Vela pulsar wind nebula X-rays are polarized to near the synchrotron limit

Astrofisica Nucleare e Subnucleare - Journal Club #3

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Abstract

“Pulsar wind nebulae are formed when outflows of relativistic electrons and positrons hit the surrounding supernova remnant or interstellar medium at a shock front. The Vela pulsar wind nebula is powered by a young pulsar (B0833-45, aged 11,000 years) and located inside an extended structure called Vela X, which is itself inside the supernova remnant. Previous X-ray observations revealed two prominent arcs that are bisected by a jet and counter jet. Radio maps have shown high linear polarization of 60% in the outer regions of the nebula. Here we report an X-ray observation of the inner part of the nebula, where polarization can exceed 60% at the leading edge— approaching the theoretical limit of what can be produced by synchrotron emission. We infer that, in contrast with the case of the supernova remnant, the electrons in the pulsar wind nebula are accelerated with little or no turbulence in a highly uniform magnetic field.”

IXPE Chandra Hubble

Scope of the paper

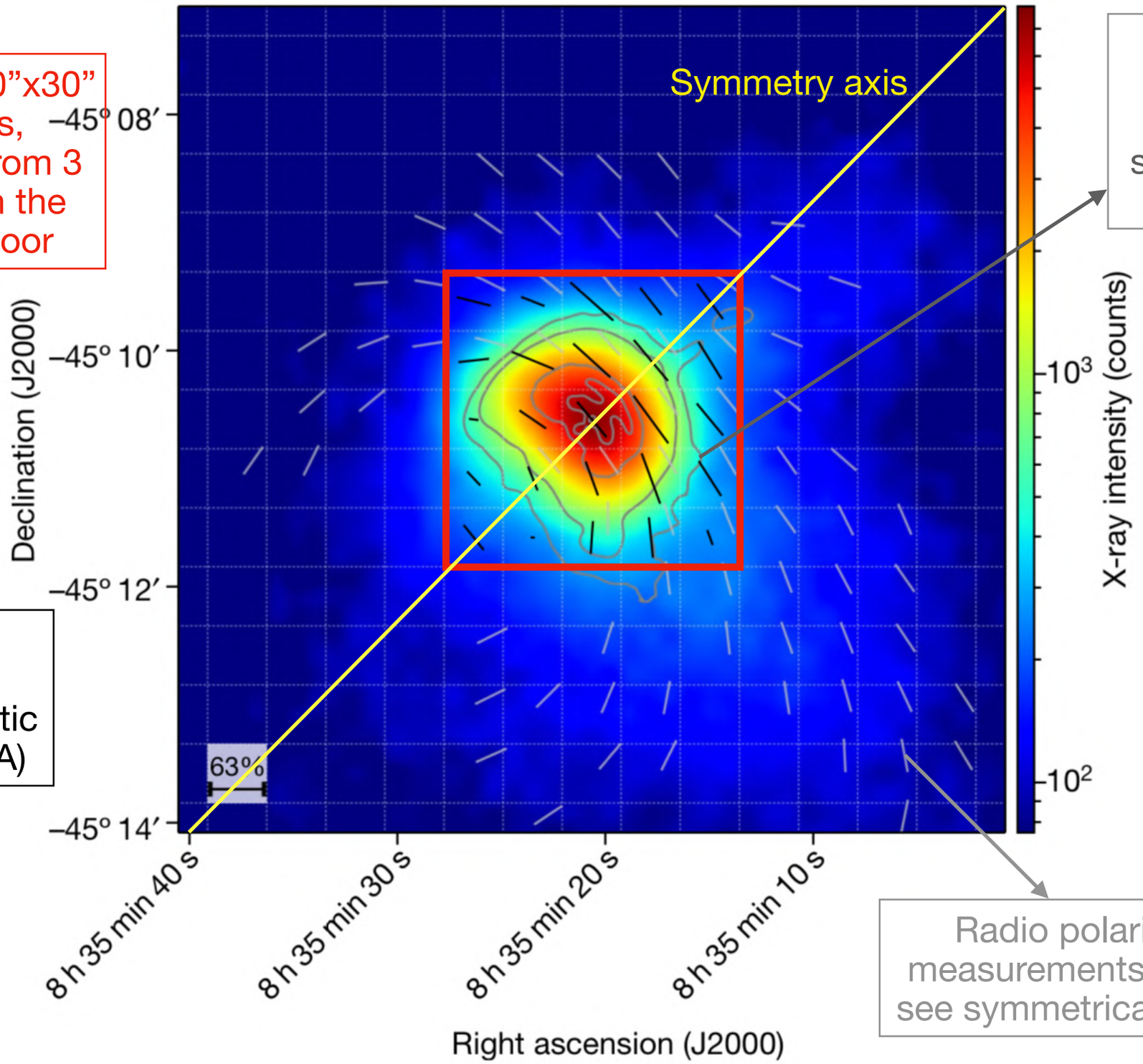
- Previously, only the Crab PWN has been studied by X-ray polarization; the classic 1976 and 1978 OSO-8 results have recently been confirmed by the Polarlight cube-sat. However, these observations provided only an integrated polarization measurement and the image-averaged PD was less than half of that found here for Vela.
- IXPE's imaging abilities enable a **spatially resolved polarimetric measurement** of the PWN.

Illustrate results obtained from the analysis of IXPE's data of Vela PWN:

1. Study the **spatial** distribution of the polarization degree and angle
2. Study their dependence from **energy**
3. First studies separating **pulsar** contribution to PD

1. Spatially resolved analysis

25 independent 30”x30” square regions, combining data from 3 DUs, statistics in the outer bins are poor

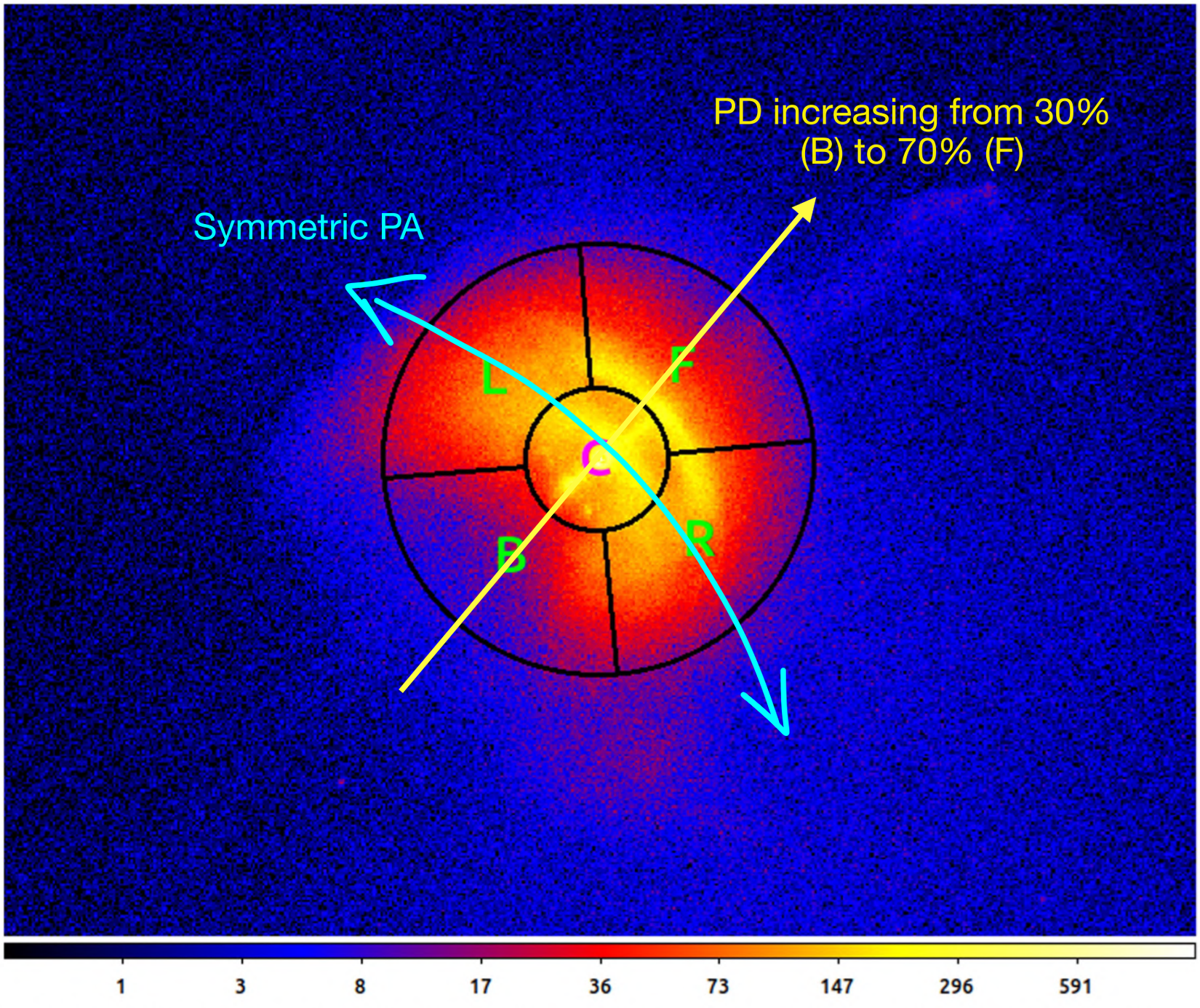


Contours from Chandra, to see pulsar, arc-jet structure, emission shell, outer jet

Lenght is PD, orientation is projected magnetic field (90° from PA)

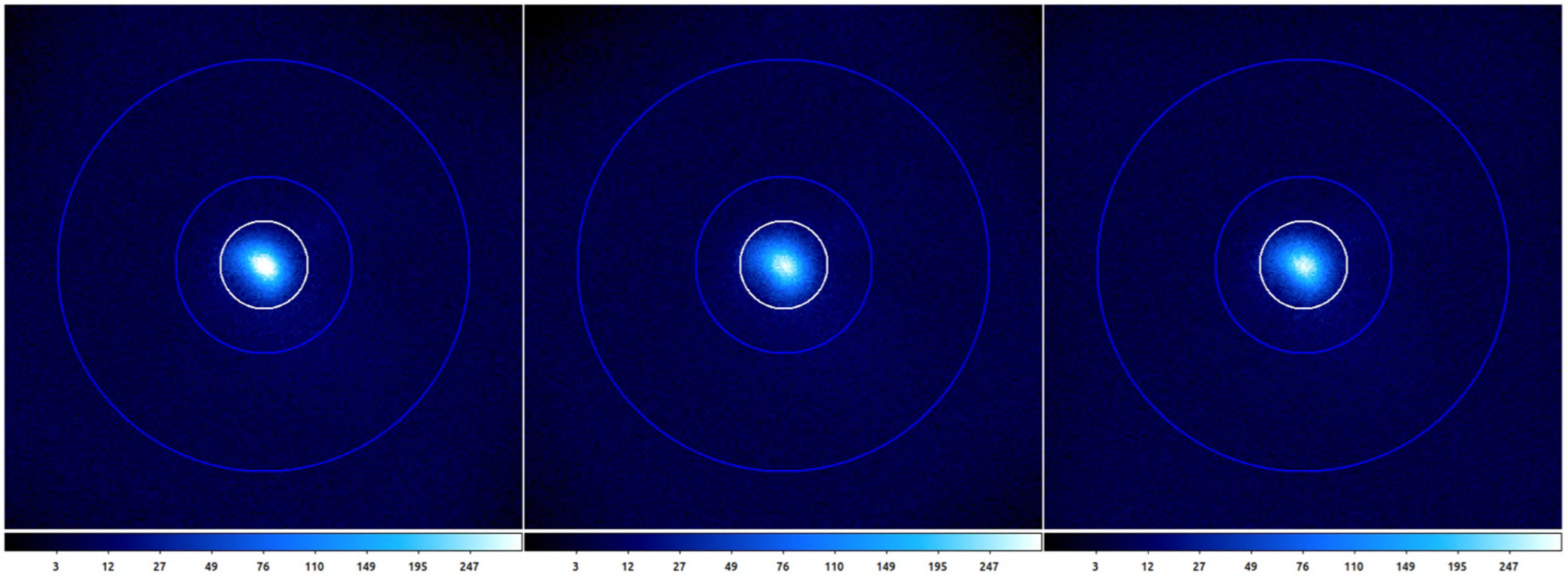
Radio polarization measurements to better see symmetrical strutture

1. Spatially resolved analysis



Extended Data Fig. 5 | An alternative spatial partition of the PWN with regions aligned with the PWN symmetry axis on image observed by Chandra. *L*, *R*, *F*, *B* label the left, right, front, back regions with respect to the *C* centre region respectively, corresponding to the analysis tabulated in Extended Data Table 4. The inner circle has a radius of 15″ and the outer circle radius is 45″.

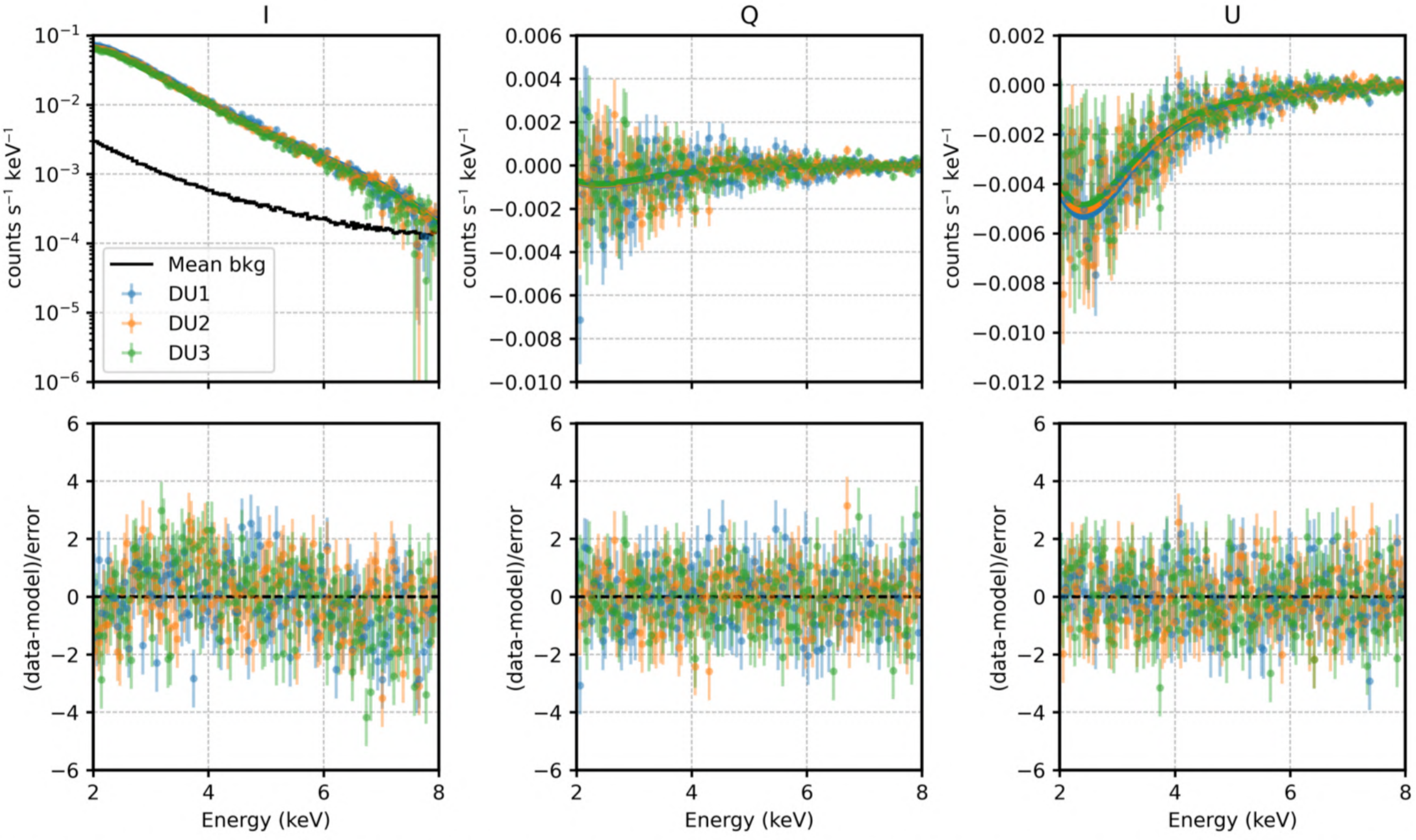
2. Energy resolved analysis



Extended Data Fig. 2 | Total nebula source (white 1′ radius circle) and background (blue annulus, inner radius 2′, outer radius 4.7′) regions shown on images from DU1 (left) to DU3 (right). Intensity is on a logarithmic scale to bring out the faint background.

Here background subtraction because background events not negligible at high energies

2. Energy resolved analysis



Extended Data Fig. 3 | Spectral joint fitting for the Stokes parameters in the 2–8 keV energy band for the three DUs using model TBABS*POWERLAW* POLCONST with previously fit spectral parameters fixed. The average background count / spectrum for the three DUs is shown in black. Fit residuals are shown at the bottom.

2. Energy resolved analysis

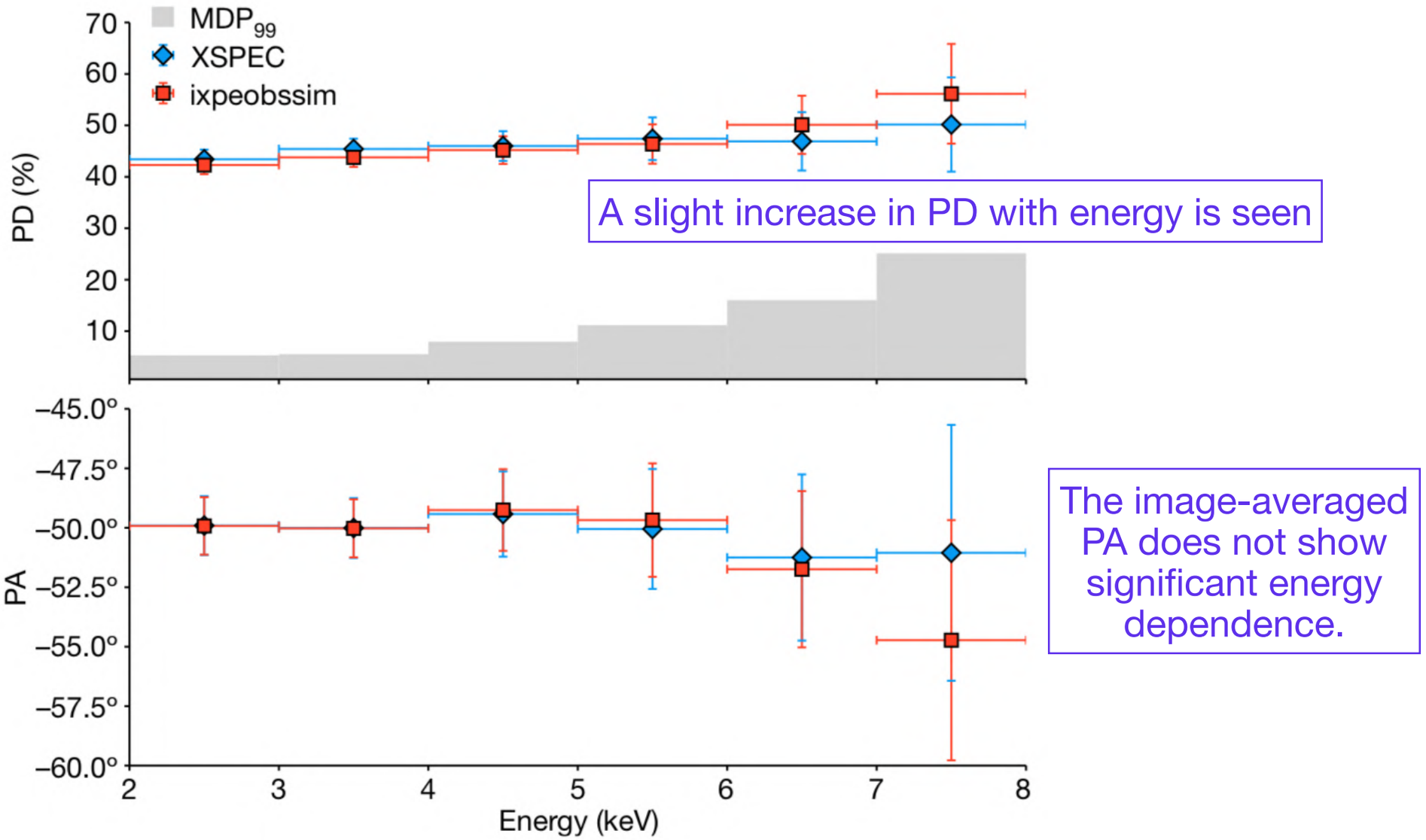
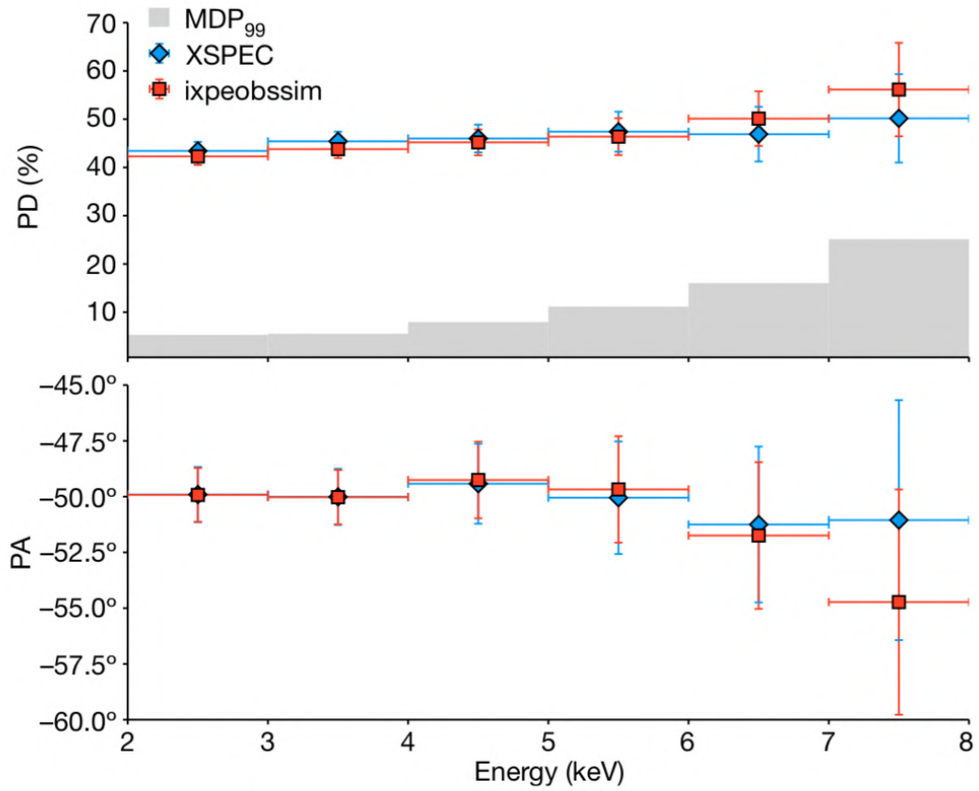


Fig. 2 | Image-average polarization of the Vela PWN as a function of energy. PD (top) and PA (bottom) were derived using ixpeobssim (red) and XSPEC (blue) independently. The results are from the joint analysis of three detector units with uncertainties calculated at a 68.3% confidence level. PD values in all of the energy bins are significantly higher than the minimum detectable polarization at the 99% confidence level (MDP_{99}), shown as a grey histogram.

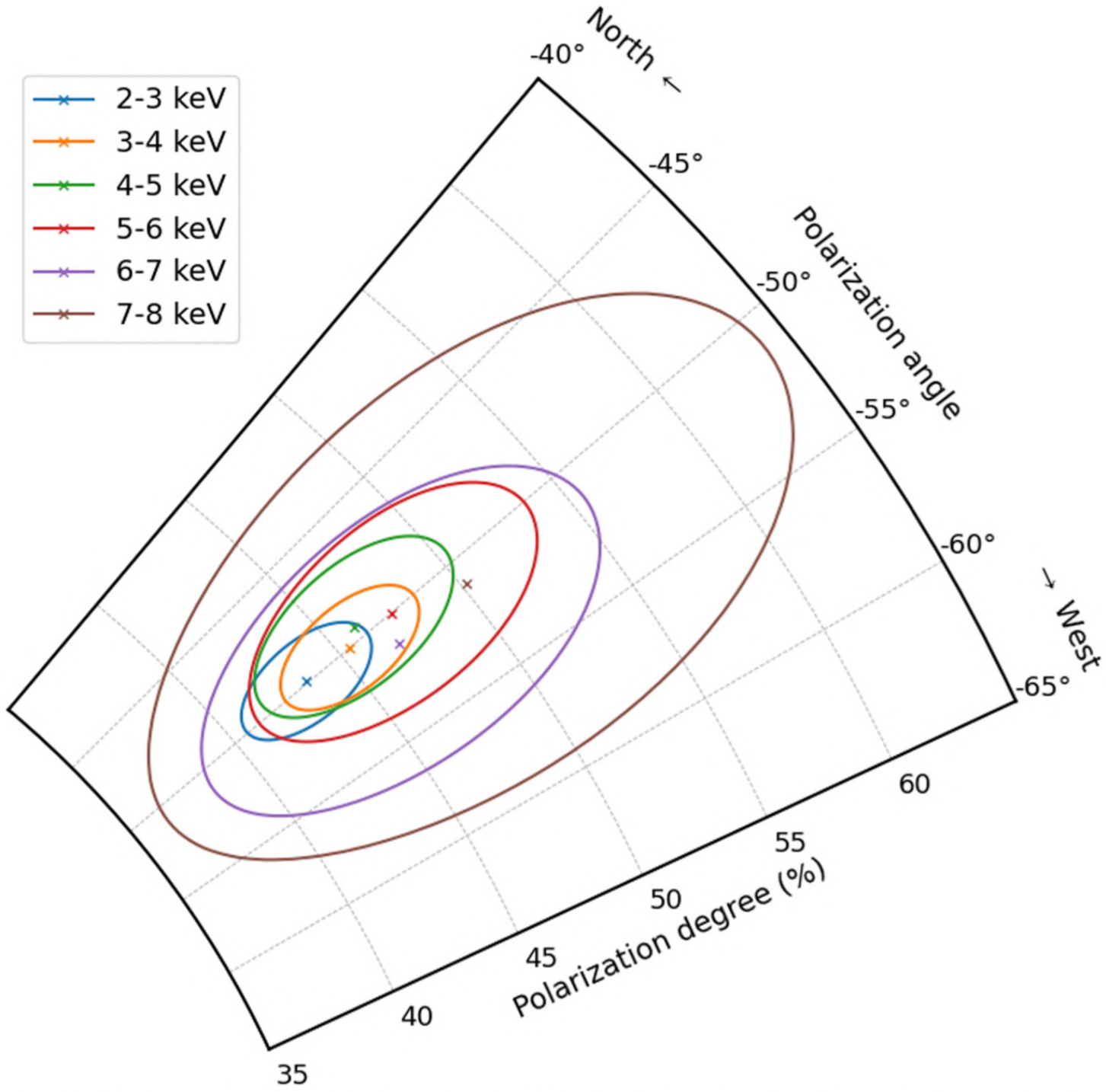
2. Energy resolved analysis



Constant PD *vs* Linear PD

We have attempted to quantify the significance of the PD(E) trend in Fig. 2. Although a χ^2 test found that a constant PD is acceptable at the 57% level, a run-test analysis accepted this hypothesis at only 7.7% and a Kolmogorov–Smirnov test at only 3.6%. By contrast, a linear PD(E) model gives an acceptable χ^2 probability at the 98% level, the run-test statistic is allowed at 41% and a Kolmogorov–Smirnov test accepted the hypothesis at the 98% level. Thus, a linear model with slope $1.8 \times 10^{-2} \pm 0.9 \times 10^{-2}$ keV^{-1}, while not demanded by the data, is preferred over a simple constant PD model at the 2σ confidence level.

2. Energy resolved analysis



Extended Data Fig. 4 | Polar plot showing the polarization degree (PD) and polarization angle (PA) fit with data from the three DUs, for different energy bands. Ellipses show the 68.3% confidence level errors obtained with XSPEC.

3. The effect of the pulsar on the PWN polarization

- The X-rays of the Vela pulsar are largely thermal and make a negligible contribution to the 2–8 keV PWN flux **as a whole**. Thus, they cannot notably affect our image-averaged PD and PA.
- However, from high-resolution Chandra images, we see that the pulsar contributes around 10% of the 2–8 keV flux in the **central** square region of Fig. 1 and it might therefore affect its polarization.
- If the pulsar contributes an unpolarized background, the corrected nebula-only PD rises to 55%. By contrast, if the pulsar emission is 100% polarized parallel (perpendicular) to the PA measured for the central square region, then the pulsar-subtracted polarization falls (rises) to 39% (66%).
- In practice, the pulsar polarization is quite low in the optical band and, by **analogy with the Crab**, will be even lower in the X-rays, so the true effect should be close to the unpolarized case, boosting the inferred PWN central PD.
- We apply this correction to the central bin in Fig. 1.

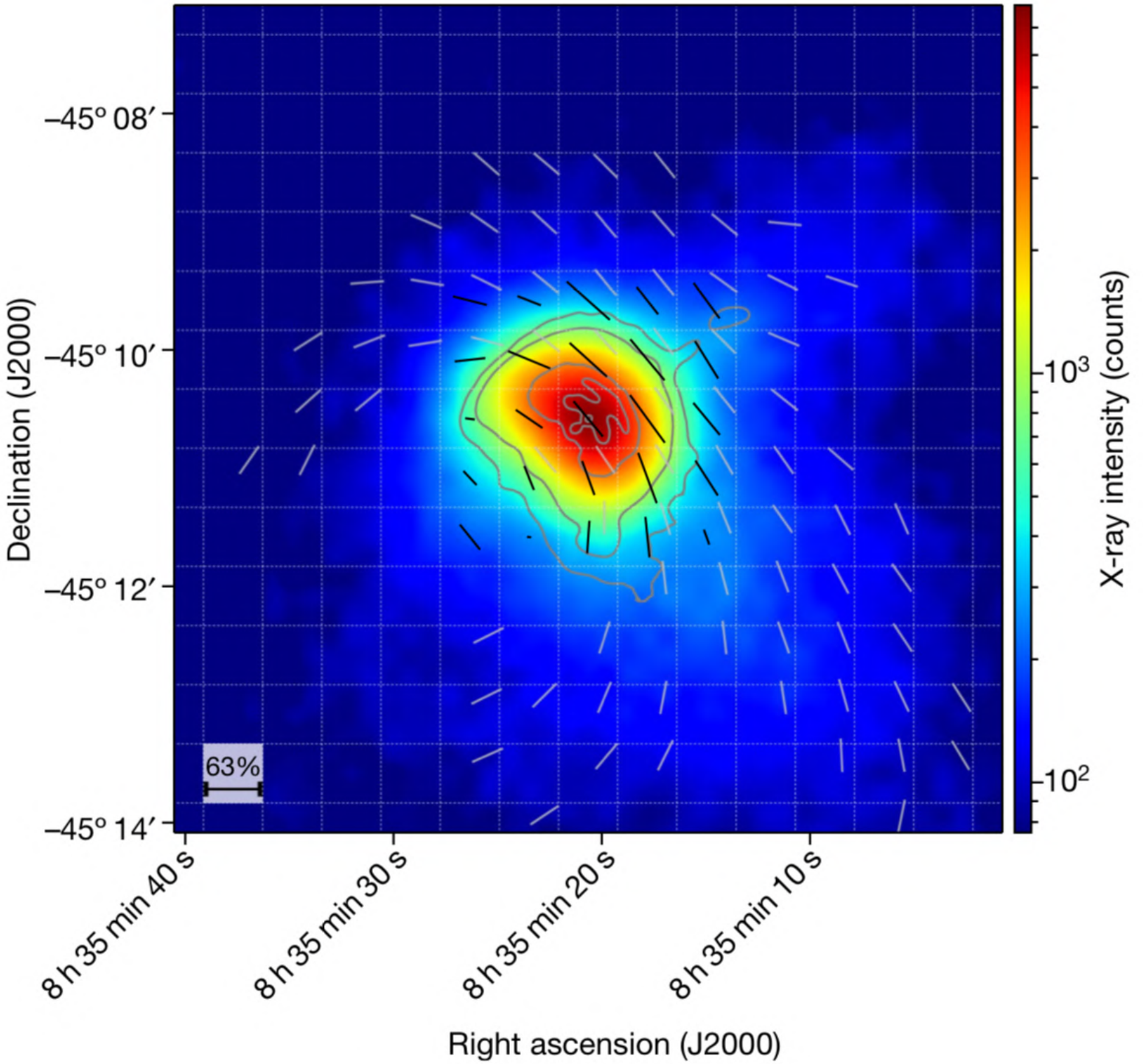
Results

- We found a notable high X-ray polarization in the Vela PWN, reaching an image and energy-averaged PD of about 45%.
- **Vela's high PD and symmetric pattern imply a highly ordered magnetic** field following the PWN's toroidal structure. The ordered and minimally turbulent fields probed by IXPE extend into this radio-emitting zone at much larger radii.
- The non-thermal radio and X-ray spectra of the Vela PWN already indicated domination by **synchrotron emission**. The high linear X-ray polarization, measured here using IXPE, strengthens this conclusion.
- The high PD gives information on the PWN particles acceleration mechanism, suggesting the mechanism of **reconnection of magnetic field lines**.

Future prospects

- Much deeper observations (and probably at a higher spatial resolution) will be required to isolate this **component** and compare with the optical phase average polarization.
- If, like the Crab pulsar, the phase-average X-ray PD is well below that of the optical emission, **corrections** to our nebular estimates will be very **small**.
- Further IXPE studies of Vela and other bright PWNe should connect the X-ray polarization pattern with the details of the compact structures, further probing the physics of relativistic shock acceleration.

Thank you!



https://www.nature.com/articles/s41586-022-05476-5