scintillating active Transverse Energy Filter

a novel detector concept for low-energy electron background discrimination

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for the KATRIN Collaboration

March 22nd, 2023 – T 74.2

DPG Spring Meeting of the Matter and Cosmos Section

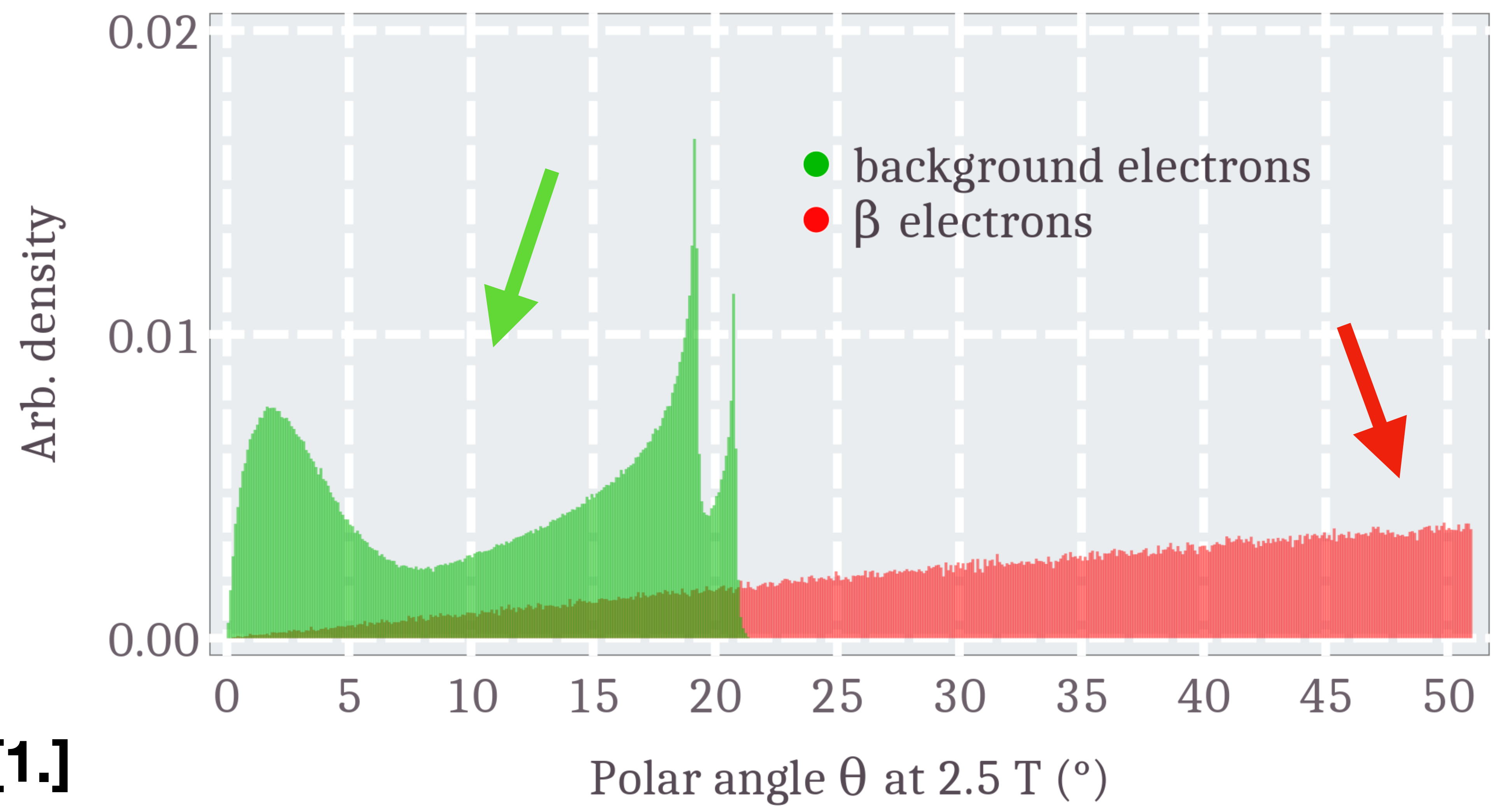
Transverse Energy Filter (TEF)

the TEF principle

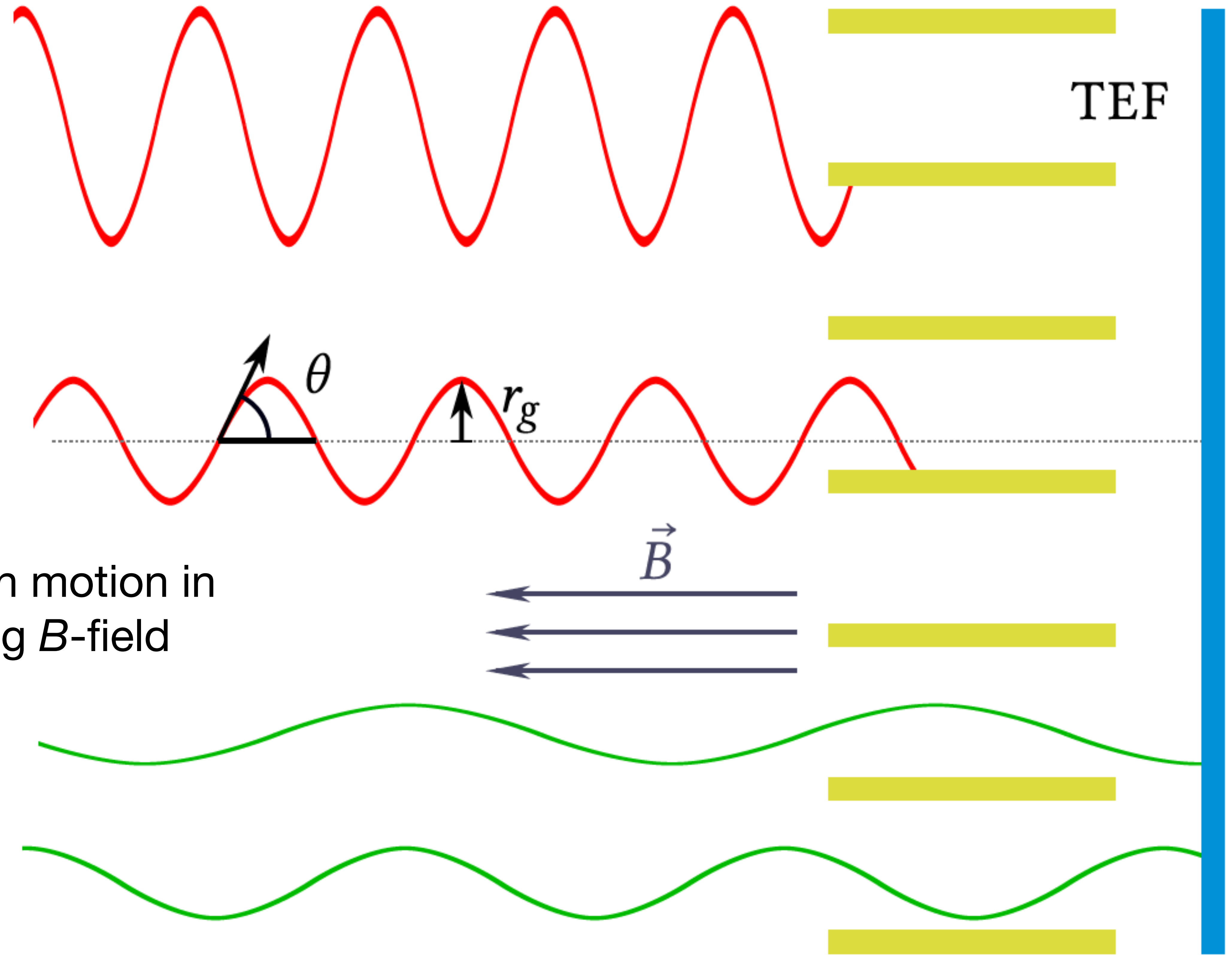
$E_T = E \sin^2(\theta)$

- background electrons
- tritium β electrons
- detector: ***active*** TEF = "**aTEF** fraction"

→ background discrimination for tritium β spectroscopy with KATRIN



[1.]



cyclotron motion in guiding *B*-field

KATRIN: low energy (origin) ↔ low angles (detector)

detector concept: active TEF (aTEF)

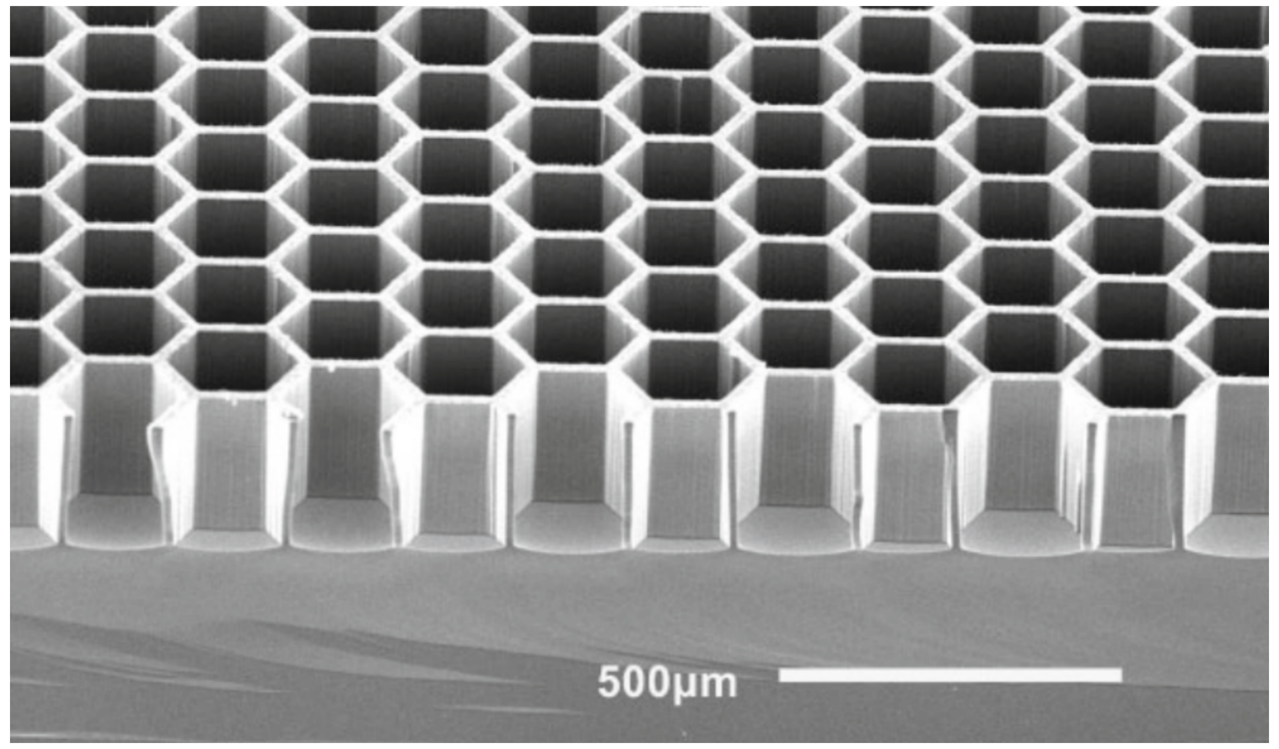
two different approaches by KATRIN

Si-*aTEF*

Eur. Phys. J. C 82, 922 (2022) **[2.]**

- *silicon*-based aTEF detector
- etched Si-PIN diodes
- **T 123.6**, tomorrow at 17:05
- **HK 74.28**, tomorrow at 17:30
- **T 143.5**, tomorrow at 18:30

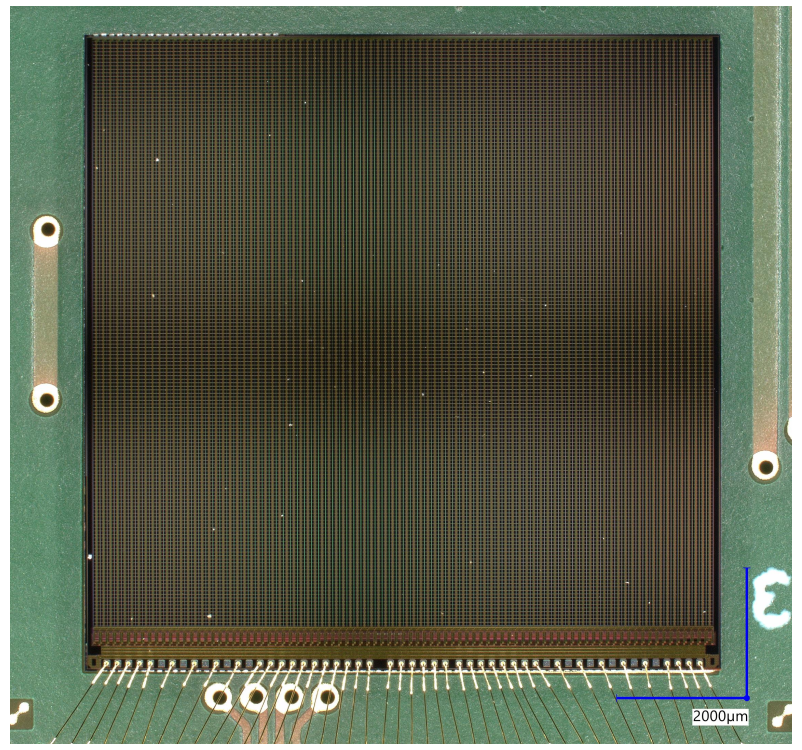
[2.]

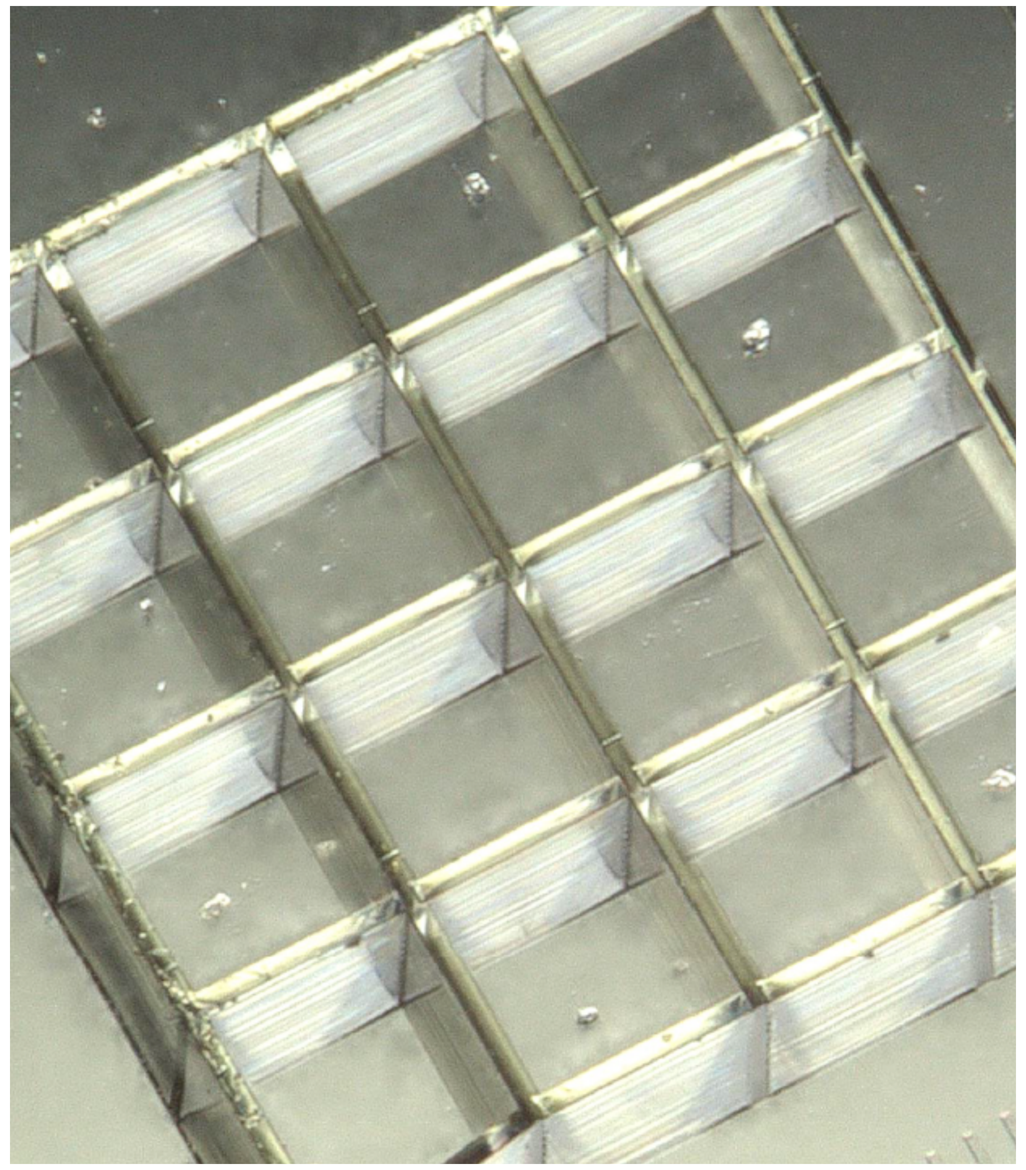


scint-*aTEF*

- *scintillator*-based aTEF detector
- scintillator grid and single-photon detector
- **T 74.2**, today at 16:05
- **T 74.3**, today at 16:20
- **T 74.4**, today at 16:35

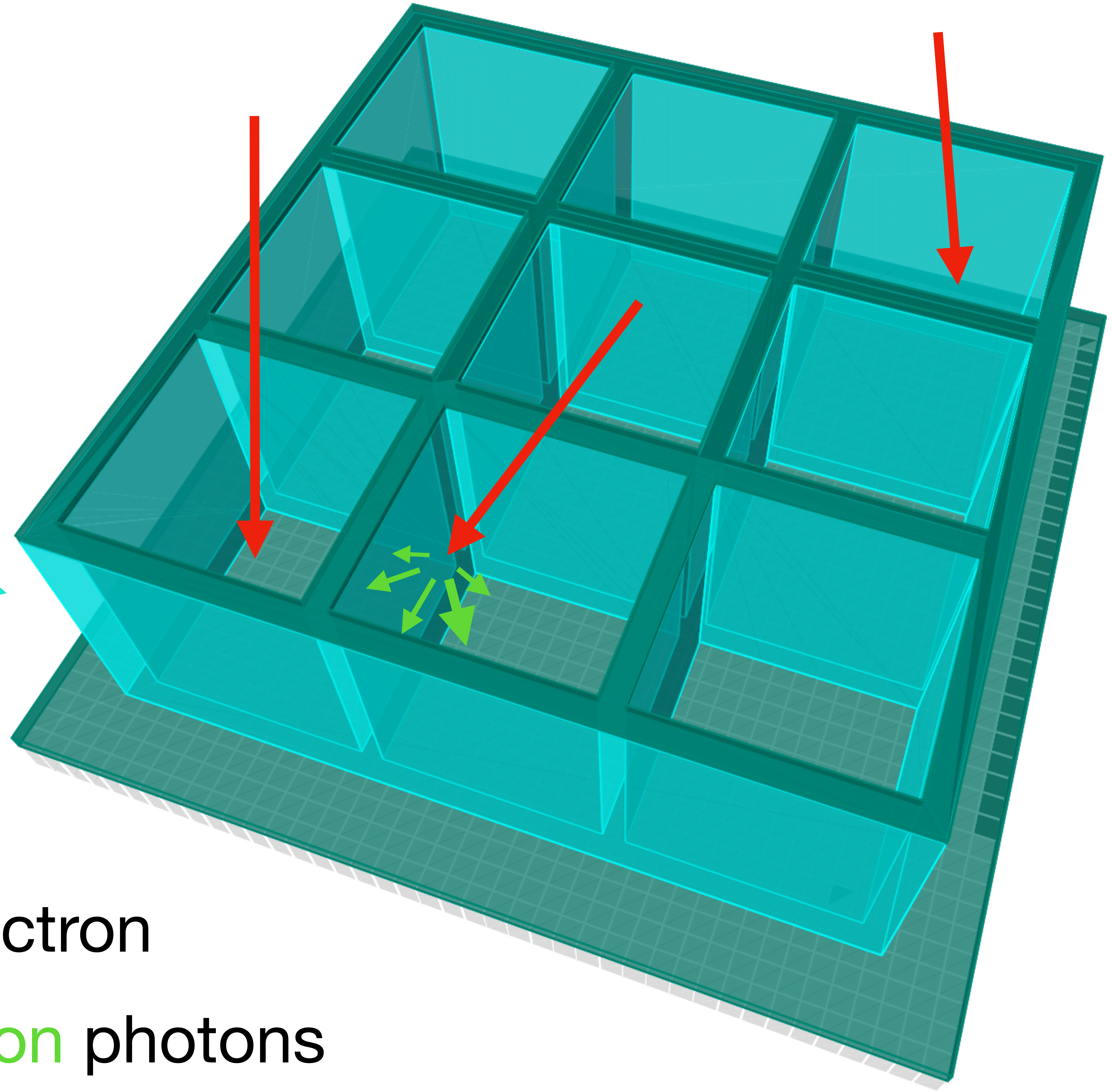
[3.]





scintillator-based aTEF

the scintillating approach



scint-aTEF

1. incident single low-energy (~18.6 keV) electron

2. if θ / r_g sufficiently large: multiple scintillation photons

3. photon footprint on detector

scintillator

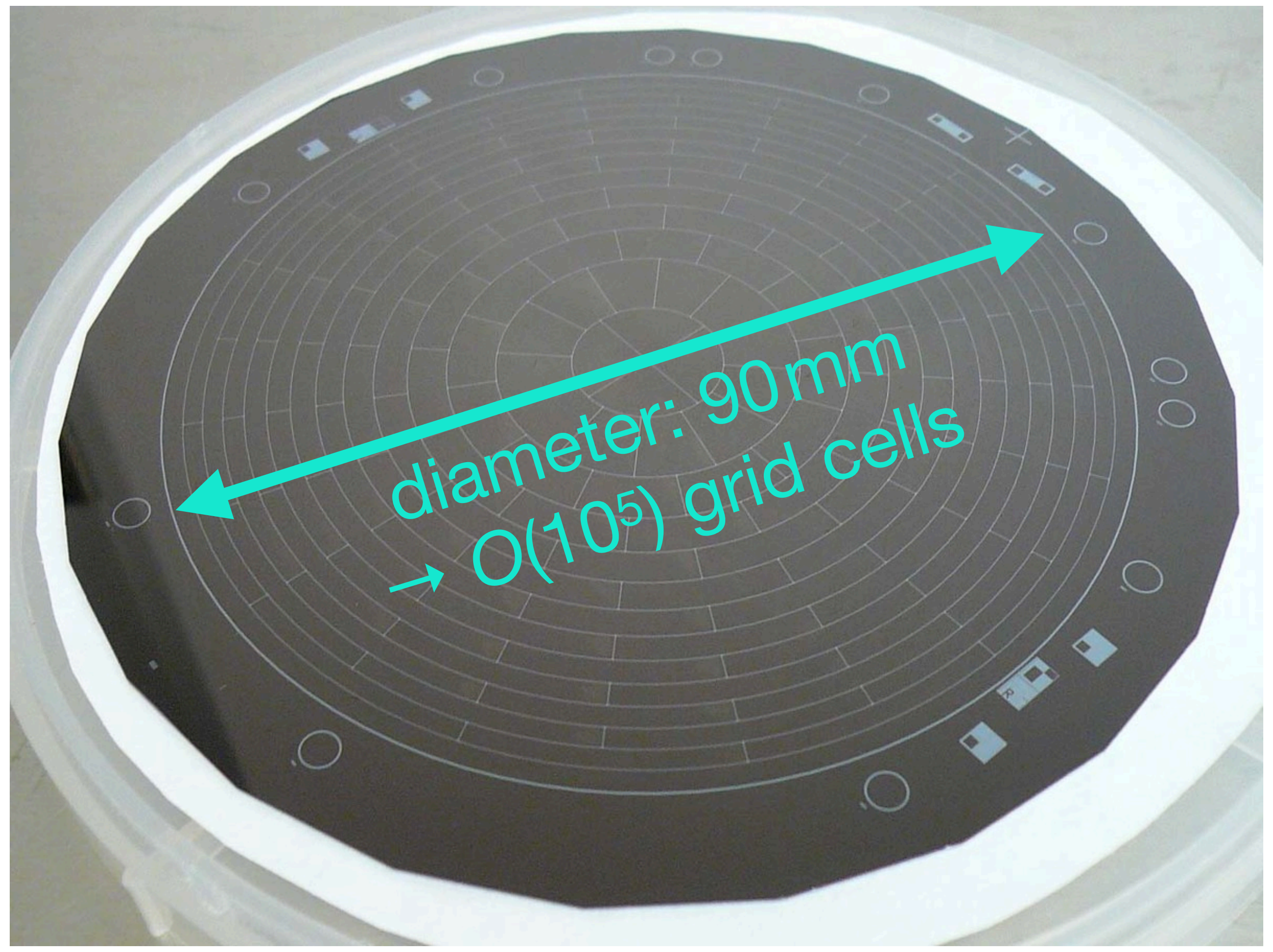
3d-microstructured plastic grid

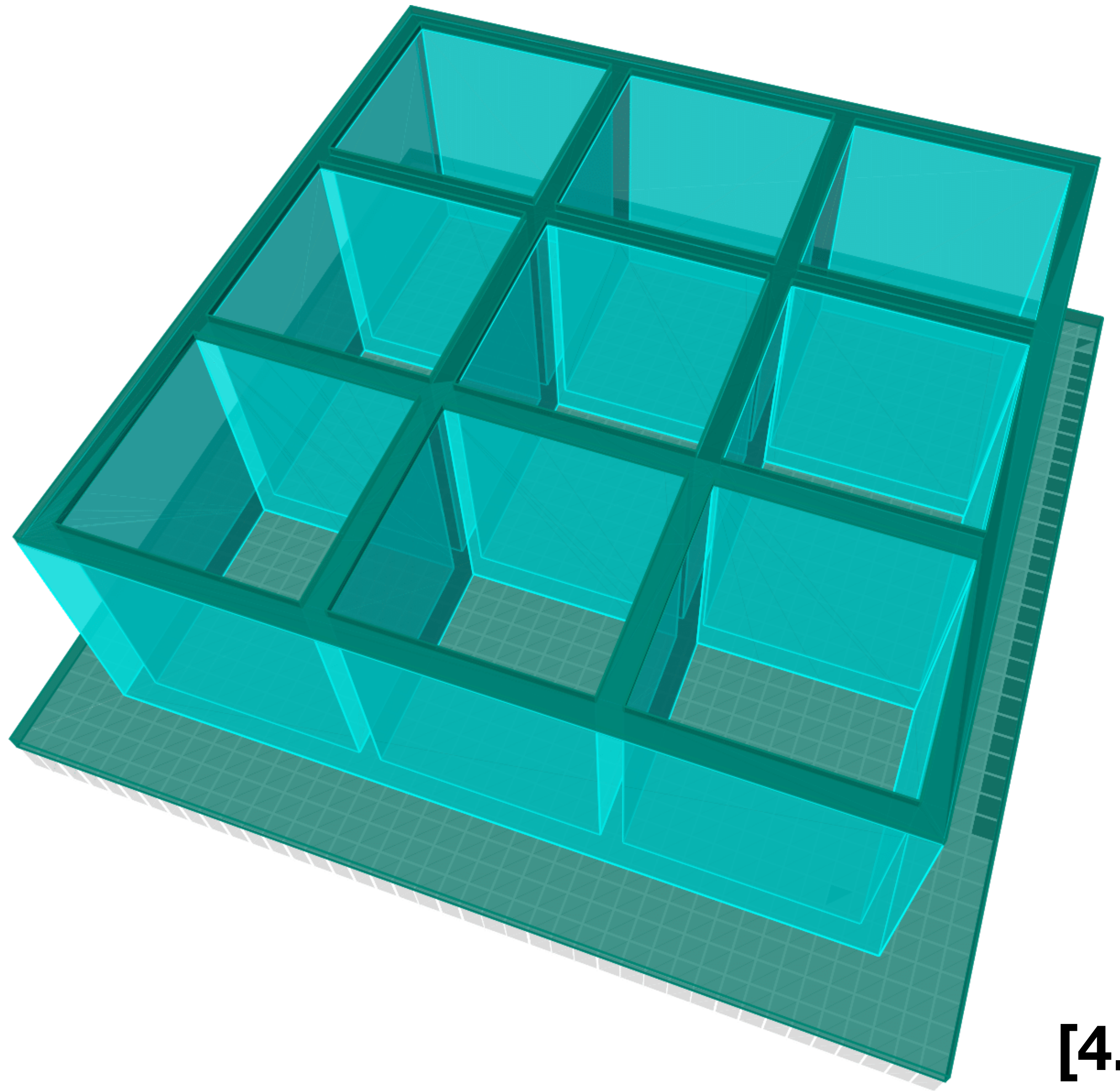
- plastic scintillator: low Z → low backscattering
- non-scint. low Z top/bottom: e.g. PMMA
- quadratic 3d grid dimensions:
  - cells of ~250×250 μm^2, ~25 μm walls
  - until now ~300 μm height

→ geometry optimizations using *Geant4* are ongoing

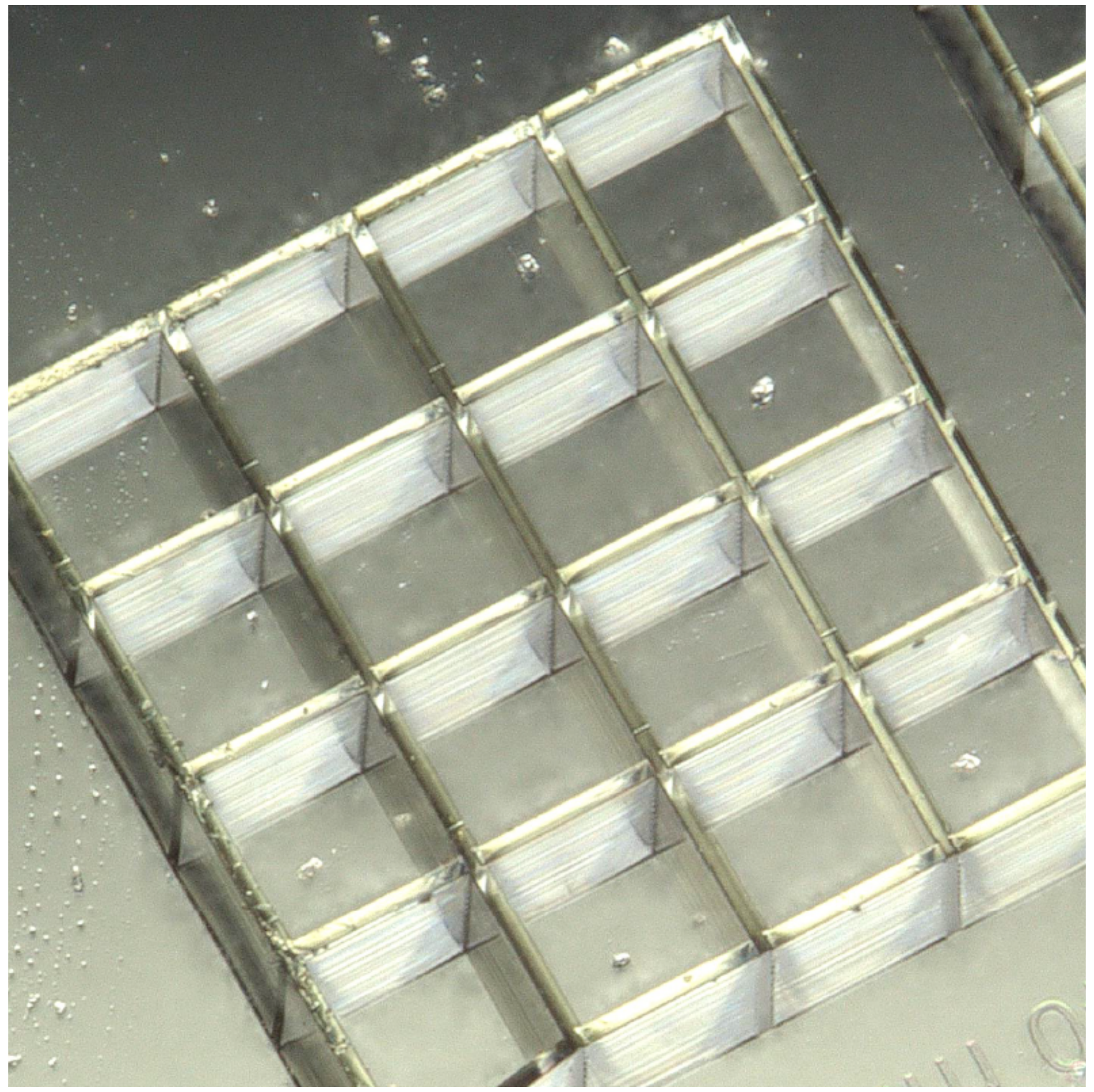
T 74.3, today at 16:20

[3.]
KATRIN Focal Plane Detector



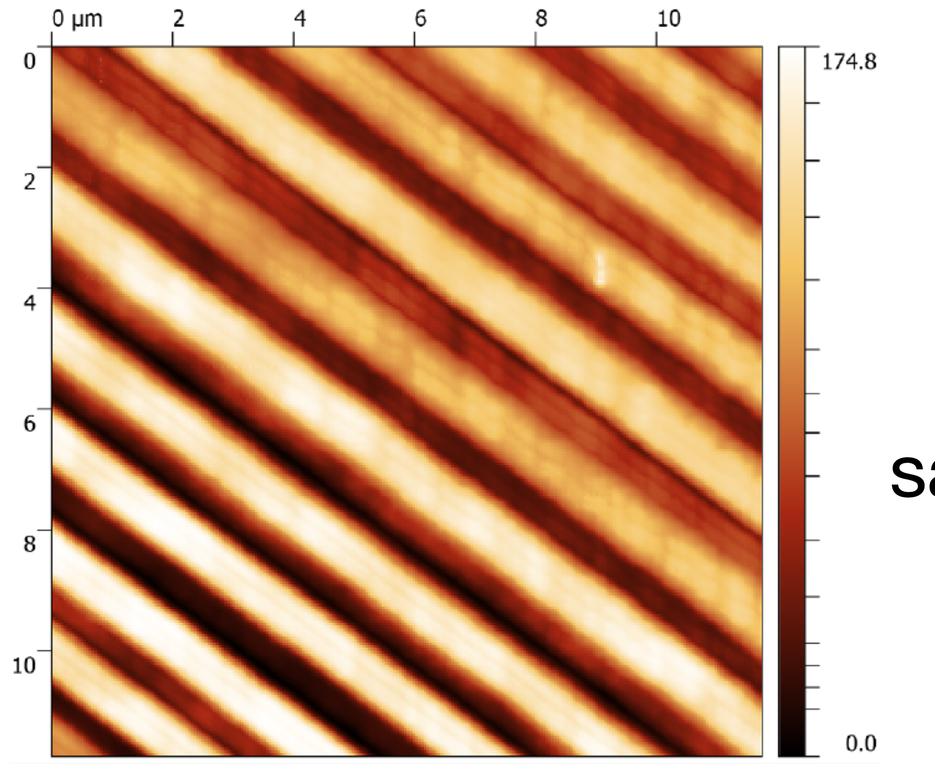


[4.]



scintillator

3d-microstructured plastic grid

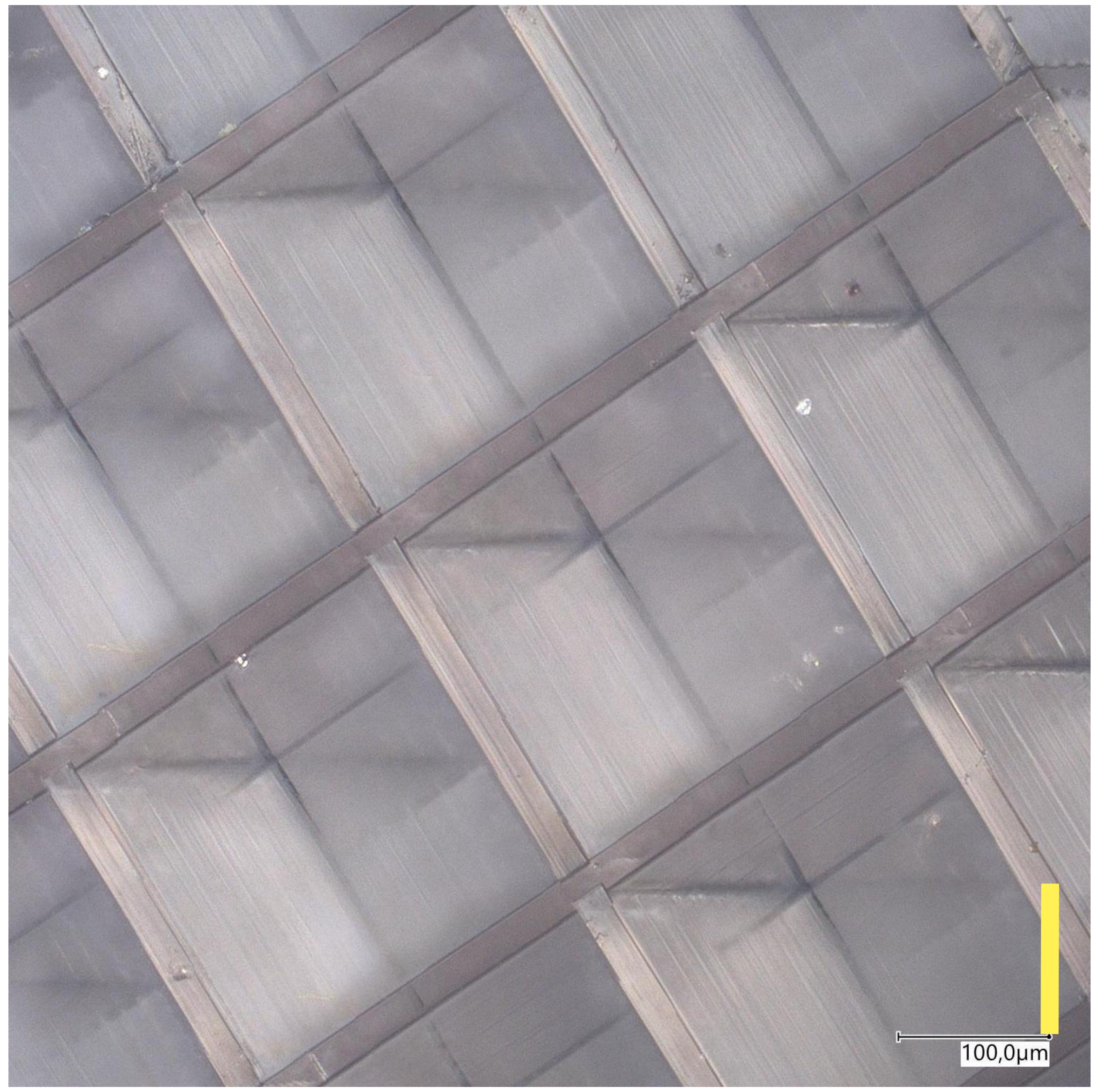


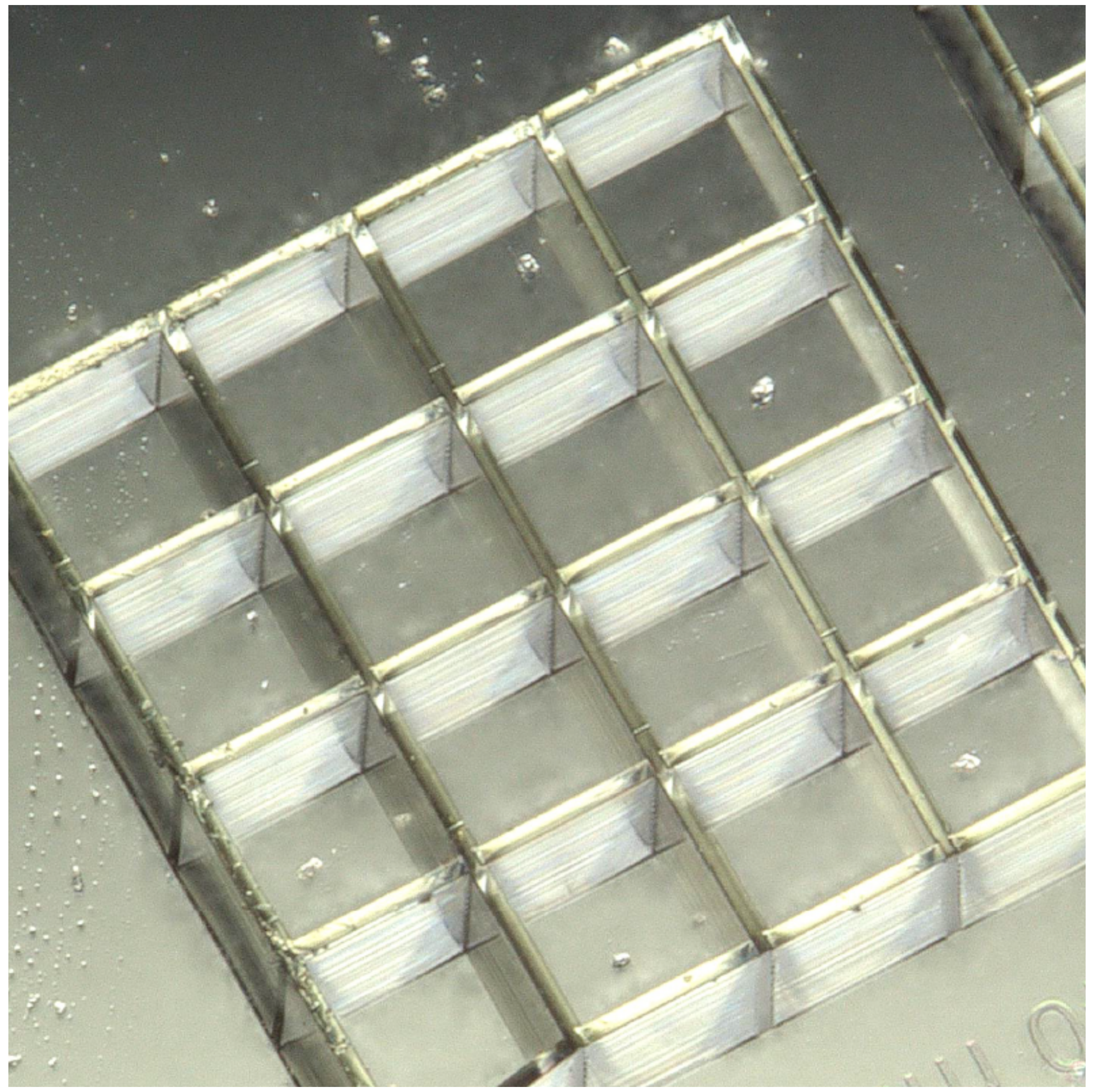
[5.]
AFM image:
sample surface

- manufacturing by 2-Photon Polymerization (2PP)
- R&D: suitable resin for 2PP of plastic scintillator & printing strategies
- important aspects:
  - surface properties ($\sigma_\alpha < 5°$)
  - light yield (max. ~10 ɣ/keV deposit)
  - emission spectrum

T 74.4, today at **16:35**

[4.]

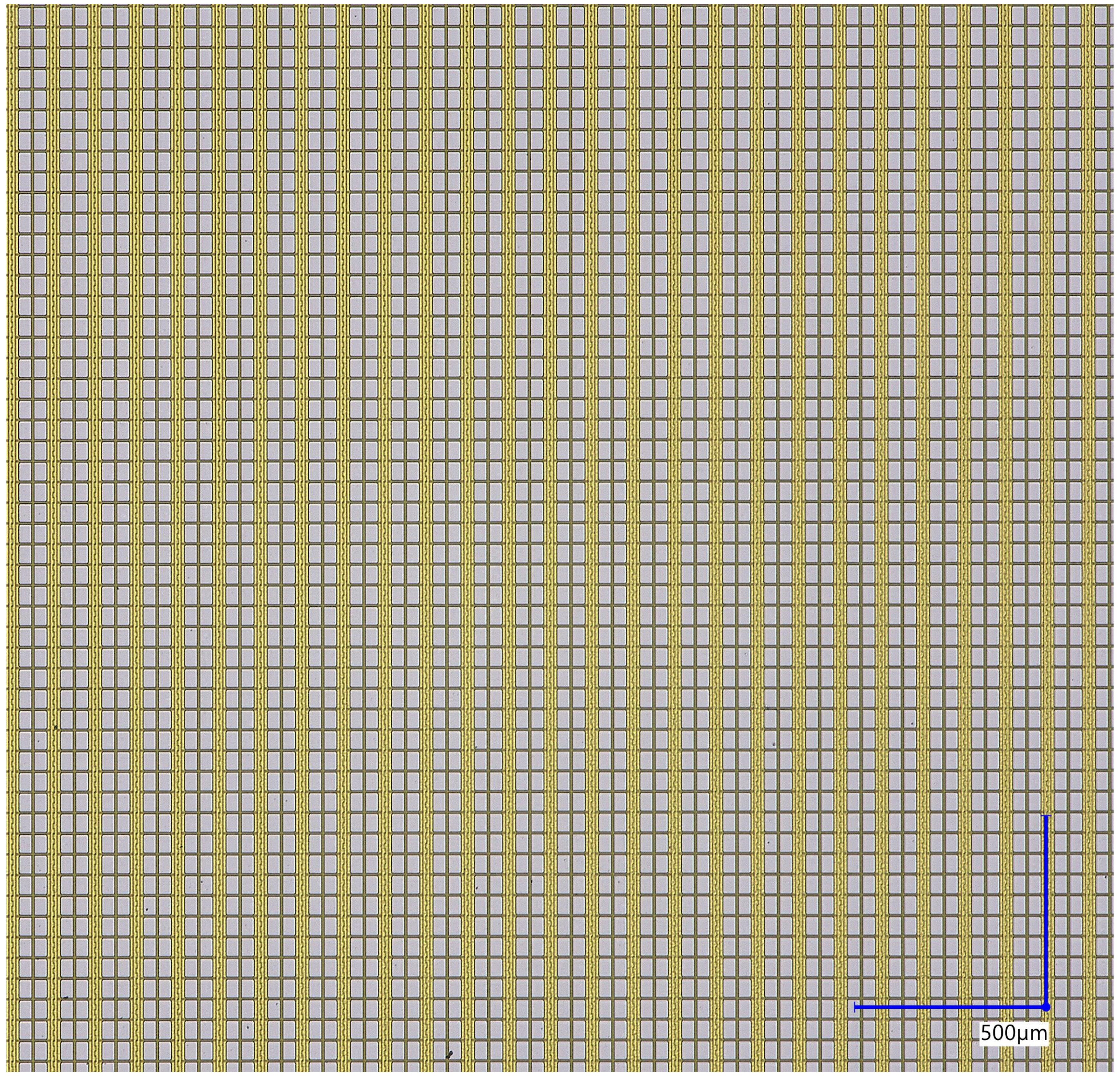




detector

CMOS-SPAD-based single photon detection

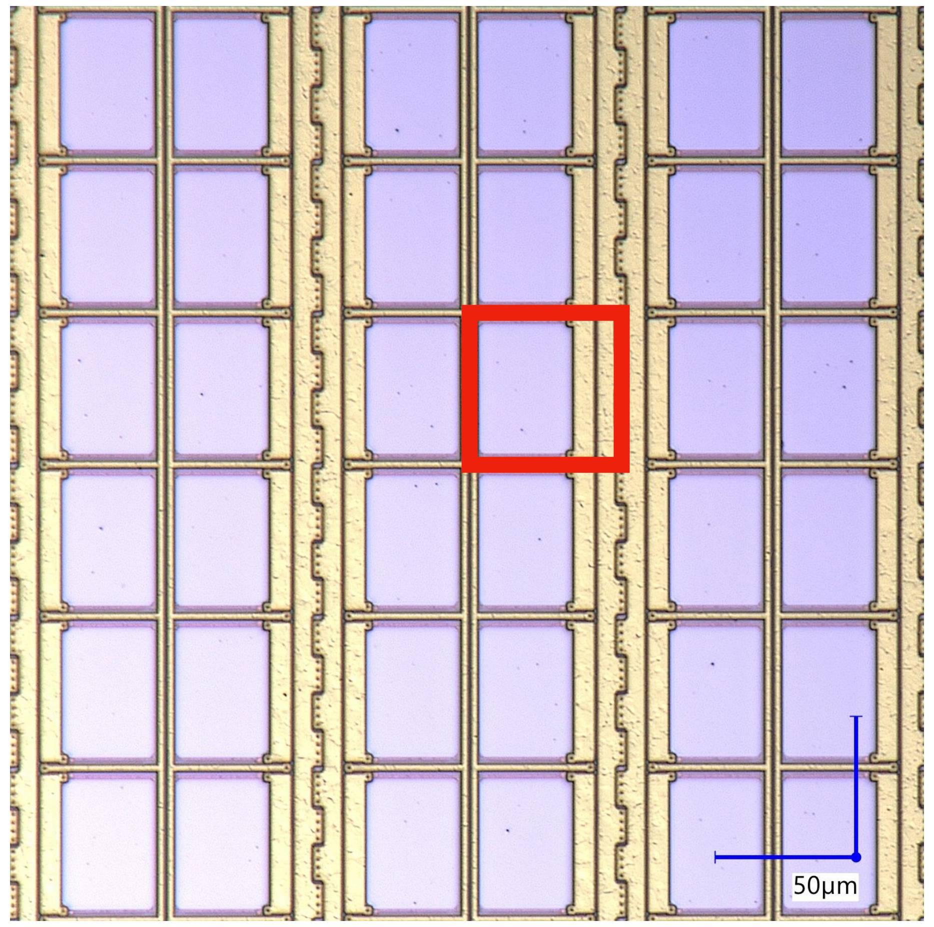
- **Single-Photon Avalanche Diode** (SPAD) array
- operation above breakdown voltage V_{BD} in GEIGER mode
- triggered avalanche only creates small fast external signal
- → combination with **CMOS** (Complementary Metal-Oxide-Semiconductor) technology → "*digital* SiPM"
- single noisy SPAD impairs whole array → hot SPADs can be disengaged in real time

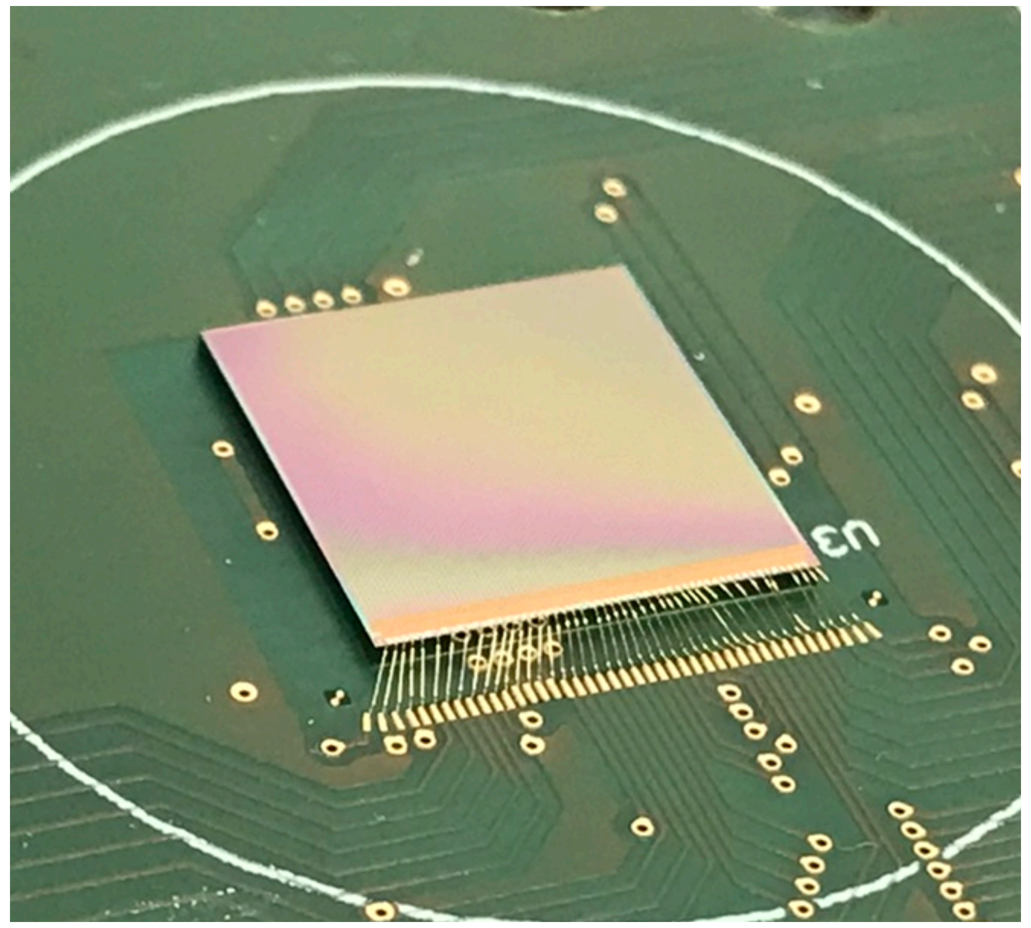


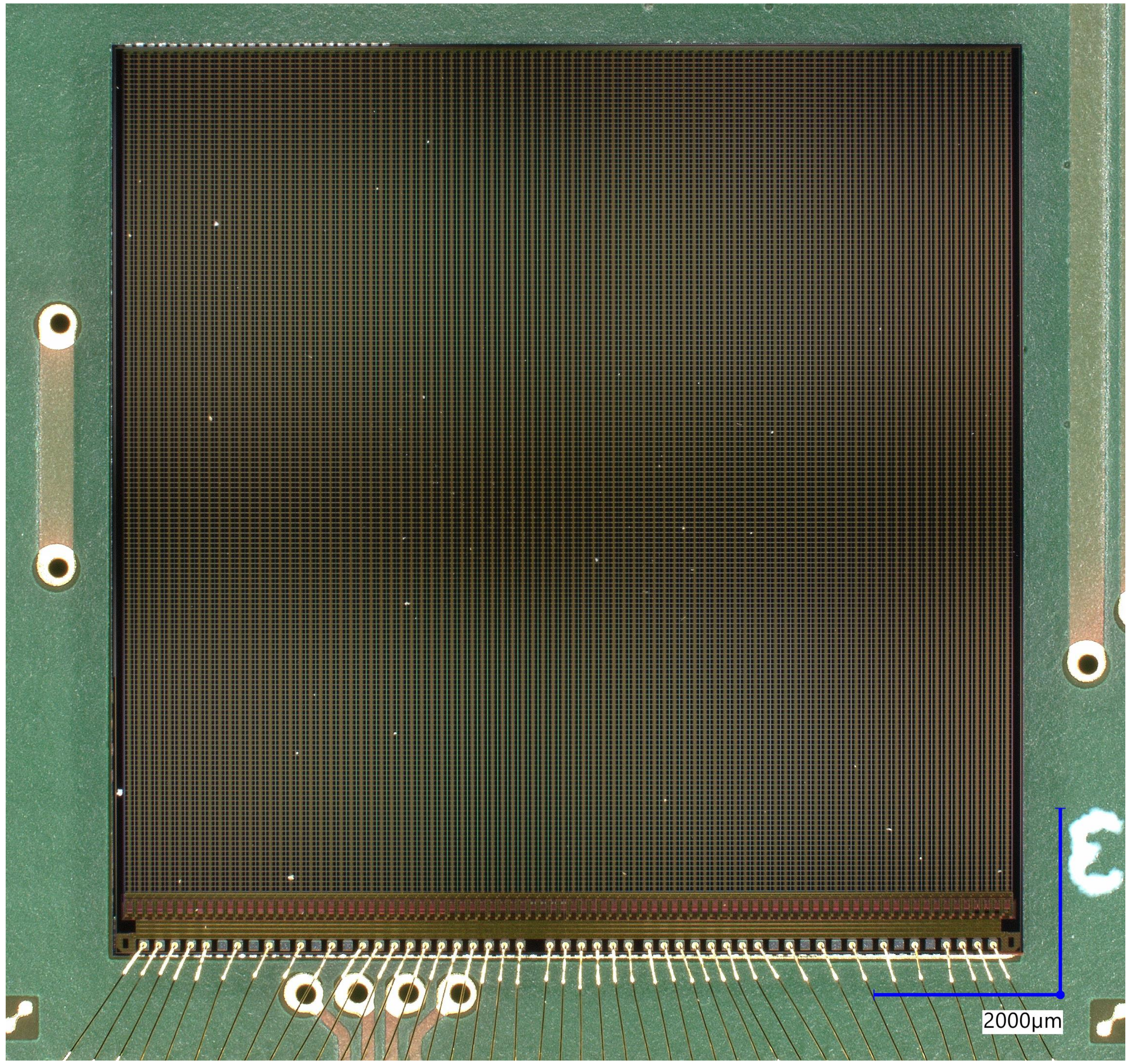
detector

Interpolating Digital Photosensor 4 (IDP4, by ZITI in Heidelberg)

- *IDP4*: CMOS-SPAD-based photodetector developed at ZITI (Uni Heidelberg) [6.]
- 9.7 × 9.7 mm² (176 × 166 = 29.2 k SPADs)
- 52 % fill factor (active area)
- pixel: 54 × 54 µm²



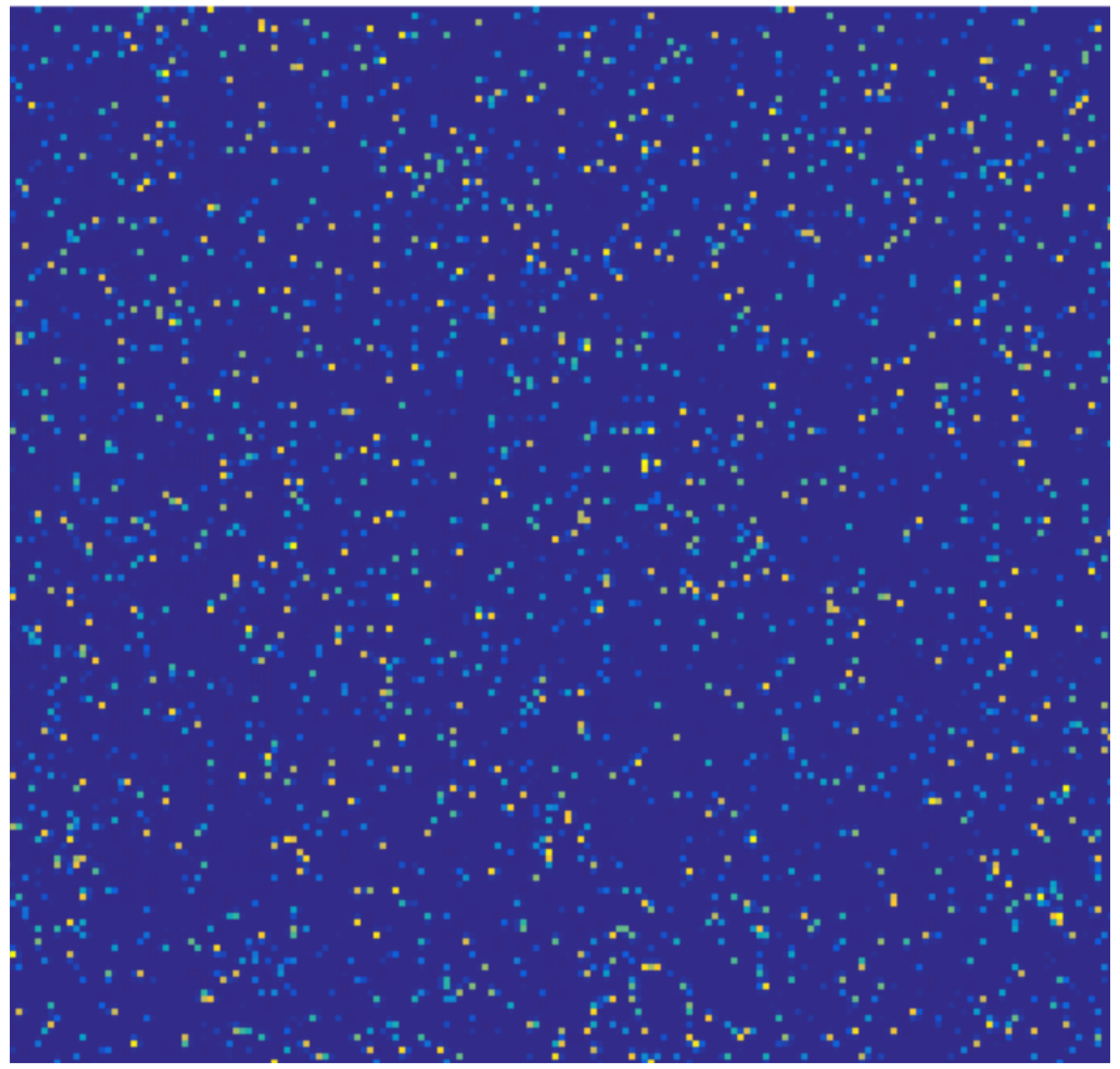




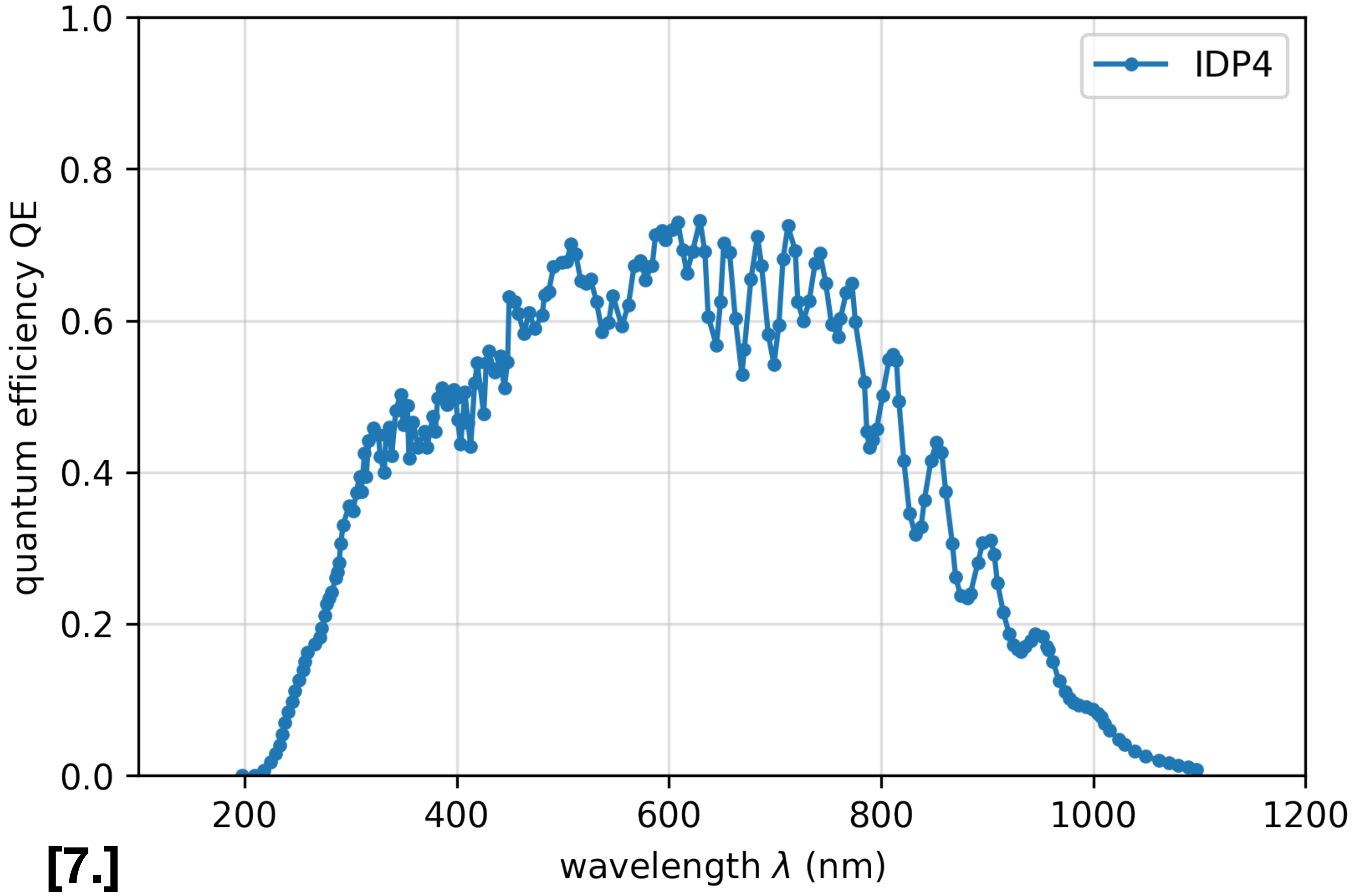
detector

CMOS-SPAD-based IDP4

- single-photon detection with $\mathcal{O}(10\,\mathrm{ns})$ scale time resolution
- spatial information (pixel size):
  - reconstruction of local events
  - discrimination from noise
- binary (`I/O`) serial array readout
- low noise achievable



accumulated noise of hot SPADs

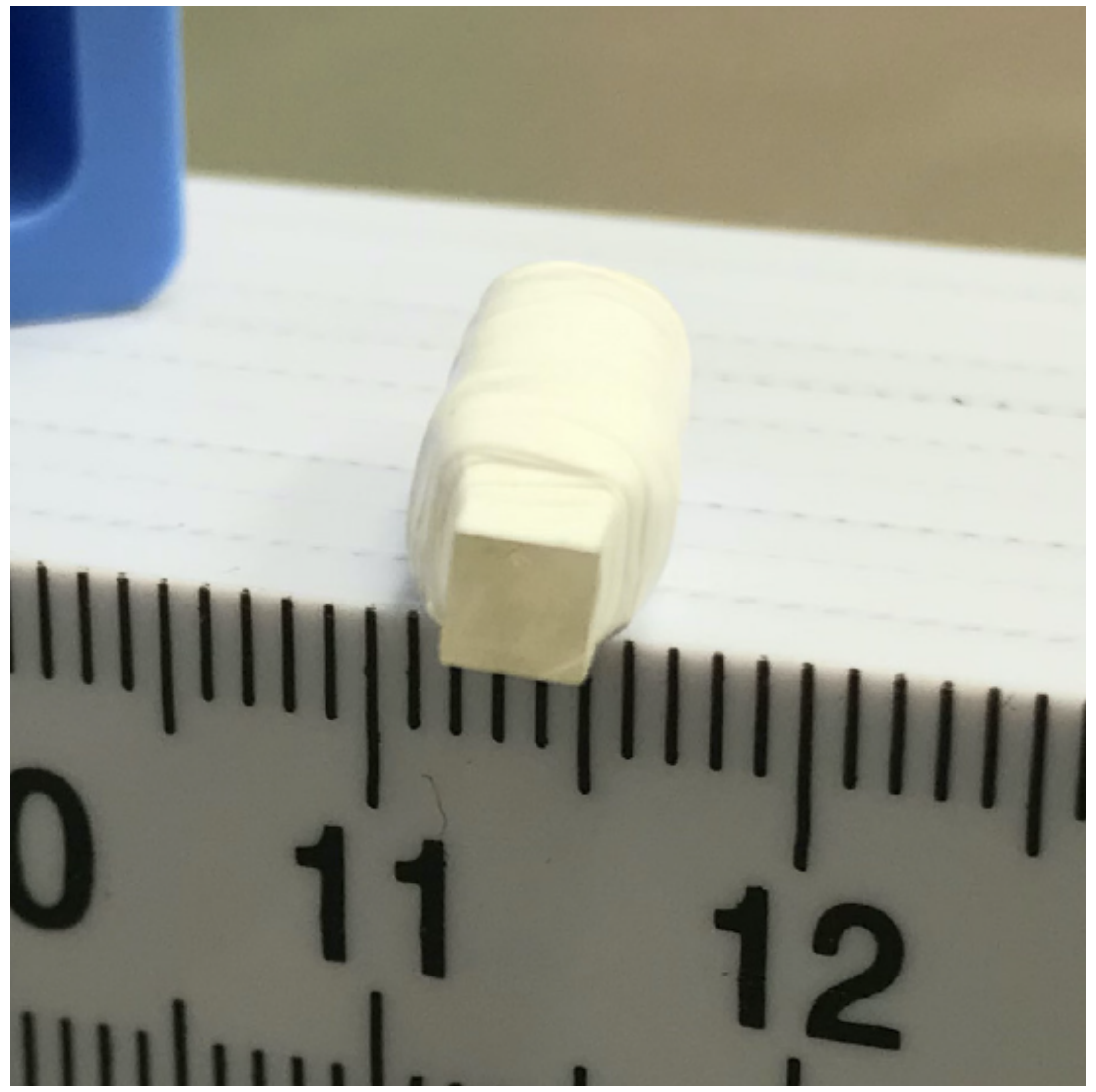


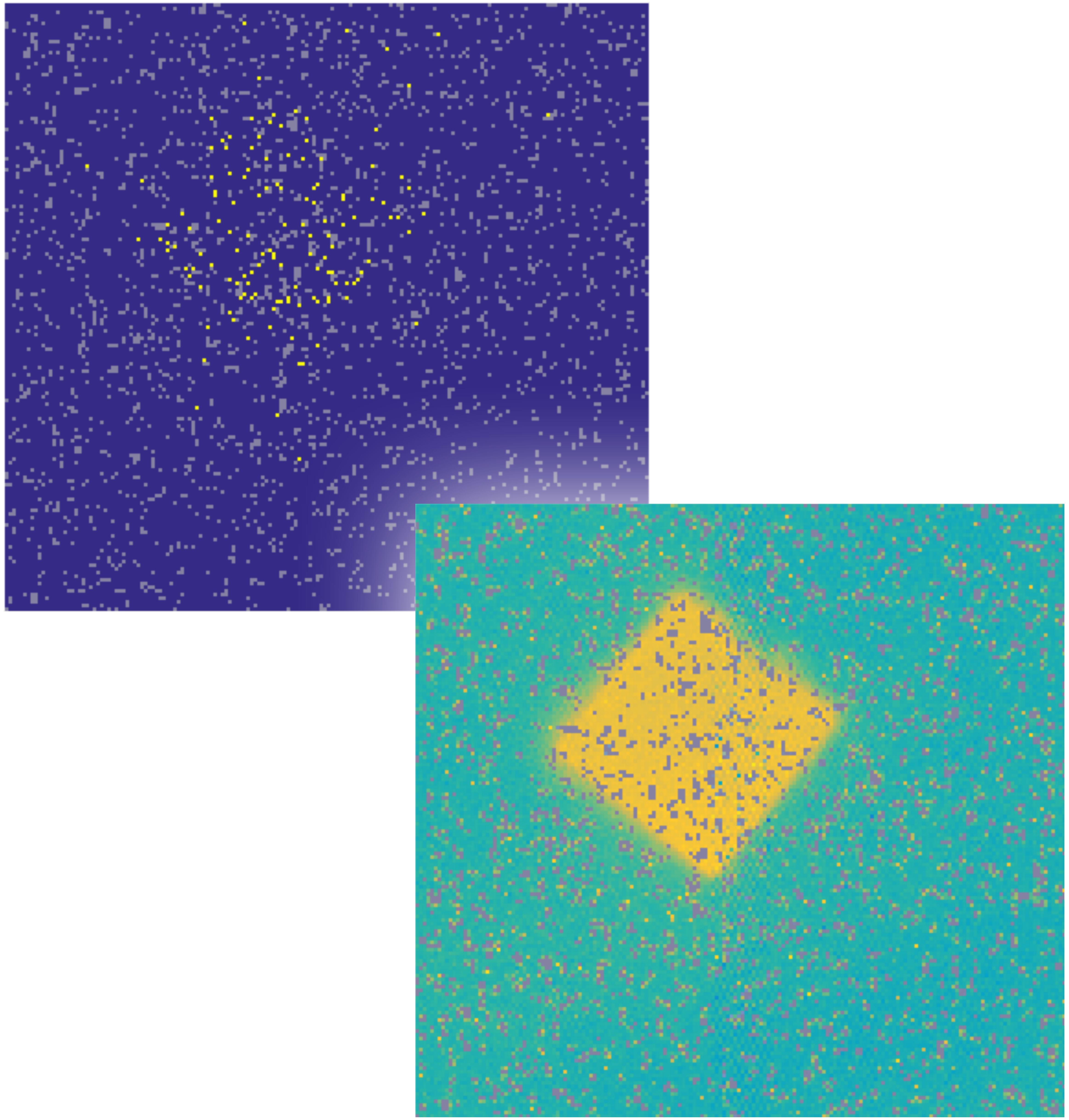
[7.]

photon detection

imaging scintillation events

- *LYSO*: Lutetium-yttrium oxyorthosilicate crystal (Ce-doped) = anorganic scintillator
- naturally 2.6 % ^{176}Lu ($\rightarrow \beta^{-} + {}^{176}\mathrm{Hf}^{*} \rightarrow \gamma$s) = intrinsic scintillation

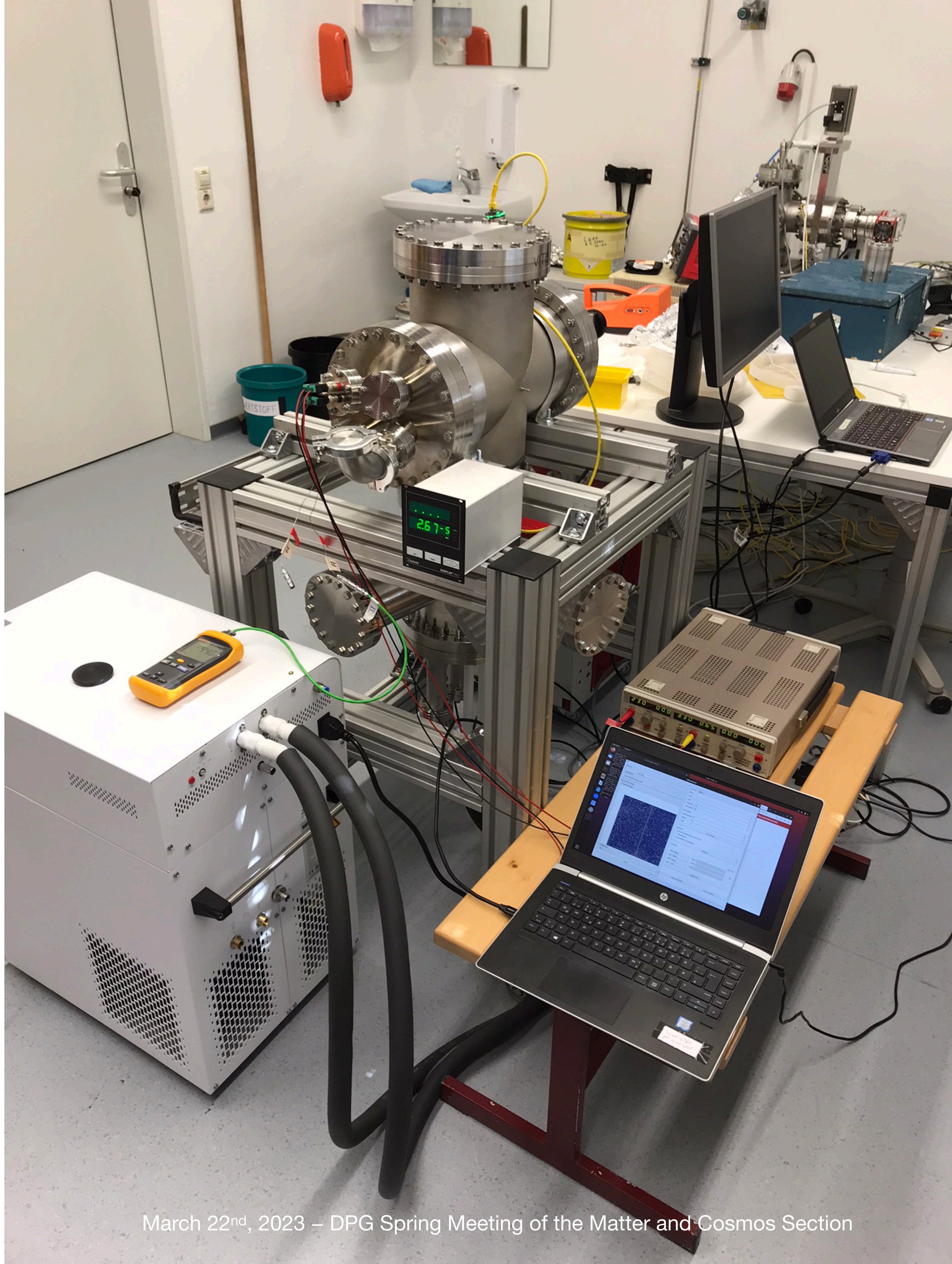




test setup

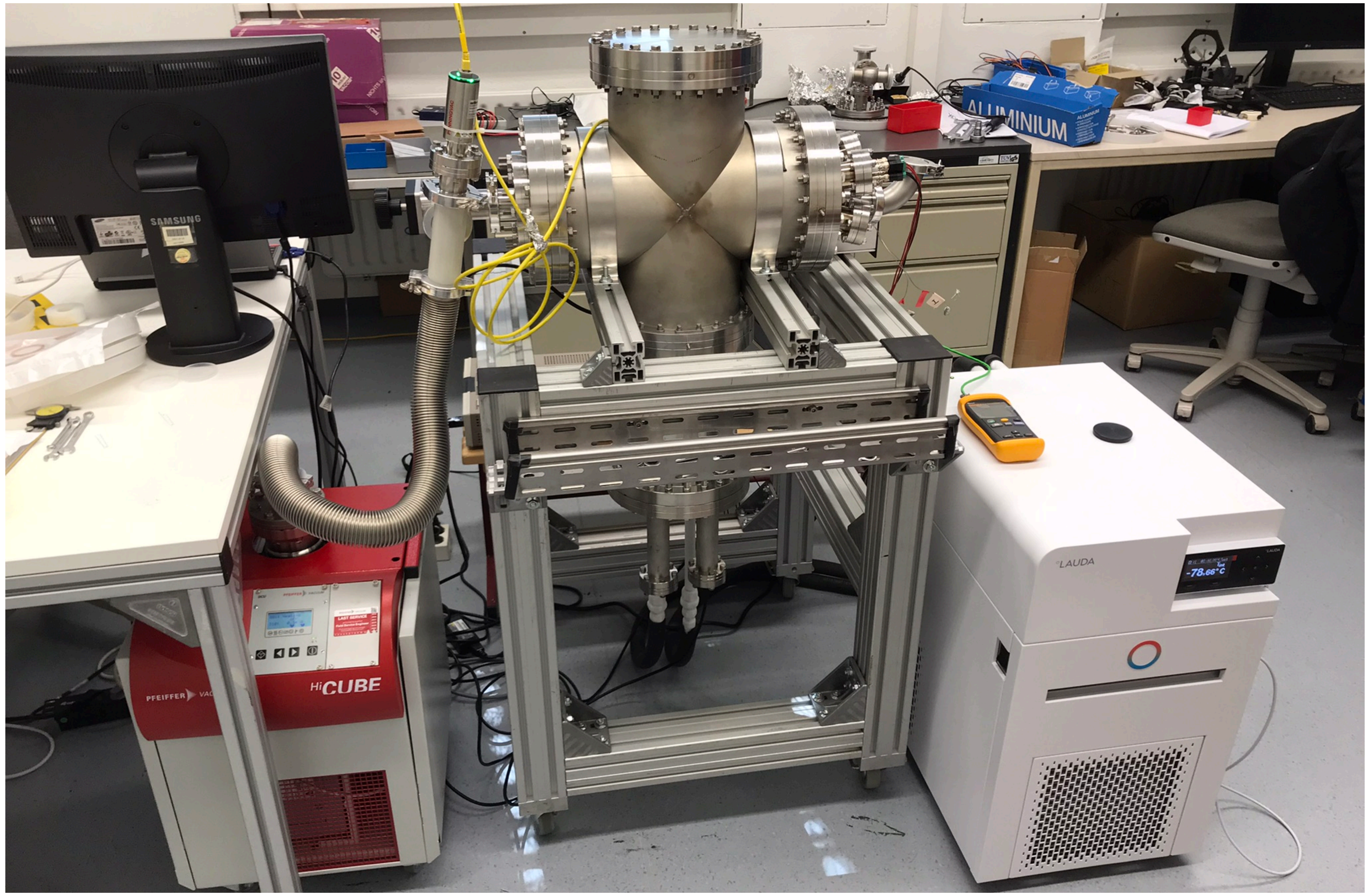
low-noise SPAD operation

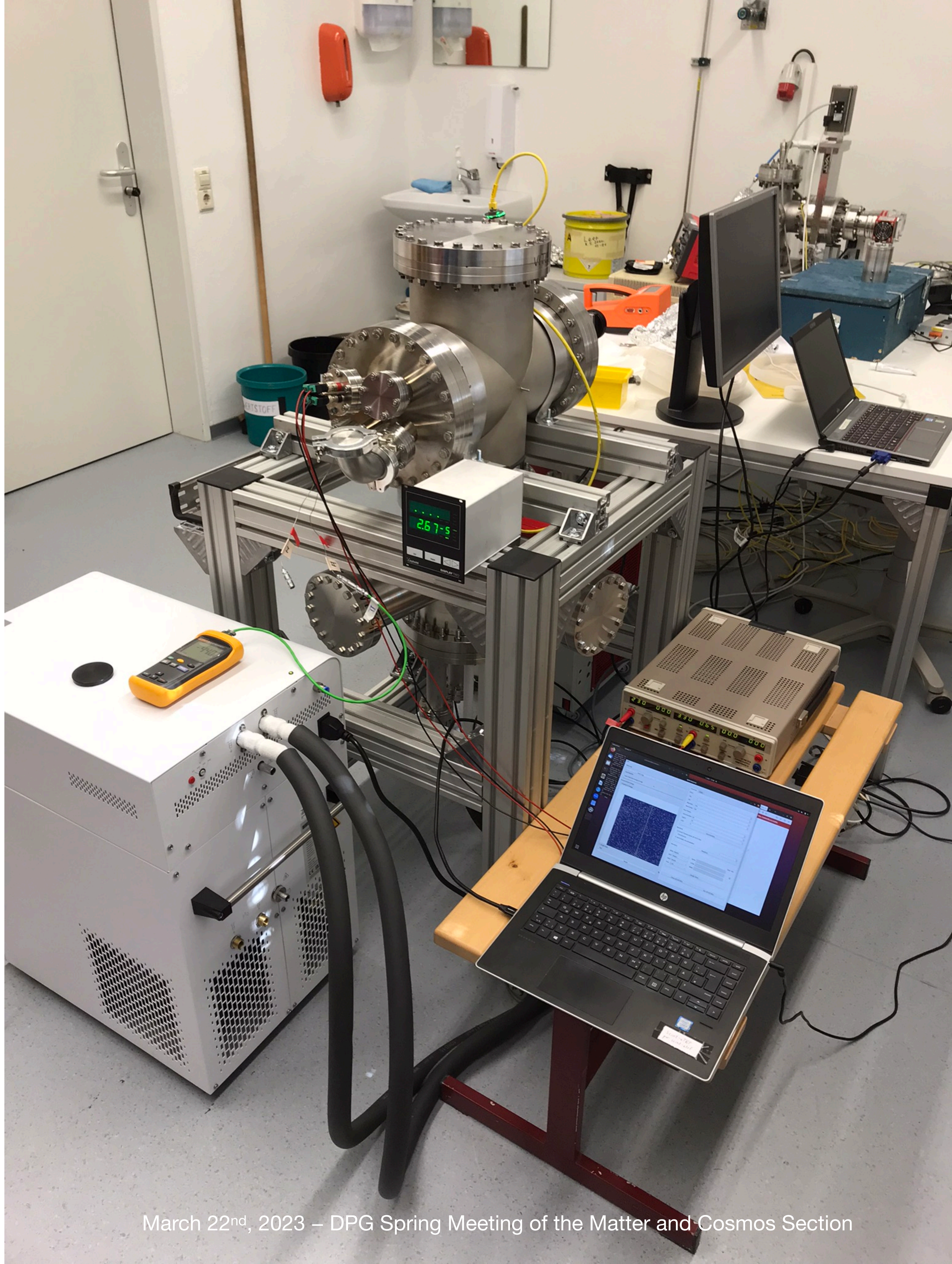
- coolable setup for measurements with the IDP4
- absolute darkness required
- USB and voltage access



test setup

low-noise SPAD operation

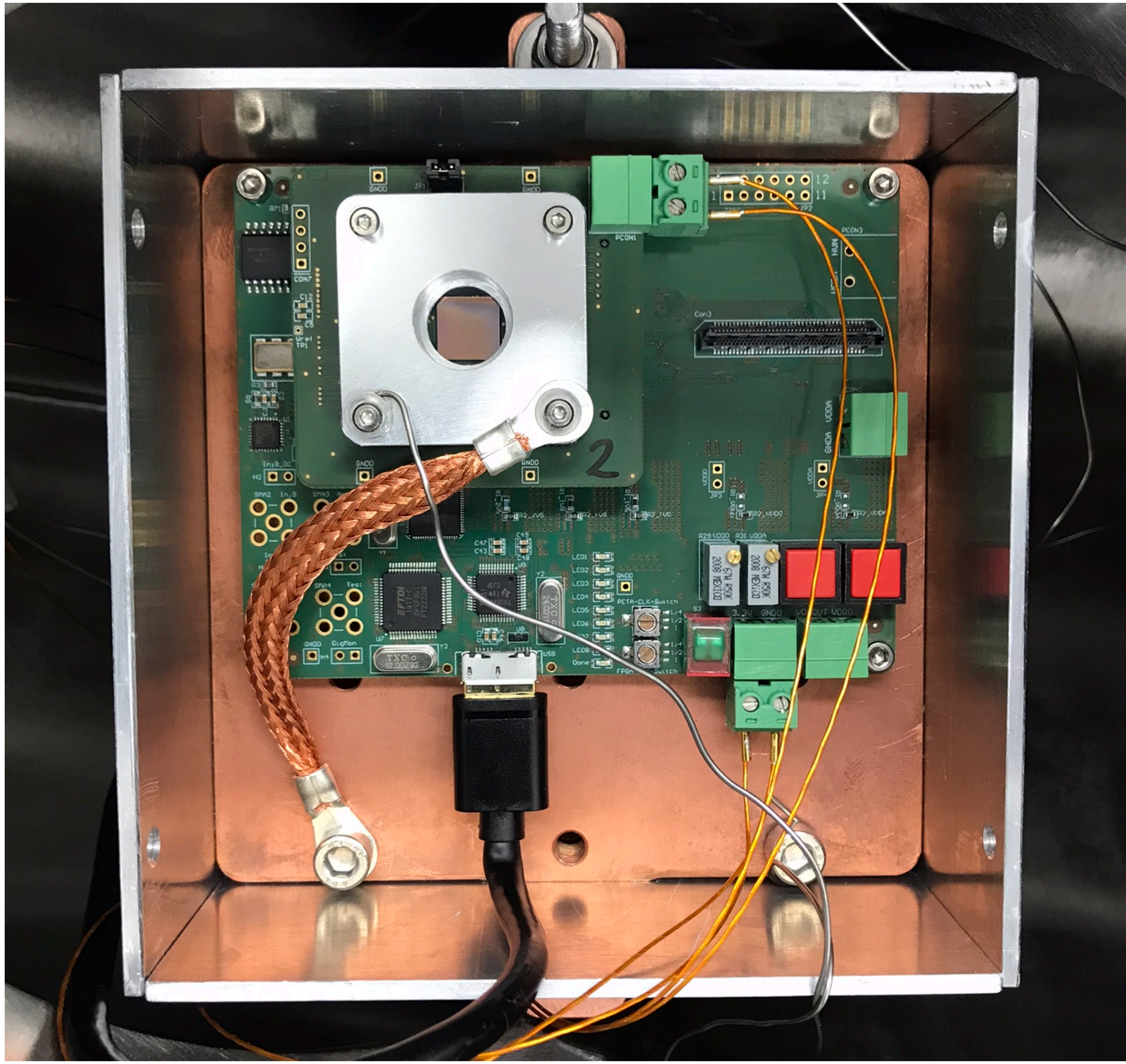




test setup

low-noise SPAD operation

- externally liquid-cooled copper block
- IDP4 PCB with cooling-coupled bulky cold aluminum cover
- cover temperature monitored (Pt100)
- temperatures down to approx. –50°C

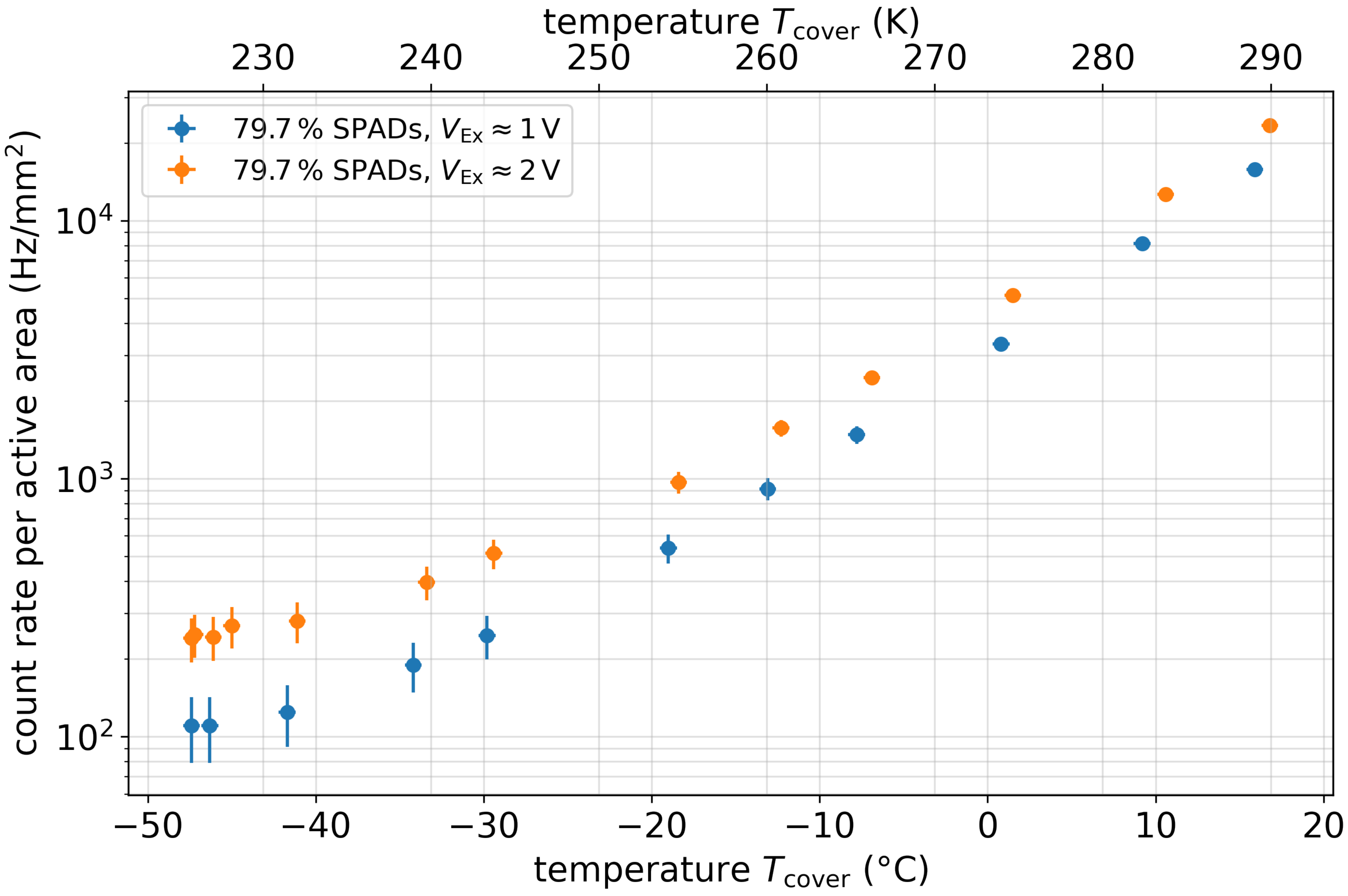


SPAD noise
measurement in setup

- hot SPADs are disengaged at RT
- bias voltage V_{bias} is adjusted at every temperature:

$$V_{bias} = V_{BD}(T) + V_{Ex}$$

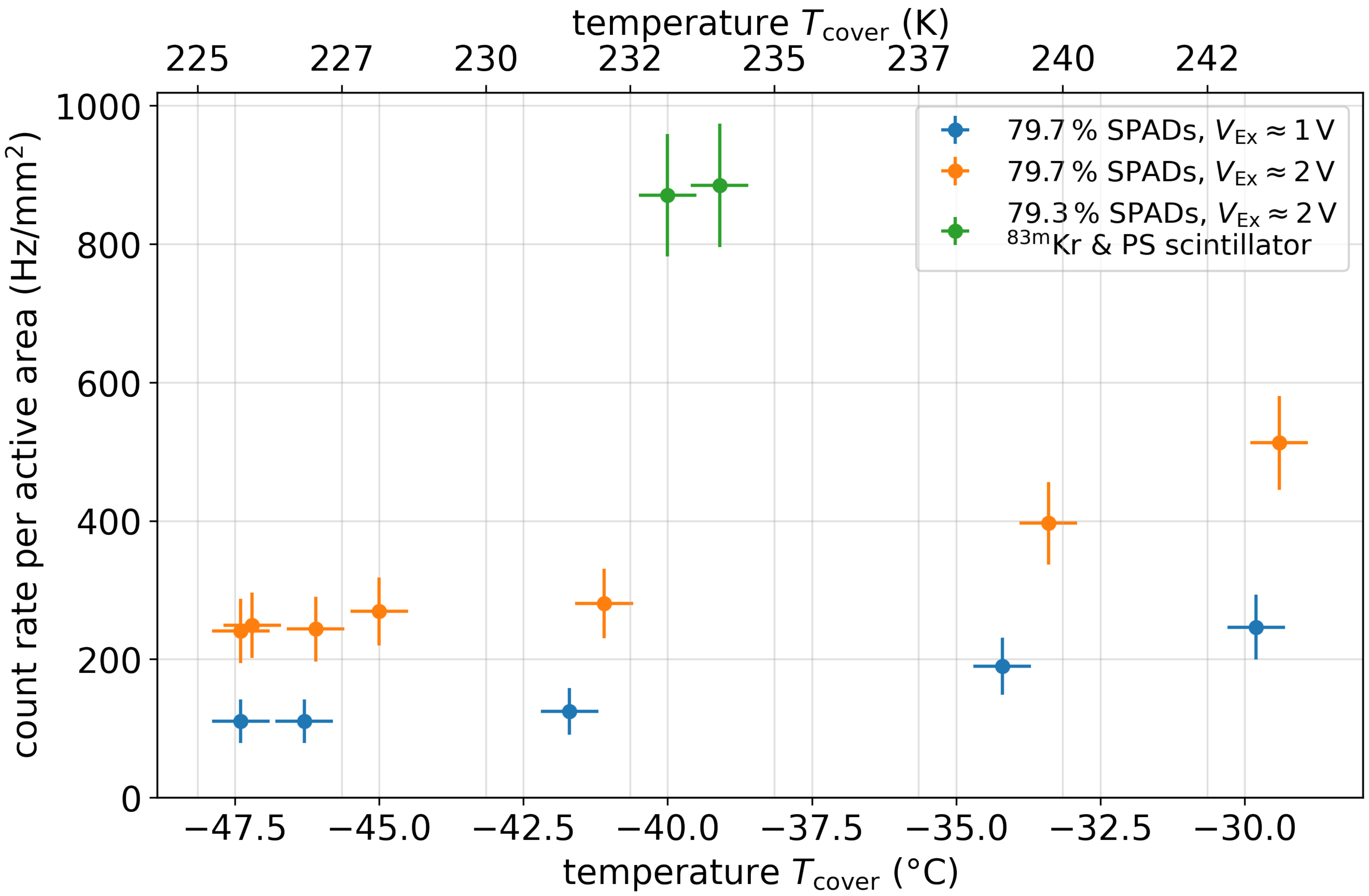
- excess voltage (GEIGER regime) V_{Ex} = const.
- noise can be further reduced by triggering strategies (on event multiplicity)



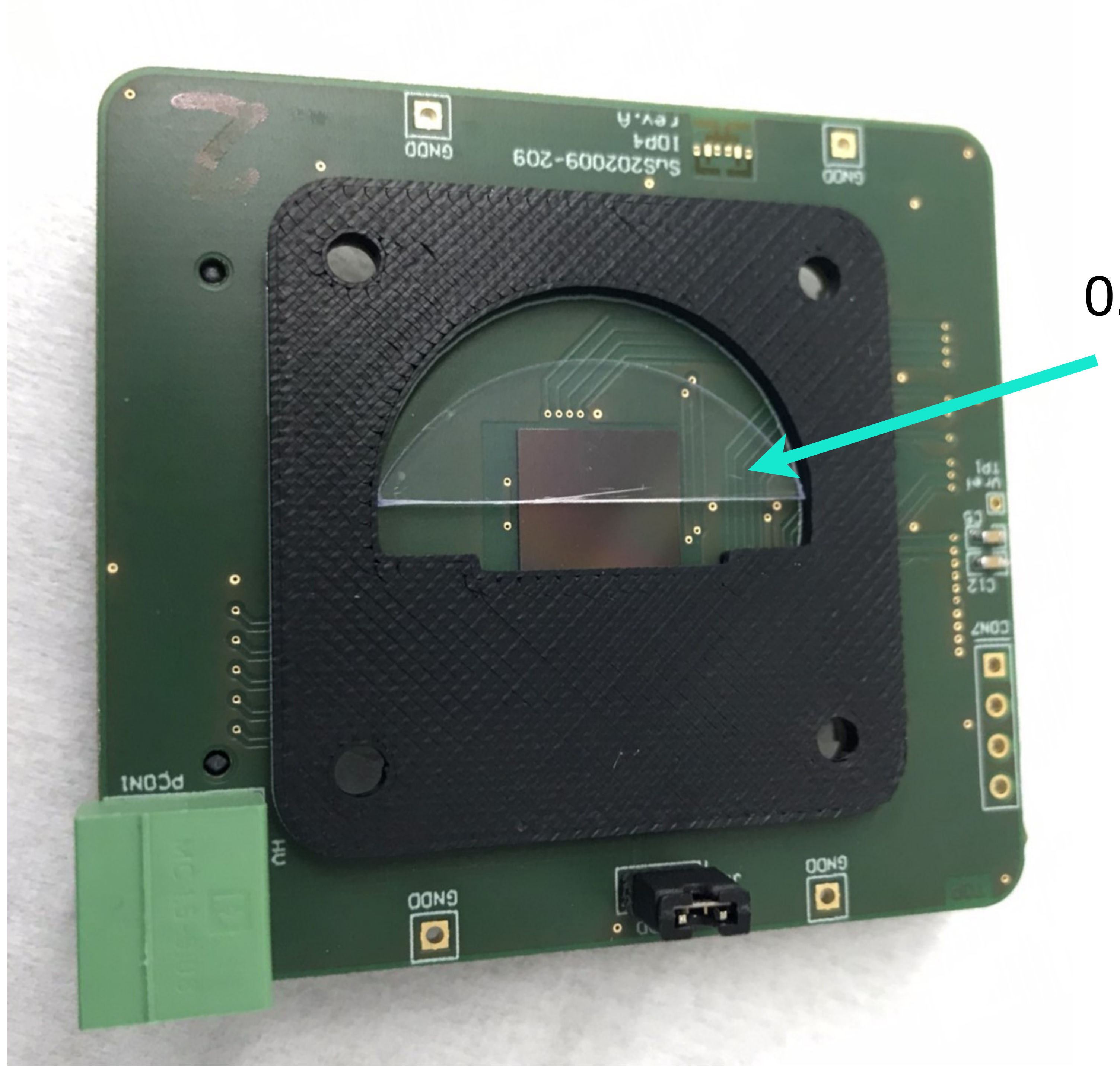
first light

PS + ^{83m}Kr scintillation

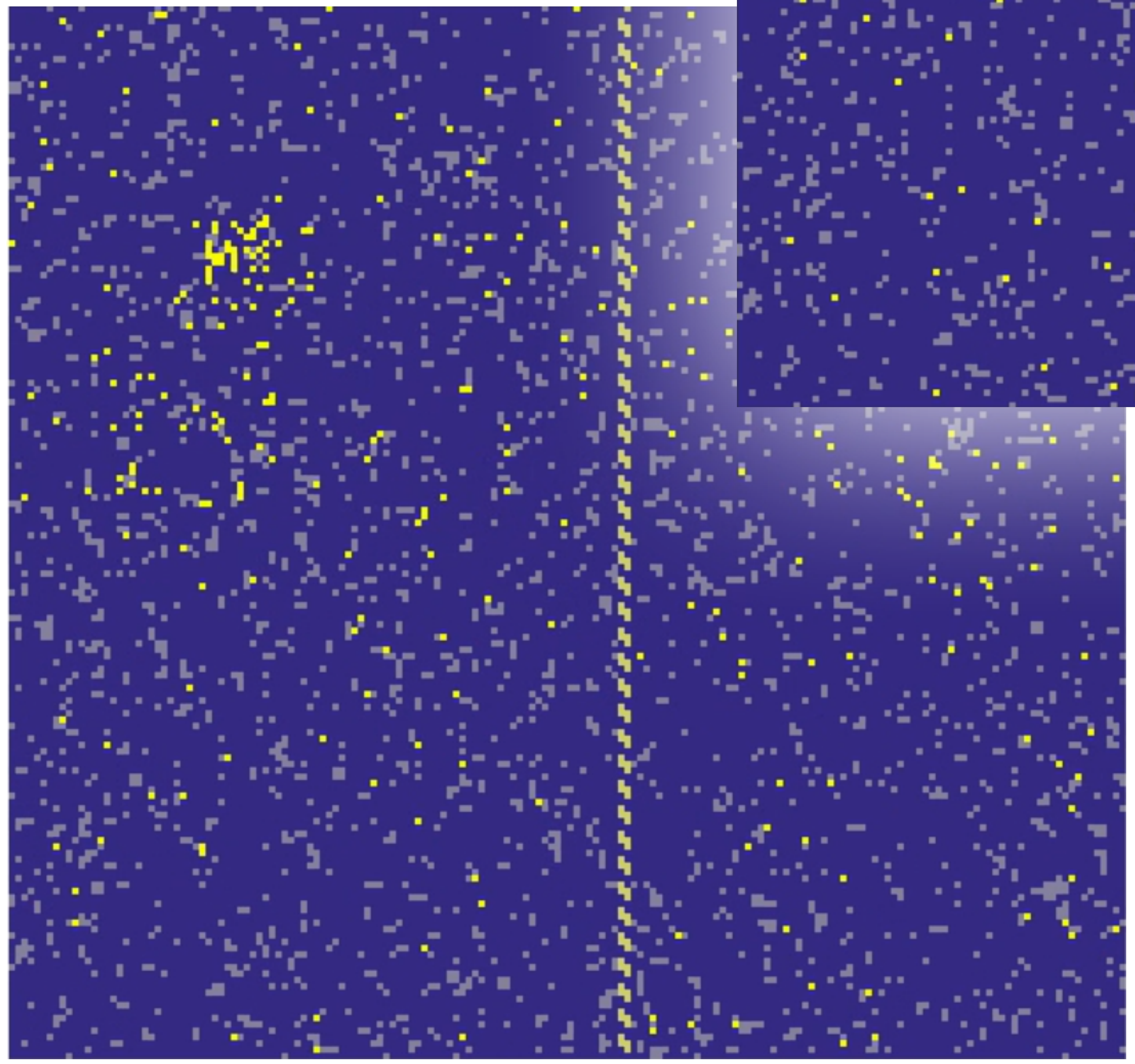
- 0.5 × 7 × 8 mm³ PS plastic scintillator plate (Epic Crystal)
- 1 mm above chip
- irradiation: ~0.55 MBq ^{83m}Kr source
- ^{83m}Kr: O(10 keV) electrons
- excess of roughly 600 Hz/mm²
- implications for scint-aTEF in terms of e.g. electron detection efficiency? → simulations

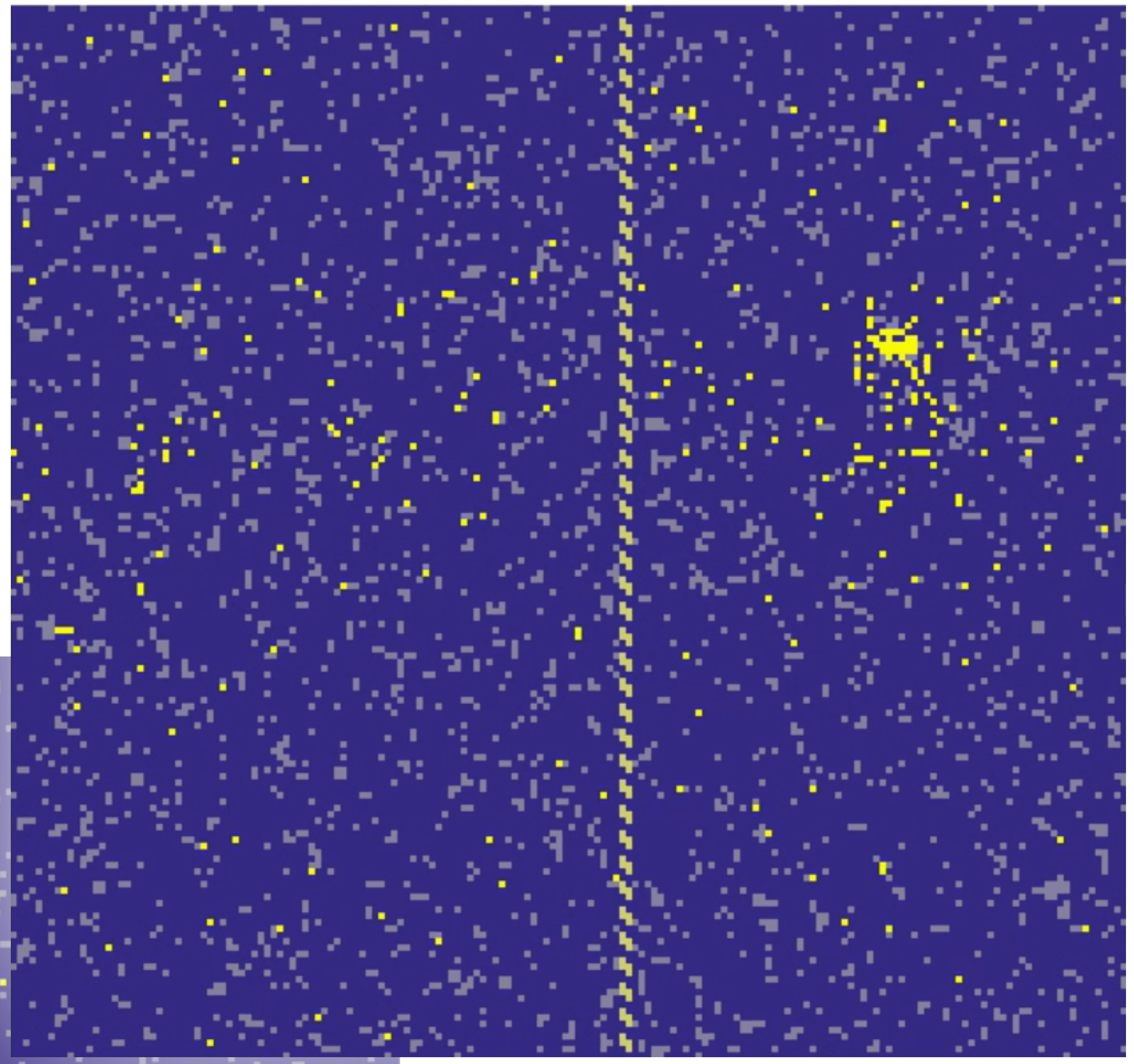


PS + ^{83m}Kr: single scintillation events



0.5 mm thick PS plastic scintillator plate





- same measurement with direct contact (no gap) and partial IDP4 coverage
- single scintillation events resolved

summary & outlook

scintillating active Transverse Energy Filter (scint-aTEF)

- detector concept *scint-aTEF*: angle-dependent background discrimination in KATRIN-like setups
- scint-aTEF is a device for precise electron counting via scintillation
- *digital SiPMs* (CMOS-SPAD-based photosensor arrays): outstanding candidates for our purpose of single-photon detection and spatial event reconstruction
- first observation of thin plastic plate scintillation by keV electrons using the digital SiPM *IDP4*
- aim: investigation of single scintillation events and extension of corresponding simulation environment
- future: characterization of homemade scintillator samples and microstructures

acknowledgements

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references

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3. Karlsruhe Institute of Technology, KATRIN: *Backside of wafer with segmentation*. https://www.katrin.kit.edu/681.php, visited on March 21st, 2023.
4. J. Weinacker *et al.*: *2PP microgrid samples manufacturedd with Quantum X.* Institute of Applied Physics (APH), Karlsruhe Institute of Technology. November 2021.
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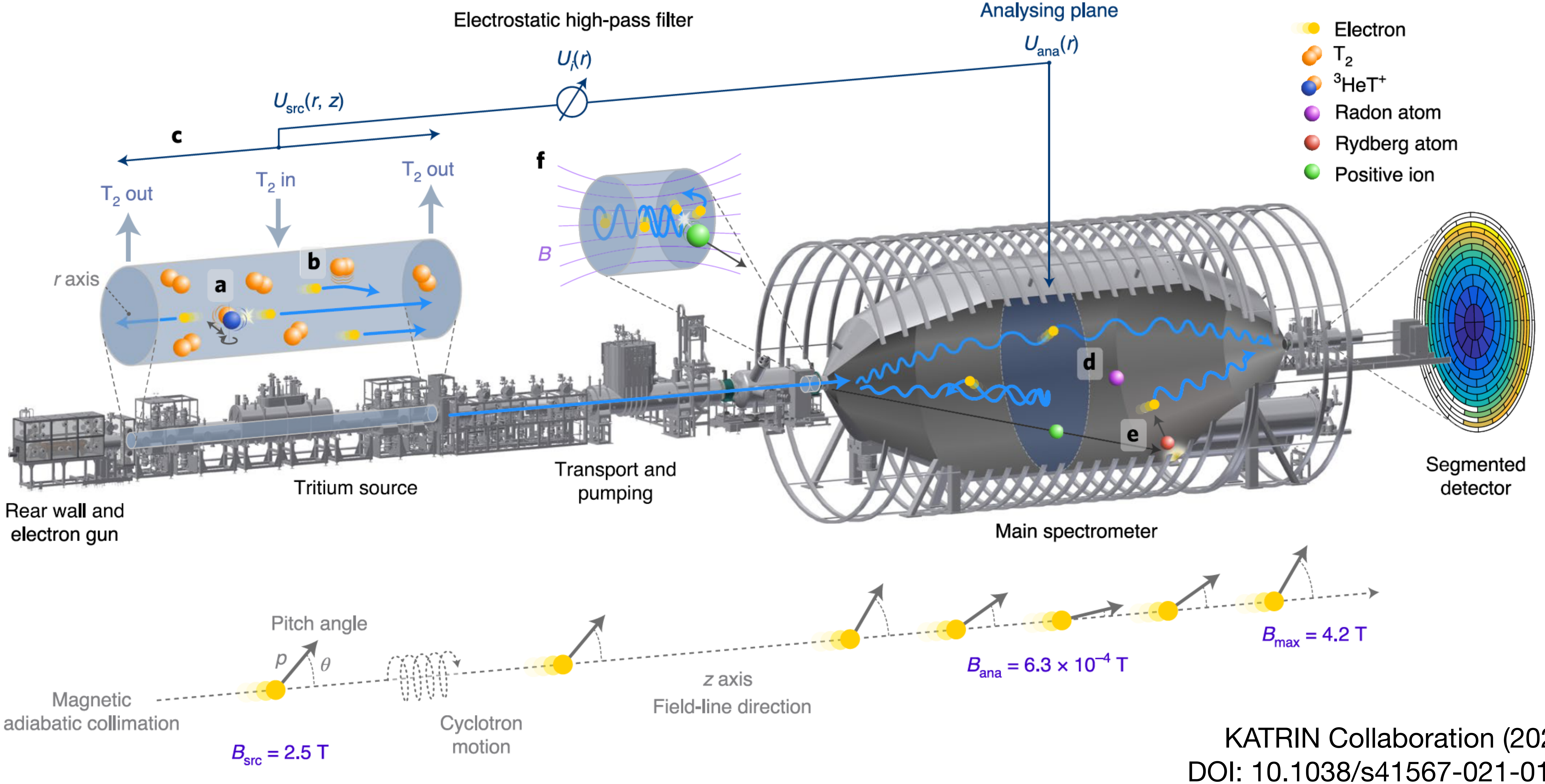
6. P. Fischer: *ASICs for Photon Detection Integrating Avalanche Diodes and CMOS Readout*. In 14th Terascale Detector Workshop 2022. Institute of Computer Engineering (ZITI), Heidelberg University. February 2022.
7. M. Ritzert: *Personal communication*. Institute of Computer Engineering (ZITI), Heidelberg University. February 2023.
8. M. Keller: *Design and low temperature characterization of low noise single photon detector arrays for rare event search experiments with liquid noble gases*. PhD thesis, Heidelberg University. July 2022.

backup

KATRIN setup



KATRIN Collaboration (2022):
DOI: 10.1038/s41567-021-01463-1

magnetic adiabatic guiding in KATRIN

$$\theta(\vec{r}) = \arcsin\left(\sqrt{\frac{E(\vec{r}_0)}{E(\vec{r})}\,\frac{|\vec{B}(\vec{r})|}{|\vec{B}(\vec{r}_0)|}}\,\sin(\theta_0)\right)$$

$$\theta_{\mathrm{max}} = \arcsin\left(\sqrt{\frac{B_{\mathrm{s}}}{B_{\mathrm{max}}}}\right) = 50.77^\circ$$

electron cyclotron motion in KATRIN

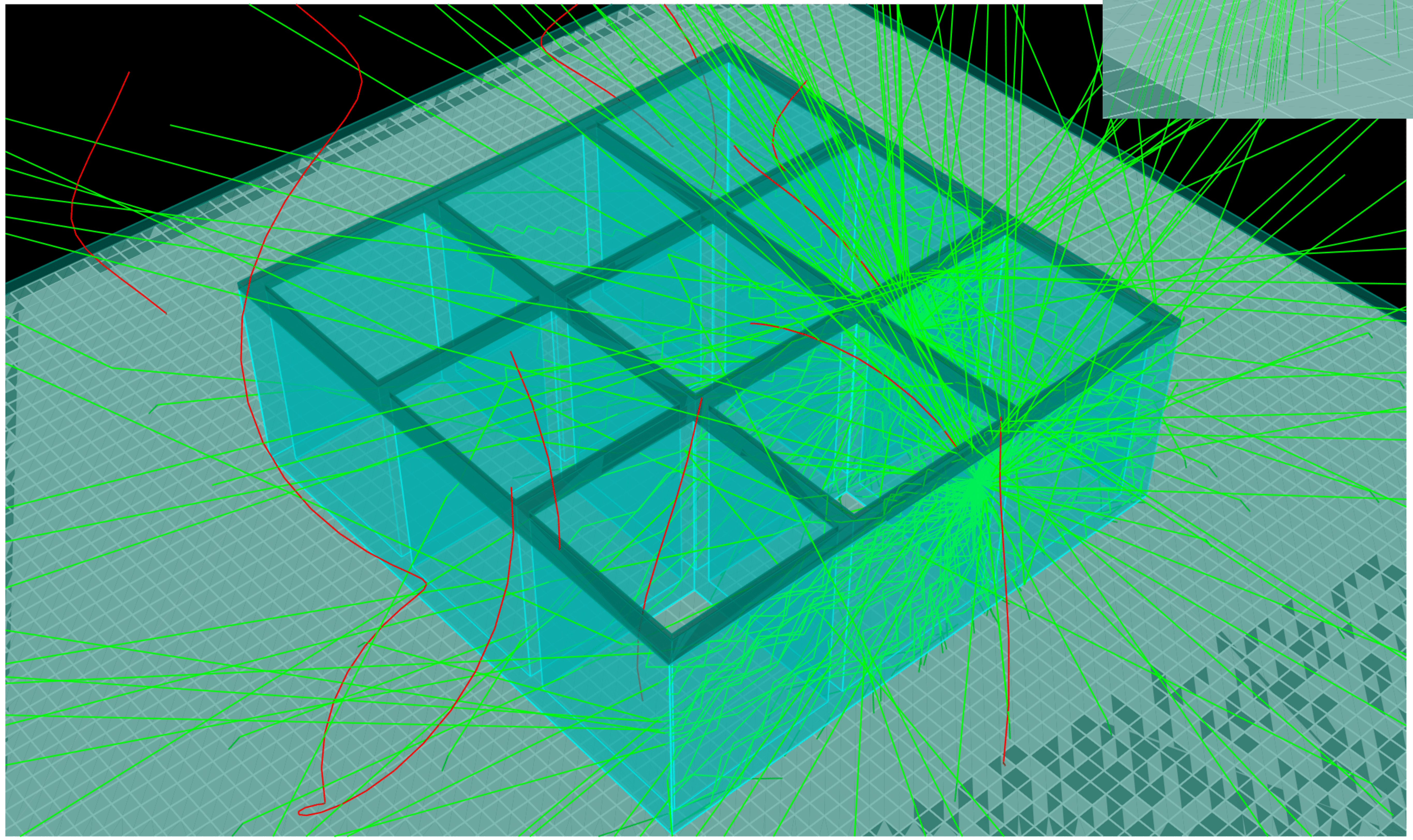
$$r_g(\theta, B, U_0) = \frac{\gamma}{e}\sqrt{e|U_0|(e|U_0| + 2m_e))}\,\frac{\sin(\theta)}{B}$$

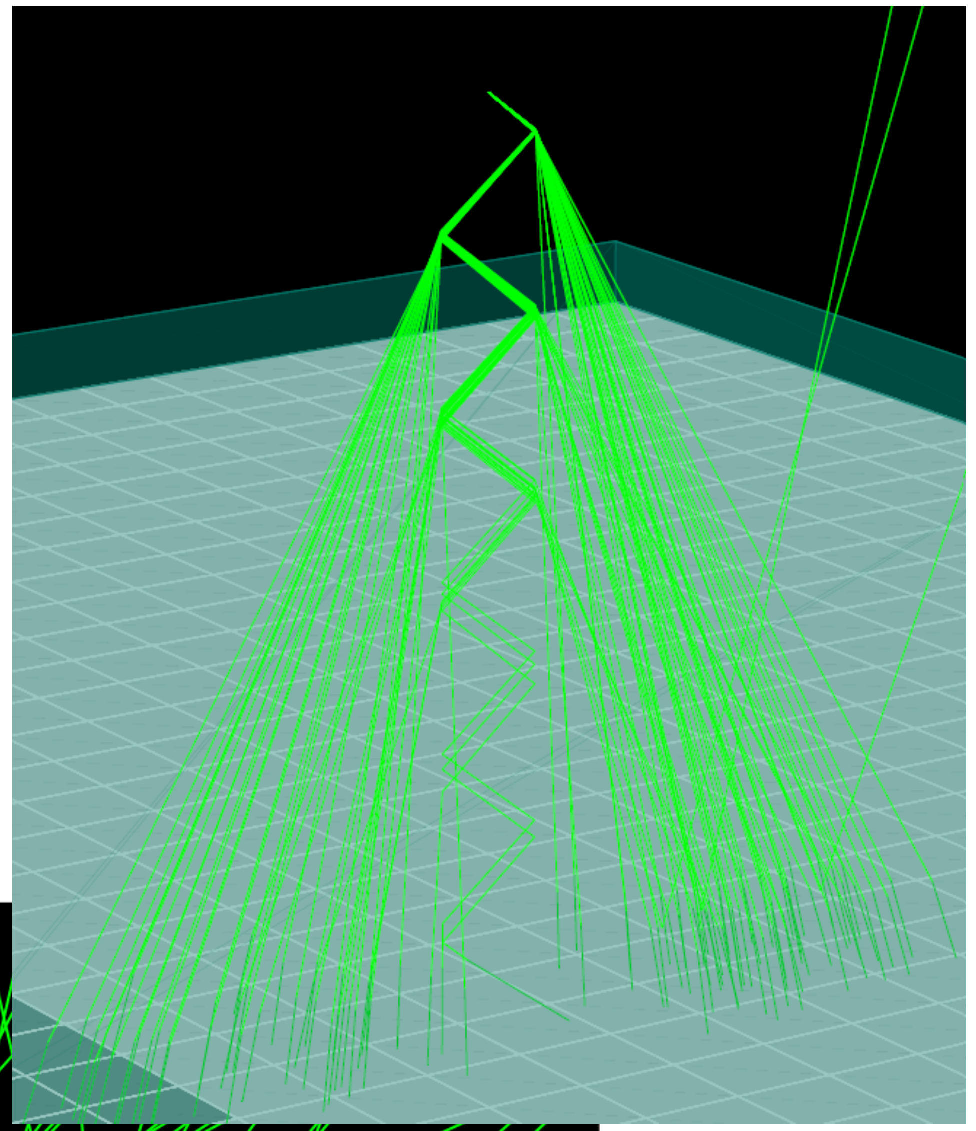
$$\ell_g(\theta, B, U_0) = 2\pi|U_0|\sqrt{1 + \frac{2m_e}{e|U_0|}}\,\frac{\cos(\theta)}{B}$$

scint-aTEF simulations

Geant4 approach

- included:
  - physics processes (scintillation, scattering,...)
  - optical properties (surface, reflection, attenuation,...)
  - homogen. *B*-field
- not included:
  - absorption & emission spectra
  - detailed electromagnetic environment



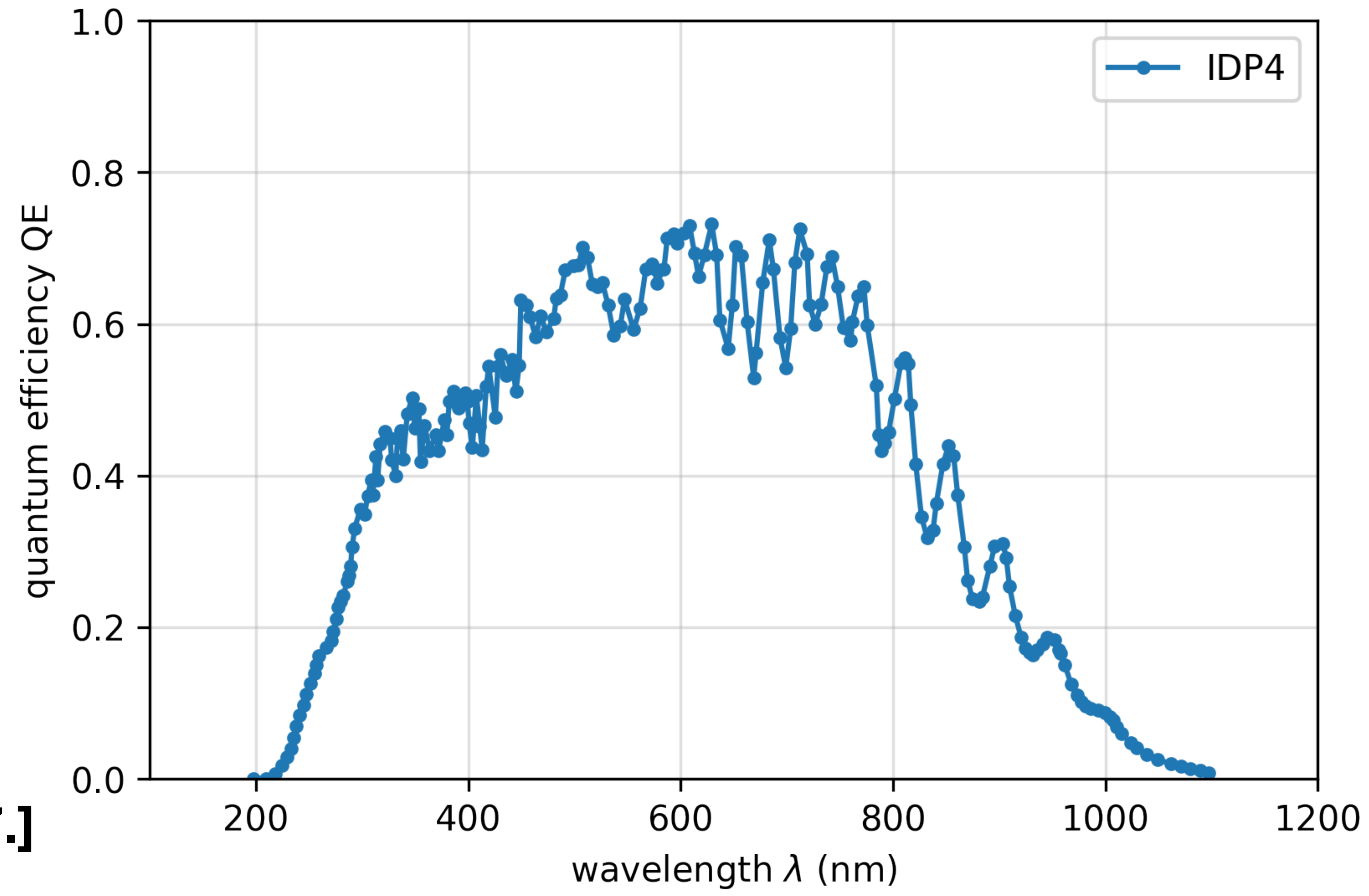


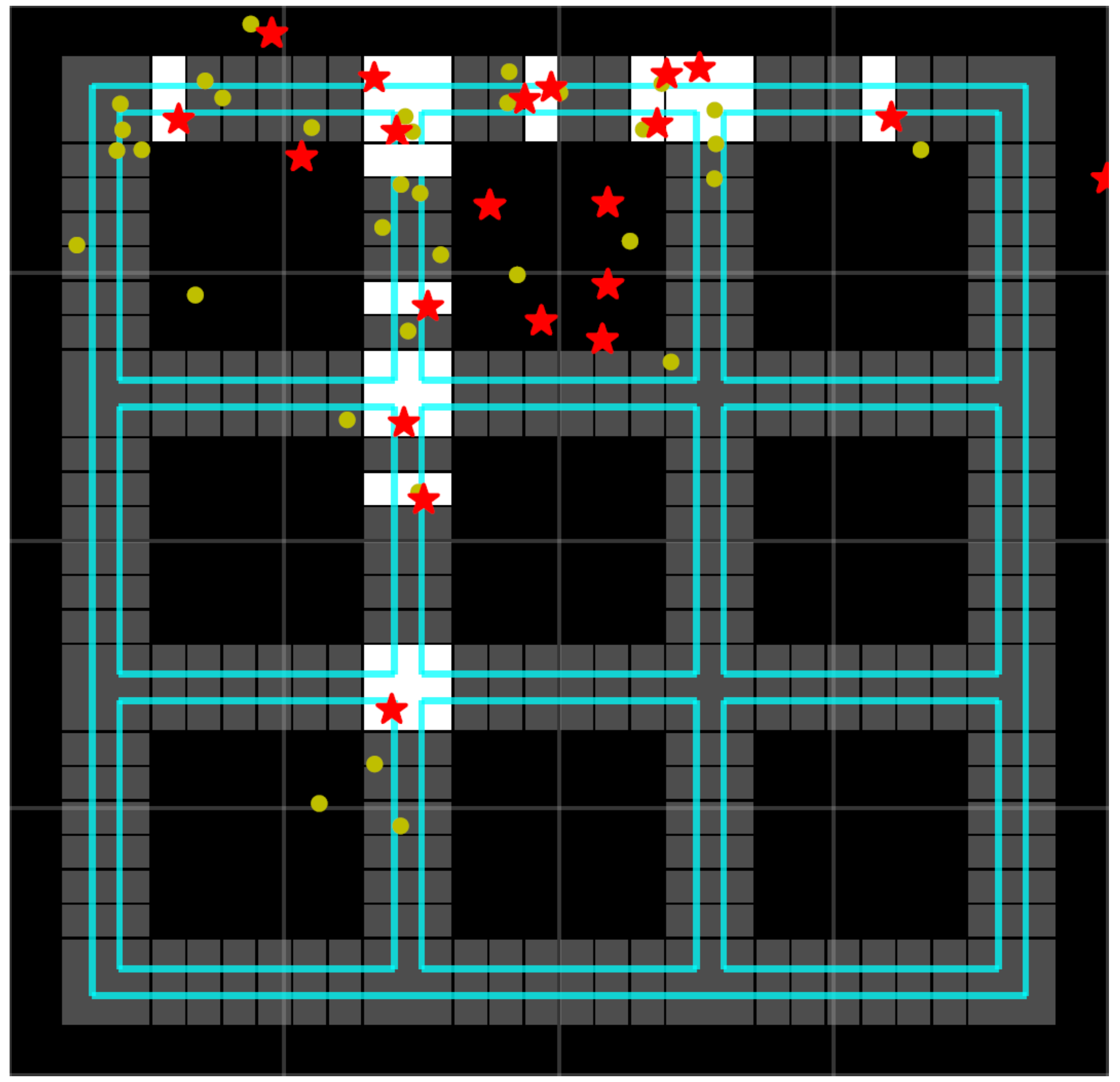
scint-aTEF simulations

setup performance & optimization

- PDE = $\varepsilon_{coll} \cdot \varepsilon_{geom} \cdot QE \cdot \varepsilon_{trig}$
- results:
  - ~50–60 % guiding/collection efficiency ε_{coll} for scintillation light (with stated parameters, s. 4)
  - >10 detected γs/signature
- optimization of β detection and signal-to-background ratio
- investigation of different trigger strategies to discriminate remaining noise

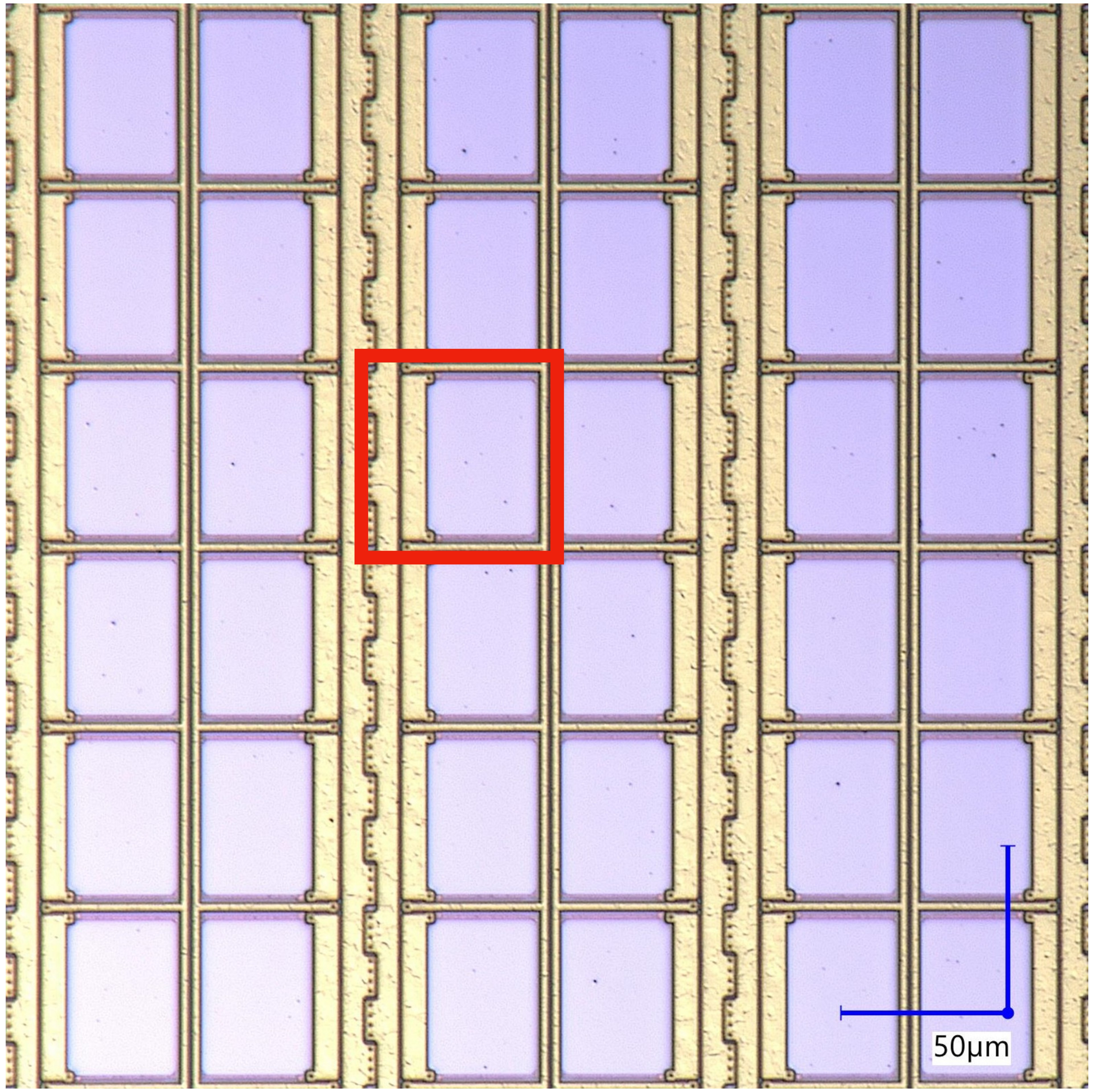
[7.]

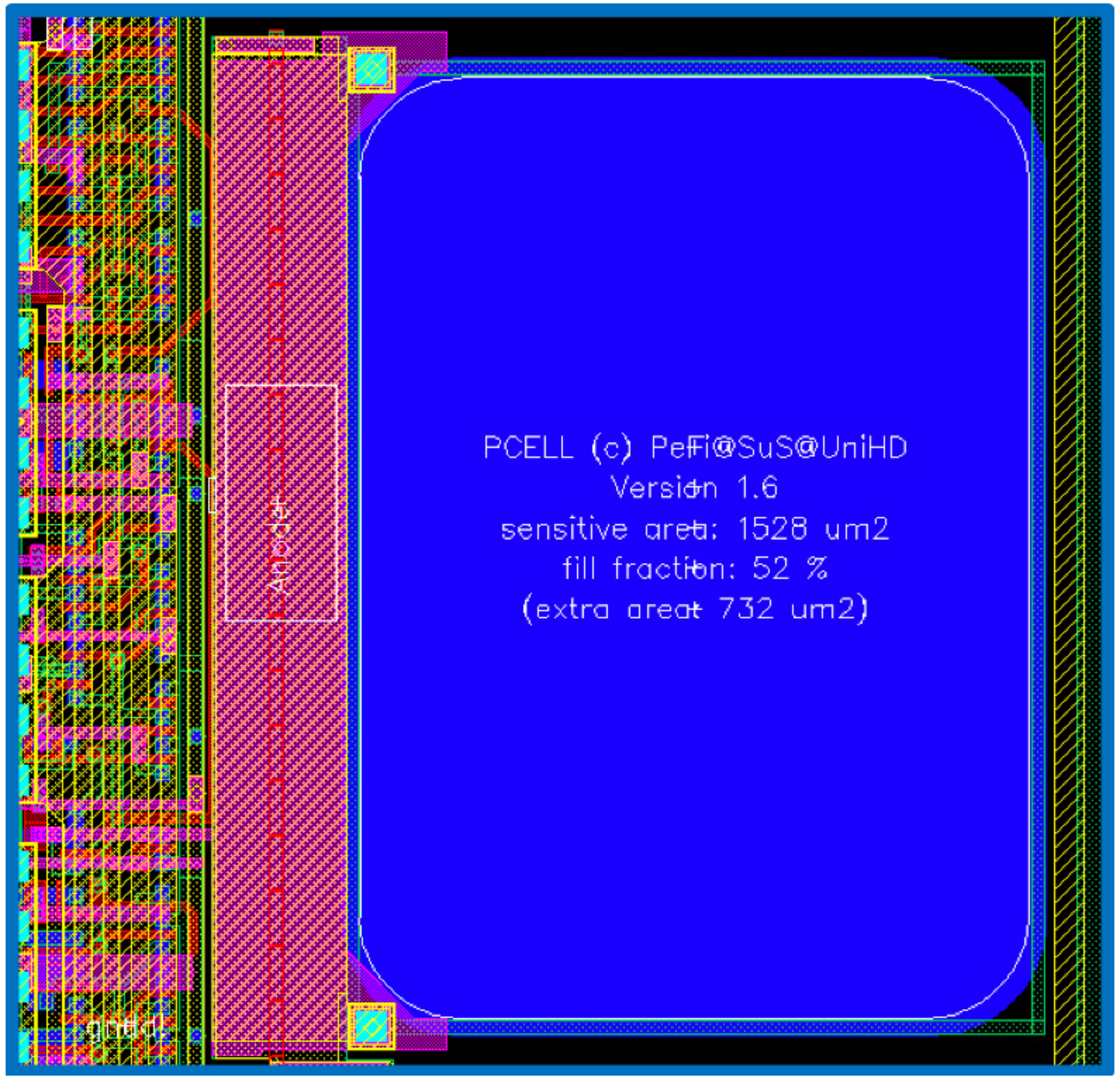




potential response

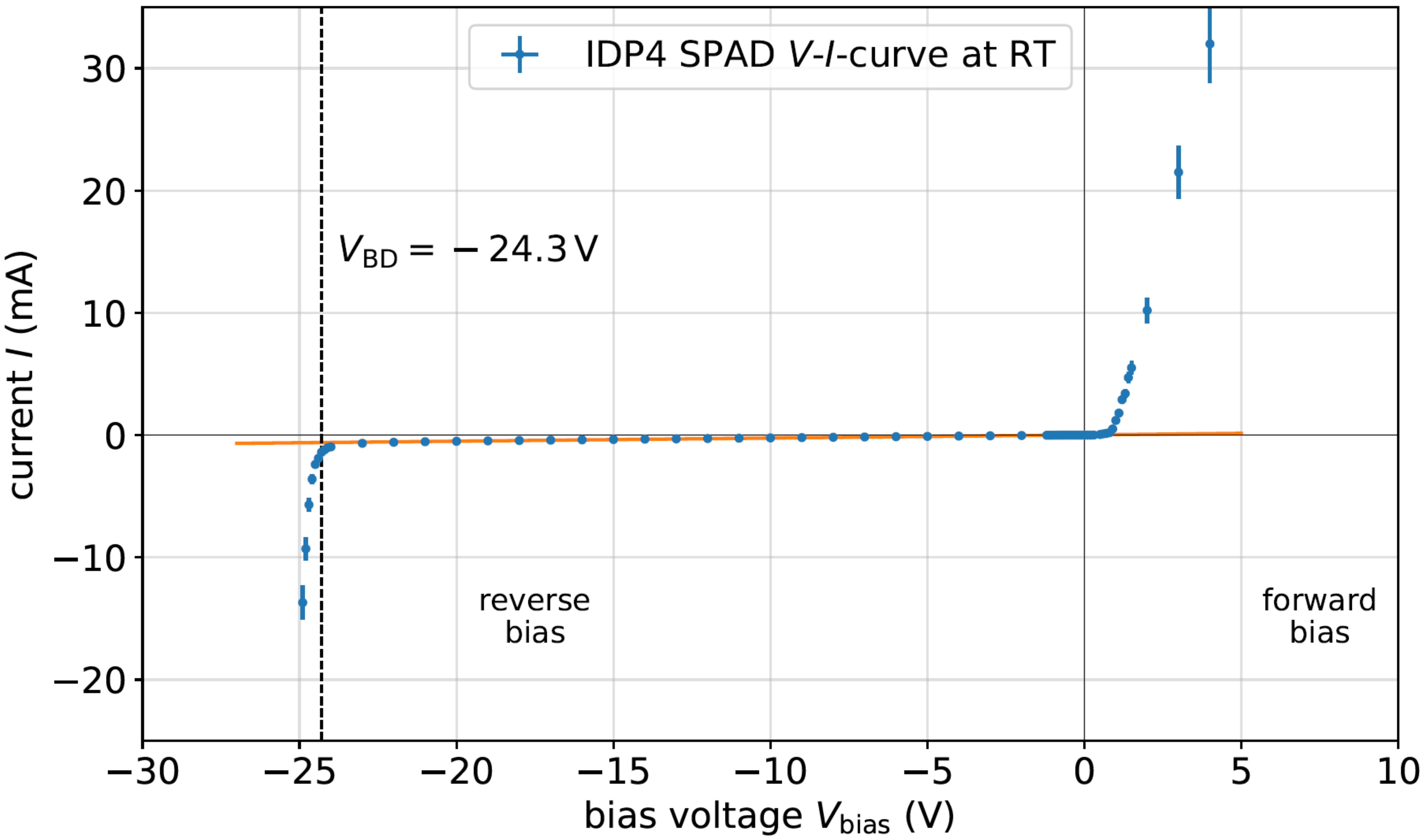
SPAD layout on the IDP4





[6.]

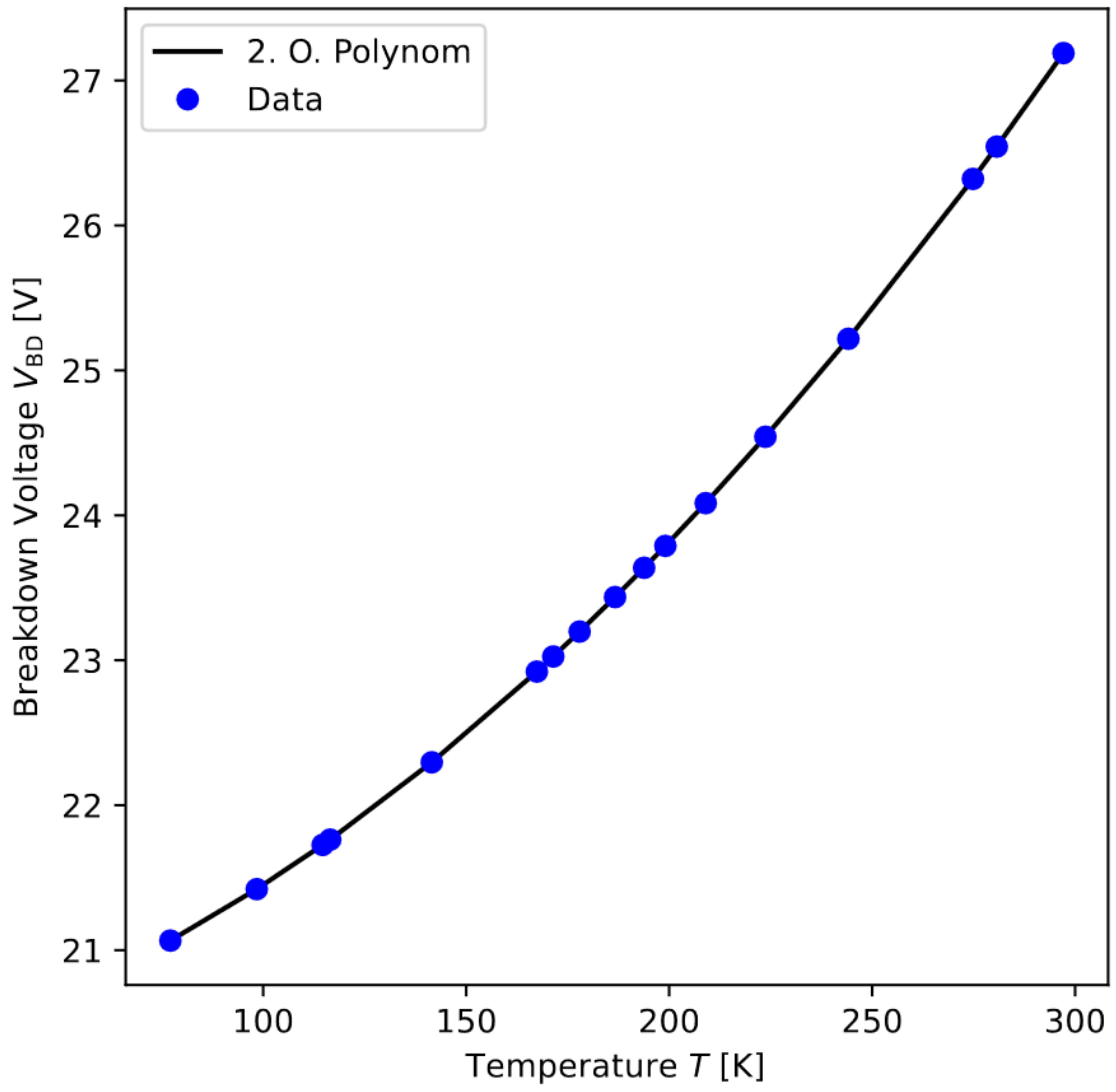
SPAD *V*-*I*-curve (IDP4)



SPAD breakdown voltage

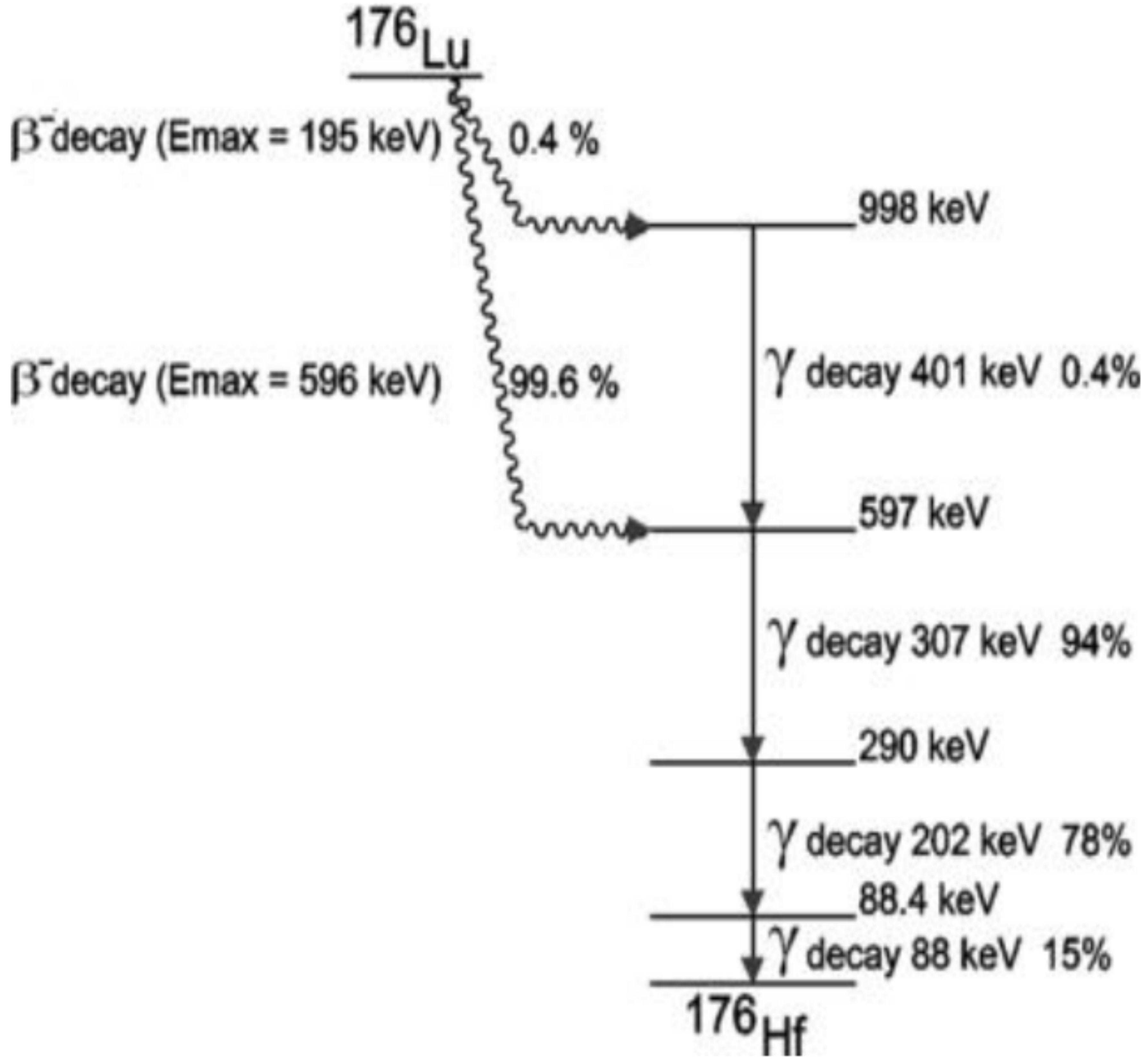
temperature dependence

- temperature dependence of IDP2 SPAD breakdown voltage V_{BD}
- IDP2: predecessor of IDP4 with different absolute values



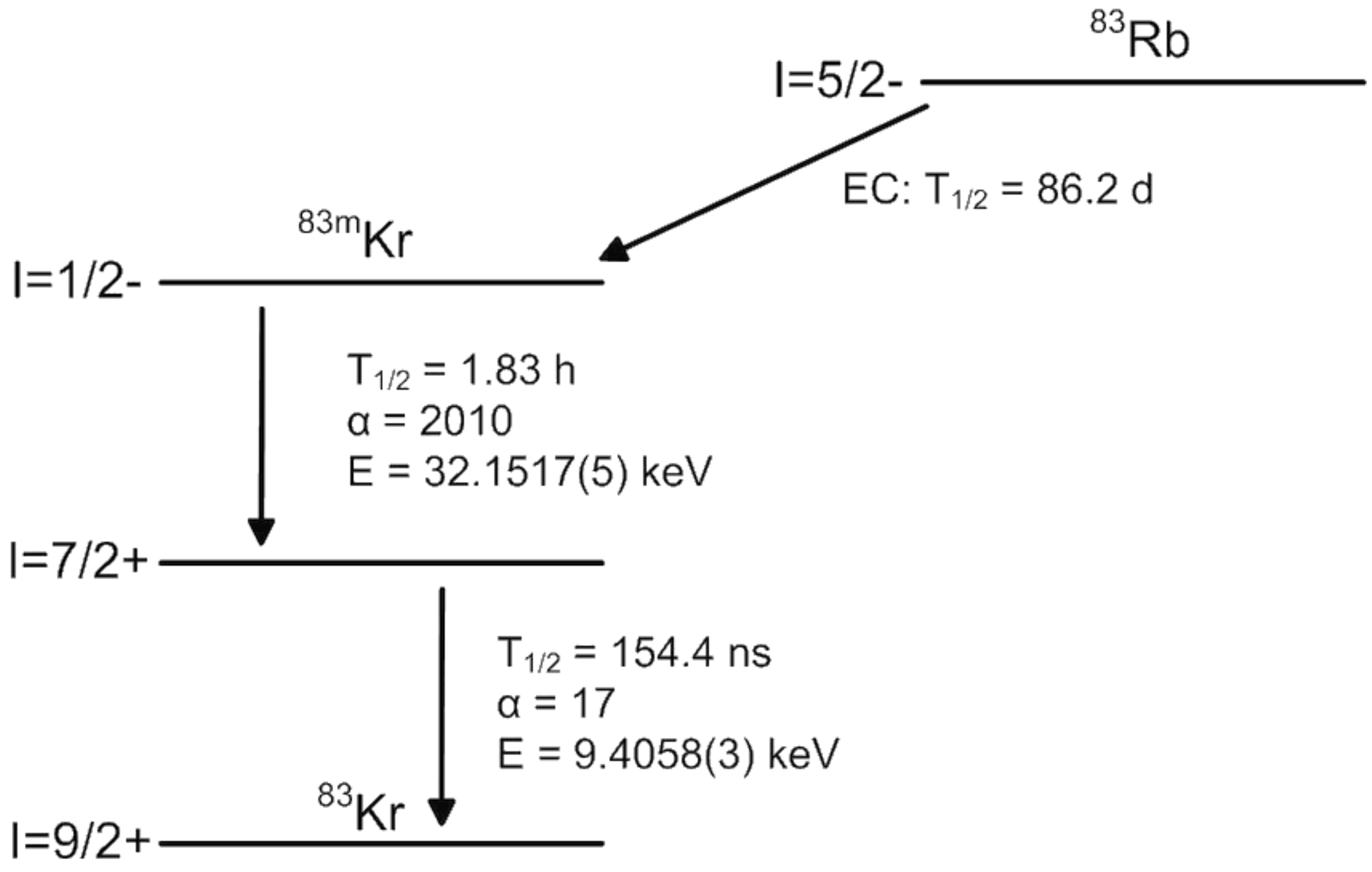
[8.]

LYSO: ^{176}Lu decay scheme



T. Kaltsas *et al.* (2015):
DOI: 10.1109/NSSMIC.2015.7582211

^{83m}Kr: ^{83}Rb decay scheme



NEXT Collaboration (2018):
arXiv: 1804.01780v1