

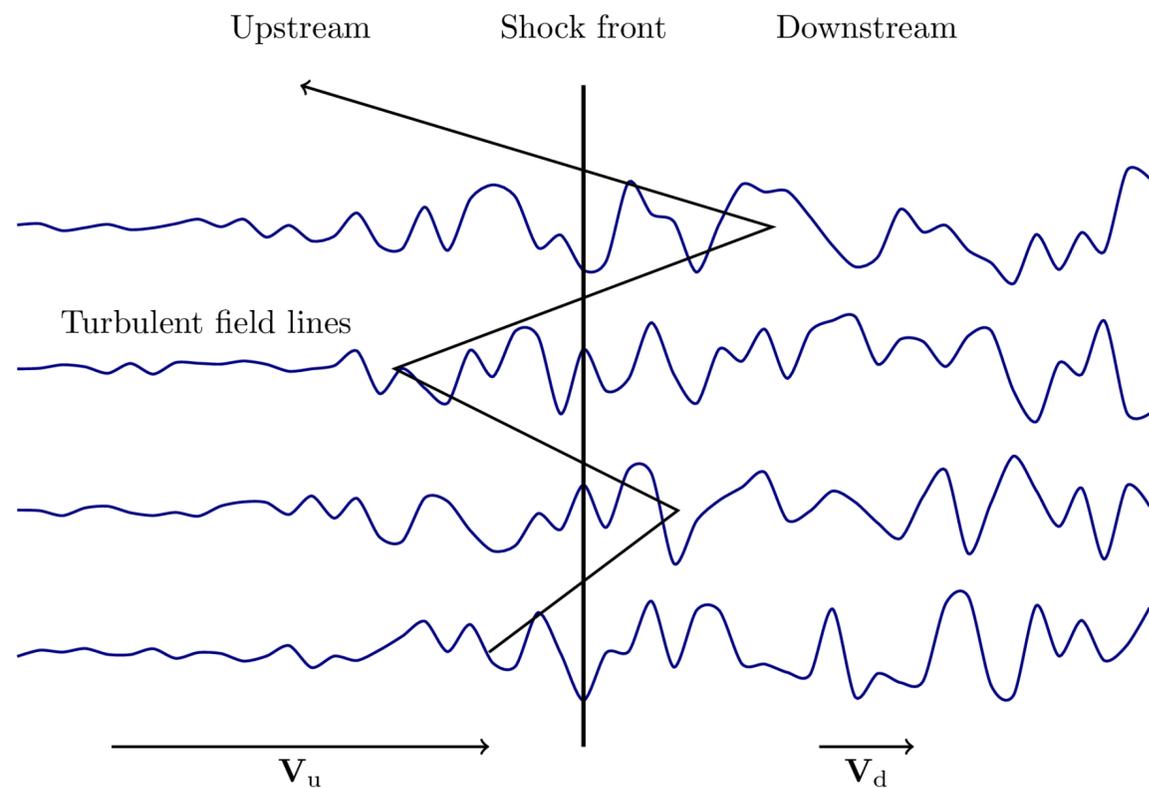
Tracing Magnetic Field Variation in SNRs: An X-ray and Radio Polarization comparison

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SNR symposium @ Kuming | Mar 1, 2026

Collaborators: Patrick Slane, Dmitry Prokhorov, Jacco Vink, Riccardo Ferrazzoli, William Cotton, Niccolo Bucciantini, Yi-Jung Yang, Stefano Silvetri, Estela Reynoso, more IXPE members

Importance of Magnetic fields in CR acceleration



- The maximum energy of CRs can be accelerated for young SNRs $E_{\max} \approx 50 \text{ TeV} \left(\frac{B}{\mu\text{G}} \right) \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{-1/6} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{1/2} \left(\frac{n_0}{\text{cm}^{-3}} \right)^{-1/3}$
 t_{acc} = ejecta-dominated phase time (Morlino+2016)

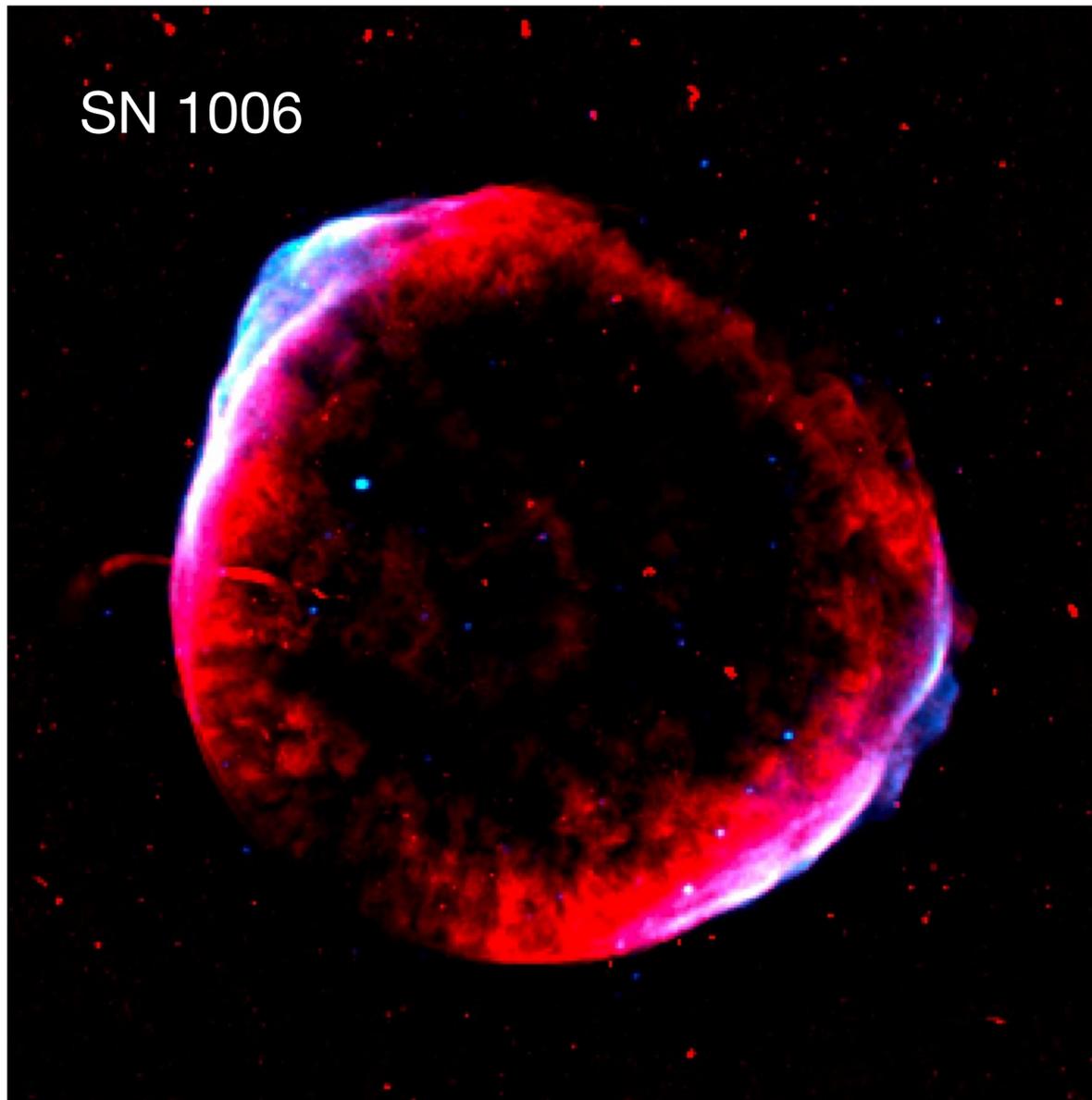
Accelerating particles to the PeV energy requires the magnetic field amplification (100x)

<https://sprg.ssl.berkeley.edu/~pulupa/illustrations/>

How and where is B amplified?

Radio vs. X-ray synchrotron emission

Radio (broad) X-ray (narrow)



- Photon energy $\nu \uparrow$ electron energy $E \uparrow$

$$h\nu = 19 \left(\frac{E}{100 \text{ TeV}} \right)^2 \left(\frac{B_{\perp}}{100 \mu\text{G}} \right) \text{ keV}$$

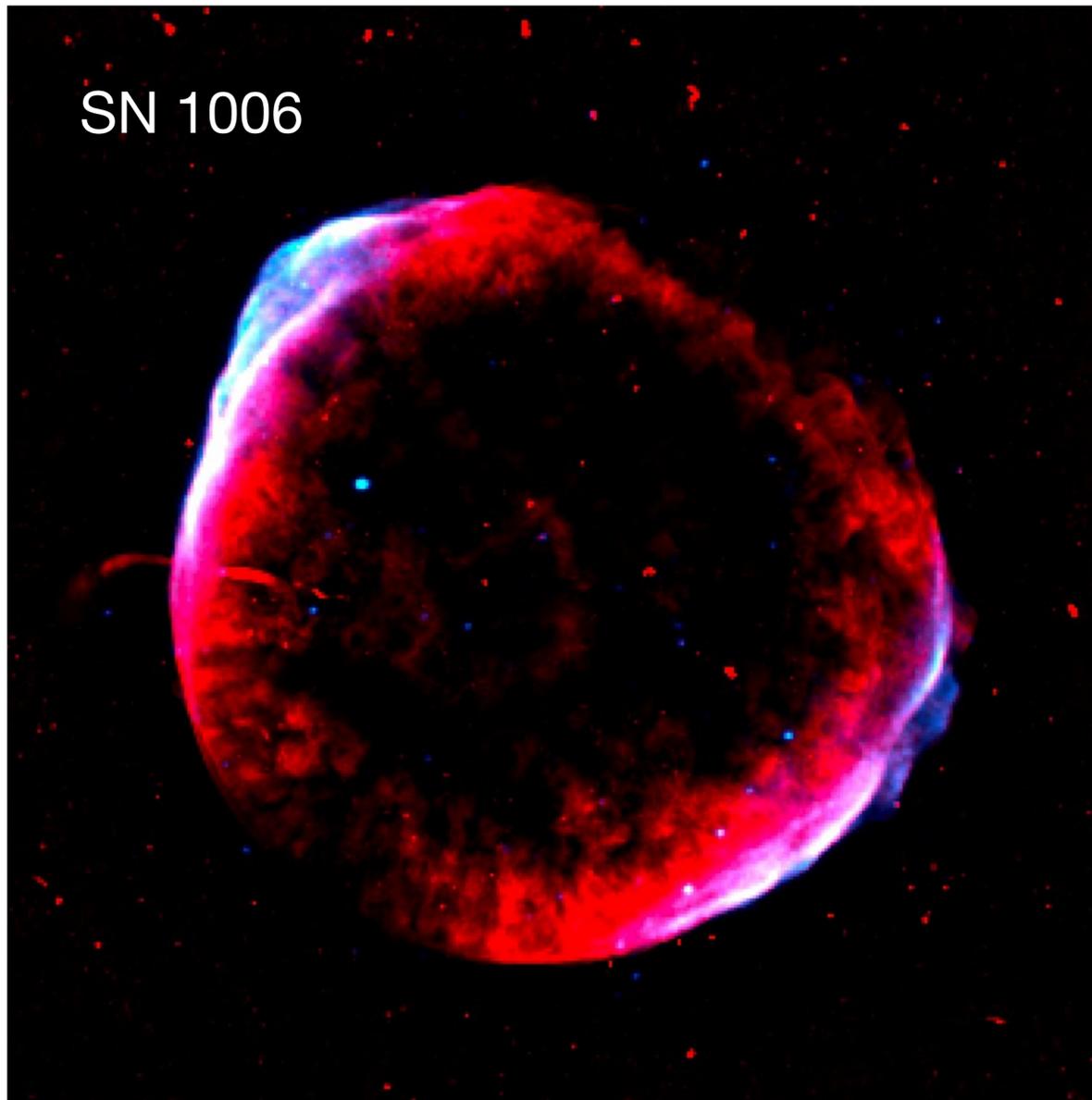
- X-ray emission is sharper, nearer the shock front
- X-ray photons lose energy faster, with the synchrotron cooling time:

$$\tau_{\text{loss}} = \frac{E}{|dE/dt|} = 12.5 \left(\frac{E}{100 \text{ TeV}} \right)^{-1} \left(\frac{B}{100 \mu\text{G}} \right)^{-2} \text{ yr}$$

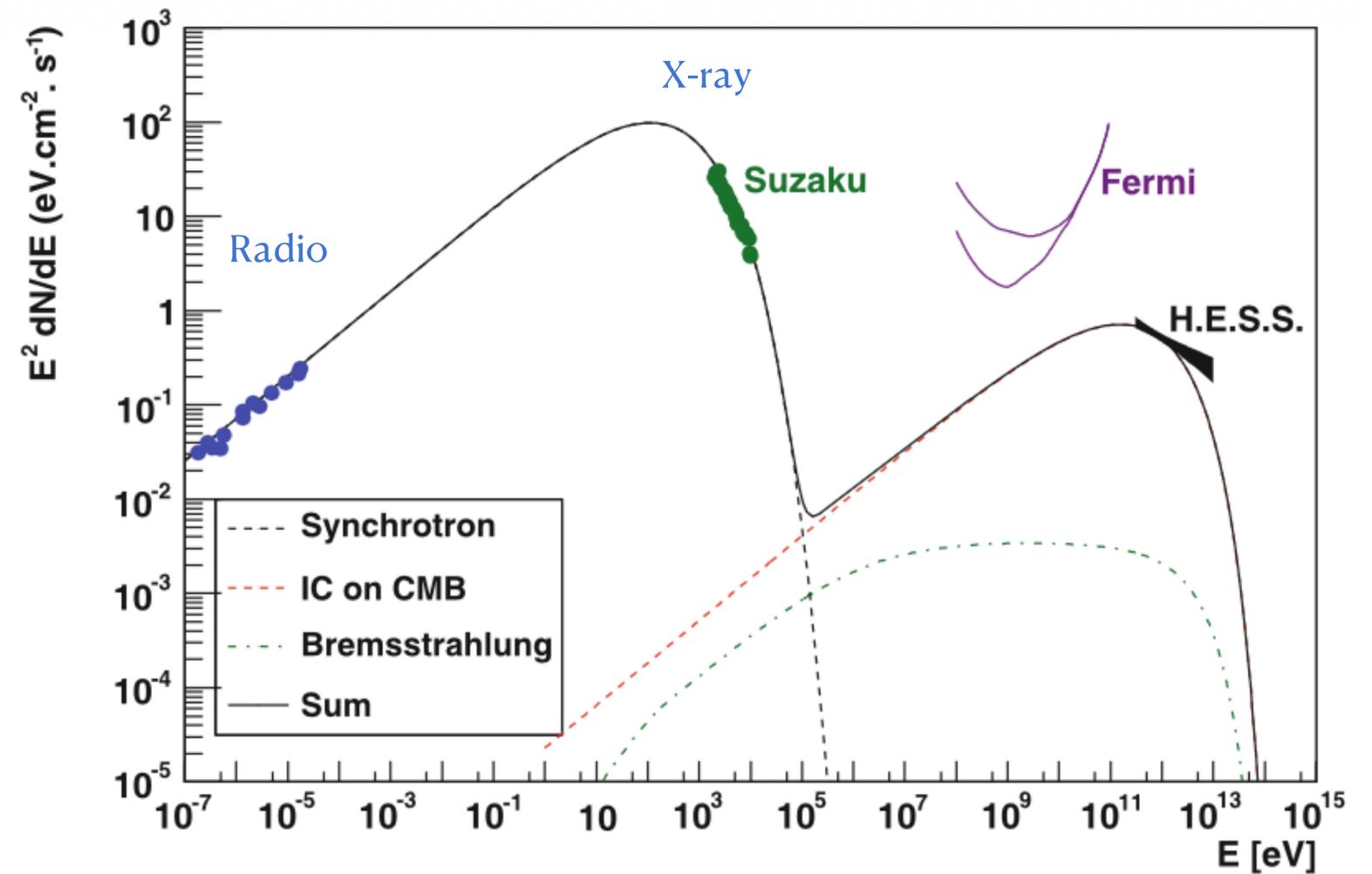
Because radio and X-ray emissions come from different regions, they **probably do not experience the same magnetic fields!**

A uniform magnetic field assumed for broadband SED

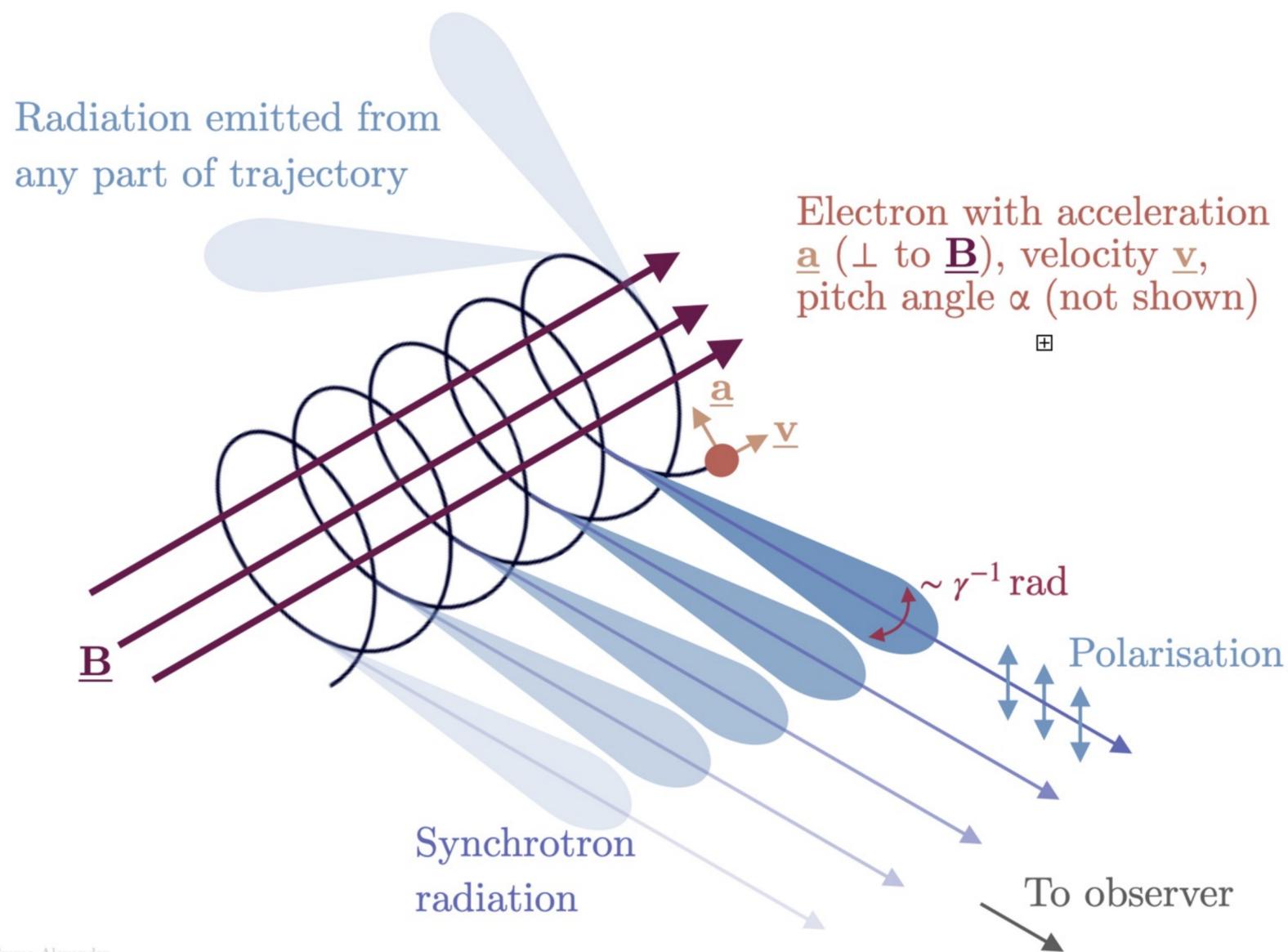
Radio (broad) X-ray (narrow)



Is this a correct assumption?



Synchrotron emission and polarization parameters



I : Total intensity

PA: Orientation of the polarization (polarization angle)

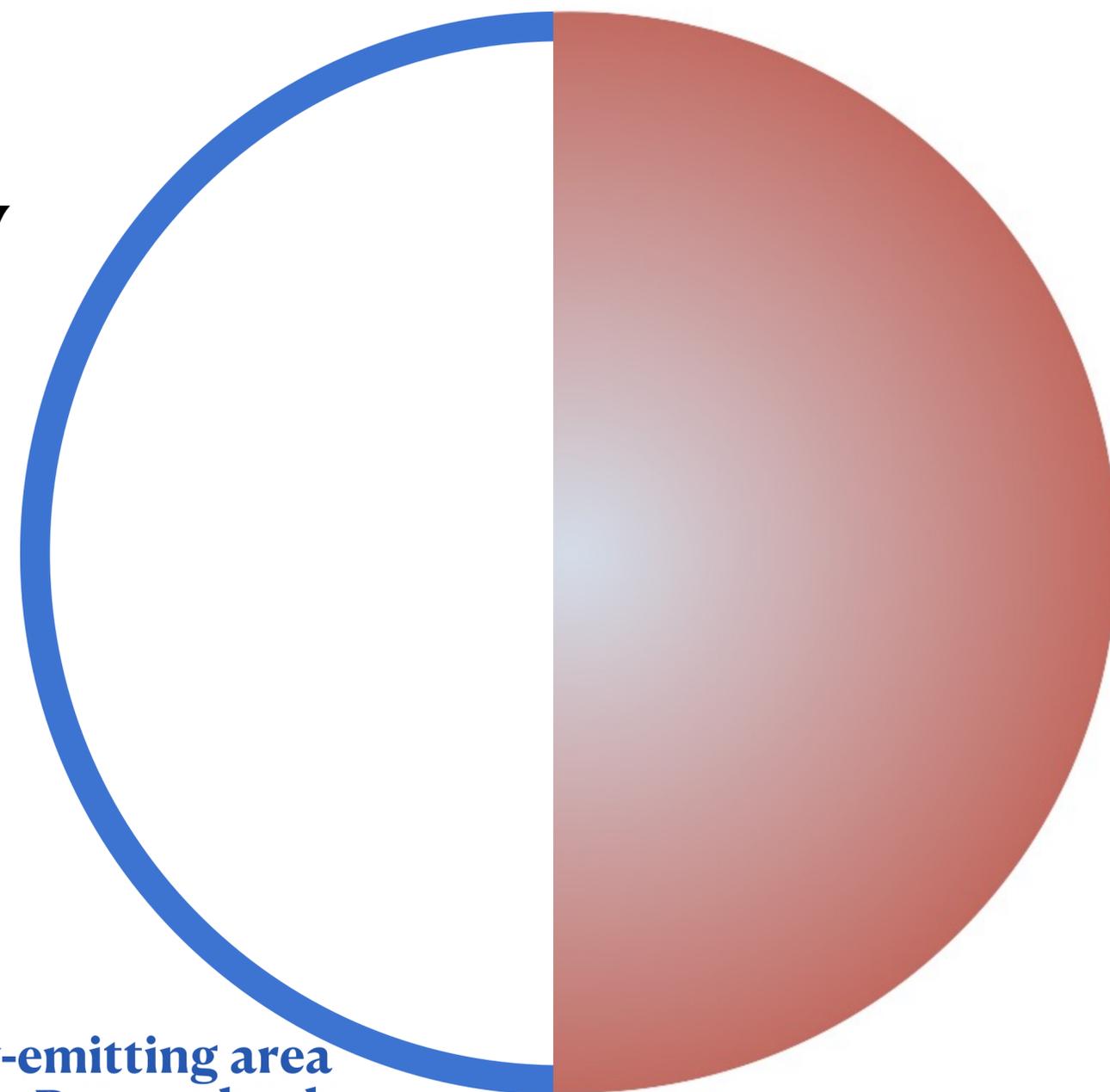
PD: Fraction of the polarization (polarization degree)

PA \perp magnetic orientation
 PD magnetic turbulence



Radio-emitting area
Probes B along a thick layer

We need multi-band polarimetry
to study B variation across SNRs

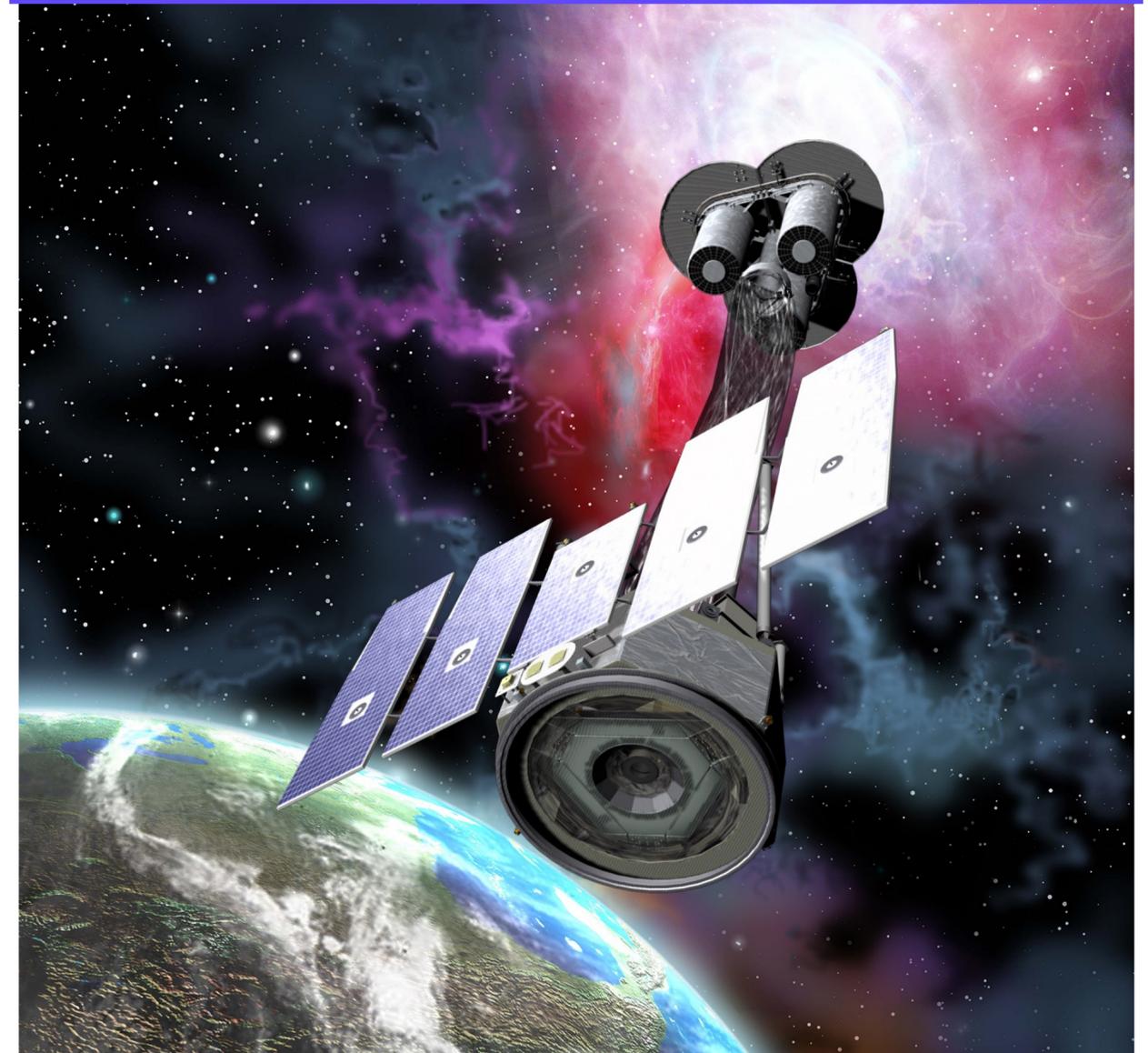


X-ray-emitting area
Probes B near shock
(non-thermal)

X-ray polarimetry

- X-rays probe the **electrons with the very high energies**
- Measure the **B-field close to the shock front** (X-ray emission is closer to the shock)
- Free from Faraday depolarization
- Does X-ray polarimetry show the same results as the radio?

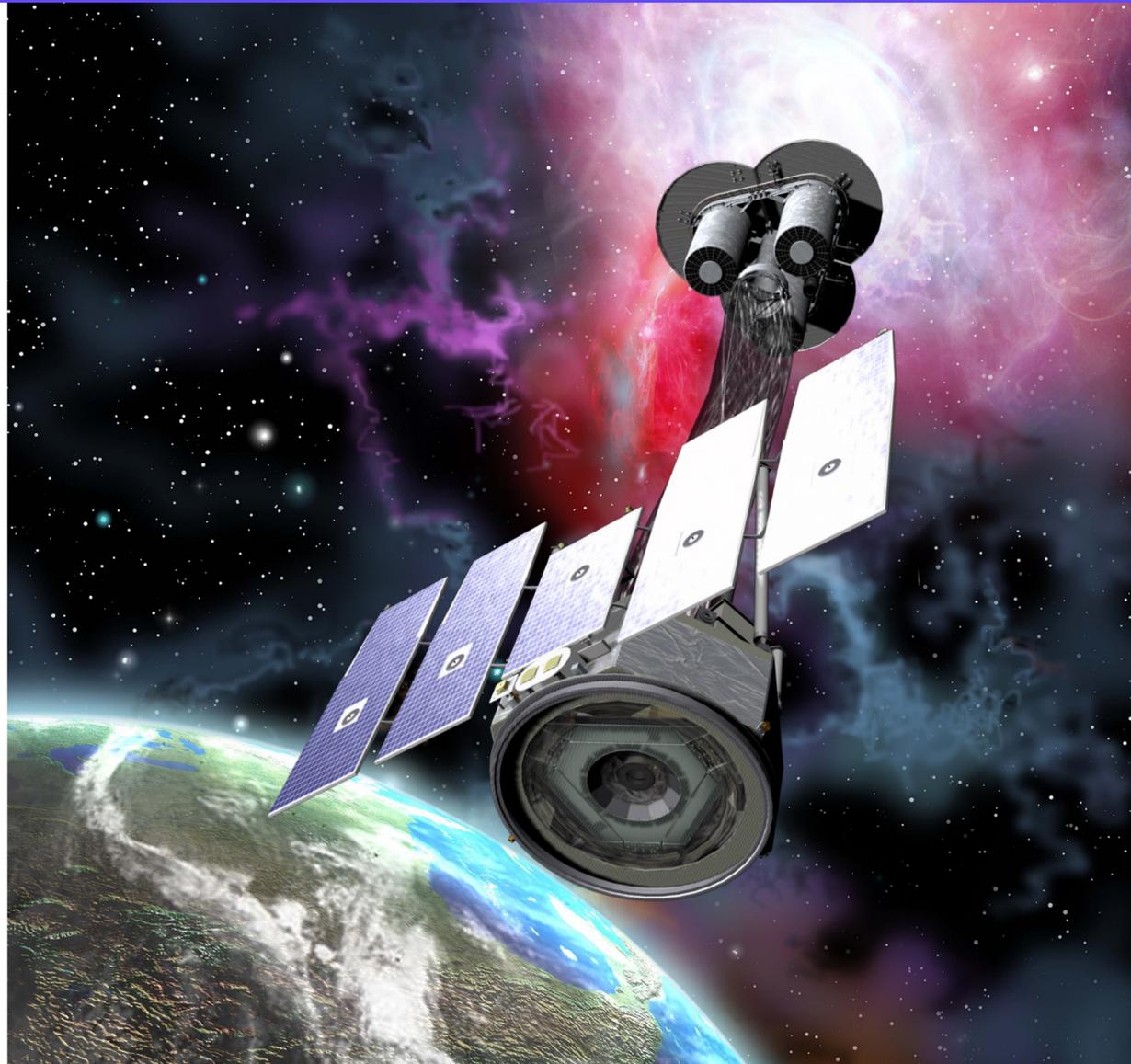
IXPE
(Imaging X-ray polarimetry explorer)



2– 8 keV
angular resolution <30''
field-of-view ~13'

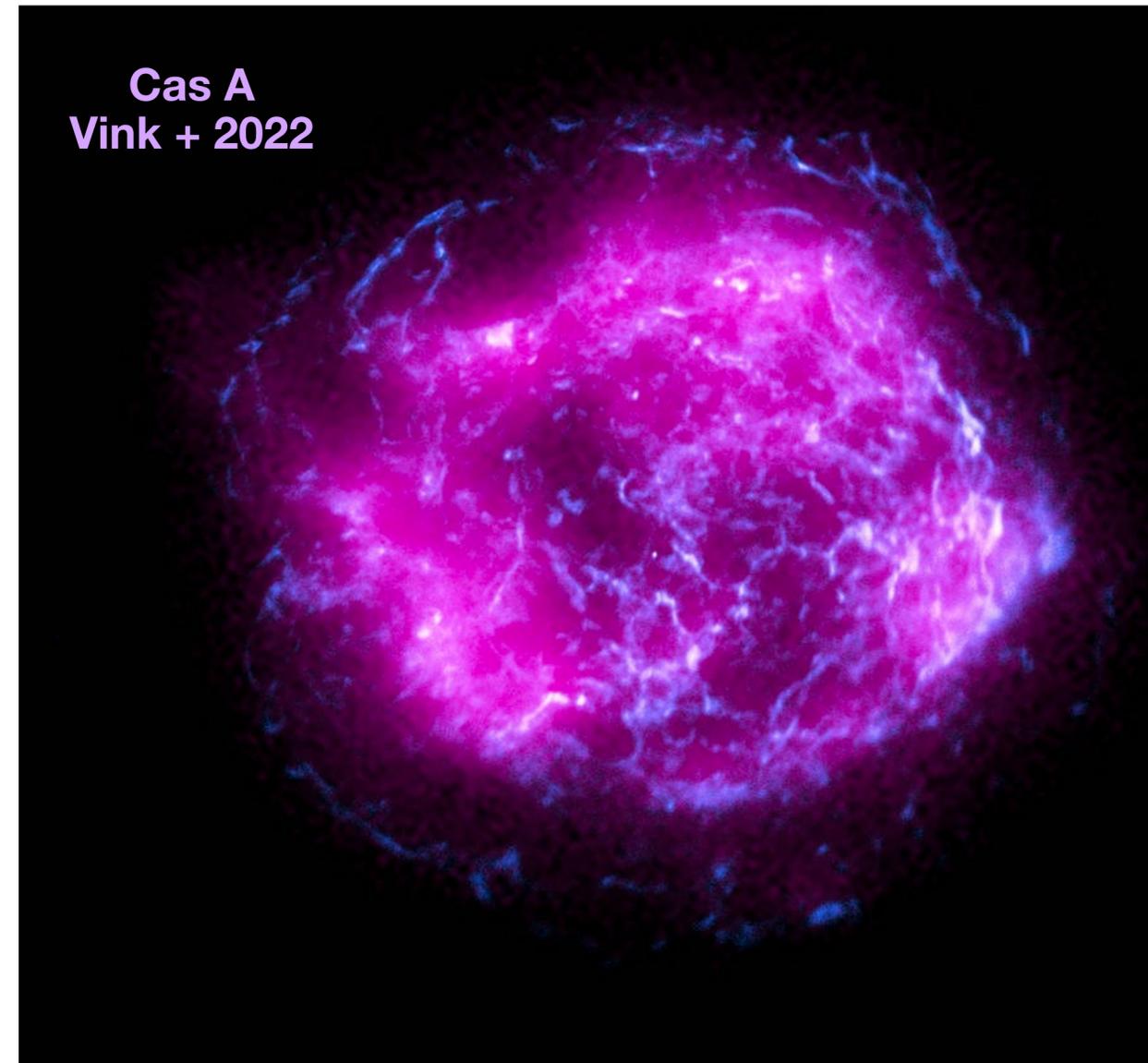
Imaging X-ray polarimetry — a new window opened in 2021

IXPE
(Imaging X-ray polarimetry explorer)



2— 8 keV
angular resolution $<30''$
field-of-view $\sim 13'$

The first target of IXPE



First X-ray polarization measurements of SNRs (8 Ms)

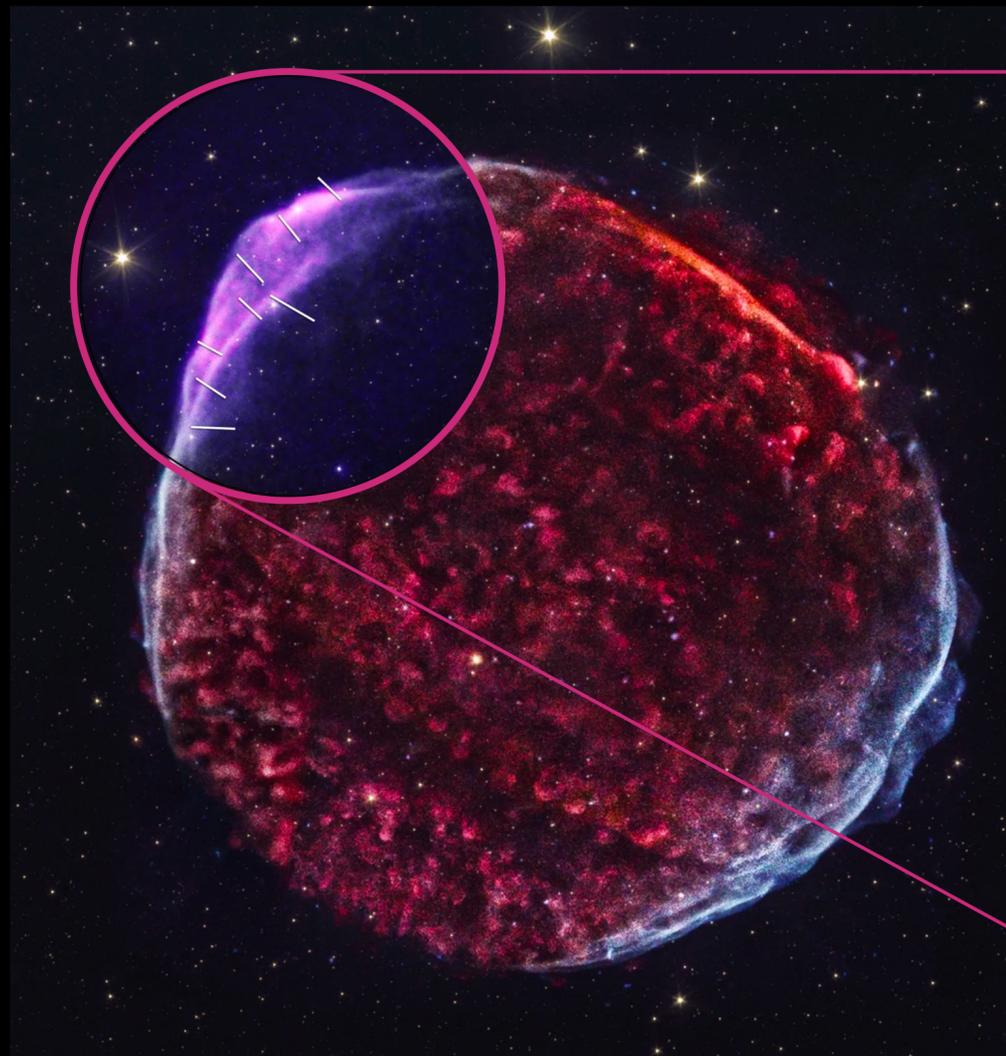
PA	Radial B			Tangential B	
PD	low ~ 4.5%	12%	22%	13%	16%
	Cas A Vink + 2022	Tycho Ferrazzoli + 2023	SN1006 Zhou + 2023, 2025	RX J1713.7-3946 Ferrazzoli + 2024	Vela Jr. Prokhorov + 2024
Density	high density	low density	very low-density ($<0.1 \text{ cm}^{-3}$)		
Age	355 yr			3000 yr	

1. Magnetic fields are radially oriented for the youngest SNRs
2. $d\rho/\rho \uparrow$, PD \downarrow (turbulence \uparrow), PD=5%—40%
3. X-ray and radio polarization parameters show a large difference.

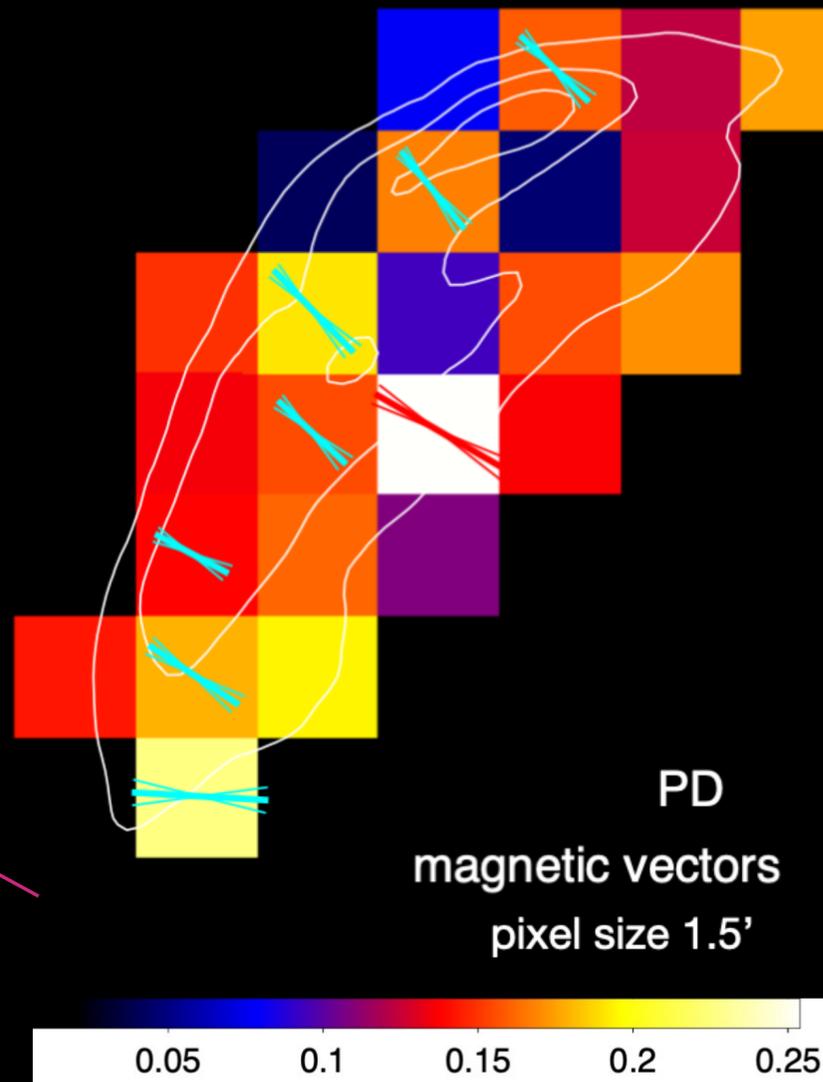
RCW86
<3 sigma

Radially distributed Magnetic fields

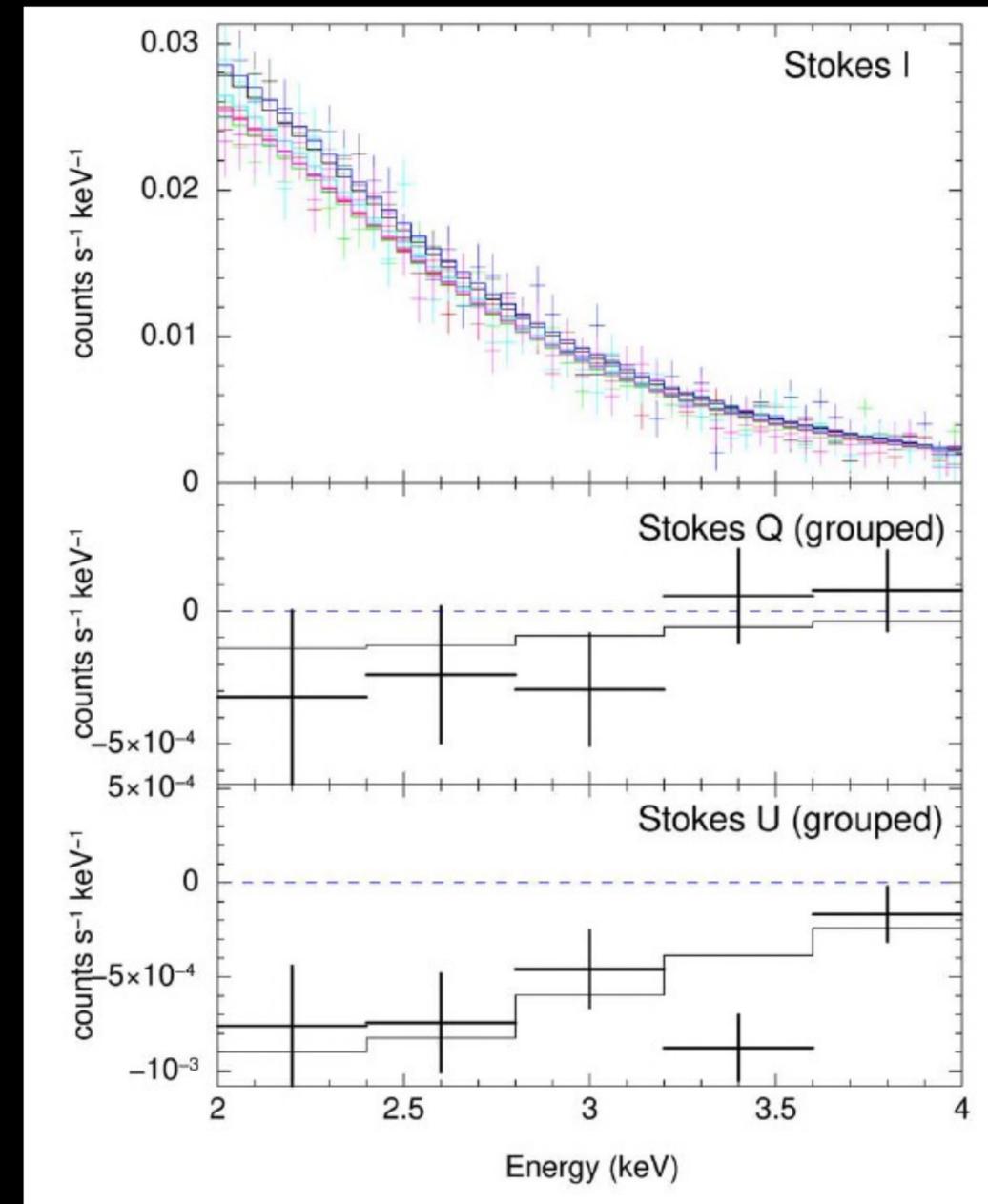
Average PD=22% (6.3σ)
Radial magnetic field



Chandra background + IXPE (NE circle+ vectors)



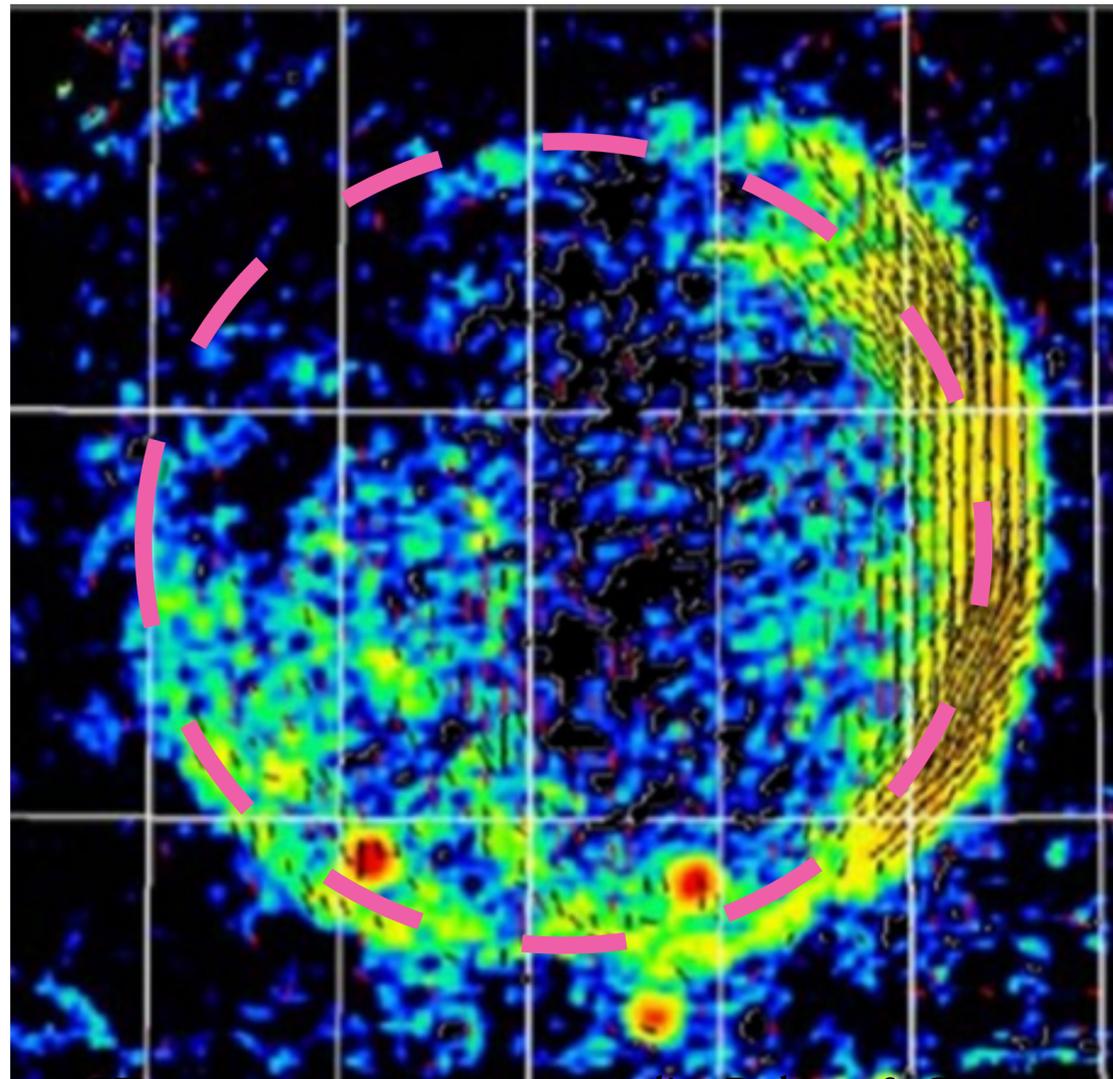
Spectropolarimetric analysis



Different magnetic properties between young and old SNRs

old SNRs

$B \perp$ shock direction

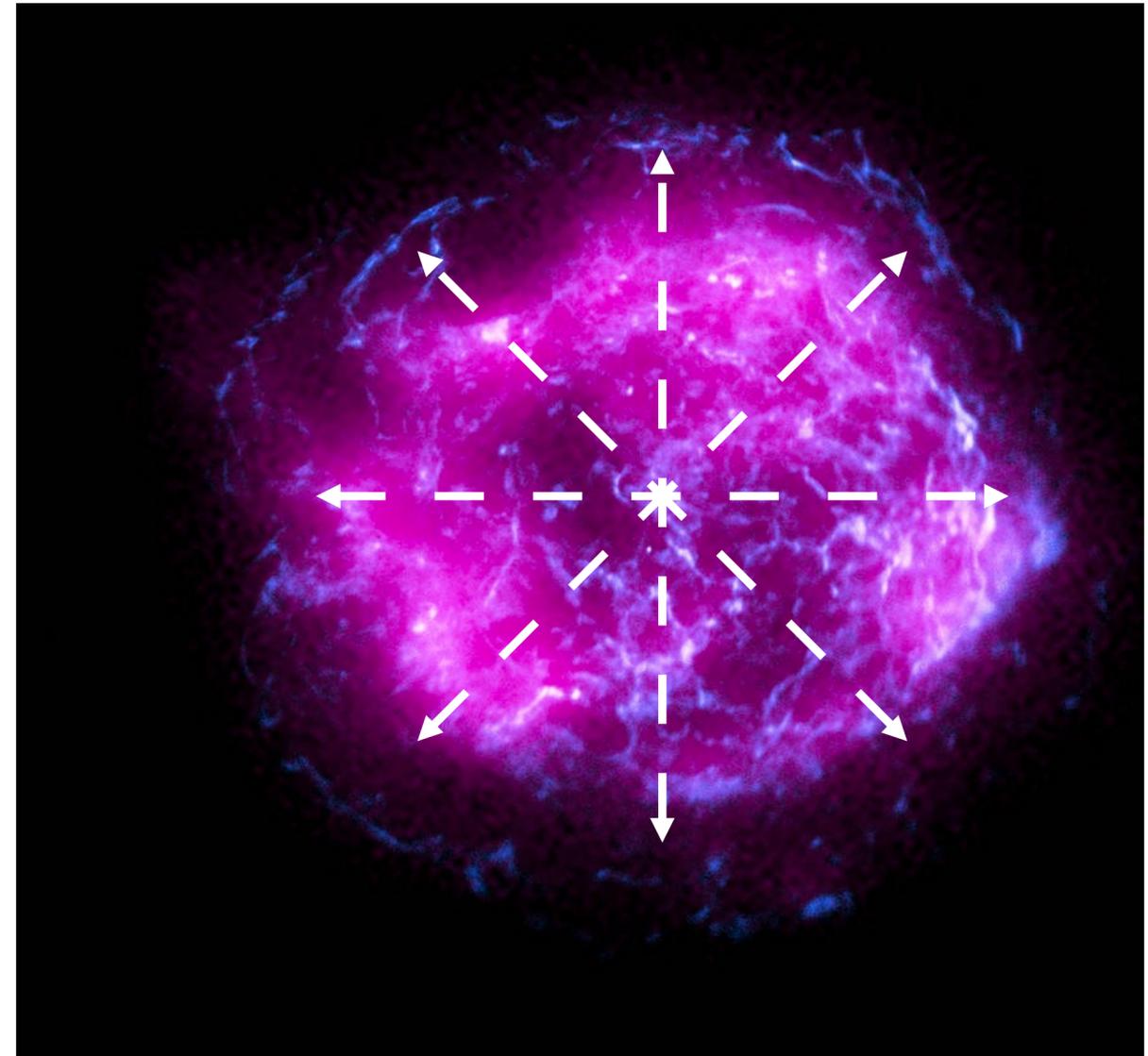


CTA 1 + magnetic vectors (Radio; Dubner & Giacani 2015)

B orientation due to a compression of the ISM

3 Young SNRs

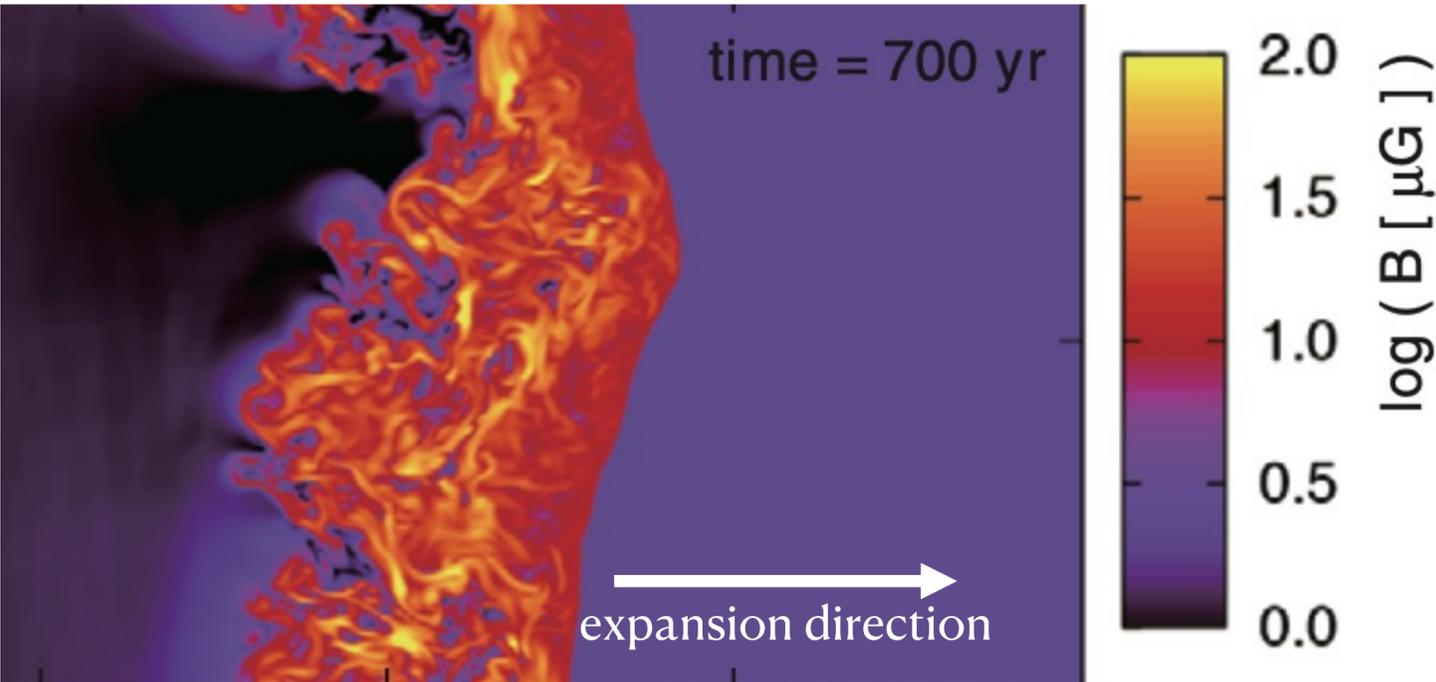
$B \parallel$ shock direction



Radially distributed B in young SNRs \rightarrow B turbulent amplification

Radial MHD turbulence stretches the fields

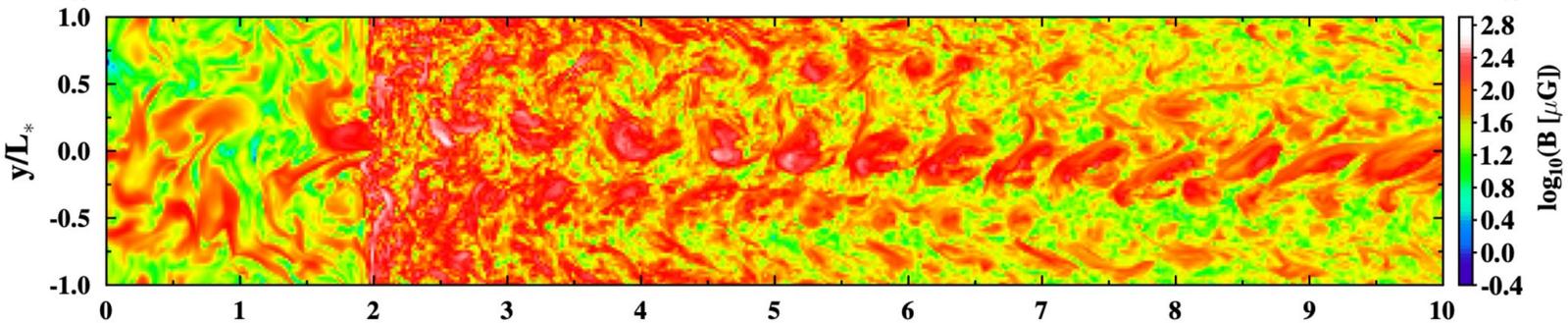
MHD turbulence due to density fluctuation



Inoue+2013

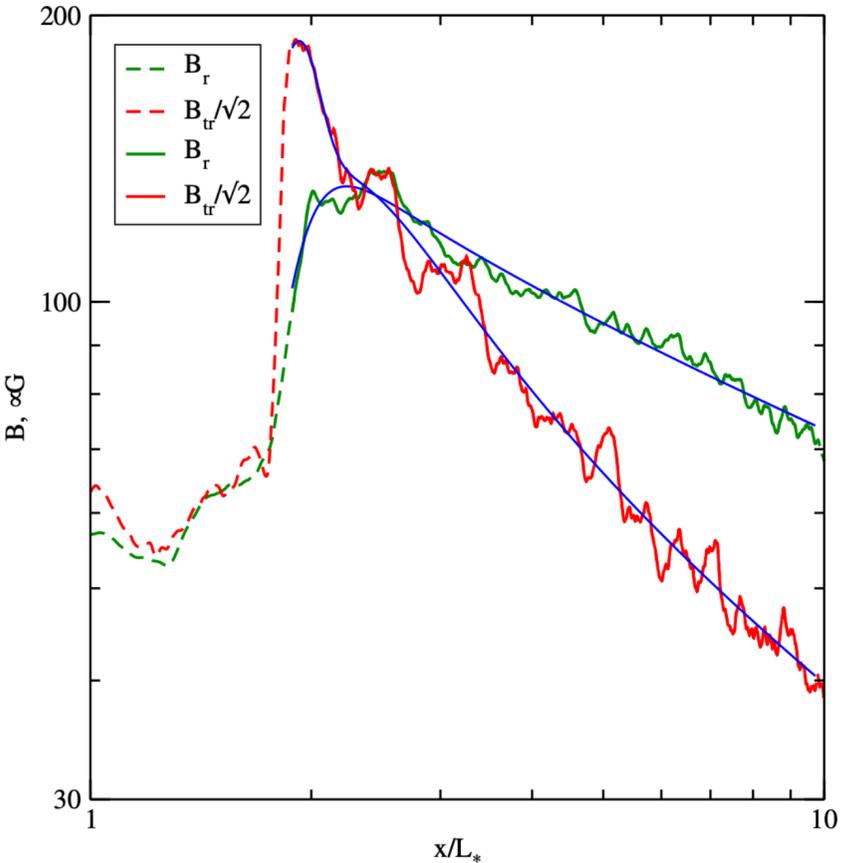
require inhomogeneous environment

CR-induced instability (Bell instability)



Bell 2004
Bykov+2024

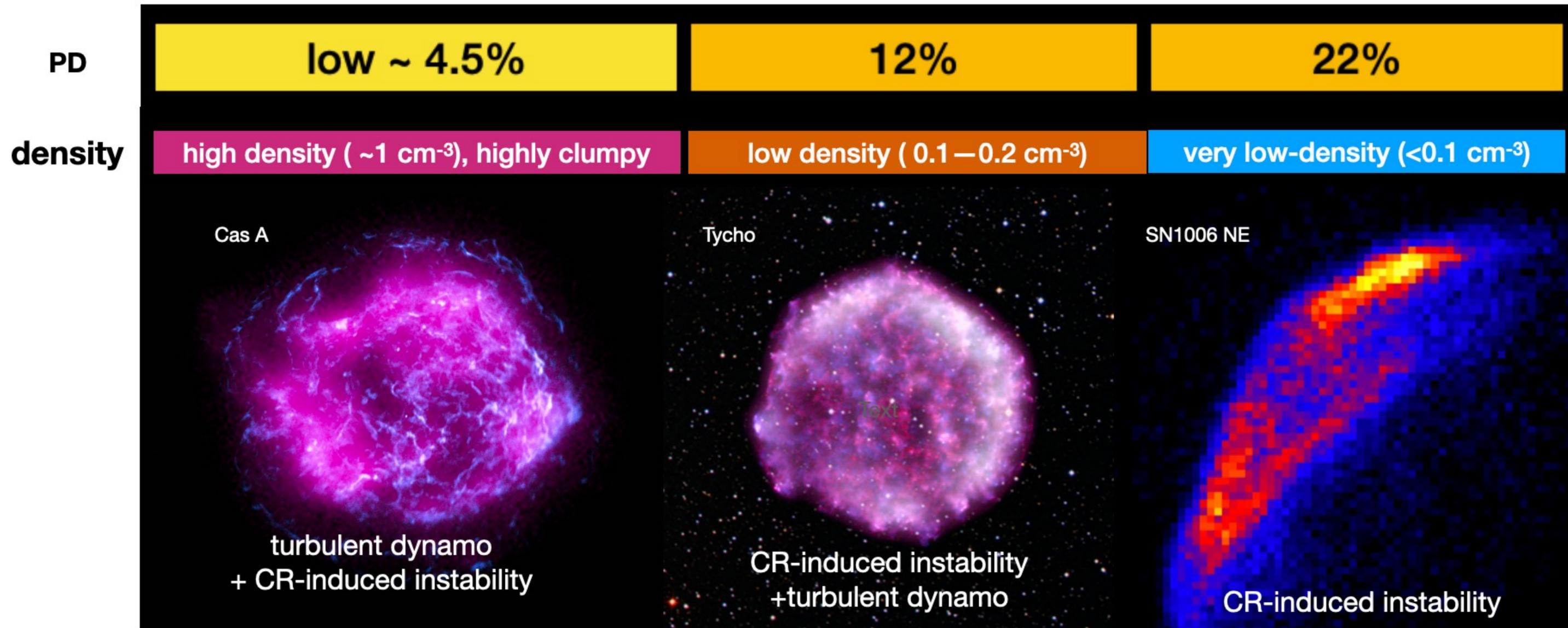
can work even for uniform medium



Magnetic turbulence and amplification is environment-dependent

Comparison of PD between SNRs

$\delta\rho/\rho \uparrow$ turbulence \uparrow



density fluctuation $\Delta\rho/\rho$



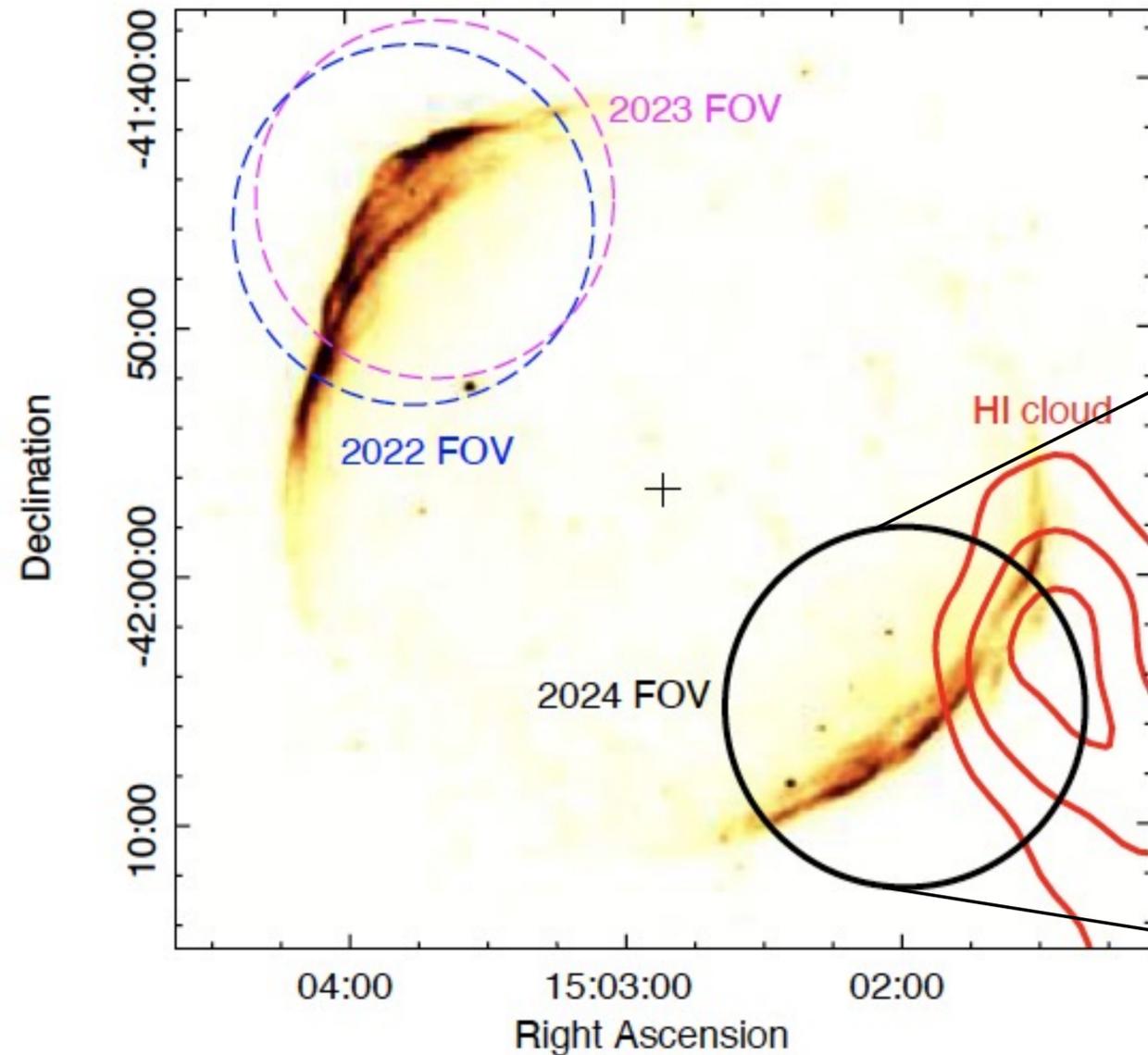
turbulent dynamo

Zhou+23b

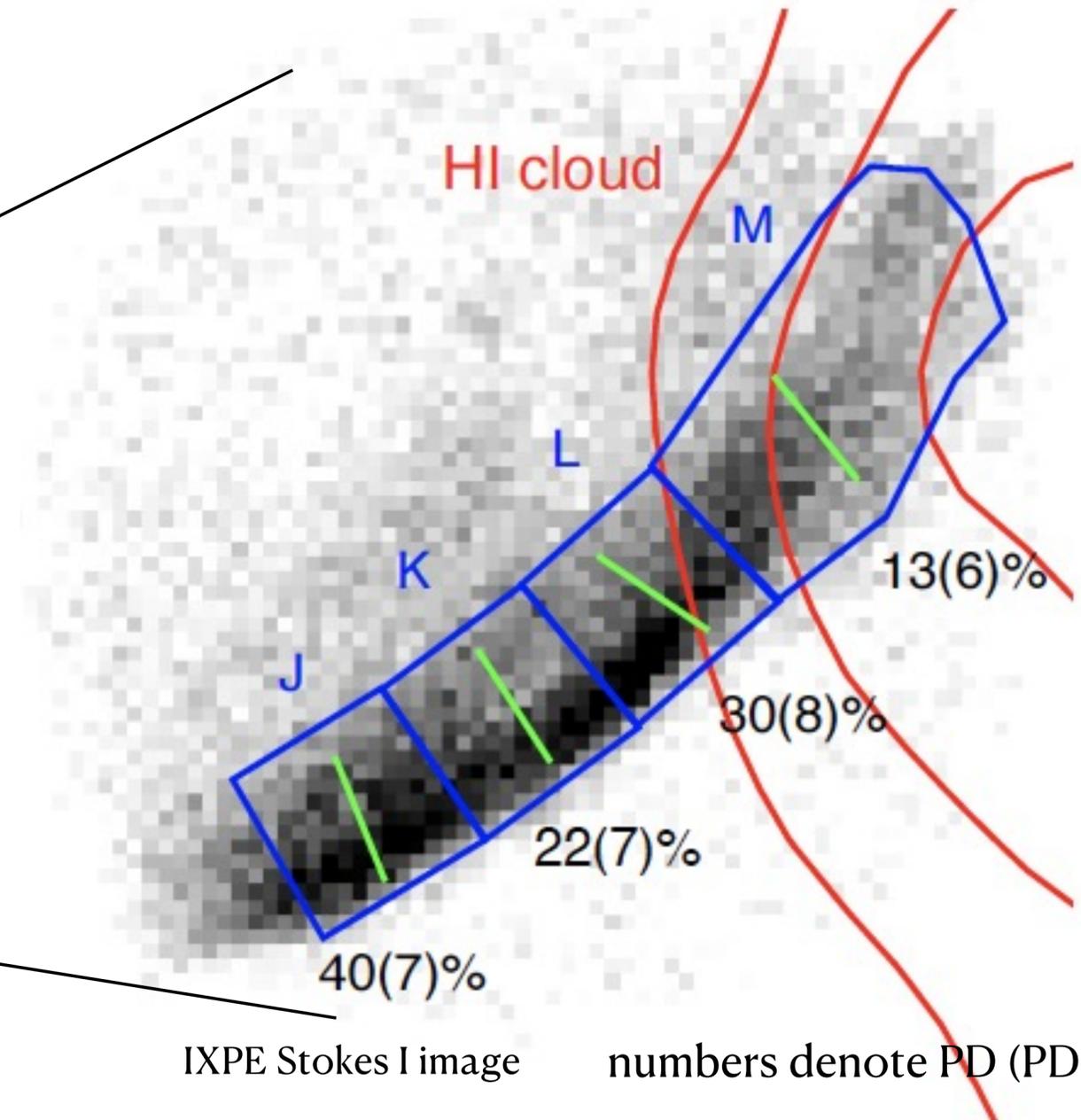
Magnetic turbulence and amplification is environment-dependent

PD is significantly reduced in regions with high density fluctuation

XMM-Newton image + IXPE FOVs



SNR-cloud association: Miceli +2014, Sano +2022



IXPE Stokes I image

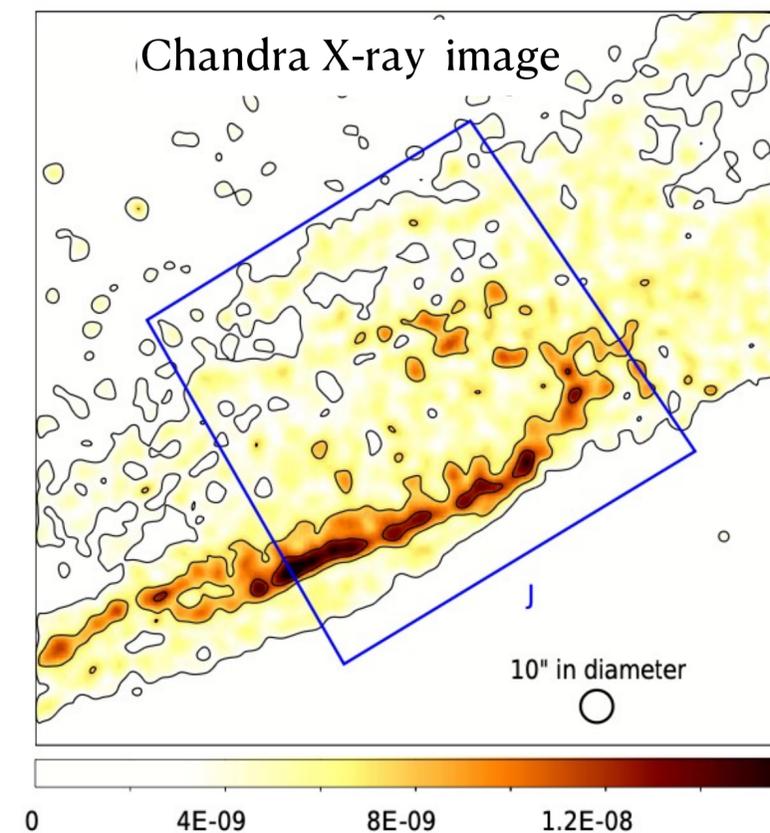
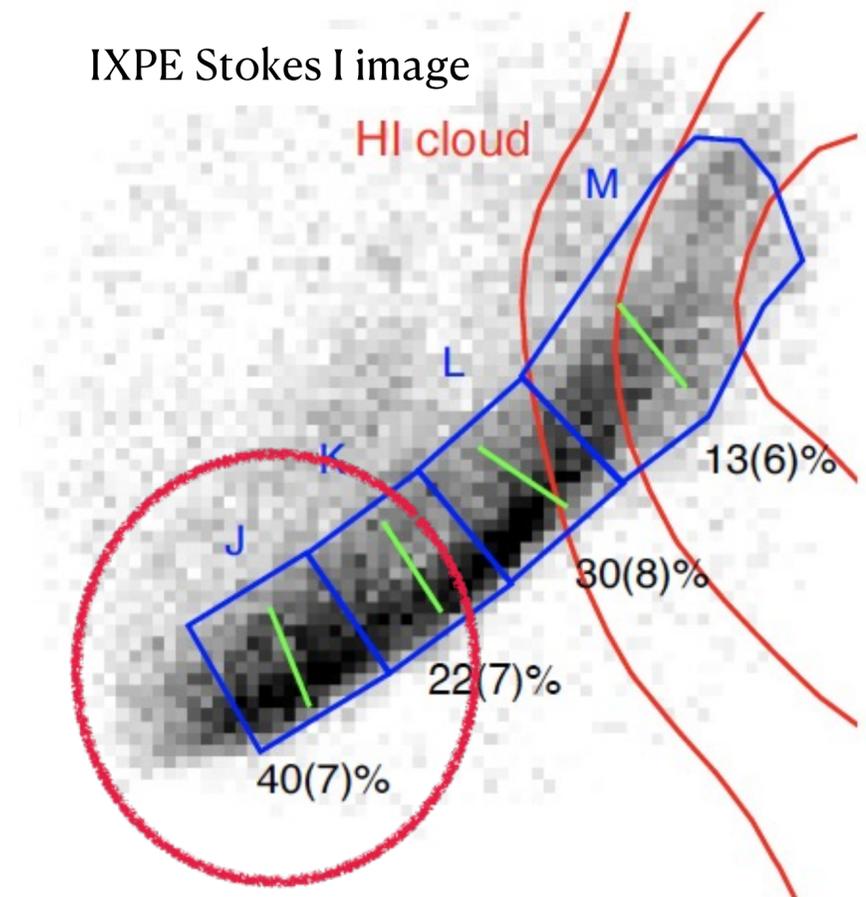
numbers denote PD (PD error)

Constrain magnetic field turbulent scale

- Region J has moderately ordered B at the scale of ~0.1 pc (the width of the X-ray rim).
- This scale should \lesssim B turbulence scale
- Characteristic length scale of nonresonant Bell instability ~0.1 pc for SN 1006 (pre-shock)

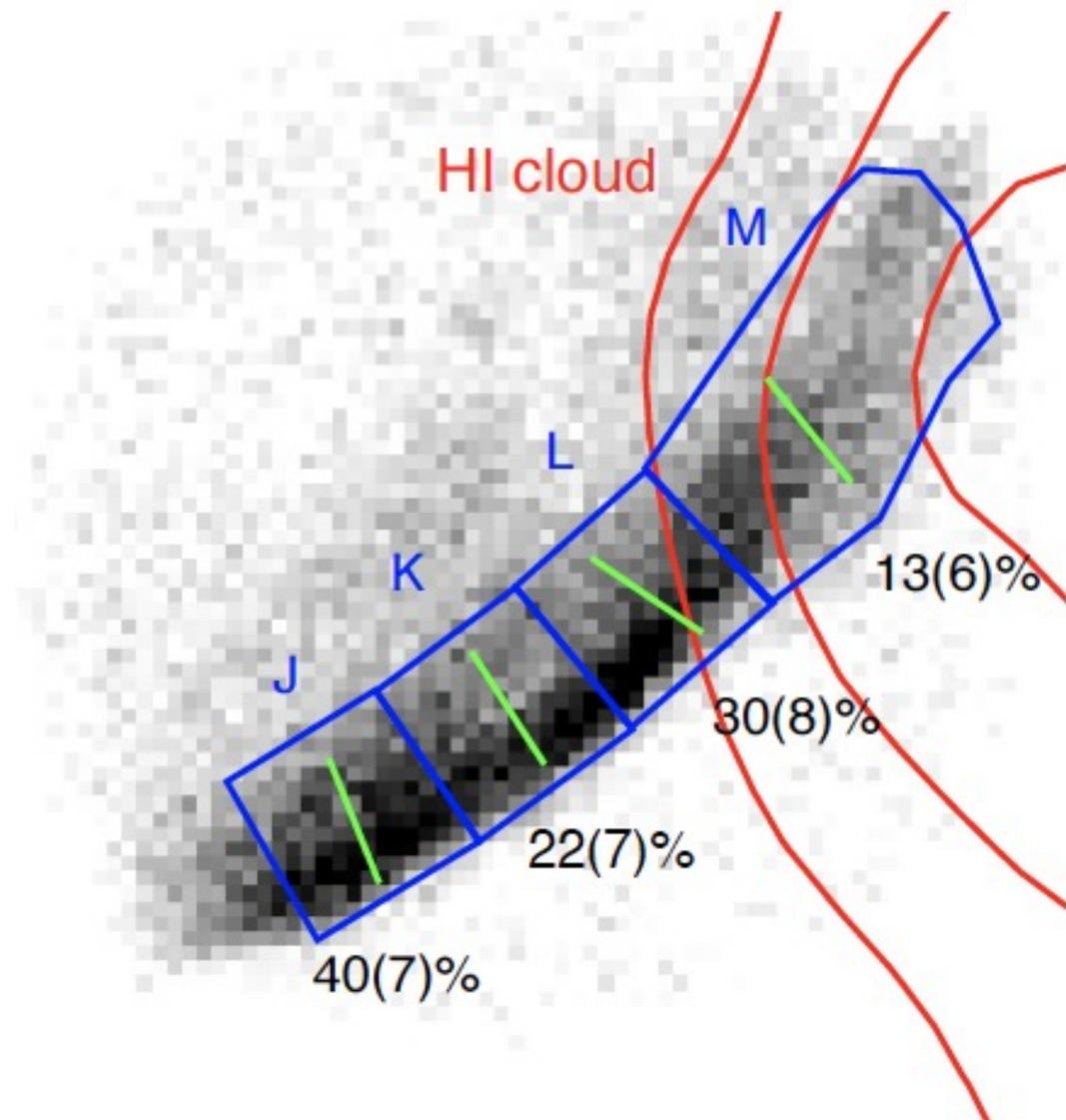
$$l_{\text{Bell}} \sim 2 \times 10^{17} \text{ cm} \left(\frac{V_s}{5 \times 10^3 \text{ km s}^{-1}} \right)^{-3} \left(\frac{n_0}{0.05 \text{ cm}^{-3}} \right)^{-1} \left(\frac{E_{\text{max}}}{100 \text{ TeV}} \right) \left(\frac{B_0}{3 \mu\text{G}} \right),$$

- Clumps seen in the X-ray image \leftarrow B turbulence can create inhomogeneous X-ray structures



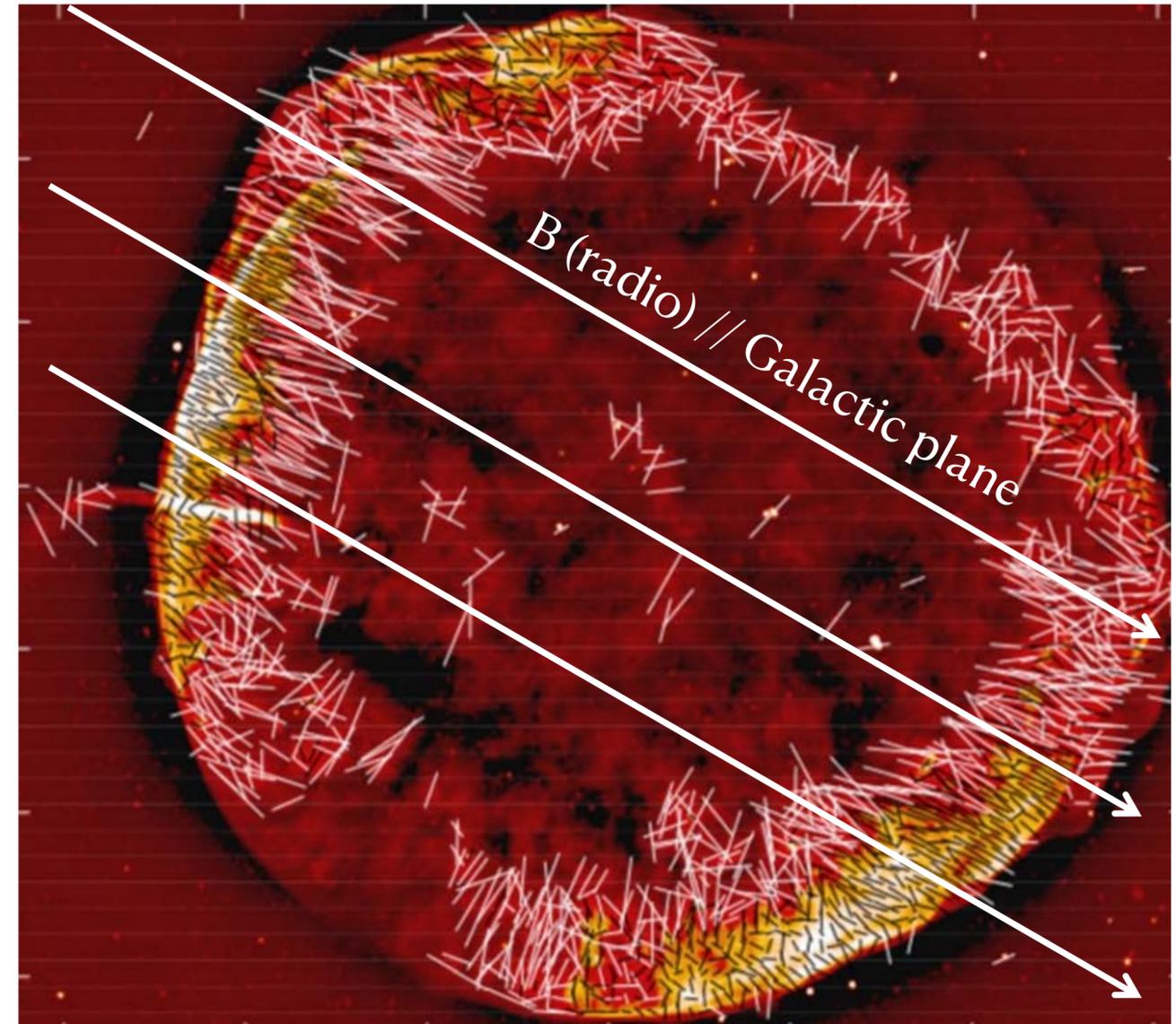
X-ray and radio polarimetry probe different B-fields

X-ray polarimetry: radial B-field



Radio polarimetry: predominately parallel B-field

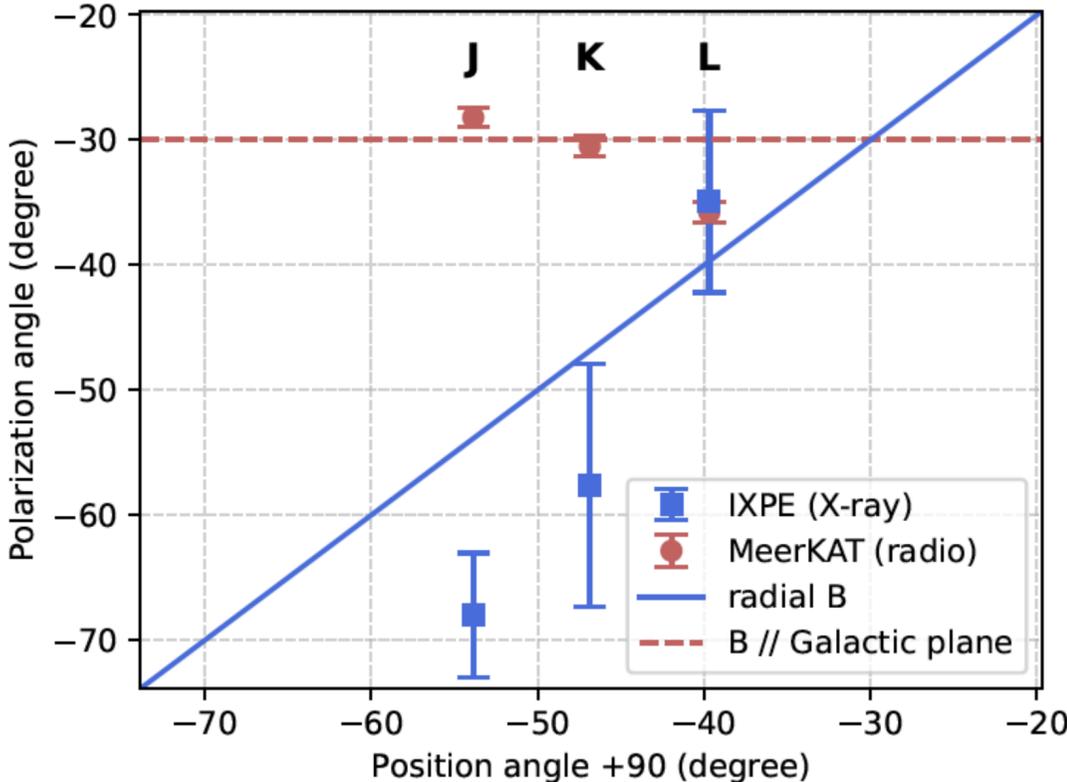
MeerKAT radio image + magnetic vectors
(Cotton et al. 2024)



X-ray and radio polarimetry probe different B-fields

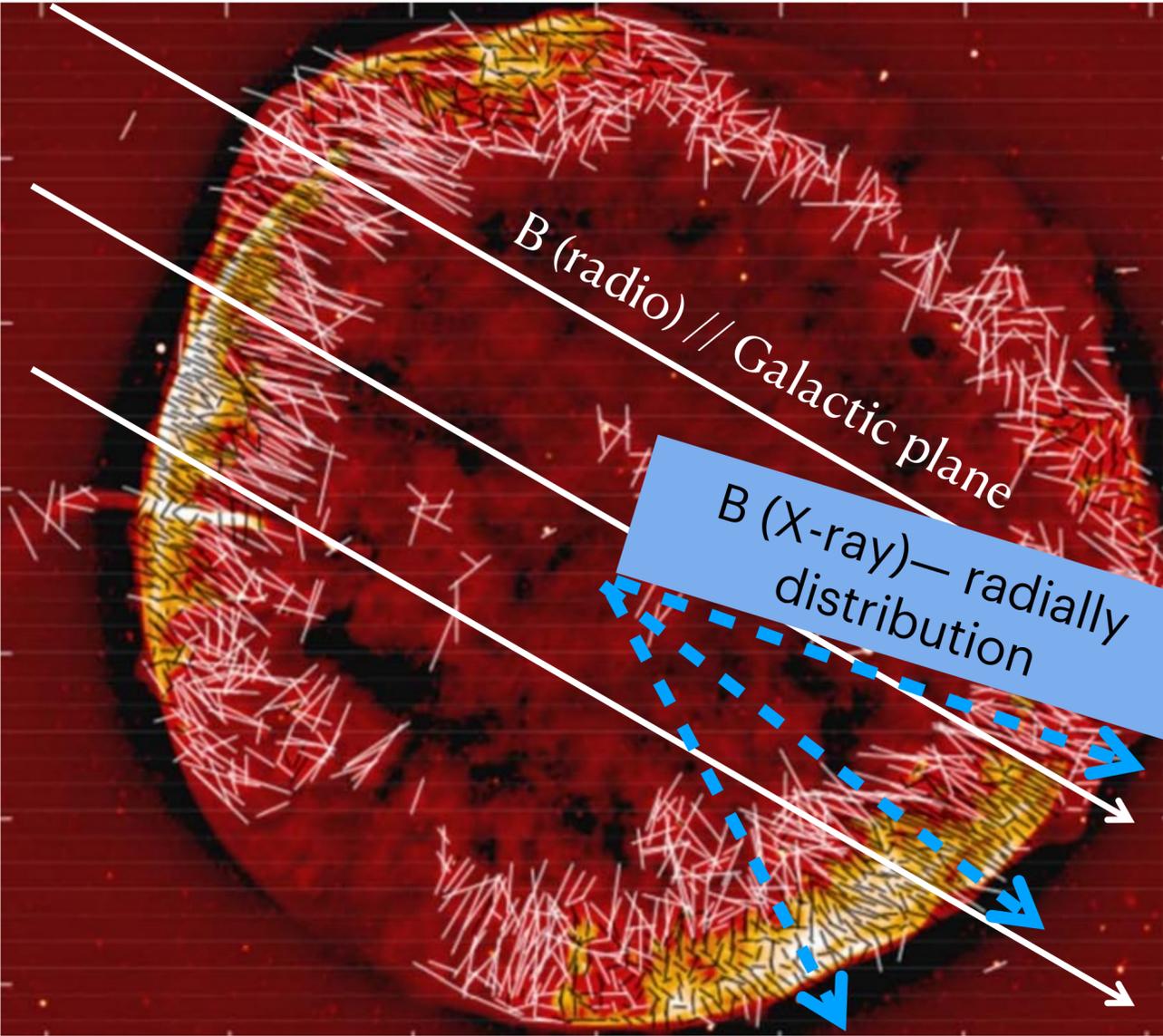
Radio polarimetry: predominately parallel B-field
X-ray polarimetry: radial B-field

- **Different layers:** X-rays come from a thin layer immediately behind the shock
- **Different B-fields:** X-rays probe freshly amplified B-field, radio likely reflects much of the pre-existing field



Zhou+ 2025a

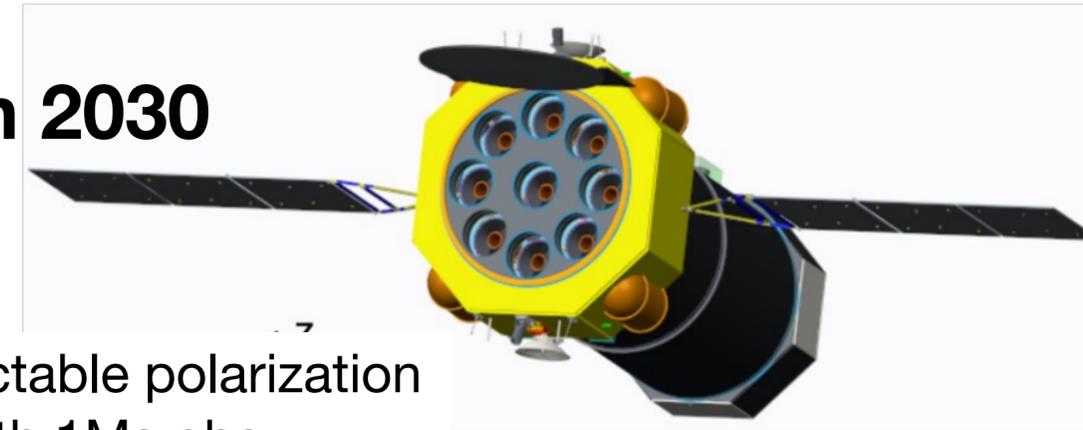
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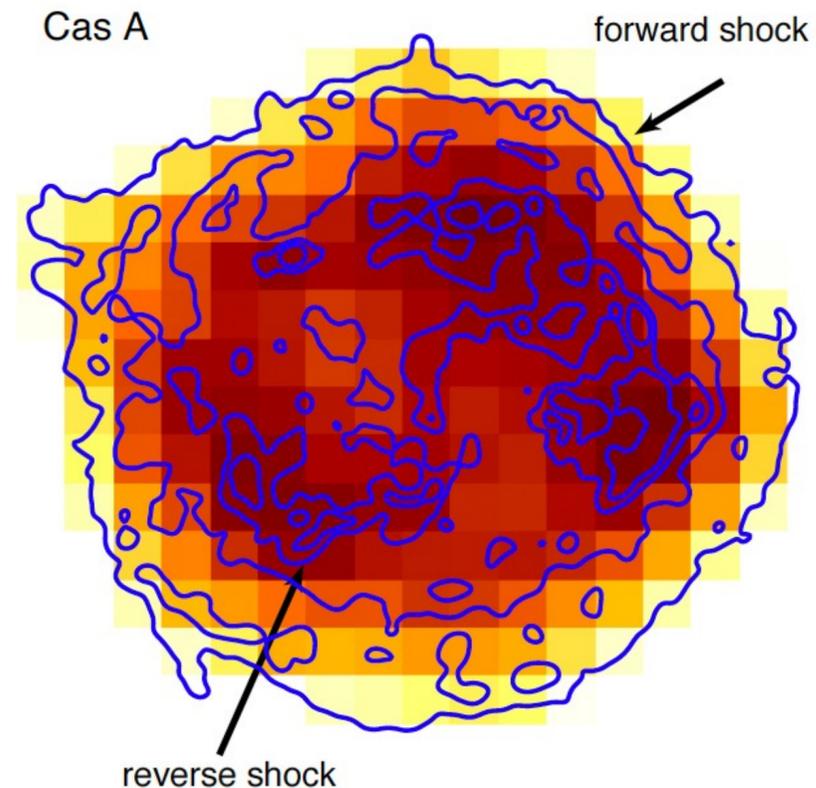
Planning Chinese X-ray missions for polarimetry

eXTP (extended X-ray Timing and Polarization) – launch in 2030

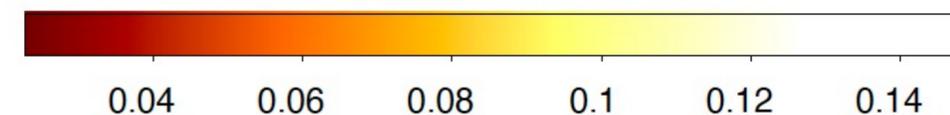
- Limitations of current IXPE measurements
 - low-sensitivity, 30" angular resolution has never been really used due to the low statistics ($S/N \lesssim 6$ for each observation, 5 for Cas A)
- **eXTP/PFAs with 5 times better collecting area** than IXPE
- will measure B orientation and turbulence spatial distribution with much better accuracy



minimum detectable polarization (99%) with 1Ms obs.



MDP₉₉ ~ 10% at forward shock
~2.5% at reverse shock
(30" resolution)



Zhou + 2025b
(Observatory Science with eXTP)

Summary

- Magnetic turbulence and amplification are **environment-dependent**
- **X-ray polarimetry probes amplified/turbulent B-fields**, while radio polarimetry traces more extended regions that may keep an imprint of the ambient B-field.
- Future **multi-band polarimetry and theoretical studies will be important** to understand the B structures within SNRs

Thank you!