

The background of the slide is a vibrant space scene. In the upper right, a large, glowing nebula in shades of red and purple dominates the view. Below it, the Earth's horizon is visible, showing green landmasses and blue oceans. The IXPE satellite is the central focus, positioned diagonally from the top right towards the bottom left. It features a large cylindrical telescope at the front, a central body with solar panels, and a secondary instrument package at the rear. The text is overlaid on this scene in a bright yellow font.

# Introduction to IXPE Data Archive and Analysis Tools

Douglas Swartz  
USRA/MSFC

## Outline:

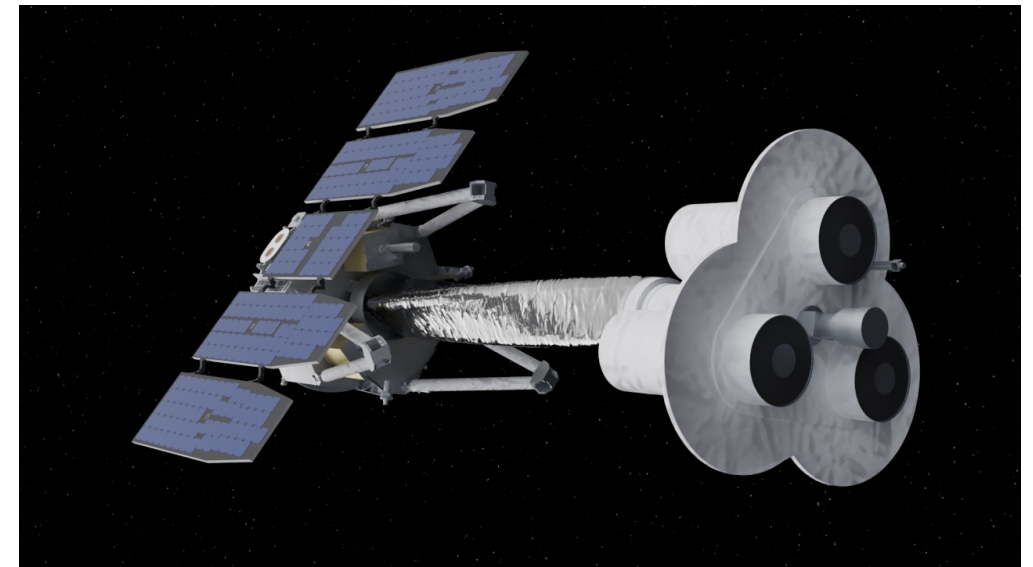
- IXPE Data Archive
- Response Files
- An XSPEC example

**The main goals of this presentation are to help the User Community:**

- Navigate the IXPE Data Archive
- Construct Instrument Response Files
- Perform basic Spectro-polarimetric analysis of IXPE observations using XSPEC

**Some important IXPE features:**

- Three telescopes: 3 sets of spectro-polarimetric data, 3 sets of instrument response files
- Photon counting: E, t, x, y, +Stokes I, Q, U (each event)
- LEO: point & stare at target (+dither) for >57min/orbit, ~70 day visibility x 2/year, very bright sources observed in segments to allow for telemetry of data
- >100ks, up to >1Ms observations: very large datasets



❑ All IXPE data become public once processed & validated (or after an exclusive use period of up to 6 months)

❑ Public access is through HEASARC  
<https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/>

- ▶ Browse interface
- ▶ Xamin interface (+ command-line batch)
- ▶ FTP via HTTPS
- ▶ Python

#### 4. Do you want to change your current query settings?

**Object Name or Coordinates:**   
 (e.g. 'Cyg X-1' or '12 00 00, 4 12 6')  
 Use semicolons (;) to separate multiple object names or coordinates

**Coordinate System:** J2000

**Search Radius:** Default  arcsec  Default uses the optimum

**Name Resolver:** GRB, then SIMBAD, then VizieR (Sesame), then NED

**Observation Dates:**   
 Not all tables have observation dates/times. For those that do, the times are always in UTC. Separate multiple dates/ranges with semicolons (e.g. '1992-12-31; 48980.5; 1995-01-15 12:00:00; 1997-03-20 .. 2000-03-20')

**Limit Results To:** 1000 rows

**Output Format:** HTML Table

**Show All Parameters:**  Select to display all catalog parameters instead of only defaults.

5.

<https://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3query.pl>

- IXPE Level 1 Data files are many 100s Mb
- Only IXPE Level 2 Data and housekeeping Attitude Files are needed for most analyses
- Be sure to select “Preview and Retrieve”

## Data Products Retrieval:

- Select the checkboxes for the rows of interest above,
- Un-check any data products below you are not interested in
- Select the Data Products Retrieval tab for retrieval options

### Data Products available for ixmaster:

- All
- IXPE All Data for the Observation (ixpe.obs)
- IXPE Auxilliary Data (ixpe.obs.auxil)
- IXPE Housekeeping Data (ixpe.obs.hk)
- IXPE Level 1 Data (ixpe.obs.l1)
- IXPE Level 2 Data (ixpe.obs.l2)

- optionally, add a file name constraint to specify product types, e.g., `*/hri/*.gif*`  
Use a semicolon (;) for multiple constraints, e.g., `*fits*;*.gif*`

File name filter

- then click a button below.

Create Download Script for data products for selected rows

Preview and Retrieve data products for selected rows

Retrieve data products for selected rows

Save to Hera data products for selected rows

[What is Hera?](#)

[Browse Feedback](#)

- ❑ IXPE Level 1 Data files are many 100s Mb
- ❑ Only IXPE Level 2 Data and housekeeping Attitude Files are needed for most analyses
- ❑ Be sure to select “Preview and Retrieve”
- ❑ Select (hk) DIRECTORY to see full listing; click on each \*\_att\_\* file (fits, gzip'd) to download each individually
- ❑ then go back and Select all Level 2 files (or Select (event\_I2) DIRECTORY)
- ❑ and then Create Download Script or TAR Selected Products

[IXPE Master Catalog \(ixmaster\)](#) [FTOOLS](#)

obsid	name	ra	dec	time	exposure_1	exposure_2	exposure_3	processing_c
02001099	Crab	05 34 31.9	+22 00 52	2023-02-22 00:14:02.058	68077.1596	68444.9447	68657.4485	2023-04-10 05:10

Select all products in this row

#### IXPE Housekeeping Data

IXPE Housekeeping Data (hk) [DIRECTORY](#) 878653 kB

#### IXPE Level 2 Data

IXPE Level 2 Data (event\_I2) [DIRECTORY](#) 1140417 kB

IXPE Level 2 Detector 1 Events (ixpe02001099\_det1\_evt2\_v02.fits.gz) [FITS](#) 401554 kB

IXPE Level 2 Detector 2 Events (ixpe02001099\_det2\_evt2\_v02.fits.gz) [FITS](#) 377233 kB

IXPE Level 2 Detector 3 Events (ixpe02001099\_det3\_evt2\_v02.fits.gz) [FITS](#) 361630 kB

[What is Hera?](#)

[Browse Feedback](#)

- IXPE Level 2 files are cleaned, gain- and aspect-corrected FITS event lists
- Columns: TIME, PI (Pulse Invariant energy), X, Y sky locations
- Additional Stokes parameter columns: I=W\_MOM, Q, U

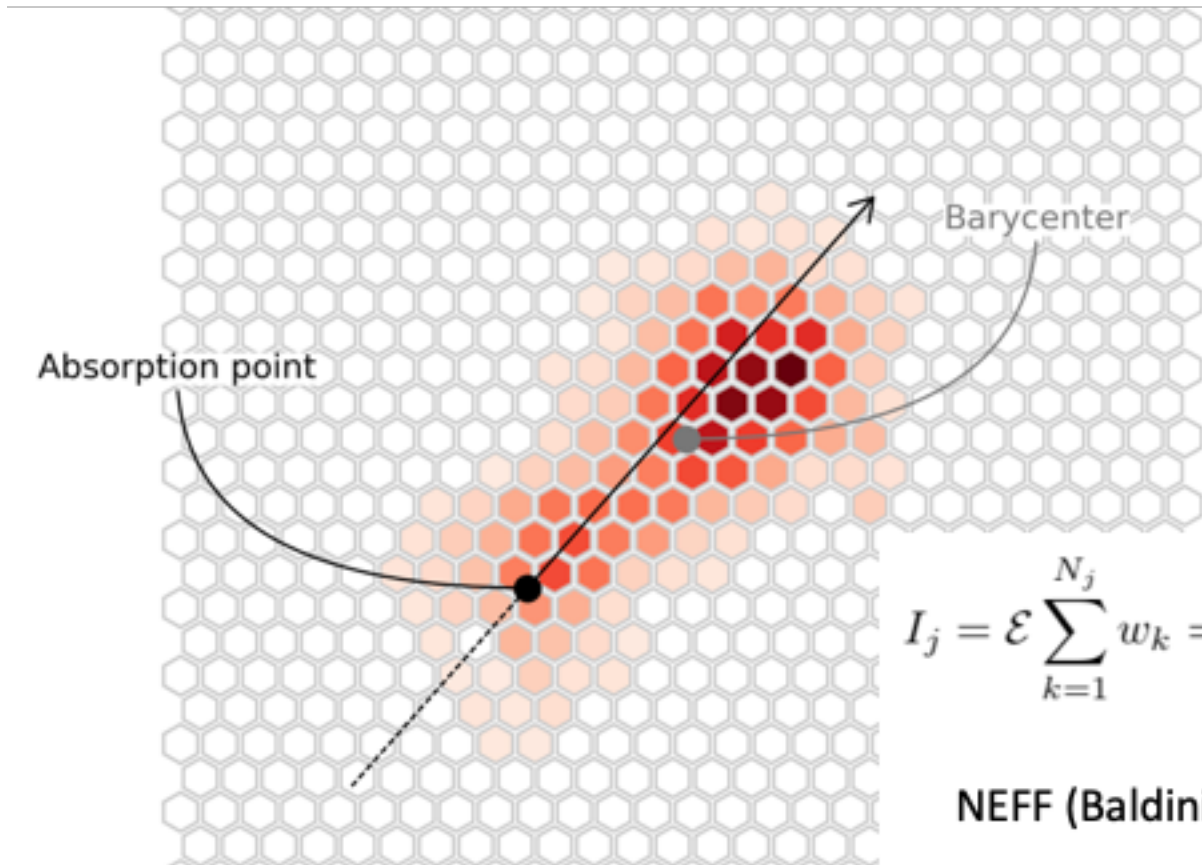
Let  $q = \langle q_i \rangle$  and  $u = \langle u_i \rangle$  then

Polarization Degree:  $\Pi = \sqrt{q^2 + u^2}$

Polarization Angle:  $\psi = \frac{1}{2} \tan^{-1} \left( \frac{u}{q} \right)$

$$\begin{aligned} q &= \Pi \cos(2\psi) \\ u &= \Pi \sin(2\psi) \end{aligned}$$

where the data can be binned by time and/or energy and/or sky location



Pipeline processing computes moments of the electron track distribution to determine the photon absorption point and photoelectron initial direction.

The event weight is defined in terms of the 2<sup>nd</sup> moment track length and width as:

$$\text{event weight} = \left( \frac{TL - TW}{TL + TW} \right)^{0.75} = w_k$$

$$I_j = \mathcal{E} \sum_{k=1}^{N_j} w_k = \mathcal{E} \sum_{k=1}^{N_j} W\_MOM_k \quad Q_j = \mathcal{E} \sum_{k=1}^{N_j} w_k Q_k \quad U_j = \mathcal{E} \sum_{k=1}^{N_j} w_k U_k$$

$$\text{NEFF (Baldini+22)} \quad \mathcal{E} = (1/T) \left( \frac{\sum_{k=1}^N w_k}{\sum_{k=1}^N (w_k)^2} \right) \equiv (1/TI) N_{\text{eff}}$$

$$\text{SIMPLE (Kislat+15)} \quad \mathcal{E} = 1/T \quad \text{UNWEIGHTED} \quad \mathcal{E} = 1/T \quad w_k \equiv 1$$

<https://heasarc.gsfc.nasa.gov/heasoft/ftools/xselect/xsel.html>

```
> xselect prefix=mrk501
xsel> read event "./ixpe01004701_det1_evt2_v01.fits.gz"
xsel> filter region "src.reg"
xsel> extract SPEC stokes=NEFF
xsel> save spec ixpe_det1_src_
```

**Saves 3 spectral FITS files:**

```
ixpe_det1_src_I.pha
ixpe_det1_src_Q.pha
ixpe_det1_src_U.pha
```

**Repeat for all DUs, similar commands for other filters**

**stokes takes one of 4 values:**

```
xsel> extract SPEC stokes=NEFF
xsel> extract SPEC stokes=SIMPLE
xsel> extract SPEC stokes=UNWEIGHTED
xsel> extract SPEC stokes=NONE
```



- ❑ There are 3 instrument response files: RMF, ARF, and MRF
  - ❑ There are 3 choices of weights: SIMPLE, NEFF, and UNWEIGHTED
- The CALDB contains the RMF files for these 9 choices:

	NEFF or SIMPLE	UNWEIGHTED
<b>DU1</b>	lxpe_d1_alpha075_02.rmf	lxpe_d1_02.rmf
<b>DU2</b>	lxpe_d2_alpha075_02.rmf	lxpe_d2_02.rmf
<b>DU3</b>	lxpe_d3_alpha075_02.rmf	lxpe_d3_02.rmf

- ❑ There are 3 instrument response files: RMF, ARF, and MRF
- ❑ There are 3 choices of weights: SIMPLE, NEFF, and UNWEIGHTED

The FTOTOL *ixpecalcarf* is used to build the ARF and MRF files, e.g.:

```
> ixpecalcarf evtfile=ixpe01004701_det1_evt2_v01.fits.gz \  
attfile=ixpe01004701_det1_att_v01.fits.gz arfout=ixpe_det1_Q.mrf \  
specfile=none radius=1.0 weight=1 resptype=mrf
```

Where:

- ❑ `weight=0, 1, or 2` for UNWEIGHTED, NEFF, SIMPLE
- ❑ `resptype=mrf` for modulated response function
- ❑ `resptype= arf` for ancillary response file
- ❑ `radius=` the source extraction region radius in arcminutes

Now have a set of I, Q, U source spectra and, optionally, a set for bkgd

- Assign same RMF to all three source spectra, I, Q, & U, for detector
- Assign ARF to I spectrum
- Assign MRF to Q and U spectra (same MRF for each)

e.g.,

```
> fthedit ixpe_det1_src_I.pha keyword=RESPFILE operation=add  
value=" '$CALDB/ixpe_d1_alpha075_02.rmf' "  
> fthedit ixpe_det1_src_I.pha keyword=ANCRFILE operation=add  
value=" '$PATH/ixpe_det1_I.arf' "  
> fthedit ixpe_det1_src_Q.pha keyword=ANCRFILE operation=add  
value=" '$PATH/ixpe_det1_Q.mrf' "
```

- Repeat for the spectral sets for the other two detectors

In *XSPEC*, group the spectra into 3 groups for the 3 detectors:

```
xspec> data 1:1 ixpe_det1_src_I.pha
xspec> data 1:2 ixpe_det1_src_Q.pha
xspec> data 1:3 ixpe_det1_src_U.pha

xspec> data 2:4 ixpe_det2_src_I.pha
xspec> data 2:5 ixpe_det2_src_Q.pha
xspec> data 2:6 ixpe_det2_src_U.pha

xspec> data 3:7 ixpe_det3_src_I.pha
xspec> data 3:8 ixpe_det3_src_Q.pha
xspec> data 3:9 ixpe_det3_src_U.pha
```

Then, assign the backgrounds:

```
xspec> backgrnd 1 ixpe_det1_bkg_I.pha
xspec> backgrnd 2 ixpe_det1_bkg_Q.pha
xspec> backgrnd 3 ixpe_det1_bkg_U.pha

xspec> backgrnd 4 ixpe_det2_bkg_I.pha
xspec> backgrnd 5 ixpe_det2_bkg_Q.pha
xspec> backgrnd 6 ixpe_det2_bkg_U.pha

xspec> backgrnd 7 ixpe_det3_bkg_I.pha
xspec> backgrnd 8 ixpe_det3_bkg_Q.pha
xspec> backgrnd 9 ixpe_det3_bkg_U.pha
```

Limit analysis to 2-8 keV:

```
xspec> ignore *:0.0-2.0 8.0-*
```

Pick a model including multiplicative polarization model: `polconst`, `pollin`, `polpow`

```
xspec> model constant*tbabs(polconst*powerlaw)
```

Tie all Group 2 and Group 3 parameters to Group 1 values except the `constant`; set the parameter `constant=1` for Group 1 and allow it vary for the other Groups.

Simultaneously fit the model to all the data:

```
xspec> fit
```

The parameters of interest are the polarization fraction and polarization angle. Compute confidence intervals (for 1 parameter of interest), e.g., 99% confidence interval:

```
xspec> error 6.635 3
```

Visualize the 2-D error contours for these parameters:

```
xspec> steppar 3 0.00 0.21 41 4 -90 0 36
```

```
xspec> plot contour ,,4 1.386, 4.61 9.21 13.81
```

# Spectro-polarimetric Analysis with XSPEC

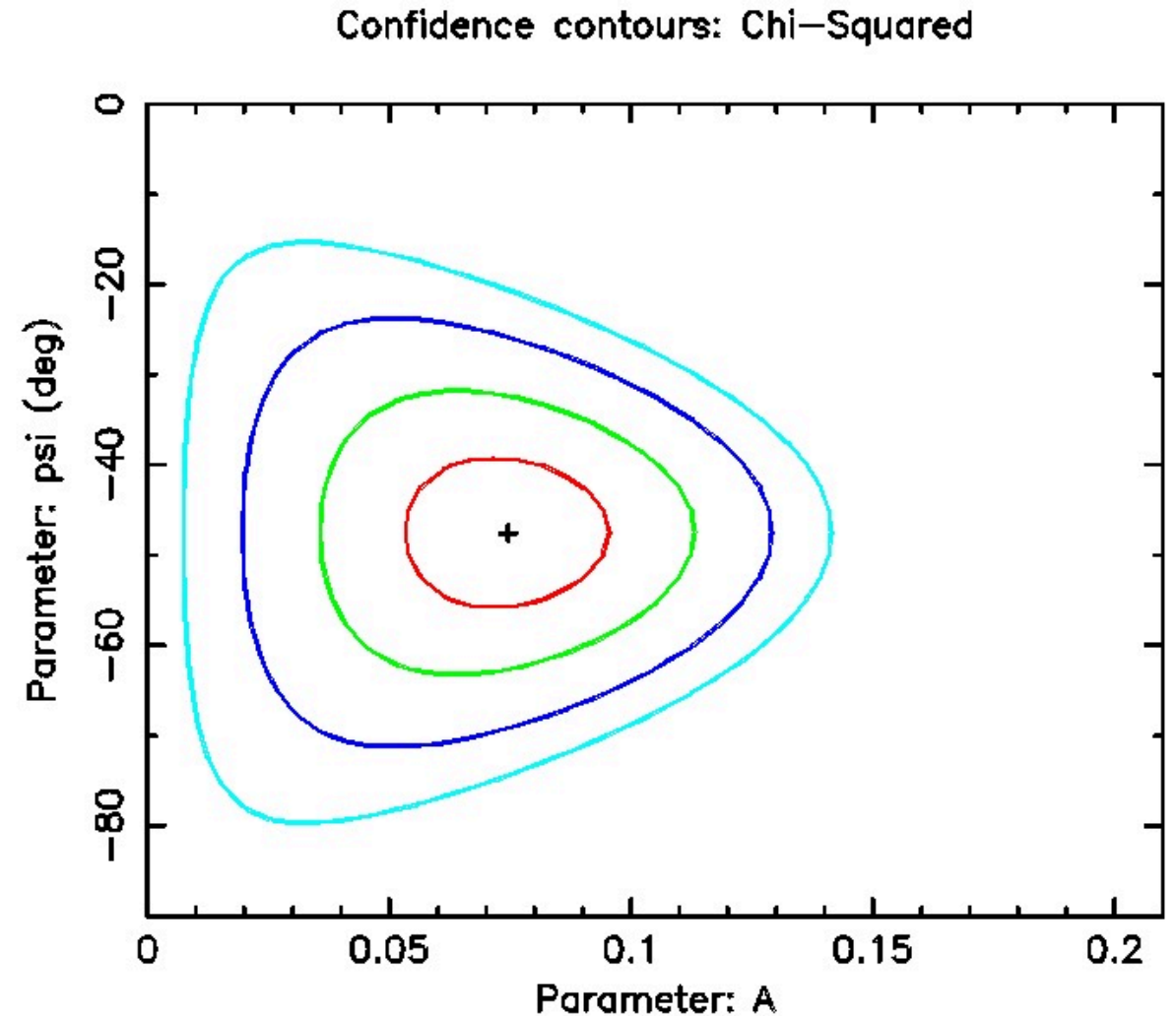
```

=====
Model constant<1>*TBabs<2>(polconst<3>*powerlaw<4>) Source No.: 1 Active/On
Model Model Component Parameter Unit Value
par comp
      Data group: 1
  1  1  constant  factor                1.00000  frozen
  2  2  TBabs     nH                 10^22    0.449126 +/- 0.104618
  3  3  polconst  A                   7.48253E-02 +/- 1.82077E-02
  4  3  polconst  psi                 deg       -47.5330 +/- 7.00793
  5  4  powerlaw  PhoIndex           2.58825  +/- 5.11245E-02
  6  4  powerlaw  norm                8.95929E-02 +/- 6.80765E-03
      Data group: 2
  7  1  constant  factor                1.00140  +/- 9.91860E-03
  8  2  TBabs     nH                 10^22    0.449126 = p2
  9  3  polconst  A                   7.48253E-02 = p3
 10  3  polconst  psi                 deg       -47.5330 = p4
 11  4  powerlaw  PhoIndex           2.58825  = p5
 12  4  powerlaw  norm                8.95929E-02 = p6
      Data group: 3
 13  1  constant  factor                0.969766 +/- 9.61954E-03
 14  2  TBabs     nH                 10^22    0.449126 = p2
 15  3  polconst  A                   7.48253E-02 = p3
 16  3  polconst  psi                 deg       -47.5330 = p4
 17  4  powerlaw  PhoIndex           2.58825  = p5
 18  4  powerlaw  norm                8.95929E-02 = p6
  
```

- Parameter `constant` allows for different relative normalizations
- Parameters `A` and `psi` are the polarization degree and angle; here, about 7.45% and  $-47^\circ$  (measured East of North,) respectively

# Spectro-polarimetric Analysis with XSPEC

- XSPEC-generated  $\chi^2$  image in  $(A, \text{psi})$  space.
- Best-fit values  $(0.0745, -47.45^\circ)$  denoted by the small cross.
- Contour levels shown for confidence levels of 50, 90, 99, and 99.9% for two parameters of interest.



☐ See also the IXPE Quick Start Guide:

[https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/ixpe\\_quickstart\\_v2.pdf](https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/ixpe_quickstart_v2.pdf)

☐ IXPE-specific FTOOL tasks (including *ixpecalcarf*):

<https://heasarc.gsfc.nasa.gov/lheasoft/ftools/headas/ixpe.html>

☐ HEASARC Xselect & XSPEC manuals:

<https://heasarc.gsfc.nasa.gov/lheasoft/xanadu/xspec/index.html>

<https://heasarc.gsfc.nasa.gov/lheasoft/ftools/xselect/xselect.html>



**#SaveChandra**

**<https://www.savechandra.org/>**