PULSAR WIND NEBULAE:

THE PRESENT STATUS AND FUTURE PROSPECTS

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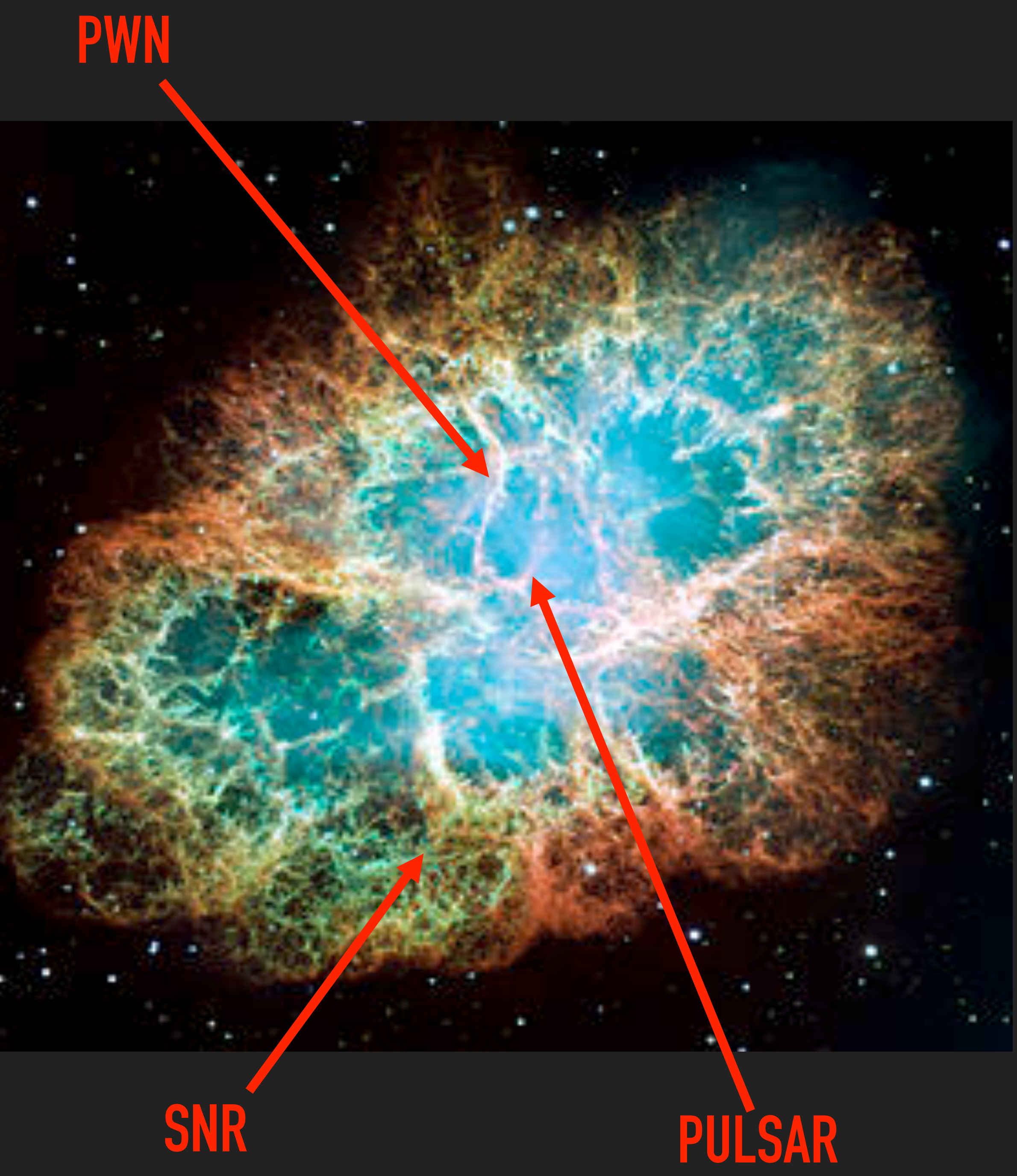
INFN Istituto Nazionale di Fisica Nucleare

PWNE



PWNE ARE HOT BUBBLES OF RELATIVISTIC PARTICLES AND MAGNETIC FIELD EMITTING NON-THERMAL RADIATION.

ORIGINATED BY THE INTERACTION OF THE ULTRA-RELATIVISTIC MAGNETISED PULSAR WIND WITH THE EXPANDING SNR (OR WITH THE ISM)

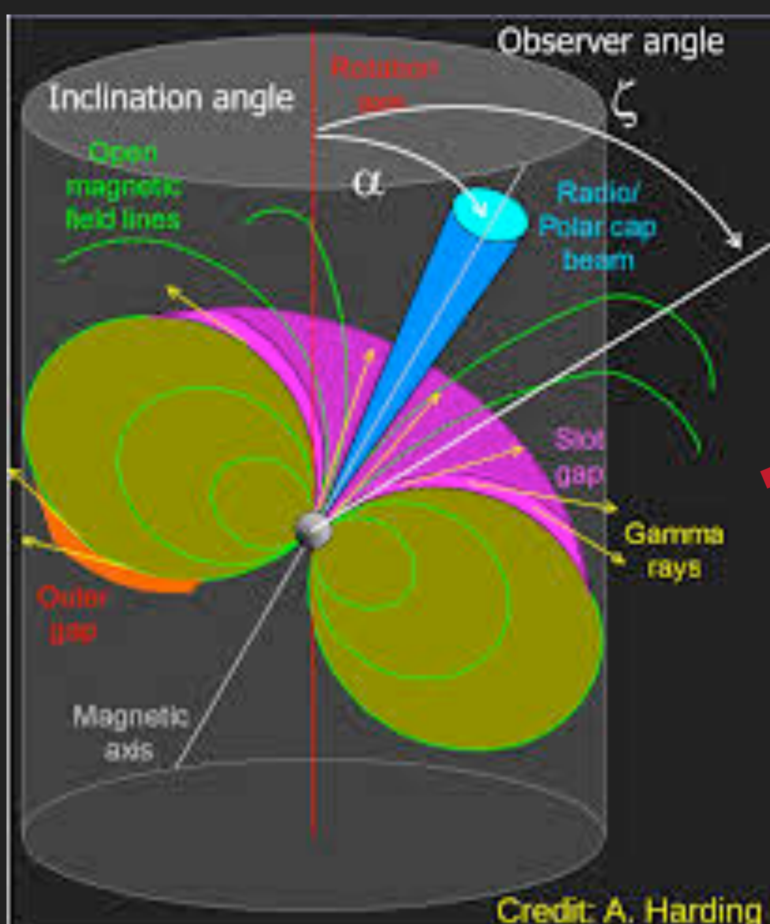
GALACTIC ACCELERATORS. THE ONLY PLACE WHERE WE CAN STUDY THE PROPERTIES OF RELATIVISTIC SHOCKS (AS IN GRBS AND AGNS

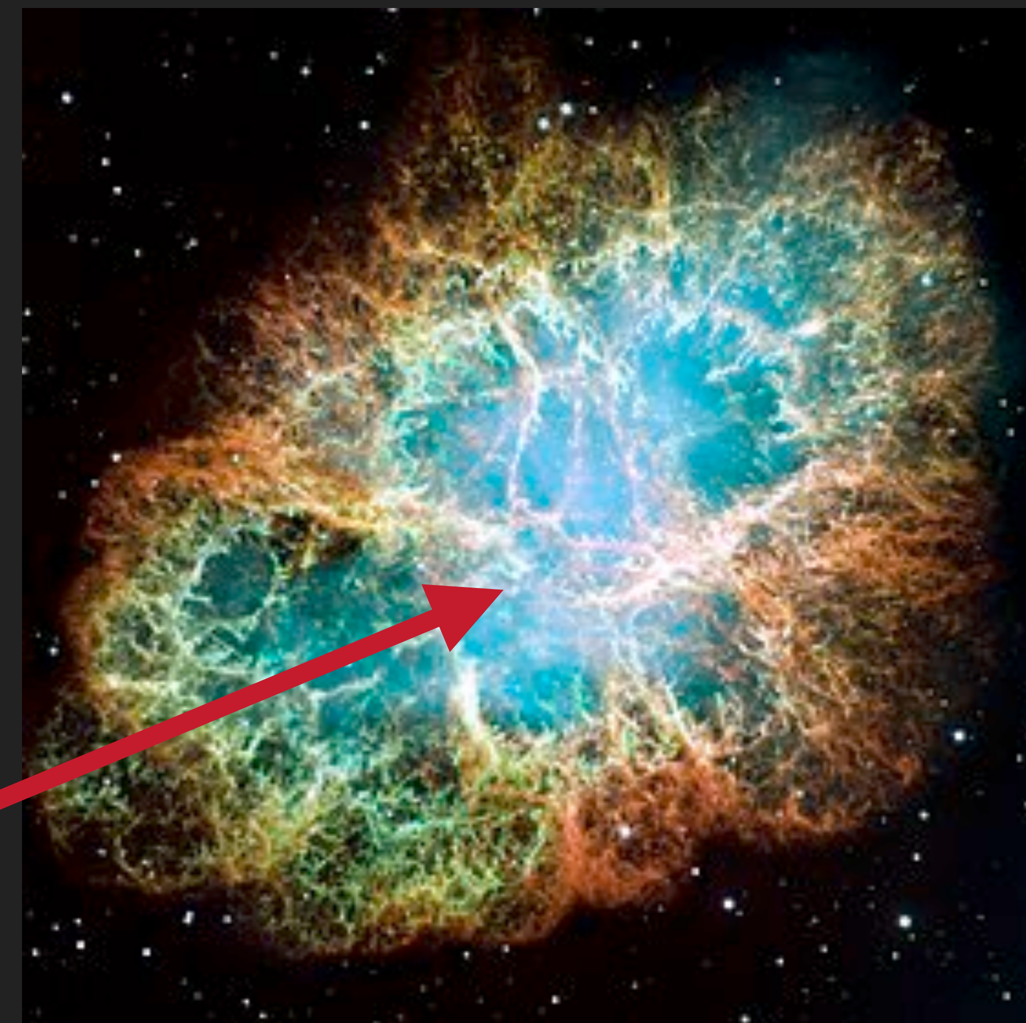
ALLOW US TO INVESTIGATE THE DYNAMICS OF RELATIVISTIC OUTFLOWS

DEATH OF A MASSIVE STAR - THE BIRTH OF PULSAR

STAR MORE MASSIVE THAN 8 MSUN END THEIR LIFE IN SUPERNOVA EXPLOSION

STAR LESS MASSIVE THAN 25-30 MSUN LEAVE BEHIND A COMPACT STELLAR REMNANT IN THE FORM OF A NEUTRON STAR





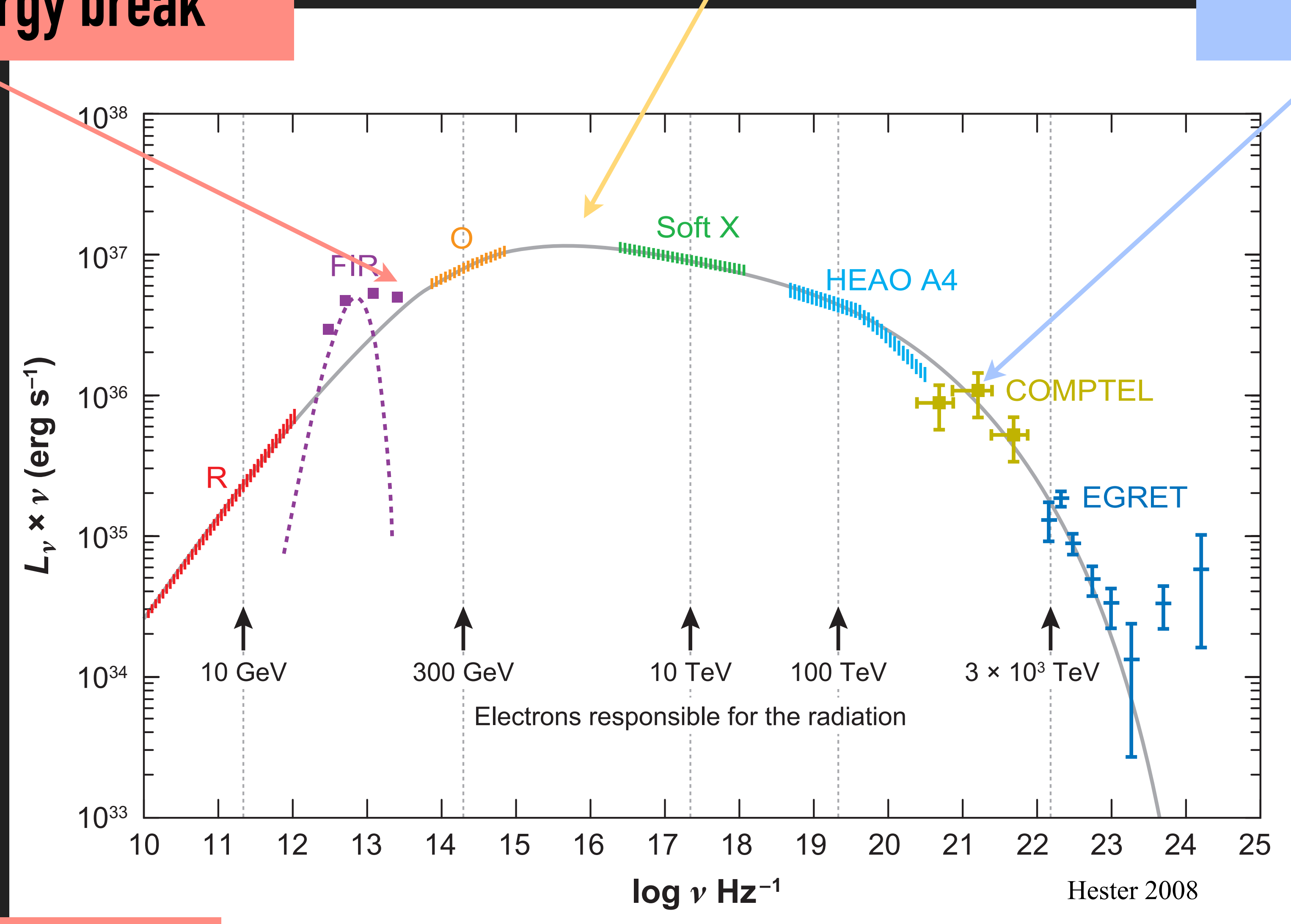
THE COMBINATION OF STRONG MAGNETIC FIELD (10^{12}G) AND RAPID ROTATION (P=0.001-1S) CRATE STRONG ELECTRIC FIELD AT THE SURFACE, EXTRACTION PAIRS AND PRODUCING PAIR CASCADES. OBSERVED AS PULSARS

CRAB SYNCHROTRON SPECTRUM

High energy break

Low energy break

MeV cutoff



Injection break

Synchr. cooling

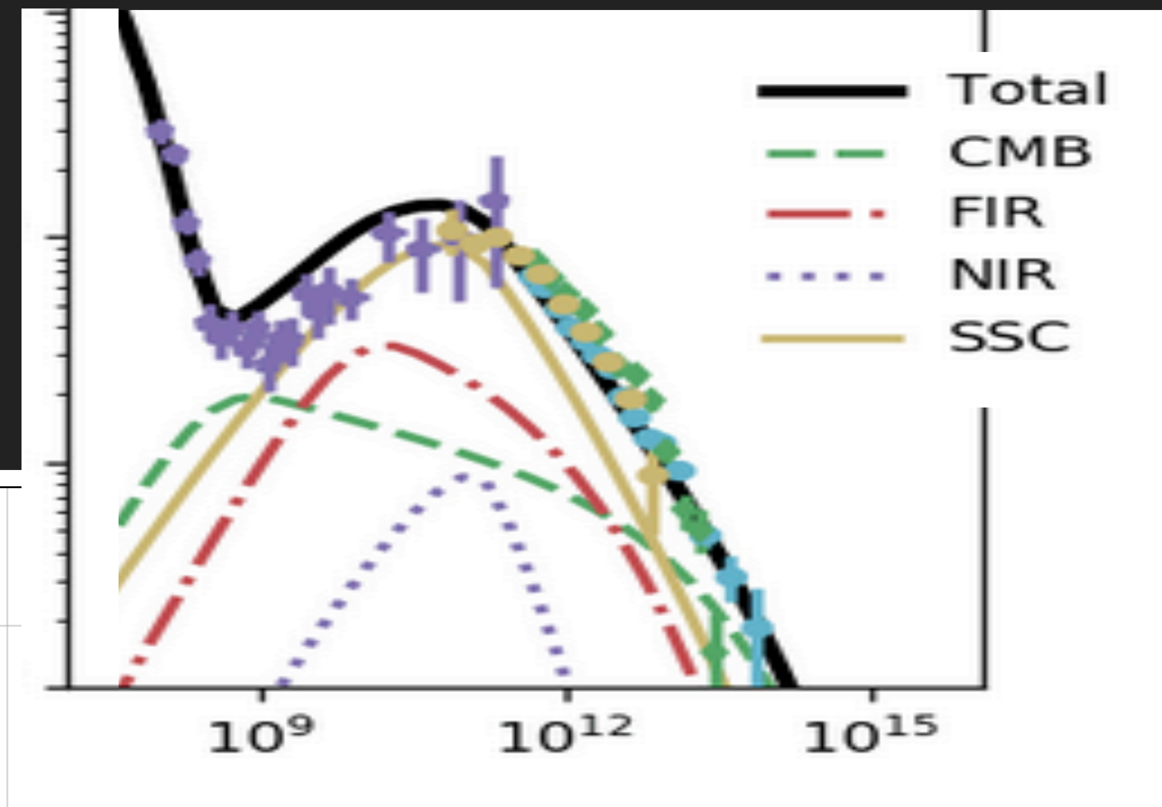
Acceler. cutoff

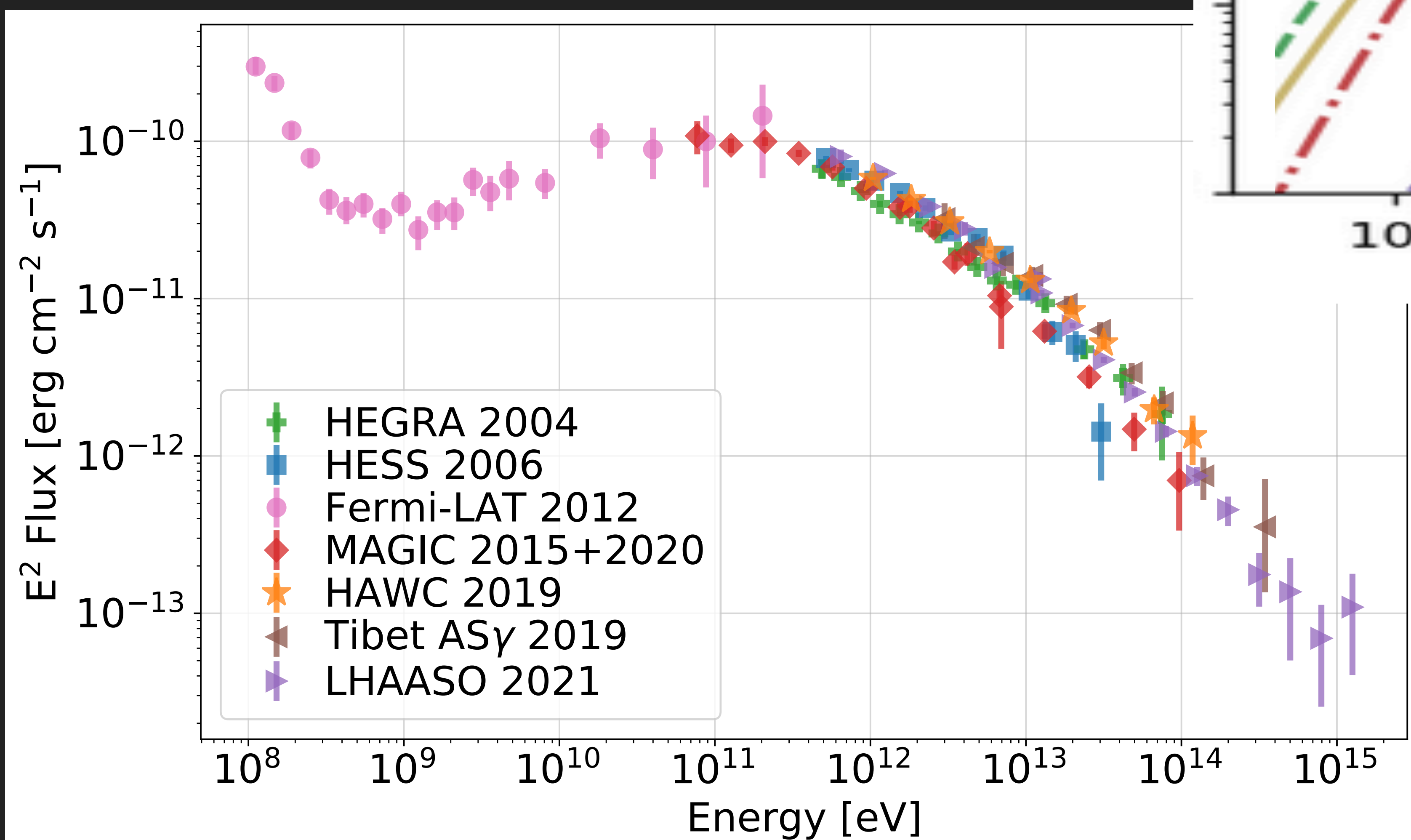
The most efficient non-thermal accelerator.

IC GAMMA SPECTRUM

ONLY SYSTEM SSC DOMINATED

OTHER PWNE ARE NIR/FIR DOMINATED





TREND SET BY RADIO-OPT PARTICLES

X-RAY PARTICLES IN KN

IC GAMMA SPECTRUM

ONLY SYSTEM SSC DOMINATED

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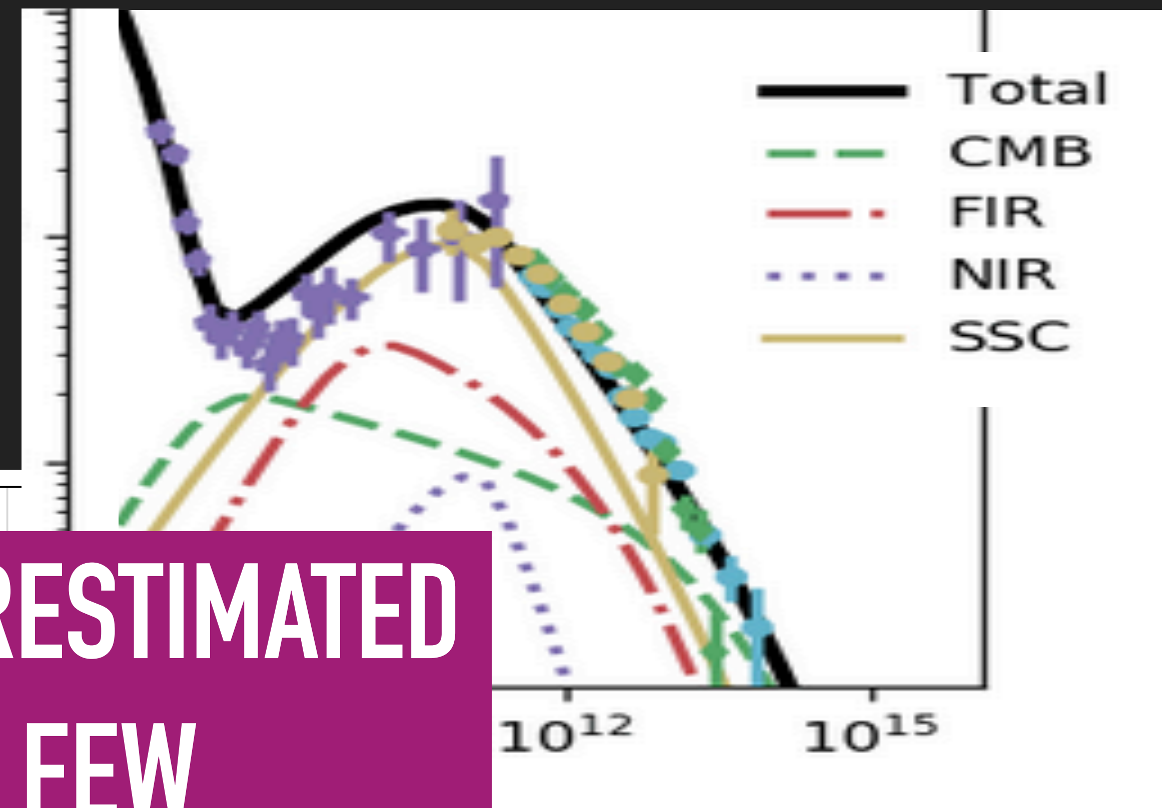
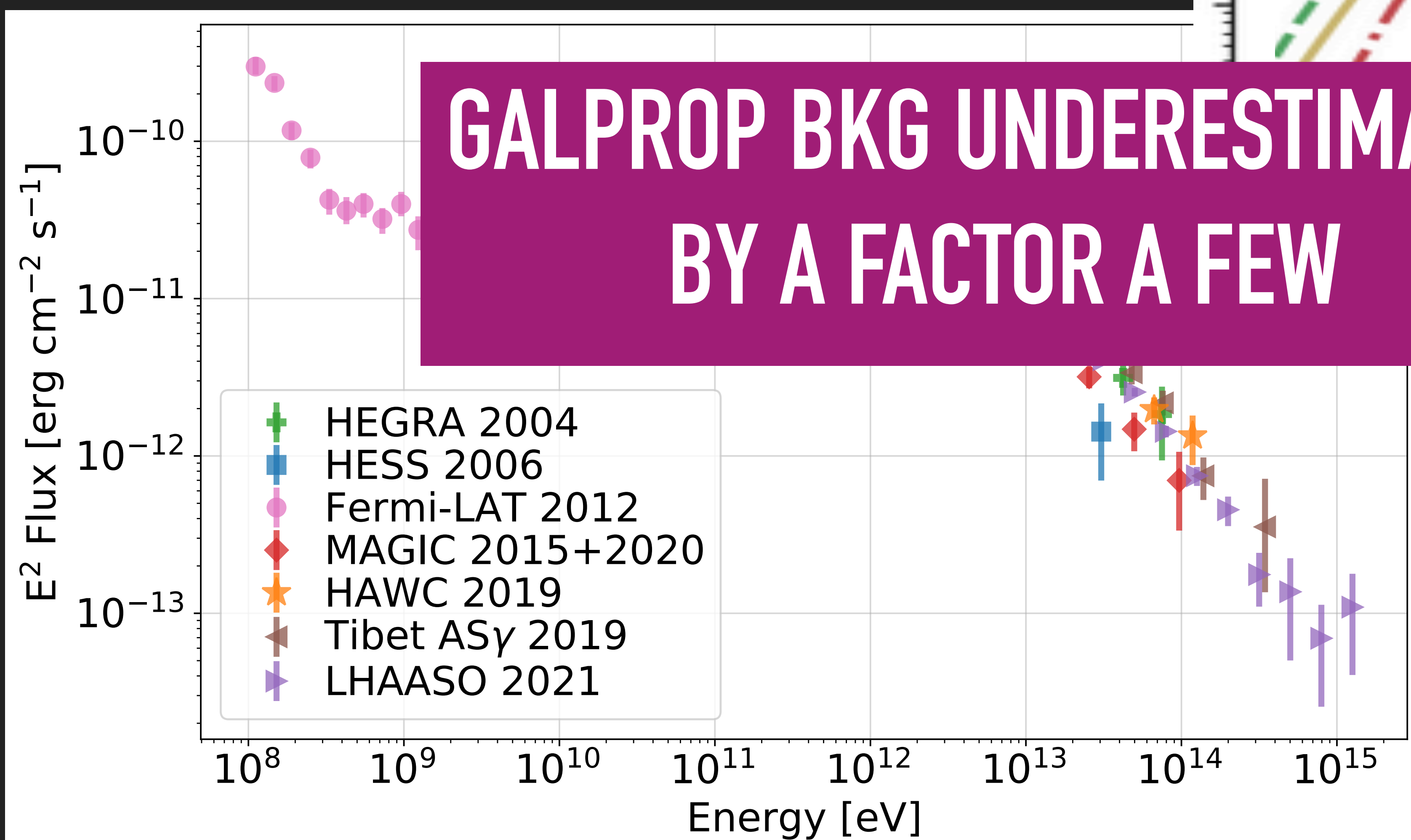


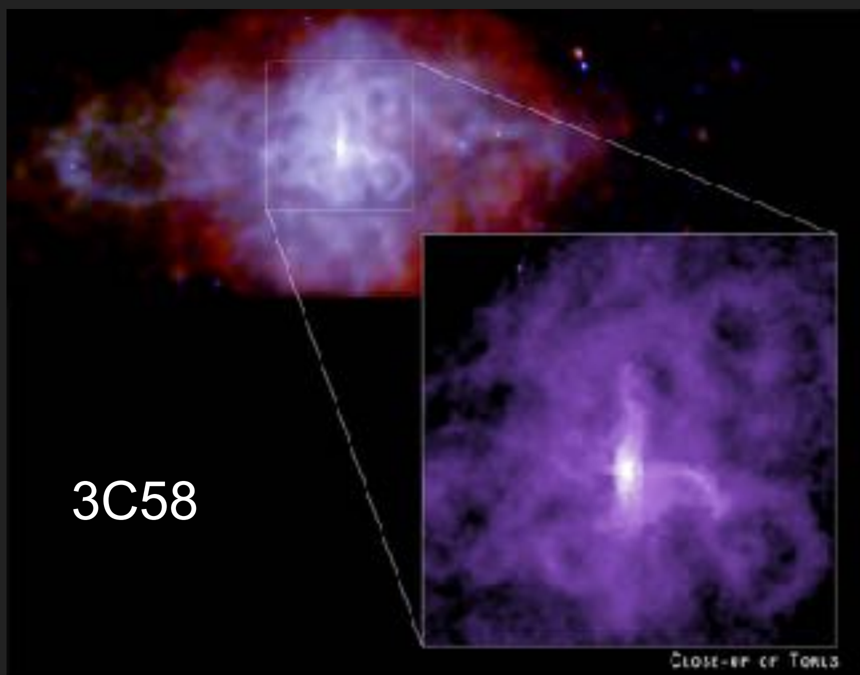


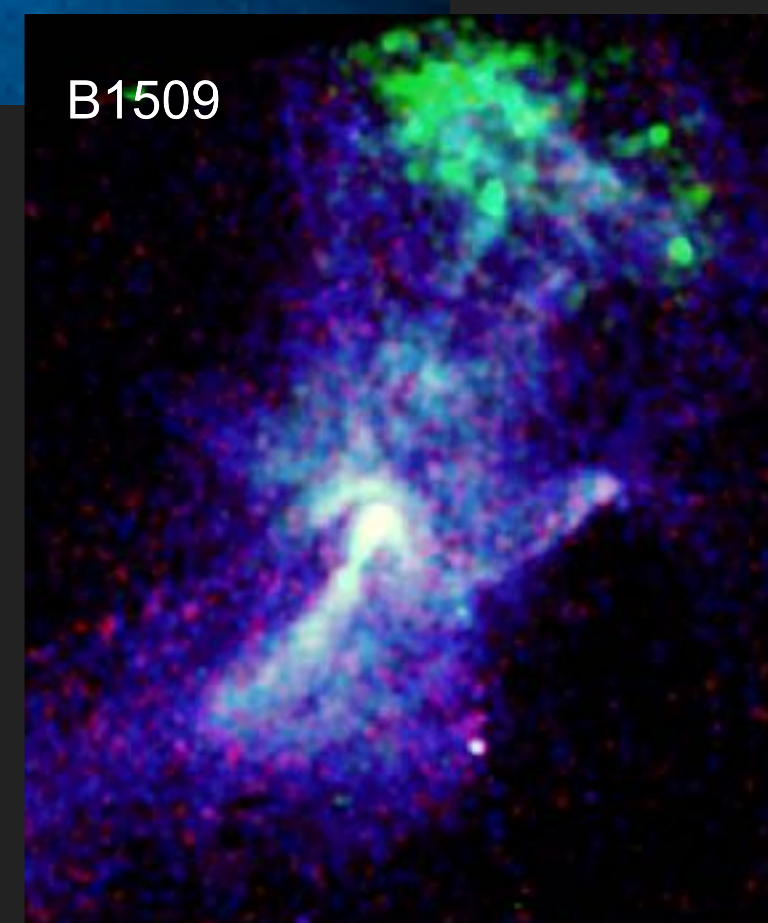
GALPROP BKG UNDERESTIMATED BY A FACTOR A FEW

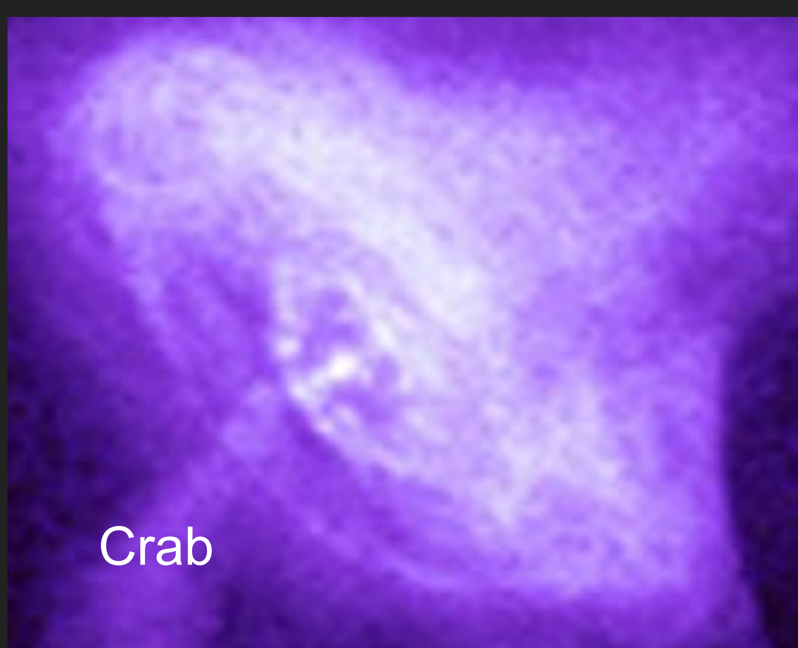
TREND SET BY RADIO-OPT PARTICLES

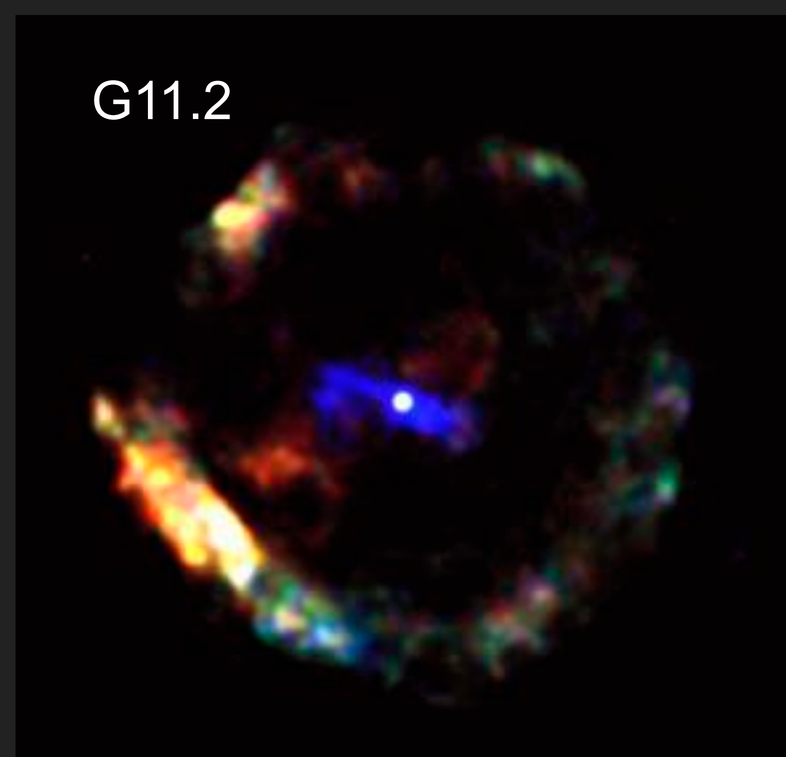
X-RAY PARTICLES IN KN

FINE STRUCTURES – A LAB FOR RELTIVISTICN FLUID DYNAMICS

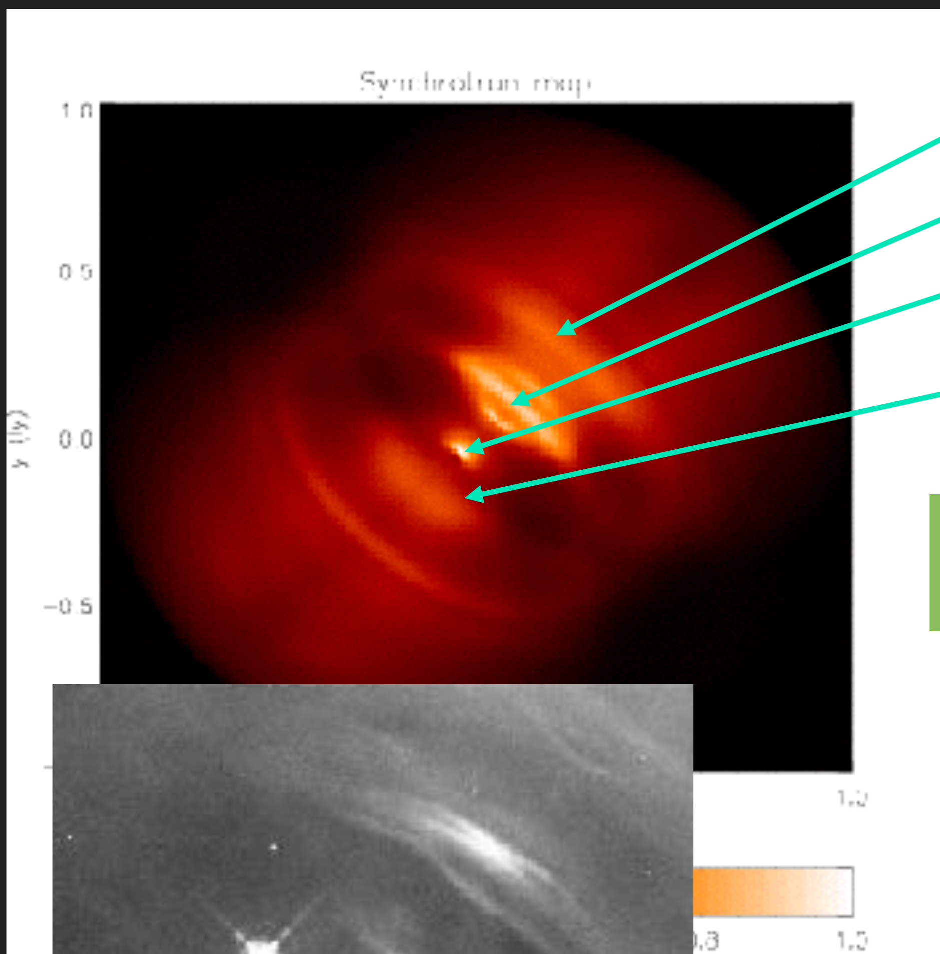








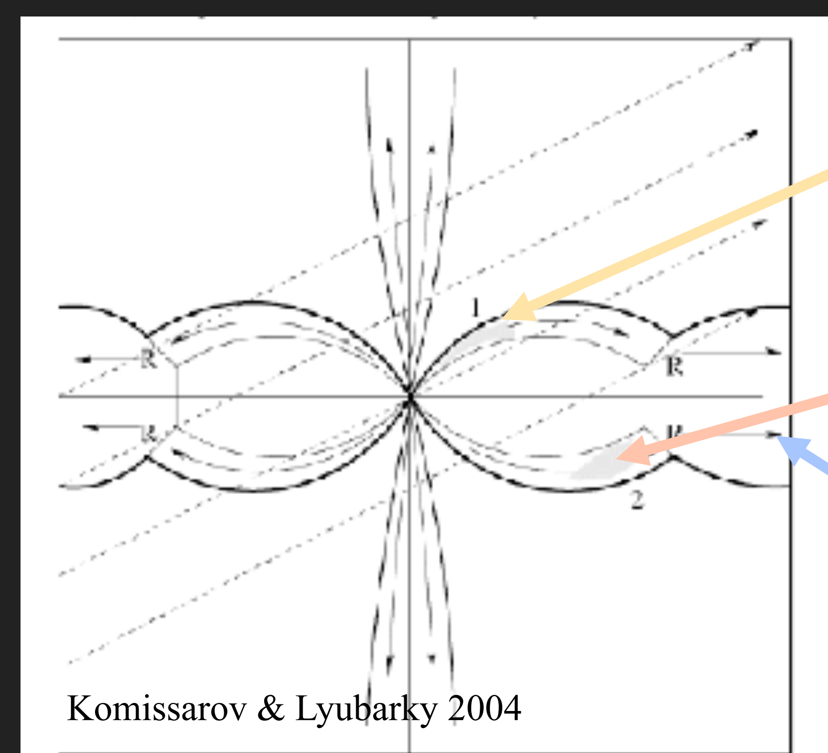
REPRODUCING OBSERVATIONS



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

Hester et al. 1995

EACH FEATURE TRACES AN EMITTING REGION



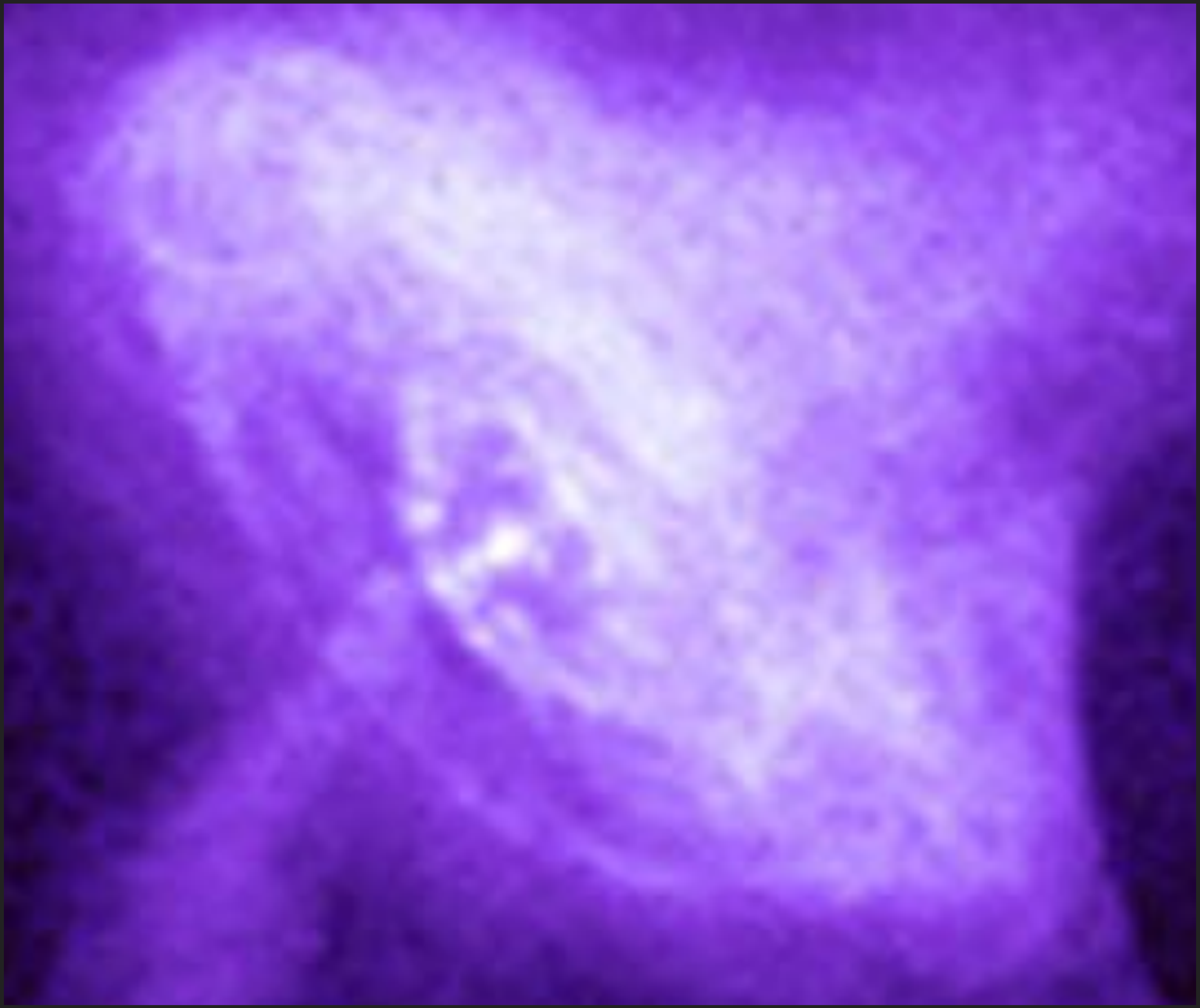
Komissarov & Lyubarky 2004

Knot

Ring

Torus

REPRODUCING OBSERVATIONS



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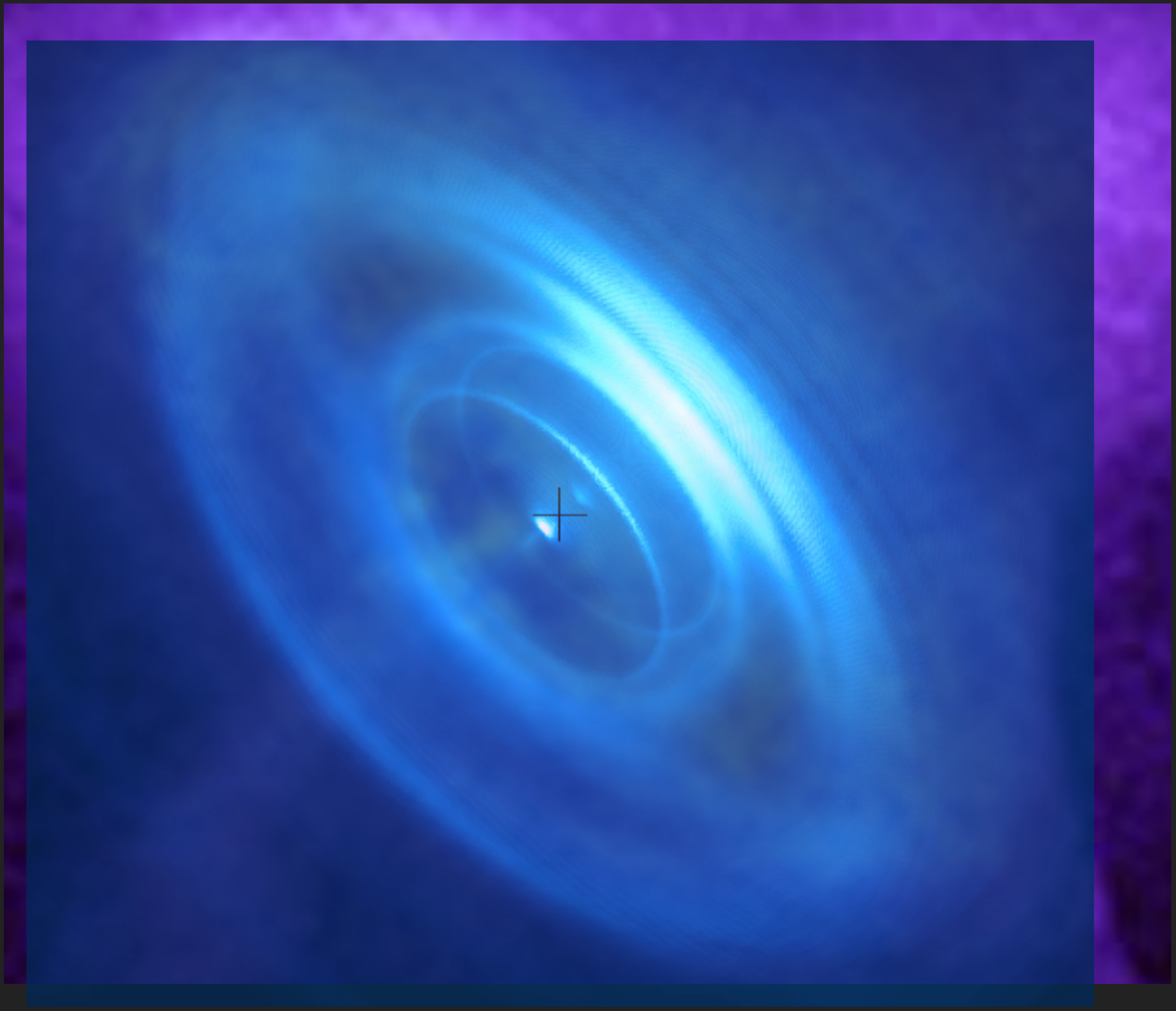
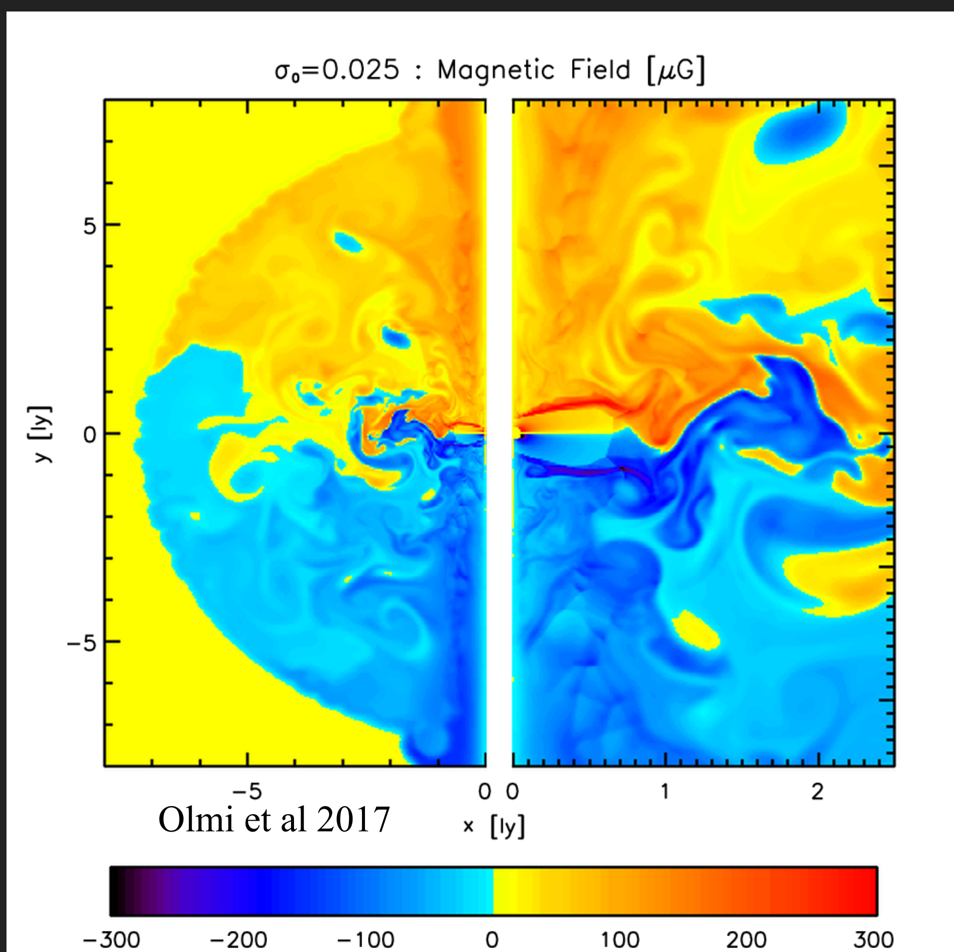
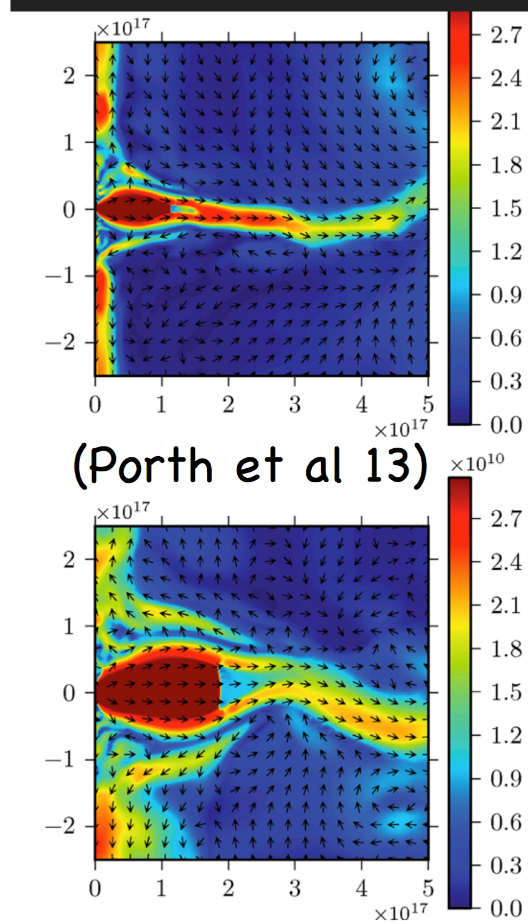


THE COMPLEXITY OF GOING 3D - STATE OF THE ART COMPUTATIONS

3D ALLOWS FOR HIGHER MAGNETIZATIONS

INNER REGION STILL AXISYMMETRIC TORUS-JET





(Porth et al 13)

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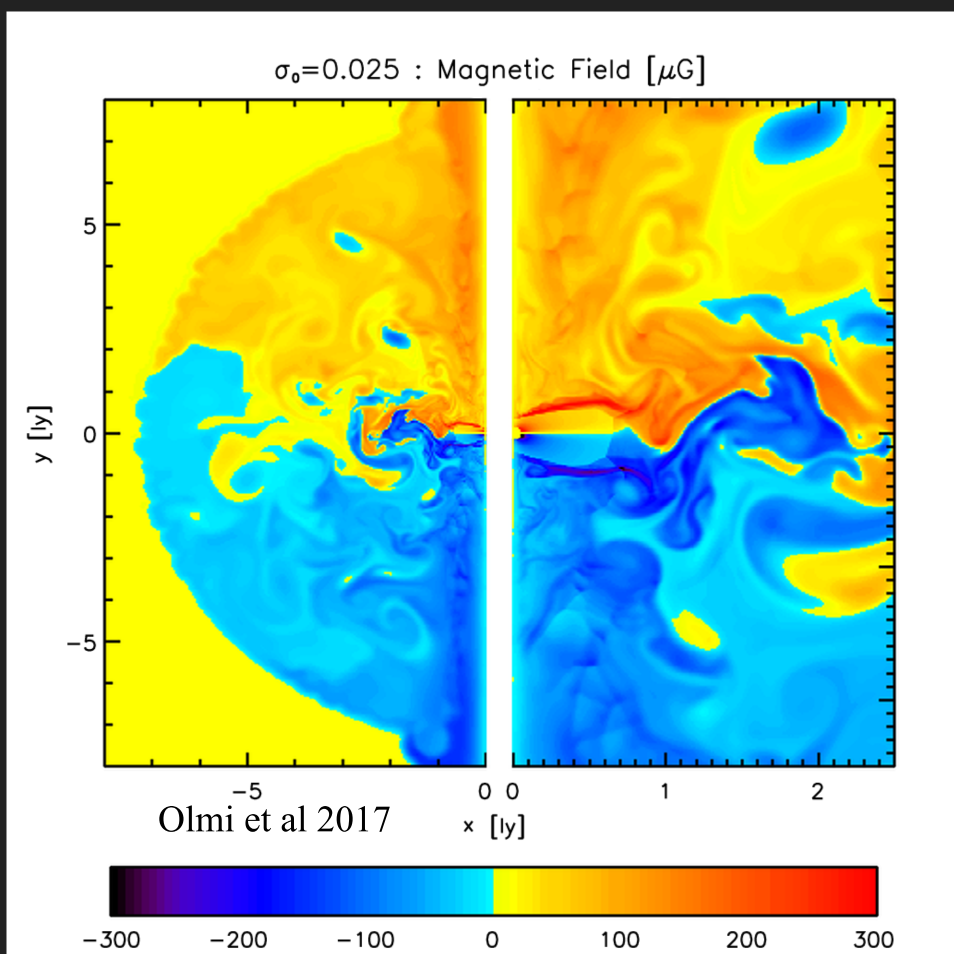
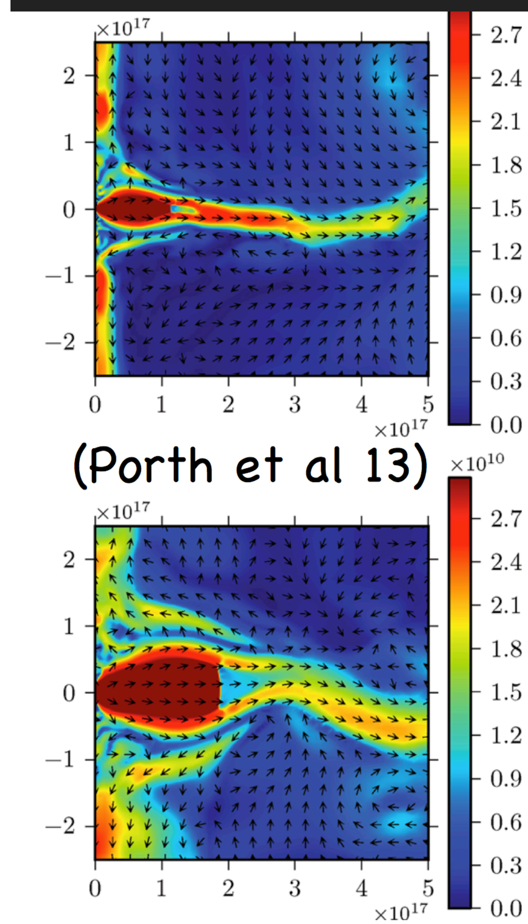


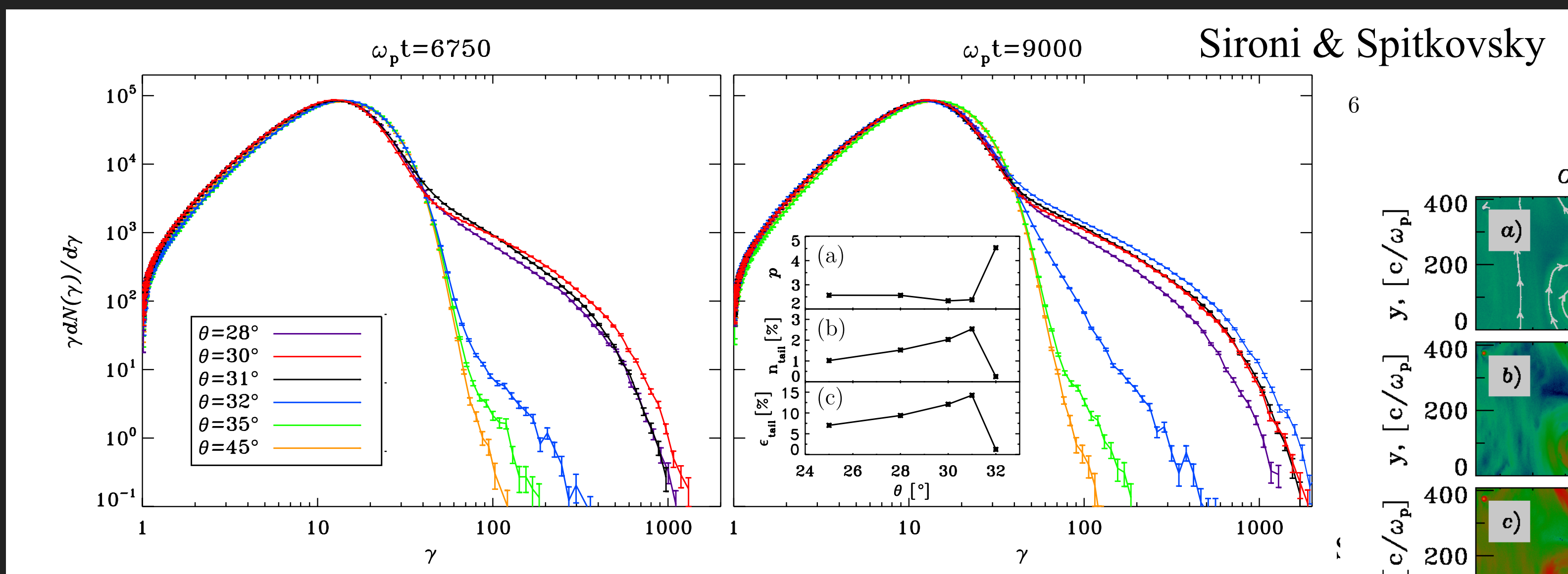


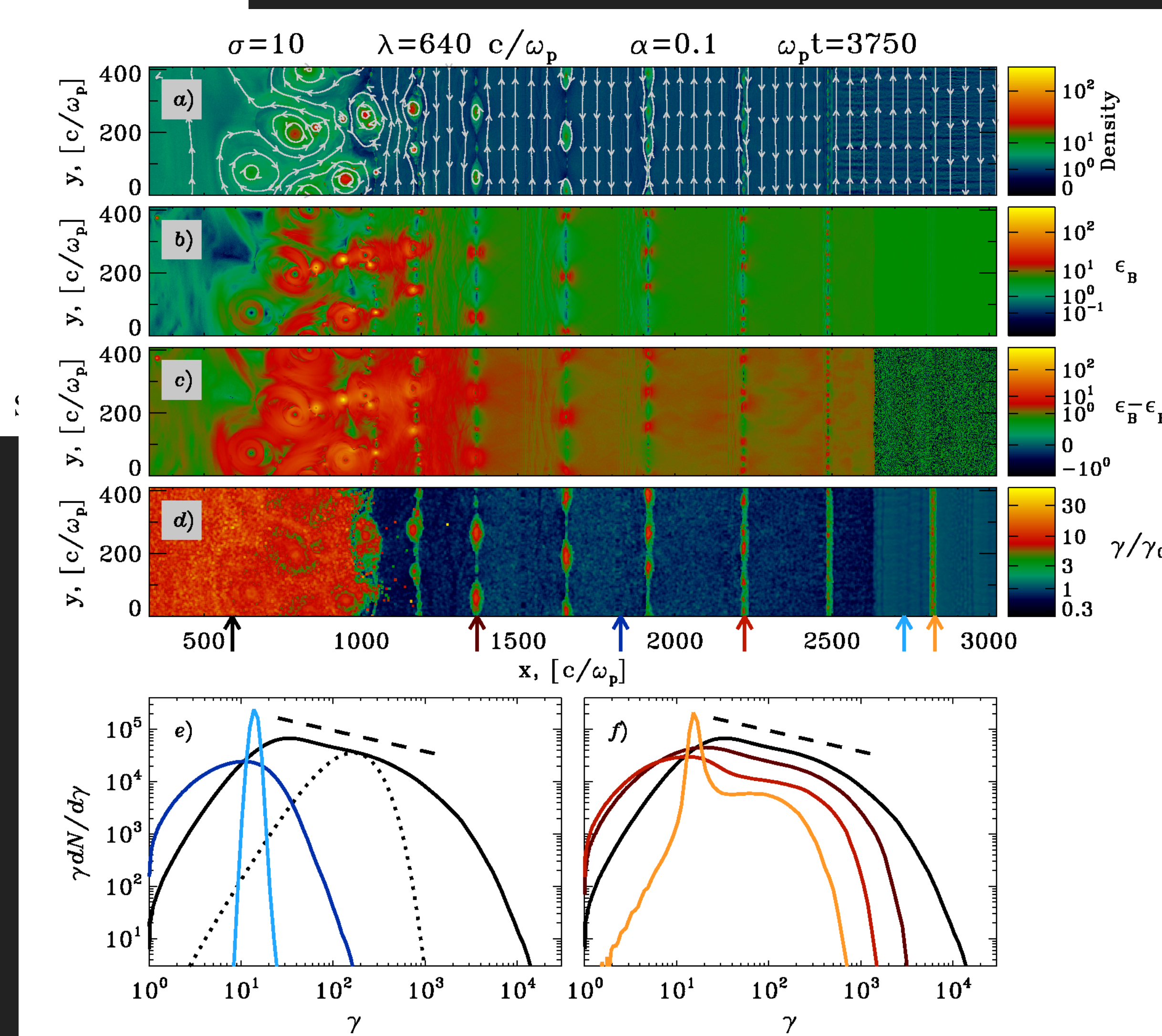
WEAKER JET AND POLATIZATION

TOO MUCH TIME VARIABILITY

FERMI VS RECONNECTION

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





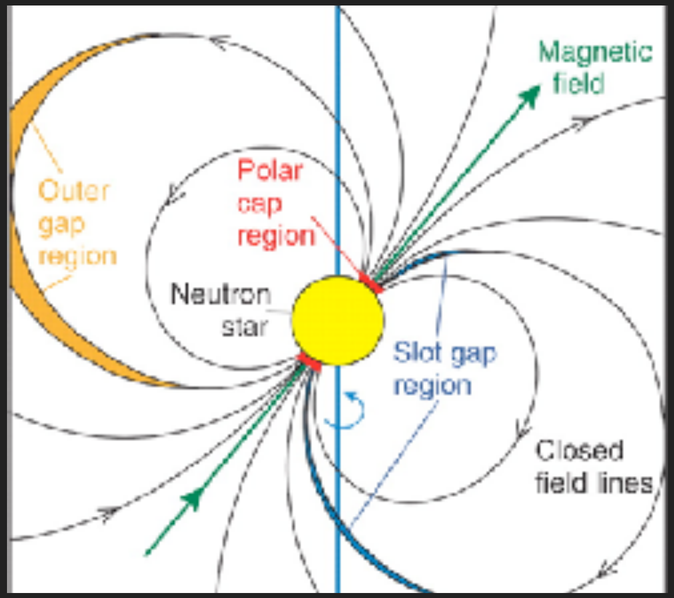
RECONNECTION OF THE STRIPED WIND MORE VERSATILE

WORKS WELL FOR HIGH MAGNETIZATION

REQUIRES VERY HIGH MULTIPLICITY

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

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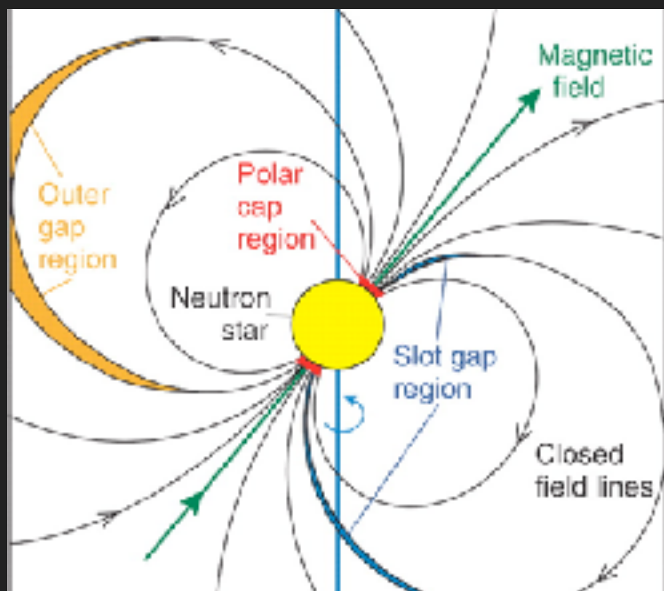
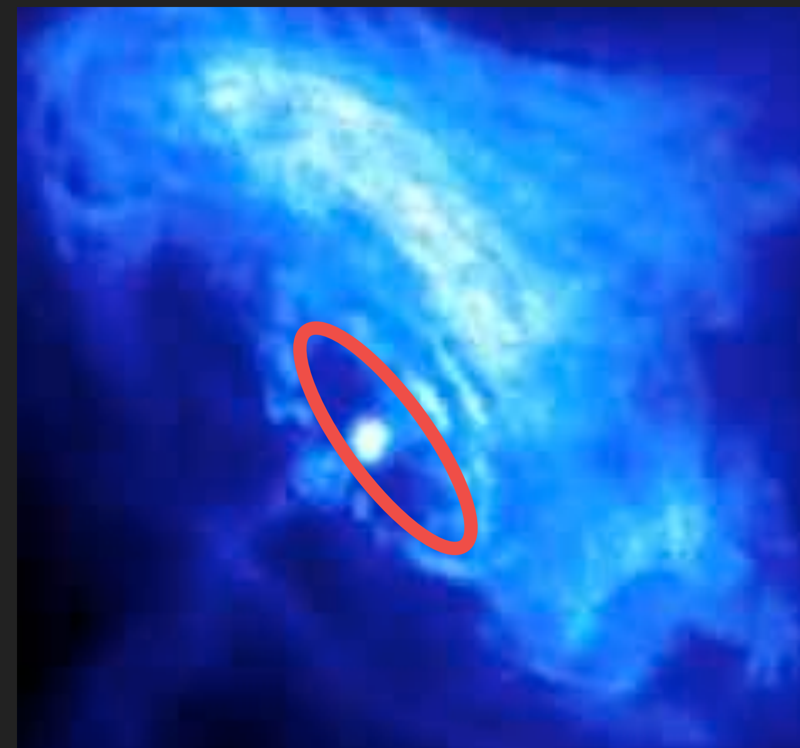




$$\frac{L}{4\pi c R_{ts}^2} = \frac{1}{2}\frac{3Lt}{4\pi R_n^3}$$

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

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

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

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

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

ACCELERATION LIMIT AT THE TS

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

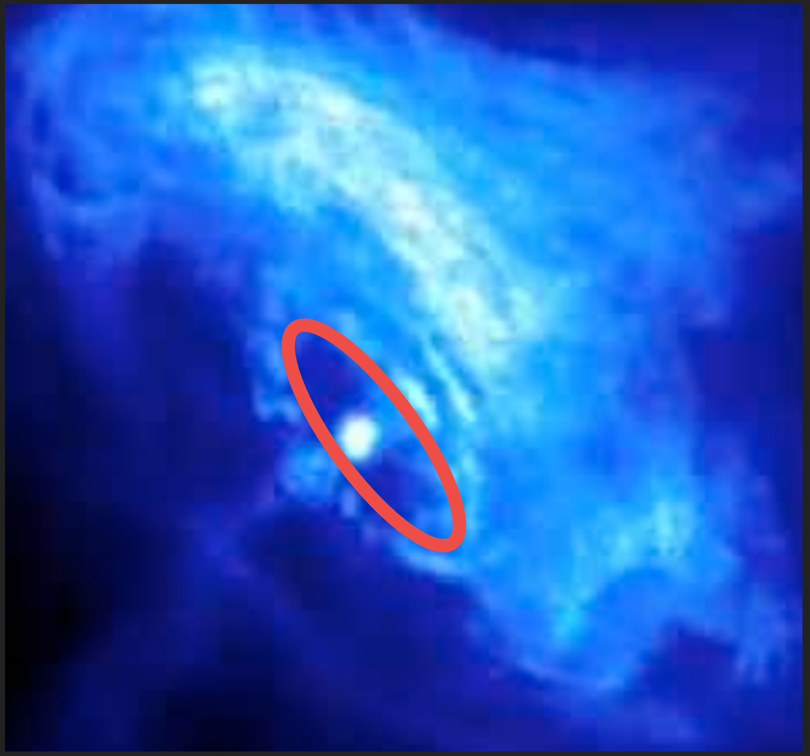
MAGNETISATION IN THE CRAB IS JUST BELOW EQUIPARTITION
B ~ 150-120 UG

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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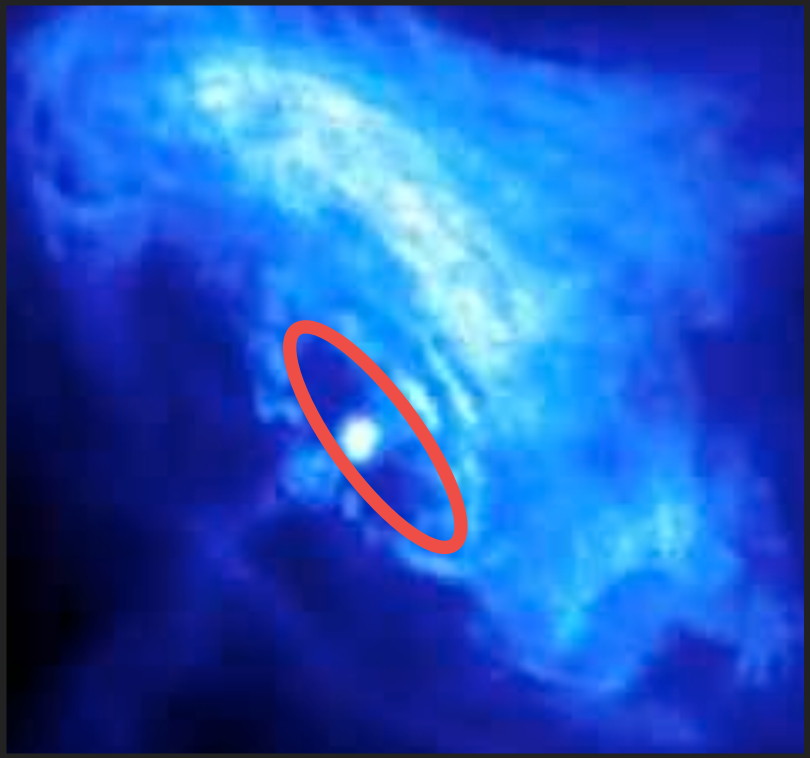

MAXIMUM FREQUENCY IS FIXED

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

ORIGIN OF THE SYNCHROTRON CUTOFF

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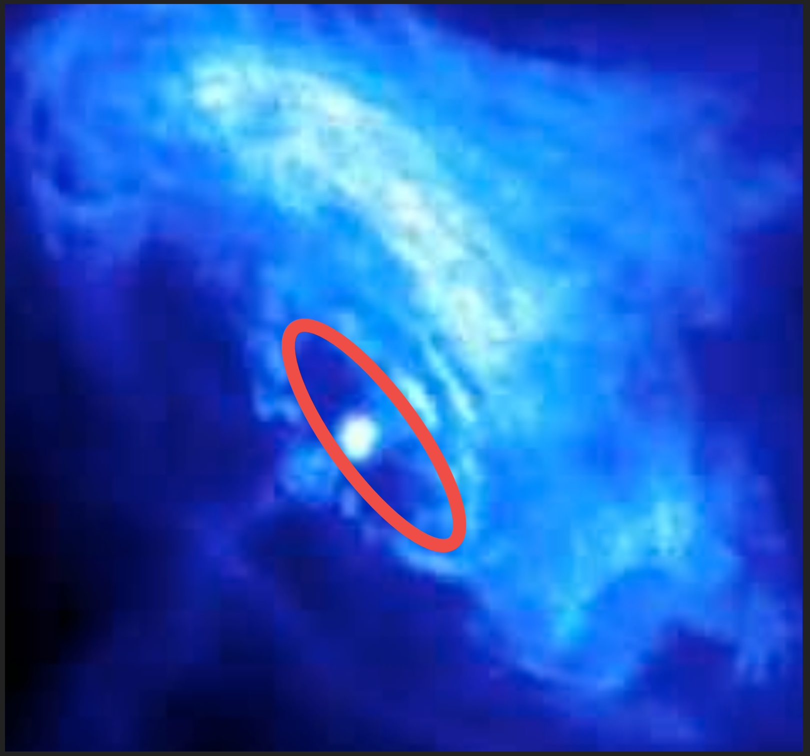
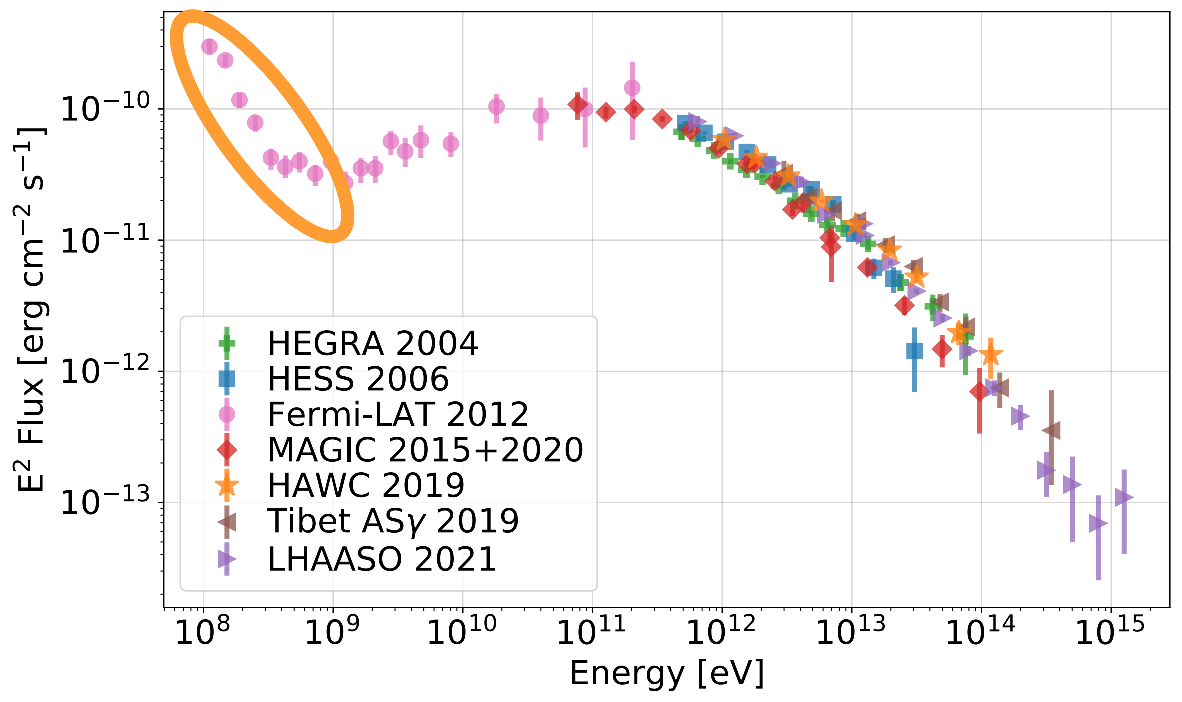


MAXIMUM FREQUENCY IS FIXED

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

IN CRAB THE LIMITS ALL COINCIDE

OTHERS ALL POTENTIAL LIMITED



12 (NOW MORE) SOURCES DETECTED BY LHAASO ABOVE 100 TEV

Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26\,_{-0.10}^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71\,_{-0.07}^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

PEV PROTONS OR ELECTRONS?

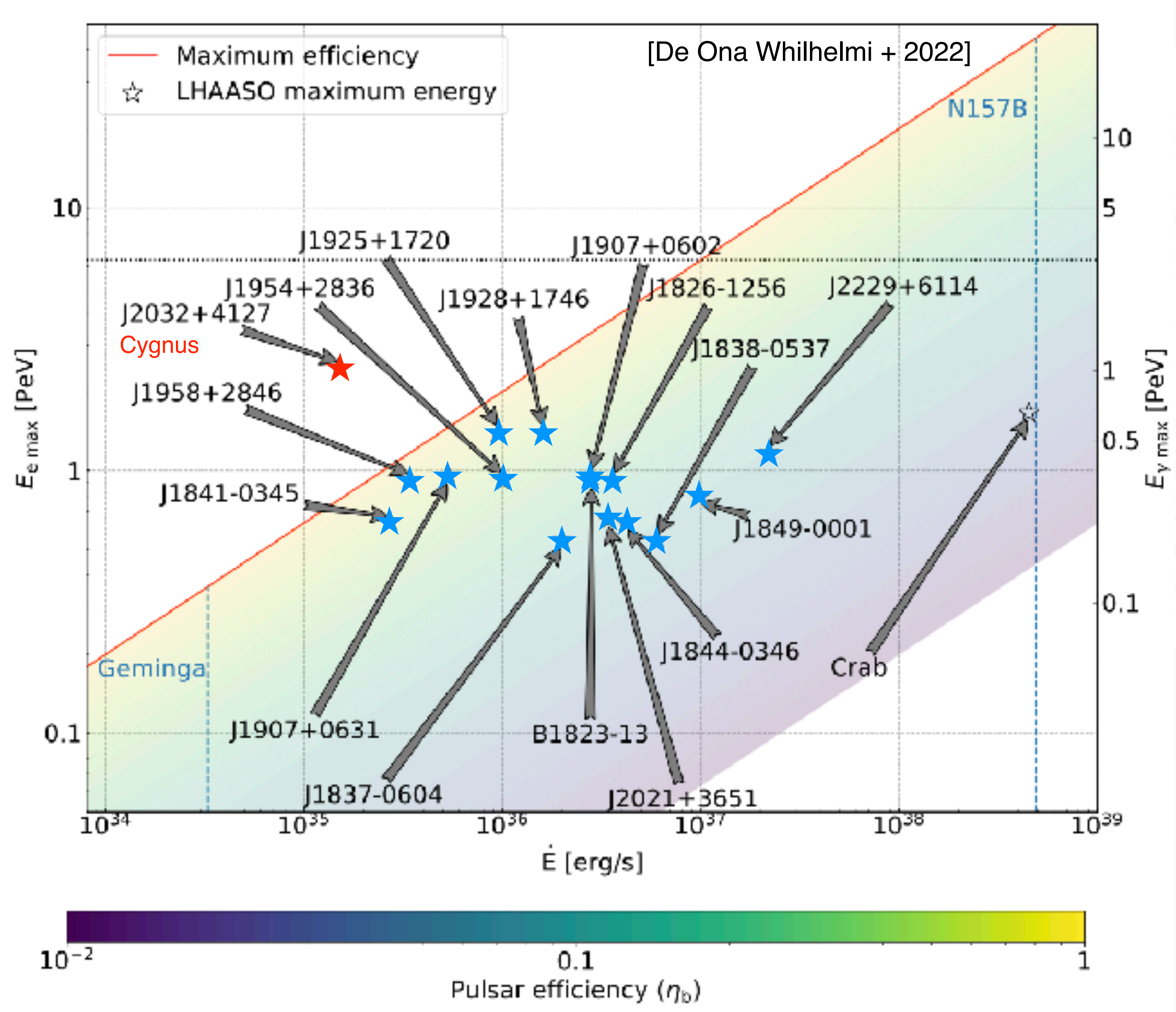
ALL SOURCES HAVE A PSR IN THE FIELD EXCEPT ONE

12 (NOW MORE) SOURCES DETECTED BY LHAASO ABOVE 100 TEV

Table 1 | UHE γ-ray sour

Source name
LHAASO J0534+2202
LHAASO J1825-1326
LHAASO J1839-0545
LHAASO J1843-0338
LHAASO J1849-0003
LHAASO J1908+0621
LHAASO J1929+1745
LHAASO J1956+2845
LHAASO J2018+3651
LHAASO J2032+4102
LHAASO J2108+5157
LHAASO J2226+6057

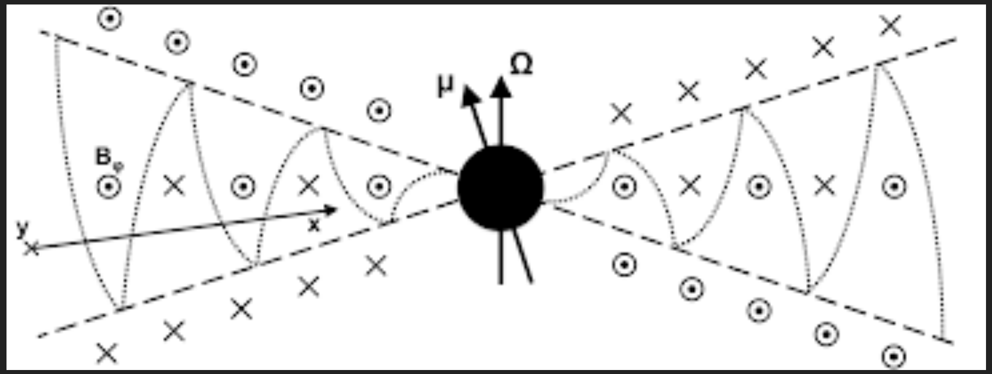
0 TeV (CU)



RECONNECTION

RECONNECTION

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



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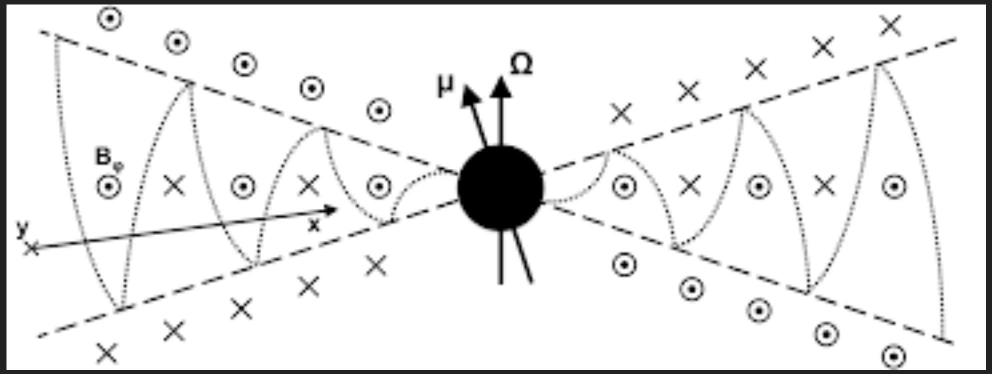
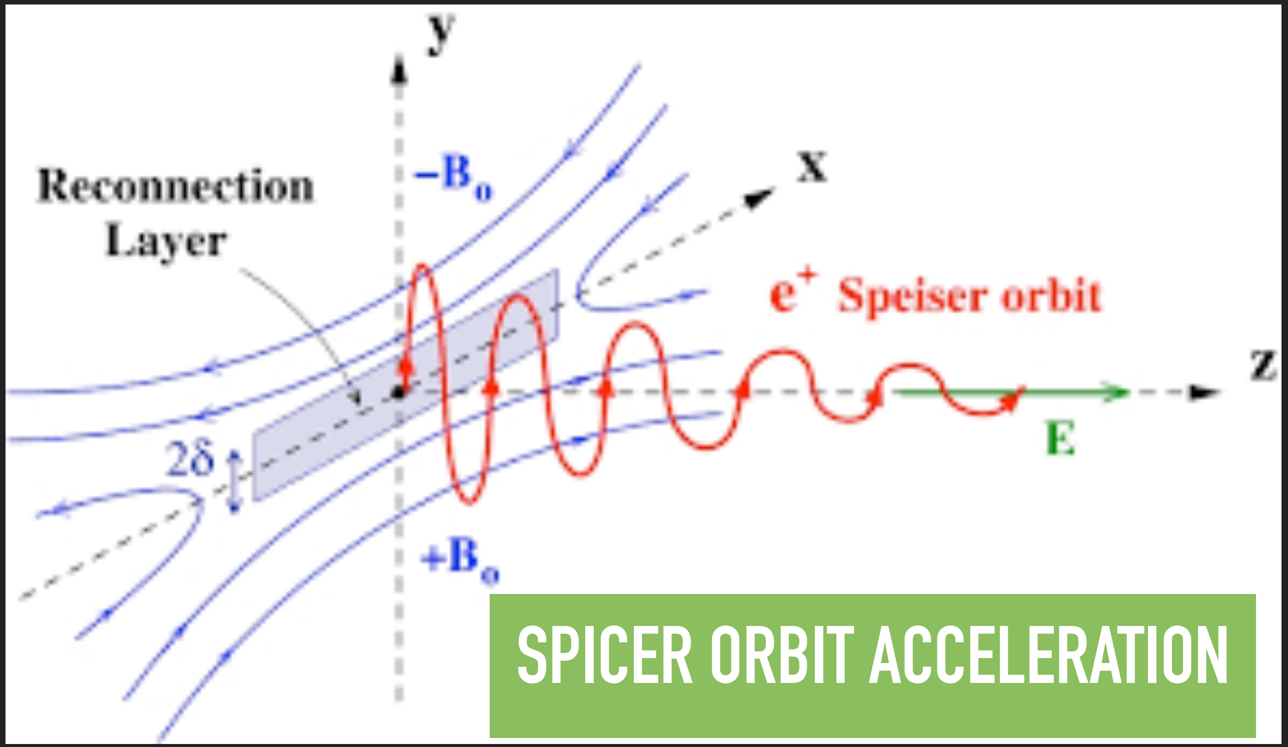
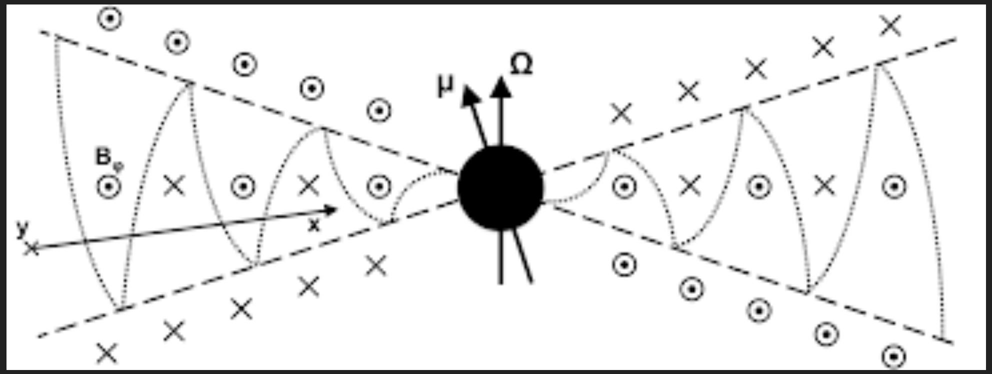


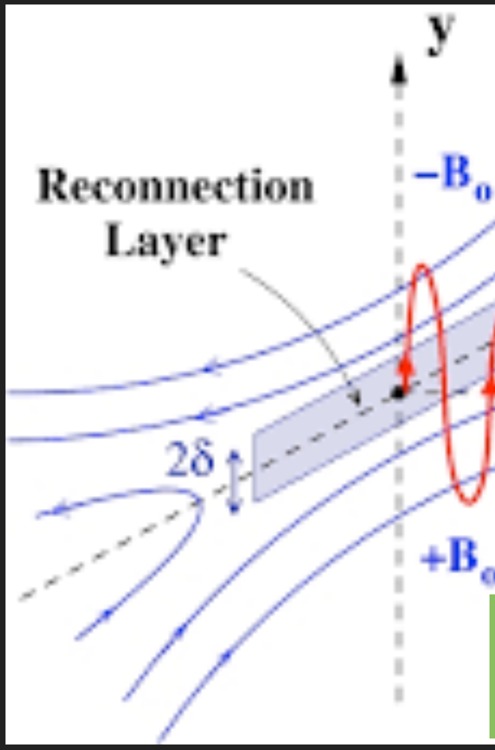


SPICER ORBIT ACCELERATION

RECONNECTION

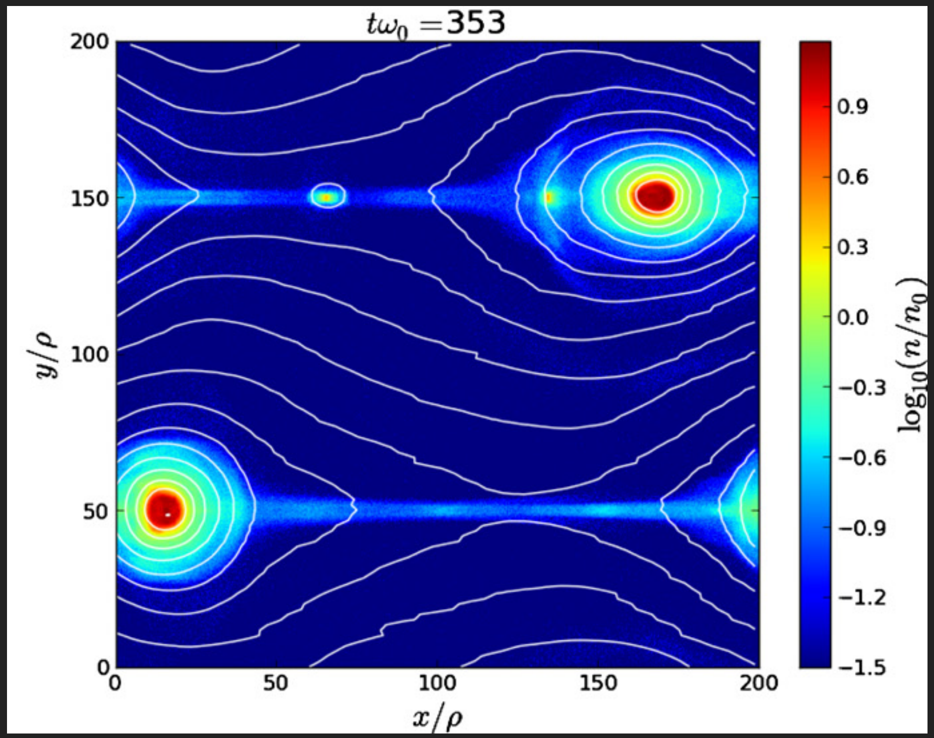
PSR WINDS ARE STRIPED AND THIS IMPLIES ALTERNATING FIELD POLARITIES IN THE PWN





SPICER ORBIT ACCELERATION

TEARING INSTAB



RECONNECTION

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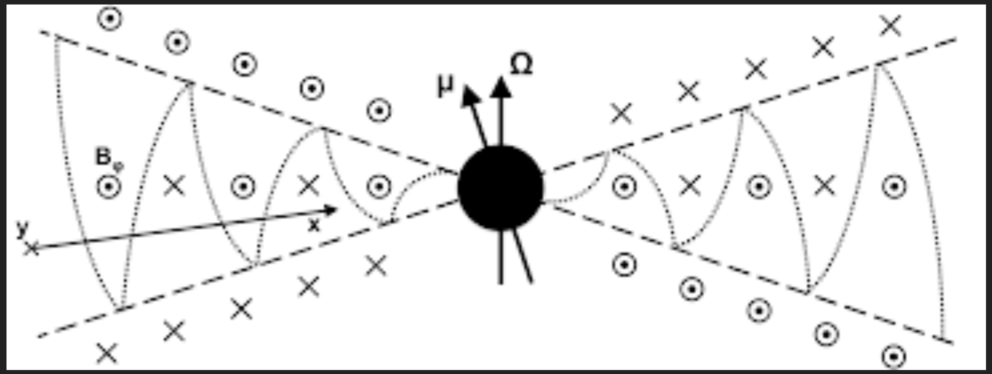
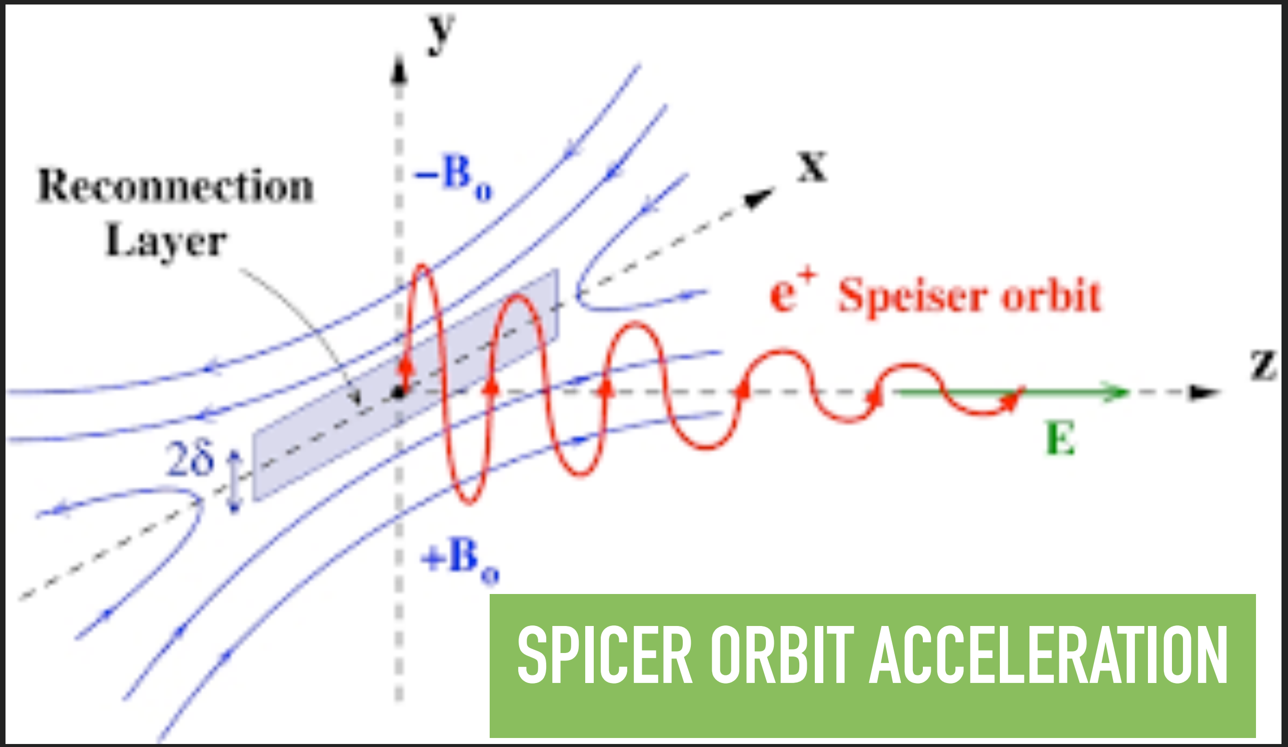
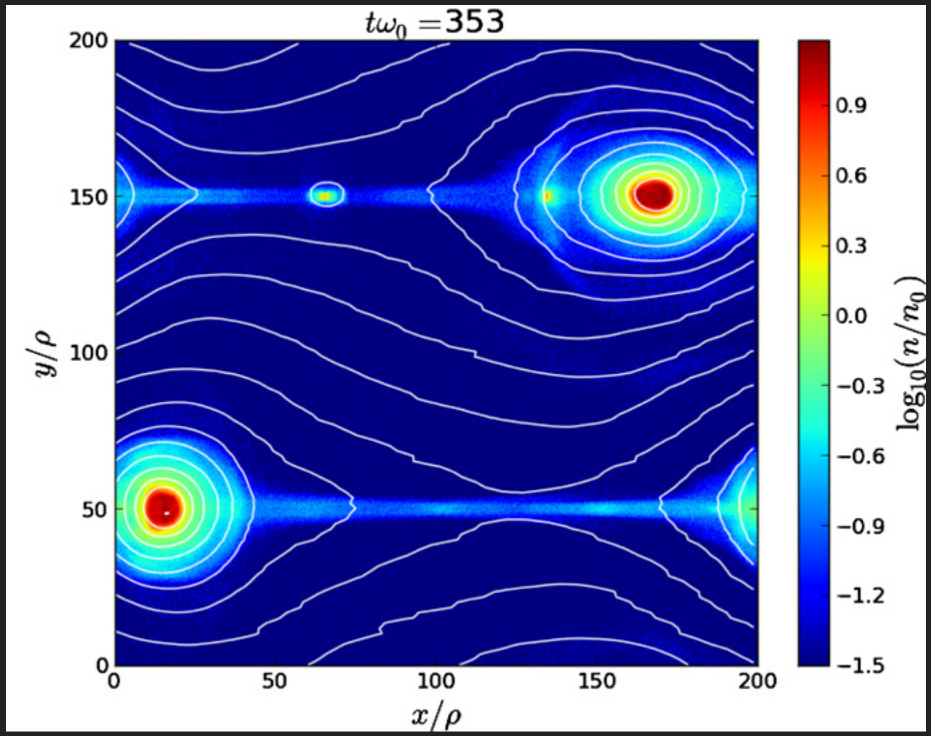


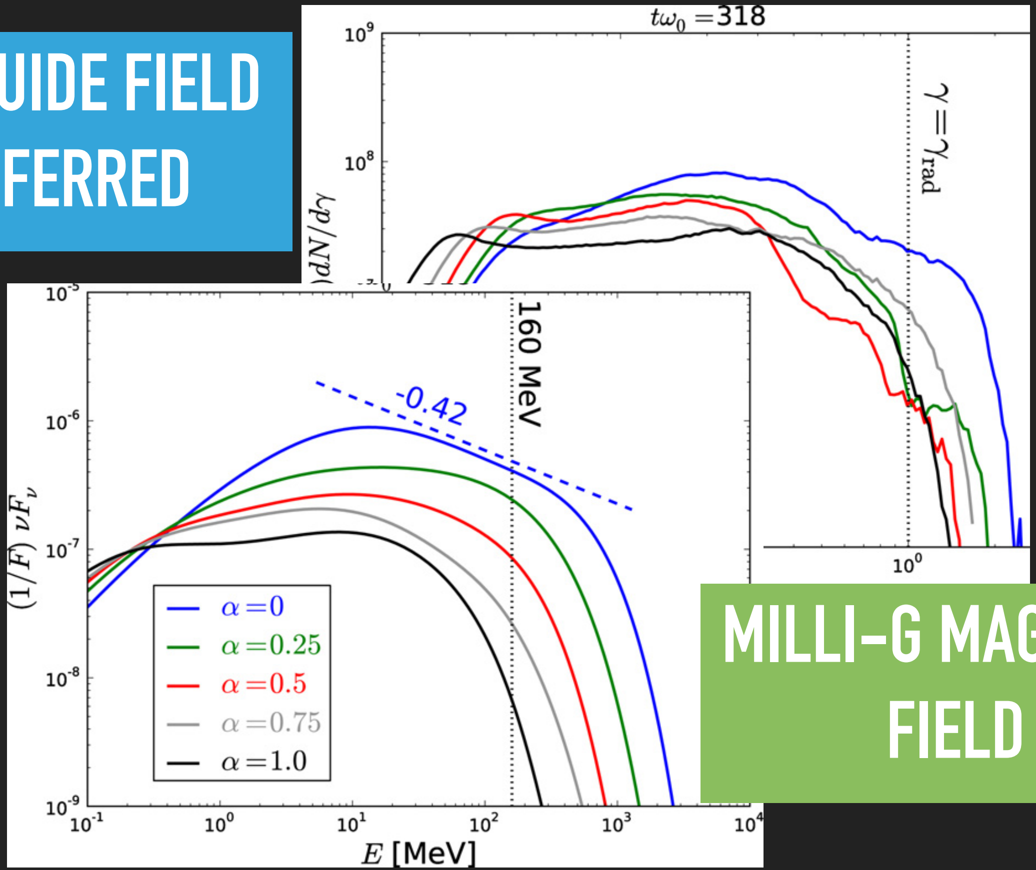


SPICER ORBIT ACCELERATION

TEARING INSTAB



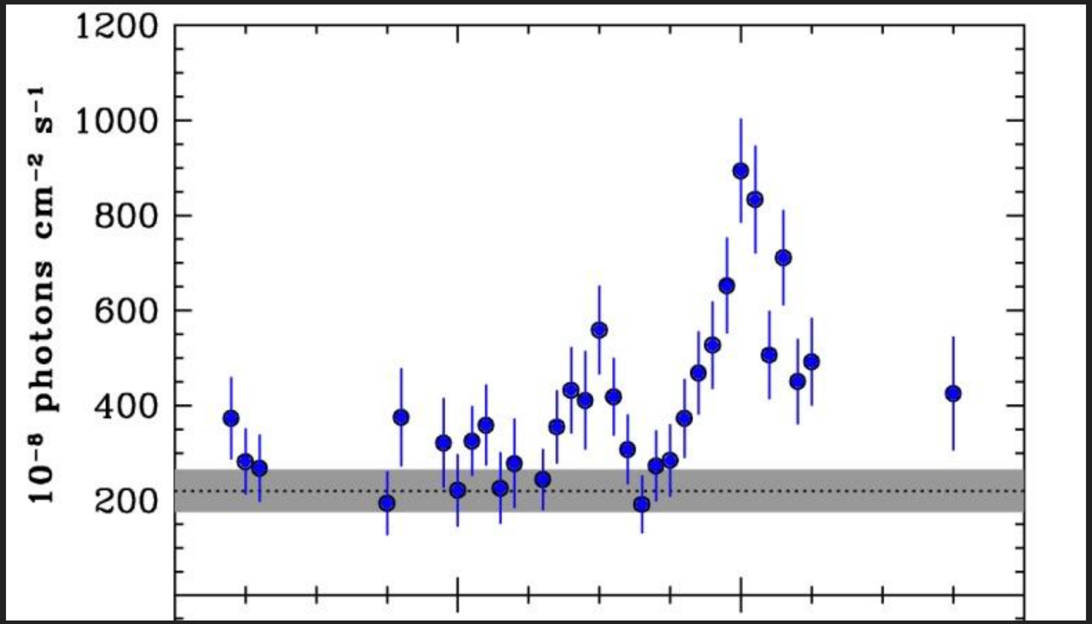
LOW GUIDE FIELD PREFERRED



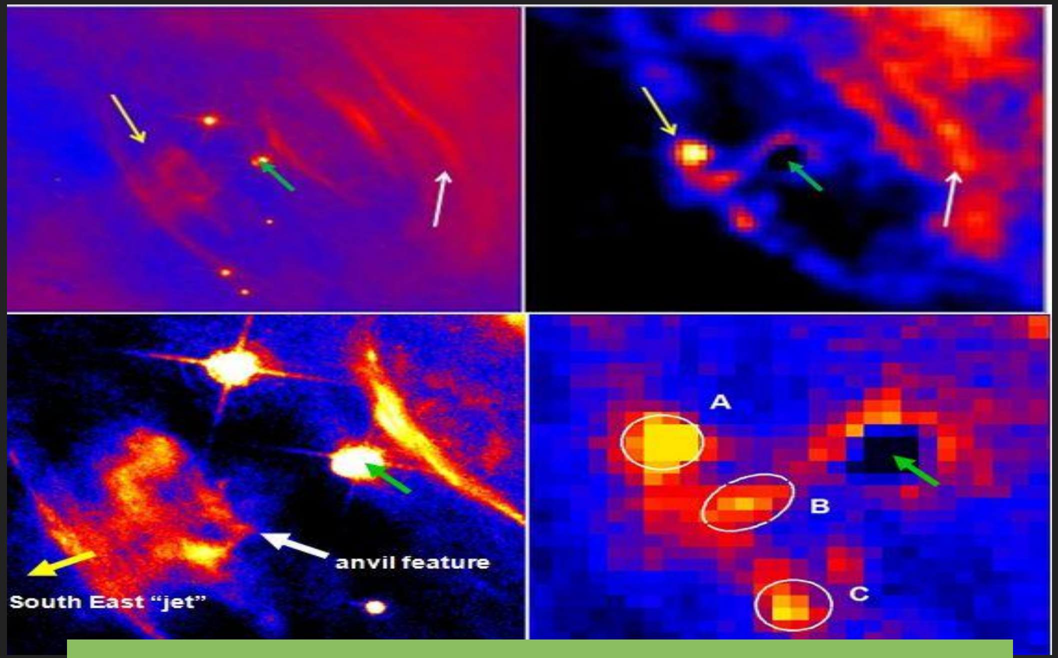
MILLI-G MAGNETIC FIELD

2010 FLARE

~4 TIME OVER QUIESCENT

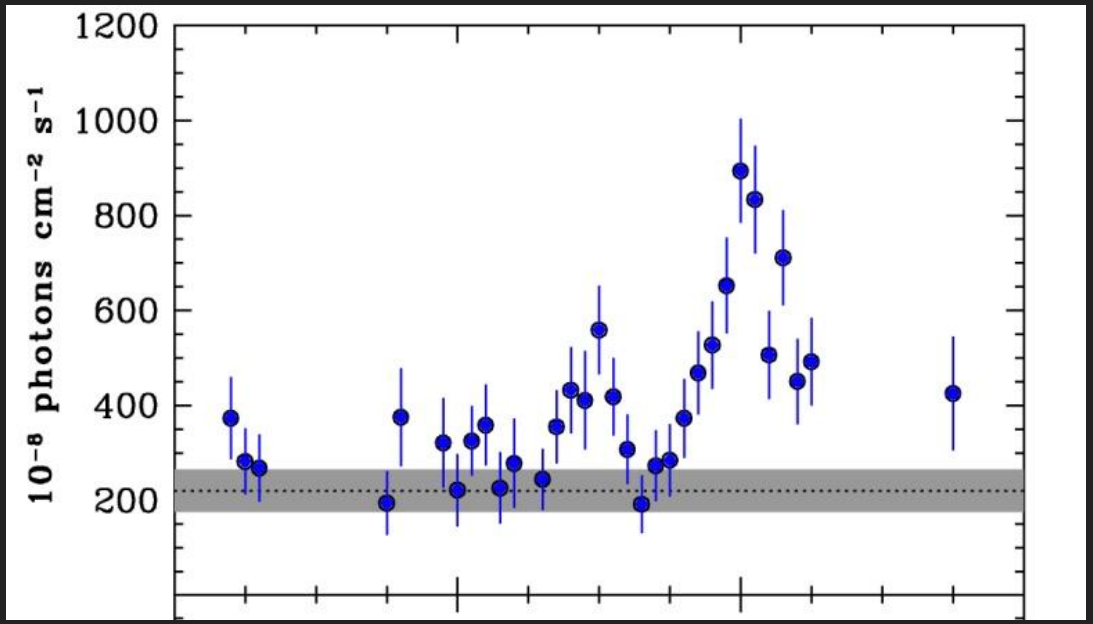


2010 FLARE

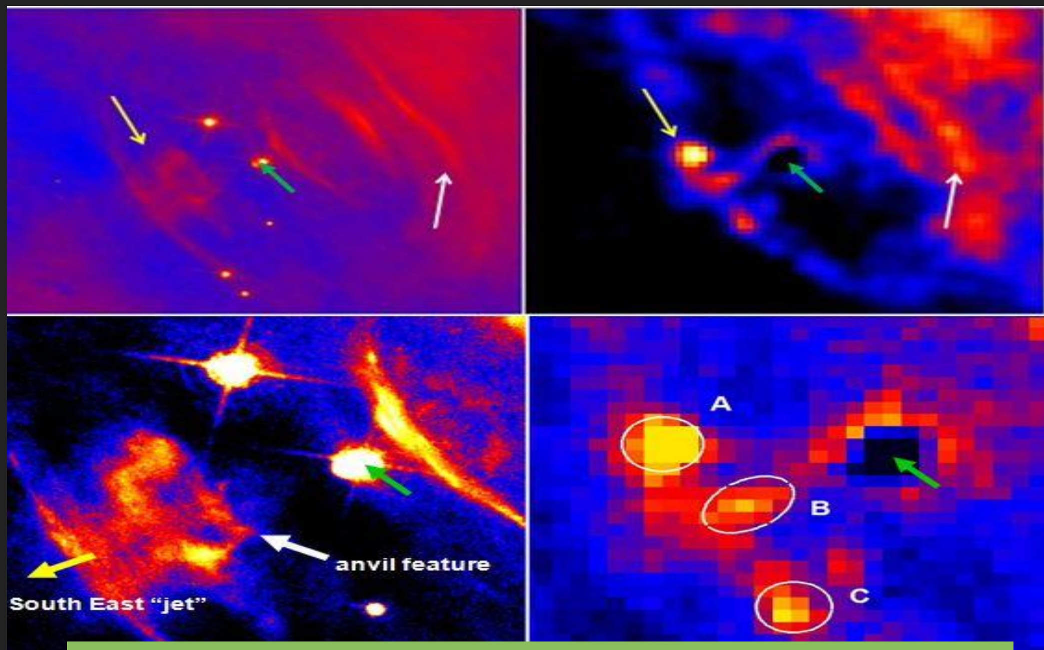


MINOR EVIDENCE IN X

~4 TIME OVER QUIESCENT



2010 FLARE



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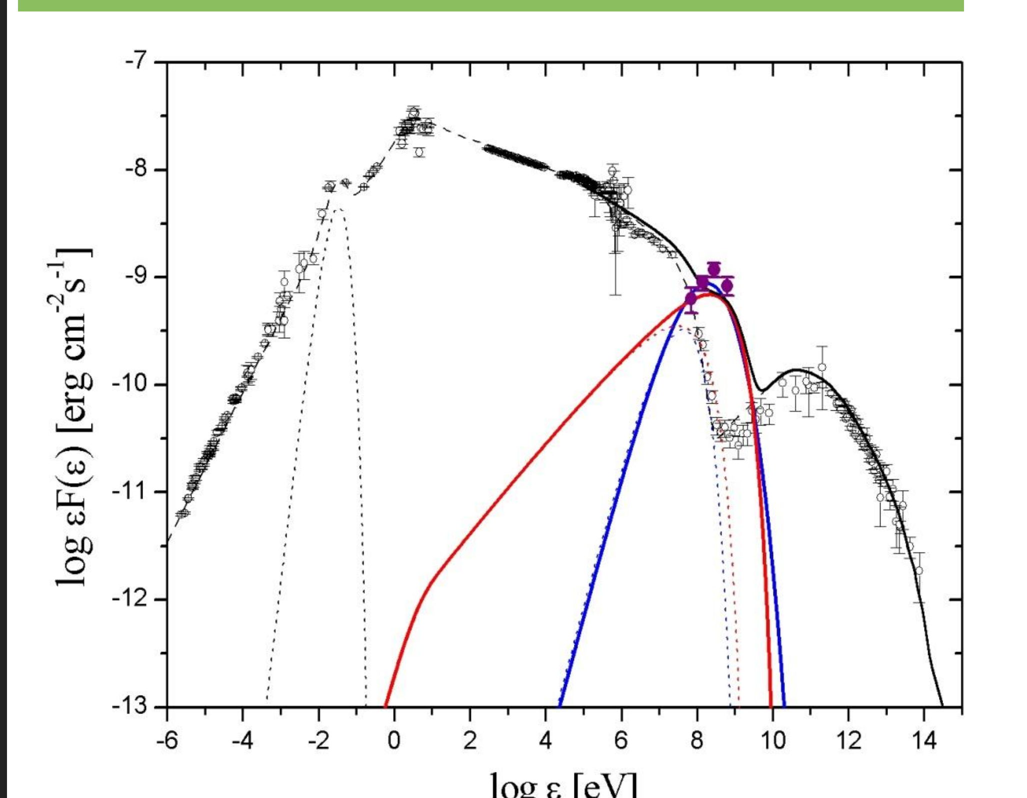

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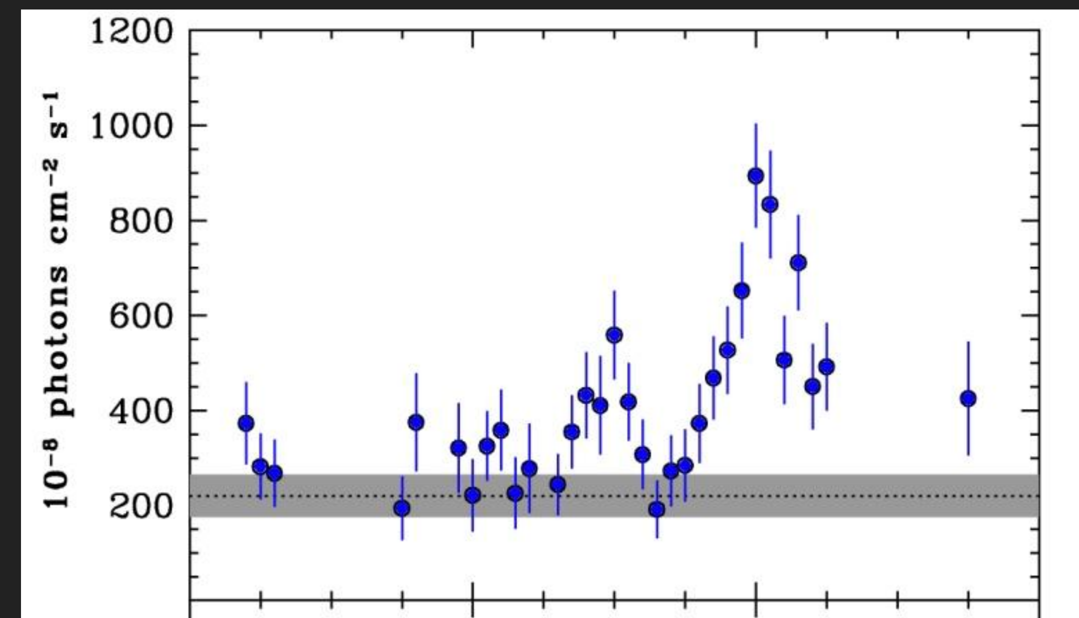

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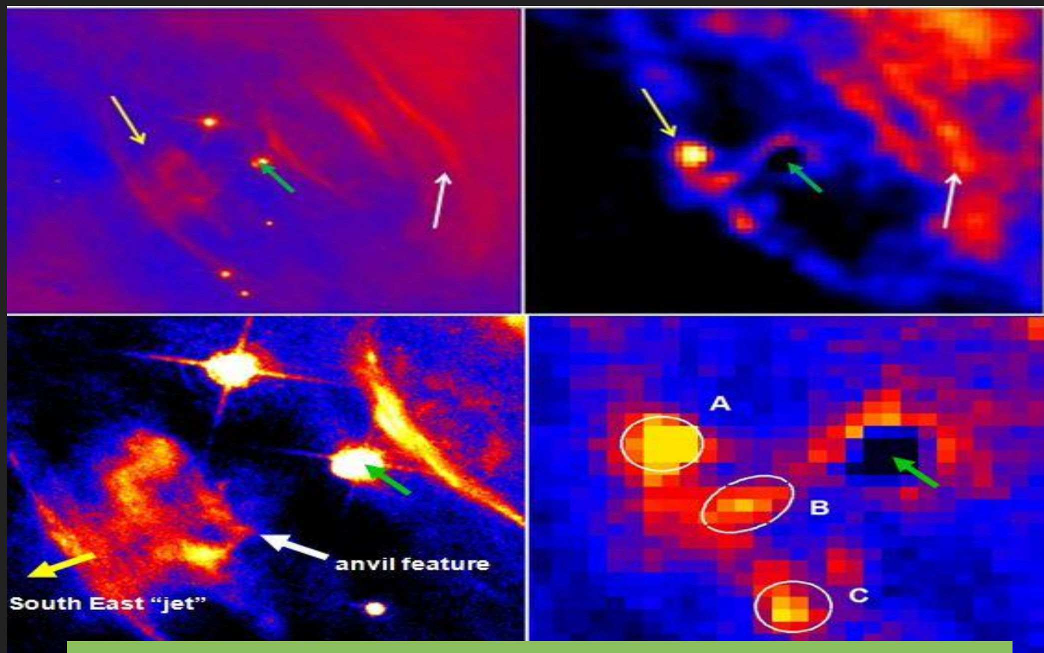
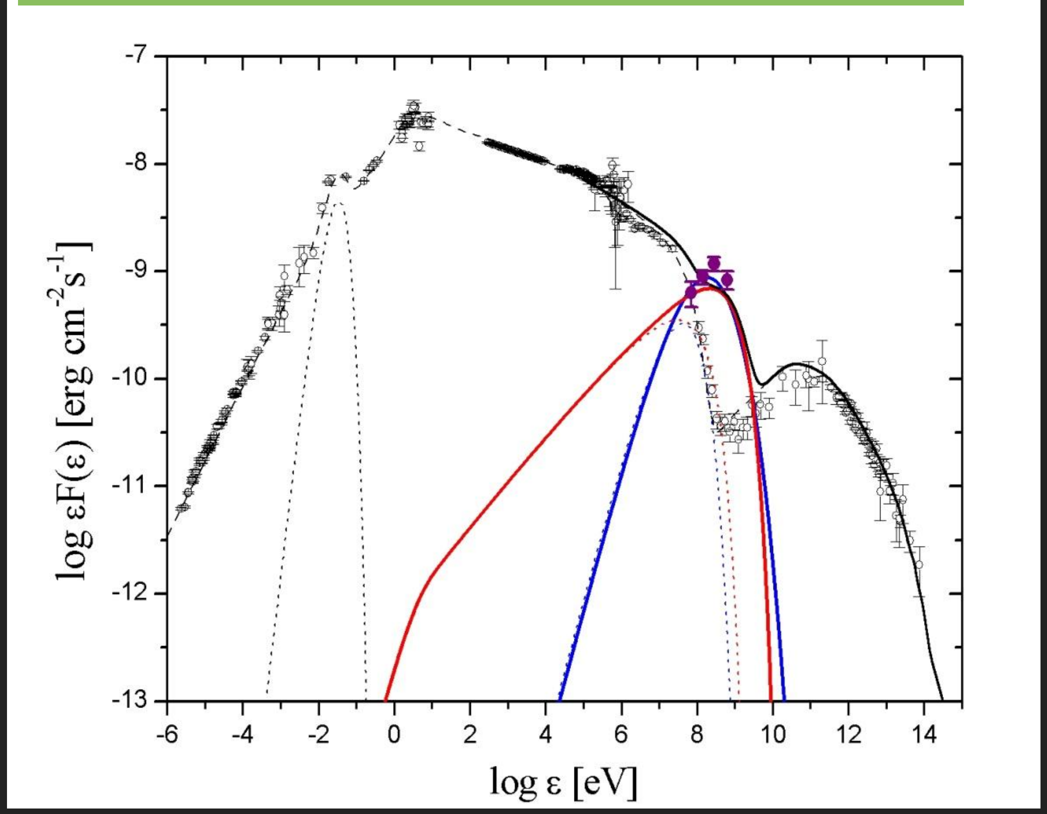
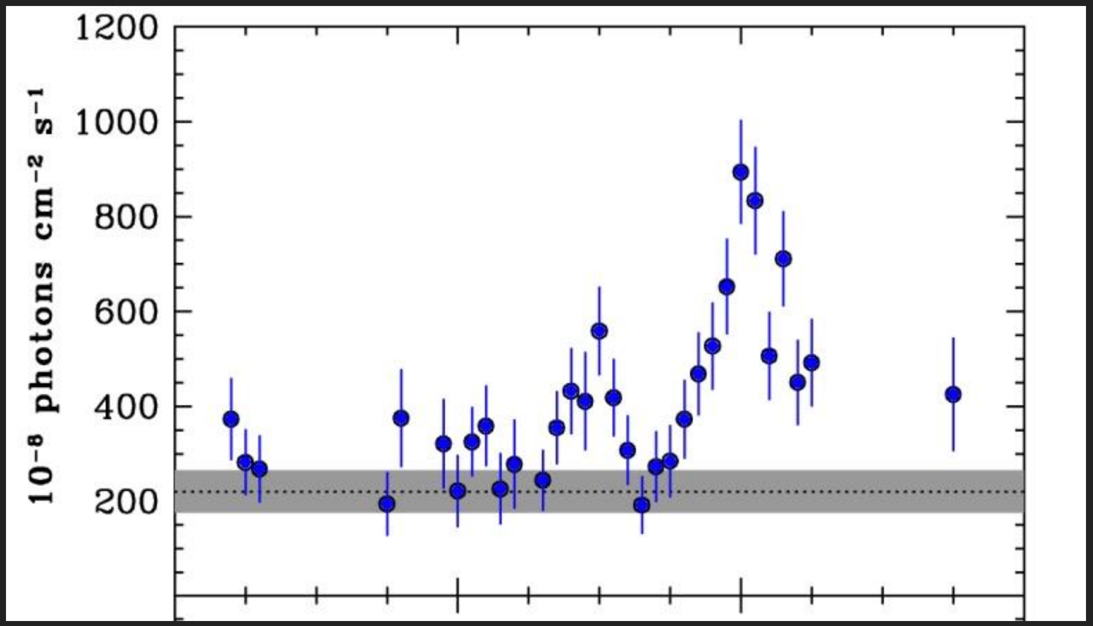


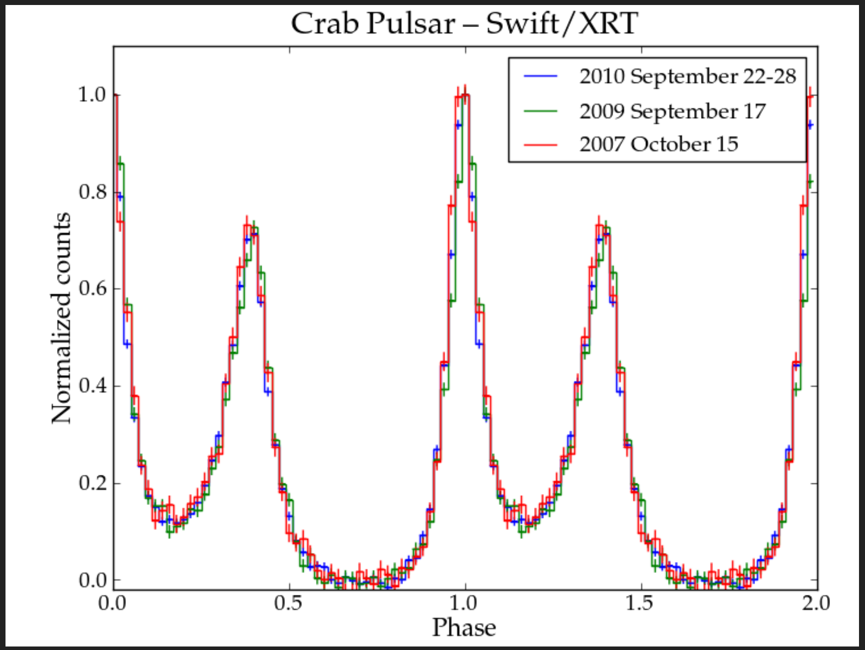
MINOR EVIDENCE IN X



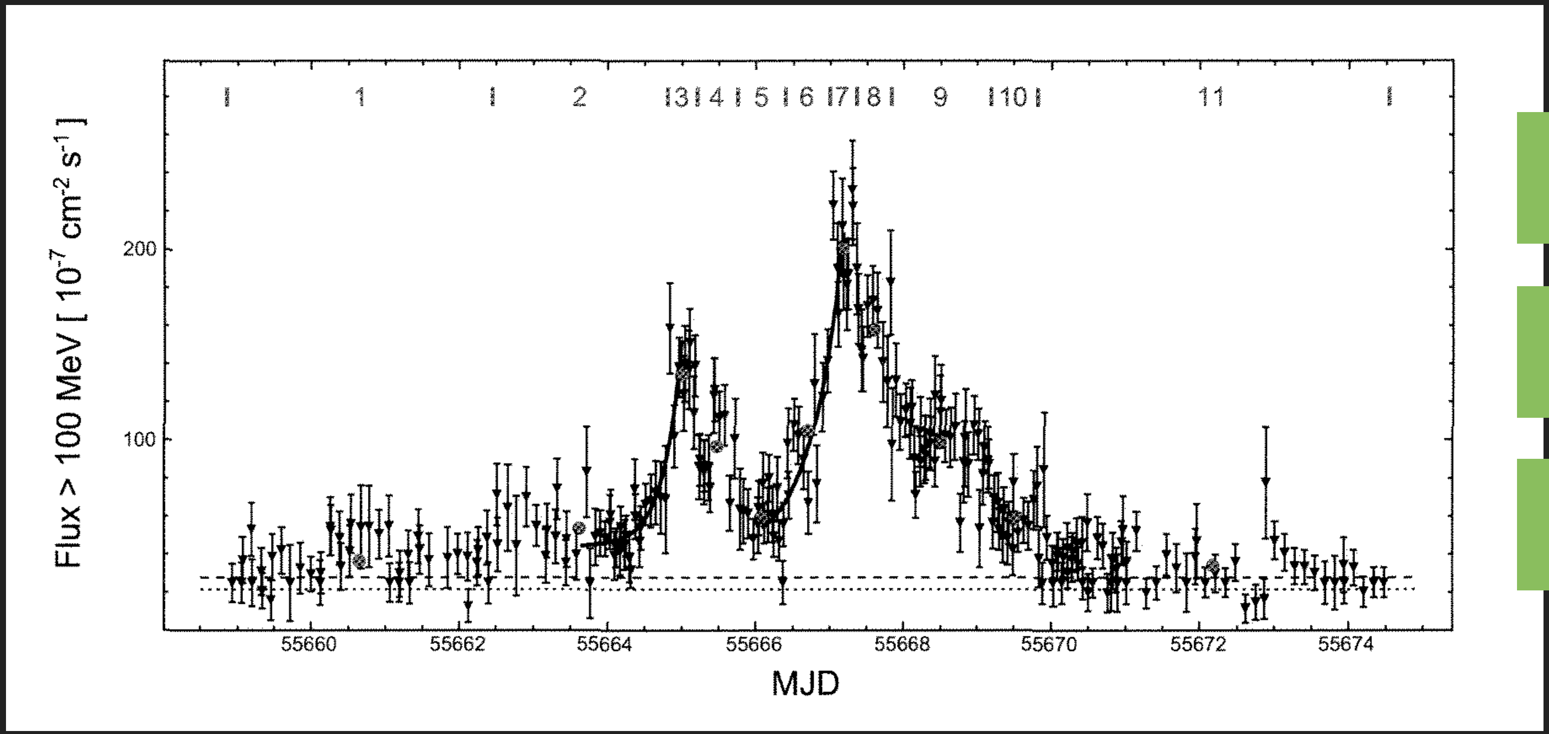
~4 TIME OVER QUIESCENT



NO CHANGE IN PSR



2011 FLARE

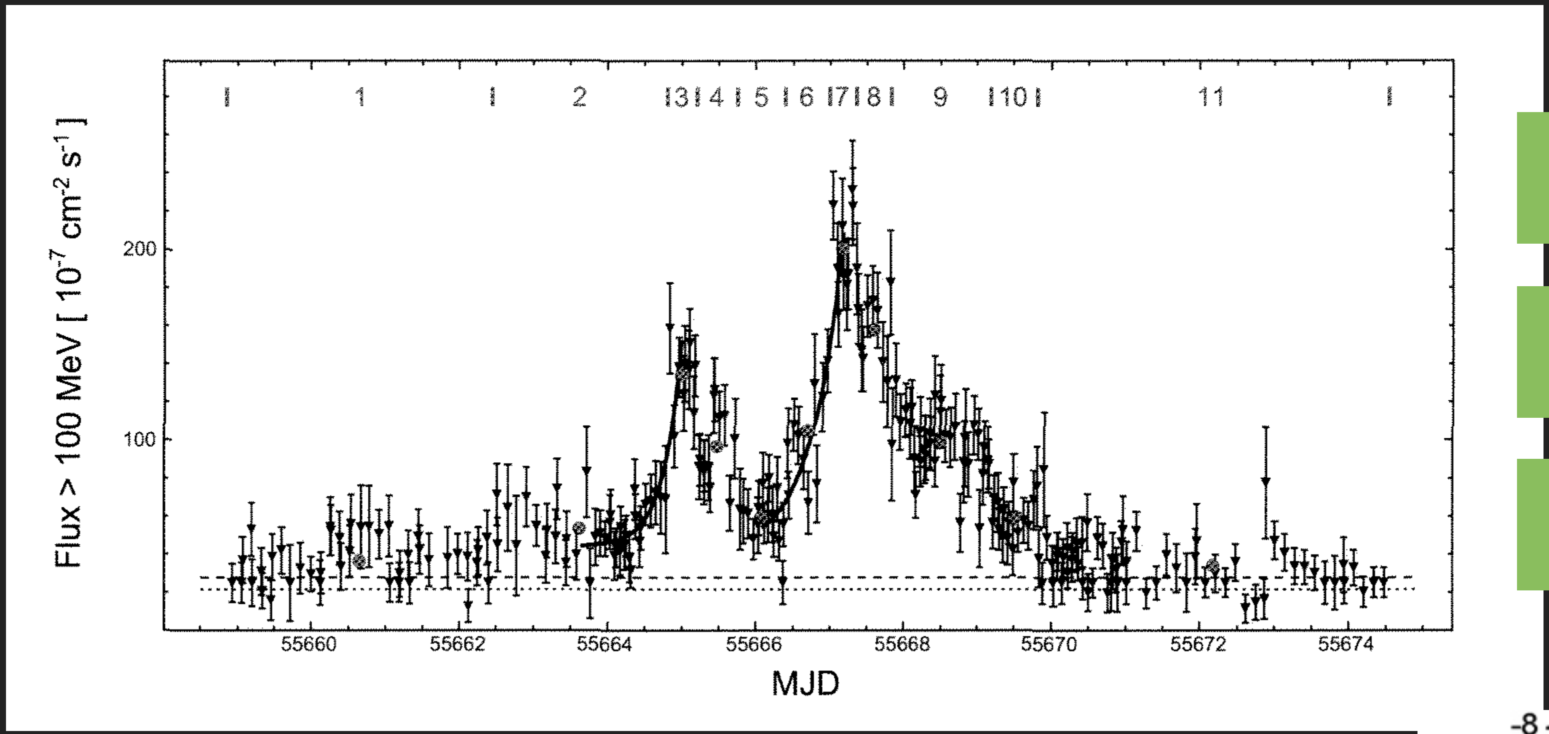


25 TIMES ABOVE QUIESCENT

FLARE IS STRUCTURED

FLARE DURATION DAYS-WEEK

2011 FLARE



25 TIMES ABOVE QUIESCENT

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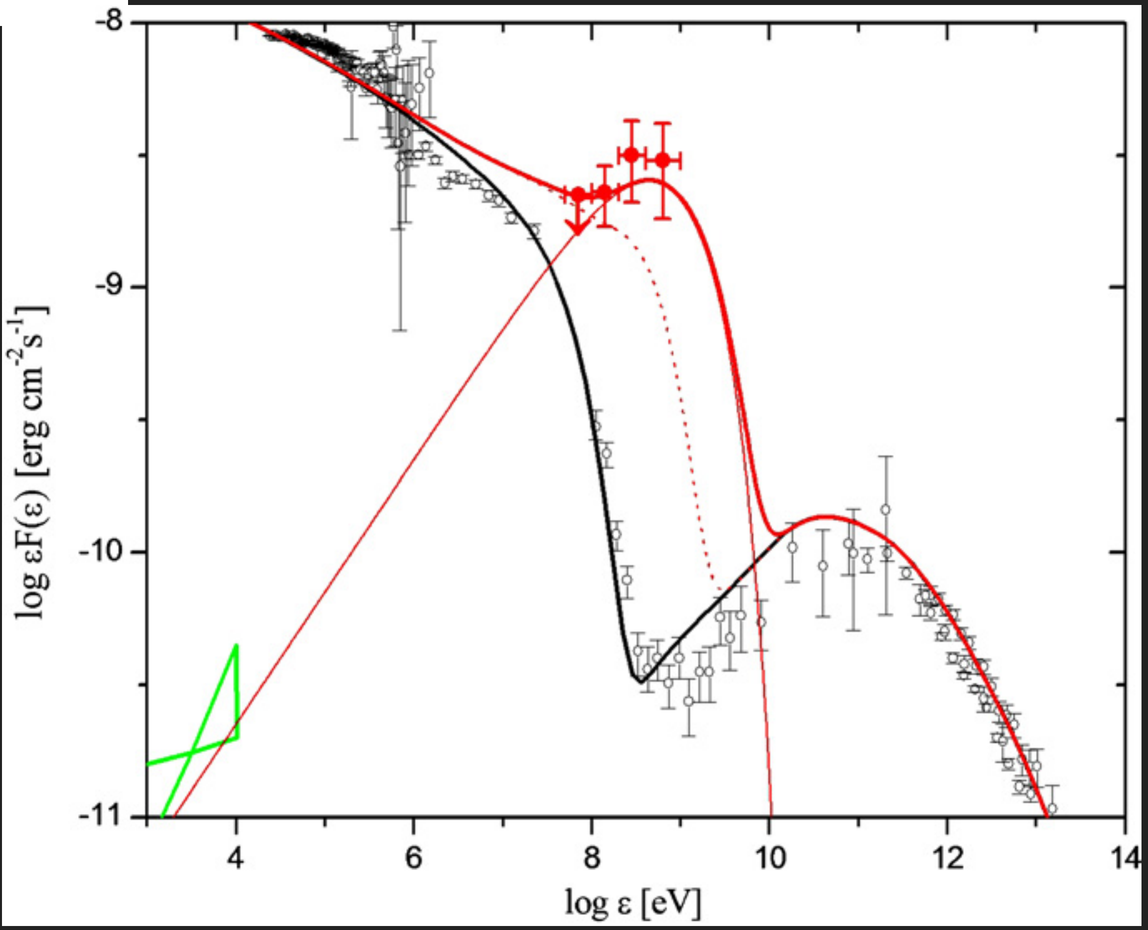
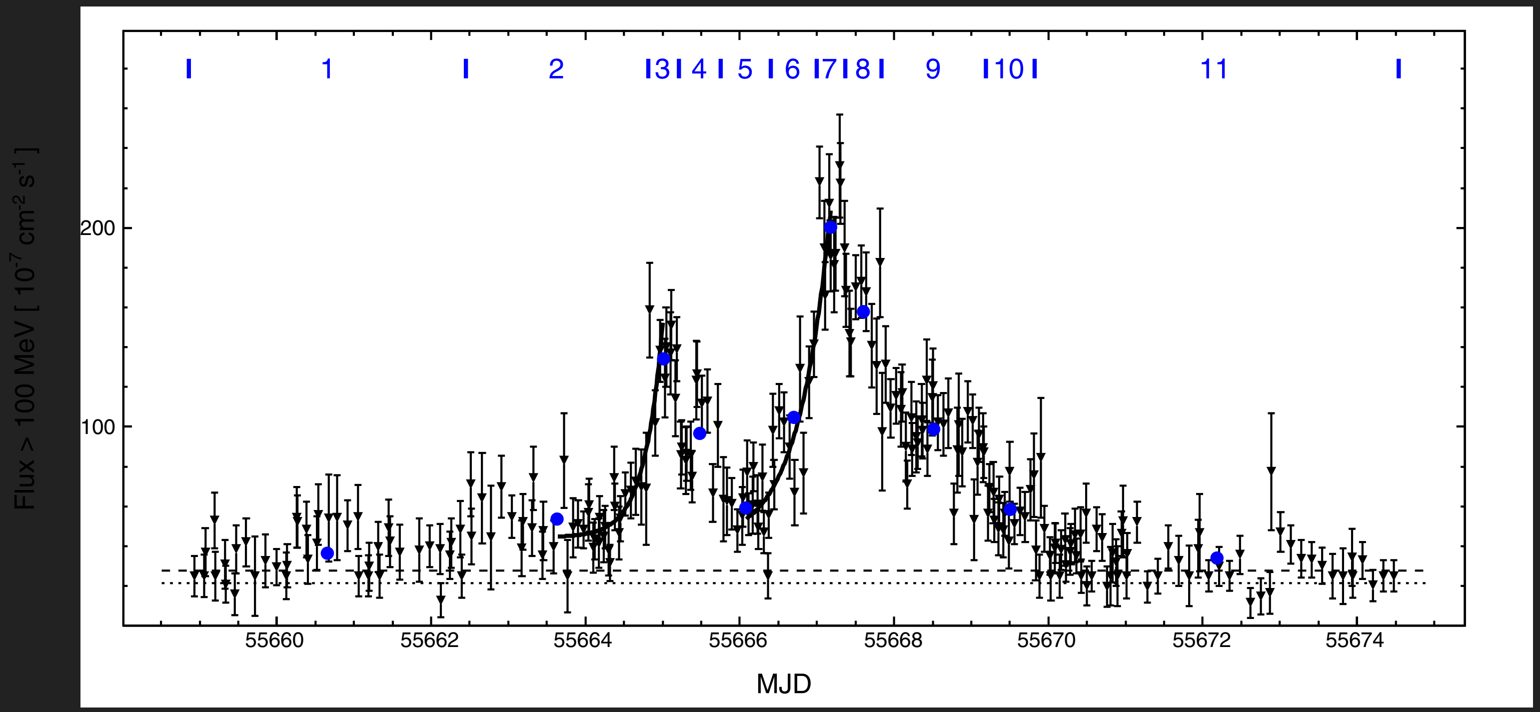


COMPATIBLE WITH ALMOST MONOCHROMATIC

REQUIRES DOPPLER BOOSTING

LOCATION – KNOT?

SPECTRAL EVOLUTION



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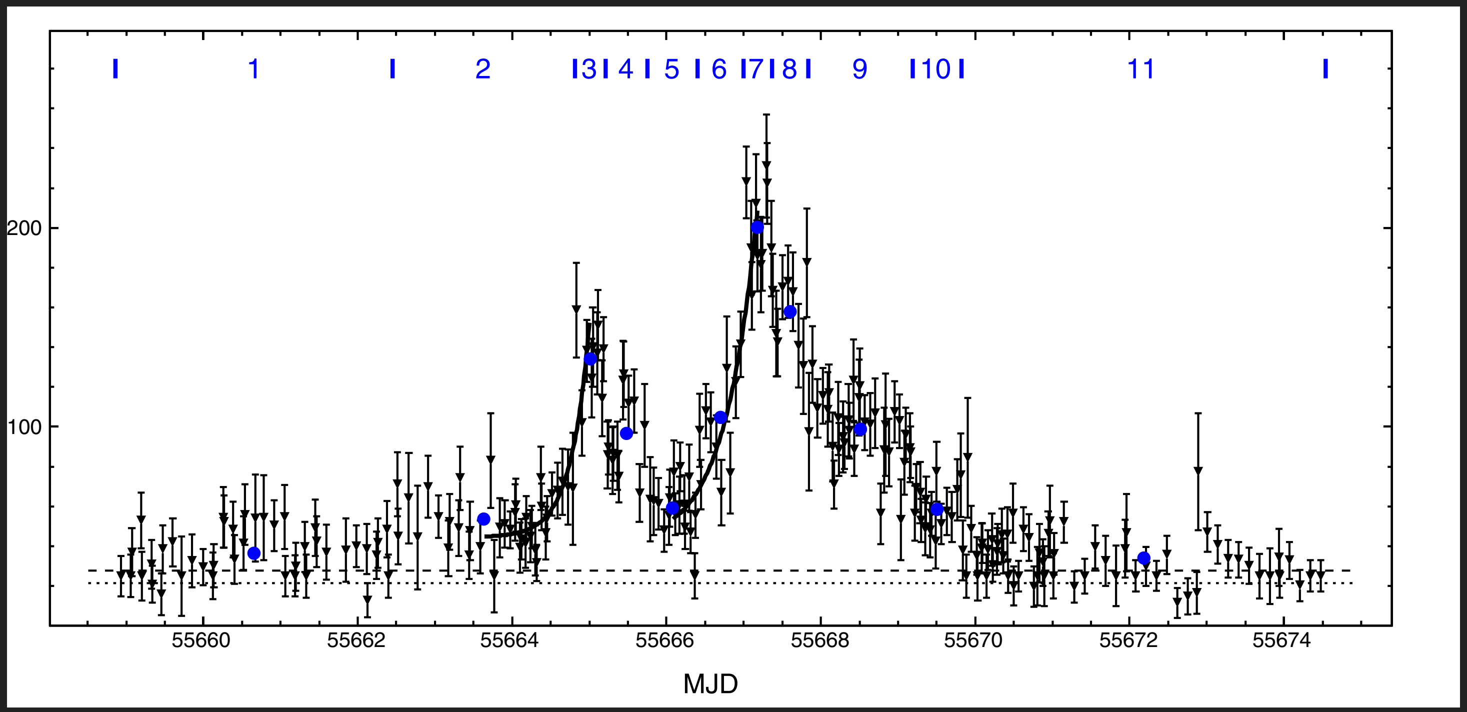
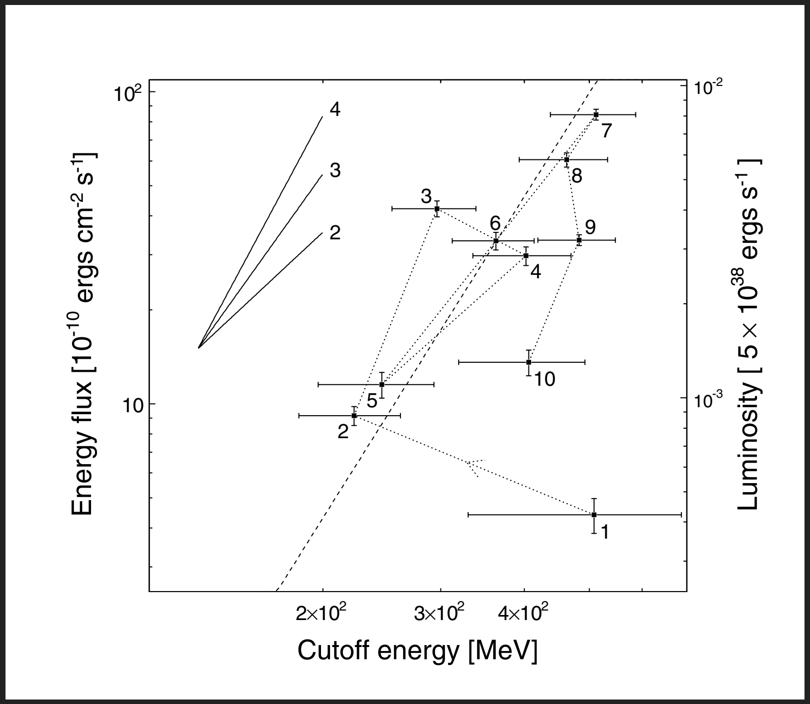
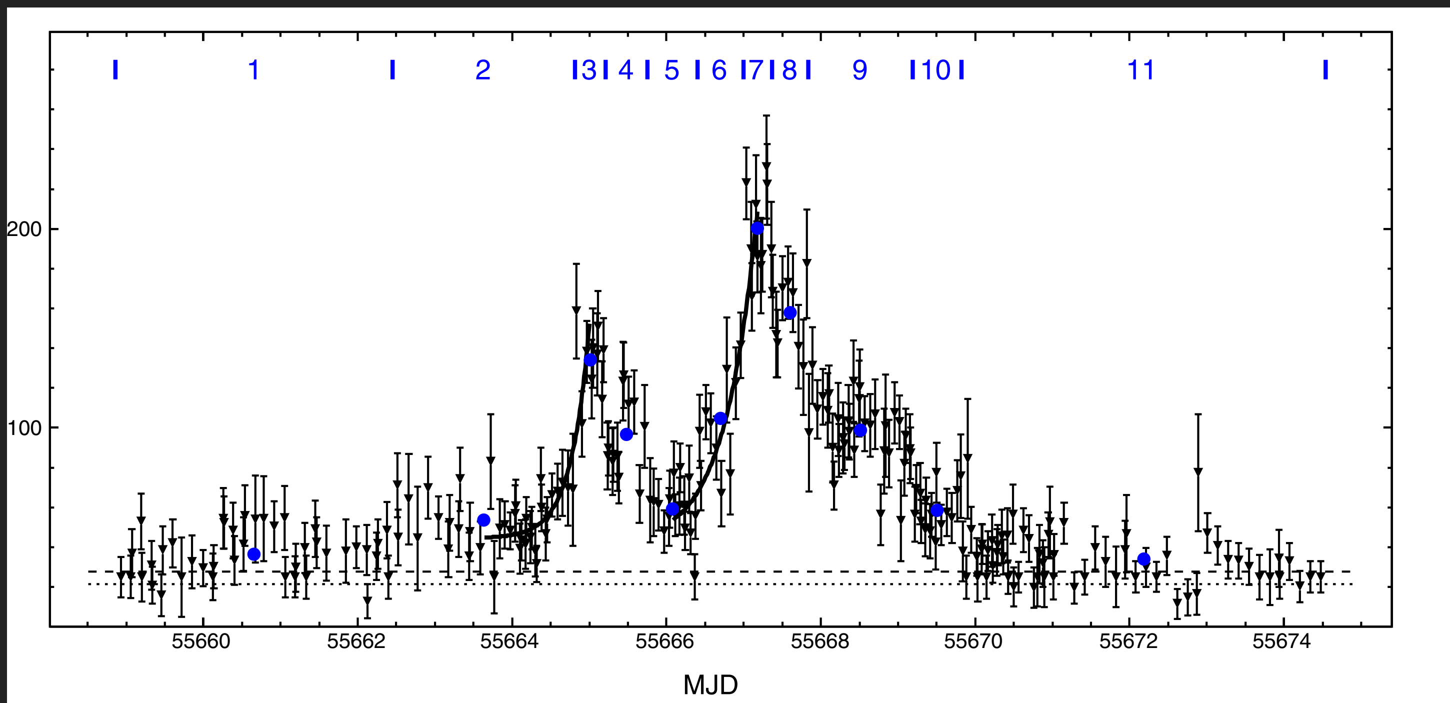
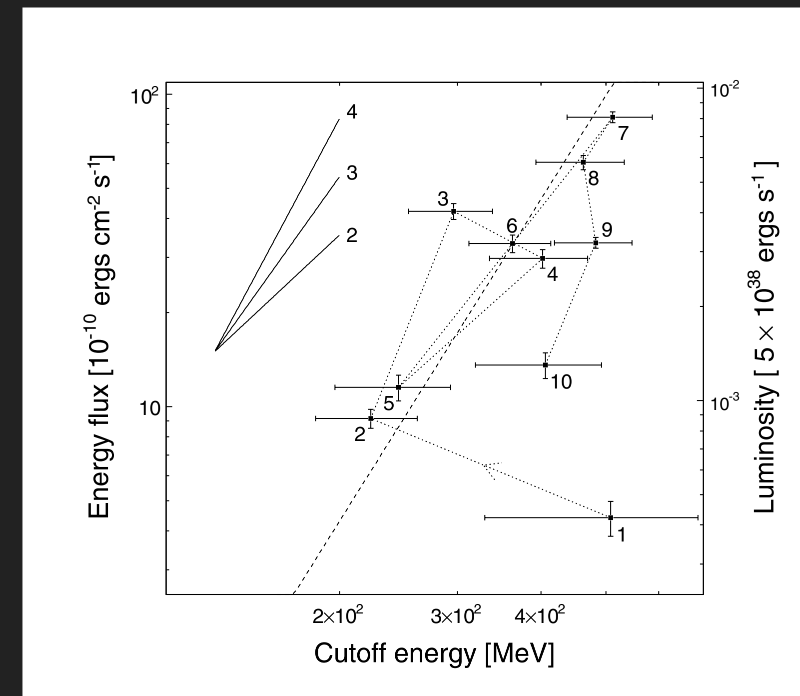




CUTOFF ENERGY IS HIGHER AT PEAK

SPECTRAL EVOLUTION



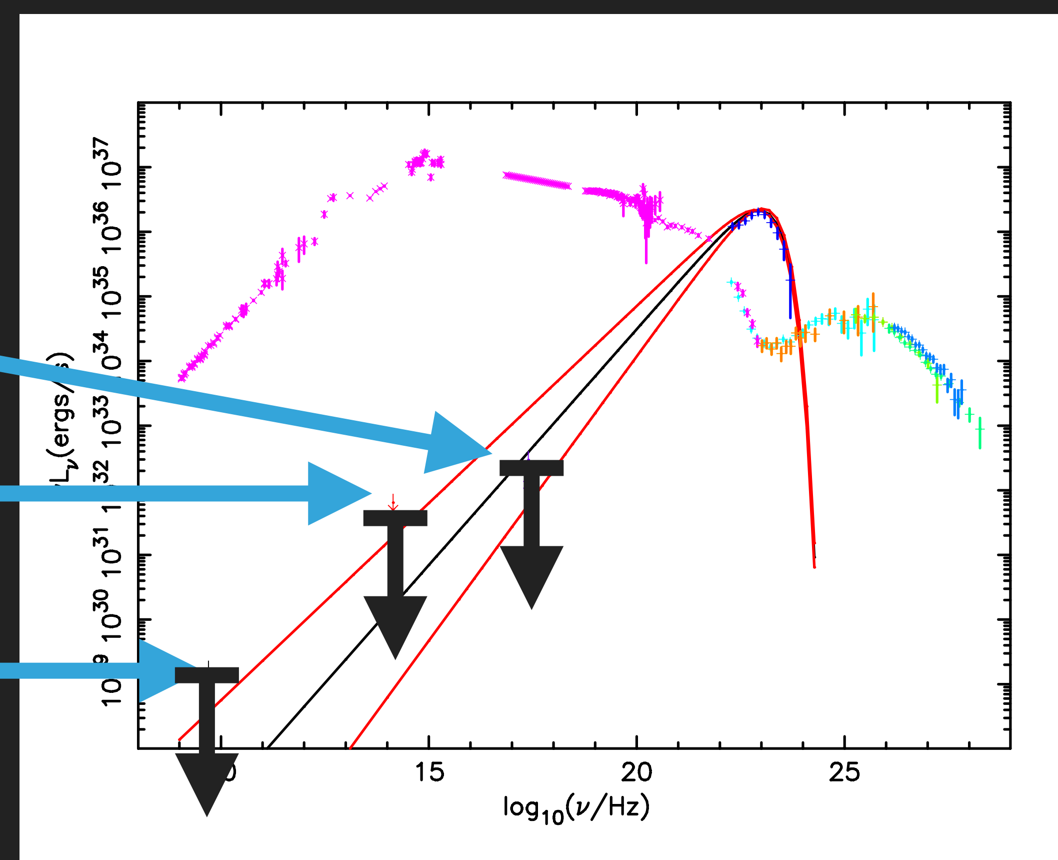


CUTOFF ENERGY IS HIGHER AT PEAK

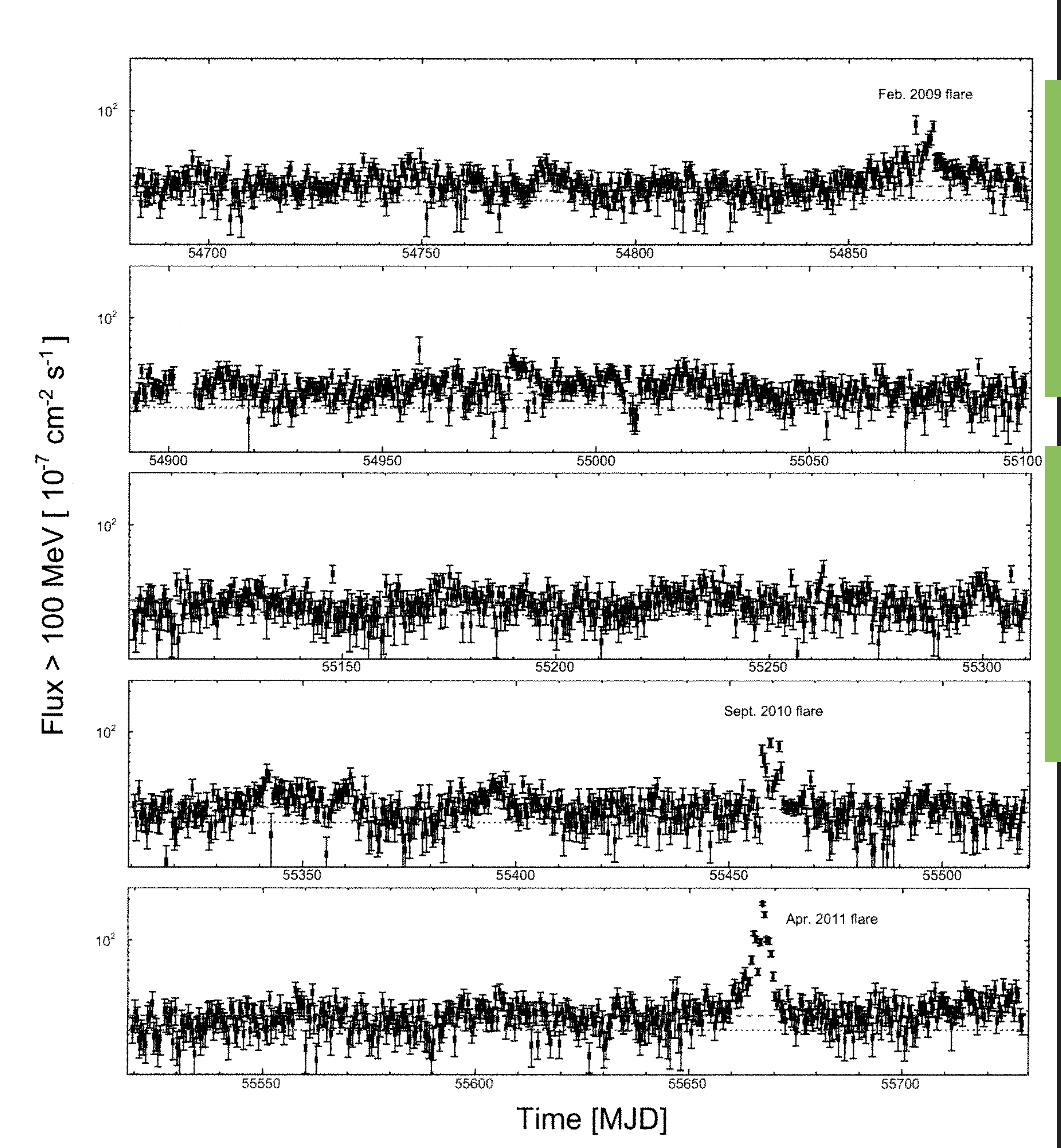
CHANDRA UPPER LIMIT

KNOT IR UPPER LIMIT

1GHZ VLA UPPER LIMIT



GAMMA-RAY VARIABILITY



VARIABILITY PRESENT ALSO FOR QUIESCENT EMISSION IN THE FORM OF MONTH-LONG MODULATION

LIKELY ORIGINATING IN THE VARIABILITY OF THE WISPS KNOT REGION

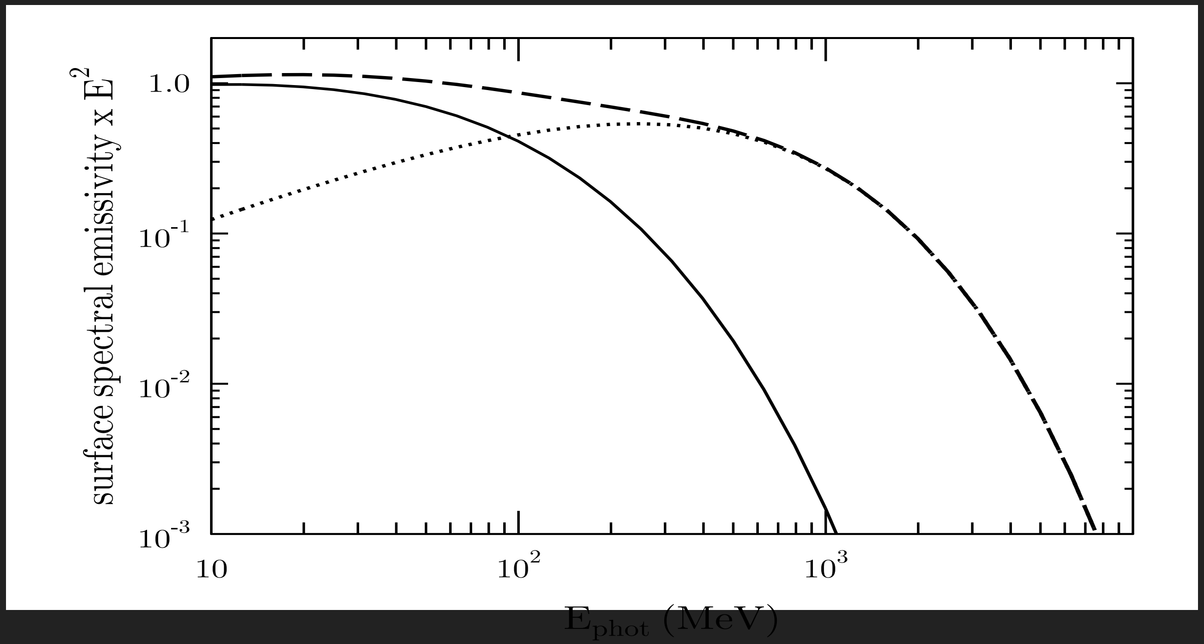
TWINKING

IMPOSSIBLE TO GET ACCELERATION AND EMISSION FROM THE SAME REGION IN A NAIVE DSA APPROACH

DECOUPLE EMISSION FROM ACCELERATION

INTRODUCE REGIONS OF VERY HIGH MAGNETIC FIELD THAT ARE RESPONSIBLE FOR RADIATION

FLARE PROPERTIES DEPENDS ON THE MAGNETIC FIELD IN THESE REGIONS



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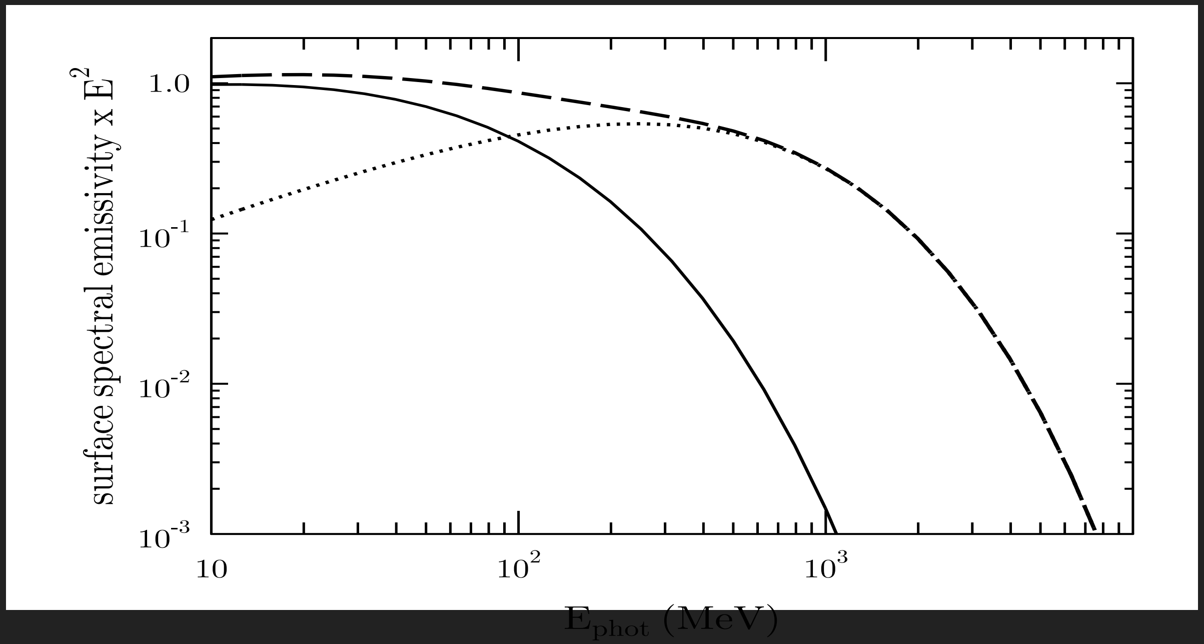
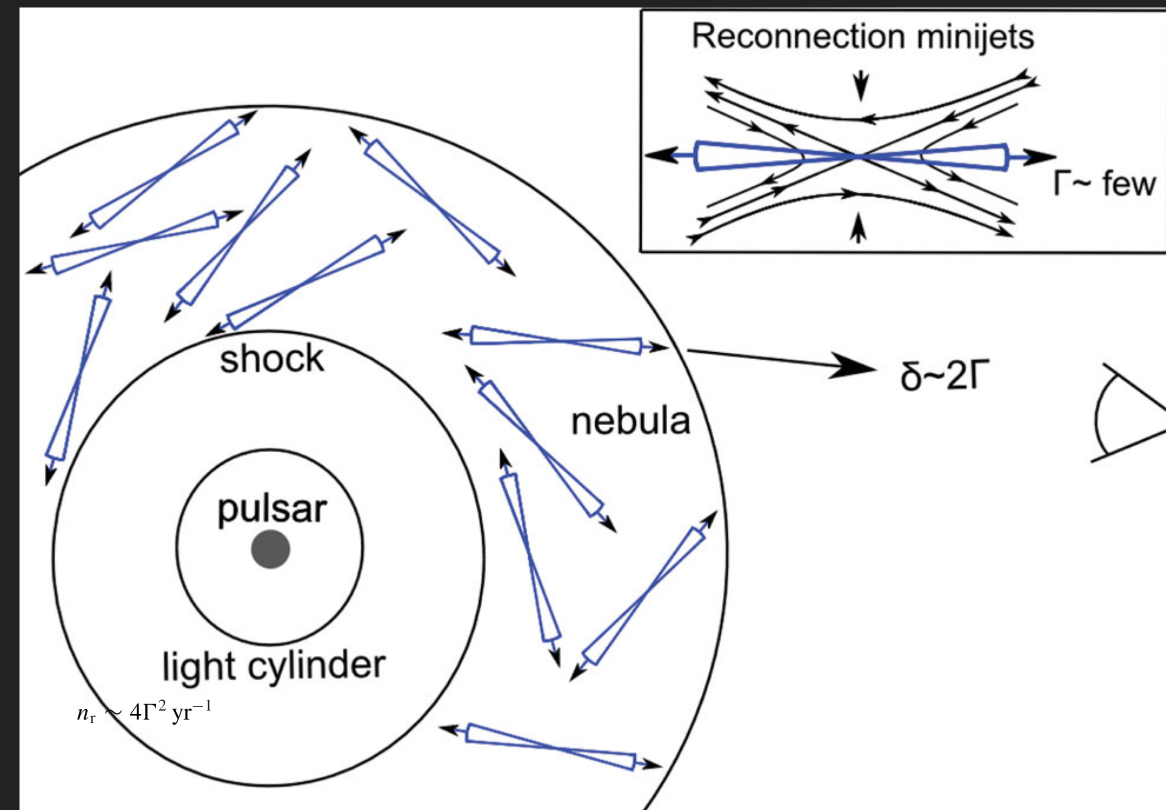


REQUIRE VERY LOCALISED REGIONS (FEW DAY LIGHT) WITH MAGNETIC FIELD UP TO MILLI-G

REQUIRE EMISSION TO COME TO REGIONS VERY CLOSE TO THE TS

JETLETS

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



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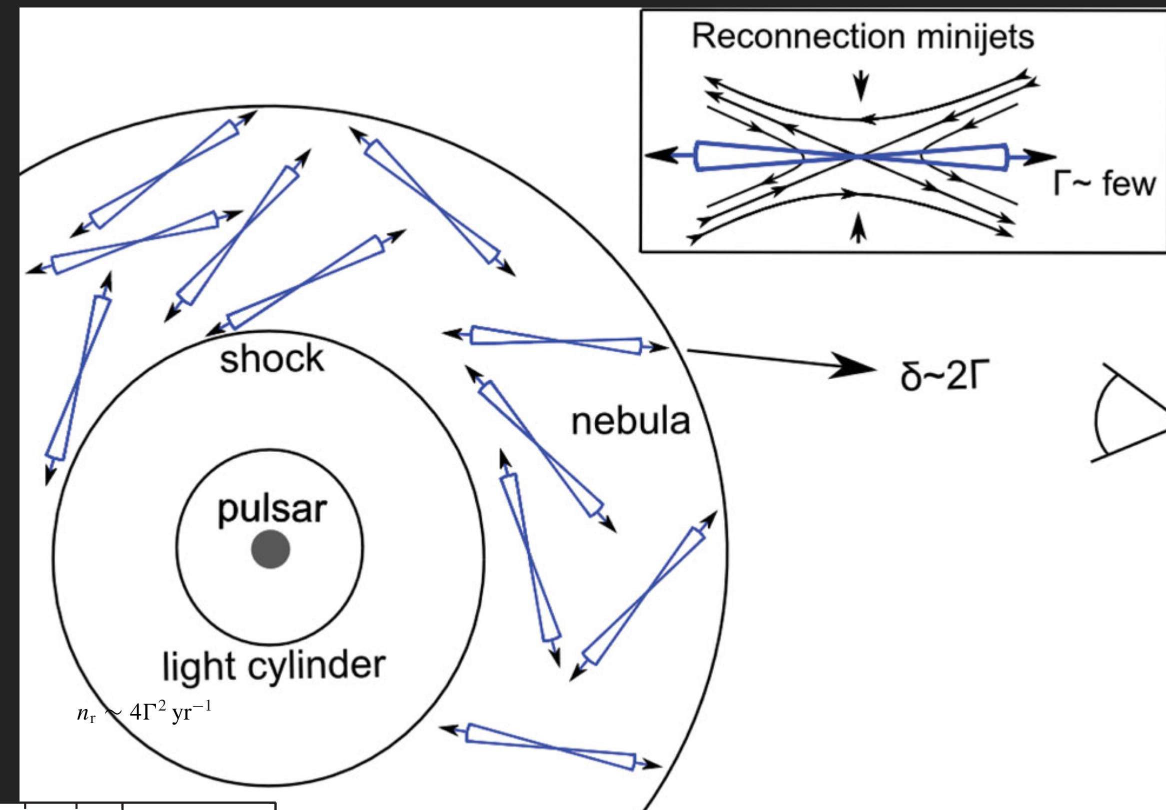
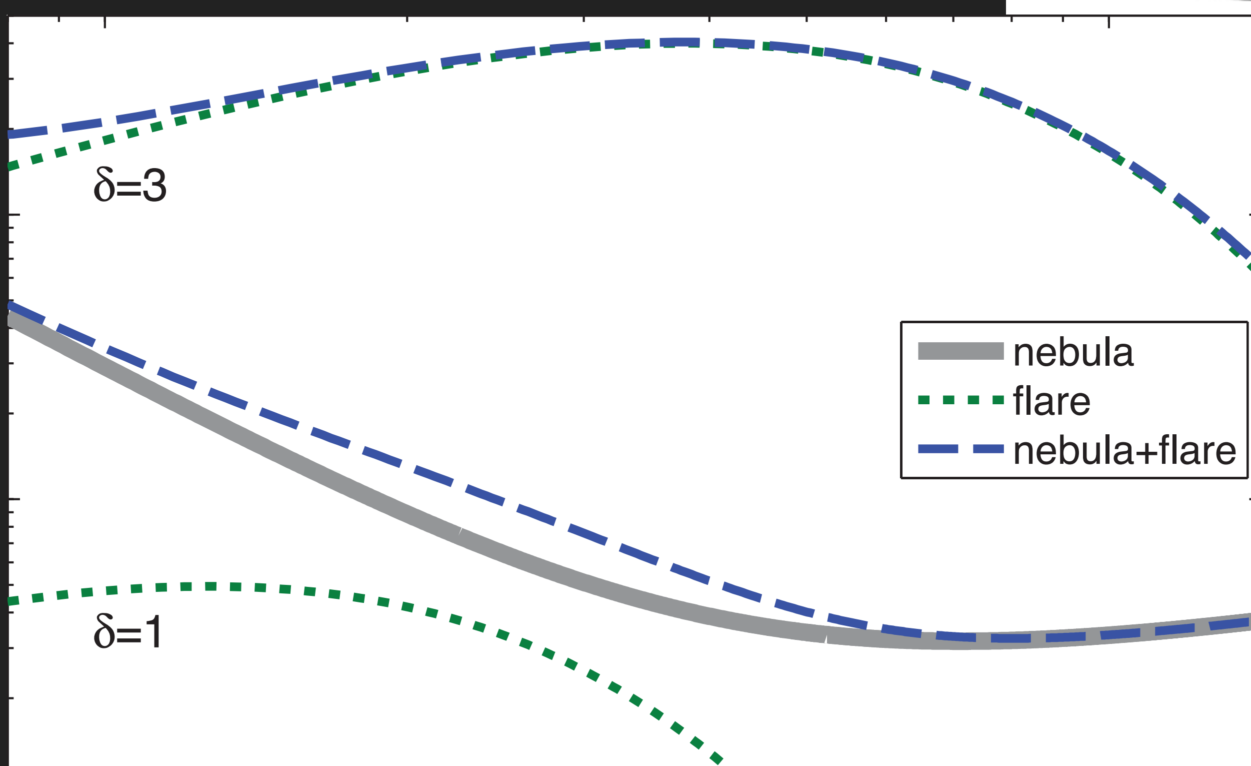


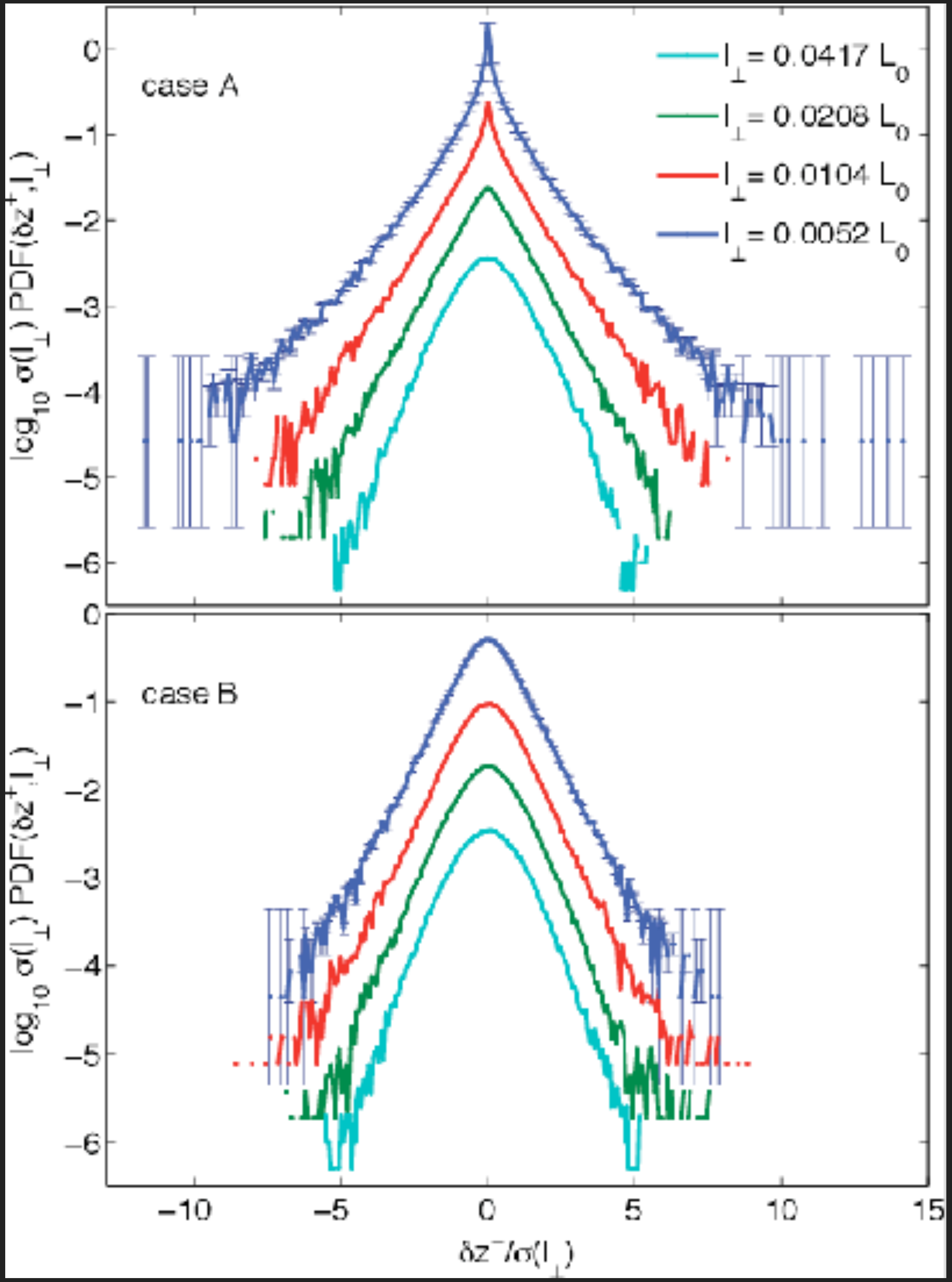


$$n_{\rm r} \sim 4\Gamma^2\,{\rm yr}^{-1}$$

BOOSTING OF ORDER 3 ARE REQUIRED

INTERMITTENCY

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



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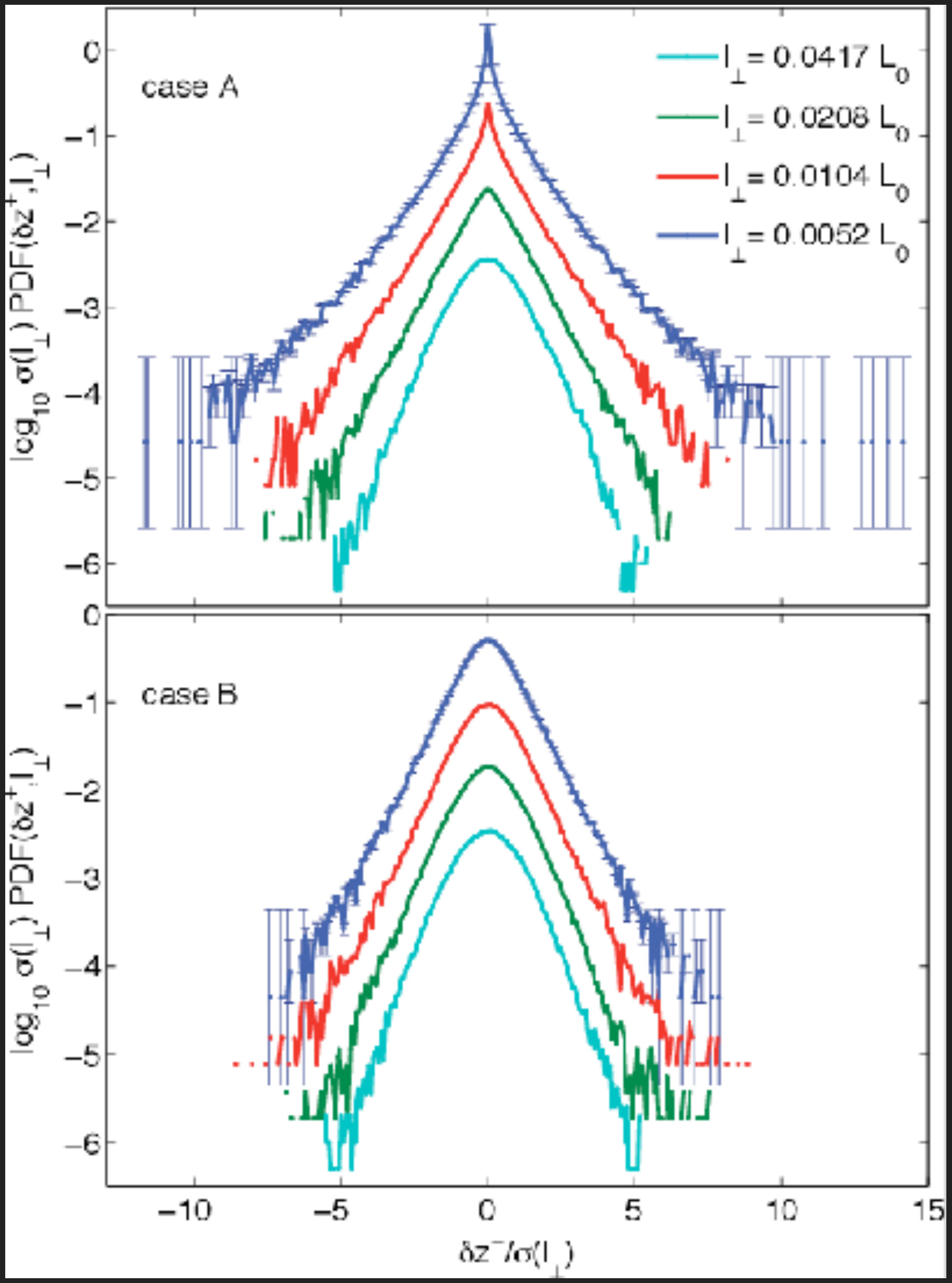

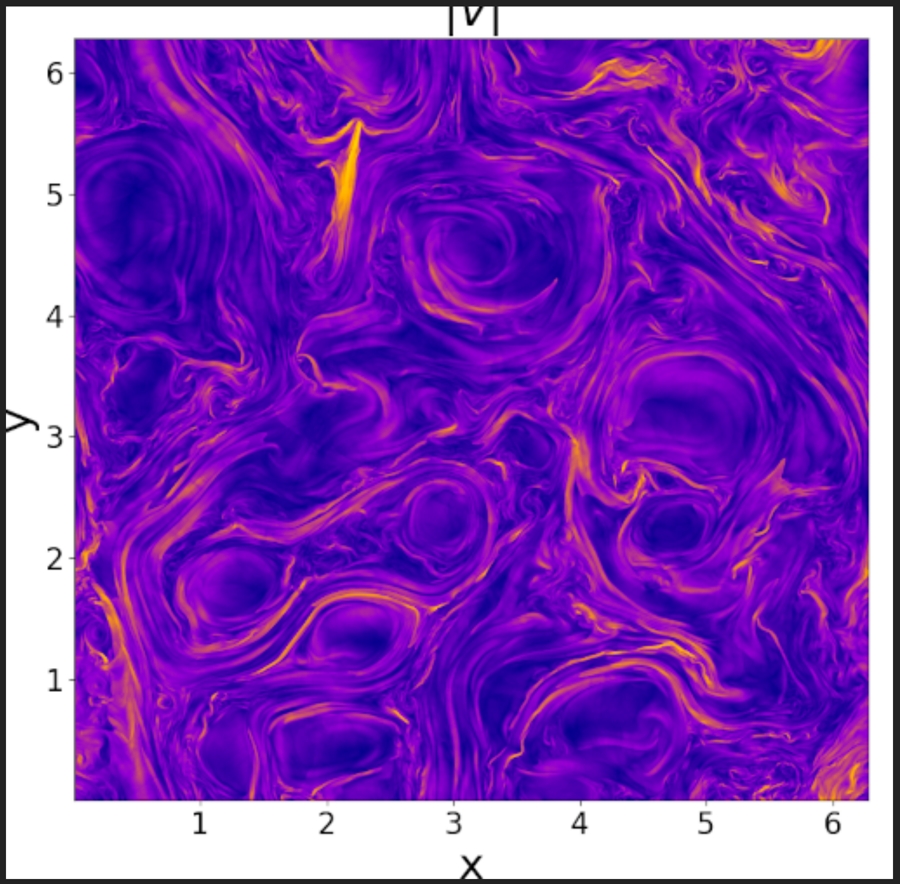

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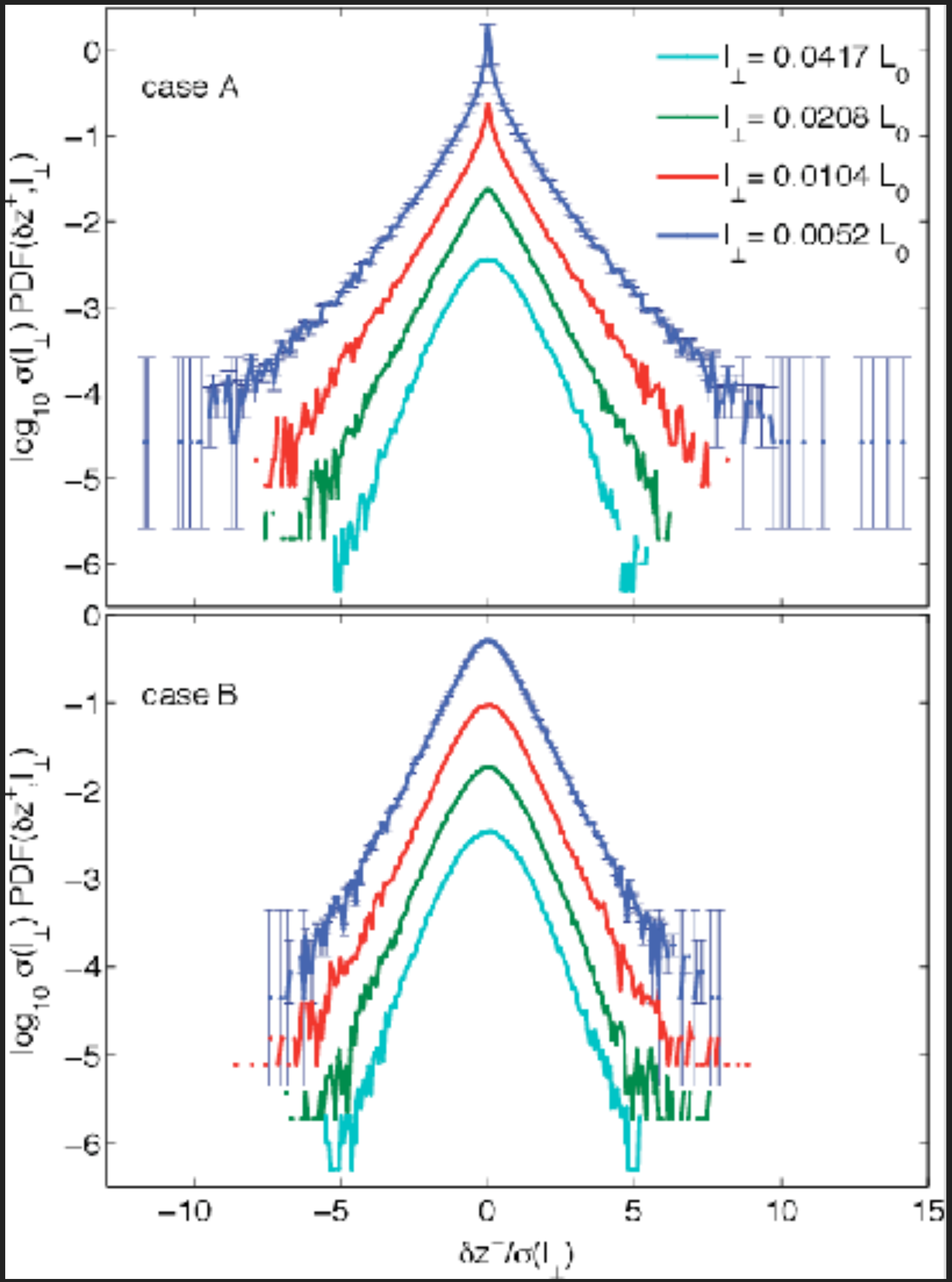

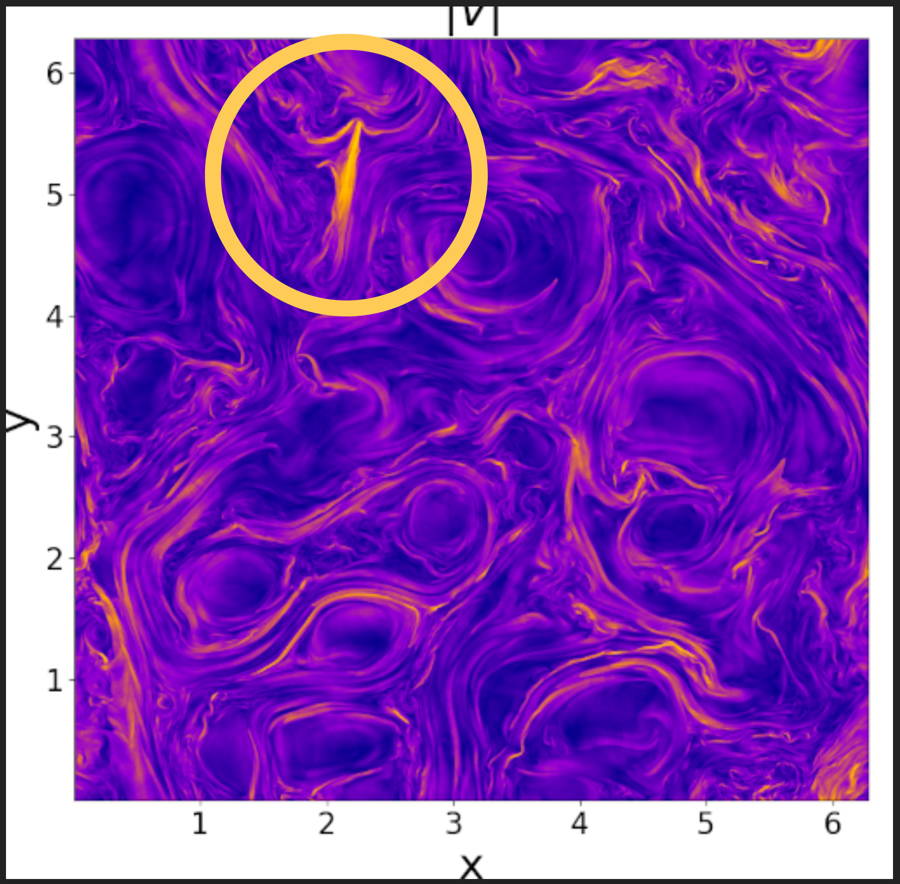

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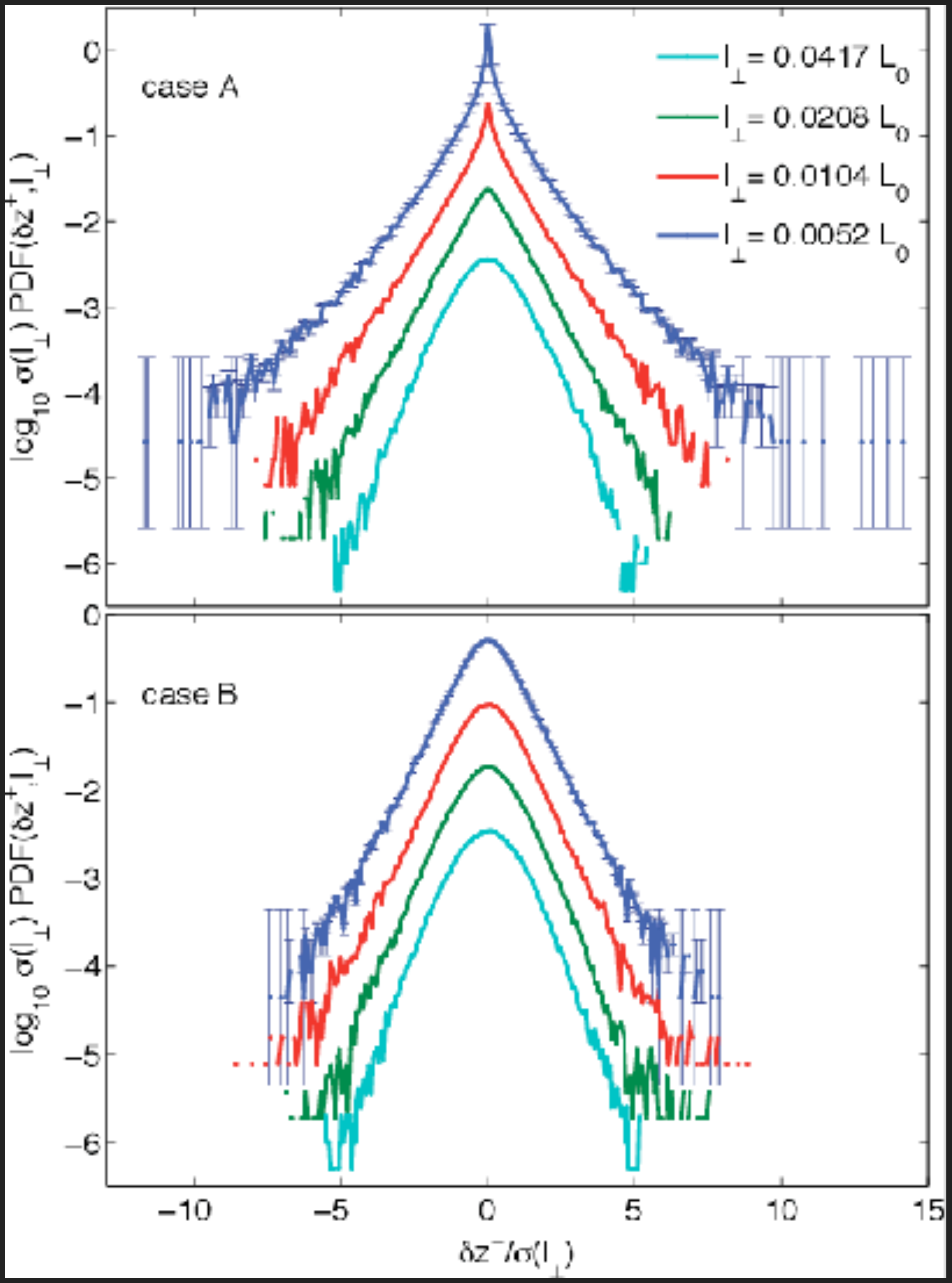
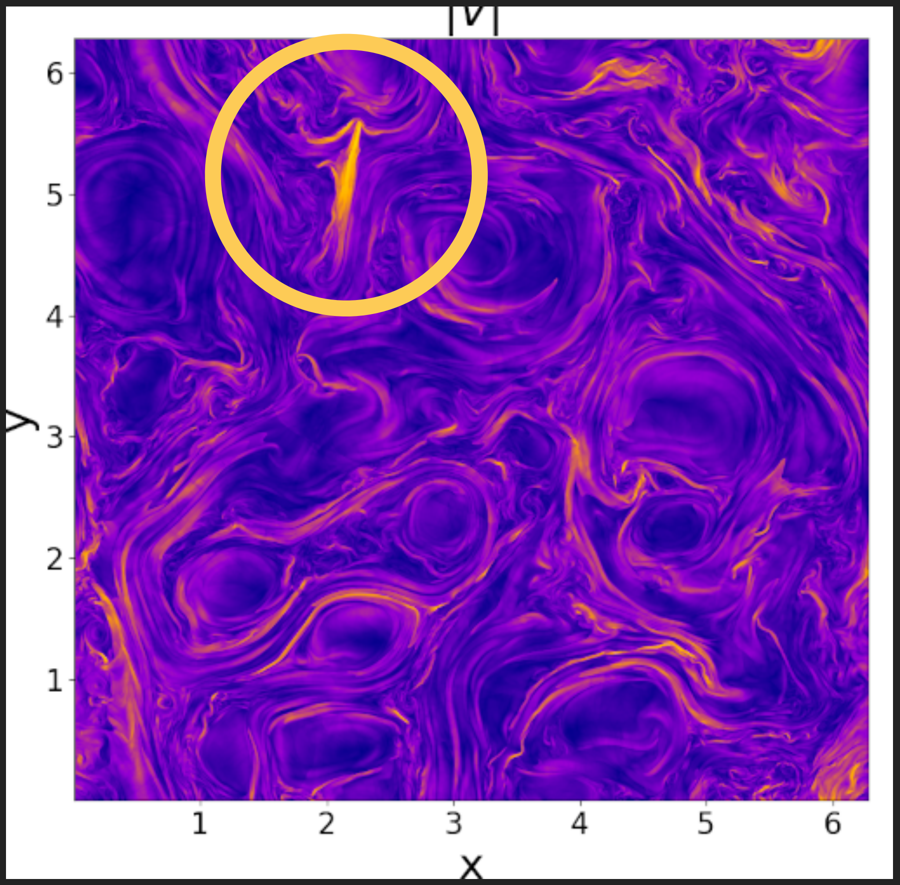
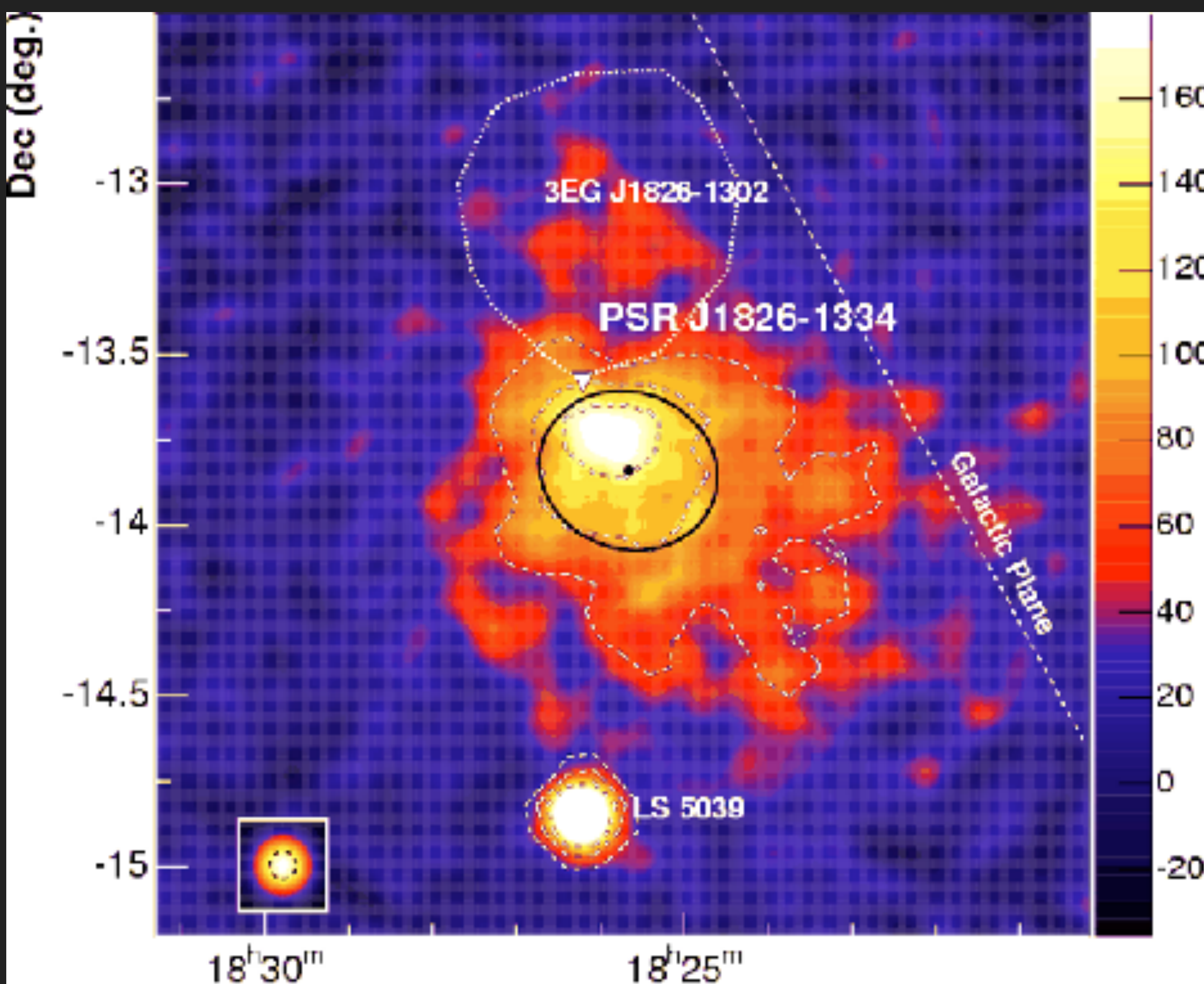




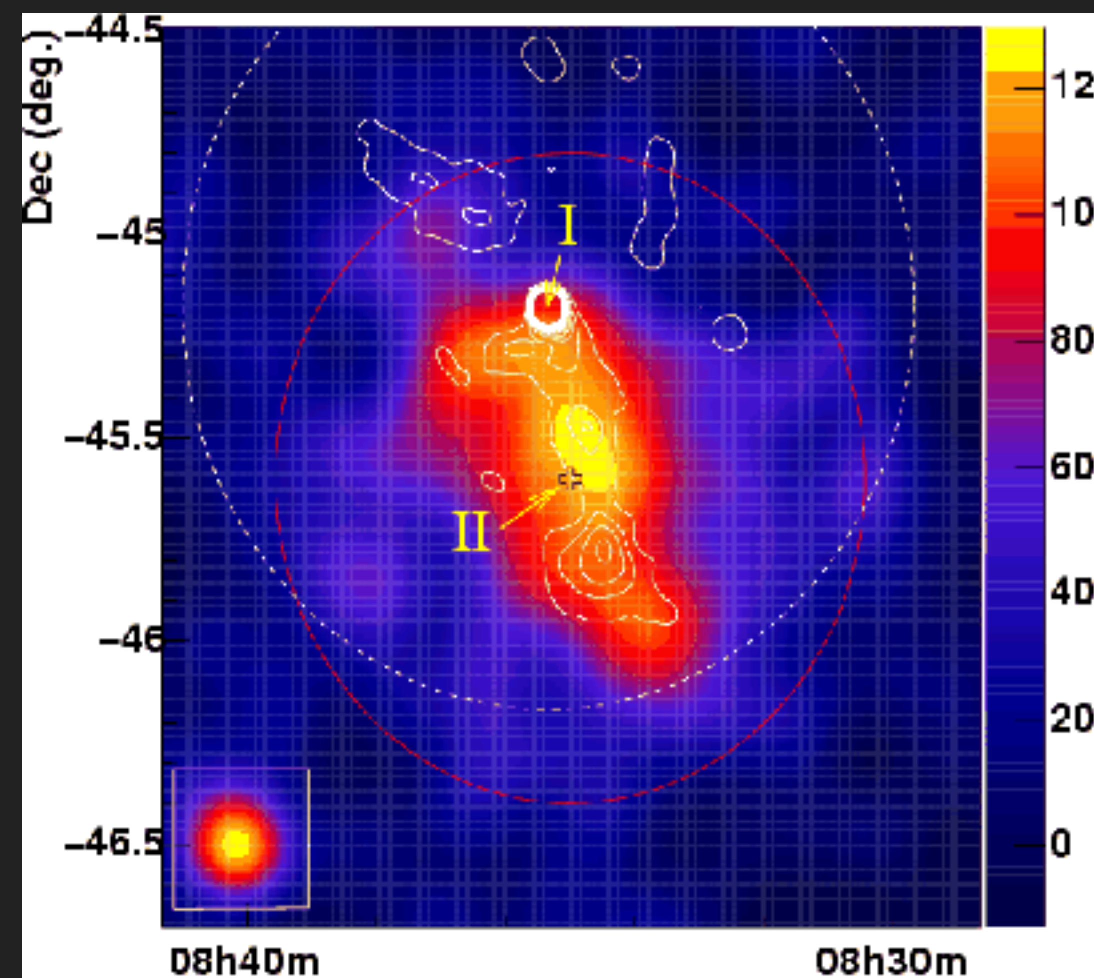
NOT CLEAR IF STATISTICS OF INTERMITTENCY COMPATIBLE WITH MILL-G FIELD

OLD SYSTEMS

OLDER SYSTEMS SHOW A DISPLACEMENT OF THE TEV GAMMA EMISSION FROM THE PULSAR: REVERBERATION, BOW-SHOCK



J1825-137 (HESS; Aharonian et al. 2005)

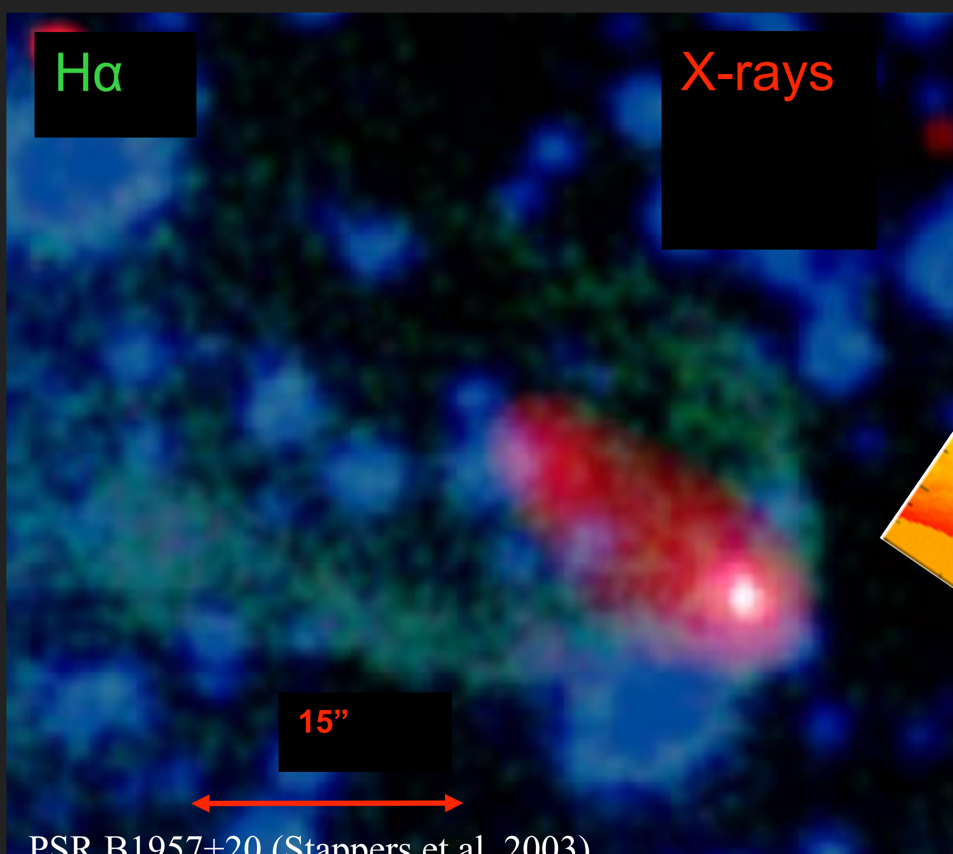


Vela (HESS; Aharonian et al. 2005)

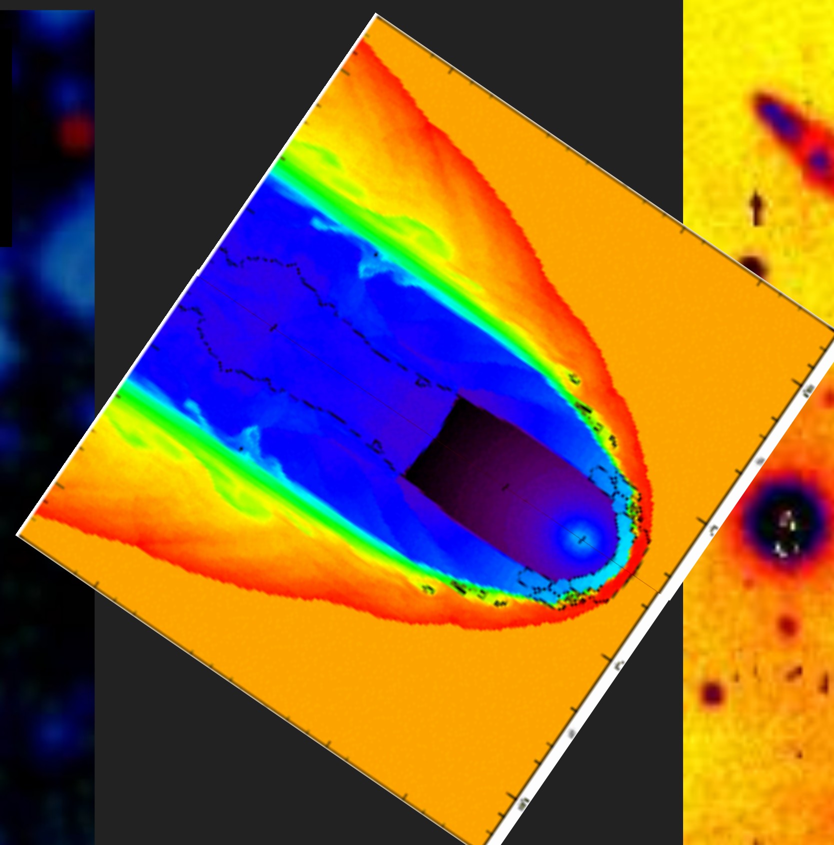
BOW SHOCK PWNE

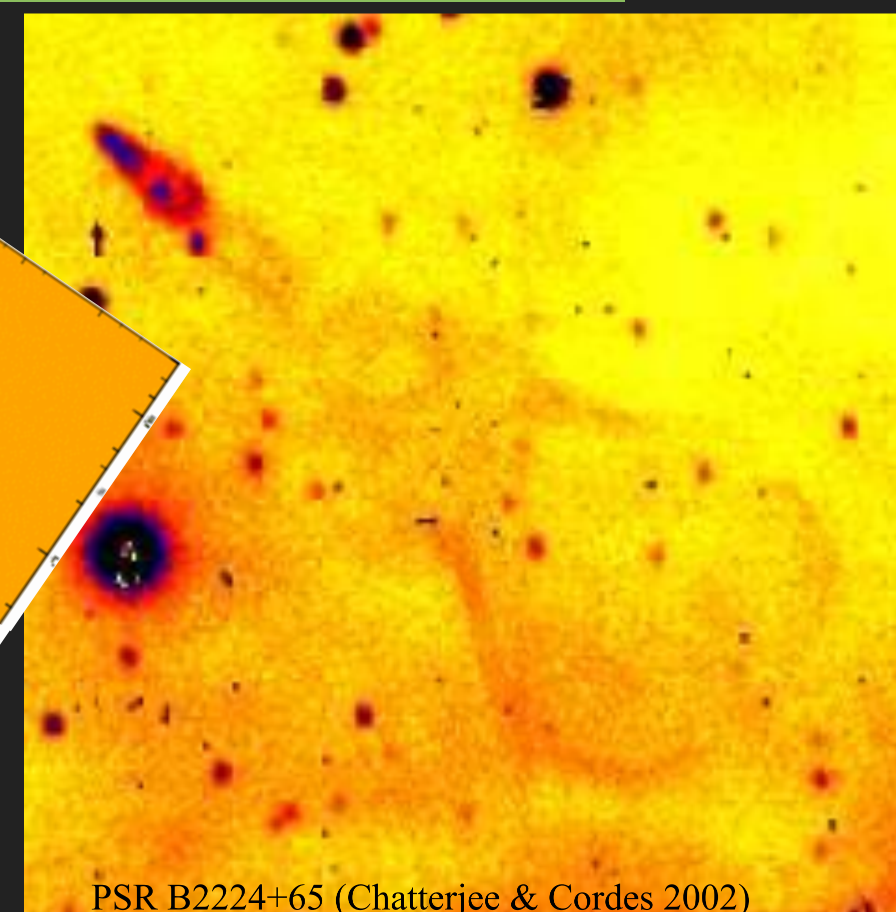
MOST PULSARS KICK VELOCITY IS SUPERSONIC IN ISM

FORWARD SHOCK VISIBLE IN HA
PWN VISIBLE AS A RADIO AND X-RAYS TAIL



PSR B1957+20 (Stappers et al. 2003)

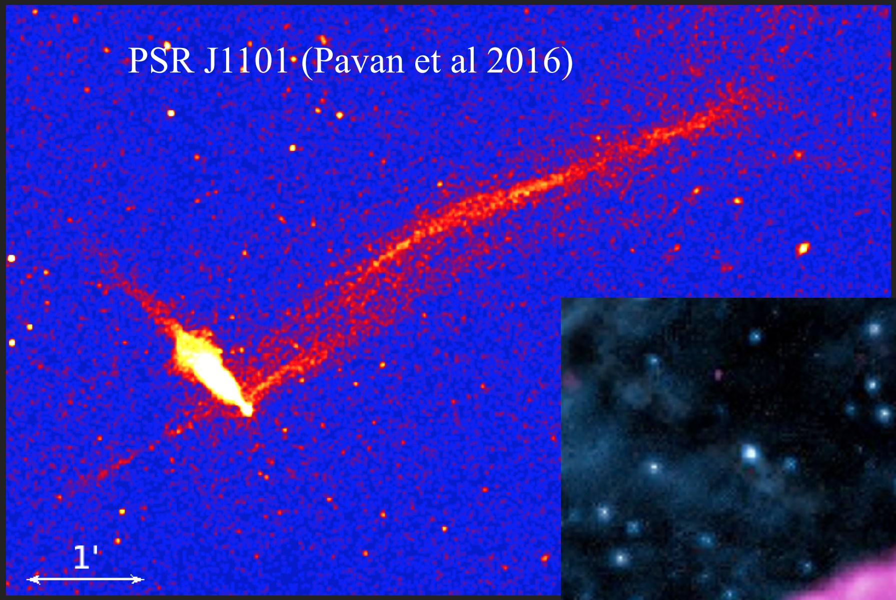



PSR B2224+65 (Chatterjee & Cordes 2002)

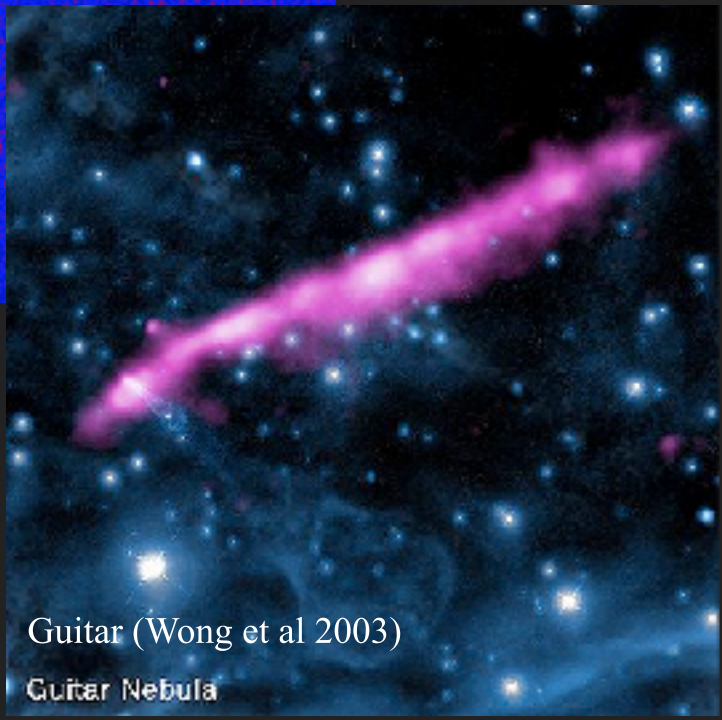
PAIR ESCAPE

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

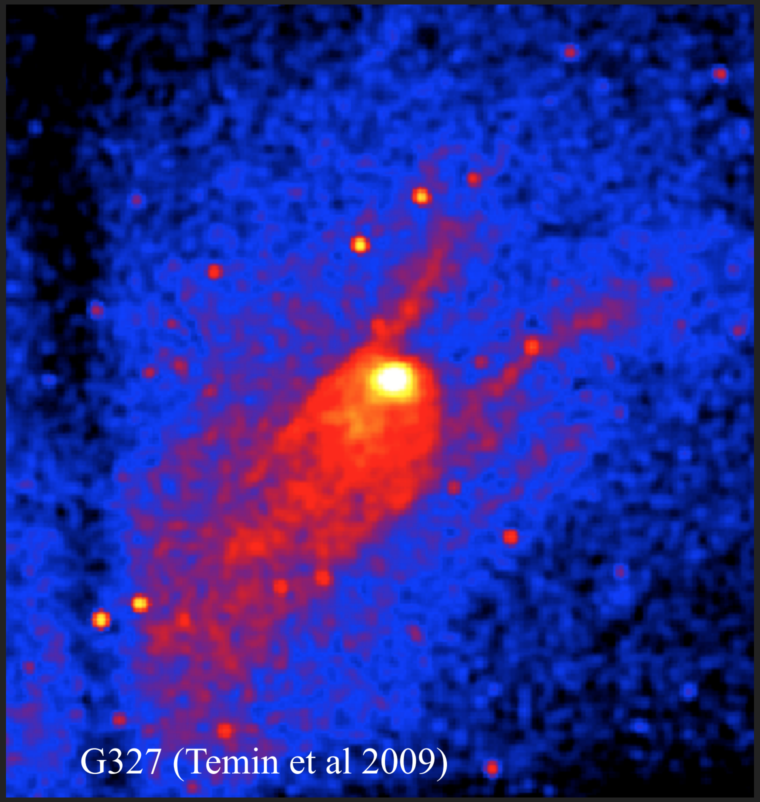
The particles in these features are ~ PSR voltage

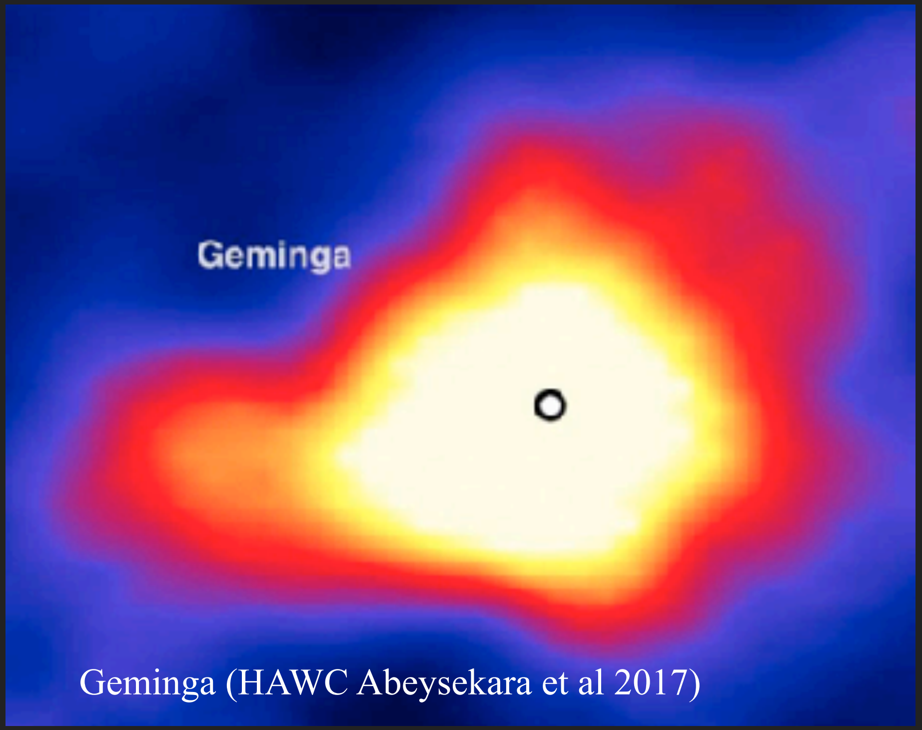


PSR J1101 (Pavan et al 2016)



Guitar (Wong et al 2003)

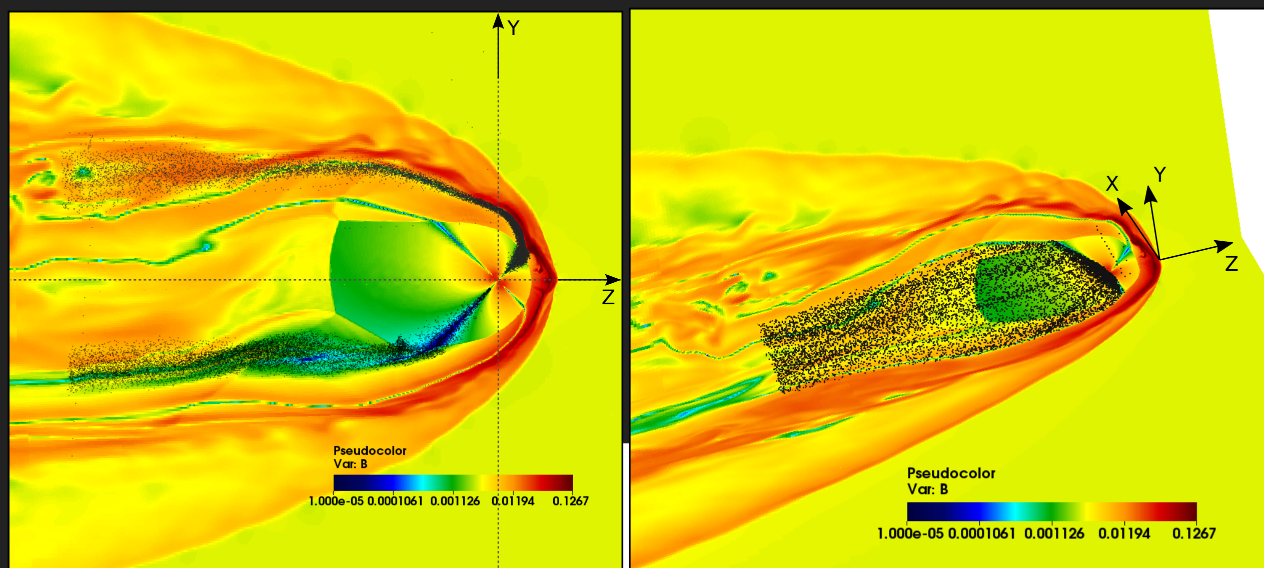

G327 (Temin et al 2009)



Geminga (HAWC Abeysekara et al 2017)

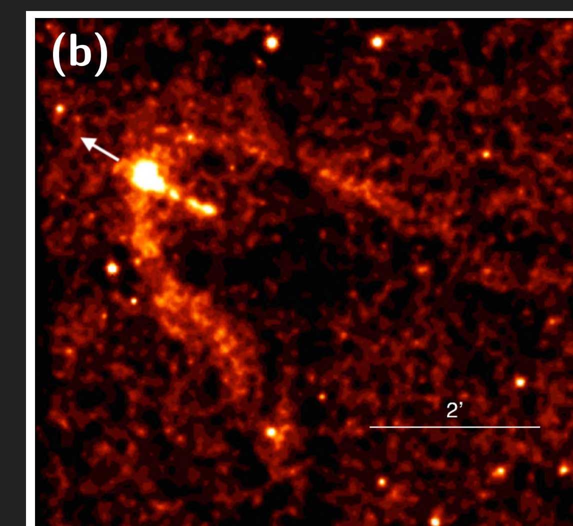
TeV halo suggest strong diffusion

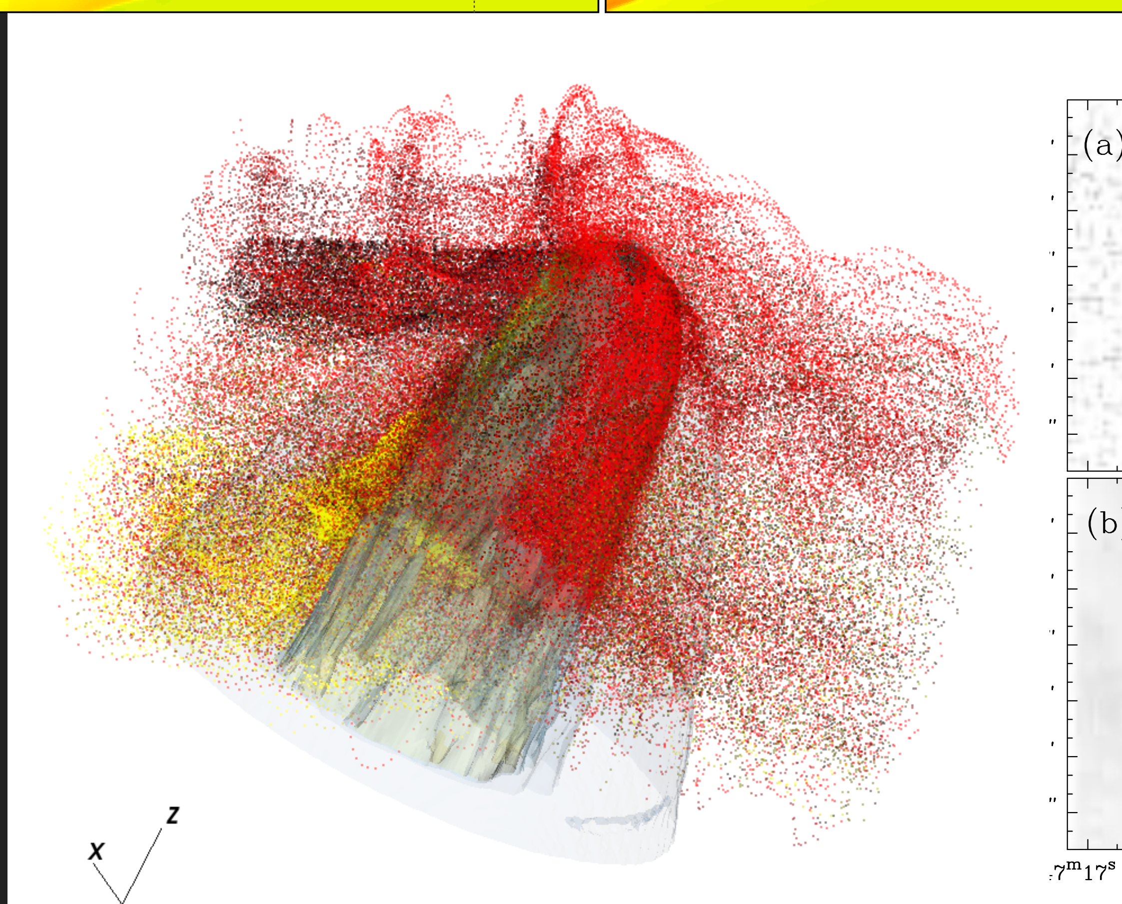
PAIR ESCAPE IN MHD MODELS

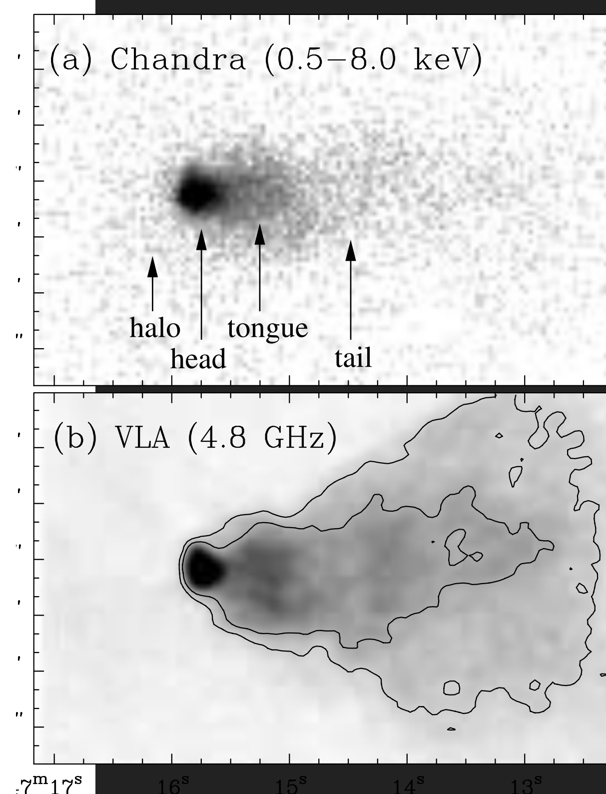


LOW ENERGY PARTICLES REMAIN CONFINED IN CURRENTS

GEMINGA HARD TAILS



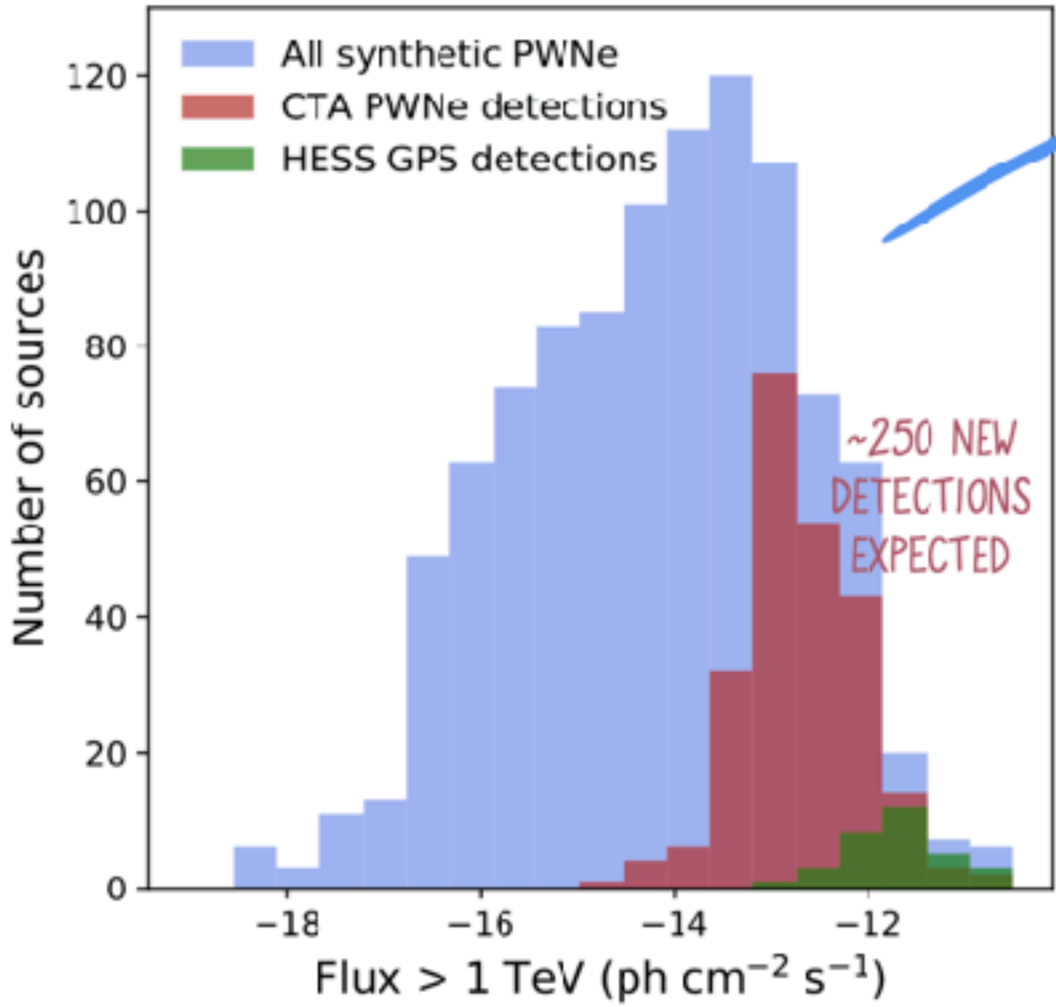


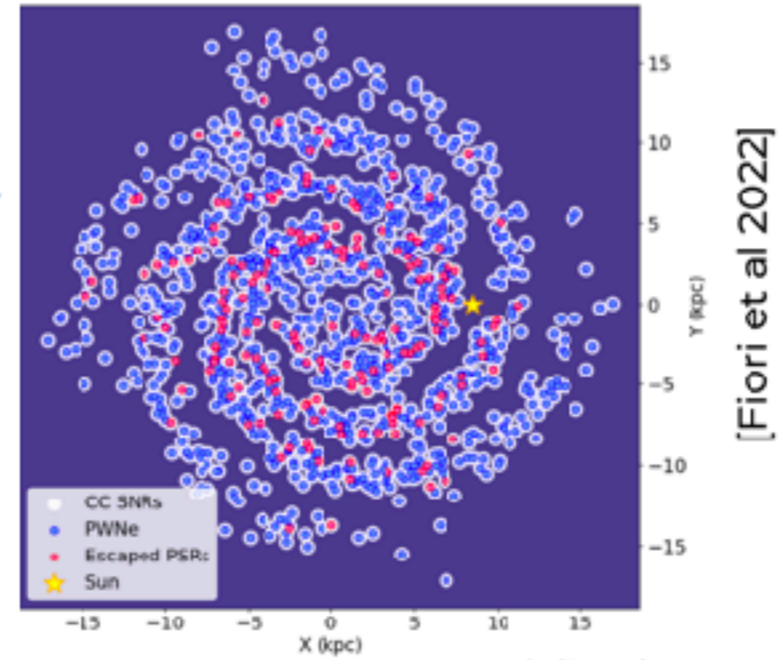


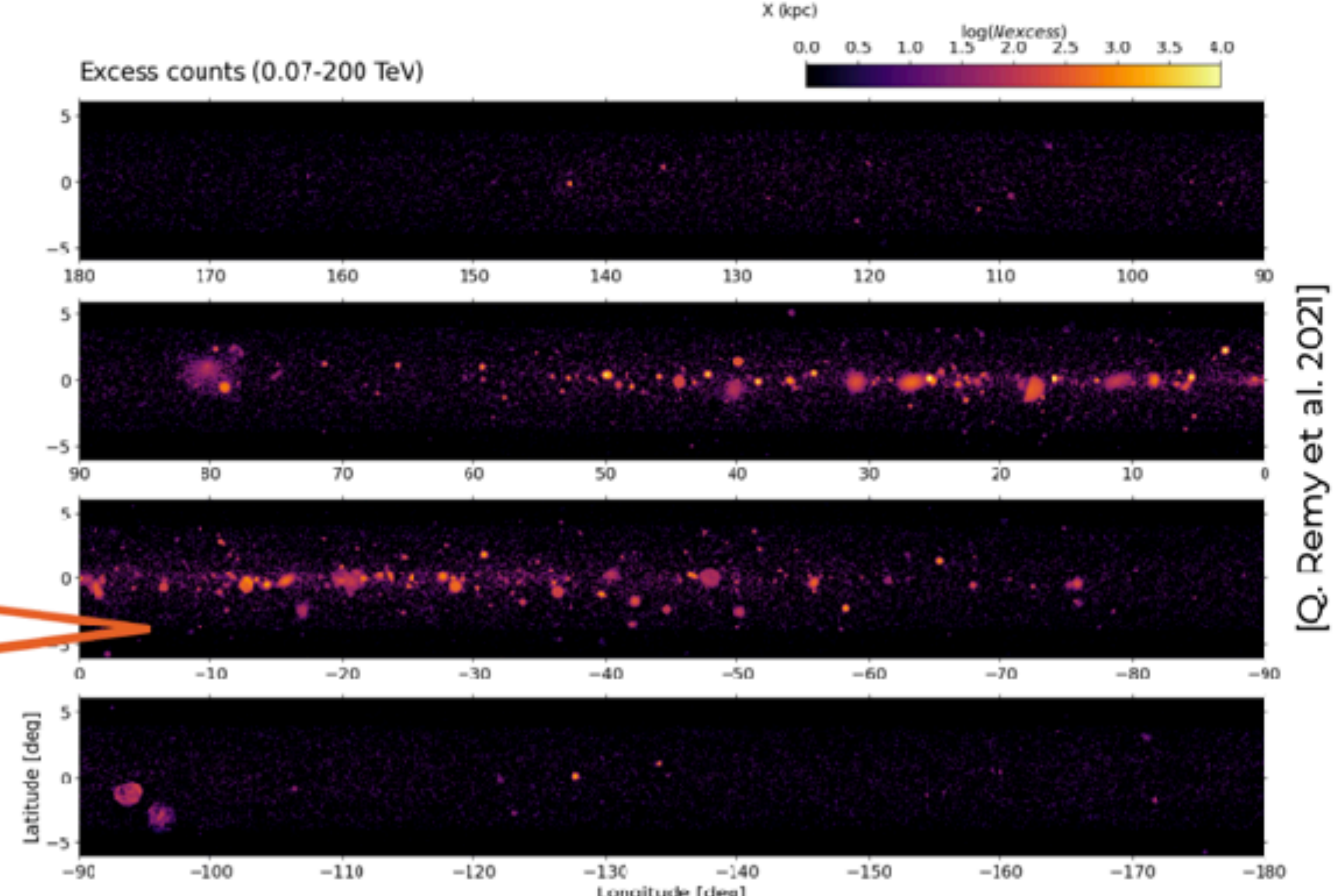
VERY HIGH ENERGY PARTICLES CAN ALSO DIFFUSE AHEAD

MAUSE
X-RAY HALO

EXPECTED DETECTION WITH CTA





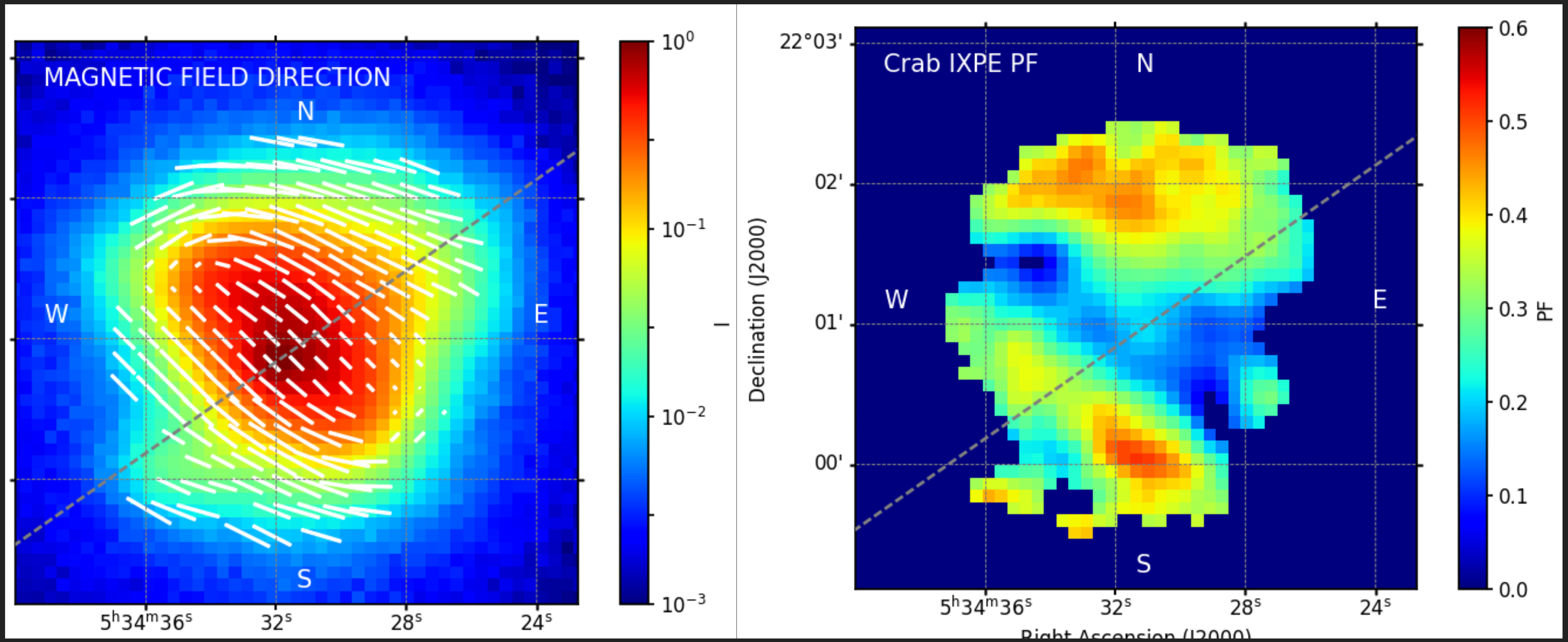


PWNE ~ 60%
SNRS ~ 10%

[CTA GPS consortium paper, in prep.]

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

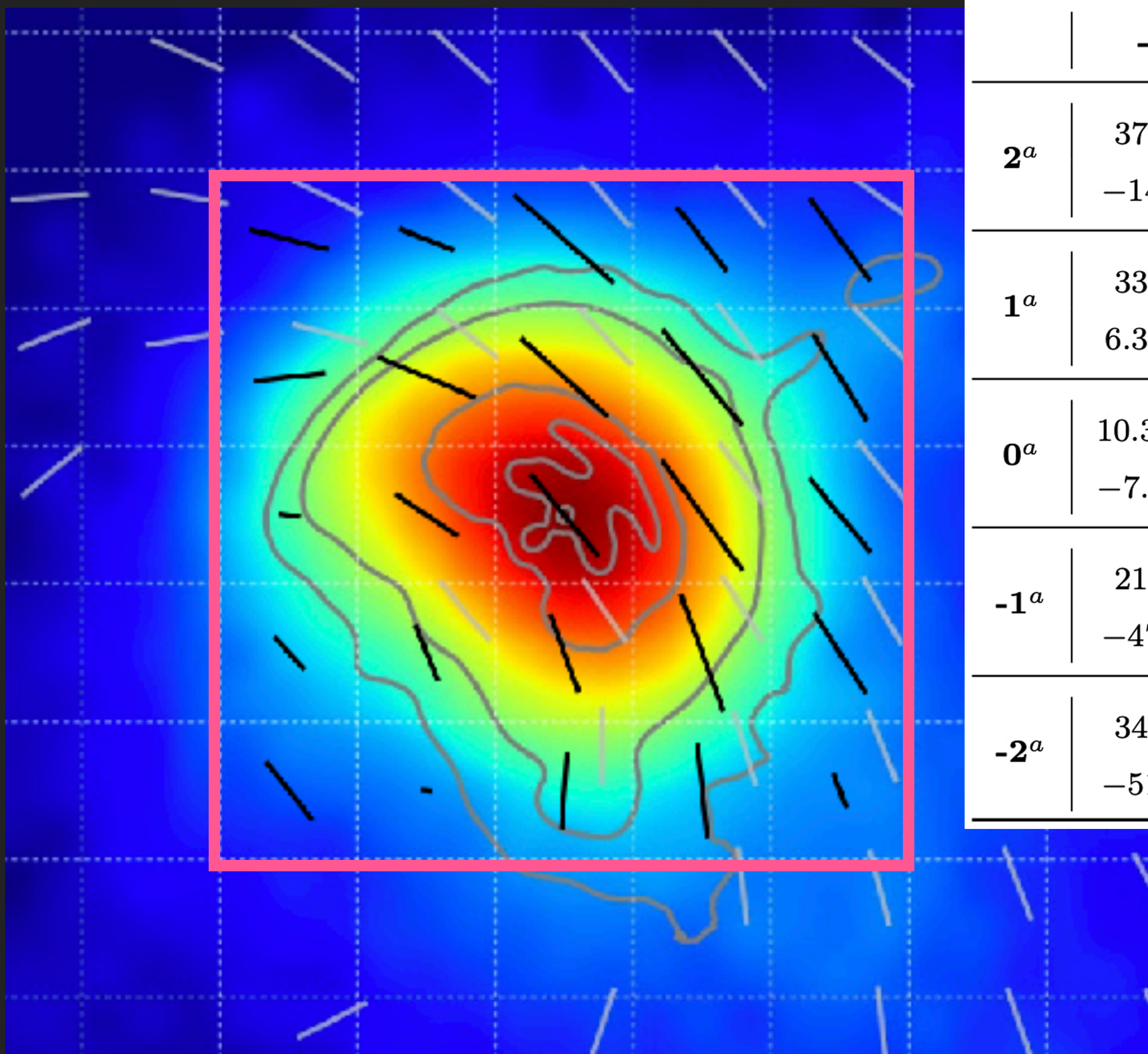
Local high level of polarisation in outer regions

Nebular Axis not consistent with PSR axis

Turbulence likely very patchy inside the PWN

IXPE - X-RAY POLARIMETRY - VELA

Fei et al 2023



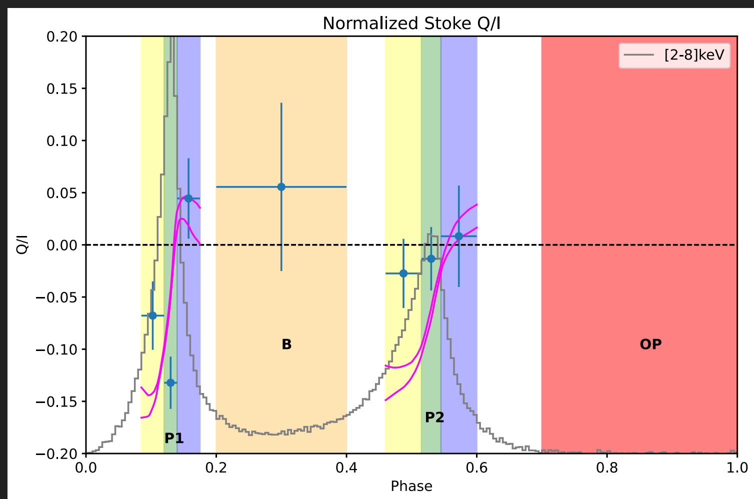
	-2[b]	-1[b]	0[b]	1[b]	2[b]	
2[a]	37±18	27±13	61±12	37±13	47±15	PD[c]
	−14±14	−21±14	−41.7±5.3	−52±10	−53.8±8.9	PA[d]
1[a]	33±10	48.5±5.0	53.5±4.1	56.8±7.1	47±13	PD[c]
	6.3±9.0	−22.4±3.0	−42.2±2.2	−50.2±3.6	−58.2±7.7	PA[d]
0[a]	10.3±8.8	34.4±3.9	49.0±2.5	62.8±4.0	44±11	PD[c]
	−7.4±24	−34.3±3.3	−50.3±1.5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

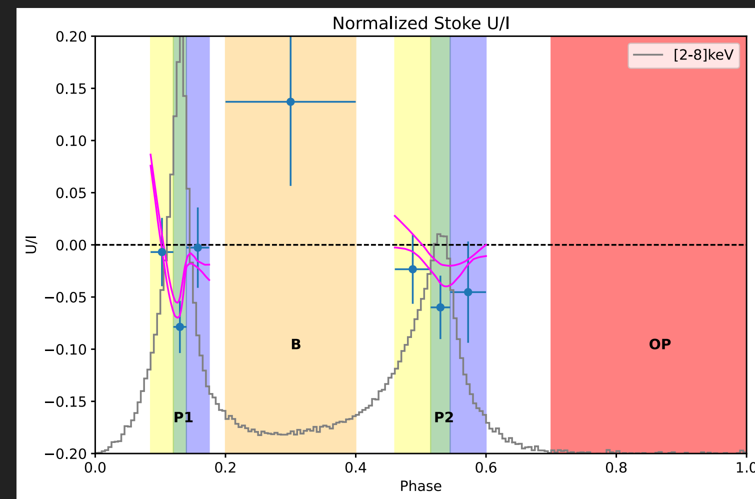
Very high PF suggest no turbulence in the PWNe

Unlikely reconnection to play a major role in accelerating particles

Old sytems should be more turbulent.

IXPE – X-RAY POLARIMETRY – CRAB PSR



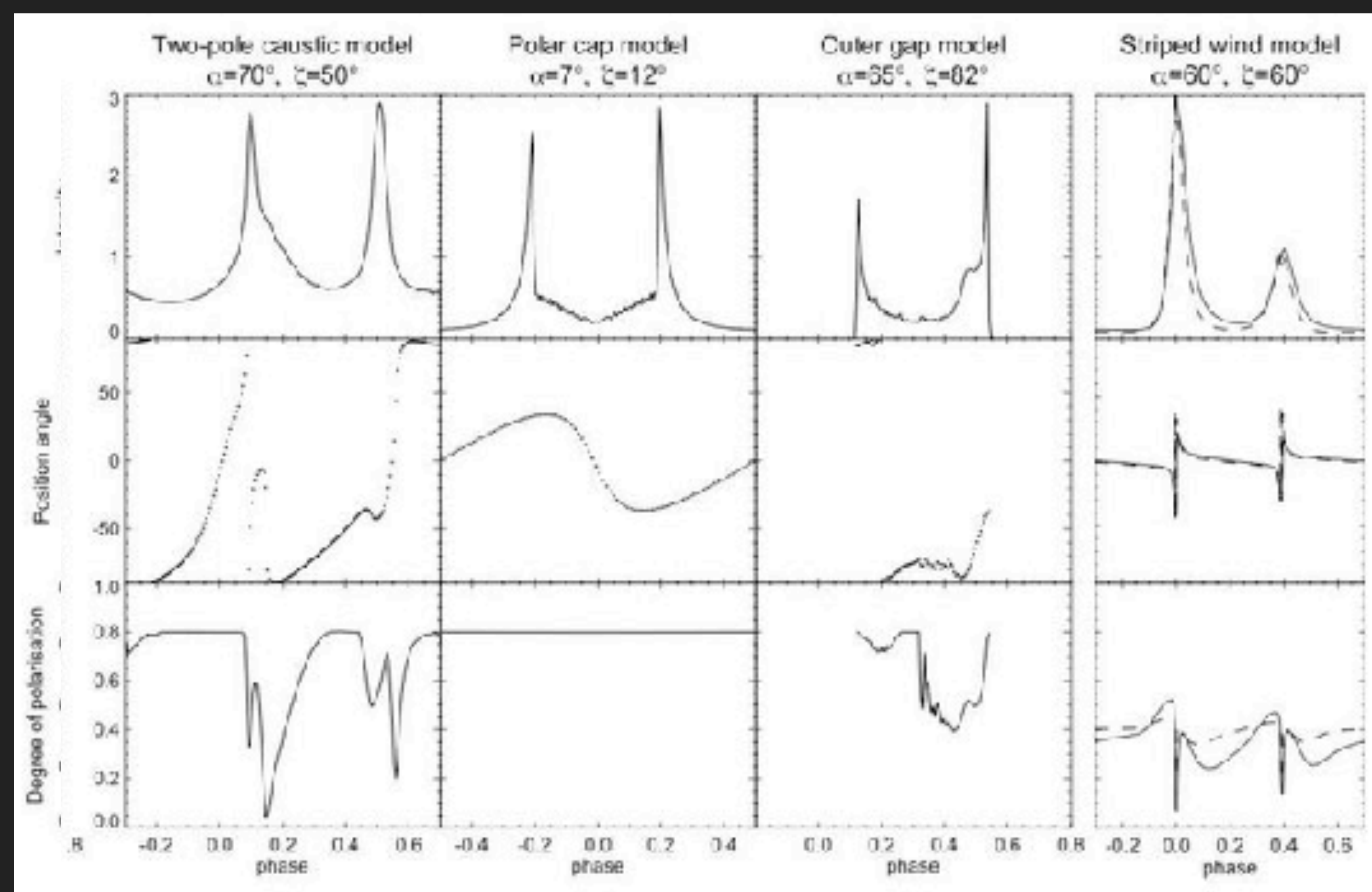


5- sigma detection in the core of P1

15% PF in the core of P1

Bucciantini et al 2023

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



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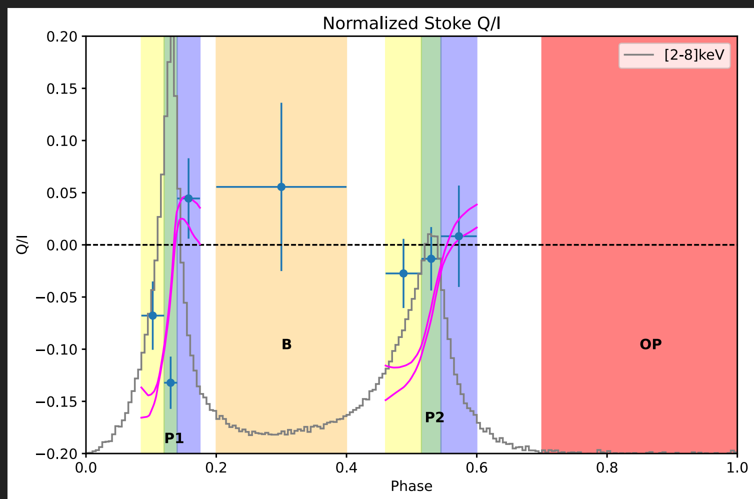

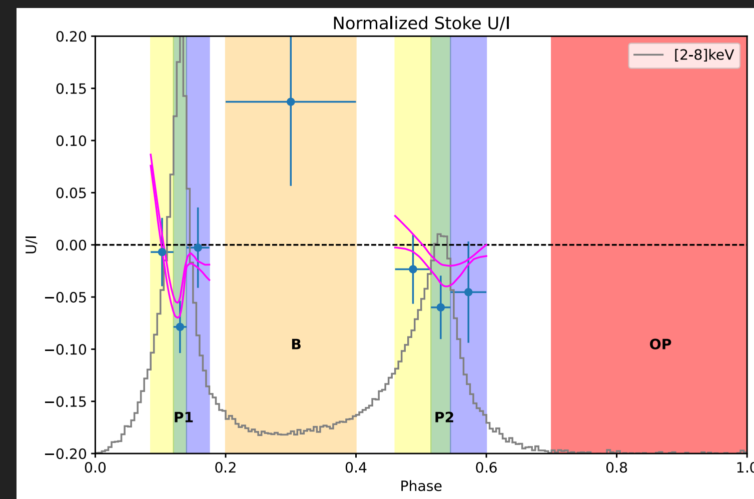

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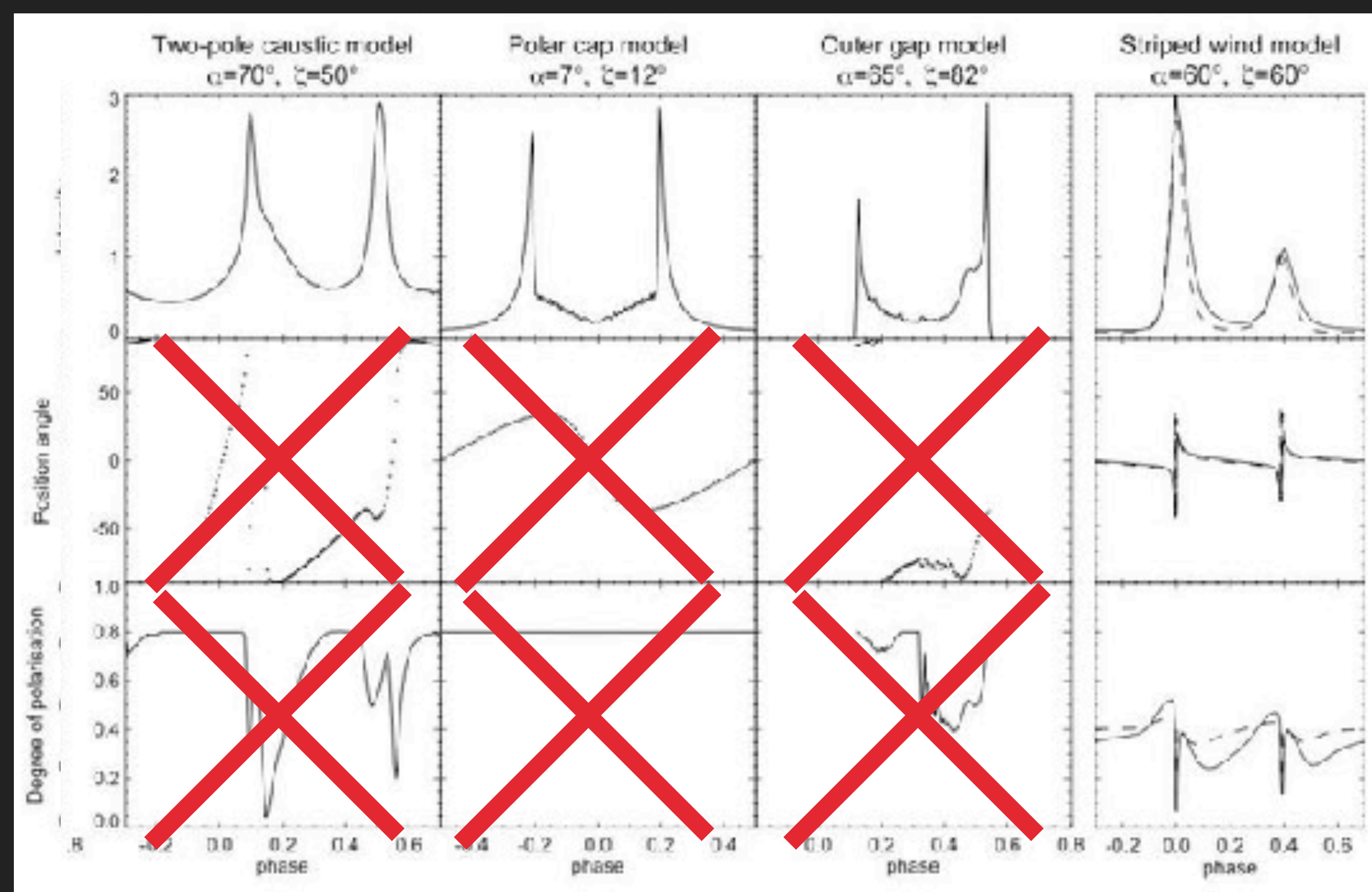

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CONCLUSIONS

CURRENT CANONICAL PICTURE WELL ESTABLISHED

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POLARISATION IN GENERAL IN LINE WITH EXPECTATION

HIGH PD SUGGEST MINOR TURBULENCE IN THE PWNE

NONE OF CURRENT PSR MODEL SEEMS TO WORK