Introduction to IXPE Data Archive and Analysis Tools

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Outline:

- IXPE Data Archive
- Response Files
- An XSPEC example

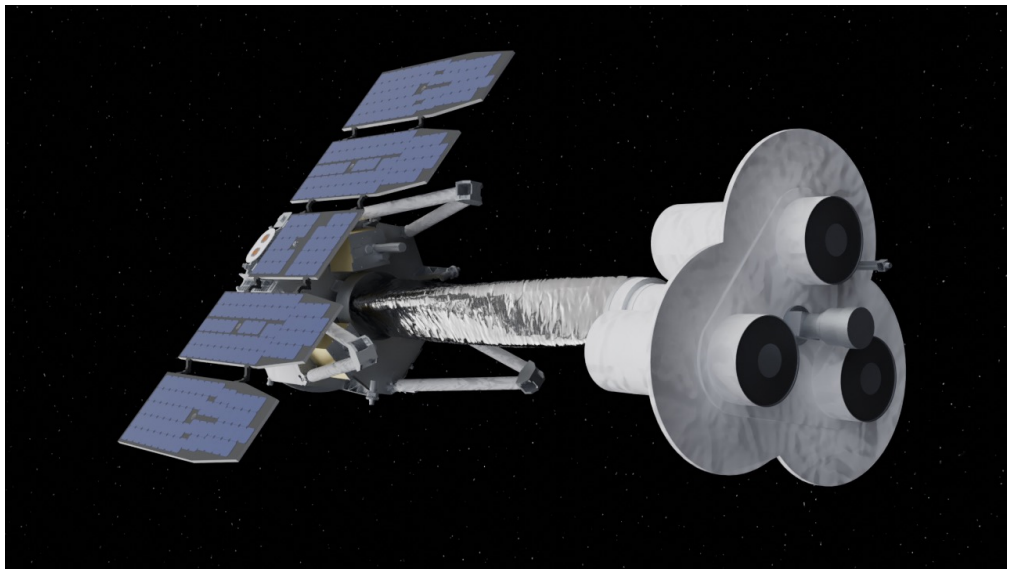
Overview

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

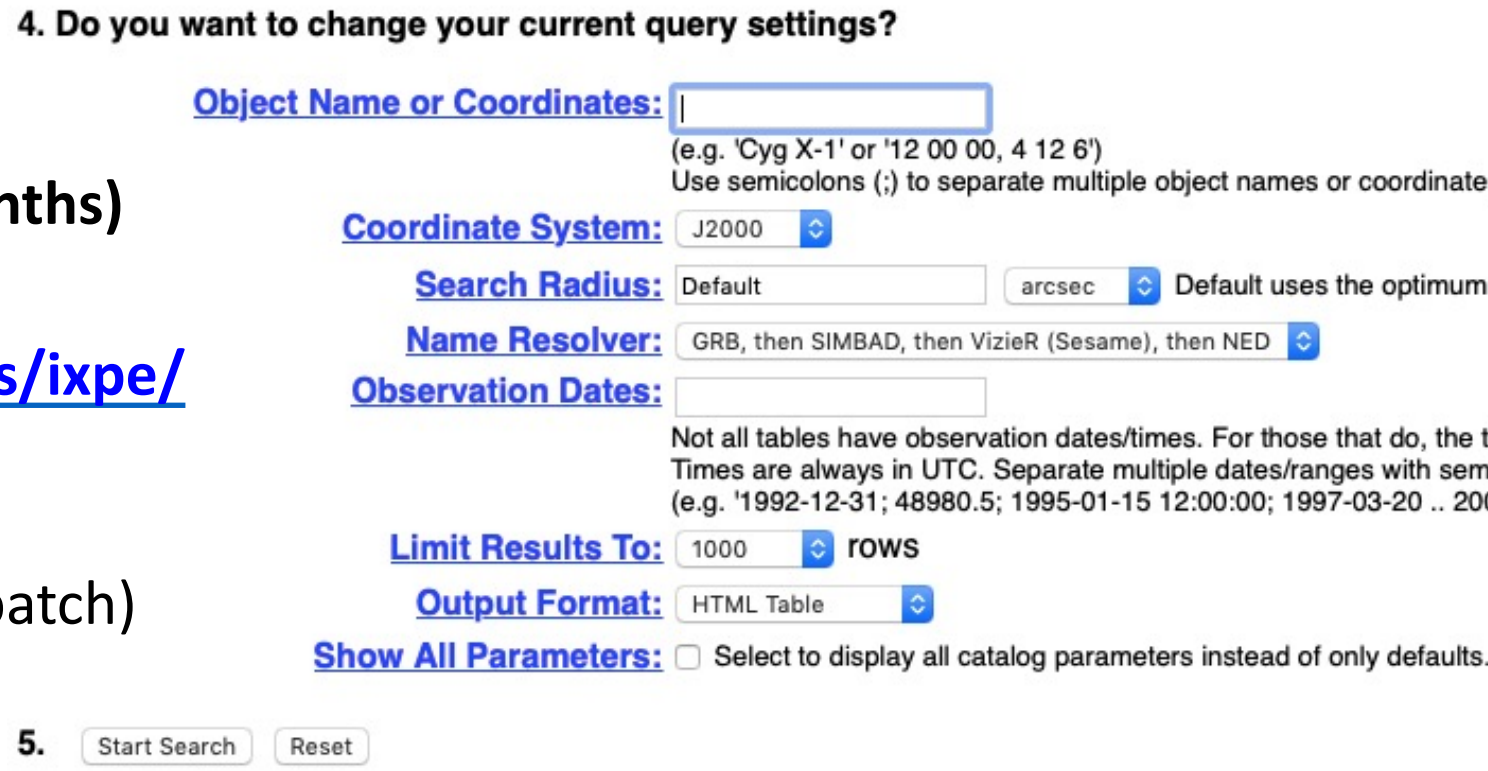
Some important IXPE features:

- 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



IXPE Data Archive

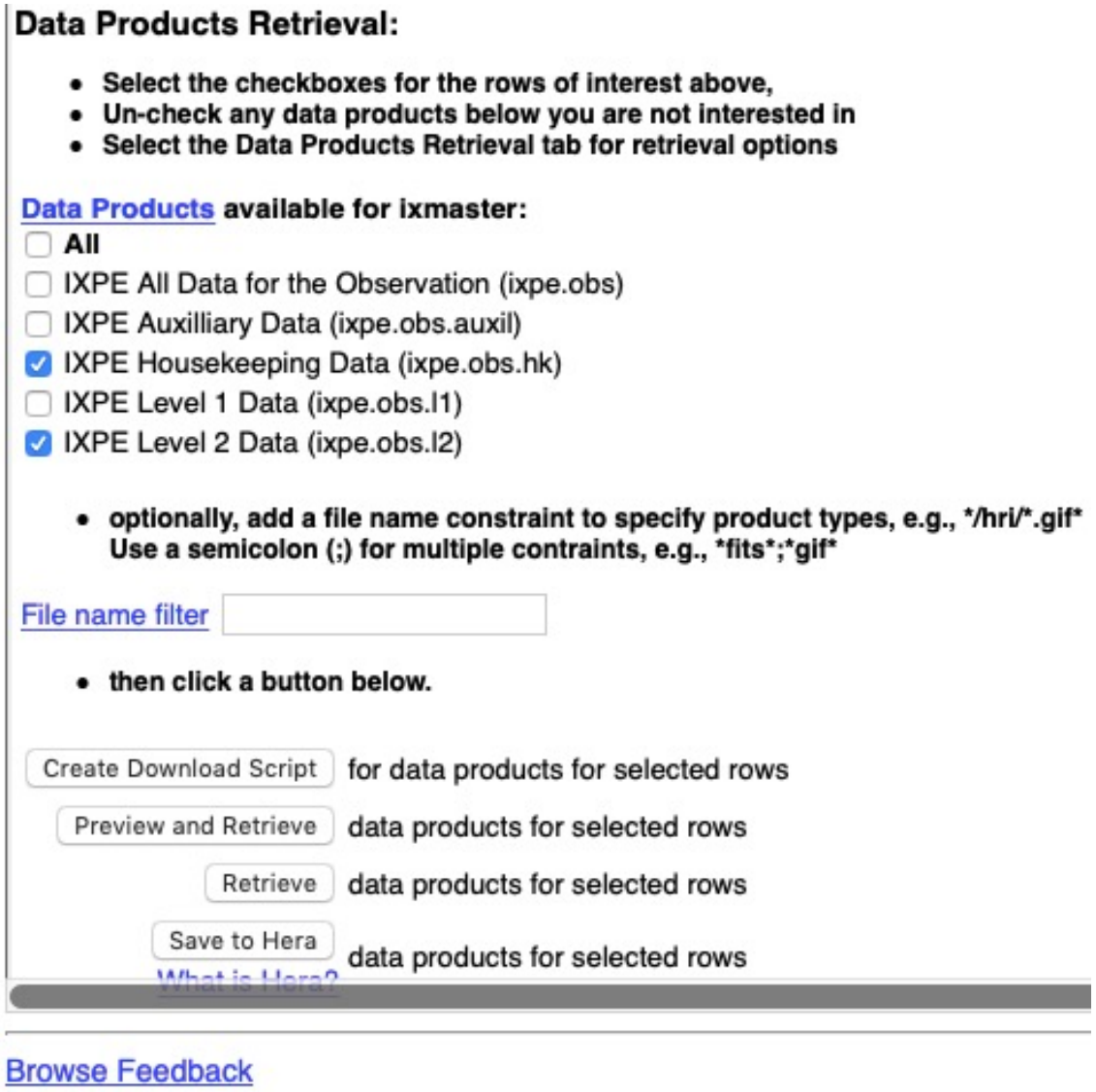
- **All IXPE data become public once processed & validated (or after an exclusive use period of up to 6 months)**
- **Public access is through HEASARC https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/**
  - Browse interface
  - Xamin interface (+ command-line batch)
  - FTP via HTTPS
  - Python



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

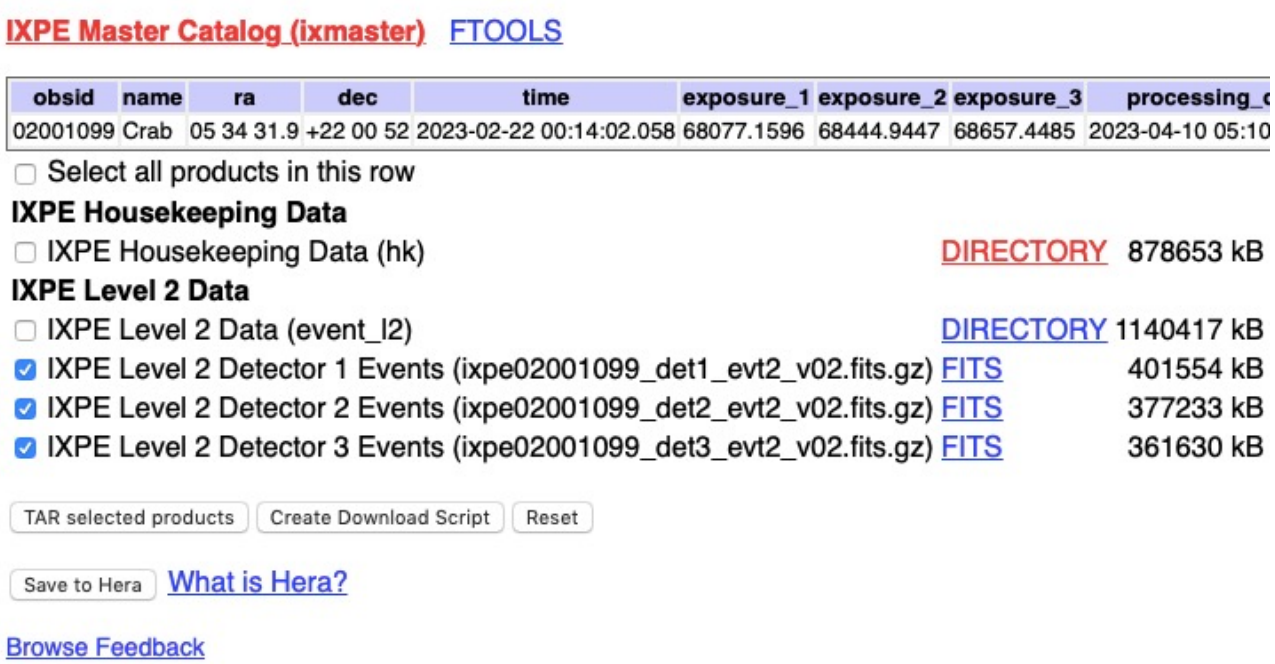
IXPE Data Archive

- 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”



IXPE Data Archive

- 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_l2) DIRECTORY)
- and then Create Download Script or TAR Selected Products



IXPE Level 2 Data

- 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

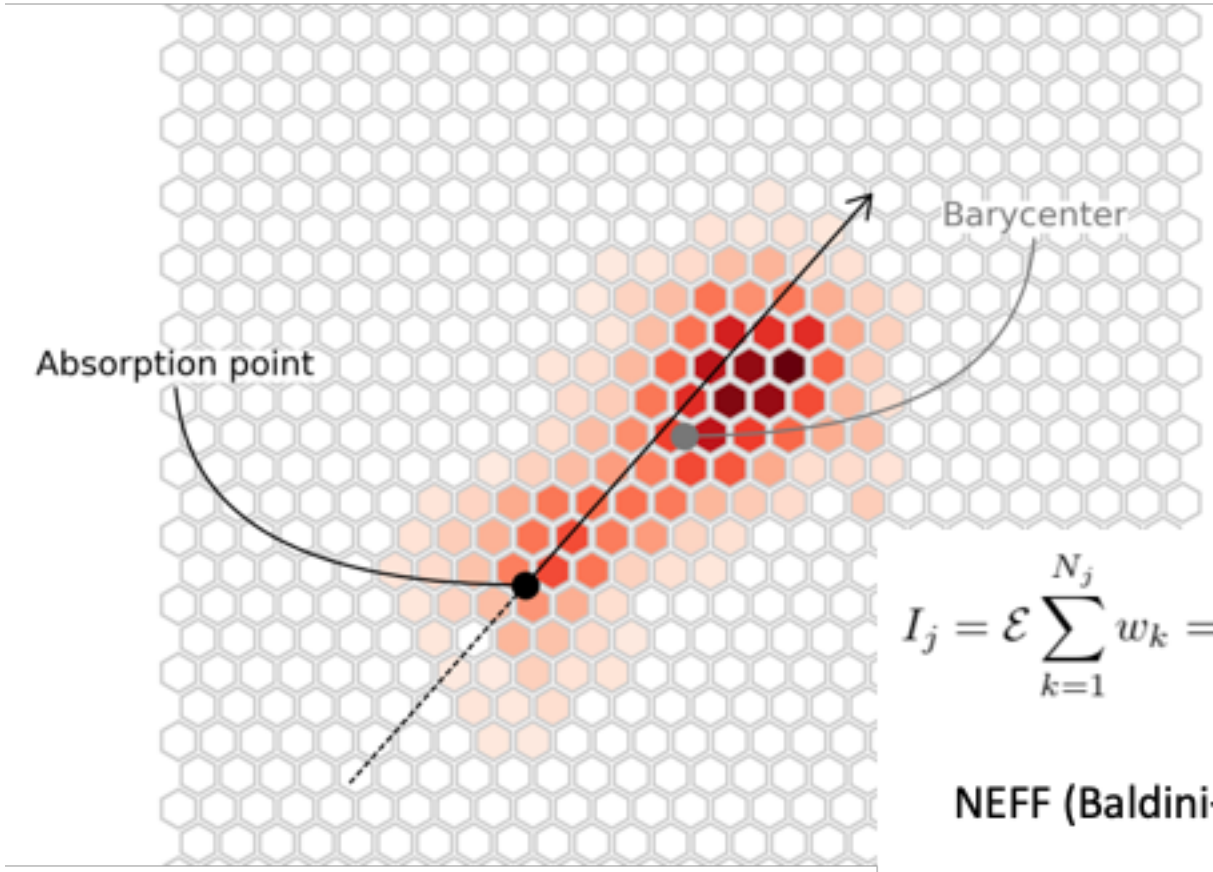
Polarization Degree: $\Pi = \sqrt{q^2 + u^2}$

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

$$q = \Pi \cos(2\psi)$$
$$u = \Pi \sin(2\psi)$$

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

Event Weighting



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 2nd moment track length and width as:

event weight = $\left(\mathrm{TL} - \mathrm{TW} \,/\, \mathrm{TL} + \mathrm{TW}\right)^{0.75} = w_k$

$$I_j = \mathcal{E}\sum_{k=1}^{N_j} w_k = \mathcal{E}\sum_{k=1}^{N_j} \mathtt{W\_MOM}_k \qquad Q_j = \mathcal{E}\sum_{k=1}^{N_j} w_k \mathtt{Q}_k \qquad U_j = \mathcal{E}\sum_{k=1}^{N_j} w_k \mathtt{U}_k$$

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

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

Data Extraction with Xselect

https://heasarc.gsfc.nasa.gov/lheasoft/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
```

Instrument Response Files

- 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
DU1	ixpe_d1_alpha075_02.rmf	ixpe_d1_02.rmf
DU2	ixpe_d2_alpha075_02.rmf	ixpe_d2_02.rmf
DU3	ixpe_d3_alpha075_02.rmf	ixpe_d3_02.rmf

Instrument Response Files

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

The FTOOL *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

Spectro-polarimetric Analysis with XSPEC

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

Spectro-polarimetric Analysis with XSPEC

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
```

Spectro-polarimetric Analysis with XSPEC

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
```

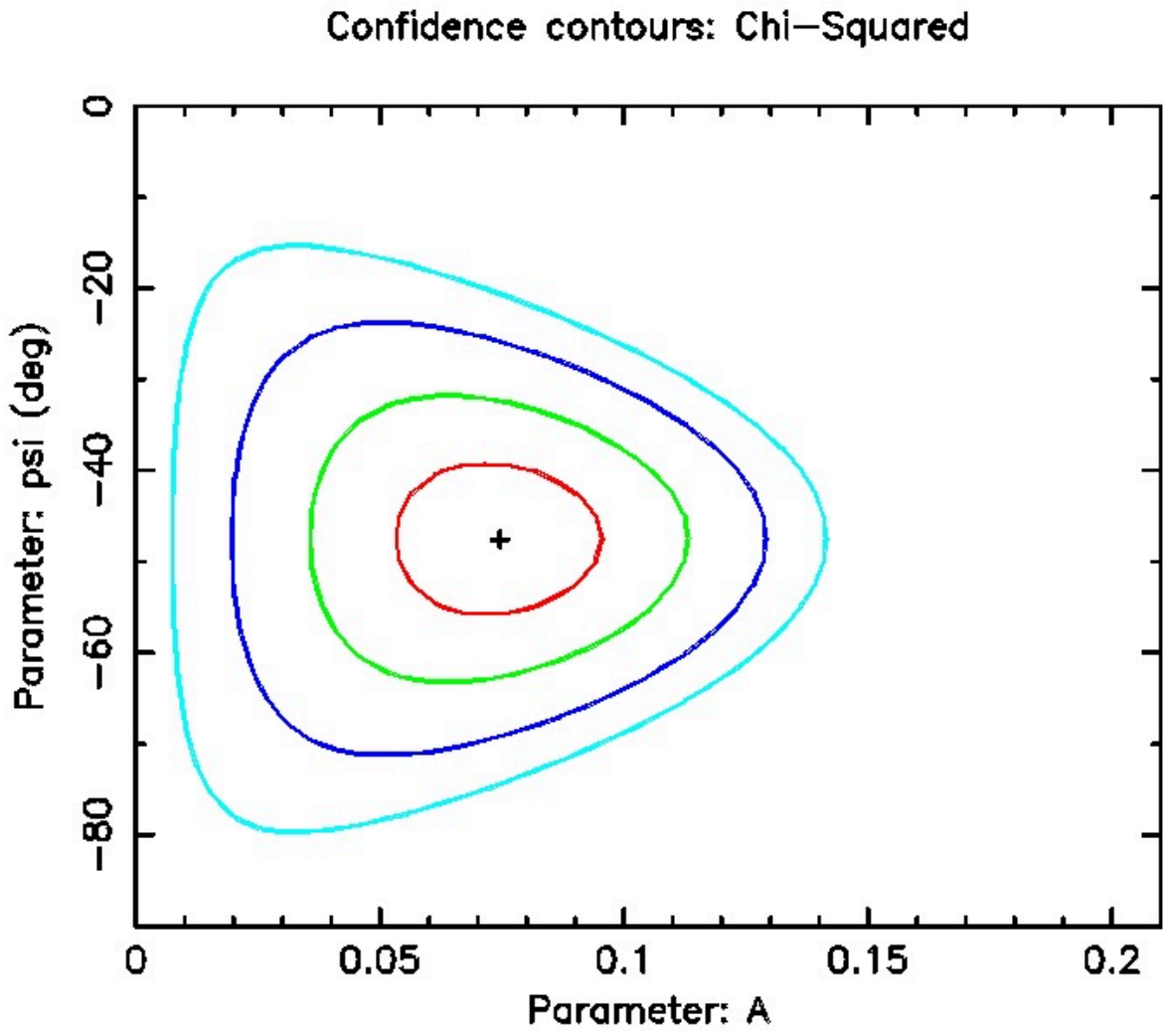
Spectro-polarimetric Analysis with XSPEC

```
========================================================================
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 -47^0 (measured East of North,) respectively

Spectro-polarimetric Analysis with XSPEC

- *XSPEC*-generated χ^2 image in (`A,psi`) space.
- Best-fit values (0.0745,-47.45^0) denoted by the small cross.
- Contour levels shown for confidence levels of 50, 90, 99, and 99.9% for two parameters of interest.



Thank You!

- ❑ **See also the IXPE Quick Start Guide:**

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

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