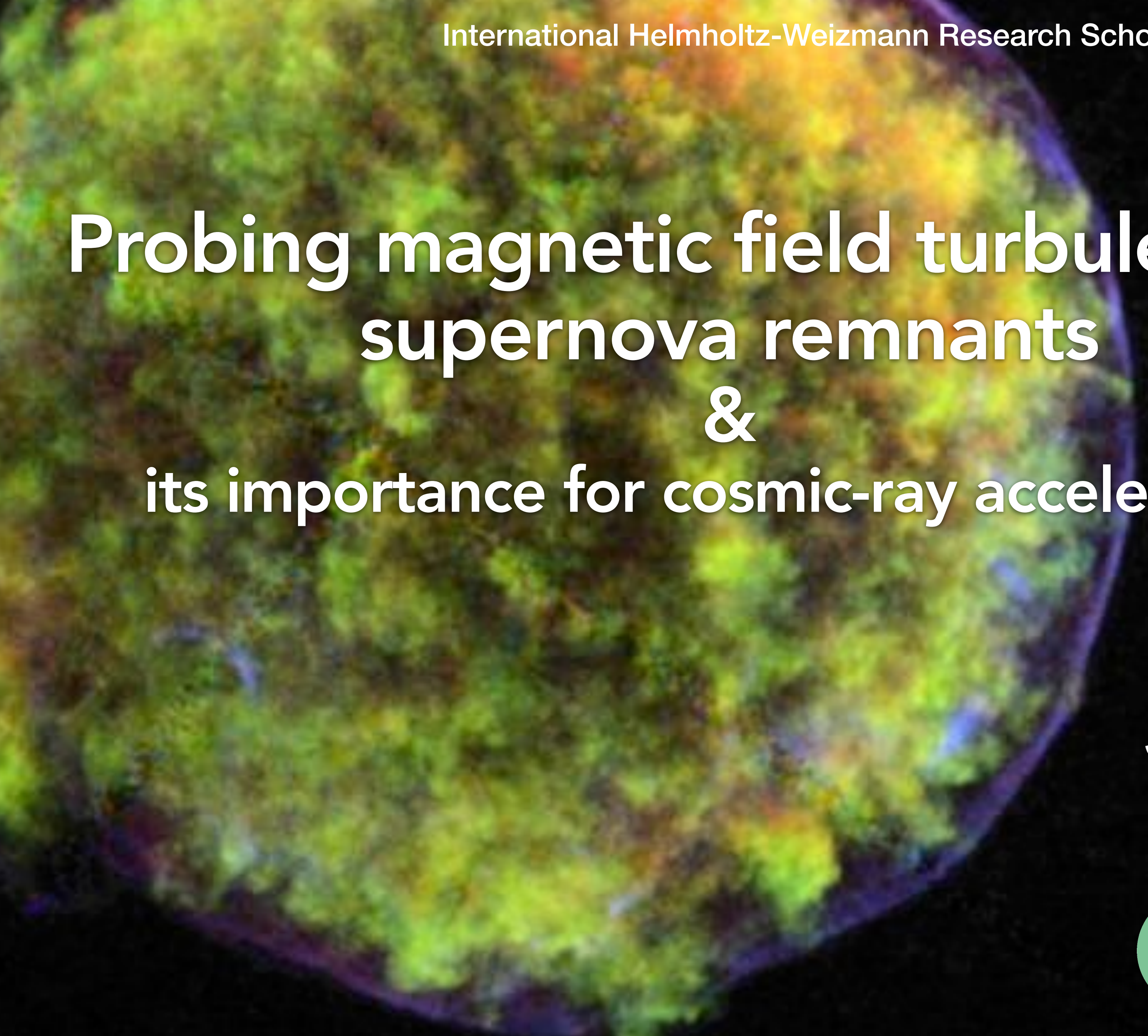
International Helmholtz-Weizmann Research School on Multimessenger Astronomy, June 4, 2025



Probing magnetic field turbulence in supernova remnants & its importance for cosmic-ray acceleration

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UNTERSTÜTZT VON / SUPPORTED BY
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IXPE Collaborators

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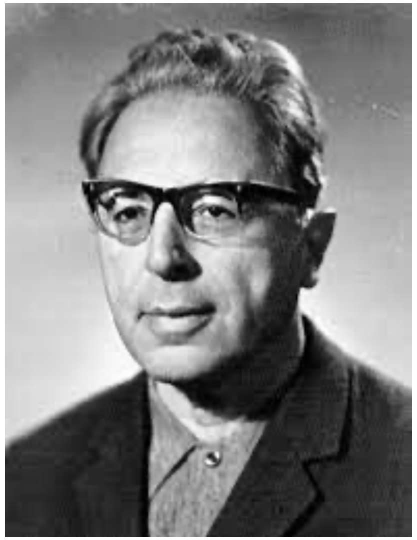
- Dmitry Prokhorov (now Würzburg former postdoc Amsterdam)
- Yi-Jun Yang (Hong Kong)
- Luca Baldini (Pisa)
- Niccolo Buciantini (Arcetri)
- The IXPE team!

Some history

Victor Hess

Walter Baade

Fritz Zwicky



Iosif Shklovsky

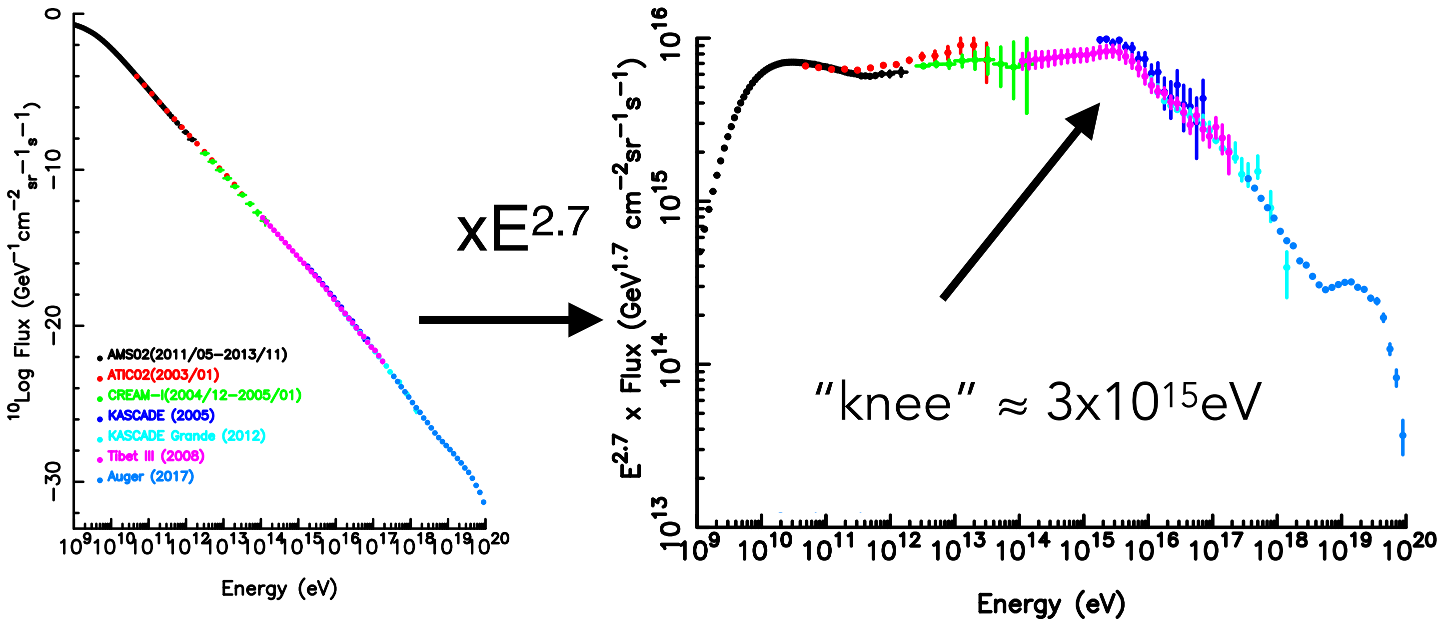
1911: Victor Hess discovers “cosmic rays”

1930s: cosmic rays are energetic particles!

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

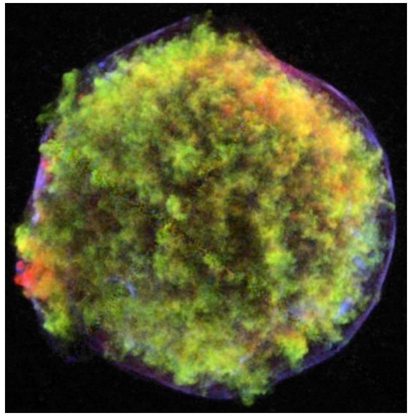
1950: Shklovsky suggests supernova radio emission is caused by relativistic electrons (electron cosmic rays) → synchrotron radiation → predict polarization

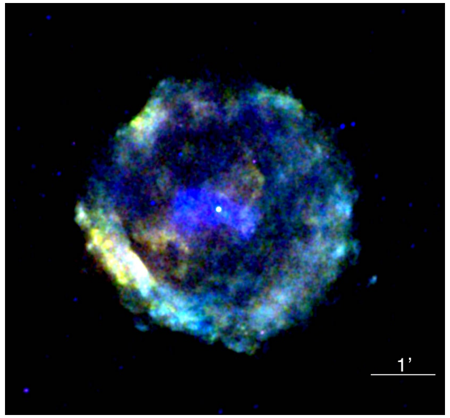
Cosmic rays

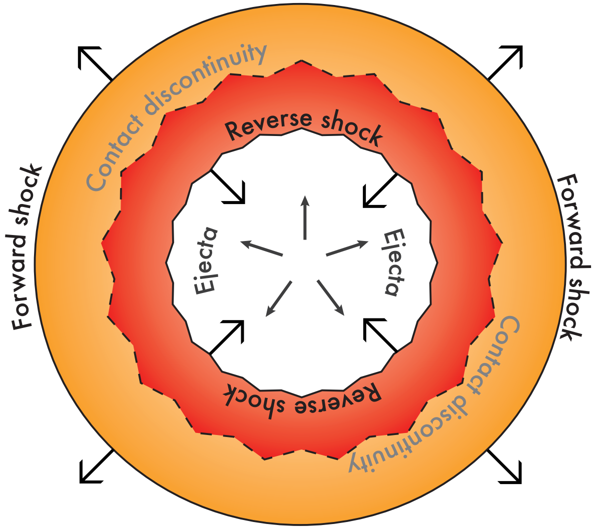


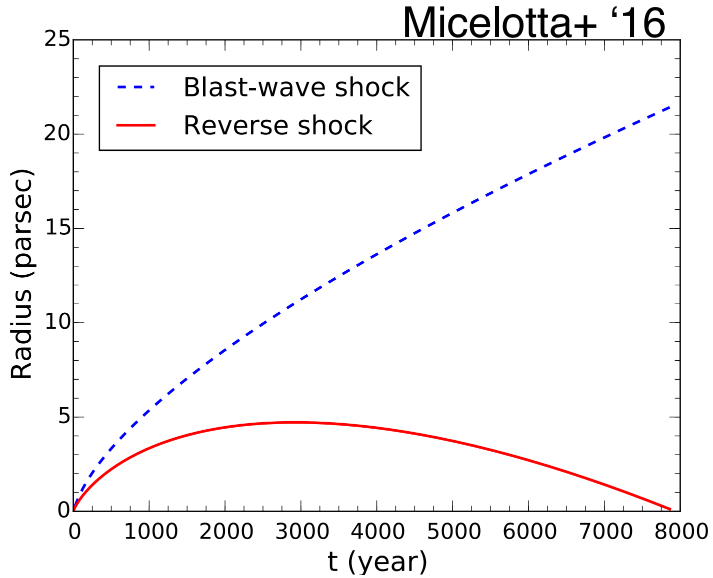
- ISM energy density CRs ≈ 1 eV cm^{-3}, escape time **τ**≈15x10^6 yr
- To fill Galaxy: need a power of dE/dt≈6x10^{40} erg/s
- SN power: dE/dt≈6x10^{41} erg/s (10^{51} erg/SN, 2SNe/100yr)
  - SNRs considered primary sources of cosmic rays!
  - electron/positrons <1%; origin
- Problem: SNRs can explain CR power needed, but not the "knee"

Supernova remnants (SNRs)





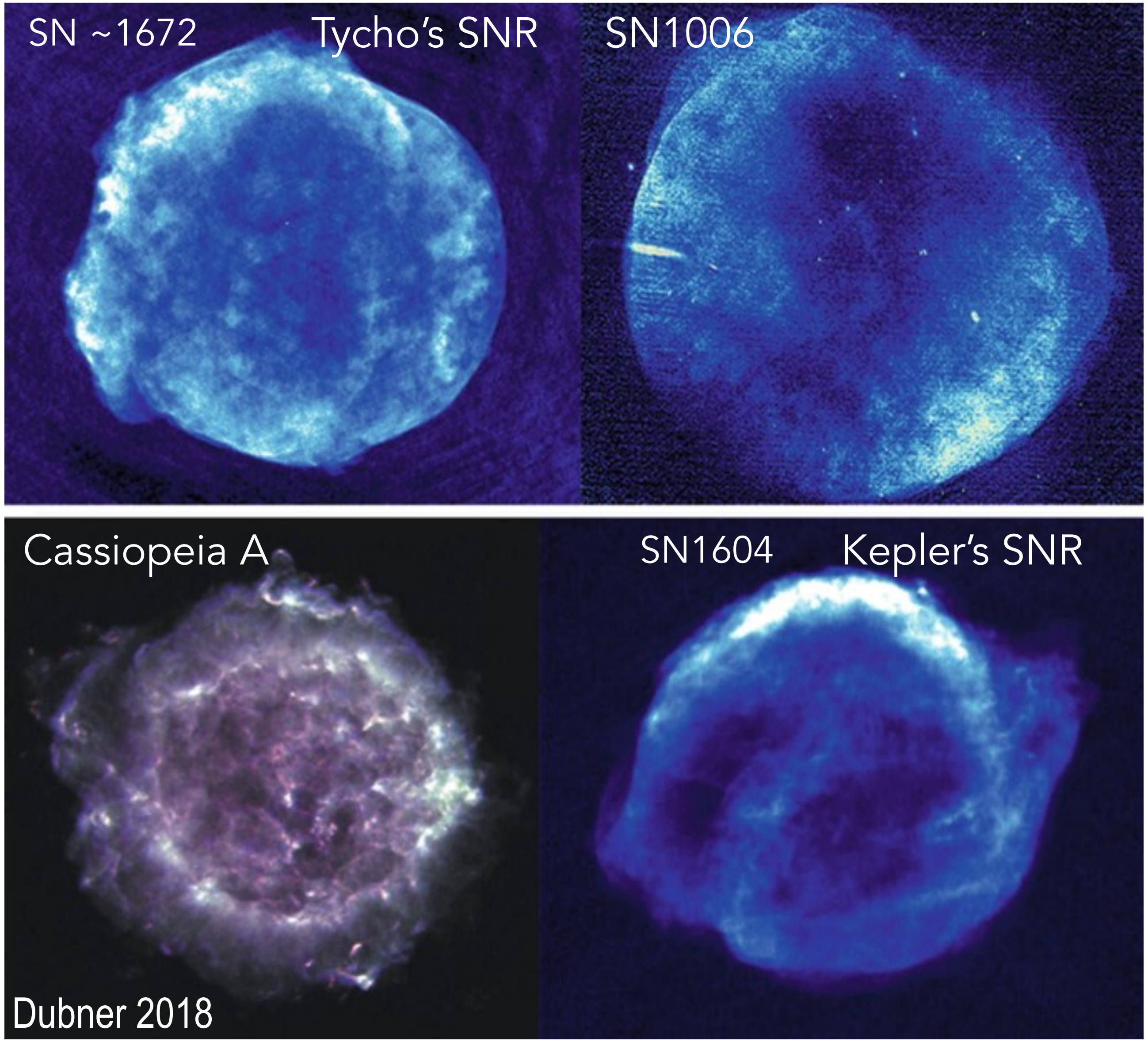




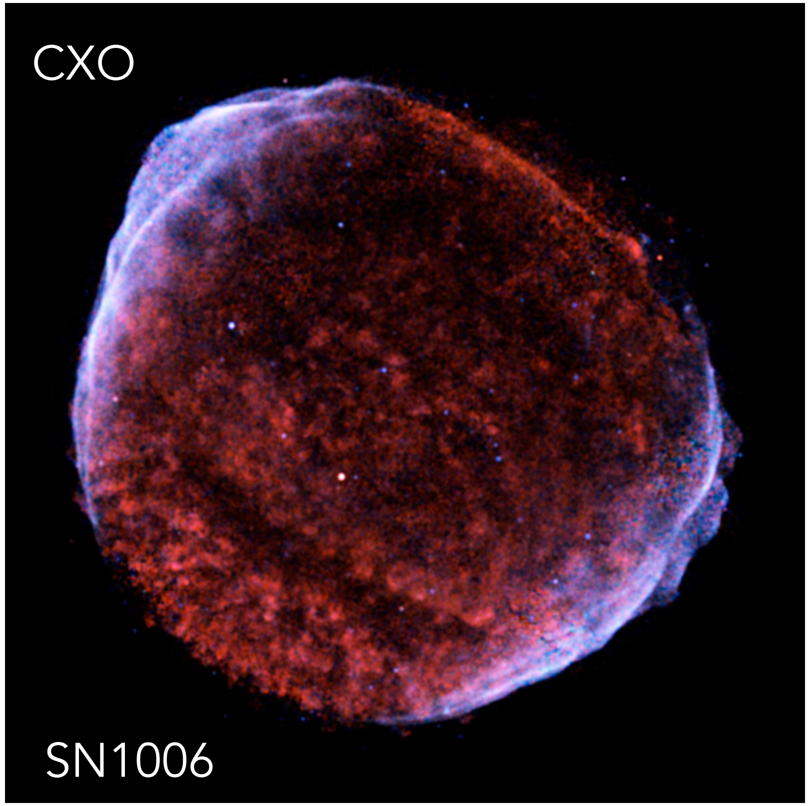
- Initiated by fast/energetic gas ejected by supernova explosion
- SNR shock are *collisionless* shocks:
  - shock transitions *not* due to atom-atom collisions
  - allows for (or results in?) cosmic-ray acceleration
- Young SNRs have two shocks:
  - forward shock (blast wave): shocks CSM/ISM
  - reverse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

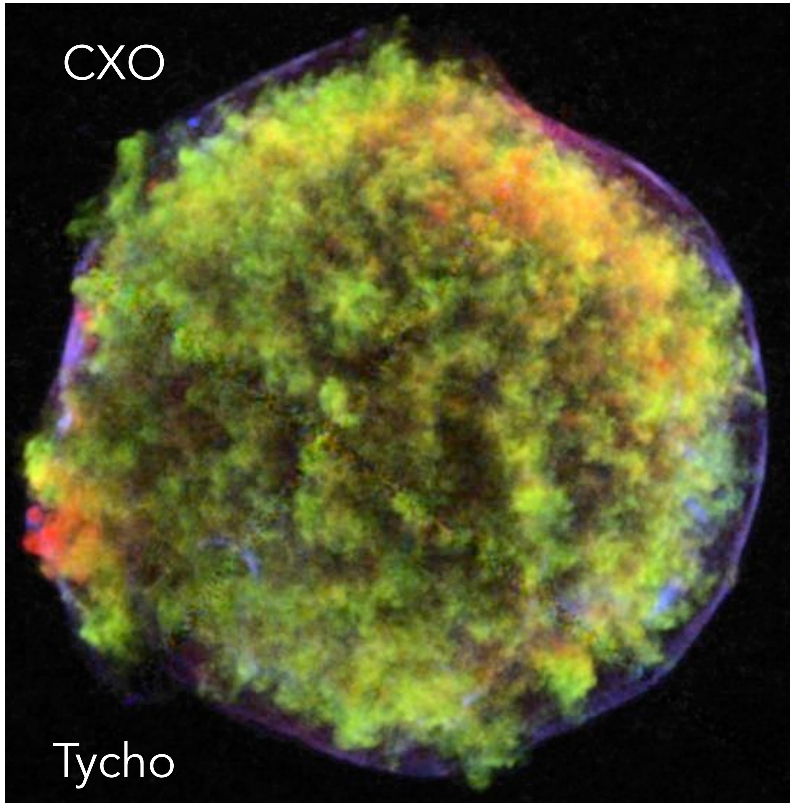
Radio maps of young supernova remnants (VLA)

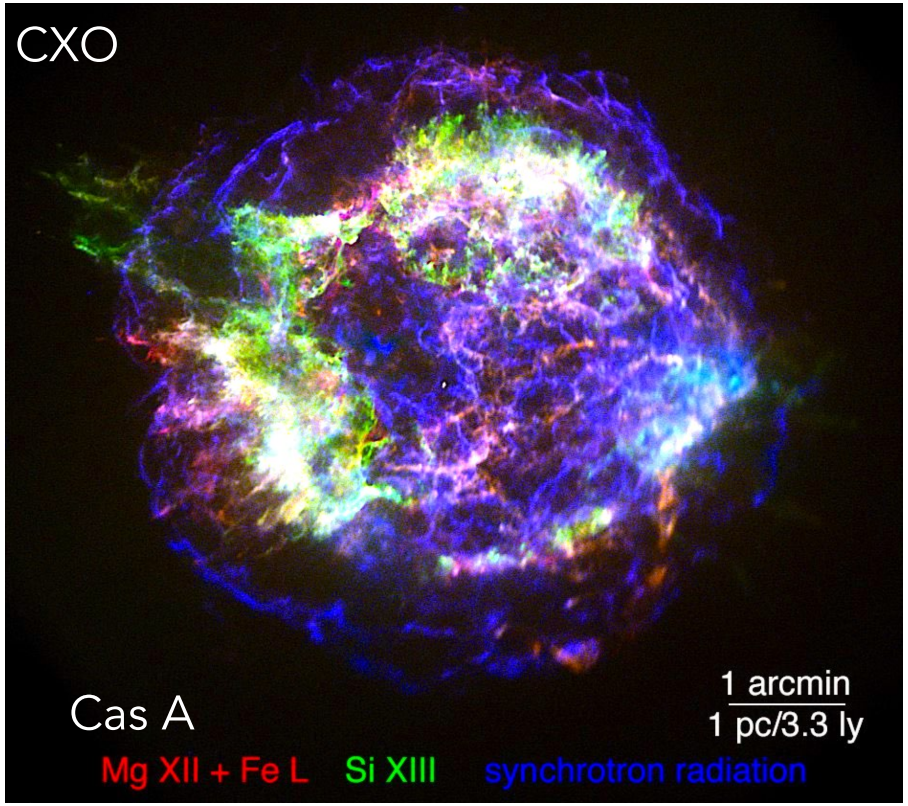
- Radio synchrotron emisson
- Requires ~GeV electrons
- Early evidence that SNRs accelerated particles (electrons) to relavistic energies



X-ray synchrotron emission from young SNRs

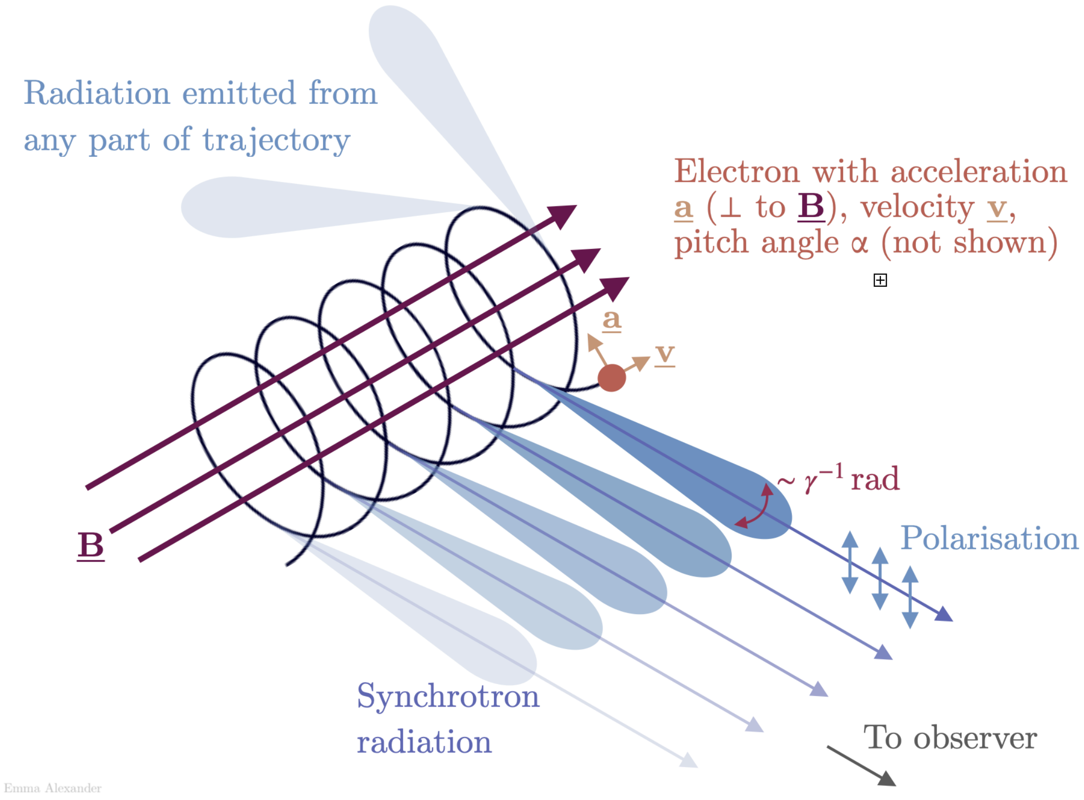






- Since 1995 (Koyama+ 95): young SNRs identified as X-ray synchrotron sources
- Requires 10-100 TeV electrons!

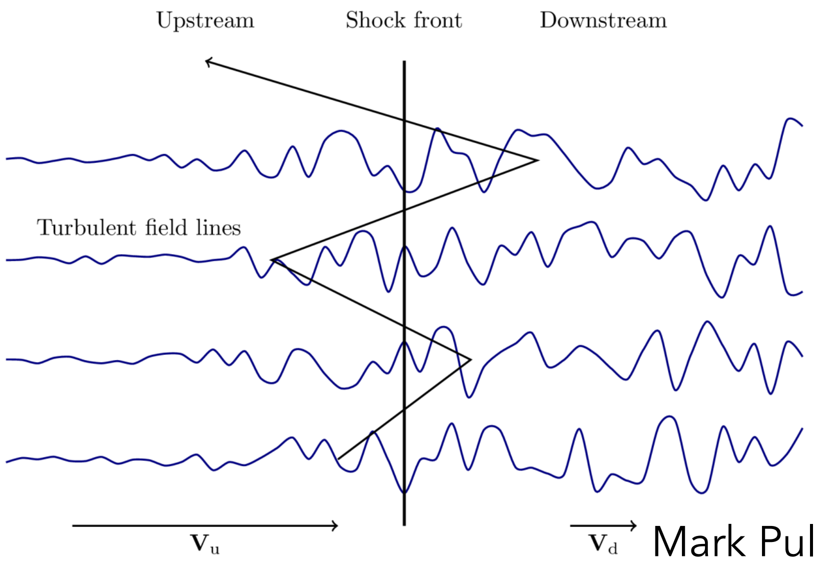
Polarization in astrophysics



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

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

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



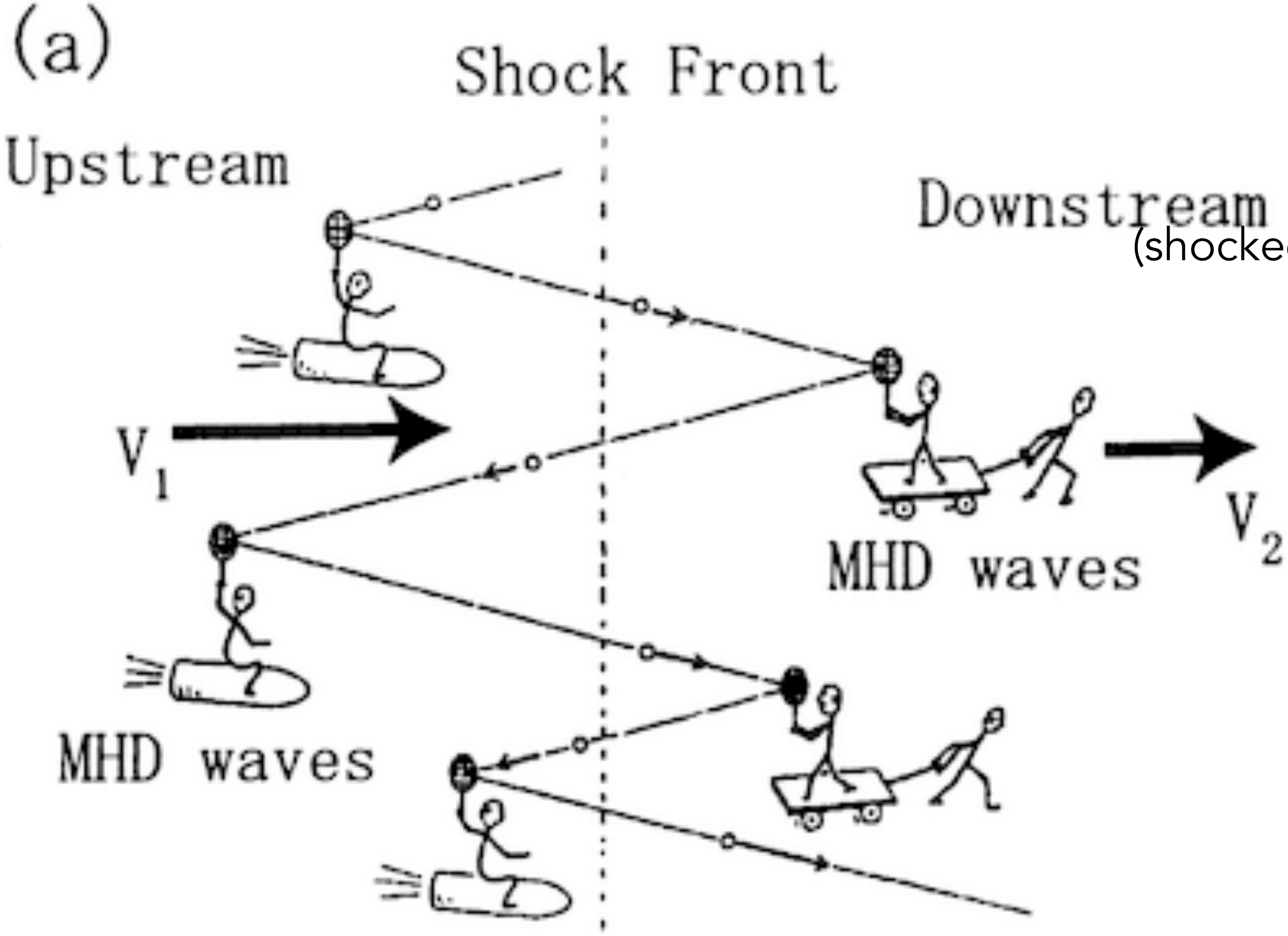
Mark Pullupa

- Particles gain energy by crossing shock:
  - ΔV_{plasma} → Lorentz boost of $\dfrac{\Delta E}{E} \approx \dfrac{\Delta V}{c}$
  - Diffusion: particle can cross shock $D = \dfrac{1}{3}c\lambda_{\text{mfp}} = \dfrac{1}{3}\eta r_{\text{g}} = \dfrac{1}{3}\eta\dfrac{E}{eB}$
  - Acceleration time: $\tau \approx \dfrac{8D_0}{V_{\text{s}}^2}$ → $E_{\text{max}} \propto \eta^{-1}BV_{\text{s}}^2 t$
- Higher energy: V_s high, B high and $\eta \approx \left\langle (\delta B/B)^2 \right\rangle^{-1} \approx 1$

turbulent fields!

DSA cartoon

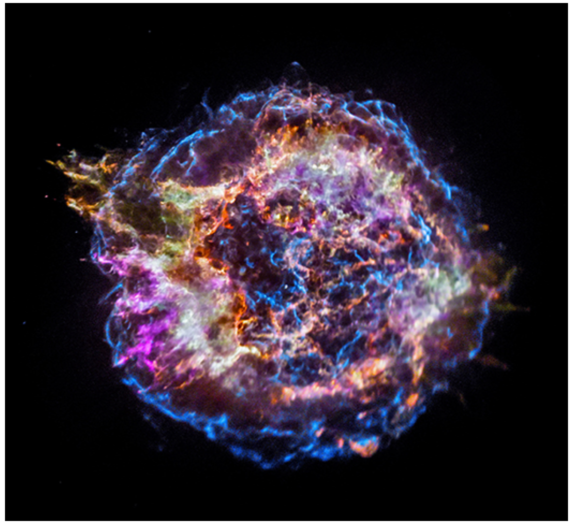
(unshocked)



(shocked)

M. Scholer

X-ray synchrotron radiation

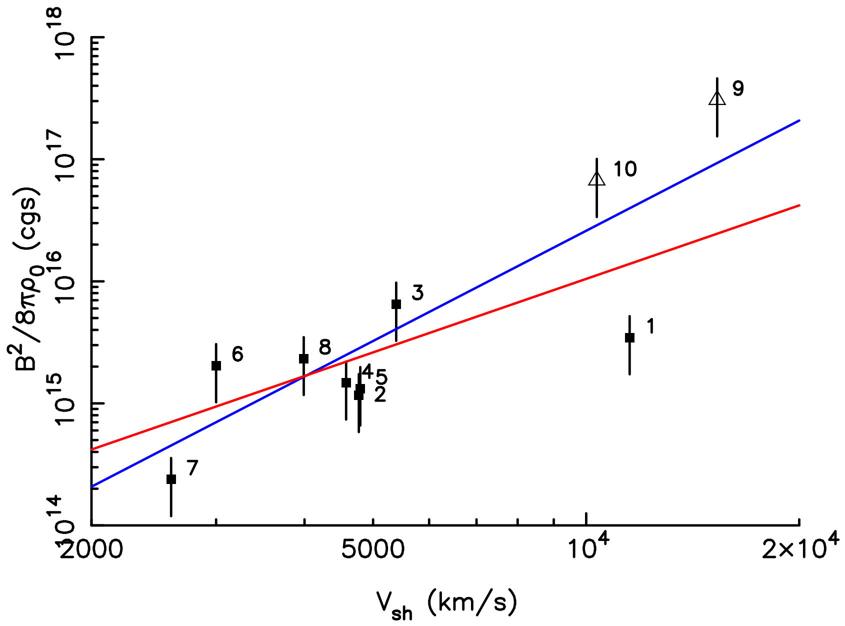


- Requires >10 TeV electrons:
  - $h\nu \approx 19 \left(\frac{B}{100\ \mu\mathrm{G}}\right)\left(\frac{E}{100\ \mathrm{TeV}}\right)^2\ \mathrm{keV}$
- Electrons cool fast:
  - $\tau_{\mathrm{cool}} \approx 12.5 \left(\frac{B}{100\ \mu\mathrm{G}}\right)^{-2}\left(\frac{E}{100\ \mathrm{teV}}\right)^{-1}\ \mathrm{yr}$
  - →Acceleration needs to be fast
  - →Electrons "out of contact with shock" will not emit X-rays
  - →Narrow X-ray filaments
- Combination of acceleration and cooling: $h\nu_{\mathrm{cutoff}} \approx 1.4\eta^{-1}\left(\frac{V_{\mathrm{sh}}}{5000\ \mathrm{km/s}}\right)^2\ \mathrm{keV}$
  - $\eta \approx \left\langle (\delta B/B)^2 \right\rangle^{-1} \approx 1$ turbulence parameter
- Electrons have cooled when far from shock: $B \approx 110 \left(\frac{l}{10^{17}\ \mathrm{cm}}\right)^{-2/3}\ \mu\mathrm{G}$

Magnetic -field amplification

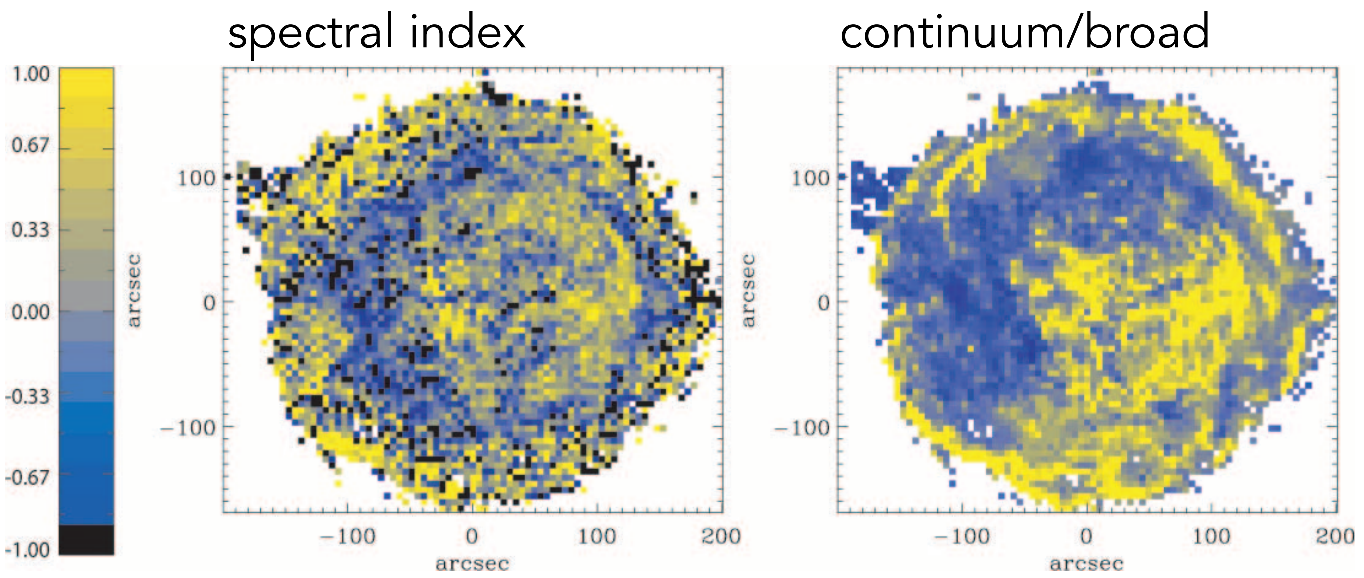
Helder, JV, + 2012

ID	SNR	Dist (kpc)	$n_{H,0}$ (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

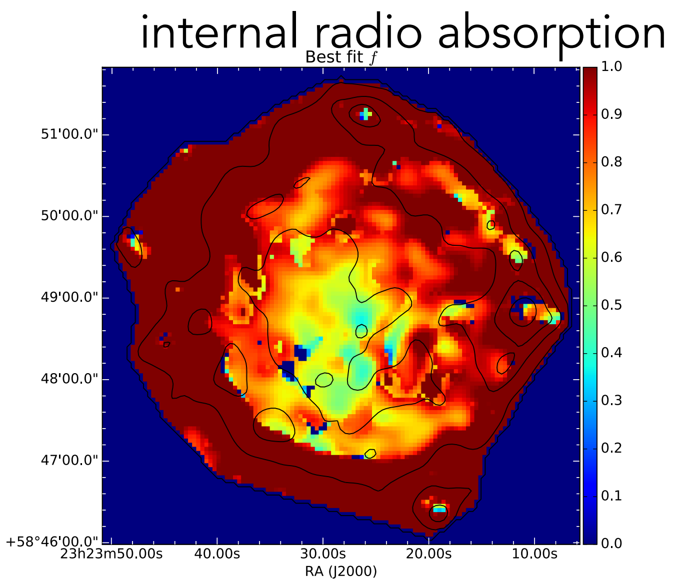


- Magnetic fields much larger than ISM: B≈30 — 300 μG
- Likely mechanism: Bell (2004) instability
- Bell (2004): $B^2 \propto \rho V_s^3$
  - Indeed: higher densities associated with larger B

Cassiopeia A: X-ray synchrotron from western *reverse* shock



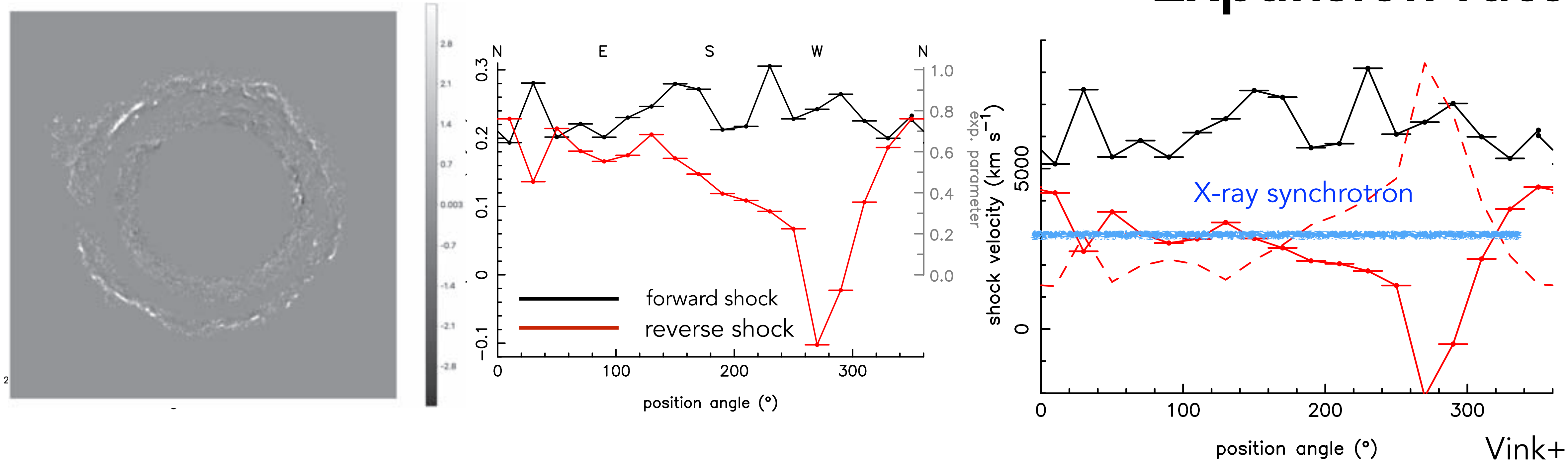
Helder & Vink 2008



Arias, Vink, et al 2018

- X-ray synchrotron radiation: requirese V_s>3000 km/s
- Narrow filaments: B ~ 200 μG
    - Apperently B-field amplification even with low seed fields (ejecta)!

Expansion rates



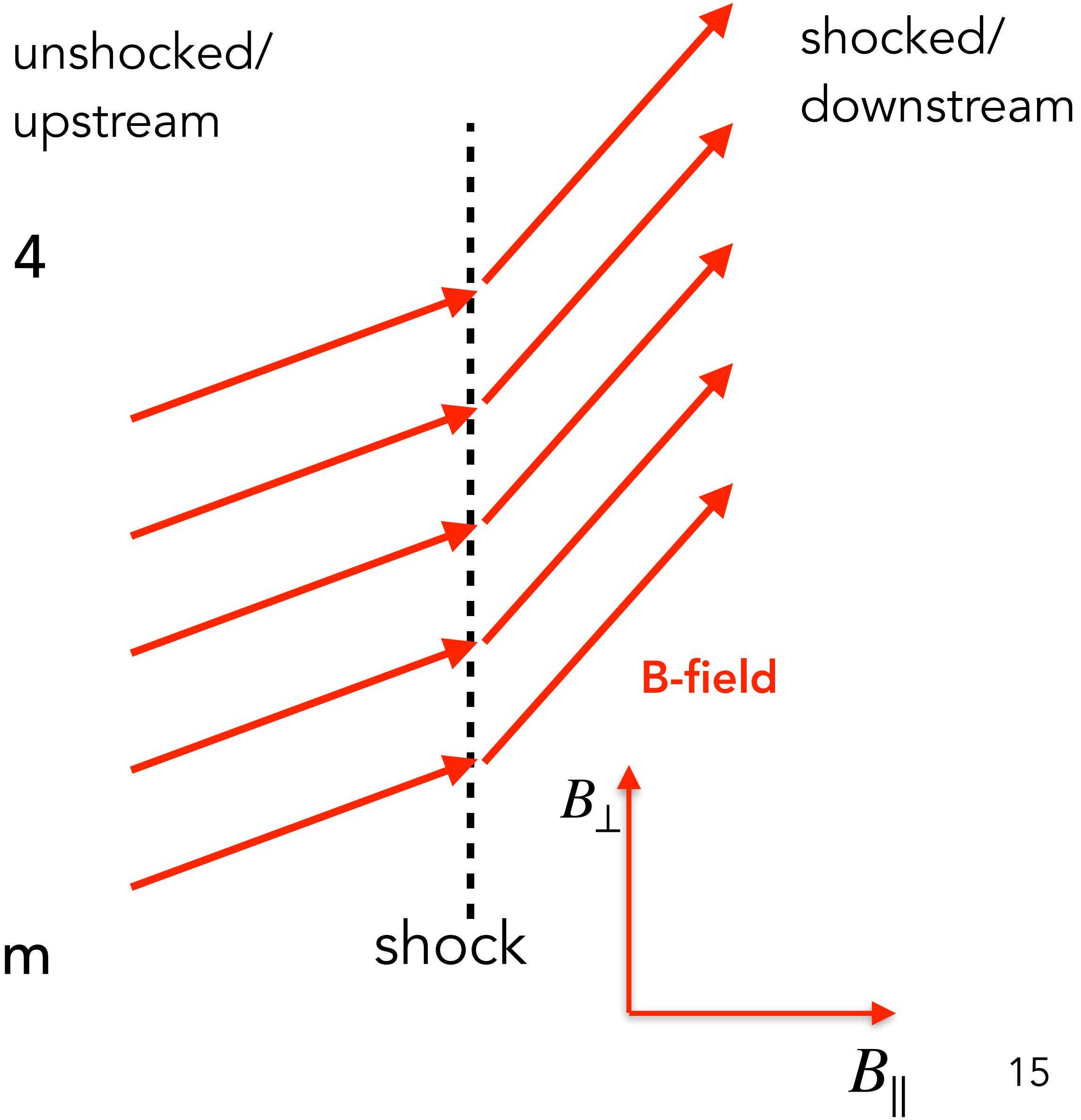
Vink+ '22a

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

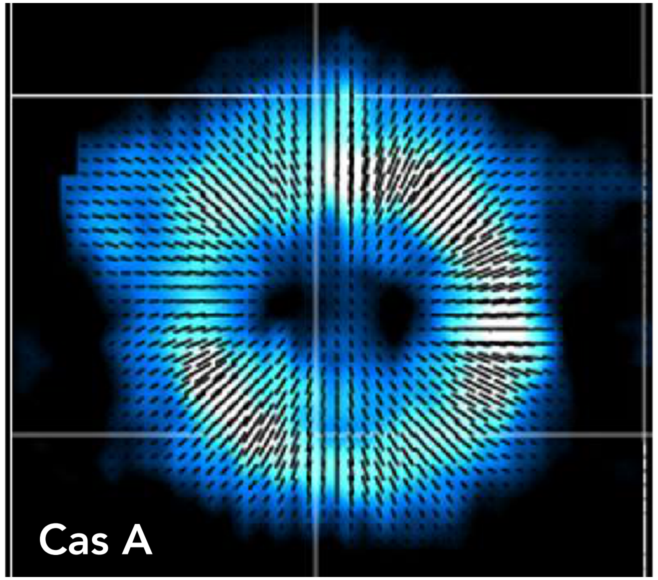
Shock aligns B-fields

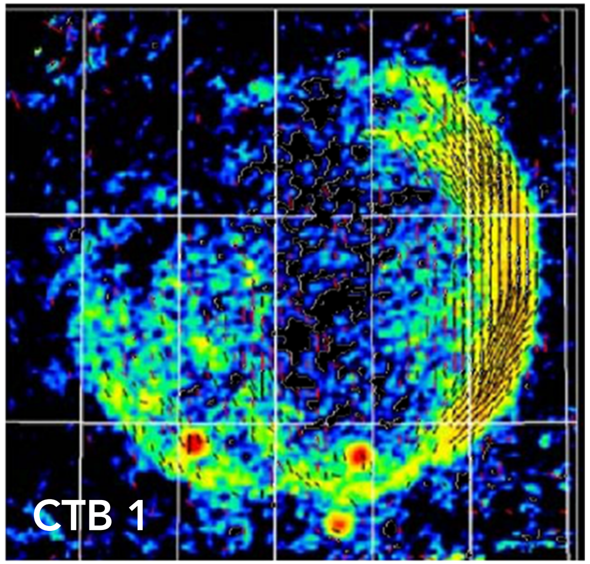
- Strong shock: plasma compressed by factor 4
- $B_\perp$ compressed by 4
- $B_{||}$ uncompressed

- B-field turbulence for DSA:
  - self-generated by cosmic rays!
    - resonant (wavelength ≈ gyroradius)
    - non-resonant (Bell '04)
- Theories consider mostly upstream medium



Radio synchrotron *polarization* from SNRs

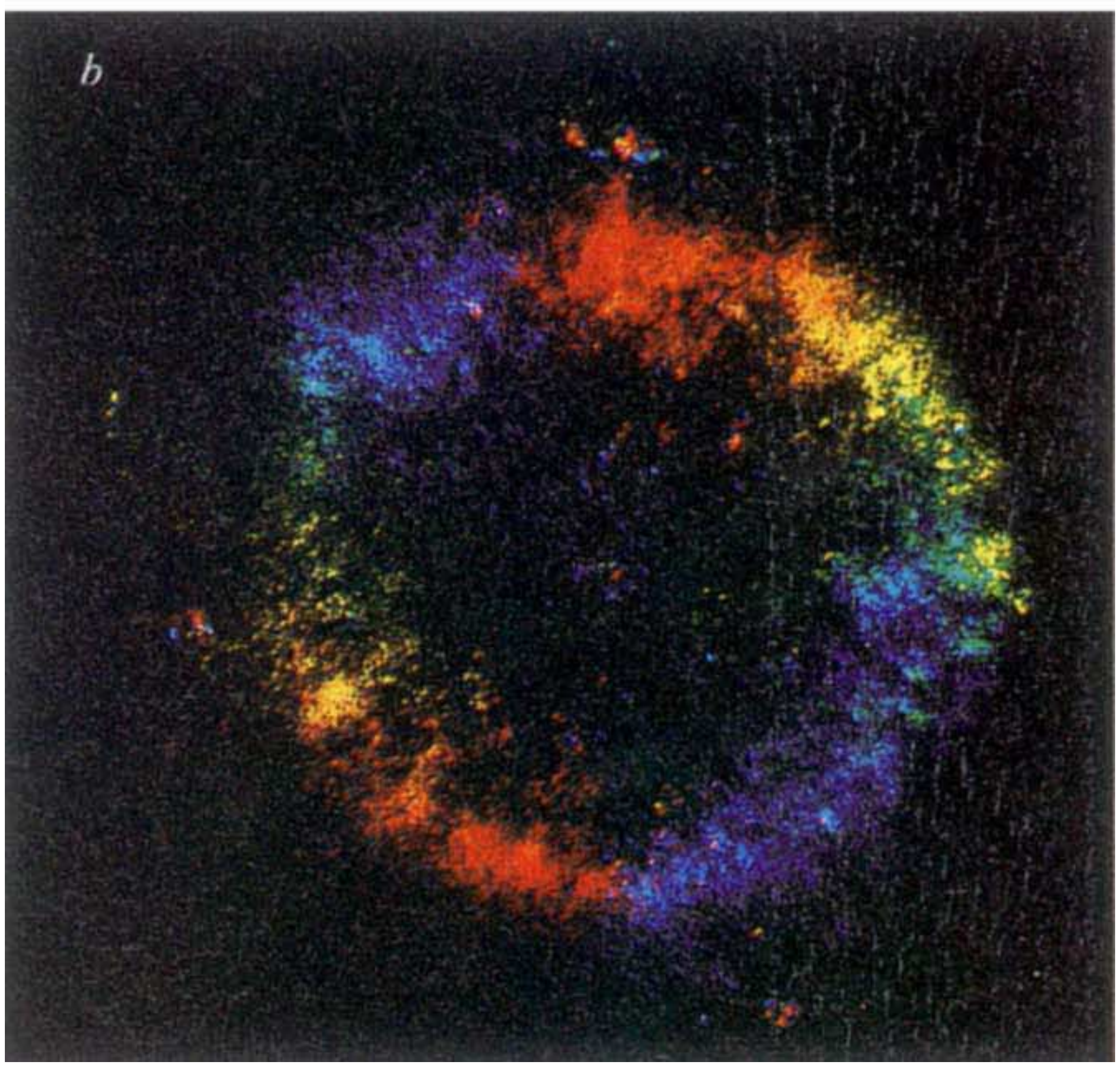




Dubner&Giacani (2015)
(Magnetic-field vectors)

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

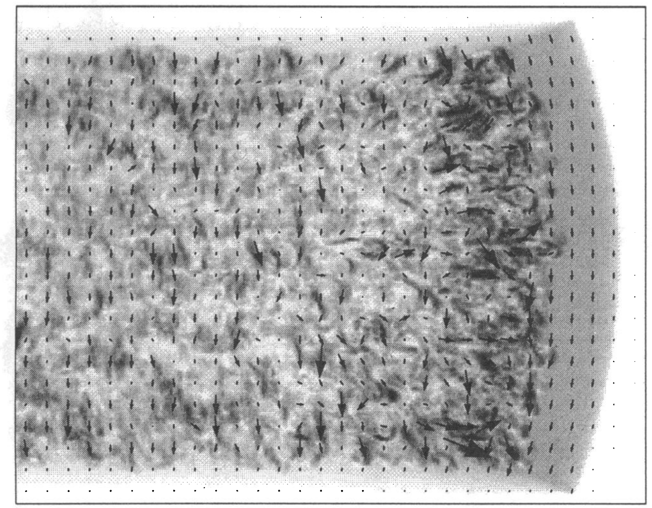
POLARIZATION AND MAGNETIC FIELDS



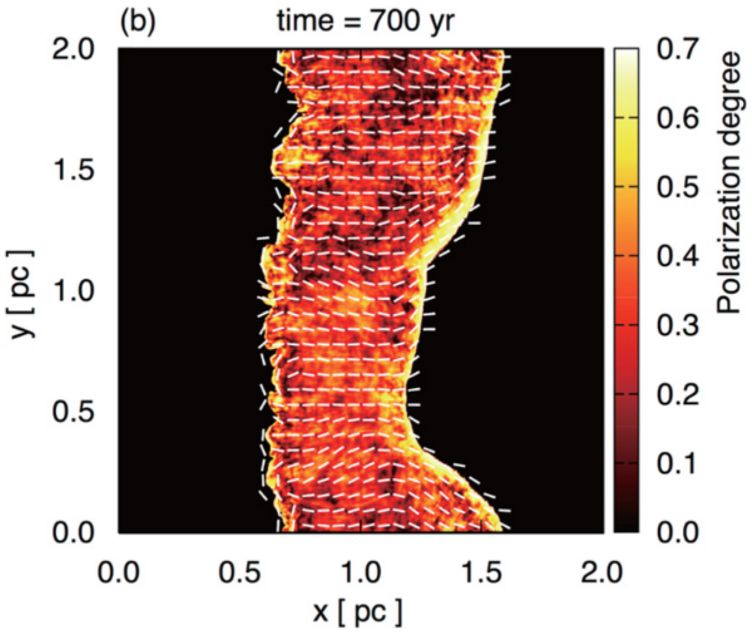
Braun+ ‘87

Explanations for radial B-fields in young SNRs

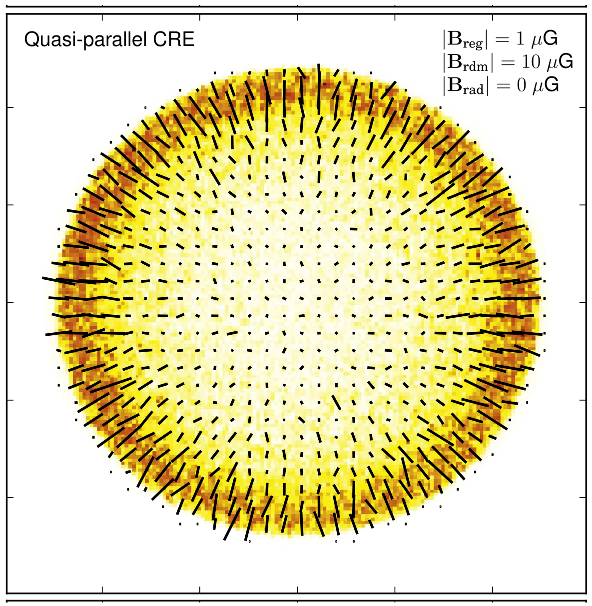
Jun&Norman '96



Inoue+ '13

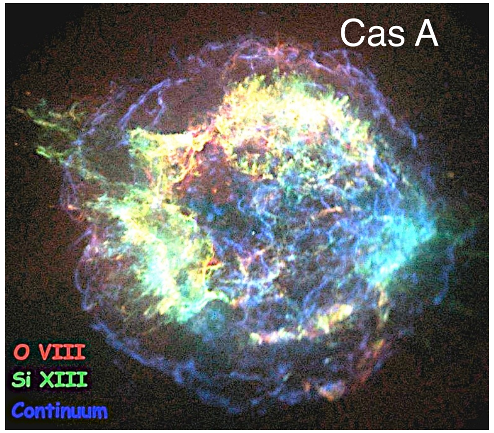


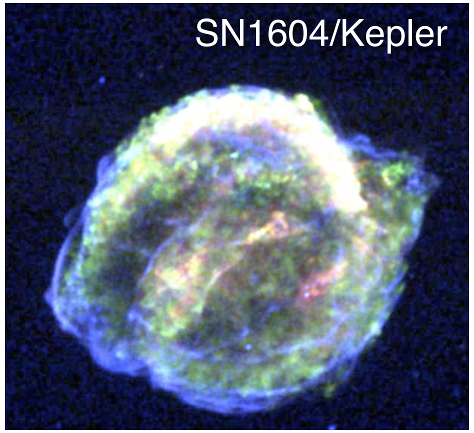
West+ '17

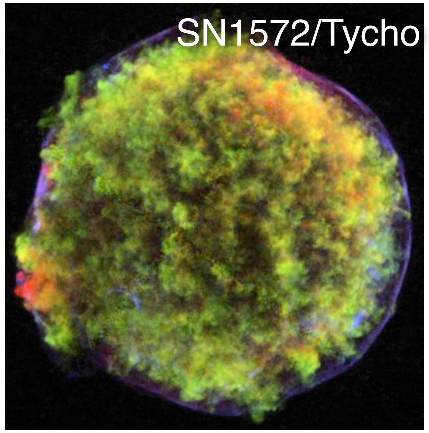


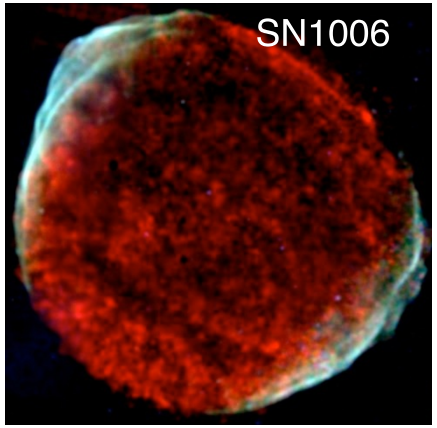
- Two schools of thoughts:
  1. Hydrodynamical filamentation, due to Rayleigh-Taylor or other instabilities
     - Assumes tangential magnetic field at shock, and radial further downstream
  2. Acceleration happens where B-field is parallel (i.e. radial): only emission from these regions

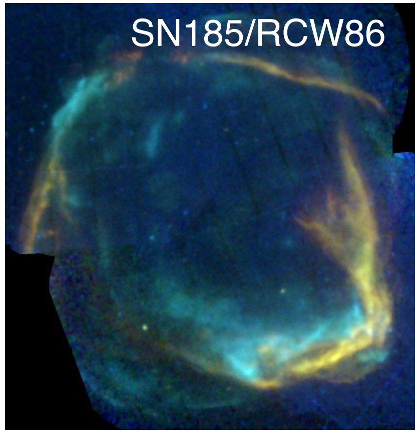
Why X-ray polarization if we have radio polarization?

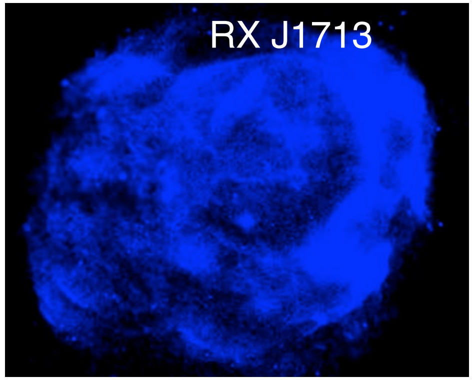


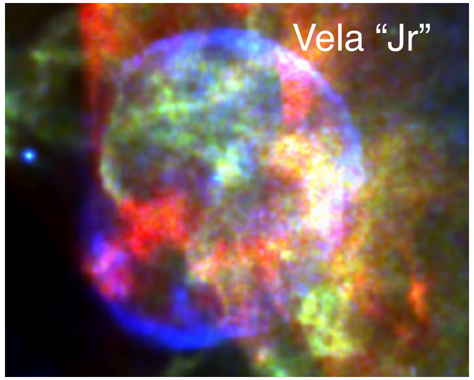












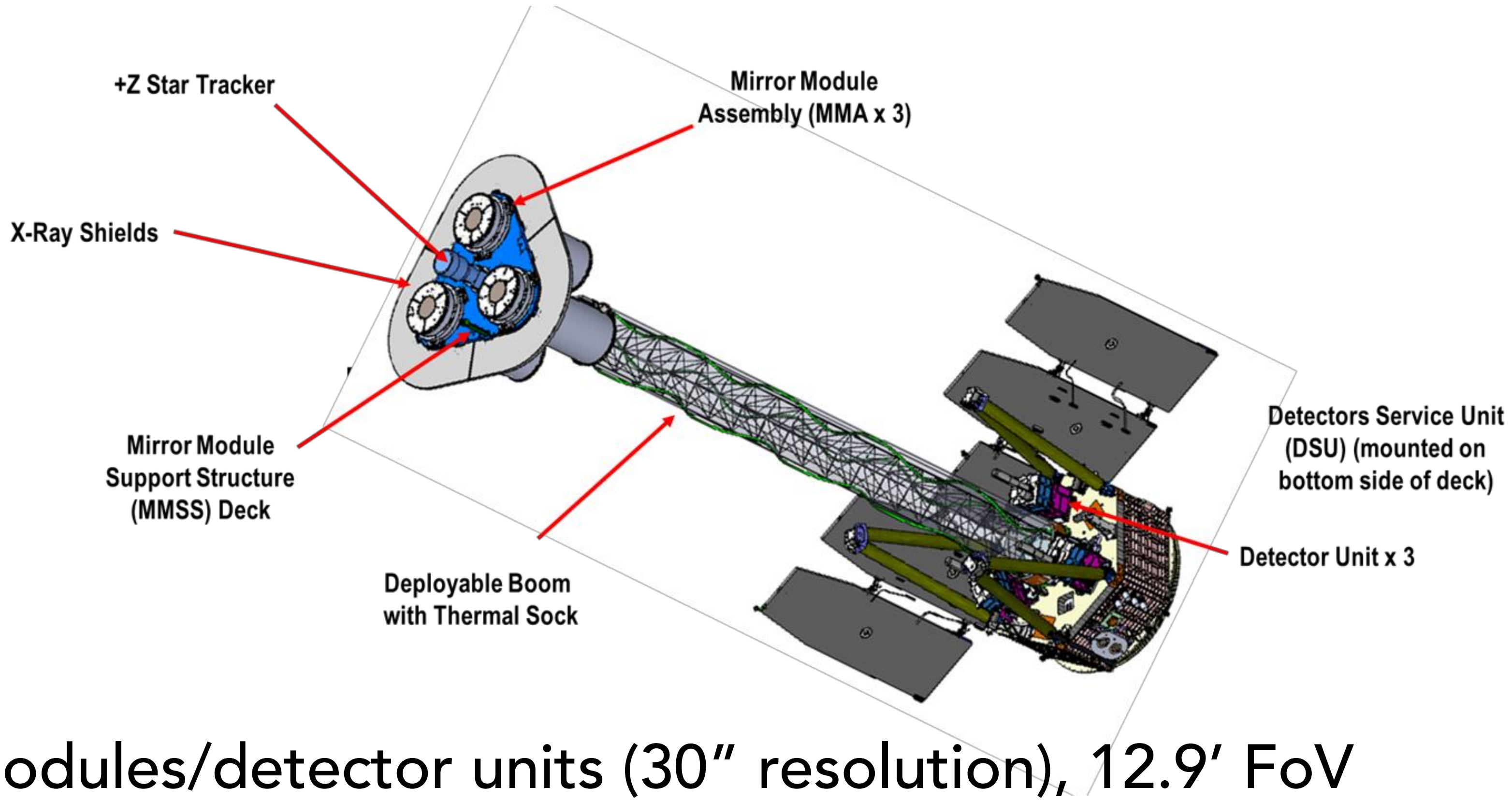
- X-ray synchrotron radiation → only near shocks (not contact discontinuity!)
  - Turbulence expected to be high here (at least upstream)
- Only young (<3000 yr) SNRs show X-ray synchrotron radiation
- Complication: also thermal X-rays (except Vela Jr, RXJ1713)

IXPE
Imaging
X-Ray
Polarimetry
Explorer

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

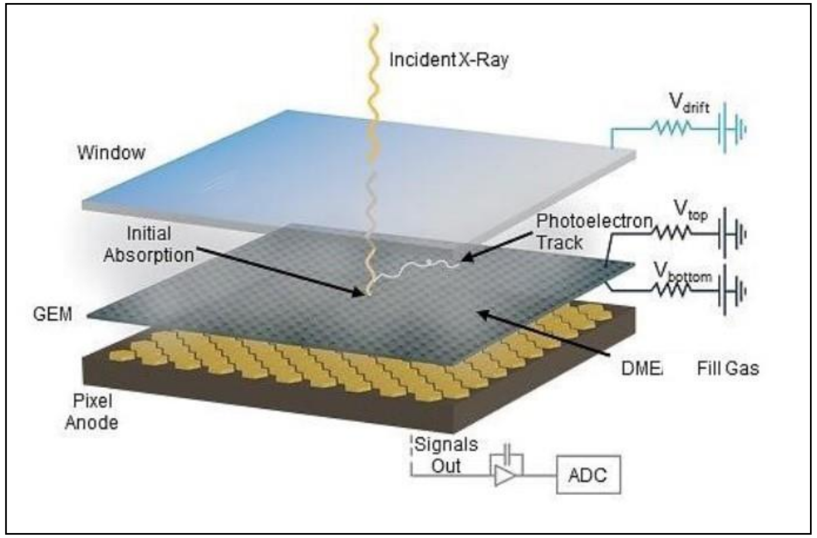
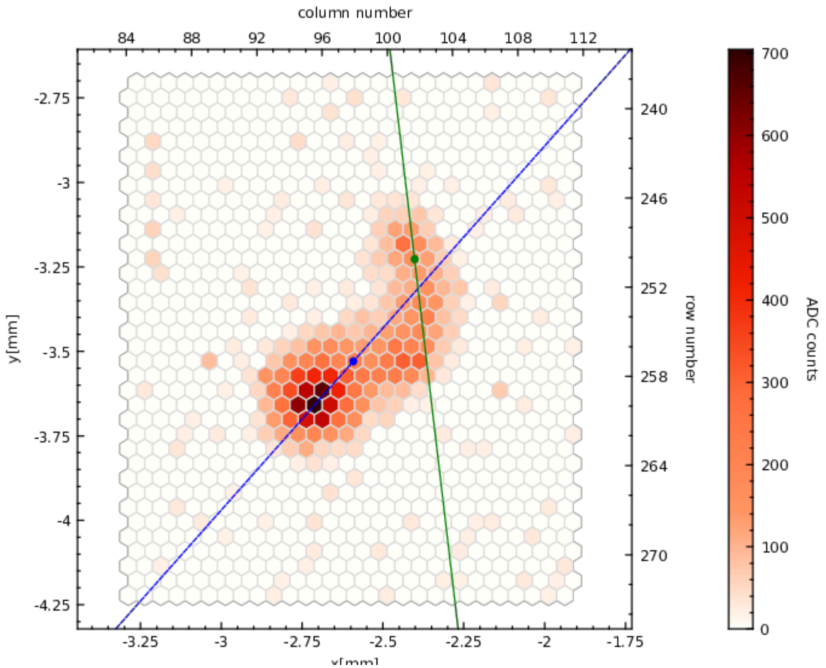
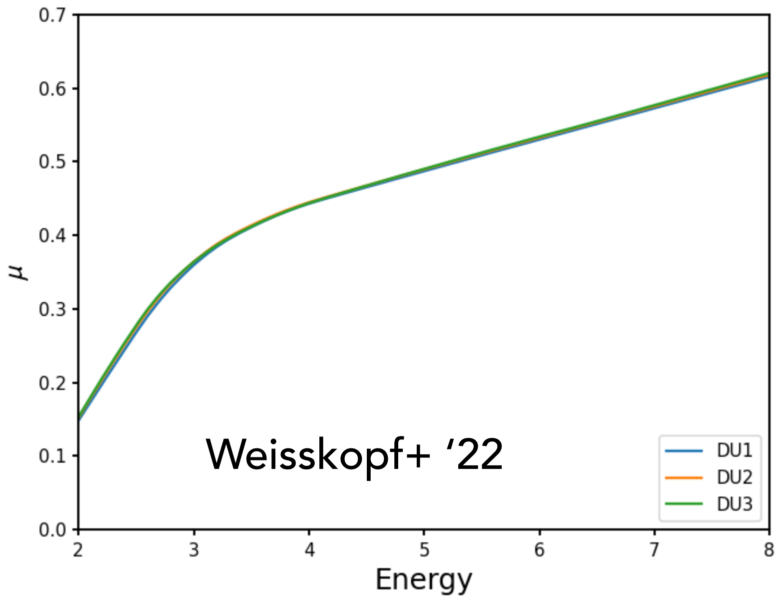


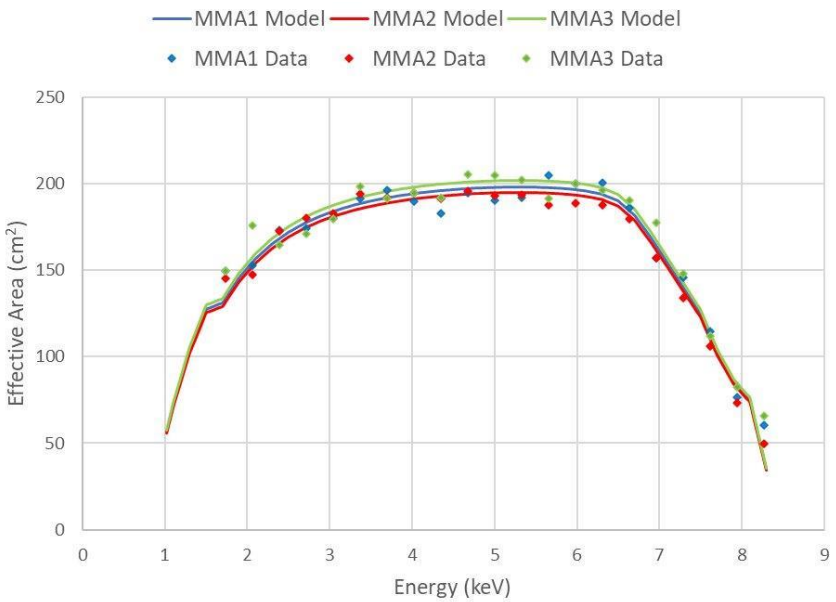
Figure 9: Schematic of the Gas Pixel Detector (GPD)

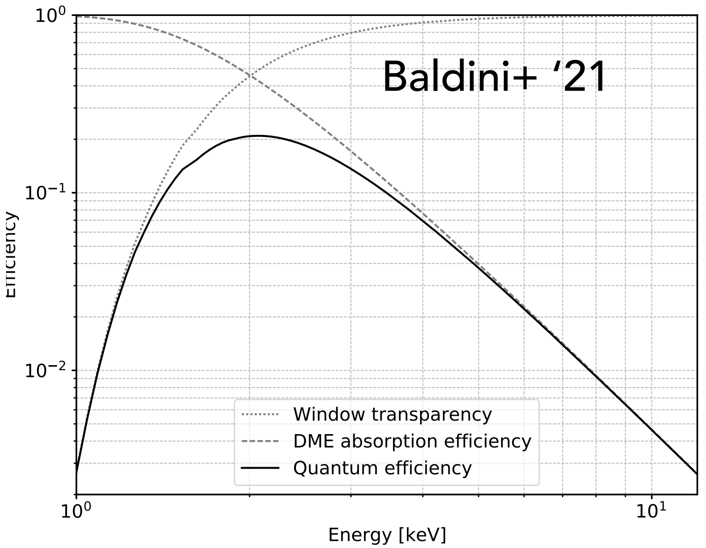


- Gas Pixel Detector: photo-electron (*pe*) angle $\phi \propto \cos^2 \psi$
    - *pe* creates secondary electron cloud: shape used to determine **Φ**
- **Φ** determined from shape of secondary electron clouds

Modulation curve and efficiency





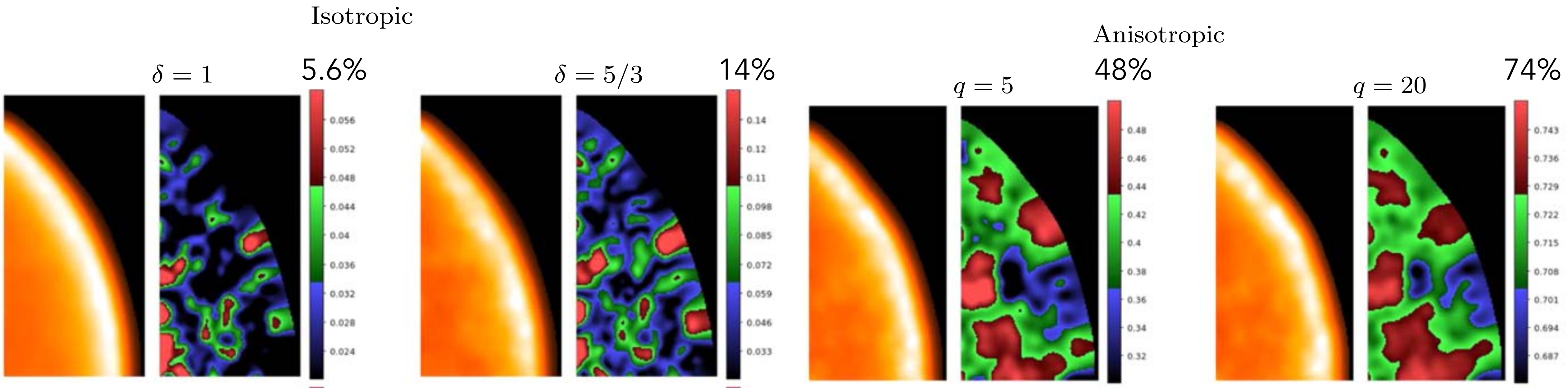


- For ideal detector estimator for Q and U:
  - $Q = \sum_i q_i = \sum_i 2\cos(2\phi_i),\ U = \sum_i q_i = \sum_i 2\sin(2\phi_i)$
  - factor 2: needed as response $\propto \cos^2\psi$ (not $\propto \cos\psi$)
- GPD detector: errors in measuring **Φ** → degradation of polarization signal
- Degradation 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 near shock?
    - 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 synchroton 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): apply to *upstream* magnetic field

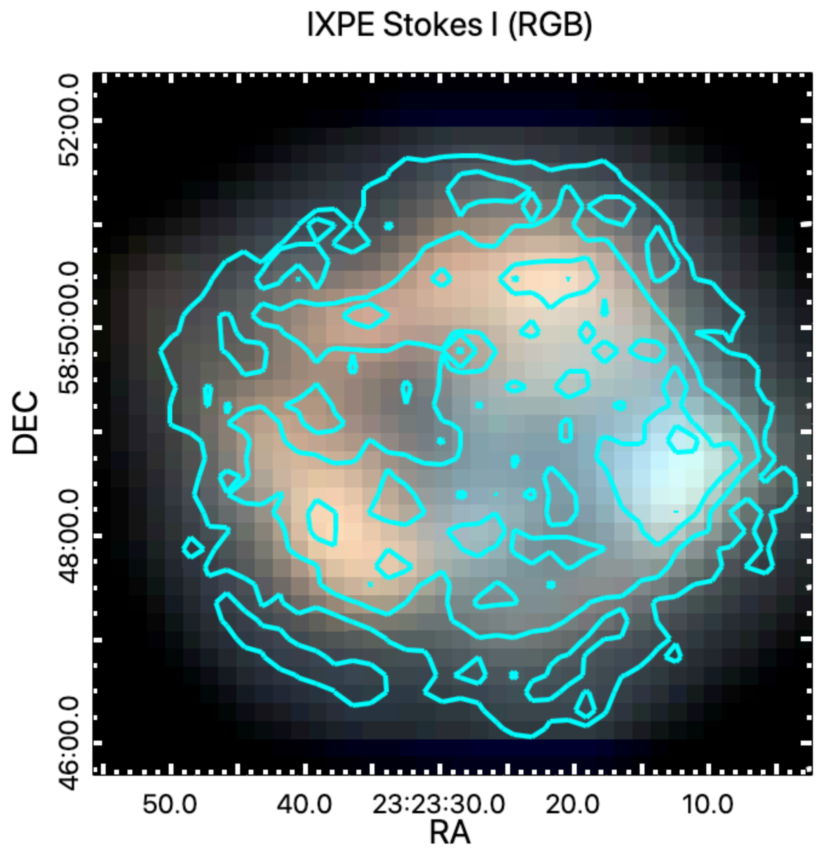
IXPE -like simulations Bykov et al. 2020



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

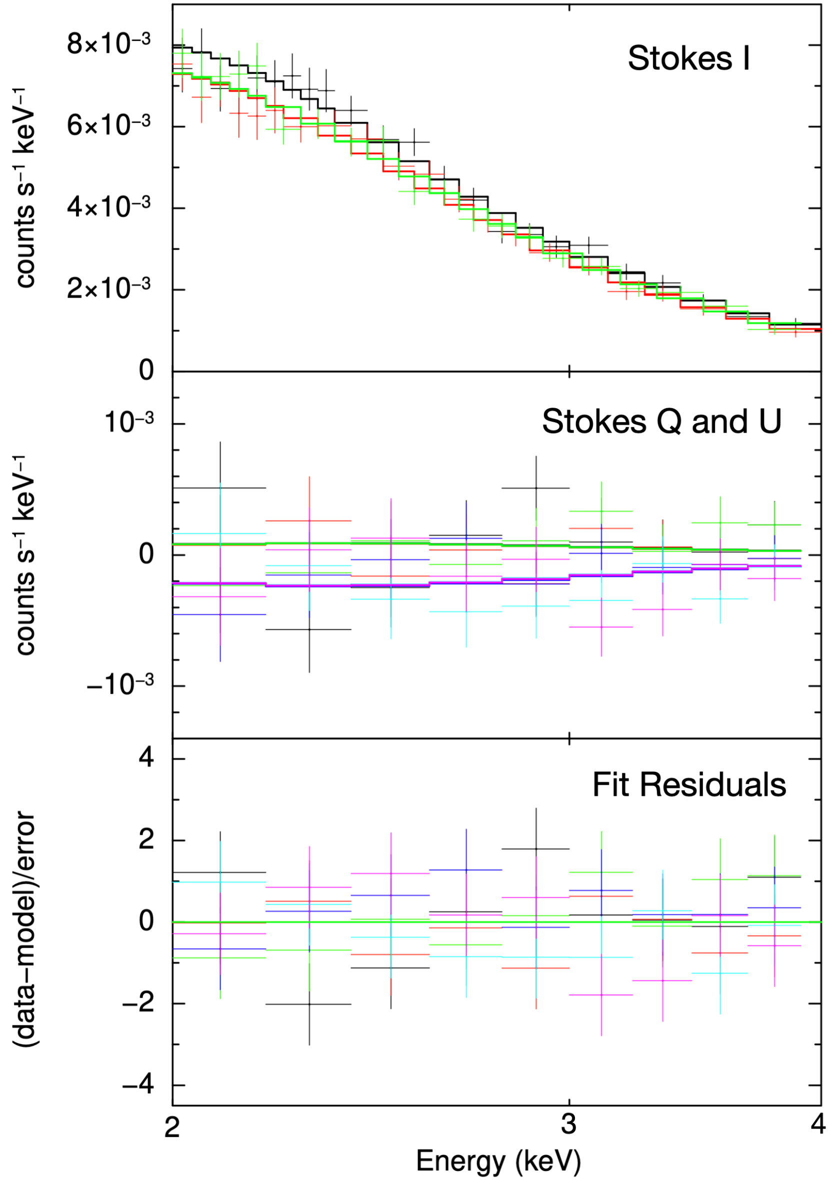
Analysis of IXPE data

- Main SW tool: *ixpeobsim* (Baldini+ '21)
- Additional method: spectral polarimetry
- Cas A, Tycho: account for thermal emission
- Use of chi-square statistics:
  - $Q = \bar{\mu}^{-1} \sum_k q_k, \quad U = \bar{\mu}^{-1} \sum_k u_k$
  - Expection values E[Q]=0, E[U]=0
  - Hence $S \equiv \frac{Q^2}{\mathrm{Var}(Q)} + \frac{U^2}{\mathrm{Var}(U)}$ has χ^2_2 distribution
  - Significances: **2σ**: $\chi^2 = 6.18$, **3σ**: $\chi^2 = 11.8$, **4σ**: $\chi^2 = 19.3$



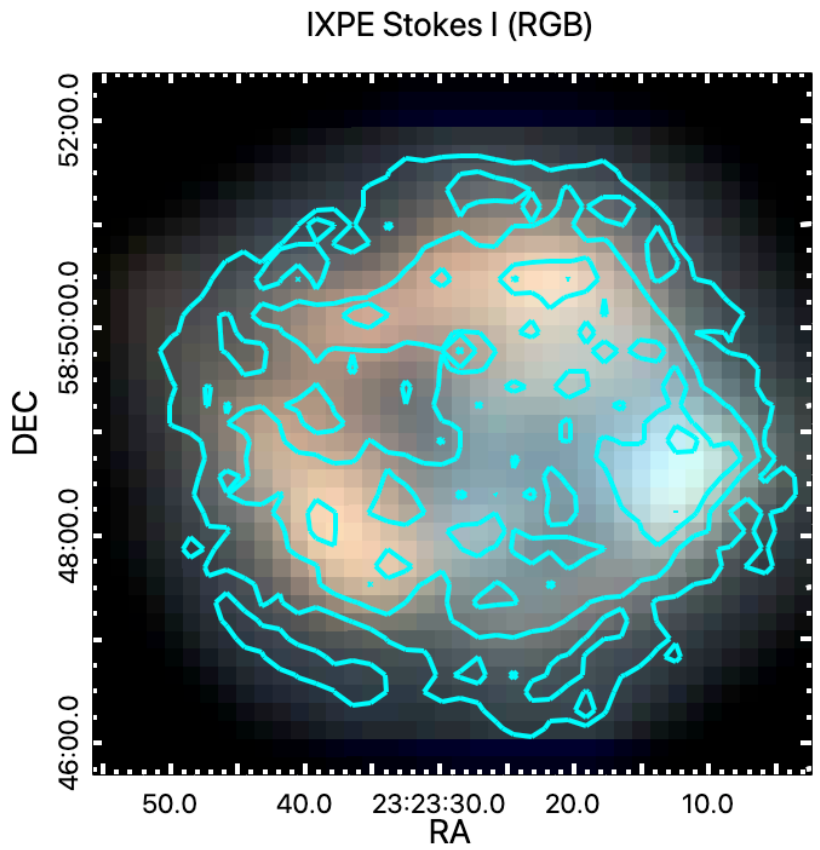
X-ray spectroscopic analysis

- Per energy bin:
  - $Q(E_j) = \frac{1}{\sum_i w_i} \sum_i w_i q_i(E_j),\ U(E_j) = \frac{1}{\sum_i w_i} \sum_i w_i u_i(E_j)$
- 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

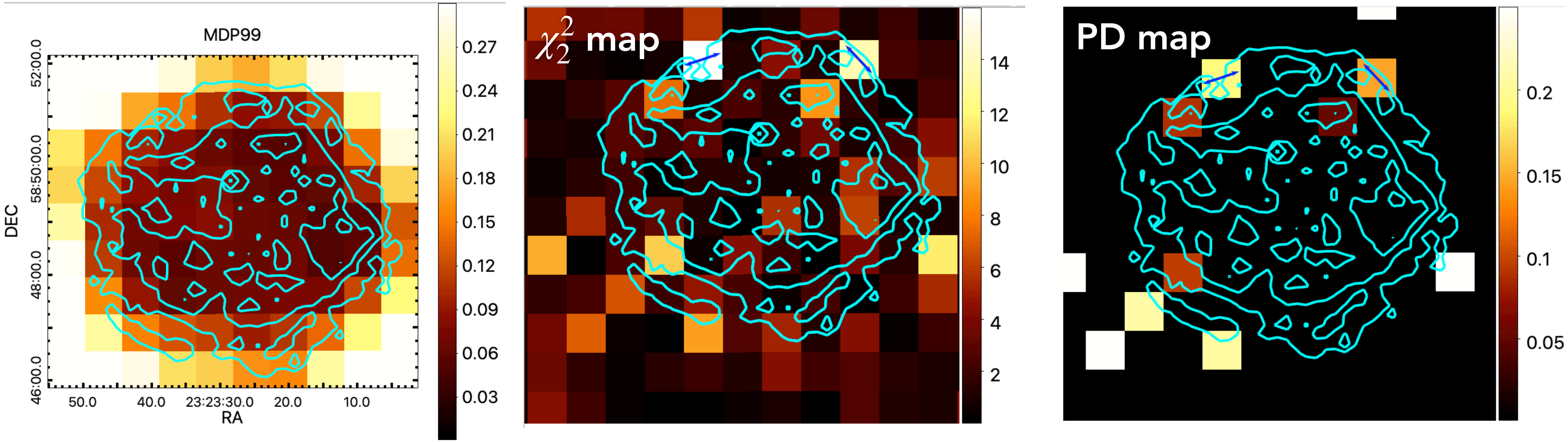


The IXPE observations of Cas A

- 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 builtup) and det. unit dependent
- Effective exposure: 819 ks



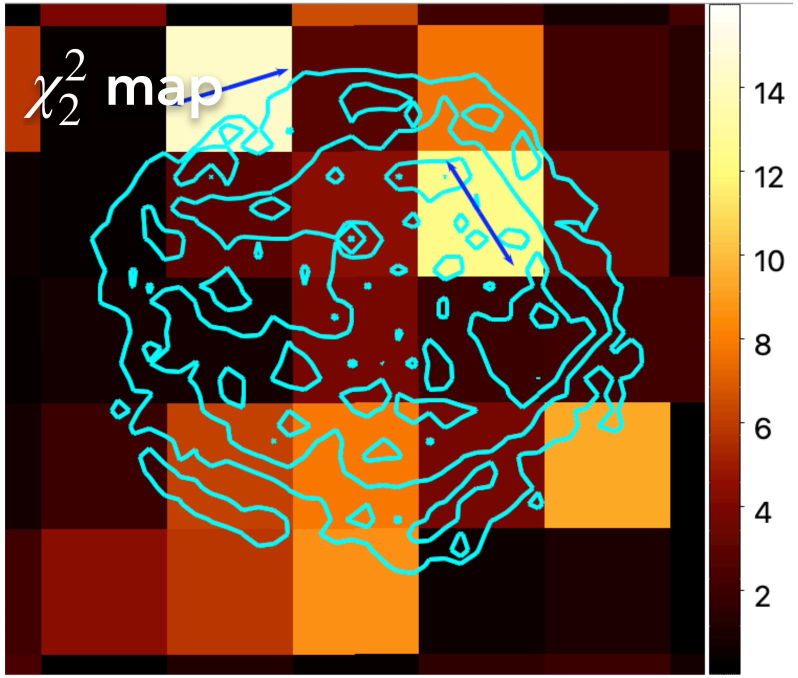
Pixel-by-pixel analysis

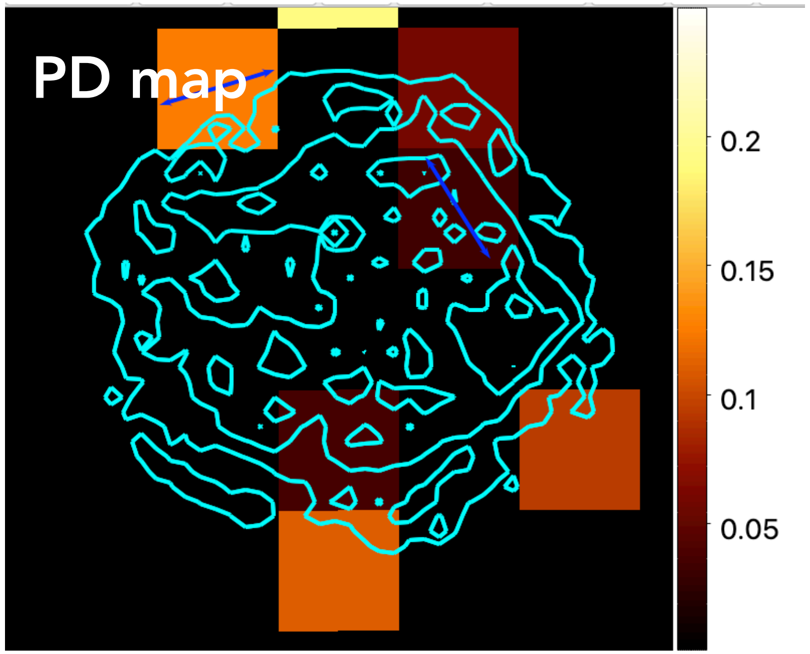


Vink+ 2022

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

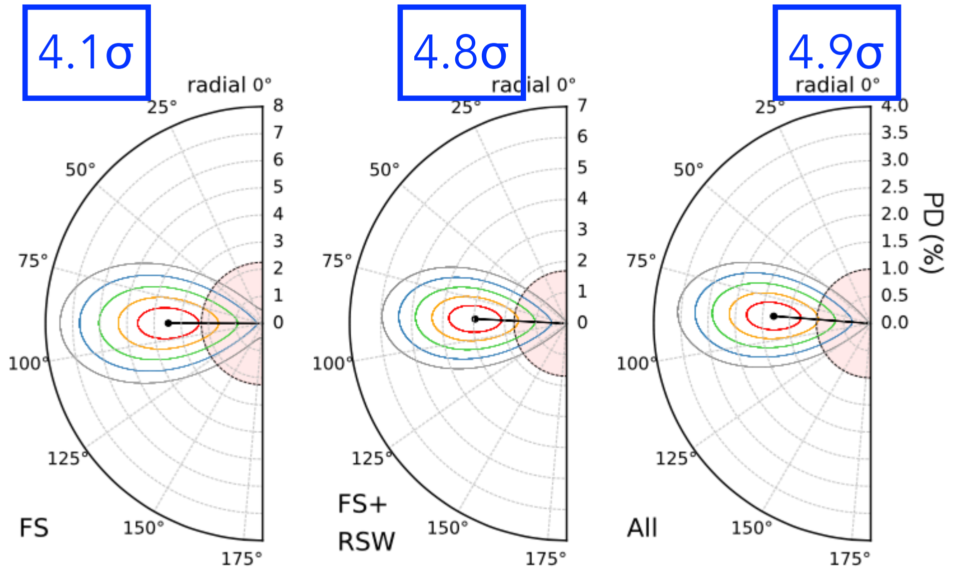
Pixel-by-pixel analysis





- 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

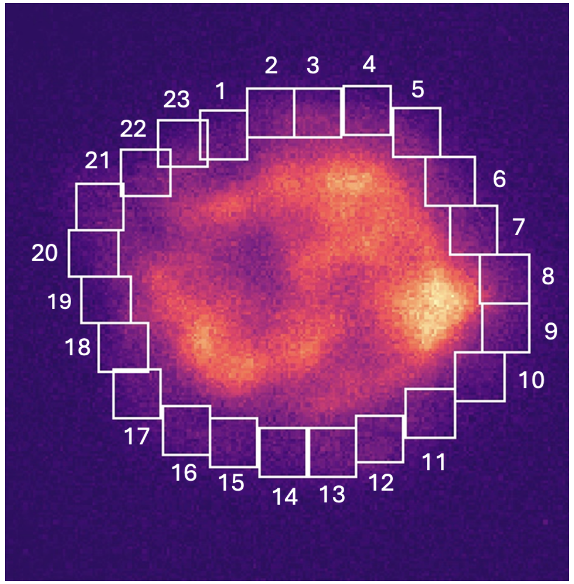
Results assuming circular symmetry

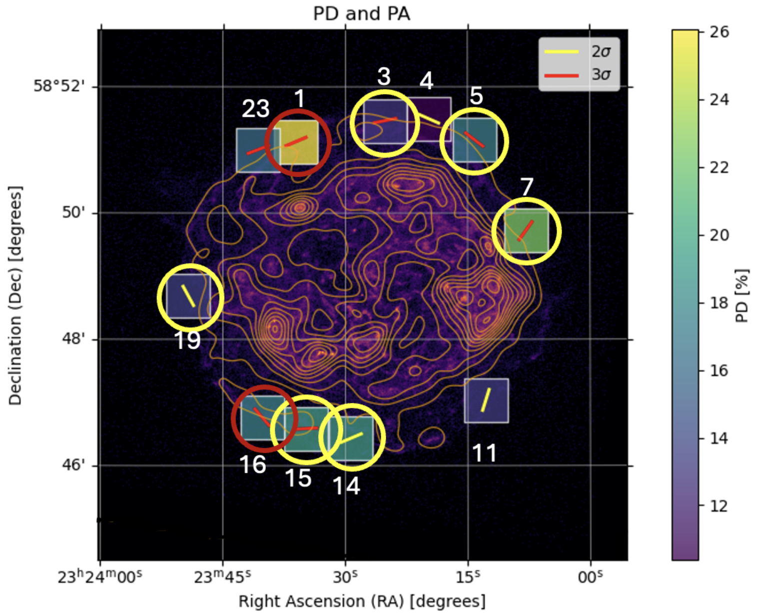


Outer ring | Outer+West | Entire SNR

- 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!*

Reanalysis Cas A data using spectroscopic polarization

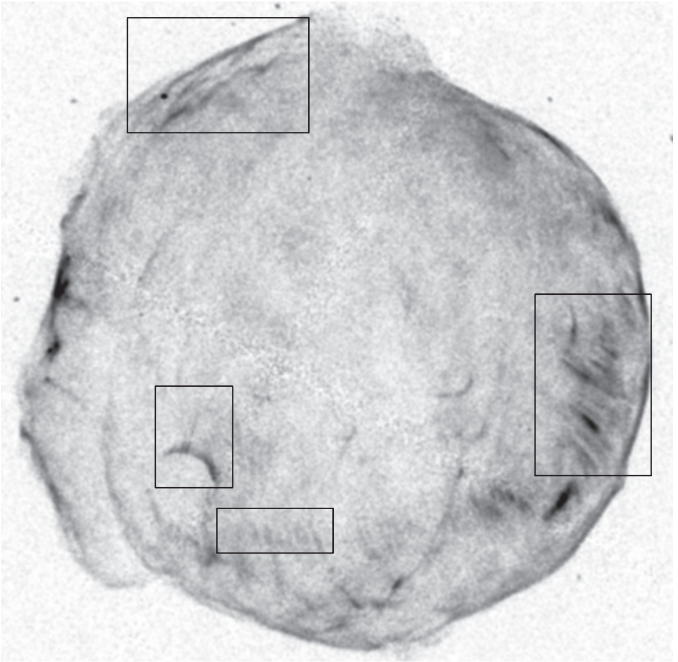




Mercuri, Greco, Vink, Ferrazzoli, Perri, 202

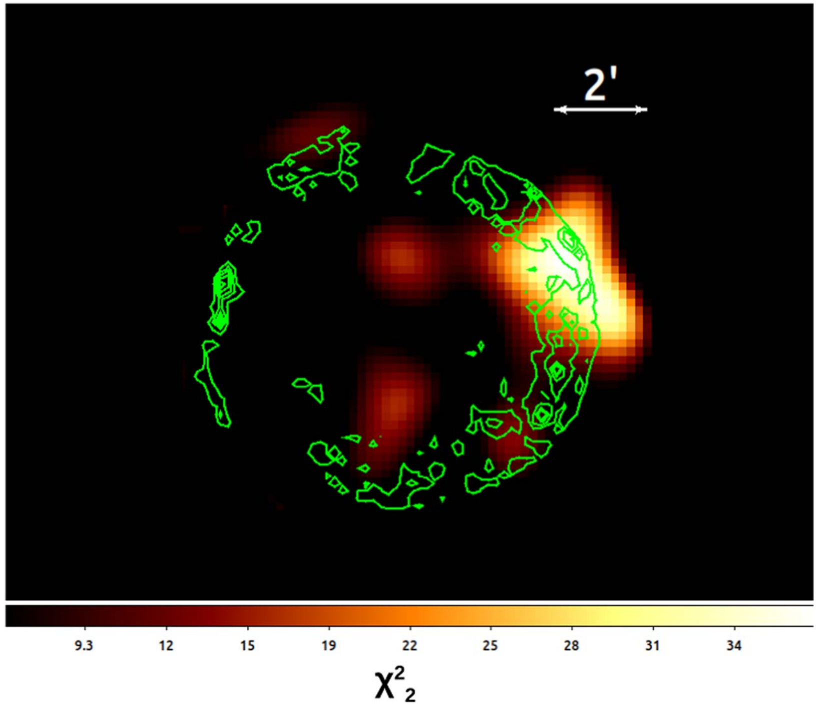
- Uses spectroscopy with I, Q & U spectra
- Automatically corrects for thermal emission (but with poor spectral resolution)
- Finds 3-4sigma detections at outskirts with PD ~11-26%

Tycho's SNR/SN1572



Eriksen+ 2011

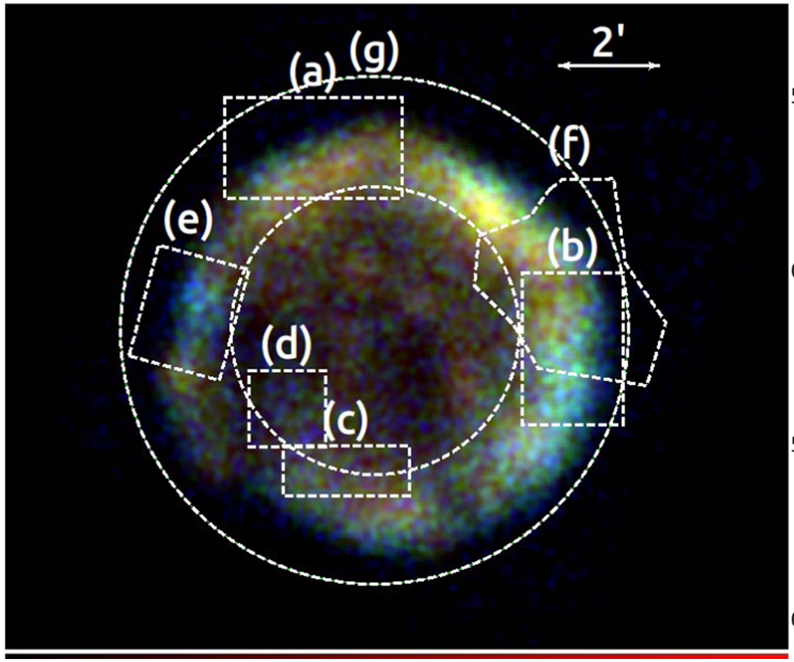
Tycho's stripes!

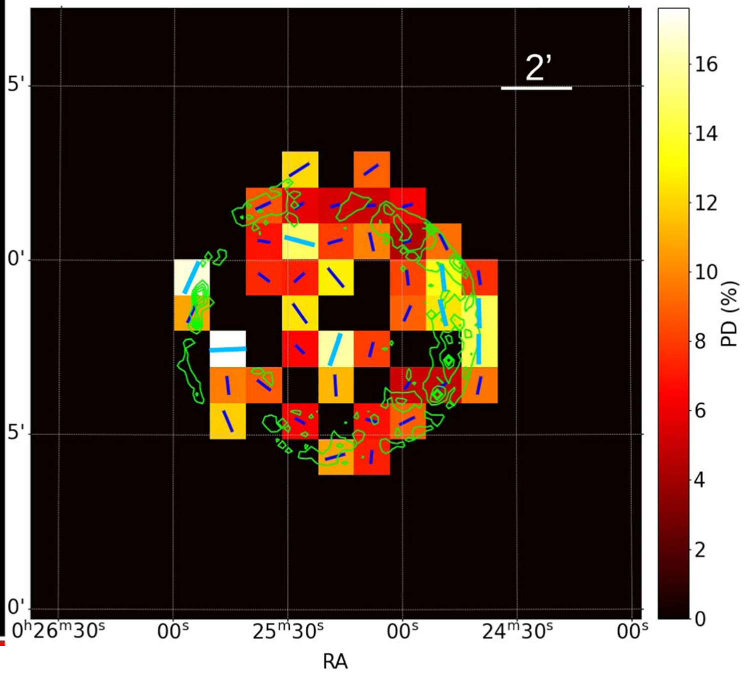


Ferrazzoli+ 2023

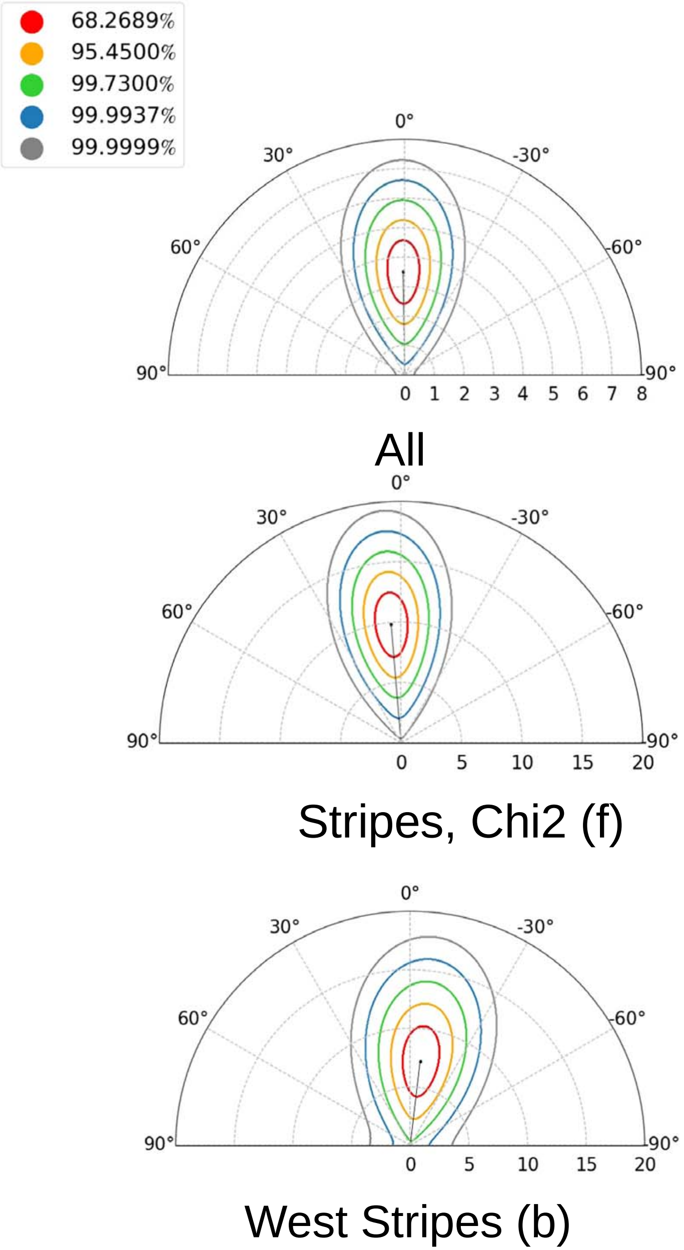
- Like Cas A: narrow rims, indicating B~200 μG
- Special mysterious structures: Tycho's stripes!
    - Is is a magnetic-field pattern → expect high polarization fraction!

Tycho's SNR/SN1572 IXPE results



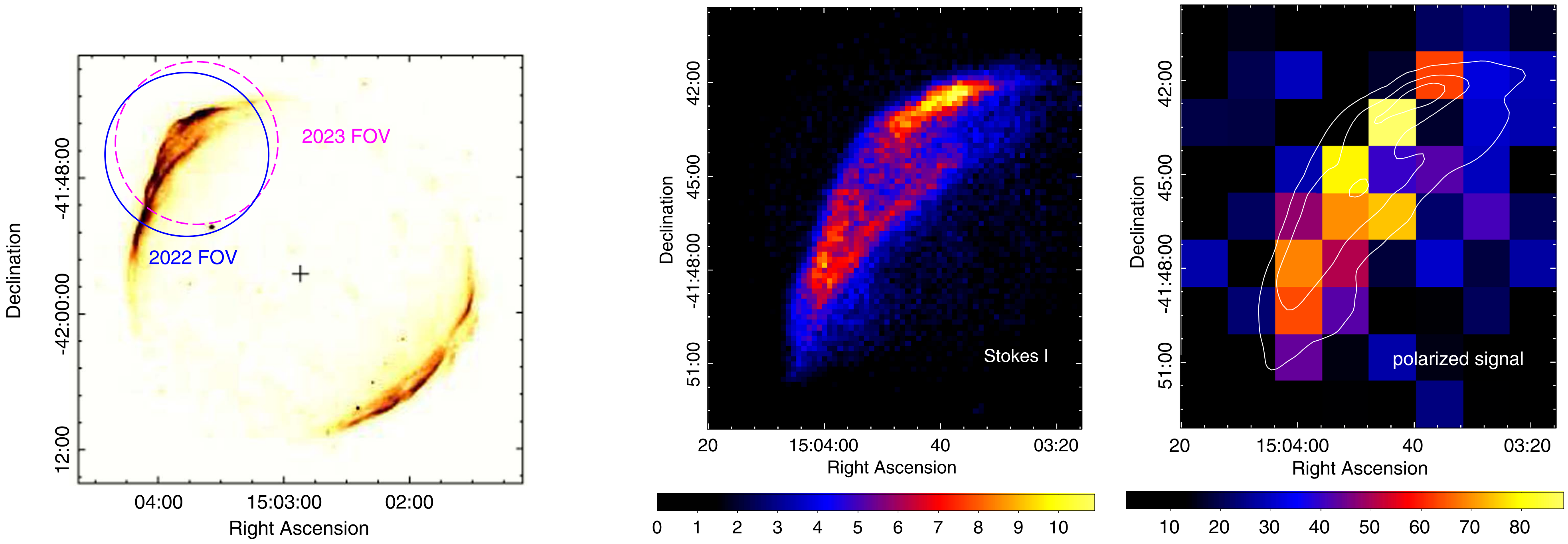


Ferrazzoli+ 2023



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

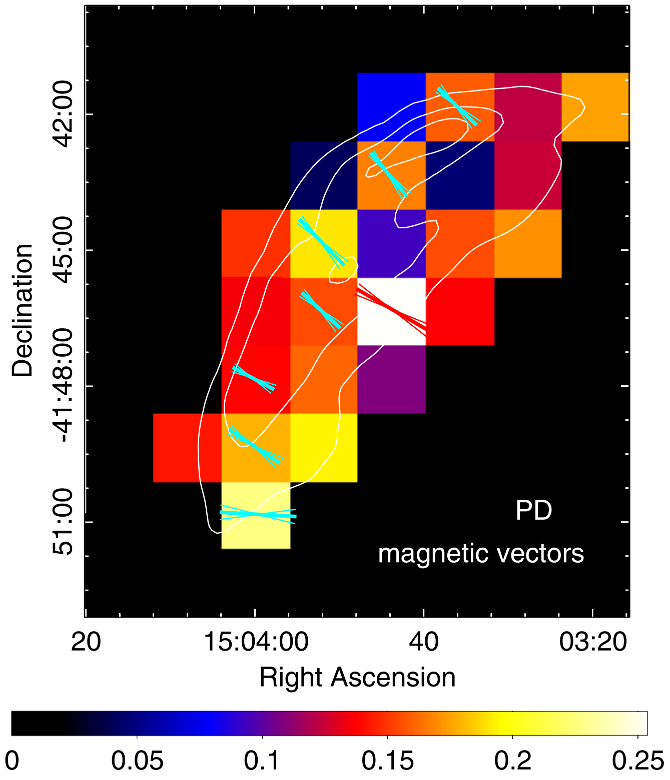
SN1006



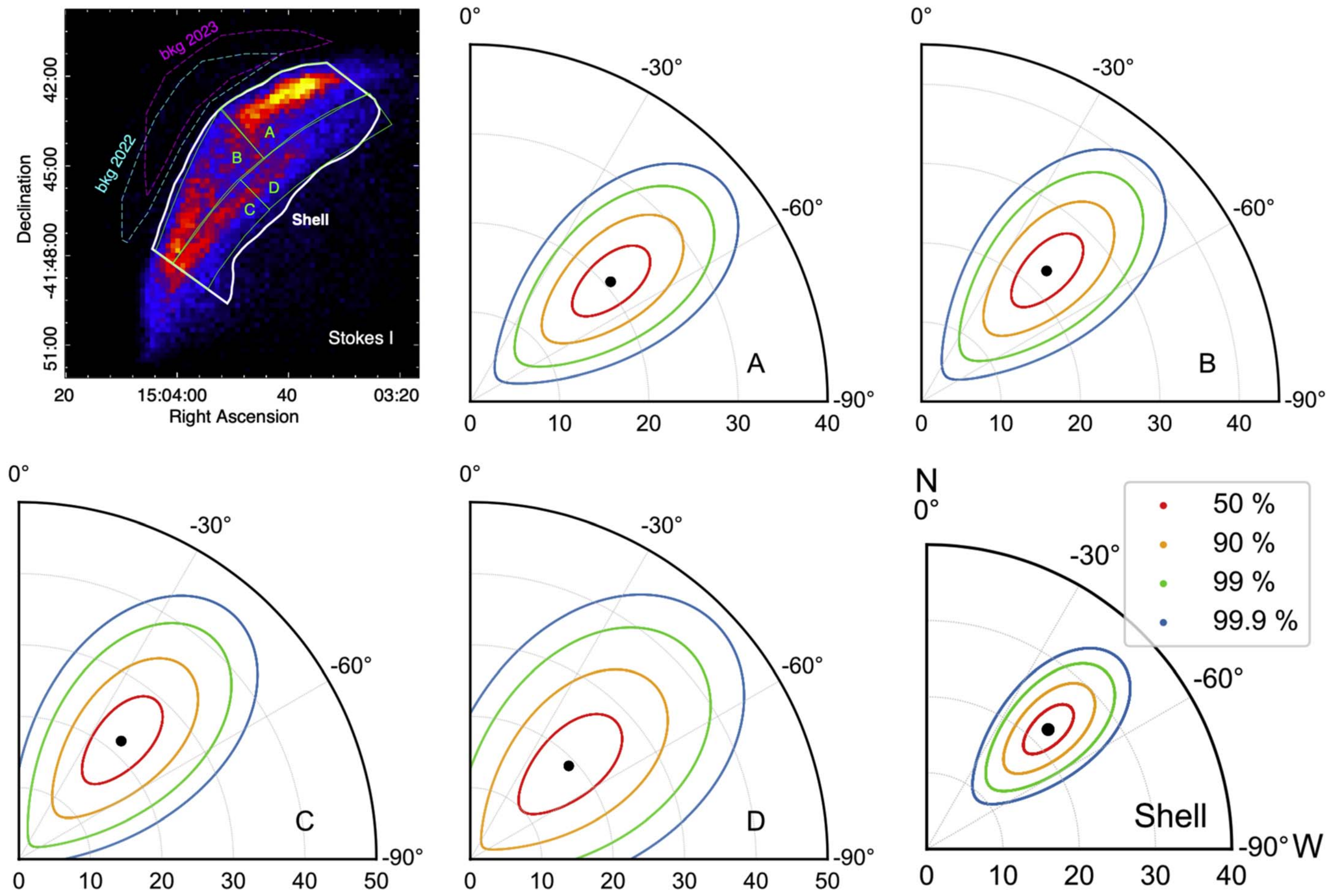
Zhou+ 2023

- 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~80 μG

SN1006 IXPE results

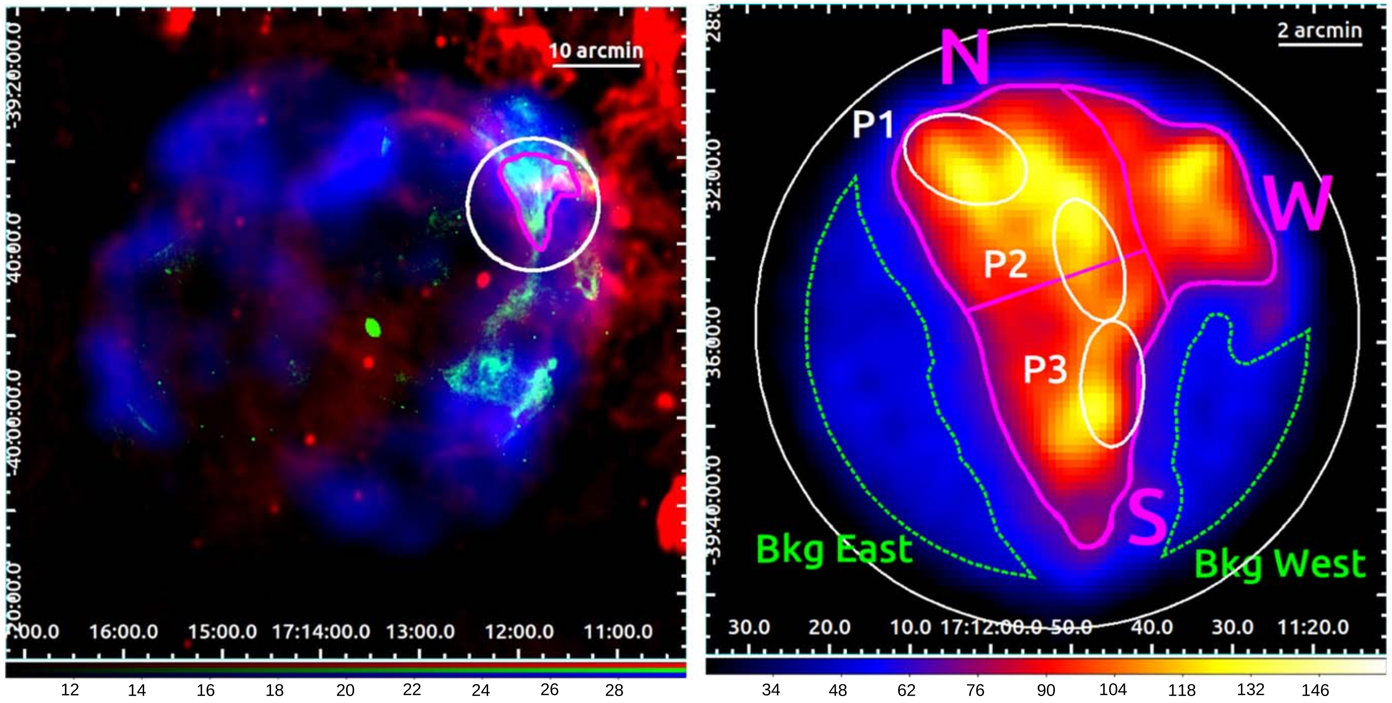


Zhou+ 2023



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

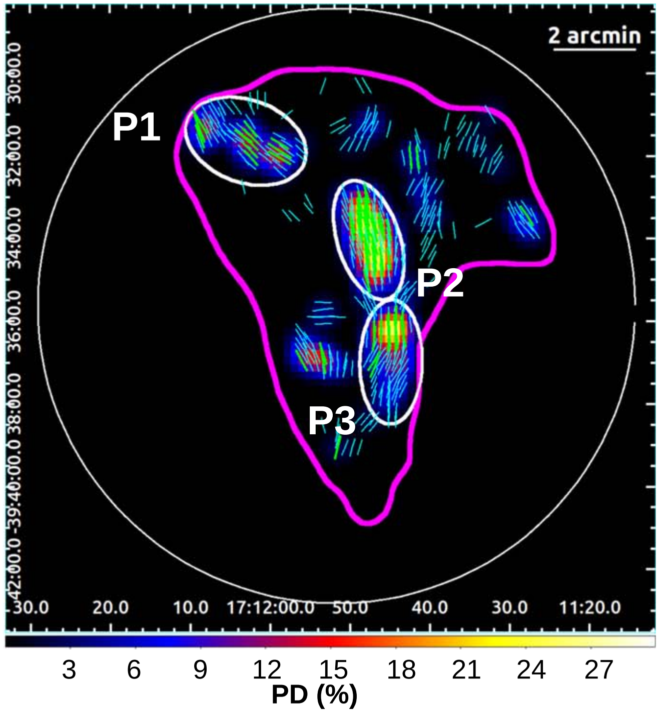
RX J1713.7–3946

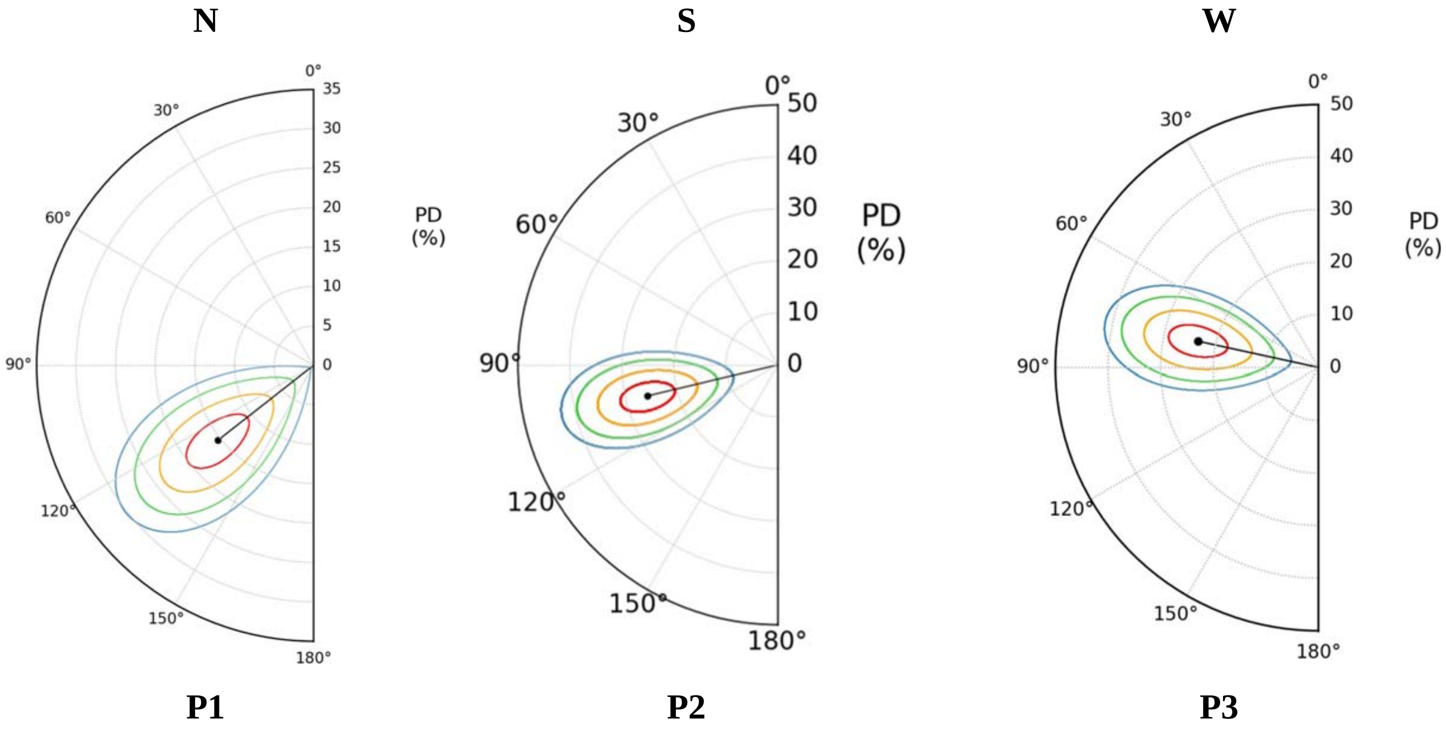


Ferrazzoli+ 2024

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

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

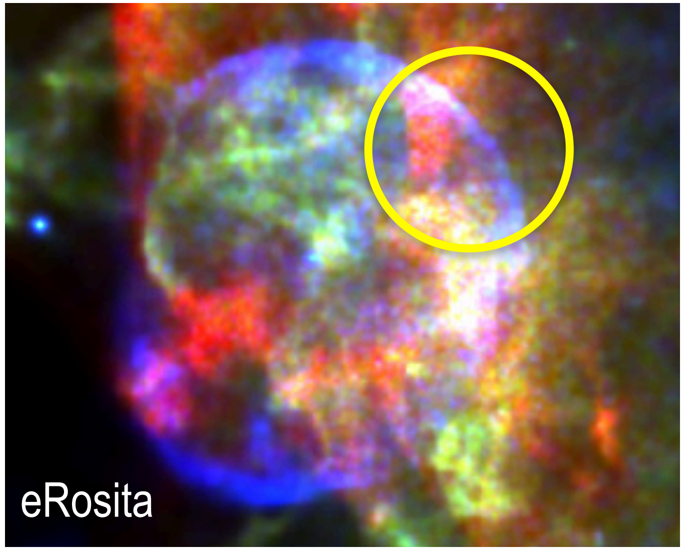


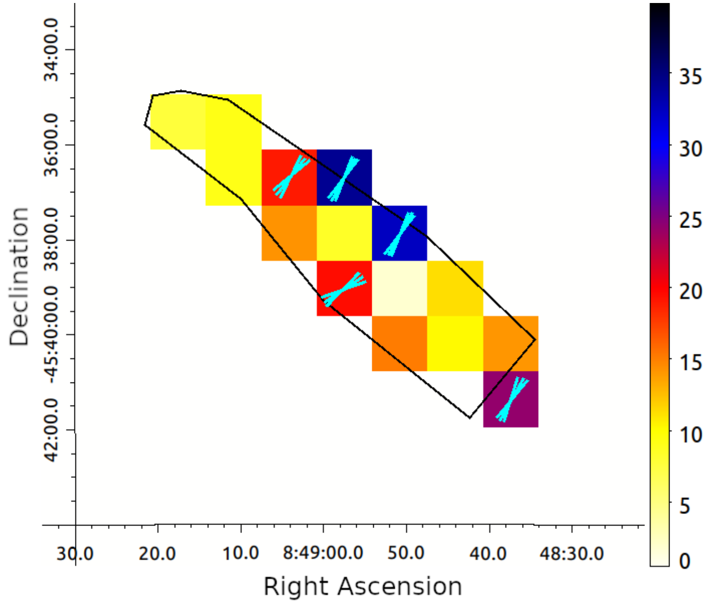


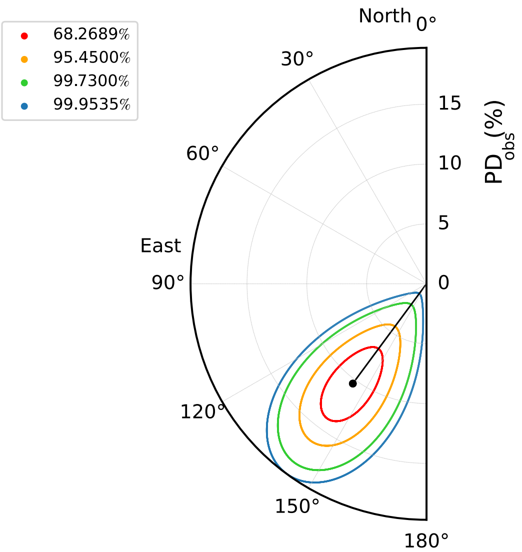
Ferrazzoli+ 2024

- 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)

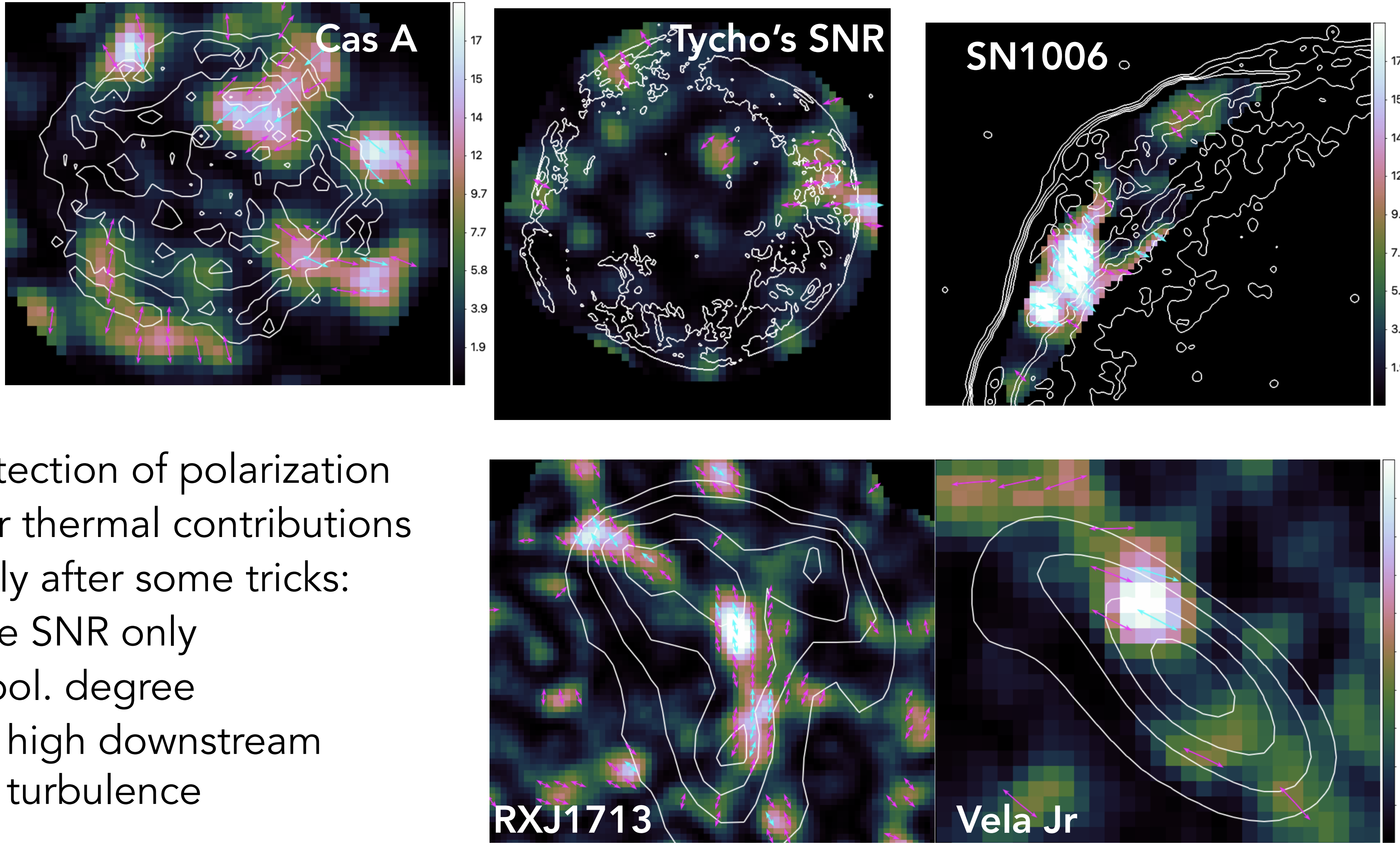






- Large shell: 2 degree, on top of Vela SNR
- B-field estimate (H.E.S.S.): $B_2 \approx 10\ \mu\mathrm{G}$
- Probably oldest SNR (~3000 yr) with X-ray synchrotron:
  - requires evolution in low density bubble
- IXPE:
  - B- field is *tangential* (like RXJ1713)!
  - PD≈16±5%

IXPE Statistical maps (χ_2^2)



- ~4-5σ 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 → 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
  - ~10^{16} - 10^{17} cm for Bell instability
  - ~10^{15} cm for resonant instability (=gyroradius 10 TeV particles, B=100 μG)
  - Turbulence at these scales needed for X-ray synchroton → but not resolved!
  - Bykov+ '20 simulations assumed spectrum up to 10^{18} cm → (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

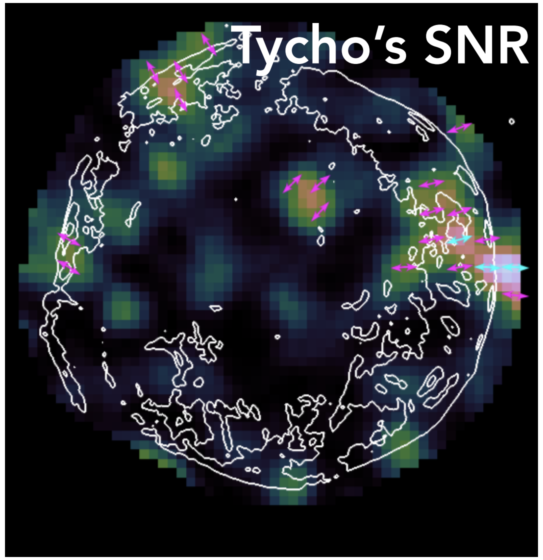
Final suggestion

- 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 $B_{\rm Bell} \approx B_0$
- Largest polarisation fraction: RXJ1713 and SN 1006 → lowest ρ and B
  - Normalizing to Cas A (n_H~2cm^{-3}, V_s=6000 km/s): K=0.15%
- For what density and Vs=3000 km/s is $B_{\rm Bell} \approx B_0 \approx 20\ \mu G$?
  - *Answer: n_H~0.05 cm^{-3} comparable to RX J1713, Vela jr!*
  - *But still need sufficent 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

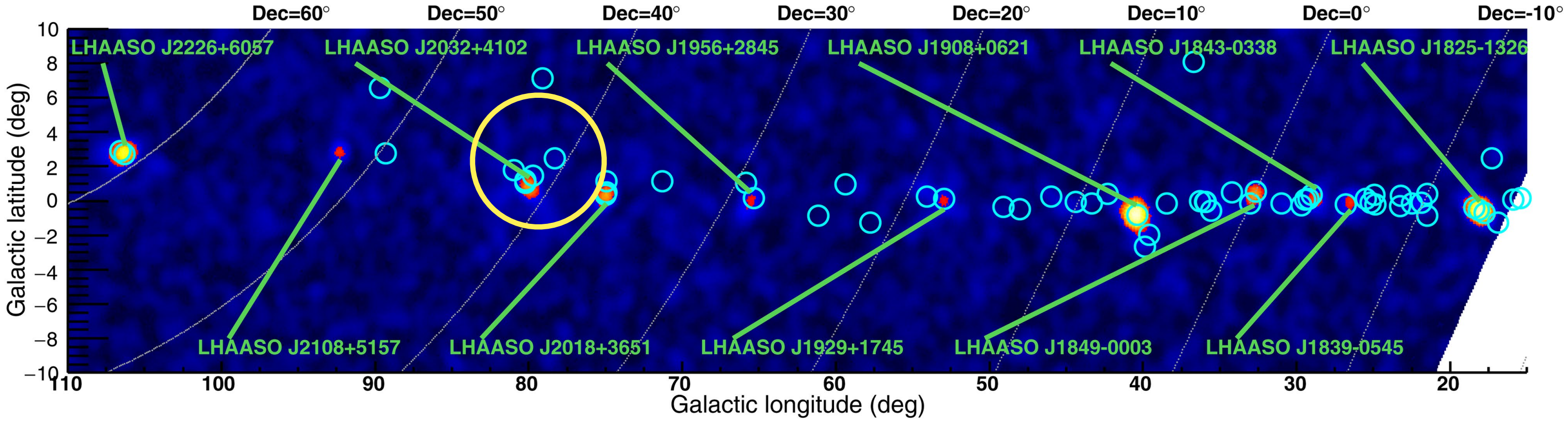
- A new window on SNRs has opened: X-ray polarimetry with IXPE
- Target young SNRs:
  - X-ray synchrotron emission associated with the shock regions
  - X-ray synchrotron → requires V_s>3000 km/s and turbulent (*upstream*?) fields
  - Evidence for magnetic-field amplification (Bell 2004)
- IXPE results:
  - 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-flelds 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!



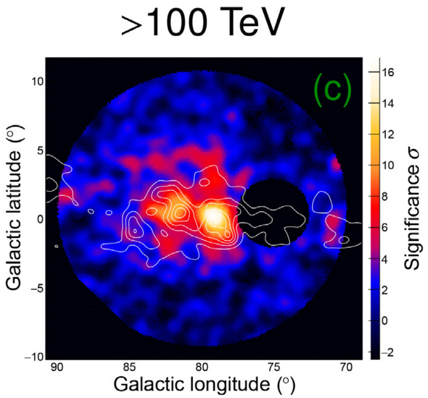
Ferrazzoli+ 2023

Part II:
Can stochastic acceleration create PeVatrons

LHAASO PeVatrons: 100-1400 TeV sources



LHAASO coll, Nat. '21

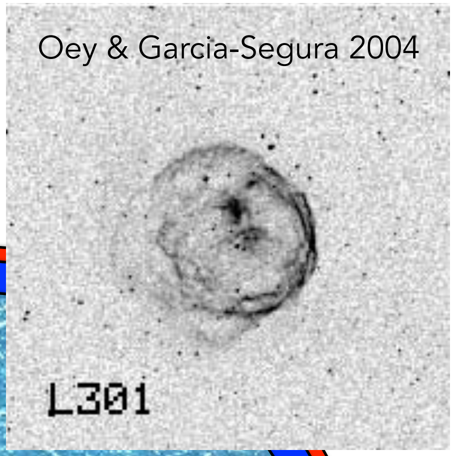


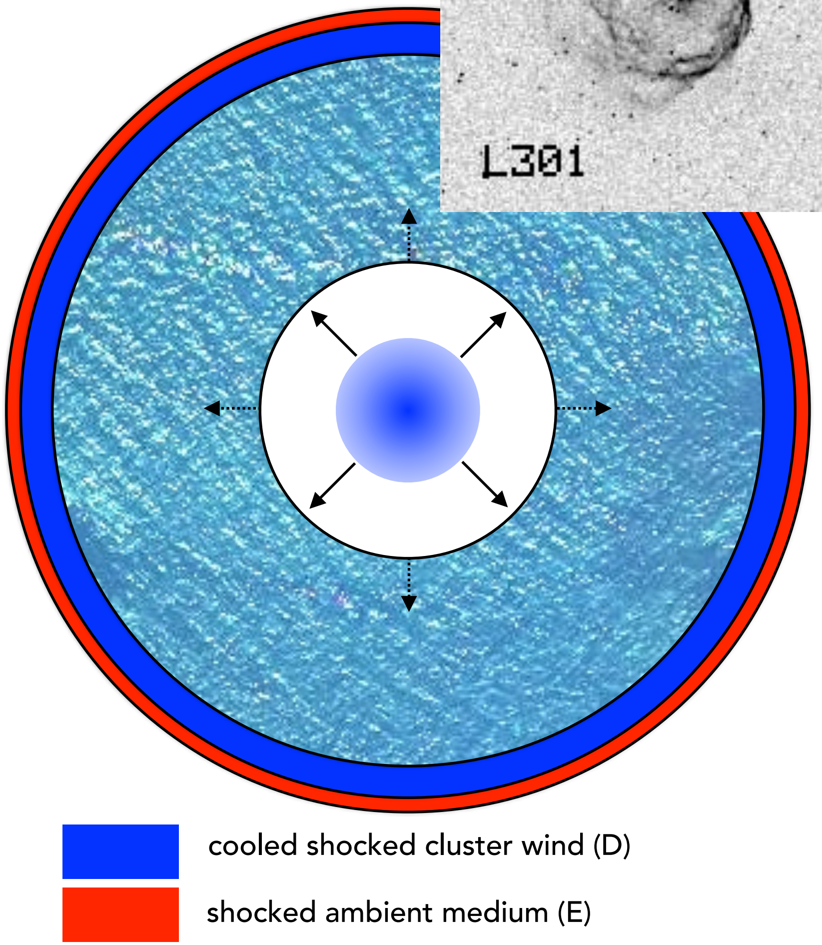
Cygnus Bubble: LHAASO coll, Sc. Bull. '24

- SNe can explain CR power, but not the CR "knee"! -> Where/what are the PeVatrons?
- LHAASO detected PeV photons! -> PeVatron case solved?
- The situation is still complicated:
  - Many sources are pulsars → do not (?) accelerate protons, but leptons
  - LHAASO PSF is poor: multiple source within PSF → which (if any) is the true PeVatron?
- One source may provide a hint: *the Cygnus OB2 association/Cygnus Bubble*
  - Combined effects SNe & Stellar winds? (Bykov & Toptygin '92, Parizot+ '04, Vieu+ '22-24)

Could superbubbles be the major sites of Galactic Cosmic Rays?

- Superbubbles are the giant bubbles (>40—200 pc) created by young massive clusters
- Bubble energized by
  - stellar winds (up to 3000 km/s)
    - main power for t≲ 4 Myr
  - supernovae (dominates lifetime budget)
- Long history of being considered important for CR acceleration (Montmerle c.s., Bykov, Parizot c.s.)
- Questions:
  - Are there collective effects?
  - And if so: can they be PeVatrons? And how?



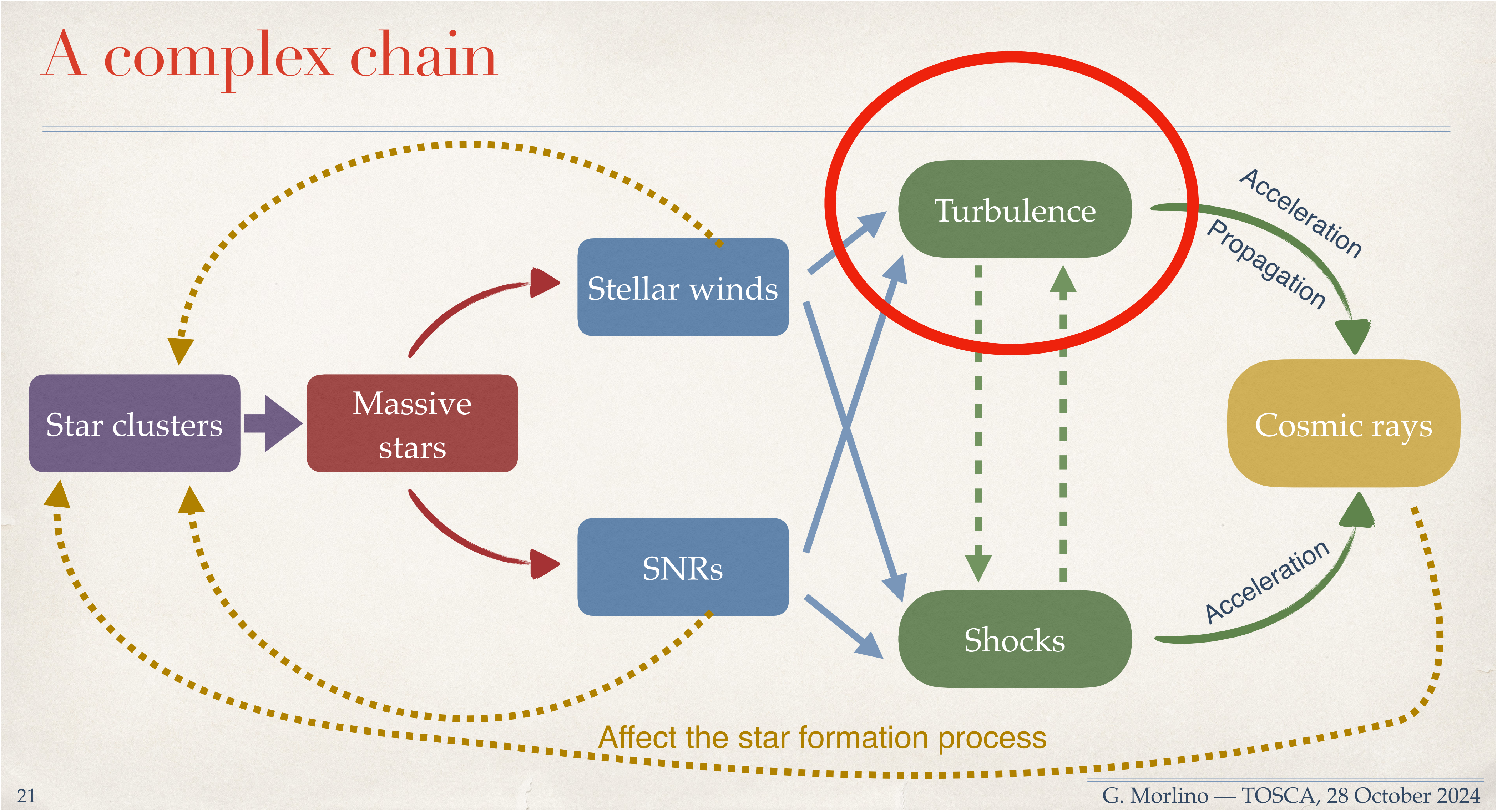


Superbubbles as (PeV) sources of cosmic rays

- SNRs appear *not* to be PeVatrons
  - Observationally/theoretically $E_{\rm max} \lesssim 10^{14}$ eV
  - But: SNe/SNRs perhaps PeVatrons early on? (if dense winds)
  - Or in special environments (*superbubbles?!*)
- Details in cosmic ray composition favor a wind-enriched environment
- SBs: Just many individual sources or collective phenomena?
  - *Is the whole more than the sum of the invidual parts?*
- Collective SB phenomena:
  - Multiple shocks (winds/snrs) keep interacting and accelerating particles (e.g. Bykov)
  - Long-lived and fast (2000 km/s) cluster wind termination shock
  - This talk: second order Fermi acceleration by magnetic field turbulence

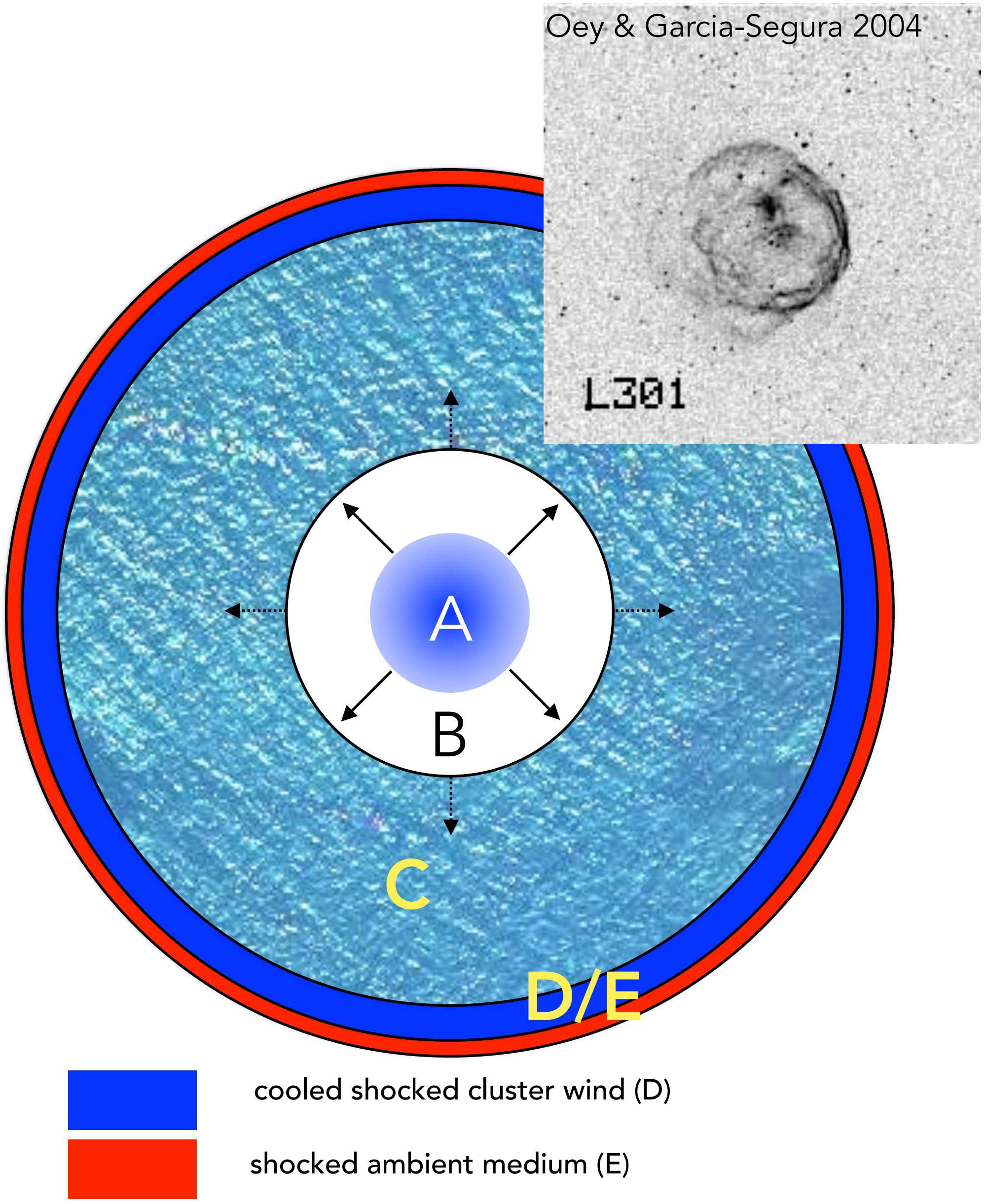
Superbubbles: are they more than the sum of their parts?

Sketch courtesy of G. Morlino

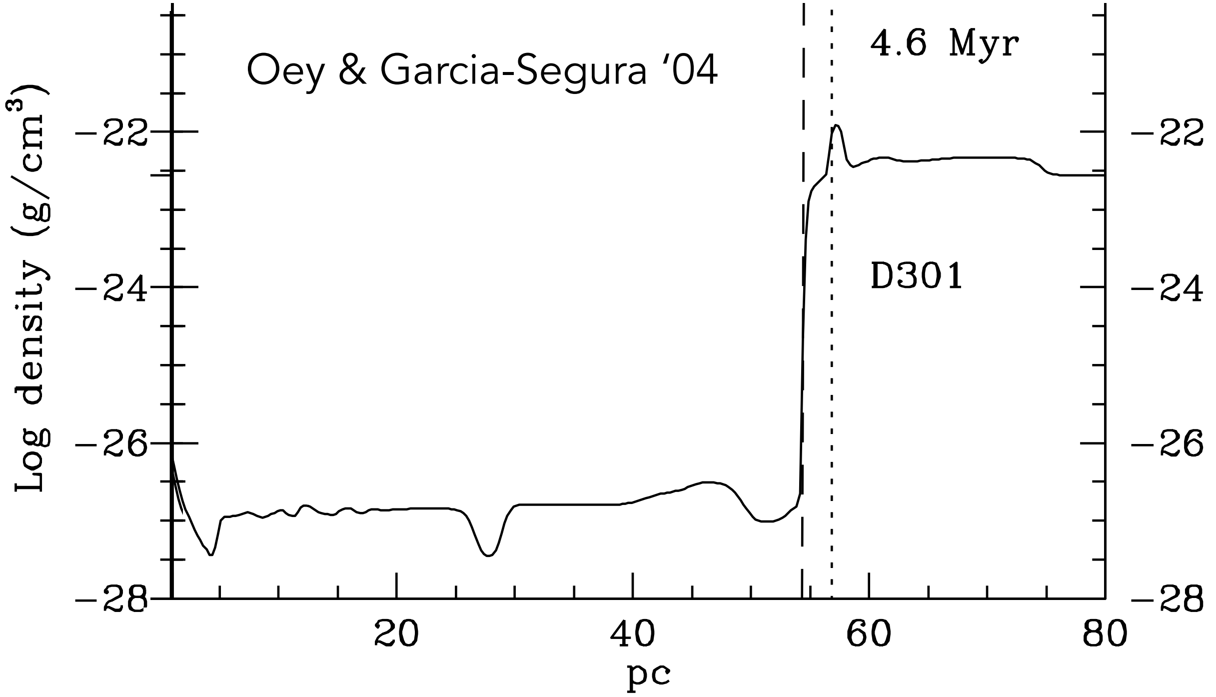


Superbubbles

- Several options for CR acceleration:
  - Cluster itself: colliding winds (A)
    - DSA
  - Termination shock cluster wind (boundary B/C)
    - DSA
  - Inside tenuous superbubble ©
    - Stochastic/2nd order Fermi
  - Occasional supernova remnant in (mostly in C)
    - e.g. 30DorC (H.E.S.S. '15, Kavanagh+ '19)
- All may contribute!
  - But which is responsible for PeV CRs?
- Region D/E could be site of (hadronic) gamma-rays
  - (bombarded by CRs from A,B,C)



Superbubble



- Models predict 100-200 pc (Weaver+ '77)
- But typical sizes LMC: 50 pc
  - Likely cause: ISM pressure locally high (Oey & Garcia Segura '04)
- Superbubble itself: could be very low density!
  - $\rho \approx 10^{-27} - 10^{-26}$ g cm^{-3} ($n_\mathrm{H} \sim 0.0005 - 0.005$ cm^{-3})
  - expected Alfvén speed: $V_\mathrm{A} = \dfrac{B}{\sqrt{4\pi\rho}} \approx 585 \left(\dfrac{B}{10\ \mu\mathrm{G}}\right)\left(\dfrac{n_\mathrm{H}}{0.001\ \mathrm{cm}^{-3}}\right)^{-1/2}$ km/s
- SB surrounding shell: $n_\mathrm{H} \sim 1 - 100$ cm^{-3}

Second-order shock acceleration inside SB

- Fermi's (1948) original idea
  - Particles scatter off moving magnetic irregularities (Alfvén waves)→ gain or lose energy
  - On average gain: $\frac{\Delta E}{E} = \xi \left(\frac{V_A}{c}\right)^2 \quad (\xi \sim 1)$
  - Space diffusion also based on scattering: $D = \frac{1}{3}\lambda_{mfp} c \rightarrow \Delta t = \frac{\lambda_{mfp}}{c} = \frac{3D}{c^2}$
  - Assume $D = D_0 \left(\frac{E}{E_0}\right)^\delta$ (ISM δ≈0.3-0.7; Bohm diffusion δ≈1)
  - Rate of energy gain: $\frac{1}{E}\frac{dE}{dt} \approx \frac{1}{E}\frac{\Delta E}{\Delta t} = \xi \frac{1}{3D_0}\left(\frac{E}{E_0}\right)^{-\delta} V_A^2$

NB connection acceleration-diffusion often expressed as

$D_{xx}D_{pp} = \frac{1}{9}p^2V_A^2$ **(e.g. Thornbury & Drury, 2014)**

Remarkable: Fermi-2 as efficient as Fermi-1?

- Expression for maximum energy: $E_{\max} = \left[E_{\rm inj}^{\delta} + \frac{\delta\xi}{3D_0} V_{\rm A}^2 E_0^{\delta} t \right]^{1/\delta}$
- 2nd order Fermi acceleration time scale: $\tau_{\rm acc,2nd} \approx \frac{3D_0}{\delta\xi V_{\rm A}^2} \left(\frac{E_{\max}}{E_0} \right)^{\delta} = \frac{3D(E_{\max})}{\delta\xi V_{\rm A}^2}$
- 1st order Fermi acceleration time scale: $\tau_{\rm acc,1st} \approx \frac{8D_0}{\delta V_{\rm s}^2} \left(\frac{E_{\max}}{E_0} \right)^{\delta} = \frac{8D(E_{\rm emax})}{\delta V_{\rm s}^2}$

- For relevant velocities 1st and 2nd order Fermi have similar timescales!
- In reality: SNRs can have V~ 5000 km/s, Alfvén speed is rarely that high!

- NB: a similar equation was derived by Thornbury&Drury (2014)
- Their conclusion: Fermi-2 not important for ISM ($V_{\rm A} \sim 10 - 30$ km/s)

Maximum energy taking into account escape

- High energies particles leak away due to diffusion, limits E_{max}:
  - $R = \sqrt{6Dt} \;\; \rightarrow \;\; \tau_{esc} = \dfrac{R^2}{6D}$
  - $\tau_{acc} \approx \tau_{esc}$, $D = \dfrac{1}{3}\lambda_{mfp}c = \dfrac{1}{3}\eta\dfrac{cE}{eB}$:

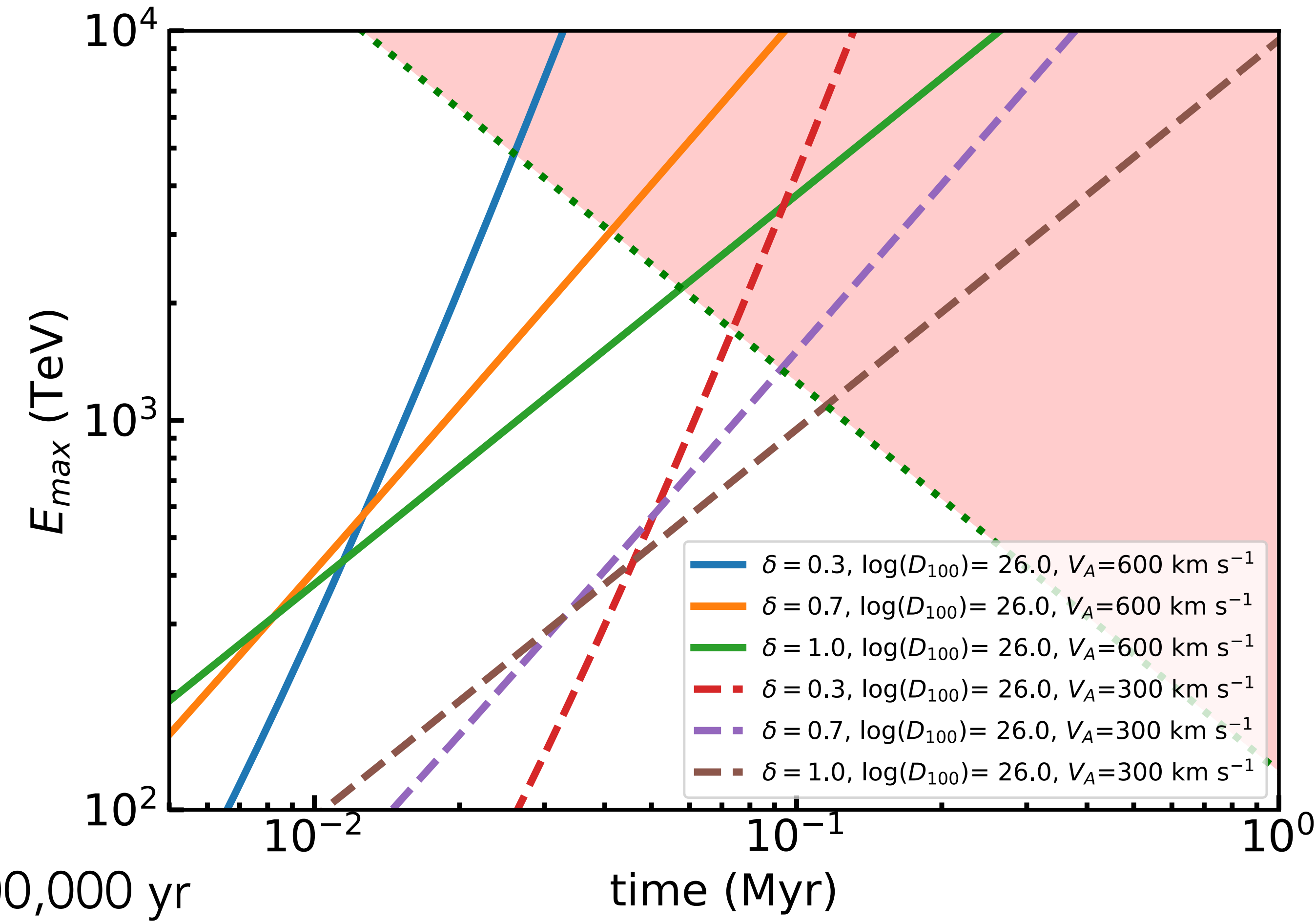
$$E_{max} = 5.5 \times 10^{14}\eta^{-1}\sqrt{\delta\xi}\left(\frac{B}{10\ \mu\mathrm{G}}\right)\left(\frac{R}{50\ \mathrm{pc}}\right)\left(\frac{V_A}{500\ \mathrm{km\ s^{-1}}}\right)\ \mathrm{eV}$$

  - or using $V_A = \dfrac{B}{\sqrt{4\pi\rho}}$:

$$E_{max} = 6.4 \times 10^{14}\eta^{-1}\sqrt{\delta\xi}\left(\frac{B}{10\ \mu\mathrm{G}}\right)^2\left(\frac{R}{50\ \mathrm{pc}}\right)\left(\frac{n_H}{0.001\ \mathrm{cm^{-3}}}\right)^{-1/2}\ \mathrm{eV}$$

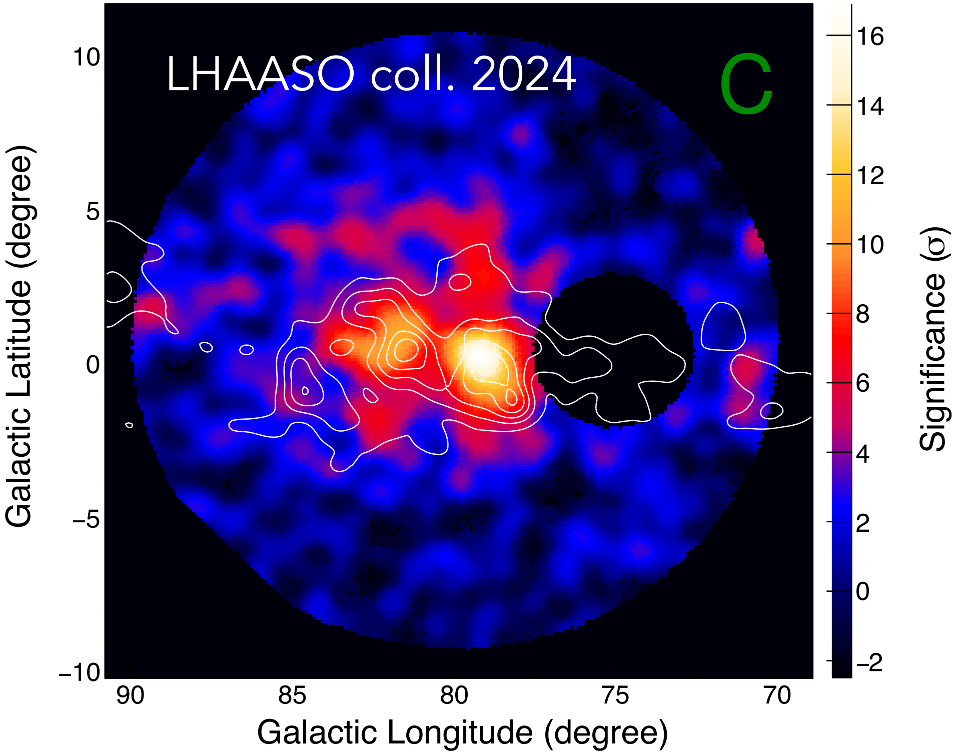
- For multi-PeV protons: high B and η~1 (Bohm diffusion):
  - E.g. B=30 μG gives $E_{max} \approx 6.8 \times 10^{15}$ eV

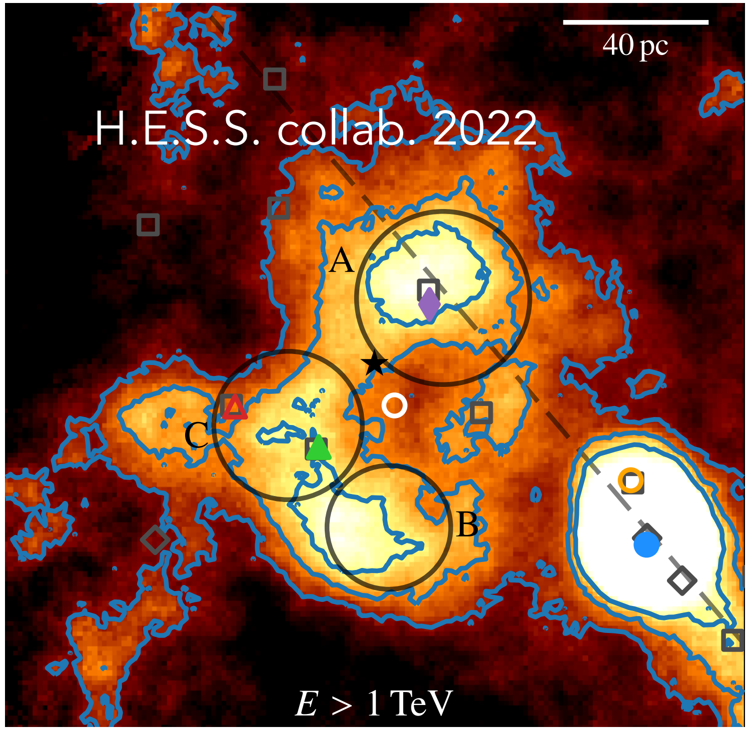
Conditions needed for Fermi-2 PeVatrons?



- Need fast Alfvén speeds:
  - $V_A \gtrsim 500$ km/s
    - $n_H \approx 0.001$ cm^{-3}, $B \approx 10 - 50\mu$G
  - Need very slow diffusion:
    - $D(100\ \text{TeV}) \approx 10^{26}$ cm^{3}s^{-1}
    - likely Bohm diffusion
  - Mechanism can be quite fast, 20,000-100,000 yr
- Injection: CRs pre-accelerated by wind shocks, termination shocks, SNRs

Cygnus Cocoon & Westerlund 1



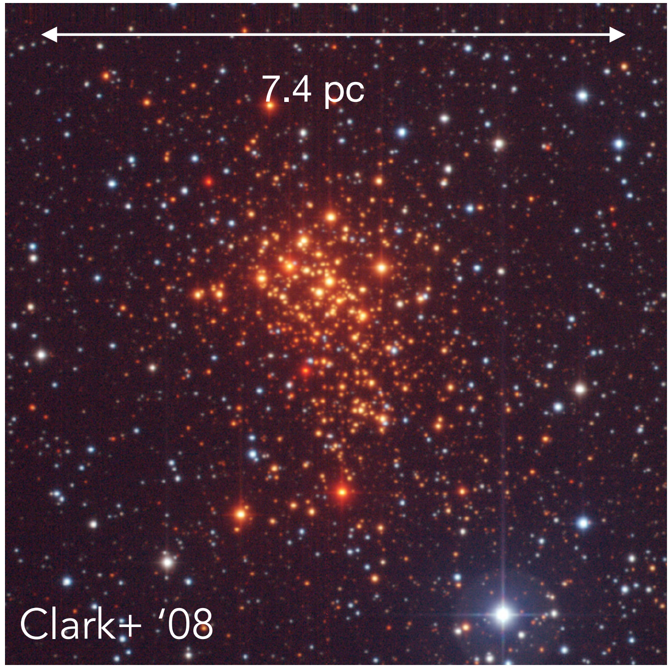


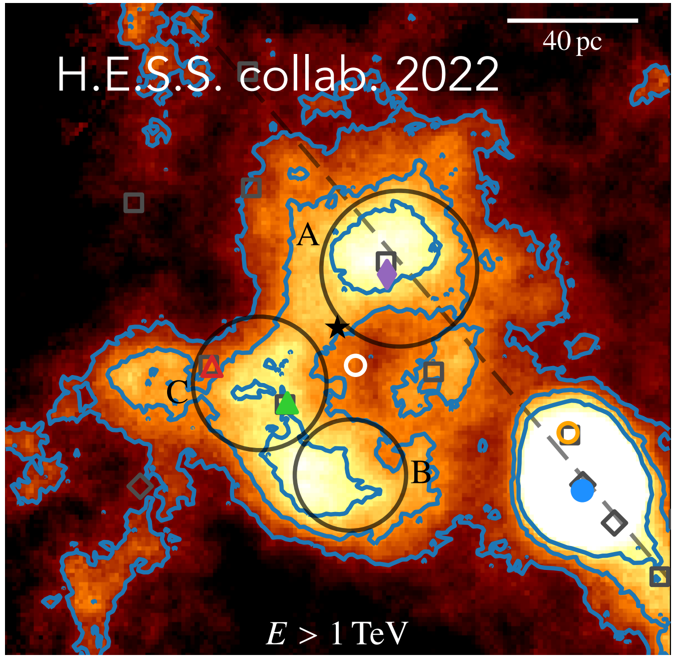
- >0.6 PeV photons
- R~55 pc
- $D(100\ \mathrm{TeV}) \approx \frac{R^2}{6t} \approx 1.4 \times 10^{26} \left(\frac{t}{\mathrm{Myr}}\right)^{-1}$
- Absence of termination shock? (Vieu+ '24)

- proton break > 200 TeV
- R~50 pc
- $D(100\ \mathrm{TeV}) \approx \frac{R^2}{6t} \approx 1.2 \times 10^{26} \left(\frac{t}{\mathrm{Myr}}\right)^{-1}$
- H.E.S.S. coll. '22: $B \gtrsim 50\ \mu$G

(Bohm diffusion, 200 TeV particles and t=1 Myr)

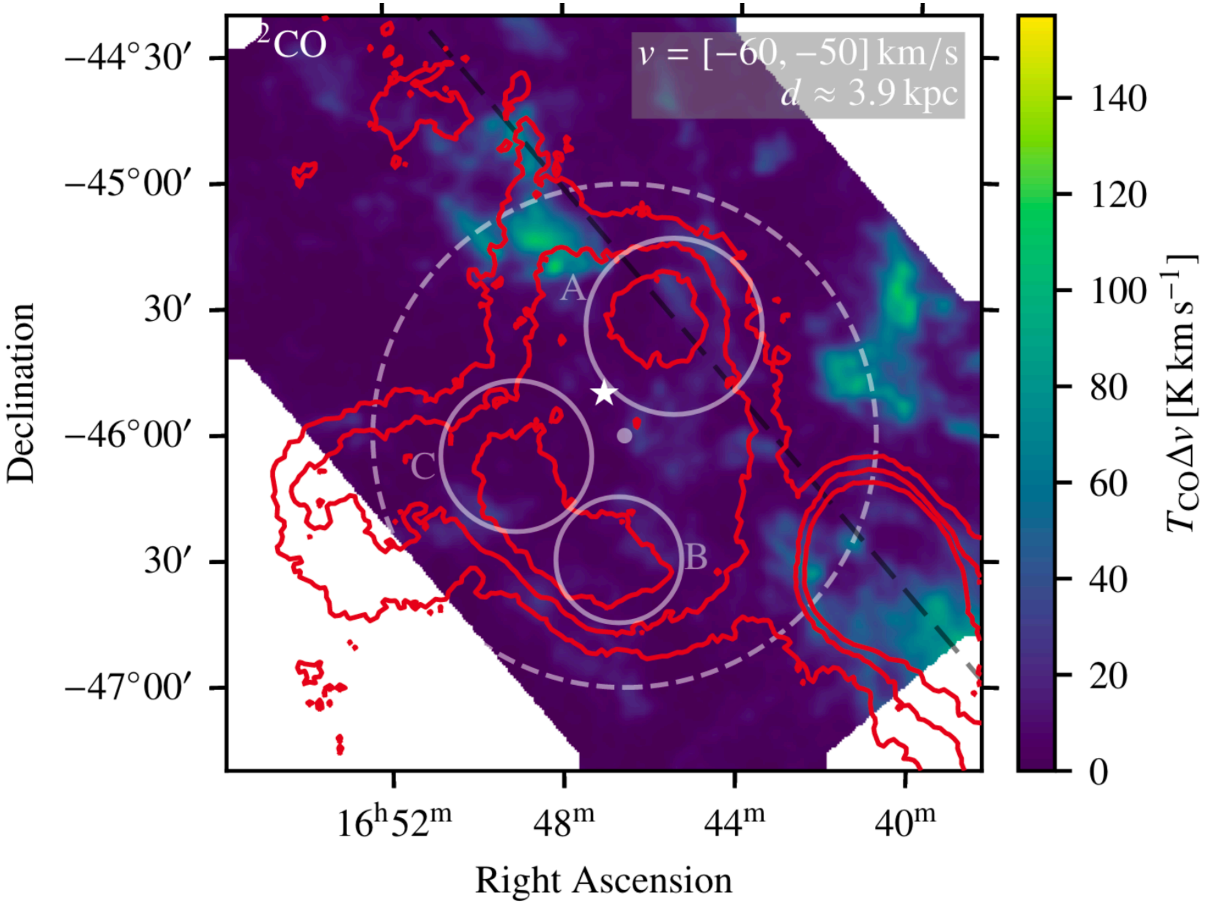
Starforming region Westerlund 1

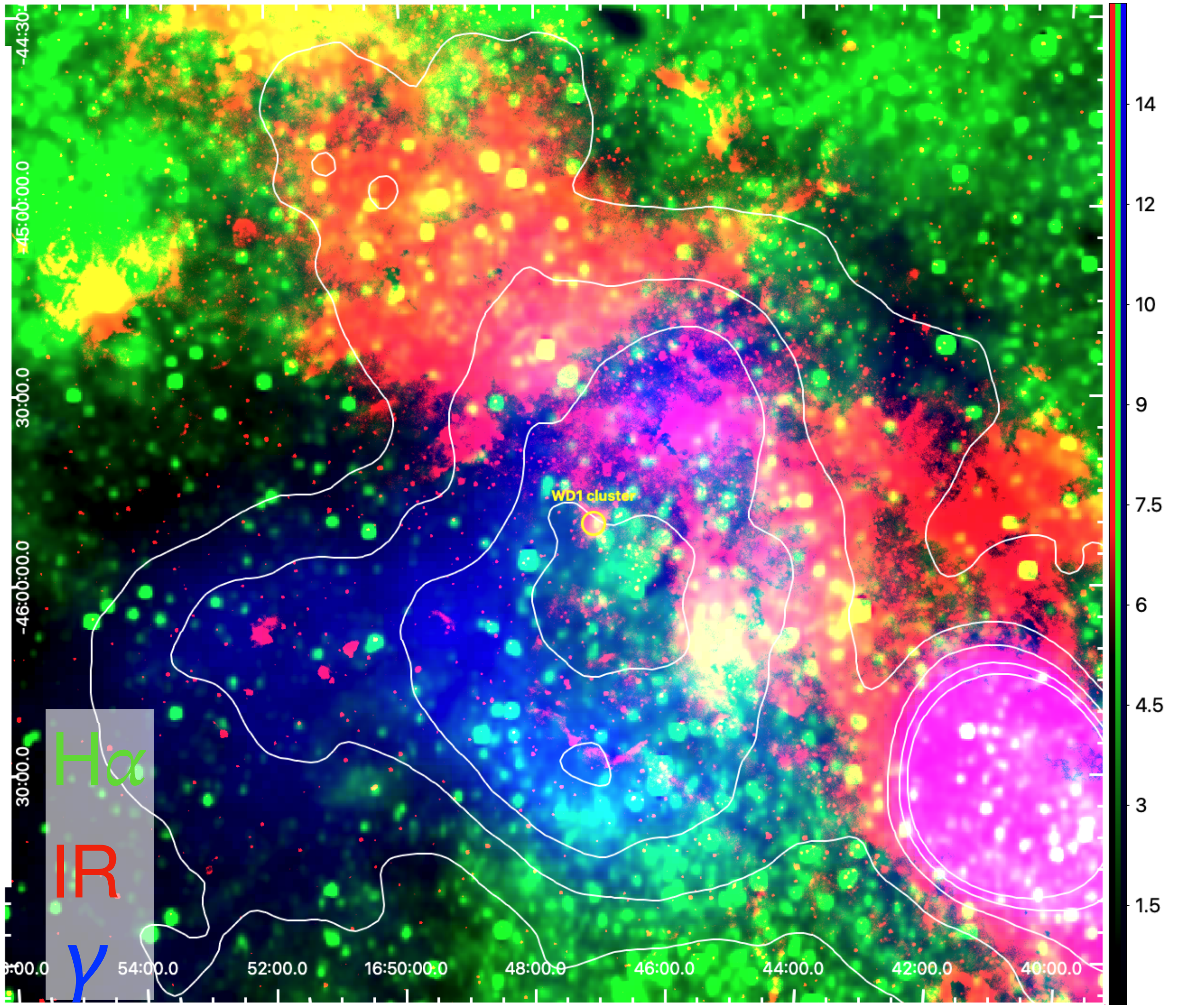




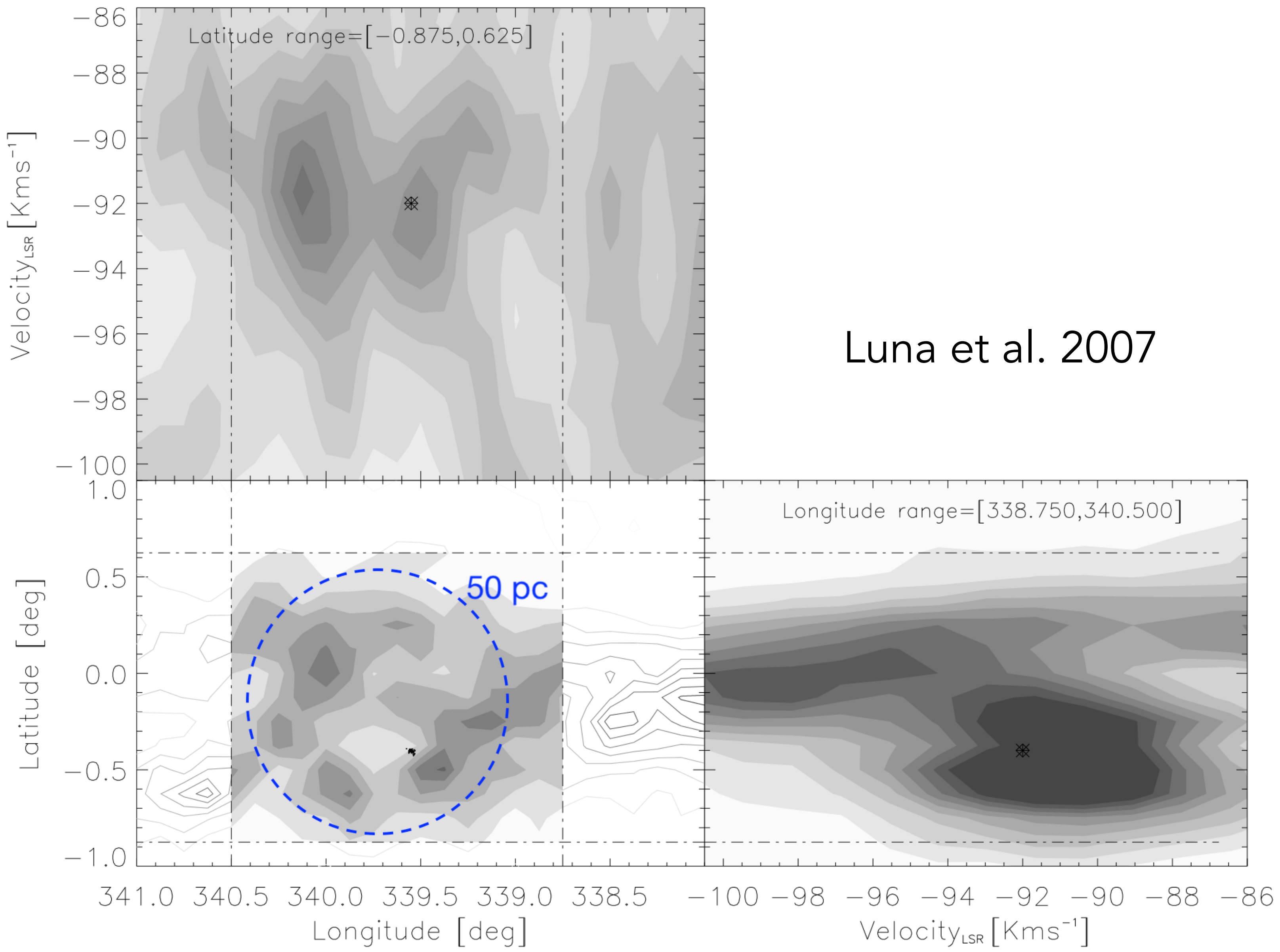
- Very rich massive cluster (27 Wolf-Rayet stars!): $L_{\rm w} \approx 10^{39}$ erg/s
- About 4 Myr old
- Associated with TeV gamma-ray source: HESS J1646−458
- Gamma-ray emission up to 200 TeV:
- Total CR energy: $W_{\rm p} \approx 6 \times 10^{51} d^2_{4.9kpc} n_{\rm H}$ erg (~20% of $E_w=L_w t$)

Westerlund 1 multiwavelength picture: an ISM hole





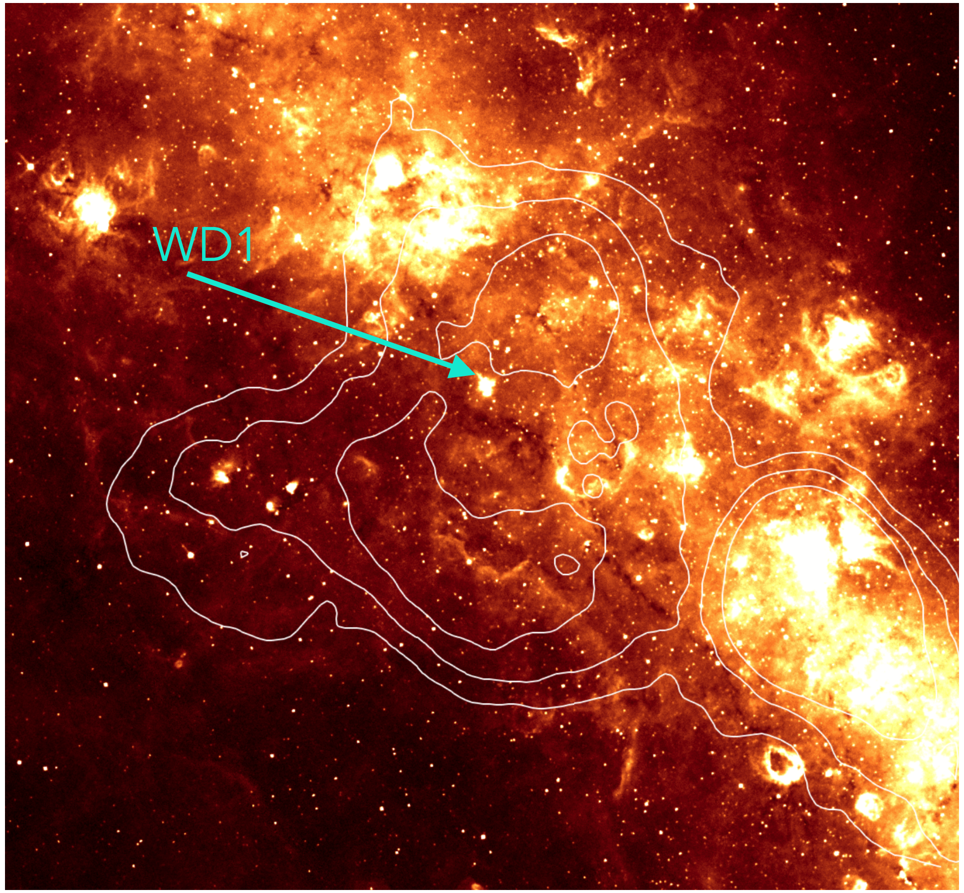
Is WD1 TeV source inside a cavity of 50~pc?



Luna et al. 2007

TeV source WD 1: termination shock or shell?

- **Termination shock model:**
  - size TeV source << size superbubble
  - termination shock in low density: emission likely leptonic (Härrer+ '23)
  - Requires V_{ts}=2500 km/s
  - Problem 1: average stellar wind $\sqrt{\overline{v_w^2}} \approx 1350\ \mathrm{km/s}$ (Fenech+ '18)
  - problem 2: why is starcluster so close to gamma-ray shell in NE? and why not brighter there?
- **Shell model:**
  - TeV emission hadronic (shell $n_{\rm H} \approx 1 - 10\ \mathrm{cm}^{-3}$)
  - Most TeV CRs in SB do not produce radiation
  - shell size small: ~50 pc
    - Gamma-ray shell fits within gap of ISM
  - Why is dense shell not visible in IR/CO/optical?



IR map (8micron) with H.E.S.S. contours

Energetic constraints Westerlund 1

- Very rich massive cluster: $L_{\rm w} \approx 10^{39}$ erg/s
- Age: 5~Myr (but active for ~Myr?)
- Total energy: $E_{\rm w} = L_{\rm w}t \approx 3 \times 10^{52} L_{\rm w,39} t_{\rm Myr}$ erg

- H.E.S.S.: $W_{\rm p} \approx 6 \times 10^{51} d^2_{4.9kpc} n_{\rm H}$ erg (~20% $E_{\rm w}$)
- Magnetic field: $E_B \approx \frac{B^2}{8\pi} V \approx \frac{1}{6} B^2 R^3 \approx 6 \times 10^{49} (B/10\ \mu{\rm G})^2$ erg (0.2% $E_{\rm w}$)
  - For Fermi-2: turbulent field needs to be continuously replenished

- What about CR energy in bubble vs shell?
  - $< n > = \dfrac{V_{\rm shell} n_{\rm shell} + V_{\rm bubble} n_{\rm bubble}}{V_{\rm tot}}$
  - $\Delta R/R \approx 10\,\%$: $< n > \approx 30\,\%\, n_{\rm shell} \approx 0.3 - 3\ {\rm cm}^{-3}$
  - So $W_{\rm p}$ estimate H.E.S.S. approximately valid, but may be off by factor ~3

Pros and Cons Fermi-2 in superbubbles

- DSA/Fermi-1:
  - Pros: DSA proven to be important in many environments to work
    - spectral slope more or less right ($\sim E^{-2.3}$)
  - Cons:
    - Invidual stellar winds not powerful enough, but maybe CR encounter multiple shocks
    - Cluster termination shock: is it always there? and is it fast enough?
      - density is low -> no direct source of hadronic emission
- Fermi-2:
  - Requires extreme circumstances: D(100 TeV)~10^{26} cm^2/s, V_A>500 km/s
    - But evidence for low D, and high B and low n!
    - Works even if termination shock is weak/absent, provided enough turbulence
  - Cons: *Fermi-2 spectrum intrinsically hard* (no built-in escape mechanism)
    - PIC simulations Fermi-2: softer spectra due to backreaction on B-turbulence
    - Feeds off turbulent field: needs continuous generation of Alfvén waves

Could supernovae inside SBs PeVatrons?

- We concentrated on either DS by termination shock, or Fermi-2 inside tenuous bubble
- Both have their pros and cons
- What if it is just supernovae?
    - Both Cygnus Cocoon & WD1 are old enough for a few SNe!
- What is special about supernovae inside superbubbles?
    - Low density (<0.001 cm^{-3})
        - may never really reach radiation phase
        - takes much longer time to slow down
            - expected total energy in CRs generated should be similar (~10% of E_{sn})
            - but more time allows particle to reach PeV domain!
        - But: hot plasma -> low Mach number!

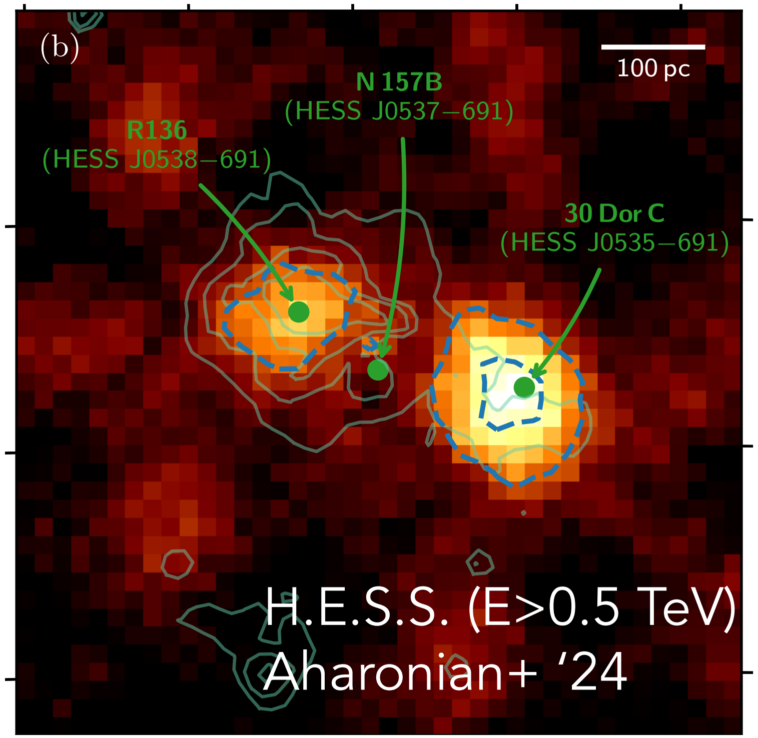
30 Dor C

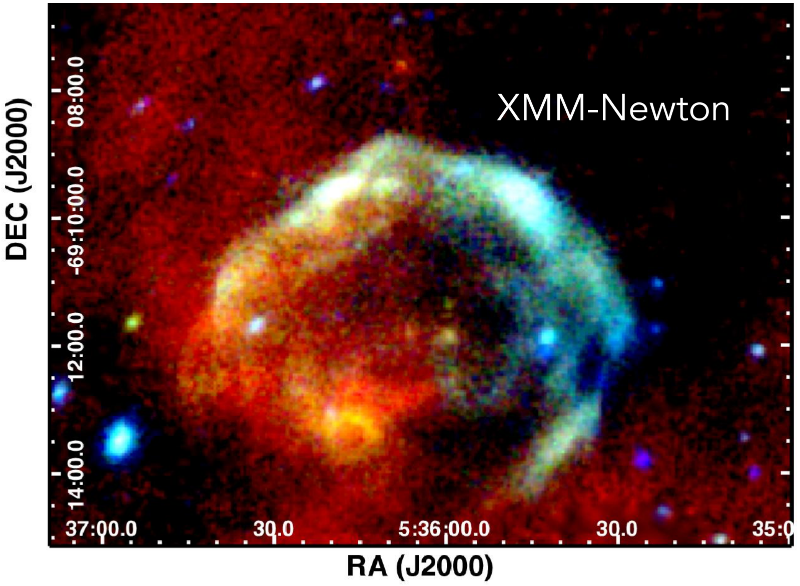
- Radius ~ 45-50 pc
- Non-thermal X-ray and VHE gamma-ray
- X-ray synchrotron: V_{sh} > 3000 km/s
- Optical HII: V<100 km/s (Kavanagh+ '19)
- Most likely explanation X-ray synchrotron:
    - Single SNR, t~6000 yr
    - X-ray width & leptonic model: B~10-20 μG
    - gamma-rays: leptonic

(Bamba+ '04, H.E.S.S. coll+ '15, Kavanagh+ '19, Aharonian+ '24)

•Single SNR, R~50 pc, V> 3000 km/s: n_H~0.0005 cm^{-3}

$$\bullet R \approx (Et^2/\rho)^{1/5},\ V_s = \frac{2}{5}\frac{R}{t}$$





Summary

- Despite textbook case: Fermi-2 can be very efficient provided V_A is high and D is small
    - Physics: 2nd order in (V/c), but boost per scattering
    - DSA: multiple scatterings needed before boost
- In superbubbles environment for Fermi-2 potentially ideal:
    - If n~0.001 cm^{-3}: V_A>500 km/s
    - Observational evidence for D(100 TeV)~ 10^{26} $cm^{-3}s$
    - PeV energies cn be reached in those circumstances!
- What needs to be done:
    - realistic calculations of spectrum
    - does Fermi2 predict too hard spectra or will it be softened by transport?
    - does it drain the magnetic-field turbulence too quickly?
        - and if so: what will happen? quenching acceleration? are we sometimes lucky?
- Supernovae inside SBs may be an alternative (or additional?) scenario