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

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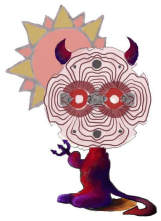
Physikalisches Institut



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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 $0.7R_\odot$ with $B_{\text{max}} \sim 10\,\text{T}$)
- Magnetic fields in tachocline caused by differential rotation
- Temperature at tachocline region results in solar chameleon flux peaking below 1 keV
- Could be detected by axion helioscope experiments: 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)

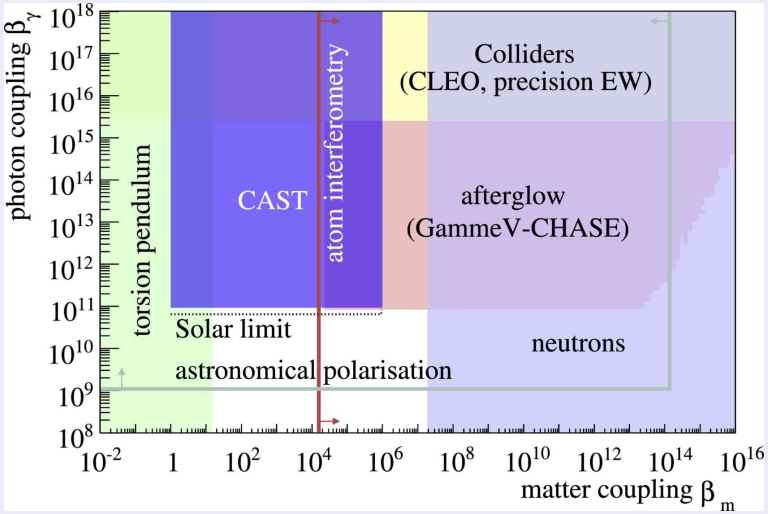
CAST pointing at the Sun

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 limit given by solar luminosity ($\mathcal{L}_{\text{Sun}}^{\text{chameleon}} \leq 10\,\% \cdot \mathcal{L}_{\text{Sun}} \rightarrow \beta_\gamma \leq 10^{10.81} \approx 6.5 \times 10^{10}$)

Phys. Lett. B 749(2015), 172



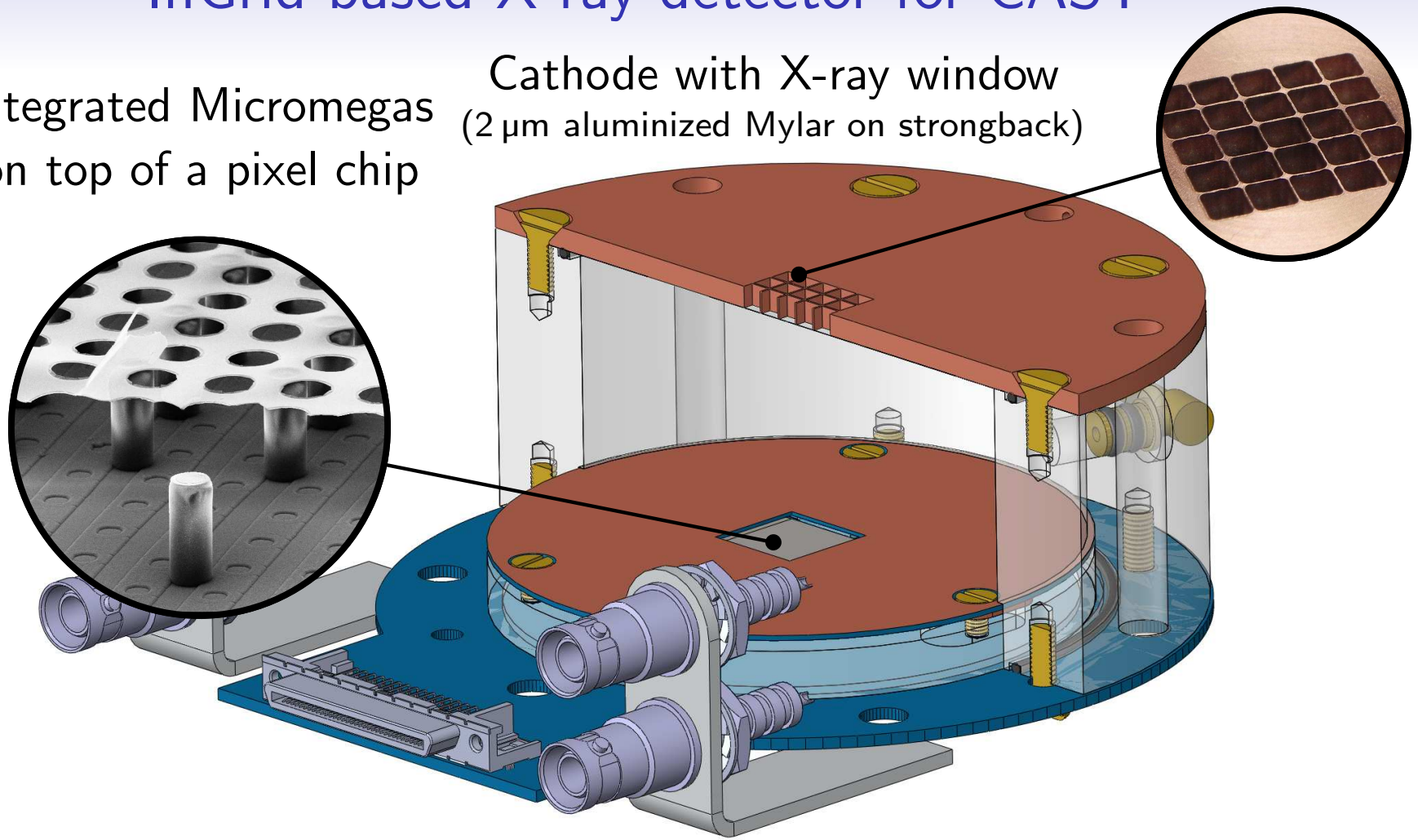
To be continued

- 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

Integrated Micromegas
on top of a pixel chip

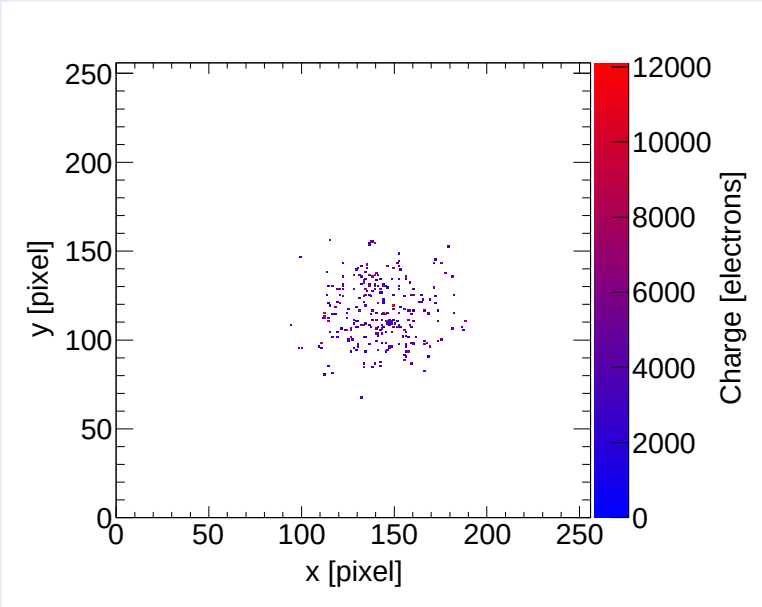
Cathode with X-ray window
(2 µm aluminized Mylar on strongback)



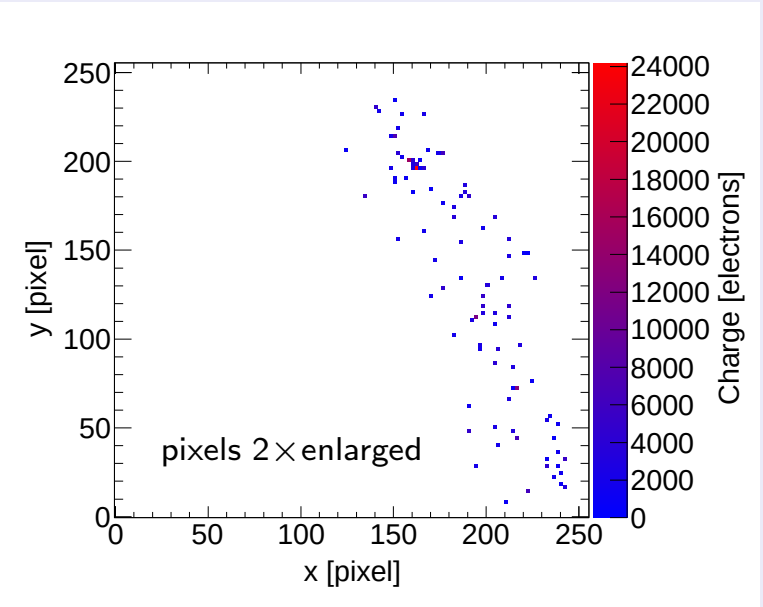
Drift volume flushed with Ar/iC_4H_{10} 97.7/2.3

Typical events

X-ray event (5.9 keV)



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

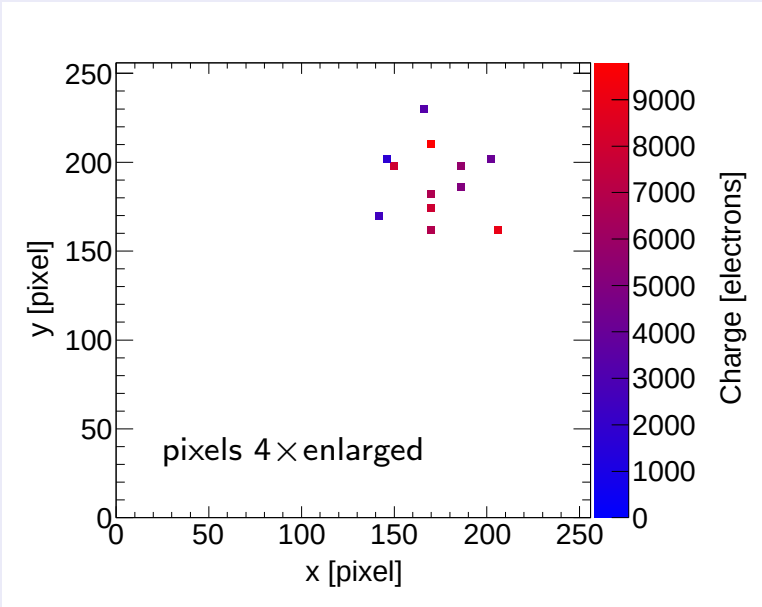


Benefits from high spatial resolution

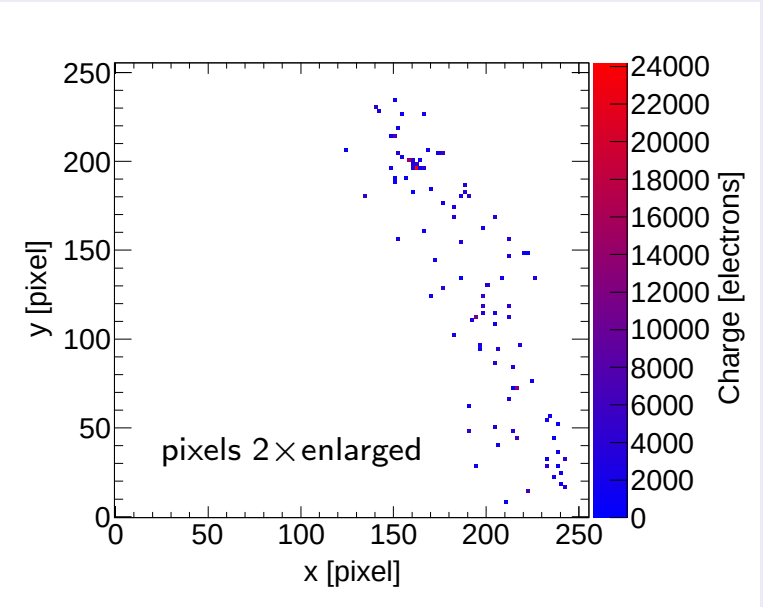
- Each primary electron can be detected individually on the chip
- Low energy X-ray photons can be detected
- Event shape can be used for suppression of non X-ray events

Typical events

X-ray event (277 eV)



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



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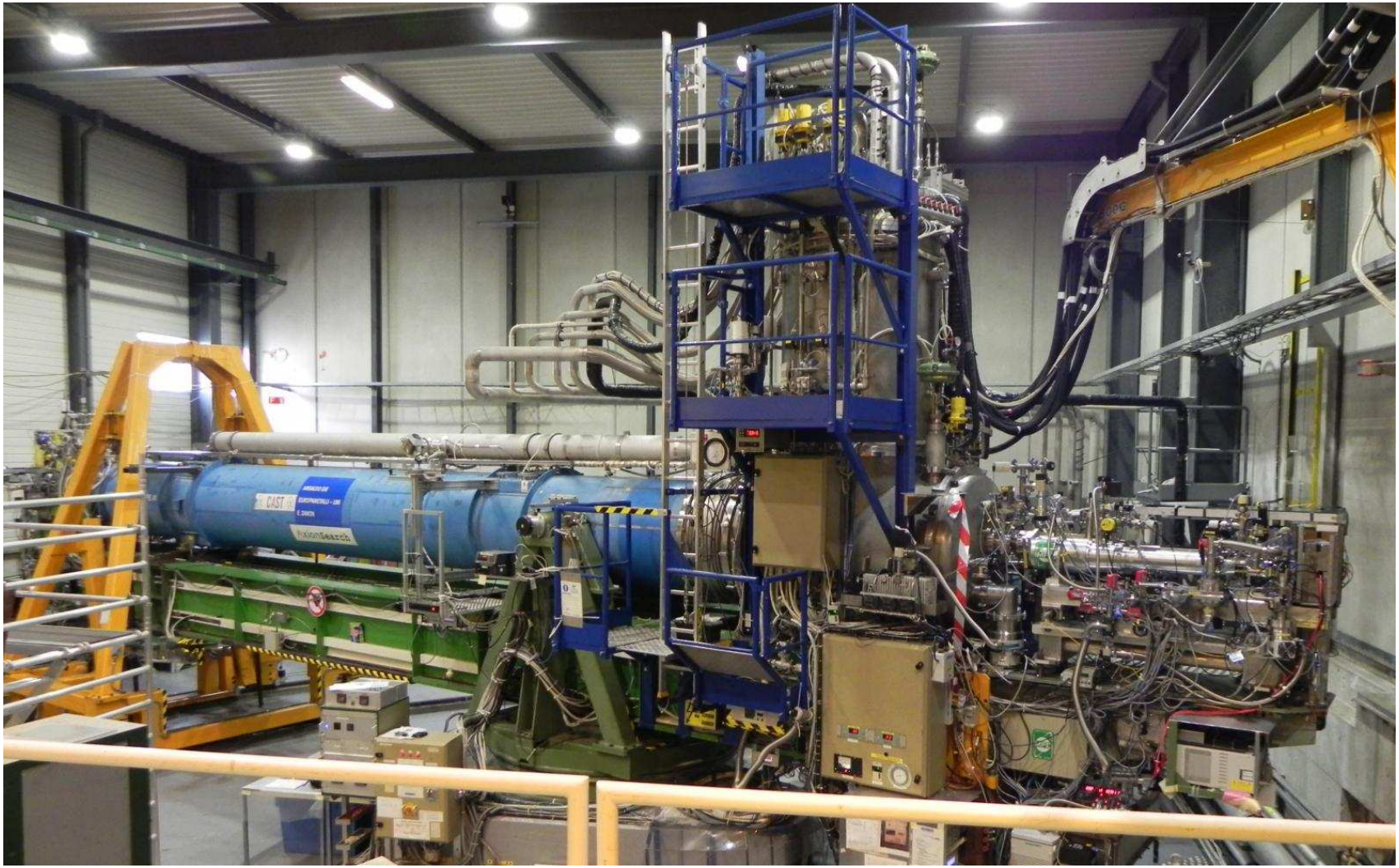
InGrid based X-ray detector & its infrastructure at CAST



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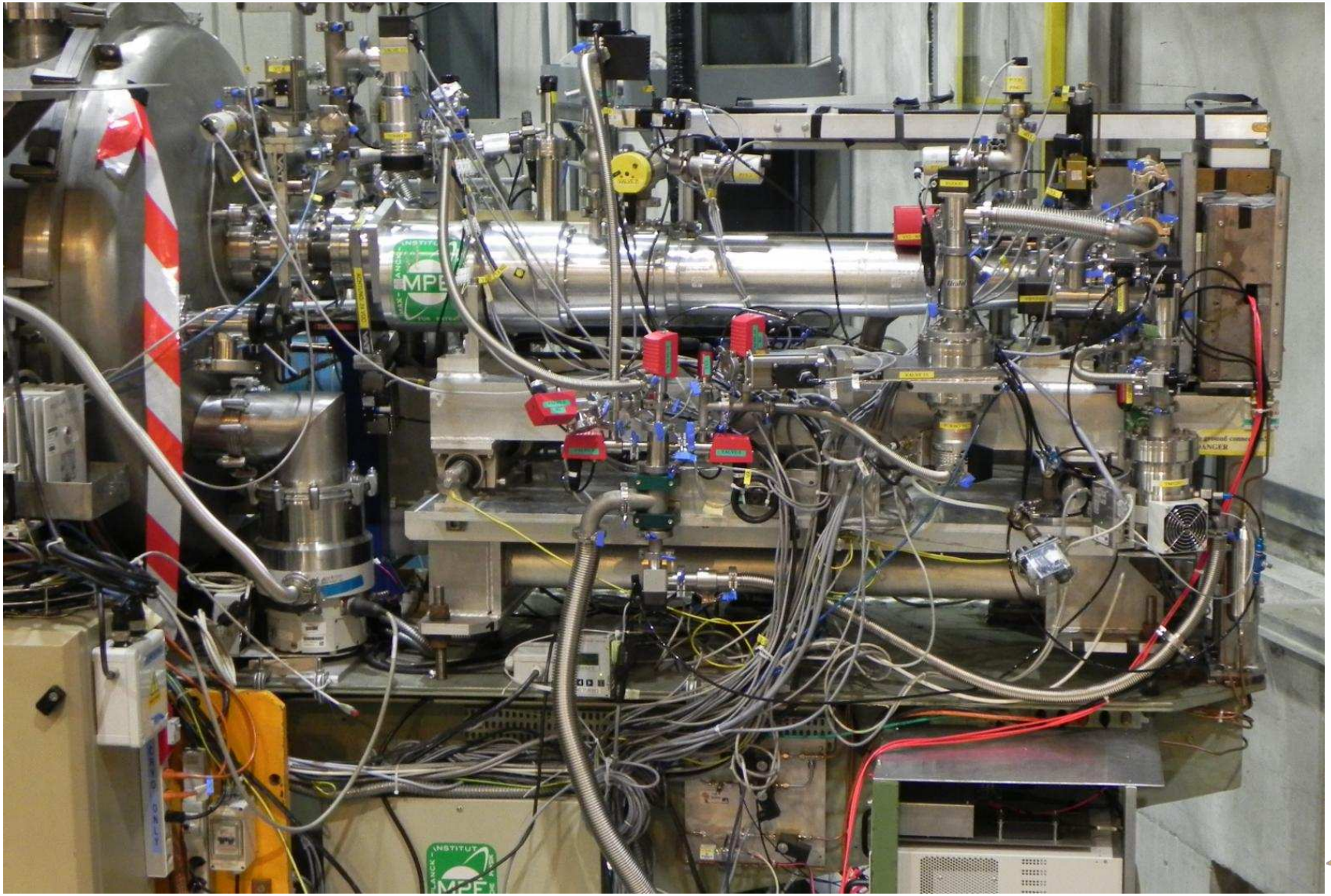

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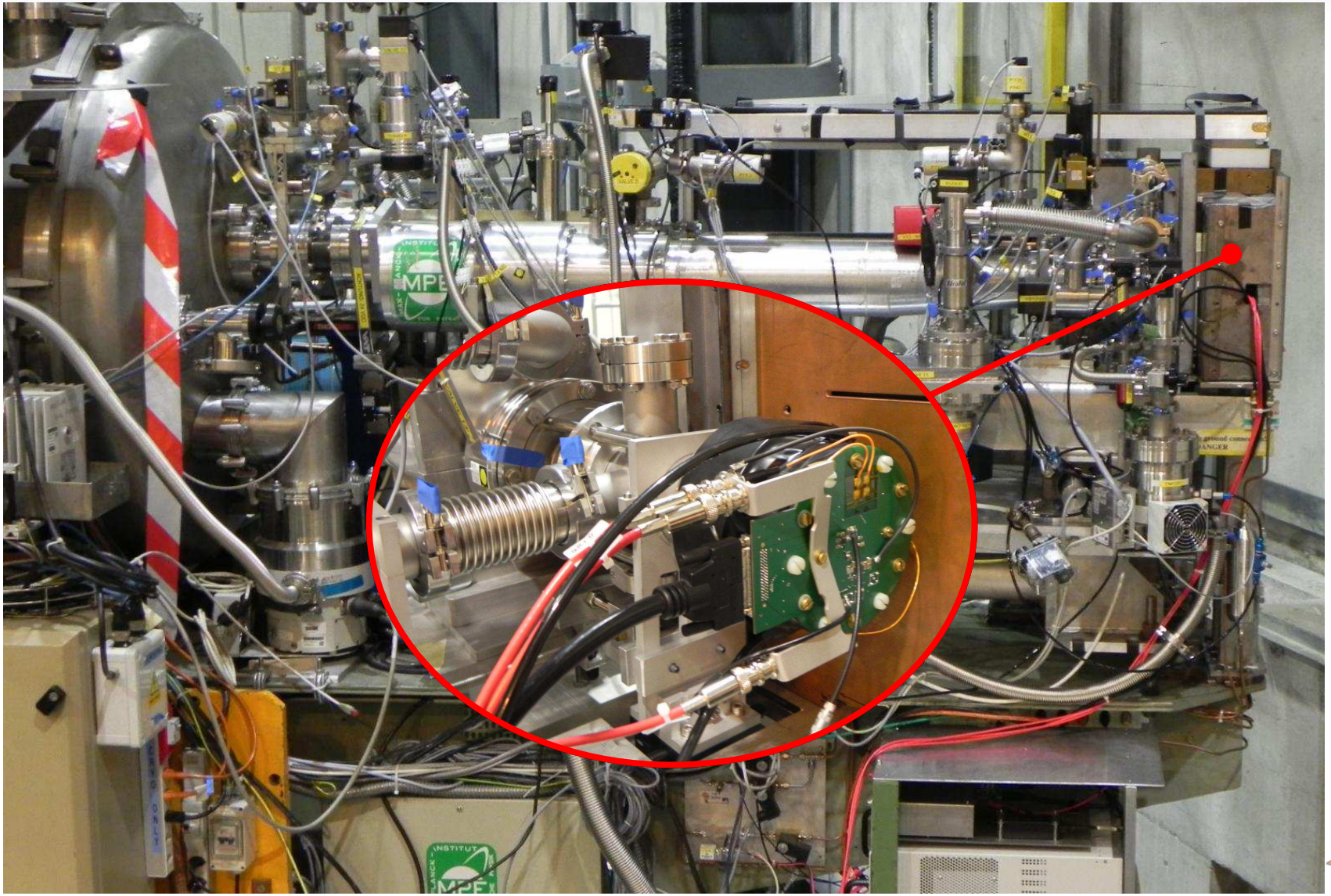


Operation at the CAST experiment

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 long, untriggered)
- 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

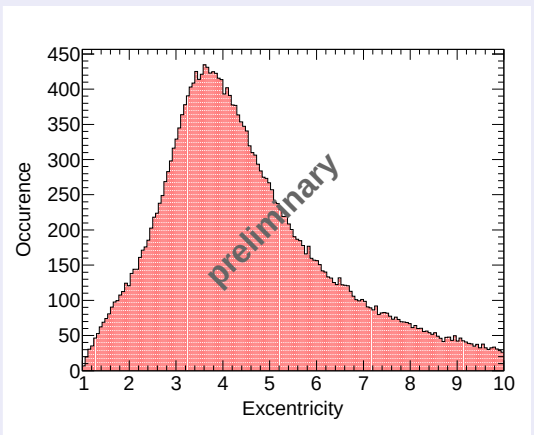
Likelihood for background rejection

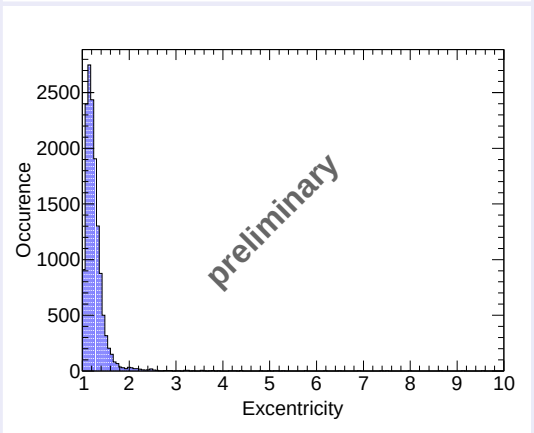
- Likelihood calculated from reference distributions for different energy ranges (from tests at an X-ray generator)
- **Three** variables are used for likelihood:
  - Eccentricity (Measure for circularity)
  - Length along long axis divided by RMS along short axis
  - Fraction of pixels within radius 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

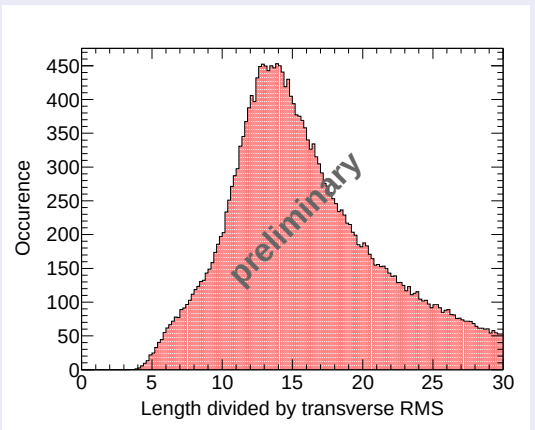
$1.2\,\text{keV} < E < 2.1\,\text{keV}$ – Aluminium K_α line

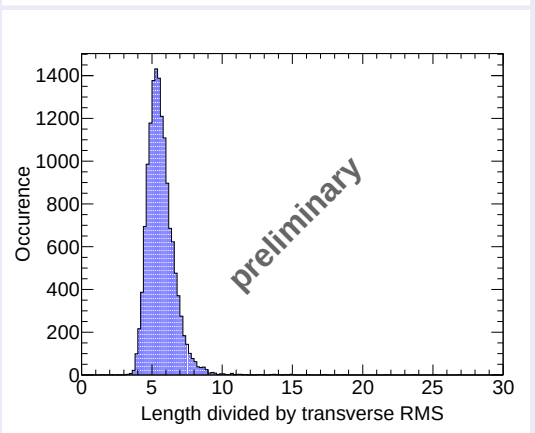
Eccentricity



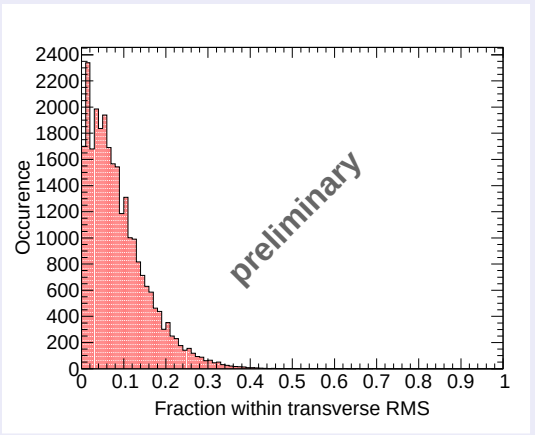


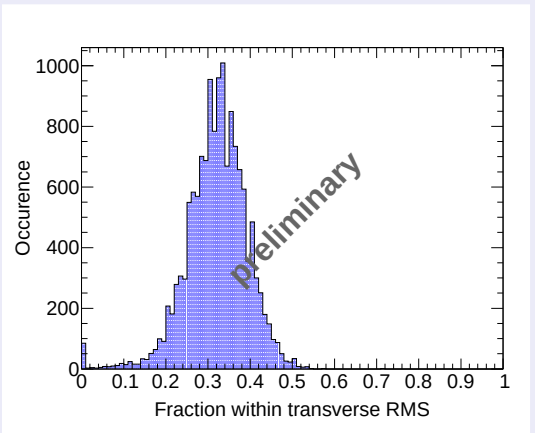
Length/RMS





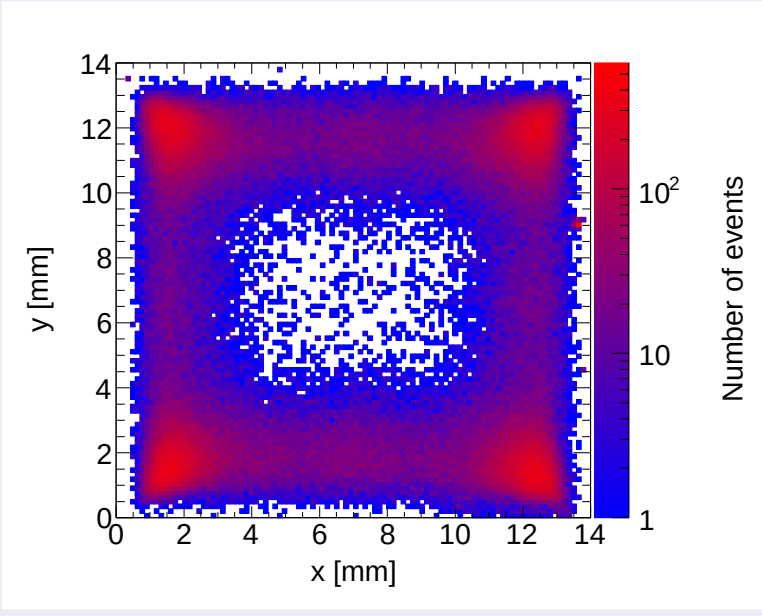
Fraction within RMS





Background events after suppression

Below 2 keV



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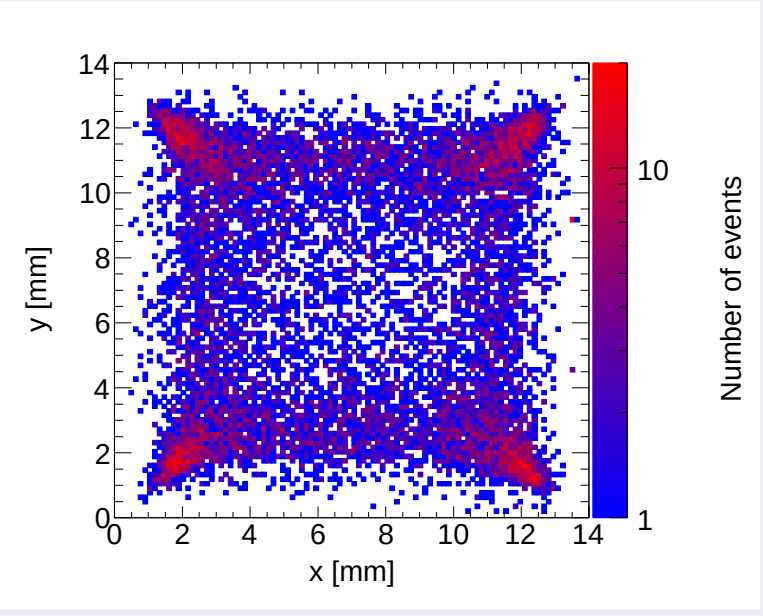

- Background rate is much lower in chip centre
- Most probable: partially contained tracks at sides & corners
- Maybe also X-ray fluorescence photons from detector material
- Split data in three regions: gold, silver & bronze

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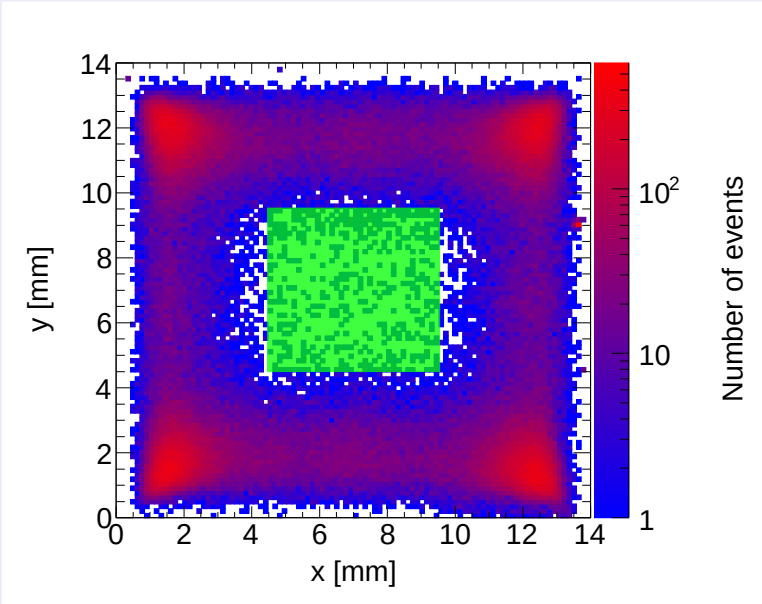

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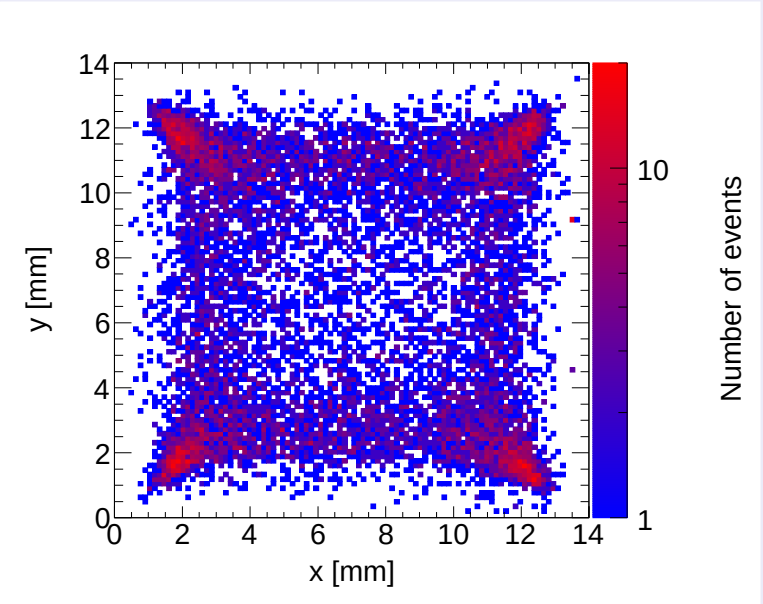

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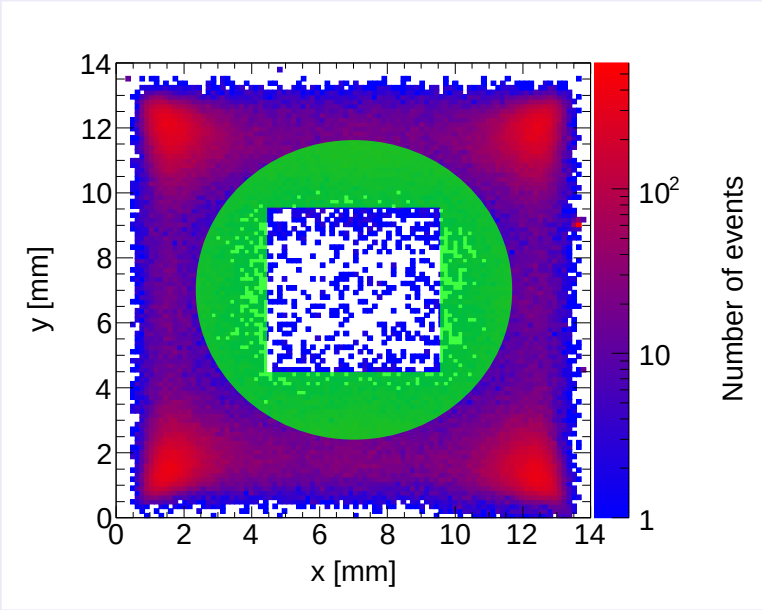

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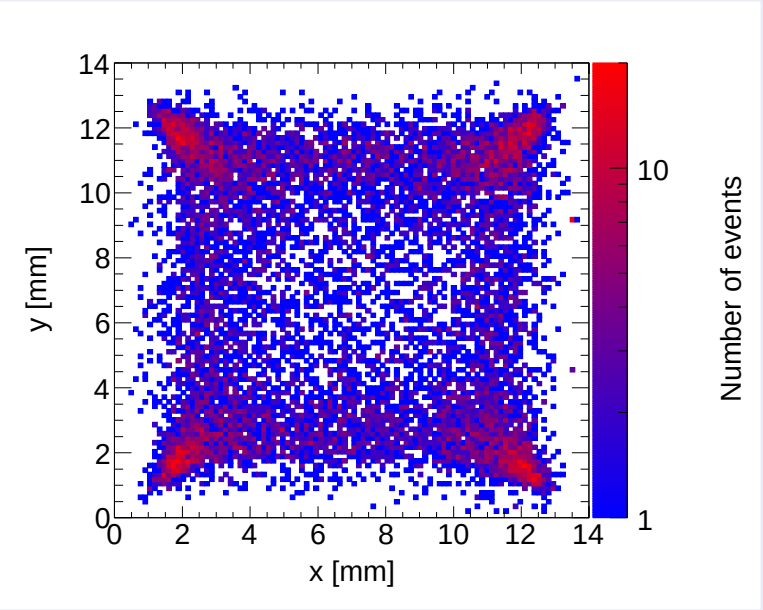

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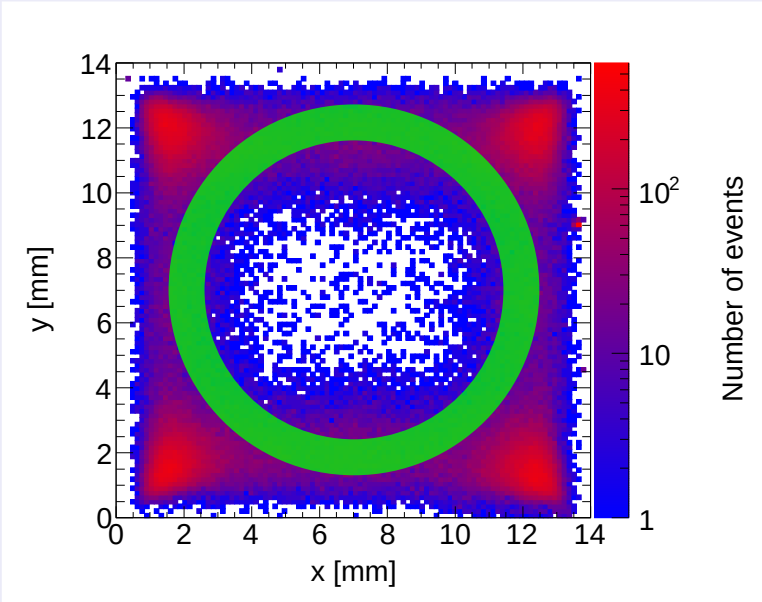

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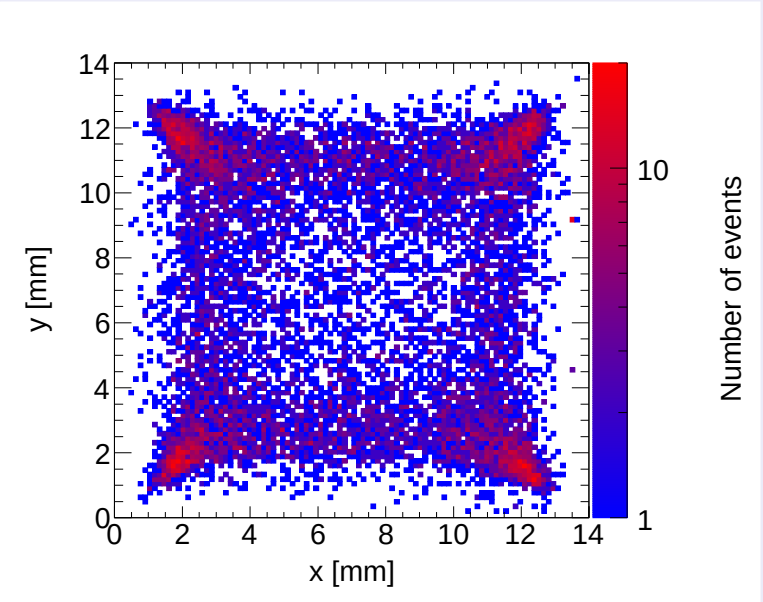

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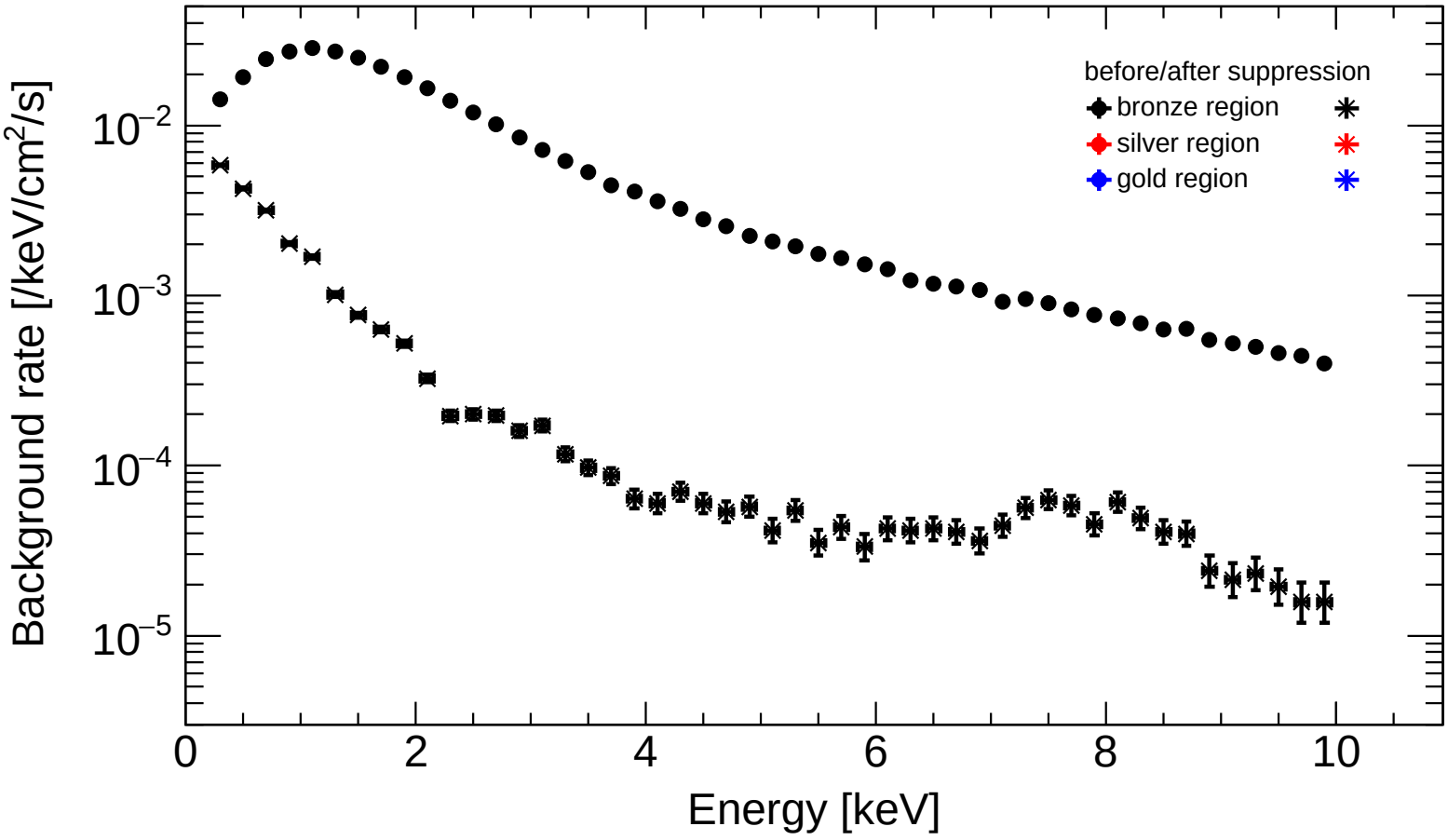
Measured background rate before & after suppression



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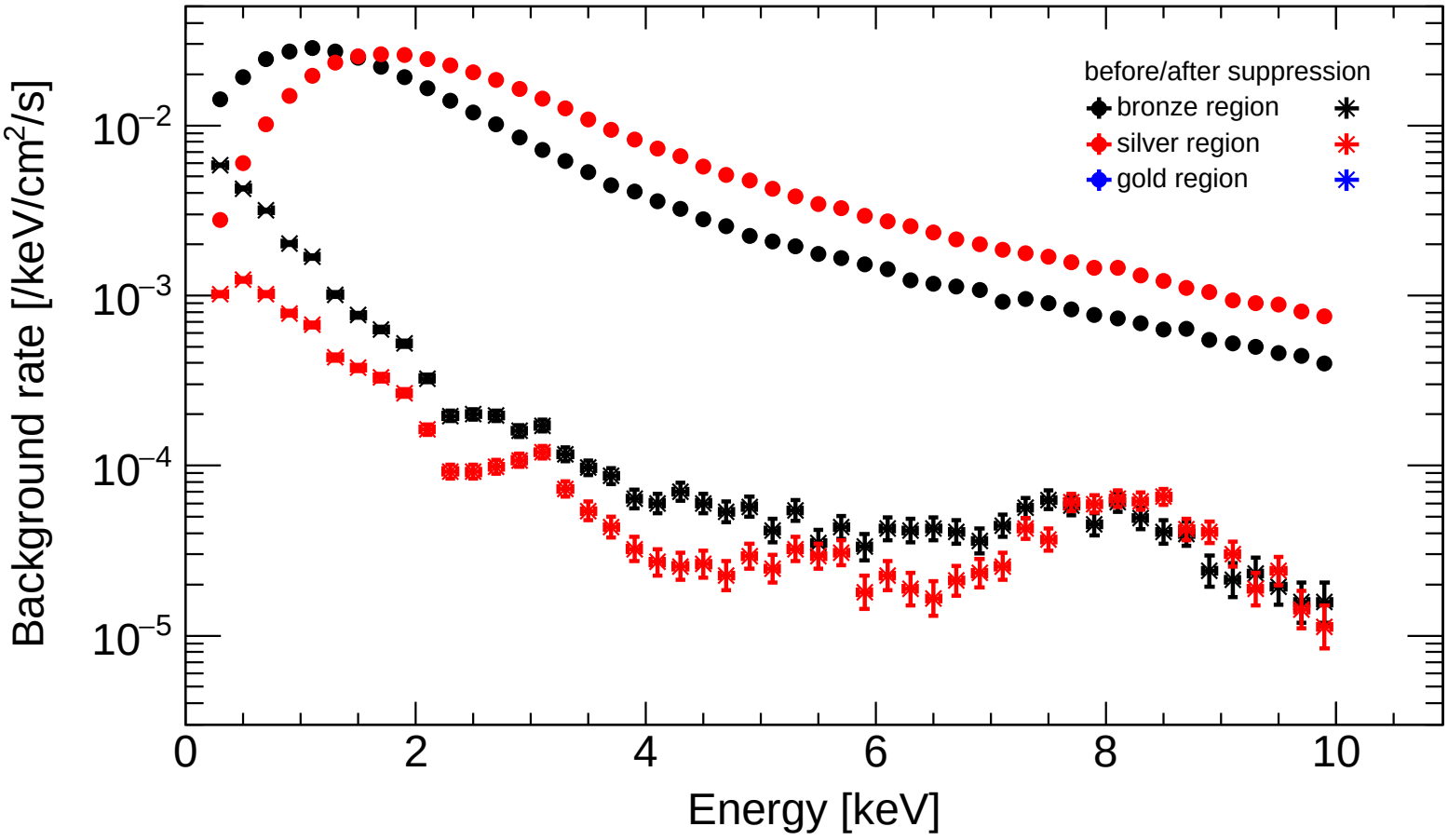

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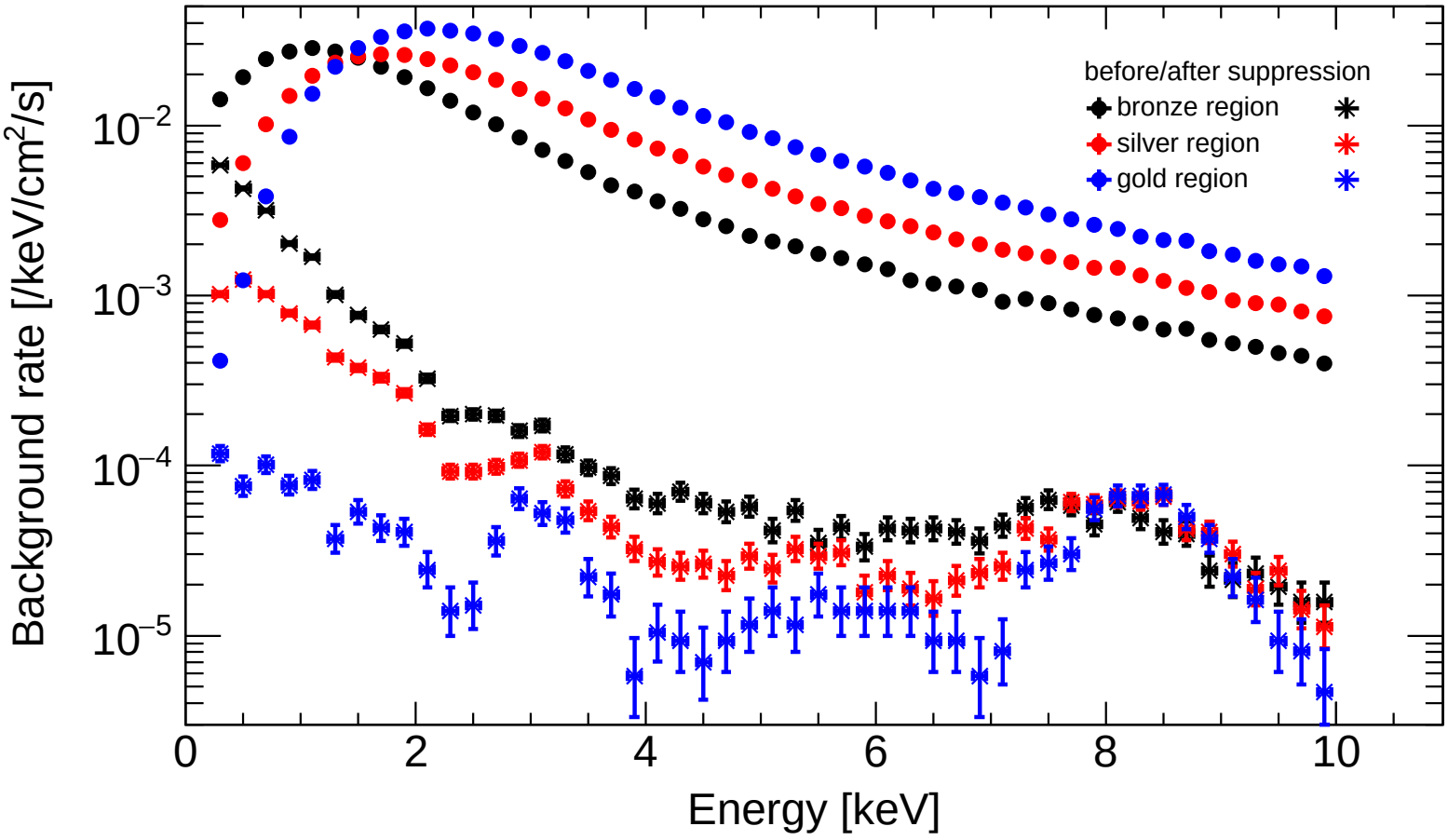
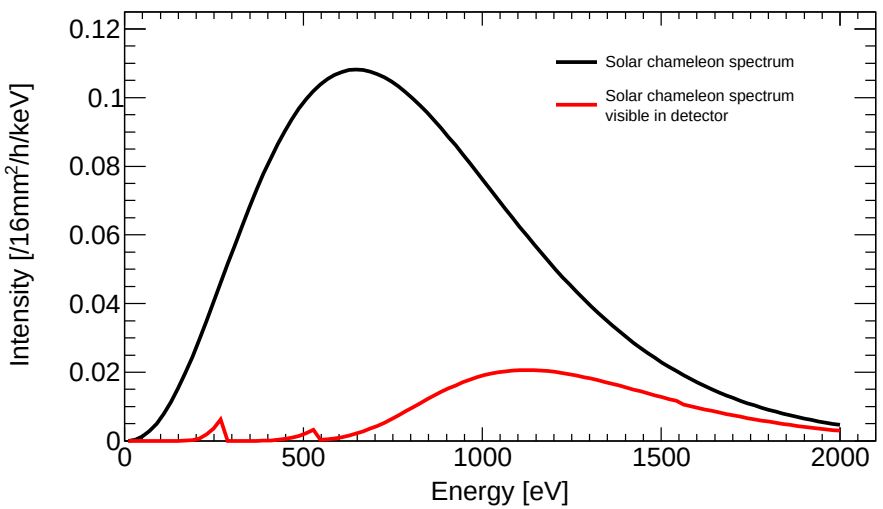


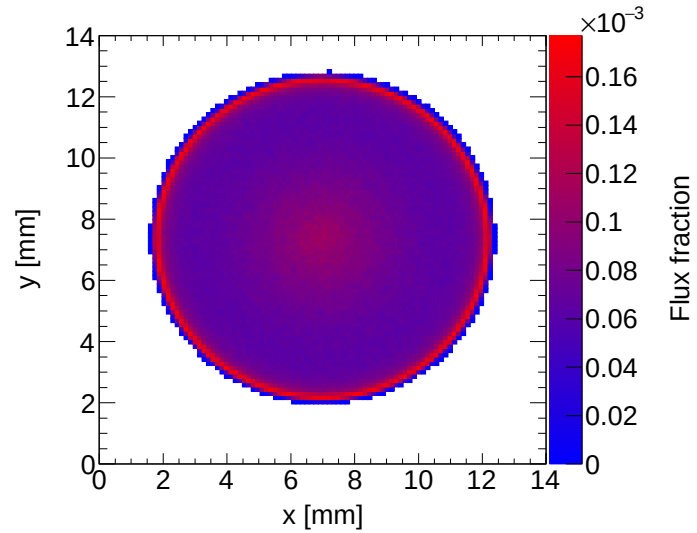
Calculating the expected chameleon signal

- Chameleon spectrum from Phys. Rev. D 85(2012), 043014
- Fold with window & X-ray telescope transmissions
- Take into account detector properties (software efficiency, energy resolution, etc) & measurement time
- Take into account CAST magnet & XRT optics (e.g. path length in magnet & off-axis behaviour of XRT)

Solar chameleon spectrum



Chameleon image of Sun



Deriving a limit on chameleon photon coupling β_γ

Finding the 95 % CL_s limit

- Utilize `ROOT` implementation of `mclimit` code
- Feed `TLimit` with expected background(s) & signal(s) (plus observed data)
- Add statistical bin errors and estimated systematic uncertainties (e.g. from possible misalignments)
- Rescale signal histogram(s) according $\sim \beta_\gamma^4$
- Scan over β_γ to find point with $1 - CL_s = 95\,\%$

Expected 95 % CL_s limit

- Taking into account gold, silver & bronze region of full 2014 and 2015 datataking period: $\beta_\gamma \leq 5.6 \times 10^{10}$
- Below upper solar limit $\rightarrow$ **Ready to discover!**
- Data has been unblinded...

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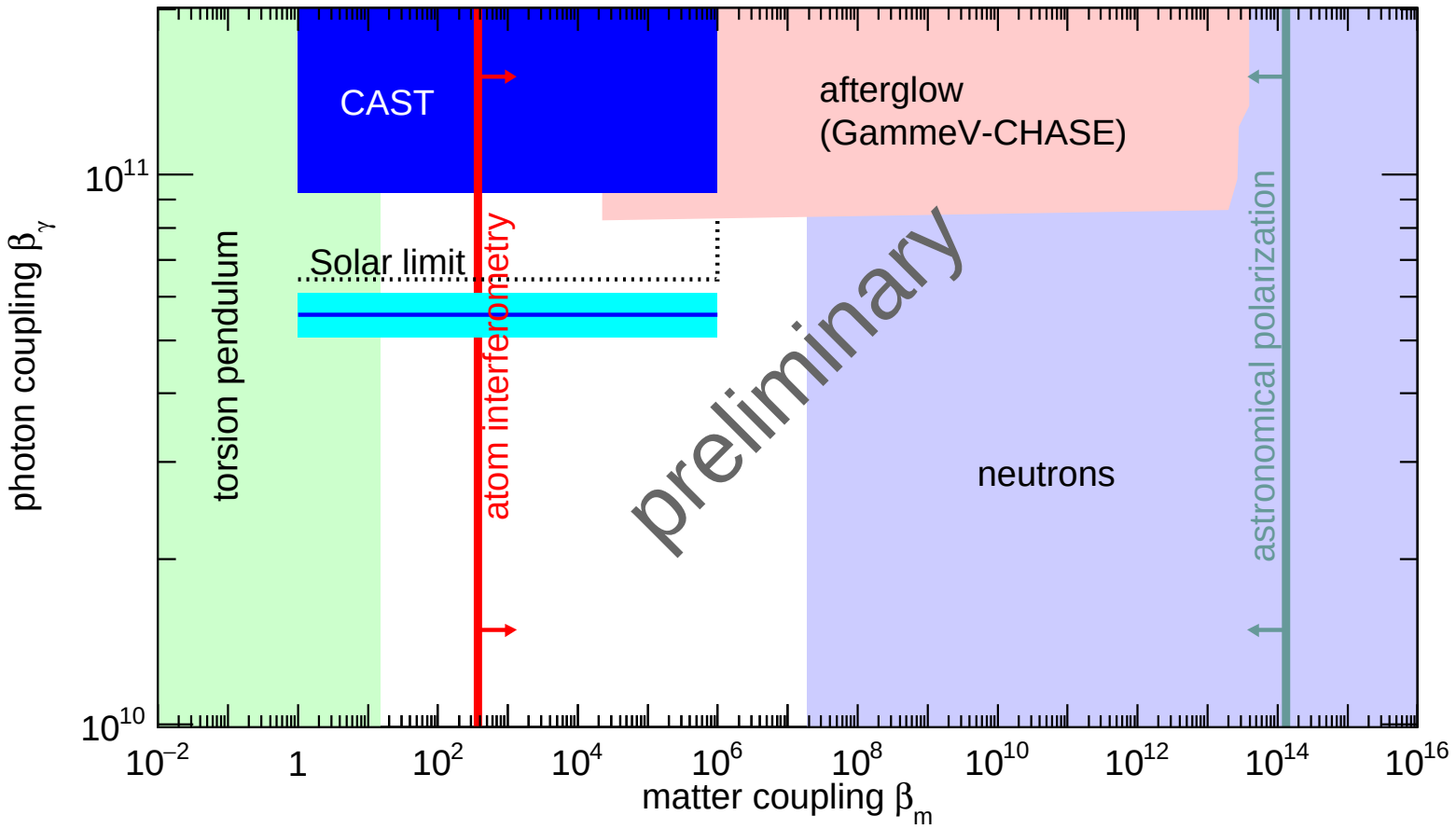
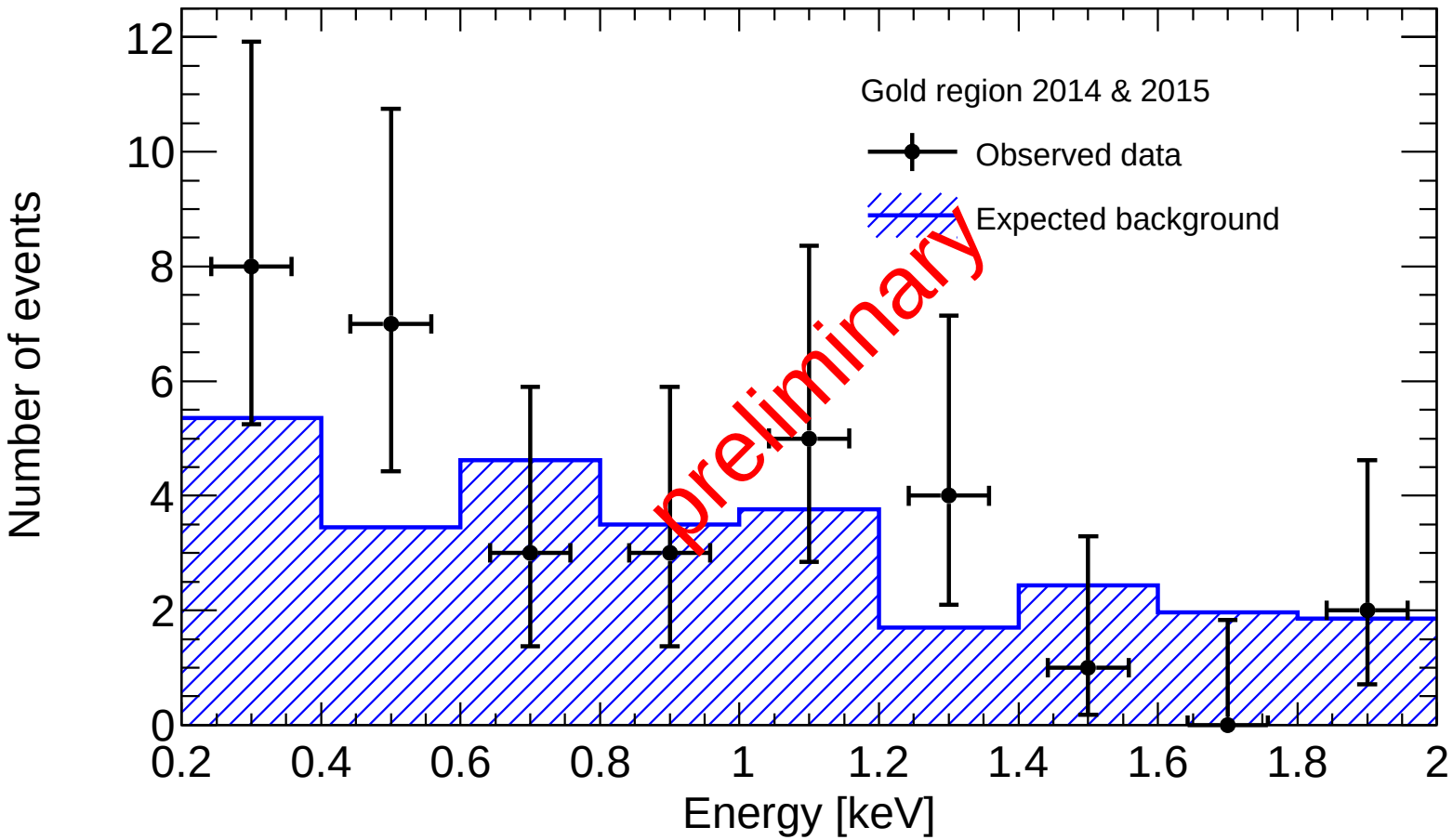
Expected 95 % CL_s limit on β_γ



Ready for discovery!

Unblinding the data



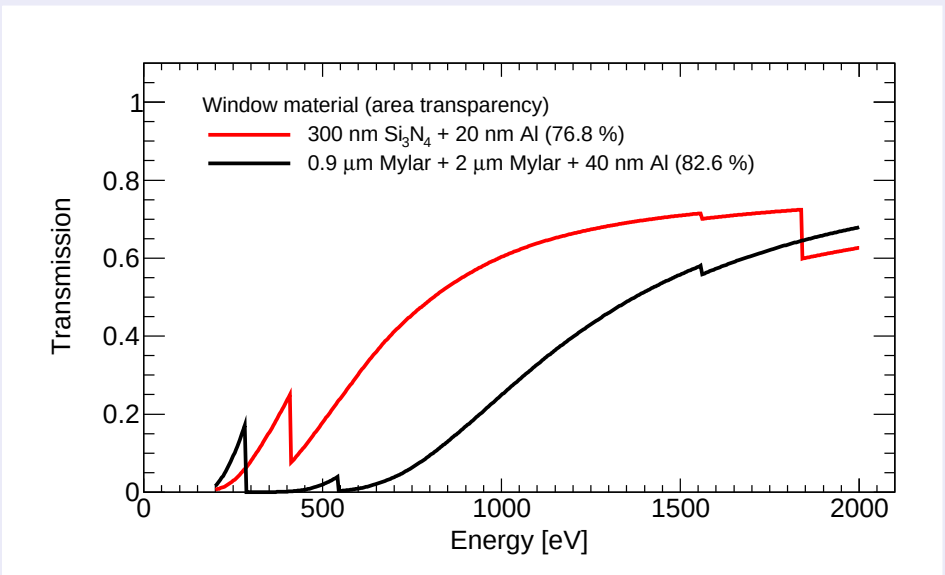
No chameleons so far. . .

Prospects for improvement

Increasing the signal

- Change Mylar foil for ultrathin silicon nitride windows
- First 300 nm silicon nitride windows withstanding 1500 mbar pressure difference tested end of last year
- Development in cooperation with Canadian company Norcada

Comparison of window transmissions



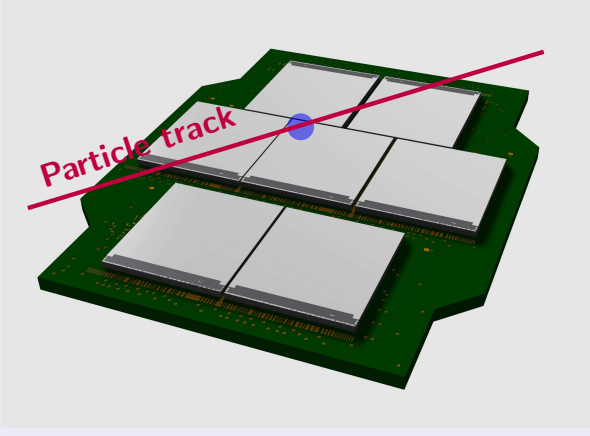
SiN under pressure

Prospects for improvement

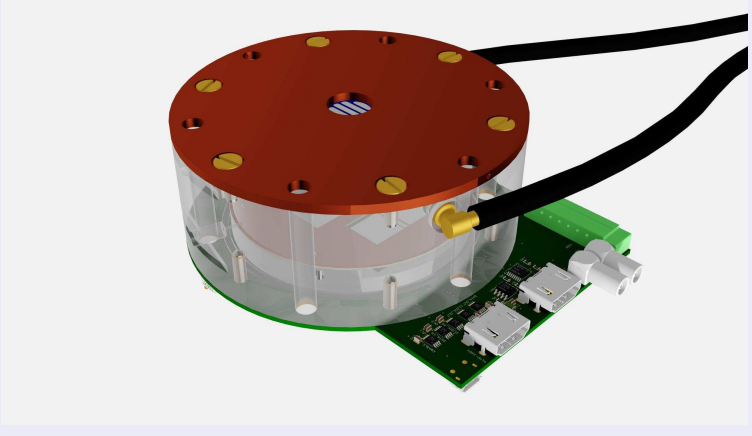
Reducing the background

- New background suppression method based on convolutional neural networks (see next talk!)
- Veto scintillators above and on the back of the detector
  $\rightarrow$ X-ray fluorescence photons induced by cosmic rays
  $\rightarrow$ perpendicular tracks mimicing X-ray photons
- Septemboard: Surround central InGrid with six "veto" InGrids
  $\rightarrow$ Reject partial tracks mimicking X-ray photons

Septemboard

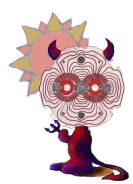


The 2017 detector



Summary & Outlook

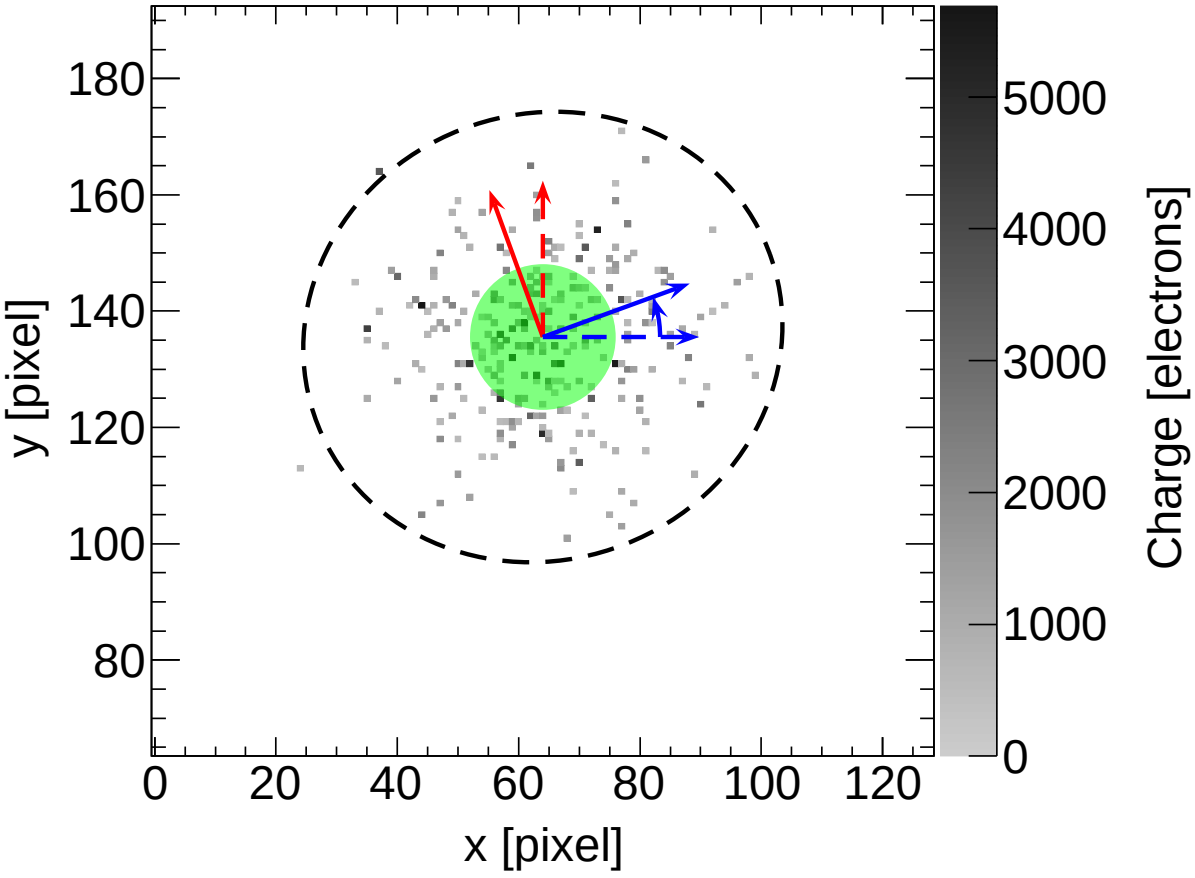
- An InGrid based X-ray detector has been installed & successfully operated at CAST in 2014 & 2015 to continue search for Solar chameleons at CAST
- Background suppression via likelihood method using event shape variables has shown good performance
- Background rate in inner chip region is $\mathcal{O}(10^{-4}\,/\mathrm{cm}^2/\mathrm{keV/s})$ below 2 keV
- Expected 95 % $\mathrm{CL_s}$ limit for chameleon photon coupling calculated with `TLimit` is $\beta_\gamma \leq 5.6 \times 10^{10}$
- First detector at CAST to get below upper bound on β_γ given by solar luminosity $\rightarrow$ Ready for discovery!
- Data has been unblinded: No chameleons found ☹
- Soon: Final observed limit
- Improved InGrid based X-ray detector to be installed this year
- Continue hunt for Solar chameleons with increased sensitivity!



Questions?

Backup Slides

Variables entering likelihood – Definition



Eccentricity:

$$\frac{\text{RMS along short axis}}{\text{RMS along long axis}}$$

Length/RMS:

$$\frac{\text{length along long axis}}{\text{RMS along short axis}}$$

Fraction within RMS:

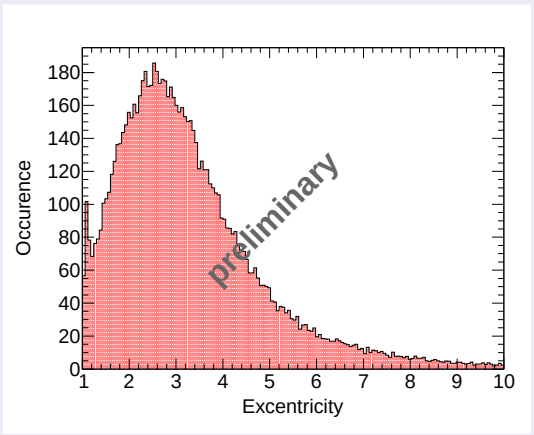
$$\frac{\text{pixels within radius of RMS}^{*}}{\text{all pixels in cluster}}$$

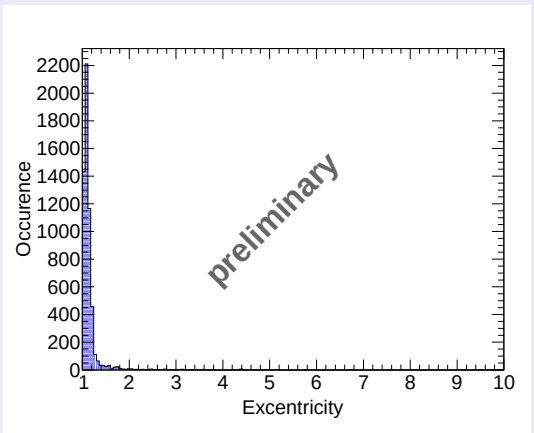
* along short axis

Variables entering likelihood – Background & Reference

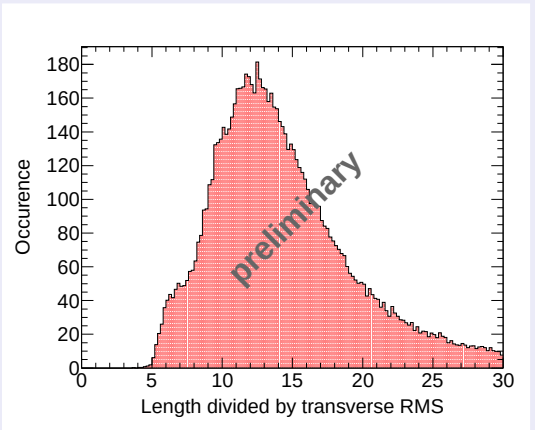
$E > 6.9\,\text{keV}$ – Copper K_α line

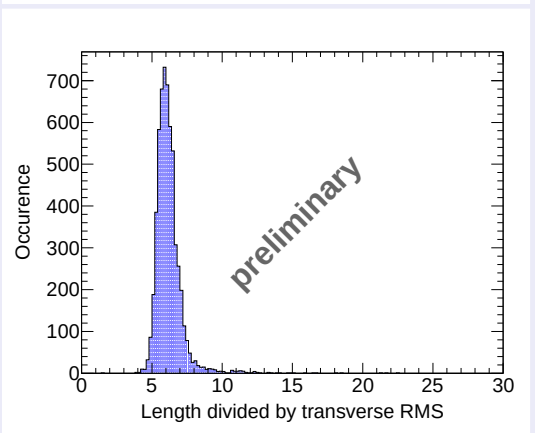
Eccentricity



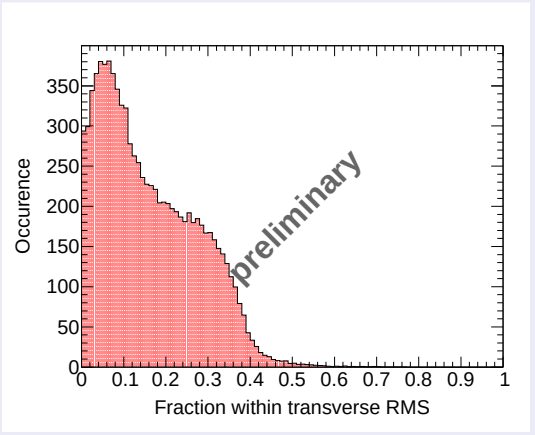


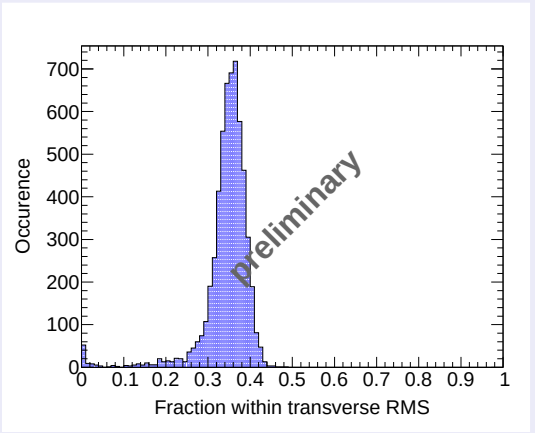
Length/RMS





Fraction within RMS

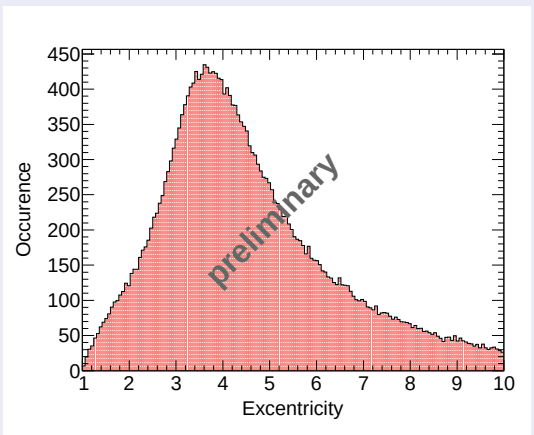


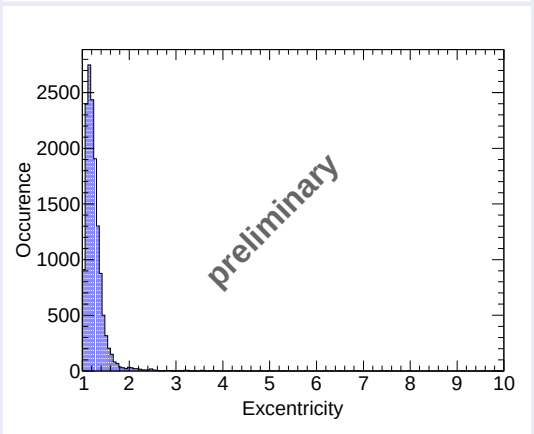


Variables entering likelihood – Background & Reference

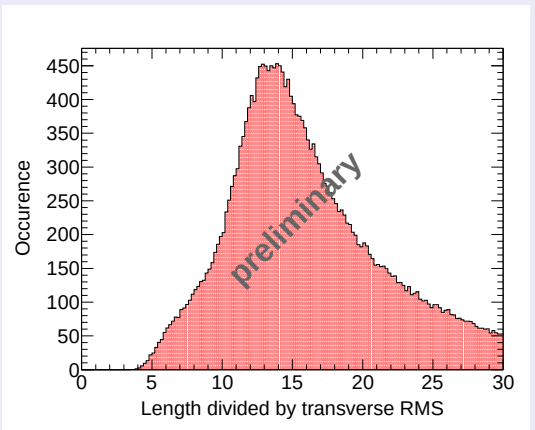
$1.2\,\text{keV} < E < 2.1\,\text{keV}$ – Aluminium K_α line

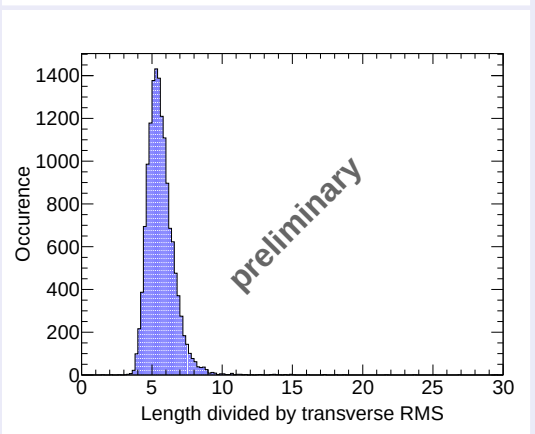
Eccentricity



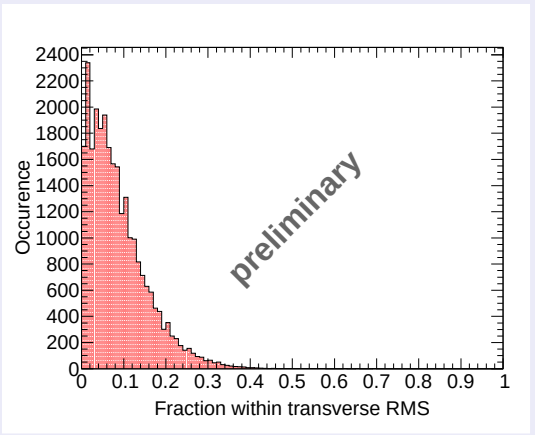


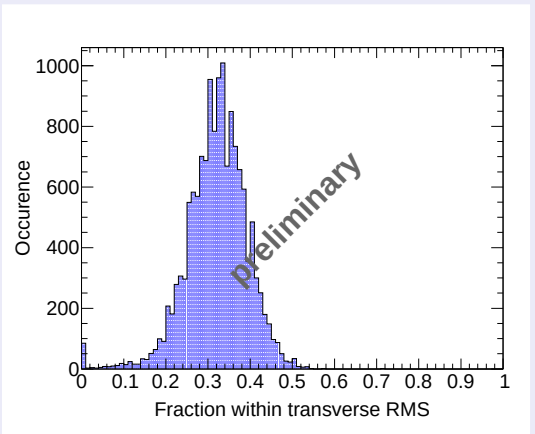
Length/RMS





Fraction within RMS

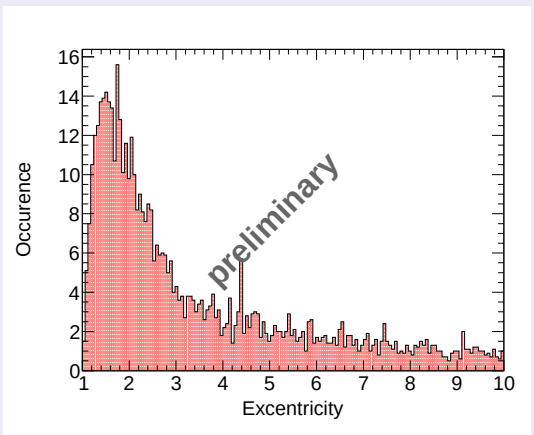


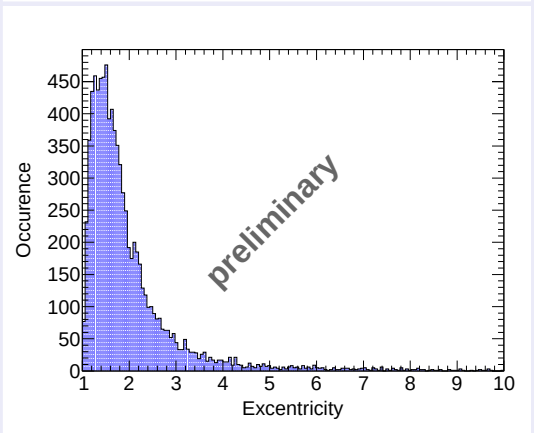


Variables entering likelihood – Background & Reference

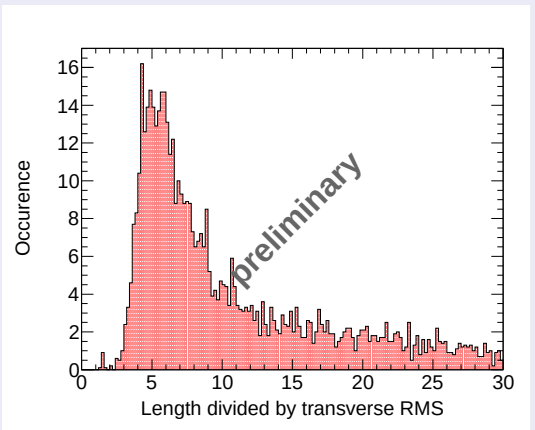
$E < 0.4\,\text{keV}$ – Carbon K_α line

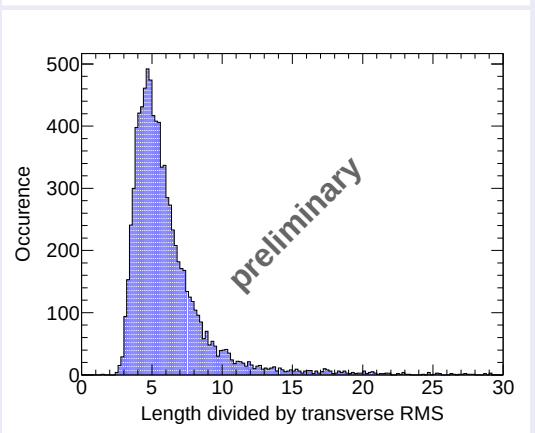
Eccentricity



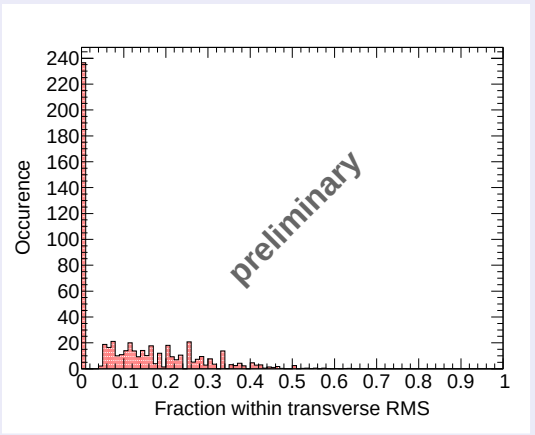


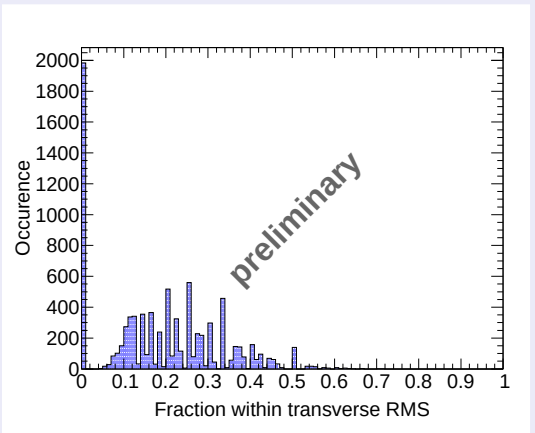
Length/RMS



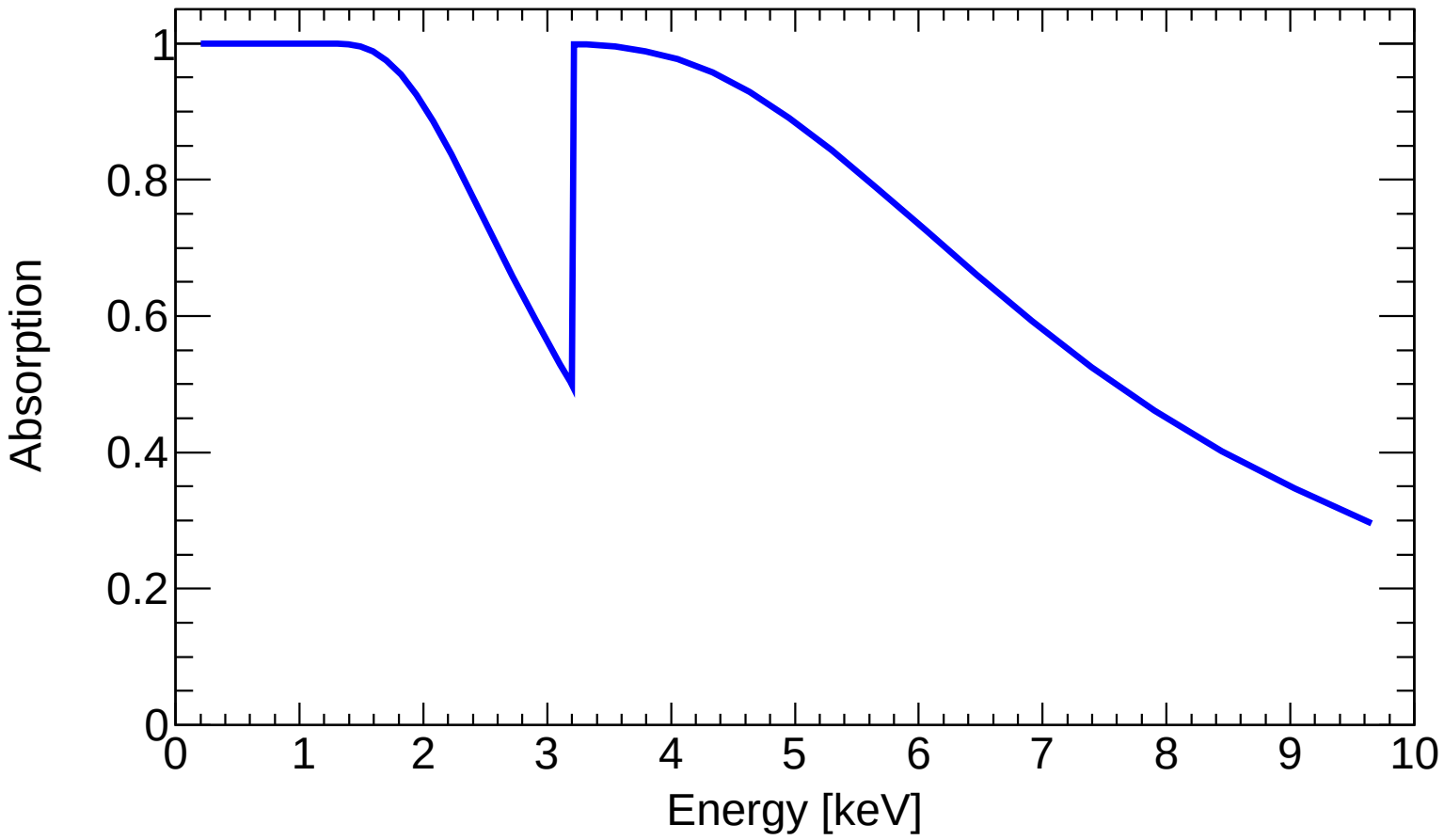


Fraction within RMS

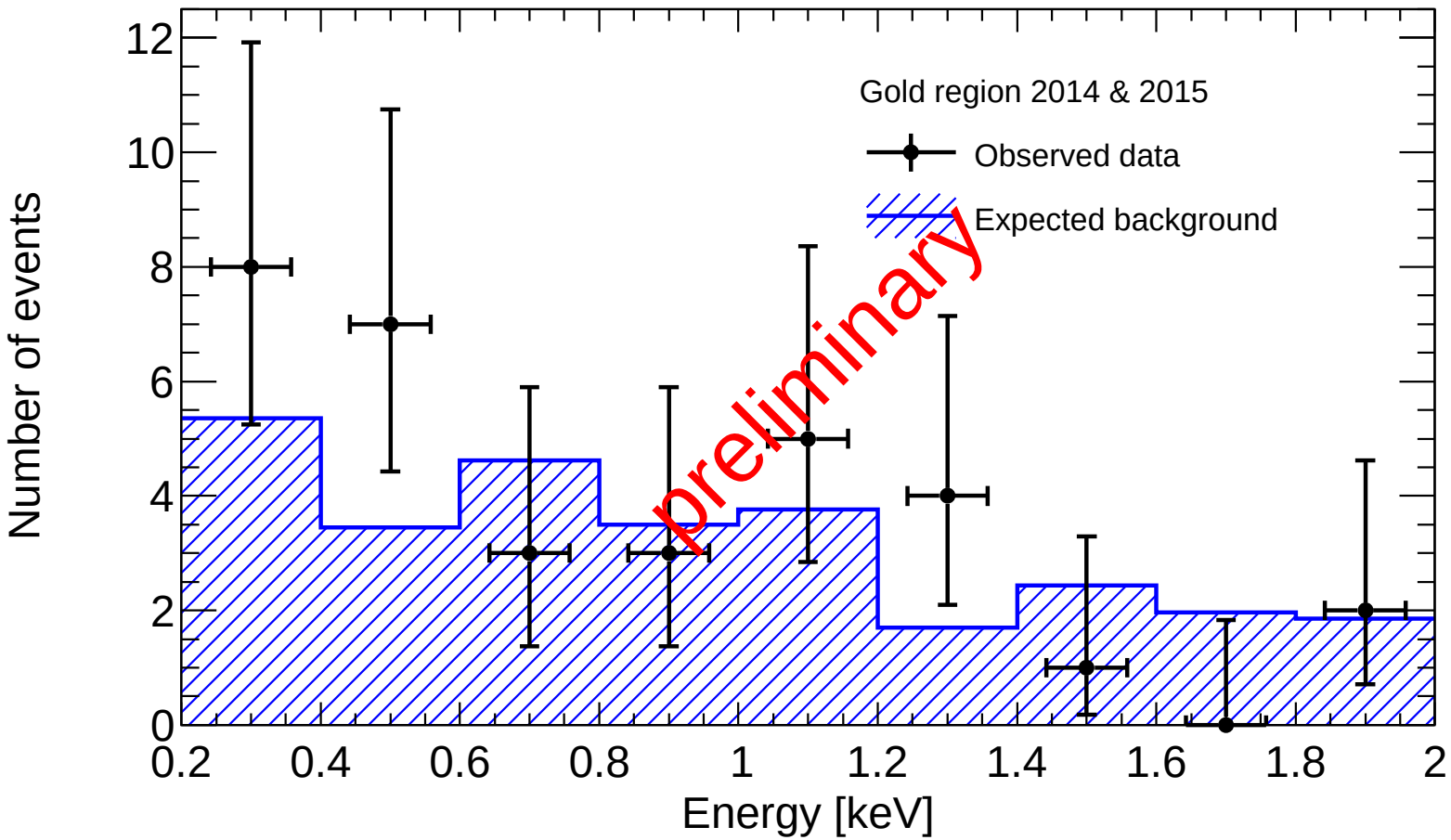




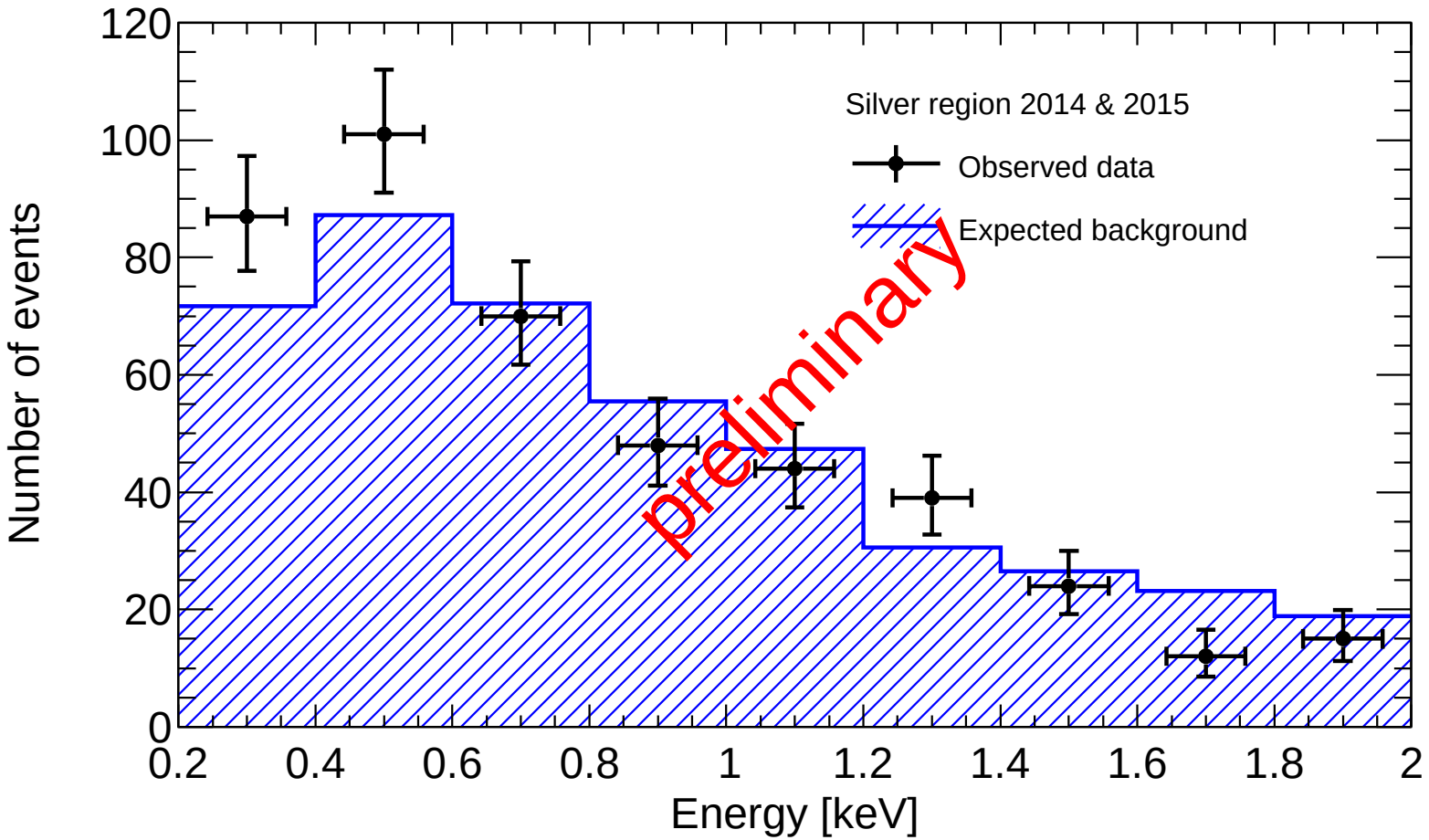
X-ray absorption in 3 cm Argon at 1050 mbar



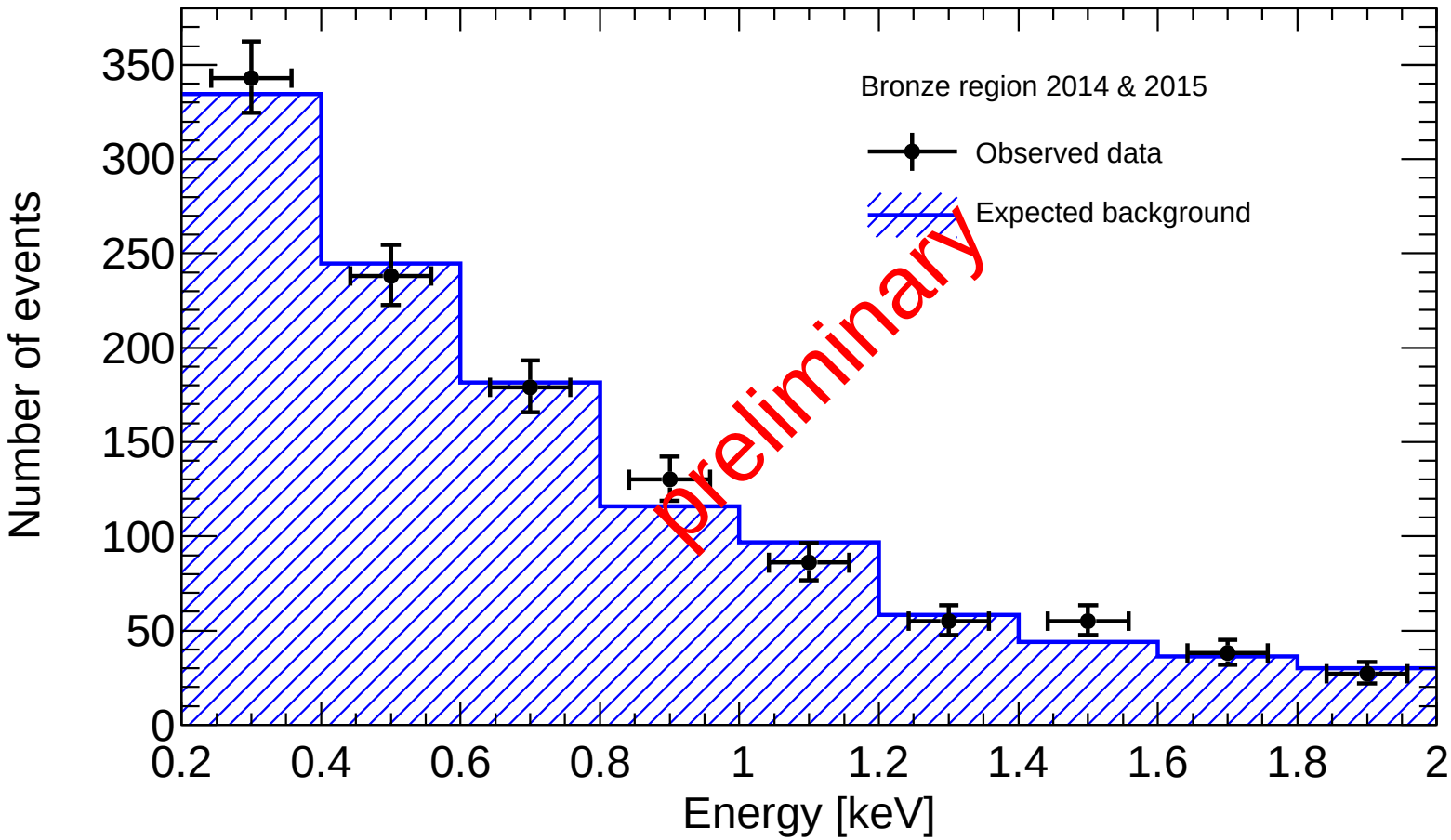
Unblinding the data



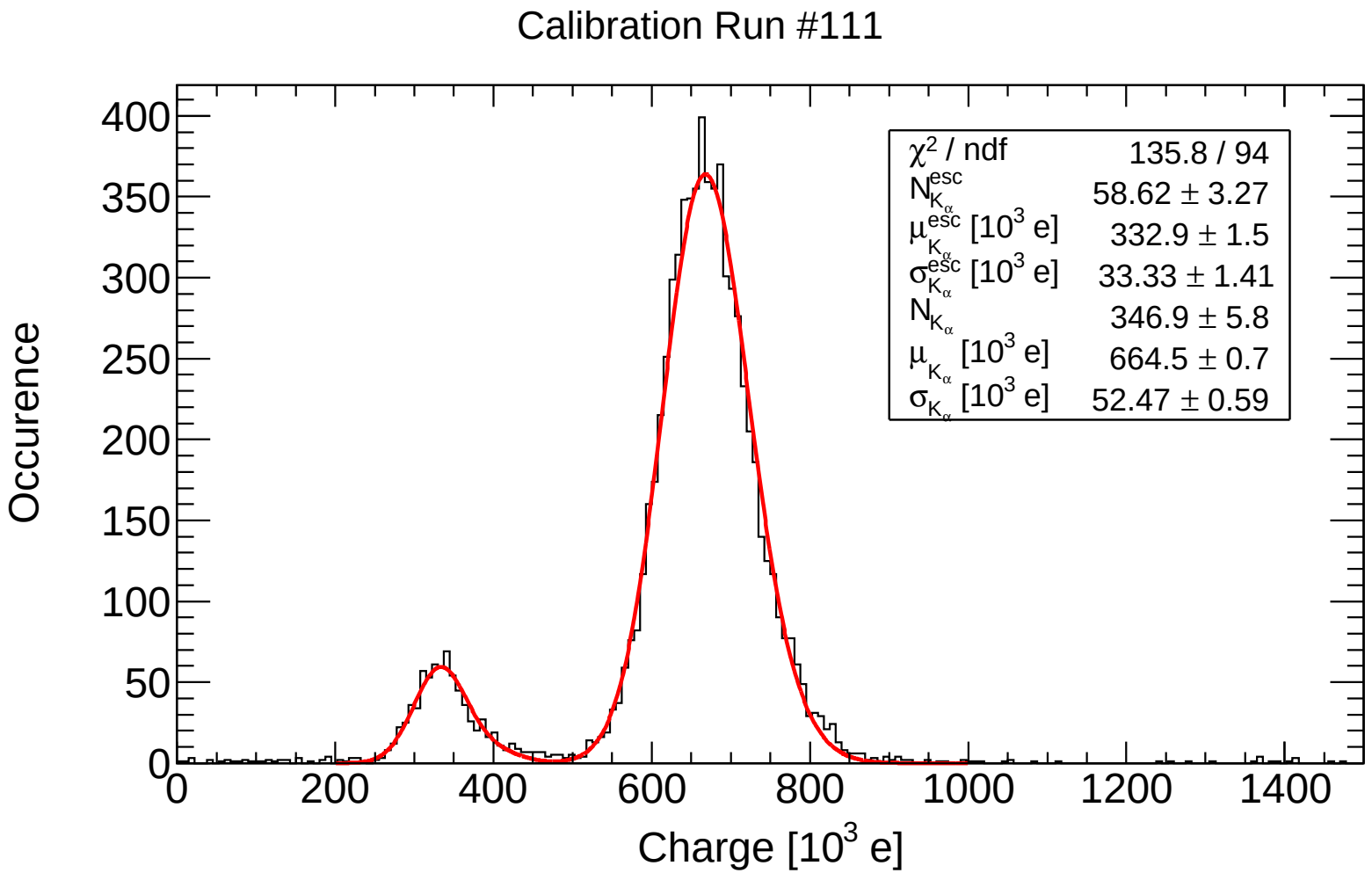
Unblinding the data



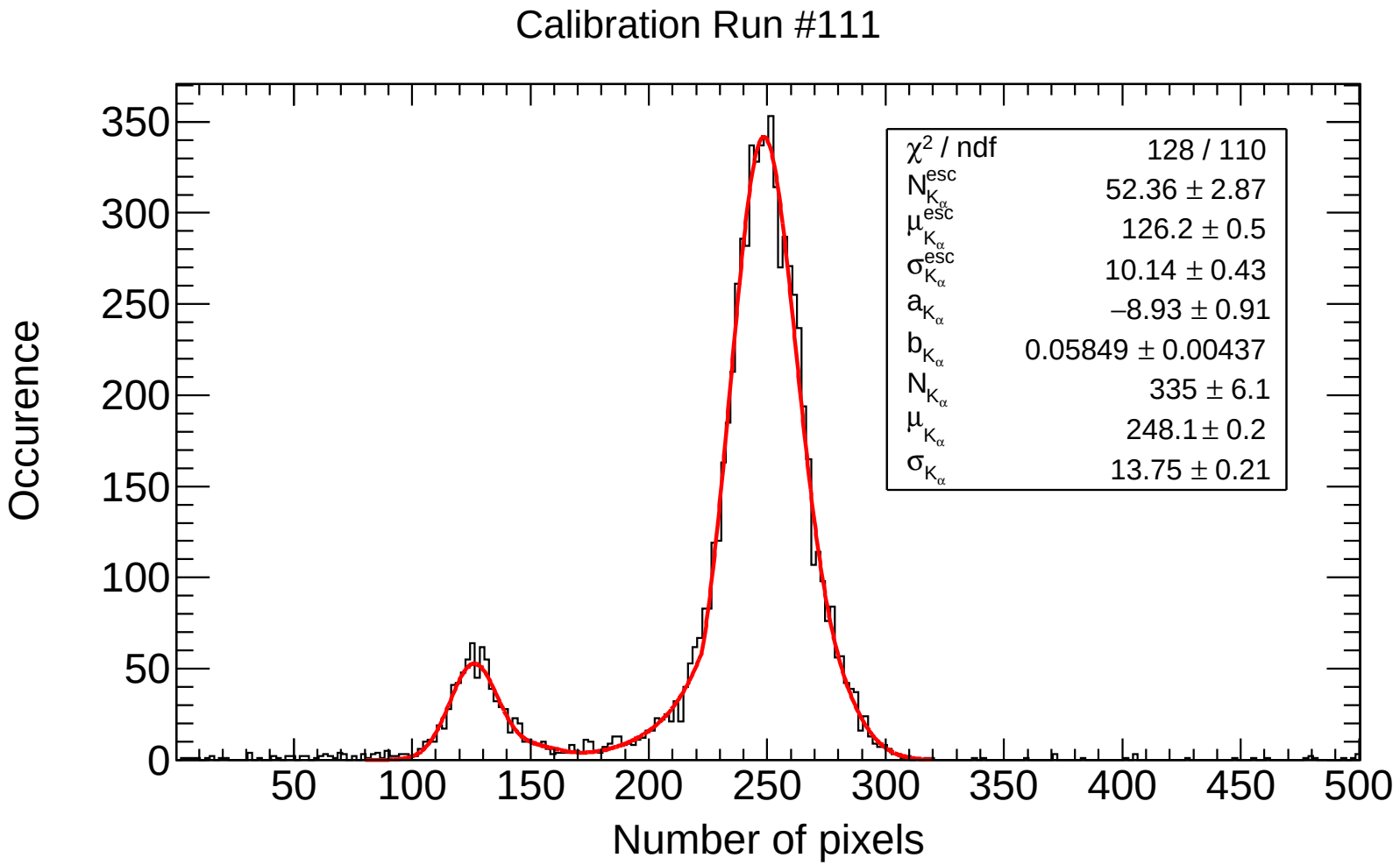
Unblinding the data



Calibration measurements with ^{55}Fe source



Calibration measurements with ^{55}Fe source



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