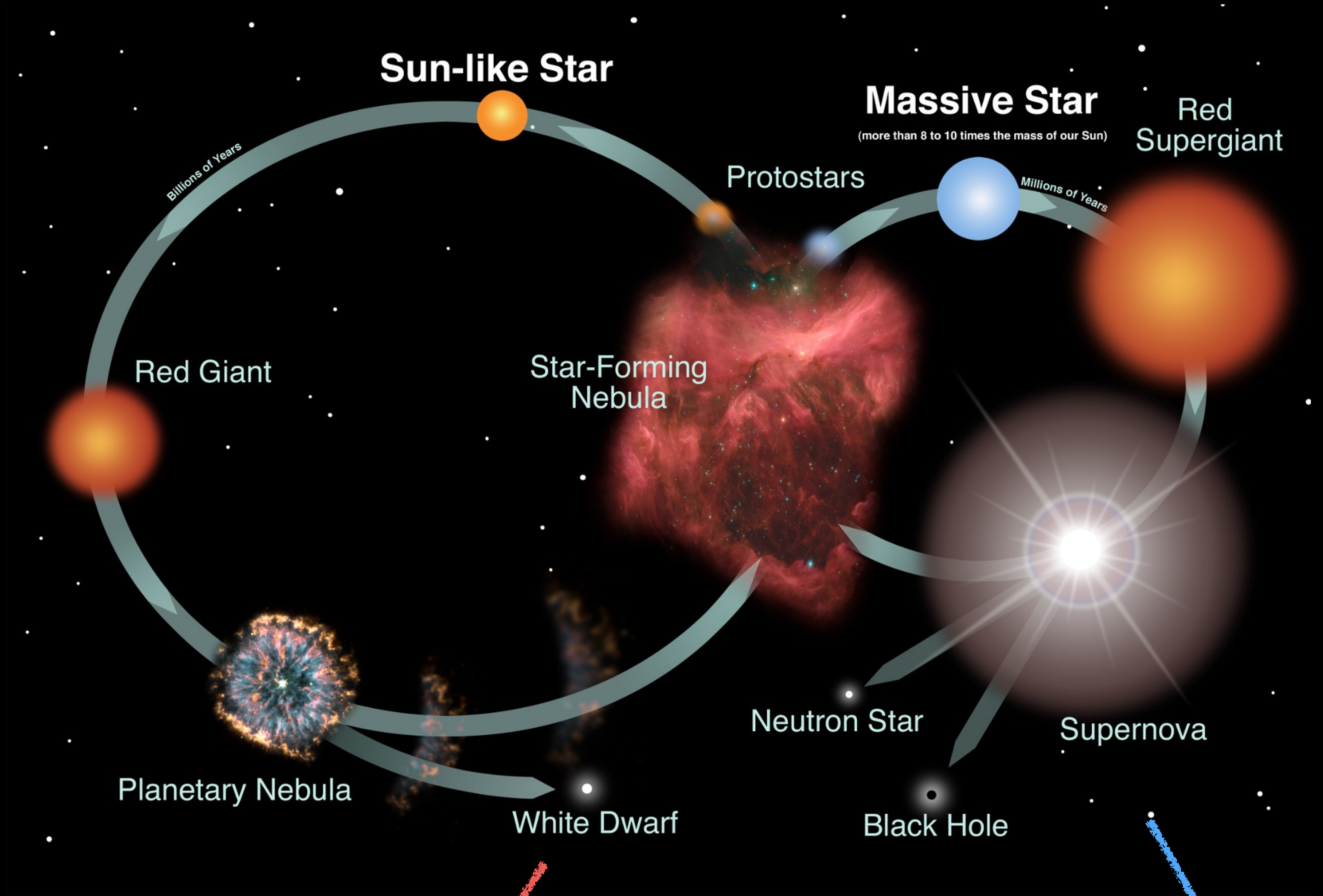
X-ray polarization study of supernova remnants

Ping Zhou
(Nanjing University)

Collaborators and IXPE SNR group

- Patrick Slane (CfA, IXPE SNR coordinator)
- Riccardo Ferrazoli (INAF; Tycho & RX J1713)
- Jacco Vink (Amsterdam; Cas A)
- Dmitry Prokhorov (Wurzburg; Vela Jr.)
- Stefano Silvestri (INFA; RCW 86)
- Yi-Jung Yang (National Central University)
- Niccolo Bucciantini (INAF)
- IXPE SNR topical working group
- Estela Reynoso, William Cotton, David Moffet (radio polarimetry), Wenlang He
- IXPE team

An end of stellar evolution — supernova remnant (SNR)

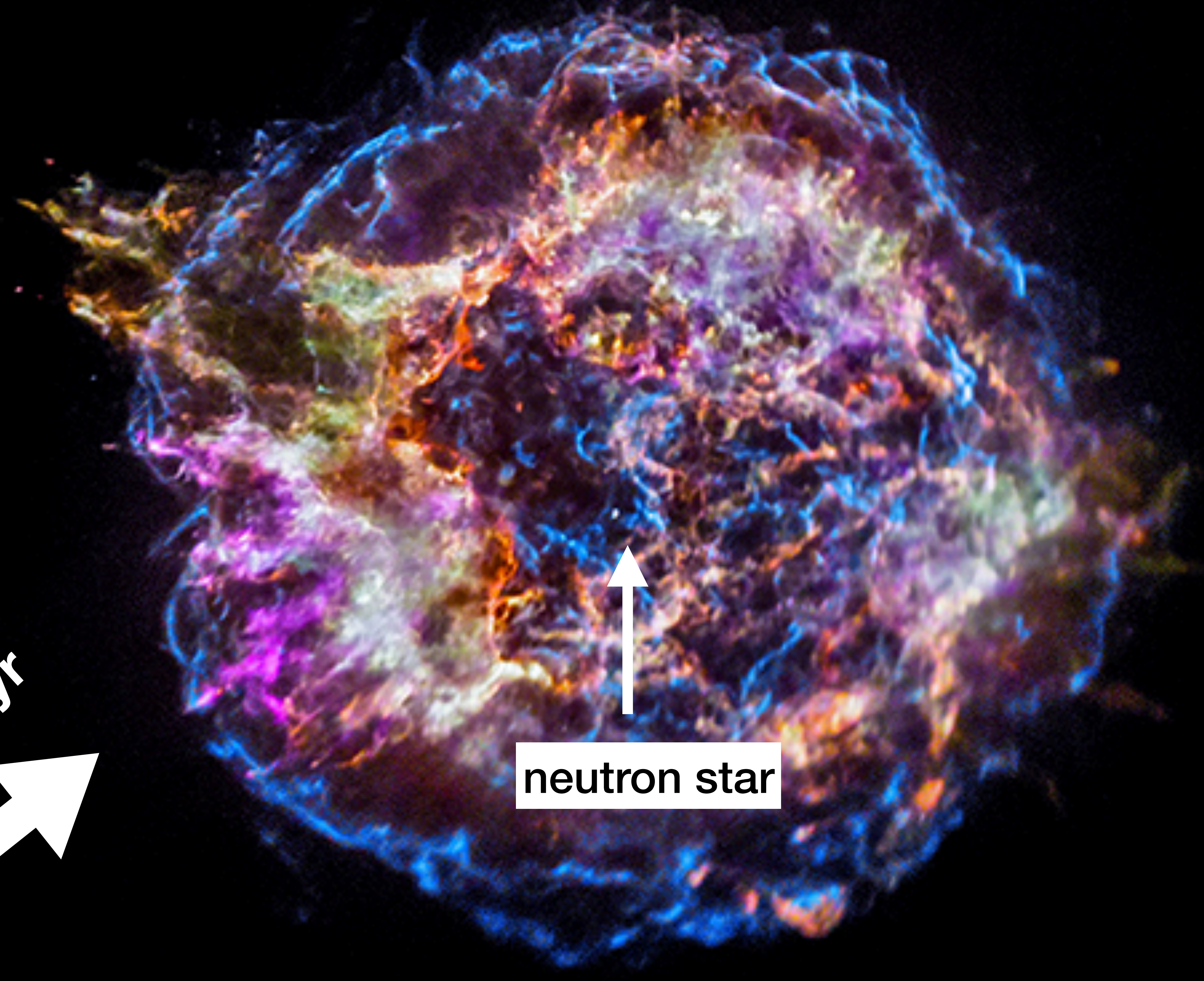


Thermonuclear Supernova

Core-collapse Supernova

~355 yr

Cassiopeia A SNR
with Chandra X-ray observatory

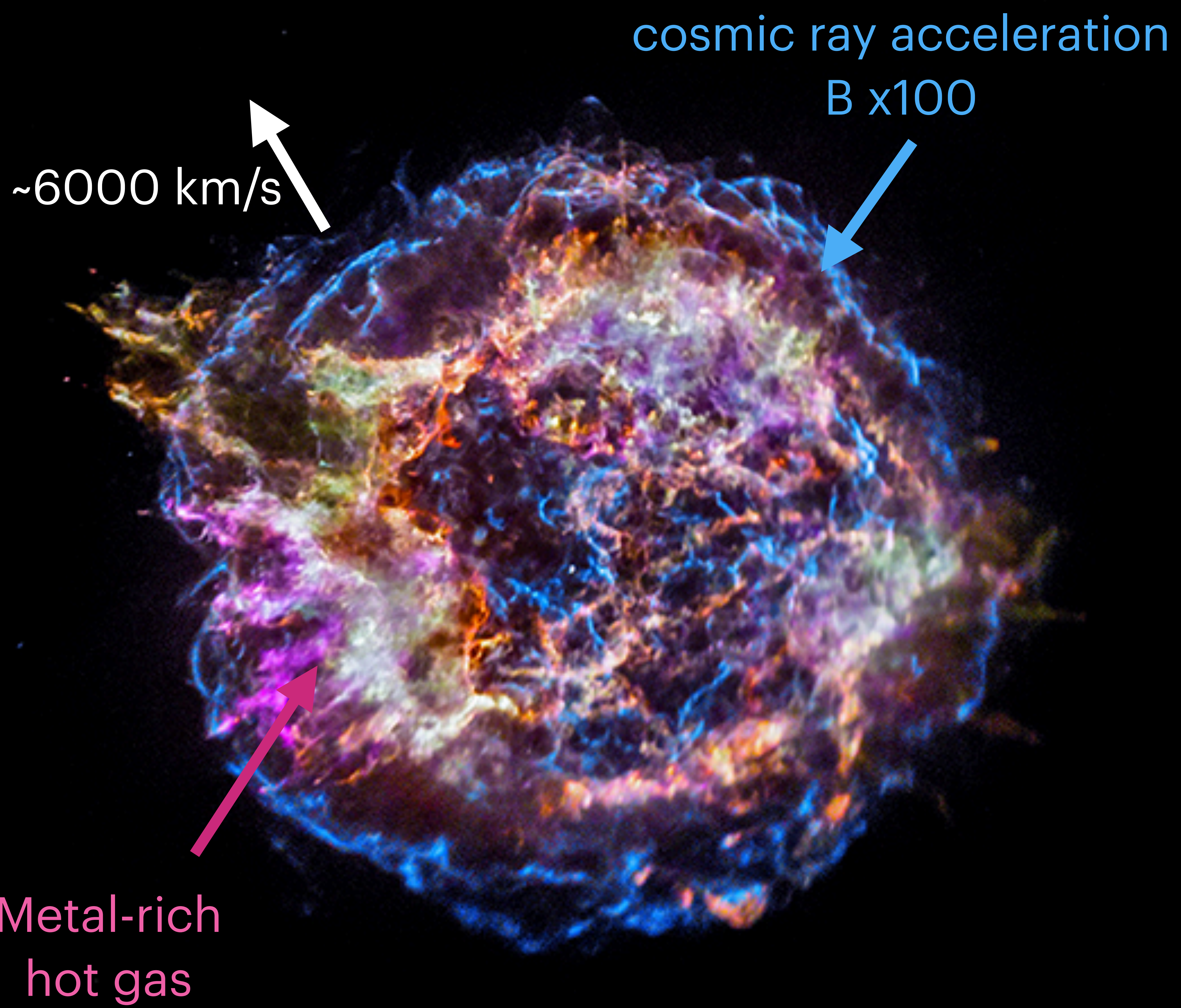


SNR — Nebula resulted from the interaction of SN materials with the interstellar medium

Credit: NASA/CXC

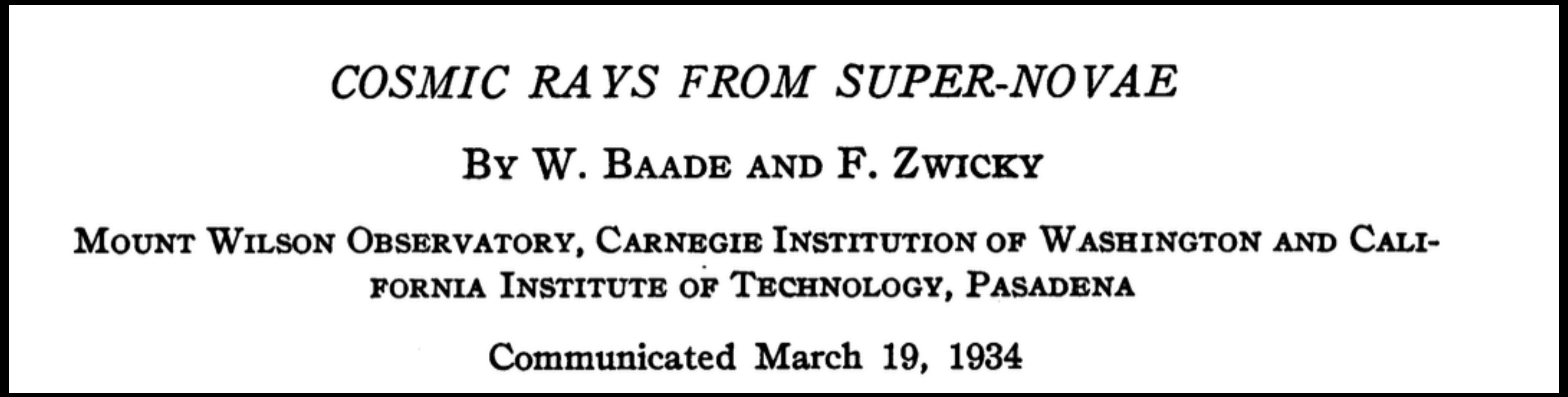
SNRs influence every component of the interstellar medium

- Kinetic energy: 10^{50}—10^{52} erg
- Emission: radio to gamma-ray bands
- Gas: produce hot ionized medium (X-ray)
- Dust: factory + destroyer
- Cosmic rays: factory
- **Magnetic fields: Amplify/modify**



For Cas A
Shock velocity ~ 6000 km/s
Metal mass ~ 2–4 M_{sun}
Heated CSM ~ 10 M_{sun}
Kinetic energy ~ 1—2 x 10^{51} erg
(Vink +1996,2022)

SNRs as factories of cosmic rays



COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

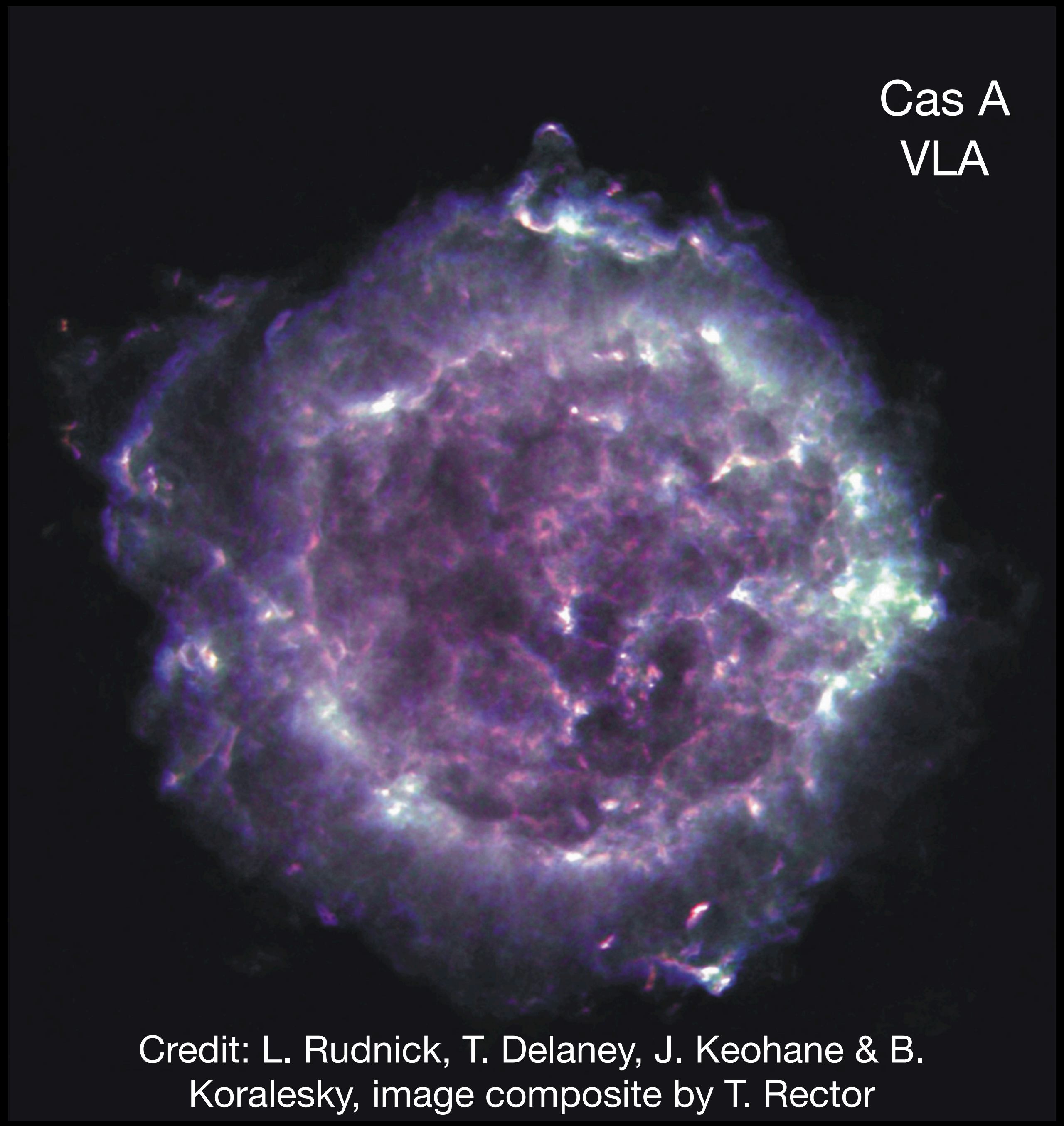
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

Walter Baade

Fritz Zwicky

Radio image of Cas A

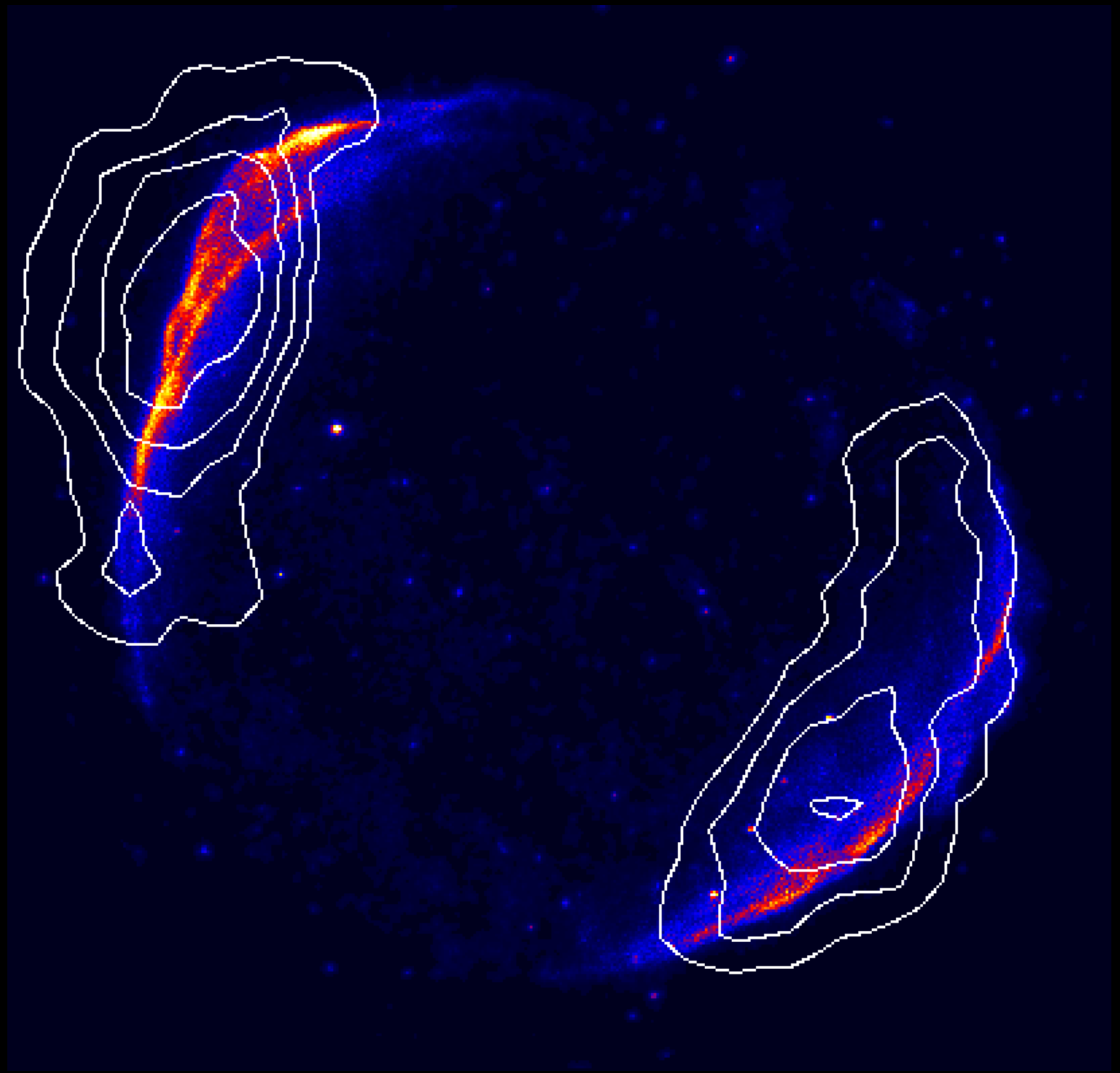


Credit: L. Rudnick, T. Delaney, J. Keohane & B. Koralesky, image composite by T. Rector

Radio emission from GeV-energy electrons

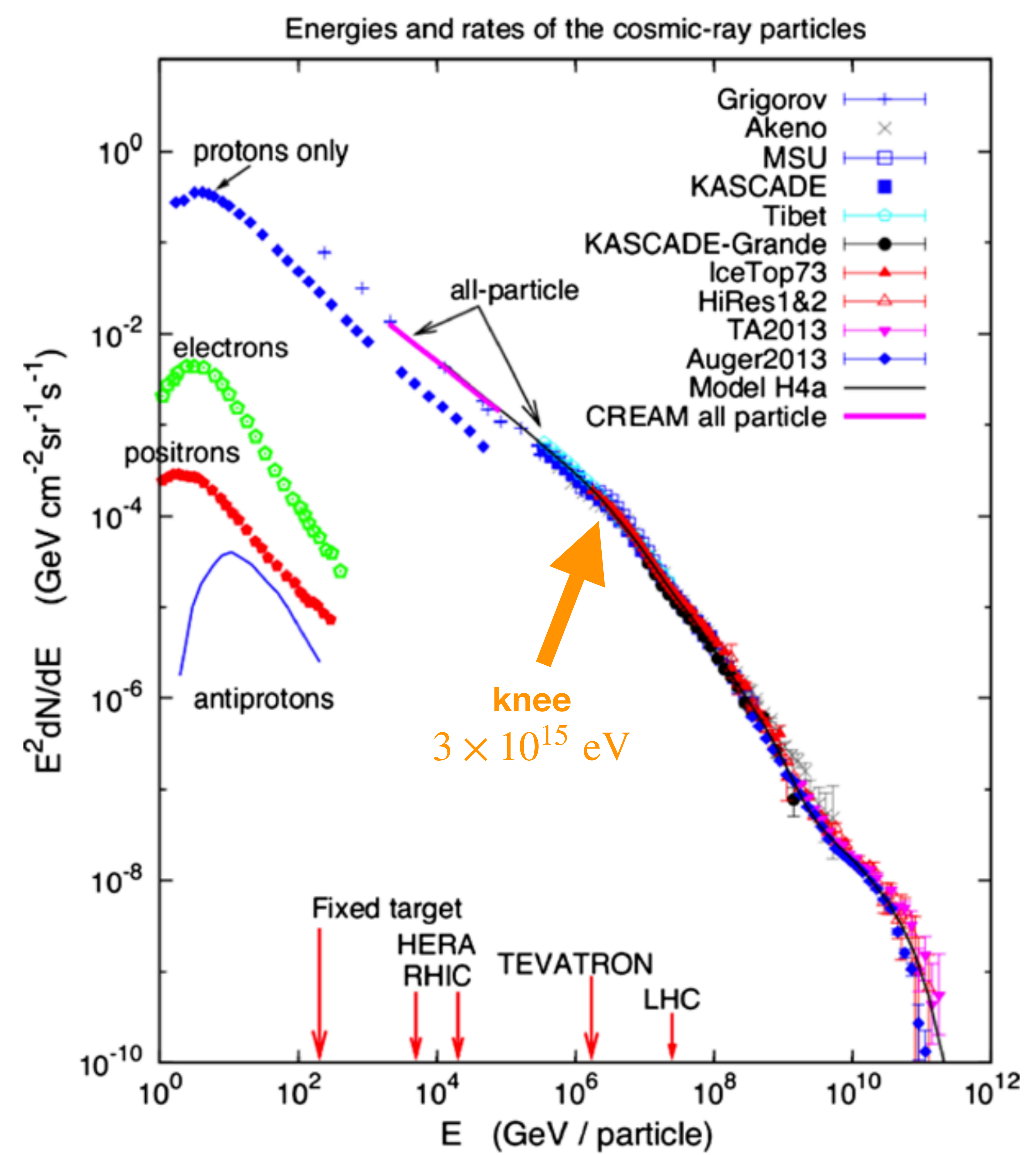
X-ray image of SN1006

Contours: HESS TeV



X-ray emission from over 10 TeV-energy electrons

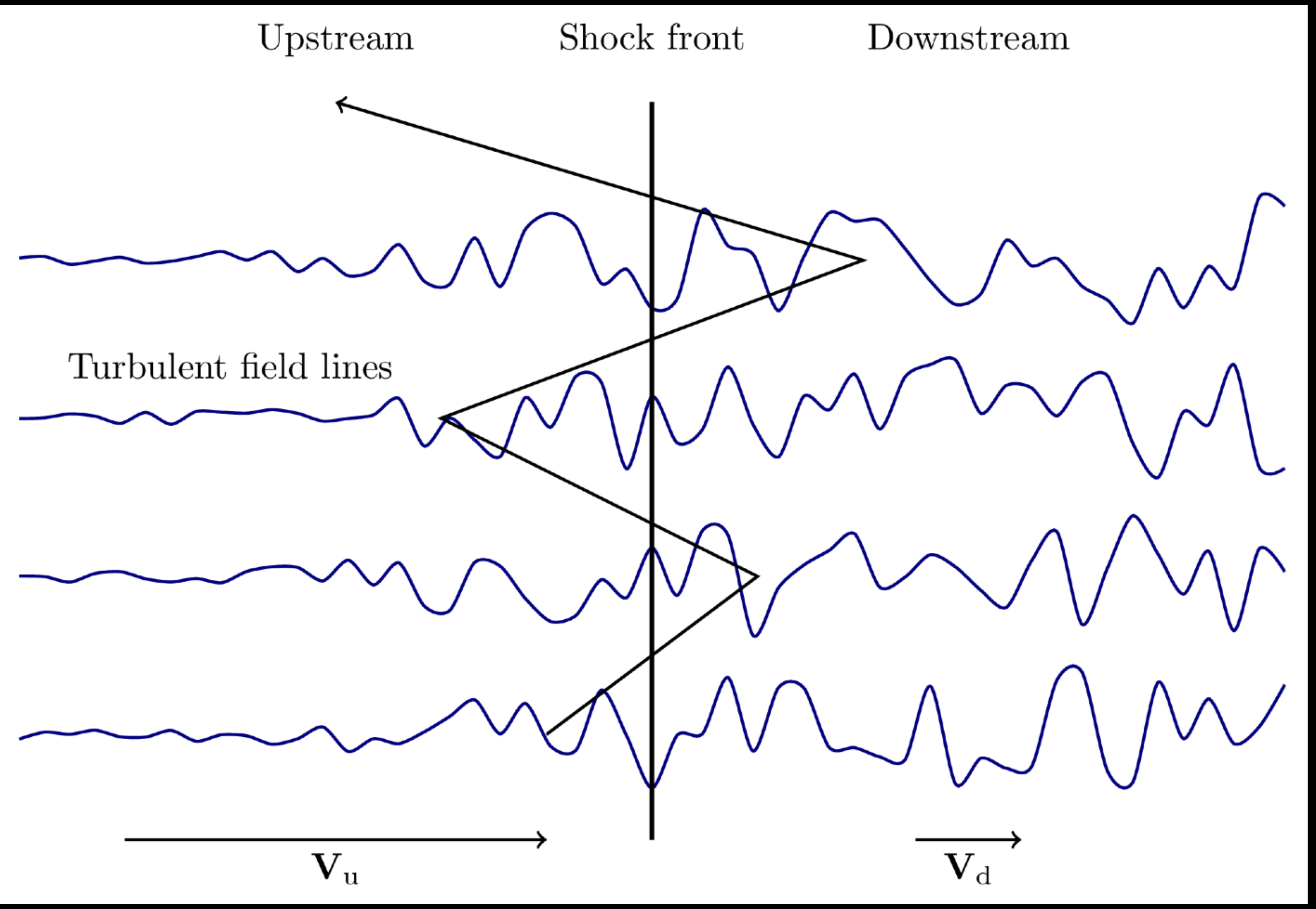
Are SNRs the primary sources of Galactic CRs?



Blasi 2013

- **Two basic requirements**
  - Energy: SNRs must transfer ~10% of SN explosion energy to CRs.
  - Maximum energy: some SNRs must accelerate CRs to PeV energy.

Importance of magnetic fields in CR acceleration



Diffusive shock acceleration of CRs

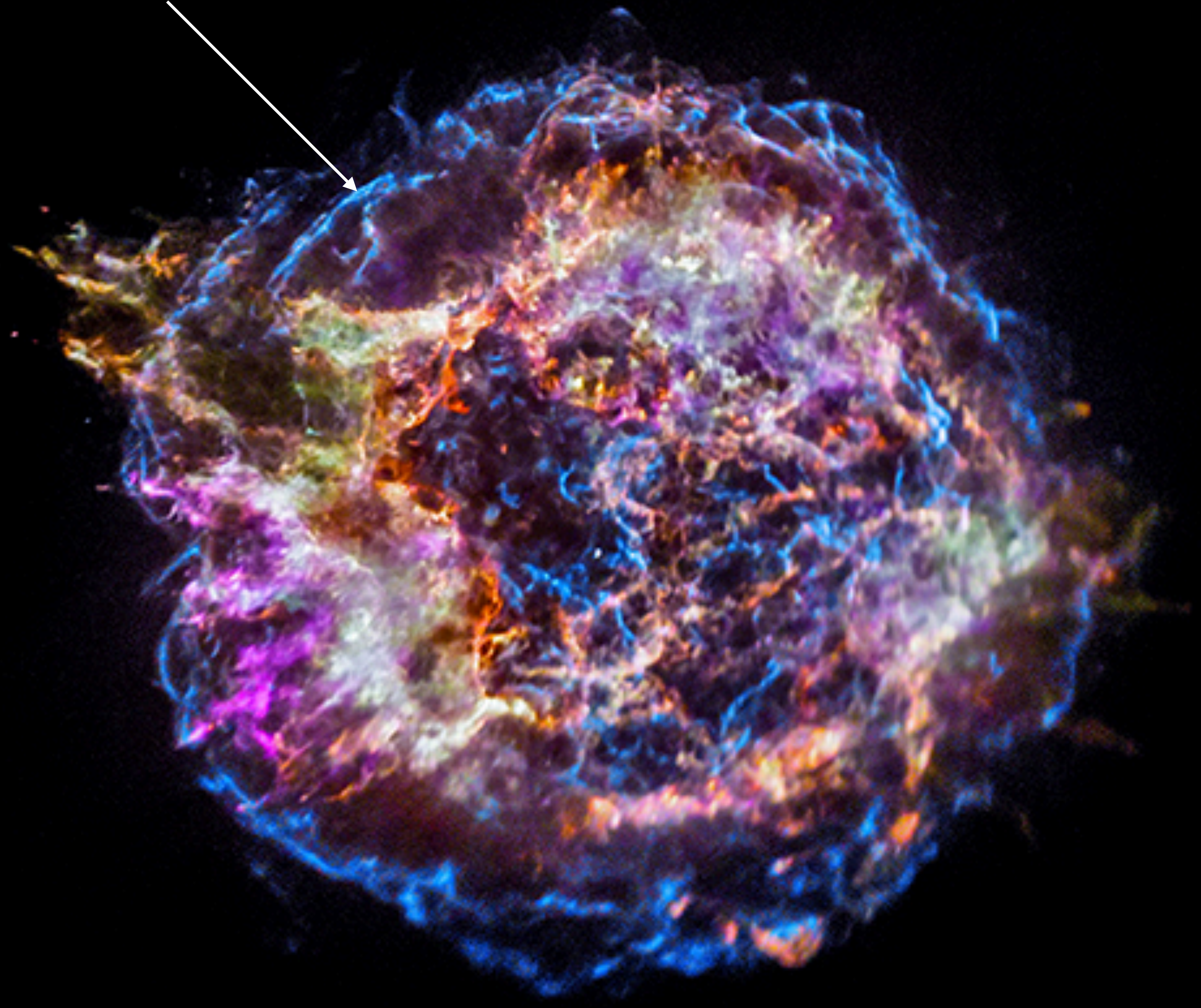
https://sprg.ssl.berkeley.edu/~pulupa/illustrations/

- **Magnetic fields trap the CRs near the shock**
- $E_{\max} \approx 50\ \mathrm{TeV} \left(\frac{B}{\mu\mathrm{G}}\right) \overset{\sim 1}{\boxed{\left(\frac{M_{\mathrm{ej}}}{M_\odot}\right)^{-1/6} \left(\frac{E_{\mathrm{SN}}}{10^{51}\ \mathrm{erg}}\right)^{1/2} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{-1/3}}}$

  t_{acc}=ejecta-dominated phase time (Morlino+2016)
- In the diffuse ISM, $B_0 \sim 1\ \mu\mathrm{G} \left(\frac{n_0}{\mathrm{cm}^{-3}}\right)^{1/2}$
- Need the magnetic field amplification to increase $E_{\max}$ to the “knee” (3×10^{15}eV)

Magnetic amplification in young SNRs

Narrow **X-ray** synchrotron filaments with widths $l = 1'' \sim 4''$



Cas A

X-ray synchrotron emission comes from multi-TeV electrons.

Synchrotron loss timescale

$$\tau_{\rm loss} = 637/(B^2 E_e)\ \mathrm{s} \sim 20\ \mathrm{yr} \ll \text{SNR age}$$

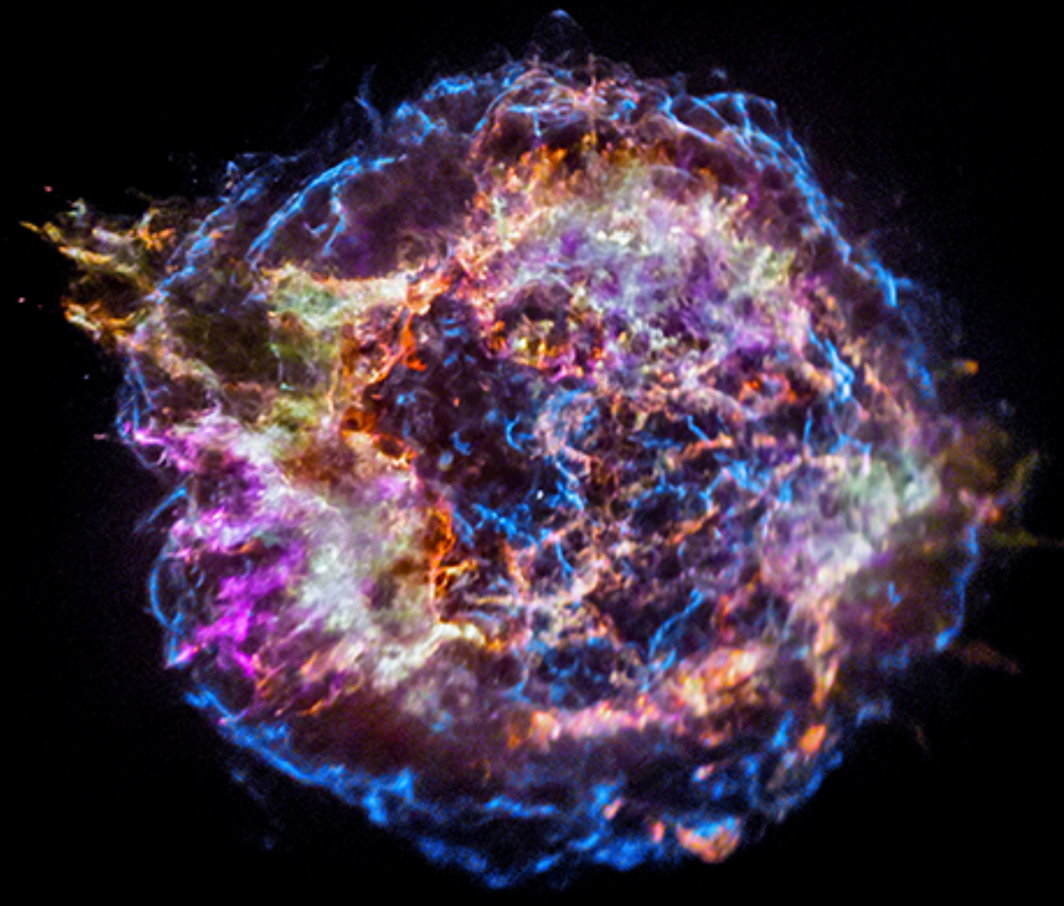
Filament width $l_{\rm loss} = v_d \tau_{\rm loss} \propto B^{-2} E_e^{-1}$

Strongly amplified $B \sim 10^2 \times B_{\rm ISM} \sim 0.1\ \mathrm{mG}$ (Vink & Laming 2003)

Magnetic amplification in young SNRs

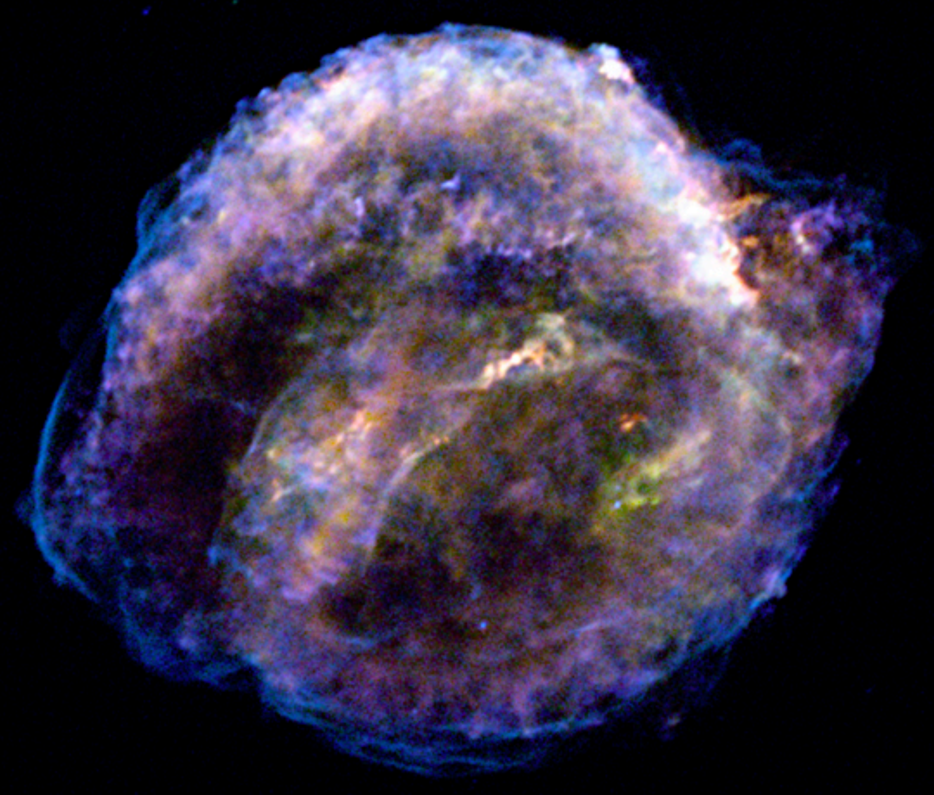
Narrow **X-ray** synchrotron filaments —> evidence of magnetic amplification

210 μG



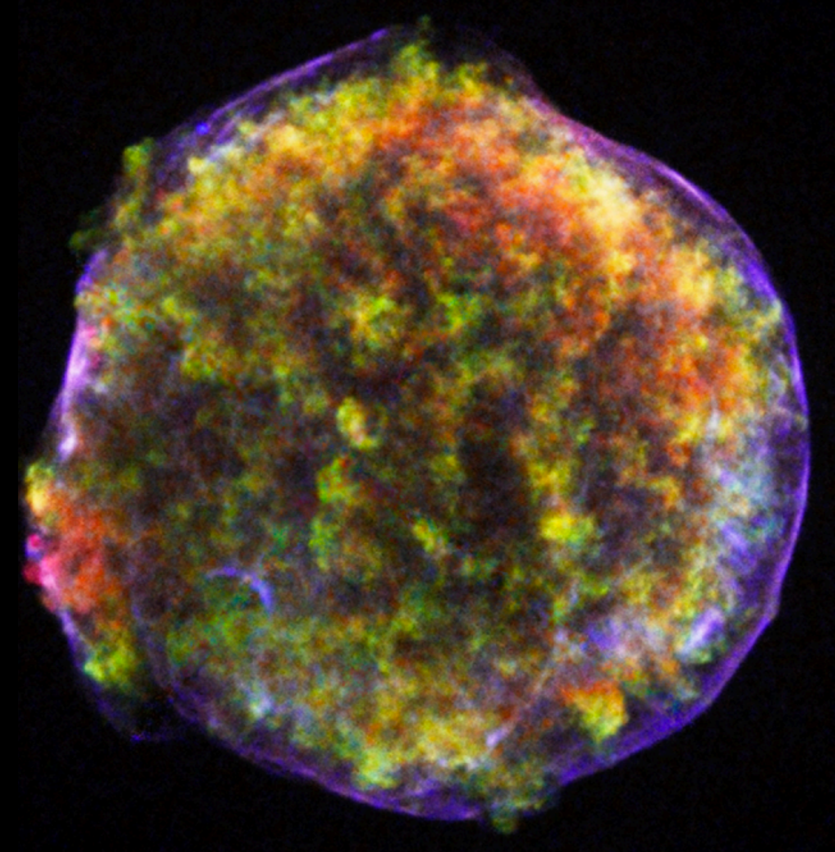
Cas A

170 μG



Kepler

200 μG



Tycho

60 μG

SN1006

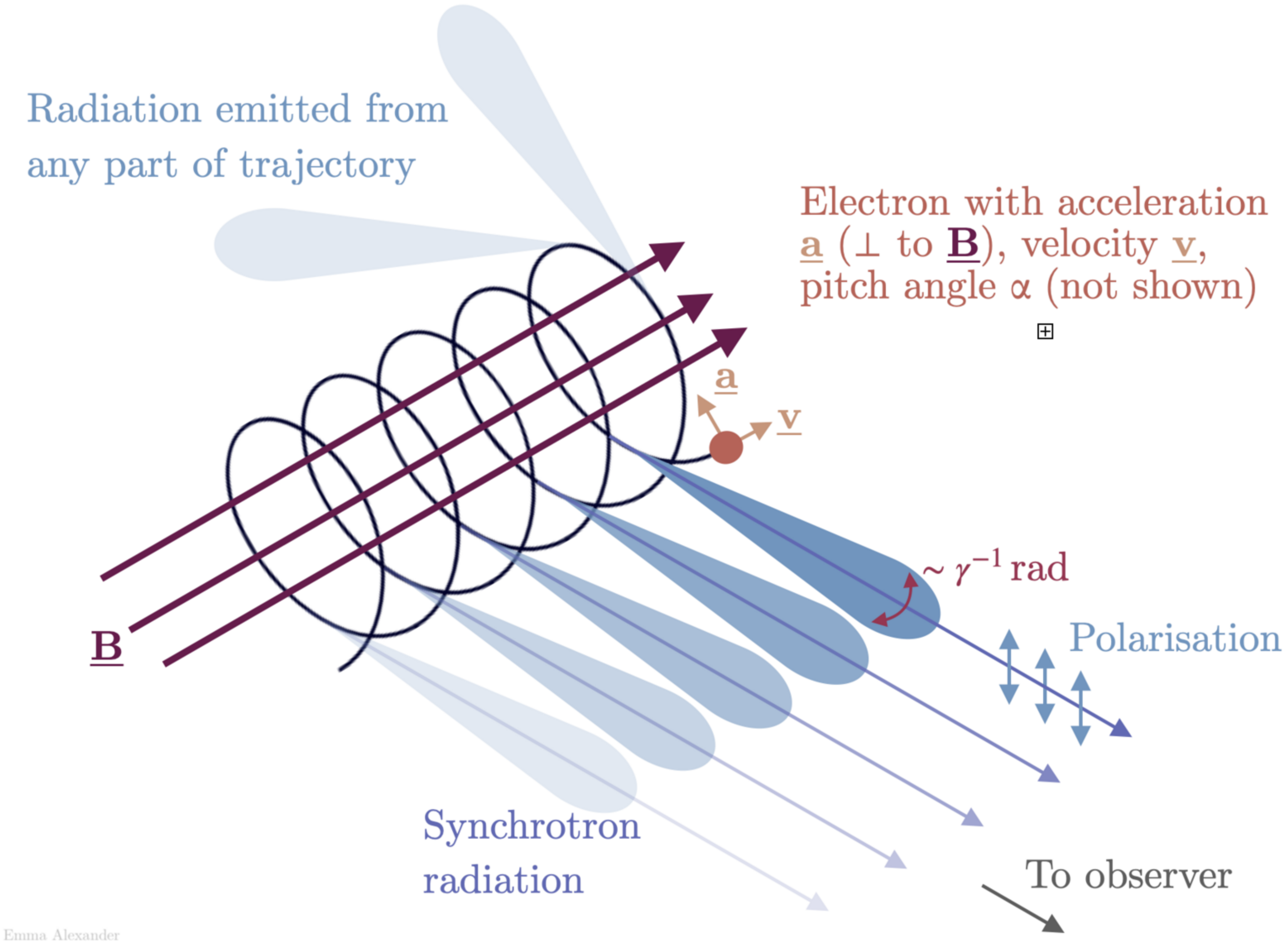
≫ 1 μG (ISM)

see Vink & Laming 2003, Parizot+ 2006

How are the magnetic fields amplified?
What is the geometry of magnetic fields?
Are they ordered or disordered?

Credit: NASA/CXC/SAO

Synchrotron emission (polarized) and Stokes parameters



Maximum polarization degree

$$p_{\max} = \frac{\alpha + 1}{\alpha + 7/3} \approx 70\,\%$$

for electron spectral index $\alpha = 2$

Stokes parameters (linear polarization)

$$\boxed{\begin{aligned} I &= S_0 = I \\ Q &= S_1 = Ip\cos 2\varphi \\ U &= S_2 = Ip\sin 2\varphi \end{aligned}}$$

I : Total intensity

φ (PA): Orientation of the polarization (polarization angle)

p (PD): Fraction of the polarization (polarization degree)

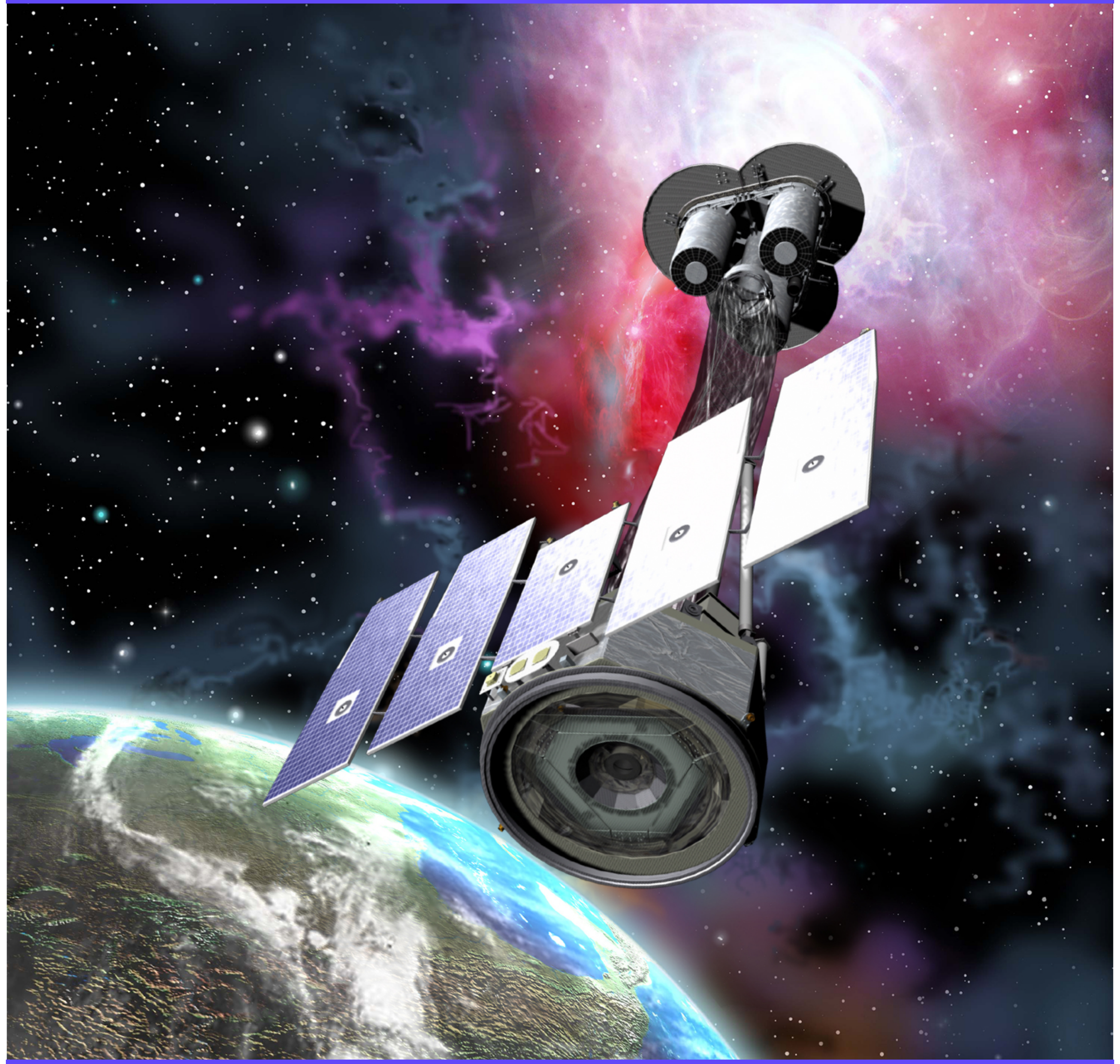
φ or PA $= 0.5\arctan(U/Q)$ ⊥ magnetic orientation

p or PD $= \sqrt{Q^2 + U^2}/I$ magnetic turbulence

X-ray polarimetry — a new frontier

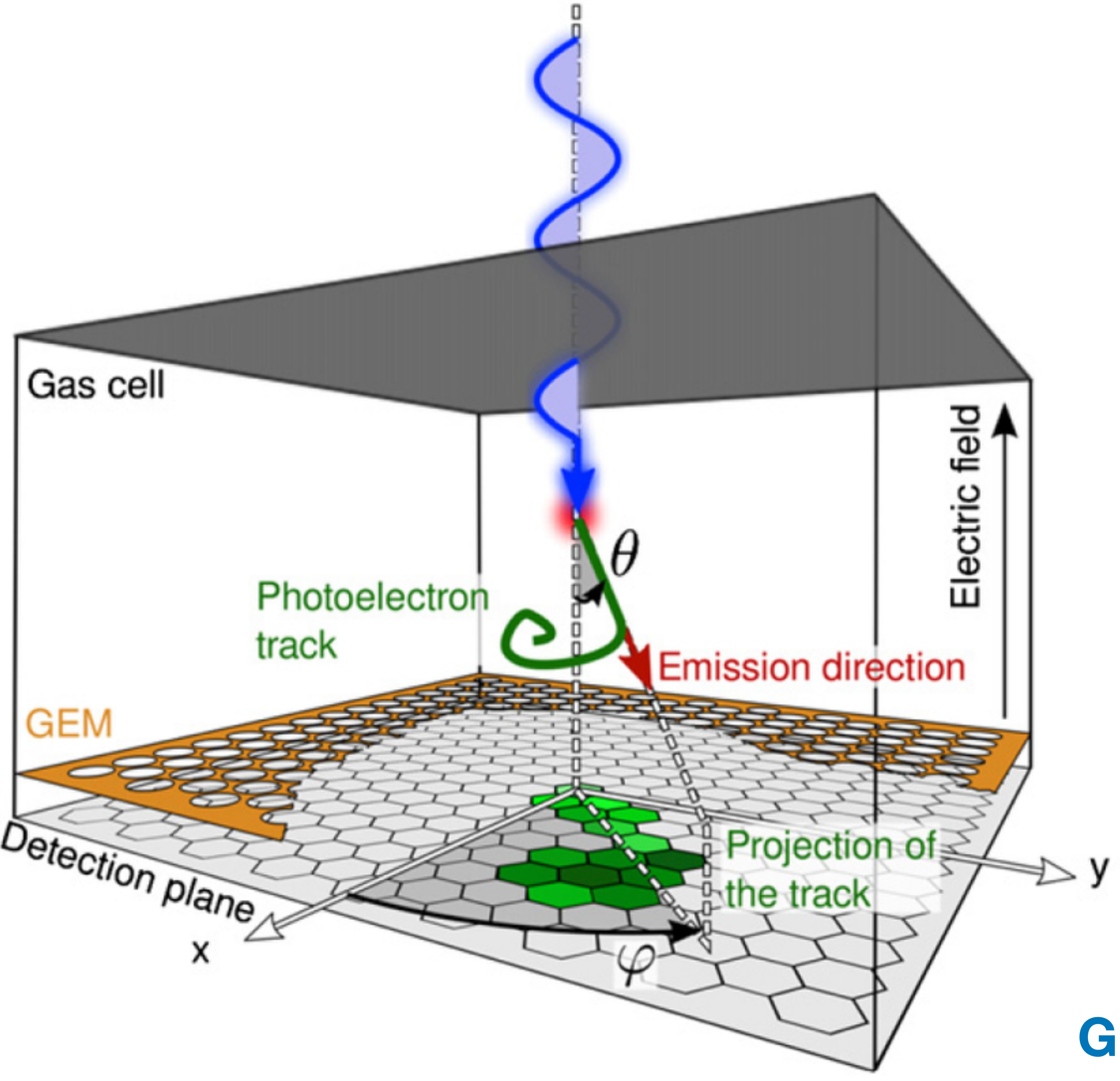
- X-ray polarimetry probes the electrons with the energy > TeV
- Measure B-field close to the shock front:
  $\tau_{\rm loss} = 637/(B^2E)$ s
- Free from Faraday depolarization

IXPE
(Imaging X-ray polarimetry explorer)



angular resolution <30”
2— 8 keV
field-of-view ~13’

Gas pixel detector — principle for X-ray polarimetry



Taverna & Turolla 2024

- Incoming X-ray photon —> photoelectrons
- Photoelectrons tend to follow the X-ray polarization direction

photoelectronic cross-section

$$\frac{d\sigma}{d\Omega} \propto \cos^2 \phi$$

ϕ — azimuth angle relative to the electronic field direction

- Photoelectron number reflects X-ray energy
- Photoelectron distribution as a function of φ gives PA and PD

GPD measures coordinates, E, t, PA and PD for every photon

6 young SNRs observed with IXPE

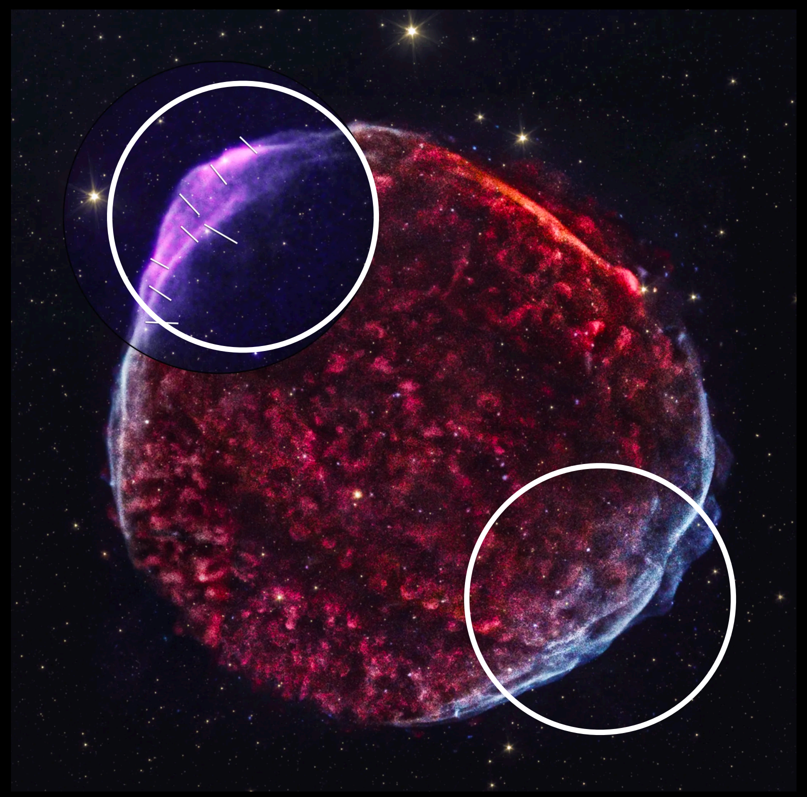
SN 1680?

Cas A
Vink + 2022

SN 1572

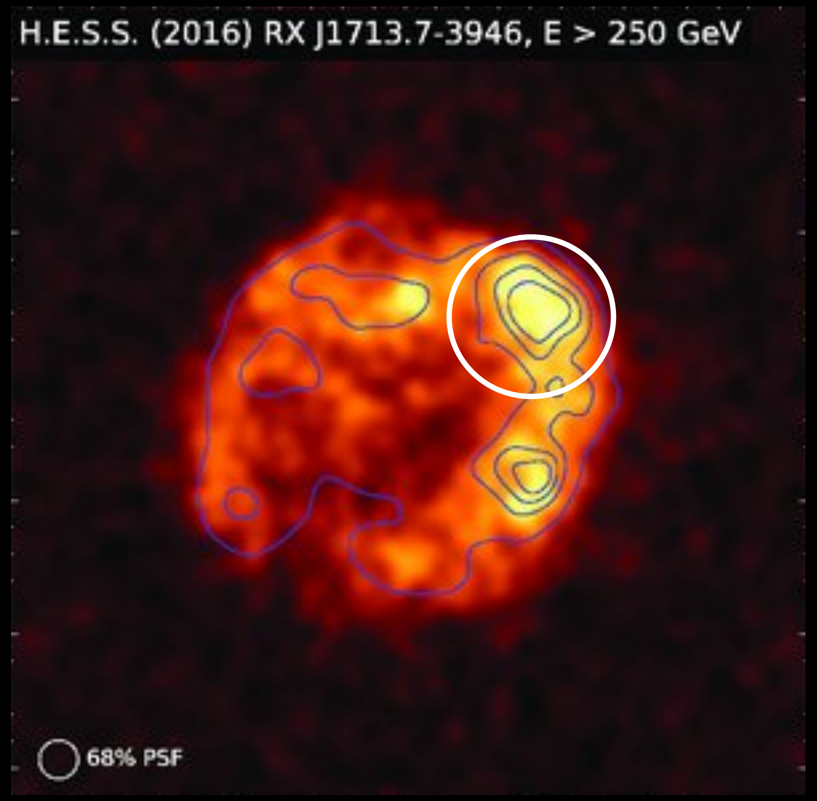
Tycho
Ferrazzoli + 2023

SN 1006



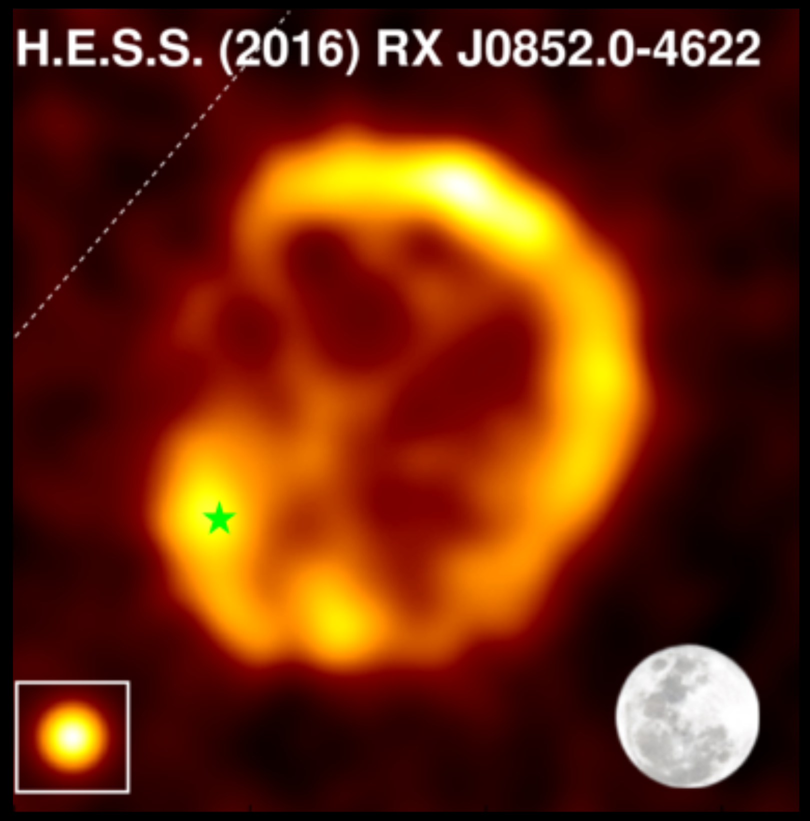
SN1006
Zhou + 2023, 2025

SN 393?



RX J1713.7-3946
Ferrazzoli + 2024

3000 yr



Vela Jr.
Prokhorov + 2024

SN 185

RCW86
Silvestri + in prep.

~1 Ms for each pointing

Credits:
Cas A: NASA/CXC/SAO/IXPE

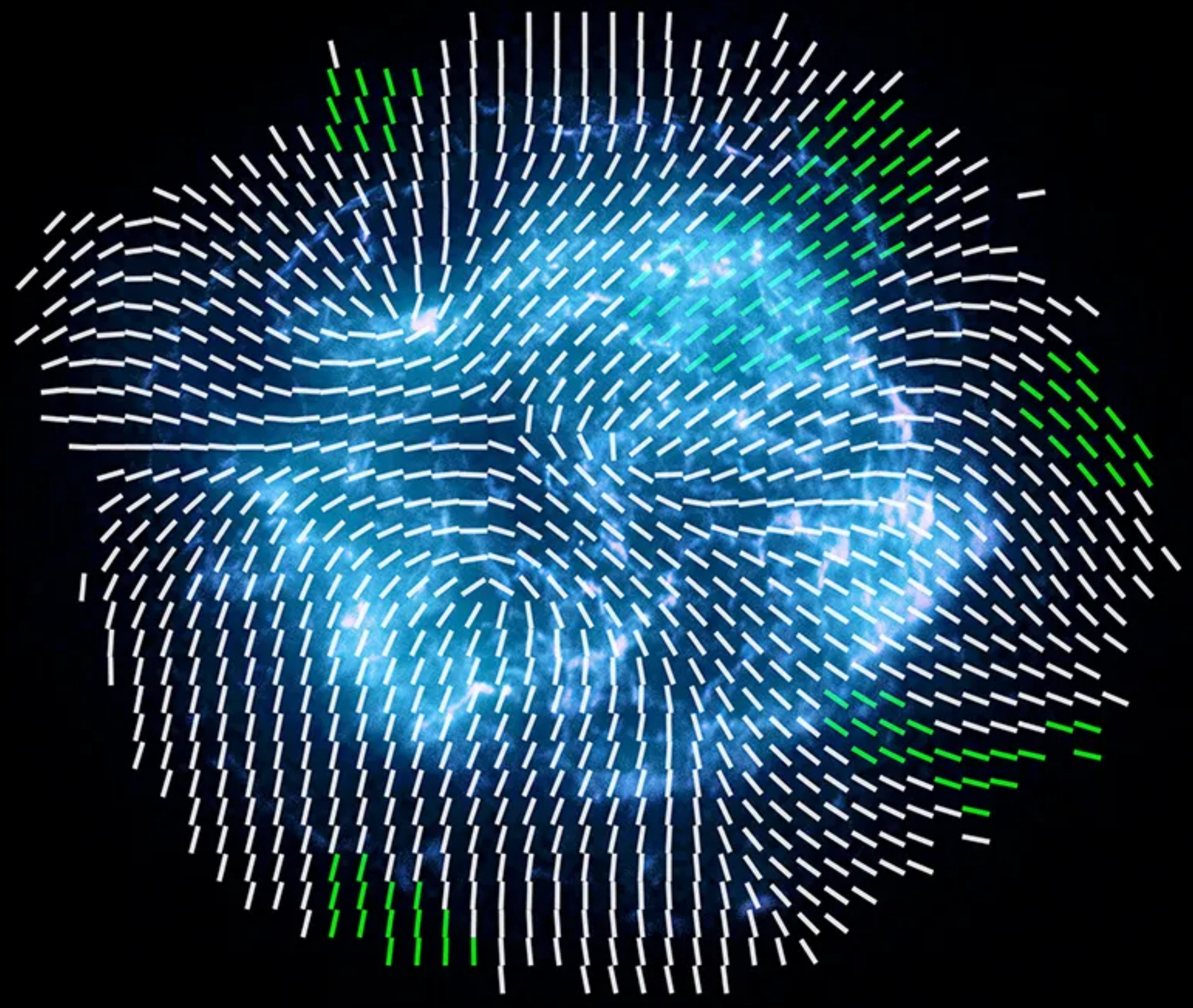
Tycho : X-ray (IXPE: NASA/ASI/MSFC/INAF/R. Ferrazzoli, et al.), (Chandra: NASA/CXC/RIKEN & GSFC/T. Sato et al.) Optical: DSS Image processing: NASA/CXC/SAO/K. Arcand, L.Frattare & N.Wolk

SN 1006 X-ray: NASA/CXC/SAO (Chandra); NASA/MSFC/Nanjing Univ./P. Zhou et al. (IXPE); IR: NASA/JPL/CalTech/Spitzer; Image Processing: NASA/CXC/SAO/J.Schmidt

RCW 86: Sjors Broersen

IXPE’s first science target — Cas A

Magenta — IXPE image (resolution ~ 30”)
Blue — Chandra image (resolution ~0.5”)



Magnetic vectors over X-ray image
green: highly significant region

Low PD in Cas A

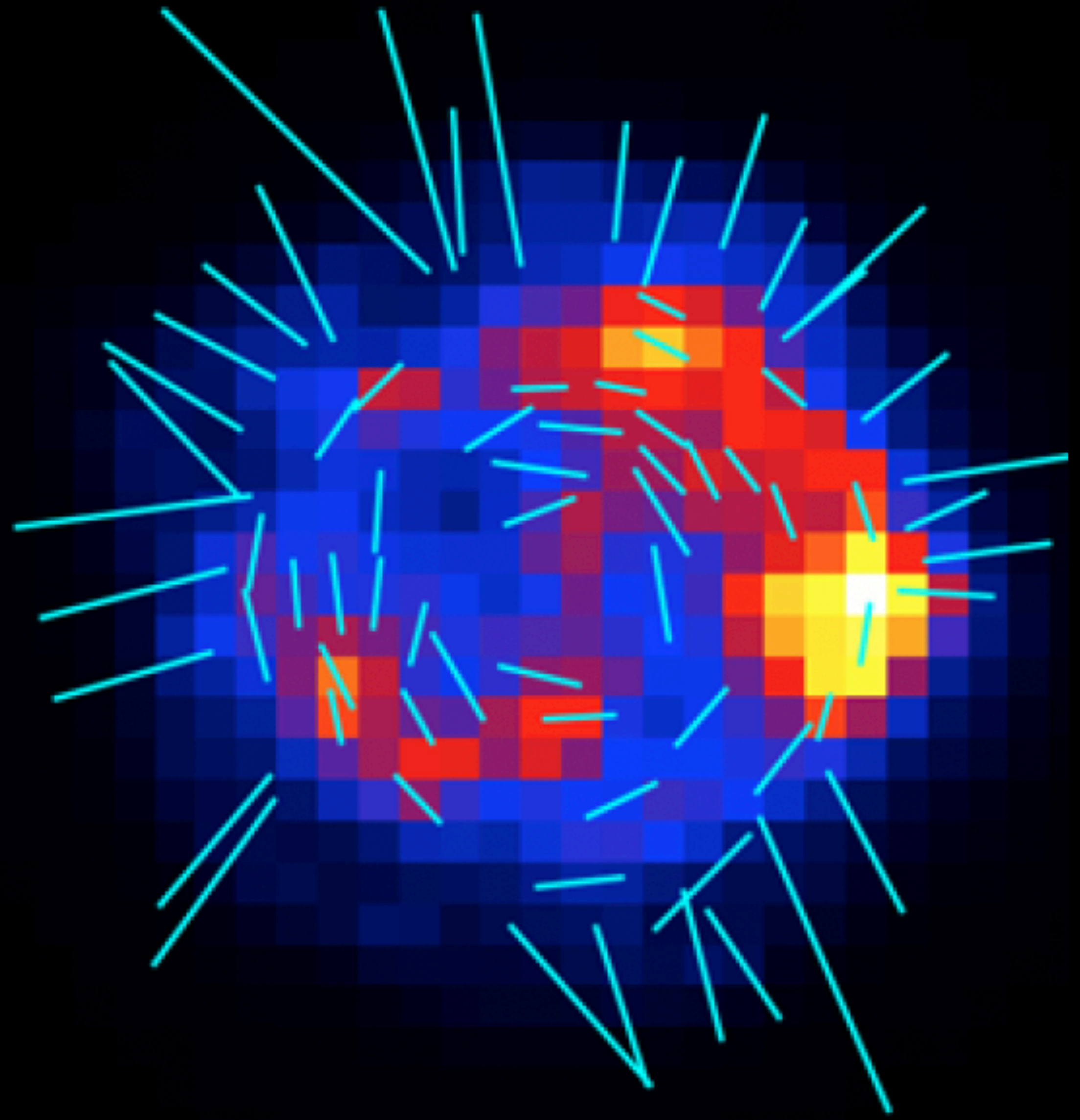
Average PD $= 2.5\% \pm 0.5\,\%$ for the SNR (5σ)

Average PD $= 4.5\% \pm 1.0\,\%$ at the rim
(radio PD ~8—10%)

Highly turbulent B!—> Low PD

Magnetic fields are almost radially distributed.
(B//shock normal)

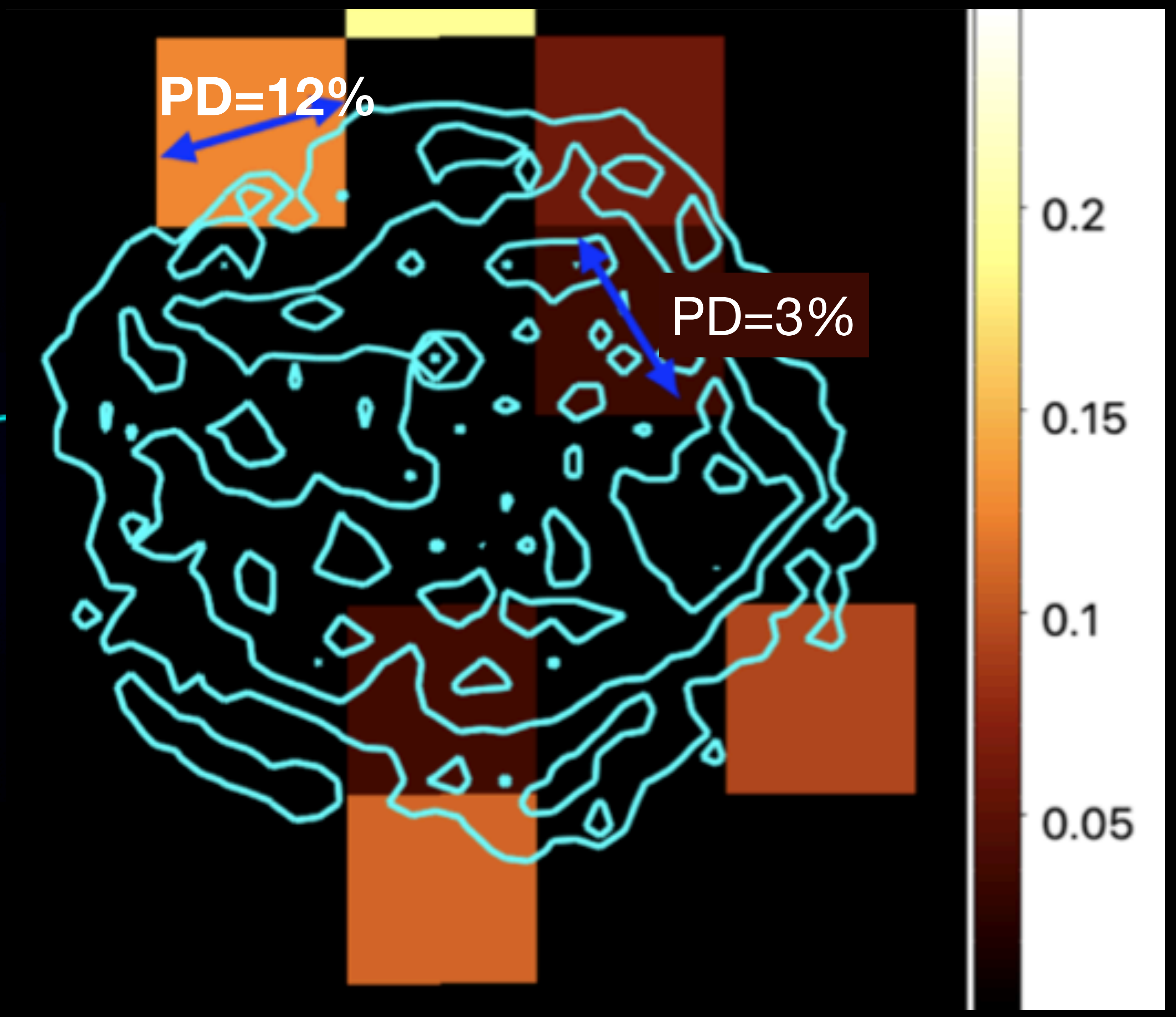
卖家秀



Predicted image before the launch of IXPE
Vink & Zhou 2018

买家秀

Polarization degree + E vectors

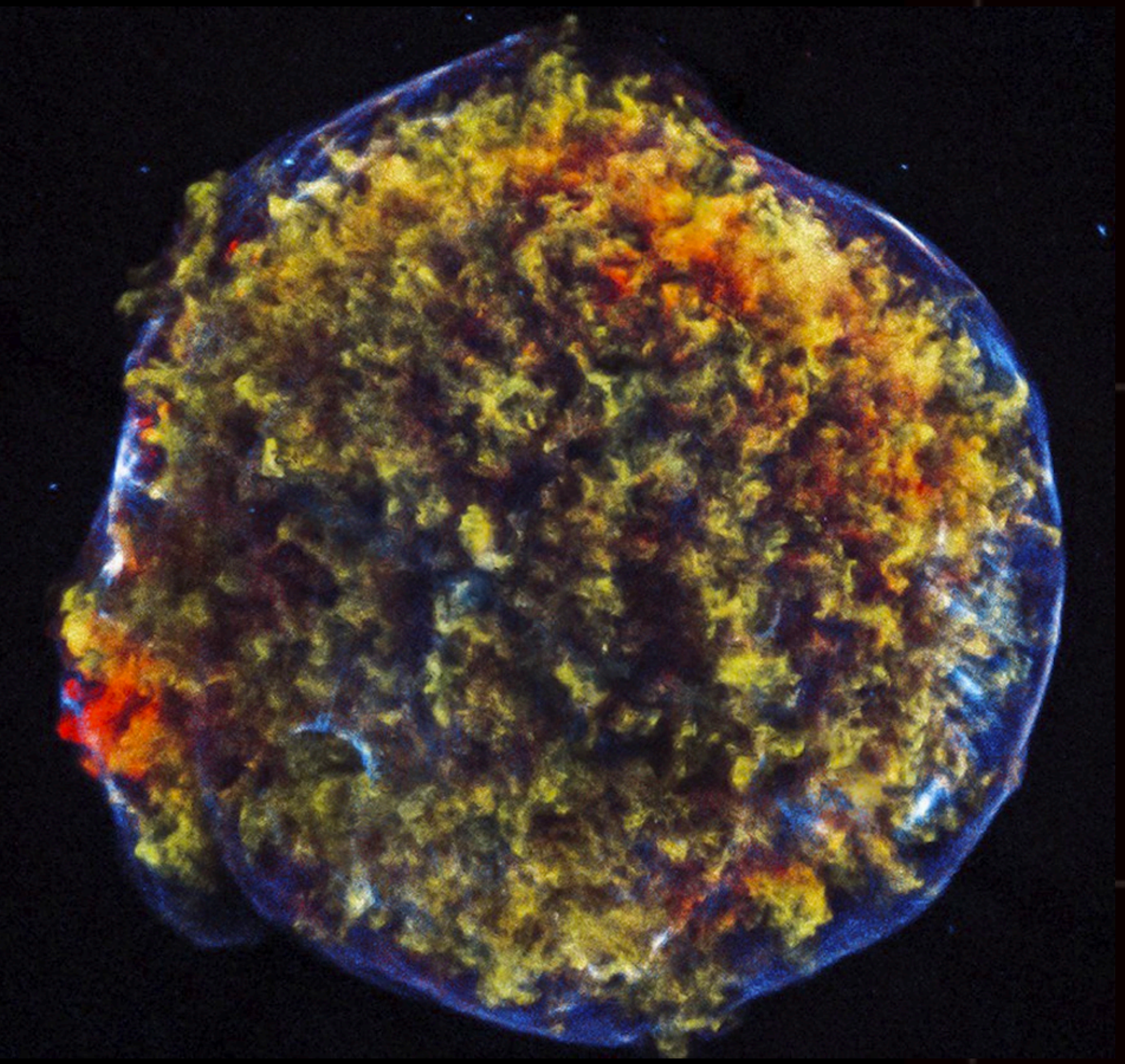


3—6 keV
pixels >2 σ, vectors> 3σ, pixel size =84”

Vink+2022

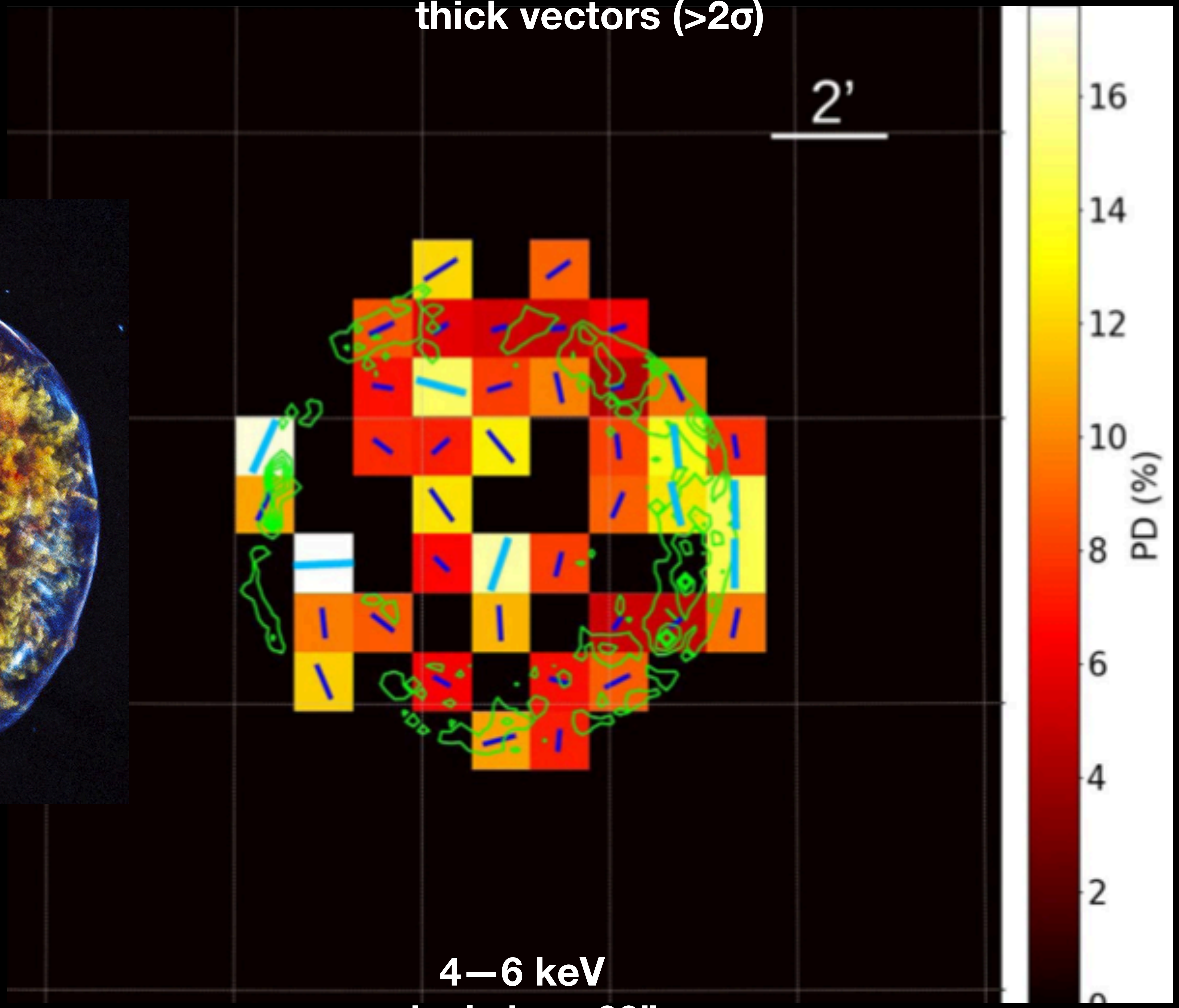
IXPE observation of Tycho (SN 1572)

Chandra X-ray image



Credit: NASA/CXC/SAO

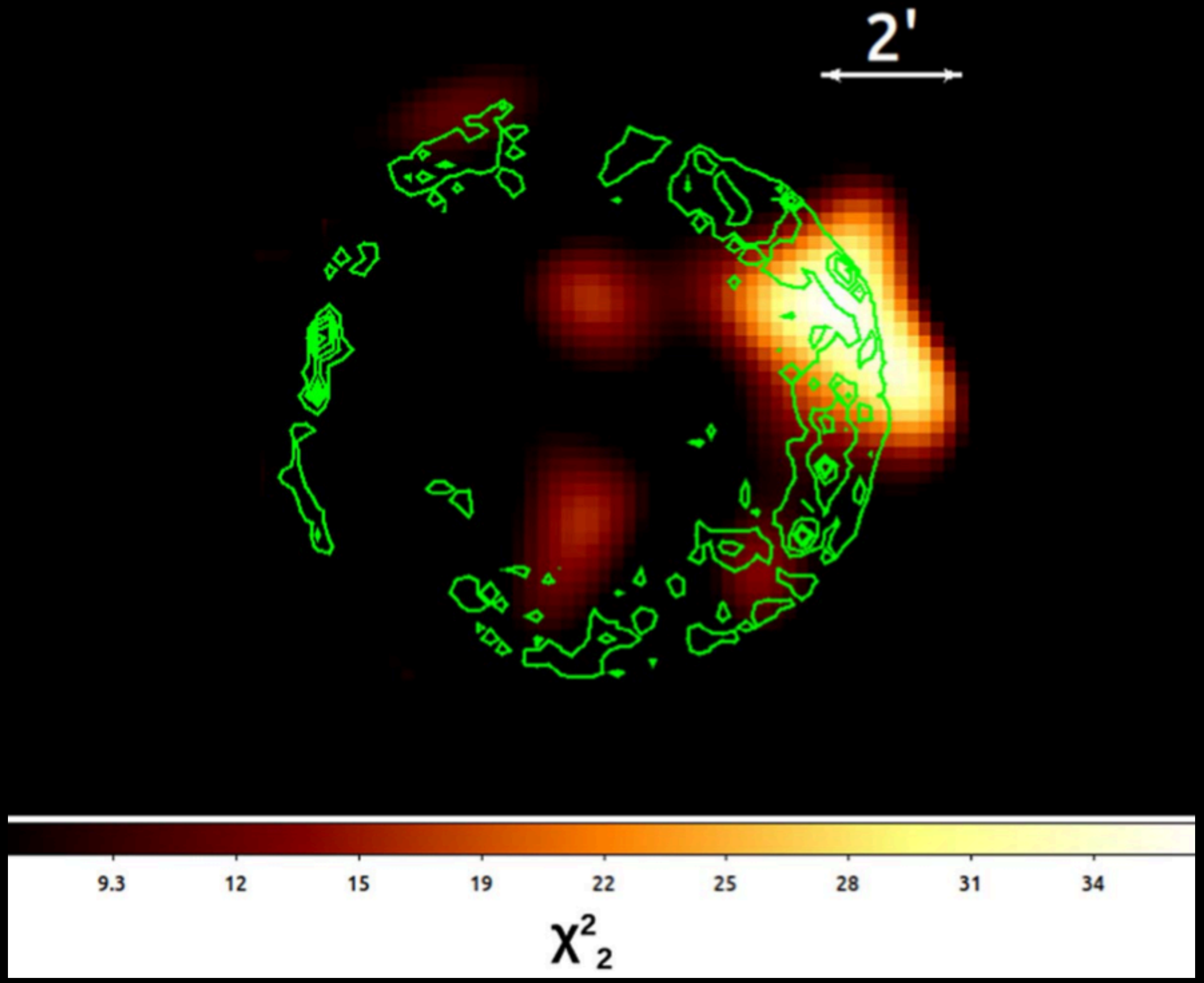
polarization degree and vectors (>1σ)
thick vectors (>2σ)



4—6 keV
pixel size =60”

Ferrazzoli + 2023

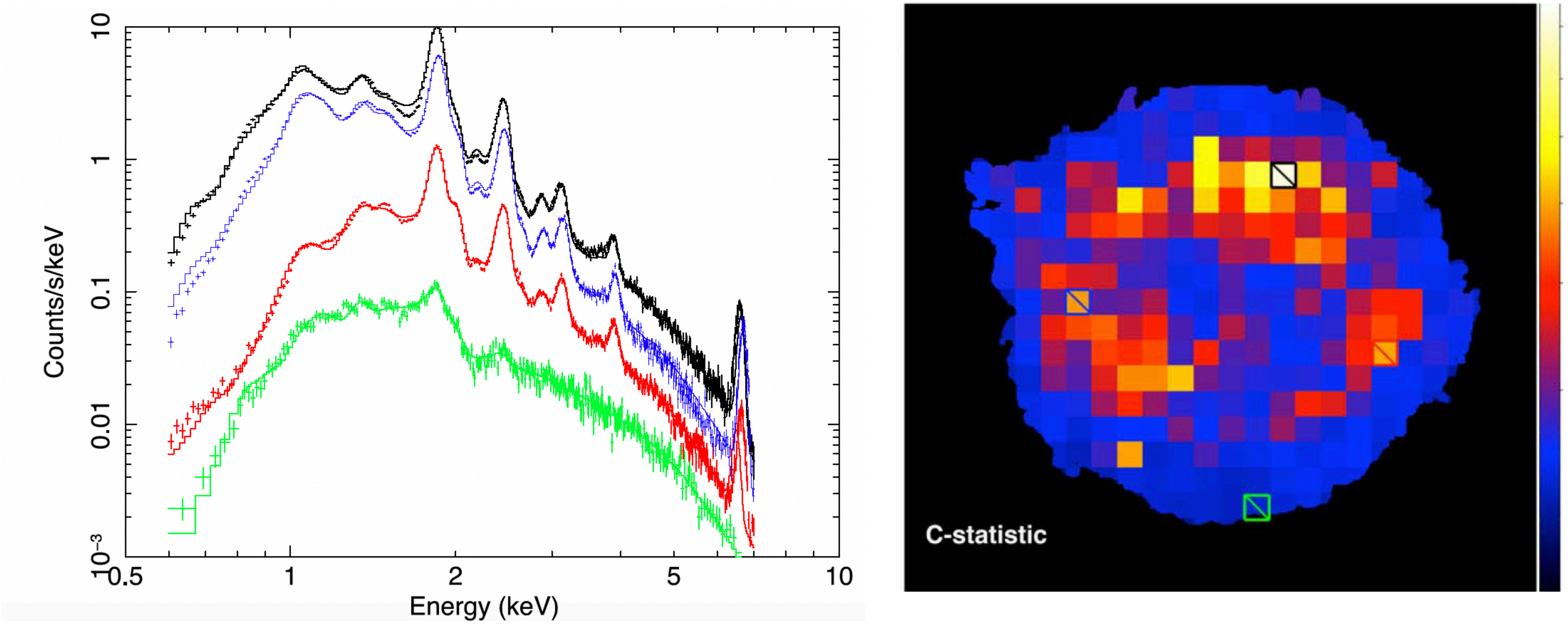
significance map



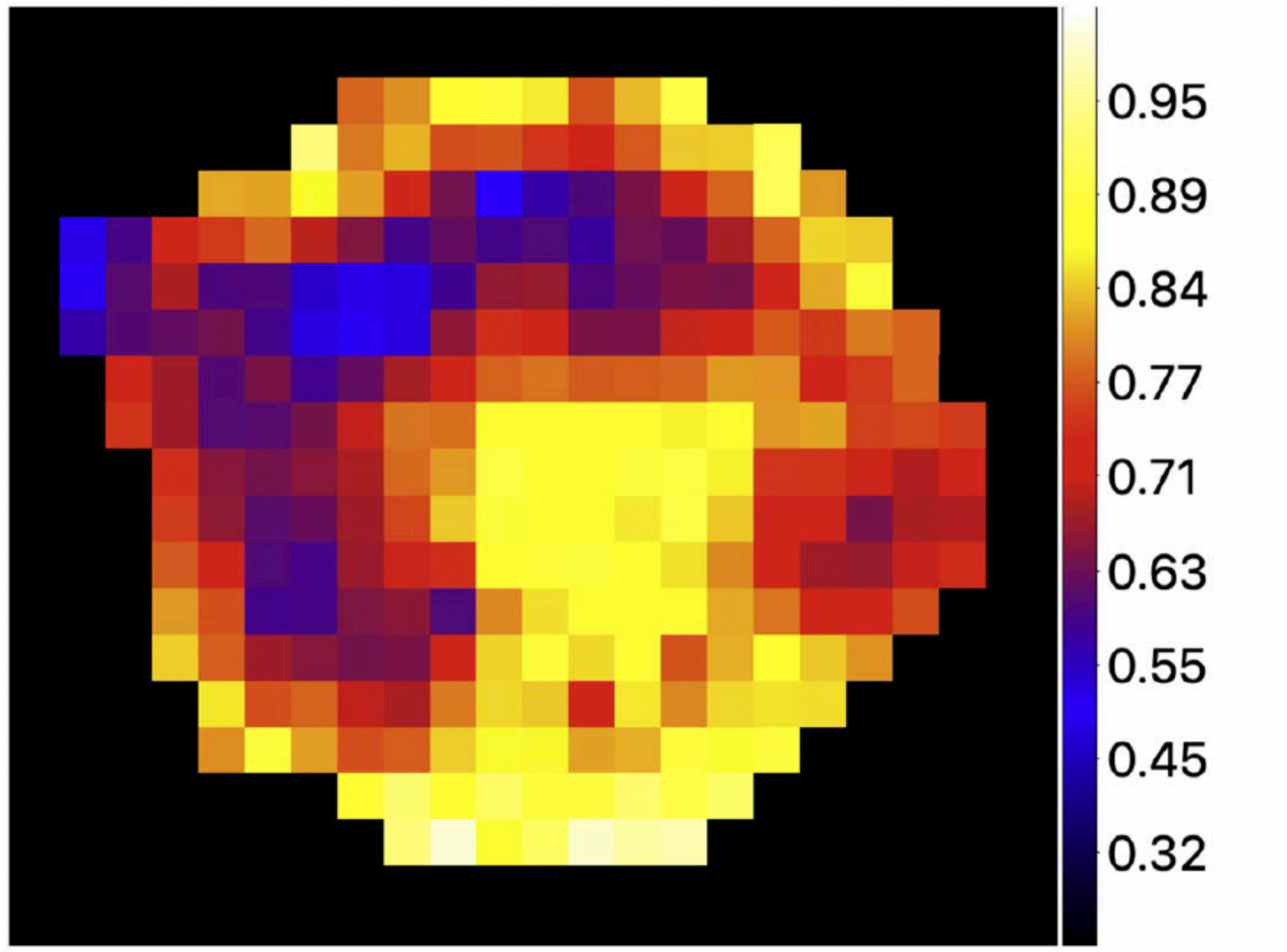
Average PD of the SNR ~ 9%
Average PD at the rim ~ 12%
Peak PD~20% at the NW
Magnetic field is radially distributed

Extract nonthermal flux from Cas A and Tycho

Fit Chandra X-ray spectra with thermal+nonthermal models



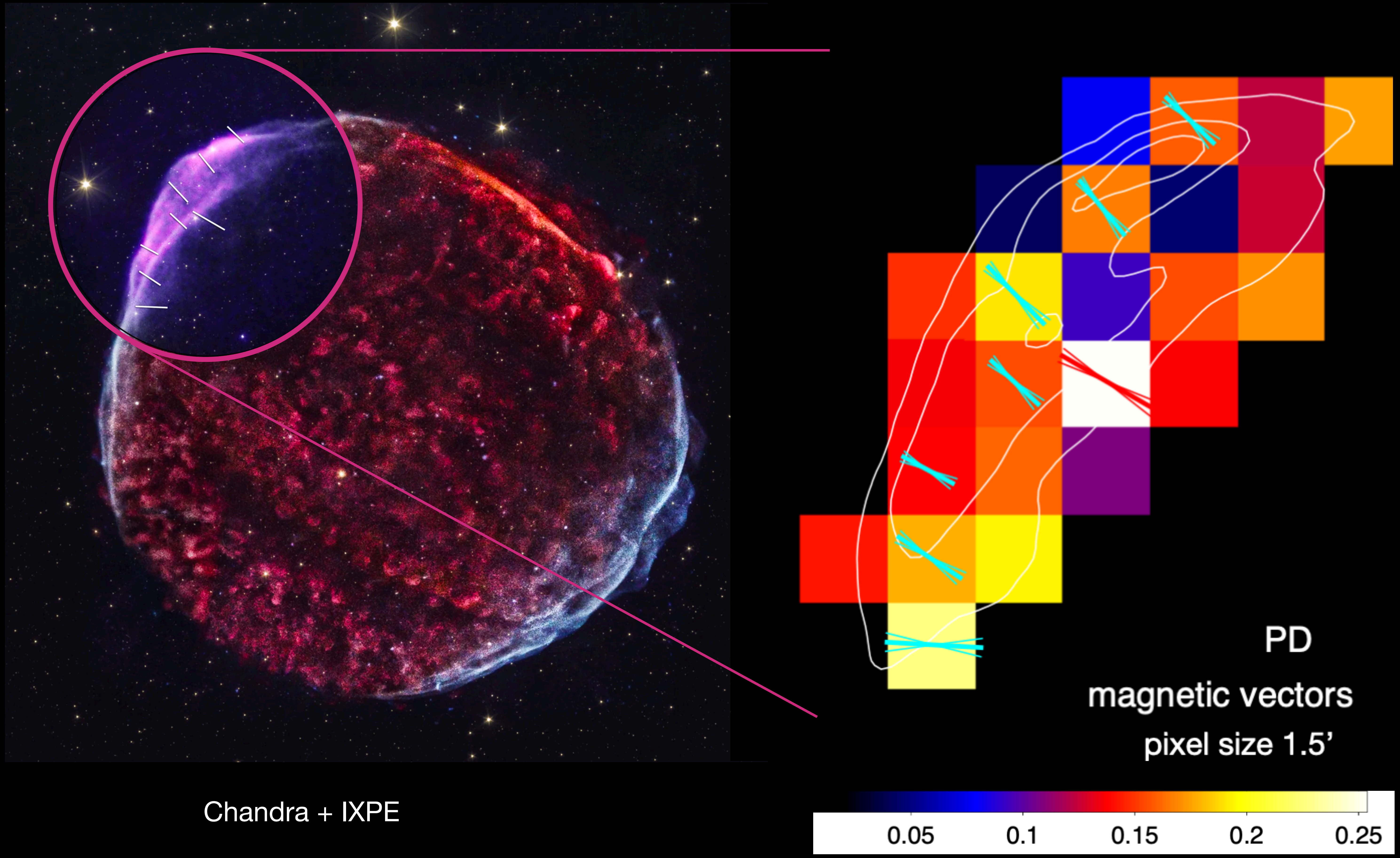
Nonthermal flux fraction in 3—6 keV



Vink + 2022

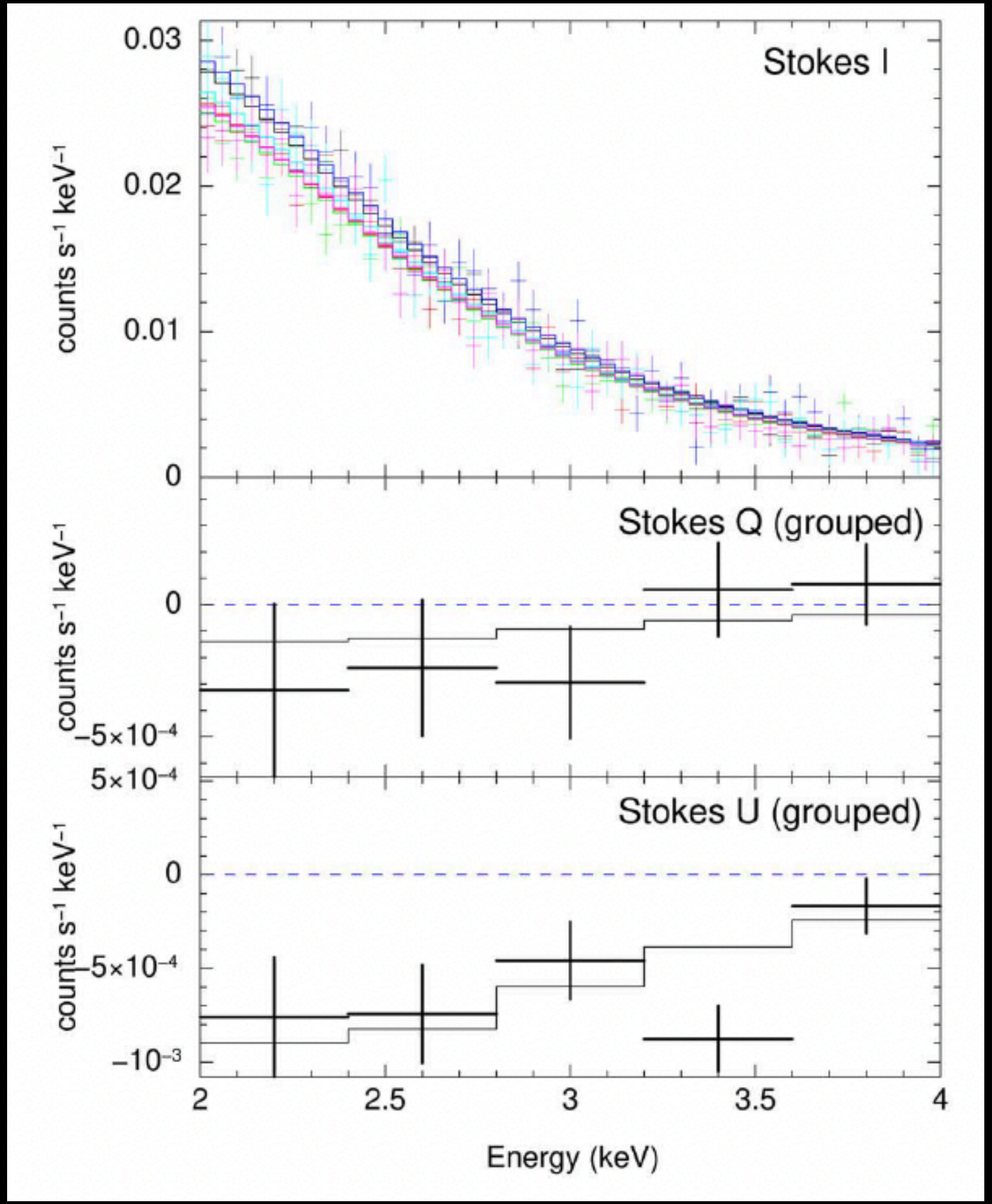
IXPE observation of SN 1006

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



Chandra + IXPE

Spectropolarimetric analysis

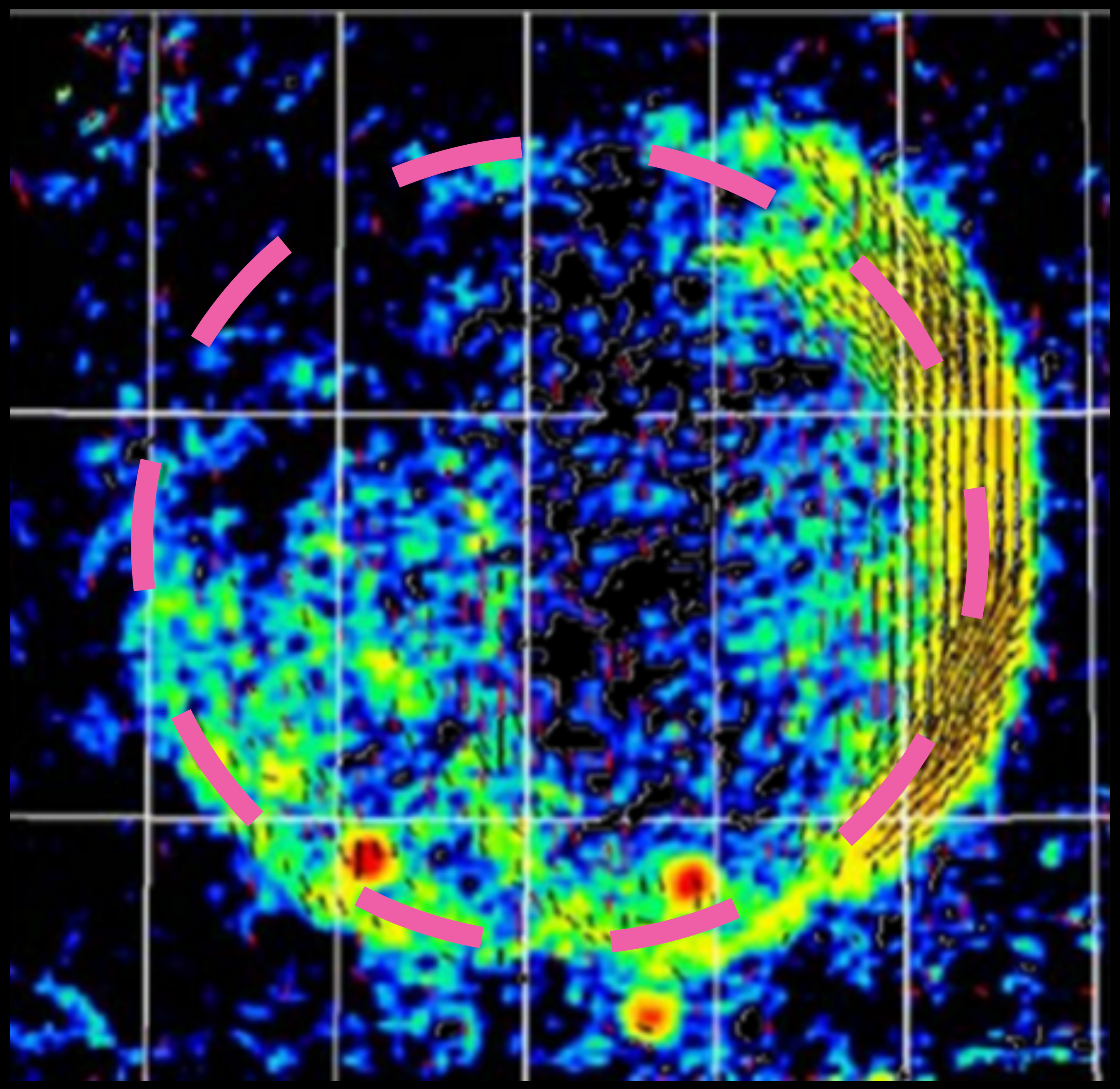


Zhou + 2023

Different magnetic properties between young and old SNRs

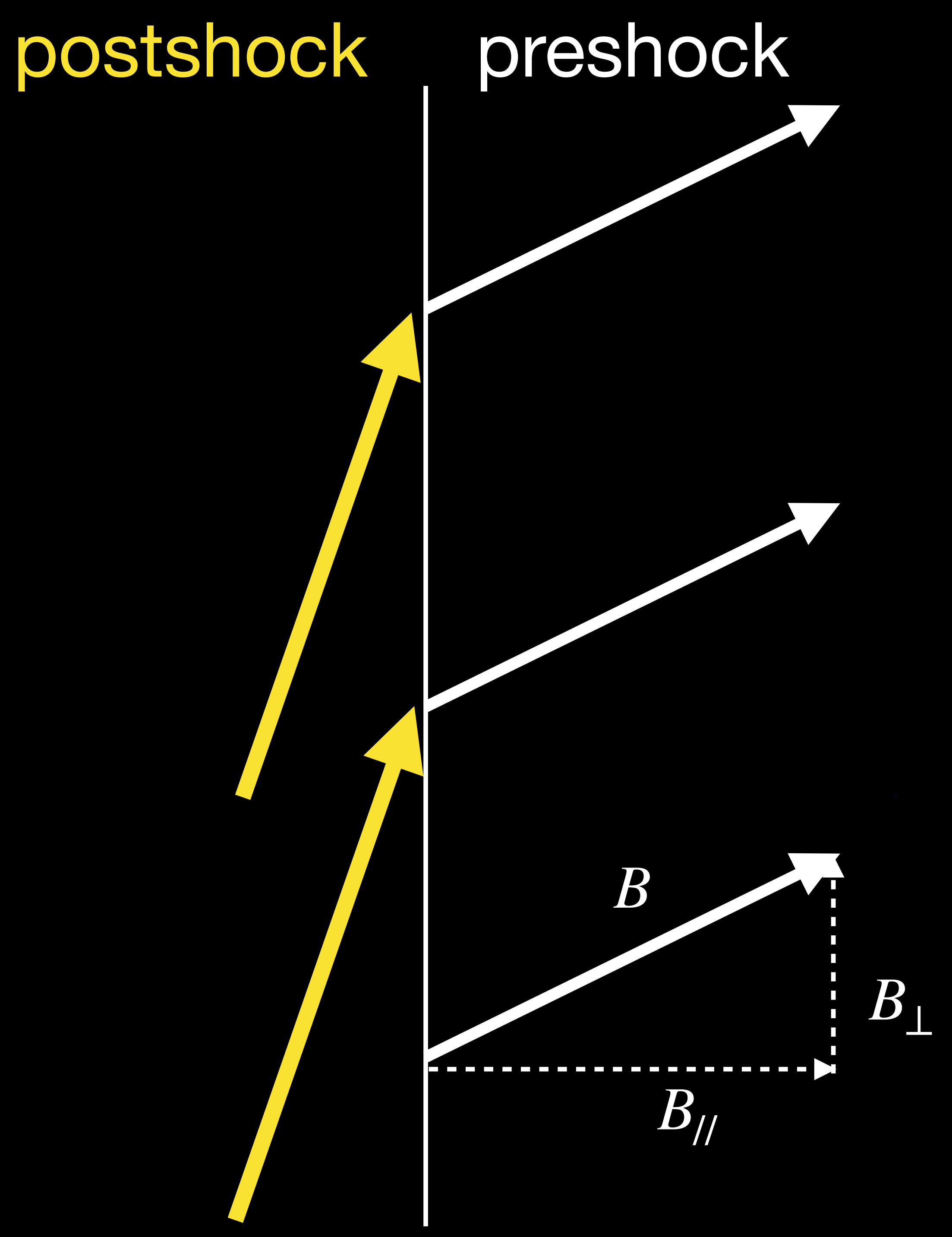
old SNRs

B ⊥ shock direction



CTA 1 + magnetic vectors (Radio; Dubner & Giacani2015)

B orientation due to a compression of the ISM

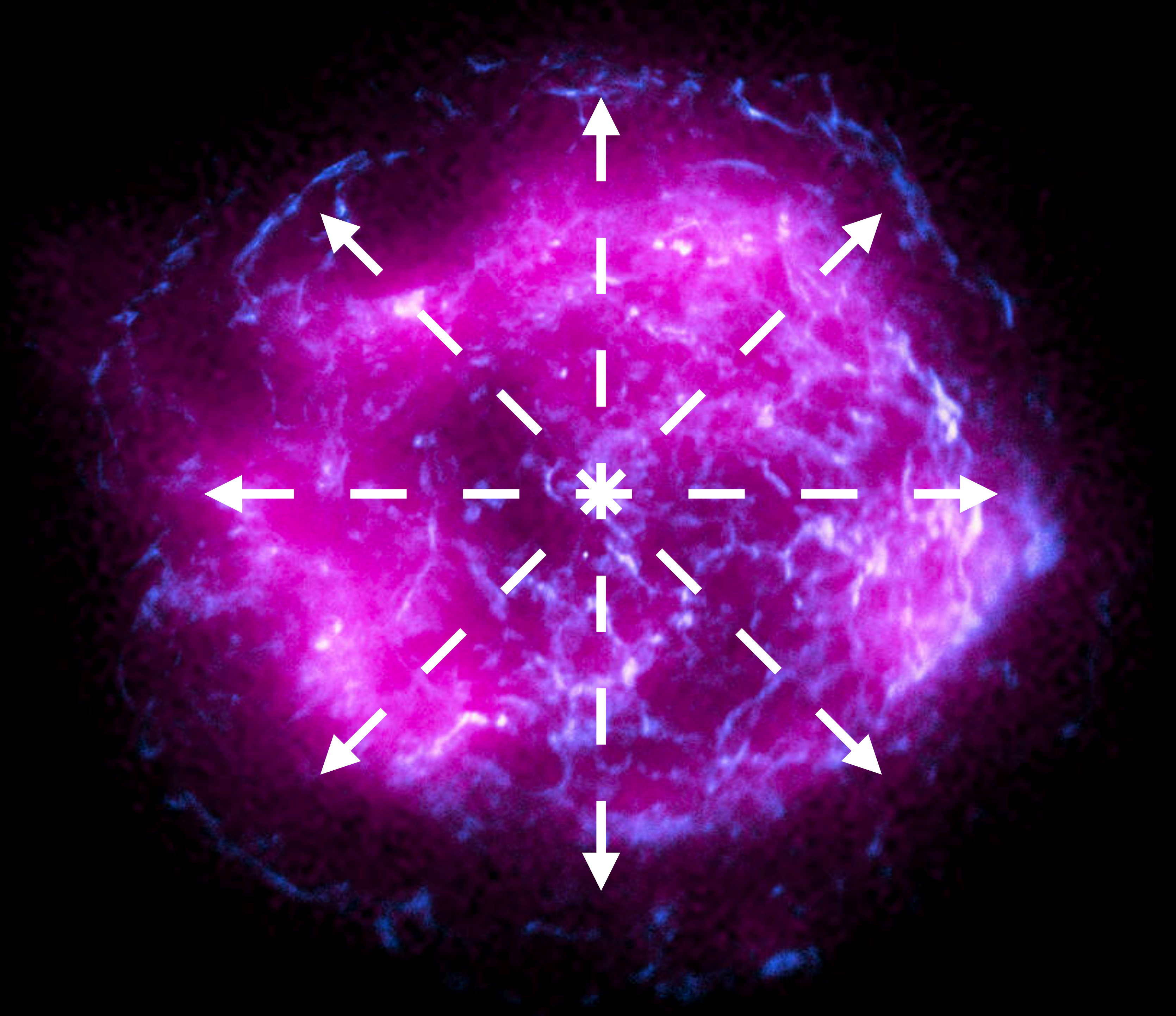


$B_{//}$ (postshock)=$B_{//}$ (preshock)

$B_\perp$ (postshock)=$4B_\perp$ (preshock)

3 Young SNRs

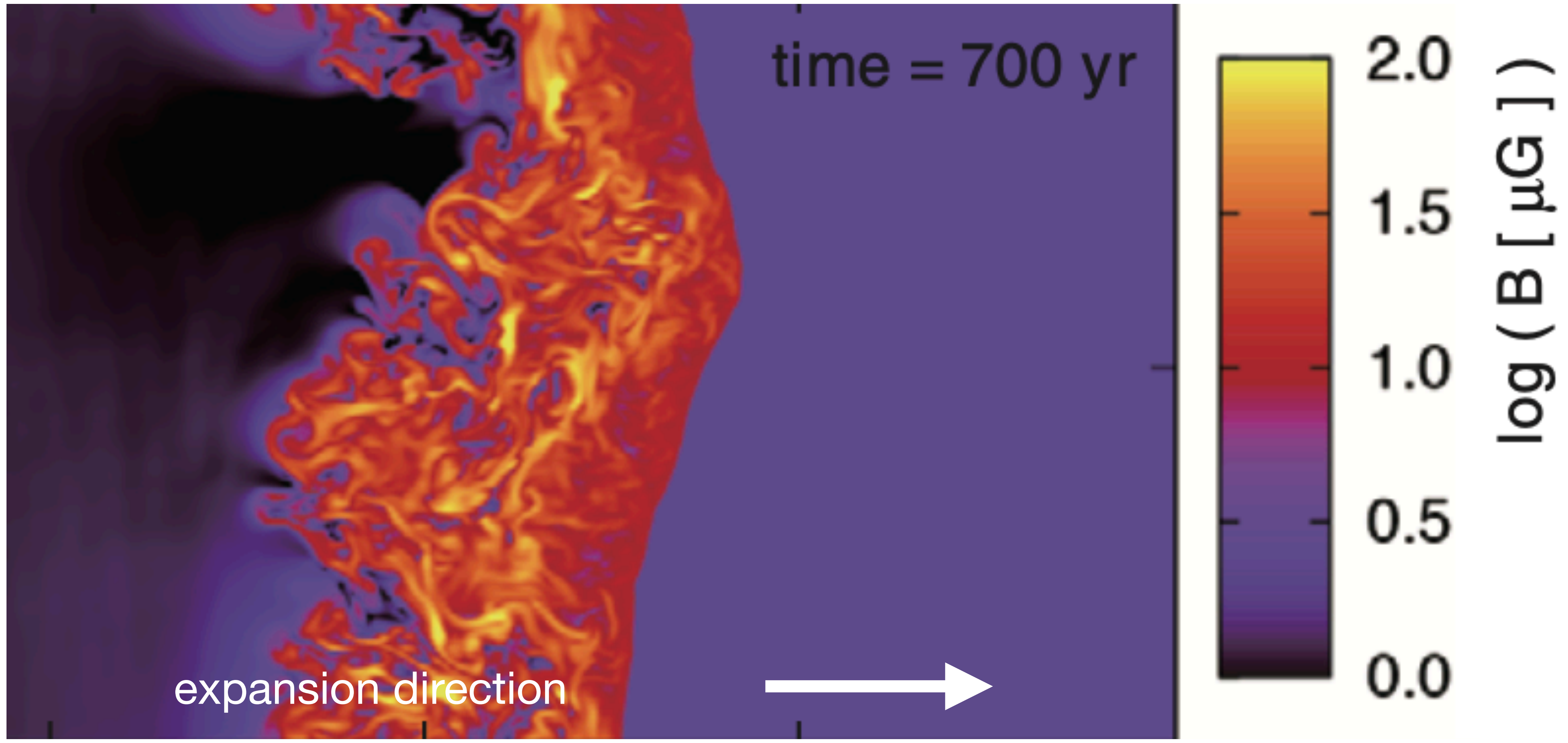
B // shock direction



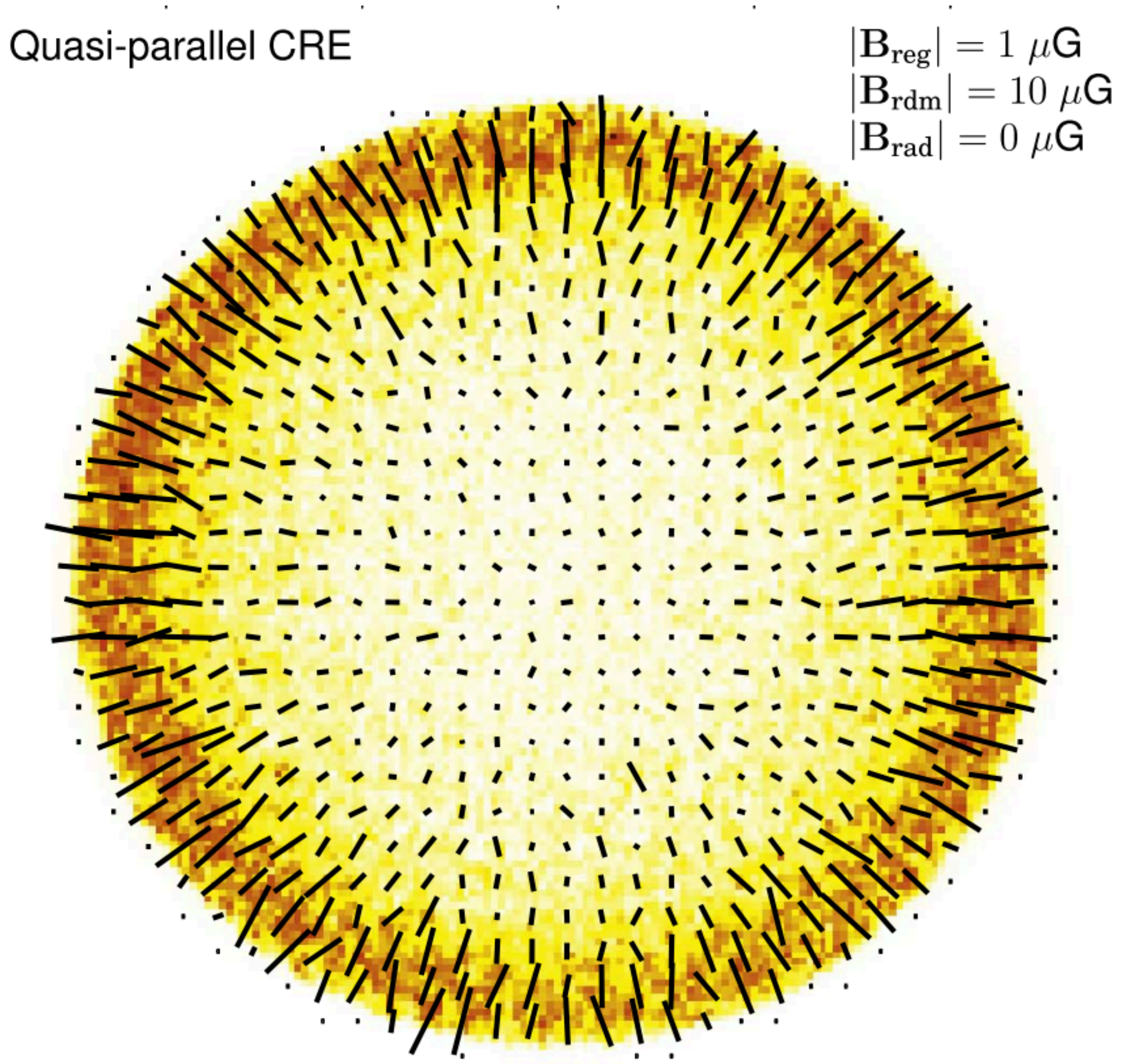
Why radially distributed B in young SNRs

MHD turbulence can stretch the fields

Selection effect efficient acceleration of CRs when shock // B
(higher density of CRs —> stronger emission; a.k.a., quasi-parallel acceleration)



Inoue+2013

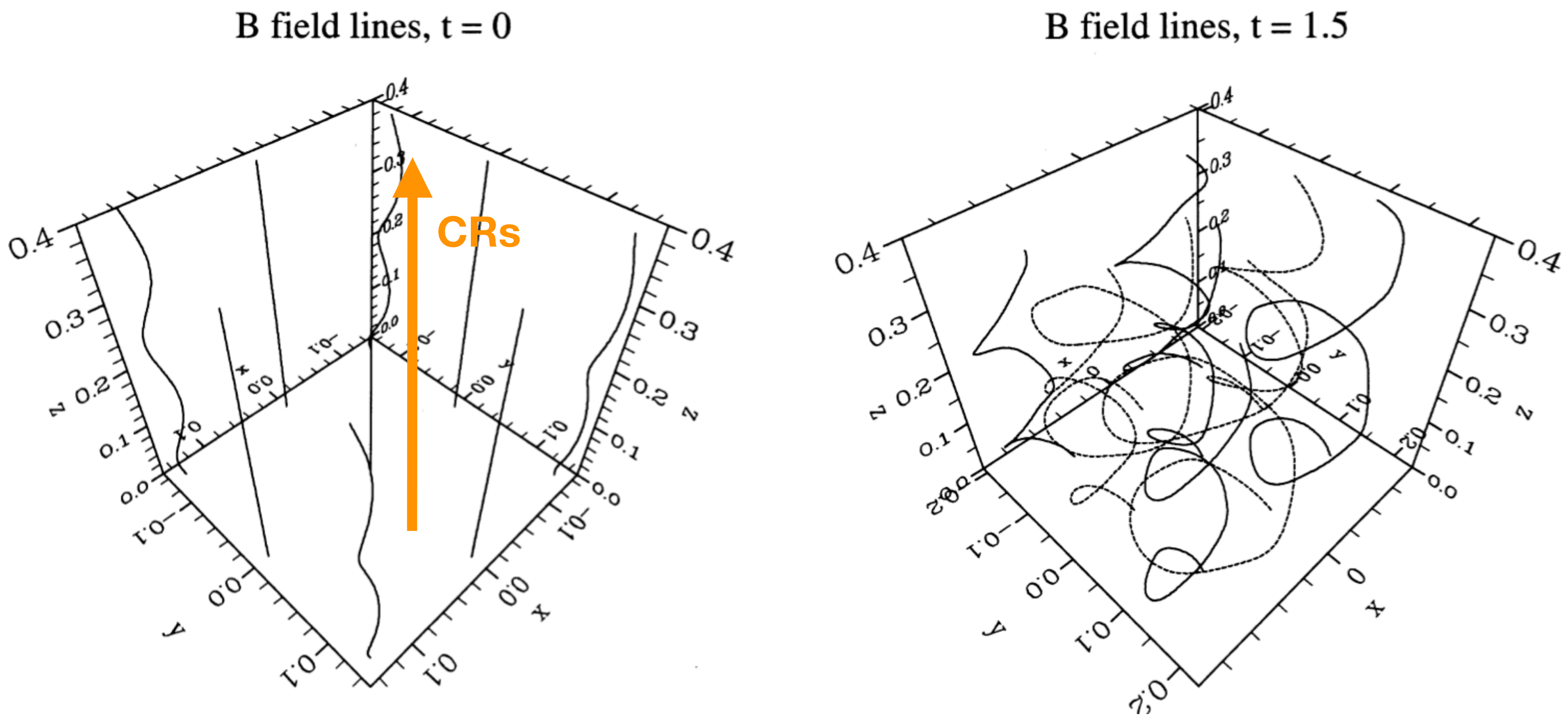


West + 2017

Mechanisms for turbulent magnetic amplification

a. CR-induced instability

(Bell 2004)



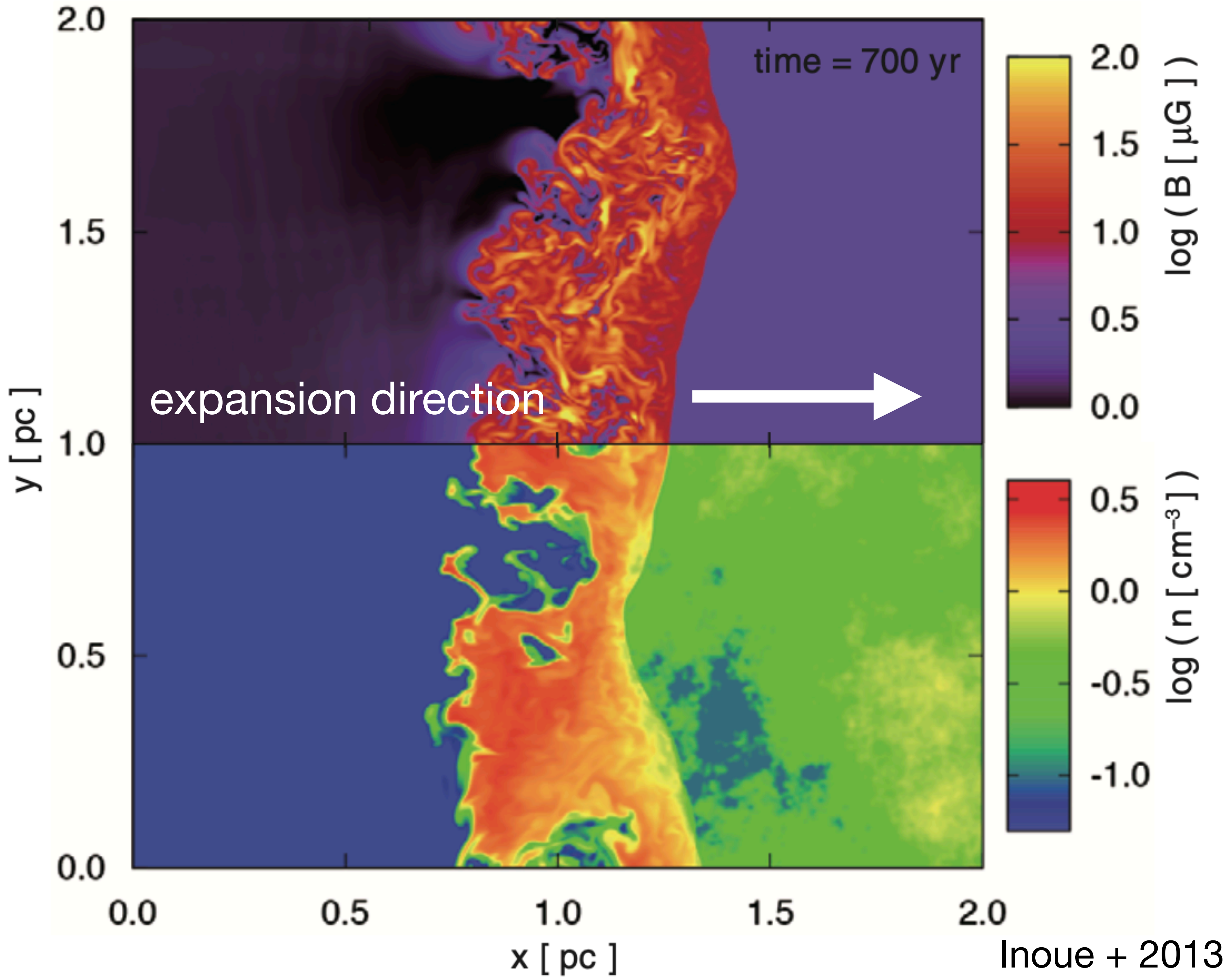
Lucek & Bell 2000

- CR energy is transferred to perturbed magnetic fields

  (predicted for the pre-shock region, unclear for the post-shock)

b. turbulent dynamo due to density fluctuation

(Giacalone & Jokipii 2007, Inoue+2013, Xu & Lazarian 2017)



Inoue + 2013

- highly depends on the density fluctuation level $\Delta\rho/\rho$ and scale $l_{\Delta\rho}$
- tends to create radial magnetic fields

PD and turbulence scales in young SNRs

			length scale of CR-induced instability	length scale of turbulent dynamo
	PD (rim) (%)	n_0 (cm^{-3})	l_{Bell} (cm)	$l_{\Delta B} \sim l_{\Delta\rho}$ density fluctuation scale
Cas A	4.5 ± 1.0	0.9 ± 0.3	8e16	√
Tycho	12 ± 2	~ 0.1–0.2	3e16	√
SN 1006 NE	22.4 ± 3.5	~ 0.05–0.085	2e17	X since SN 1006 NE in a nearly uniform medium

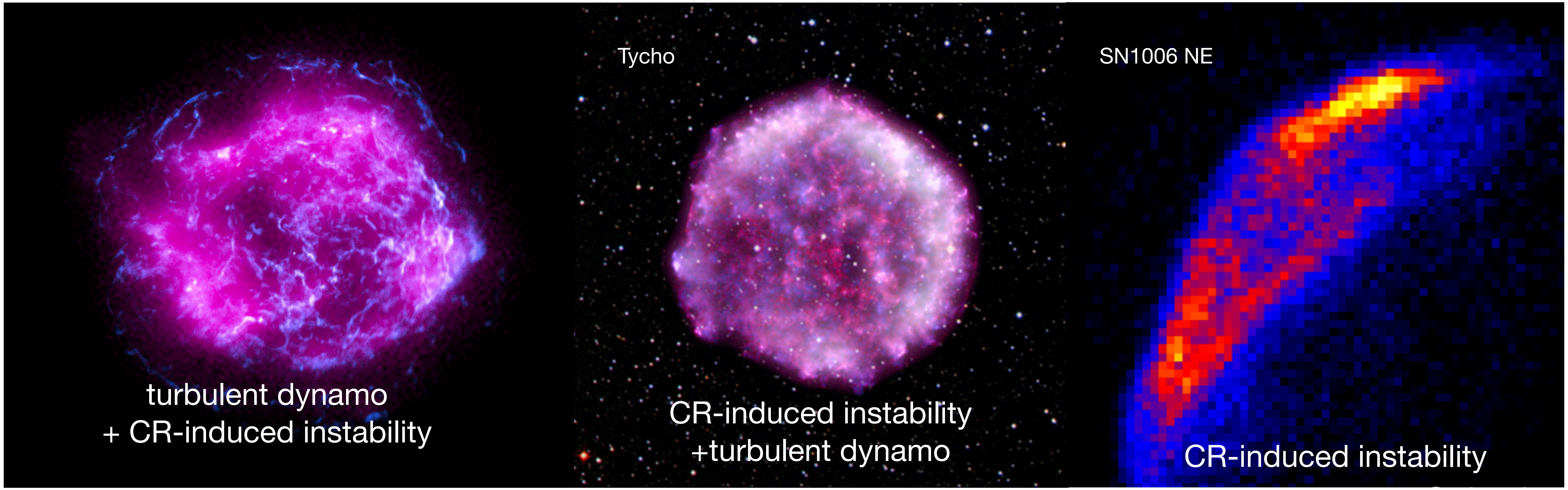
The turbulence scales are not resolved with IXPE(resolution of ~ 10^{18} cm at 2 kpc)

This can cause a depolarization

$$l_{\text{Bell}} \sim 2 \times 10^{17}\ \text{cm} \left(\frac{V_s}{5000\ \text{km/s}}\right)^{-3} \left(\frac{n_0}{0.05\ \text{cm}^{-3}}\right)^{-1} \left(\frac{E_{\text{max}}}{100\ \text{TeV}}\right) \left(\frac{B_0}{3\ \mu\text{G}}\right)$$

Bell 2004

Magnetic turbulence is environment-dependent



density fluctuation $\Delta\rho/\rho$

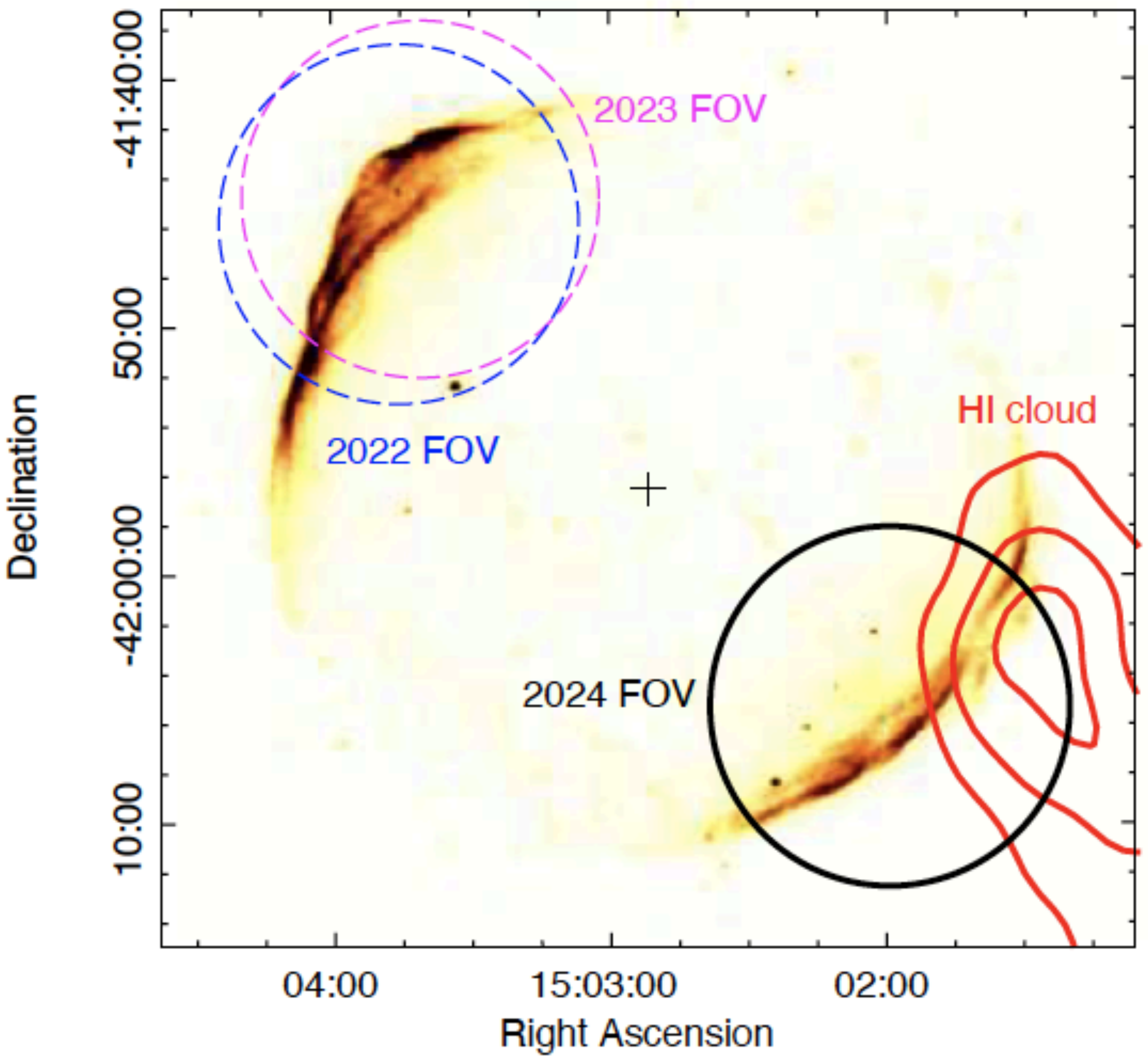
←

turbulent dynamo

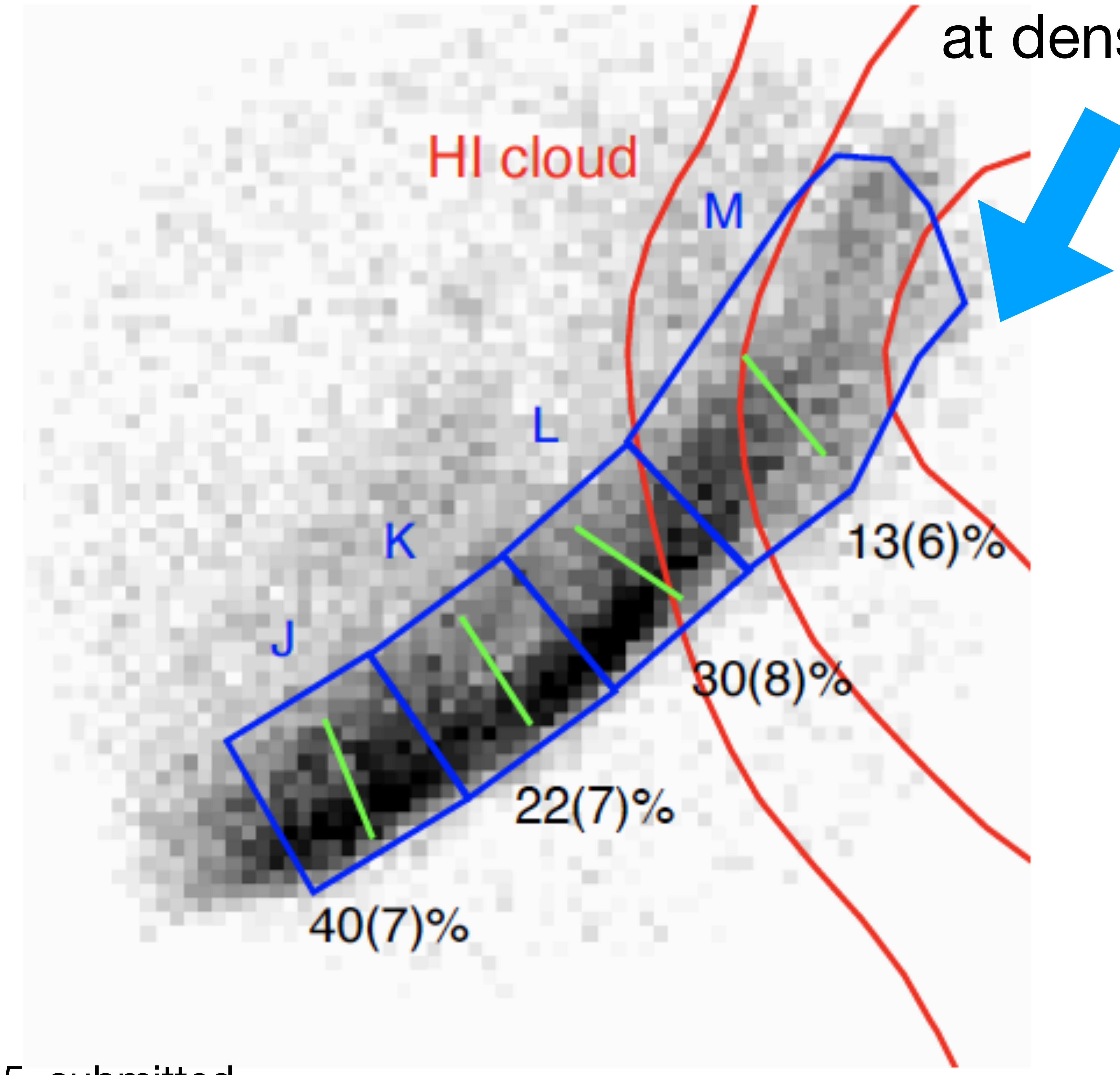
Can we justify this for a single SNR?

SN 1006 SW shows a variation of PD

XMM-Newton image + IXPE FOVs



Lower PD
at denser region



Zhou+ 2025, submitted

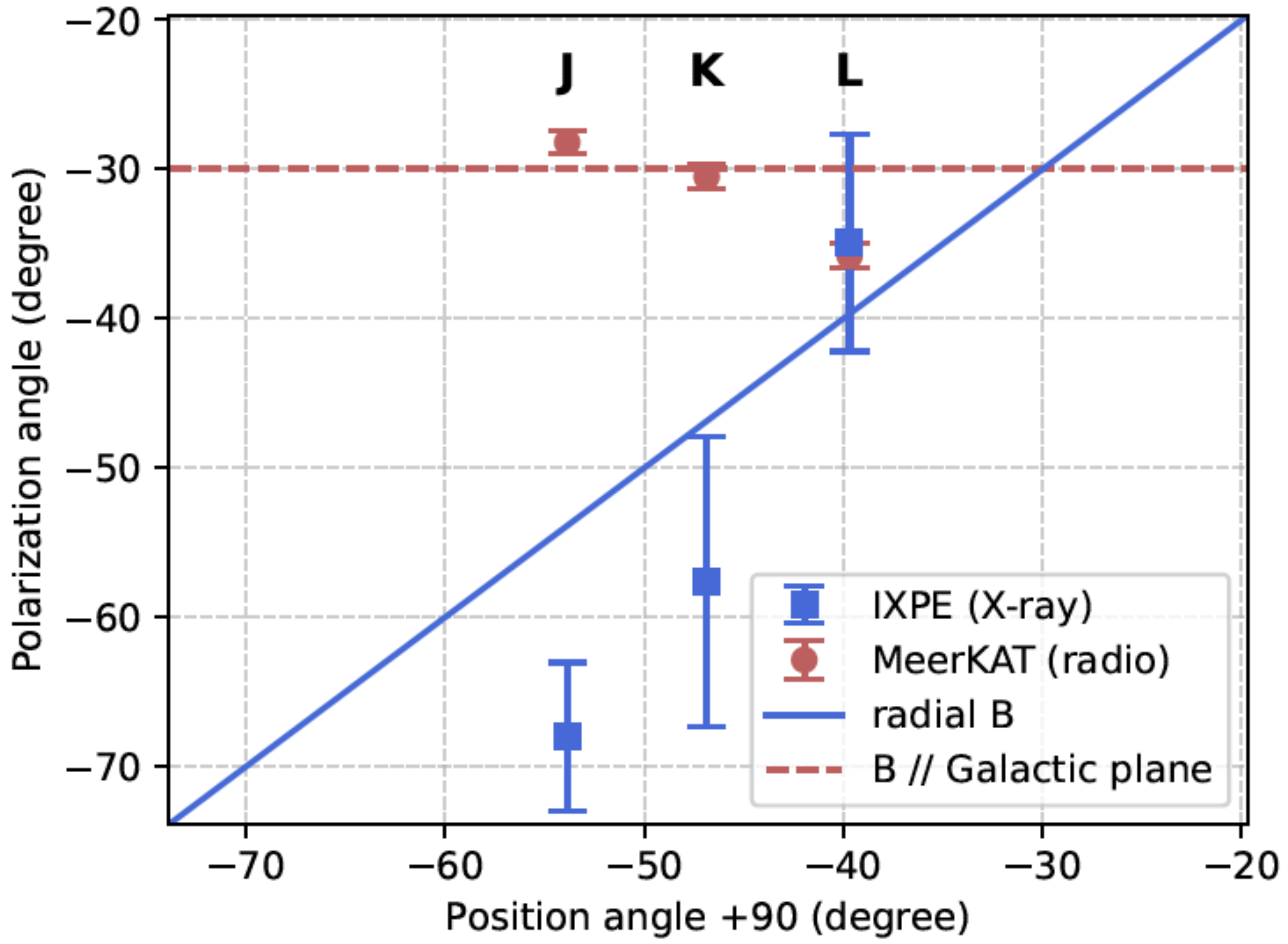
X-ray and radio polarimetry probes different B-fields

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

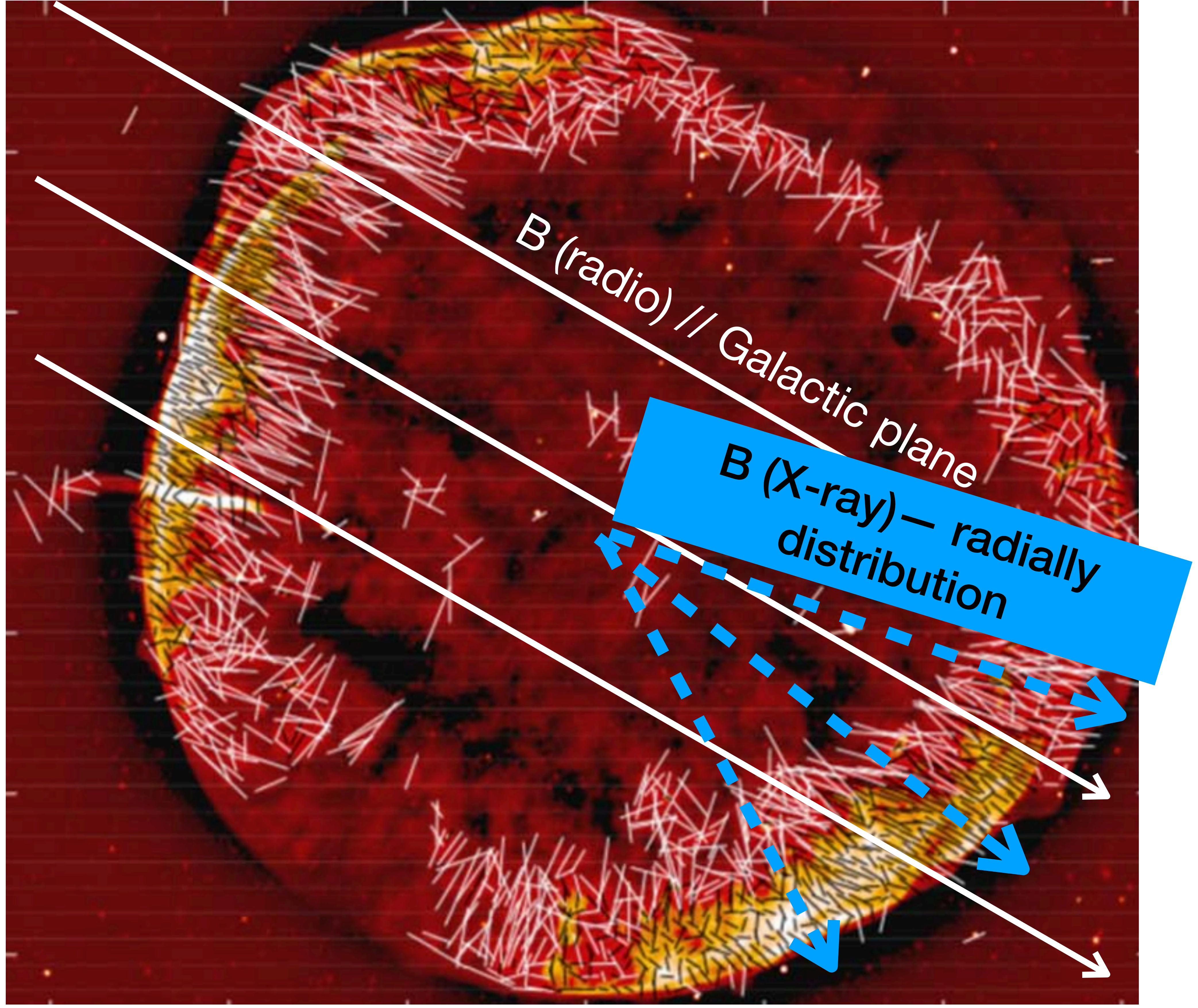
- **Different layers:** X-rays come from a thin layer immediately behind the shock

$$l_{\text{loss}} = v_d \tau_{\text{loss}} \propto B^{-2} E_e^{-1}$$

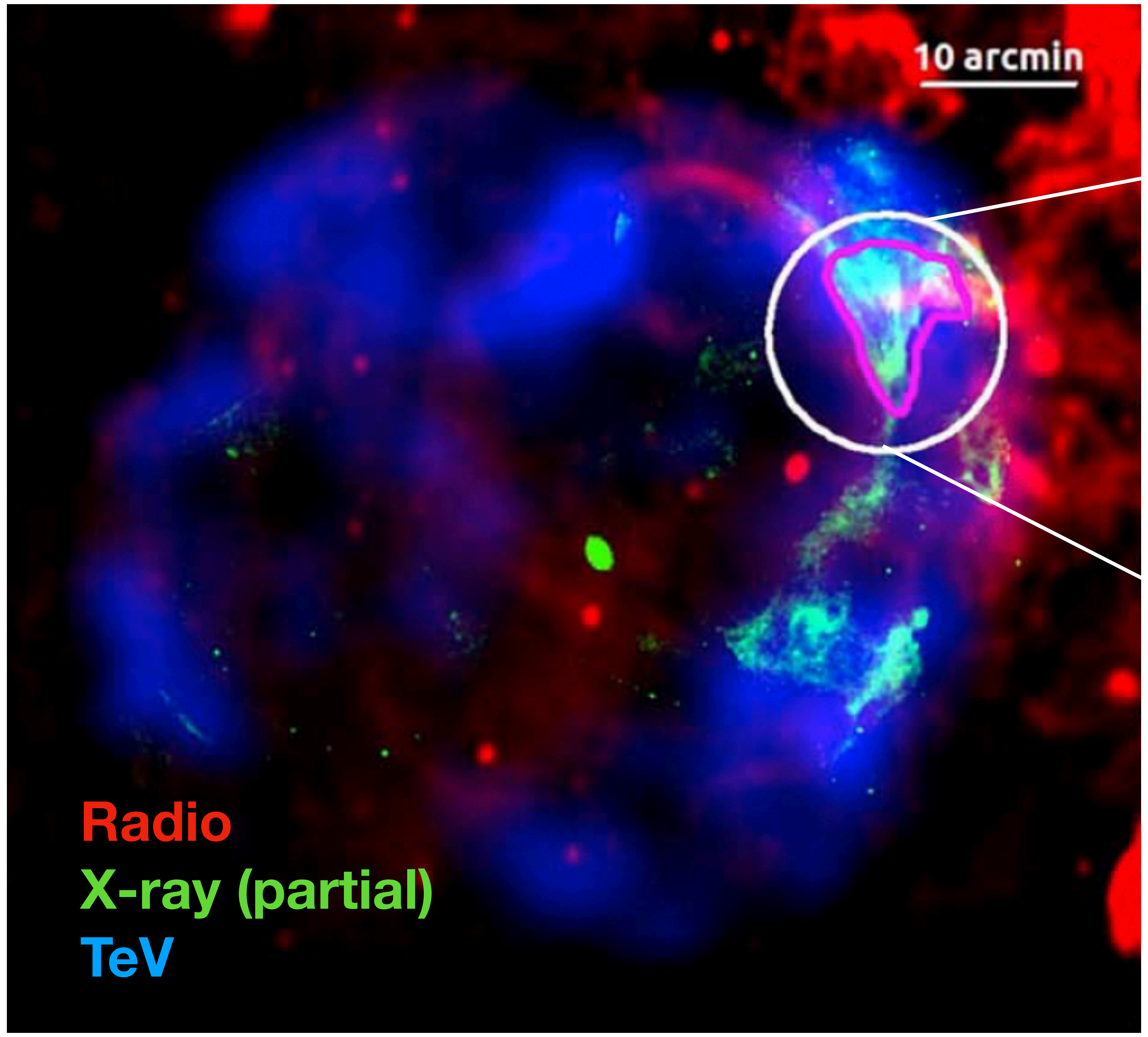
- **Different B-fields:** X-rays probe freshly amplified B-field, radio likely reflects much of the pre-existing field



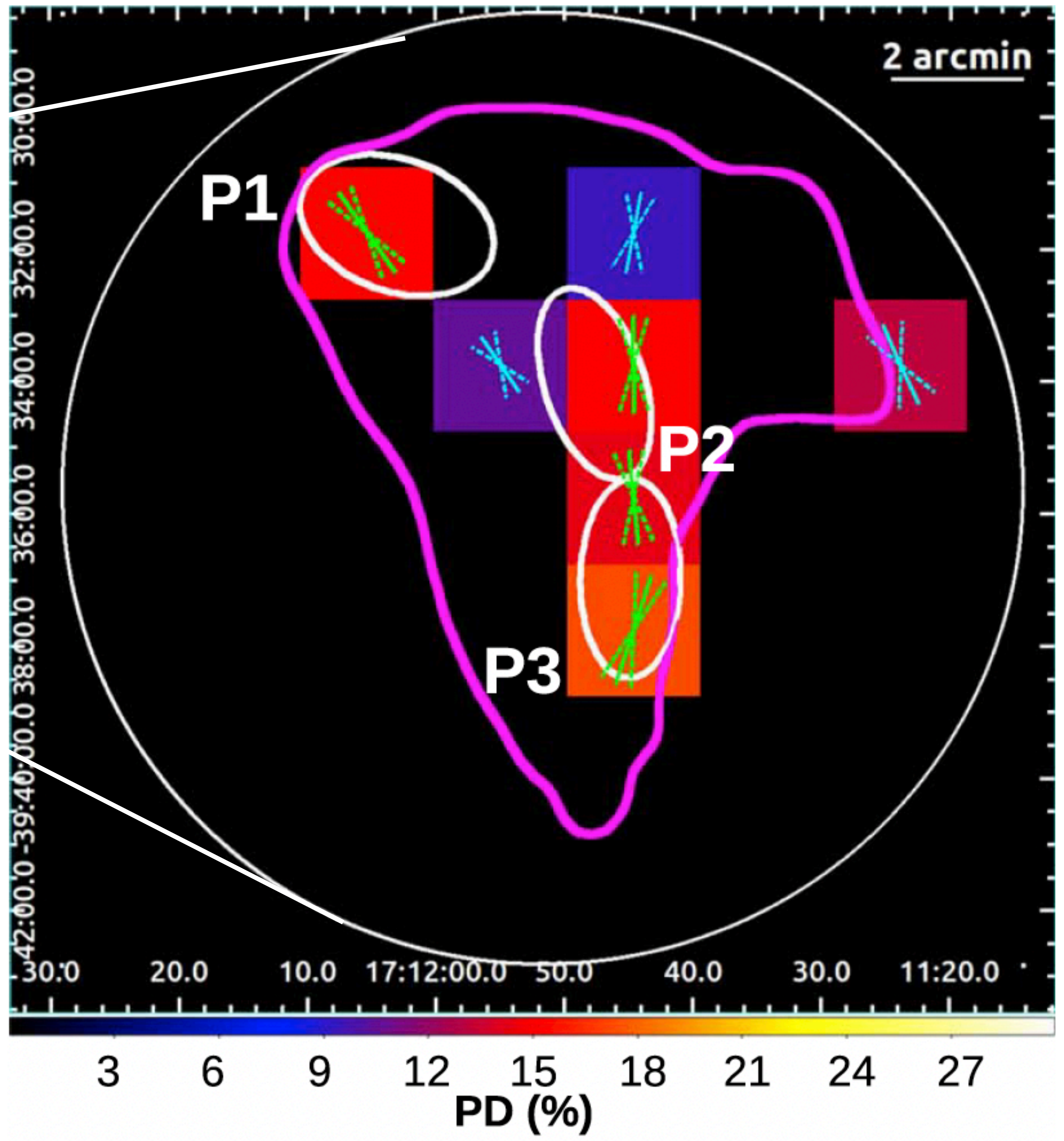
MeerKAT radio image + magnetic vectors (Cotton et al. 2024)



Unexpected tangential B-field in two older SNRs — compression?

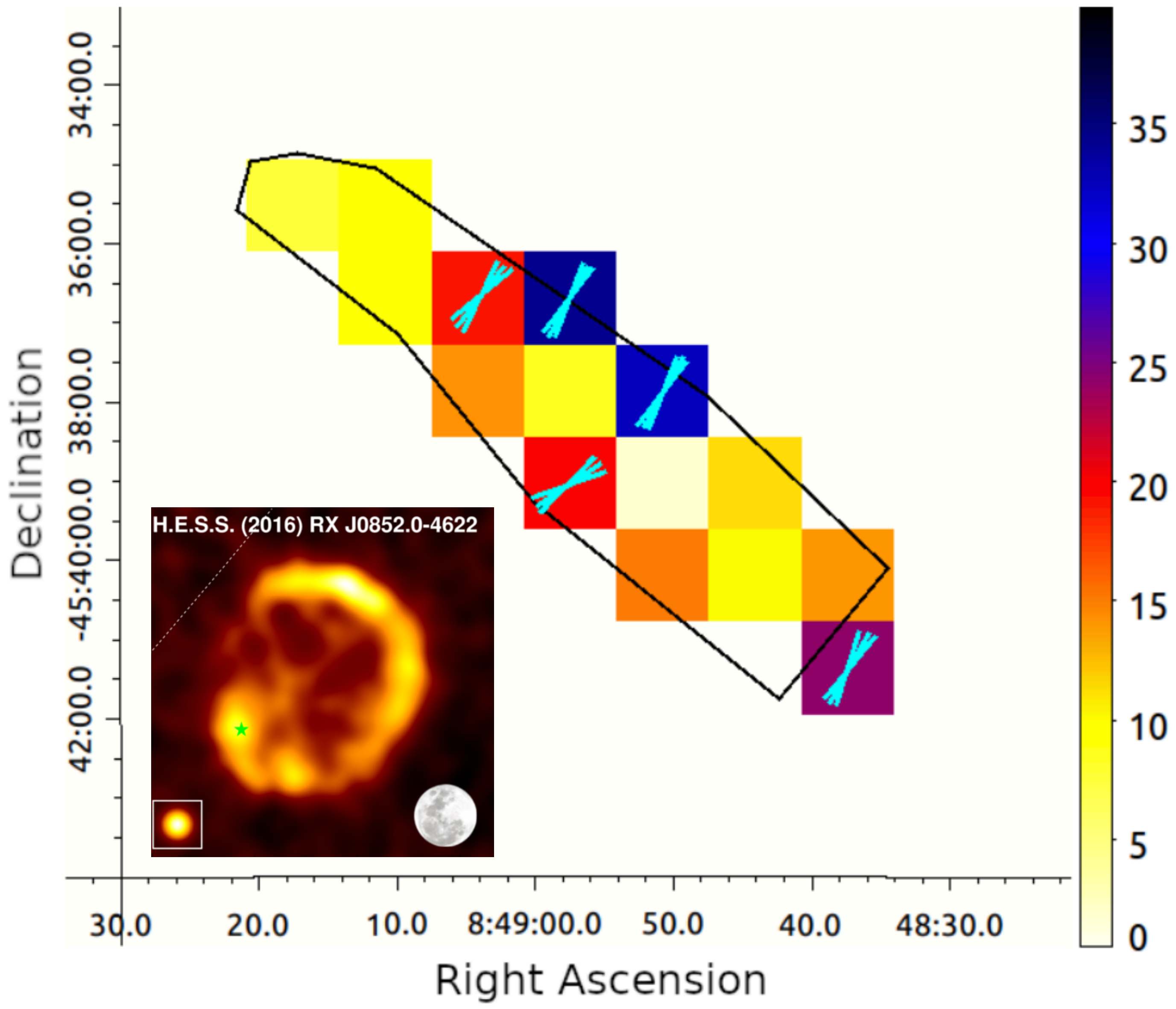


SNR RX J1713 (SN 393?)
PD image + magnetic vectors



Ferrazzoli + 2024

Vela Jr.
PD image + polarization vectors



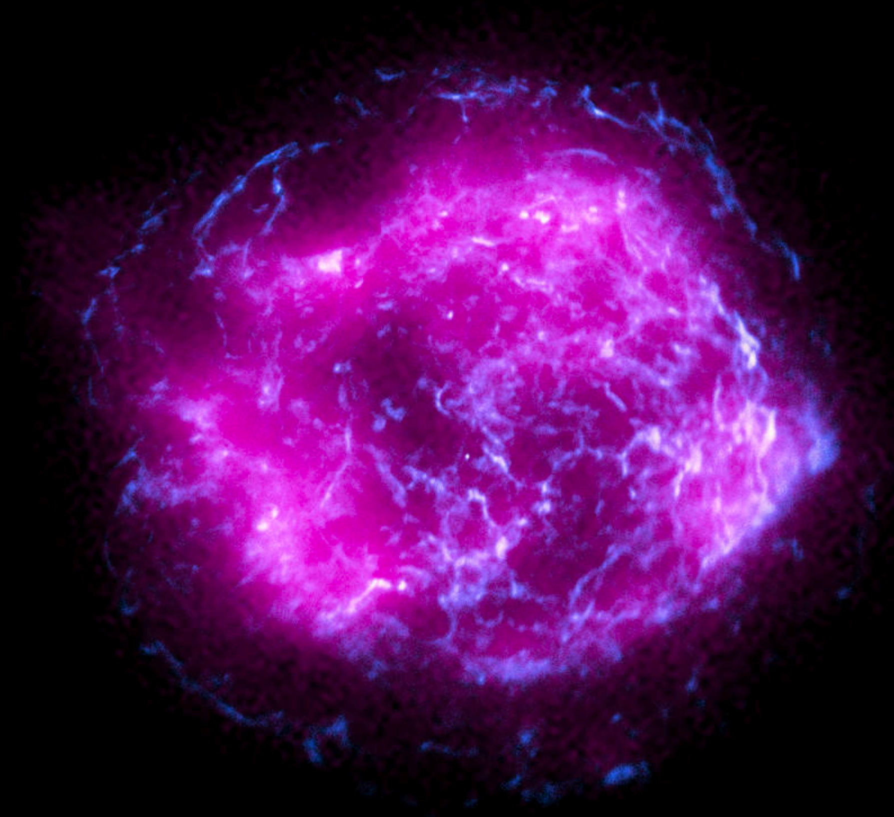
Prokhorov + 2024

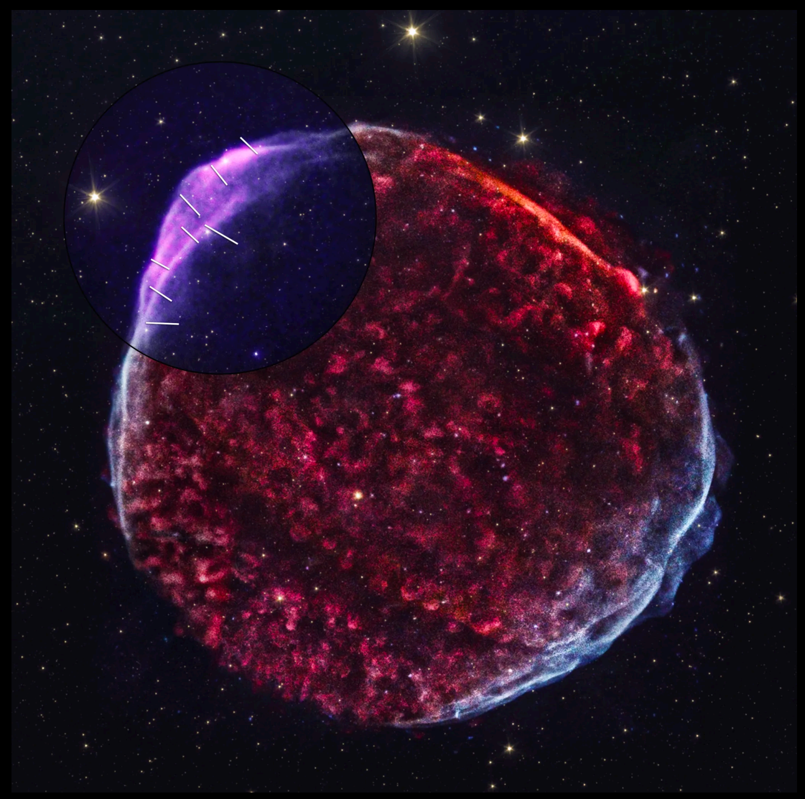
RX J1713: Average PD=$12.5\% \pm 3.3\,\%$, maximum PD $= 46\% \pm 10\,\%$

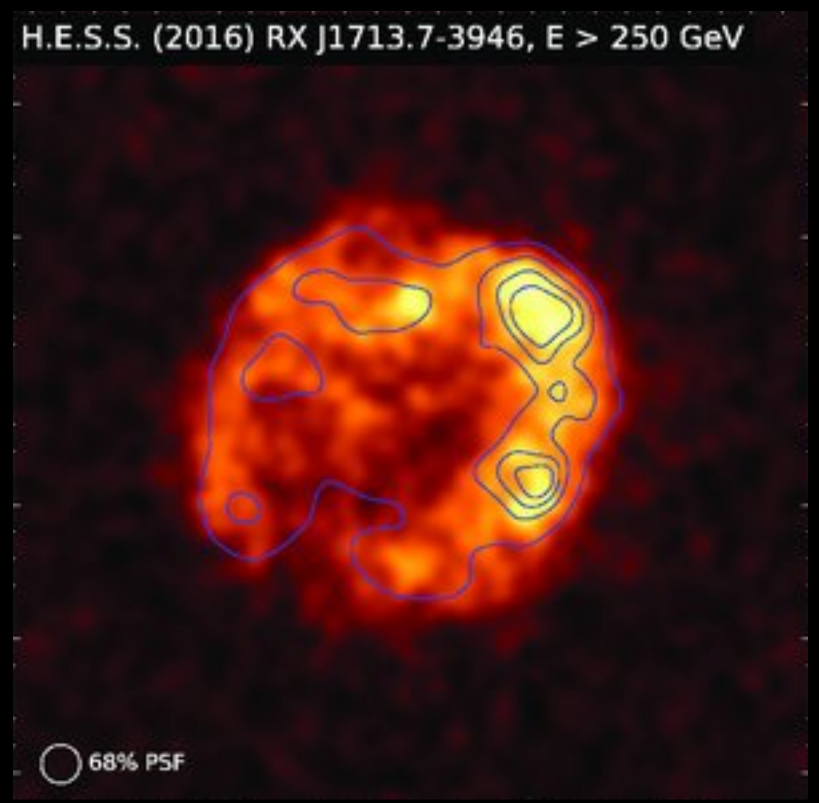
Vela Jr. : Average PD=$16.4\% \pm 5.2\,\%$, maximum PD $= 34\% \pm 10\,\%$

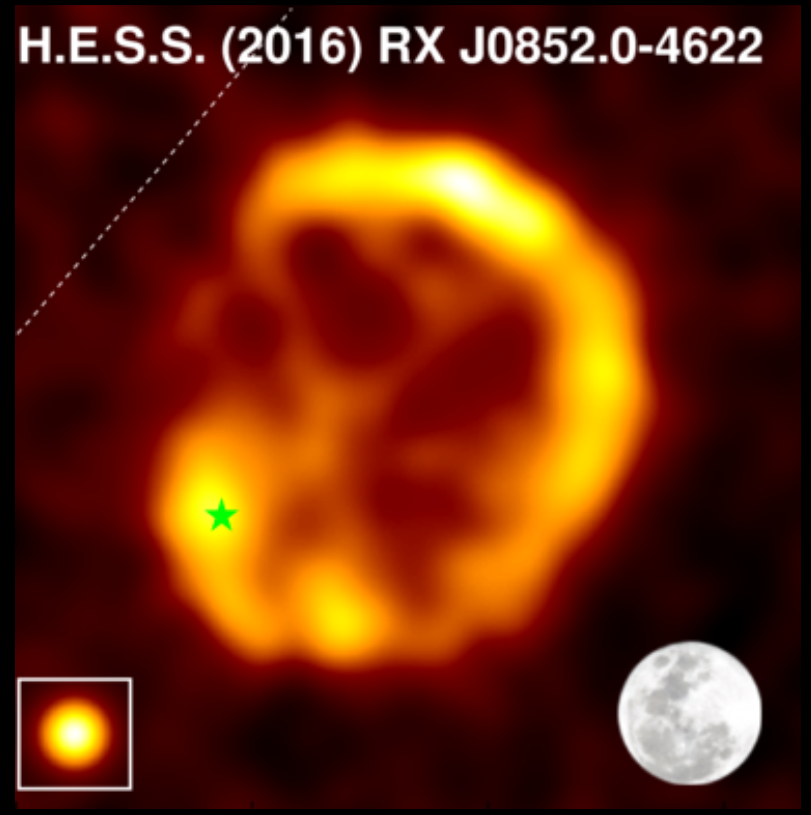
X-ray polarization results for SNRs

PA	Radial B			Tangential B	
PD	low ~ 4.5%	12%	22%	13%	16%









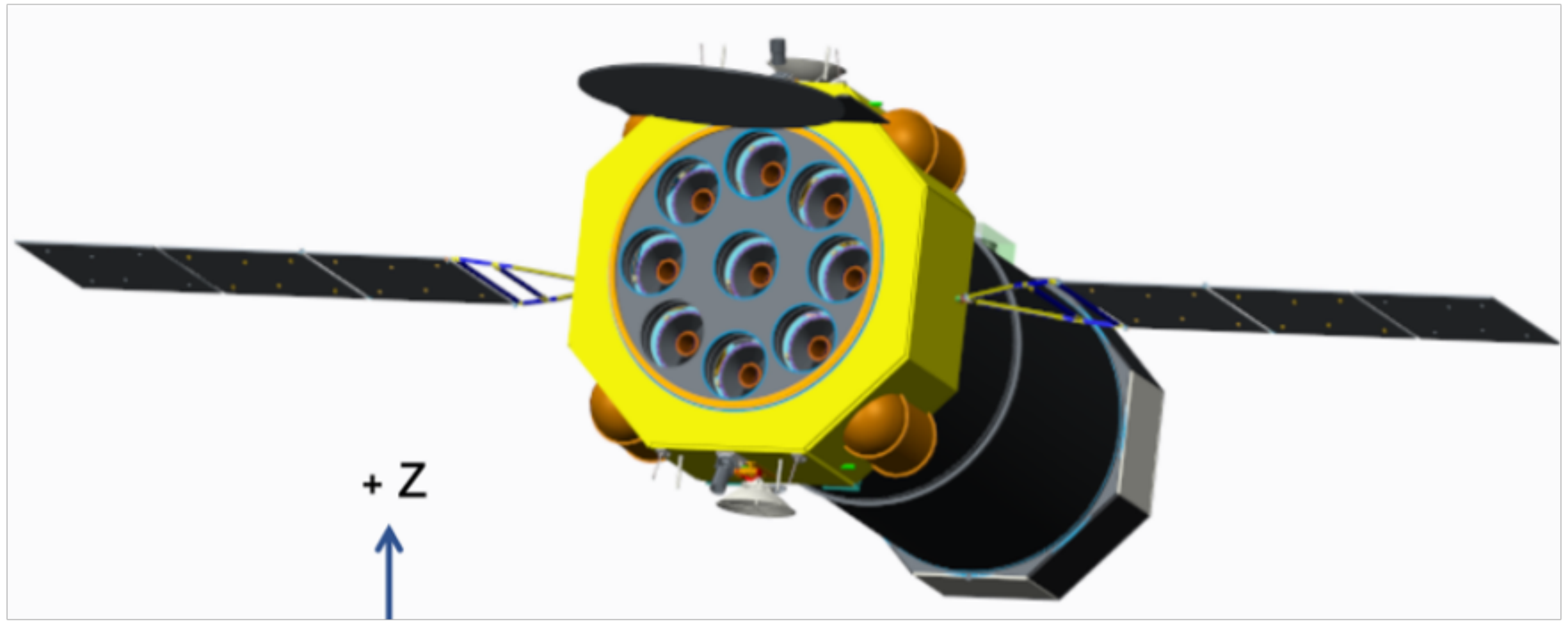
high density | low density | very low-density (<0.1 cm^{-3})

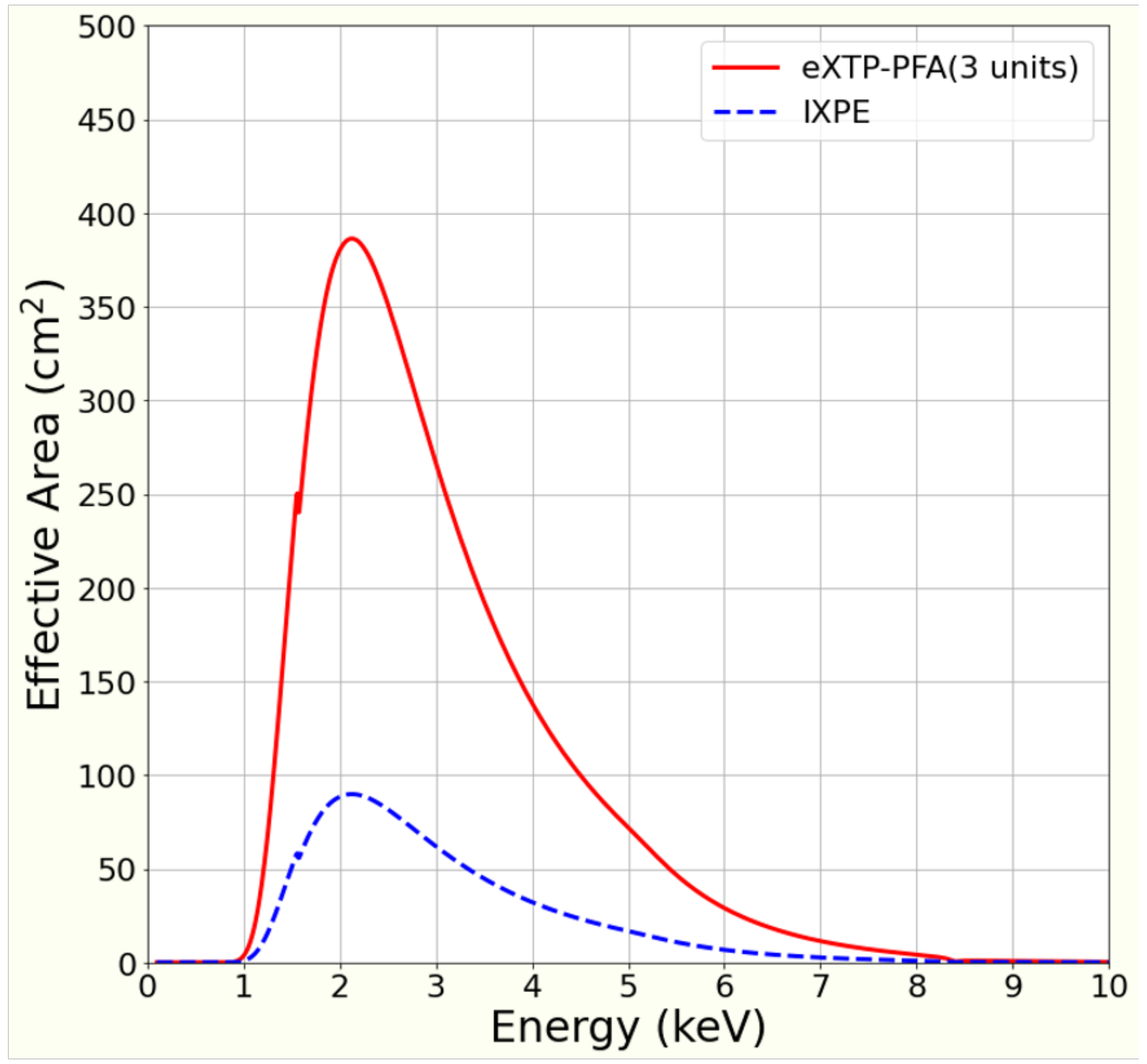
355 yr → 3000 yr

Prospects for X-ray polarization measurements of SNRs

- Limitation of current IXPE measurements
  - low-sensitivity
  - 30” angular resolution has not been exploited due to the low statistics
- eXTP will provide the PD and PA distribution with the sub-arcminute resolution for SNRs —> quantify turbulence scale and orientation

eXTP (extended X-ray Timing and Polarization) mission scheduled for launch in 2030





Summary

- **IXPE measured six young SNRs and renewed our understanding of B in SNRs**
- A range of PD=4.5% to 46% (very turbulent B to nearly ordered B)
- Magnetic turbulence and amplification are likely environment-dependent
- X-ray polarimetry probes amplified/turbulent B-fields, while radio polarimetry traces more extended regions influenced by ambient B-field.
- Radially distributed B in Cas A, Tycho, and SN1006, but tangential B in two older SNRs.
- Our results are new and not fully explained, demanding further theoretical and observational studies on magnetic turbulence.