PULSAR WIND NEBULAE:

THE WONDROUS MACHINES OF HIGH ENERGY ASTROPHYSICS

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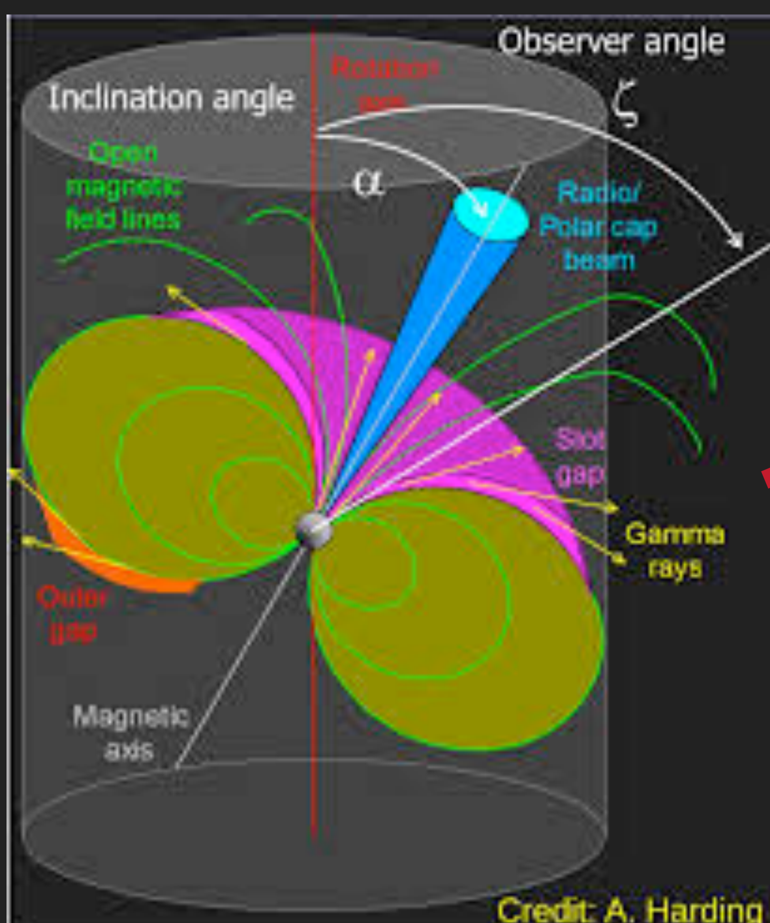
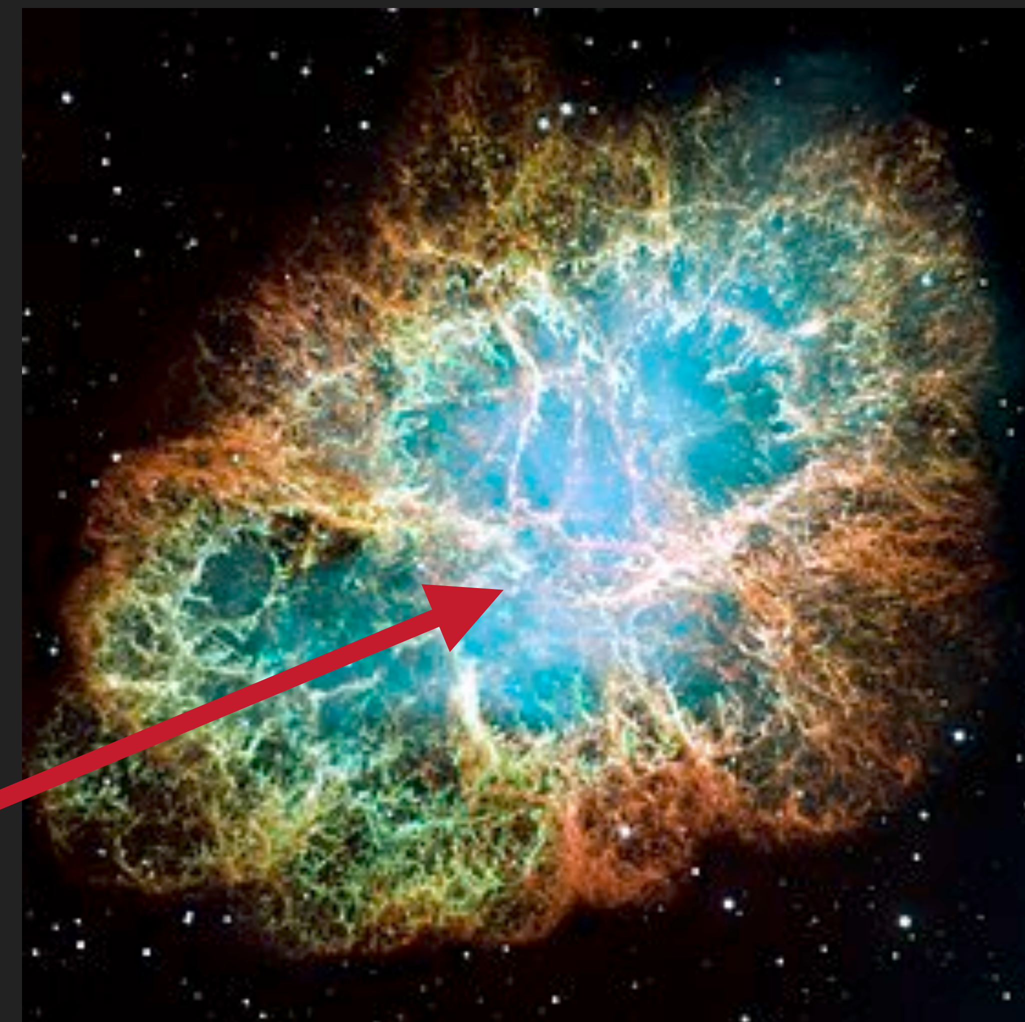
DEATH OF A MASSIVE STAR – THE BIRTH OF PULSAR

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





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

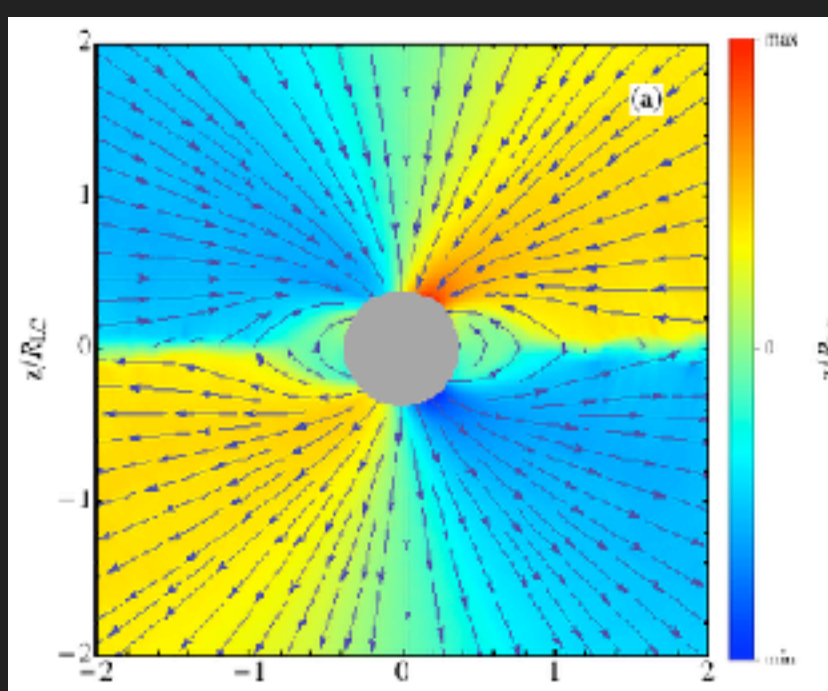
THE PUSAR WIND

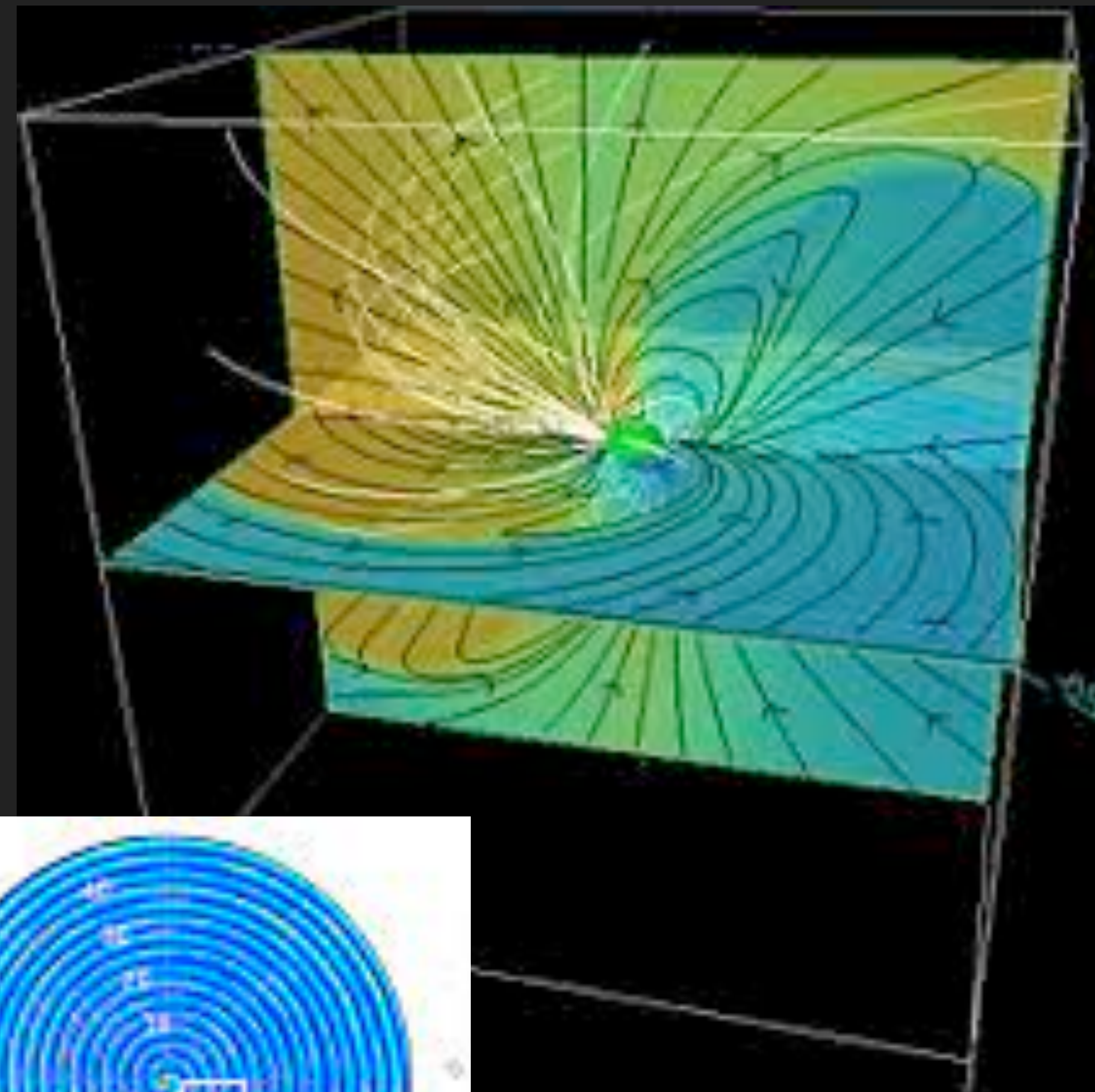
PSR WIND & MAGNETOSPHERE WELL DESCRIBED BY FORCE FREE RMHD

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

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

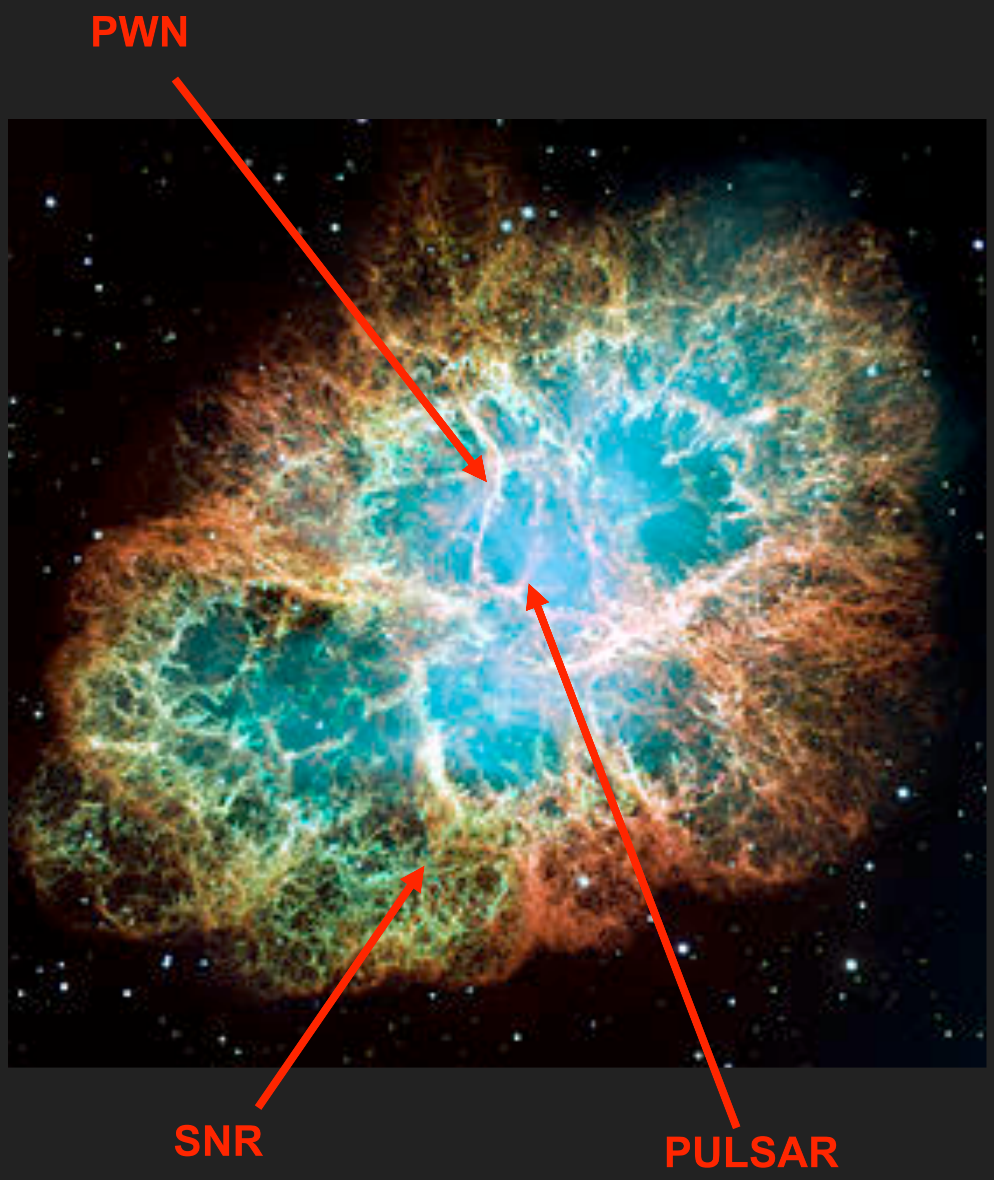
RHO & J SET BY VANISHING LORENTZ FORCE





STRIPED WIND OF ALTERNATING POLARITIES

PUSAR WIND NEBULAE & SUPERNOVA REMNANTS



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

MULTI-WAVELENGTHS PUSAR WIND NEBULAE

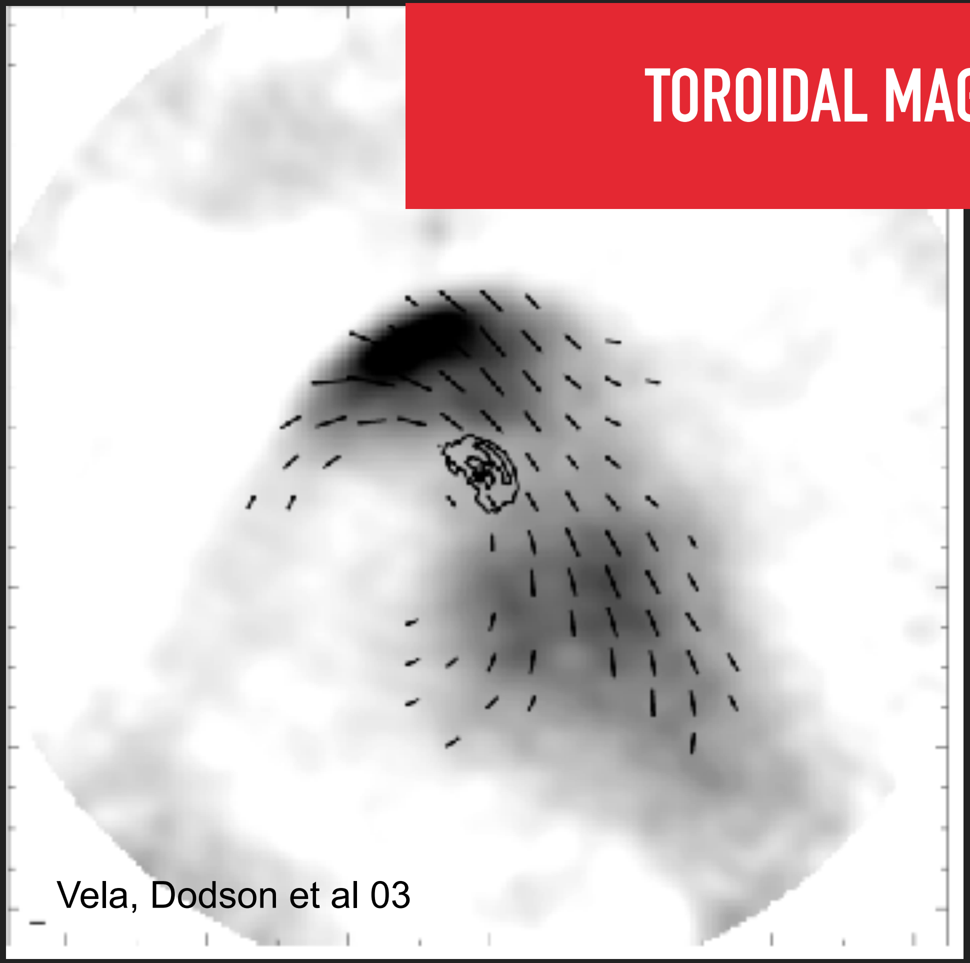
γ—rays (<100 MeV)

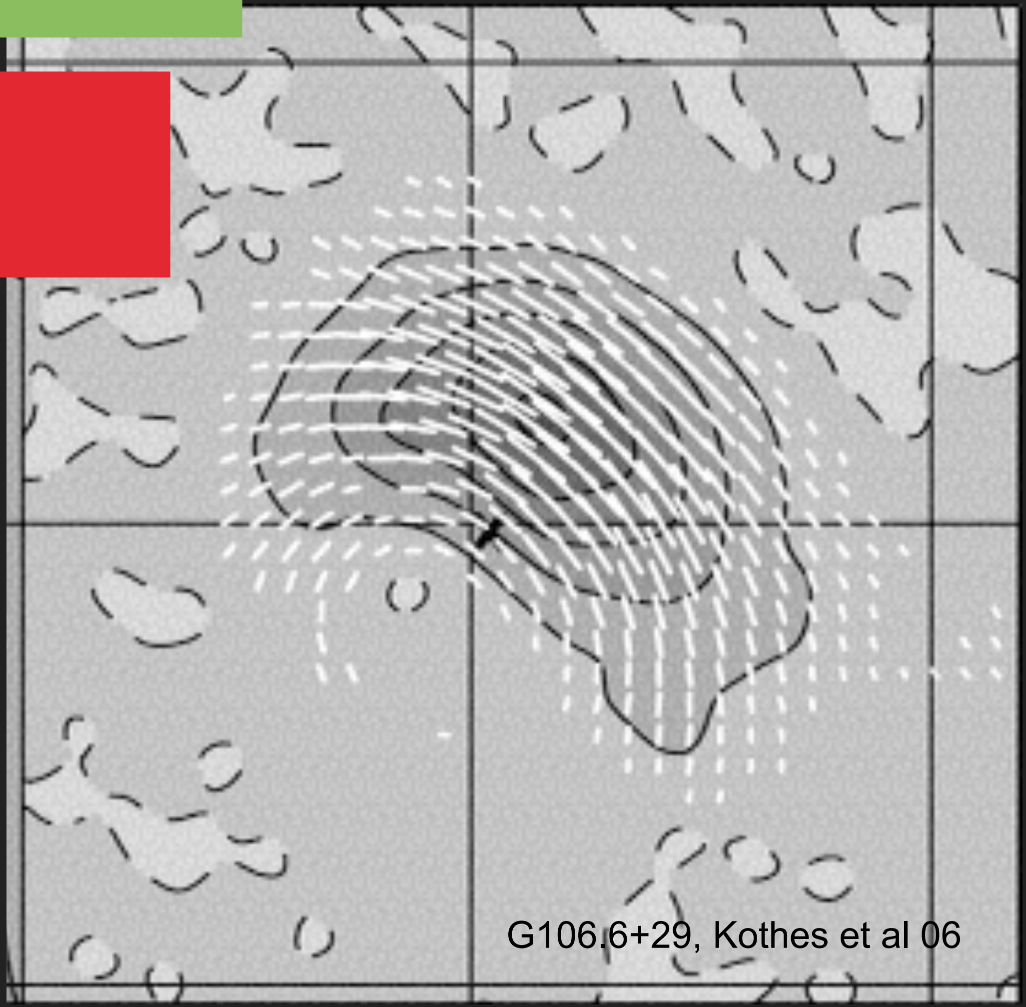
SIZE SHRINKS WITH ENERGY - NOT ALWAYS!

WIND SNR INTERACTION

HIGH POLARIZATION 30-40%=> SYNCHROTRON

TOROIDAL MAGNETIC FIELD





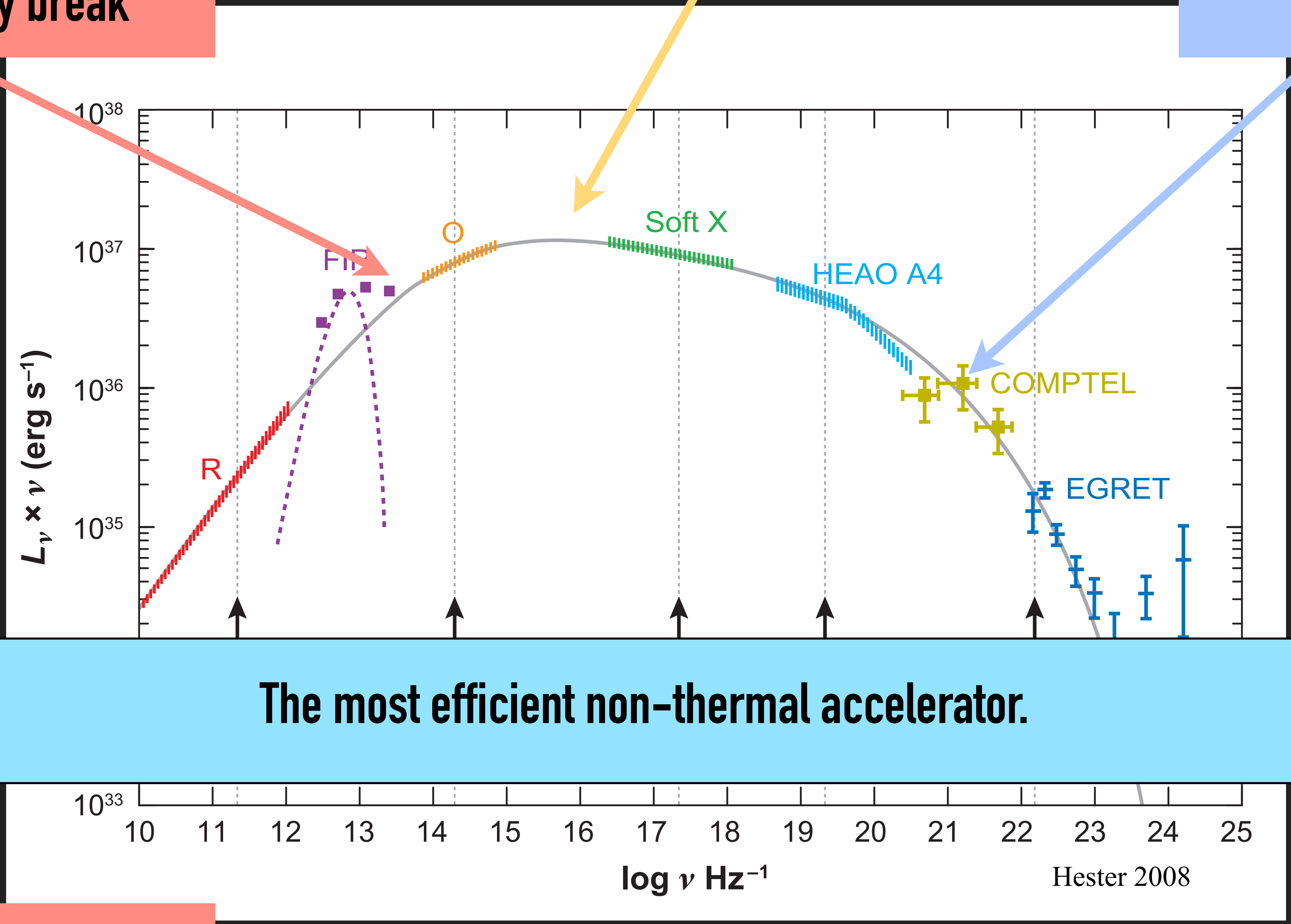
NOT ALL PWNE HAVE CLEARLY DEFINED POLARIZATION GEOMETRY

THE NON THERMAL ACCELERATORE

High energy break

Low energy break

MeV cutoff



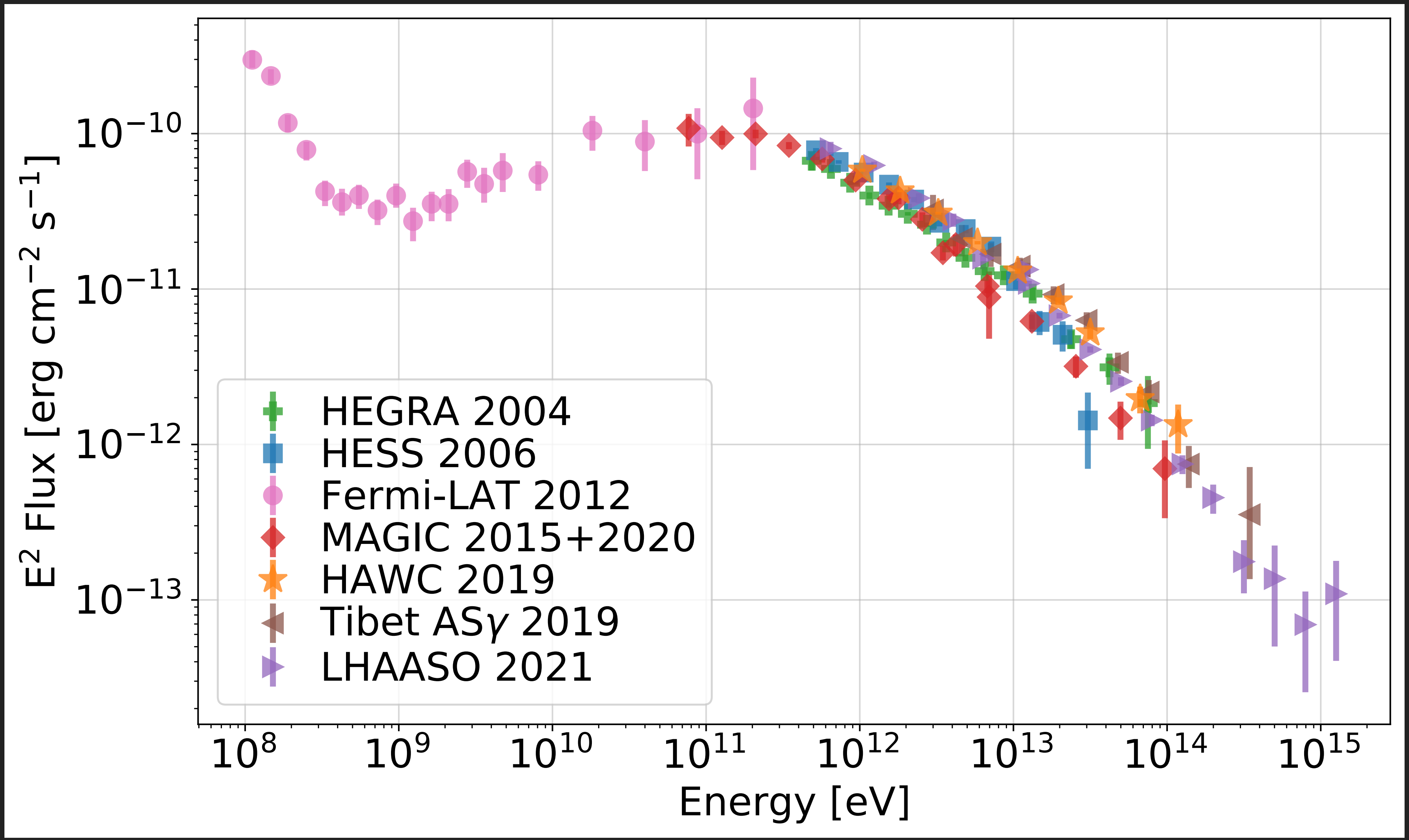
The most efficient non-thermal accelerator.

Injection break

Synchr. cooling

Acceler. cutoff

CRAB IN THE GAMMA-RAYS



HIGHEST ENERGY LHAASO DATA POINT ⟷ $E_{\rm e} \approx 2.4$ PeV

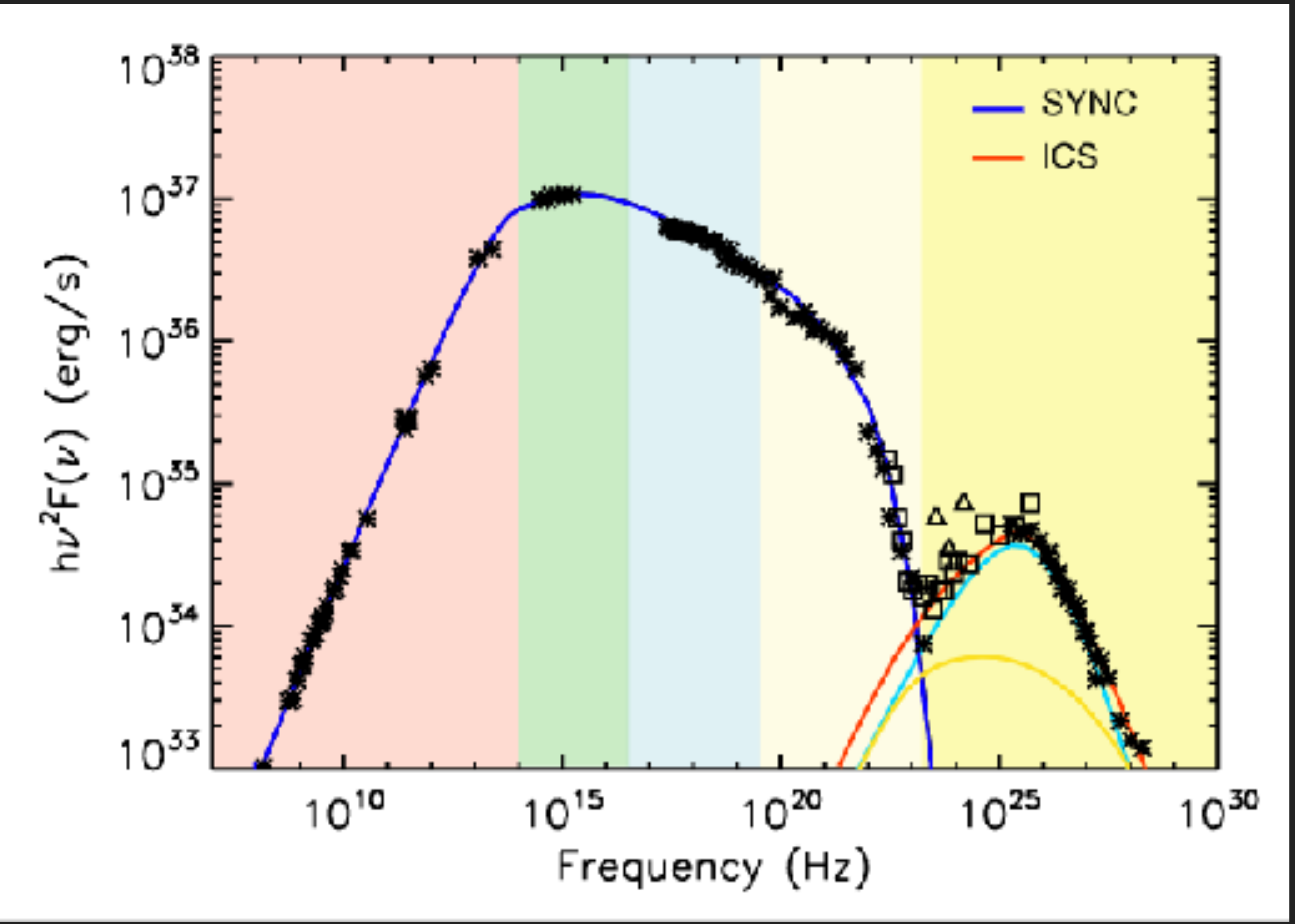
FOR ICS ON CMB

$$\epsilon_\gamma \approx 0.37\ (E_{\rm e}/\mathrm{PeV})^{1.3}\ \mathrm{PeV}$$

MODELLING RELATIVISTIC PLASMA BUBBLES

The PWN is treated as a uniform expanding bubble, with no internal gradients

At each time one define various quantities:
The nebular radius-size
The nebular magnetic field



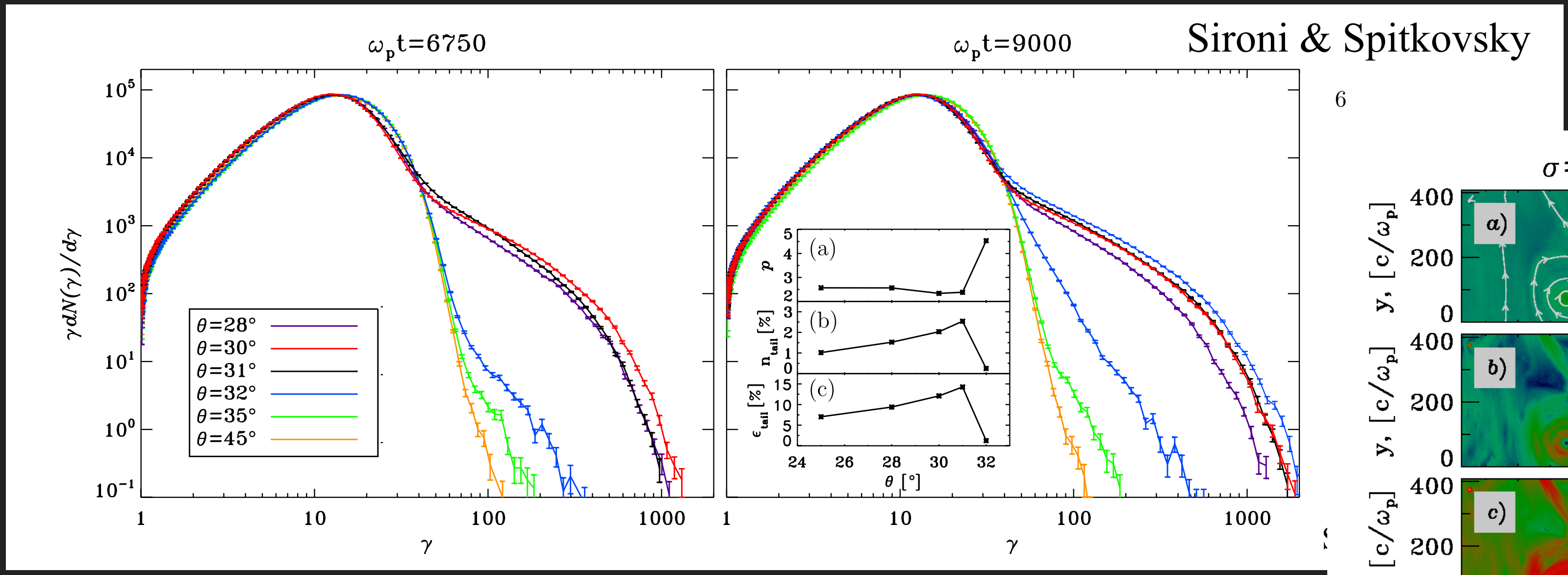
One can then follow the evolution of emitting particles injected inside the nebula and subject to losses, and compute emission

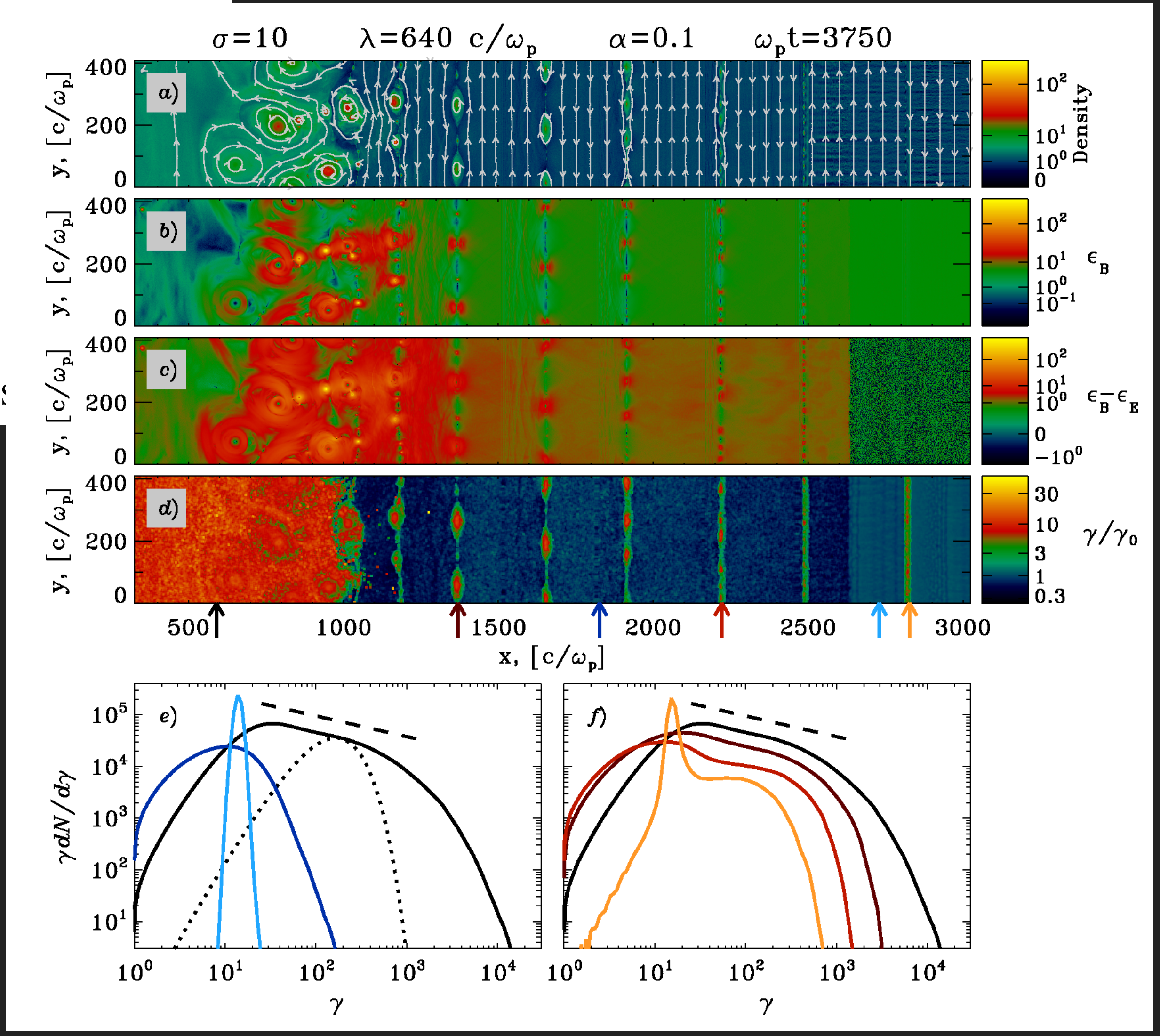
$$\frac{\mathrm{d}E(t)}{\mathrm{d}t} = -\frac{\dot{R}(t)}{R(t)}E(t) - \frac{4\sigma_t}{3m^2c^3}E^2(t)\left(\frac{B(t)^2}{8\pi} + U(t)\right),$$

BEWARE CORRELATIONS!!!!!!

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

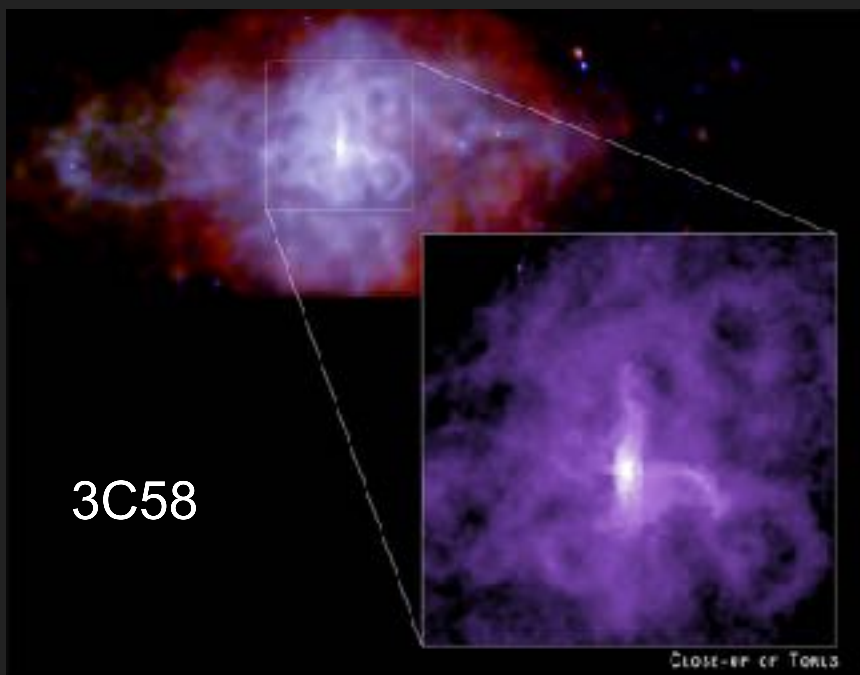
ACCELERATION RECIPES - TAKE HOME MESSAGE

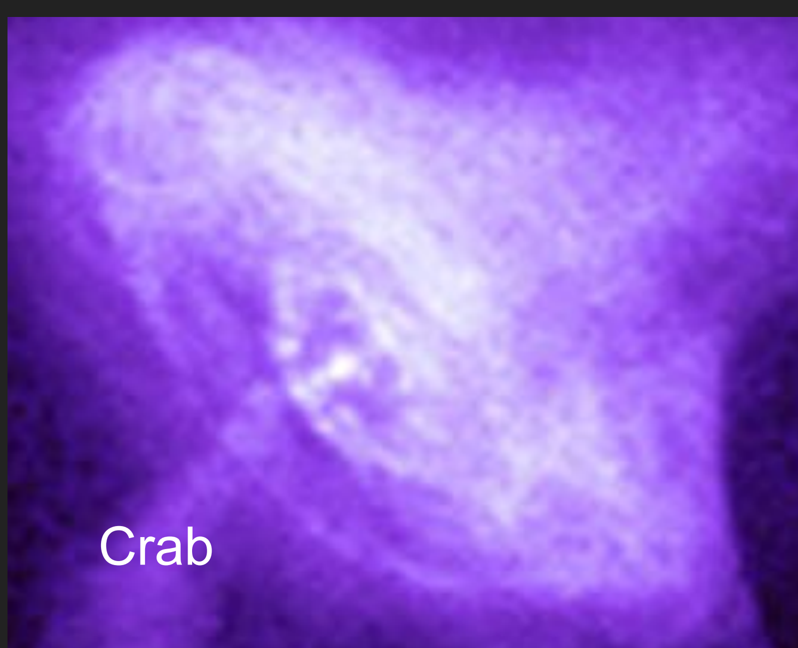
NEBULAR DYNAMICS AND HIGH ENERGY EMISSION PROPERTIES → $\sigma \gtrsim 1$ → TOO LARGE FOR FERMI ACCELERATION BUT TURBULENCE MIGHT HELP

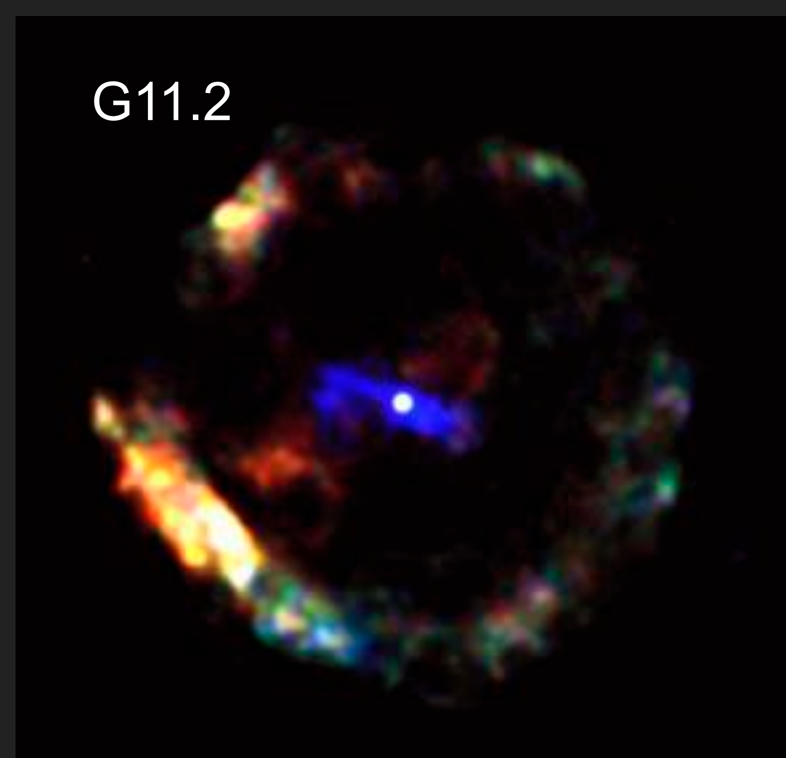
MODELLING OF RADIO EMISSION → $\kappa \approx \text{few} \times 10^3$ AND $\Gamma > \text{few} \times 10^6$ VIABLE → ION CYCLOTRON VIABLE

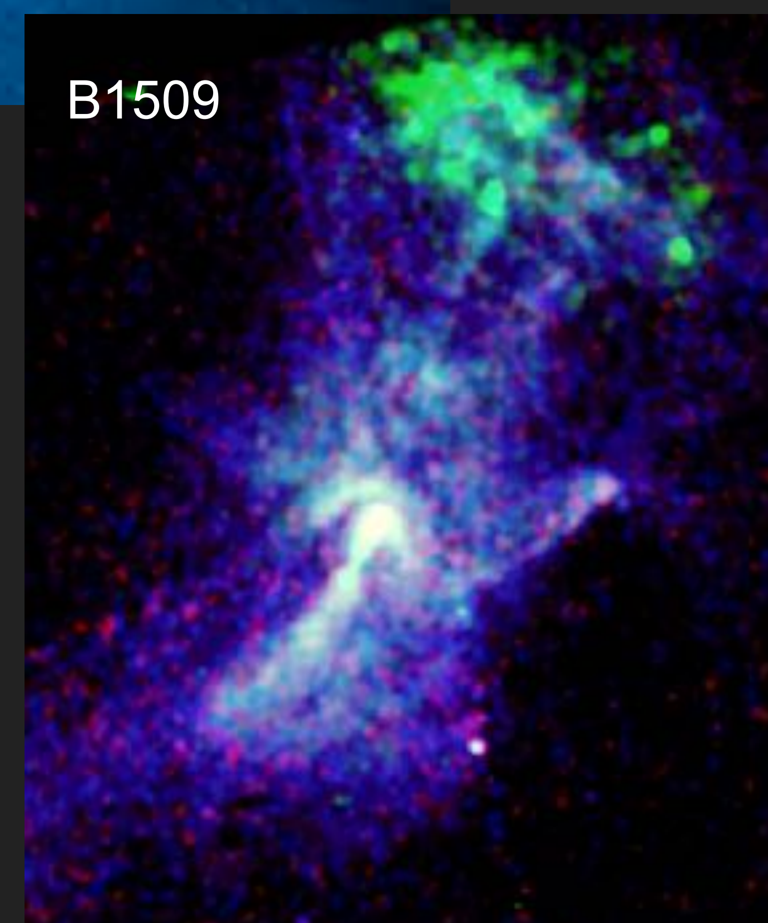
MODELLING OF MULTIFREQUENCY VARIABILITY OF INNER NEBULA → ACCELERATION OF LOW AND HIGH ENERGY PARTICLES IN DIFFERENT REGIONS → LOW ENERGY FROM TURBULENT ACCELERATION IN THE NEBULA?

FINE STRUCTURES - A LAB FOR RELTIVISTICN FLUID DYNAMICS



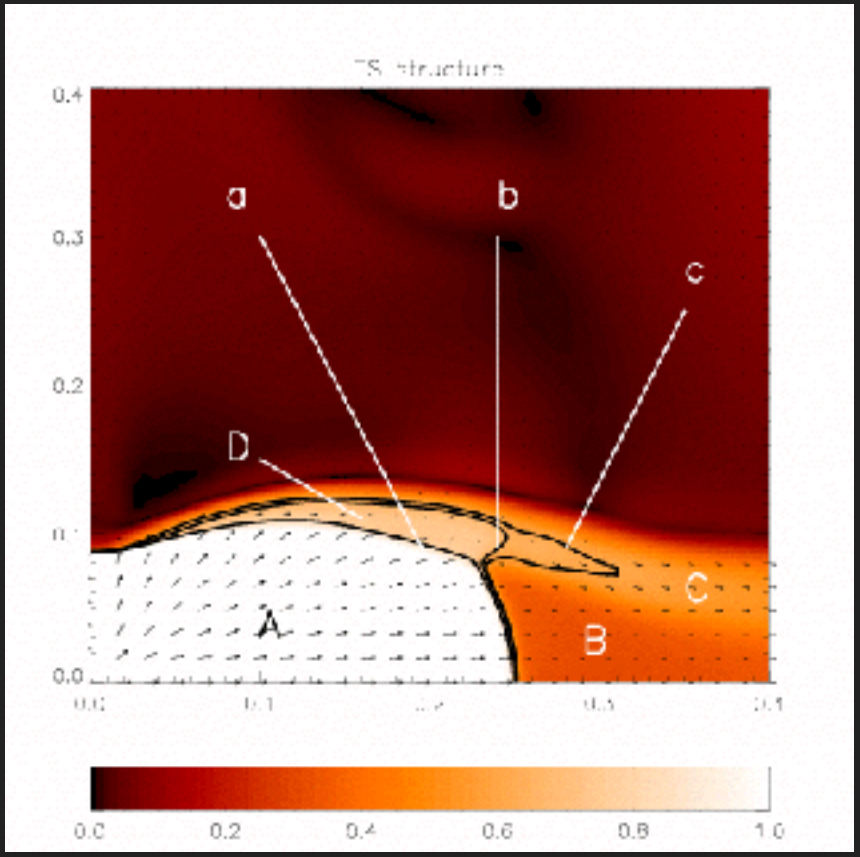






RELATIVISTIC MHD MODELS

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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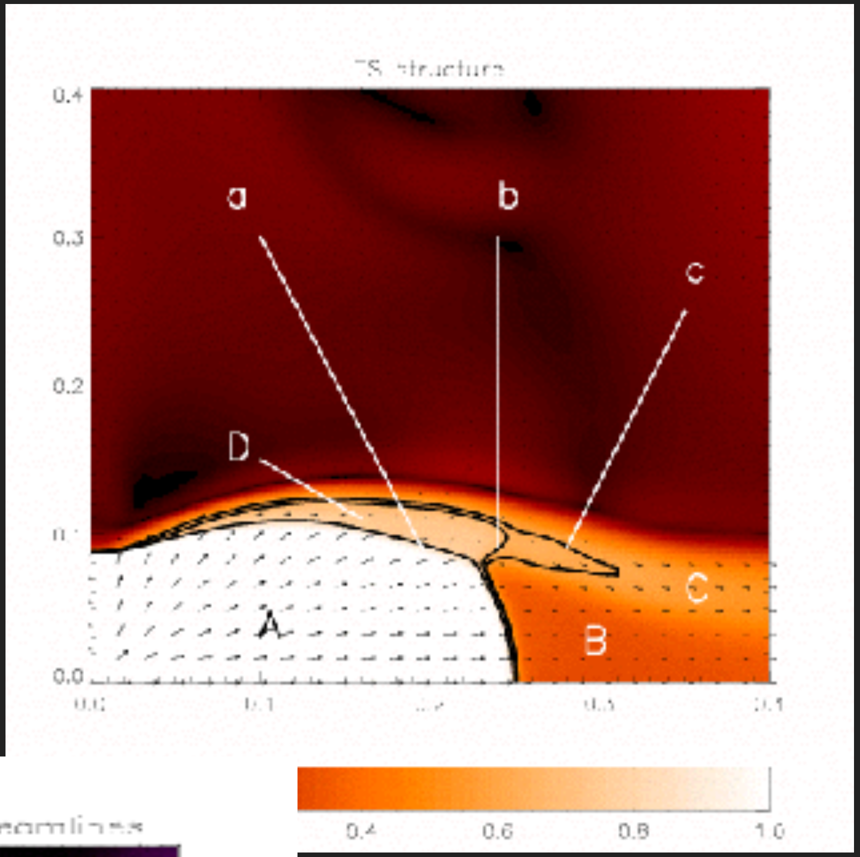
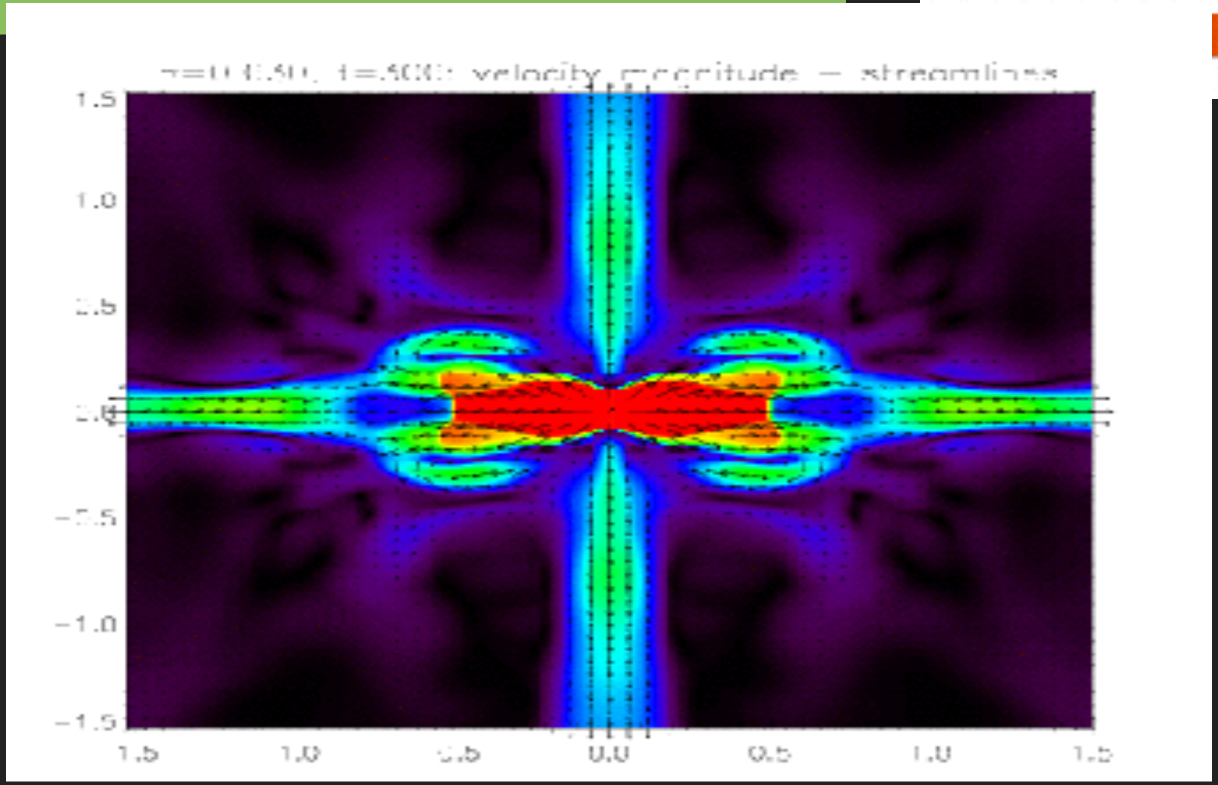
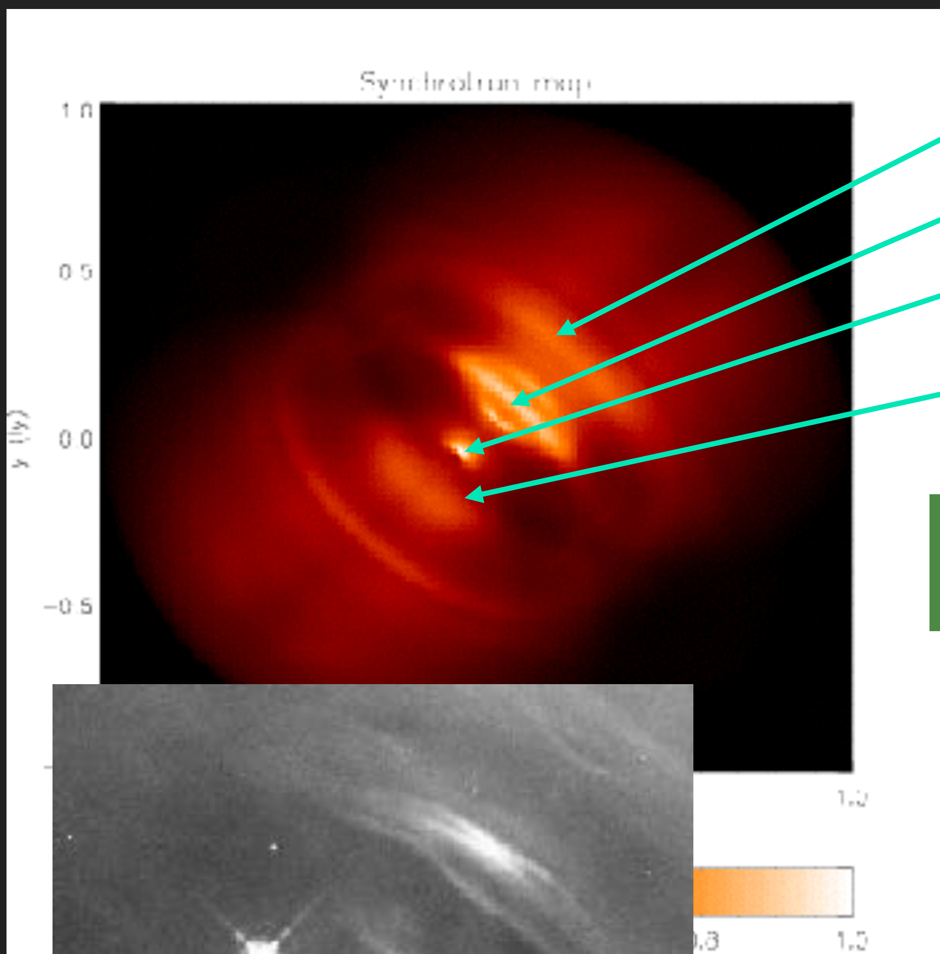




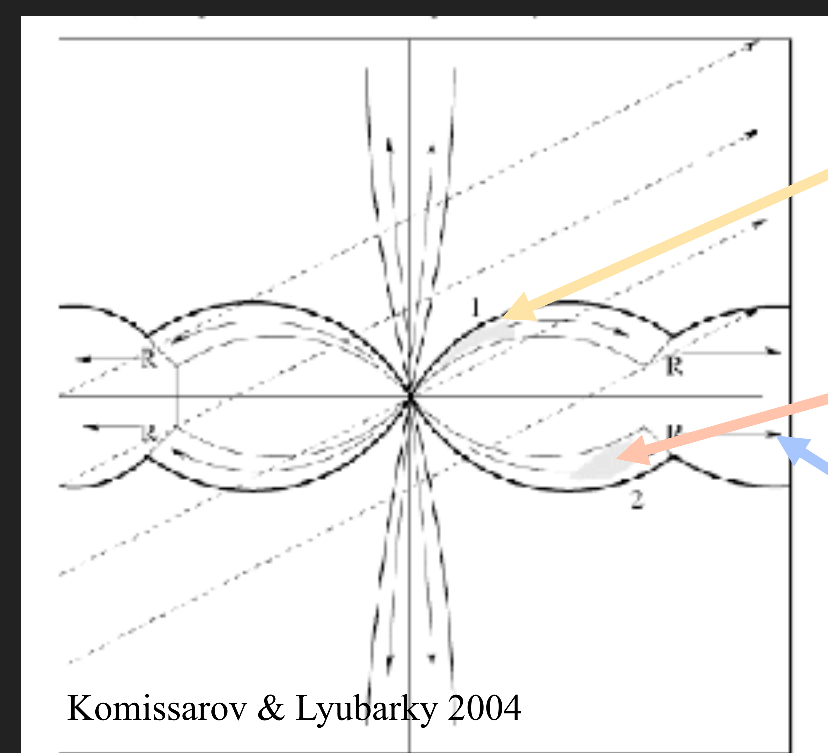
REPRODUCING OBSERVATIONS



Hester et al. 1995

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

Each feature traces an emitting region



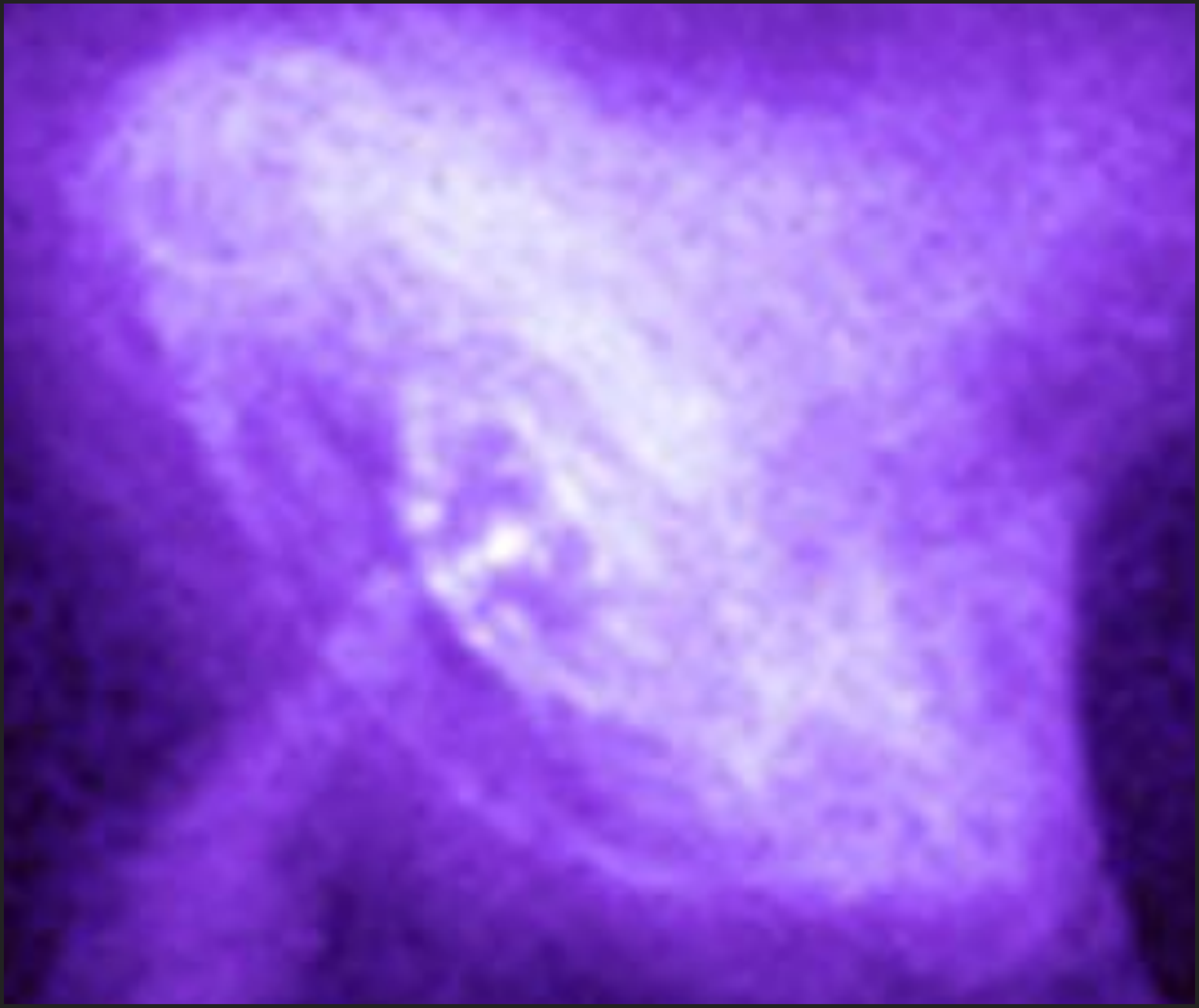
Komissarov & Lyubarky 2004

Knot

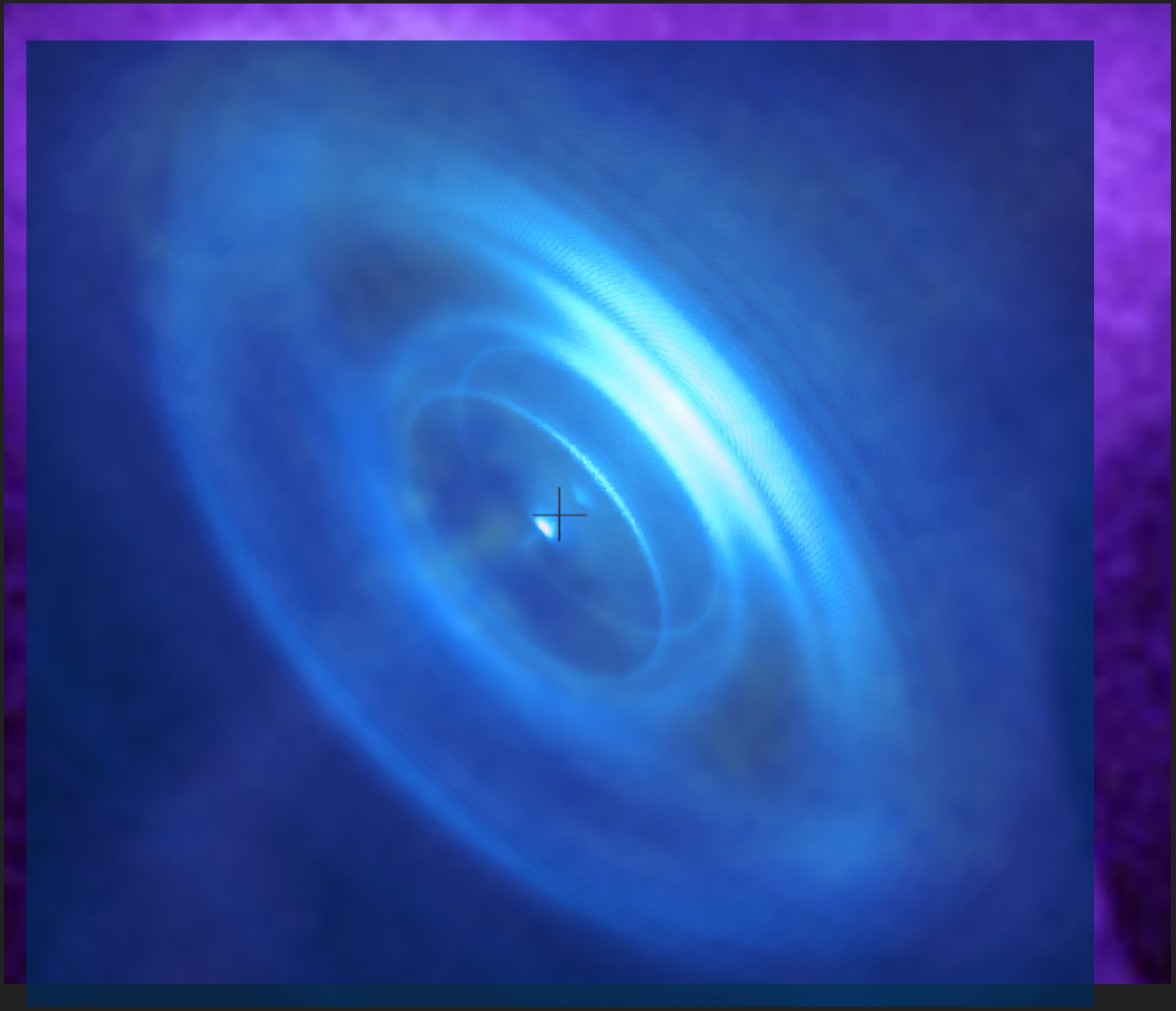
Ring

Torus

REPRODUCING OBSERVATIONS



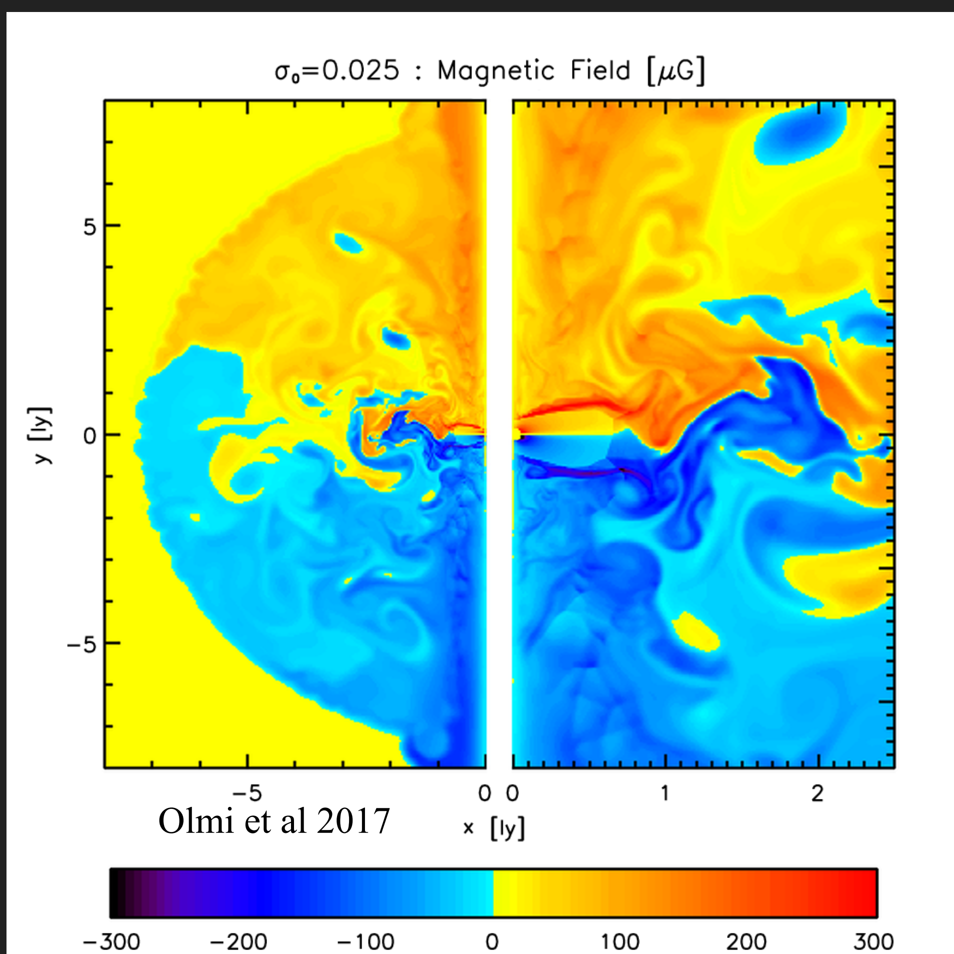
REPRODUCING OBSERVATIONS

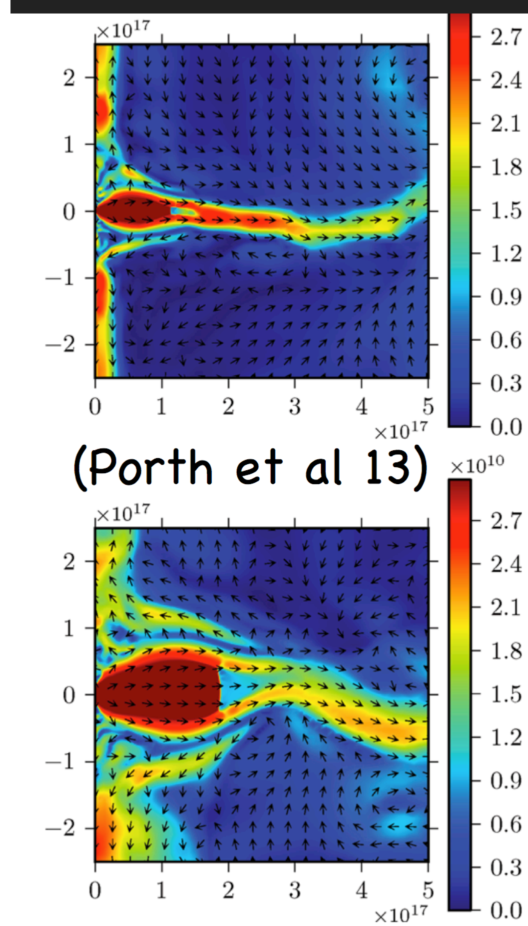


THE COMPLEXITY OF GOING 3D - STATE OF THE ART COMPUTATIONS

INNER REGION STILL AXISYMMETRIC TORUS-JET

3D ALLOWS FOR HIGHER MAGNETIZATIONS

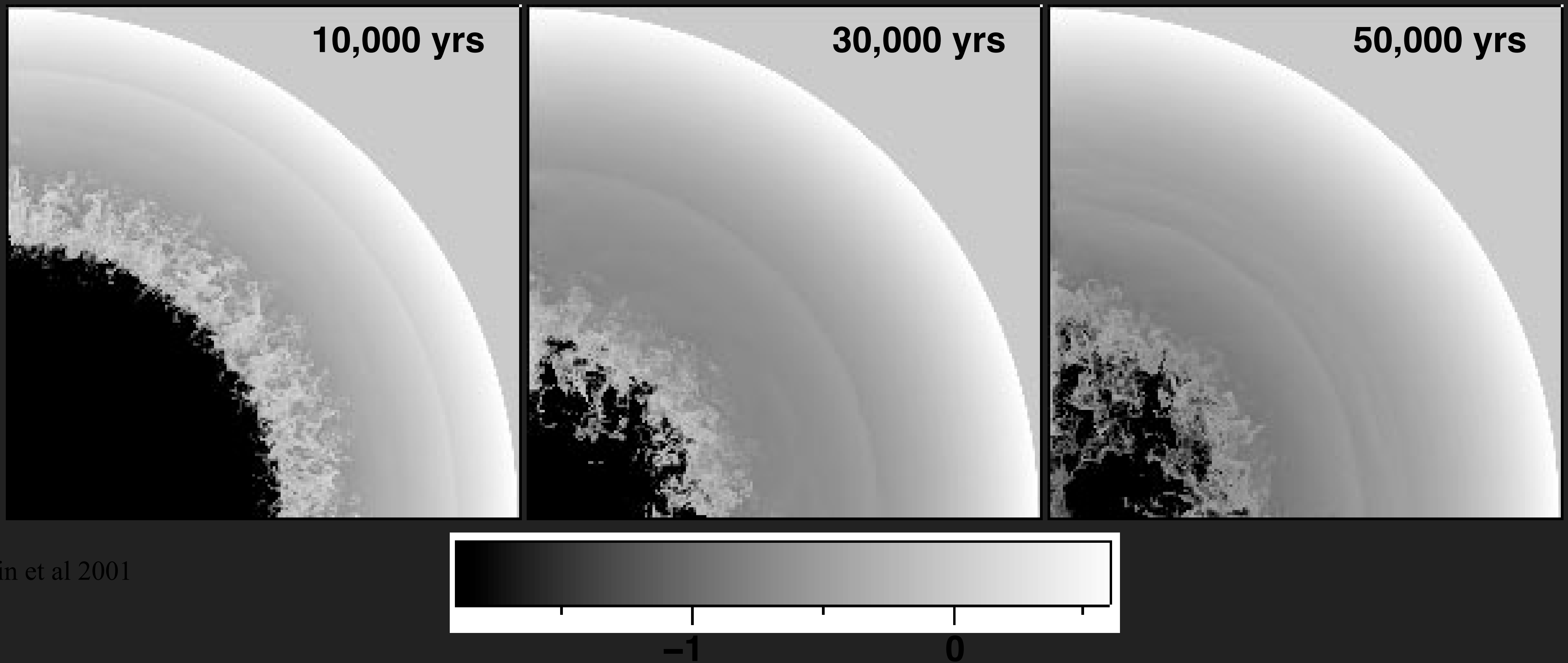




WEAKER JET AND POLATIZATION

TIME EVOLUTION I

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



Blondin et al 2001

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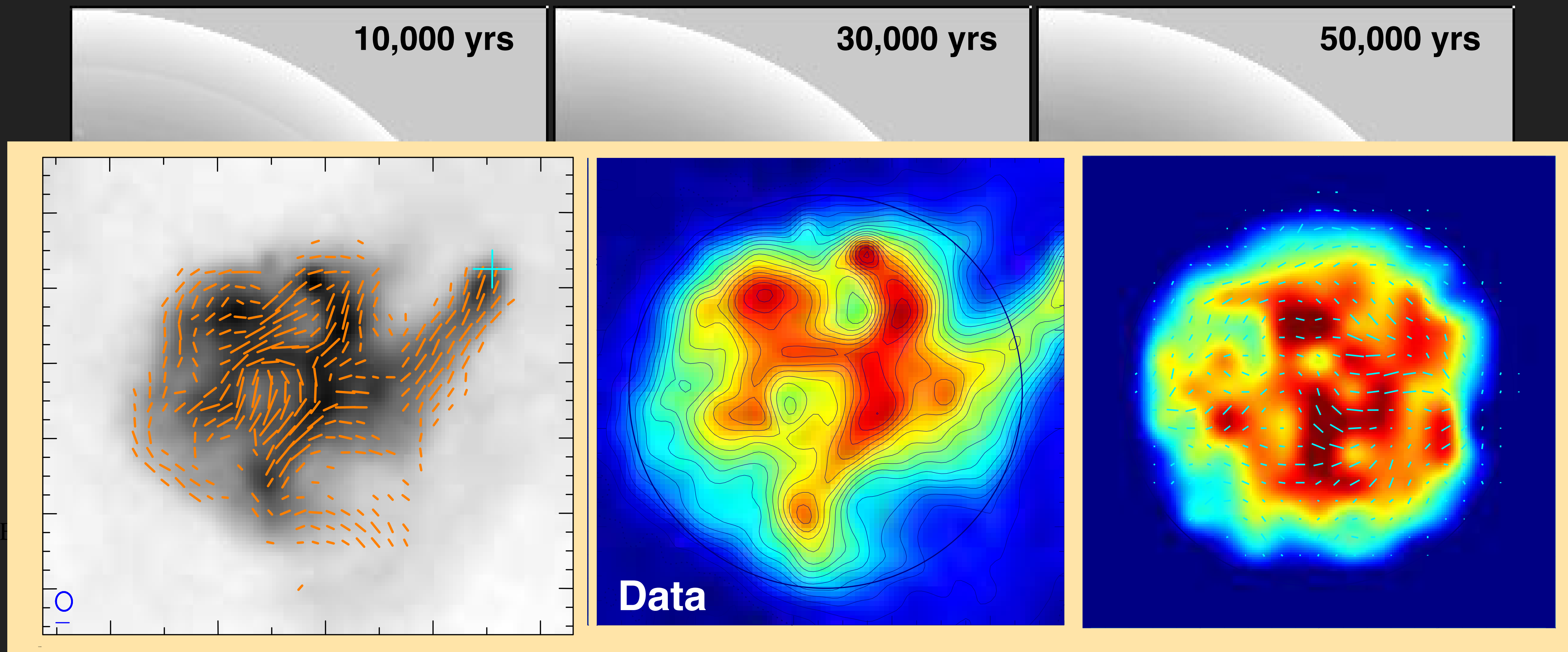
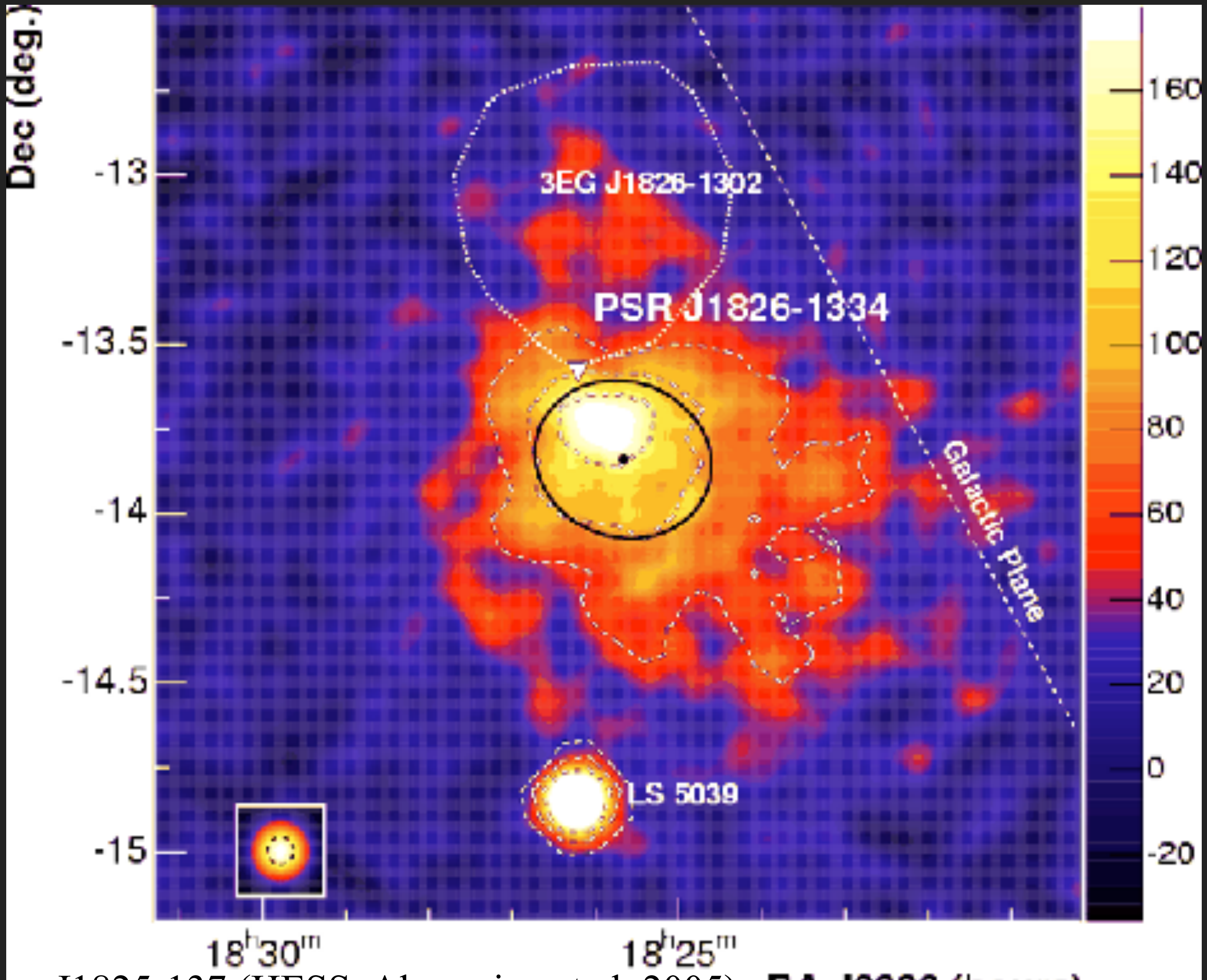


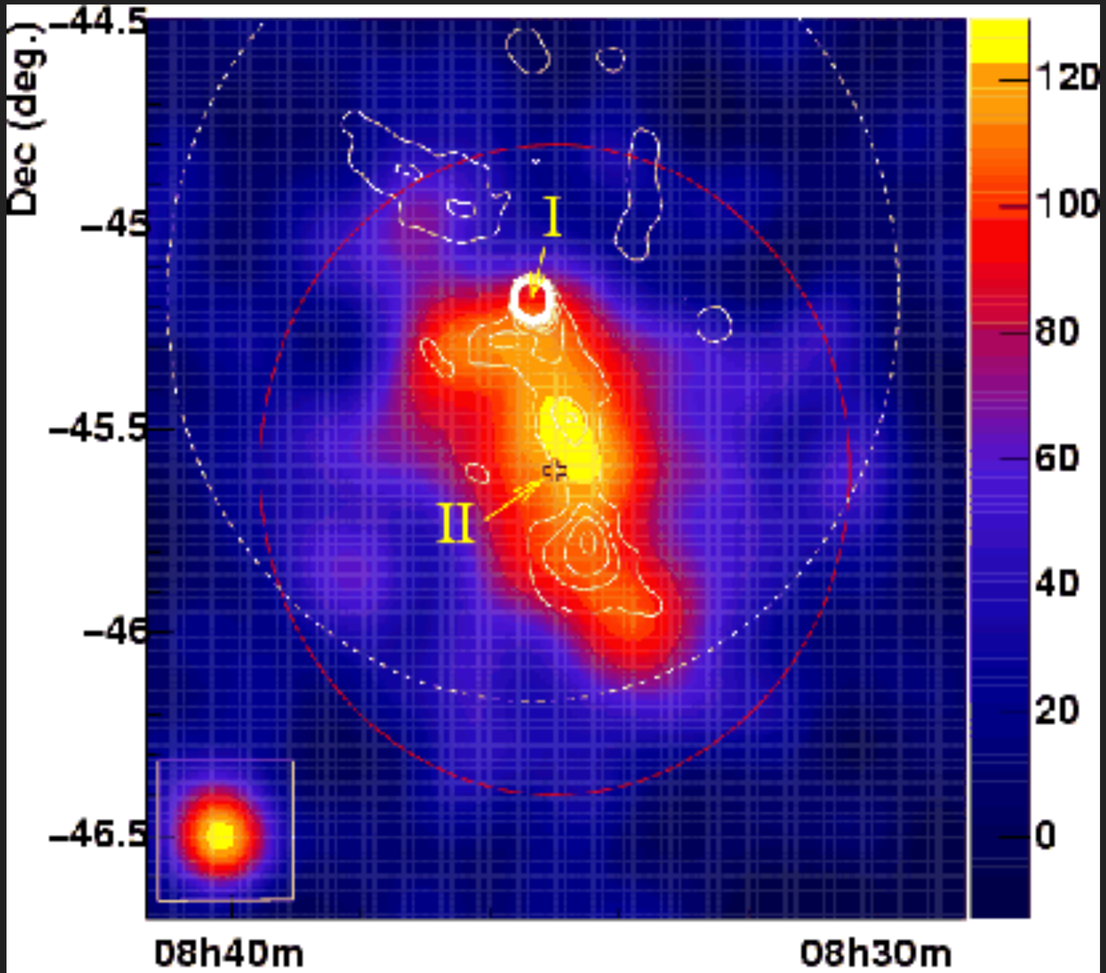
G327 Ma et al. 2015

TIME EVOLUTION II

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



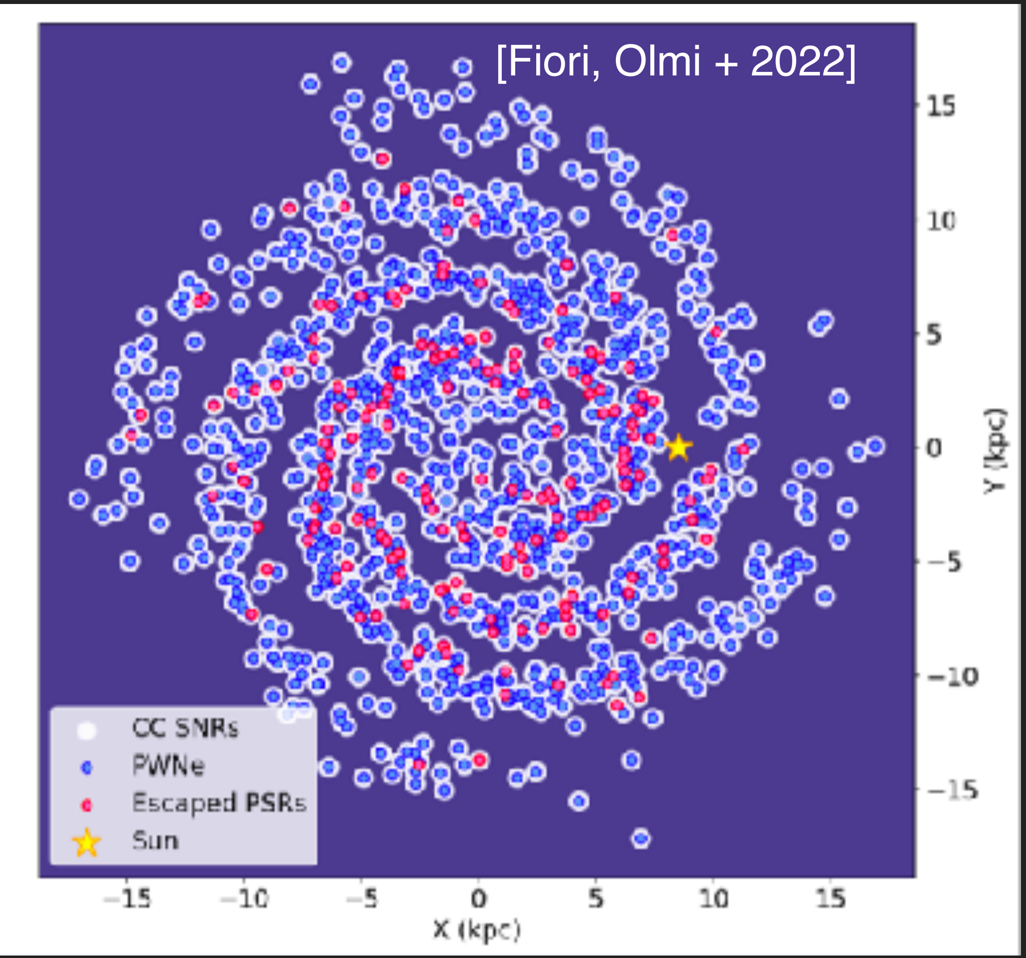
J1825-137 (HESS; Aharonian et al. 2005)



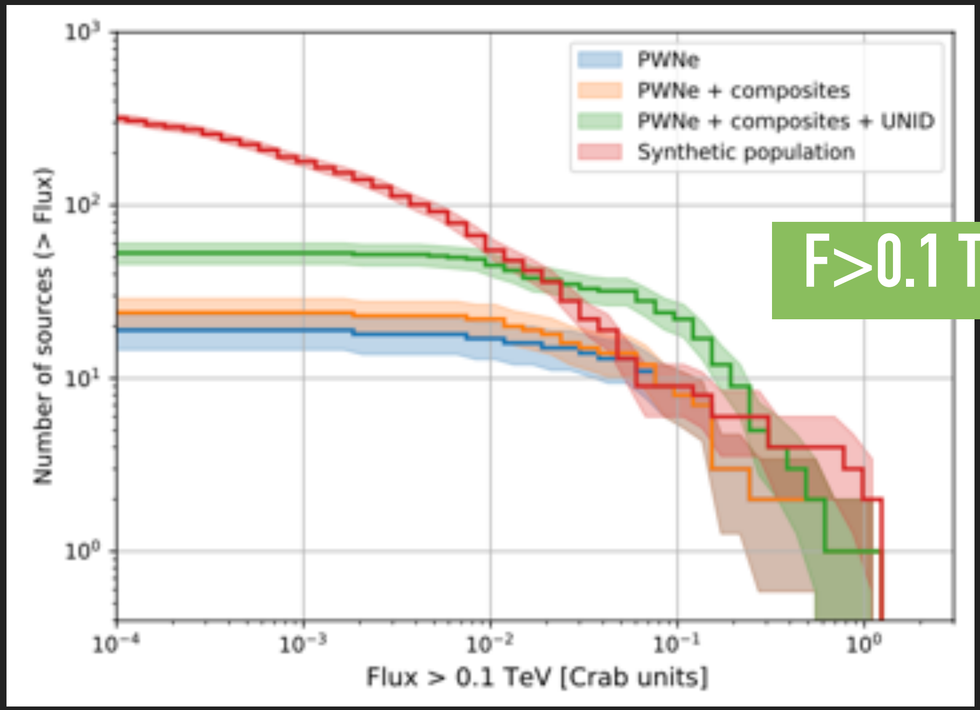
Vela (HESS; Aharonian et al. 2005)

PWNE WILL BE THE MOST NUMEROUS GALACTIC GAMMA-RAY SOURCES

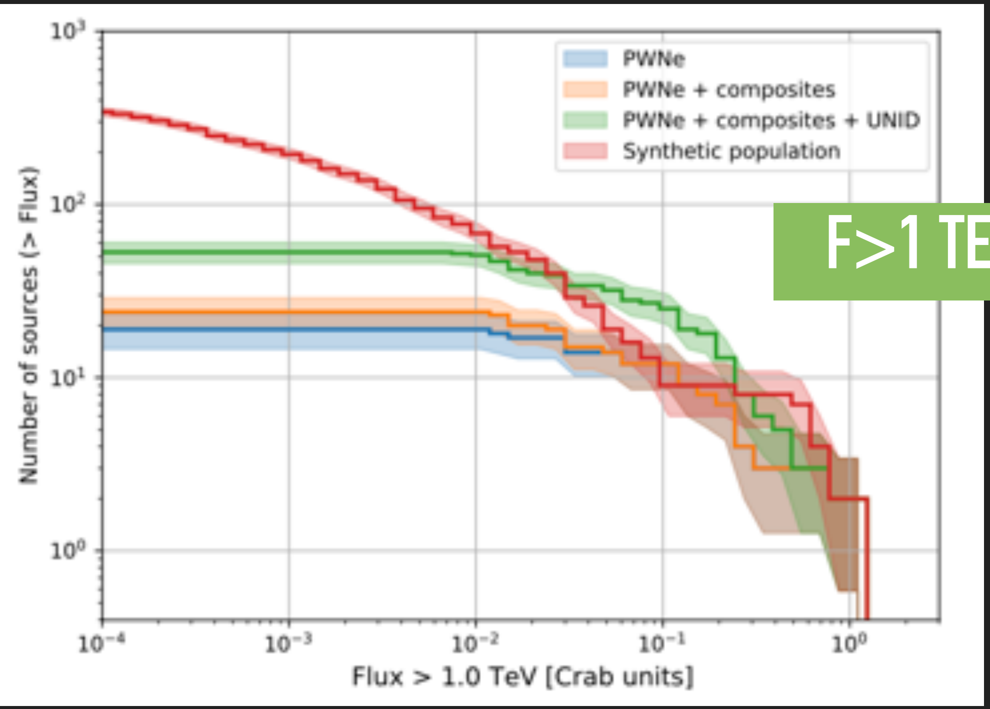
DISTRIBUTION IN THE GALAXY



CONTRIBUTION AT GAMMA-RAYS



F>0.1 TEV



F>1 TEV

PWN IN THE GALAXY MODELLED WITH NUMERICAL SIMULATIONS + RADIATIVE CODE

PWN ARE PRIMARY TARGETS FOR CTA AND ASTRI MA

PWNE AND LHAASO SOURCES

12 SOURCES DETECTED BY LHAASO ABOVE 100 TEV

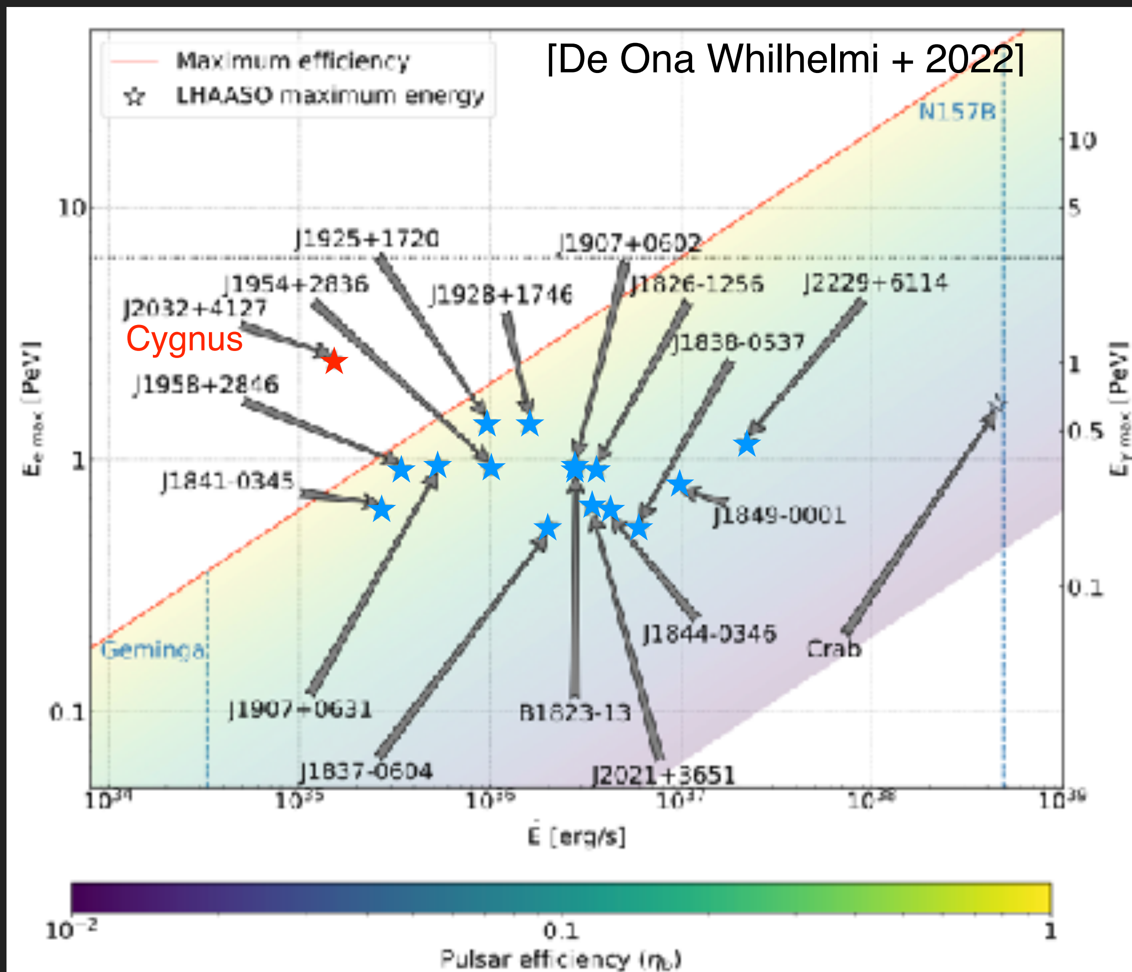
Table 1 | UHE γ-ray sources

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



STRICT LIMIT FROM THE PSR POTENTIAL DROP

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

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

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

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

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

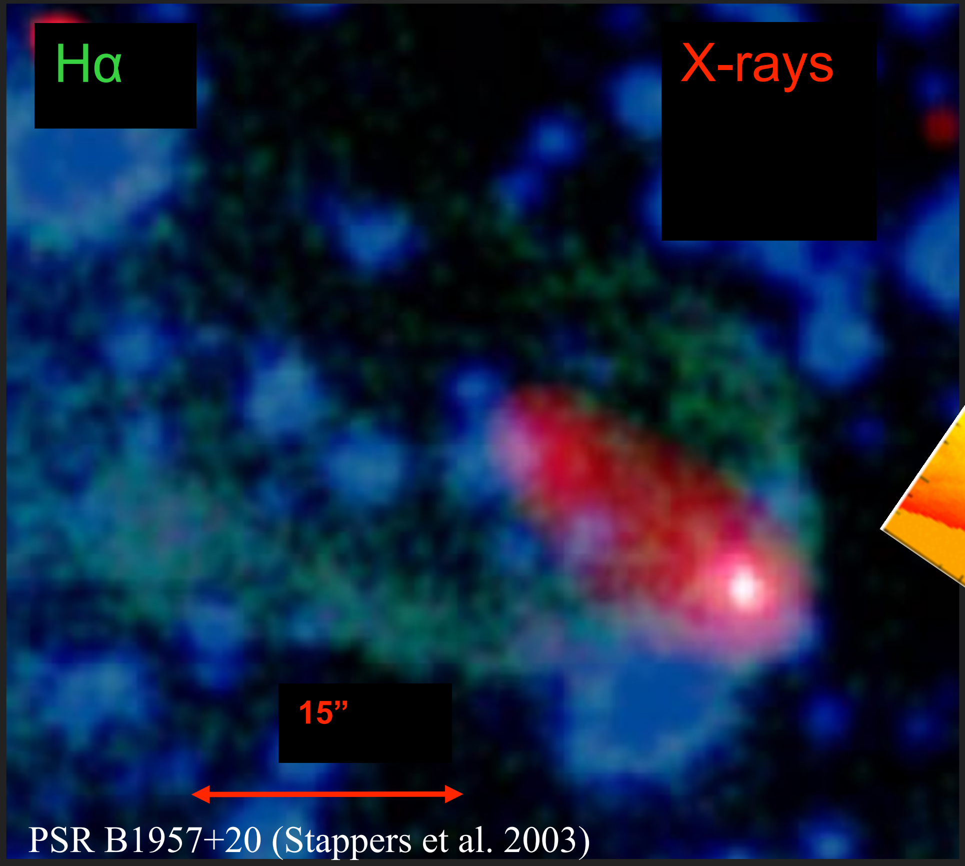
IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LIKELY LOSS LIMITED

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

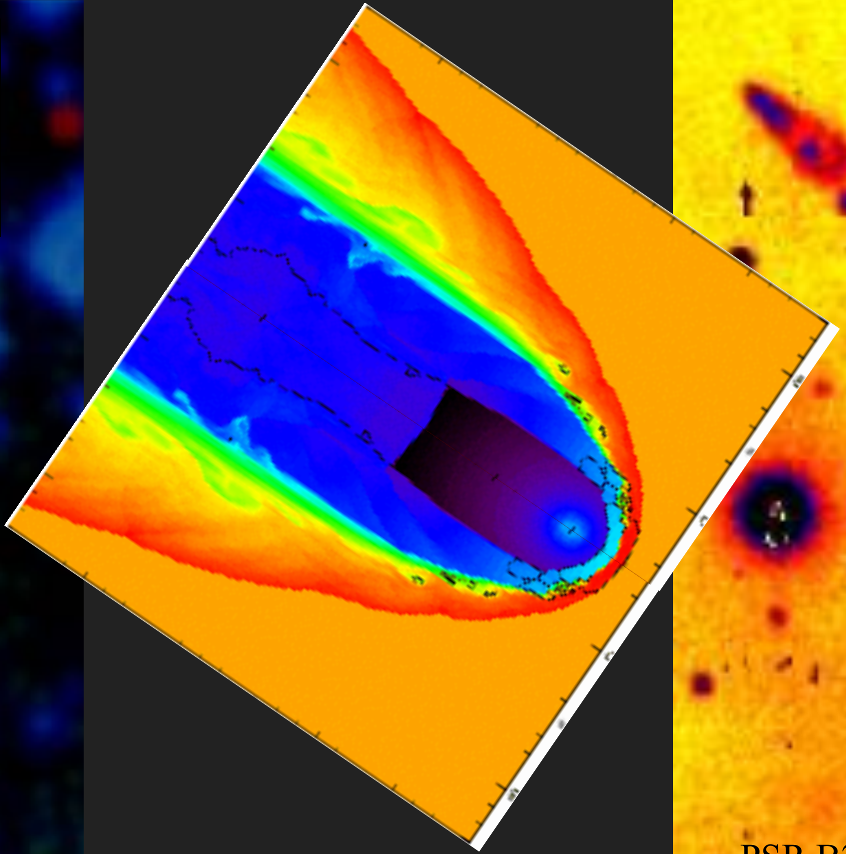
$$E_{max} \approx 6\ PeV\ \xi_e^{1/2}\ B_{-4}^{-1/2}$$

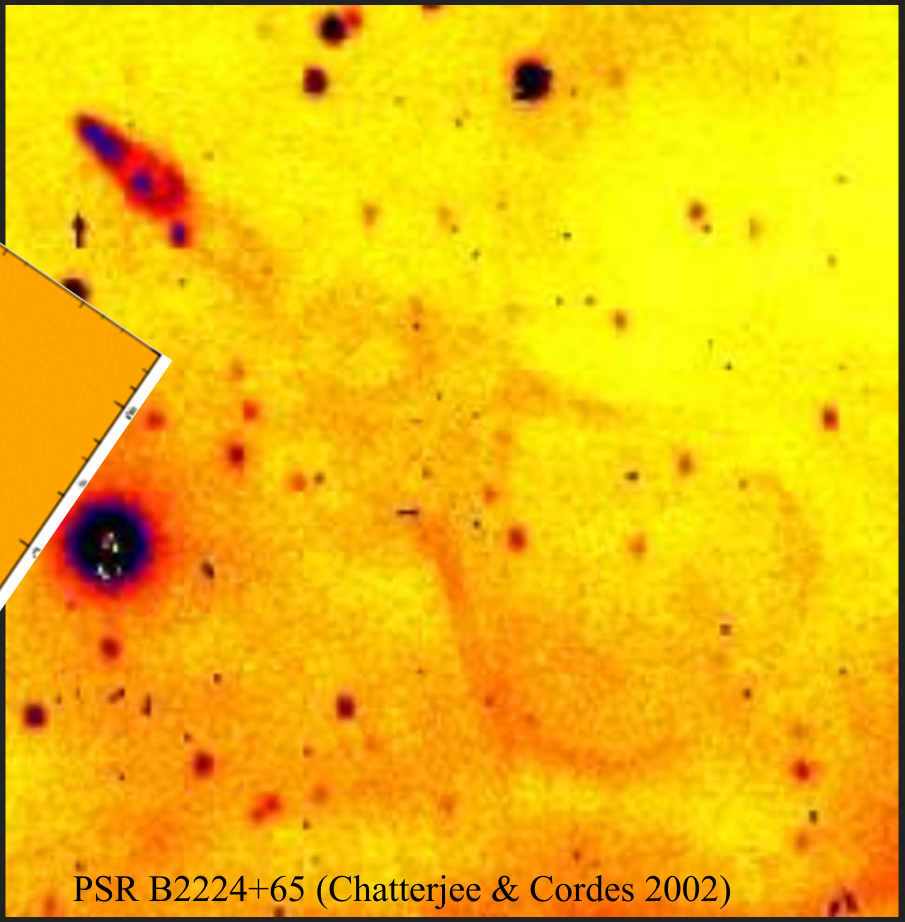
MOST PULSARS KICK VELOCITY IS SUPERSONIC IN ISM

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



PSR B1957+20 (Stappers et al. 2003)

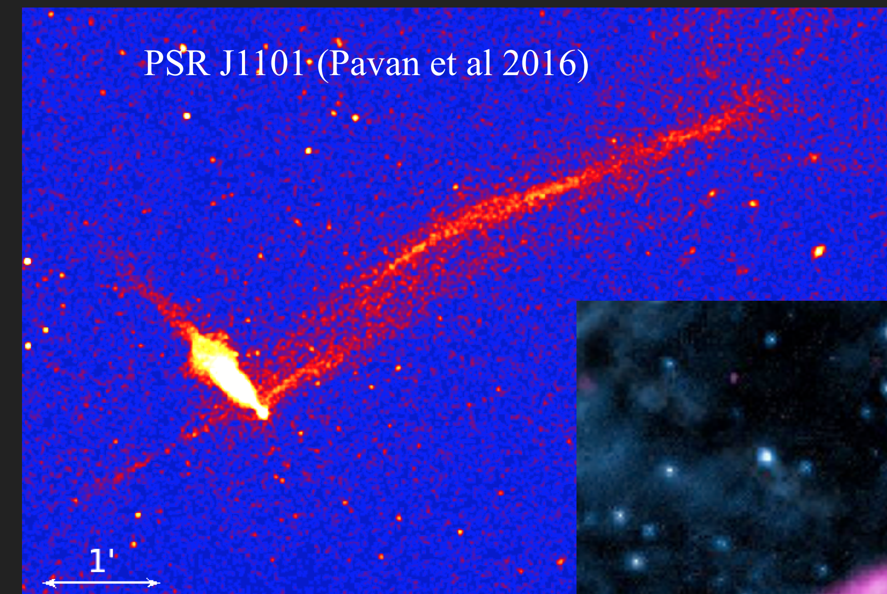



PSR B2224+65 (Chatterjee & Cordes 2002)

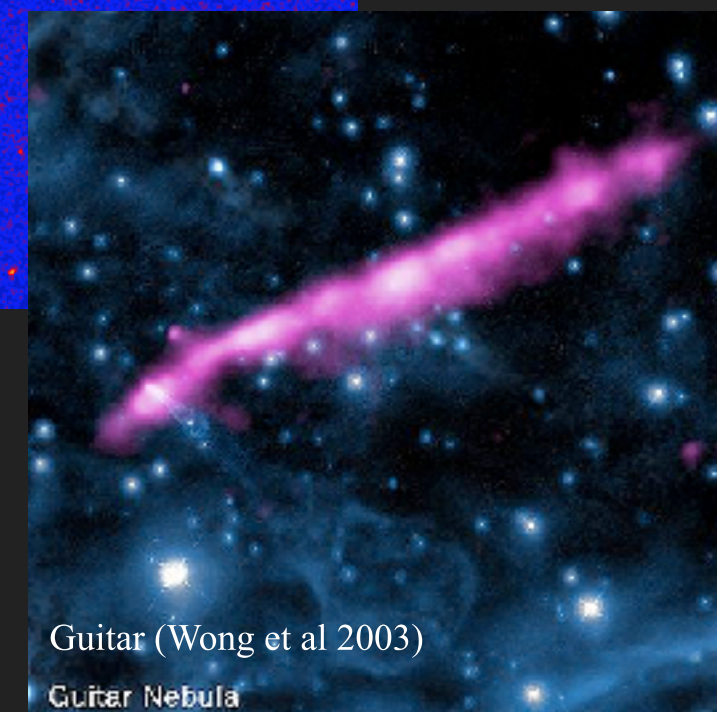
PAIR ESCAPE

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

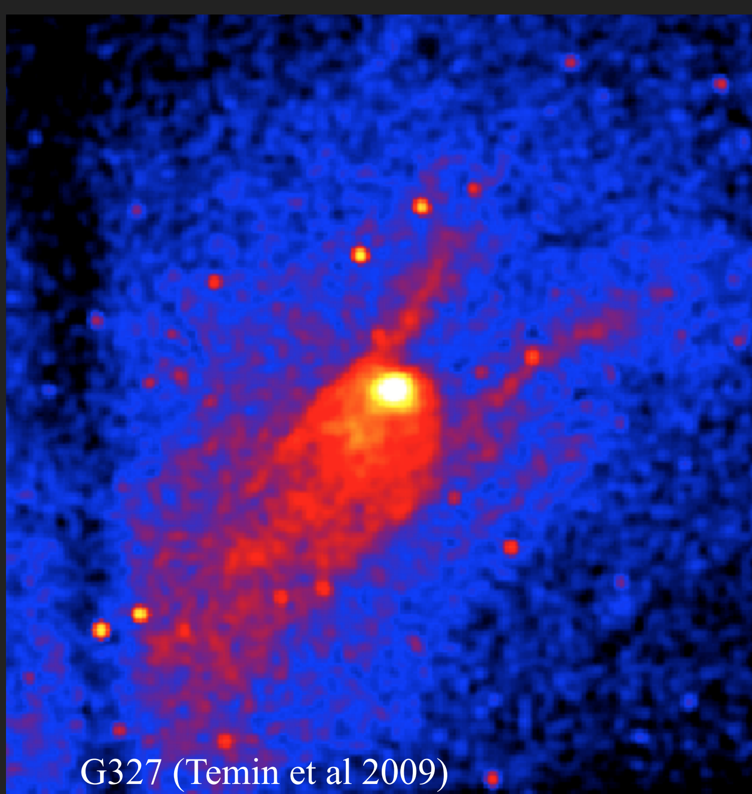
The particles in these features are ~ PSR voltage

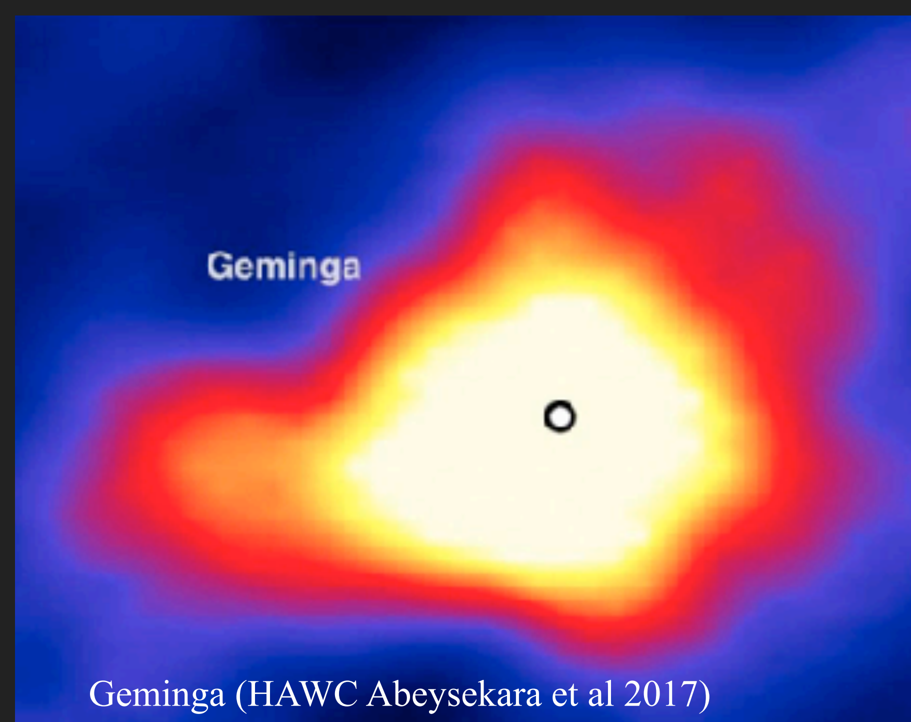


PSR J1101 (Pavan et al 2016)



Guitar (Wong et al 2003)

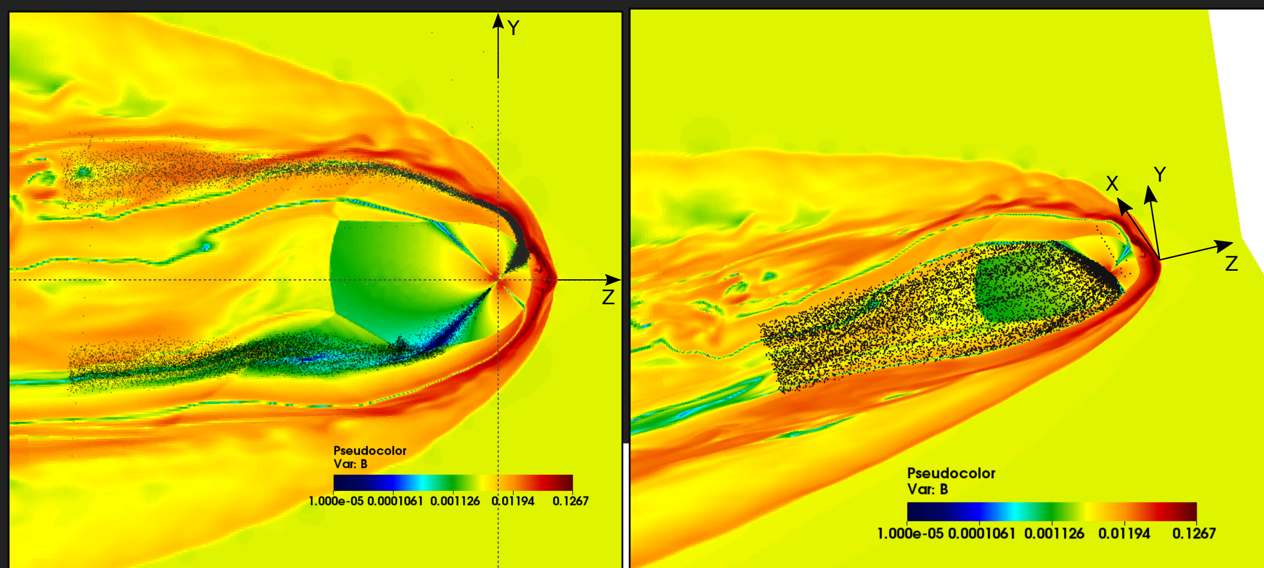

G327 (Temin et al 2009)

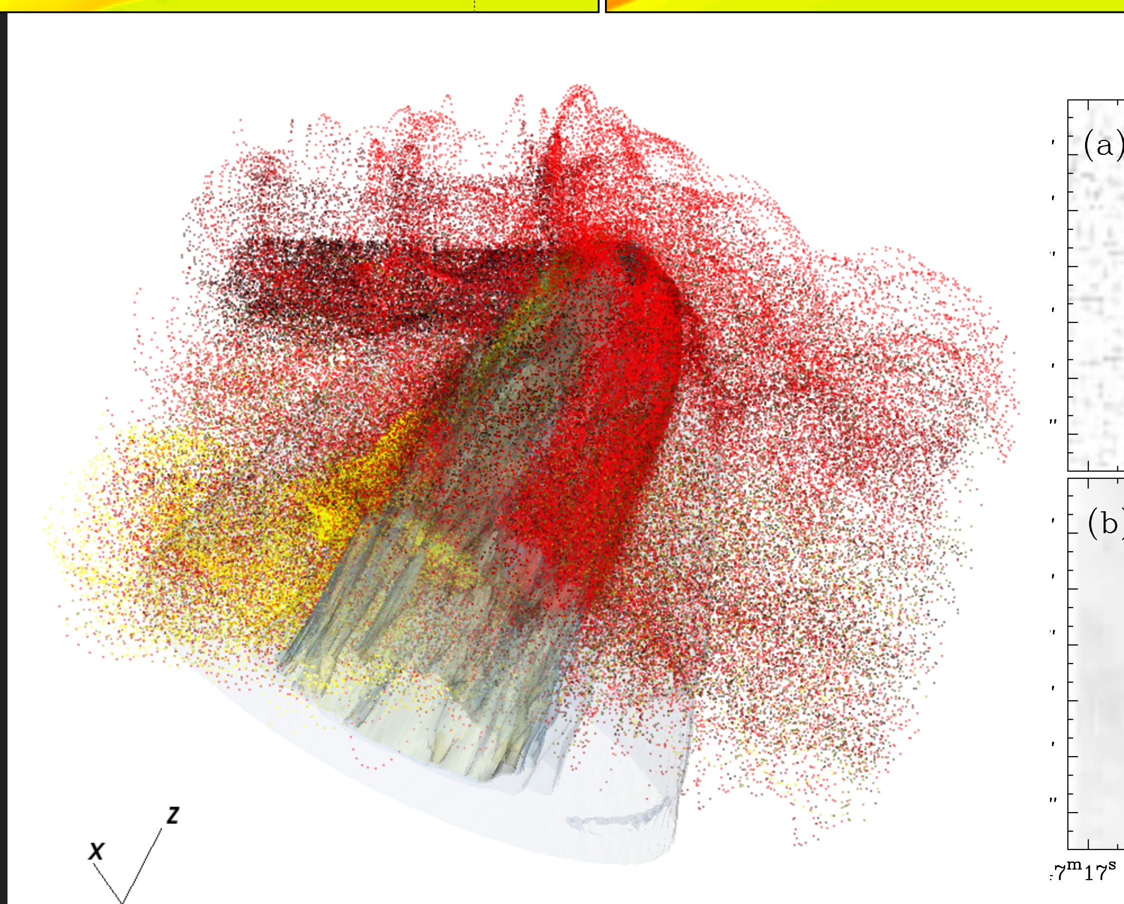


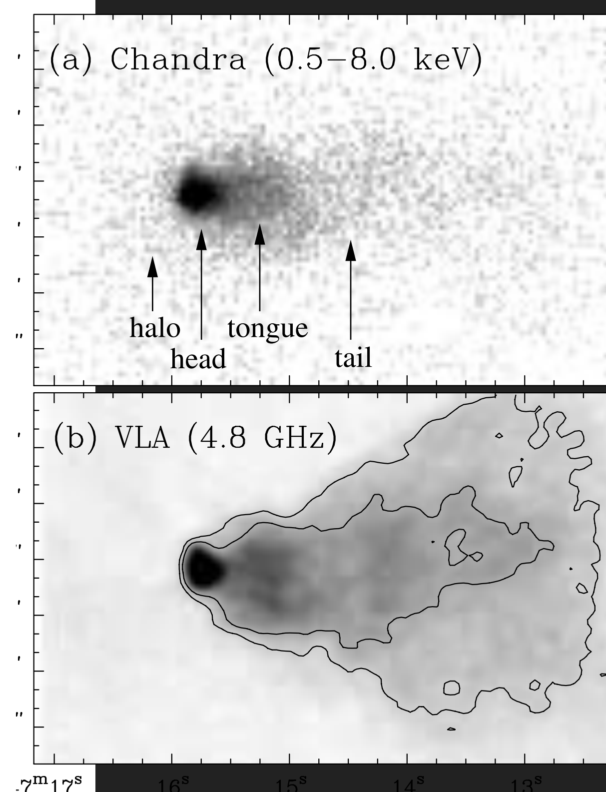
Geminga (HAWC Abeysekara et al 2017)

TeV halo suggest strong diffusion

PAIR ESCAPE IN MHD MODELS

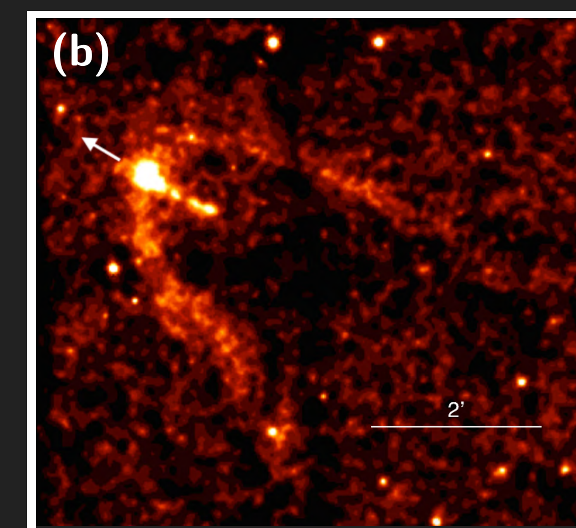






LOW ENERGY PARTICLES REMAIN CONFINED IN CURRENTS

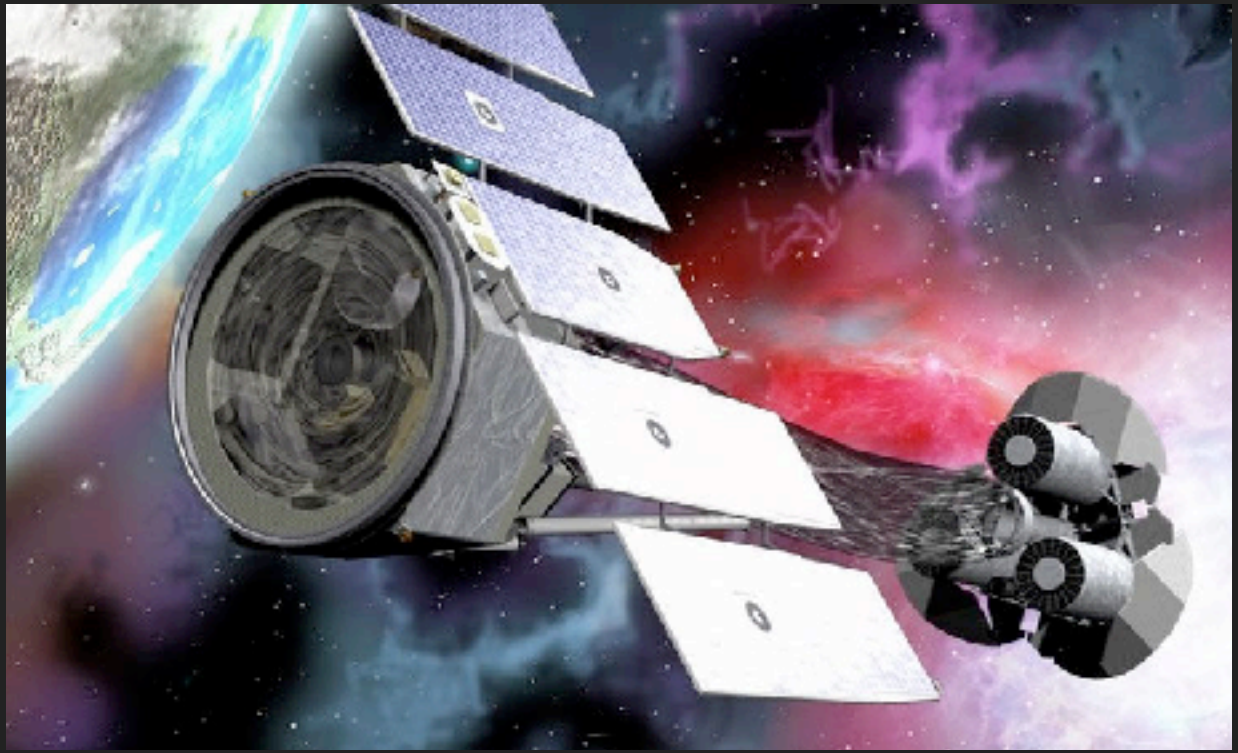
GEMINGA HARD TAILS



VERY HIGH ENERGY PARTICLES CAN ALSO DIFFUSE AHEAD

MAUSE X-RAY HALO

IXPE – X-RAY POLARIMETRY

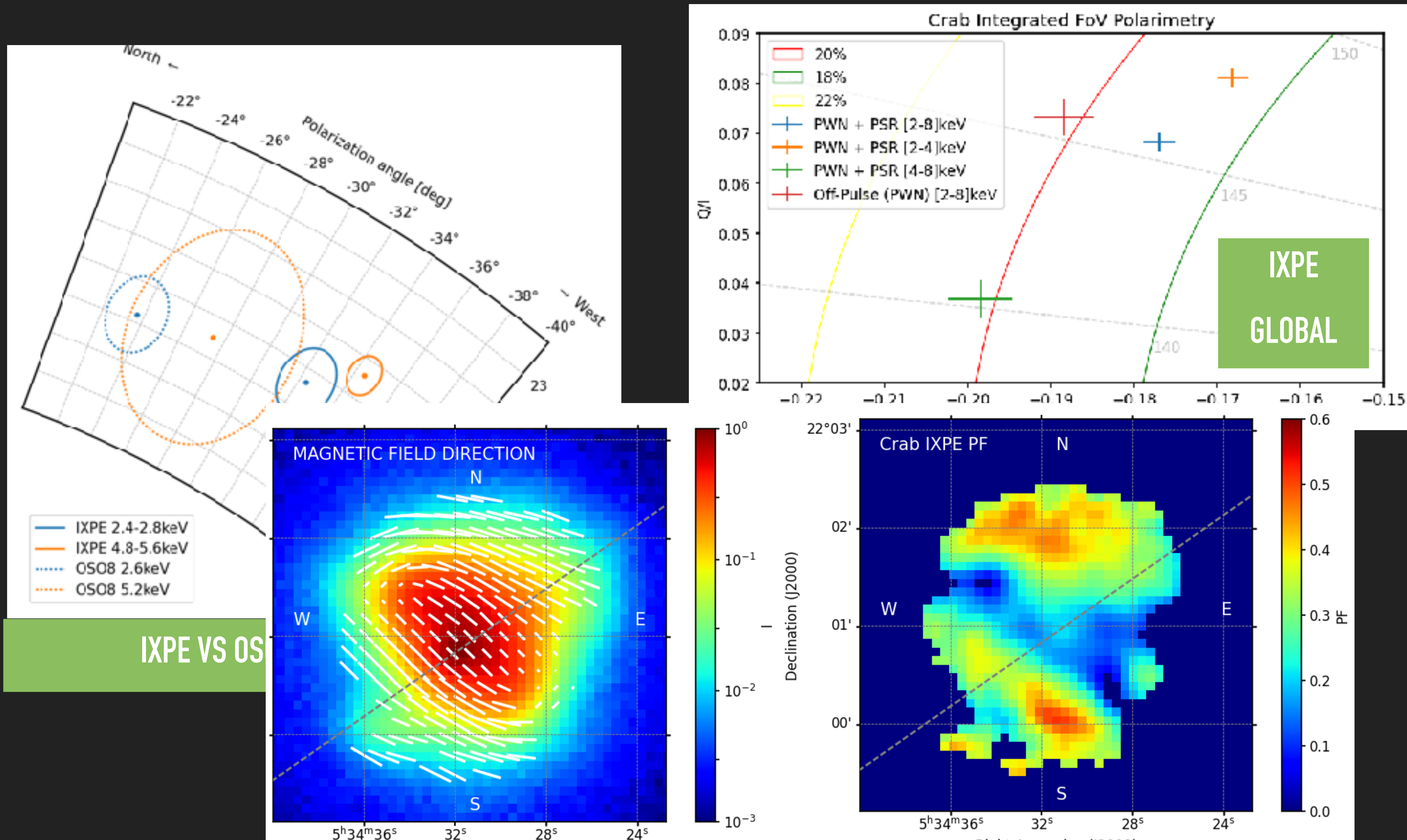


24 NI-CO W1 SHELLS

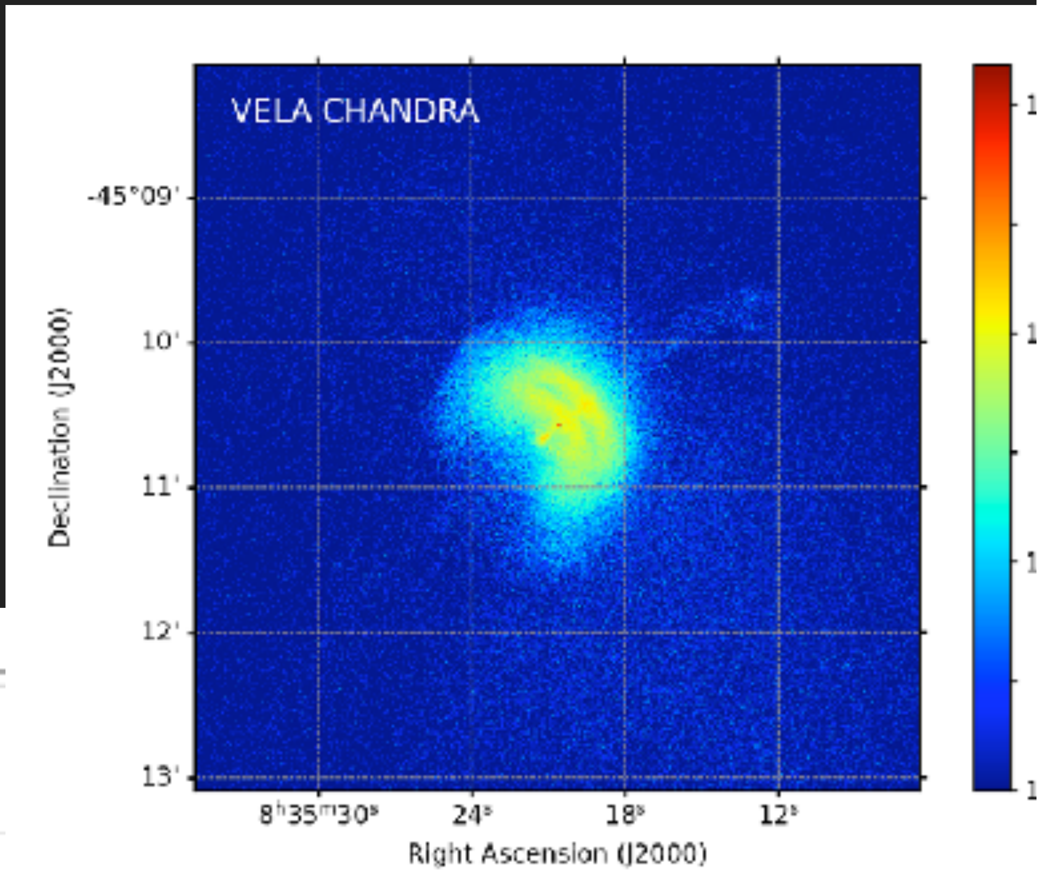
2-8 KEV BAND

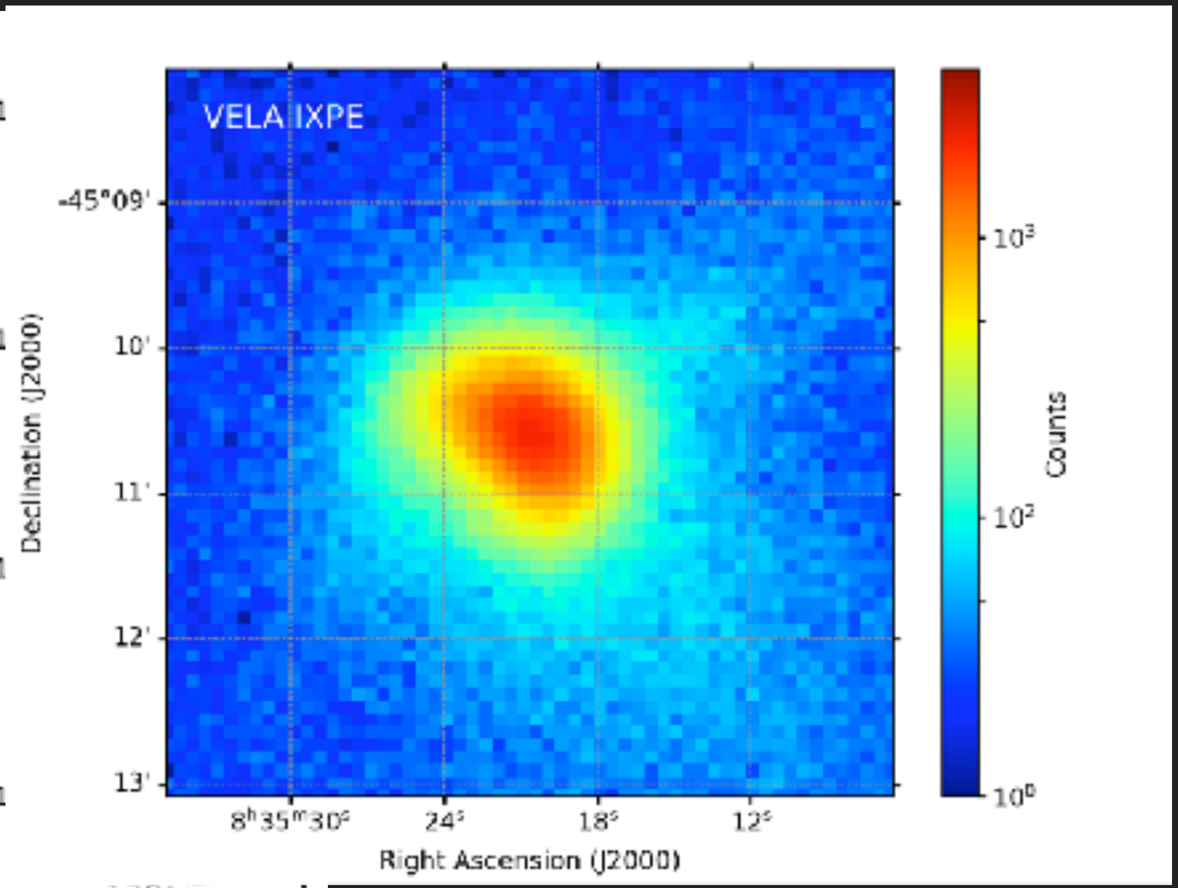
Mission name	Imaging X-ray Polarimetry Explorer (IXPE)
Mission category	NASA Astrophysics Small Explorer (SMEX)
Operational phase	2021 launch, 2 years following 1 month commissioning, extension possible
Orbital parameters	Circular at 540–620 km altitude, equatorial; one ground station near equator
Spacecraft 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

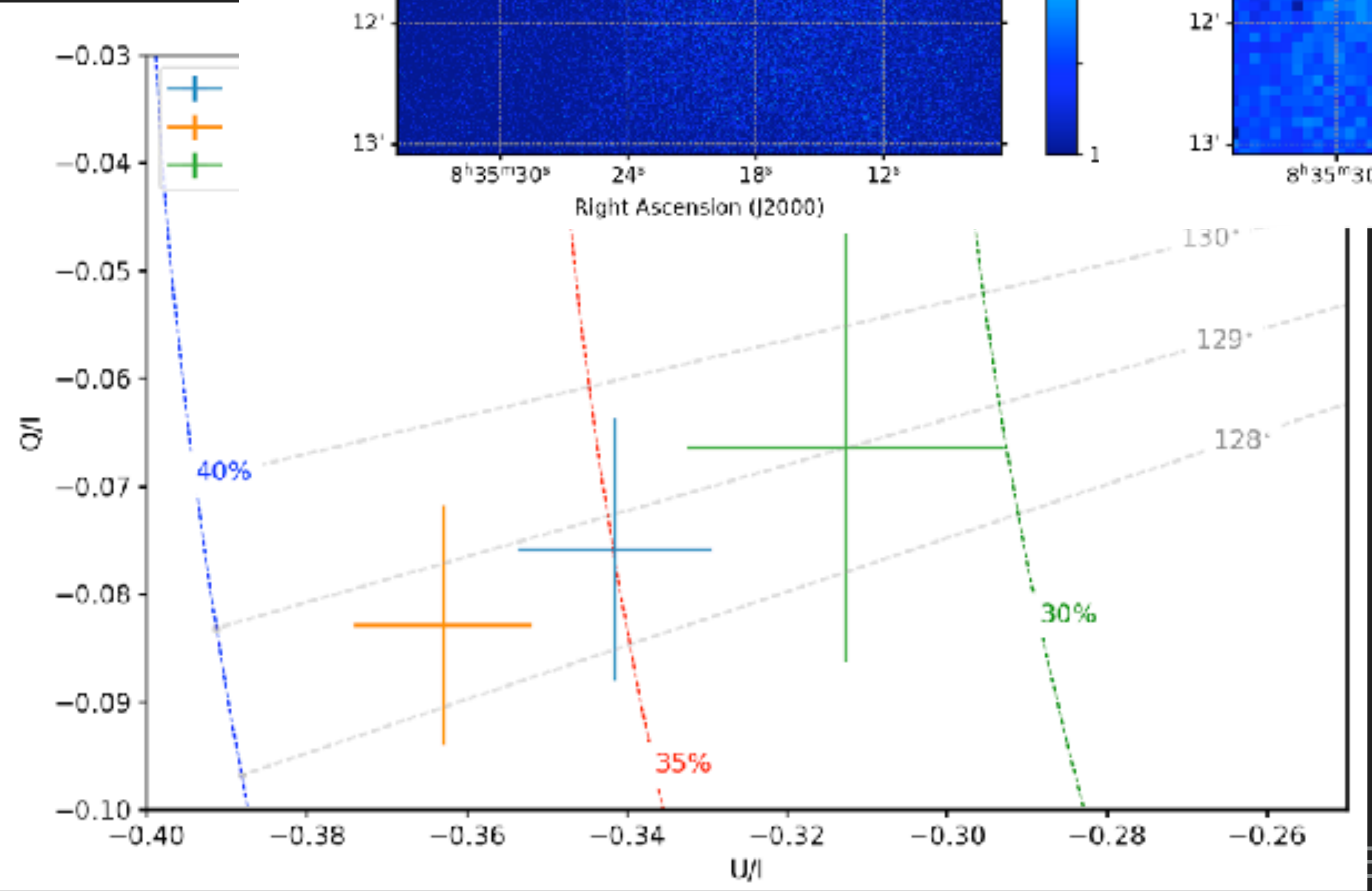
IXPE – X-RAY POLARIMETRY – CRAB



IXPE – X-RAY POLARIMETRY – VELA







LOCAL PD AS HIGH AS 60% VERY CLOSE TO THE SYNCHOTRON LIMIT

TURBULENCE IS ALMOST ABSENT IN THIS SYSTEM

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 THE PSW WIND FORM AND EVOLVE?
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