IXPE Results on Supernova Remnants

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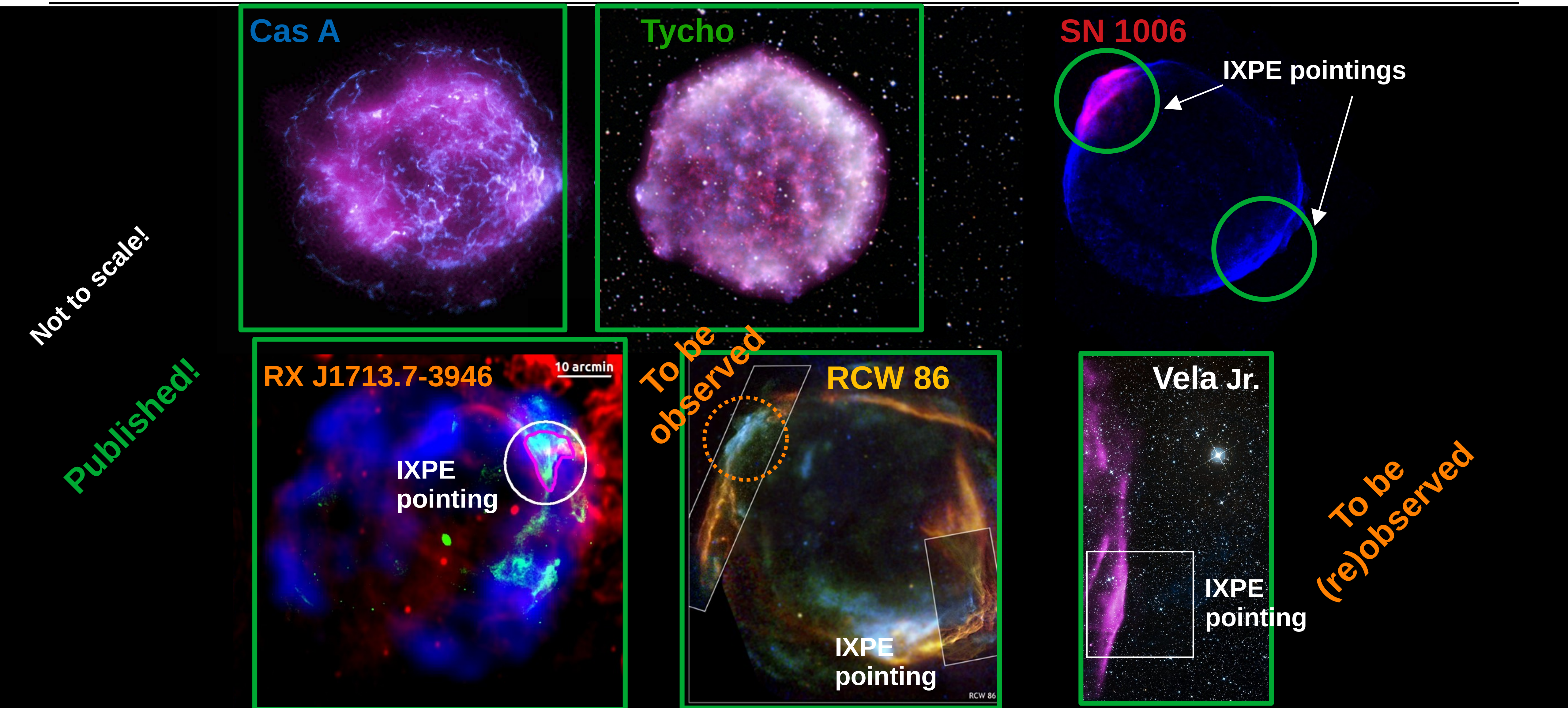
First Friends of IXPE Forum, 2026/04/16

IXPE Imaging X-Ray Polarimetry Explorer

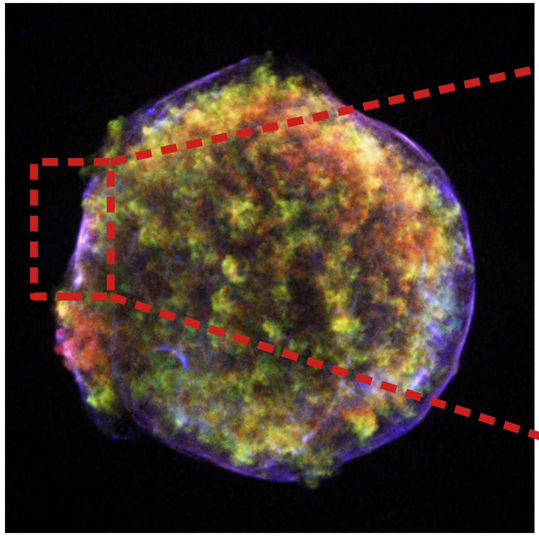
SNR WITH IXPE
THE SIX CURRENT TARGETS

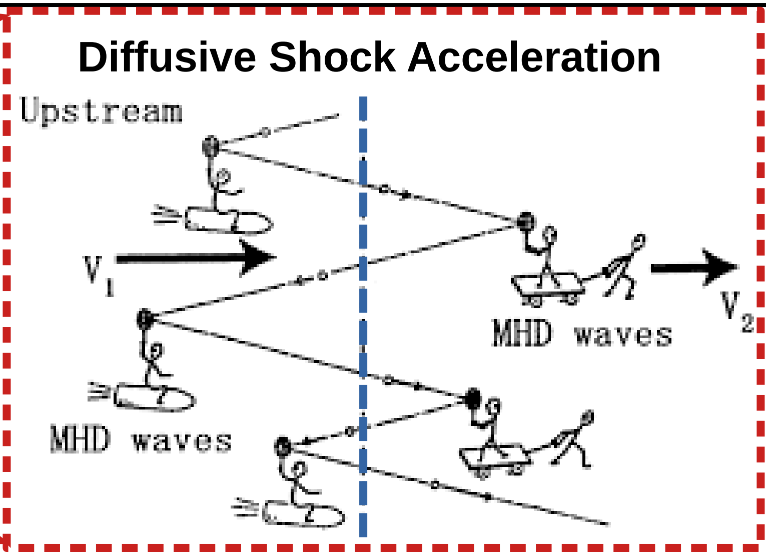


SNR KEY SCIENCE TOPICS
MAGNETIC FIELDS AND PARTICLE ACCELERATION

SNR are particle accelerators, *possibly* responsible for most of Galactic Cosmic Rays.

Particles scatter from **turbulence** in background plasma (**D**iffusive **S**hock **A**cceleration)
- Turbulence preexisting, or **generated** by the streaming ions themselves.





Up-stream (Unshocked)

Down-stream (Shocked)

(M. Scholer)

Shock-Front

- **Scattering mean-free-path**: $\lambda_{mfp} = \eta r_g = \eta \frac{E}{eB}$

  Where $\eta = \left(\frac{B}{\delta B}\right)^2 \geqslant 1$ is the **"Bohm factor"** **(proxy for acceleration efficiency)**

Efficient acceleration requires
strong/amplified, <u>turbulent</u> B-fields

- For loss-limited acceleration of electrons, maximum energy E_{max}:

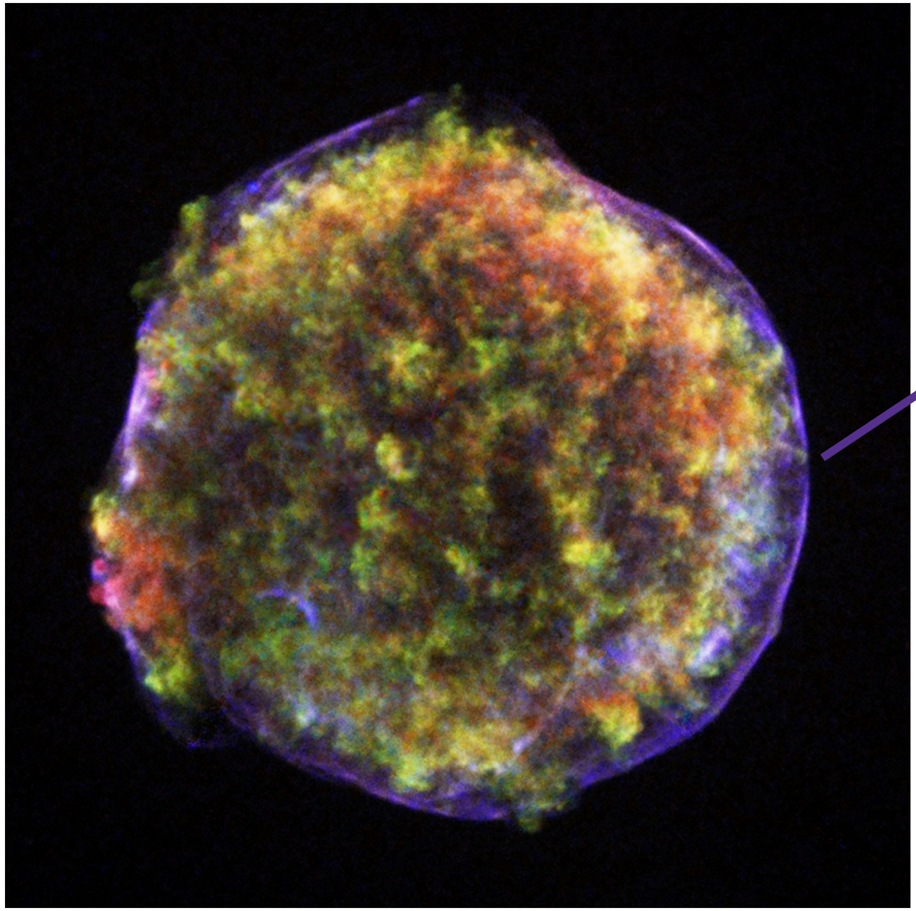
$$E_{max,synch} \sim 73\, \eta^{-\frac{1}{2}} \left(\frac{v_{sh}}{3000\, km\, s^{-1}}\right) \left(\frac{B}{10\, \mu G}\right)^{-\frac{1}{2}} TeV$$

- Leading to synchrotron **cut-off energy** ε_0:

$$\epsilon_0 = 1.55 \left(\frac{v_{sh}}{3900\, km\, s^{-1}}\right)^2 \eta^{-1}\, keV$$

- Measurement of ε_0 and v_{sh} provides η

SNR KEY SCIENCE TOPICS
MAGNETIC FIELDS AND PARTICLE ACCELERATION

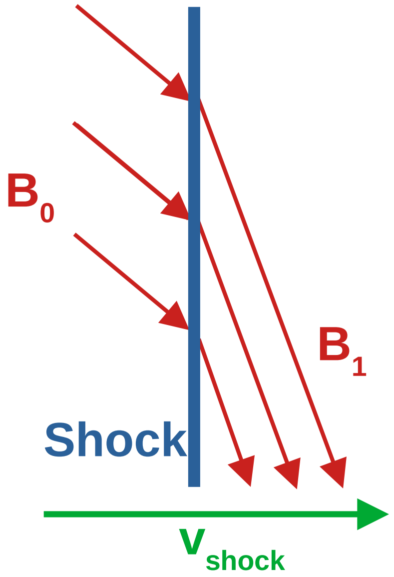


Blue: Synchrotron emission
Red/Green: Thermal emission

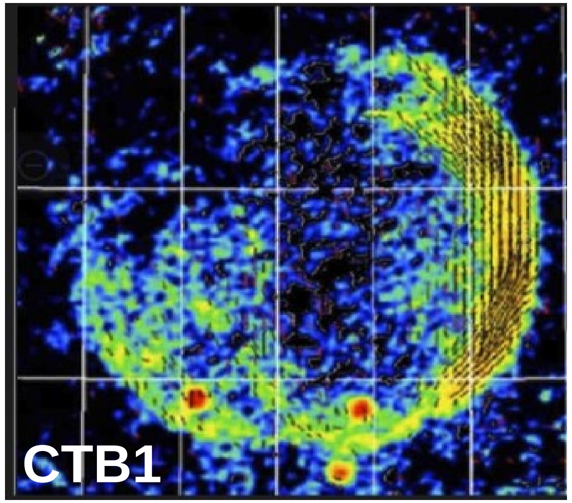
- X-ray synchrotron emission demonstrates electron acceleration to tens of TeV energies.
- Generally confined to **thin X-ray rims** (**~10^{17} cm**) due to short lifetime of energetic electrons.
- **Synchrotron** emission produced by relativistic electrons is **intrinsically polarized**
- Maximum polarization fraction depends on spectrum: $PD_{max} = \Gamma/(\Gamma + 2/3) \approx 80\%$ for typical X-ray spectra (**~70%** for radio spectra)
- **X-ray polarization probes fields and magnetic field isotropy very close to acceleration site.**
  - **High isotropy ⇒ strong polarization signal**
  - **Low isotropy ⇒ weak polarization signal…**

SNR KEY SCIENCE TOPICS
MAGNETIC FIELDS AND PARTICLE ACCELERATION

Shock-compression of ambient field

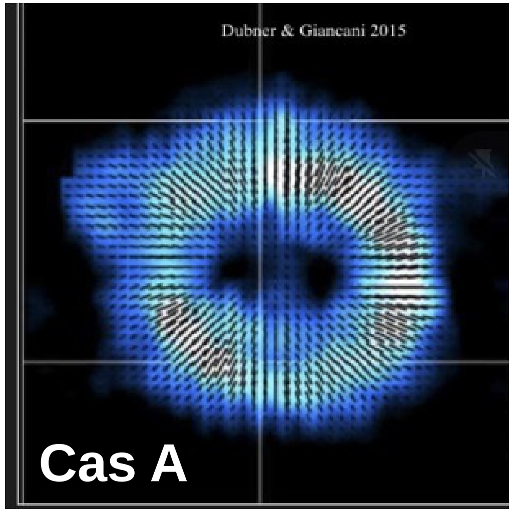


Old SNRs:
mostly **tangential** magnetic field

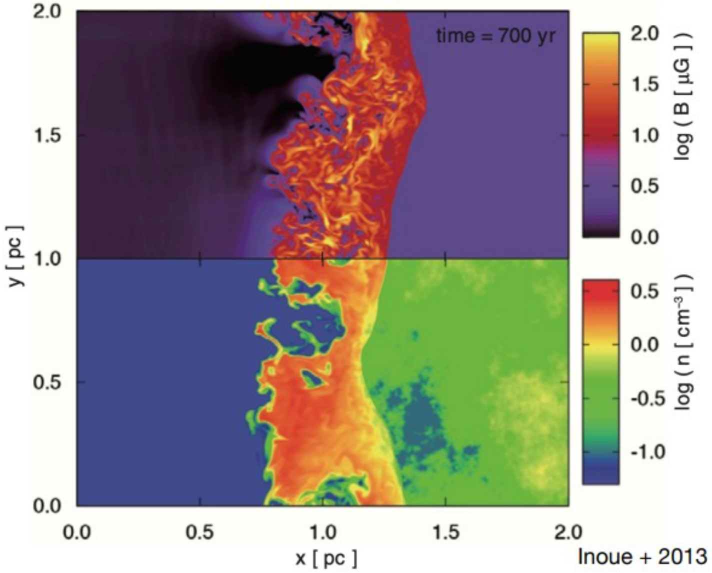


Dubner & Giacani 2015

Young SNRs:
mostly **radial** magnetic field



Turbulent dynamo due to density fluctuations



Inoue + 2013

- Shock compresses tangential component of the ambient **B** field: reasonable to expect largely tangential field in post-shock region.
- **Radio** observations show **tangential field** in **old** remnants, but **radial** in **young** SNRs.

Why?

- Radial stretching from hydro-dynamical instabilities (e.g. *Gull 1973, Jun & Norman 1996, Inoue et al. 2013*).
- "Selection effect" due to observation of radiation only along radial field where acceleration is more efficient (*e.g. West et al 2017*).

IXPE RESULTS ON SNR
CAS A, TYCHO, AND SN 1006

Vink et al. 2022, ApJ

Ferrazzoli et al. 2023, ApJ

Zhou et al. 2023, ApJ

Zhou et al., 2025, ApJ

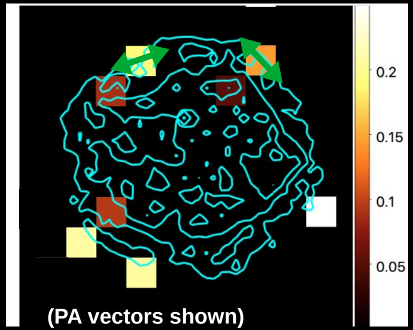
(Chandra – IXPE composite images from press releases)

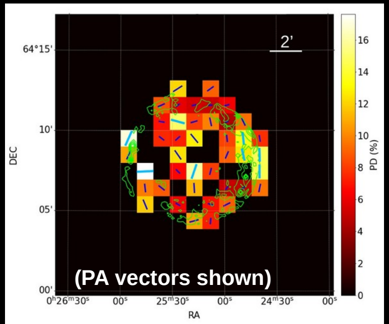
Cassiopea A

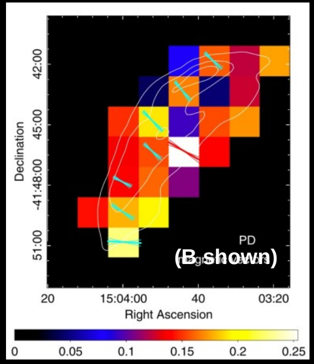
Tycho

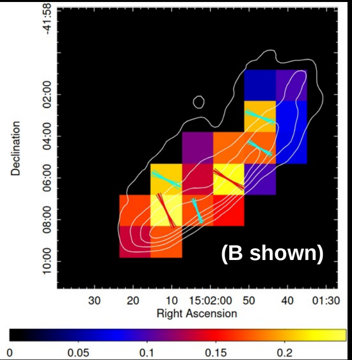
SN 1006 NE & SW

Polarization maps









We found in Cas A, Tycho, and SN 1006 radial magnetic fields.

- In Cas A the PD was also very low, no higher than 4.5% ± 1%, pointing to very high turbulence.

- In Tycho PD somewhat higher, up to 12% ± 2% in the forward shock, longer turbulence scale than Cas A or lower turbulence?

- Ever higher in SN1006: 22% ± 3.5% (NE), 21.6% ± 4.5% (SW). However, the spatial dependence of PD in the SW region is caused by HI cloud interaction suppressing PD ⇒ Environment-dependent magnetic turbulence:

higher density ⇒ stronger field disorder

Low-ish Polarization degree 5% – 30% ⇒ high level of turbulence, as expected for efficient particle acceleration. However, values vary significantly between remnants, suggesting inherent properties that drive instability amplitudes and scales.

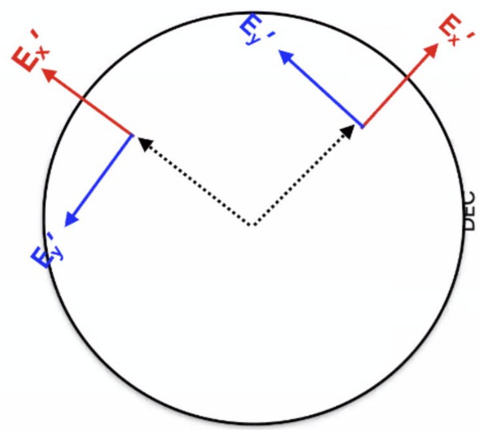
IXPE Imaging X-Ray Polarimetry Explorer

A NEAT DATA ANALYSIS TRICK YOU SHOULD KNOW
XPSTOKESALIGN

Problem: If you sum over large regions (or the entire SNR!) you cancel-out the polarization.

BUT!

- **Most SNRs have (roughly) circular symmetry**
- **From theoretical expectations:** either **radial** (from radio) or **tangential** (shock compression) **B-field.**
- **Stokes parameters are additive**
- **Solution: improve the statistics by summing over large regions by assuming a circular symmetry of the polarization direction.**

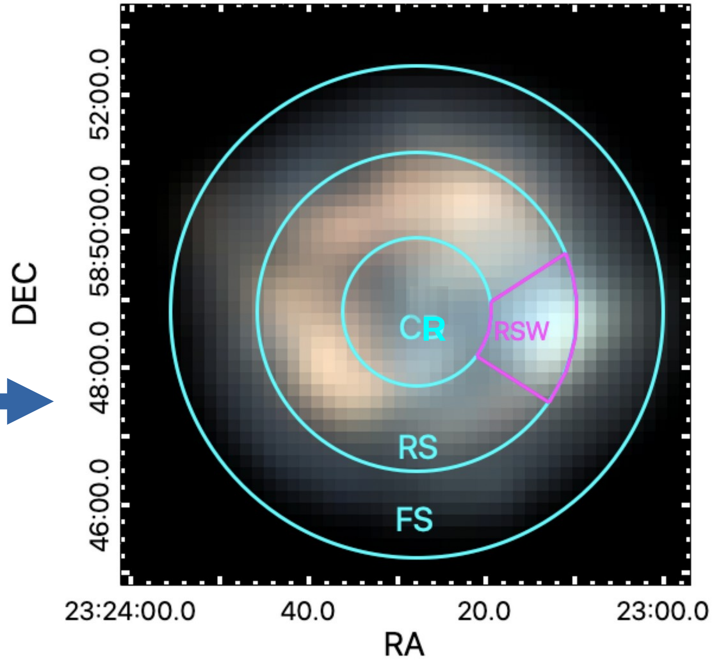


To do this, we used the **ixpeobssim** tool **xpstokesalign:**

"rotates" the Stokes parameters so that, on an event-by-event basis, the zero for the measurement of the photoelectron direction is aligned to a given input model at the position of the event.

Stokes-aligned Cas A regions as an example

- **CR:** Central Region (mostly thermal emission);
- **RS:** Reverse Shock;
- **RSW:** Reverse Shock West;
- **FS:** Forward Shock;
- **FS+RSW:** Forward Shock and Reverse Shock West (most non-thermal emitting regions);
- **All:** whole SNR.



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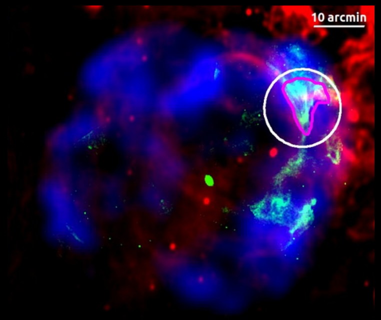
IXPE RESULTS ON SNR
RX J1713.3, VELA JR., AND RCW 86

Ferrazzoli et al. 2024 ApJL

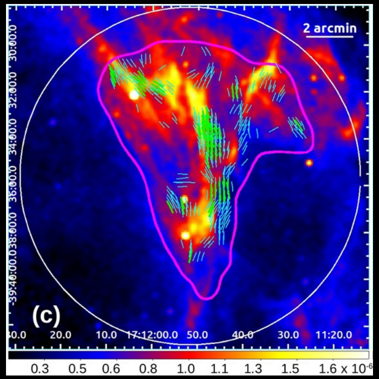
Prokhorov et al. 2025 A&A

Silvestri et al. 2026 ApJ

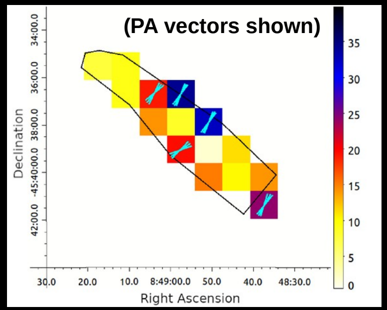
Polarization maps

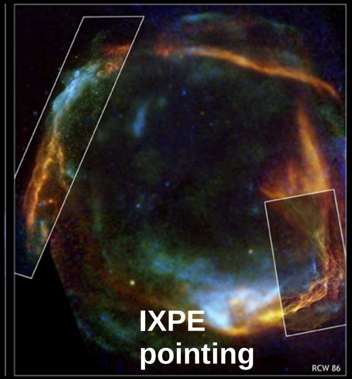


RX J1713.3 NW

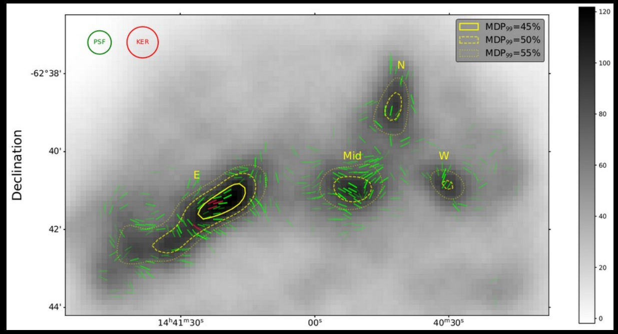


Vela Jr. NW





RCW 86 SW



Surprise! In RX J1713.3 and Vela Jr. the inferred magnetic field is tangential!!!

Polarization degree similar to Tycho:
- RX J1713.3 NW PD = 13%± 3.5%,

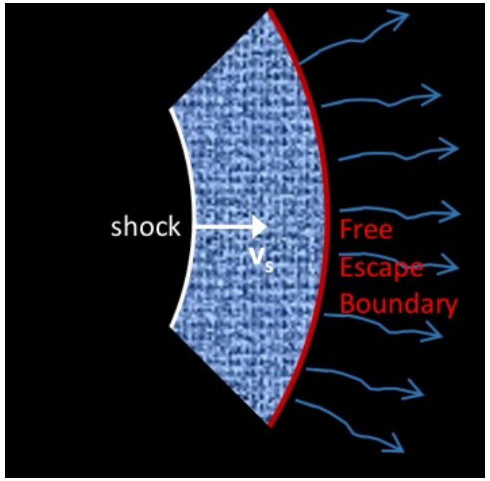
- Vela Jr NW PD = 16.4% ± 5.2%

These are slightly older SNRs (RX J1713.3: 1600 yrs, Vel Jr.: 1700-4300 years) ⇒ earlier time of magnetic field morphology inversion w.r.t. radio? Different physical conditions?

Finally, In RCW 86 SW, no detection:
- PD ≤ 15% in bright regions
- PD ≤ 30 - 40% in sub-regions

Absence of ordered magnetic field on < 1 pc scales ⇒ highly turbulent or disordered field, likely due to reflected shocks and cavity-wall interaction

THE CURRENT PICTURE
ONE POSSIBLE INTERPRETATION

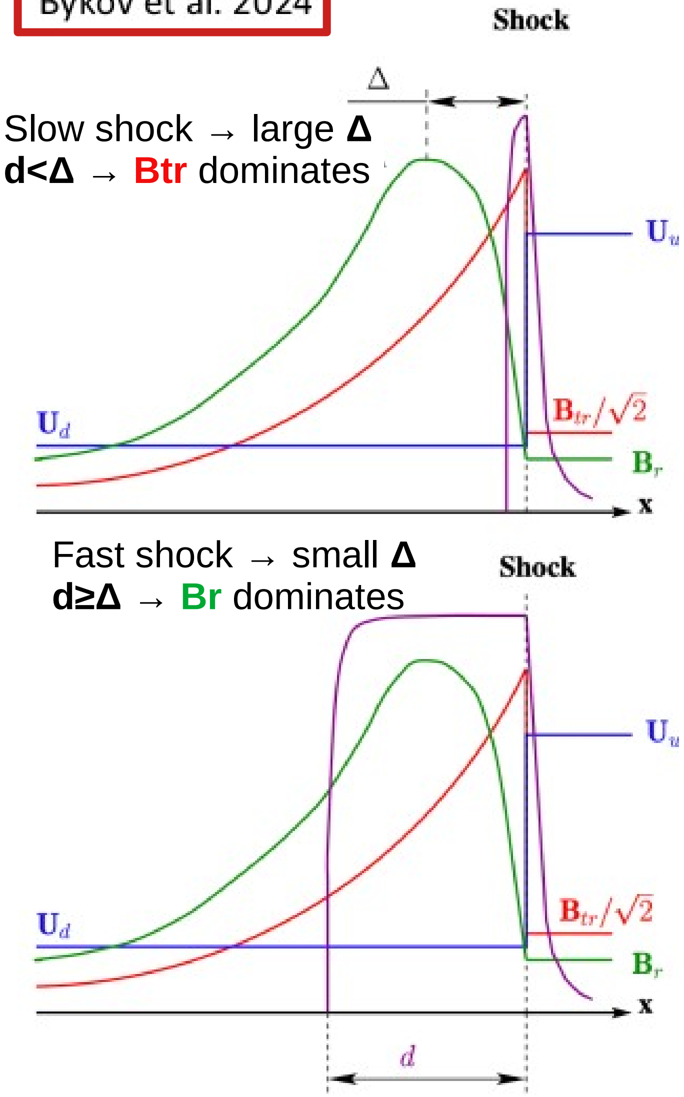


- Cosmic-ray current generates magnetic and density fluctuations through Bell instability.
- Upon passing through sub-shock, density fluctuations generate anisotropic vortex turbulence that produces radial magnetic field component.
- **d = depth of the thin layer of synchrotron photons X-ray emission.**
- **Δ =** distance between the **position of the peak of the radial magnetic field component** generated near the shock and the position of the **peak of the tangential field component**.
- **For Cas A, Tycho, and SN 1006, d >> Δ results in radial field.**
- **For RX J1713, Vela Jr., perhaps d << Δ due to smaller shock speed and magnetic field.**

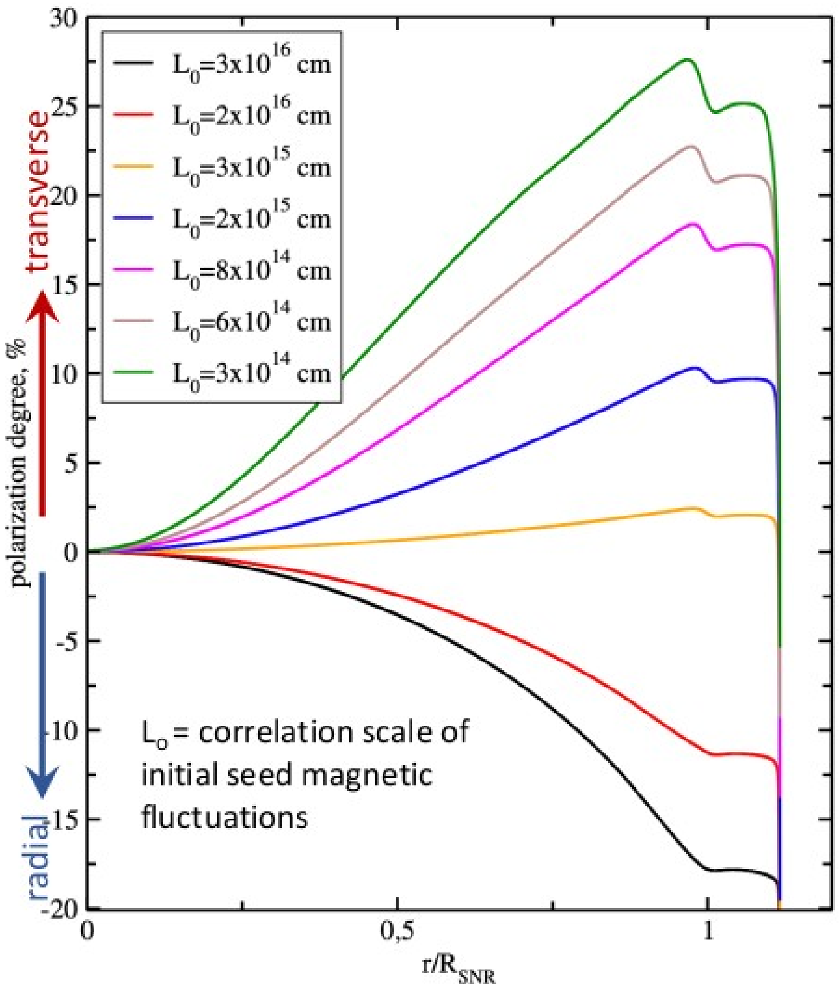
Bykov et al. 2024

Slow shock → large **Δ**
d<Δ → **Btr** dominates

Fast shock → small **Δ**
d≥Δ → **Br** dominates



L_0 turbulence scale as a function of **PD** and **B** orientation



IXPE
Imaging X-Ray Polarimetry Explorer

CONCLUSIONS AND FUTURE PROSPECTS

A new window in SNR is now open thanks to X-ray polarimetry with IXPE

P. Slane et al., 2024
Review paper

- **X-ray polarization in young SNR (<2000 yrs) probes magnetic field and turbulence information in regions close to shock.**
- Provides crucial information on particle acceleration in SNR shocks.

IXPE results

- Polarization detected in **Cas A, Tycho, SN 1006, RX J1713, and Vela Jr.**
- **Low-ish PD 5% – 30%** ⇒ **high level of turbulence**, as expected for efficient particle acceleration.
- But, values vary significantly between remnants ⇒ inherent properties drive instability amplitudes and scales.
- **Radial magnetic field very near shock presents constraints on the formation of instabilities and the cascading of anisotropic turbulence in fast shocks.**
- **Two exceptions!** Tangential fields in **RX J1713** and **Vela Jr.** consistent with shock compression of isotropic (or partially-tangential) upstream field, with little development of radial field in downstream region.
- **Breakthrough SNR science with IXPE, with more results (RCW 86 NE, more Vela Jr) incoming!**

X-RAY POLARIMETRY OF SNR WITH IXPE
A BIBLIOGRAPHY

1) **X-Ray Polarization Detection of Cassiopeia A with IXPE, J. Vink et al.**, ApJ, Volume 938, Issue 1, id.40, 14 pp. **(2022)**
https://iopscience.iop.org/article/10.3847/1538-4357/ac8b7b/pdf

2) **X-Ray Polarimetry Reveals the Magnetic-field Topology on Sub-parsec Scales in Tycho's Supernova Remnant, R. Ferrazzoli et al.**, ApJ, Volume 945, Issue 1, id.52, 14 pp. **(2023)**
https://iopscience.iop.org/article/10.3847/1538-4357/acb496/pdf

3) **Magnetic Structures and Turbulence in SN 1006 Revealed with Imaging X-Ray Polarimetry, P. Zhou et al.**, ApJ, Volume 957, Issue 1, id.55, 12 pp. **(2023)**
https://iopscience.iop.org/article/10.3847/1538-4357/acf3e6/pdf

4) **Discovery of a Shock-compressed Magnetic Field in the Northwestern Rim of the Young Supernova Remnant RX J1713.7—3946 with X-Ray Polarimetry, R. Ferrazzoli et al.,** ApJ Letters, Volume 967, Issue 2, id.L38, 15 pp. **(2024)**
https://iopscience.iop.org/article/10.3847/2041-8213/ad4a68/pdf

5) **X-ray polarization: A view deep inside cosmic ray driven turbulence and particle acceleration in supernova remnants, A .Bykov et al.**, Physical Review D, Volume 110, Issue 2, article id.023041 **(2024)**
https://arxiv.org/pdf/2407.04160

6) **Probing Magnetic Fields in Young Supernova Remnants with IXPE, P. Slane et al.**, Galaxies, Volume 12, Issue 5, id.59 **(2024)**
https://www.mdpi.com/2075-4434/12/5/59

Review paper

7) **Evidence for a shock-compressed magnetic field in the northwestern rim of Vela Jr. from X-ray polarimetry, D. Prokhorov et al.,** A&A, Volume 692, id.A59, 11 pp. **(2024)**
https://www.aanda.org/articles/aa/pdf/2024/12/aa52062-24.pdf

8) **X-Ray Polarization in SN 1006 Southwest Shows Spatial Variations and Differences in the Radio Band, P. Zhou et al.**, ApJ, Volume 986, Issue 2, id.210, 11 pp. **(2025)**
https://iopscience.iop.org/article/10.3847/1538-4357/add532/pdf

9) **Revisiting the X-Ray Polarization of the Shell of Cassiopeia A Using Spectropolarimetric Analysis, A. Mercuri et al.**, ApJ, Volume 986, Issue 1, id.6, 13 pp. **(2025)**
https://iopscience.iop.org/article/10.3847/1538-4357/adcedb/pdf

10) **Magnetic-field Order in the Southwestern Rim of RCW 86 Constrained Using X-Ray Polarimetry, S. Silvestri et al.,** ApJ, Volume 998, Issue 1, id.172, 12 pp. **(2026)**
https://iopscience.iop.org/article/10.3847/1538-4357/ae3004/pdf