Search for chameleons with an InGrid based X-ray detector at the CAST experiment

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Hamburg

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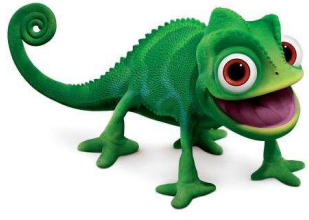
Physikalisches Institut



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Outline

1. Chameleons & the CERN Axion Solar Telescope
2. InGrid based X-ray detector
3. Operation at the CAST experiment
4. Data analysis
   - Background suppression method
   - Calculating the expected chameleon signal
   - Deriving a limit on chameleon photon coupling β_γ
5. Summary & Outlook

Chameleons – Dark Energy Particles

Dark Energy & chameleons

- Scalar fields interacting with matter & photons to create Dark Energy potential $\rightarrow$ new particle
- Avoid unnatural effects (e.g. long range fifth force) by screening mechanism
- Chameleon screening: density dependent effective mass
- Matter & photon coupling: β_m & β_γ

Solar chameleons

- Production by conversion of photons within magnetic field of tachocline region (thin shell at $0.7R_\odot$)
- Magnetic fields in tachocline caused by differential rotation
- Temperature at tachocline region results in solar chameleon flux peaking below 1 keV
- Brax, Lindner & Zioutas - Phys. Rev. D 85(2012), 043014

The CERN Axion Solar Telescope

Looking for solar chameleons with CAST

- Chameleons can be (re)converted into photons inside of strong magnetic field
- For CAST use decommissioned LHC prototype: 9 T, 10 m
- Photons are focused by X-ray telescope and then detected
- Magnet pointed at the Sun for 2×1.5 h/d (sunrise & sunset)

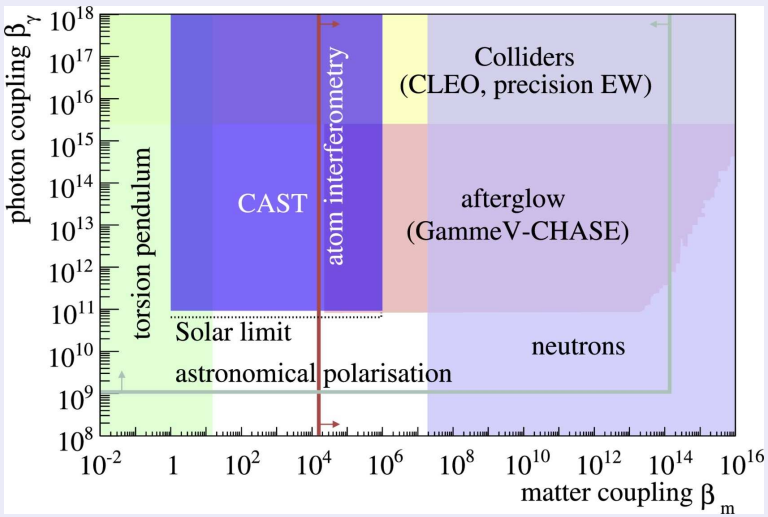
CAST pointing at the Sun

First chameleon search with CAST

Search with an Silicon Drift Detector

- SDD installed end of 2013 (without X-ray telescope)
- First ever chameleon search with CAST & commercial detector components as a first shot
- Could set world class limit: $\beta_\gamma \leq 9.3 \times 10^{10}$ at 95 % CL
- But still above upper solar limit given by luminosity ($\beta_\gamma \leq 10^{10.81} \approx 6.5 \times 10^{10}$)

Phys. Lett. B 749(2015), 172

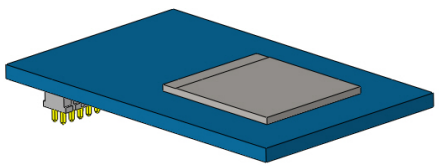


To be continued

- Expected signal $\sim \beta_\gamma^4$
- InGrid based X-ray detector
- Lower background rate
- X-ray telescope
- Should pass the solar limit

InGrid based X-ray detector for CAST

Timepix with InGrid on carrier board

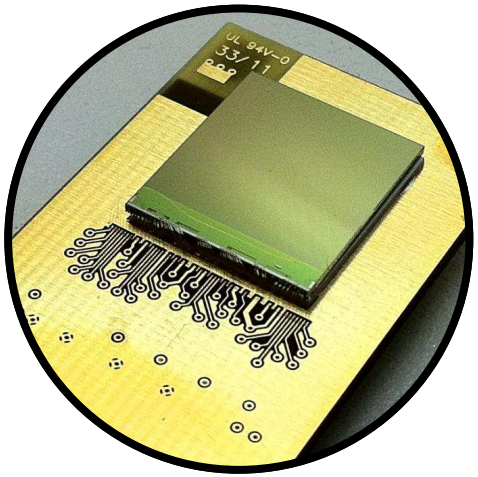


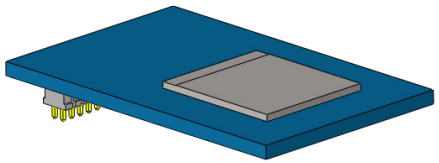
InGrid based X-ray detector for CAST

Timepix with InGrid on carrier board

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

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

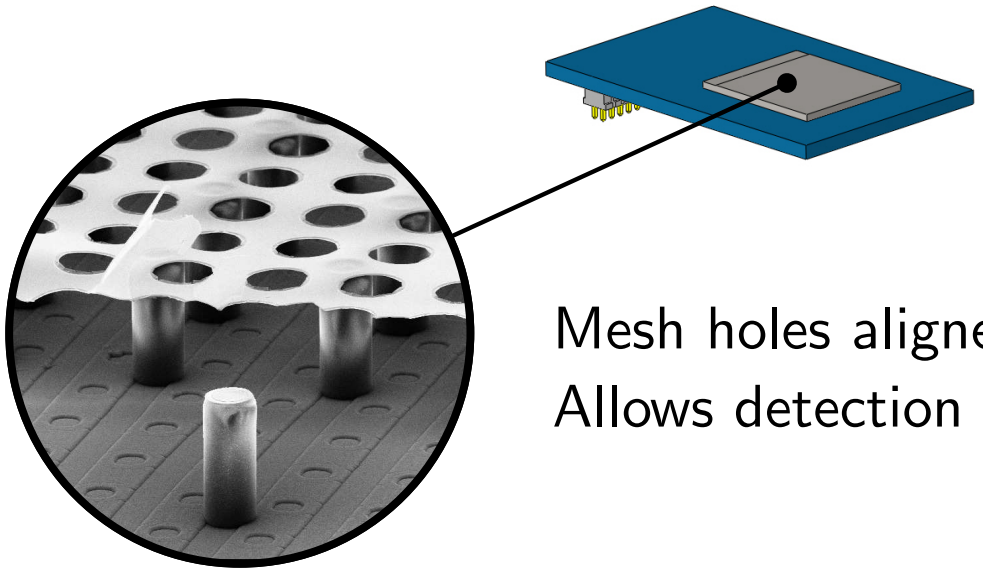




InGrid based X-ray detector for CAST

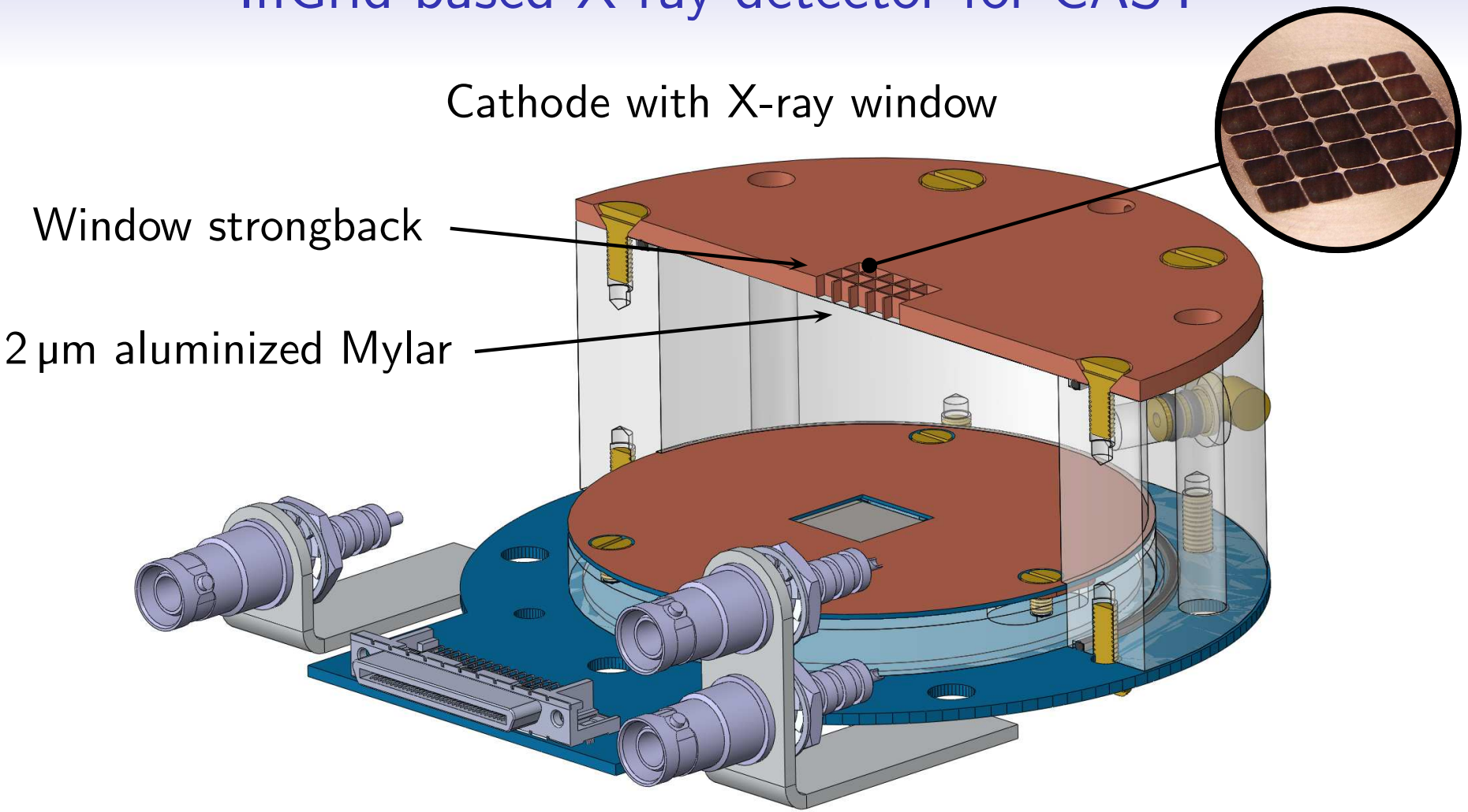
Timepix with **InGrid** on carrier board

Integrated Micromegas stage
Photolithographic postprocessing technology



Mesh holes aligned with pixels
Allows detection of single electrons

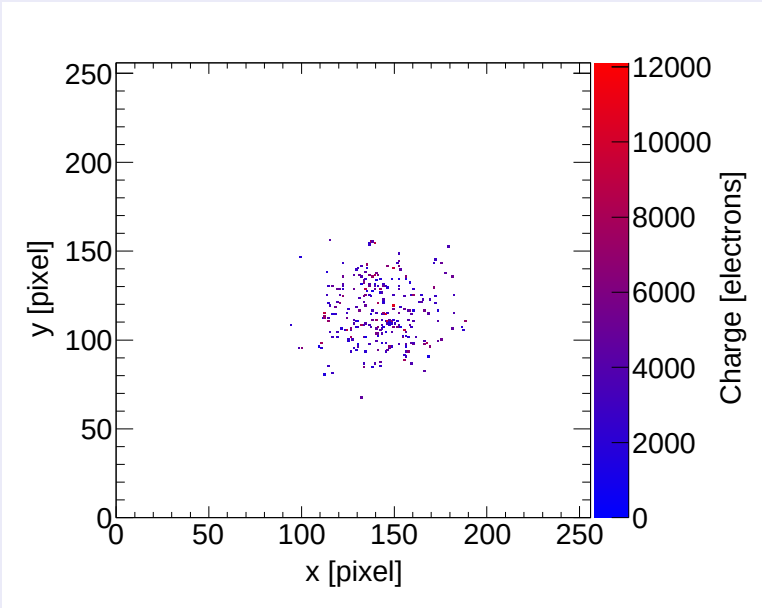
InGrid based X-ray detector for CAST



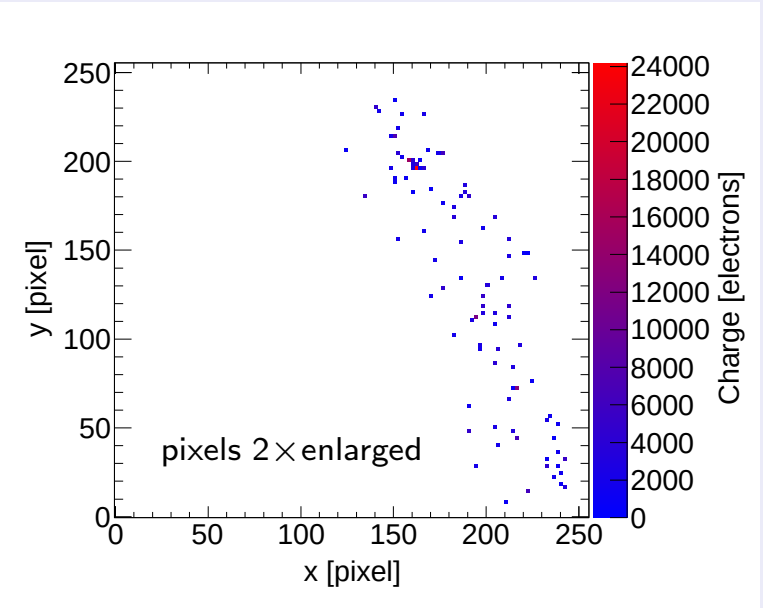
Drift volume flushed with Ar/iC_4H_{10} 97.7/2.3

Typical events

X-ray event (5.9 keV)



Non-X-ray event (e.g. cosmic)

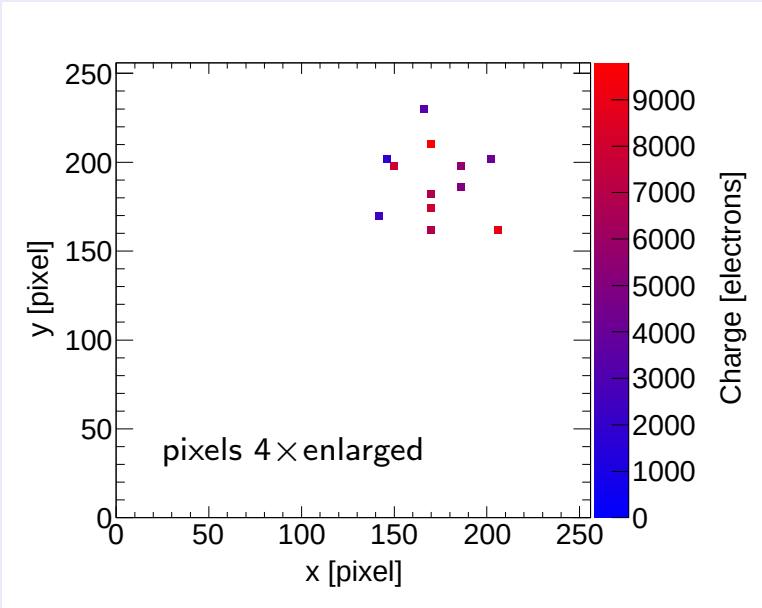


Benefits from high spatial resolution

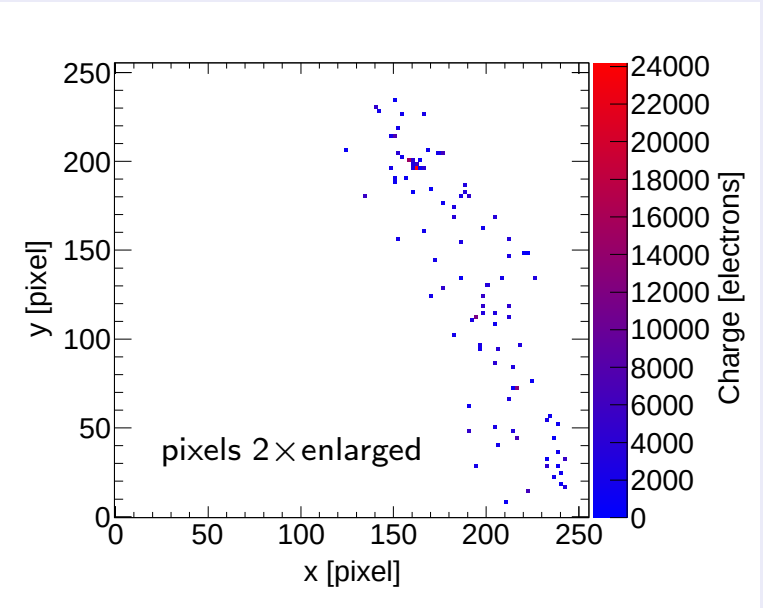
- Each primary electron can be detected individually on the chip
- Low energy X-ray photons can be detected
- Event shape can be used for suppression of non X-ray events

Typical events

X-ray event (277 eV)



Non-X-ray event (e.g. cosmic)



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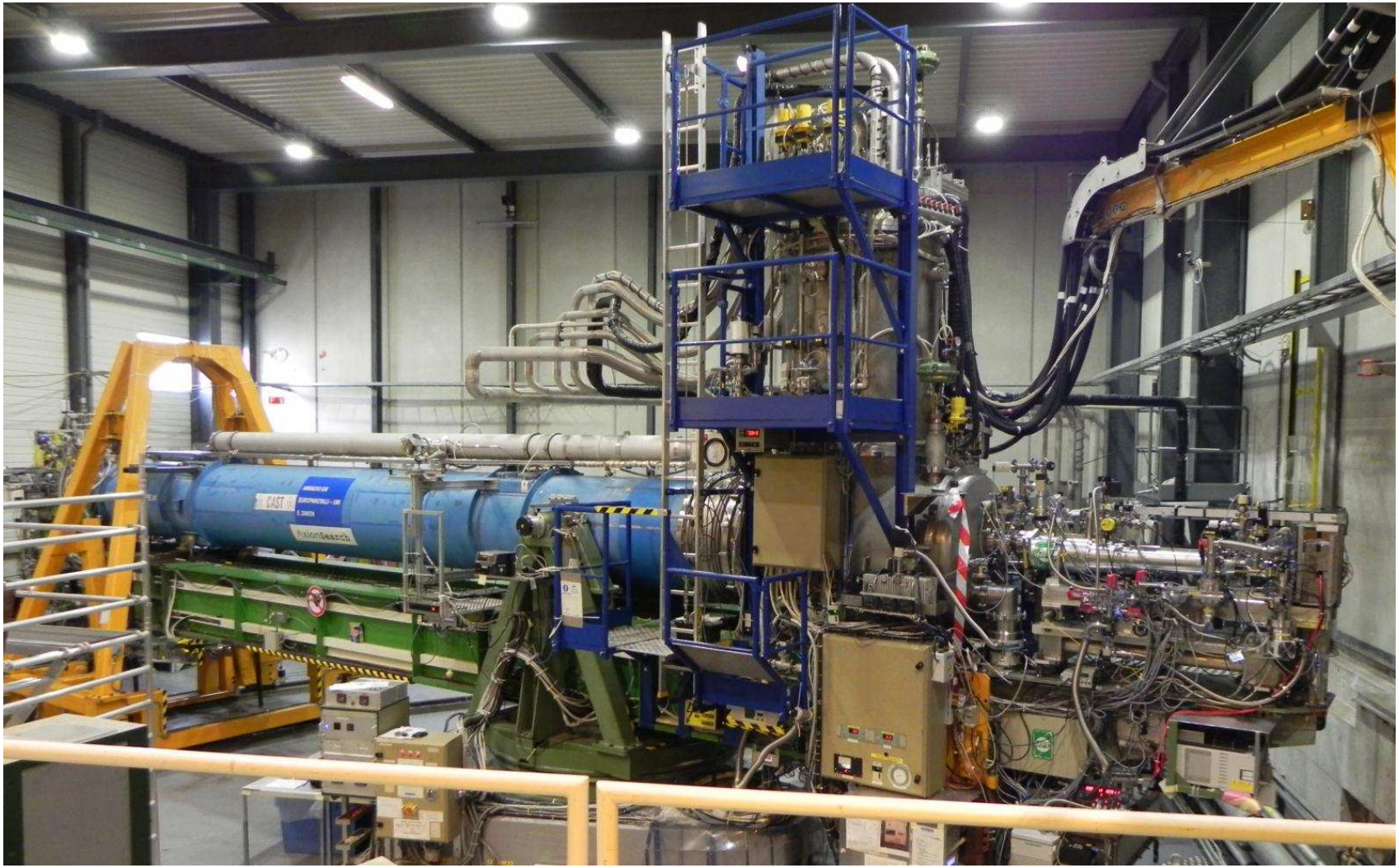
InGrid based X-ray detector & its infrastructure at CAST



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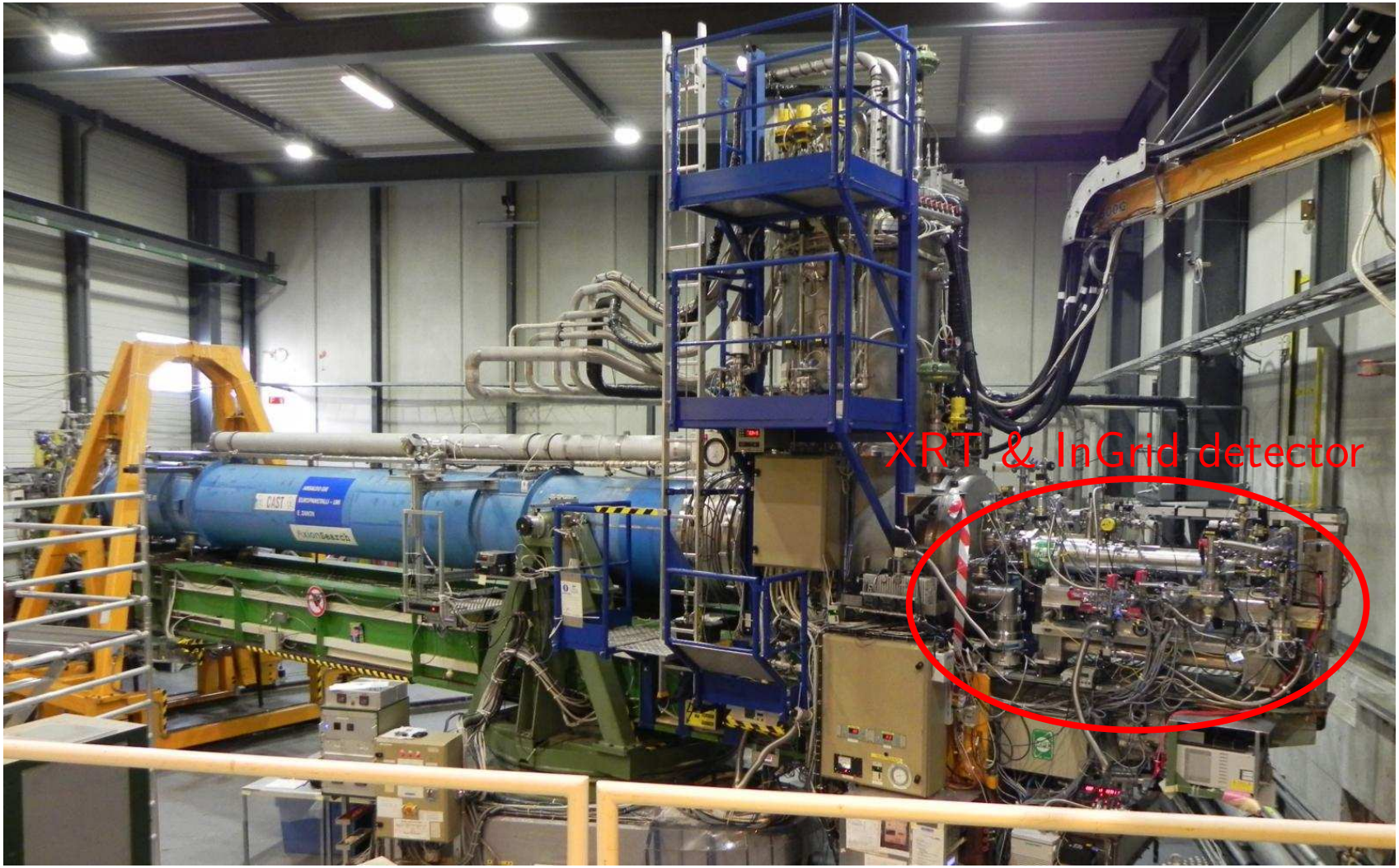

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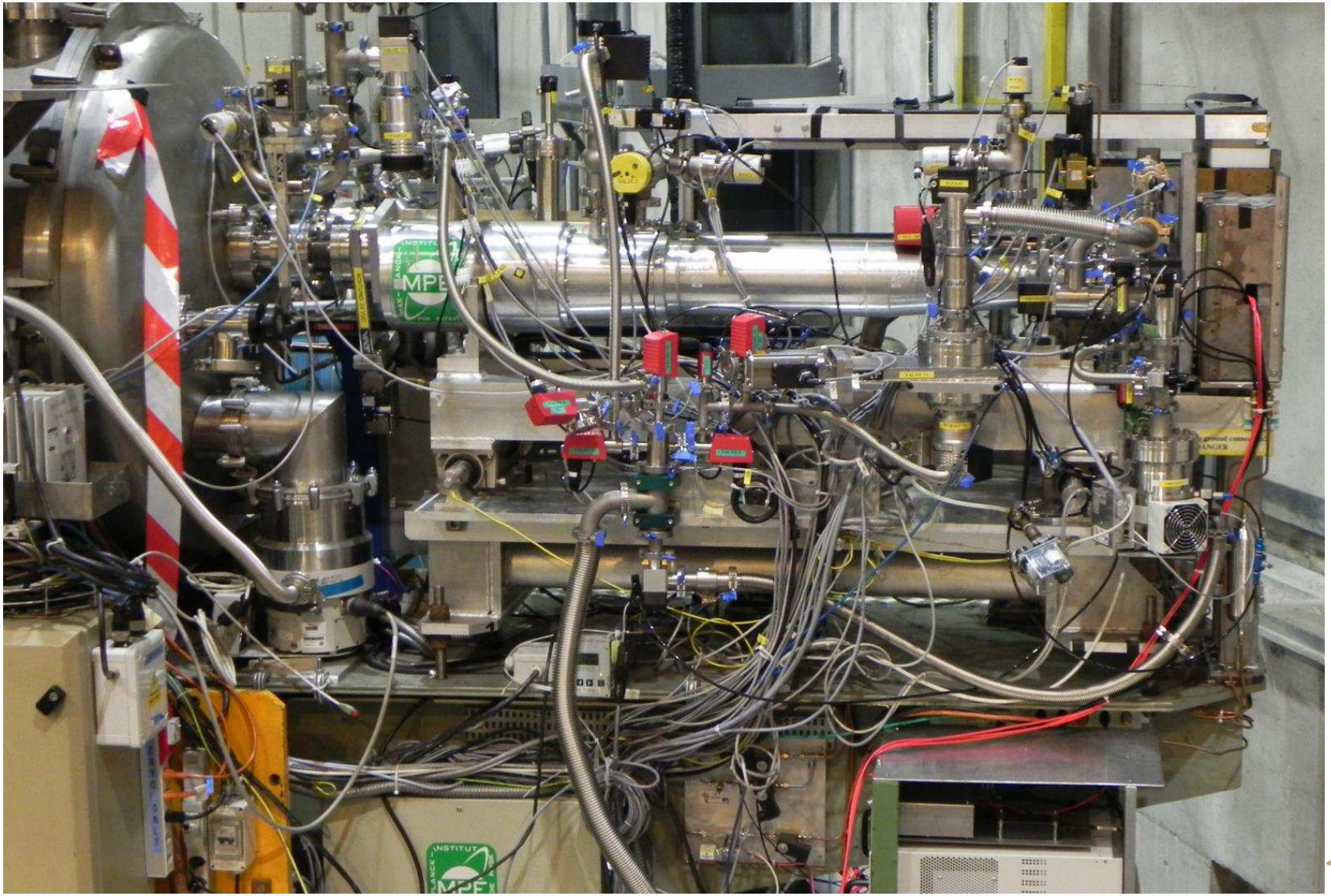

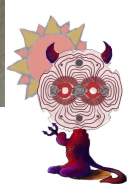

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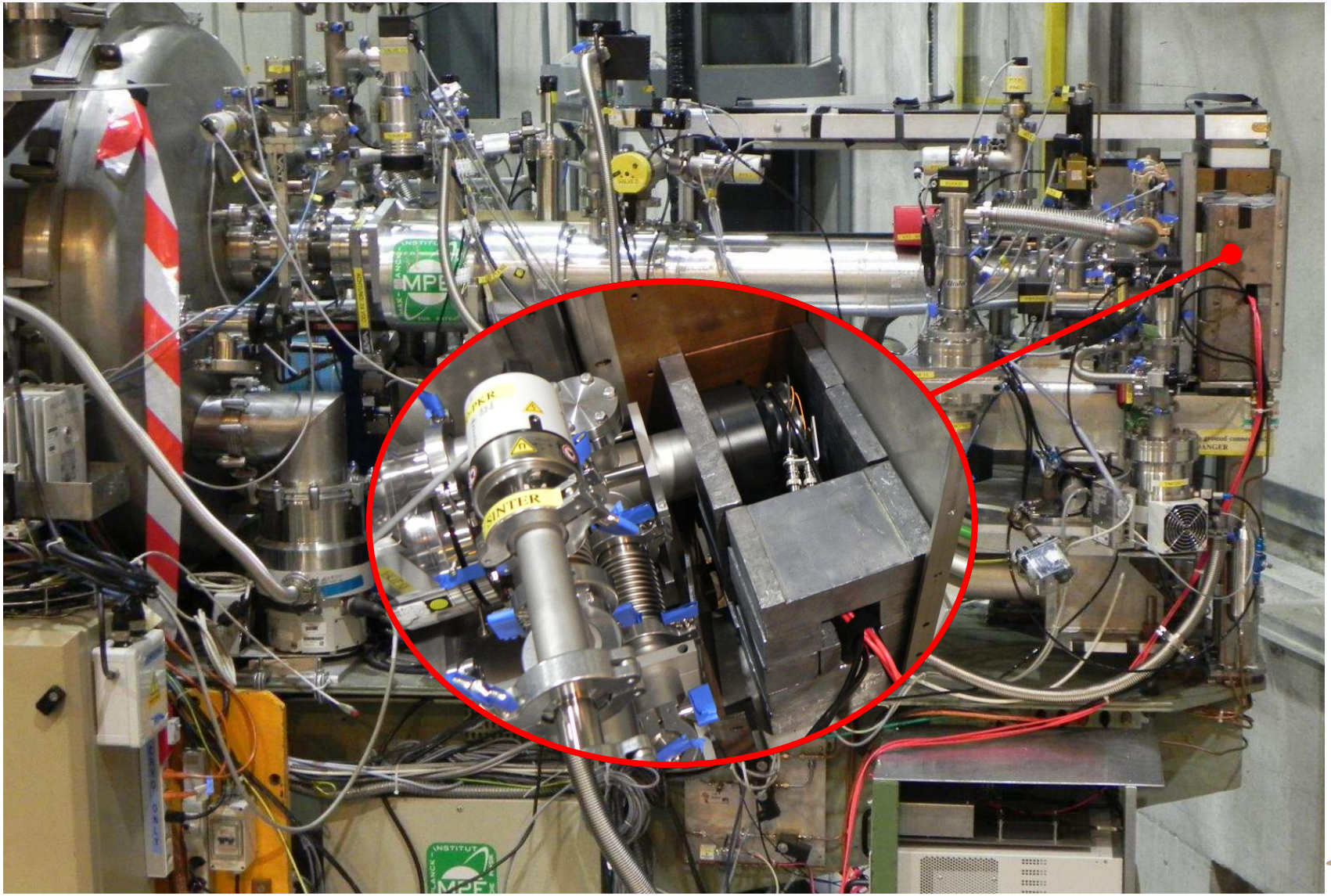

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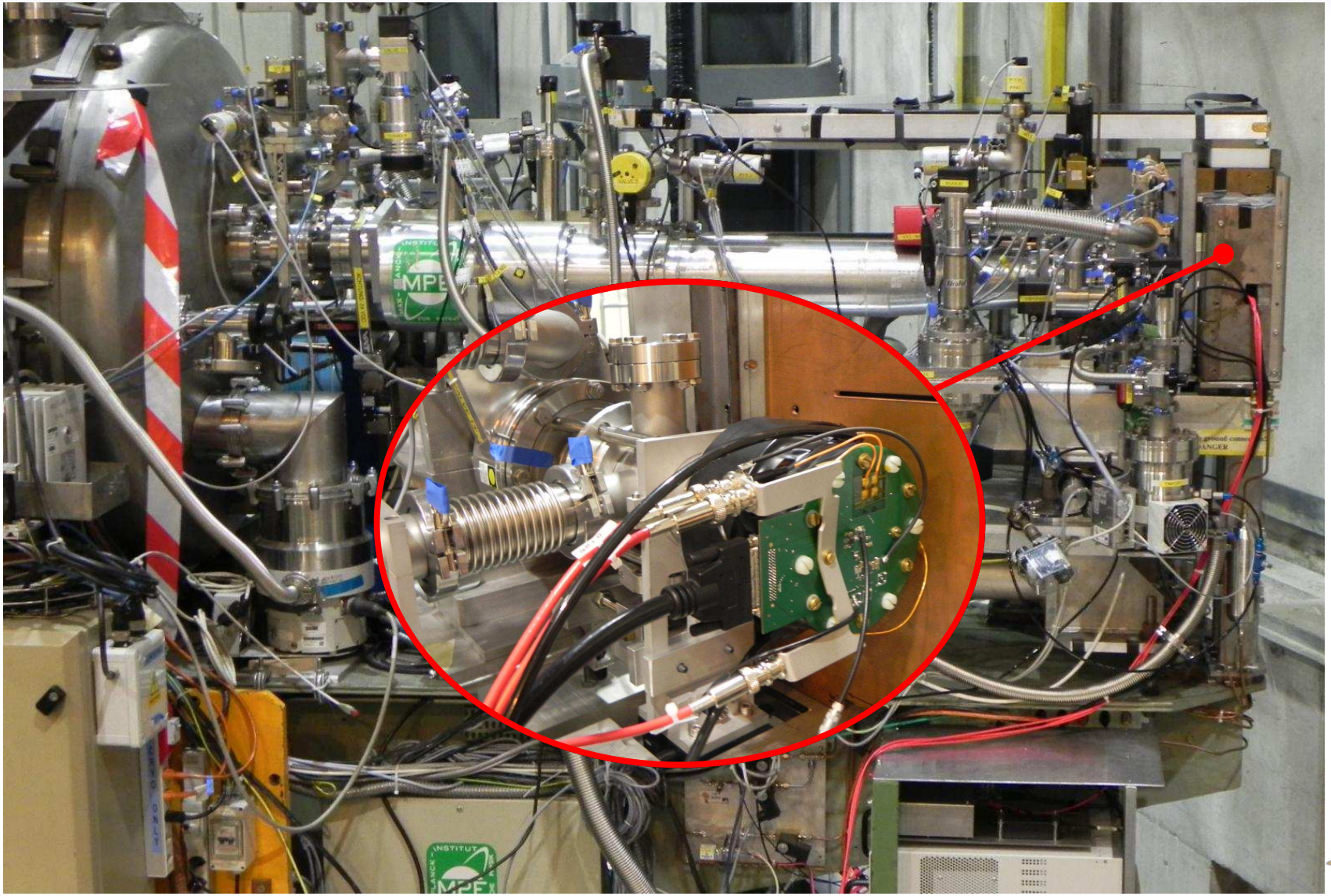


Operation at the CAST experiment

Operation in 2014 and 2015

- Detector & infrastructure installed in October 2014
- Successful operation until dismantling in November 2015
- Until then NO detector related stops or interruptions!

Some numbers

- Total number of frames recorded: 19 401 770 (each 0.98 s)
- Of these $\sim 80\,\%$ are empty! (except for one noisy pixel)
- Total background measurement time: 4785 h
- Total solar tracking time (sunrise): 254 h (171 trackings)
- 196 calibration runs with ^{55}Fe source in situ

Background suppression 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

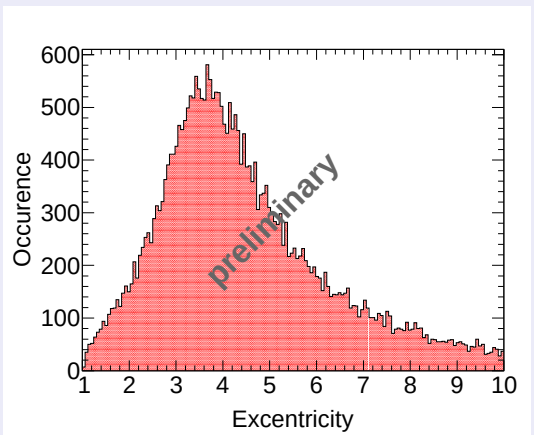
Likelihood for background rejection

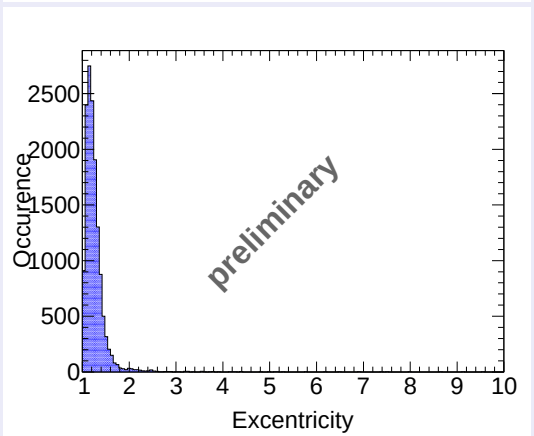
- Likelihood calculated from reference distributions for different energy ranges (from tests at an X-ray generator)
- **Three** variables are used for likelihood:
  - Excentricity (Measure for circularity)
  - Length along long axis divided by RMS along short axis
  - Fraction of pixels within radius of one RMS (along short axis)
- Variables chosen to be independent of gas properties (e.g T)
- Likelihood cuts set so 80 % of real X-ray photons pass

Variables entering likelihood – Background & Reference

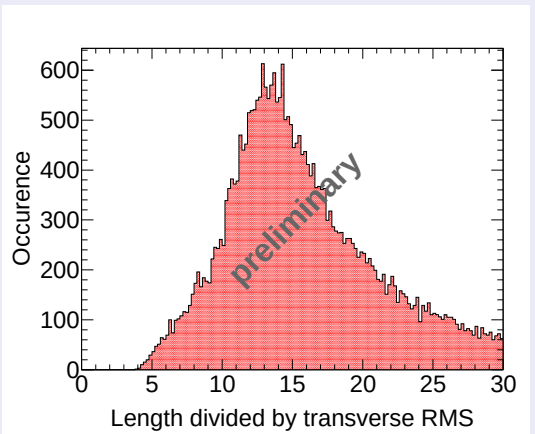
$1.2\,\text{keV} < E < 2.1\,\text{keV}$ – Aluminium K_α line

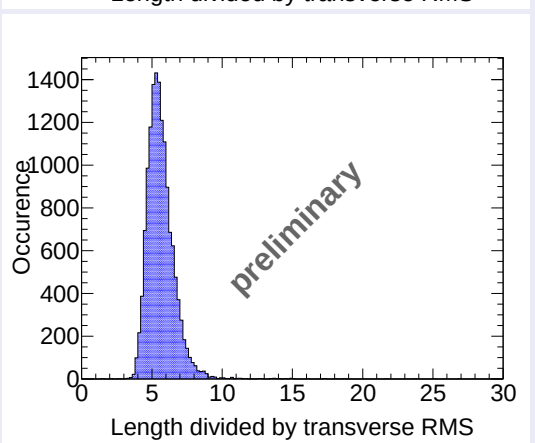
Excentricity



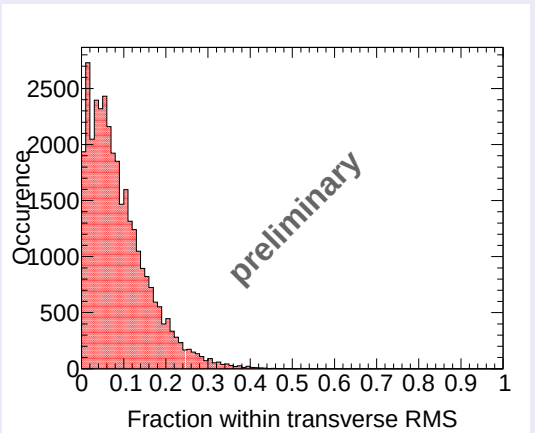


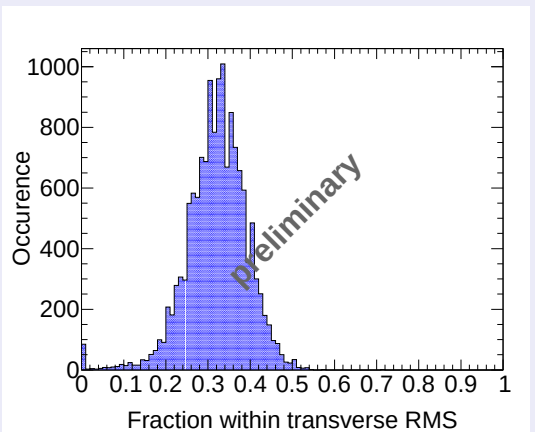
Length/RMS





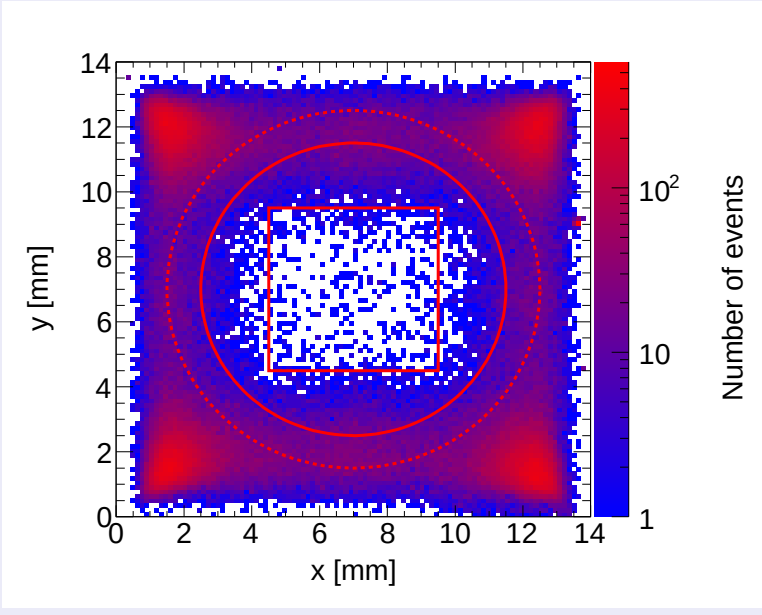
Fraction within RMS





Background events after suppression

Below 2 keV



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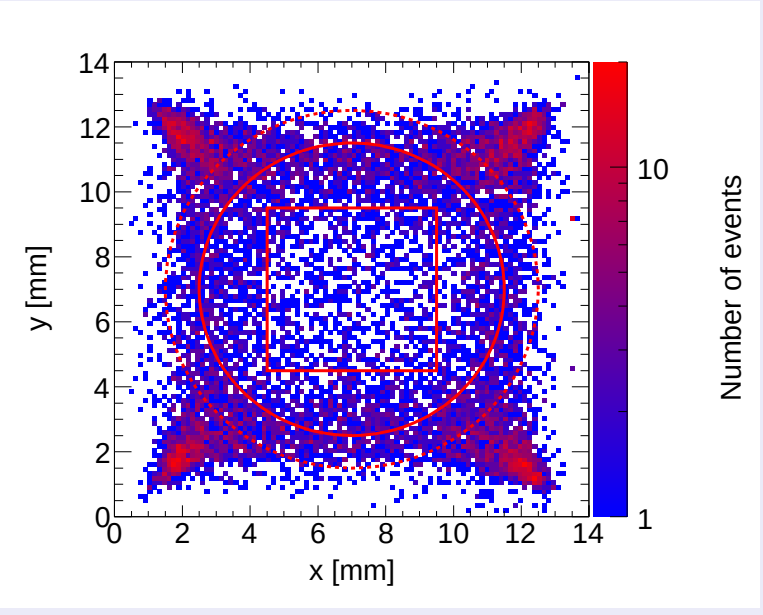

- Background rate is much lower in chip centre
- Most probable: partially contained tracks at sides & corners
- Maybe also X-ray fluorescence photons from detector material
- Split data in three regions: gold, silver & bronze

Background events after suppression

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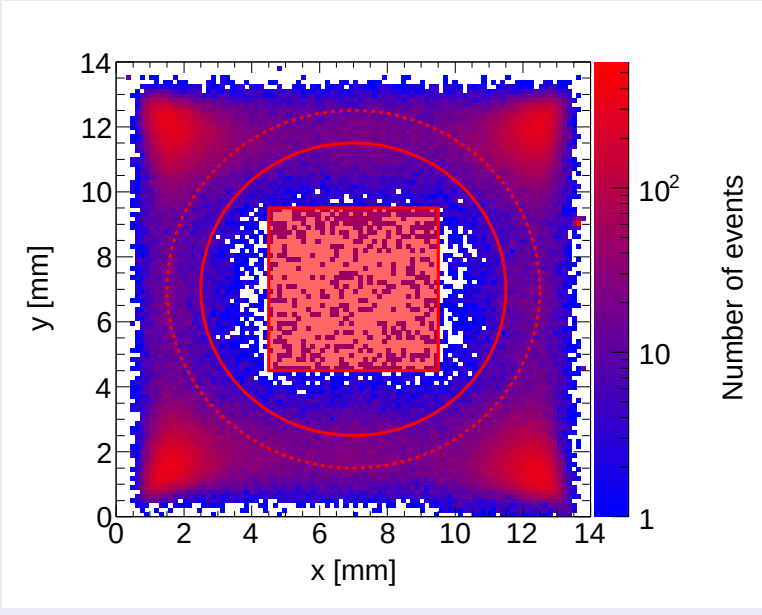

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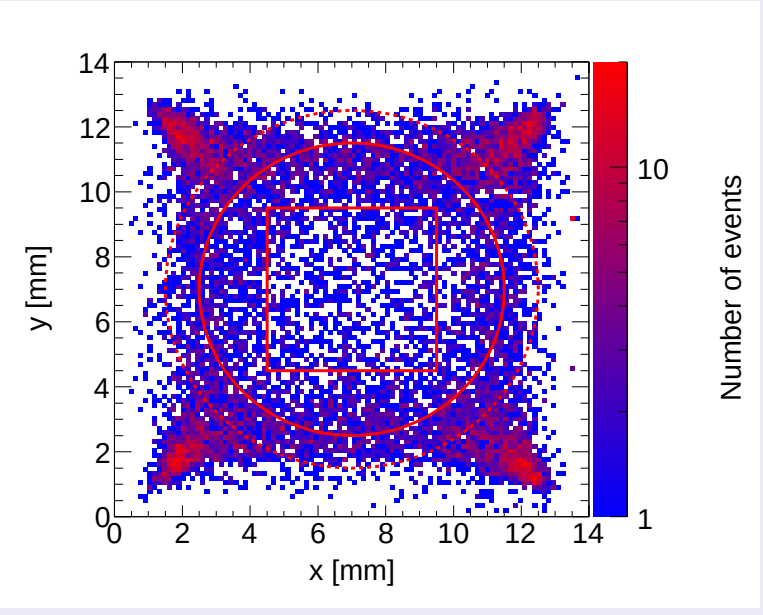

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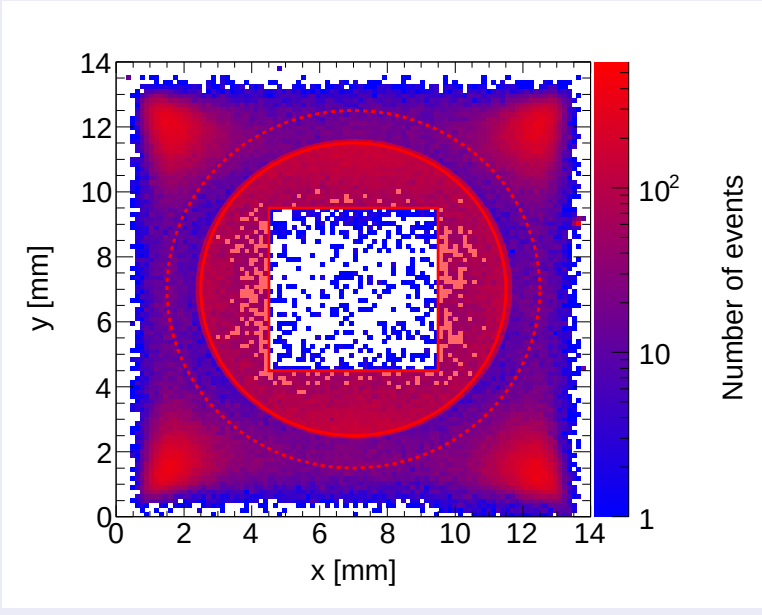
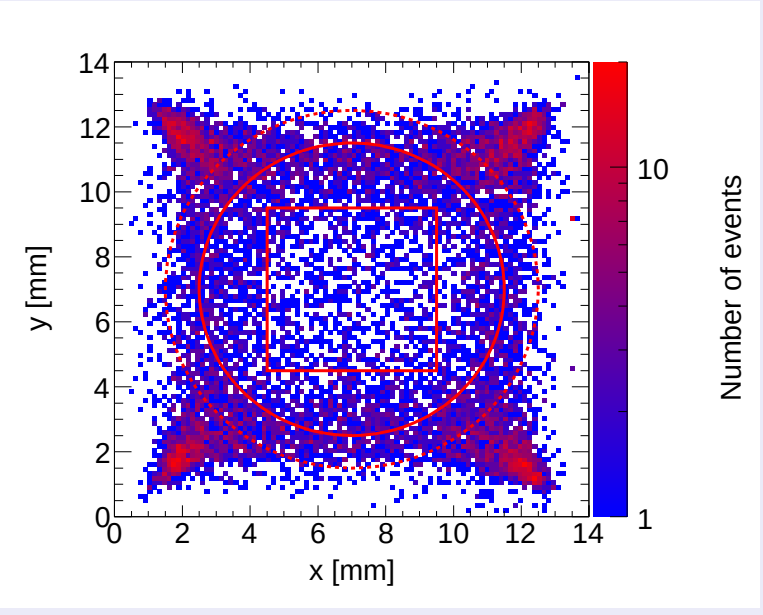


Above 2 keV



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Background events after suppression

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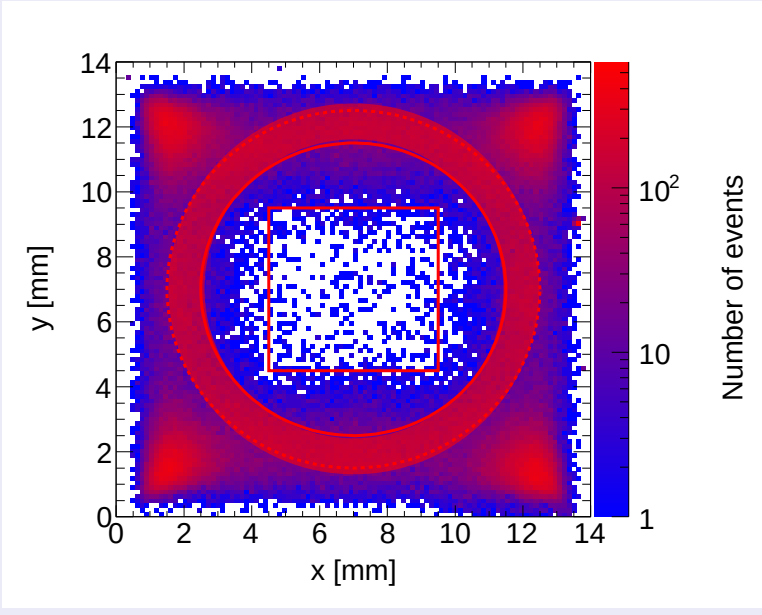

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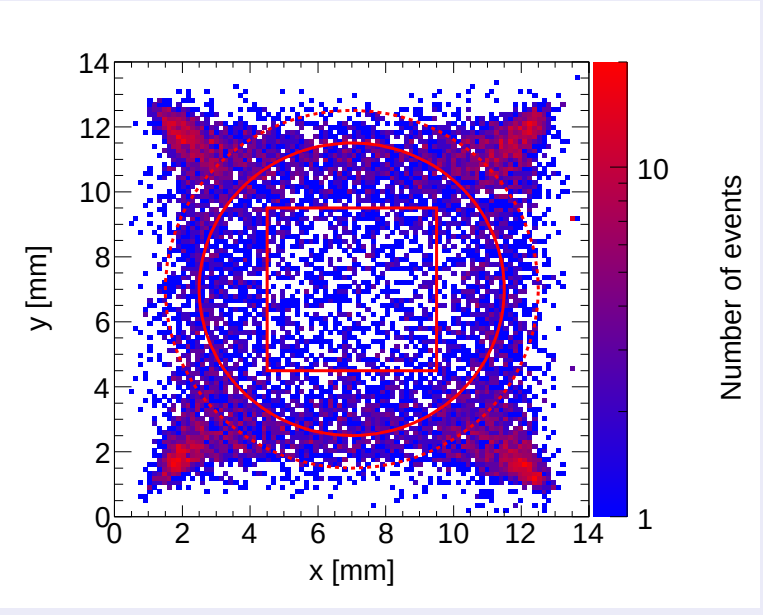
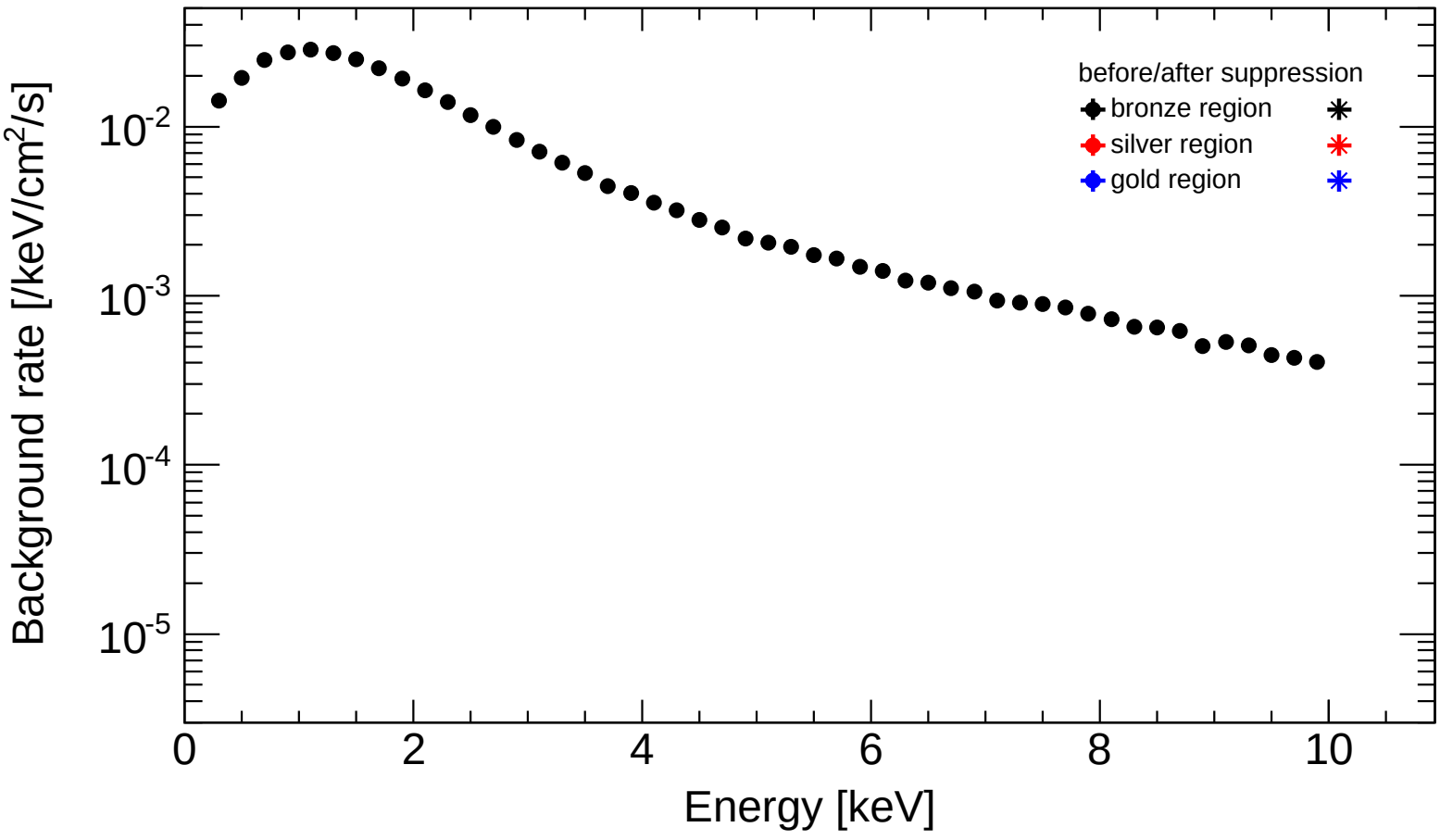


- Background rate is much lower in chip centre
- Most probable: partially contained tracks at sides & corners
- Maybe also X-ray fluorescence photons from detector material
- Split data in three regions: gold, silver & **bronze**

Measured background rate before & after suppression



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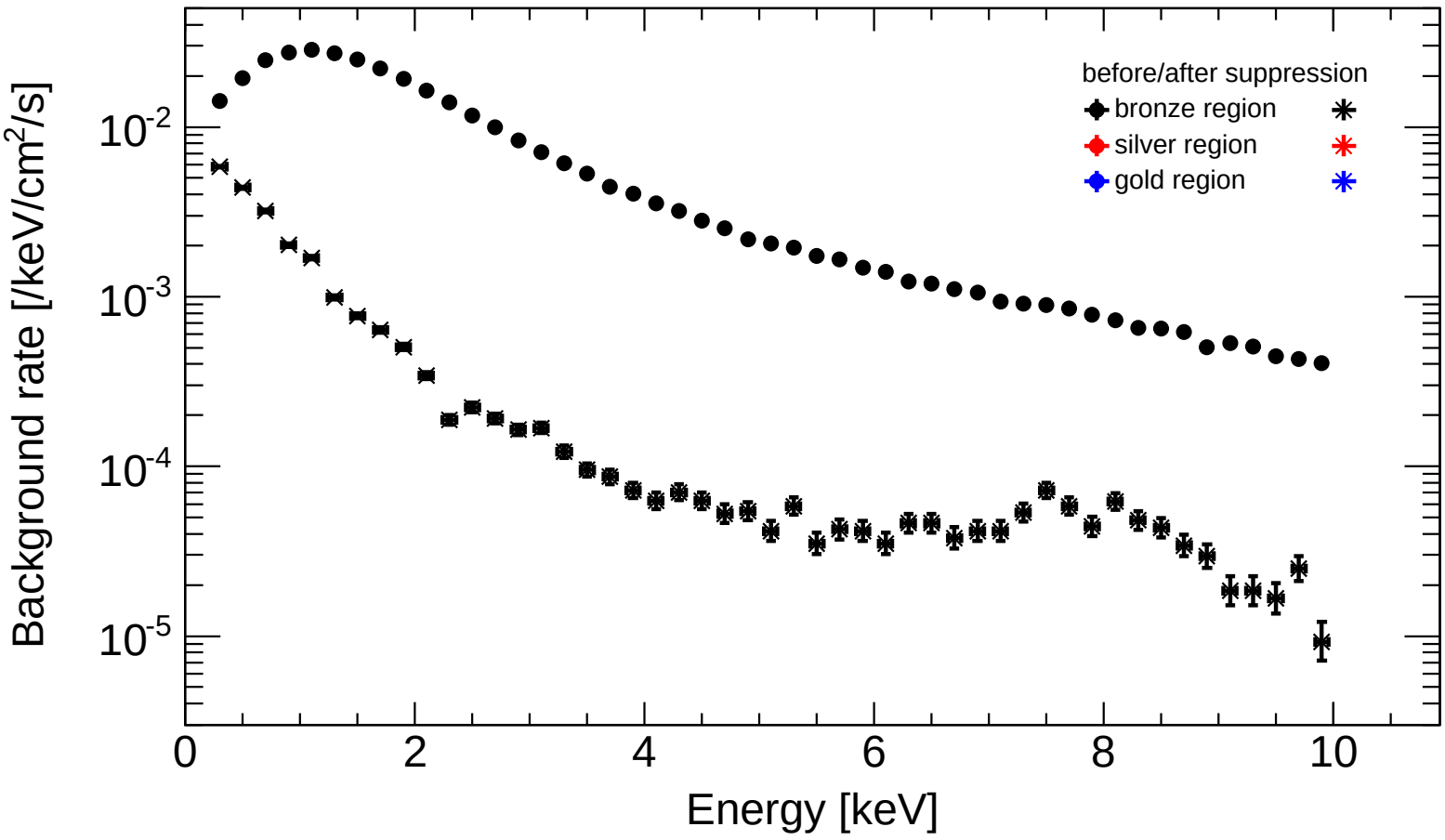

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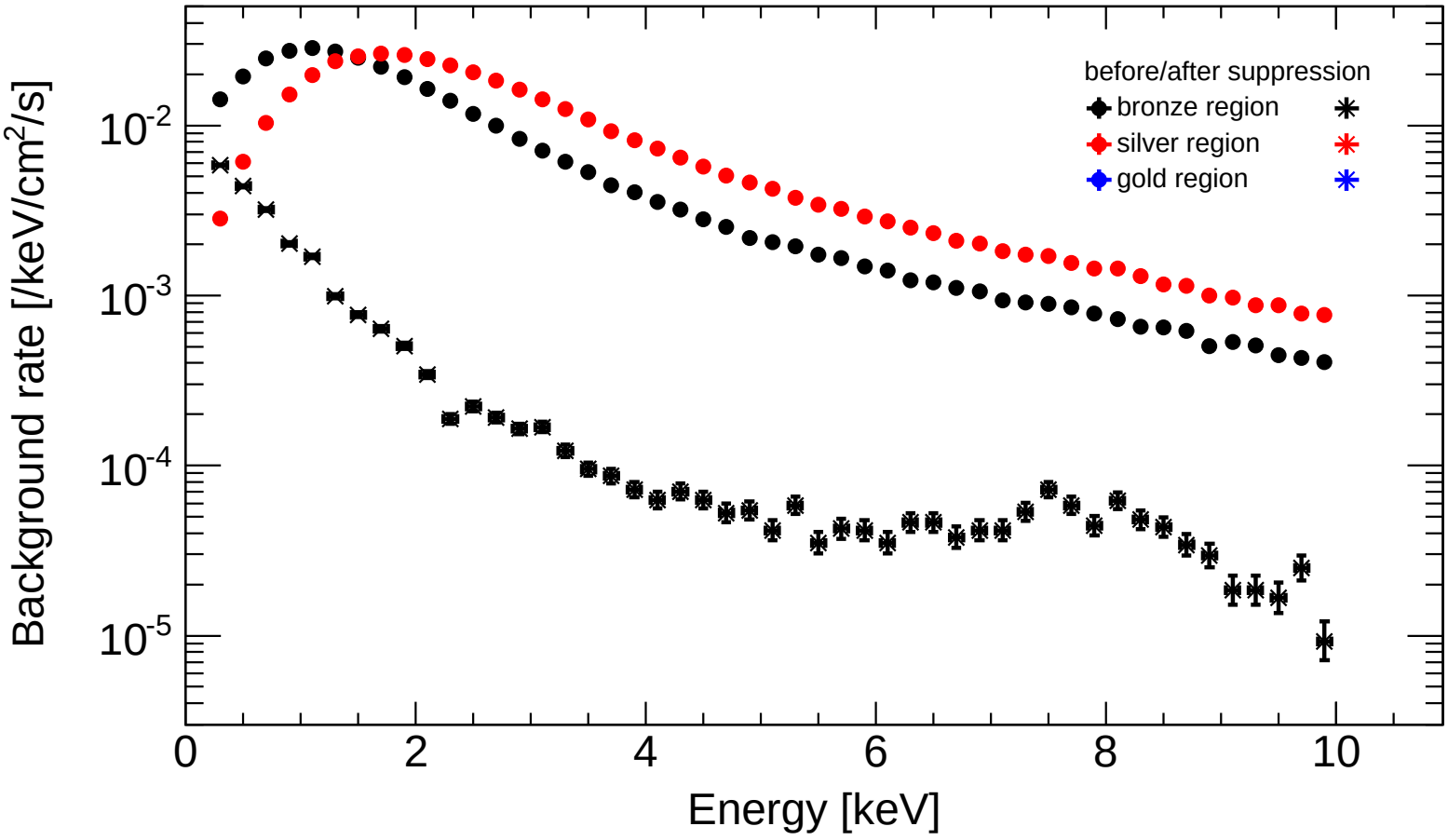

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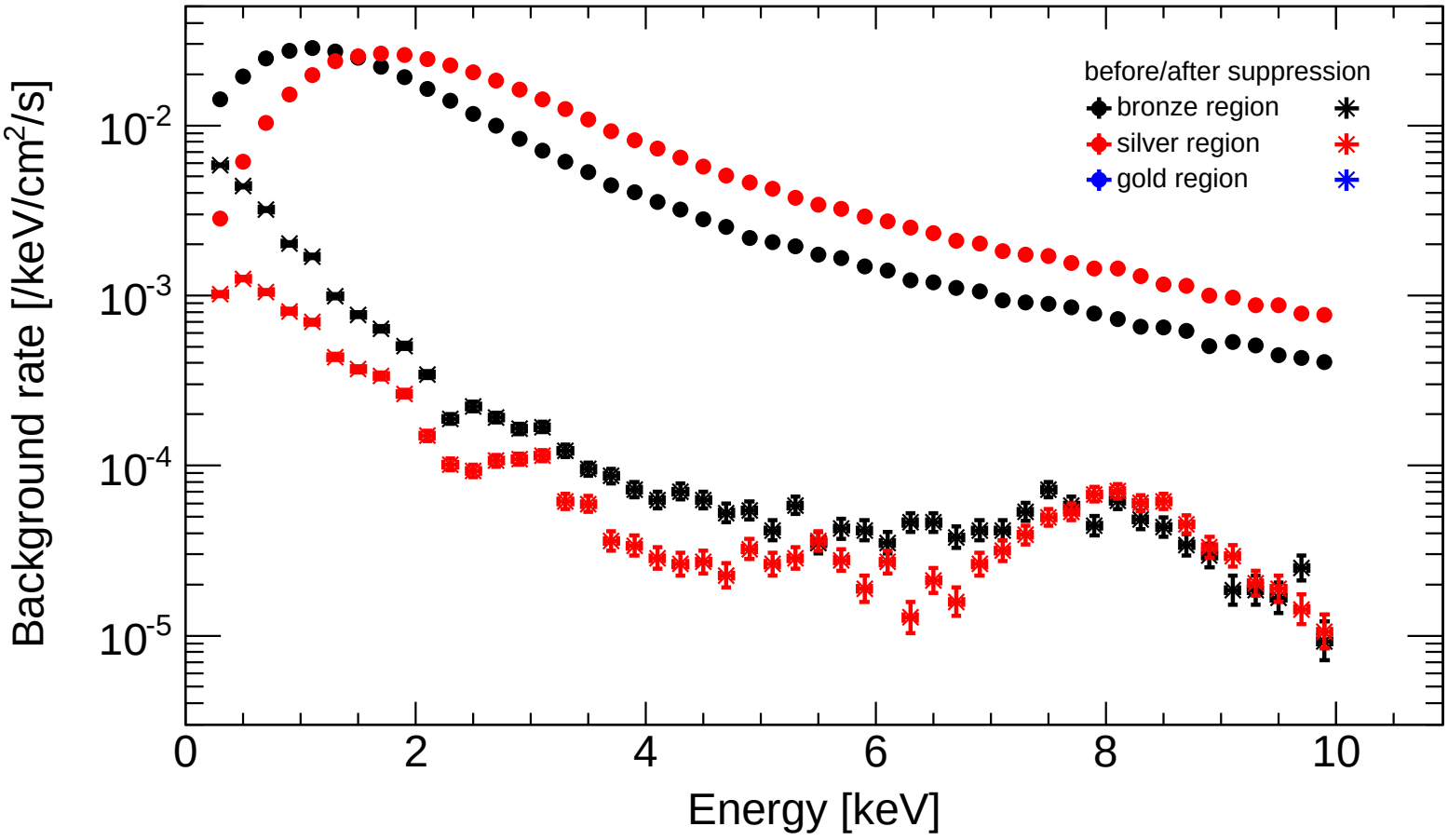

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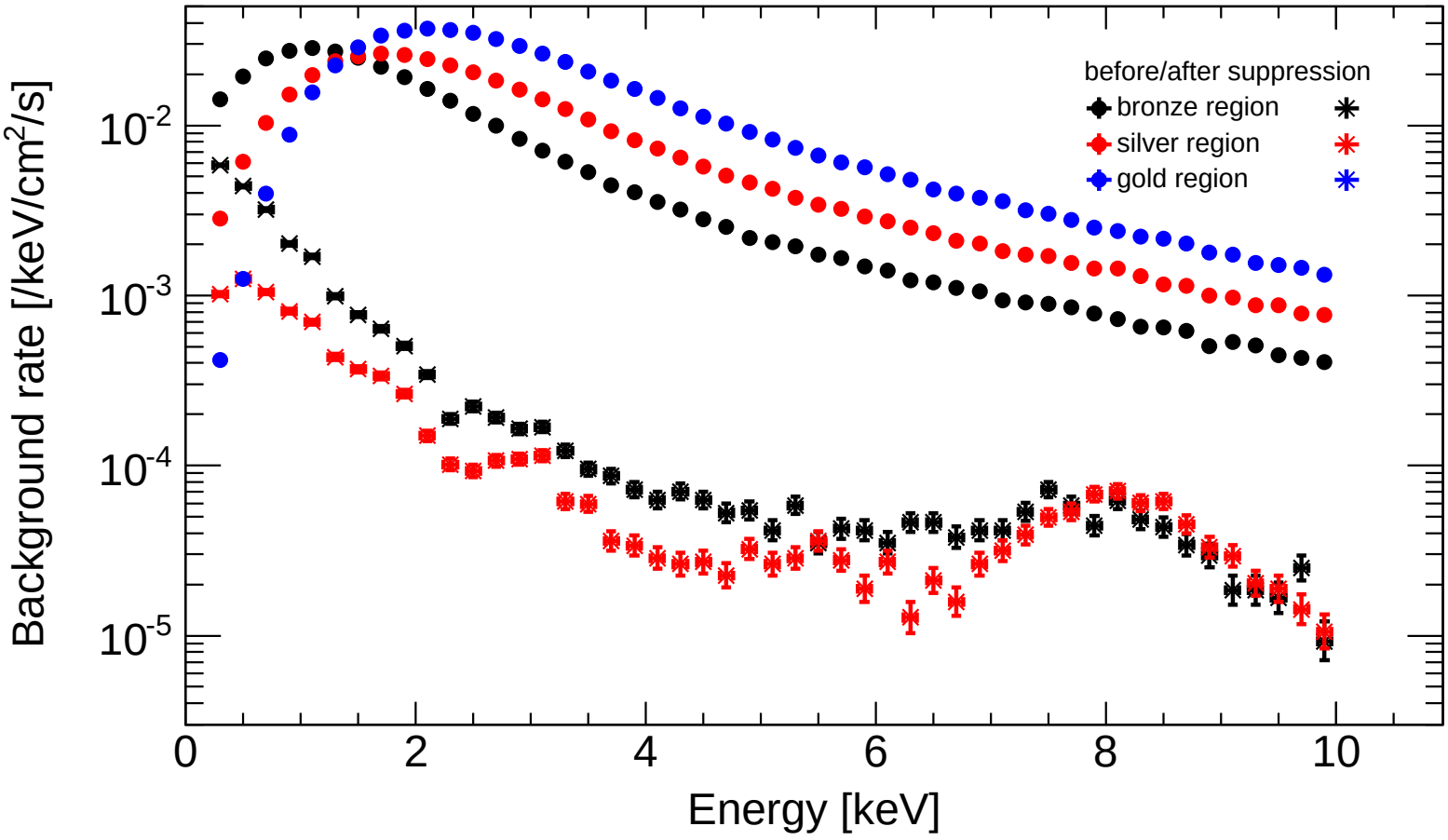

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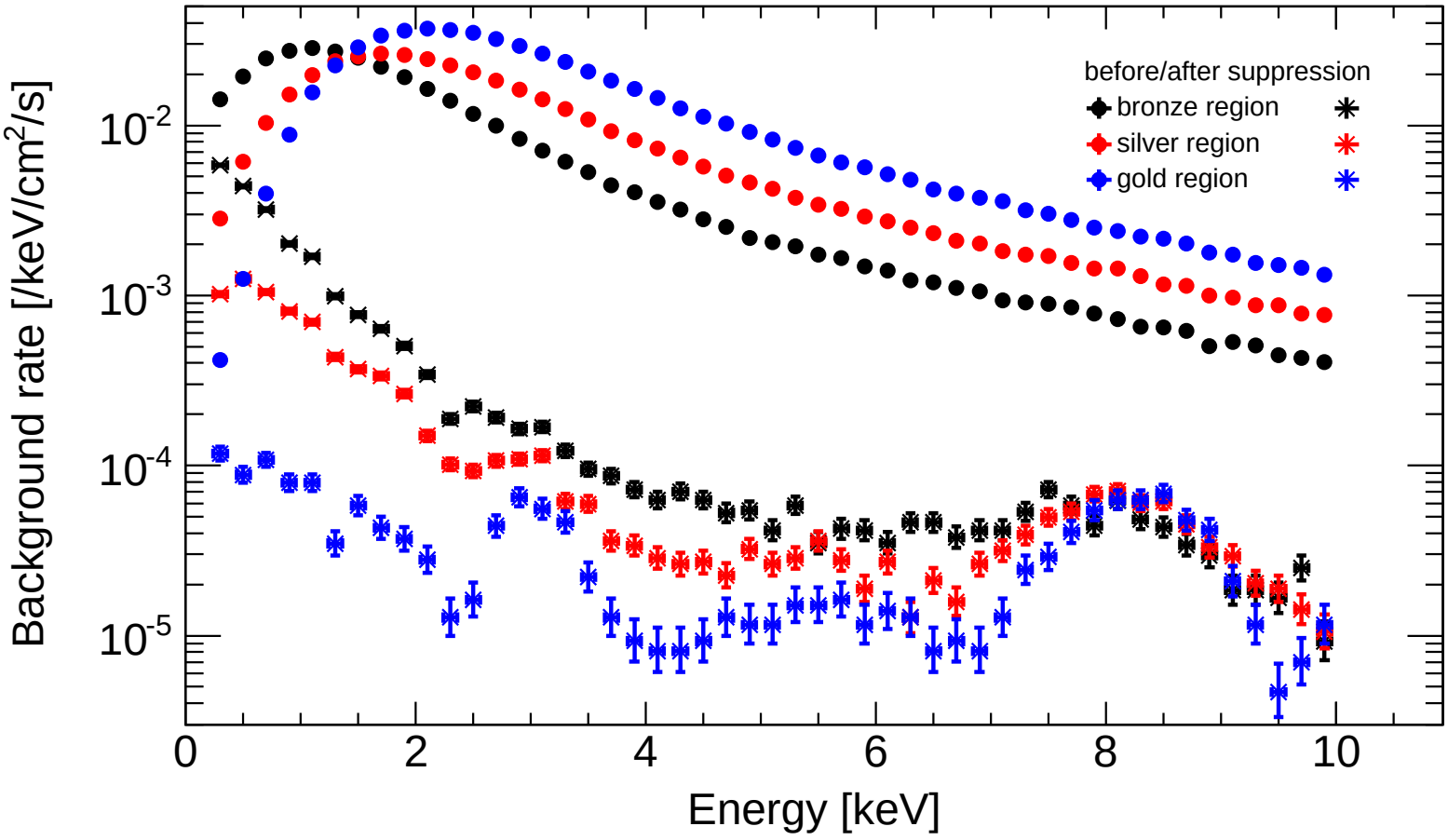
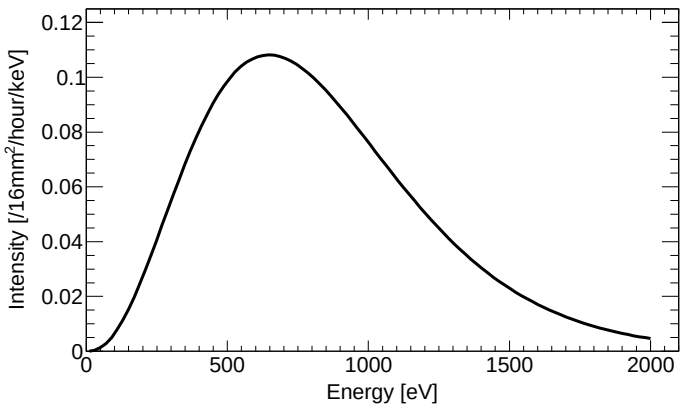


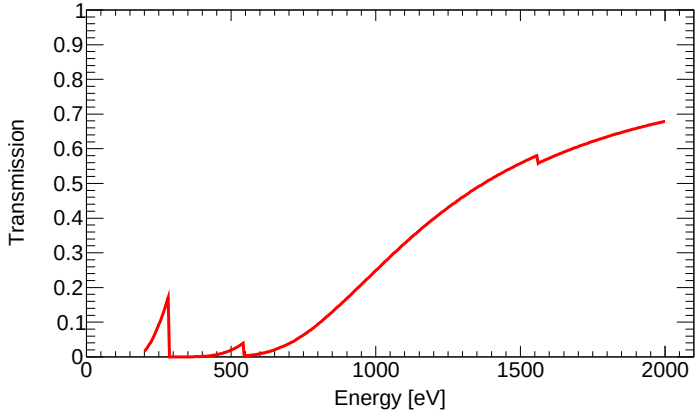
Calculating the expected chameleon signal

- Chameleon spectrum from Phys. Rev. D 85(2012), 043014
- Fold with window & X-ray telescope transmissions
- Multiply with software efficiency & measurement time
- Multiply with magnet's cross section
- Take into account CAST & XRT optics:
  What fraction of the flux ends in which region?

Chameleon spectrum



Window transmission

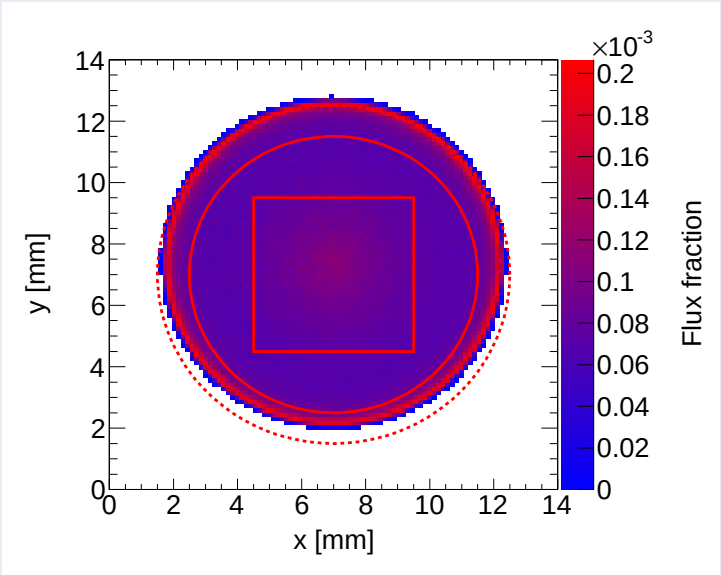


The chameleon image of the Sun

Simple ray tracing MC

- Source is a transparent glowing hollow sphere
- Not all chameleon trajectories see full length of magnetic field ($\sim l^2$)
- XRT's transmission depends on incident angle: $\frac{T_{\mathrm{XRT}}(10')}{T_{\mathrm{XRT}}(0')} = 70\,\%$
- Simple approach: XRT treated as a lens
- Reweight events according to l and $T_{\mathrm{XRT}}(\Theta)$

Chameleon image



Chameleon flux fractions

- Gold: 10.6 %
- Silver: 14.1 %
- Bronze: 13.5 %

Deriving a limit on chameleon photon coupling β_γ

TLimit

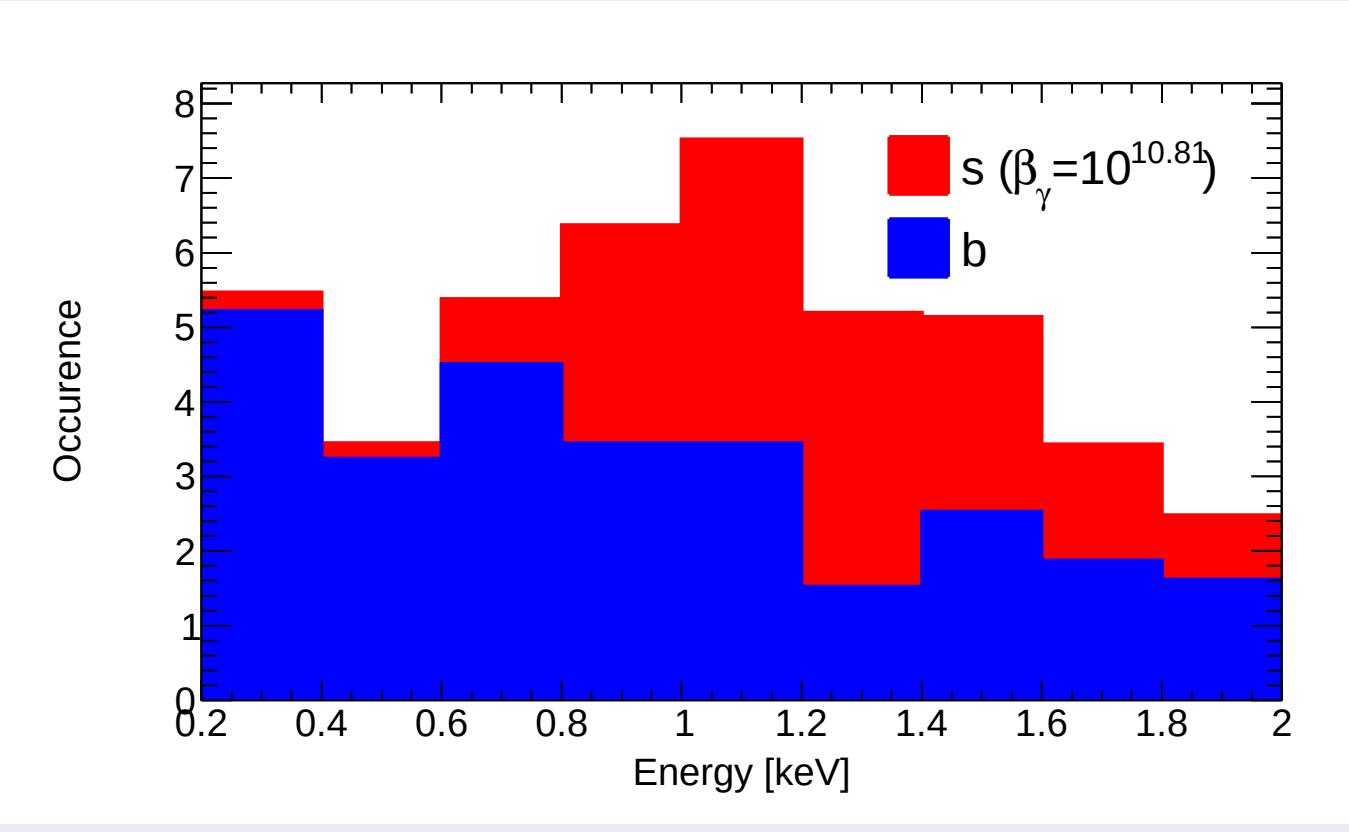
- ROOT implementation of mclimit code
- Takes expected background & signal histograms as input
- Statistical bin errors can be treated as well as systematic uncertainties
- Multiple search channels can be given
- Outputs observed & expected CLs (CL_b, CL_s, $\langle CL_s \rangle_b$, etc)

Finding the 95 % CL_s limit on chameleon photon coupling β_γ

- Feed TLimit with expected background(s) & signal(s) (plus observed data)
- Rescale signal histogram(s) according $\sim \beta_\gamma^4$
- Scan over β_γ for point with $1 - CL_s = 95\,\%$

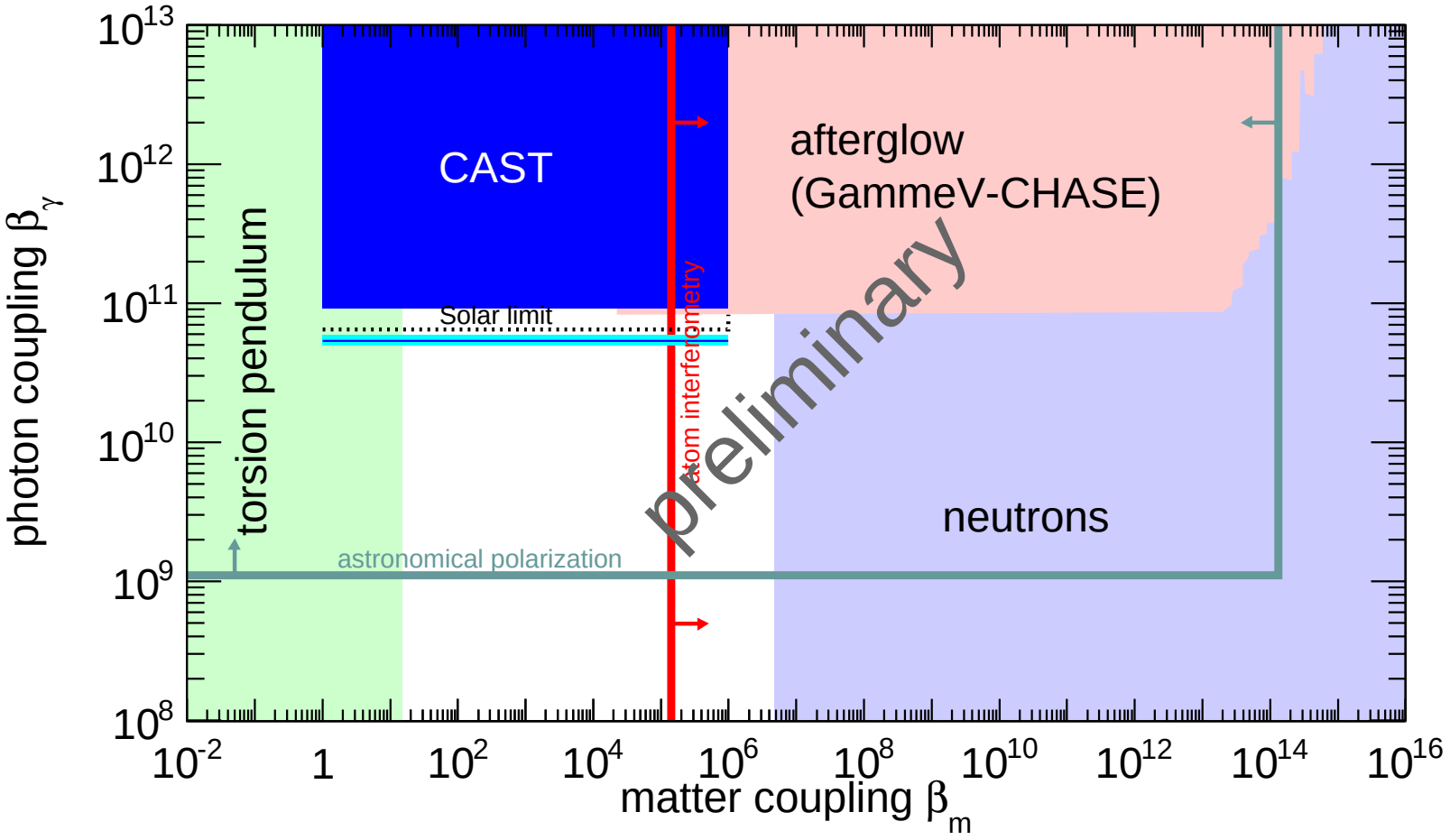
Feeding TLimit

Expected background & signal in gold region



- Unblinding of data is imminent
- Taking into account gold, silver & bronze region: expected 95 % CL_s limit: $\beta_\gamma \leq 5.4 \times 10^{10}$

Expected 95 % CL_s limit on β_γ



Summary & Outlook

- An InGrid based X-ray detector has been installed & successfully operated at CAST in 2014 & 2015 to continue search for Solar chameleons at CAST
- Background suppression via likelihood method using event shape variables has shown good performance
- Background rate in inner chip region is $\mathcal{O}(10^{-4}\,/\mathrm{cm}^2/\mathrm{keV/s})$ below 2 keV
- Expected 95 % $\mathrm{CL_s}$ limit for chameleon photon coupling calculated with `TLimit` is $\beta_\gamma \leq 5.4 \times 10^{10}$
- First detector at CAST to get below upper bound on β_γ given by solar luminosity
- Very soon: unblinding of data
- Improved InGrid based X-ray detector (see next talk!) to be installed this year
- Continue hunt for Solar chameleons with increased sensitivity!

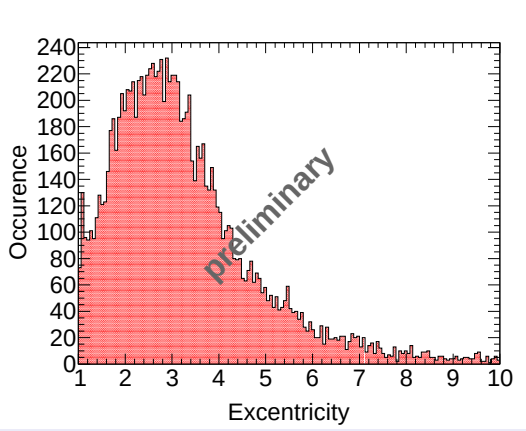
Questions?

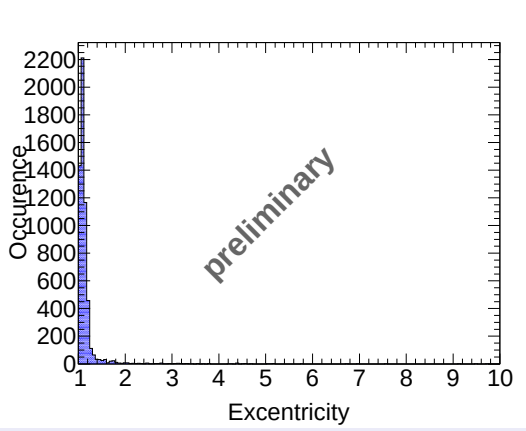
Backup Slides

Variables entering likelihood – Background & Reference

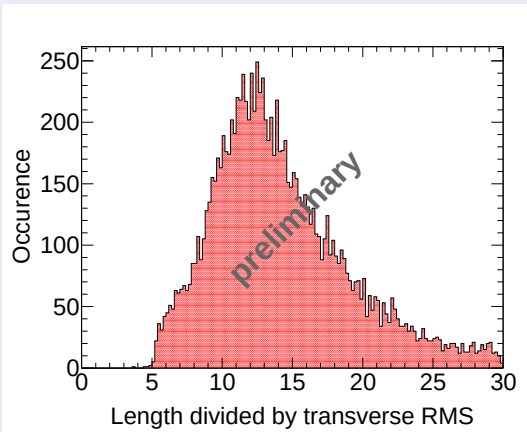
$E > 6.9\,\text{keV}$ – Copper K_α line

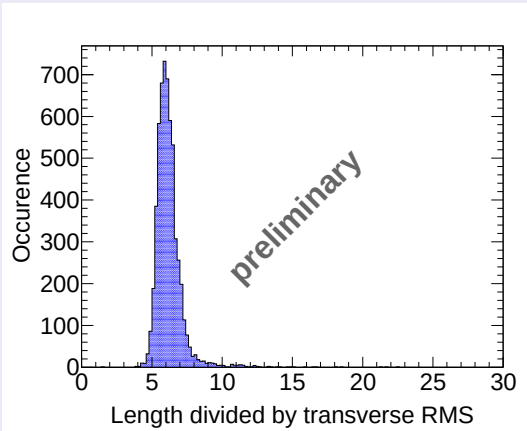
Excentricity



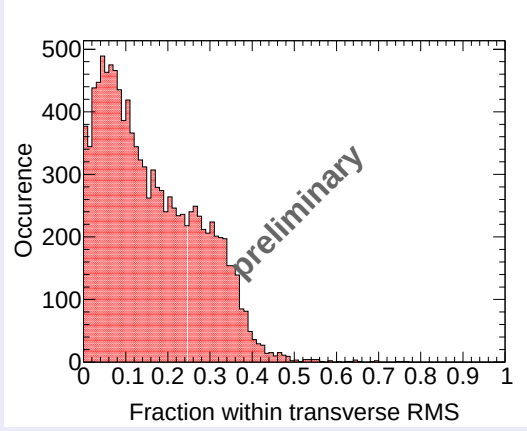


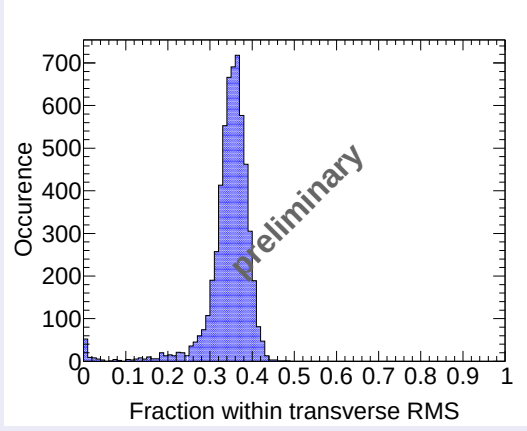
Length/RMS





Fraction within RMS

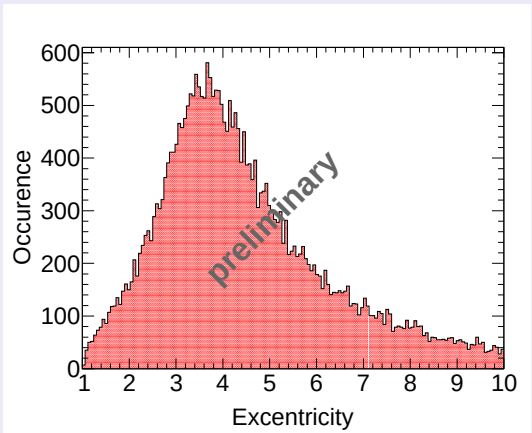


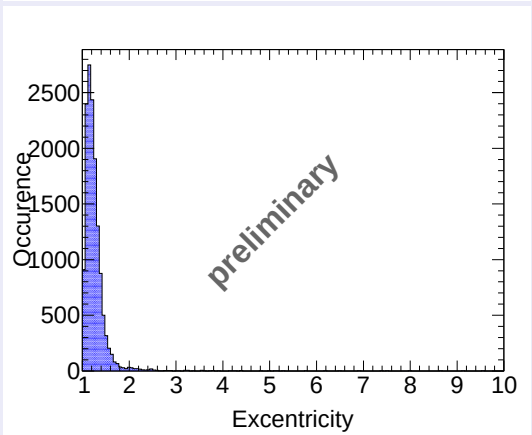


Variables entering likelihood – Background & Reference

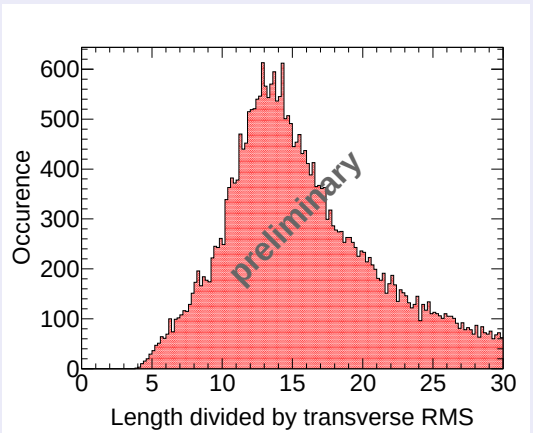
$1.2\,\text{keV} < E < 2.1\,\text{keV}$ – Aluminium K_α line

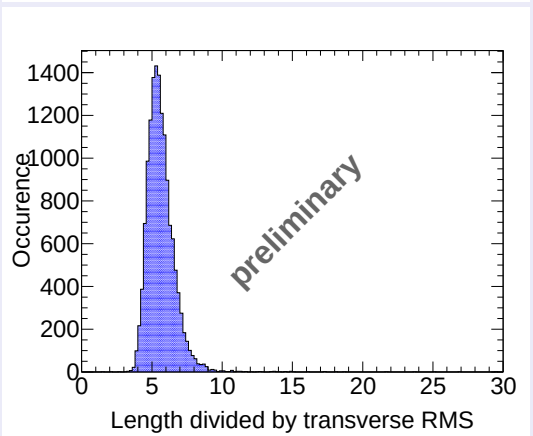
Excentricity



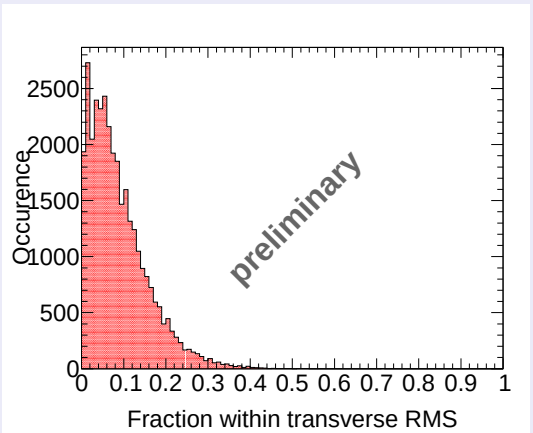


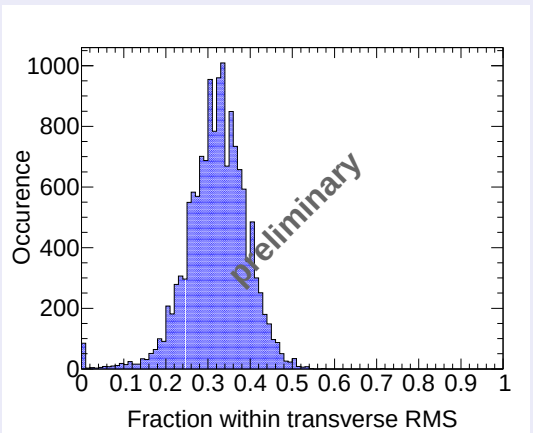
Length/RMS





Fraction within RMS

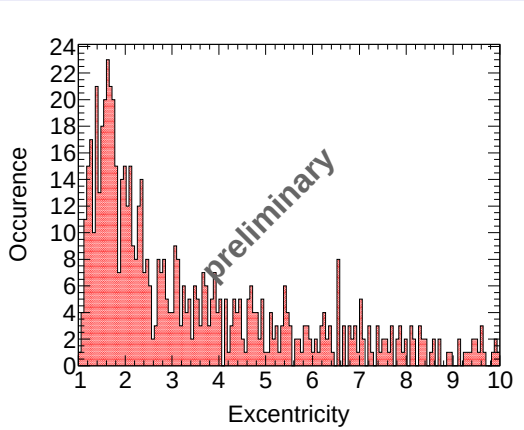


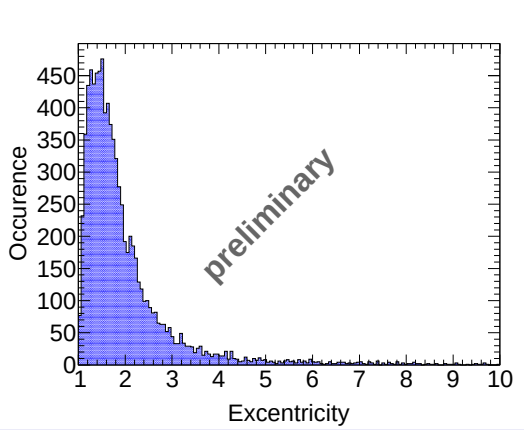


Variables entering likelihood – Background & Reference

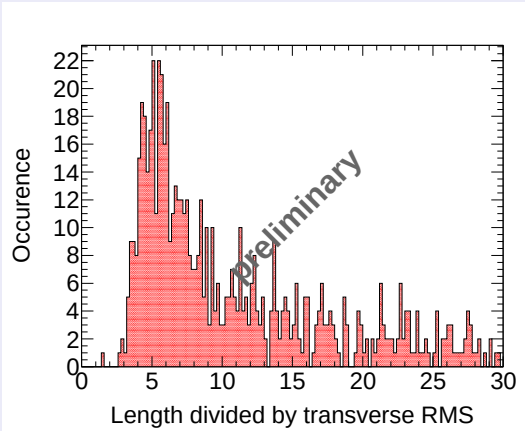
$E < 0.4\,\text{keV}$ – Carbon K_α line

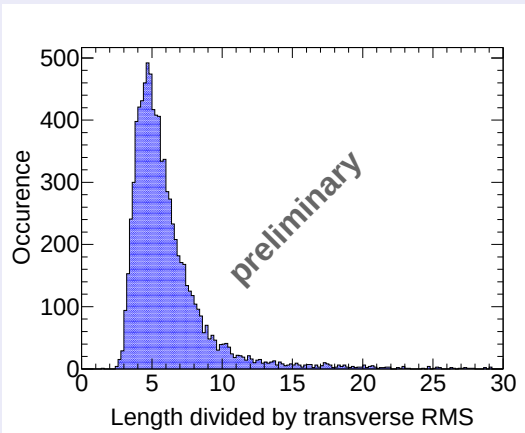
Excentricity



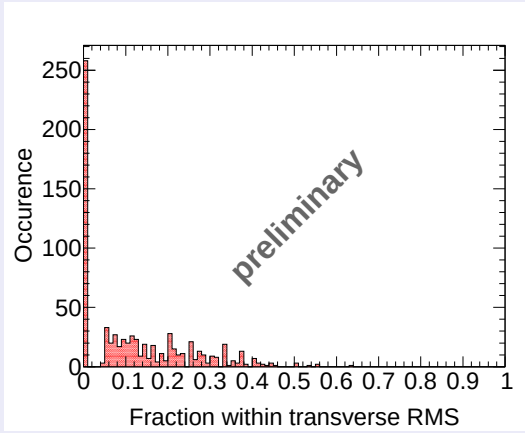


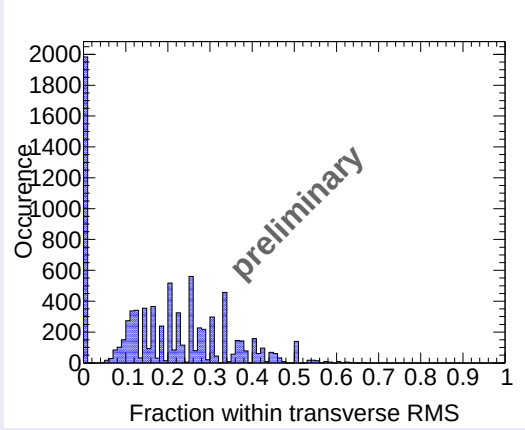
Length/RMS



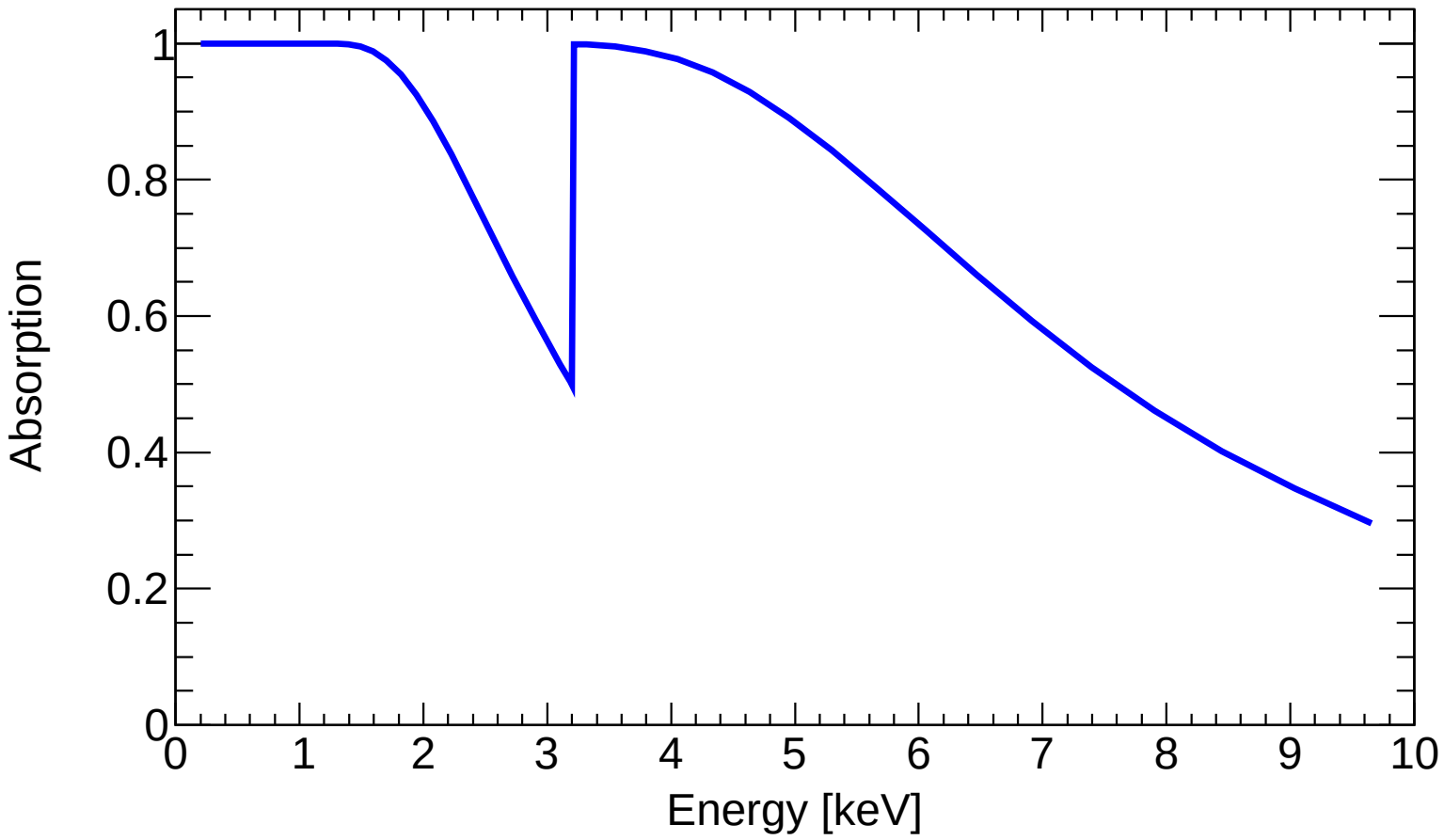


Fraction within RMS



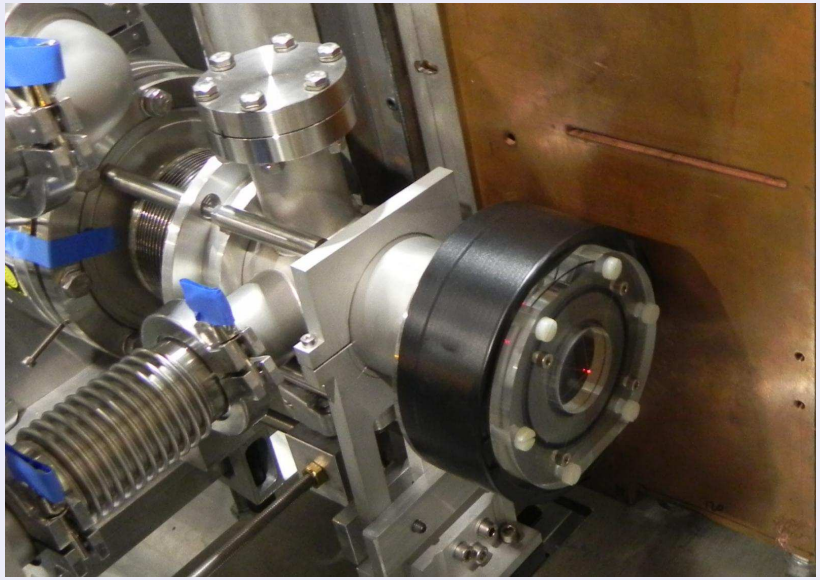


X-ray absorption in 3 cm Argon at 1050 mbar

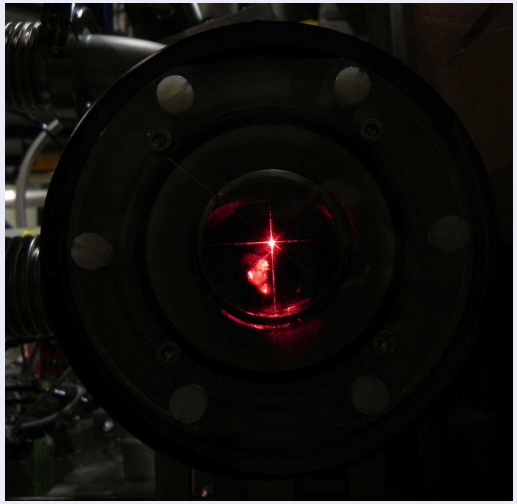


Alignment

Alignment target with laser spot



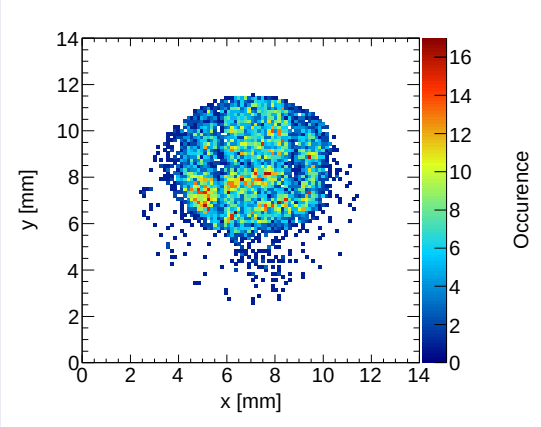
Alignment crosshair



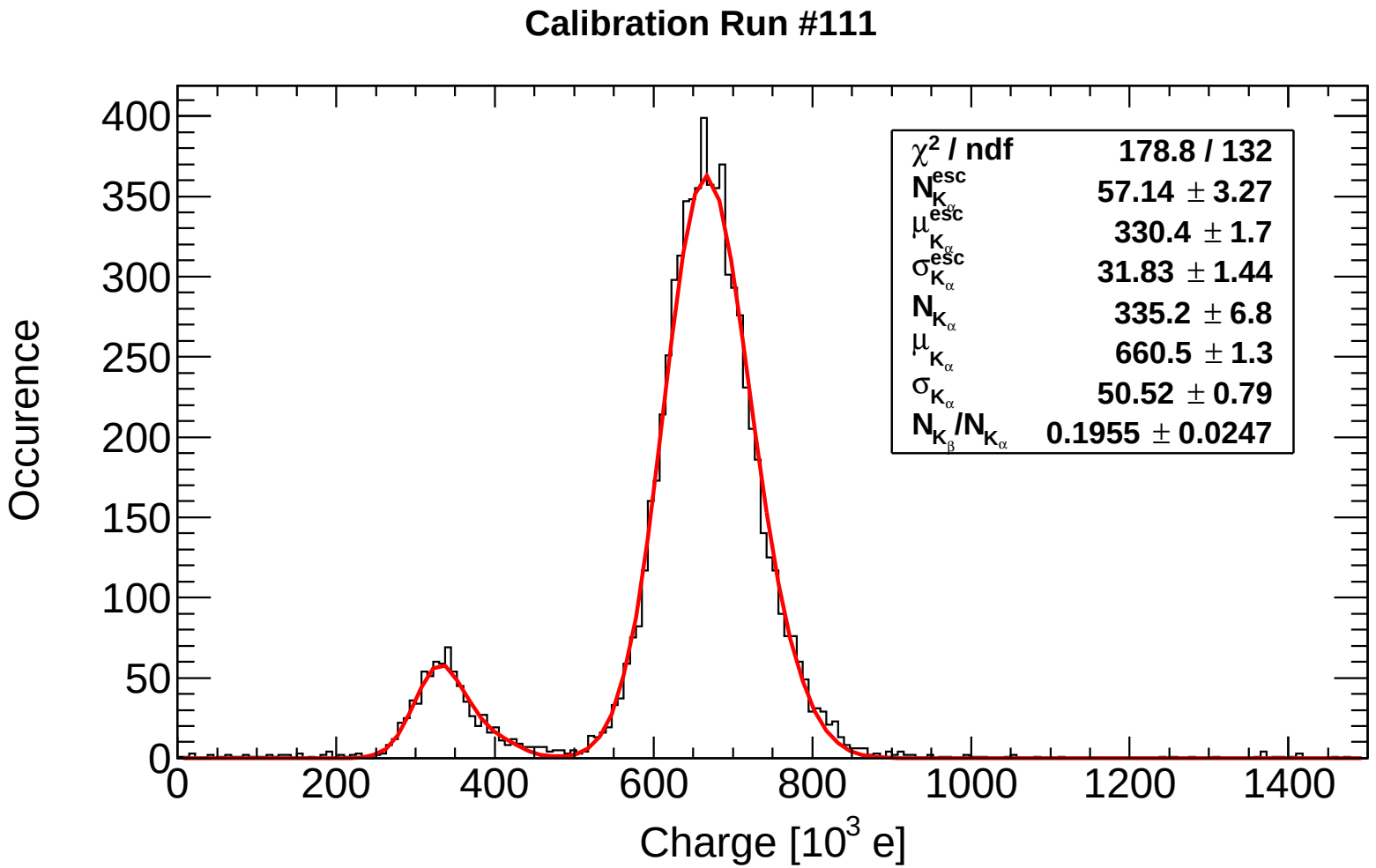
Alignment methods

- 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

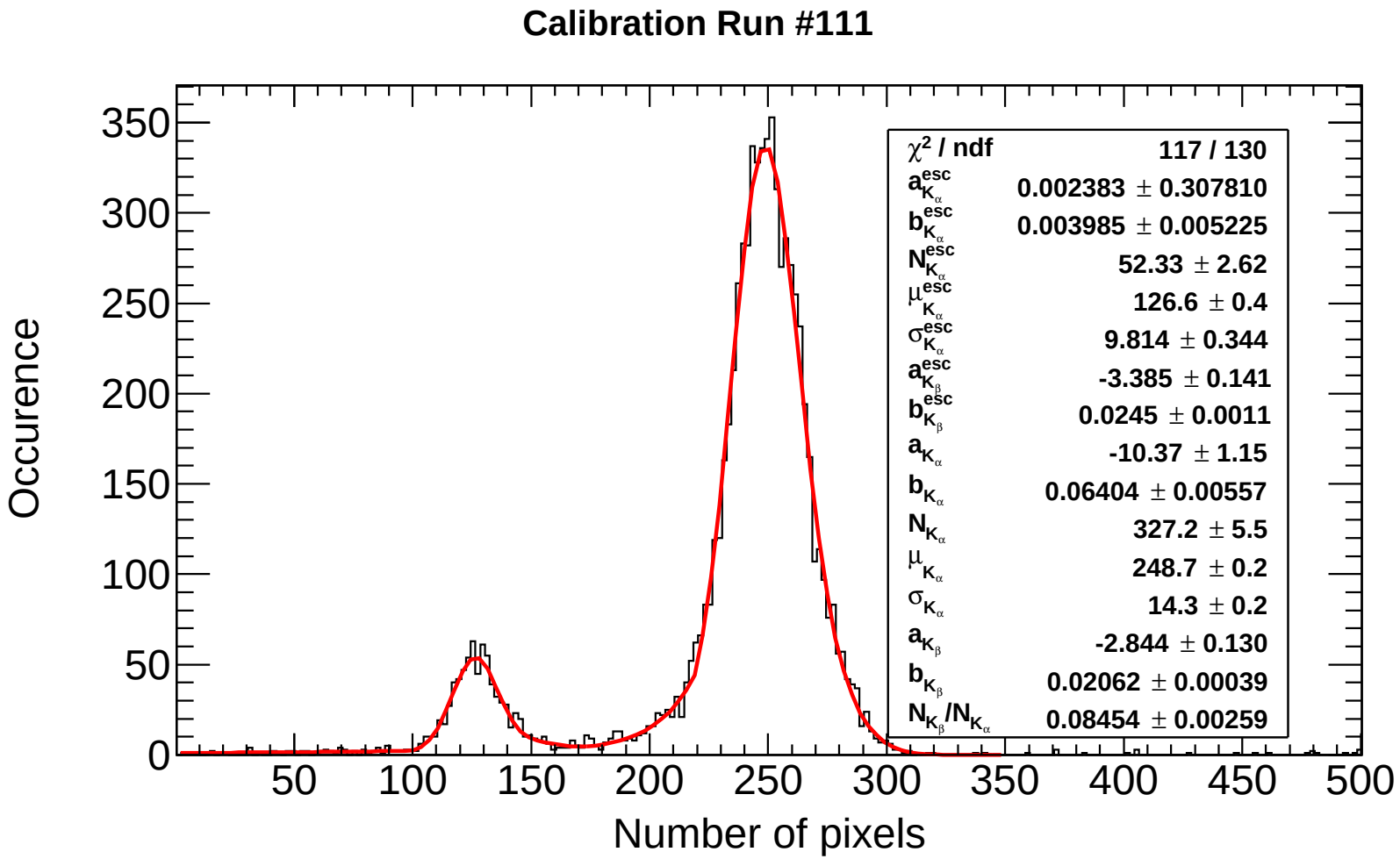
X-ray finger image



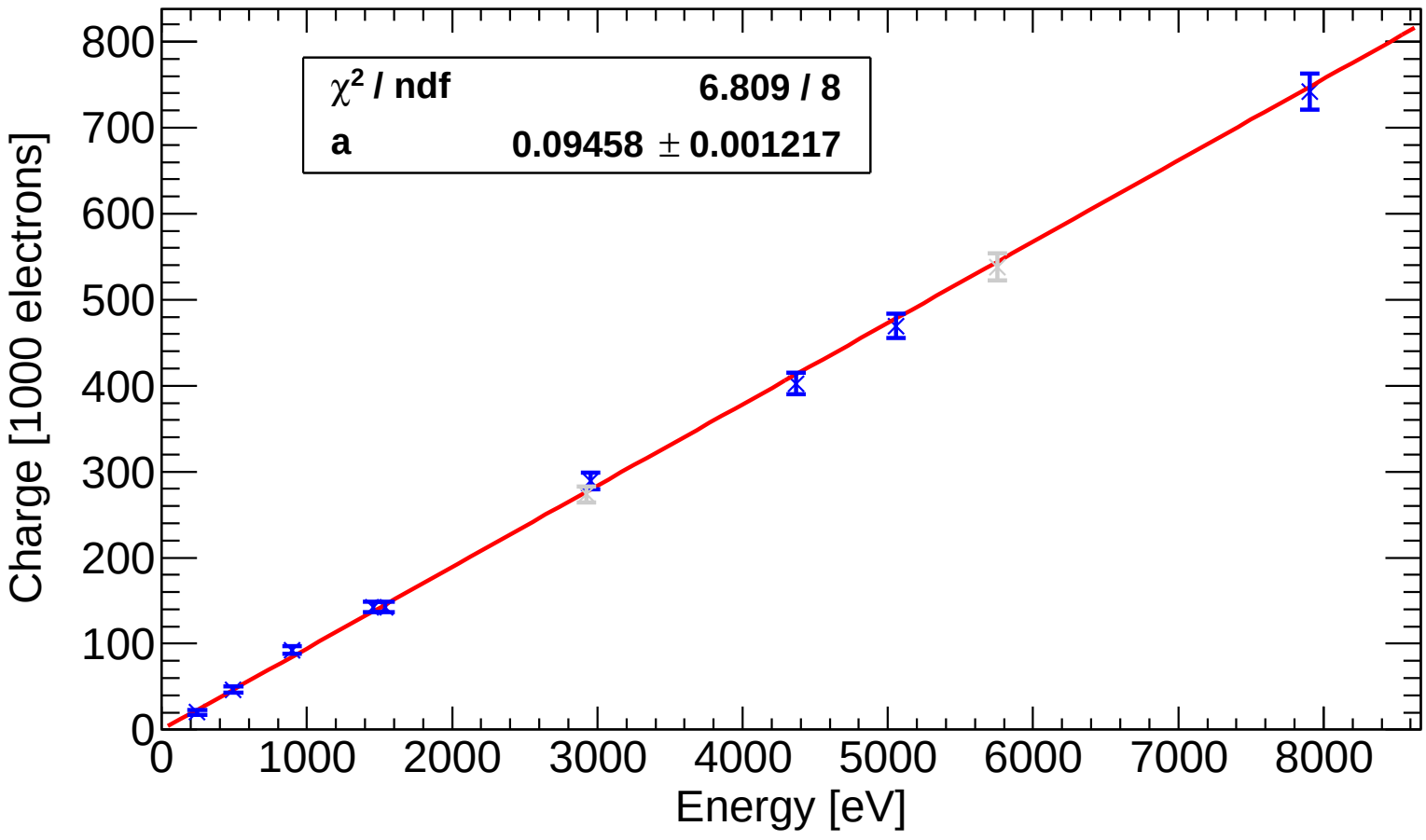
Calibration measurements with ^{55}Fe source



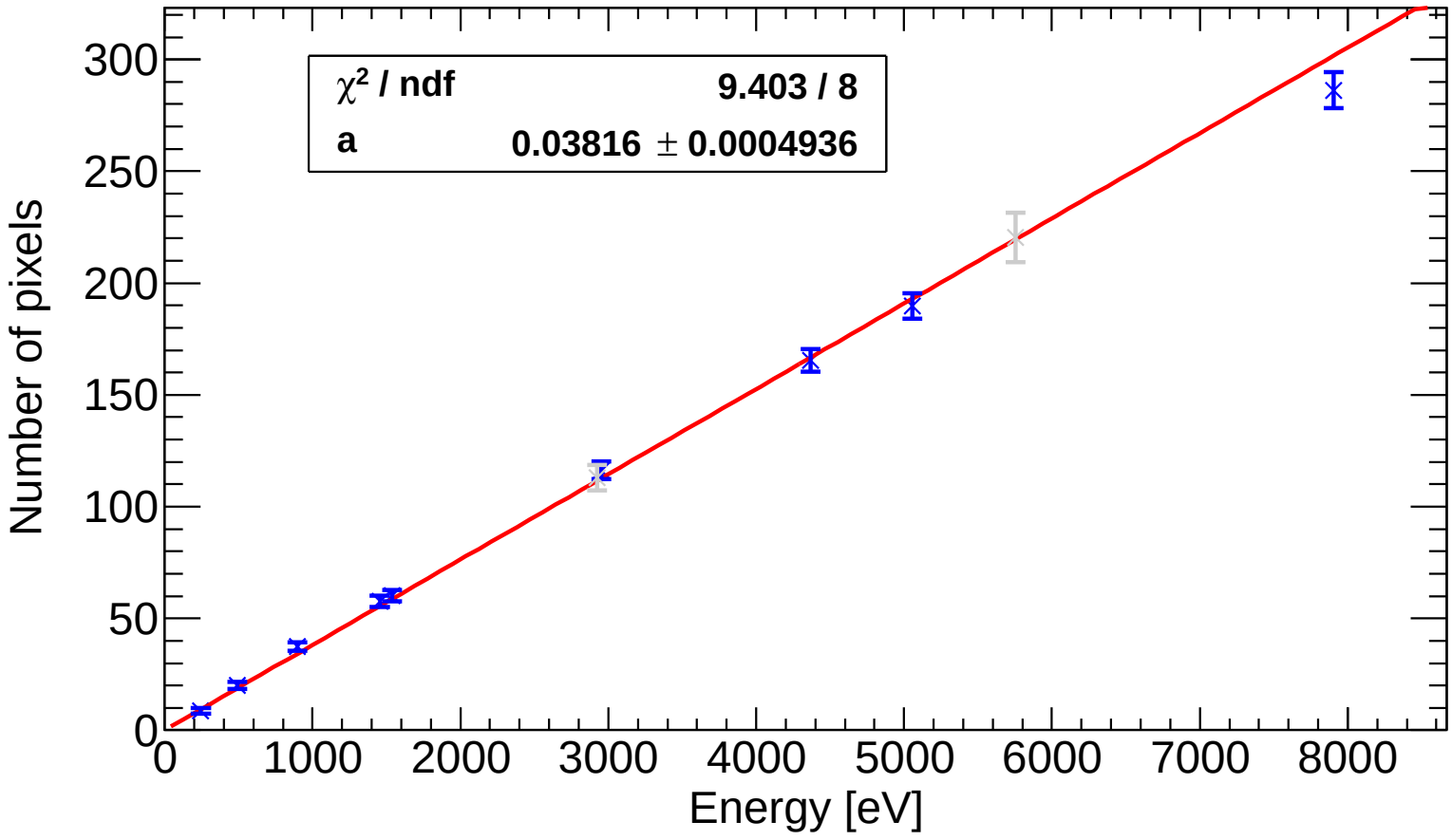
Calibration measurements with ^{55}Fe source



Energy Calibration



Energy Calibration



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