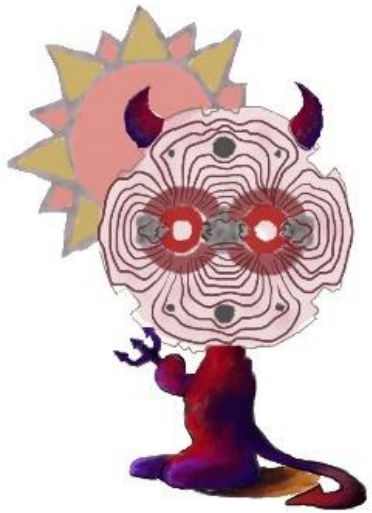
Search for solar chameleons with a GridPix detector at the CAST experiment



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University of Bonn

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On behalf of the CAST collaboration

14th Patras Workshop on Axions, WIMPs and WISPs

18th – 22nd June 2018

DESY Hamburg

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Dark Energy & Chameleons

Dark Energy & Chameleons

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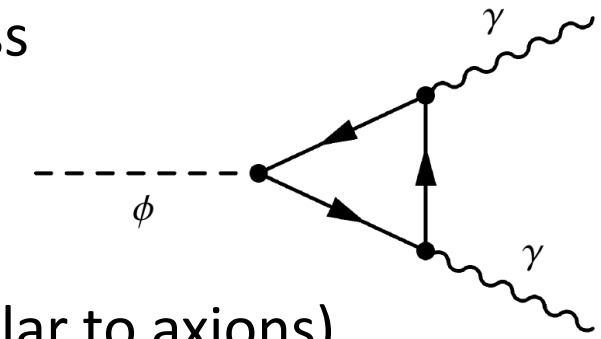
- Scalar field interacting with matter to model Dark Energy potential
- Introduction of new scalar particle

Phys. Rev. Lett. 93 (2004) 171104
Phys. Rev. D 69 (2004) 044026

- Screening mechanism to avoid unnatural effects (e.g. long range fifth force)
- Chameleon screening: (energy) density dependent effective mass
- Effective photon coupling can be introduced
- Matter & photon coupling: β_m & β_γ



- Chameleons can be produced through Primakoff-like effect (similar to axions)
- Photons can be converted into chameleons in strong magnetic fields of solar tachocline region (thin shell at 0.7 $R_\odot$ with $B_{max} \approx 10$ T caused by diff. rotation)
- Solar chameleon flux peaks below 1 keV (temperature at tachocline)
- Axion helioscopes could be used to detect solar chameleons

Phys. Rev. D 82 (2010) 043007
Phys. Rev. D 85 (2012) 043014

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The CERN Axion Solar Telescope

The CERN Axion Solar Telescope

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- Axions/chameleons produced in the Sun
- Reconversion to X-ray photons in strong *B* field

axions/chameleons

- Decommissioned LHC prototype dipole magnet (10 m long, 9 T, 1.8 K)
- Movable structure:
  Vertical ~±8°
  Horizontal ~±40°
- Sun can be tracked during sunrise & sunset
  (2x 1.5 h per day)

CAST Physics Program

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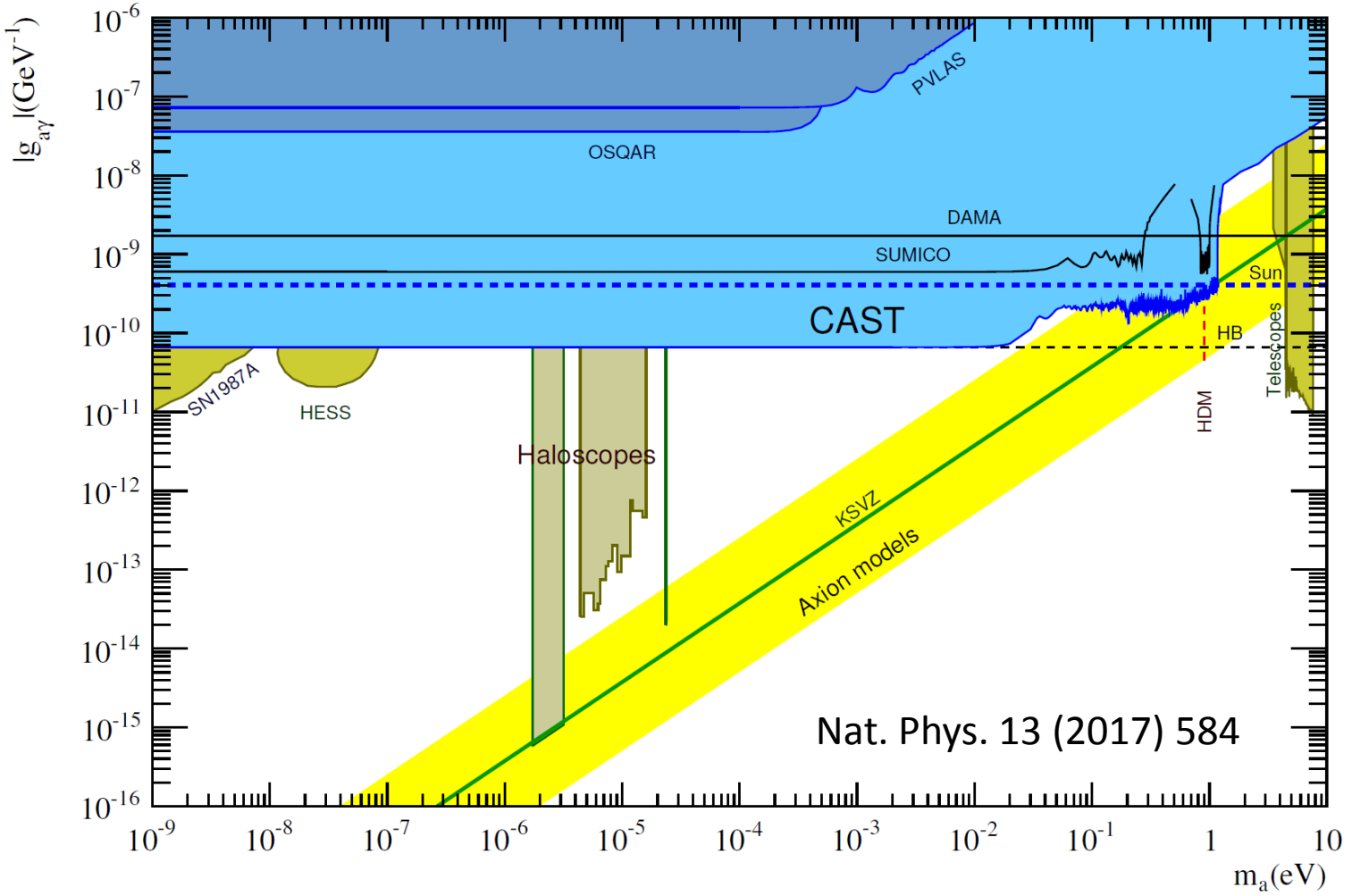
- CAST first proposed in 1999
- Solar axion search 2003 to 2015
- CAST has achieved world-leading result on solar axions

Current physics program:

- KWISP (chameleon search with force sensor)
- CAST-CAPP (relic axion search)
- RADES (cavity R & D)
- GridPix detector
  (solar chameleon search
  → first results in this talk)



CAST's First Chameleon Search

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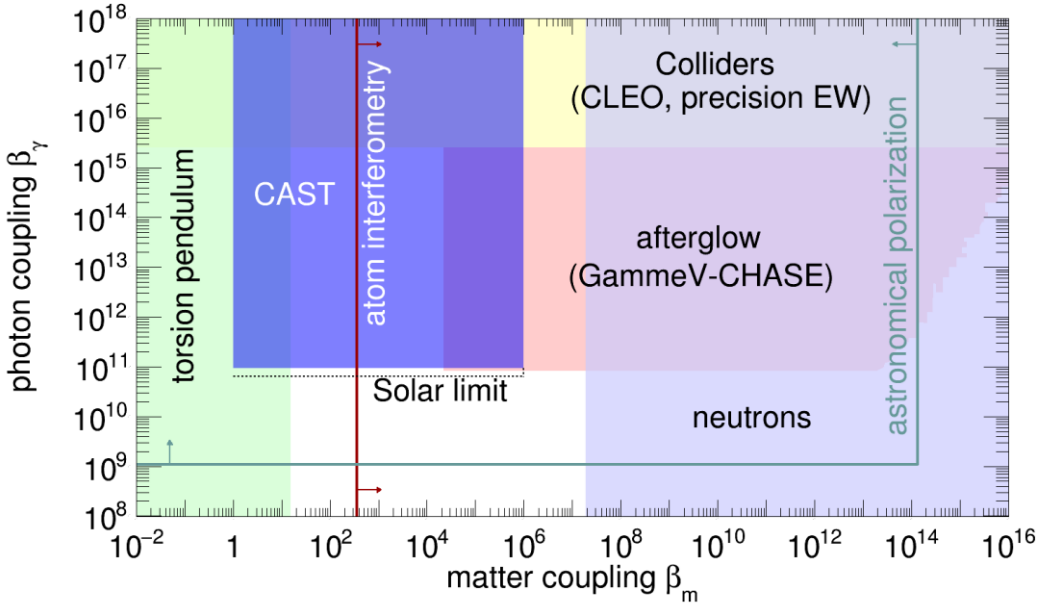
- Silicon Drift Detector (SDD) built from commercially available detector components
- Used for solar chameleon search end of 2013
- Could set limit: $\beta_\gamma \leq 9.3 \cdot 10^{10}$ at 95 % CL (Phys. Lett. B 749(2015), 172)
- But still above upper limit given by solar luminosity ($\mathcal{L}_{\text{Sun}}^{\text{chameleon}} \leq 10\,\% \cdot \mathcal{L}_{\text{Sun}} \rightarrow \beta_\gamma \leq 10^{10.81} \approx 6.5 \cdot 10^{10}$)



To be continued…

- Expected signal $\sim \beta_\gamma^4$
- GridPix detector
- Lower background rate
- X-ray telescope
- Should pass solar luminosity bound

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The GridPix Detector

The GridPix Detector

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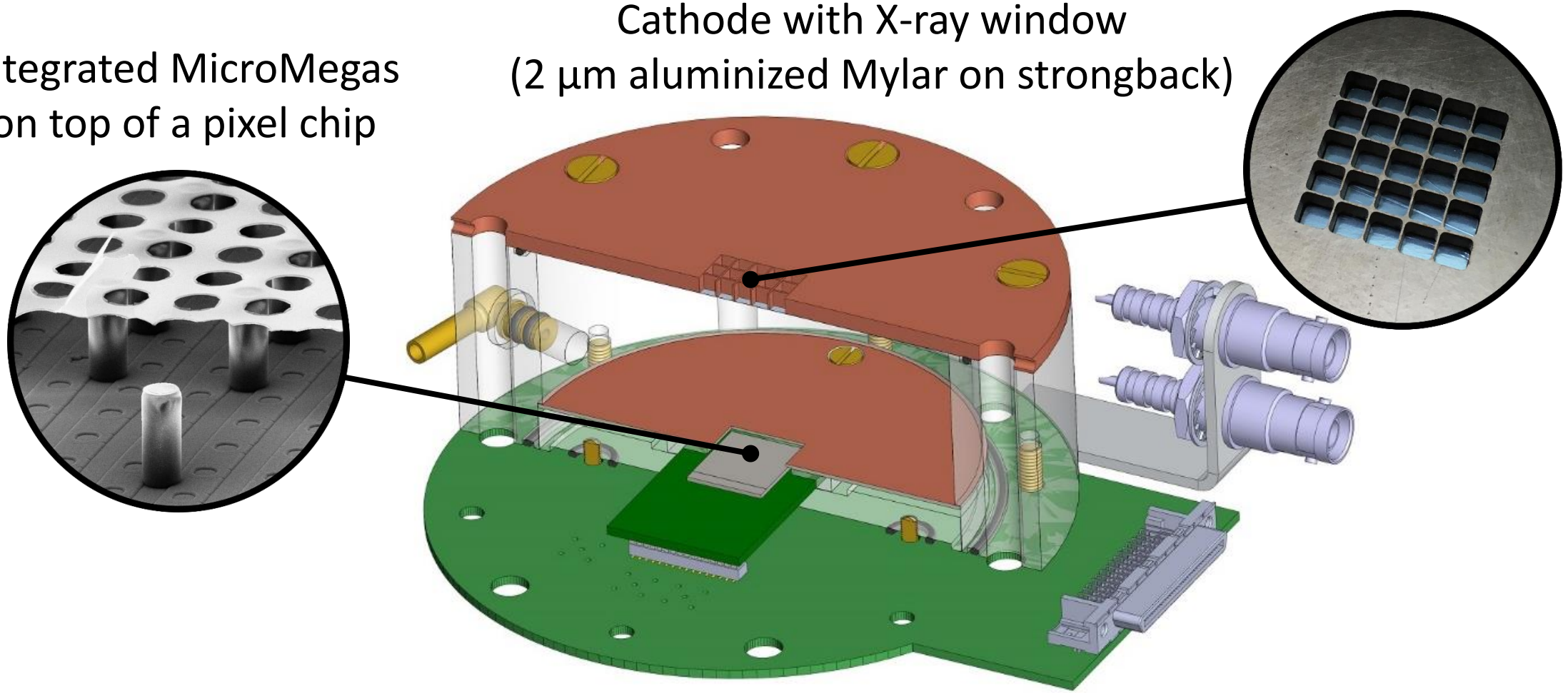
Integrated MicroMegas
on top of a pixel chip

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



Drift volume flushed with Ar/iC$_4$H$_{10}$ 97.7/2.3 @ 1050 mbar(a)

Typical events

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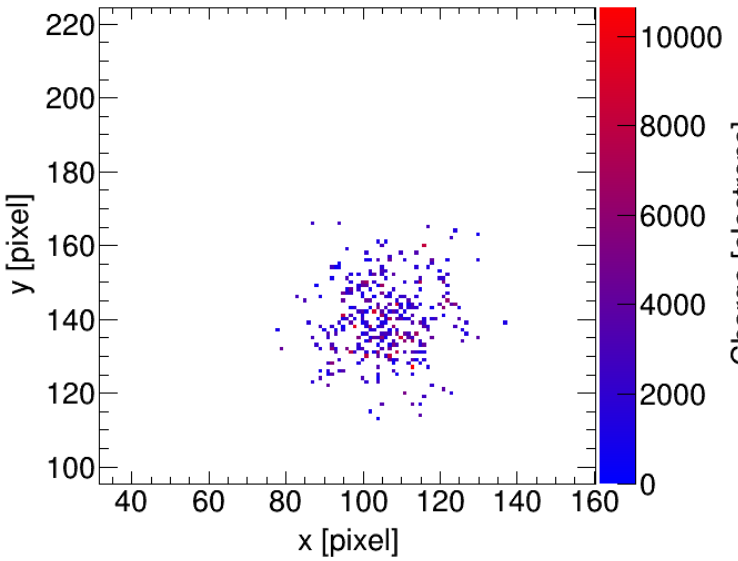
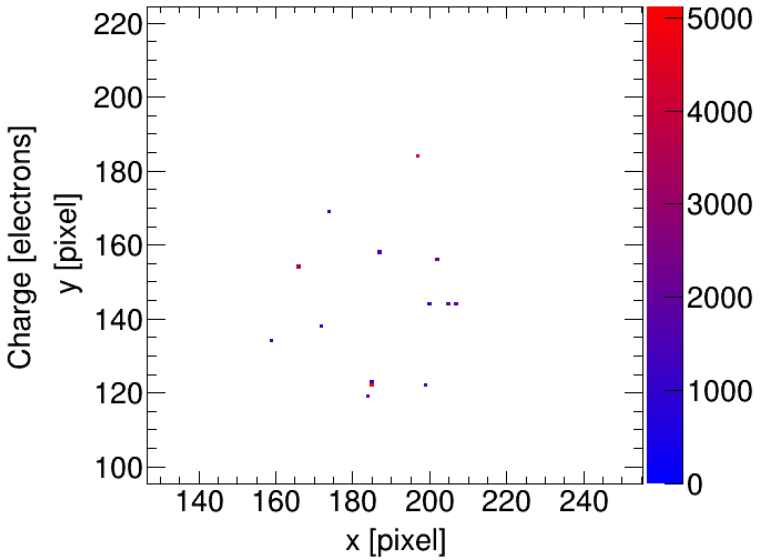
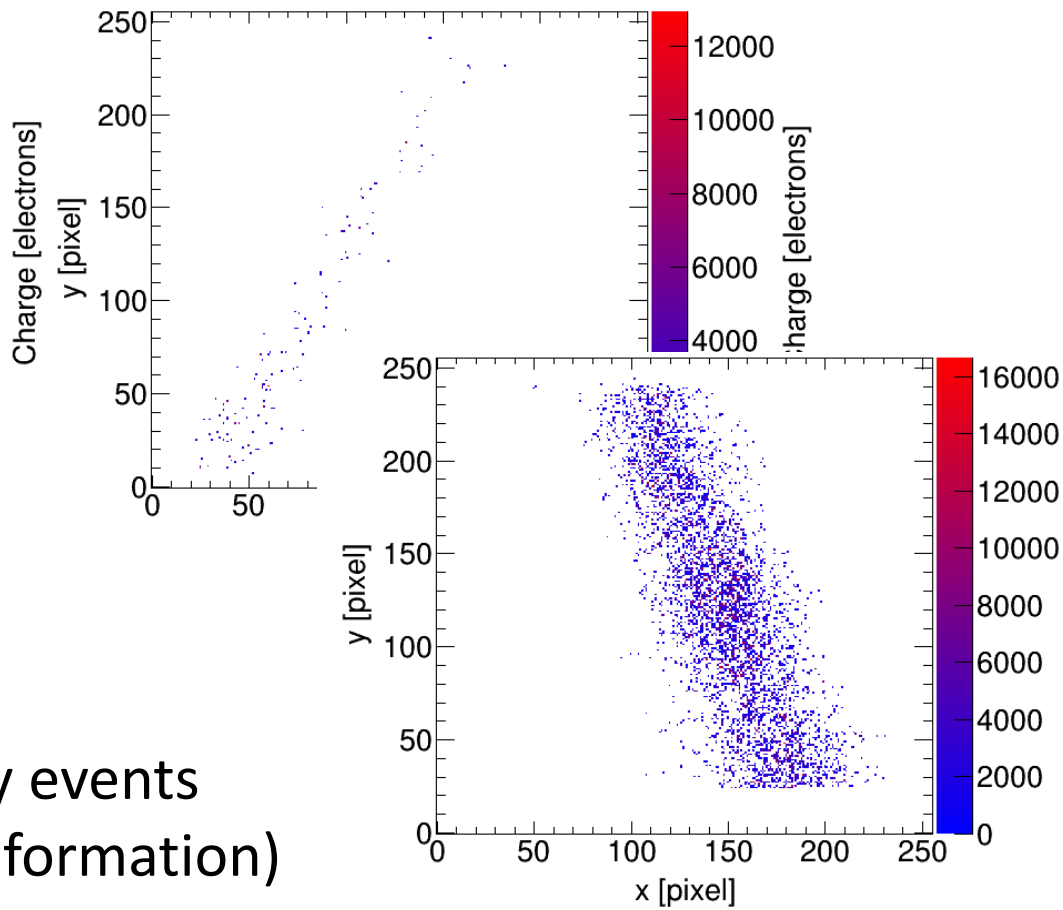
X-ray event (5.9 keV)



X-ray event (277 eV)



Non-X-ray events (e.g. cosmic or α)



- Each primary electron can be detected individually
- Low energy X-ray photons can be detected
- Event shape can be used for suppression of non-X-ray events
  (High spatial resolution gives benefit of topological information)

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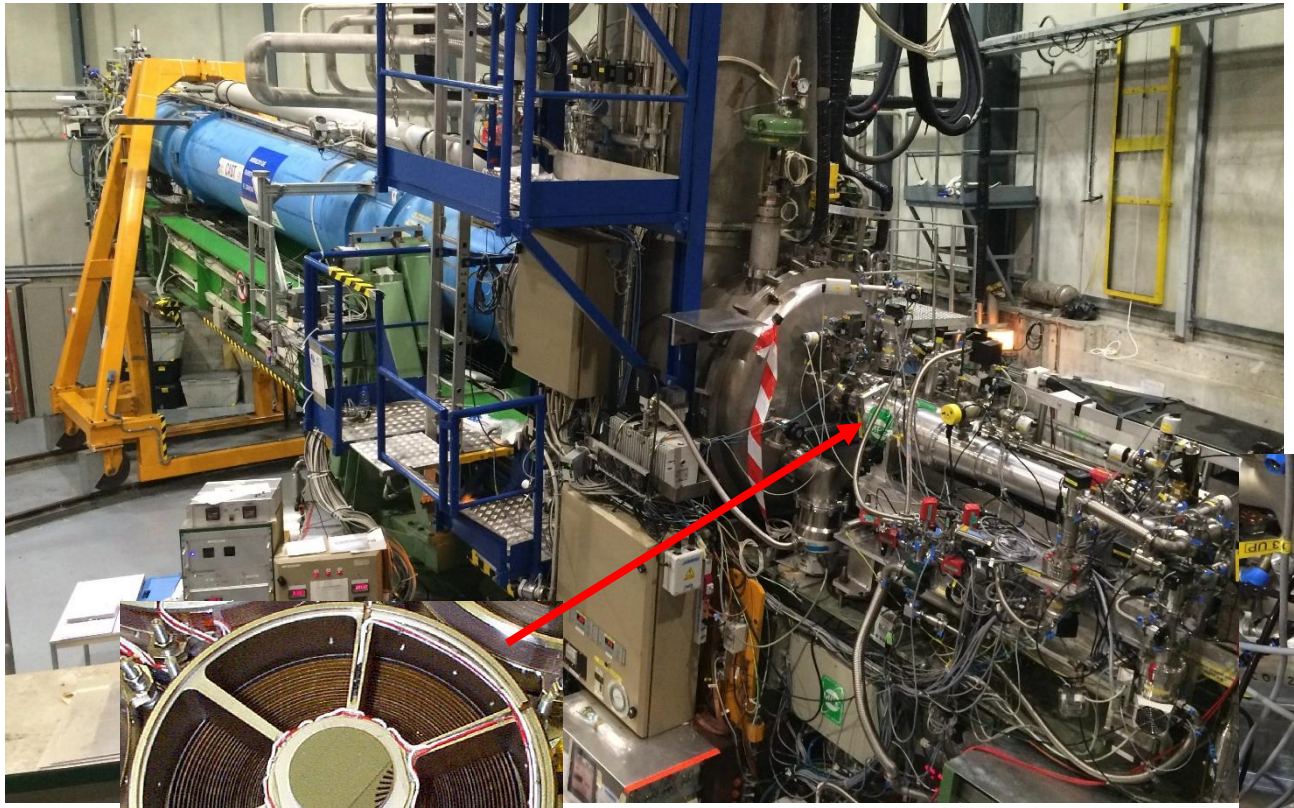
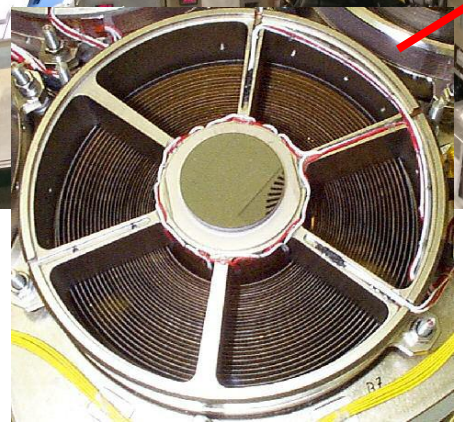
Operation at CAST

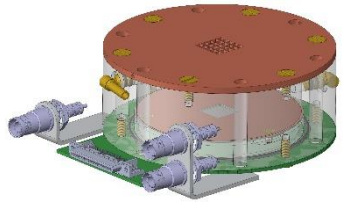
The GridPix Detector @ CAST



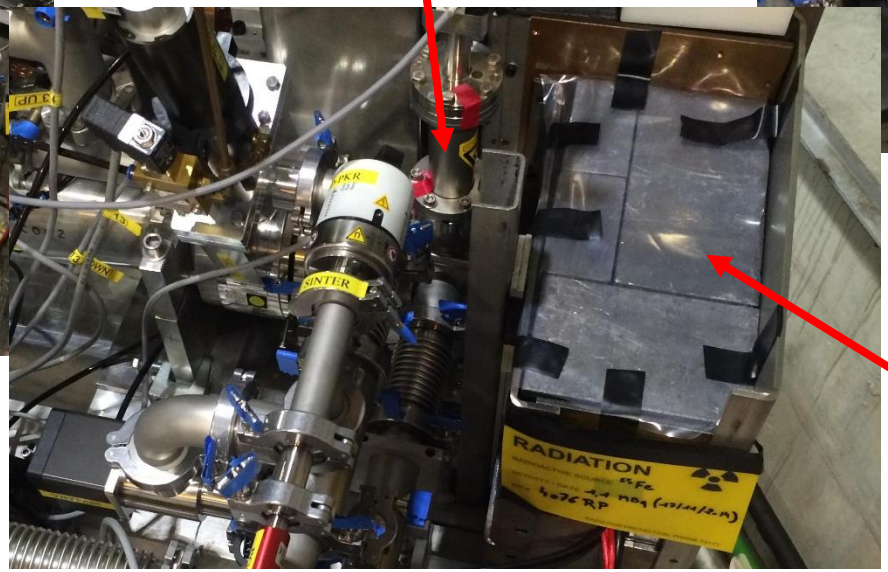


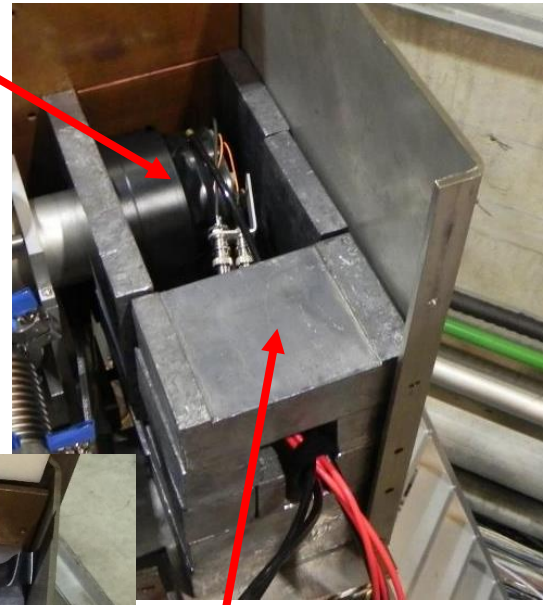
MPE X-ray telescope

GridPix detector



Calibration source (^{55}Fe)





Lead shielding

Operation at CAST

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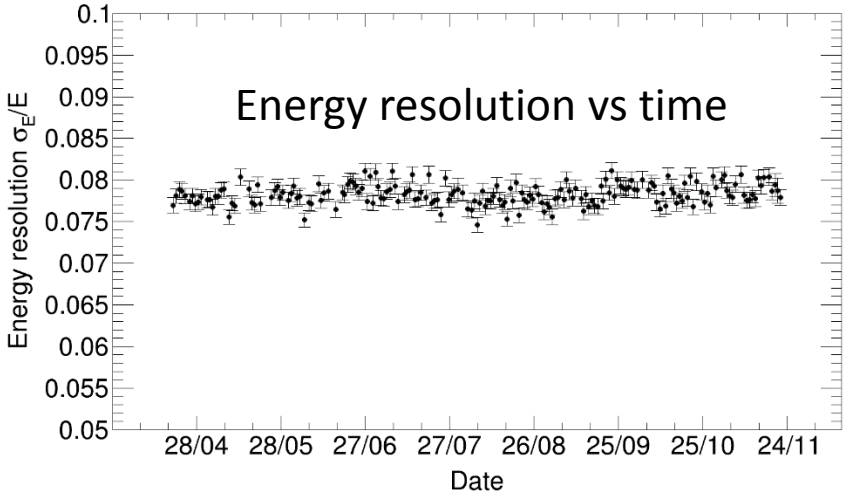
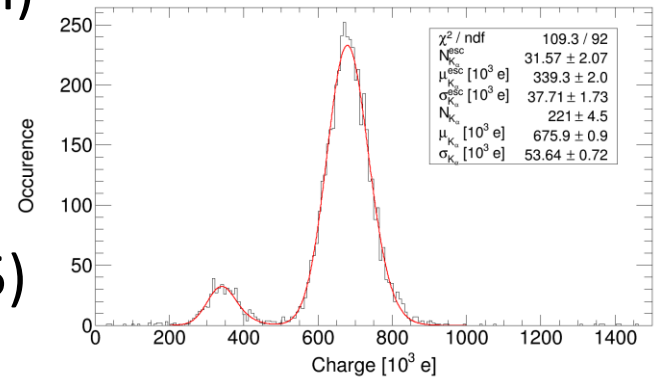
- Detector & infrastructure installed in October 2014
- Succesful operation until dismantling in November 2015
- Until then NO detector related stops or interruptions



Some numbers:

- Total numbers of frames recorded: 19,401,770 (each 0.98 s long, untriggered)
- Of these about 80 % are empty! (except for one known, 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 (installed in April 2015)



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Data Analysis - The Expected Background

Background Rate After Suppression

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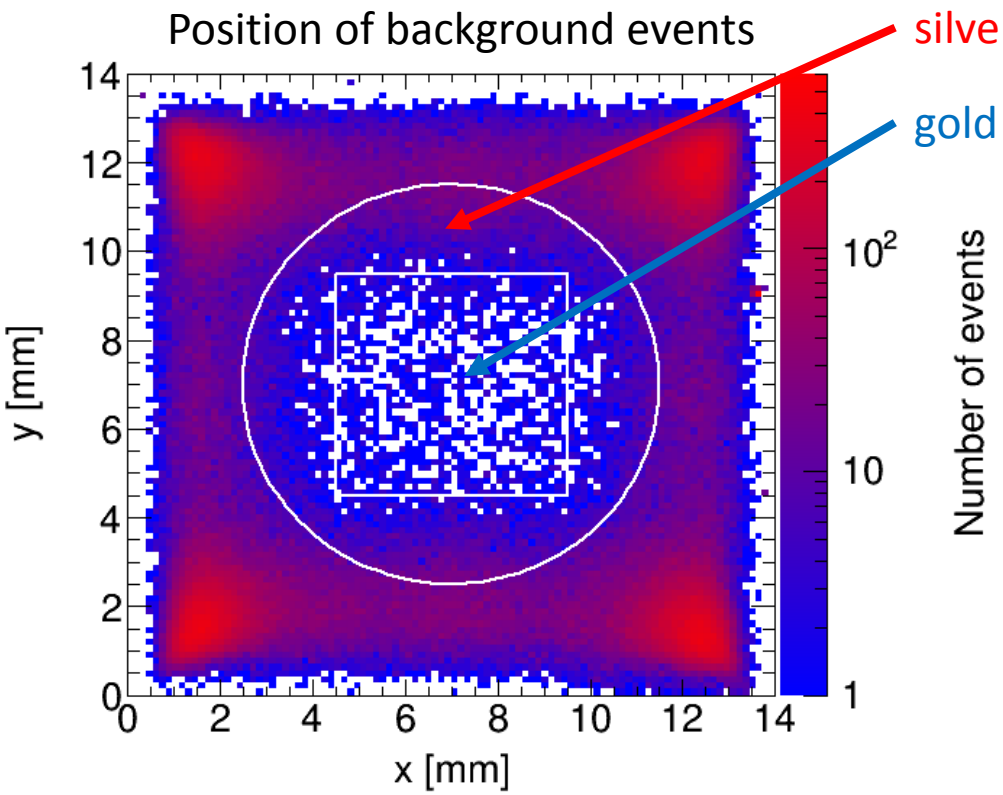
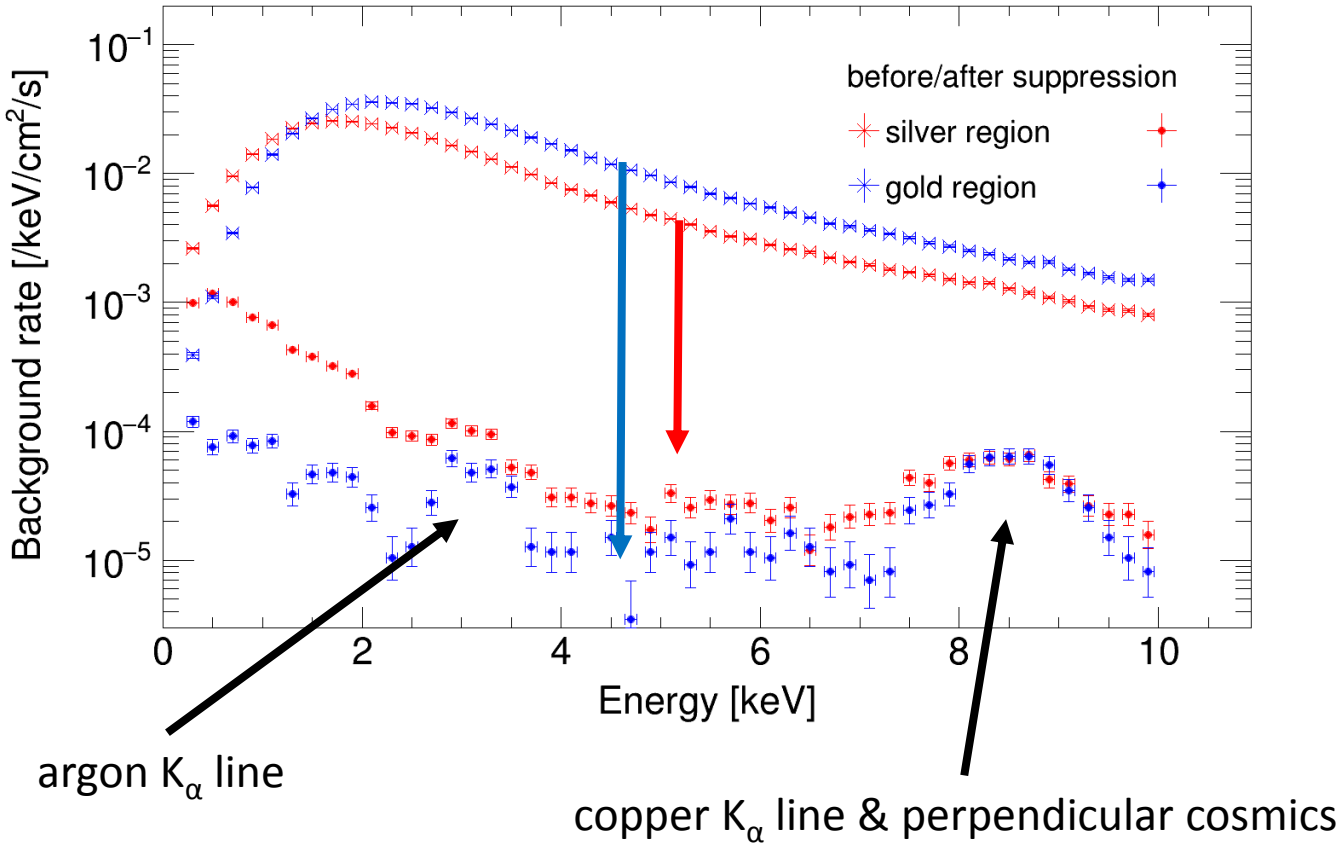
- Likelihood based background suppression using eventshape variables
- Background level much lower in chip center → split data in two regions: gold & silver
- Most probable: partially contained tracks at sides & corners; maybe also X-ray fluorescence





Expected Background

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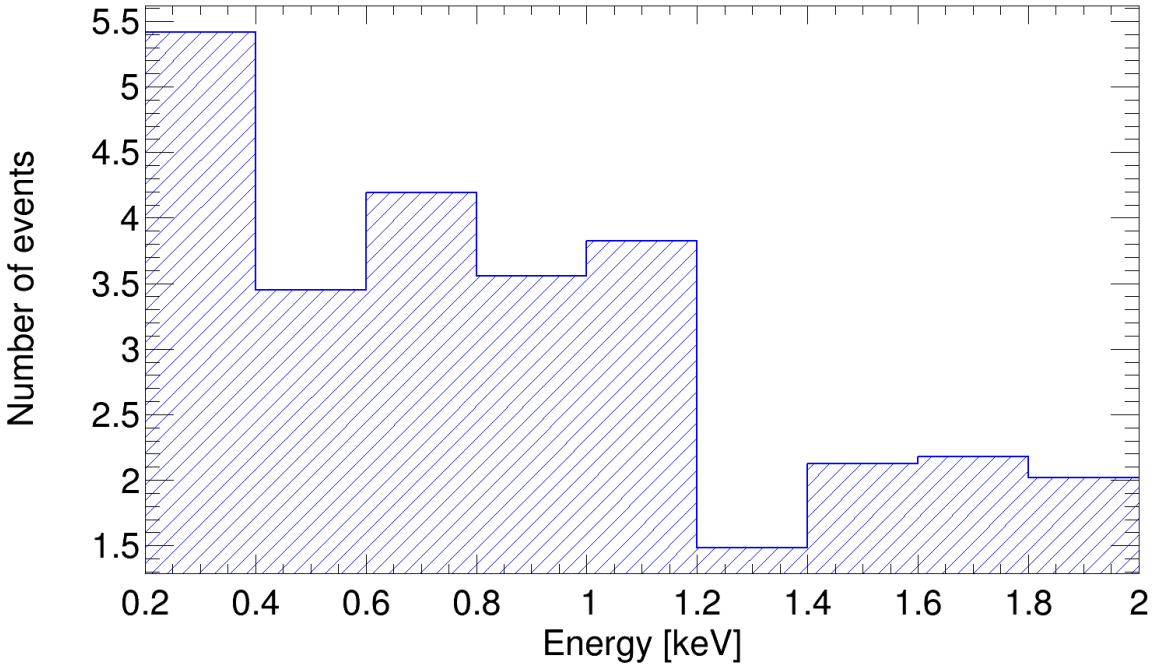
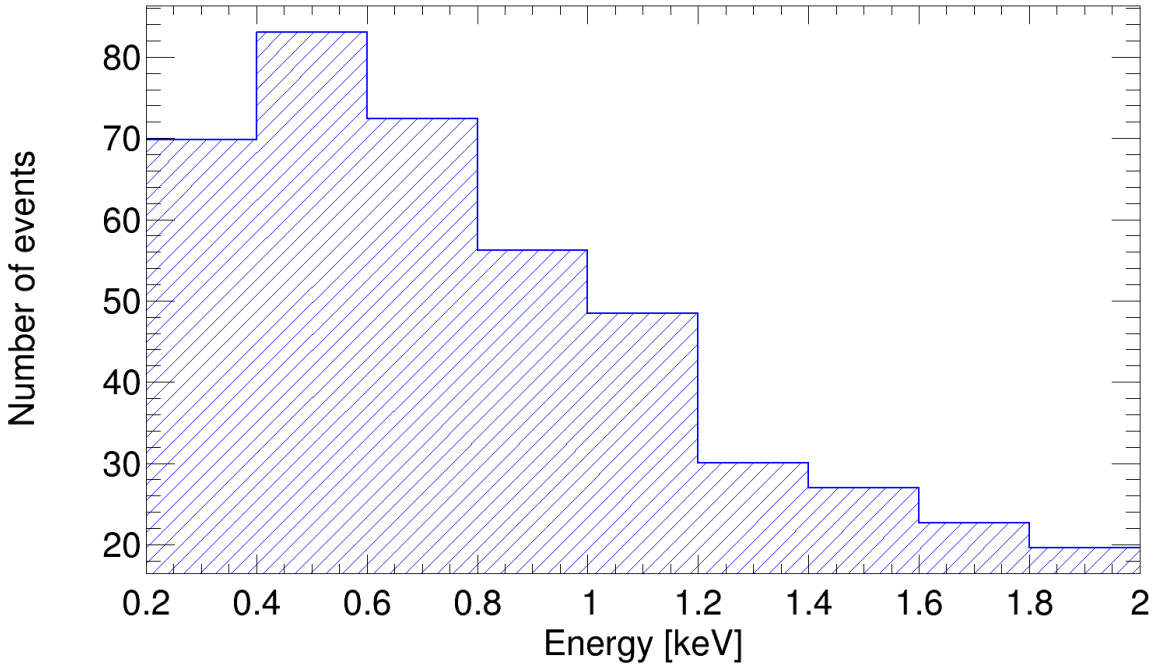
gold region



silver region



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Data Analysis - The Expected Chameleon Signal

Computing the Expected Signal

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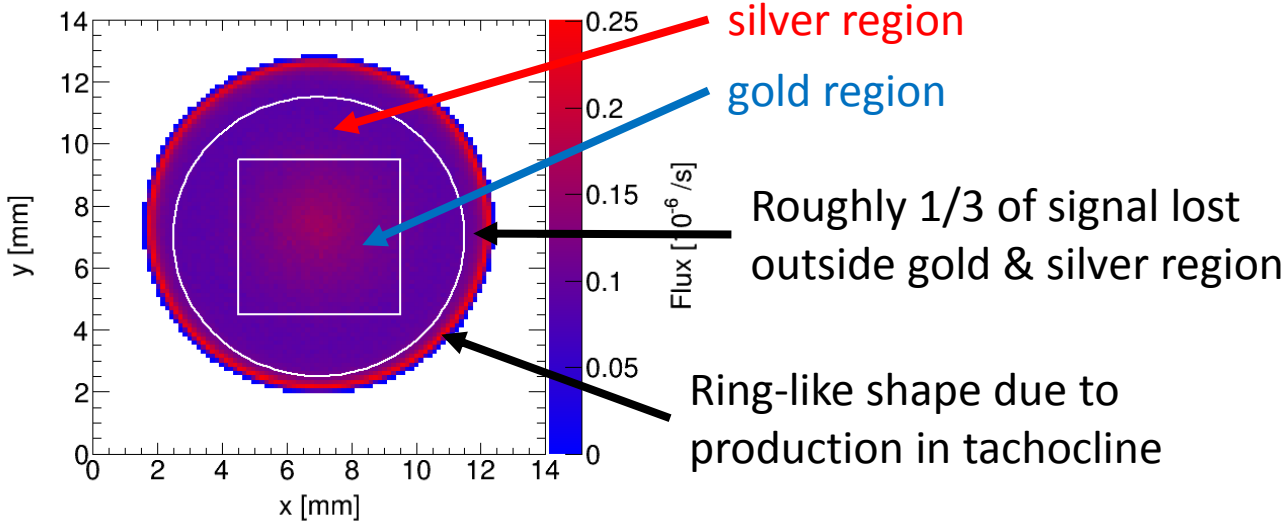
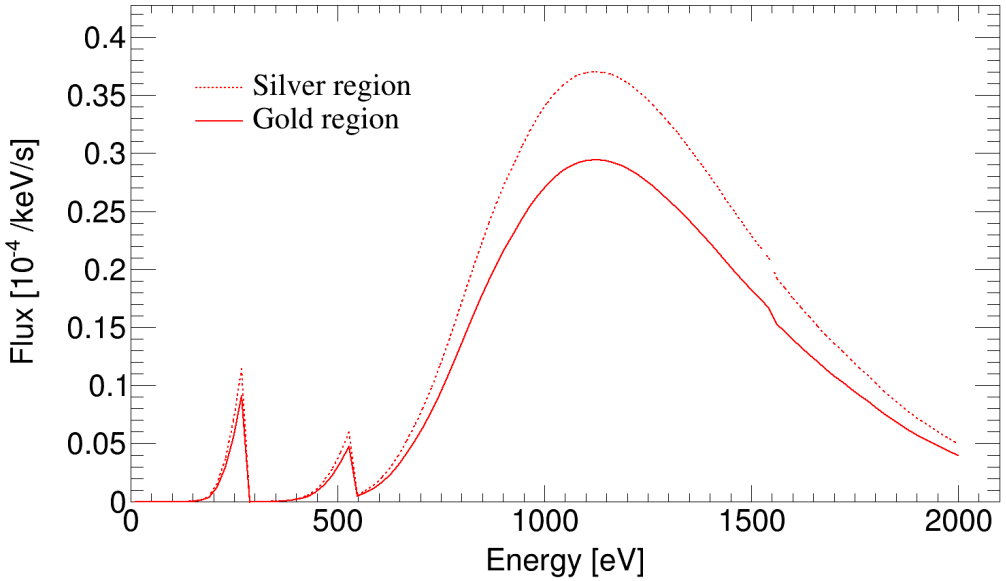
- Start with solar chameleon spectrum
- Take into account geometry of CAST magnet and reconversion to photons
- Fold with XRT transmission & off-axis behavior
- Simple raytracing simulation to get chameleon image of Sun
- Include detection efficiency (window transmission & absorption in 30 mm argon)
- Software efficiency of 80 %





Expected Signal

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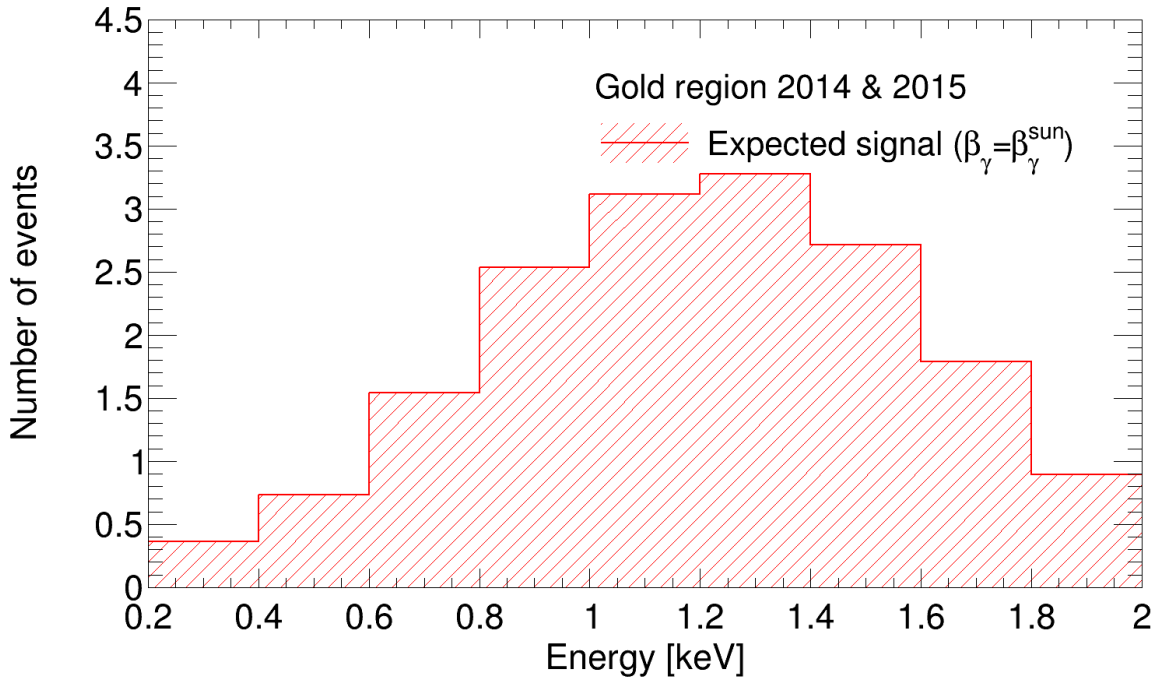
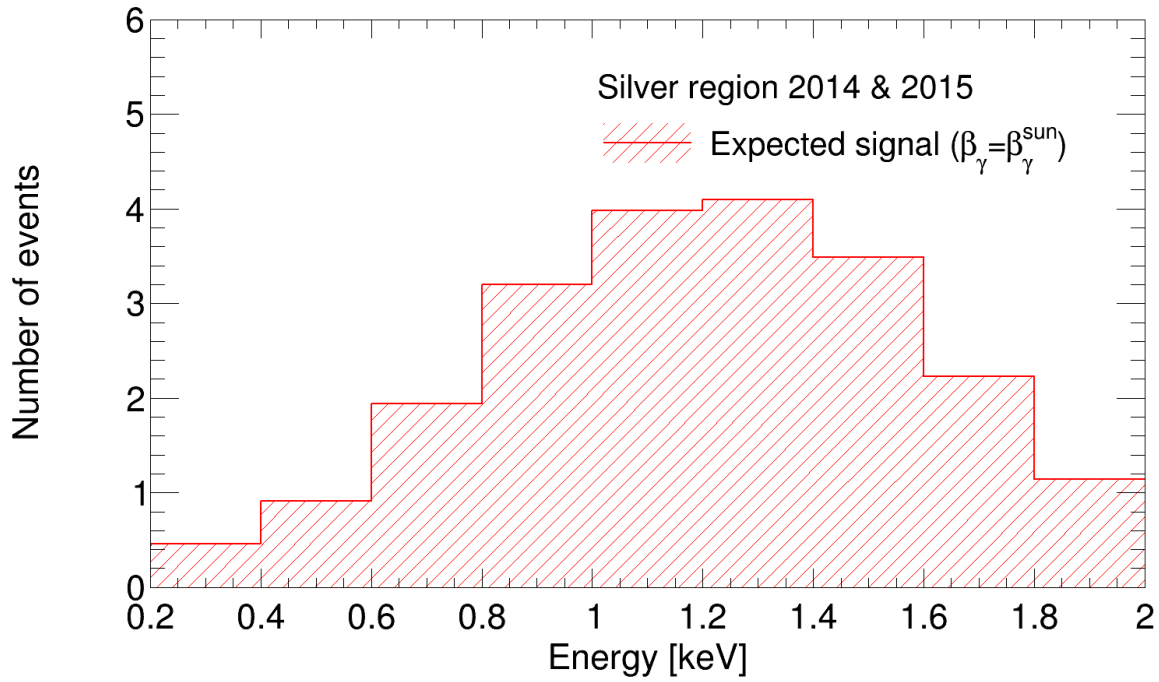
gold region



silver region



- Rescaling according to $\sim \beta_\gamma^4$ gives expected signal for different values of β_γ

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Data Analysis - Expected Sensitivity

Deriving the Expected Sensitivity

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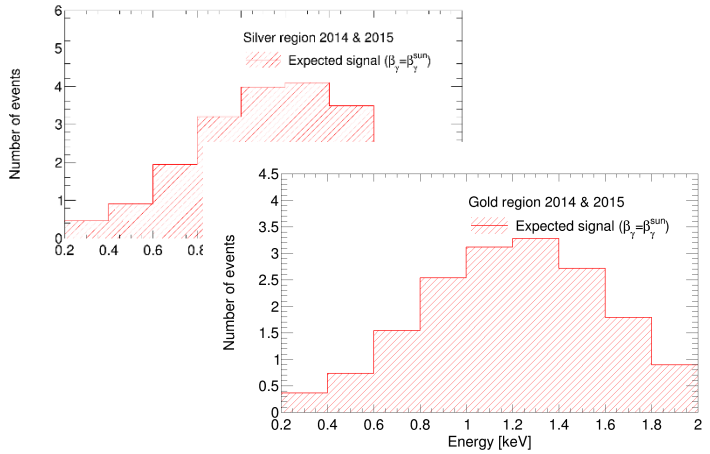
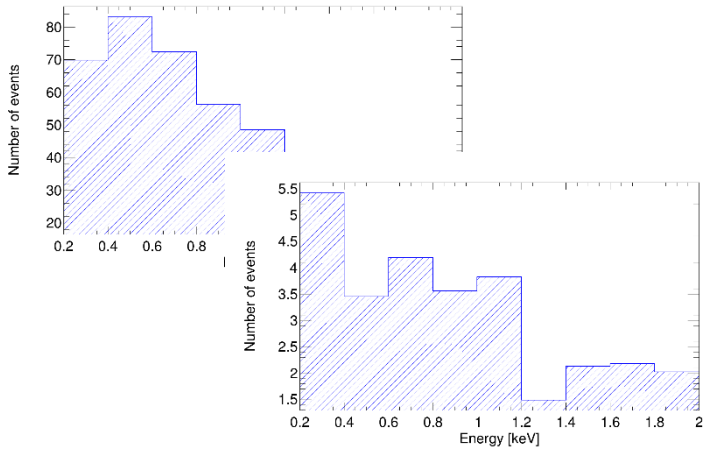
Expected signal



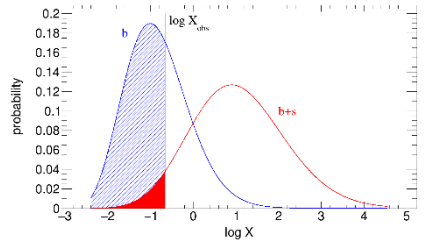
Expected background



- Use **`TLimit`** (**`ROOT`** implementation of **`mclimit`**) to compute confidence levels, especially CL_s and $< CL_s >_b$
- **`Tlimit`** applies the likelihood ratio method for small statistics
- Feed in expected signal and background histograms
- Estimated systematic uncertainties for expected signal
- Statistical bin errors for predicted background
- Vary until 1 - CL_s > 95 % is found

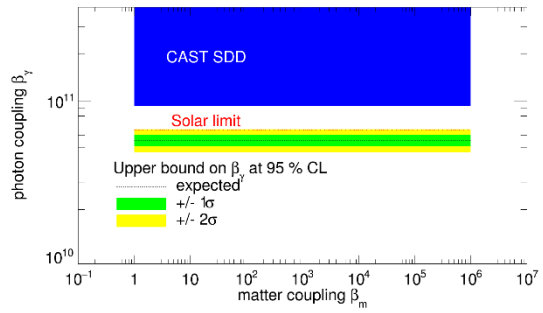
+ Syst. Uncert.

+Stat. Uncert.

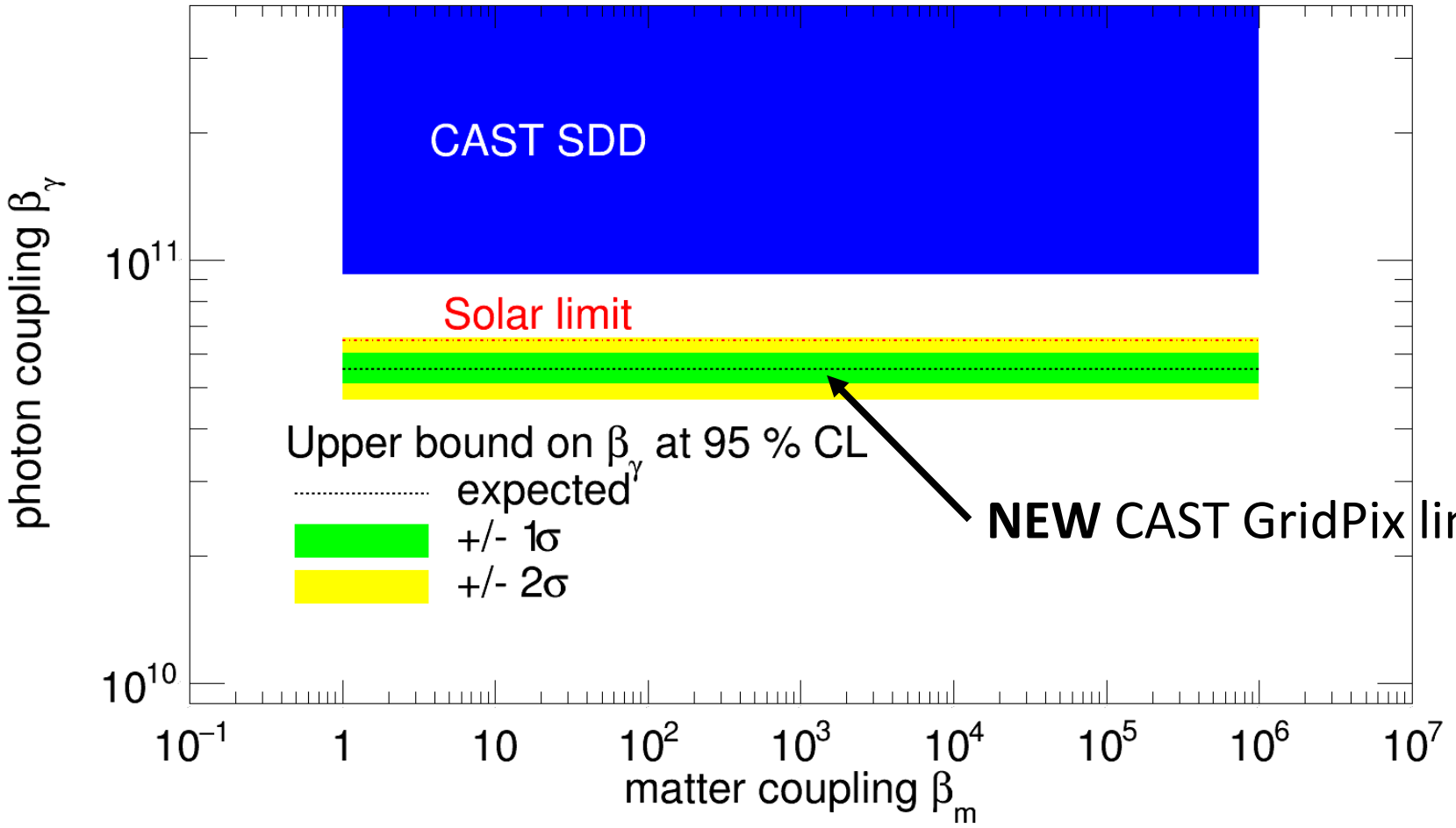


`TLimit`

Expected sensitivity



Expected Sensitivity



- Expected upper bound (absence of a signal): $\beta_\gamma \leq 5.53 \cdot 10^{10}$
- Below solar limit!
- Ready for unblinding!

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Data Analysis – Unblinding…

Unblinding the Data

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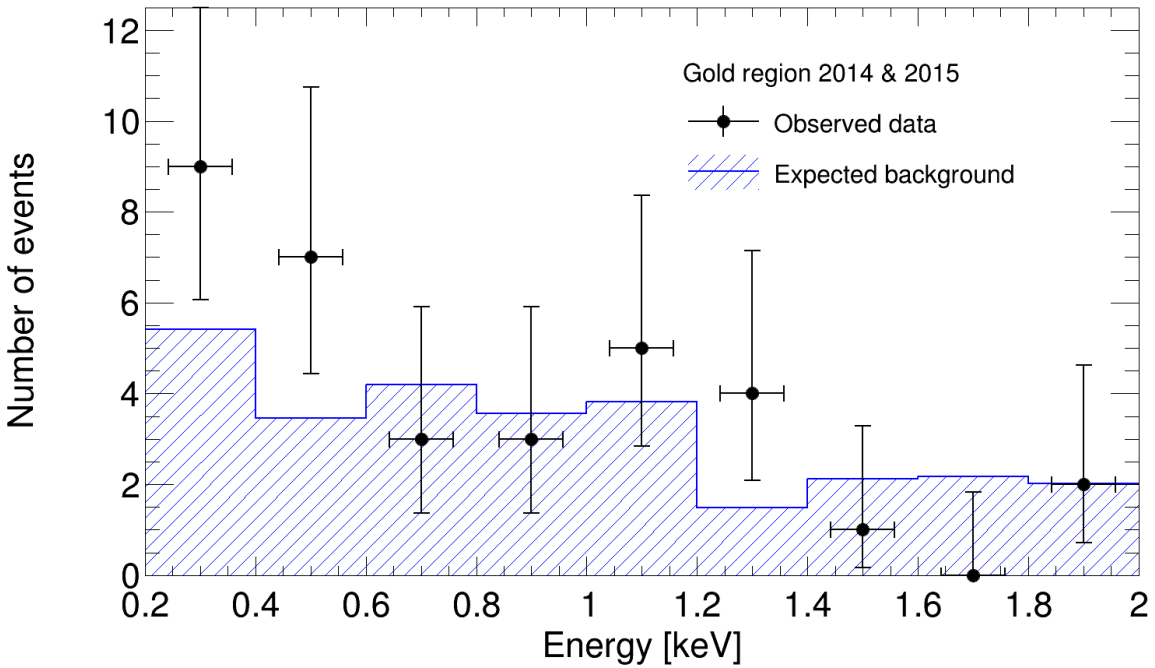
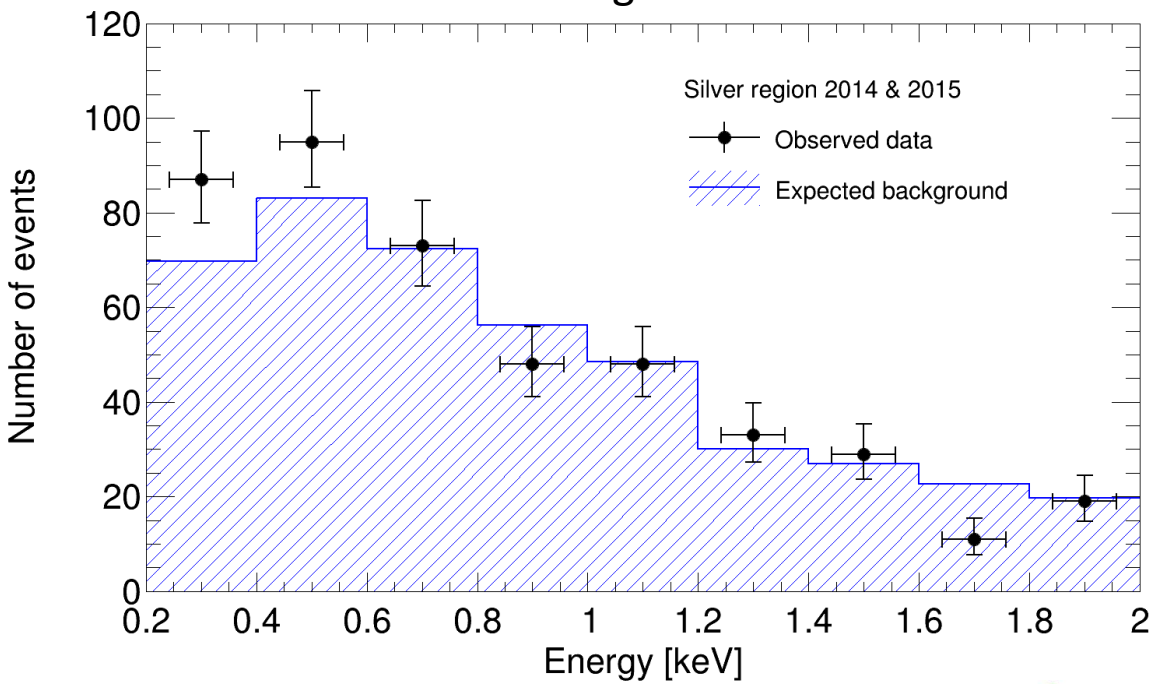
gold region

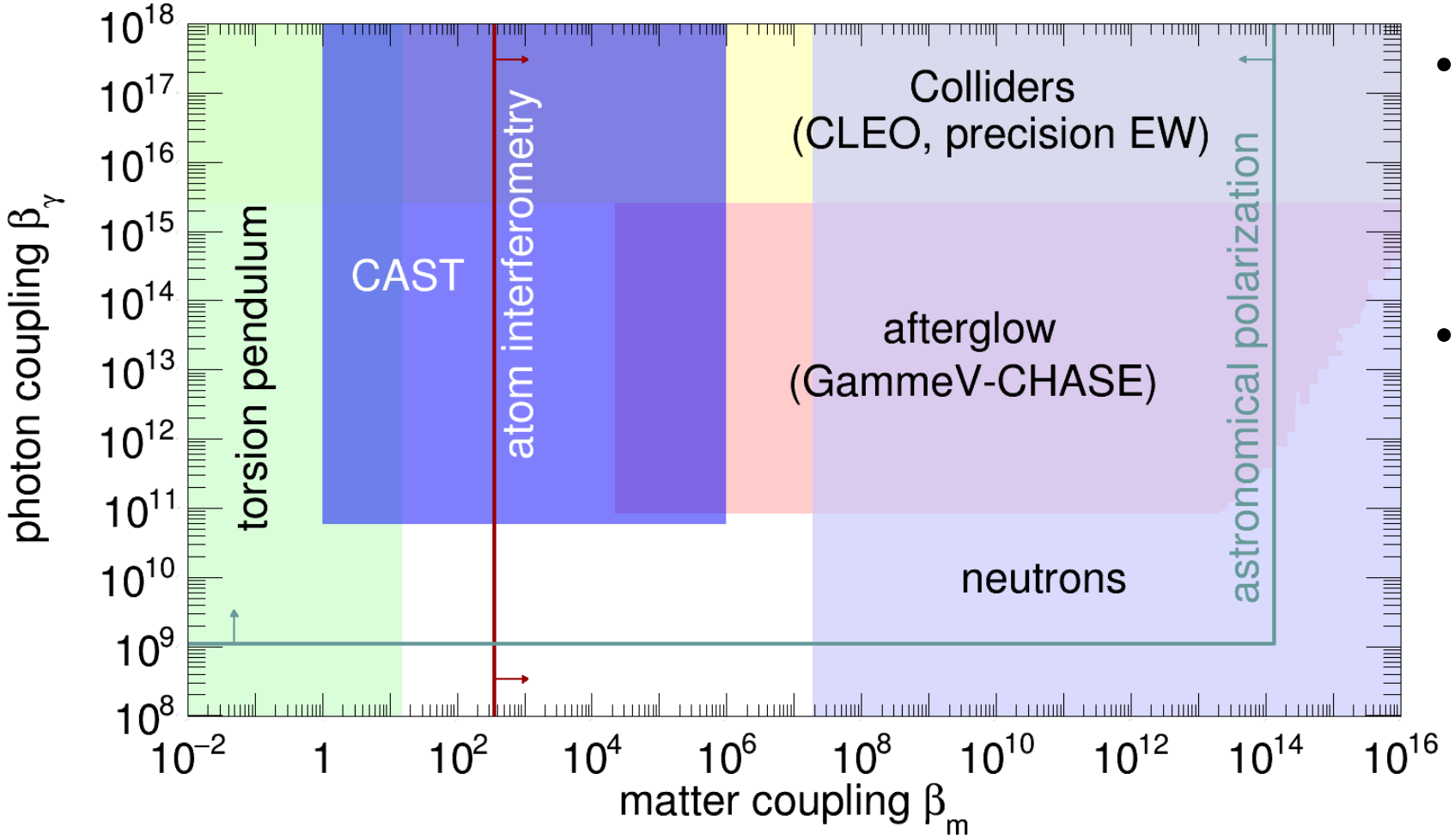


silver region



- Data is compatible with background prediction (within statistical uncertainties)
- No chameleon discovered → Derive observed upper bound on β_γ

Exclusion Plot



- Observed upper bound:
  $\beta_\gamma \leq 5.74 \cdot 10^{10}$
  for $1 < \beta_m < 10^6$
  (non-resonant production)
- Improvement compared to previous CAST limit:
  roughly factor 2 in β_γ

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Prospects for Improvement

Prospects for Improvement

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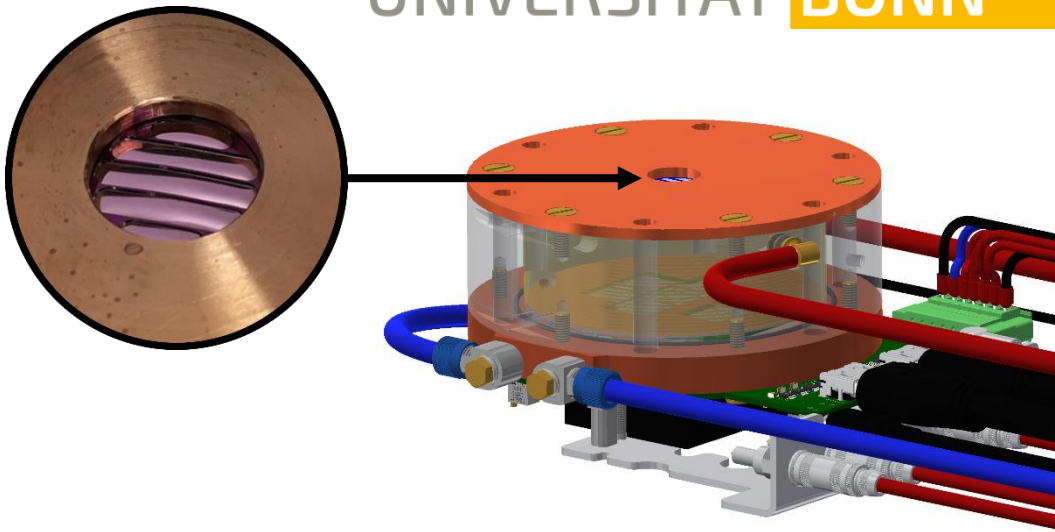
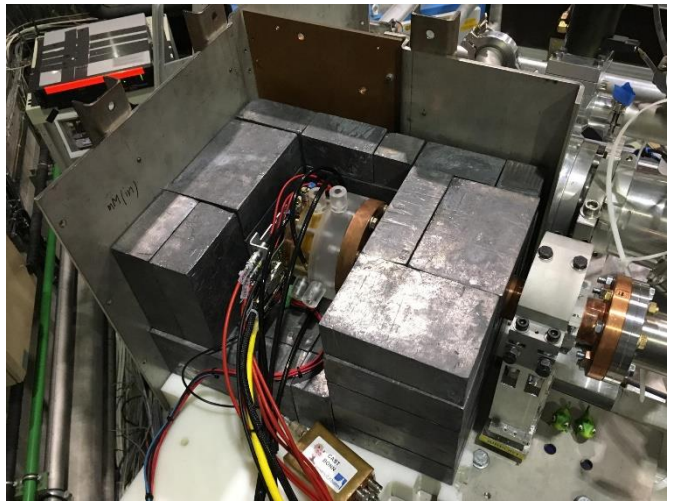
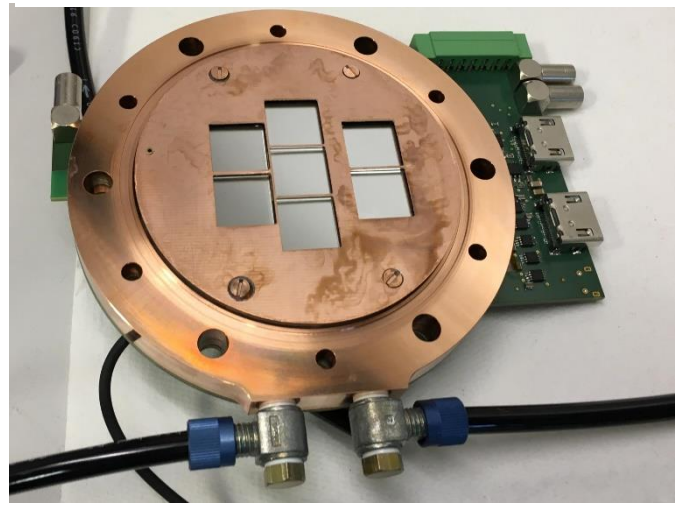
- Development of improved GridPix detector
- Increasing the signal:
  - Ultra-thin SiN windows (300 nm)
- Reducing the background:
  - Increase instrumented area (7 instead of 1 GridPix)
  - Implement readout of analog signal induced on grid
  - Implement veto scintillators
- Further improvements: readout system, active cooling, thicker lead shielding, etc.
- Improved detector deployed at CAST in 2017 (taking data until end of 2018)







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Summary & Outlook

Summary & Outlook

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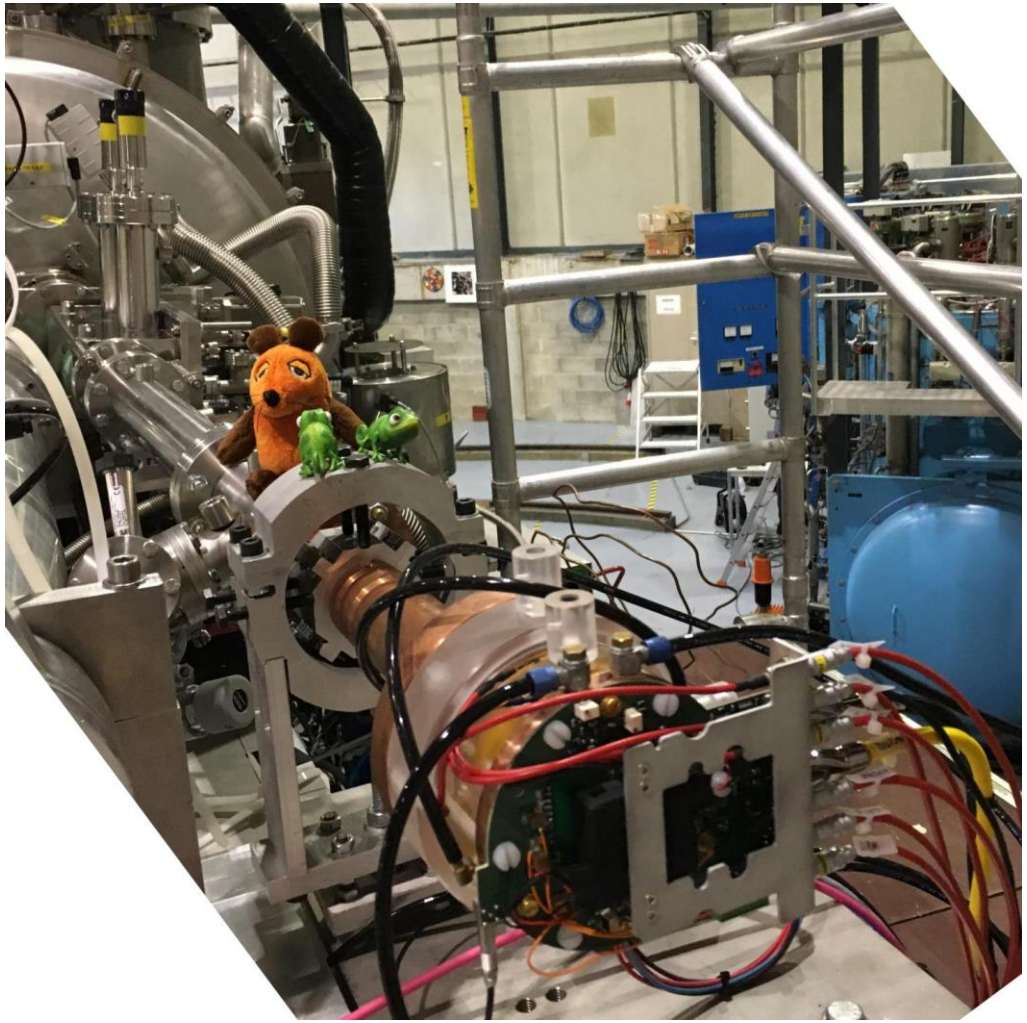
- GridPix detector installed at CAST in 2014 to continue CAST's search for solar chameleons
- Successful data taking until end of 2015
- No excess in data over background prediction
- Could improve CAST's previous limit by a factor of 2:

$$\beta_\gamma \leq 5.74 \cdot 10^{10} \text{ for } 1 < \beta_m < 10^6$$

- Results soon to be published
- Improved detector commissioned and installed at CAST in 2017
- The hunt for solar chameleons at CAST continues
- Also with a different approach: KWISP @ CAST (force sensor, sensitive to β_m & β_γ)



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Backup

Where is CAST located?

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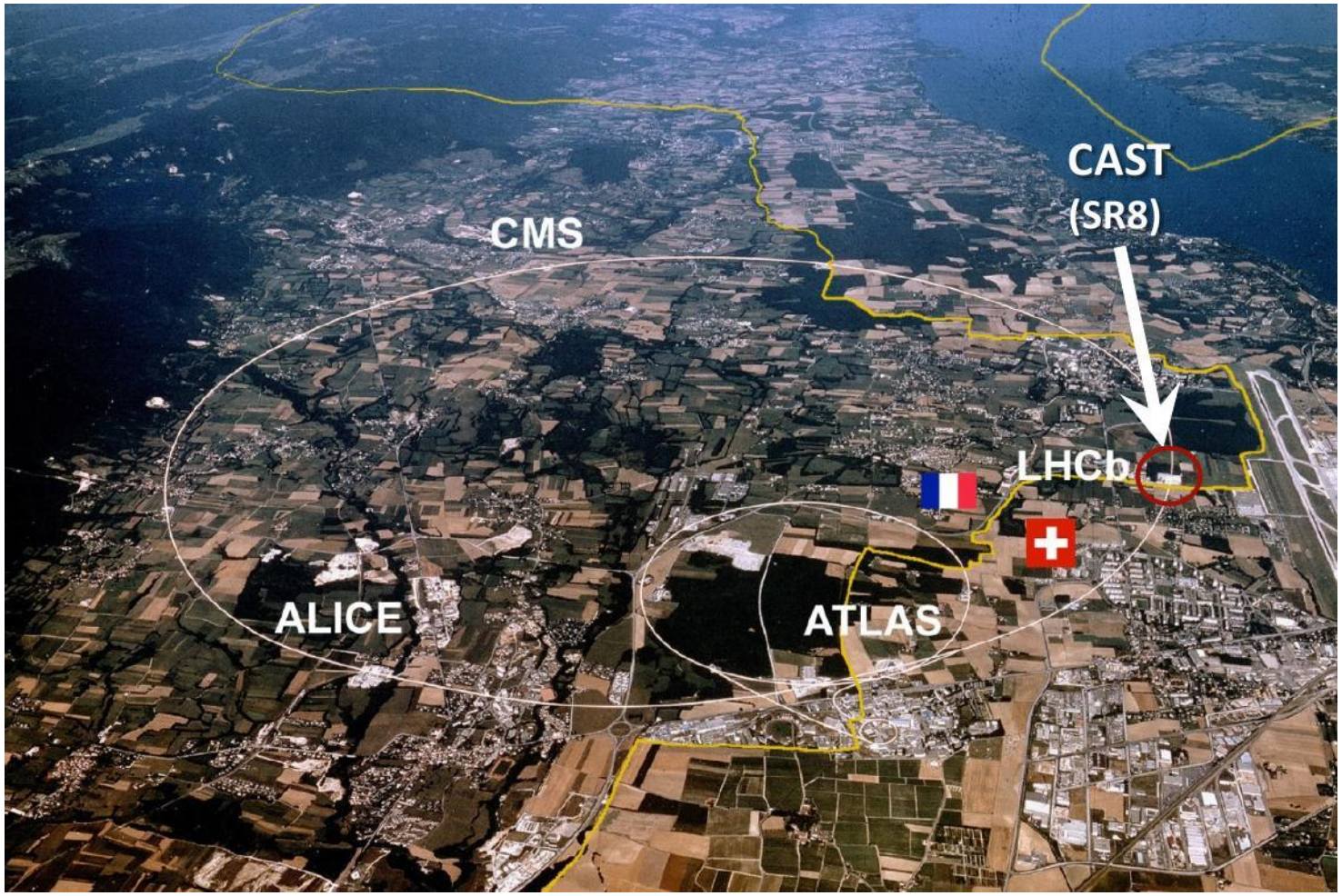

GridPix Production

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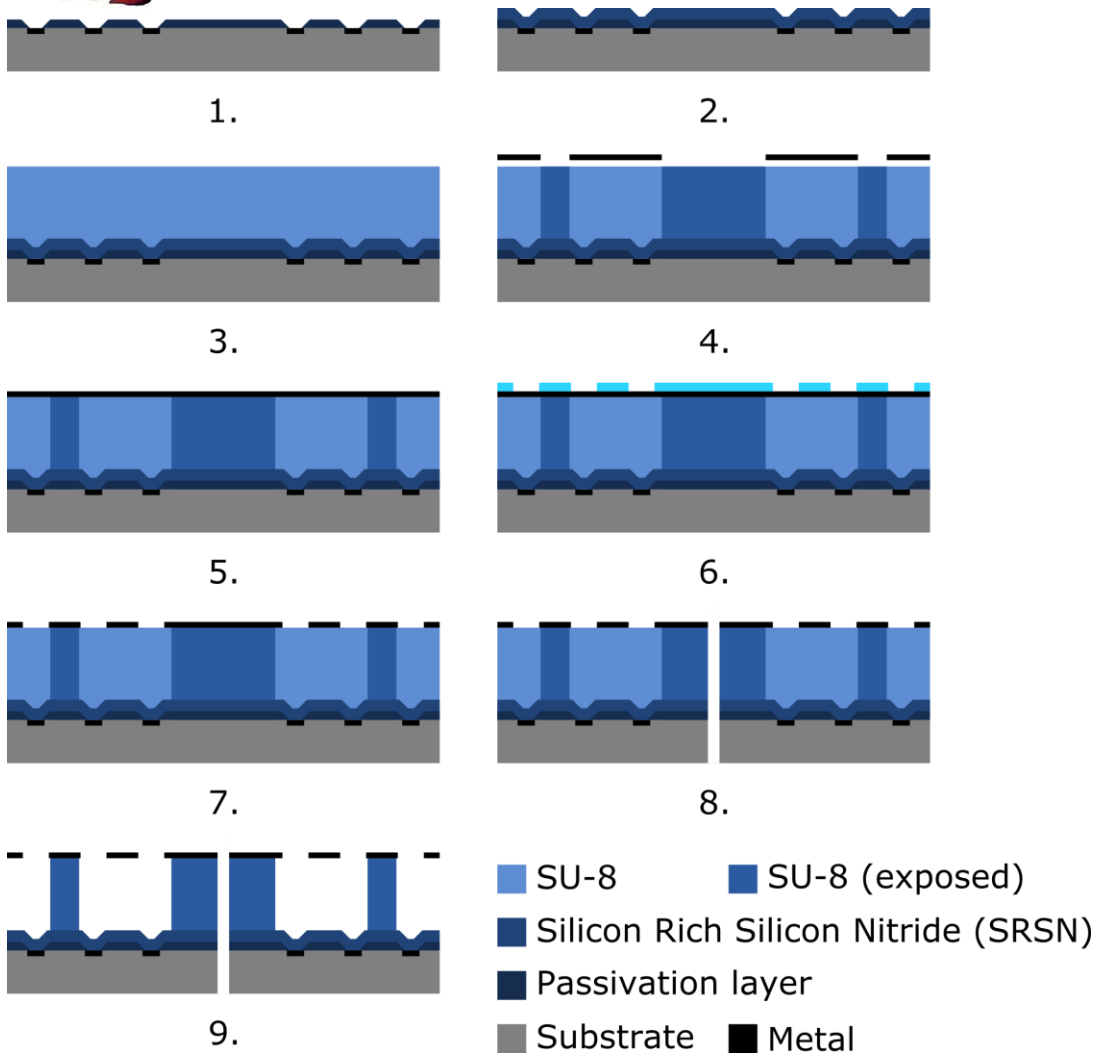

- Technology & production pioneered at Nikhef / University of Twente (Mesa+ institute) on single/few chip level
- Production on wafer scale (8” Timepix wafer) developed at IZM Berlin

1. Start with bare Timepix wafer
2. Deposit protection layer (4 to 8 µm SRSN)
3. Spin coat 50 µm SU-8
4. Create pillars & dikes (Expose SU-8)
5. Sputter aluminium layer (1 µm)
6. Create mask on top of aluminium layer
7. Open grid holes by wet etching
8. Dice wafer
9. Remove unexposed SU-8

Fraunhofer IZM

Timepix ASIC

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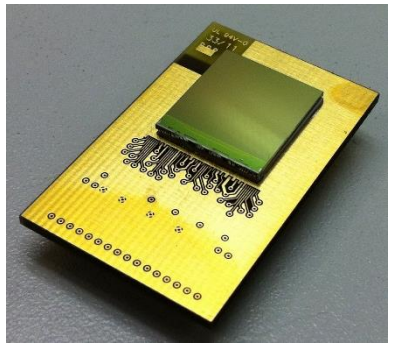
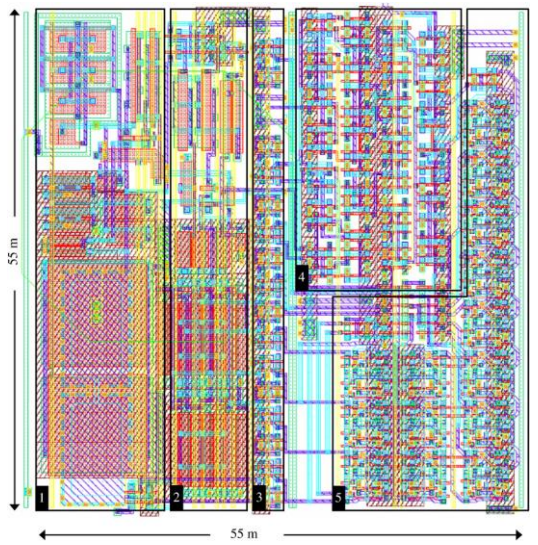
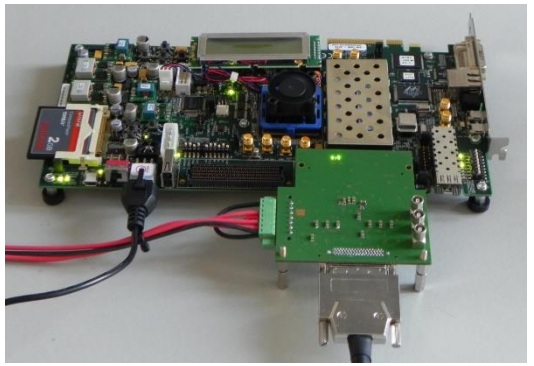
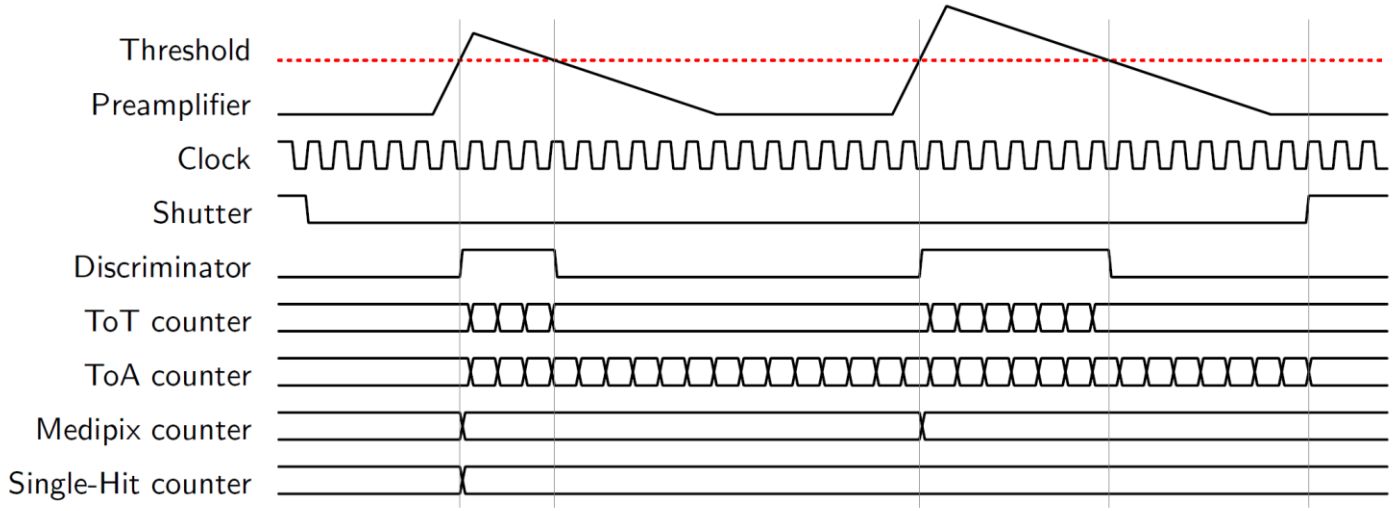
- Pixelized readout ASIC
- Bump bond pads can be used as charge collecting anodes
- Based on Medipix2 ASIC
- 256 x 256 pixels
- 55 µm pitch
- 2 cm² active area
- ENC: 90 e^-
- CSA & discriminator in each pixel
- Each pixel can be configured in one of four modes:
  - ToT (Charge measurement)
  - ToA (Timing information)
  - Medipix (Hit counter)
  - Single-Hit
- Successor: Timepix3 (now available)





Readout system

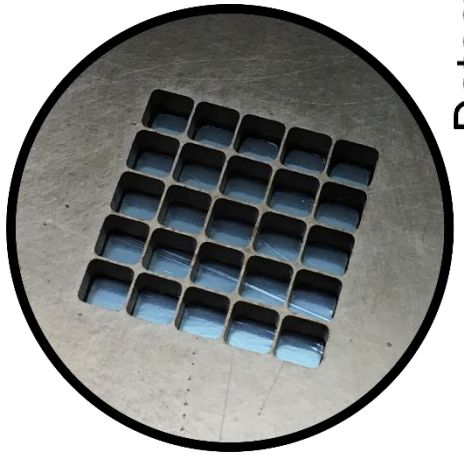


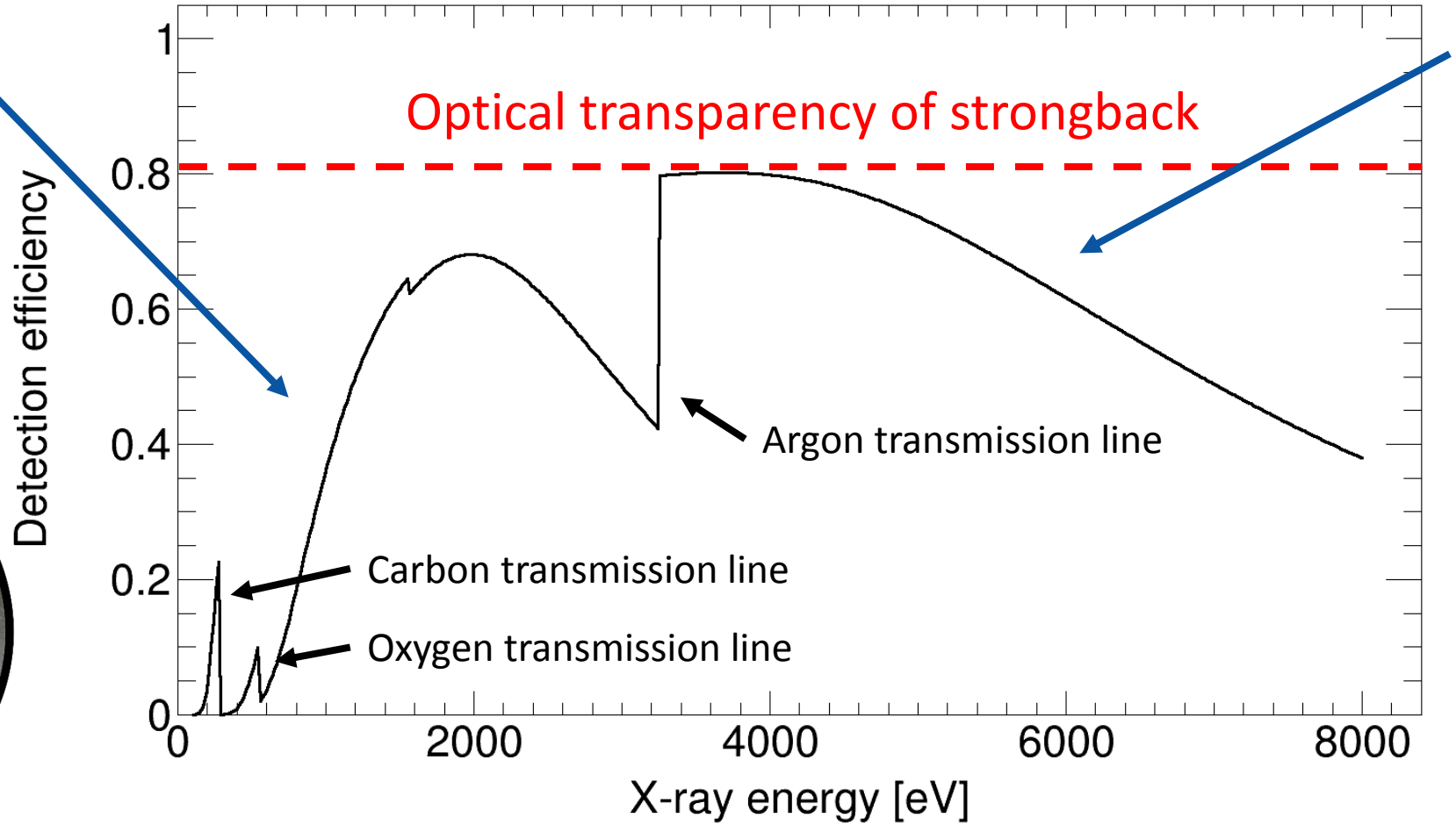


Detection Efficiency

Dominated by window transmission

Dominated by absorption in 30 mm argon





Different Window Materials

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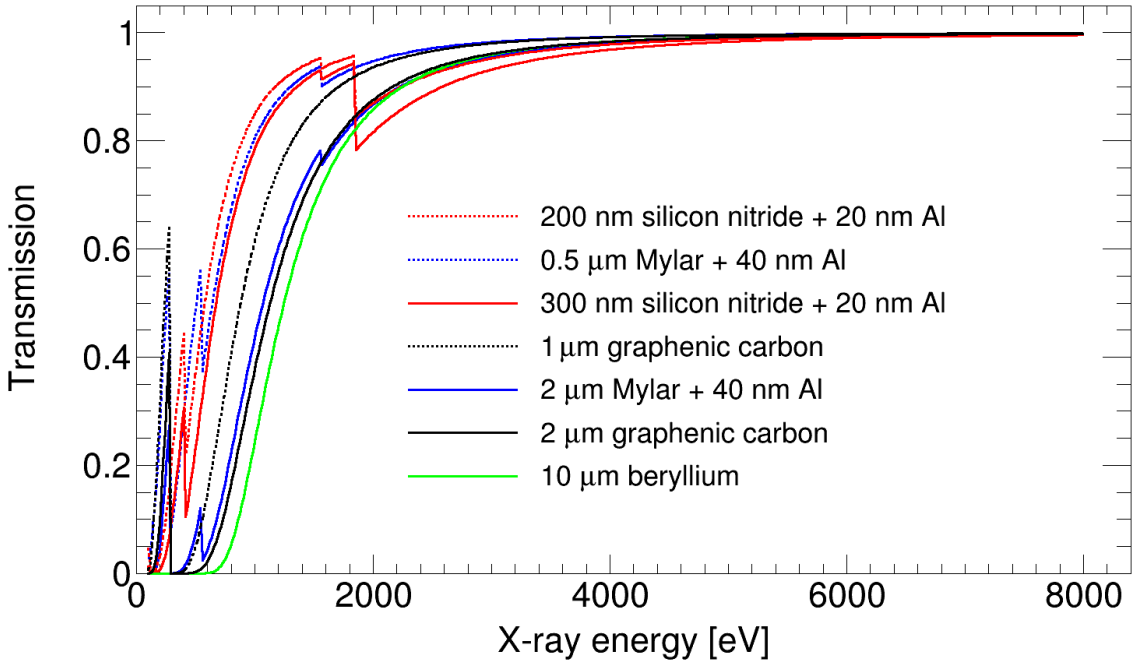
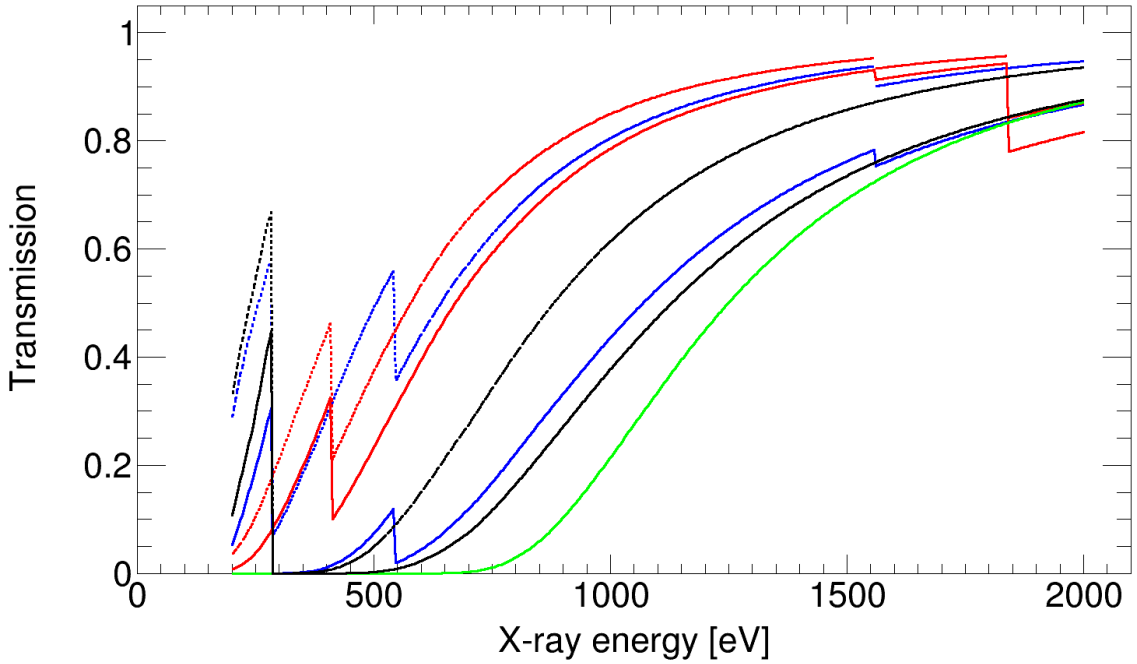
0 to 8 keV



0 to 2 keV



Optical transparency not included!

Energy Calibration

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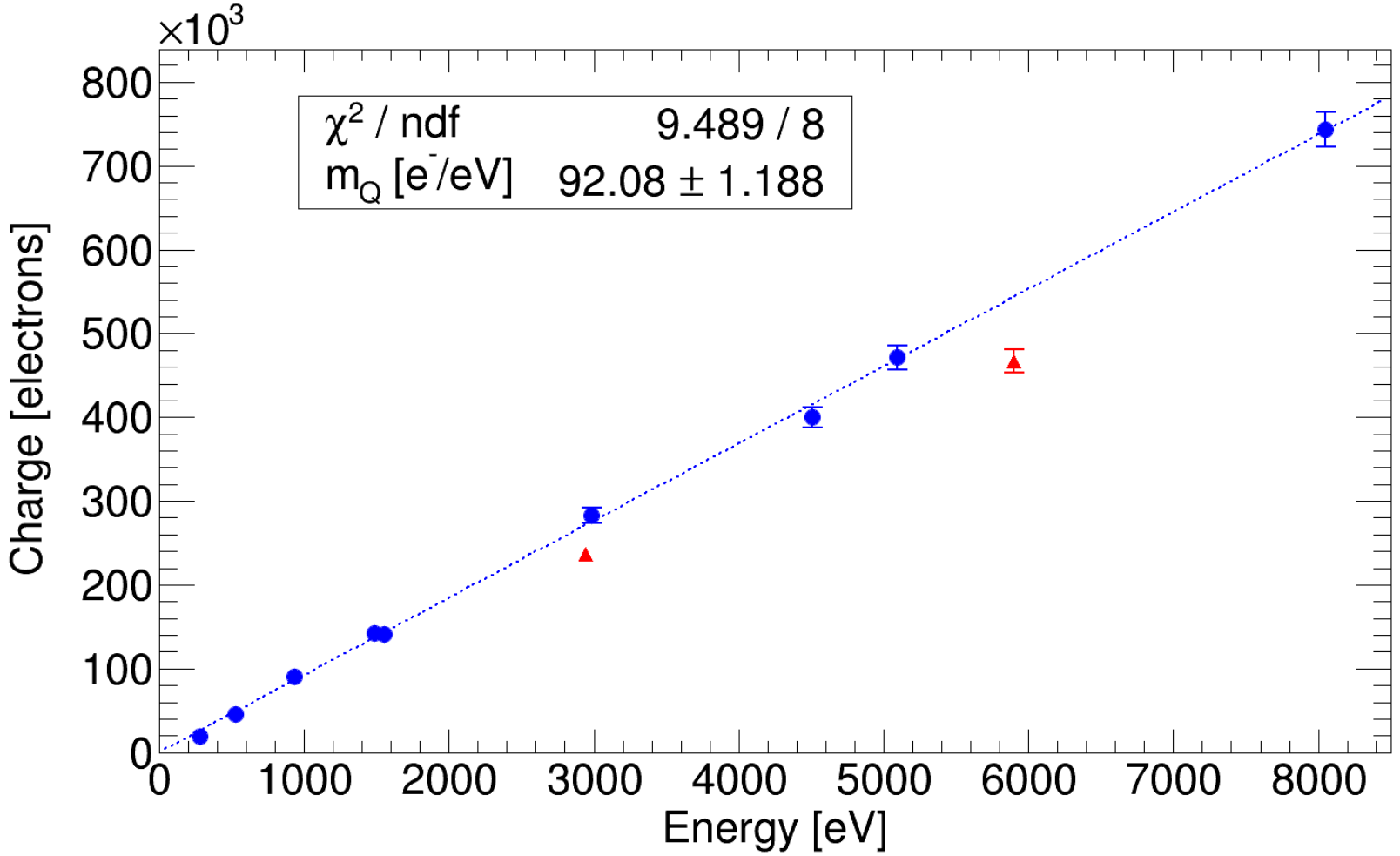

Energy Resolution

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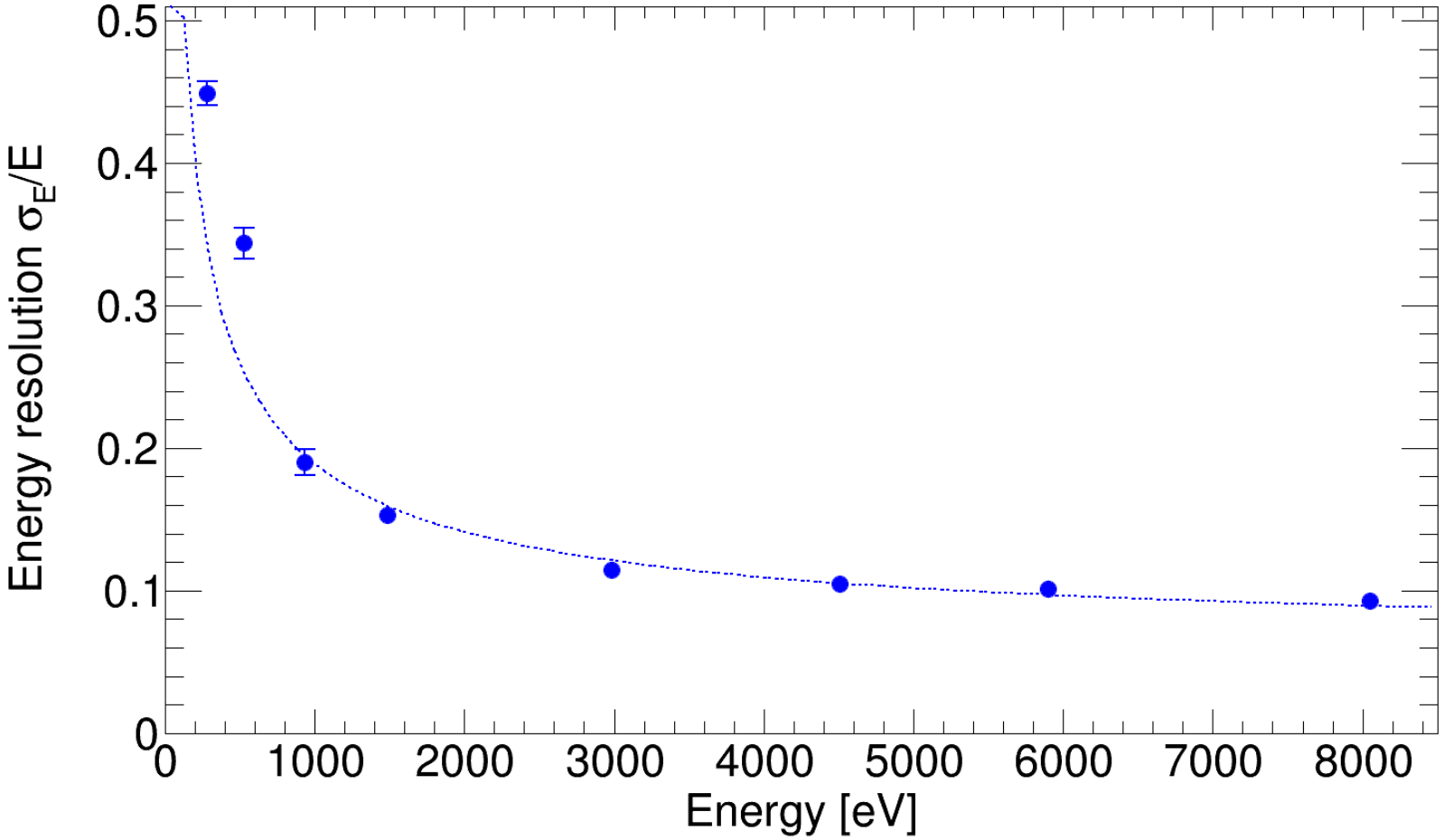

Wolter I Type X-ray Optic

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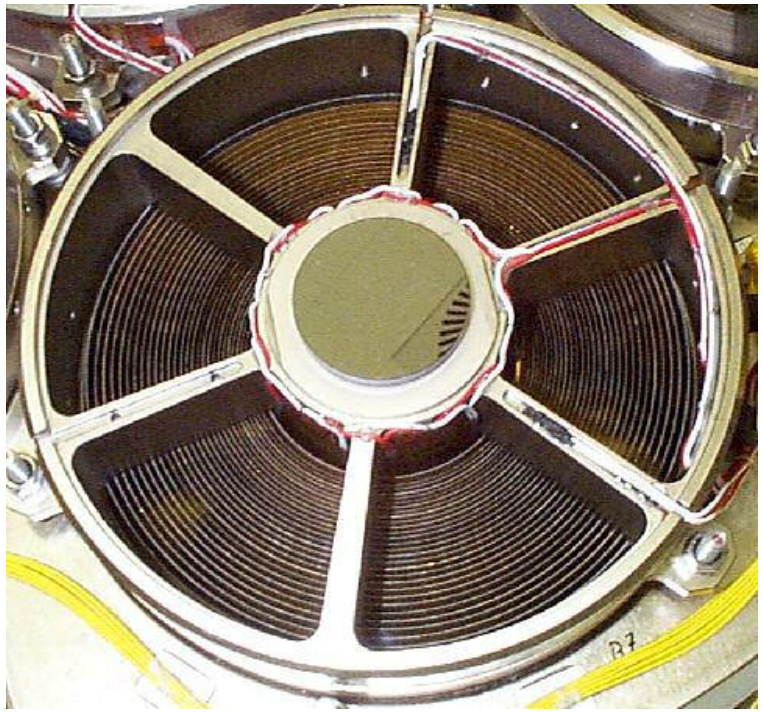
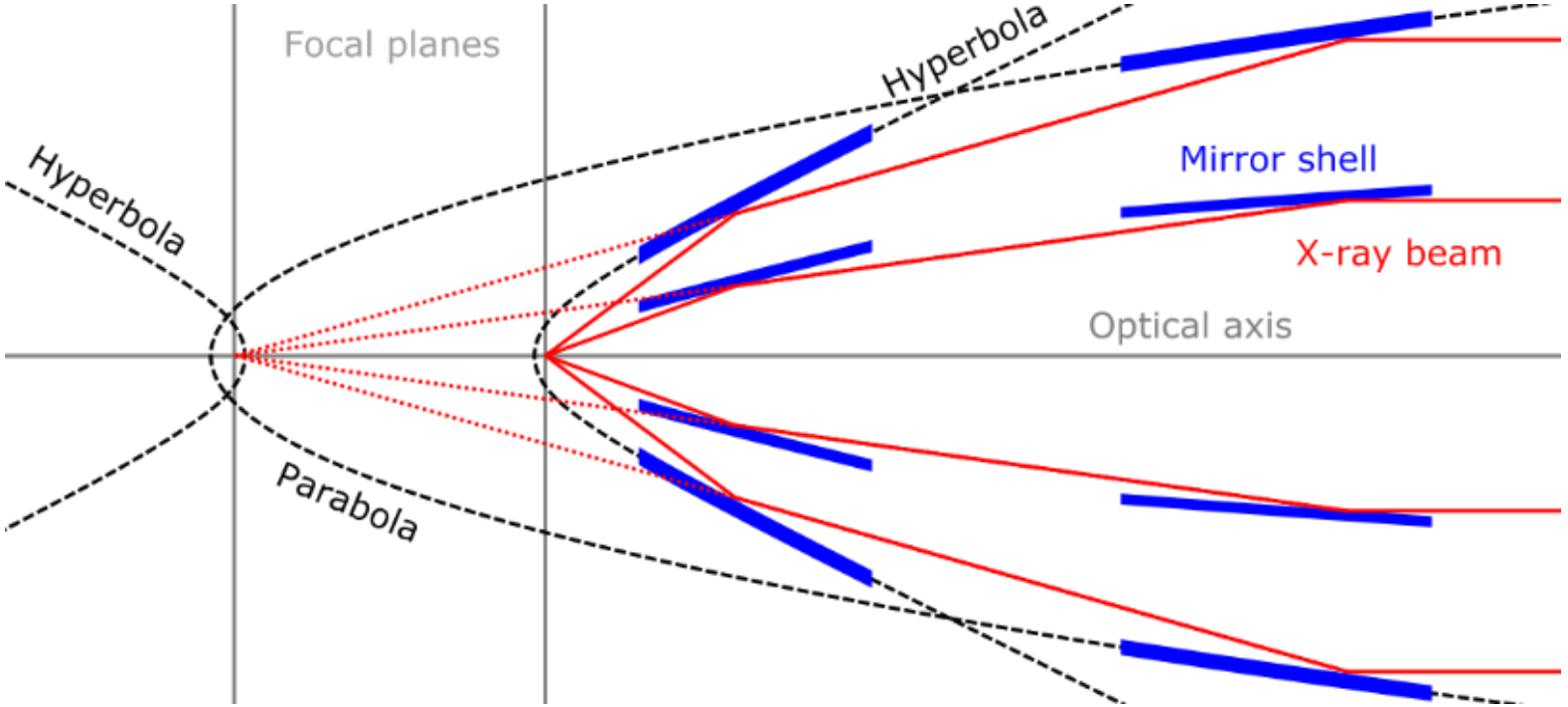
Nested mirror shells



Grazing incidence reflection on hyperbolic & parabolic surfaces



Background Suppression Method

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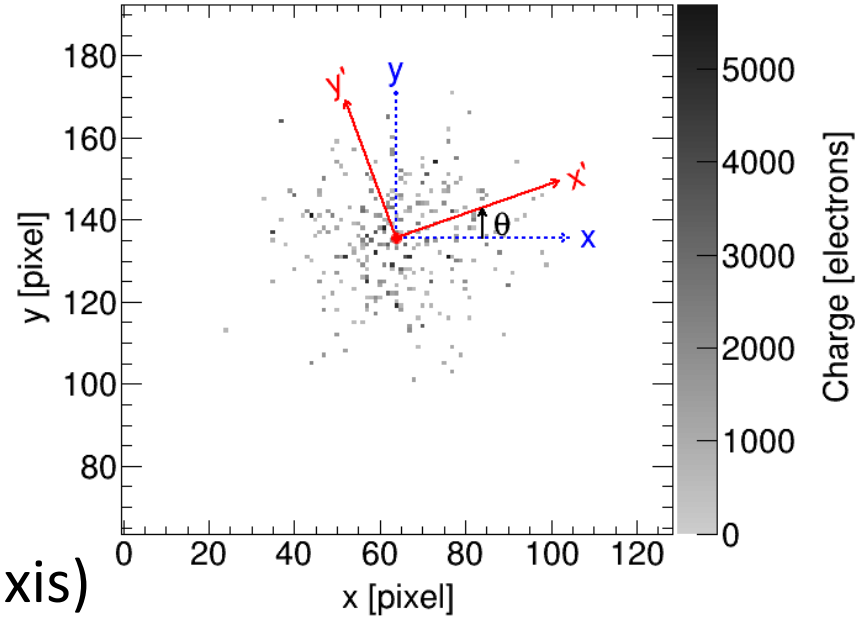
Reconstruction of X-ray photons:

- Pixel clusters identified by modified clustering algorithm as possible X-ray photons
- Long and short axis are identified (rotation of coordinate system: x,y → x',y')
- Geometrical properties are computed



Likelihood for background rejection:

- Likelihood calculated from reference distributions for different energy ranges (from tests at X-ray generator)
- **Three** variables are used for likelihood:
  - Eccentricity (Measure for circularity)
  - Length along short 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 adjusted so 80 % of real X-ray photons pass

Variables Entering Likelihood

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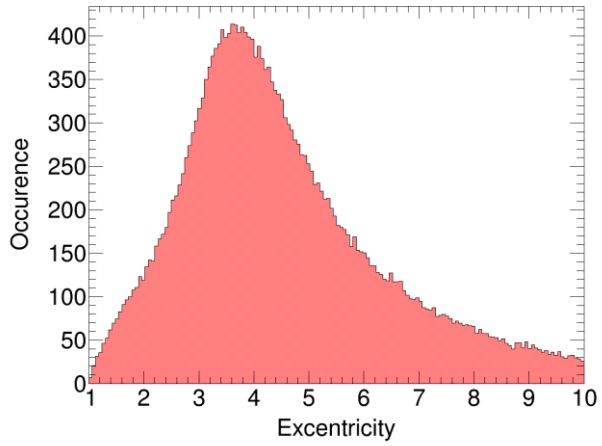
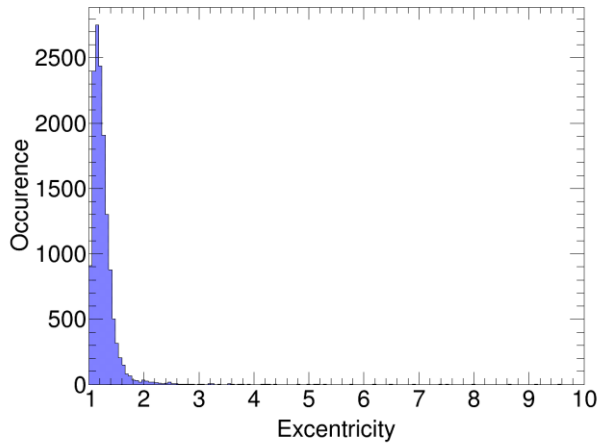
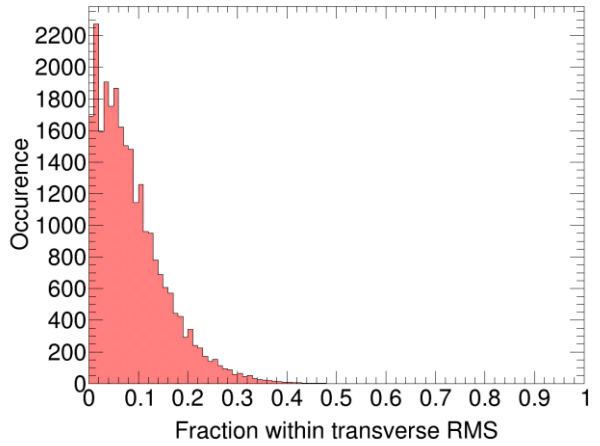
Background (1.2 keV < *E* < 2.1 keV) – Reference (aluminium K_α line)

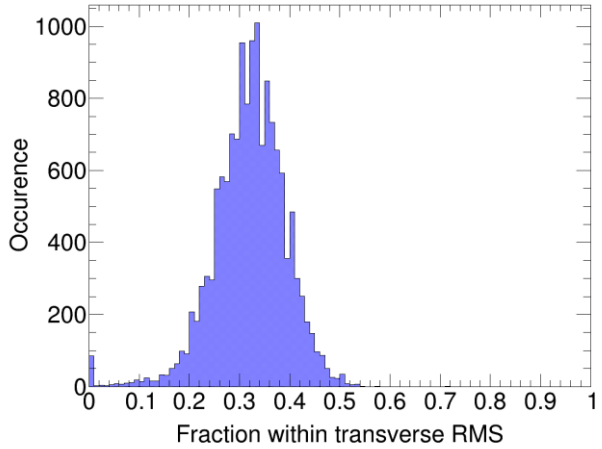
Eccentricity



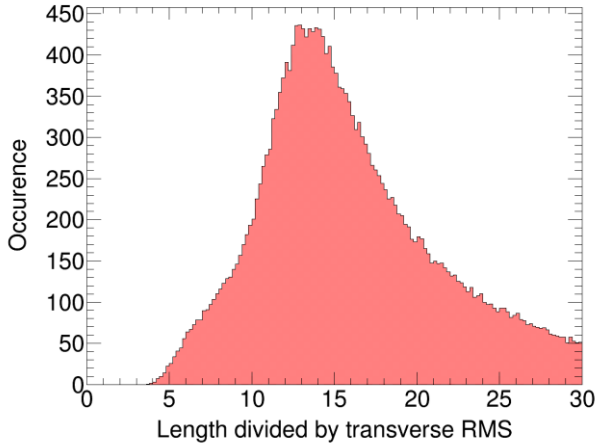


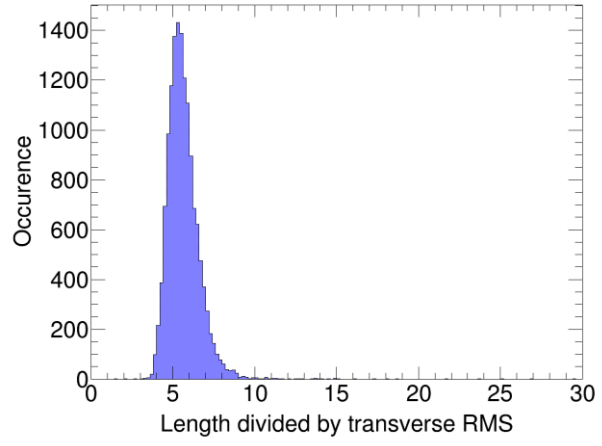
Fraction within one RMS





Length/RMS





Likelihood & Working Point

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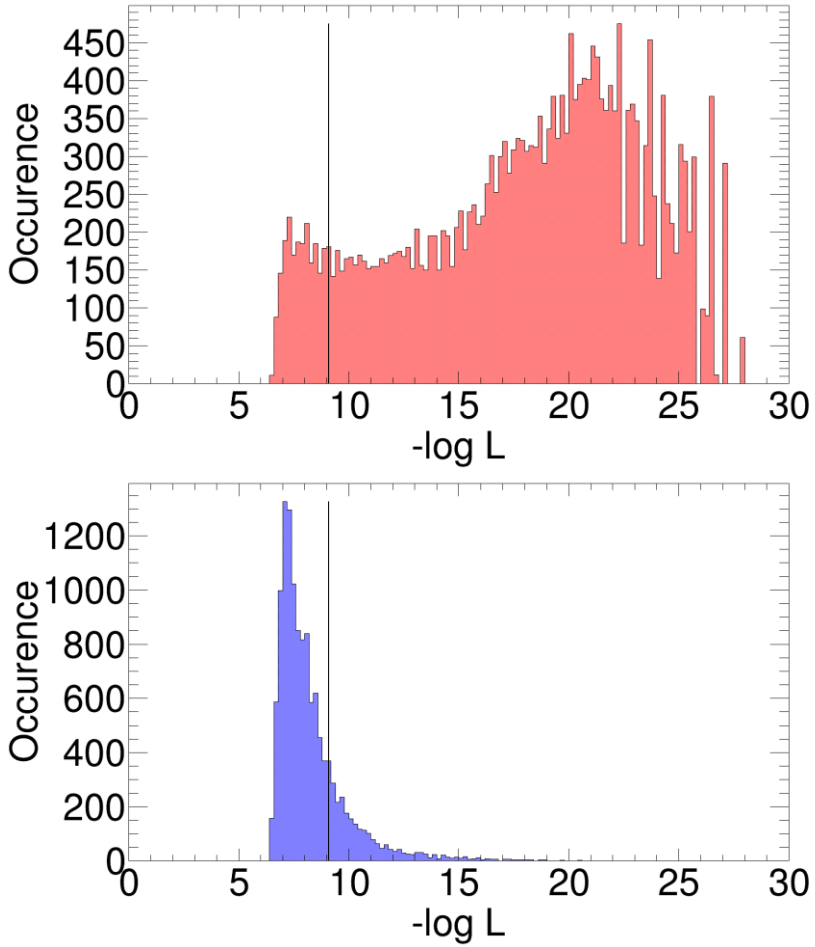
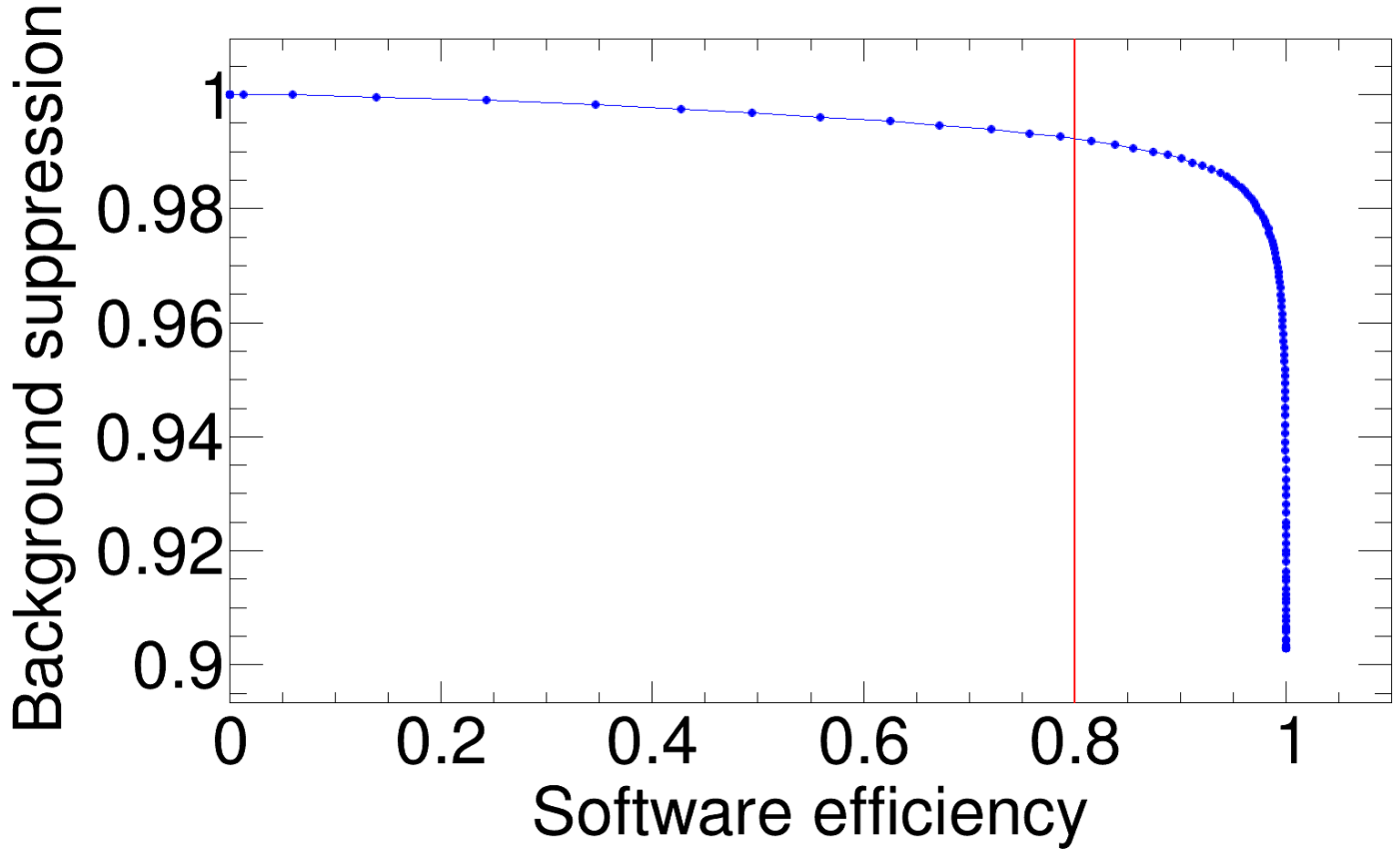
Background (1.2 keV < *E* < 2.1 keV) – Reference (aluminium K_α line)





Influence of CAST Geometry & Optics

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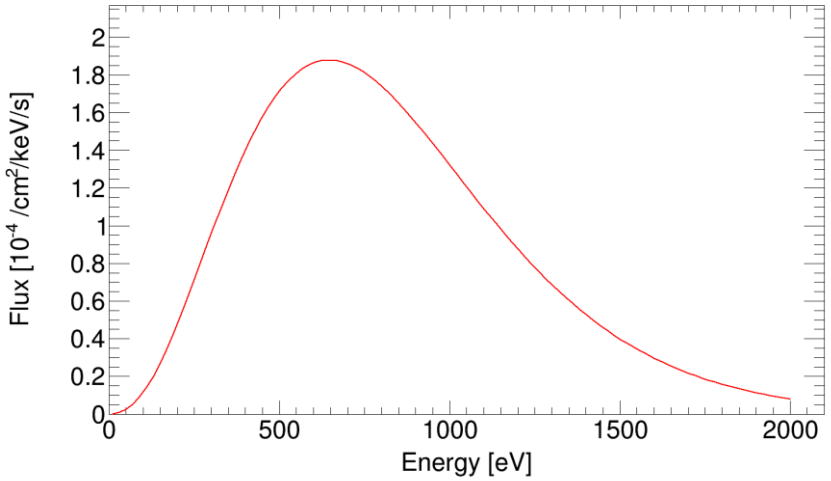
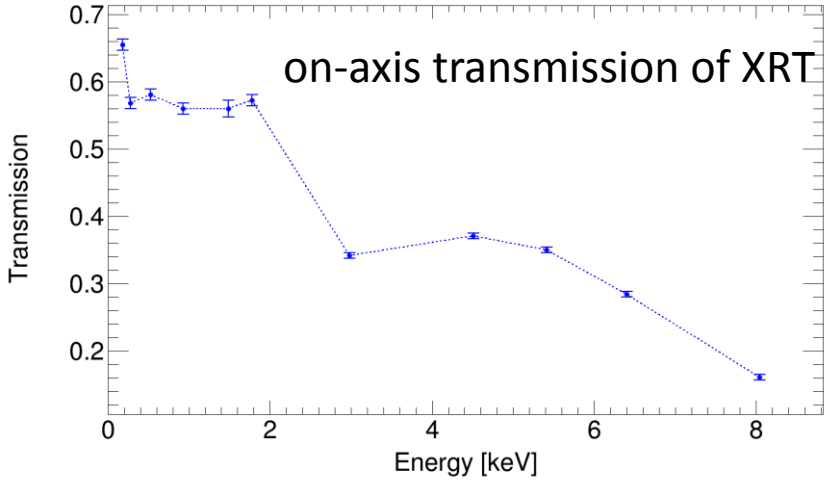
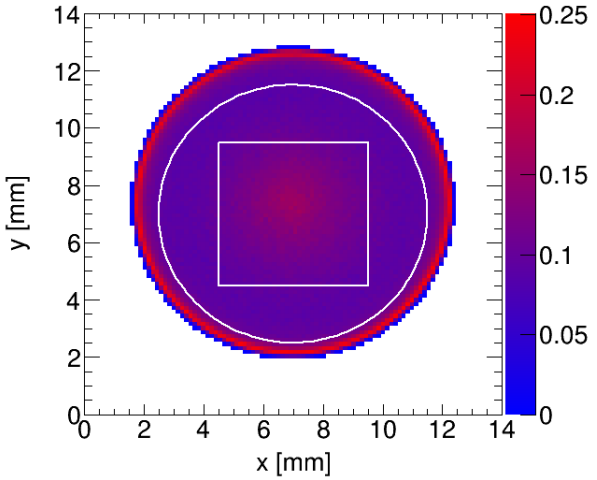
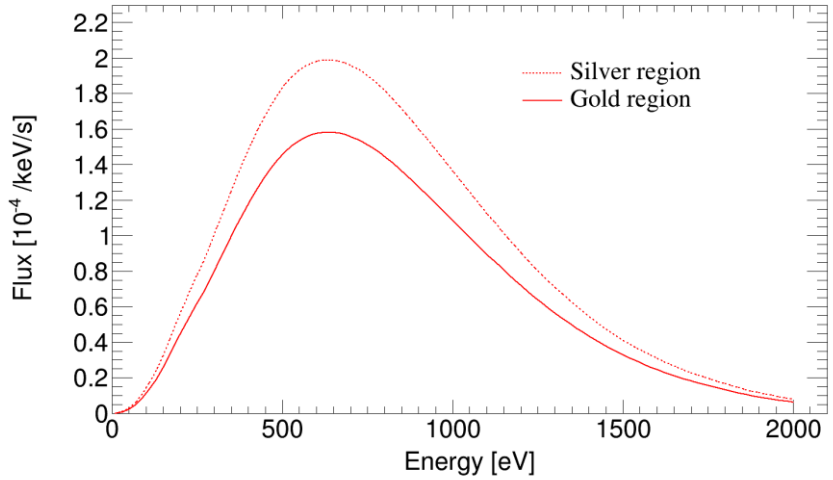
Solar chameleon spectrum
(reconversion in magnet 9T, 9.26 m)





- Start with solar chameleon spectrum
- Take into account geometry of CAST magnet
- Fold with XRT transmission & off-axis behavior
- Simple raytracing simulation to get chameleon image of Sun





- Ring-like shape due to production in tachocline
- Roughly 1/3 of signal lost outside gold & silver region

Influence of Detector Properties

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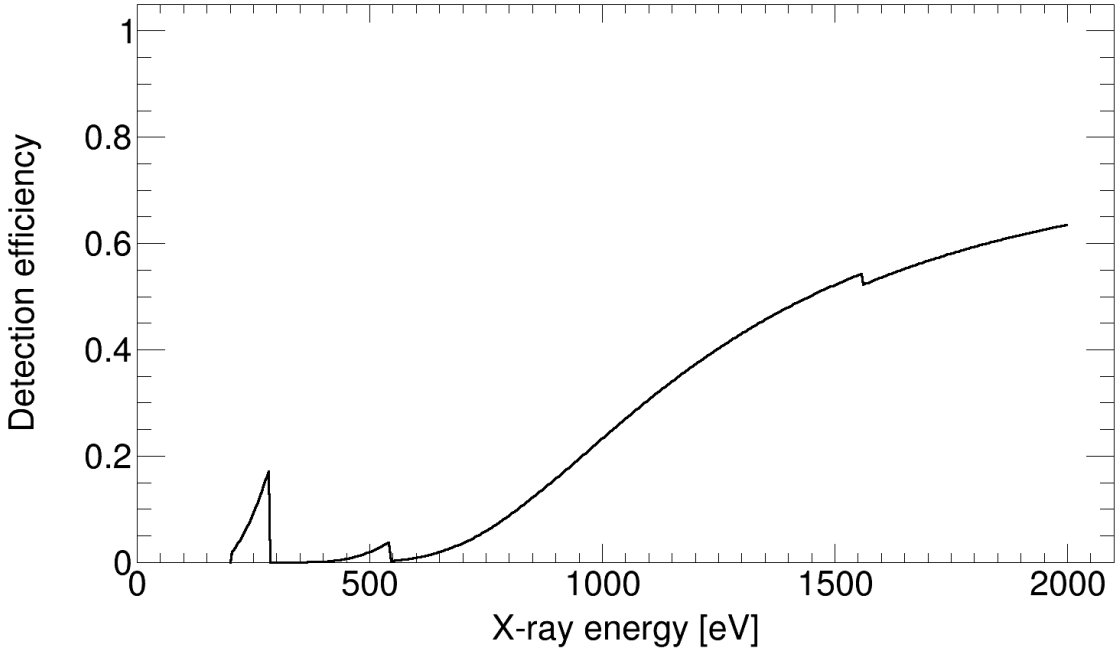
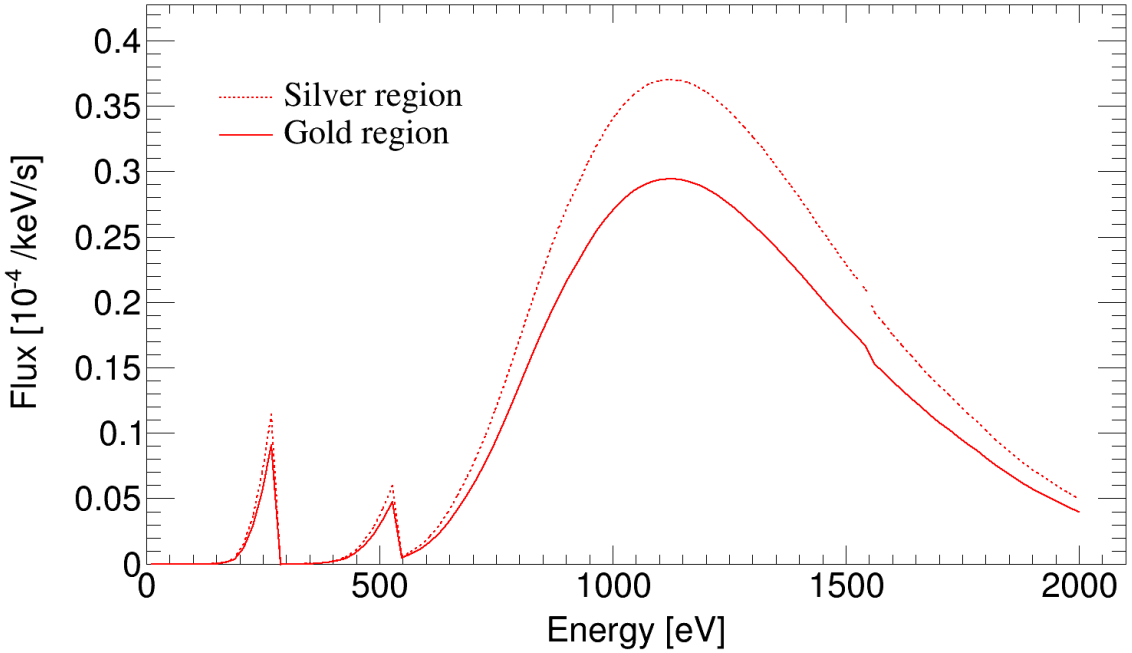
Detection efficiency
(window transmission & absorption in argon)



Detectable solar chameleon flux



- Fold chameleon spectrum with detection efficiency of GridPix detector
- Take into account window transmissions as well as absorption in 30 mm of argon
- Smear with energy resolution…

Expected Signal - Systematic Uncertainties

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	systematic uncertainty	
chip region	**gold**	**silver**
pointing accuracy	3.0 %	9.0 %
detector alignment	1.0 %	5.0 %
XRT off-axis behavior	1.5 %	3.0 %
XRT on-axis transmission	1.8 %	
differential window transmission	1.7 %	
detector window transmission	3.9 %	
detector window optical transparency	2.0 %	
detector gas absorption	0.1 %	
software eciency	3.7 %	
total	**7.2 %**	**12.4 %**