Introduction to ixpeobssim for data analysis

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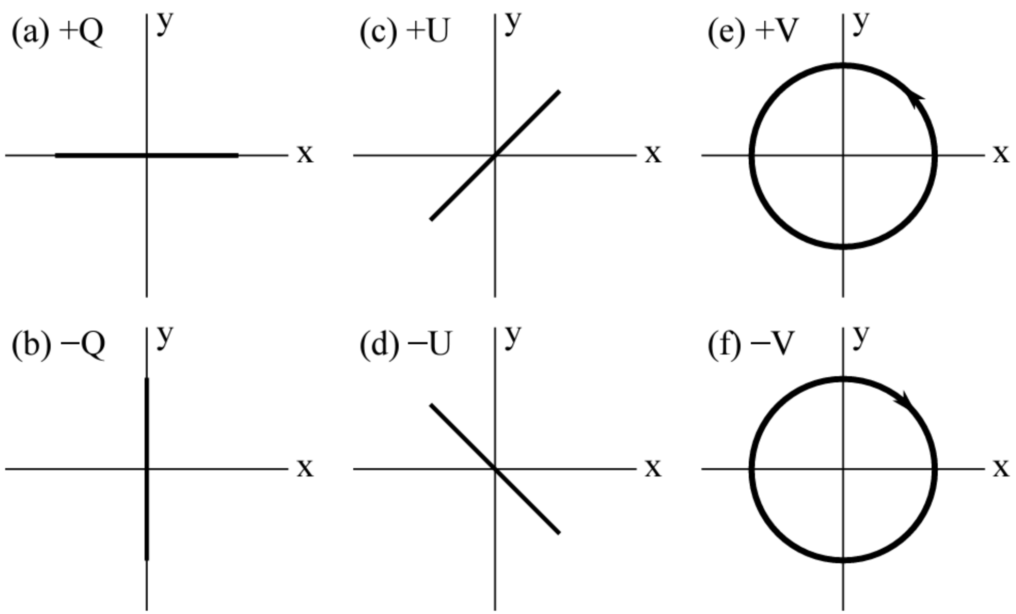
Joint NICER/IXPE Workshop 2024

Joint NICER + IXPE Capabilities

- IXPE (polarization)
  - 2-8 keV
  - Provides two new observables (Stokes Q, U -> polarization degree and polarization angle)
  - Measures geometry (e.g., accretion geometry, magnetic field structure)
- NICER (timing, spectroscopy)
  - 0.3-12 keV (“anchors” the spectrum on either side of IXPE)
  - Much larger effective area
  - Scheduling agility
- Other (X-ray) missions:
  - NuSTAR, XMM-Newton, AstroSat, Insight-HXMT

X-ray Polarization Measurements

- See formalism in [Kislat+ 15 (APh, 68, 45K)] and [Baldini+ 22 (SoftX, 1901194B)]
- For each event k, photoelectron direction ψ_k,
  - $i_k = 1, q_k = \cos(2\psi_k), u_k = \sin(2\psi_k)$
  - NOTE: Stokes parameters are divided by μ on an event-by-event basis
- $I = \sum_{k=1}^{N} i_k = N$, $\mathrm{Q} = \sum_{k=1}^{N} q_k$, $\mathrm{U} = \sum_{k=1}^{N} u_k$
- Polarization Degree (PD) $= \frac{\sqrt{Q^2+U^2}}{I}$
- Polarization Angle (PA) $= \frac{1}{2}\arctan\frac{U}{Q}$
- Other caveats: weights, gray filter, background



Typical Workflow (Data)

- Download the data you need (HEASARC)
  - Level 2 event files (e.g., ixpe01002701_det1_evt2_v04.fits)
  - *From housekeeping:* orbit file (e.g., ixpe01002701_all_orb_v01.fits), possibly
  - *From auxiliary:* usually none
  - *Possibly:* level 1 event files for background rejection
- Inspect the level 2 event files with SAOImage DS9
  - Typically ~60-90” source extraction regions (use *xpselect* to filter, with the --regfile flag)
  - Background rejection + subtraction considerations (see 3pm talk by Alessandro Di Marco; Di Marco+ 23, ApJ, 165, 143)
  - Background region: annulus with inner radius 150” and outer radius 300”
  - See https://github.com/aledimarco/IXPE-background
  - Calculate the total count rate (c/s/arcmin^2)
    - If bright (rate > 2 c/s/arcmin^2): no background subtraction or rejection
    - If faint (rate < 1 c/s/arcmin^2): apply background rejection and background subtraction
    - If intermediate: background rejection is recommended, background subtraction not recommended
  - Output from xpselect: ixpe01002701_det1_evt2_v04_select.fits -> ixpe01002701_du1_src.fits

Data Products – Polarization Cubes

- Provides binned data information
- Example command:
  - xpbin ixpe01002701_du?_src.fits --suffix all --algorithm PCUBE --irfname ixpe:obssim20211209_alpha075:v13 --weights True --ebinalg LIST --ebins 1 --ebinning [2,8]
  - Input event files – note the "?" wildcard
  - Suffix for output files for custom naming (I use "all" to mean all events)
  - PCUBE = "Polarization Cube"
  - Response files (important!) – latest is v13, see Niccolo's presentation
  - Specifying energy bins

fv: Binary Table of ixpe02006801_du1_src_all.fits[1] in /Volumes/Samsung_T5/IXPE-data/gx13+1/event_l2/

File Edit Tools Help

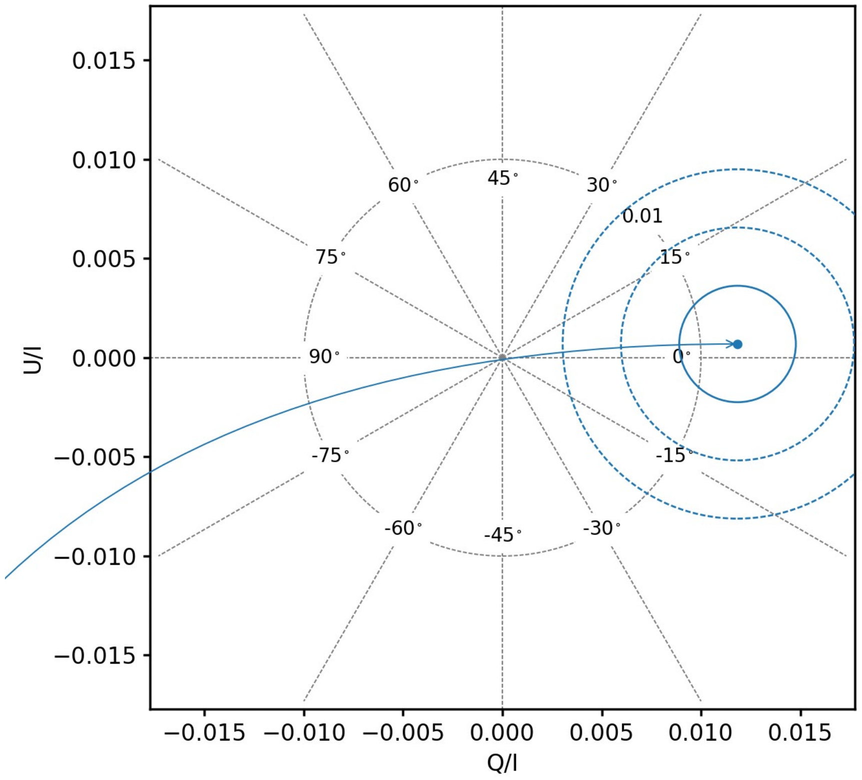
Select	ENERG_LO	ENERG_HI	E_MEAN	COUNTS	MU	W2	N_EFF	FRAC_W	MDP_99	I	I_ERR
All	E keV	E keV	E keV	J	E	E	E	E	E	E	E
Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	2.000000E+00	8.000000E+00	4.001209E+00	1078598	4.140167E-01	1.165868E+04	5.194118E+05	4.815620E-01	1.437750E-02	7.781810E+04	1.079754E+02

Go to: Edit cell:

Data Products – Visualizing Polarization Cubes

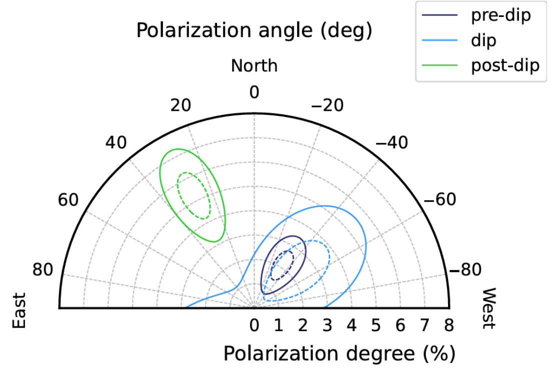
- Example command:
  - xpbinview ixpe01002701_du?_src_all.fits

```
>>> xBinnedPolarizationCube content:
Quantity      2.00--8.00 keV
-------- -----------------------
  E_MEAN      3.9988972328306174
  COUNTS               3050388.0
      MU      0.4135977172814372
      W2          38949.76953125
   N_EFF             1357041.875
  FRAC_W      0.4448751683392408
  MDP_99    0.008903946659024907
       I          229905.34375
   I_ERR      197.35696411132812
       Q        2722.40869140625
   Q_ERR       674.8180672566731
       U       158.5612335205078
   U_ERR       674.8221001773712
      QN     0.011841433122754097
  QN_ERR    0.0029351995749627856
      UN    0.0006896805134601891
  UN_ERR    0.002935217116619853 5
 QUN_COV -6.0180940826408585e-12
      PD     0.011861500330269337
  PD_ERR     0.002935205886274062
      PA      1.6666560171593792
  PA_ERR       7.089150751136133
 P_VALUE  0.00028434160864330727
  CONFID      0.9997156583913567
  SIGNIF      3.4461269118979954
```



Further Analysis

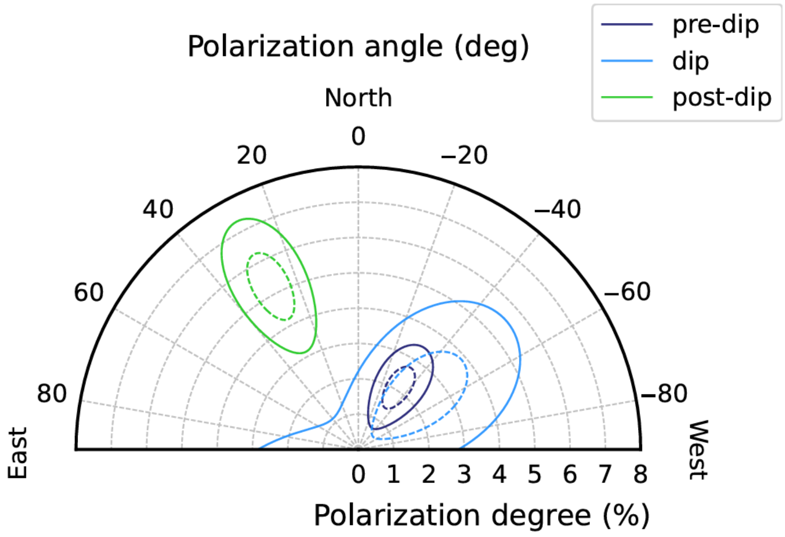
- Energy-resolved PCUBEs:
  - Can do "--ebins 2 --ebinning [2,4,8]" for 2-4 keV and 4-8 keV
- Background-subtraction:
  - Not available by default in ixpeobssim
  - Pythonic implementation – see https://ixpeobssim.readthedocs.io/en/latest/pipeline.html
  - Grab PCUBE information for source and background (xBinnedPolarizationCube class within ixpeobssim.binning.polarization)
- Statistics: see Statistics Guide, available here
- Protractor plots:
  - Not available by default in ixpeobssim, but can be added (defining contour radii of error * $\sqrt{\chi^2}$)



Bobrikova+ 24

More on protractor/polar plots

- Given measurement of Stokes parameters, q_0, u_0:
  - Define contour radius $\varepsilon = \sigma\sqrt{\chi_2^2}$
  - $\sigma = \sigma_q = \sigma_u$ (standard deviation)
  - χ_2^2 is the chi-squared for the desired confidence level (2 d.o.f.)
- Parametric equation for the contour:
  - $q = q_0 + \varepsilon\cos(\zeta)$
  - $u = u_0 + \varepsilon\sin(\zeta)$
  - $0 \leq \zeta < 2\pi$
- Parametric equation for polarization error contours:
  - $p = \sqrt{q^2 + u^2}$
  - $\psi = \frac{1}{2}\arctan\left(\frac{u}{q}\right)$
- $\sqrt{\chi_2^2} = 1.515\ (68.3\%), 2.146\ (90\%), 3.035\ (99\%)$
  - Calculated from $\sqrt{-2\ln(1 - \text{confidence})}$



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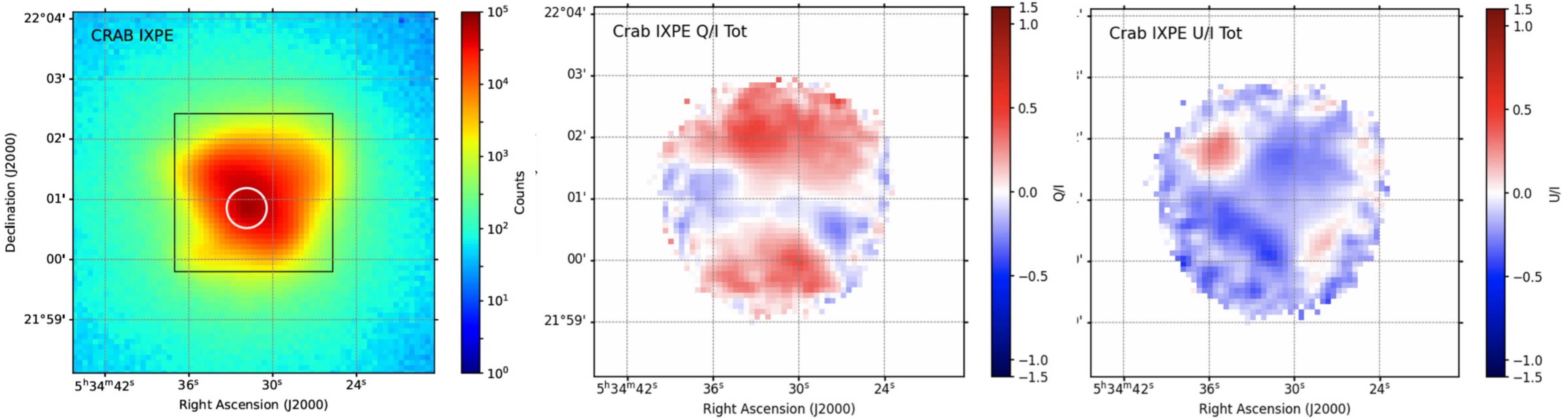
IXPE Imaging X-Ray Polarimetry Explorer

Data Products – Polarization Map Cubes

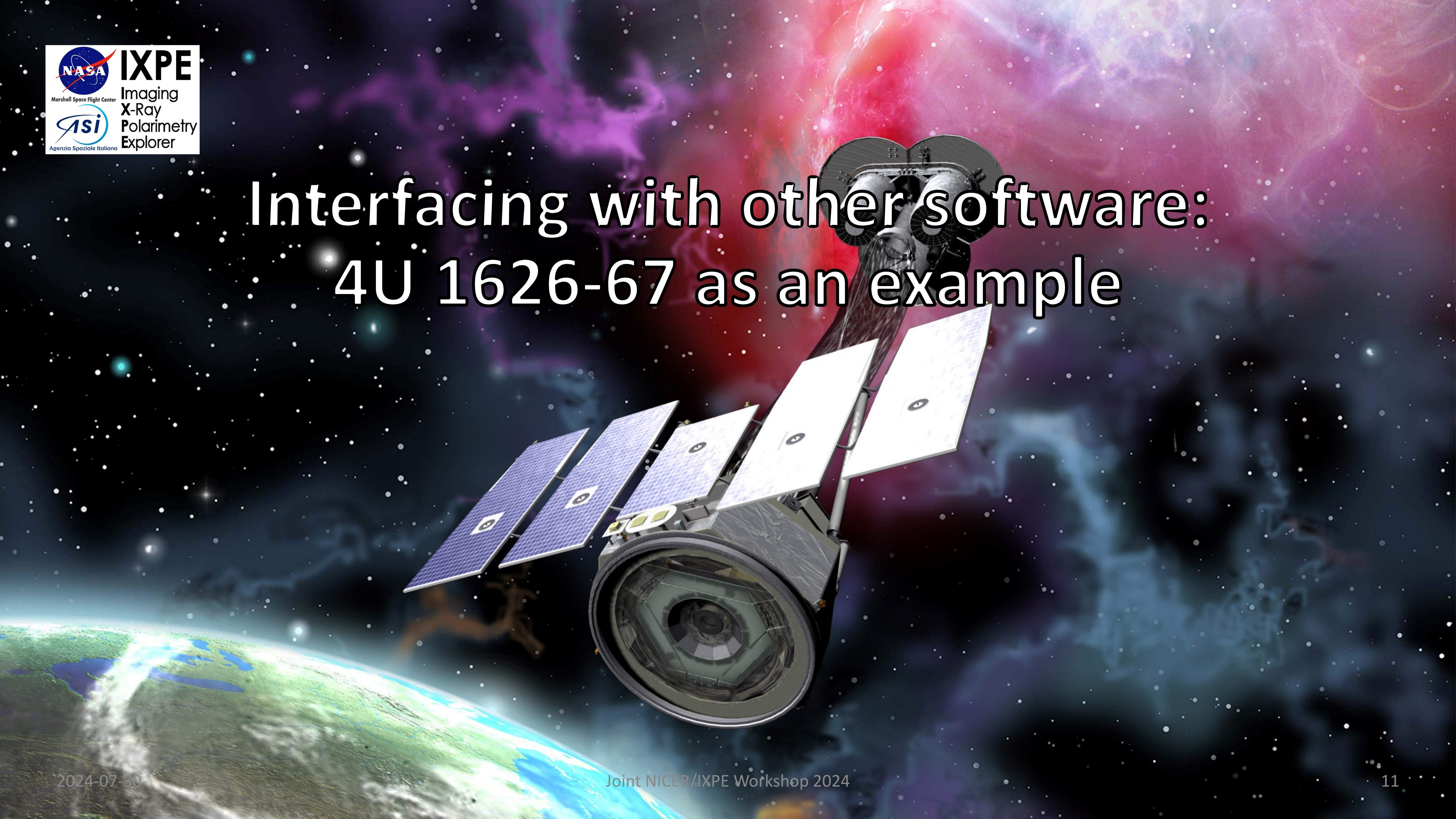


Bucciantini+ 23

- Crab system: Pulsar wind nebula + central pulsar
- Q/I is far more asymmetric
- U/I shows high symmetry

Data Products – Spectropolarimetry

- Example command:
  - xpbin ixpe01002701_du?_src.fits --algorithm PHA1 --irfname ixpe:obssim20211209_alpha075:v13 --acceptcorr True --weights True
  - xpbin ixpe01002701_du?_src.fits --algorithm PHA1Q --irfname ixpe:obssim20211209_alpha075:v13 --acceptcorr True --weights True
  - xpbin ixpe01002701_du?_src.fits --algorithm PHA1U --irfname ixpe:obssim20211209_alpha075:v13 --acceptcorr True --weights True
  - (Response files are added to the Stokes spectra files for you!)
- Can fit with XSPEC (*xpxspec*), Sherpa and 3ML
- See Quick Start Guide for guidance on fitting Stokes spectra in XSPEC

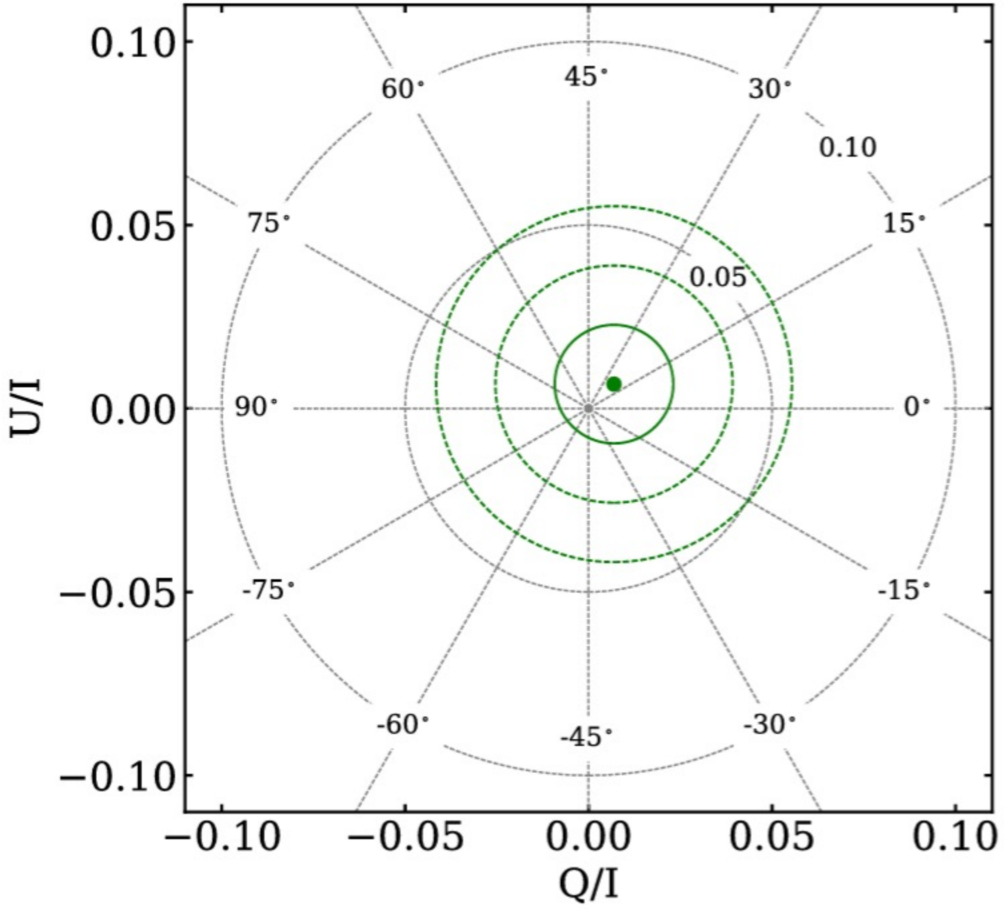


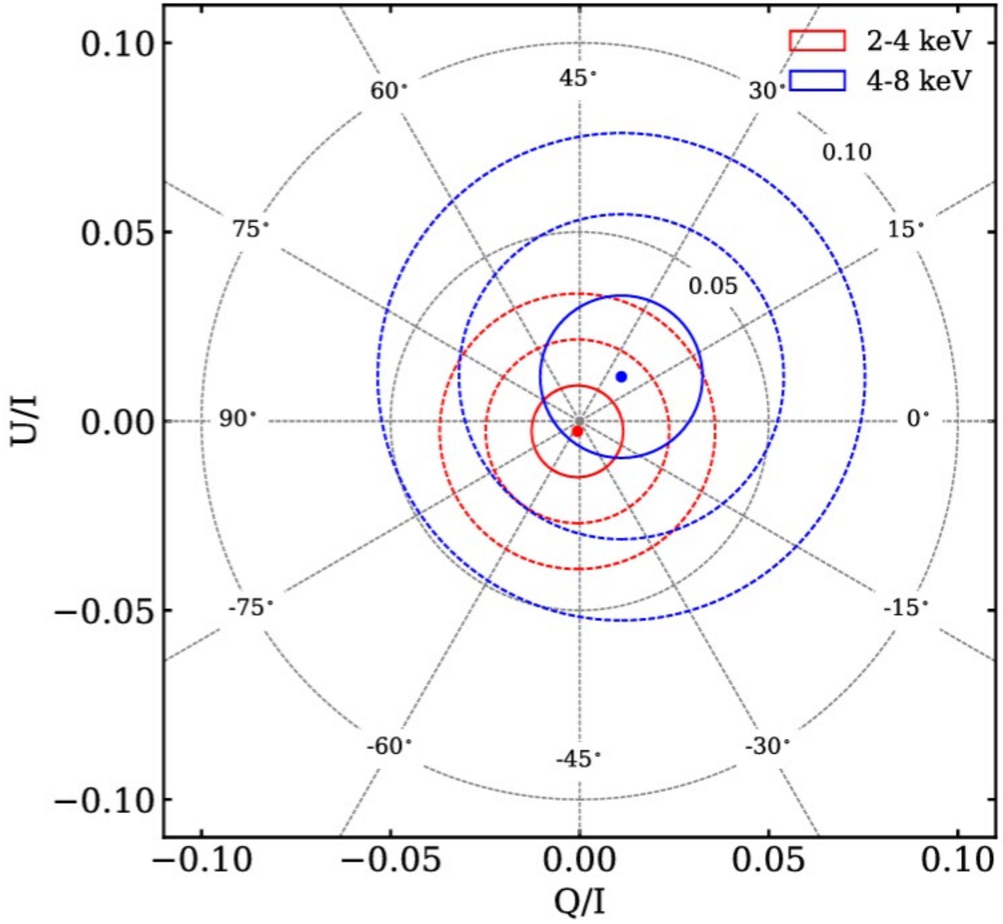
Interfacing with other software: 4U 1626-67 as an example

Quick Primer on 4U 1626-67

- 7.67 s pulsar
- 42-minute ultracompact low-mass X-ray binary
- 190 ks of 2-8 keV observations in March 2022
- Contemporaneous NICER + Chandra observations
  - Note: Source does not generally change significantly over the course of weeks
- Continuum generally well-fit with a blackbody + power law (plus rich Ne, O emission complexes)

4U 1626-67 Result: Phase-Averaged





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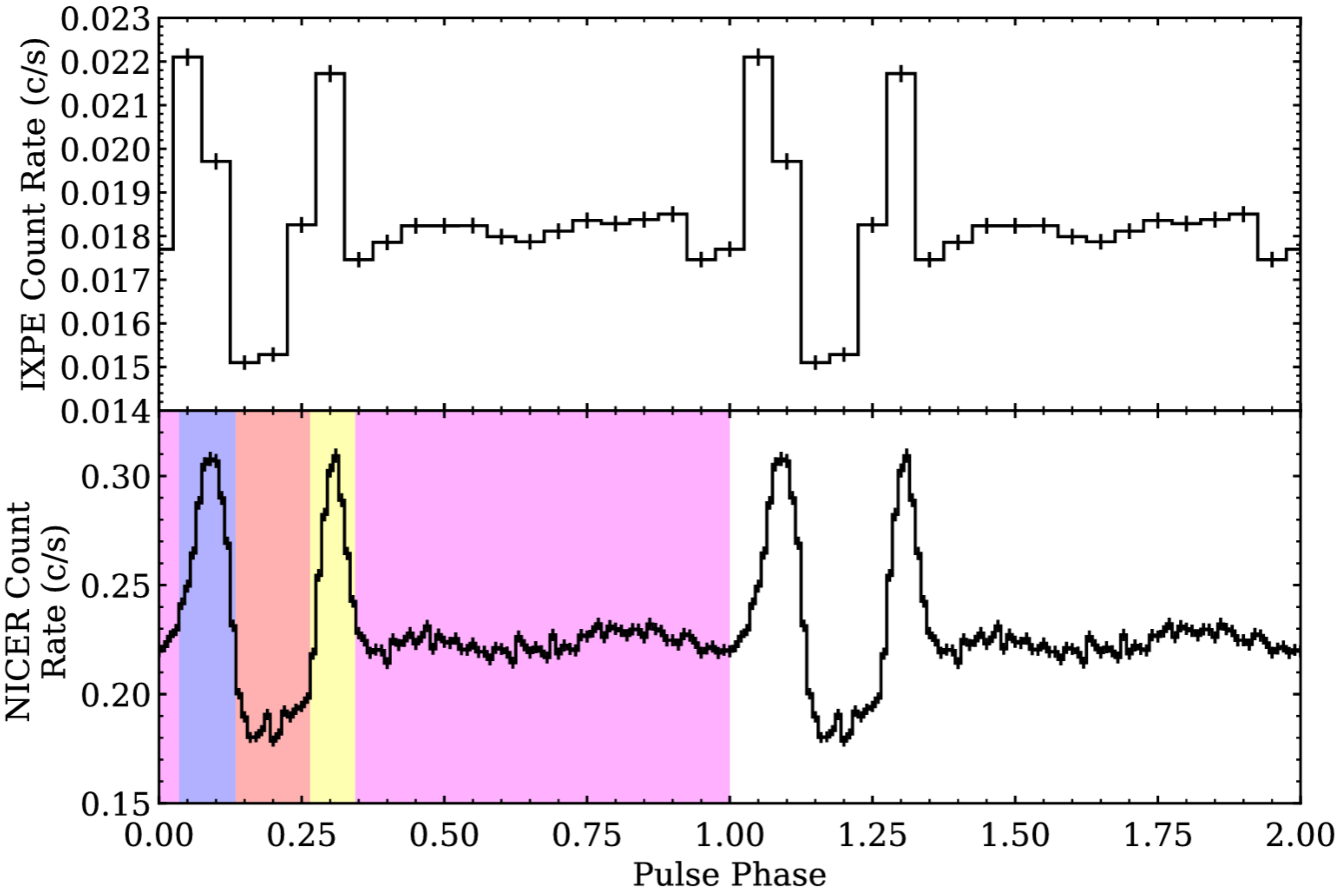
4U 1626-67: NICER



Looking at phase "slices"!

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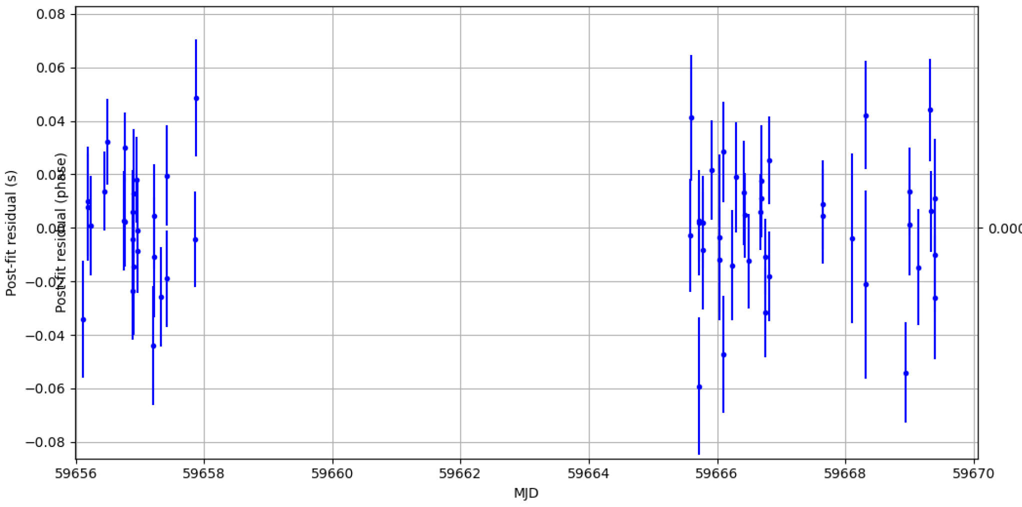
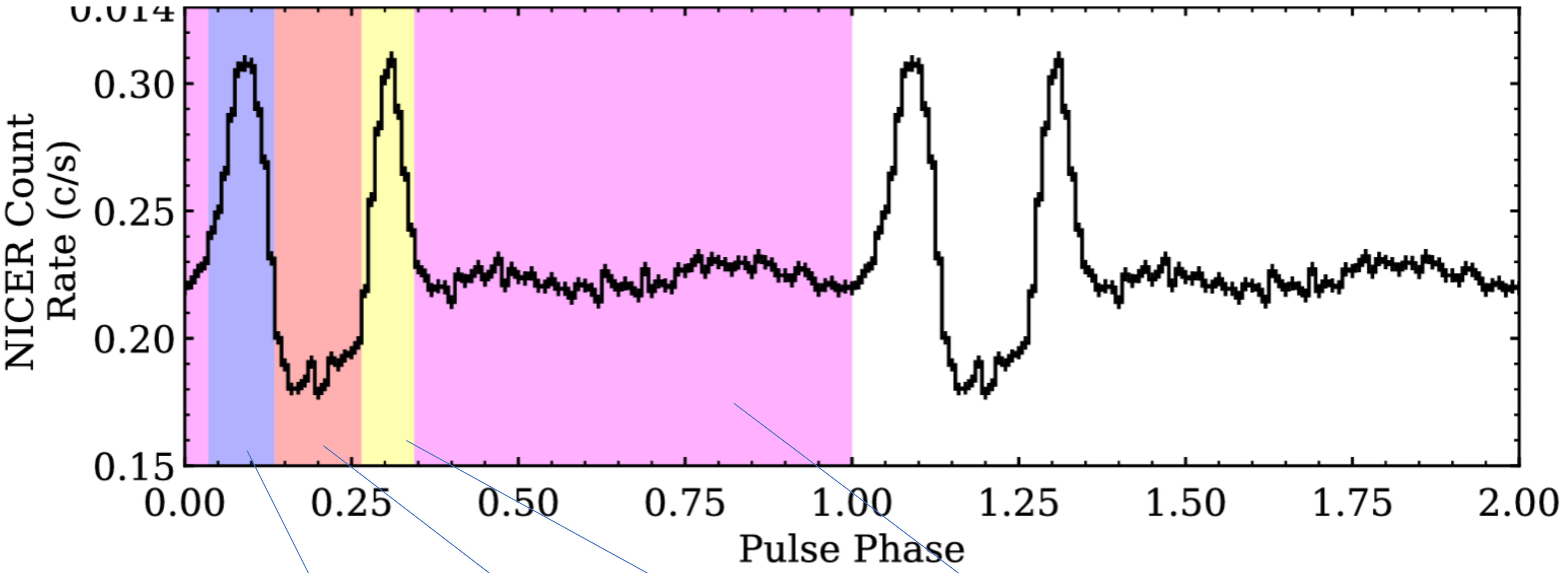
X-ray Timing and Polarimetry

- Run Solar System barycenter corrections:
  - barycorr ixpe01002701_du1_src.fits outfile=ixpe01002701_du1_src_bary.fits orbitfiles=/path/to/ixpe01002701_all_orb_v01.fits ra=248.06996 dec=-67.46091 refframe=ICRS ephem=JPLEPH.421 clobber=YES
- Used PINT for X-ray timing
  - See Megan DeCesar's talk tomorrow for more
  - Example command: photonphase --ephem DE421 --outfile $OUTFILE $INFILE $TRIAL_PARFILE
  - Can run *niextract-events*, [*nitemplate.py*](nitemplate.py) (for example)
  - Re-run *photonphase* with final PARFILE to update phases
  - Use *xpselect* (on phase) to extract phase-resolved data
  - Example command:
    xpselect ixpe01002701_du?_src_bary_phase.fits
    --phasemin 0.035 --phasemax 0.135 --suffix 0035-0135





Probability that the measurement is consistent with zero polarization

Pulse Phase	0.035-0.135	0.135-0.265	0.265-0.345	0.345-1.035
PD_{PL}	$0.046^{+0.048}_{-0.046}$	$0.10^{+0.06}_{-0.07}$	$0.10^{+0.06}_{-0.07}$	$0.03^{+0.03}_{-0.03}$
PA_{PL} (deg)	-17[e]	-19^{+23}_{-23}	53^{+22}_{-21}	-32[e]
$P(>\Delta\chi^2)$[c]	0.377	0.080	0.059	0.265

χ^2_{red} (d.o.f.) = 1.09 (7573)

Caveat on using PINT with ixpeobssim

- /path/to/ixpeobssim/evt/event.py

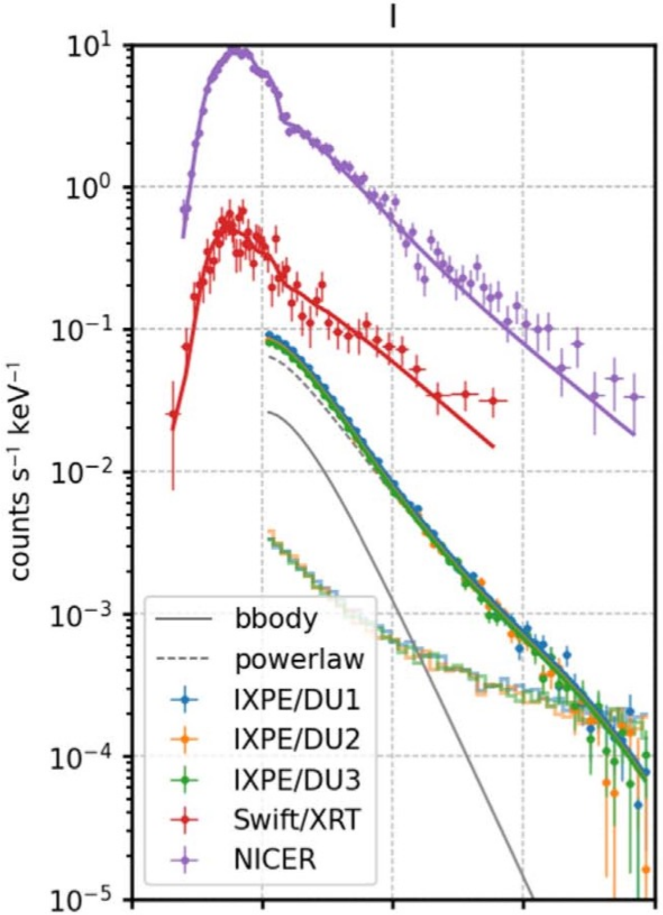
```
def phase_data(self):
    """Return the PHASE column.
    """
    try:
        return self.event_data['PHASE']
    except KeyError:
        logger.warning('Event file has no PHASE column, you might need to run xpphase.py...')
        return None
```

- PINT produces “PULSE_PHASE” columns

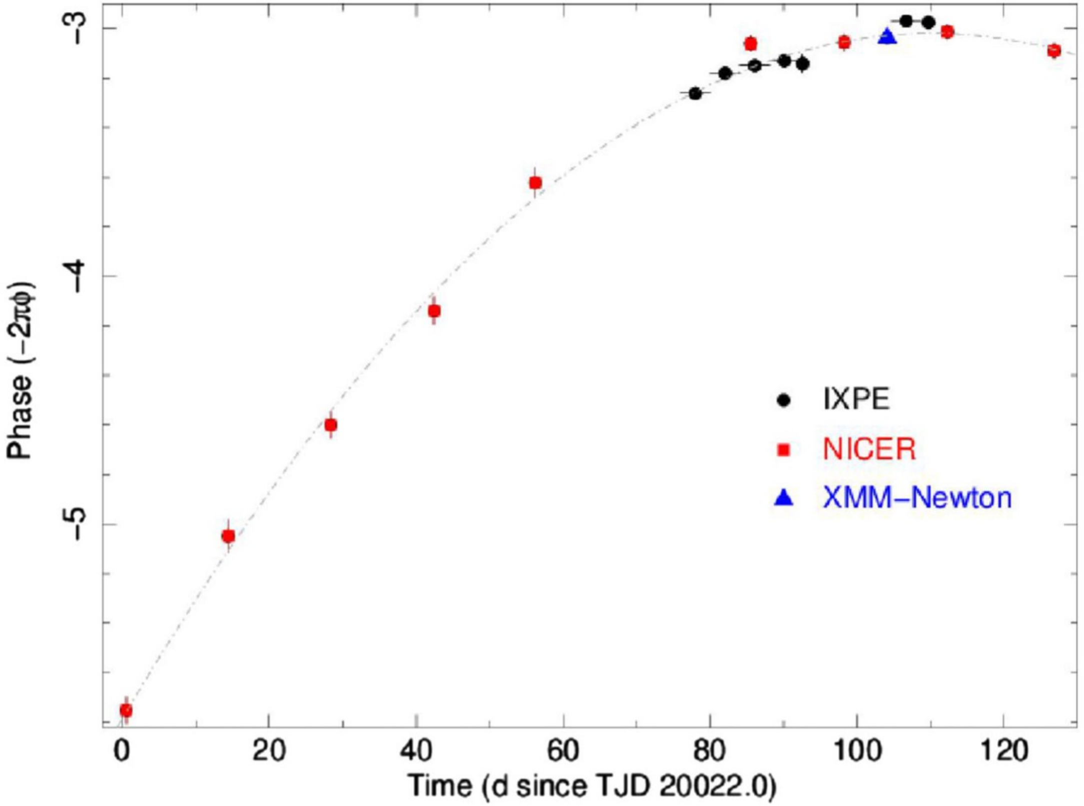
```
def phase_data(self):
    """Return the PHASE column.
    """
    try:
        return self.event_data['PHASE']
    except KeyError:
        try:
            return self.event_data['PULSE_PHASE']
        except KeyError:
            logger.warning('Event file has no PHASE or PULSE_PHASE column. You might need to run xpphase.py.')
```

Magnetars

- 1RXS J170849.0-400910 (Zane+ 23)



- 1E 2259+586 (Heyl+ 23)



IXPE + NICER (+ more)

- Workshop Presentations featuring IXPE and NICER observations:
  - **Yash Bhargava** (7/30, Afternoon Session II) - X-ray Polarization in Neutron star Low mass X-ray Binary GX 340+0
    - + NuSTAR + AstroSat + Insight-HXMT + ATCA + GMRT
  - **Alessandro Di Marco** (7/31, Morning Session I) - First detection of X-ray polarization in the UCXB 4U 1820-30 with IXPE
    - + Swift + NuSTAR + ATCA
  - **Fabio La Monaca** (7/31, Morning Session I) - IXPE Highly Significant Detection of Polarization in Scorpius X-1
    - + NuSTAR + Insight-HXMT
  - **Jack Steiner** (7/31, Afternoon Session I) - Synergies between Spectroscopy and Polarimetry using NICER and IXPE to Explore Accreting Stellar-Mass Black Holes
    - + Swift + NuSTAR + INTEGRAL + AstroSat

Note on simulations

- End-to-end simulation workflow exists
  - Different to *xpobssim*
    - xpobssim: Given an arbitrary source model, simulate an IXPE observation
    - ixpesim: full detector simulation, based on the GEANT4 framework, following each interaction with the detector at a microscopic level
- Improving polarization track reconstruction algorithms
  - Neural network methods
  - See Cibrario+ 23, Peirson+ 21a, 21b, Kitaguchi+ 19
  - See book chapter by Peirson 22 - Handbook of X-ray and Gamma-ray Astrophysics.

Conclusions

- Presented a possible workflow for analyzing IXPE observations + tips and caveats
- Data products in the form of polarization cubes, polarization map cubes, and I/Q/U Stokes spectra
- *Extension:* pulse phase-resolved polarimetry and spectropolarimetry
- Contemporaneous or simultaneous multi-mission and even multi-wavelength campaigns are now the norm!
  - Stay on to hear about them!