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# First X-ray polarimetry measurements of supernova remnants with IXPE

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**on behalf of the IXPE SNR TWG and IXPE Science Team**
**(https://ixpe.msfc.nasa.gov/partners_sci_team.html)**
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**PASTO - Particle Acceleration in Astrophysical Objects**
Sep 5 – 7, 2022
Astronomical Observatory of Rome

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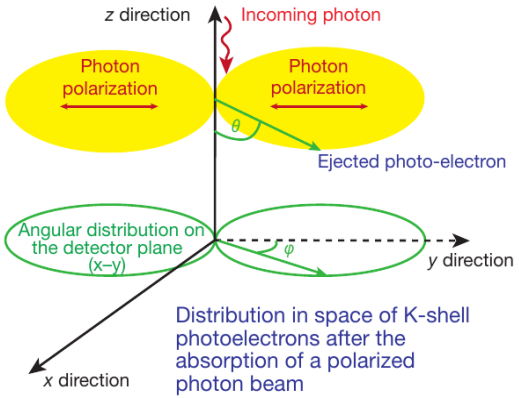
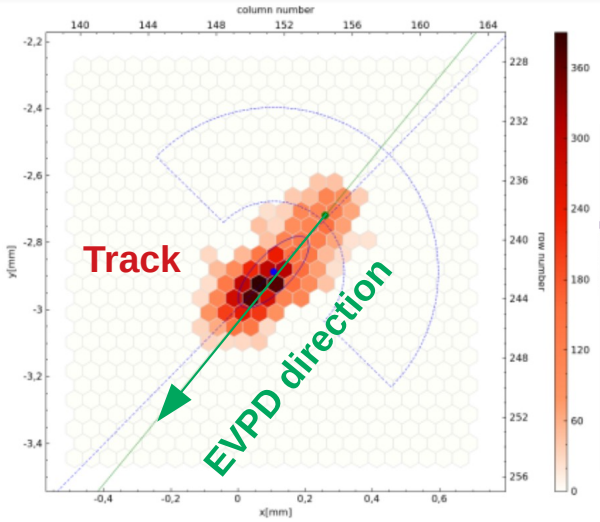
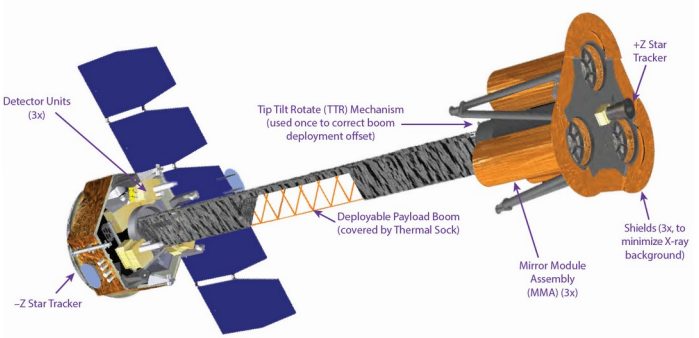
# DETECTING X-RAY POLARIZATION

# THE IMAGING X-RAY POLARIMETRY EXPLORER (IXPE) AND THE GAS PIXEL DETECTOR (GPD)

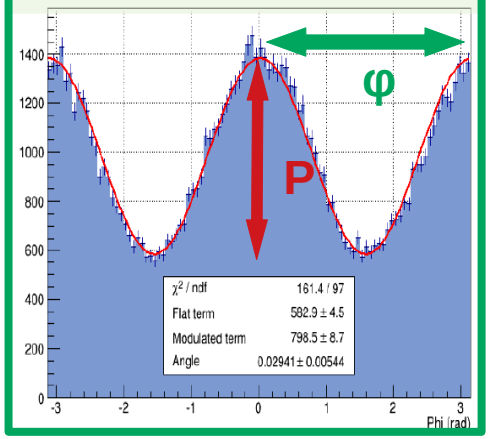



## IXPE




## Polarized photons:
Modulation curve




**Minimum Detectable Polarization**

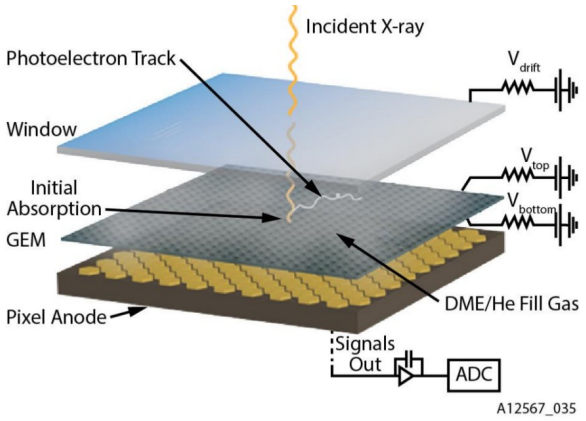
$$MDP_{99} = 4.292 \frac{\sqrt{C_S + C_B}}{C_S \langle \mu \rangle}$$

**Synchrotron Polarization Degree**

$$\Pi \equiv \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} \rightarrow \frac{p+1}{p+7/3} \rightarrow \frac{3}{4}$$

max

## GPD



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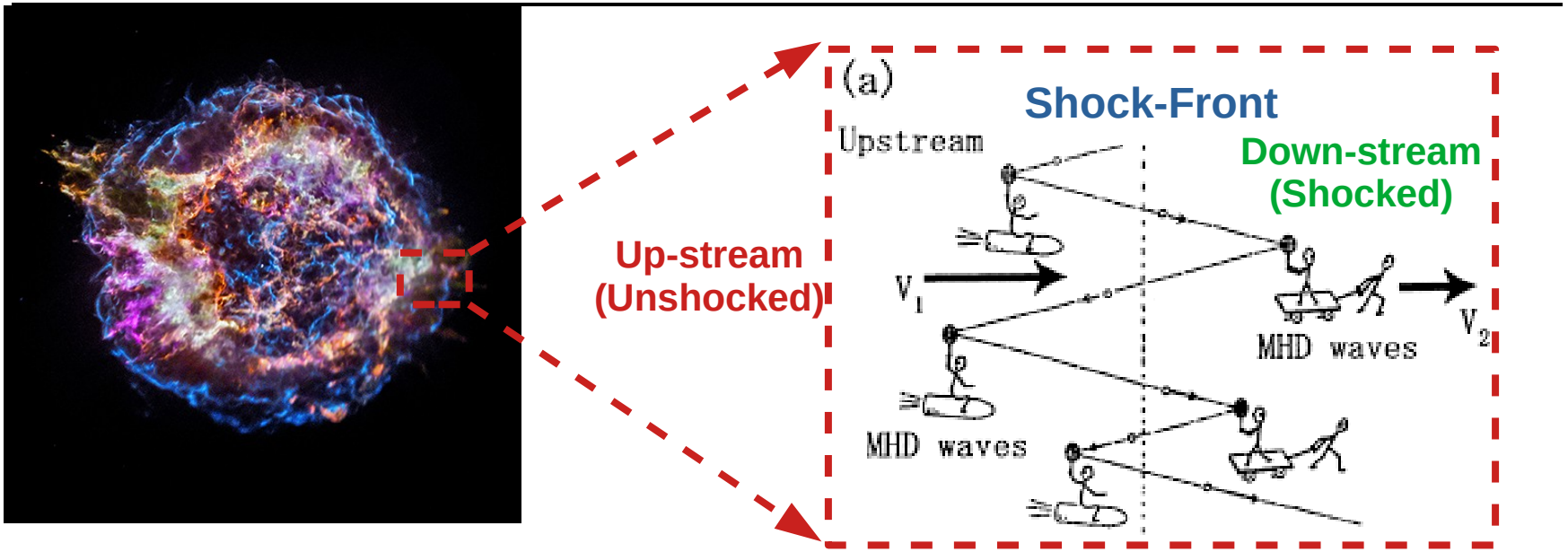
# MAGNETIC FIELDS AND PARTICLE ACCELERATION
## KEY SCIENCE TOPICS

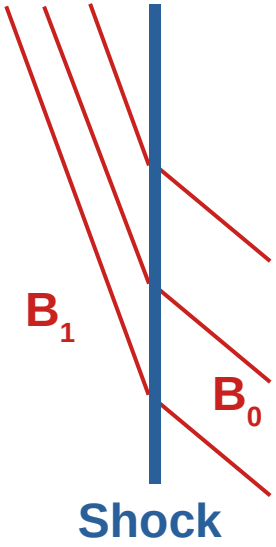


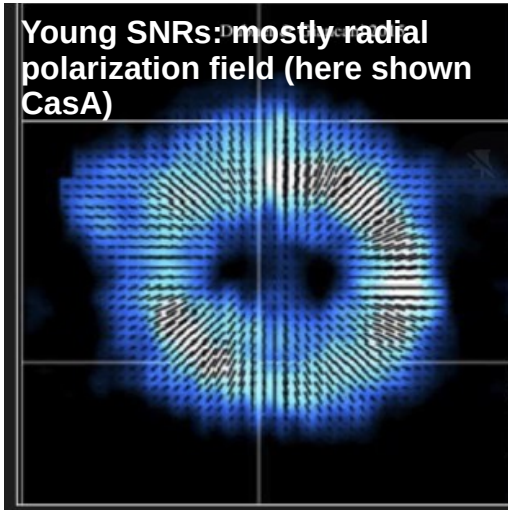

*(M. Scholer)*

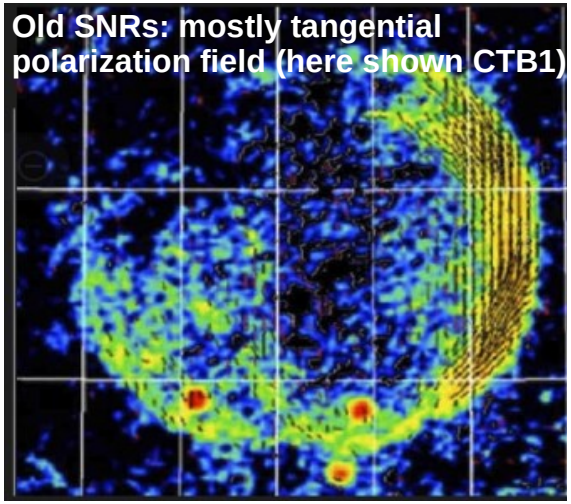
- Particles scatter from **turbulence** in background plasma
  - **Pre-existing, or generated by streaming ions themselves**
- Efficient acceleration requires **strong, turbulent B-fields**
  - $\mathbf{E_{max}}$ depends on turbulence on scales of $\boldsymbol{\lambda_{mfp} \approx r_g}$
- Synchrotron emission produced by relativistic electrons is polarized
  - Thin X-ray rims (**$10^{17}$ cm**) due to short lifetime of energetic electrons

**X-ray polarization probes fields and turbulence very close to the shocks!**

# MAGNETIC FIELDS AND PARTICLE ACCELERATION
## KEY SCIENCE TOPICS




*Dubner & Giacani 2015*

*Jun & Norman 1996*

- Shock compresses tangential component of the ambient magnetic field: reasonable to expect largely tangential field in post-shock region.
- Radio observations show tangential field in old remnants, but radial in young SNRs. **Why?**
  - Radial stretching from instabilities (e.g. *Gull 1973, Inoue et al. 2013*)
  - "Selection effect" due to observation of radiation only along radial field where acceleration is more efficient (*e.g. West et al 2017*).

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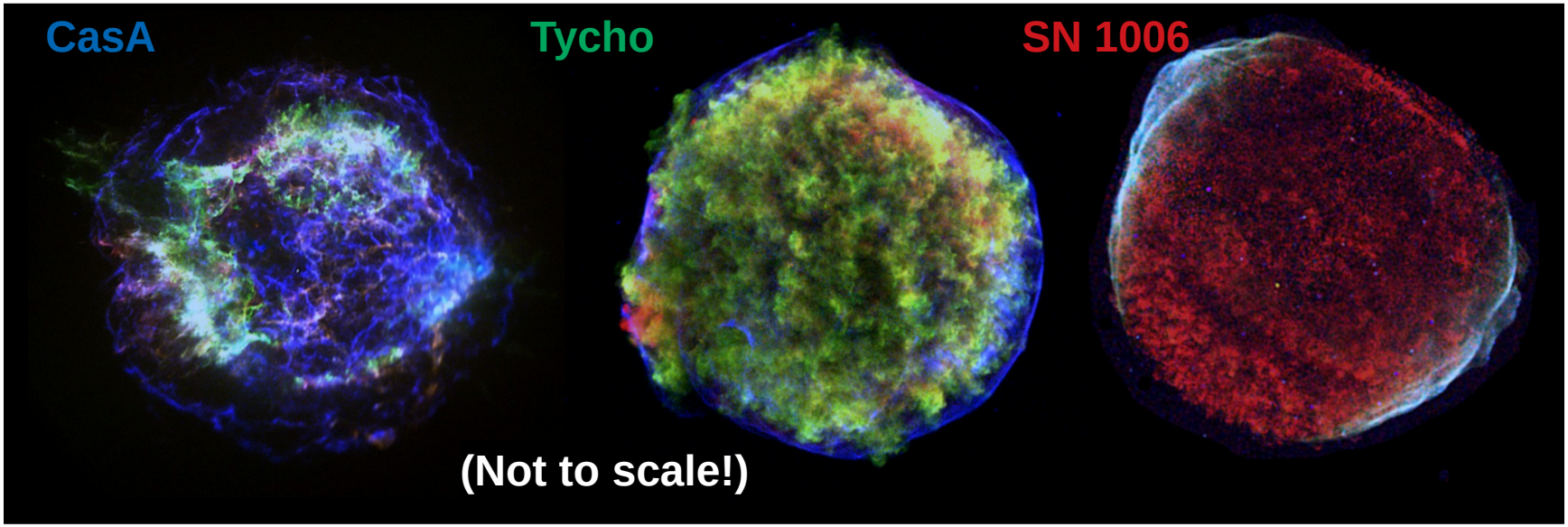
# SNR WITH IXPE
# THE THREE TARGETS

**CasA**, **Tycho**, and **SN 1006** are part of the IXPE 1st year observation plan.




Observed in January 2022
900 ks
**Results published!**

Observed in June-July 2022
770 ks
Data analysis ongoing

Observed in August 2022
600 ks
We just got the data

**Vink et al. 2022, arXiv:2206.06713**

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# IXPE OBSERVATION OF CAS A

## SOURCE AND OBSERVATION CHARACTERISTICS

* 350 yr old Core-collapse SNR (2.6 pc radius);

* X-ray emission:

  - Bright line emission;

  - Synchrotron-dominated continuum;

  - Reverse shock present;

* First IXPE science target;

* Observed in January 2022;

* 1 Ms nominal exposure (~900 ks actual);

* Dithered observation.


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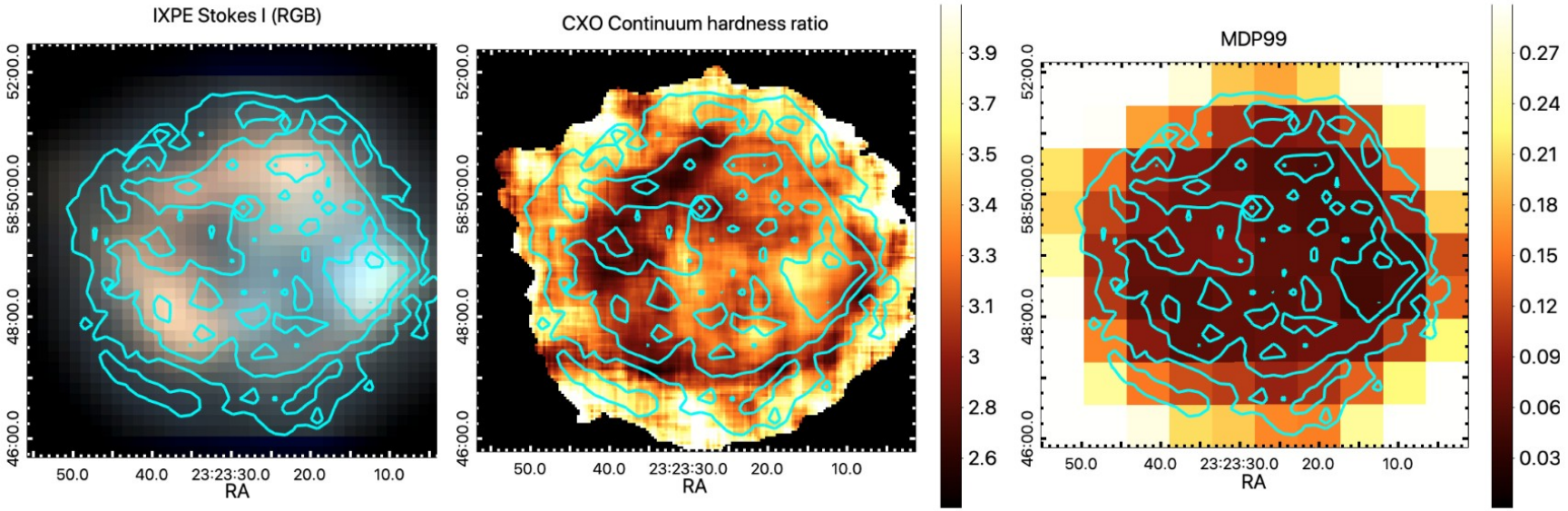
# IXPE OBSERVATION OF CAS A
## SENSITIVITY TO POLARIZATION




Energy resolution shows regions where **synchrotron (polarized)** emission dominates **thermal (unpolarized)**

Sensitivity to polarization varies from **5 – 20%** for **42”** pixels

- Lower for larger regions, but then, decoherence is a potential issue, depending on geometry

**Vink et al. 2022, arXiv:2206.06713**

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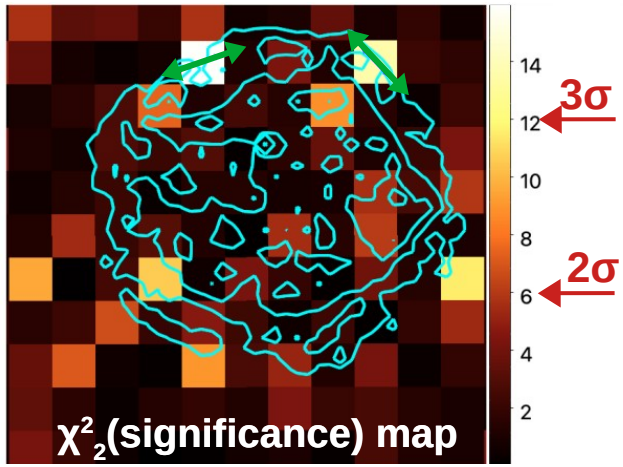
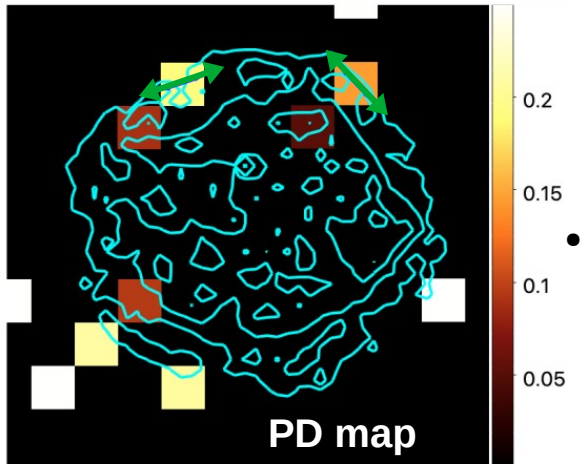
# IXPE OBSERVATION OF CAS A
## PIXEL-BY-PIXEL SEARCH

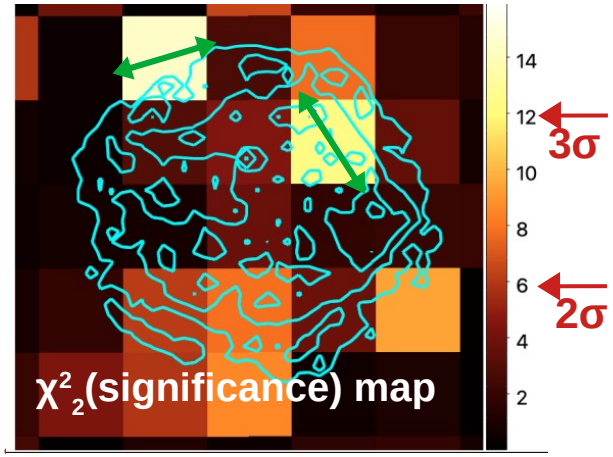
**Green arrows: polarization direction**

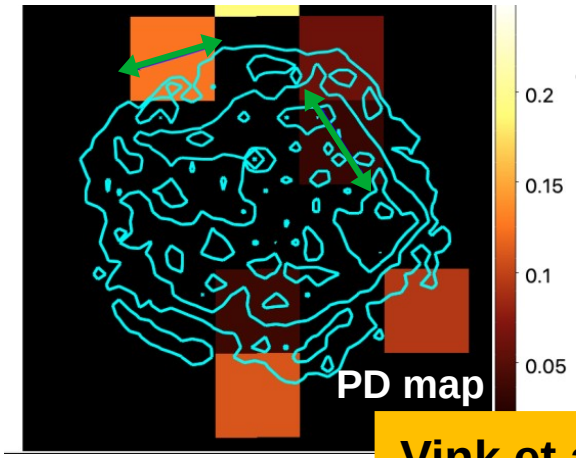
42" pixels




84" pixels




- Some indication of polarization on small scales, but marginally significant given the number of bins.
- **FACT:** Polarization degree is low on some spatial scales, must be **<4% in inner regions, 15% - 20% in outer region.**
- **HINT:** for marginally significant bins, polarization direction appears tangential (corresponding to **radial B**)

**Vink et al. 2022, arXiv:2206.06713**

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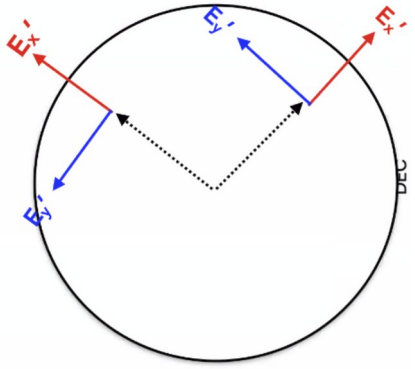
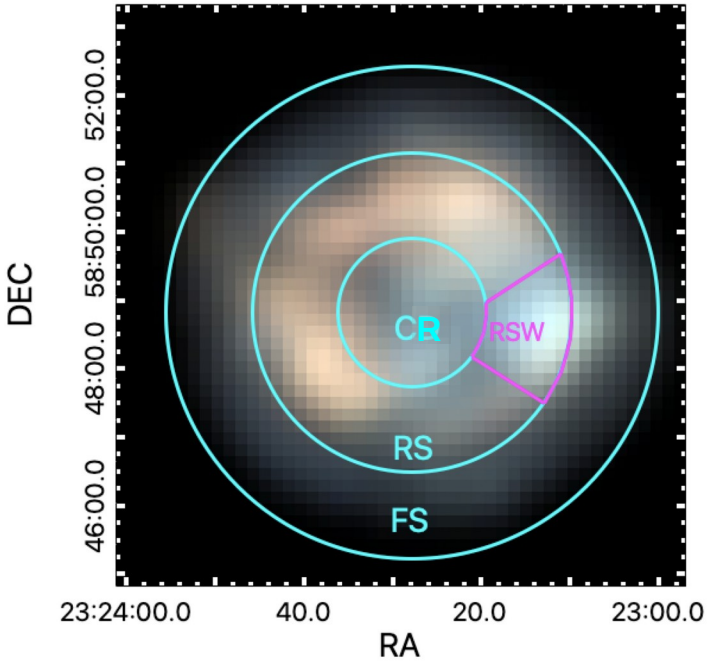
# IXPE OBSERVATION OF CAS A
## LARGE-SCALE SEARCH

- No solid detections from pixel-by-pixel search: **PD is low, but how low?**
- **Expectations:** either **radial** (from radio) or **tangential** (shock compression) **B-field.**
- **Cas A is spherically symmetric** → improve the statistics by summing over large regions by assuming a circular symmetry to the polarization direction.




- **CR:** Central Region (mostly thermal emission);
- **RS:** Reverse Shock;
- **RSW:** Reverse Shock West;
- **FS:** Forward Shock;
- **FS+RSW:** Forward Shock and Reverse Shock West
- (most non-thermal emitting regions);
- **All:** whole SNR.




**Vink et al. 2022, arXiv:2206.06713**

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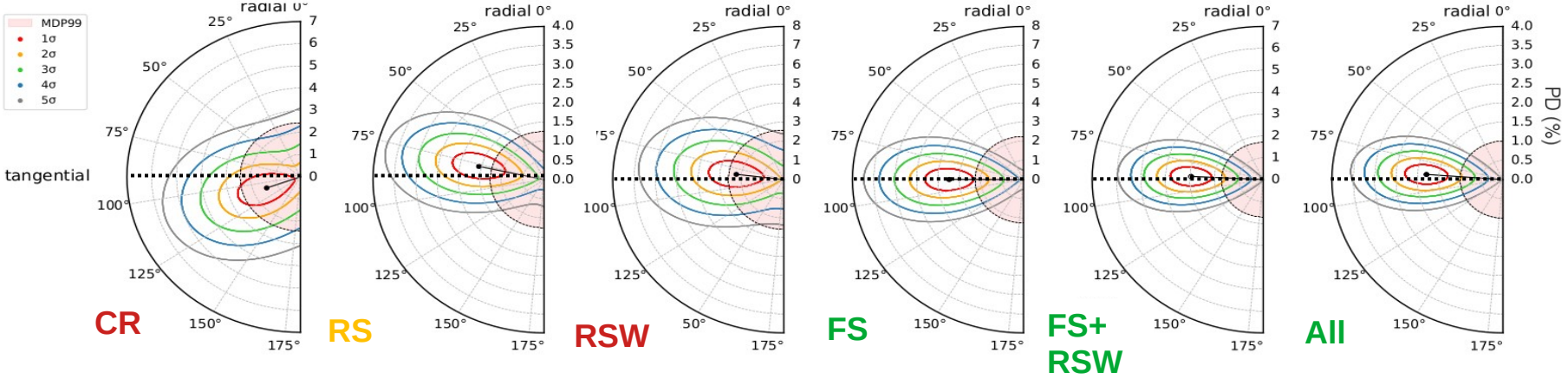
# RESULTS
# LARGE-SCALE SEARCH




- For **Forward Shock (FS), FS+West,** and **All**, detections at **4σ – 5σ** level!
- **Low polarization degree:** **2% – 3.5%** (**2.5% – 4.5%** after accounting for thermal dilution) implying very turbulent magnetic field ;
- Polarization angle implies **radial B-field dominates within $10^{17}$ cm of shock;**
- **Similar morphology than radio, but lower polarization degree.**

| | $R_{\rm min}$ [b] (arcsec) | $R_{\rm max}$ (arcsec) | MDP99 (%) | Pol. Degree (%) | PD Corrected [c] (%) | Angle [d] (°) | Significance |
|---|---|---|---|---|---|---|---|
| Central region (CR) | 0 | 65 | 2.4 | $< 3.1$ | $< 3.7$ | N/A | $0.9\sigma$ |
| Reverse shock (RS) | 65 | 140 | 1.3 | $1.6 \pm 0.4$ | $2.2 \pm 0.6$ | $77.2 \pm 7.6$ | $3.1\sigma$ |
| RS West (RSW) [e] | 65 | 140 | 2.6 | $< 3.9$ | $< 5.1$ | N/A | $1.9\sigma$ |
| Forward shock (FS) | 140 | 216 | 2.3 | $3.5 \pm 0.7$ | $4.5 \pm 1.0$ | $89.8 \pm 6.1$ | $4.1\sigma$ |
| FS + RSW [f] | 216 | 216 | 1.7 | $3.0 \pm 0.6$ | $3.8 \pm 0.7$ | $87.2 \pm 5.4$ | $4.8\sigma$ |
| All | 0 | 216 | 1.0 | $1.8 \pm 0.3$ | $2.5 \pm 0.5$ | $85.7 \pm 5.2$ | $4.9\sigma$ |

**Vink et al. 2022, arXiv:2206.06713**

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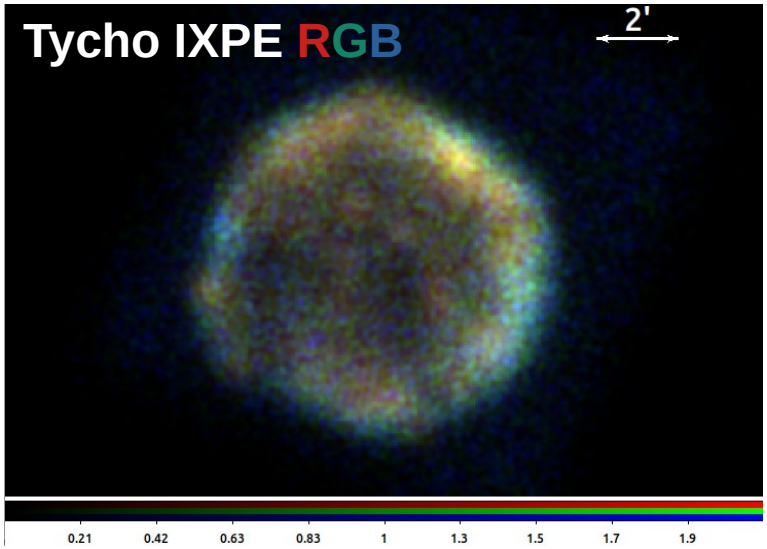
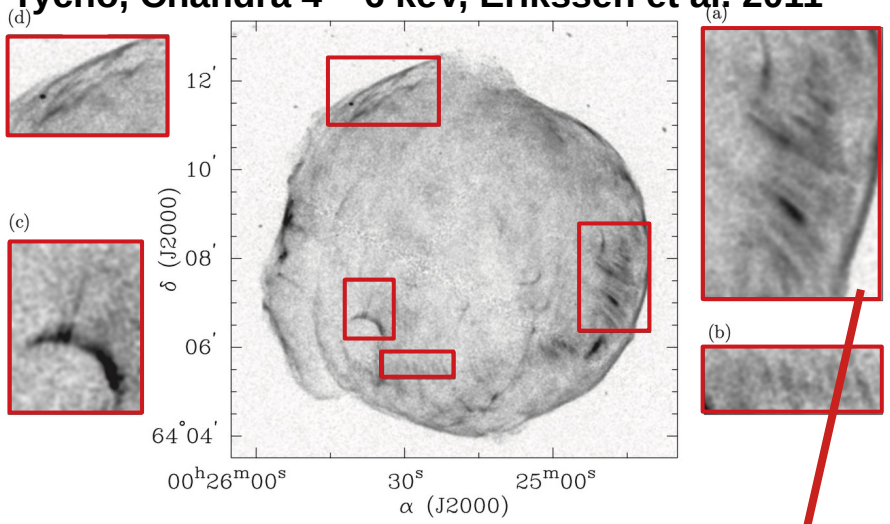
# IXPE OBSERVATION OF TYCHO
## STAY TUNED FOR RESULTS!



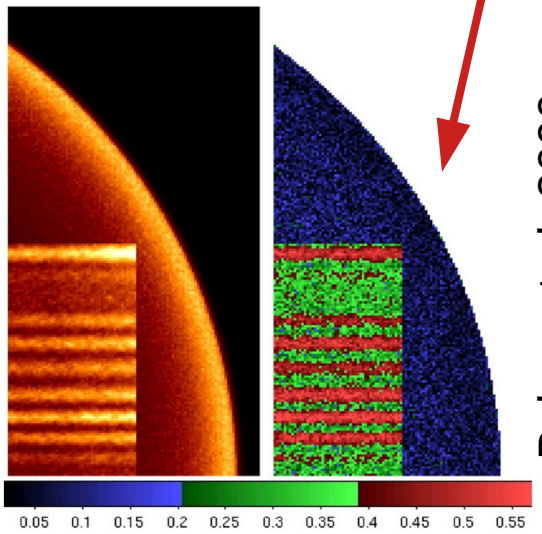

Tycho, Chandra 4 – 6 keV, Eriksen et al. 2011




- Thin synchrotron X-ray rims around most of SNRs: search for small scale polarization associated with turbulence scale (e.g. Bykov et al. 2021)

- Distinct stripe-like structures observed in discrete regions:
  - -Sites of acceleration to higher energies?
  - -Field direction correlated with stripes orientation?

**IXPE observation of Tycho is complete, and analysis is underway!**




Bykov et al. 2009

**Ferrazzoli et al., in preparation**

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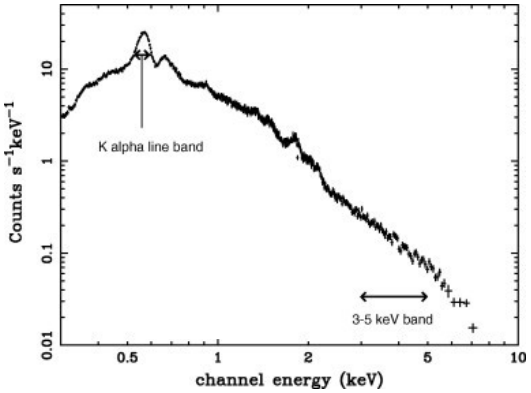
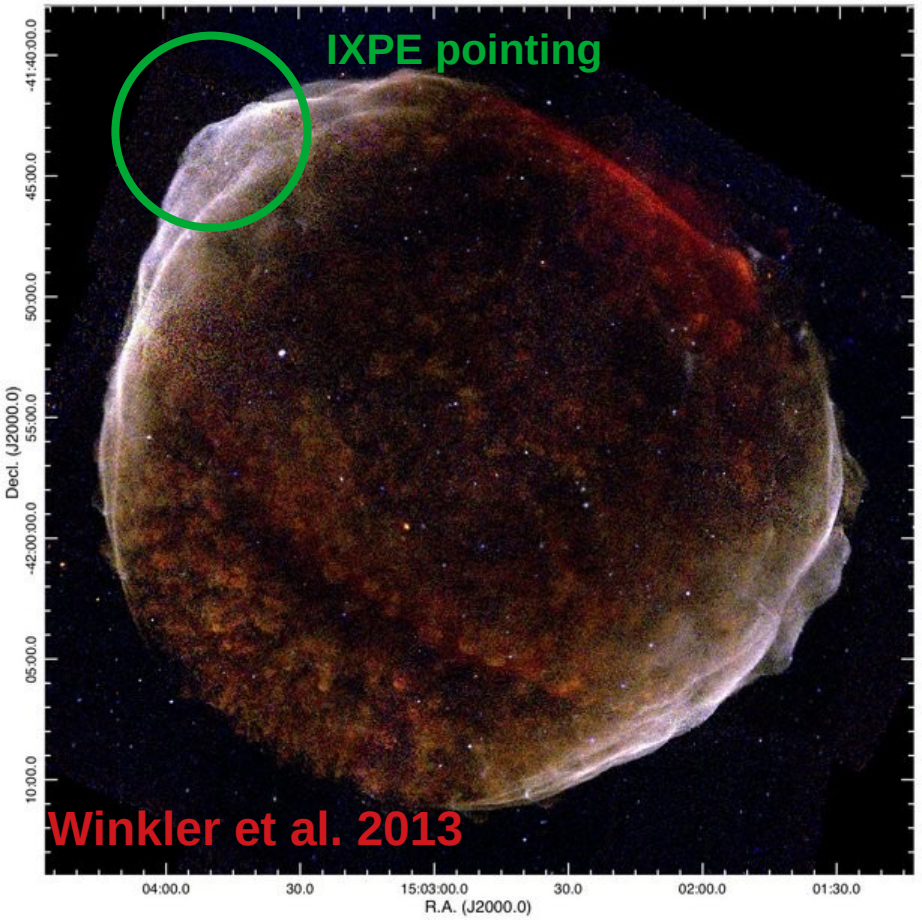
# IXPE OBSERVATION OF SN1006
## STAY TUNED FOR RESULTS!
## (WITH A BIT MORE PATIENCE...)

- Thin synchrotron X-ray rims in NE and SW
  - presumably indicative of ambient field orientation
  - Search for variation in polarization angle and acceleration efficiency
- Unlike Cas A and Tycho, spectrum is synchrotron dominated




- SNR is VERY large, we covered only NE rim in Year 1.
- Observation completed, data just delivered.



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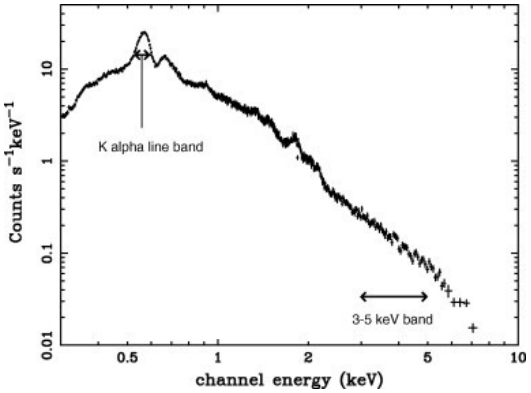
# IXPE OBSERVATION OF SN1006
## STAY TUNED FOR RESULTS! (WITH A BIT MORE PATIENCE...)

- Thin synchrotron X-ray rims in NE and SW
  - presumably indicative of ambient field orientation
  - Search for variation in polarization angle and acceleration efficiency
- Unlike Cas A and Tycho, spectrum is synchrotron dominated

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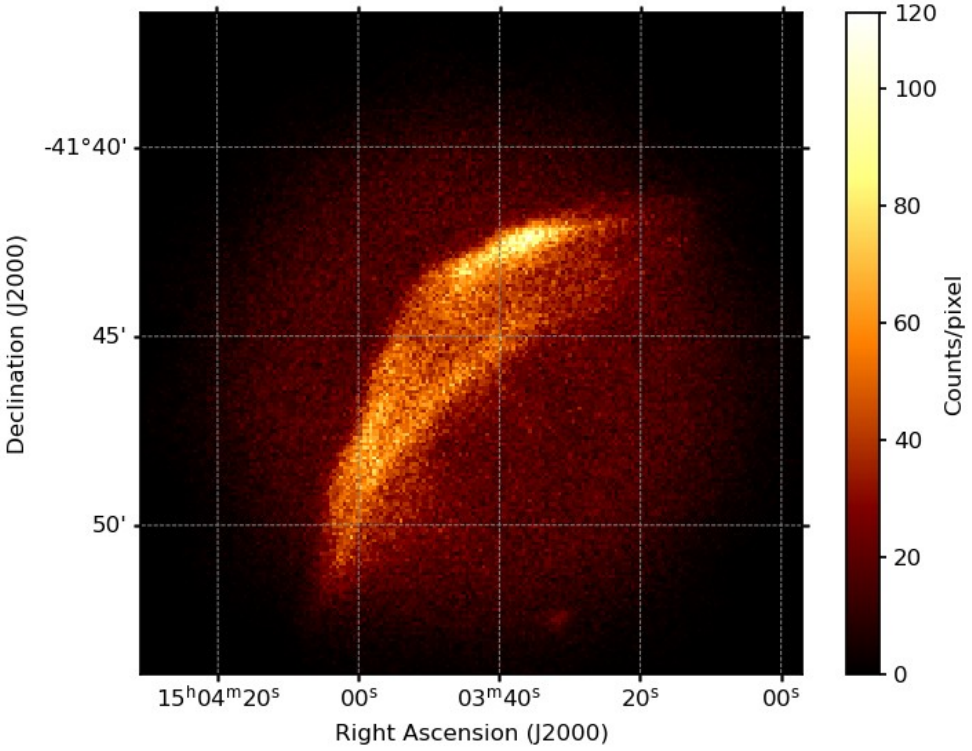


**Zhou et al., in preparation**

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## SUMMARY

- X-ray polarization in SNRs probes magnetic field and turbulence information:
  -probes regions close to the shock;
  -provides crucial information on particle acceleration in SNR shocks.

- **X- ray Polarization detected in Cas A!**
  -Polarization degree lower/no higher than radio: **~5%;**
  -Orientation implies that radial magnetic field originates very close to the shocks in SNRs.

- Recent observations of Tycho and SN1006 will provide polarization information for young type Ia SNRs.

**Breakthrough science with IXPE!**

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# Thank you for your attention!