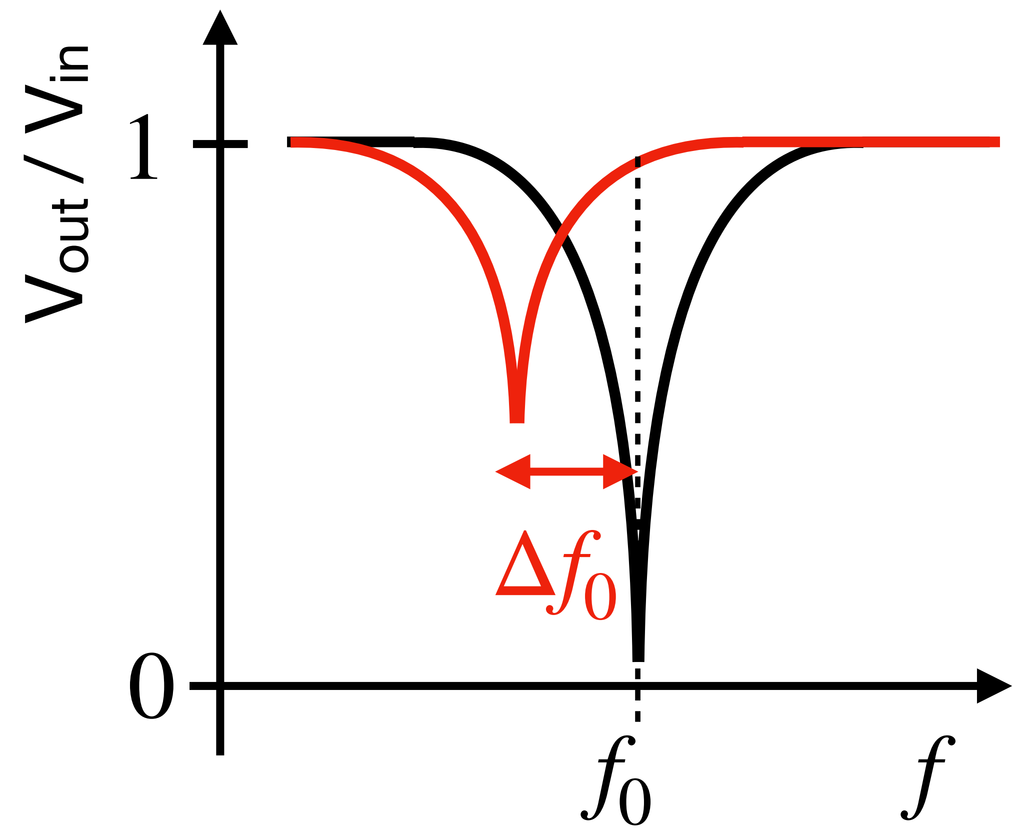

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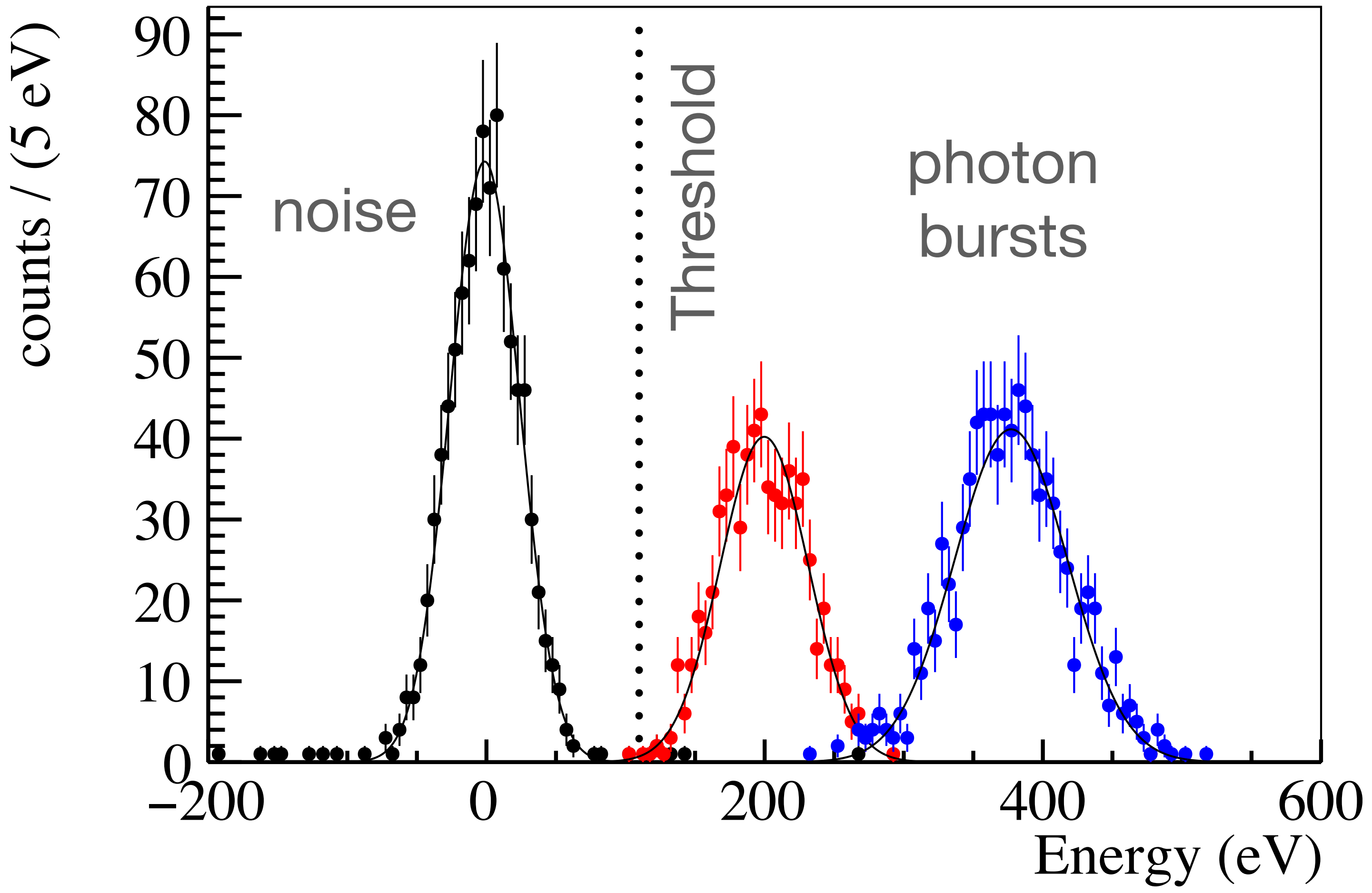
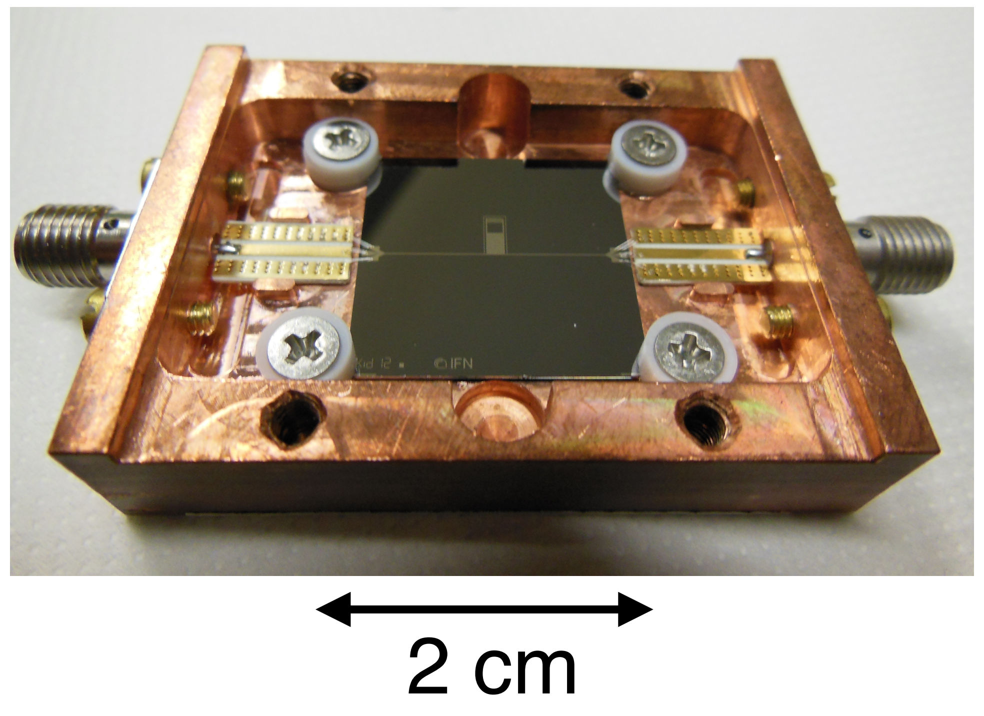
KID-based **photon sensors:**

✓ Energy threshold = 125 eV





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

BULLKID team

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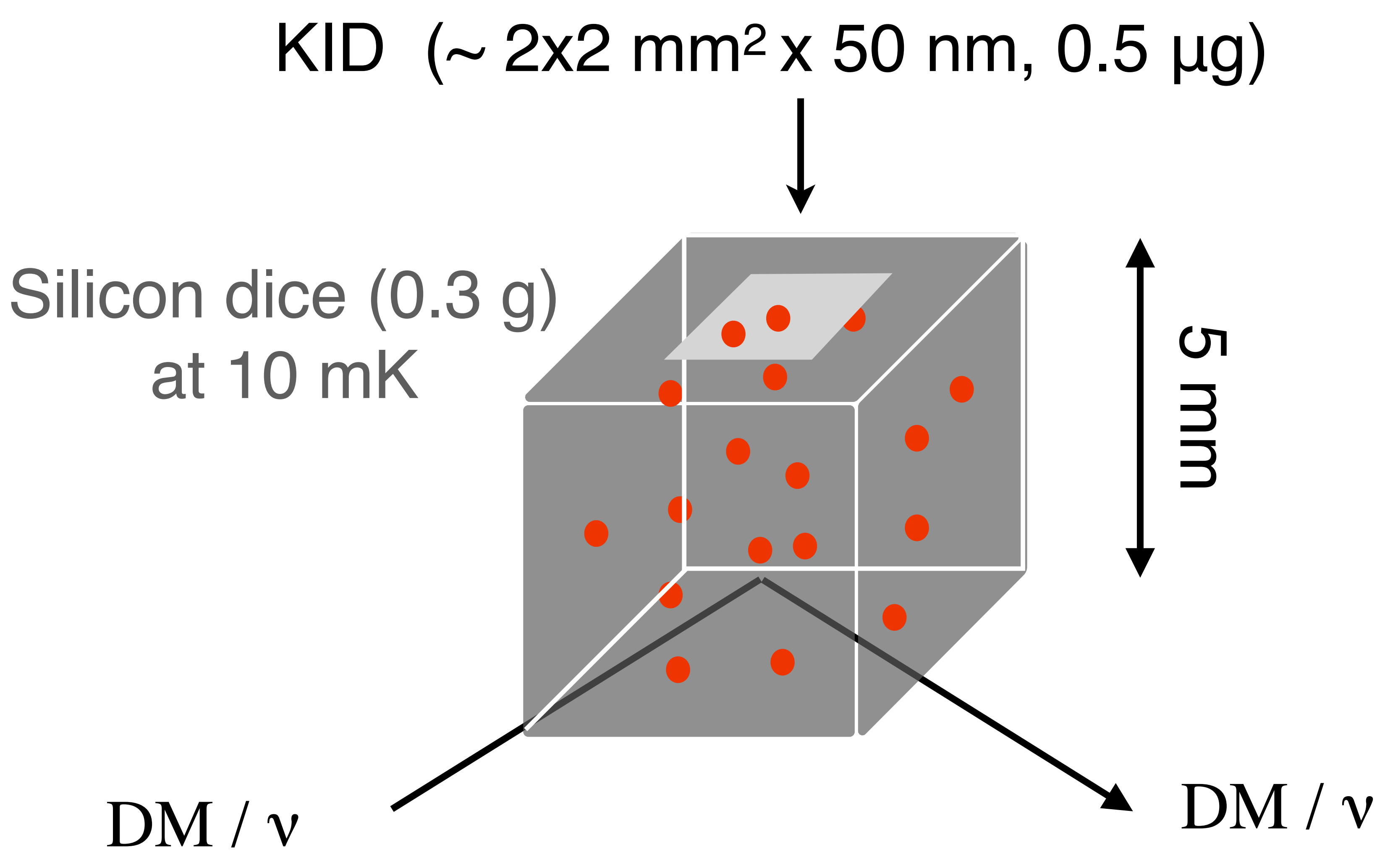
S. Di Domizio.

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

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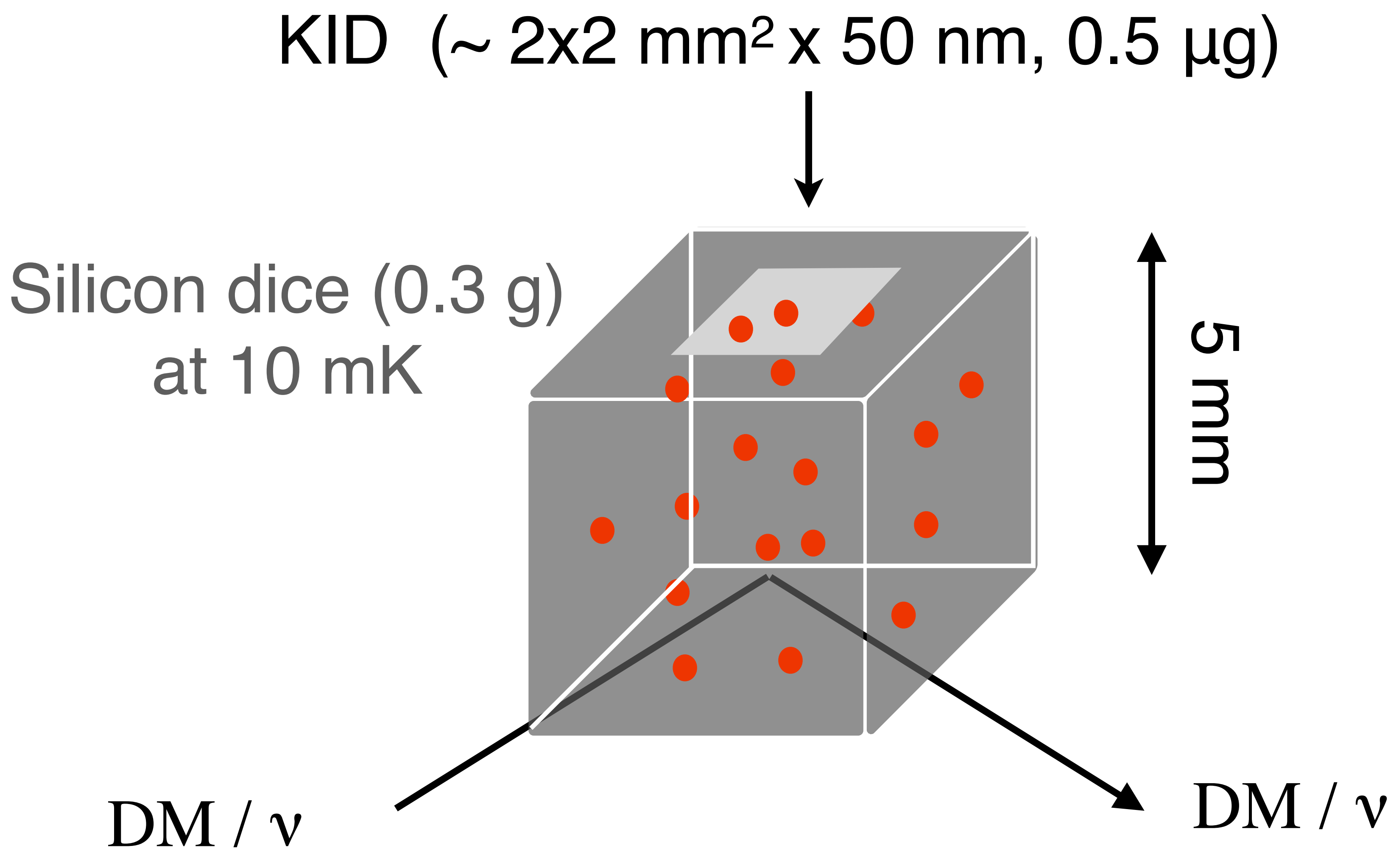
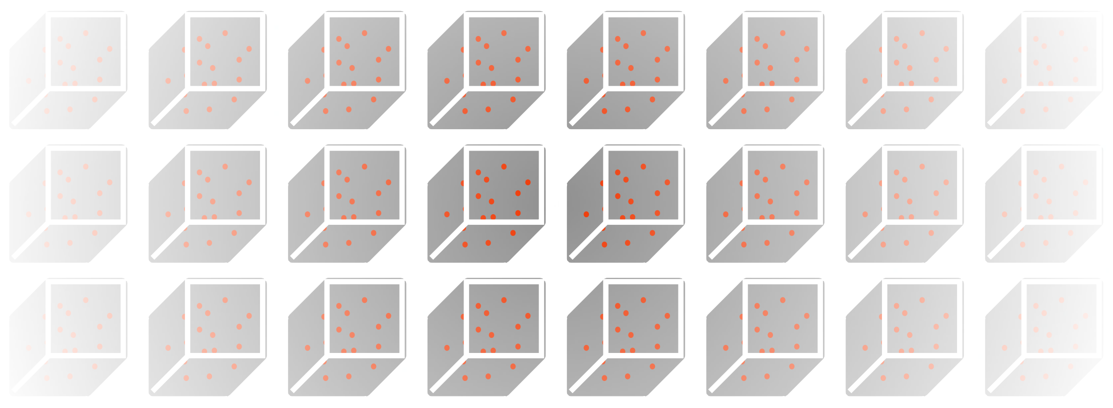
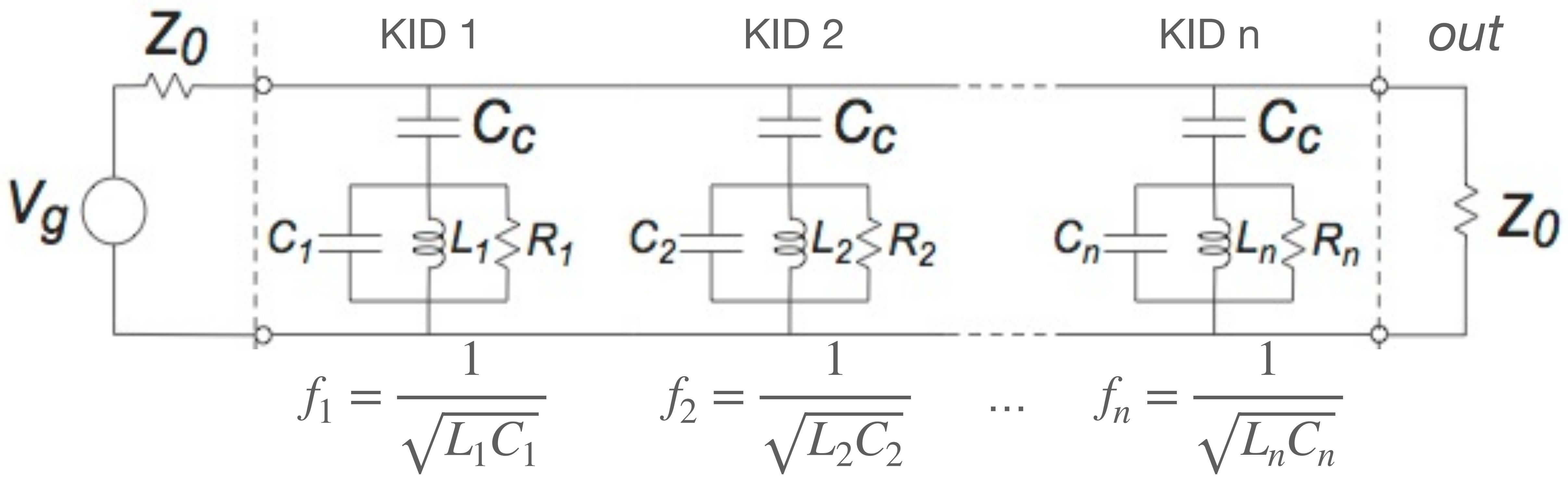


kg mass: array of 3000 Si-dices / KIDs



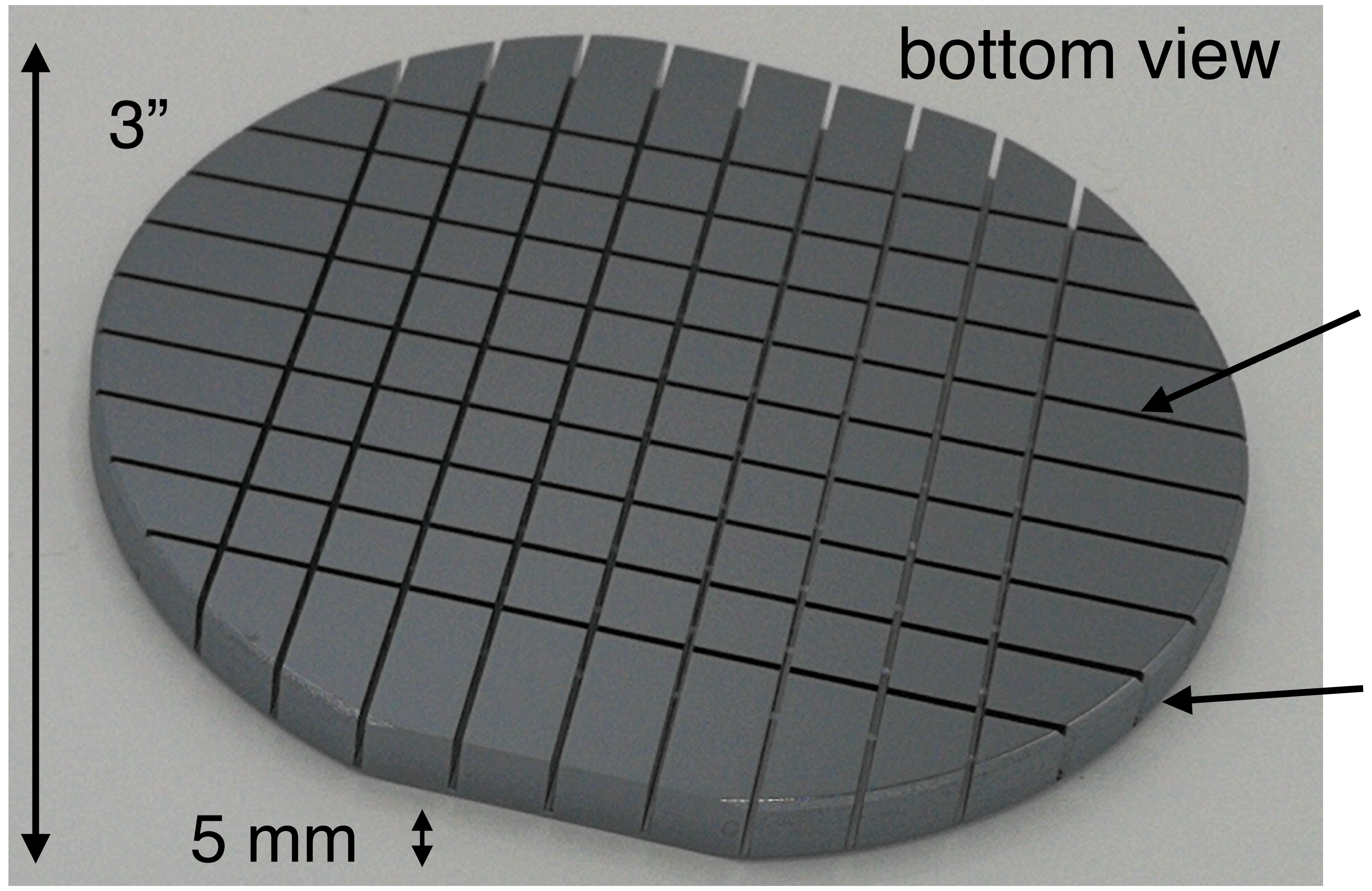
unique feature of KIDs: multiplexed readout

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

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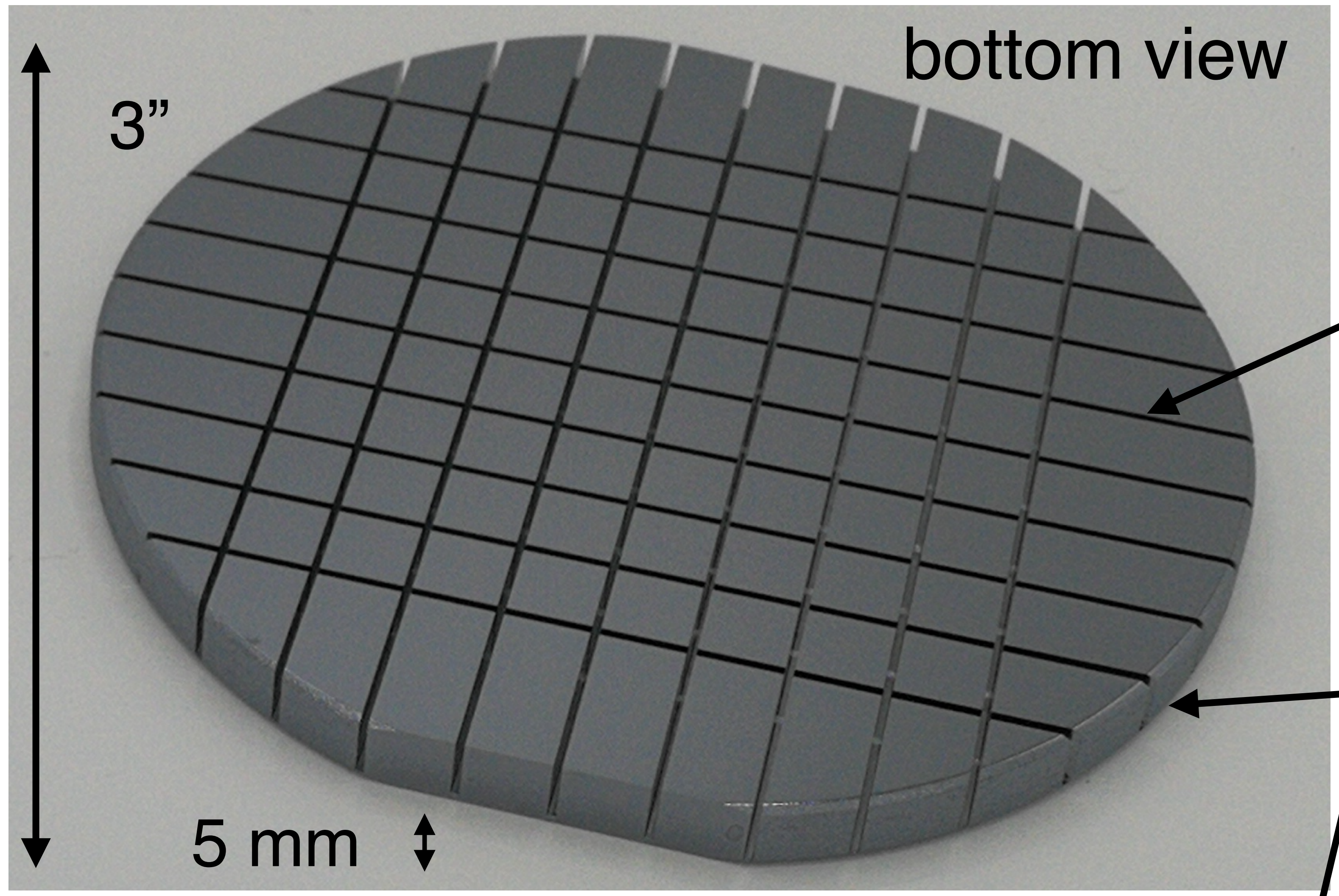


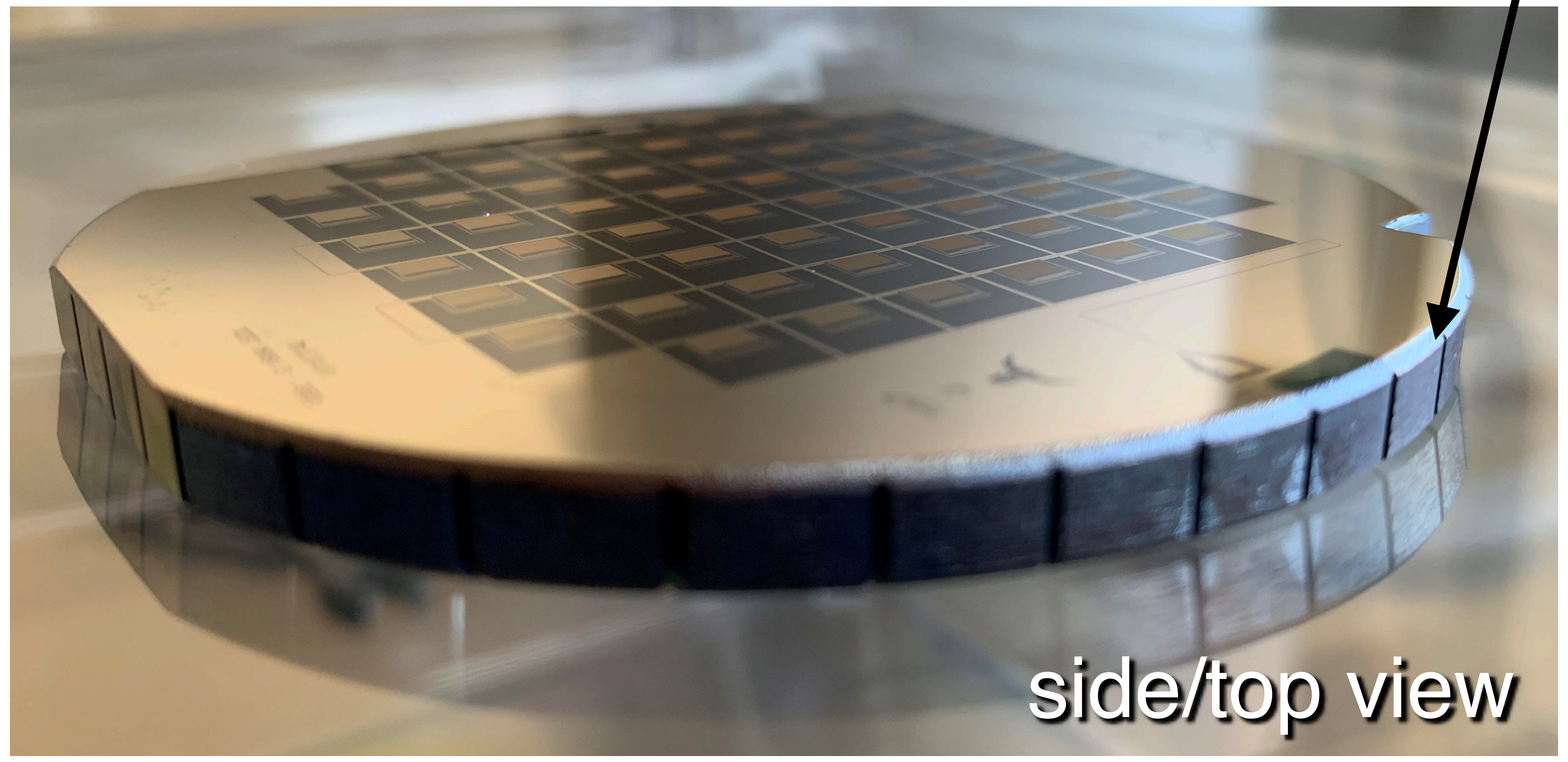
4.5 mm deep grooves

- 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

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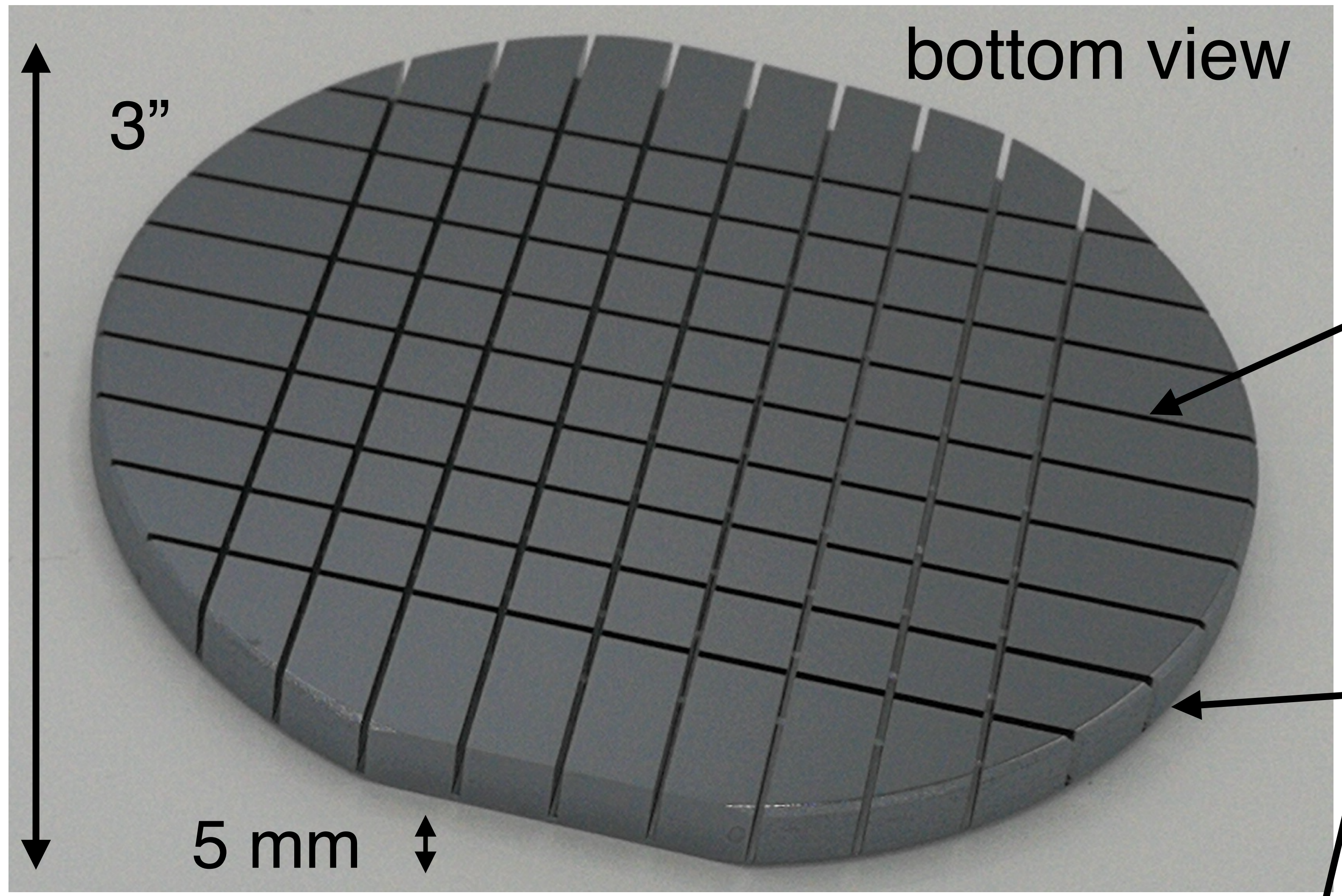

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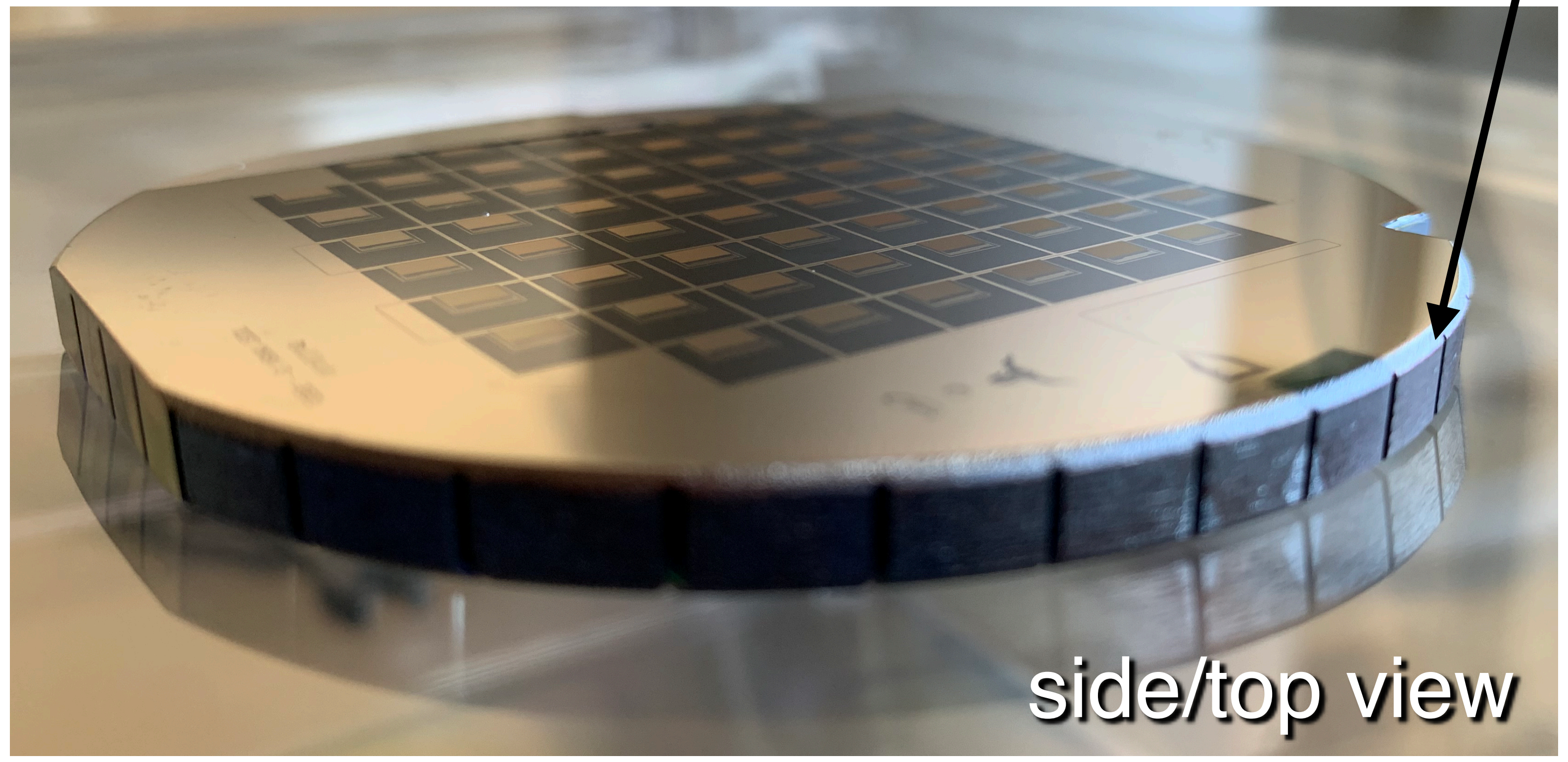

KID array
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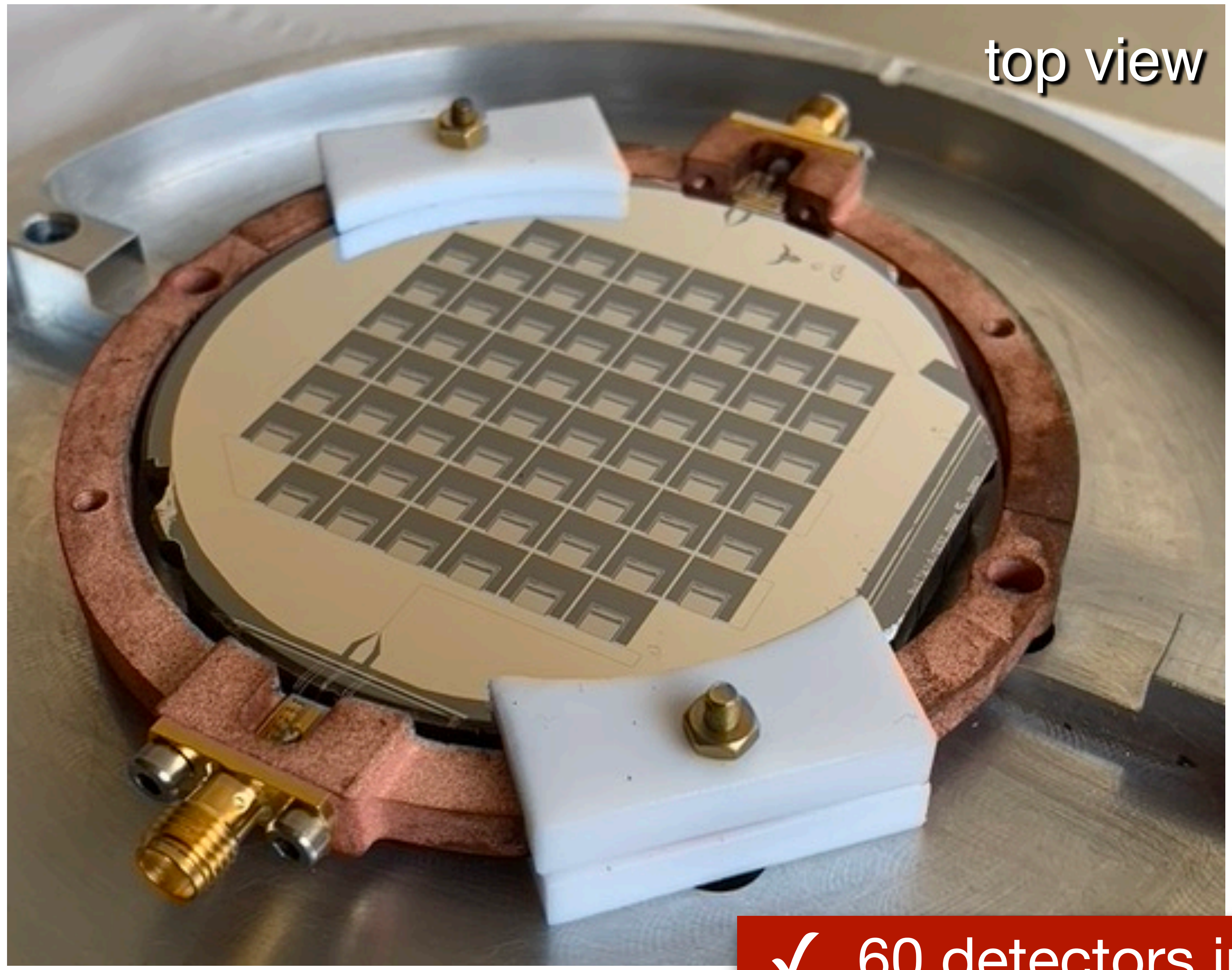
3. assembly

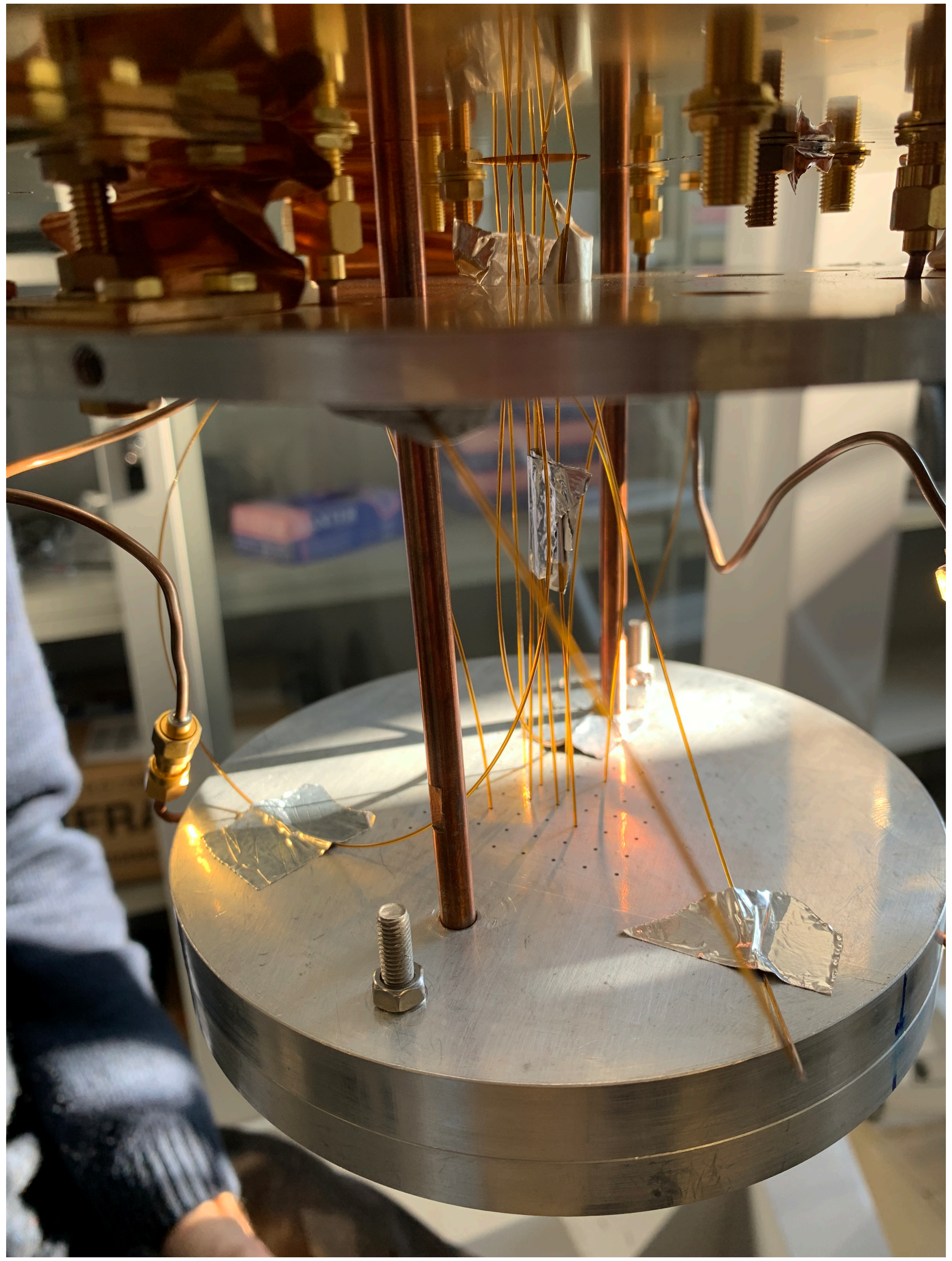


✓ 60 detectors in 1

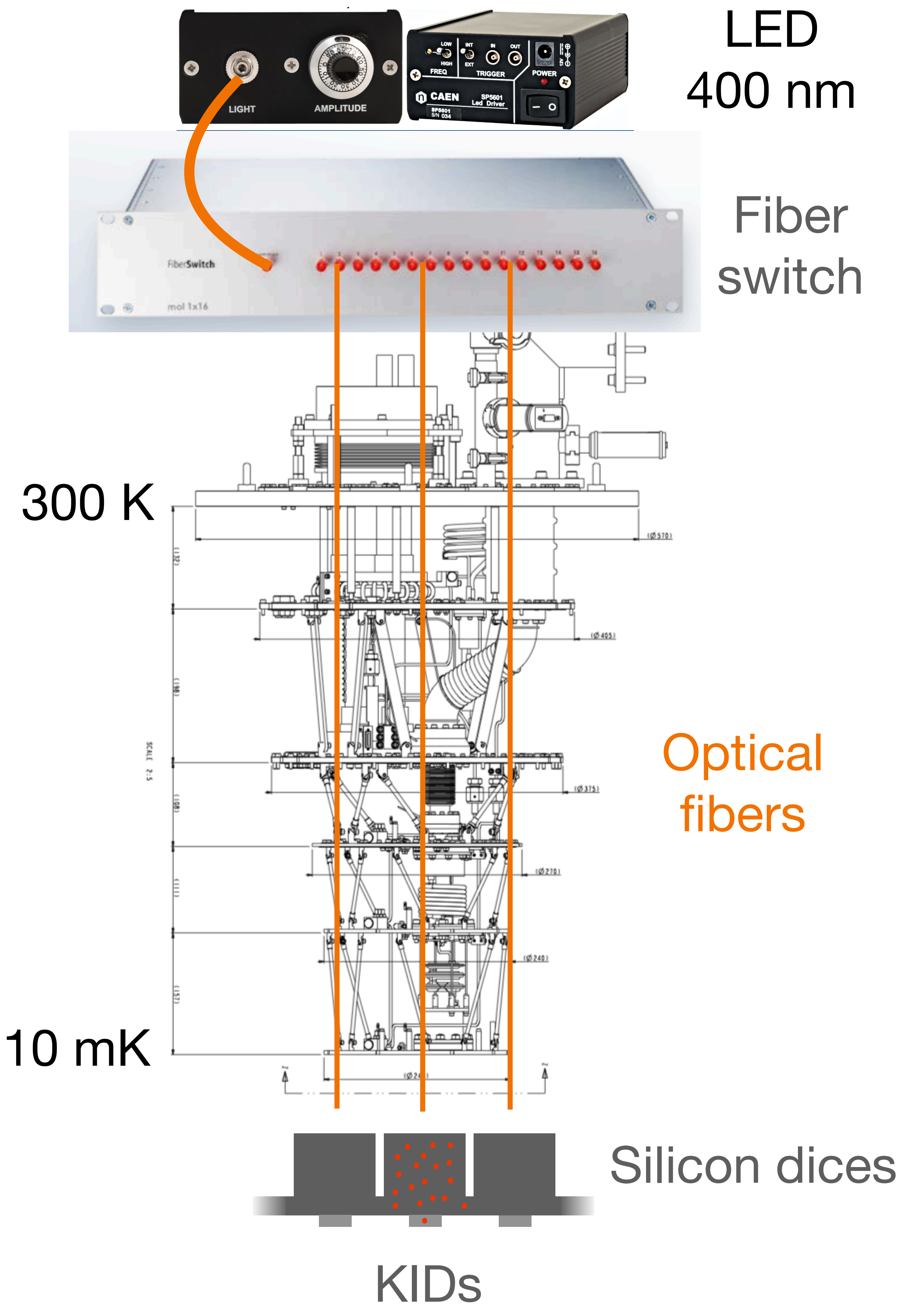
60 dices 0.3 g each
1 readout line

Design and assembly
- 3D-printed Cu holder
- Aluminum case

Operation in refrigerator

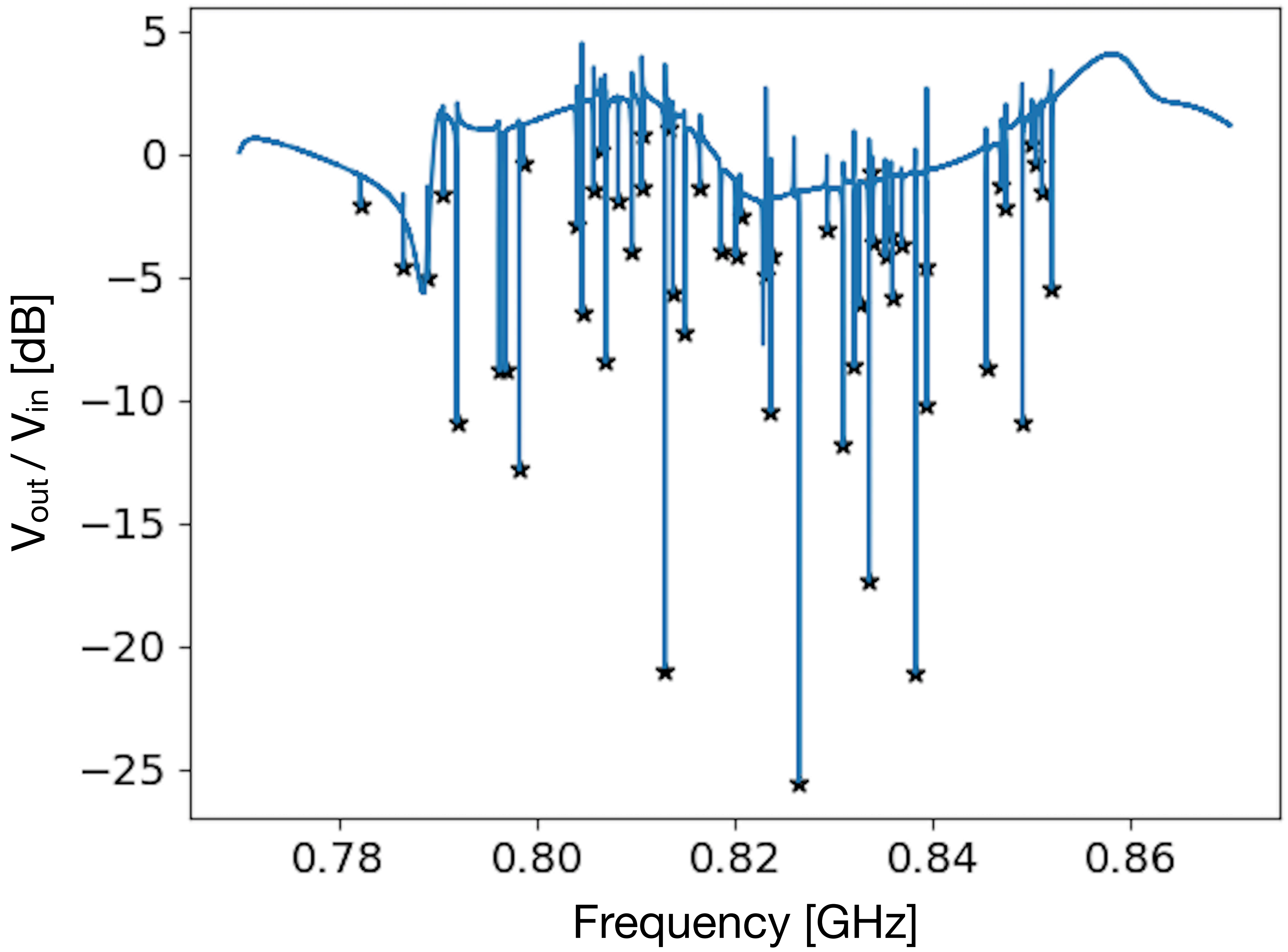


Optical calibration

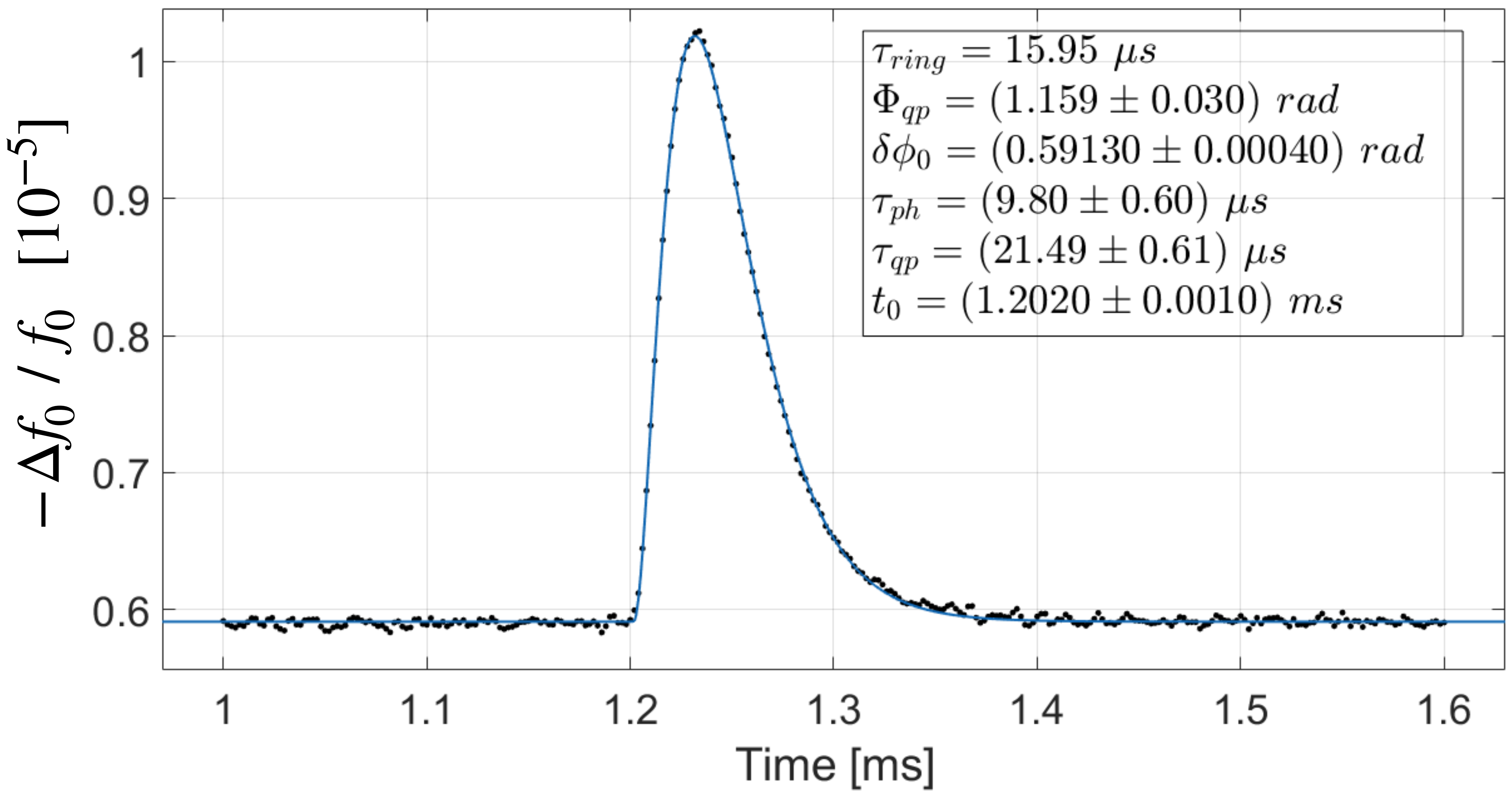


First prototype (9/2021)

Frequency scan of the KID array



Signal from a dice

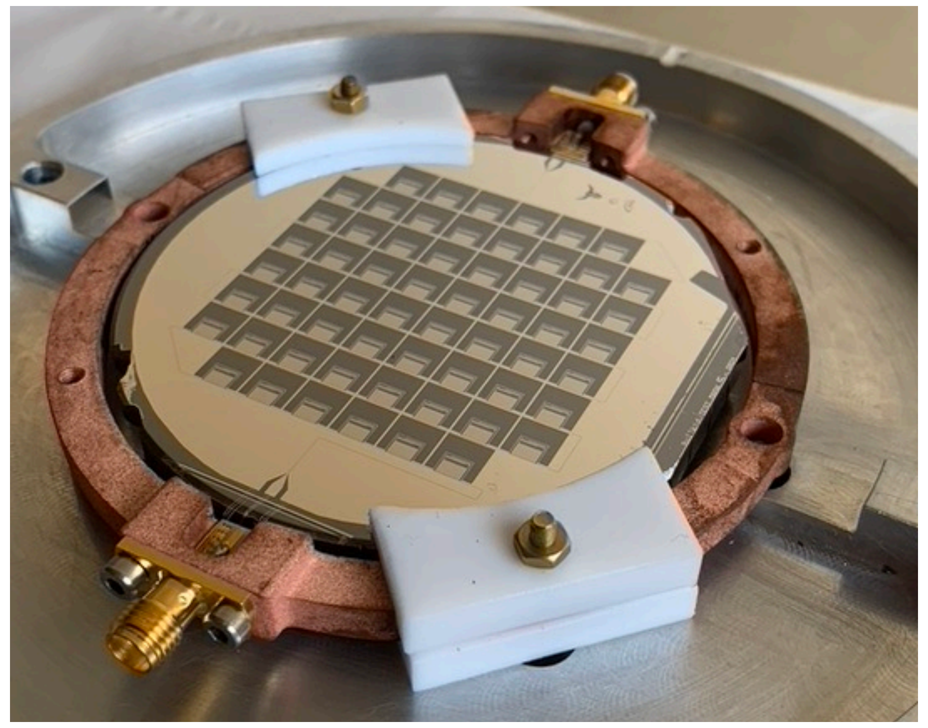


👍 **Proved that detector concept works**

👎 Poor uniformity across the array

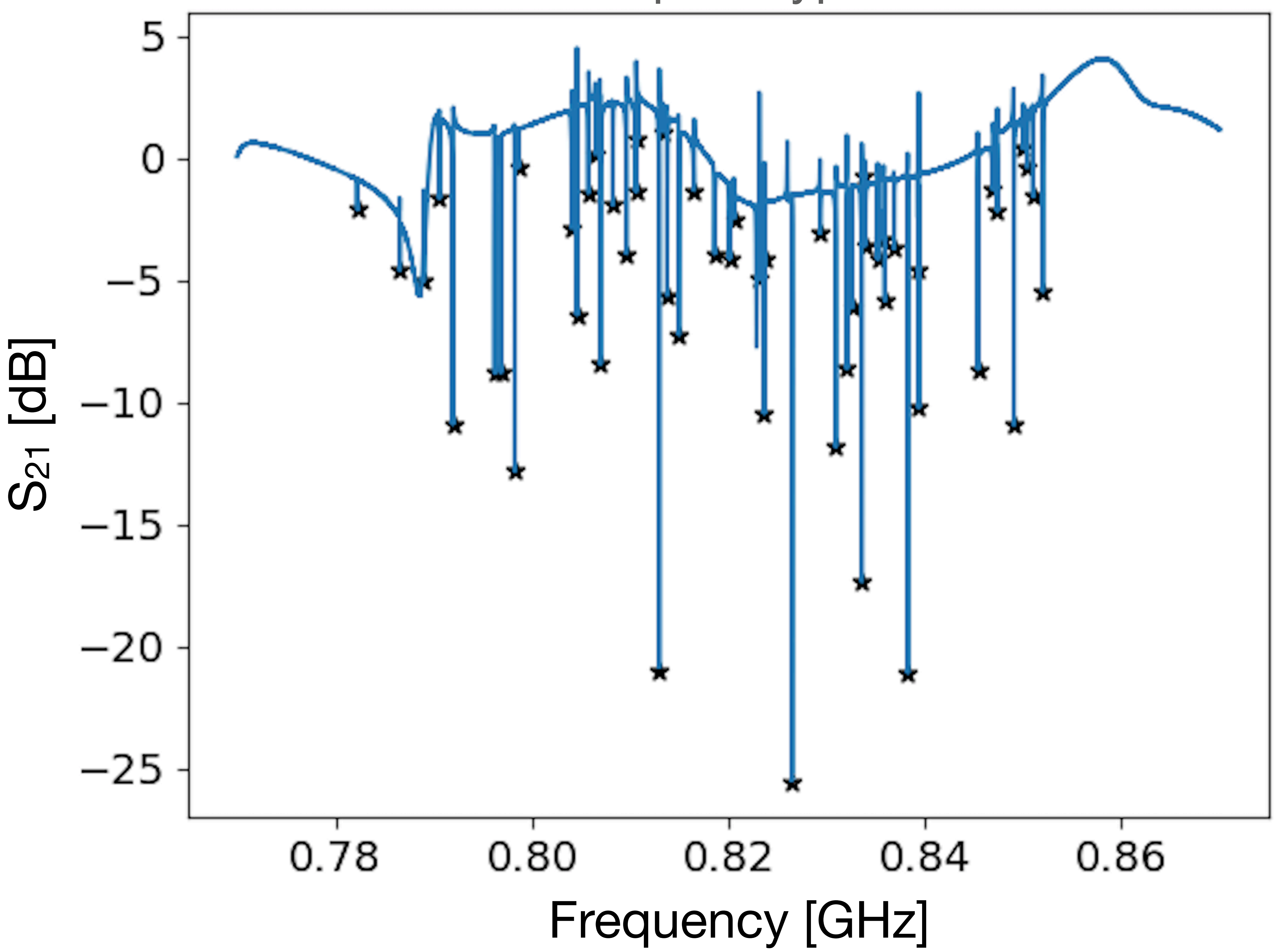
👎 Low quality factor of the resonators (0.2×10^5, aiming at > 10^5)

Second prototype (5/2022)

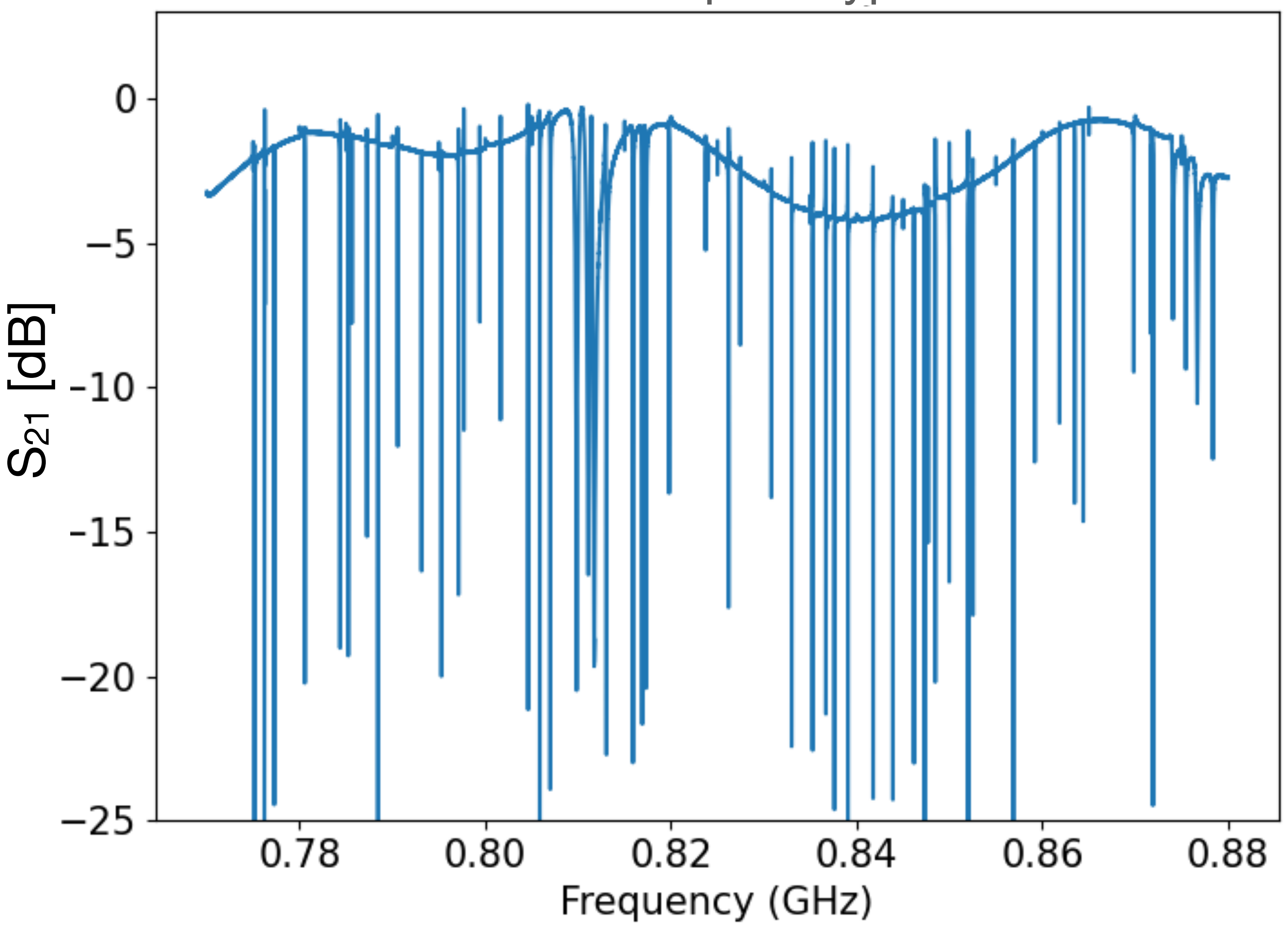


- Reduced electrical x-talk (frequency spacing from 1 to 2 MHz)
- Improved film quality of the KIDs (uniform etching of the wafer surface)

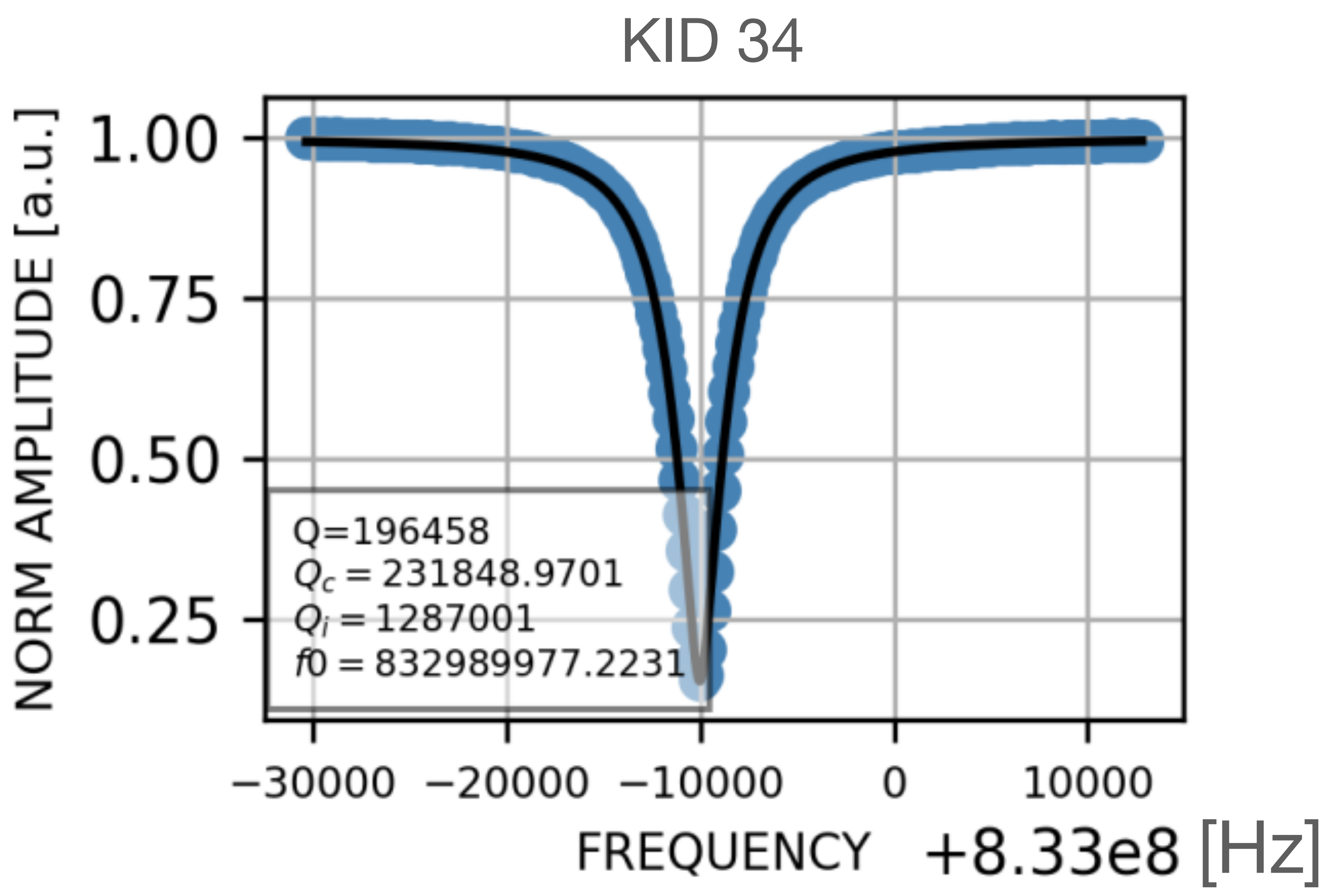
First prototype



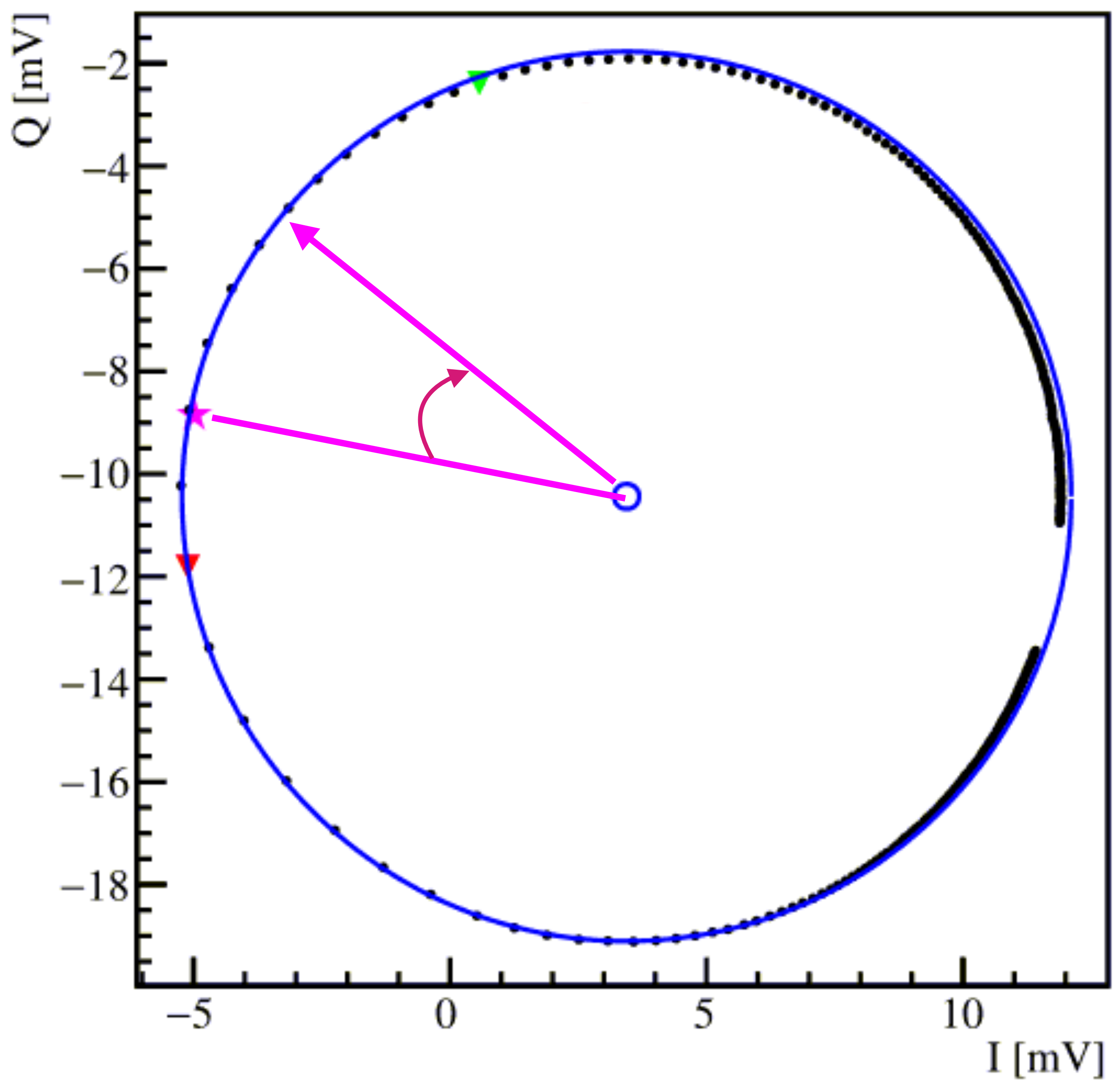
Second prototype

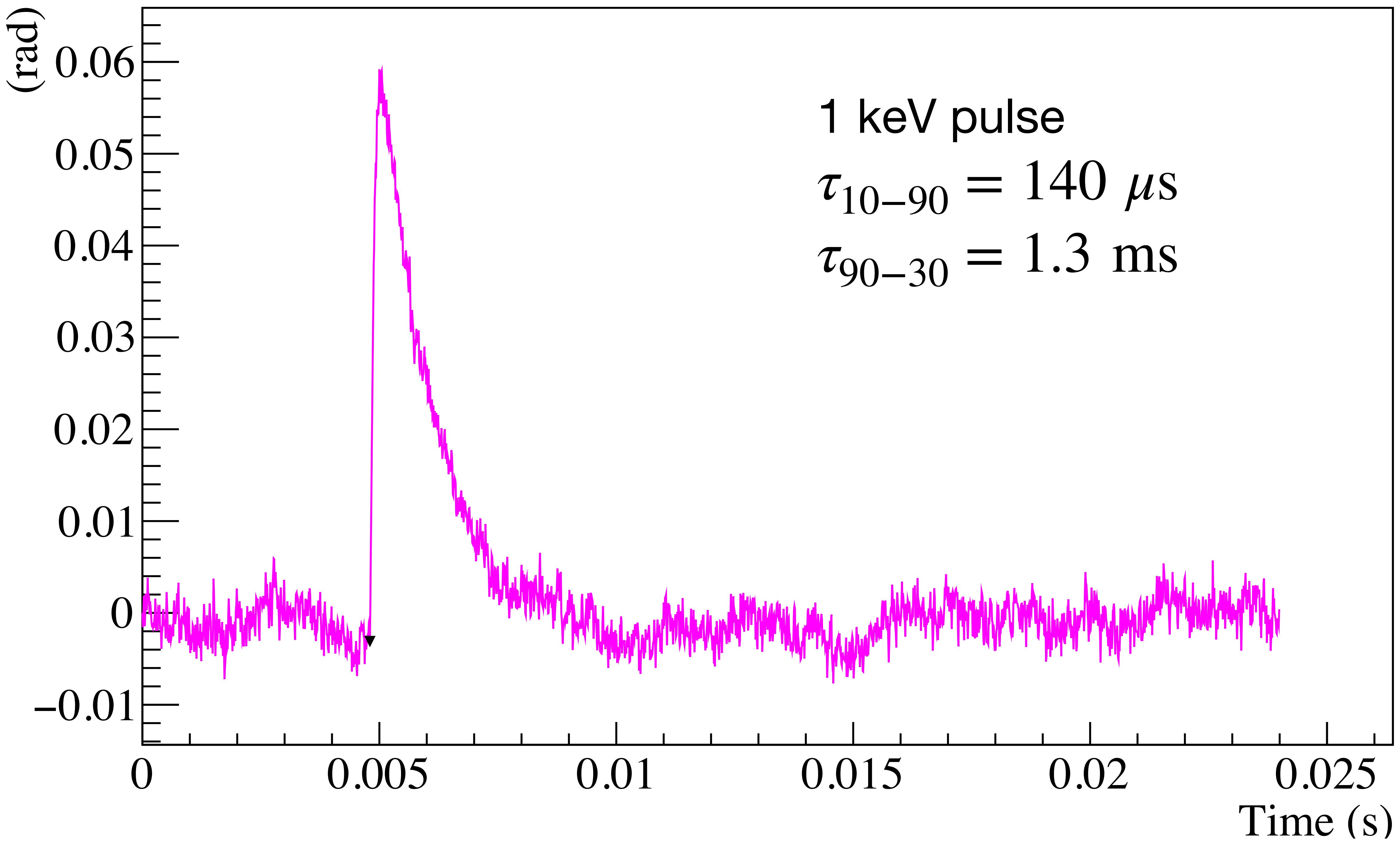


Readout



Ettus X310
can MUX the entire array





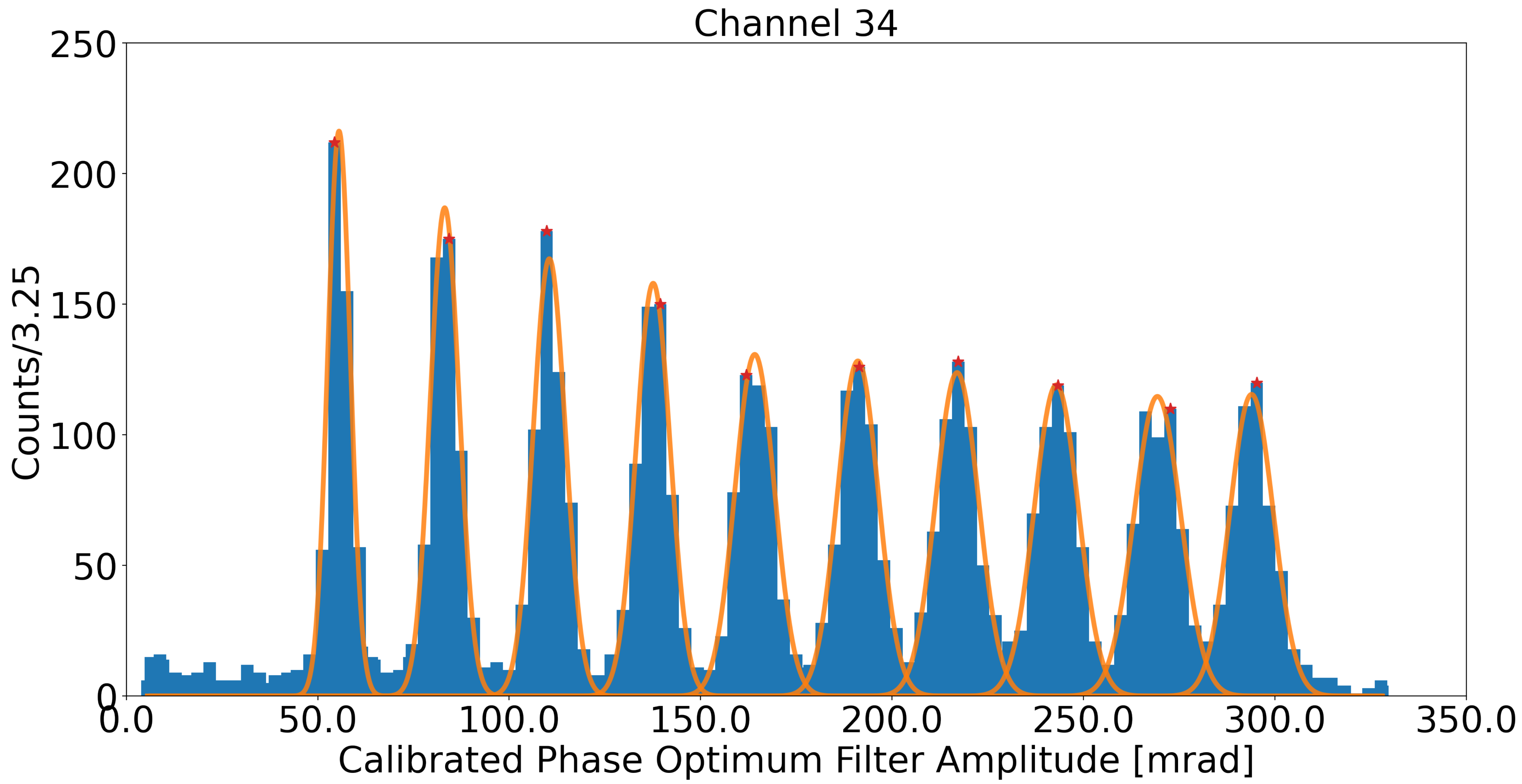
Energy calibration

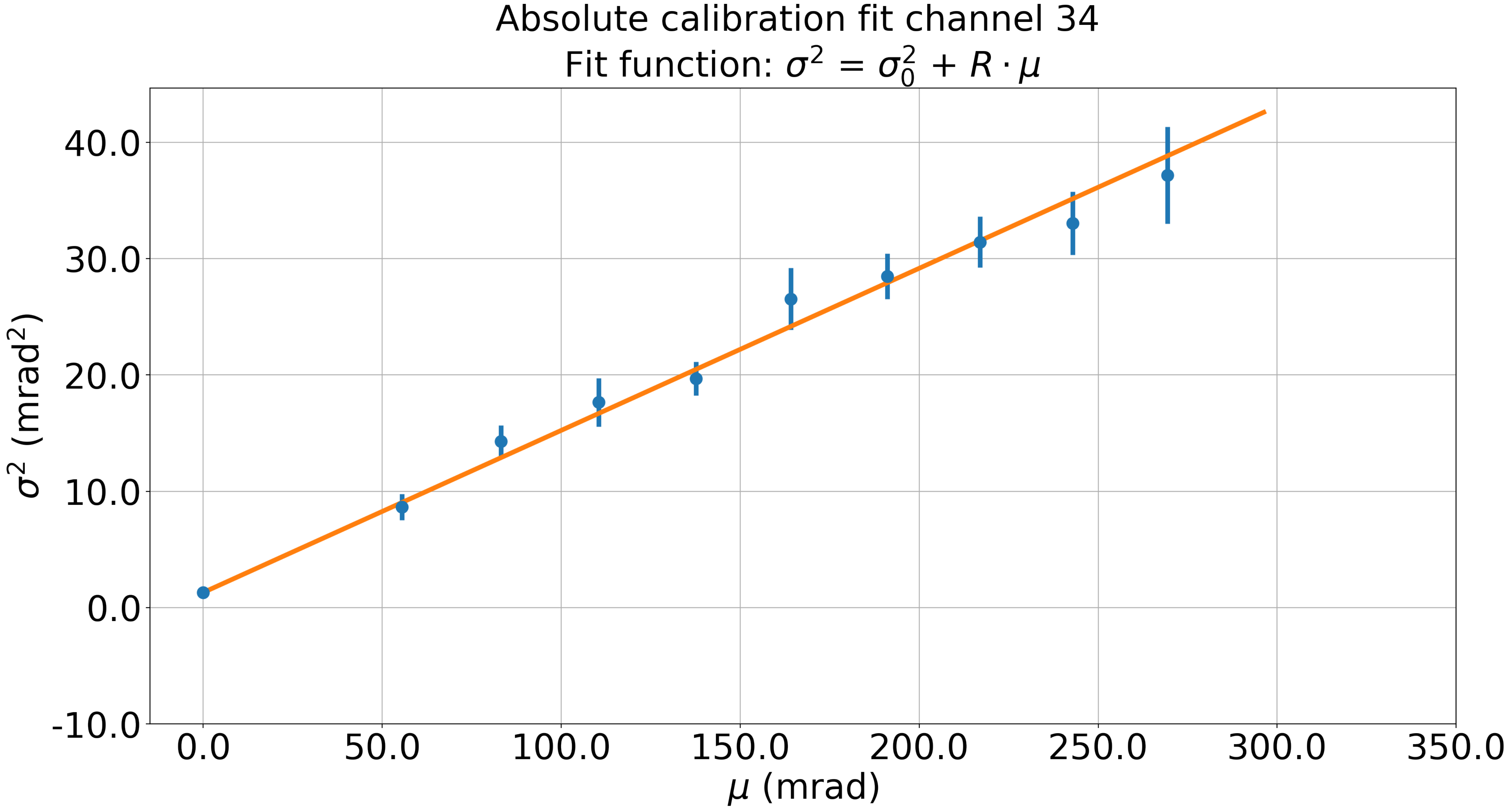
Exploit the Poisson's statistics of bursts of *N* optical photons of known energy ϵ to extract the calibration constant *k*:

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

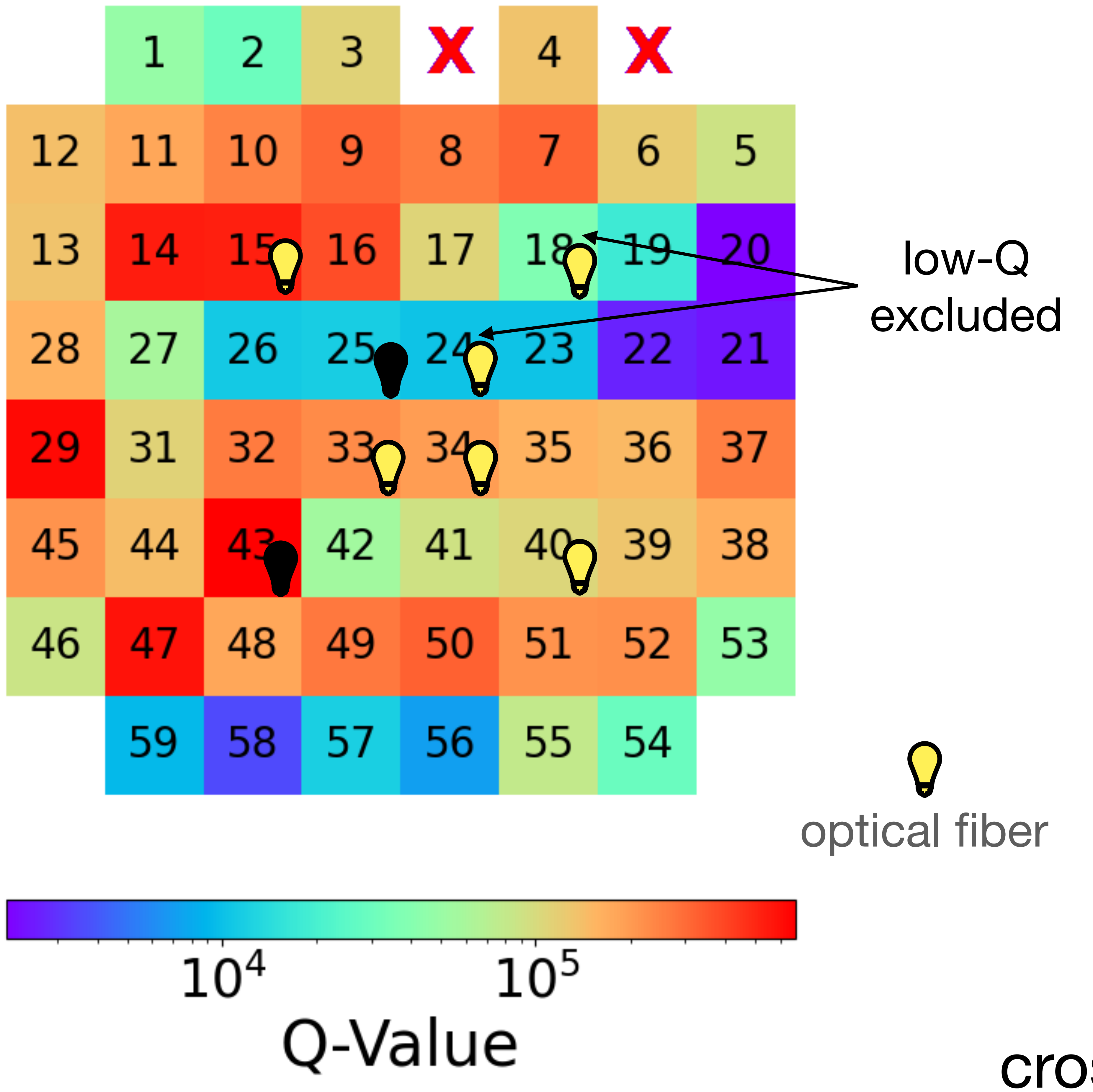
Linear fit for σ_0^2 and $R = k\epsilon$:

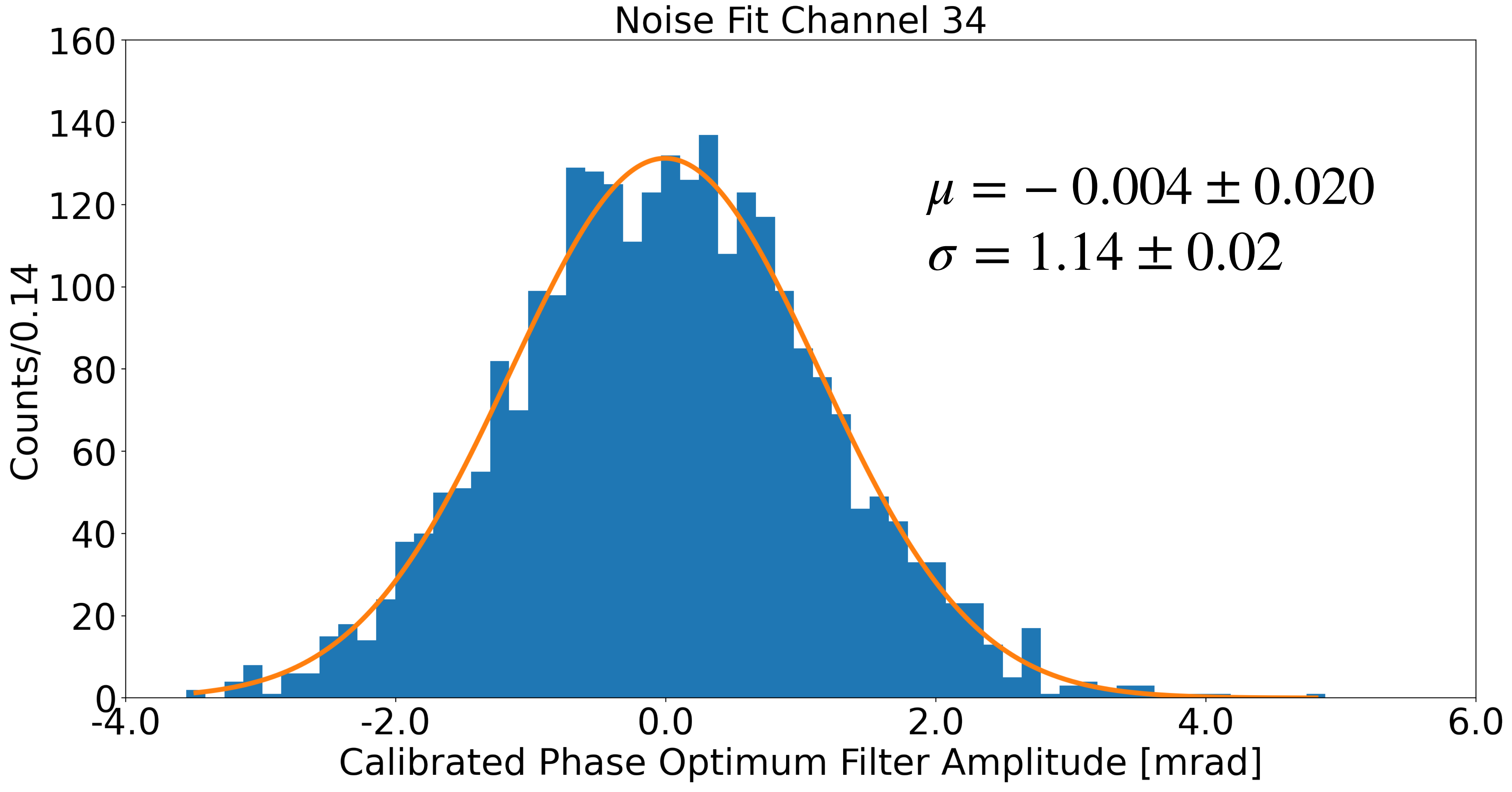
- $k = \dfrac{R}{\epsilon}\,, \quad \epsilon(400\ \mathrm{nm}) = 3.1\ \mathrm{eV}$





Preliminary results





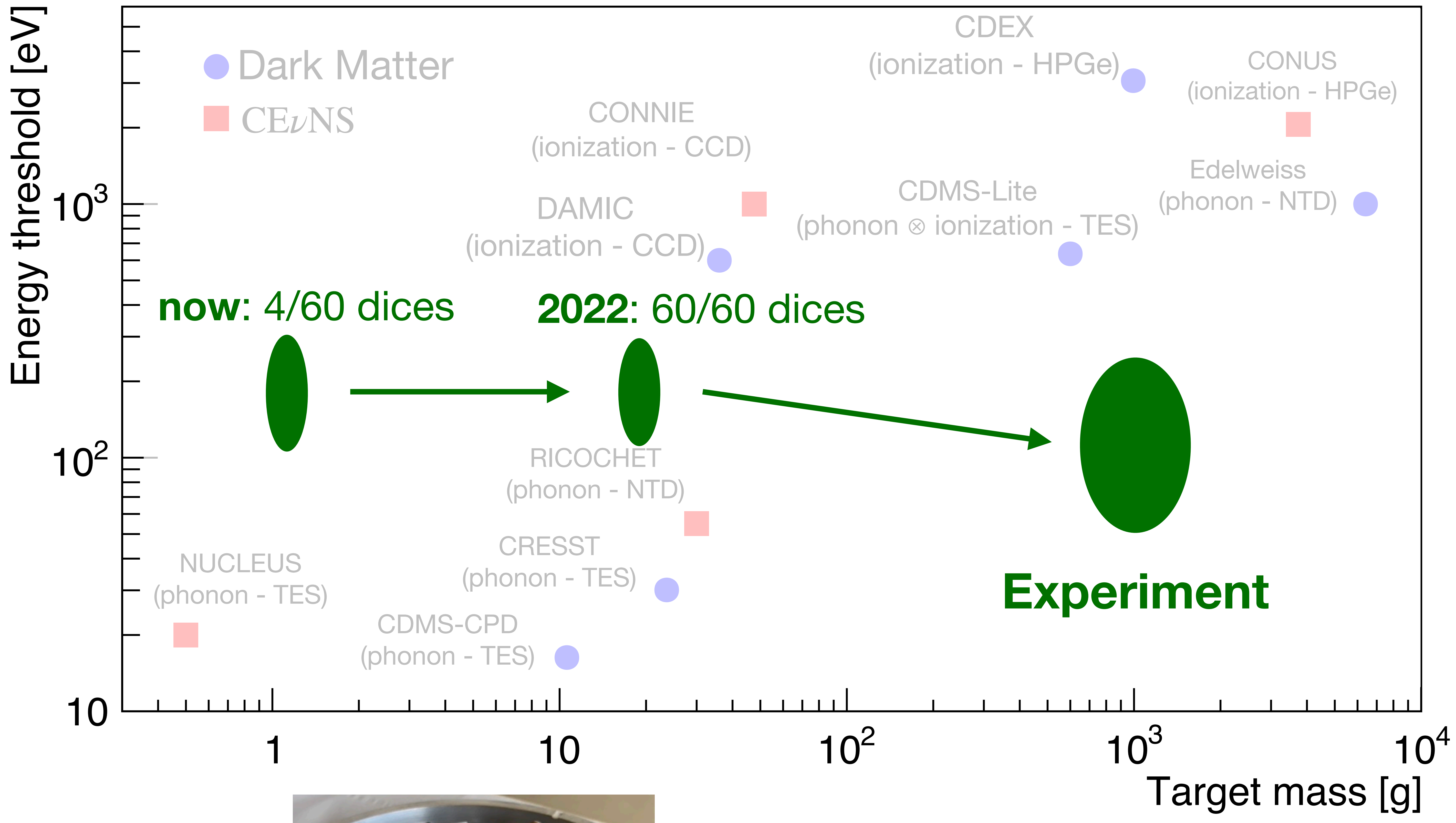
KID	σ_0 [mrad]	σ_0 [eV]
15	3.4±0.1	*25.0±1.2*
33	1.78±0.03	*22.9±0.8*
34	1.14±0.02	*25.4±0.5*
40	0.73±0.01	*20.6±0.9*

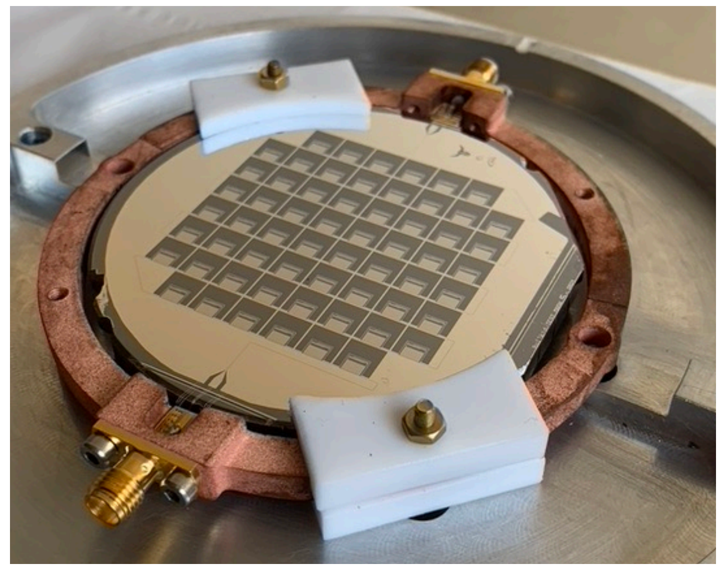
optical cal

threshold ~120 *eV*

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

Towards the experiment





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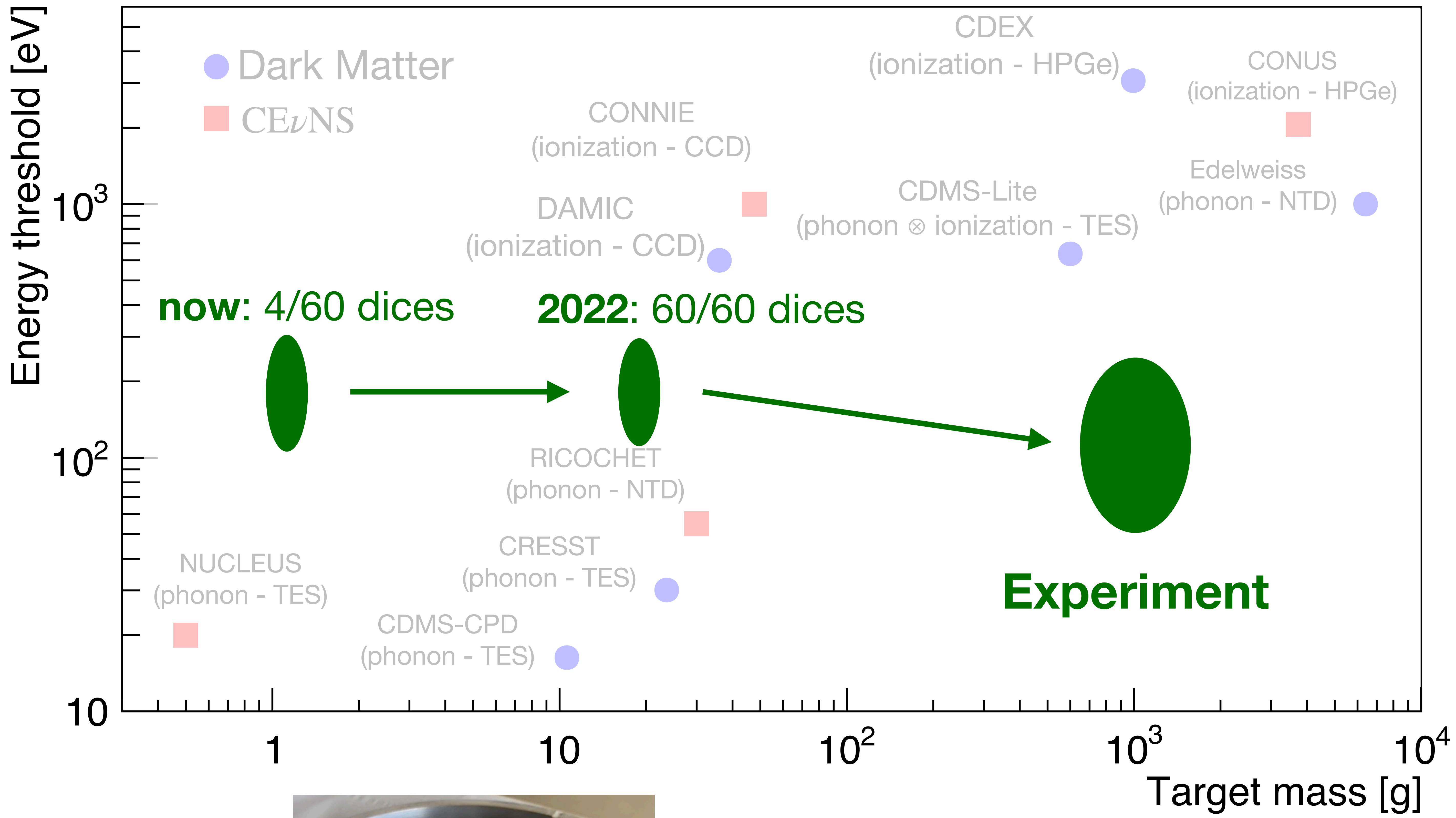
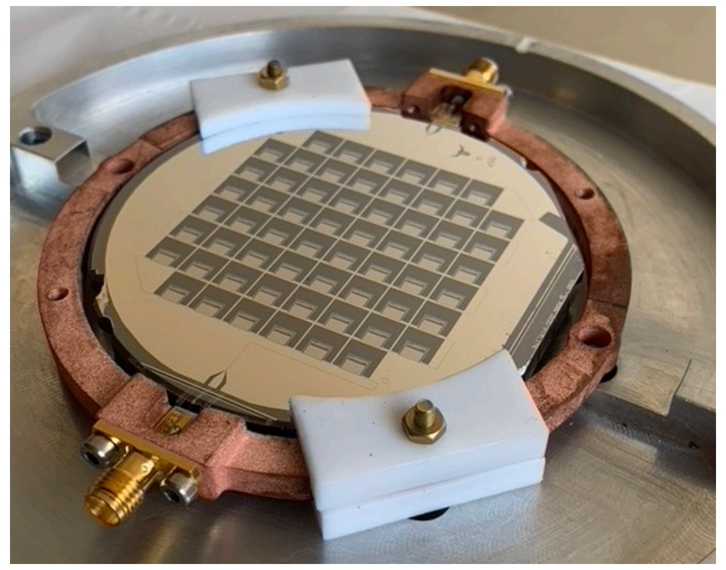
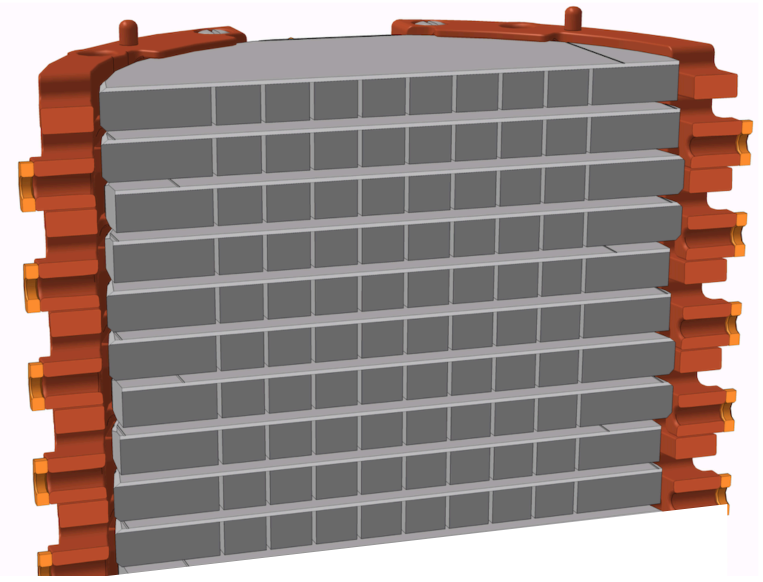


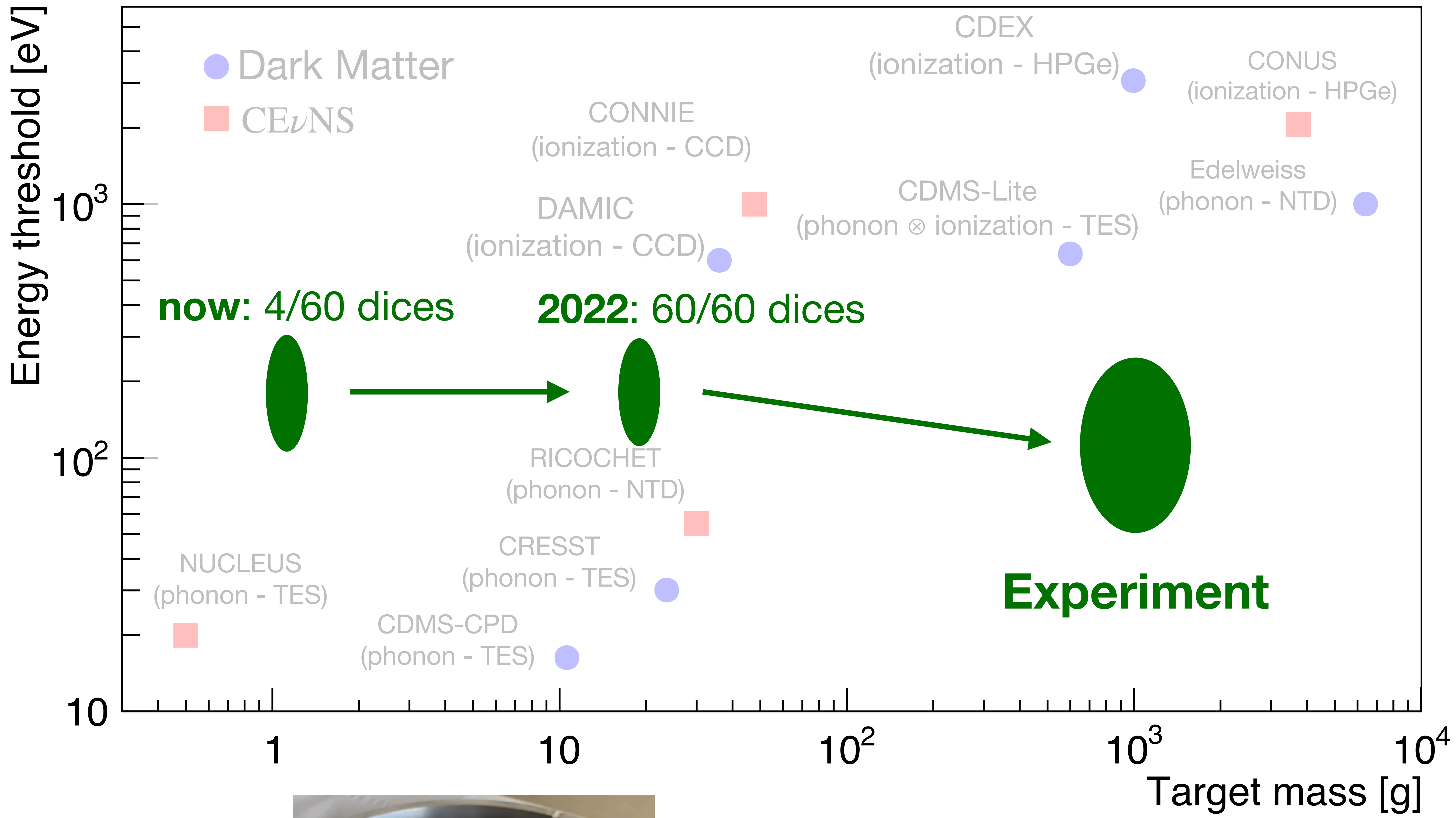


Mass:
from 3” to 4” wafers
stack of wafers



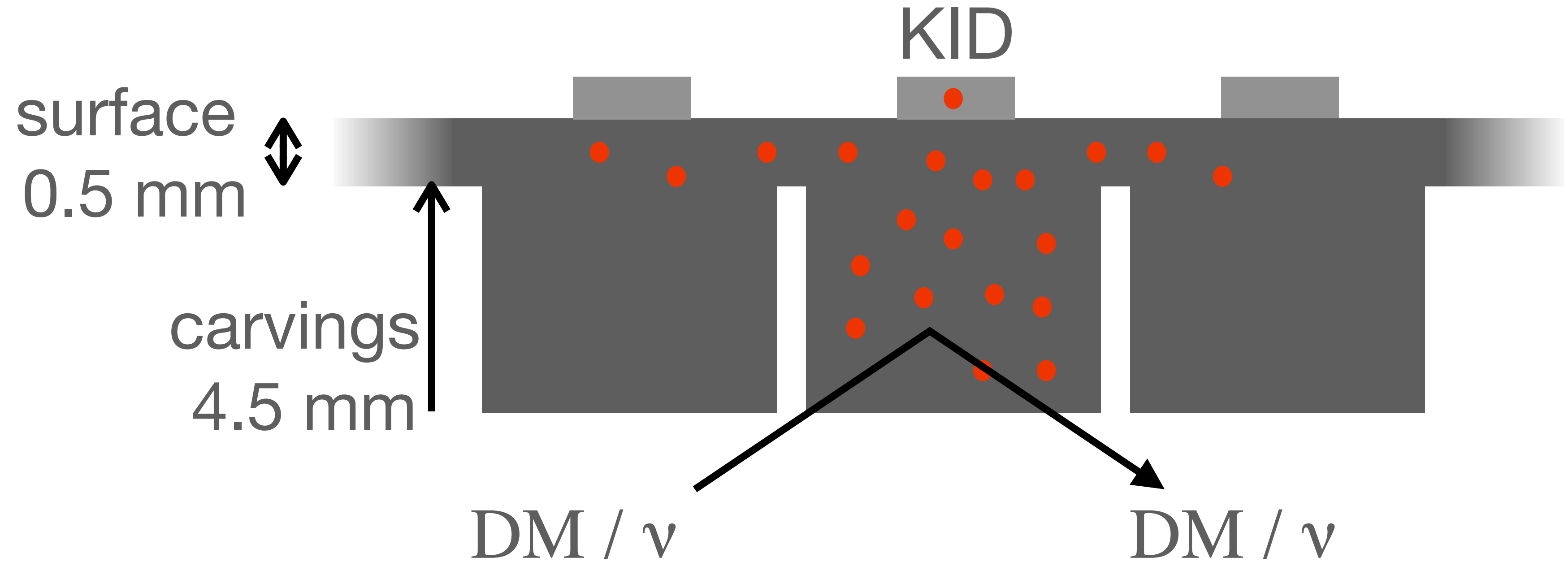
3D-printed Cu stacking prototype

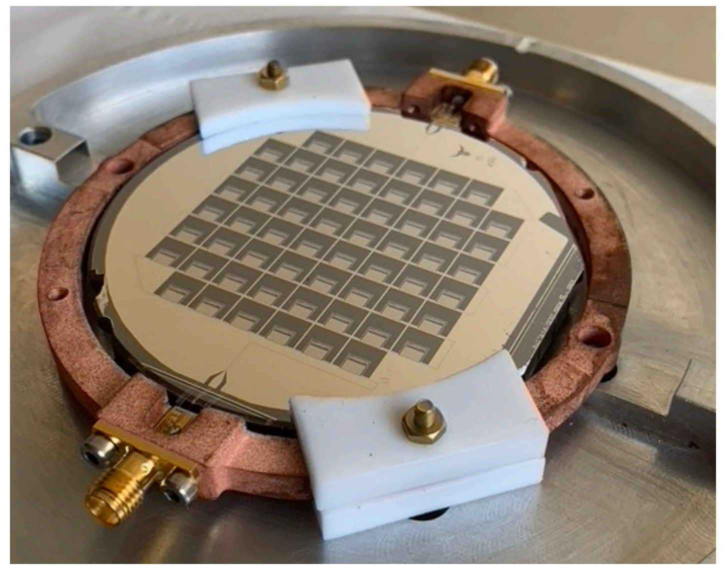
Towards the experiment



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





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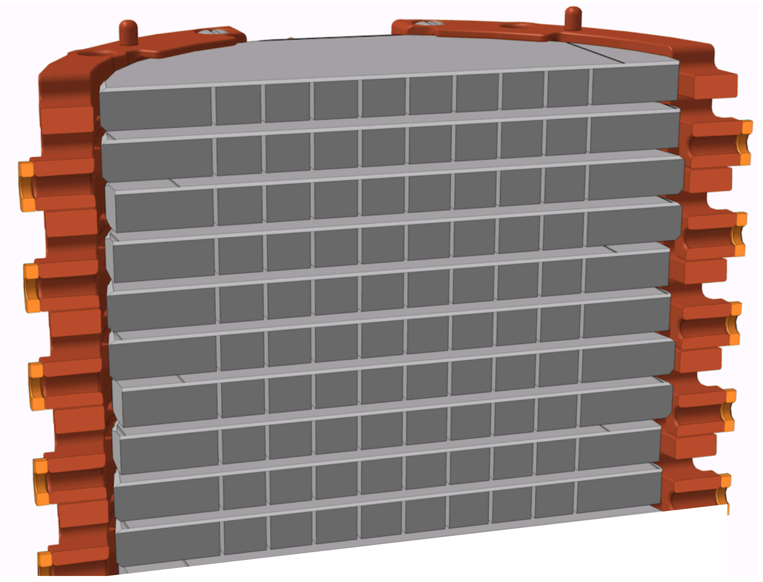

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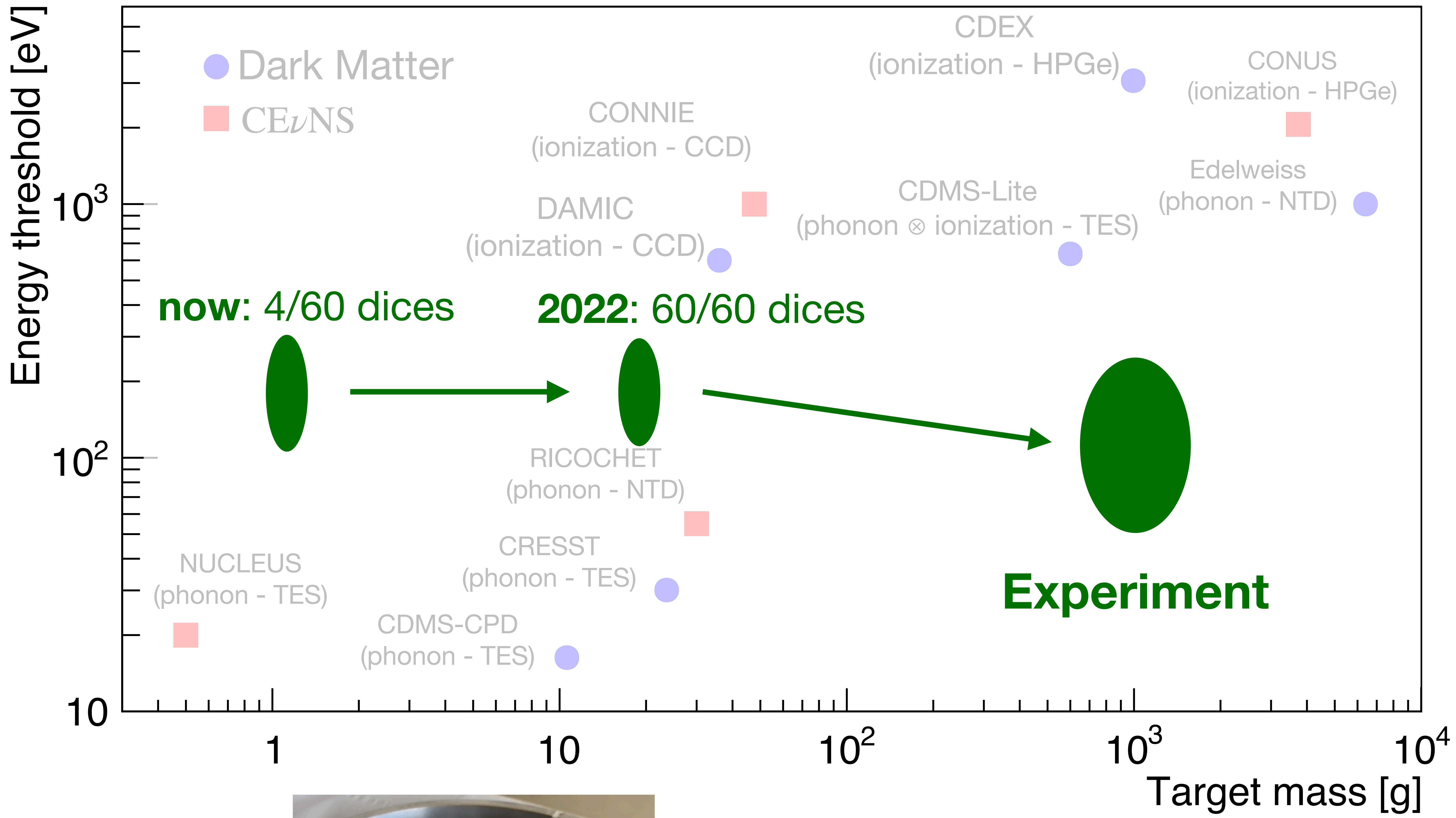

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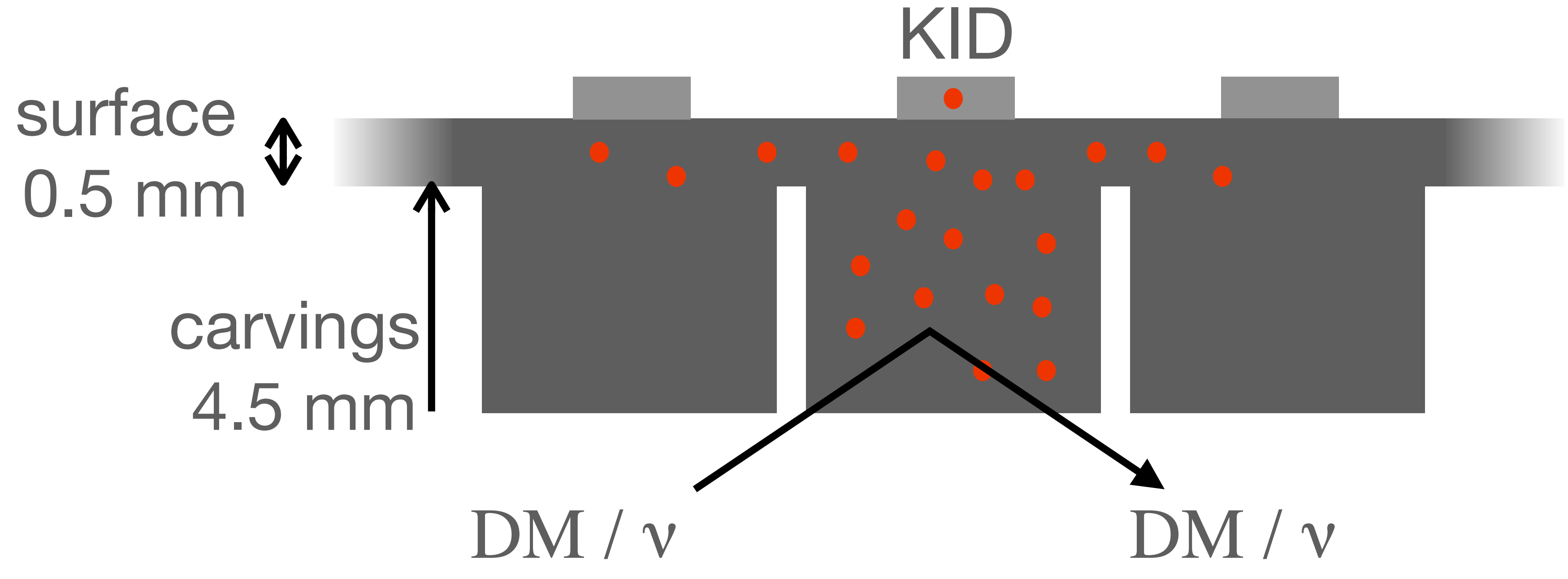
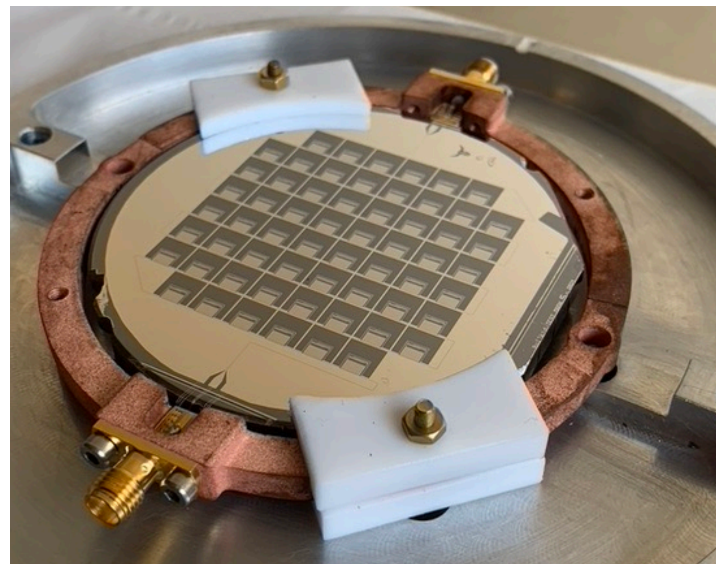


+ port the technology to Germanium wafers
(10x neutrino x-sec, does not apply to Dark Matter)



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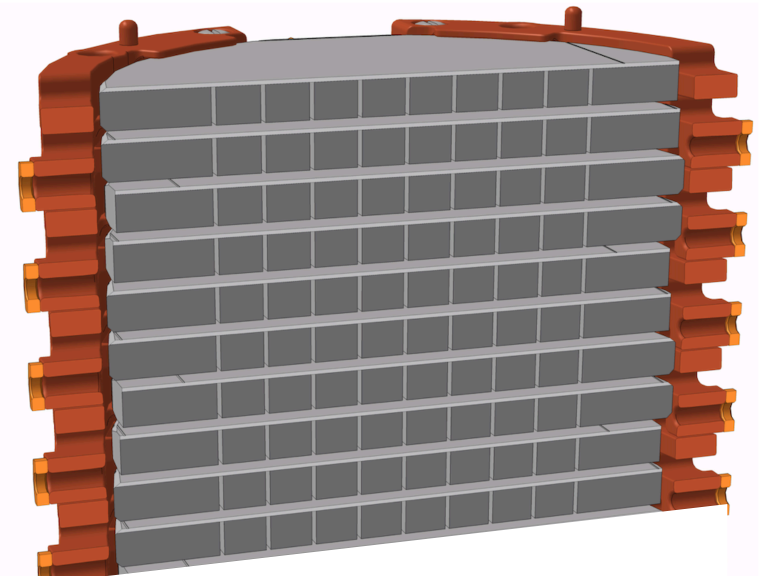
from 3” to 4” wafers
stack of wafers



3D-printed Cu stacking prototype