PULSAR WIND NEBULAE:

THE WONDROUS MACHINES OF HIGH ENERGY ASTROPHYSICS

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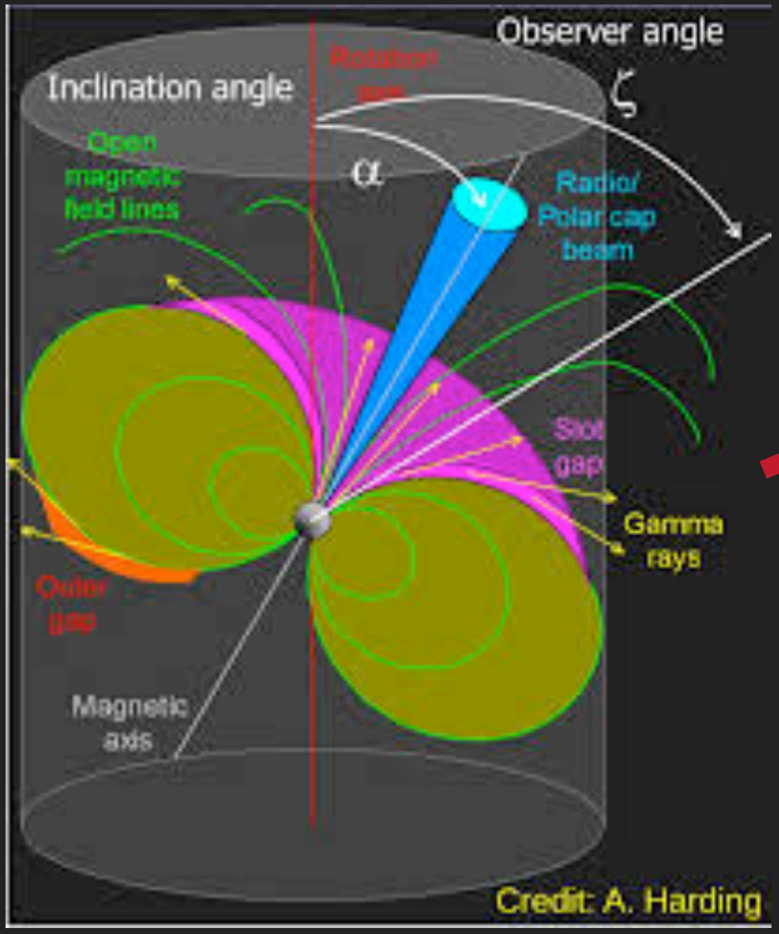
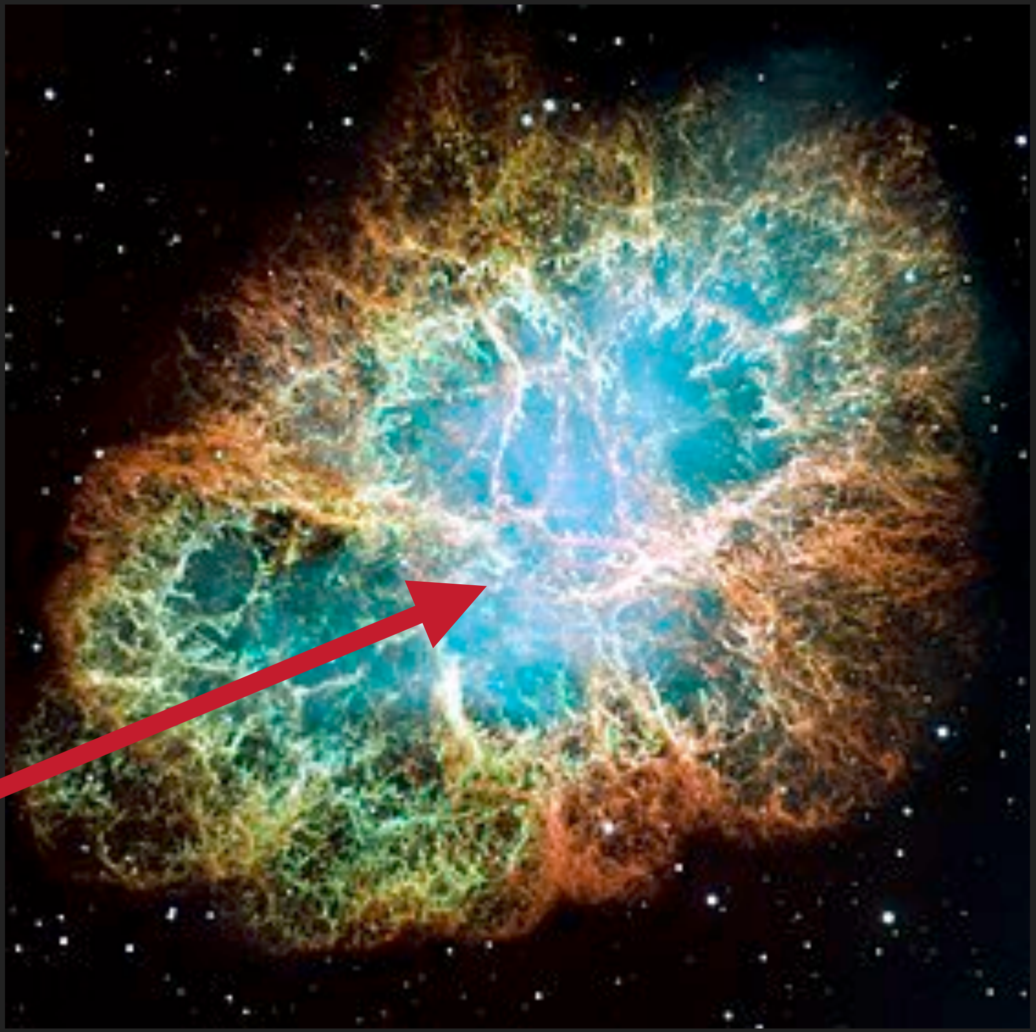
DEATH OF A MASSIVE STAR - THE BIRTH OF PULSAR

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

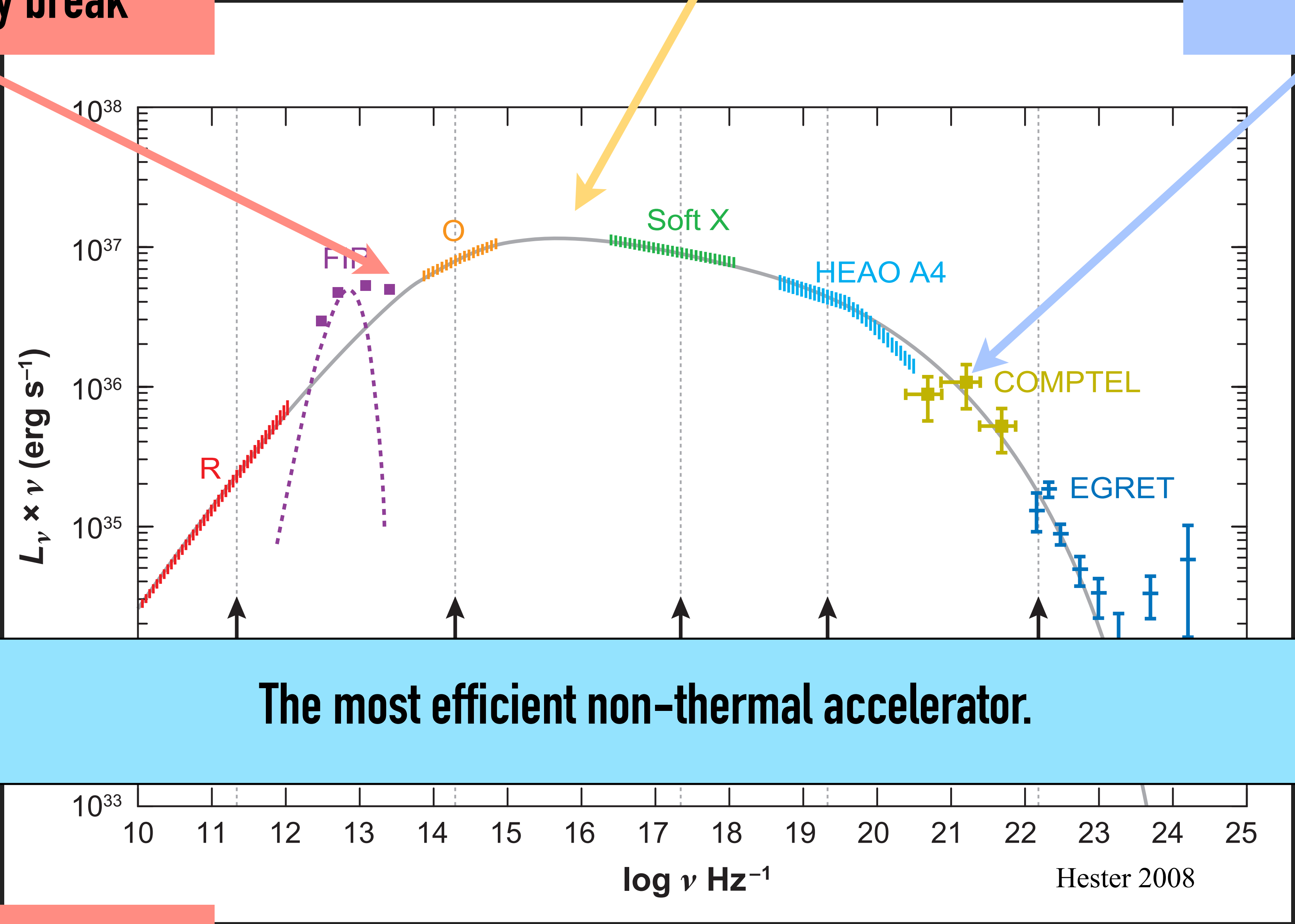


Credit: A. Harding



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

THE NON THERMAL ACCELERATORE



Hester 2008

Low energy break

High energy break

MeV cutoff

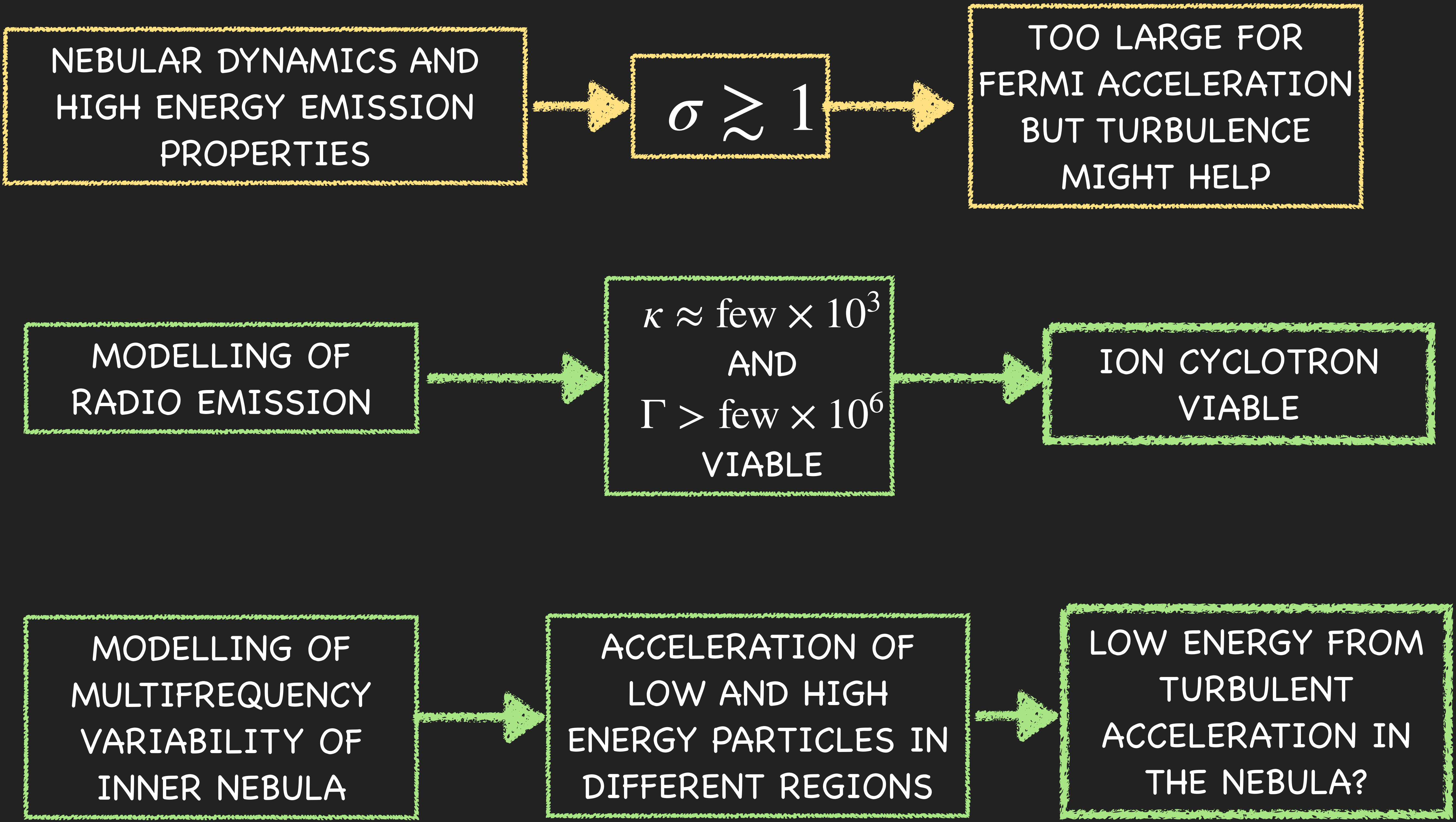
The most efficient non-thermal accelerator.

Injection break

Synchr. cooling

Acceler. cutoff

ACCELERATION RECIPES – TAKE HOME MESSAGE



NEBULAR DYNAMICS AND HIGH ENERGY EMISSION PROPERTIES

$\sigma \gtrsim 1$

TOO LARGE FOR FERMI ACCELERATION BUT TURBULENCE MIGHT HELP

MODELLING OF RADIO EMISSION

$\kappa \approx \mathrm{few} \times 10^3$

AND

$\Gamma > \mathrm{few} \times 10^6$

VIABLE

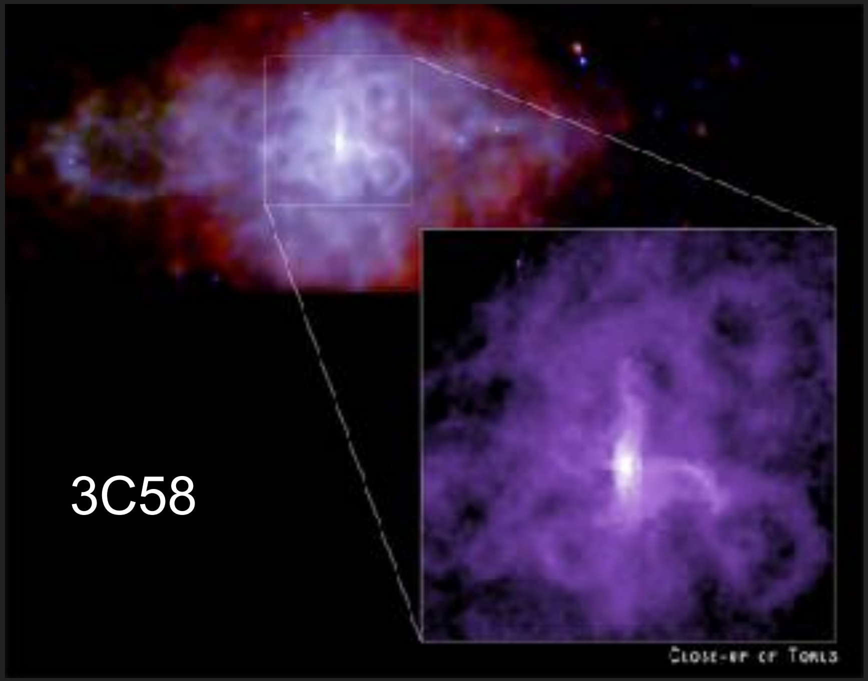
ION CYCLOTRON VIABLE

MODELLING OF MULTIFREQUENCY VARIABILITY OF INNER NEBULA

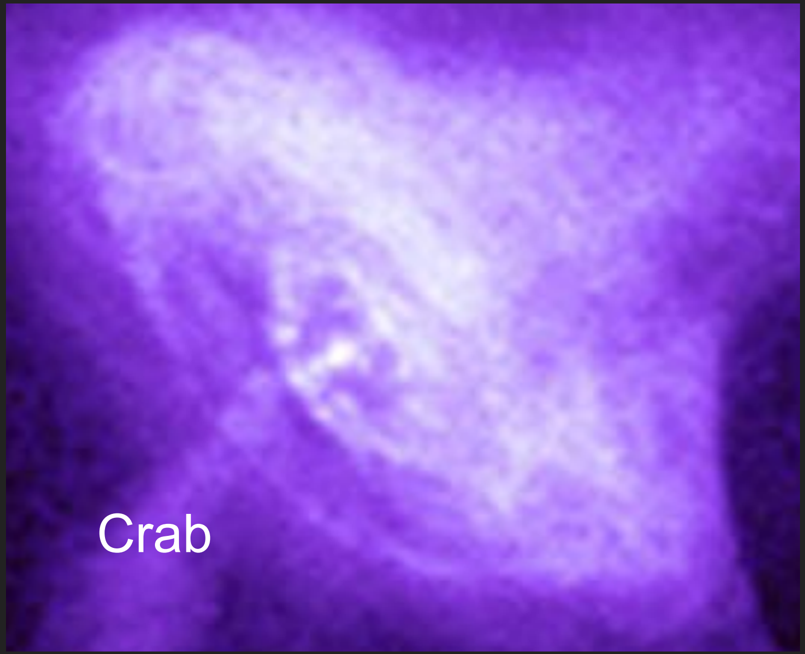
ACCELERATION OF LOW AND HIGH ENERGY PARTICLES IN DIFFERENT REGIONS

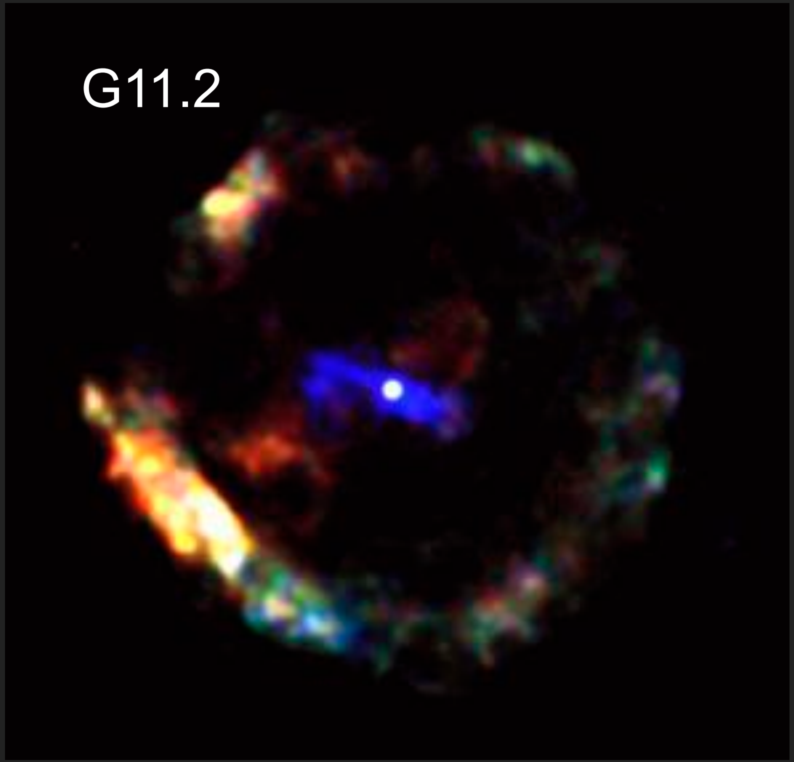
LOW ENERGY FROM TURBULENT ACCELERATION IN THE NEBULA?

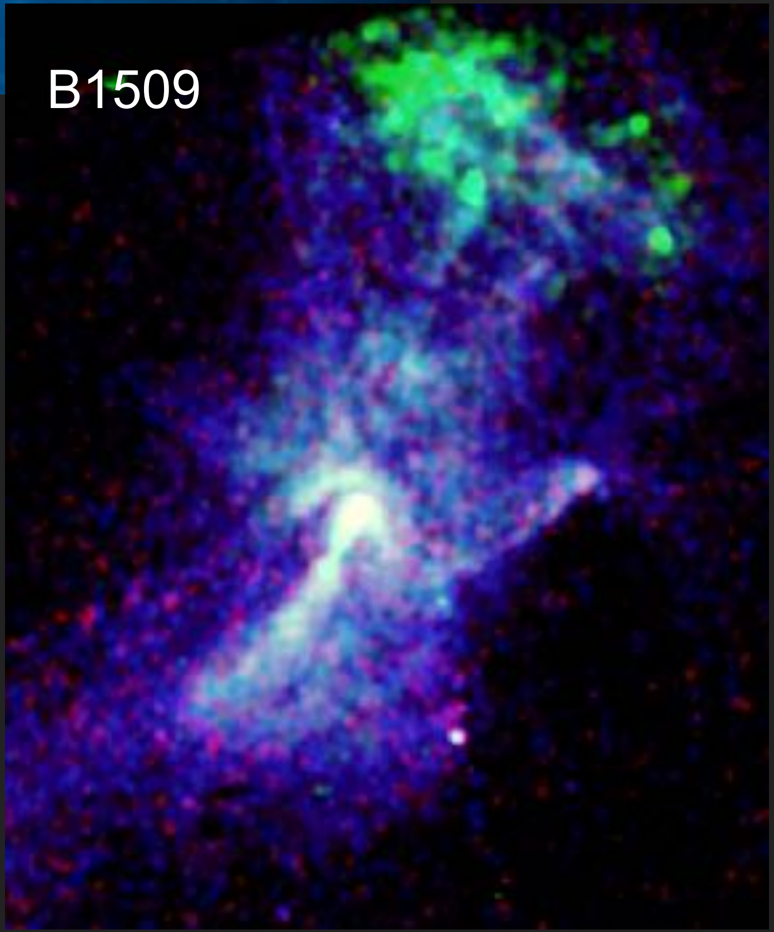
FINE STRUCTURES – A LAB FOR RELTIVISTICN FLUID DYNAMICS


3C58

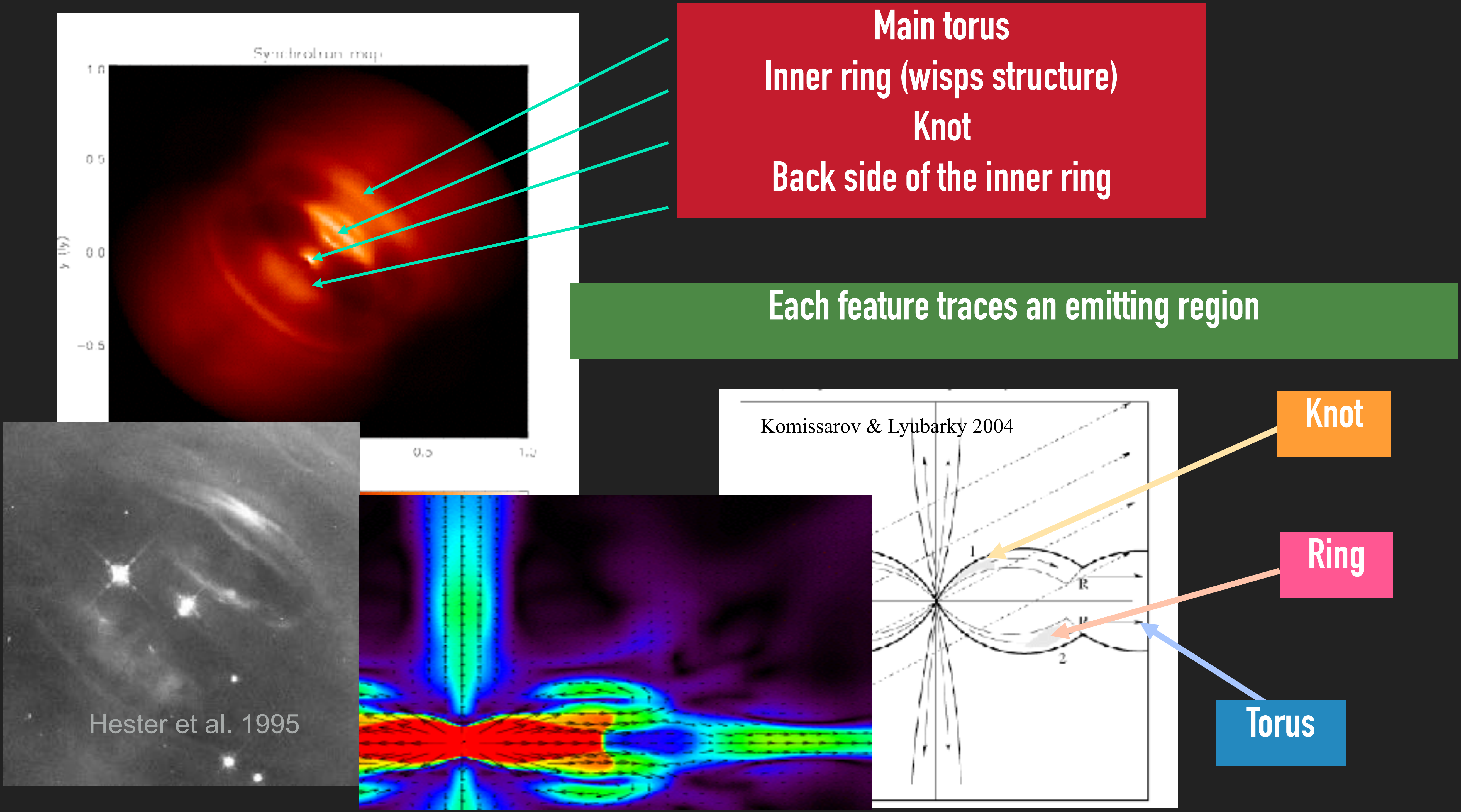

Vela


Crab


G11.2


B1509

REPRODUCING OBSERVATIONS



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

Each feature traces an emitting region

Komissarov & Lyubarky 2004

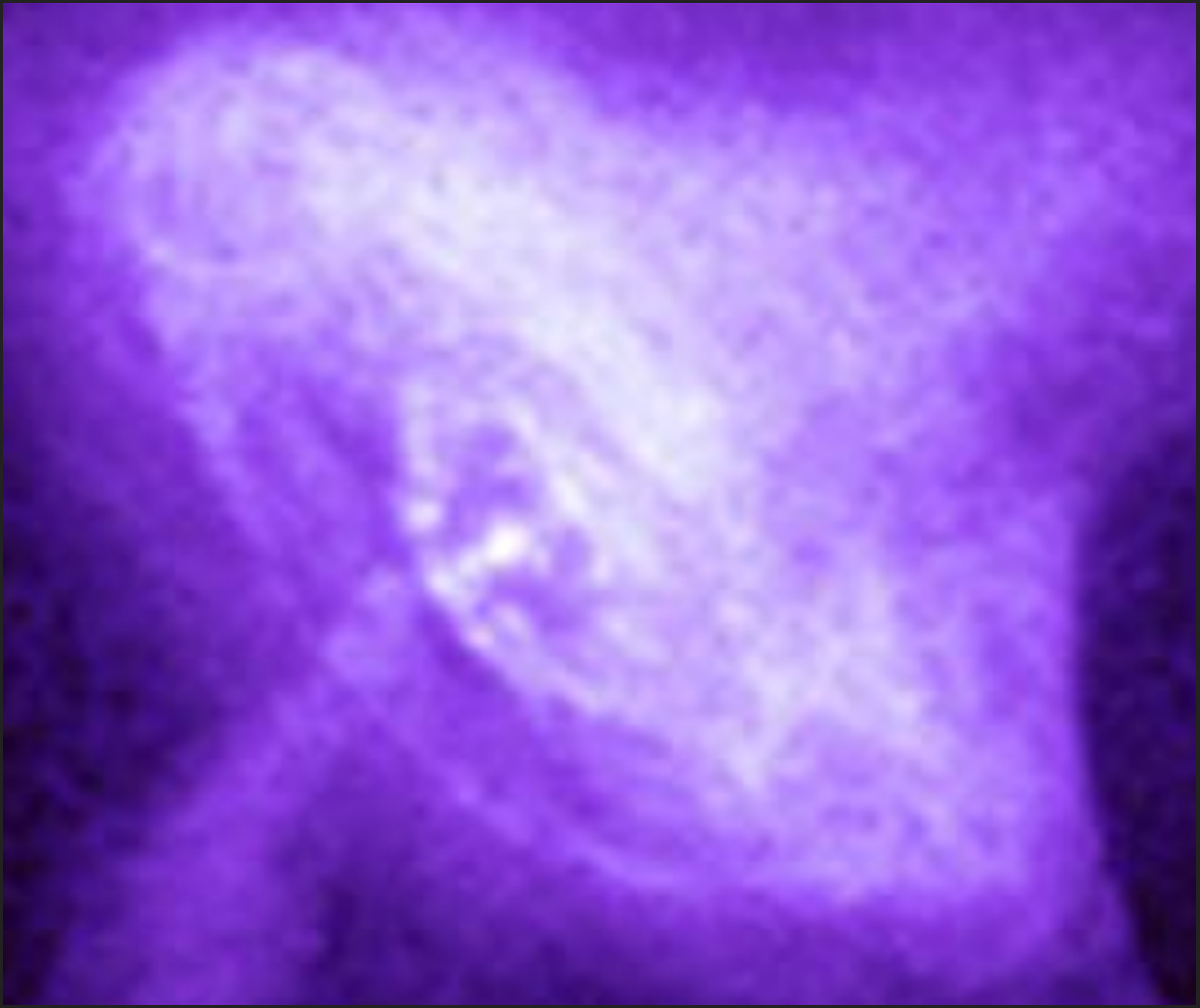
Hester et al. 1995

Knot

Ring

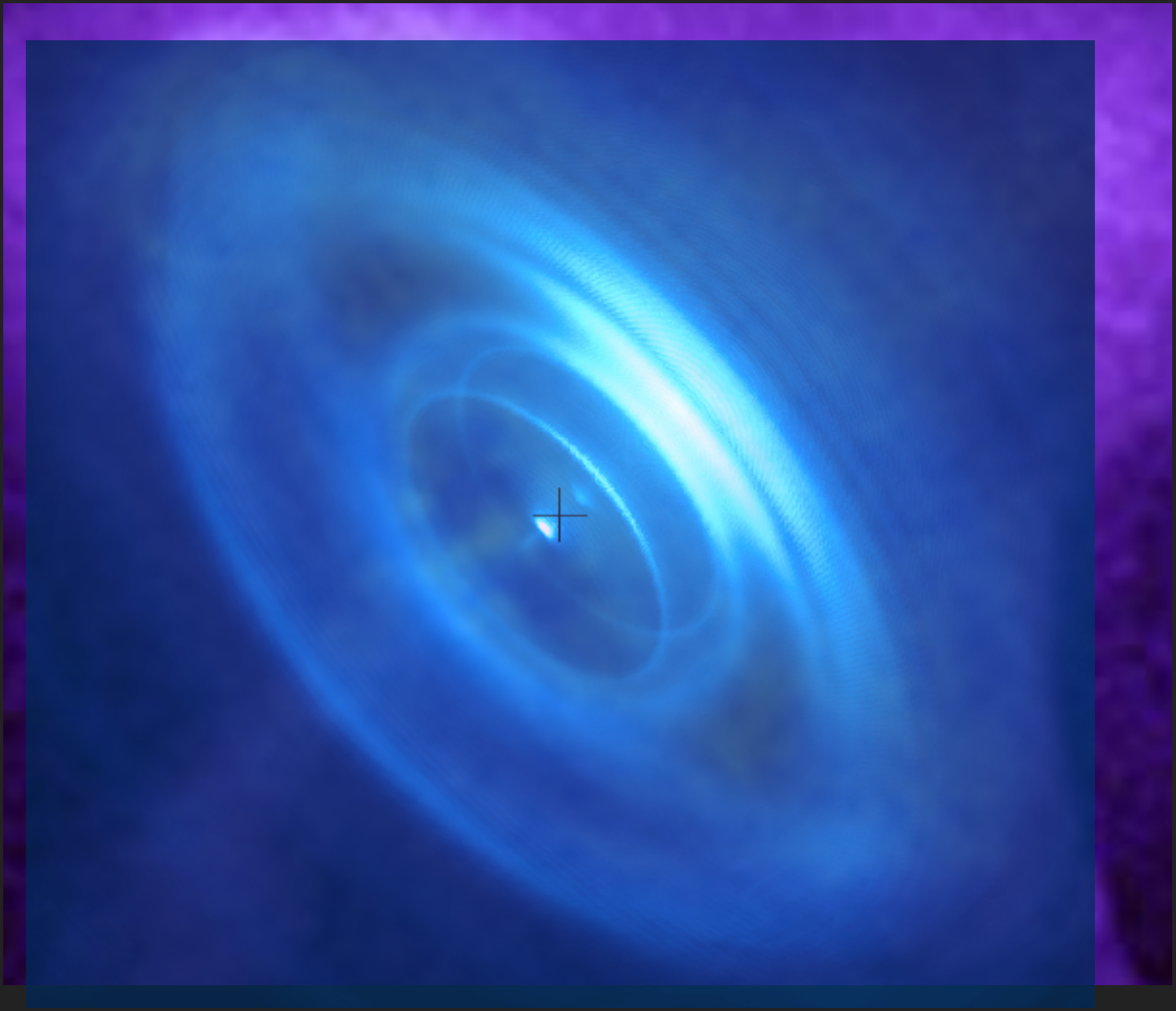
Torus

REPRODUCING OBSERVATIONS



Camus et al 2008

REPRODUCING OBSERVATIONS



Camus et al 2008

PWNE AND LHAASO SOURCES

12 SOURCES DETECTED BY LHAASO ABOVE 100 TEV

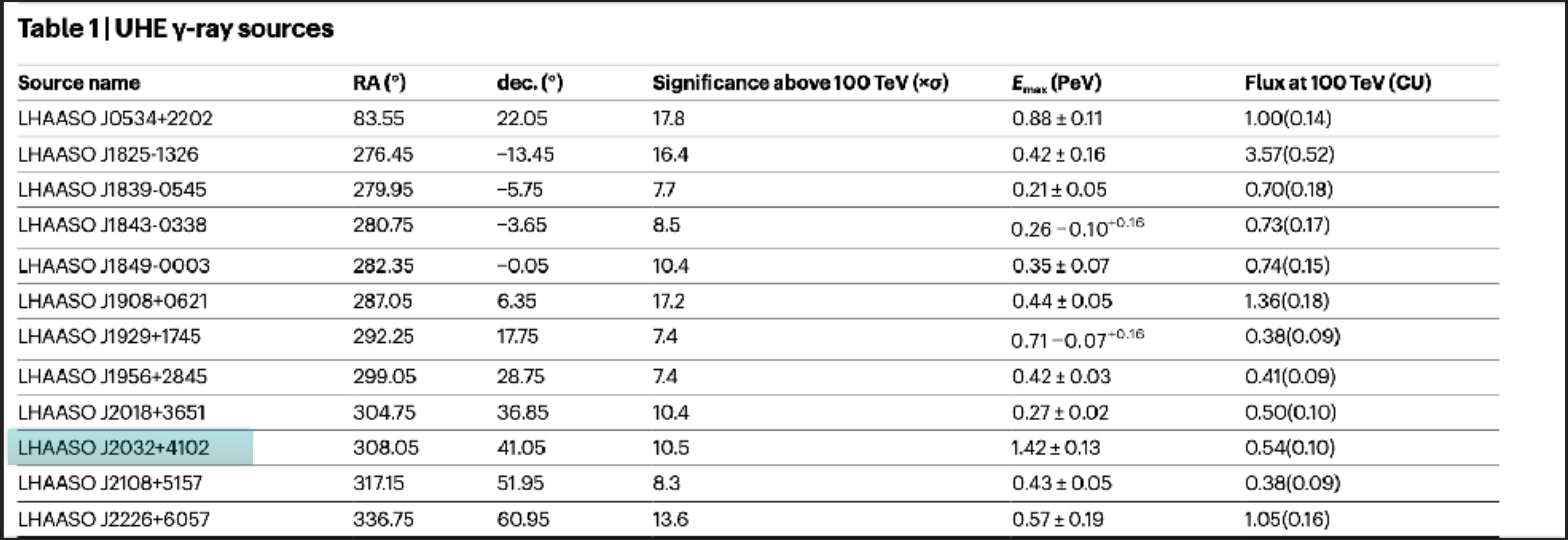


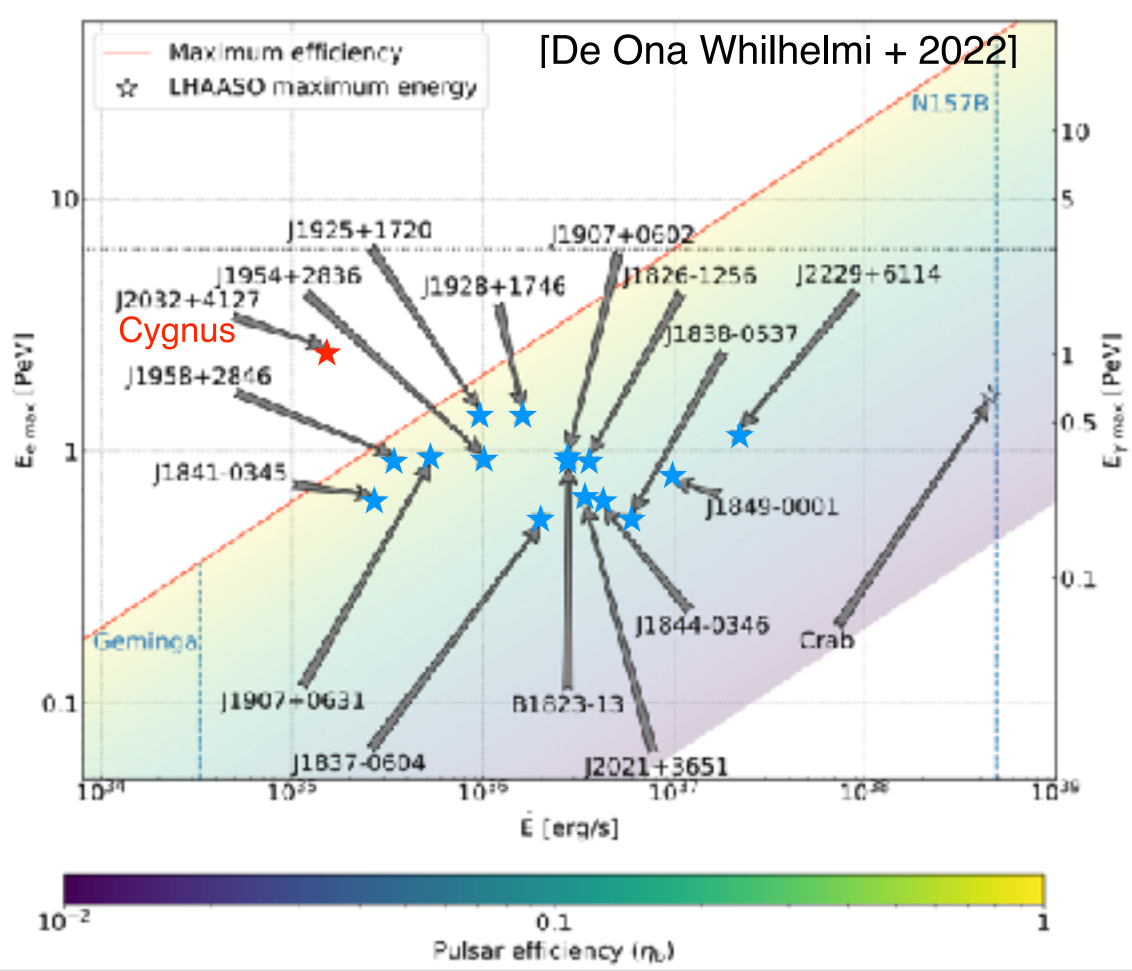
Table 1 | UHE γ-ray sources

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

PSR VOLTAGE


[De Ona Whilhelmi + 2022]

STRICT LIMIT FROM THE PSR POTENTIAL DROP

$$E_{max,abs} = e\xi_E B_{TS}\ R_{TS}$$

$$\frac{B_{TS}^2}{8\pi} = \xi_B \frac{\dot{E}}{4\pi R_{TS}^2 c}$$

$$\Phi_{PSR} = \sqrt{\dot{E}/c}$$

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

$$E_{max,Crab} \approx 30\ \mathrm{PeV}$$

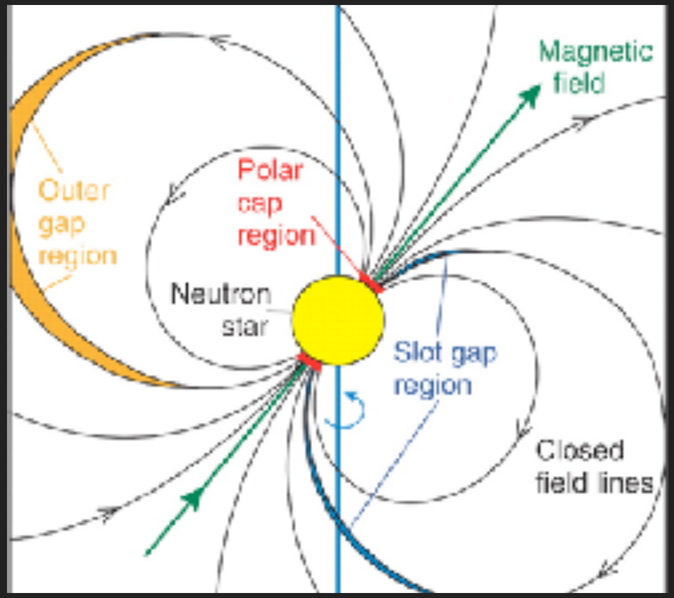
IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LIKELY LOSS LIMITED

$$t_{acc} = \frac{E}{e\xi_e Bc} < t_{loss} = \frac{6\pi(mc^2)^2}{\sigma_T c B^2 E}$$

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

ORIGIN OF THE SYNCHROTRON CUTOFF

POTENTIAL LIMITED ACCELERATION



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

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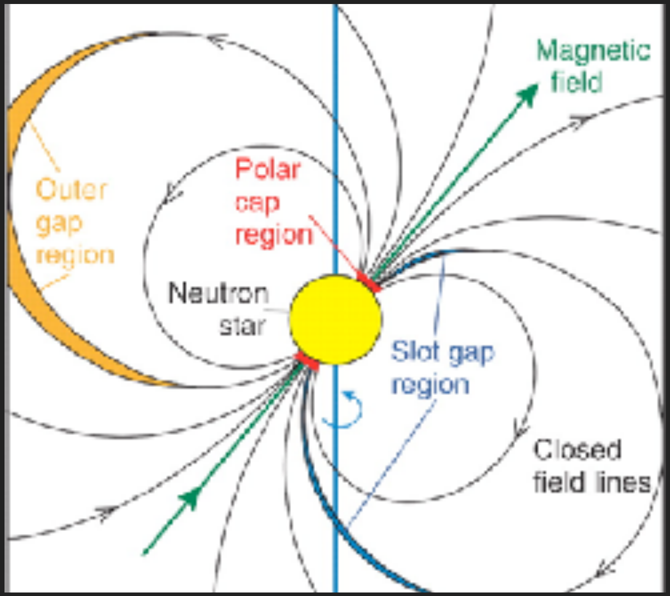

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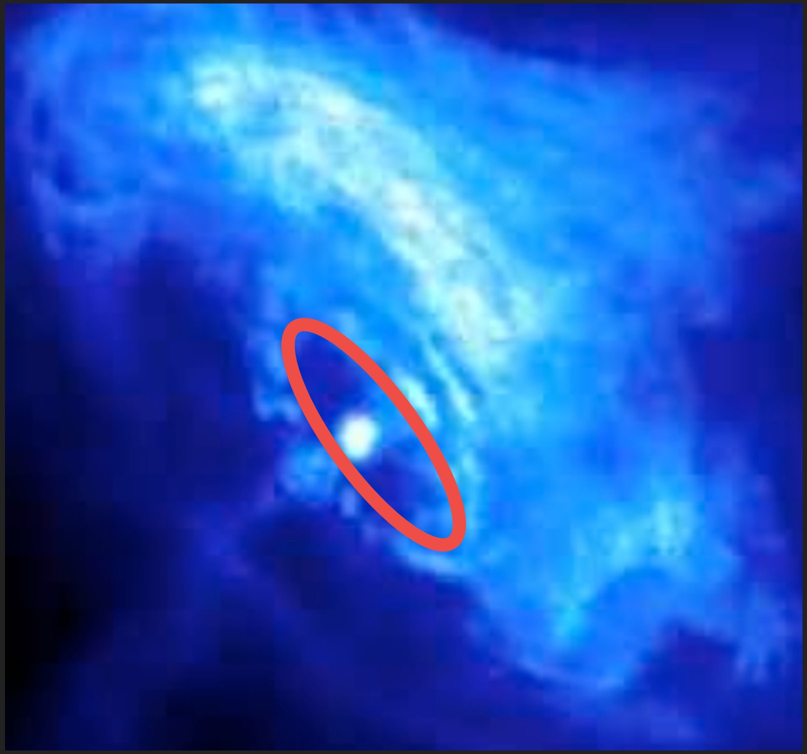


ACCELERATION LIMIT AT THE TS

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

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

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

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

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

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

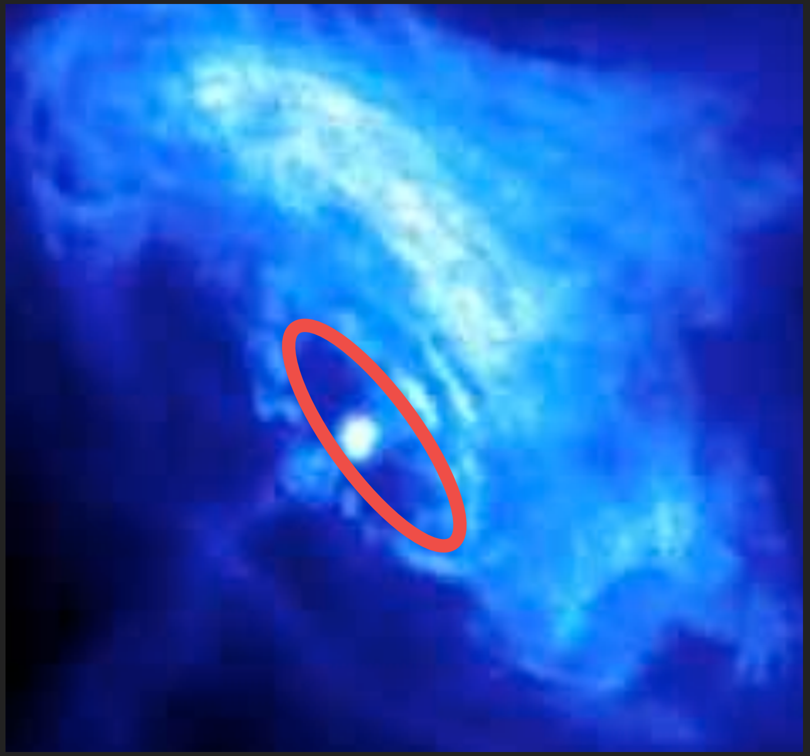
MAGNETISATION IN THE CRAB IS JUST BELOW EQUIPARTITION
B ~ 150-120 UG

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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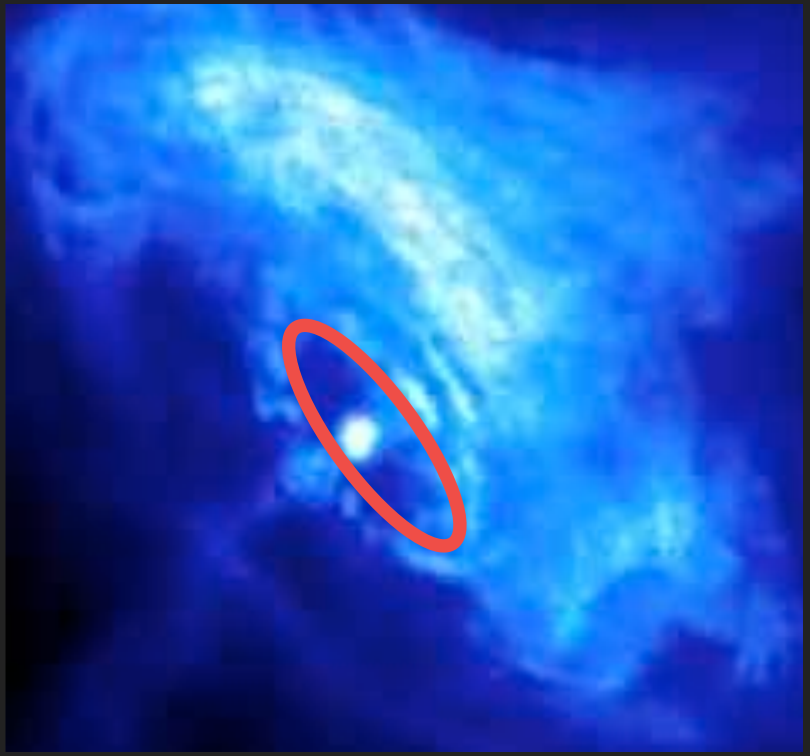

MAXIMUM FREQUENCY IS FIXED

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

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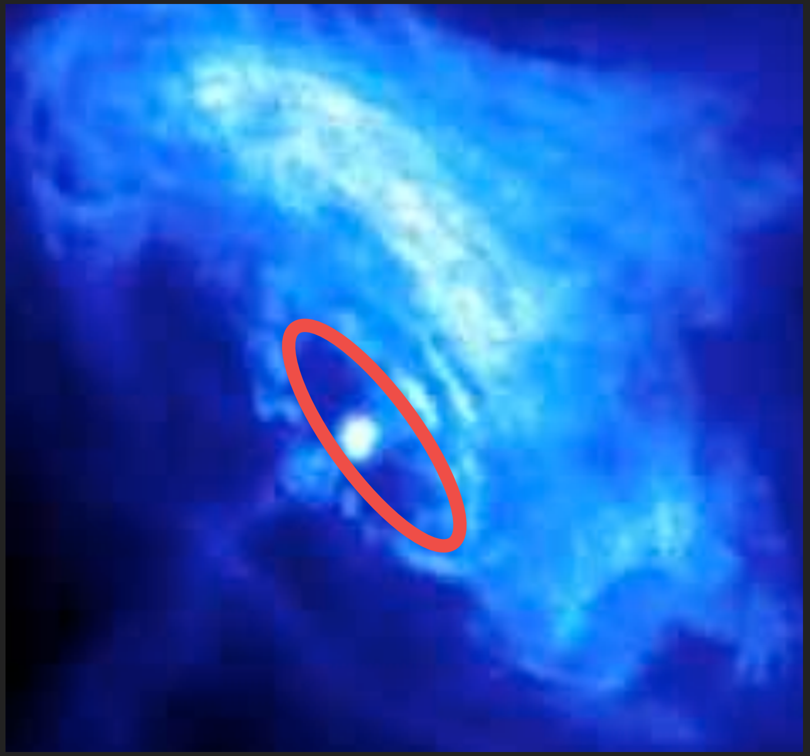

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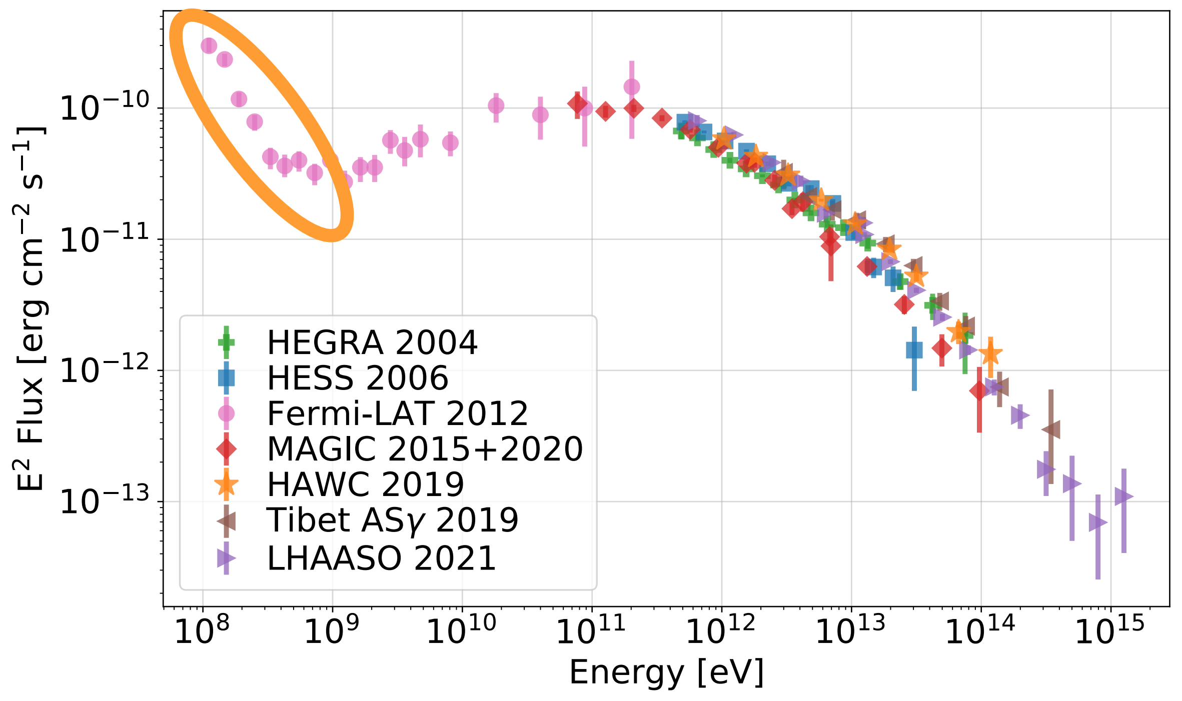
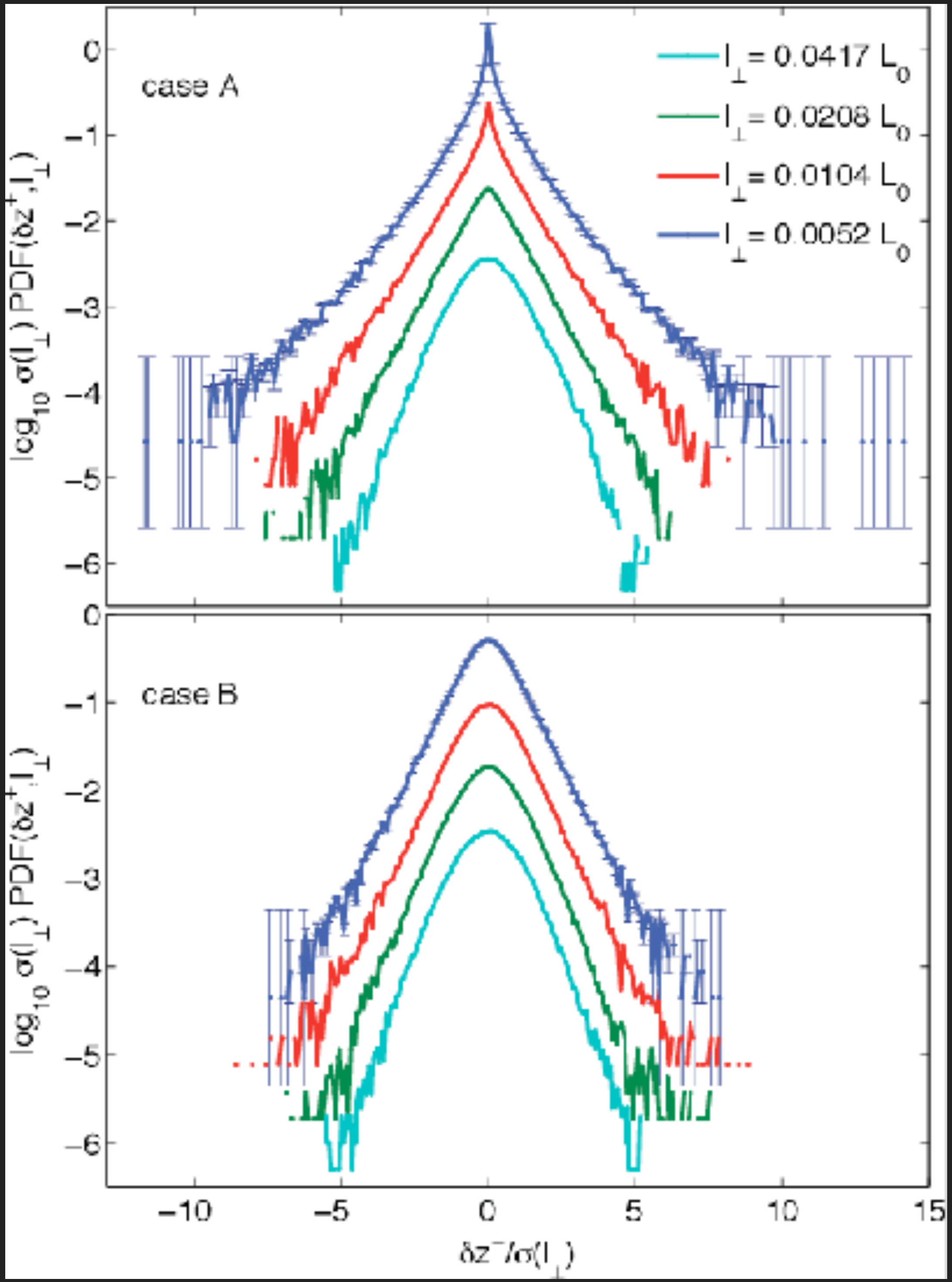
IN CRAB THE LIMITS ALL COINCIDE

OTHERS ALL POTENTIAL LIMITED



INTERMITTENCY

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



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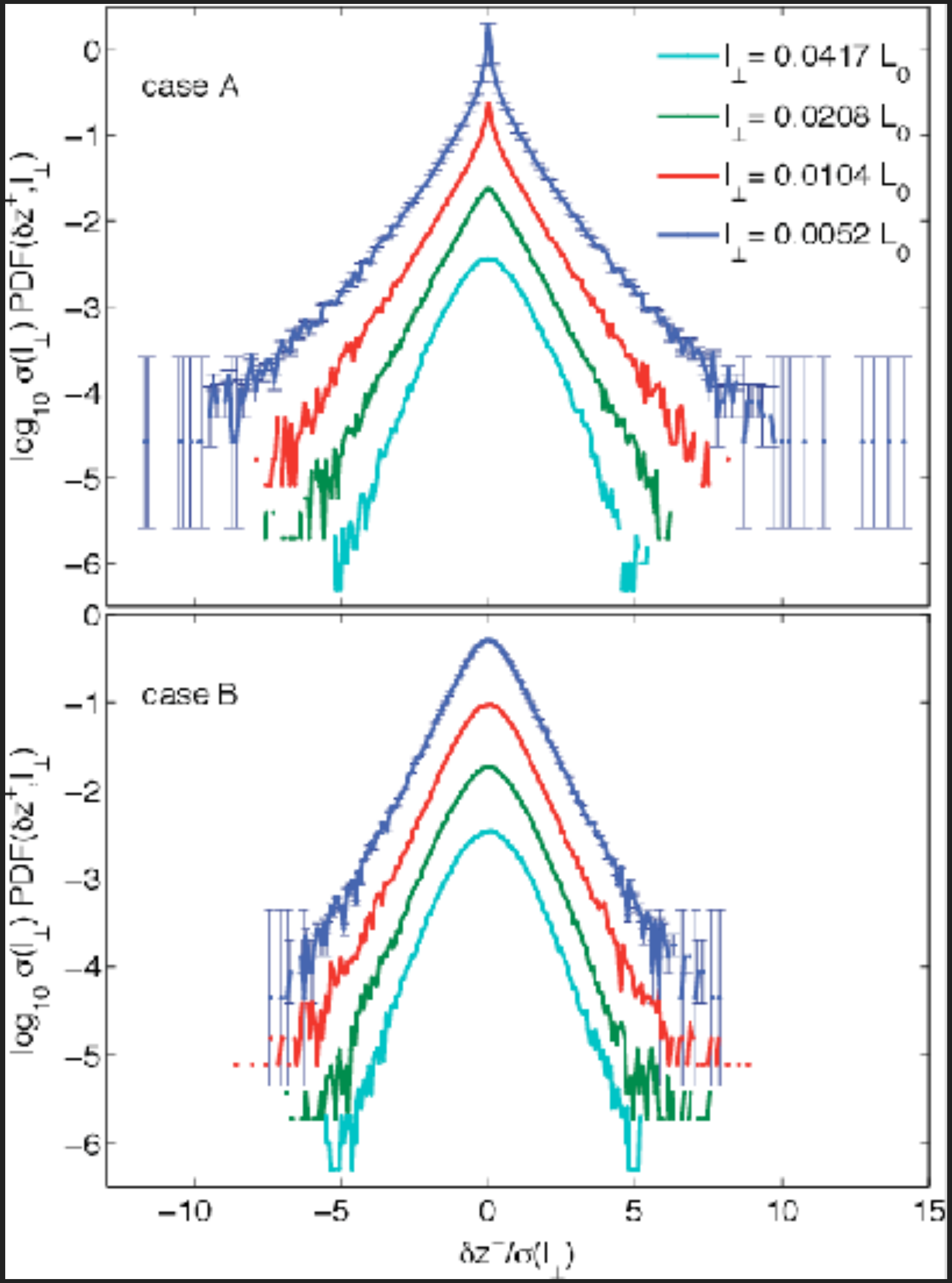

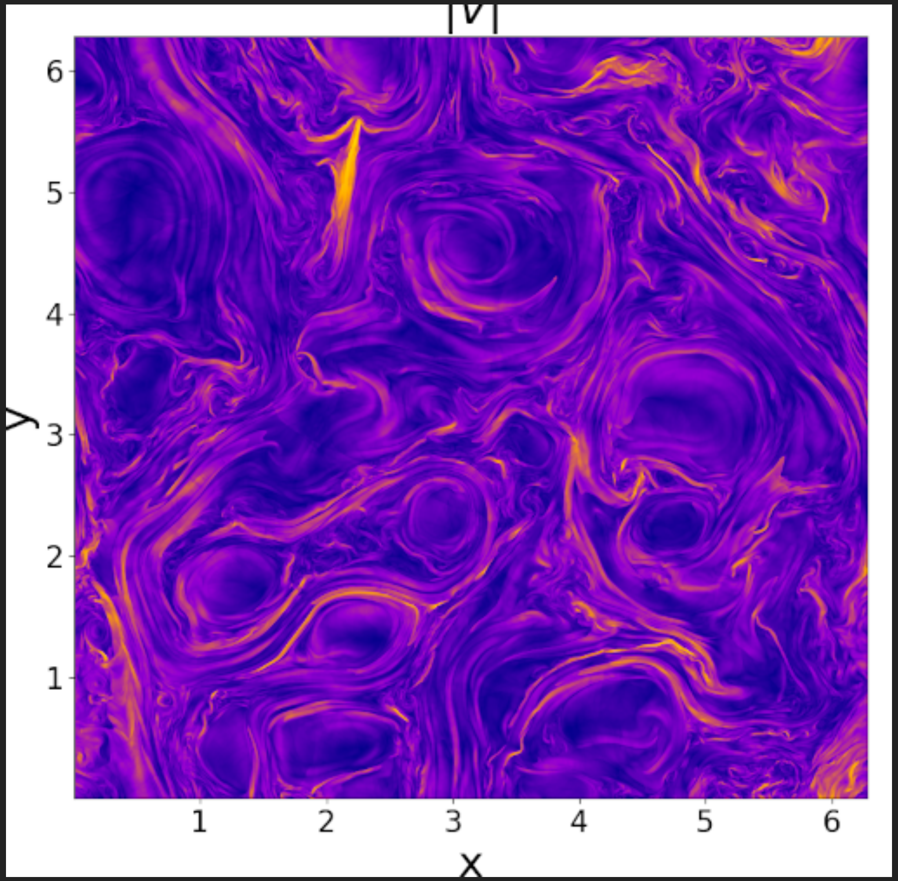

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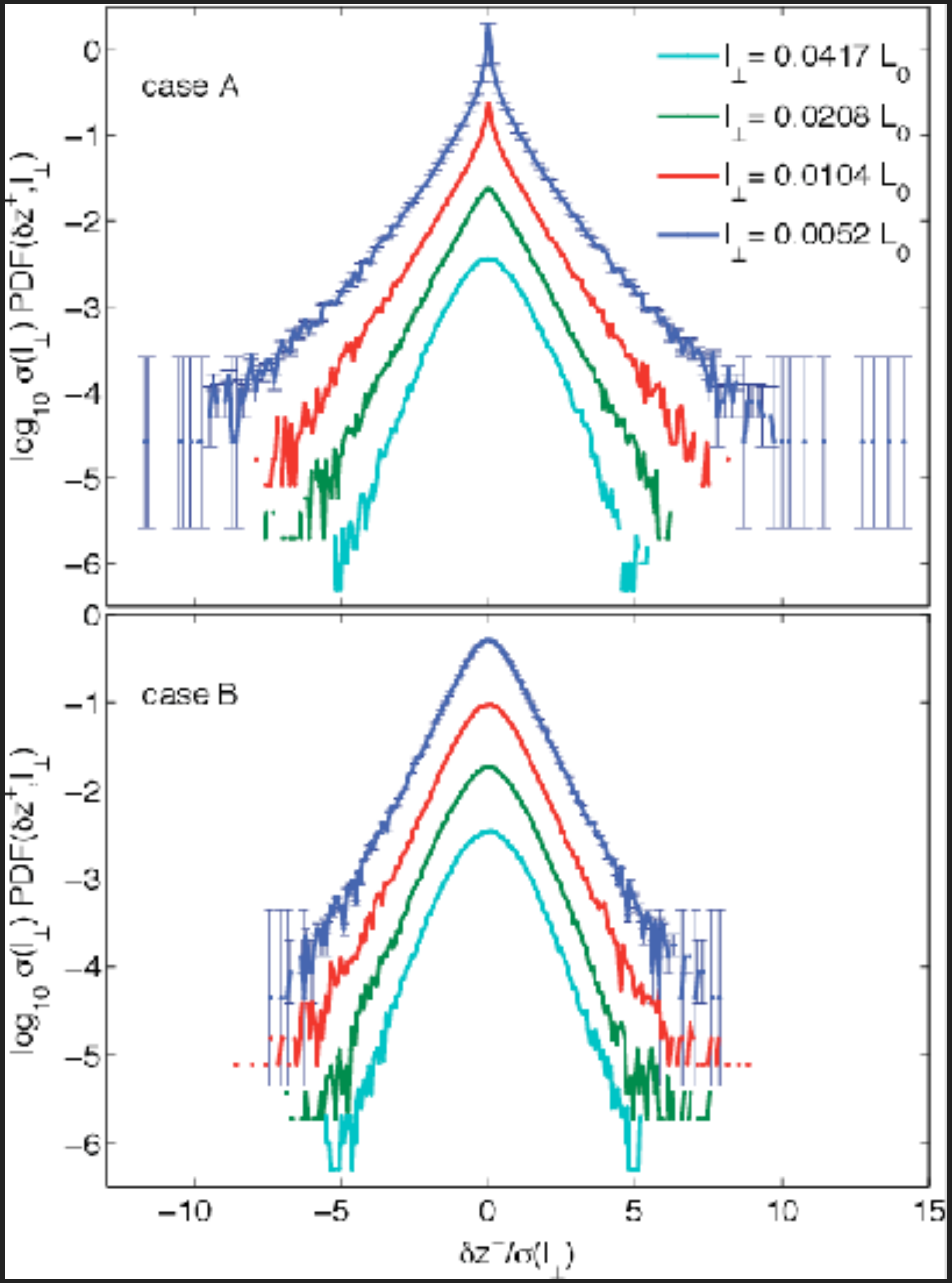

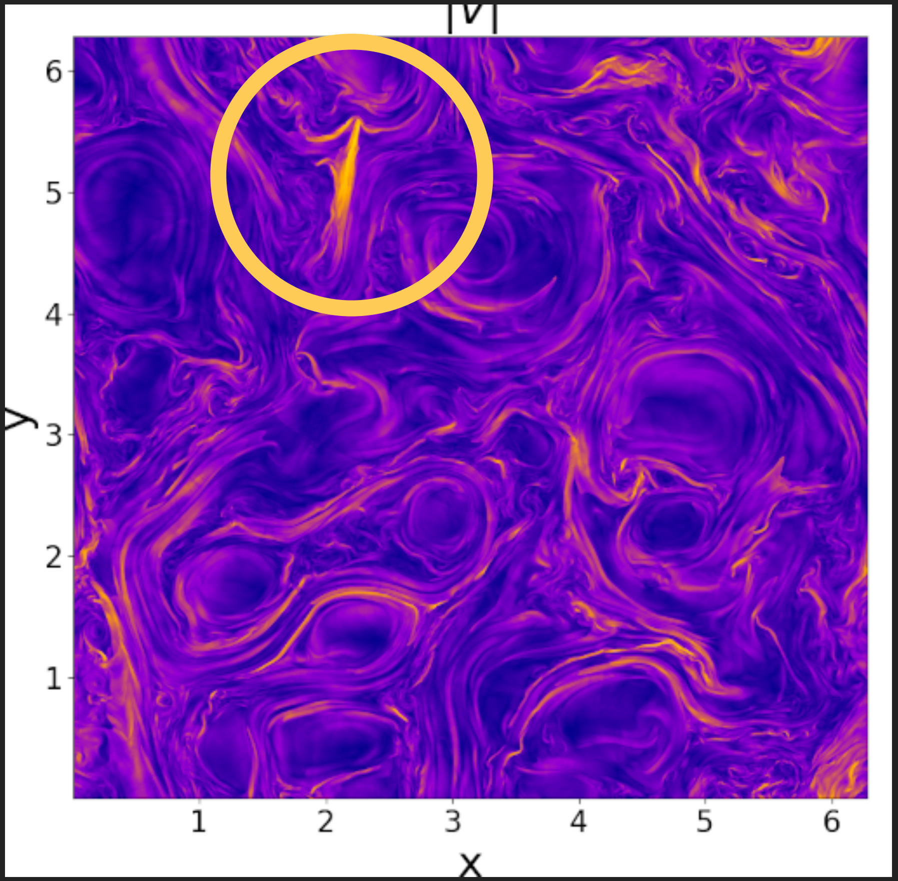

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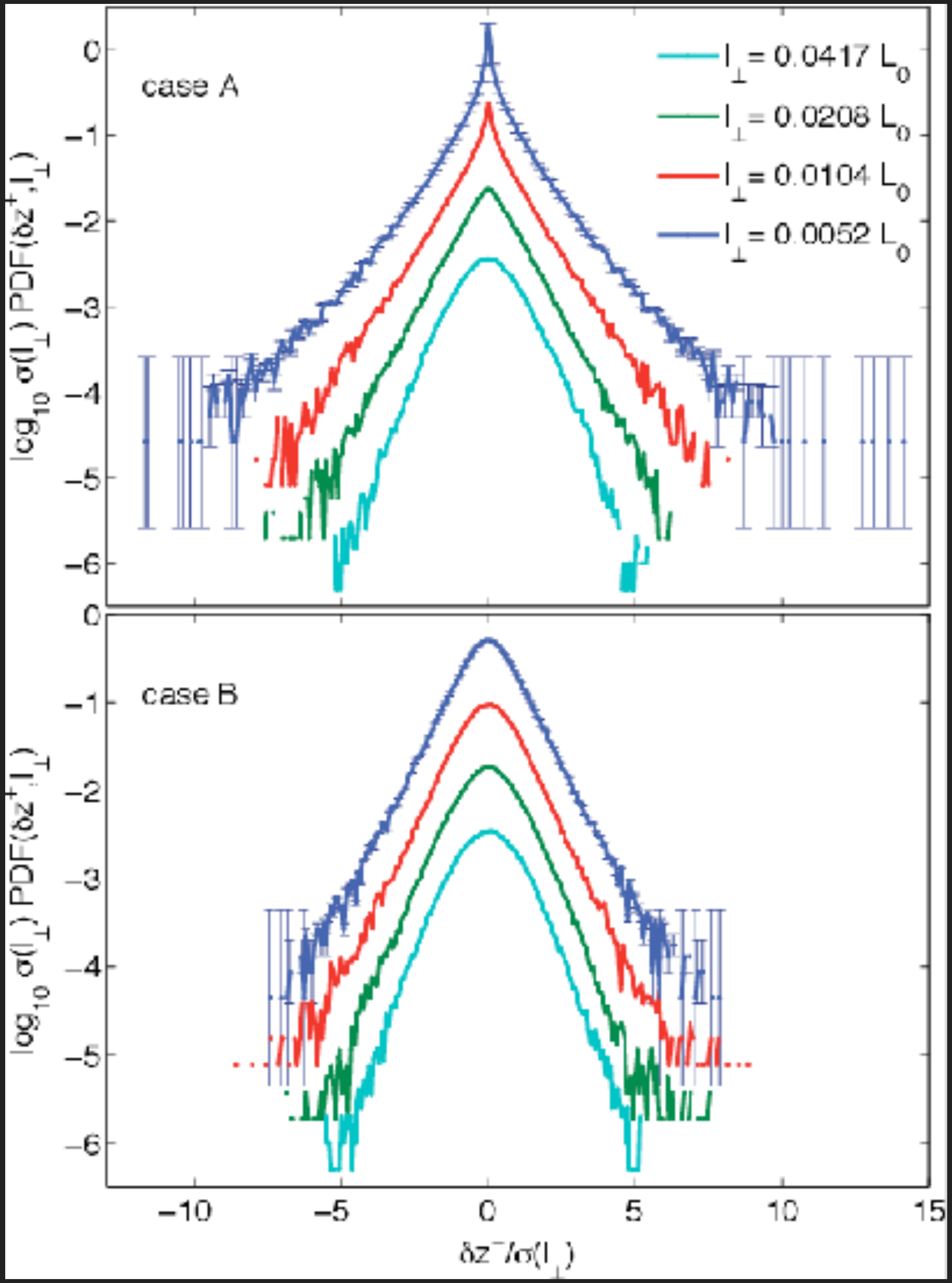
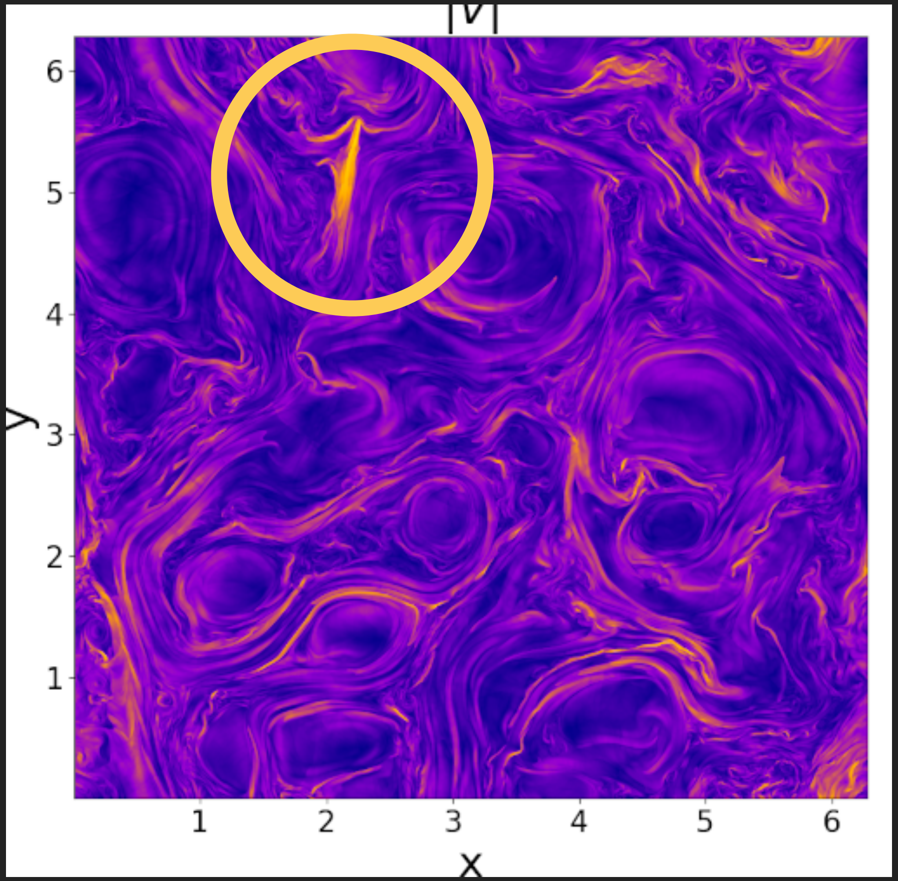


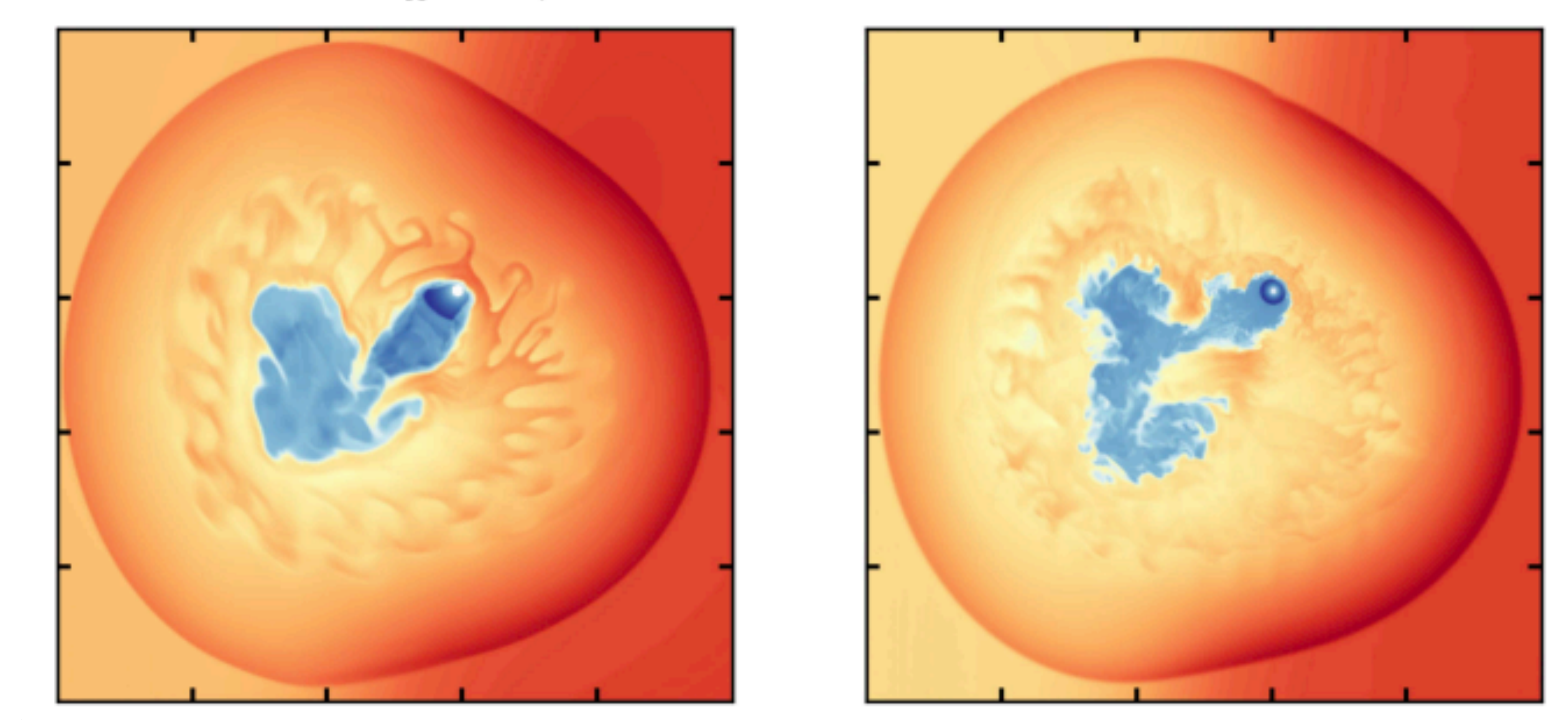


NOT CLEAR IF STATISTICS OF INTERMITTENCY COMPATIBLE WITH MILL-G FIELD

TIME EVOLUTION I

MIXING WITH THE SNR MATTER
LARGER RADII E KNOTTY STRUCTURE
RE-ENERGIZATION DUE TO COMPRESSION

Kolb et al 2017



Blondin et al 2001

Ma et al 2016

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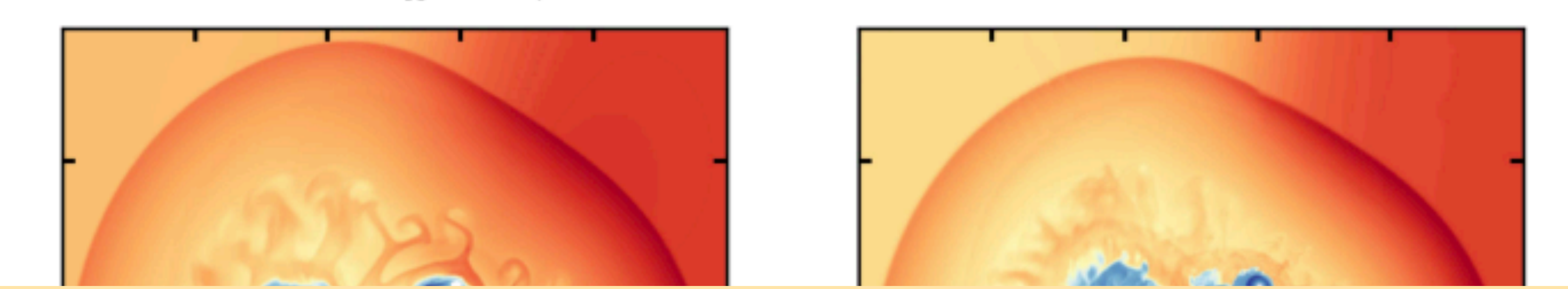
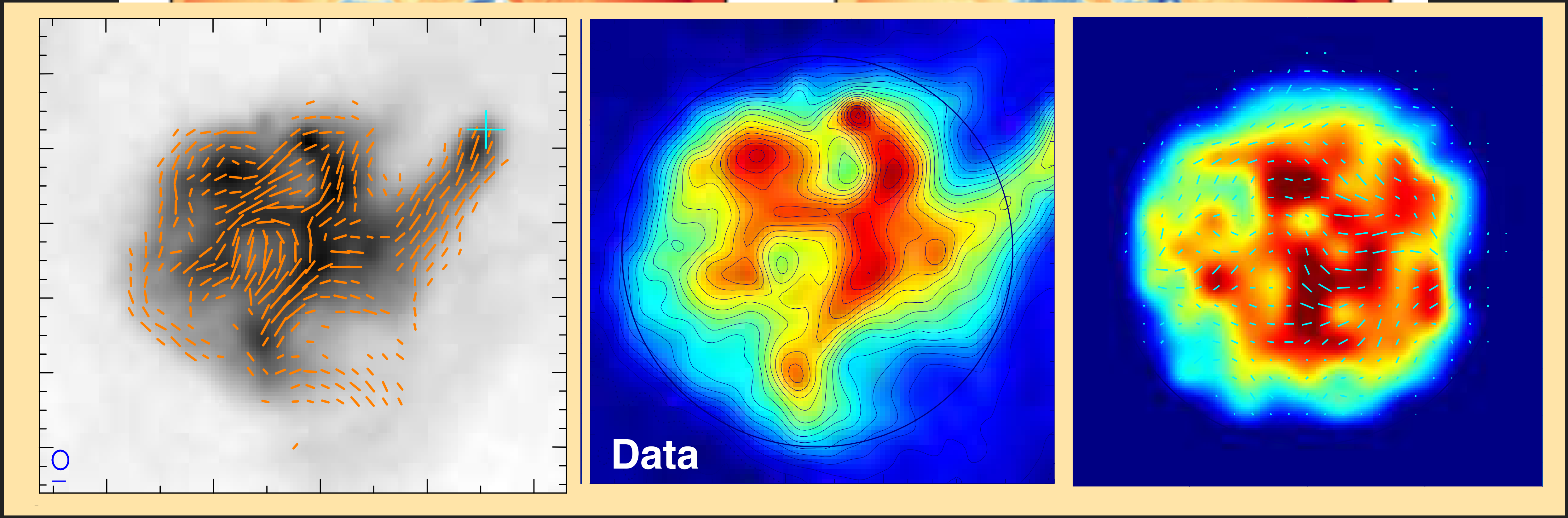


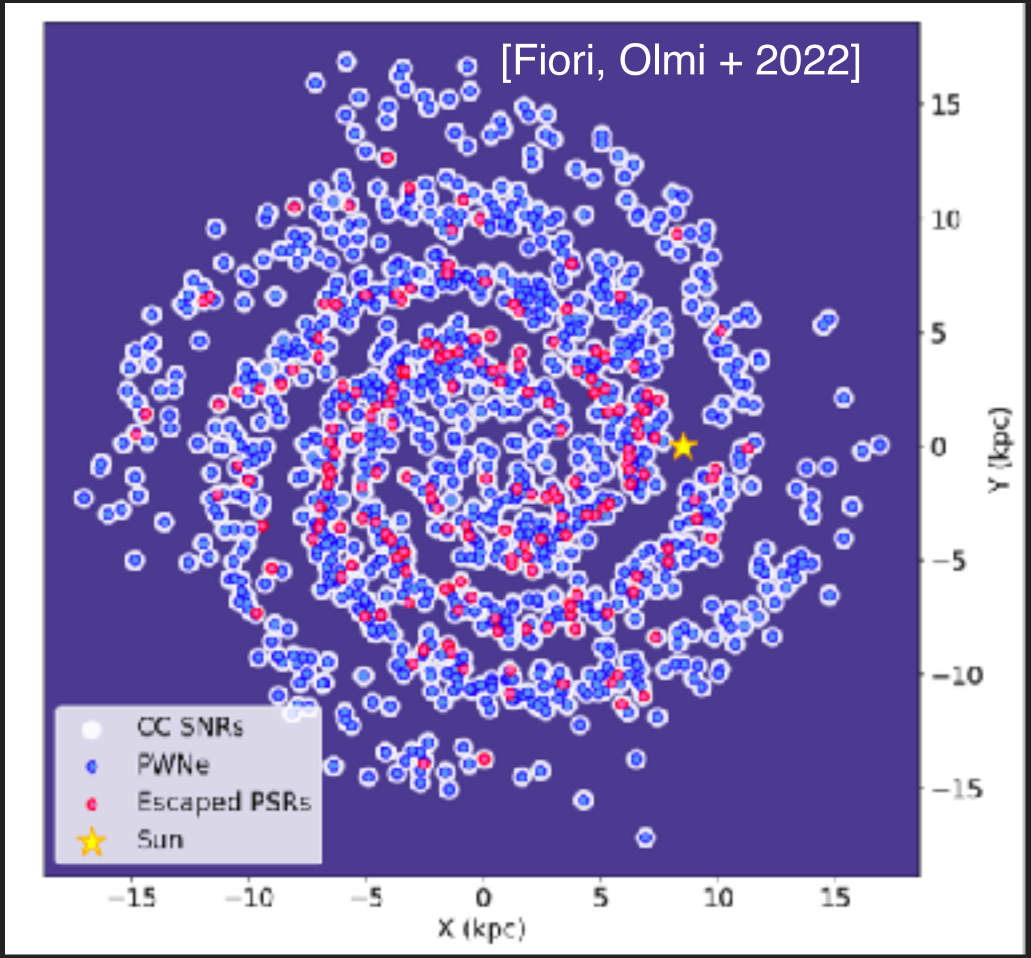


G327 Ma et al. 2015

Ma et al 2016

PWNE WILL BE THE MOST NUMEROUS GALACTIC GAMMA-RAY SOURCES

DISTRIBUTION IN THE GALAXY

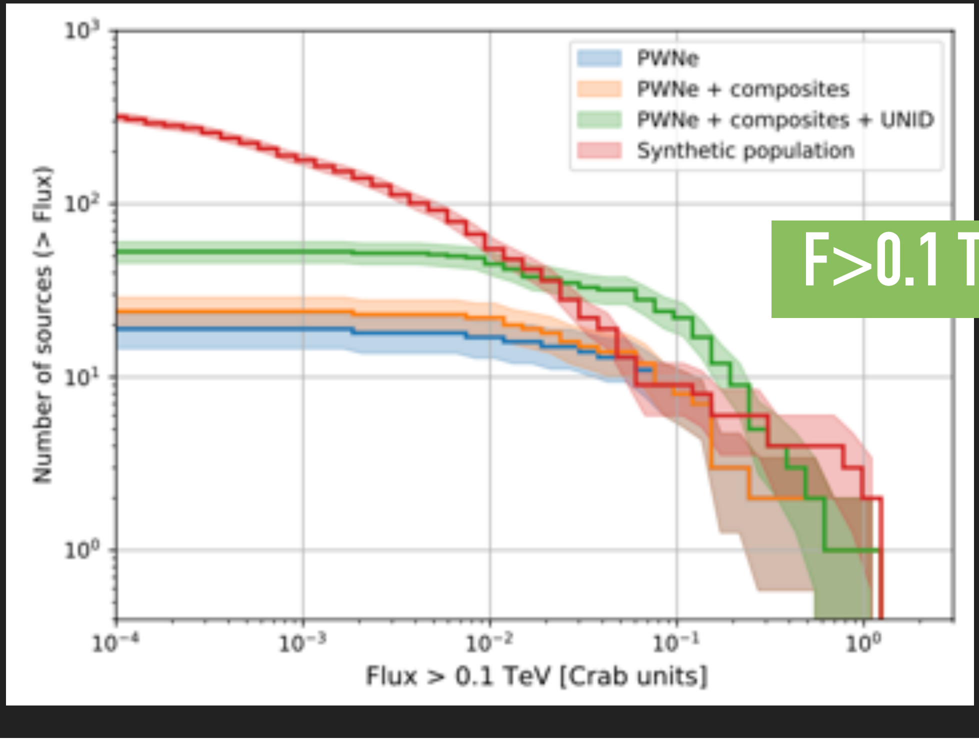


[Fiori, Olmi + 2022]

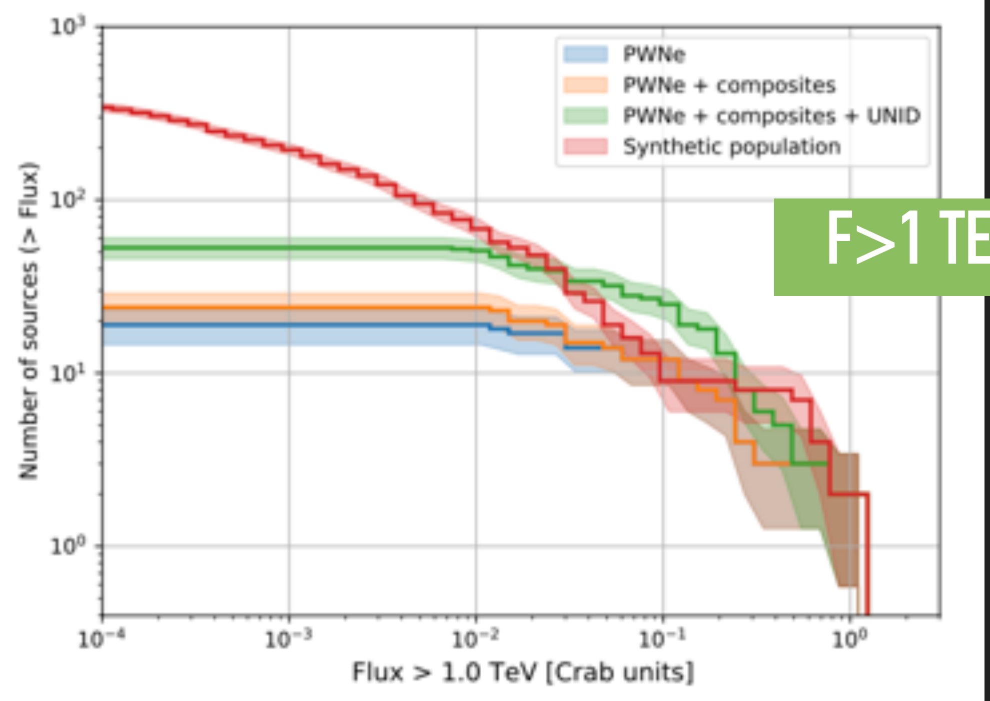
PWN IN THE GALAXY MODELLED WITH NUMERICAL SIMULATIONS + RADIATIVE CODE

PWN ARE PRIMARY TARGETS FOR CTA AND ASTRI MA

CONTRIBUTION AT GAMMA-RAYS



F>0.1 TEV

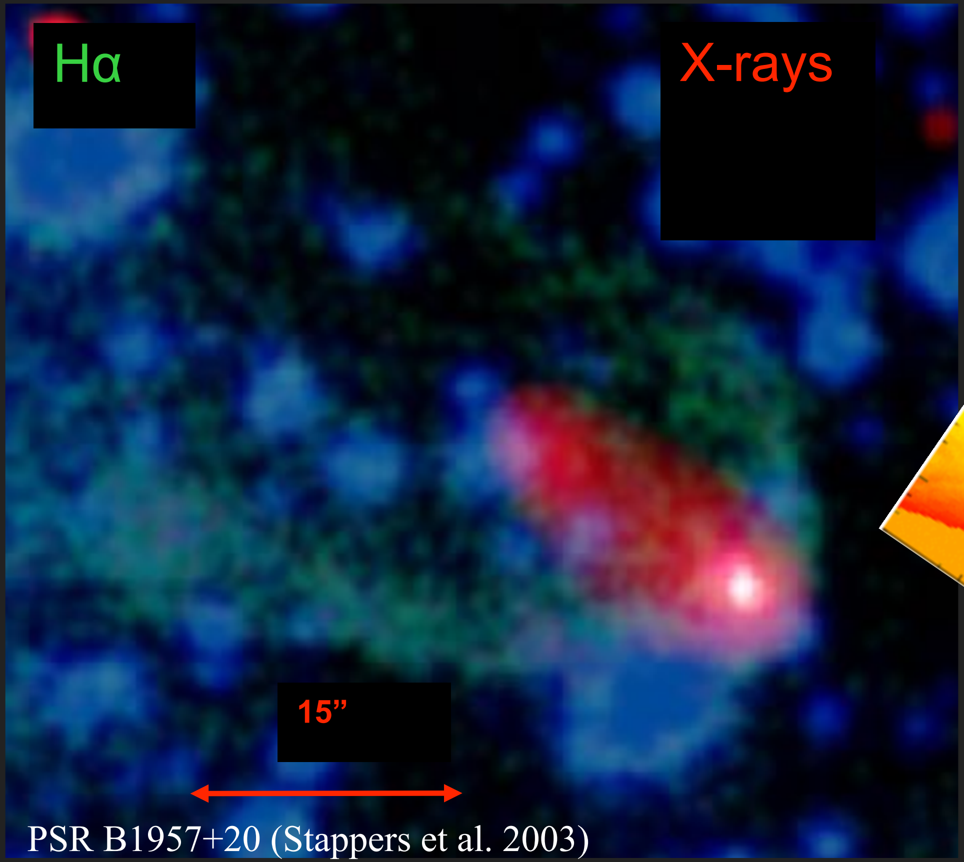


F>1 TEV

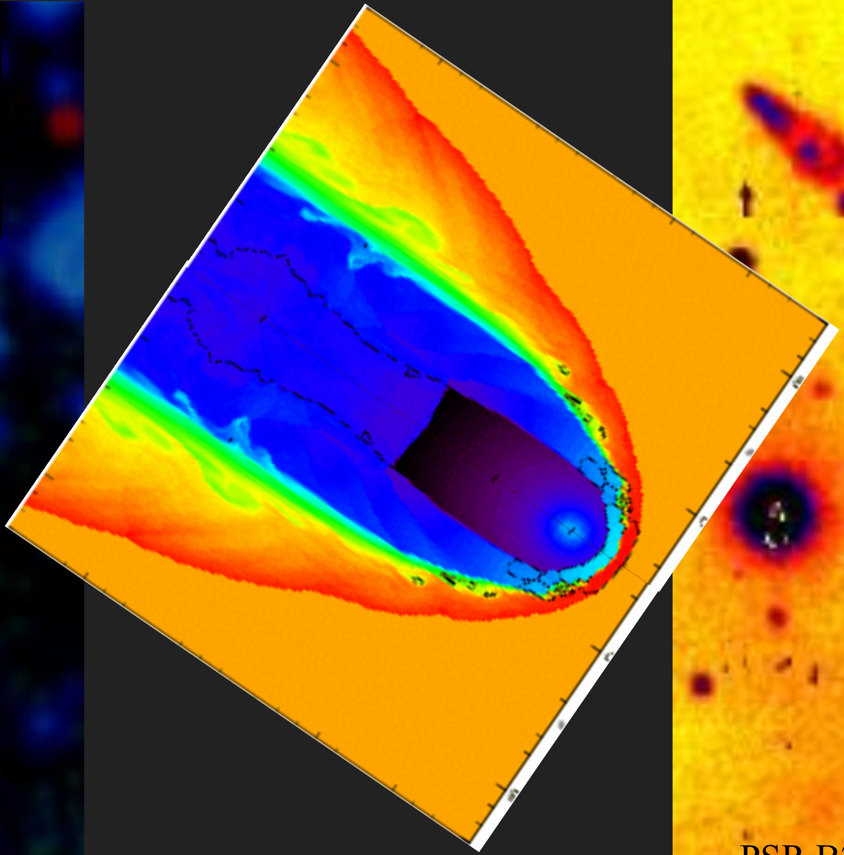
TIME EVOLUTION III

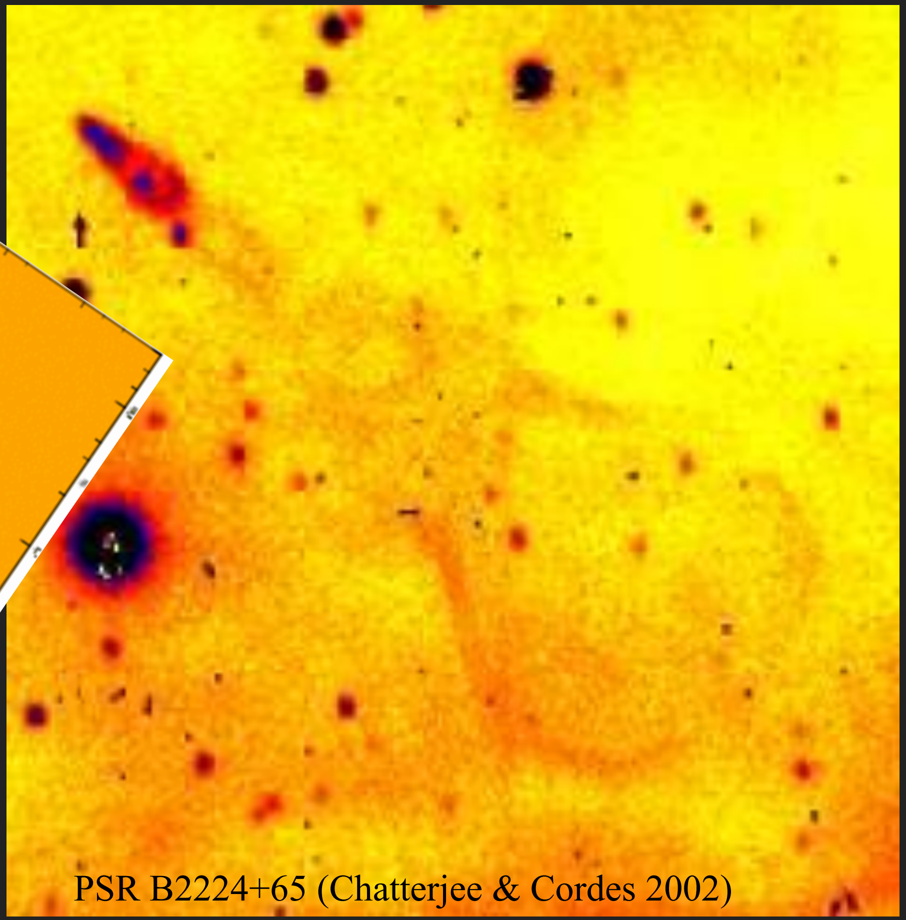
MOST PULSARS KICK VELOCITY IS SUPERSONIC IN ISM

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



PSR B1957+20 (Stappers et al. 2003)



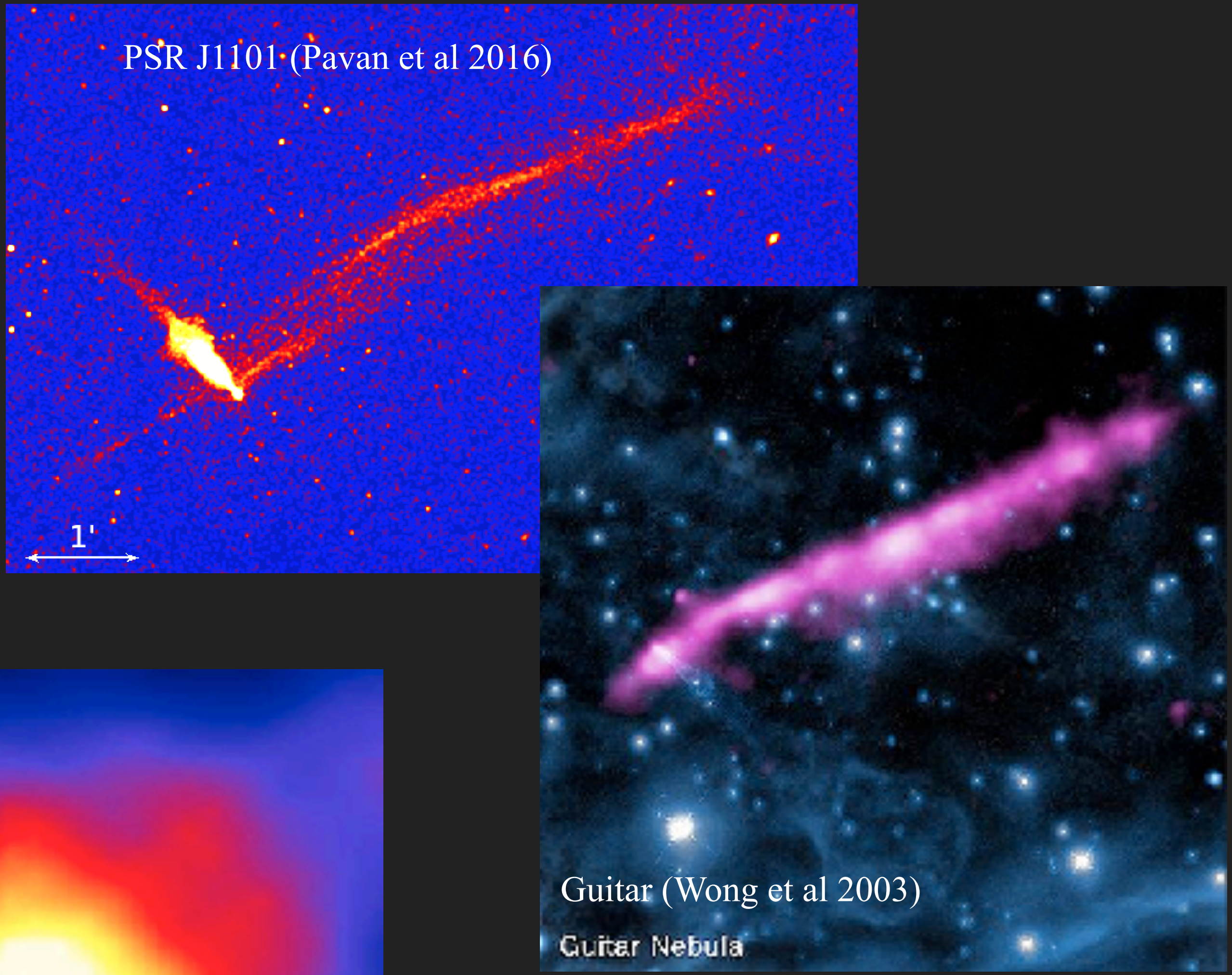


PSR B2224+65 (Chatterjee & Cordes 2002)

PAIR ESCAPE

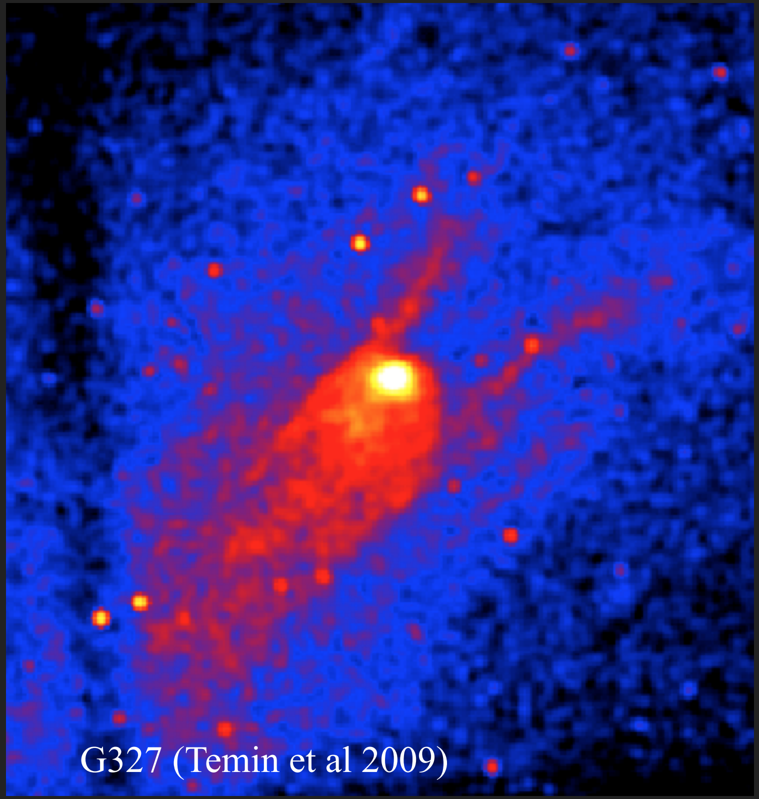
The are BS PWNe where the X-ray “tail” is where it should not be!

The particles in these features are ~ PSR voltage

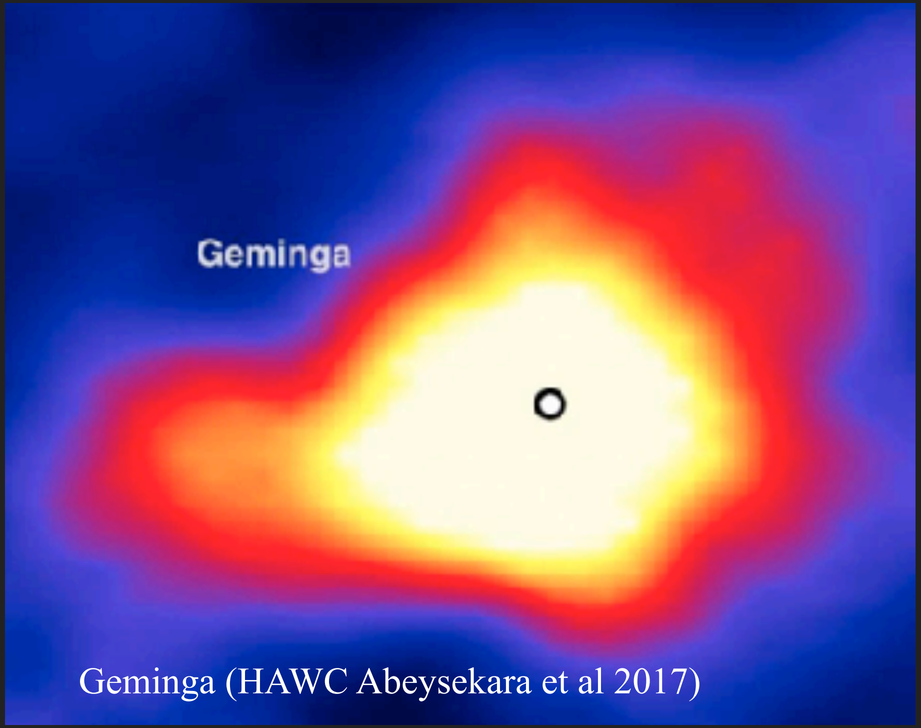


PSR J1101 (Pavan et al 2016)

Guitar (Wong et al 2003)



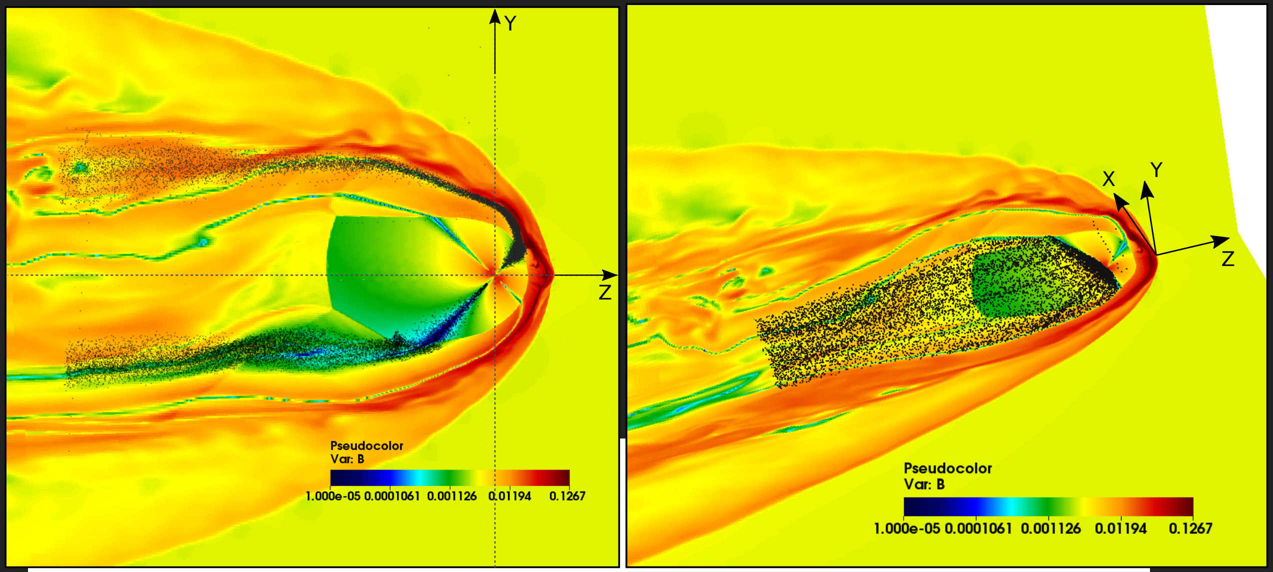
G327 (Temin et al 2009)



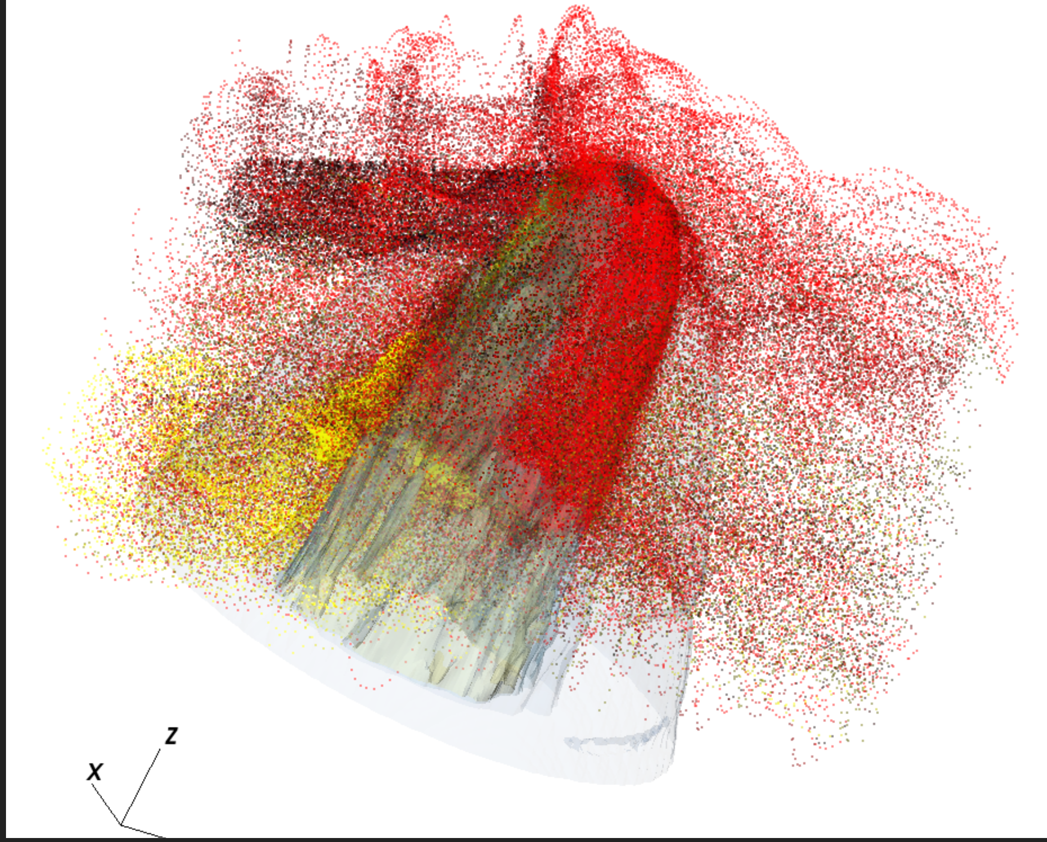
Geminga (HAWC Abeysekara et al 2017)

TeV halo suggest strong diffusion

PAIR ESCAPE IN MHD MODELS

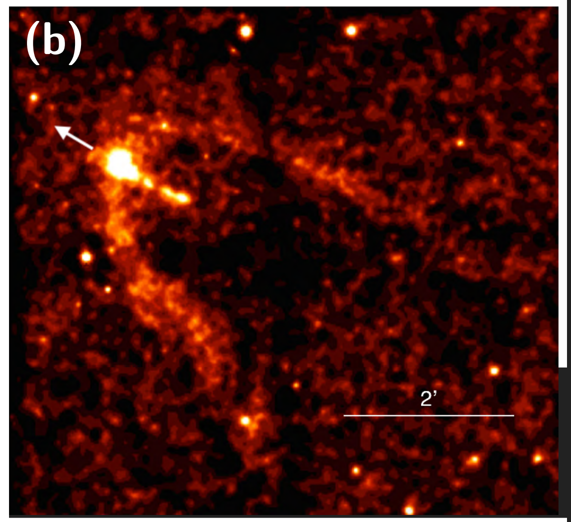


Olmi & Bucciantini 2019



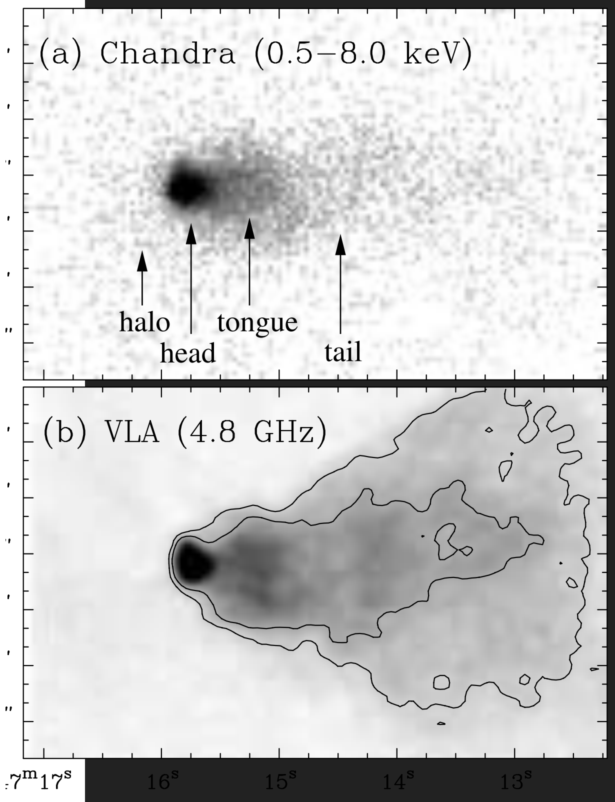
LOW ENERGY PARTICLES REMAIN CONFINED IN CURRENTS

GEMINGA HARD TAILS



VERY HIGH ENERGY PARTICLES CAN ALSO DIFFUSE AHEAD

MAUSE
X-RAY HALO



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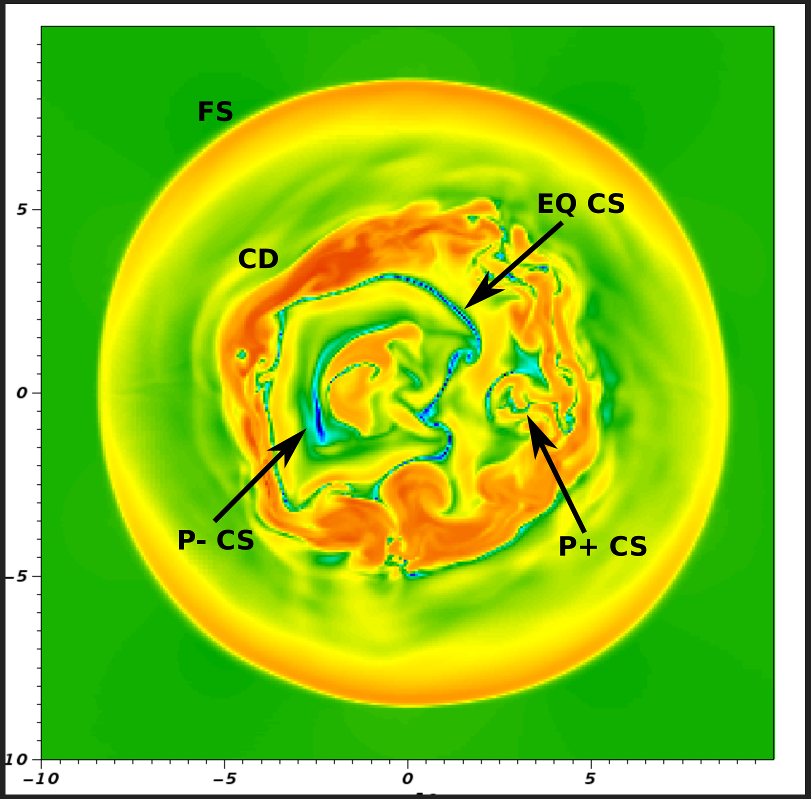


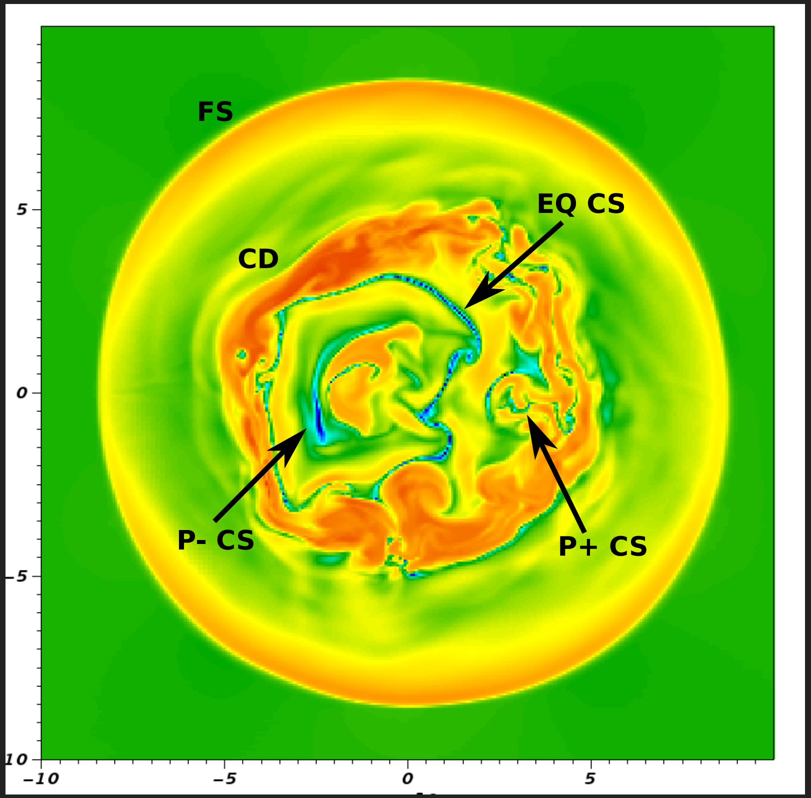
Olmi & Bucciantini 2019

TURBULENCE IN THE TAIL DEPENDENT ON INTERACTION GEOMETRY

ESCAPE ASSOCIATED TO RECONNECTION SITES AT THE MAGNETOPAUSE

STRONG ENERGY DEPENDENCE

PAIR ESCAPE IN MHD MODELS



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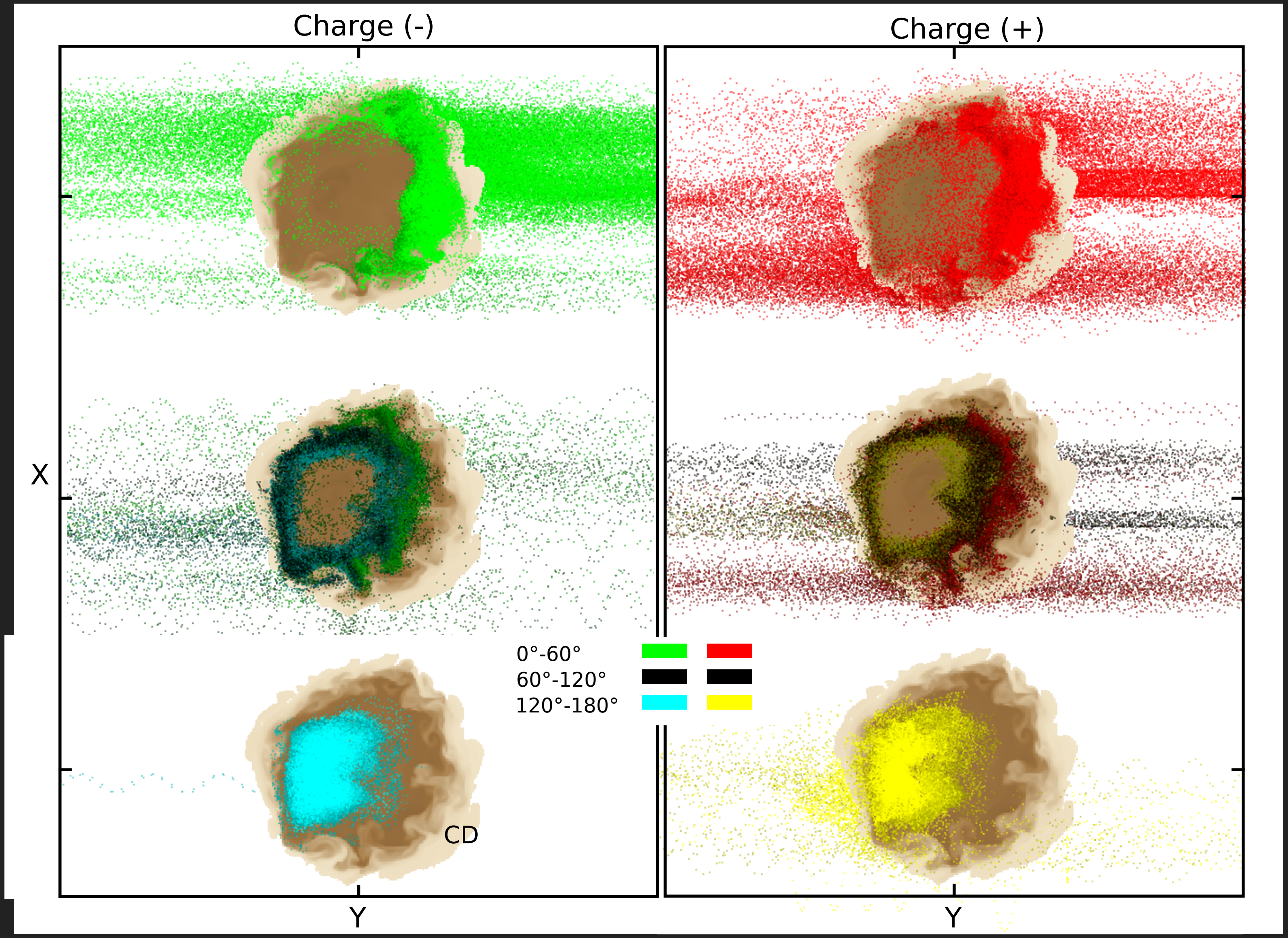


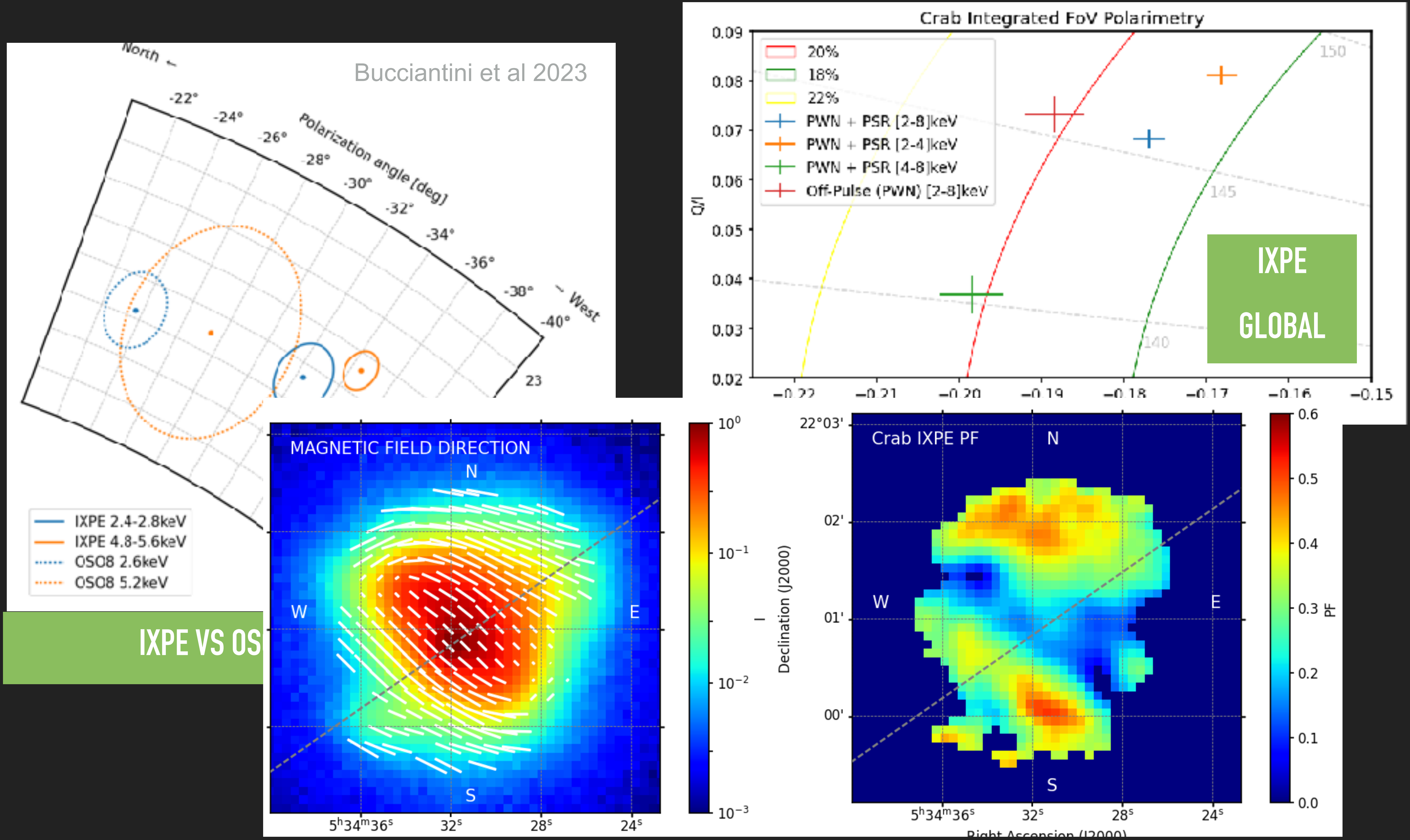
IXPE – X-RAY POLARIMETRY

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



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IXPE VS OS

IXPE

GLOBAL

IXPE - X-RAY POLARIMETRY - VELA

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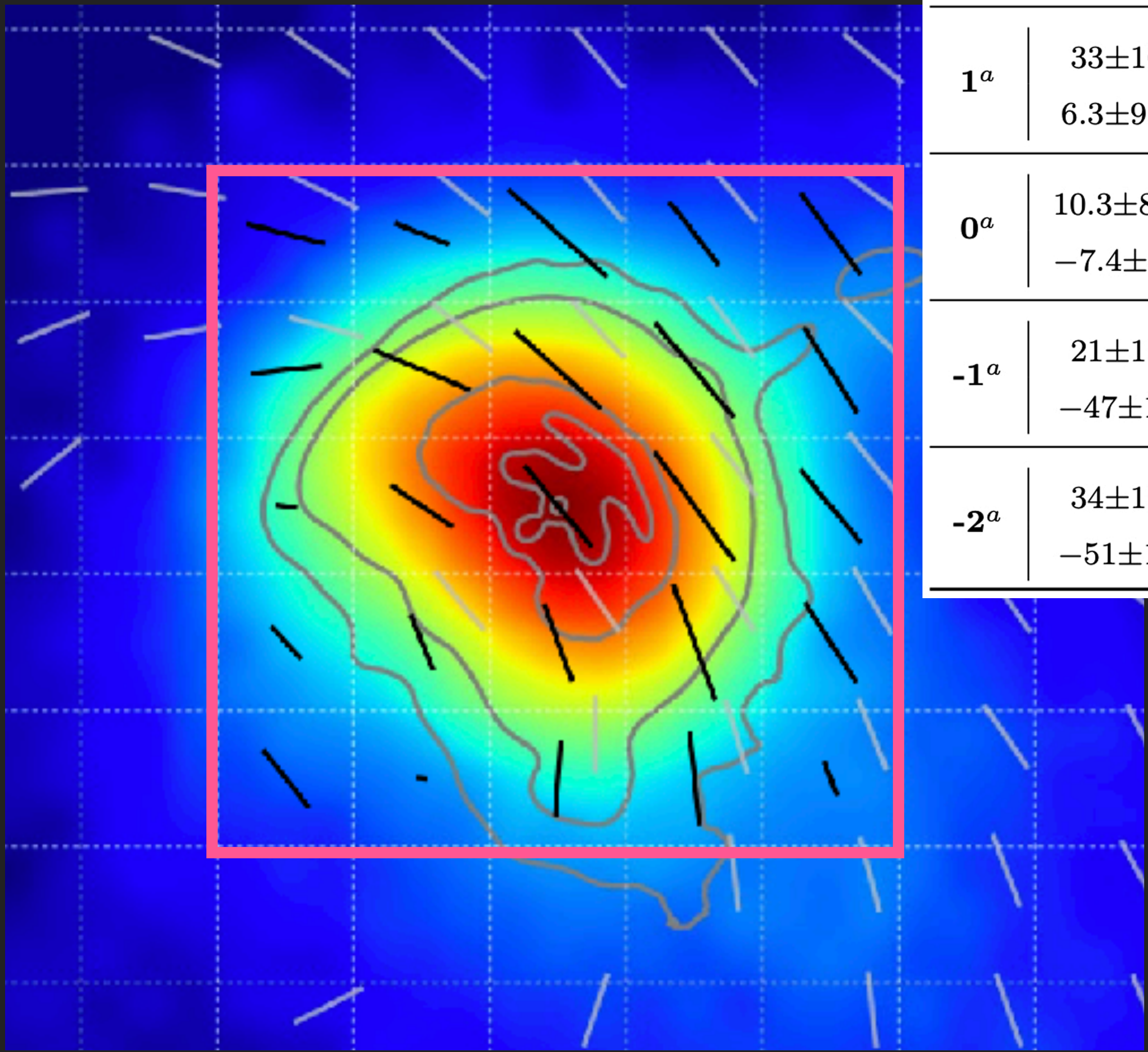
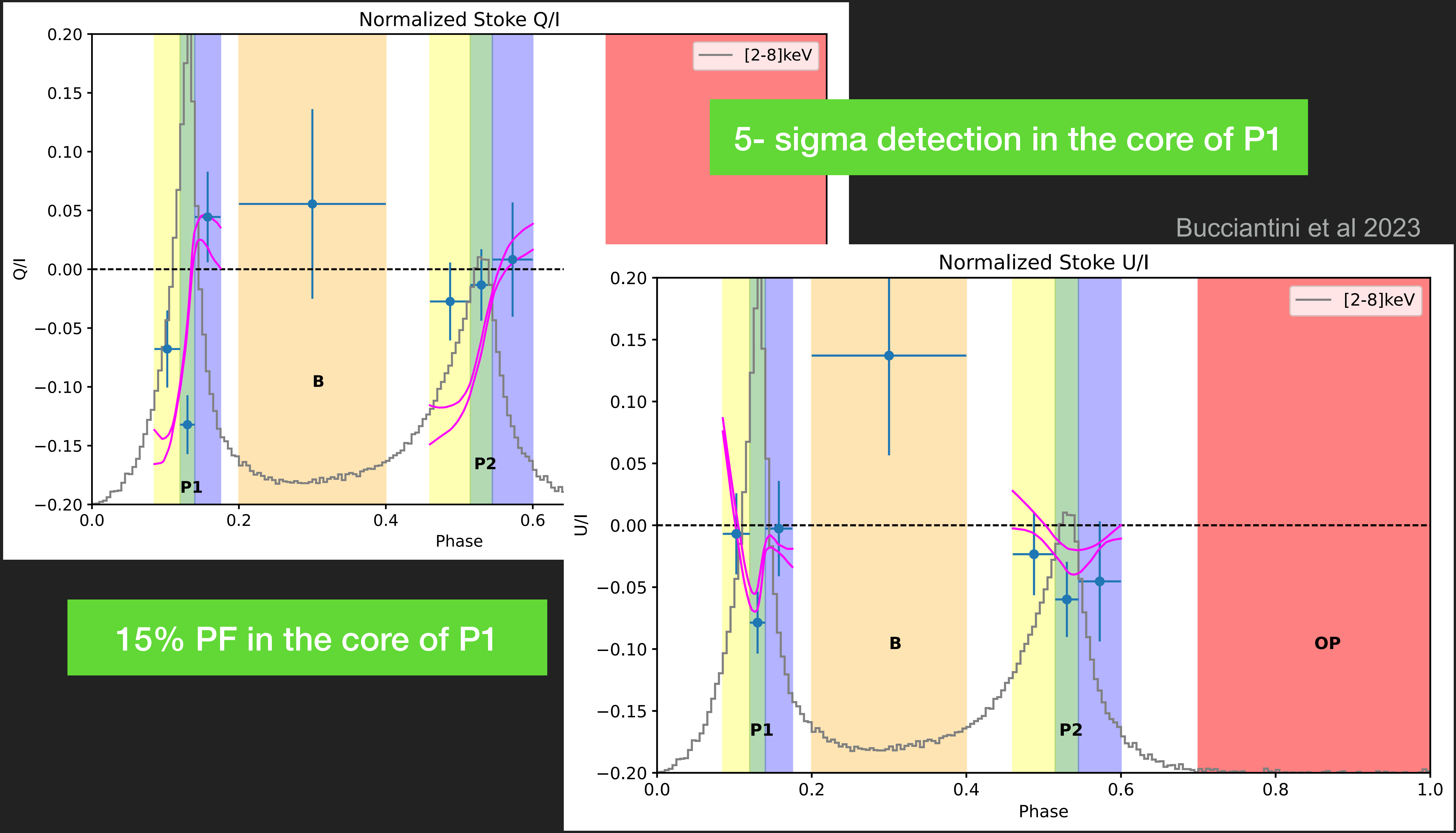


	-2^b	-1^b	0^b	1^b	2^b	
2^a	37±18	27±13	61±12	37±13	47±15	PD^c
	−14±14	−21±14	−41.7±5.3	−52±10	−53.8±8.9	PA^d
1^a	33±10	48.5±5.0	53.5±4.1	56.8±7.1	47±13	PD^c
	6.3±9.0	−22.4±3.0	−42.2±2.2	−50.2±3.6	−58.2±7.7	PA^d
0^a	10.3±8.8	34.4±3.9	49.0±2.5	62.8±4.0	44±11	PD^c
	−7.4±24	−34.3±3.3	−50.3±1.5	−53.9±1.9	−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

IXPE - X-RAY POLARIMETRY - CRAB PSR



5- sigma detection in the core of P1

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15% PF in the core of P1

CONCLUSIONS

PWNE HAVE BEEN AT THE HEART OF HIGH ENERGY ASTROPHYSICS & THE CRAB NEBULA IS ONE OF THE MOST STUDIED OBJET IN THE SKY WHERE MANY HIGH ENERGY PROCESSES HAVE BEEN DISCOVERED/IDENTIFIED

PWNE & PSRS REMAIN ONE OF THE MOST INTERESTING ENVIRONMENT OF MODERN PHYSICS AND KEEPS SURPRISING US WITH NEW PHENOMENOLOGY

STILL MANY OPEN QUESTIONS NED TO BE ANSWERED:

HOW DOES EVOLVED PWNE BEHAVE?
WHAT ACCELERATION PROCESS IS AT WORK AND WHERE?
HOW PARTICLE MANAGE TO ESCAPE?
WHAT IS THE SOURCE OF THE GAMMA-RAY VARIABILITY?
WHAT IS THE ROLE OF TURBULENCE AND WHAT POLARISATION CAN TELL US?

THANK YOU