Towards an InGrid based low energy X-ray detector for the CAST experiment

DPG Frühjahrstagung 2014
Mainz

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24th March 2014

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Outline

Axions

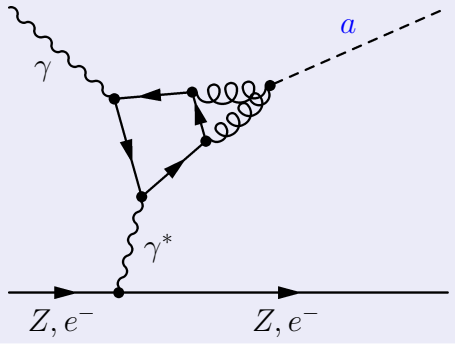
What are Axions? & Where do they come from?

- PQ mechanism is elegant solution for the strong CP problem
  - Non-observation of CP violation in strong interaction
  - Smallness of electric dipole moment of neutron ($d < 0.29 \times 10^{-25}\, e\,\mathrm{cm}$)
- Goldstone-Boson arising from Peccei-Quinn mechanism
- Candidate for parts of **Cold Dark Matter**

Coupling to ordinary matter

- Very small coupling constants
- Coupling to gluons realized in all axion models
- Mixing with π^0 leads to coupling to two photons

Primakoff effect



CERN Axion Solar Telescope

Axions from the sun

- Primakoff effect generates huge axion flux from the sun
- Axions can reconvert to photons inside large $\vec{B}$ fields
- Energy of solar axions below 15 keV (flux peaks at 3 keV)

Current X-ray Detectors

- Microbulk Micromegas
- X-ray Telescope plus pnCCD (until mid of 2013)
- Prototype SDD

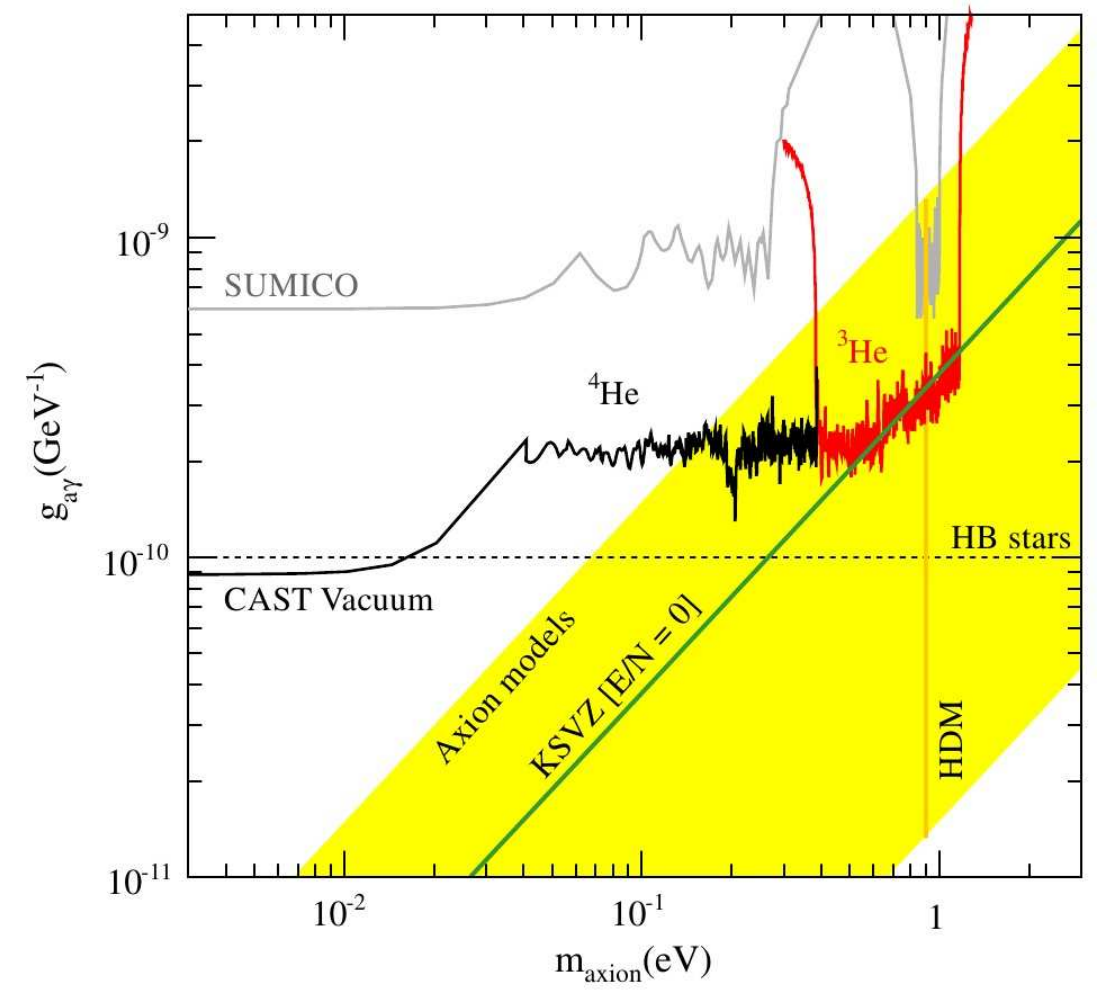
CAST – An axion helioscope

CAST – Data taking

- Magnet can track sun $2 \times 1.5\,\mathrm{h}$ per day
- Otherwise: background data
- Alignment can be checked by sun- and moon-filmings

CAST – Results

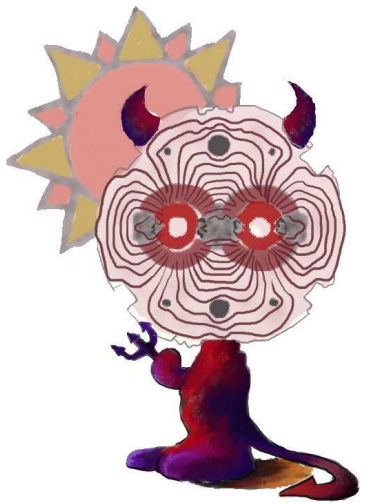
Exclusion plot



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 Detector for CAST – Why?

Why a new CAST detector is needed

- Replacement for pnCCD is needed
- Planned search for Chameleons (**Dark Energy** particle candidate) requires low threshold X-ray detectors ($< 1\,\text{keV}$)

Benefits of a Micromegas with pixelized readout

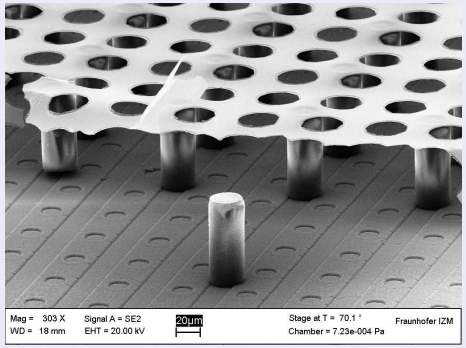
- Detection/Resolution of single electrons possible
- High spatial resolution can be exploited for event shape analysis (may be used for background rejection)
- Low threshold should be possible: about 300 eV (10 electrons)
- Purely digital data output due to integrated electronics

Integrated Micromegas – InGrid

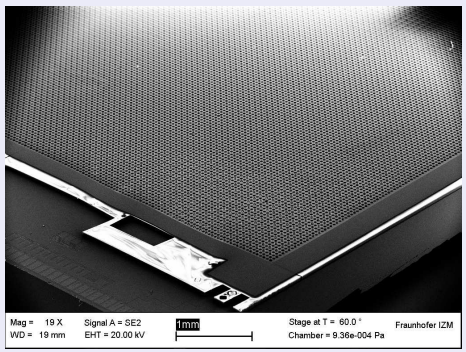
Micromegas on top of Timepix ASIC

- Fabrication by means of photolithographic postprocessing
- Very good alignment of grid and pixels
- Each avalanche is collected on one pixel
- Detection of single electrons possible

InGrid - SEM



Timepix + InGrid



Production of InGrids

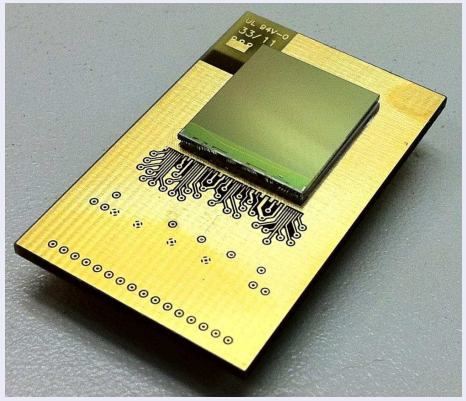
- Single and few chip processing: NIKHEF / Mesa+ (Twente)
- Wafer processing (~ 100 chips at once): in cooperation with IZM Berlin

Timepix ASIC

Facts about the Timepix ASIC

- 256×256 pixels, $55 \times 55\,\mu m^2$ pitch
- $1.4 \times 1.4\,cm^2$ active area
- Charge sensitive amplifier and discriminator in each pixel, $90\,e$ ENC
- Two modes: **Charge** or **Time**

Carrier board

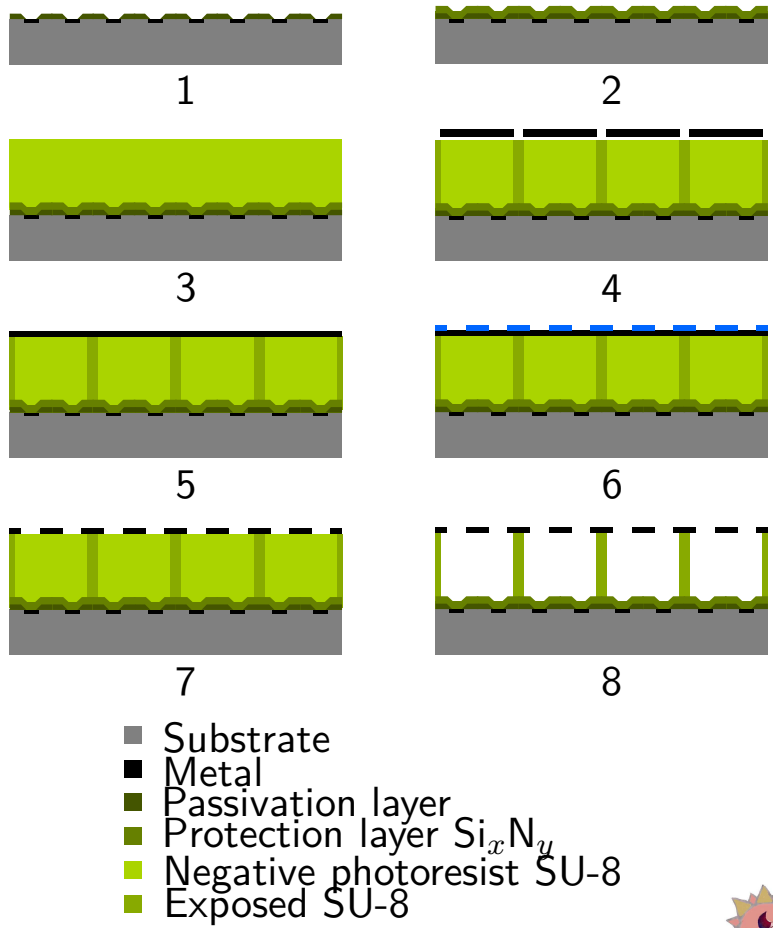


Protection of electronics

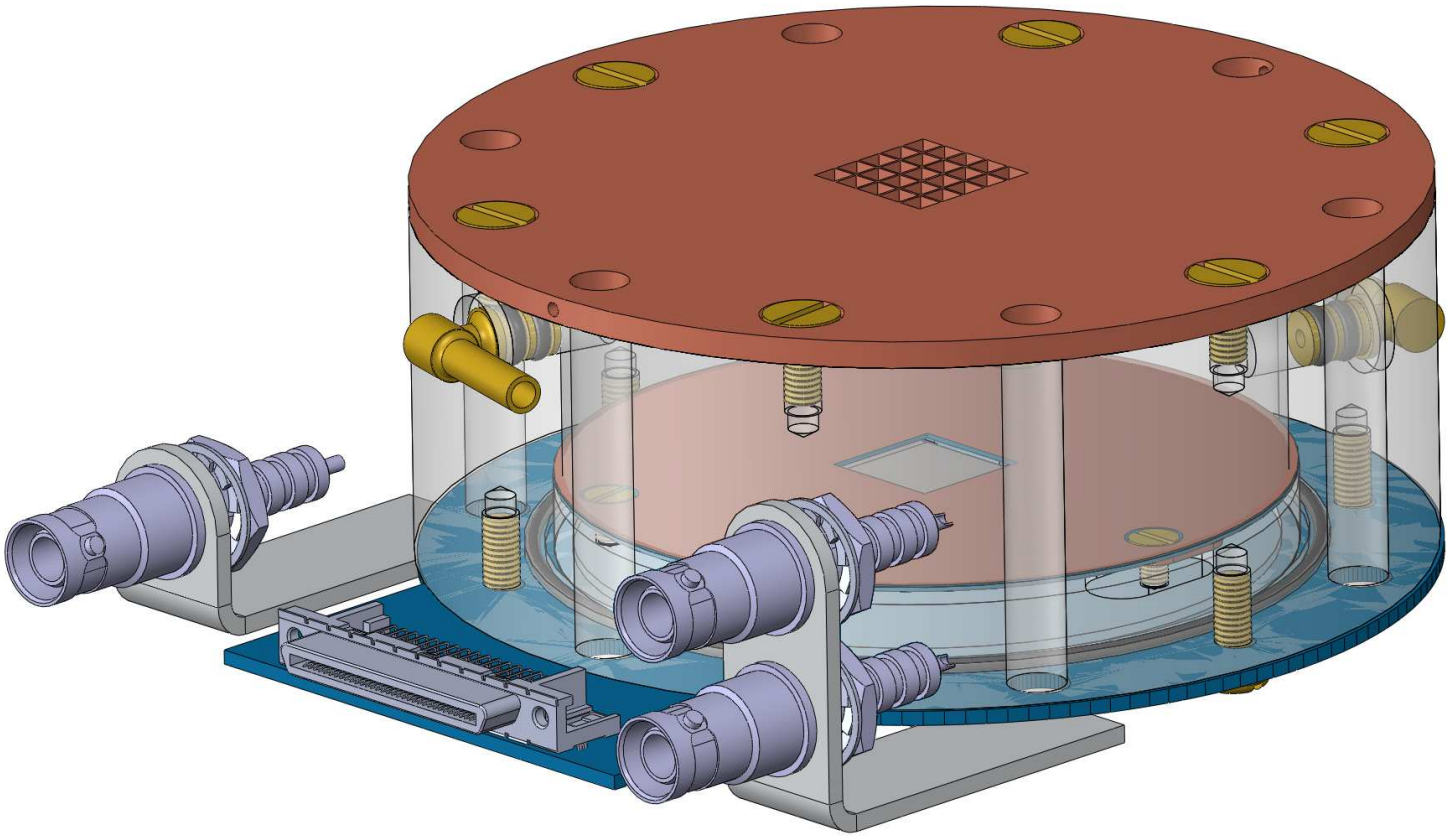
- Timepix ASIC is designed for imaging as readout electronics to be bump bonded on a silicon sensor
- Bump bond pads can be used as charge collecting anodes but electronics not designed to survive discharges
- Need resistive protection layer (e.g. 2-8 µm silicon nitride) to spread charge in case of discharge

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

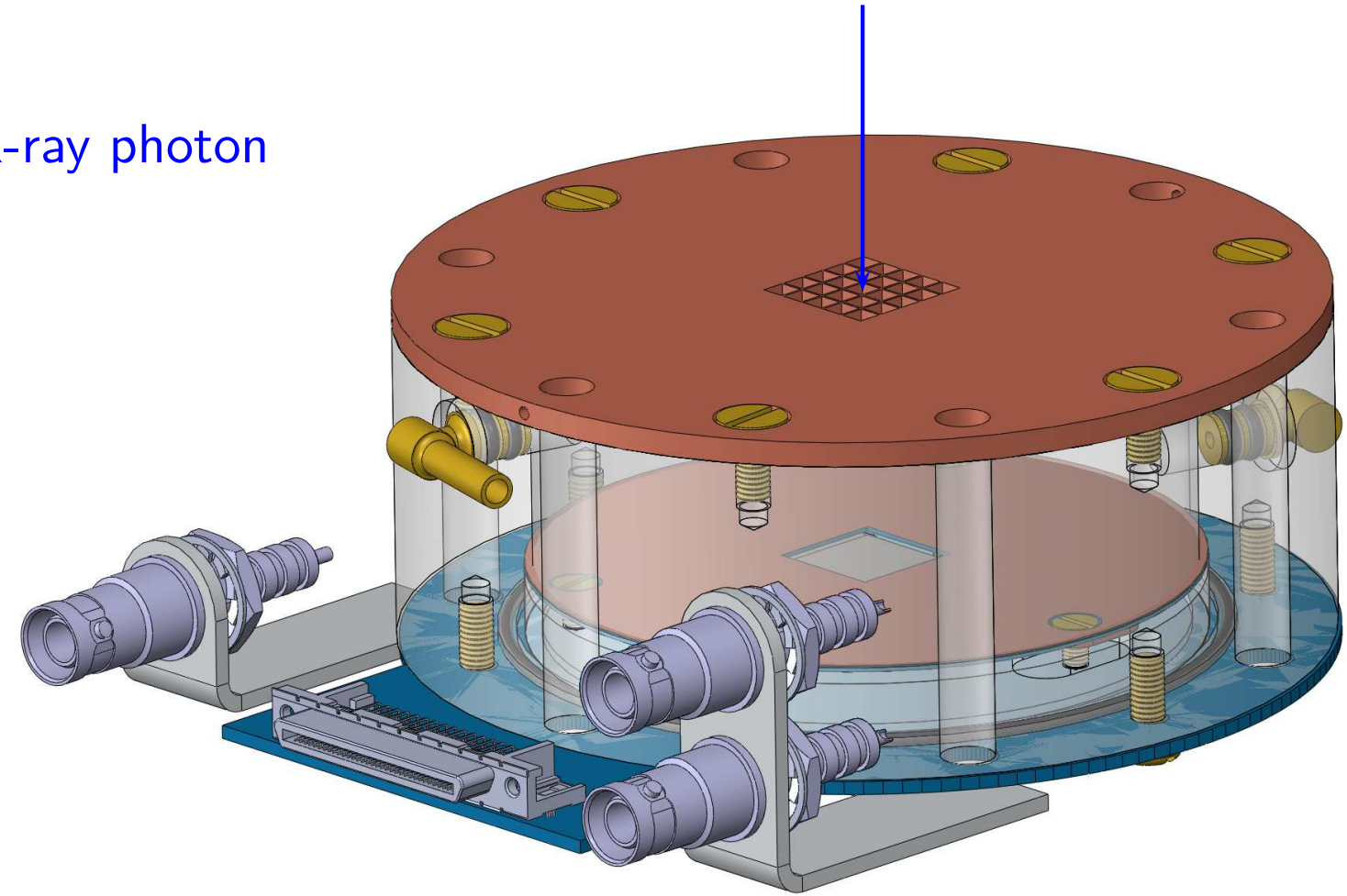


Detector Concept



Detector Concept

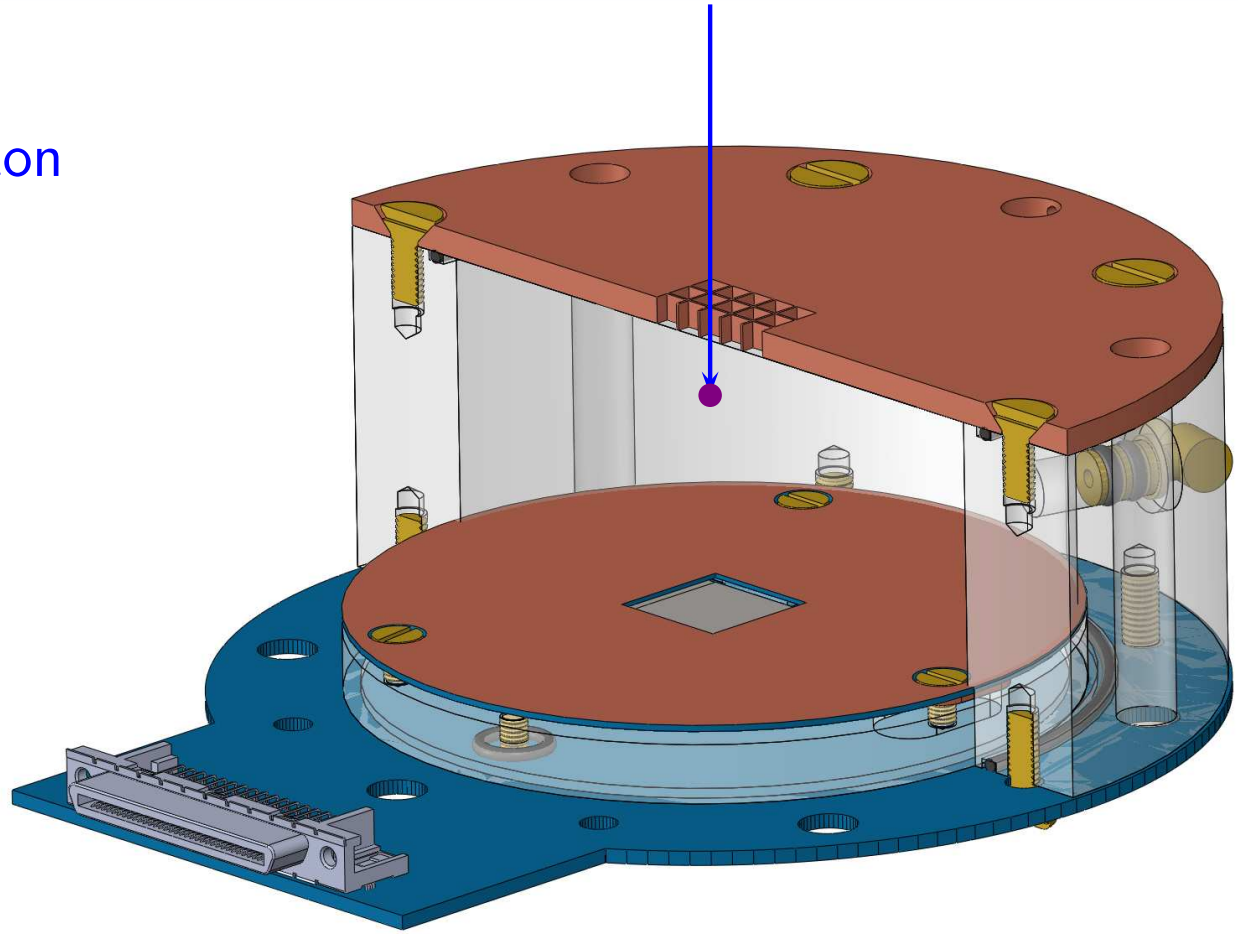
X-ray photon



Detector Concept

X-ray photon

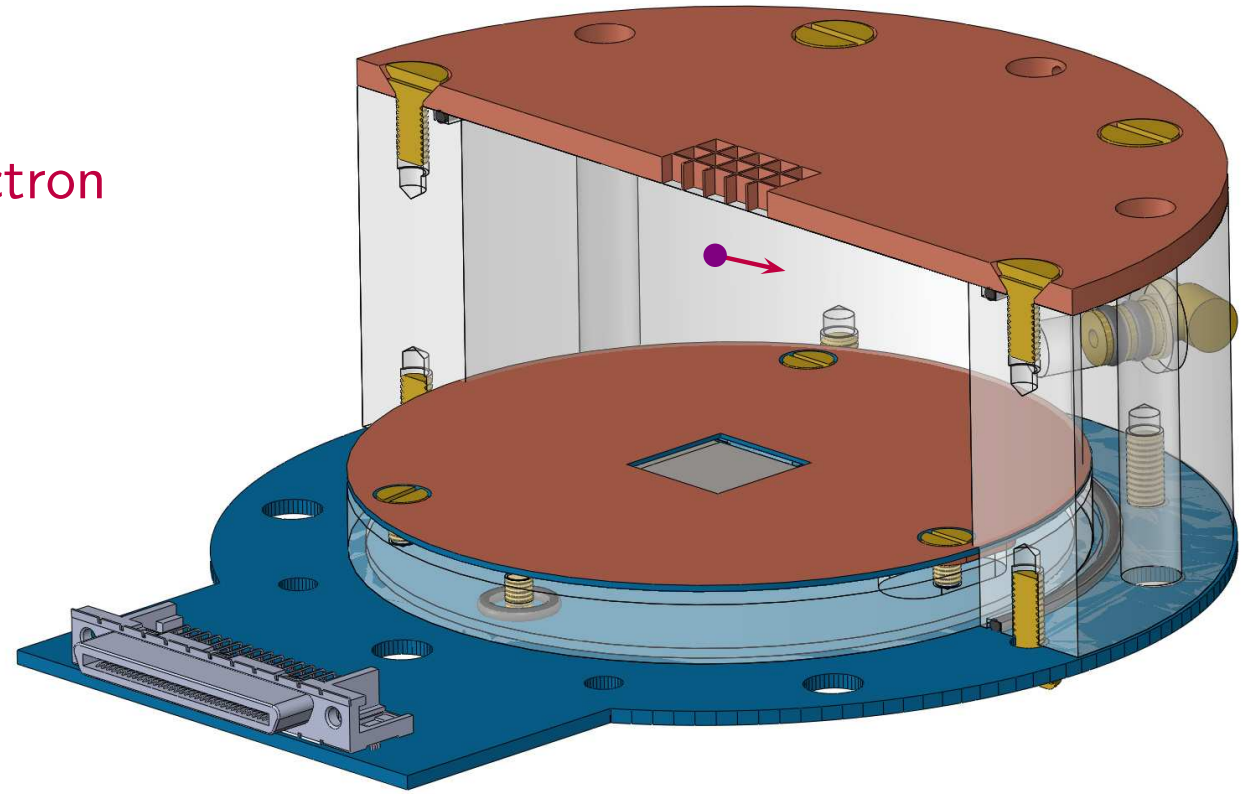
Gas atom



Detector Concept

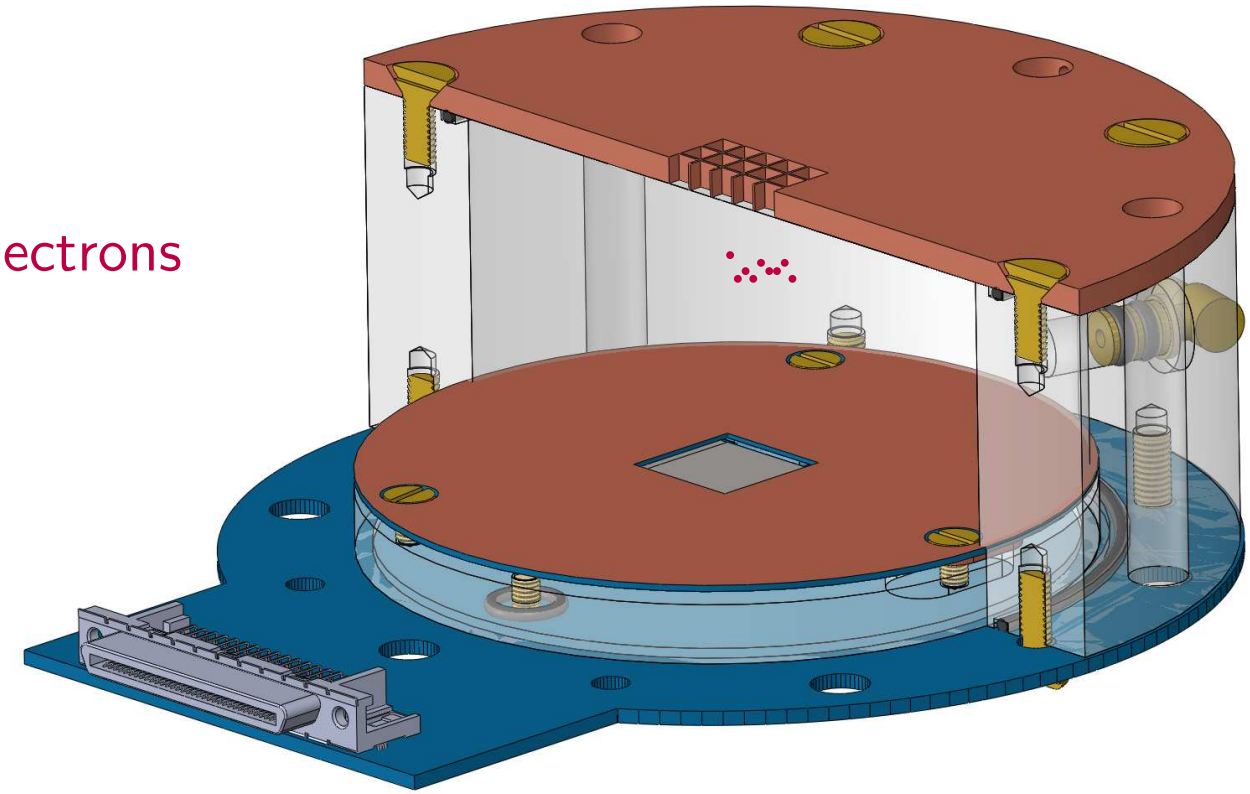
Gas atom

Photo electron



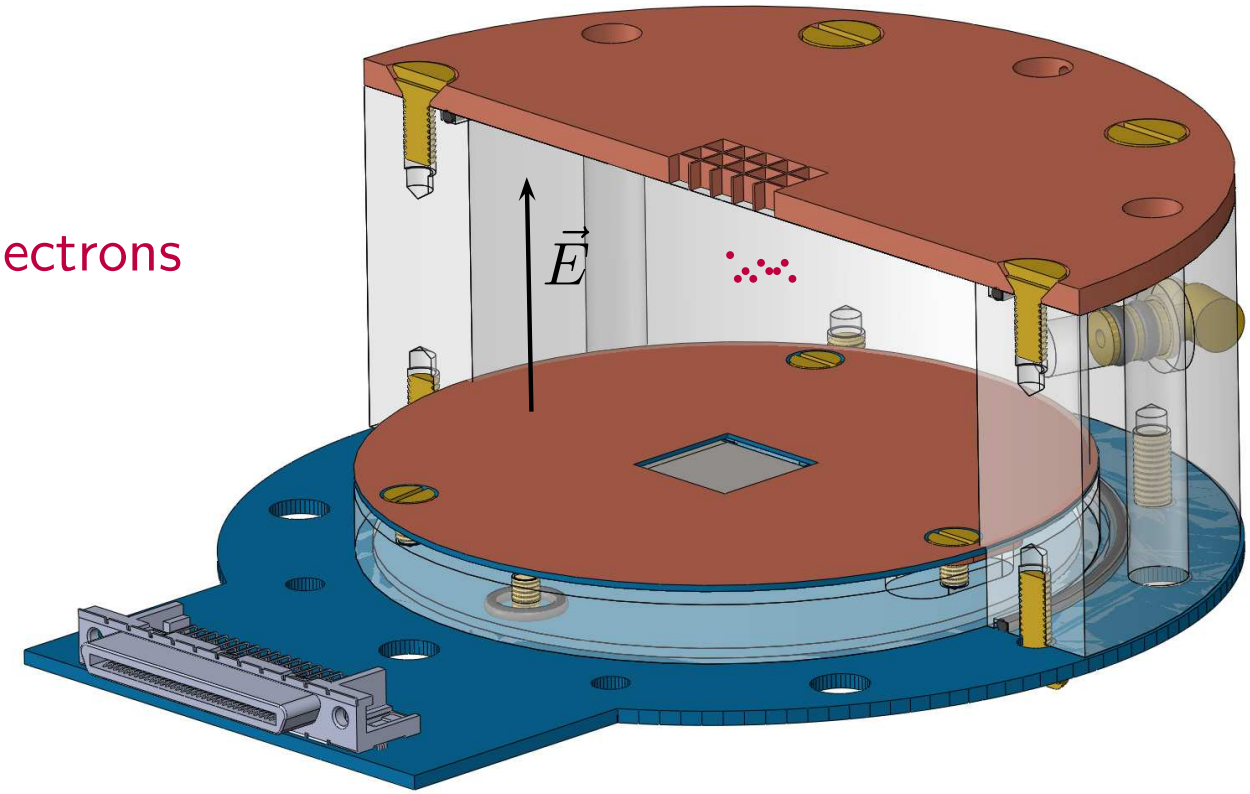
Detector Concept

Primary electrons



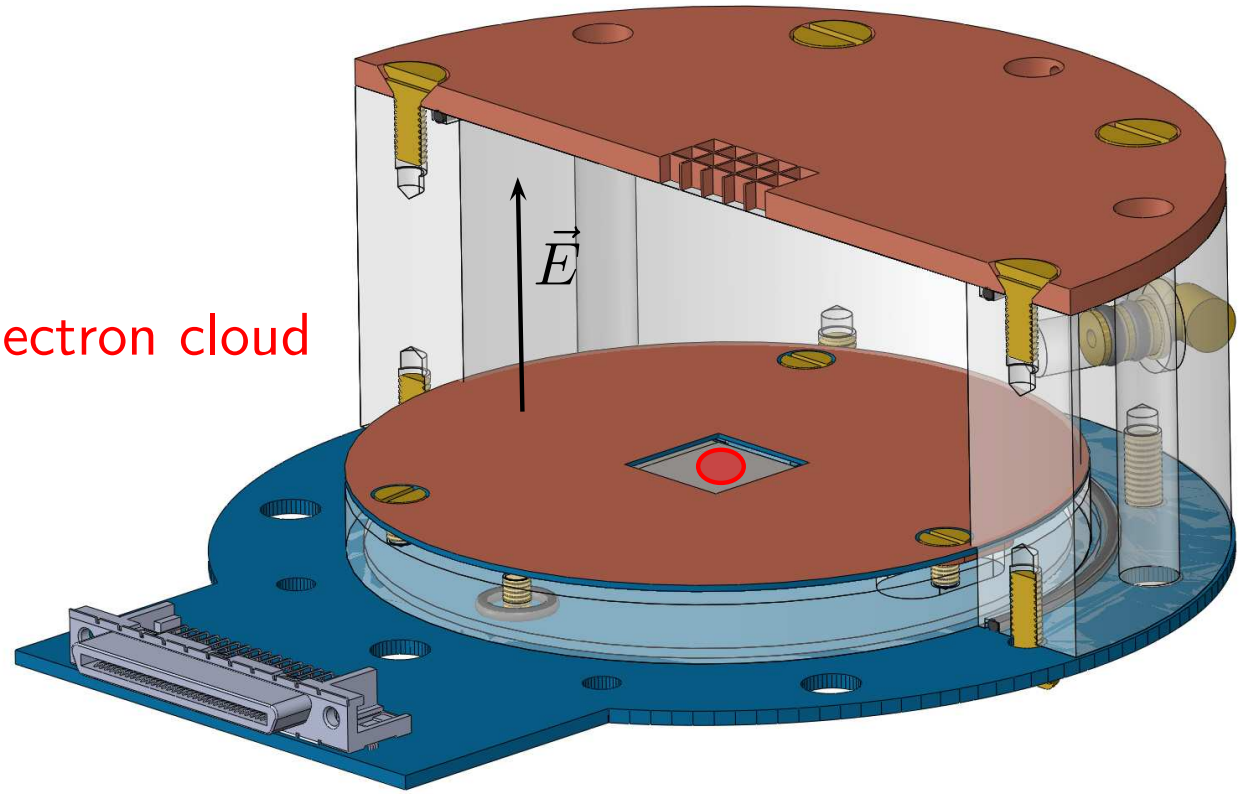
Detector Concept

Primary electrons

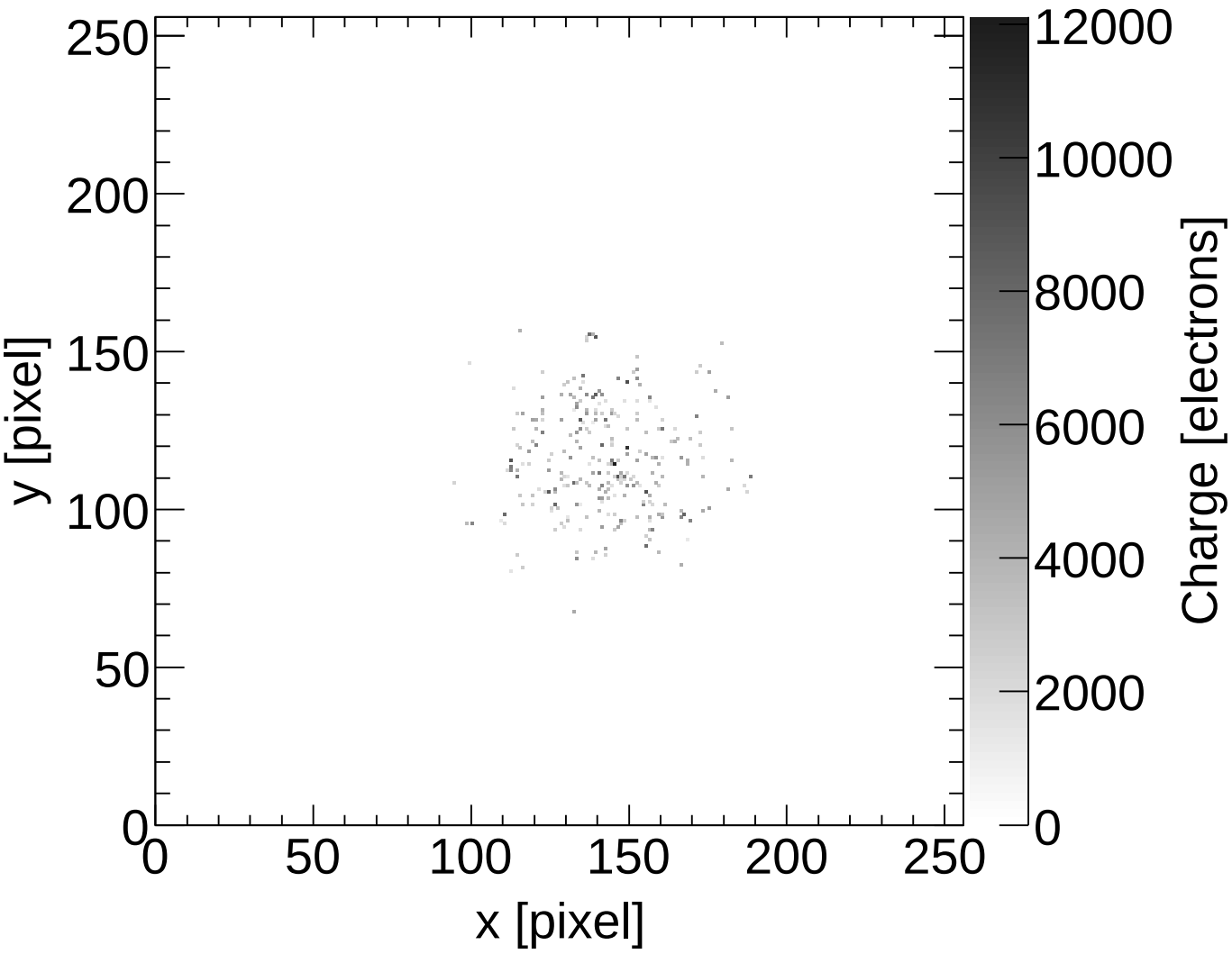


Detector Concept

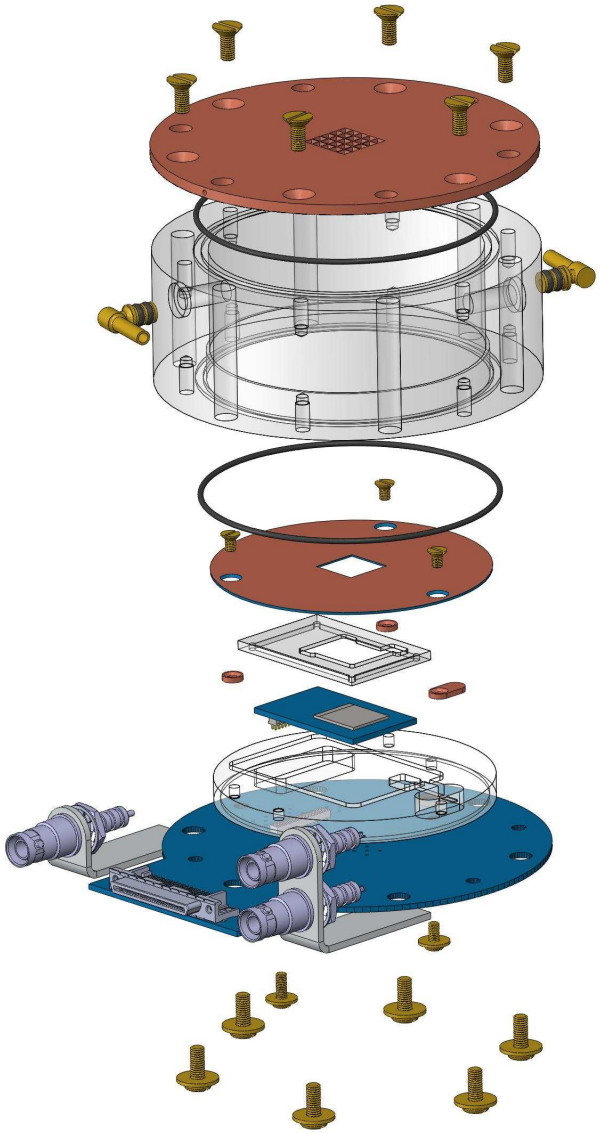
Diffused electron cloud



Typical X-ray Event

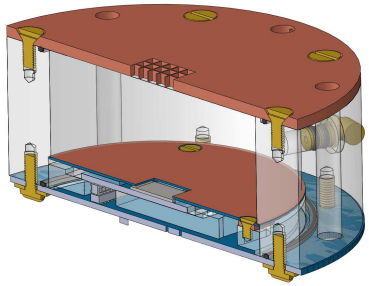


An InGrid based Detector for CAST

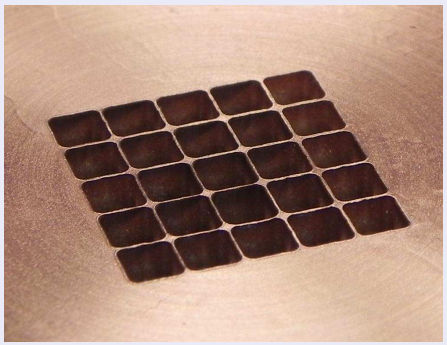


Features

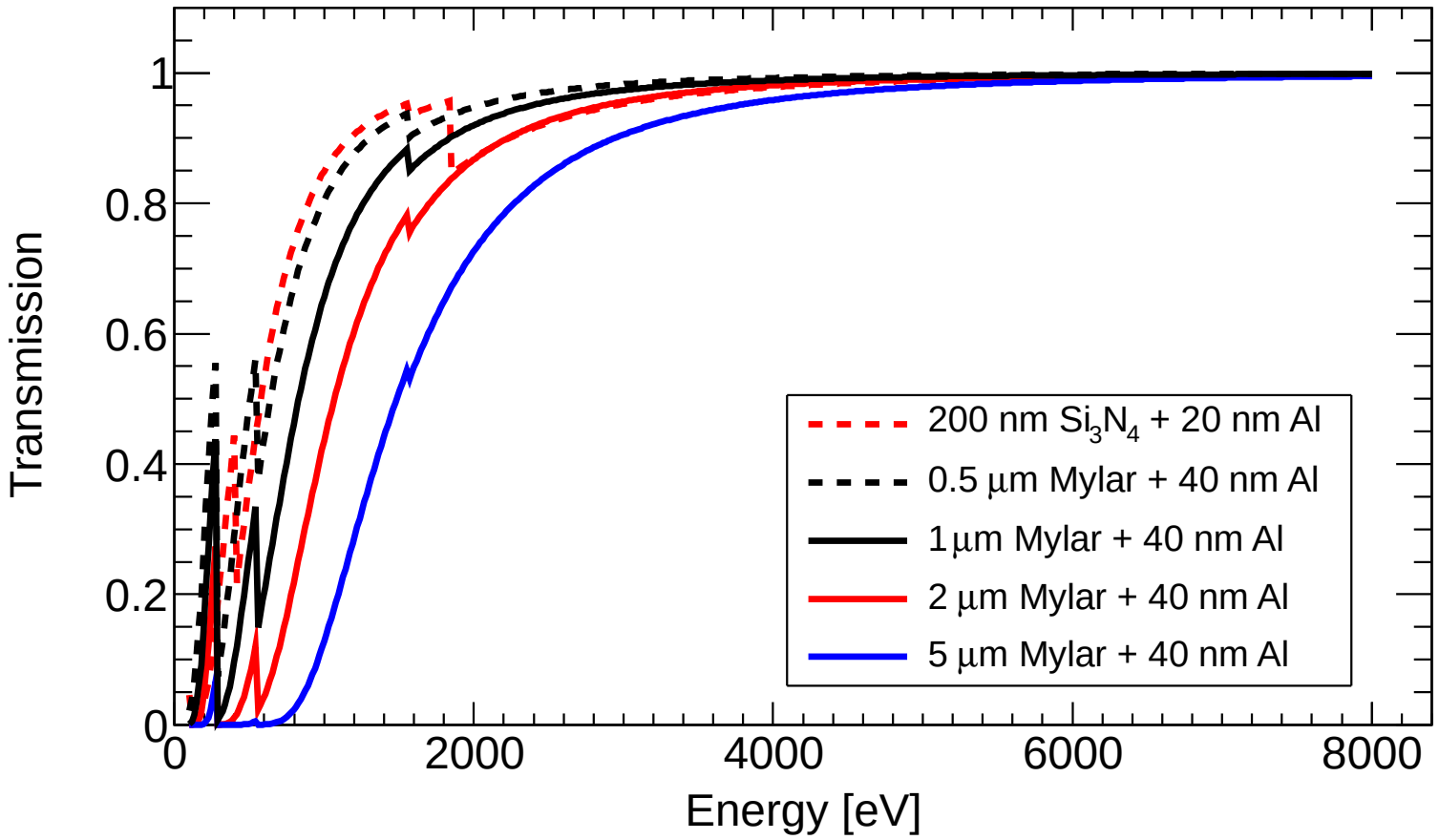
- Modular design based on the 2012 CAST Micromegas
- Body made of plexiglas
- Gas: Ar/iC$_4$H$_{10}$ 97.7/2.3 (→T10.3 Mo 11:30 P12)
- X-ray Window made of 2 µm Mylar with copper strongback



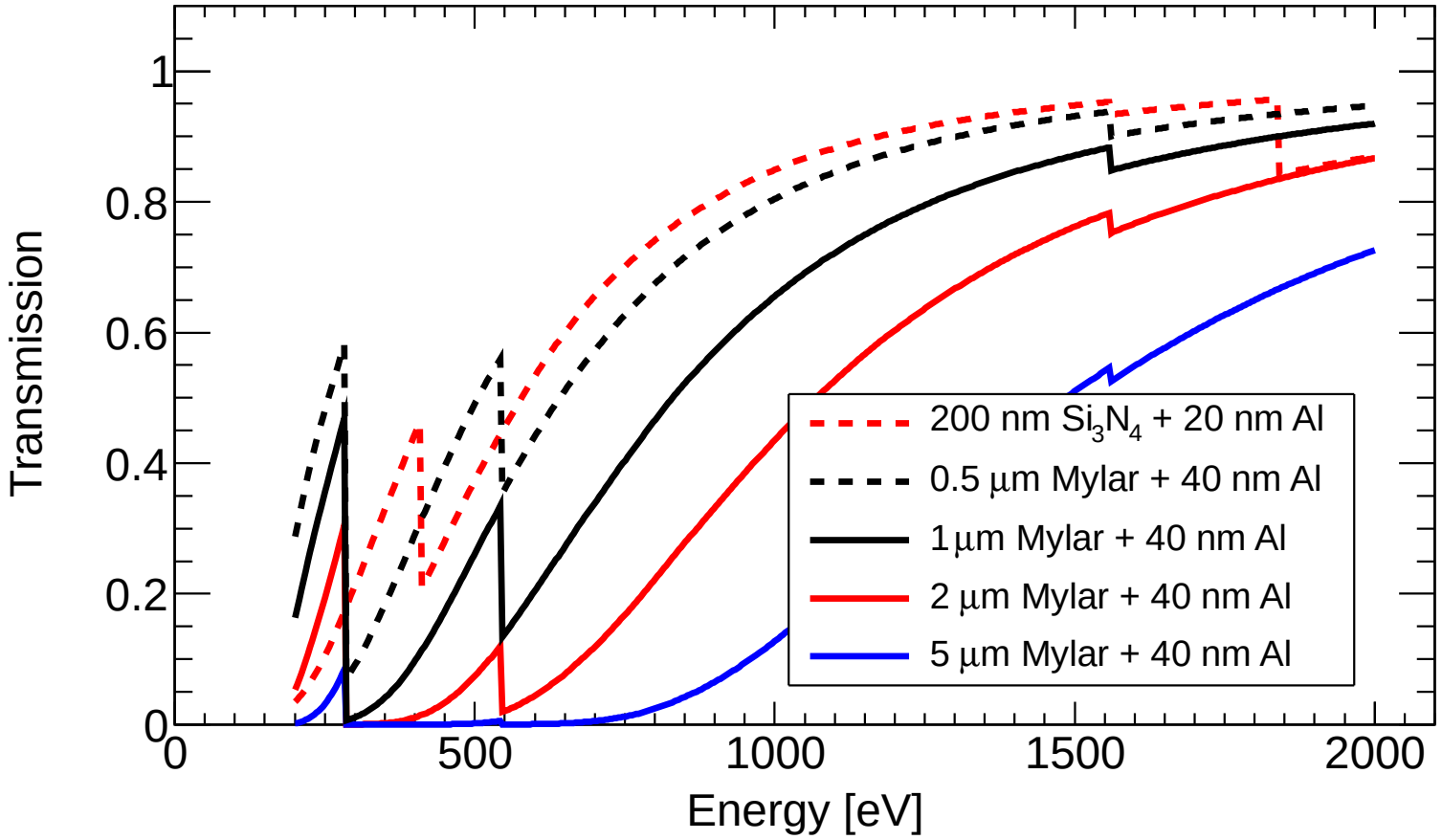
Strongback



X-ray Window Transparency

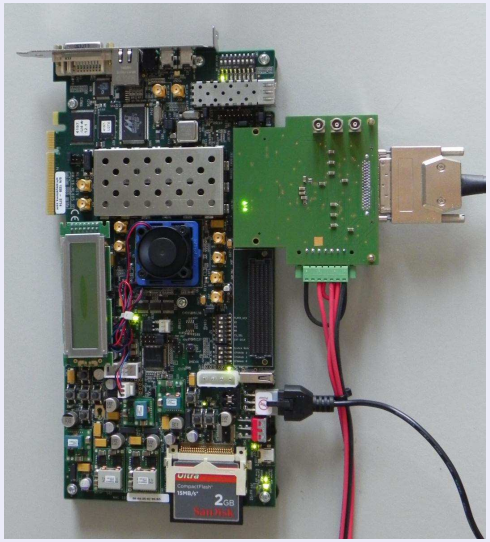


X-ray Window Transparency



Readout System

Virtex6 Readout



FPGA based readout system

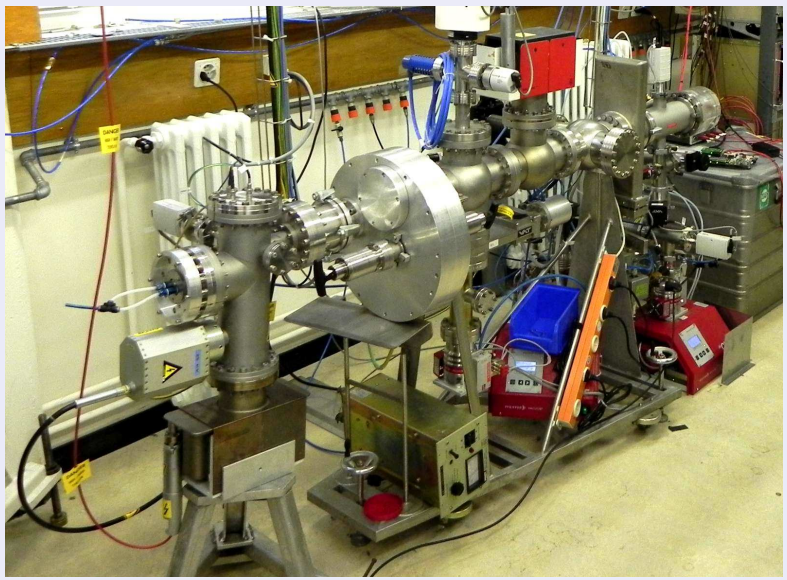
- New SRS based readout system for Timepix ASIC has been developed at Bonn (→ T33.2 Mo 17:05 P12)
- FPGA based, flexible and customizable
- Full access to firm- and software
- For CAST an adopted system based on a Virtex6 evaluation board will be used

Implementing the grid signal in the readout scheme

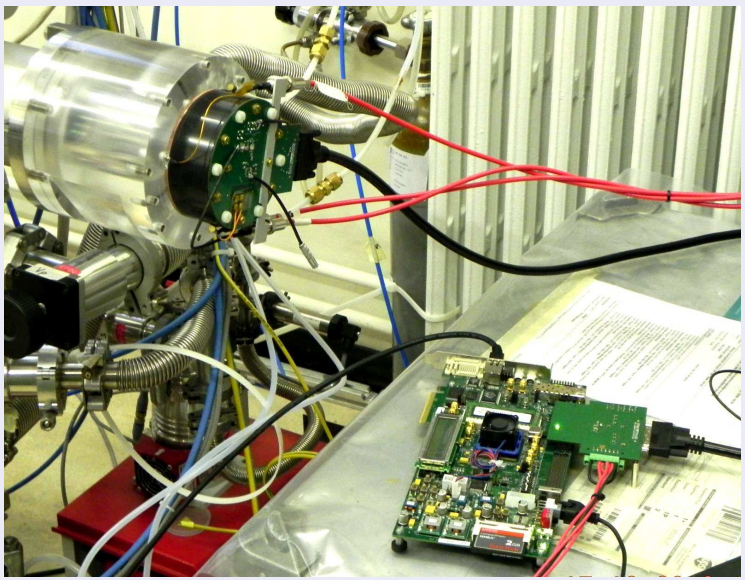
- Idea: Record grid signal with FADC and 'trigger' on it
- Close Timepix frame few µs after trigger signal
- Maybe recorded grid signal can be used for background discrimination (→ T10.4 Mo 11:45 P12)

The CAST Detector Lab

X-ray Generator & Beamline



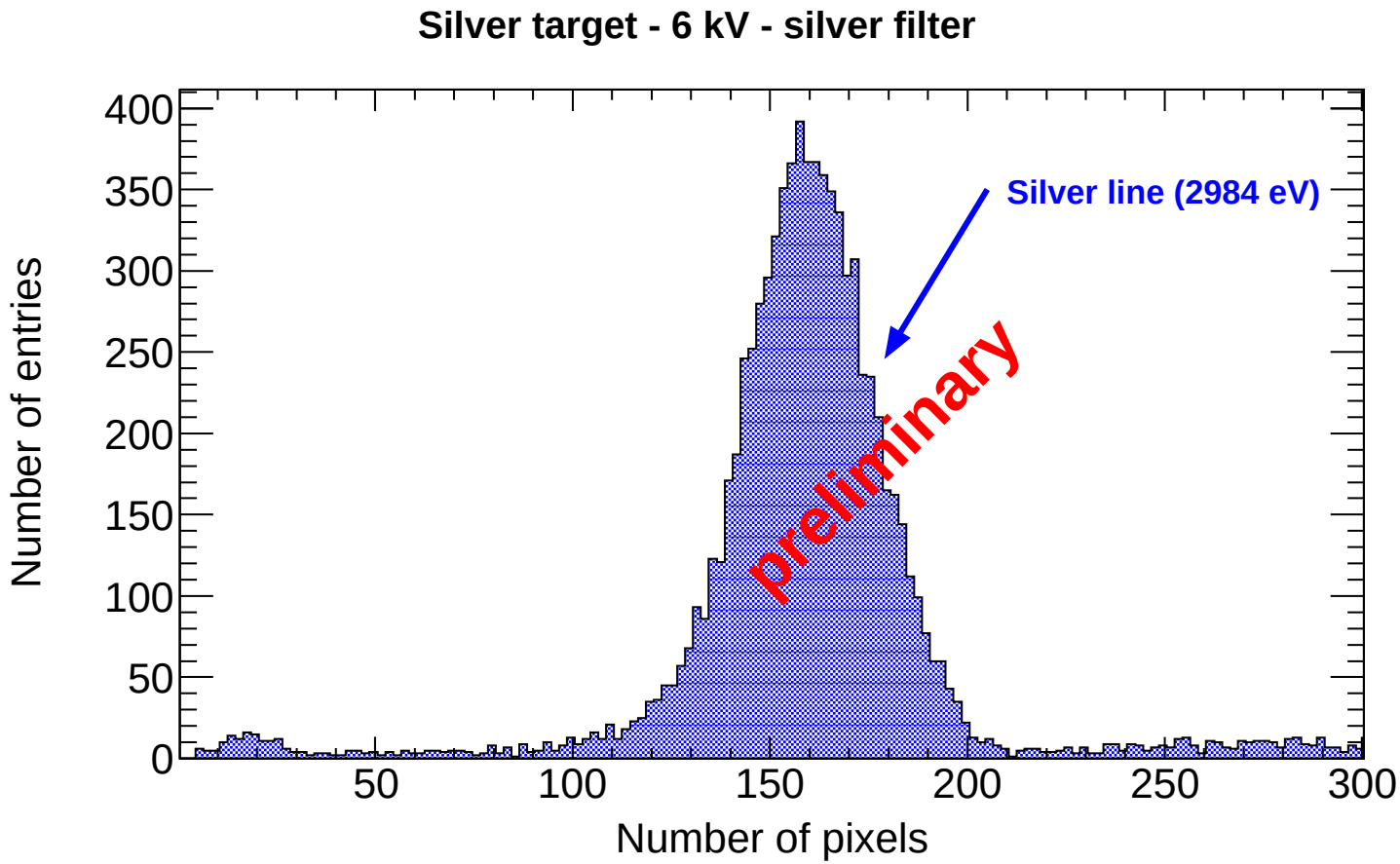
InGrid Detector at CDL



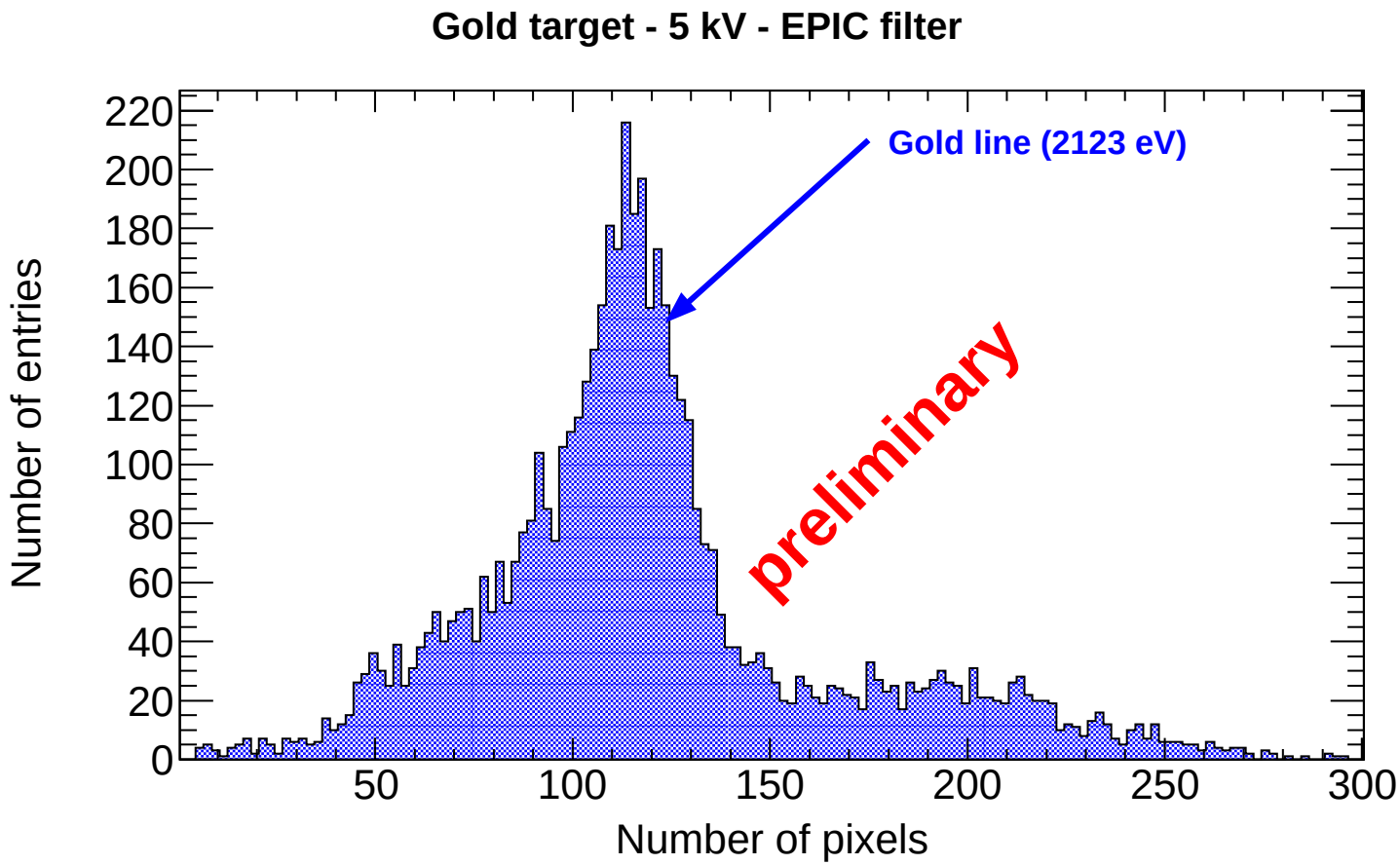
Infrastructure

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

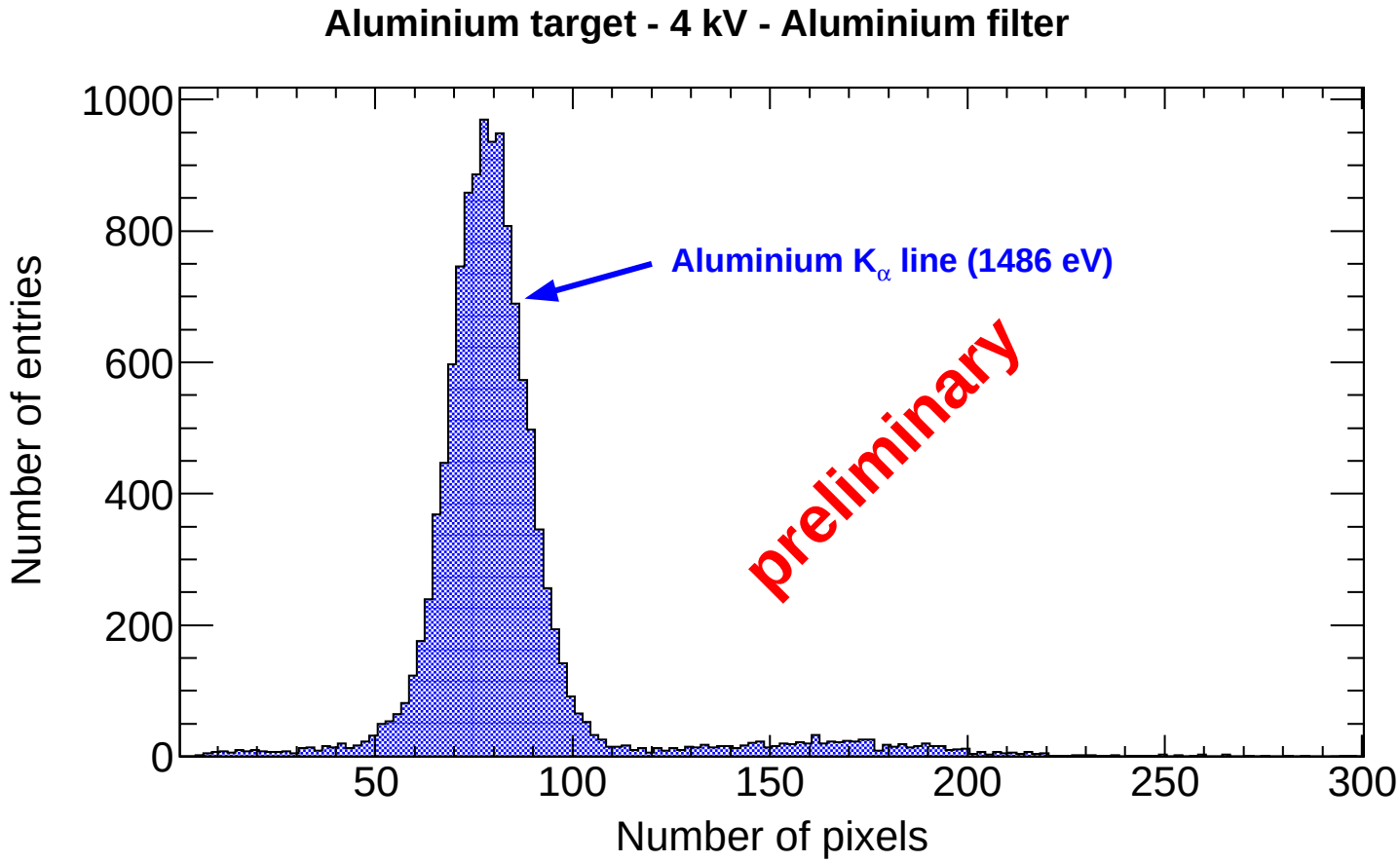
X-ray Spectra



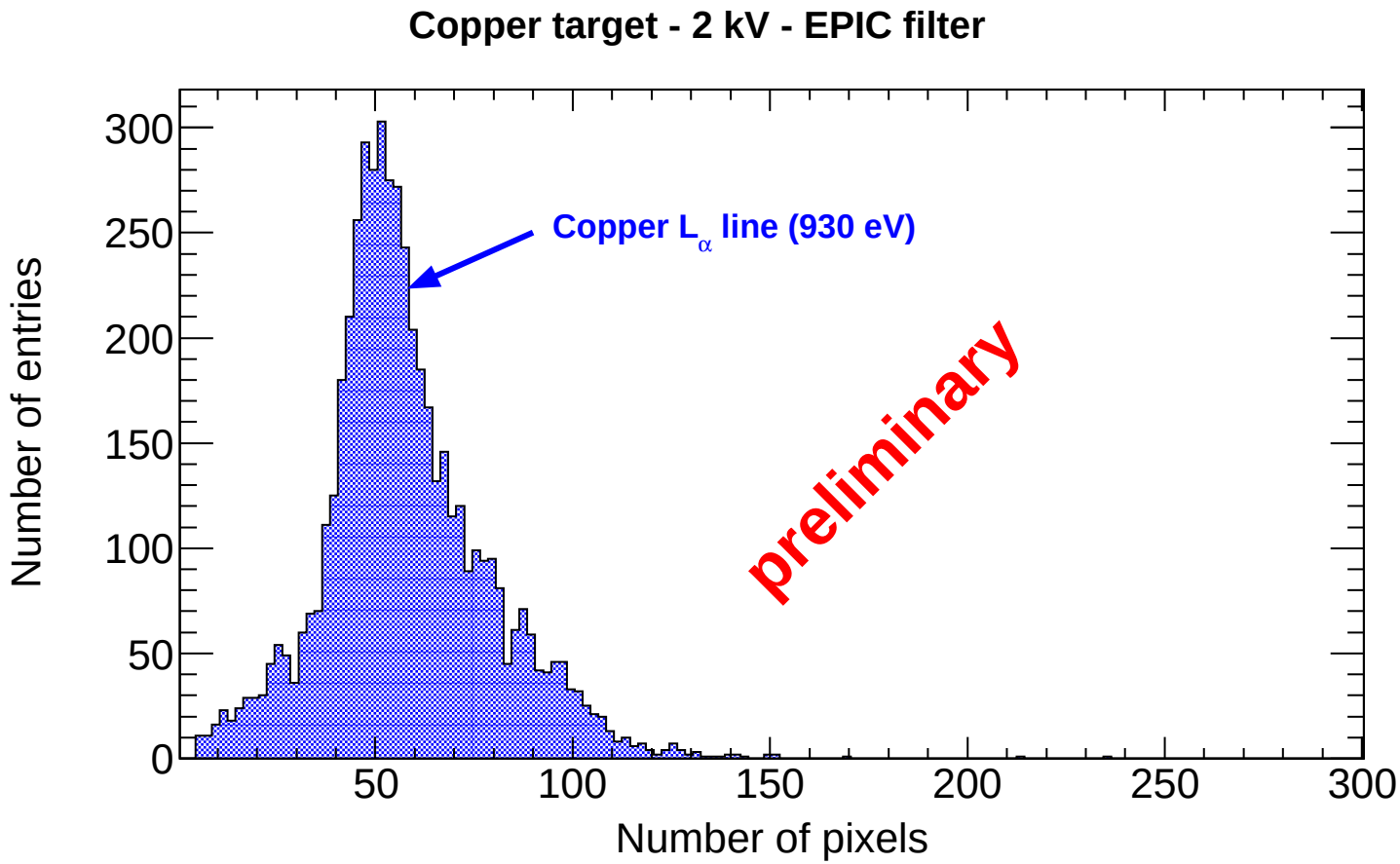
X-ray Spectra



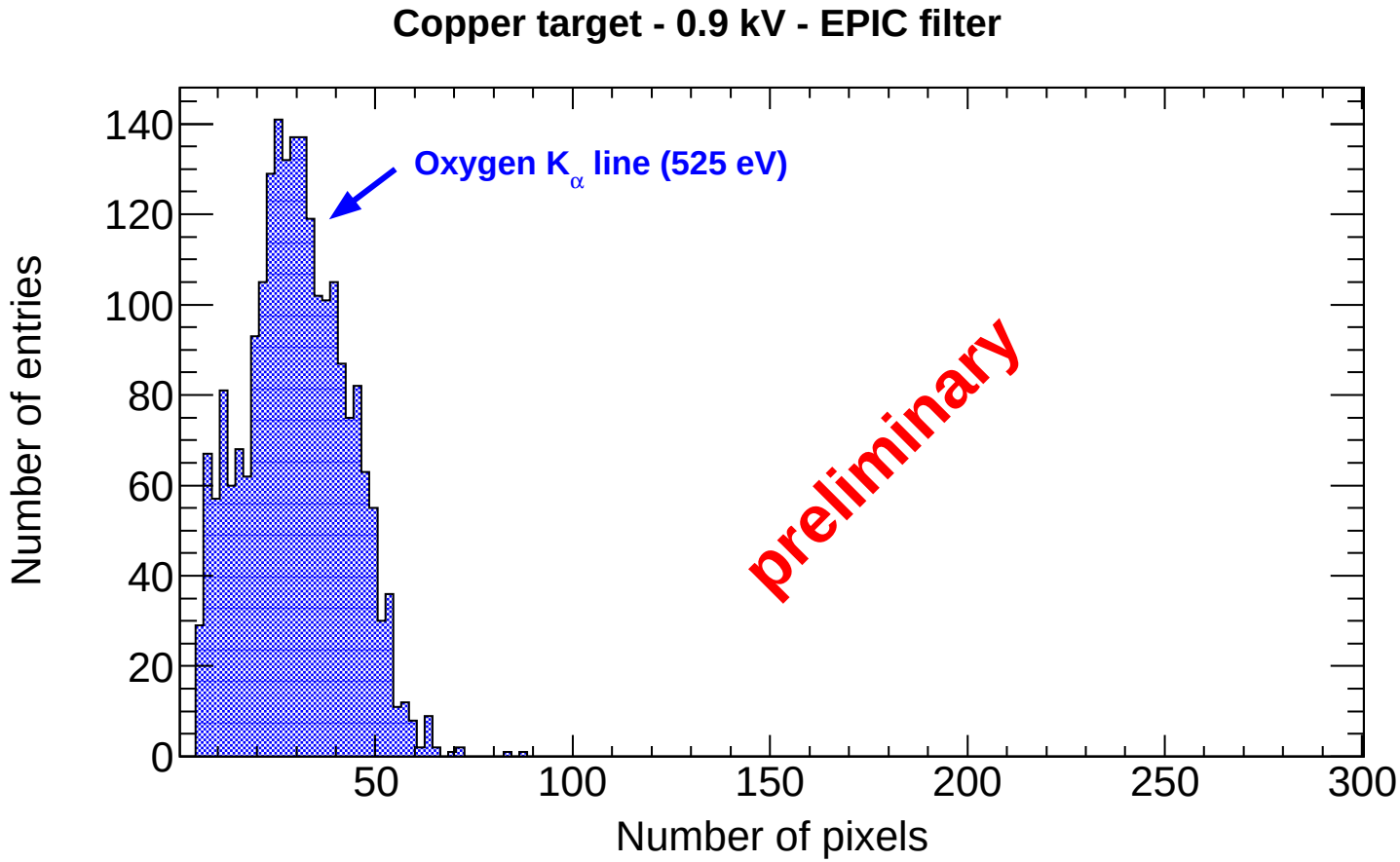
X-ray Spectra



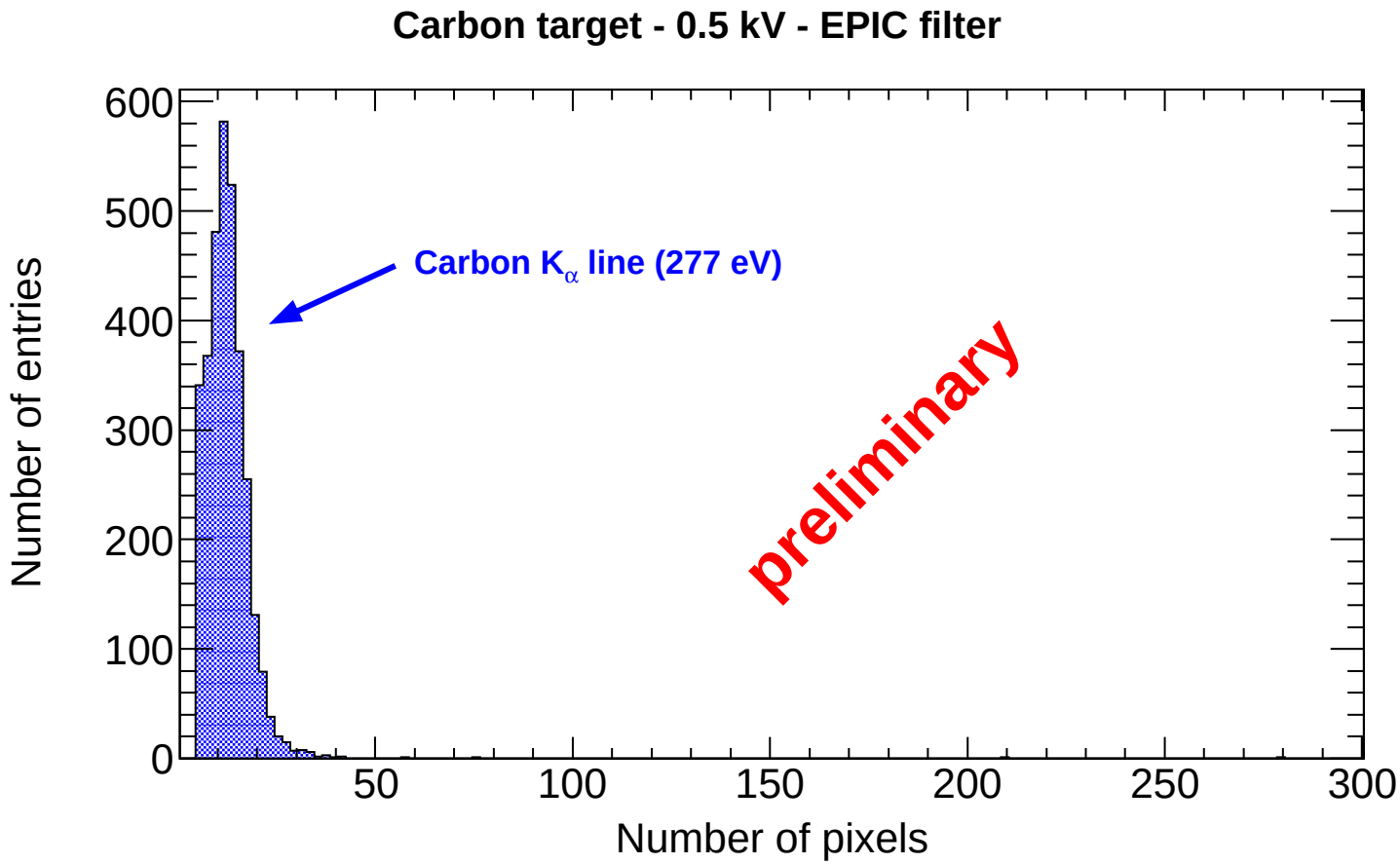
X-ray Spectra



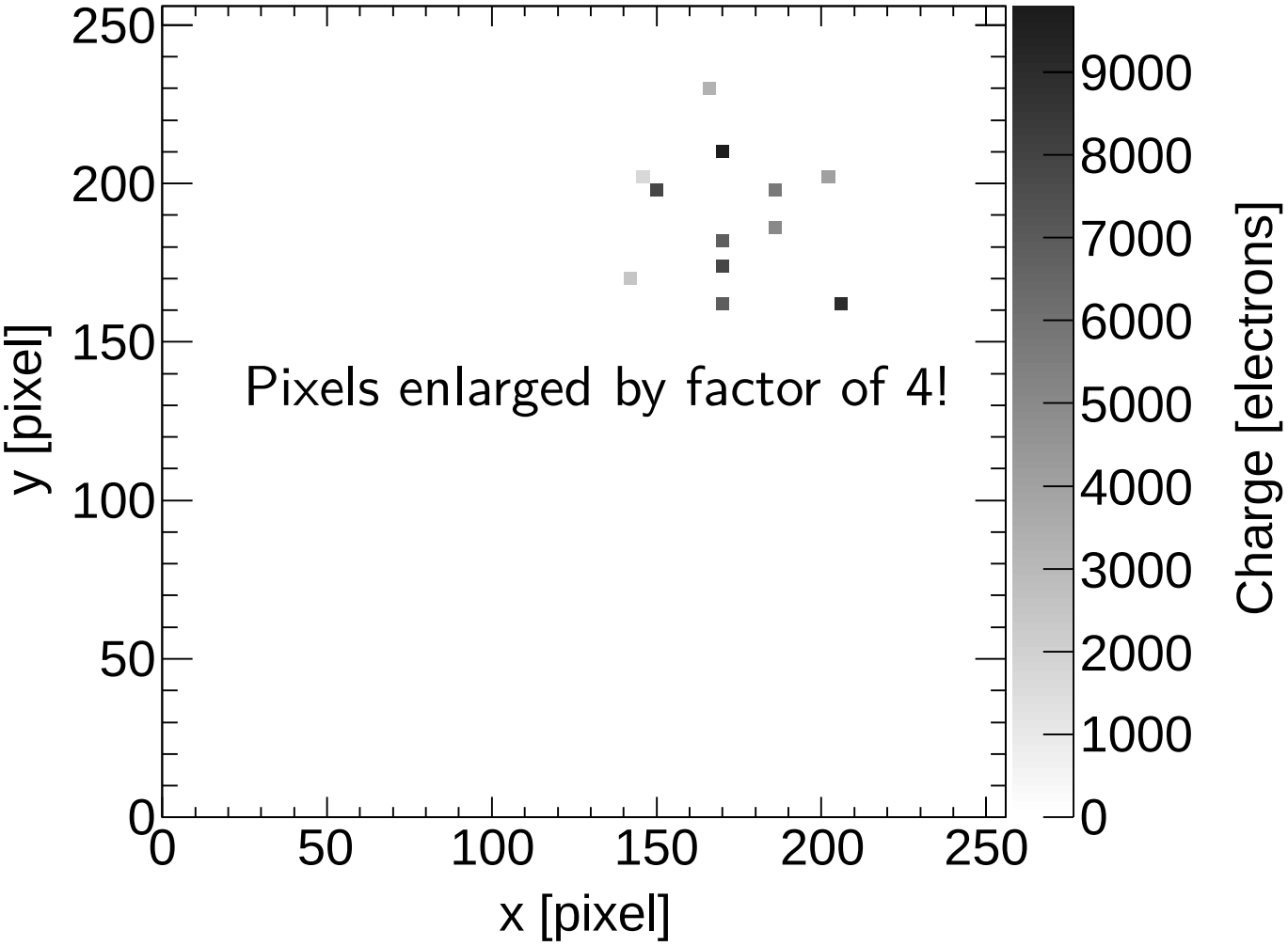
X-ray Spectra



X-ray Spectra

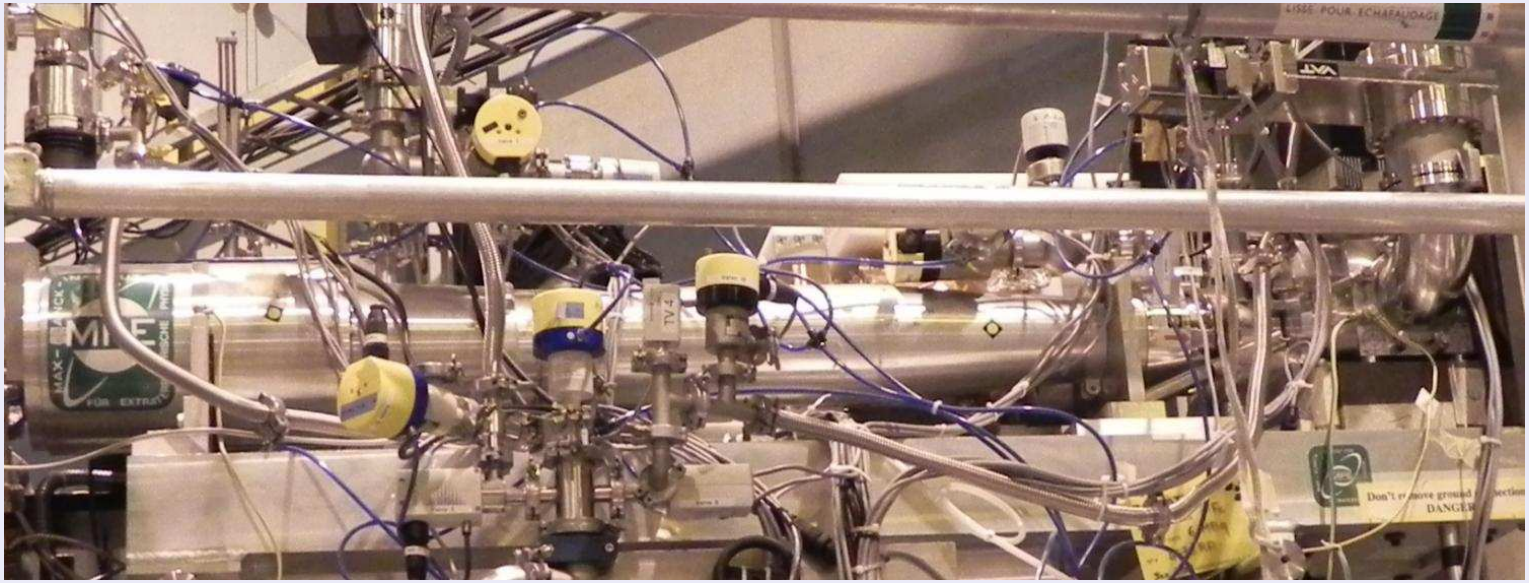


Sample Carbon K_α event



Replacing the pnCCD at the XRT

X-ray Telescope & pnCCD

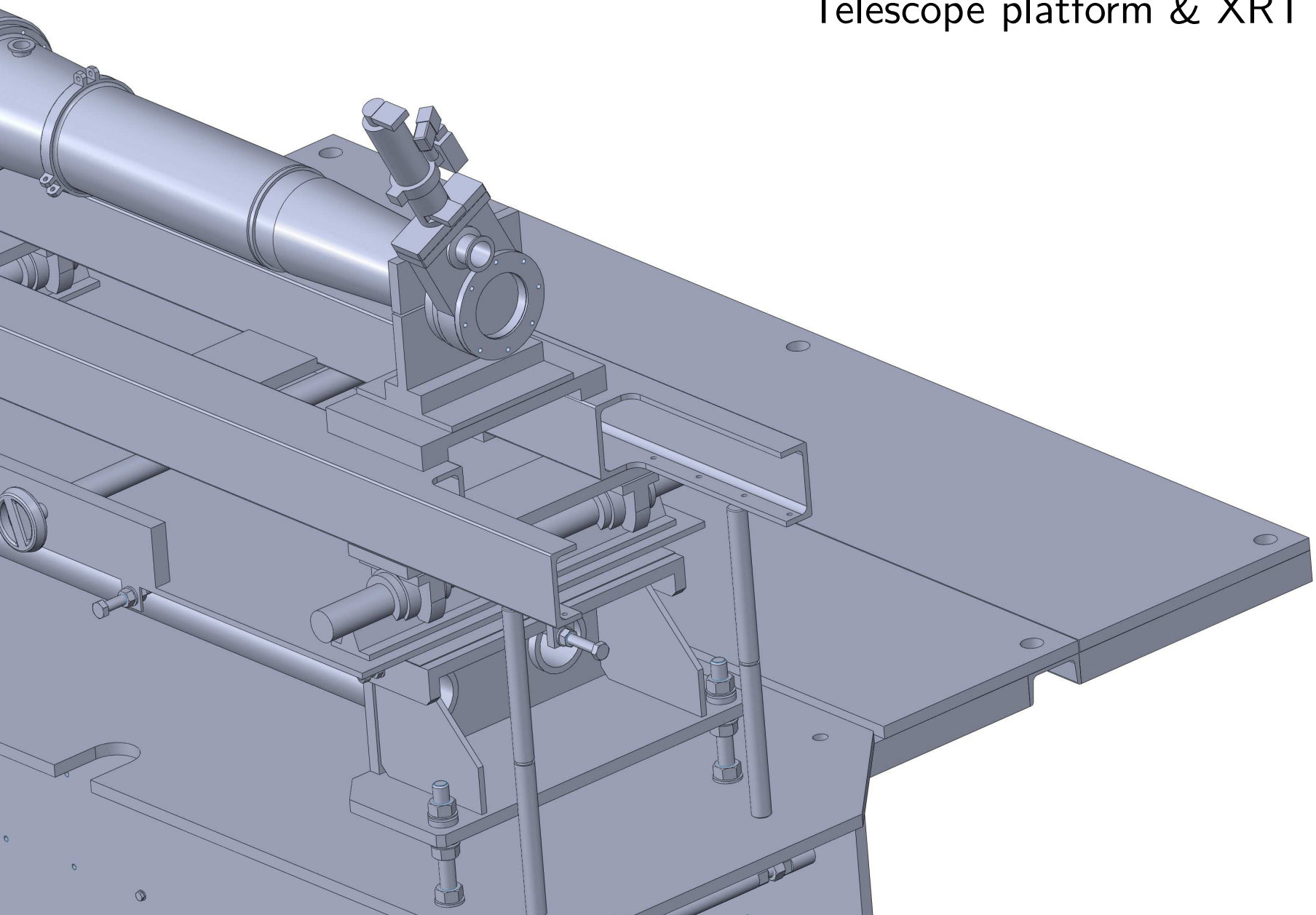


Interfacing the InGrid Detector with the XRT

- Very limited space: $\sim 300\,\text{mm}$ from gate valve to focal plane
- Need space for lead shielding and ^{55}Fe source manipulator
- Differential pumping necessary to ensure good vacuum in XRT

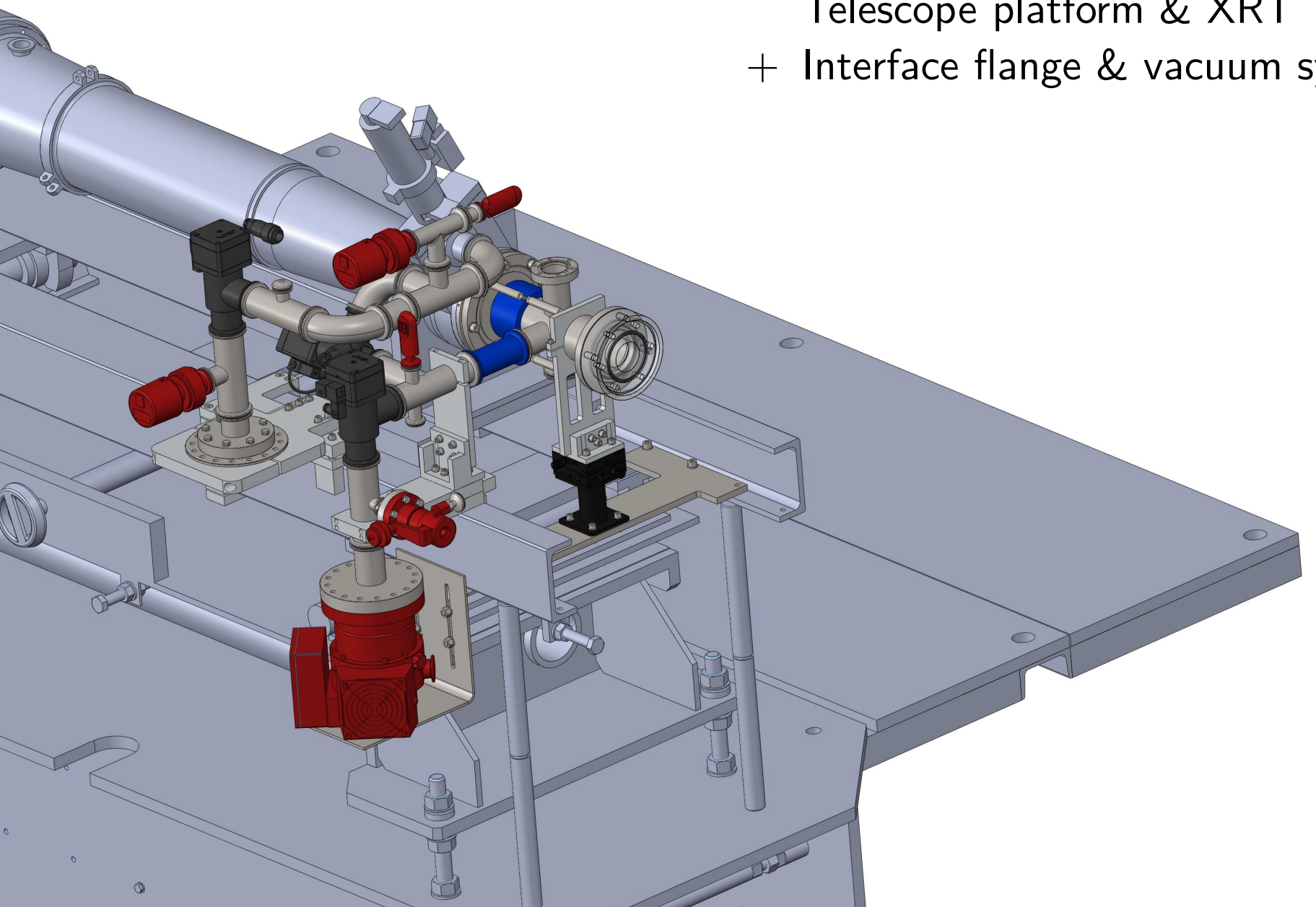
CAD Integration

Telescope platform & XRT

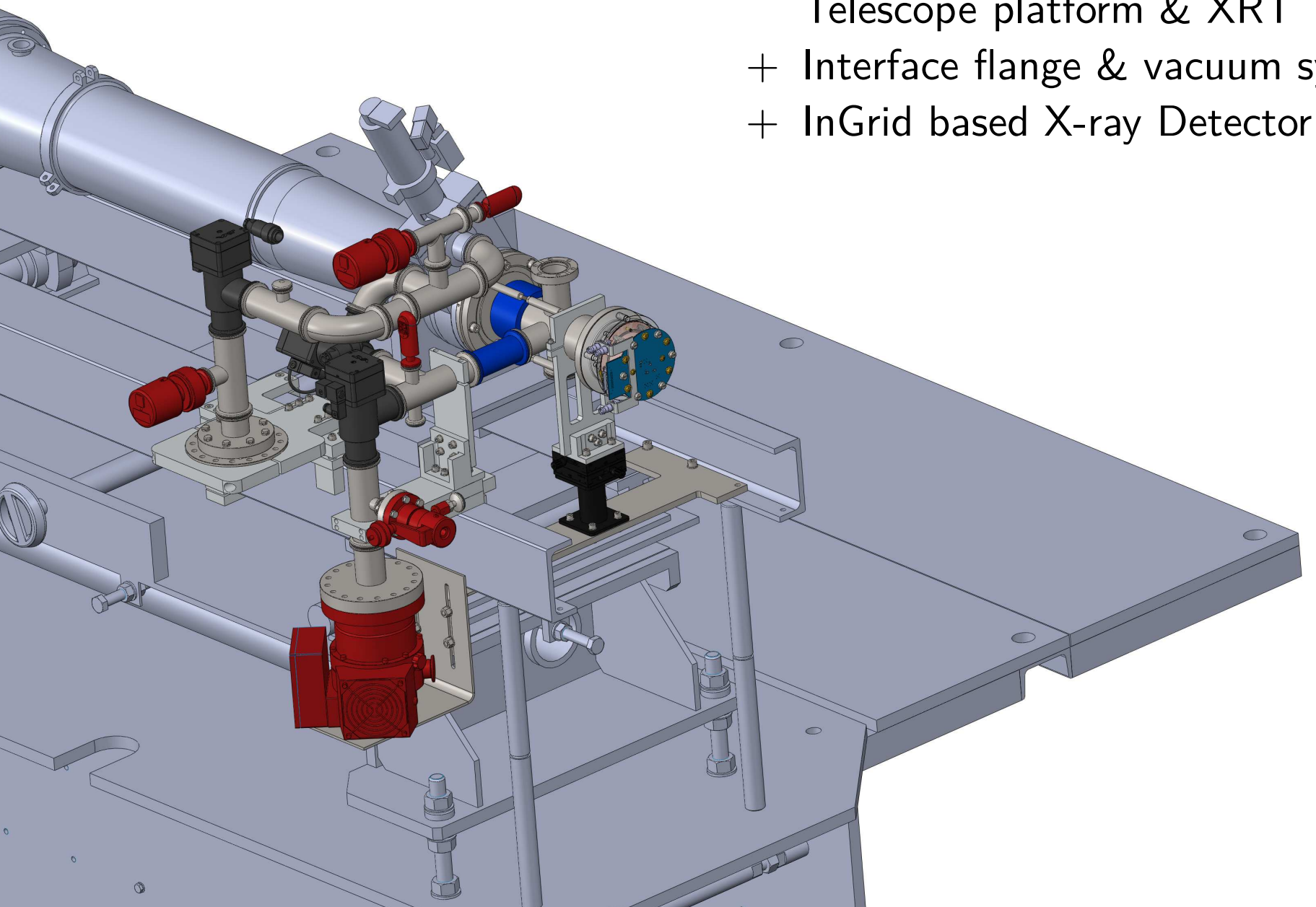


CAD Integration

Telescope platform & XRT
\+ Interface flange & vacuum system

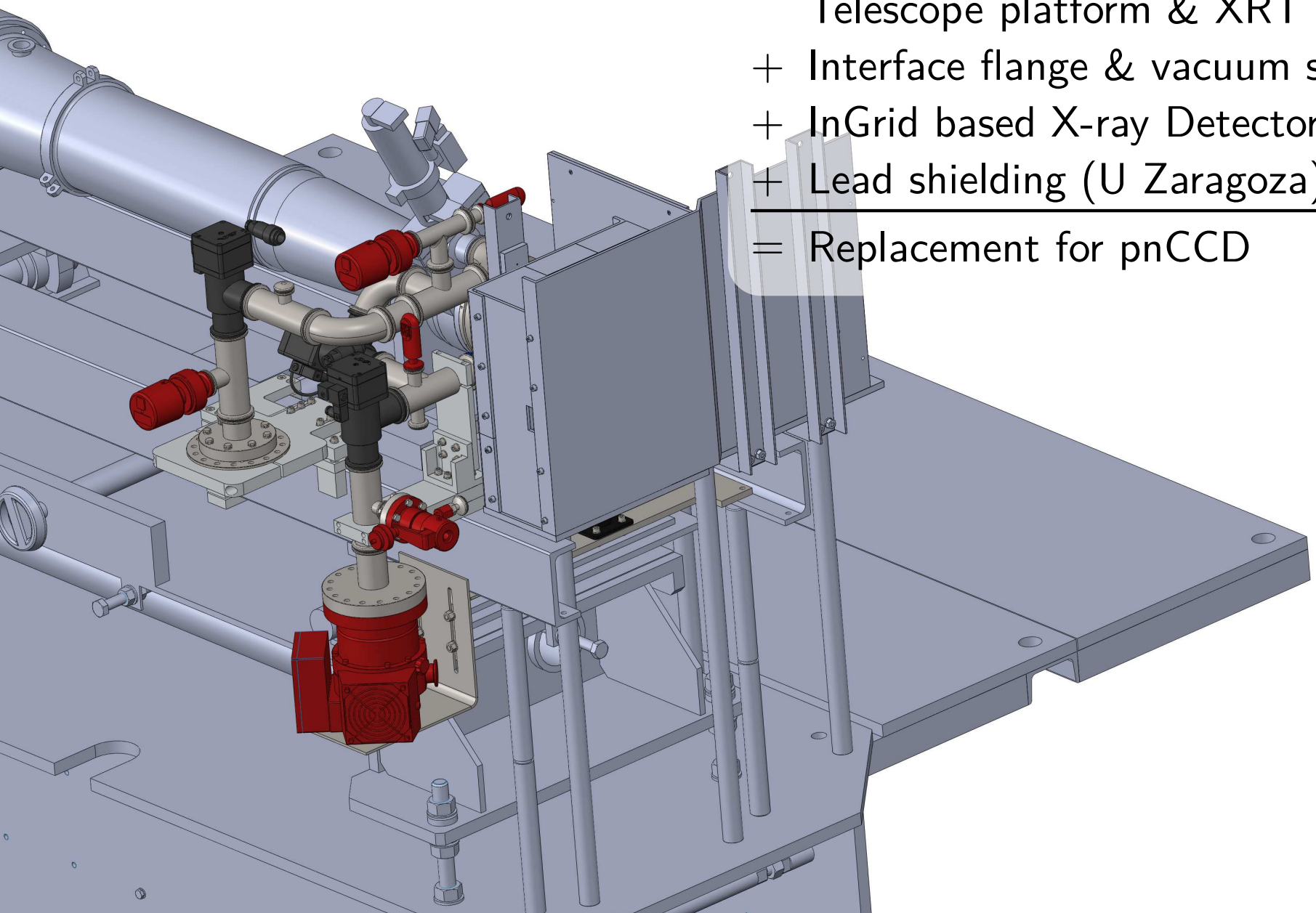


CAD Integration



Telescope platform & XRT
+ Interface flange & vacuum system
+ InGrid based X-ray Detector

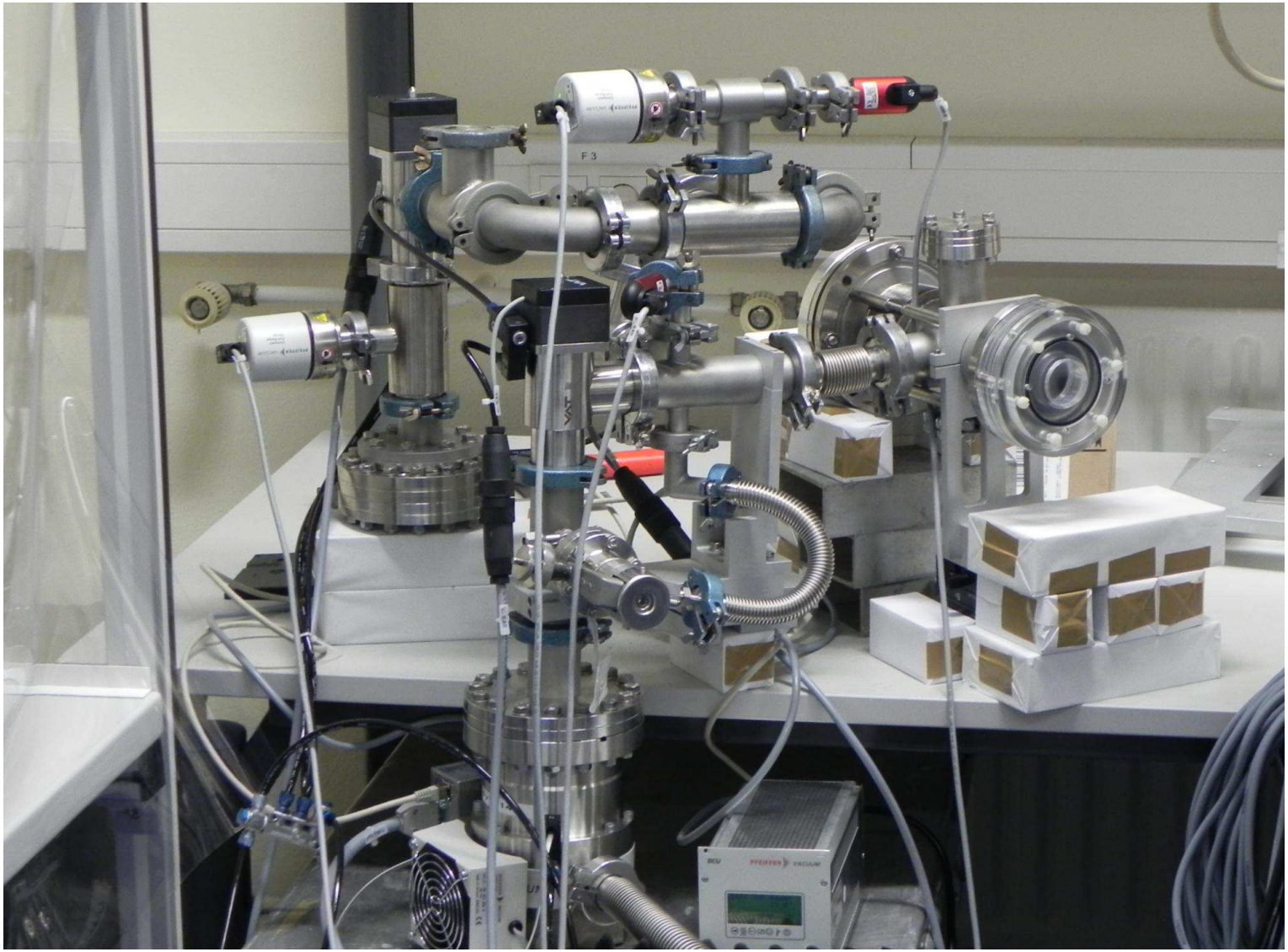
CAD Integration



Telescope platform & XRT
+ Interface flange & vacuum system
+ InGrid based X-ray Detector
+ Lead shielding (U Zaragoza)

= Replacement for pnCCD

Assembled vacuum system



Conclusion & Outlook

Conclusion

- InGrid based X-ray Detector provides promising candidate for future CAST detector as replacement for pnCCD
- Detection of carbon K_α line at 277 eV is possible
- Efforts to interface and install InGrid based detector at the CAST XRT are ongoing

Outlook

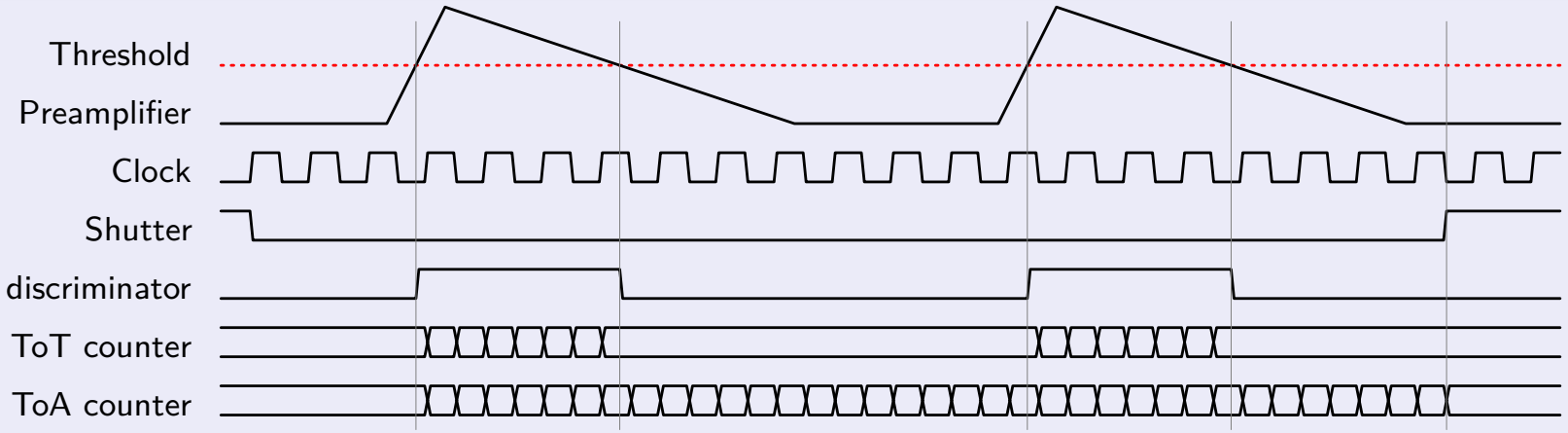
- Start installation of infrastructure and detector at CAST in April 2014 (including additional tests in CDL)
- Search for axions & chameleons with InGrid based detector during CAST run 2014
- Work on final implementation of grid signal in readout scheme and optimize setup


PHASE 2
CAST
ANSALDO GIE
EUROPAMETALLI – LMI
E. ZANON
TWICE
THE CHALLENGE
AxionSearch

Backup Slides

Timepix ASIC – More Details

Timing Diagram



Timepix 3

- Has been submitted 2013 – First chips are available
- Ability to recognize multihits and to measure Charge and Time simultaneously
- Allows for data driven readout

The Peccei-Quinn Mechanism

Strong CP problem

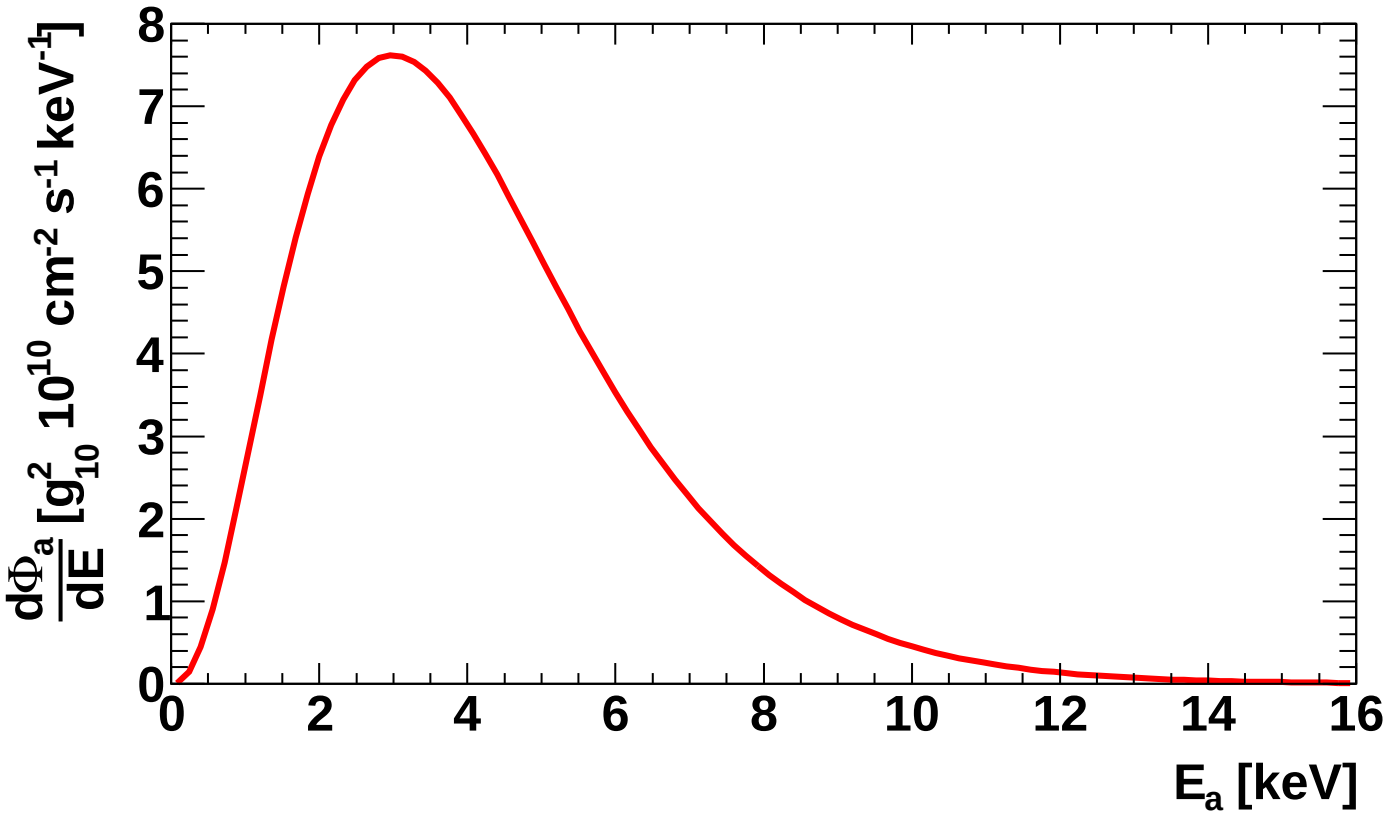
- Lagrangian of strong interaction contains CP violating term

$$\mathcal{L} = \underbrace{\sum_n \bar{q}_n(\gamma^\mu i D_\mu - m_n)q_n - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\mathcal{L}_{\text{QCD}}} + \theta\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

An elegant solution – The Peccei-Quinn mechanism

- A bit similar to Higgs mechanism
- Introduction of new global, chiral symmetry $U(1)_{\text{PQ}}$ which is spontaneously broken at energy scale f_a
- θ becomes dynamic variable instead of theory parameter
- Spontaneous symmetry breaking gives rise to a Goldstone boson called **axion**

Solar Axion Flux



Chameleons – Dark Energy Particles?

Dark energy as a new form of matter

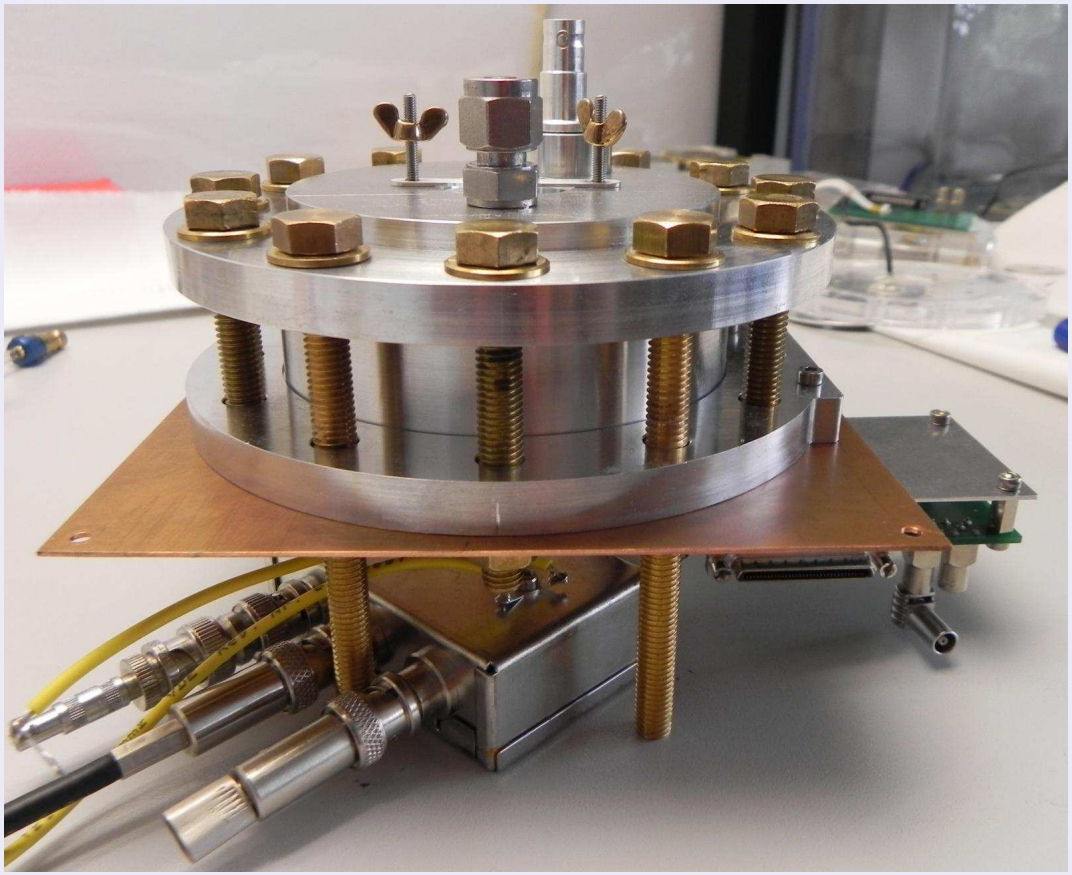
- Scalar fields interacting with matter and photons could be strong candidates
- Constraints would lead to large gravitational effects and a fifth force with long range
- Exploit screening mechanisms to avoid unnatural models
- Chameleon screening: Models with a density dependent effective mass

Solar Chameleons

- Chameleons could be produced in the sun a bit similar to axions via a Primakoff-like effect
- Production not in the suns core but in a small shell around the tachocline and an energy spectrum peaking below 1 keV

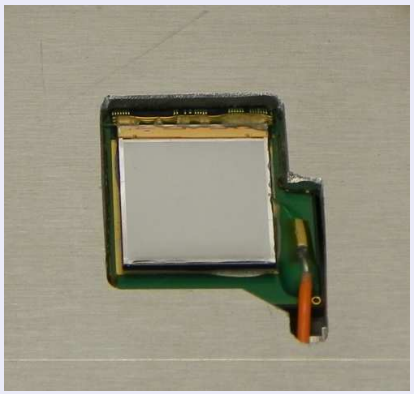
Prototype Detector

X-ray detector



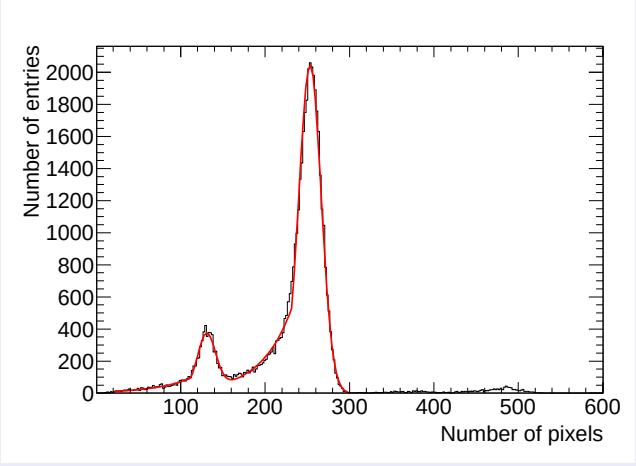
Cathode

Anode

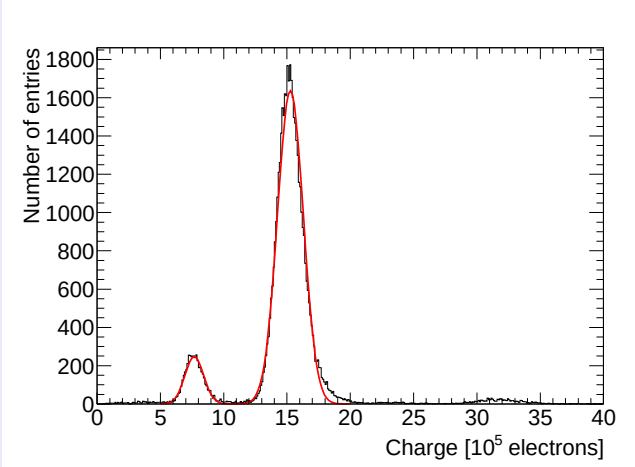


Detector Performance – Tests with ^{55}Fe

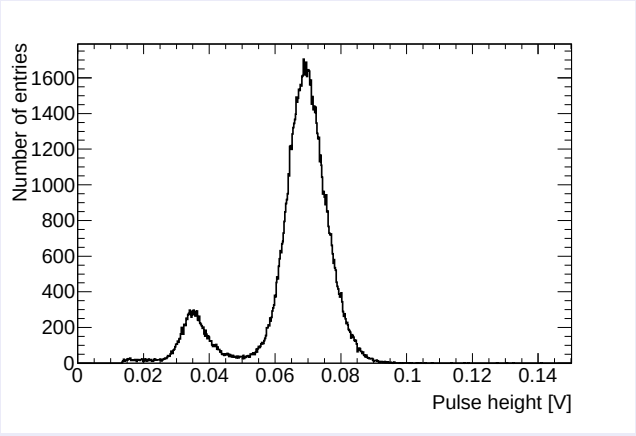
Spectrum - Pixels



Spectrum - Charge



Spectrum - Grid

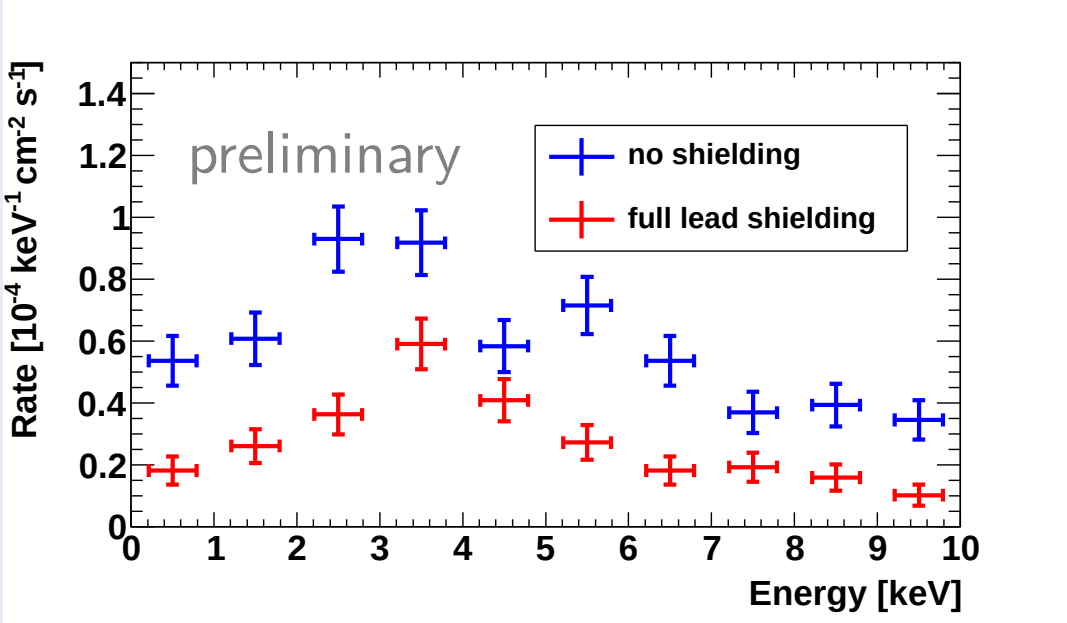


Energy resolution

- Ar/iC$_4$H$_{10}$ 95/5
- Cr foil to suppress 6.1 keV
- Pixels: $\sigma_N/N \approx 5.2\,\%$
- Charge: $\sigma_Q/Q \approx 6.7\,\%$
- Grid: $\sigma_U/U \approx 8\,\%$

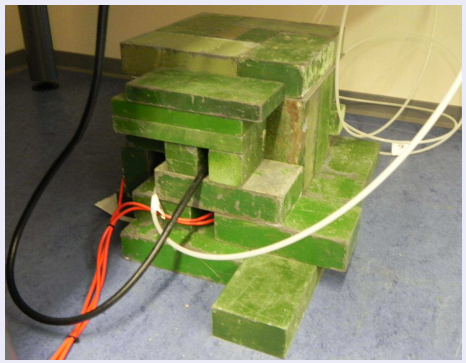
Background Rates

After Likelihood-Ratio based discrimination

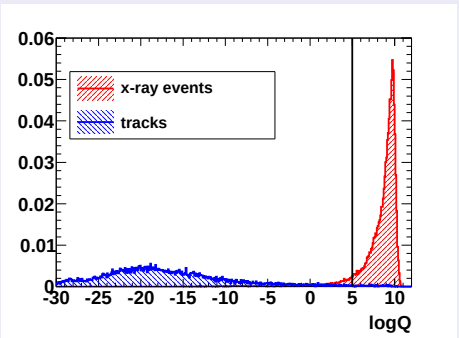


- Reduction should be possible by improvement of algorithm

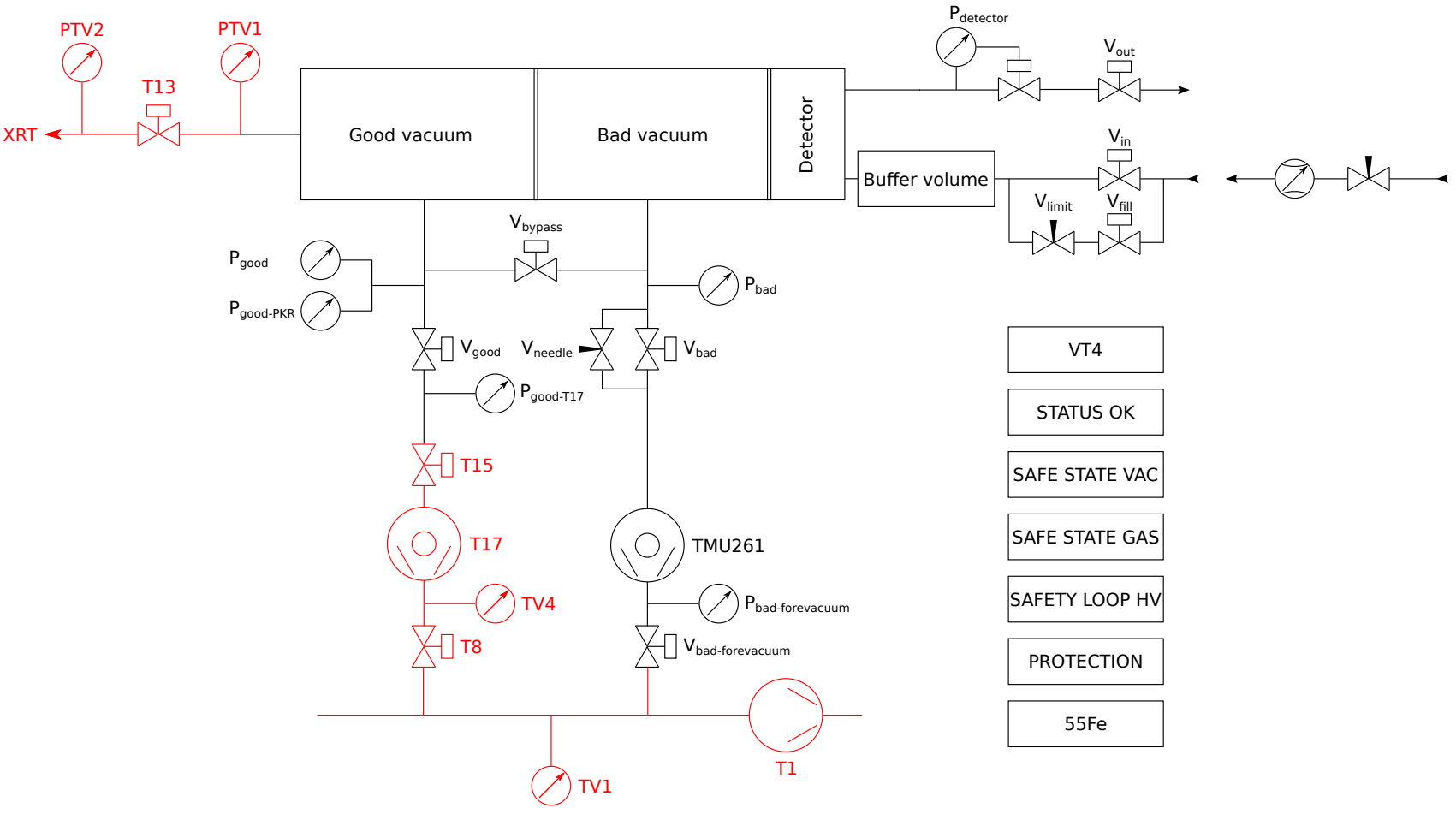
Lead shielding



Likelihood-Ratio



Vacuum System for Differential Pumping



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