The hitchhiker's guide to the IXPE data analysis

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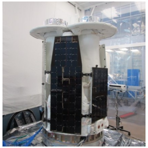
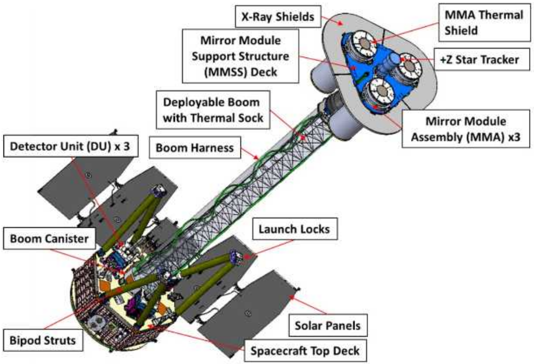
Imaging X-ray Polarimetry Explorer (IXPE)

- NASA-ASI SMall EXplorer mission dedicated to (linear) X-ray imaging polarimetry

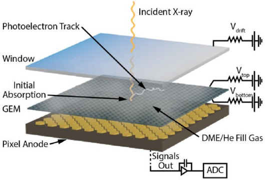
IXPE launch on 9 December 2021

Stowed Configuration





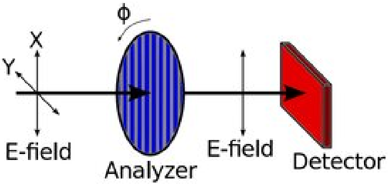
- Energy range: 2–8 keV
- 3 identical telescopes
  - ➥ Grazing-incidence X-ray mirrors (3+1 spare)
  - ➥ Imaging X-ray photoelectric polarimeters based on Gas Pixel Detector design (3+1 spare)
  - ➥ The two are separated by an extensible boom

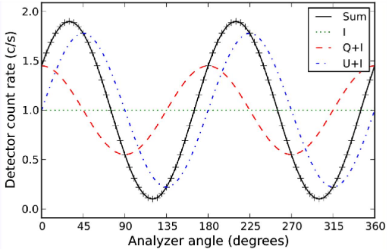


[M. Weisskopf,...A. Di Marco,...et al.,JATIS, 8 (2), 2022]

Introduction

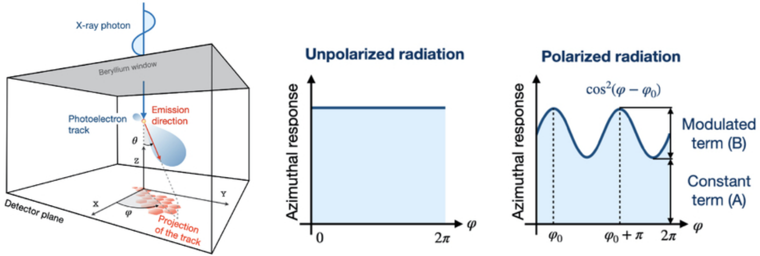
Measuring (linear) polarization





- Measure polarization by rotating the analyzer and finding the rate versus angle
- Angle where the modulation peaks gives the polarization angle
- Amplitude of modulation gives polarization degree (PD)
- Needing to take into account polarization sensitivity:
  - Use "modulation factor" μ that is the modulation for 100% polarized beam
  - PD $=$ modulation$/\mu$
- Stokes parameters are the amplitudes of the constant (I), cosine (Q), and sine (U) components

For IXPE we measure ϕ instead of rotating the analyzer



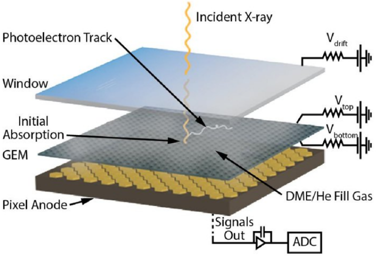
Dawoon E. Kim et al. 2024 JINST 19 C02028

- IXPE uses the photoelectric effect (dominant for X-ray with energy <10 keV) to measure linear polarization
  - ➥ Photoelectron ejected along photon E field (ϕ_0 angle in detector coordinates)

$$\frac{d\sigma_K}{d\Omega} \propto Z^5 E^{-7/2} \frac{sin^2\theta cos^2(\phi - \phi_0)}{(1+\beta cos^4\theta)}$$

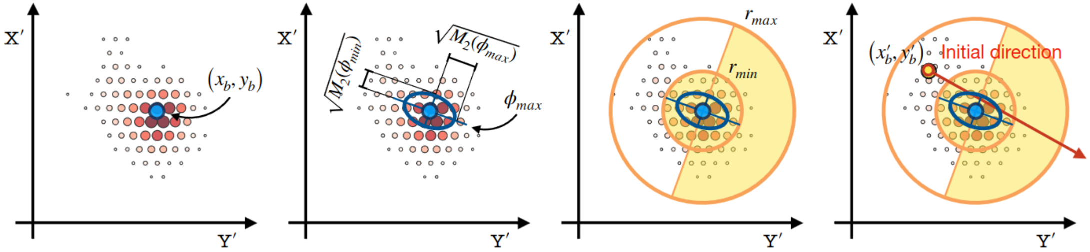
  - ➥ K-shell photoelectron emission modulated for linearly polarized radiation
  - ➥ key is to find photoelectron direction at interaction point

IXPE focal plane detectors



- X-rays absorbed in the gas gap
- Signal amplified via Gas Electron Multiplier (GEM)
- Finely pixelized ASIC as anode readout
- Full 2D imaging and spectroscopy
- Sensitive in the 2–8 keV energy band

- Baseline IXPE algorithm for track reconstruction based on moment analysis
- Some tracks are better reconstructed than others



How to determine polarization from tracks

As presented in A. Di Marco et al. AJ 164 (2022) 103: three possible approaches are available

Classical approach

Fitting with:

$$\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0),$$

modulation is:

$$M = \frac{\mathcal{M}_{max} - \mathcal{M}_{min}}{\mathcal{M}_{max} + \mathcal{M}_{min}} = \frac{B}{2A + B}$$

$PA = \phi_0$ and $PD = \frac{1}{\mu}\frac{B}{2A+B}$

Binned Stokes parameters

Strohmayer & Kallman ApJ 773 (2013) 103

Fitting with:

$$\mathcal{M}(\phi) = I + Q\cos(2\phi) + U\sin(2\phi)$$

$PD = \frac{\sqrt{U^2+Q^2}}{\mu I}$ and

$PA = \frac{1}{2}\arctan\left(\frac{u}{q}\right)$

Unbinned Stokes parameters

Kislat et al. AP 68 (2015) 45

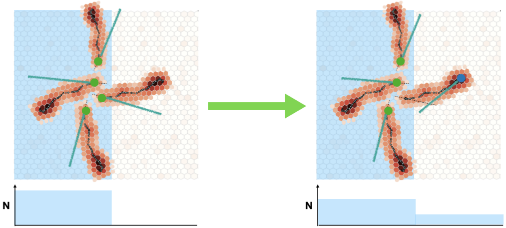
$$\begin{aligned} i_k &= 1 \\ u_k &= 2\sin 2\phi_k \\ q_k &= 2\cos 2\phi_k \\ I &= \sum i_k \\ U &= \sum u_k \\ Q &= \sum q_k \end{aligned}$$

IXPE approach: using event-by event Stokes parameters

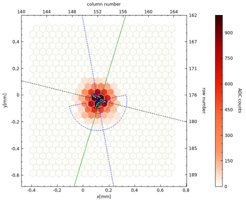
- Stokes parameters I, Q and U are almost independent (except large values of PD) and normally distributed
- They are additive allowing for subtraction of multi-components (useful for both instrumental and astrophysical analyses)
- Unbinned event-by-event analysis is possible

- Correction for spurious effects applied event-by-event:
  - ➥ $i_k = i_{m,k}$ $\quad q_k = q_{m,k} - q_{sm,k}$ $\quad u_k = u_{m,k} - u_{sm,k}$
  - ➥ sm Stokes parameters measured for unpolarized radiation and they depend on energy and position on the detector [Rankin+ AJ 163 (2022) 39]
- **A 'weighted' approach can be applied and systematical effects can be easily removed**

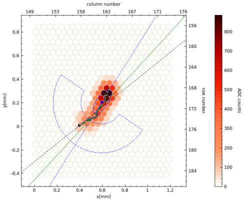
- In the IXPE algorithm for track reconstruction some tracks are better reconstructed than others



Bucciantini et al., A&A 672, A66 (2023)



Round track at $\simeq 4$ keV



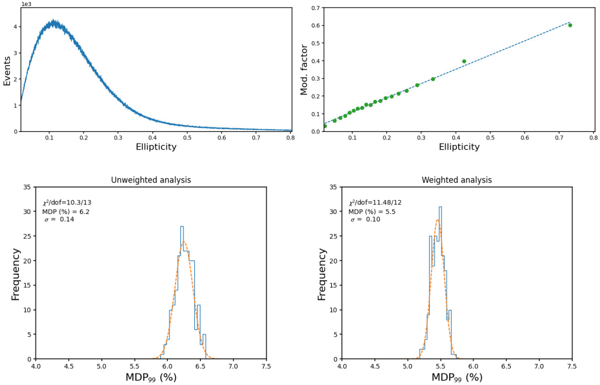
Linear track at $\simeq 4$ keV

- In standard analysis every track has the same impact on the estimate of polarization parameters
- Is there a way to evaluate the different contribution of different tracks? (e.g. efficiency $\simeq 0$ for rounded tracks and $\simeq 1$ for linear ones) $\rightarrow$ **weights!**

Best-weight parameter choice I

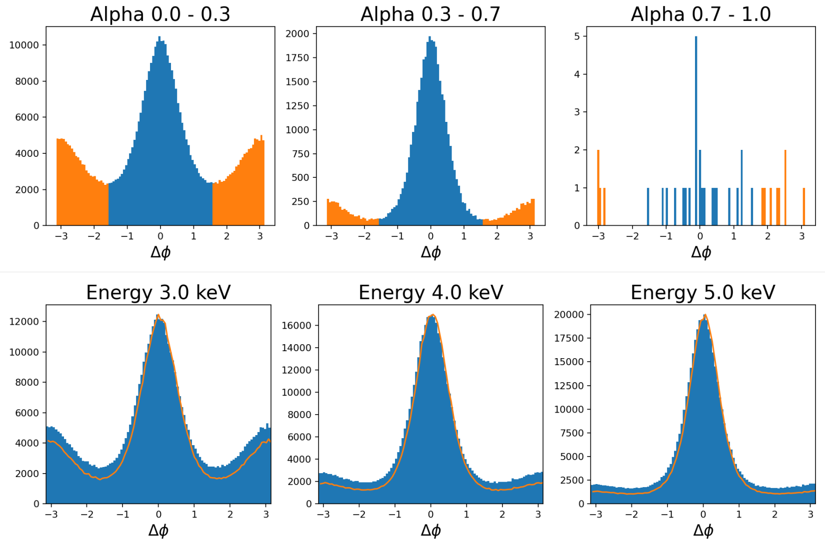
- **μ is the best-weight parameter**
- Tested several parameters determined by the track analysis
- **The best proxy for μ is the track ellipticity**
  - ➥ $\alpha = \frac{TL-TW}{TL+TW}$
  - ➥ defined in the range [0;1] (0 for circular tracks and 1 for linear ones)
  - ➥ not energy-proxy
- Monte Carlo simulation of a source with a power-law energy spectrum (index -2)
- several functions of α have been considered as a weight
- α^{λ} gave the best performance

Di Marco et al., AJ 163 (2022) 170



$\alpha^{0.75}$ allows to improve significance of 13%

Bonus: reduction of polarization leakage



Event-by-event weighted Stokes parameters I

Using the approach of Kislat et al., AP 68 (2015) 45 and Di Marco et al., AJ 163 (2022) 170

Unweighted analysis

$$\begin{aligned} i_k &= 1 \\ u_k &= 2\sin 2\phi_k \\ q_k &= 2\cos 2\phi_k \end{aligned}$$

Weighted analysis

$$\begin{aligned} i_k &= w_k \\ u_k &= 2w_k \sin 2\phi_k \\ q_k &= 2w_k \cos 2\phi_k \end{aligned}$$

Overall values

$$\begin{aligned} I &= \sum i_k \\ U &= \sum u_k \\ Q &= \sum q_k \end{aligned}$$

Following the angular distribution:

$$f(\phi) = \frac{1}{2\pi}\left(1 + \mathcal{P}\mu\cos(2(\phi-\phi_0))\right)$$

- $\mathcal{P}$ is the polarization degree
- ϕ_0 is the polarization angle
- μ is the modulation factor

Event-by-event weighted Stokes parameters II

The expected $\mathcal{U}$ and $\mathcal{Q}$ values are:

$$\begin{aligned}
\langle \mathcal{Q} \rangle &= \sum_{k=1}^{N} 2 w_k \int_0^{2\pi} \cos 2\phi f(\phi) d\phi = \mathcal{I}\mathcal{P}\mu \cos(2\phi_0) \\
\langle \mathcal{U} \rangle &= \sum_{k=1}^{N} 2 w_k \int_0^{2\pi} \sin 2\phi f(\phi) d\phi = \mathcal{I}\mathcal{P}\mu \sin(2\phi_0)
\end{aligned}$$

and the variance is given by:

$$\begin{aligned}
Var(\mathcal{Q}) &= W_2 \int_0^{2\pi} \left(2\cos 2\phi - \mathcal{P}\mu\cos(2\phi_0)\right)^2 f(\phi) d\phi = W_2 \left[2 - \mu^2\mathcal{P}^2\cos^2(2\phi_0)\right] \\
Var(\mathcal{U}) &= W_2 \left[2 - \mu^2\mathcal{P}^2\sin^2(2\phi_0)\right] \\
W_2 &= \sum_{k=1}^{N} w_k^2
\end{aligned}$$

$$
\begin{aligned}
I &= \sum w_k \\
Q_r &= \frac{2}{\mu} \sum w_k \cos 2\phi_k \\
U_r &= \frac{2}{\mu} \sum w_k \sin 2\phi_k \\
W_2 &= \sum w_k^2
\end{aligned}
$$

$$
\begin{aligned}
\sigma_{Q_r} &= \sqrt{\frac{W_2}{\mathcal{I}^2}\left(\frac{2}{\mu^2} - Q_r^2\right)} \\
\sigma_{U_r} &= \sqrt{\frac{W_2}{\mathcal{I}^2}\left(\frac{2}{\mu^2} - U_r^2\right)} \\
\rho(Q_r, U_r) &= -\frac{\mathcal{P}_r^2 \sin(4\phi_r)}{\sqrt{16 - 8\mathcal{P}_r^2 + \mathcal{P}_r^4 \sin^2(2\phi_r)}}
\end{aligned}
$$

then the polarization degree and angle are:

$$
\begin{aligned}
\mathcal{P} &= \frac{\sqrt{U_r^2 + Q_r^2}}{I} \\
\phi_0 &= \frac{1}{2} \arctan\left(\frac{U_r}{Q_r}\right)
\end{aligned}
$$

$$
\begin{aligned}
\sigma_{\mathcal{P}} &\approx \sqrt{\frac{1}{N_{eff} - 1}\left(1 - \frac{\mathcal{P}^2\mu^2}{2}\right)} \\
\sigma_{\phi_0} &\approx \frac{1}{\mathcal{P}\mu\sqrt{\frac{1}{N_{eff} - 1}}} \qquad N_{eff} = I^2/W_2
\end{aligned}
$$

How to determine the polarimetric significance I

We can start from posterior probability [Kislat et al., AP 68 (2015) 45 & Di Marco et al., AJ 163 (2022) 170]

$$P(\hat{\mathcal{P}}, \hat{\phi}_0 | \mathcal{P}, \phi_0) = \frac{\sqrt{N_{eff}}\hat{\mathcal{P}}^2\mu^2}{2\pi\sigma} \times exp\left(-\frac{\mu^2}{4\sigma^2}\left[\hat{\mathcal{P}}^2 + \mathcal{P}^2 - 2\hat{\mathcal{P}}\mathcal{P}\cos(2(\phi_0 - \hat{\phi}_0)) - \frac{\hat{\mathcal{P}}^2\mathcal{P}^2\mu^2}{2}\sin^2(2(\phi_0 - \hat{\phi}_0))\right]\right)$$

The **Minimum Detectable Polarization (MDP)** is the maximum polarization which we expect to measure with a probability of 99% when the true polarization is zero because of possible statistical fluctuations:

$$0.99 = \int_0^{2\pi}\int_0^{MDP} P(\hat{\mathcal{P}}, \hat{\phi}_0 | \mathcal{P} = 0, \phi_0) d\hat{\mathcal{P}} d\hat{\phi}_0 \quad \rightarrow \quad MDP_C = \sqrt{-2\ln(1 - C)}\sigma_{\mathcal{P}}$$

Weighted analysis $MDP_{99\%} = \frac{4.29\sqrt{W_2}}{\mu I} = \frac{4.29}{\mu\sqrt{N_{eff}}} \ (N_{eff} = \frac{I^2}{W_2} < N)$

Cuts are a strong weight with two event families: good (weight=1) and bad (weight=0)

Unweighted analysis $MDP_{99\%} = \frac{4.29}{\mu\sqrt{N}}$

Example:

I measure PD$=3.0 \pm 1.1\%$ *and MDP is 3.9%*

Significance $= \frac{PD}{\sigma_{PD}} = 2.7$ 2.7σ significance corresponds to $\geq 99\%$ confidence level with Gaussian uncertainties, but my PD value is below MDP... why?

How to determine the polarimetric significance III

Because I am evaluating two different things... MDP is the maximum polarization degree I can reach if the source is unpolarized, then the PD is assumed 0!

But I measured a polarization of 3.0% with uncertainty at 1.1% its significance is about 99% CL

Furthermore... I am assuming no correlation of parameters and Gaussian uncertainties, it holds only for high signal-to-noise measurement!

Weisskopf, Elsner, O'Dell, arXiv:1006.3711

Uncertainties for two correlated parameters, such as PD and PA, should be represented in a plane with an allowed region at a given confidence level

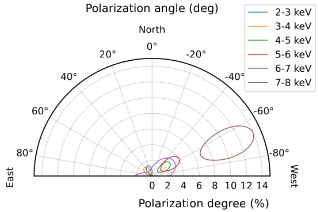
- Same approach of MDP, but PD$\neq$ 0 and CL is no more 0.99 but the one you prefer:

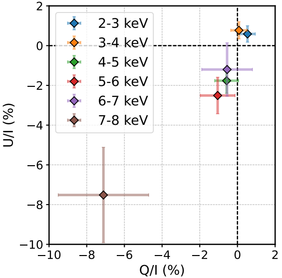
$$\mathcal{P} = \sqrt{\mathcal{P}_0^2 + \Delta_{\rm CL}^2 + 2\mathcal{P}_0\Delta_{\rm CL}\cos(\phi - 2\phi_0)}$$

$$\phi = \frac{1}{2}\arctan\frac{\mathcal{P}_0\sin(2\phi_0) + \Delta_{\rm CL}\sin\phi}{\mathcal{P}_0\cos(2\phi_0) + \Delta_{\rm CL}\cos\phi}$$

- $\Delta_{CL} = \Delta\chi^2$

CL (%)	Δ_{CL}
50	1.386
90	4.605
99	9.210

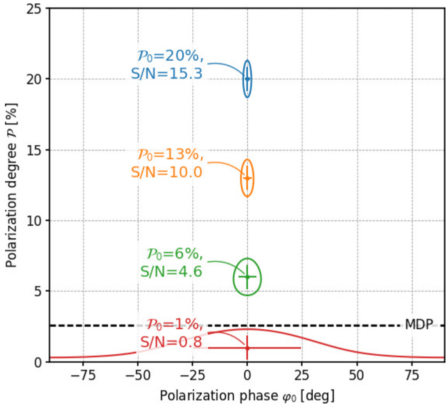




1D or 2D uncertainties?

- Not significant $PD/\sigma_{PD} < 1$: contours of the allowed region are opened $\rightarrow$ 2D is a better representation
- Low significance $PD/\sigma_{PD} < 3$: contours of the allowed region are closed but not symmetric $\rightarrow$ 2D is a better representation
- High significance detection show symmetric regions $\rightarrow$ 1D can be used, but in any case the uncertainties are underestimated

- IXPE Statistic guide:
  - probable detection: 99% CL
  - highly probable detection 99.9% CL
  - secure detection 99.99% CL



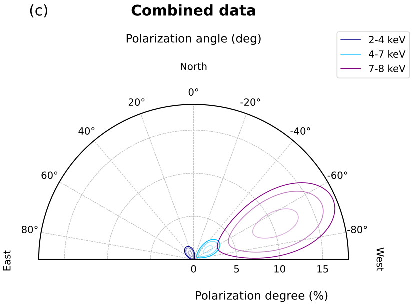
- In case data are binned in J bins (trials), the significance is given by:

$$\chi^2 = \sum_{k=1}^{J} (\mathrm{PD}_k - (\mathrm{PD}_0 = 0))^2 / \sigma_k^2$$

and the significance is the χ^2 Probability Cumulative Distribution Function (P_{CDF}) for $2J$ degree of freedom

Example:

- 4U 1820–303 show PD$= 0.7^{+0.4}_{-0.7}$% in 2-8 keV
  - ➥ 2–4 keV: $PD = 0.8 \pm 0.3\%$
  - ➥ 4–7 keV: $PD = 2.0 \pm 0.5\%$
  - ➥ 7–8 keV: $PD = 10 \pm 2\%$
- 3 energy bins $\rightarrow \chi^2 = 48.1$
- It means that the χ^2 for compatibility with null polarization is $48.1/6$
  - ➥ Null polarization is excluded at 99.99997%



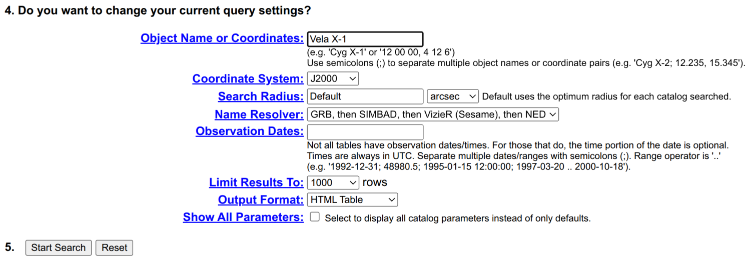
IXPE data

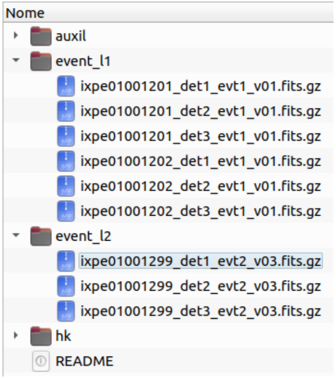
Overview

- **Target observed by IXPE are available in the As-run page:** https://ixpe.msfc.nasa.gov/for_scientists/asrun.html
- **Official SOC page at NASA-MSFC:** https://ixpe.msfc.nasa.gov/index.html
- **Official page on HEASARC** https://heasarc.gsfc.nasa.gov/docs/ixpe/
- **IXPE-specific CALDB** https://heasarc.gsfc.nasa.gov/docs/ixpe/caldb/
- **HEASoft FTOOL specific for IXPE** https://heasarc.gsfc.nasa.gov/lheasoft/ftools/headas/ixpe.html
- **Documentation** https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/
- **IXPE Contributed software** https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/contributed.html

Custom Python-based software is provided by the IXPE collaboration: IXPEOBSSIM: https://ixpeobssim.readthedocs.io/en/latest/

- Data can be downloaded from IXPE Master Catalog (IXMASTER) on HEASARC



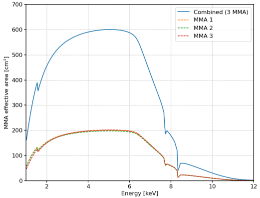


wget -q -nH –no-check-certificate –cut-dirs=5 -r -w1 -l0 -c -N -np -R ’index*’ -erobots=off –retr-symlinks https://heasarc.gsfc.nasa.gov/FTP/ixpe/data/obs/01//01002501/

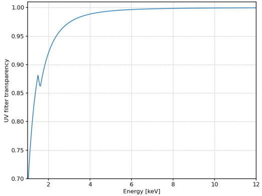
- Source spectrum has to be convoluted for the instrumental response before comparing it with real data in a fit

$$S_m(E) = \int_{E'} S_s(E')\epsilon(E')R(E',E)dE'$$

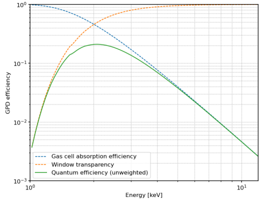
- ➥ $S_m(E)$ is the measured spectral distribution
- ➥ $S_s(E')$ is the spectral distribution from the source
- ➥ $\epsilon(E')$ is the effective area that quantifies the collecting area as a function of energy
- ➥ $R(E',E)$ is the probability that a photon of energy E' is detected in channel E



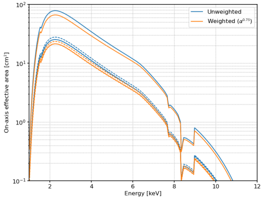
Optics



UV filters



GPD efficiency



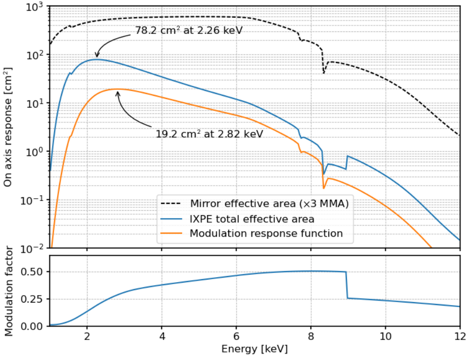
Effective area

- This approach can be extended to polarimetry in a Spectro-polarimetric analysis [Strohmayer ApJ 838 (2017) 72]
  - We need models for Stokes parameters I, Q, U
  - We need to account for the modulation factor as a function of energy $\mu(E)$

$$I_m(E) = \int_{E'} I_s(E')\epsilon(E')R(E',E)dE'$$

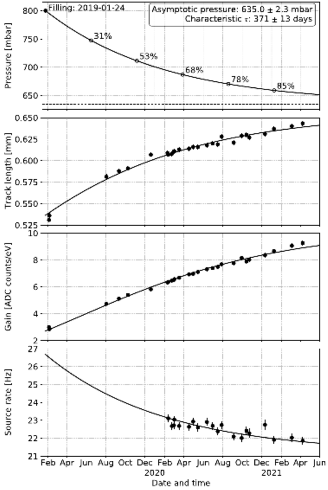
$$U_m(E) = \int_{E'} U_s(E')\mu(E')\epsilon(E')R(E',E)dE'$$

$$Q_m(E) = \int_{E'} Q_s(E')\mu(E')\epsilon(E')R(E',E)dE'$$



Response functions and IXPE CALDB III

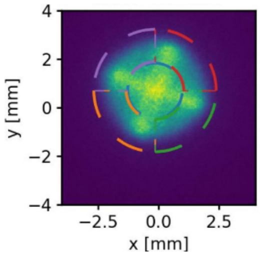
- IXPE has the following response files:
  - energy dispersion (.rmf) $R(E', E)$
  - effective area (.arf) $\epsilon(E')$
  - modulation response function (.mrf) $\mu(E')\epsilon(E')$
- If you are familiar with XSPEC, the .arf and .rmf files have exactly the meaning that you would expect, while the .mrf files have the exact same format as the .arf files but for U and Q spectra
- responses are provided for 3 possible cases: weighted-NEFF (alpha075), UNWEIGHTED and SIMPLE (alpha075simple)
- for bright sources responses are provided for the usage of a grey-filter

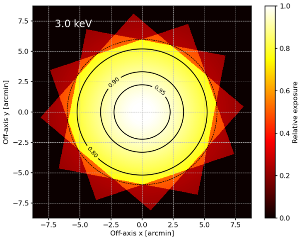


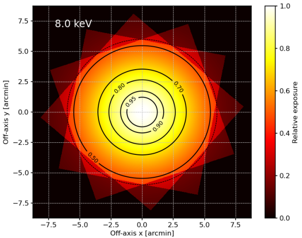
- a tool provides you proper responses: `ixpecalcarf`

IXPE CALDB updates at ∼6-month cadence

IXPE images: source selection and data cleaning

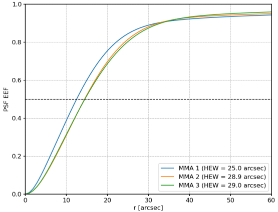






Although one detector has a FoV$\sim$ 13 arcmin^2, due to dithering and the clock of the 3 DUs the FoV reduces to 9 arcmin^2 or less

- IXPE PSF is $\sim$30 arcsec in radius
- No selection smaller than a circle having radius 30 arcsec



Impact of background on polarimetric observations

$$MDP_{99} = \frac{4.29}{\mu\sqrt{S}}\sqrt{\frac{S+B}{T}}$$

- 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:

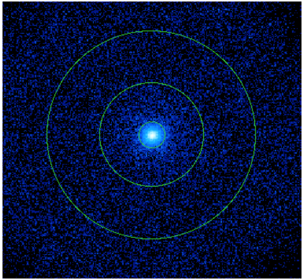
$$P_{detected} = P_{source}\left(1 + \frac{rate\ of\ \ background}{rate\ of\ \ source}\right)^{-1}$$

  - ➥ background needs to be carefully rejected

Background mitigation in data analysis

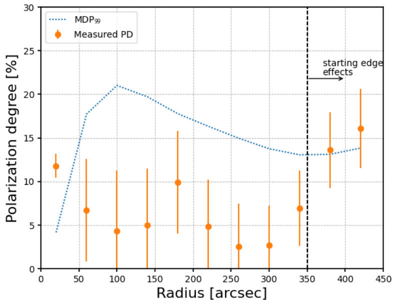
- Depending on the detector architecture, events due to charged particles can be recognized and filtered out
- In imaging detectors it is possible to select the background and the source regions
- In case of no-imaging and no rejection is possible a refined modeling for the background is needed
  - ➥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

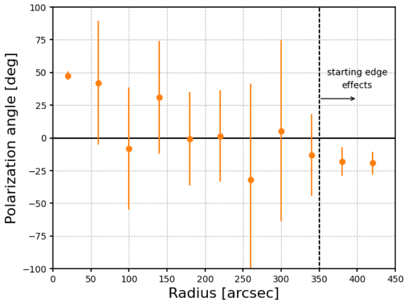
- In A. Di Marco et al., AJ 165 143 (2023), 18 point-like sources used to systematically study IXPE background



- 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?

Background selection with annular regions

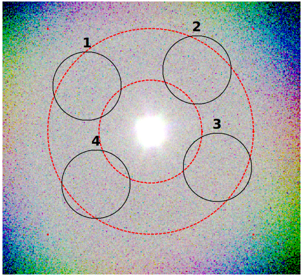


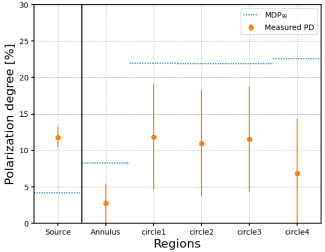


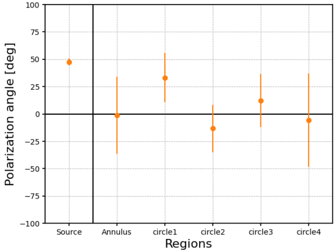
- Using data from 4U 0142+16 with a long exposure time:
  - image centered using a Gaussian fit
  - several radii have been applied with a ∼ 40 arcsec step
  - polarization effects from the source are present up to ∼ 100 arcsec
  - from ∼350–400 arcsec border effect starts to be present
  - from 500 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**

Background selection with circular regions

- Using data from 4U 0142+16 with a long exposure time:
  - 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

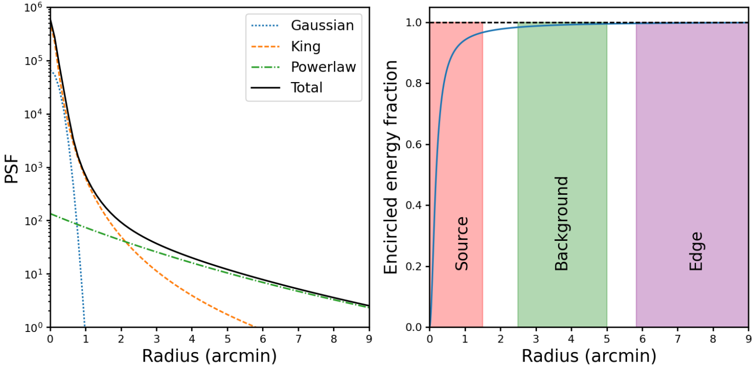






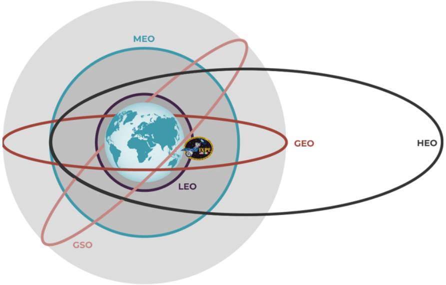
- **the best approach is to select an annular region with inner radius 150 arcsec and outer radius 300 arcsec**

Source and background selection



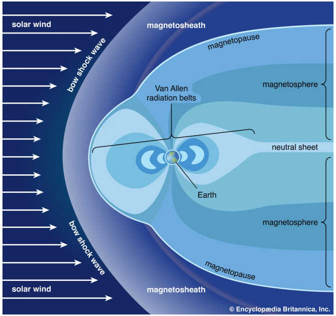
Source should be selected in a central circular region with radius at least 30" up to 100"
Background should be selected in an annular centered region with radius between 150" and 300"

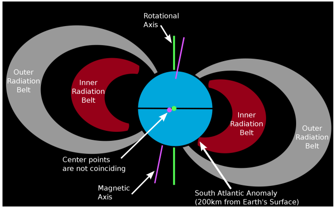
X-ray observatories orbits



- **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): are highly eccentric orbits bringing the satellite closer to the Earth on one end and far away on the other (e.g. XMM-Newton)
- **Lagrangian Points**: equilibrium points at 1.5 million km from Earth (e.g. Planck)

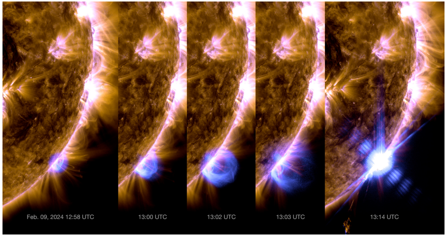
Geomagnetic field





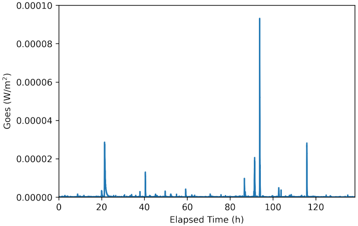
- Earth surrounded by the geomagnetic field (magnitude about 0.5 G at surface)
- First approximation (good especially at lower altitudes) the geomagnetic field can be described by an inclined dipole offset from Earth center by about 500 km and tilted by about 10° with respect to the rotation axis
- At 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

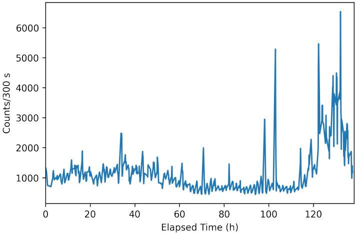
Background: Solar particles



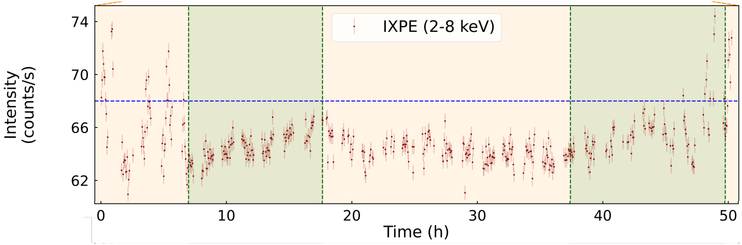
- Solar wind + continuous stream of soft (< 10 keV) charged particles (electrons, protons, ...) produced and accelerated in the solar corona
- Sun also emits the so-called solar energetic particles (SEP), for which the kinetic energies can range from 10 keV to GeVs
- SEP produced by solar flares and 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

Observation: Vela X-1 (obsID=01002501)





- When strong solar activity is present:
  - ➥ it affects SAA amplitude
  - ➥ in IXPE light curve we observe the effects of solar activity
- Earth occultation and SAA passages result in interruptions in the light curve



GX 349+2

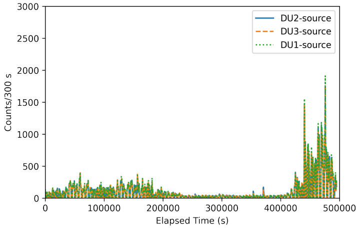
Light curve to check possible anomalies II

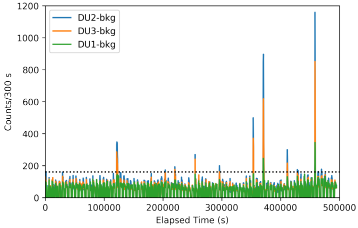
- To identify to remove spikes due to background form the data:
  - Align images in 3 DUs (if needed this is reported in a README) or produce three different source/background regions to select source and background
  - use xselect or ftselect for the selection
    `xselect @xselect_sel_region1.txt`
- In the background LC we observe spikes that can be removed using a cut given by:

$$R_{DU1} + 3 \times \sigma_{R_{DU1}}$$

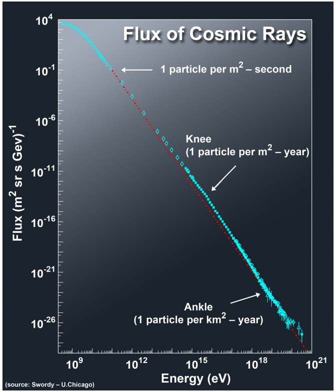
- Use xselect for time filtering with new GTIs
  `xselect @xselect_sel_time_src1.txt`

See jupyter-notebook cleaning_gtis.ipynb





Background: Cosmic rays



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):

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

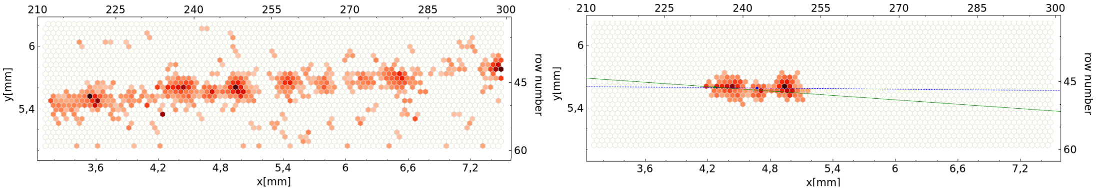
A refined background rejection approach

A. Di Marco et al., AJ 165 143 (2023)

Software available on: **https://github.com/aledimarco/IXPE-background**

- 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



How it works

```
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

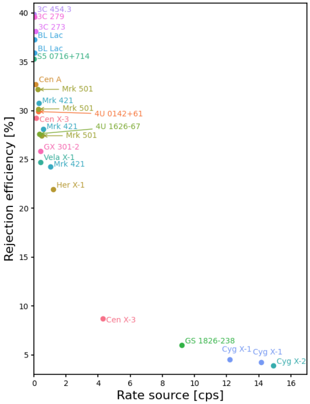
```
python filter_background.py
ixpe02007899_det3_evt2_v05_c01.fits
ixpe02007801_det3_evt1_v04.fits ixpe02007802_det3_evt1_v04.fits
```

How to use after December 2024

Data processed by SOC after 18 Dec 2024 have a flag for particle background

```
ftselect clobber=yes
./event_l2/ixpe04000099_det1_evt2_v??.fits
./event_l2/ixpe04000099_det1_evt2_rej.fits
status.NE.bxxxxxxx1xxxxxxxx
```

```
ATE     = '2025-09-16T14:39:41.681' / FITS File creation date
REATOR  = 'ixpesciobsort'      / Software that produced the file
REAT_ID= '1.9.3   '            / Version of software that created the file
RIGIN   = 'MSFC    '           / Location where the FITS file was created
BSERVER= 'DI MARCO; ALESSANDRO'
ILE_TYP= 'EVENTS  '            / File type
CW_POS  =                    0 / Commanded Hall position
A_OBJ   =            273.63146 / Right Ascension of target in J2000
EC_OBJ  =            -17.15742 / Declination of target in J2000
BJECT   = 'GX 13+1 '           / Source name
DUCLASS= 'OGIP    '            / format conforms to OGIP standard
DUCLAS1= 'EVENTS  '            / Conforms to format defined in "The Proposed Tim
ILE_LVL= '2       '            / Level of file of this type
ILE_VER= '1.0     '
ROCVER  = '00.02   '           / Processing version
OFTVER  = 'Hea_26Mar2025_V6.35.1_IXPE_03MAR2025_1.10' / HEASOFT and IXPE specifi
LM2FITS= '1.10    '            / Software version number in the form AA.BB, wher
PTGAIN  =                    T / Temperature gain correction applied
PPKGAIN=                     T / Peak Gain correction applied
PSTOKES=                     T / Spurious Modulation correction applied
PWEIGHT=                     T / Event-by-event weights calculated
PADJMOD=                     T / Spurious Modulation correction applied
PFLGBGD=                     T / A. Di Marco et al., AJ 165 143 (2023)
PBOMCOR=                     T / Boom drift correction applied to image
PASPCOR=                     T / Aspect correction applied to image
PIXMEAN=  305.97273276731426  / Value (pixel) of ixpeaspcorr input parameter 'x
PIXMEAN=  303.98945667521434  / Value (pixel) of ixpeaspcorr input parameter 'y
V2_VER  =                    1 / The version of the LV2 file format
OLCCONV= 'IAU     '            / Stokes coordinates follow IAU convention
INLIVET=                    15 / [us] Reject all events .le. this value.
TYPE1   = 'TRG_ID  '
FORM1   = 'J       '
TYPE2   = 'TIME    '
FORM2   = 'D       '
UNIT2   = 's       '
TYPE3   = 'STATUS  '
FORM3   = '16X     '
TYPE4   = 'STATUS2 '
```



Source events must simultaneously satisfy the rejection conditions

For 4U 0142+16:

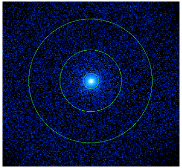
- 0.47% in 2–8 keV of events removed from the source – identified by spatial selection – and 0.59% in the whole energy band
- 35.78% in 2–8 keV events removed from the background – identified by spatial selection – and 25.39% of whole energy band

For Cyg X-2:

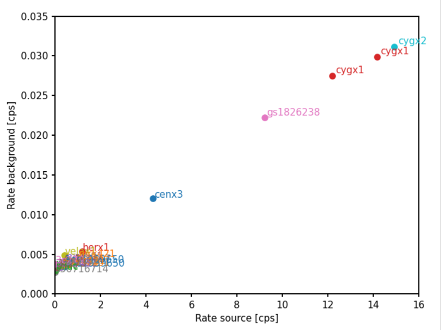
- 0.34% in 2–8 keV of events removed from the source and 0.36% in the whole energy band
- 5.32% in 2–8 keV of events removed from the background and 7.15% in the whole energy band

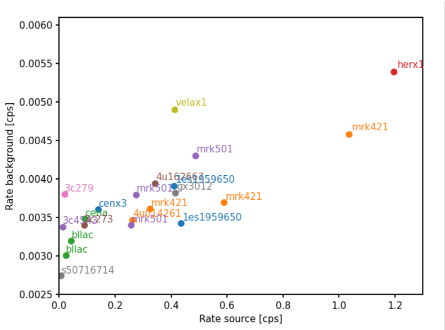
The rejection appears to be not so effective for Cyg X-2, why?

Background vs Source rates



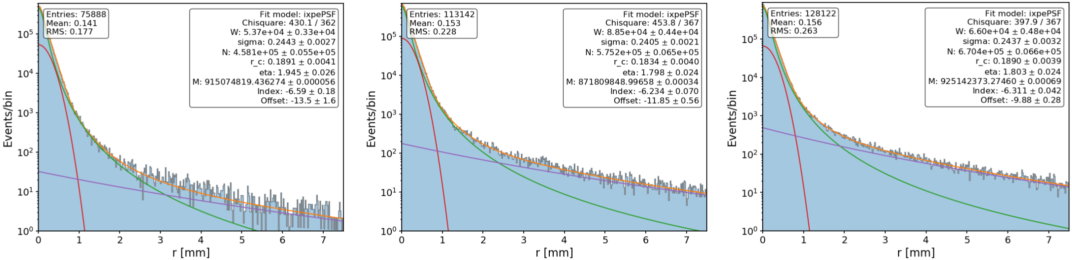
The source and the background counting rates – normalized at π arcmin^2 – for each observed point-like source have been estimated





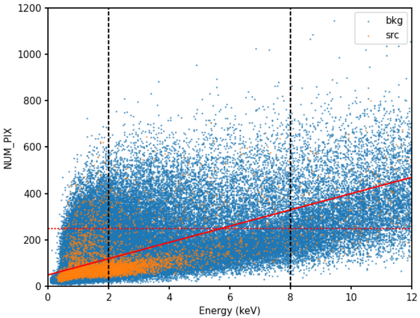
Background is overwhelmed by source because of PSF at high rate

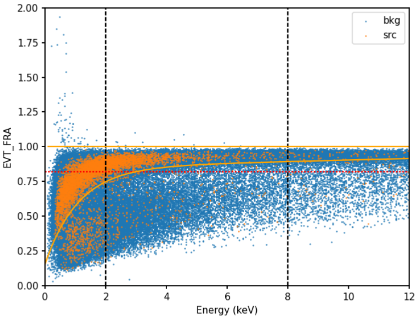
Possible explanation



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

Background: Cosmic X-ray

- 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 $< 10^\circ$)

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**

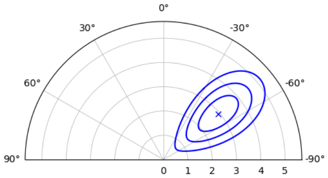
Polarimetric analysis

How to extract polarimetric information I

- **Only after background rejection (needing level 1 files comparison) you can apply timing corrections e.g.** `barycorr`
  - Here I will focus on polarimetric and spectro-polarimetric analysis

- **Model independent analysis**:
  - IXPEOBSSIM: https://ixpeobssim.readthedocs.io/en/latest/index.html
  - `ixpe_protractor.py`
    https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/contributed/ixpe_protractor.html

```
python3 ixpe_protractor.py
ixpe01002501_det?_evt2_v02_src_gti_rej.fits
--region=src.reg --eband='2.0 8.0'
```



Energy band 2.0 to 8.0

Det	PD (%)	PA (deg)	Counts	U	Q	mod	MDP99
DU1	1.99 ± 1.14	-42.8 ± 16.4	119738	0.002±0.011	-0.020±0.011	0.406	3.4
DU2	3.41 ± 1.12	-56.1 ± 9.4	115925	-0.013±0.011	-0.032±0.011	0.418	3.4
DU3	3.52 ± 1.14	-48.3 ± 9.3	113766	-0.004±0.011	-0.035±0.011	0.414	3.5
Sum	2.92 ± 0.65	-50.1 ± 6.4	349429	-0.005±0.007	-0.029±0.007	0.413	2.0

How to subtract the background I

- using `ixpe_protractor` we estimate polarization for source

```
Energy band 2.0 to 8.0
Det    PD (%)           PA (deg)        Counts  U               Q              mod    MDP99
DU1    1.99 ± 1.14    -42.8 ± 16.4    119738   0.002±0.011  -0.020±0.011   0.406    3.4
DU2    3.41 ± 1.12    -56.1 ±  9.4    115925  -0.013±0.011  -0.032±0.011   0.418    3.4
DU3    3.52 ± 1.14    -48.3 ±  9.3    113766  -0.004±0.011  -0.035±0.011   0.414    3.5
Sum    2.92 ± 0.65    -50.1 ±  6.4    349429  -0.005±0.007  -0.029±0.007   0.413    2.0
```

- using `ixpe_protractor` we estimate polarization for background

```
Det    PD (%)           PA (deg)        Counts  U               Q              mod    MDP99
DU1    5.11 ± 3.45     75.9 ± 19.4     13816  -0.045±0.034   0.024±0.035   0.394   10.5
DU2    6.47 ± 3.14    -74.2 ± 13.9     17453  -0.055±0.031  -0.034±0.032   0.387    9.6
DU3    8.56 ± 3.25     25.1 ± 10.9     16177   0.055±0.032   0.066±0.033   0.389    9.9
Sum    2.29 ± 1.89     65.4 ± 23.6     47446  -0.015±0.019   0.017±0.019   0.390    5.7
```

- We have U_r and Q_r from slide 15 divided by I_r

How to subtract the background II

$$\begin{aligned} I_m &= I_{src} + \zeta I_{bkg} \\ Q_m &= Q_{src} + \zeta Q_{bkg} \\ U_m &= U_{src} + \zeta U_{bkg} \end{aligned} \quad \Rightarrow \quad \begin{aligned} I_{src} &= I_m - \zeta I_{bkg} \\ Q_{src} &= Q_m - \zeta Q_{bkg} \\ U_{src} &= U_m - \zeta U_{bkg} \end{aligned}$$

here $\zeta = \frac{A_{src} T_{src}}{A_{bkg} T_{bkg}}$

- we have $T_{bkg} = T_{src}$, $A_{src} = \pi \times 90^2$ arcsec^2 ~ 25447 arcsec^2 and $A_{bkg} = \pi \times (300^2 - 150^2)$ arcsec^2 ~ 212058 arcsec^2
- Thus $\zeta \sim 0.12$
- From this value we obtain:
  - $\mathrm{I}_{src} = 349429 - 0.12 * 47446 = 343735$
  - $\mathrm{Q}_{src} = -10133,441 - 0.12 * 806.582 = -10230,23084$
  - $\mathrm{U}_{src} = -1747,145 - 0.12 * (-711,69) = -1661,7422$

How to subtract the background III

- For the uncertainties:

$$\sigma_{src} = \sqrt{\sigma_m^2 + \zeta^2 \times \sigma_{bkg}^2}$$

- So we obtain:
  - ➥ $Q_m/I_m = -0.030 \pm 0.007$
  - ➥ $U_m/I_m = -0.005 \pm 0.007$
  - ➥ $PD = (3.0 \pm 0.7)\%$
  - ➥ $PA = (-50 \pm 6)^\circ$
- For this bright source there is no impact from background!

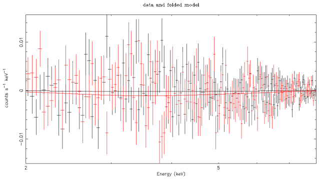
Data extraction for model-dependent analysis

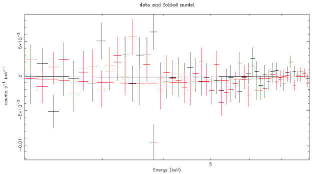
- Model-dependent analysis is based on XPSEC
- Data can be extracted with XSELECT or the new tool `ixpestartx`
  https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/contributed/ixpestartx.html
  - `ixpestartx 01002501 neff /path/to/src.reg /path/to/bkg.reg`
  - this tool extract spectra and .arf/.mrf using attitude and a .xcm to open data in XSPEC
- 3 possible extractions for IXPE spectra: neff, simple, unweighted
- response files available in caldb or tailored for the observation by `ixpecalcarf`
  https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/help/ixpecalcarf.py.html

Load data and rebinning

- IXPE spectra have bins 40 eV each
- I is a standard spectrum and it can be rebinned for χ^2 statistic to have at least 30 counts/bin
- Q and U are a fraction of I, to have enough statistical significance a constant binning of 120–200 eV can be applied

- `grppha ixpe_det3_src_NEF_I.pha ixpe_det3_src_NEF_I_rb.pha comm="group min 30 & chkey ANCRFILE ixpe_det3_NEF.arf & chkey RESPFILE ixpe_d3_20170101_alpha075_02.rmf & exit"`
- `grppha ixpe_det3_src_NEF_U.pha ixpe_det3_src_NEF_U_rb.pha comm="group 1 375 3 & chkey ANCRFILE ixpe_det3_NEF.mrf & chkey RESPFILE ixpe_d3_20170101_alpha075_02.rmf & exit"`





xspec available models

- All the spectral models can be used
  - ➥ IXPE spectral capabilities are limited
  - ➥ use simple models or other observatories to determine the parameters

- Only 3 polarimetric models are available
  - ➥ `polconst`: constant polarization
    - `A` – amplitude
    - `psi` – polarization angle in deg
  - ➥ `pollin`: having both PD and PA linearly dependent on energy

$$\mathrm{PD}(E) = A_1 + A_{\mathrm{slope}}(E - 1\ \mathrm{keV}) \tag{1}$$

$$\mathrm{PA}(E) = \psi_1 + \psi_{\mathrm{slope}}(E - 1\ \mathrm{keV}) \tag{2}$$

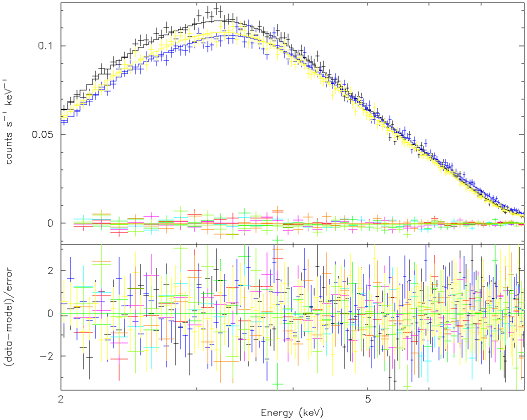
  - ➥ `polpow`: having PD and PA with a powerlaw behavior:

$$\mathrm{PD}(E) = A_{\mathrm{norm}}(E/\mathrm{keV})^{-A_{\mathrm{index}}} \tag{3}$$

$$\mathrm{PA}(E) = \psi_{\mathrm{norm}}(E/\mathrm{keV})^{-\psi_{\mathrm{index}}} \tag{4}$$

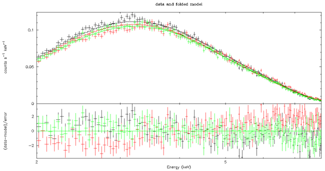
How to load data

```
data 1:1 ixpe_det1_src_NEF_I_rb.pha
data 1:2 ixpe_det1_src_NEF_Q_rb.pha
data 1:3 ixpe_det1_src_NEF_U_rb.pha
data 2:4 ixpe_det2_src_NEF_I_rb.pha
data 2:5 ixpe_det2_src_NEF_Q_rb.pha
data 2:6 ixpe_det2_src_NEF_U_rb.pha
data 3:7 ixpe_det3_src_NEF_I_rb.pha
data 3:8 ixpe_det3_src_NEF_Q_rb.pha
data 3:9 ixpe_det3_src_NEF_U_rb.pha
```



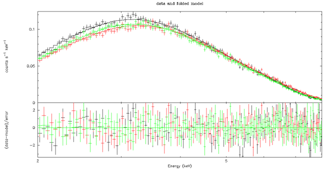
```
Fit statistic  : Chi-Squared                 234.85     using 149 bins, spectrum 1, group 1.
                 Chi-Squared                  36.96     using 49 bins, spectrum 2, group 1.
                 Chi-Squared                  62.20     using 49 bins, spectrum 3, group 1.
                 Chi-Squared                 342.08     using 149 bins, spectrum 4, group 2.
                 Chi-Squared                  40.04     using 49 bins, spectrum 5, group 2.
                 Chi-Squared                  40.90     using 49 bins, spectrum 6, group 2.
                 Chi-Squared                 164.25     using 149 bins, spectrum 7, group 3.
                 Chi-Squared                  69.49     using 49 bins, spectrum 8, group 3.
                 Chi-Squared                  70.86     using 49 bins, spectrum 9, group 3.
Total fit statistic                         1061.63     with 732 d.o.f.

Test statistic : Chi-Squared                1061.63     using 741 bins.
 Null hypothesis probability of 1.49e-14 with 732 degrees of freedom
```




```
Fit statistic  : Chi-Squared                 175.35     using 149 bins, spectrum 1, group 1.
                 Chi-Squared                  37.00     using 49 bins, spectrum 2, group 1.
                 Chi-Squared                  62.47     using 49 bins, spectrum 3, group 1.
                 Chi-Squared                 132.32     using 149 bins, spectrum 4, group 2.
                 Chi-Squared                  39.99     using 49 bins, spectrum 5, group 2.
                 Chi-Squared                  40.63     using 49 bins, spectrum 6, group 2.
                 Chi-Squared                 124.80     using 149 bins, spectrum 7, group 3.
                 Chi-Squared                  69.48     using 49 bins, spectrum 8, group 3.
                 Chi-Squared                  71.18     using 49 bins, spectrum 9, group 3.
Total fit statistic                          753.22     with 726 d.o.f.

Test statistic : Chi-Squared                 753.22     using 741 bins.
 Null hypothesis probability of 2.35e-01 with 726 degrees of freedom
```



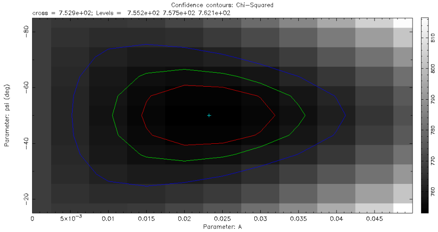
- In the example.xcm file you can find an example of spectro-polarimetric analysis
- *I* spectra have a bad χ^2, this can happen because of 'charging':
  - ➥ For bright sources
  - ➥ For older observations
- Charging effect can introduce time-dependant response which is different in the 3 DUs
- You can adjust it (if needed) by applying gain fit
  - ➥ **No systematics have to be added**
  - ➥ *I*, *Q* and *U* spectra from the same DU must have same gain parameters
- In the file example_gain.xcm you can find an example

Spectro-polarimetry: uncertainties

- Using example_gain.xcm we obtain:
  - `polconst A 2.35163E-02 +/- 5.96189E-03`
  - `polconst psi deg -50.1596 +/- 7.19046`

- Running `error 8-9` we obtain 1-D errors at 90% CL:
  - $PD = (2.4 \pm 1.1)\%$
  - $PA = (-50 \pm 12)^\circ$

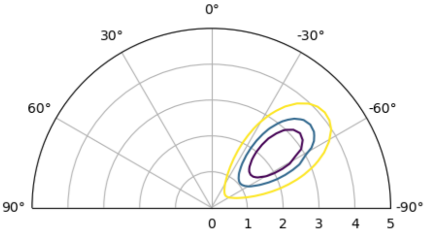
- To obtain 2-D errors, we have to run `steppar 8 0 0.05 30 9 15 85 30` (to make it faster, use `parallel steppar 4`): $0.011 < PD < 0.036$ and $-63 < PA < -35$



- XSPEC allows one for trying fit in an iterative way
- PYXSPEC offer the possibility to work on Python and to obtain fancy plots

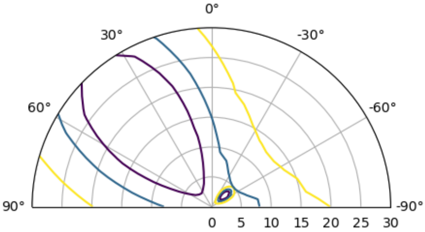
- **Test models with xspec and when you obtain your best fit you can use Pyxspec to obtain better plots**

- In PyXspecIXPEPolarPlot.ipynb you can find the official tutorial, while in pyxspec_example1.ipynb an example where xcm is used



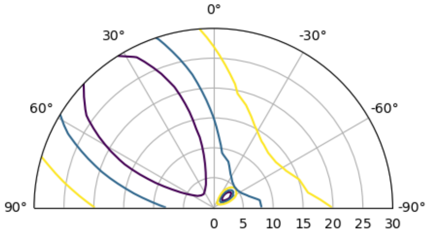
Why is spectropolarimetry a powerful tool? I

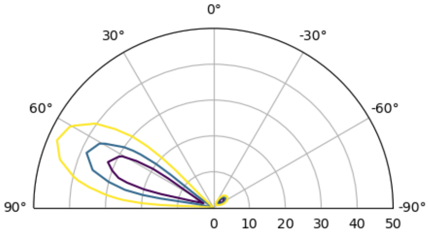
- Assume a complex spectral model with more components as in Forsblom+ A&A 696, A224 (2025): `const*Tbabs*Tbpcf*(pow*polconst+bremss*polconst)`
  - ➥ We can associate polarization to each spectral component to disentangle them and test theoretical models
  - ➥ See example2.xcm and pyxspec_example2.ipynb



Why is spectropolarimetry a powerful tool? II

- **Attention: if you force one PA to be aligned with respect to the other one, you are introducing a further correlation!**
  - if $PA_2 = PA_1 \rightarrow PD_{tot} = PD_1 + PD_2$
  - see the following examples for $PA_2 = PA_1 + 90^{\circ}$
- In this case, you should pass to a 3D representation of the correlation!





Conclusion

- In case you have multiple observatories and complex spectral models:
  - ➥ Fit only I spectra and determine gain if needed
  - ➥ Freeze all the I spectral model parameters and then fit also Q and U spectra

- A tutorial is available at this link: https://drive.google.com/drive/folders/1WevJHXTFON_3yd4LeEnp8Z-BIv0K6j6i

- Time-resolved, phase-resolved and energy-binned analysis can be performed the same approach after data selection

- In case you have doubts or needing support for more complex analysis, you can contact me: alessandro.dimarco@inaf.it