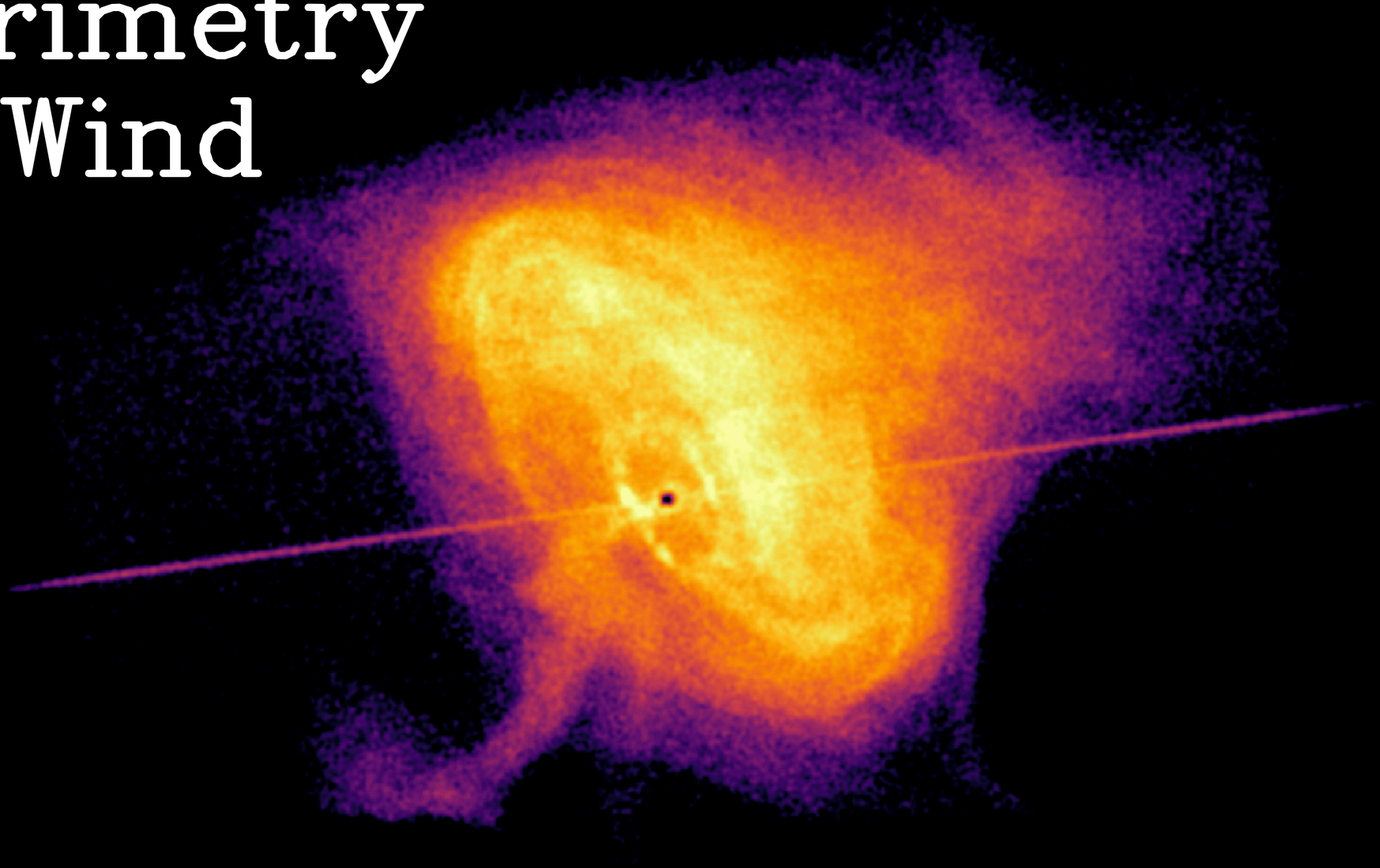
# IXPE Polarimetry of Pulsar Wind Nebulae



Jack T. Dinsmore
Stanford University

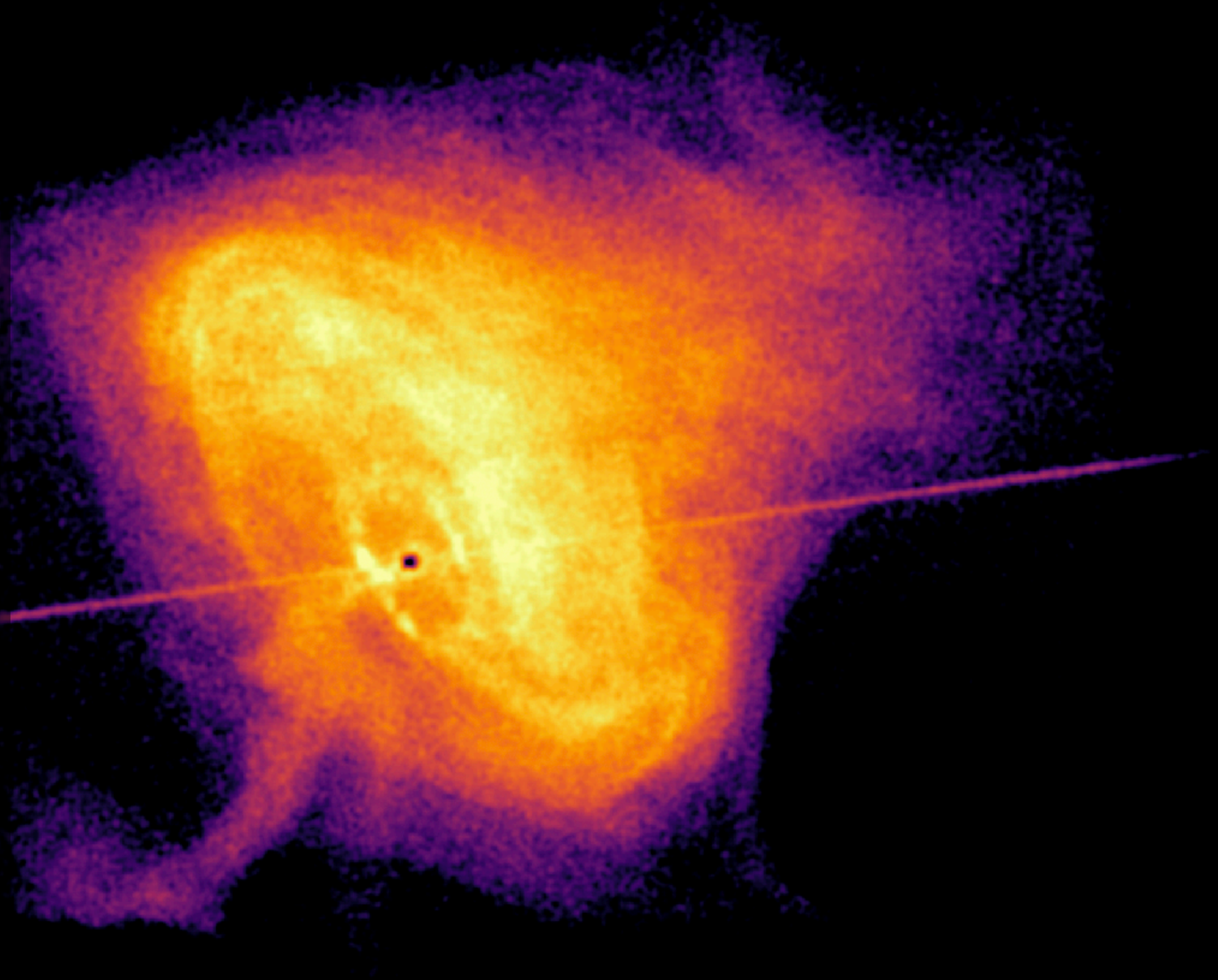
Friends of IXPE Meeting, July 16

# Why study PWNe?

- Formed by the interaction of pulsar-generated e+/e− with the ISM
  - Opportunity to study astrophysical phenomena in a variety of regimes

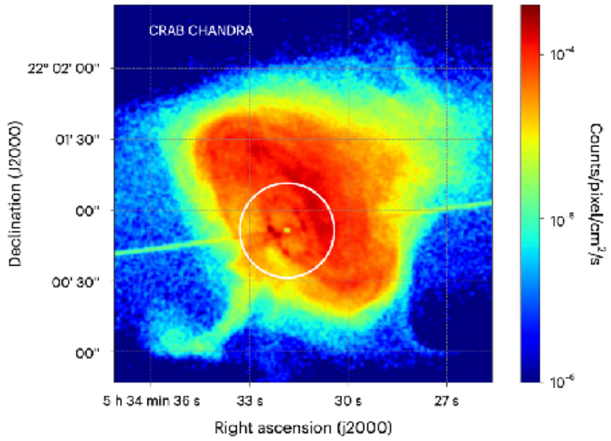
- Synchrotron EVPA constrains the magnetic field orientation, and PD constrains the amount of turbulence

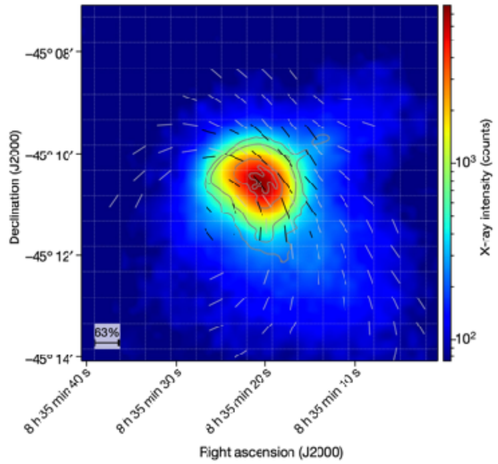
- “2 for the price of 1” if the pulsar can also be constrained!

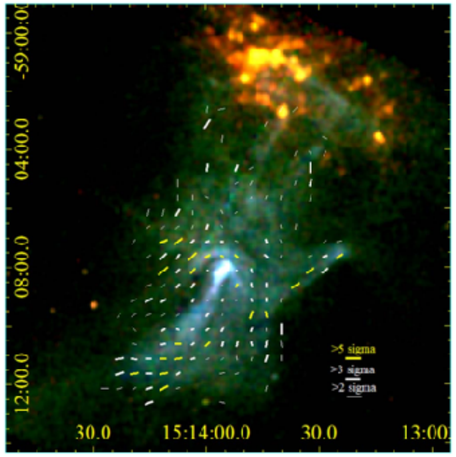


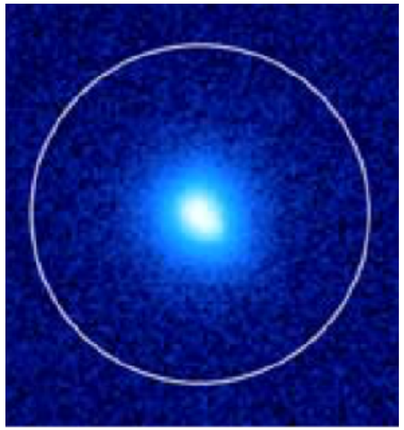
# IXPE Measurements of PWNe

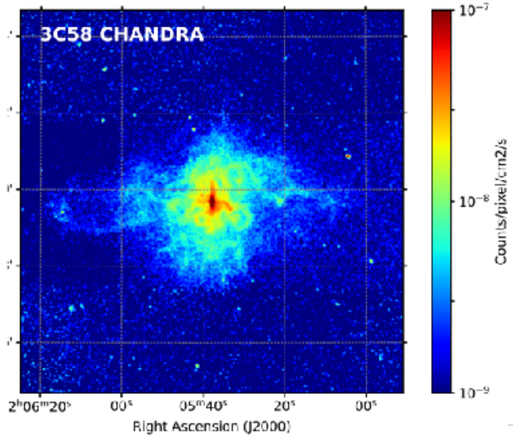
- PWNe within the SNR
  - **Crab** (Bucciantini+ 2022)
  - **Vela** (Xie+ 2022)
  - **MSH 15−52** (Romani+ 2023)
  - **B0540−69** (Xie+ 2024)
  - **3C 58** (Bucciantini+ 2025)
  - **G21.5−0.9** (Di Lalla+ 2025)
  - **Kes 75** (Wong+ 2025)
- X−ray filaments / candidates
  - **G0.13−0.11?** (Churazov+ 2024)
  - **Lighthouse** (Dinsmore+ 2026)

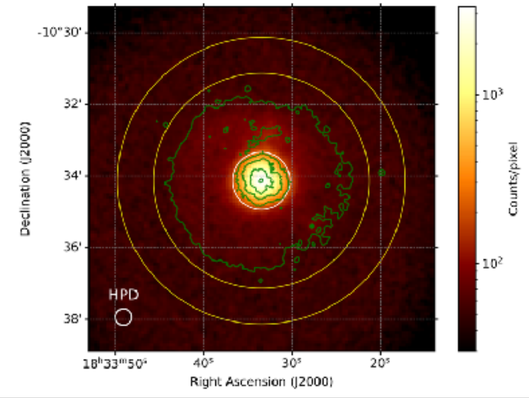


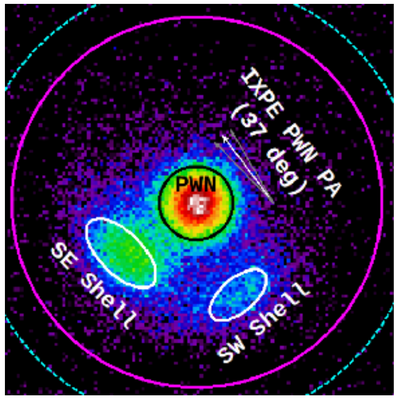



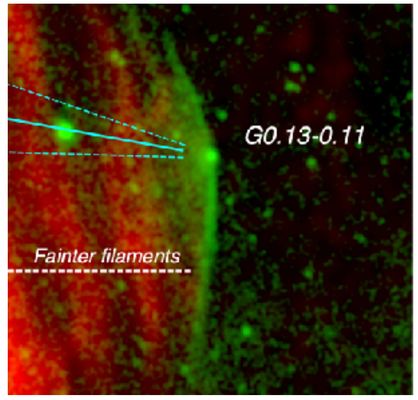



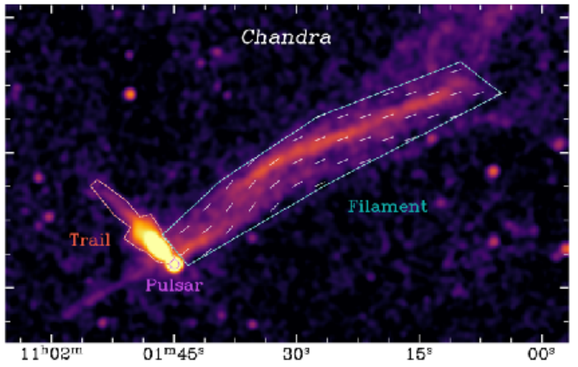





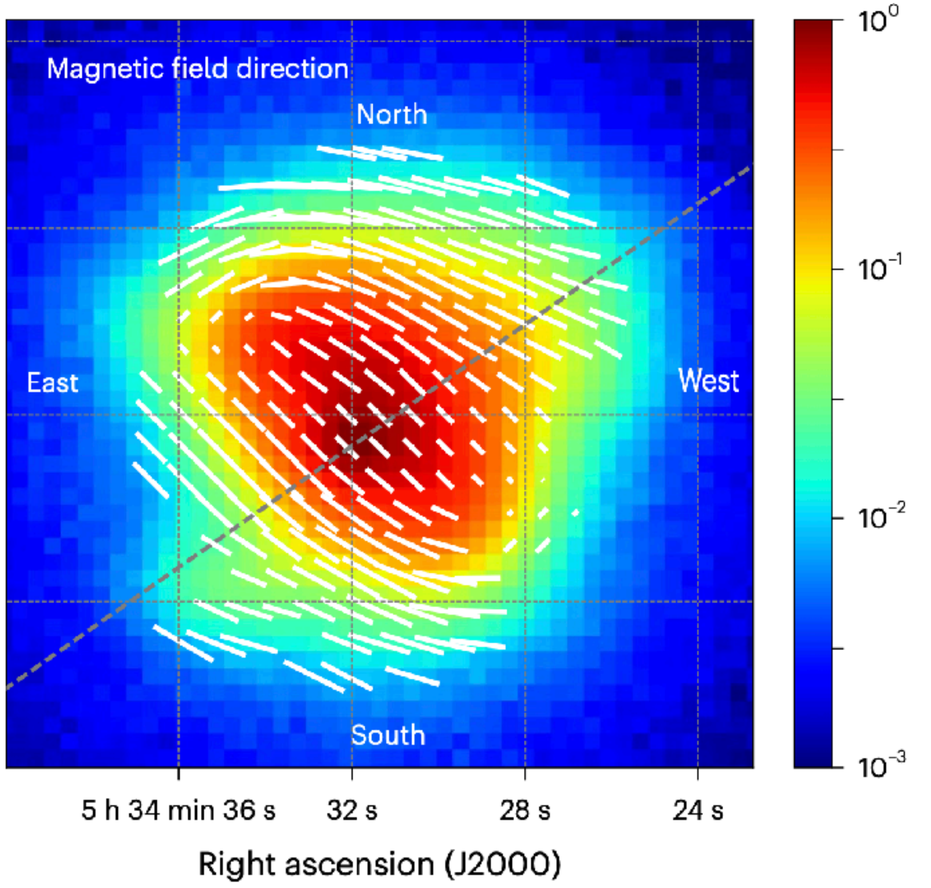




(List contains citations for the first analysis only)

# *Nebulae*

# Nebular EVPA is generally consistent with a toroidal magnetic geometry

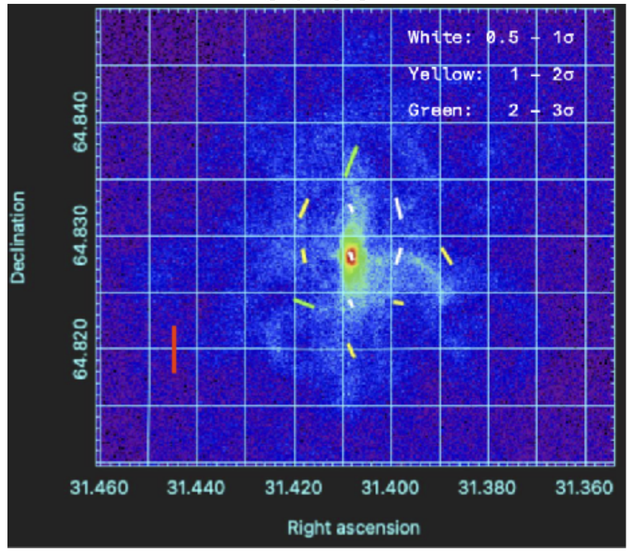
Crab




Bucciantini et al (2022)

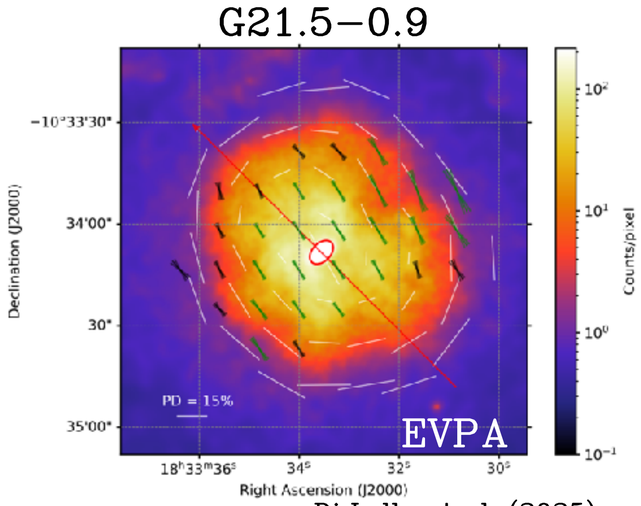
- Easiest to see with Crab's resolved polarimetry
  - seen with fewer spatial bins elsewhere (Vela, 3C 58, G21.5−0.9, maybe B0540−69, and Kes 75)

3C 58




Bucciantini et al. (2025)

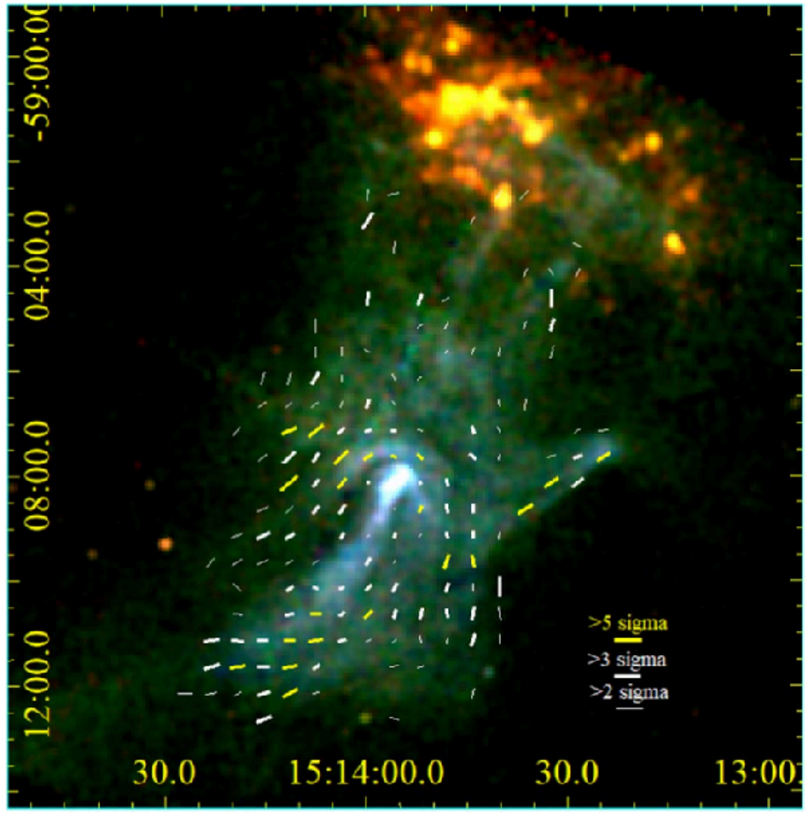
G21.5−0.9




Di Lalla et al. (2025)

# Additional structures at SNR edge or compressed by reverse shock

MSH 15−52




Romani et al. (2023)

- Easiest to see with Crab's resolved polarimetry
  - seen with fewer spatial bins elsewhere (Vela, 3C 58, G21.5−0.9, maybe B0540−69, and Kes 75)
- Additional structure farther in the PWN can also be probed

# Common themes in IXPE PWN analyses: Highly polarized nebulae

- Averaged polarization degrees 10–30% (Kes75, G21.5–0.9, 3C 58, Crab, B0540–69)

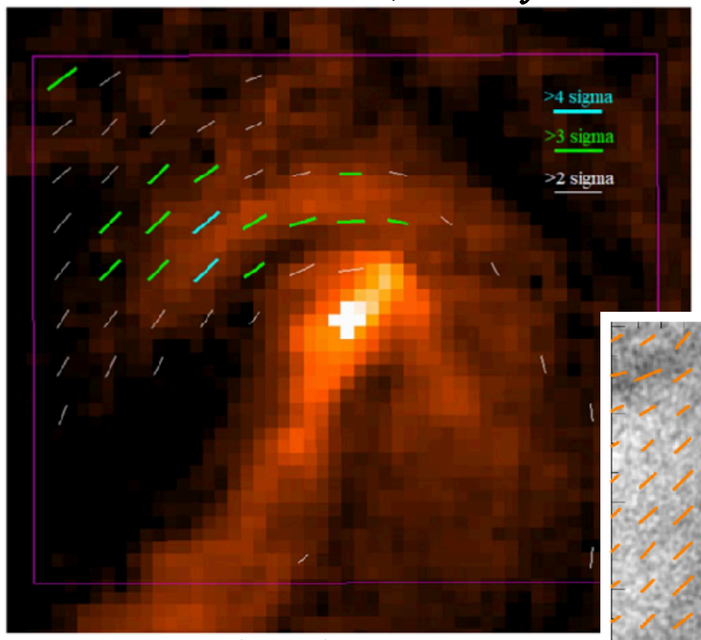
- Resolved studies detect higher polarizations up to 70%
  - Case study: Crab's nebula—averaged result is 20%, but the highest polarization bin is 50%

- Implies magnetic fields are highly ordered and possibly less turbulent than expected, especially near the outer edges.

# Differences between nebula X–ray and radio/optical polarizations often occur

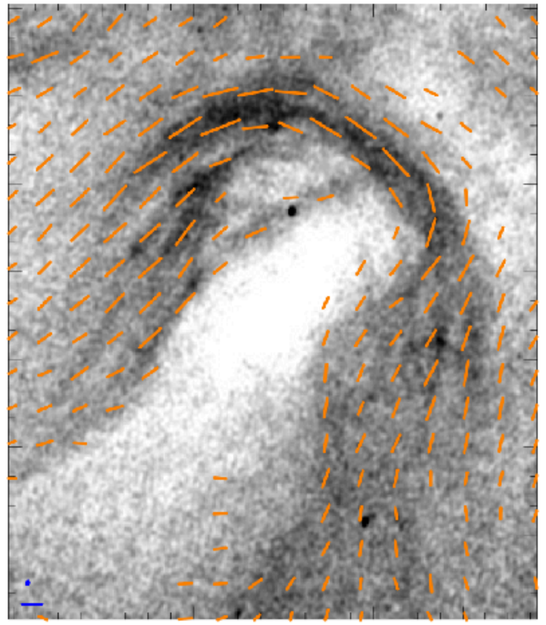
- PD: Often disagreement
  - Crab: Optical most polarized in the center, X–ray at the edges
  - MSH 15–52: Radio PD is larger in the X–ray structure and smaller in the SNR. Jet highly polarized in X–ray, not seen in radio
- EVPA: alignment is more common, but not general
  - Aligned for Vela, MSH 15–52
  - Misaligned for Crab, parts of G21.5–0.9

MSH 15–52, X–ray




Romani et al (2023)

MSH 15–52, radio



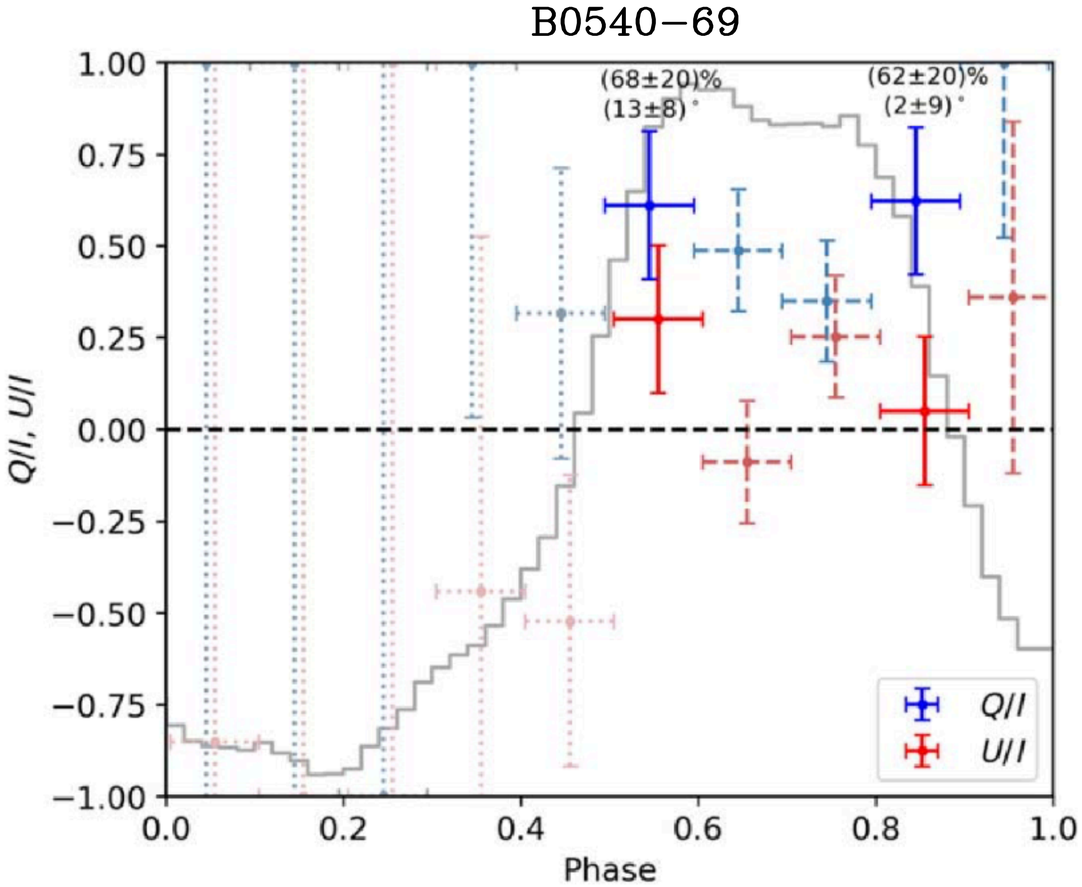
Zhang et al (2025)

# *Pulsars*

# Pulsars can be highly polarized in X−rays

- When it can be measured, the maximum pulsar PD is…
  - ~15−25% for Crab and MSH 15−52
  - 59±16% for Lighthouse
  - 70±20% for B0540−69
  - Pegged at synchrotron limit for Kes75

- Compare synchrotron limit of 60−70%



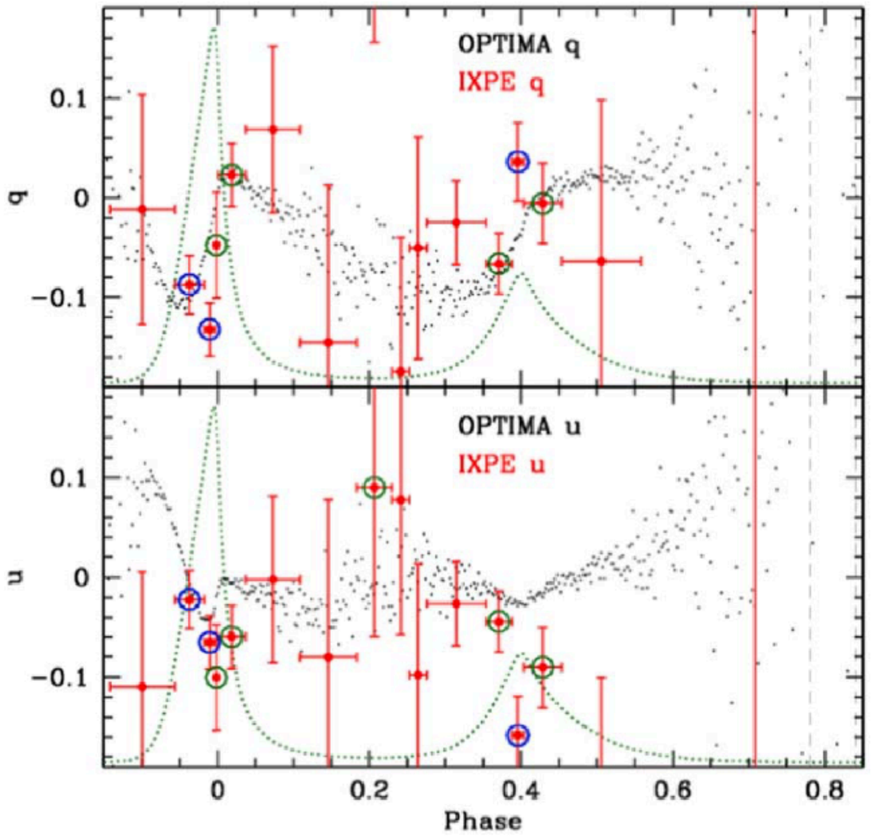

Xie et al. (2024)

# The X−ray EVPA sweep is increasingly accessible

- The EVPA can significantly sweep (Crab, MSH 15−52, B0540−69, Kes75, Lighthouse)

- Polarization sweep can differ significantly between bands (Crab, maybe MSH 15−52)

Crab

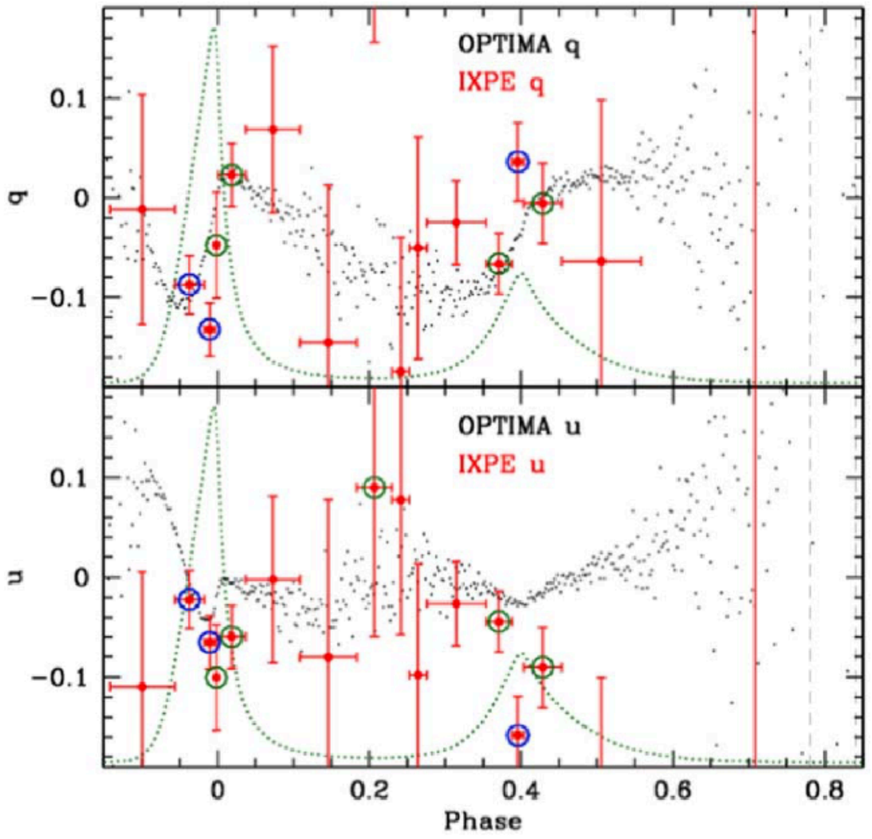



Wong et al. (2023)

# The X-ray EVPA sweep is increasingly accessible

- The EVPA can significantly sweep (Crab, MSH 15−52, B0540−69, Kes75, Lighthouse)
- Polarization sweep can differ significantly between bands (Crab, maybe MSH 15−52)
- The rotating vector model (RVM), developed for radio, sometimes fits the data (Lighthouse, Kes75, maybe MSH 15−52, not Crab)
  - But we lack a good model for pulsed X-ray polarization

Crab



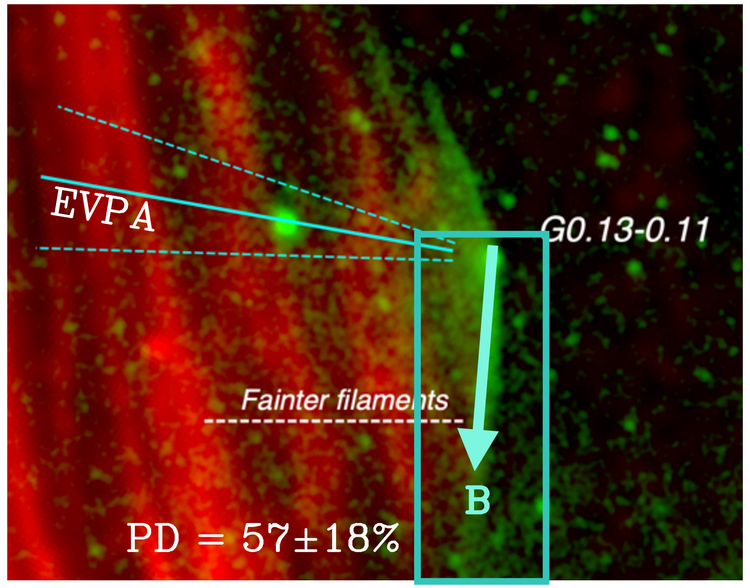

Wong et al. (2023)

# *Pulsars outside the SNR*

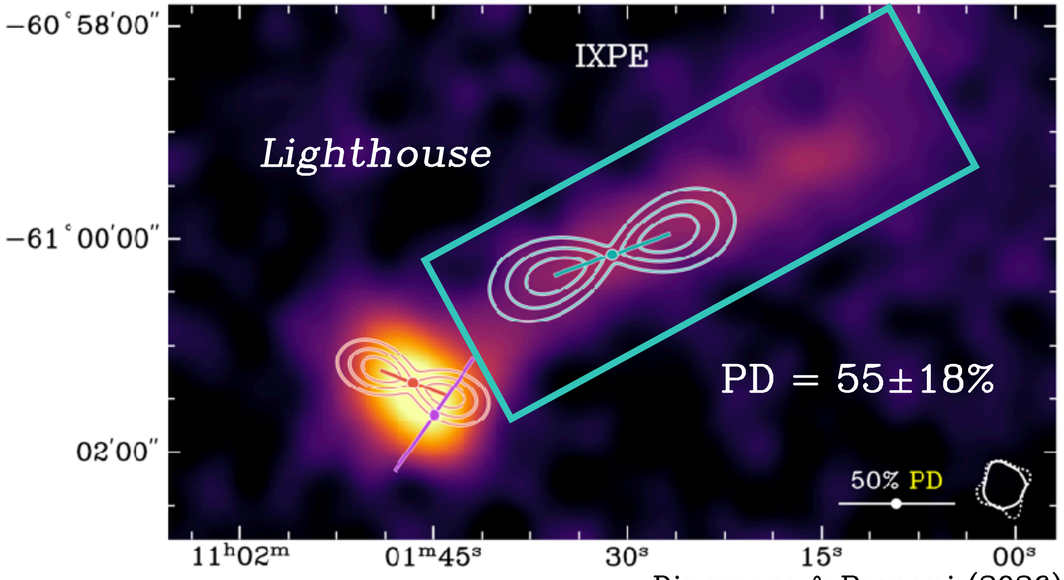
# X-ray filaments are highly polarized

- Lighthouse is an X-ray filament (electrons flowing along ISM magnetic field line with no enclosing SNR)
- G0.13−0.11 is a filament candidate

- IXPE revealed the expected EVPAs & high polarization degrees in both objects
  - May indicate reduced turbulence in this structure



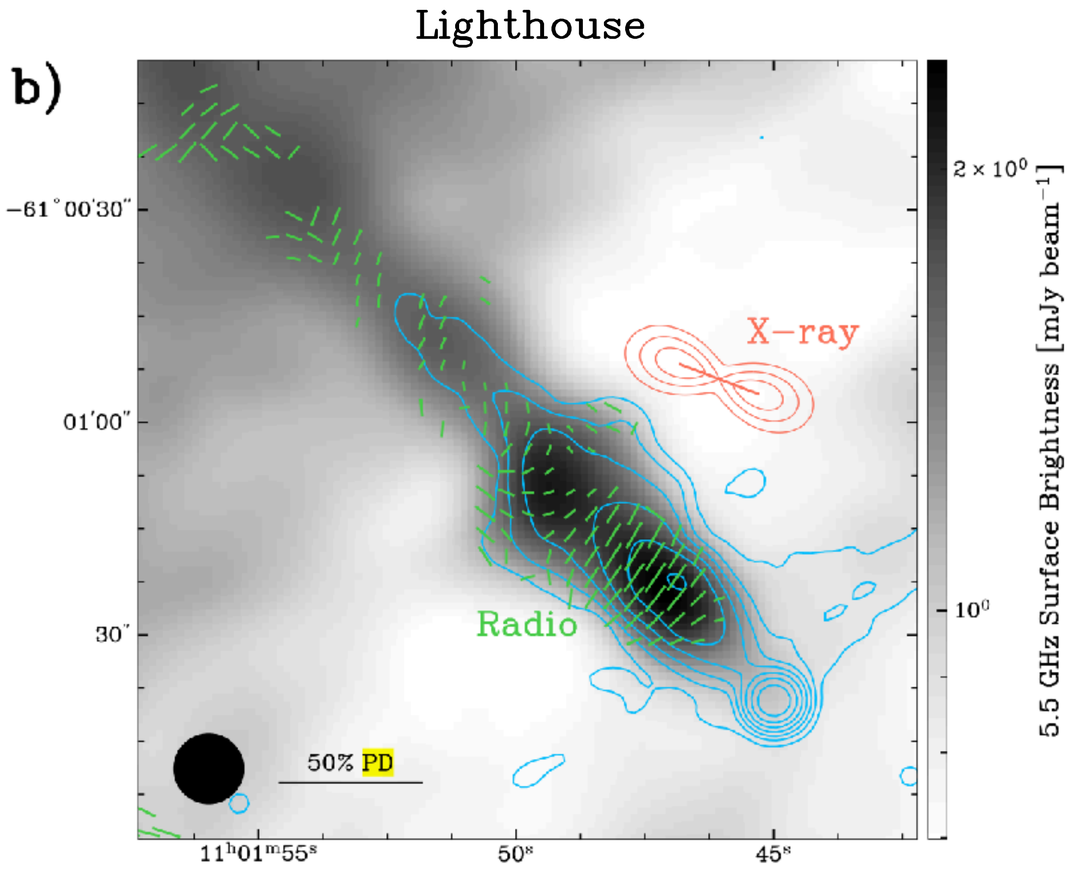

Churazov et al. (2023)




Dinsmore & Romani (2026)

# Bow shock trails are polarized in X−rays

- Created from supersonic pulsars outside the SNR
- Lighthouse's is the only bow shock trail yet observed by IXPE
- The X−ray emission may be more polarized than radio
- The EVPAs are significantly different between radio & X−ray




Dinsmore & Romani (2026)

# *Methodological Advances*

# Method developments: Background rejection

- Particle events can be rejected based on the event properties (Di Marco et al. 2023)

  *Applied to:* *MSH 15−52*, *B0540−69*, *G21.5−0.9*, *G0.13−0.11*, *Kes 75*, *3C 58* (*modified*), ***non−PWNe***

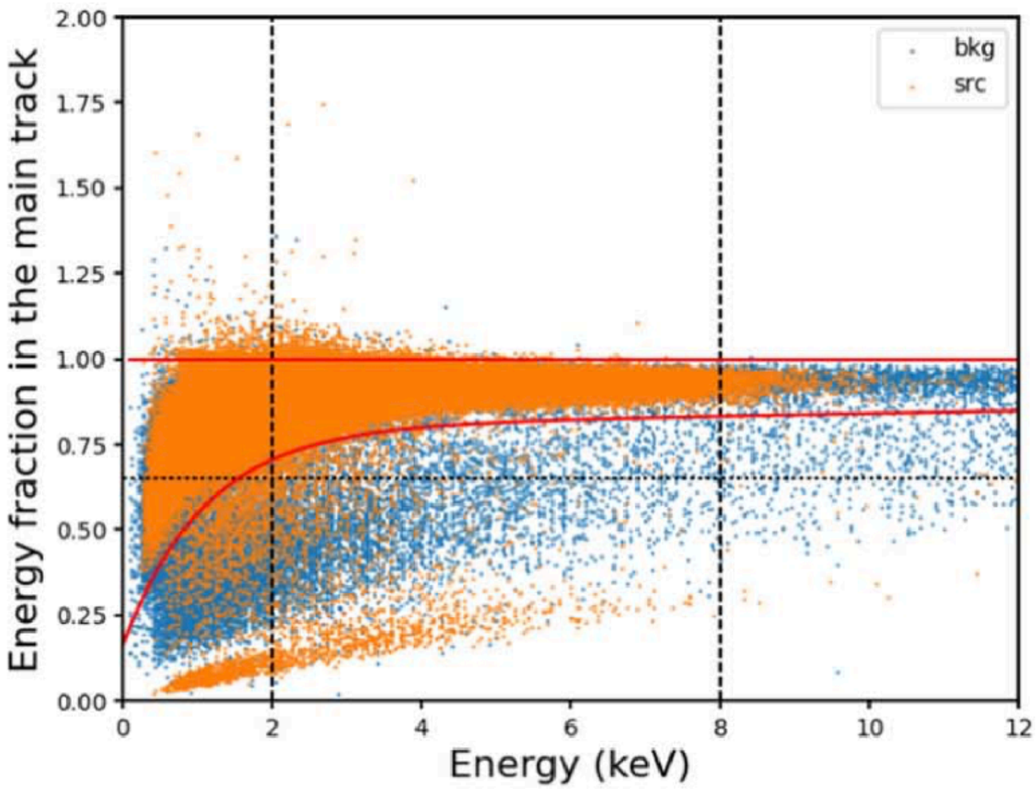
- Improved spectral modeling of photon background (Silvestri)

- Machine learning−based background detection (Dinsmore & Romani 2025)

- Reprocessing the events with machine learning techniques (Peirson et al 2022)

  *Applied to:* *Lighthouse*, *Kes 75*, ***non−PWNe***

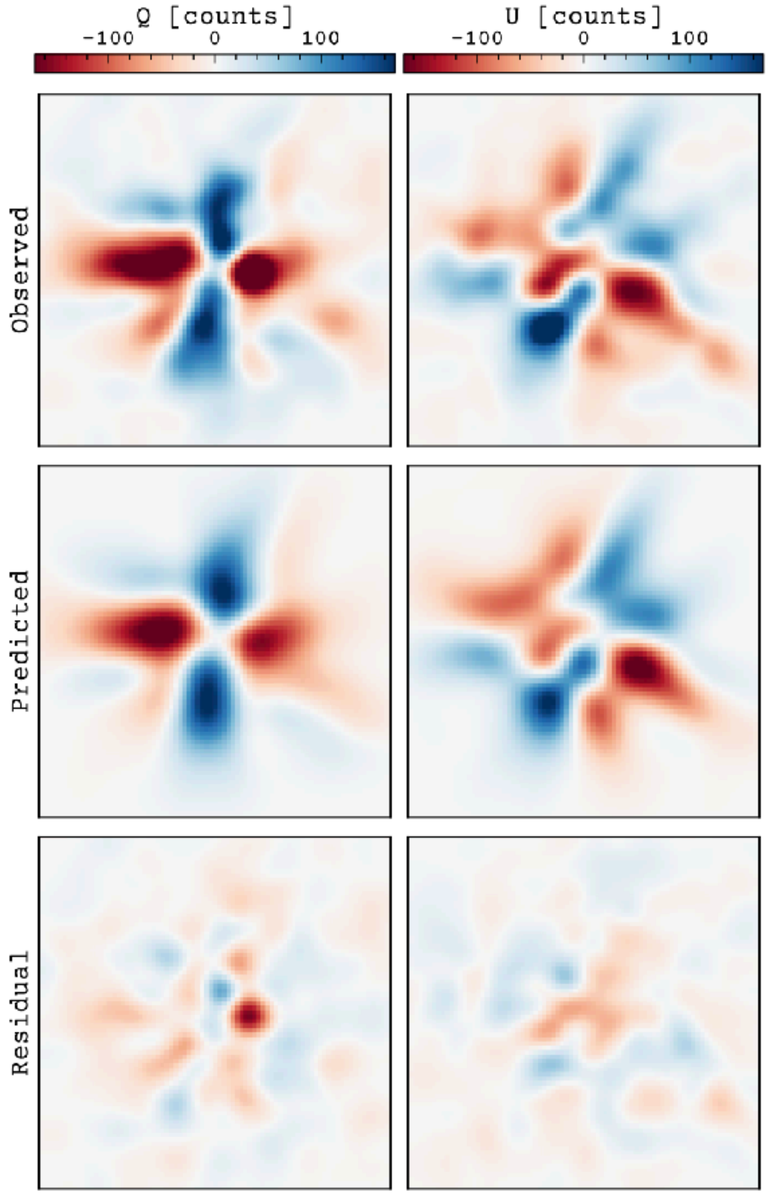
- All publicly available!




Di Marco et al (2023)

# Method developments: Polarization leakage correction

- Bright point sources have polarized haloes around them due to errors in event reconstruction.
  - Termed "polarization leakage" (Bucciantini et al. 2023)
  - Affects spatially resolved PWNe maps
- This effect can be predicted & removed
  - LeakageLib package: (Dinsmore & Romani 2024). Publicly available!




Dinsmore & Romani (2022)

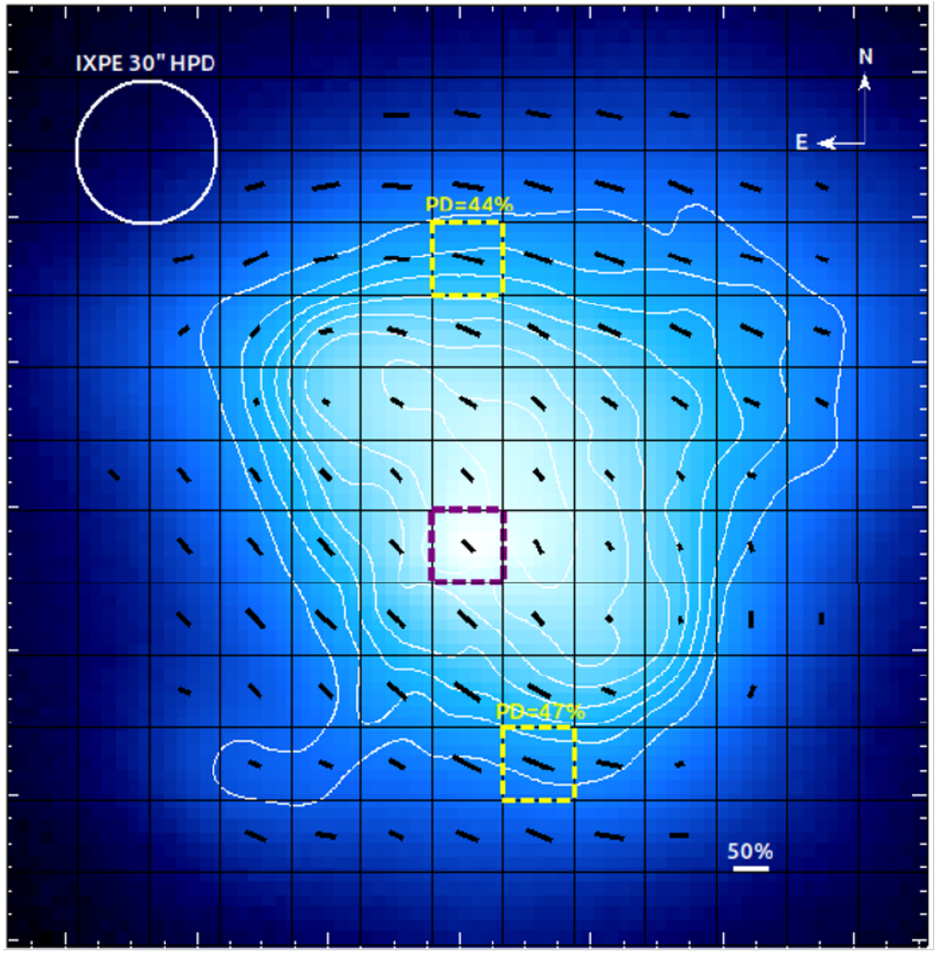
*Applied to*: *Crab*, *G21.5−0.9*, *B0540*, *Lighthouse*, *Kes75*, ***non−PWNe***

# Method developments: Simultaneous fitting

- IXPE's PSF causes polarization to spread between bins
  - Particularly affect bins near the pulsar

- Simultaneously fitting the bins removes these PSF effects (Wong et al. 2023)
  - Chandra observation assumed as ground truth

*Applied to: Crab, MSH 15−52*




Wong et al. (2023)

# Method developments: Advanced weights

- Using “polarization weights” that indicate EVPA accuracy can improve analyses (Di Marco et al. 2022)
- Idea: every available track property to weight by the probability that the track is a source photon
  - LeakageLib (Dinsmore & Romani 2025), QUEEN−BEE (Ravi et al. 2025) (both Publicly available!)

- **These weights can deliver 1.8× IXPE significances for faint sources**

*Applied to*: *Crab*, *B0540−69*, *Lighthouse*, *Kes 75*, ***non−PWNe***


Snapshots from LeakageLib’s documentation: jack−dinsmore.github.io/leakagelib

# Conclusions

X–ray polarizations reveal the magnetic field structure of the PWNe

Both PWNe and their host pulsars are often more highly polarized than expected, constraining acceleration mechanisms

Pulsars' X–ray polarization sweeps are beginning to be significantly constrained and they exhibit several modeling challenges

New measurements and new techniques are both paving the way to more IXPE discoveries