Joint NICER/IXPE Workshop 2024

Dealing with background in IXPE data analysis

Alessandro Di Marco alessandro.dimarco@inaf.it

INAF-IAPS, Rome, Italy

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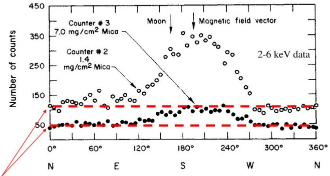
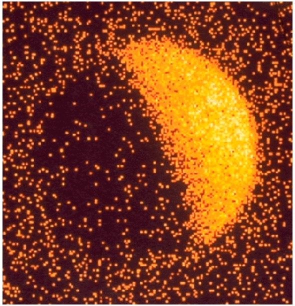
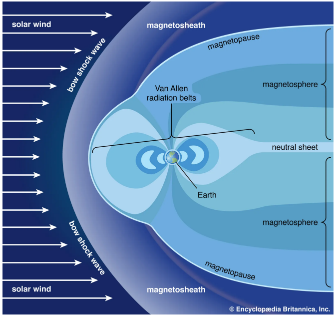
Introduction

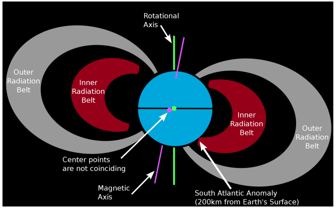




- Since Sco X-1 discovery [Giacconi et al., PRL 9, 439, 1962] other two X-ray sources detected: **diffuse X-ray background** and **instrumental background**
- Detectors are affected by **noise** limiting sensitivity and performances of the instrument in measuring the **signal** of interest
  - ➥ Noise: intrinsic to the detector (e.g. the electronic noise) or depending on the environment: **enviromental noise**
- X-ray instrument for astrophysics work in space that will induce background
- Correct understanding and handling of the background is crucial for the scientific exploitation of the data
- Background properties depend on several factors

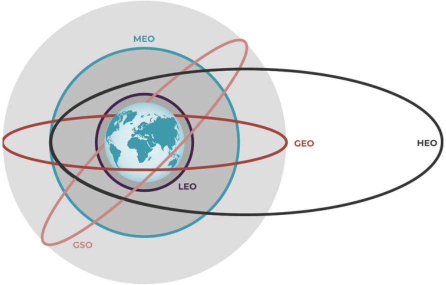
Source of background





- Earth surrounded by the geomagnetic field (magnitude about 0.5 G at surface)
- First approximation (good especially at lower altitudes) the geomagnetic field can be described by an inclined dipole offset from Earth center by about 500 km and tilted by about 10° with respect to the rotation axis
- At high altitudes, the geomagnetic field interacts with and is shaped by the solar wind
  - ➥ Interplay between solar wind, cosmic rays and the geomagnetic field lines is the formation of regions trapping charged particles: **Van Allen radiation belts**
  - ➥ The **South Atlantic Anomaly** (SAA) is the result of the inner Van Allen radiation belt which comes closest to the Earth's surface down to an altitude of 200 km

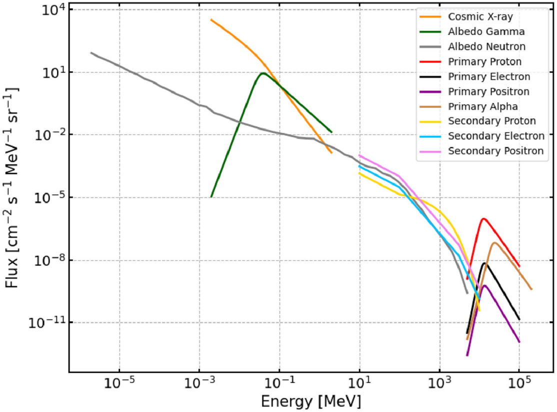
X-ray observatories orbits



- **Geostationary/Geosynchronous orbits** (GEO/GES): mainly for telecommunication satellites
- **Low Earth orbits** (LEO): relatively close to Earth's surface between 160 and 2000 km of altitude, most commonly used for satellite imaging (IXPE) is the one used by the ISS
- **Medium Earth orbits** (MEO): between LEO and GEO, used mainly for navigation satellites such as Galileo constellation
- **Polar orbit and Sun-synchronous orbits** (SSO): similar to LEO but following a fixed position with respect to Sun, allowing e.g. synchronized passages on a town
- **Highly Elliptical orbits** (HEO): High Earth orbits much closer to the Earth on one end than the other (e.g. XMM-Newton)
- **Lagrangian Points**: equilibrium points at 1.5 million km from Earth (e.g. Planck)

Pre-launch study of IXPE background

- A preliminary study of IXPE background based on Geant4 simulator was published before the launch [Xie et al., Astroparticle Physics, 128, 102566, 2021.]



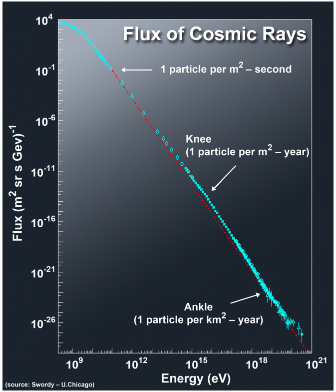
Component	Rate in total [s^{-1}]	Rate in 2–8 keV [s^{-1}]
Cosmic X-ray	3.19E−03	1.73E−03
Albedo Gamma	3.39E−03	1.24E−03
Albedo Neutron	1.14E−03	2.97E−04
Primary Proton	9.77E−02	3.16E−02
Primary Electron	8.67E−04	2.39E−04
Primary Positron	7.45E−05	1.91E−05
Primary Alpha	3.03E−02	1.09E−02
Secondary Proton	4.50E−02	1.41E−02
Secondary Electron	4.16E−02	1.11E−02
Secondary Positron	1.32E−01	3.36E−02
Total	3.56E−01	1.05E−01

- Discovered during the very first X-ray astronomy experiments in the '60s
  - ➥ main source of photon background for a space-borne X-ray astronomy mission
  - ➥ nearly isotropic diffuse cosmic X-ray background due to integrated emission of photons from galactic and extra-galactic sources not spatially resolved from the detector

- **extra-galactic CXB** dominated by emission from quasars, Seyfert galaxies, and highly absorbed AGNs
  - ➥ peaked at about 30 keV
  - ➥ model by Gruber et al., ApJ 520, 124, 1999:

$$F(E) = 7.877(E/\mathrm{keV})^{-1.29} e^{-E/41.13}\ \mathrm{ph.\ cm^{-2}\ s^{-1}\ sr^{-1}\ keV^{-1}}$$

- **galactic CXB** non-spatially uniform due to the integrated contribution of different classes of sources (e.g., cataclysmic variables, coronally active binaries, ...)
  - ➥ strongest in the central radians of the Galaxy (i.e., approximately for absolute Galactic longitudes $< 30^\circ$ and latitudes $< 10^\circ$)



credit: HAP/A. Chantelauze

- Composition: 85% protons, 13% ions, 2% electrons
- Differential spectrum well described above 1 GeV/nucleon by a power-law distribution with index 2.8 (ranging 2.7-3.0-3.3-2.7)
- Flux is also modulated by solar modulation potential on an 11 years solar-cycle basis

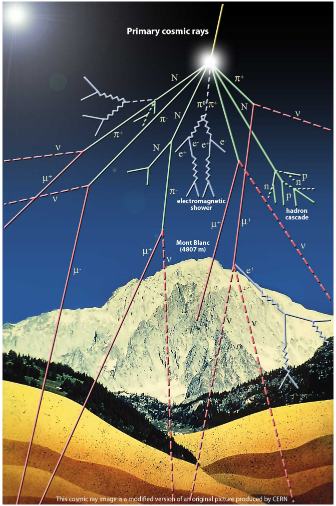
- Earth geomagnetic field can change the observed flux on the basis of the **rigidity = pc/q**
- only particle having rigidity higher than the cutoff rigidity (Størmer formula) can reach a certain altitude (h) at a given latitude (λ):

$$pc/q > 14.5\left(1+\frac{h}{R_\oplus}\right)^{-2}\cos^4\lambda \text{ GV}$$

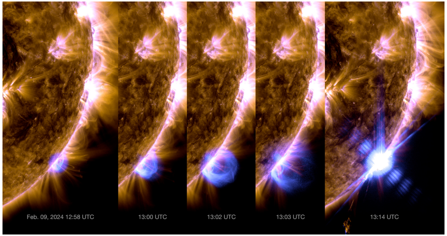
Albedo γ and neutrons

- Primary cosmic rays interacting with the atmosphere produce showers of secondary particles that can reach Earth's surface but can also be reflected back into space
  - ➥ resulting secondary flux will depend on the geomagnetic latitude
- neutrons are able to reach LEO altitudes before decaying
  - ➥ scattering with atmospheric nuclei will thermalise neutrons giving rise to a spectrum ranging from eV to GeV
- photons can be reflected dominating the total atmospheric emission below a few tens of keV
  - ➥ Swift-BAT data allowed for a model [Ajello ApJ, 689, 666, 2008]

$$F(E) = \frac{0.0148}{\left(\frac{E}{33.7\text{keV}}\right)^{-5} + \left(\frac{E}{33.7\text{keV}}\right)^{1.72}} \text{ ph. cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}\text{ keV}^{-1}$$



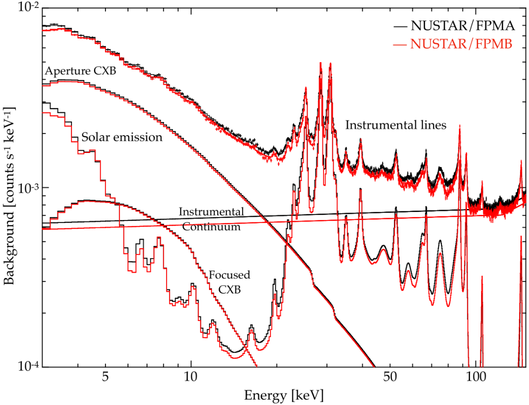
Background: Solar particles



- Solar wind + continuous stream of soft (< 10 keV) charged particles (electrons, protons, ...) produced and accelerated in the solar corona
- Sun also emits the so-called solar energetic particles (SEP), for which the kinetic energies can range from 10 keV to GeVs
- SEP produced by solar flares and in shock regions associated with **coronal mass ejections**
  - ➥ Bursts of high energy accelerated particles have strongly variable fluxes and fluences
  - ➥ Extremely difficult to predict
  - ➥ Very challenging for space missions, especially for their sensitive electronics
- The geomagnetic field provides some shielding, in particular at low altitudes and inclinations
- SEP events are a concern mostly for missions in HEOs

Background: implications and mitigation

Impact of background on timing and spectral observations



- Timing: variable background sources can impact the detected count rate with both short-term (e.g., flares) and long-term effects (e.g., average count rate level drifts)
- Spectral: background sources can leave their imprint in the detected spectra, both as an additional continuum or line contribution (e.g., by inducing fluorescence in the detector materials themselves)

Impact of background on polarimetric observations

$$MDP_{99} = \frac{4.29}{\mu\sqrt{S}}\sqrt{\frac{S+B}{T}} \qquad (1)$$

- For point-like sources:
  - ➥ spatial selection allow to select source events and background events
  - ➥ background rejection/subtraction can be easily applied

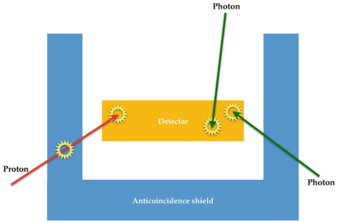
- For extended sources:
  - ➥ spatial selection is not so effective in background rejection
  - ➥ in case of faint sources background can be comparable with source counting rate
  - ➥ high levels of unpolarized background can dilute the polarization degree of the source:

$$P_{detected} = P_{source}\left(1 + \frac{rate\ of\ background}{rate\ of\ source}\right)^{-1} \qquad (2)$$

  - ➥ background needs to be carefully rejected

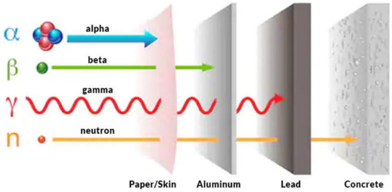
Active or off-line filter

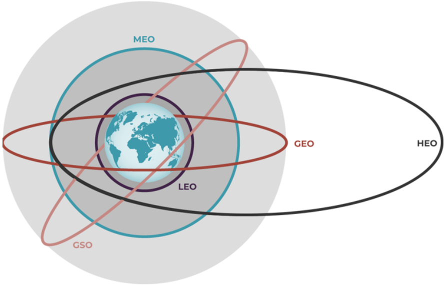
- Active anticoincidence obtained surrounding the instrument with a fast, particle-sensitive detector (e.g., a thin slab of plastic scintillator) which triggers a veto signal allowing to discard any event occurring in the detector of interest by the same particle



Passive shield

- Suppress the background due to high-energy photons by shielding the detectors using suitable thicknesses of a high-Z and high density materials
  - ➥ These shields can still produce a large amount of secondary radiation
- Use a graded-Z shielding





Mission	Orbital Parameter	Instrument	Single det. geom. area (cm^2)	Energy Band (keV)	Residual back. ($cts/s/keV/cm^2$)
OSO-8[8]	LEO 550 km 32.95° 1975-1978	**Wisconsin**			
		CH_4 0.5 atm	52	0.13-3.65	1.61E-3
		Neon CO_2 1.25 Atm	43	0.75-6.0	1.58E-4
		Xenon-Argon-CH_4 1.25 Atm	42	1.47-55	6.4 E-4
HEAO1[9,10]	LEO 445 km 22.75° 1977-1979	**A2**			
		MED Ar-CH_4 1 Atm	800	1.5-20	1.1E-4
		HED Xe-CH_4 1 Atm	800	2-60	1.0E-4
EXOSAT[11]	Elliptical (355-191570 km) 72.75° 1983-1986	**Medium Energy**			
		Argon-CO_2 2 Atm	1500	2-10	2.0E-3
		Xenon-CO_2 2 Atm	1500	5-50	8.0E-3
RXTE[12]	LEO 580 km 23° 1995-2012	**PCA**			
		Xenon-CH_4 90-10	1562	2-60	2.6E-4

P. Soffitta et al., Proc. of SPIE Vol. 8443, 2012, 84431F

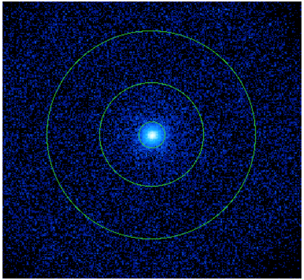
- **IXPE predicted background:** $\sim 7.8 \times 10^{-3}\ s^{-1} keV^{-1} cm^{-2}$

Background mitigation in data analysis

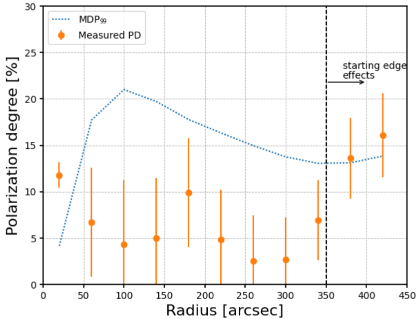
- Depending on the detector architecture, events due to charged particles can be recognized and filtered out
- In imaging detectors it is possible to select the background and the source regions
- In case of no-imaging and no rejection is possible a refined modeling for the background is needed
  - ➥ NICER background treatment follows this approach

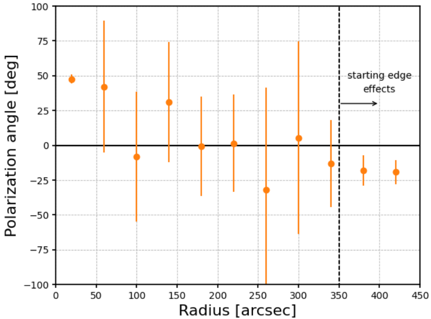
IXPE background

- In A. Di Marco et al., AJ 165 143 (2023), 18 point-like sources used to systematically study IXPE background

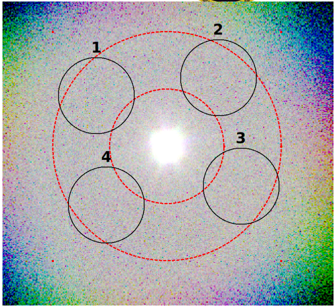


- Thanks to imaging capabilities source events and background events can be selected
  - ➥ source: inner circular region with radius 60"
  - ➥ background: **what is the best strategy?**
    - circular regions?
    - annular regions?
    - when subtract it?
    - when reject it?

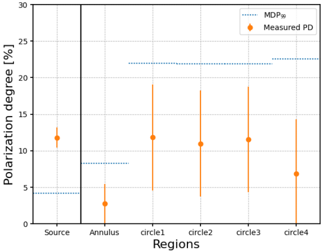


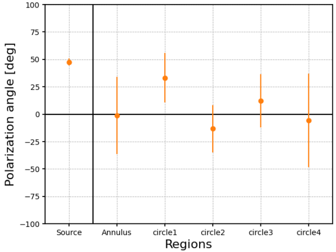


- Using data from 4U 0142+16 with a long exposure time:
  - ➥ image centered using a Gaussian fit
  - ➥ several radii have been applied with a $\sim$ 40 arcsec step
  - ➥ polarization effects from the source are present up to $\sim$ 100 arcsec
  - ➥ from $\sim$350–400 arcsec border effect starts to be present
  - ➥ from 500 arcsec starts to enter in the corners
- **the best approach is to select an annular region with inner radius 150 arcsec and outer radius 300 arcsec**



- Using data from 4U 0142+16 with a long exposure time:
  - ➡ image centered using a Gaussian fit
  - ➡ using prescription from the previous slide for annular regions
  - ➡ 4 circular regions have been considered in each DU, centered at $\sim \pm 150$ arcsec form the source and with radius $\sim$100 arcsec
  - ➡ circular regions include less events – higher uncertainty
  - ➡ circular regions are not symmetric with respect to the source, thus they can introduce some overestimate of background PD



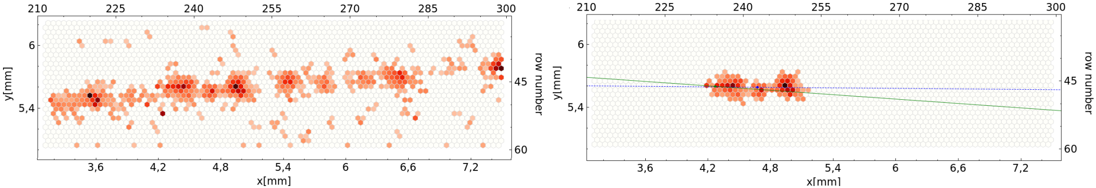


- **the best approach is to select an annular region with inner radius 150 arcsec and outer radius 300 arcsec**

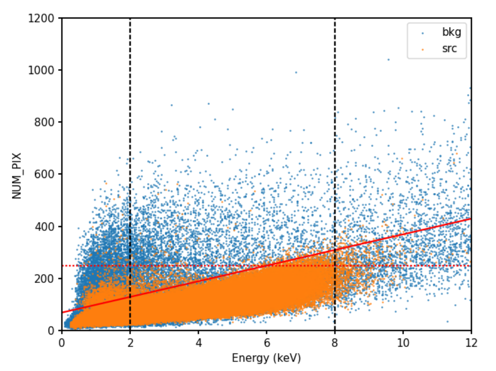
A refined background rejection approach

- Using a sample of IXPE observations:
  - source: inner 60” circular region
  - background: outer annular region from 150” up to 300”
- events in IXPE energy band [2–8] keV have been considered
- **3 parameters appear to be promising to identify source events**:
  - NUM_PIX: Number of active pixels in the event-track ROI
  - EVT_FRA: Fraction of the event energy in the track (PI major cluster/PI from all the clusters)
  - TRK_BORD: Number of border pixels in the track

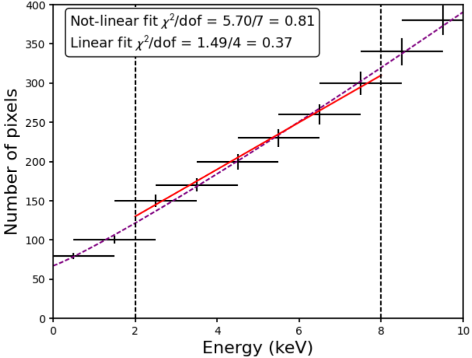
a refined rejection based on their energy dependence is shown here



Cyg X-2



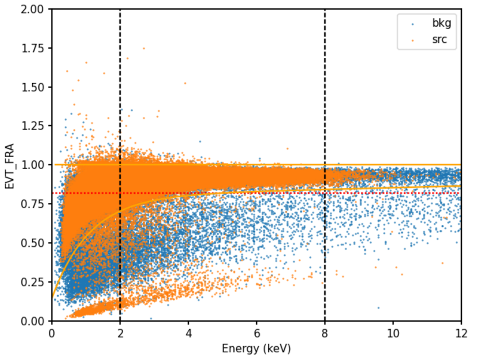
Fit



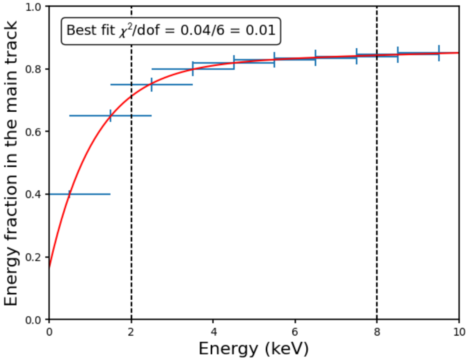
$$\text{NUM\_PIX} < 67 + 25\left(\frac{E}{keV}\right)^{1.11}$$

rejection: $\text{NUM\_PIX} < 70 + 30E[\text{keV}]$

Cyg X-2

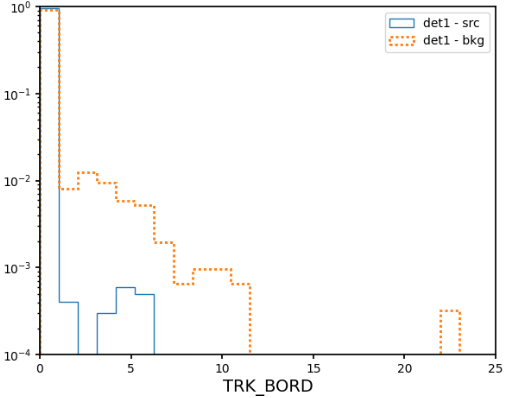


Fit



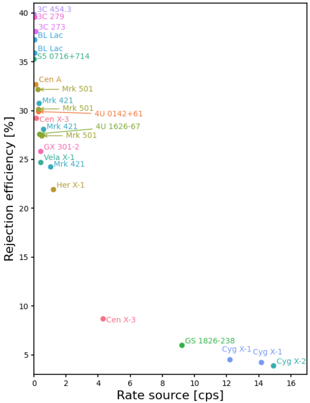
rejection: $0.8(1 - e^{-\frac{E[\text{keV}]+0.25\ [\text{keV}]}{1.1\ [\text{keV}]}}) + 0.004E[\text{ keV}] < \text{EVT\_FRA} < 1$

TRK_BORD



rejection: $TRK\_BORD < 2$

Rejection efficiency



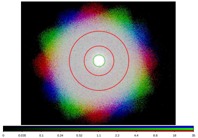
Source events must simultaneously satisfy the rejection conditions
For 4U 0142+16:

- 0.47% in 2–8 keV of events removed from the source – identified by spatial selection – and 0.59% in the whole energy band
- 35.78% in 2–8 keV events removed from the background – identified by spatial selection – and 25.39% of whole energy band

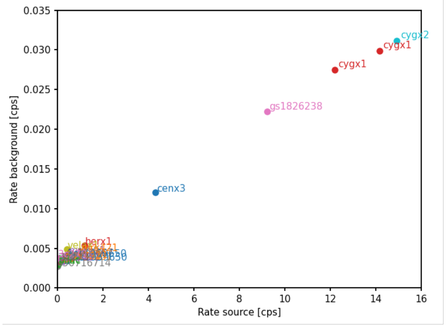
For Cyg X-2:

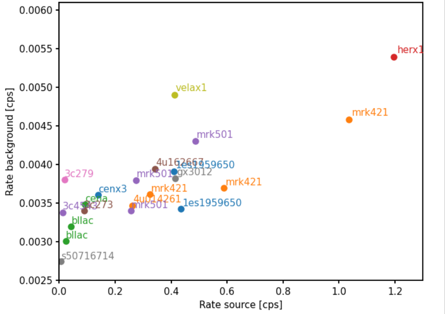
- 0.34% in 2–8 keV of events removed from the source and 0.36% in the whole energy band
- 5.32% in 2–8 keV of events removed from the background and 7.15% in the whole energy band

The rejection appears to be not so effective for Cyg X-2, why?

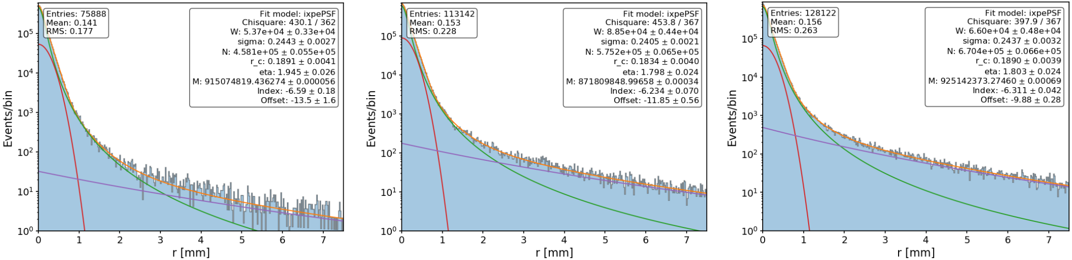


The source and the background counting rates – normalized at π arcmin^2 – for each observed point-like source have been estimated



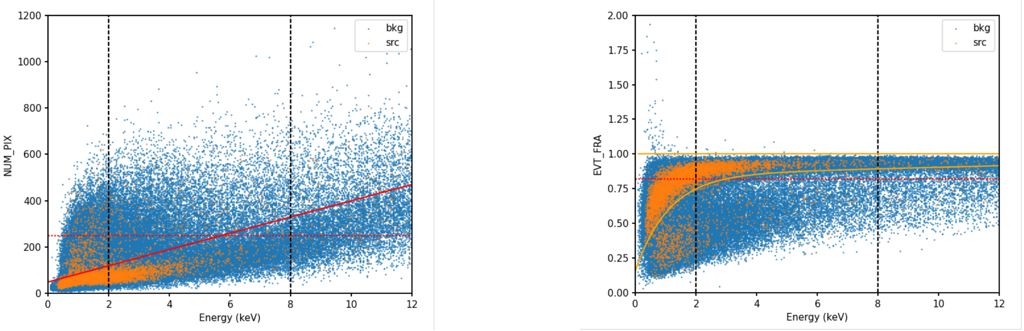


Background is overwhelmed by source because of PSF at high rate



Total PSF = Gaussian + King function + Power law

The effect may be due to the powerlaw component?

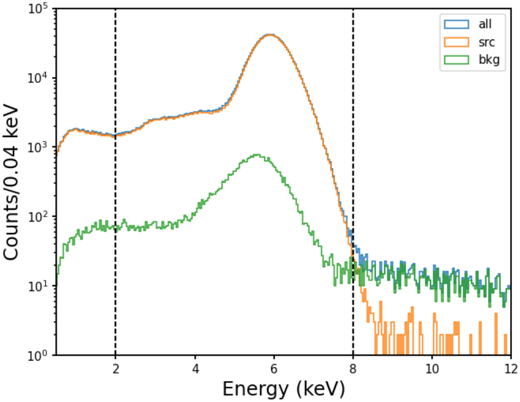


For this faint source:

- 16.5% of events in 2–8 keV are removed from the source region
- 41% of events in 2–8 keV are removed from the background region
- background rate 0.0027 cps per DU per π arcmin^2

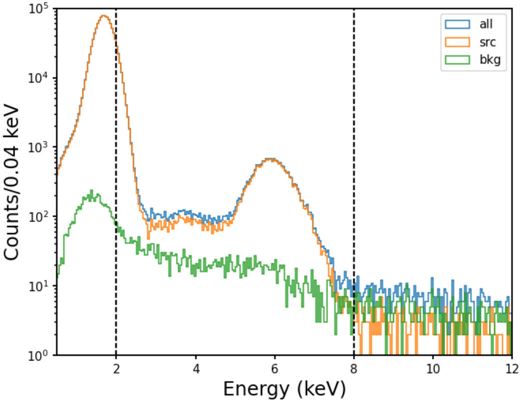
The new rejection is capable to reject up to $\sim$40% of background events

Cal C

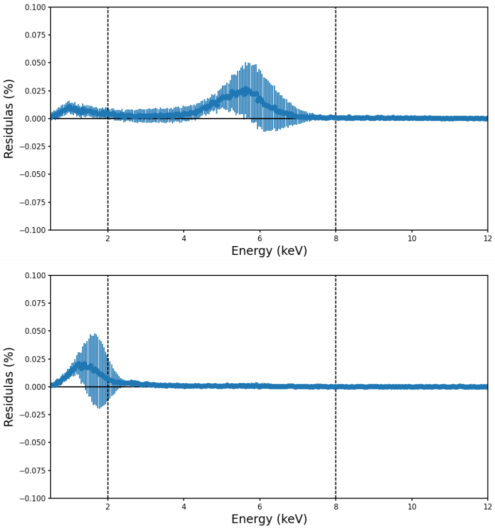


Rejected <2% of events

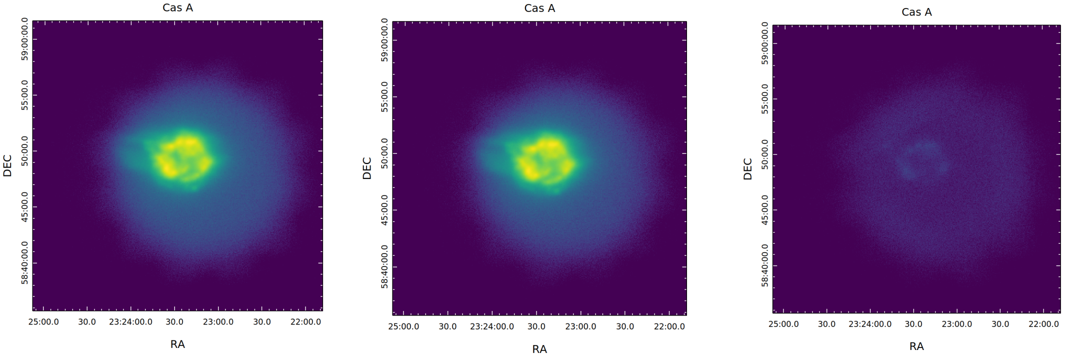
Cal D



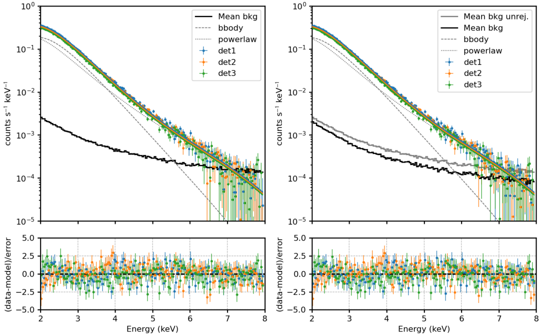
Rejected <2% of events

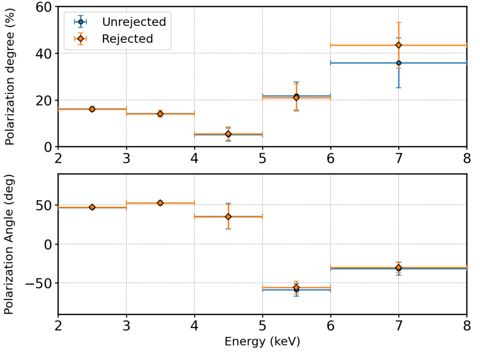


Effect on the response matrices is negligible



Cas A as a case study





- After rejection usually the χ^2 improves
- In the case of 4U 0142+16 the last bin significance pass from 1.5σ to 2.8σ

Suggested background approach

Some consideration:

- Background is proportional to the source counting rate $rate_{induced} \sim 0.0015 \times rate_{src}$
- $rate_{bkg} \sim 0.003$ cps/π arcmin^2 per DU in the limit of zero-counting rate source [0.0705 counts/sec/cm^{-2} that is $\sim$1.5 times the pre-launch simulated value]
- for $rate_{src} \sim 2$ cps we have $rate_{induced} \sim rate_{bkg}$
- for $rate_{src} \sim 1$ cps we have $rate_{induced} \sim 0.5 rate_{bkg}$

Possible prescription:

- source rate > 2 cps the background region is dominated by source events, rejection is not so effective, subtraction should be avoided
- source rate in [1–2] cps interval rejection can be applied, but subtraction should be avoided
- source rate < 1 cps the background is dominant both rejection and subtraction should be applied

A reference background could be estimated by using fainter sources
A. Di Marco et al., AJ 165 143 (2023)
Software available on: **https://github.com/aledimarco/IXPE-background**

Background rejection tool

```
usage: filter_background.py [-h]
[--output OUTPUT] path_lv2 path_lv1 [path_lv1 ...]

Filter a lv2 file based on a lv1 cut

positional arguments:
  path_lv2          Input file lv2
  path_lv1          Input file lv1

optional arguments:
  -h, --help        show this help message and exit
  --output OUTPUT   Output file: rej (includes only source events),
                             bkg (includes only rejected events) and
                             tag (includes a tag column where events
                                 having 1 are src and 0 are bkg)
```

How to use

- reject event_l2 files one DU per time
- to reject all the event_l1 files corresponding to the observation have to be listed after the event_l2

- Example:
  - ➥ ObsID 02007899 has event_l2: ixpe02007899_det3_evt2_v05_c01.fits
  - ➥ corresponding to event_l1: ixpe02007801_det3_evt1_v04.fits and ixpe02007802_det3_evt1_v04.fits

- output: rej to obtain a cleaned data-set without bkg events

```
python filter_background.py
ixpe02007899_det3_evt2_v05_c01.fits
ixpe02007801_det3_evt1_v04.fits ixpe02007802_det3_evt1_v04.fits
```