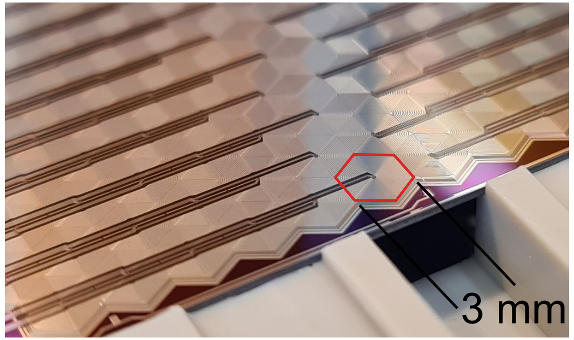
Technical University of Munich
Department for Physics

A Silicon Drift Detector to Search for Sterile Neutrinos at the KATRIN Experiment

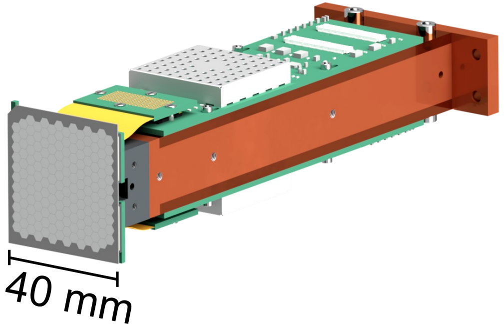


Korbinian Urban
Technical University of Munich

KATRIN collaboration

iWoRiD 2024 – Lisbon

TRISTAN detector

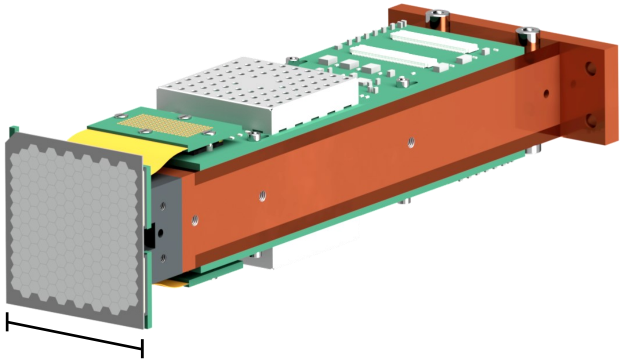


Content

- **introduction**

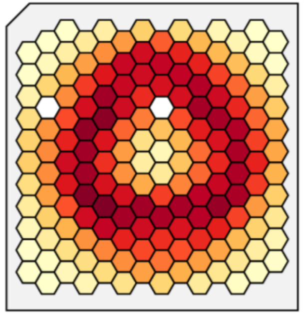
+

- **TRISTAN detector design**



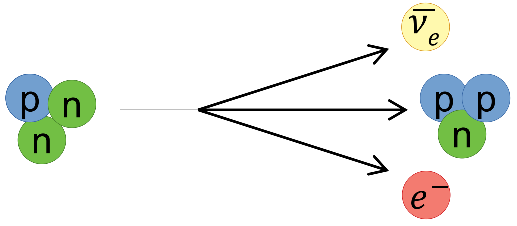
- **detector characterizations**

b)

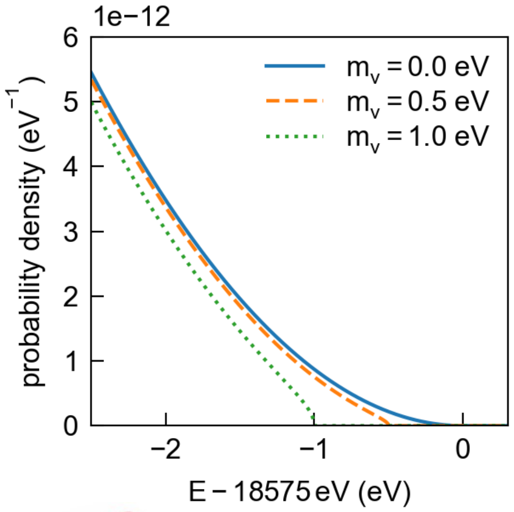


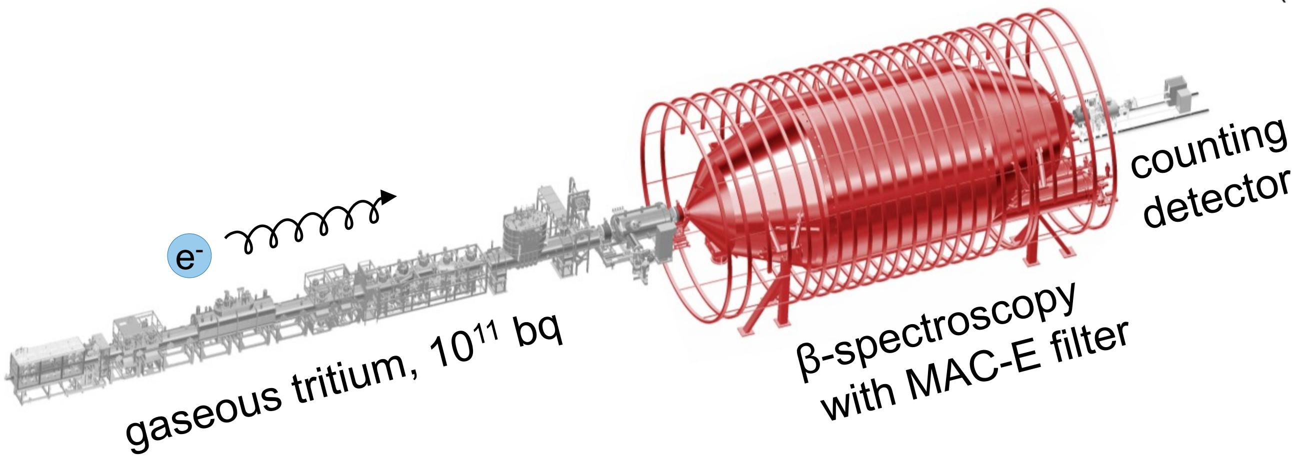
Introduction: KATRIN experiment

- **Ka**rlsruhe **Tri**tium **N**eutrino (KATRIN) experiment
- around 120 collaborators around the world
- goal: measure the neutrino mass



$$^3\mathrm{H} \longrightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_e$$



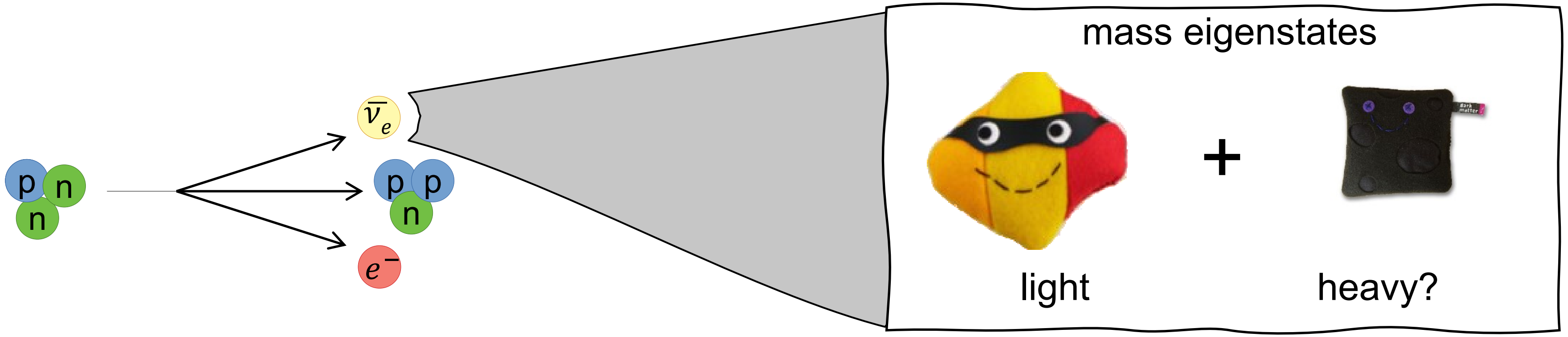


latest result:

$$m_\nu < 0.45\ \mathrm{eV/c^2}$$
$$(90\%\ C.L.)$$

Aker et. al. (2024) https://doi.org/10.48550/arXiv.2406.13516

Future: keV sterile neutrino search with KATRIN

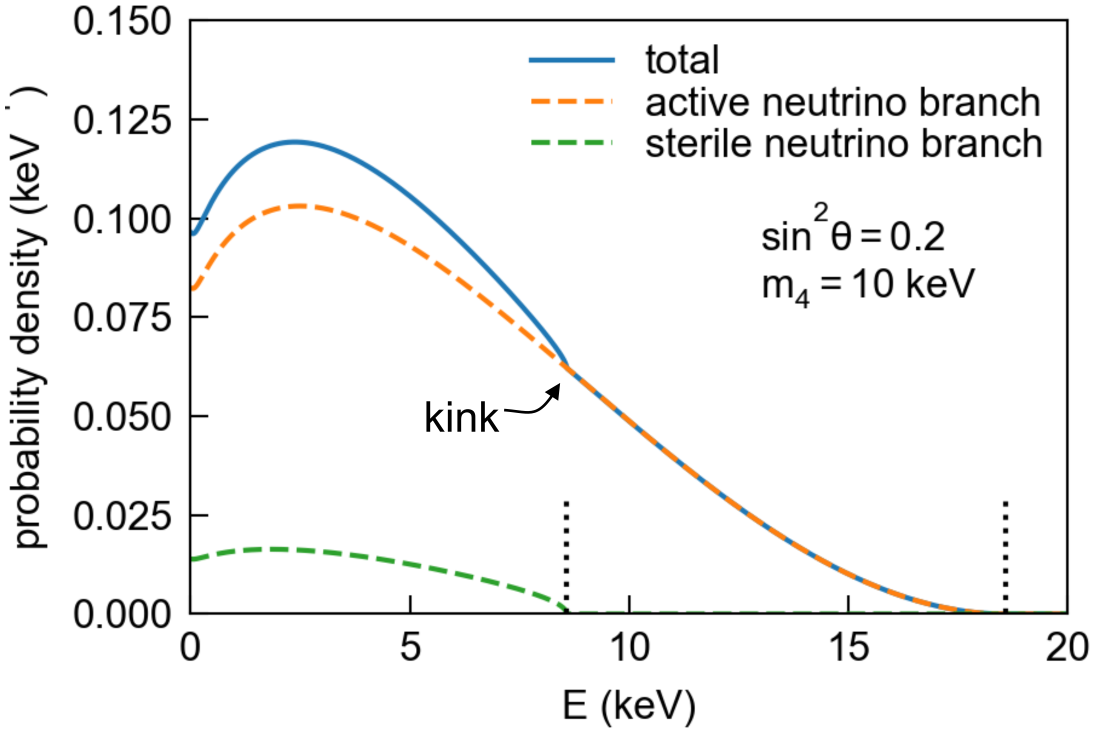


sterile neutrino motivated by:
- right handed neutrino
- keV-mass: dark matter candidate

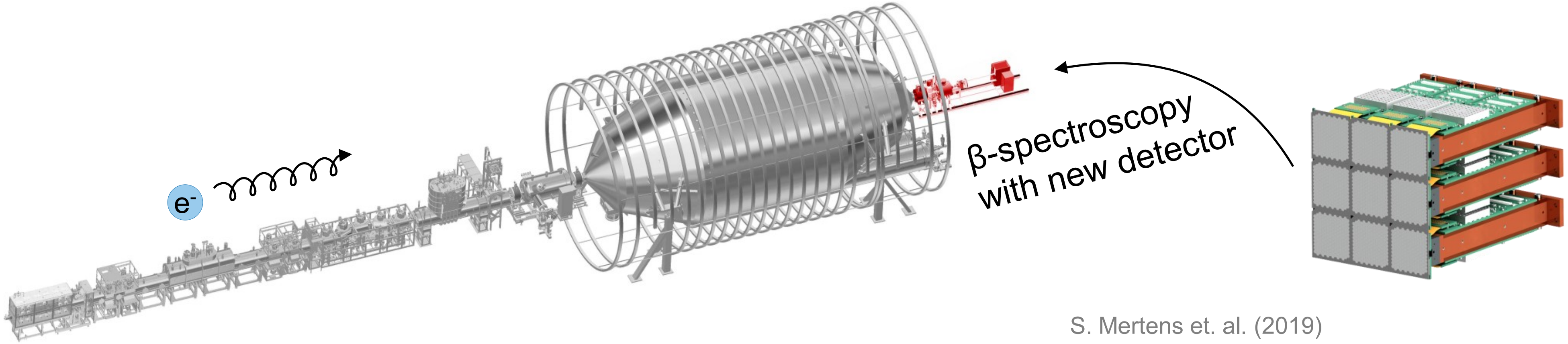
signature: kink in tritium β-decay spectrum

➢ What do we need to search for this kink with KATRIN?

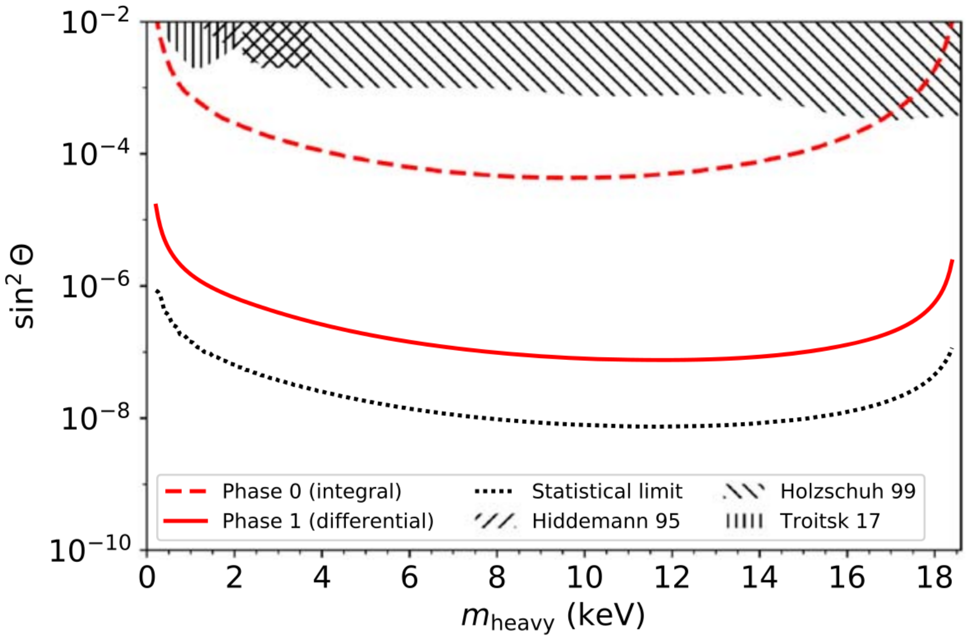
- precise **spectral shape** measurement (FWHM <300 eV) across entire energy range
- ability to handle **high rates** at the detector (~10^8 cps)



TRISTAN detector for KATRIN



S. Mertens et. al. (2019)
https://doi.org/10.1088/1361-6471/ab12fe



- **Silicon Drift Detector (SDD)**, known from X-ray spectroscopy
- challenges:
  1. scaling to focal plane array (>1000 pixels)
  2. electron spectroscopy
  3. difficult environment:
     UHV, magnetic fields, high voltage etc.

➢ statistically, $\sin^2\theta < 10^{-6}$ can be reached after 1 year

TRISTAN detector design

Silicon Drift Detector (SDD) chip

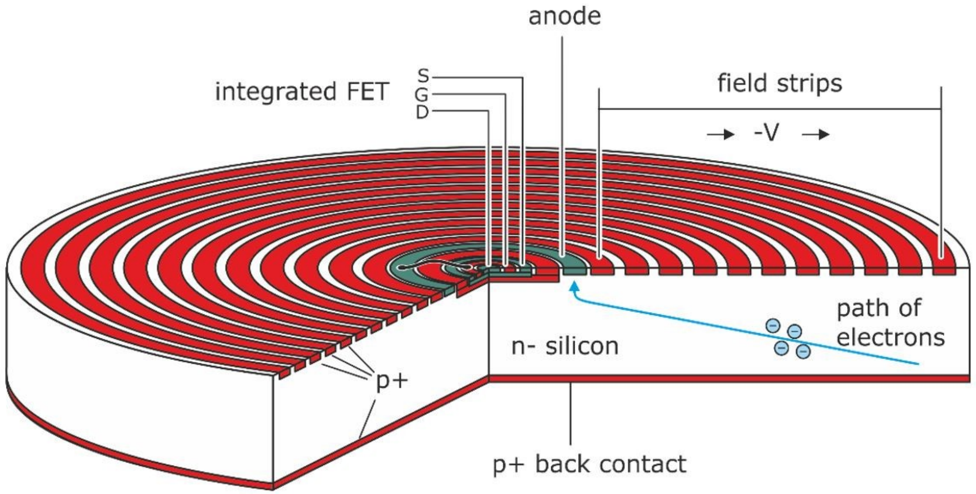
SDD design and production by

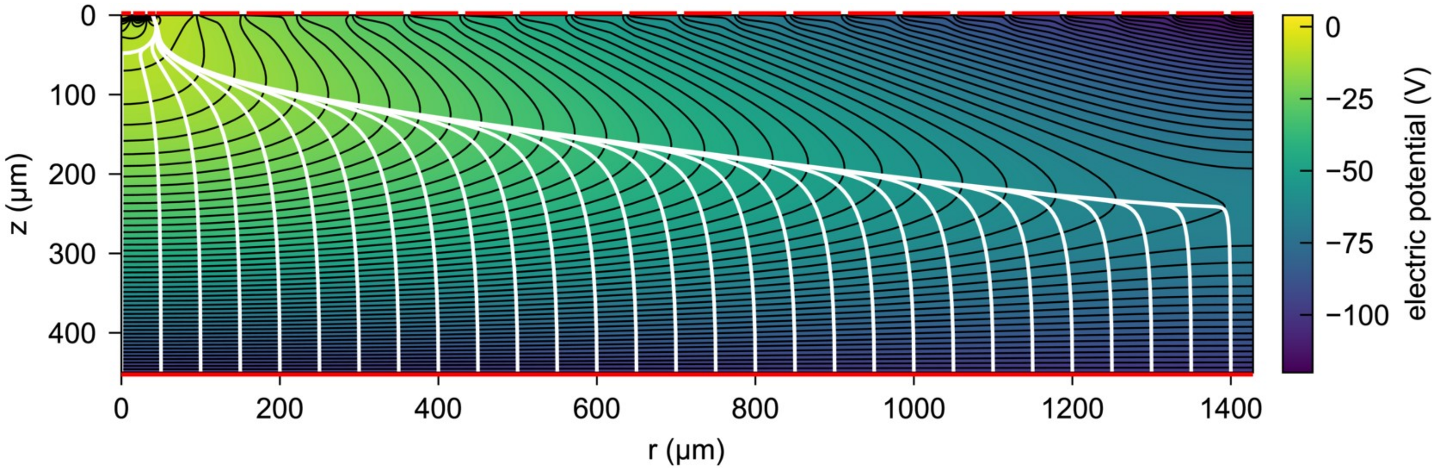
MAX PLANCK SEMICONDUCTOR LABORATORY

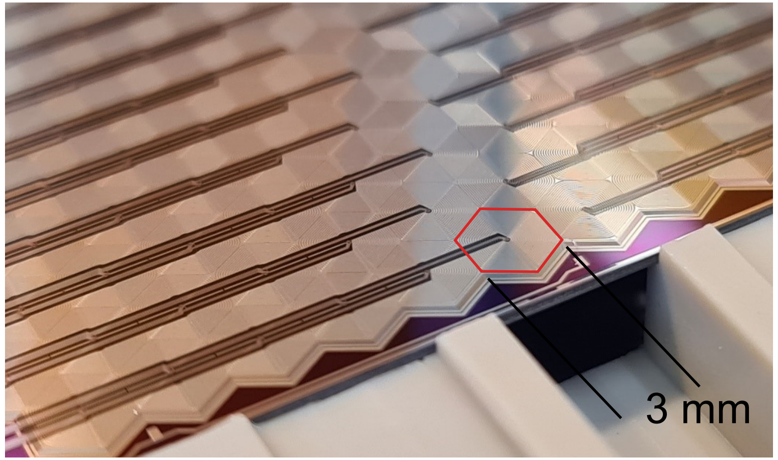
- SDD: PIN diode with point-like anode
  - low anode capacitance
  - ➢ low noise

- hexagonal pixels with 3 mm diameter
- 166 pixels on monolithic chip (38x40 mm)

- JFET integrated in anode



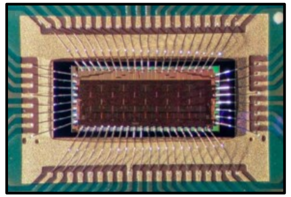




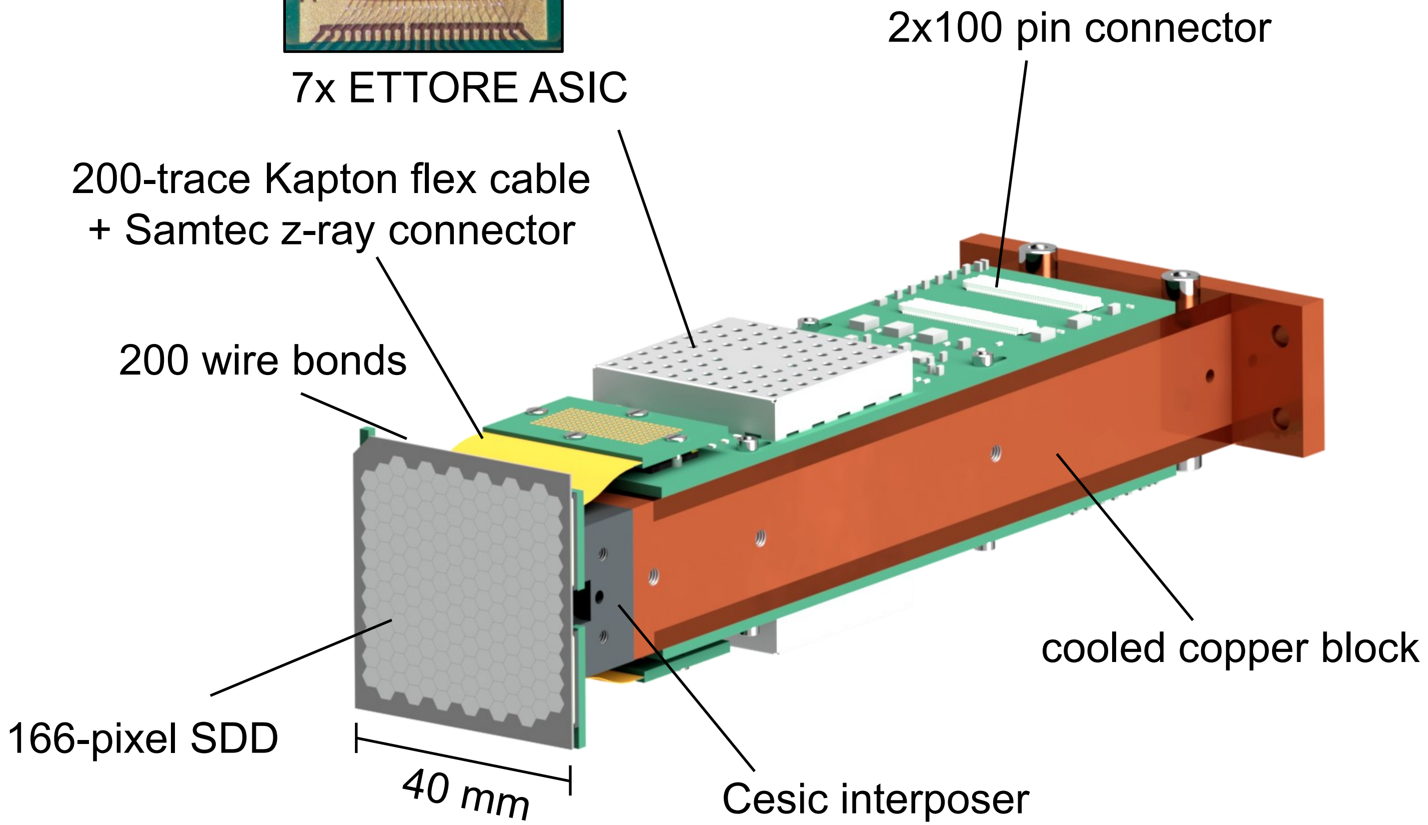
TRISTAN detector module

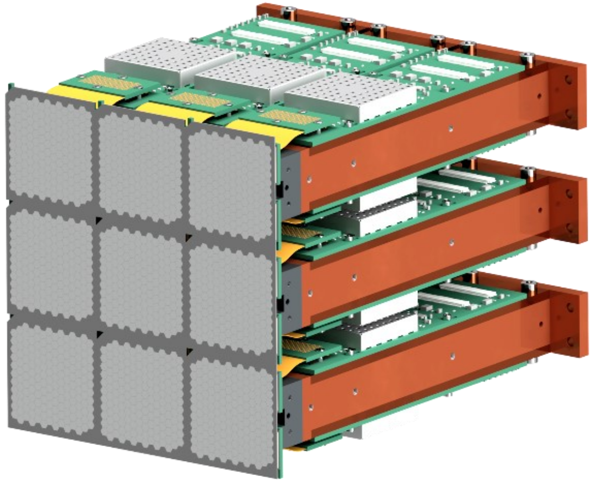
first TRISTAN detector modules assembled and characterized

D. Siegmann et. al. (2024) https://doi.org/10.1088/1361-6471/ad4bf8



7x ETTORE ASIC





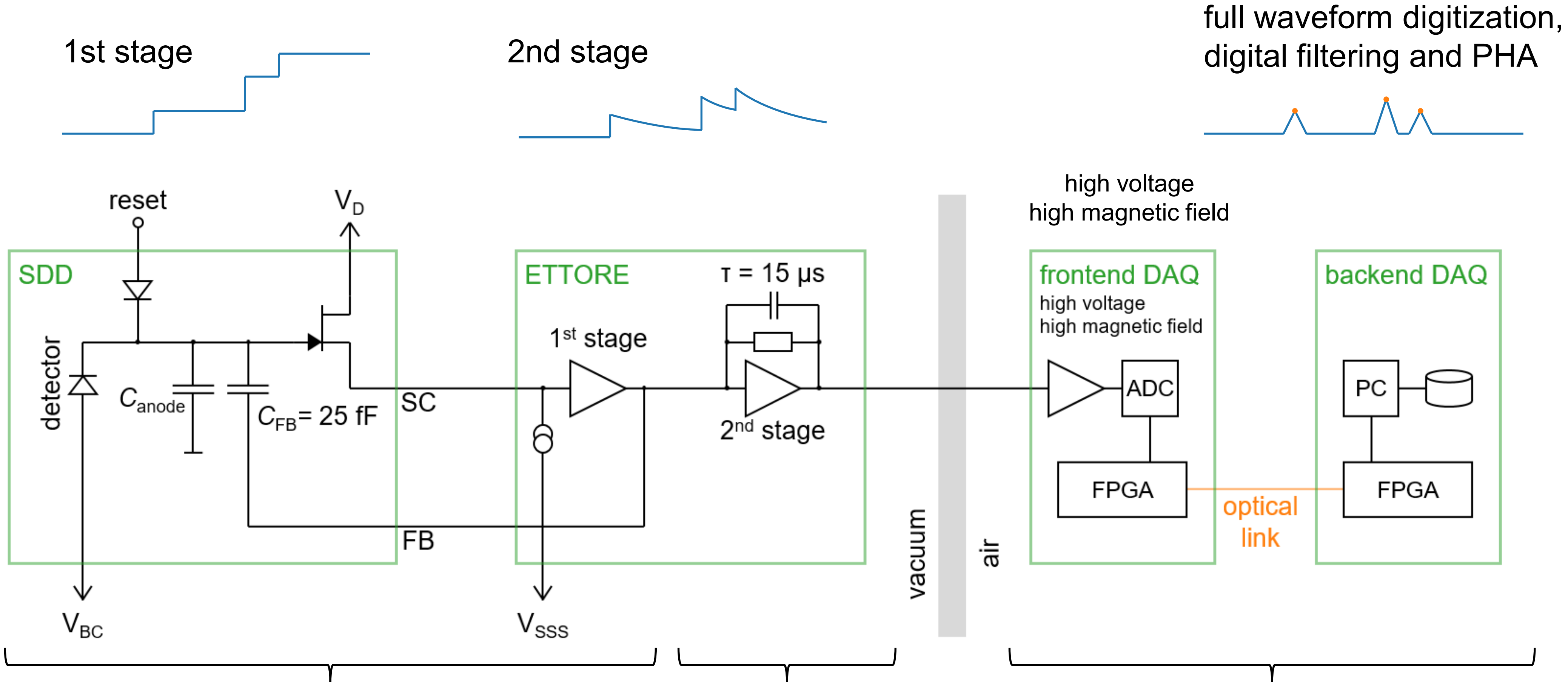
readout electronics by

POLITECNICO MILANO 1863

M. Gugiatti et. al. (2022) https://doi.org/10.1016/j.nima.2021.166102
P. Trigilio et al, (2018) https://doi.org/10.1109/NSSMIC.2018.8824675

all x166 for one module

TRISTAN detector readout



CSA (charge sensitive amplifier)

- 25 fF feedback capacitance
- pulsed reset mode

2nd stage

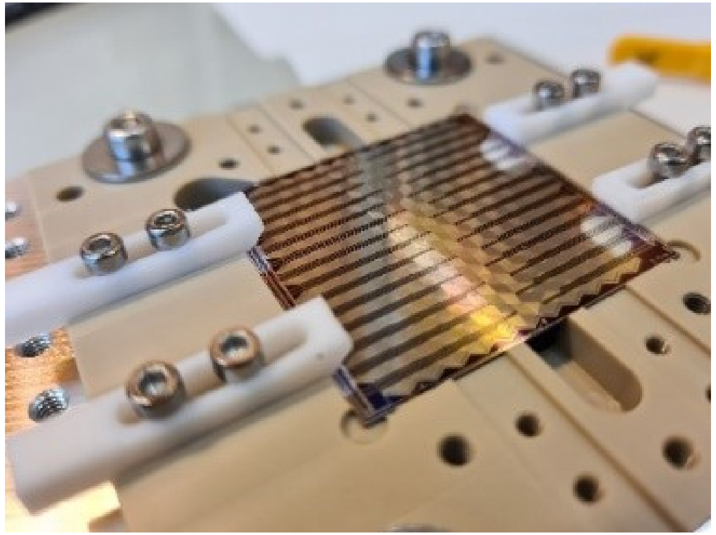
- decaying signals (15 µs)
- additional gain

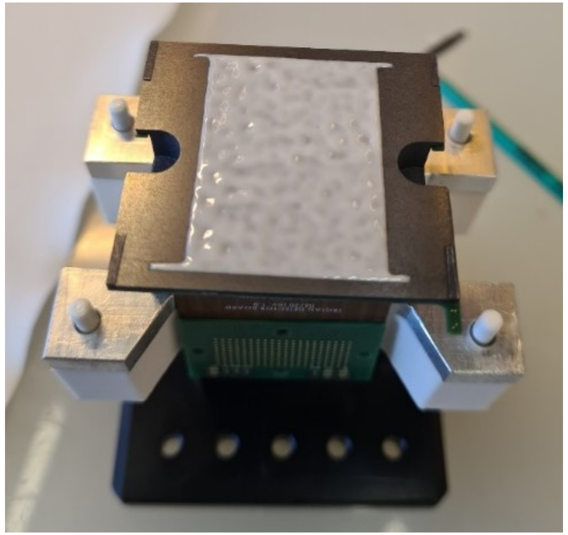
DAQ system

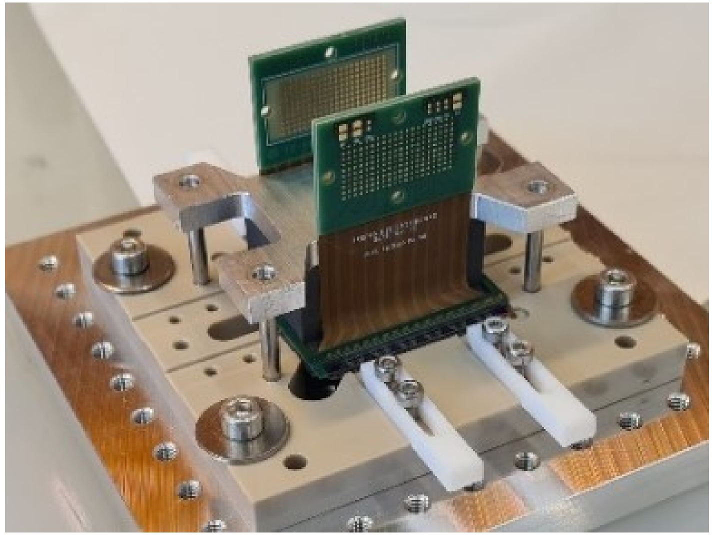
- 14-bit, 62.5 Msps ADC
- remote ADC concept
- online signal processing

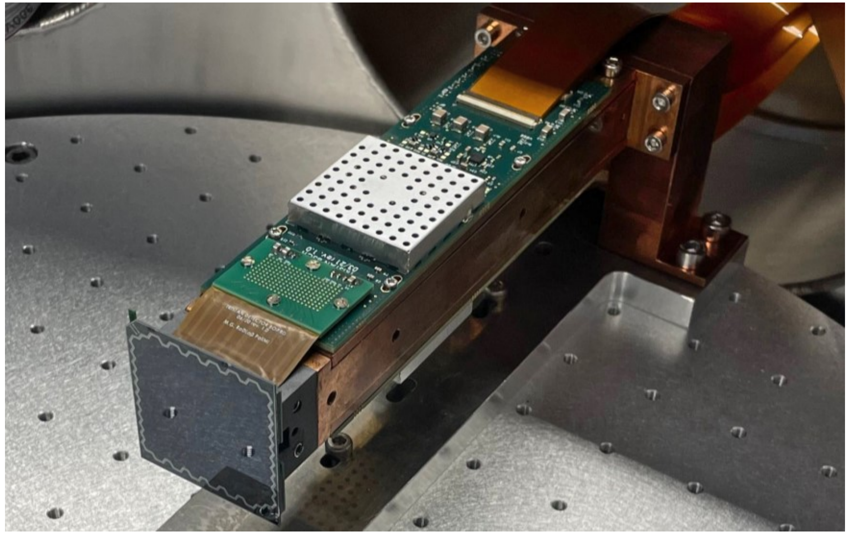
Karlsruher Institut für Technologie

Detector glueing and assembly







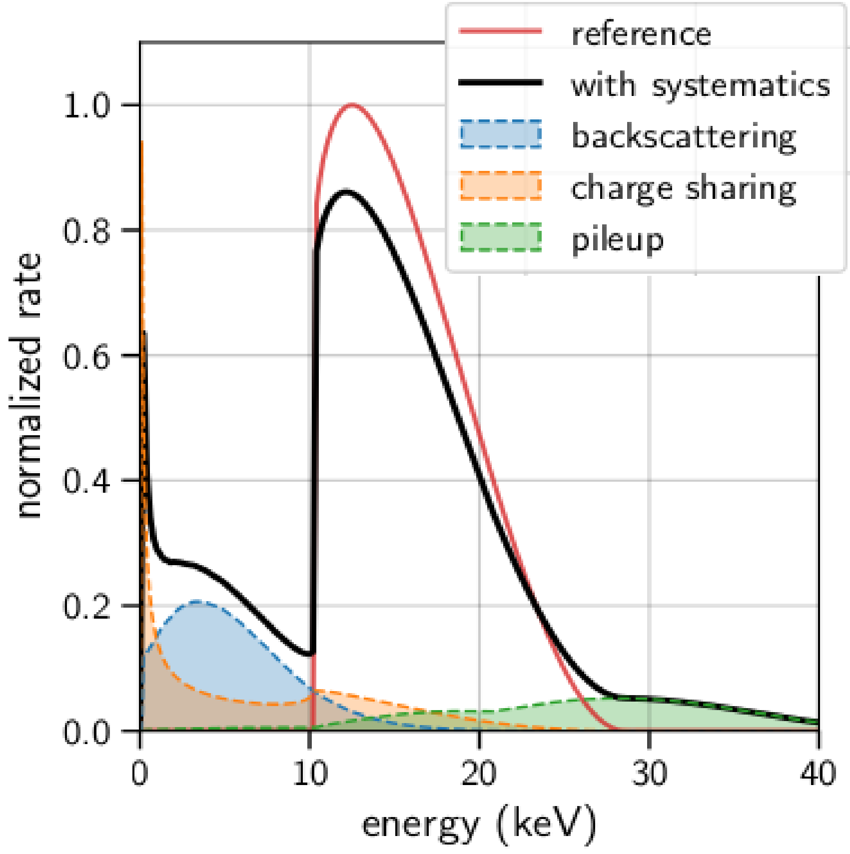


Detector characterization

Why is the detector characterization so important?

detector effects:

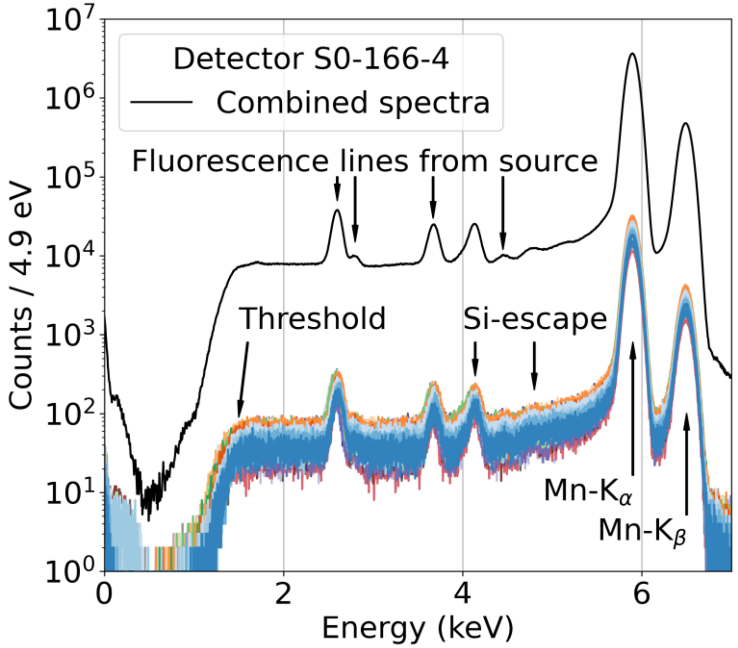
- backscattering
- charge sharing
- pileup
- entrance window effect
- crosstalk
- ...

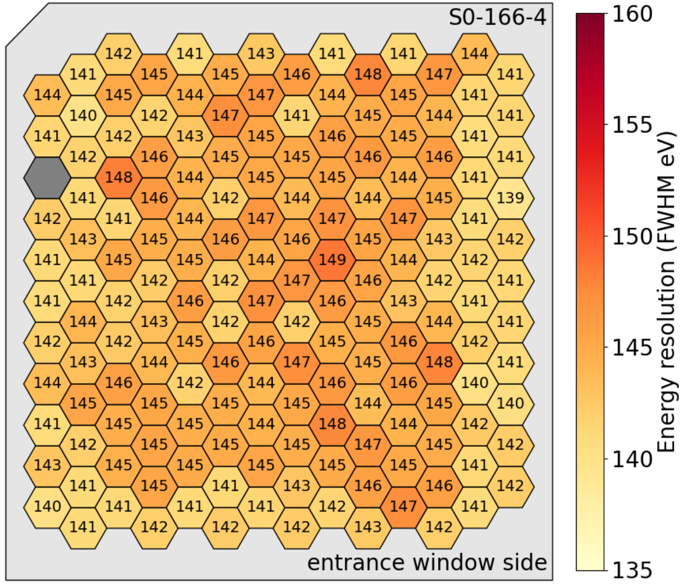


- sensitivity will be limited by systematic effects
- ➢ precise understanding of **detector response** is crucial for sterile neutrino search

X-ray performance

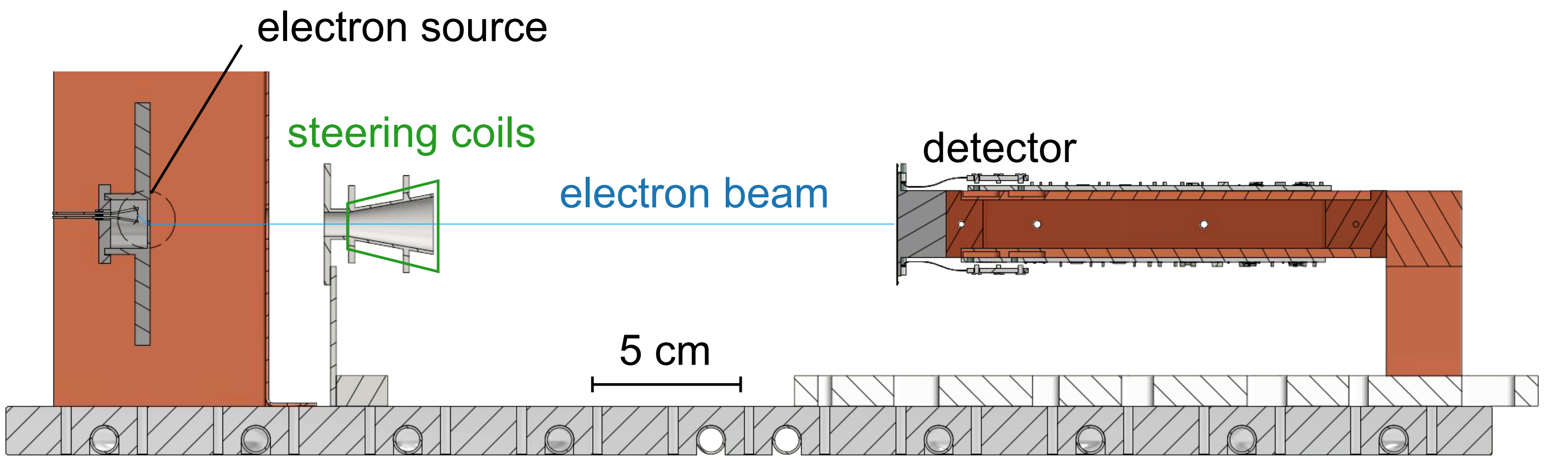
excellent mean energy resolution: **144 eV FWHM** at 5.9 keV corresponding to ENC = 10 e_{rms}
at 2 µs trapezoidal peaking time
at -30°C

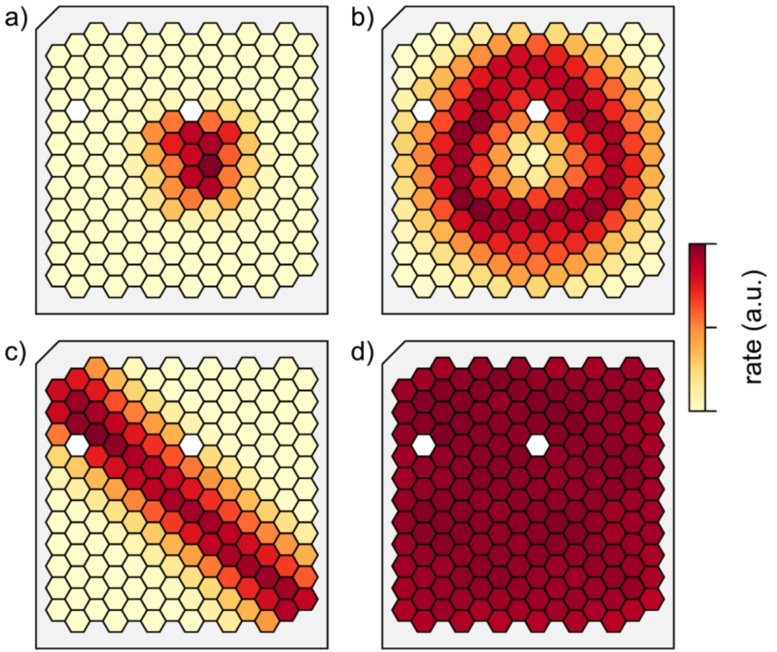




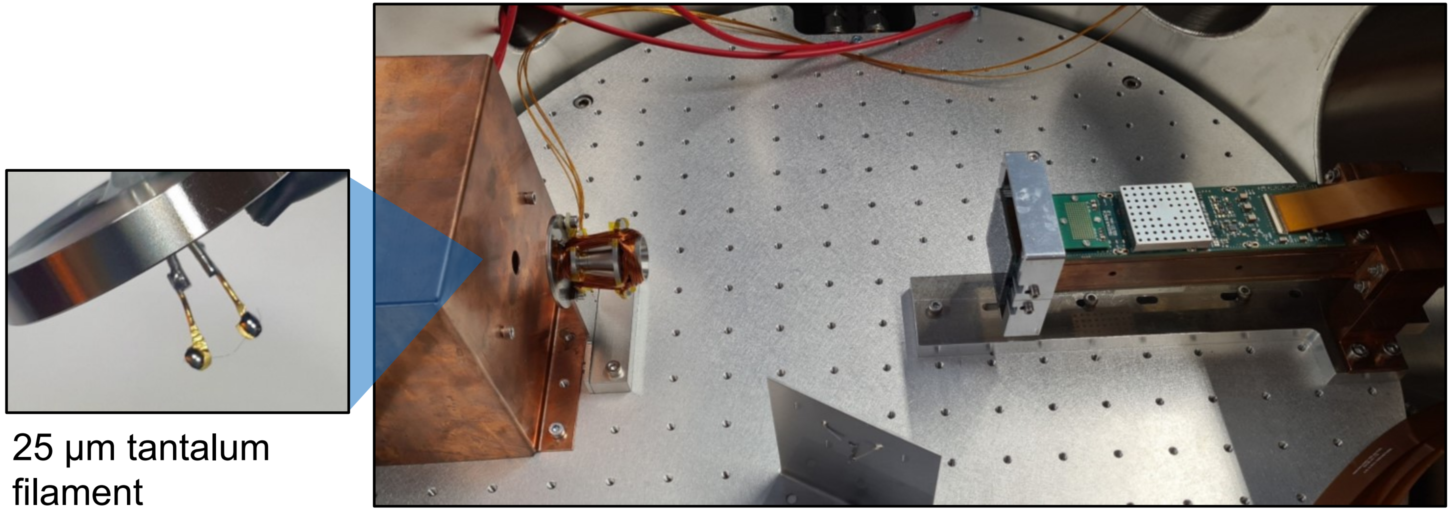
D. Siegmann et. al. (2024) https://doi.org/10.1088/1361-6471/ad4bf8

Setup for electron characterization





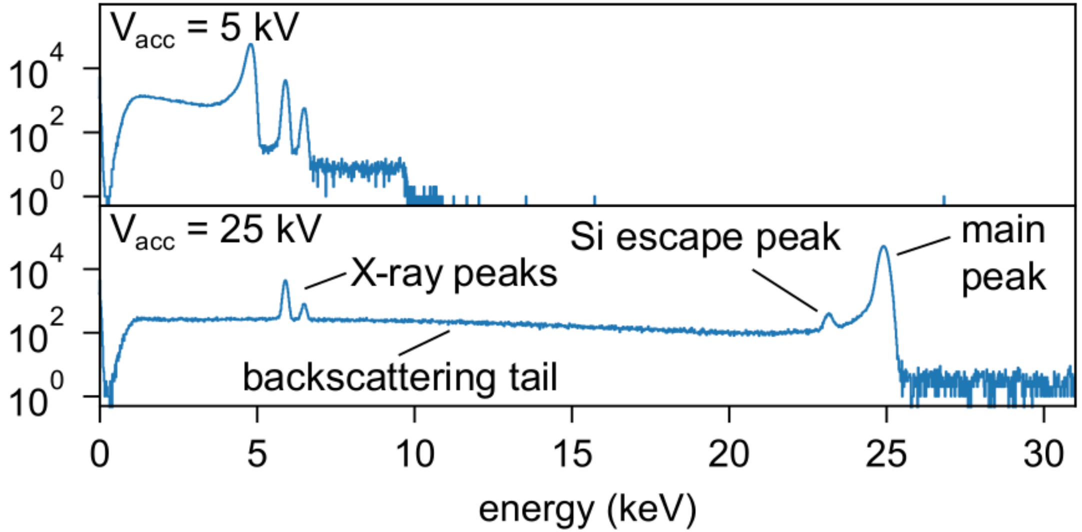
features:
- heat emission from hot tantalum wire
- magnetic steering coils
- rates from 1 cps to 100 kcps
- low light emission

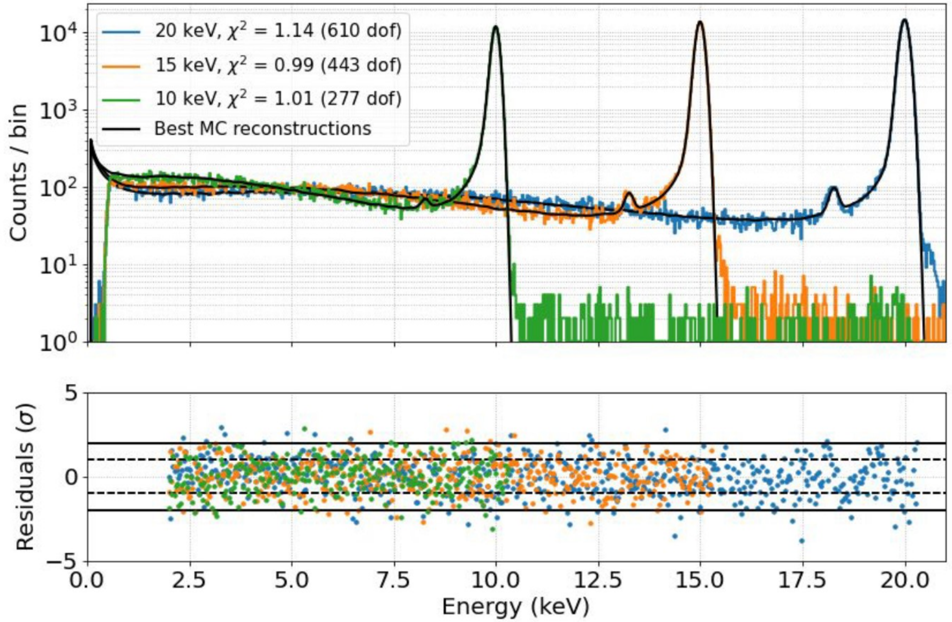


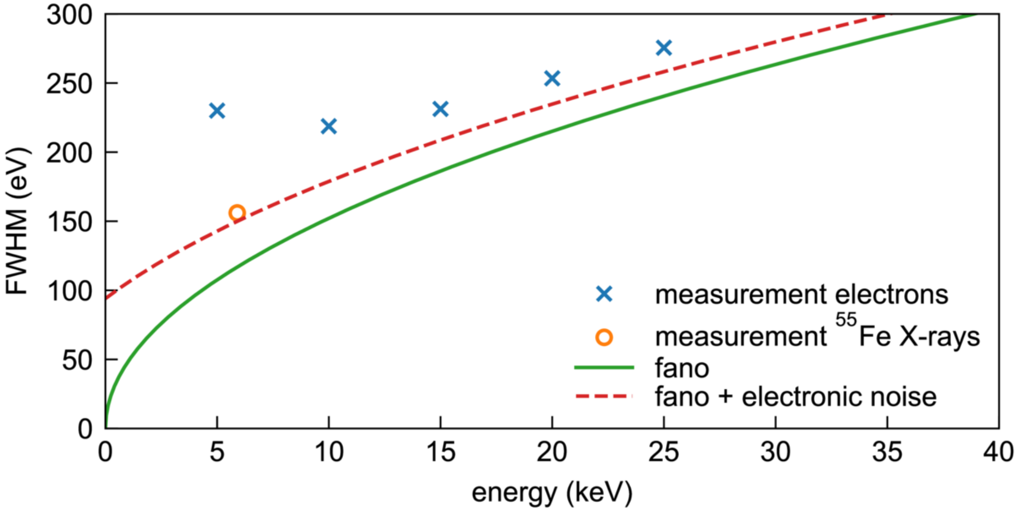
25 µm tantalum filament

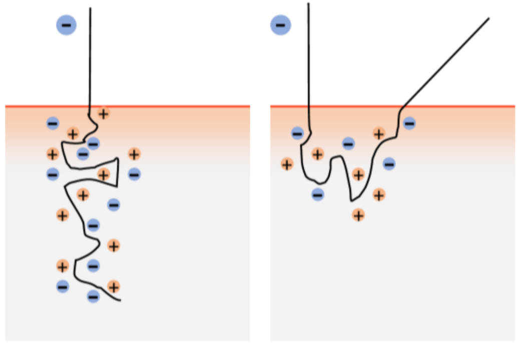
Urban et. al. (2024) https://doi.org/10.1088/1748-0221/19/06/P06004

Electron response









entrance window effect

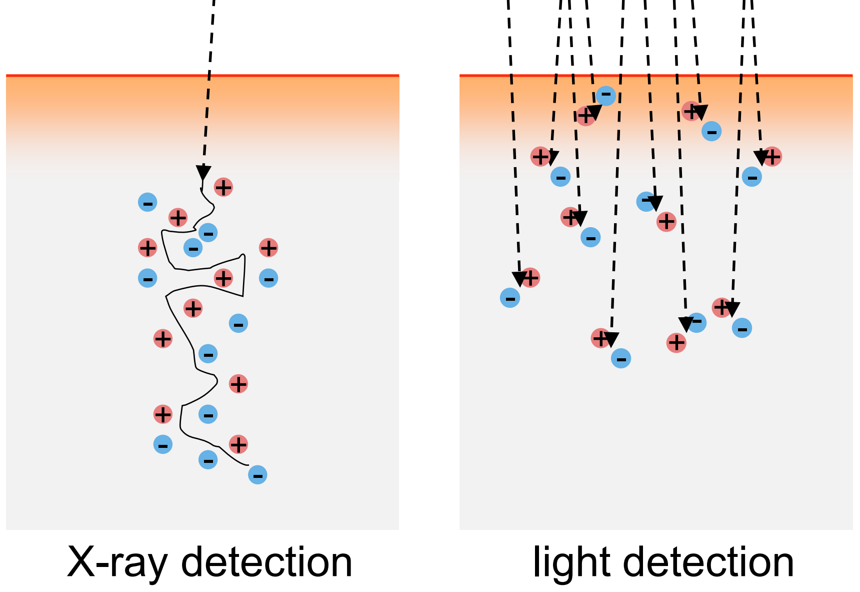
backscattering

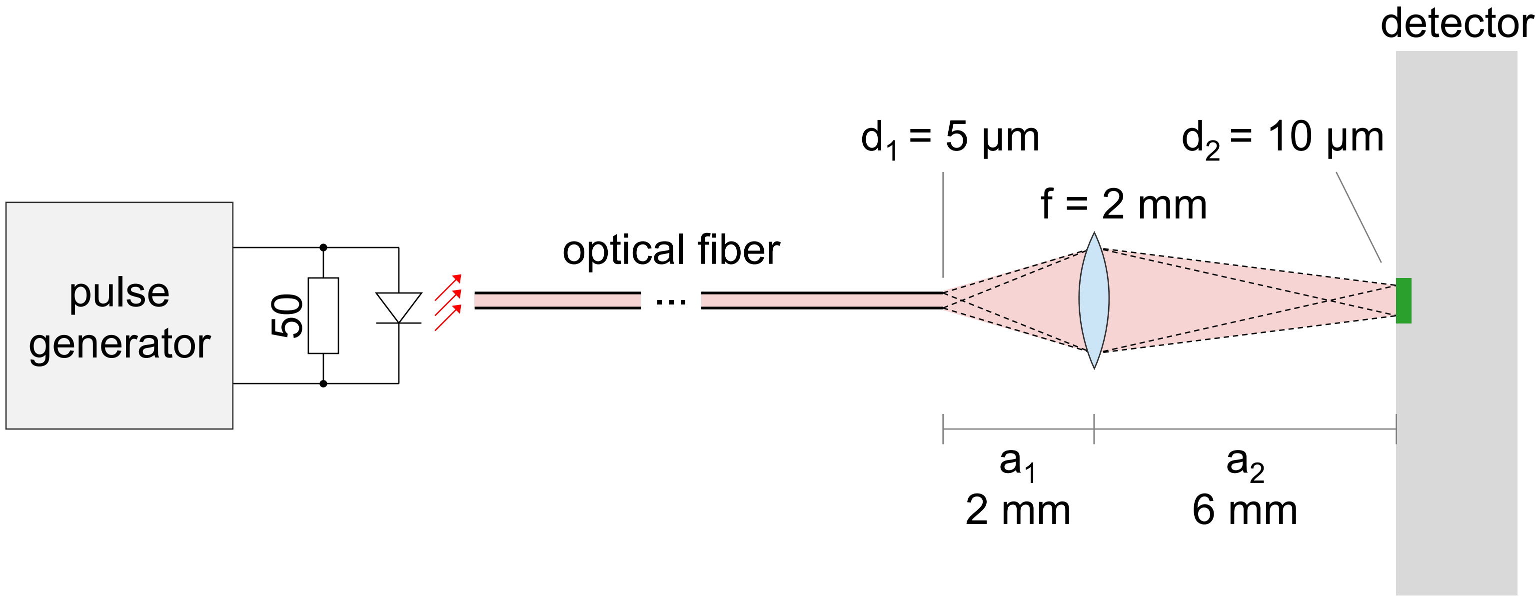
- ✓ 247 eV FWHM at 20 keV
- ✓ verification of Geant4 simulations

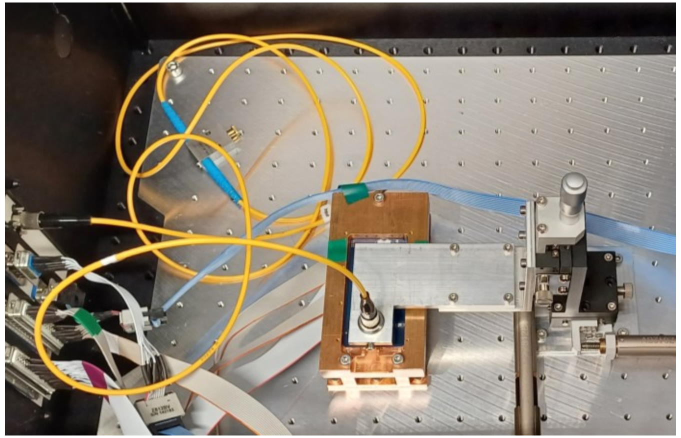
A. Nava et. al. (2021) https://dx.doi.org/10.1088/1742-6596/2156/1/012177
D. Spreng et. al. (2024) https://doi.org/10.48550/arXiv.2405.12776
Urban et. al. (2024) https://doi.org/10.1088/1748-0221/19/06/P06004
D. Siegmann et. al. (2024) https://doi.org/10.1088/1361-6471/ad4bf8

Pulsed light characterization

- induce charge cloud at **defined time** and **defined location** in detector volume
- inspired by scanning Transient Current Technique (TCT)

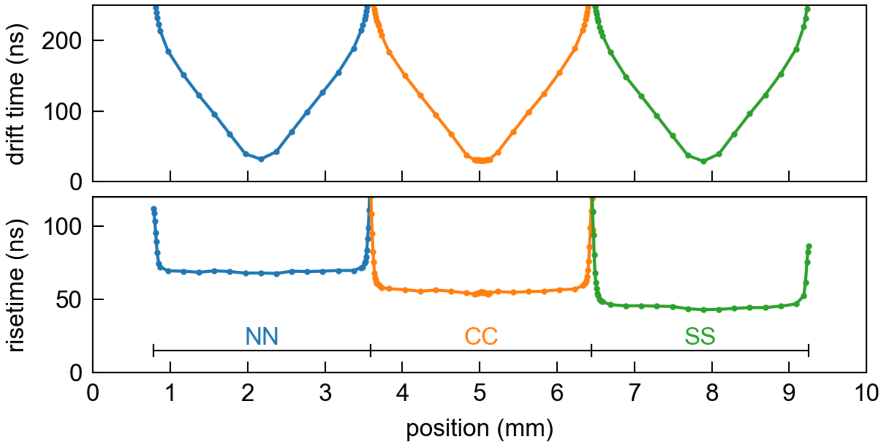


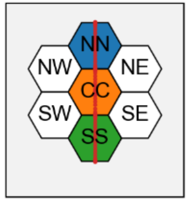




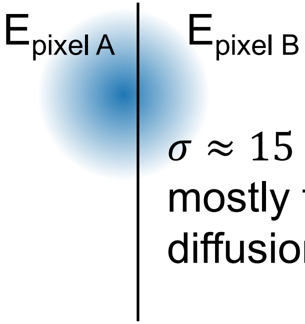
Pulsed light characterization

✓**drift time** in detector up to 200 ns

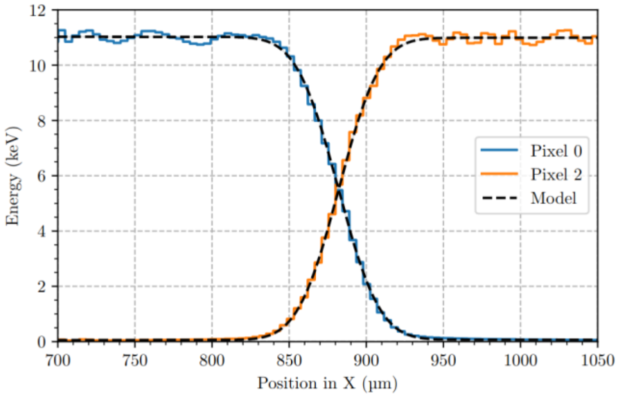




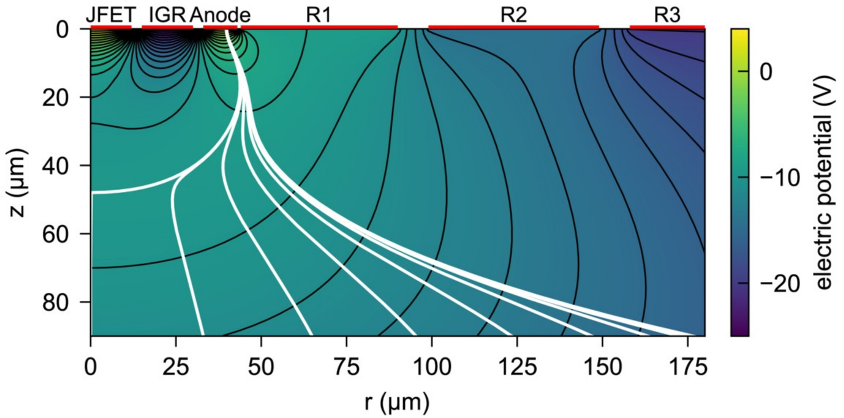
✓characterize **charge sharing** effect



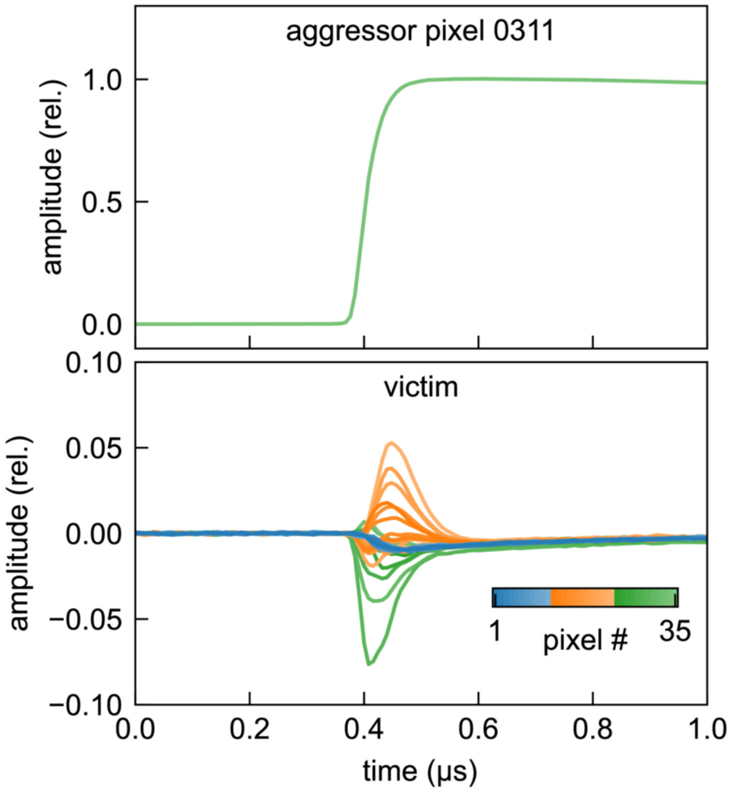
$\sigma \approx 15\ \mu m$
mostly from diffusion

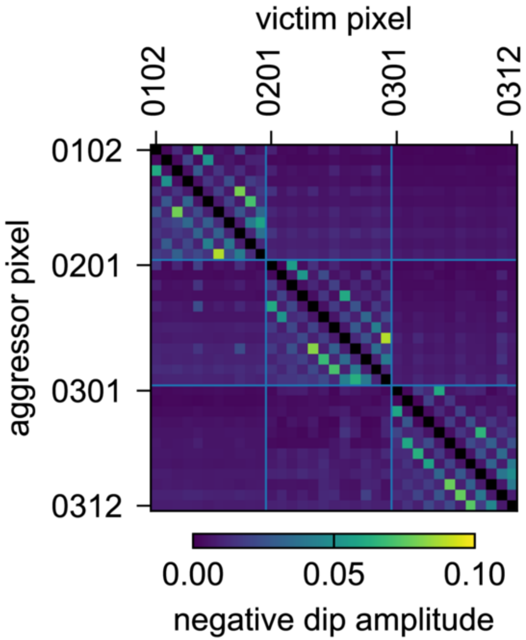


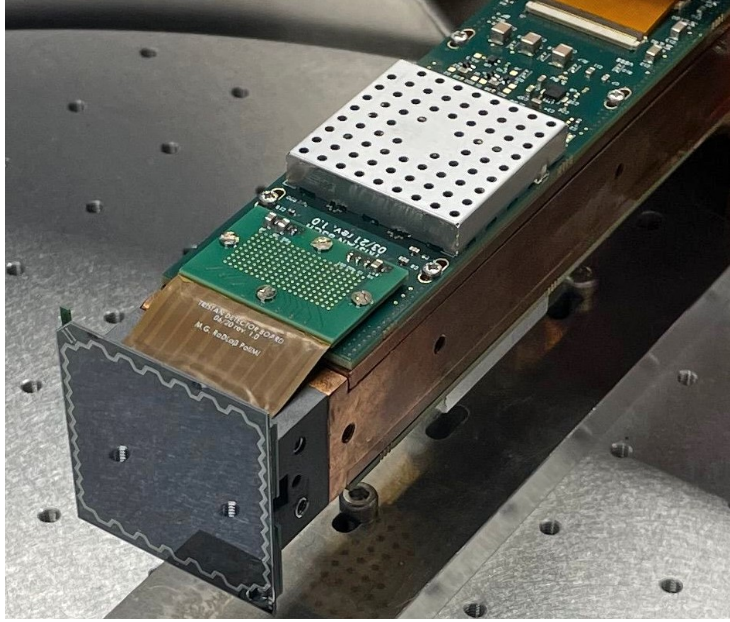
✓validate **no charge loss** above JFET

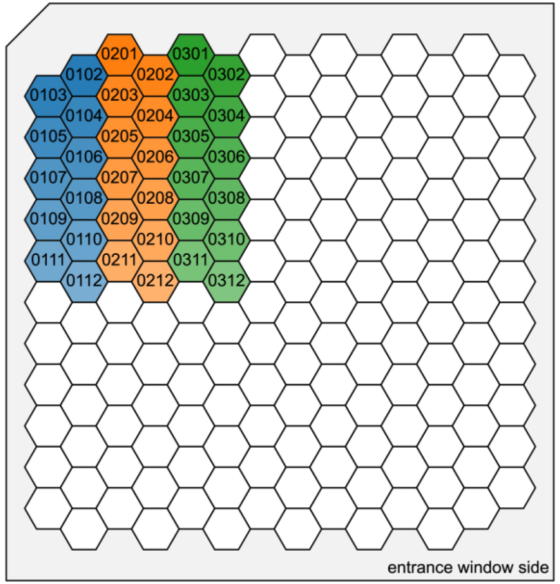


Crosstalk in front-end electronics







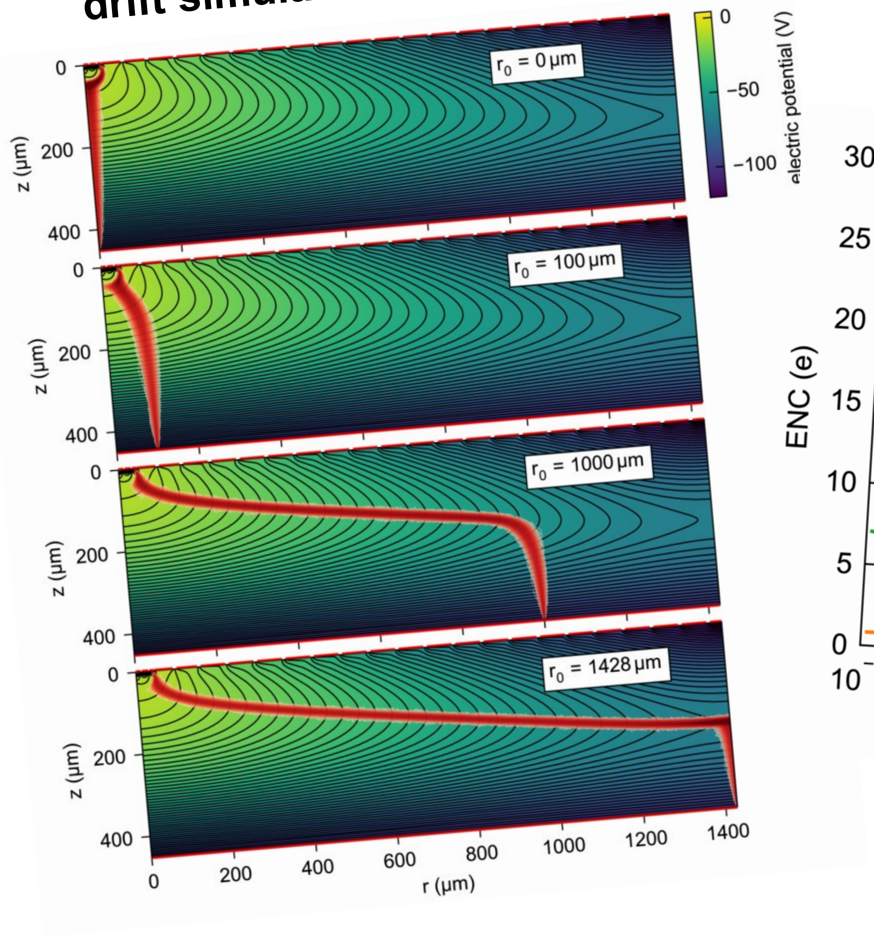


- origin: capacitive couplings in CSA
  → differential distortions on %-level

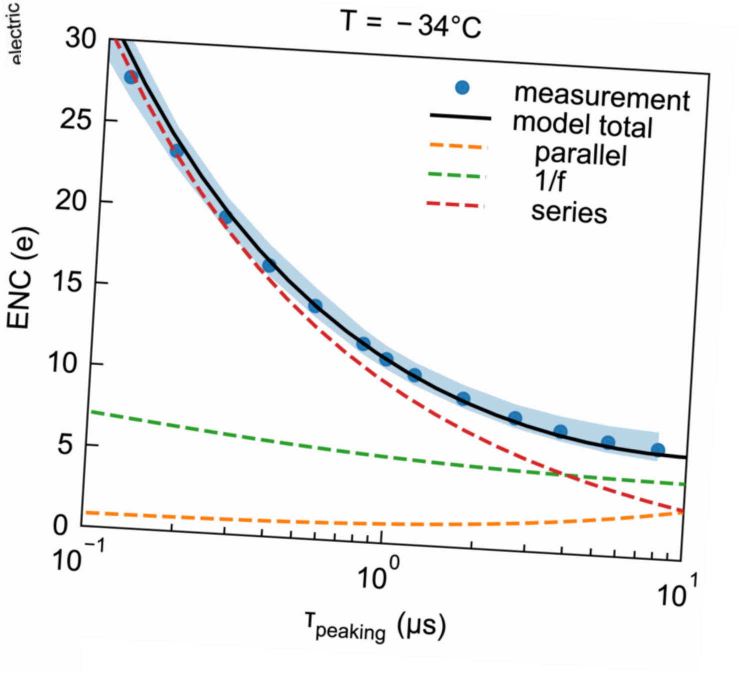
✓ crosstalk on SDD chip reduced by factor ~3 by design improvements
✓ crosstalk simulation to estimate impact on spectroscopy

Many more characterizations

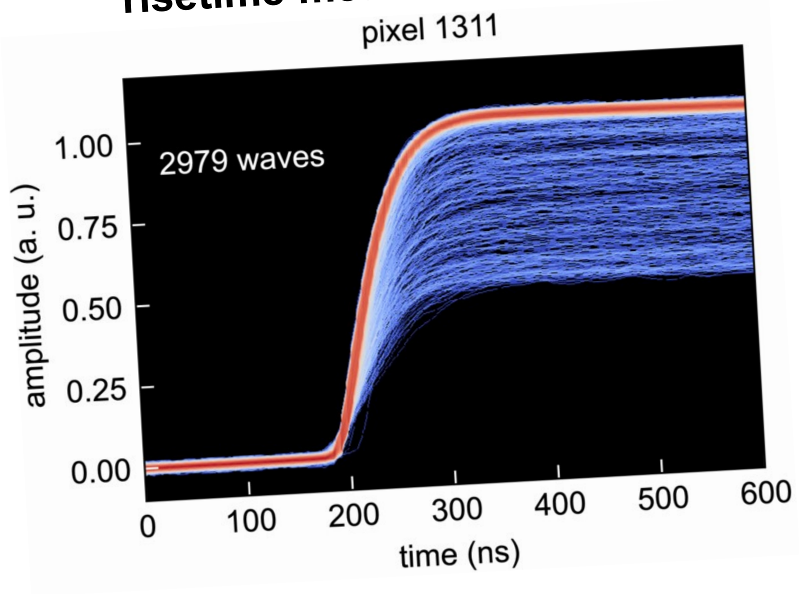
drift simulation



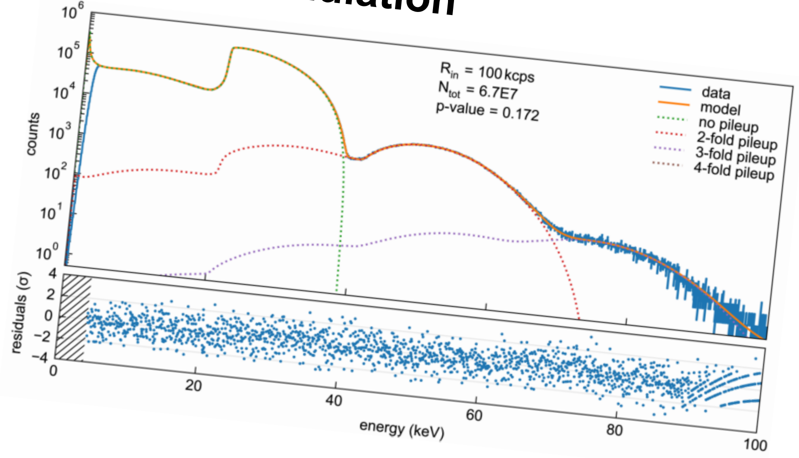
noise measurement and modelling



risetime measurement



pileup simulation



Outlook

end 2024:

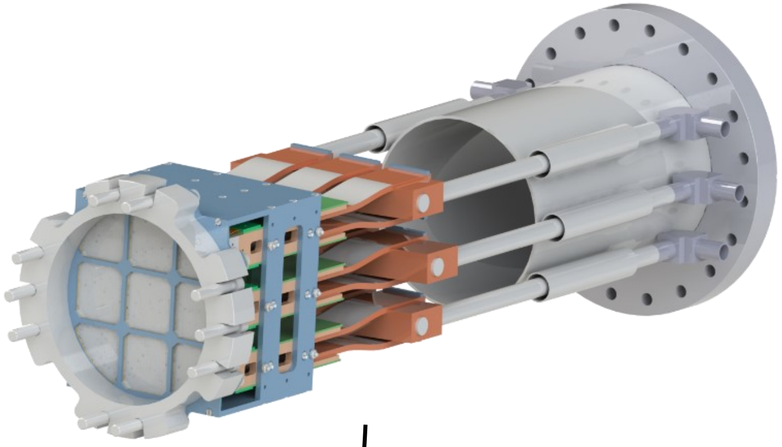
- 3 modules in replica of KATRIN detector section
- first tests of final DAQ system

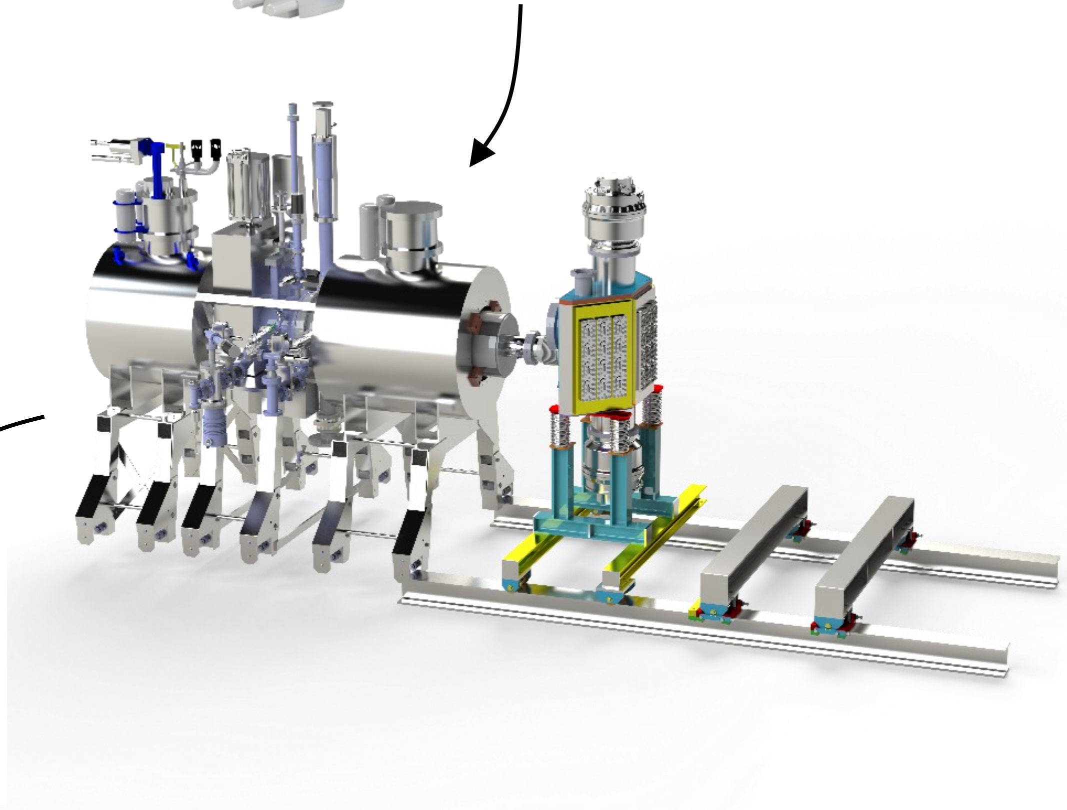
2025:

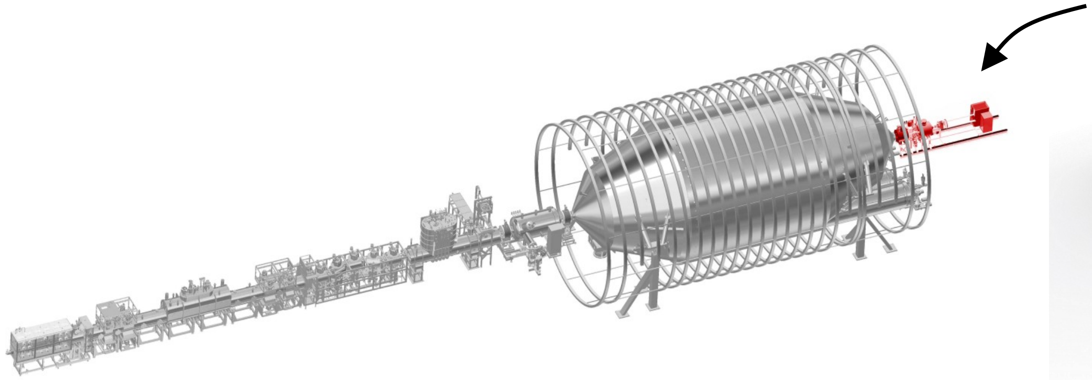
- 9 modules in replica of KATRIN detector section

2026:

- installation in KATRIN beamline
- start of sterile neutrino physics program (~1 year)

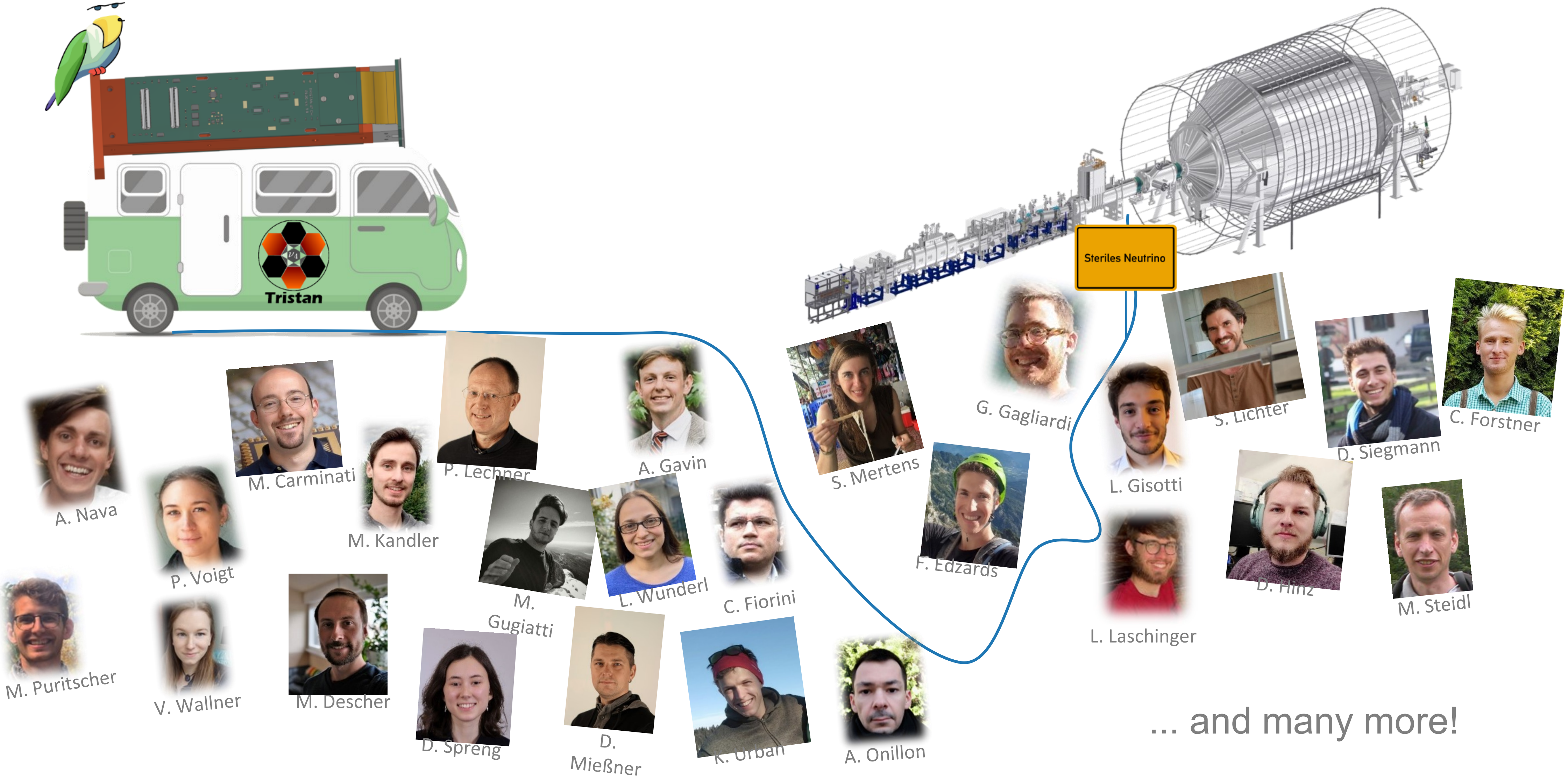






Thanks for your attention!

This project has received funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme (grant agreement No. 852845)

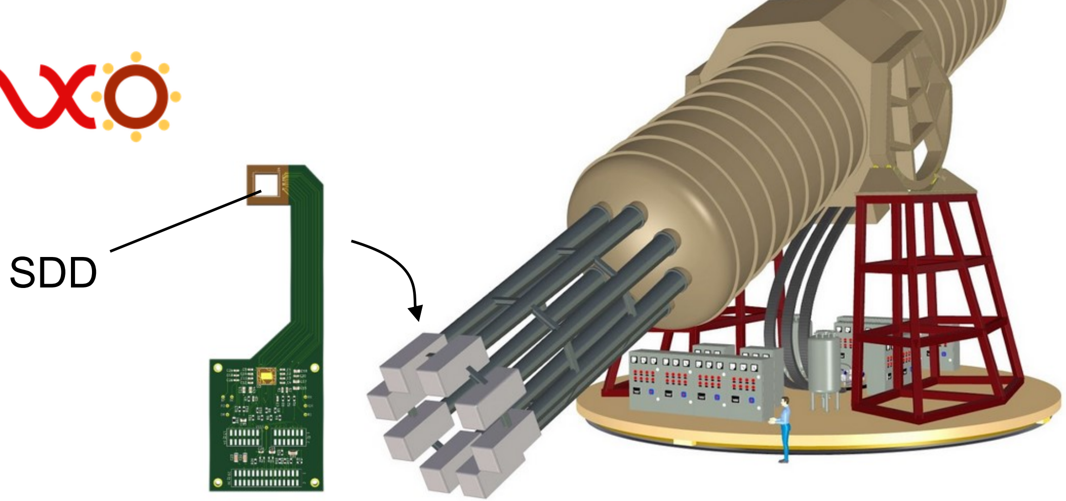


... and many more!

Backup

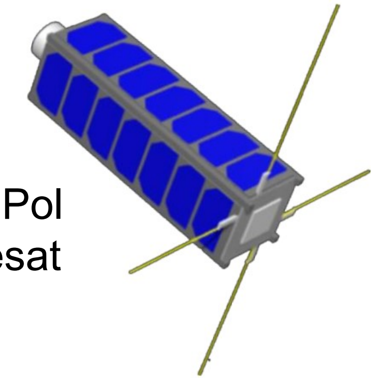
Other applications of TRISTAN SDD technology

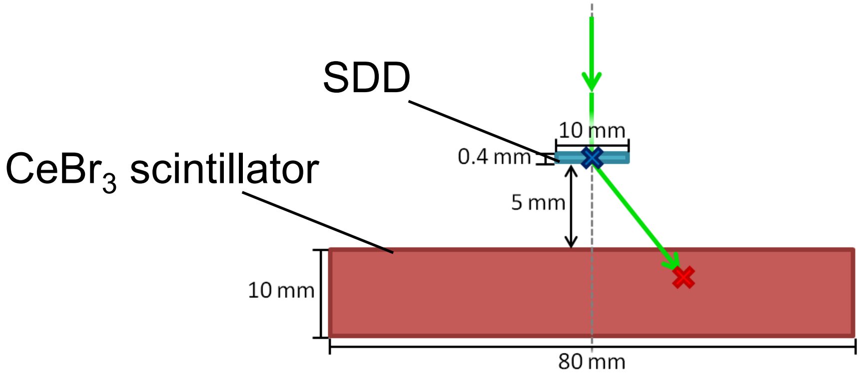
option as detector for IAXO (dark matter search)
- low background and clean materials are key



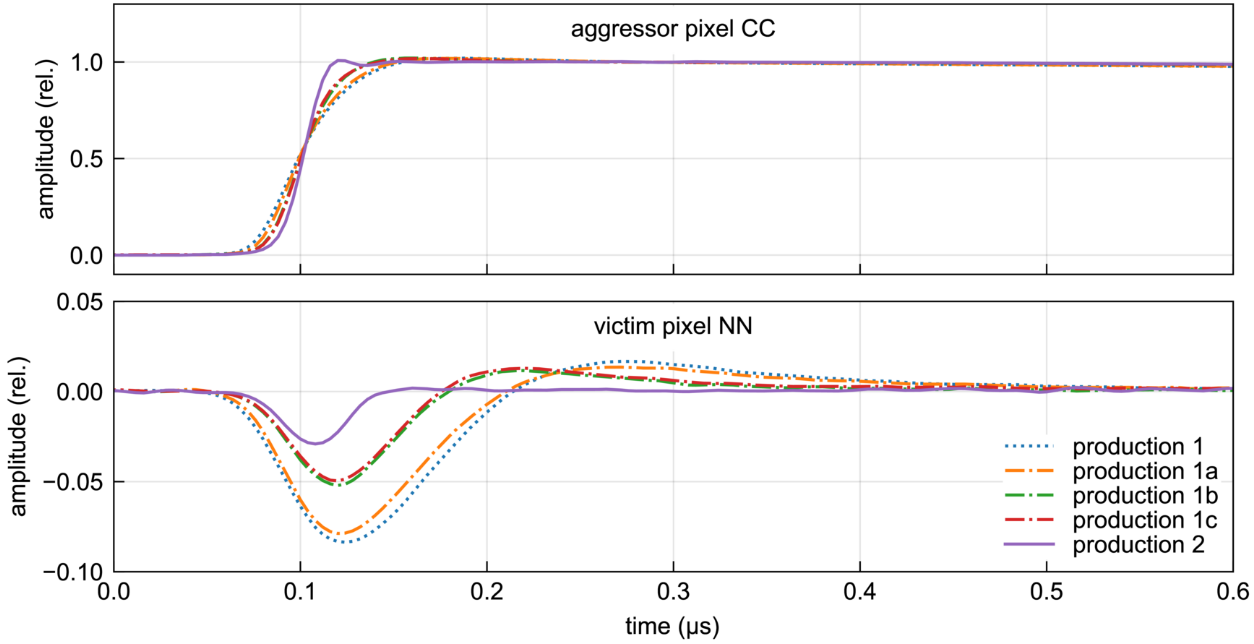
detector for ComPol cubesat mission
- goal: measure polarisation of X-rays from Cygnus X-1

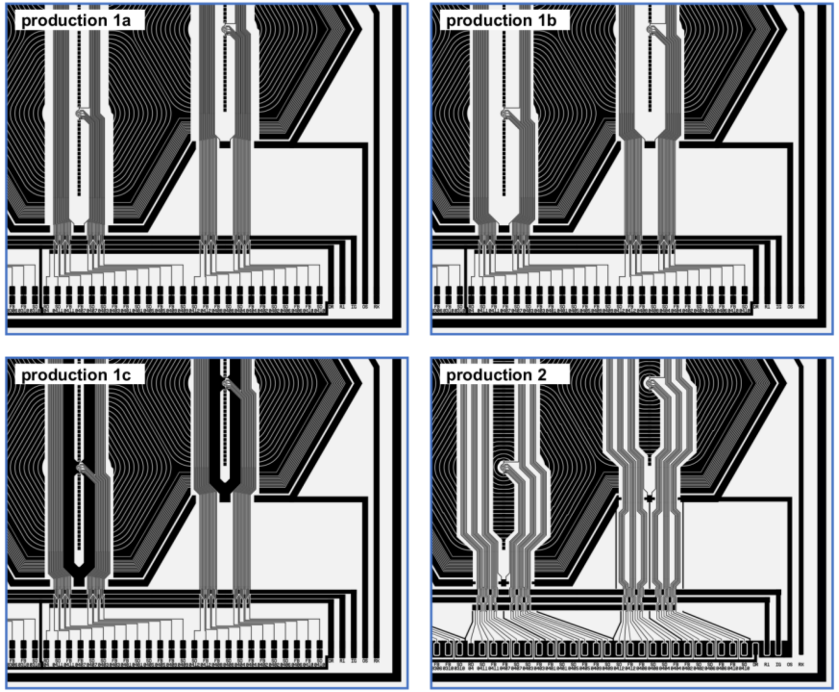
ComPol cubesat





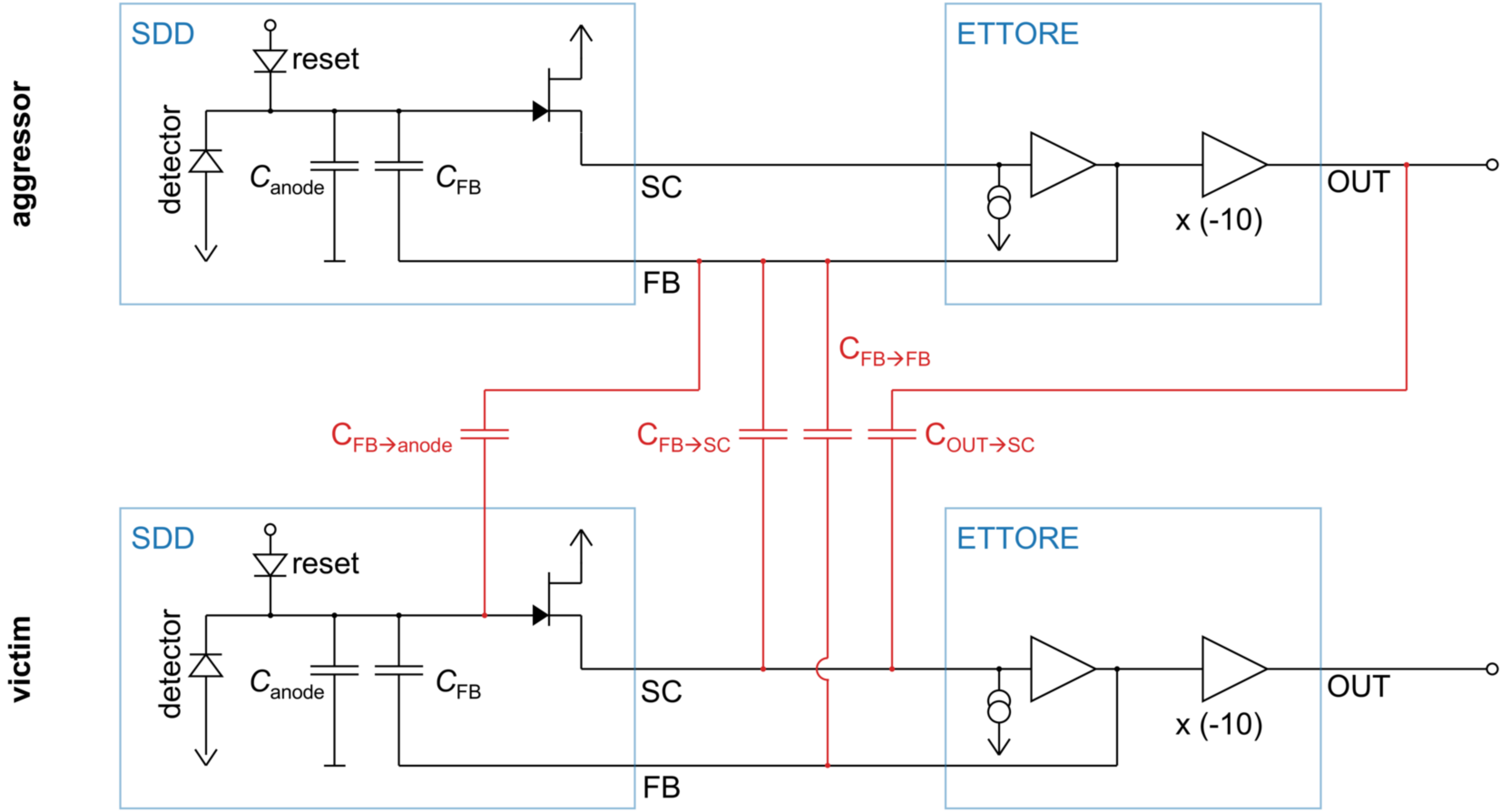
Crosstalk layout modifications



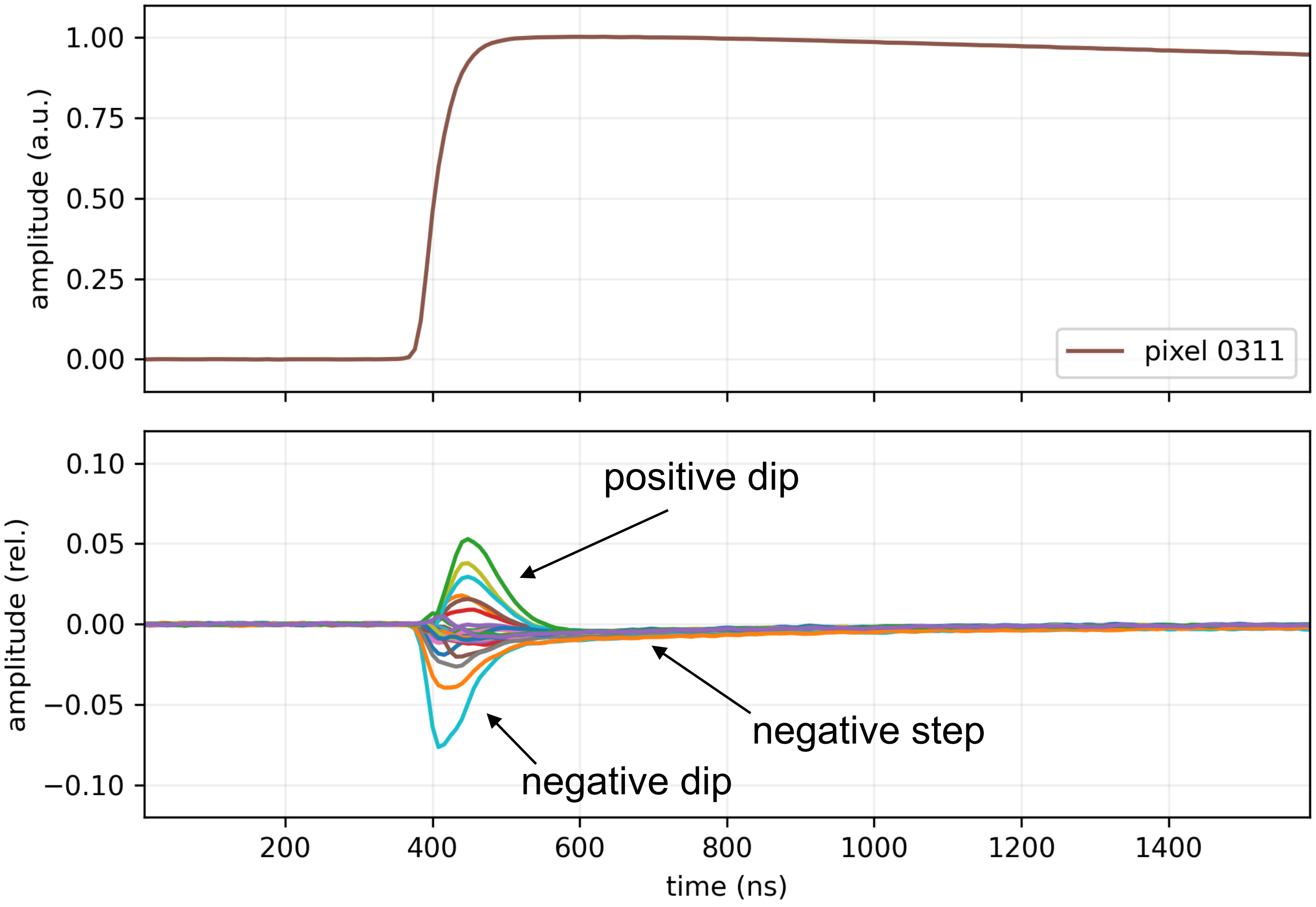


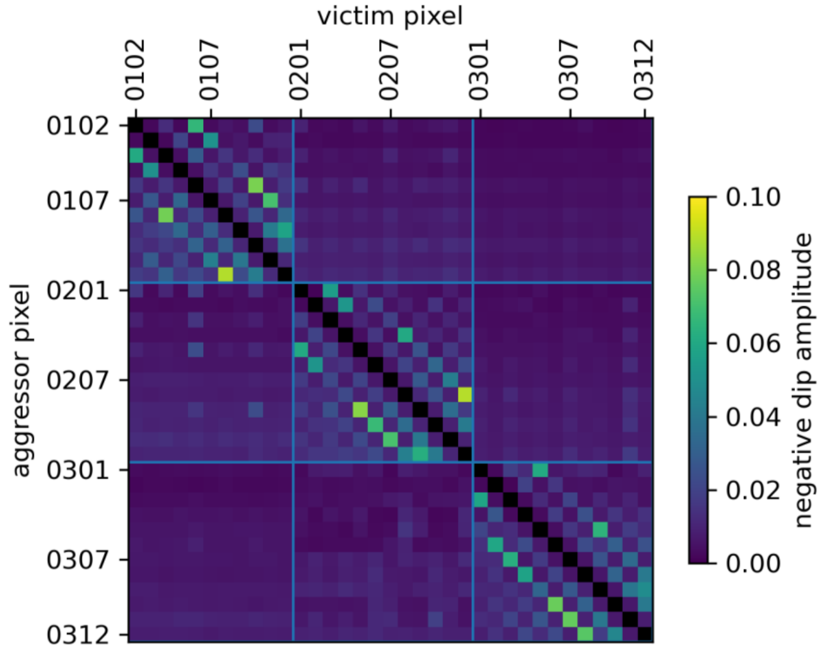
+ increased SiO_2 thickness

Crosstalk couplings

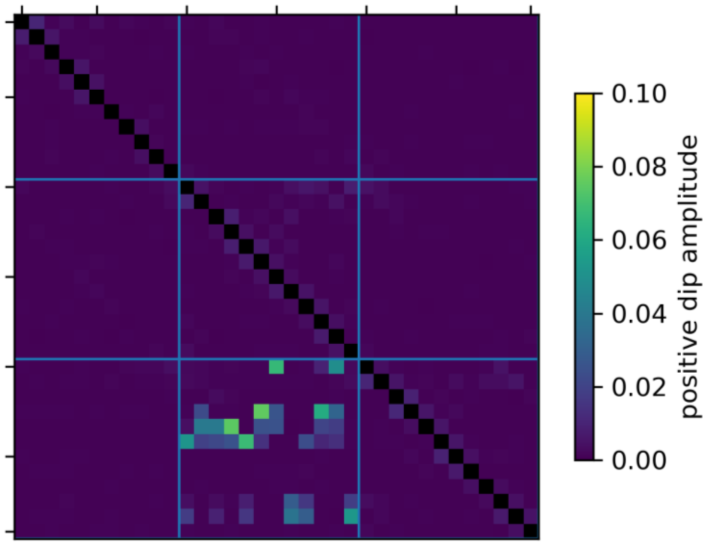


Different shapes of crosstalk

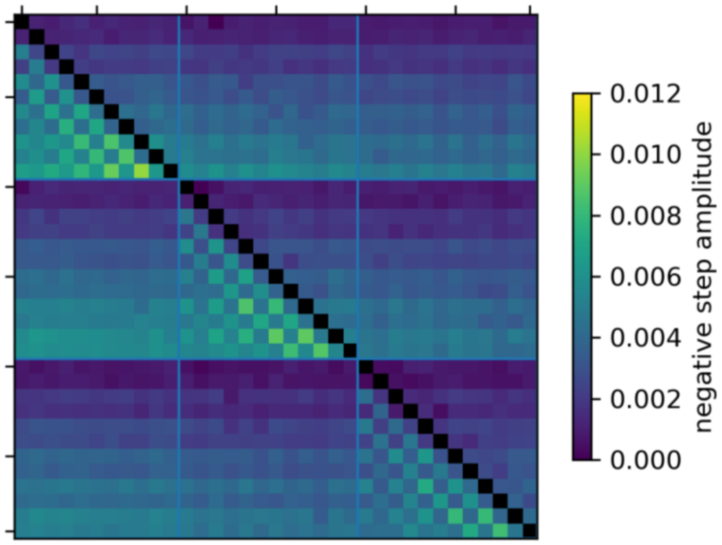




negative dip



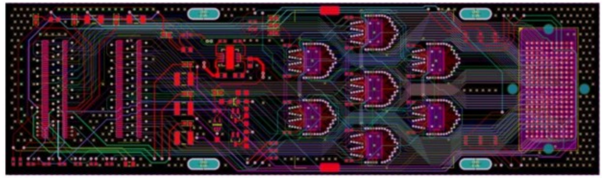
positive dip



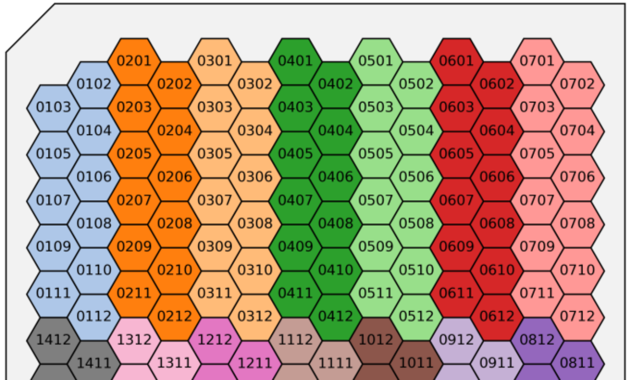
negative step

- FB→SC coupling
- already reduced by factor ~2 by SDD routing modifications
- remaining outliers fit to Z-ray connector

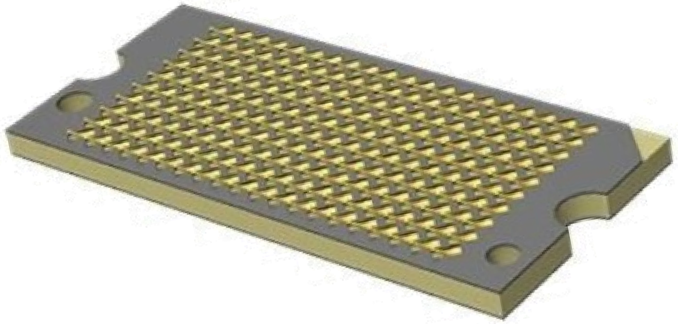
- OUT→SC coupling
- ASIC board routing

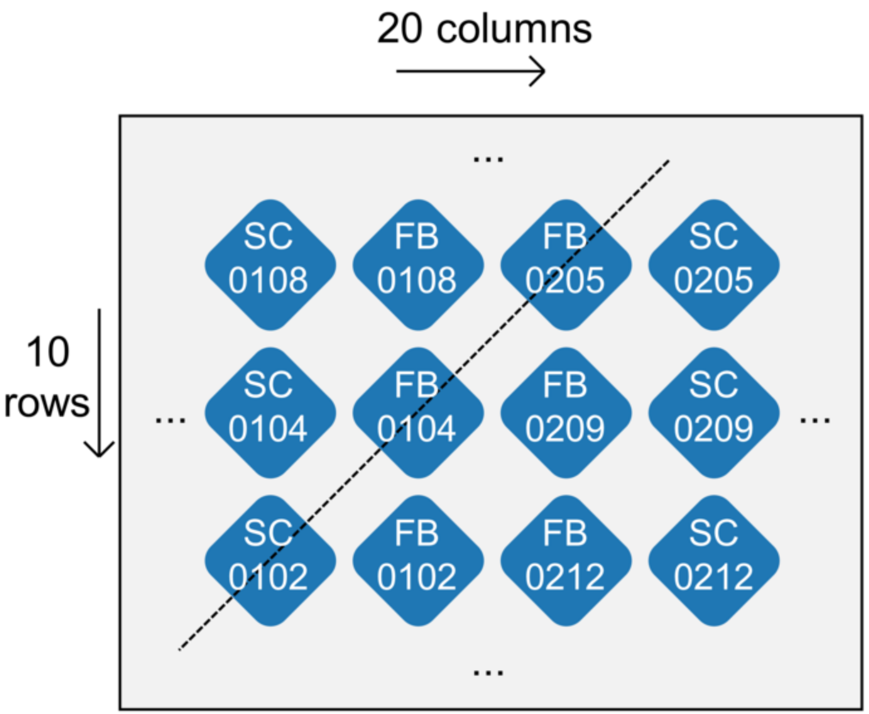


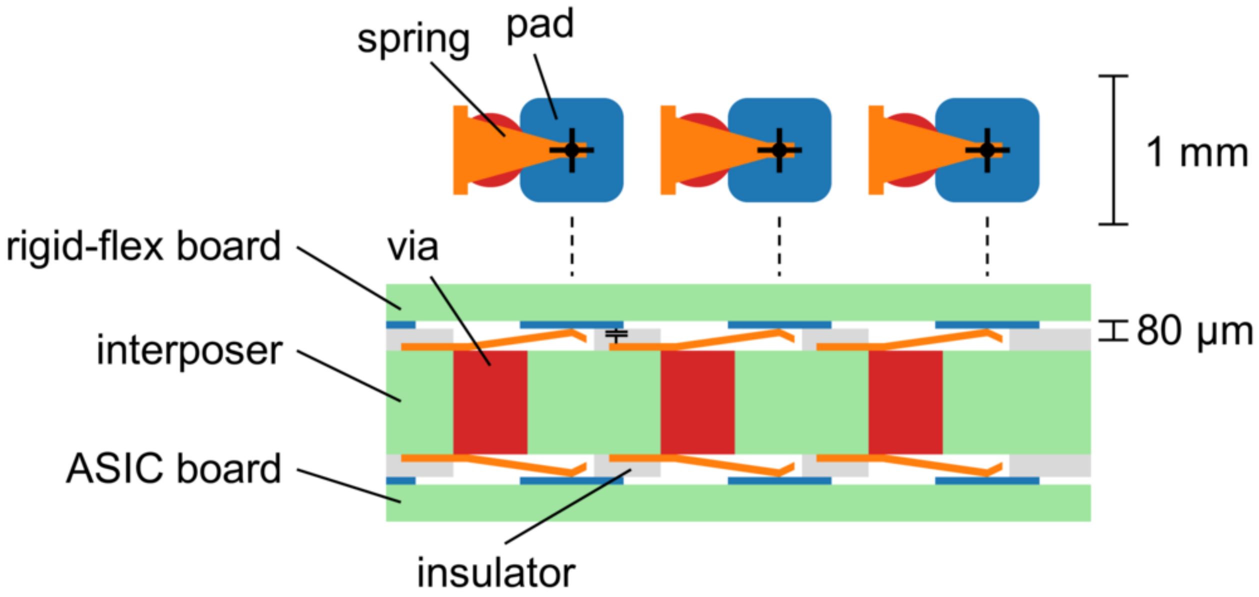
- possible mechanism: supply lines



Crosstalk in z-ray connector







Electronics noise

three dominating effects:

- thermal noise in front-end JFET
  - **series noise**, white noise independent of f

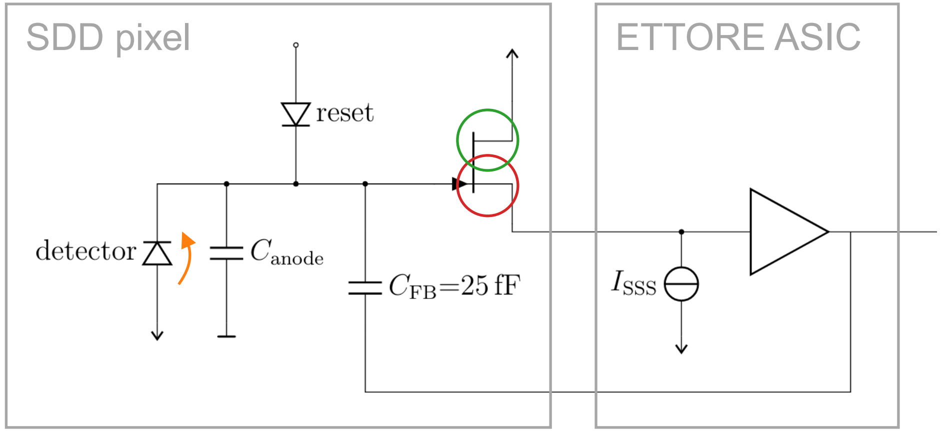
$$\frac{C^2 8 k_B T}{3 g_m}$$

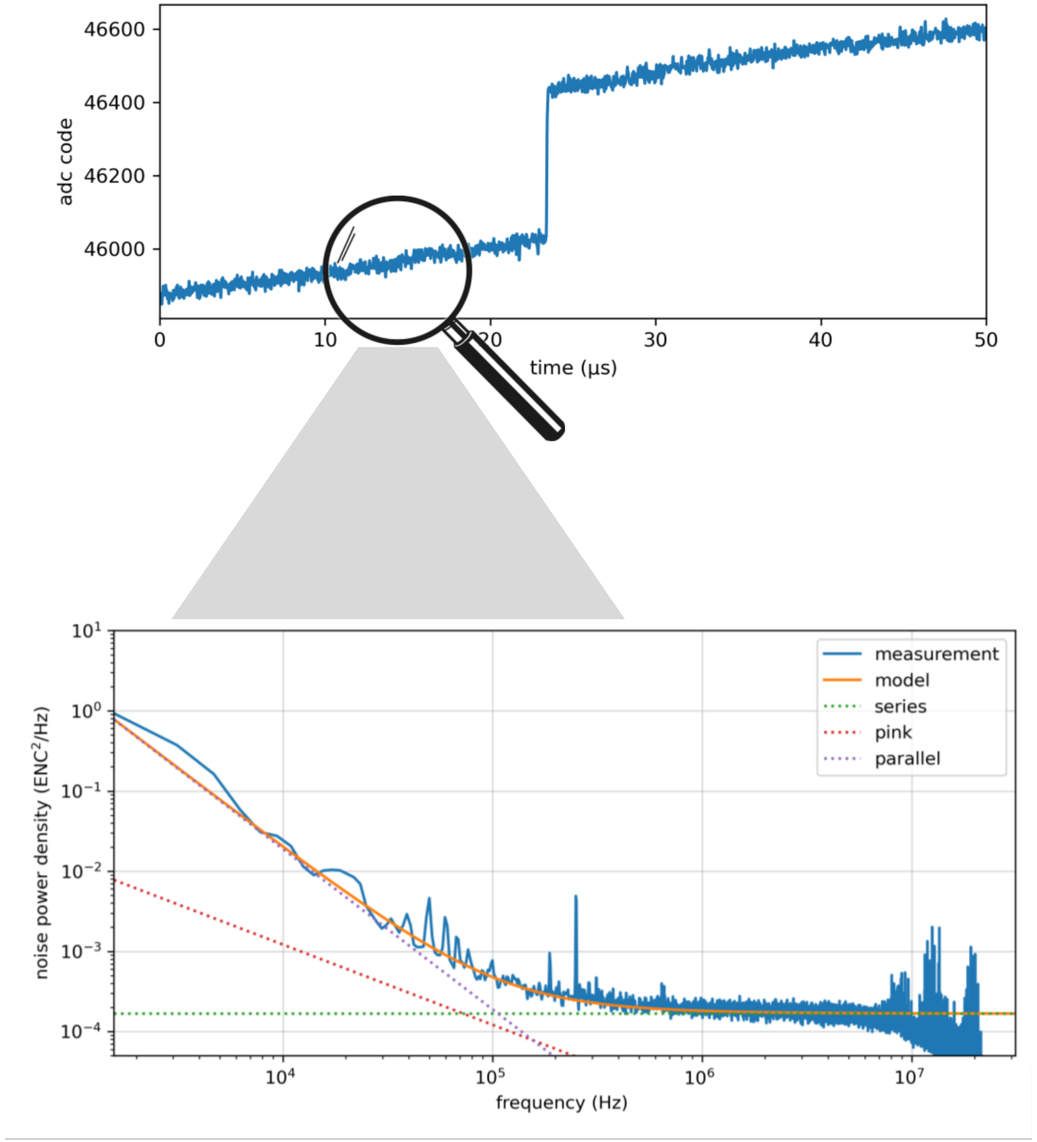
- 1/f noise in front-end JFET
  - **pink noise**, power scales with 1/f

$$C^2 H \frac{1}{f}$$

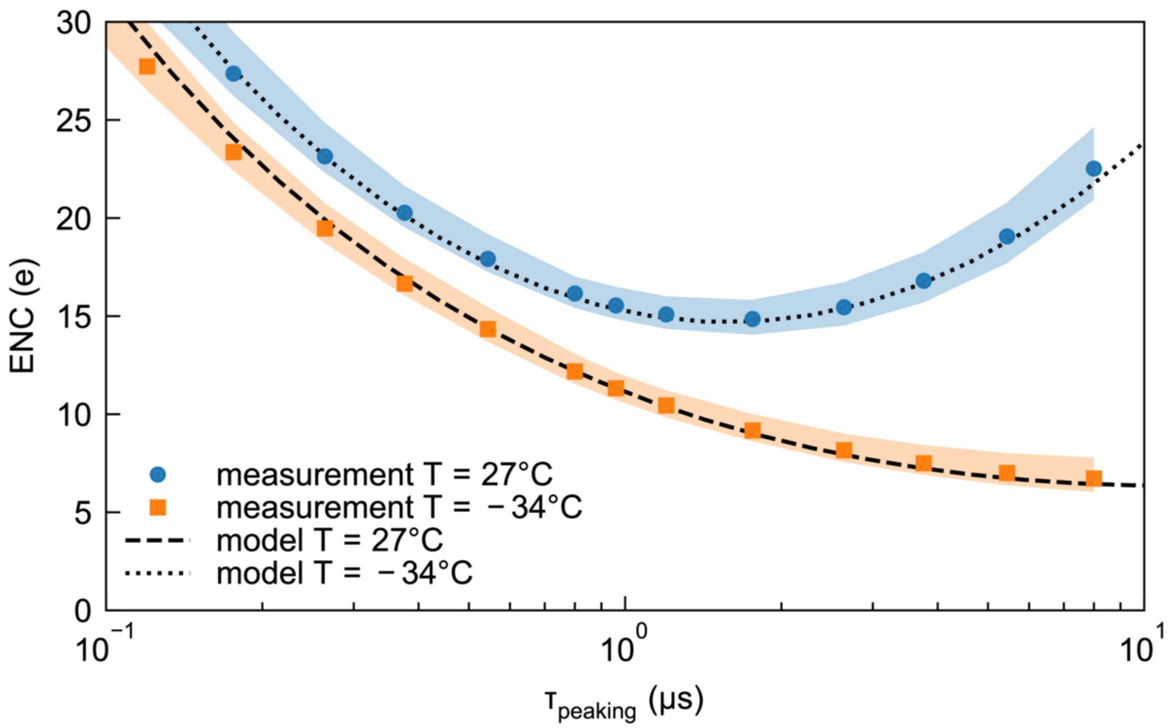
- electron statistics in leakage current
  - **parallel noise** , power scales with 1/f²

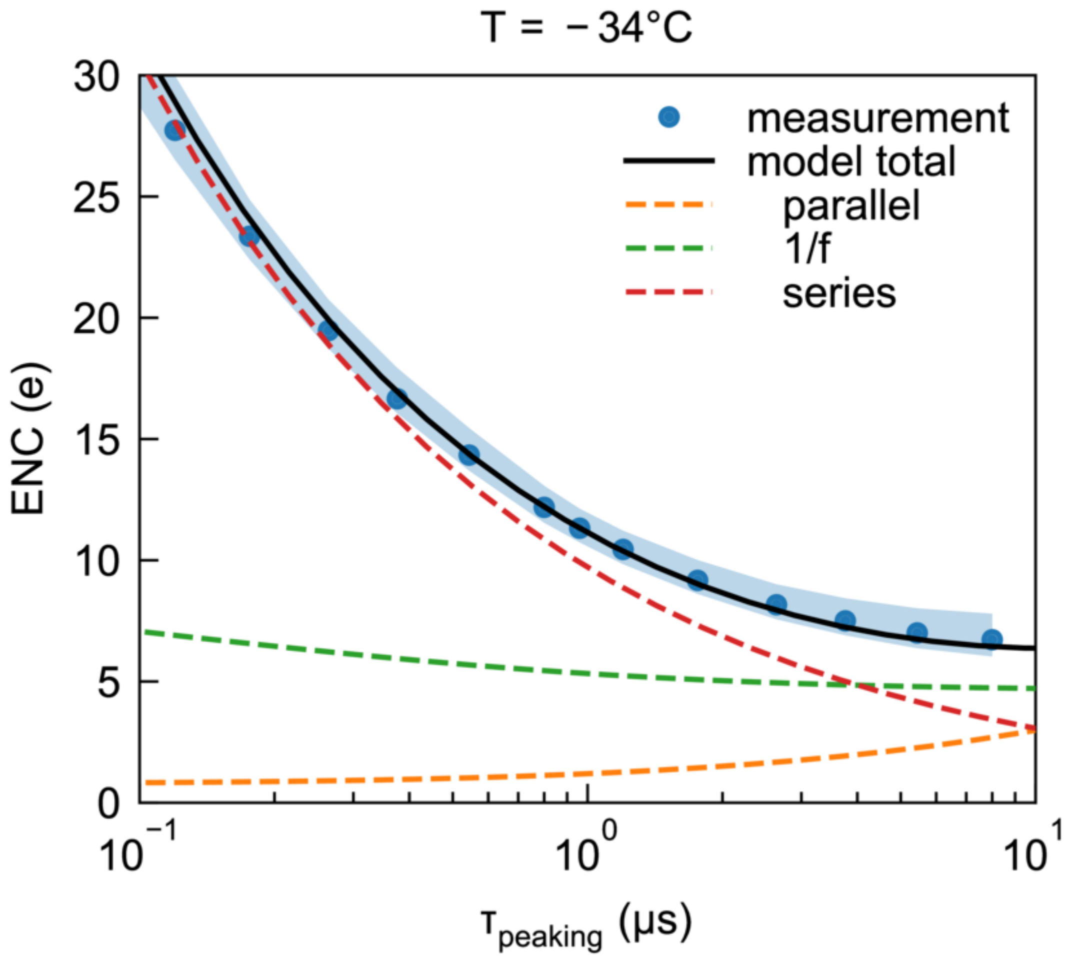
$$\frac{2eI}{(2\pi)^2} \frac{1}{f^2}$$



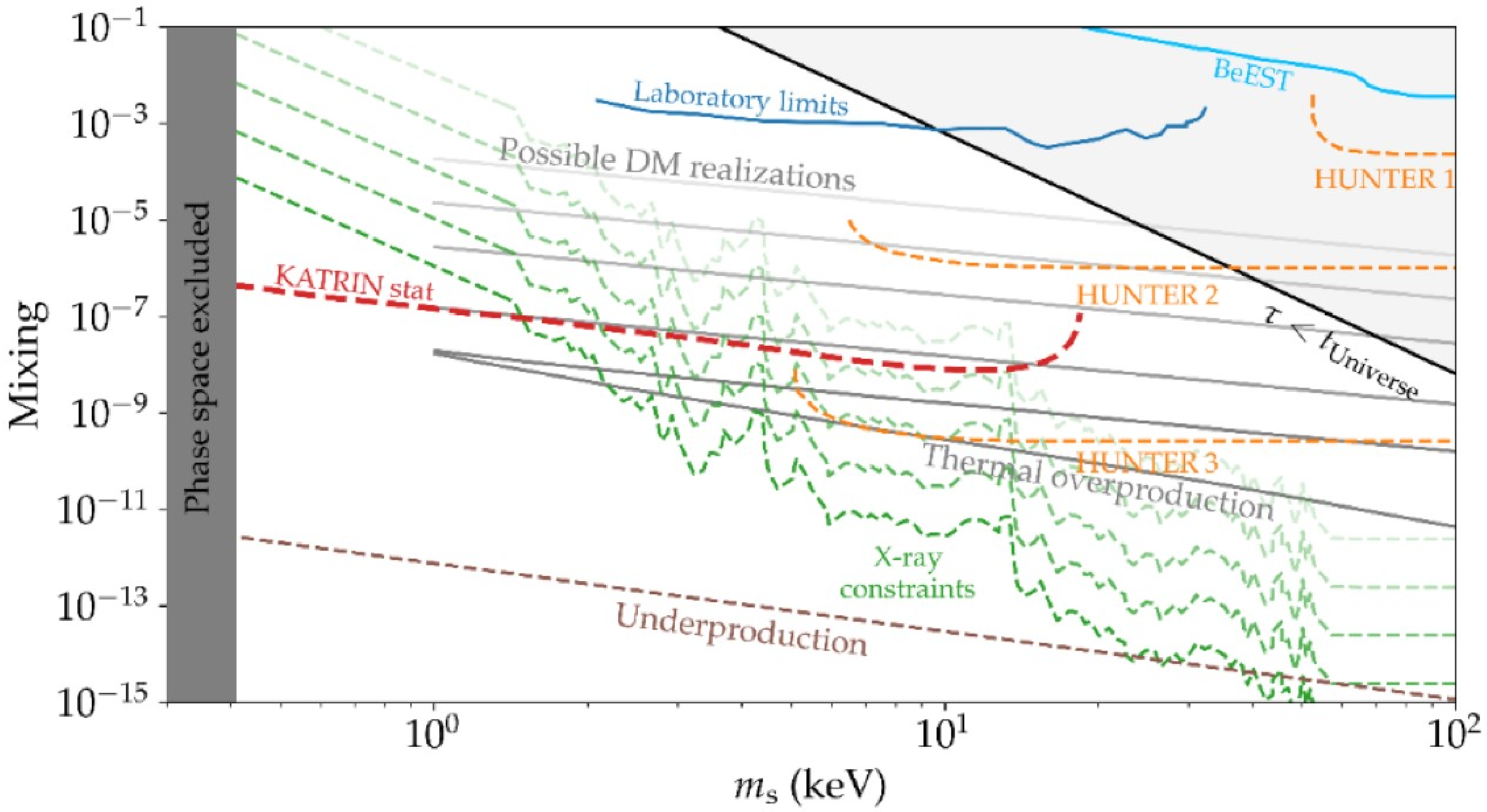


Noise curves

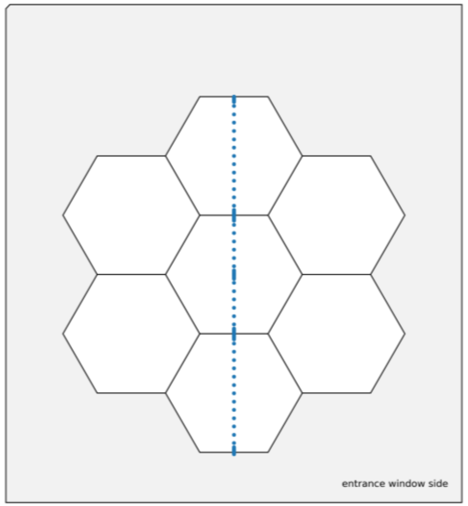




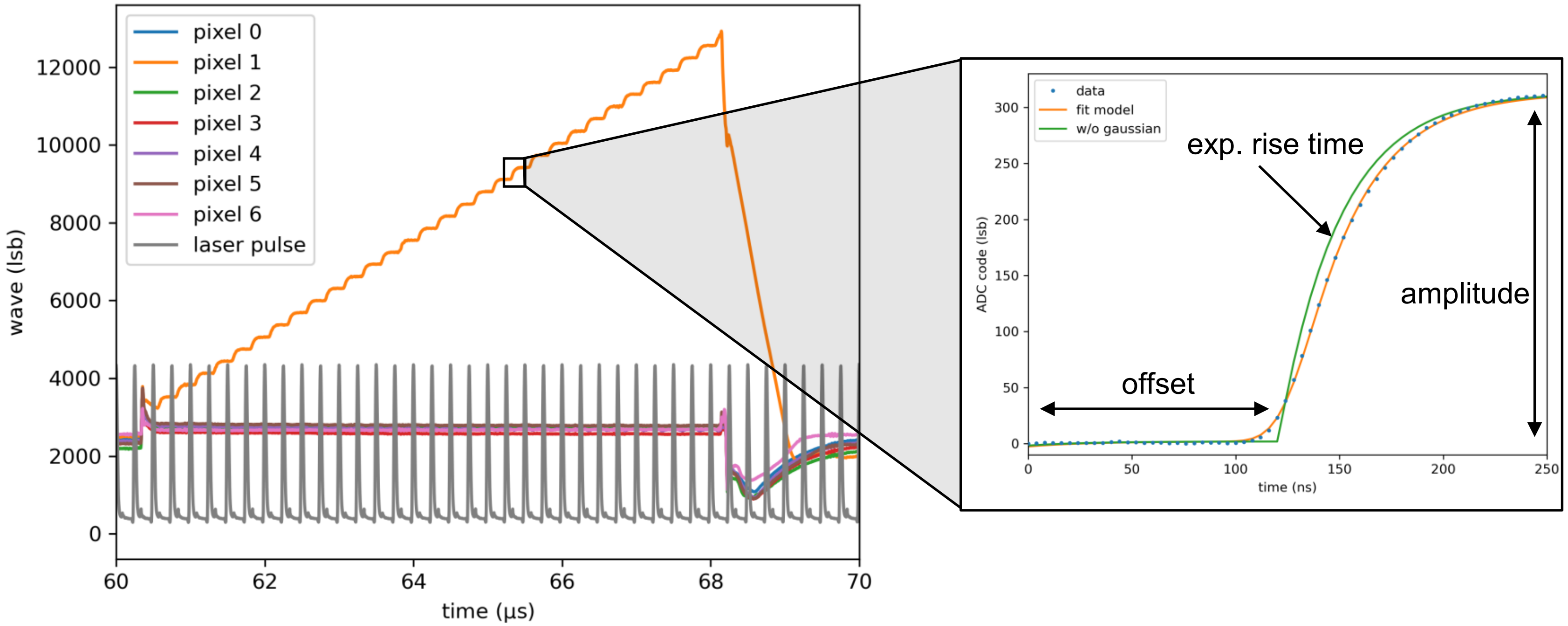
KATRIN keV sensitivity limit



Laser measurement



example waveform acquisition



- scan 125 points
- fit of detector output waveform with four parameters: **offset, amplitude, exp. rise time, gaussian width**

drift time

e.g. from electronics bandwidth

e.g. charge cloud diffusion

Electron gun