IXPE
Imaging
X-Ray
Polarimetry
Explorer

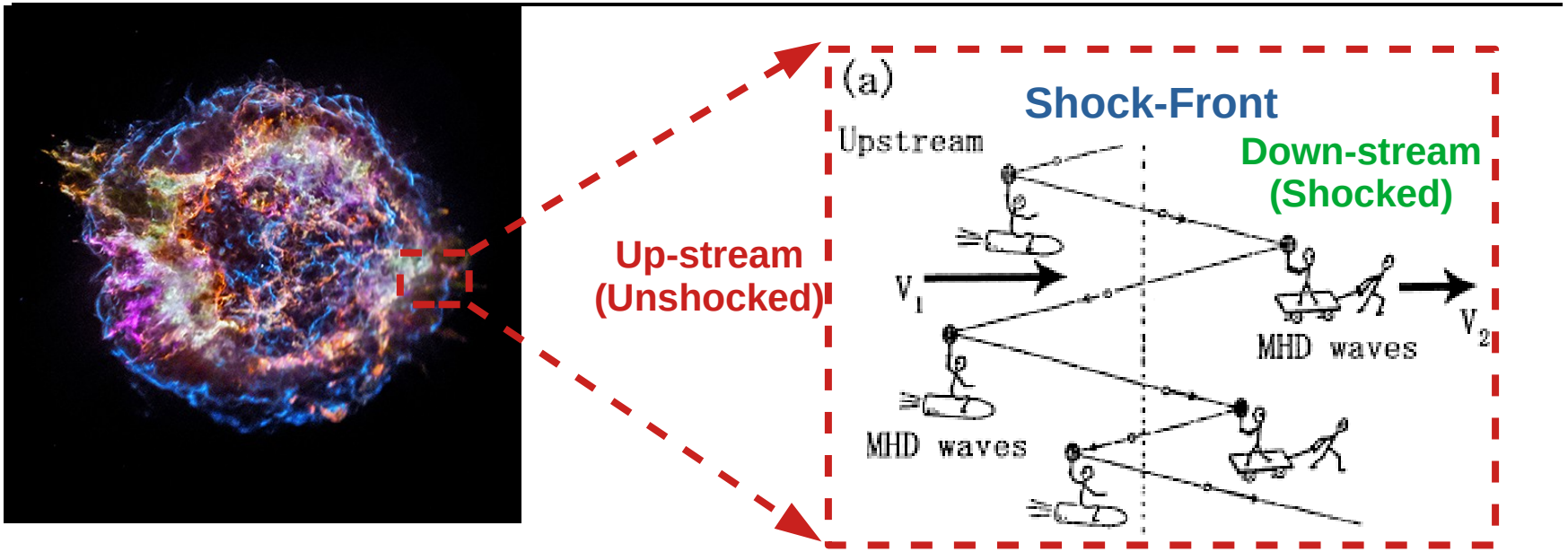
IXPE observations of supernova remnants: first results

Riccardo Ferrazzoli (INAF-IAPS)
on behalf of the IXPE SNR TWG and IXPE Science Team
(https://ixpe.msfc.nasa.gov/partners_sci_team.html)
riccardo.ferrazzoli@inaf.it

CNOC XII – Congresso Nazionale Oggetti Compatti
Sep 27 – 30, 2022
Cefalù

IXPE
Imaging X-Ray Polarimetry Explorer

MAGNETIC FIELDS AND PARTICLE ACCELERATION
KEY SCIENCE TOPICS

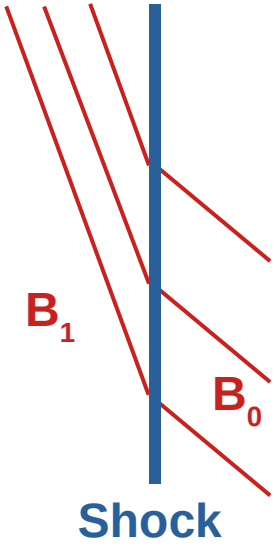


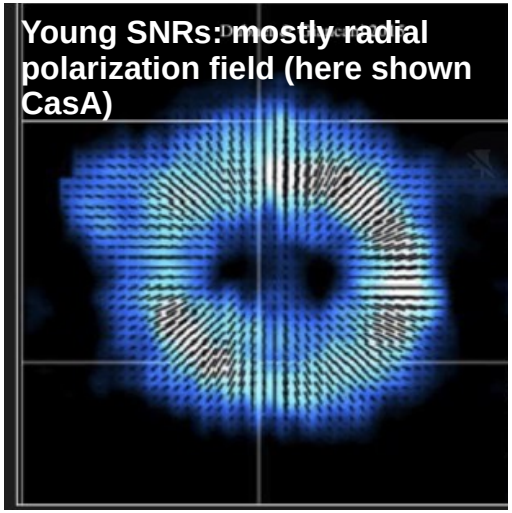
(M. Scholer)

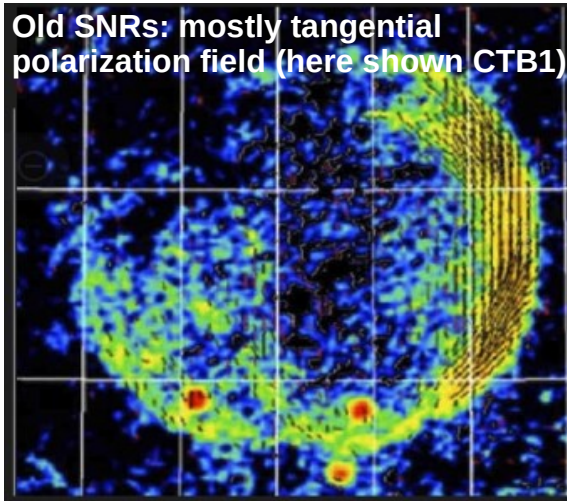
- Particles scatter from **turbulence** in background plasma
  - **Pre-existing, or generated by streaming ions themselves**
- Efficient acceleration requires **strong, turbulent B-fields**
  - $\mathbf{E_{max}}$ depends on turbulence on scales of $\boldsymbol{\lambda_{mfp} \approx r_g}$
- Synchrotron 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

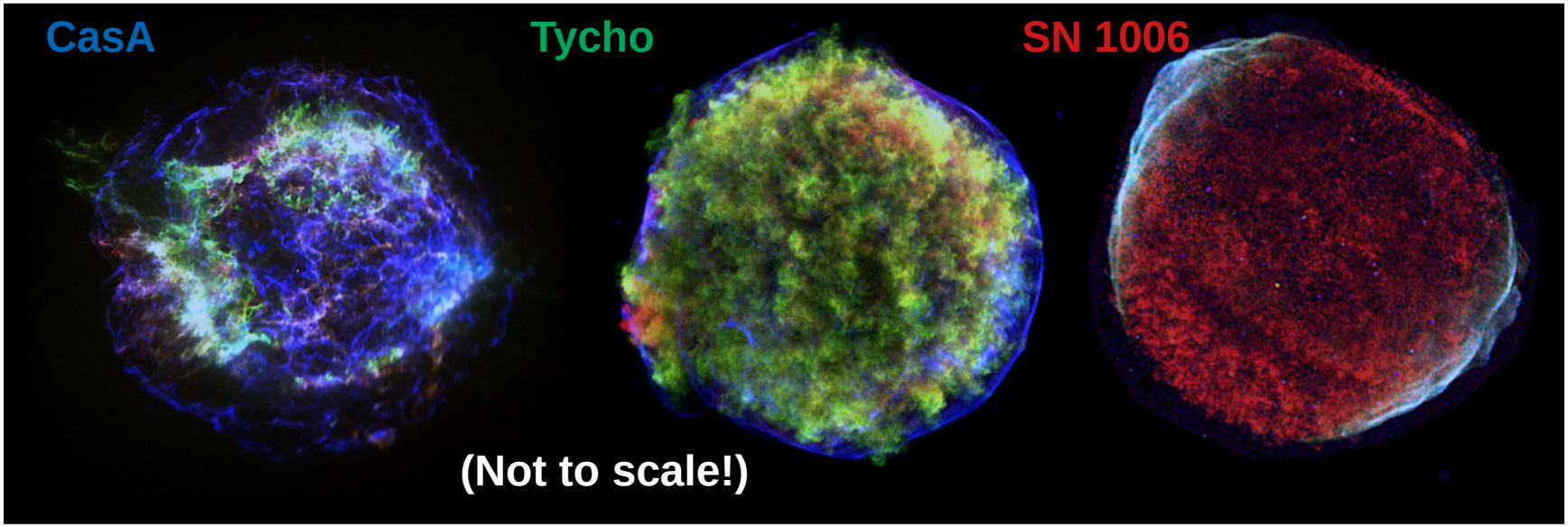
Jun & Norman 1996

- 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*).

IXPE
Imaging X-Ray Polarimetry Explorer

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

IXPE
Imaging X-Ray Polarimetry Explorer

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.

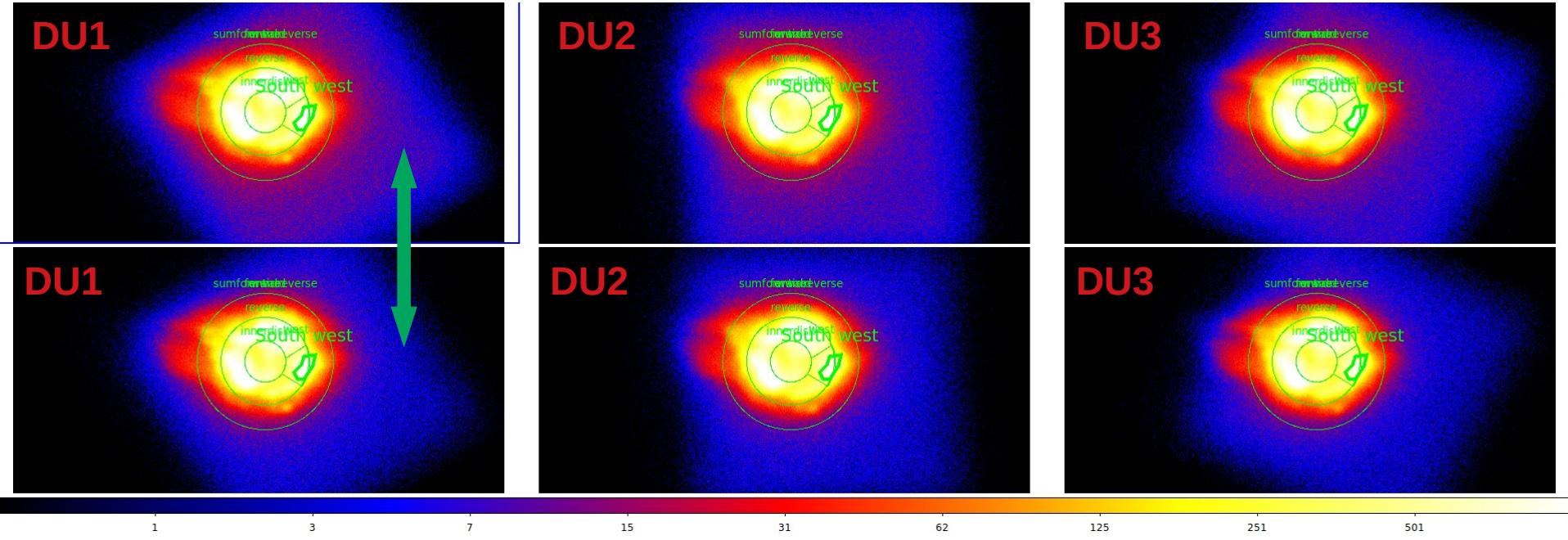
@ NASA HEASARC

IXPE
Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

Agenzia Spaziale Italiana

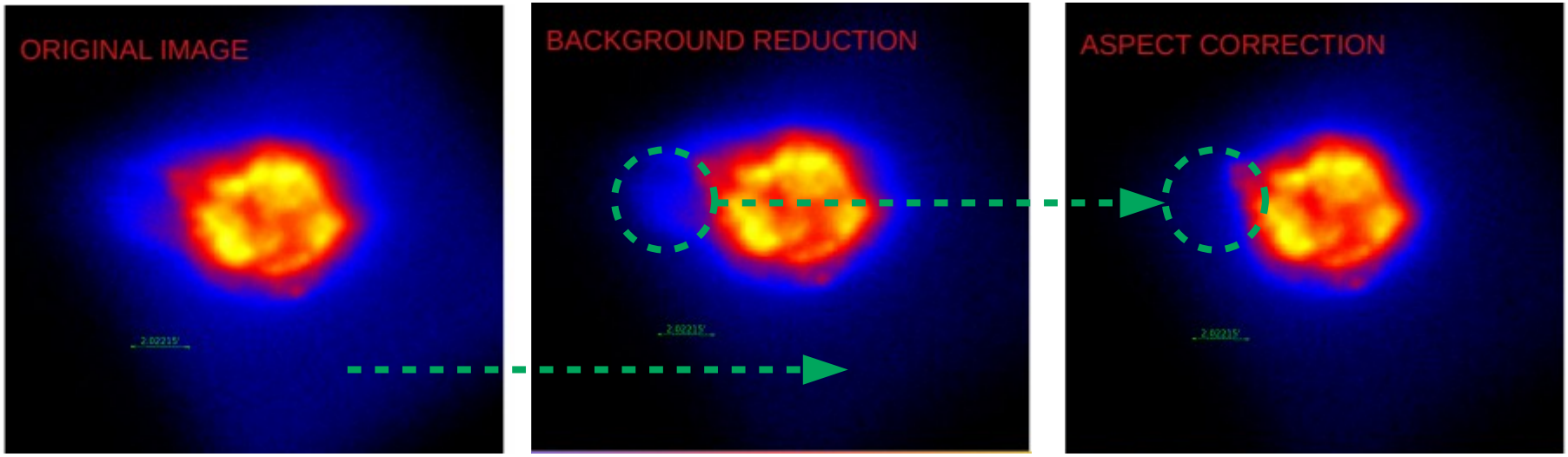
IXPE OBSERVATION OF CAS A
BACKGROUND REJECTION



The image becomes cleaner!

IXPE
Imaging X-Ray Polarimetry Explorer

IXPE OBSERVATION OF CAS A
PARTICLE BACKGROUND REJECTION AND BAD-ASPECT TIME REMOVAL



The image becomes cleaner!

Removal of spurious motion caused by thermally-induces boom oscillation further improves the image!

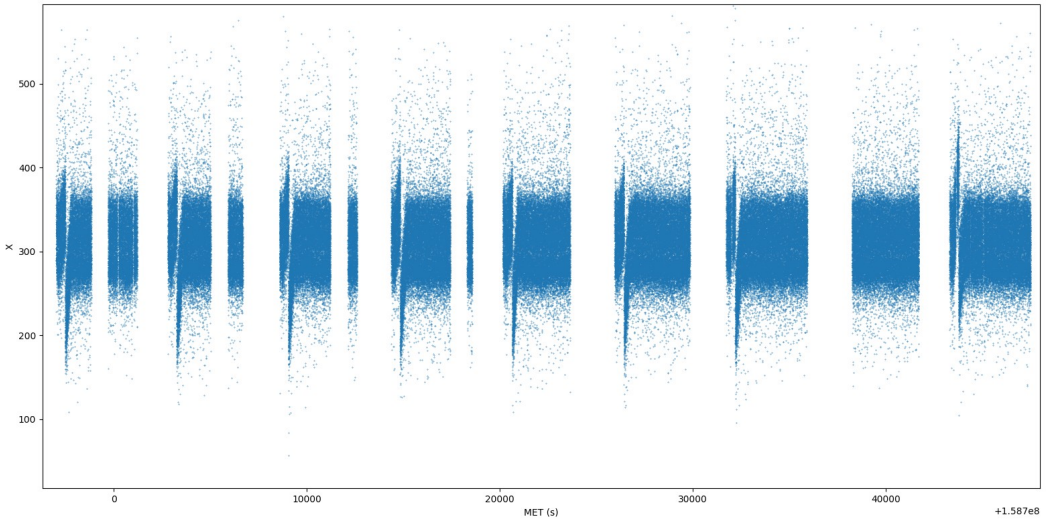
IXPE
Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

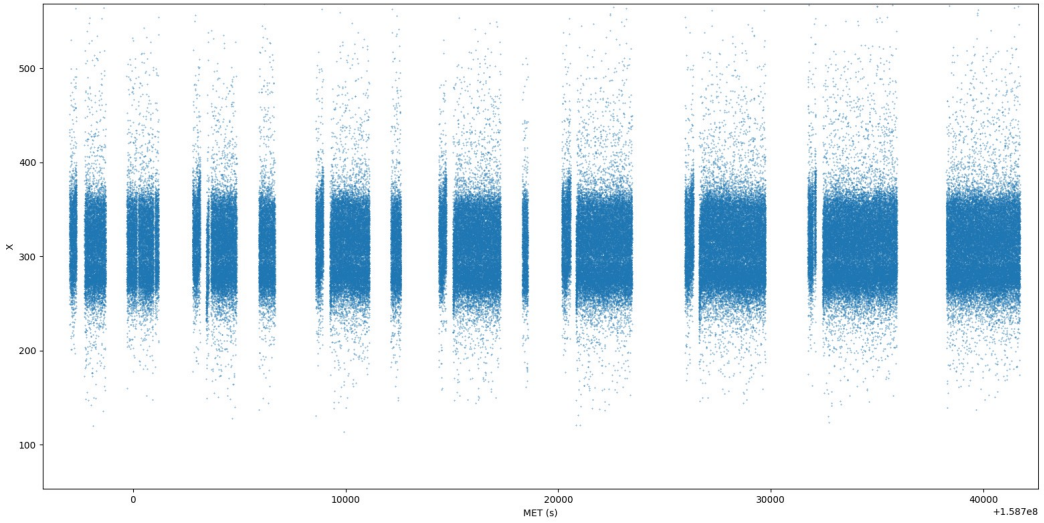
Agenzia Spaziale Italiana

IXPE OBSERVATION OF CAS A
BAD-ASPECT REMOVAL

Before
bad-aspect
time removal

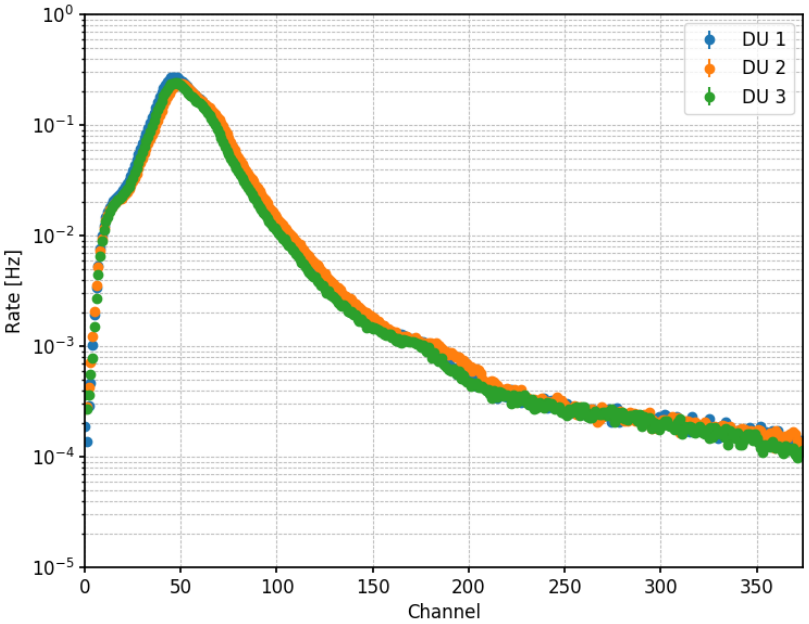


After
bad-aspect
time removal



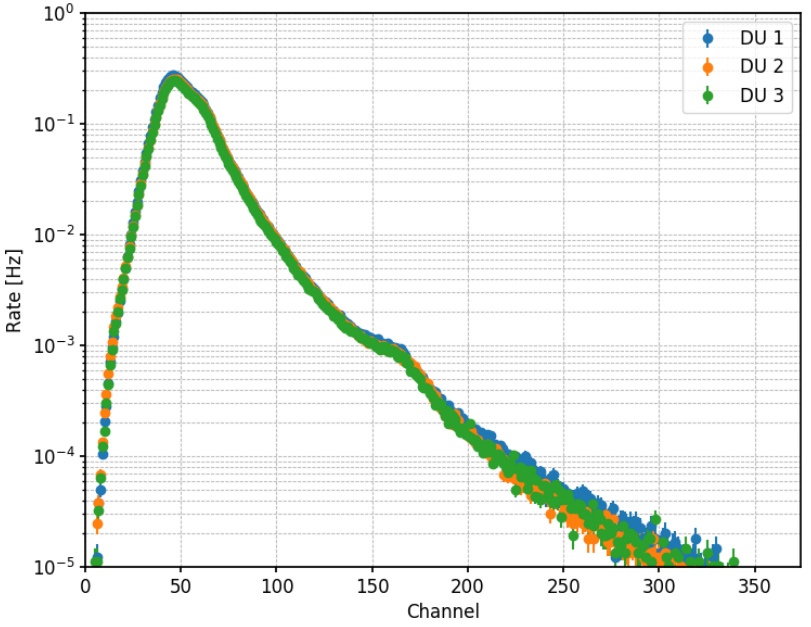
IXPE
Imaging X-Ray Polarimetry Explorer

IXPE OBSERVATION OF CAS A
ENERGY CORRECTION AND PARTICLE BACKGROUND REJECTION



Original files spectra for each DU:
Offset because of different detector gain

Bkg-filtered Spectrum
after energy correction with on board calibration sources

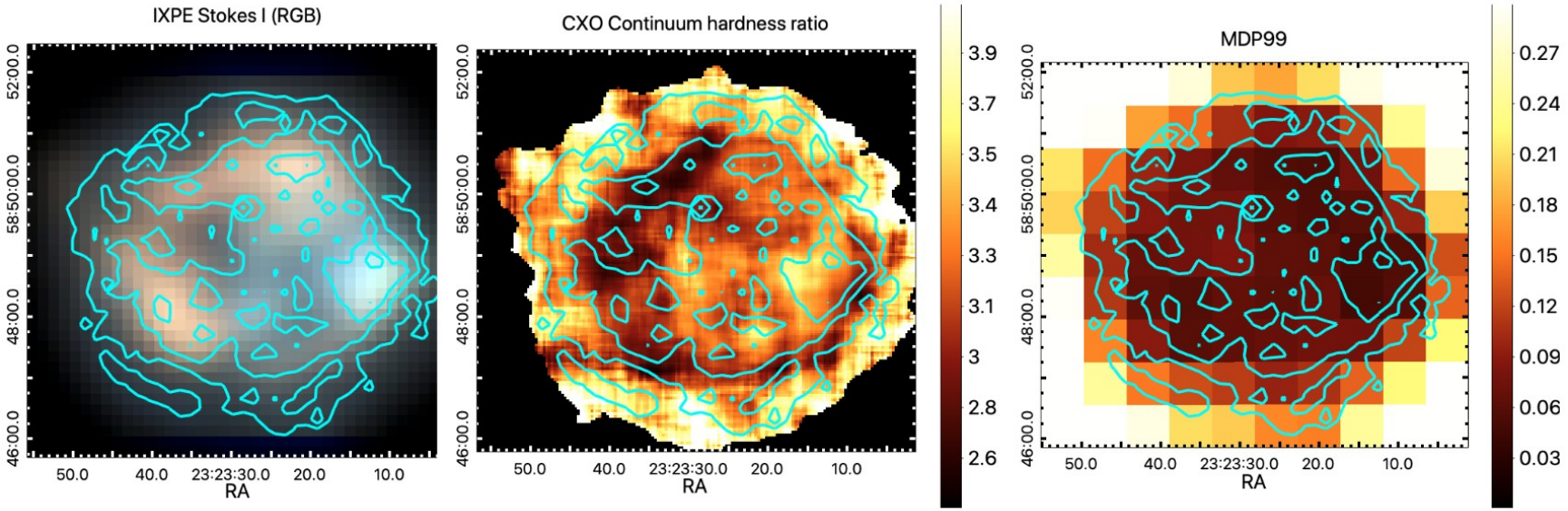


IXPE
Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

Agenzia Spaziale Italiana

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

IXPE
Imaging
X-Ray
Polarimetry
Explorer

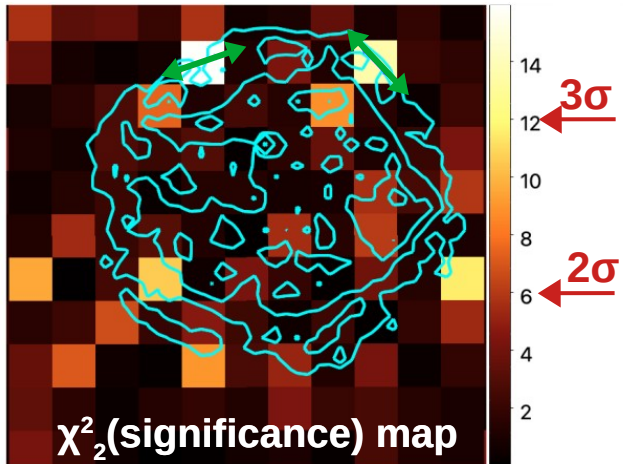
Marshall Space Flight Center

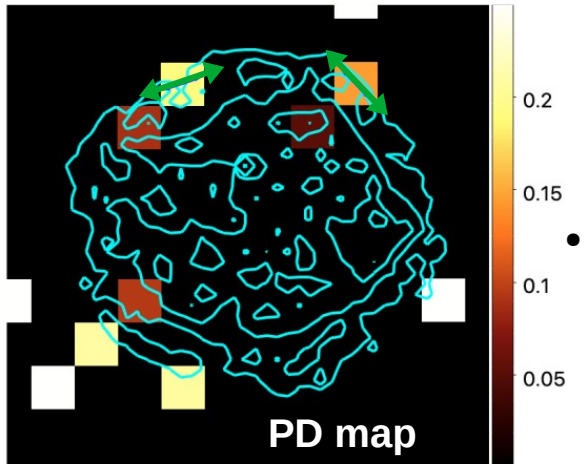
Agenzia Spaziale Italiana

IXPE OBSERVATION OF CAS A
PIXEL-BY-PIXEL SEARCH

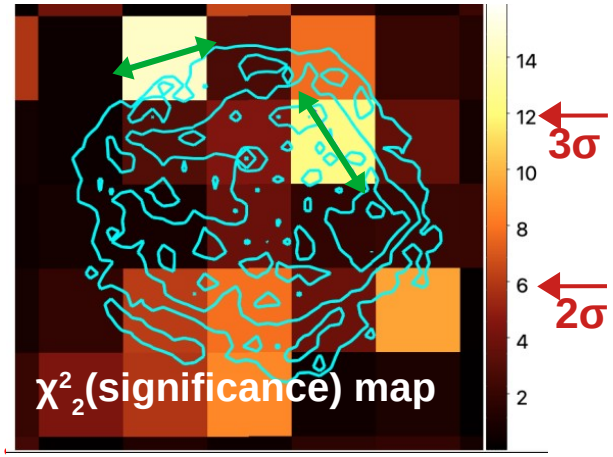
Green arrows: polarization direction

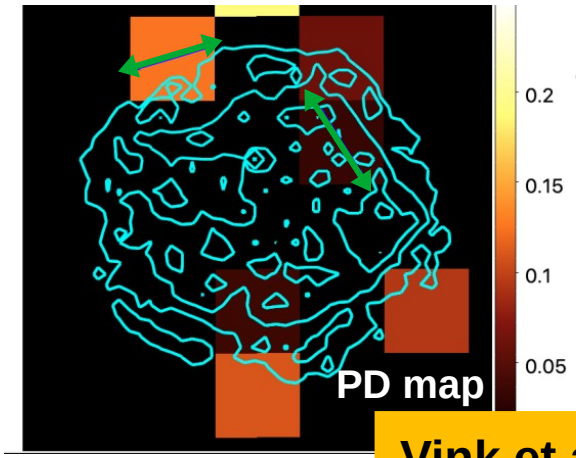
42" pixels





84" pixels





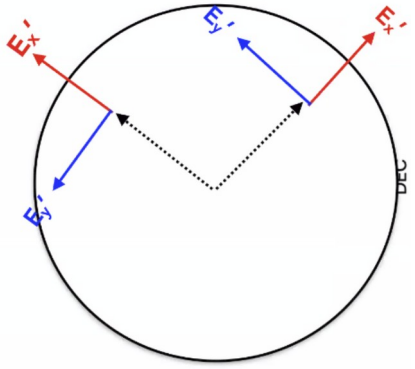
- Some indication of polarization on small scales, but marginally significant given the number of bins.
- **FACT:** Polarization degree is low on some spatial scales, must be **<4% in inner regions, 15% - 20% in outer region.**
- **HINT:** for marginally significant bins, polarization direction appears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

Vink et al. 2022, arXiv:2206.06713

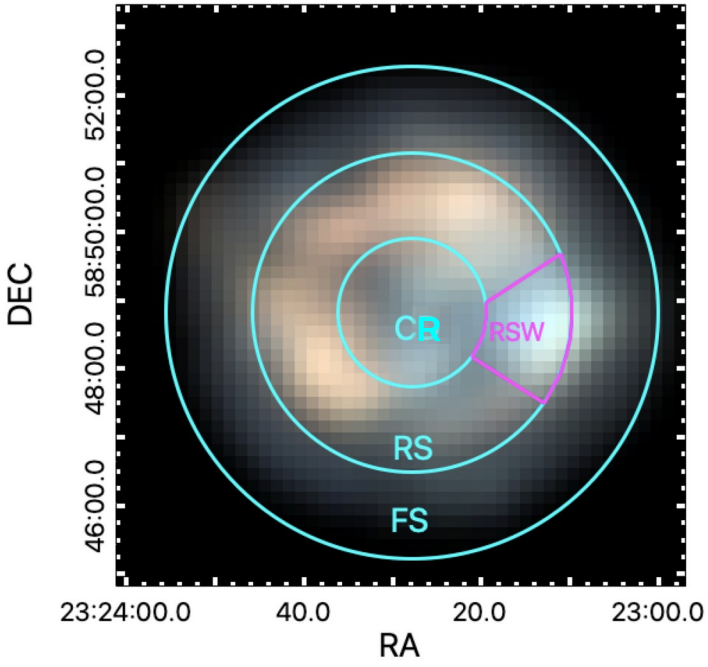
IXPE
Imaging X-Ray Polarimetry Explorer

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.



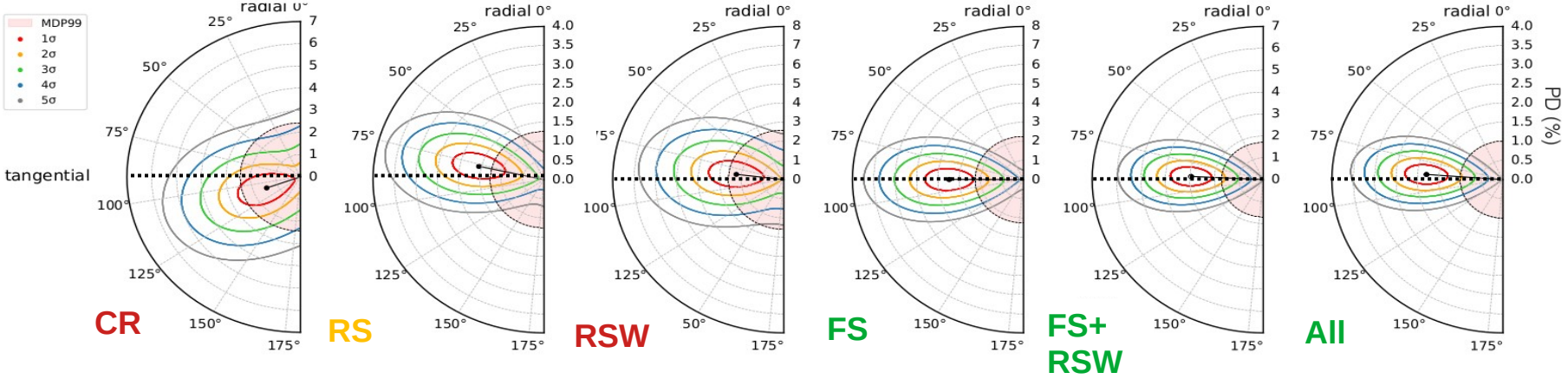
- **CR:** Central Region (mostly thermal emission);
- **RS:** Reverse Shock;
- **RSW:** Reverse Shock West;
- **FS:** Forward Shock;
- **FS+RSW:** Forward Shock and Reverse Shock West
- (most non-thermal emitting regions);
- **All:** whole SNR.



Vink et al. 2022, arXiv:2206.06713

IXPE
Imaging X-Ray Polarimetry Explorer

RESULTS
LARGE-SCALE SEARCH



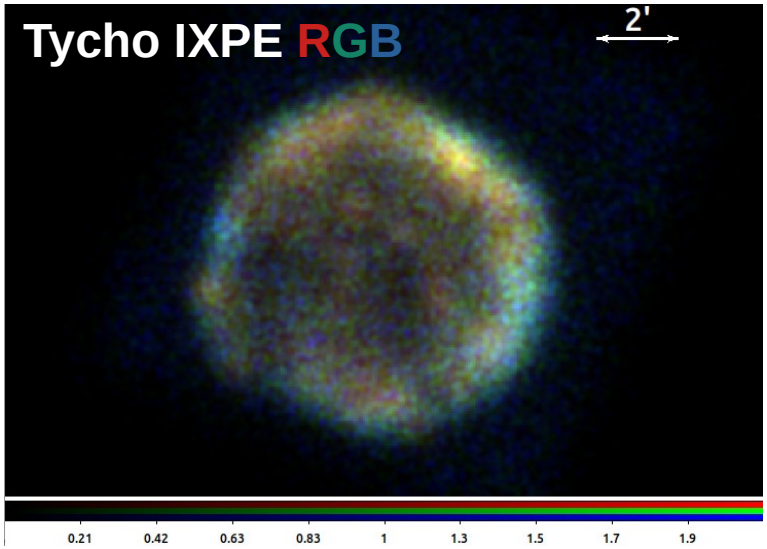
- For **Forward Shock (FS), FS+West,** and **All**, detections at **4σ – 5σ** level!
- **Low polarization degree:** **2% – 3.5%** (**2.5% – 4.5%** after accounting for thermal dilution) implying very turbulent magnetic field ;
- Polarization angle implies **radial B-field dominates within 10^{17} cm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

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

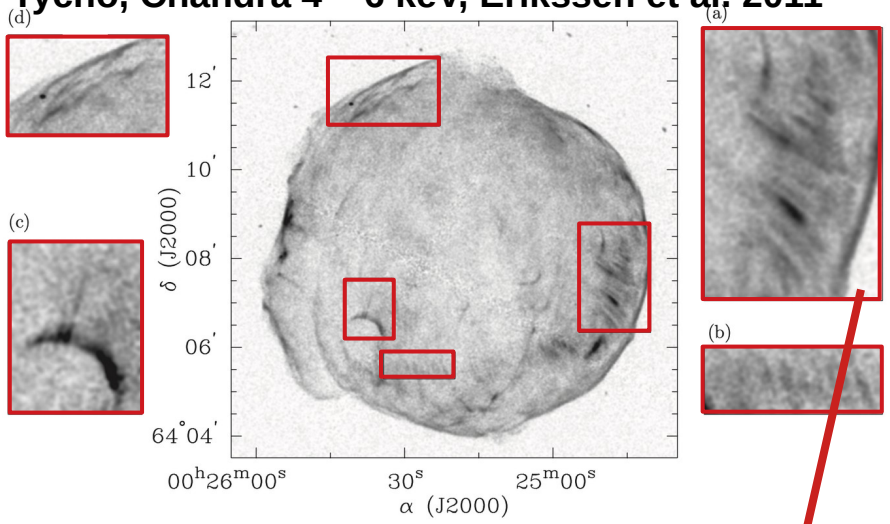
Vink et al. 2022, arXiv:2206.06713

IXPE
Imaging
X-Ray
Polarimetry
Explorer

IXPE OBSERVATION OF TYCHO
STAY TUNED FOR RESULTS!



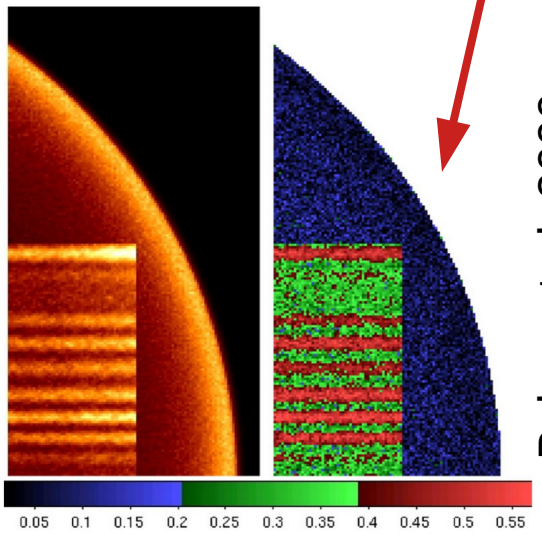
Tycho, Chandra 4 – 6 keV, Eriksen et al. 2011



- 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!



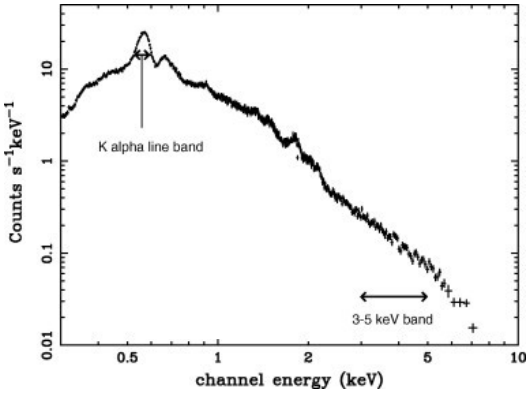
Bykov et al. 2009

Ferrazzoli et al., in preparation

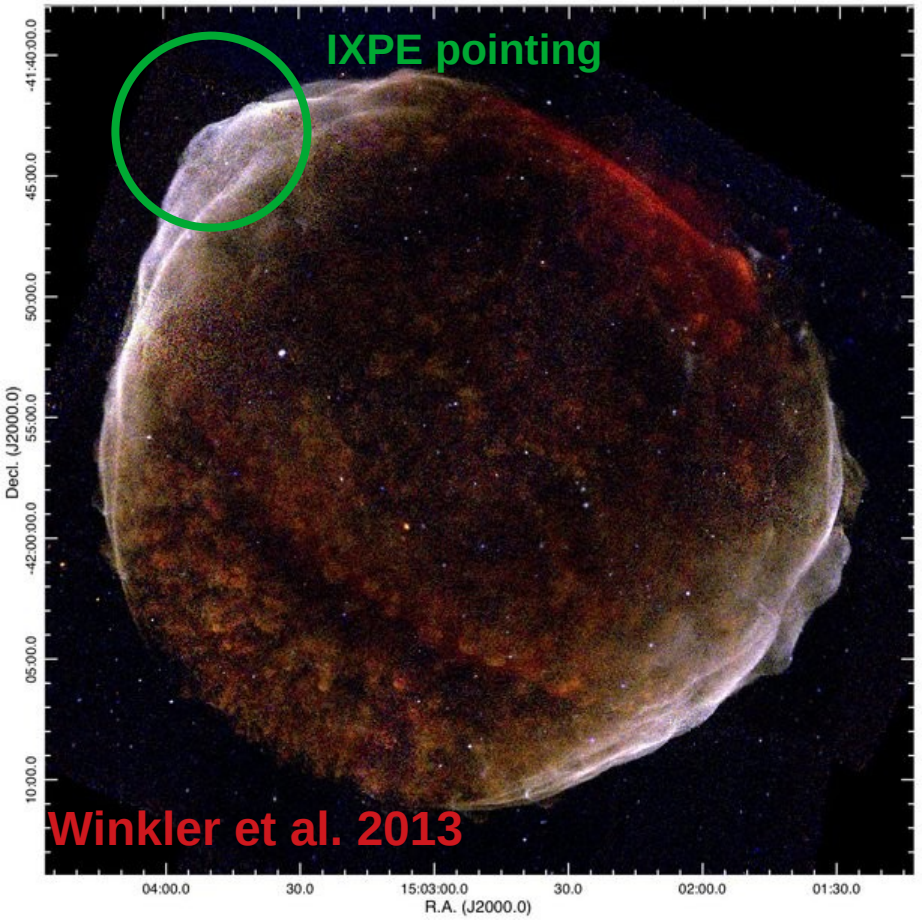
IXPE
Imaging X-Ray Polarimetry Explorer

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



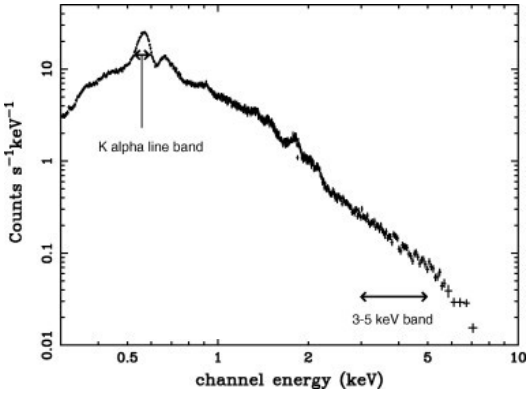
- SNR is VERY large, we covered only NE rim in Year 1.
- Observation completed, data just delivered.



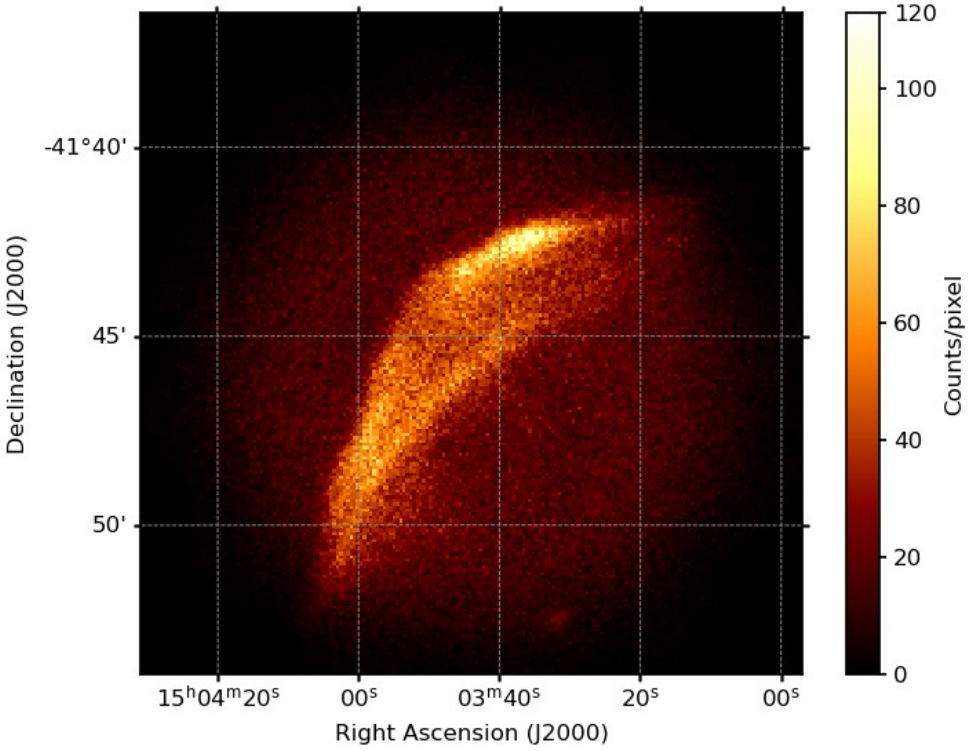
IXPE
Imaging X-Ray Polarimetry Explorer

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.



Zhou et al., in preparation

IXPE
Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

Agenzia Spaziale Italiana

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!

Thank you for your attention!