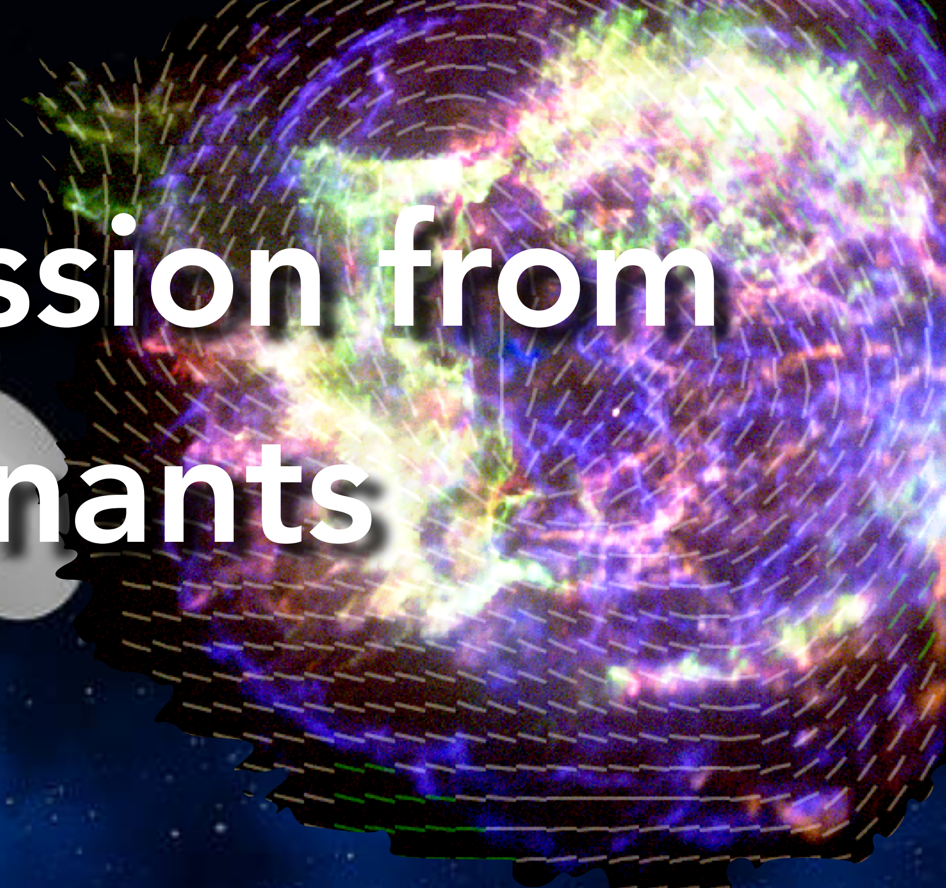
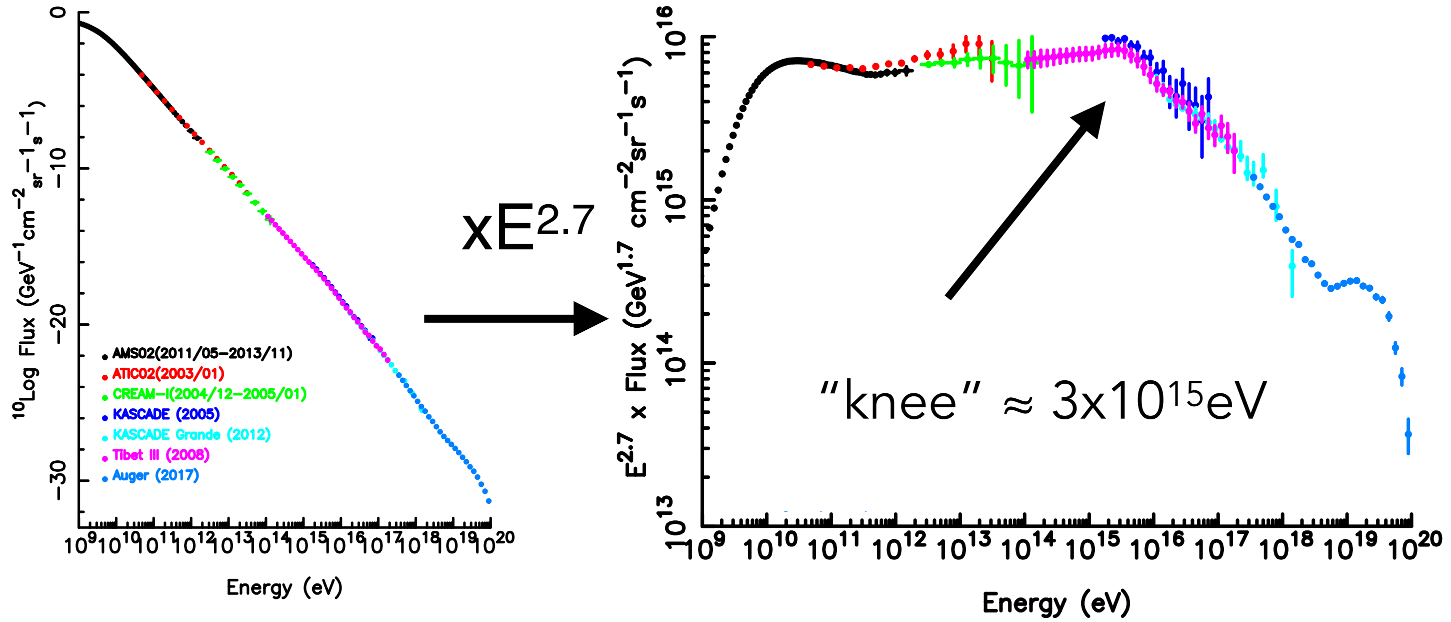
Polarized X-ray emission from supernova remnants



Jacco Vink (University of Amsterdam)

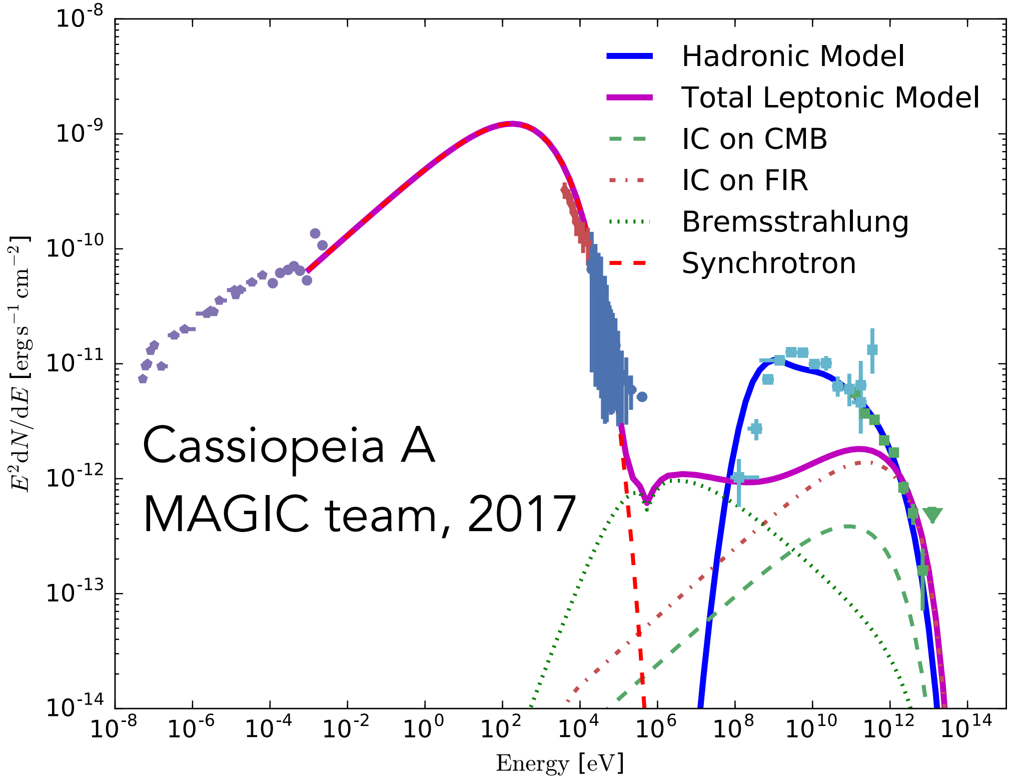
Emanuele Greco, Dmitry Prokhorov,
Ping Zhou, Riccardo Ferrazzoli, Pat Slane

Supernova remnants and cosmic rays



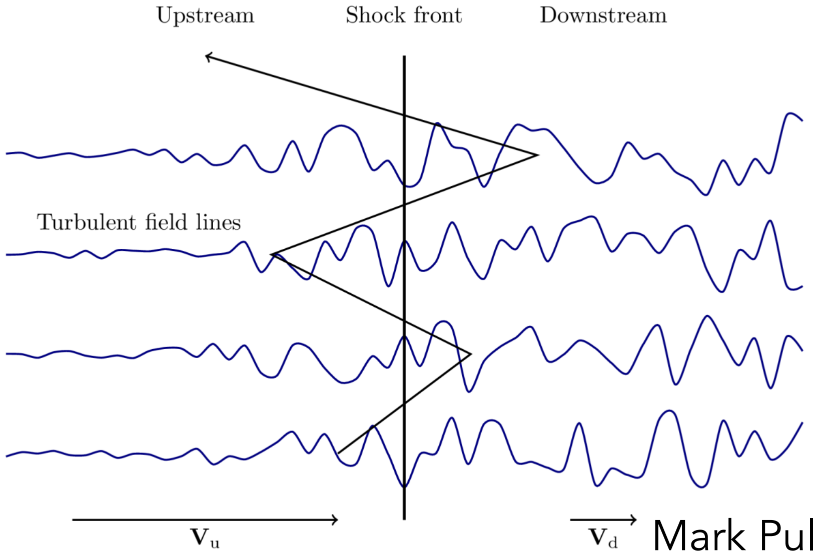
- Supernovae probably the dominant source of power for Galactic cosmic rays
- Their remnants provide probably the bulk of cosmic rays
  - But may not be able to reach 10^{15} eV!
- ~1 % of cosmic rays are electrons
- but electrons are best mean to study the acceleration process!

Nonthermal emission from SNRs



- *electrons* → synchrotron (radio to X-rays); inverse Compton (gamma)
  - synchrotron: intrinsically polarized at 70% level
    - orientation perpendicular to magnetic field
- Protons → pion decay (gamma, and neutrinos)

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



Mark Pullupa

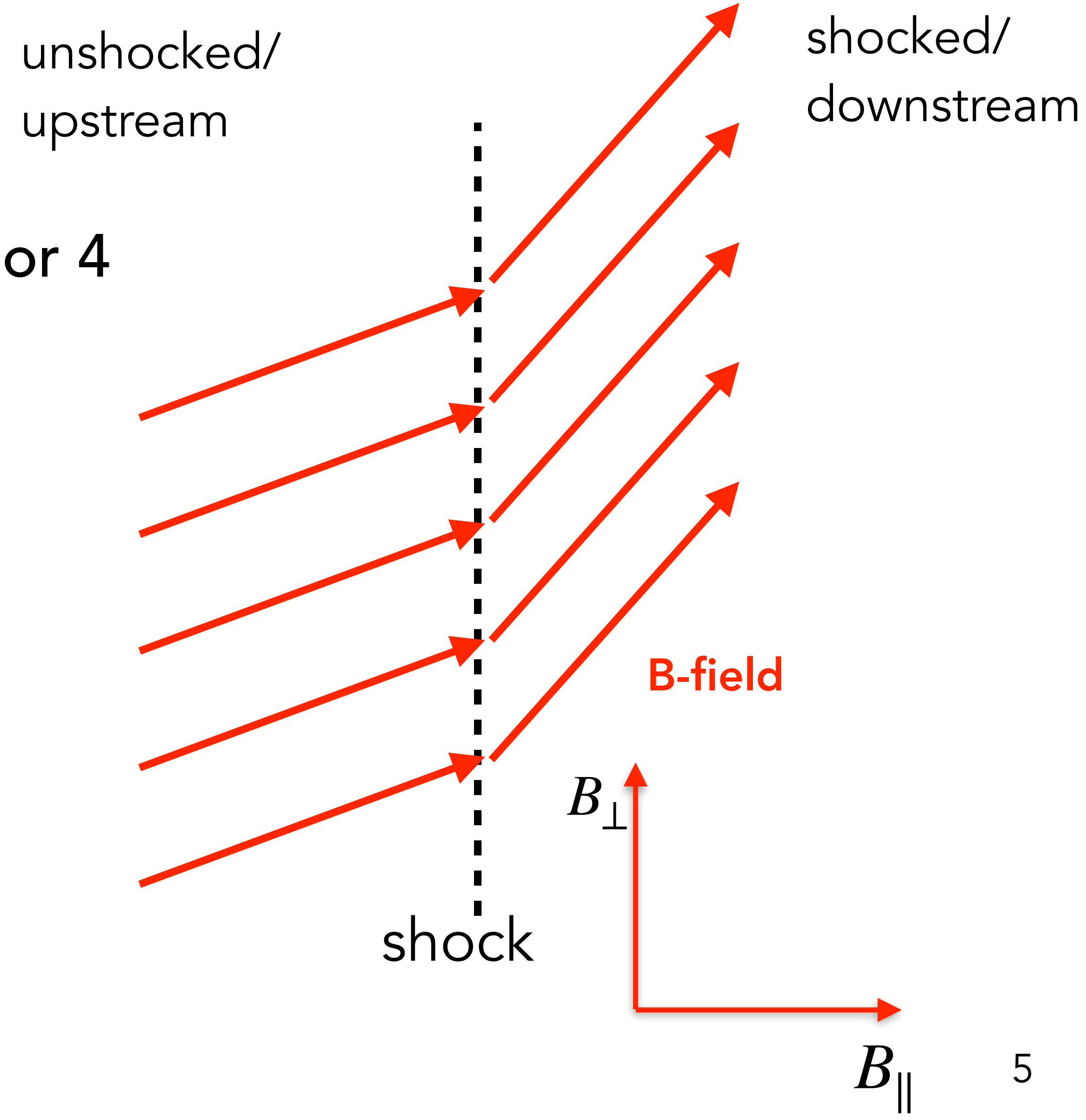
- Particles interact w. plasma thru magnetic fields
- Particles gain energy by crossing shock:
  - ΔV_{plasma} → Lorentz boost of $\dfrac{\Delta E}{E} \approx \dfrac{\Delta V}{c}$
  - Diffusion: particle can cross shock $D = \dfrac{1}{3} c\lambda_{\text{mfp}} = \dfrac{1}{3}\eta r_{\text{g}} = \dfrac{1}{3}\eta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

turbulent fields!

Shock aligns B-fields

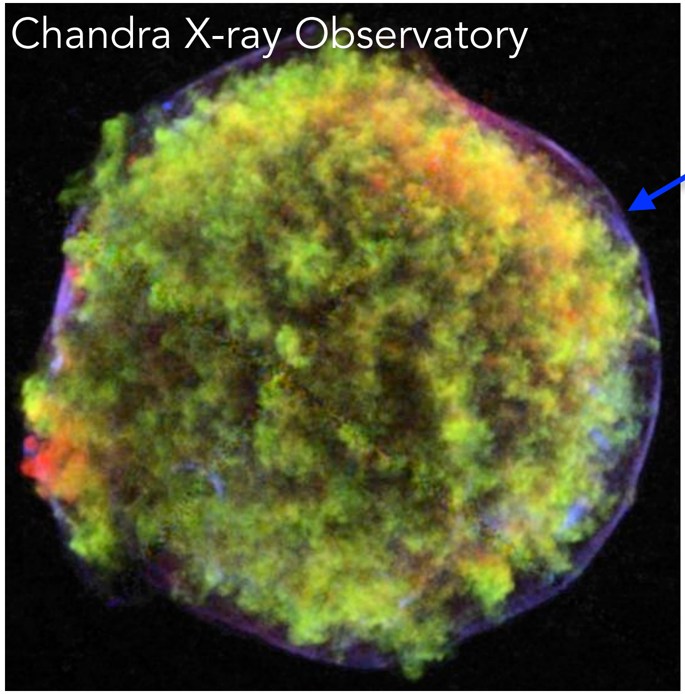
- Strong shock: plasma compressed by factor 4
- $B_\perp$ compressed by 4
- $B_{||}$ uncompressed

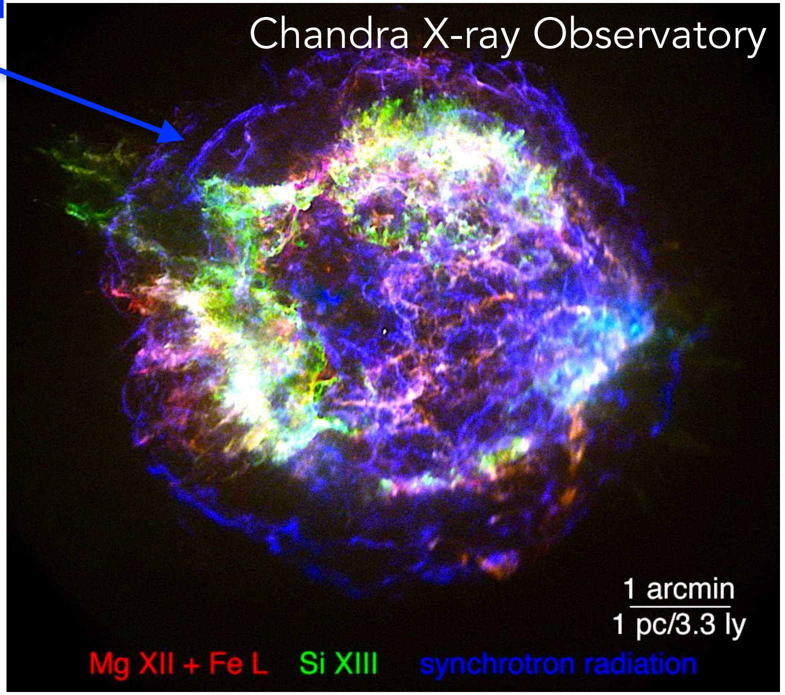
- B-field turbulence needed for DSA:
  - self-generated by cosmic rays!
- Theories consider upstream medium only



Thermal and nonthermal X-ray from supernova remnants

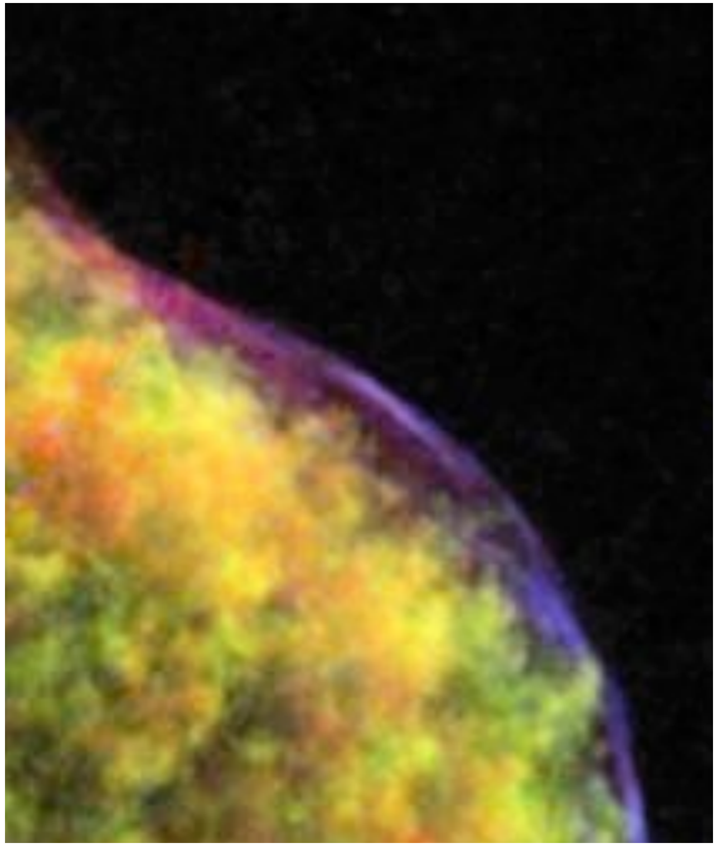
X-ray synchrotron





- Red/green/purple: thermal line emission from hot plasma → freshly made atoms!!
- Blue: X-ray synchrotron radiation from *10-100 TeV electrons!*
  - Tycho's SNR & Cas A: nonthermal filaments are ~10^{17}cm (2″) wide

What makes X-ray synchrotron interesting?



- Caused by 10-100 TeV electrons!
- Lose energy fast (years) →
  - Shows where acceleration ongoing
  - Requires acceleration to be fast
  - Sensitive to conditions near shock front
- Diffusive shock acc. + losses:

$$h\nu_{\rm cutoff} \approx 1.4\eta^{-1}\left(\frac{V_{\rm sh}}{5000\ {\rm km/s}}\right)^2\ {\rm keV}$$

→**η**~1 needed: fast acceleration/turbulent magnetic fields

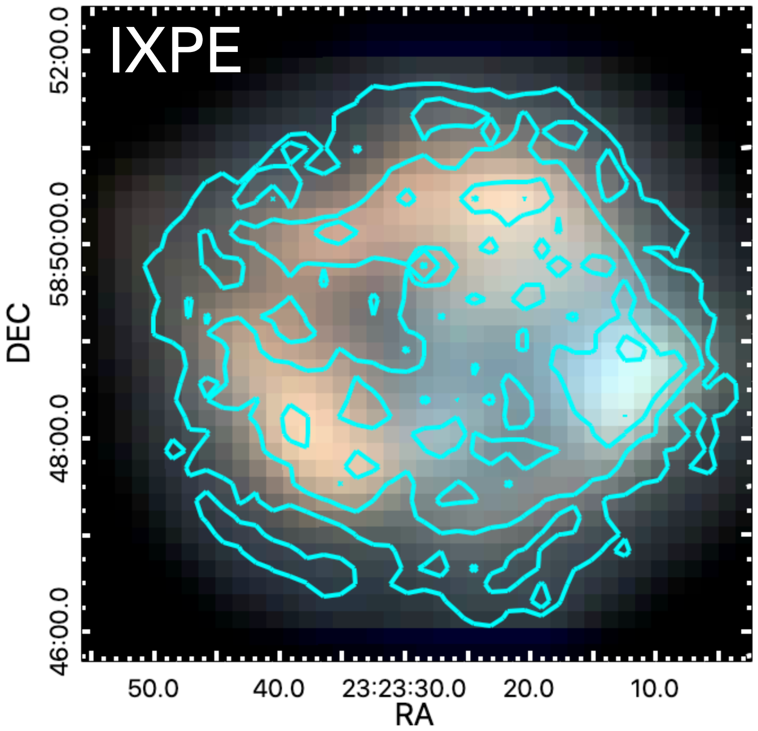
Imaging X-ray Polarimetry Explorer (IXPE)

IXPE
Imaging
X-Ray
Polarimetry
Explorer

- NASA/ASI small explorer mission (PI: M. Weisskopf): launched Dec. 9 2021
- US: spacecraft + X-ray mirrors; Italy: detectors
    - 3 telescopes: 25″ resolution, 13′ FoV,

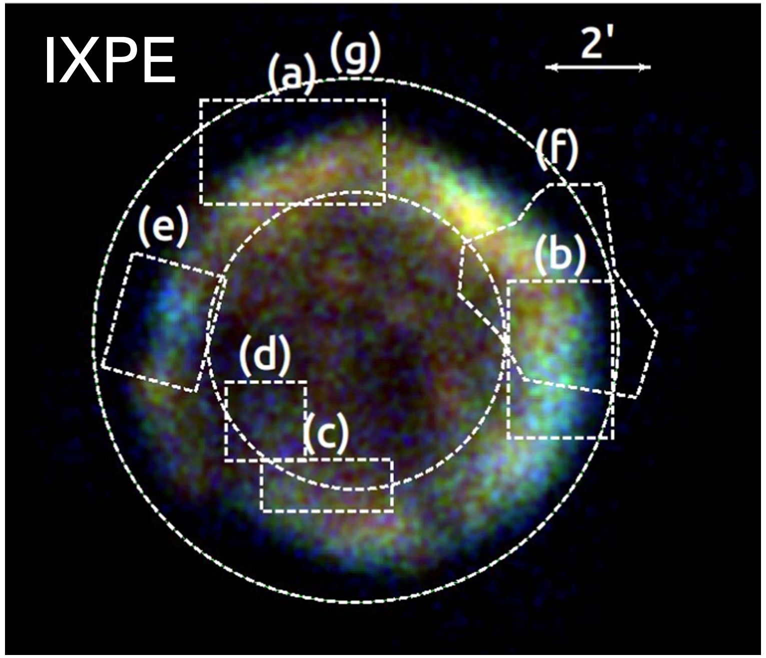
IXPE observations of supernova remnants

Cas A



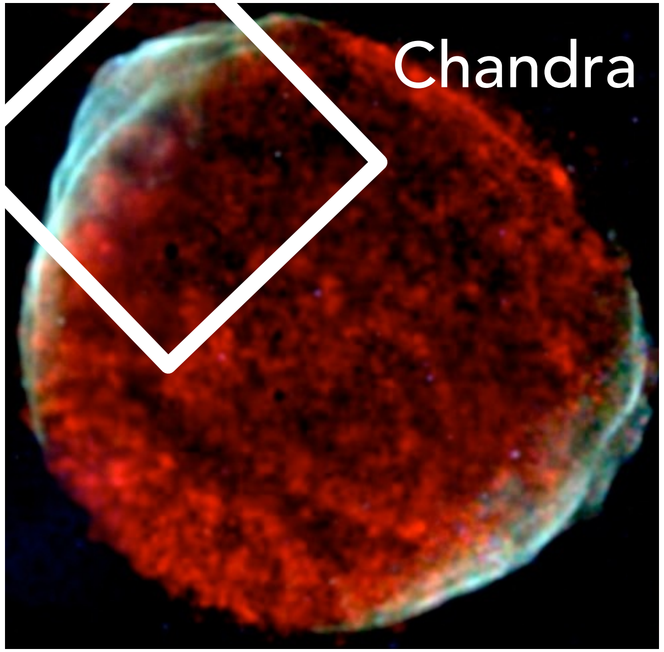
Vink, Prokhorov, Ferrazzoli+ (2022)

Tycho's SNR



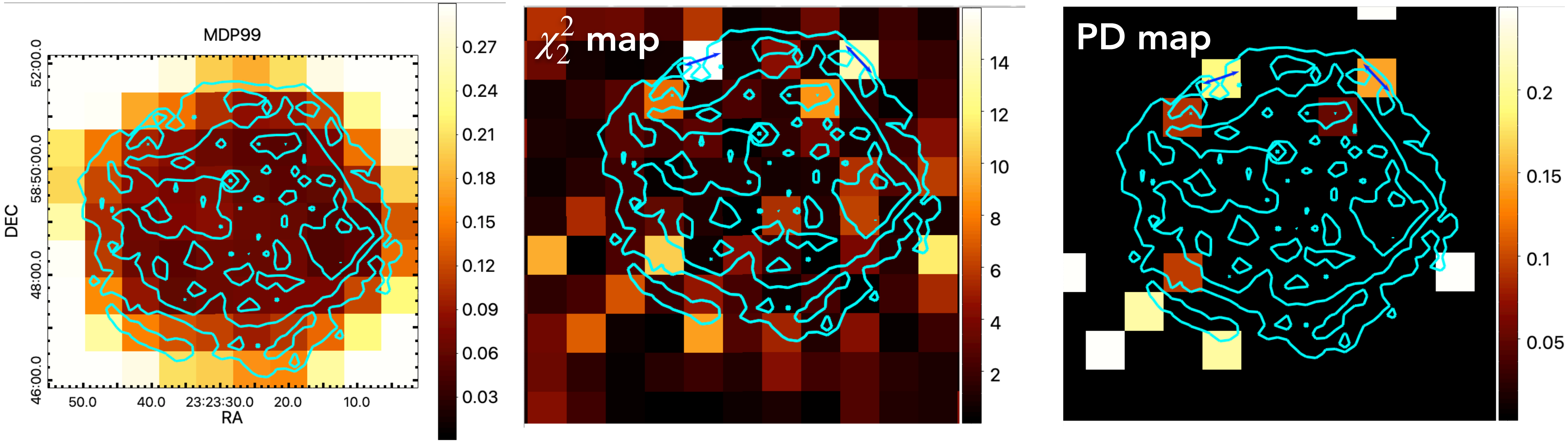
Ferrazzoli, Slane, Prokhorov+ (2023)

SN1006



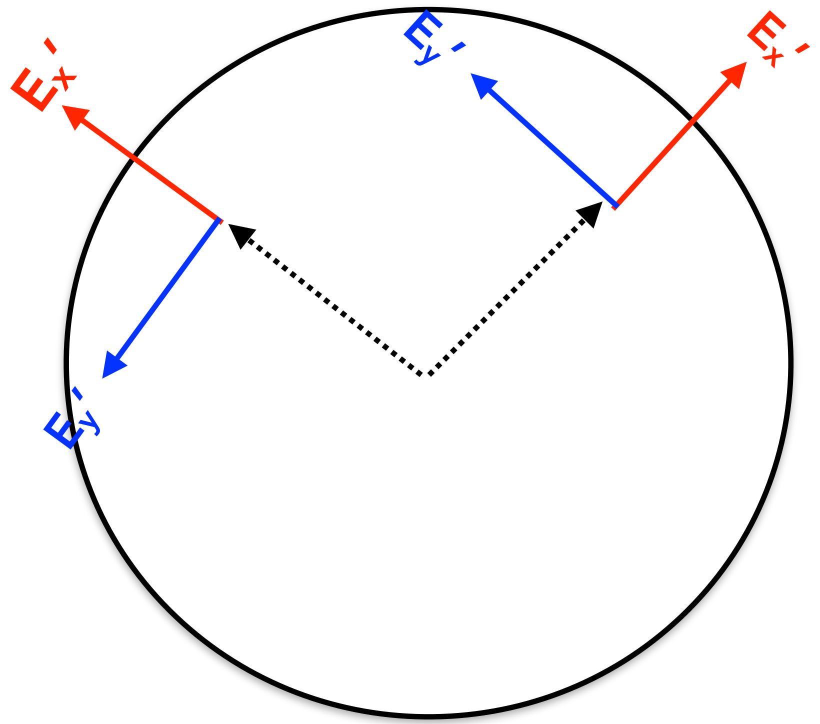
Zhou+, in prep. (2023)

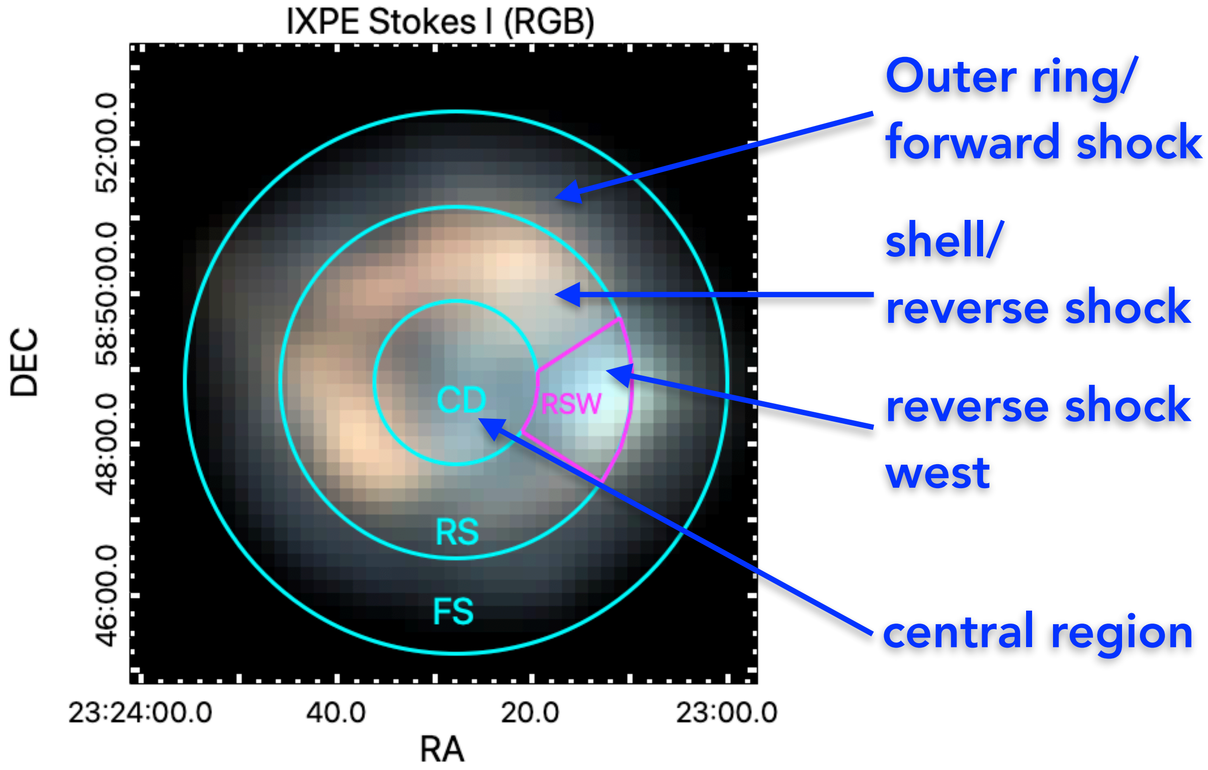
Pixel-by-pixel analysis



- 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

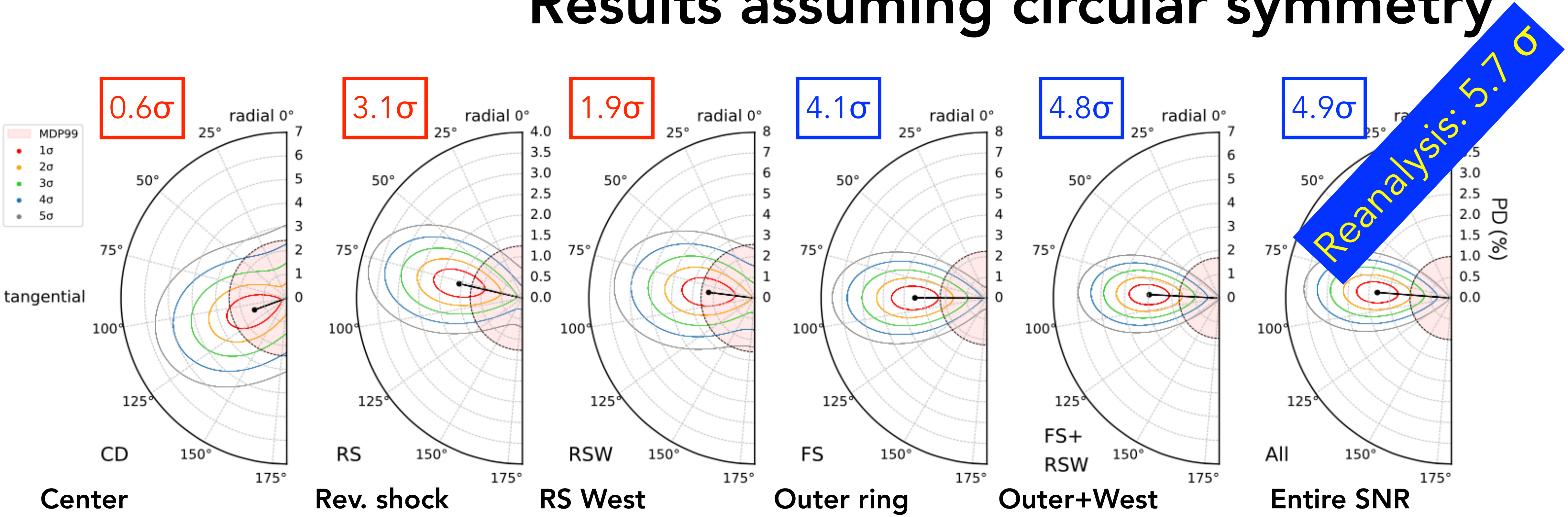
Analysis assuming circular symmetry





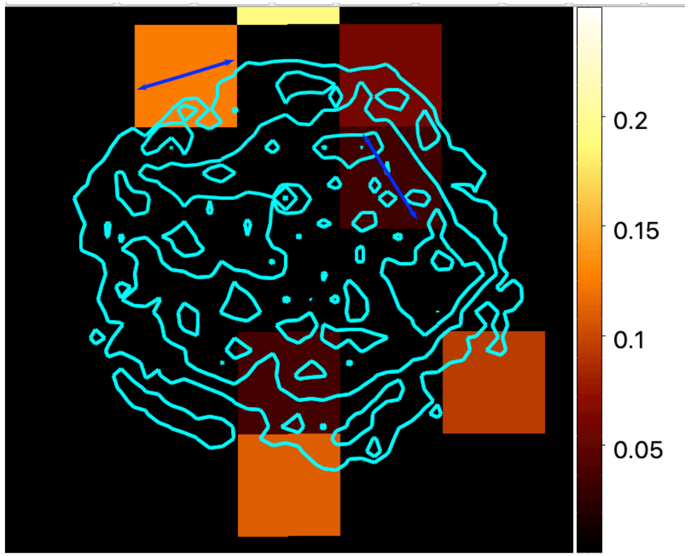
- No solid detections for pixel analysis: PD low, but how low?
- Expectations: either a radial magnetic field or tangential (shock compression)
- Spherical shell: circular symmetry expected!
- Method: specify local Stokes parameters Q′ and U′

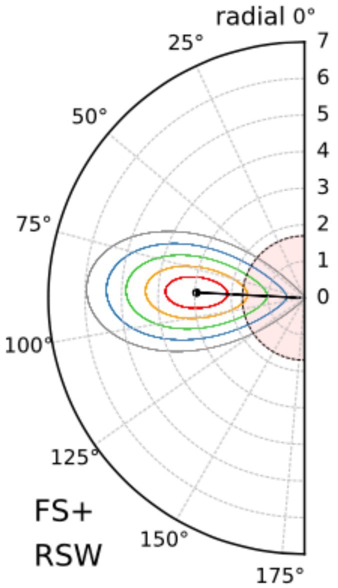
Results assuming circular symmetry



- For the outer shock region, 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!

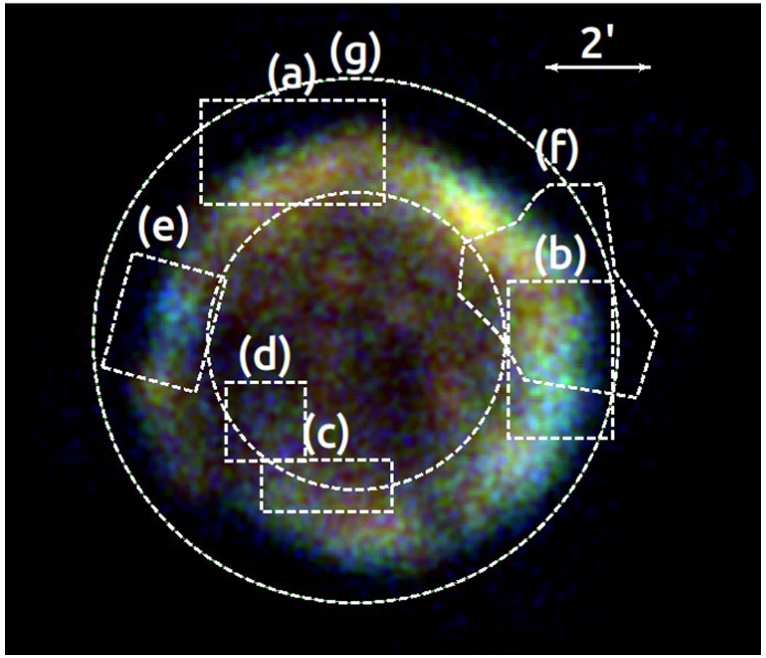
Implications

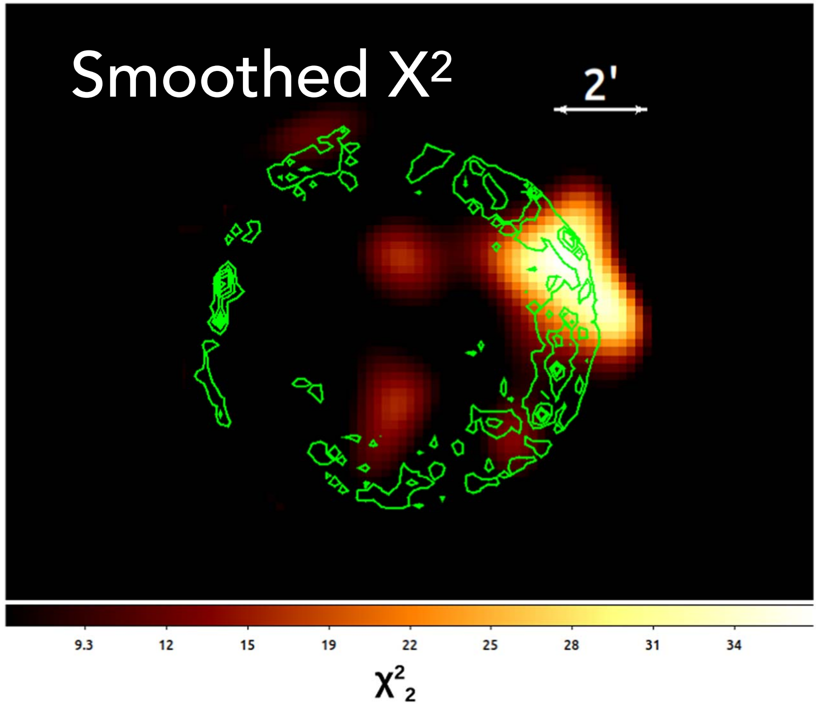


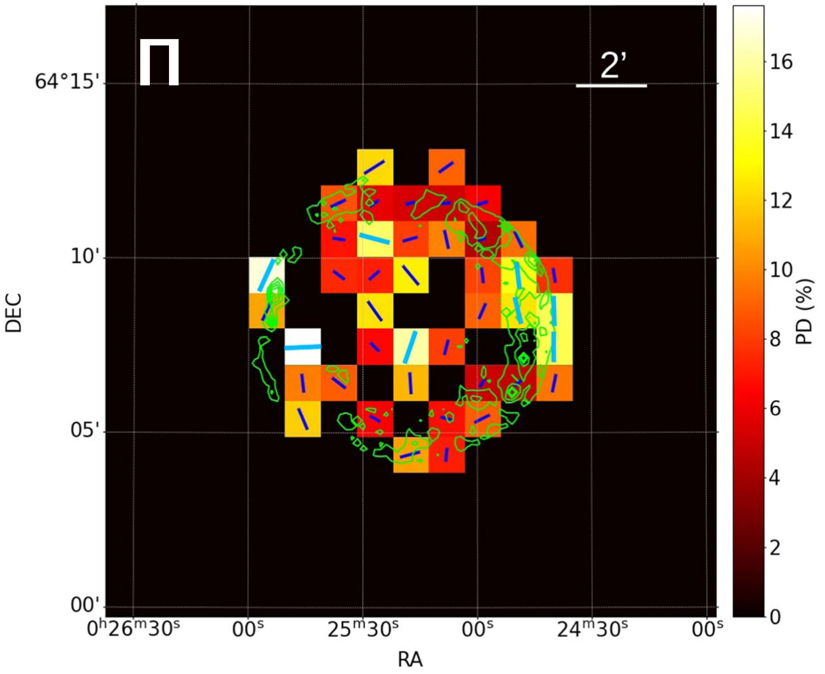


- Radial magnetic fields close to shock front!
  - Similar to radio: reorientation within 10^{17}cm of shock
  - MHD stretching: smaller scales than Inoue+ '13 (clumpy medium?)
- Low polarization:
  - magnetic field turbulent modes $<10^{17}$cm (X-ray filament widths)
  - no turbulent peaks at IXPE resolution $\sim10^{18}$cm (Bykov+ simulations)

IXPE observations of Tycho's SNR

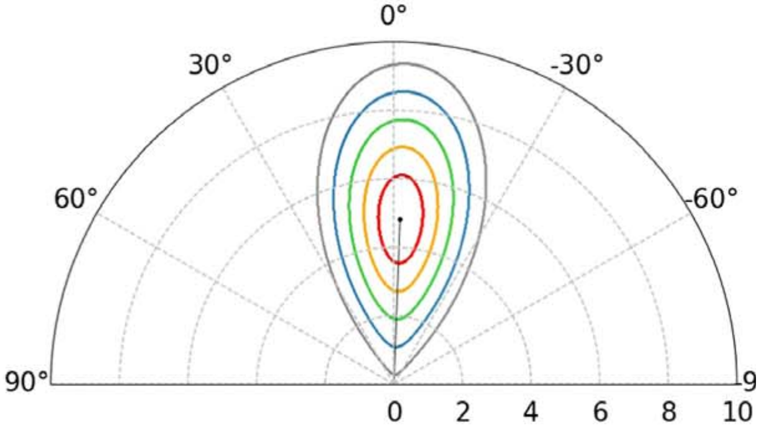




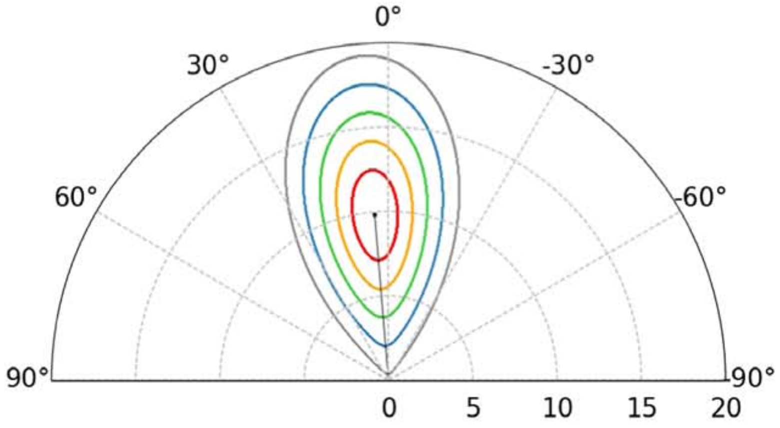


- IXPE observations: June/July + December 2022 for 990 ks
- Measured polarization (all, symmetry correction): 3.5% (measured), 9% (corrected)
- Invidual region: only West (b) signicant at 5.6σ level (**Π**=23±4% corrected)
- Again: radially oriented magnetic field!

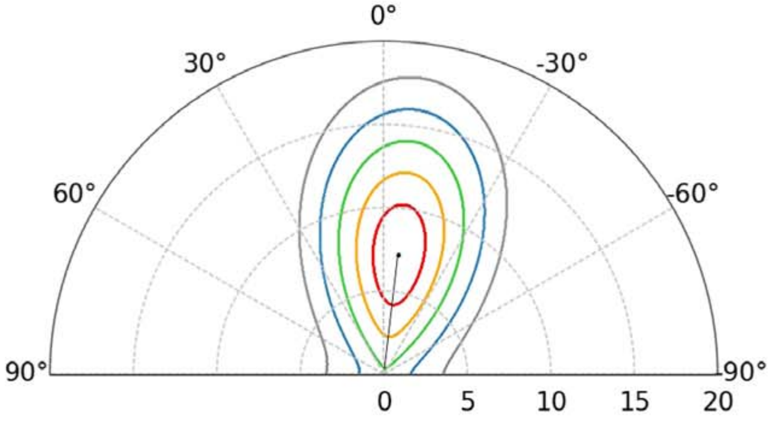
IXPE polar diagrams Tycho’s SNR



entire rim

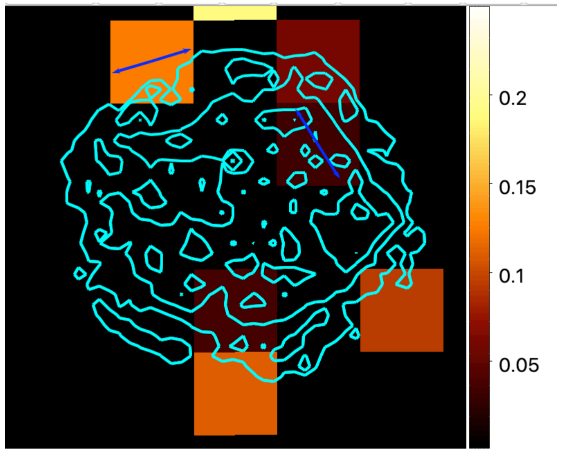


nw rim



stripes

Summary



- X-ray polarization for Cas A is low and difficult to detect
  - Requires circular symmetry assumption to detect at ~5**σ** level!
  - polarizations is 2–4.5%
  - Polarization pertains to regions with 10^{17}cm of shock
- Polarization degree is equal or smaller than in the radio band
- Polarization vectors suggest radial magnetic field
  - At odds with shockfront compression!

Backup slides

Measuring X-ray polarization with IXPE

Weisskopf+ '22

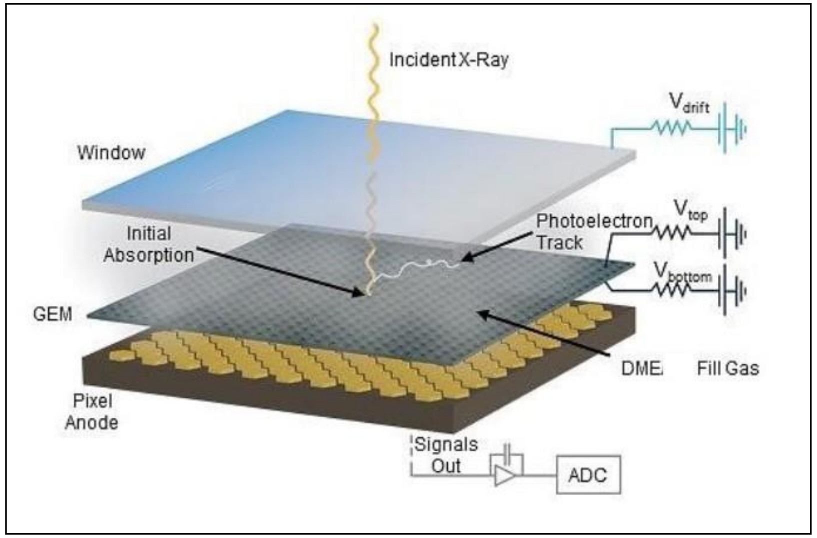
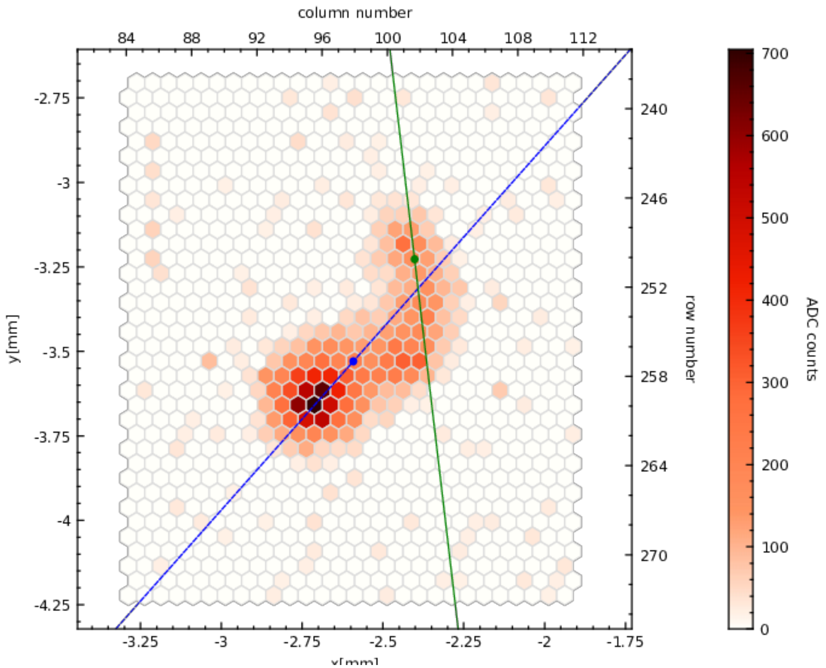
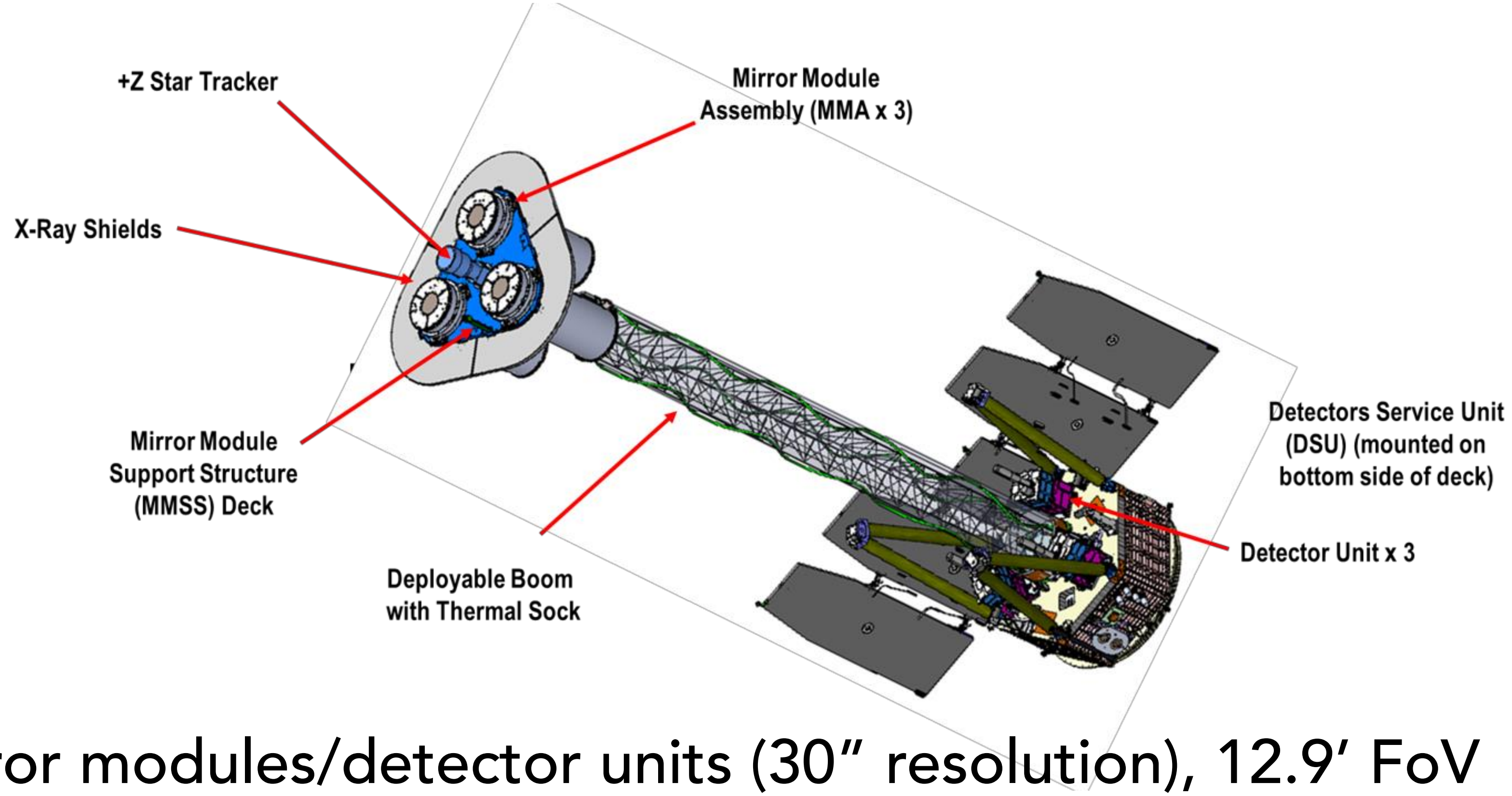


Figure 9: Schematic of the Gas Pixel Detector (GPD)



- 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

Imaging X-ray Polarimetry Explorer (IXPE)

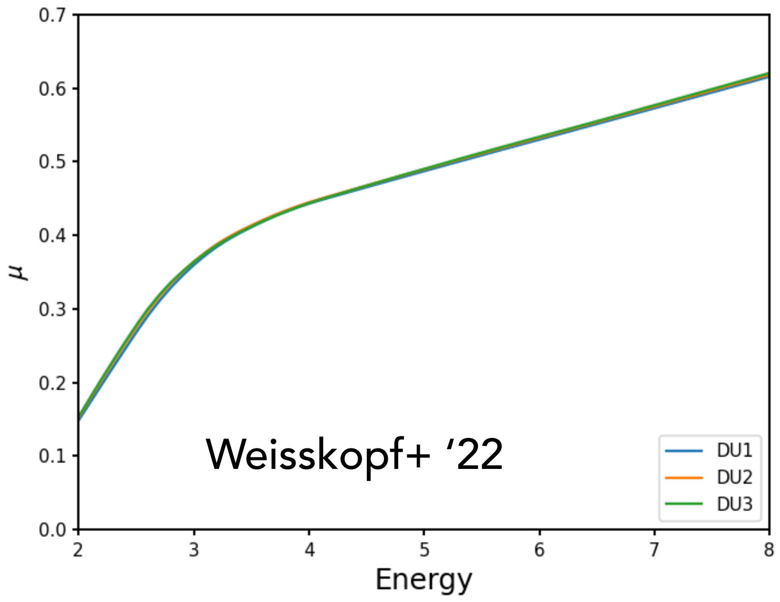


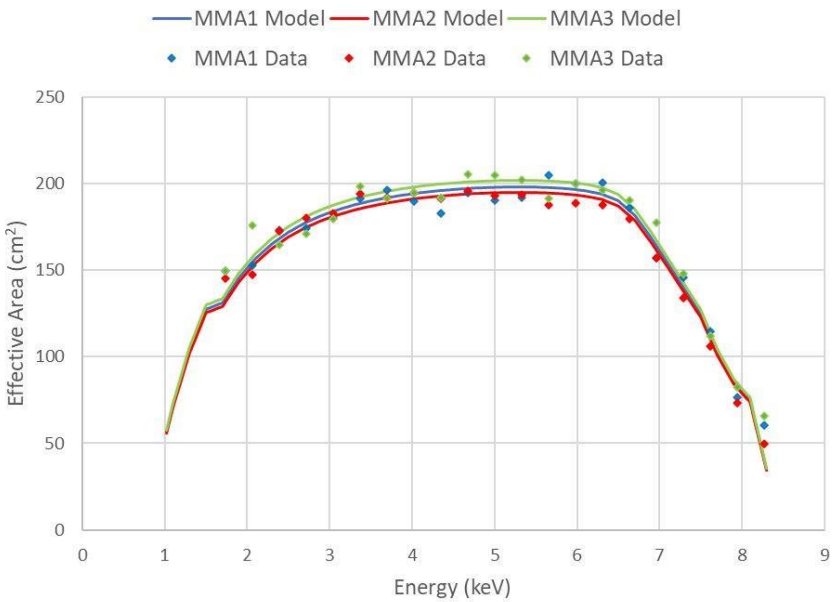
- Three X-ray mirror modules/detector units (30″ resolution), 12.9′ FoV
- Gas-pixel detectors

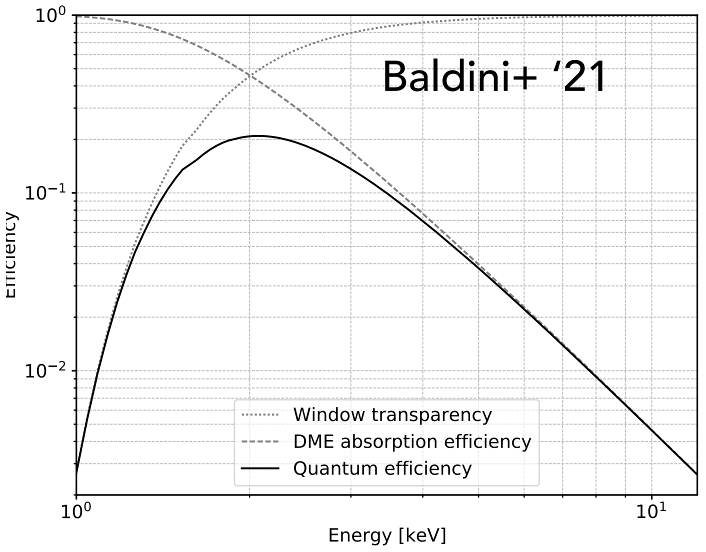
IXPE science

- Science operations started 1 month after launch!
- Science team determined targets, but data immediately public!
- Science goals:
  - Determine corona geometry X-ray binaries/AGN (inverse Compton)
  - X-ray echo SGR A* outburst gal. center (inverse Compton)
  - Polarization signals blazars: constrains acceleration mechanism (synchrotron)
  - Magnetars: geometry magnetic field/emission mechanism (radiation transport)
  - Magnetic-field topology in supernova remnants and pulsar wind nebulae (synchrotron)
- First science observation: SNR Casssiopeia A

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": response to 100% polarized source
- IXPE optimum: ~3 keV (large μ, reasonable eff. area)

X-ray synchrotron radiation

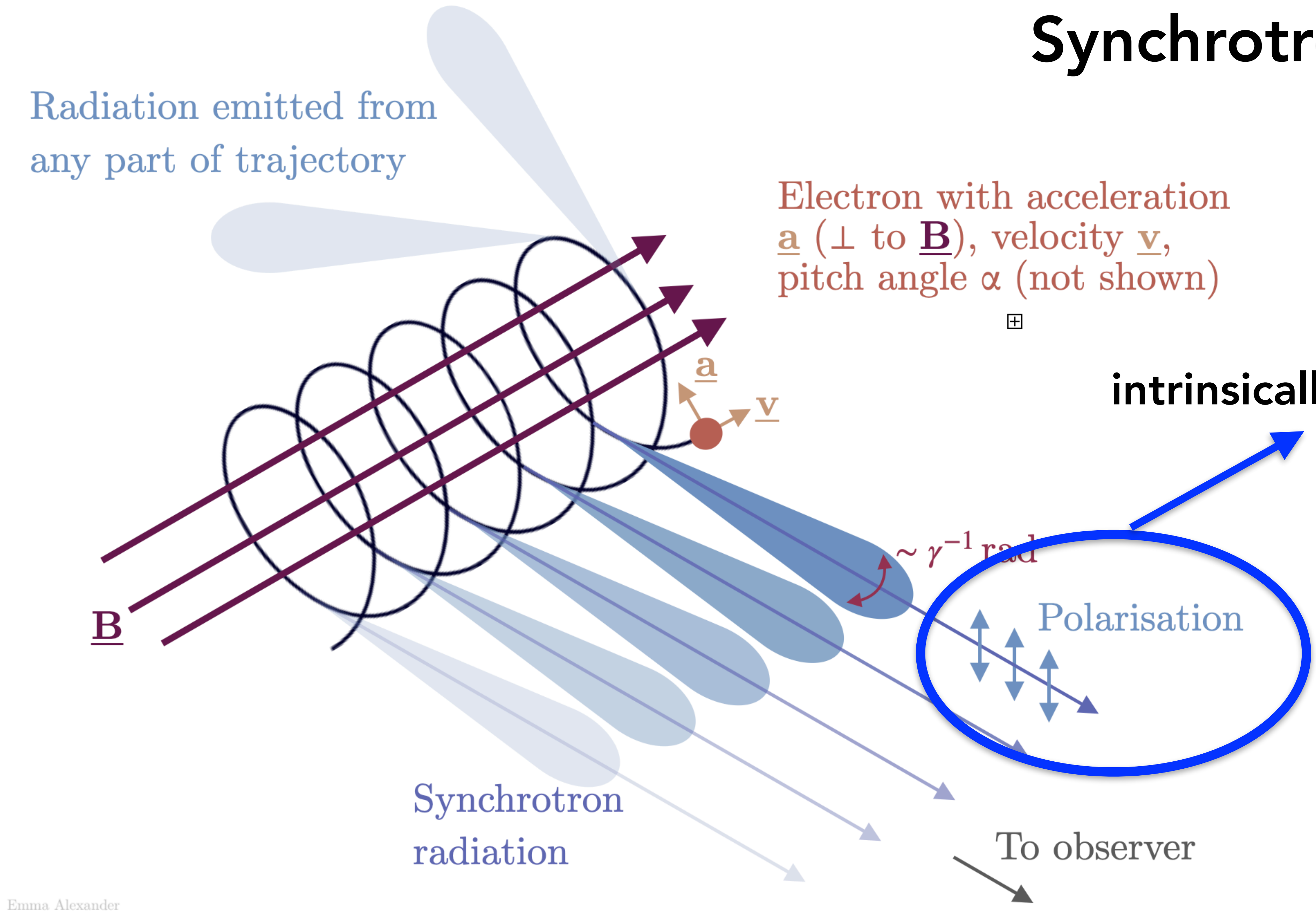
- Requires >10 TeV electrons: $h\nu \approx 19 \left(\frac{B}{100\ \mu\mathrm{G}}\right)\left(\frac{E}{100\ \mathrm{TeV}}\right)^2\ \mathrm{keV}$
- Electrons cool fast: $\tau_{\mathrm{cool}} \approx 12.5 \left(\frac{B}{100\ \mu\mathrm{G}}\right)^{-2}\left(\frac{E}{100\ \mathrm{teV}}\right)^{-1}\ \mathrm{yr}$

  →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 ($\tau_{\mathrm{acc}} \approx \tau_{\mathrm{cool}}$):
  - $h\nu_{\mathrm{cutoff}} \approx 1.4\eta^{-1}\left(\frac{V_{\mathrm{sh}}}{5000\ \mathrm{km/s}}\right)^2\ \mathrm{keV}$
- **X-ray synchrotron: requires $\eta \approx 1$ and $V_{\mathrm{sh}} \gtrsim 3000\ \mathrm{km/s}$**

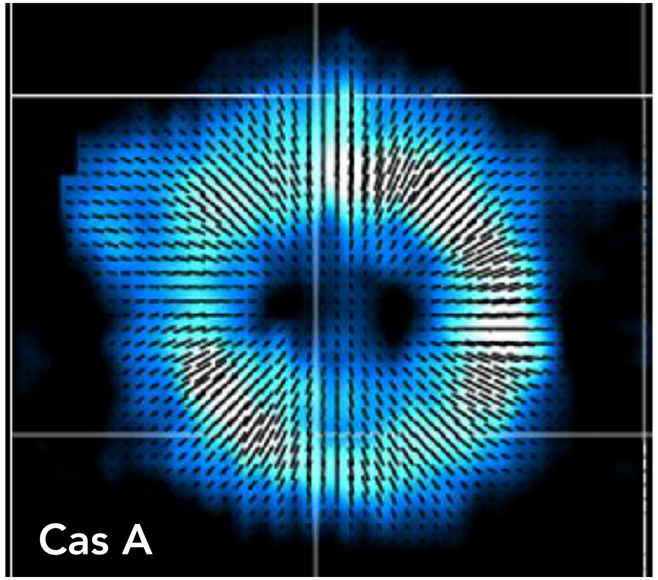
Synchrotron radiation

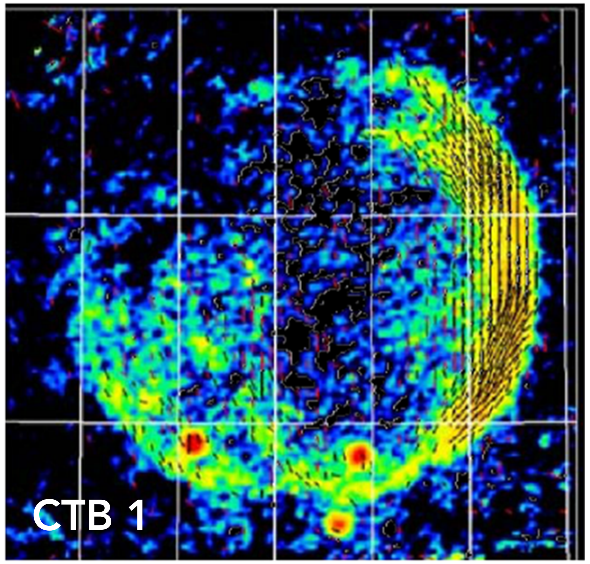


intrinsically ~70% polarized

src: wikipedia

Radio synchrotron *polarization* from SNRs

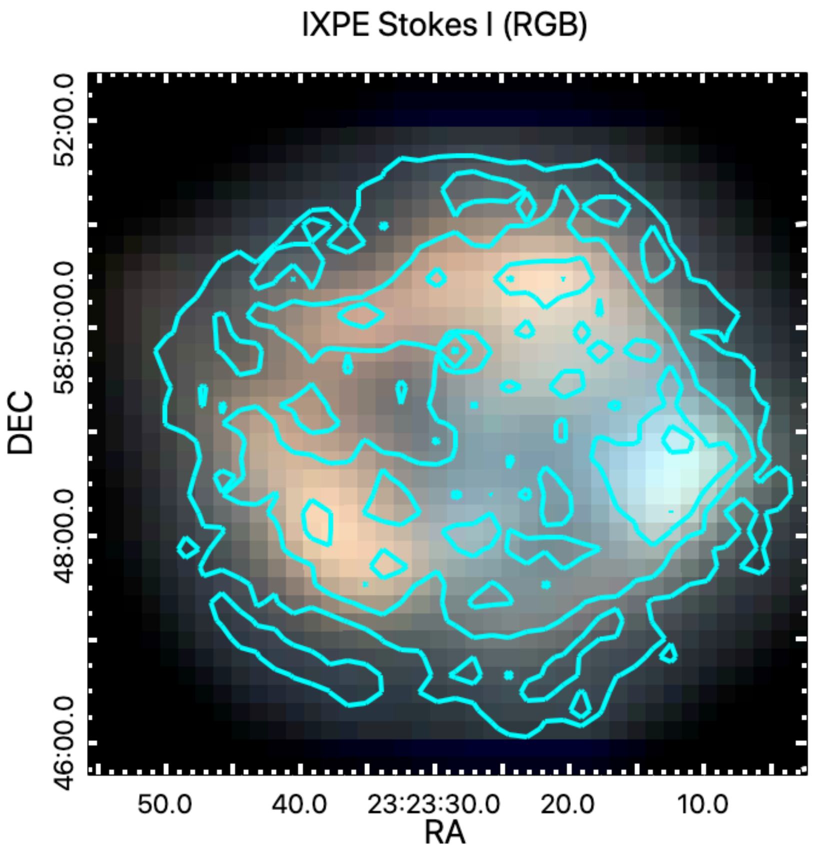




Dubner&Giacani (2015)
(Magnetic-field vectors)

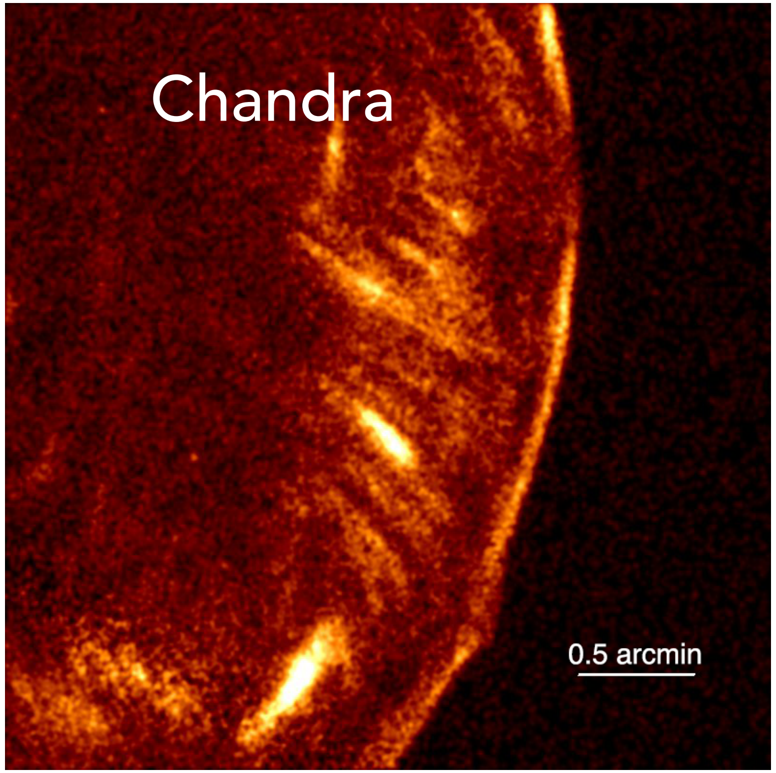
- Synchrotron radiation:
  - $h\nu \approx 0.5E_{\rm GeV}^2(B/100\ \mu{\rm G})$ GHz
- *Mature* SNRs (≳2500 yr): tangentially oriented fields
  - Makes sense: shock compresses tangential B-field components only
- *Young* SNRs (≲2500 yr): radially oriented B-fields and low **Π** (Cas A: ~5%)
  - Poorly understood

The IXPE observations of Cas A



- 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

Tycho stripes



- Tycho's contain puzzling semi-regular synchrotron structures: Tycho's stripes (Eriksen et al. 2011)
- Suggests coherent magnetic field → high polarization expected
- IXPE result (region g): no secure detection (3.7**σ**), with (**Π**=14±4% corrected)