IXPE OBSERVATIONS OF THE CRAB AND OTHER PWNE:

A CRITICAL REVIEW

NICCOLO' BUCCIANTINI

INAF ARCETRI - UNIV. FIRENZE - INFN

OUTLINE

INTRODUCTION

PWNE IN X-RAY

INTERNAL STRUCTURE & MAGNETIC FIELD

TURBULENCE & ACCELERATION

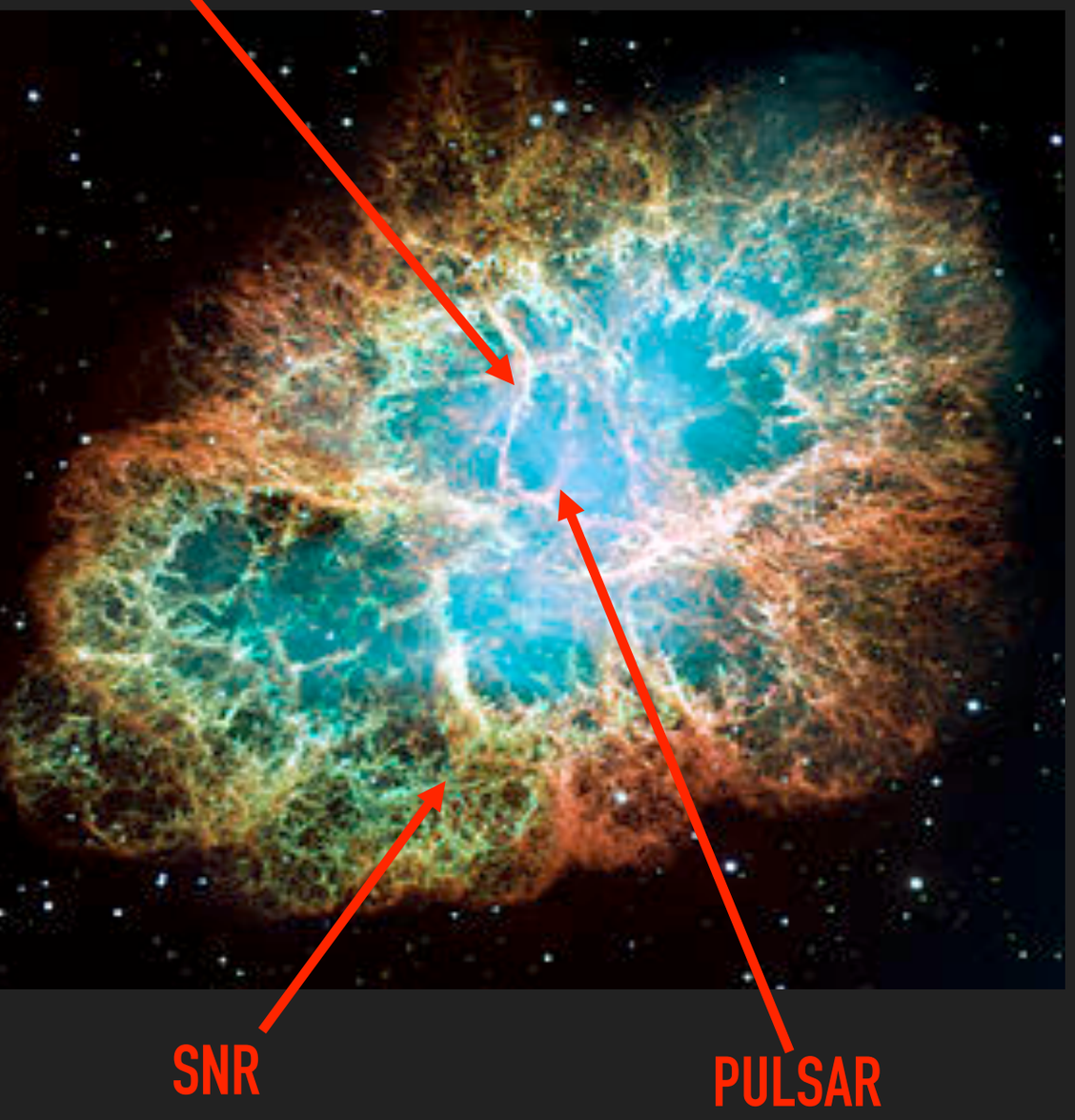
A CASE FOR X-RAY POLARIMETRY

LEAKAGE

CRAB, VELA, MHS15-52, SNR B0540

FUTURE TARGETS

PWNE



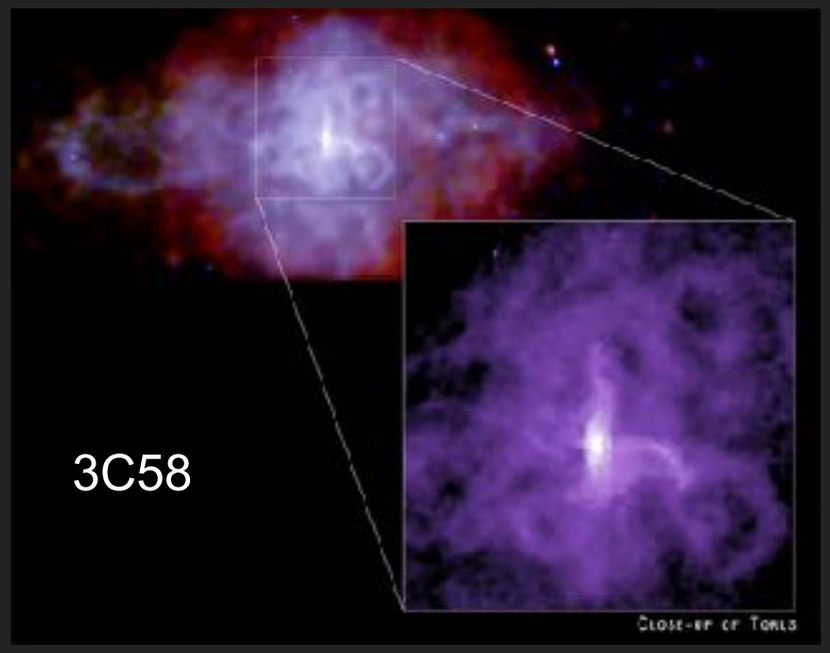
PWNe are hot bubbles of relativistic particles and magnetic field emitting non-thermal radiation.

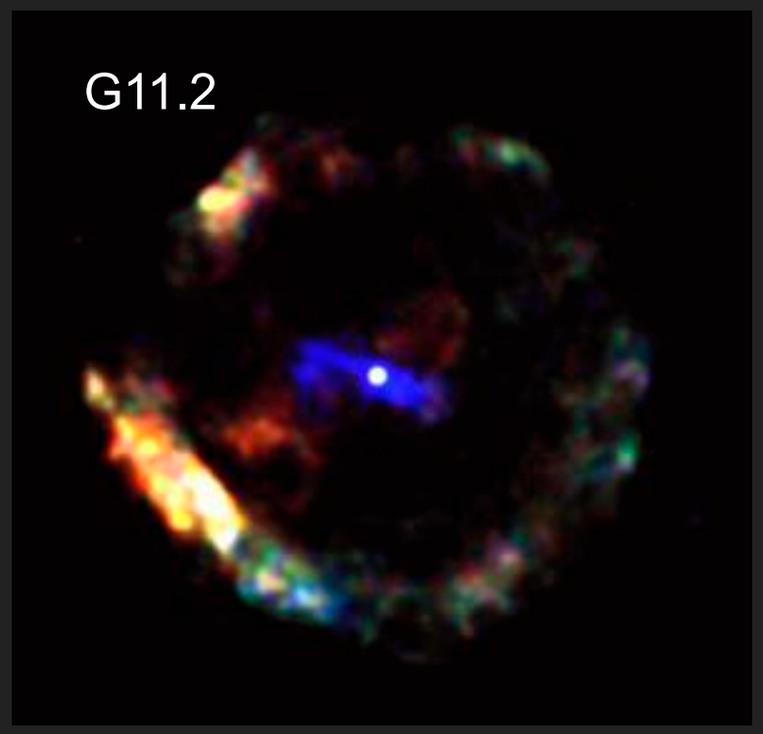
Originated by the interaction of the ultra-relativistic magnetized pulsar wind with the expanding SNR (or with the ISM)

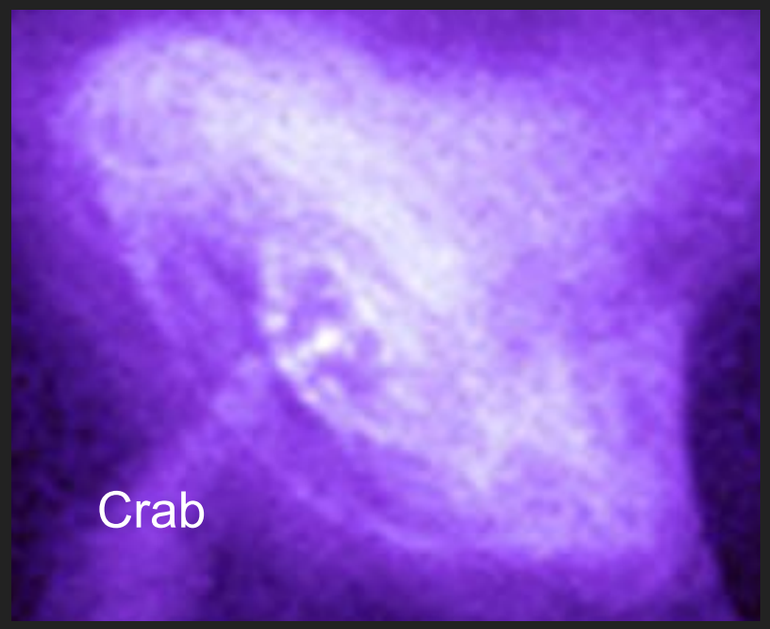
Galactic accelerators. The only place where we can study the properties of relativistic shocks (as in GRBs and AGNs

Allow us to investigate the dynamics of relativistic outflows

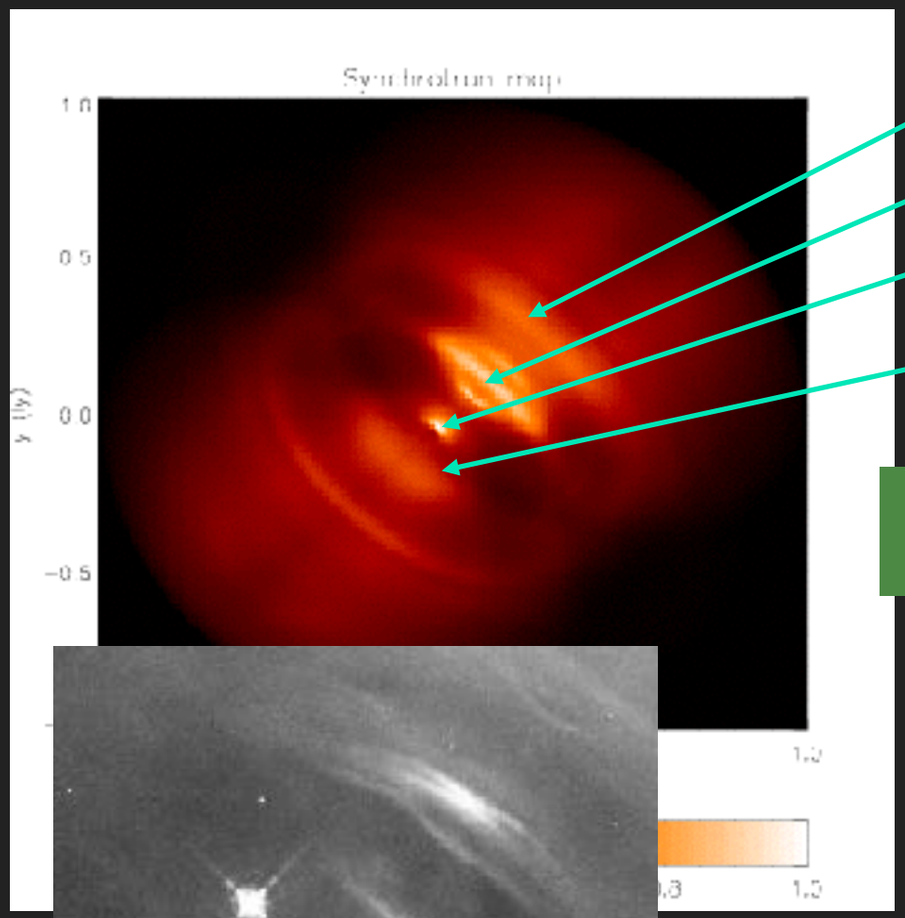
FINE STRUCTURES – A LAB FOR RELTIVISTICN FLUID DYNAMICS







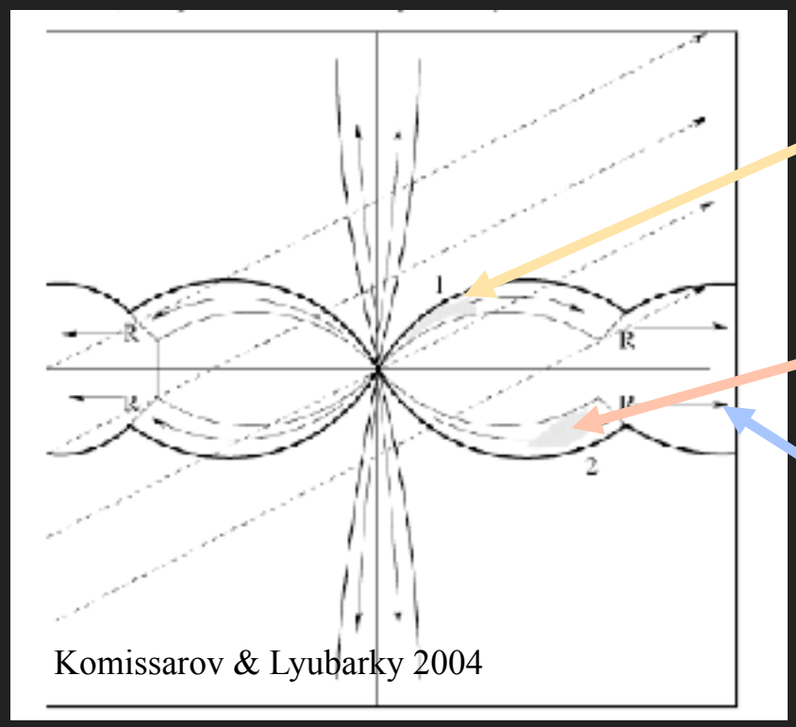
REPRODUCING OBSERVATIONS




Hester et al. 1995

Main torus
Inner ring (wisps structure)
Knot
Back side of the inner ring

Each feature traces an emitting region



Komissarov & Lyubarky 2004

Knot

Ring

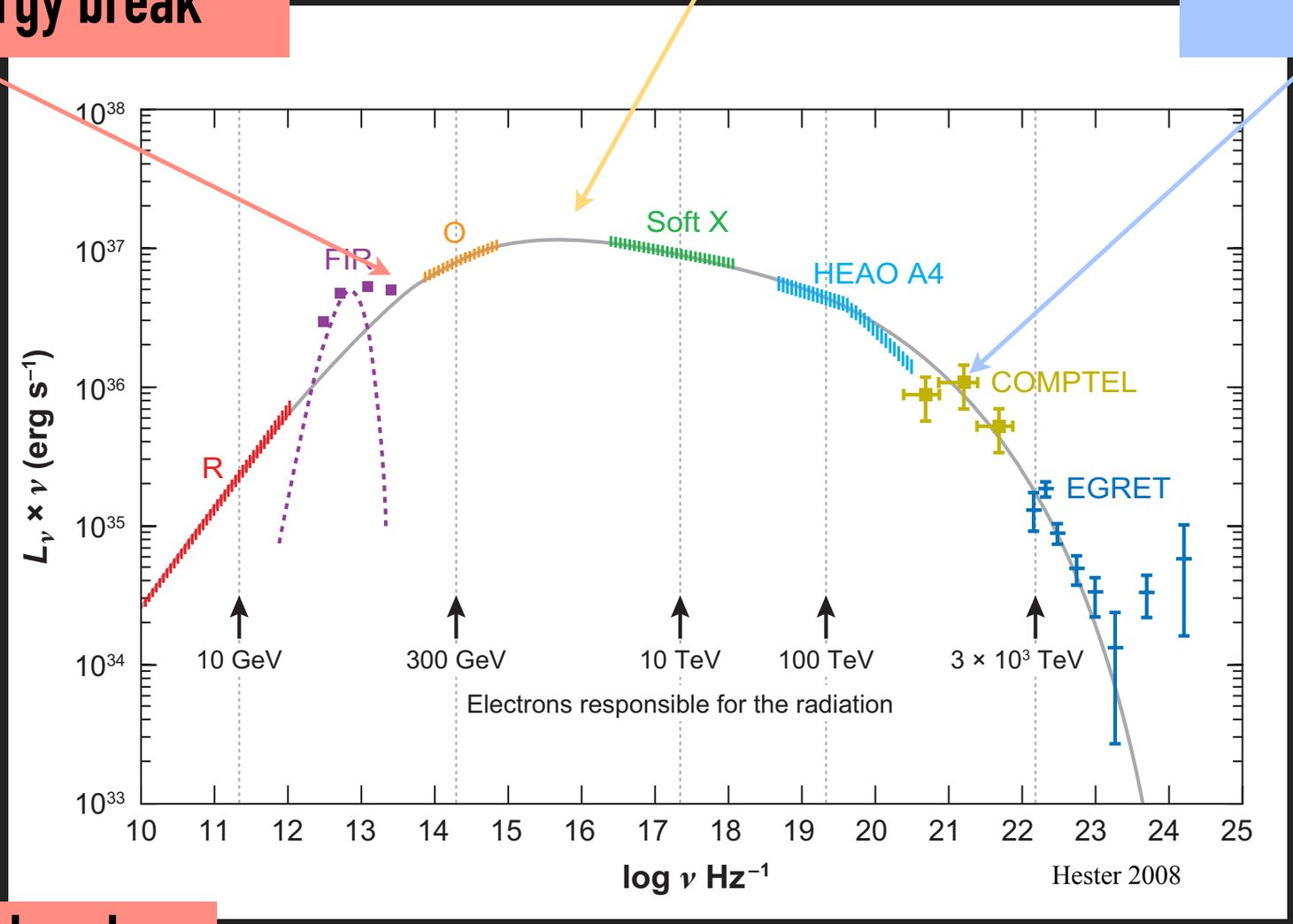
Torus

CRAB SYNCHROTRON SPECTRUM

Low energy break

High energy break

MeV cutoff



Hester 2008

Injection break

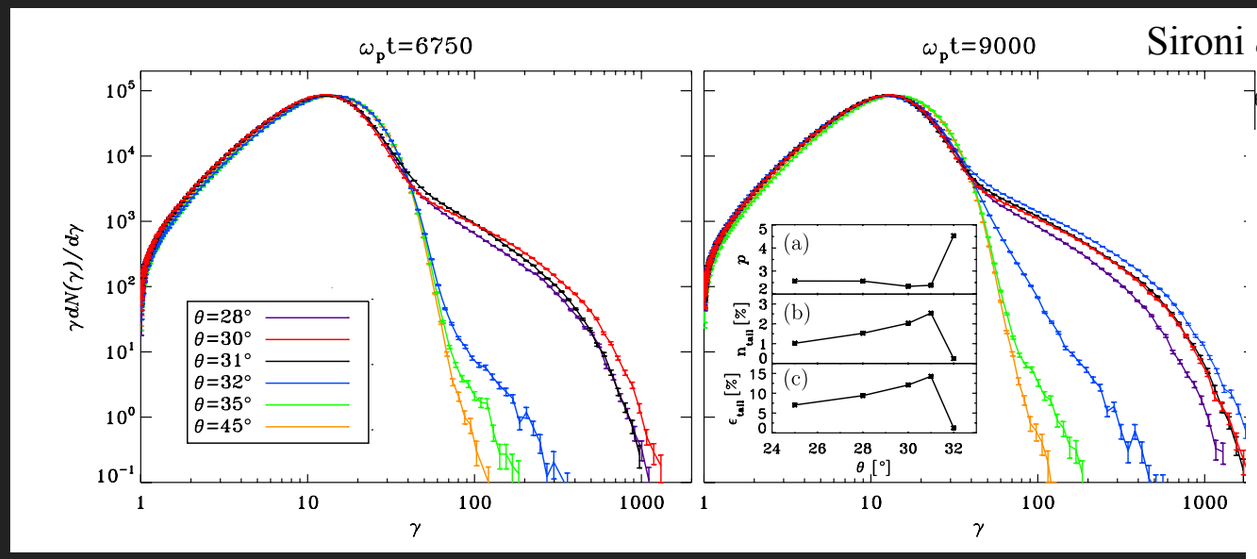
Synchr. cooling

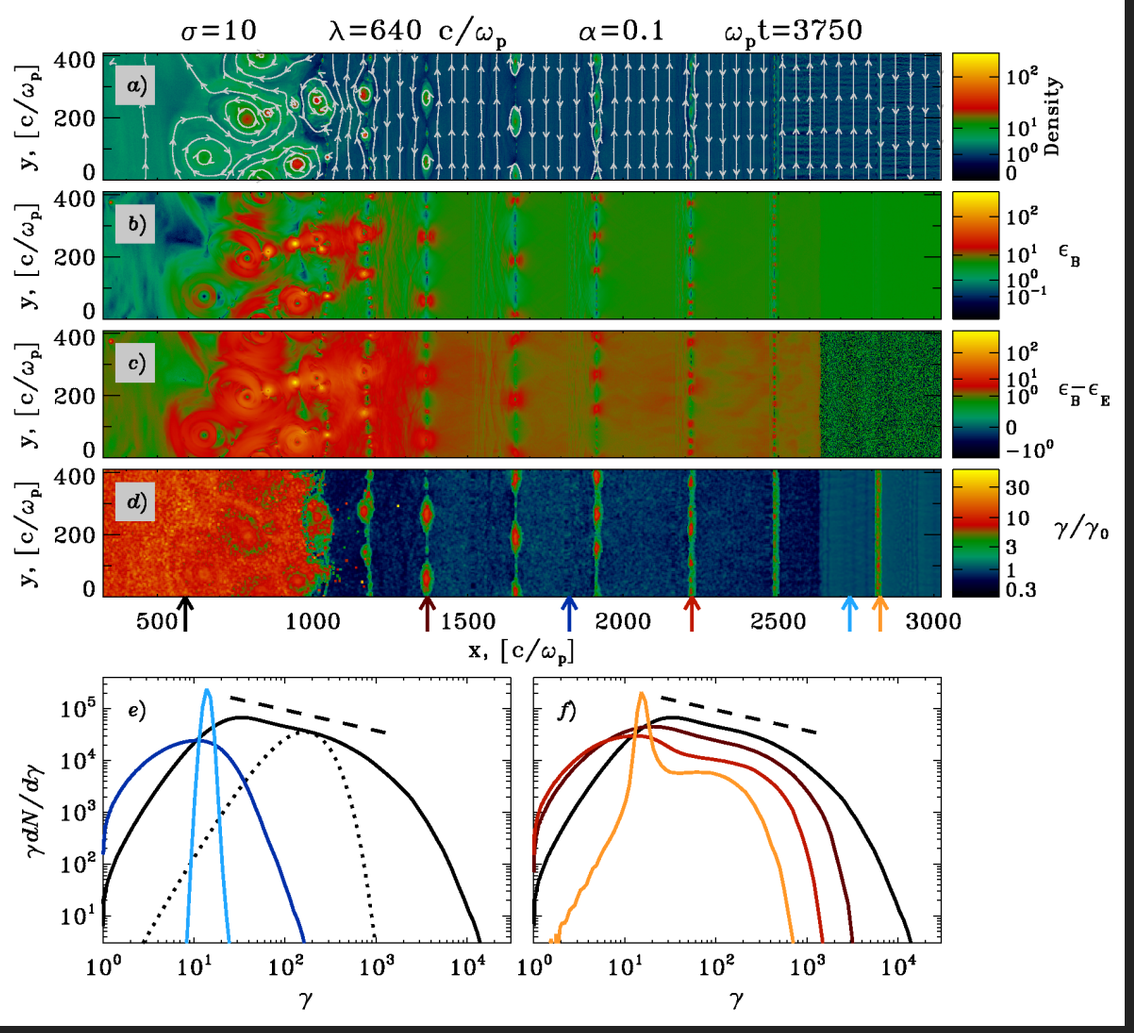
Acceler. cutoff

The most efficient non-thermal accelerator.

FERMI VS RECONNECTION

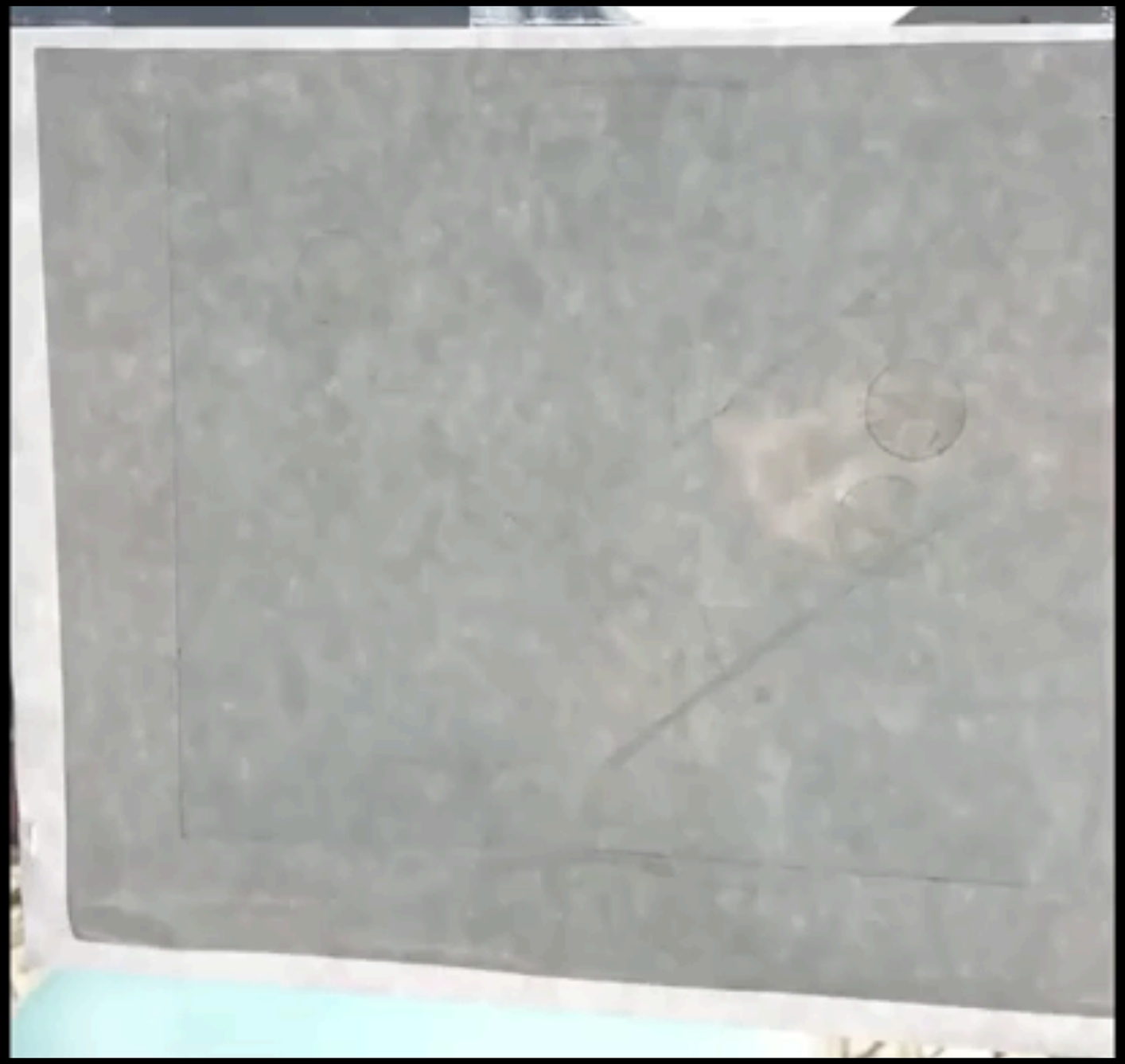
FERMI DSA HIGHLY INEFFICIENT IN PSR WIND SHOCK – VERY LOW MAGNETISATION





RECONNECTION OF THE STRIPED WIND MORE VERSATILE
WORKS WELL FOR HIGH MAGNETIZATION
REQUIRES VERY HIGH MULTIPLICITY

POWER OF POLARIMETRY



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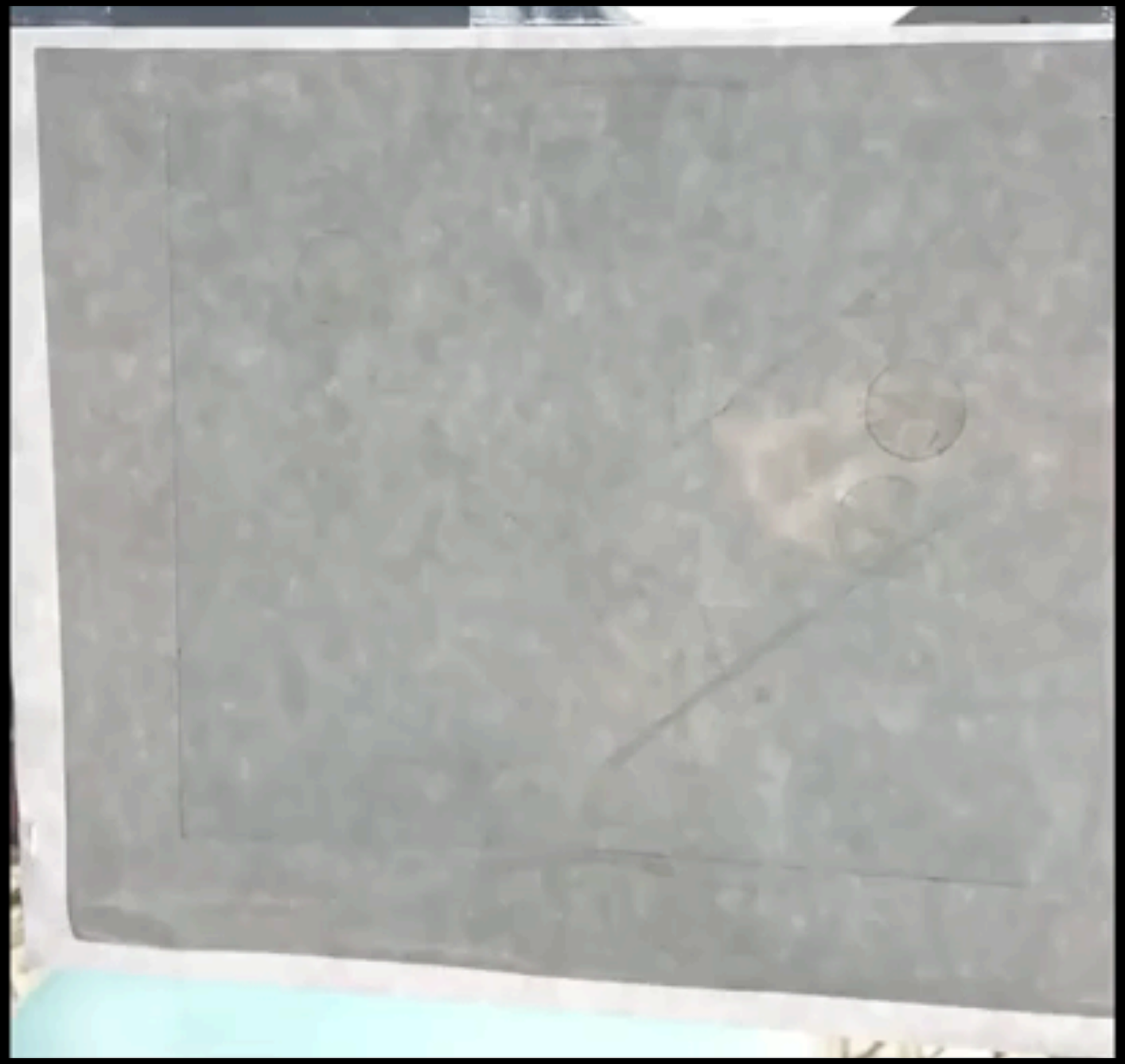
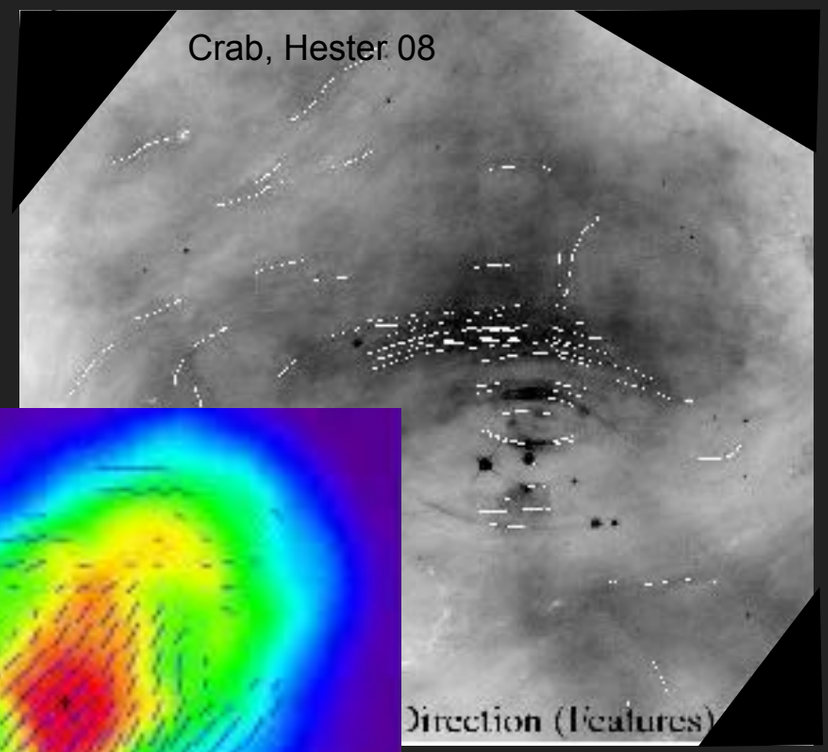
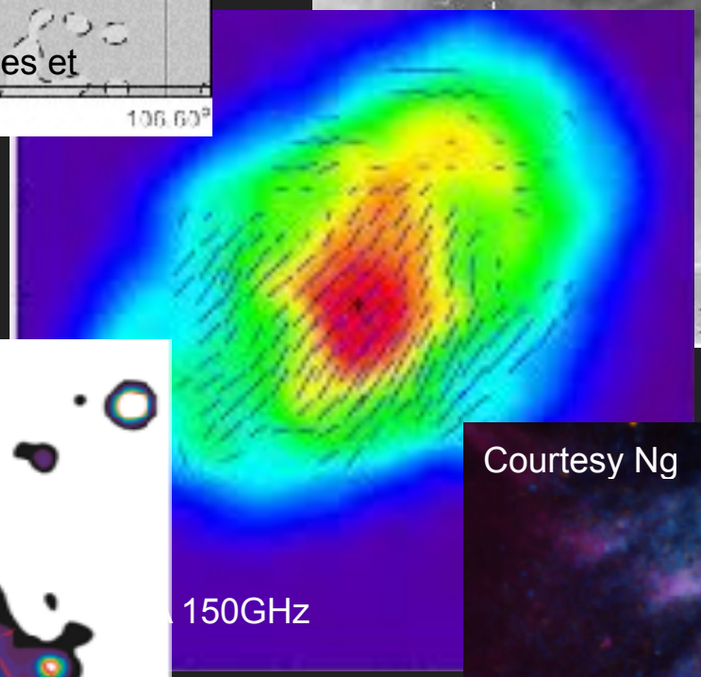


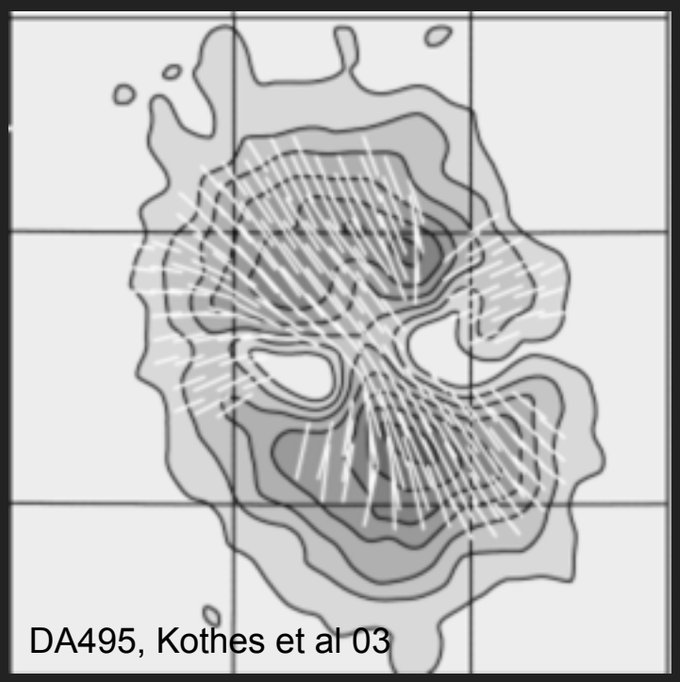
PWN - POLARIZATION

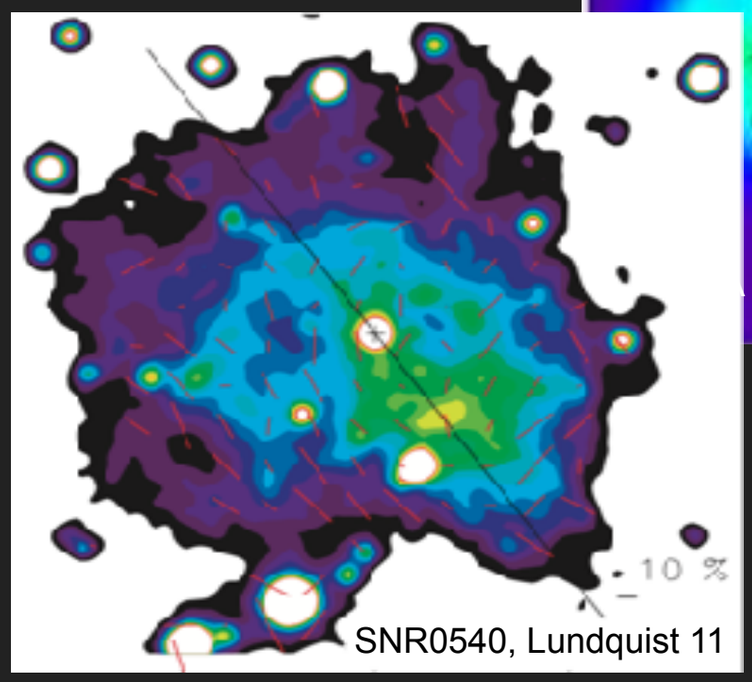
Difference in Optical vs Radio Polarisation

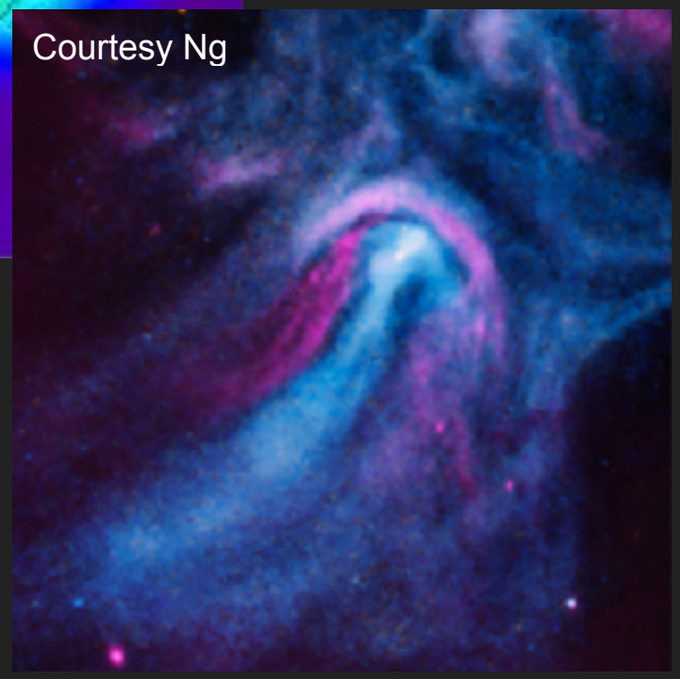
Not Always Toroidal



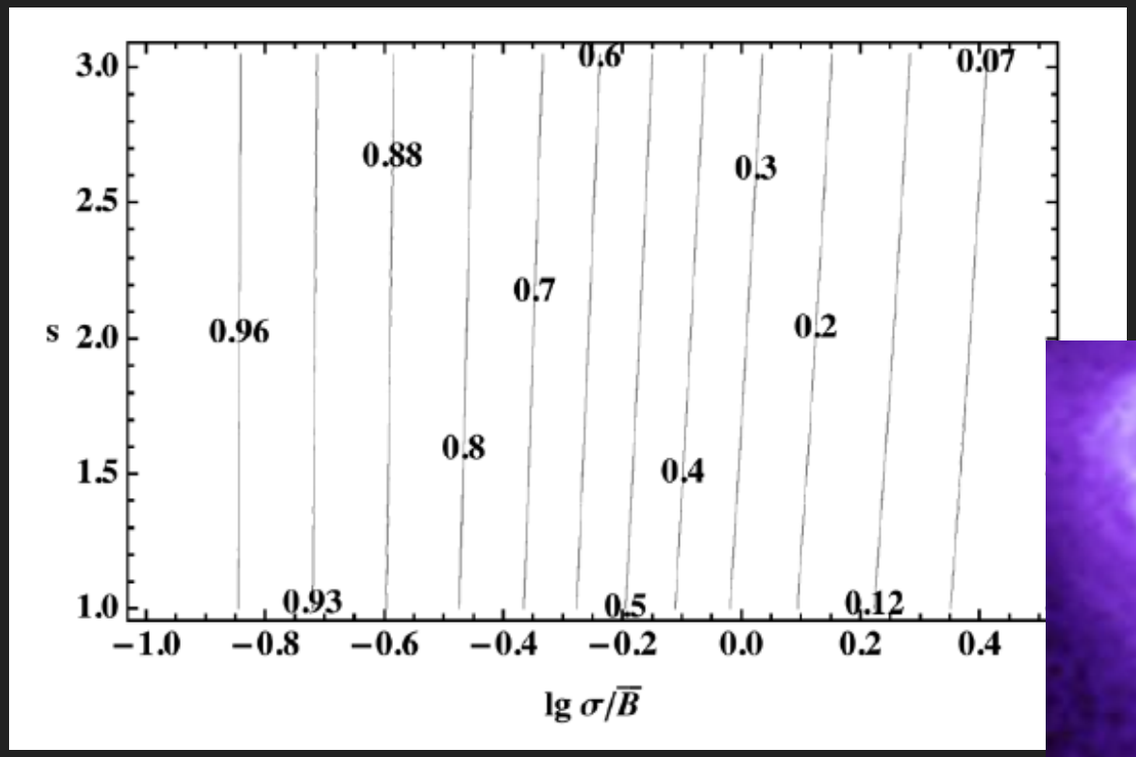




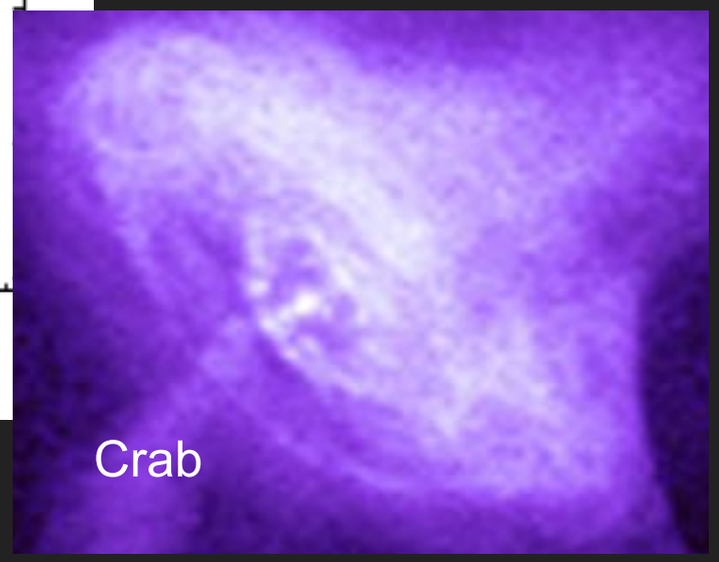


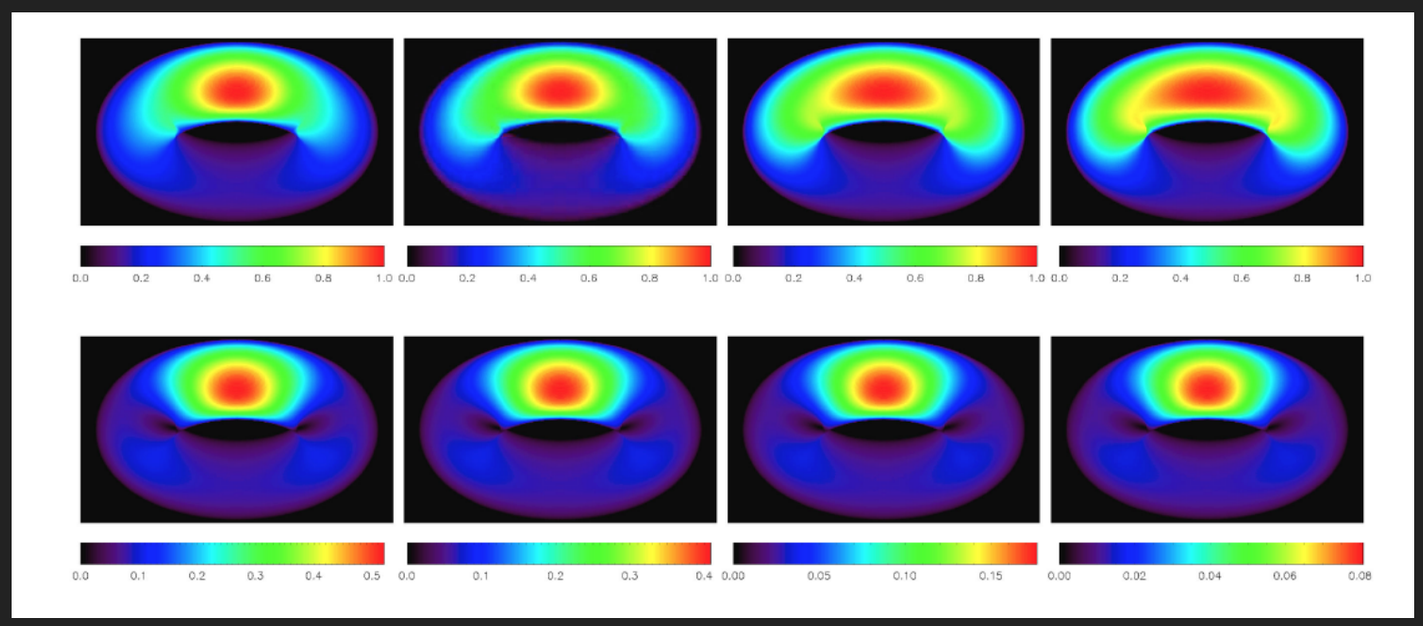


SYNCHROTRON - POLARIZATION

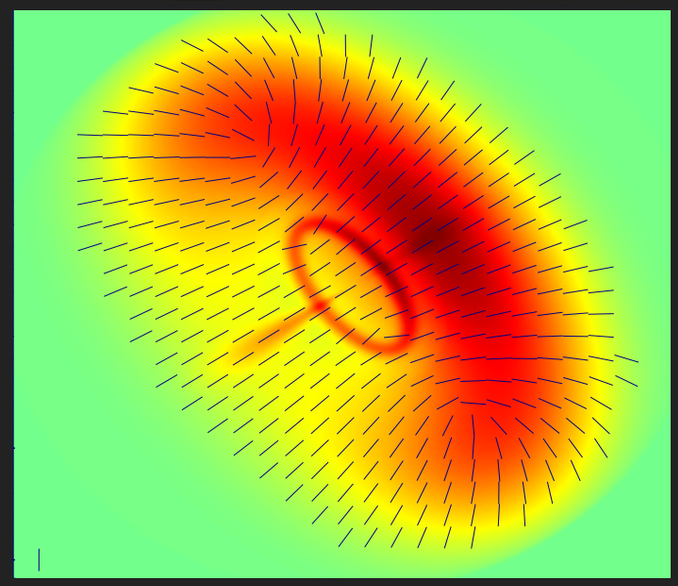


Bandiera Petruck 2016





Bucciantini 2017



IXPE – BROAD VIEW

Mission name	Imaging X-ray Polarimetry Explorer (IXPE)
Mission category	NASA Astrophysics Small Explorer (SMEX)
Operational phase	2021 launch, 2 years following 1 month commissioning, extension possible
Orbital parameters	Circular at 540–620 km altitude, equatorial; one ground station near equator
Spacecraft features	3-axis stabilized pointing (non-propellant), GPS time and position
Science payload	3 x-ray telescopes, 4.0-m focal length (deployed), co-aligned to star tracker
Telescope optics (×3)	24 monolithic (P+S surfaces) Wolter-1 electroformed shells, coaxially nested
Telescope detector (×3)	Polarization-sensitive gas pixel detector (GPD) to image photo-electron track
Polarization sensitivity	Minimum Detectible Polarization (99% confidence) $MDP_{99} < 5.5\%$, 0.5-mCrab, 10 days
Spurious modulation	< 0.3% systematic error in modulation amplitude for unpolarized source
Angular resolution	< 30-arcsec half-power diameter (HPD)
Field of view (FOV)	≈ 10-arcmin diameter overlapping FOV of 3 detectors' polarization-sensitive areas
Energy band, resolution	2–8 keV, ≈ 20% @ 5.9 keV
Timing accuracy	≈ 20 μs, using GPS pulse-per-second signal and on-board clocks
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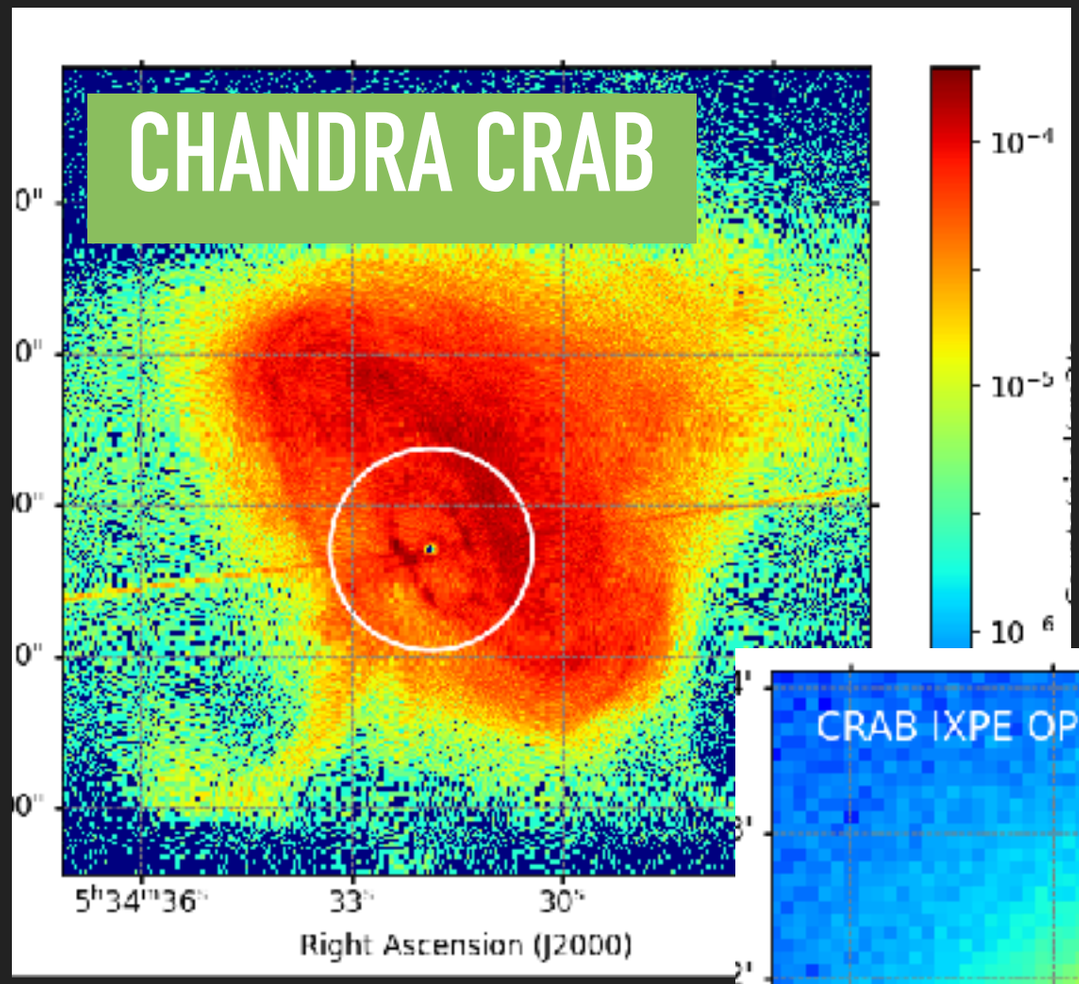
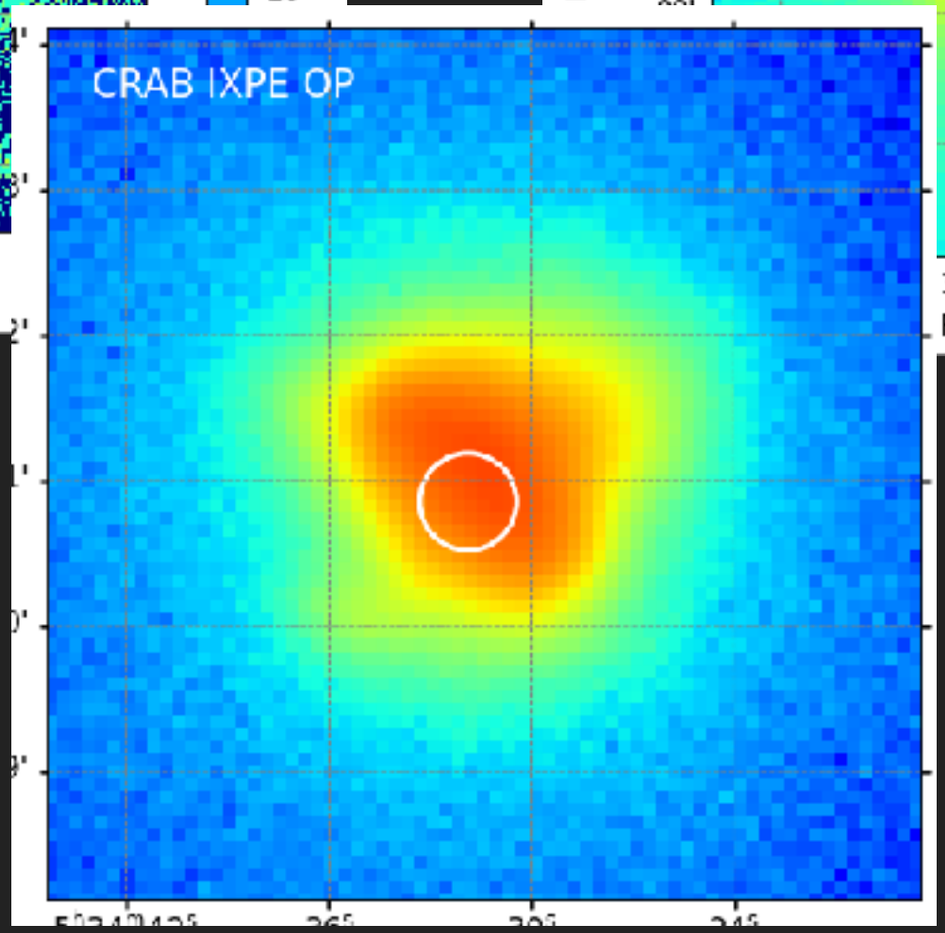
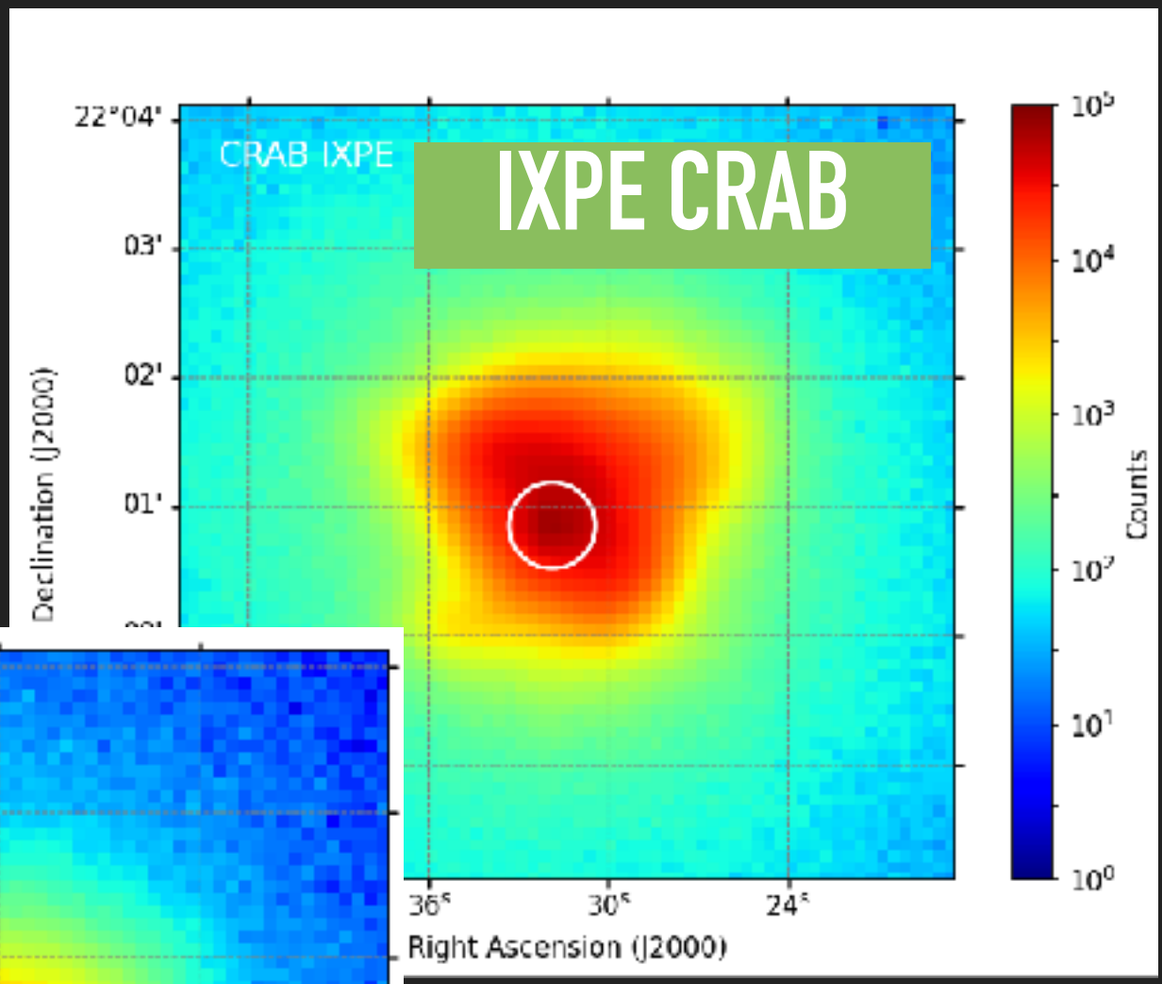
IXPE - X-RAY POLARIMETRY - CRAB

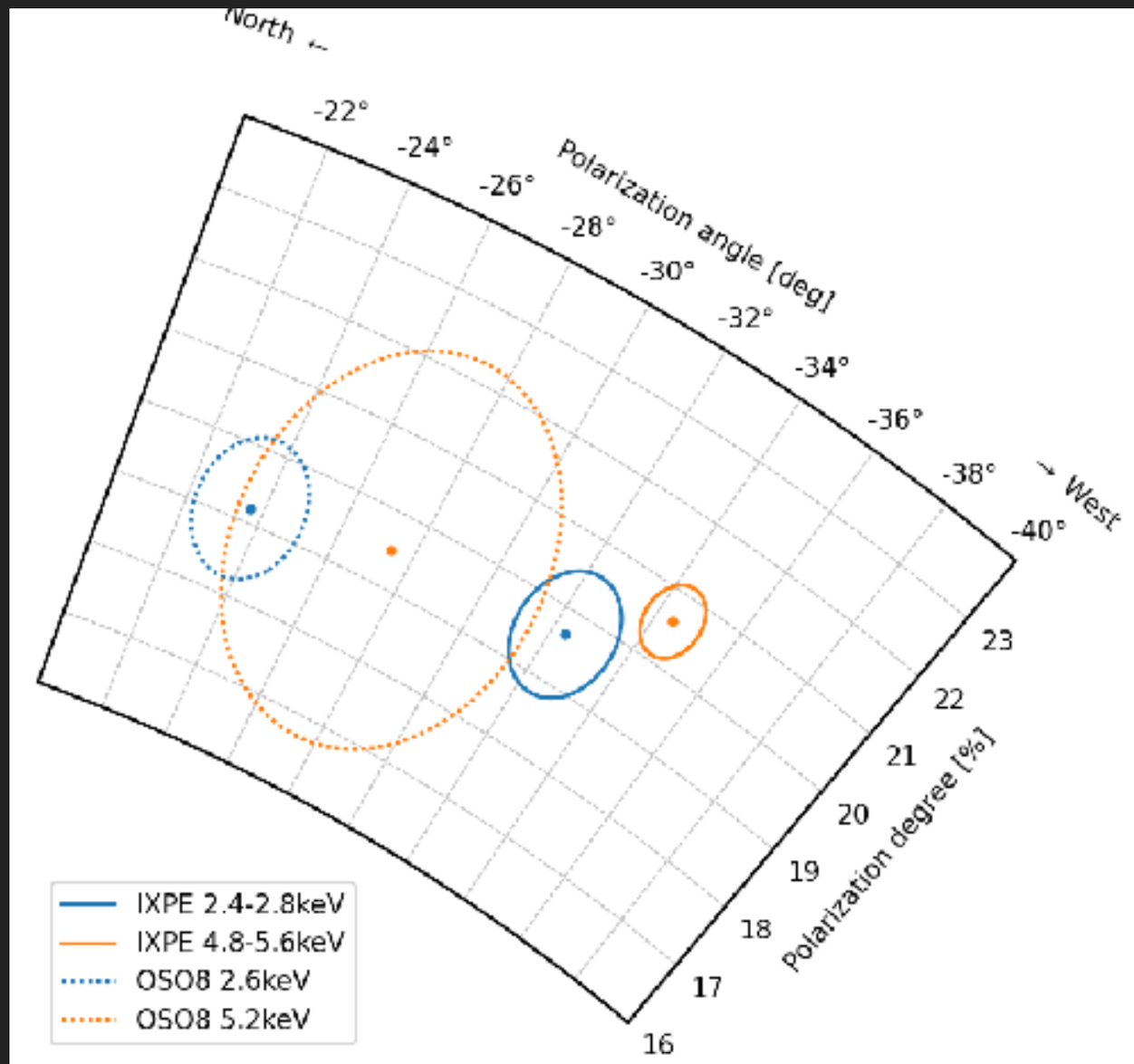




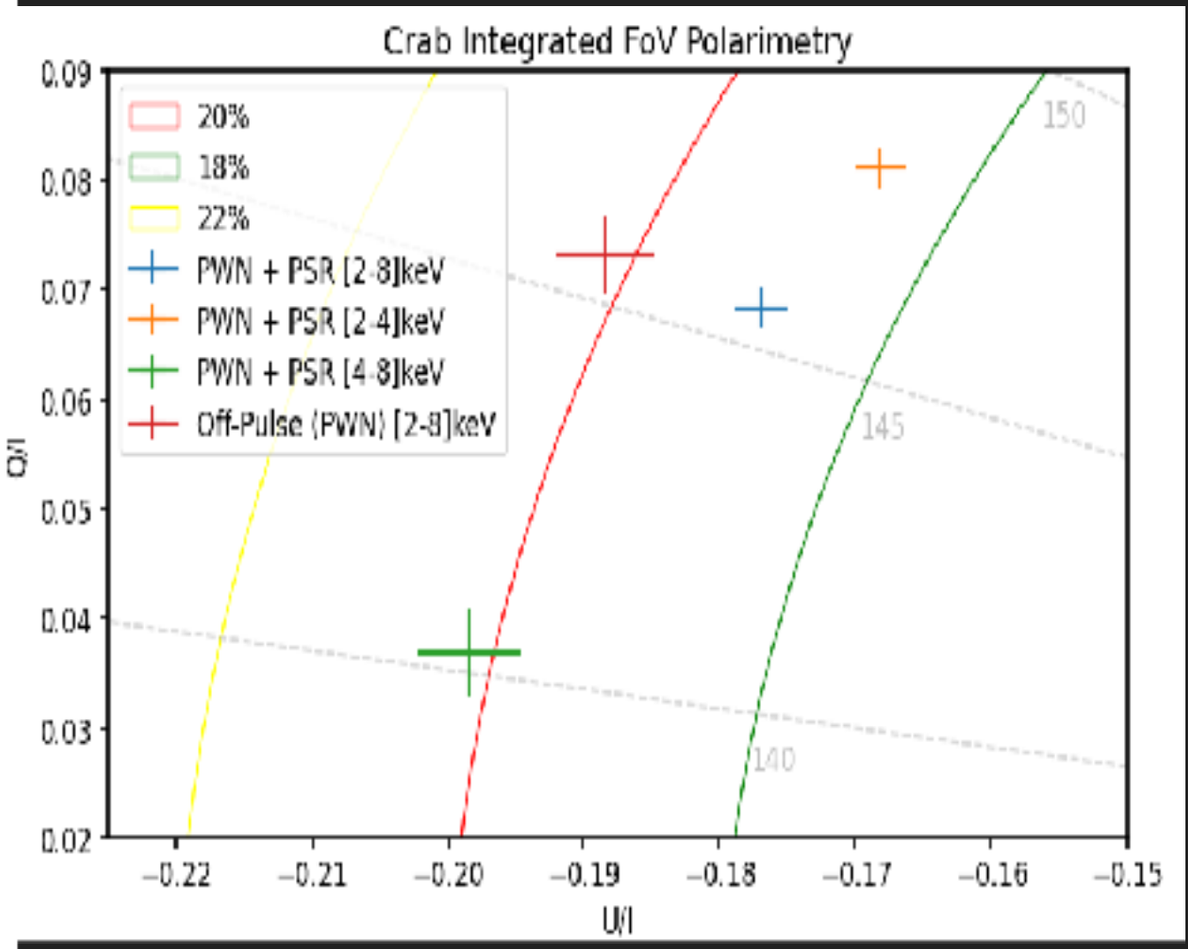


IXPE CRAB OP

IXPE – X-RAY POLARIMETRY – CRAB



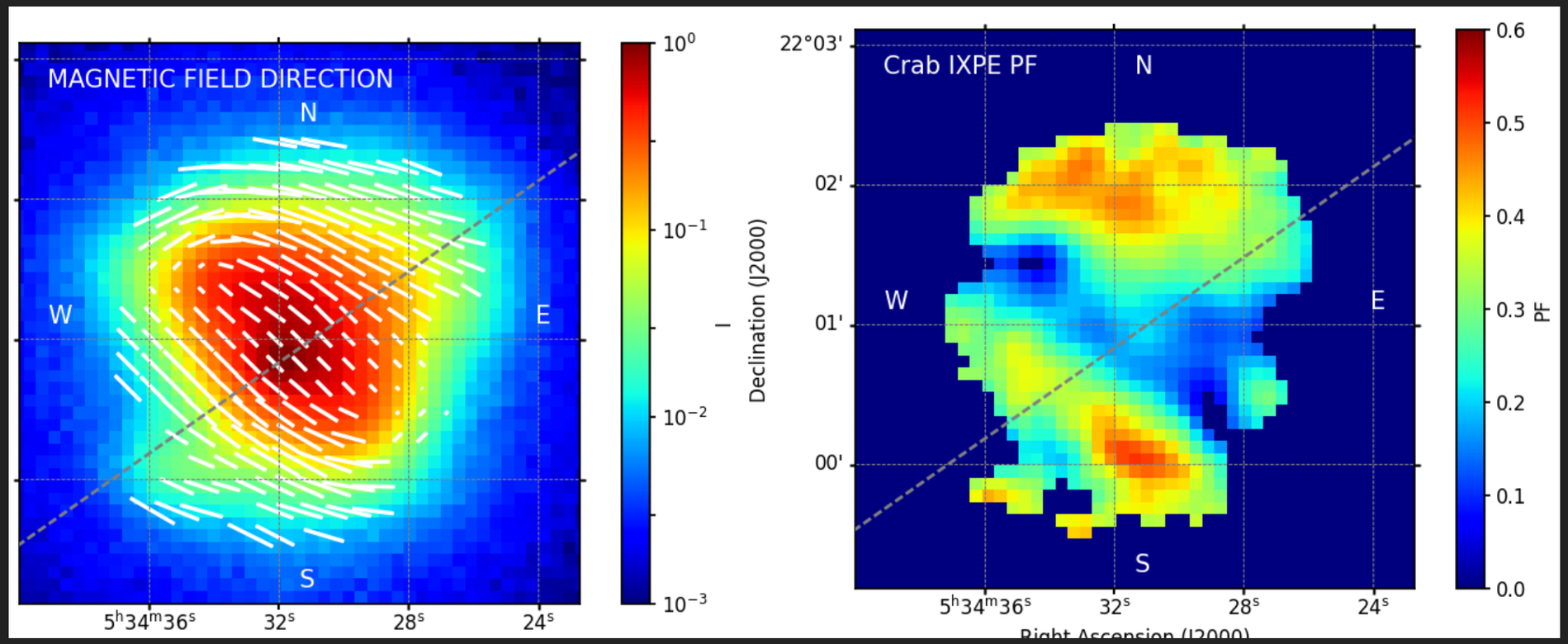
IXPE VS OSO8 – NARROW BAND



IXPE GLOBAL

IXPE – X-RAY POLARIMETRY – CRAB

Bucciantini et al 2023



Ordered field Geometry is toroidal

Polarised Fraction not symmetric with nebula

Jet polarisation is hard to measure and likely perp

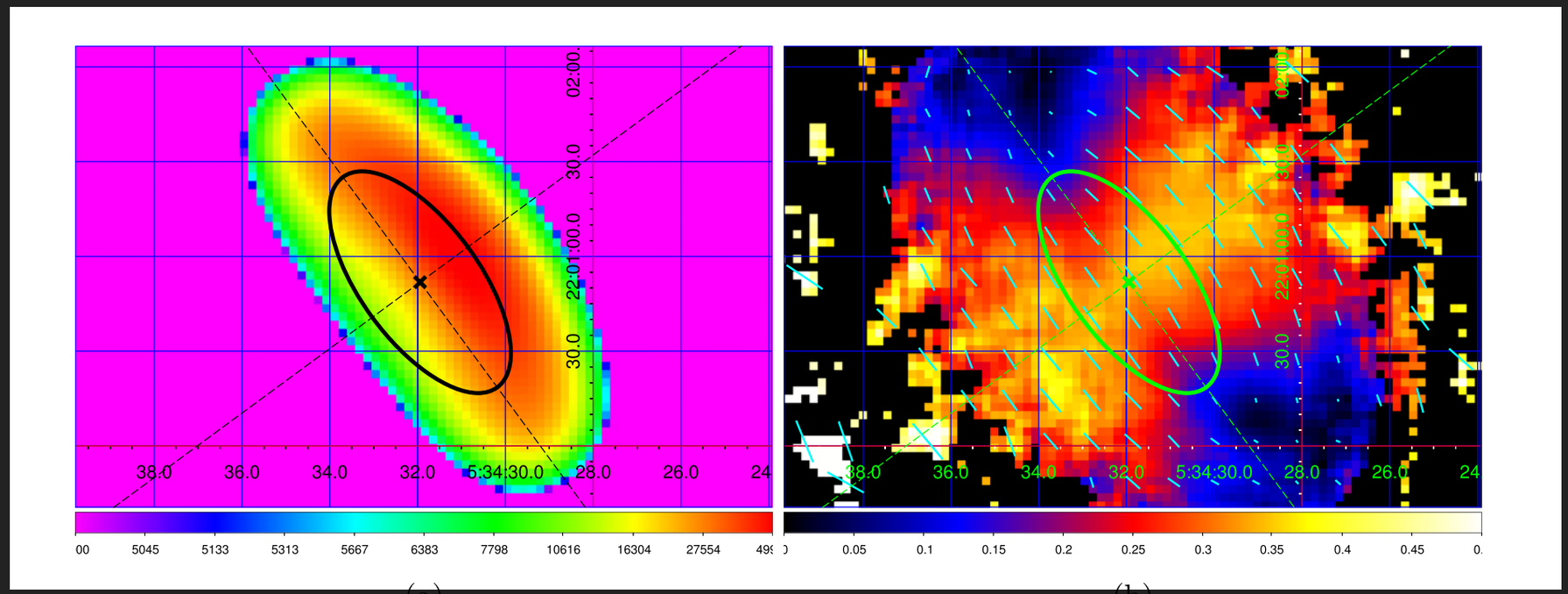
Local high level of polarisation in outer regions

Nebular Axis not consistent with PSR axis

Turbulence likely very patchy inside the PWN

IXPE – X-RAY POLARIMETRY – CRAB

Mizuno et al 2023



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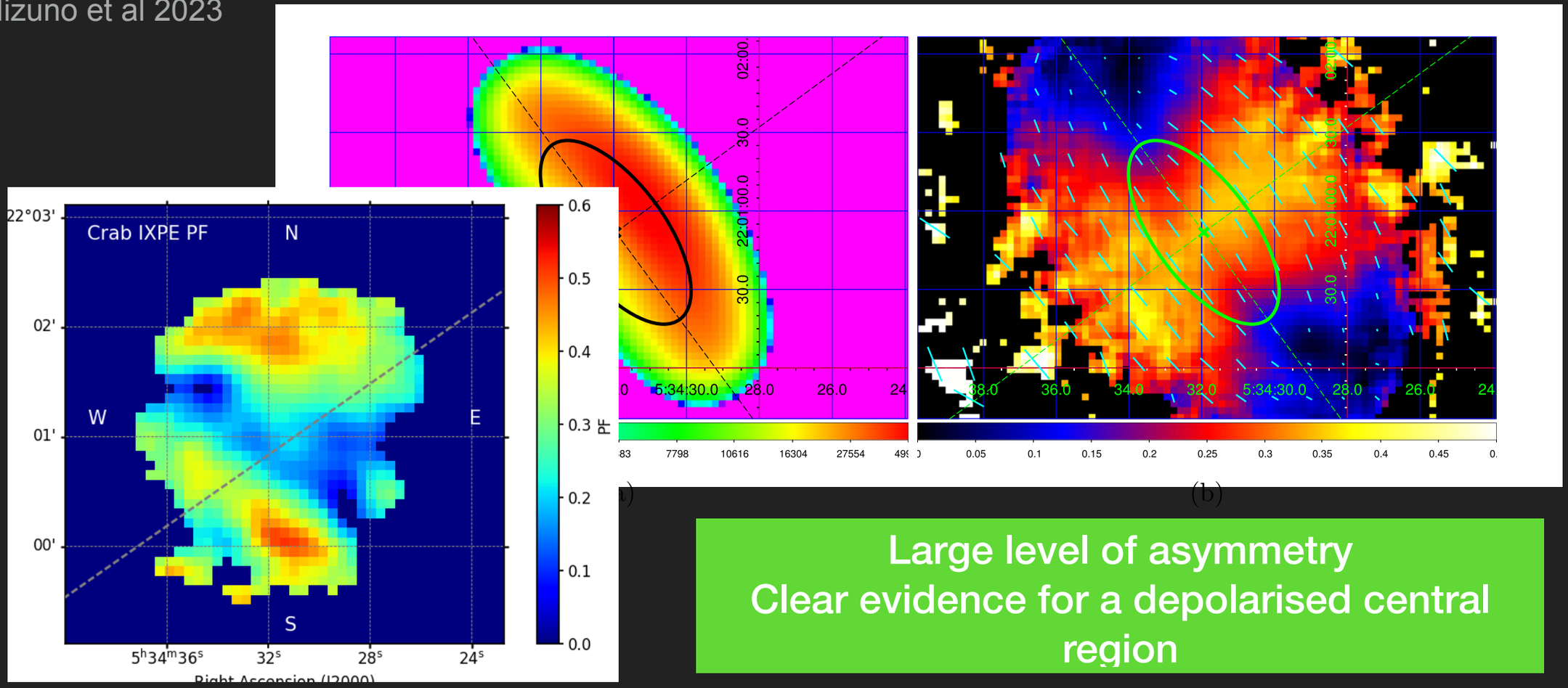
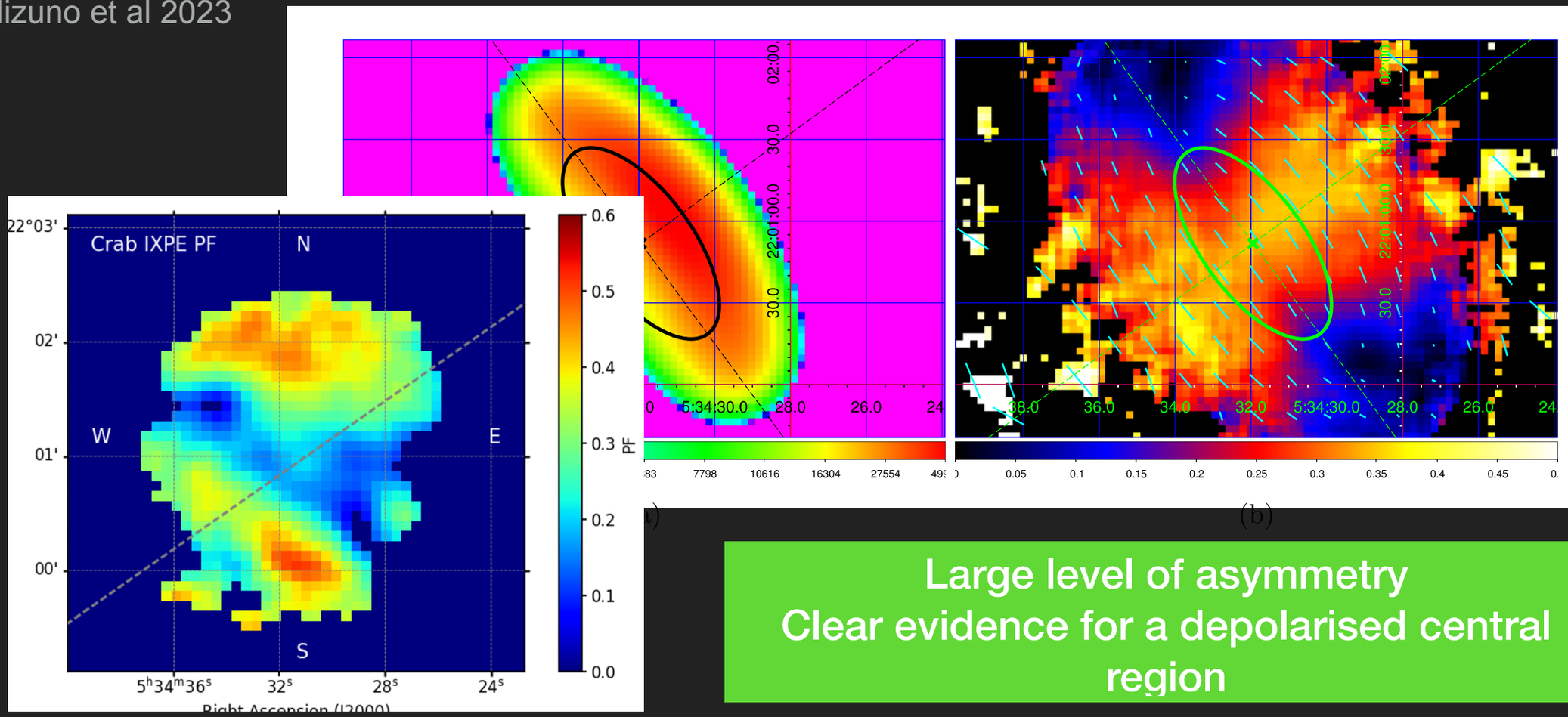


Large level of asymmetry
Clear evidence for a depolarised central region

IXPE – X-RAY POLARIMETRY – CRAB

Mizuno et al 2023



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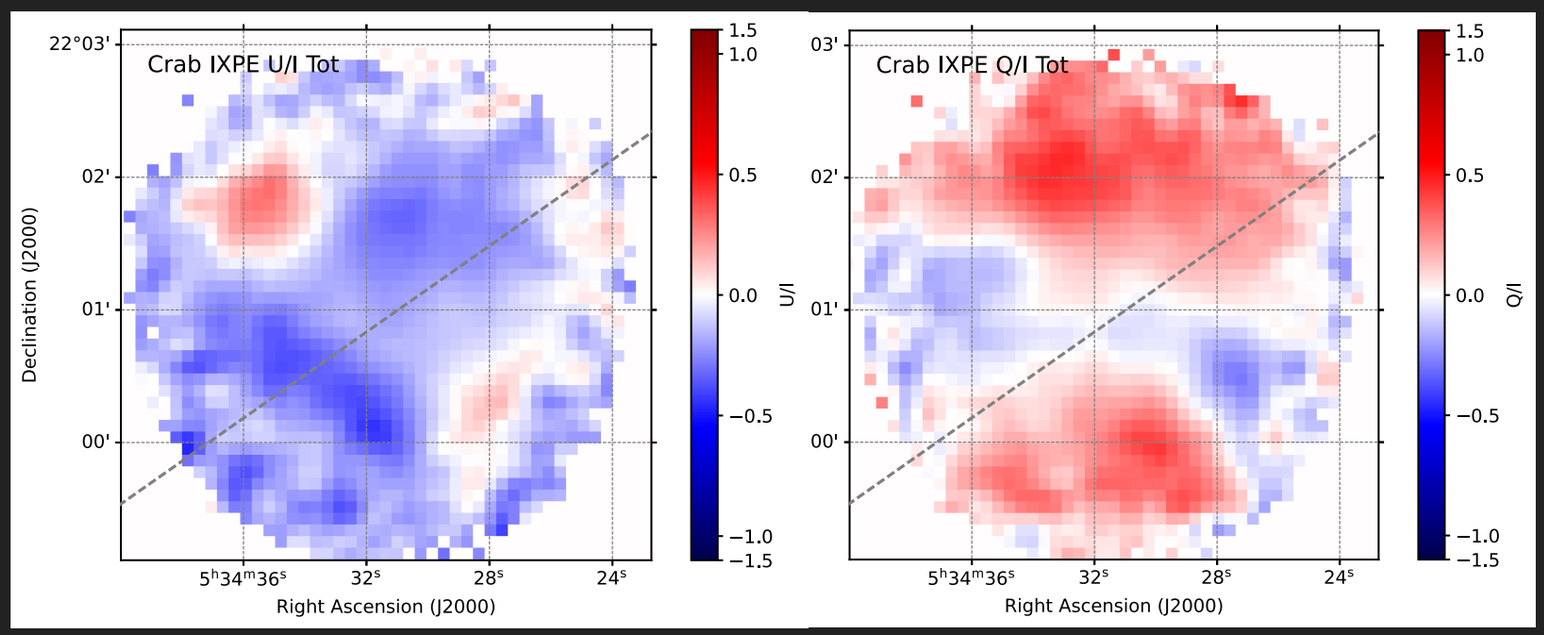
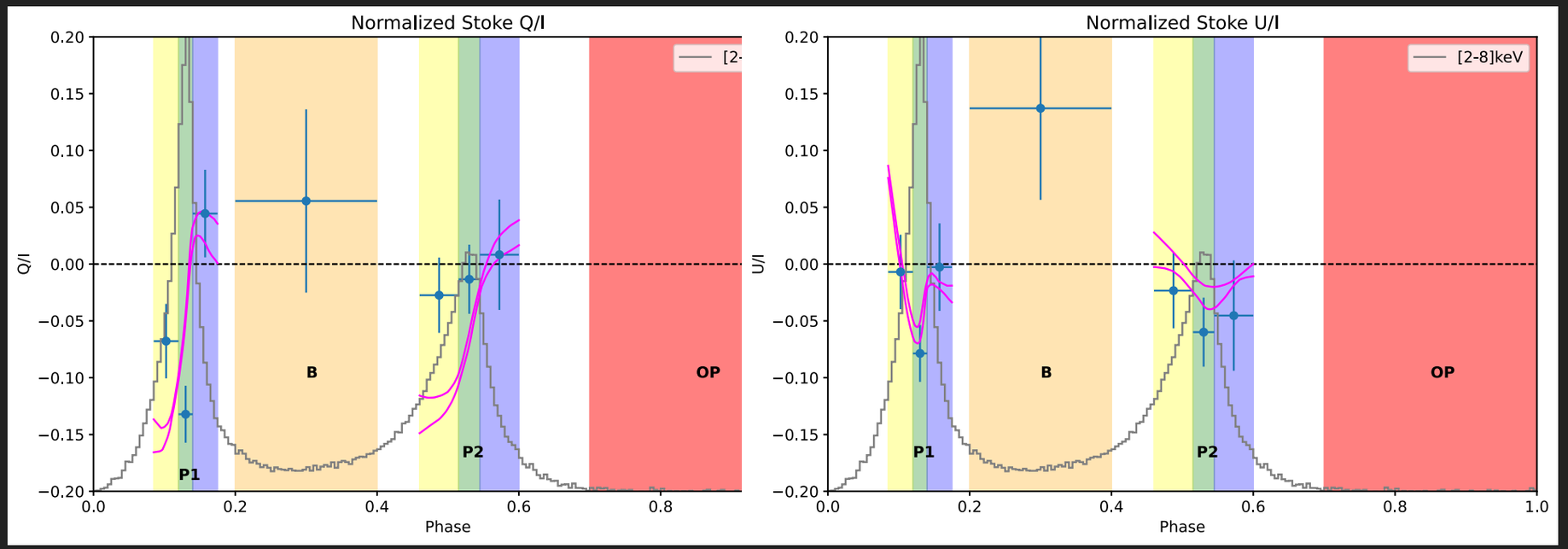


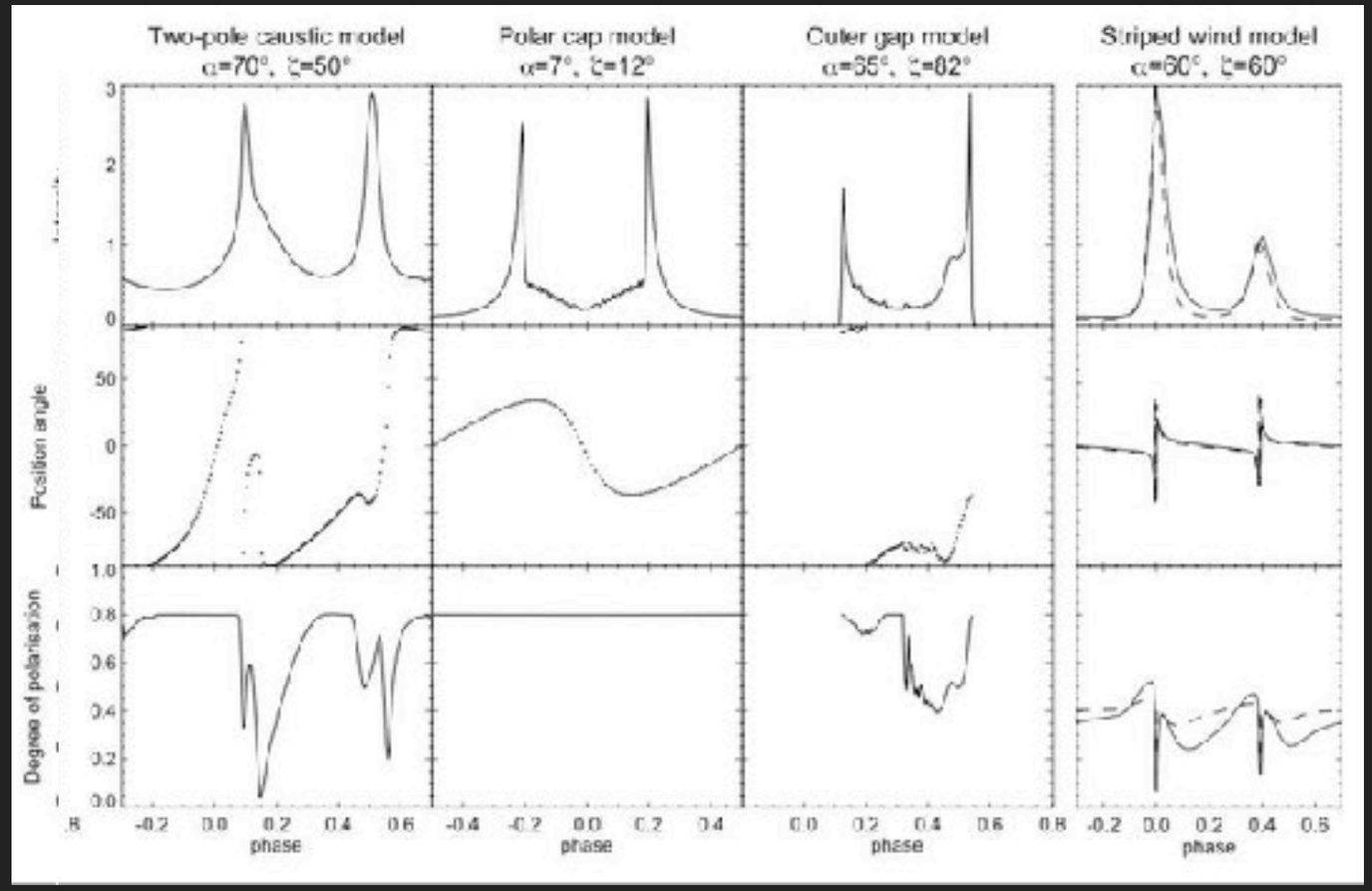
IXPE – X-RAY POLARIMETRY – CRAB PSR



5- sigma detection in the core of P1

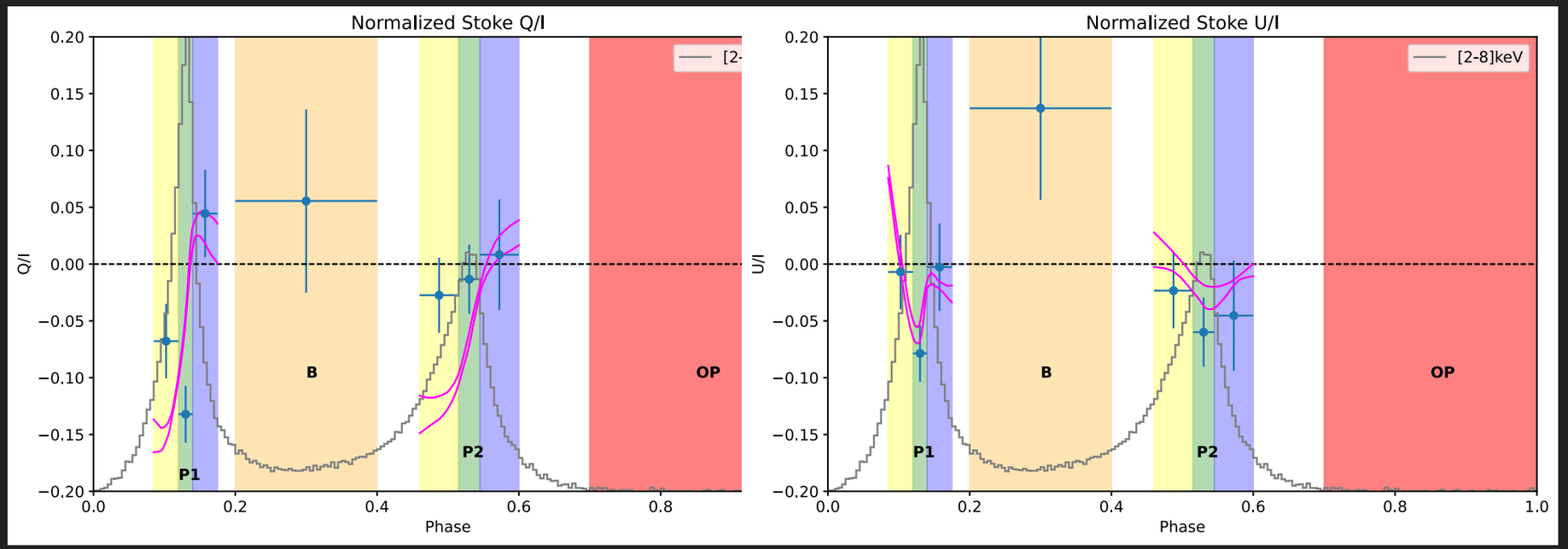
15% PF in the core of P1

Bucciantini et al 2023



Only models with emission coming from the current sheet in the wind survive

IXPE – X-RAY POLARIMETRY – CRAB PSR



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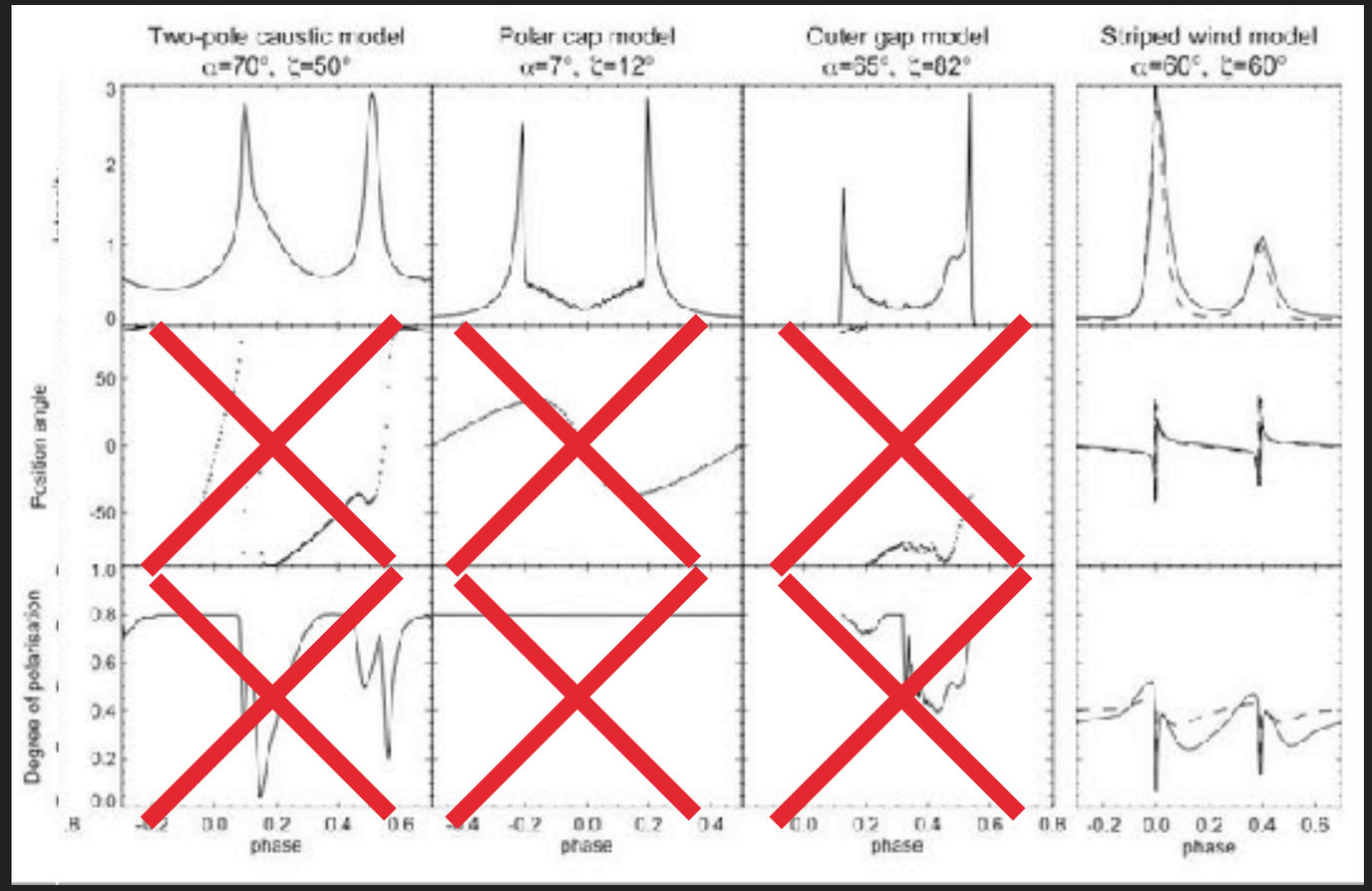
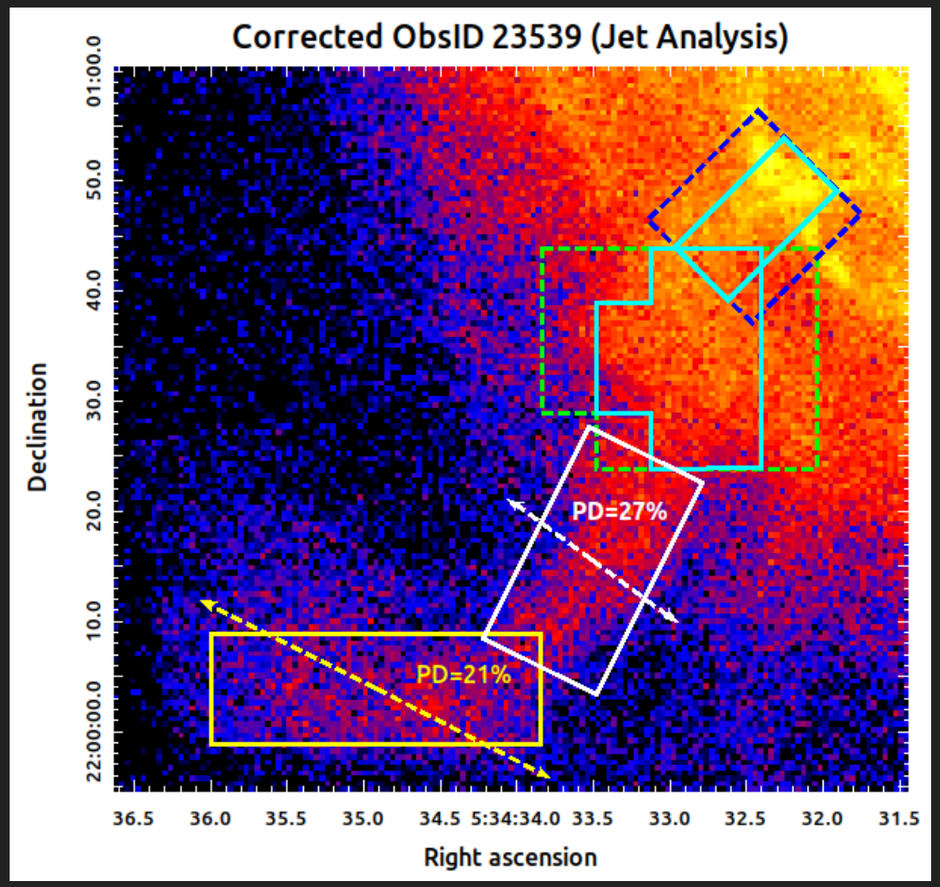
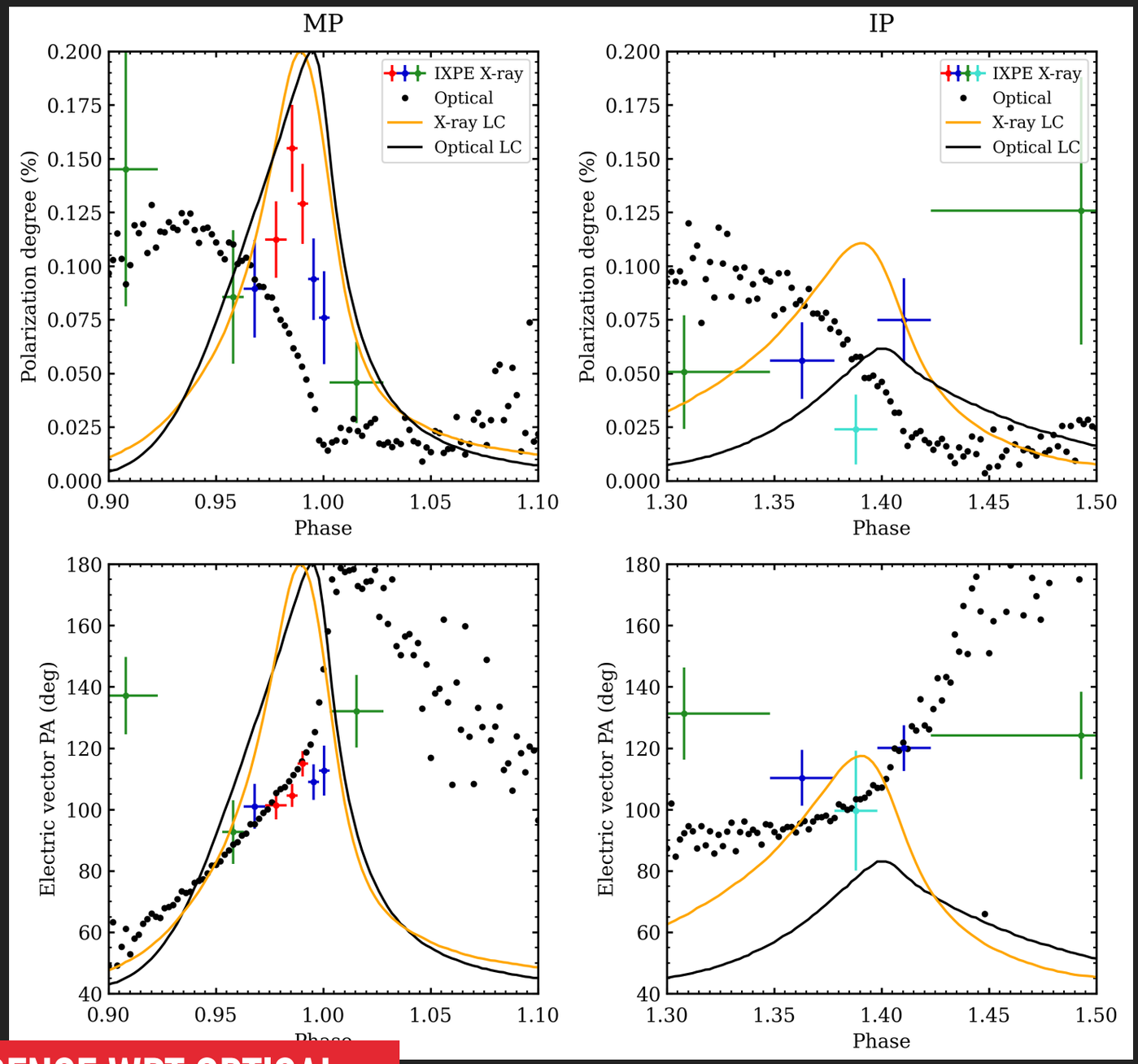


IXPE – CRAB – NEW RESULTS

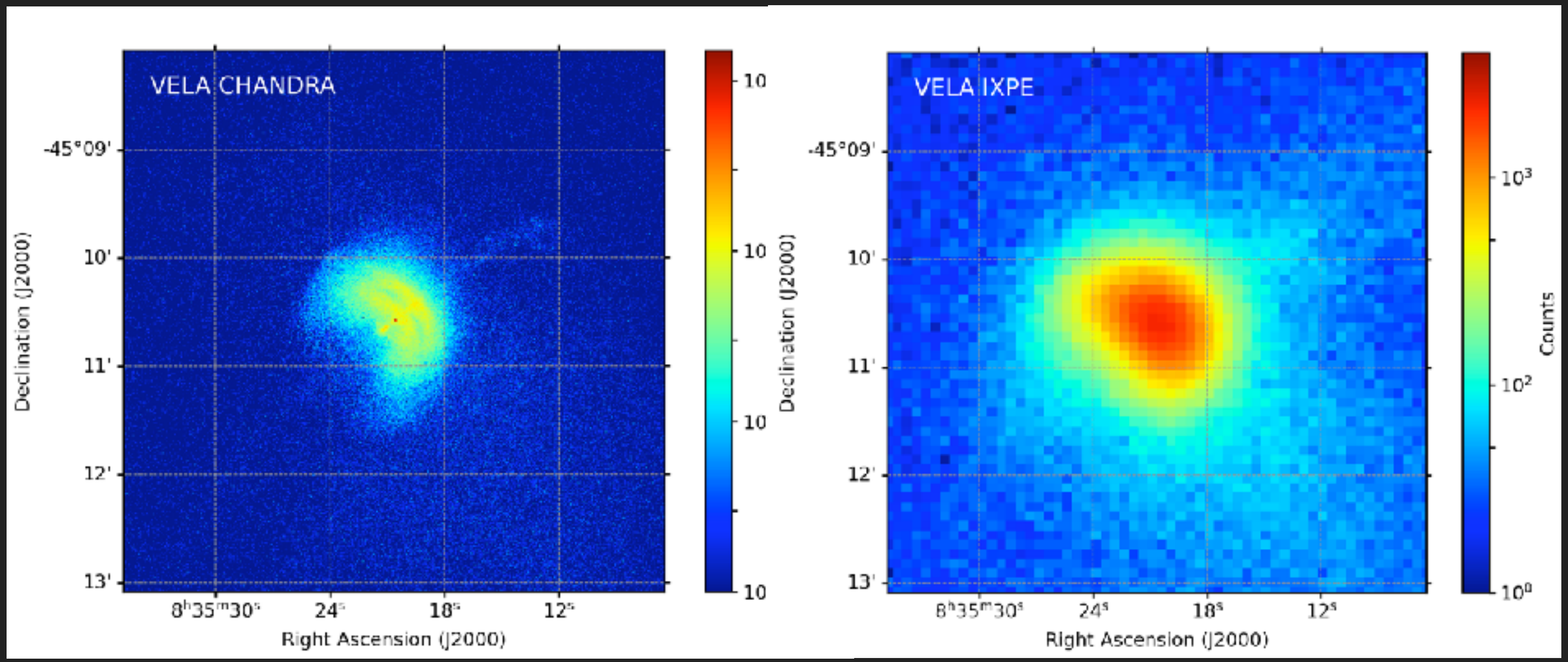


JET POLARISATION SUGGEST TOROIDAL FIELD + KINK



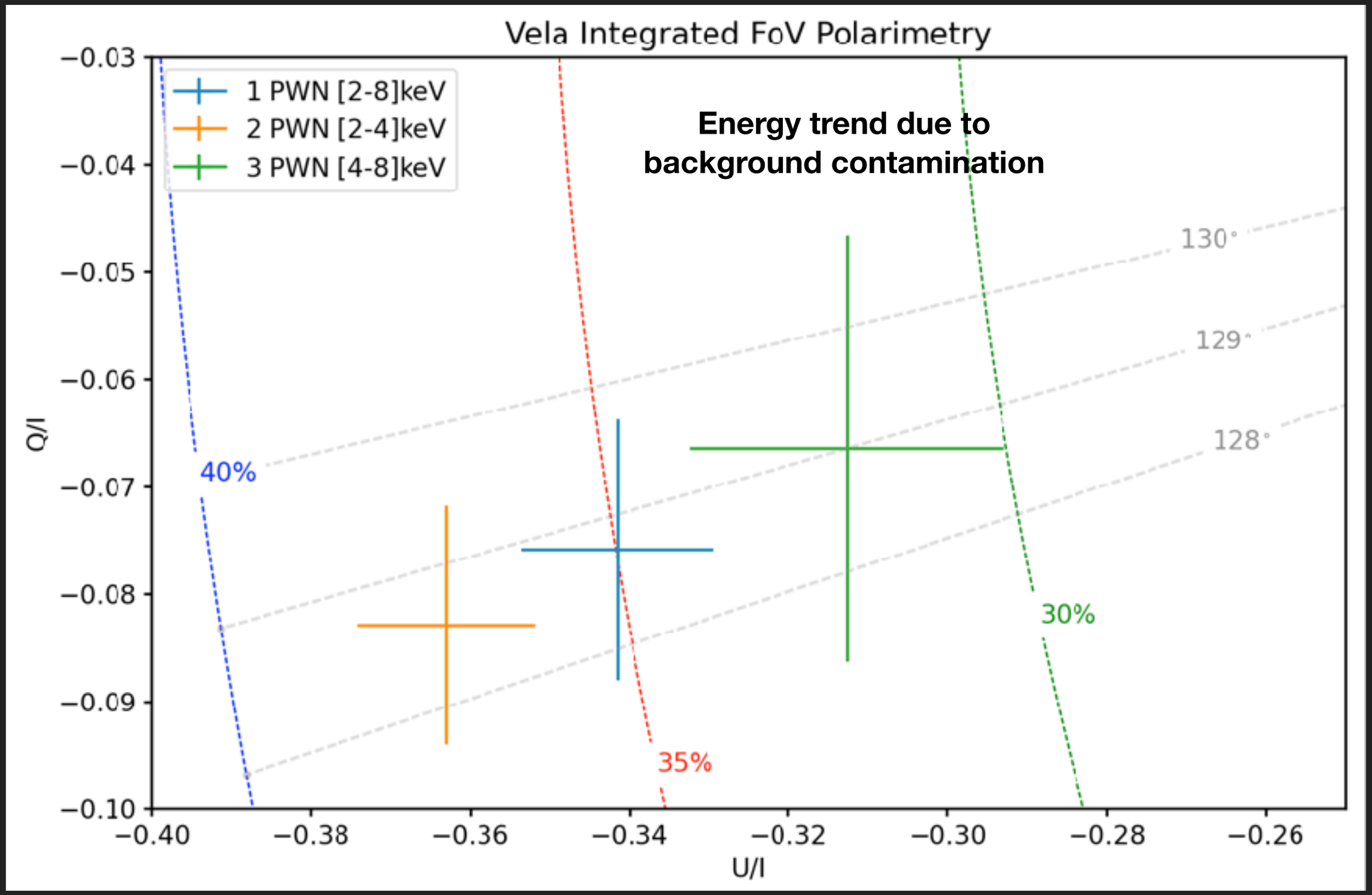
CLEAR DIFFERENCE WRT OPTICAL

IXPE VELA – PWN



Fei et al 2023

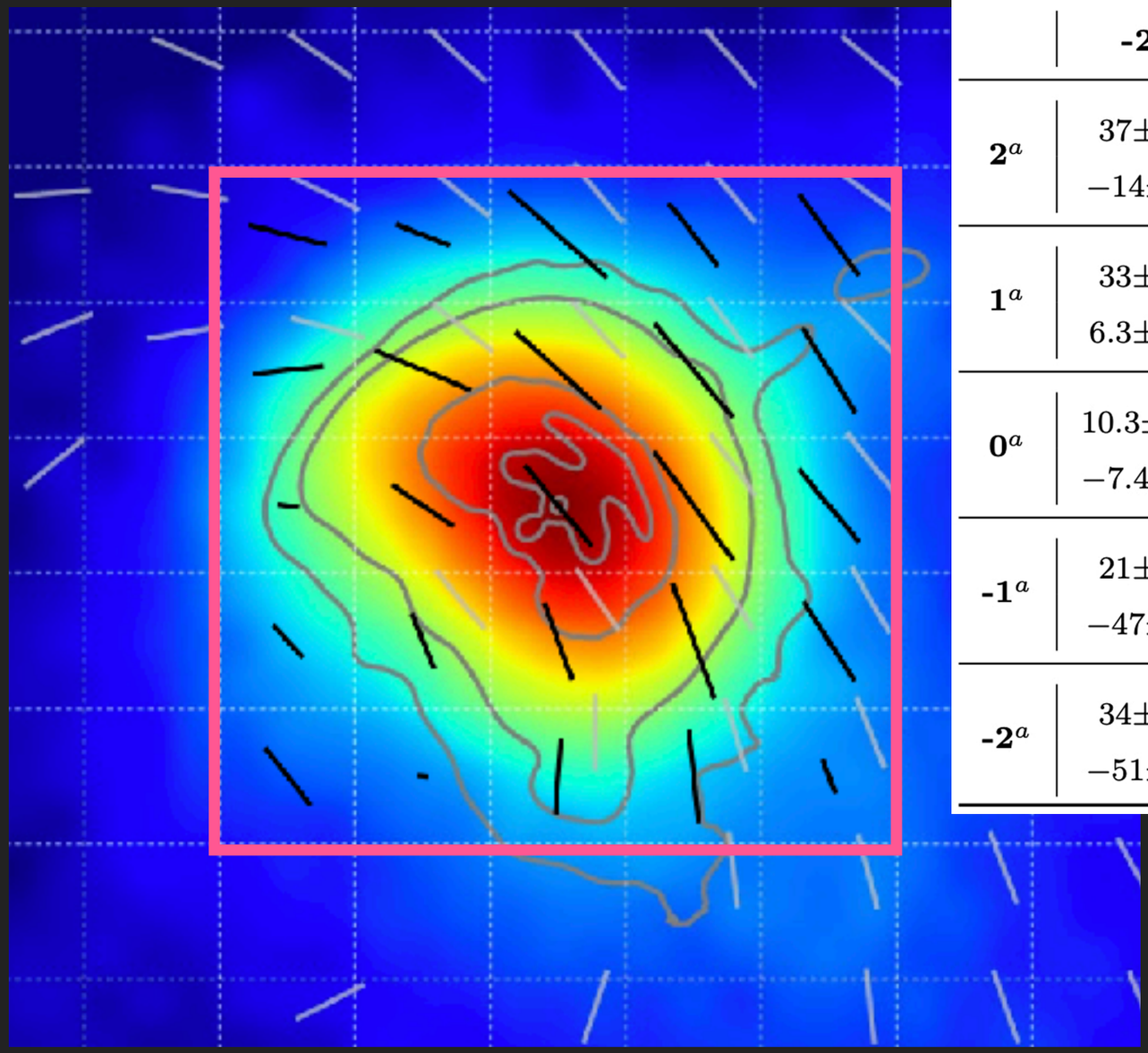
IXPE VELA 2' REGION PWN + BACKGROUND



Fei et al 2023

IXPE - X-RAY POLARIMETRY - VELA

Fei et al 2023



	-2[b]	-1[b]	0[b]	1[b]	2[b]	
2[a]	37±18	27±13	61±12	37±13	47±15	PD[c]
	−14±14	−21±14	−41.7±5.3	−52±10	−53.8±8.9	PA[d]
1[a]	33±10	48.5±5.0	53.5±4.1	56.8±7.1	47±13	PD[c]
	6.3±9.0	−22.4±3.0	−42.2±2.2	−50.2±3.6	−58.2±7.7	PA[d]
0[a]	10.3±8.8	34.4±3.9	49.0±2.5	62.8±4.0	44±11	PD[c]
	−7.4±24	−34.3±3.3	−50.3±1.5	−53.9±1.9	−50.5±7.4	PA[d]
-1[a]	21±12	27.5±7.2	38.5±4.0	57.1±5.4	44±12	PD[c]
	−47±17	−68.3±7.5	−70.0±3.0	−69.8±2.7	−57.3±7.9	PA[d]
-2[a]	34±15	$4.5^{+13}_{-4.5}$	34.9±9.5	43±12	17±14	PD[c]
	−51±13	−6.0±85	86.1±7.8	−84.2±7.6	−70±23	PA[d]

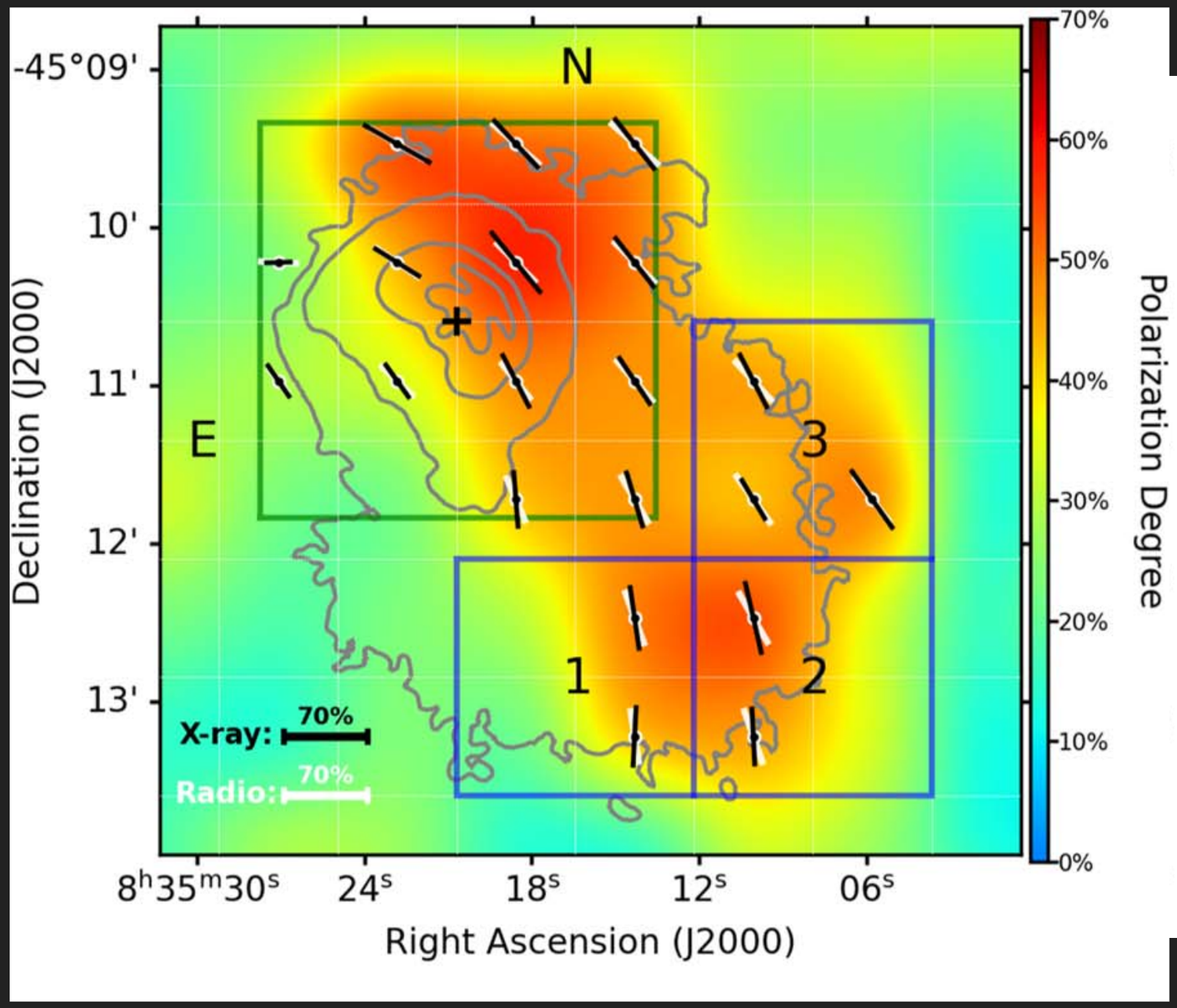
Very high PF suggest no turbulence in the PWNe

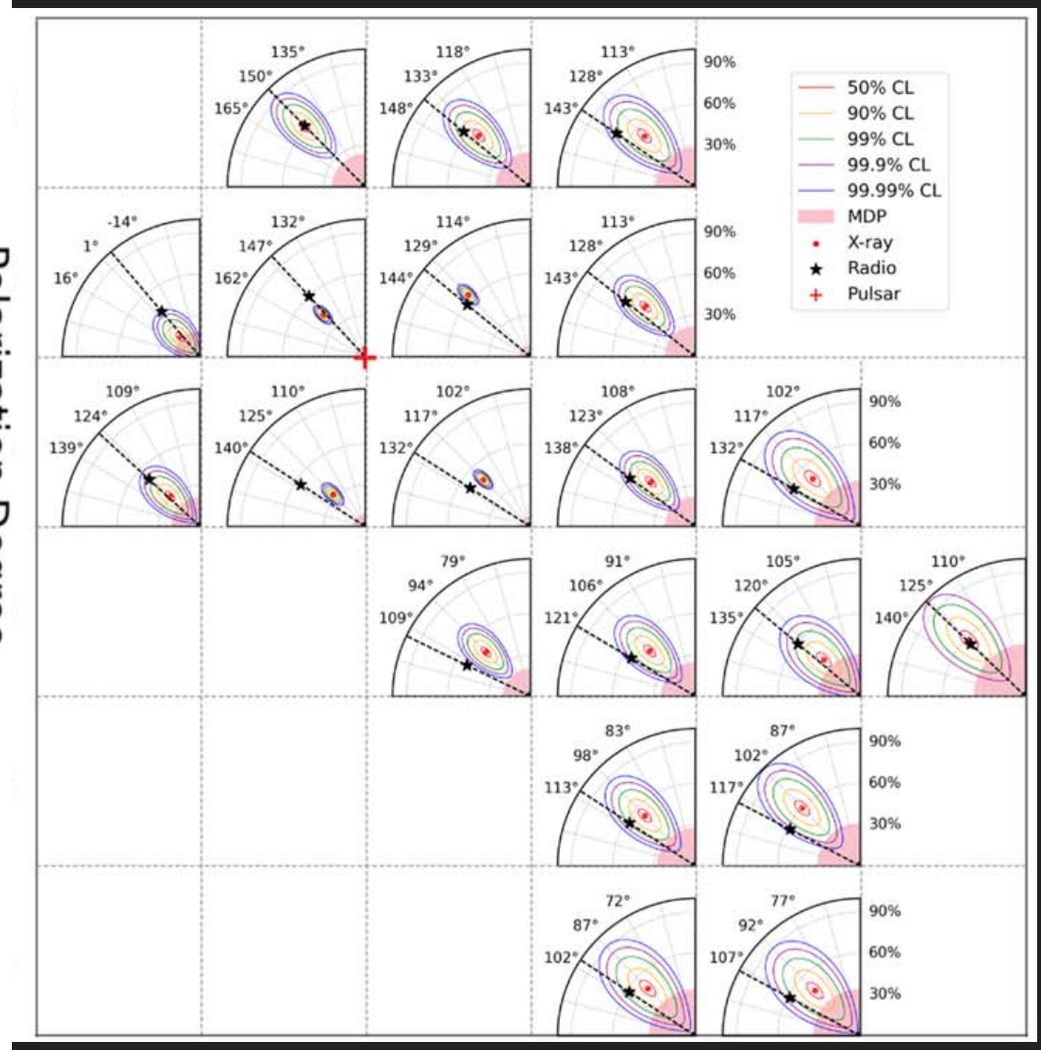
Unlikely reconnection to play a major role in accelerating particles

Old sytems should be more turbulent.

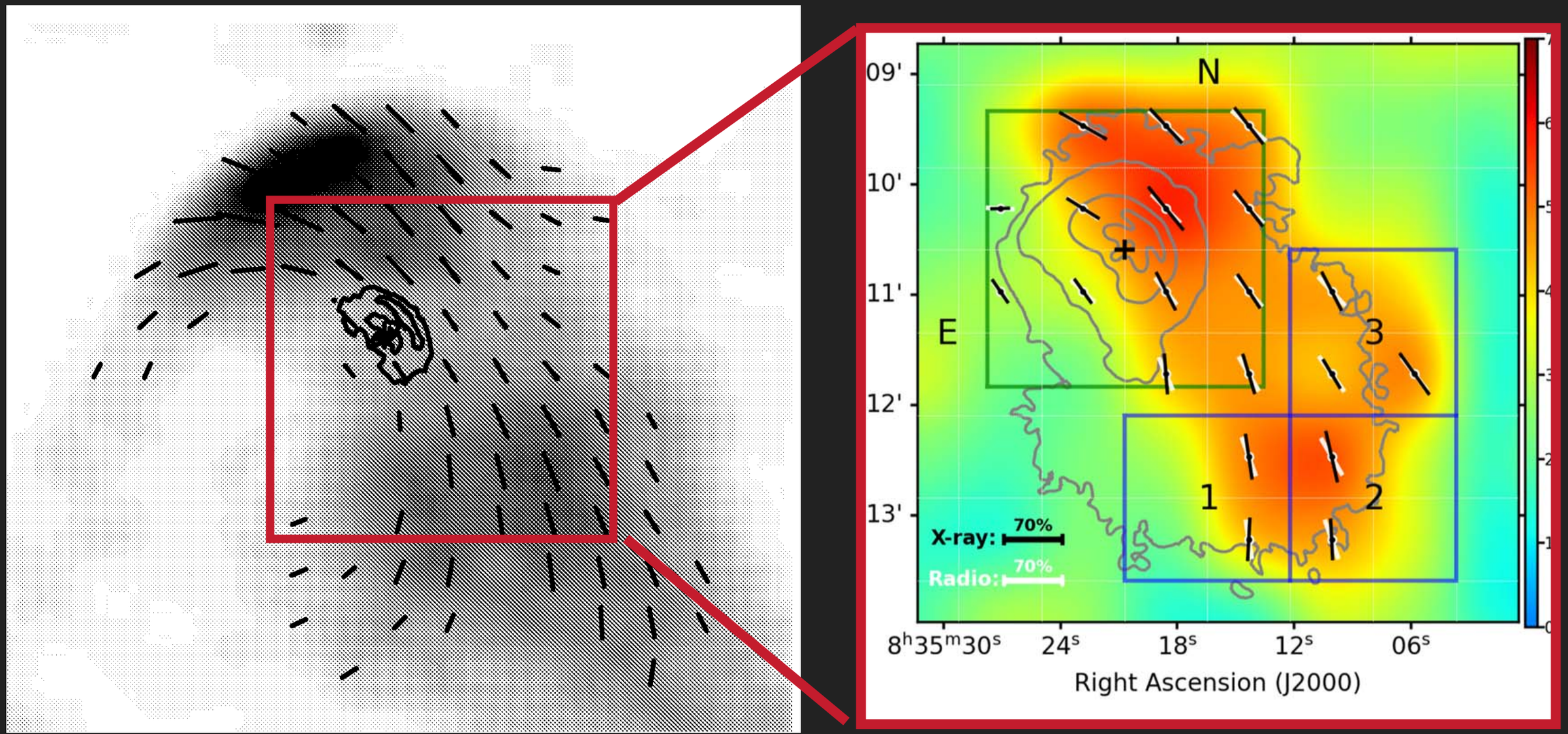
IXPE – X-RAY POLARIMETRY – VELA EXTENDED

Liu et al 2023



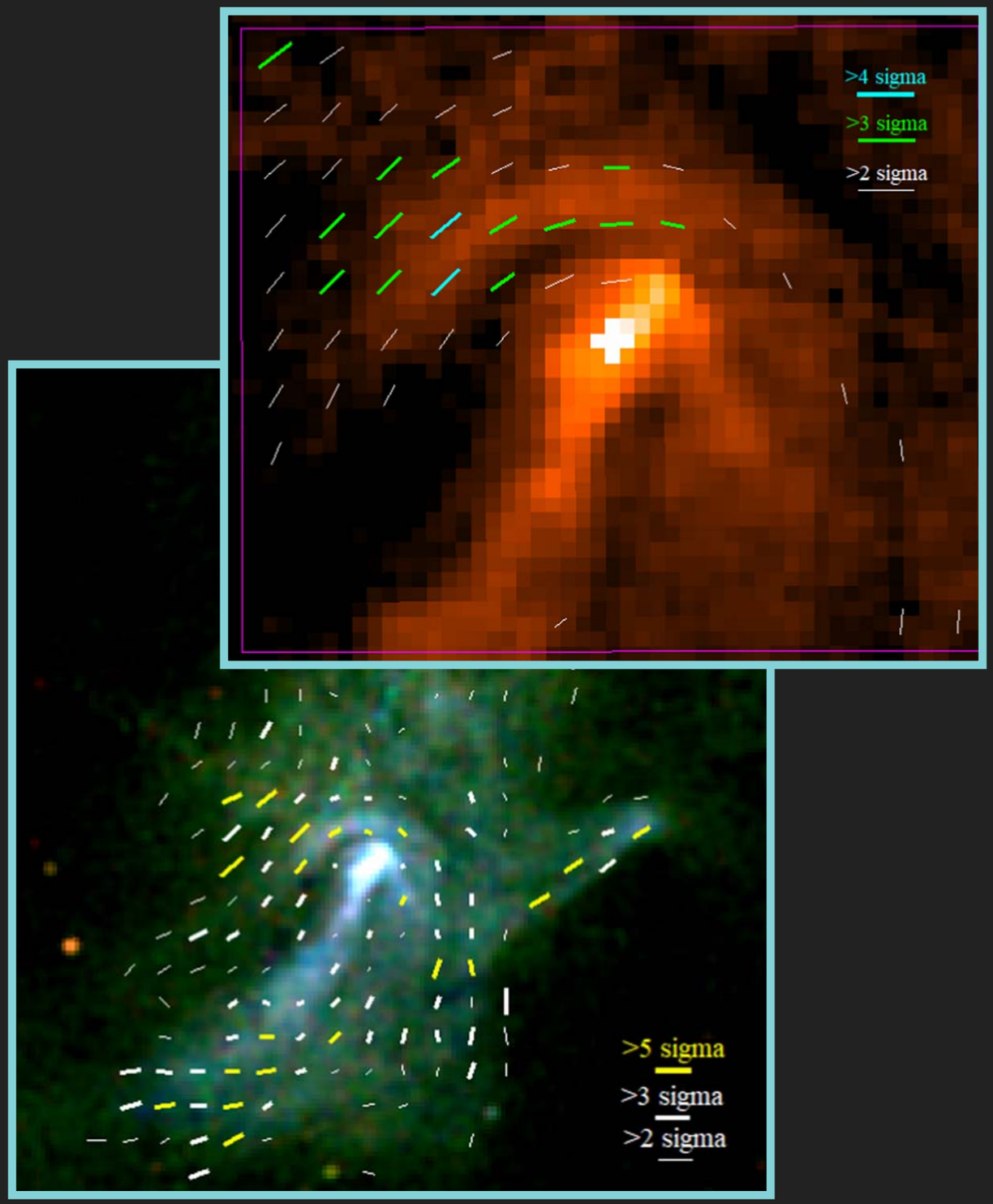


IXPE – VELA – RADIO VS X-RAY



IXPE – X-RAY POLARIMETRY – MSH 15-52

Romani et al 2023

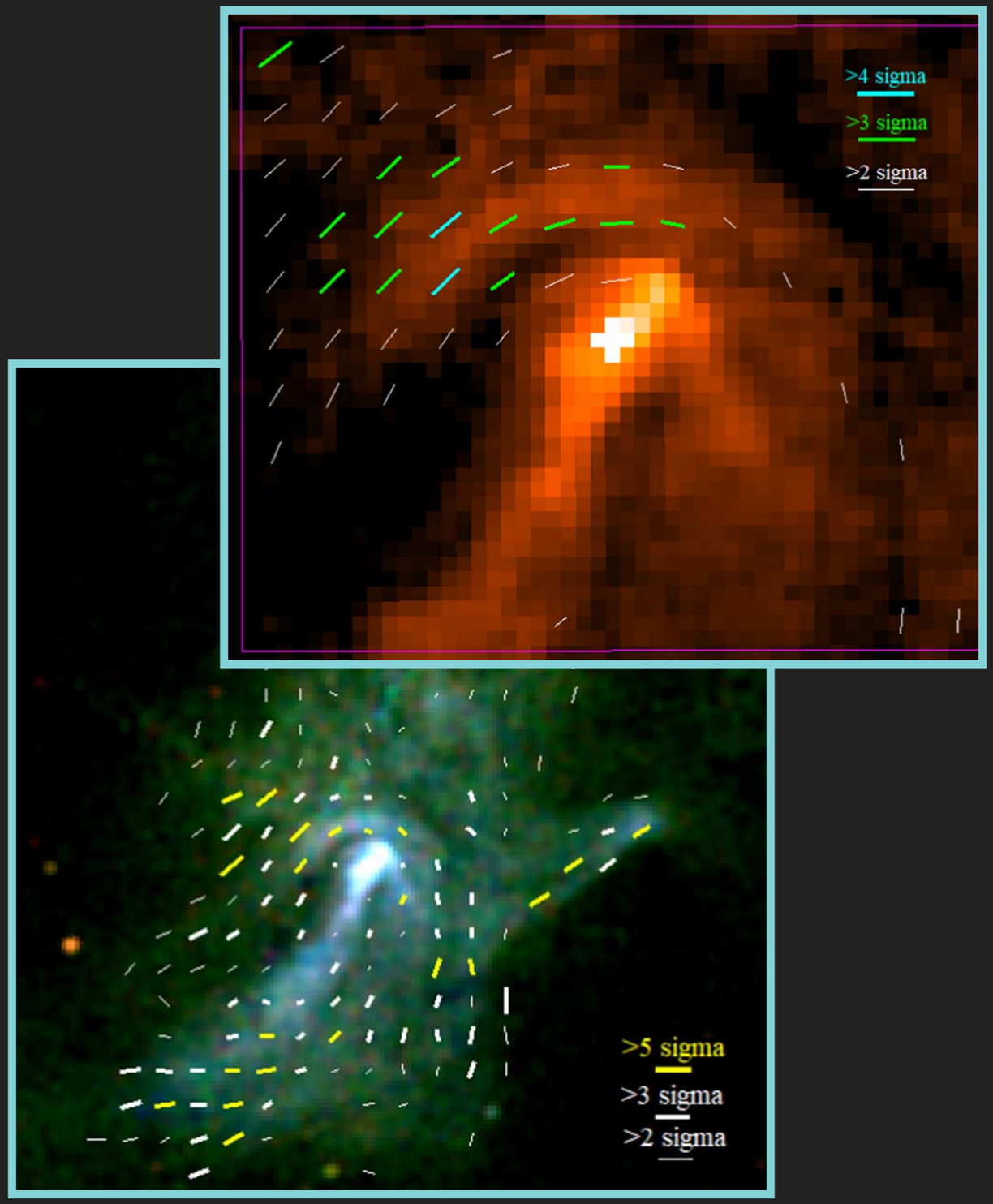


CLEAR EVIDENCE OF HIGH POLARISATION `30% IN THE TORUS

INCREASING LEVEL OF POLARISATION 30% TO 70% FOUND ALONG THE JET
PA NOT ALIGNED

IXPE – X-RAY POLARIMETRY – MSH 15-52

Romani et al 2023



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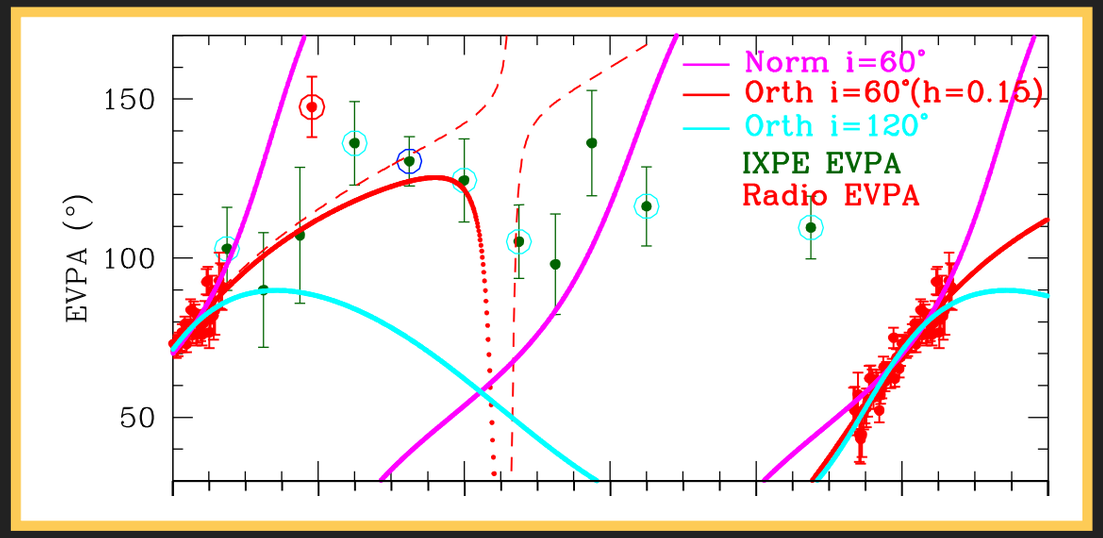
Polarisation of the Pulsed Emission suggest high altitude emission in the PSR magnetosphere



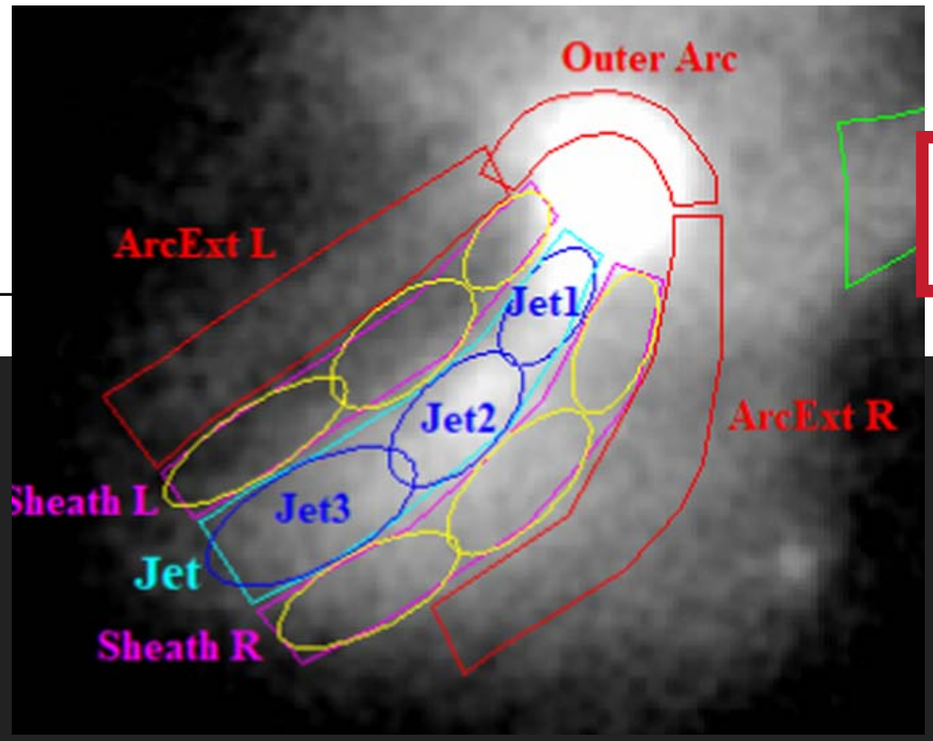
IXPE – X-RAY POLARIMETRY – MSH 15-52

Romani et al 2023

Table 1

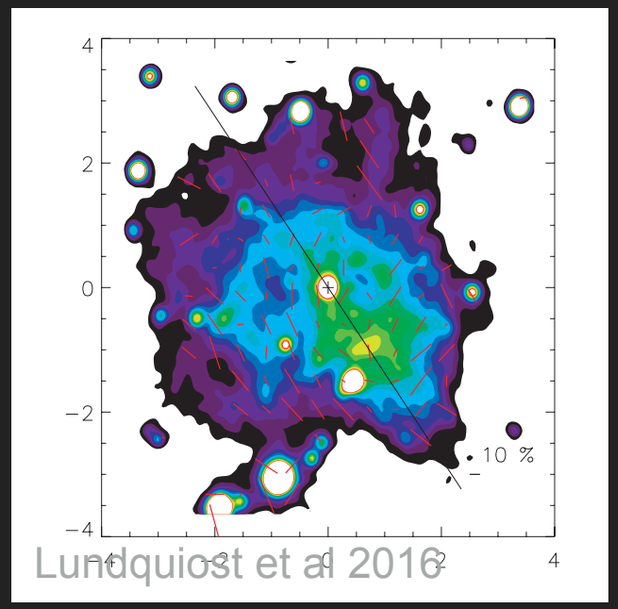
CXO Spectral Measurements and IXPE PCUBE Polarizations for the Regions of Figure 2

Region	Flux (0.5–8 keV)	Γ_X	B_{Eq} (μG)	Q	U	Q, U err	PD	ψ (deg)	Sig
Fingers	26.98	2.35 ± 0.01	21	-0.119	0.114	0.022	0.165 ± 0.022	68.0 ± 3.8	7.5
Index	5.64	2.22 ± 0.01	24	-0.216	0.065	0.044	0.225 ± 0.044	81.7 ± 5.6	5.1
Middle	6.65	2.34 ± 0.01	29	-0.055	0.183	0.043	0.191 ± 0.043	53.3 ± 6.5	4.4
Ring	4.95	2.26 ± 0.02	22	-0.177	0.121	0.050	0.214 ± 0.050	72.8 ± 6.7	4.3
Thumb[b]	6.15	1.92 ± 0.01	16	0.313	-0.085	0.038	0.324 ± 0.038	-7.6 ± 3.4	8.4
Outer arc[b]	6.38	1.87 ± 0.01	27	0.348	-0.020	0.026	0.348 ± 0.026	-1.7 ± 2.1	13.5
ArcExt L	4.10	1.93 ± 0.01	22	0.084	0.412	0.043	0.421 ± 0.043	39.2 ± 2.9	9.7
ArcExt R	9.12	1.84 ± 0.01	16	-0.109	0.075	0.027	0.133 ± 0.027	72.7 ± 5.9	4.9
Jet	15.81	1.69 ± 0.01	18	0.238	0.089	0.021	0.254 ± 0.021	10.2 ± 2.3	12.2
Sheath L	3.47	1.77 ± 0.02	16	-0.001	0.142	0.034	0.142 ± 0.034	45.2 ± 6.9	4.2
Sheath R	9.68	1.80 ± 0.01	20	0.092	0.256	0.025	0.272 ± 0.025	35.1 ± 2.6	11.0
Jet-sheath[a]				0.602	-0.146	0.075	0.620 ± 0.075	-6.8 ± 3.4	8.3
J1	4.58	1.64 ± 0.01					0.173 ± 0.037	43.1 ± 6.1	4.7
J2	6.54	1.74 ± 0.01					0.278 ± 0.035	3.5 ± 3.6	8.0
J3	4.59	1.67 ± 0.01					0.469 ± 0.041	3.2 ± 2.5	11.5
J1-Sh1[a]							0.307 ± 0.109	11.8 ± 10.1	2.8
J2-Sh2[a]							0.602 ± 0.090	-14.6 ± 4.3	6.7
J3-Sh3[a]							0.831 ± 0.159	-5.0 ± 5.3	5.2

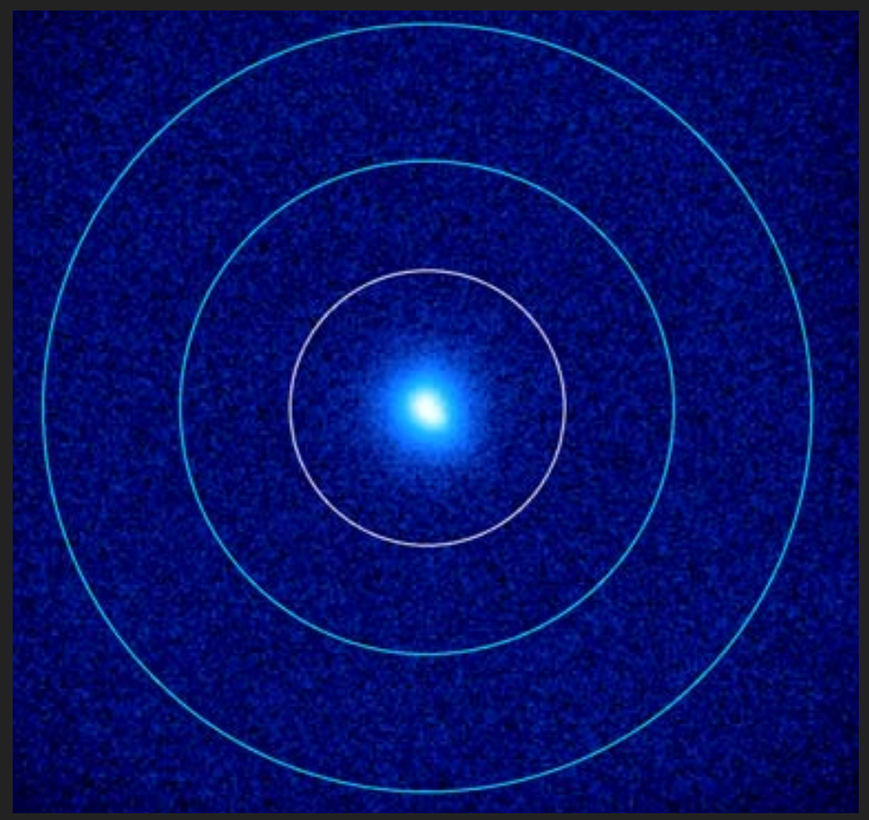


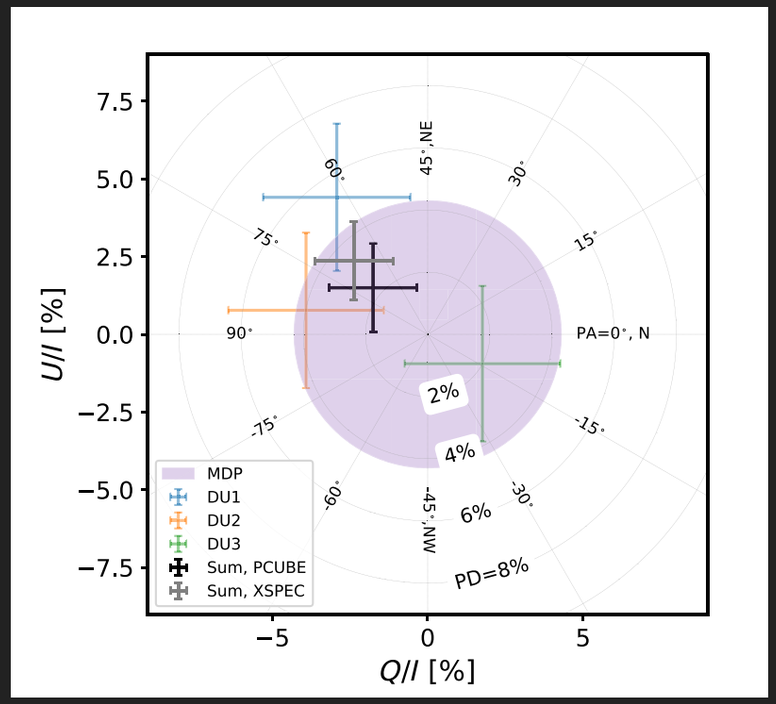
IXPE – X-RAY POLARIMETRY – SNR B0540

Fei et al 2023



Lundquist et al 2016





Optical PWN PD ~ 6% (max 30%)
PSR PD ~ 6-16%

X-ray PWN PD ~25% in agreement wrt Optical

X-ray PSR PD~50% seems anti-aligned wrt nebular axis

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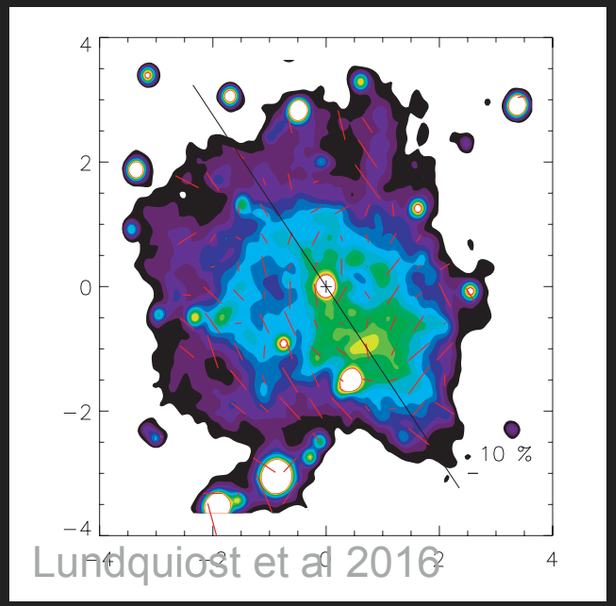
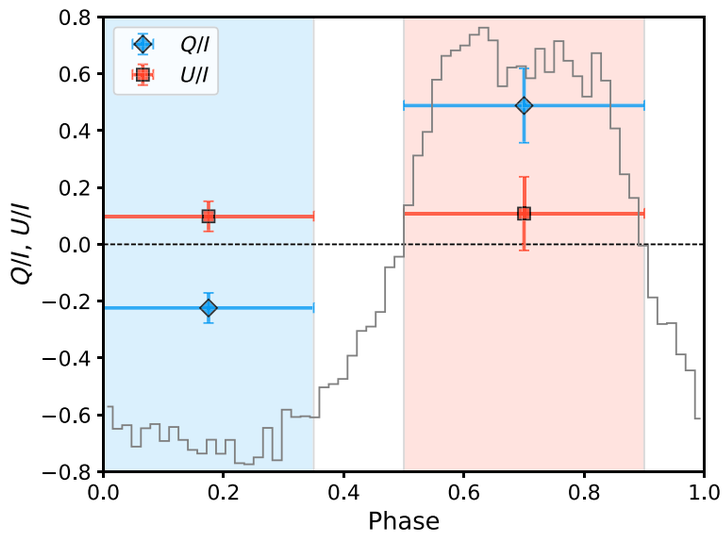
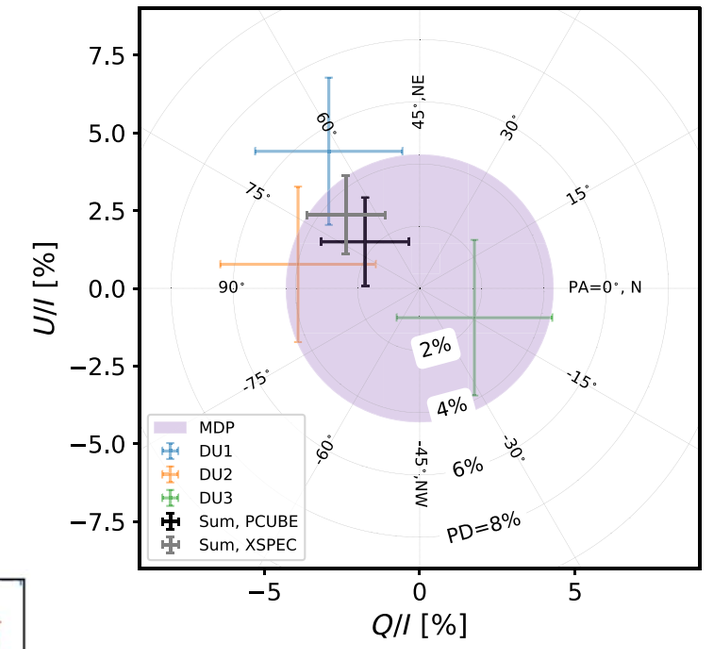
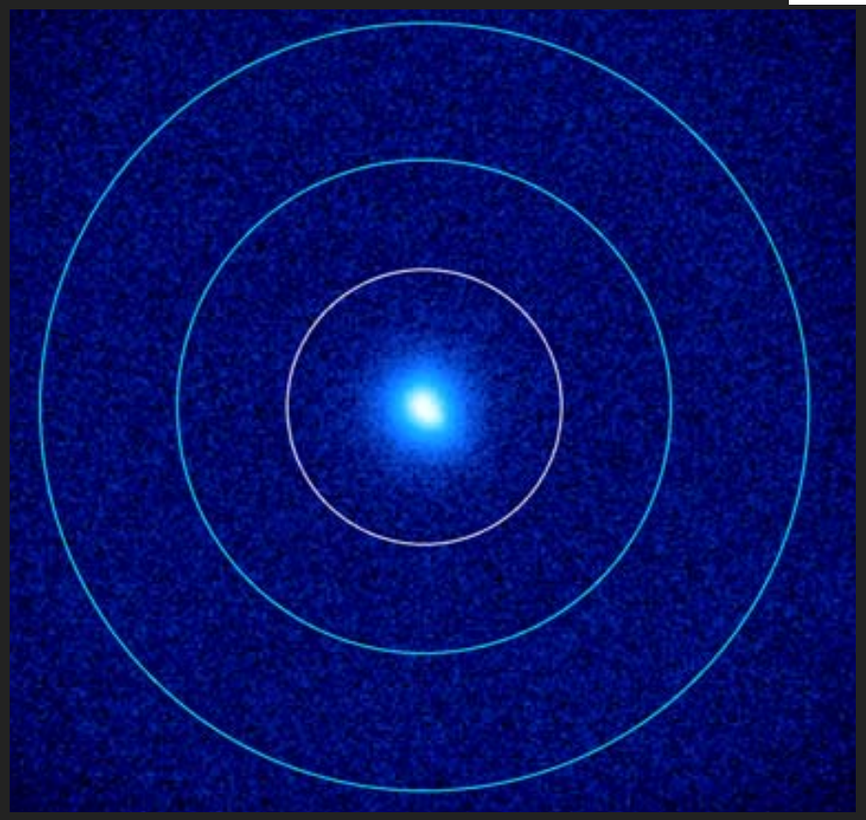
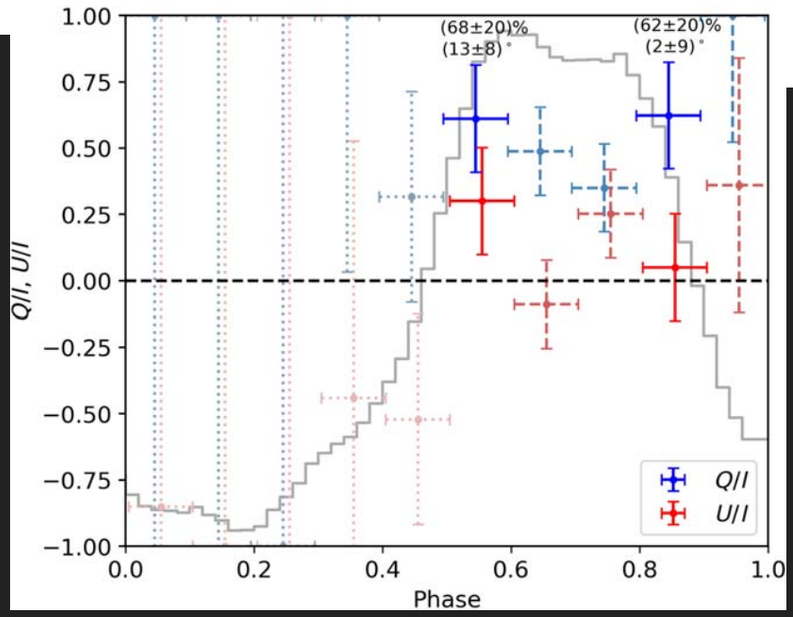


Lundquist et al 2016









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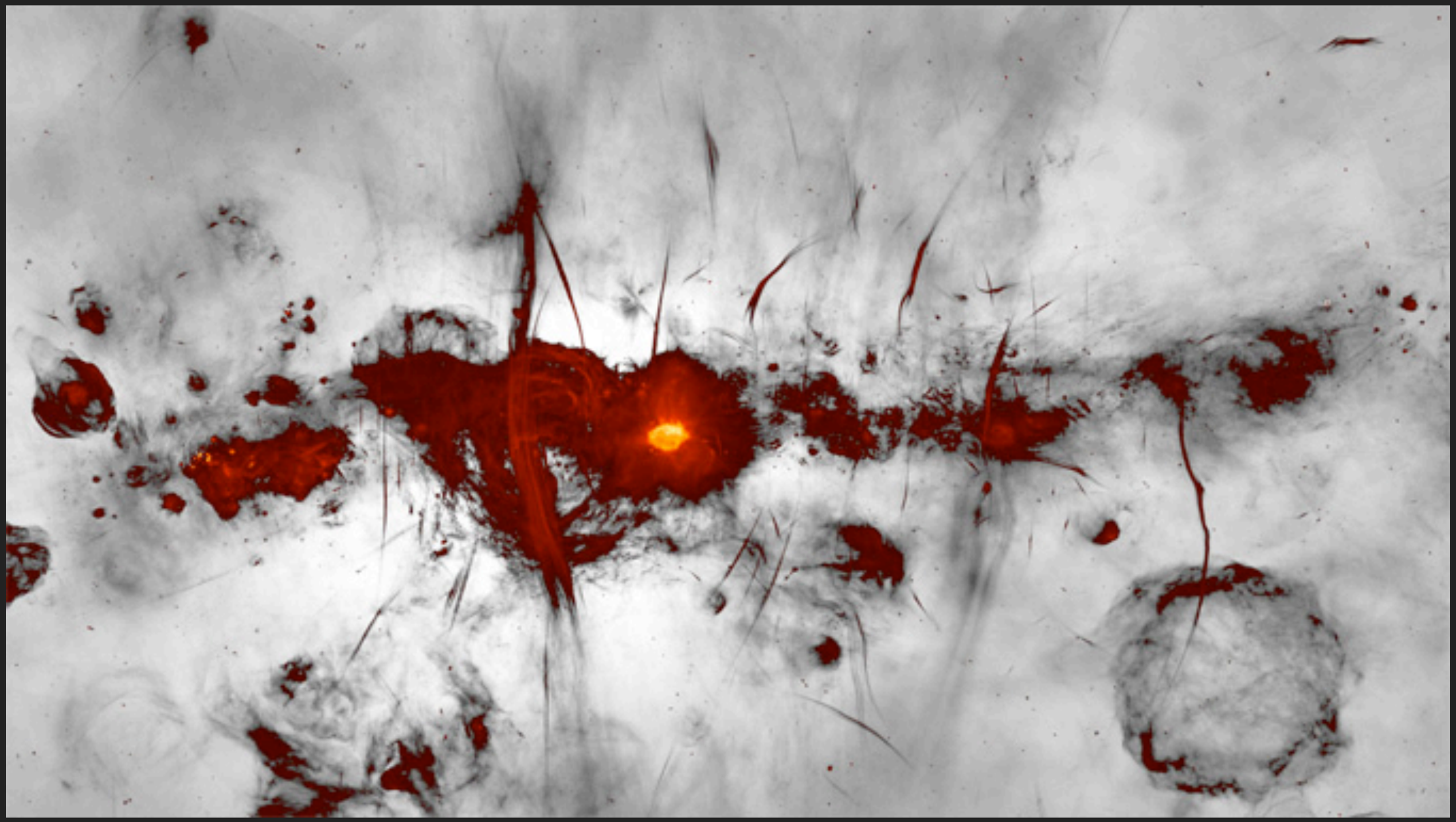
IXPE – X-RAY POLARIMETRY – G 0.13–0.11



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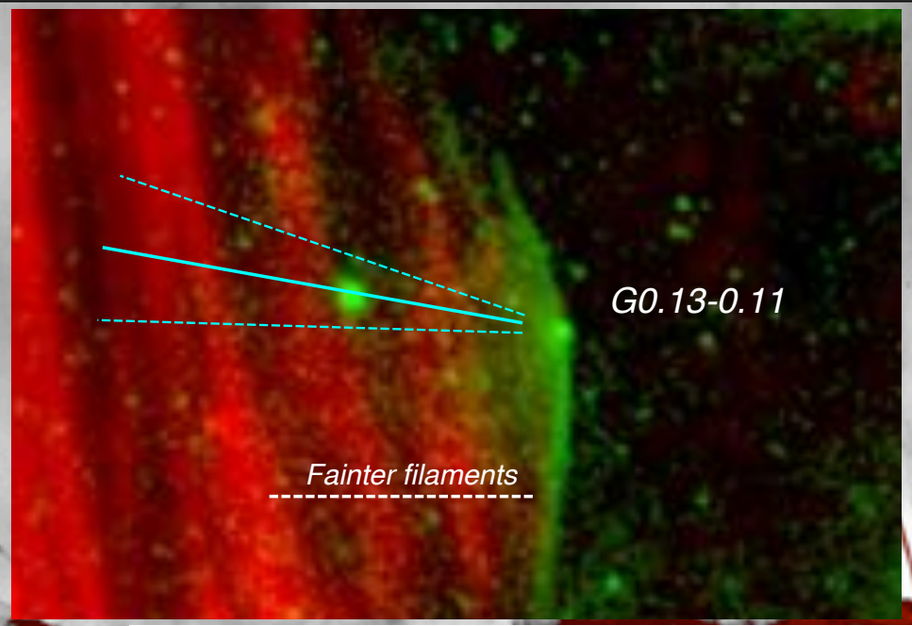

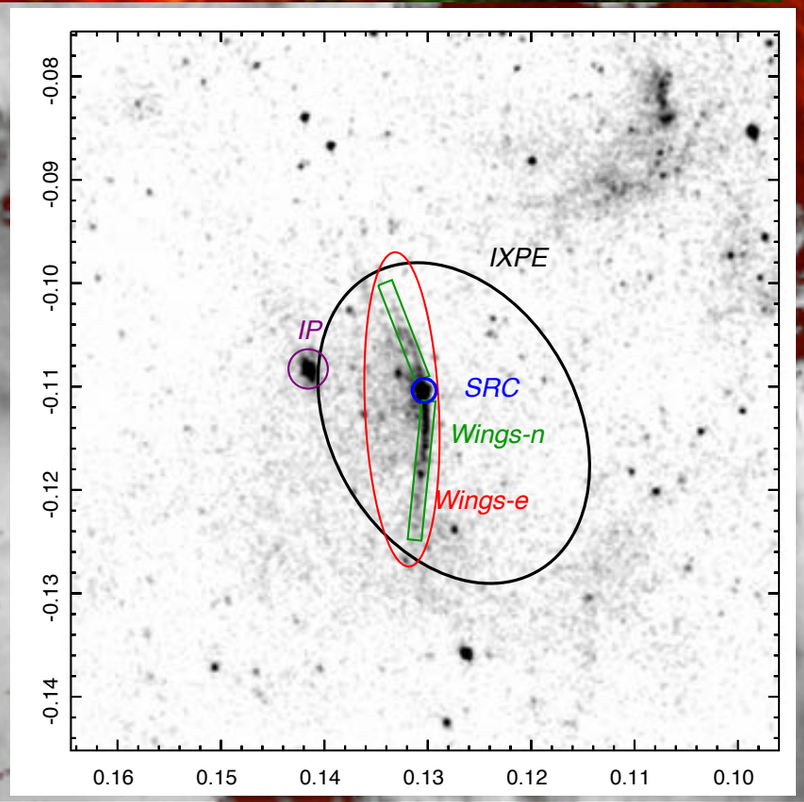

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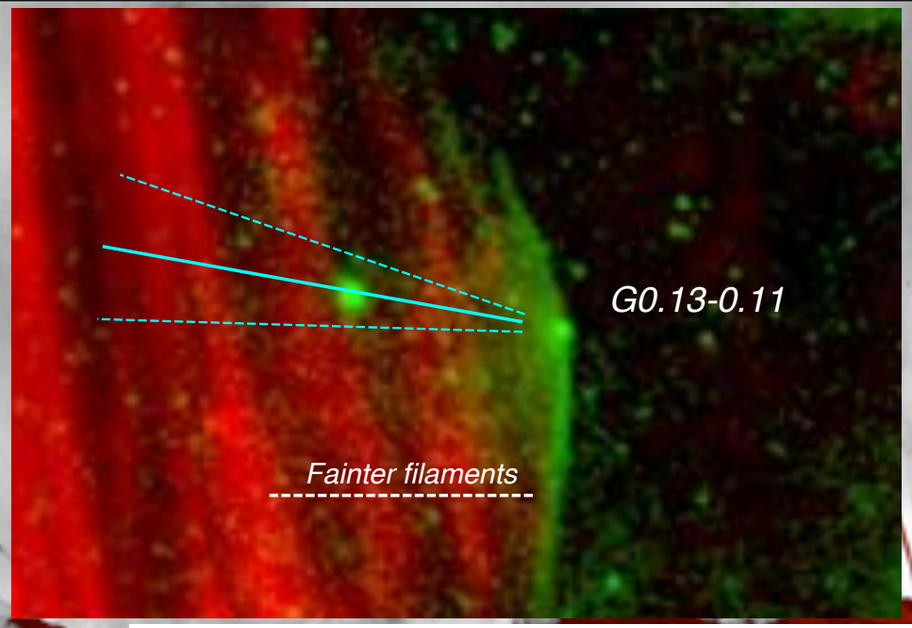

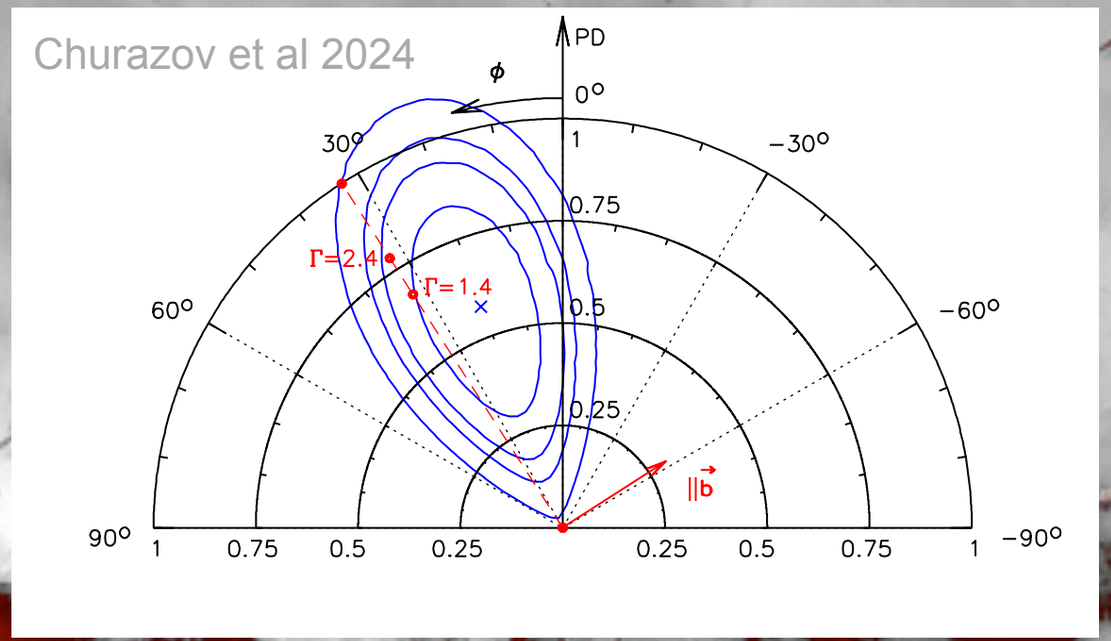

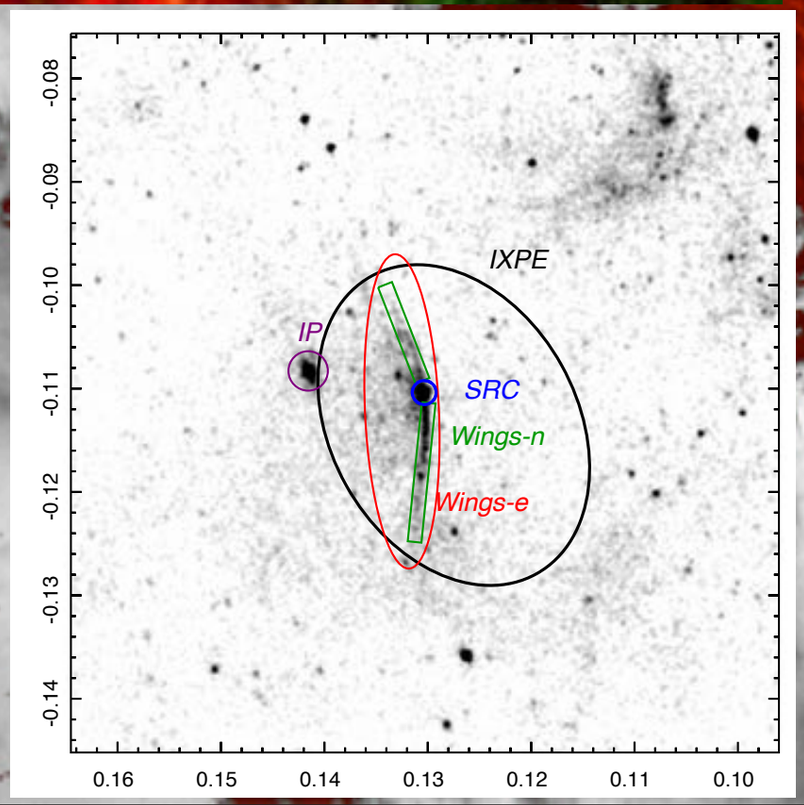

POLARIZATION DEGREE ~ 57%
MAGNETIC FIELD ALIGNED TO THE FEAATURE

CLEAR EVIDENCE FOR THE SUNCHOTRON ORIGIN OF THIS FEATURE

CONCLUSIONS

CURRENT CANONICAL PICTURE WELL ESTABLISHED

NO CLEAR IDENTIFICATION FOR THE ACCELERATION MECHANISM

NO CLEAR INDICATION FOR THE ORIGIN OF THE OBSERVED FLARING

NO GOOD UNDERSTANDING OF THE LEVEV AND ROLE OF TURBULENCE

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NEED BETTER MODELS FOR INTERNAL DYNAMICS (3D PROIBITIVE)

DOES A UNIFIED MODEL MAKE SENSE?