

Probing magnetic-field geometries & turbulence in young supernova remnants with IXPE

Jacco Vink

Collaborators

- Patrick Slane SAO/CfA (Chandra director and IXPE SNR coordinator)
- Ping Zhou (Nanjing, former postdoc Amsterdam)
- Riccardo Ferrazzoli (INAF Pisa)
- Dmitry Prokhorov (now Würzburg former postdoc Amsterdam)
- Yi-Jun Yang (Hong Kong)
- Luca Baldini (Pisa)
- Niccolo Buciantini (Arcetri)
- The IXPE team!

Some history



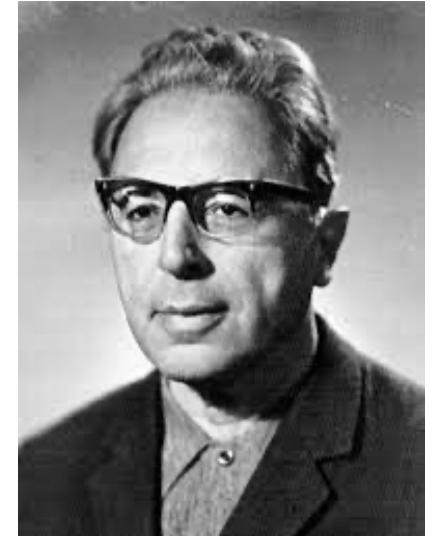
Victor Hess



Walter Baade



Fritz Zwicky



Iosif Shklovsky

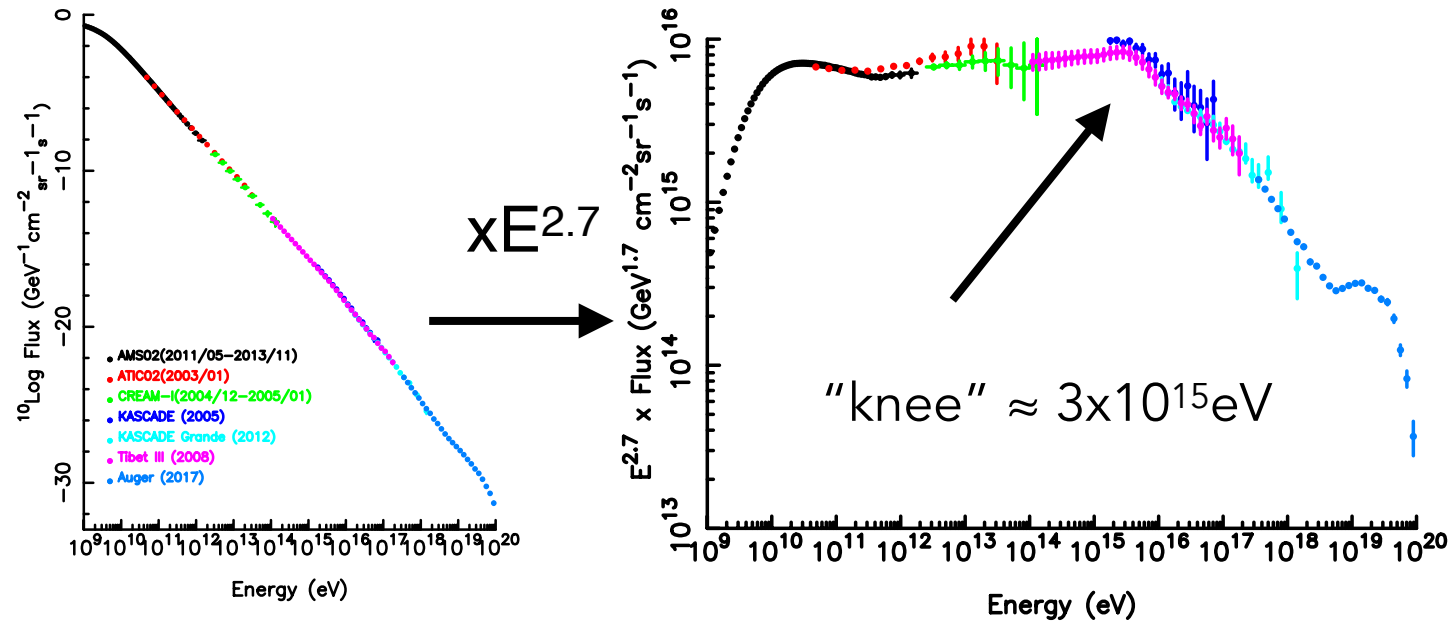
1911: Victor Hess discovers “cosmic rays”

1930s: cosmic rays are energetic particles!

1932: Baade & Zwicky: supernovae form neutron stars and are *sources of cosmic rays*

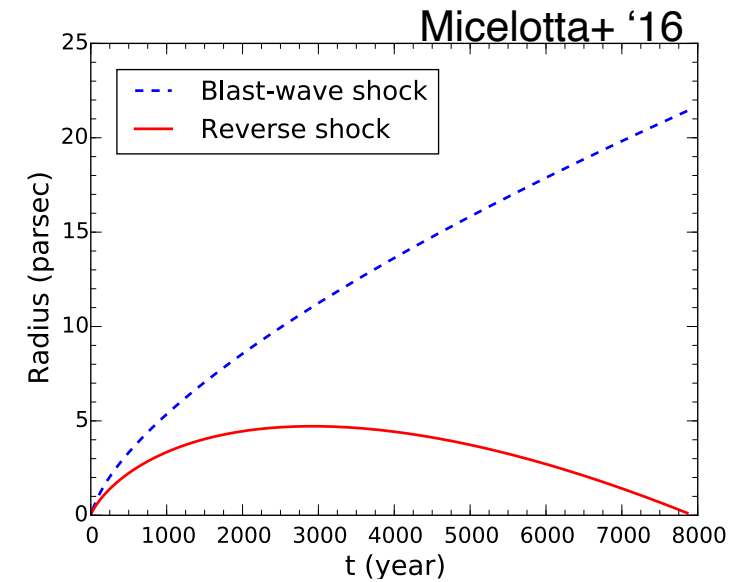
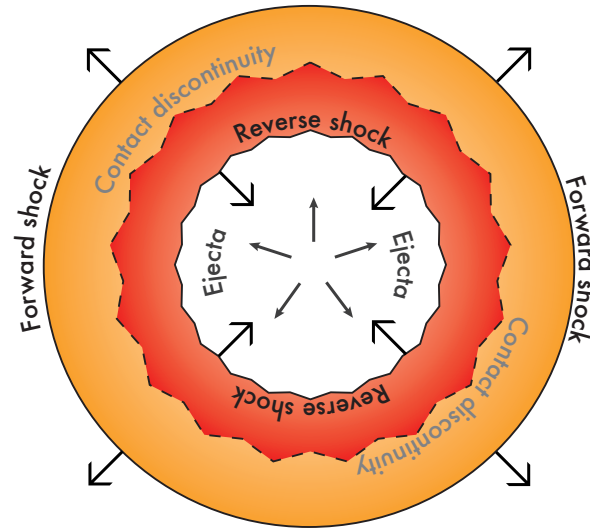
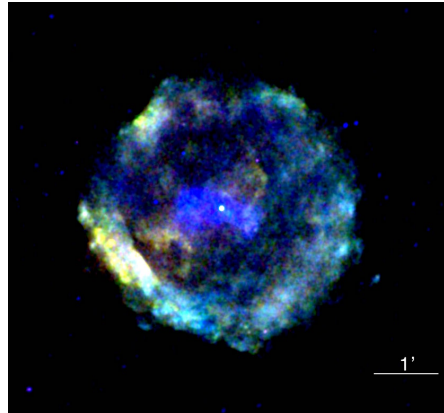
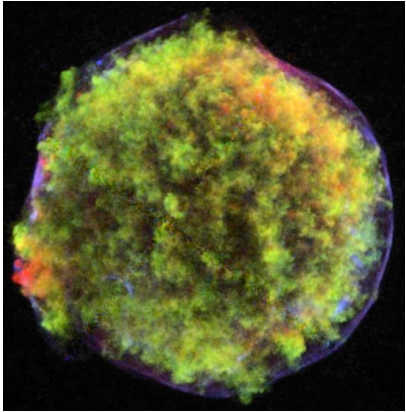
1950: Shklovsky suggests supernova radio emission is caused by relativistic electrons (electron cosmic rays) → synchrotron radiation → predict polarization

Cosmic rays



- ISM energy density CRs $\approx 1 \text{ eV cm}^{-3}$, escape time $\tau \approx 15 \times 10^6 \text{ yr}$
- To fill Galaxy: need a power of $dE/dt \approx 6 \times 10^{40} \text{ erg/s}$
- SN power: $dE/dt \approx 6 \times 10^{41} \text{ erg/s}$ (10^{51} erg/SN , 2 SNe/100yr)
 - SNRs considered primary sources of cosmic rays!
 - electron/positrons $< 1\%$; origin

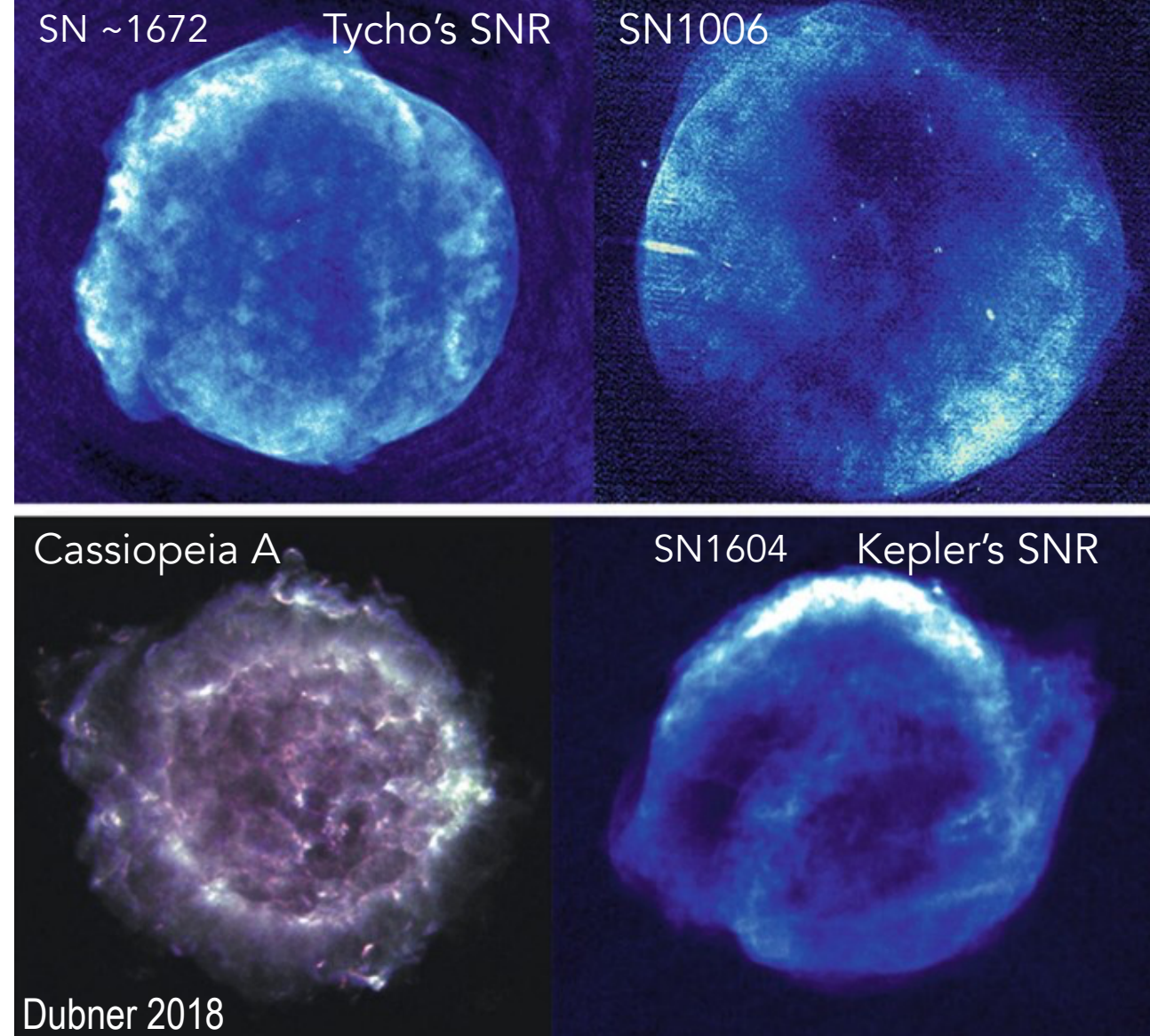
Supernova remnants (SNRs)



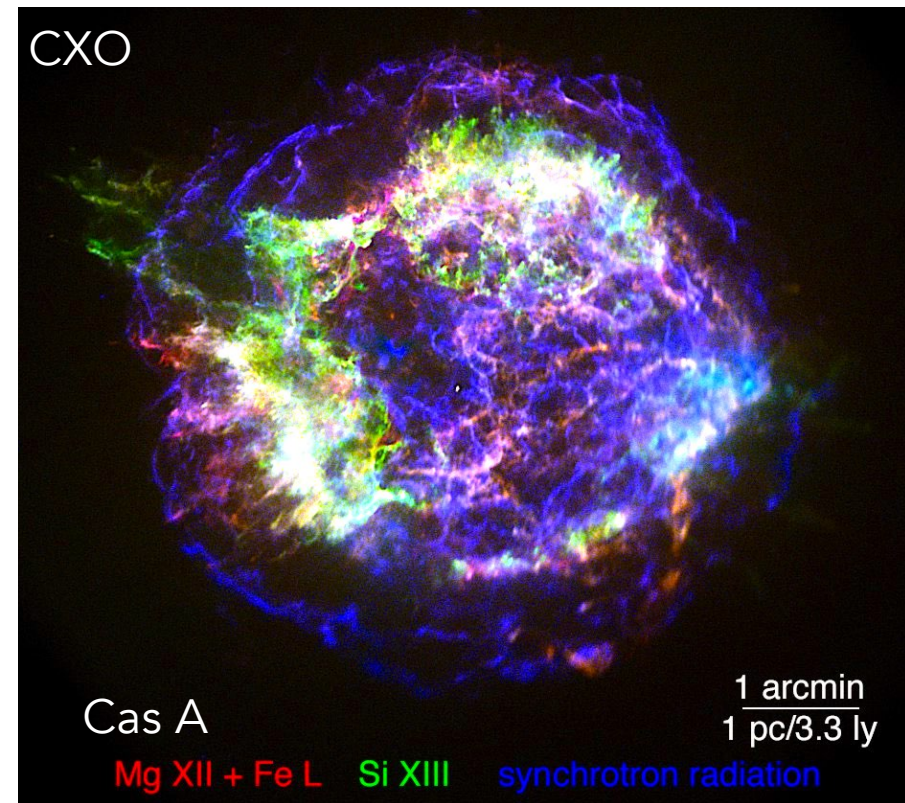
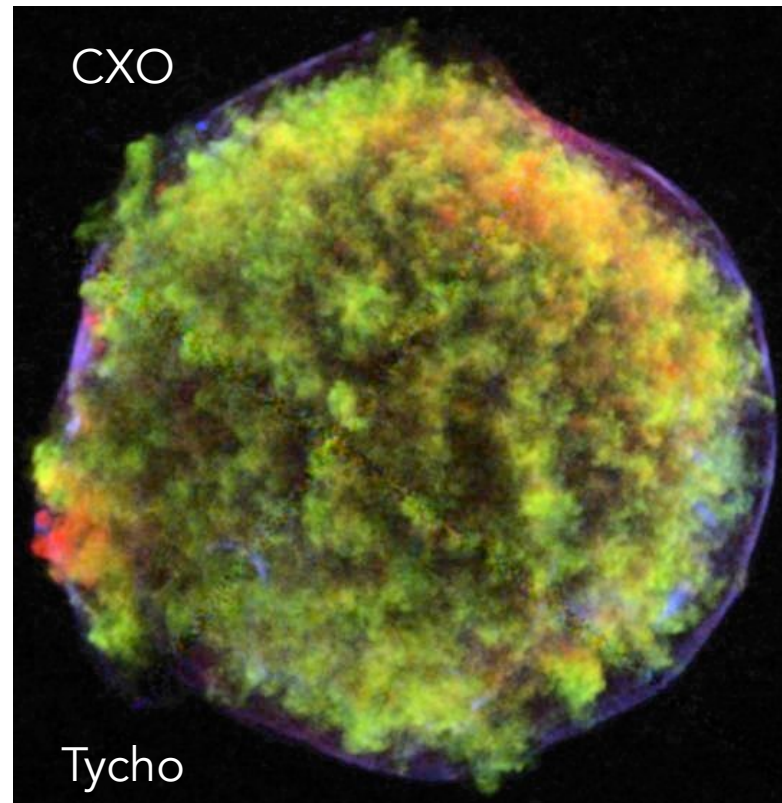
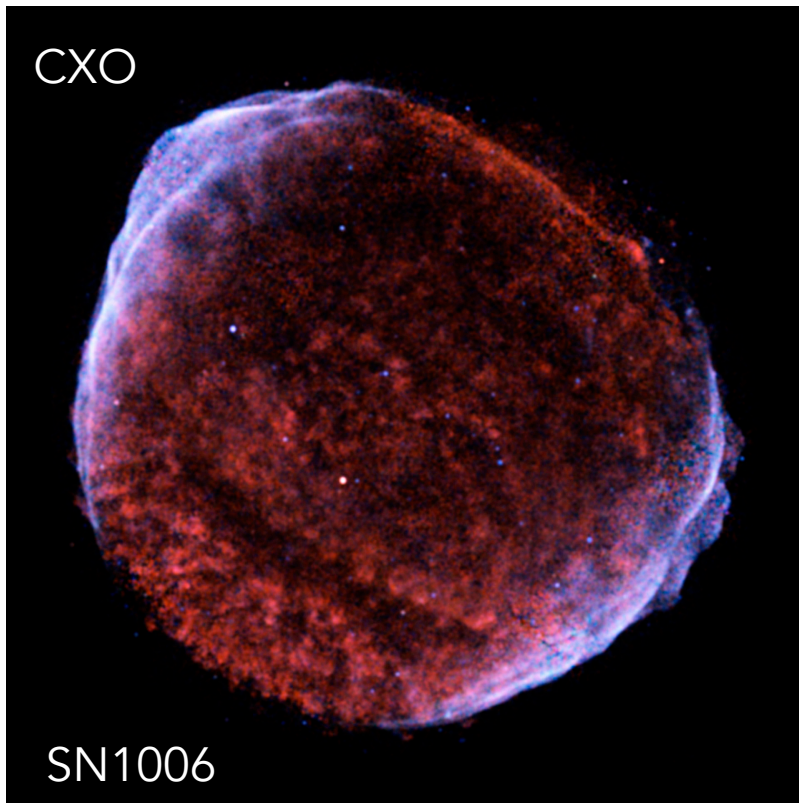
- Initiated by fast/energetic gas ejected by supernova explosion
- SNR shock are collisionless shocks:
 - shock transitions not due to atom-atom collisions
 - allows for (or results in?) cosmic-ray acceleration
- Young SNRs have two shocks:
 - forward shock (blast wave): shocks CSM
 - reverse shock: heats and compresses freely expanding SN ejecta!

Radio maps of young supernova remnants (VLA)

- Radio synchrotron emission
- Requires $\sim$ GeV electrons
- Early evidence that SNRs accelerated particles (electrons) to relativistic energies

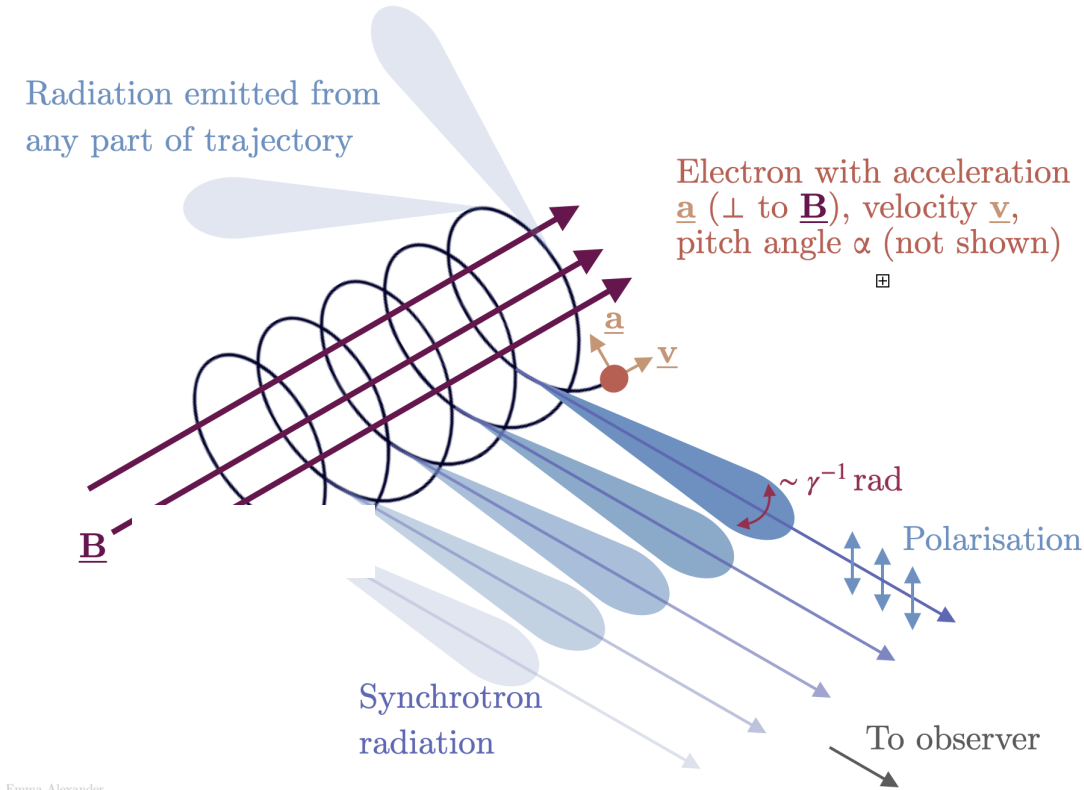


X-ray synchrotron emission from young SNRs



- Since 1995 (Koyama+ 95): young SNRs identified as X-ray synchrotron sources
- Requires 10-100 TeV electrons!

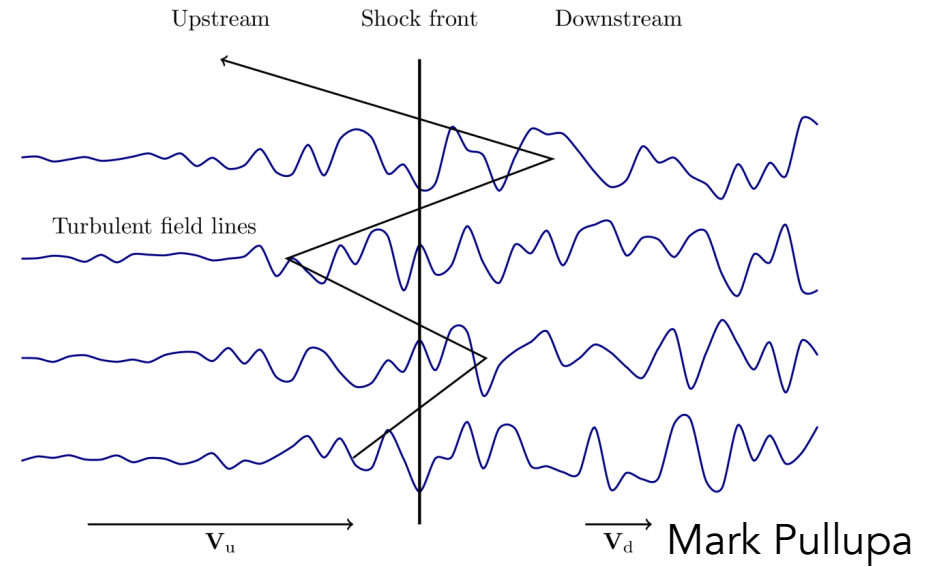
Polarization in astrophysics



- Polarization in general: geometric dependence
 - e.g. scattering geometry, or B-fields

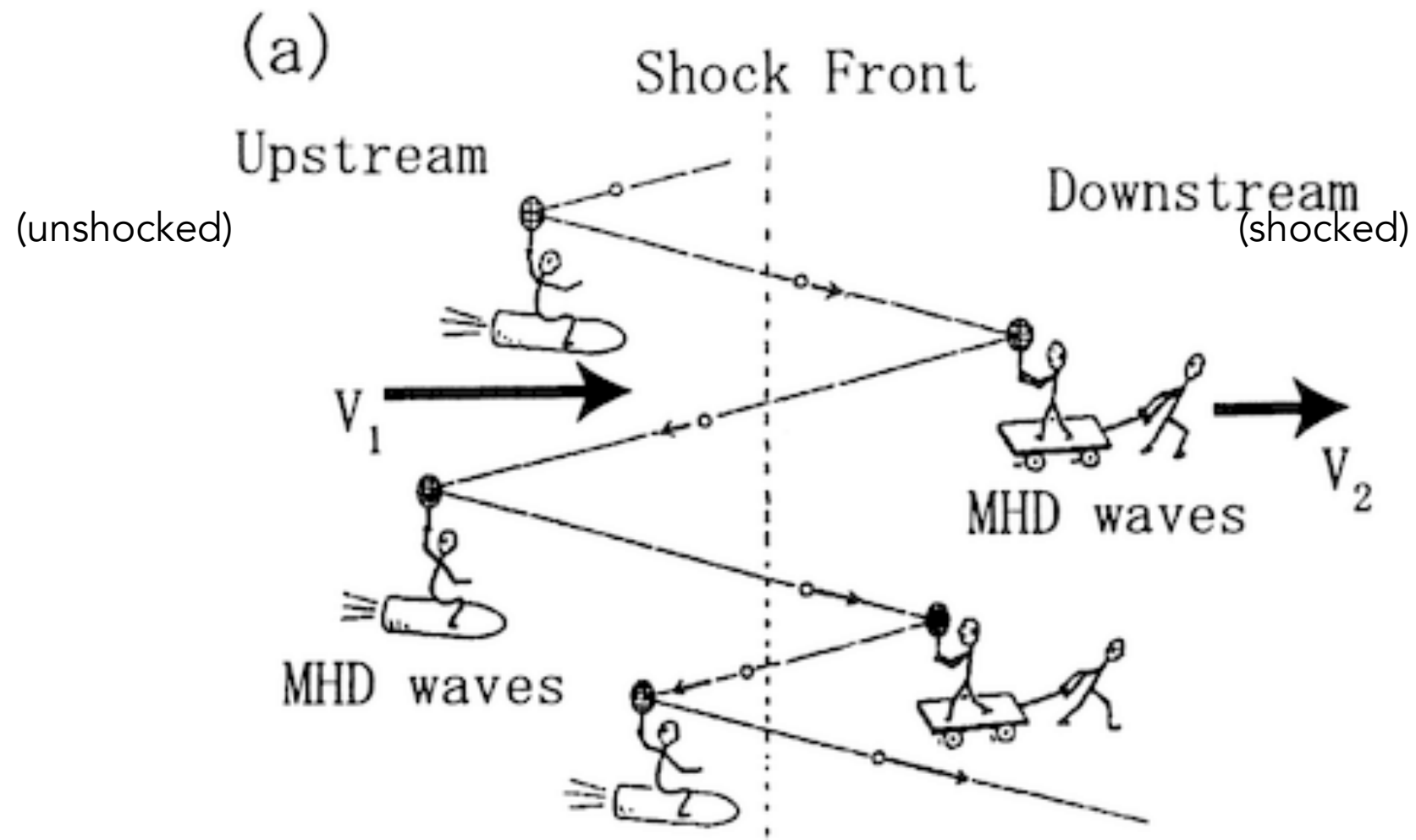
- Synchrotron radiation: relativistic e^-/e^+ spiraling around B-field
- Intrinsically polarized: power law ($F_\nu \propto \nu^{-\alpha}$): pol. fraction = $\frac{\alpha + 1}{\alpha + 5/3} \approx 70\%$
- Polarization vector perpendicular to magnetic field

Diffusive shock acceleration (DSA): B-field turbulence needed!



- Particles gain energy by crossing shock:
 - $\Delta V_{\text{plasma}} \rightarrow$ Lorentz boost of $\frac{\Delta E}{E} \approx \frac{\Delta V}{c}$
 - Diffusion: particle can cross shock $D = \frac{1}{3}c\lambda_{\text{mfp}} = \frac{1}{3}\eta r_g = \frac{1}{3}\eta \frac{E}{eB}$
 - Acceleration time: $\tau \approx \frac{8D_0}{V_s^2} \rightarrow E_{\text{max}} \propto \eta^{-1} B V_s^2 t$
- Higher energy: V_s high, B high and $\eta \approx \langle (\delta B/B)^2 \rangle^{-1} \approx 1$ **turbulent fields!**

DSA cartoon



M. Scholer

X-ray synchrotron radiation

- Requires >10 TeV electrons:

- $h\nu \approx 19 \left(\frac{B}{100 \mu\text{G}} \right) \left(\frac{E}{100 \text{ TeV}} \right)^2 \text{ keV}$

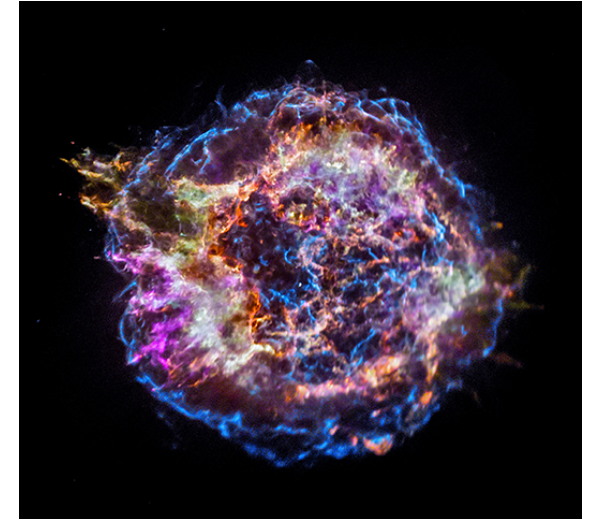
- Electrons cool fast:

- $\tau_{\text{cool}} \approx 12.5 \left(\frac{B}{100 \mu\text{G}} \right)^{-2} \left(\frac{E}{100 \text{ TeV}} \right)^{-1} \text{ yr}$

- $\rightarrow$ Acceleration needs to be fast

- $\rightarrow$ Electrons "out of contact with shock" will not emit X-rays

- $\rightarrow$ Narrow X-ray filaments



- Combination of acceleration and cooling: $h\nu_{\text{cutoff}} \approx 1.4\eta^{-1} \left(\frac{V_{\text{sh}}}{5000 \text{ km/s}} \right)^2 \text{ keV}$

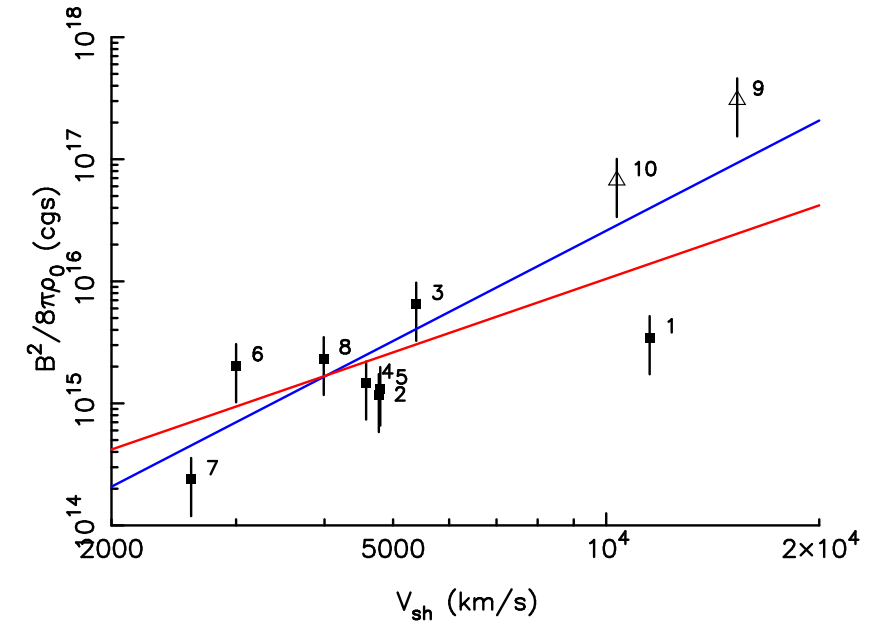
- $\eta \approx \langle (\delta B/B)^2 \rangle^{-1} \approx 1$ turbulence parameter

- Electrons have cooled when far from shock: $B \approx 110 \left(\frac{l}{10^{17} \text{ cm}} \right)^{-2/3} \mu\text{G}$

Magnetic -field amplification

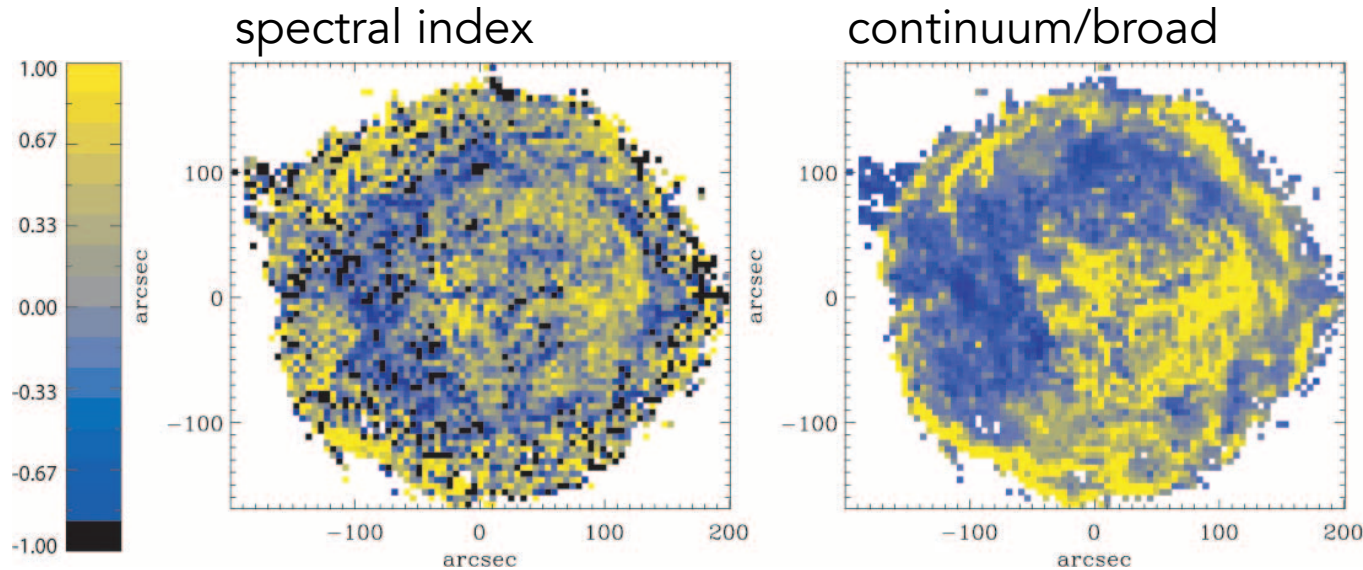
Helder, JV, + 2012

ID	SNR	Dist (kpc)	$n_{\text{H},0}$ (cm^{-3})	V_s (km/s)	ΔR ($''$)	l_{diff} (10^{17} cm)	B_2 (μG)	E_{el} (TeV)	τ_{syn} (yr)
1	G1.9+0.3 (SW)	8.5	0.022	11520	3.1	2.8	66.6	33	86
2	Cas A (NE)	3.4	0.9	4773	1.1	0.4	246.5	17	12
3	Kepler (SE)	5.0	0.05	5390	1.8	0.9	137.8	23	29
4	Tycho (W)	3.0	0.5	4579	1.6	0.5	207.0	19	16
5	SN1006 (E)	2.2	0.085	4795	9.1	2.1	81.1	30	64
6	RCW 86 (NE)	2.5	0.01	3000	28.6	7.6	34.5	46	232
7	RX J1713.7-3946	1.0	0.1	2592	63.5	6.7	37.3	44	206
8	RX J0852.0-4622	1.0	0.03	3990	28.4	3.0	63.9	34	92

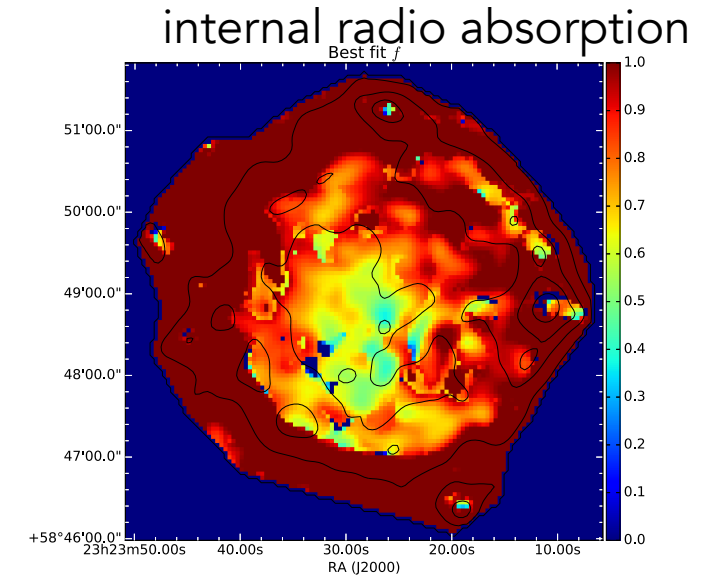


- Magnetic fields much larger than ISM: $B \approx 30 - 300 \mu\text{G}$
- Likely mechanism: Bell (2004) instability
- Bell (2004): $B^2 \propto \rho V_s^3$
 - Indeed: higher densities associated with larger B

Cassiopeia A: X-ray synchrotron from western reverse shock



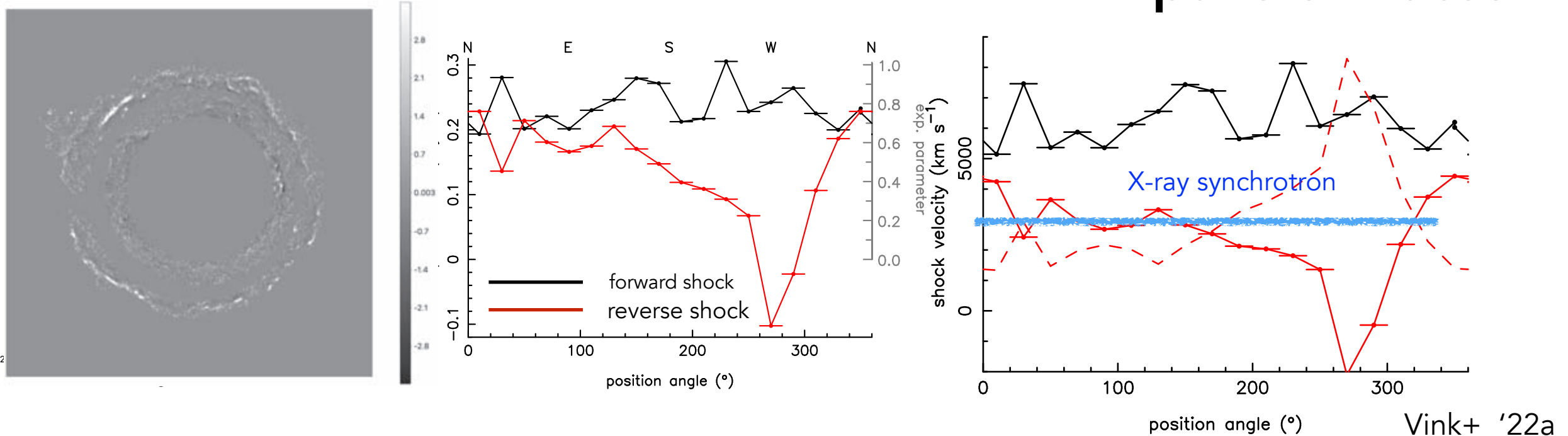
Helder & Vink 2008



Arias, Vink, et al 2018

- X-ray synchrotron radiation: requires $V_s > 3000$ km/s
- Narrow filaments: $B \sim 200 \mu\text{G}$
 - Apparently B-field amplification even with low seed fields (ejecta)!

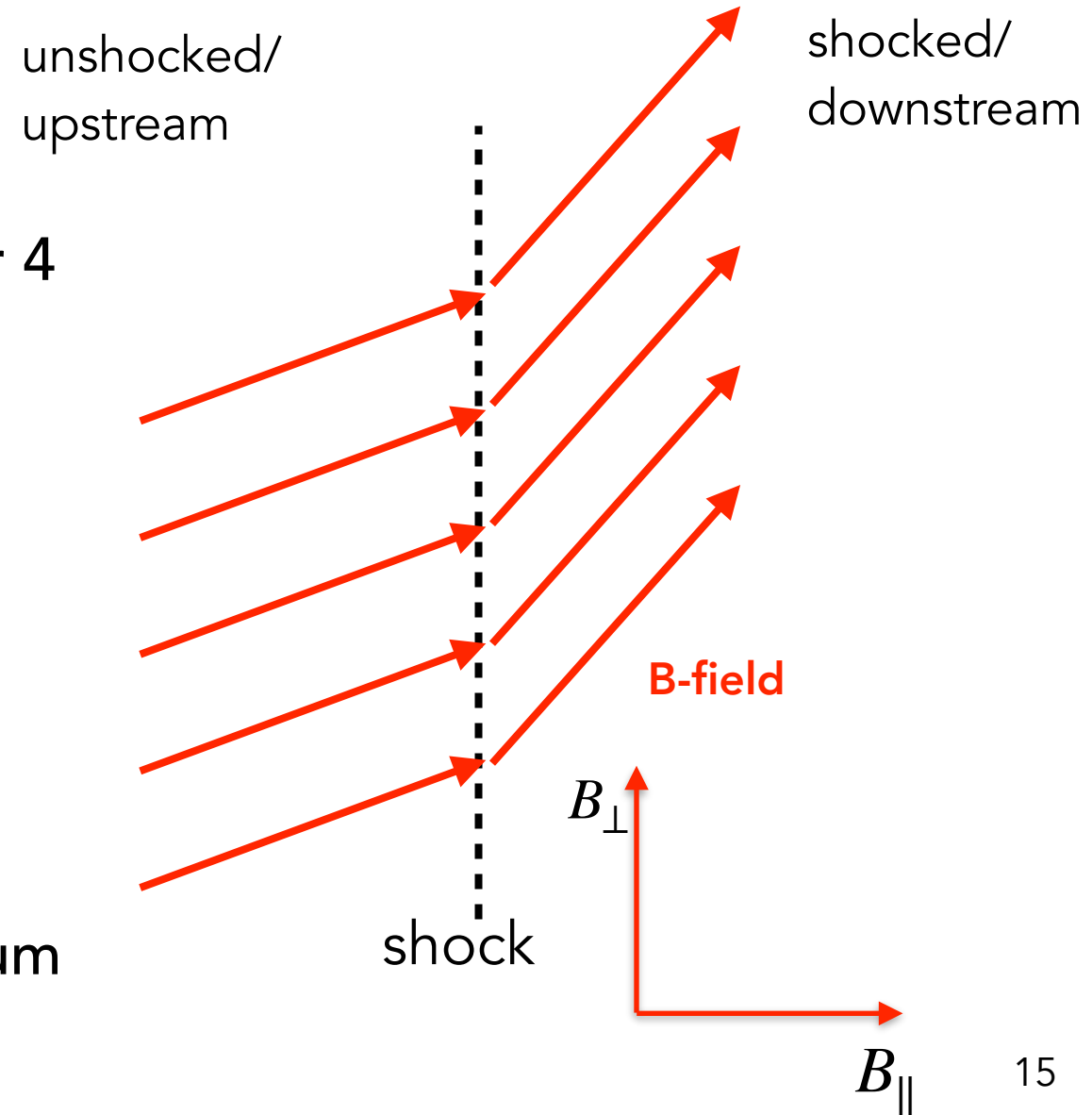
Expansion rates



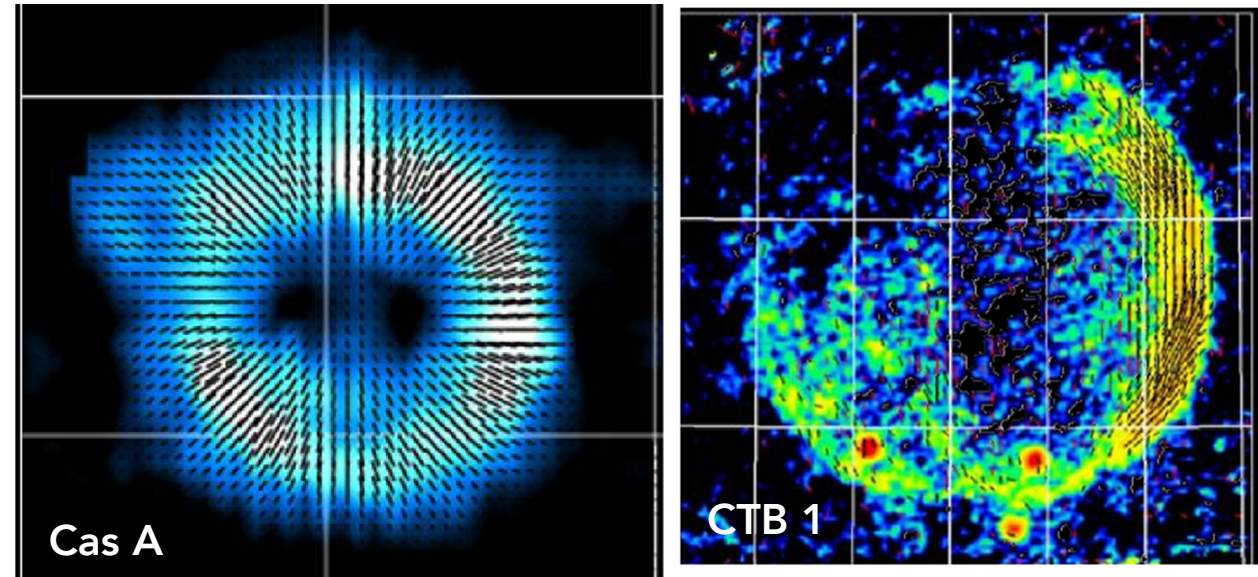
- Forward shock: rate 0.2 - 0.3 %/yr (times scale 350-550 yr)
- Expansion parameter: $R \propto t^m \rightarrow m = \frac{V_{\text{sh}}}{R_{\text{sh}}/\text{age}}$ $m=0.6-0.95$
 - bit larger than older measurements
- Reverse shock is moving inward in the West!

Shock aligns B-fields

- Strong shock: plasma compressed by factor 4
- $B_{\perp}$ compressed by 4
- $B_{\parallel}$ uncompressed
- B-field turbulence for DSA:
 - self-generated by cosmic rays!
 - resonant (wavelength $\approx$ gyroradius)
 - non-resonant (Bell '04)
- Theories consider mostly upstream medium



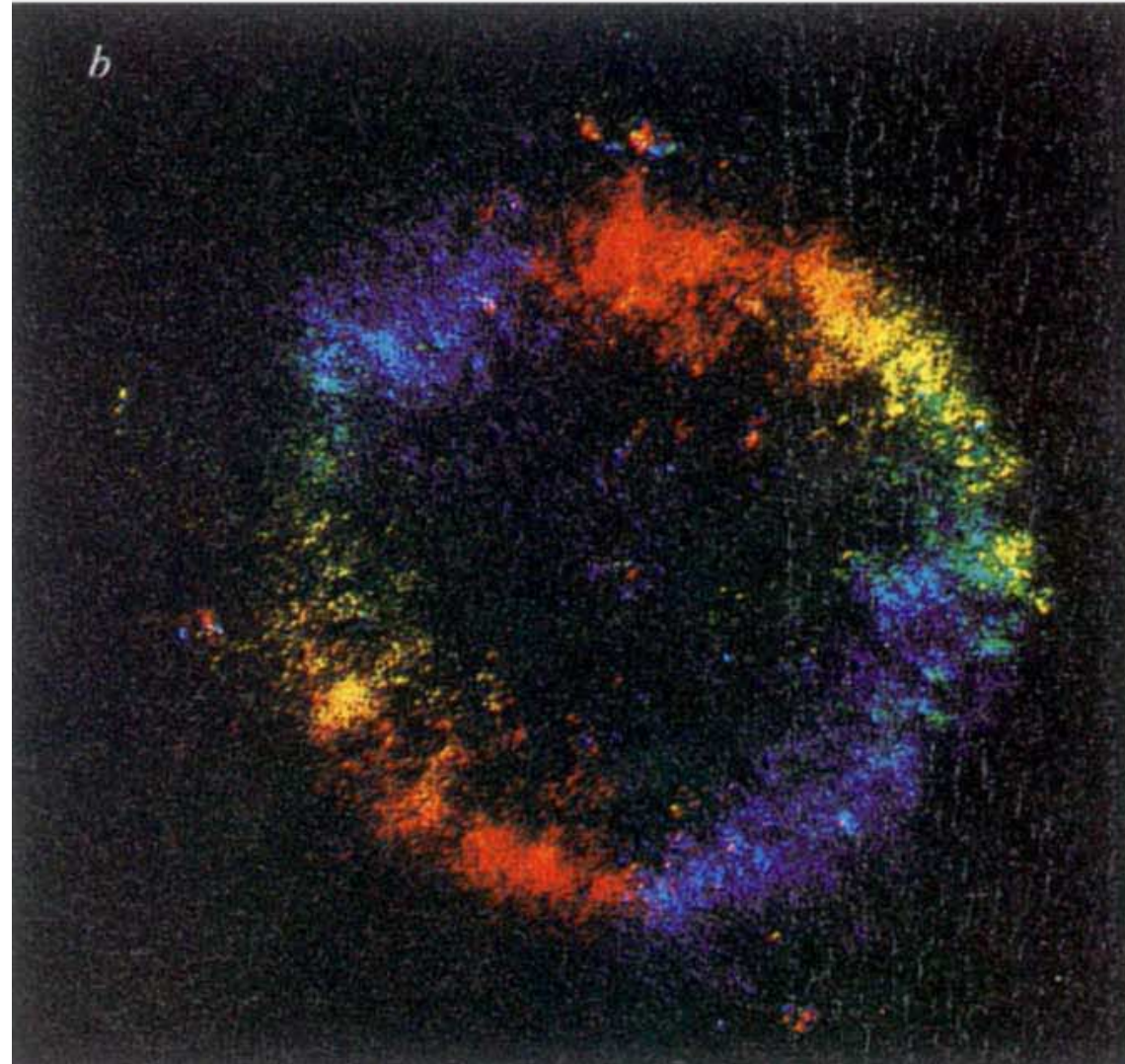
Radio synchrotron *polarization* from SNRs



Dubner&Giacani (2015)
(Magnetic-field vectors)

- *Mature* SNRs ($\gtrsim 2500$ yr): tangentially oriented fields
 - Makes sense: shock compresses tangential B-field components only
- *Young* SNRs ($\lesssim 2500$ yr): radially oriented B-fields and low pol. frac (Cas A: $\sim 5\%$)
 - Poorly understood

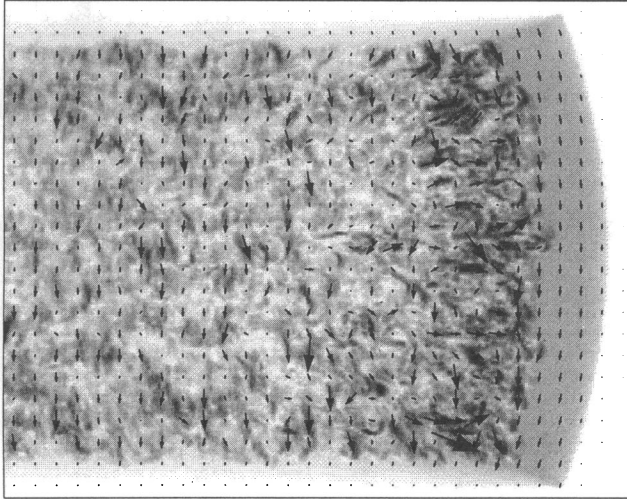
POLARIZATION AND MAGNETIC FIELDS



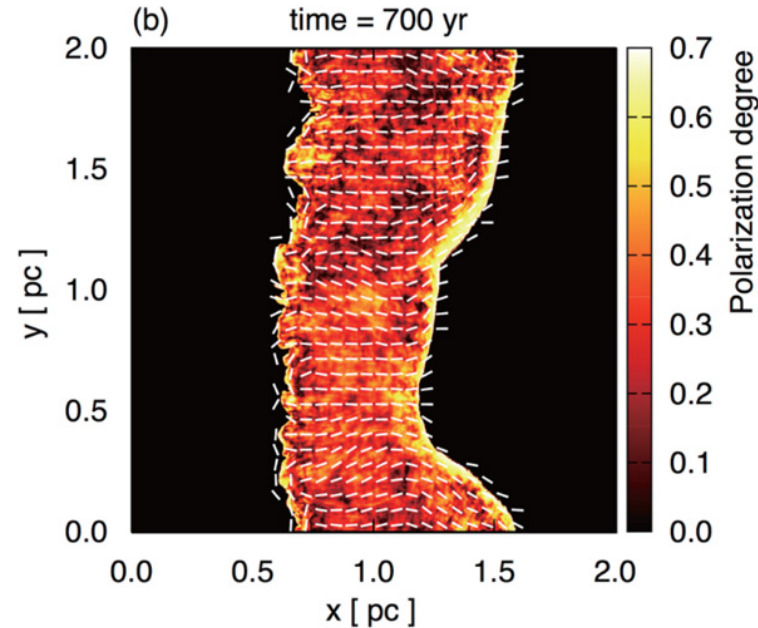
Braun+ '87

Explanations for radial B-fields in young SNRs

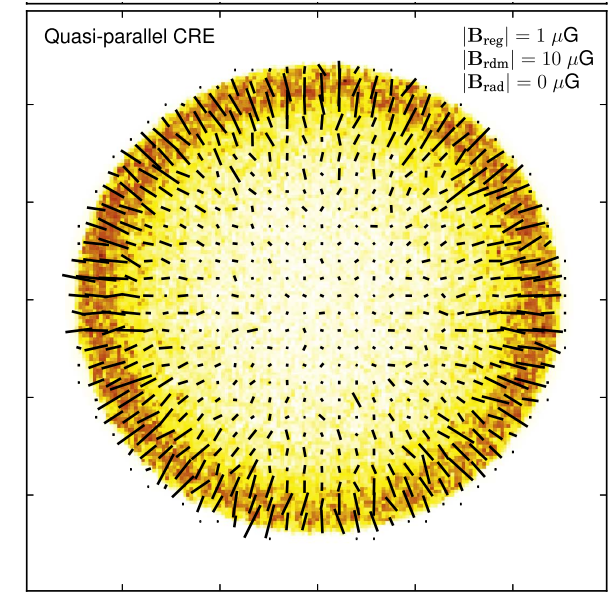
Jun&Norman '96



Inoue+ '13

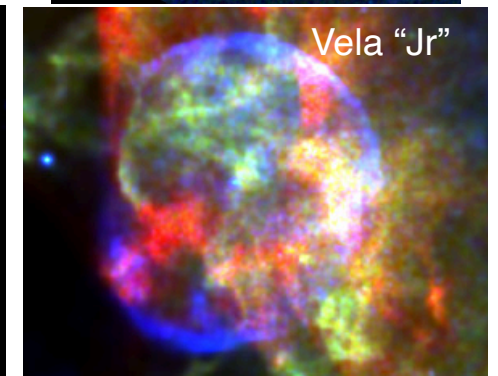
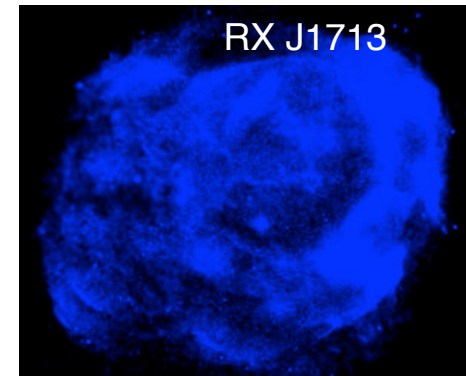
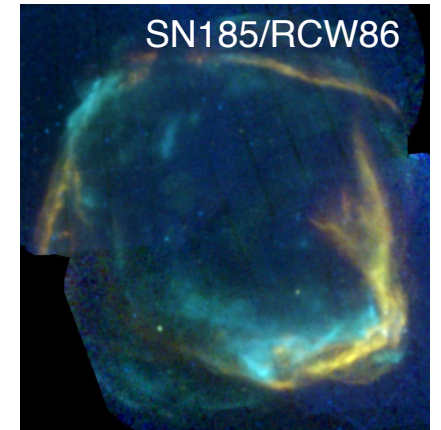
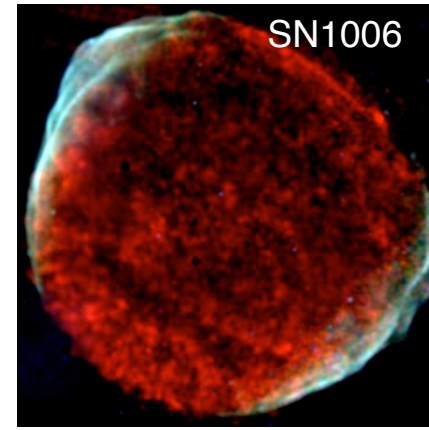
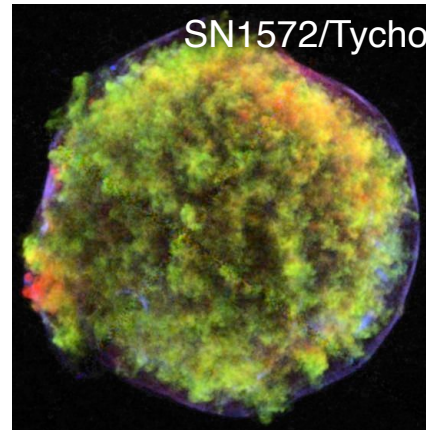
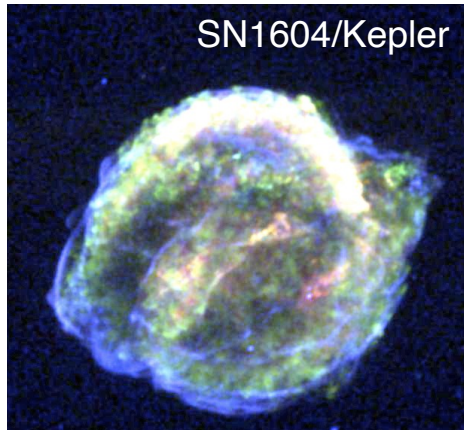
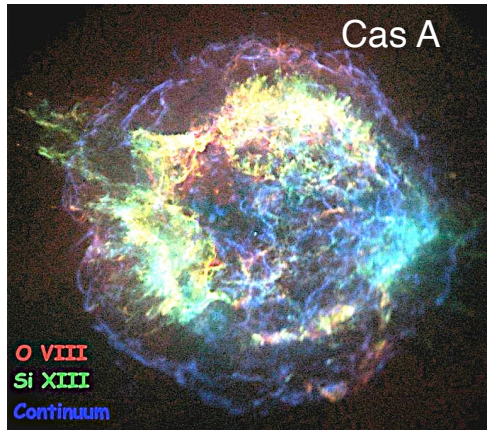


West+ '17



- Two schools of thoughts:
 1. Hydrodynamical filamentation, due to Rayleigh-Taylor or other instabilities
 - Assumes tangential magnetic field at shock, and radial further downstream
 2. Acceleration happens where B-field is parallel (i.e. radial): only emission from these regions

Why X-ray polarization if we have radio polarization?



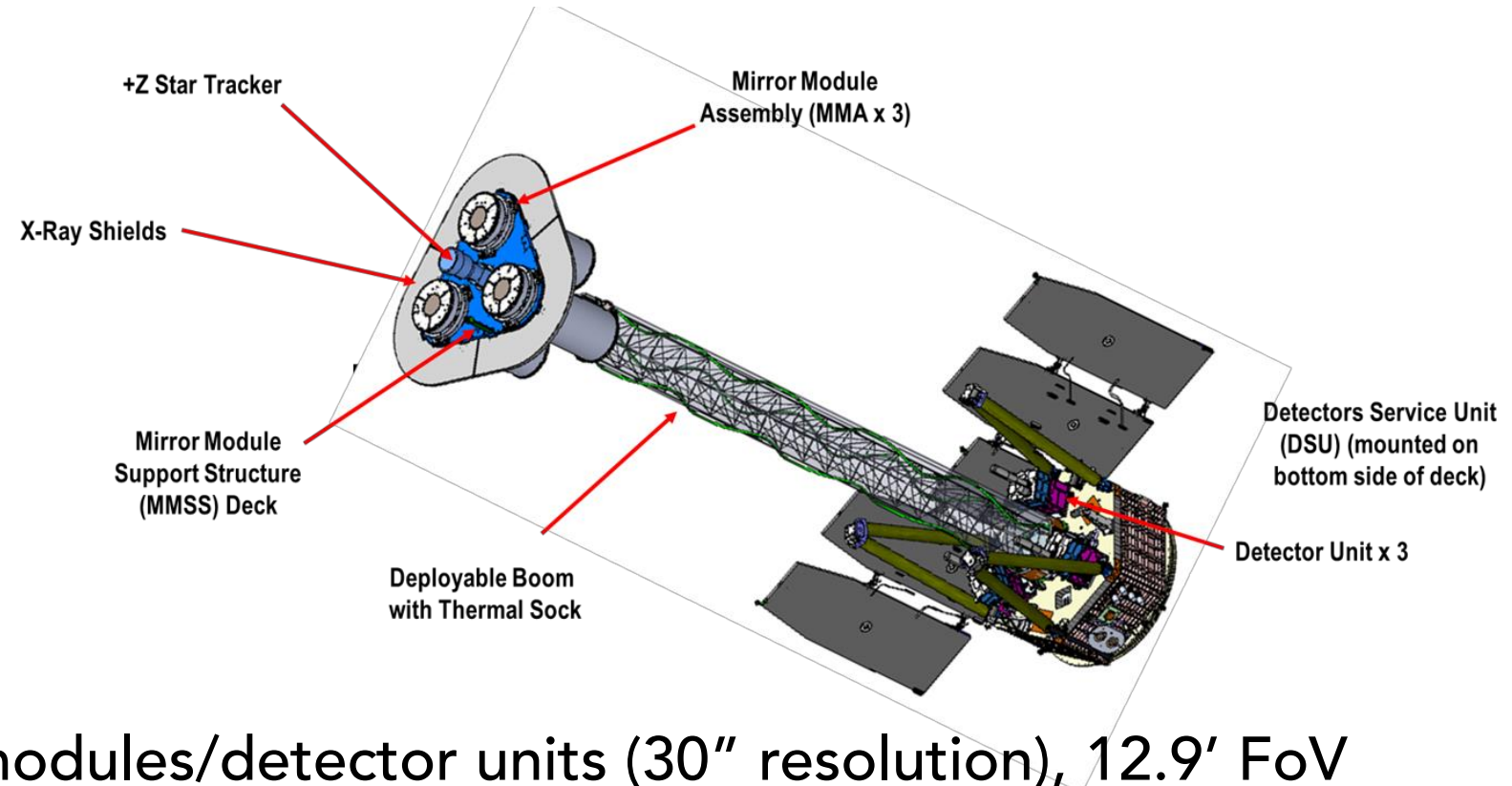
- X-ray synchrotron radiation → only near shocks (not contact discontinuity!)
 - Turbulence expected to be high here (at least upstream)
- Only young (<3000 yr) SNRs show X-ray synchrotron radiation
- Complication: also thermal X-rays (except Vela Jr, RXJ1713)

Imaging X-ray Polarimetry Explorer (IXPE)



- NASA/ASI small explorer mission: launched Dec. 9 2021
- US: spacecraft + X-ray mirrors; Italy: detectors

Imaging X-ray Polarimetry Explorer (IXPE)



- 3 X-ray mirror modules/detector units (30" resolution), 12.9' FoV
- Gas-pixel detectors

Measuring X-ray polarization with IXPE

Weisskopf+ '22

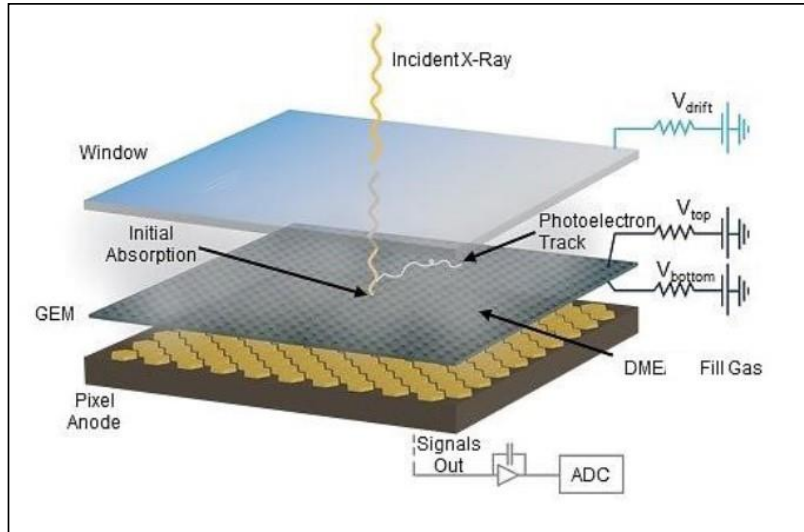
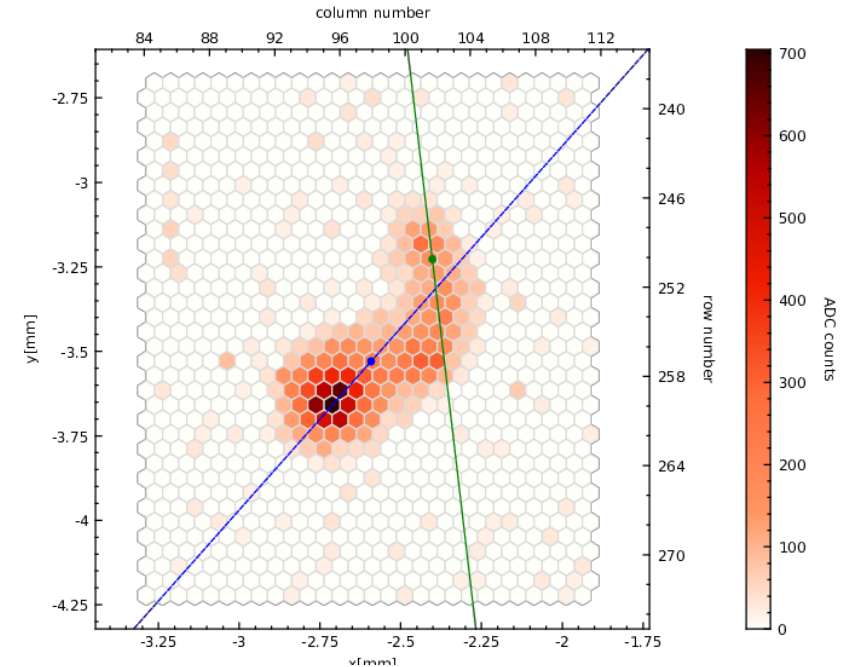
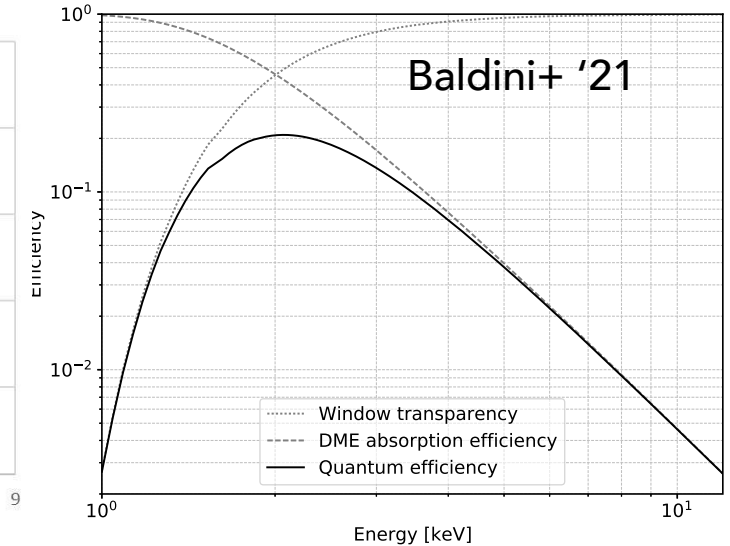
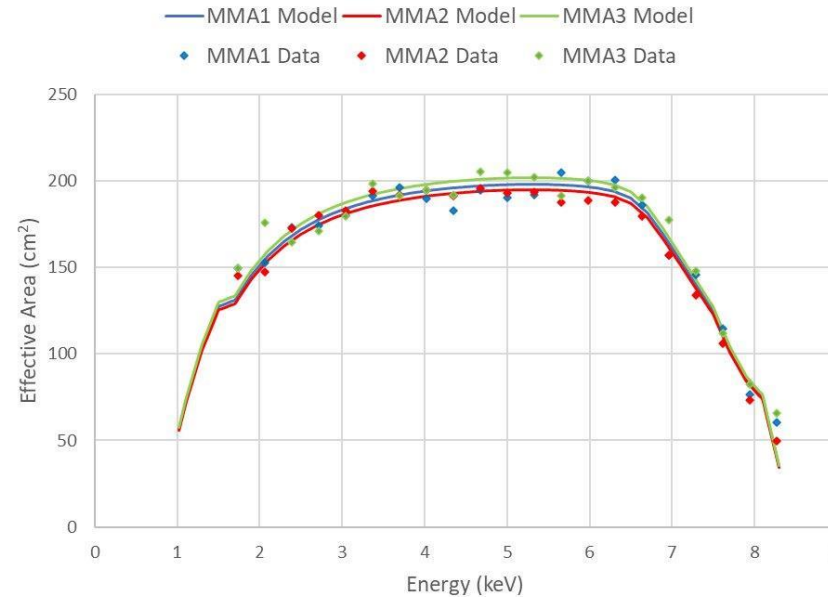
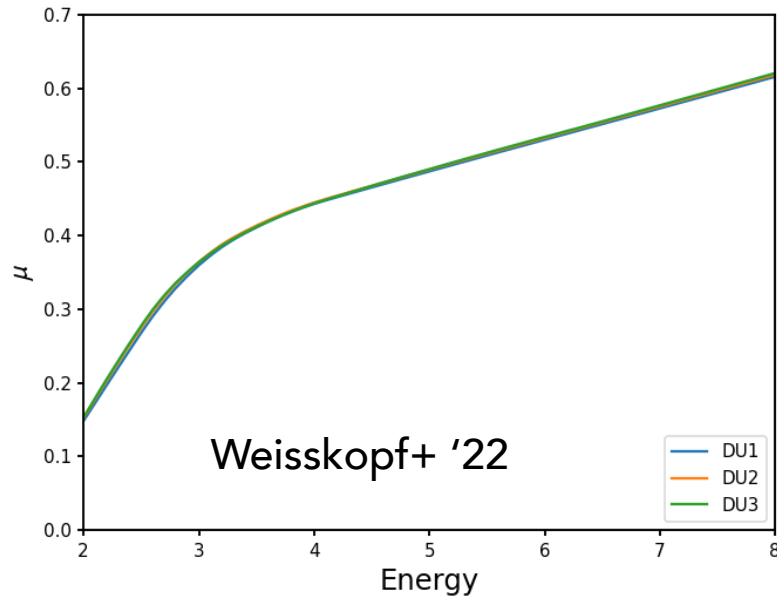


Figure 9: Schematic of the Gas Pixel Detector (GPD)



- Gas Pixel Detector: photo-electron (pe) angle $\phi \propto \cos^2 \psi$
 - pe creates secondary electron cloud: shape used to determine Φ
- Φ determined from shape of secondary electron clouds

Modulation curve and efficiency

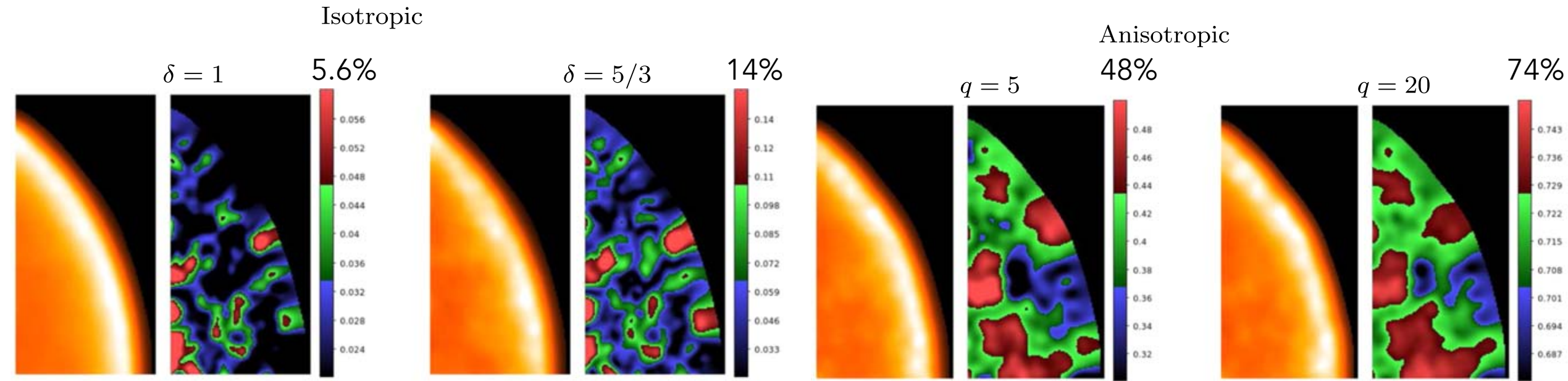


- For ideal detector estimator for Q and U:
 - $Q = \sum_i q_i = \sum_i 2 \cos(2\phi_i)$, $U = \sum_i q_i = \sum_i 2 \sin(2\phi_i)$
 - factor 2: needed as response $\propto \cos^2 \psi$ (not $\propto \cos \psi$)
- GPD detector: errors in measuring $\Phi \rightarrow$ degradation of polarization signal
- Degradation captured by "modulation curve" (μ): response to 100% polarized source
- IXPE optimum: ~ 3 keV (large μ , reasonable eff. area)

Naive expectations for IXPE observations young SNRs

- From radio observation: expect radial B-field!
 - *But:* at shock perpendicular field compressed: tangential B-field?
 - Could radial magnetic field establish further away from shock?
- We need turbulence for DSA: polarization fraction low
 - *But:*
 - B-field compressed: impinges a preferred B-field direction
 - Steep synchrotron spectrum in X-rays: intrinsically more highly polarized
 - Small filaments: less line of sight effects than in the radio
 - Turbulent field theories (e.g. Bell instability): concern upstream magnetic field

IXPE -like simulations Bykov et al. 2020



- Aimed at predictions for IXPE Tycho's observations
- Simulations assume either shock-compressed or isotropic B-field fluctuations
- Assumes turbulent spectrum $\delta B^2(k) \sim k^\delta$ ($\delta=1, 5/3$), with cutoff for $k^{-1} \sim 10^{18}\text{cm}$
 - For Cas A/Tycho 10^{18}cm : $20''$

Analysis of IXPE data

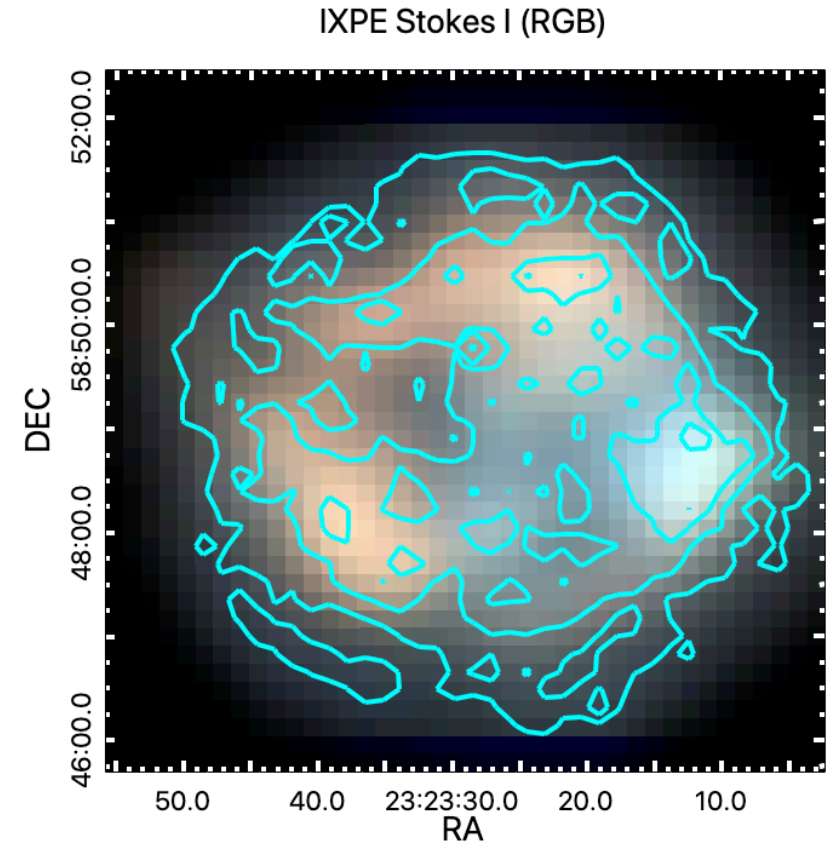
- Main SW tool: *ixpeobsim* (Baldini+ '21)
- Additional method: spectral polarimetry
- Cas A, Tycho: account for thermal emission
- Use of chi-square statistics:

$$Q = \bar{\mu}^{-1} \sum_k q_k, \quad U = \bar{\mu}^{-1} \sum_k u_k$$

- Expectation values $E[Q]=0, E[U]=0$

$$S \equiv \frac{Q^2}{\text{Var}(Q)} + \frac{U^2}{\text{Var}(U)} \text{ has } \chi^2_2 \text{ distribution}$$

- Significances: $2\sigma: \chi^2 = 6.18, 3\sigma: \chi^2 = 11.8, 4\sigma: \chi^2 = 19.3$

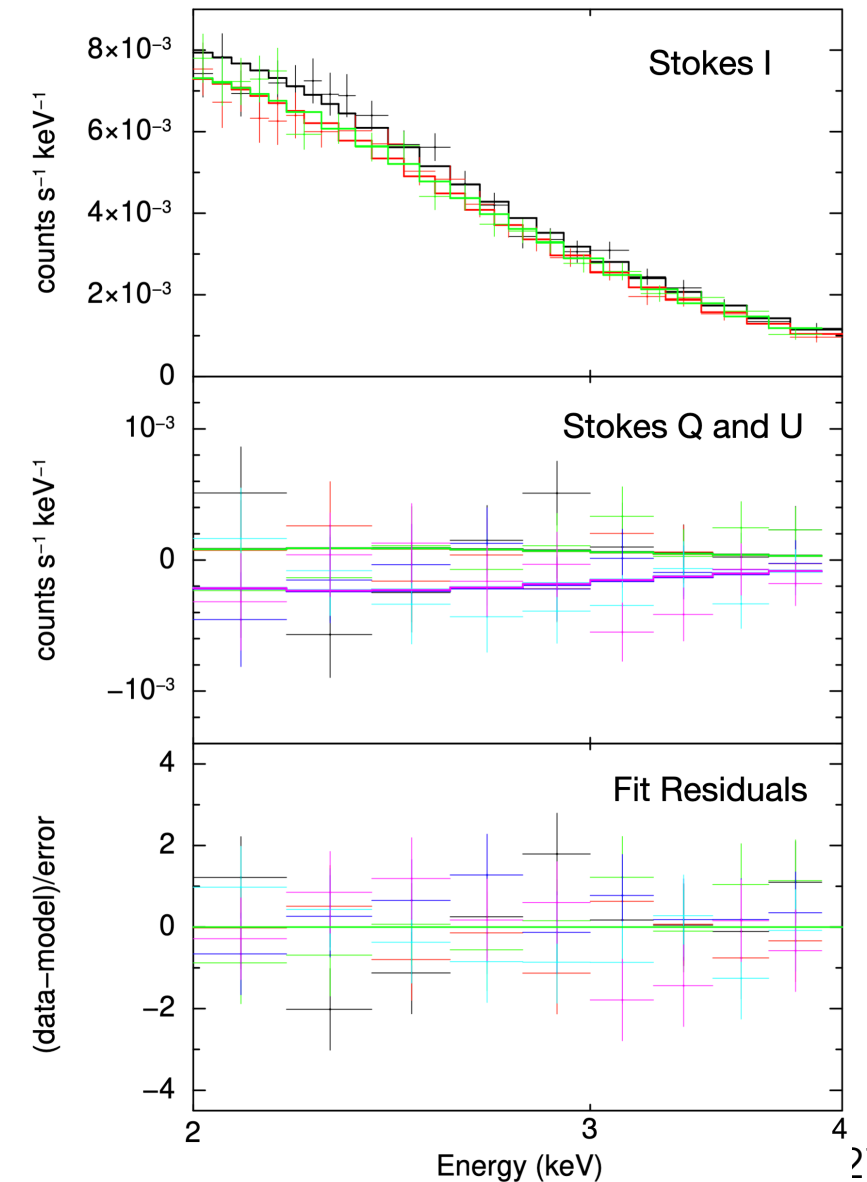


X-ray spectroscopic analysis

- Per energy bin:

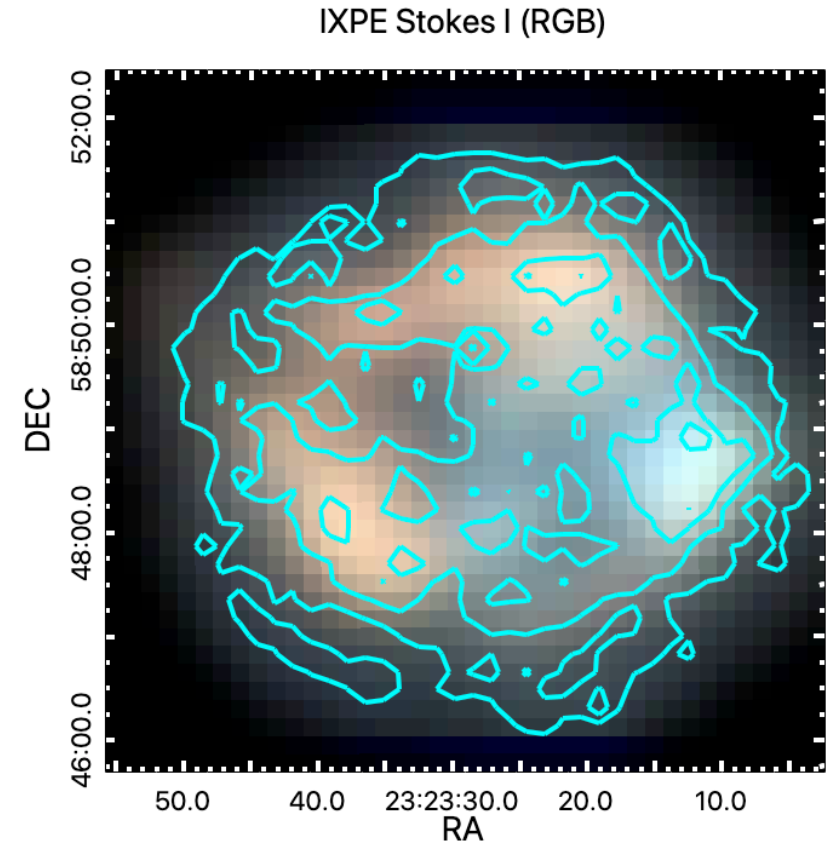
$$Q(E_j) = \frac{1}{\sum_i w_i} \sum_i w_i q_i(E_j), \quad U(E_j) = \frac{1}{\sum_i w_i} \sum_i w_i u_i(E_j)$$

- Fit simultaneously I, Q, and U spectrum
- Forward folding:
 - instrumental modulation factor prescribed
 - Polarization degree and angle: predict signal in Q, U spectra
- Big advantage over imaging technique:
 - Take care of thermal components and background

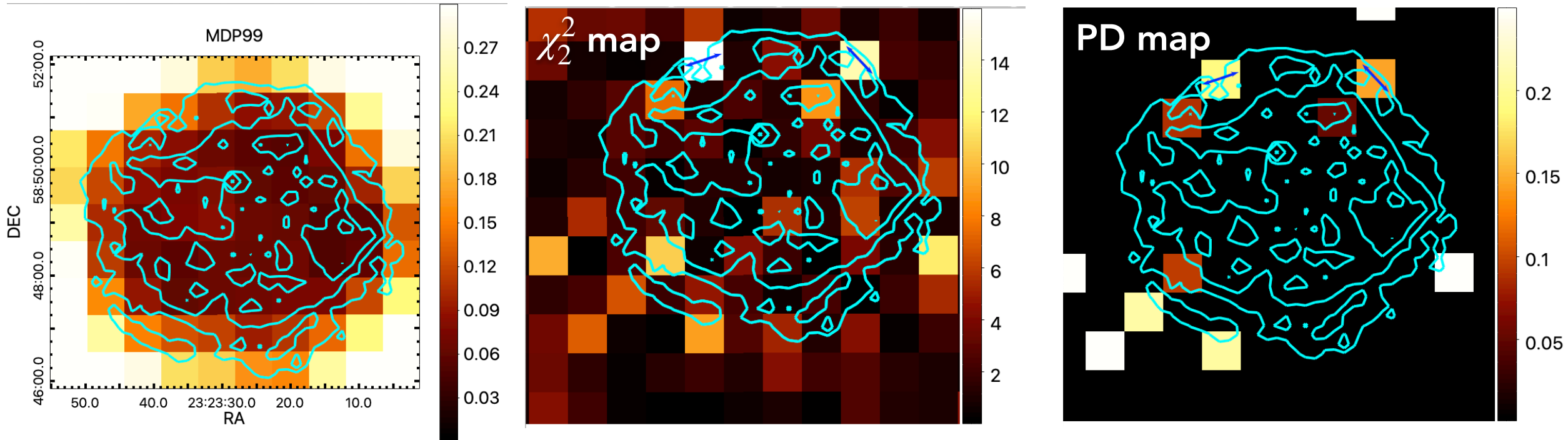


The IXPE observations of Cas A

- Youngest core collapse SNR (350 yr)
- Brightest radio source in sky
- Observations: January 11-29, 2022 (~900 ks)
- Initially some calibration/SW issues:
 - bending boom on orbital phase
 - corrected in released event list
 - remaining spurious offsets (removed by team)
 - 2.5' remaining WCS error (corrected for by team)
 - uncertainties about correctness u and q columns
 - PI/energy reconstruction imperfect (charge buildup) and det. unit dependent
- Effective exposure: 819 ks



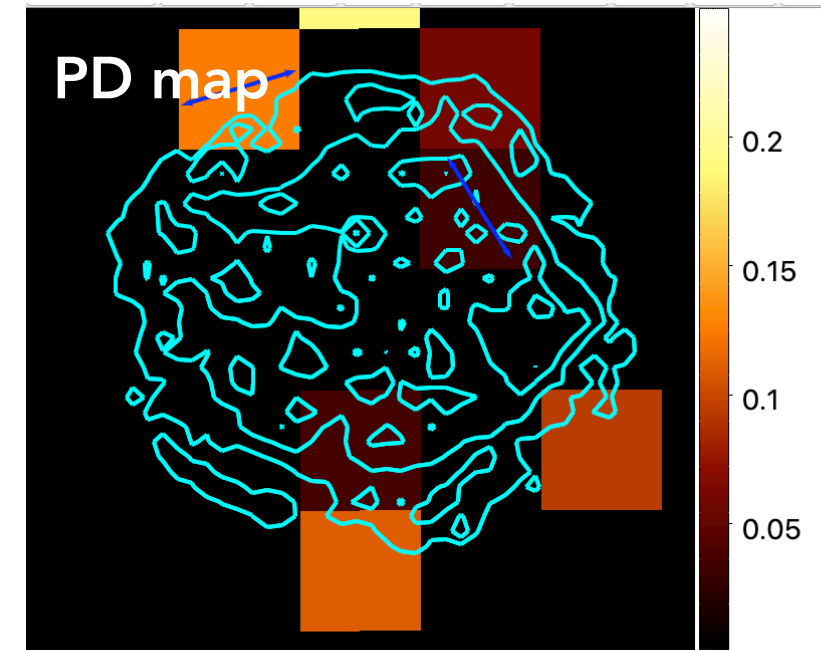
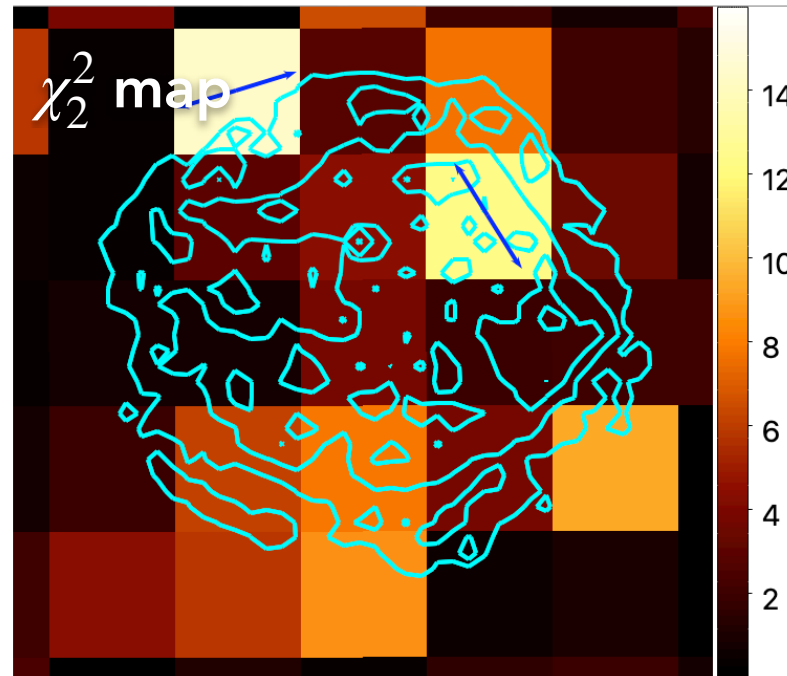
Pixel-by-pixel analysis



Vink+ 2022

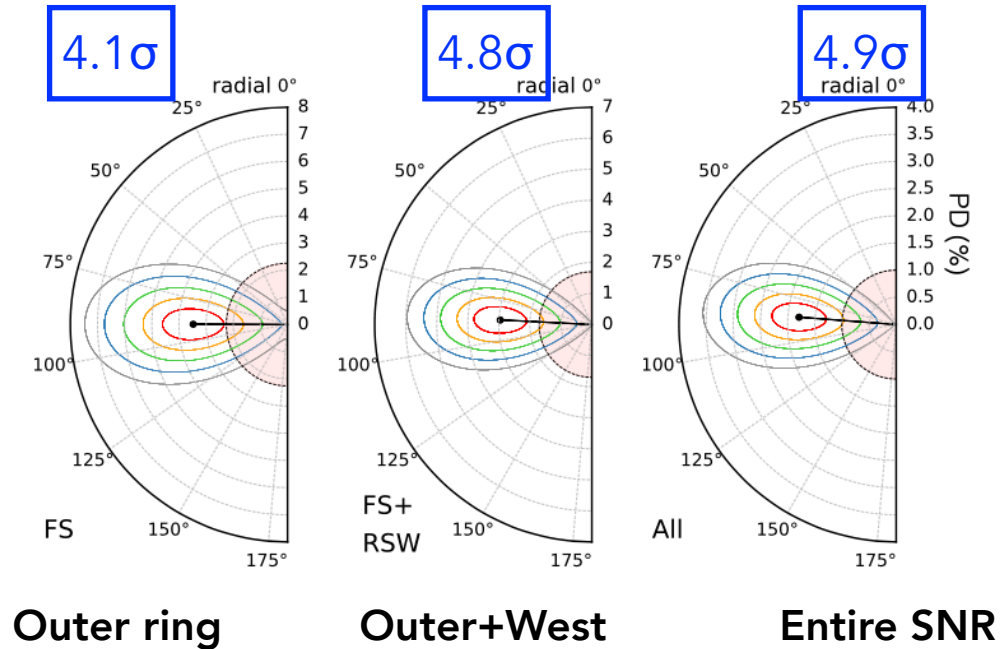
- MDP99 for Cas A (42" pixels): ~6—18% (3-6 keV)
- Typically two pixels at $>3\sigma$ ($\chi^2 > 11.8$) found, but position shifts for different binnings
- Cas A covered by ~200 resolution elements:
 - ~0.5 spurious signals at 3σ level expected $\rightarrow$ hints for pol., no solid detections

Pixel-by-pixel analysis



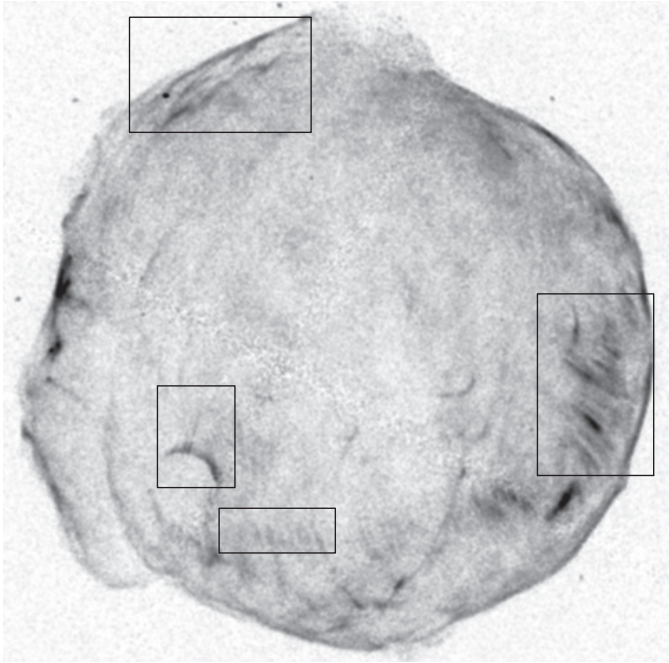
- Peaks in confidence: $\chi^2 \lesssim 15.9$ ($\lesssim 3.5\sigma$)
- Polarization degrees just above MDP99 levels: 4% to 19%
- Conclusion:
 - No solid detections
 - pol. fraction must be low: <4% for inner regions; <15—20% outskirts

Results assuming circular symmetry



- For the outer shock region and FS+W and All: detections at the 4–5 σ level!
- The polarization degree is low: 2—3.5%
 - After correction for *thermal contamination*: 2.4–5%
- The polarization vectors indicate a tangential direction: radial magnetic field!
 - Similar/lower pol. frac than radio
 - *Radial magnetic fields already at 10^{17} cm from shock!*

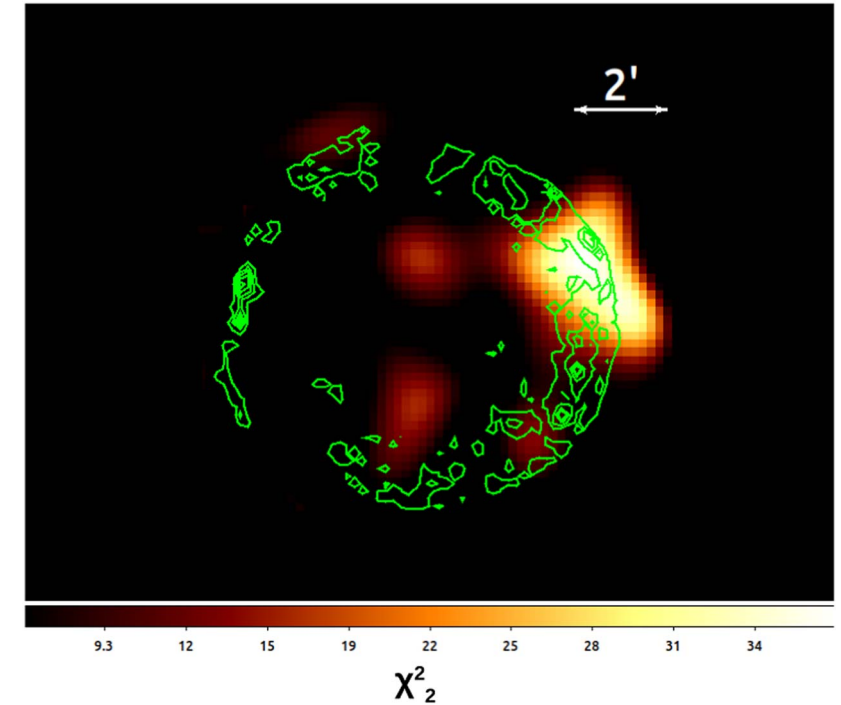
Tycho's SNR/SN1572



Eriksen+ 2011



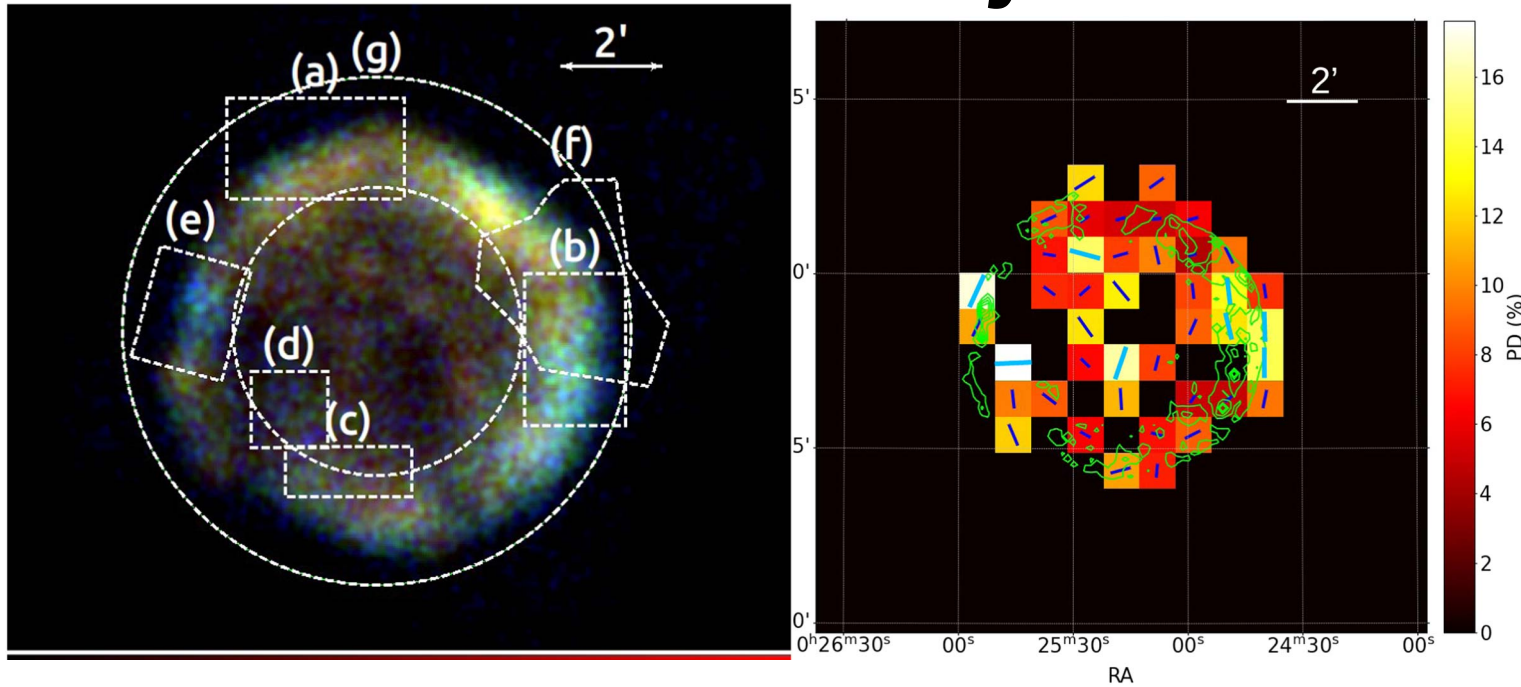
Tycho's stripes!



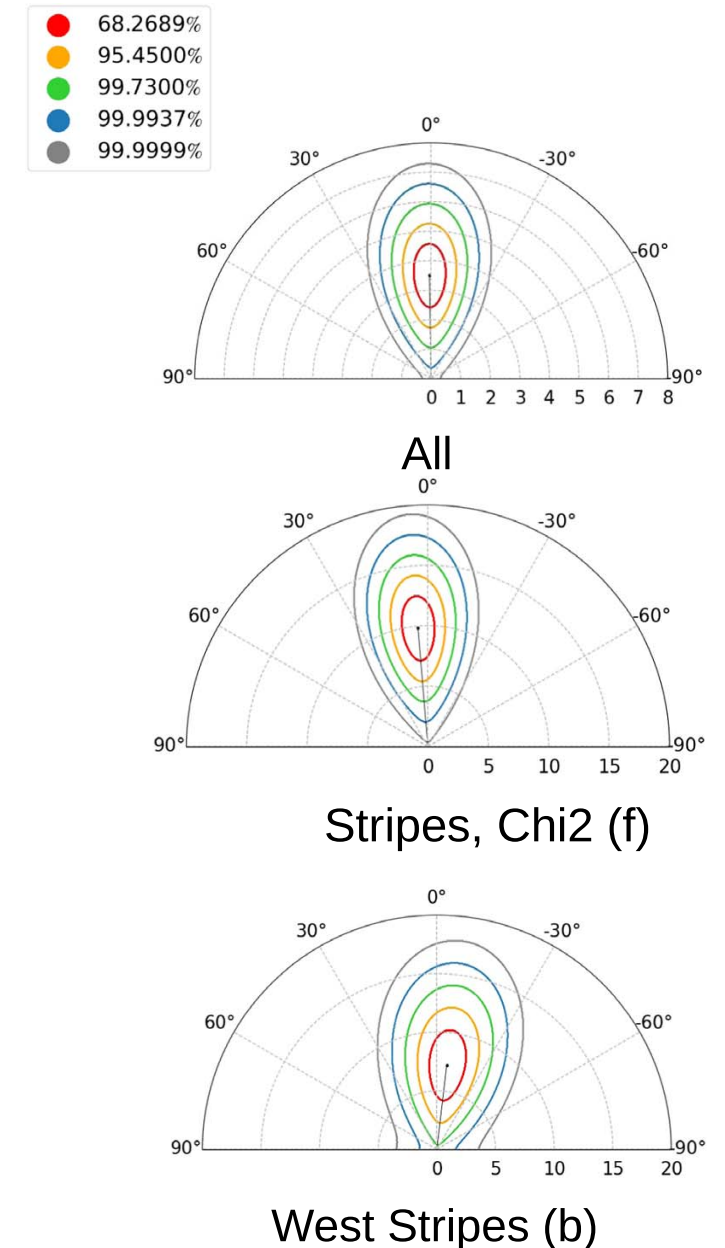
Ferrazzoli+ 2023

- Like Cas A: narrow rims, indicating $B \sim 200 \mu G$
- Special mysterious structures: Tycho's stripes!
 - Is is a magnetic-field pattern $\rightarrow$ expect high polarization fraction!

Tycho's SNR/SN1572 IXPE results

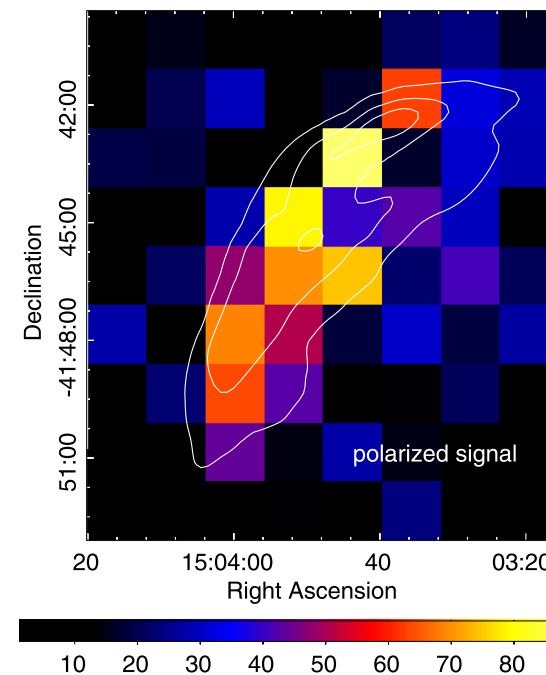
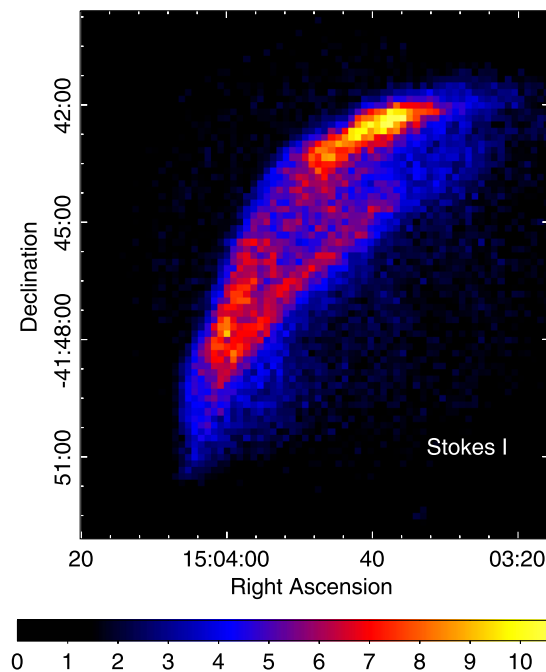
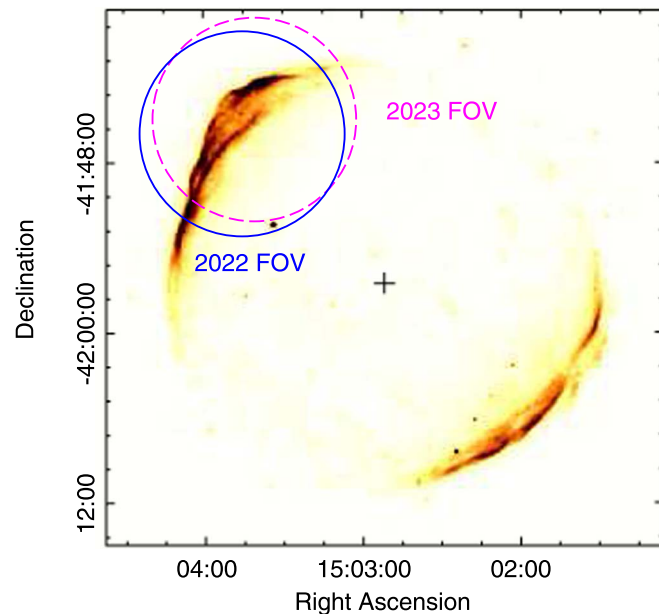


Ferrazzoli+ 2023



- PD corrected:
 - All: 9%; rim: 12%; f: 10% (all $>5\sigma$); b: 7.3% (3.7σ)
- B-field orientation: *radial*!
- *Stripes, don't stand out: PD=7%, 3.7σ , radial B-field*

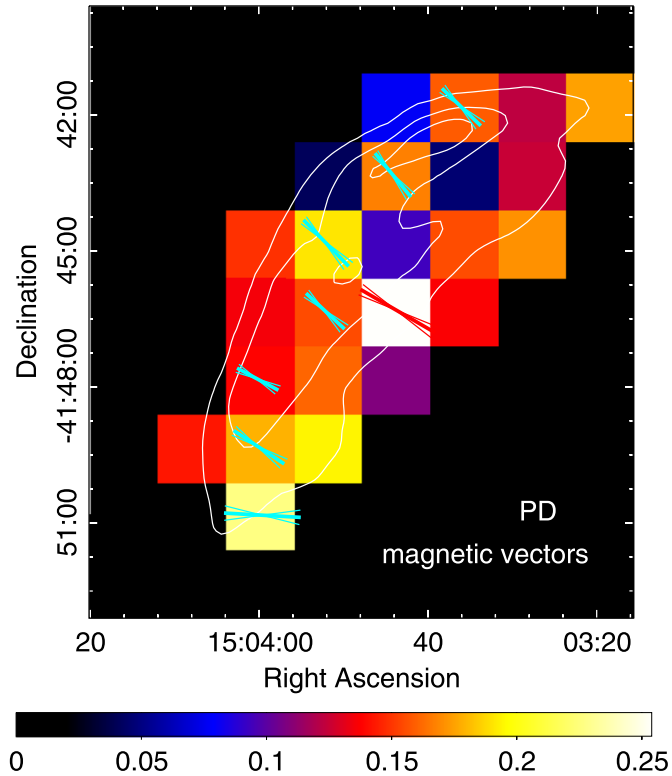
SN1006



Zhou+ 2023

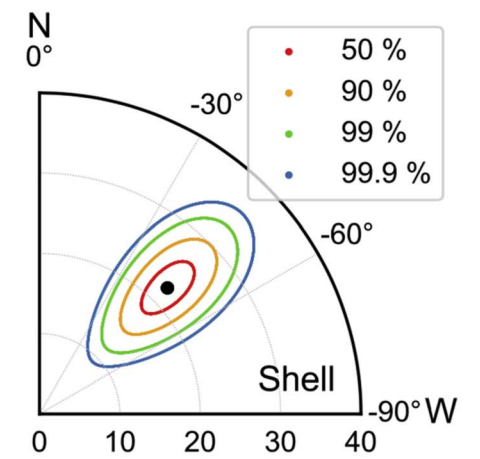
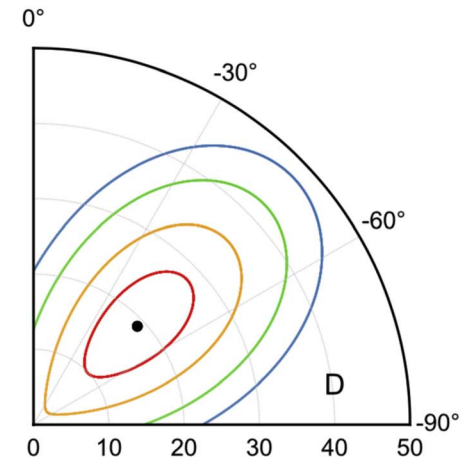
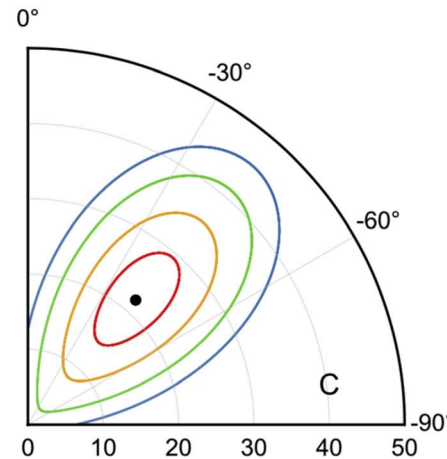
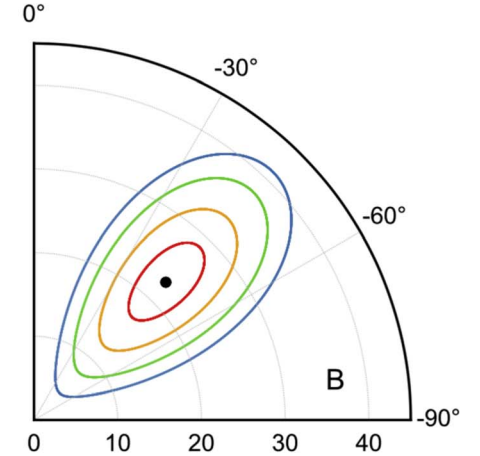
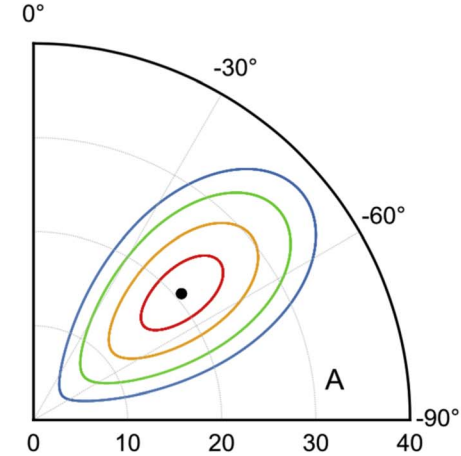
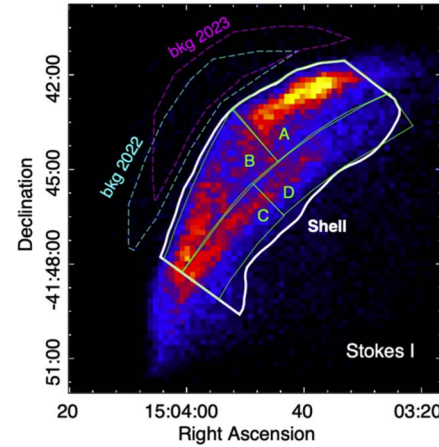
- SN1006 is first SNR for which X-ray synchrotron was discovered (Koyama+ 95)
- Large shell (30'): targetted NE rim
- NE rim: synchrotron dominated (no thermal emission)
- Synchrotron width relatively large: $B \sim 80 \mu G$

SN1006 IXPE results

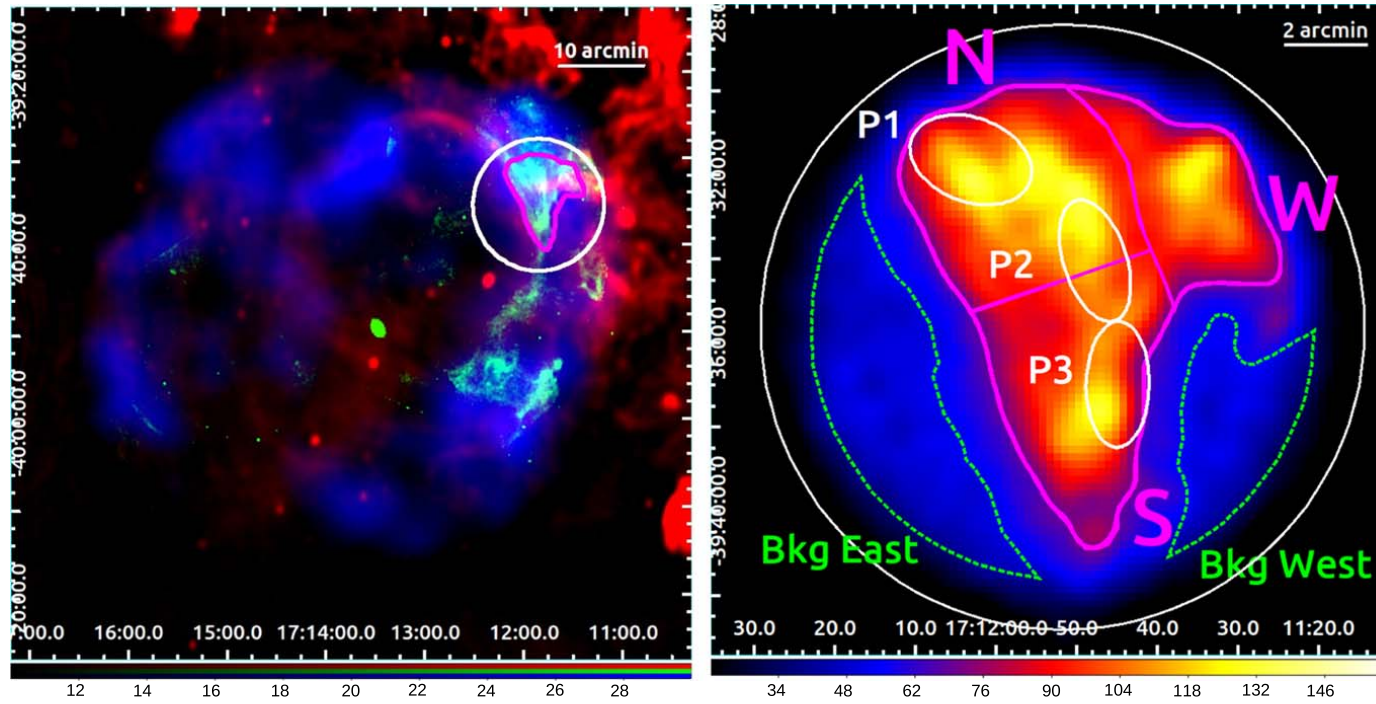


Zhou+ 2023

- Pol. degree: $\sim 22\%$
- B-field orientation: radial
- PD larger than in the radio ($\sim 13\%$)!



RX J1713.7–3946

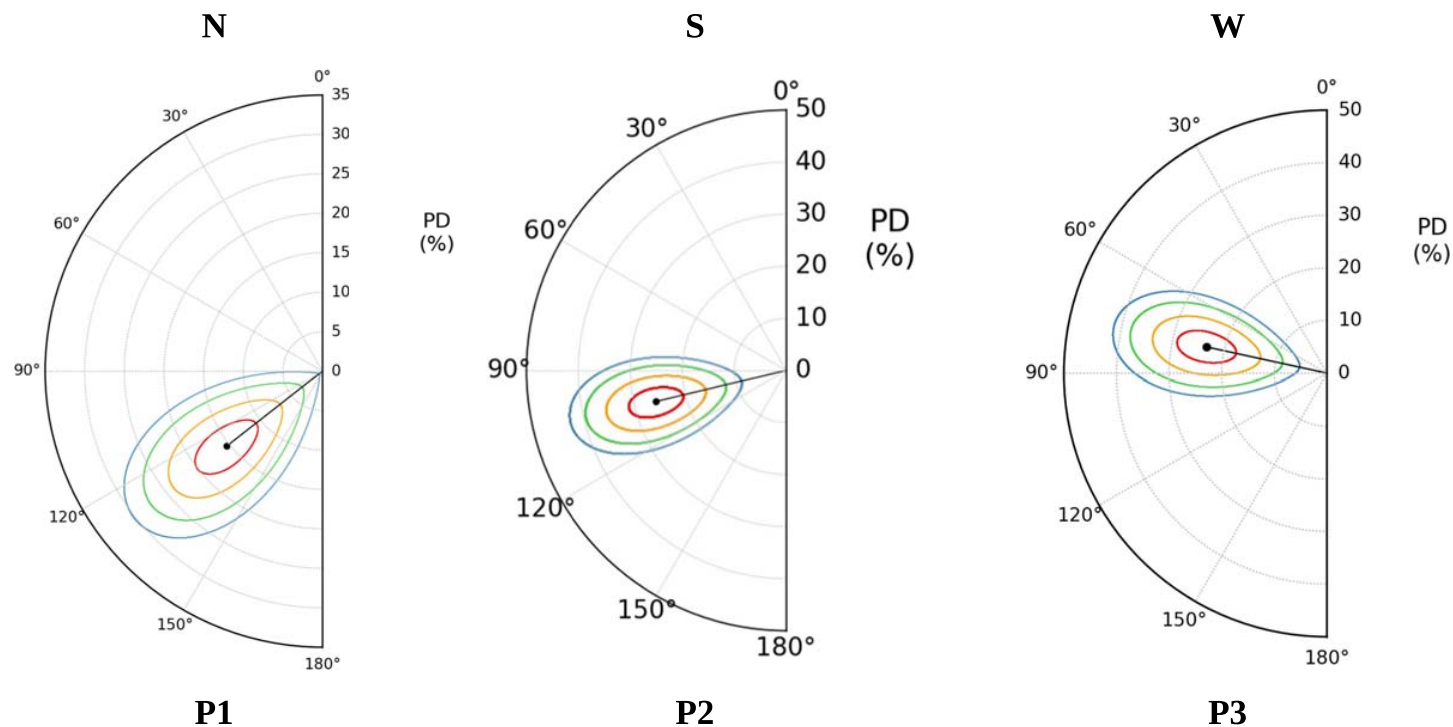
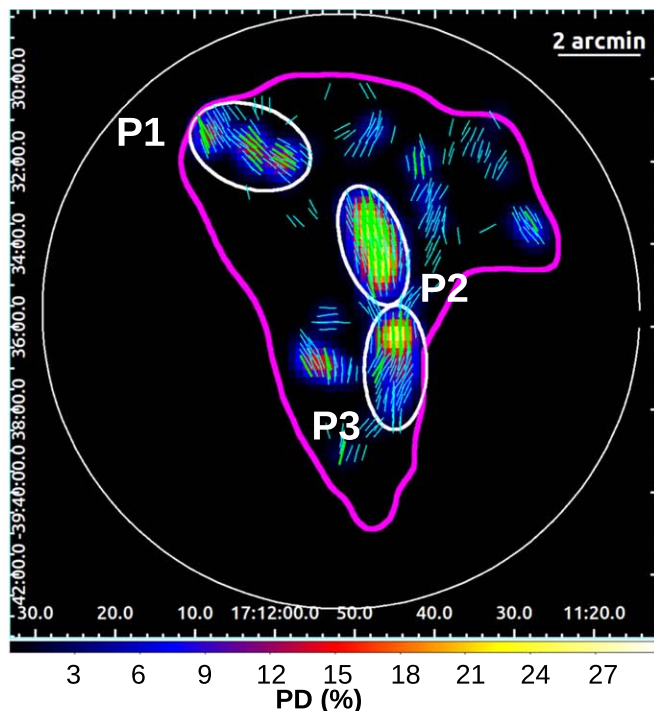


Ferrazzoli+ 2024

See talk by Riccardo Ferrazzoli

- Very large shell: 1 degree
- Nearby: 1 kpc
- No or very weak thermal X-rays
- Wide X-ray synchrotron region: $B \sim 10 - 30 \mu G$
- Faint in radio -> *no reliable radio polarization!*

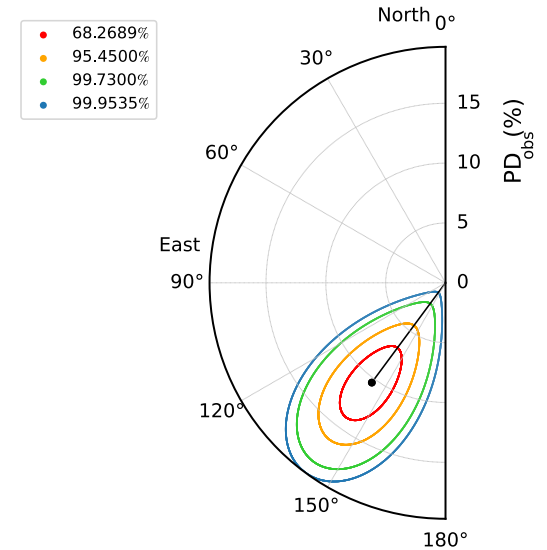
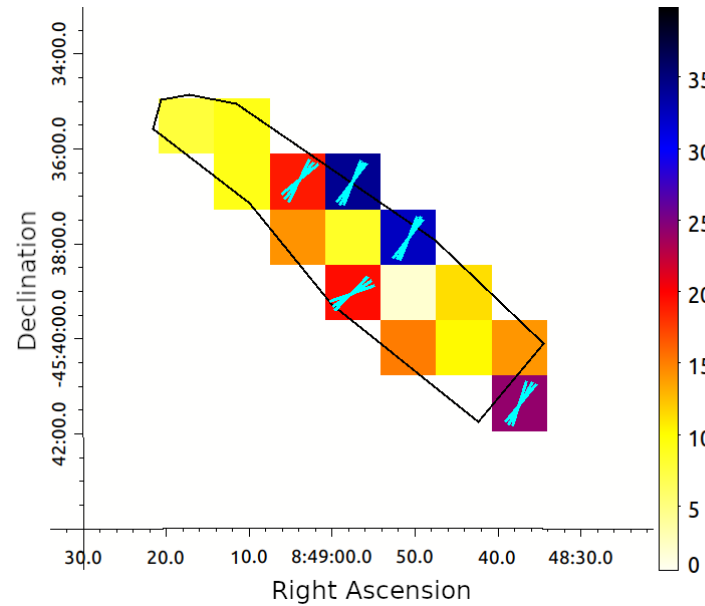
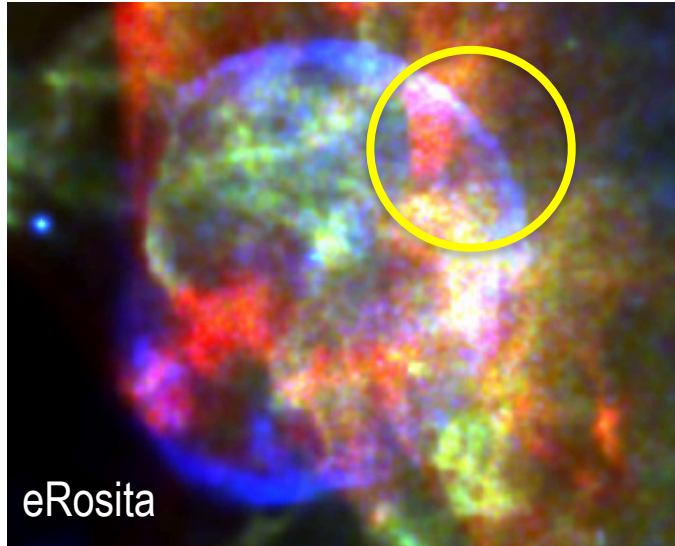
Surprising result RX J1713.7–3946: tangential field!



Ferrazzoli+ 2024

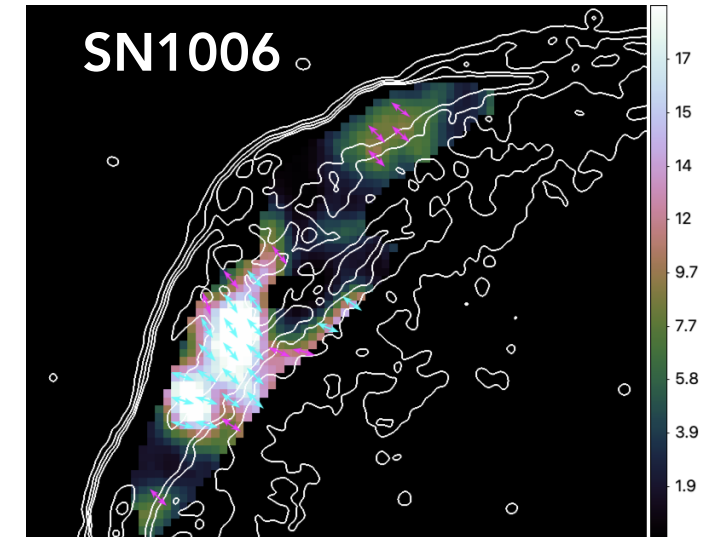
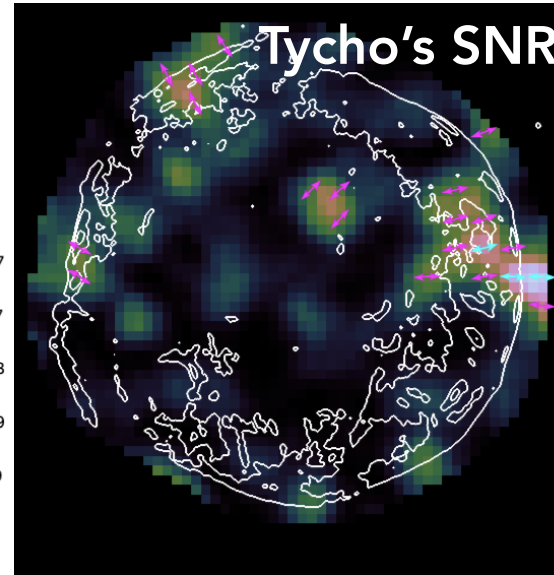
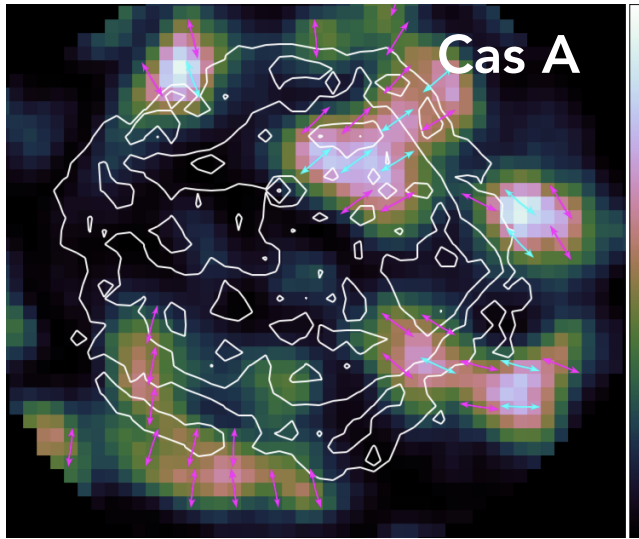
- Pol. fraction (spectral fits): 26-37%
- B-field orientation: *tangential!*
- Highest pol. fraction: very close to shock
 - reorientation/turbulence further downstream?

Vela Jr/RXJ0852.0–4622 (G266.2–1.2)

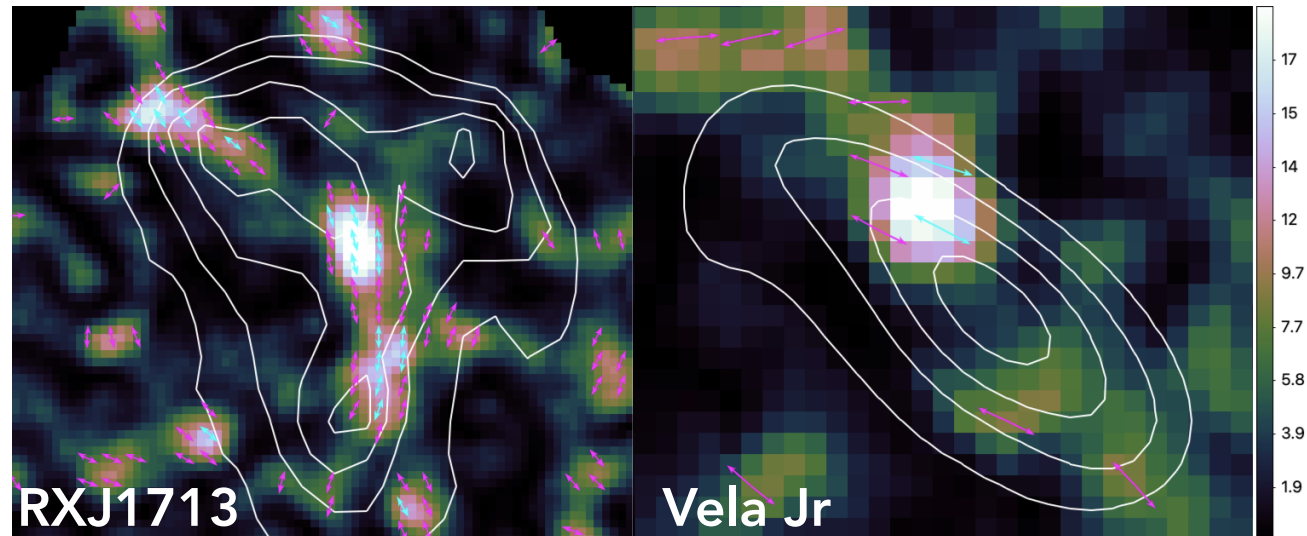


- Large shell: 2 degree, on top of Vela SNR
- B-field estimate (H.E.S.S.): $B_2 \approx 10 \mu\text{G}$
- Probably oldest SNR (~ 3000 yr) with X-ray synchrotron:
 - requires evolution in low density bubble
- IXPE:
 - B- field is *tangential* (like RXJ1713)!
 - $\text{PD} \approx 16 \pm 5\%$

IXPE Statistical maps (χ^2_2)



- $\sim 4\text{-}5\sigma$ detection of polarization
- correct for thermal contributions
- Cas A: only after some tricks:
 - entire SNR only
 - 5% pol. degree
 - high downstream turbulence



Summary PD and orientations

	Age (yr)	B field	P.D.	Orientation B-field	Ref.
Cas A	~350	~250 μG	~5%	radial	Vink+ '22
Tycho	452	~200 μG	~10%	radial	Ferrazzoli+ '23
SN1006	1018	~30-80 μG	~20%	radial	Zhou+ '23
RX J1713	~1500	~20 μG	26%—30%	tangential	Ferrazzoli+ '24
Vela Jr	~3000	~10 μG	10%—20%	tangential	Prokhorov+ '24

- Radial vs tangential: age (or B-field?) dependence in X-rays
- PD low (5-30%)/high B turbulence
- Note: turbulence must be high enough to allow X-ray synchrotron (i.e. $\eta \approx 1$)
 - But: low B $\rightarrow$ long cooling time
 - for RX J1713/Vela jr turbulence for acceleration may be in the past

Turbulence & geometry

- B-field turbulence generated by cosmic rays not resolved by IXPE
 - $\sim 10^{16} - 10^{17}$ cm for Bell instability
 - $\sim 10^{15}$ cm for resonant instability (=gyroradius 10 TeV particles, $B=100 \mu\text{G}$)
 - Turbulence at these scales needed for X-ray synchrotron $\rightarrow$ but not resolved!
 - Bykov+ '20 simulations assumed spectrum up to 10^{18} cm $\rightarrow$ (barely) resolvable
 - Shock compression: imposes preferential, tangential, B-field direction
 - Need to stretch and possibly renew turbulence downstream
- Geometry:
 - Most likely B-field stretching: clumps + Richtmeyer-Meshkov (Innoue+ 13)
 - Competing model by West+ 17 unlikely for X-rays!
 - Bykov+ '24: clumping associated with upstream Bell instability!
 - Bell scales with density and shock velocity

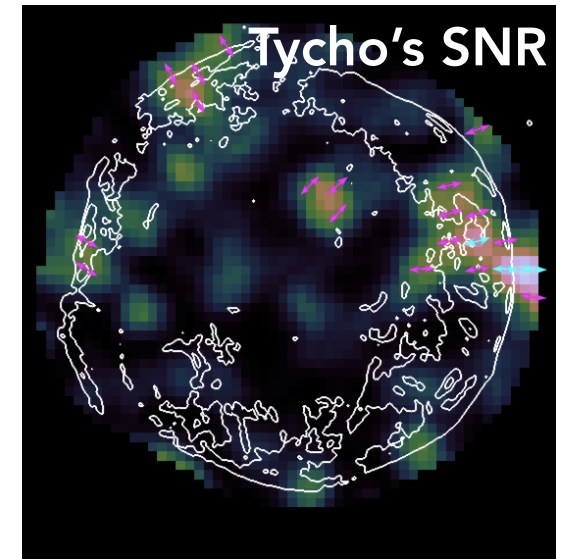
Final suggestion

- X-ray synchrotron provide evidence for Bell magnetic-field amplification
 - Suggests turbulent magnetic field
 - And $B^2 = K\rho V_s^2$ or $K\rho V_s^3$
- But for low density, lower shock velocities $B_{\text{Bell}} \approx B_0$
- Largest polarisation fraction: RXJ1713 and SN 1006 $\rightarrow$ lowest ρ and B
 - Normalizing to Cas A ($n_H \sim 2 \text{ cm}^{-3}$, $V_s = 6000 \text{ km/s}$): $K = 0.15\%$
- For what density and $V_s = 3000 \text{ km/s}$ is $B_{\text{Bell}} \approx B_0 \approx 20 \mu\text{G}$?
 - Answer: $n_H \sim 0.05 \text{ cm}^{-3}$ comparable to RX J1713, Vela jr!
 - But still need sufficient turbulence for acceleration!

Possibility: magnetic fields become tangential when Bell amplification (B_{Bell}) is subdominant compared to pre-existing magnetic-field strength (B_0)!

Summary

- A new window on SNRs has opened: X-ray polarimetry with IXPE
- Target young SNRs:
 - X-ray synchrotron emission associated with the shock regions
 - X-ray synchrotron → requires $V_s > 3000$ km/s and turbulent (*upstream?*) fields
 - Evidence for magnetic-field amplification (Bell 2004)
- IXPE results:
 - Low pol. fraction: 5-30% → requires *downstream* turbulence
 - Radial magnetic fields → stretching field lines starts at shock front
 - Exceptions: RXJ1713 and Vela Jr, both have relatively low B-fields
- Not yet fully understood:
 - Why sometimes radial B-fields close to shock?
 - What generates downstream turbulence? → theory mostly concentrates on upstream mechanisms (Bell instability)
 - RXJ1713/Vela jr: low B-fields, more CSM/Galactic fields?
 - but X-ray synchrotron requires turbulence!



Ferrazzoli+ 2023