Operation of an InGrid based X-ray detector at the CAST experiment

DPG Frühjahrstagung 2015

Wuppertal

Christoph Krieger, Klaus Desch, Jochen Kaminski & Michael Lupberger

University of Bonn

9th March 2015

Physikalisches Institut

universitätbonn

Outline

The origin of the Axion

(Some of) The open questions in physics

- What is **Dark Matter**?
- What is **Dark Energy**?
- How to solve the **Strong CP Problem**?

The Peccei-Quinn mechanism

- Similar to Higgs mechanism (symmetry breaking and . . .)
- Solution to strong CP problem plus a particle for free: **axion**

How to find a good name for a particle?

Frank Wilczek:
"I named them after a laundry detergent, since they clean up a long standing problem in theoretical physics."

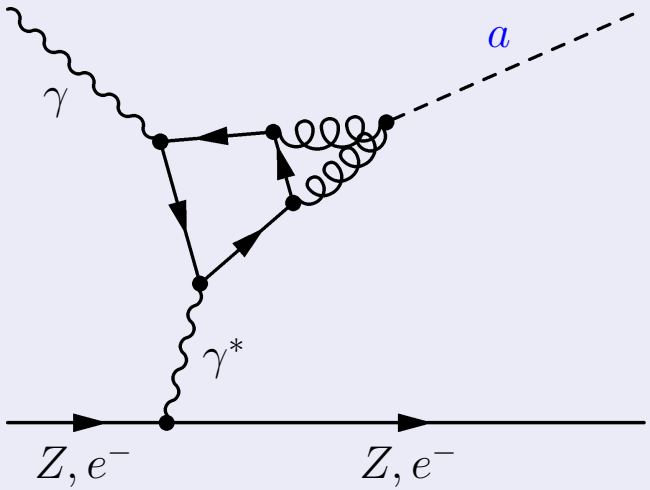
Axions in a box

The Axion as Dark Matter candidate

Axion properties

- Pseudo Nambu-Goldstone boson
- Mixing with π^0 leads to small mass and coupling to two γ
- Primakoff effect: γ-axion conversion in strong EM fields
- Small mass, weak couplings and huge lifetime make axions a good candidate for **Dark Matter**

Primakoff effect



An axion source?

- Need huge photon flux
- Need strong EM fields
- Axion production in the core of the Sun
- Black body spectrum (few keV)

The CERN Axion Solar Telescope

CAST pointing to the Sun

Some facts

- Magnet: 9 T, 1.8 K, 13 kA, 10 m long
- Structure: $\sim$ 40 t, $\pm 8^\circ$ vertical, $\pm 40^\circ$ horizontal
- Sun tracking: 2×1.5 h/d (sunrise & sunset)
- Detectors: $3\times$ Micromegas (1 with XRT), XRT + pnCCD

The CERN Axion Solar Telescope

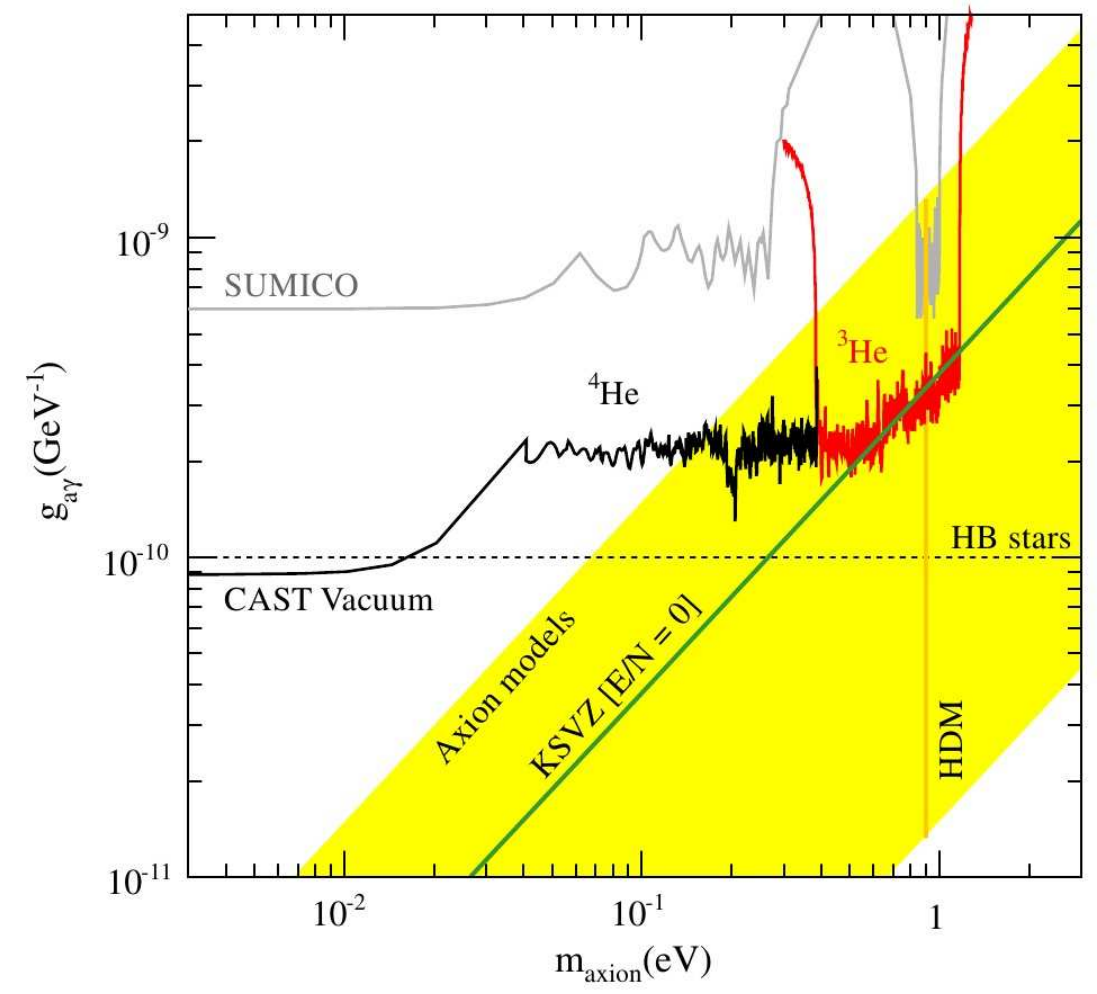
CAST pointing to the Sun

Some facts

- Magnet: 9 T, 1.8 K, 13 kA, 10 m long
- Structure: $\sim$ 40 t, $\pm 8^\circ$ vertical, $\pm 40^\circ$ horizontal
- Sun tracking: 2×1.5 h/d (sunrise & sunset)
- Detectors: $3\times$ Micromegas (1 with XRT), XRT + InGrid

CAST – Results so far

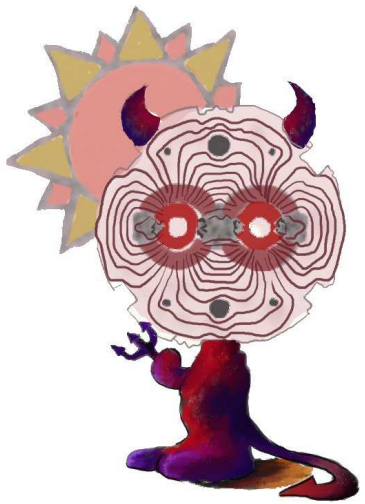
Exclusion plot



PRL-112-09-1302(2013)

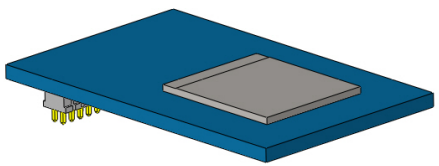
Exclusion limit

- No axions found up to now ;-)
- So far CAST could set the most stringent limit for solar axions



An InGrid based X-ray detector

Timepix with InGrid on carrier board

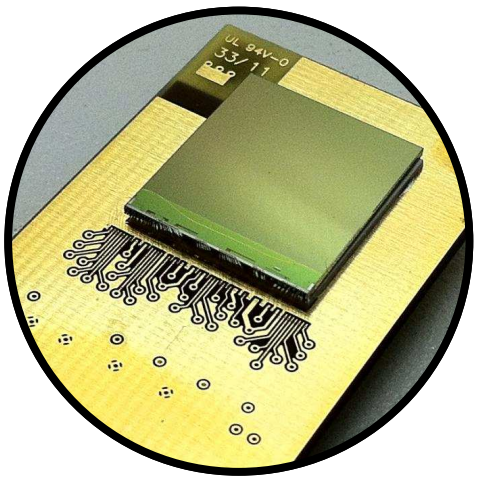


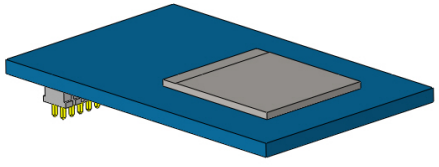
An InGrid based X-ray detector

Timepix with InGrid on carrier board

Pixelized readout chip: 256×256 pixels, 55 µm pitch

Active area: $\sim 1.4 \times 1.4\,\mathrm{cm}^2$

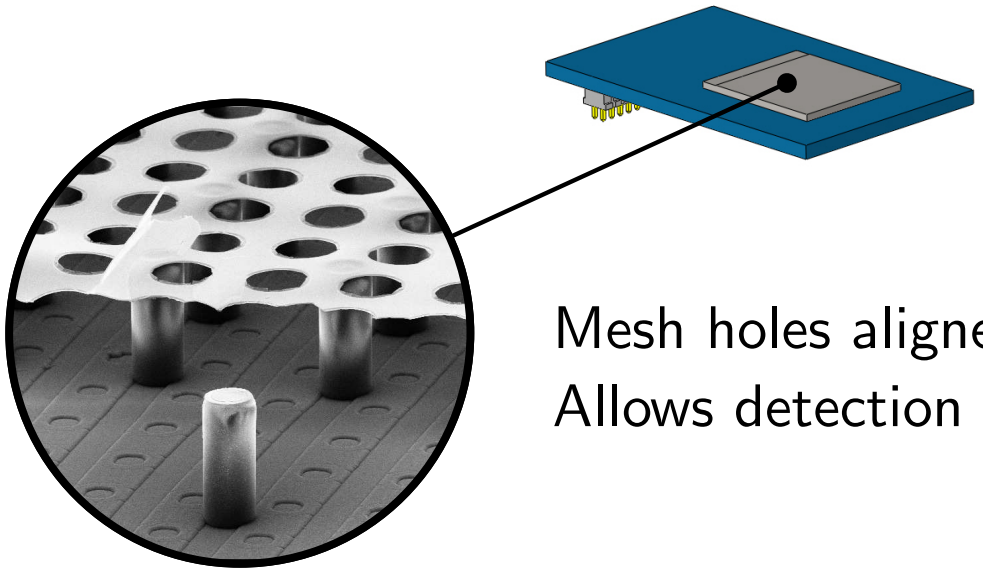




An InGrid based X-ray detector

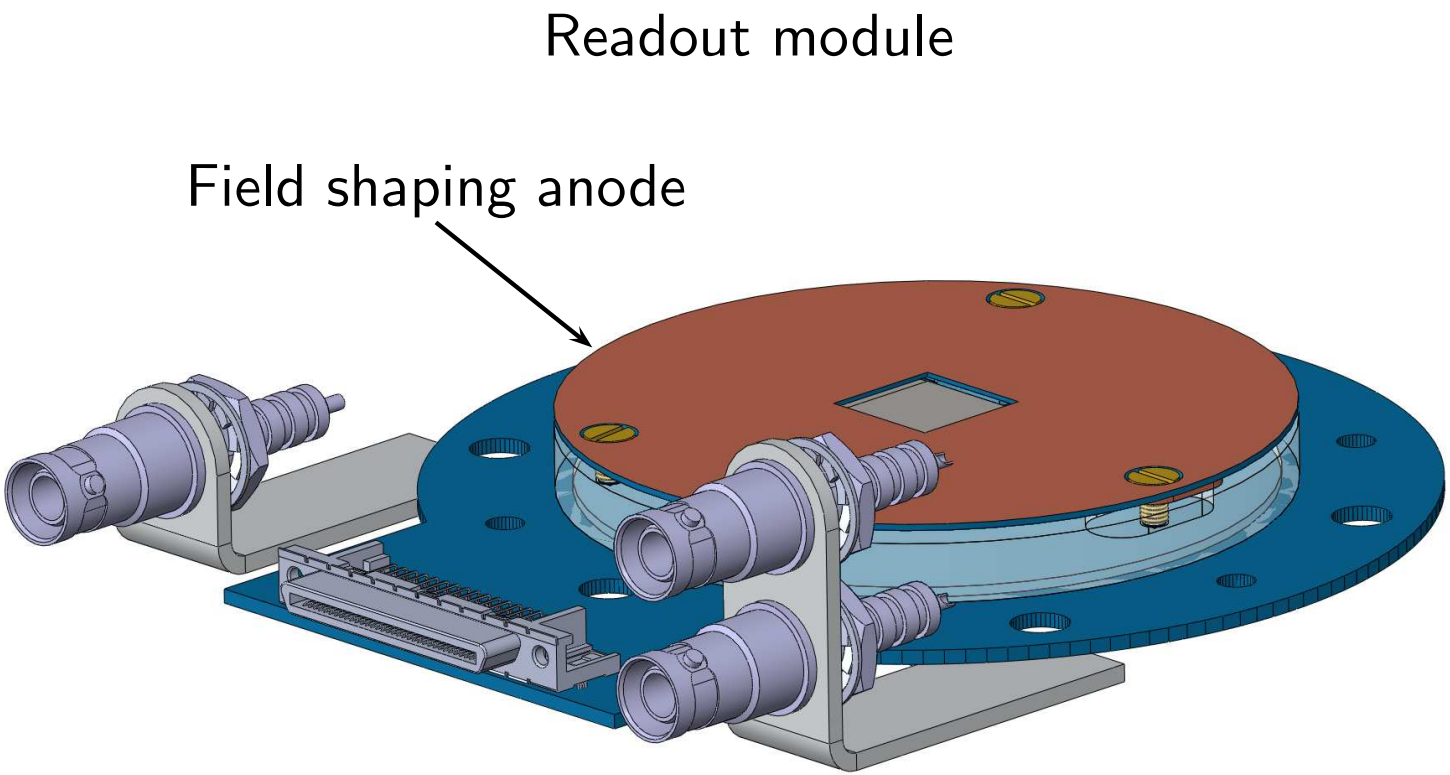
Timepix with **InGrid** on carrier board

Integrated Micromegas stage
Photolithographic postprocessing technology



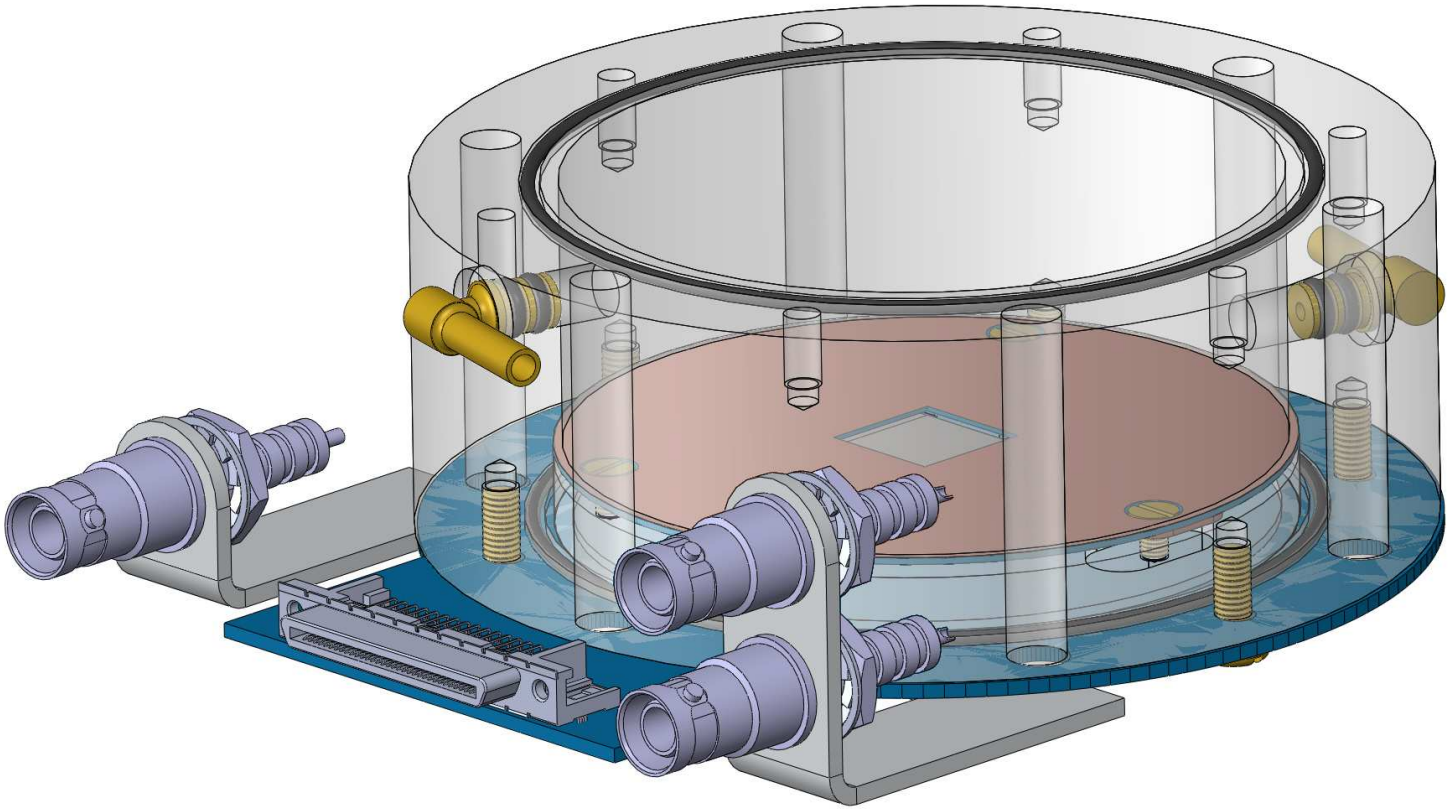
Mesh holes aligned with pixels
Allows detection of single electrons

An InGrid based X-ray detector



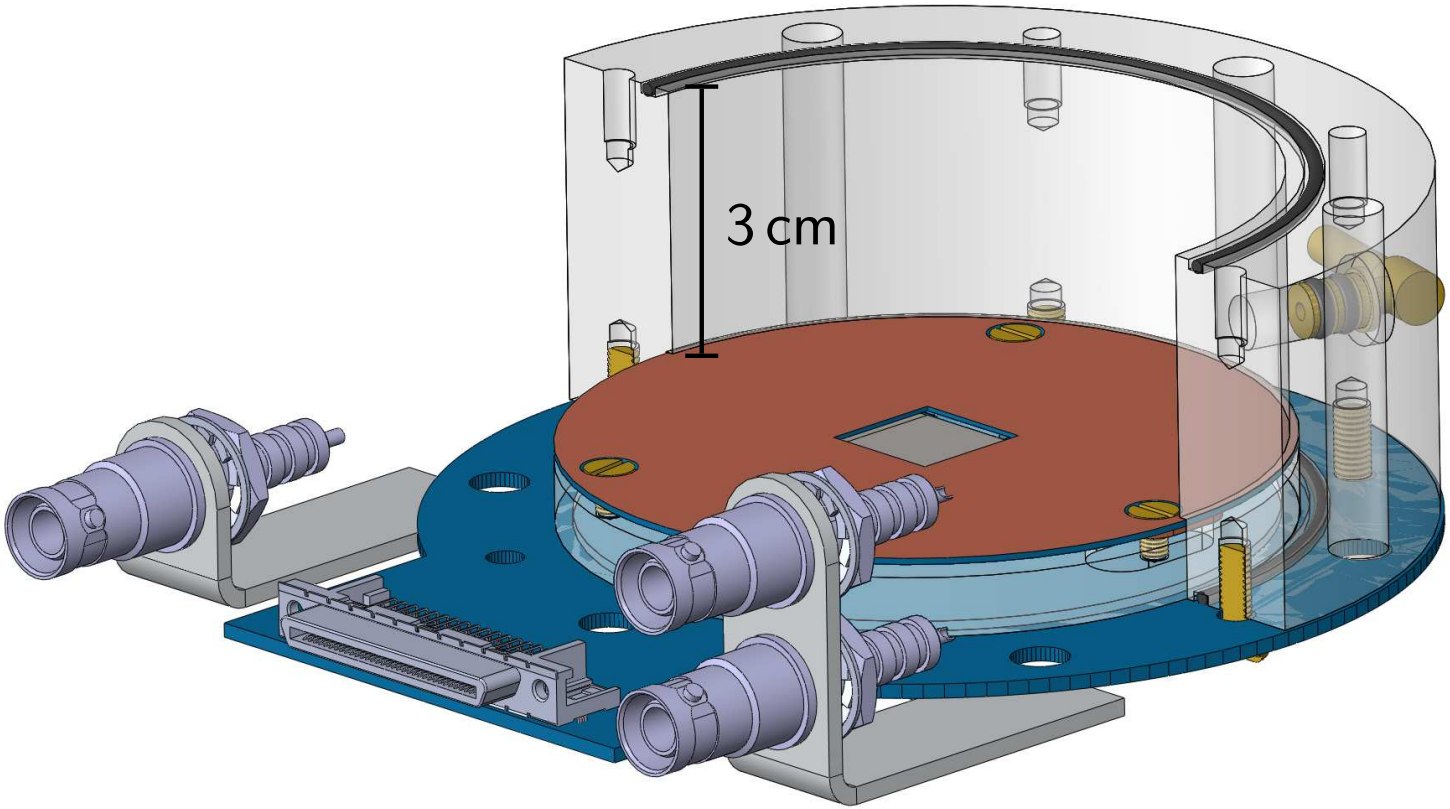
An InGrid based X-ray detector

Drift volume flushed with Ar/iC_4H_{10} $97.7/2.3$

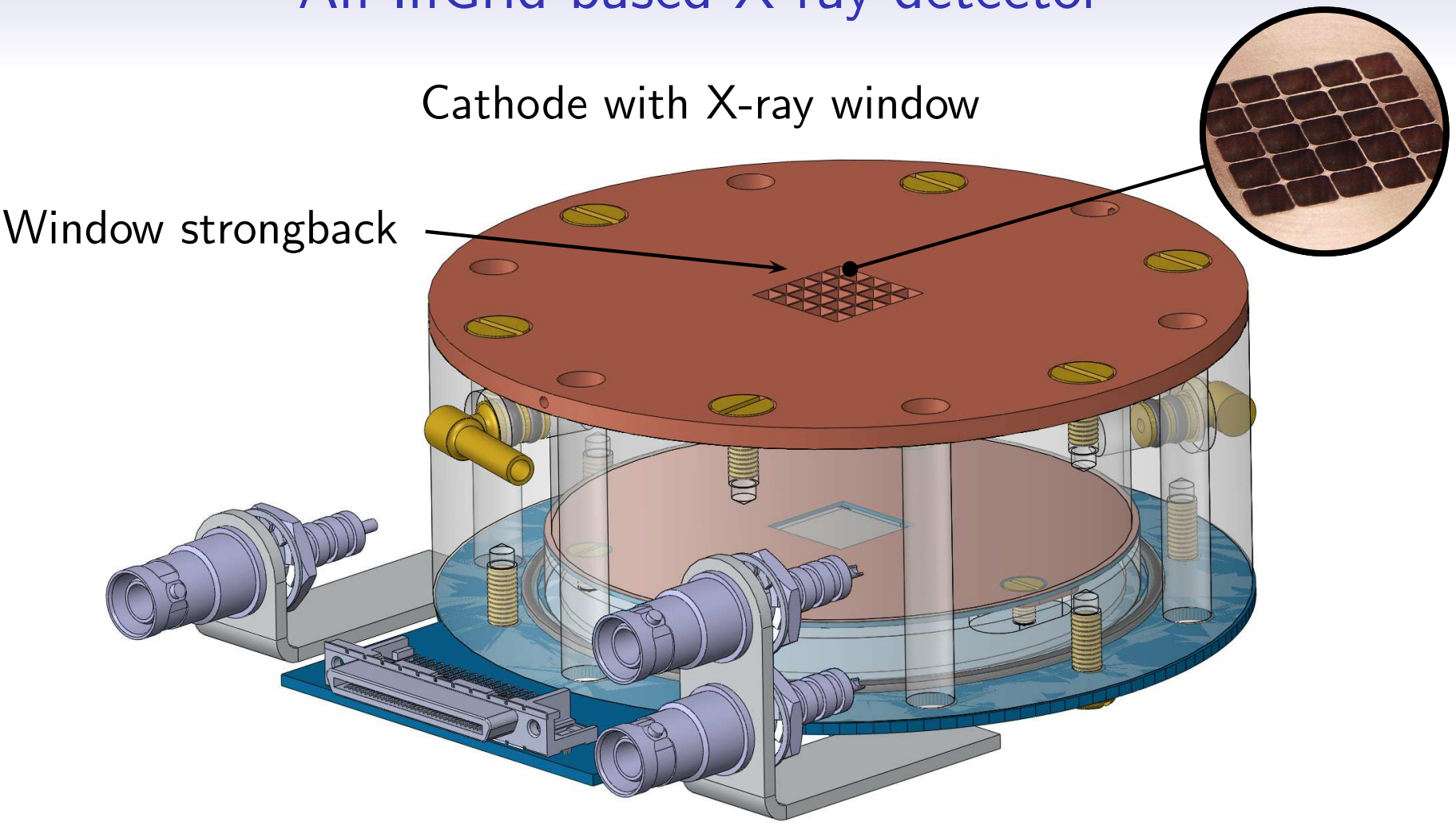


An InGrid based X-ray detector

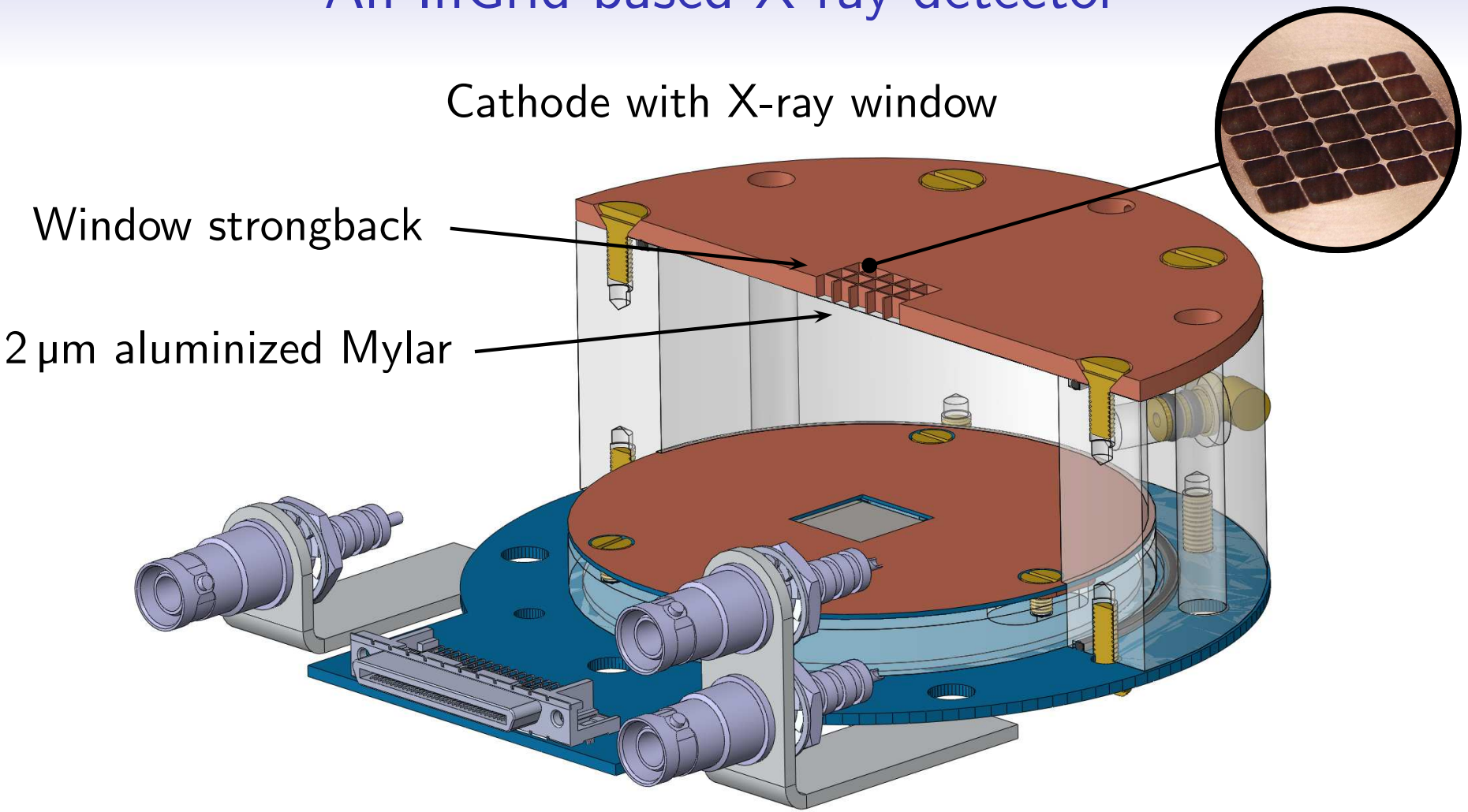
Drift volume flushed with Ar/iC_4H_{10} $97.7/2.3$



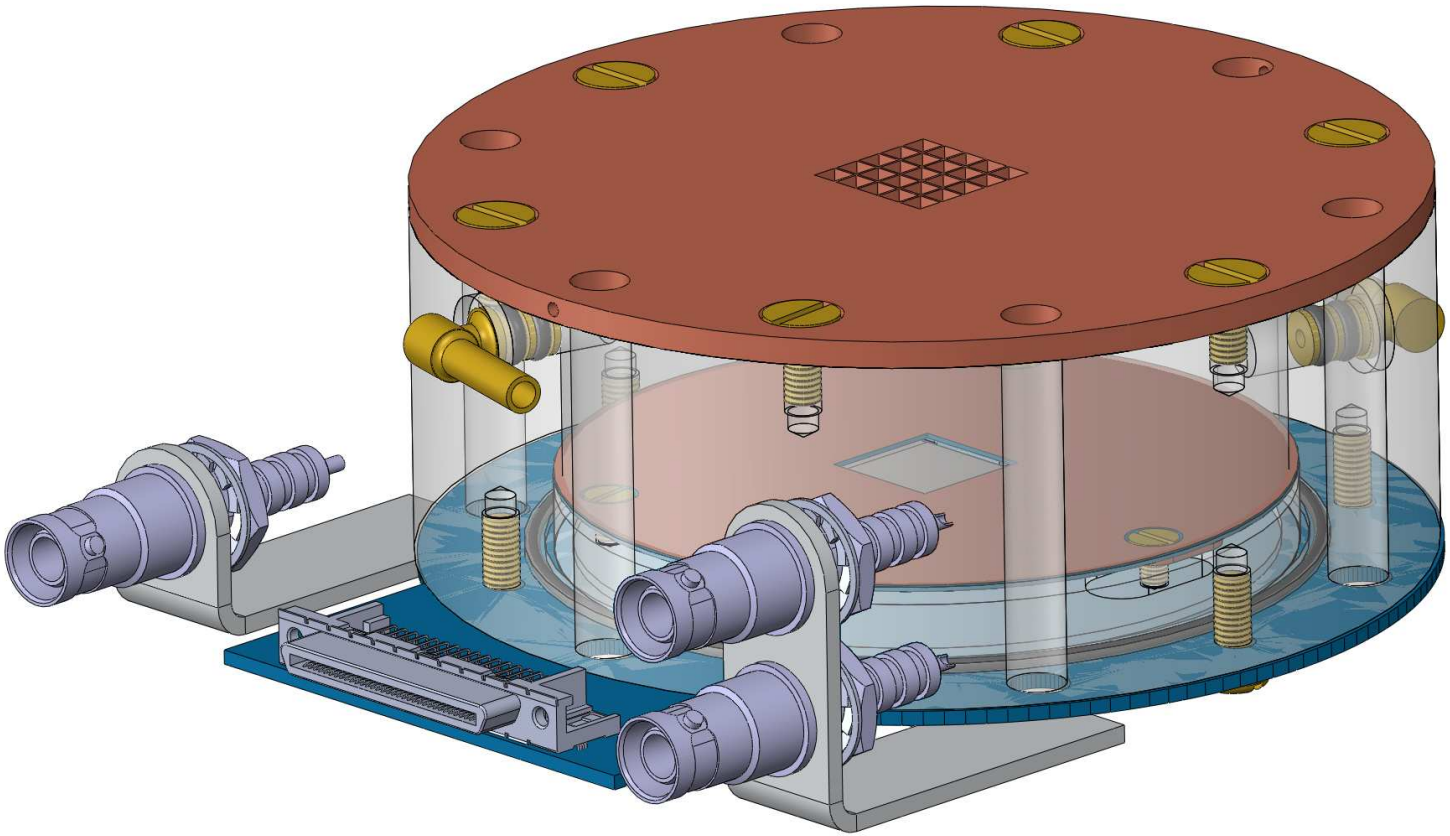
An InGrid based X-ray detector



An InGrid based X-ray detector

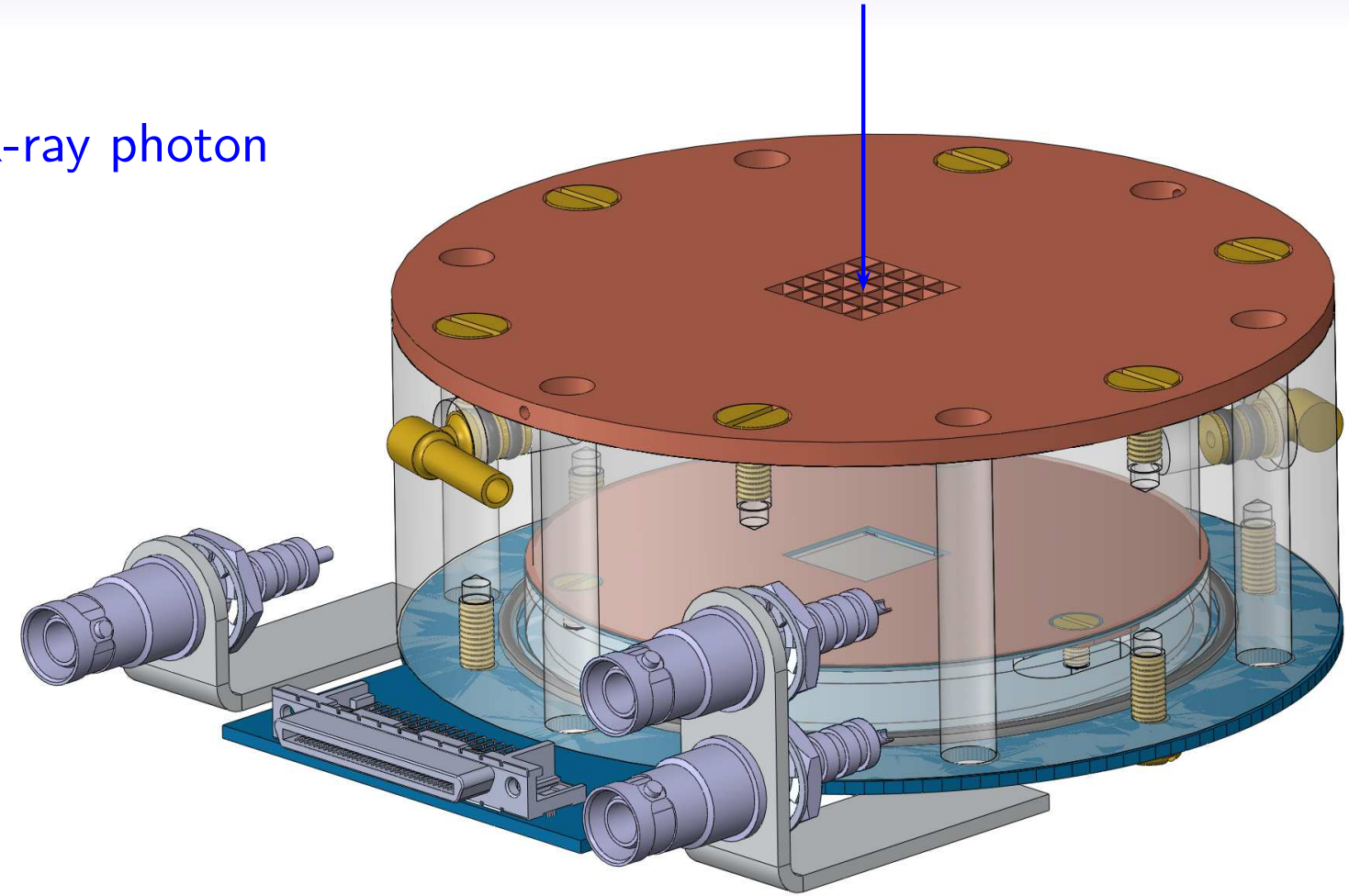


An InGrid based X-ray detector – How does it work?



An InGrid based X-ray detector – How does it work?

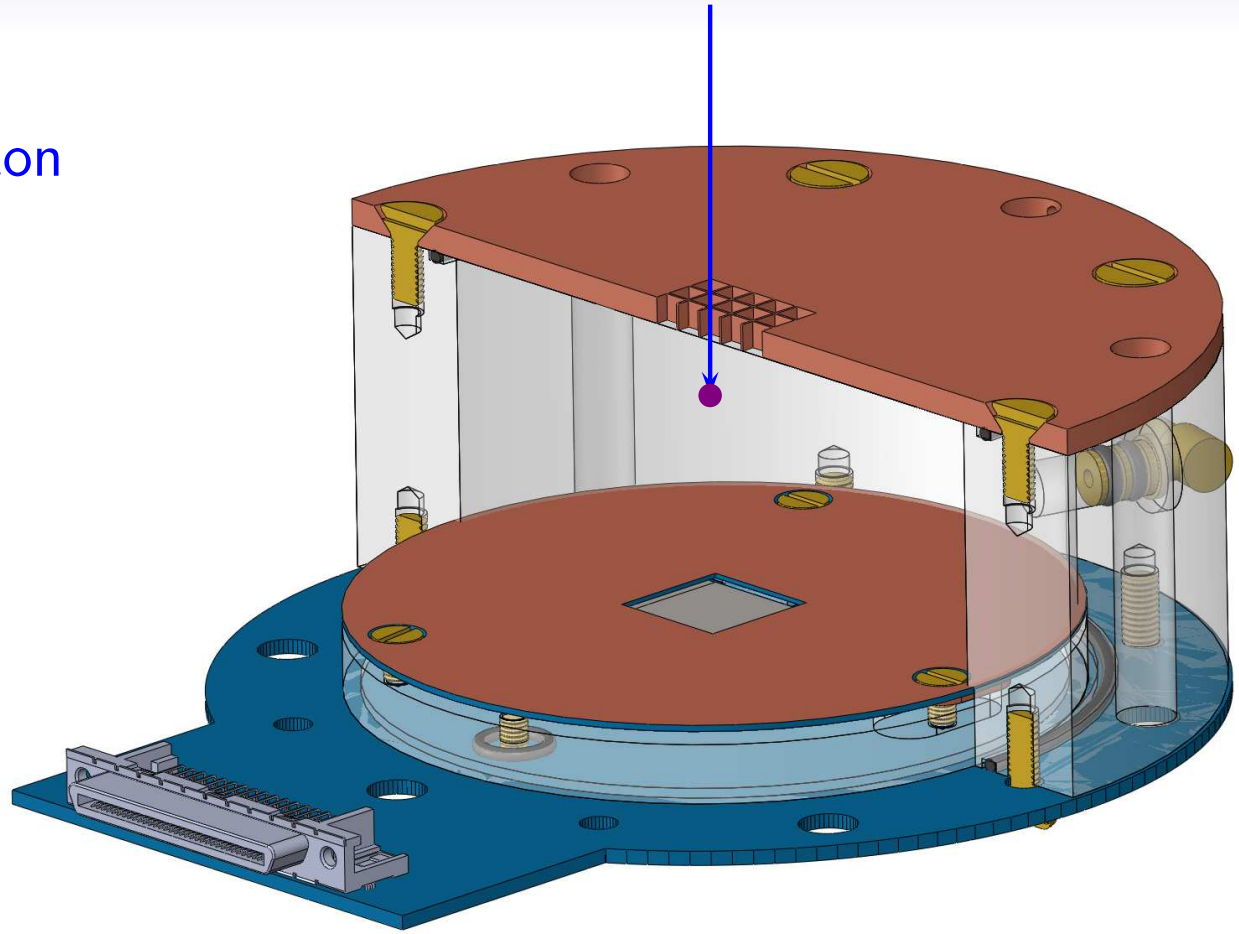
X-ray photon



An InGrid based X-ray detector – How does it work?

X-ray photon

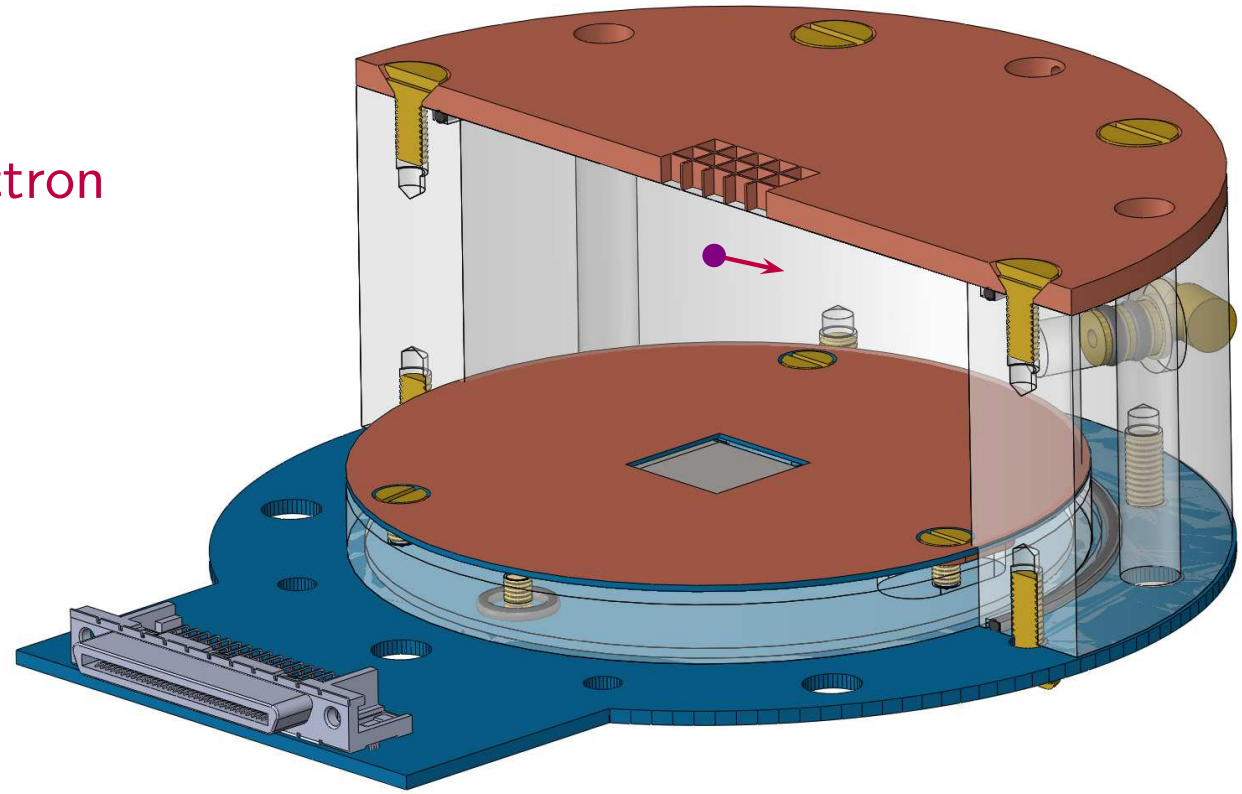
Gas atom



An InGrid based X-ray detector – How does it work?

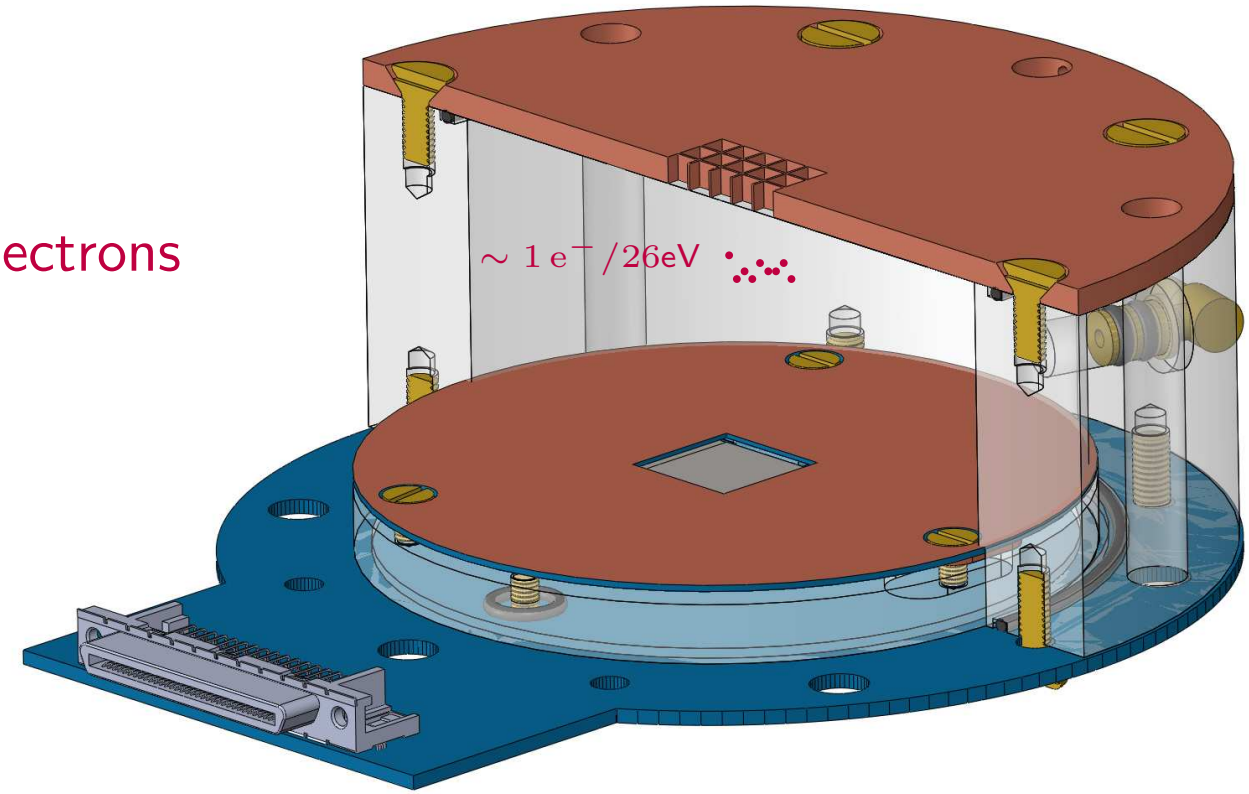
Gas atom

Photo electron



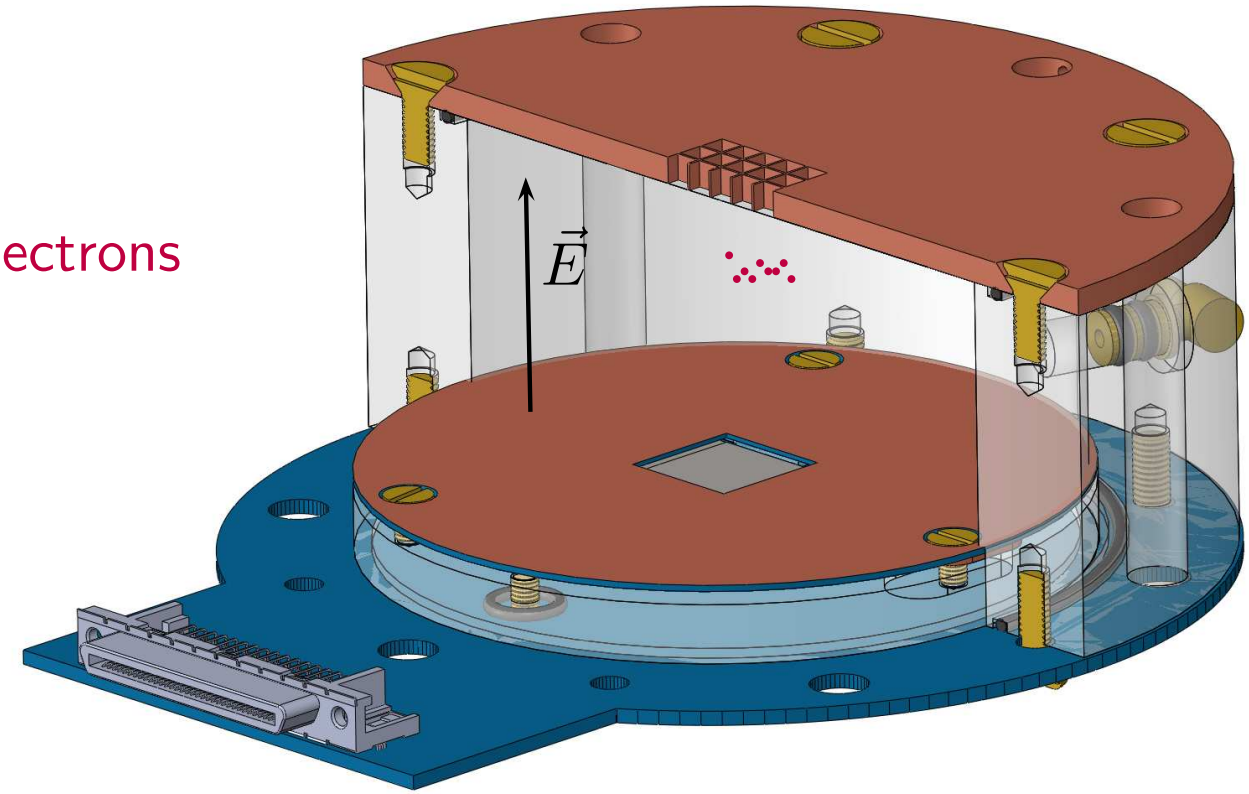
An InGrid based X-ray detector – How does it work?

Primary electrons



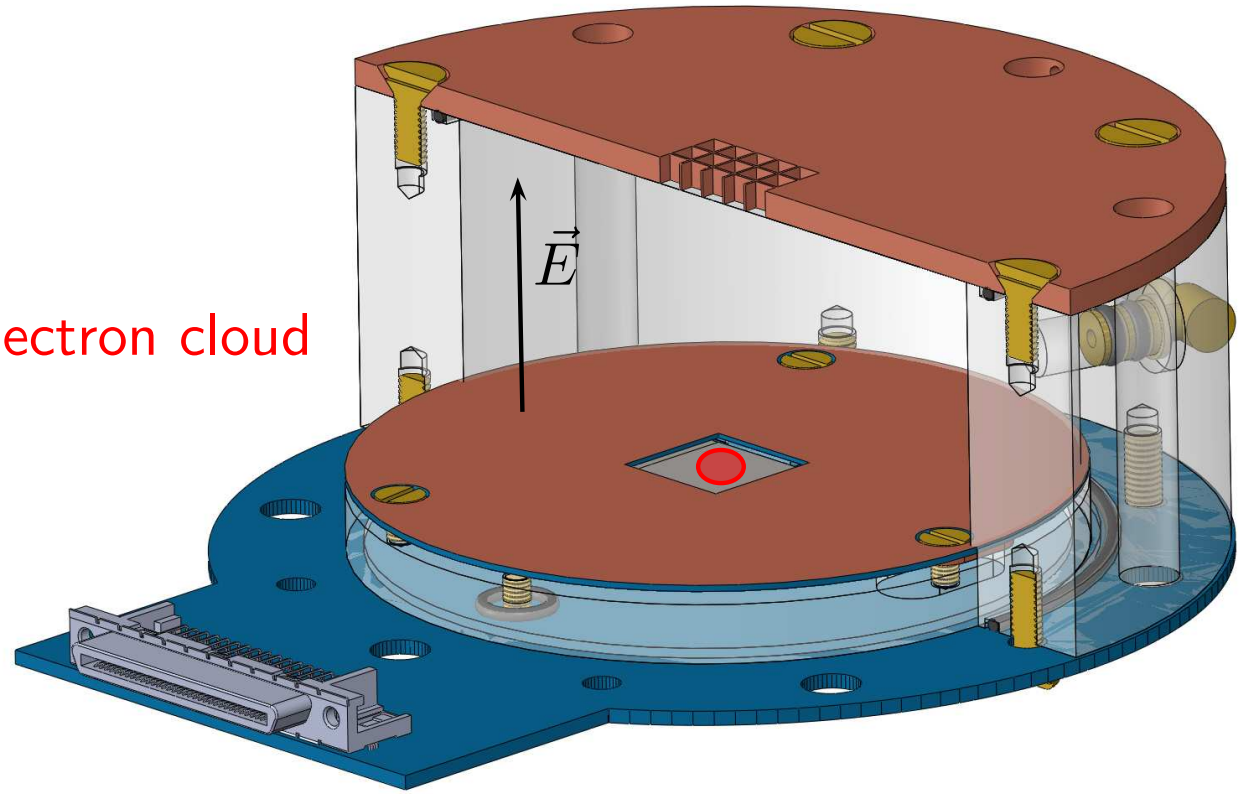
An InGrid based X-ray detector – How does it work?

Primary electrons

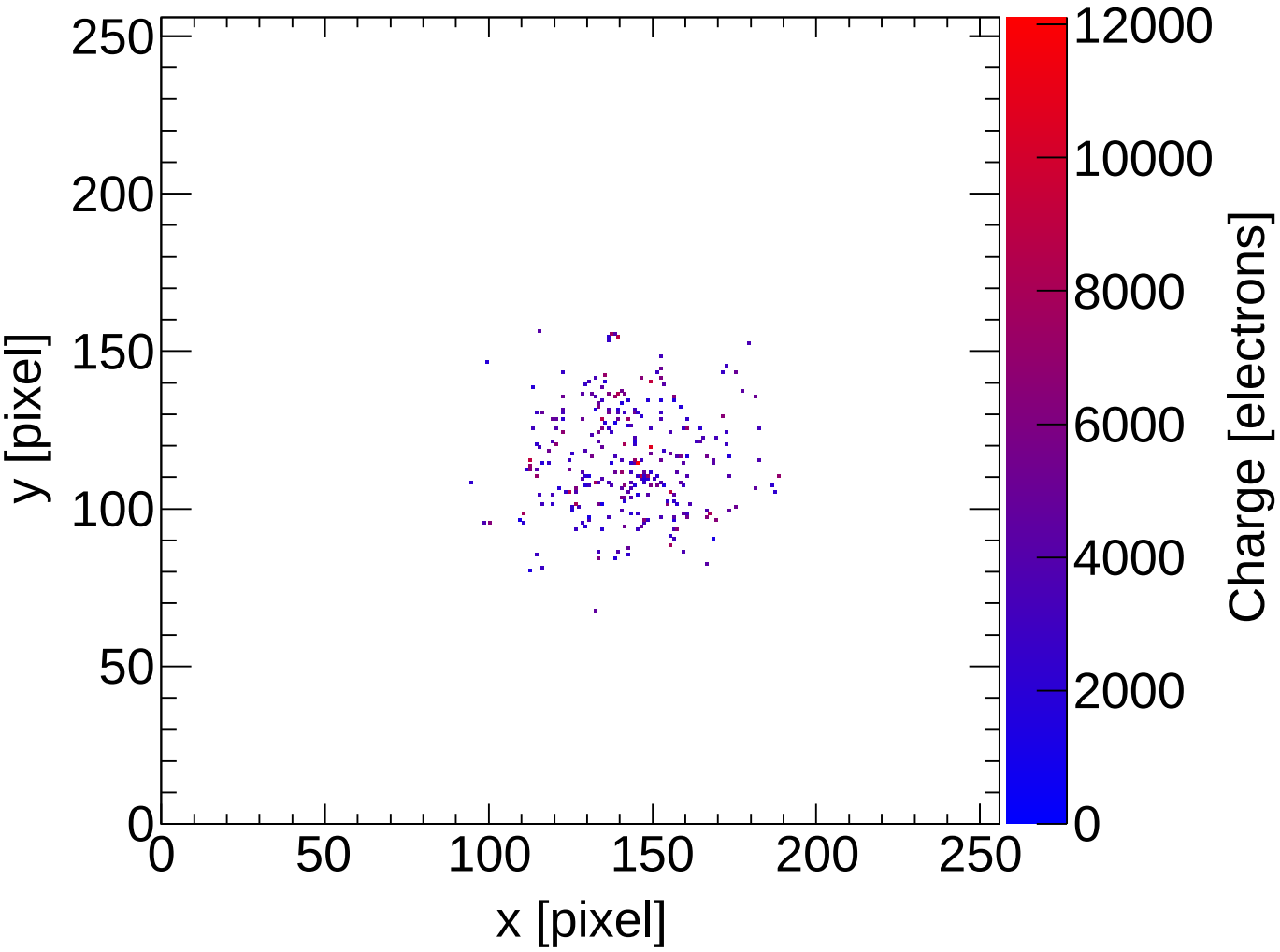


An InGrid based X-ray detector – How does it work?

Diffused electron cloud



Typical X-ray event

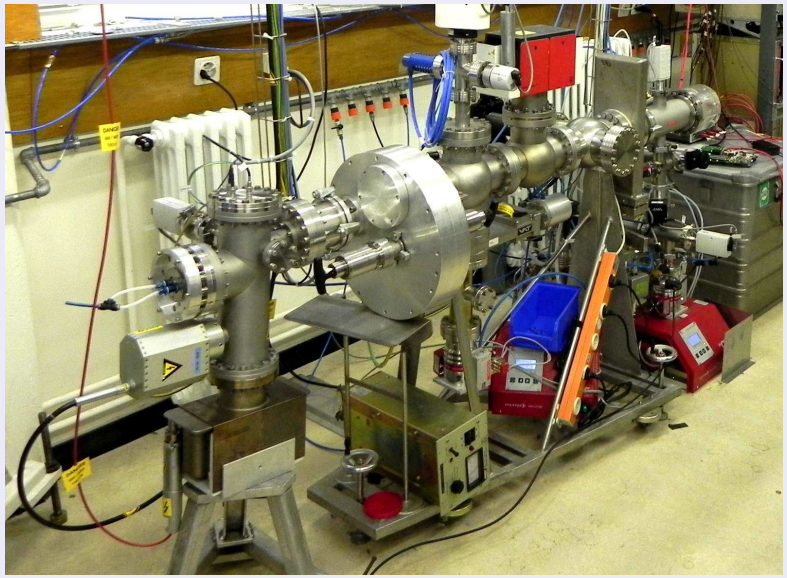


Benefits of an InGrid based X-ray detector

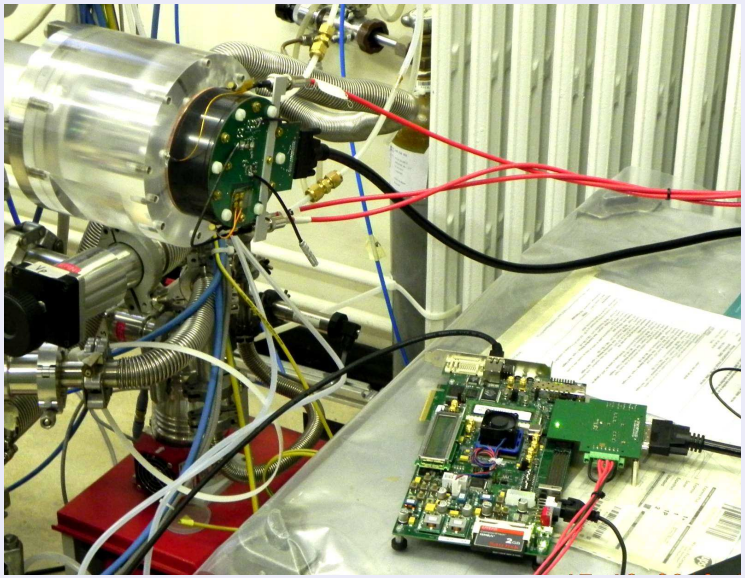
- Advantages in comparison to standard Micromegas detectors:
  - Very high spatial resolution
  - Ability to detect single electrons
  - Integrated analog electronics, no analog signal routing to outside, purely digital output
- X-ray photon detection threshold well below 1 keV
  (Each electron/pixel corresponds to ~ 26 eV)
- Background suppression through event shape analysis

The CAST Detector Lab

X-ray Generator & Beamline



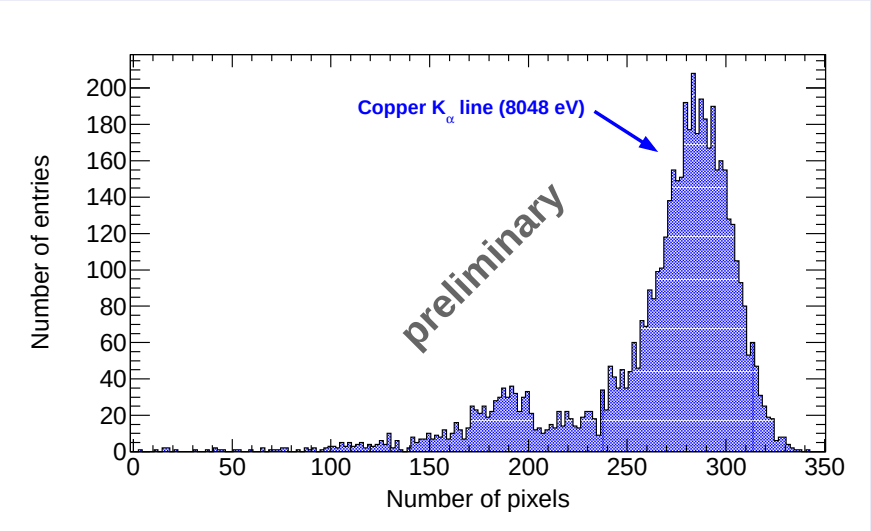
InGrid Detector at CDL

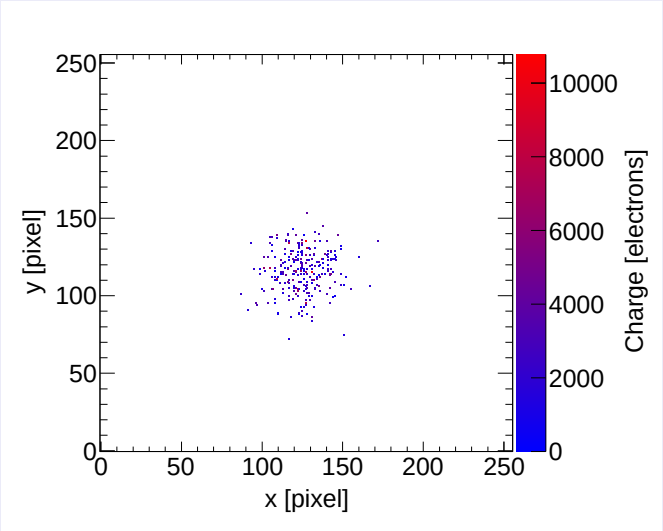


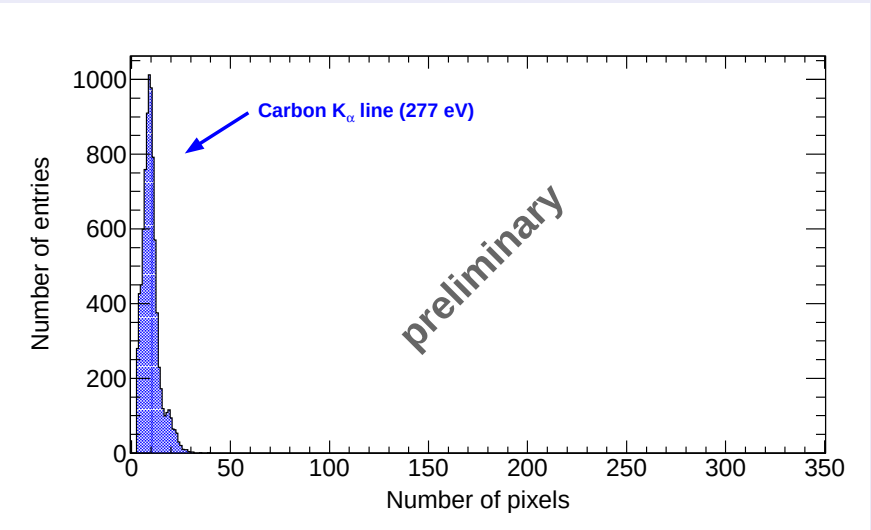
Infrastructure

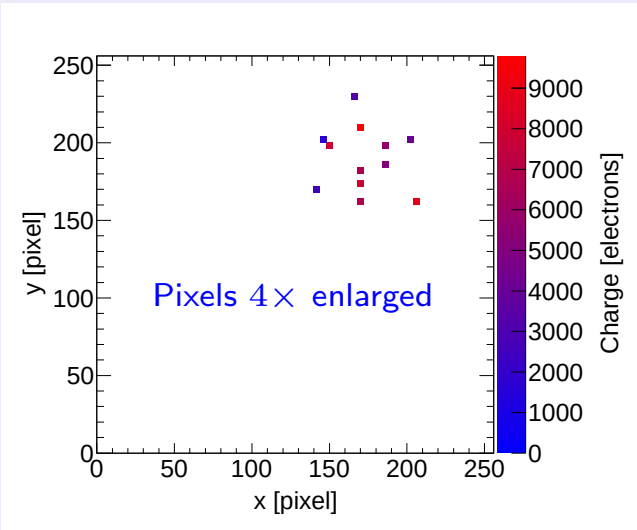
- X-ray tube with exchangeable targets and filter wheels
- X-ray energies down to few hundred eV
- Vacuum system allowing for differential pumping

From 8 keV down to 277 eV

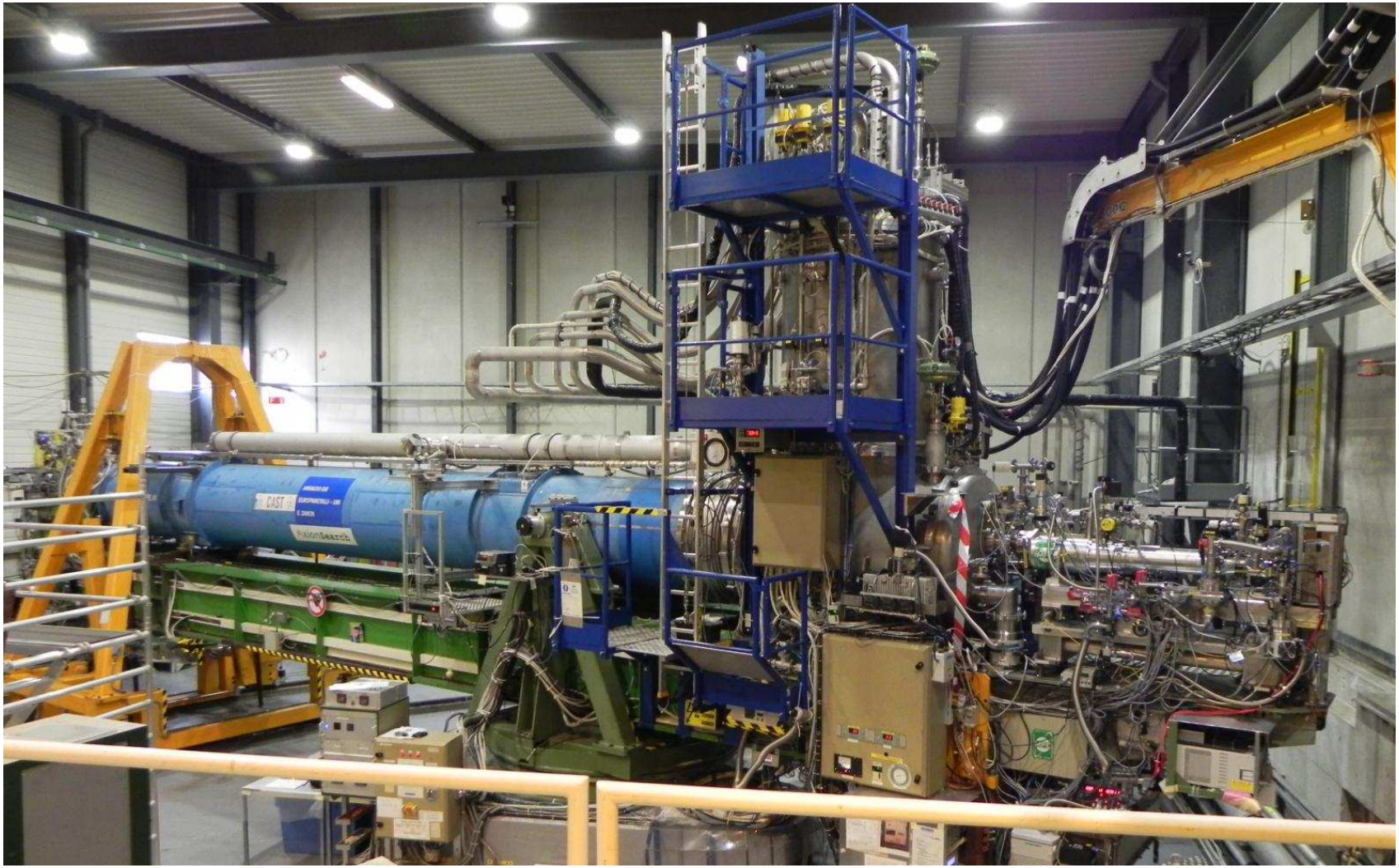




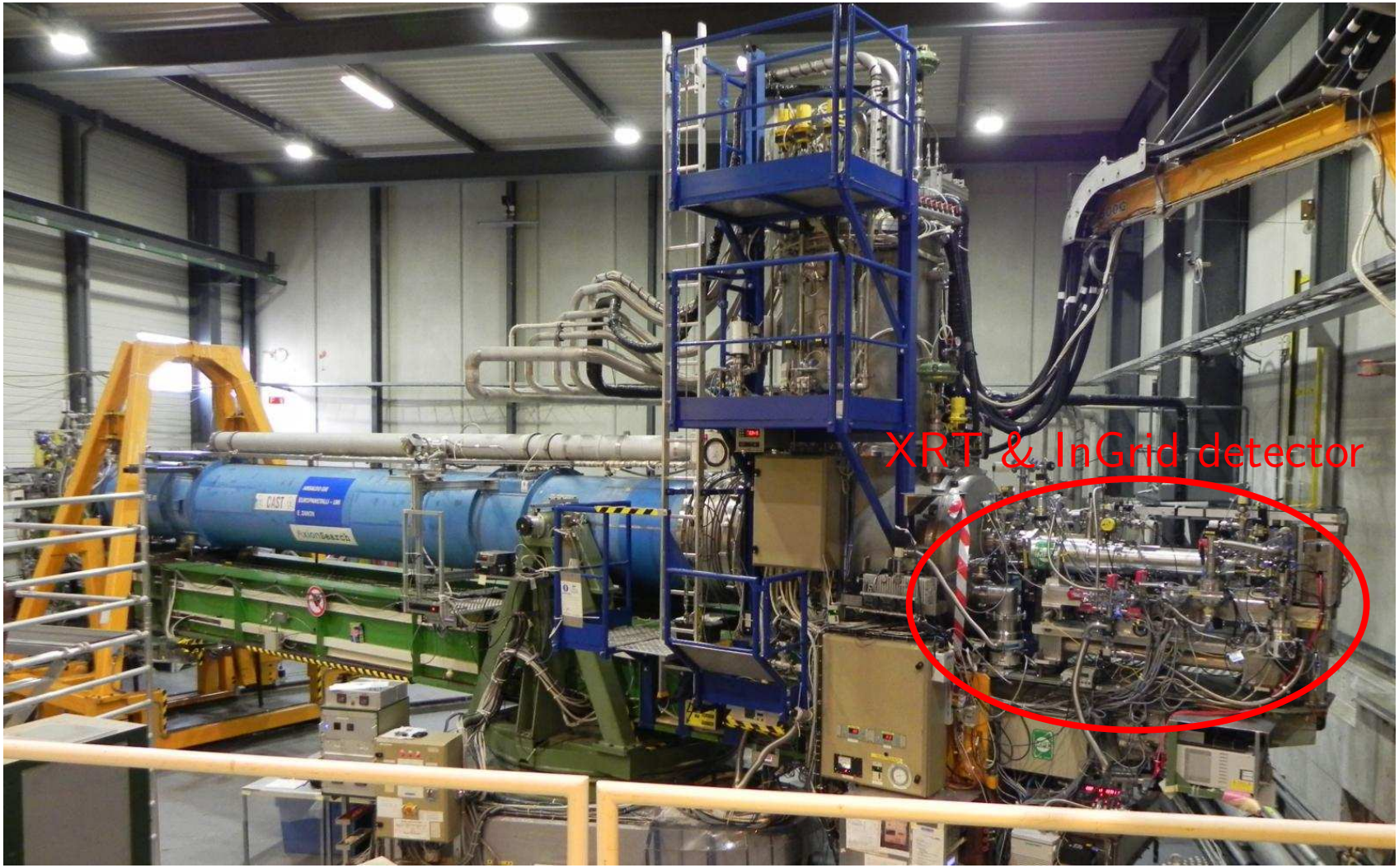




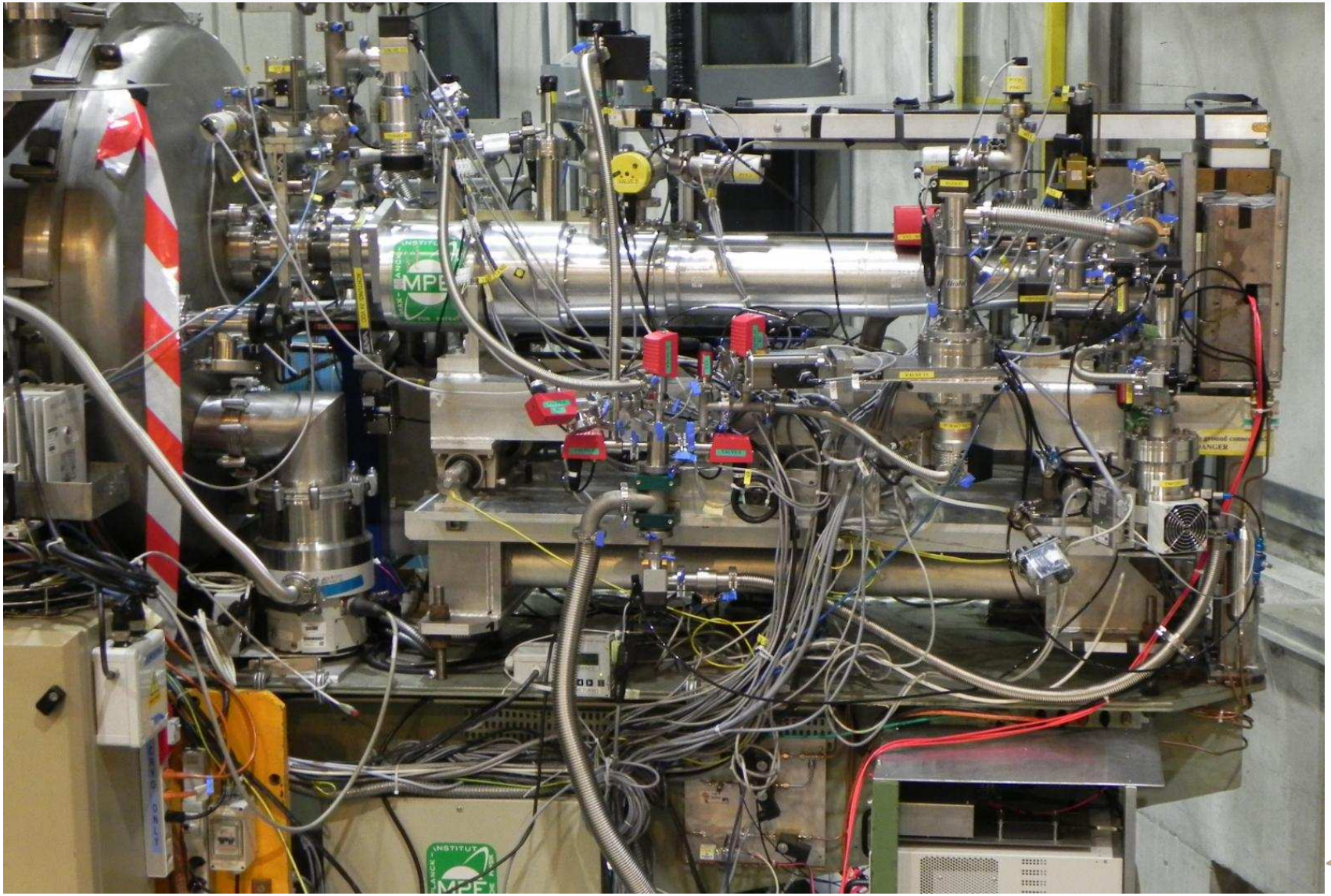
Setup at the CAST experiment

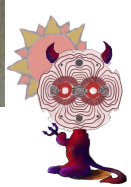


Setup at the CAST experiment

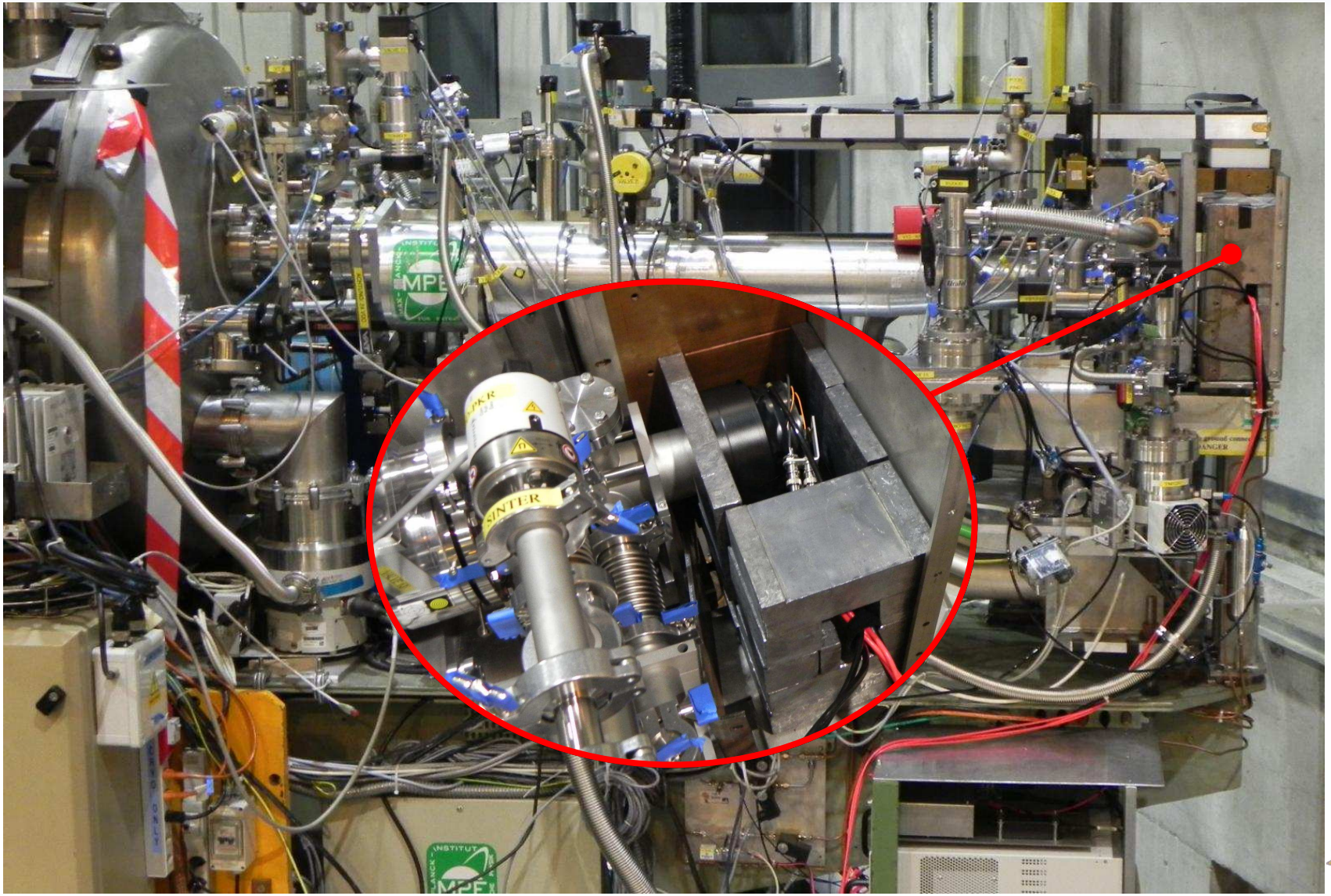


Setup at the CAST experiment

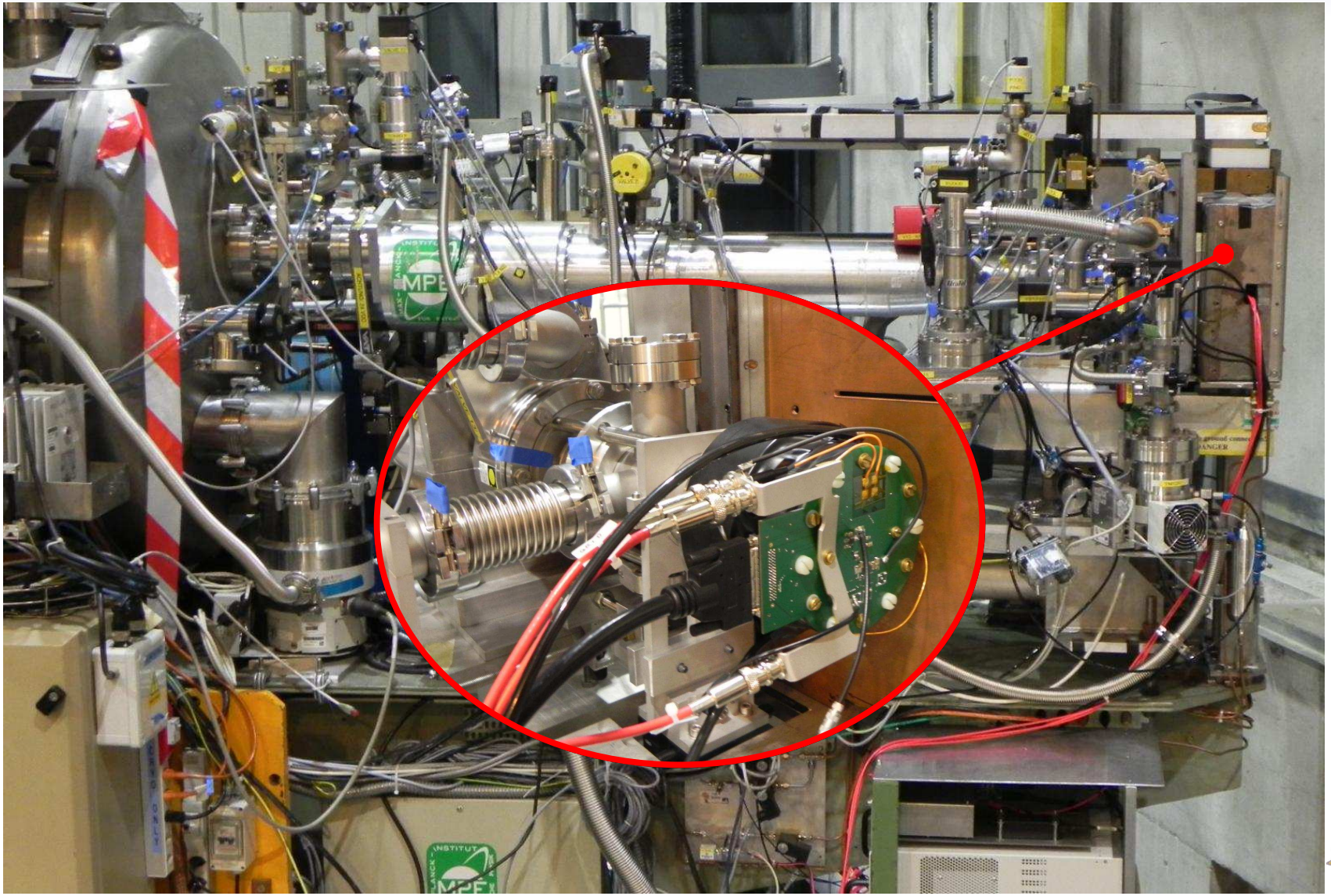




Setup at the CAST experiment



Setup at the CAST experiment



Operation at the CAST experiment

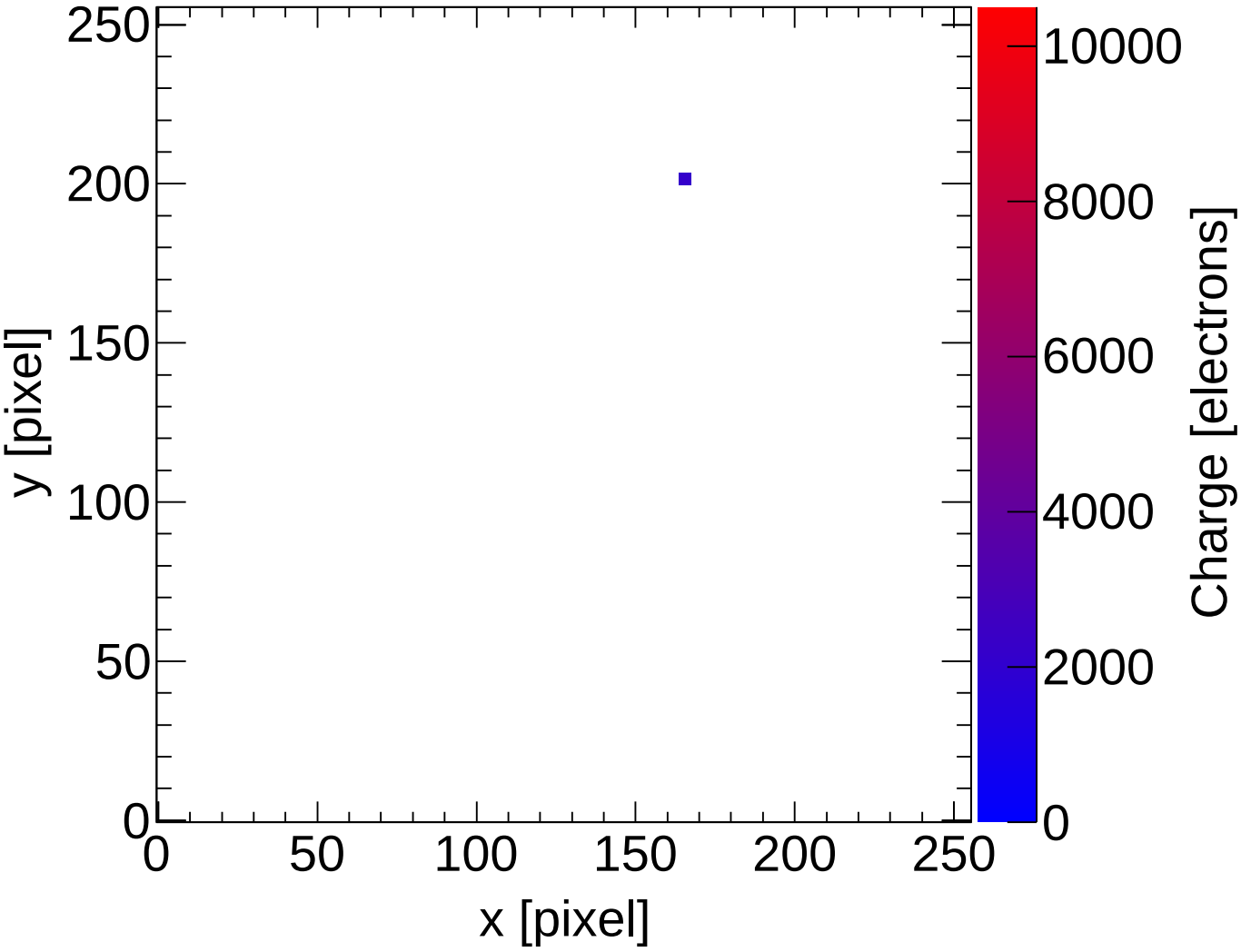
Commissioning

- Infrastructure for InGrid based detector (re)installed behind X-ray telescope in October 2014
- After alignment with telescope detector and lead shielding were mounted

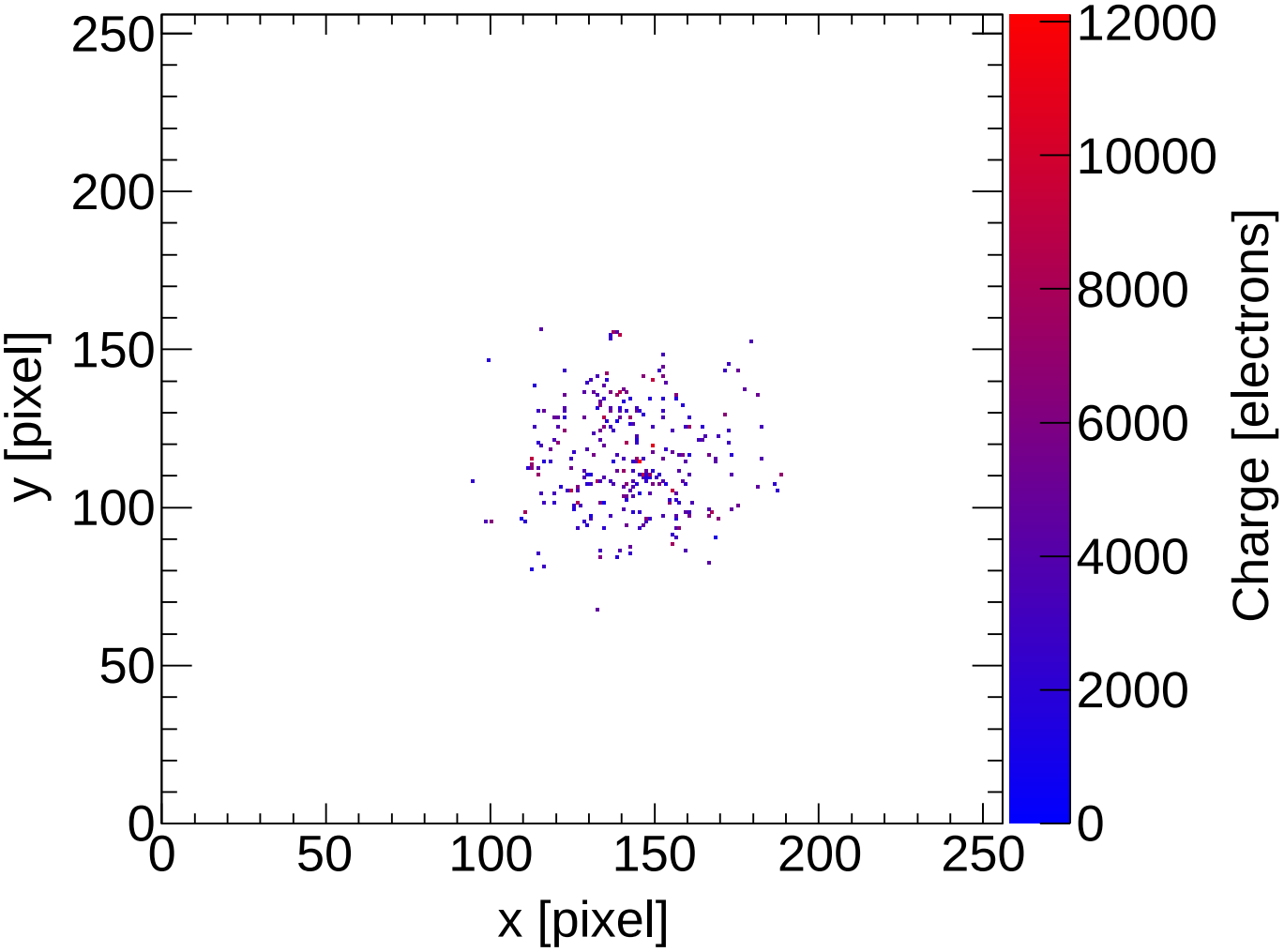
Recorded data

- $\sim 2.4 \times 10^6$ frames (0.98 s each) recorded during one month operation during CAST run 2014
- Physics data recorded during 27 sun trackings (sunrise)
- Few calibration runs with ^{55}Fe source on manipulator
- Additional datasets from commissioning period (with and without lead shielding) plus one week of data without vacuum

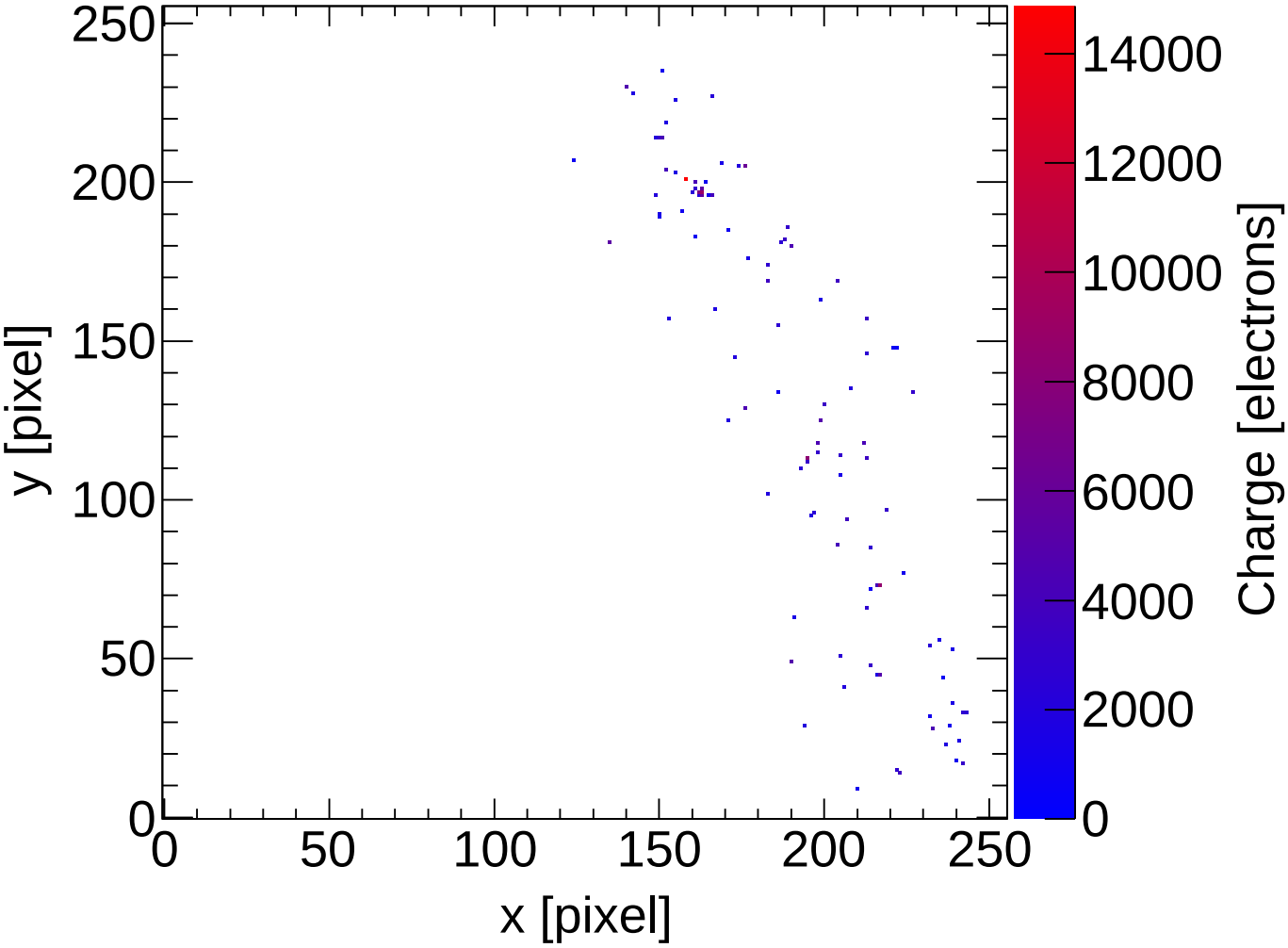
What $> 80\,\%$ of the events look like. . .



What an X-ray photon event looks like. . .



What a background event looks like...



Background rejection method

Reconstruction of X-ray photons

- Pixel clusters are identified as possible X-ray photons by modified clustering algorithm
- Long and short axis are being identified
- Geometrical properties (e.g. statistical momenta along axis, excentricity, etc) are computed

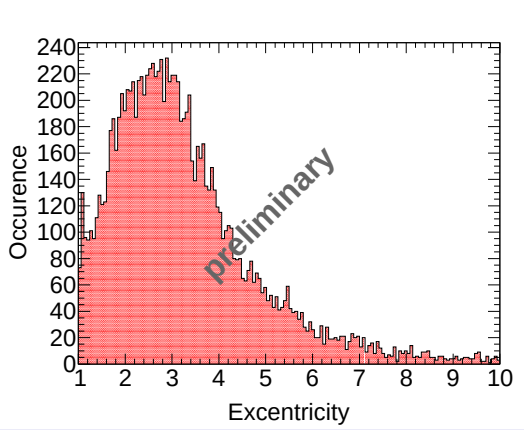
Likelihood for background rejection

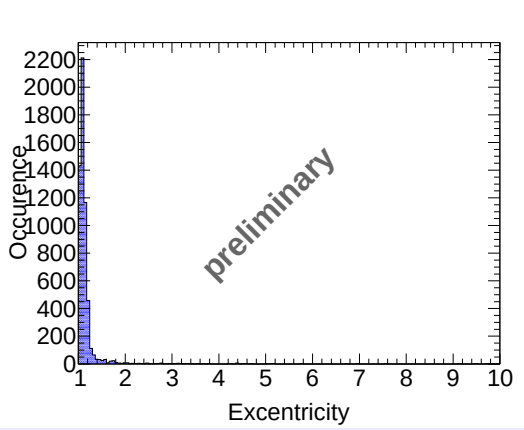
- Likelihood calculated from reference distributions for different energy ranges (CAST Detector Lab data)
- **Three** variables are used for likelihood:
  - Excentricity (Measure for circularity)
  - Length along long axis divided by RMS along short axis
  - Fraction of pixels within radius of one RMS (along short axis)
- Variables chosen to be independent of gas properties (e.g T)
- Software efficiencies derived from CAST Detector Lab data

Likelihood variables – Background & Reference

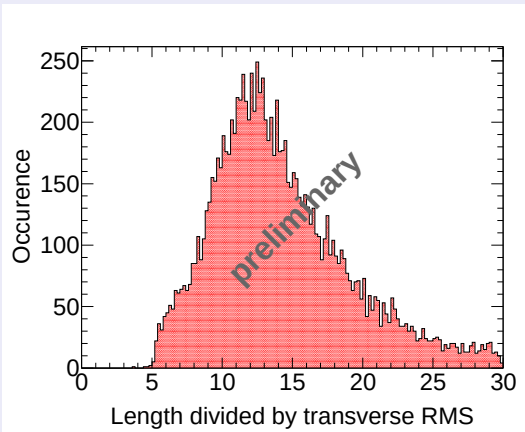
$E > 6.9\,\text{keV}$ – Copper K_α line

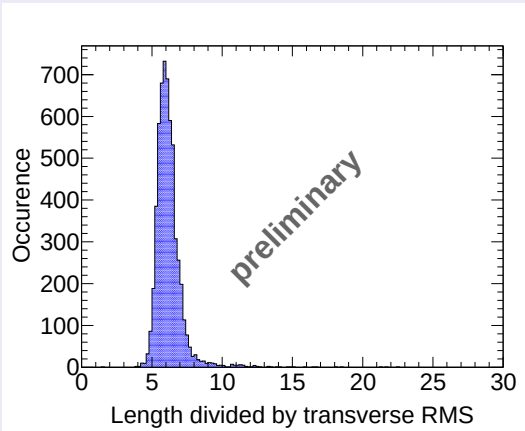
Excentricity



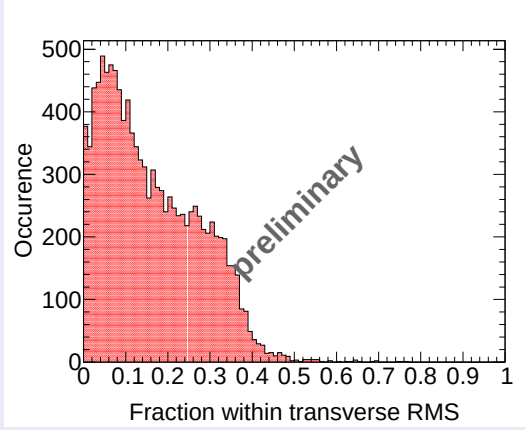


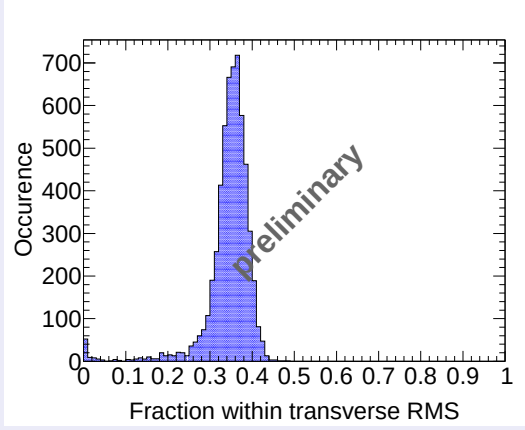
Length/RMS





Fraction within RMS

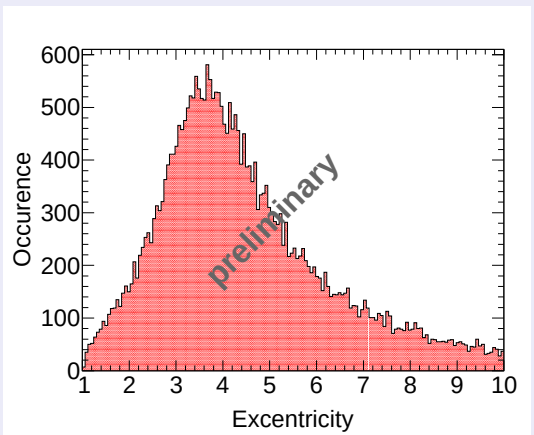


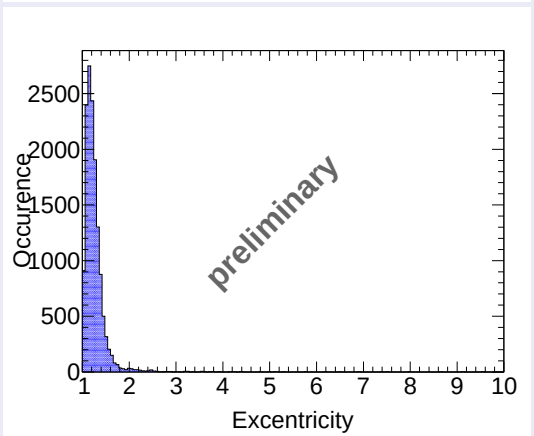


Likelihood variables – Background & Reference

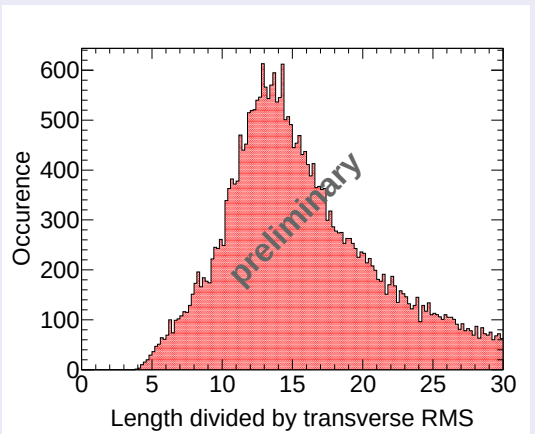
$1.2\,\text{keV} < E < 2.1\,\text{keV}$ – Aluminium K_α line

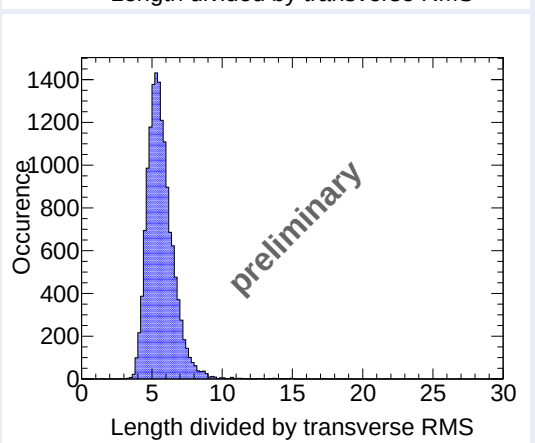
Excentricity



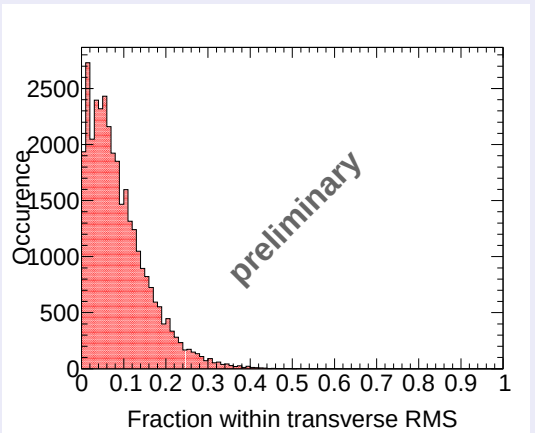


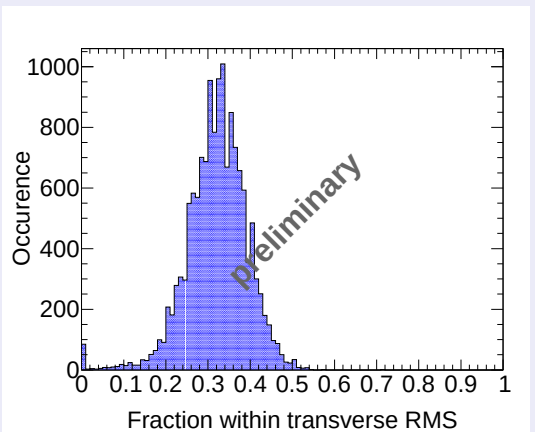
Length/RMS





Fraction within RMS

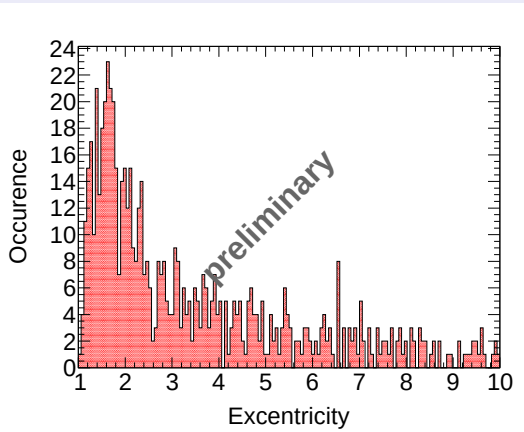


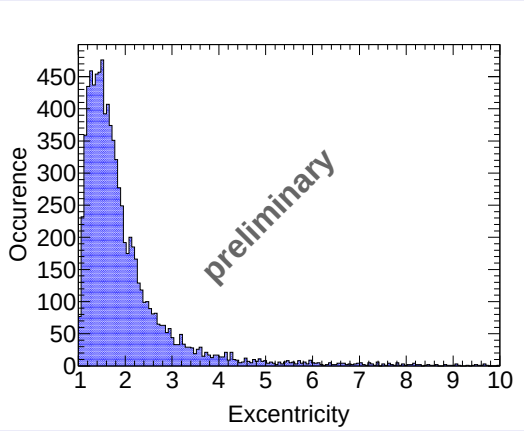


Likelihood variables – Background & Reference

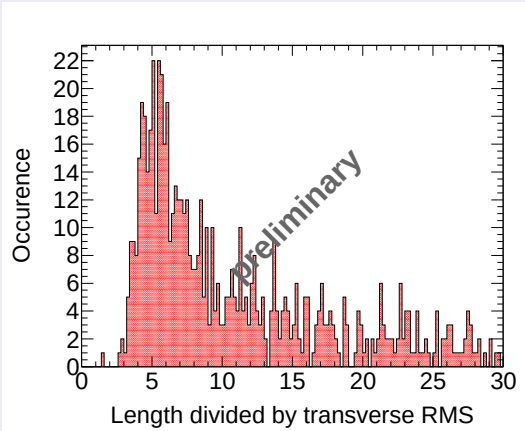
$E < 0.4\,\text{keV}$ – Carbon K_α line

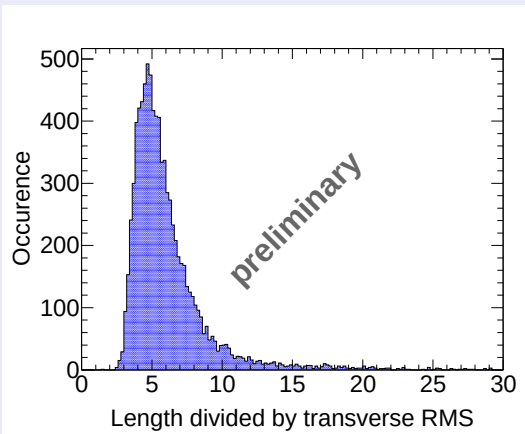
Excentricity



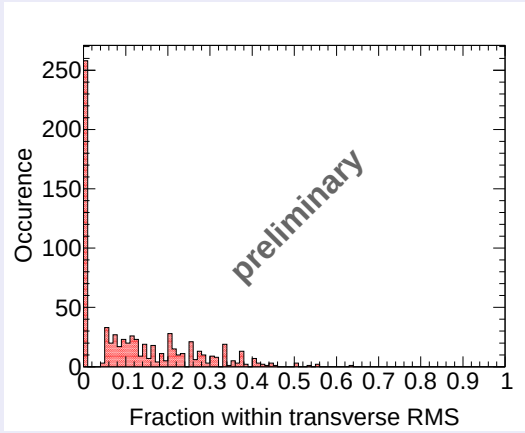


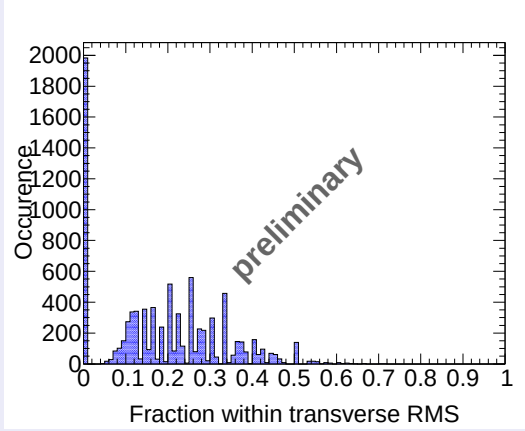
Length/RMS



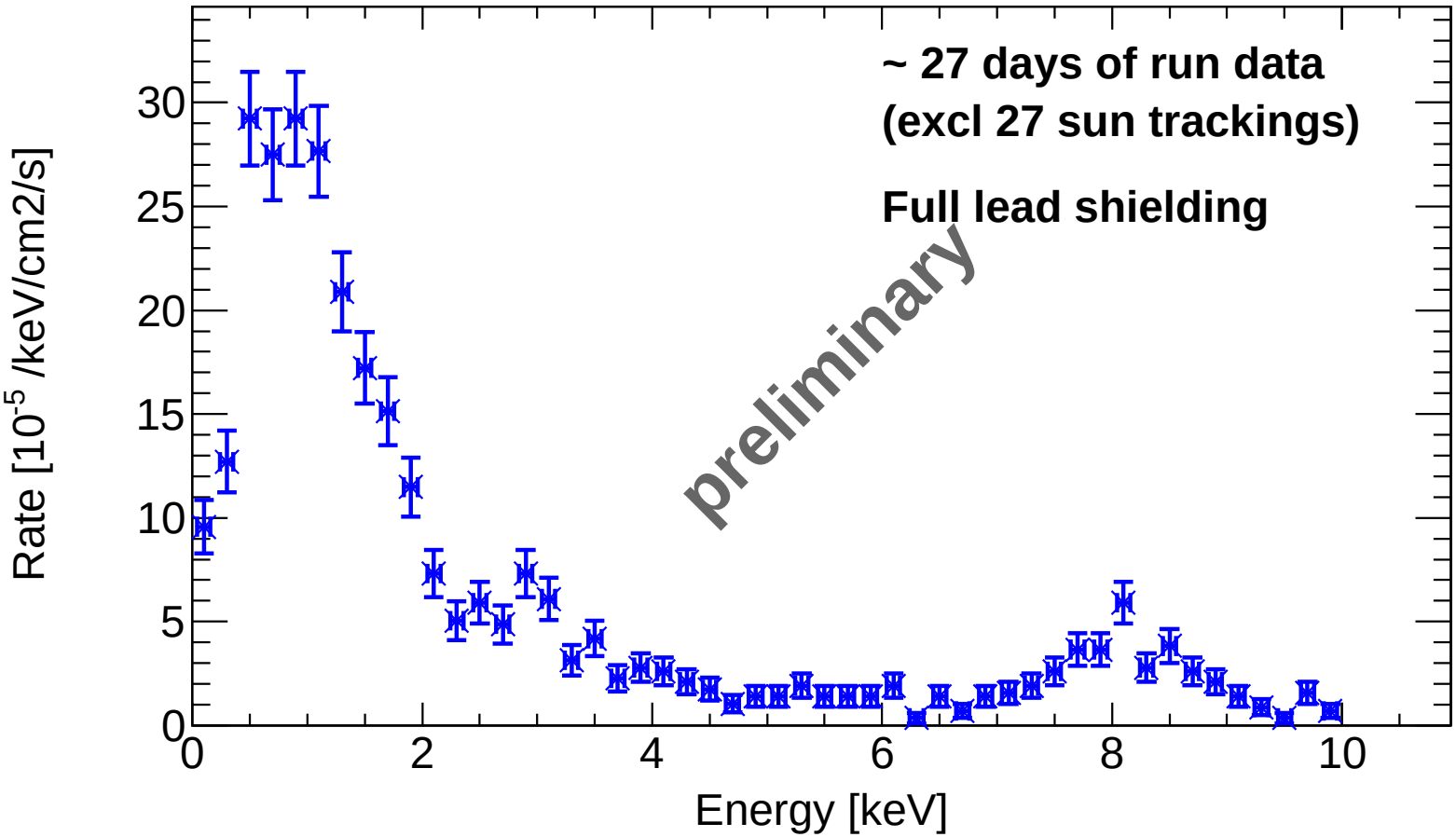


Fraction within RMS

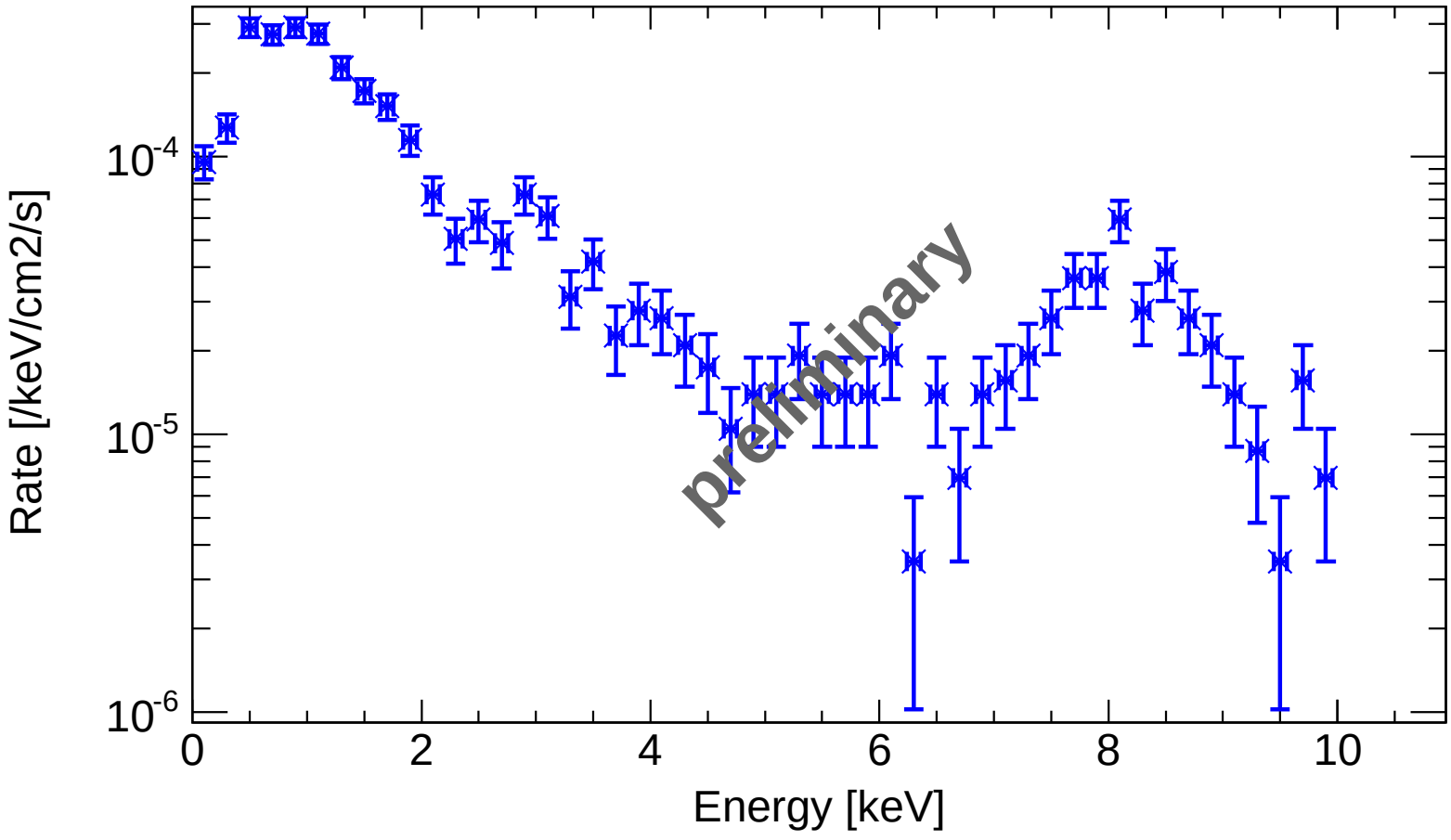




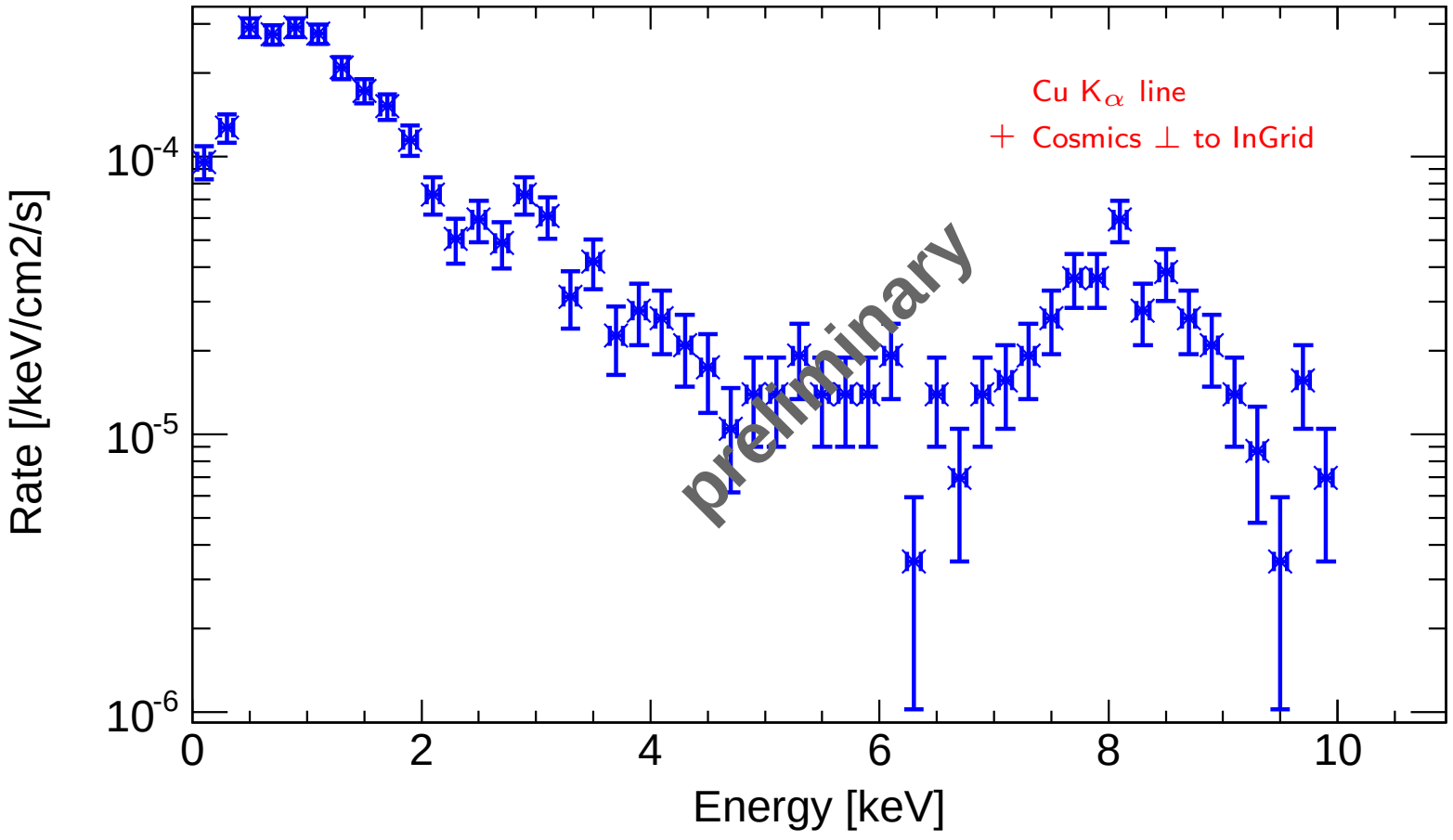
Background rate in CAST environment



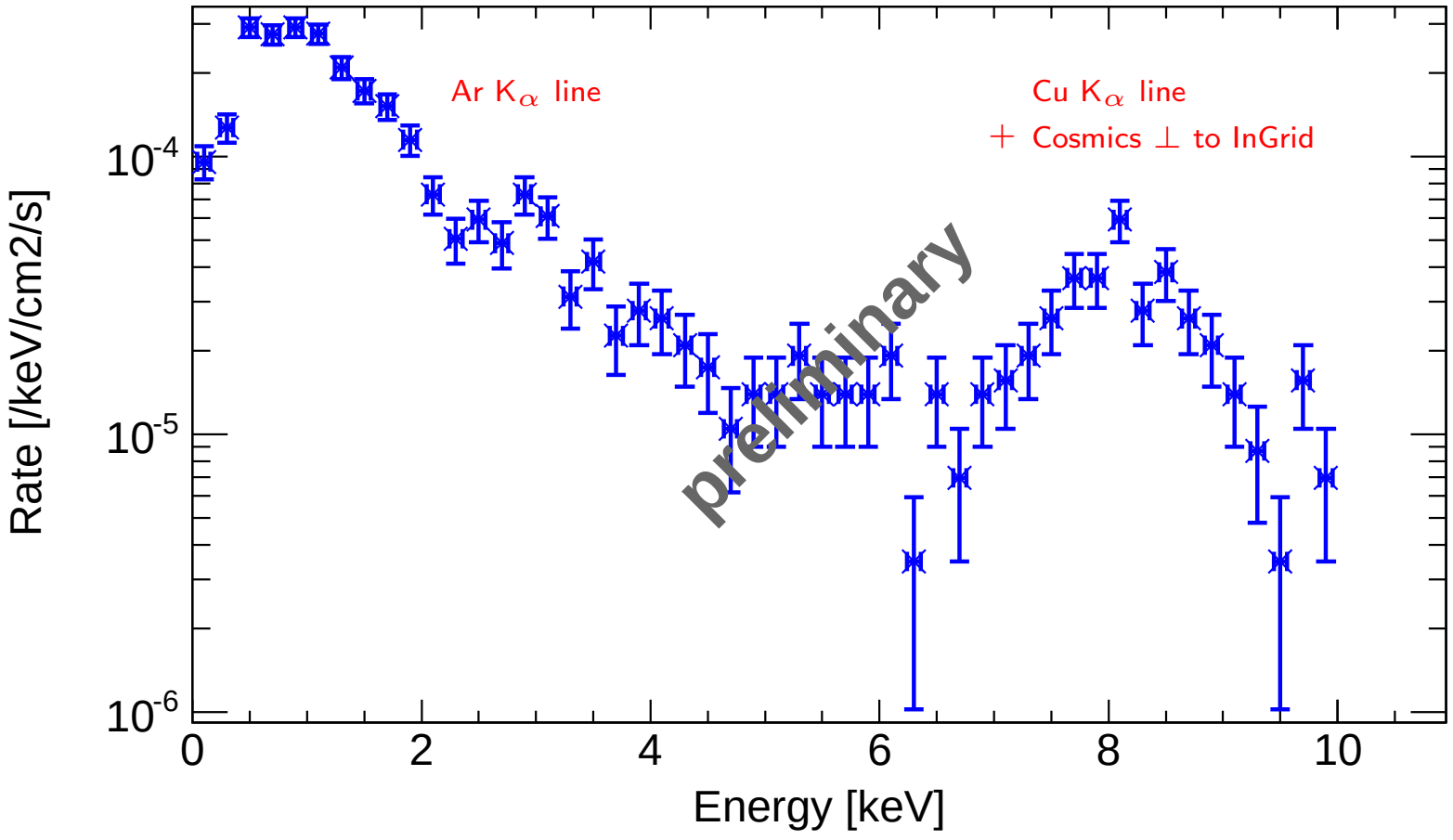
Background rate in CAST environment



Background rate in CAST environment



Background rate in CAST environment



Status quo & future steps

Status quo

- Achieved background rates look promising
- Up to now sunrise tracking periods are blinded

Next steps

- Take a closer look at features of background spectra
- Improve background rejection (may include use of multivariate analysis methods like e.g. boosted decision trees)
- Inspect and understand background spectrum of sunset tracking periods (similar conditions as during sunrise tracking but no chance of signal)
- Unblind sunrise tracking data and check for axion or chameleon signal

Summary & Outlook

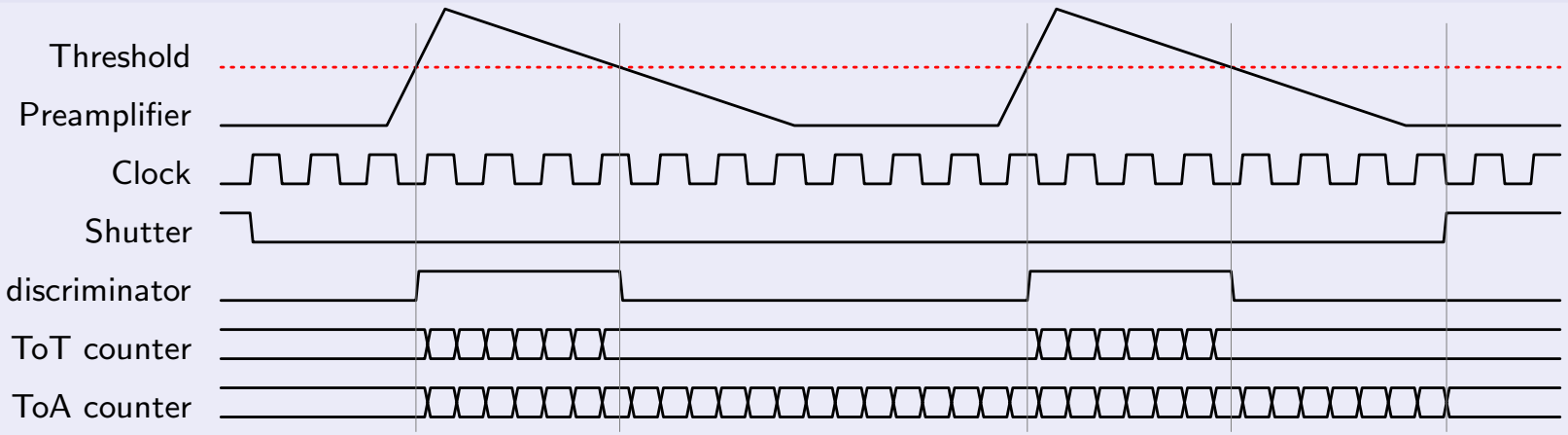
- InGrid based X-ray detector combines advantages of Micromegas stage with high granularity of pixelized readout
- InGrid technology allows detection of low energy X-ray photons down to the carbon K-alpha line
- Detector successfully installed and operated at the CAST experiment during the run 2014
- First background rates look promising although still a lot of work is to be done
- Improvement of analysis and background rejection
- Future detector upgrades (e.g. veto scintillator & grid signal)
- Closer look at background spectra plus finally search for signal

Thanks for your attention!

Backup Slides

Timepix ASIC – More details

Timing Diagram

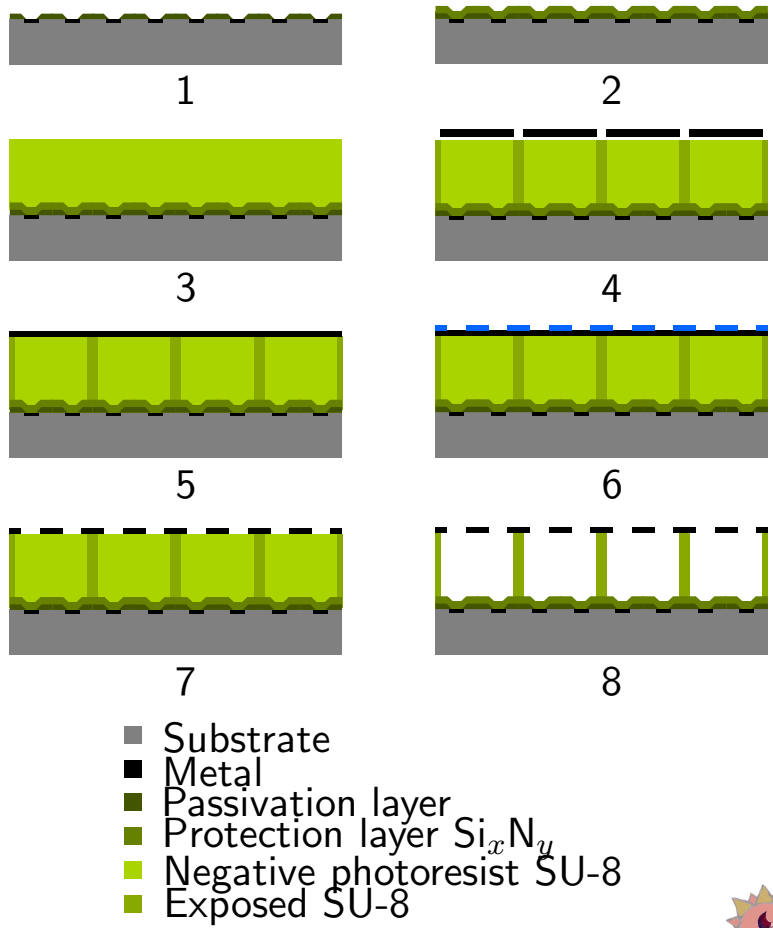


Timepix & Timepix 3

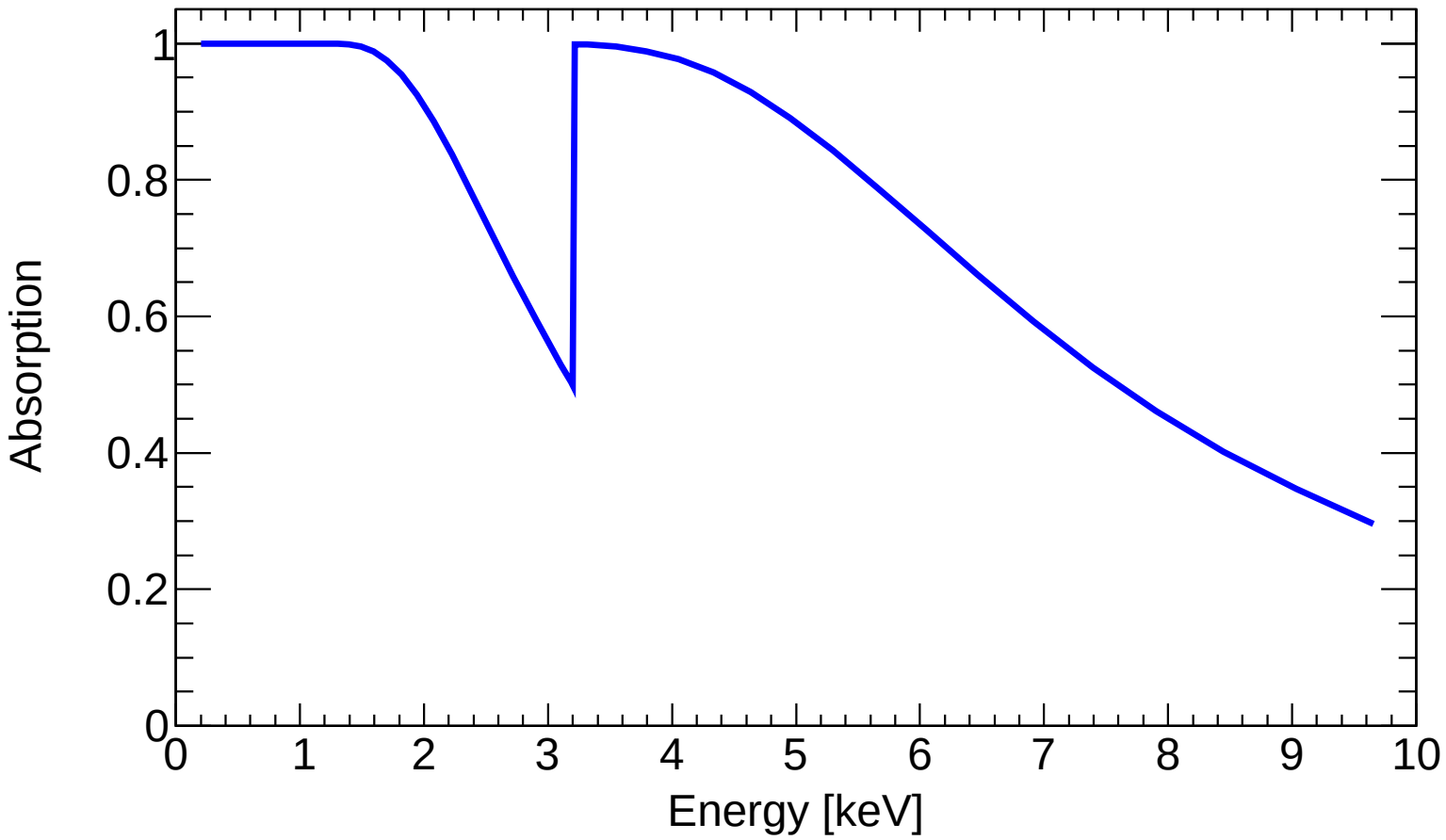
- Charge sensitive amplifier plus discriminator in each pixel
- Each pixel can either measure charge or time (time measurement needs trigger), no multihit capability
- First Timepix 3 are available (no InGrid yet); fast data driven readout, multihit capability and simultaneous charge and time measurement

How to build an InGrid on top of a Timepix?

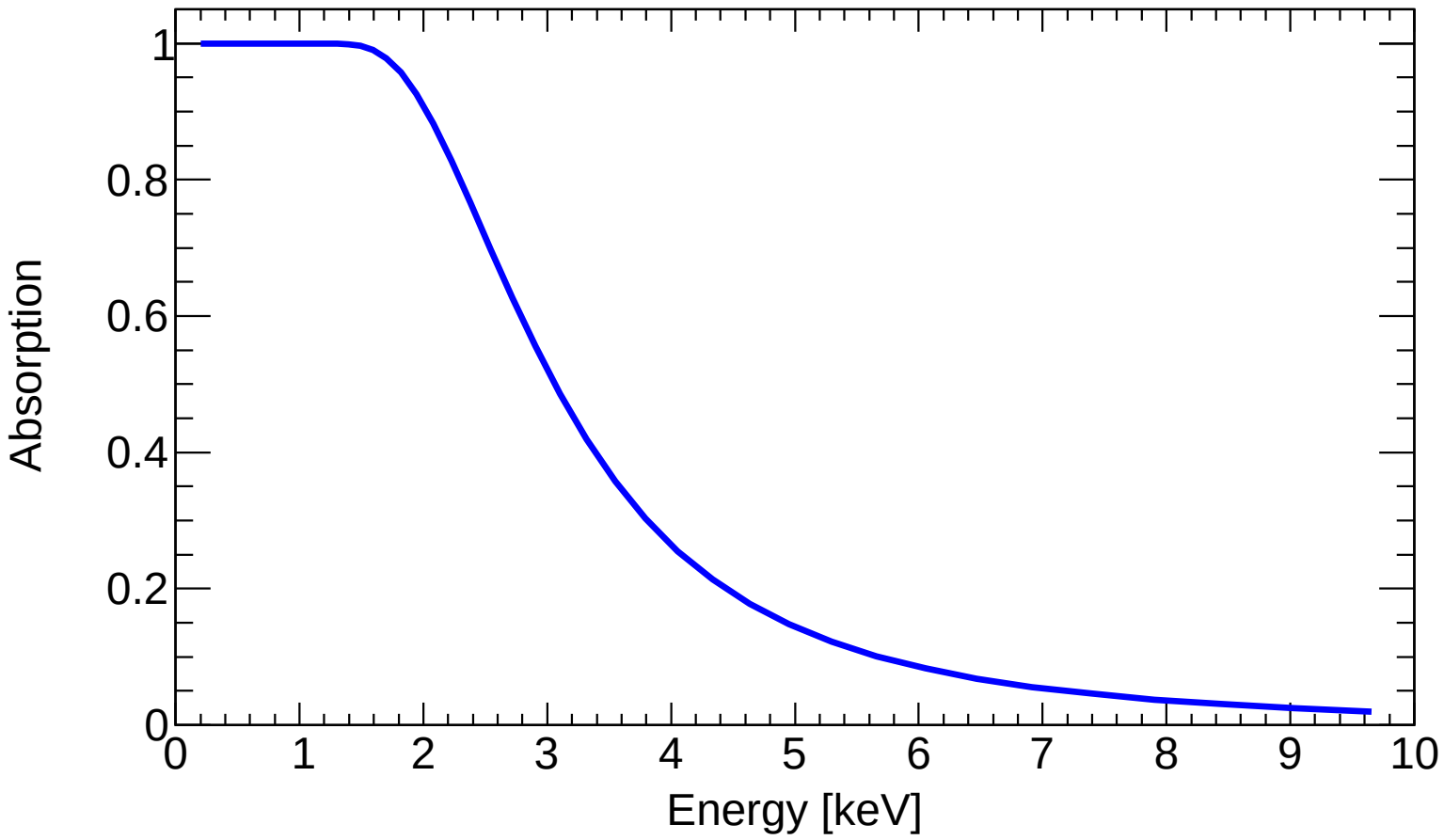
1. Starting with bare Timepix
2. Deposition of protection layer (4 or 8 µm Si_xN_y)
3. Deposition of negative photoresist SU-8 (50 µm)
4. Exposure of SU-8
5. Sputtering aluminium (1 µm)
6. Putting mask on aluminium layer (photoresist)
7. Structuring aluminum layer by etching the holes
8. Development of SU-8, cleaning of interistitials



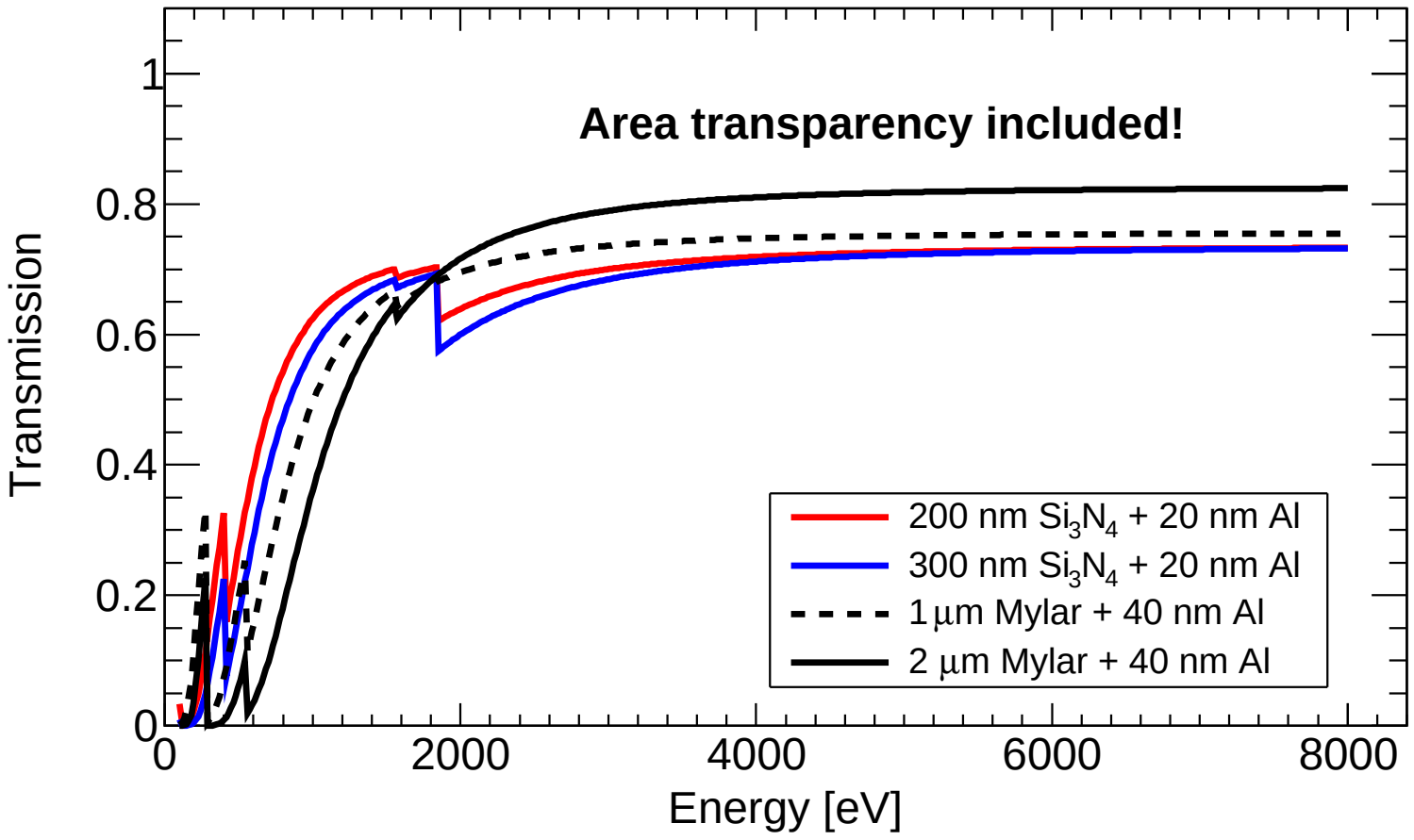
X-ray absorption in 3 cm Argon at 1050 mbar



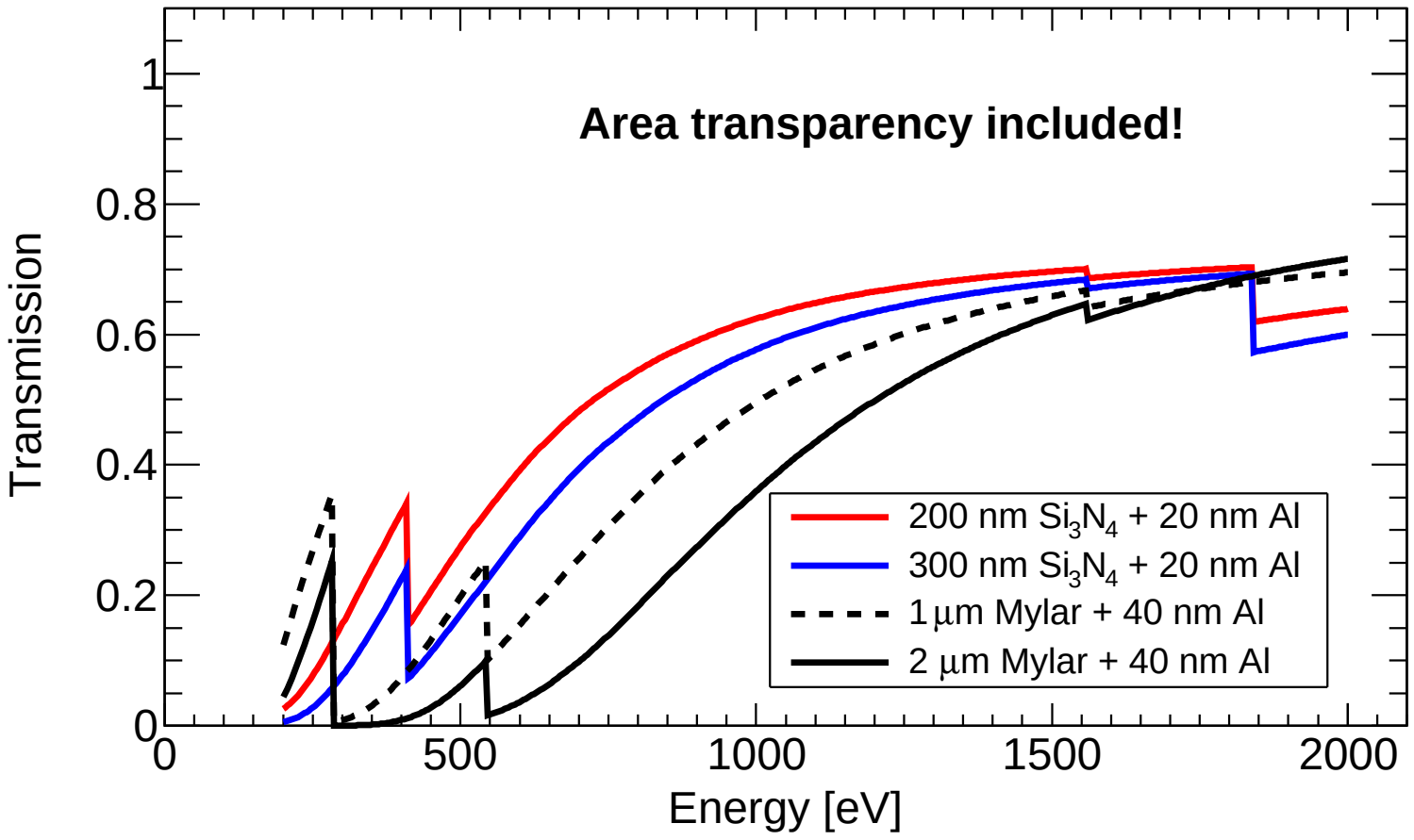
X-ray absorption in 5 cm Nitrogen at 1013 mbar



Window transparency & alternative window materials

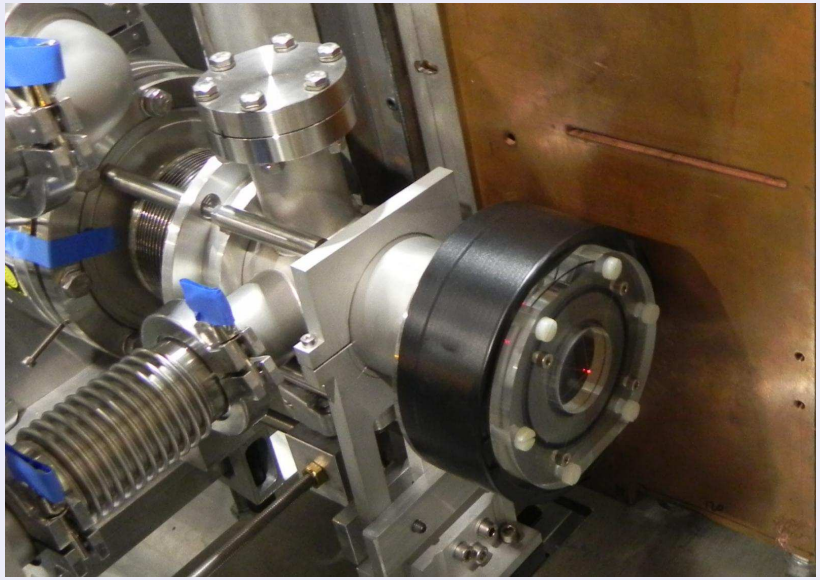


Window transparency & alternative window materials

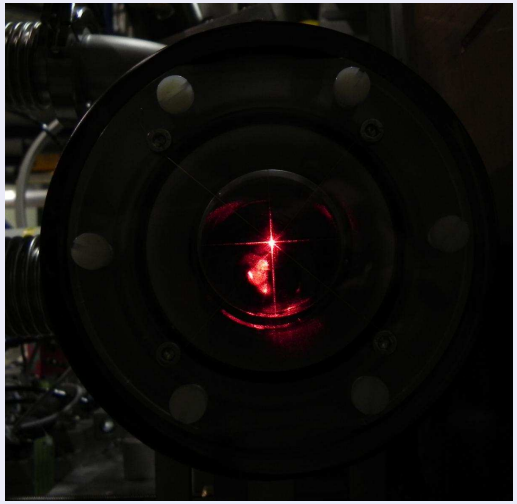


Alignment

Alignment target with laser spot



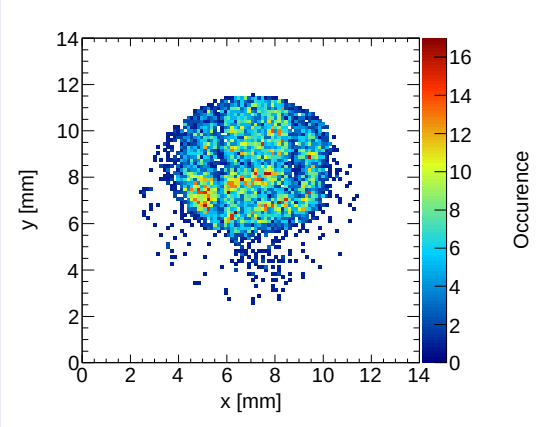
Alignment crosshair



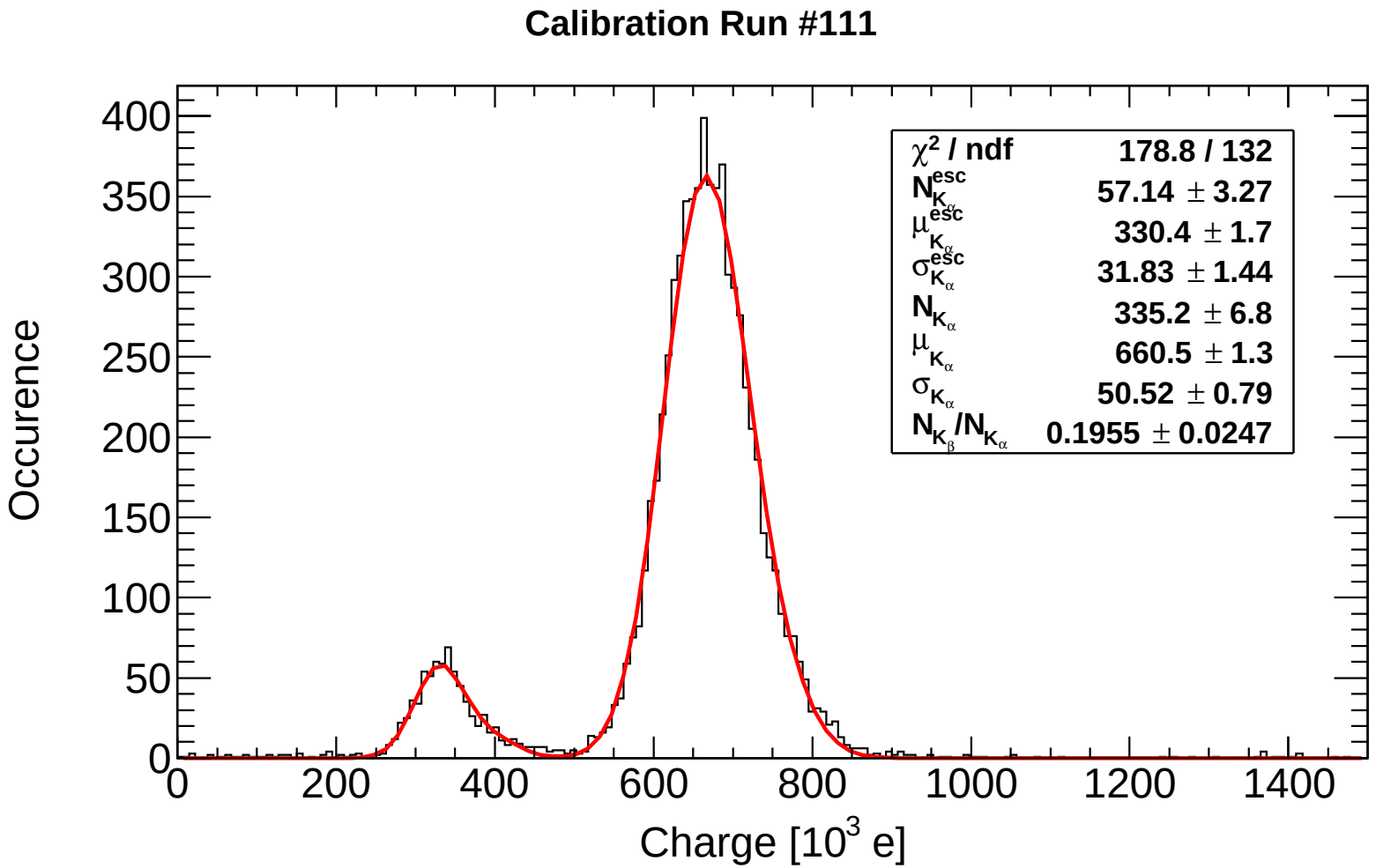
Alignment methods

- Laser setup aligned with optical axis of XRT for installation (detector replaced by target)
- Pyroelectric X-ray source (finger) upstream of XRT on optical axis

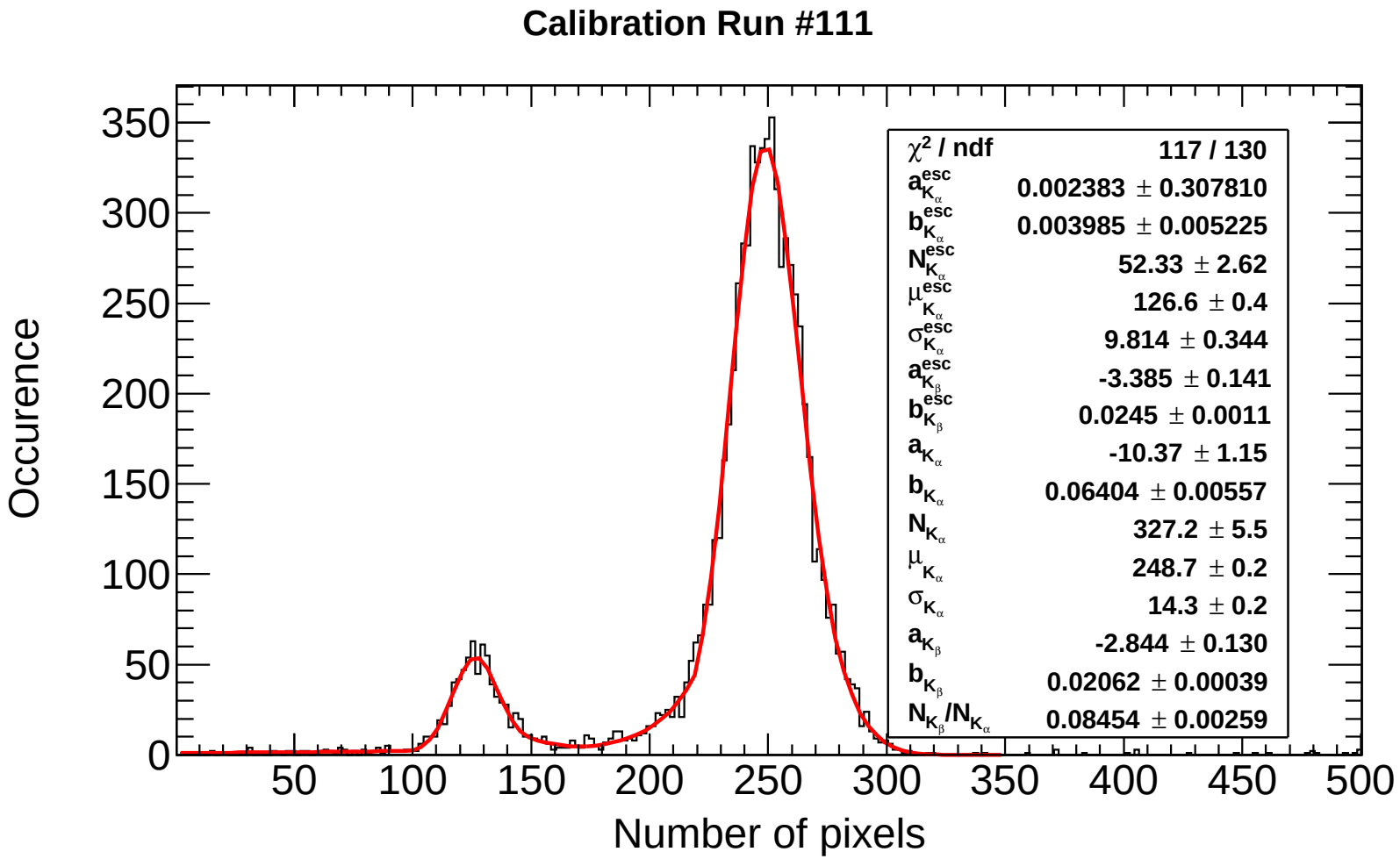
X-ray finger image



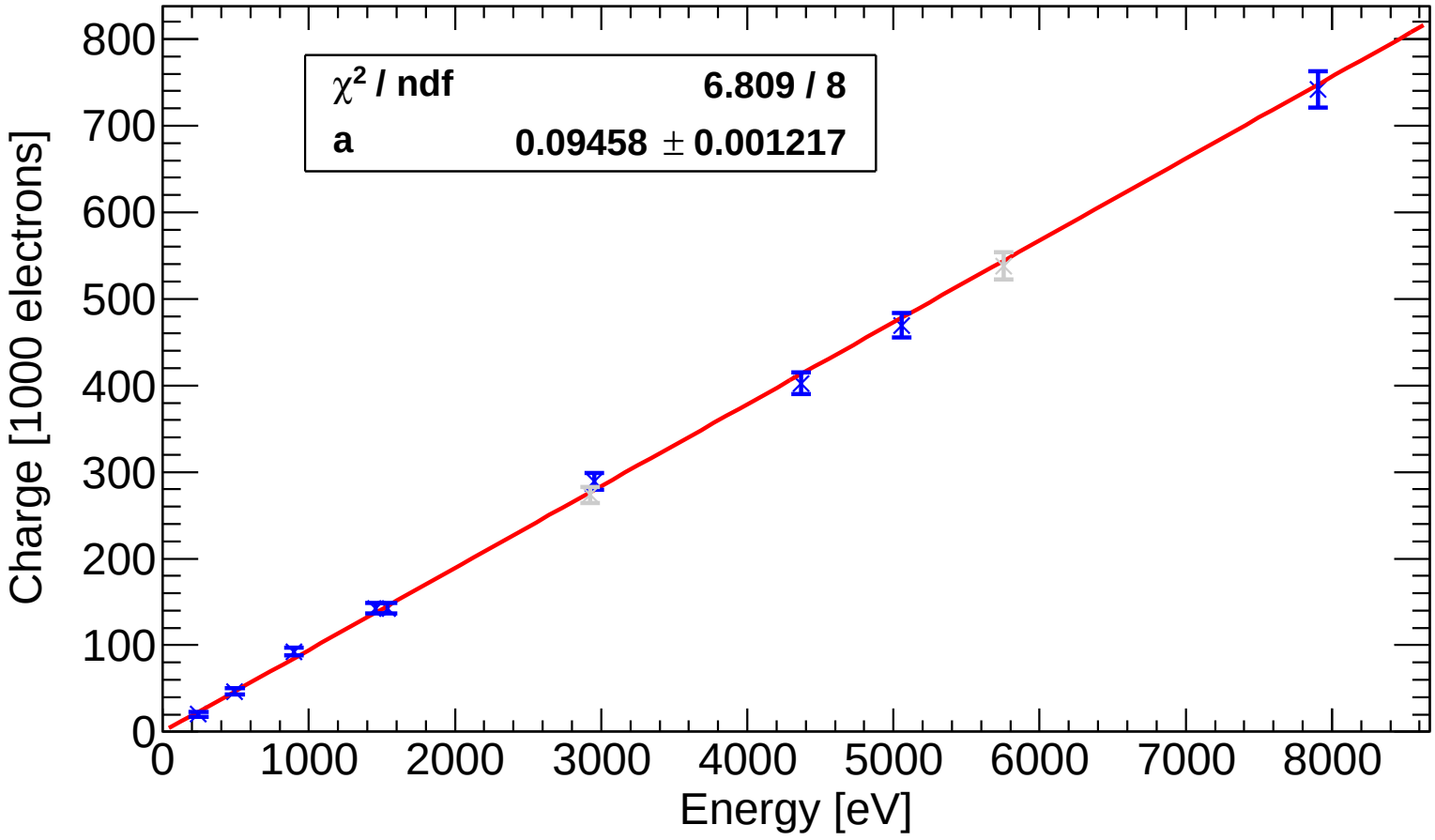
Calibration measurements with ^{55}Fe source



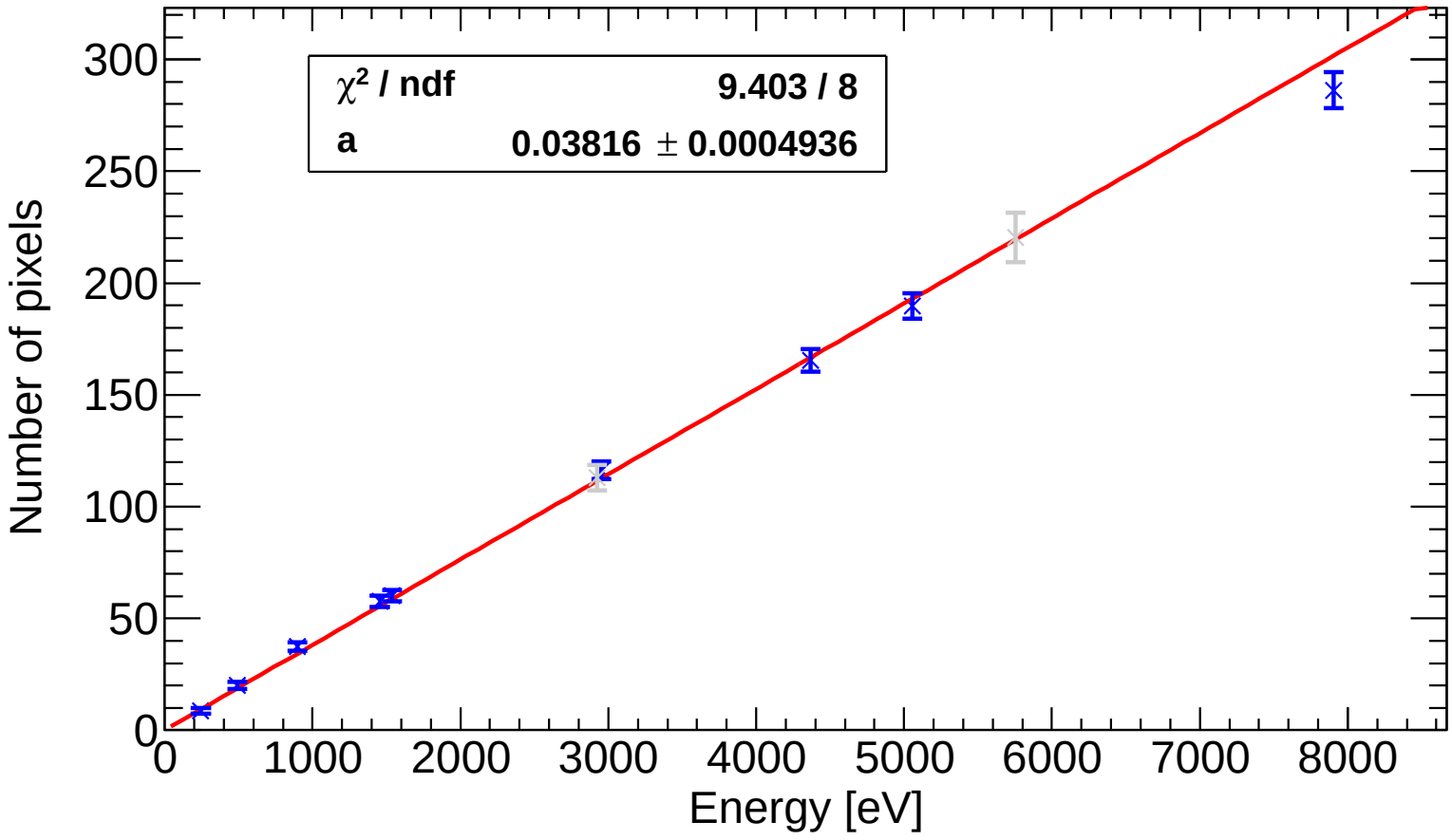
Calibration measurements with ^{55}Fe source



Energy Calibration

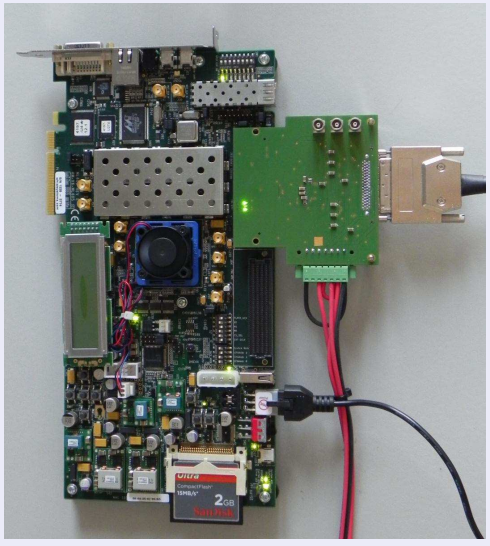


Energy Calibration



Readout System

Virtex6 Readout



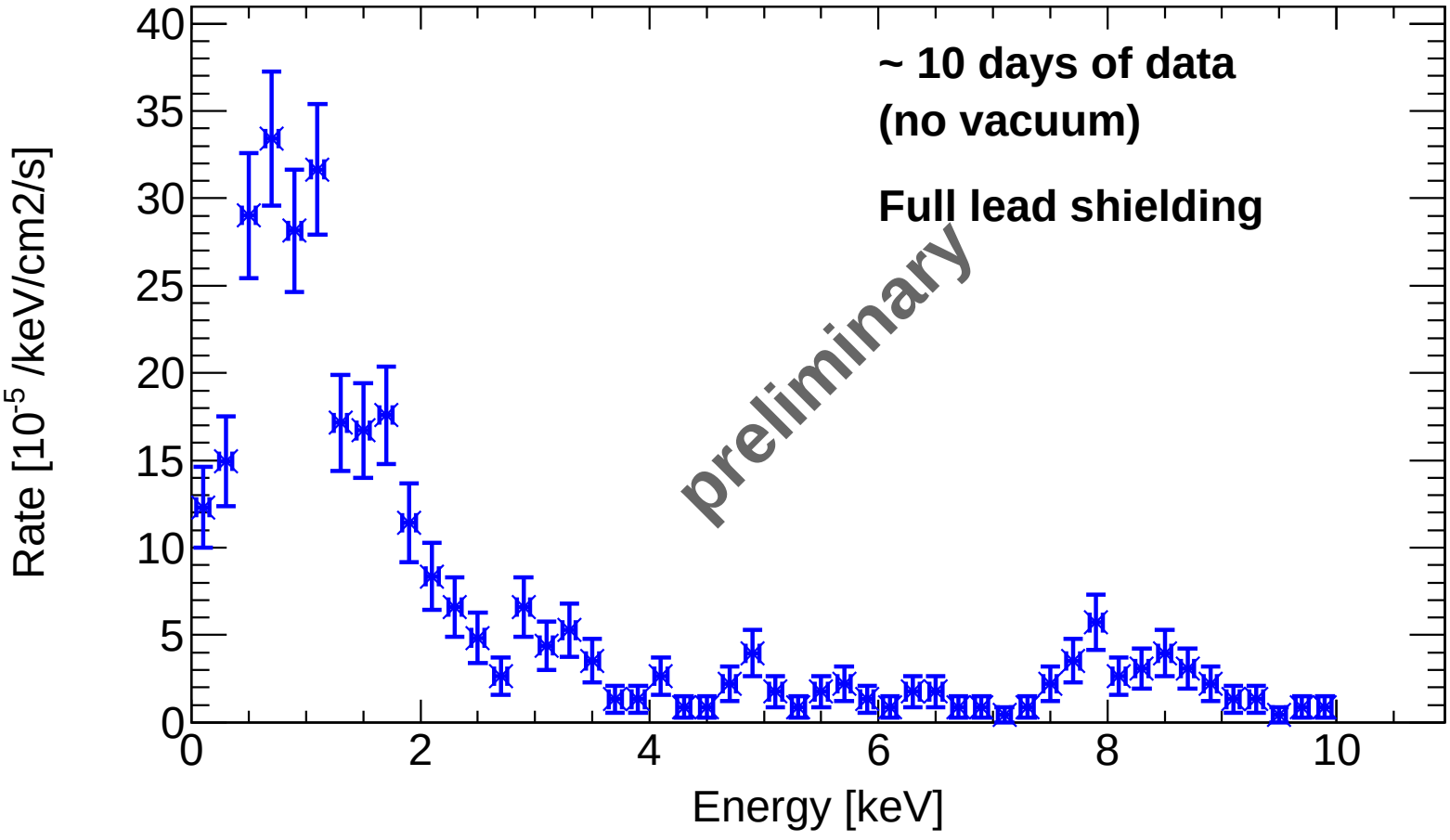
FPGA based readout system

- New readout system for Timepix ASIC based on **S**calable **R**eadout **S**ystem has been developed at Bonn
- FPGA based, flexible and customizable
- Full access to firm- and software
- For CAST an adopted system based on a Virtex6 evaluation board is used

Possible future upgrades

- Implement sampling of induced grid signal including kind of trigger scheme (needs FADC and appropriate preamp)
- Integrate small veto scintillator on back of detector

Background rate without vacuum



Background rate without vacuum