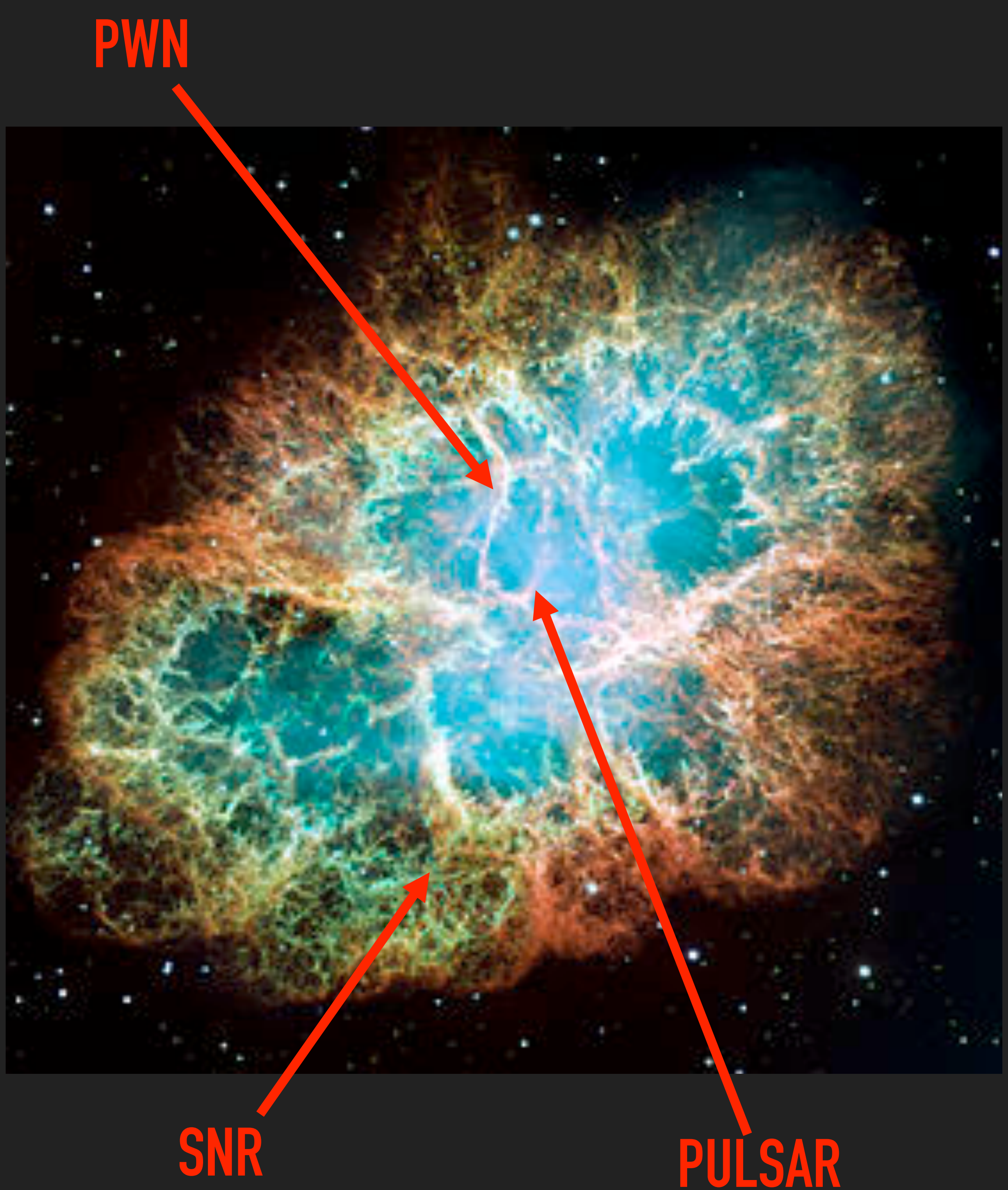
PARTICLE ACCELERATION IN PWNE

NICCOLO' BUCCIANTINI

INAF ARCETRI - UNIV. FIRENZE - INFN

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

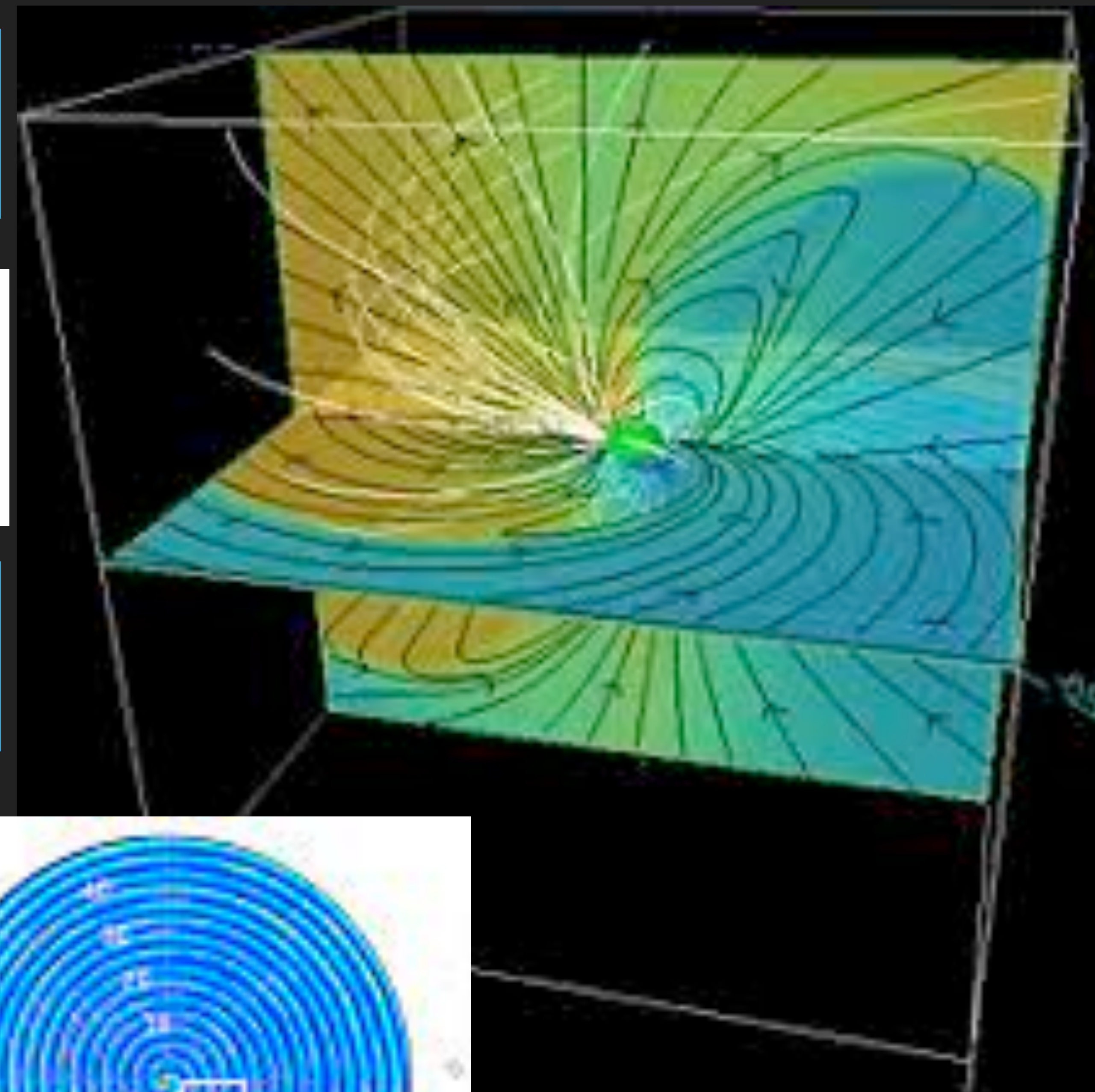
THE PUSAR WIND

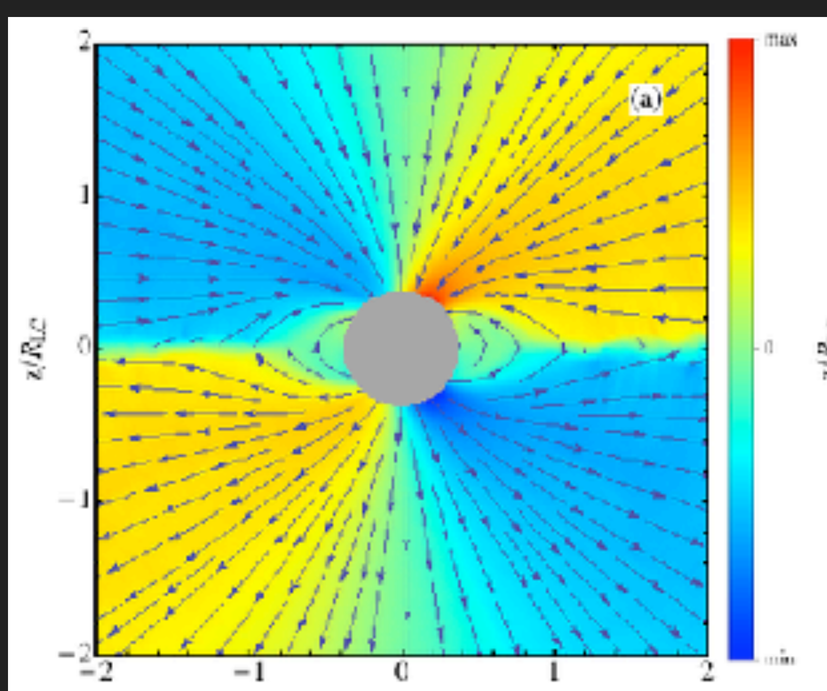
PSR WIND & MAGNETOSPHERE WELL DESCRIBED BY FORCE FREE RMHD

$$\nabla \cdot \boldsymbol{E} = 4\pi\rho_e, \quad \nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t},$$

$$\nabla \cdot \boldsymbol{B} = 0, \quad \nabla \times \boldsymbol{B} = \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t} + \frac{4\pi}{c}\boldsymbol{j},$$

RHO & J SET BY VANISHING LORENTZ FORCE





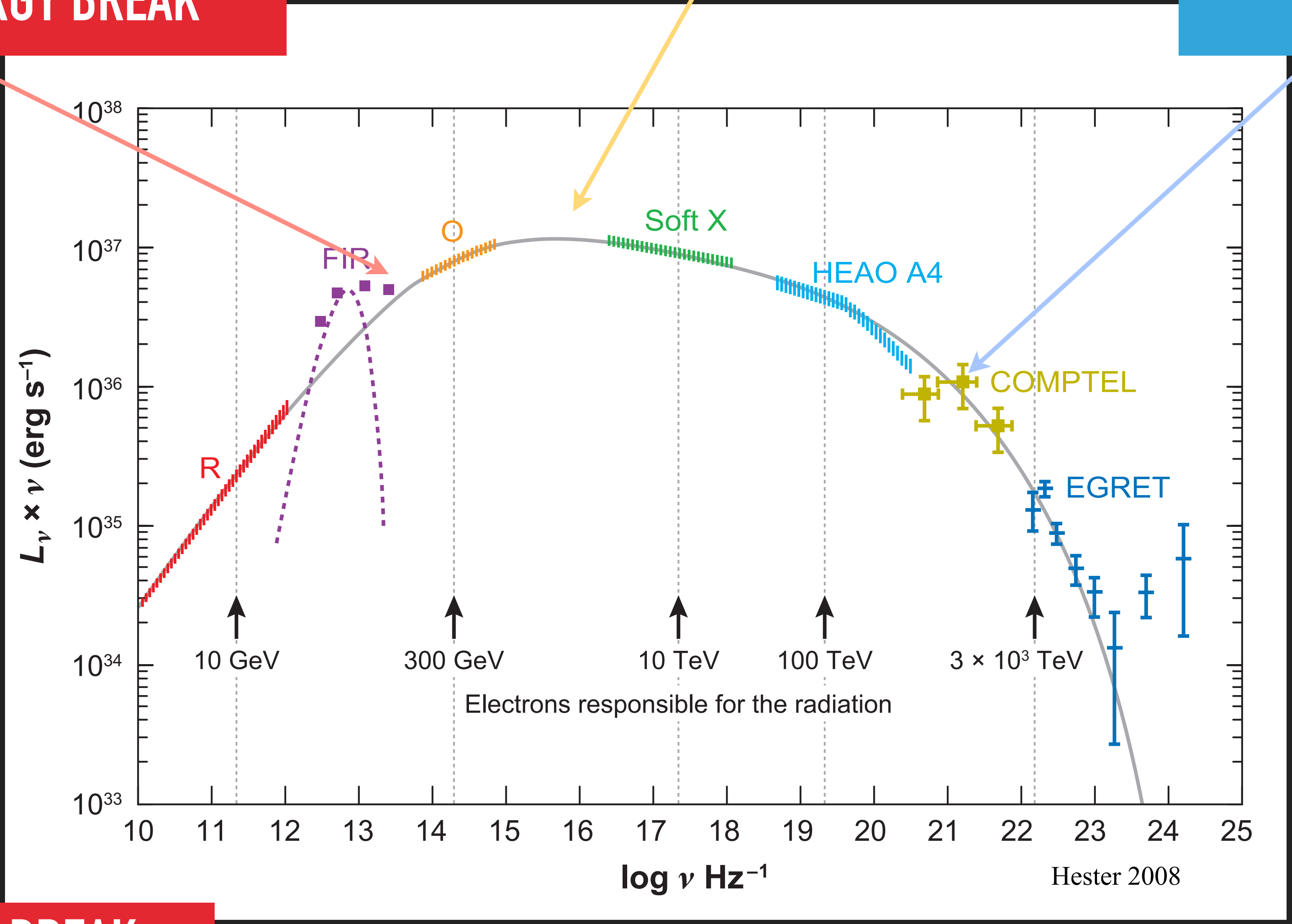
STRIPED WIND OF ALTERNATING POLARITIES

CRAB SYNCHROTRON SPECTRUM

HIGH ENERGY BREAK

LOW ENERGY BREAK

MEV CUTOFF



INJECTION BREAK

SYNCHR. COOLING

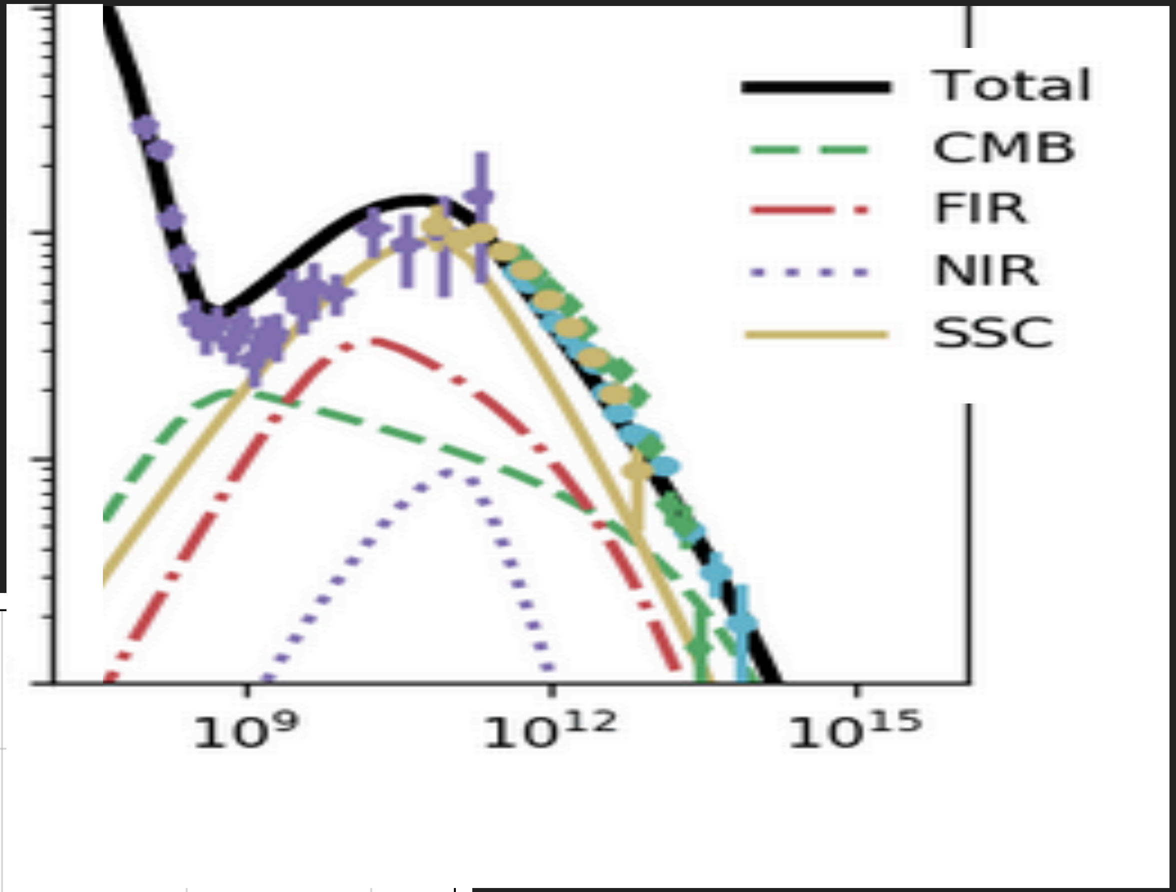
ACCELER. CUTOFF

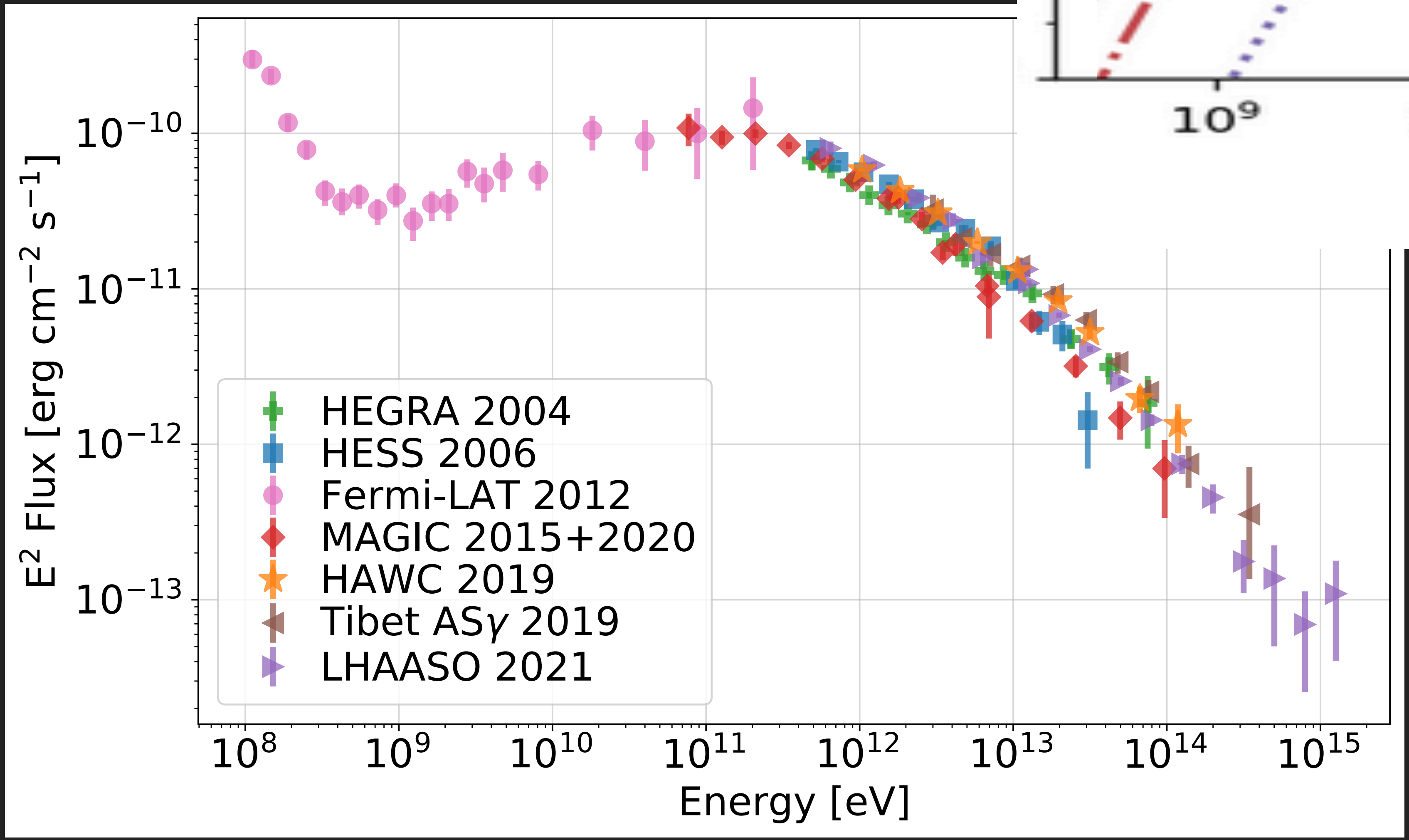
THE MOST EFFICIENT NON-THERMAL ACCELERATOR.

IC GAMMA SPECTRUM

ONLY SYSTEM SSC DOMINATED

OTHER PWNE ARE NIR/FIR DOMINATED



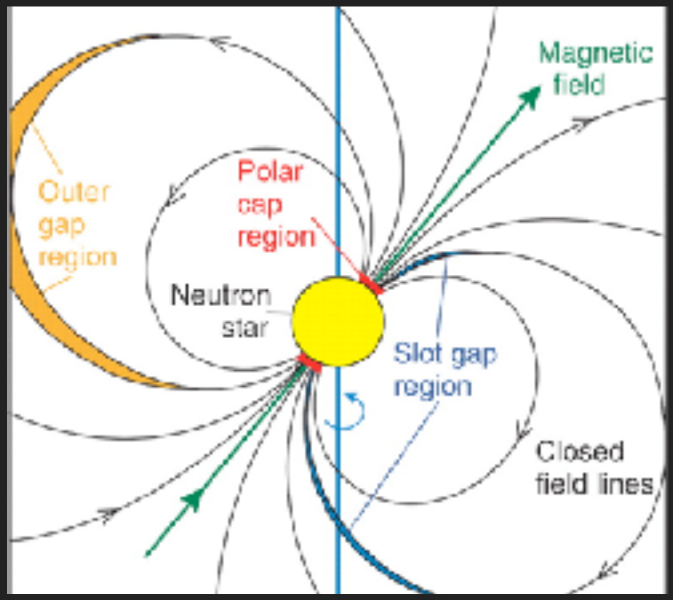


TREND SET BY RADIO-OPT PARTICLES

X-RAY PARTICLES IN KN

ORIGIN OF THE SYNCHROTRON CUTOFF

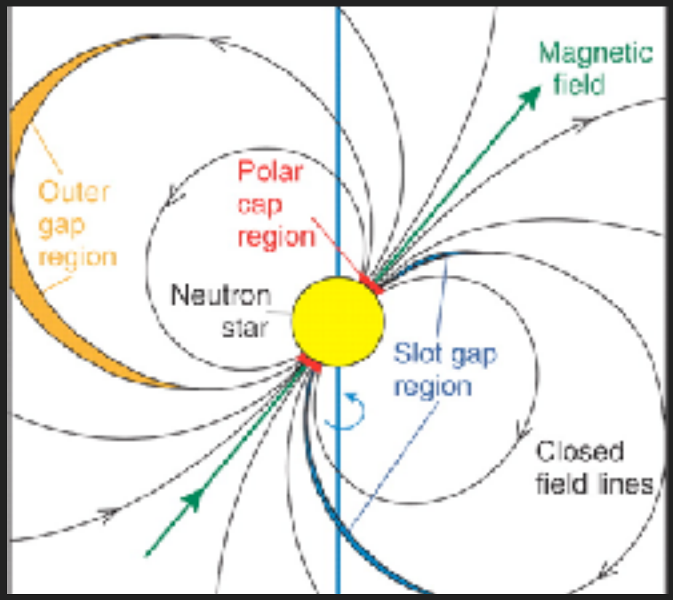
POTENTIAL LIMITED ACCELERATION

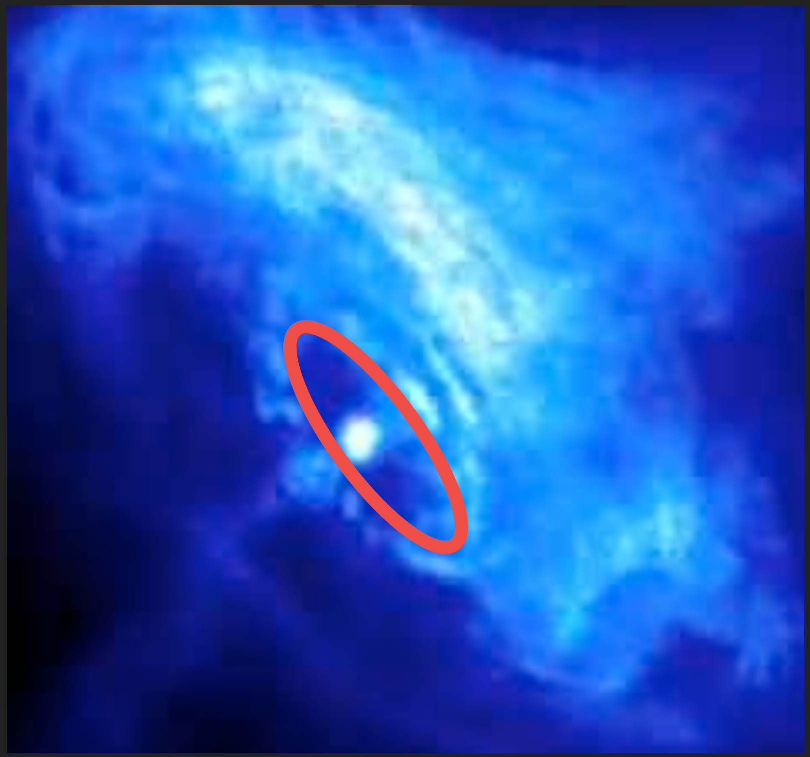


$$mc^2\gamma_{max} = e\sqrt{\frac{L}{c}} = e\Phi_{psr}$$

ORIGIN OF THE SYNCHROTRON CUTOFF

POTENTIAL LIMITED ACCELERATION





$$\frac{L}{4\pi c R_{ts}^2} = \frac{1}{2}\frac{3Lt}{4\pi R_n^3}$$

$$\frac{L}{4\pi c R_{ts}^2} = P_{neb} = \frac{1}{\sigma}\frac{B_{ts}^2}{8\pi}$$

$$R_{ts} = \frac{1}{B_{ts}}\sqrt{\frac{\sigma L}{c}}$$

$$mc^2\gamma_{max} = e\sqrt{\frac{L}{c}} = e\Phi_{psr}$$

$$\frac{eB_{ts}}{mc^2\gamma_{max}} = R_L = R_{ts}$$

$$\frac{mc^2\gamma_{max}}{eB_{ts}} = R_L = R_{ts}$$

ACCELERATION LIMIT AT THE TS

$$\frac{E_{max}}{eB_{ts}} = e\sqrt{\frac{\sigma L}{c}} = e\Phi_{psr}\sqrt{\sigma}$$

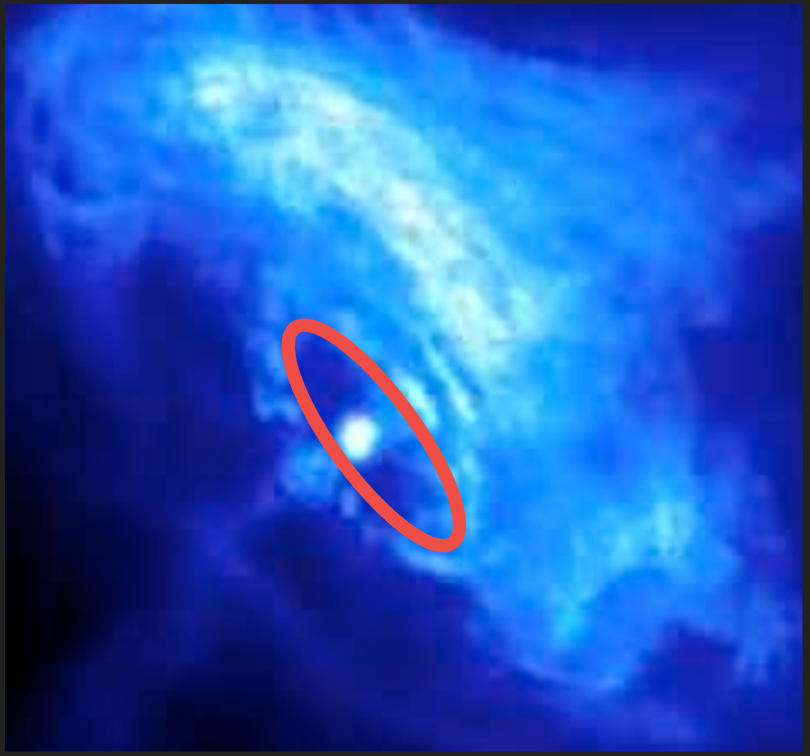
MAGNETISATION IN THE CRAB IS JUST BELOW EQUIPARTITION
B ~ 150-120 UG

ORIGIN OF THE SYNCHROTRON CUTOFF

LOSS LIMITED ACCELERATION

COMPARING GYRO-PERIOD WRT SYNCH COOLING TIME

$$\tau_{gyr} = \frac{mc\gamma}{eB} \qquad \tau_{syn} = \frac{3m^3c^5}{2e^4B^2\gamma} \qquad \gamma_{max} \simeq 10^8\frac{1}{\sqrt{B}}$$



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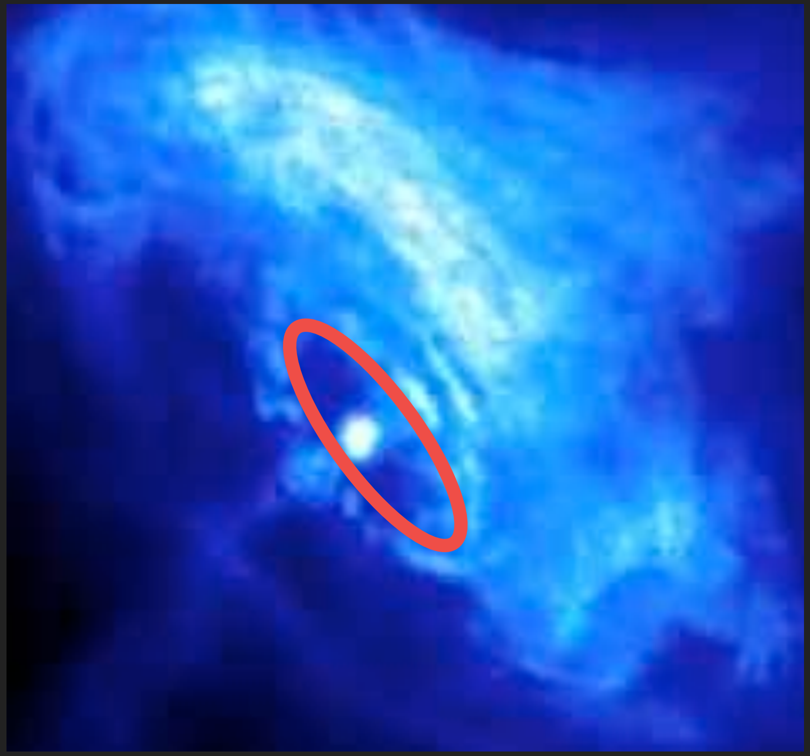
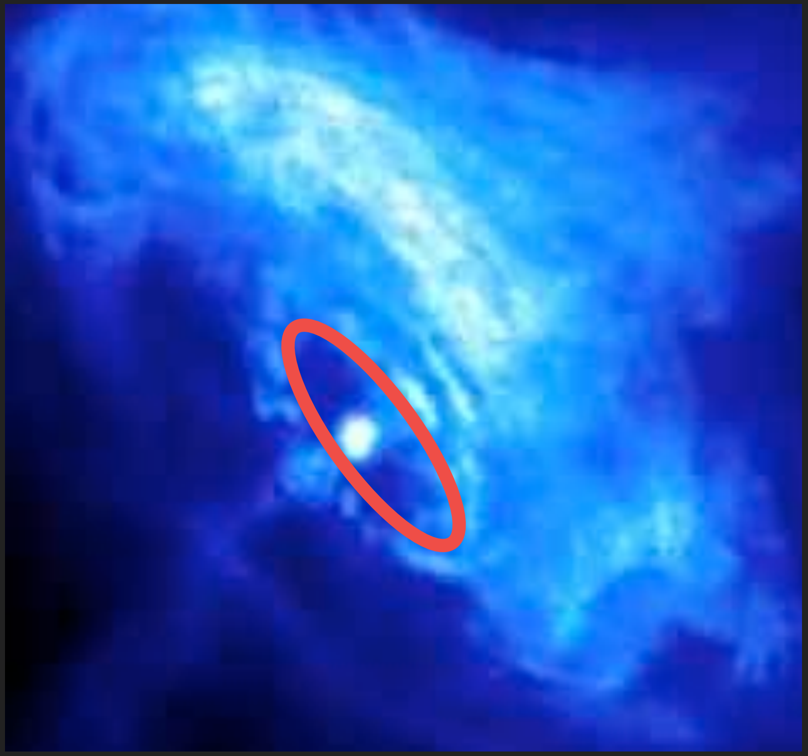
MAXIMUM FREQUENCY IS FIXED

$$\nu_{syn,max} \simeq 150MeV$$



ORIGIN OF THE SYNCHROTRON CUTOFF

LOSS LIMITED ACCELERATION



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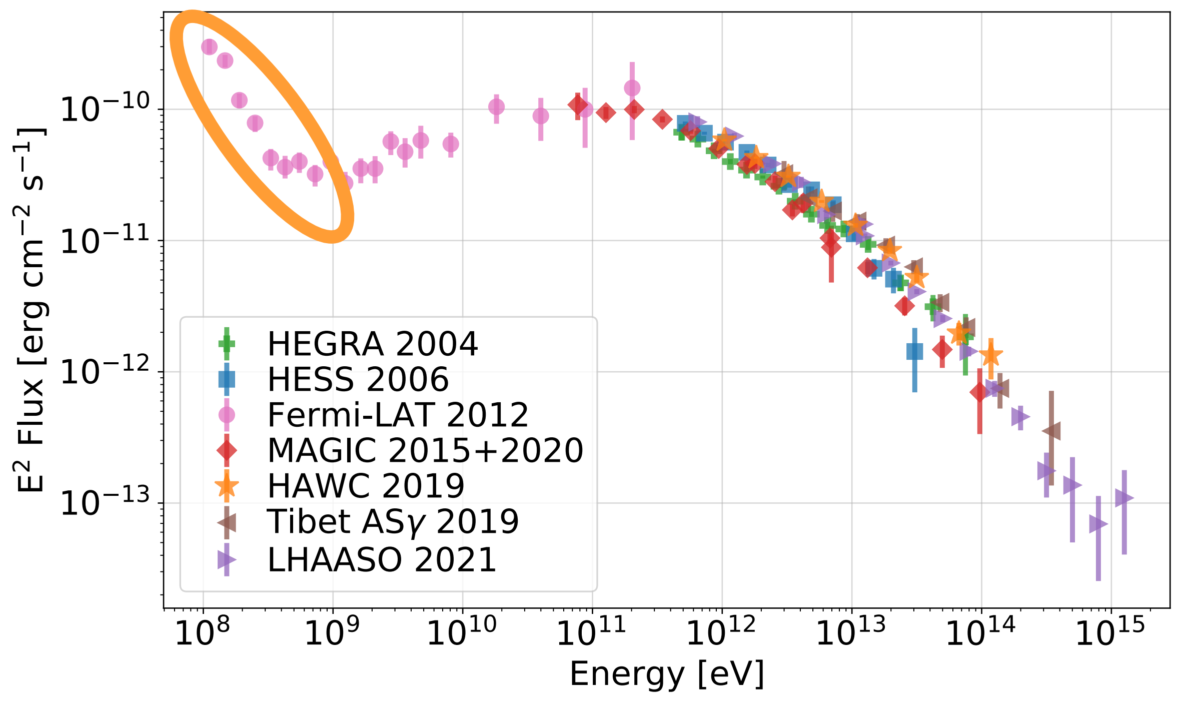


IN CRAB THE LIMITS ALL COINCIDE

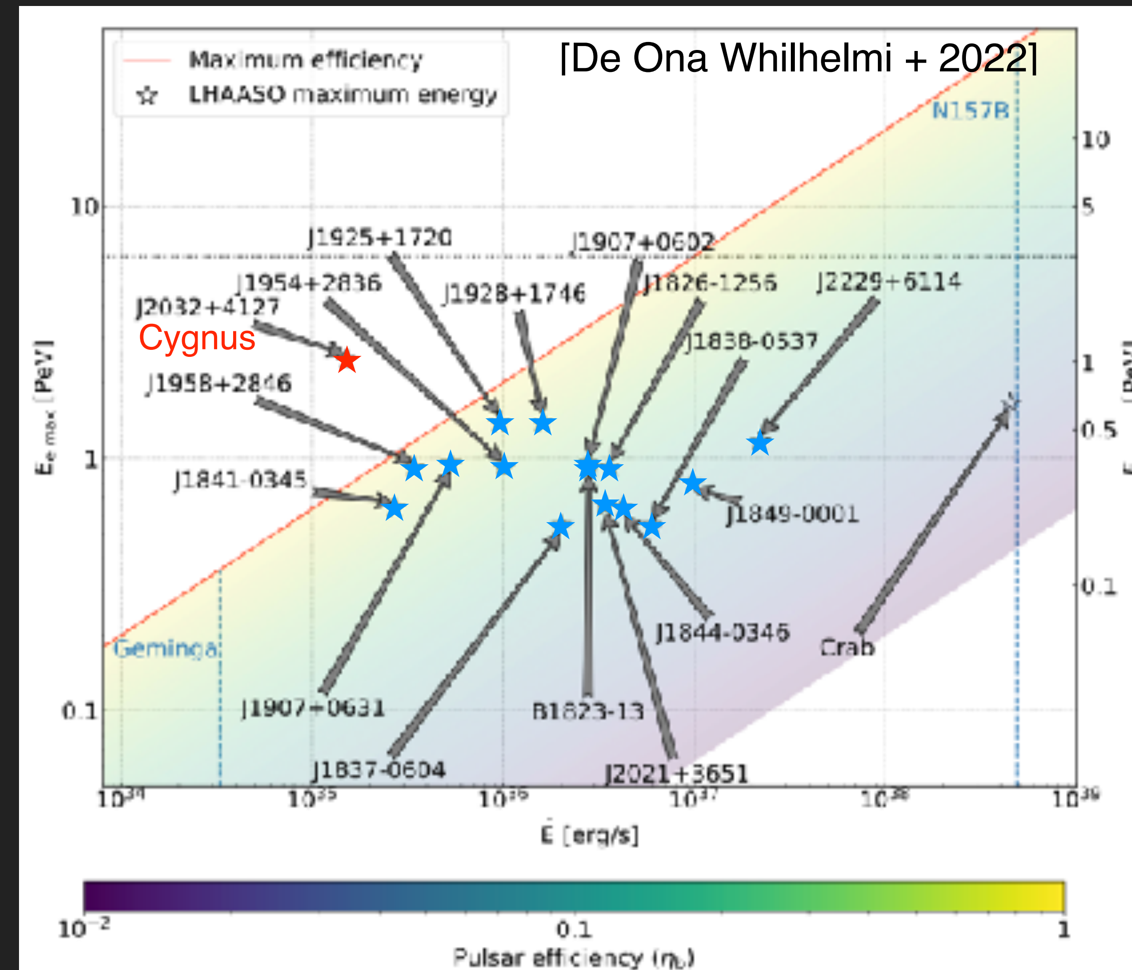
OTHERS ALL POTENTIAL LIMITED

PWNE AND LHAASO SOURCES

12 SOURCES DETECTED BY LHAASO ABOVE 100 TEV

Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	E_{max} (PeV)
LHAASO J0534+2202	83.55	22.05	0.88 ± 0.11
LHAASO J1825-1326	276.45	−13.45	0.42 ± 0.16
LHAASO J1839-0545	279.95	−5.75	0.21 ± 0.05
LHAASO J1843-0338	280.75	−3.65	$0.26_{-0.10}^{+0.16}$
LHAASO J1849-0003	282.35	−0.05	0.35 ± 0.07
LHAASO J1908+0621	287.05	6.35	0.44 ± 0.05
LHAASO J1929+1745	292.25	17.75	$0.71_{-0.07}^{+0.16}$
LHAASO J1956+2845	299.05	28.75	0.42 ± 0.03
LHAASO J2018+3651	304.75	36.85	0.27 ± 0.02
LHAASO J2032+4102	308.05	41.05	1.42 ± 0.13
LHAASO J2108+5157	317.15	51.95	0.43 ± 0.05
LHAASO J2226+6057	336.75	60.95	0.57 ± 0.19



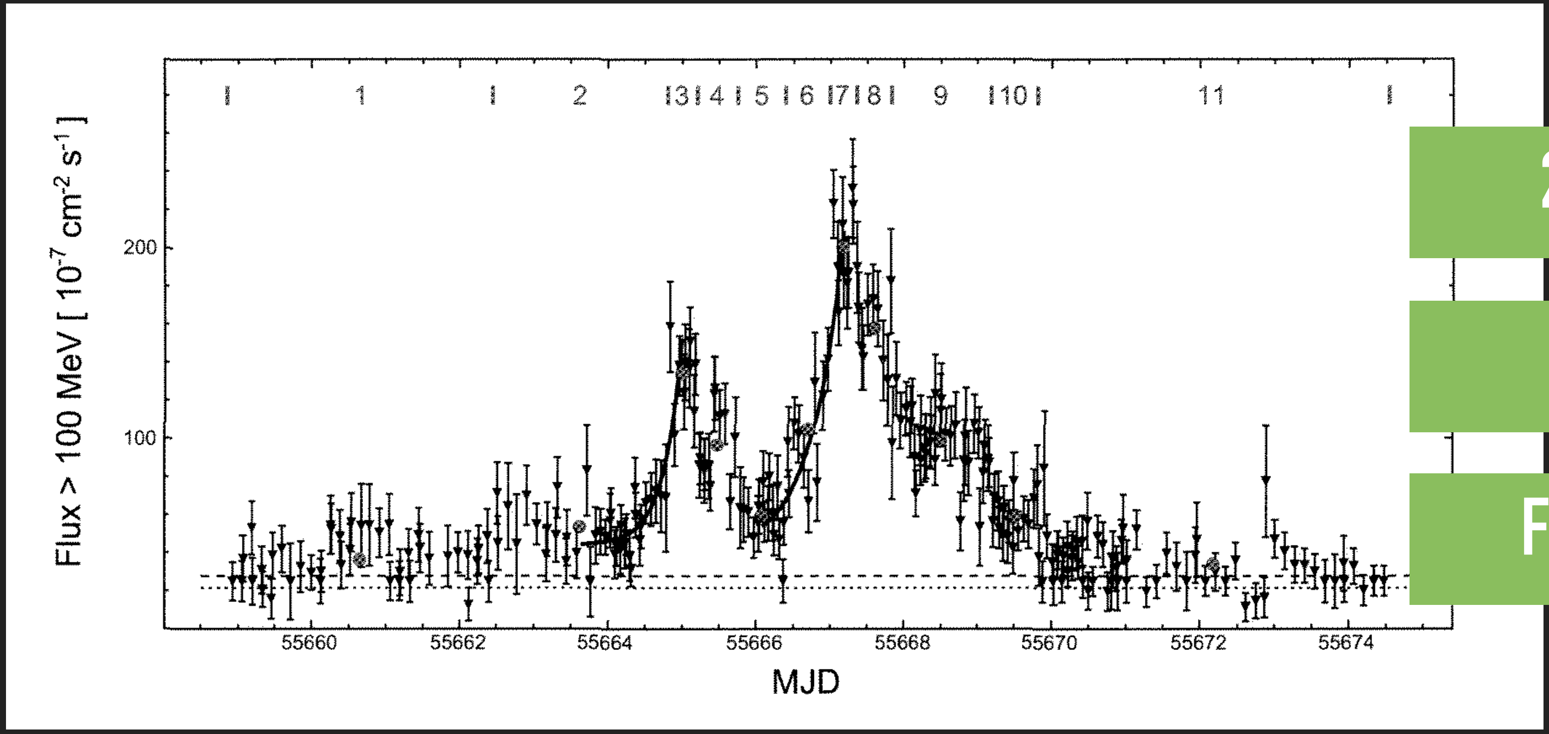
PEV PROTONS OR ELECTRONS?

ALL SOURCES HAVE A PSR IN THE FIELD EXCEPT ONE

$$E_{max,abs} = e\xi_E\ \xi_B^{1/2}\sqrt{\dot{E}/c} \approx 1.8\ PeV\ \xi_E\ \xi_B^{1/2}\ \dot{E}_{36}^{1/2}$$

$$E_{max,loss} \approx 6\ PeV\ \xi_e^{1/2}\ B_{-4}^{-1/2}$$

2011 FLARE

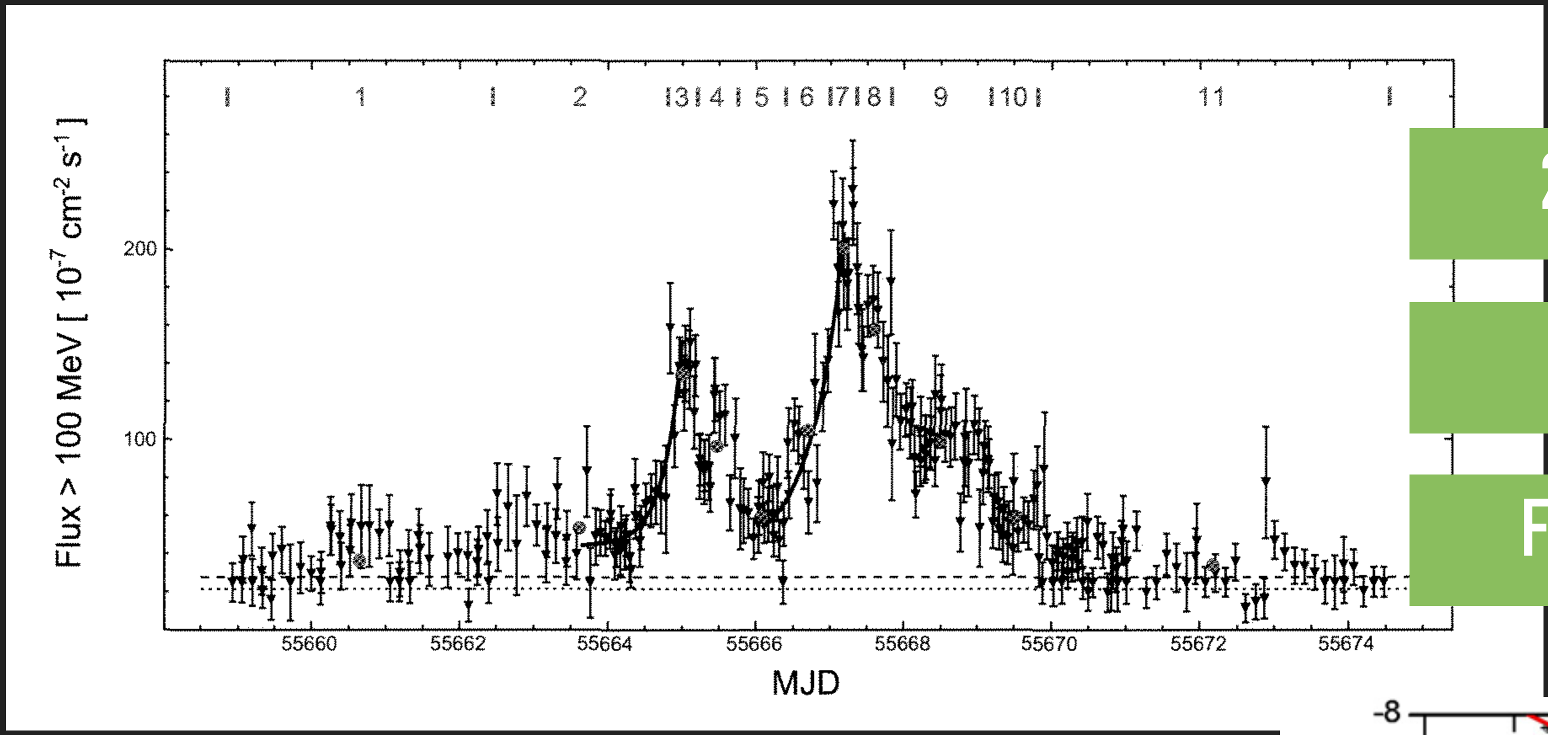


25 TIMES ABOVE QUIESCENT

FLARE IS STRUCTURED

FLARE DURATION DAYS-WEEK

2011 FLARE



25 TIMES ABOVE QUIESCENT

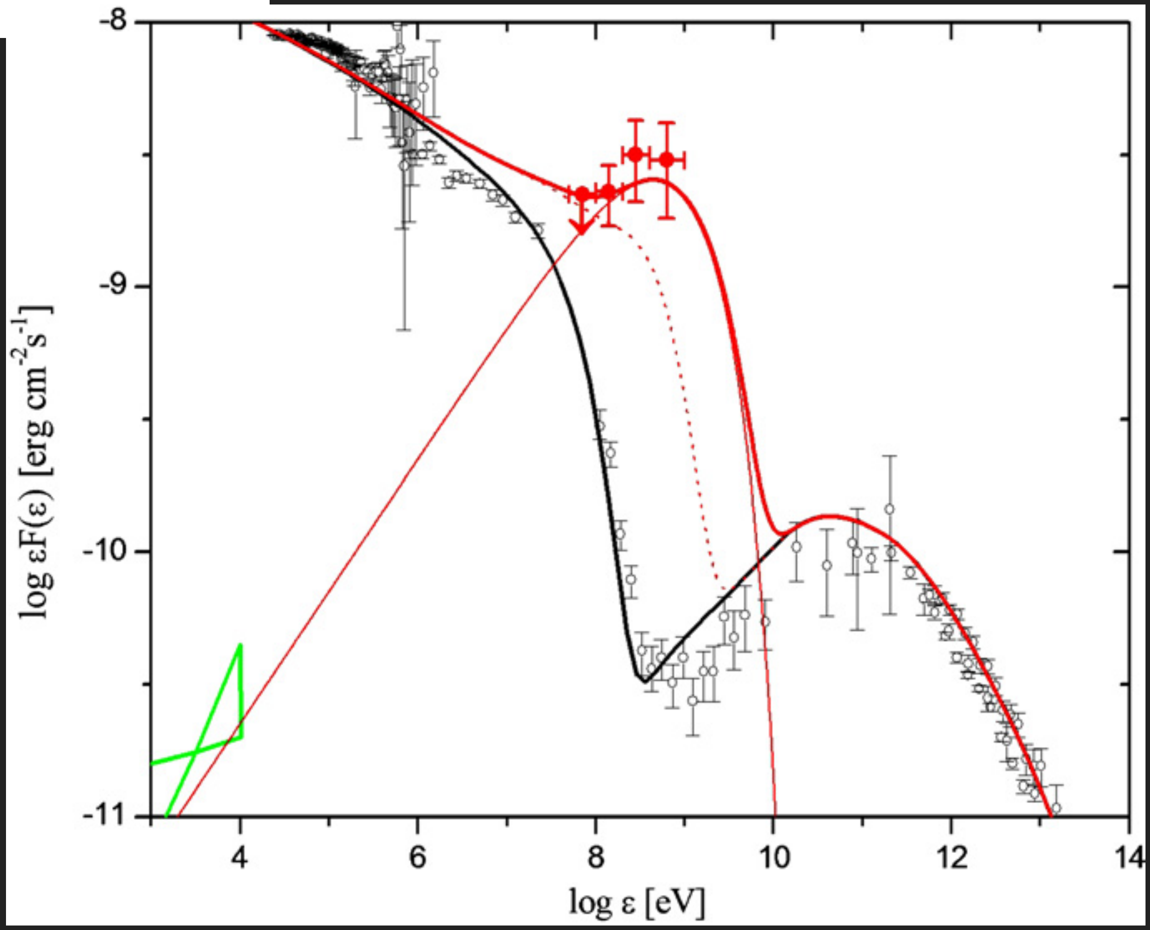
FLARE IS STRUCTURED

FLARE DURATION DAYS-WEEK

COMPATIBLE WITH ALMOST MONOCHROMATIC

REQUIRES DOPPLER BOOSTING

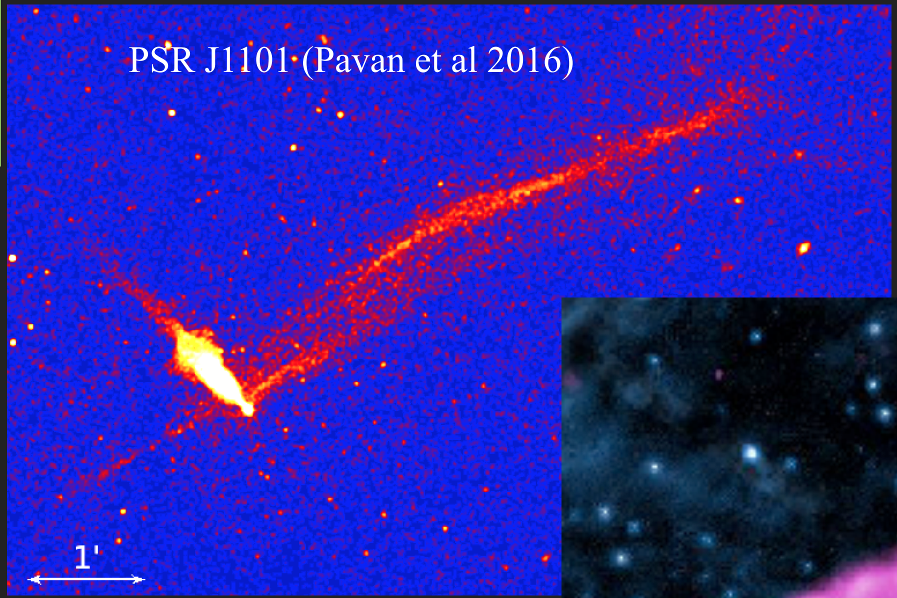
LOCATION - KNOT?



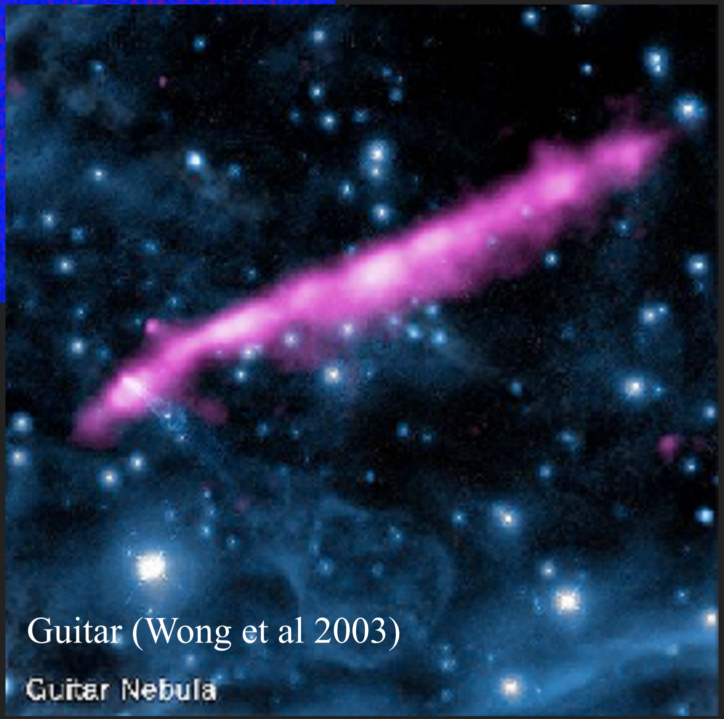
PAIR ESCAPE

THE ARE BS PWNE WHERE THE X-RAY “TAIL” IS WHERE IT SHOULD NOT BE!

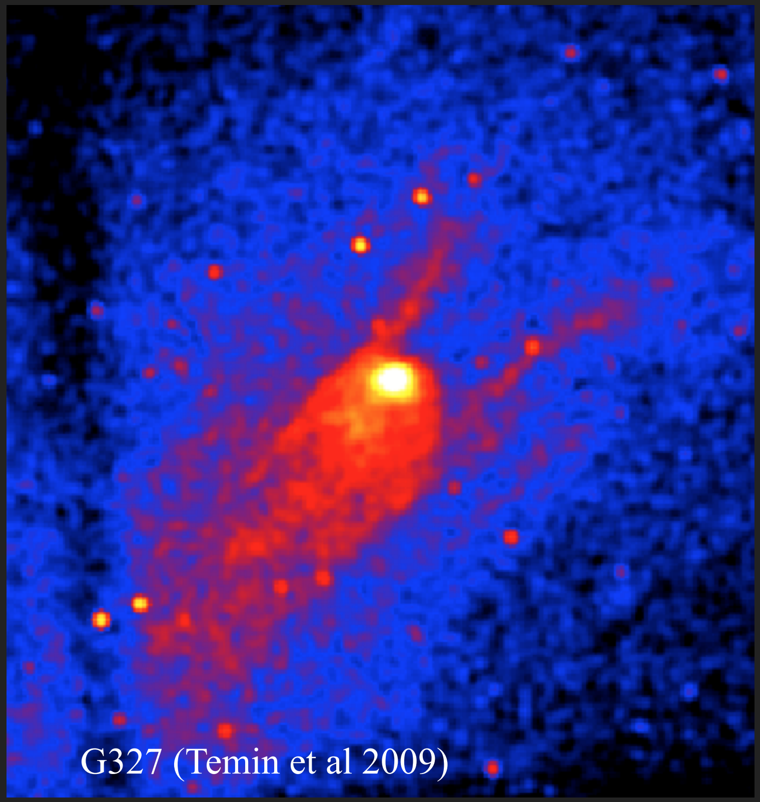
THE PARTICLES IN THESE FEATURES ARE ~ PSR VOLTAGE

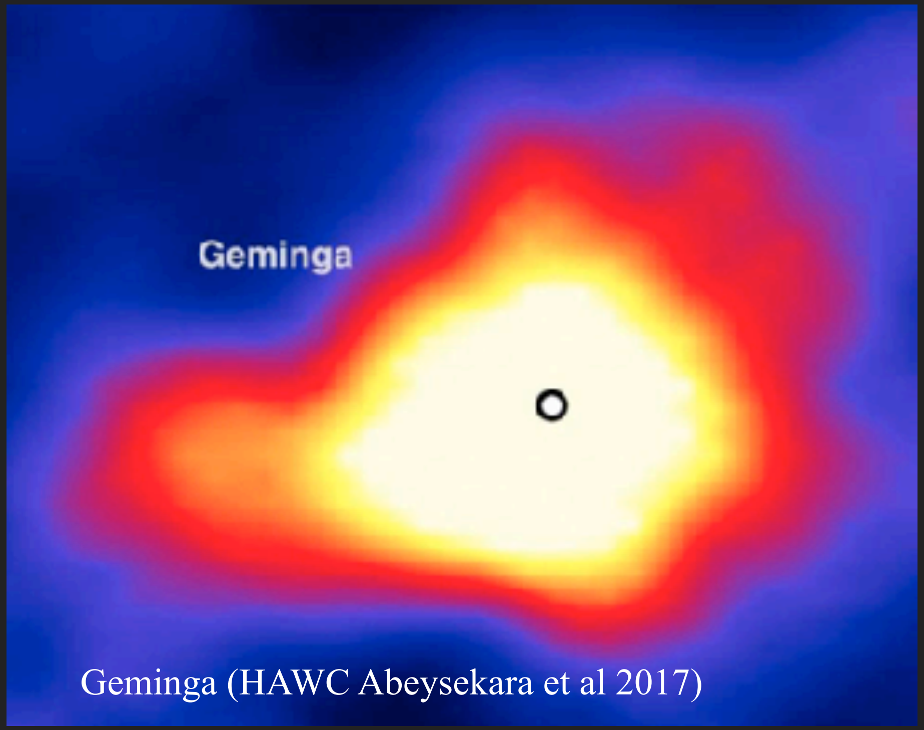


PSR J1101 (Pavan et al 2016)



Guitar (Wong et al 2003)

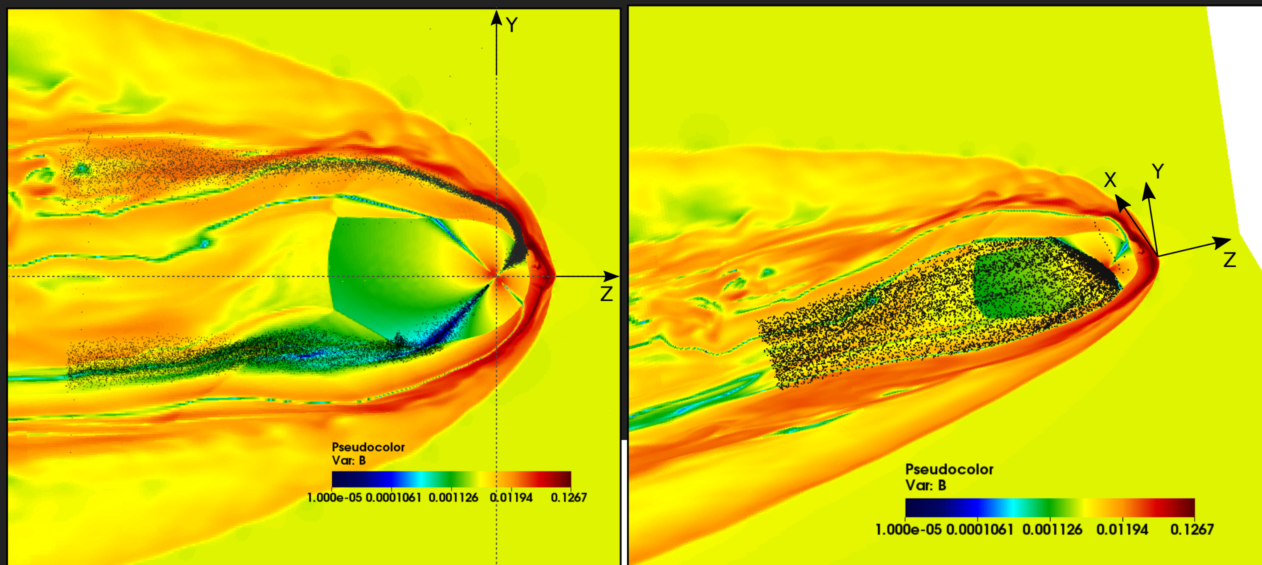

G327 (Temin et al 2009)



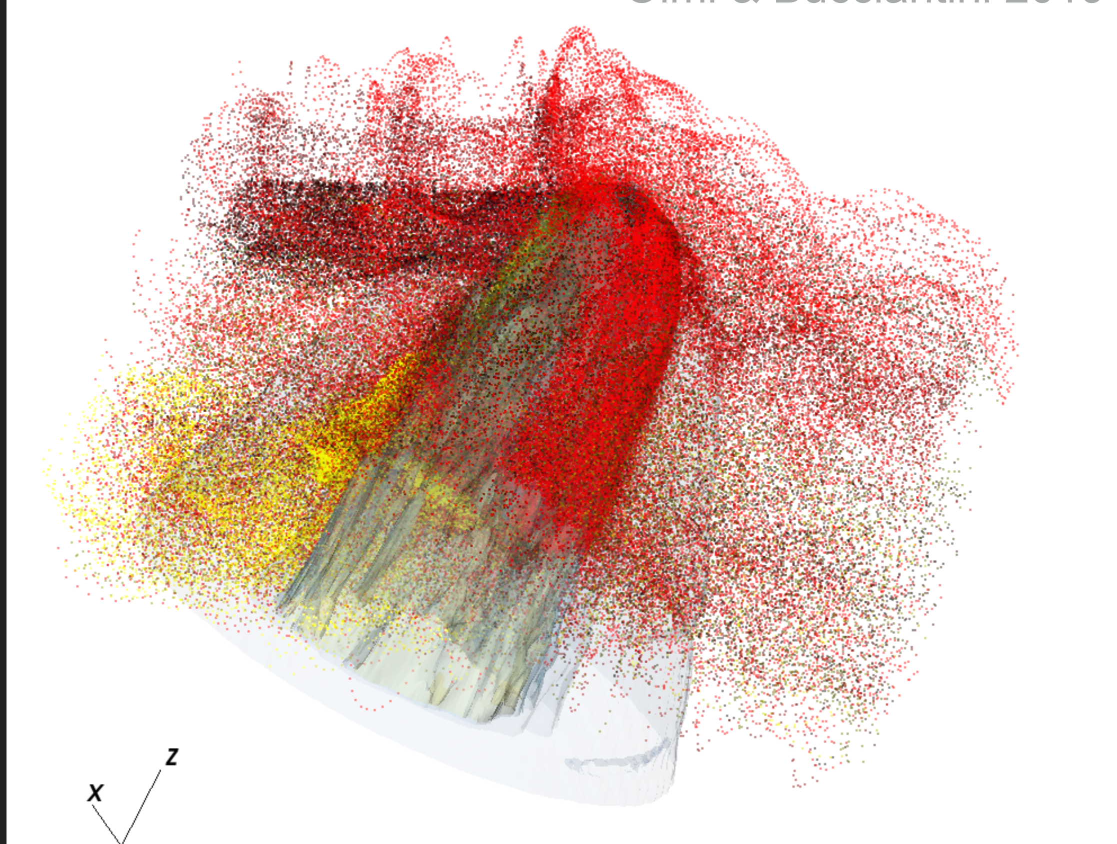
Geminga (HAWC Abeysekara et al 2017)

TEV HALO SUGGEST STRONG DIFFUSION

PAIR ESCAPE IN MHD MODELS

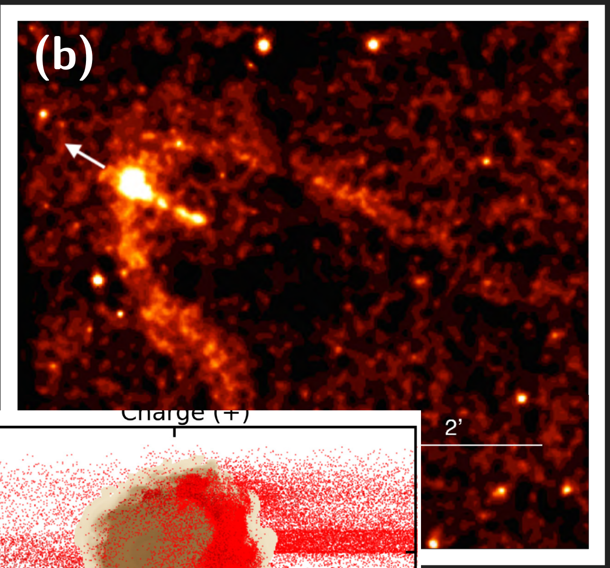


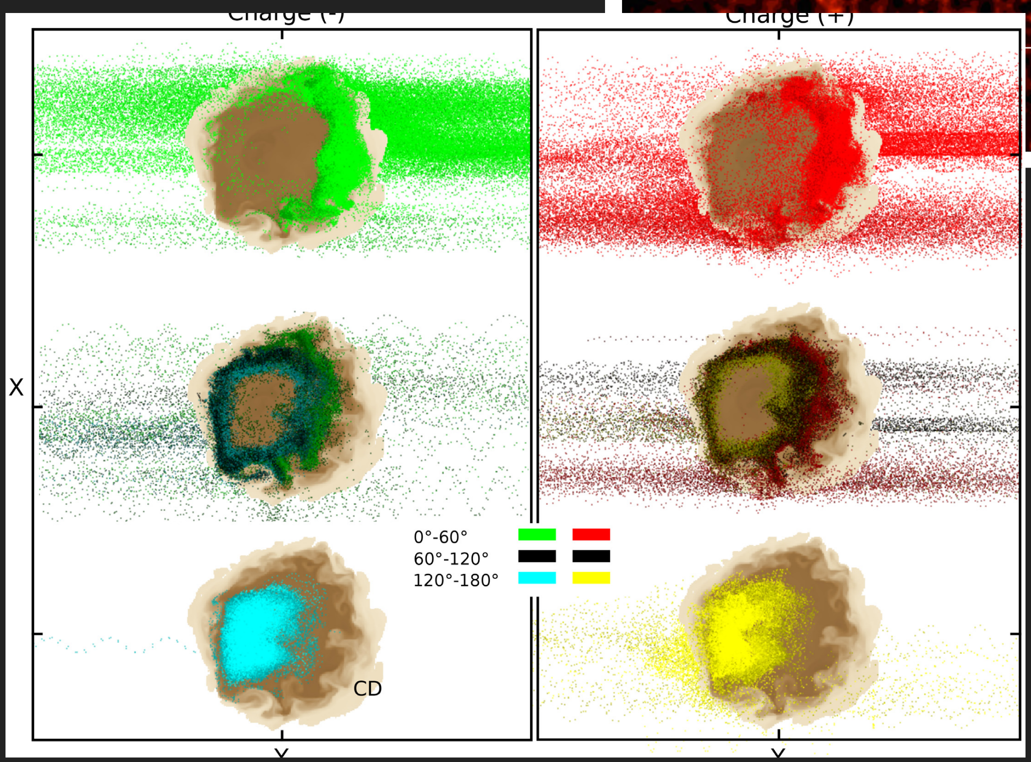
Olmi & Bucciantini 2019



LOW ENERGY PARTICLES REMAIN CONFINED IN CURRENTS

GEMINGA HARD TAILS

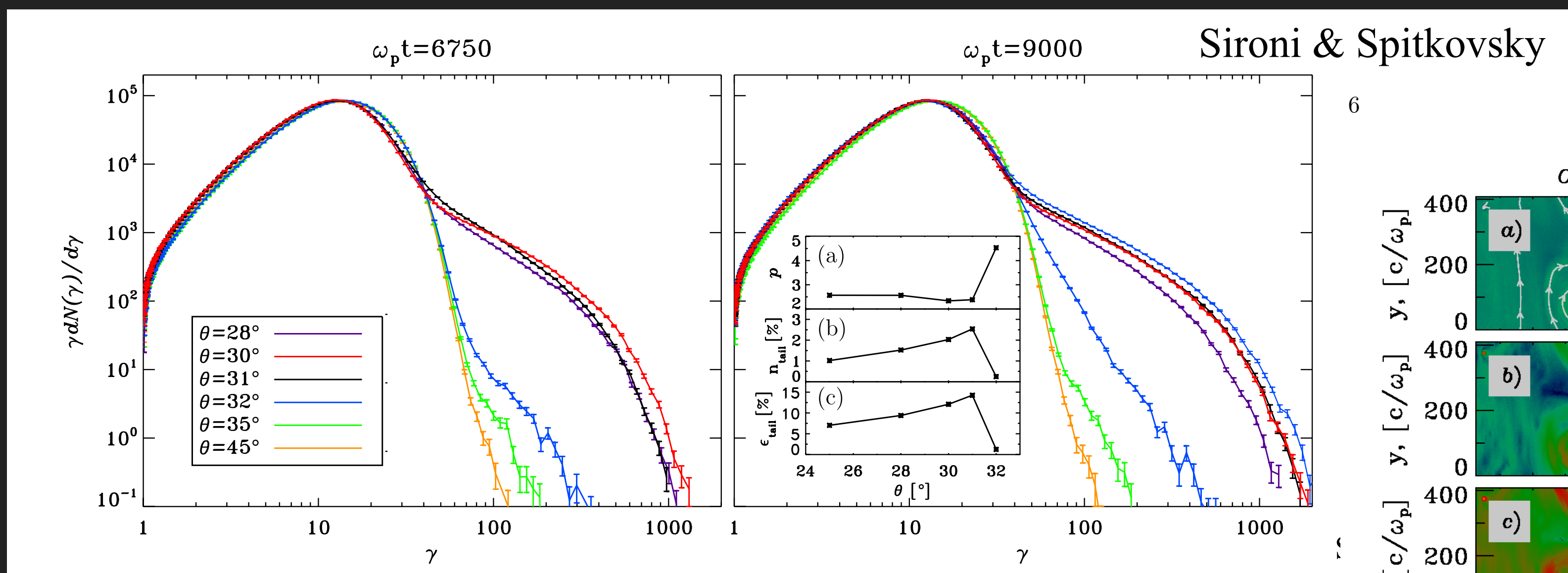


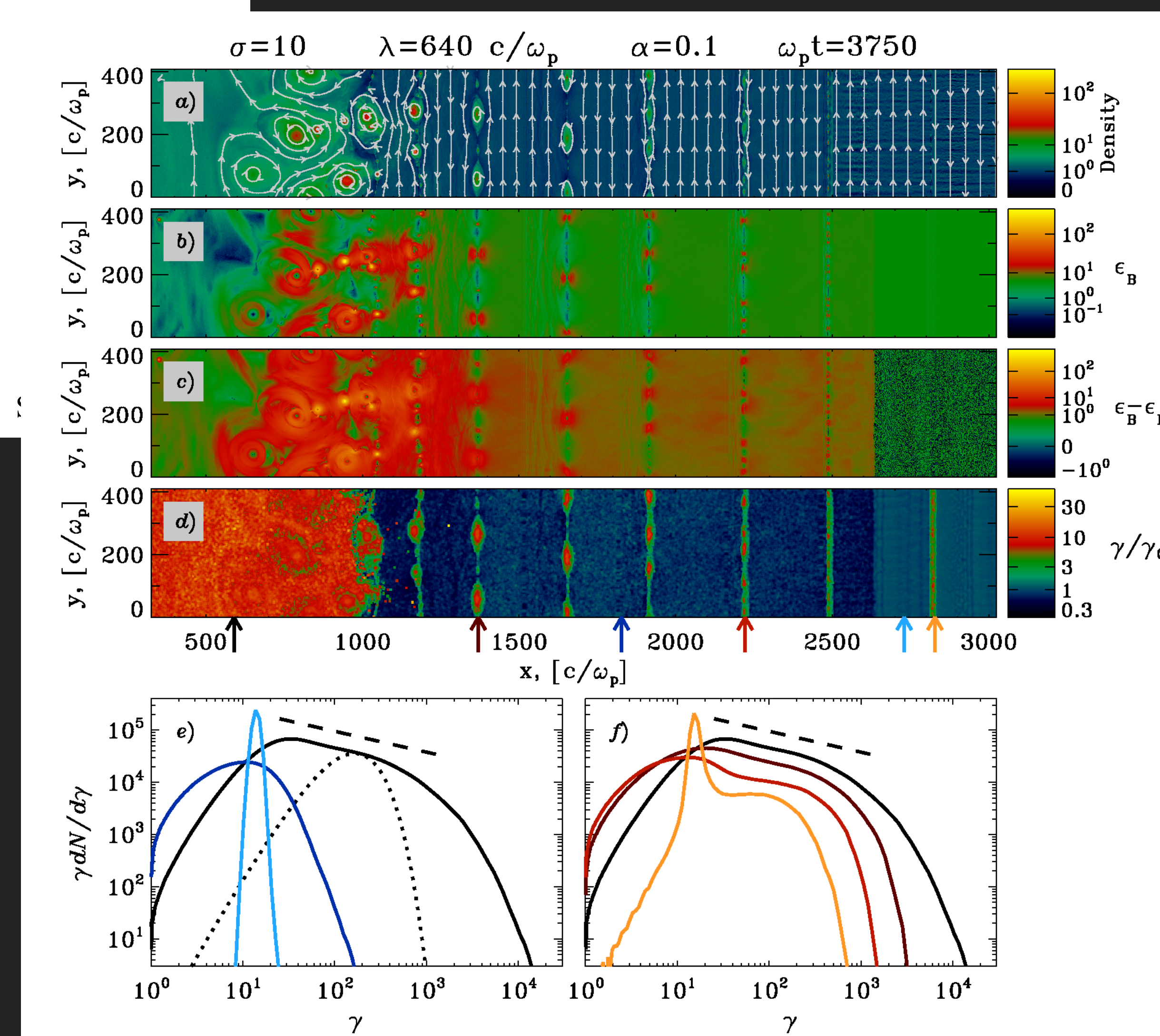


FLOW IS CHARGE SEPARATED

FERMI VS RECONNECTION

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



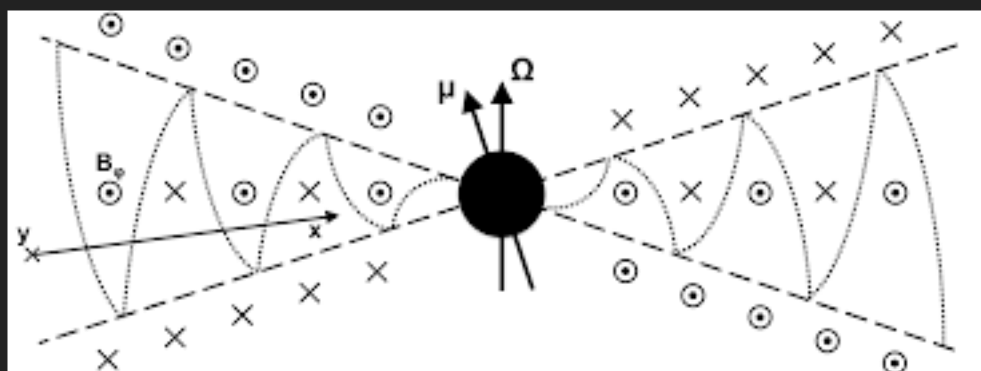


RECONNECTION OF THE STRIPED WIND MORE VERSATILE
WORKS WELL FOR HIGH MAGNETIZATION
REQUIRES VERY HIGH MULTIPLICITY

RECONNECTION

RECONNECTION

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



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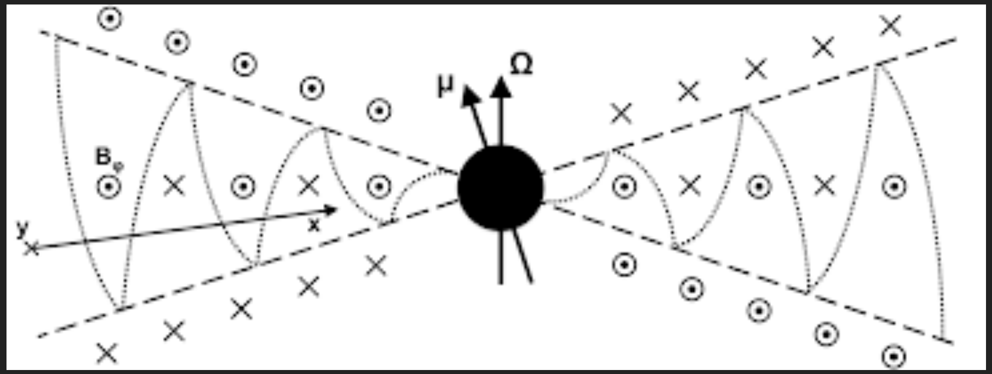
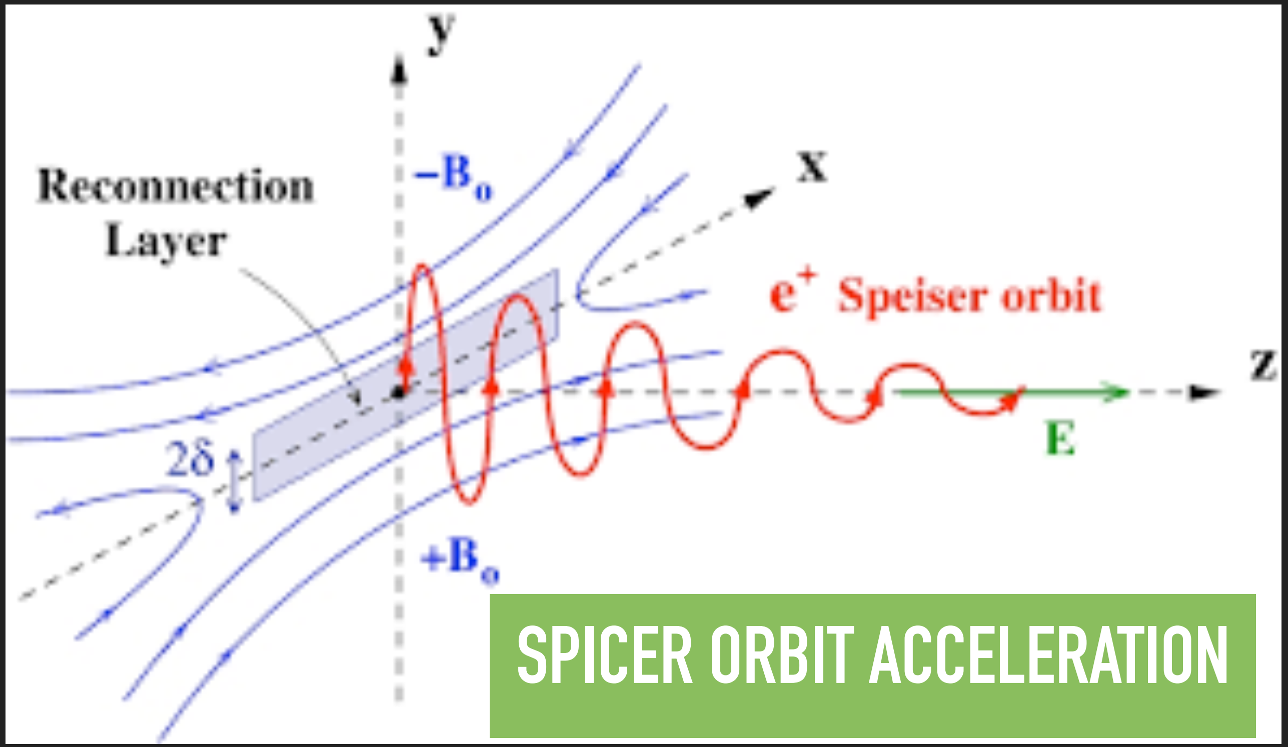
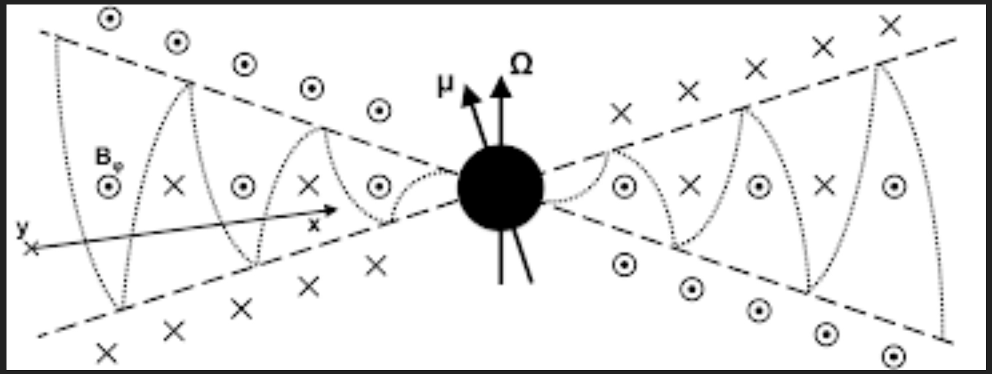


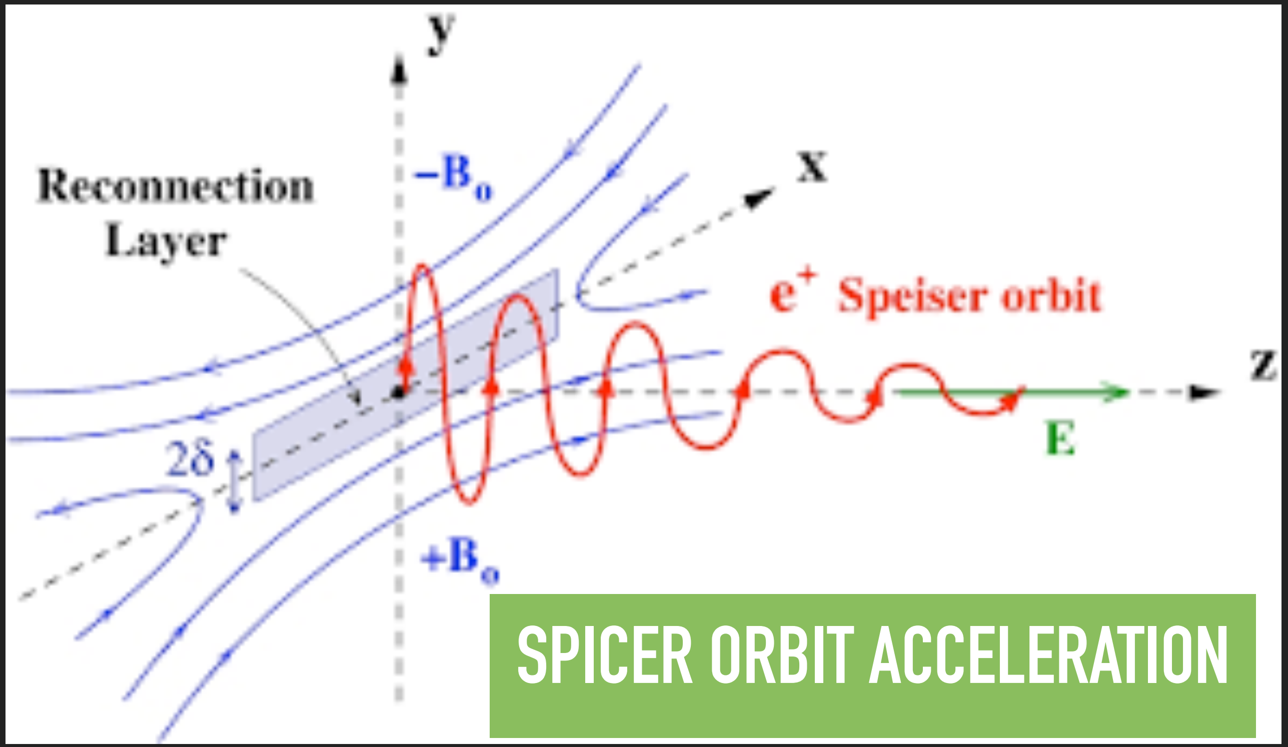


SPICER ORBIT ACCELERATION

RECONNECTION

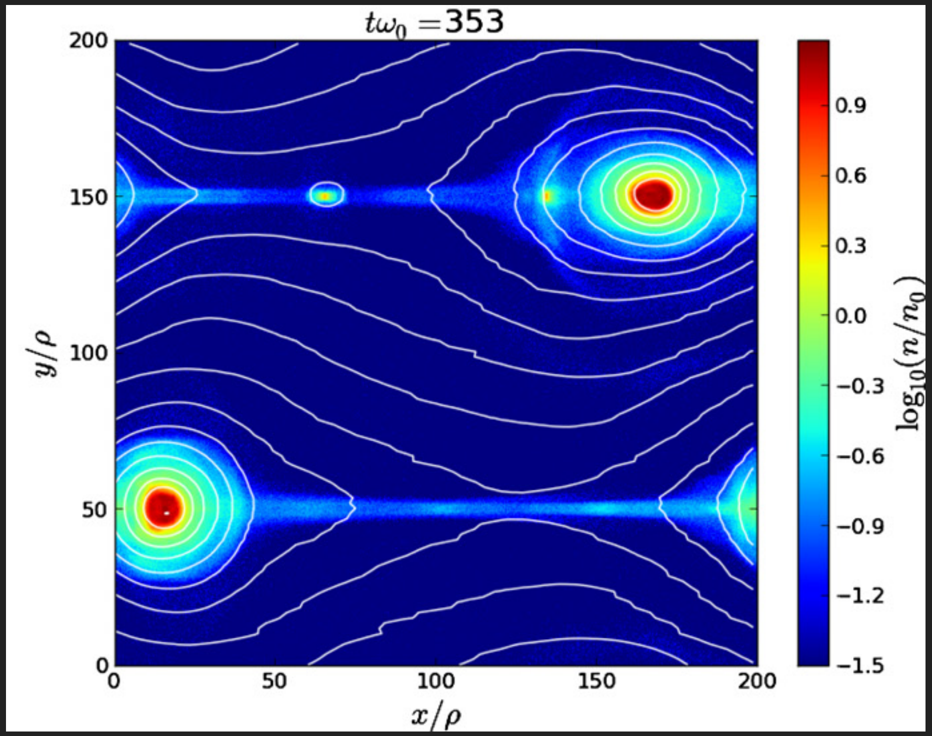
PSR WINDS ARE STRIPED AND THIS IMPLIES ALTERNATING FIELD POLARITIES IN THE PWN





SPICER ORBIT ACCELERATION

TEARING INSTAB



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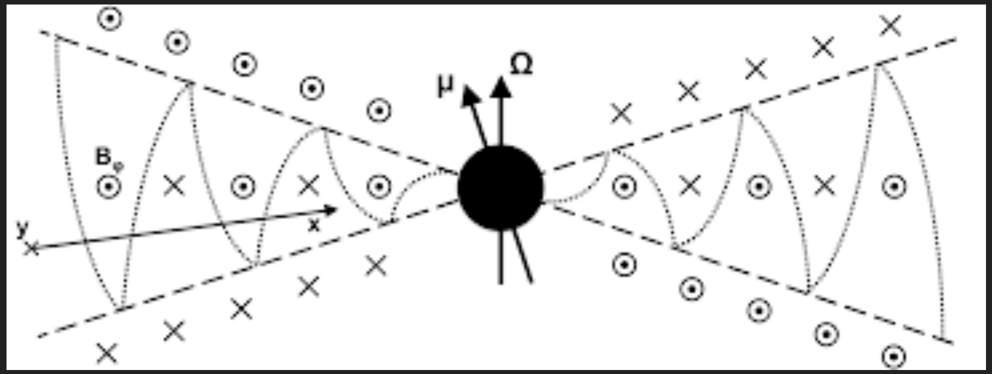

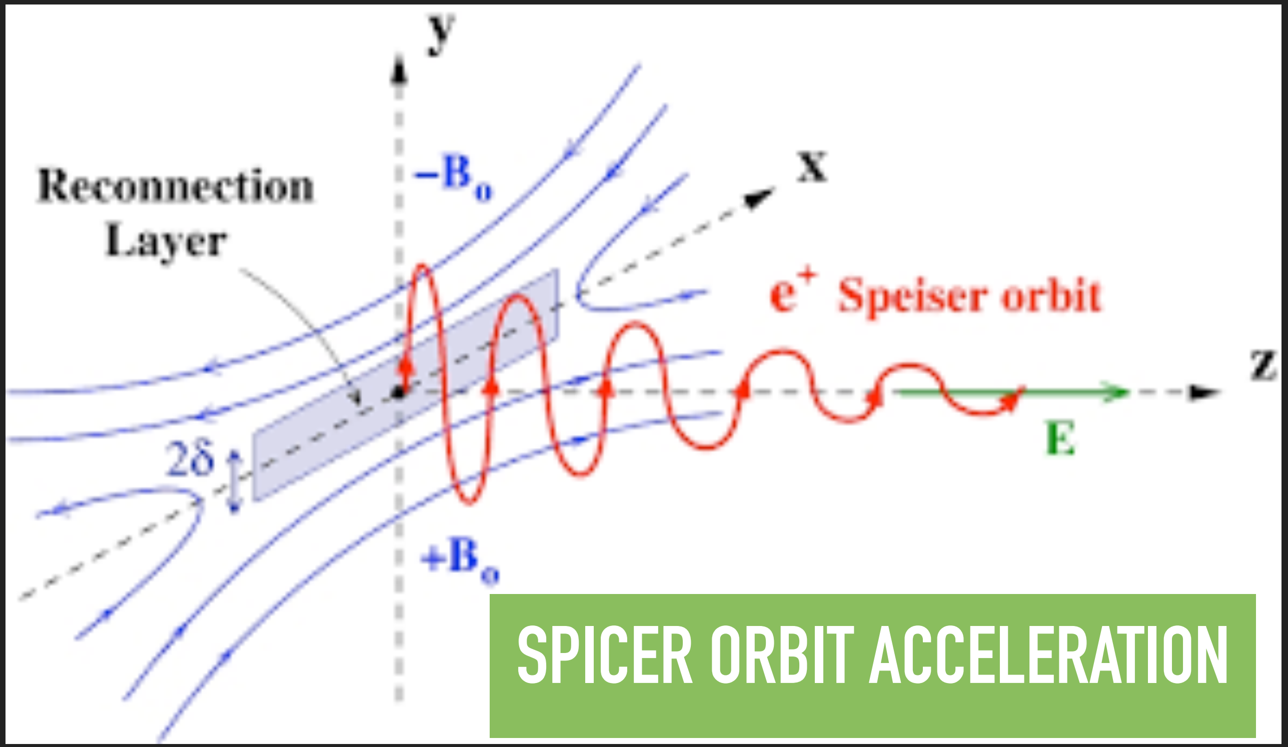

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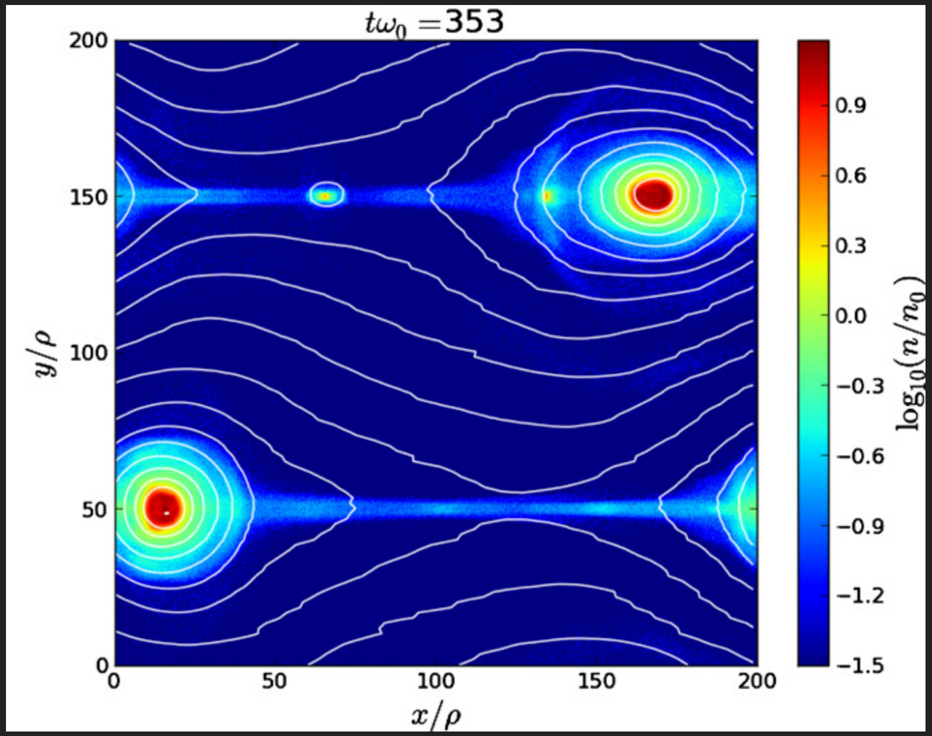
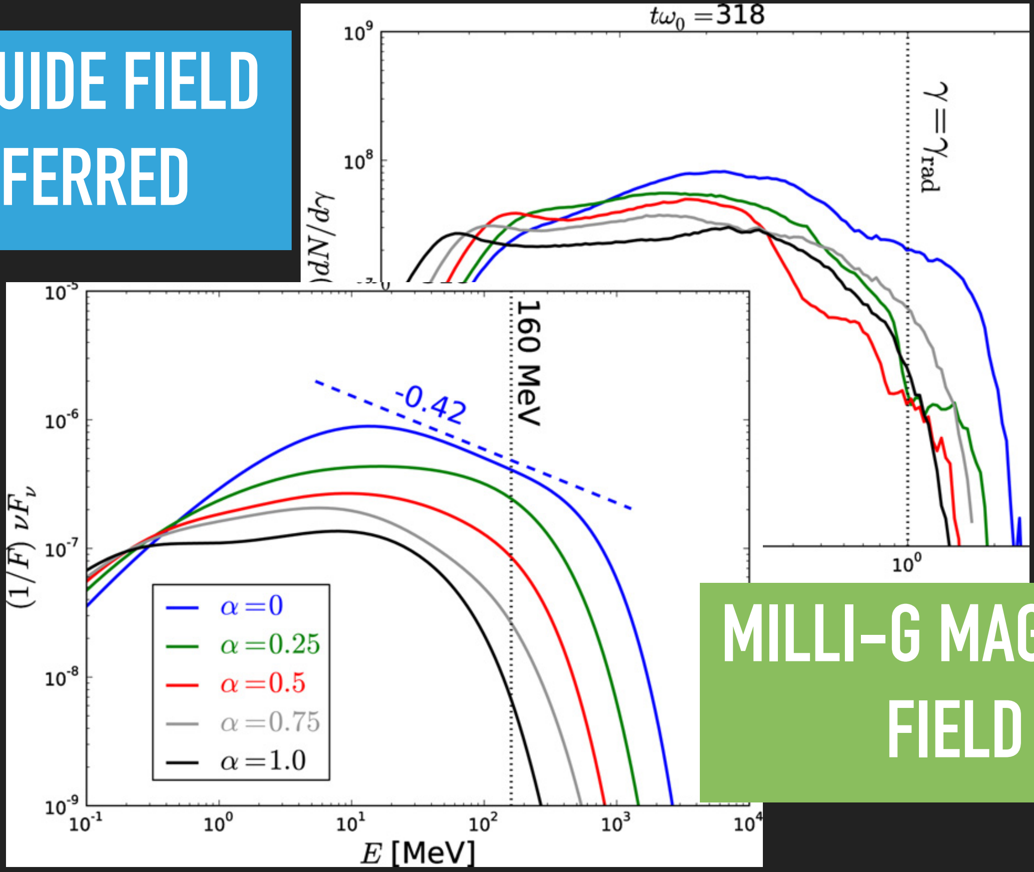


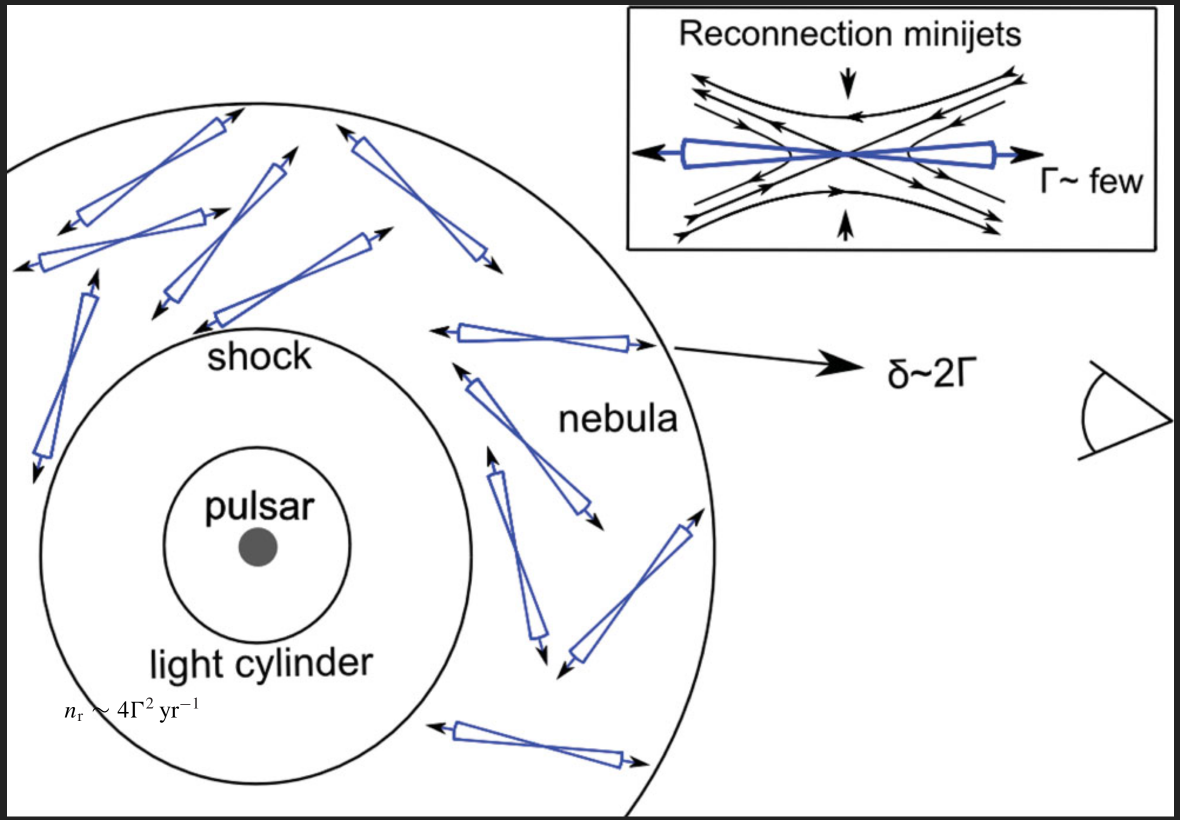
LOW GUIDE FIELD PREFERRED



MILLI-G MAGNETIC FIELD

JETLETS

MINI JETS INSIDE THE NEBULA ARISING FROM RECONNECTION LED TO BEAMED PARTICLES THAT GIVES FLARE DUE TO DOPPLER BOOSTING



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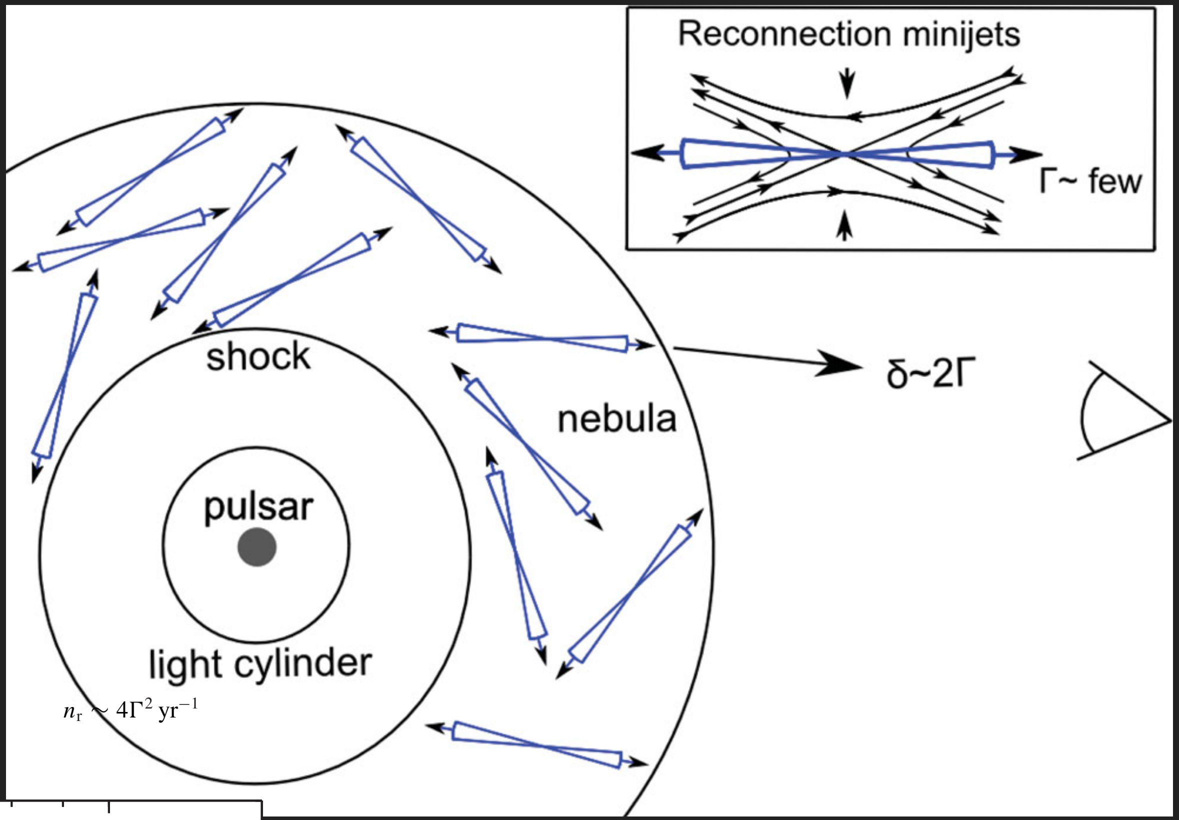
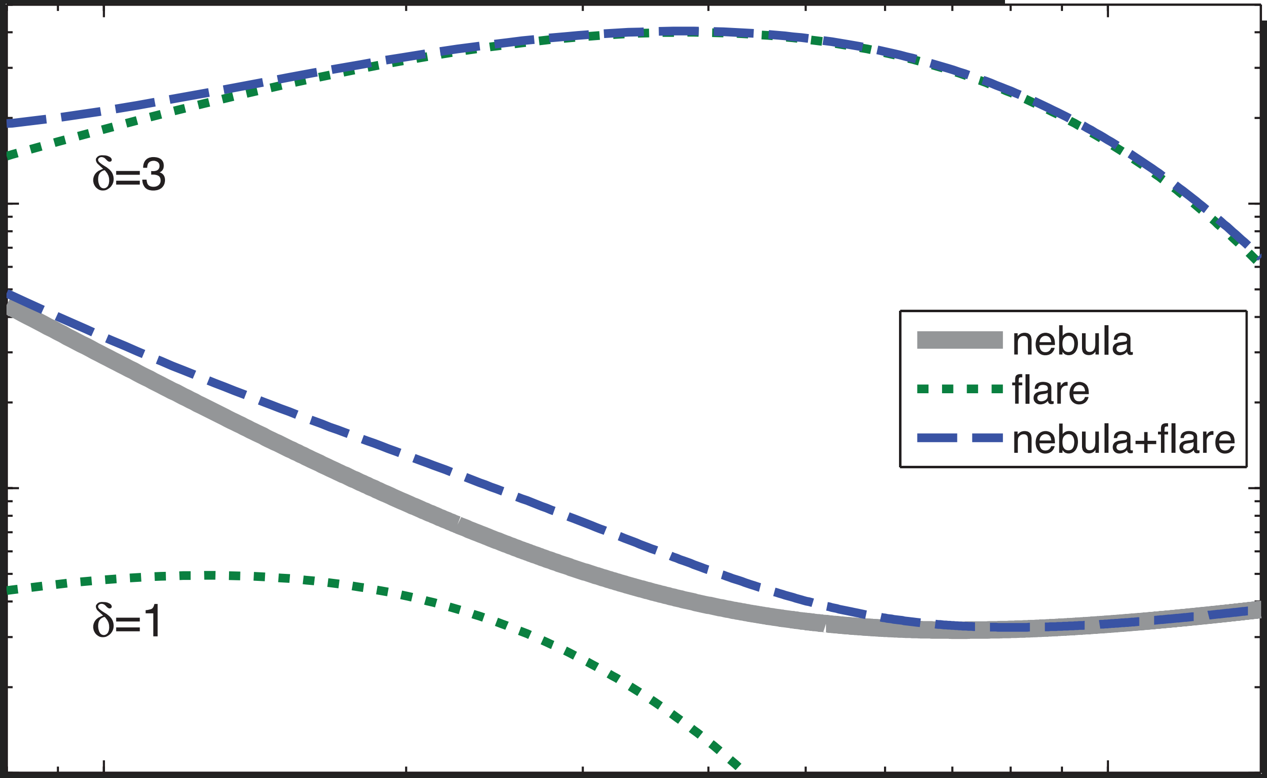


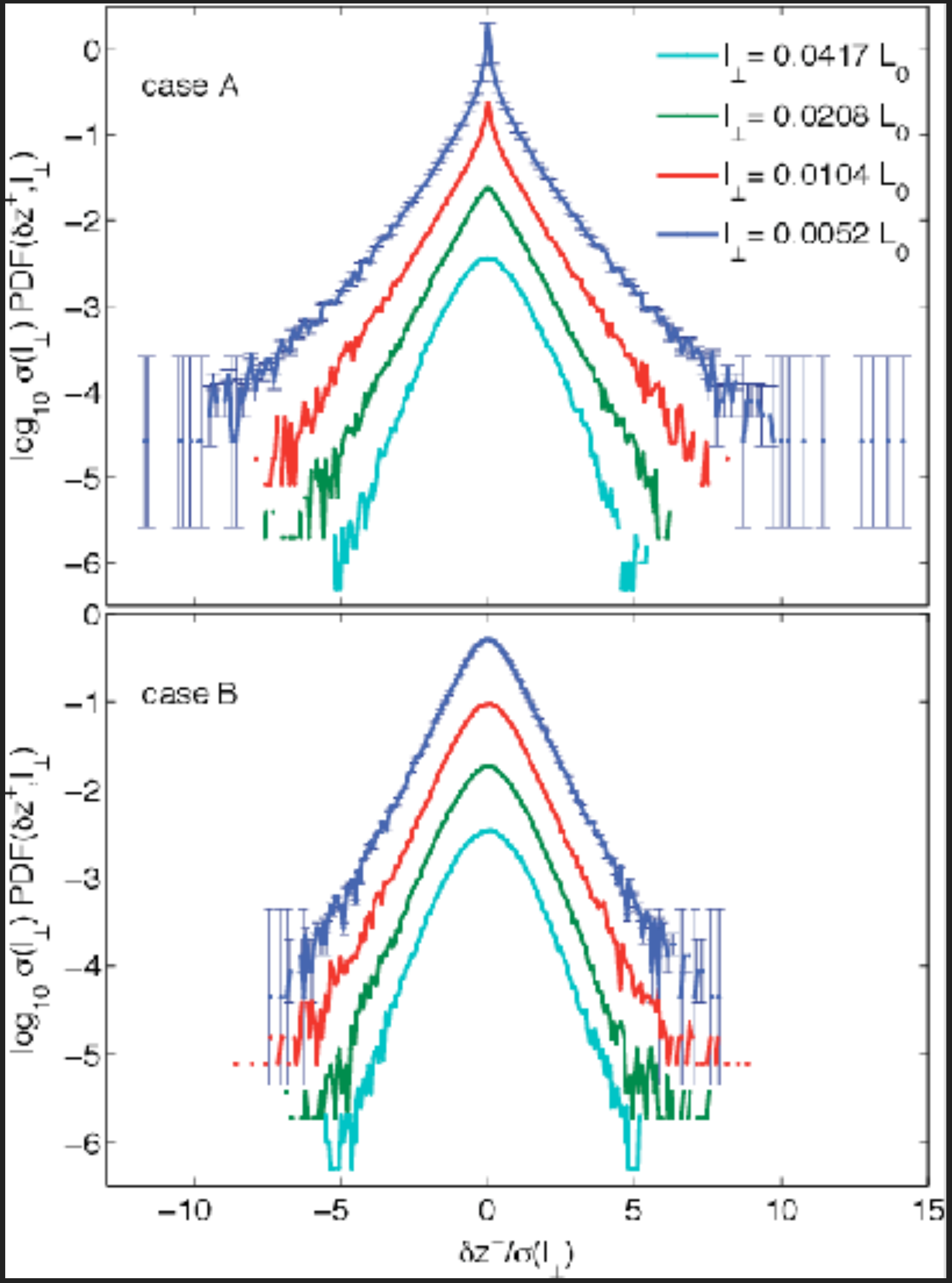


$$n_r \sim 4\Gamma^2\ \mathrm{yr}^{-1}$$

BOOSTING OF ORDER 3 ARE REQUIRED

INTERMITTENCY

IN TURBULENCE INTERMITTENCY MANIFESTS AS HIGHER TAILS AT SMALL SCALE ON THE PDE



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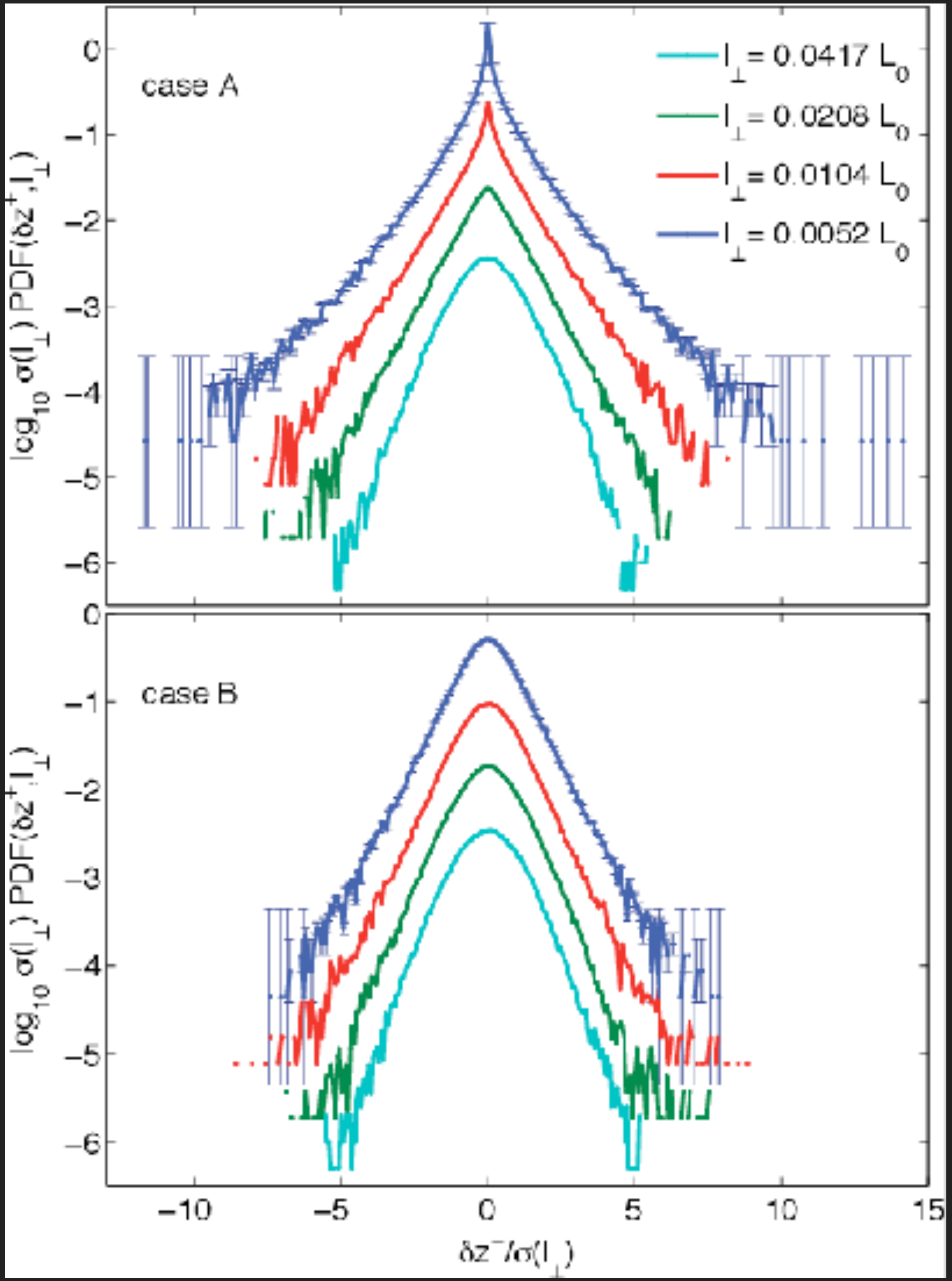

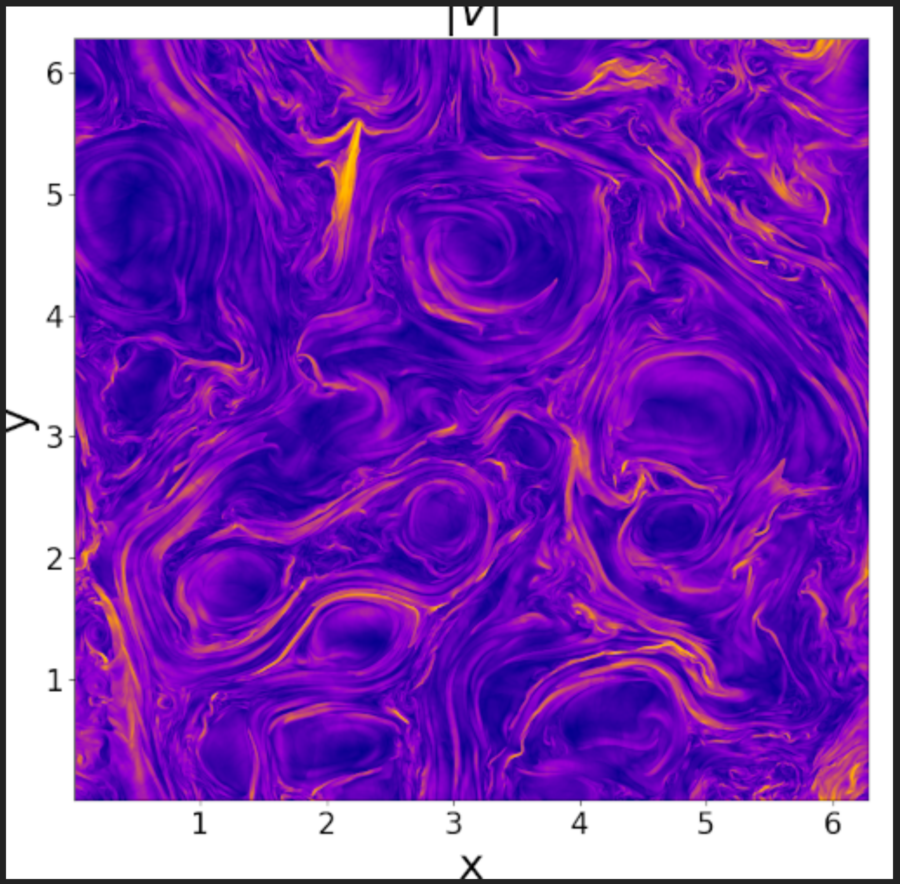

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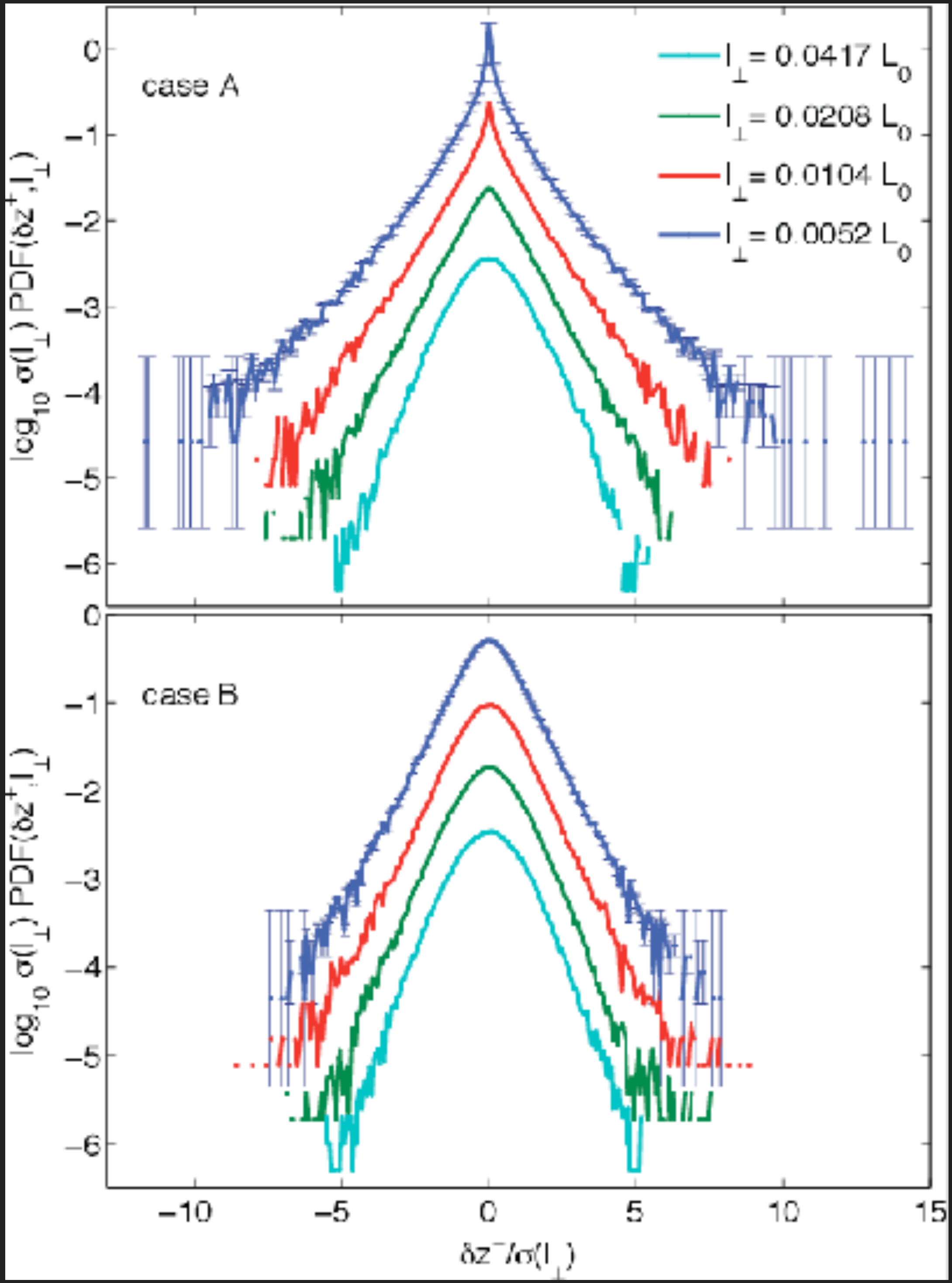

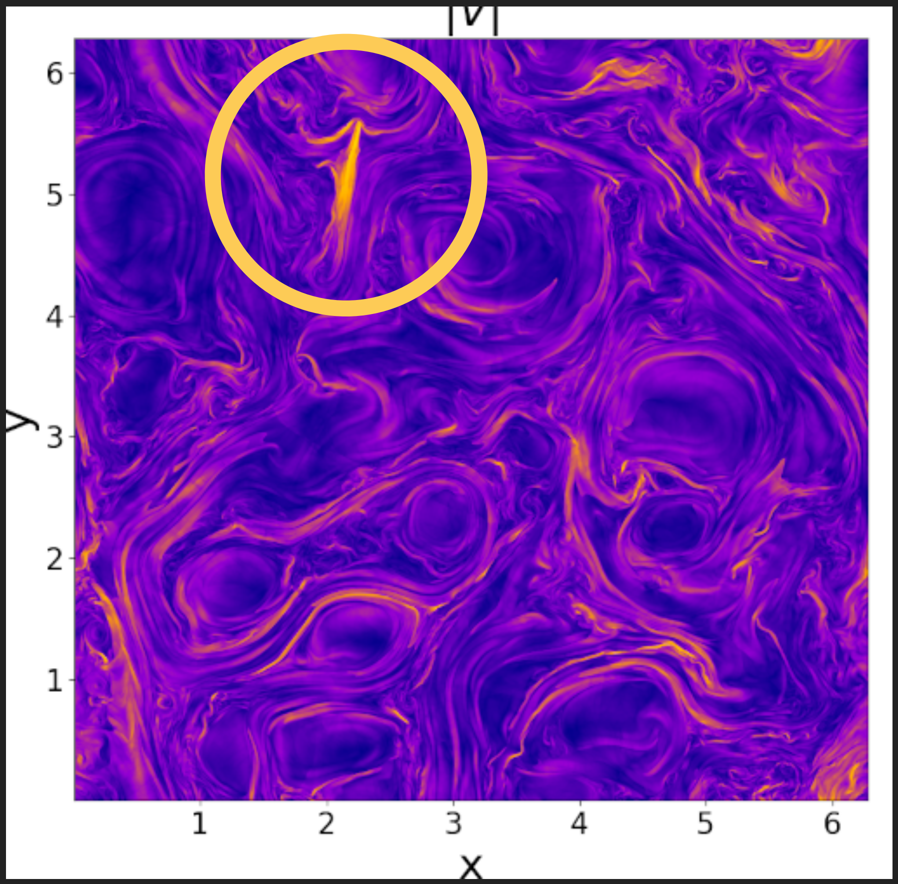

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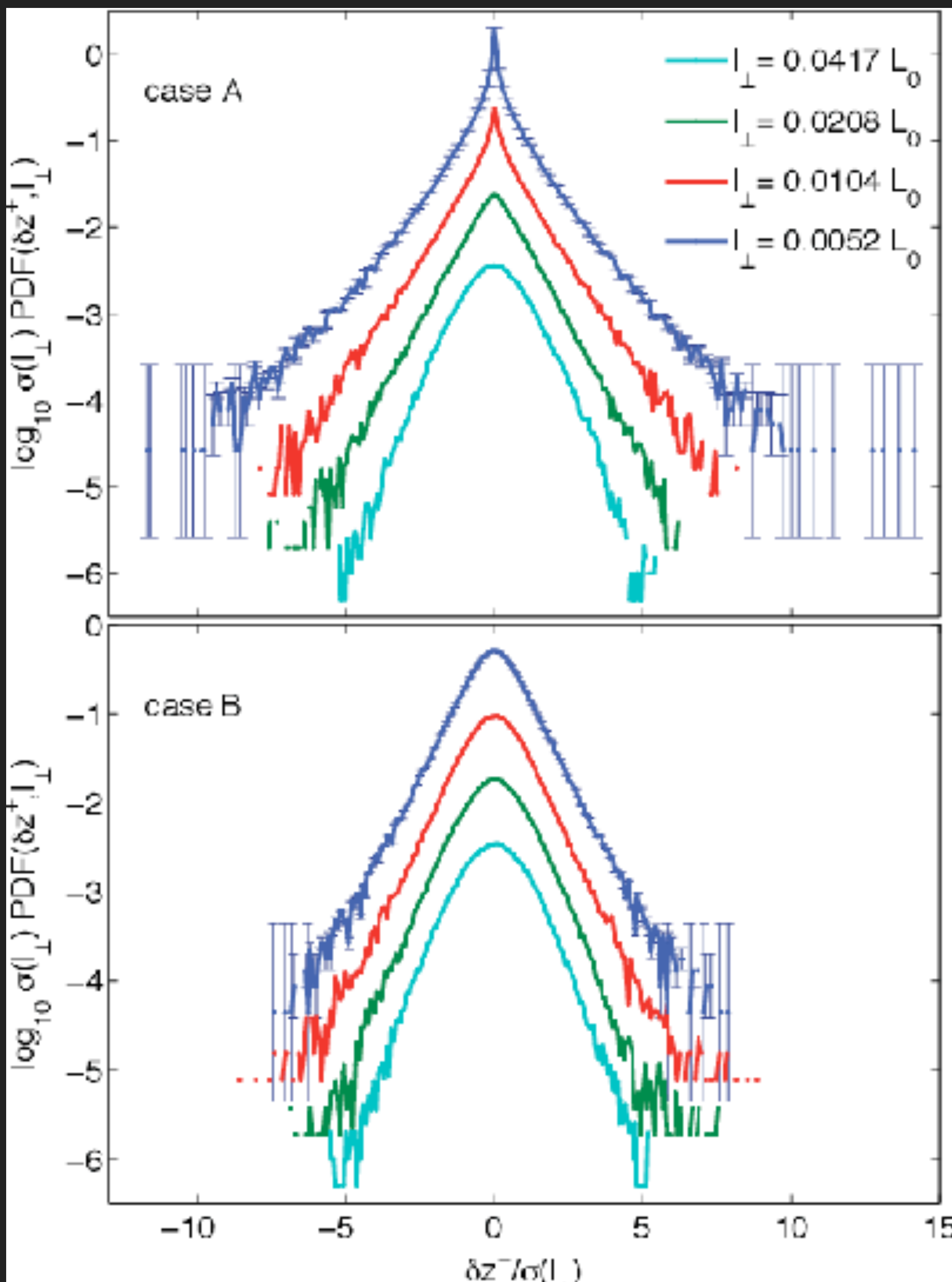
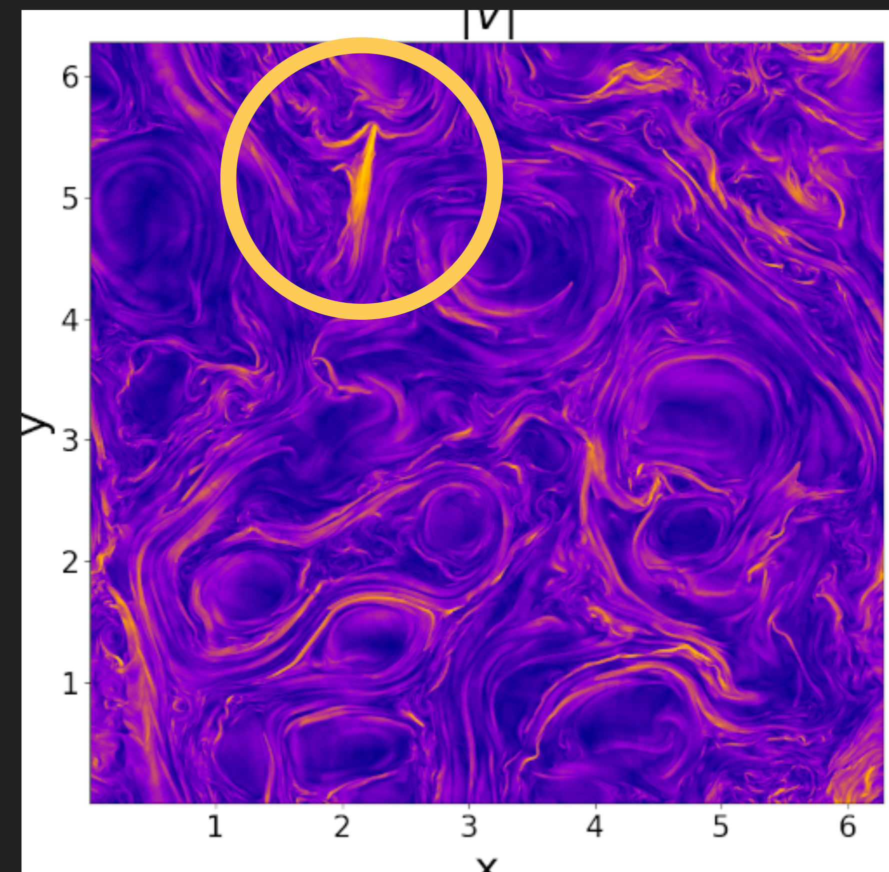




NOT CLEAR IF STATISTICS OF INTERMITTENCY COMPATIBLE WITH MILL-G FIELD

IXPE – X-RAY POLARIMETRY

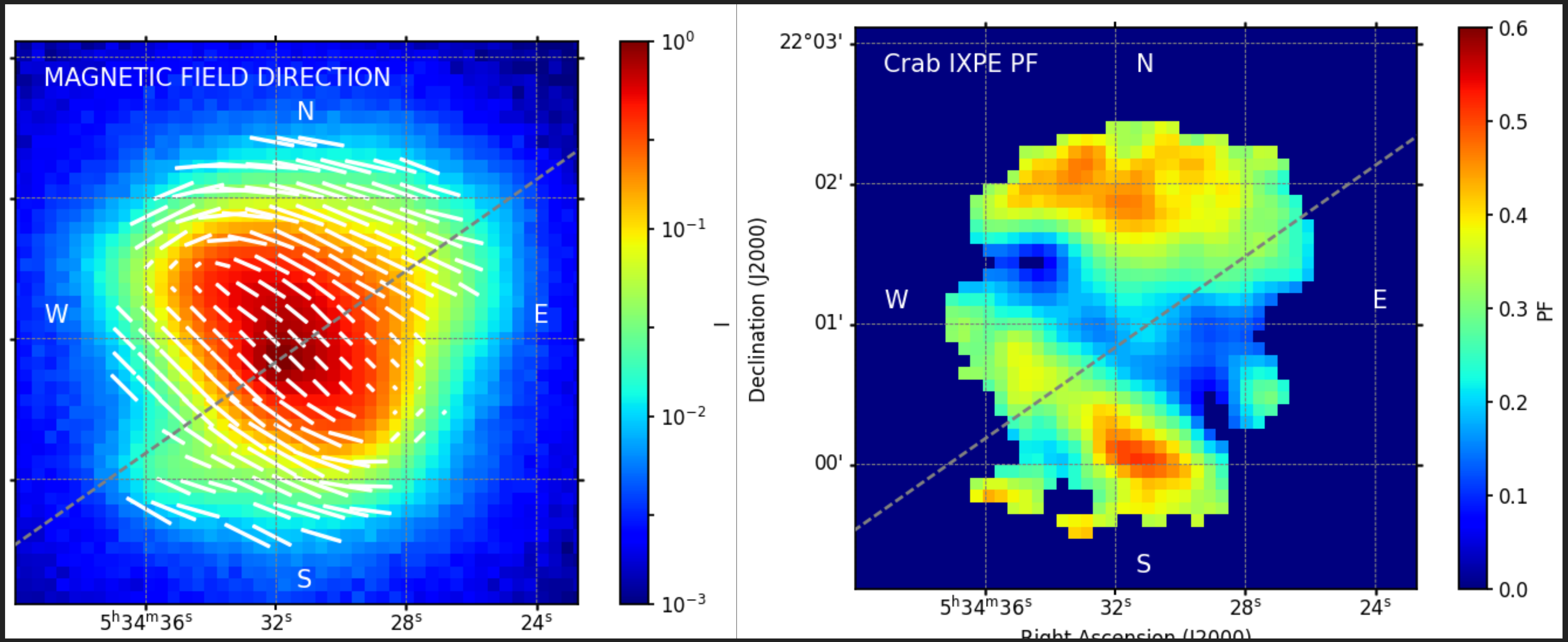
24 NI-CO W1 SHELLS

2-8 KEV BAND

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

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

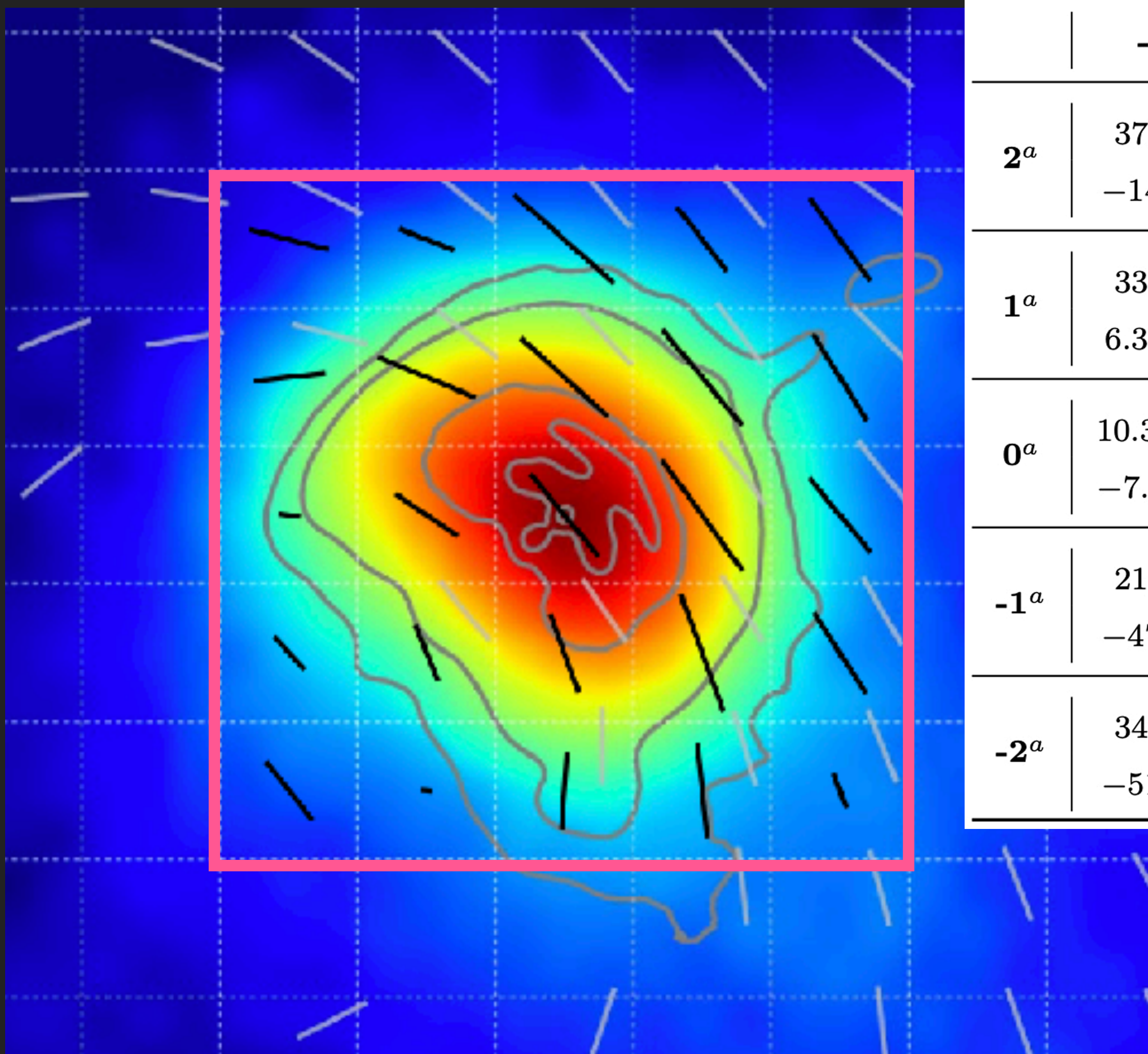
LOCAL HIGH LEVEL OF POLARISATION IN OUTER REGIONS

NEBULAR AXIS NOT CONSISTENT WITH PSR AXIS

TURBULENCE LIKELY VERY PATCHY INSIDE THE PWN

IXPE - X-RAY POLARIMETRY - VELA

Fei et al 2023



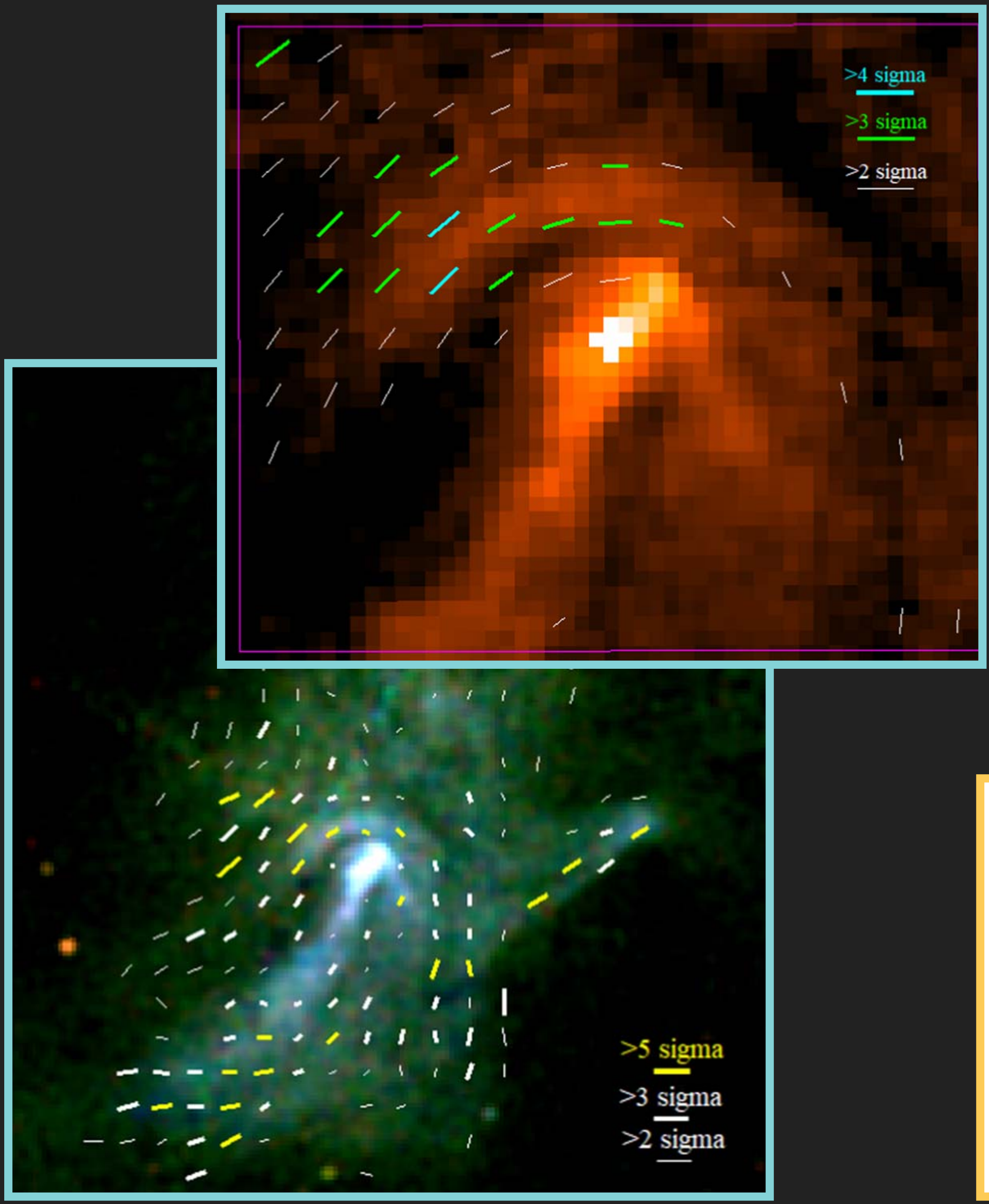
	-2[b]	-1[b]	0[b]	1[b]	2[b]	
2[a]	37±18	27±13	61±12	37±13	47±15	PD[c]
	−14±14	−21±14	−41.7±5.3	−52±10	−53.8±8.9	PA[d]
1[a]	33±10	48.5±5.0	53.5±4.1	56.8±7.1	47±13	PD[c]
	6.3±9.0	−22.4±3.0	−42.2±2.2	−50.2±3.6	−58.2±7.7	PA[d]
0[a]	10.3±8.8	34.4±3.9	49.0±2.5	62.8±4.0	44±11	PD[c]
	−7.4±24	−34.3±3.3	−50.3±1.5	−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.

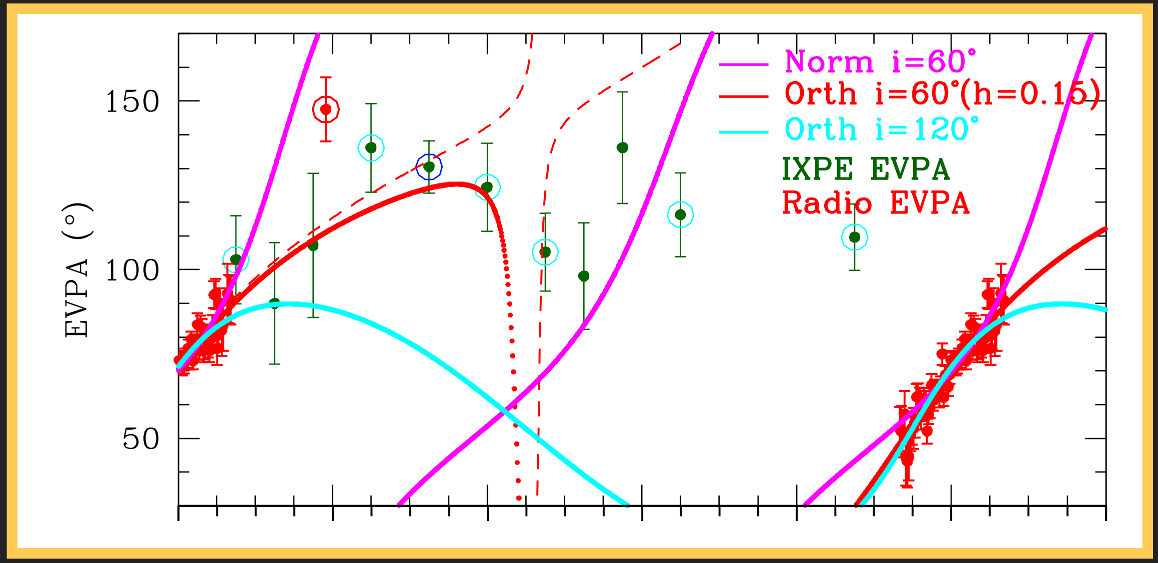
IXPE - X-RAY POLARIMETRY - MSH 15-52



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



CONCLUSIONS

PWNE ARE THE MOST "EFFICIENT" PARTICLE ACCELERATORS IN THE UNIVERSE

PWNE ARE THE ONLY WELL ESTABLISHED PEVATRONS IN THE GALAXY

PWNE WILL BE AMONG THE MAJOR CONTRIBUTORS TO THE GAMMA-RAY SKY

THERE ARE MANY EVIDENCES OF PARTICLE ESCAPE FROM PWNE

PWNE TEV HALOES STILL DEFY OUR UNDERSTANDING OF PARTICLE ACCELERATION AND TRANSPORT

STILL MISSING A COHERENT AND COMPLETE PICTURE OF PARTICLE ACCELERATION IN PWNE

TURBULENCE MIGHT BE RELEVANT BUT POLARIMETRY SET VERY STRONG CONSTRAINTS

THANK YOU