IXPE STUDIES OF PULSARS AND THEIR NEBULAE

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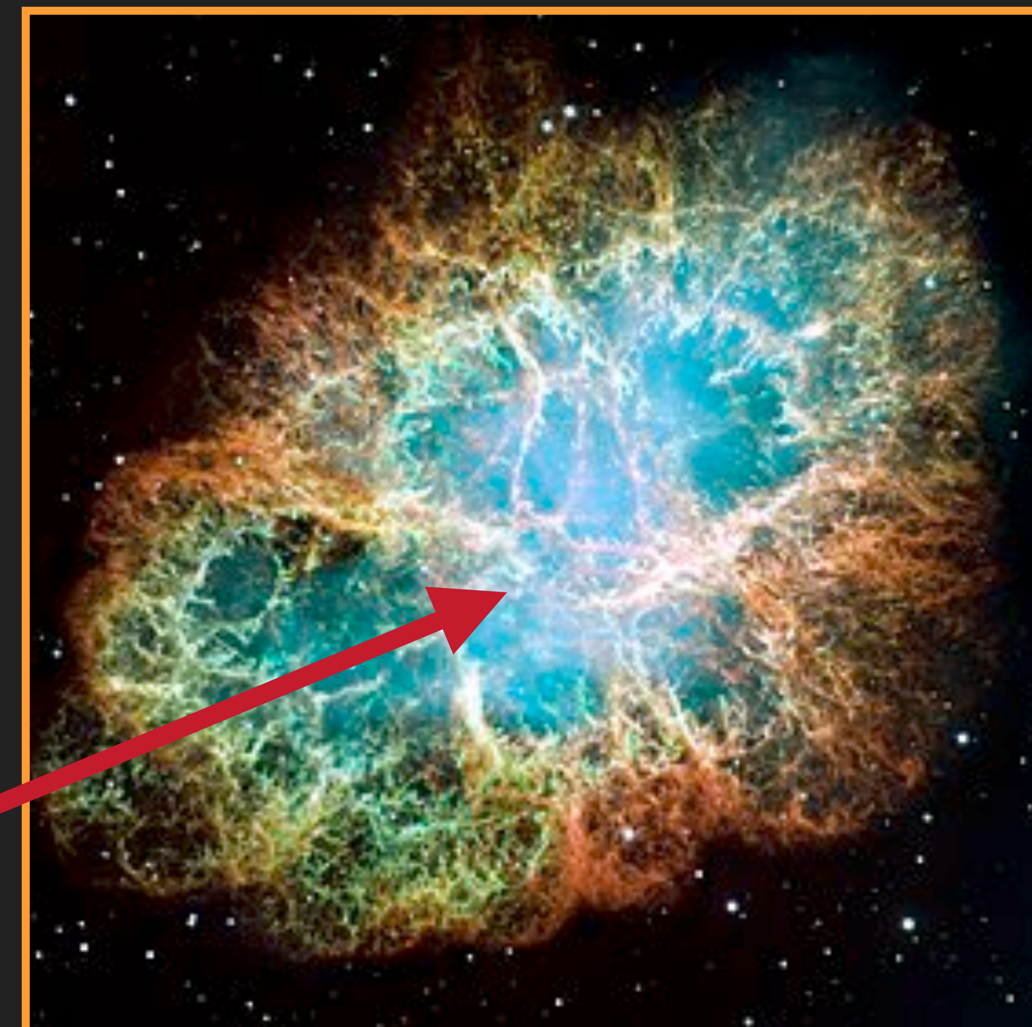
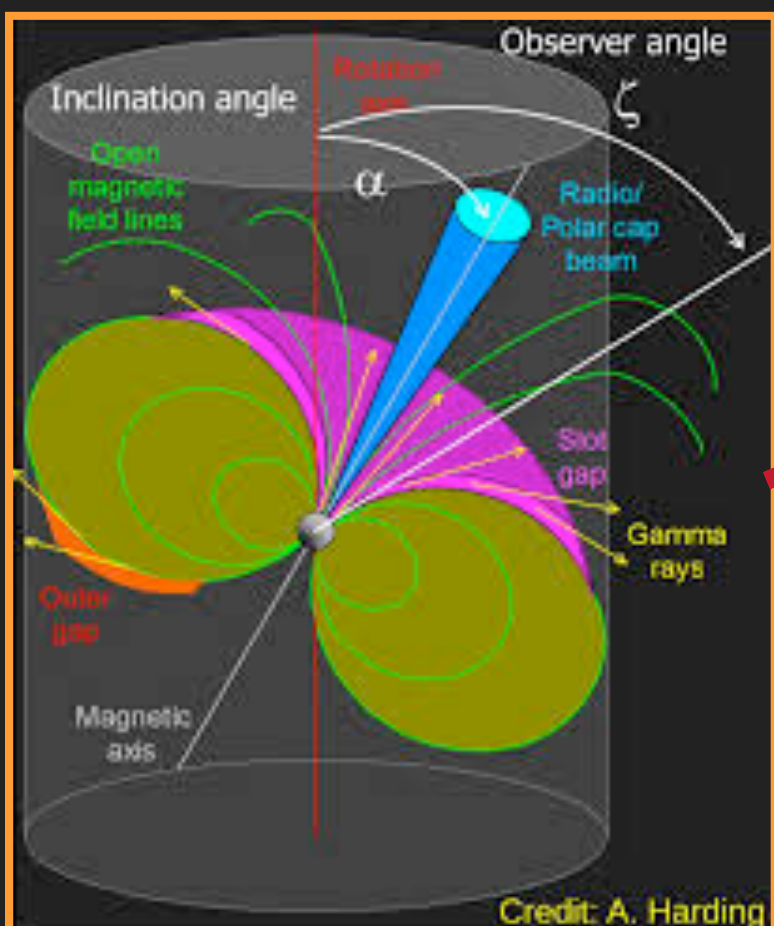
INAF ARCETRI - UNIV. FIRENZE - INFN

DEATH OF A MASSIVE STAR - BIRTH OF A PULSAR

STARS MORE MASSIVE THAN **8 M_{SUN}** END THEIR LIFE IN SUPERNOVA EXPLOSIONS

STARS LESS MASSIVE THAN 25-30 M_{SUN} LEAVE BEHIND A COMPACT STELLAR REMNANT IN THE FORM OF A NEUTRON STAR





THE COMBINATION OF STRONG MAGNETIC FIELD (10^{12}G) AND RAPID ROTATION (P=0.001-1S) CREATES A STRONG ELECTRIC FIELD AT THE SURFACE, EXTRACTING PAIRS AND PRODUCING **PAIR CASCADES.**
OBSERVED AS PULSARS

PULSAR WIND NEBULAE - PWNE

PWNE ARE HOT BUBBLES OF RELATIVISTIC PARTICLES AND MAGNETIC FIELD: **LAB FOR THE STUDY OF NON-THERMAL RADIATION**

ORIGINATED BY THE INTERACTION OF THE ULTRA-RELATIVISTIC MAGNETISED PULSAR WIND WITH THE EXPANDING SNR: **LAB FOR STELLAR EVOLUTION**

GALACTIC ACCELERATORS. THE ONLY PLACE WHERE WE CAN STUDY THE PROPERTIES OF RELATIVISTIC SHOCKS (AS IN GRBS AND AGNS): **LAB FOR PARTICLE ACCELERATION**

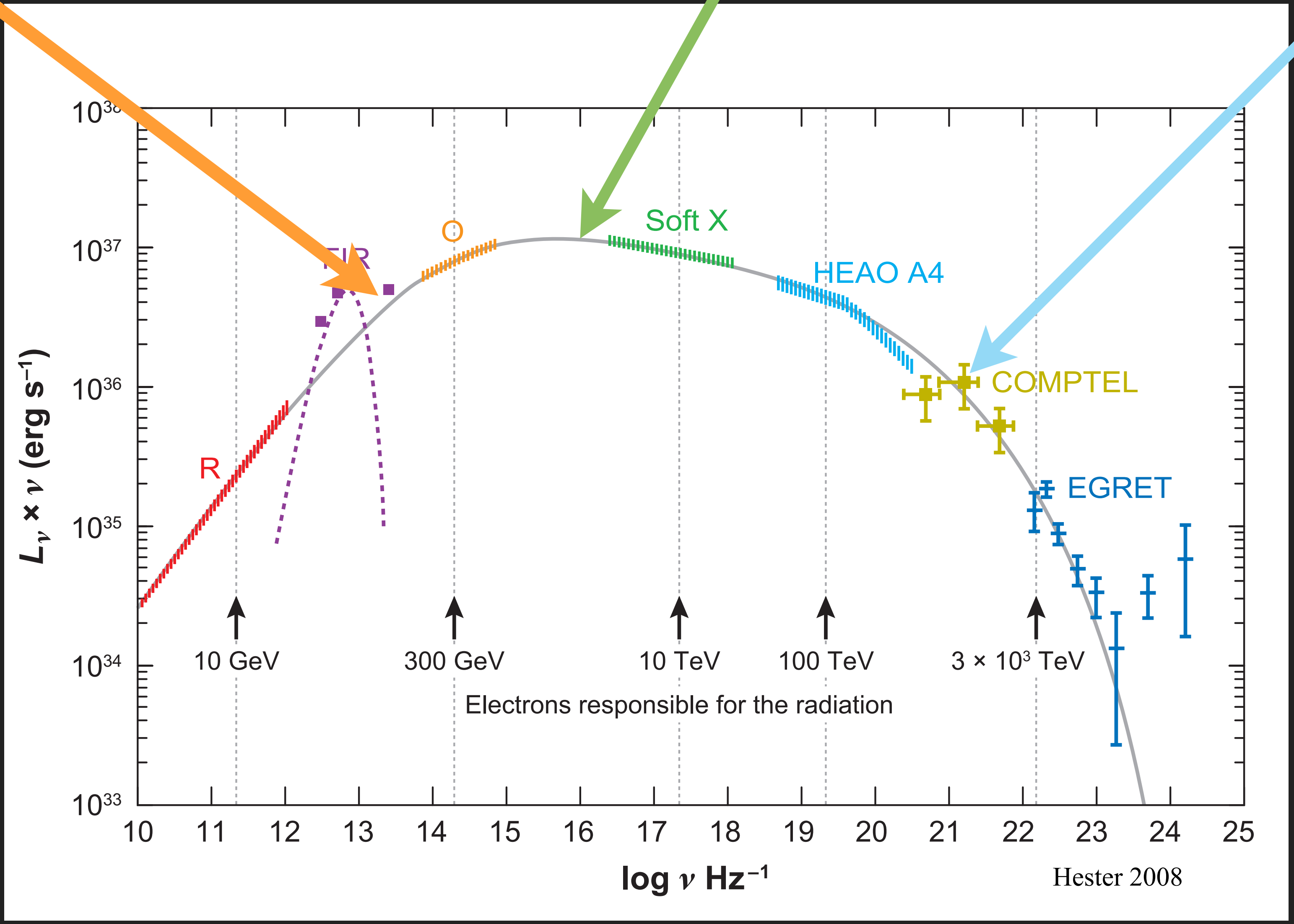
ALLOW US TO INVESTIGATE THE DYNAMICS OF RELATIVISTIC OUTFLOWS: **LAB FOR RELATIVISTIC FLUIDS**

PWNE AS NON-THERMAL ACCELERATORS

Low energy break

High energy break

MeV cutoff



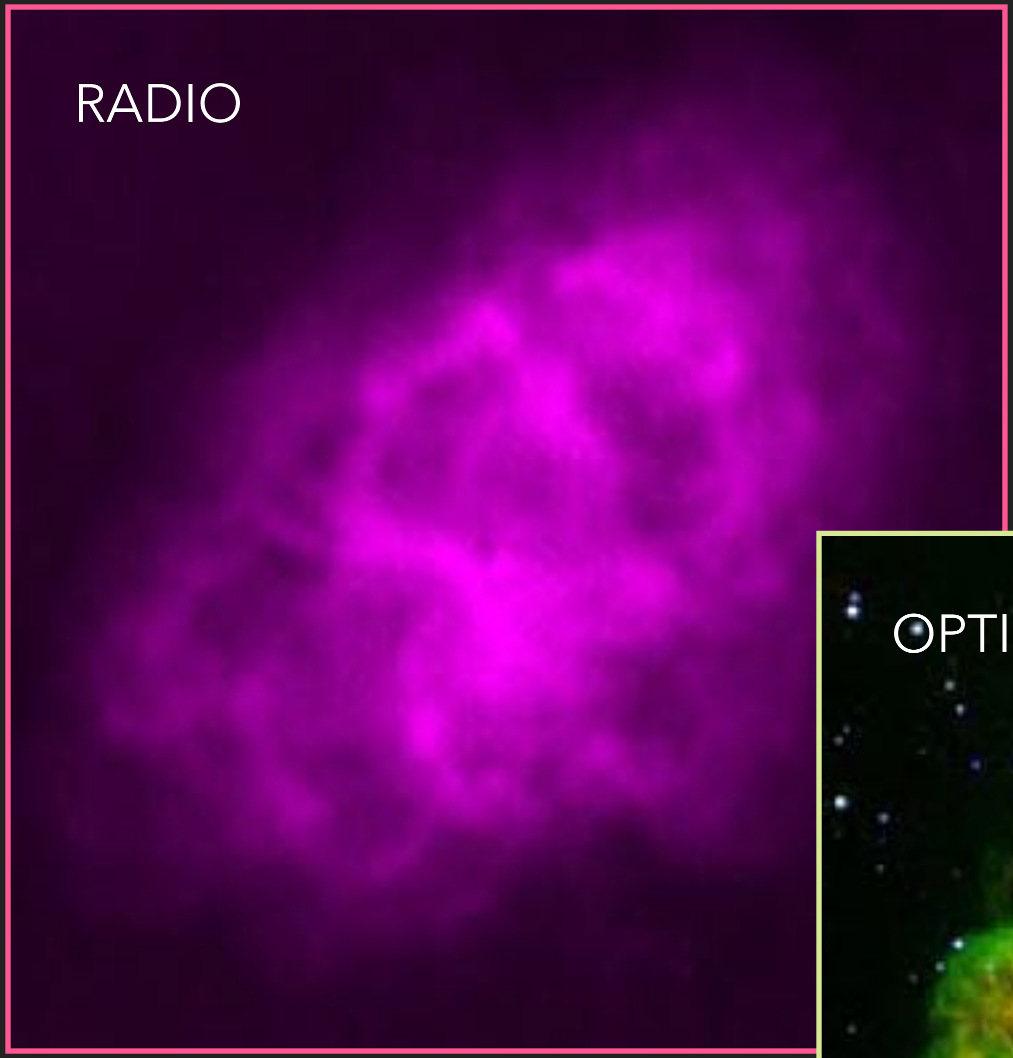
Injection Break

Synchr. cooling

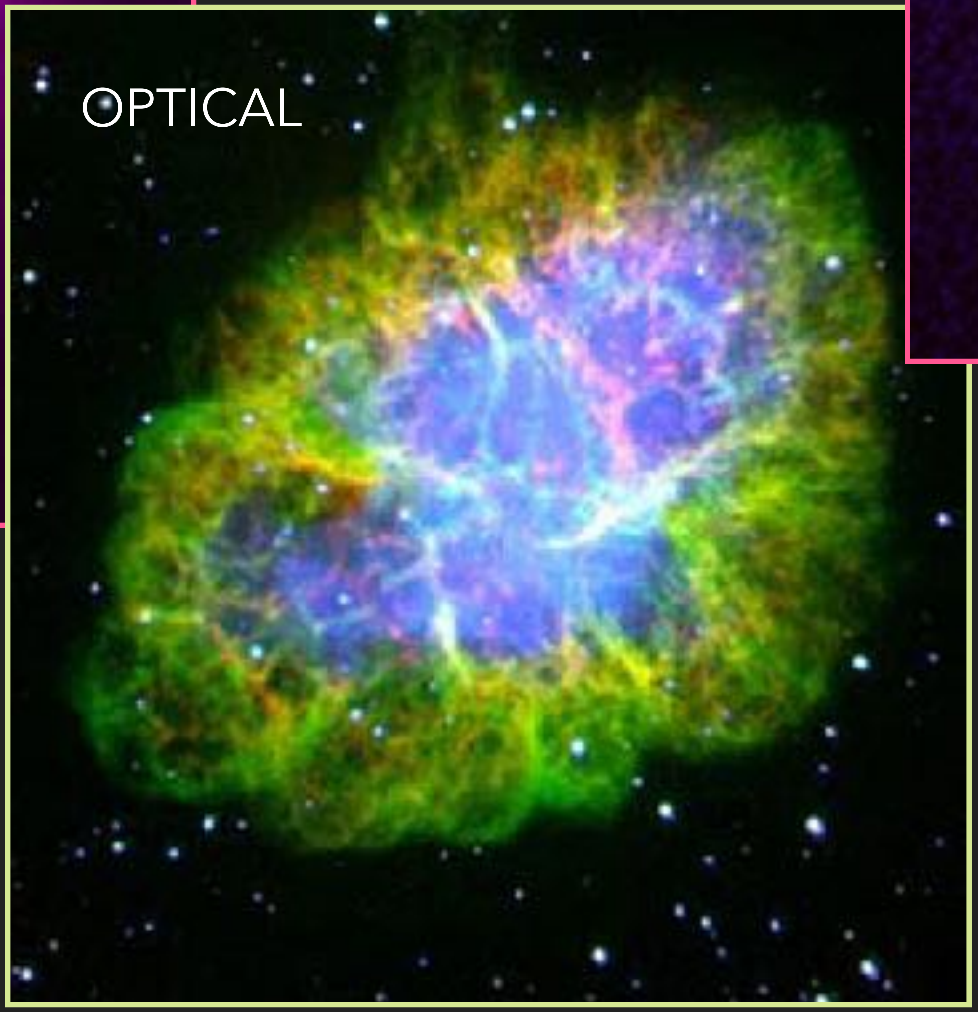
Acceler. cutoff

The most efficient non-thermal accelerator.

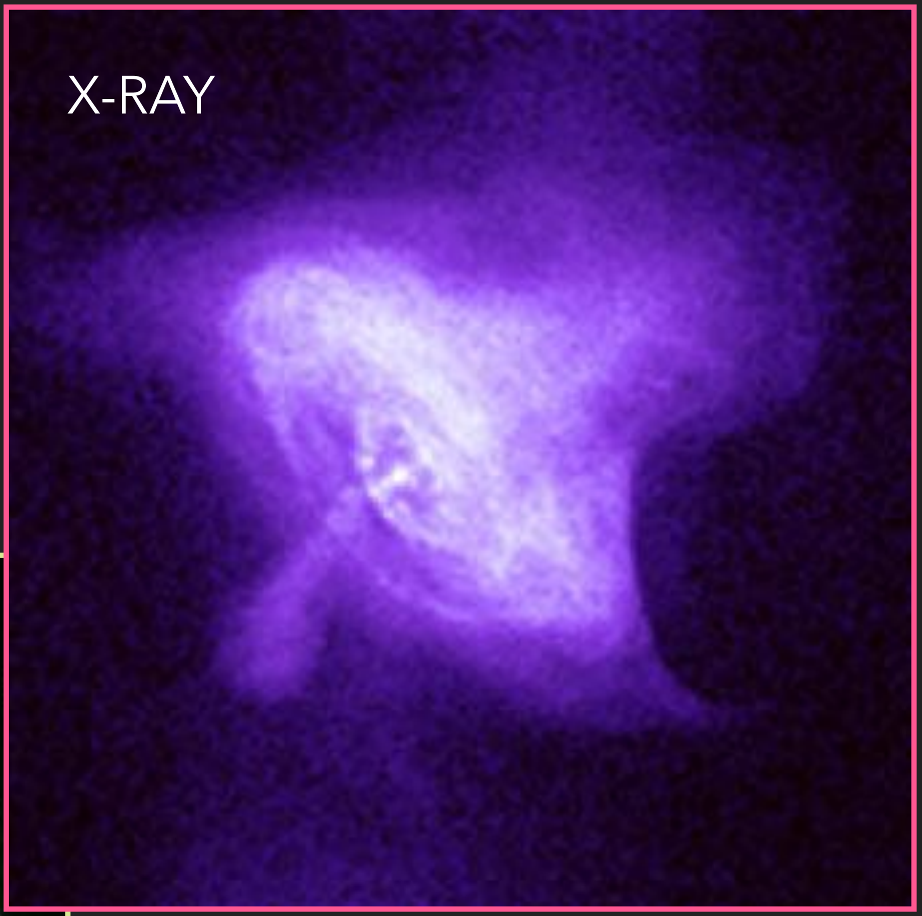
PWNE AT DIFFERENT ENERGIES



NON-THERMAL

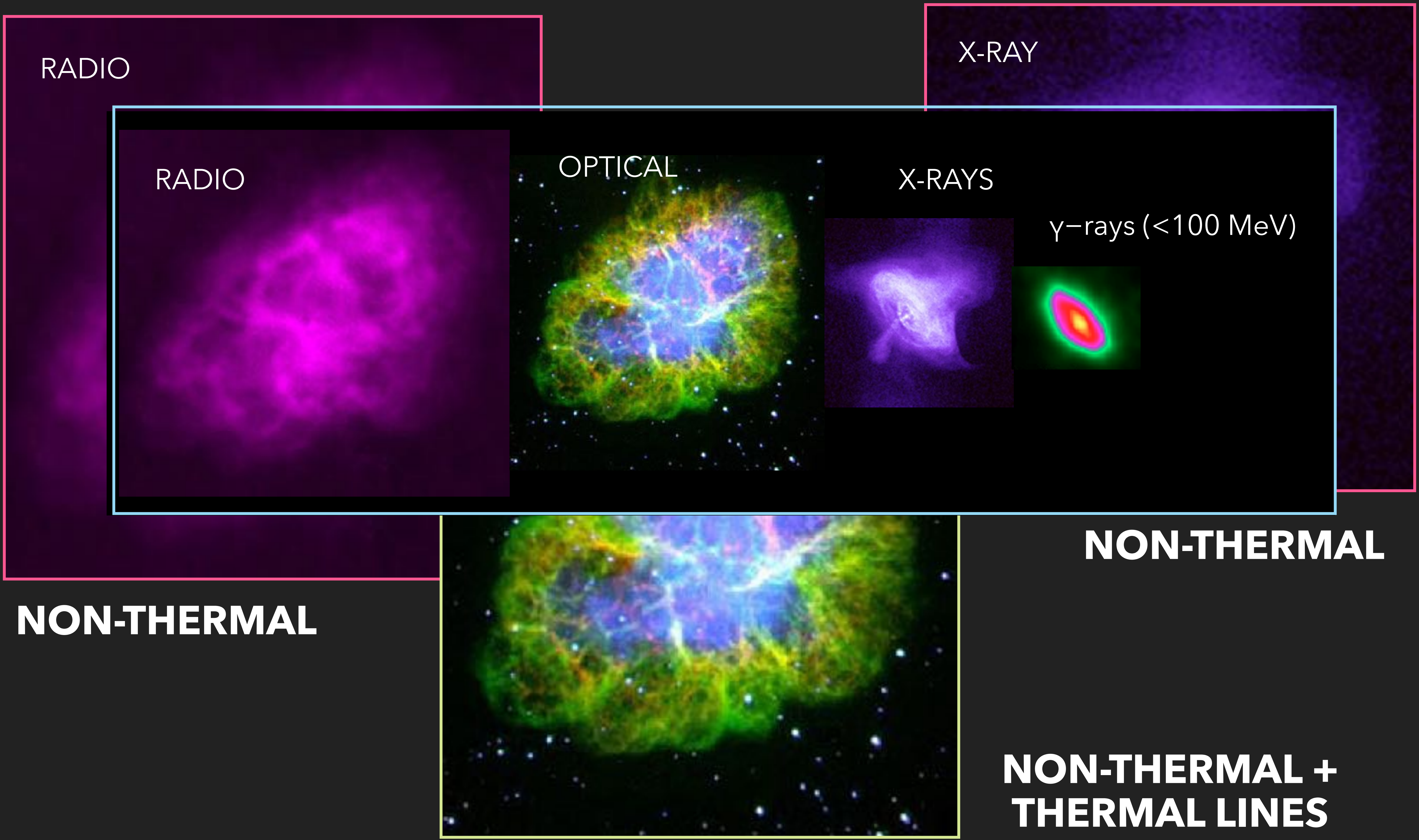


NON-THERMAL + THERMAL LINES



NON-THERMAL

PWNE AT DIFFERENT ENERGIES



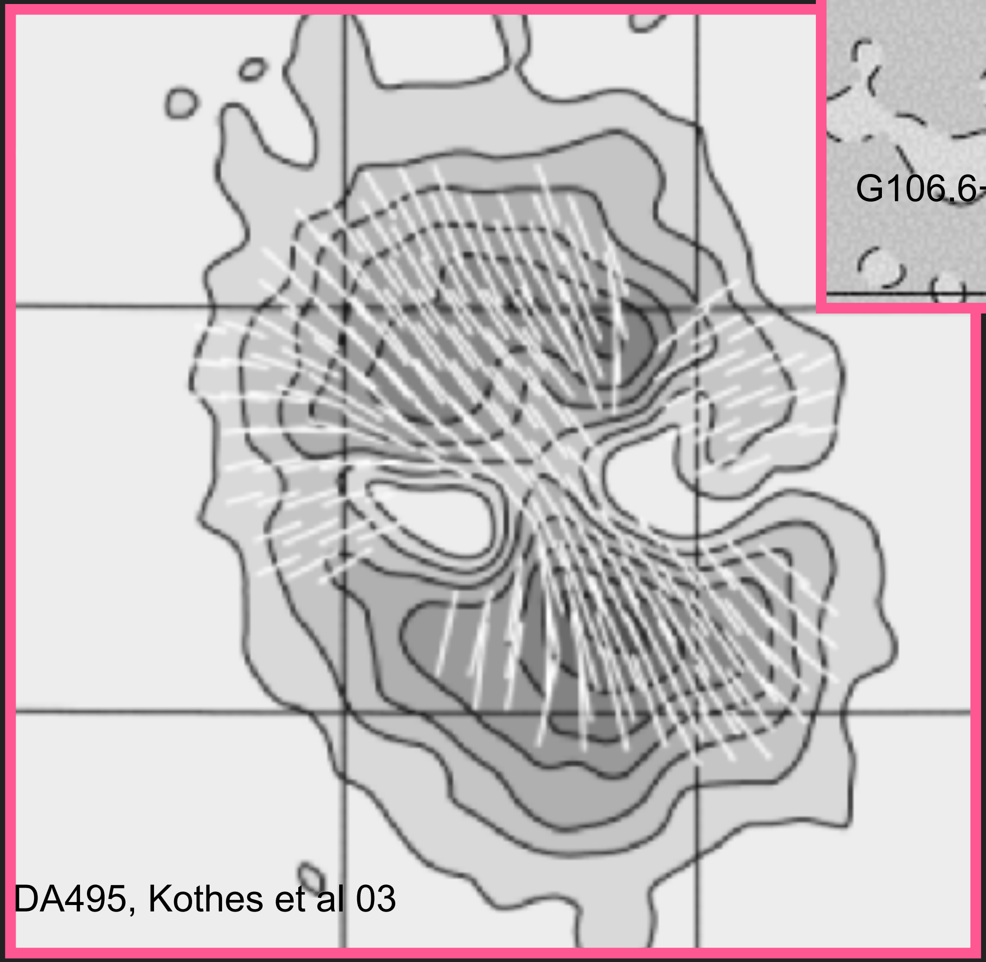
NON-THERMAL

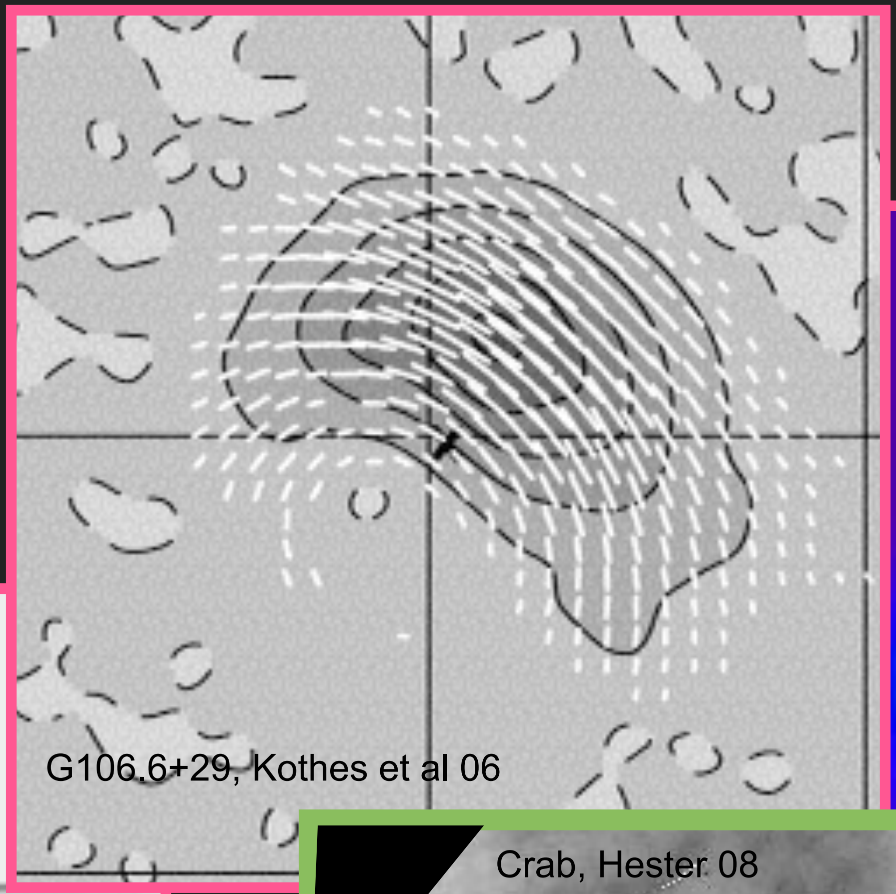
NON-THERMAL

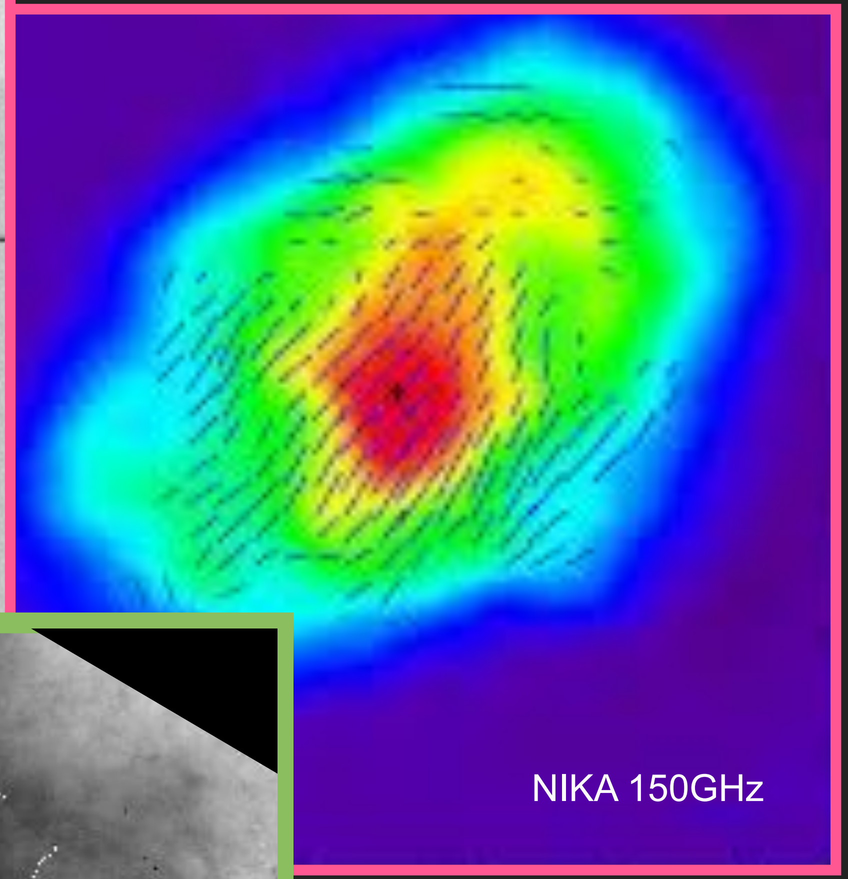
NON-THERMAL + THERMAL LINES

PWNE POLARISATION

PWNE ARE HIGHLY POLARISED



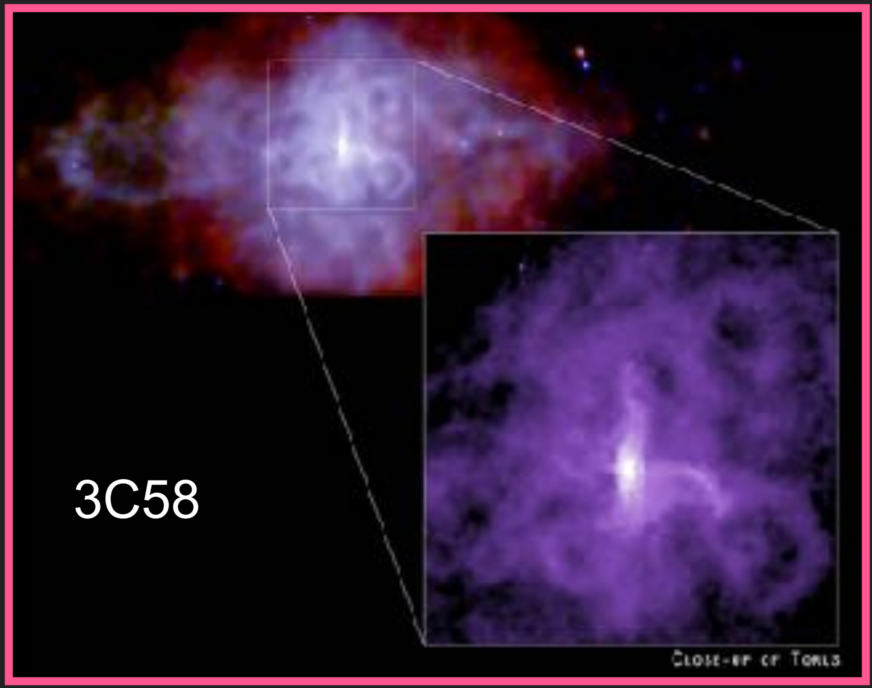


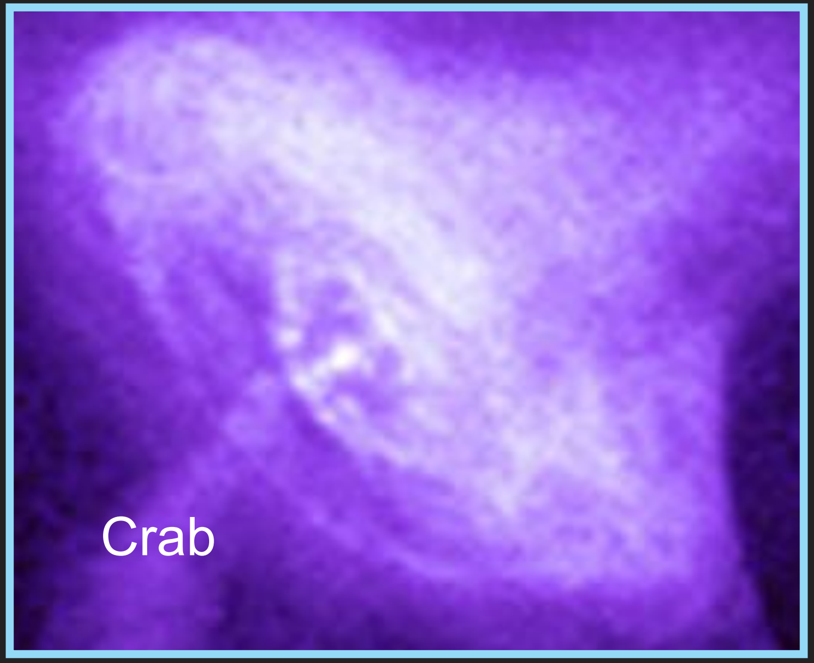


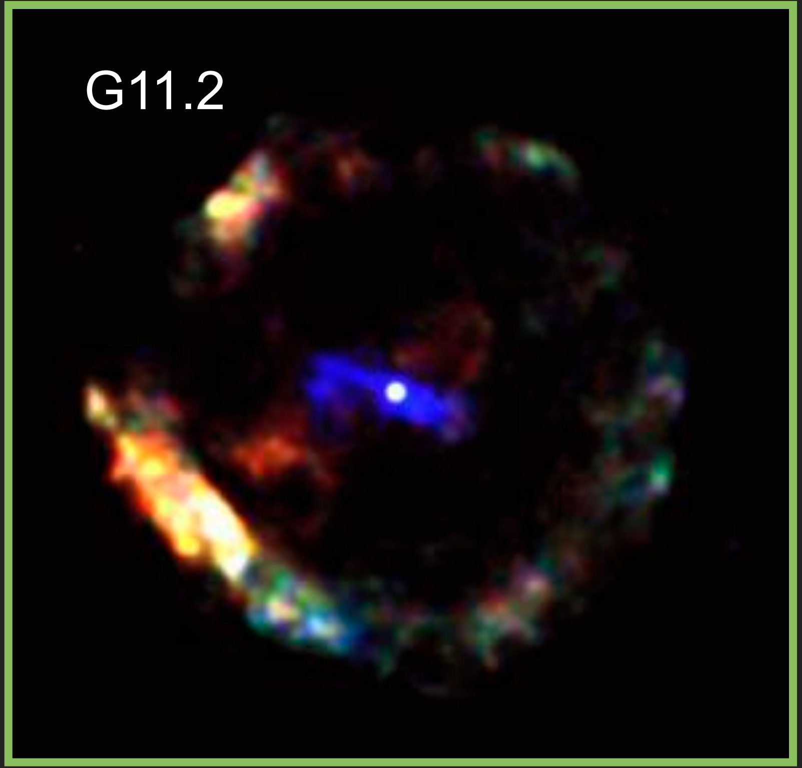
SYNCH

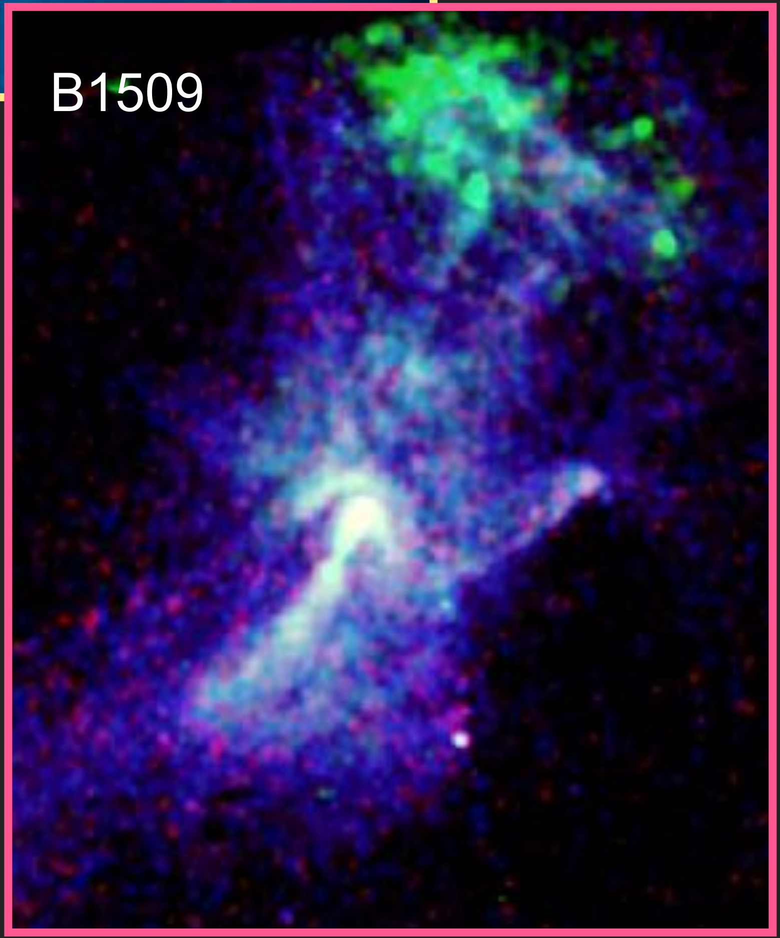
$P_{max} \sim 70\%$

FINE STRUCTURES – A LAB FOR RELTIVISTICN FLUID DYNAMICS









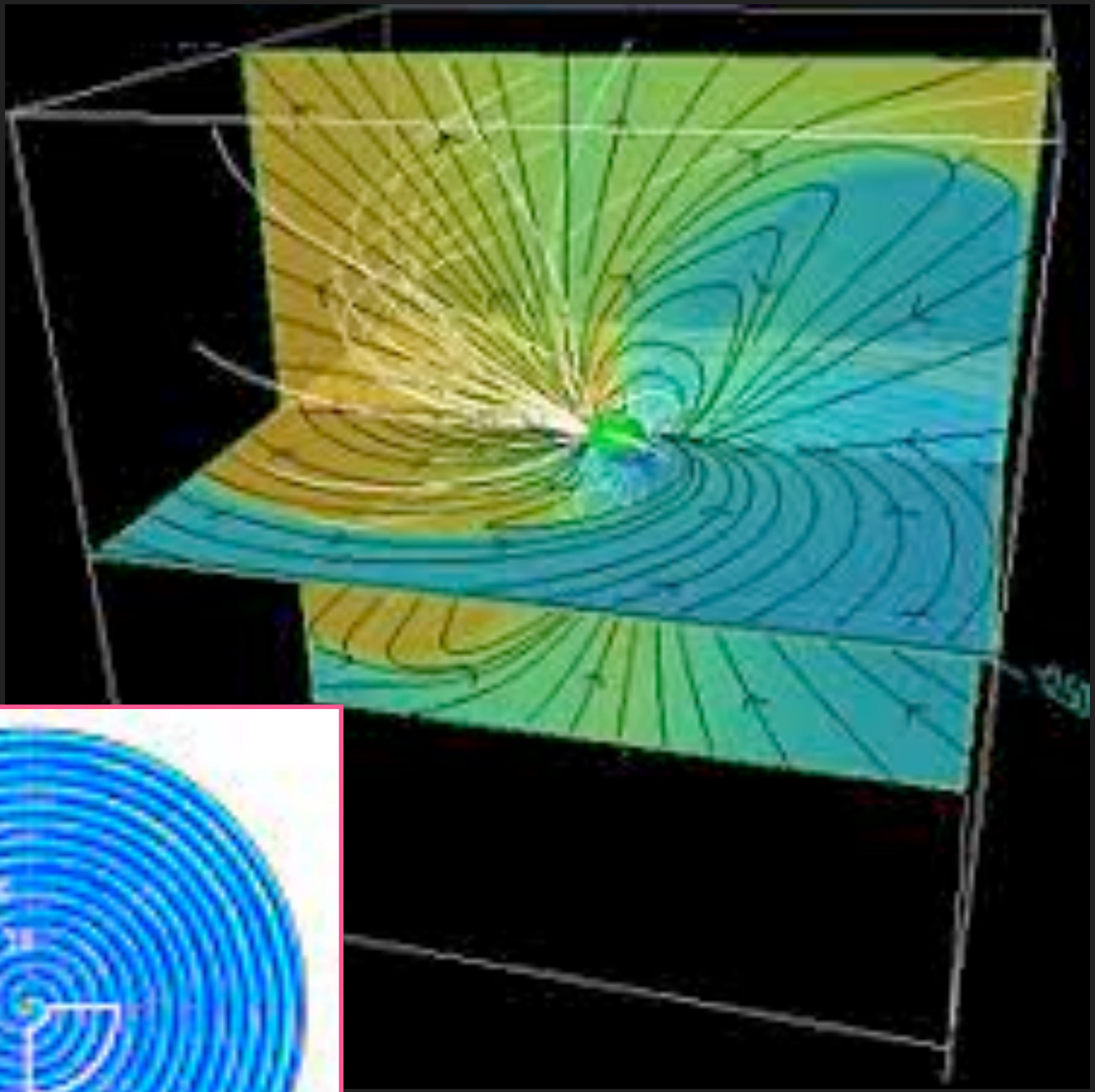
THE PULSAR WIND

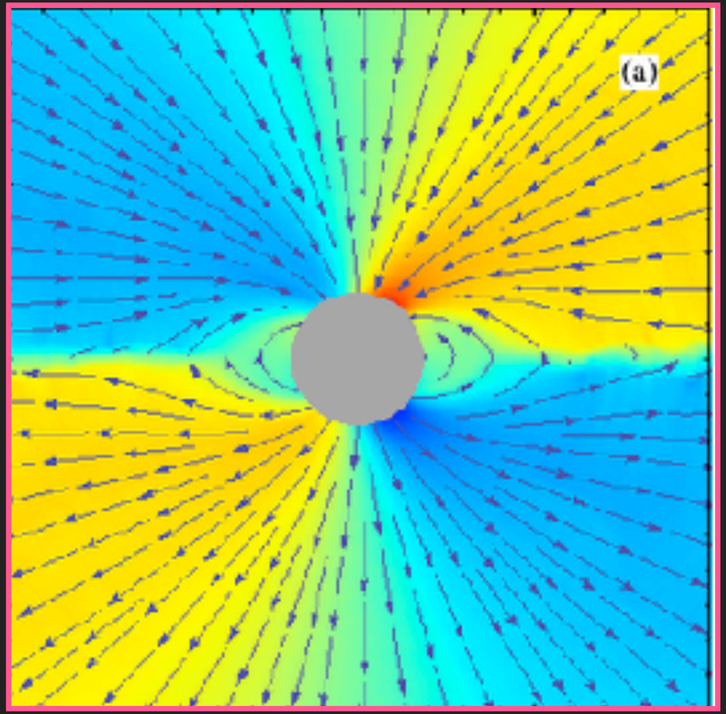
PSR WIND & MAGNETOSPHERE WELL DESCRIBED BY FORCE FREE RMHD

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho, \quad \nabla \times \boldsymbol{E} = -\partial_t \boldsymbol{B}/c$$

$$\nabla \cdot \boldsymbol{B} = 0, \quad \nabla \times \boldsymbol{B} = \partial_t \boldsymbol{E}/c + \boldsymbol{J}$$

$$\rho \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B} = 0$$





Magnetic field wound-up in a Striped wind of alternating polarities

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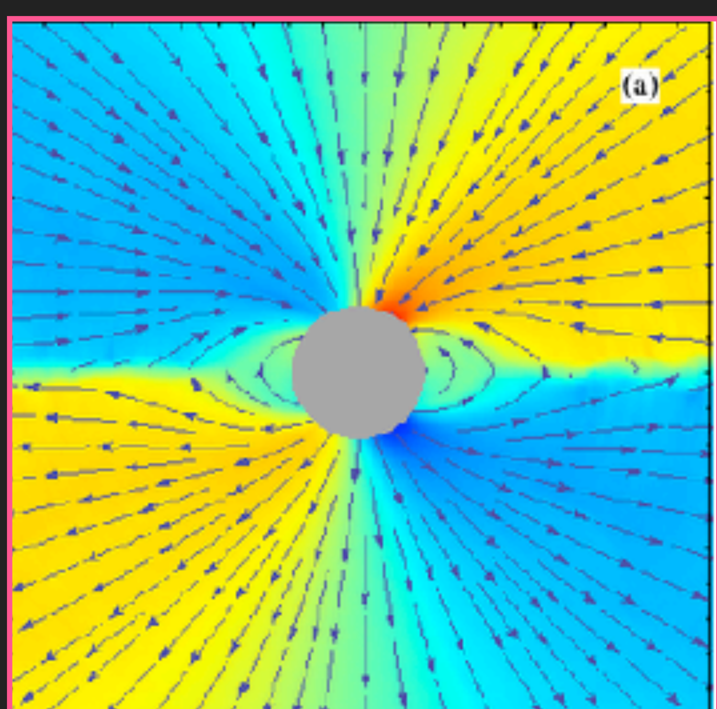

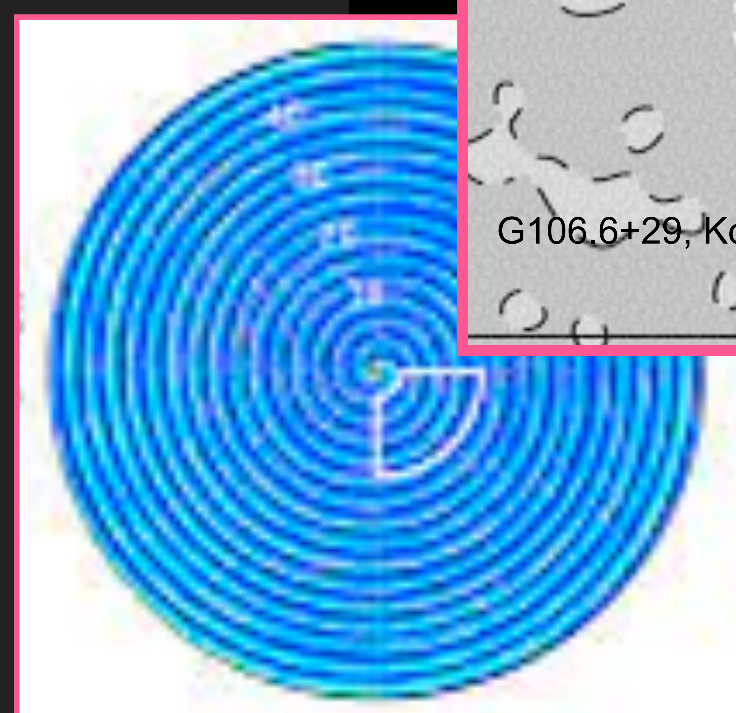

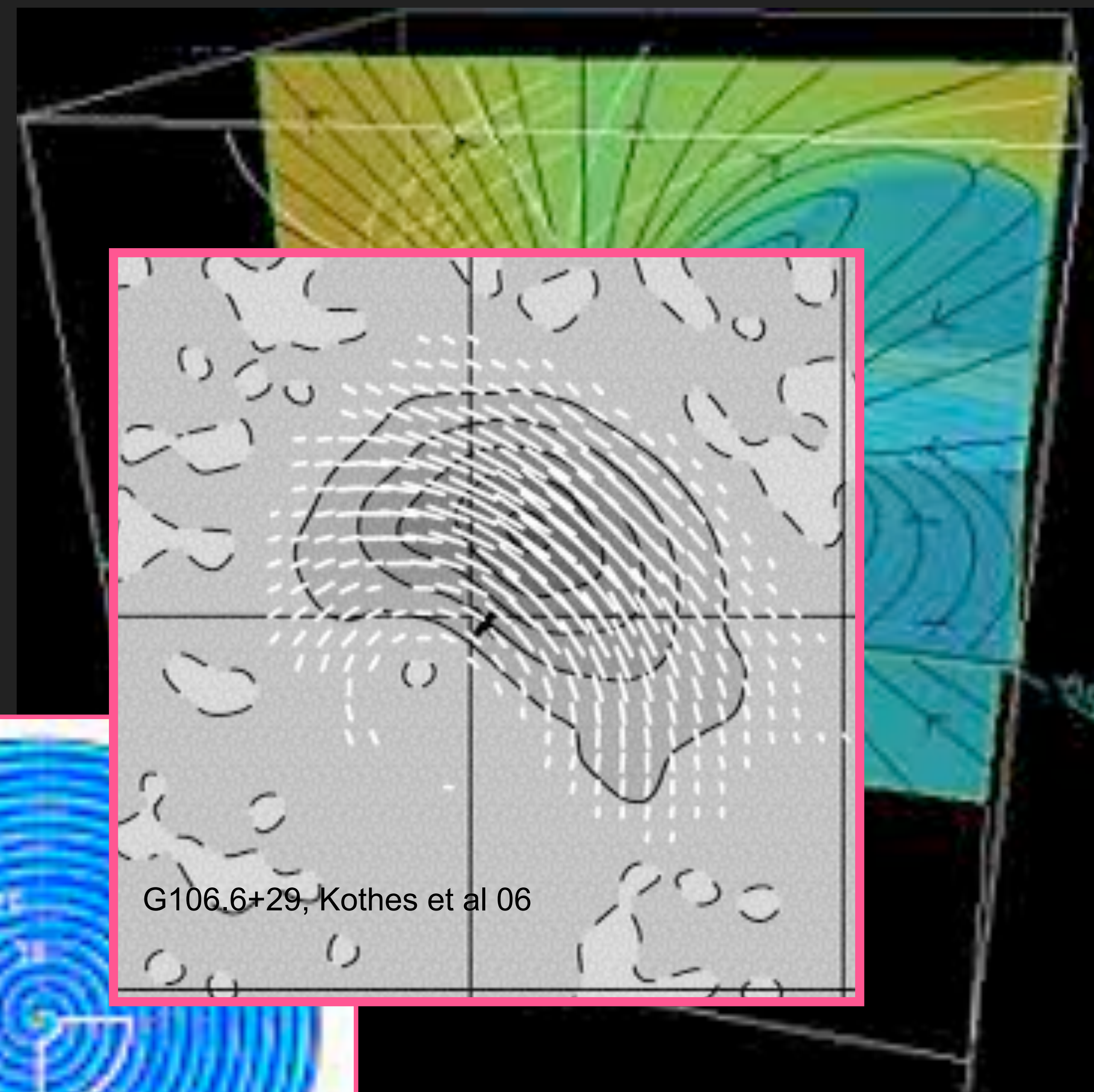

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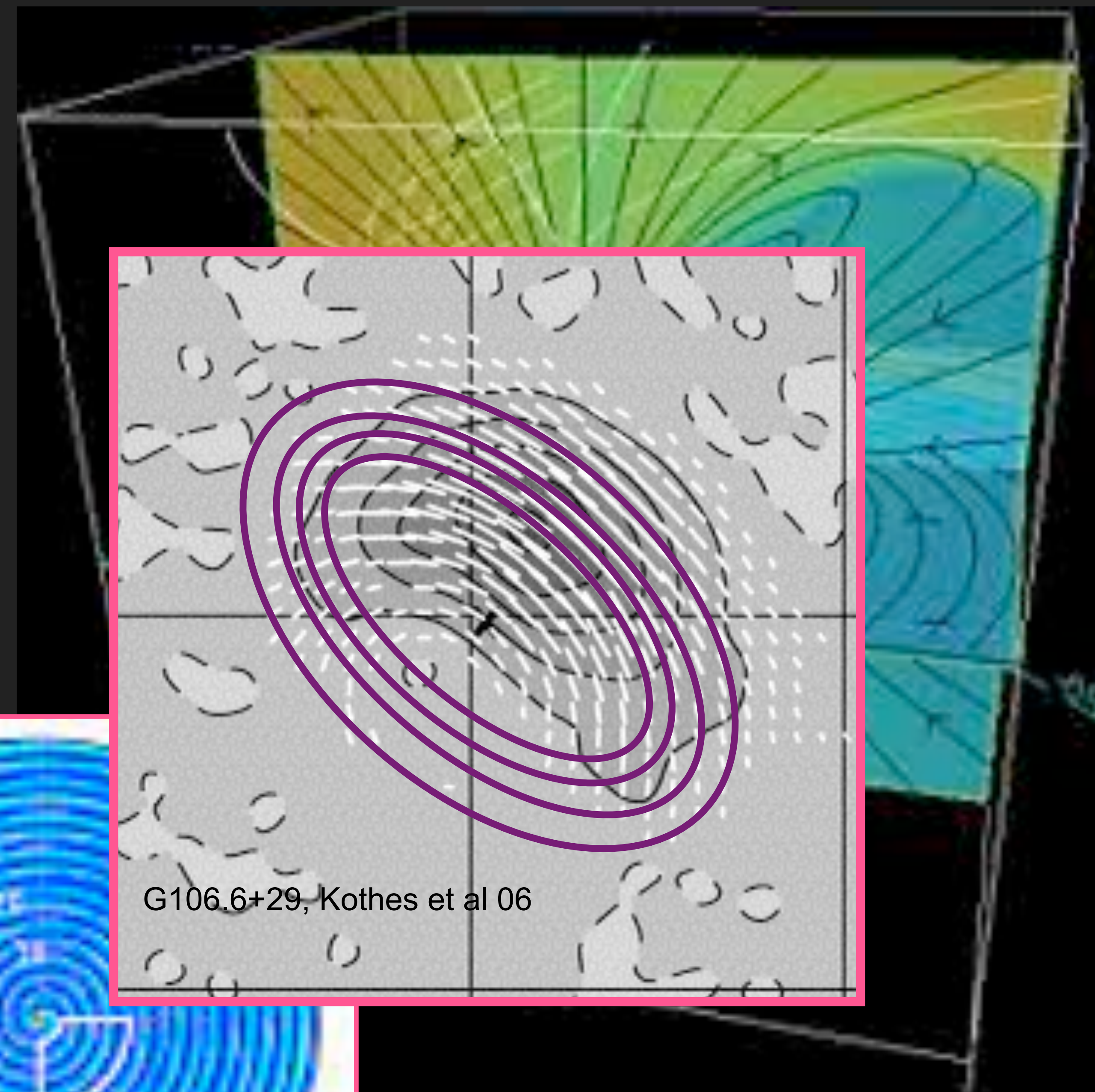
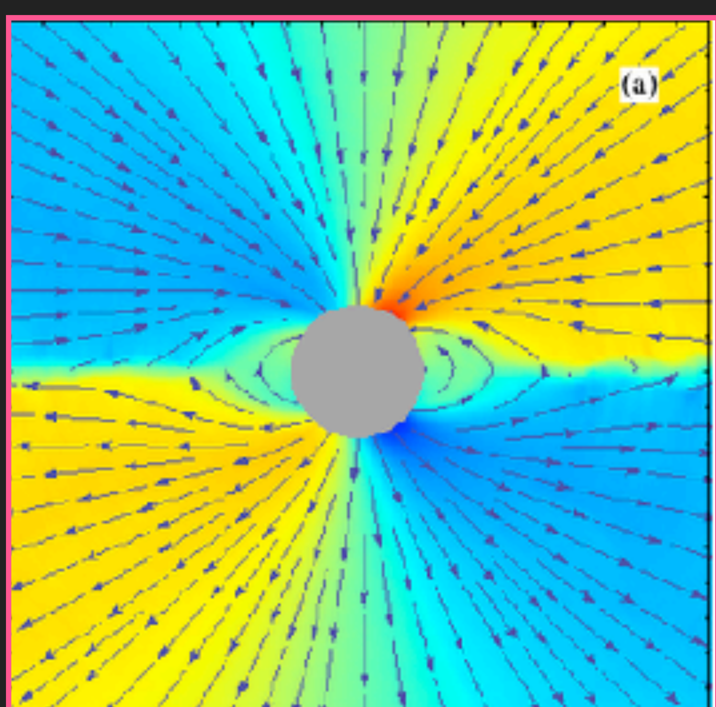
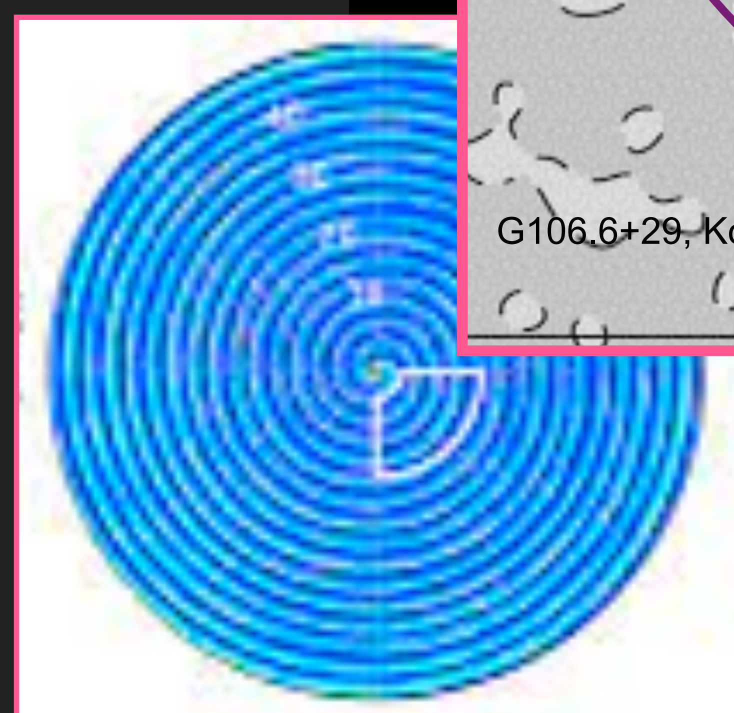




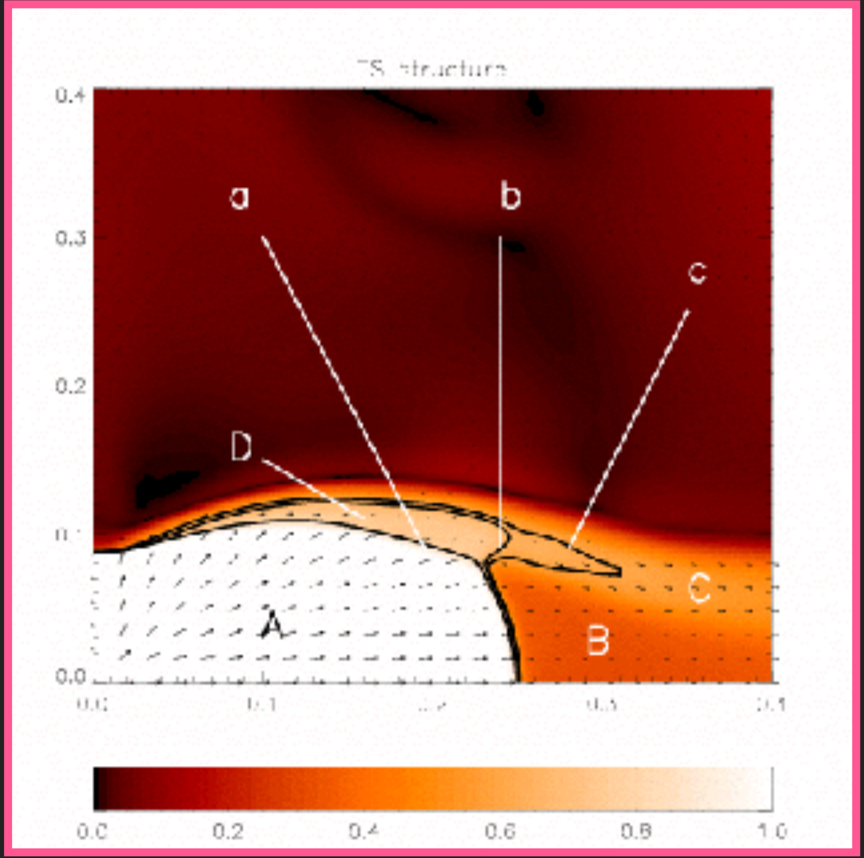


Magnetic field wound-up in a Striped wind of alternating polarities

RELATIVISTIC MHD MODELS

THE WIND ANISOTROPY SHAPES THE TS STRUCTURE. DOWNSTREAM FLOW - EQUATORIAL COLLIMATION DUE TO THE TS SHAPE:

A: ULTRARELATIVISTIC PULSAR WIND
B: SUBSONIC EQUATORIAL OUTFLOW
C: SUPERSONIC EQUATORIAL FUNNEL
D: SUPER-FASTMAGNETOSONIC FLOW
A: TERMINATION SHOCK FRONT
B: RIM SHOCK
C: FASTMAGNETOSONIC SURFACE



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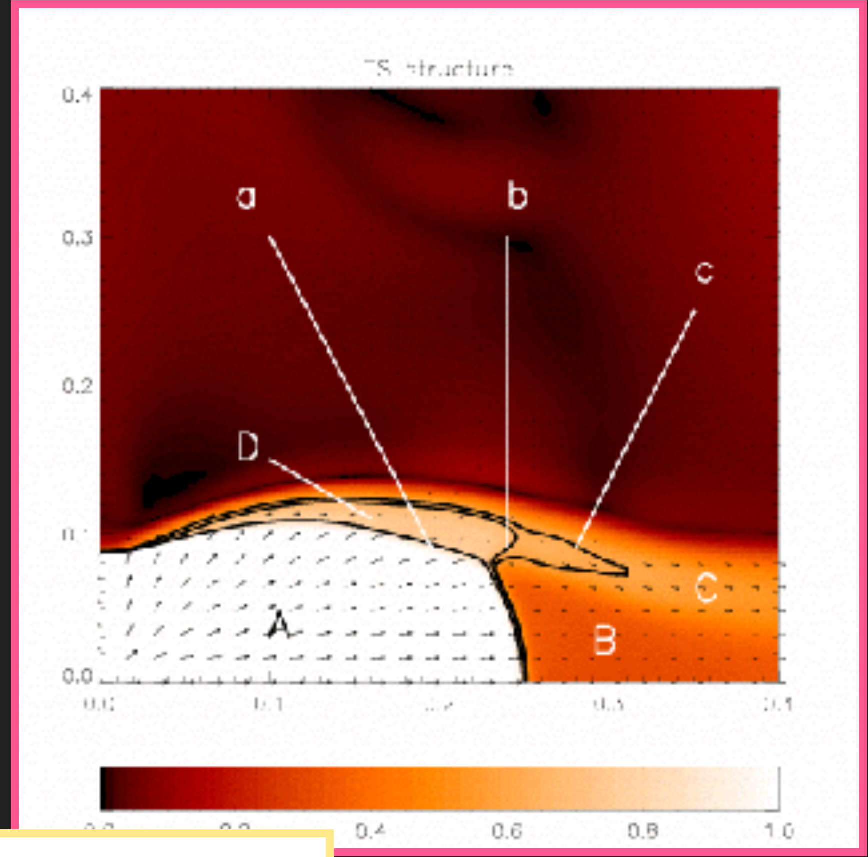
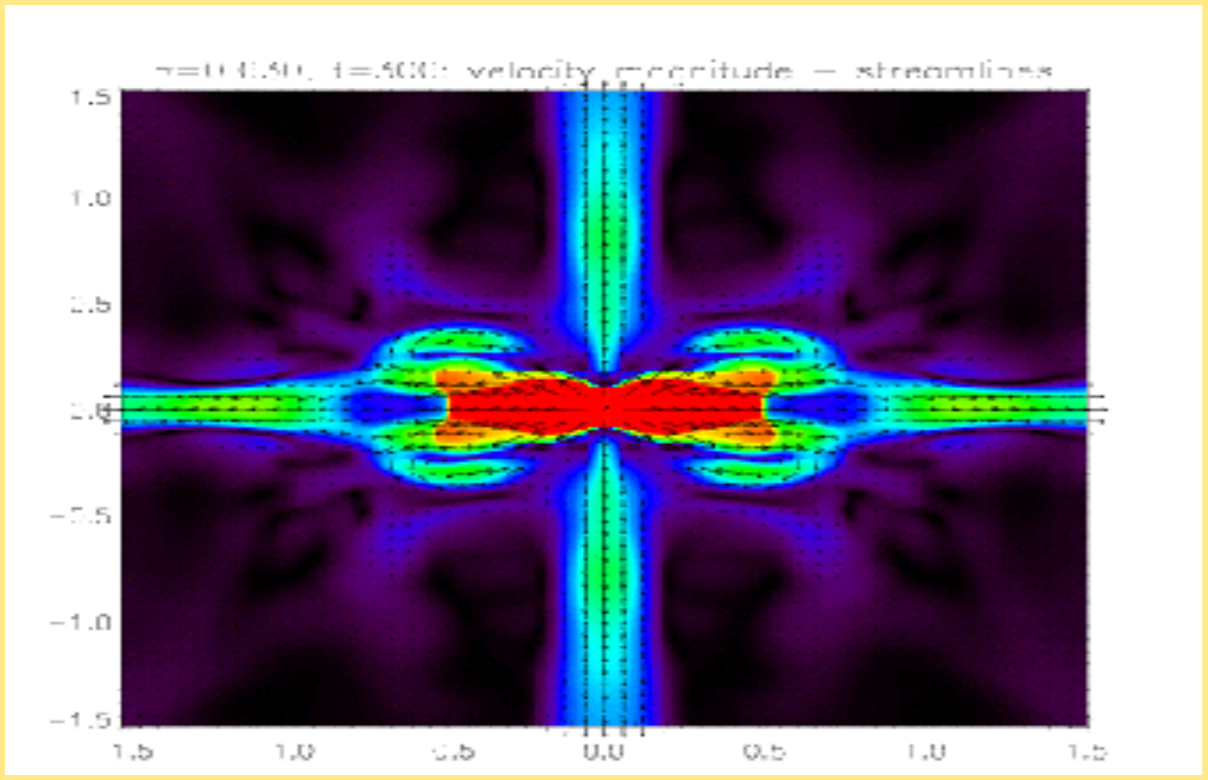
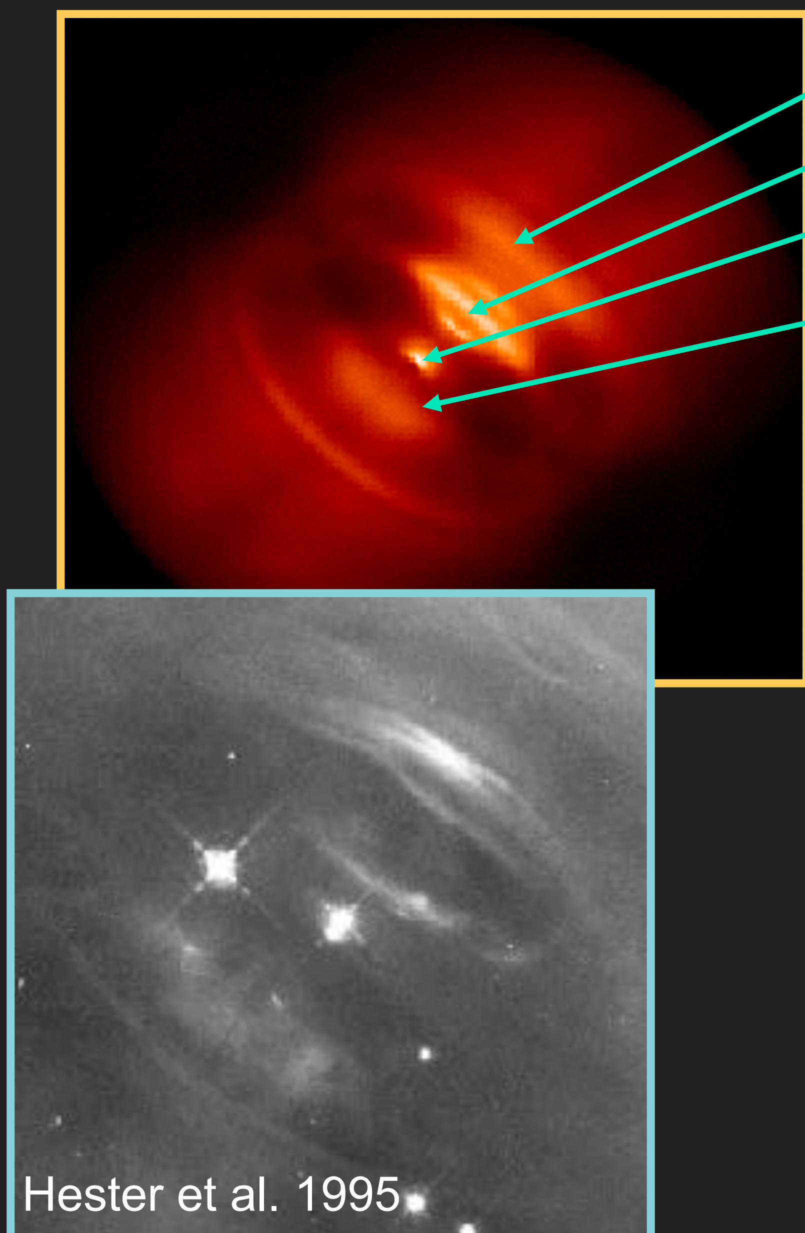


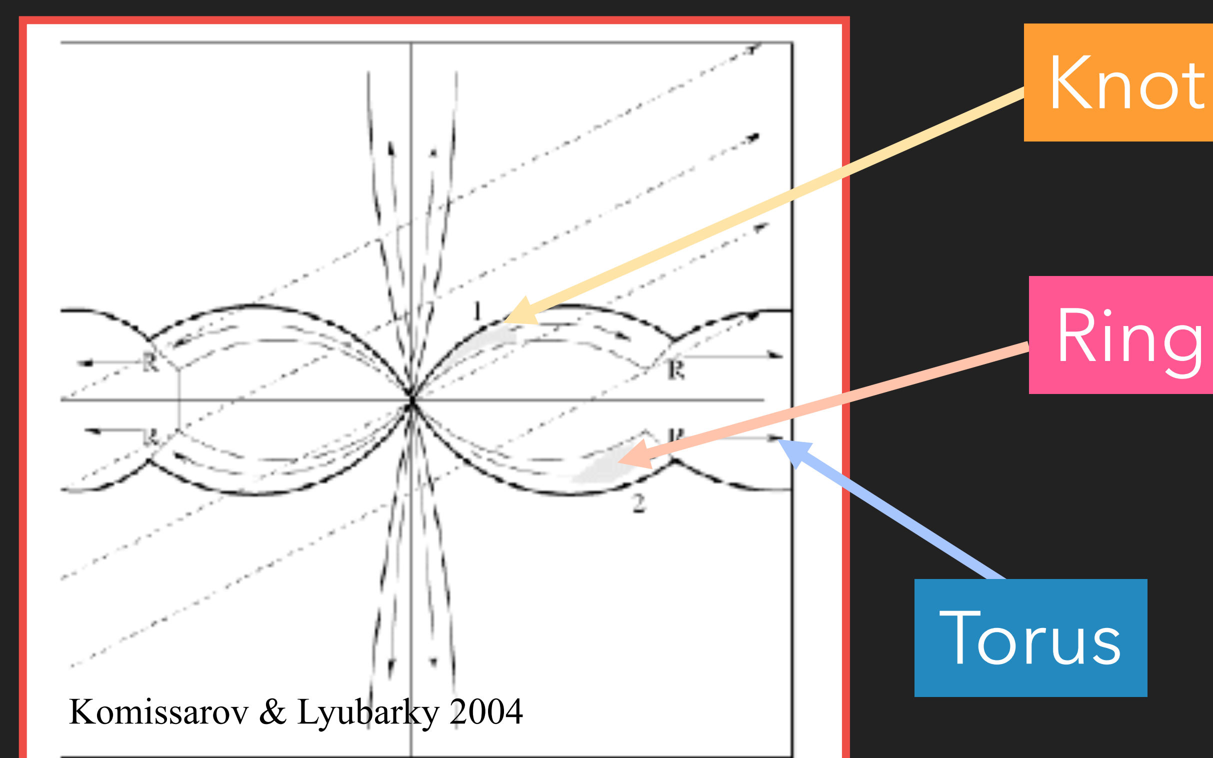


REPRODUCING OBSERVATIONS

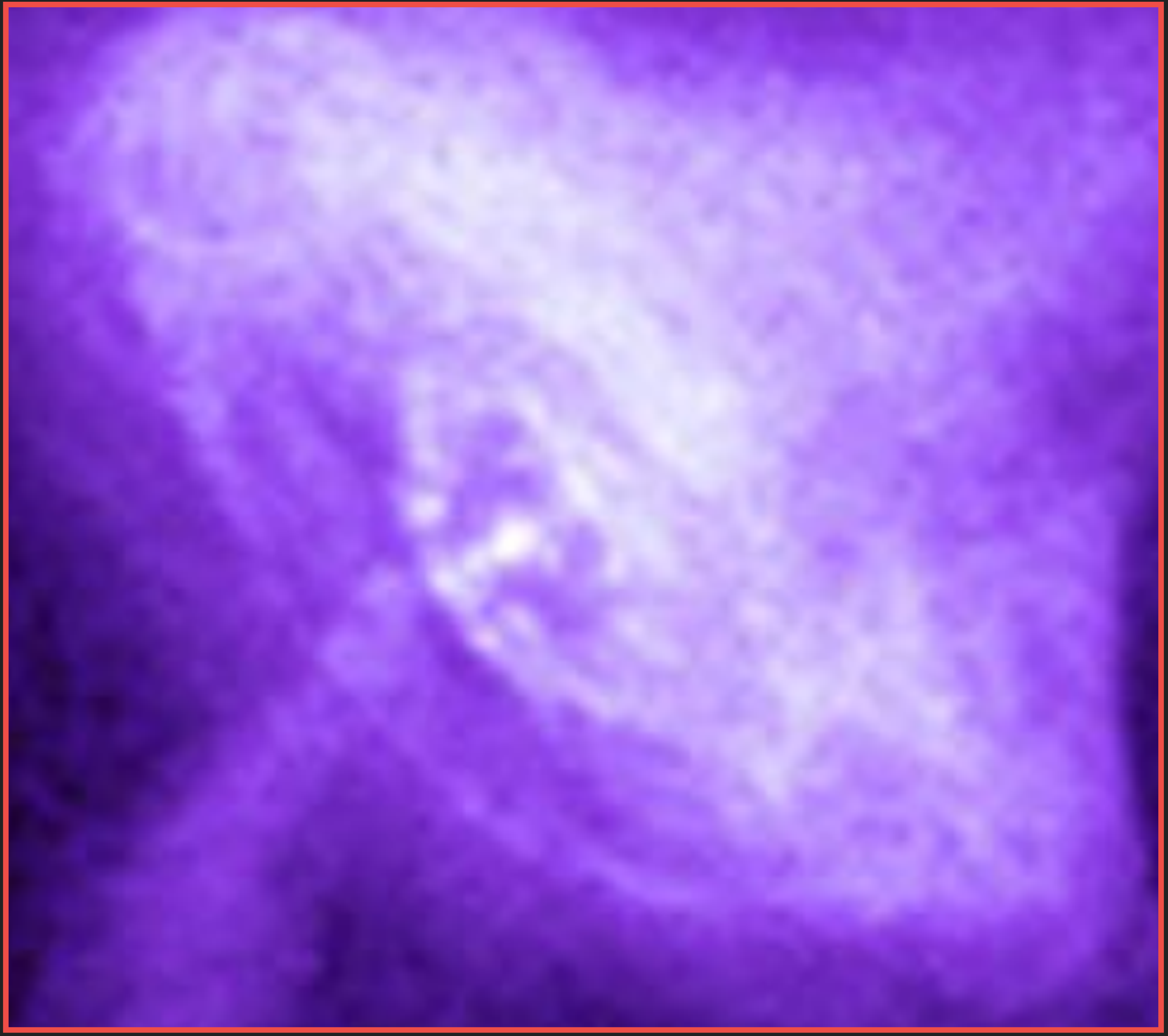
MAIN TORUS
INNER RING (WISPS STRUCTURE)
KNOT
BACK SIDE OF THE INNER RING



EACH FEATURE TRACES AN EMITTING REGION



........AS BEST AS WE CAN



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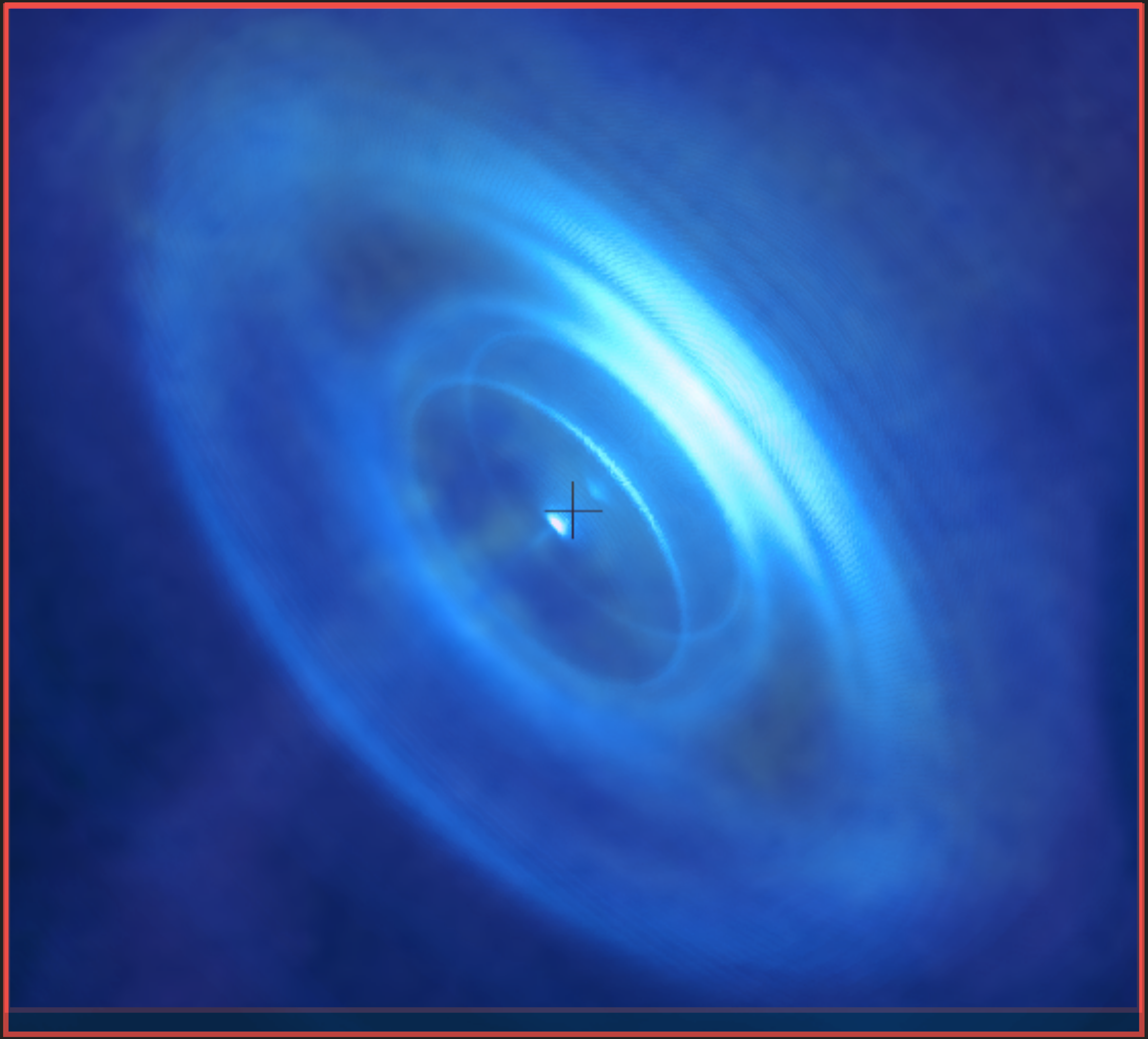
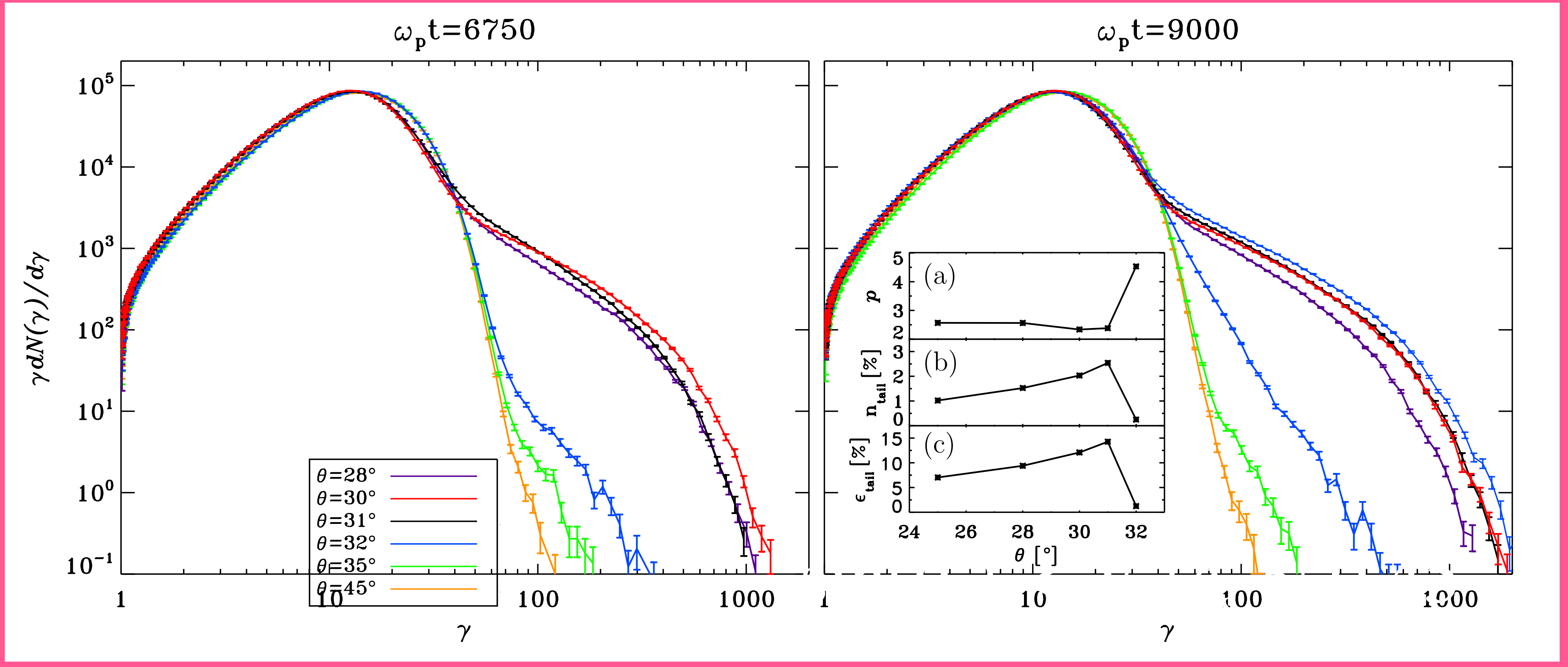


RELATIVISTIC FERMI ACCELERATION

PERPENDICULAR RELATIVISTIC SHOCK - SUPERLUMINAL

MAXWELLIAN AT LOW ENERGIES

EVIDENCE FOR NON-THERMAL TAIL ONLY FOR SUBLUMINAL SHOCK

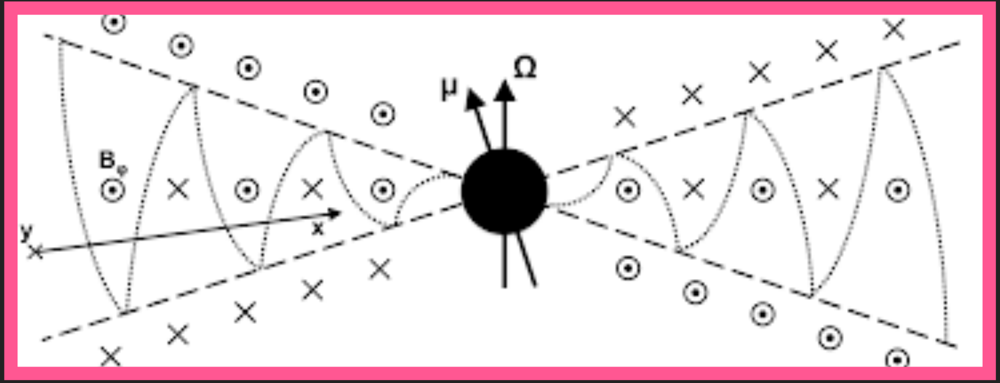


$$\sin(\theta_u) < (V_s/c_s)/\gamma \simeq 0.5/\gamma$$

RECONNECTION

RECONNECTION

PSR WINDS ARE STRIPED AND THIS IMPLIES ALTERNATING FIELD POLARITIES IN THE PWN



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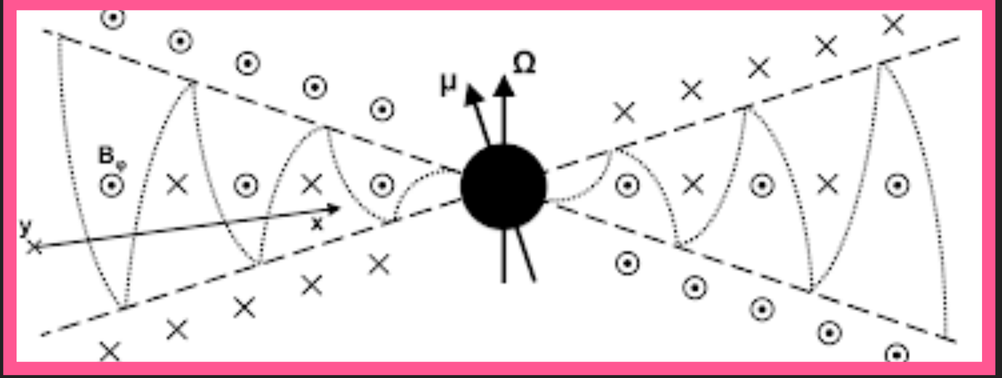
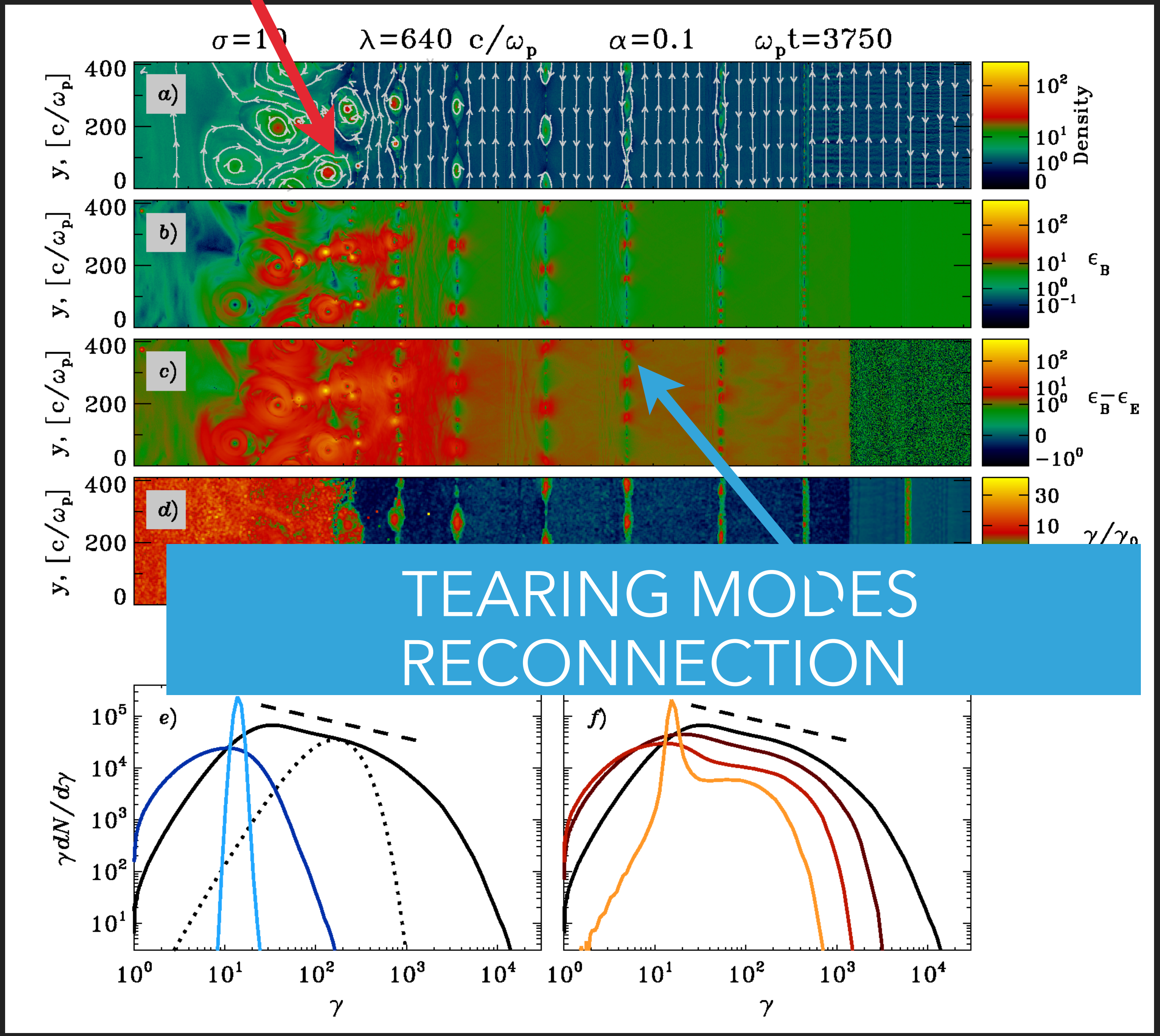


HD SHOCK



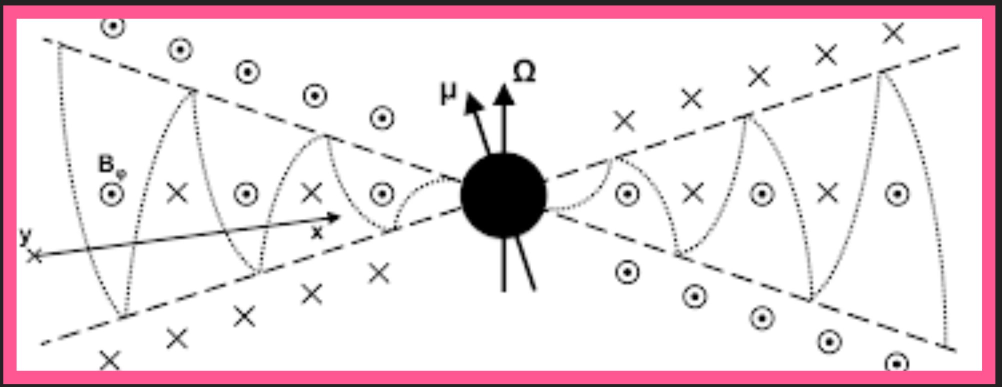
TEARING MODES RECONNECTION

FAST-MAGNETOSONIC PRECURSOR

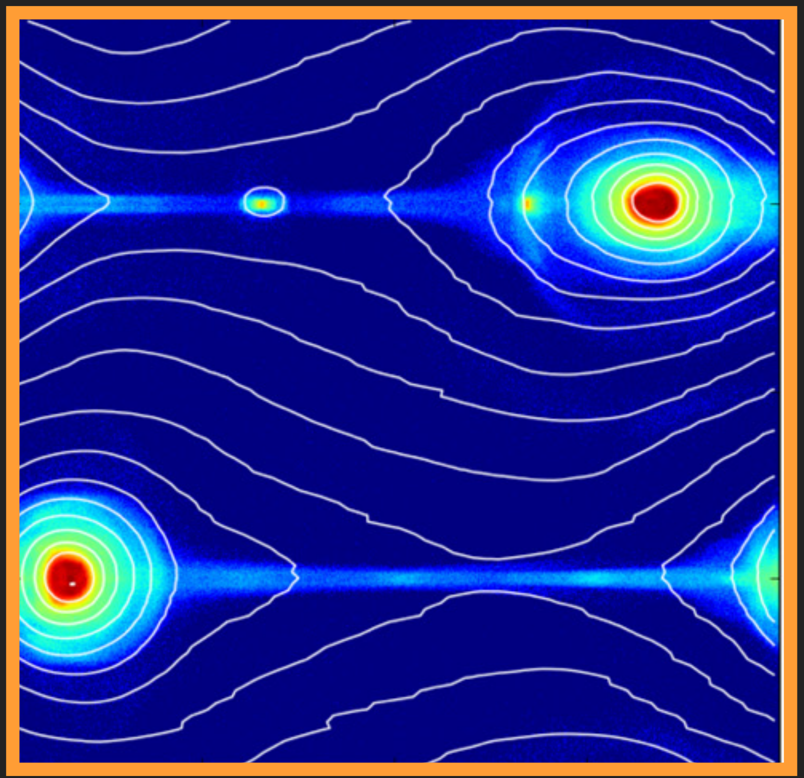
HARD SPECTRUM

RECONNECTION

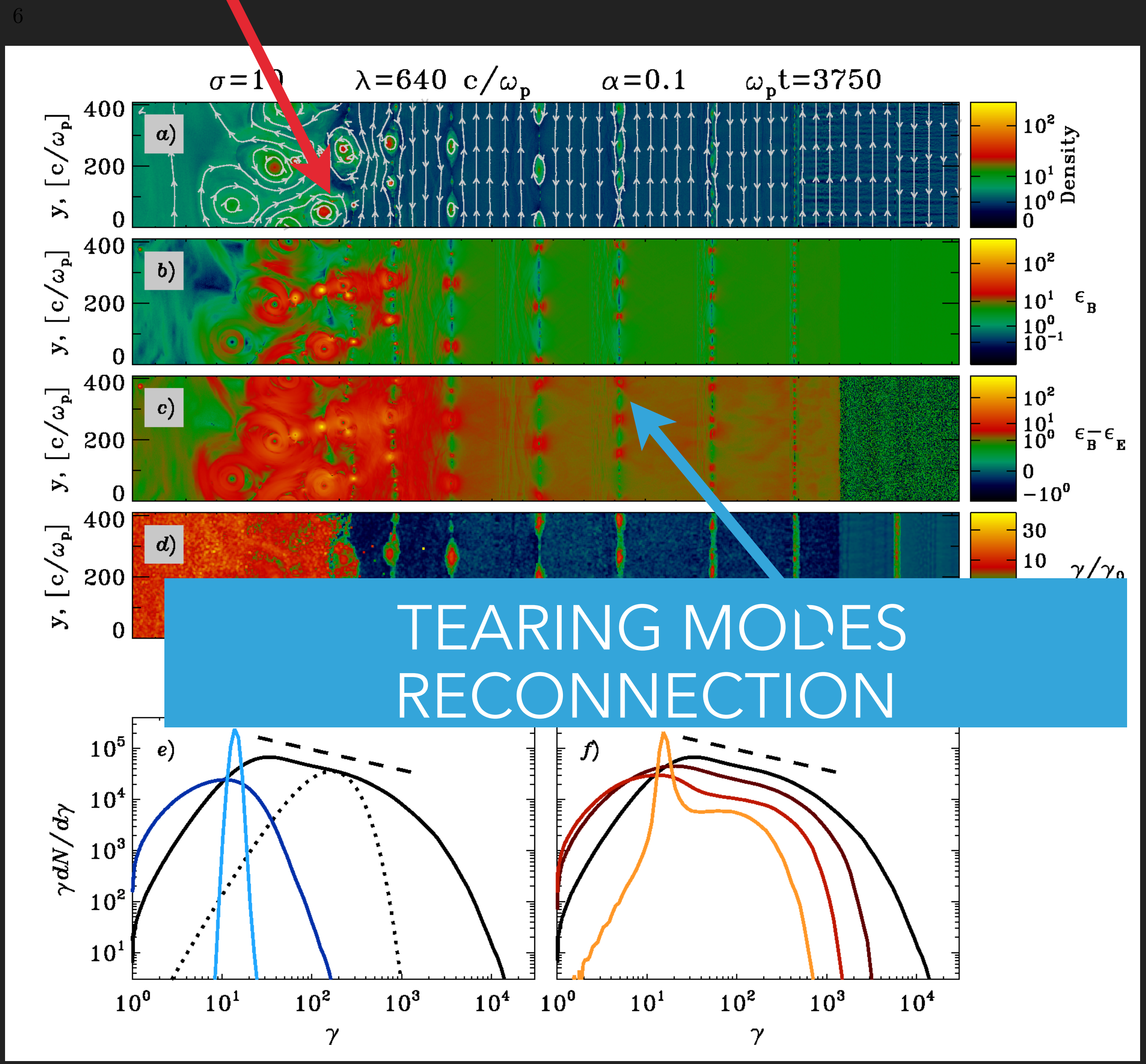
PSR WINDS ARE STRIPED AND THIS IMPLIES ALTERNATING FIELD POLARITIES IN THE PWN



TEARING INSTAB



HD SHOCK



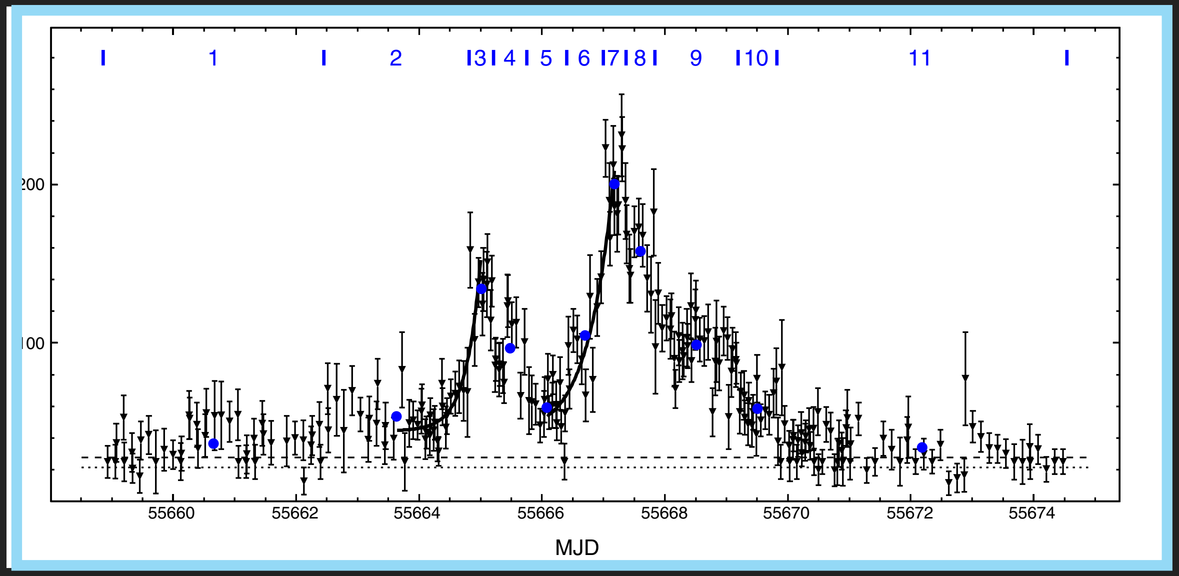
TEARING MODES RECONNECTION

FAST-MAGNETOSONIC PRECURSOR

HARD SPECTRUM

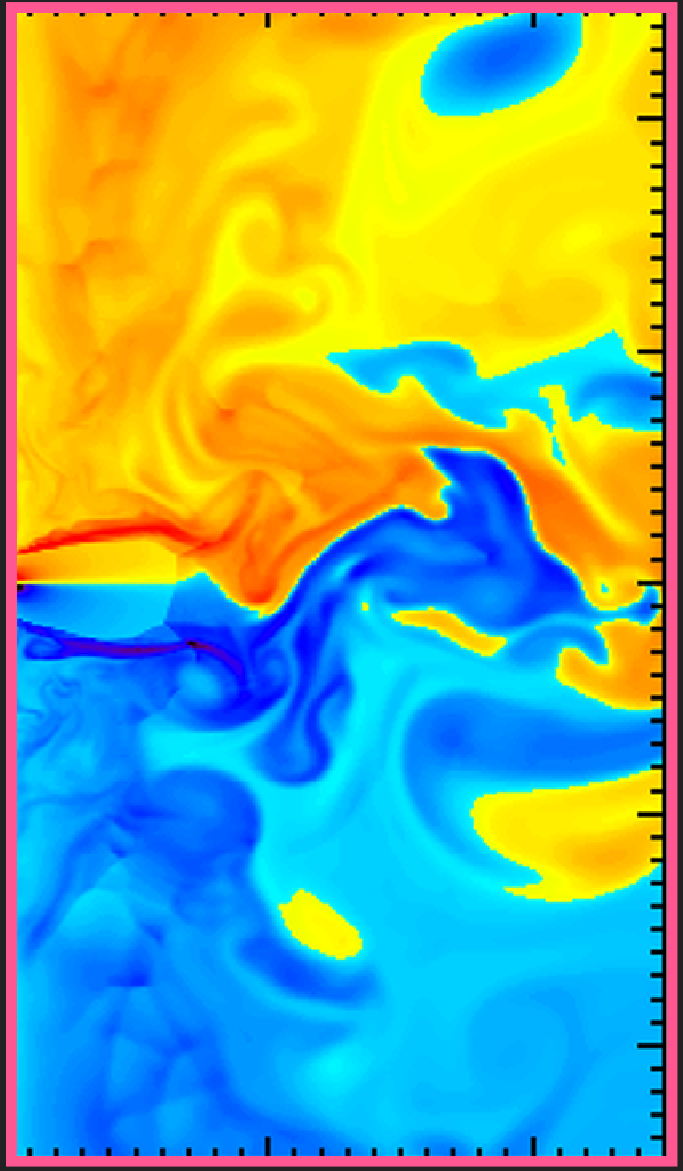
TURBULENCE

EVIDENCE FOR TURBULENCE INSIDE PWNE



GAMMA-RAY FLARES

HIGH VORTICITY



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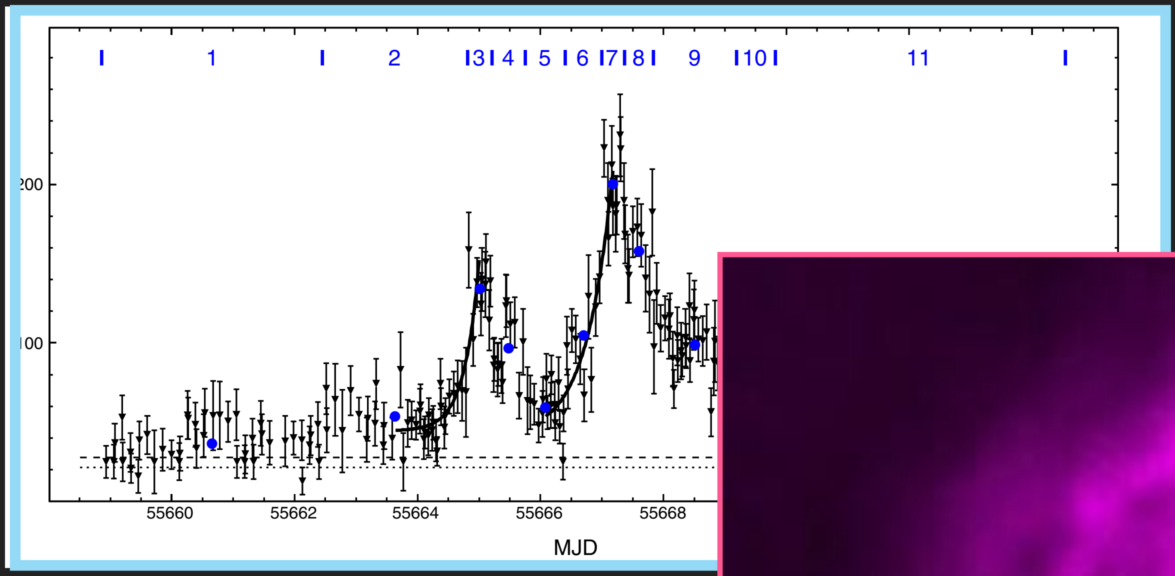

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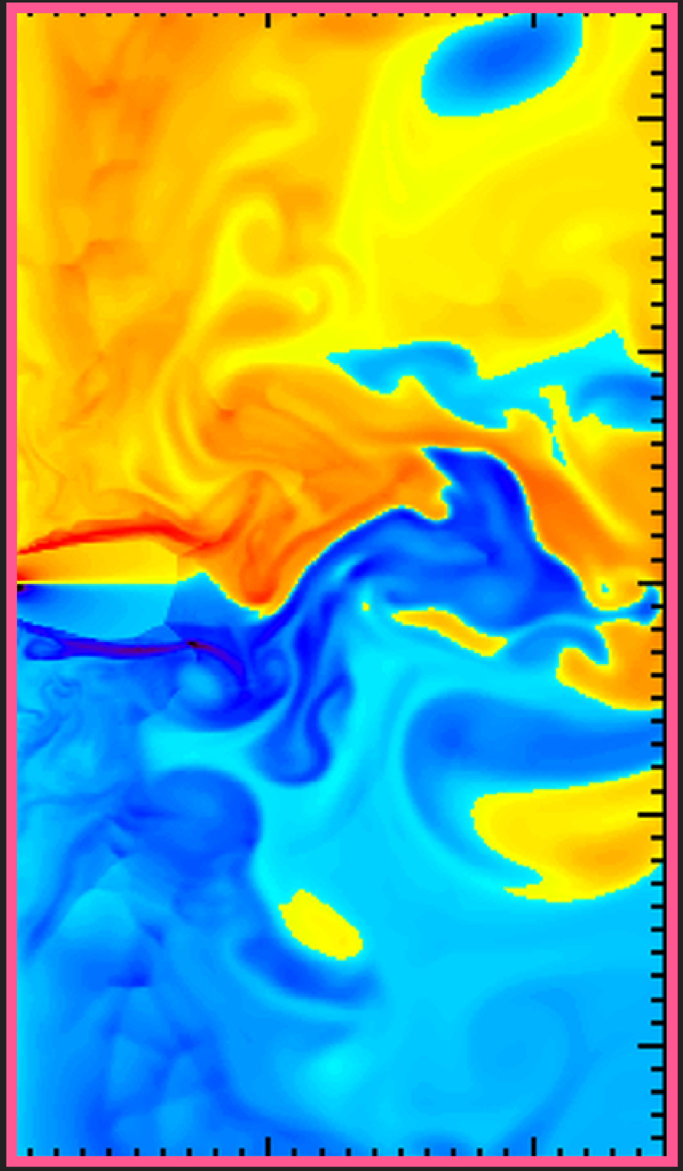

LARGE EXTENSION OF X-RAYS

TURBULENCE

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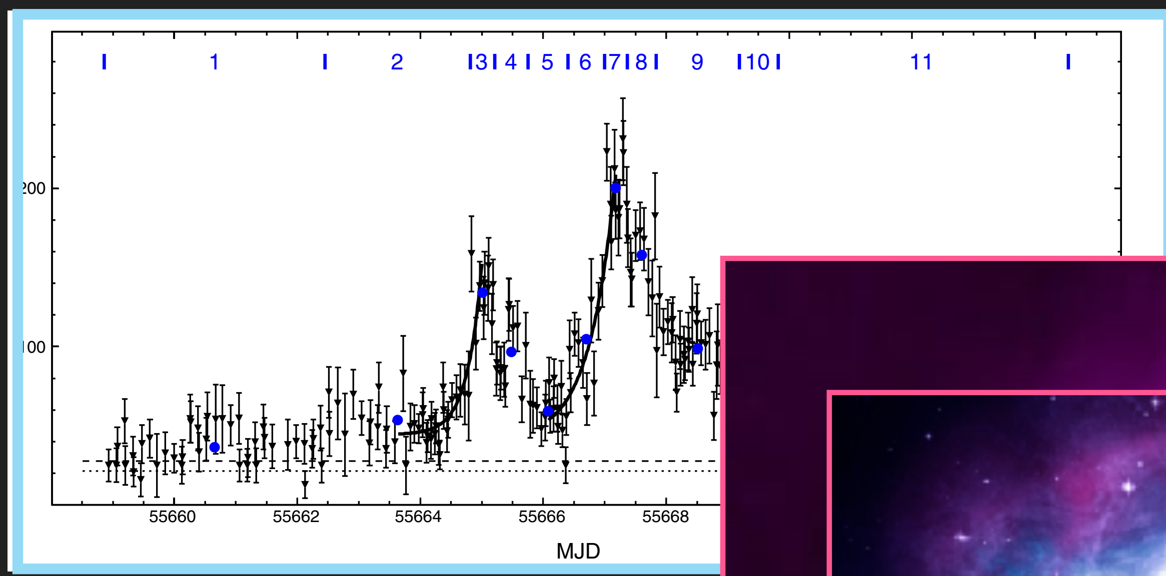

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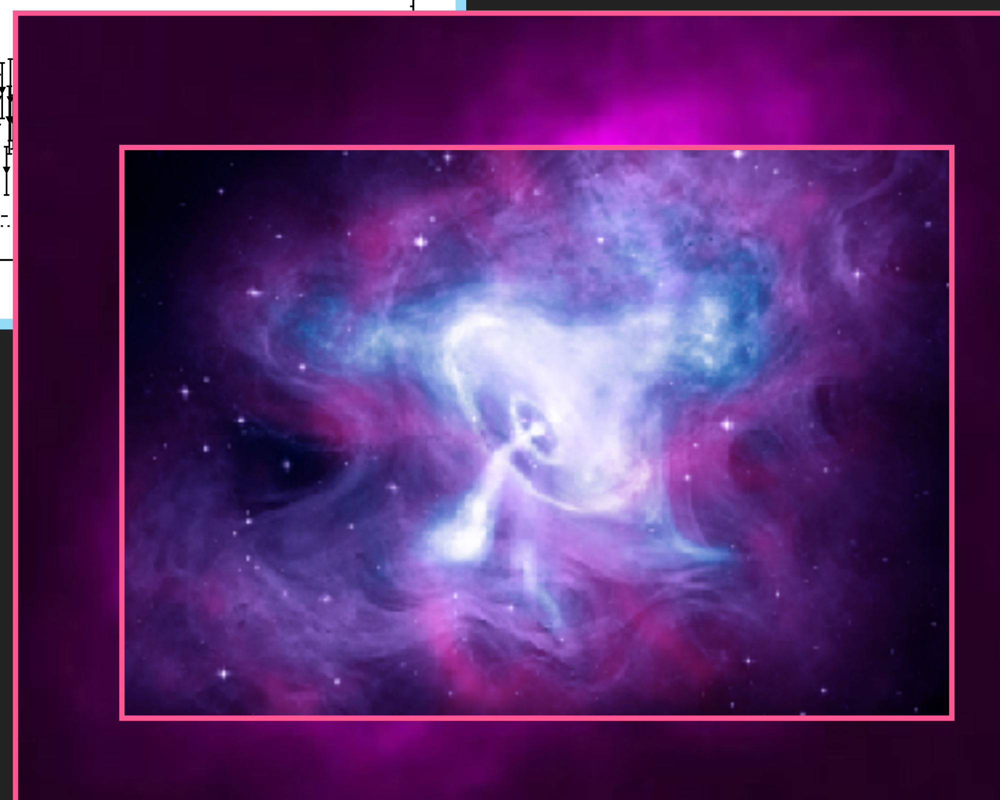
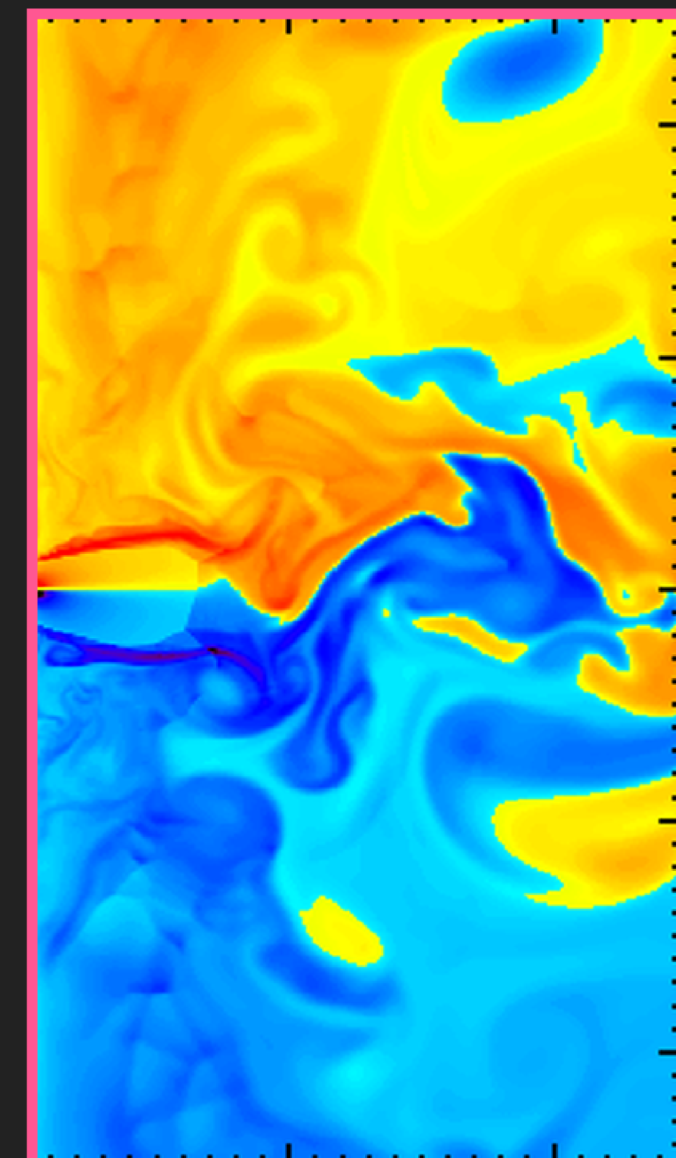
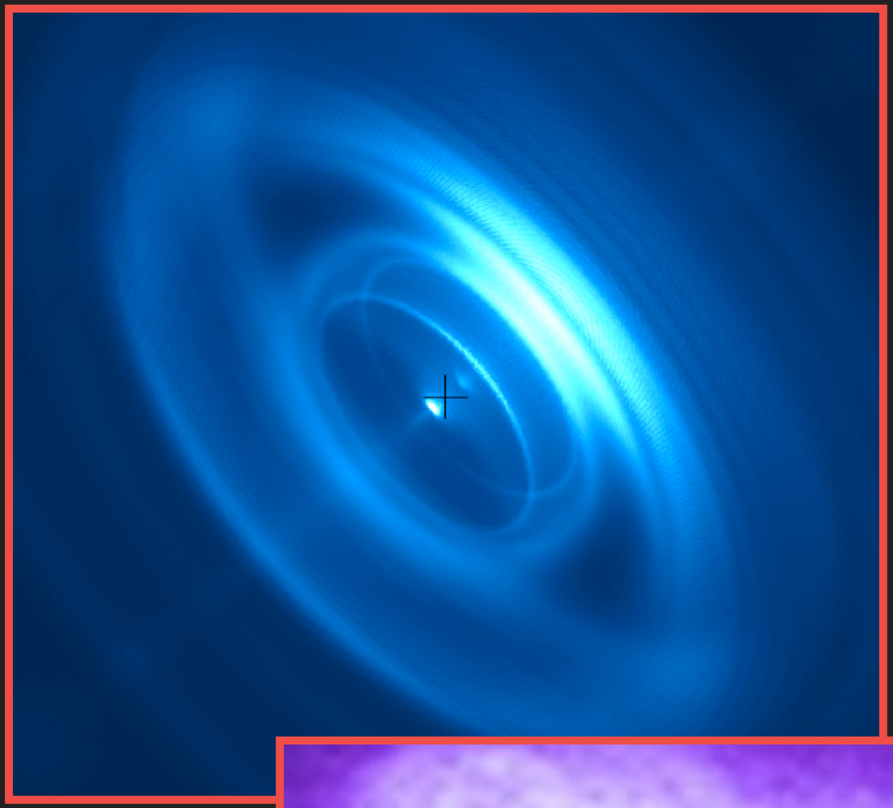
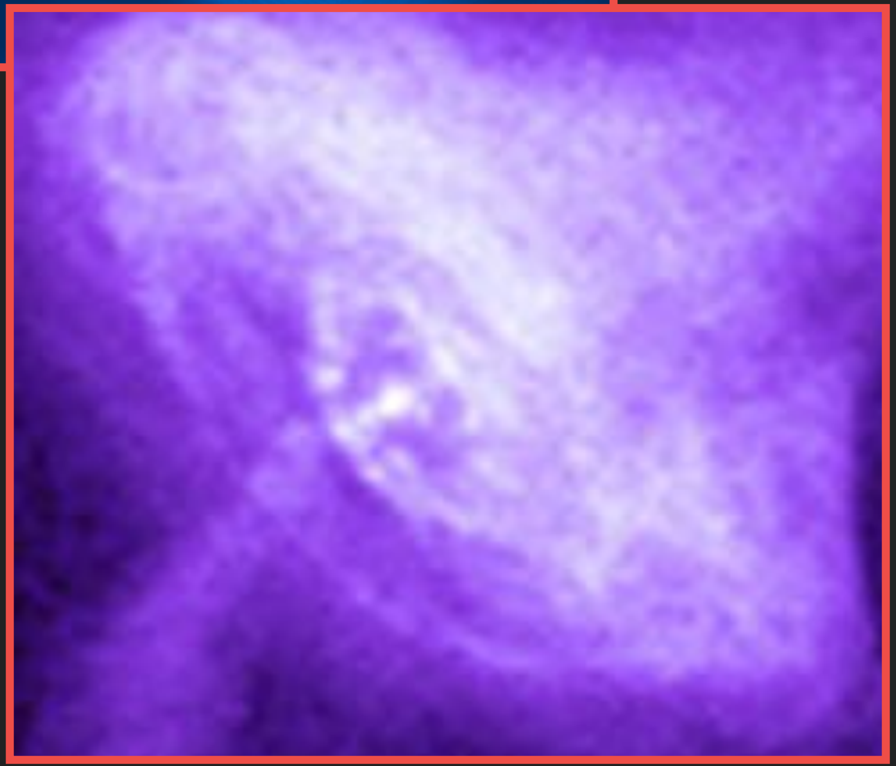




LARGE EXTENSION OF X-RAYS

.... THE BAD ....





.... THE BAD ......

LUMINOSITY IS TOO PEAKED ON AXIS

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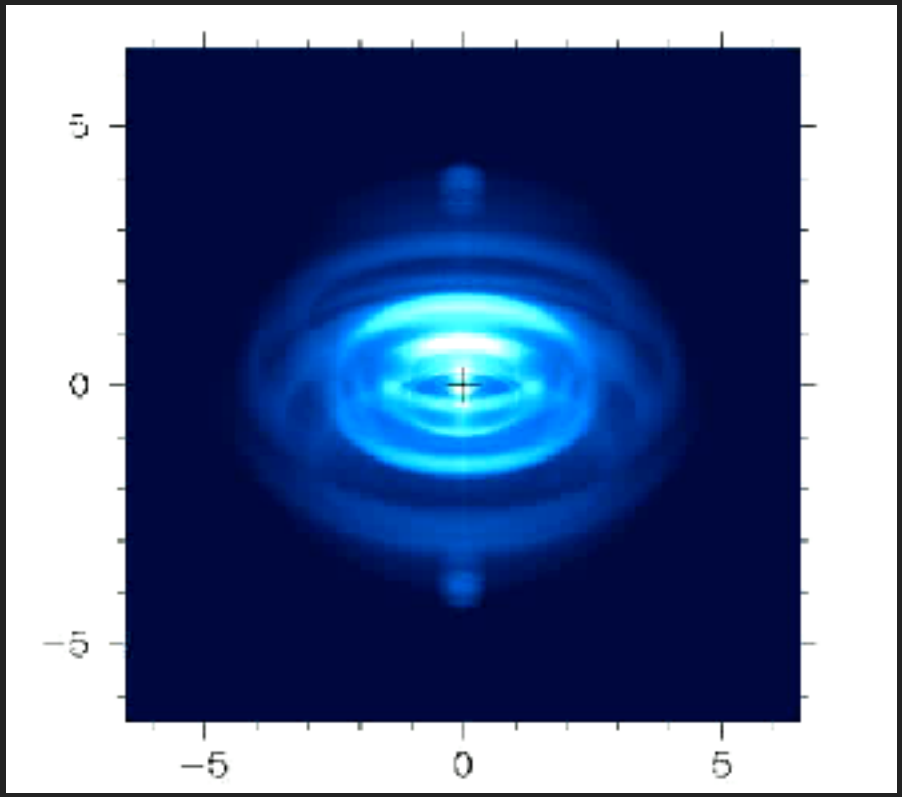

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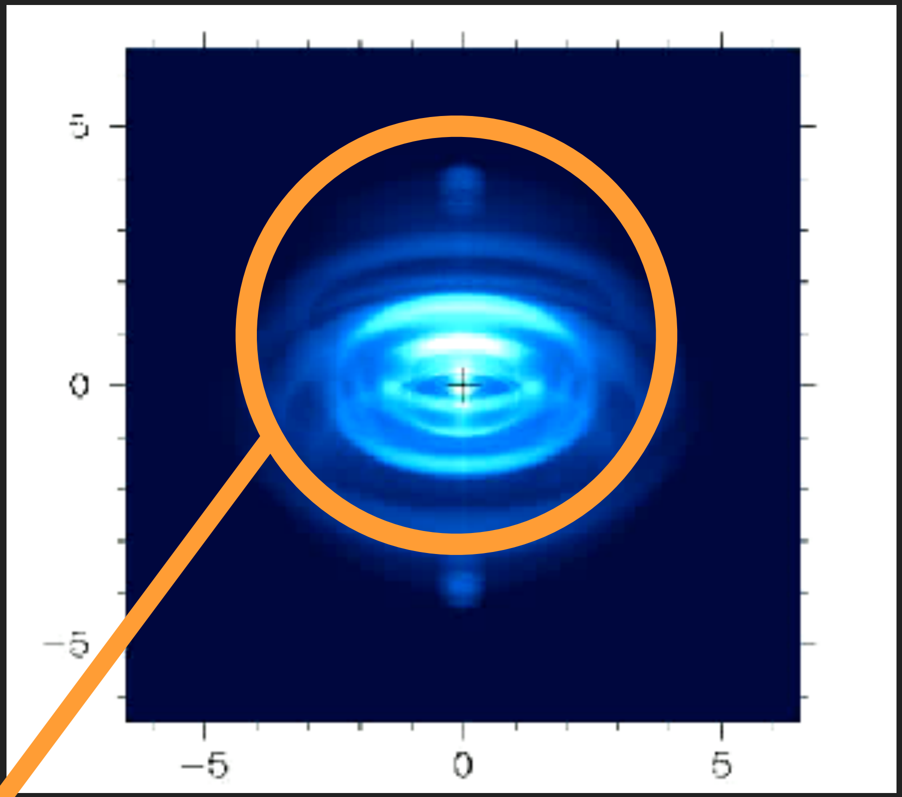

VERY LARGE INTENSITY VARIATIONS

.... THE BAD ......

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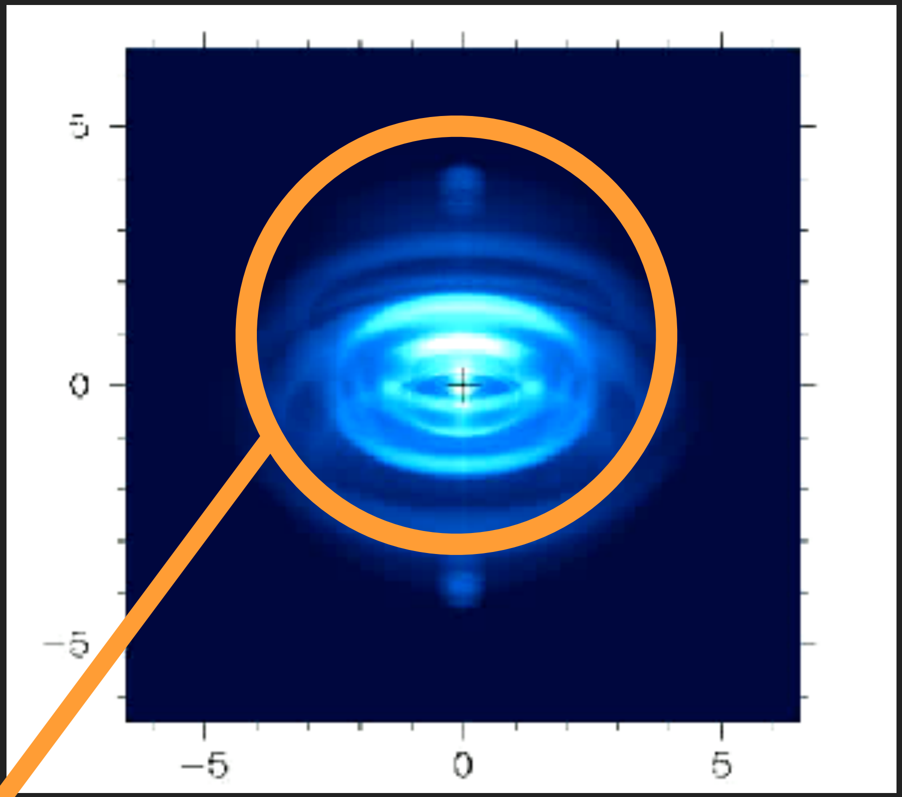


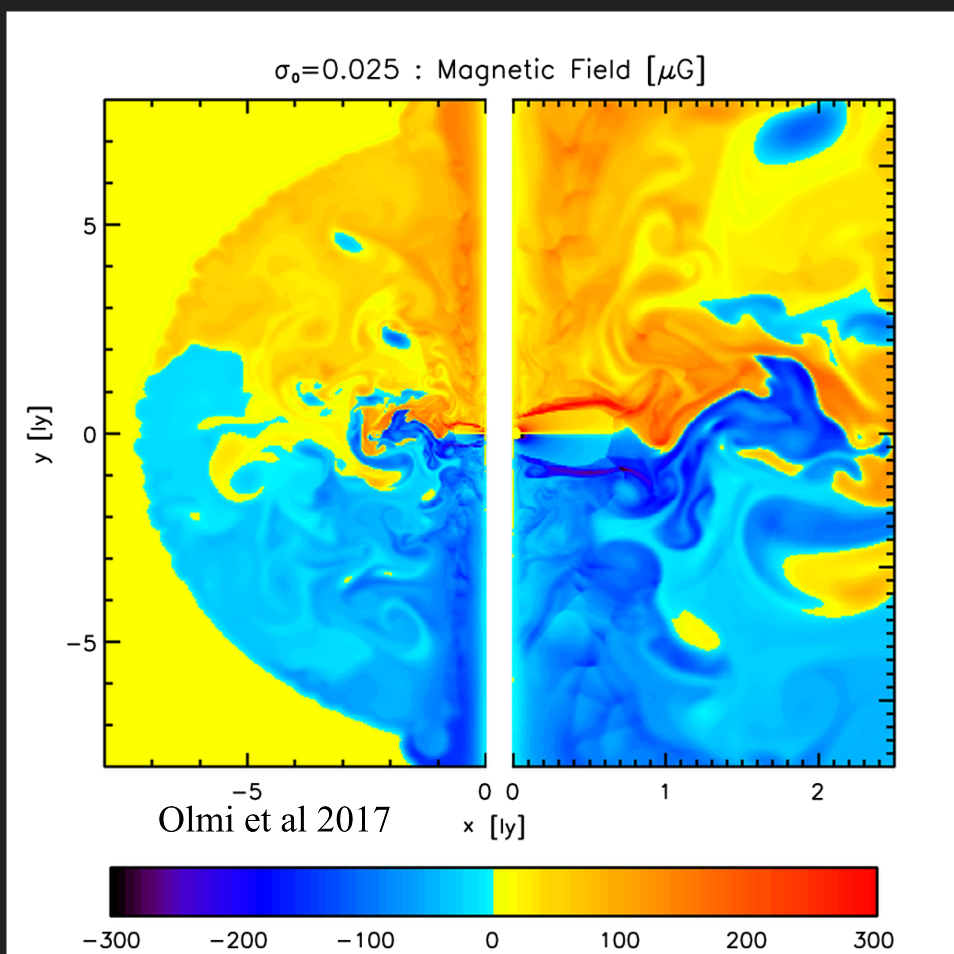
VERY LARGE INTENSITY VARIATIONS

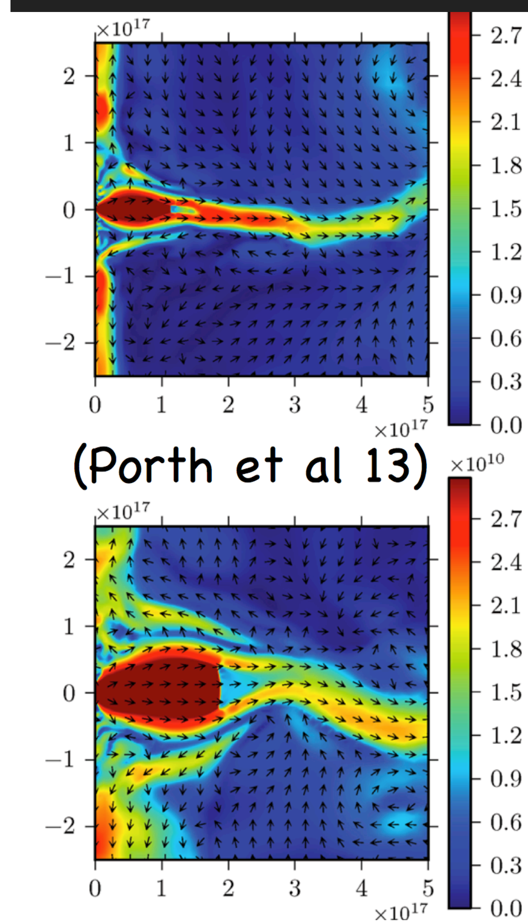
X-RAY INTEGRATED PD ~40-50%

THE UGLY?

3D ALLOWS FOR HIGHER MAGNETISATION

INNER REGION STILL AXISYMMETRIC TORUS-JET



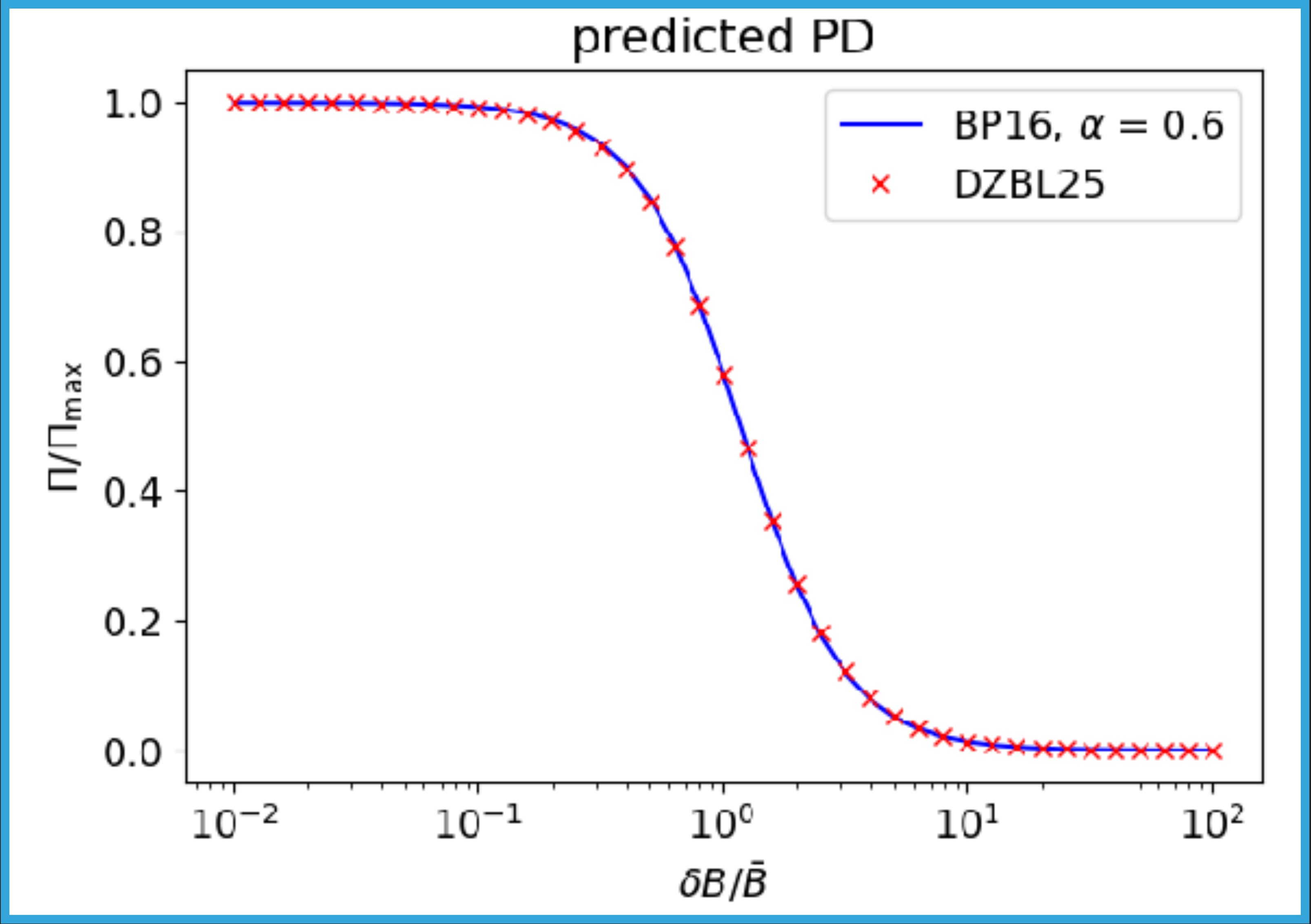


VARIABILITY PROBLEM REMAINS

AVERAGE X-RAY PD ALWAYS < 15%

LARGE SCALE 3D DYNAMICS NOT THE SOLUTION

ADDING UNRESOLVED TURBULENCE



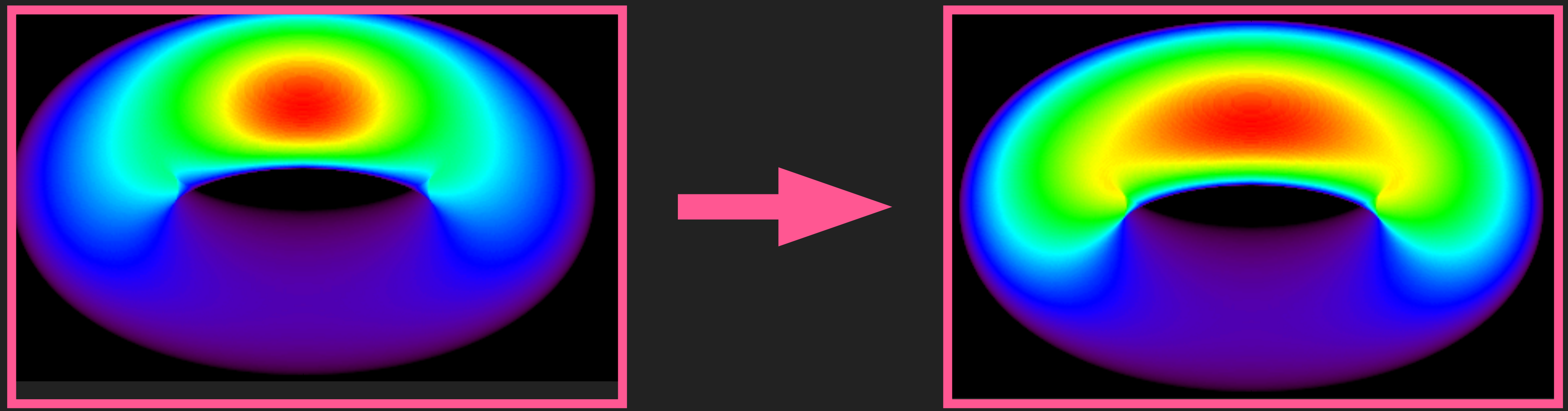
THEORY FOR UNRESOLVED TURBULENCE IN BANDIERA & PETRUK 2016

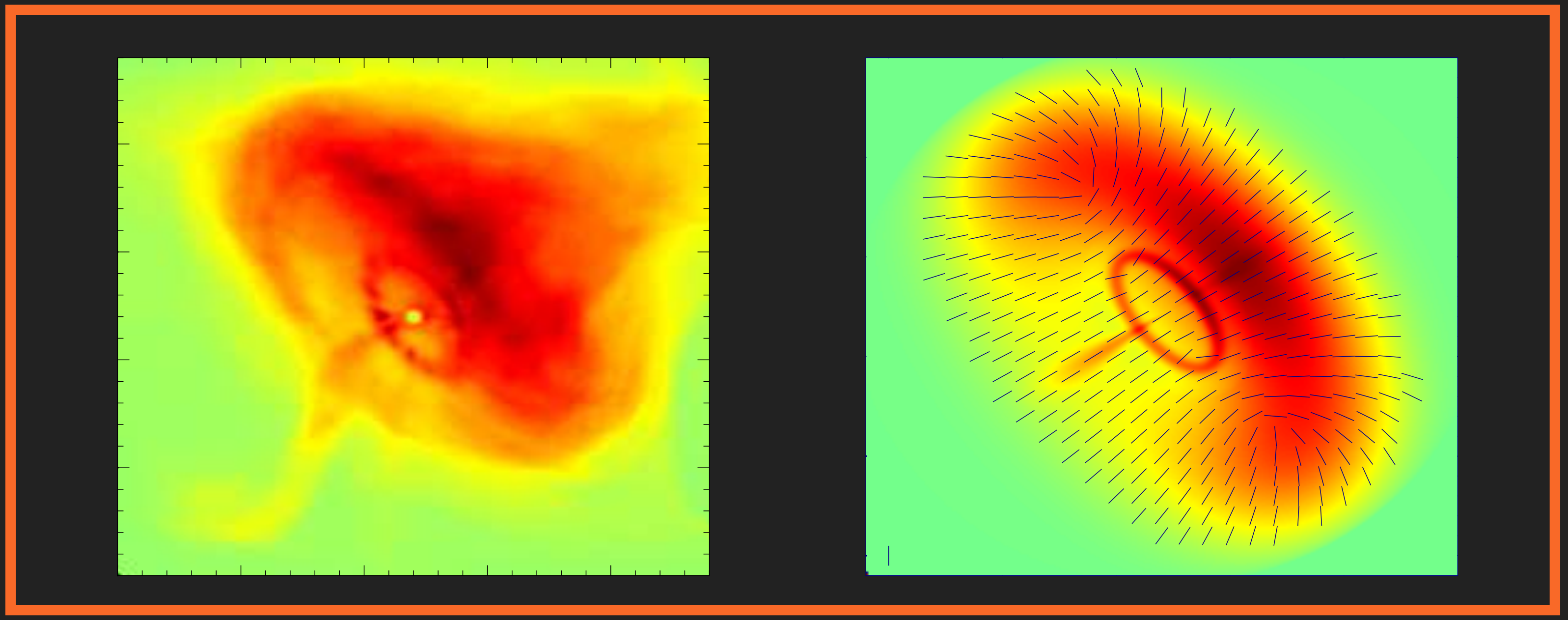
$$\frac{\Pi}{\Pi_{\rm max}} = \left[1 + A\left(\frac{\delta B}{\bar{B}}\right)^2\right]^{-1},$$

A ~ 0.72

$$\frac{\Pi}{\Pi_{\rm max}} = \frac{3+\alpha}{4}\,\xi\,\frac{{}_1F_1[\,(1-\alpha)/2, 3; -\xi\,]}{{}_1F_1[\,-(1+\alpha)/2, 1; -\xi\,]}, \quad \xi = \frac{3}{2}\left(\frac{\bar{B}}{\delta B}\right)^2,$$

ADDING UNRESOLVED TURBULENCE





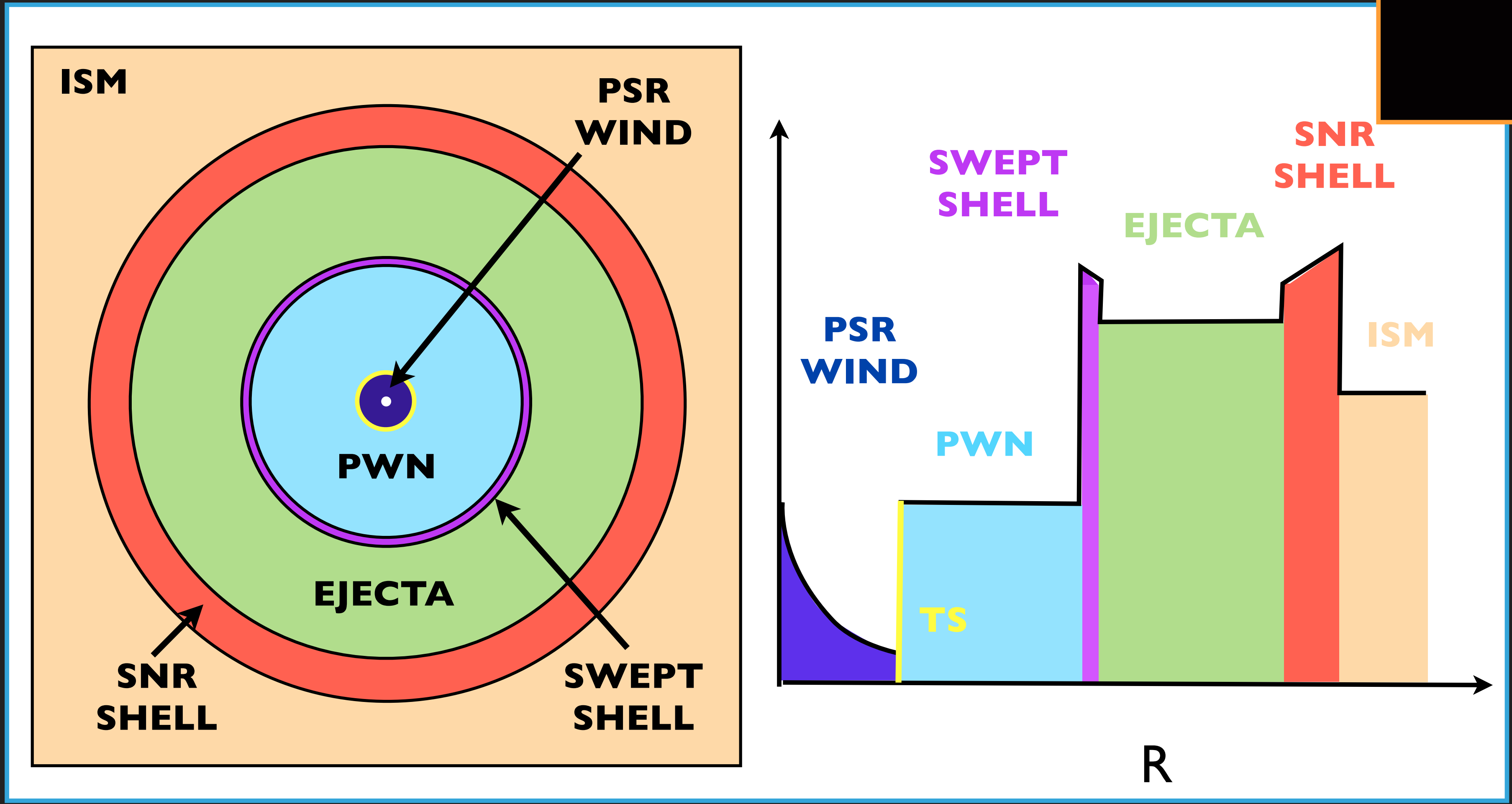
ONE NEED TO HAVE $\delta B/B \sim 1$
IN ORDER TO GET AVERAGE PD ~ 20%

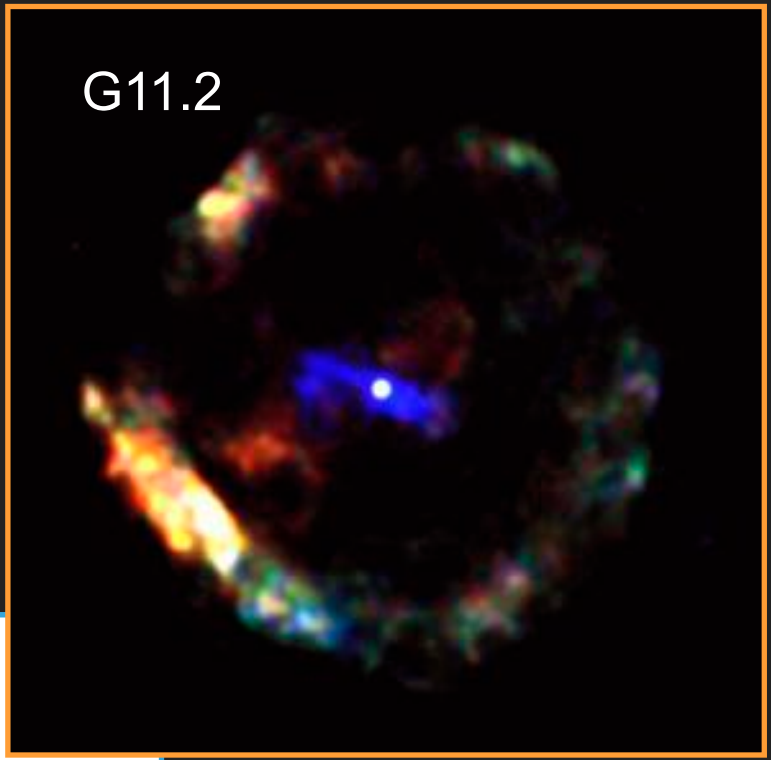
STRUCTURE OF YOUNG PWNE

$$V_{psr} \approx 100 - 400 \text{ km s}^{-1}$$
$$V_{snr} \approx 1000 - 2000 \text{ km s}^{-1}$$
$$V_{pwn} \approx 1000 - 2000 \text{ km s}^{-1}$$

PWN expands inside the cold & unshocked SNR ejecta
PWN & PSR remains almost centred inside the SNR

FREE EXPANSION PHASE



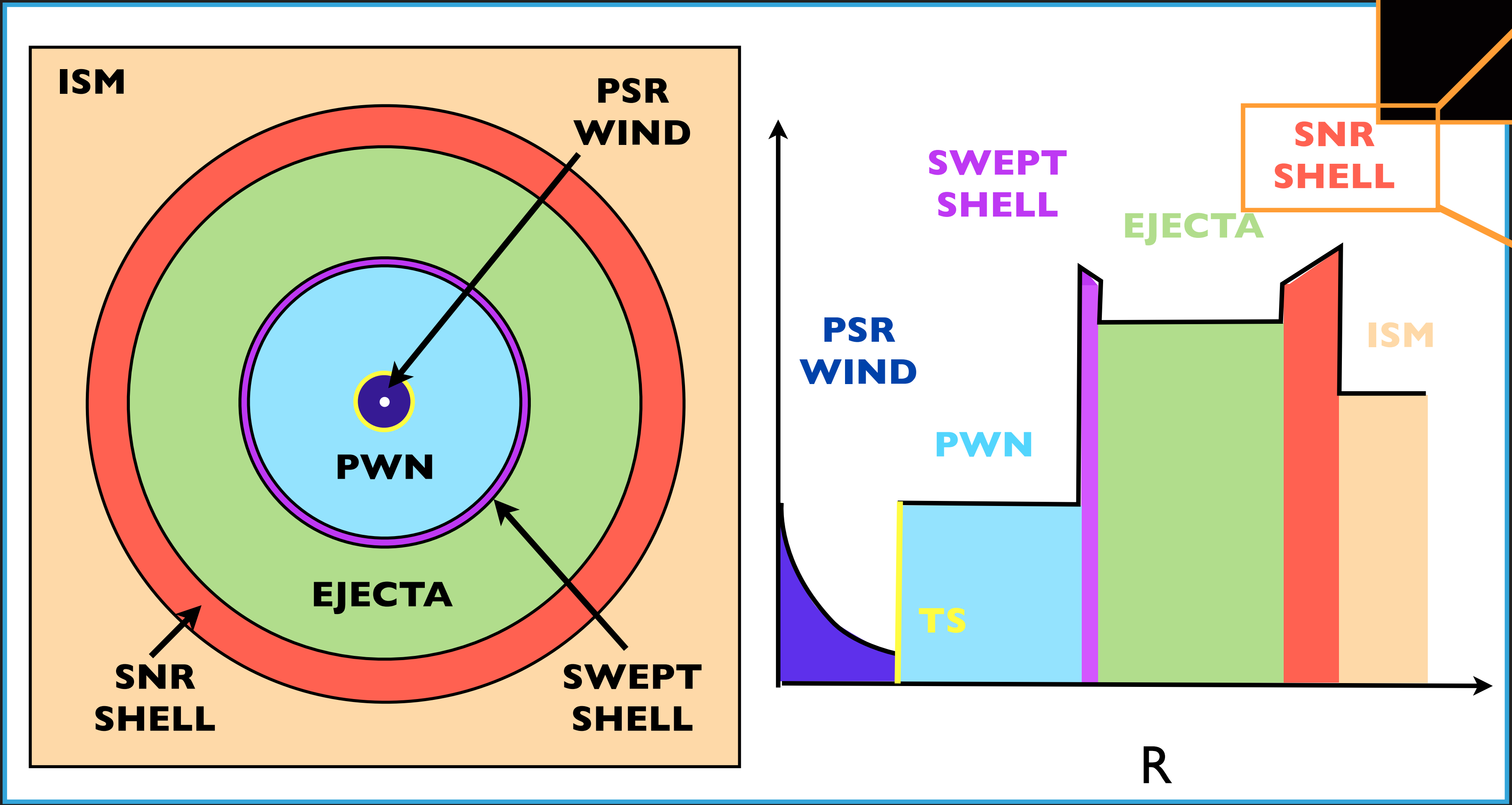


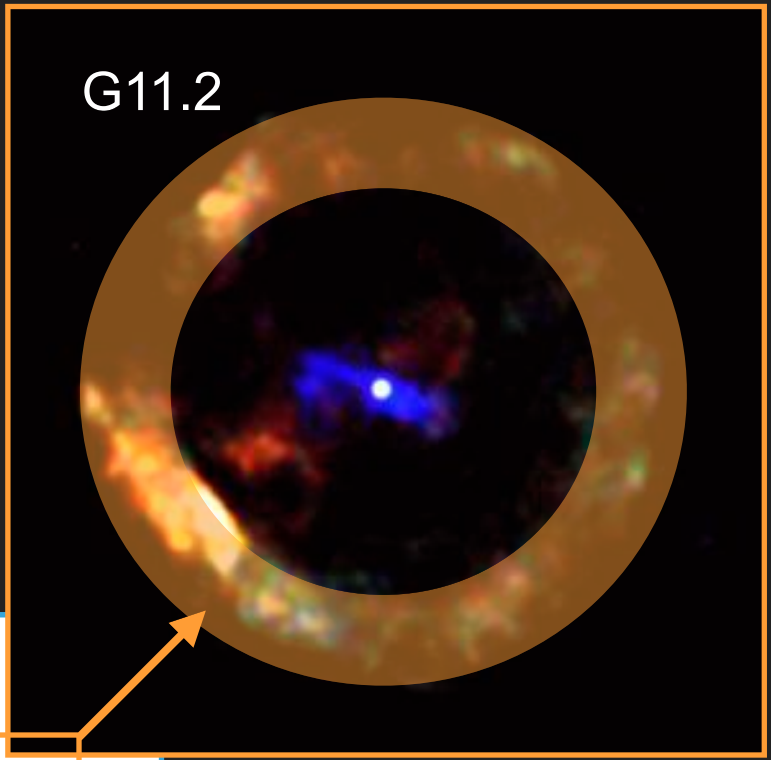
STRUCTURE OF YOUNG PWNE

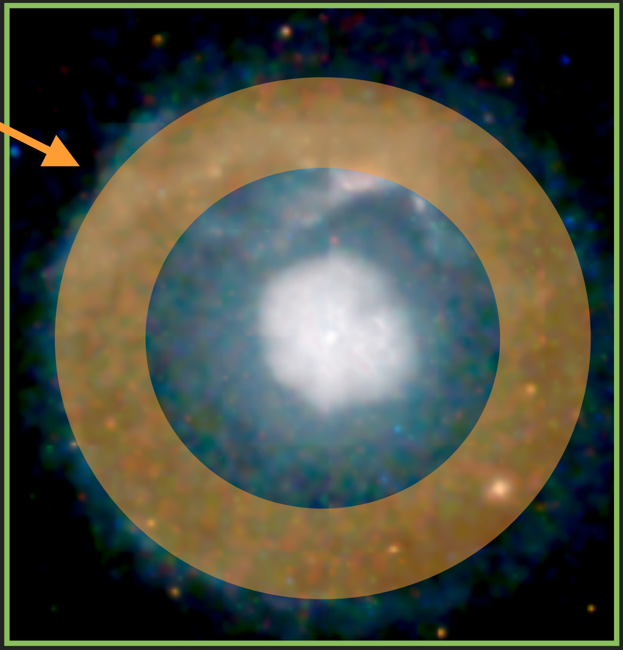
$$V_{psr} \approx 100 - 400 \text{ km s}^{-1}$$
$$V_{snr} \approx 1000 - 2000 \text{ km s}^{-1}$$
$$V_{pwn} \approx 1000 - 2000 \text{ km s}^{-1}$$

PWN expands inside the cold & unshocked SNR ejecta
PWN & PSR remains almost centred inside the SNR

FREE EXPANSION PHASE







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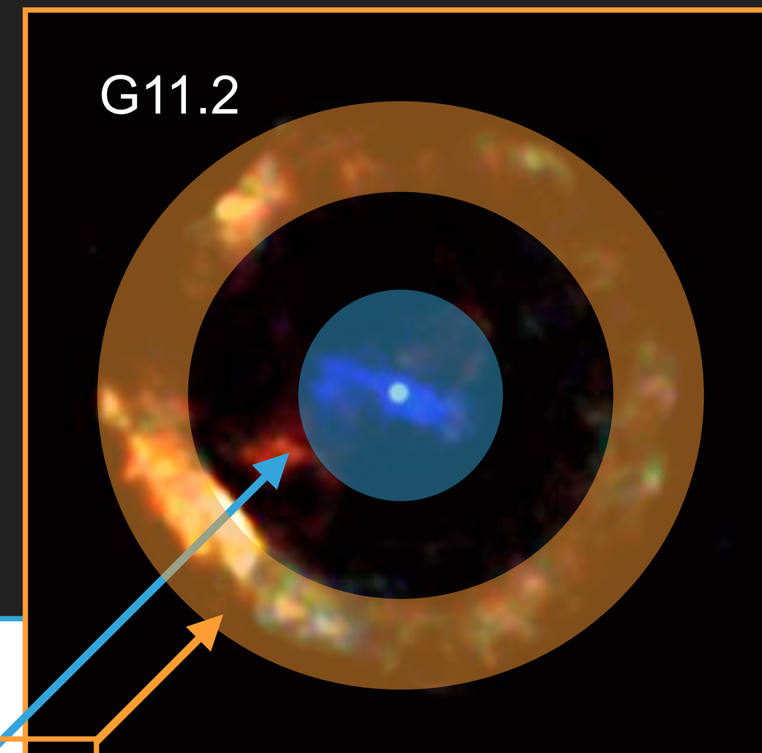
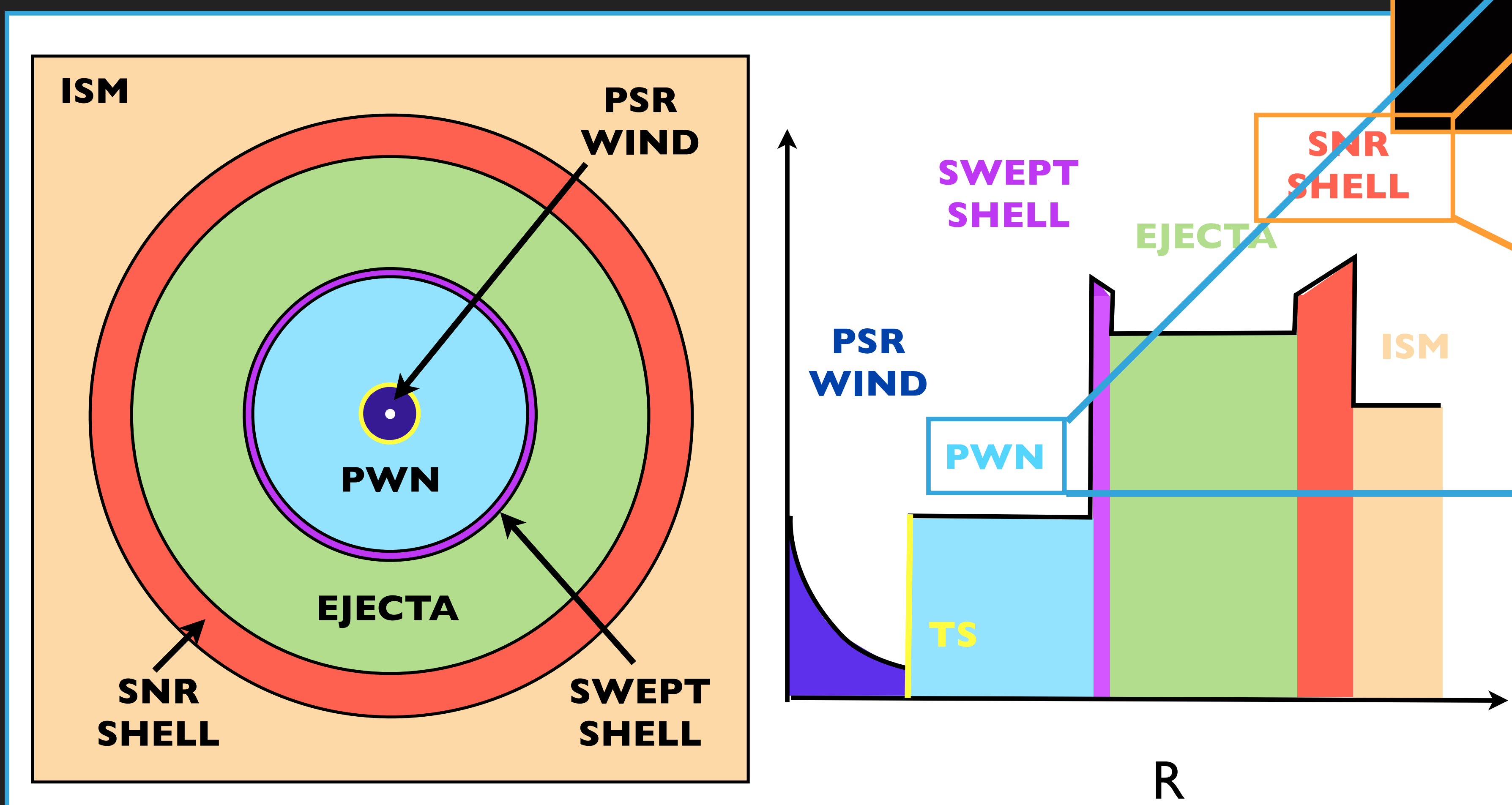
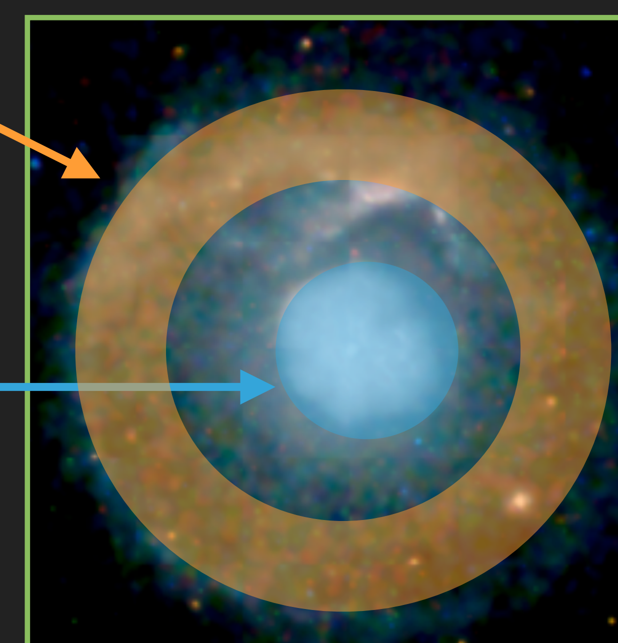






STRUCTURE & EVOLUTION OF PWNE

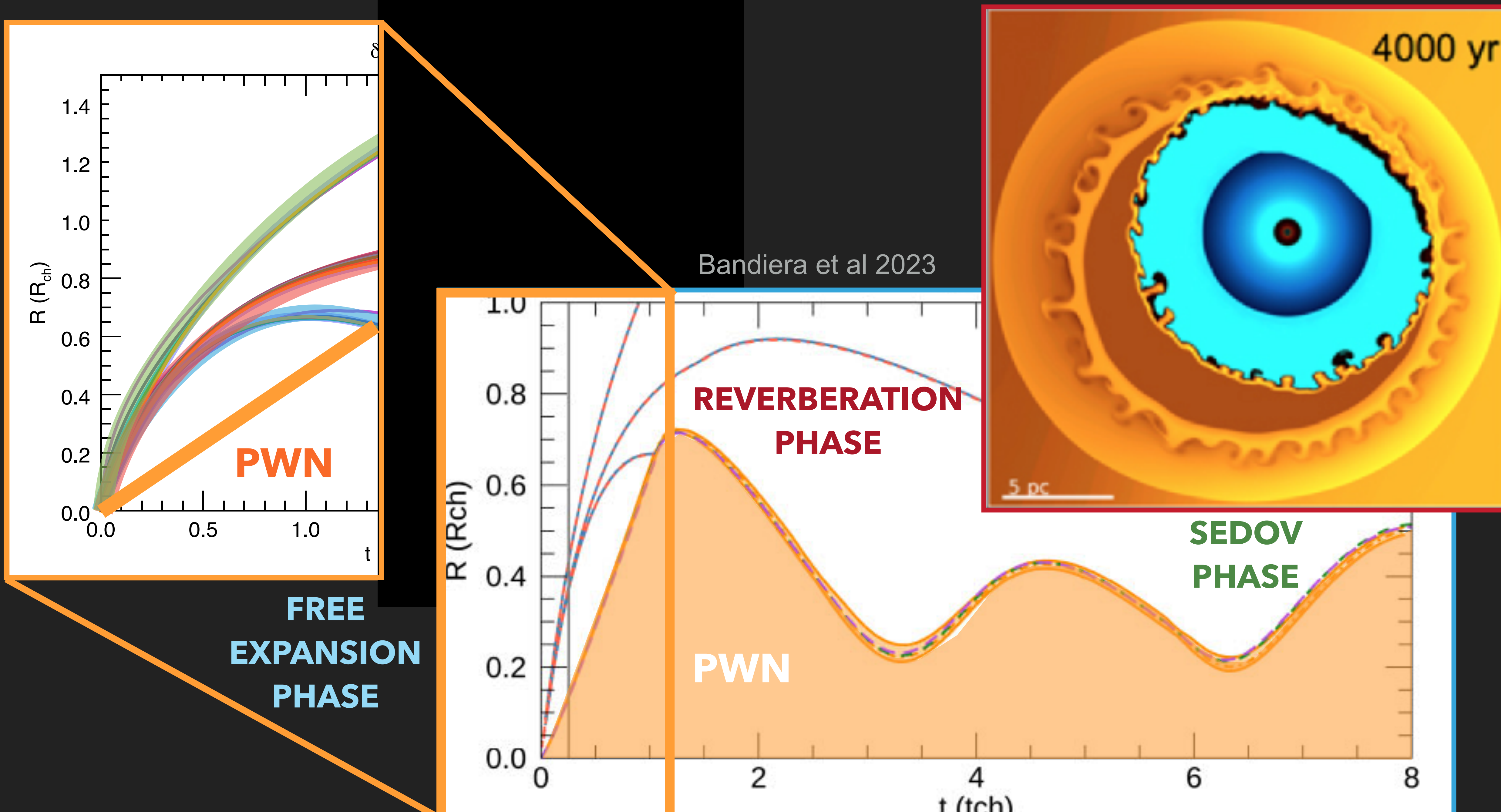
At T ~ Tch (3000-5000 yr) the PWN has expanded to reach the position of the SRN reverse shock

This is the beginning of the so called “Reverberation phase” - expected compression of the PWN

At T > few Tch the PWN should relax to the “Sedov driven phase” $R_{pwn} \propto t^{3/10}$

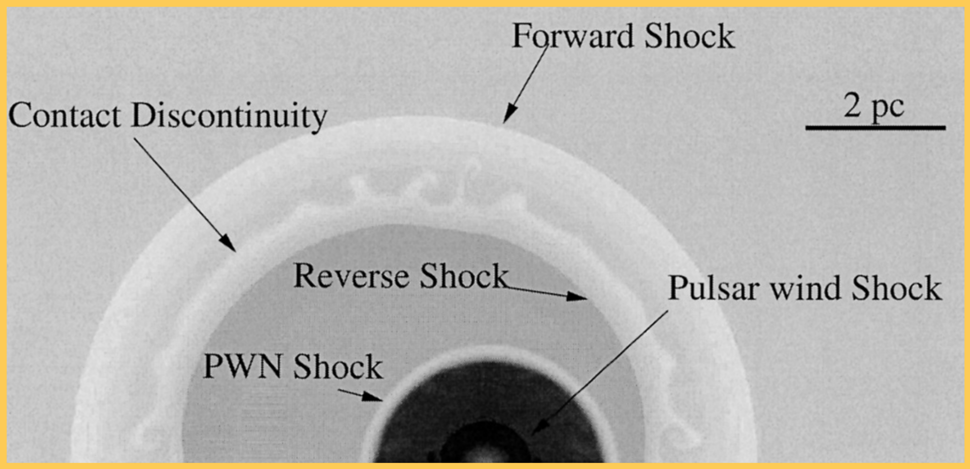
Kolb et al 2017

Bandiera et al 2023



PWNE IN REVERBERATION

Van der Swaluw 2003

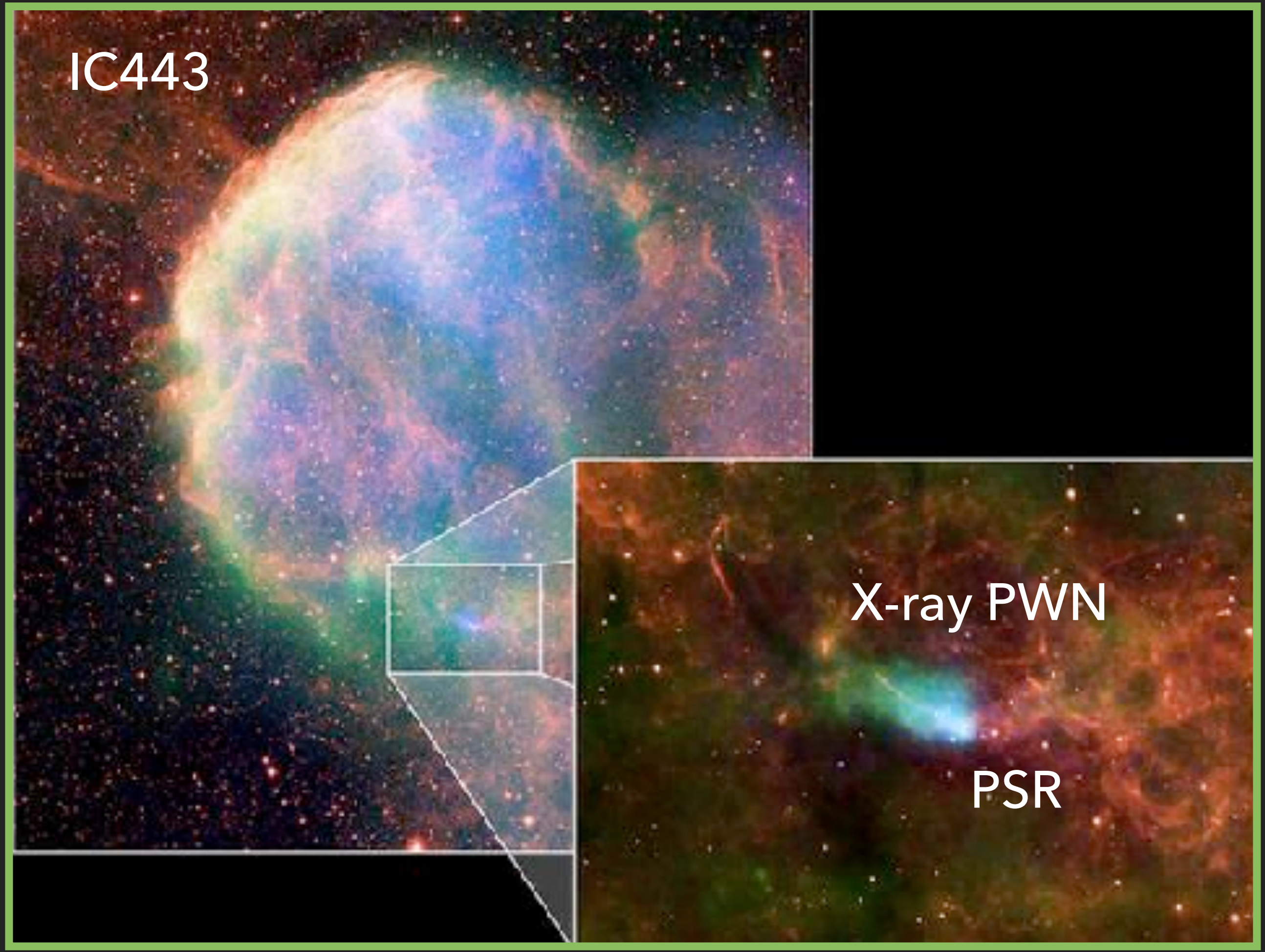


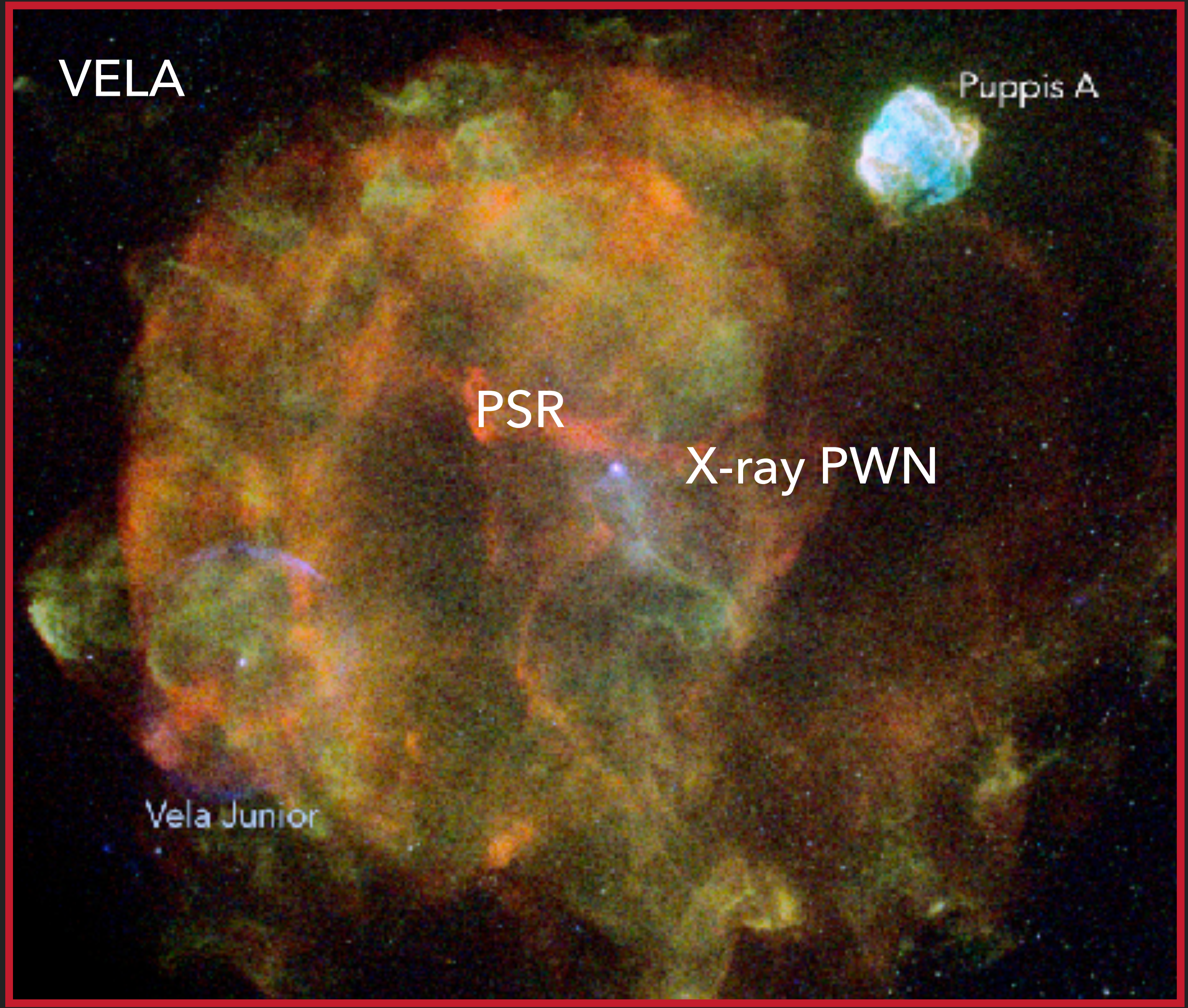
Not that many examples of PWNe in reverberation:
Short phase duration (few 1000s yr) - Low PSR luminosity

PSR & PWN often displaced wrt the SNR center

Compression might lead to re-brightening

Formation of a relic nebula





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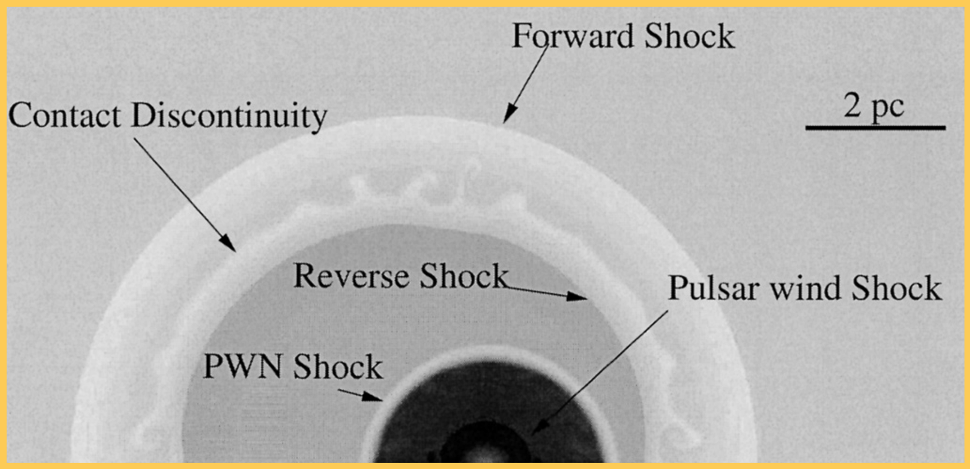

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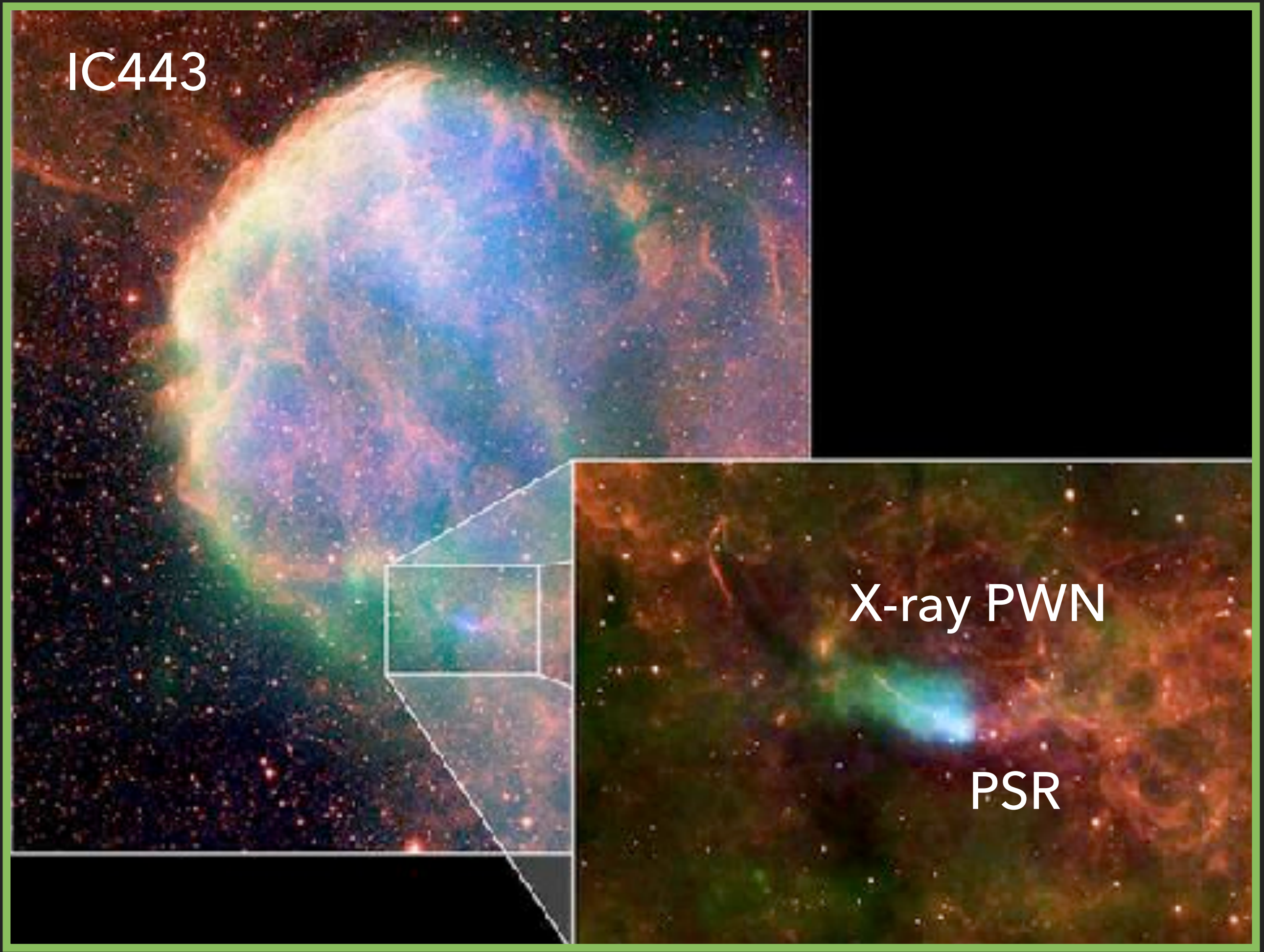
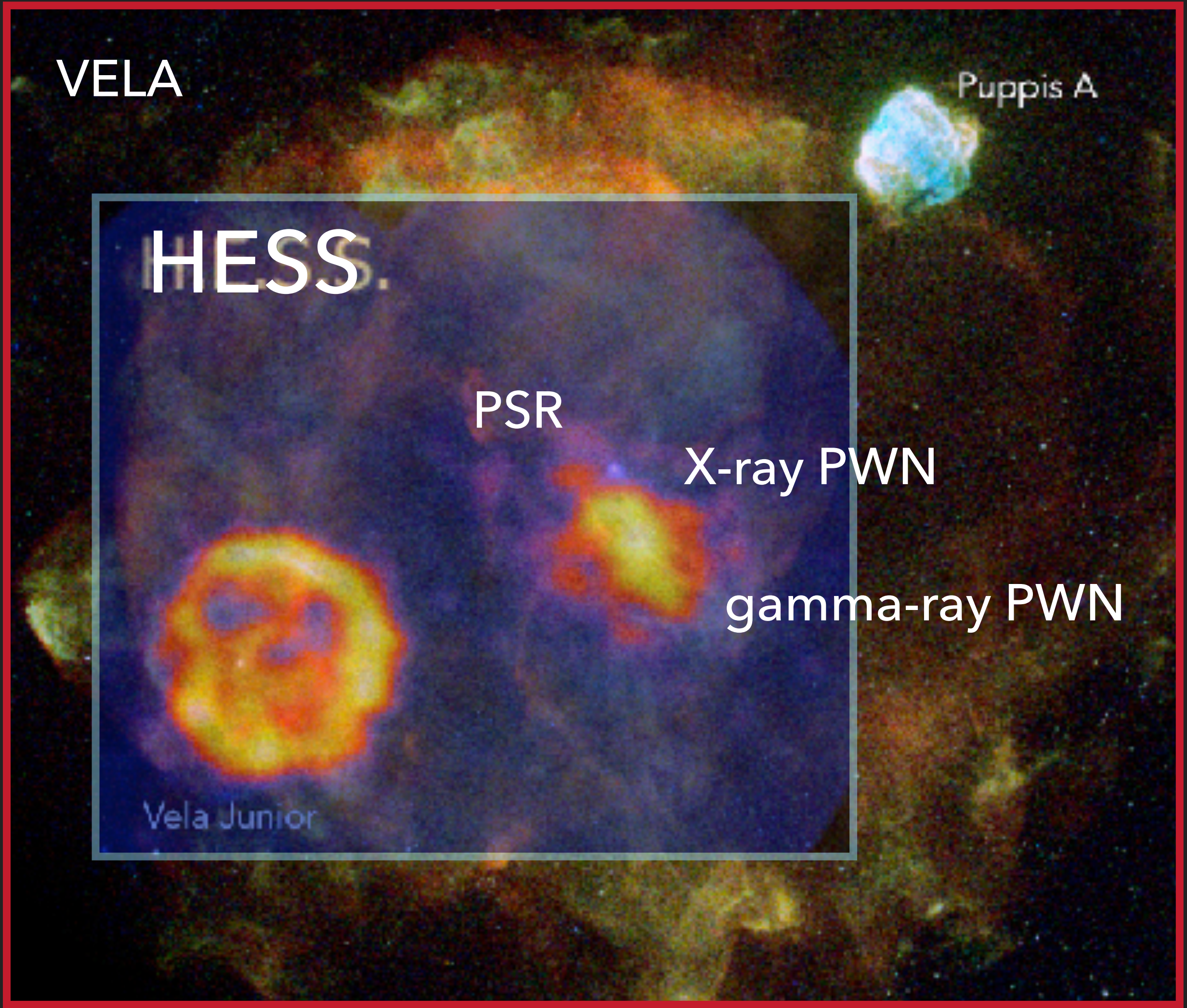
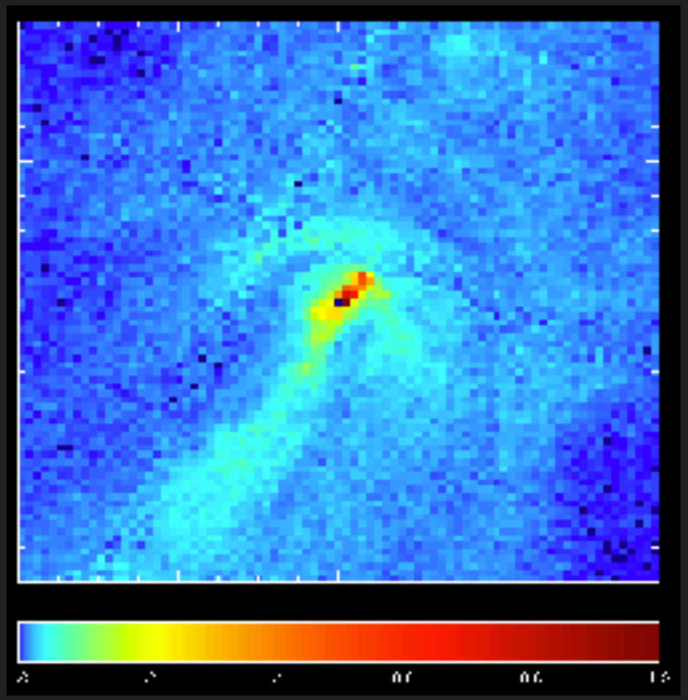




PWNE – SYNCHROTRON DEGENERACY



Jet Dominated system

Variability in the jet

Nature of variability on magn. geometry

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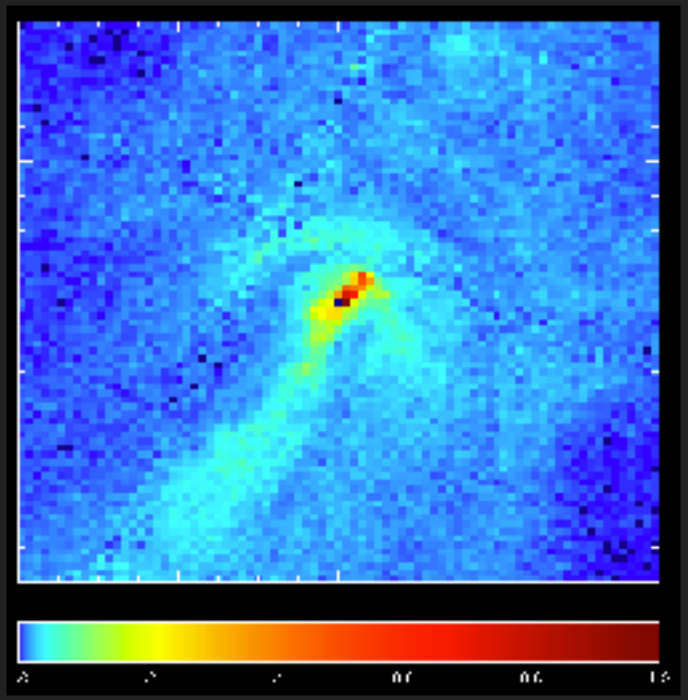

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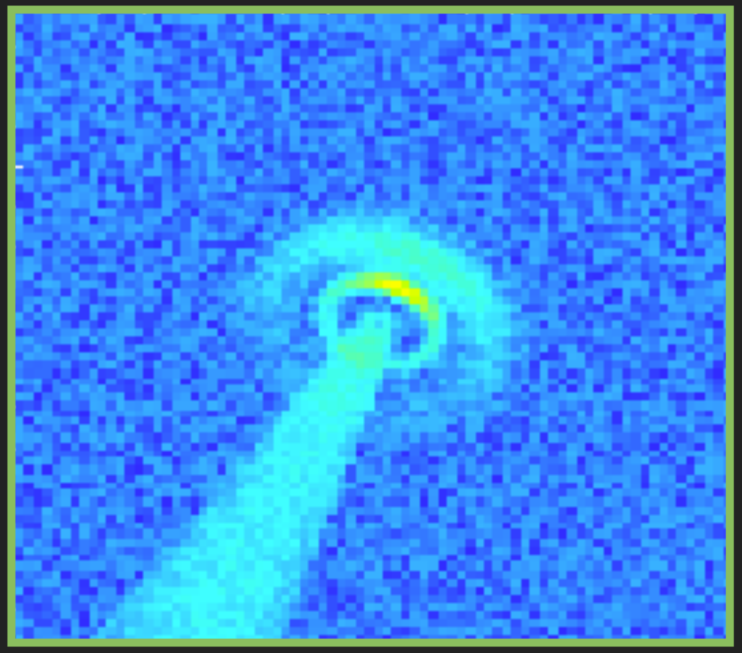

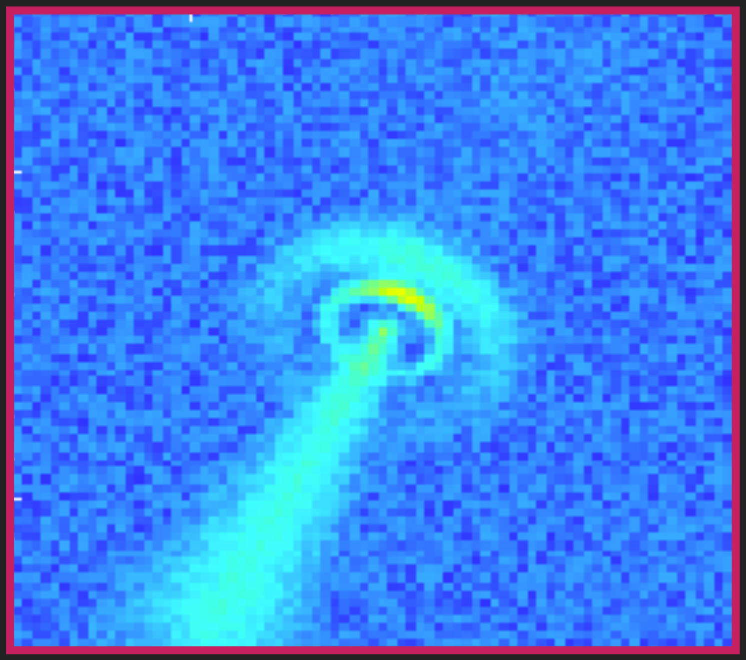

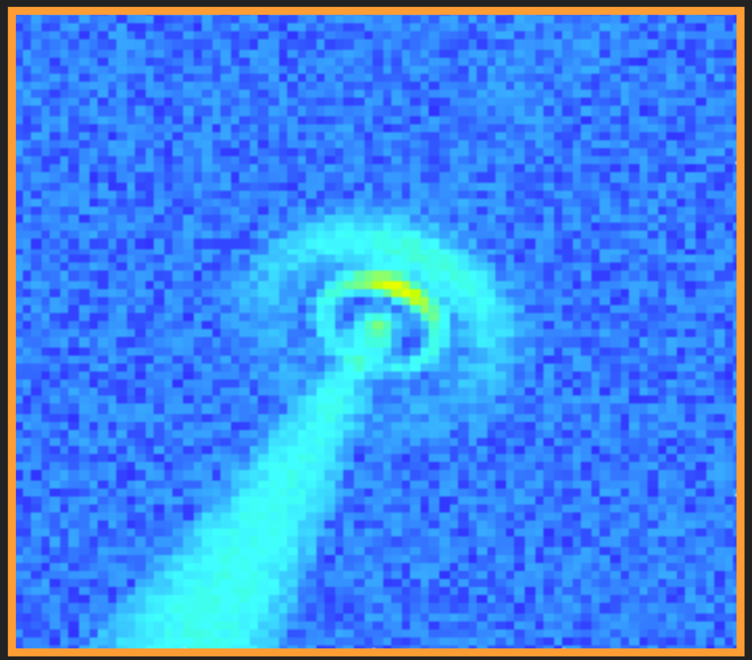

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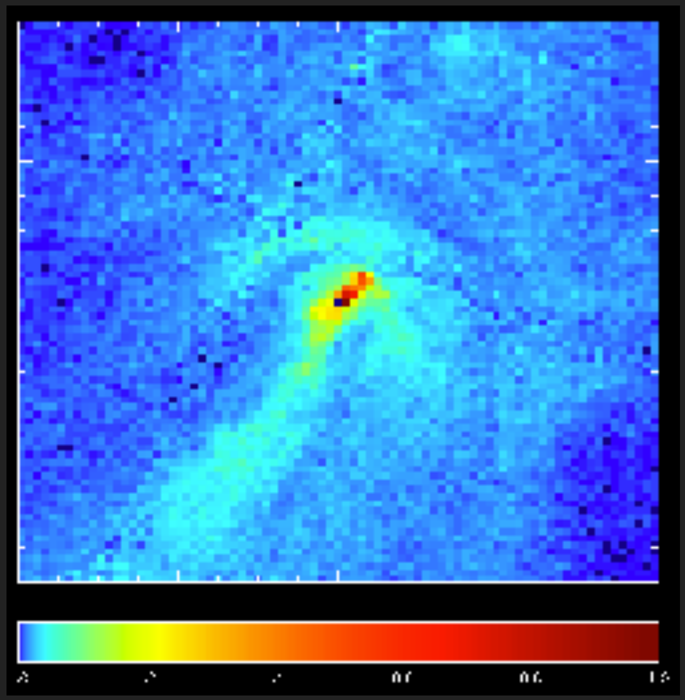

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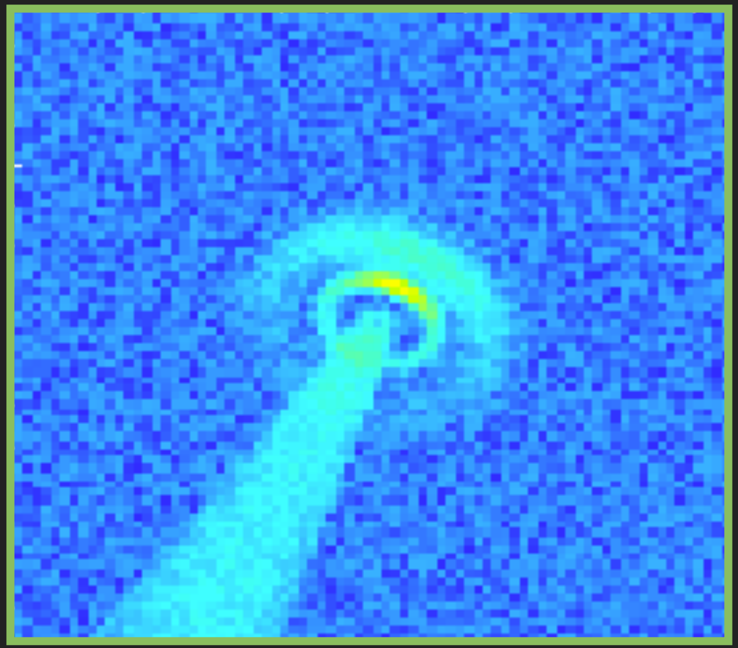
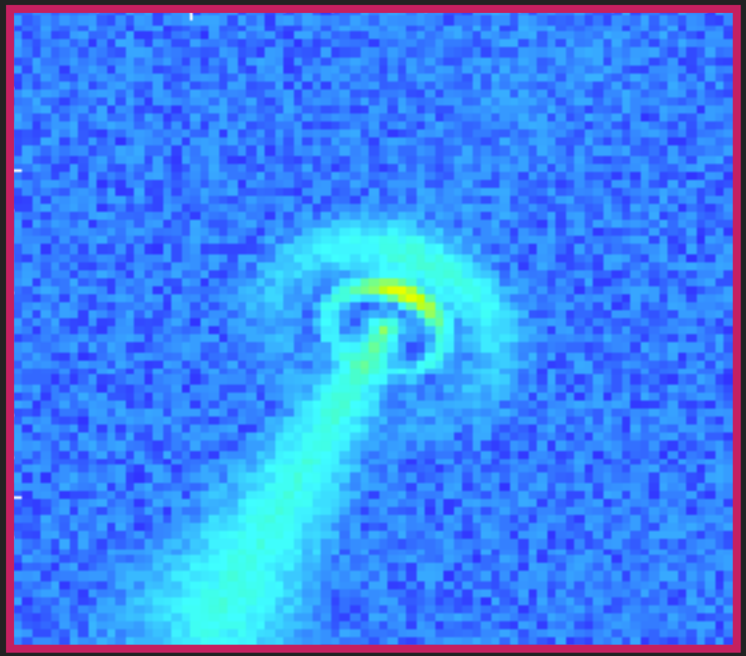
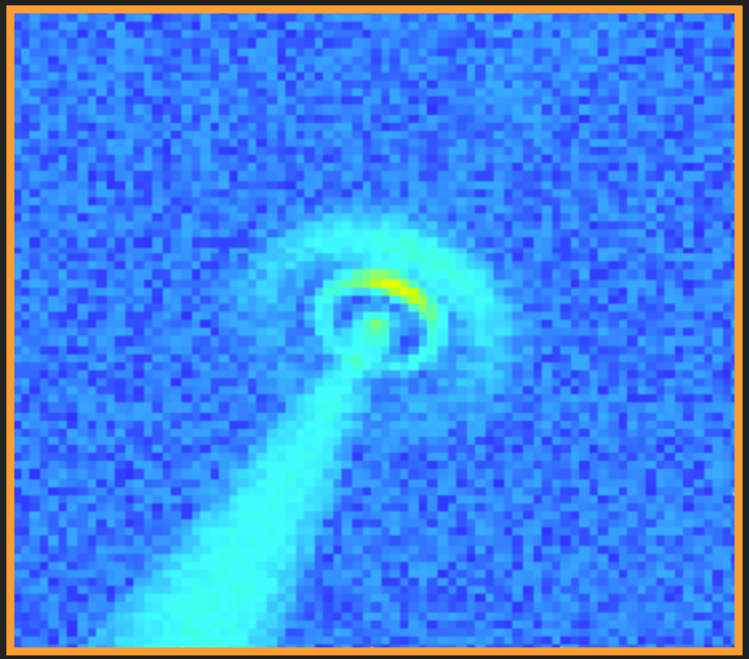




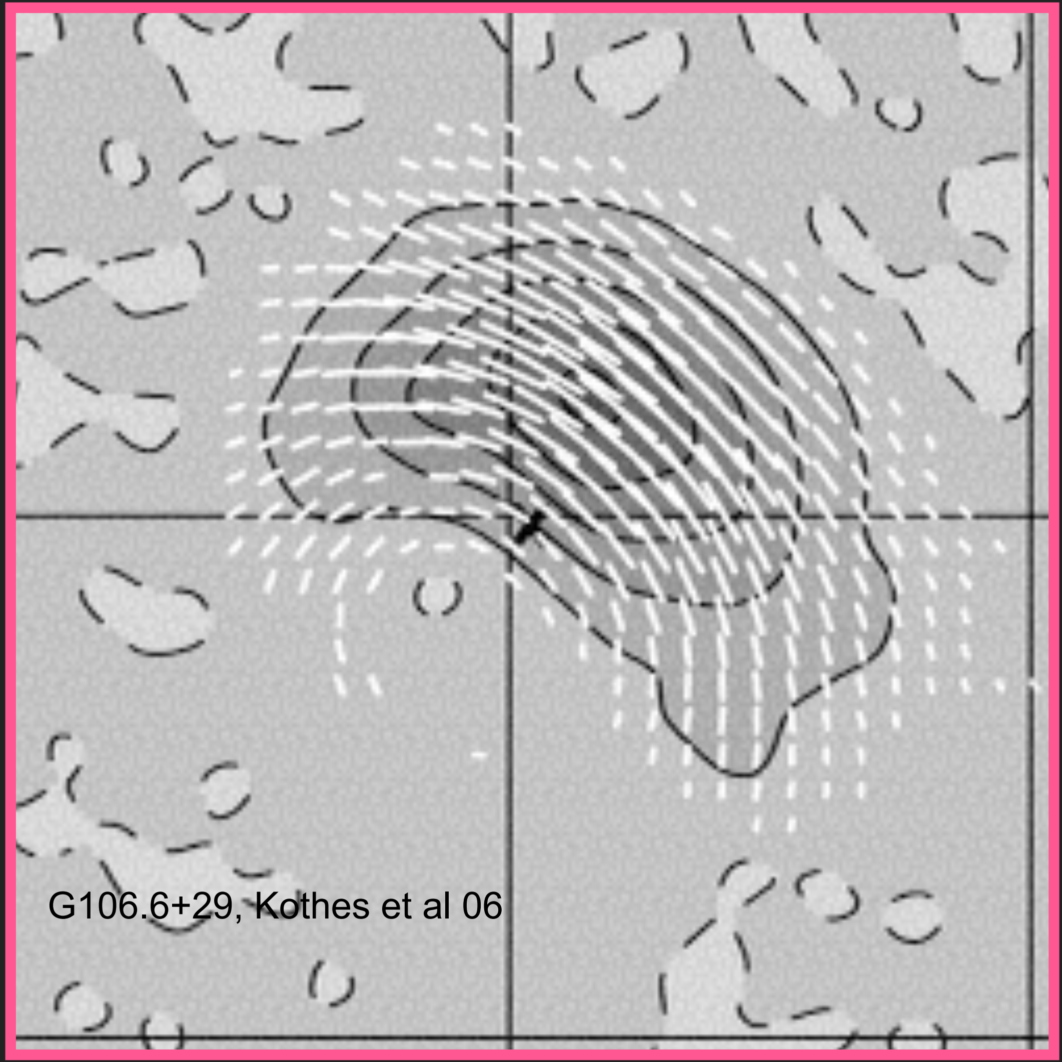


Radial **Toroidal** **Random**

RADIO POLARIZATION 1

Some PWNe show a toroidal magnetic field structure in agreement with canonical model of confined PSR wind

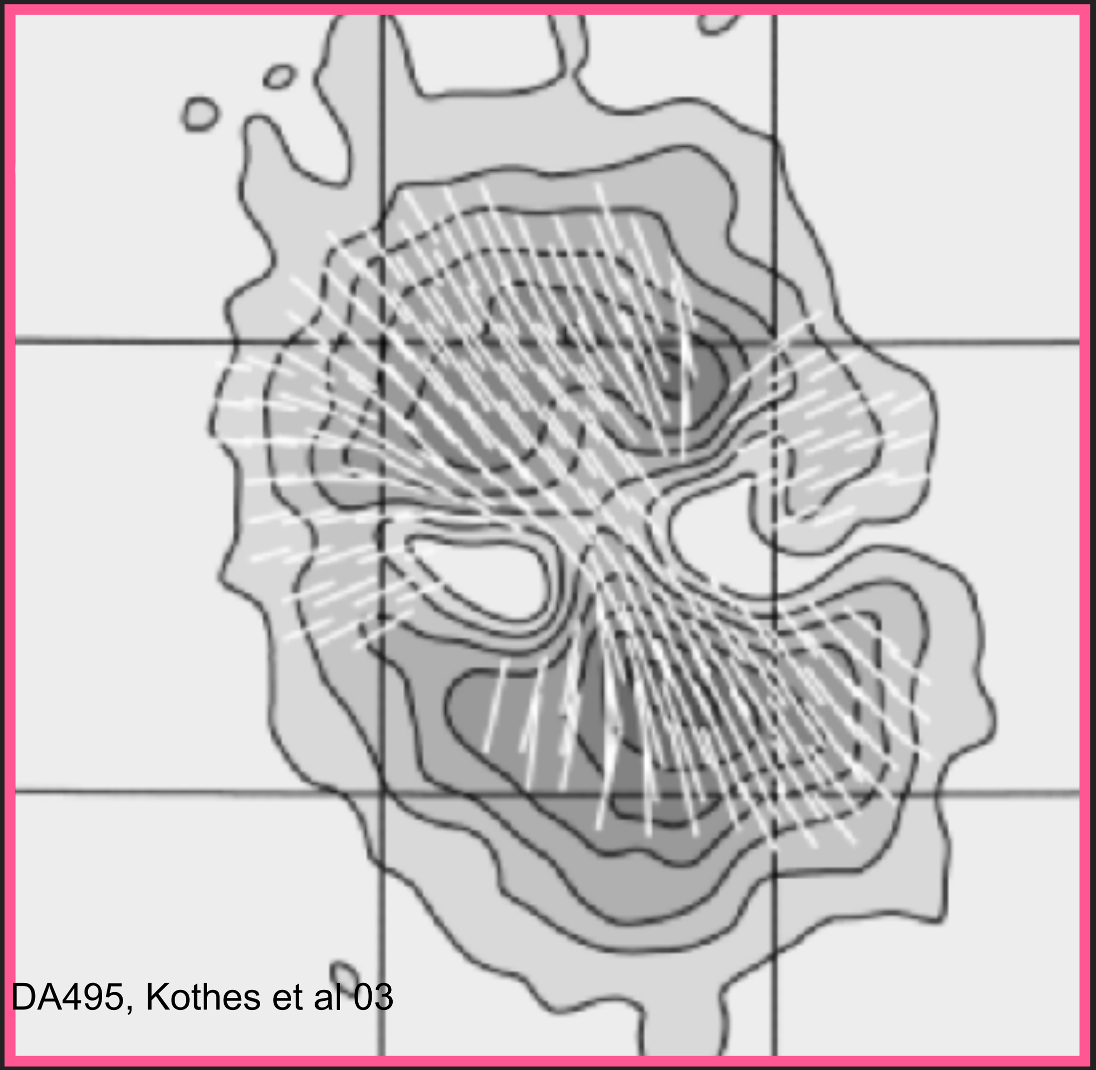
Typical polarization is high ~ 40-50%

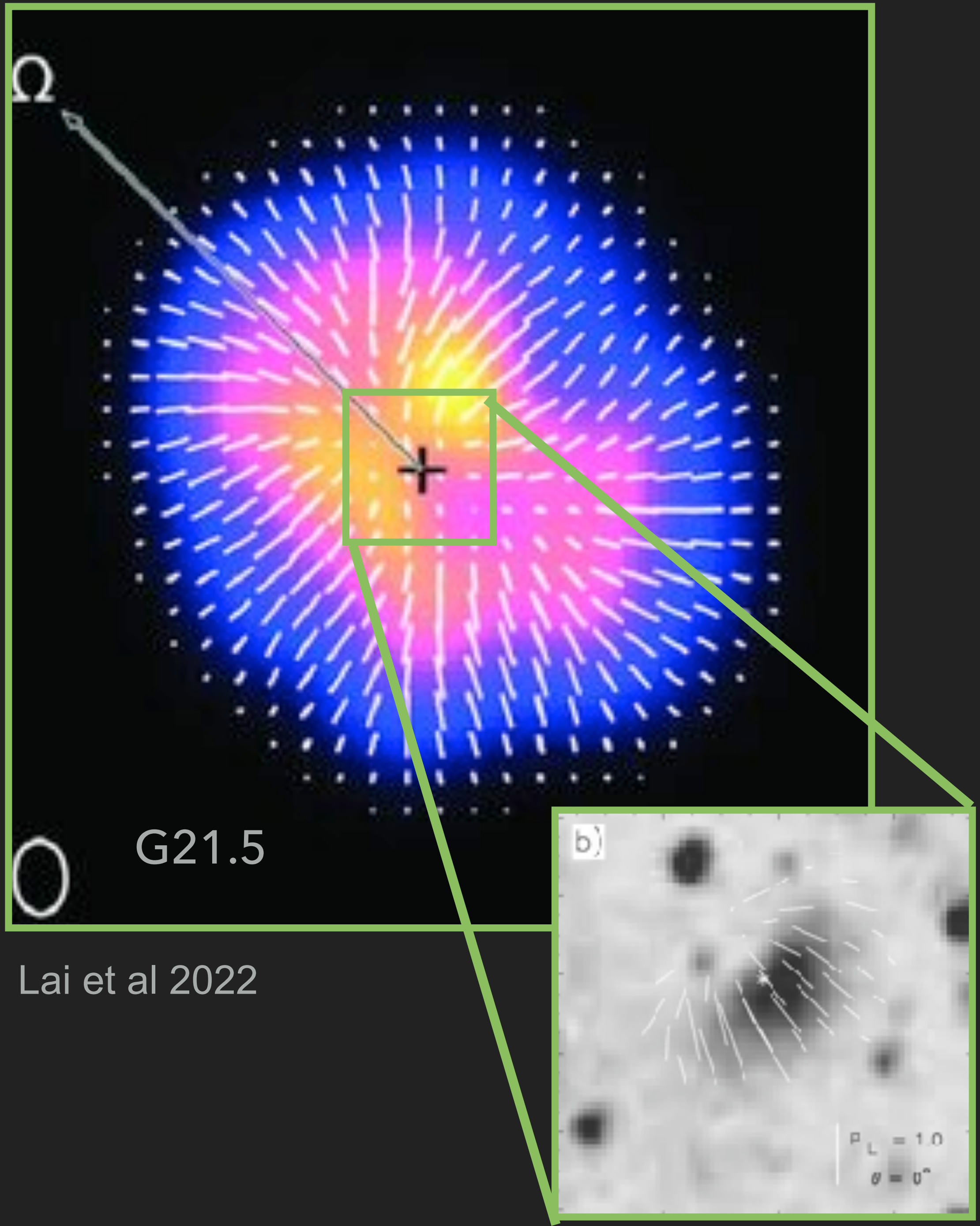


Dodson et al 2003

RADIO POLARIZATION 2

Some PWNe show a radial or dipole-like magnetic field geometry, typically attributed to RT instability from confining environment

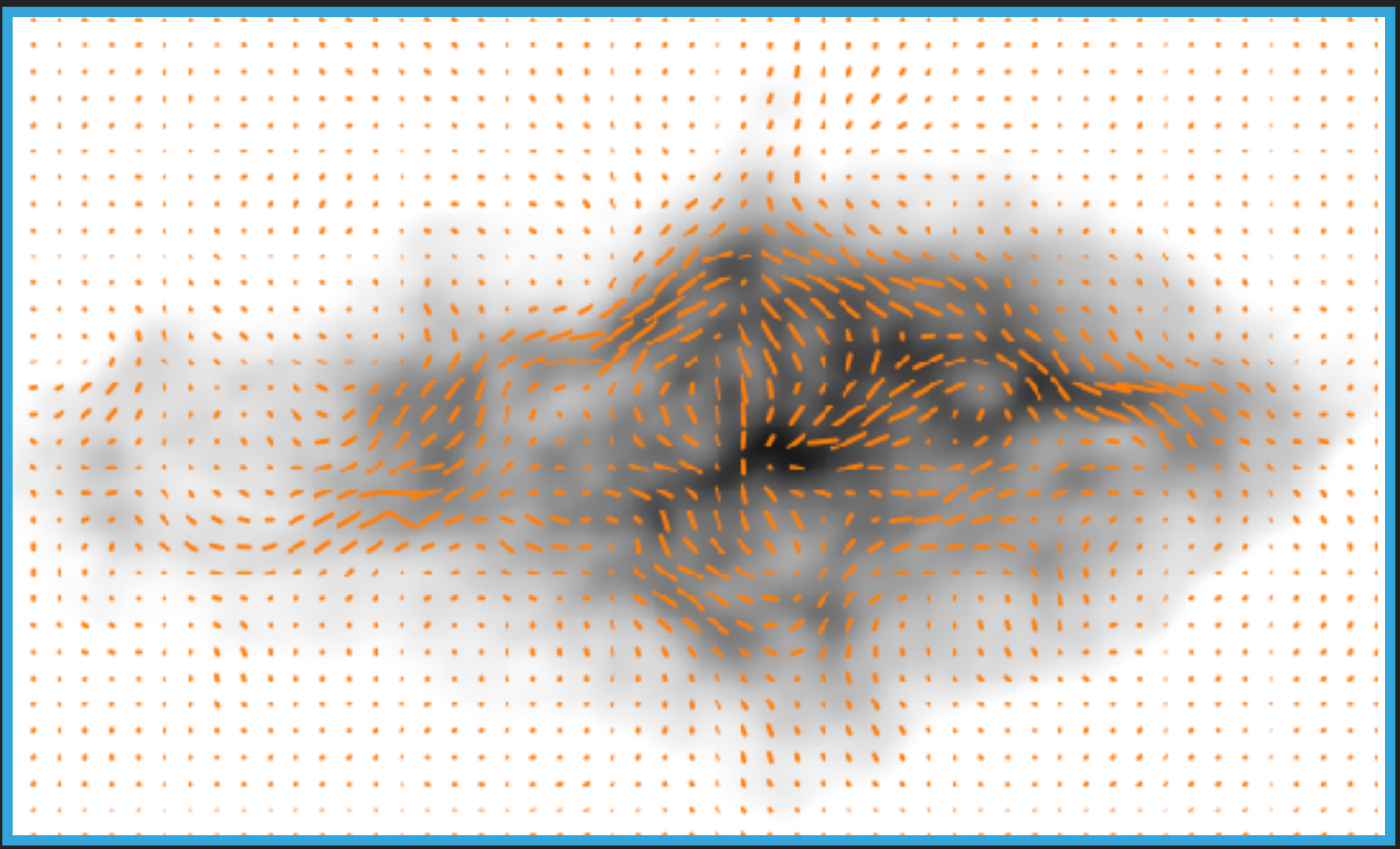




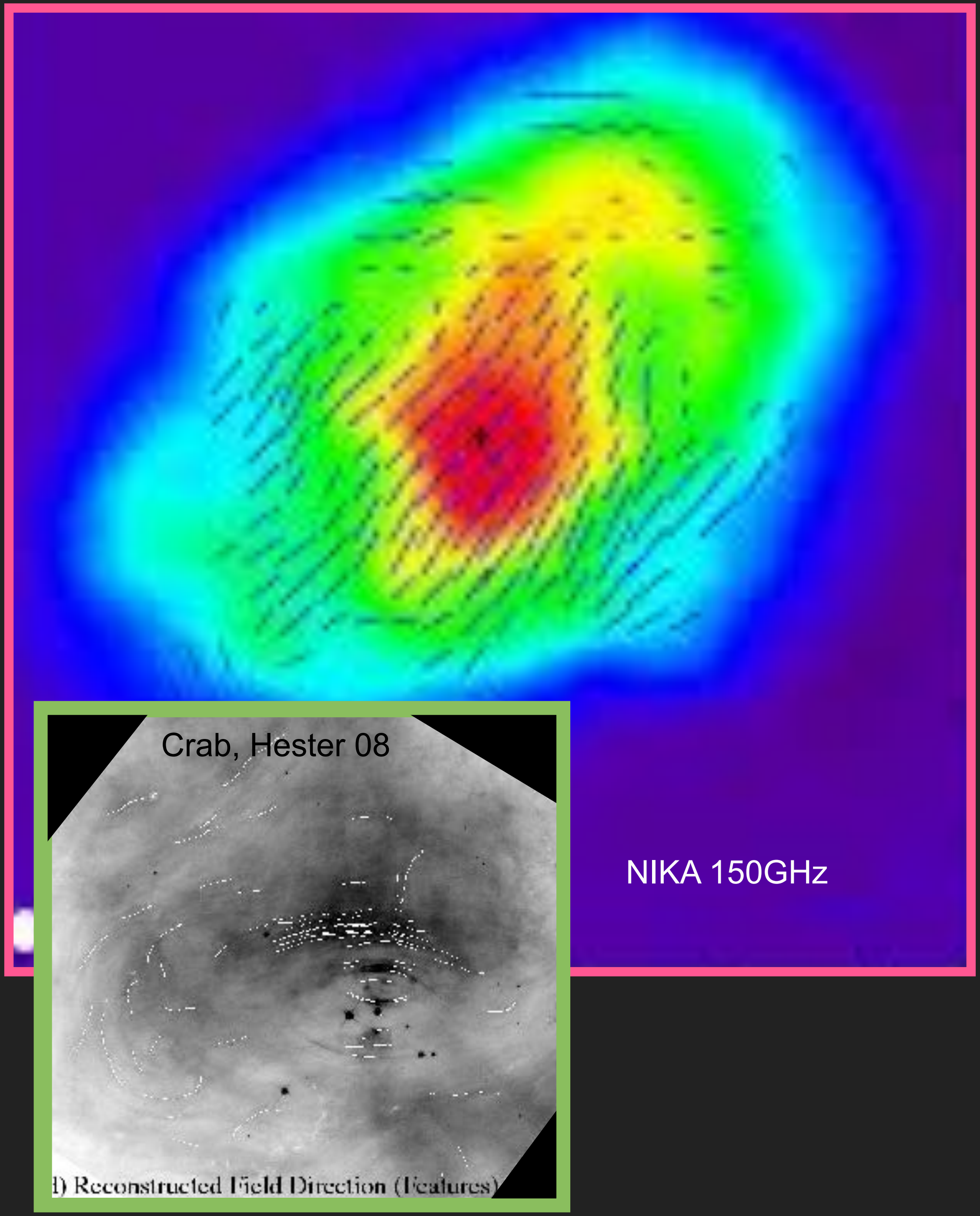
Lai et al 2022

RADIO POLARIZATION 3

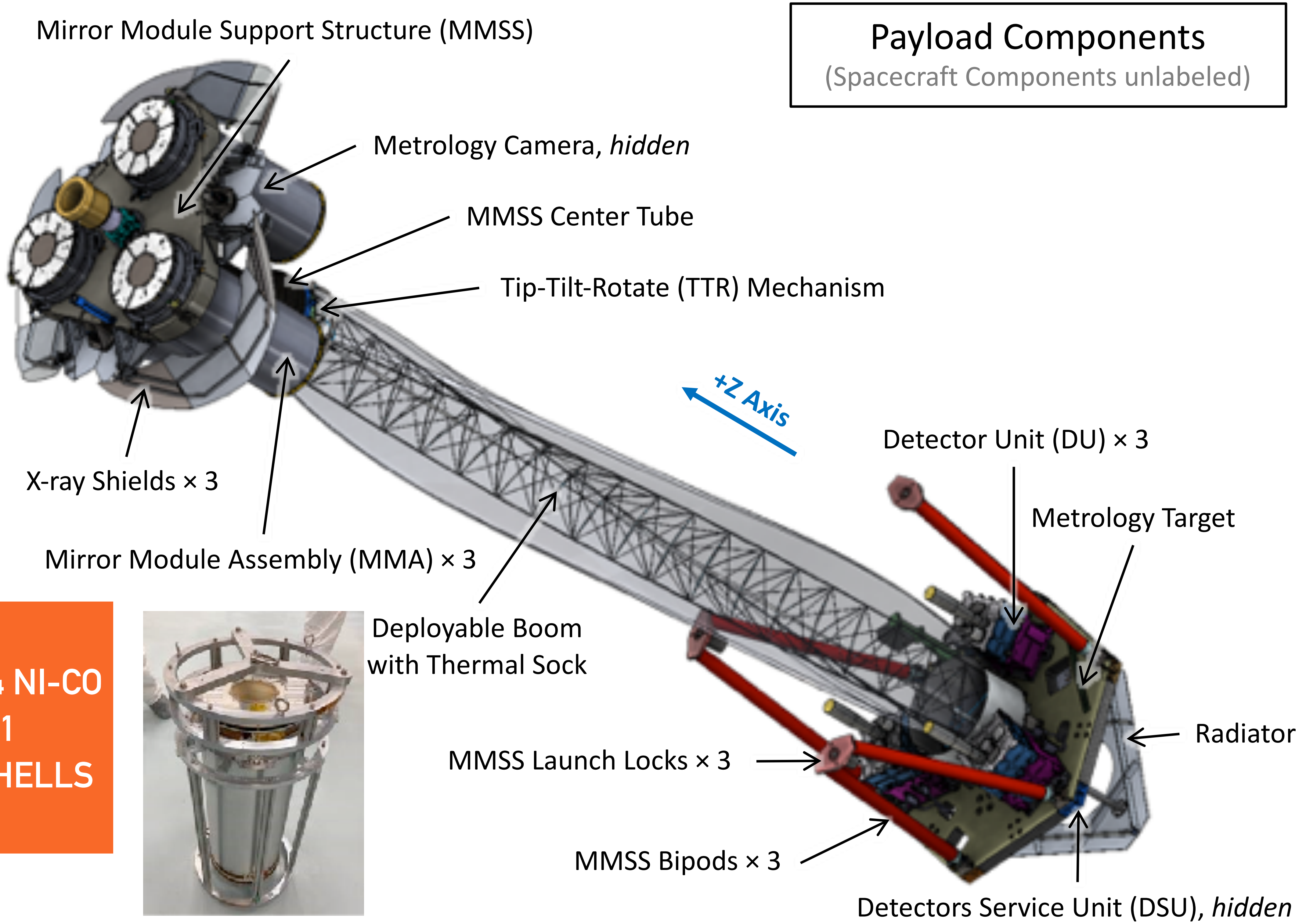
Some PWNe show irregular polarization structures that do not map other observed features, or loop-like structures that are unrelated with either injection or environment



3C 58 - Preliminary



IXPE



24 NI-CO
W1
SHELLS

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
X-ray calibration	Telescopes (optics & detector separately, combined) on-ground; detectors on-orbit

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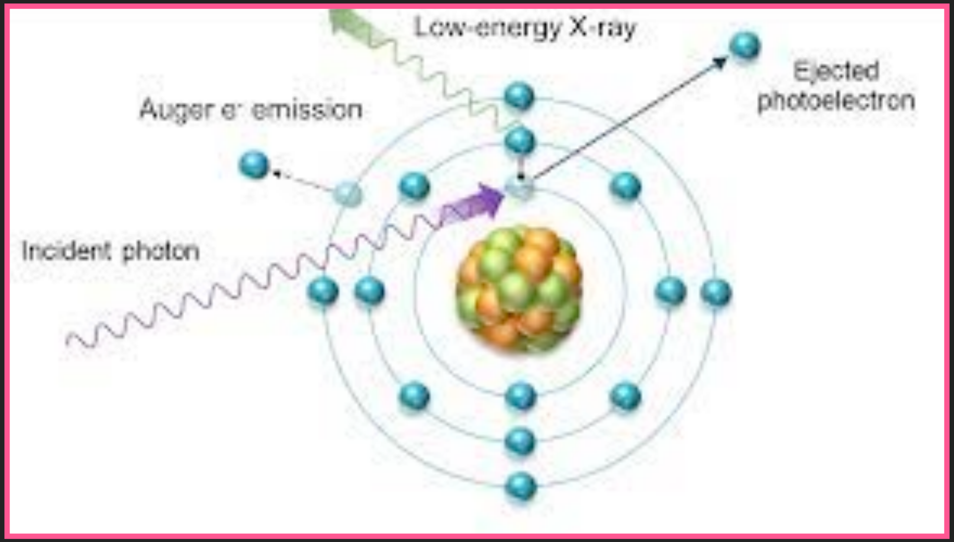
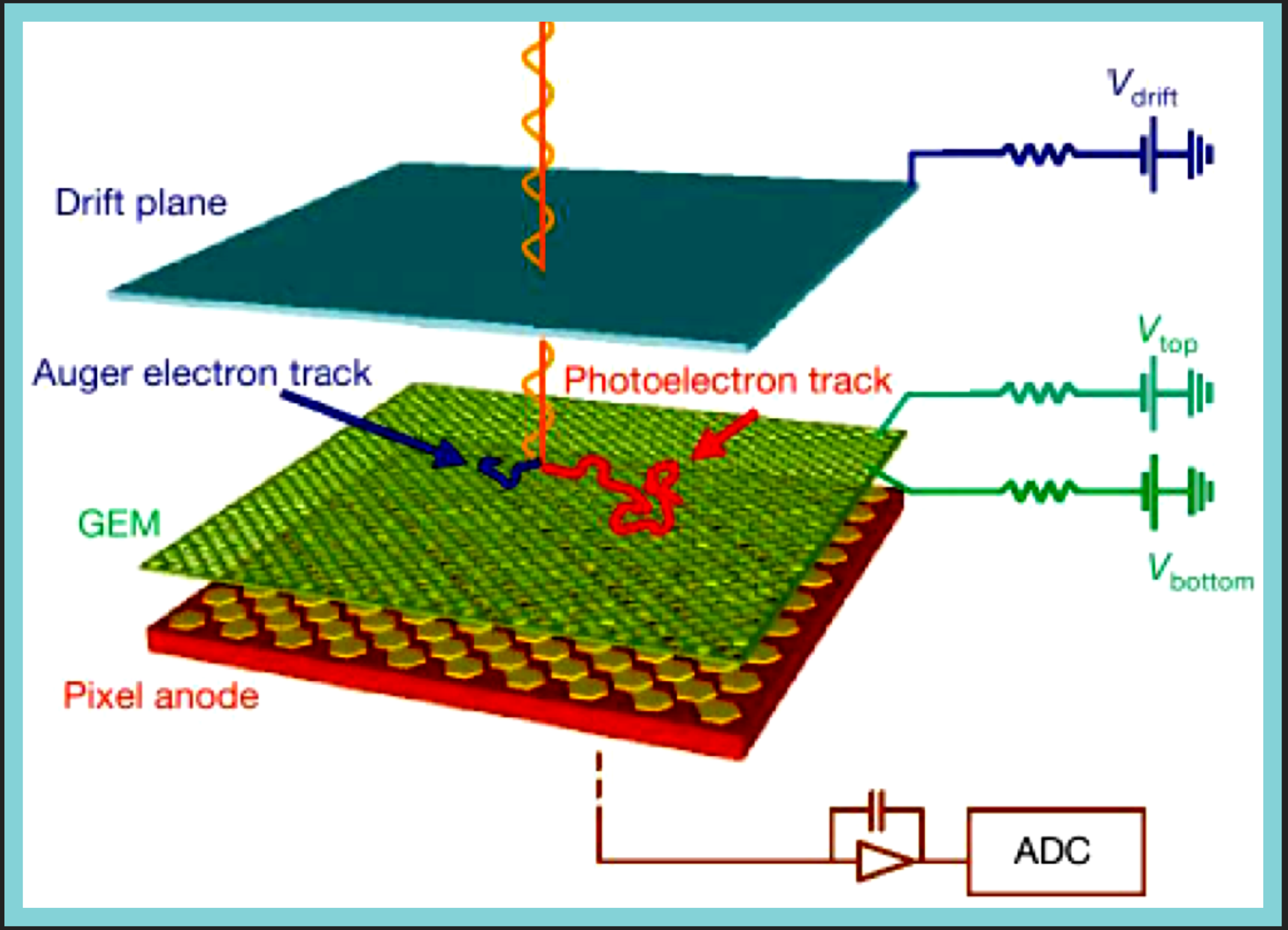
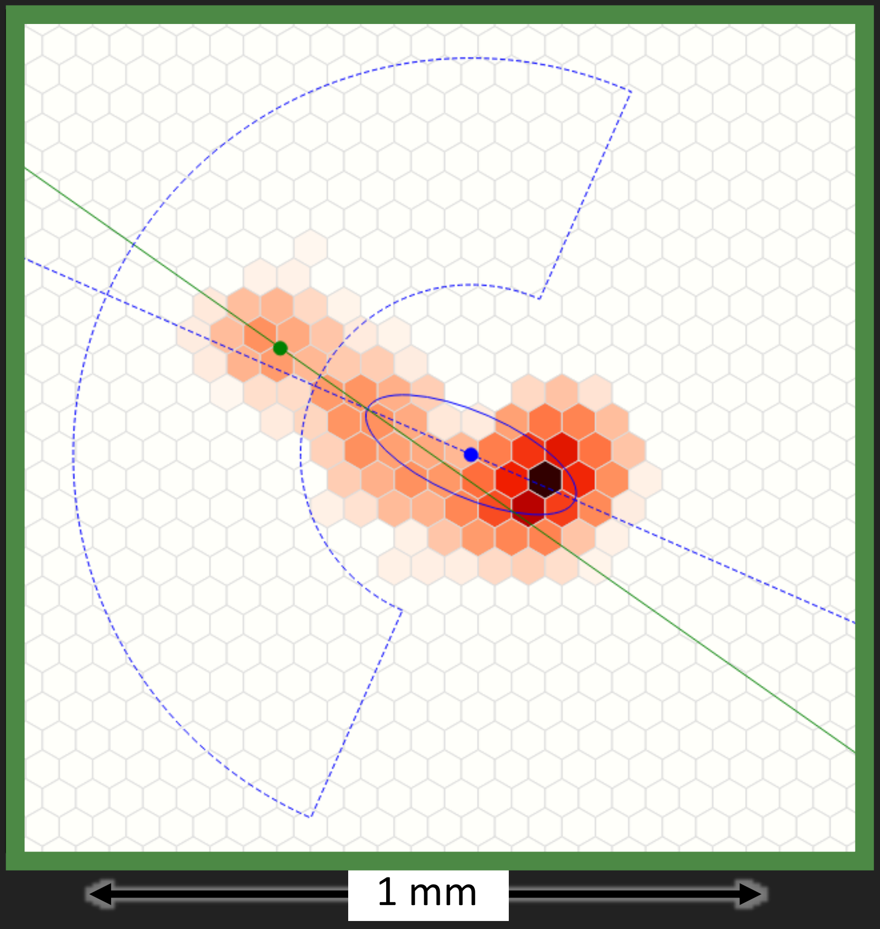
IXPE – GPD



Low-energy X-ray
Ejected photoelectron
Auger e⁻ emission
Incident photon



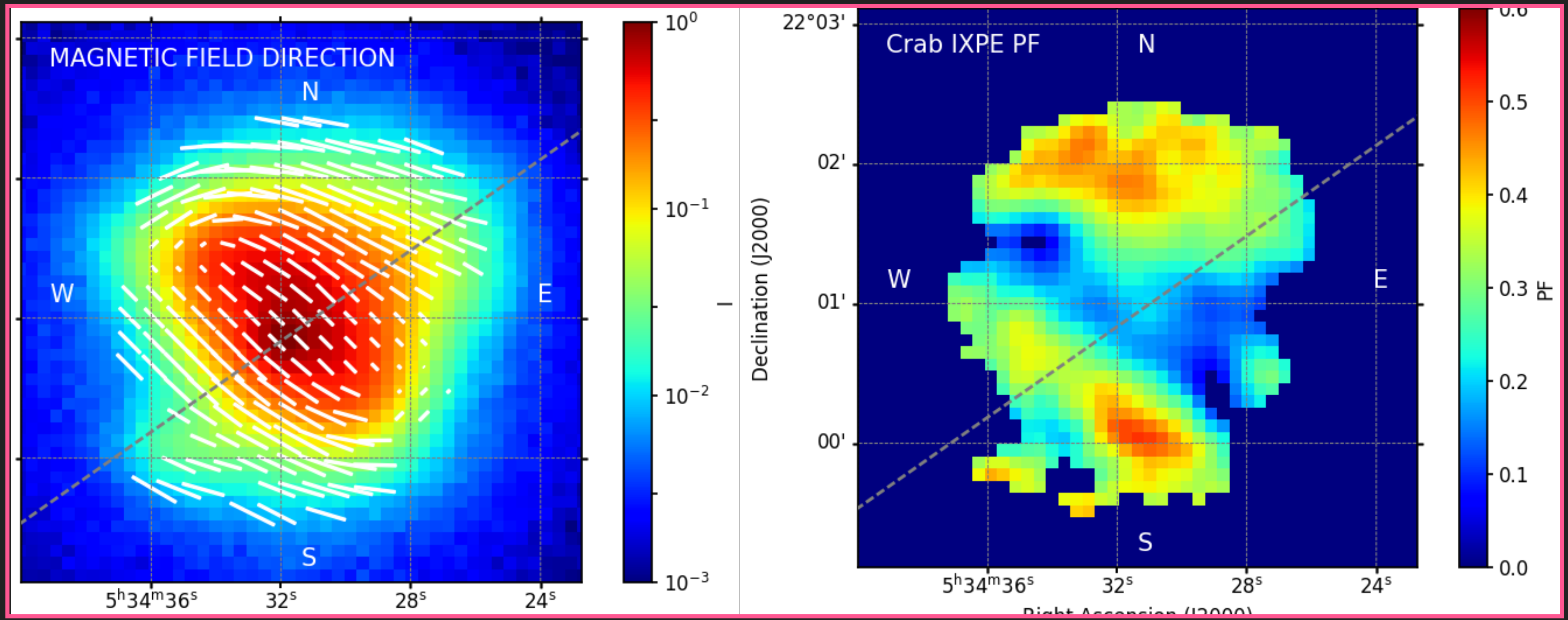
V_{drift}
Drift plane
V_{top}
Auger electron track
Photoelectron track
GEM
V_{bottom}
Pixel anode
ADC



1 mm

IXPE – X-RAY POLARIMETRY – CRAB

Bucciantini et al 2023



Ordered field Geometry is toroidal

Polarised Fraction not symmetric with nebula

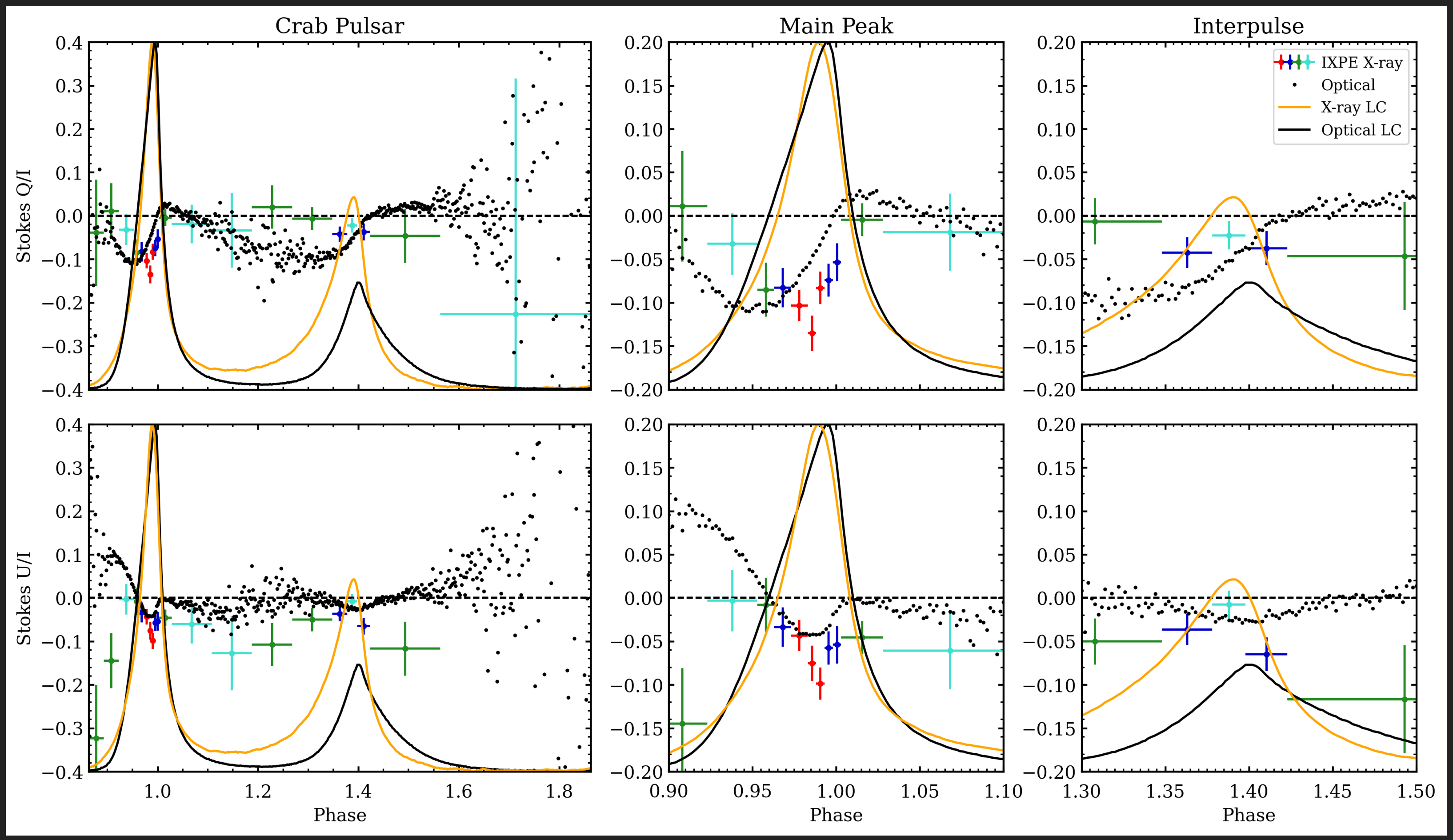
Jet polarisation is small and likely unpolarised

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 PSR

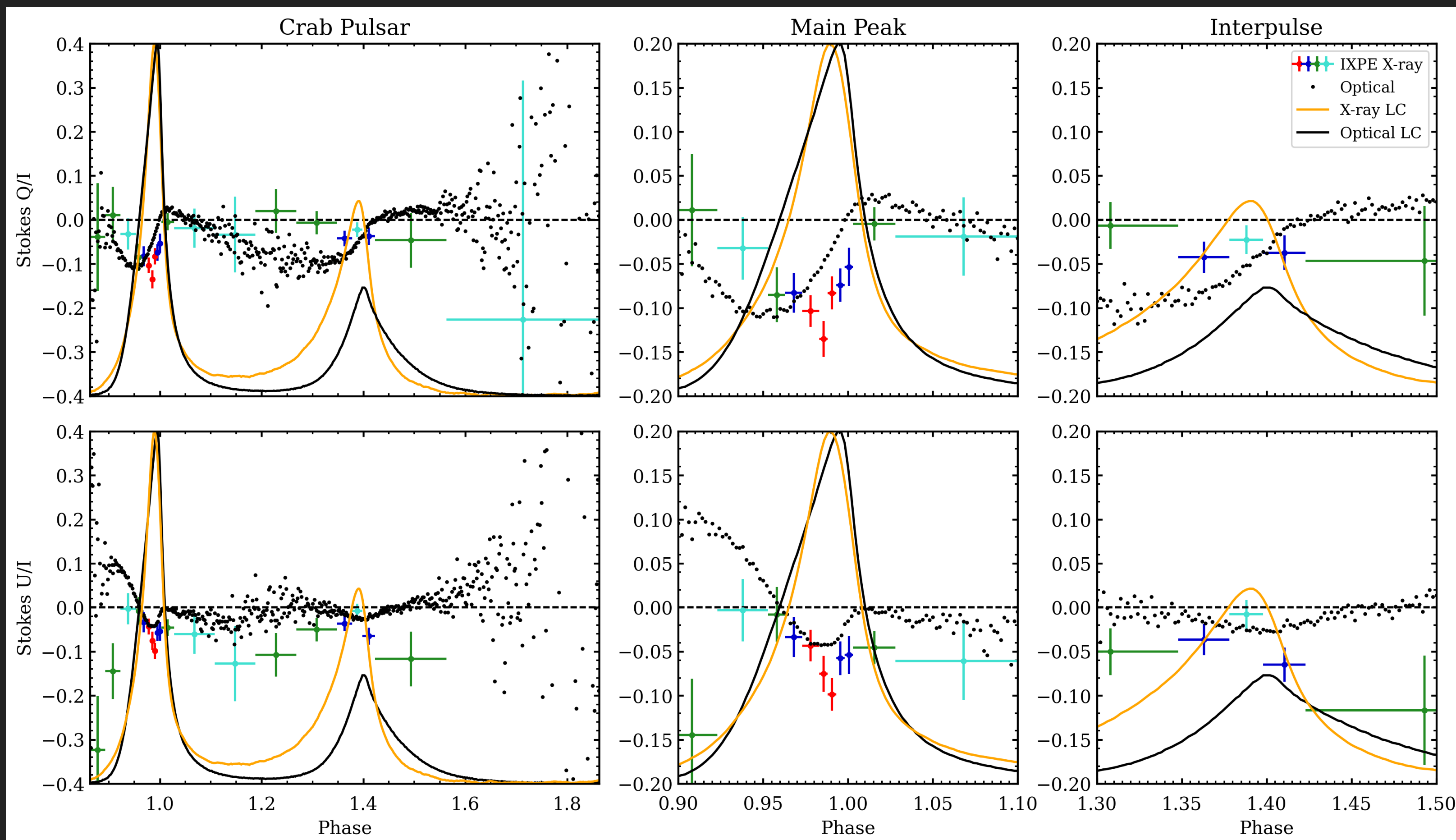


Wong et al 2024

5- sigma detection in the core of P1

15% PF in the core of P1

IXPE – X-RAY POLARIMETRY – CRAB PSR



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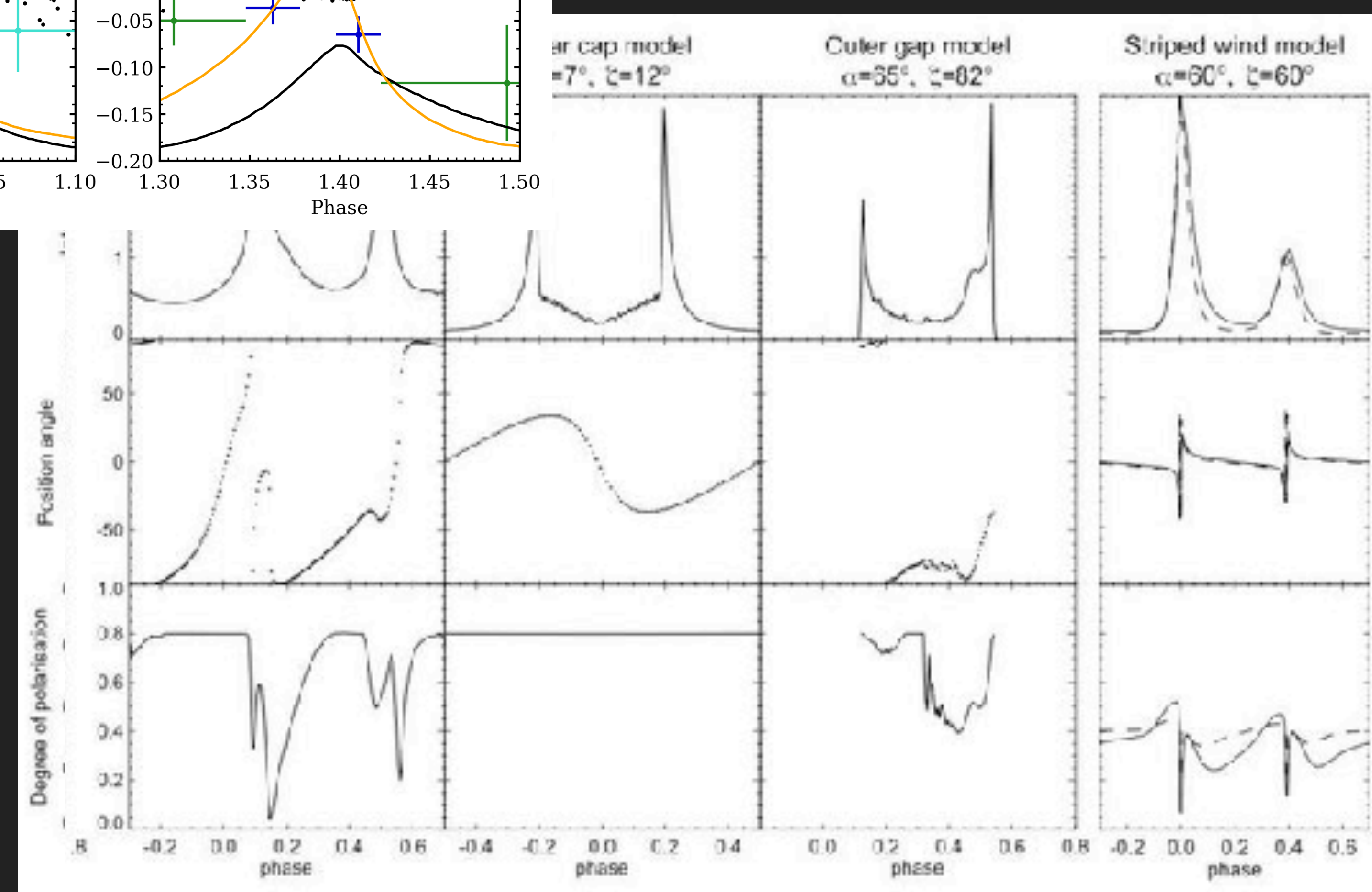

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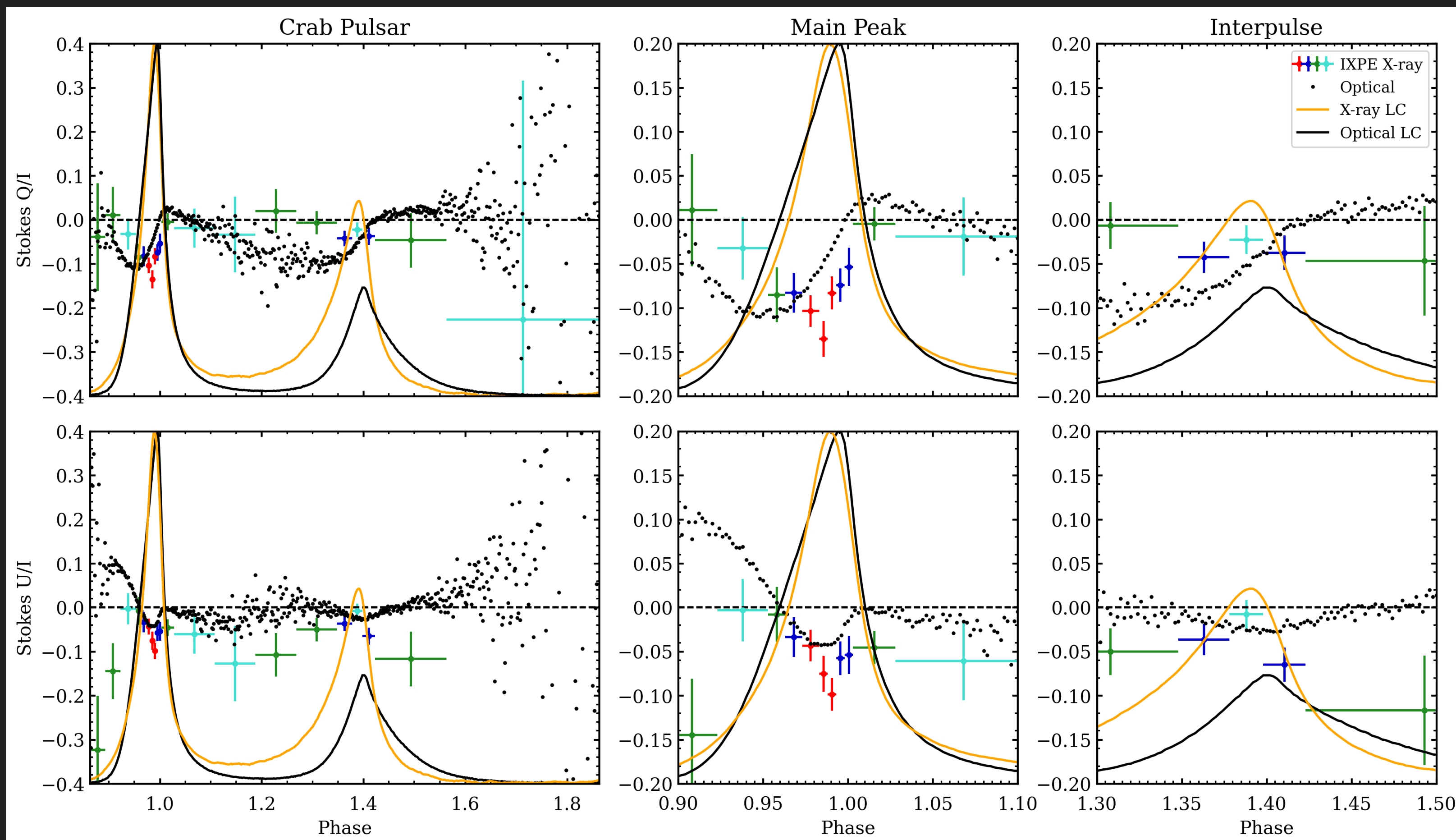

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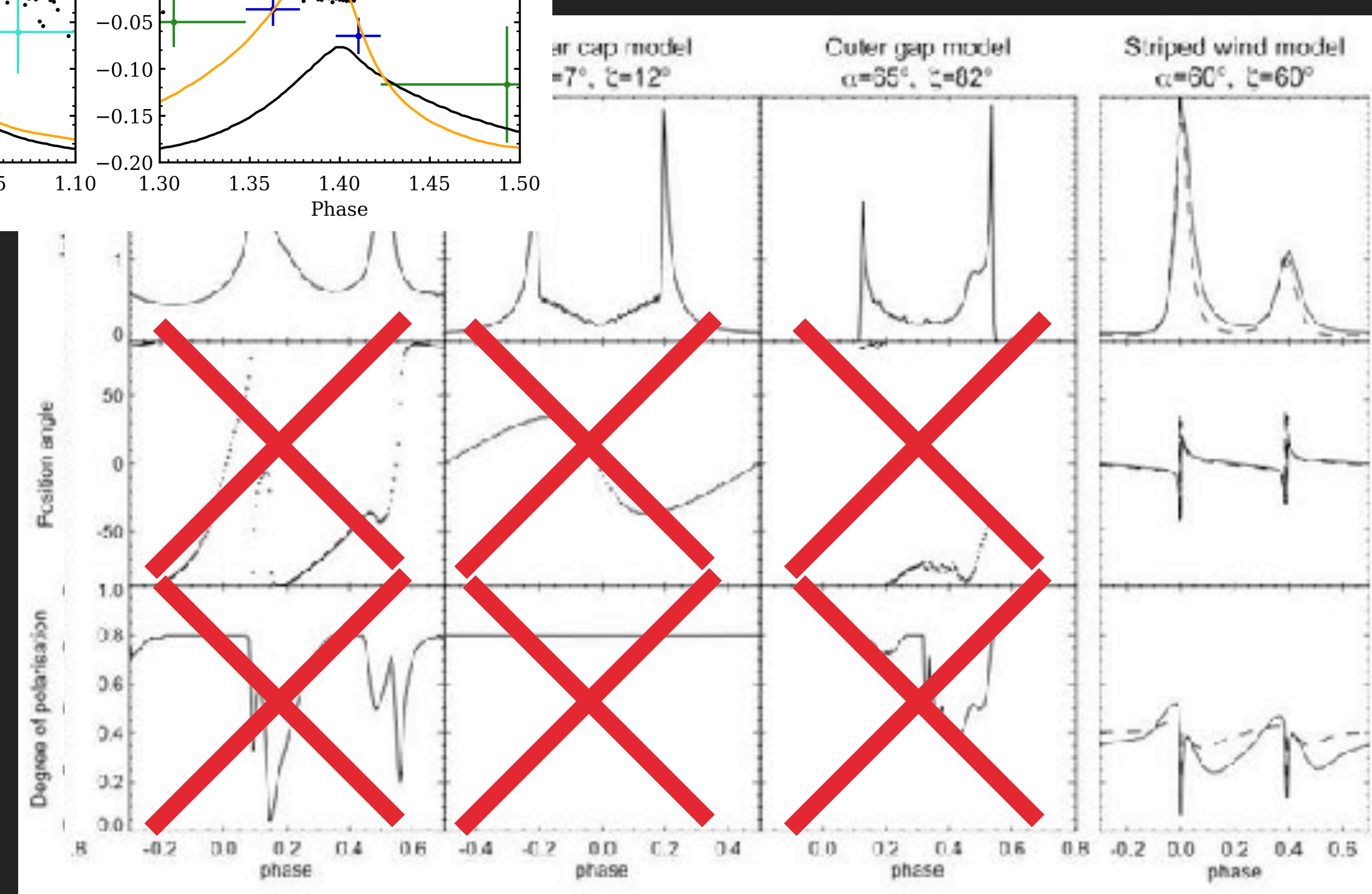

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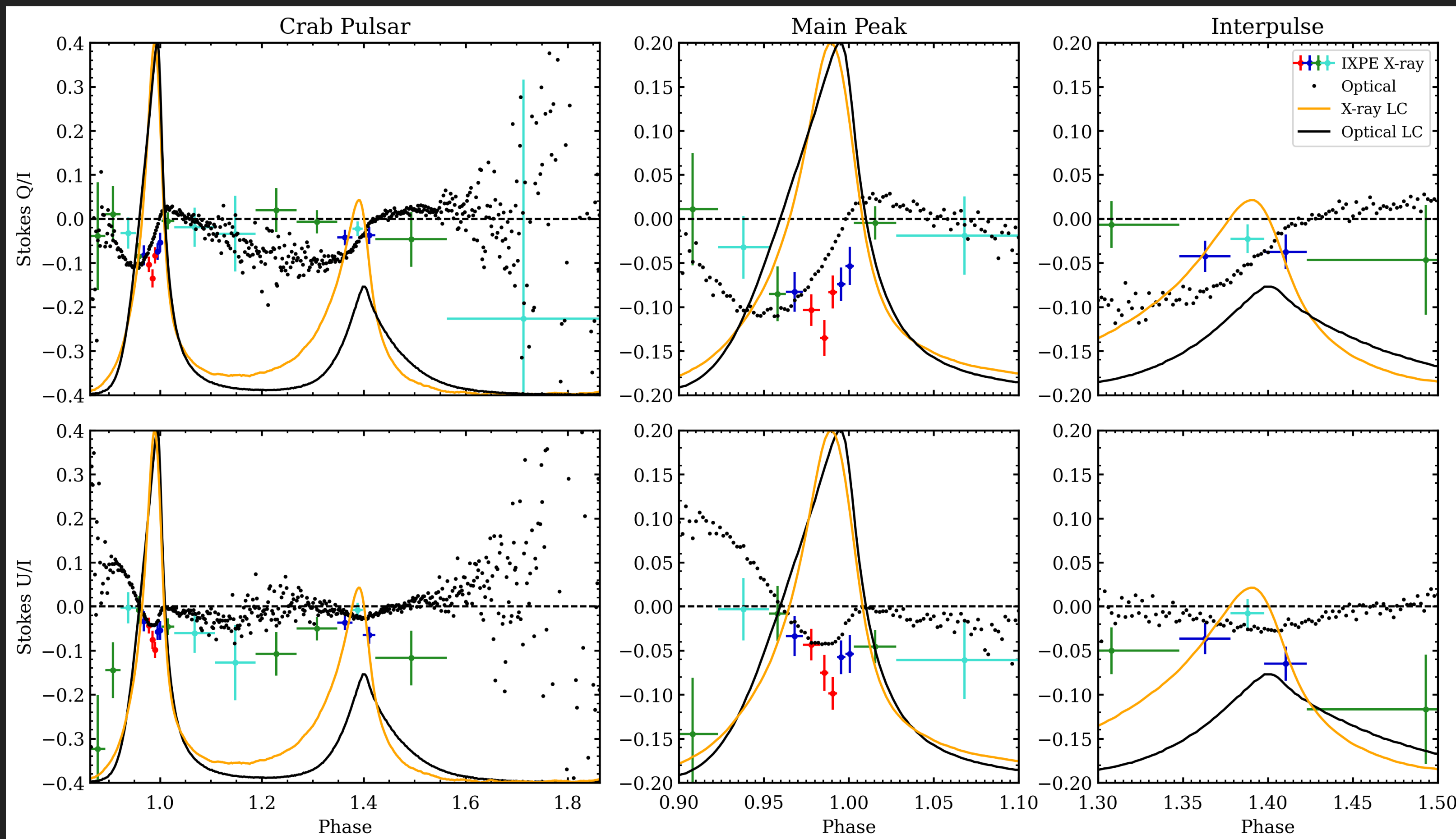

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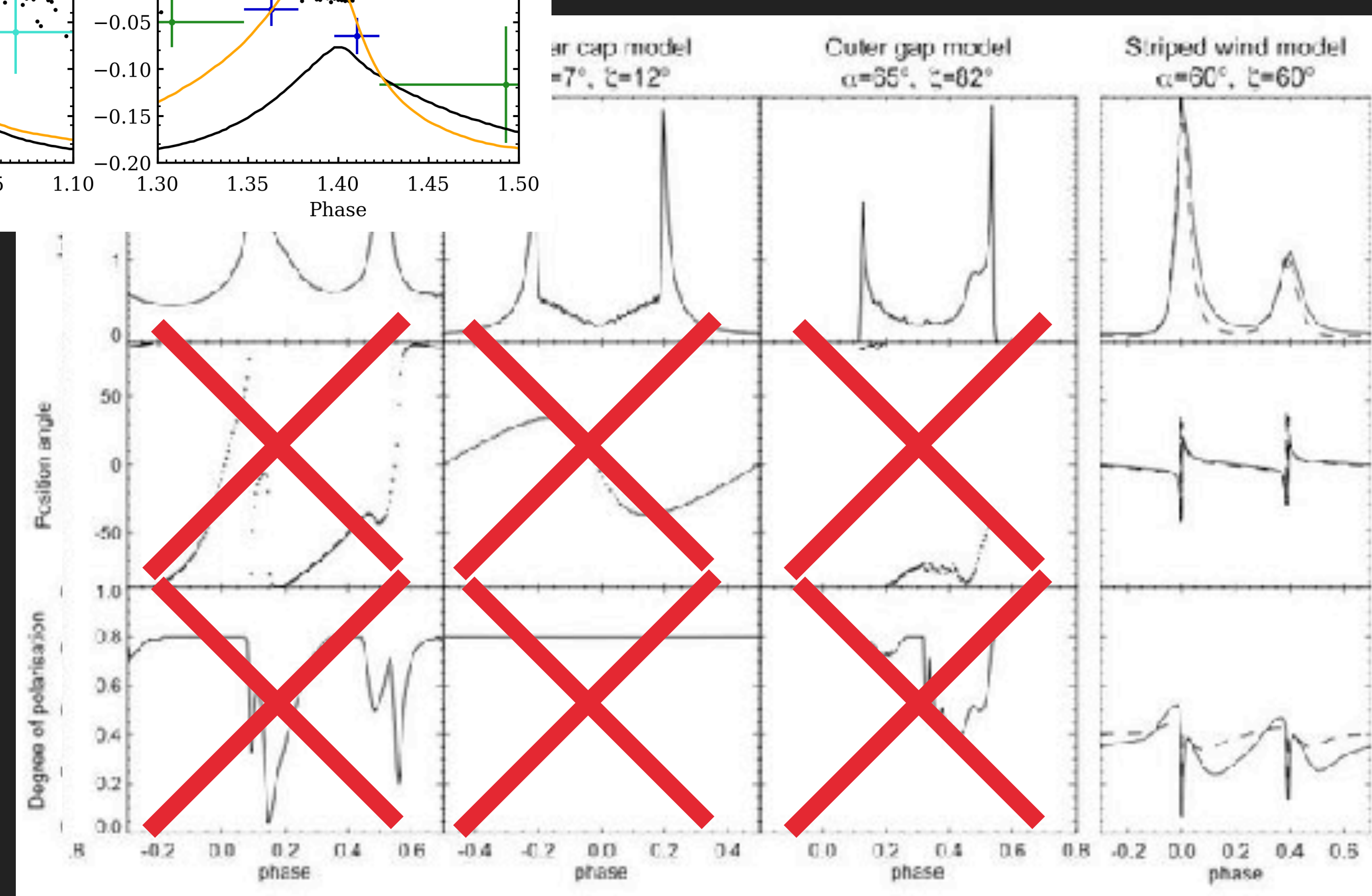
Wong et al 2024

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



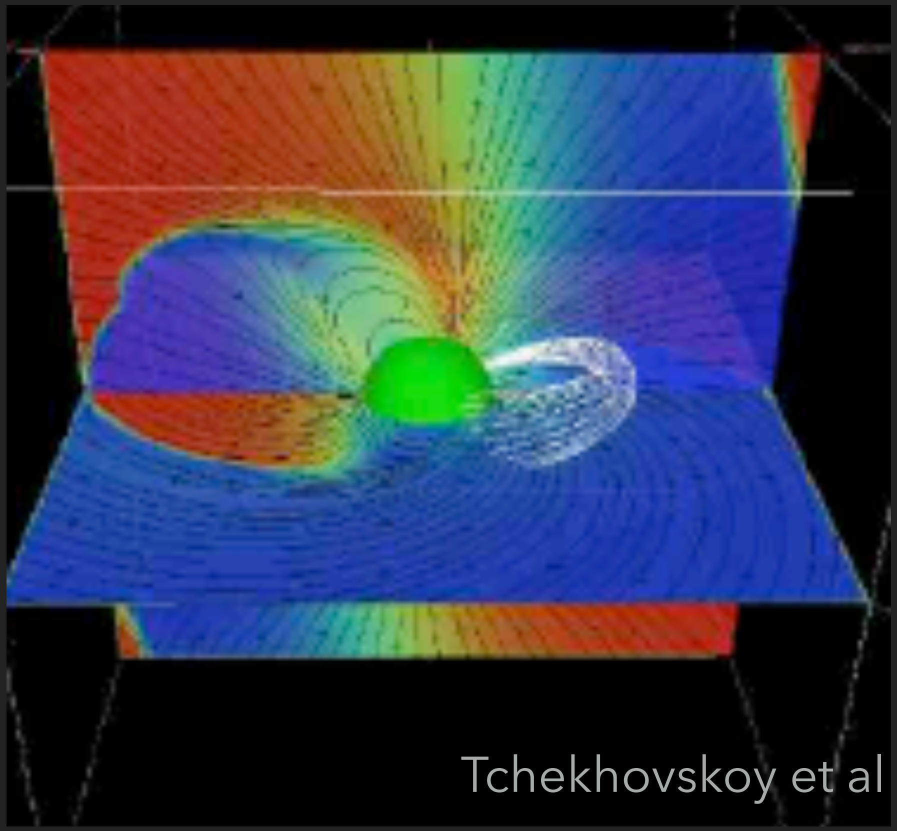
STRIPED WIND POLARIMETRY - CRAB PSR

Analytical solution for shape of the Current Sheet

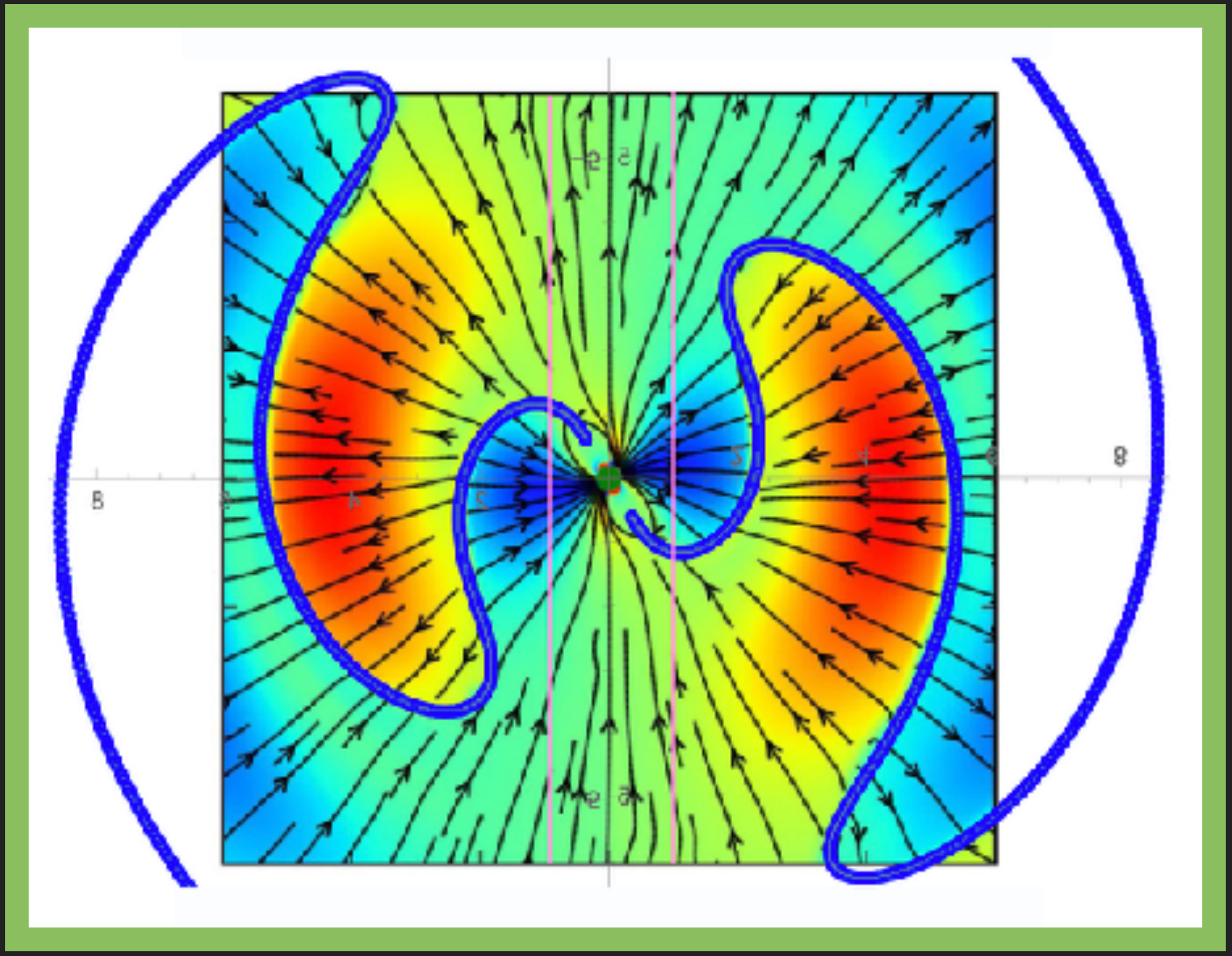
$$\Psi_s = \cos\vartheta \ \cos\chi + \sin\vartheta \ \sin\chi \ \cos\left[\varphi - \Omega\left(t - \frac{r}{\beta_{\rm v}\, c}\right)\right]$$

Mag axis inclin

Petri 2013



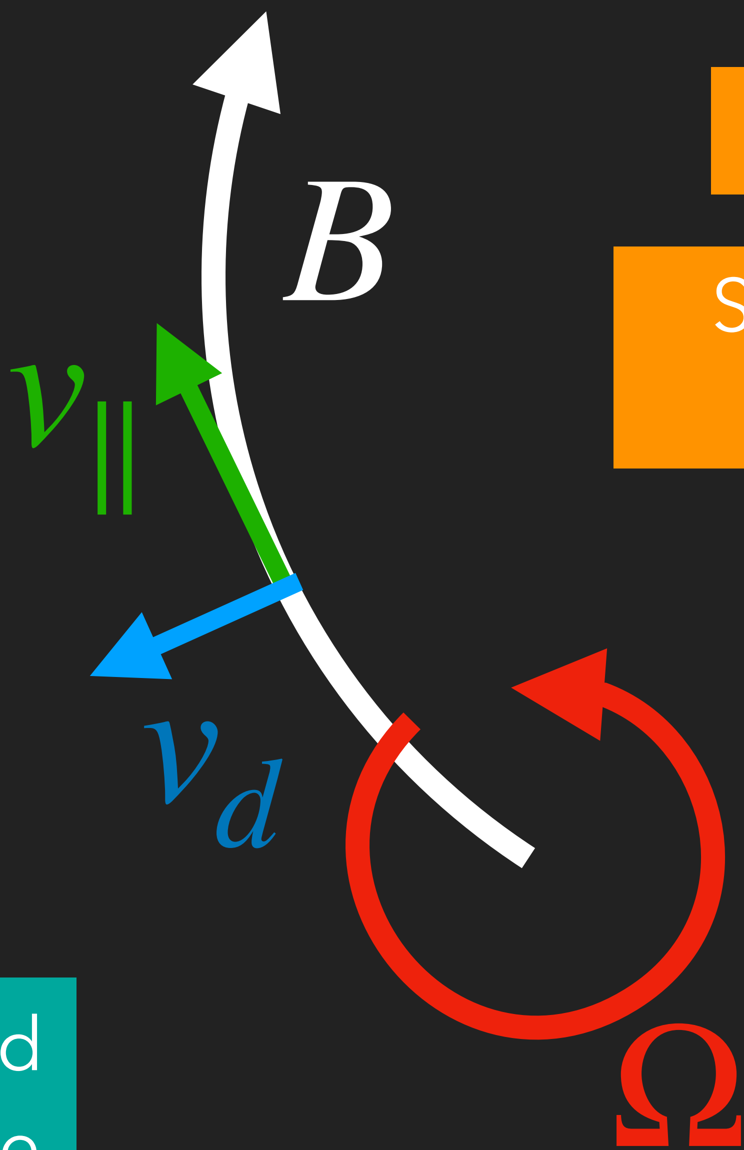
Tchekhovskoy et al 2013



STRIPED WIND POLARIMETRY - CRAB PSR

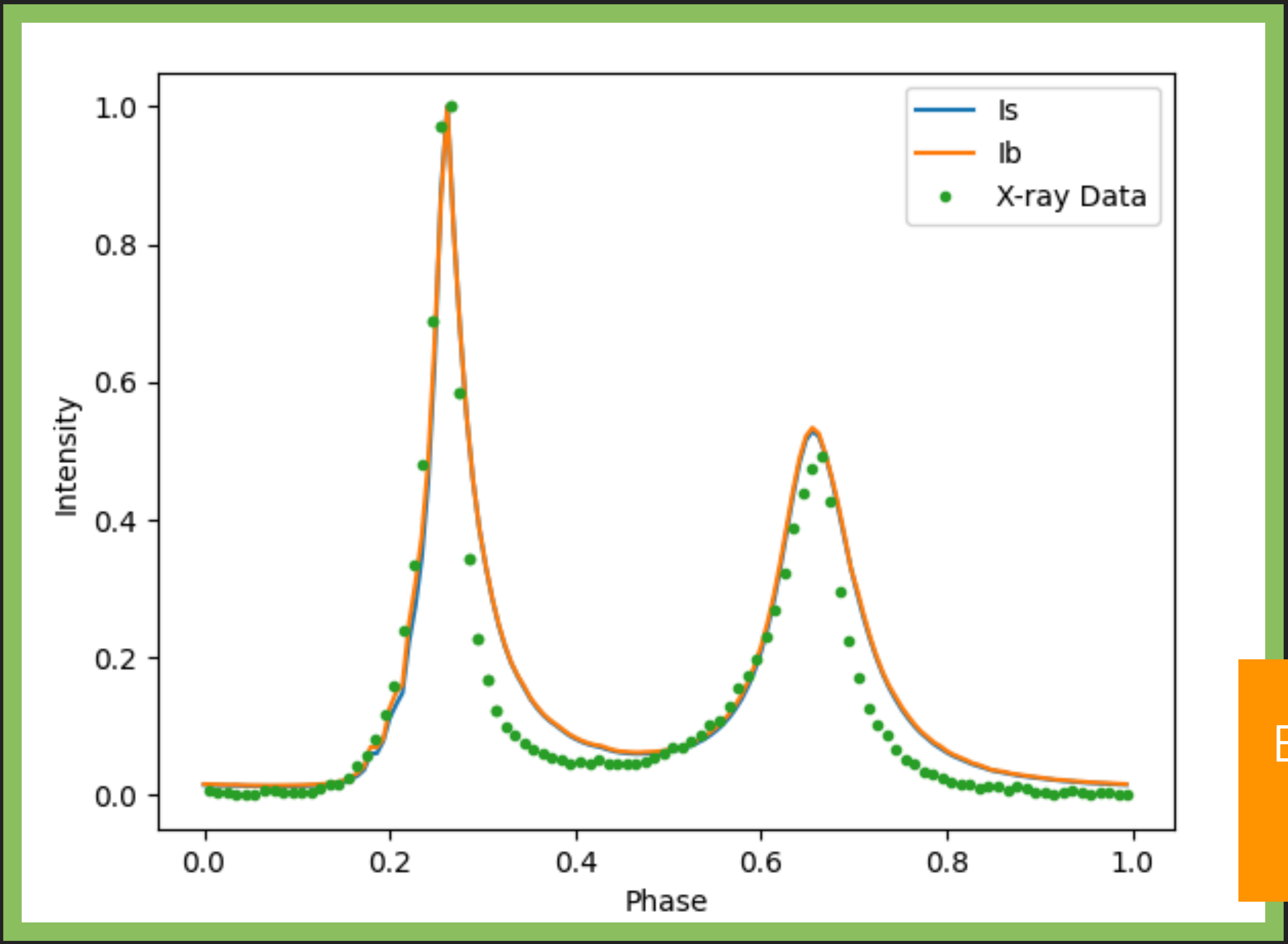
Plasma velocity ambiguity - Drift Speed does not uniquely determine Plasma

Drift velocity	Radial velocity
Peak brightness is different	Peak brightness is same
Weak dependence on Lorentz	Strong dependence on Lorentz
Peaks are broad	Peaks are narrow
Emission in the bridge	Bridge undeluminous



Emission should be confined at small radii just beyond the LC

IXPE – X-RAY POLARIMETRY – CRAB PSR



Drift velocity = 0.995c

Photon index set to 1.6

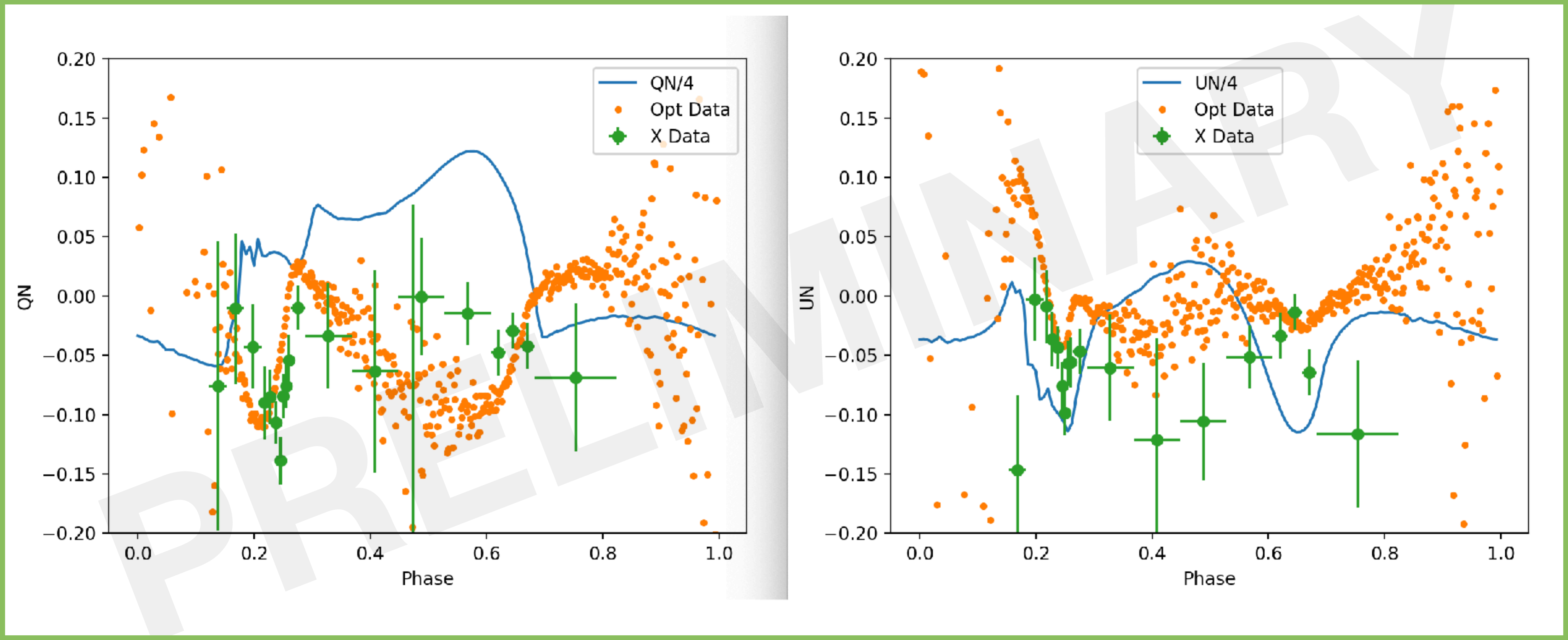
Spin Inclination = 120 deg

Magn Inclination = 60 deg

Curr Sheet Thick = 0.01

Emission Confined between Rlc & 3Rlc

IXPE - X-RAY POLARIMETRY - CRAB PSR

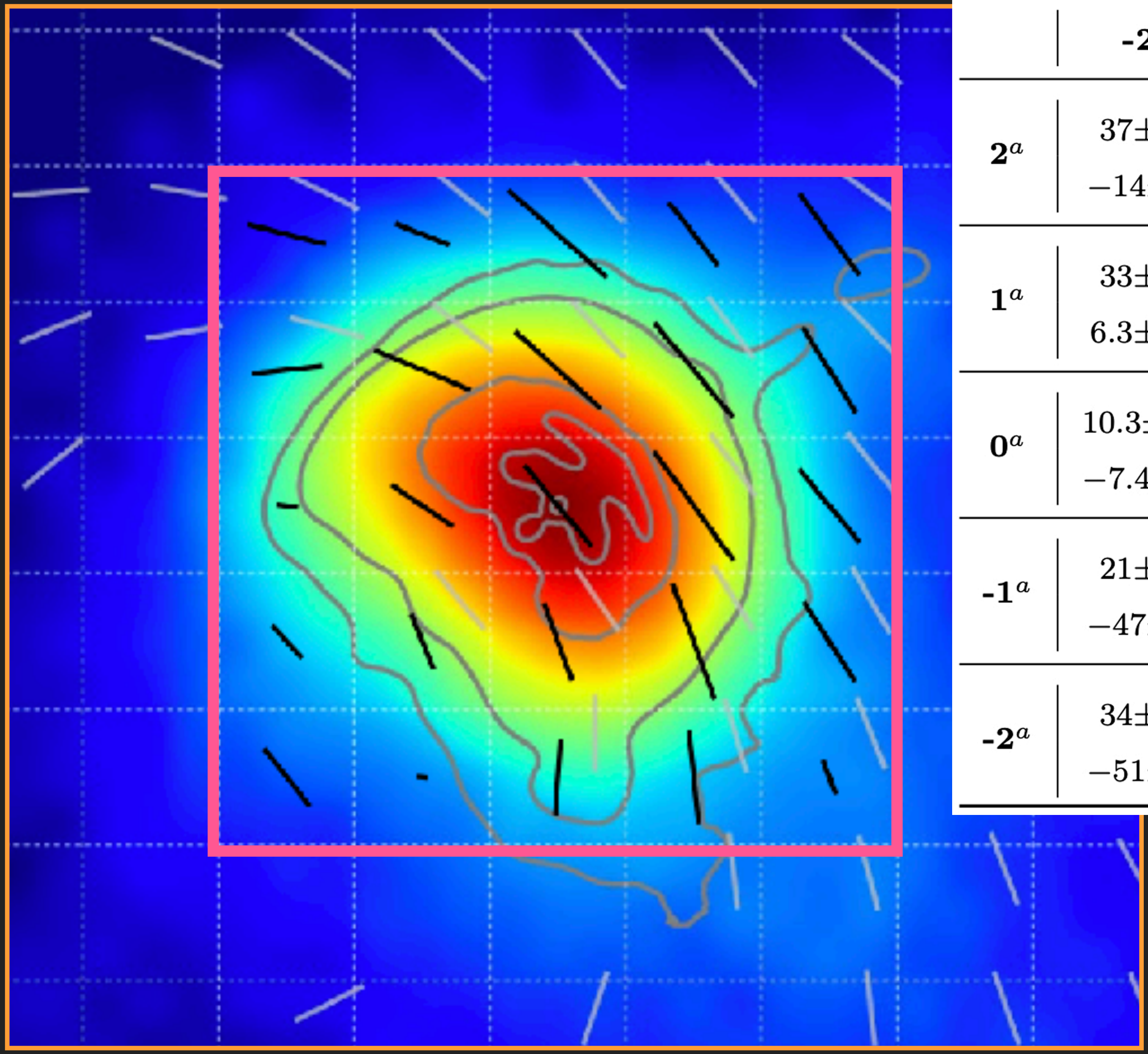


Need to introduce some intrinsic depolarisation wrt fully ordered striped wind (PD is just 1/4)

Perhaps one can ‘fit” the main peak but not the the interpulse

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]

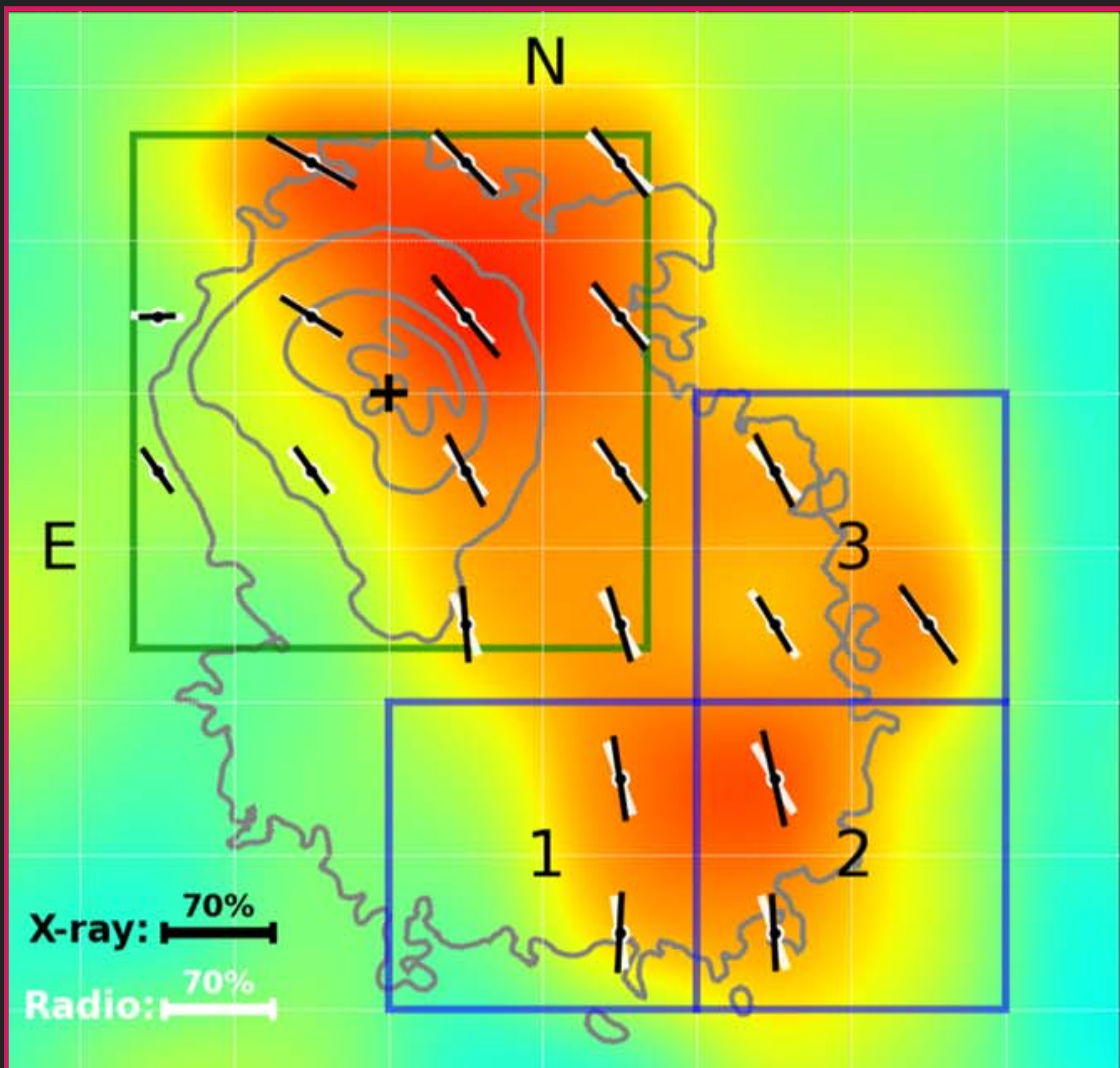
Very high PF suggest no turbulence in the PWNe

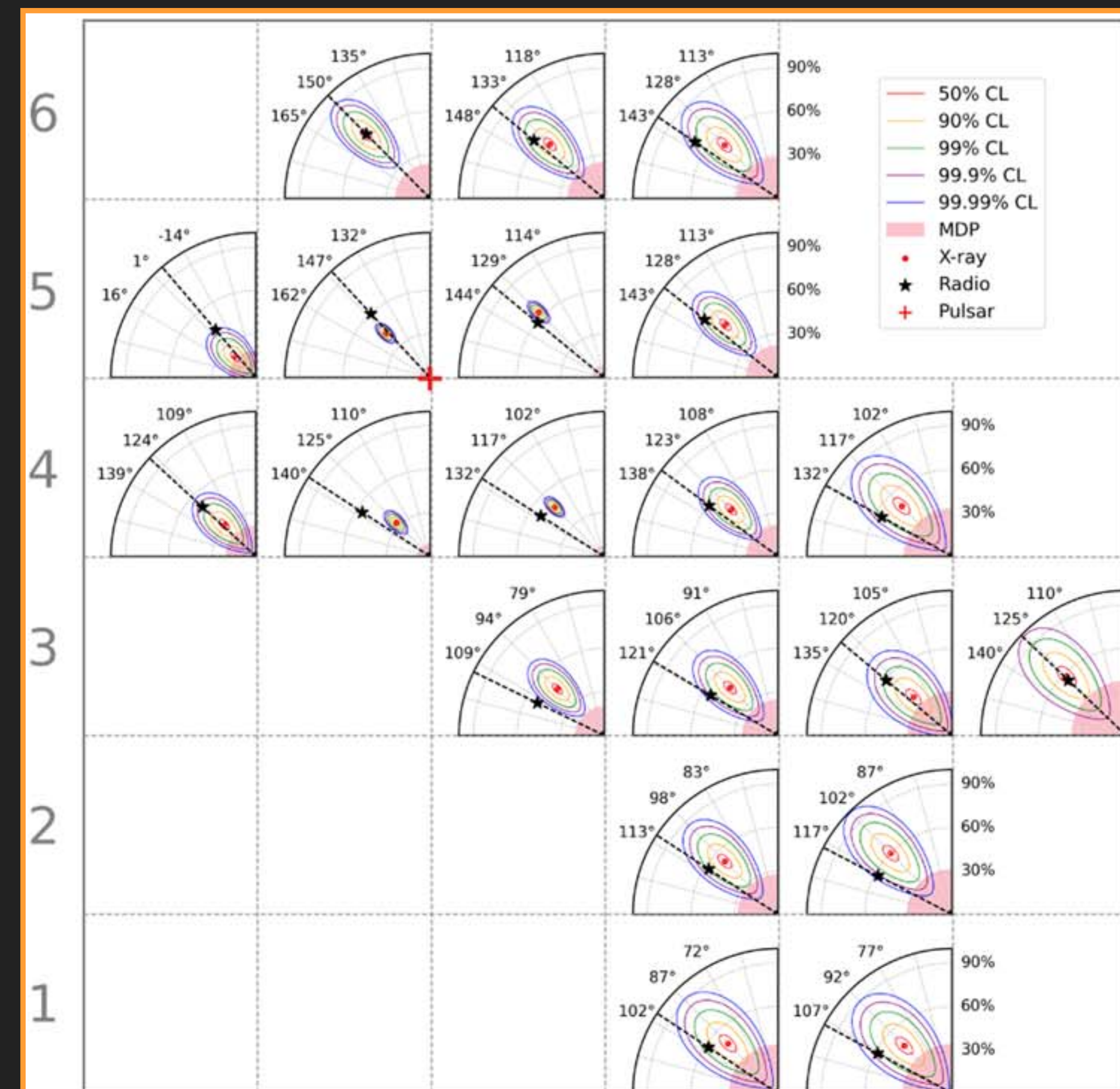
Unlikely reconnection to play a major role in accelerating particles

Old sytems should be more turbulent.

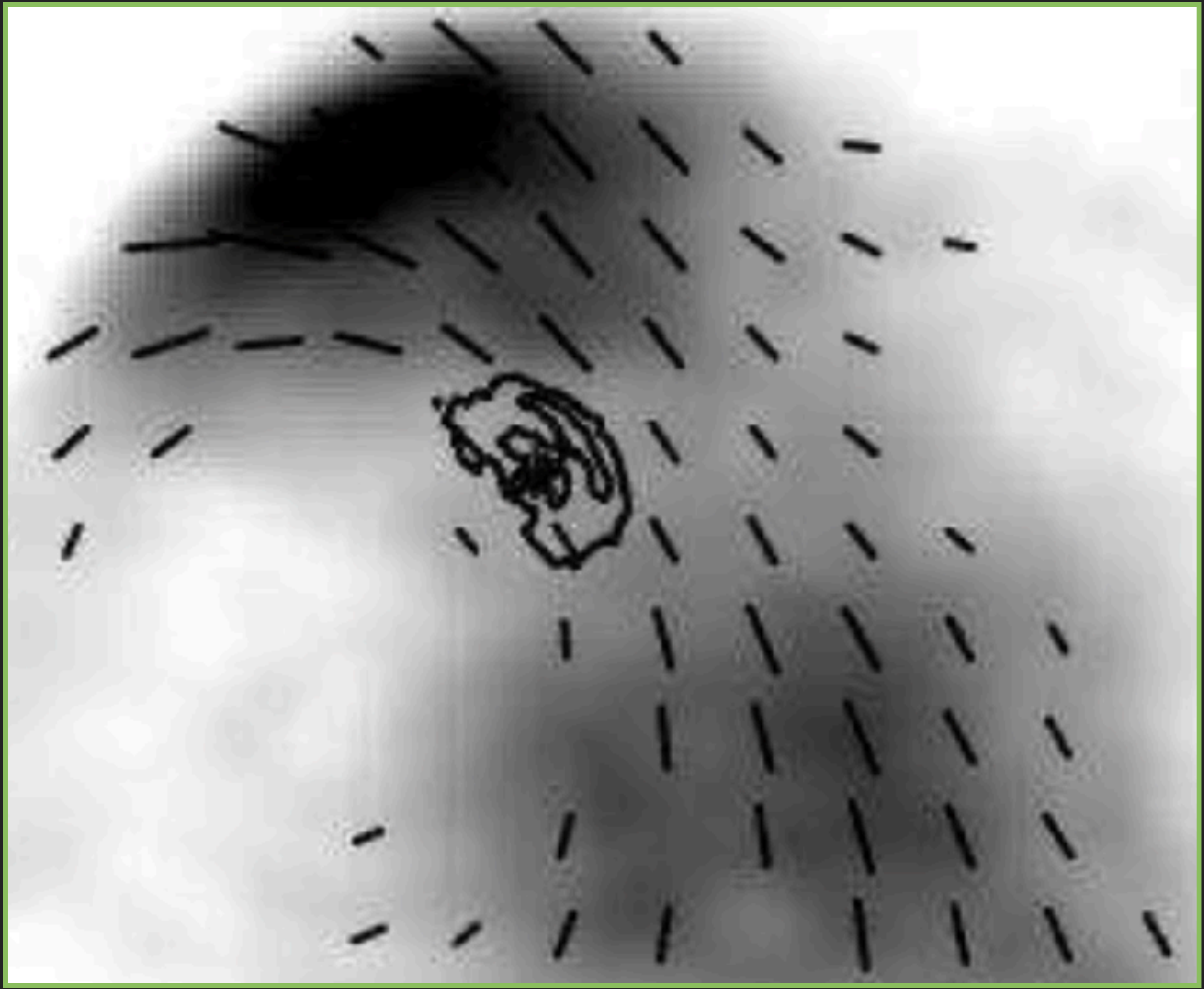
IXPE – X-RAY POLARIMETRY – VELA EXTENDED

Liu et al 2023



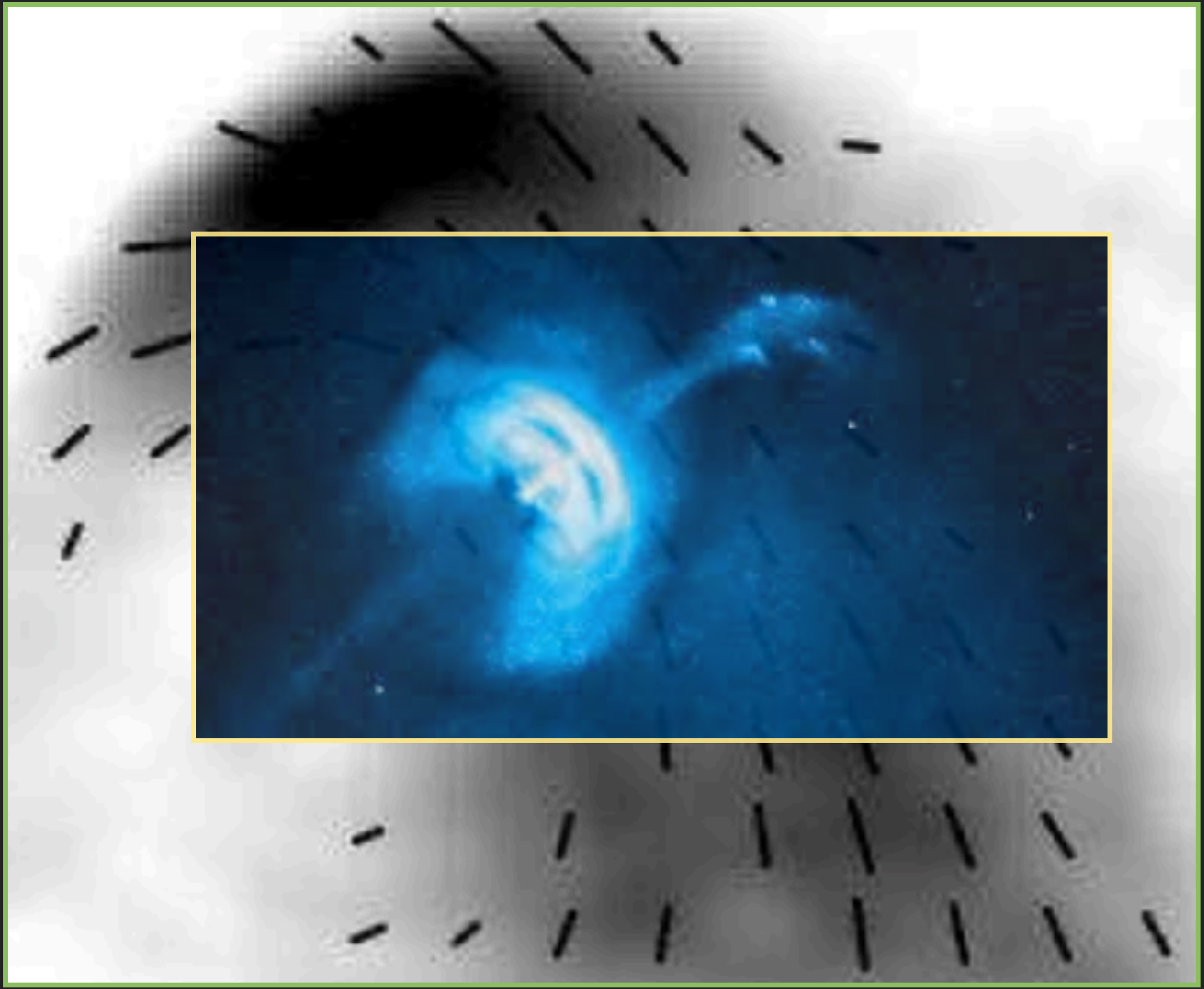


IXPE – X-RAY POLARIMETRY – VELA EXTENDED



Dodson et al 2003

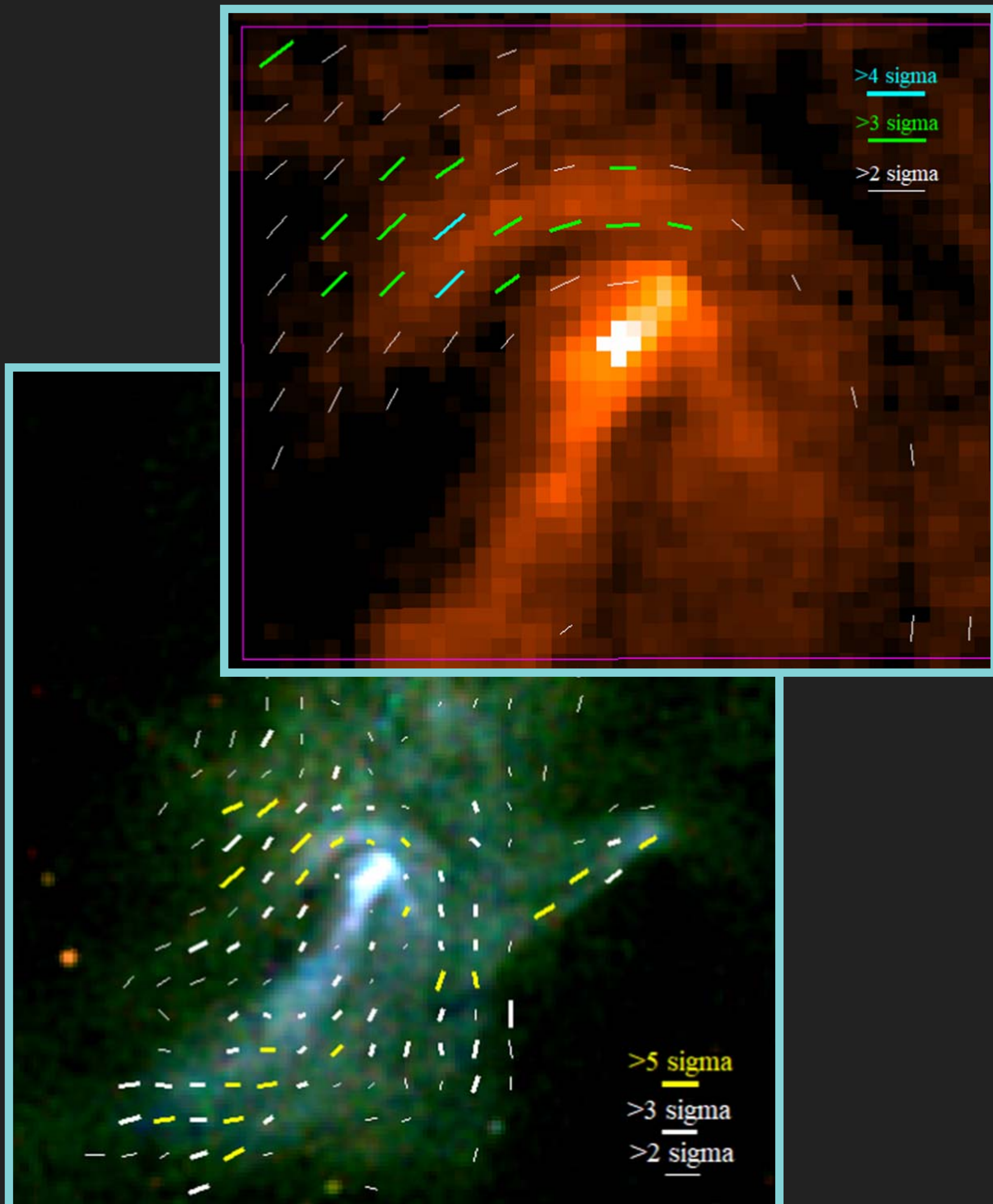
IXPE – X-RAY POLARIMETRY – VELA EXTENDED



Dodson et al 2003

IXPE – X-RAY POLARIMETRY – MSH 15-52

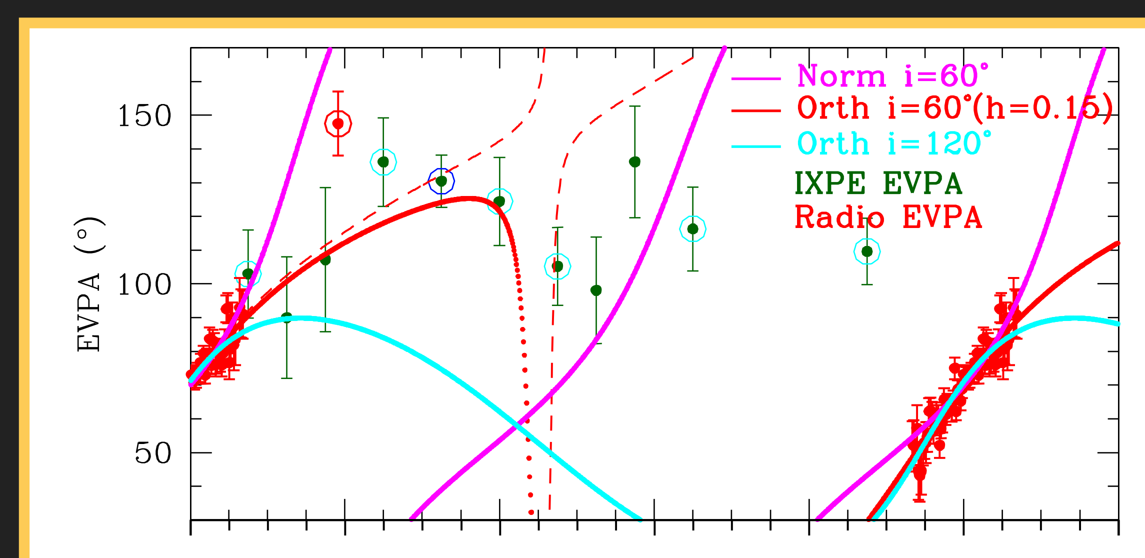
Romani et al 2023



CLEAR EVIDENCE OF HIGH POLARISATION `30% IN THE TORUS

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

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



BOW-SHOCK PWNE

At T ~ 30-50 kyr the PSR escapes the SNR

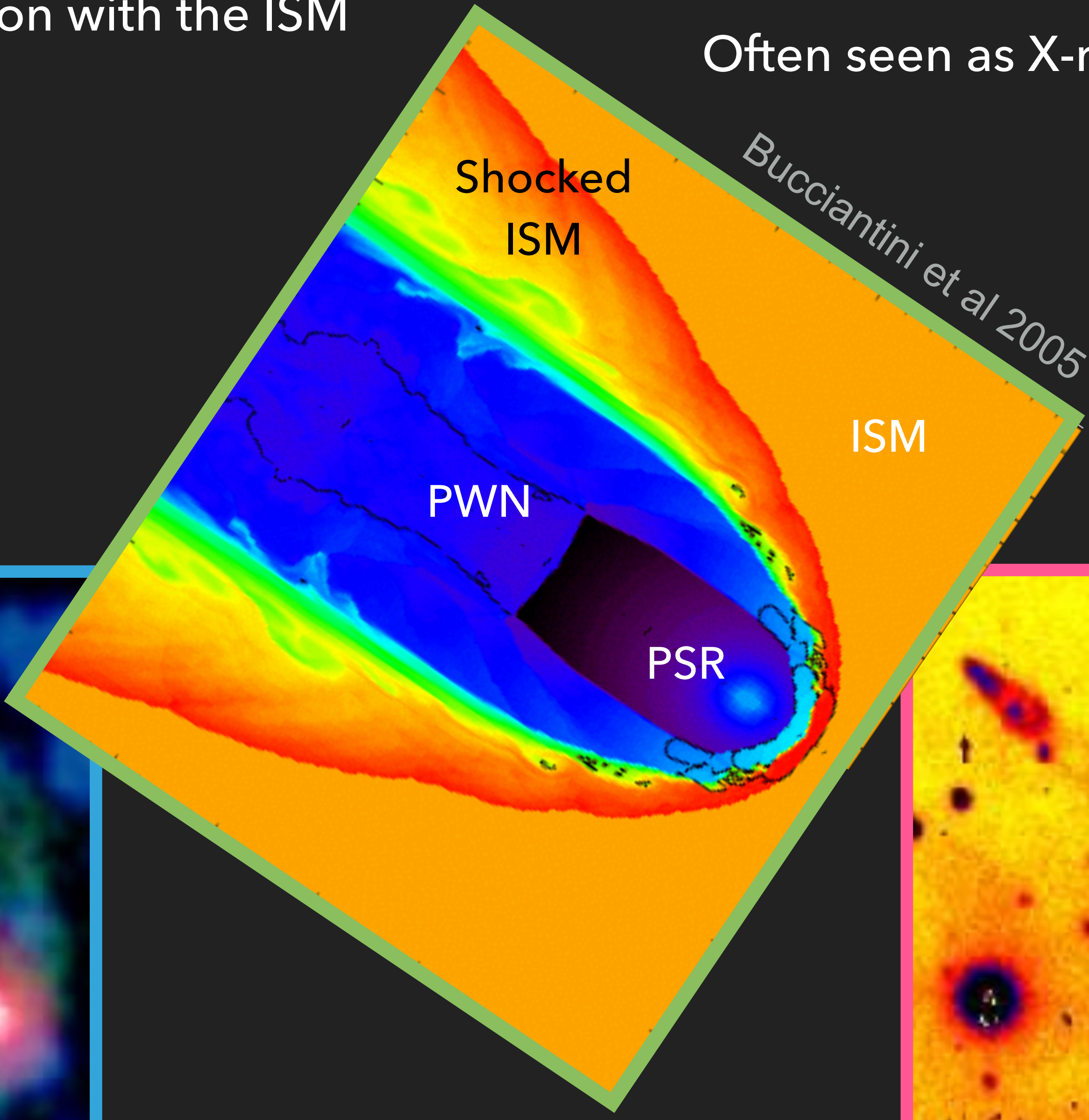
Bow shock from direct interaction with the ISM

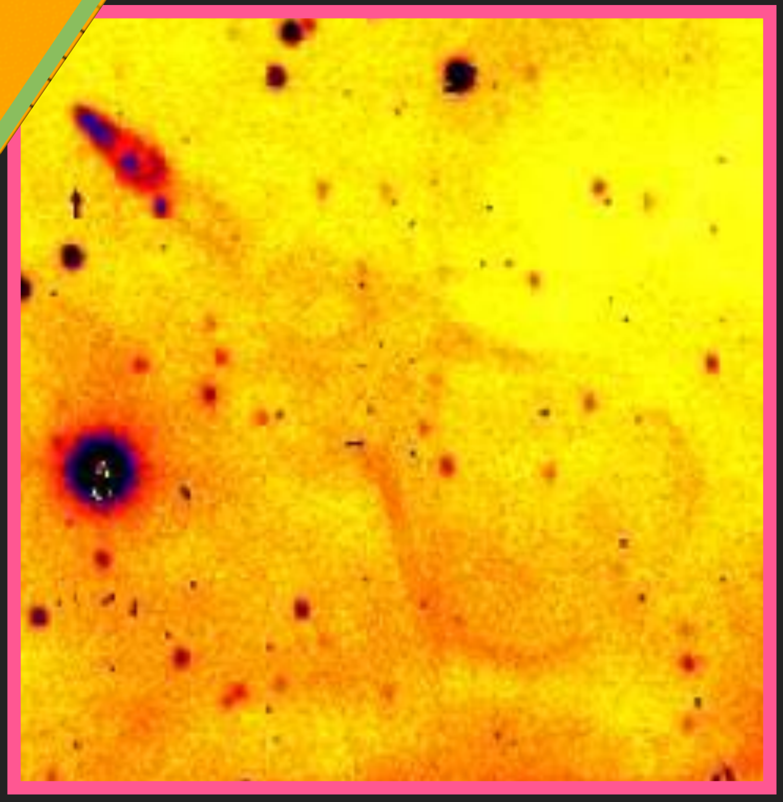
$$V_{psr} \approx 100 - 400 \text{ km s}^{-1}$$

$$d_o = \sqrt{\frac{\dot{E}_{psr}}{4\pi c \rho_{ism} V_{psr}^2}}$$

Originally found in Halpha (few cases)

Often seen as X-ray or radio tails





PSR B2224+65 (Chatterjee & Cordes 2002)

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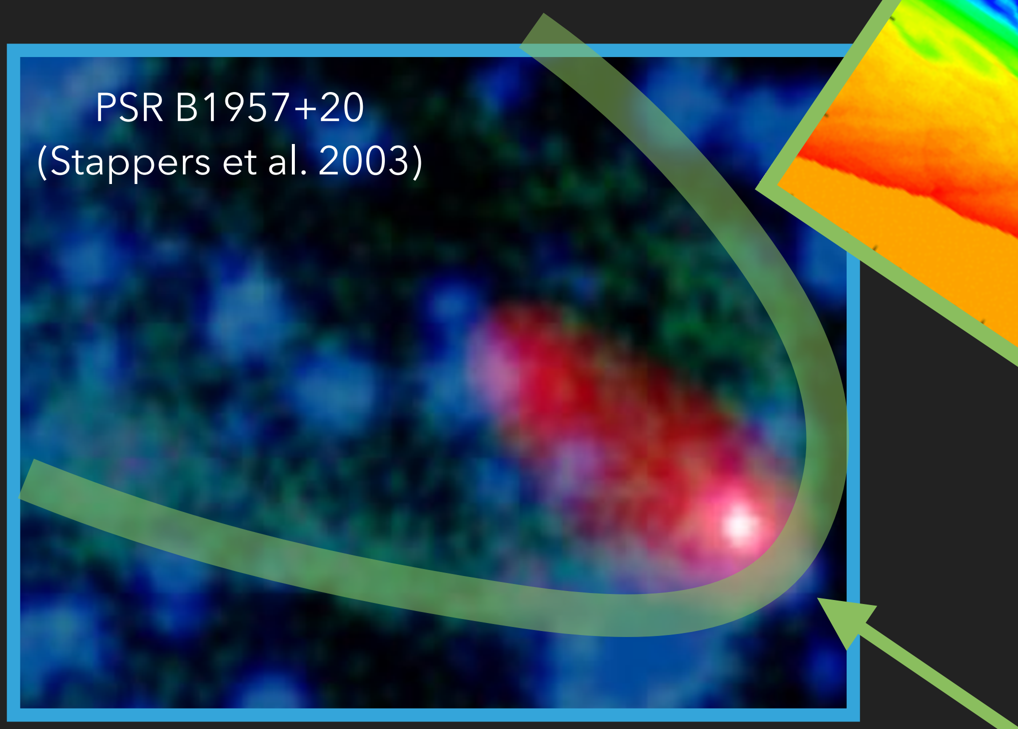
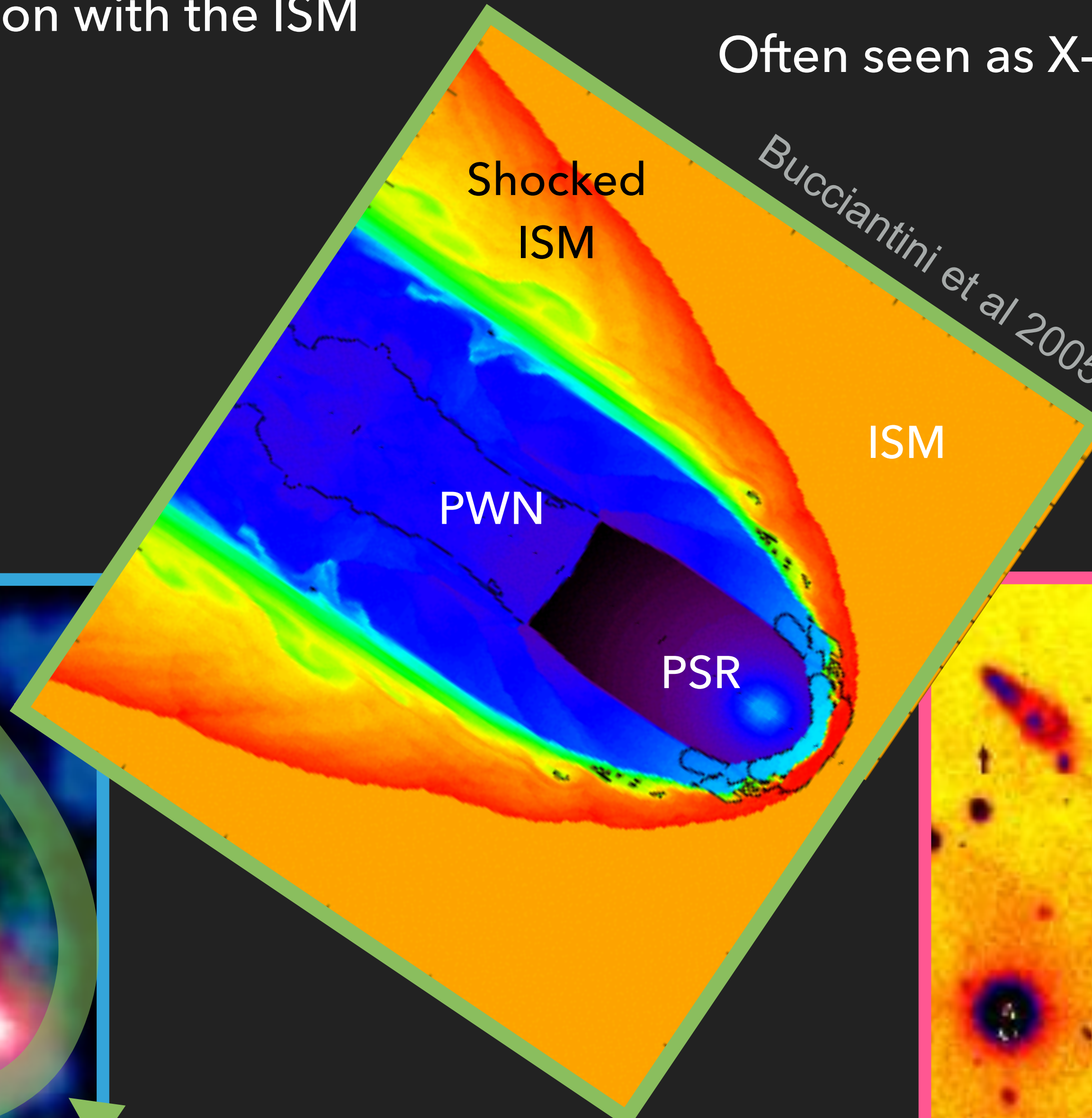
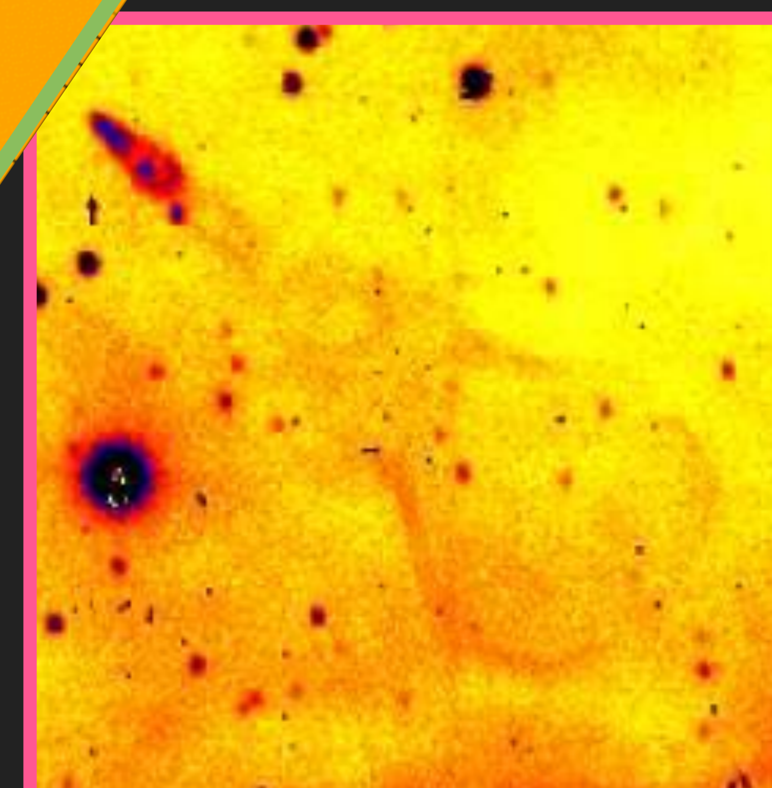




Bucciantini et al 2005

Halpha traces forward bow-shock in the ISM



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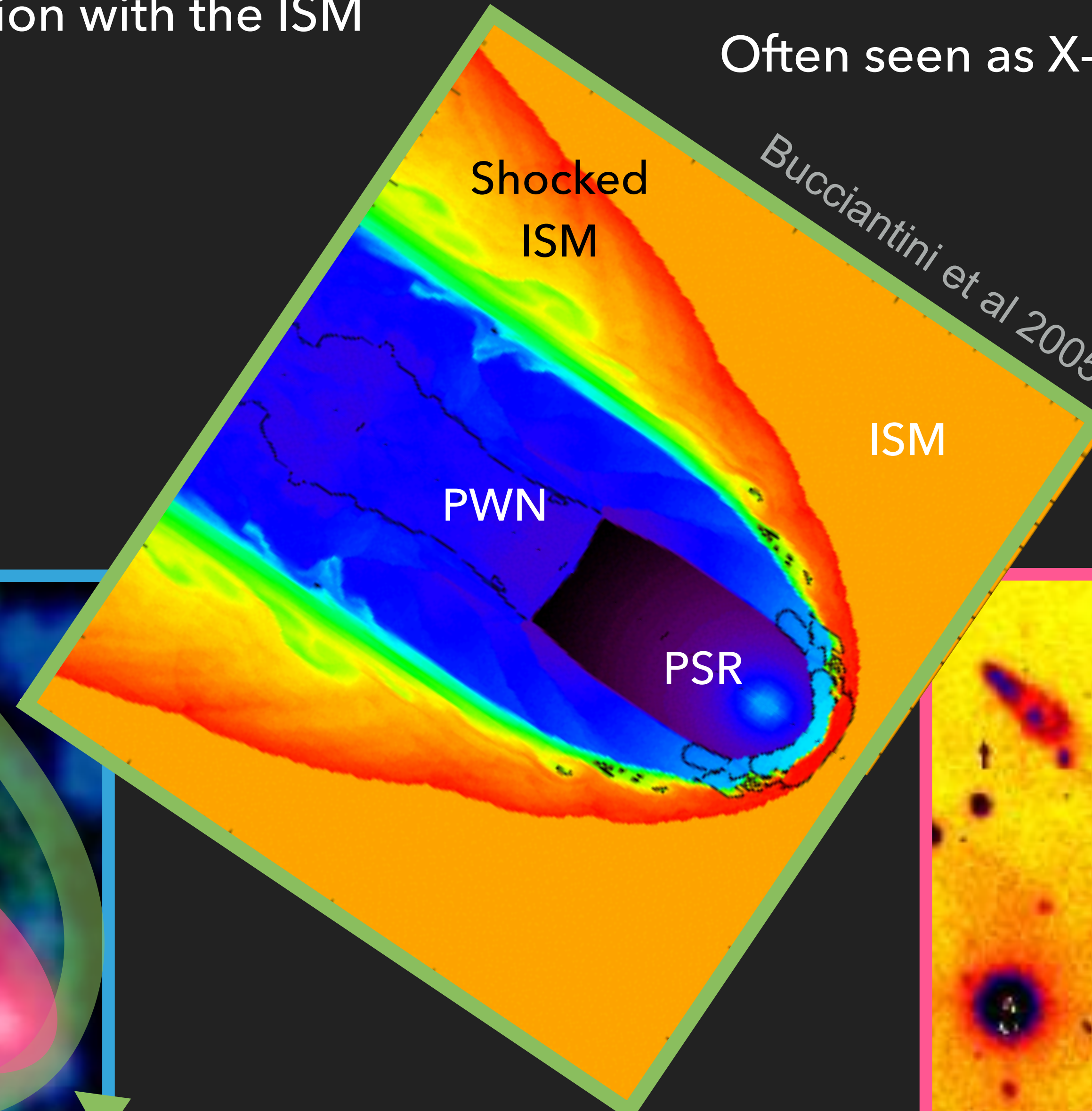

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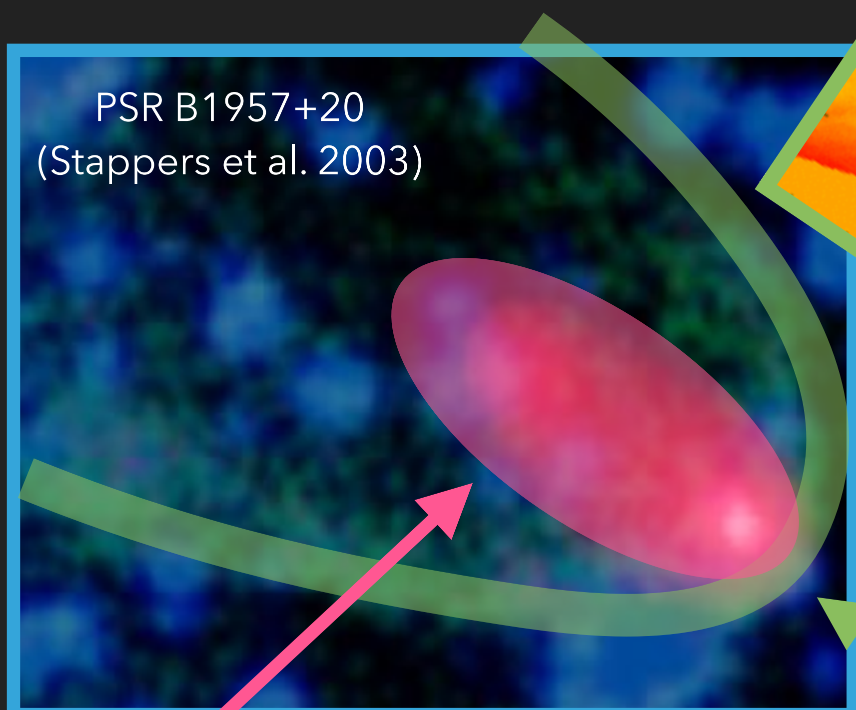
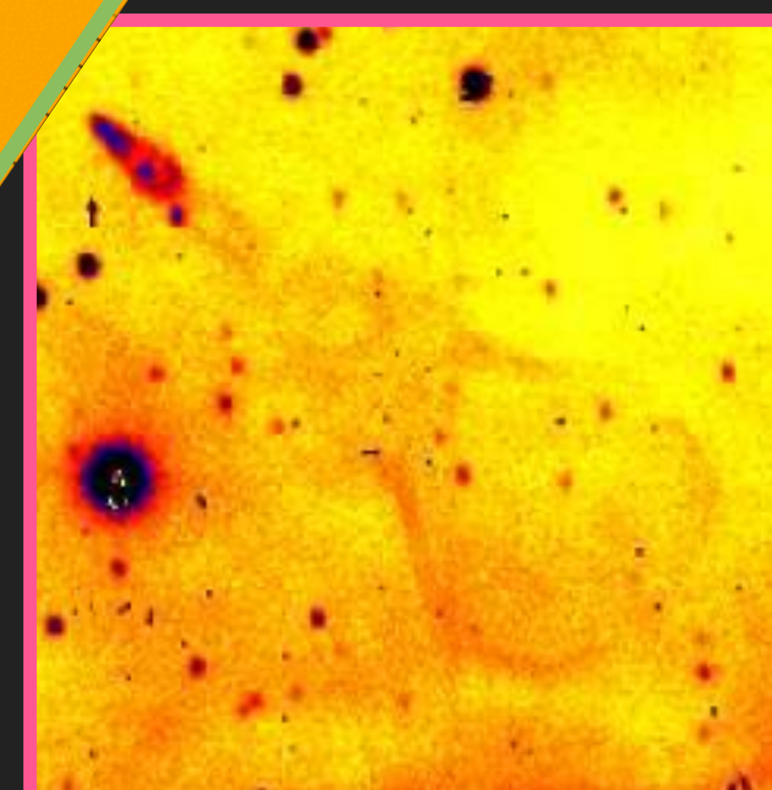


Halpha traces forward bow-shock in the ISM

X-rays trace PWN shocked wind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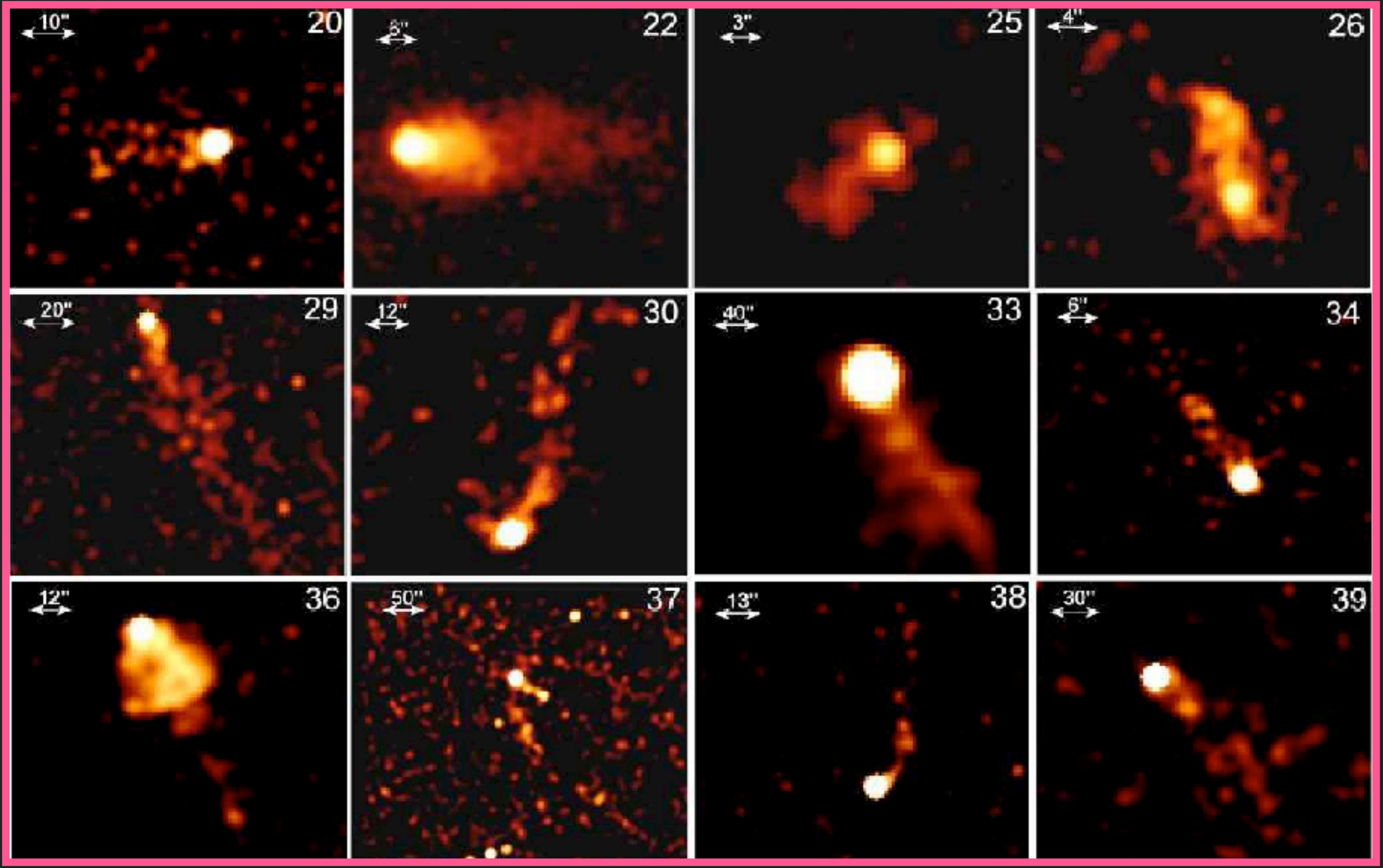
BOW-TAILS IN X-RAY

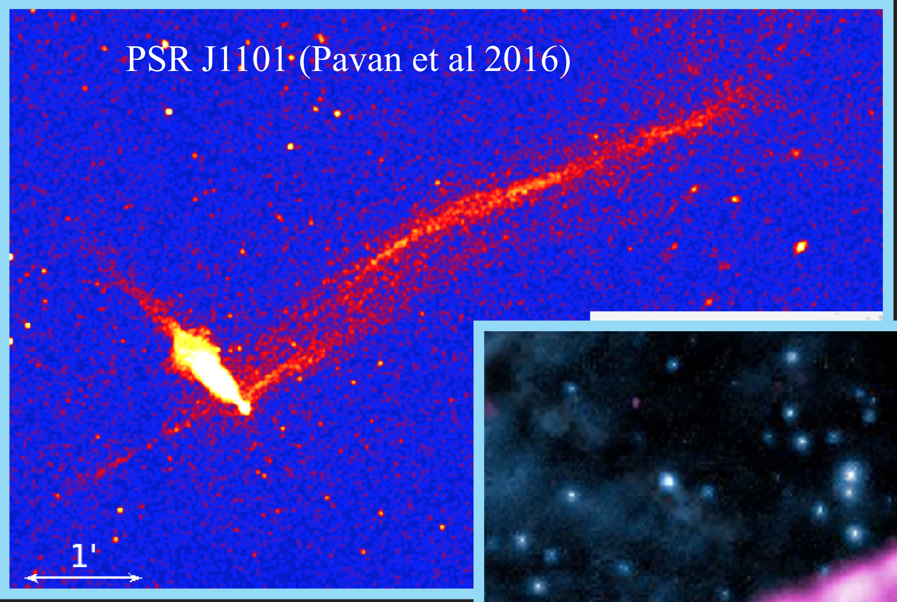
Kargaltsev & Pavlov 2008

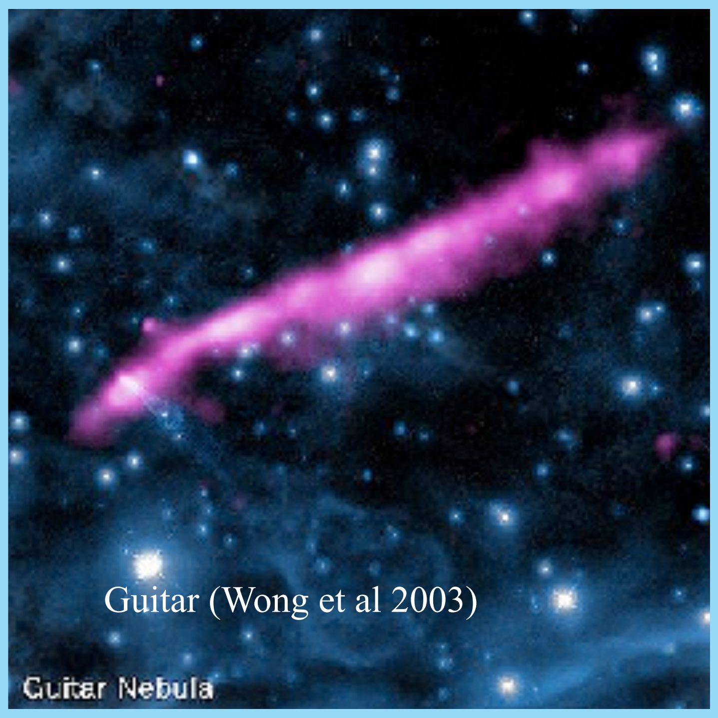


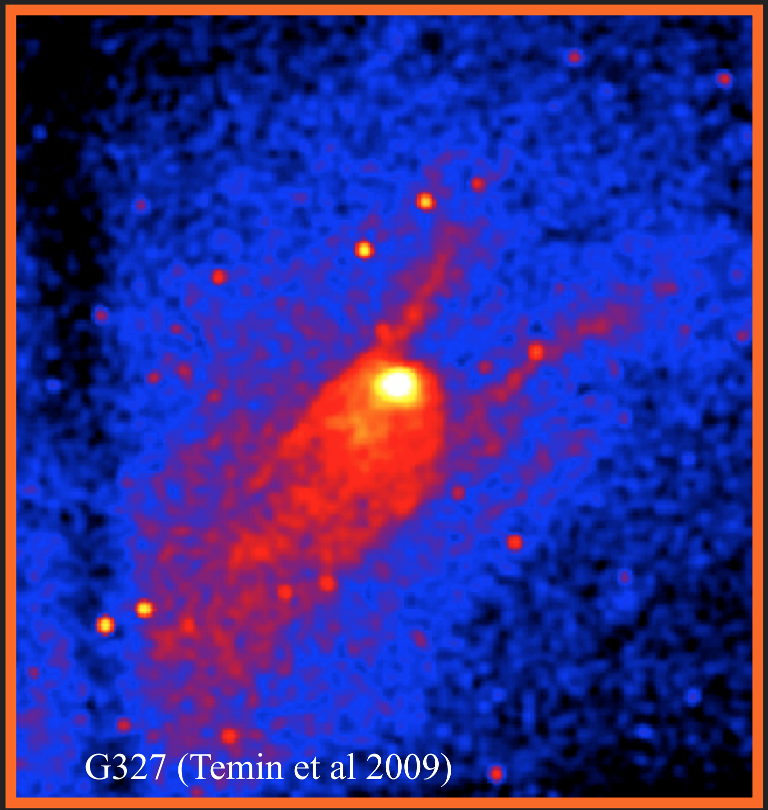
PAIR ESCAPE

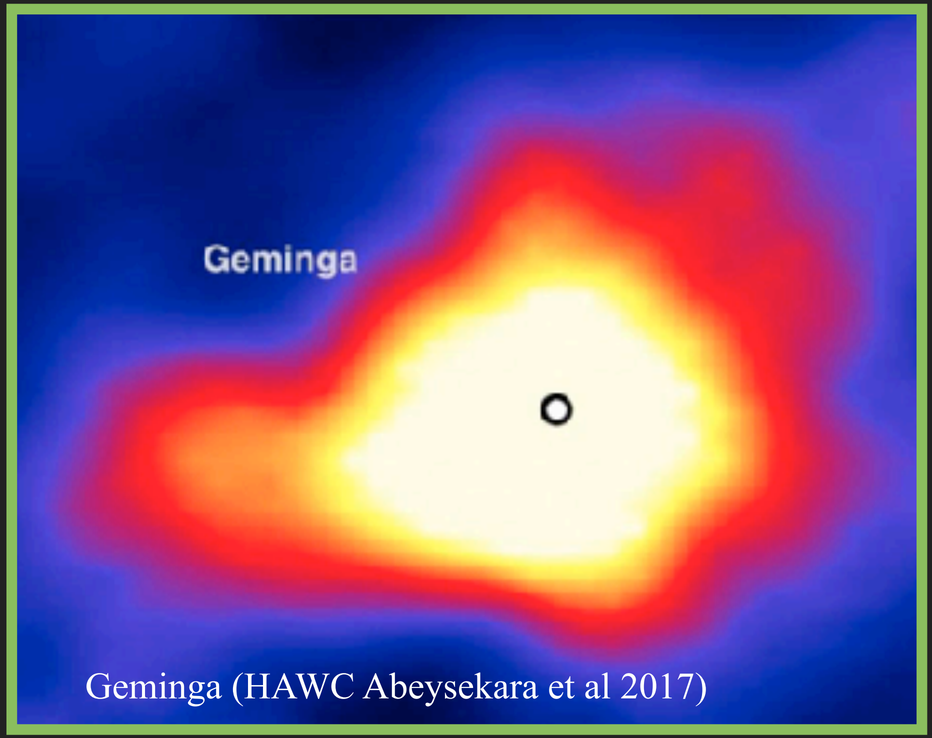
The are BS PWNe where the X-ray "tail" is where it should not be!

The particles in these features are ~ PSR voltage



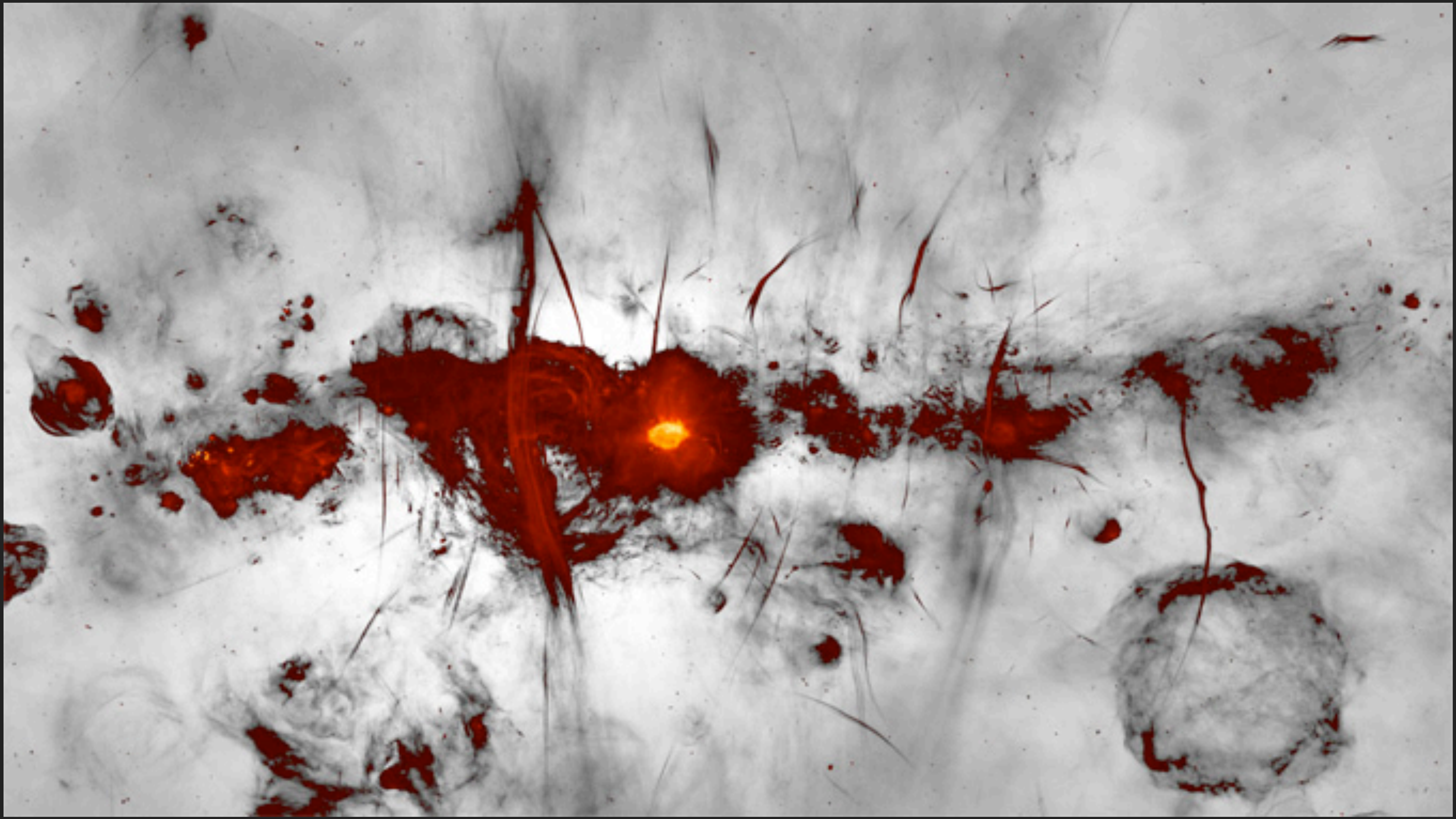






TeV halo suggest strong diffusion

IXPE - X-RAY POLARIMETRY - G 0.13-0.11



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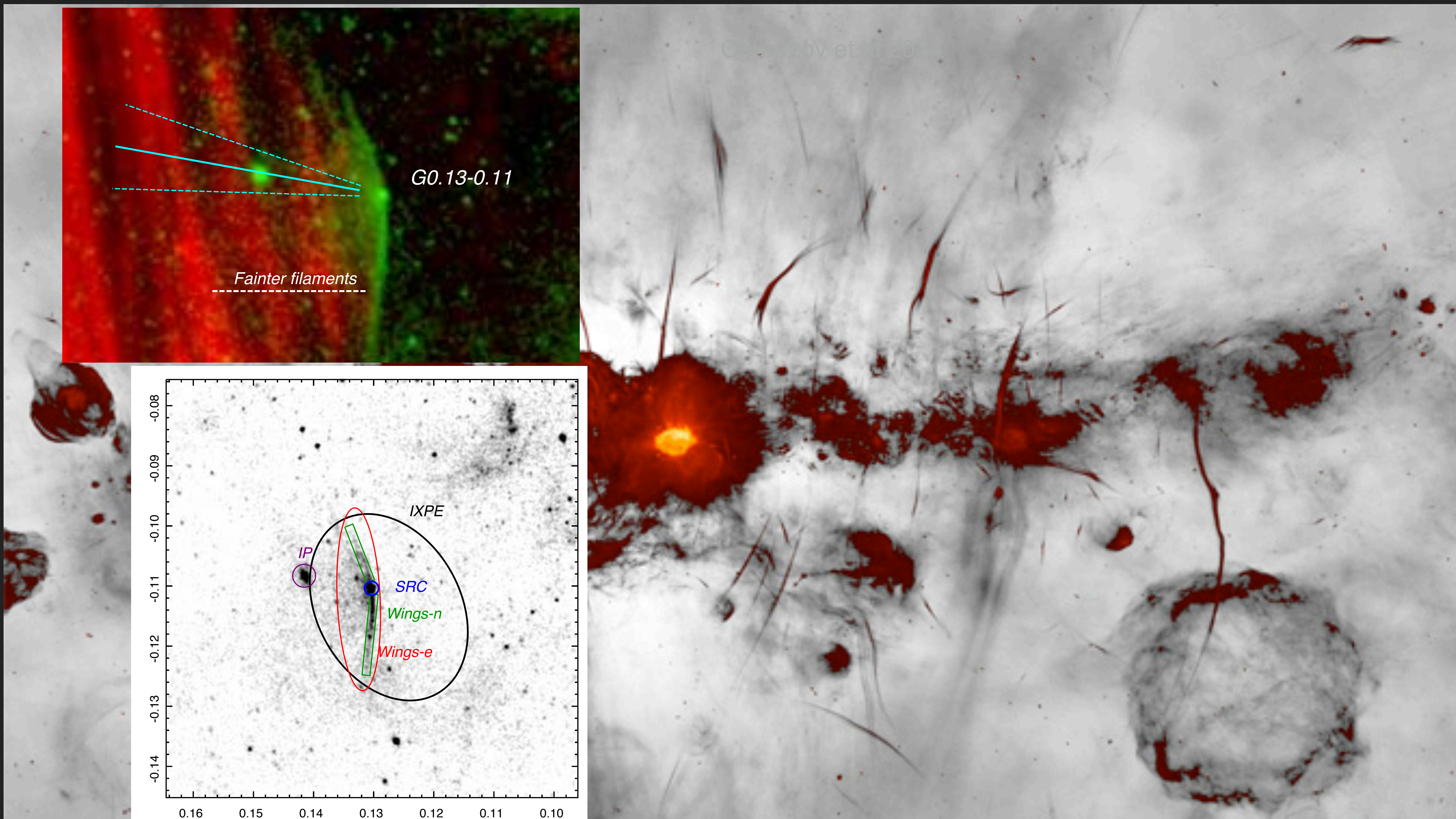

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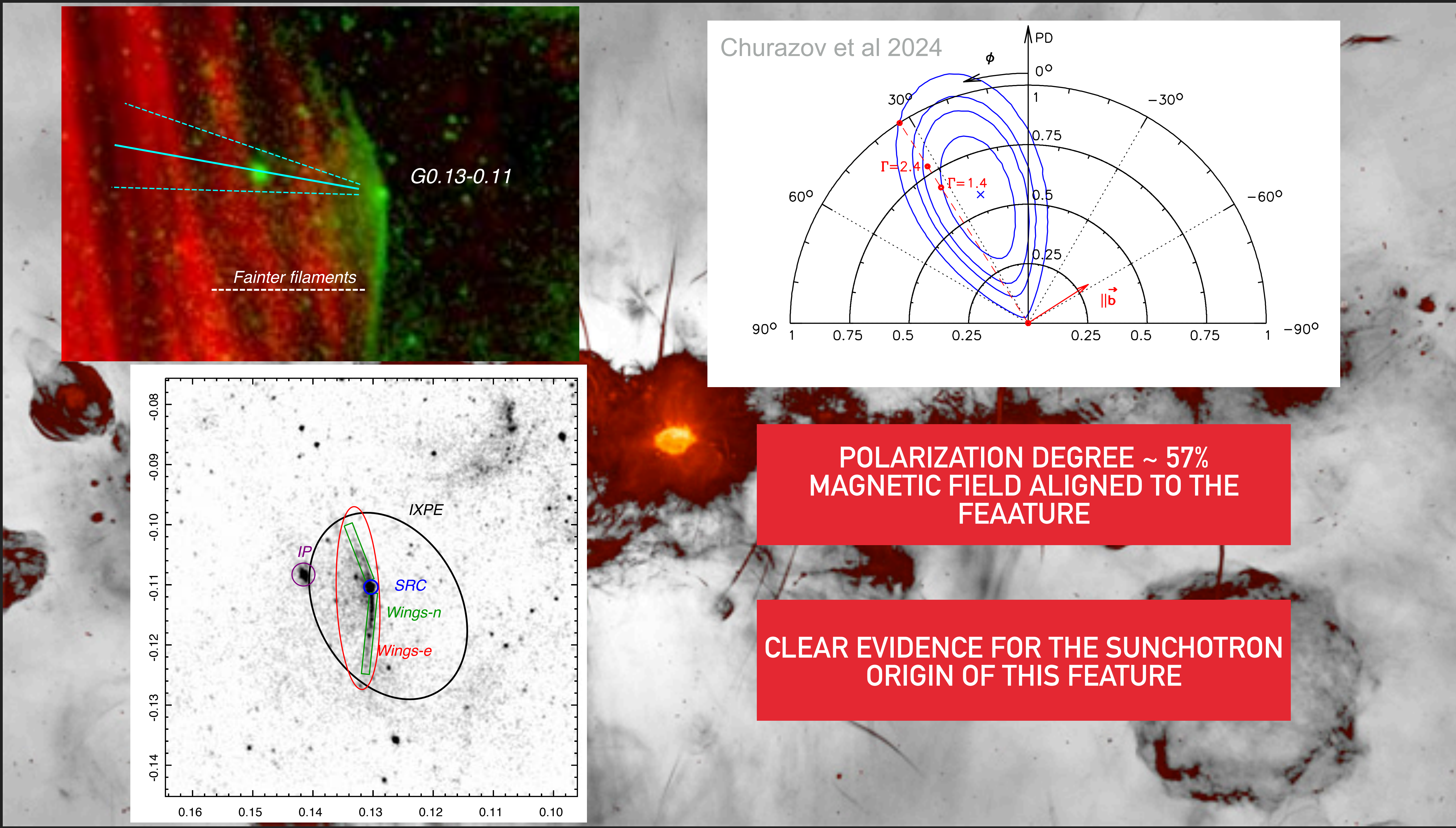
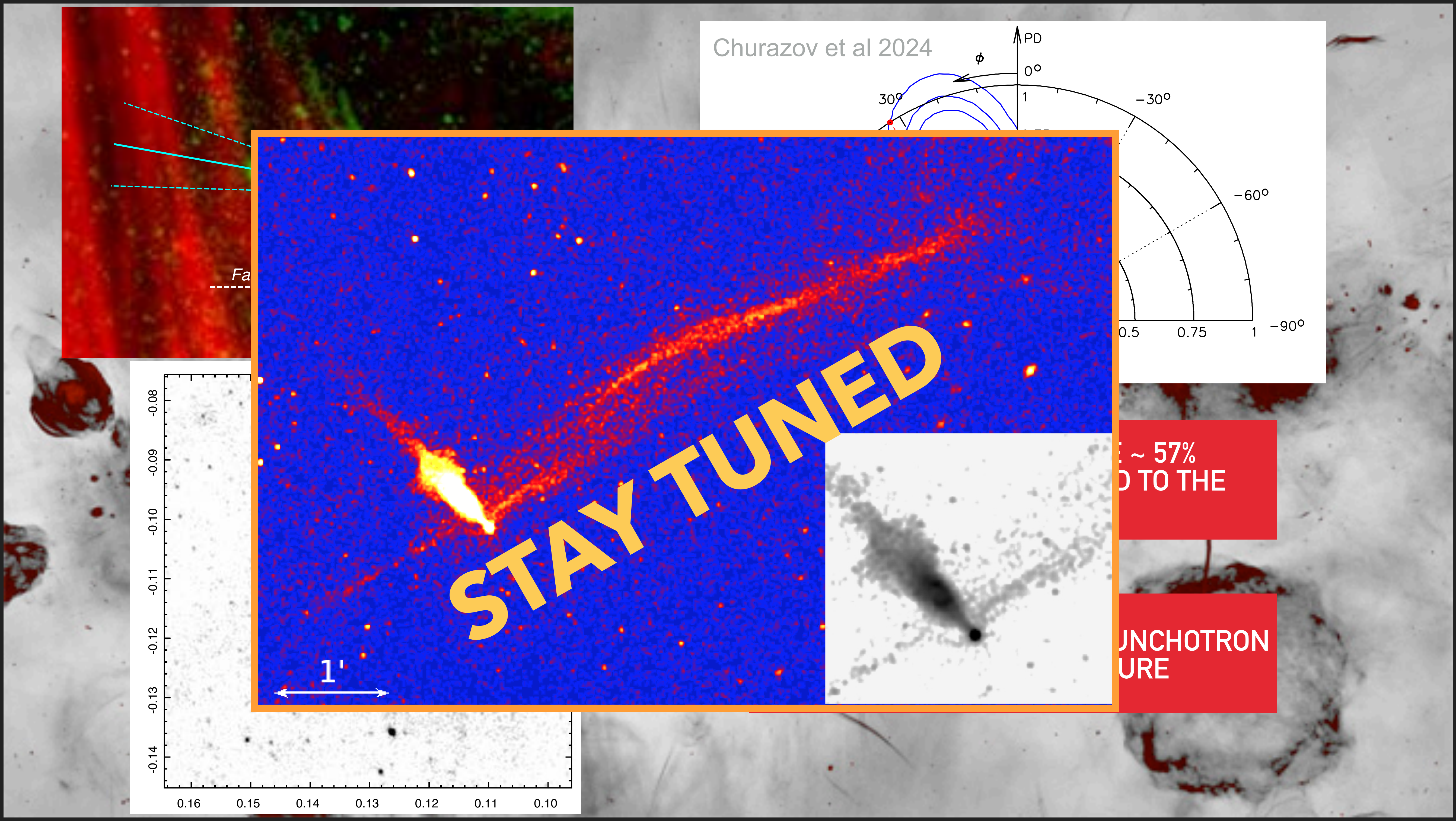


POLARIZATION DEGREE ~ 57%
MAGNETIC FIELD ALIGNED TO THE FEAATURE

CLEAR EVIDENCE FOR THE SUNCHOTRON ORIGIN OF THIS FEATURE

IXPE - X-RAY POLARIMETRY - G 0.13-0.11



CONCLUSIONS

POLARIZATION IS A VERY CONSTRAINIG PROBE OF TURBULENCE

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CANONICAL PWNR MODEL WORKS WELL BUT ……

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POLARIZATION IN CRAB PSR NEED FURTHER MODELLING