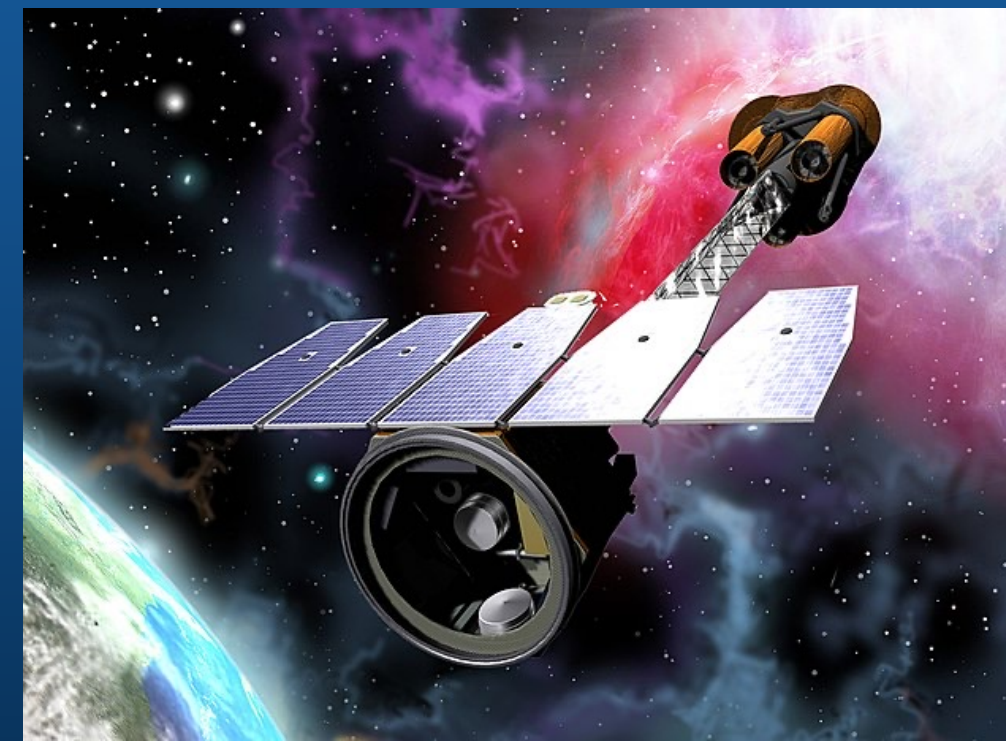


65. Spectral and Polarization Analysis of “West Bay” and Jets of the “Crab Nebula”

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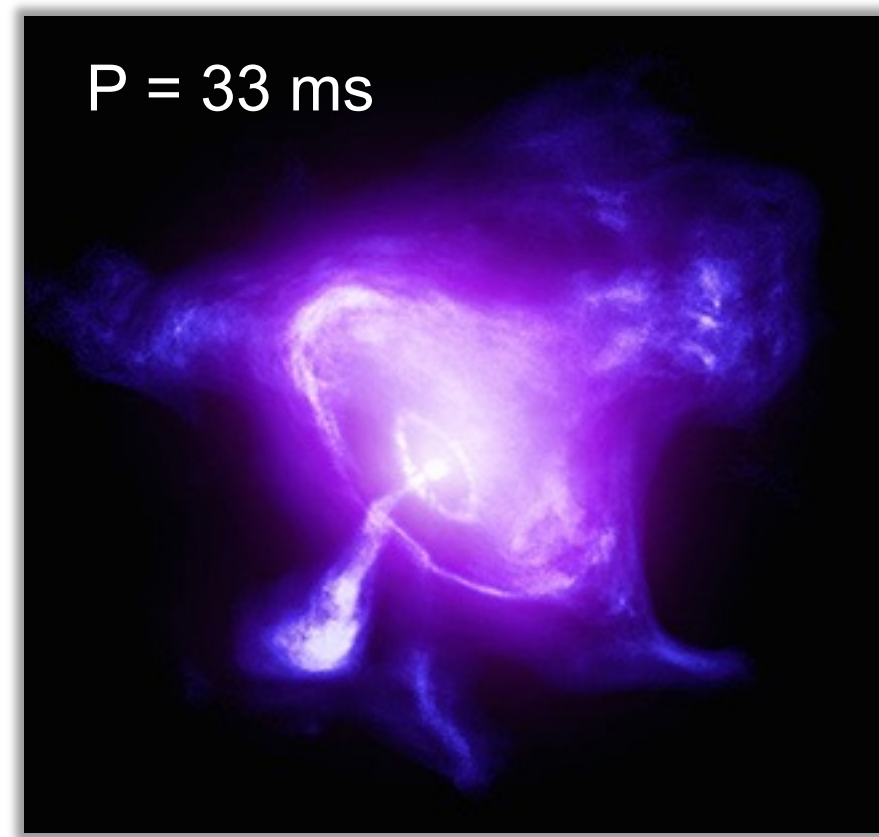


Abstract :

The IXPE, launched in December 2021, is the first satellite to perform polarimetric imaging observations in soft X-rays. In the 2nd collaboration paper of the Crab PSR/PWN (Wong *et al* 2024 *ApJ* 973 172), we analyzed PSR and PWN in detail using long observation data of IXPE for the first time. In the PWN analysis, we performed spectral and polarimetric analysis for the first time and found the spectrum was hard toward the west where PD was lower than others. We also analyzed the southern jet and found the magnetic field was parallel to the jet axis at the tip. Based on these results, we are conducting an in-depth analysis to investigate spectral and polarimetric properties of a structure called “West Bay” (F. D. Seward *et al* 2006 *ApJ* 6521277) and north/south jet. We found that PD decreases at the bay and from simulation, the B-direction is the N-S direction in the “West Bay”. In the jet analysis, B-direction is perpendicular to the jet axis in the southern/northern jet, while parallel to the folded tip at the southern jet.

Crab PSR/PWN

- Crab nebula is a remnant of supernova (1054) and pulsar wind nebula (PWN).
 - A neutron star, “Crab Pulsar (PSR)” at the center of the PWN
 - $d = 2$ kpc, $L = 10^{38}$ erg/s
- In Crab PSR/PWN, magnetic field is important in particle acceleration and radiation.

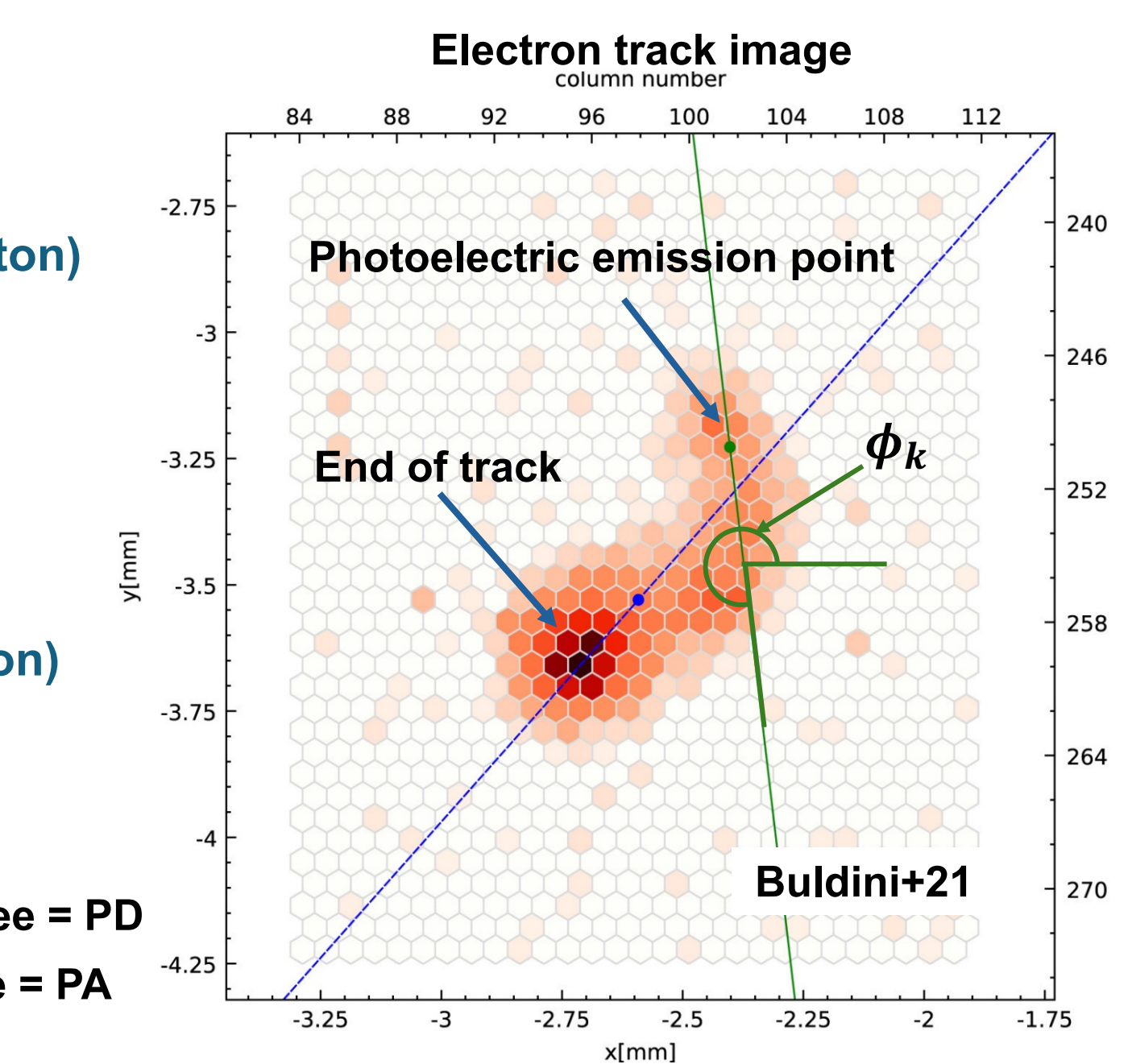
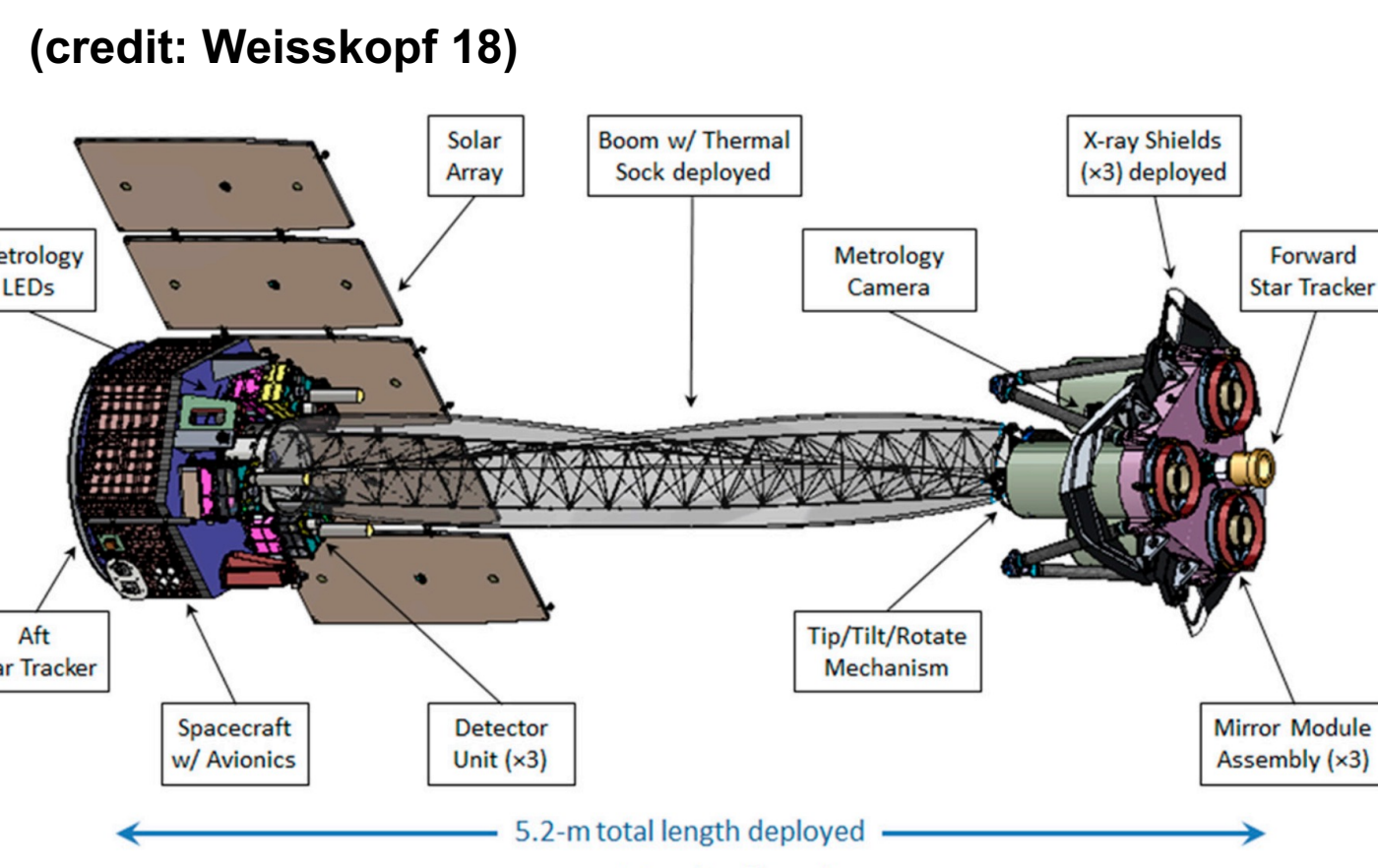


Crab in X-ray (Chandra) (credit: https://chandra.si.edu/press/23_releases/press_041023.html)

We can constrain the magnetic field structure in the particle acceleration region of crab PSR/PWN through X-ray polarimetry, and this will help us understand the acceleration mechanism.

Imaging X-ray Polarimetry Explorer (IXPE)

- IXPE was launched in December 2021.
- IXPE is the first satellite to perform polarimetric imaging observations in soft X-rays.
 - 3 x (mirror + detector)
 - Energy band : 2-8 keV
 - Angular resolution (HPD) : ≤ 25 arcsec
 - Field of View : $12.9' \times 12.9'$
 - Modulation factor (μ_{100}) : 15% @ 2 keV, 55% @ 6 keV
- Observed “Crab” about 280 ks in 2022-2024
- We evaluate Stokes parameters for each event.



$$i_k \equiv 1, \quad q_k \equiv 2 \cos 2\phi_k, \quad u_k \equiv 2 \sin 2\phi_k$$

(Stokes parameter for a photon)

$$I = \sum_{k=1}^N i_k = N, \quad Q = \sum_{k=1}^N \frac{q_k}{\mu}, \quad U = \sum_{k=1}^N \frac{u_k}{\mu}$$

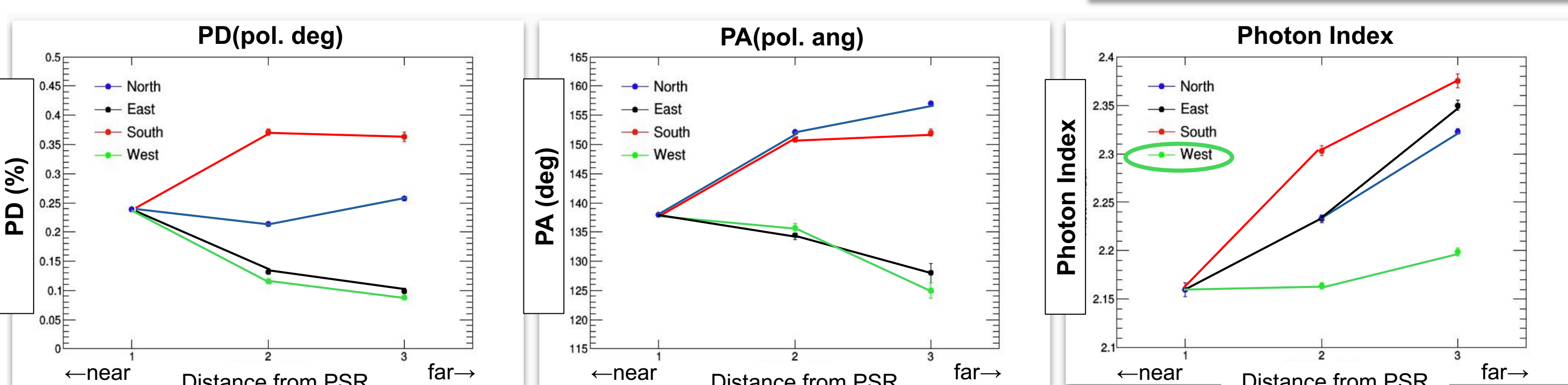
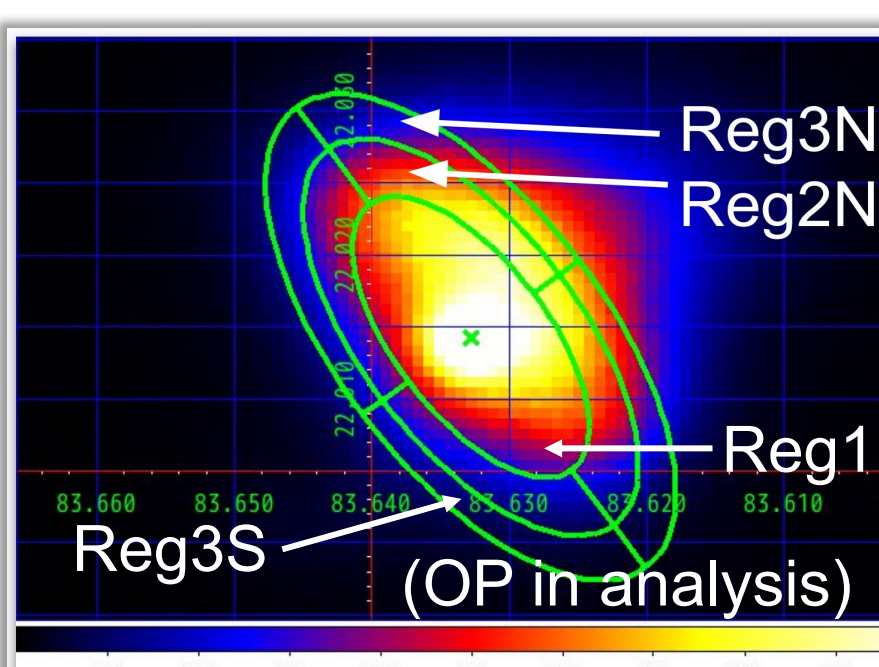
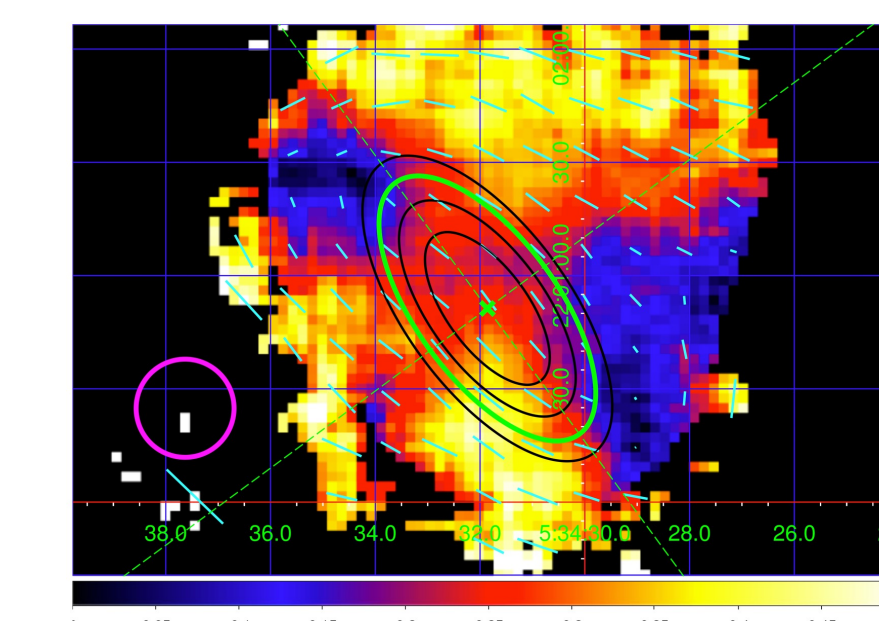
(Stokes parameter for all photon)

$$PD = \frac{\sqrt{Q^2 + U^2}}{I}, \quad PA = \frac{1}{2} \arctan\left(\frac{U}{Q}\right)$$

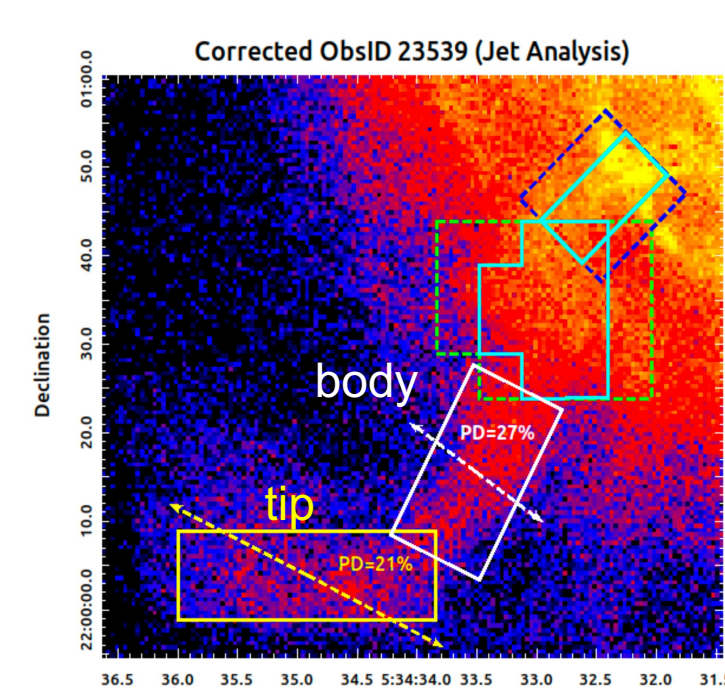
Polarization degree = PD
Polarization angle = PA

Past spectral polarimetric study (Bucciantini+23, Mizuno+23, Wong+24)

- We get the polarization map in soft X-rays for the first time (Bucciantini+23, Mizuno+23).
 - Lower PD along the jets is observed
 - High PD is observed in the outer nebula of northern/southern regions with B-direction parallel to E-W direction.
- We divided the torus into several regions (E, W, S, N), and investigated spectral and polarimetric properties, correcting for polarization leakage (Wong+24).
 - (left) PD is high in N&S and low in E&W
 - (middle) PA deviates in diametric ways btw. N&E and btw. S&W
 - (right) Spectrum remains hard in the outer nebula toward west where PD is lower than others



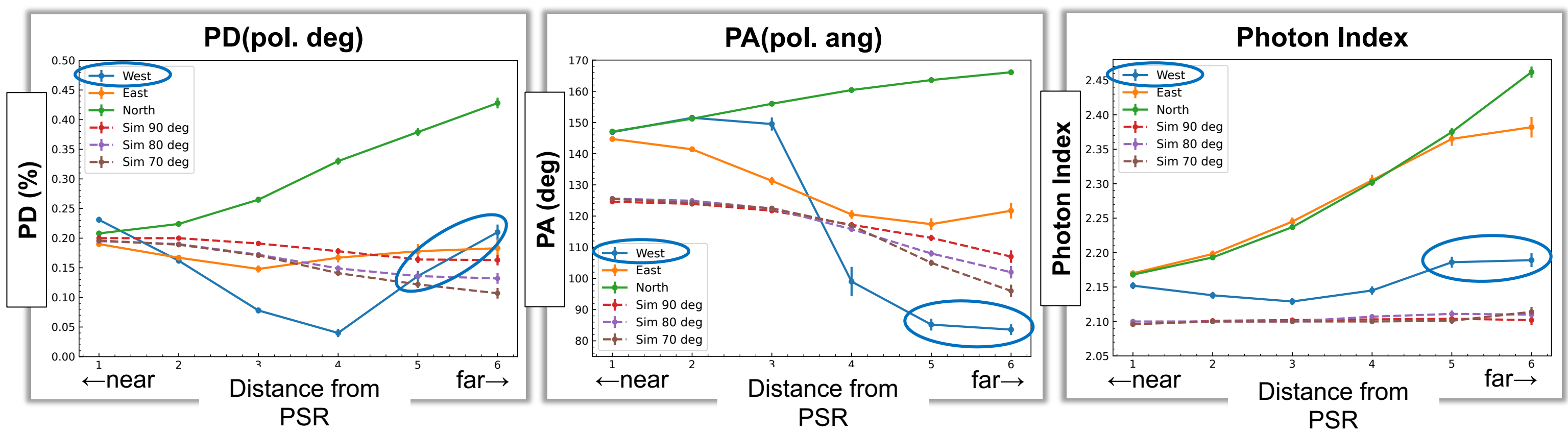
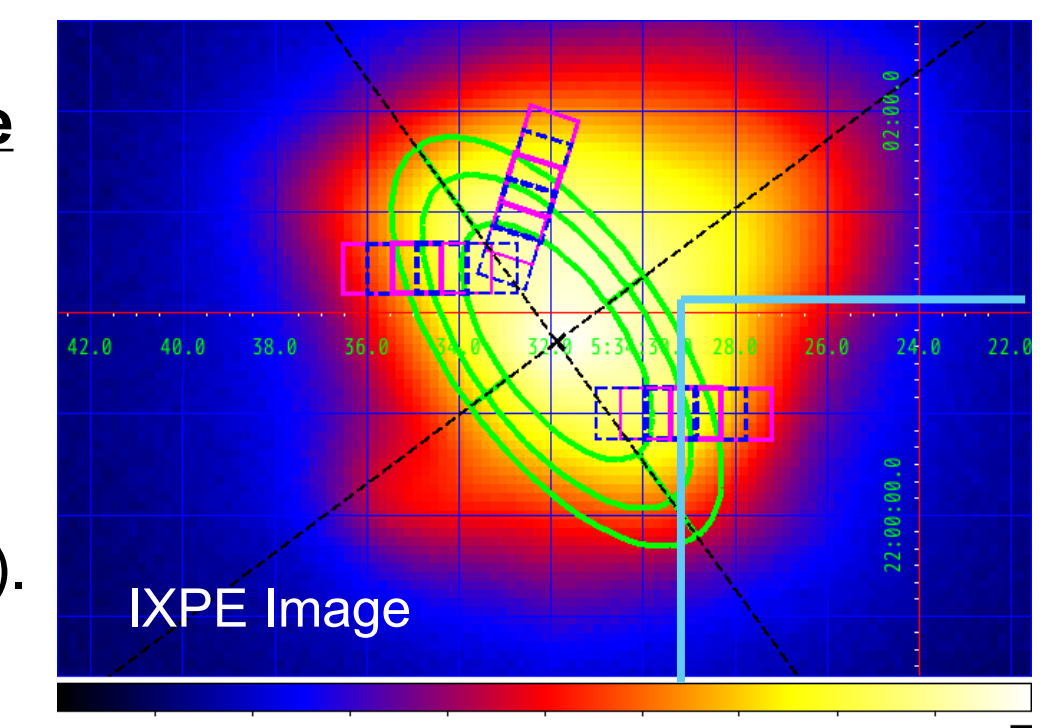
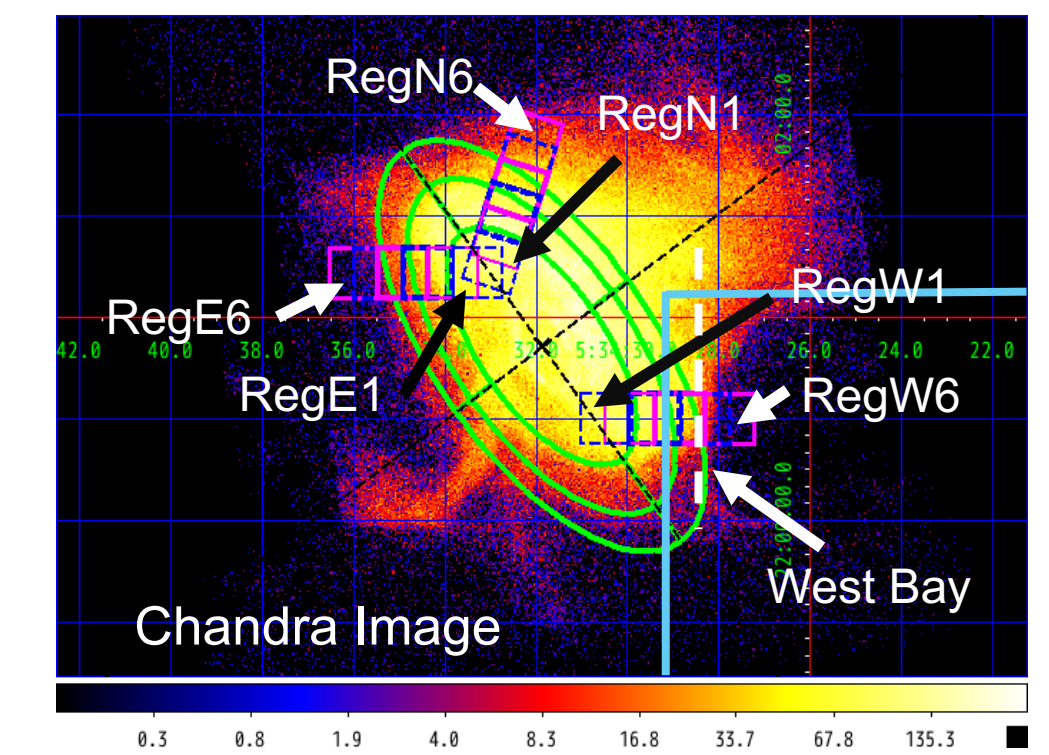
- We also analyzed southern jet, divided into 2 regions assuming background contamination is negligible.
 - PD = $(27 \pm 1)\%$ and PA = $(144 \pm 1)^\circ$ at the body
 - PD = $(21 \pm 2)\%$ and PA = $(153 \pm 1)^\circ$ at the tip
- magnetic field is perpendicular to the jet axis in the body while parallel in the tip



In depth Analysis of West Bay

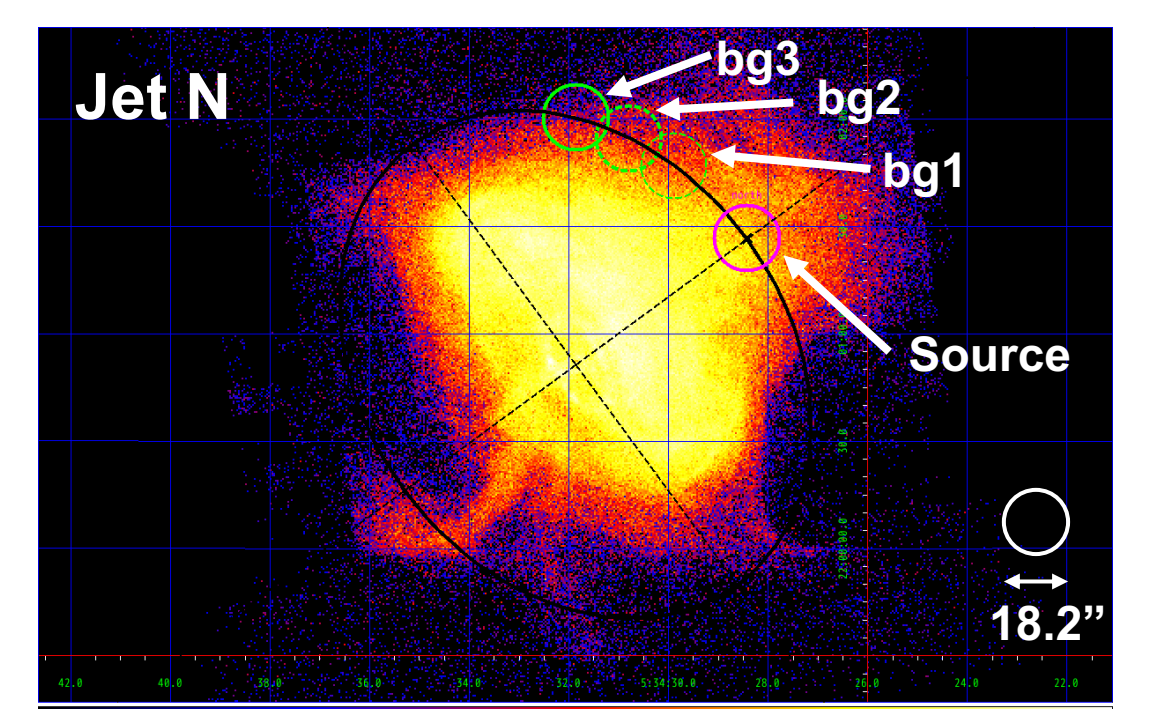
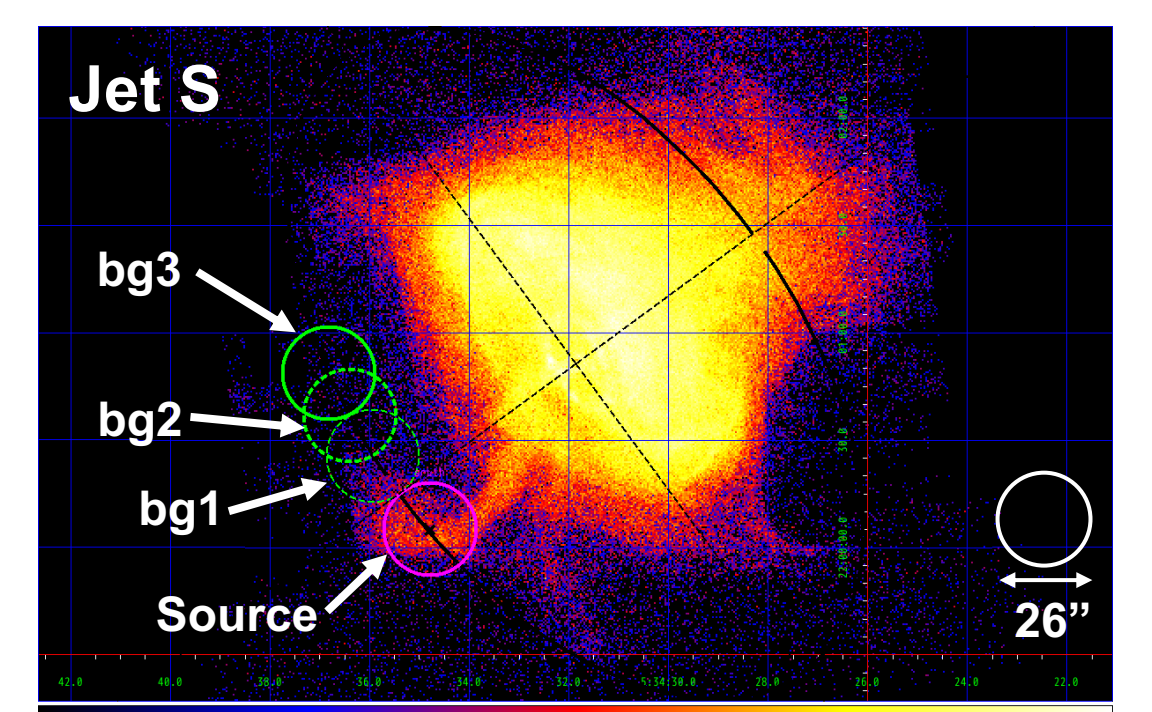
- To investigate the spectral and polarimetric properties of “West Bay” (Seward+06), we defined 6 regions along the RA axis and 6x2 regions toward north and east for comparison and fitted the Stokes I/Q/U spectrum by TBabs*(pow*polconst) with Xspec.
- We showed the results of the analysis in figures below.
 - (left) PD gradually decreases toward west up to reg 4, then PD recovers to >10% in regs 5 & 6
 - (middle) B direction is along N-S direction, or parallel to bay structure in regs 5 & 6 toward west
 - (right) Spectrum remains hard toward west
- We interpret that the photons in regs 3 and 4 are from both the inner torus and the west bay, causing decrease of PD in that regions due to PSF of IXPE, and we tested toy models in which B-direction changes abruptly at west bay (dashed line) through simulation of IXPE observation.
 - We input the PD = 20% in all region. PA = 126 deg (torus axis). PA = 90/80/70 deg at the west bay (cyan box).
 - Change of PD and PA is qualitatively compatible with observation
 - In simulation, PD does not recover in regs 5 and 6, and PA in reg1 is different from observation
- We shall assume PA ~ 145 deg in the torus to match with the data.
- We may assume B-direction start to deviate at position closer to PSR.

Adjacent boxes (15"x15") are shirtd by 7.5"



In depth Analysis of Southern/Northern Jet

- We analyzed the southern/northern jet by carefully subtracting the contamination from the torus and fit Stokes I/Q/U spectrum with Xspec.
 - Northern jet: we observed significant polarization for the first time. B-direction is perpendicular to the jet axis (126 deg).
 - Southern jet: (We will analyze at the body later.) we confirmed that B-direction is parallel to the jet at the folded tip.
- In the 3D relativistic MHD simulations of Crab nebula/jet by Mignone+ 2013, magnetic field is perpendicular to the flow velocity but parallel at the tip. Our results are consistent with this simulation.
- Northern jet, whose PA is ~130 deg and different from north of torus (~150 deg), likely cause depolarization along the jet axis.



Best fitted parameter with background 2 :

	Nh(10^{22} cm $^{-2}$)	PD(%)	PA(deg)	Photon Index	Flux(ergs/cm 2 /s)
Jet S	0.3 (fix)	22 ± 3	169 ± 4	2.72 ± 0.03	2.9×10^{-11}
Jet N	0.3 (fix)	19 ± 2	130 ± 2	2.77 ± 0.02	7.5×10^{-11}

Summary and Future Work

Summary :

- We conducted in-depth analysis to understand the properties of “West Bay”
 - Spectrum remains hard toward west, suggesting that synchrotron cooling is not so significant
 - PD decreases toward the bay. At the bay PD recovers and PA is along E-W direction.
 - Toy models which assume B-direction changes to parallel to north-south qualitatively explain observed change of PD/PA.
- We also analyzed Southern/Northern jet
 - In both southern jet and northern jet, B-direction is perpendicular to the jet axis.
 - In southern jet, B-direction is parallel to the jet at the folded tip.

Future Work :

- Improve the model to match the observed PD/PA toward the west bay
- We have no idea why spectrum remains hard toward west. If you have some ideas, please let me know!

Reference: F. D. Seward *et al* 2006 *ApJ* 6521277, Weisskopf, M. C. (2018). *Galaxies*, 6(1), 33, Baldini *et al* *Astroparticle Physics*, 133, 102628., Bucciantini *et al* *Nature Astronomy*, 7(5), 602-610, Mizuno *et al* *PASJ*, 75(6), 1298-1310, Wong *et al* 2024 *ApJ* 973 172, Mignone *et al* *MNRAS*, 436(2), 1102-1115.