# PULSAR WIND NEBULAE:

## HALOES, JETS AND THE PROBLEM OF PARTICLE ESCAPE.

NICCOLO' BUCCIANTINI

INAF ARCETRI - UNIV. FIRENZE - INFN

UNIVERSITÀ DEGLI STUDI FIRENZE

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

INFN Istituto Nazionale di Fisica Nucleare

Finanziato dall'Unione europea NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

INAF

# 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)

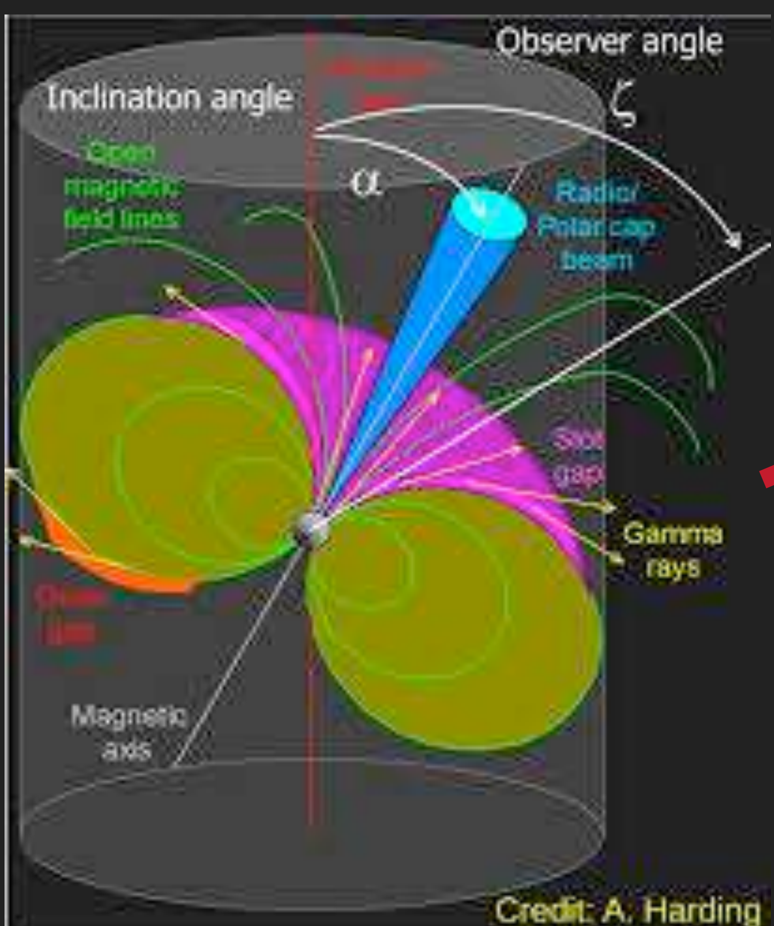
GALACTIC ACCELERATORS. THE ONLY PLACE WHERE WE CAN STUDY THE PROPERTIES OF RELATIVISTIC SHOCKS (AS IN GRBS AND AGNS)

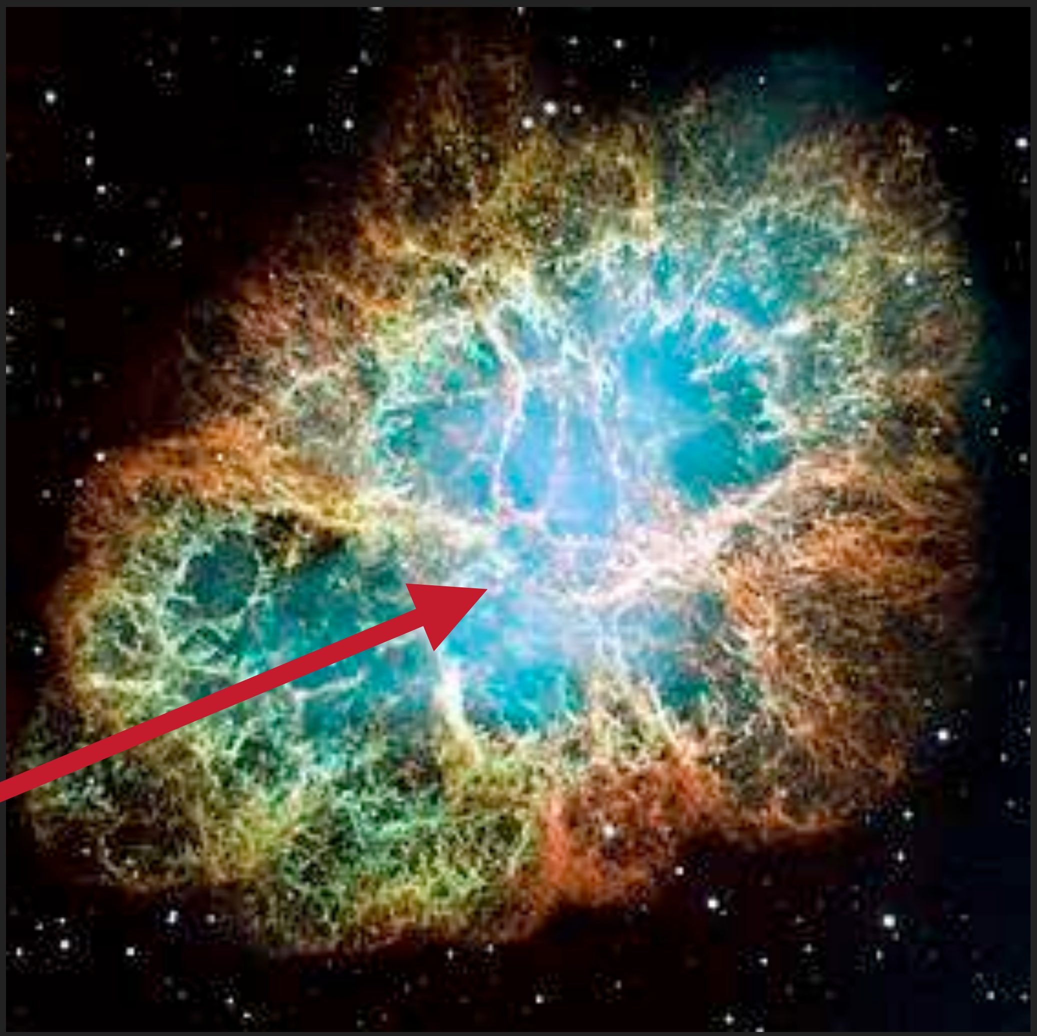
NATURAL LEPTONIC PEVATRONS, MOST EFFICIENT ANTIMATTER FACTORIES IN THE UNIVERSE

# DEATH OF A MASSIVE STAR – THE BIRTH OF PULSAR

STARS MORE MASSIVE THAN 8 $M_{SUN}$ END THEIR LIFE IN SUPERNOVA EXPLOSION

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



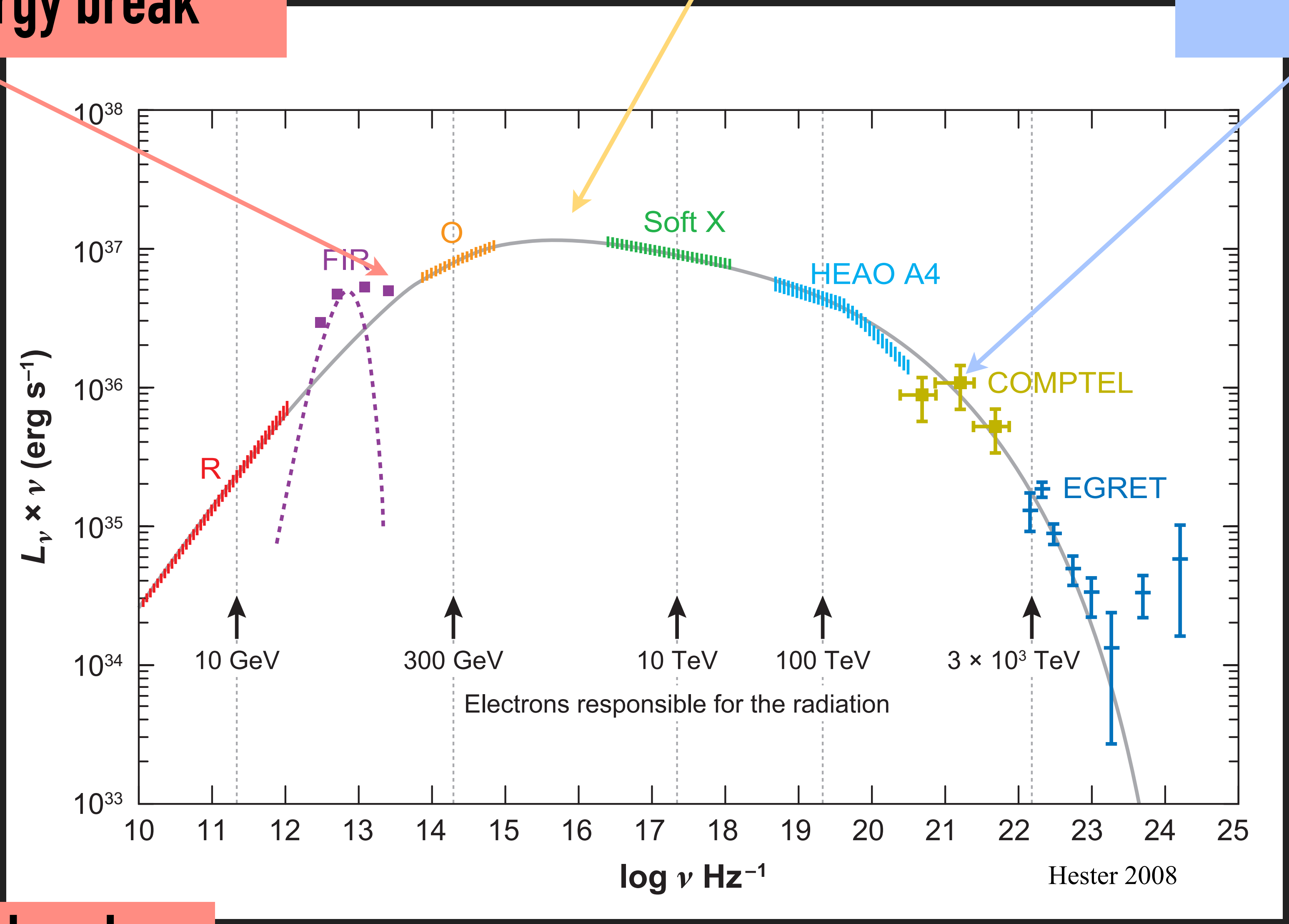
THE COMBINATION OF STRONG MAGNETIC FIELD ($10^{12}$G) AND RAPID ROTATION (P=0.001-1S) CREATES STRONG ELECTRIC FIELD AT THE SURFACE EXTRACTING PAIRS AND PRODUCING PAIR CASCADES. OBSERVED AS PULSARS

# CRAB SYNCHROTRON SPECTRUM

Low energy break

High energy break

MeV cutoff




Injection break

Synchr. cooling

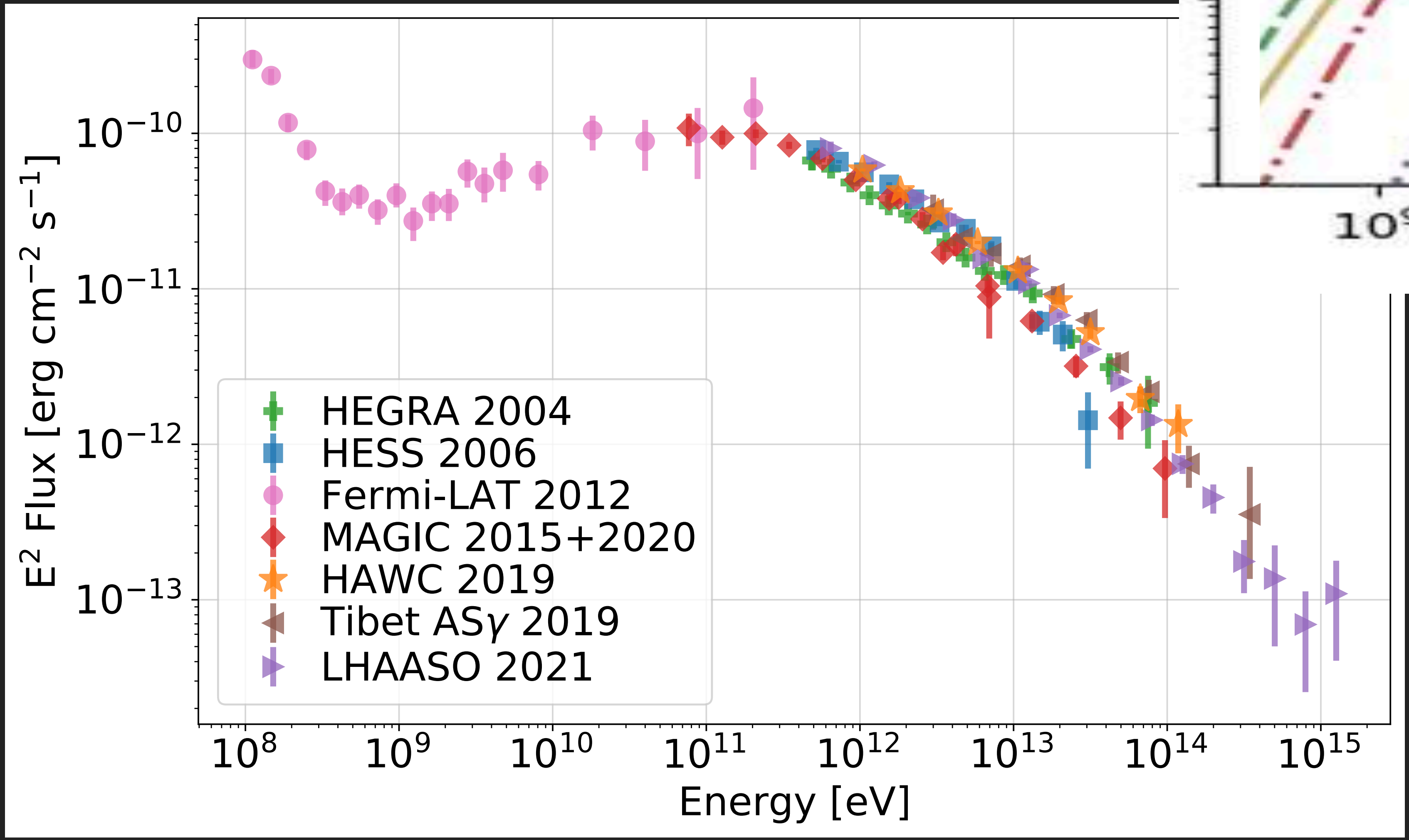
Acceler. cutoff

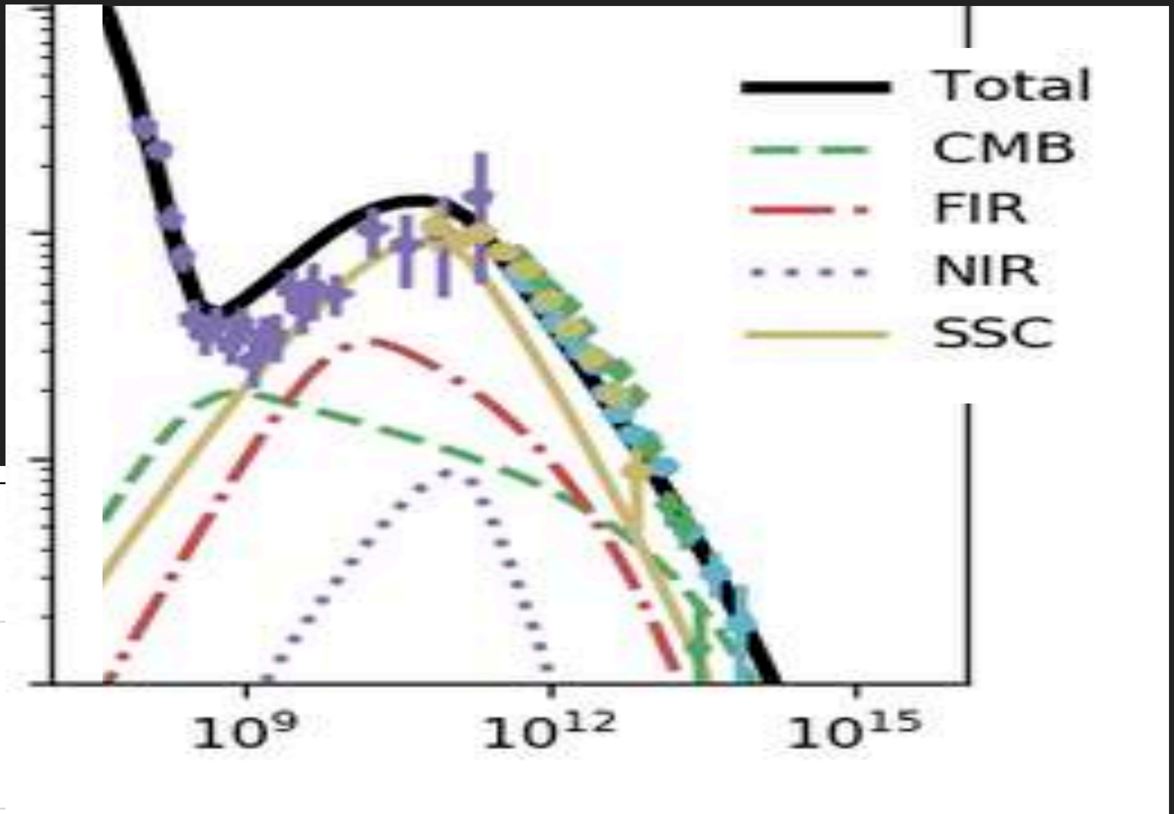
**The most efficient non-thermal accelerator.**

# IC GAMMA SPECTRUM

CRAB ONLY SYSTEM SSC DOMINATED

OTHER PWNE ARE NIR/FIR DOMINATED



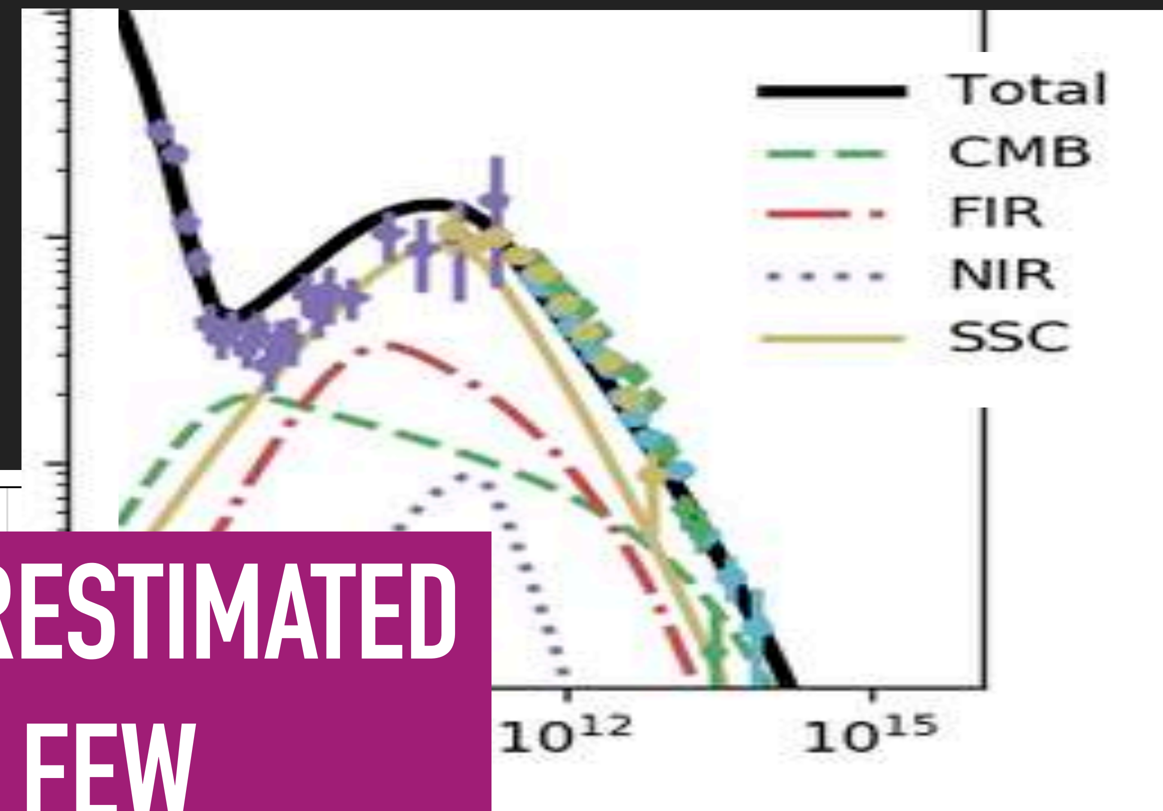

TREND SET BY RADIO-OPT PARTICLES

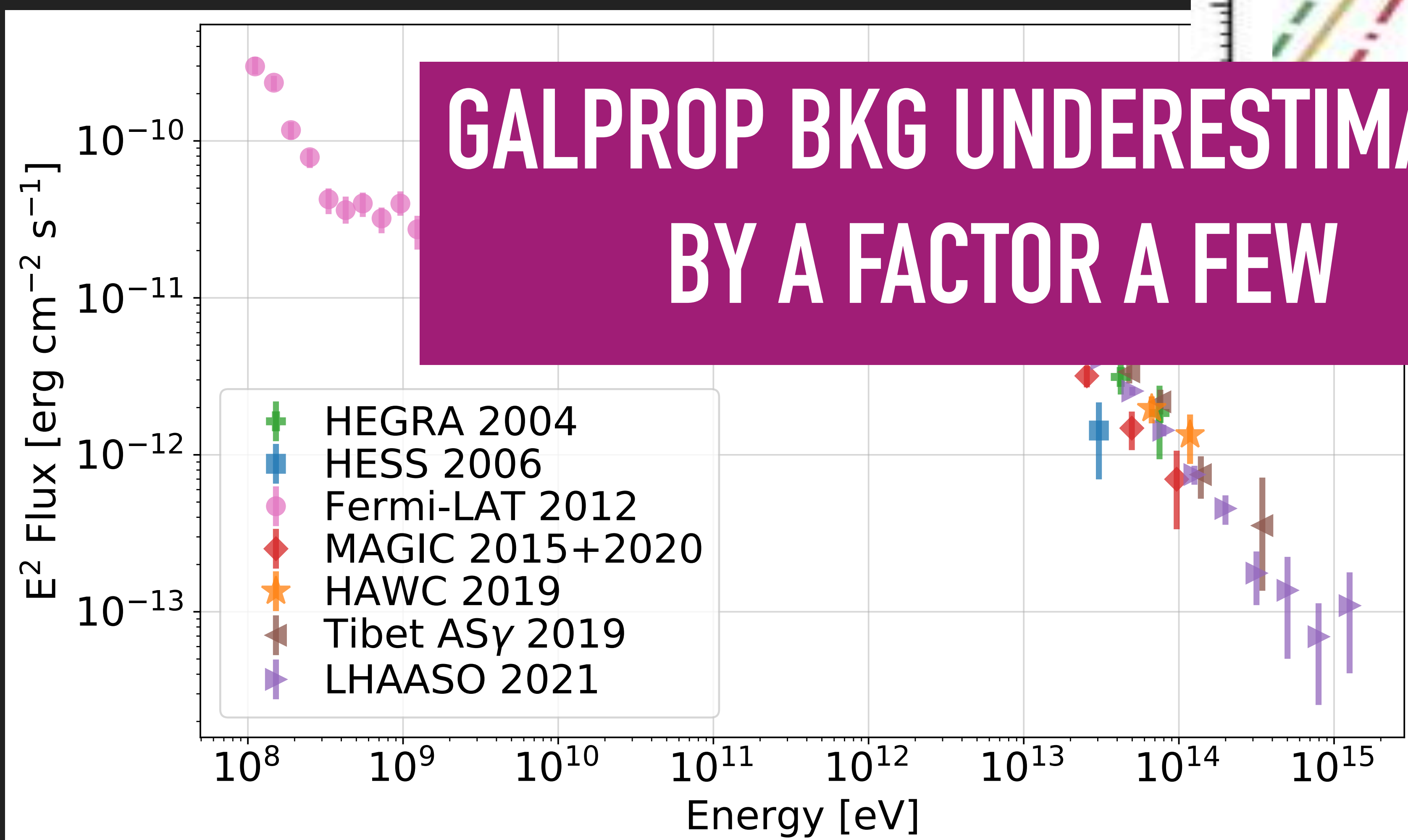
X-RAY PARTICLES IN KN

# IC GAMMA SPECTRUM

CRAB ONLY SYSTEM SSC DOMINATED

OTHER PWNE ARE NIR/FIR DOMINATED



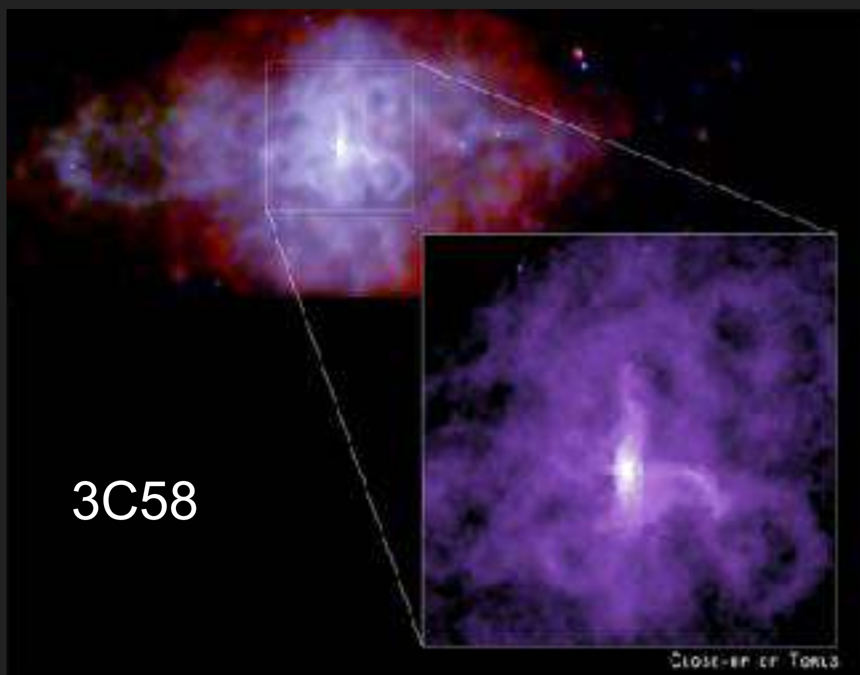




GALPROP BKG UNDERESTIMATED BY A FACTOR A FEW

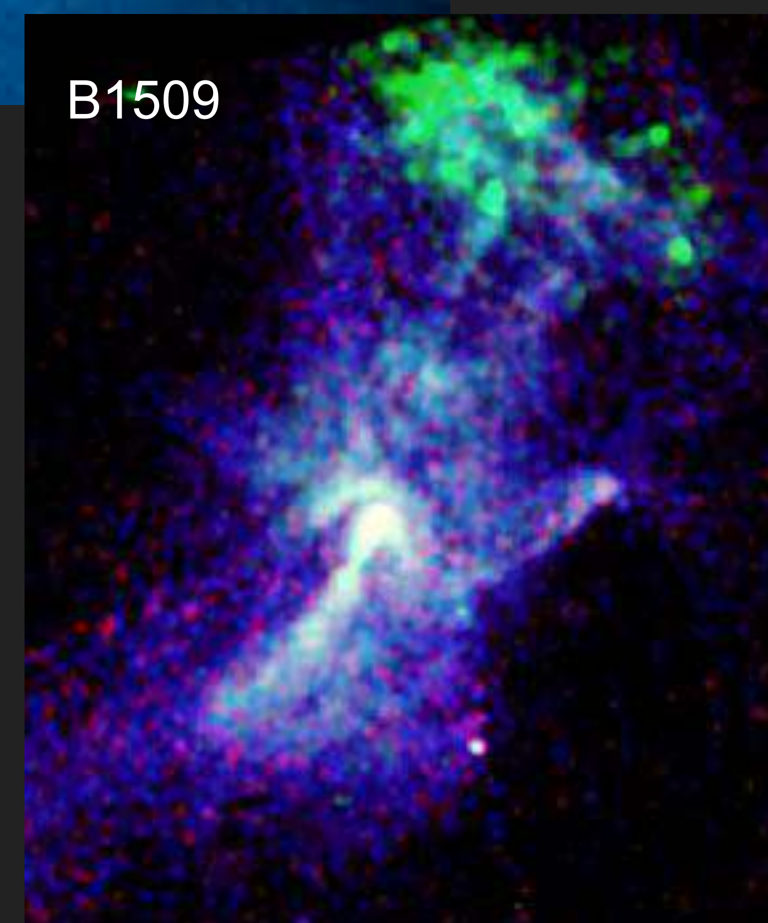
TRENDS SET BY RADIO-OPT PARTICLES

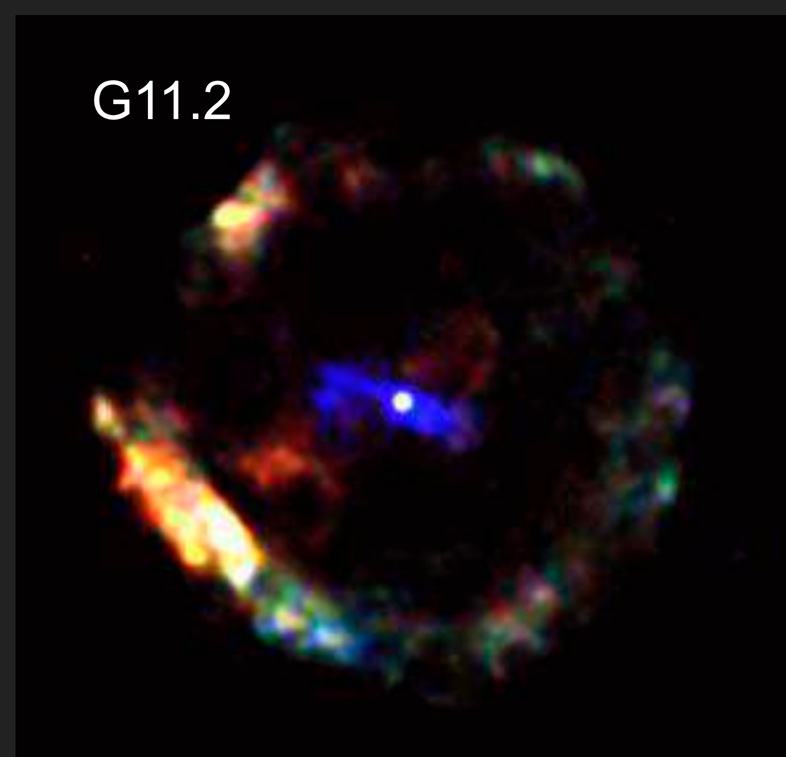
X-RAY PARTICLES IN KN

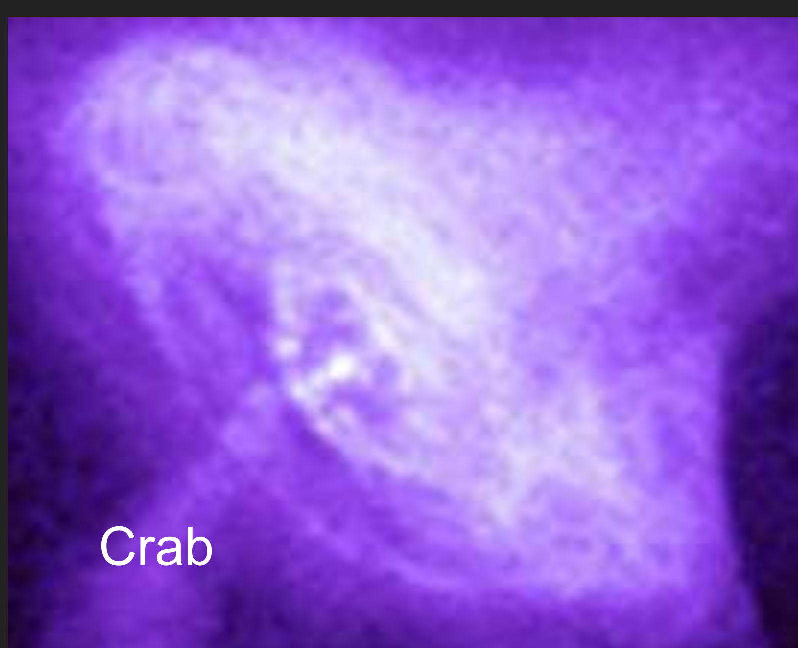
# FINE STRUCTURES – A LAB FOR RELTIVISTICN FLUID DYNAMICS







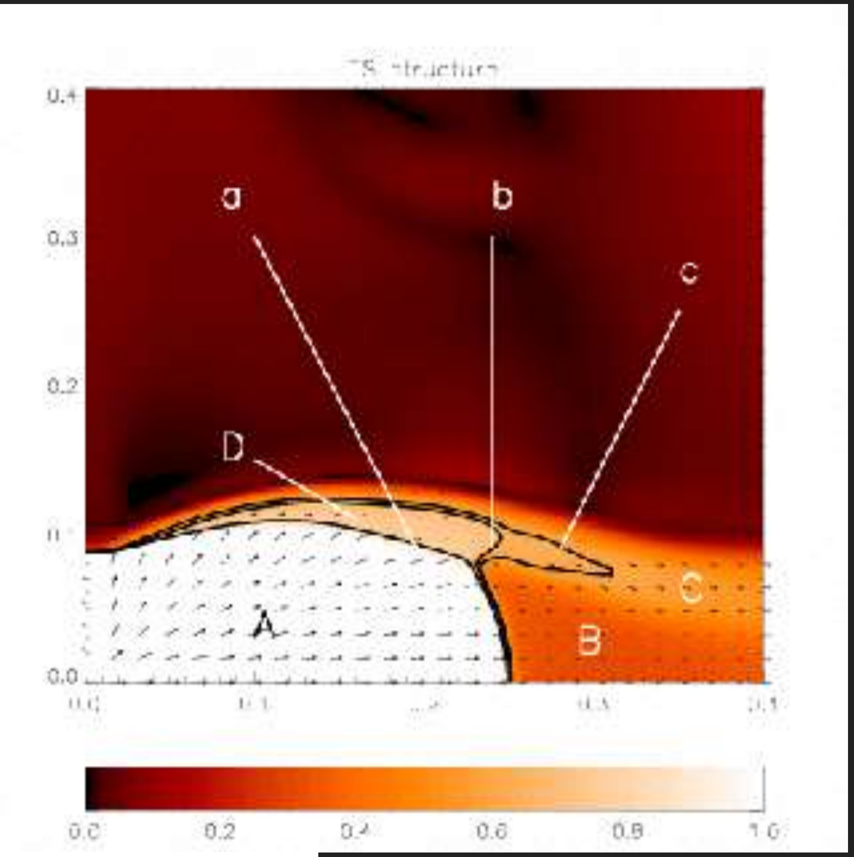



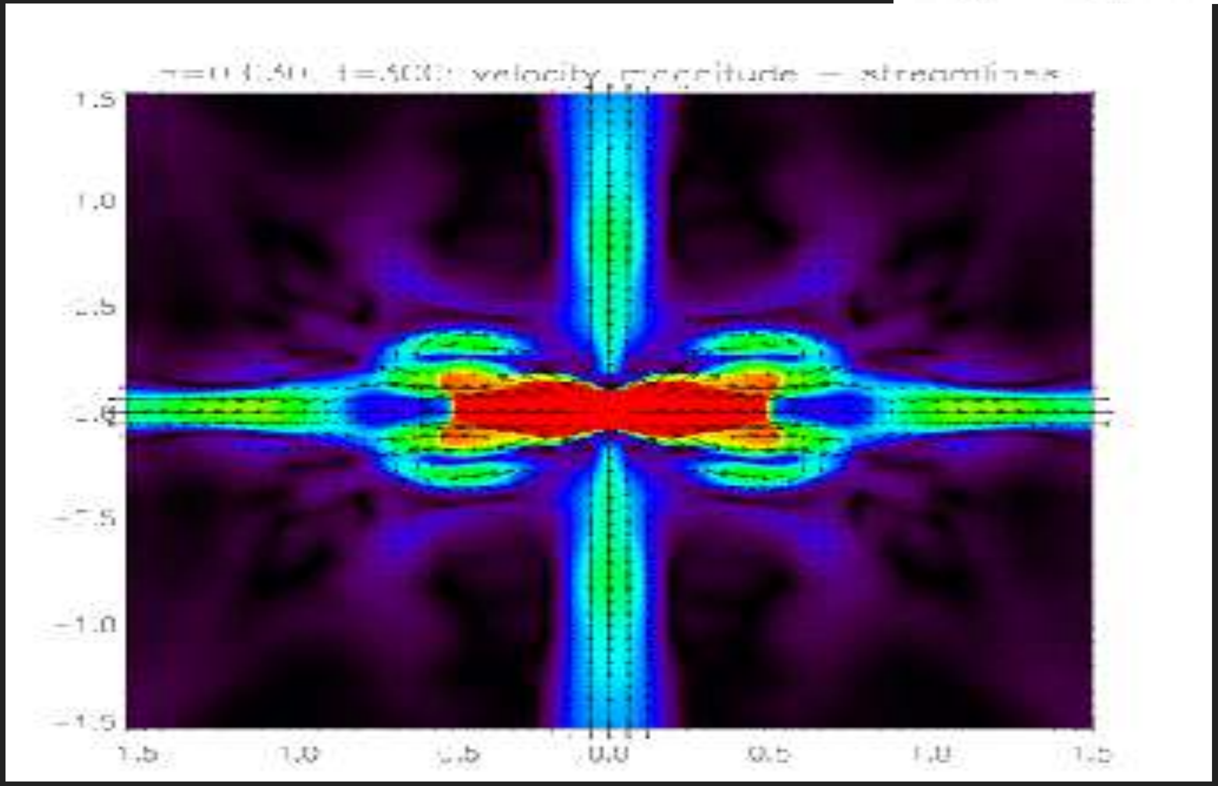



# RELATIVISTIC MHD MODELS

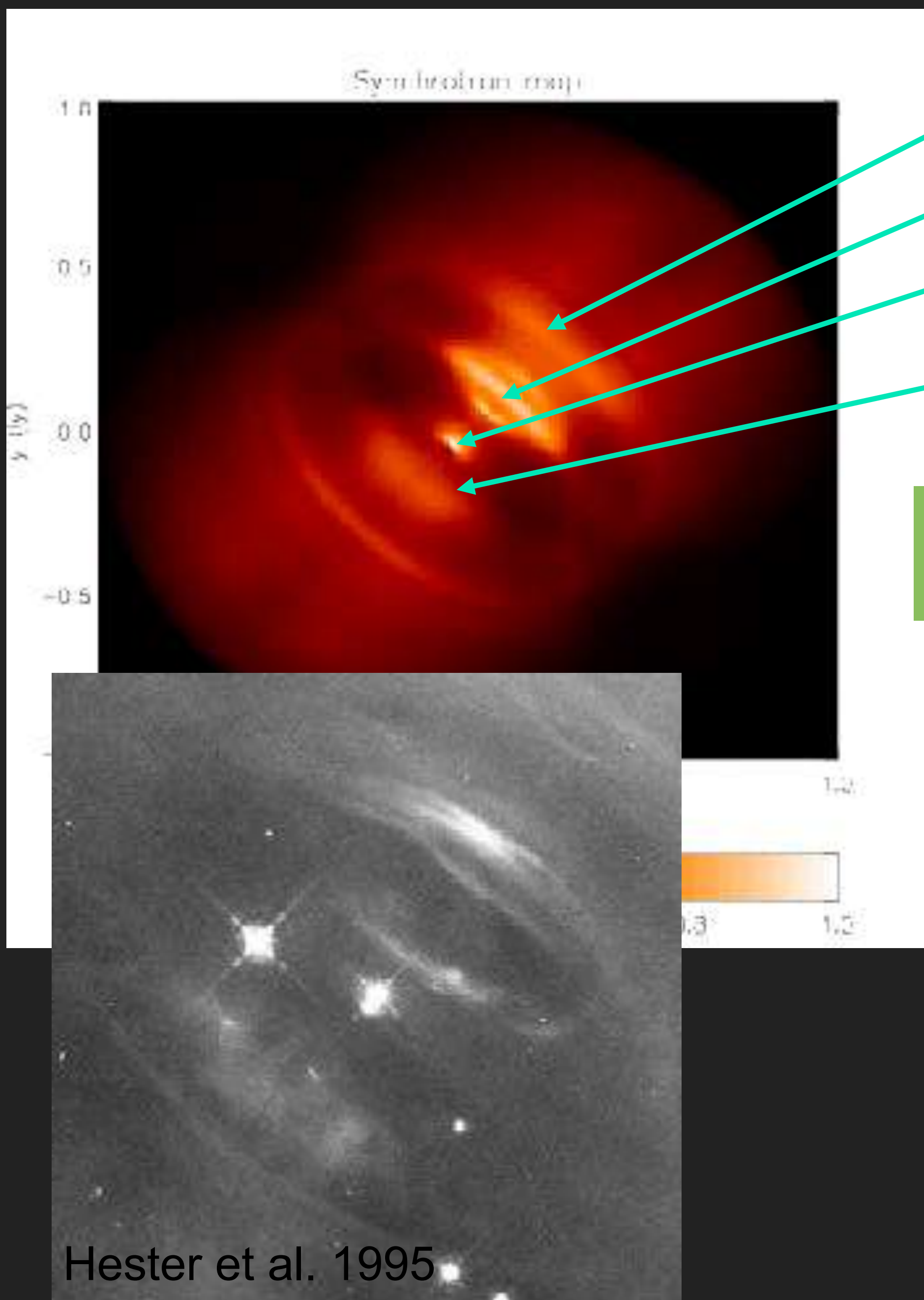
THE WIND ANISOTROPY SHAPES THE TS STRUCTURE.
DOWNSTREAM FLOW – EQUATORIAL COLLIMATION DUE TO THE TS SHAPE:

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



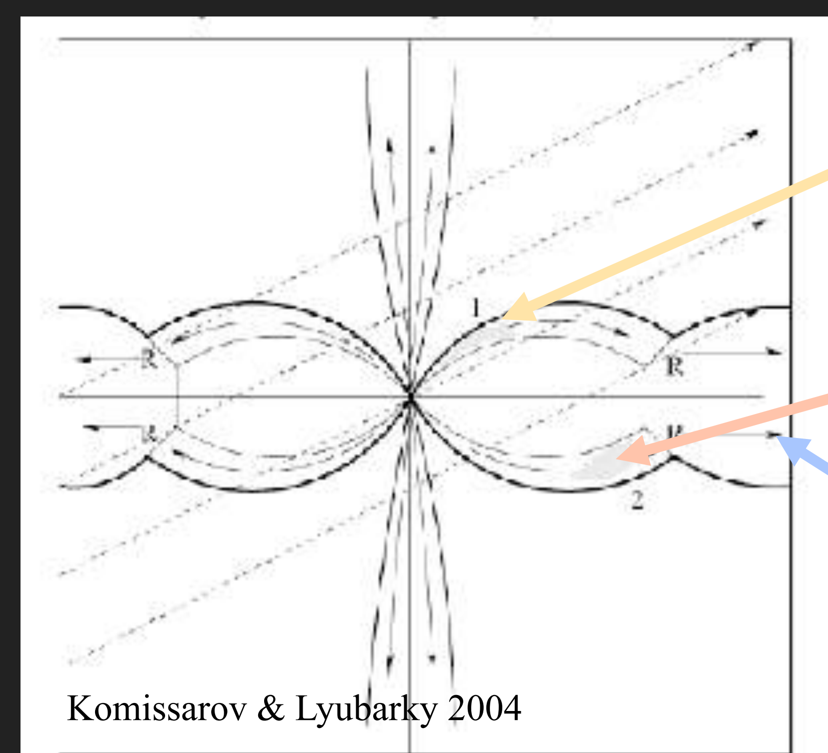



# REPRODUCING OBSERVATIONS




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

EACH FEATURE TRACES AN EMITTING REGION

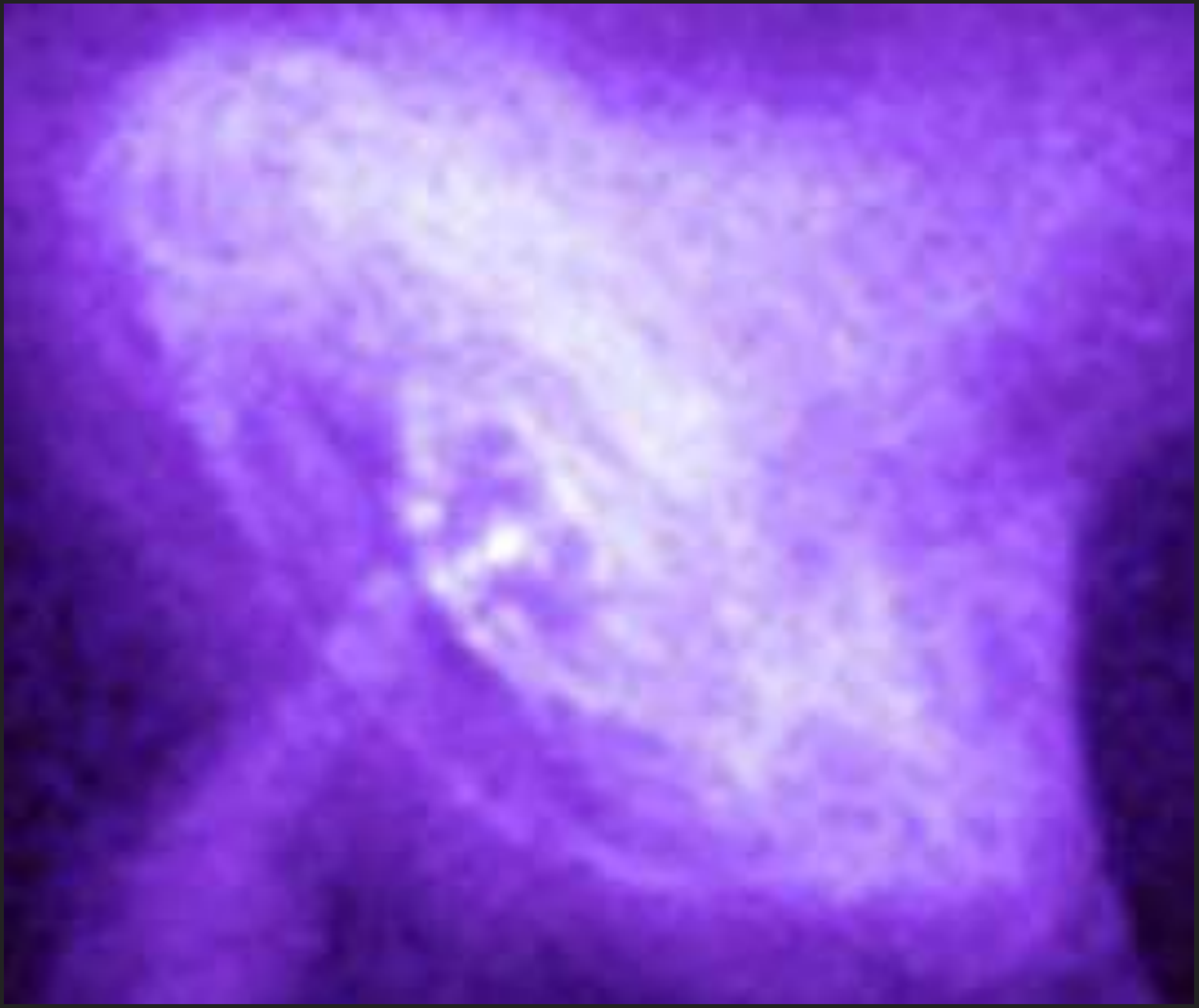



Knot

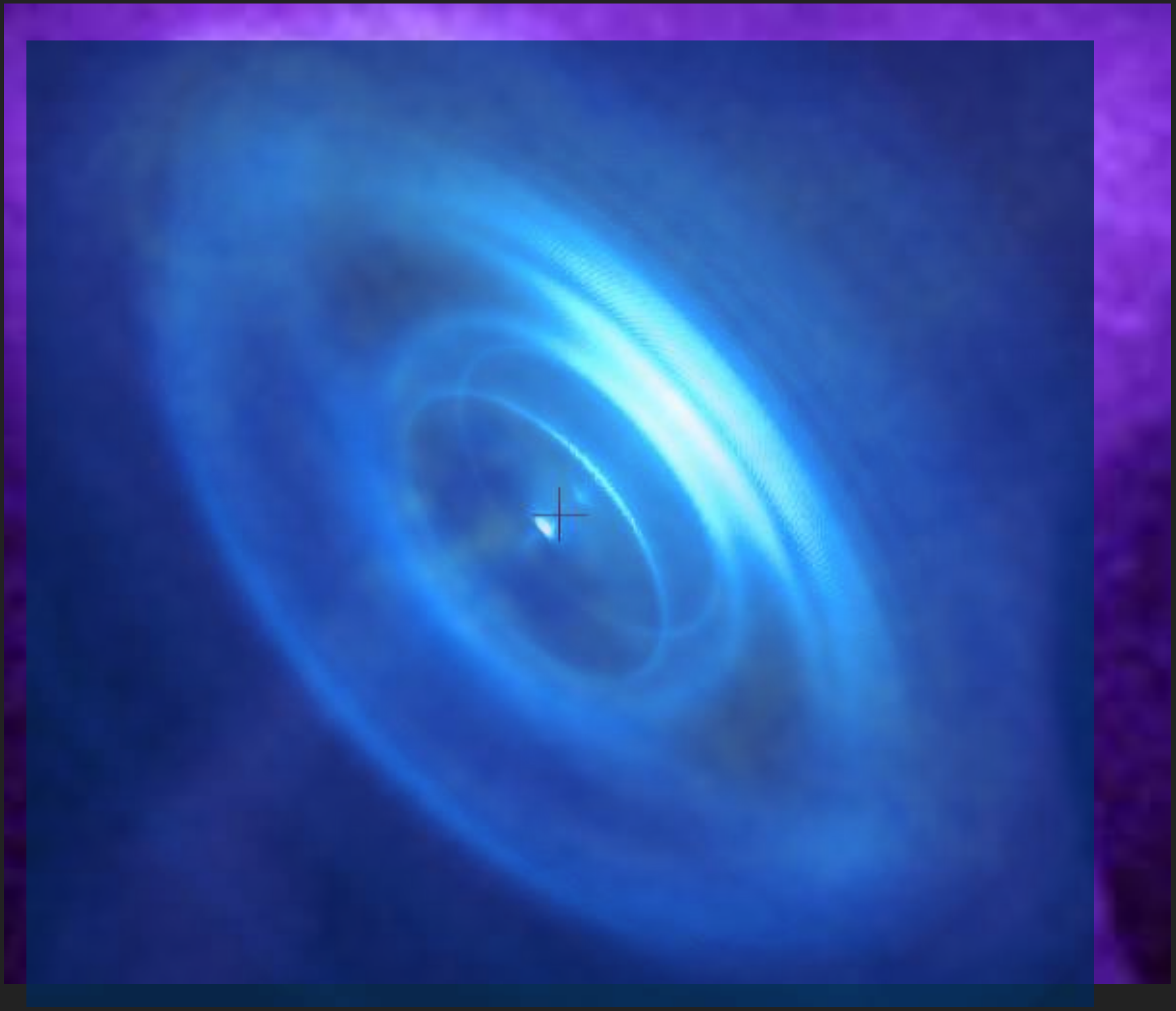
Ring

Torus

# REPRODUCING OBSERVATIONS



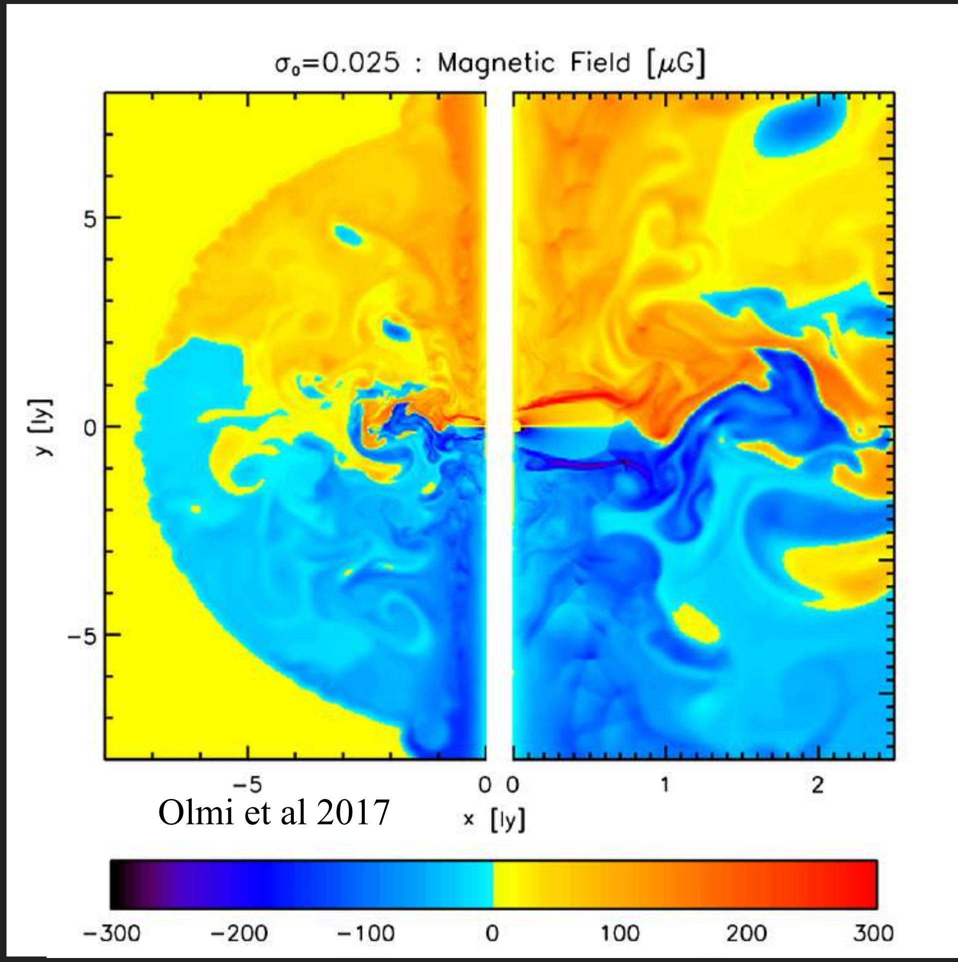
# REPRODUCING OBSERVATIONS

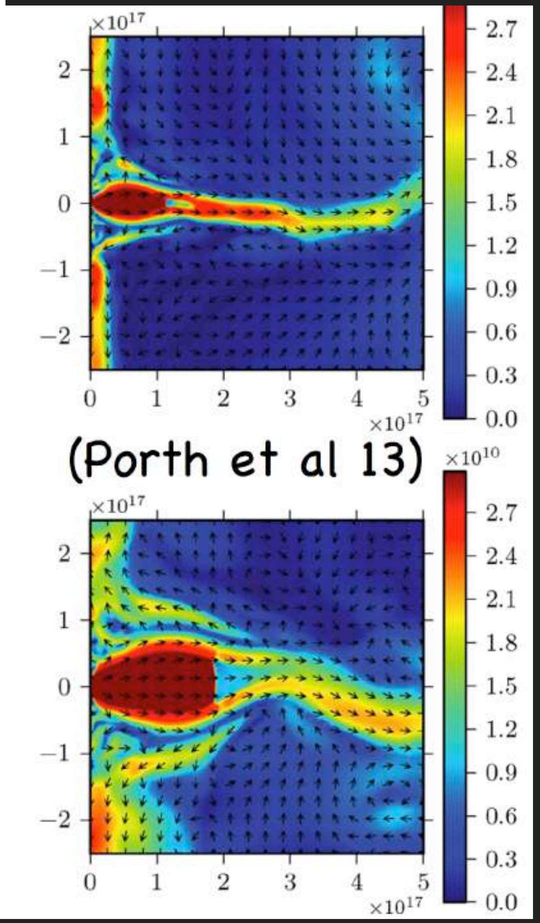


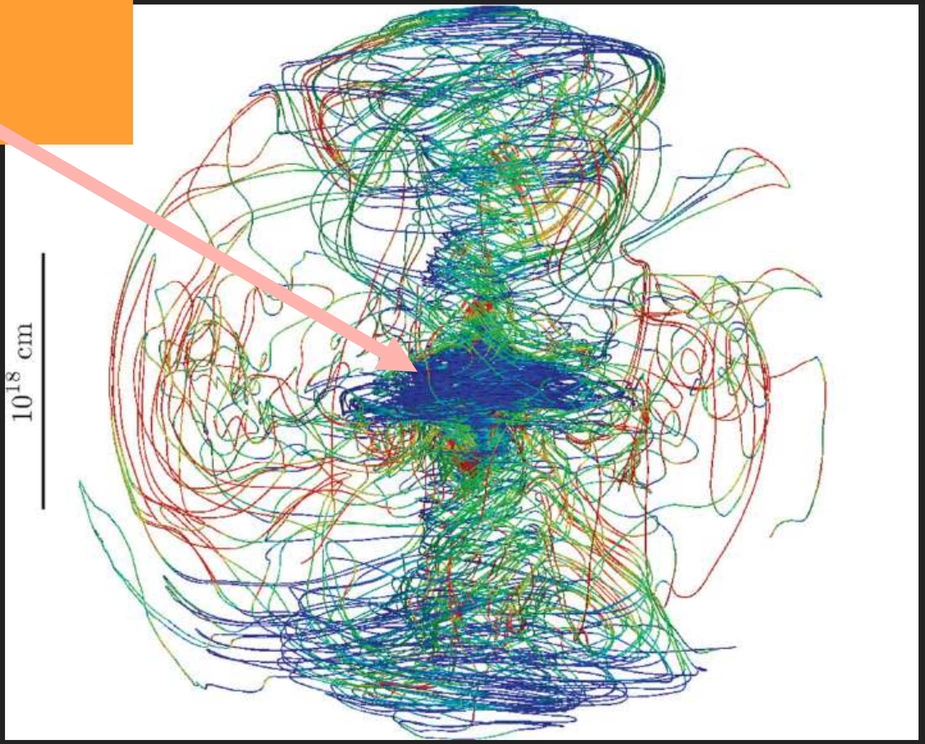
# THE COMPLEXITY OF GOING 3D - STATE OF THE ART COMPUTATIONS

3D ALLOWS FOR HIGHER MAGNETIZATIONS

INNER REGION STILL AXISYMMETRIC TORUS-JET



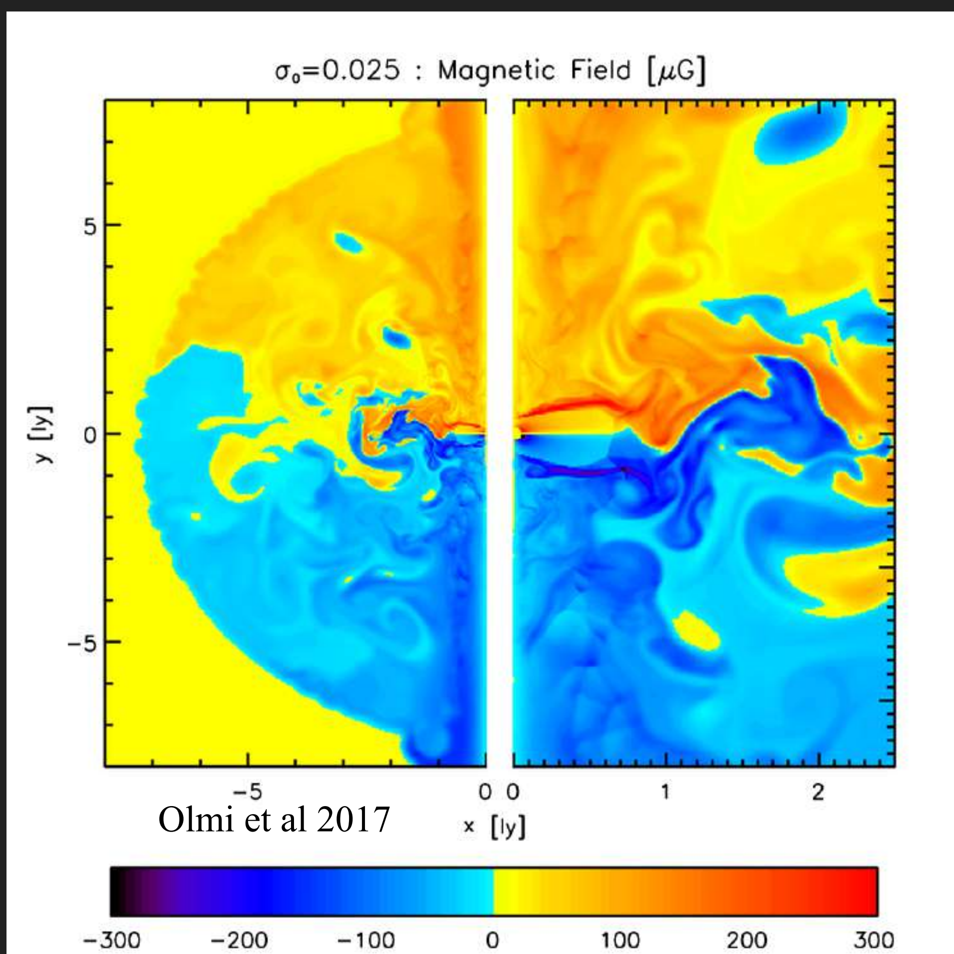



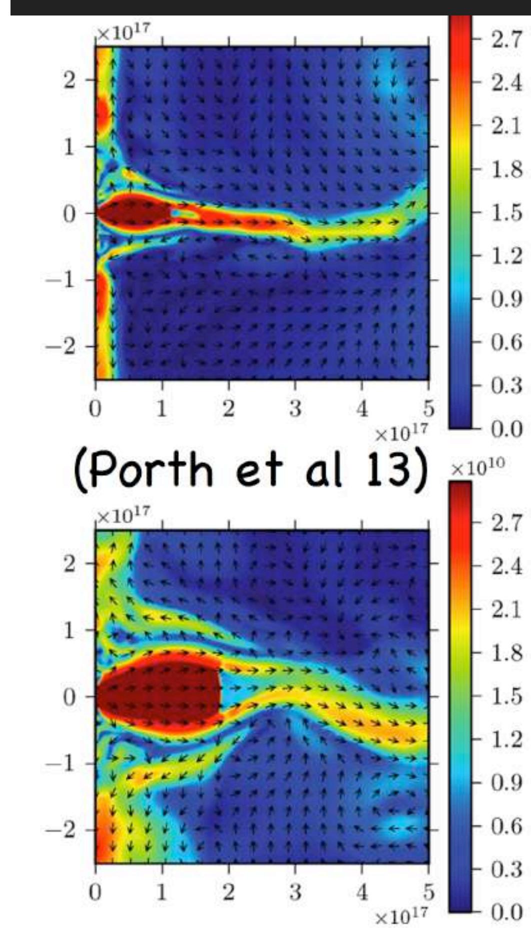
# THE COMPLEXITY OF GOING 3D - STATE OF THE ART COMPUTATIONS

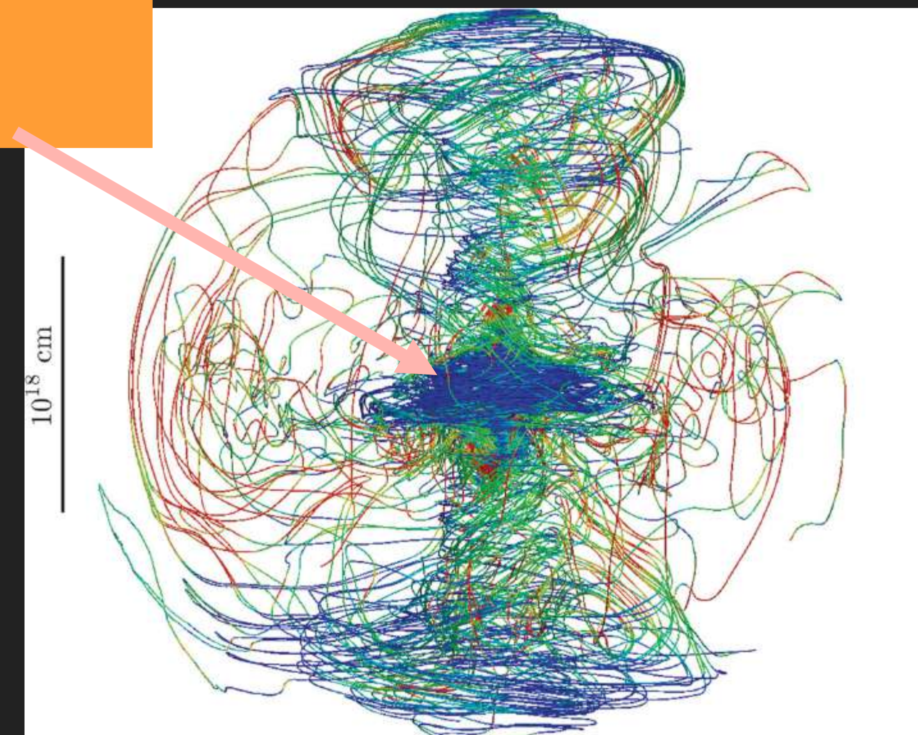
3D ALLOWS FOR HIGHER MAGNETIZATIONS

INNER REGION STILL AXISYMMETRIC TORUS-JET



Olmi et al 2017


(Porth et al 13)

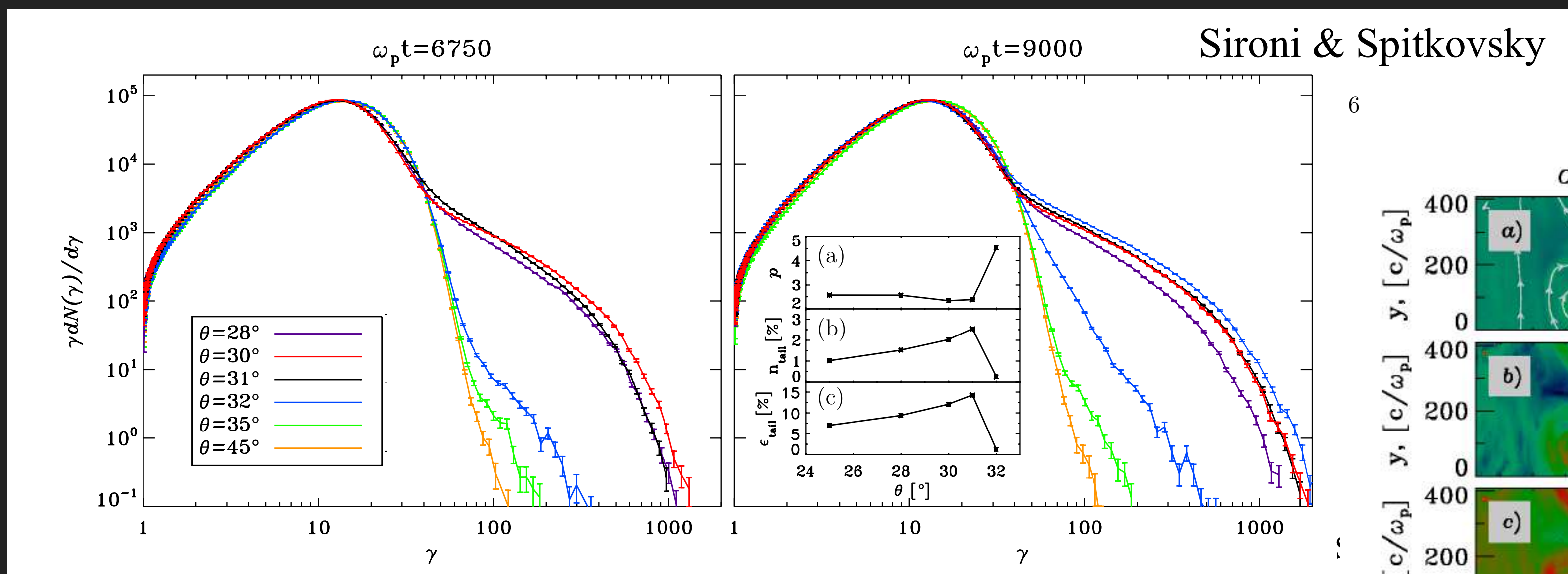


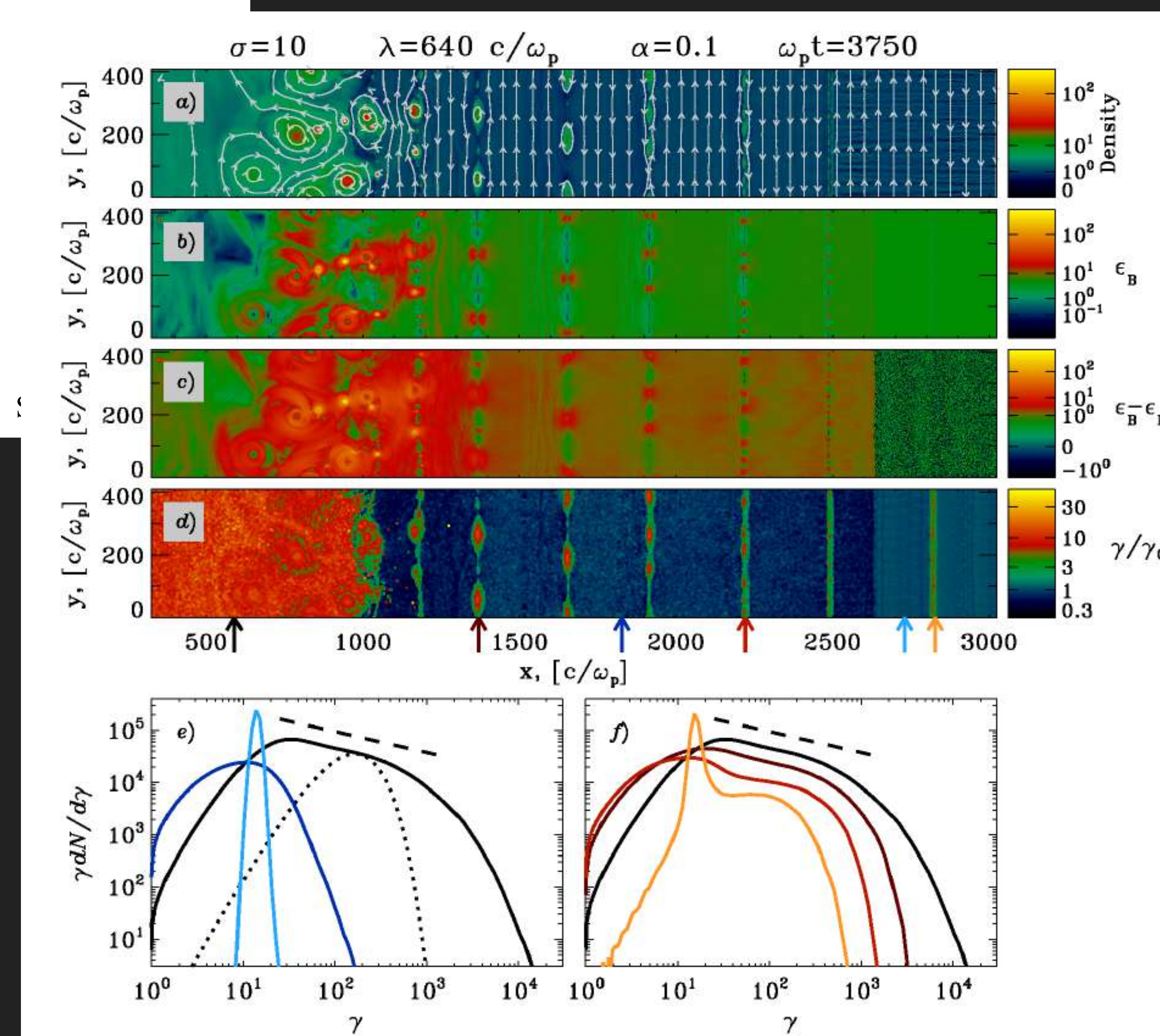

WEAKER JET AND POLATIZATION

TOO MUCH TIME VARIABILITY

# FERMI VS RECONNECTION

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



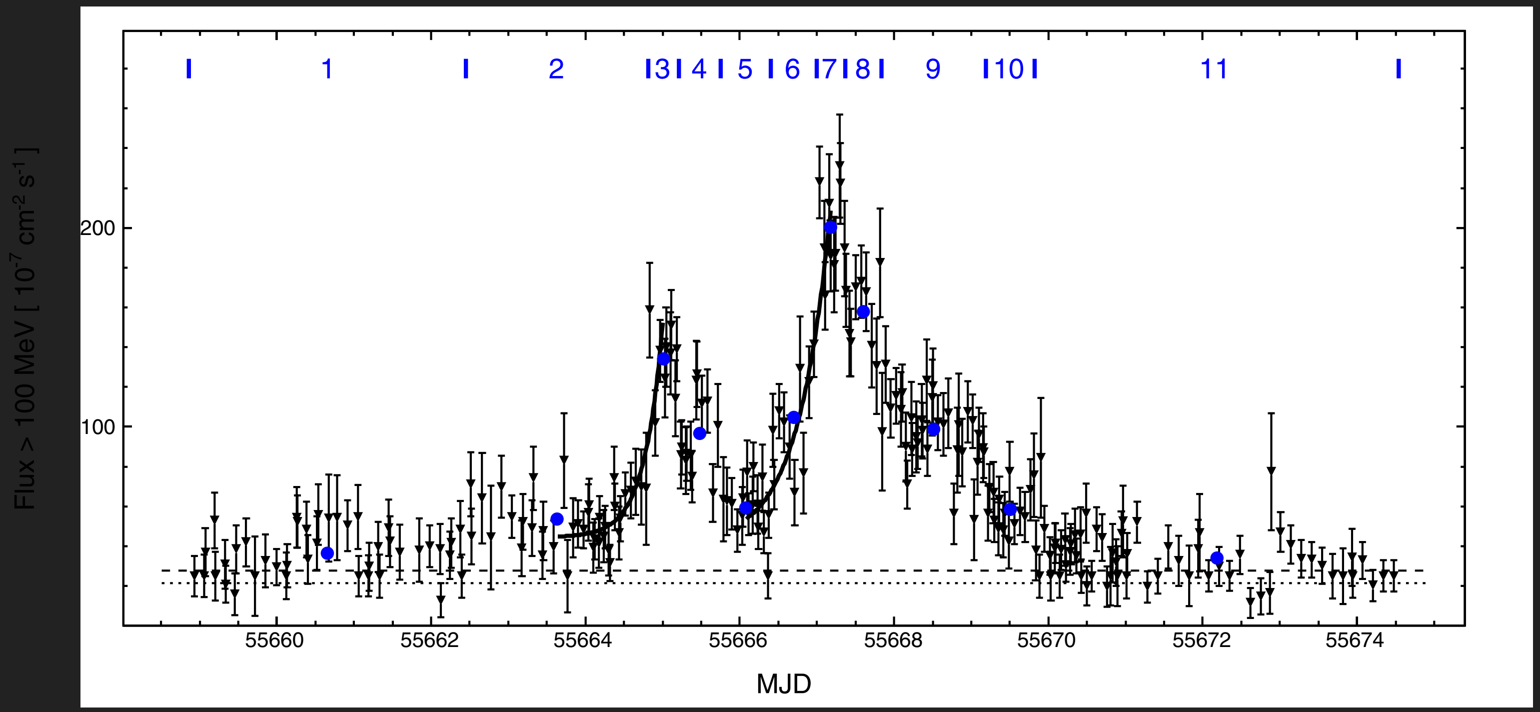




RECONNECTION OF THE STRIPED WIND MORE VERSATILE

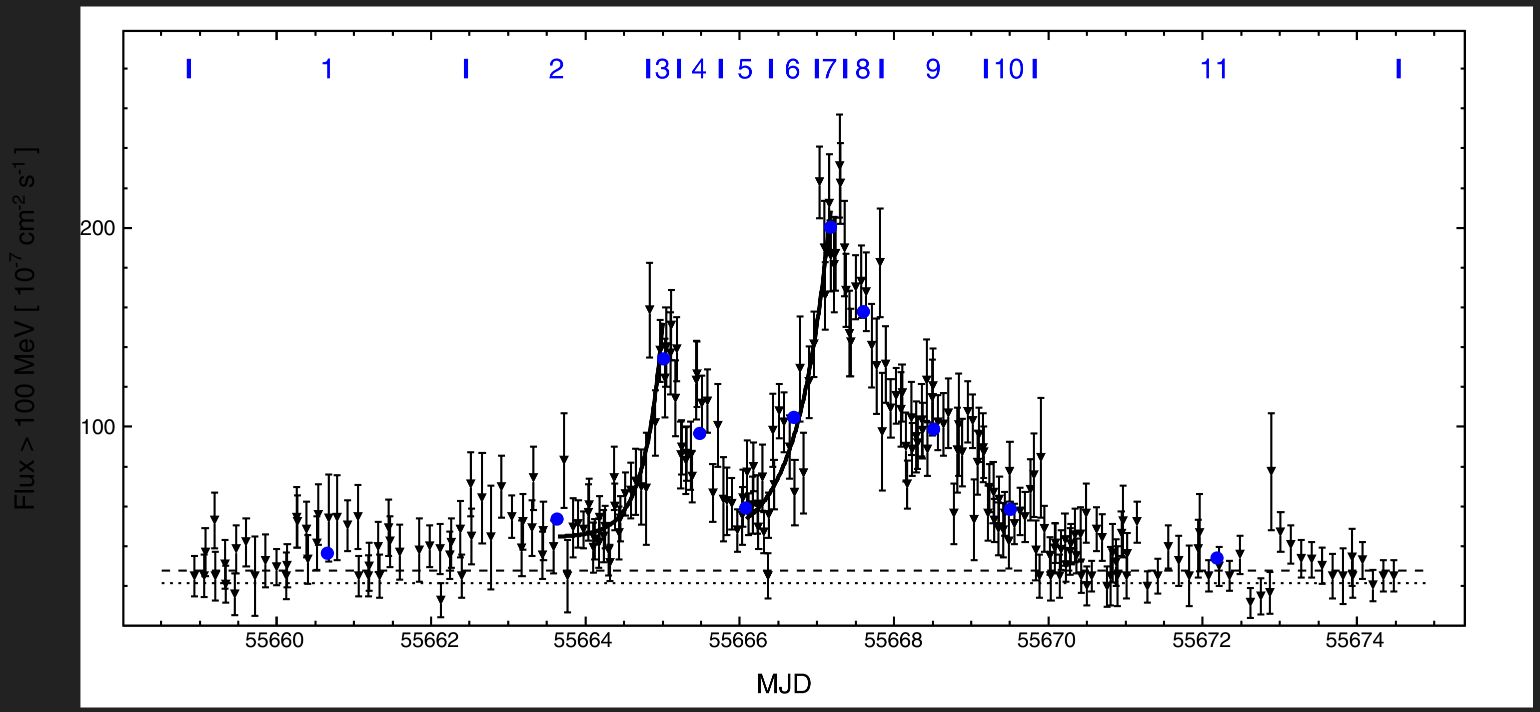
WORKS WELL FOR HIGH MAGNETIZATION

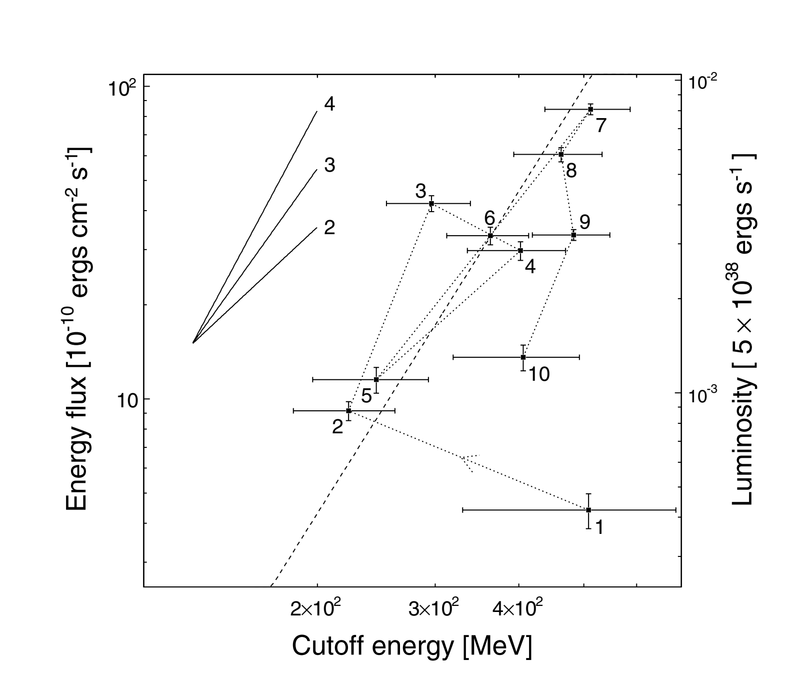
REQUIRES VERY HIGH MULTIPLICITY

# SPECTRAL EVOLUTION



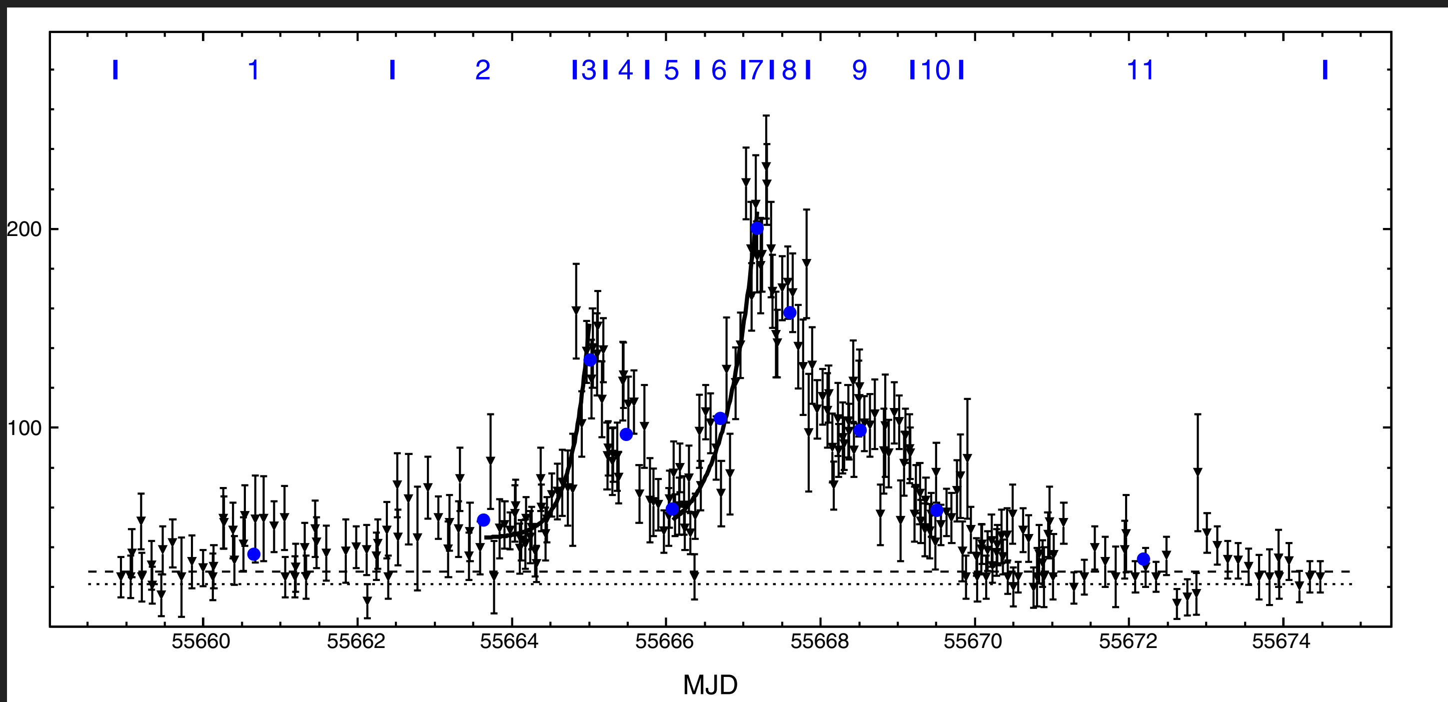
# SPECTRAL EVOLUTION

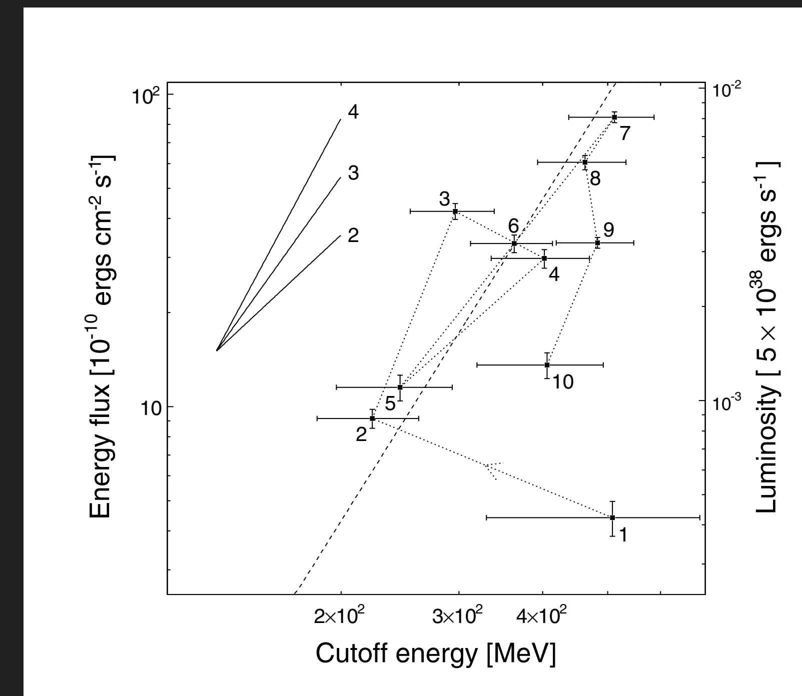



## CUTOFF ENERGY IS HIGHER AT PEAK

# SPECTRAL EVOLUTION



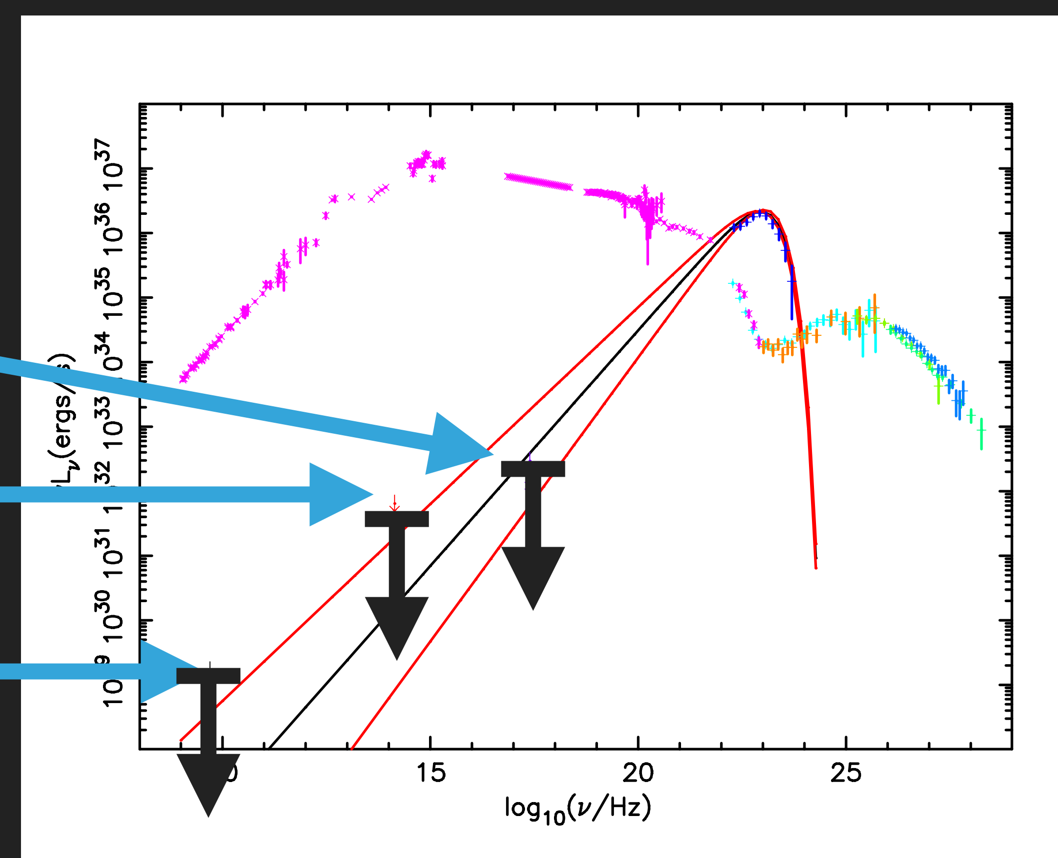




## CUTOFF ENERGY IS HIGHER AT PEAK

CHANDRA UPPER LIMIT

KNOT IR UPPER LIMIT

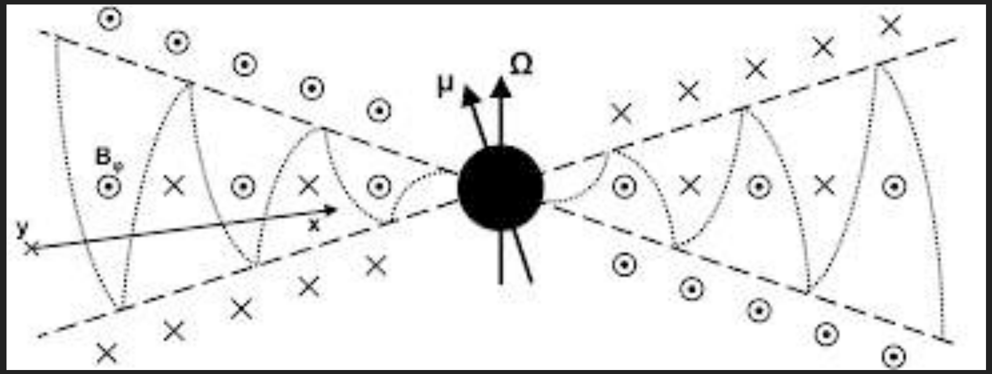
1GHZ VLA UPPER LIMIT



# RECONNECTION

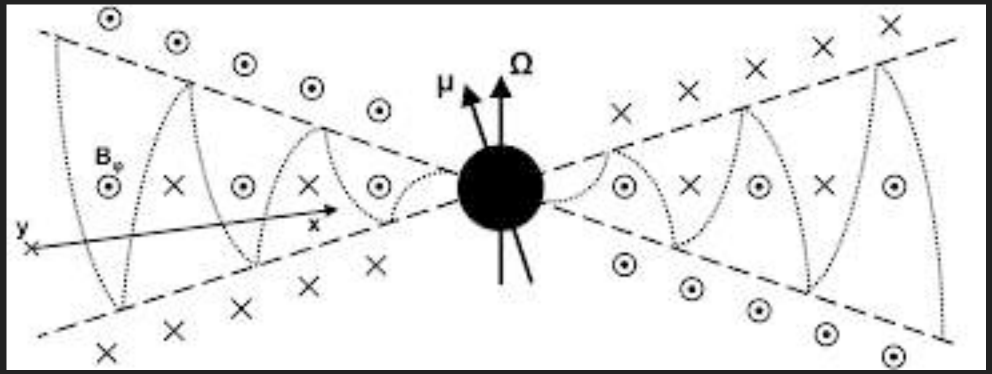
# RECONNECTION

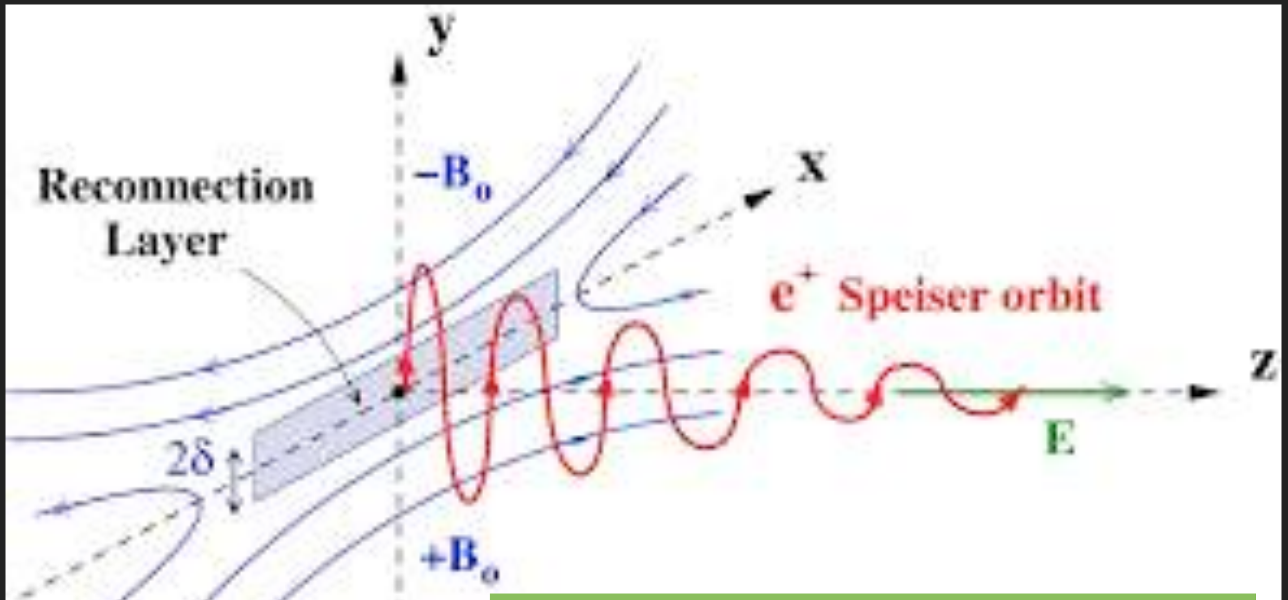
PSR WINDS ARE STRIPED AND THIS IMPLIES ALTERNATING FIELD POLARITIES IN THE PWN



# RECONNECTION

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

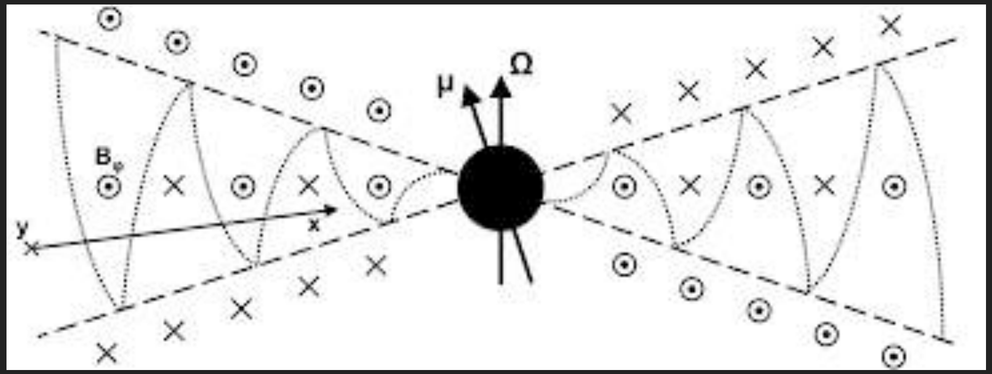


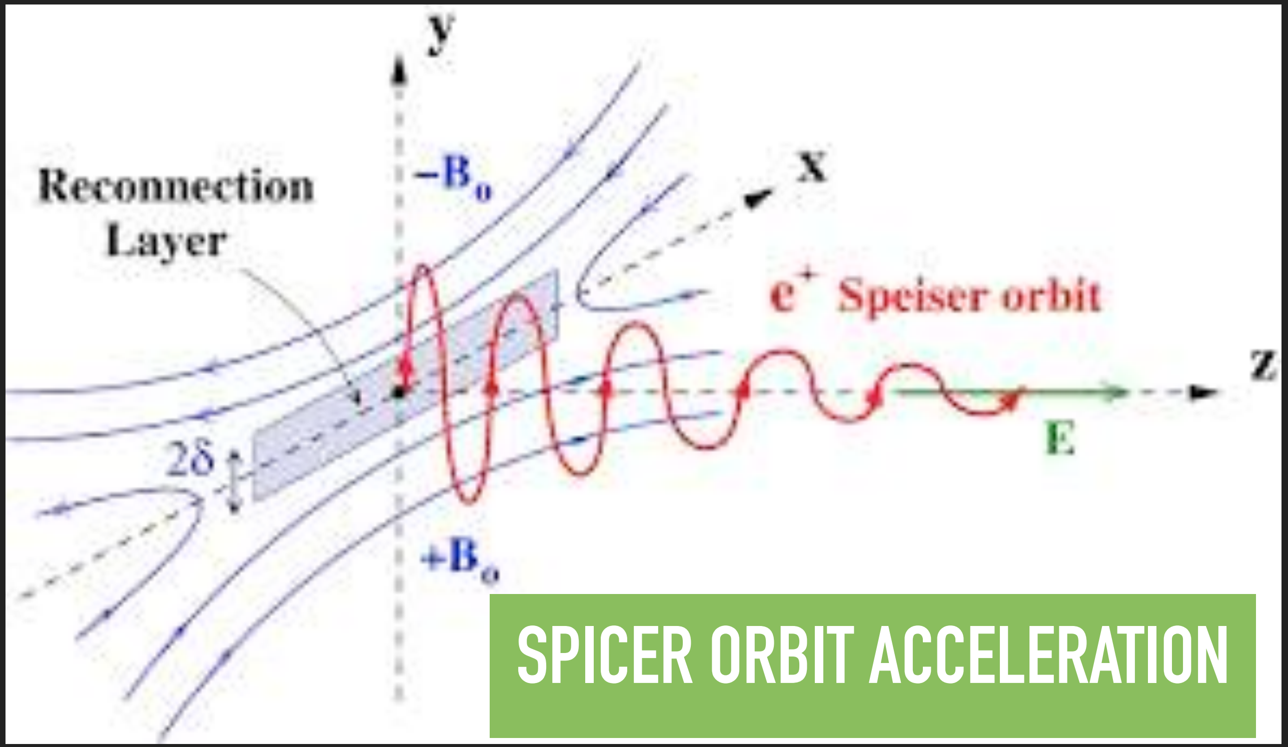



SPICER ORBIT ACCELERATION

# RECONNECTION

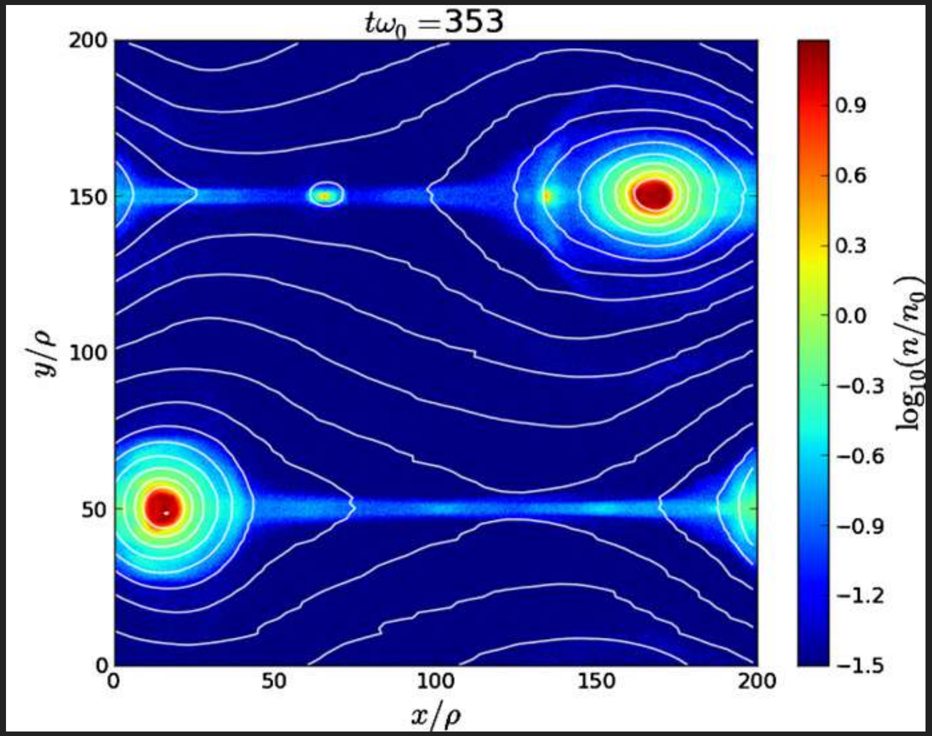
PSR WINDS ARE STRIPED AND THIS IMPLIES ALTERNATING FIELD POLARITIES IN THE PWN



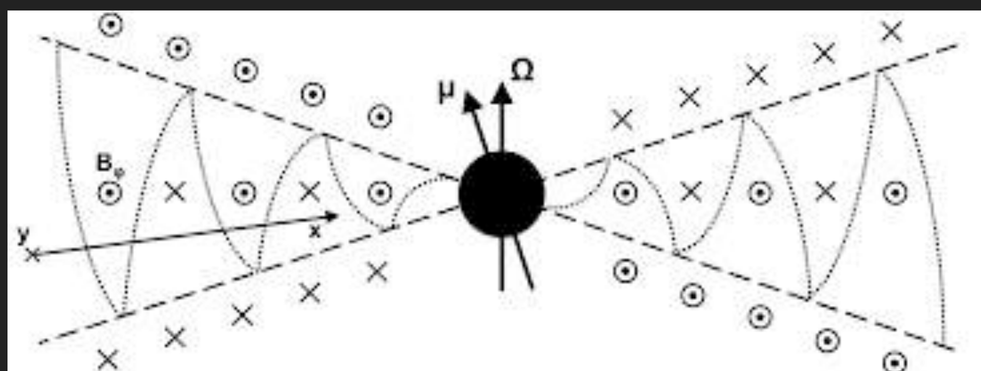

SPICER ORBIT ACCELERATION

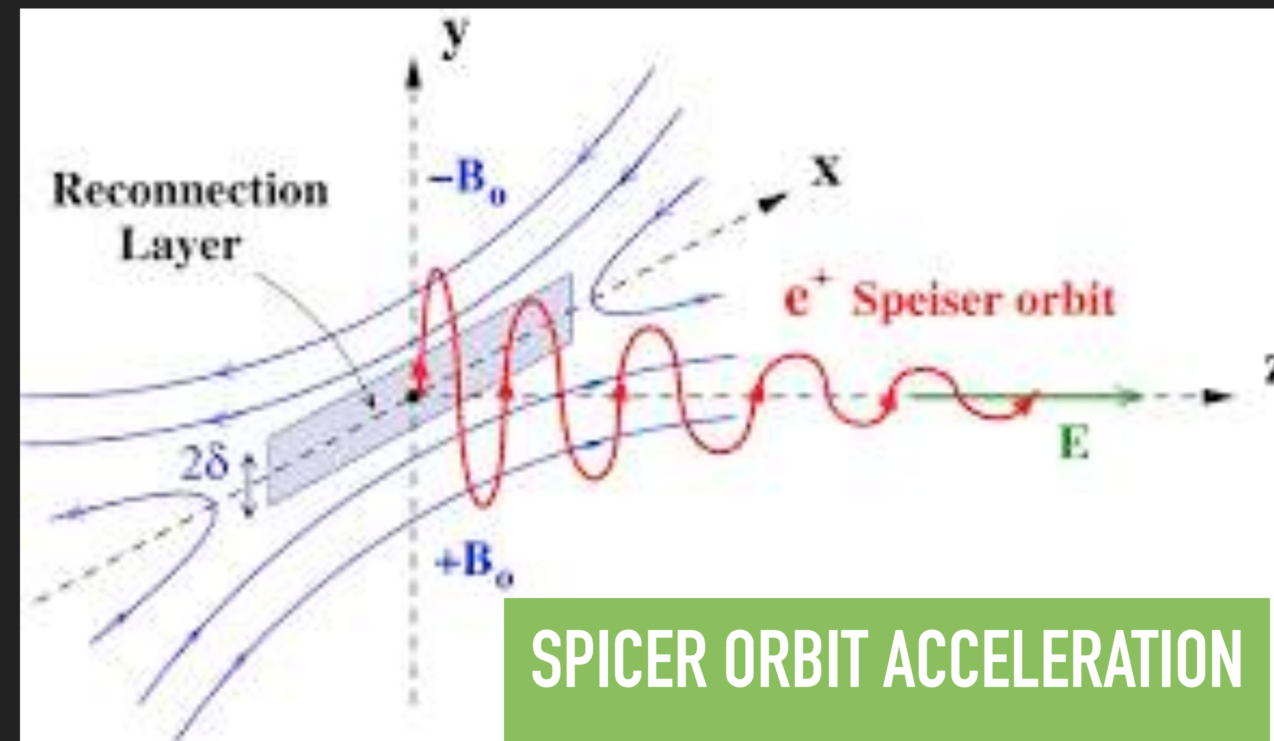
TEARING INSTAB



# RECONNECTION

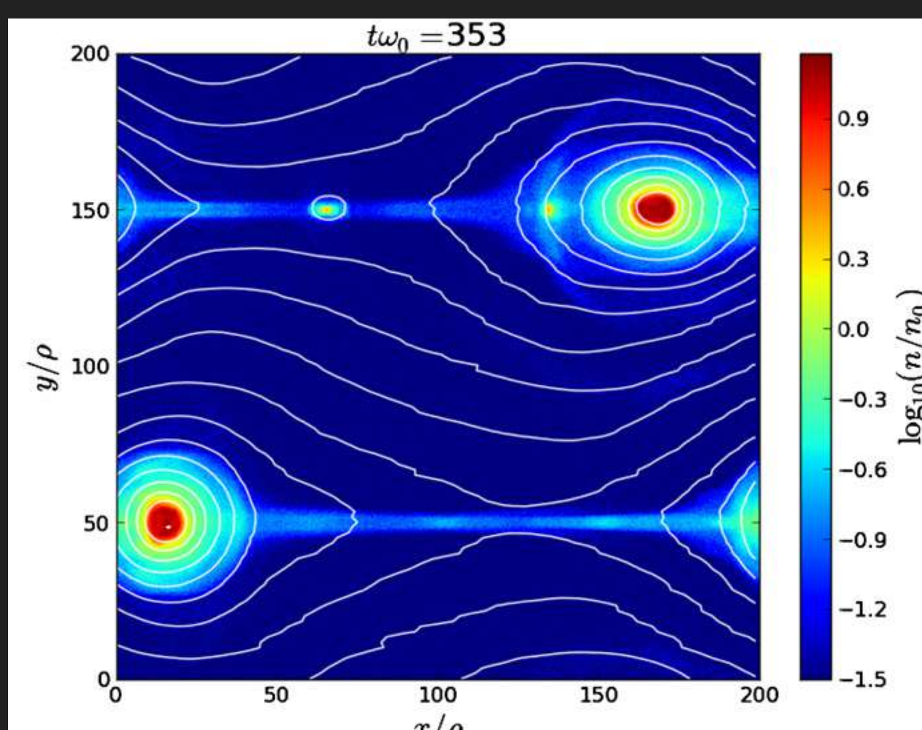
PSR WINDS ARE STRIPED AND THIS IMPLIES ALTERNATING FIELD POLARITIES IN THE PWN



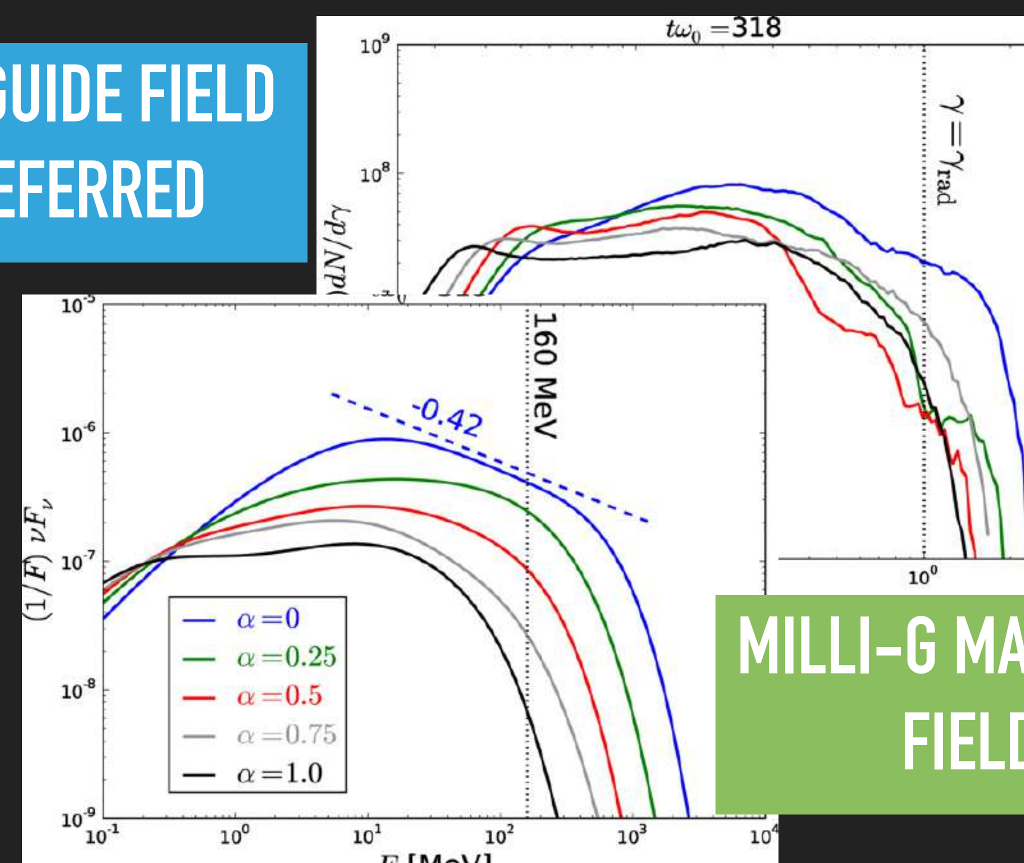




SPICER ORBIT ACCELERATION

TEARING INSTAB



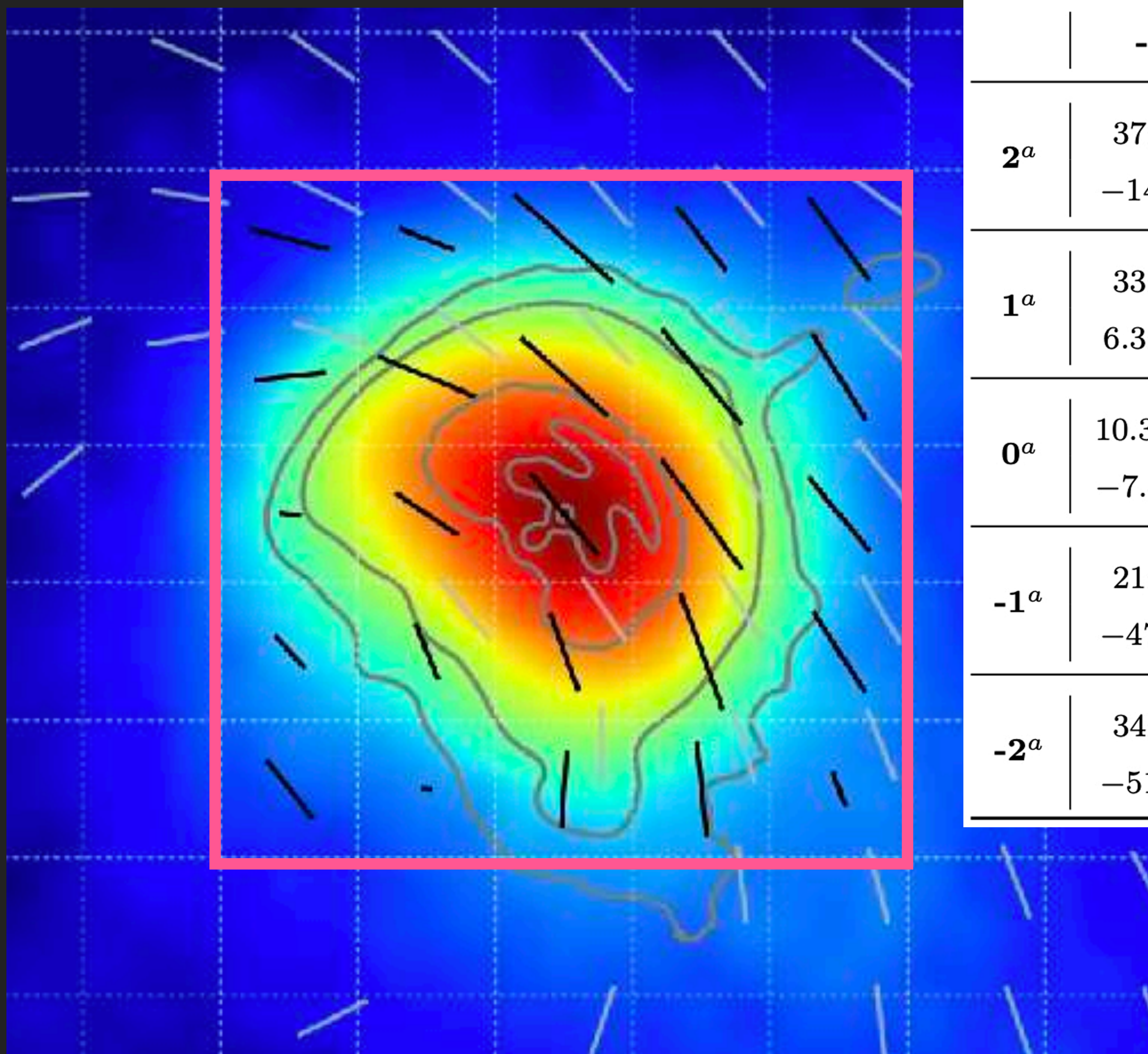

LOW GUIDE FIELD PREFERRED




MILLI-G MAGNETIC FIELD

# 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] |

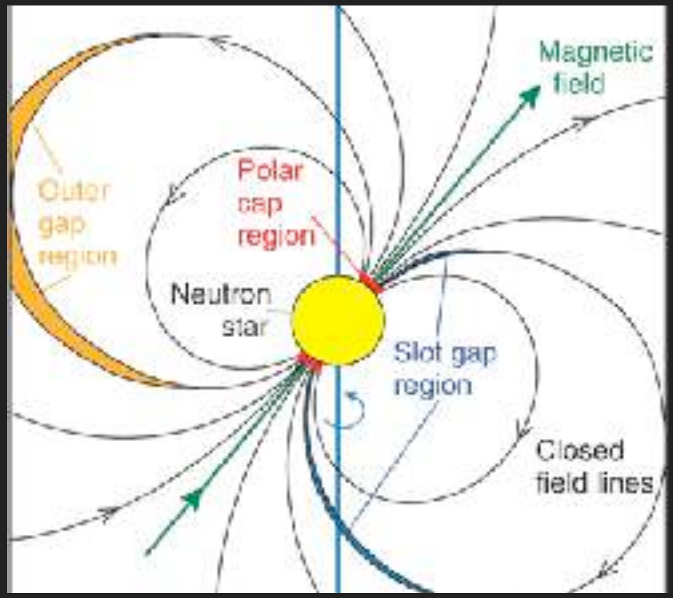
Very high PF suggest no turbulence in the PWNe

Unlikely reconnection to play a major role in accelerating particles

Old sytems should be more turbulent.

# ORIGIN OF THE SYNCHROTRON CUTOFF

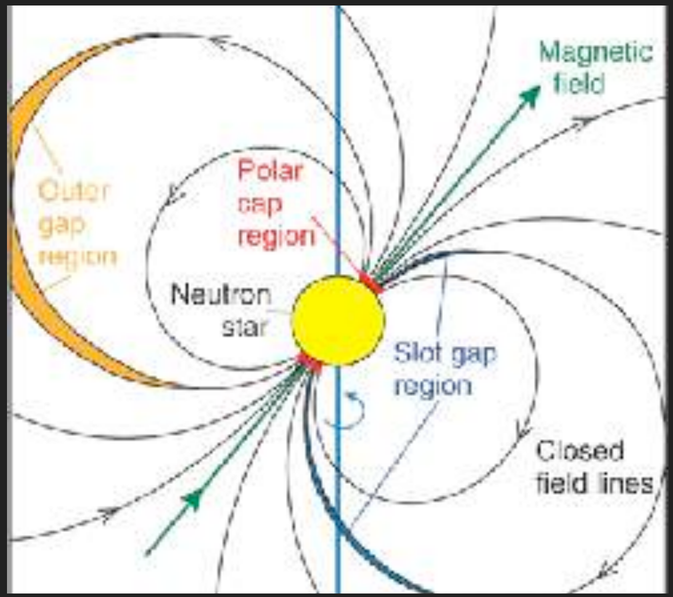
## POTENTIAL LIMITED ACCELERATION



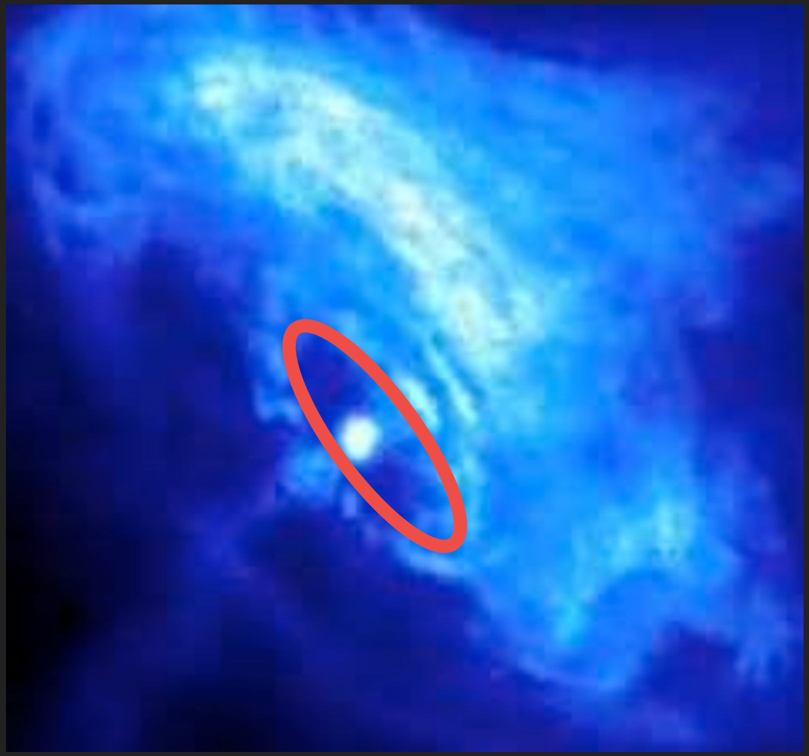

$$mc^2\gamma_{max} = e\sqrt{\frac{L}{c}} = e\Phi_{psr}$$

# ORIGIN OF THE SYNCHROTRON CUTOFF

## POTENTIAL LIMITED ACCELERATION




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



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

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

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

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

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

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

## ACCELERATION LIMIT AT THE TS

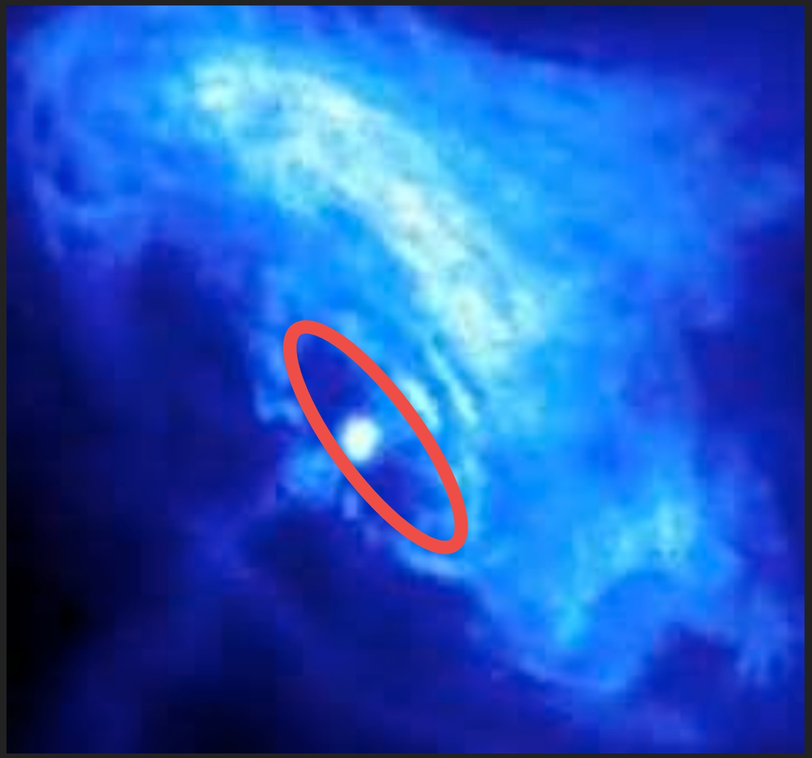
**MAGNETISATION IN THE CRAB IS JUST BELOW EQUIPARTITION**
**B ~ 150-120 UG**

# ORIGIN OF THE SYNCHROTRON CUTOFF

## LOSS LIMITED ACCELERATION

## COMPARING GYRO-PERIOD WRT SYNCH COOLING TIME

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

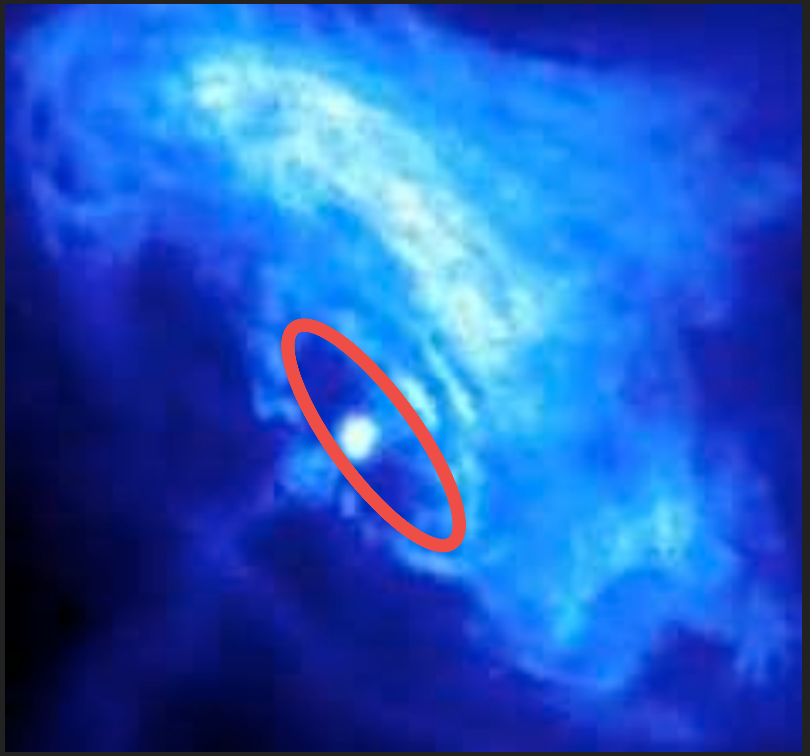


# ORIGIN OF THE SYNCHROTRON CUTOFF

## LOSS LIMITED ACCELERATION

## COMPARING GYRO-PERIOD WRT SYNCH COOLING TIME

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



## MAXIMUM FREQUENCY IS FIXED

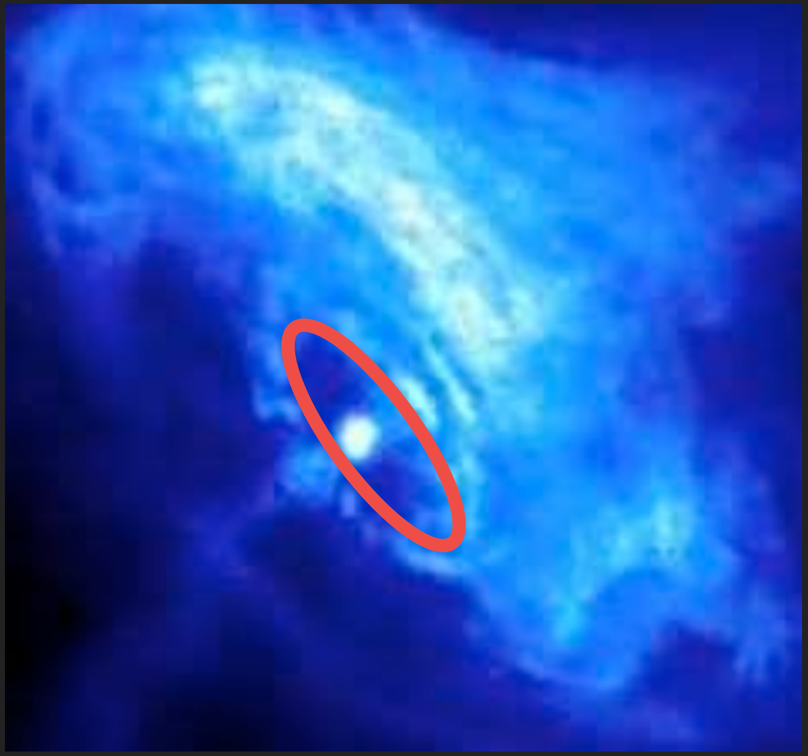
$$\nu_{syn,max} \simeq 150 MeV$$

# ORIGIN OF THE SYNCHROTRON CUTOFF

## LOSS LIMITED ACCELERATION

## COMPARING GYRO-PERIOD WRT SYNCH COOLING TIME

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

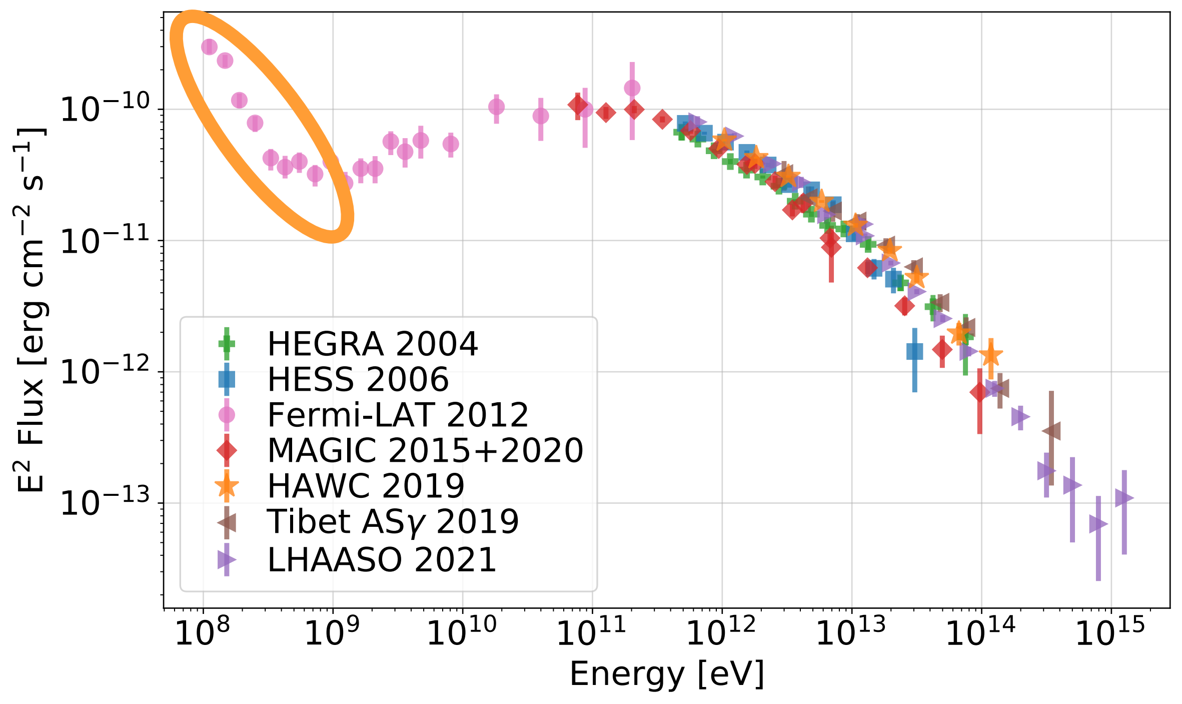


## MAXIMUM FREQUENCY IS FIXED

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

## IN CRAB THE LIMITS ALL COINCIDE

## OTHERS ALL POTENTIAL LIMITED



# 12 INITIAL SOURCES DETECTED BY LHAASO ABOVE 100 TEV

**Table 1 | UHE γ-ray sources**

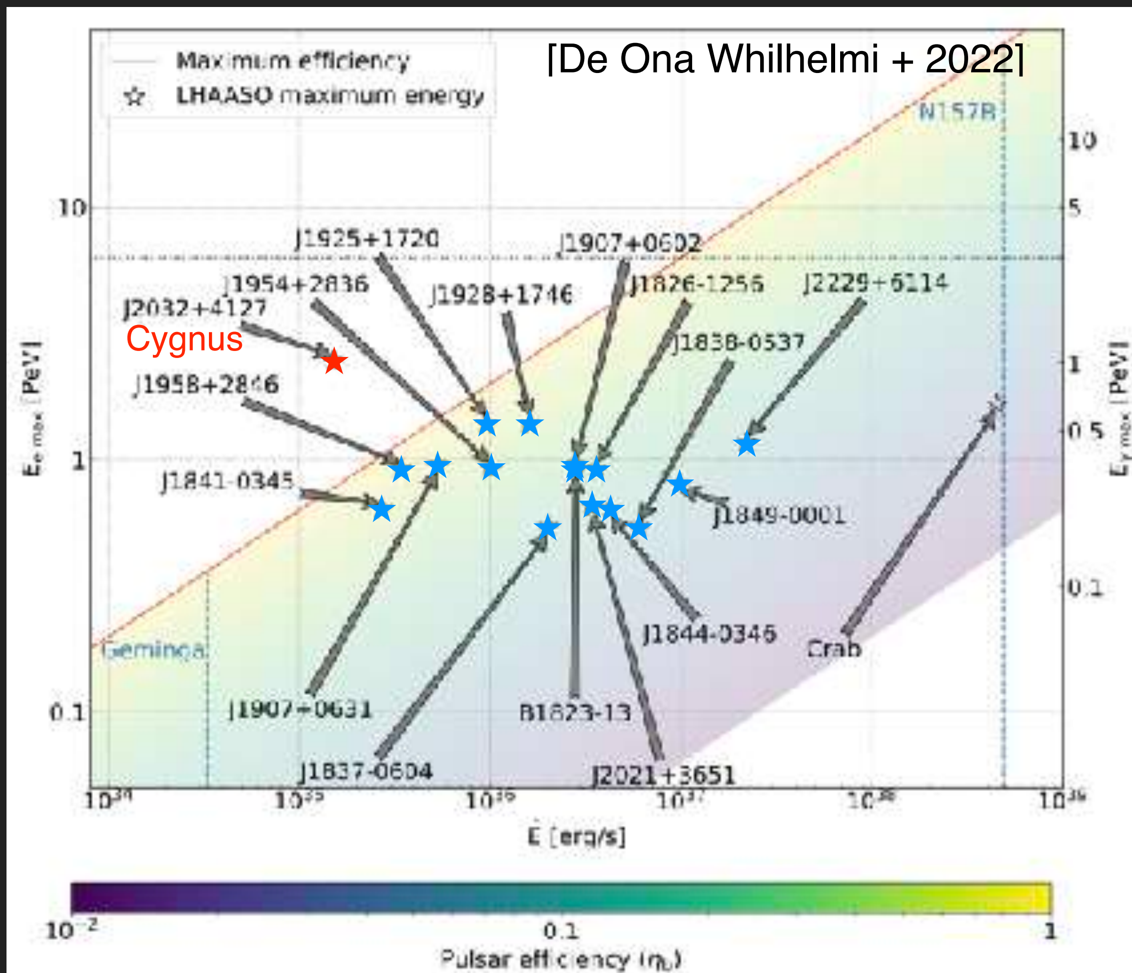
| Source name | RA (°) | dec. (°) | Significance above 100 TeV (×σ) | $E_{max}$ (PeV) | Flux at 100 TeV (CU) |
|---|---|---|---|---|---|
| LHAASO J0534+2202 | 83.55 | 22.05 | 17.8 | 0.88 ± 0.11 | 1.00(0.14) |
| LHAASO J1825-1326 | 276.45 | −13.45 | 16.4 | 0.42 ± 0.16 | 3.57(0.52) |
| LHAASO J1839-0545 | 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) |

35 OUT 43 >100 TEV SOURCES HAVE A PSR/PWN ASSOCIATED

PEV PROTONS OR ELECTRONS?

THERE ARE NO-COUNTERPART SOURCES

# PSR VOLTAGE




## STRICT LIMIT FROM THE PSR POTENTIAL DROP

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

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

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

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

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

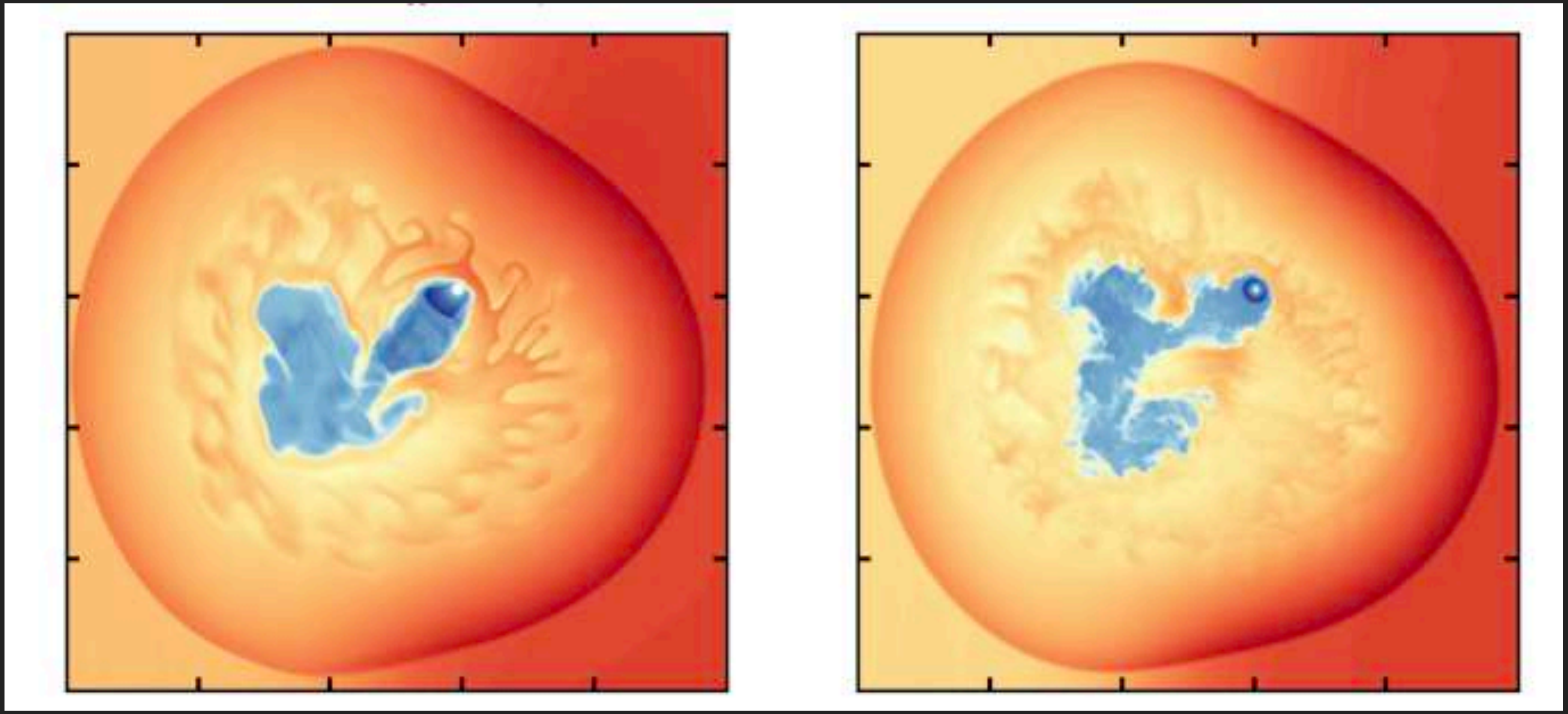
IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LIKELY LOSS LIMITED

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

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

# TIME EVOLUTION I

Kolb et al 2017

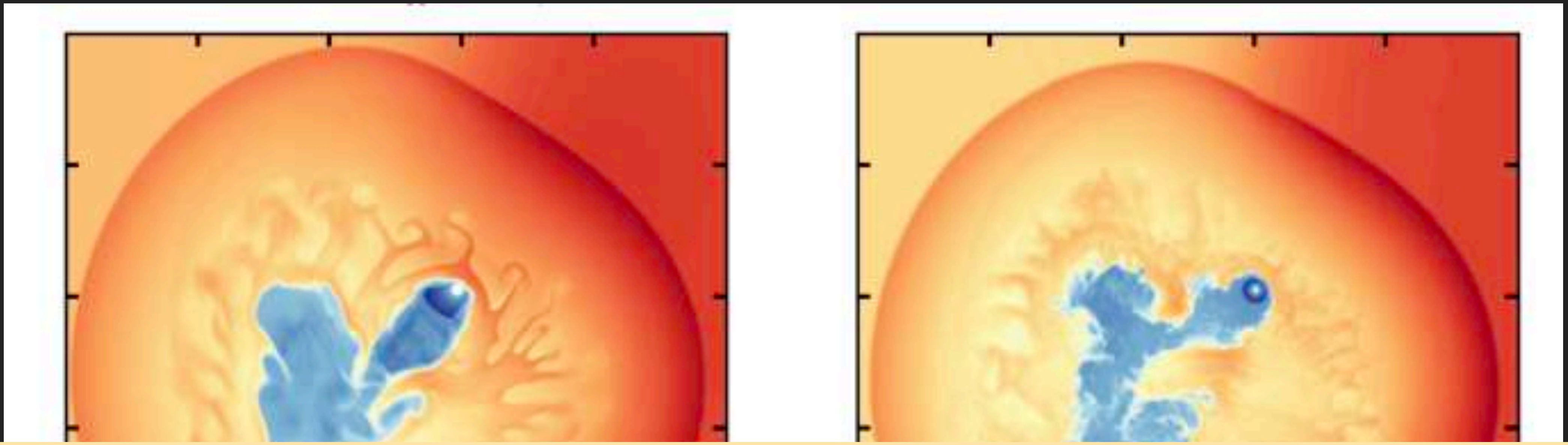


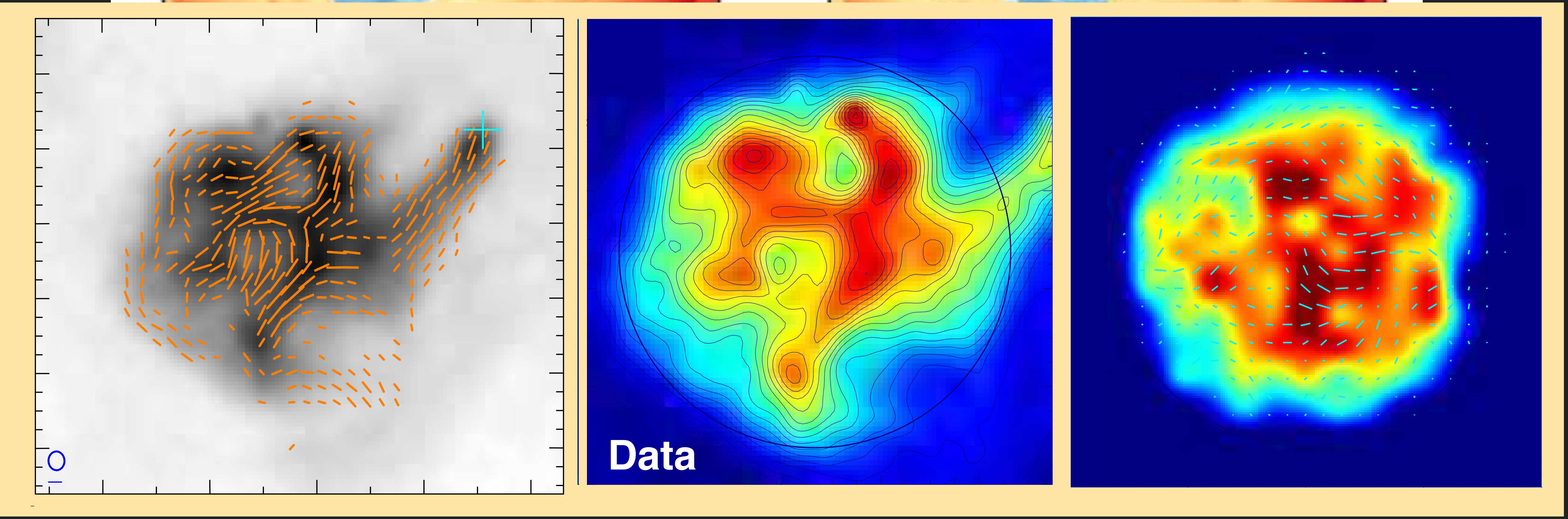
Blondin et al 2001

Ma et al 2016

# TIME EVOLUTION I

Kolb et al 2017



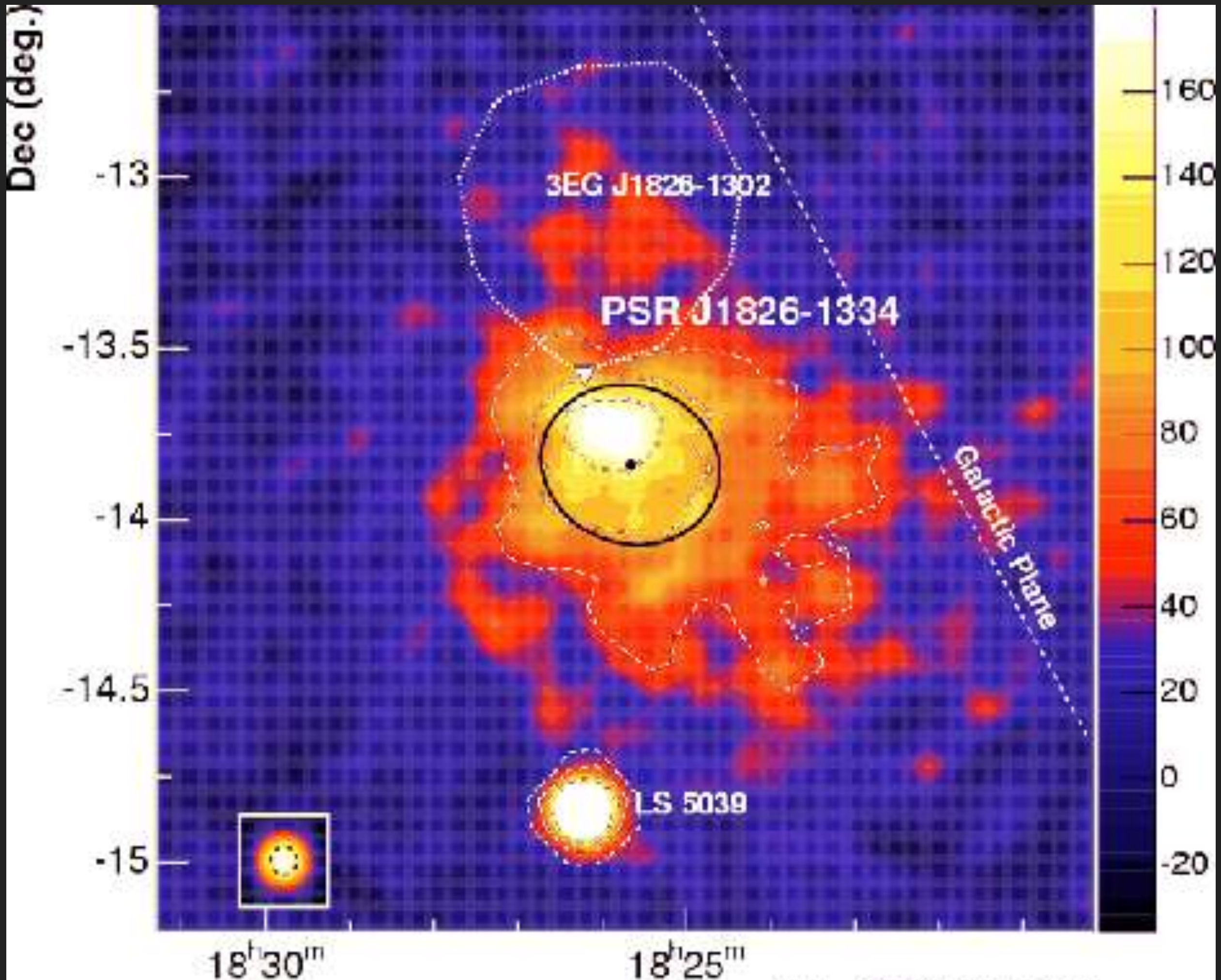



G327 Ma et al. 2015

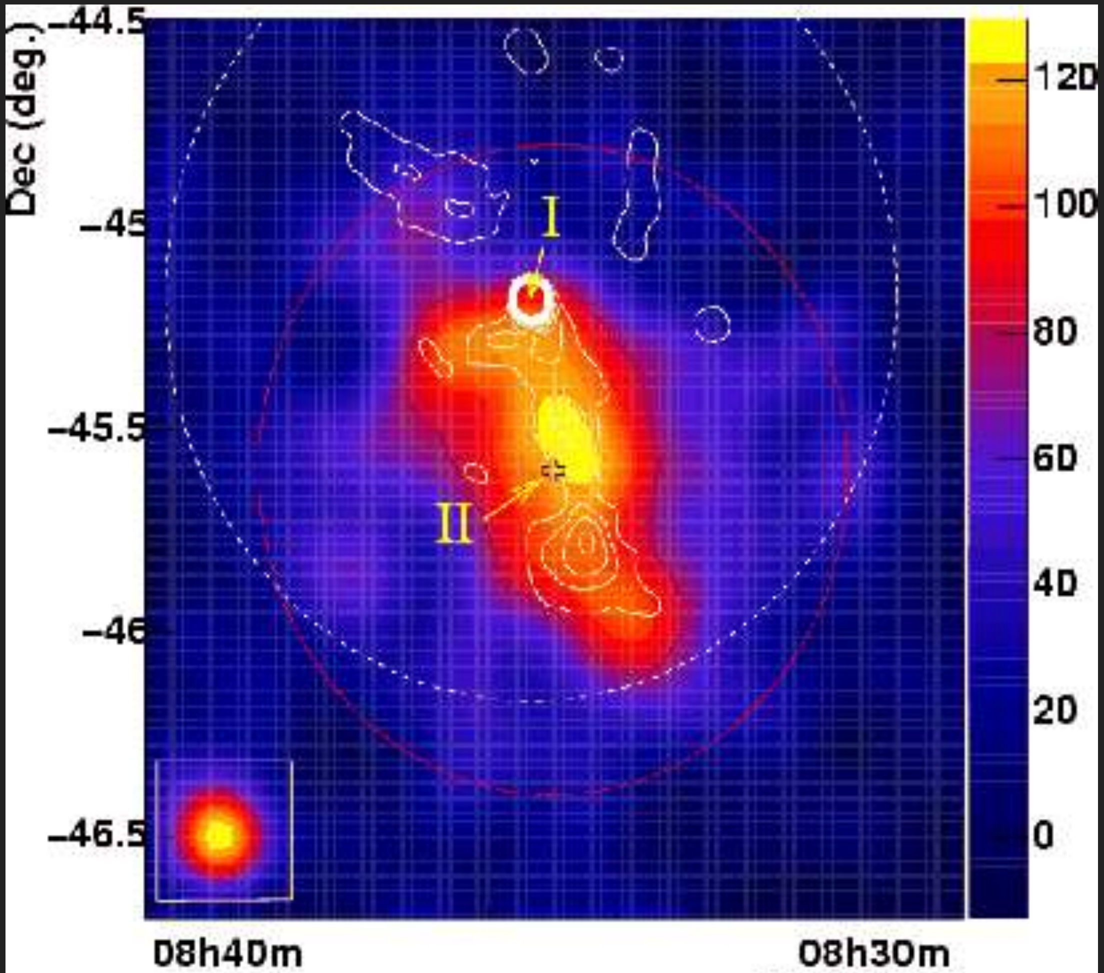
Ma et al 2016

# OLD SYSTEMS

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



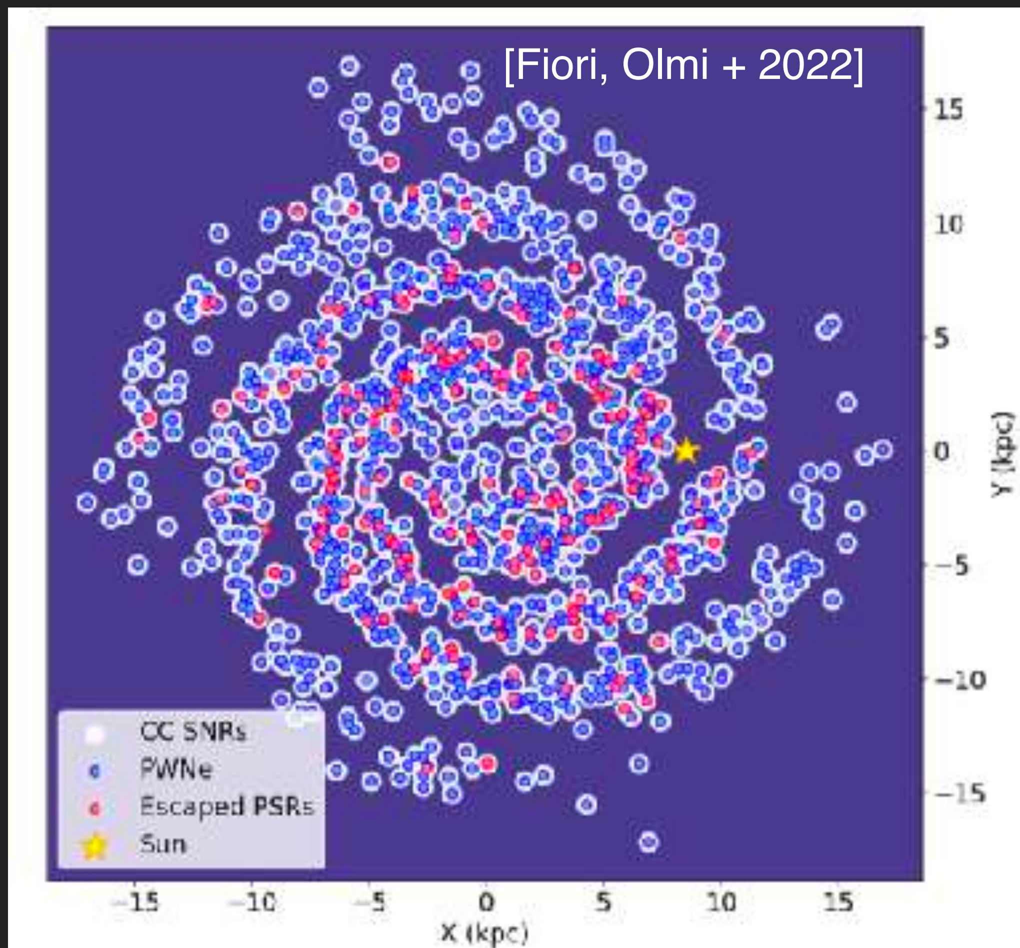

J1825-137 (HESS; Aharonian et al. 2005)




Vela (HESS; Aharonian et al. 2005)

# PWNE WILL BE THE MOST NUMEROUS GALACTIC GAMMA-RAY SOURCES

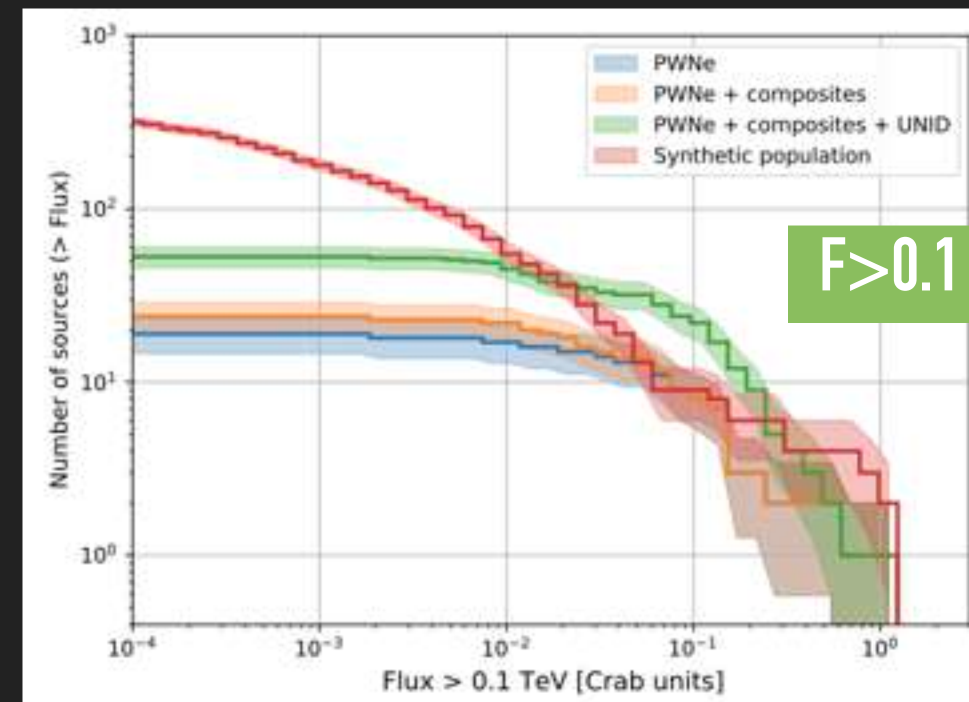
## DISTRIBUTION IN THE GALAXY



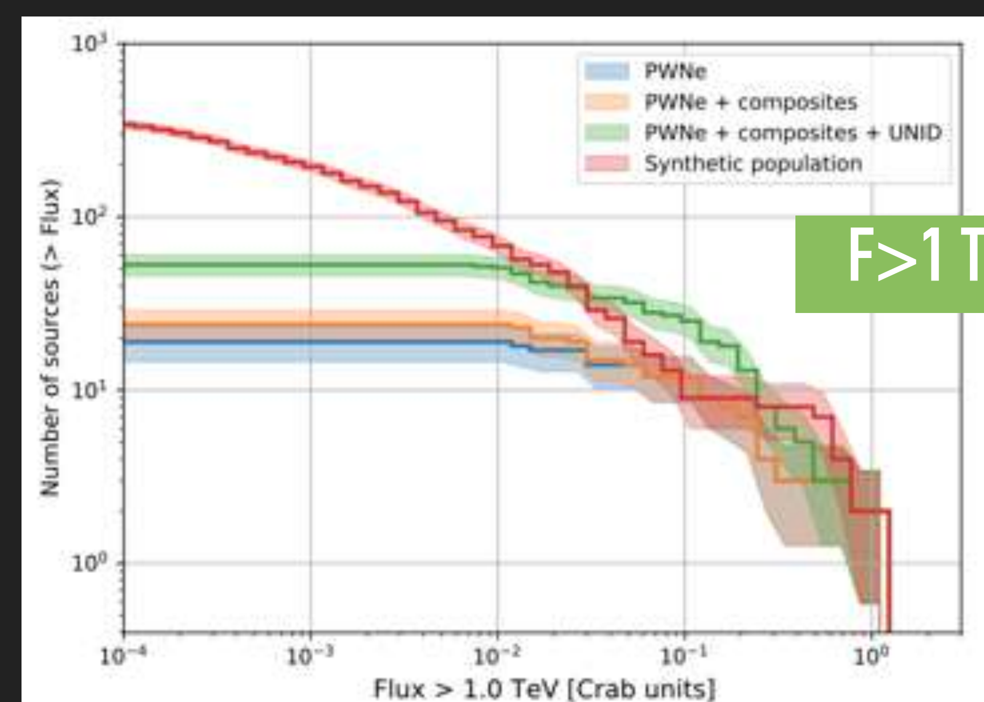

PWN IN THE GALAXY MODELLED WITH NUMERICAL SIMULATIONS + RADIATIVE CODE

PWN ARE PRIMARY TARGETS FOR CTA AND ASTRI MA

## CONTRIBUTION AT GAMMA-RAYS

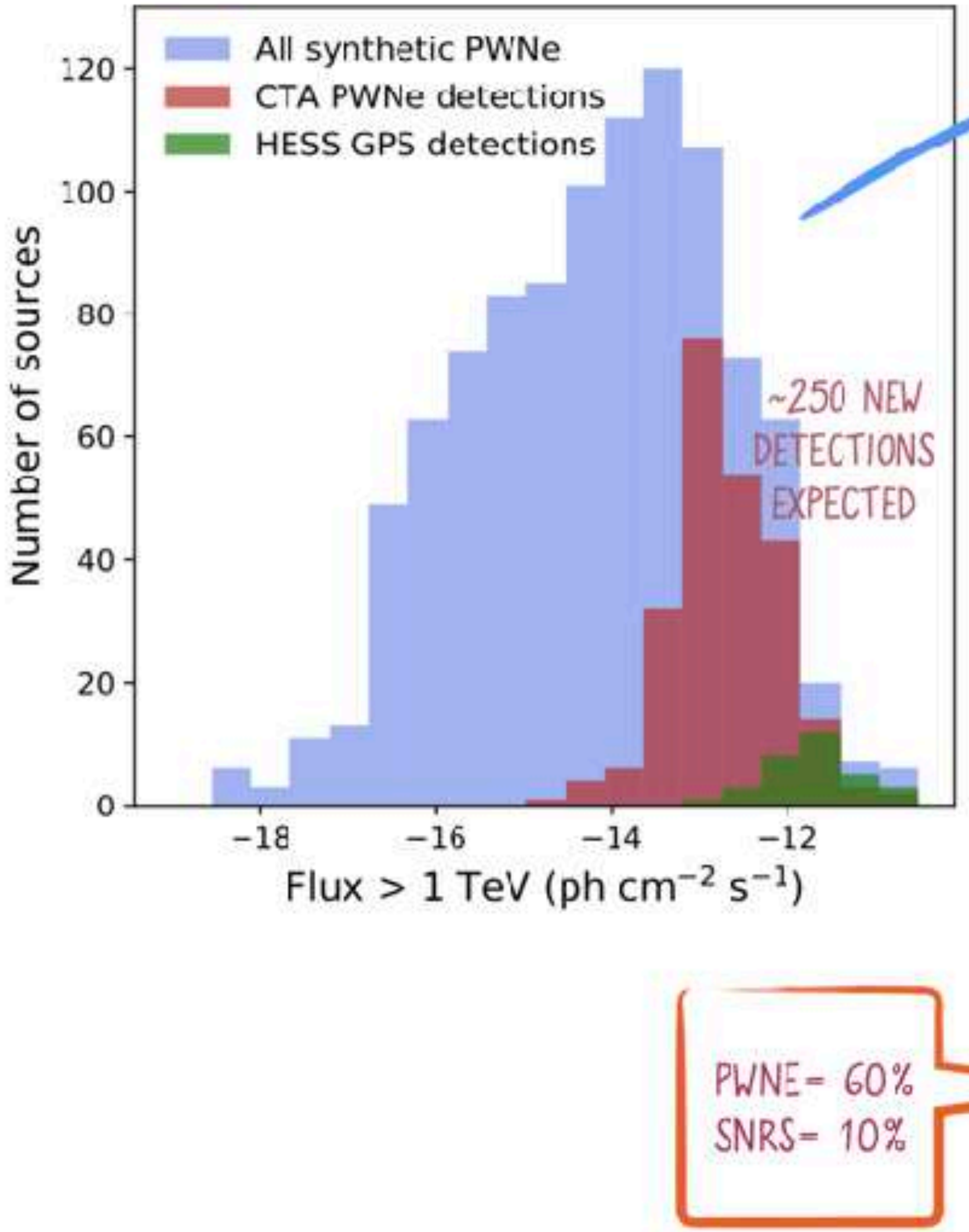



F>0.1 TEV

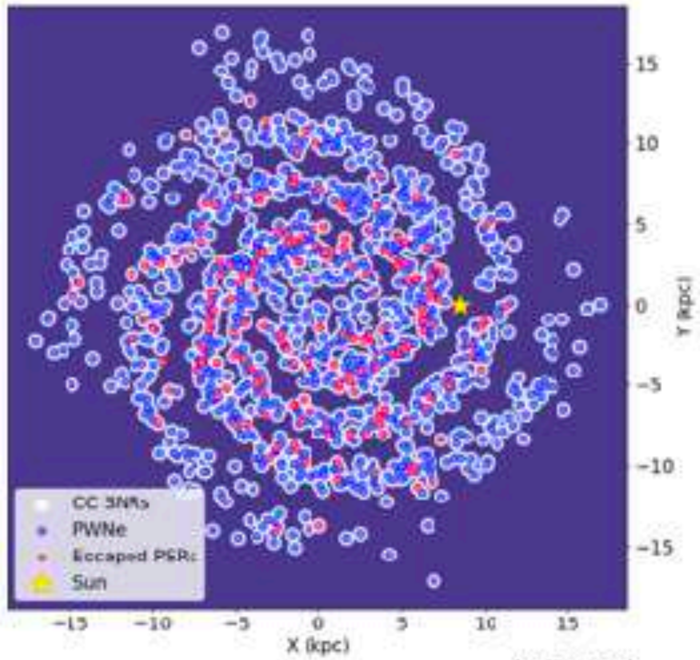


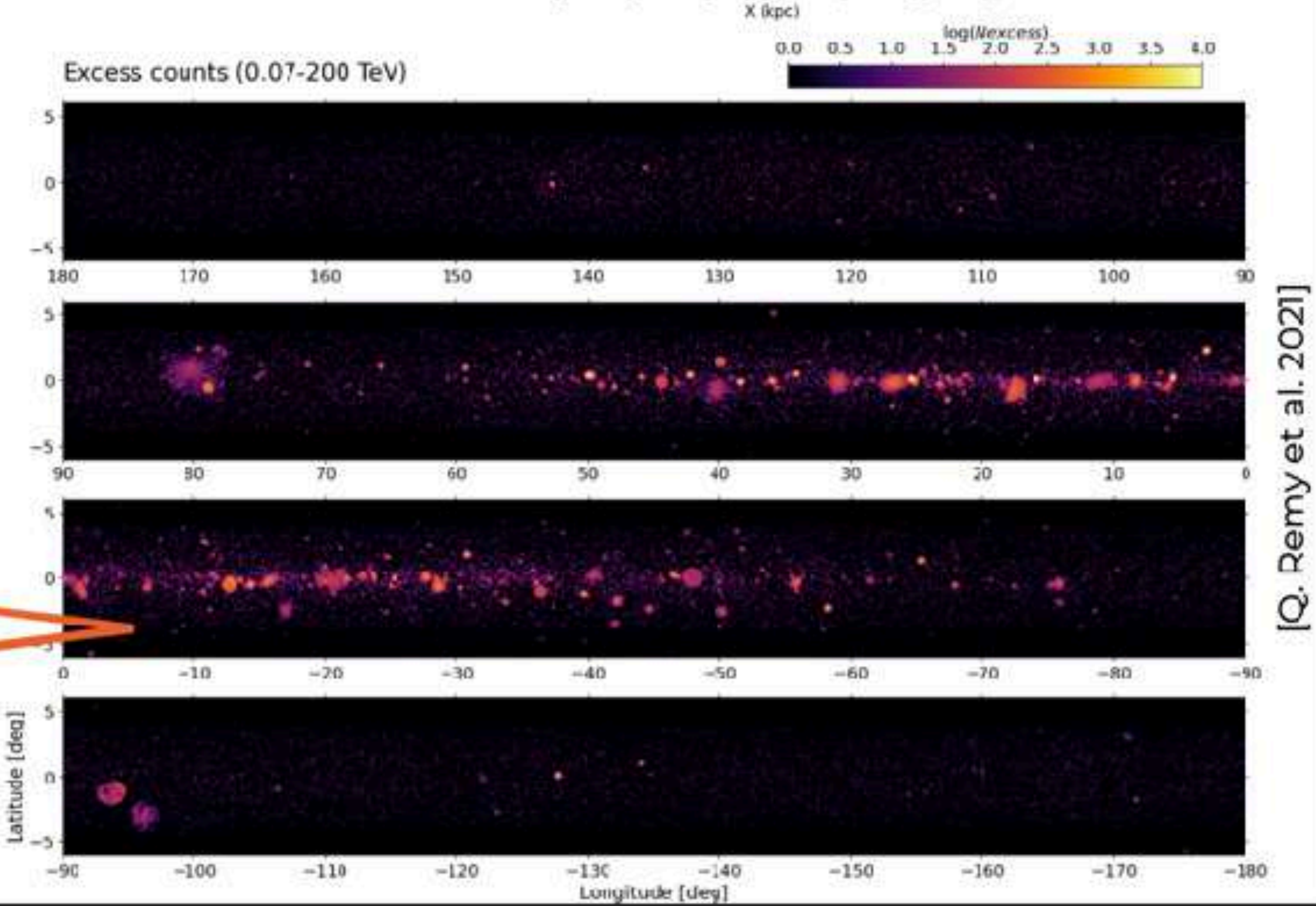

F>1 TEV

EXPECTED DETECTIONS AT GAMMA-RAYS WITH CTA




DISTRIBUTION OF SYNTHETIC SOURCES IN THE GALAXY

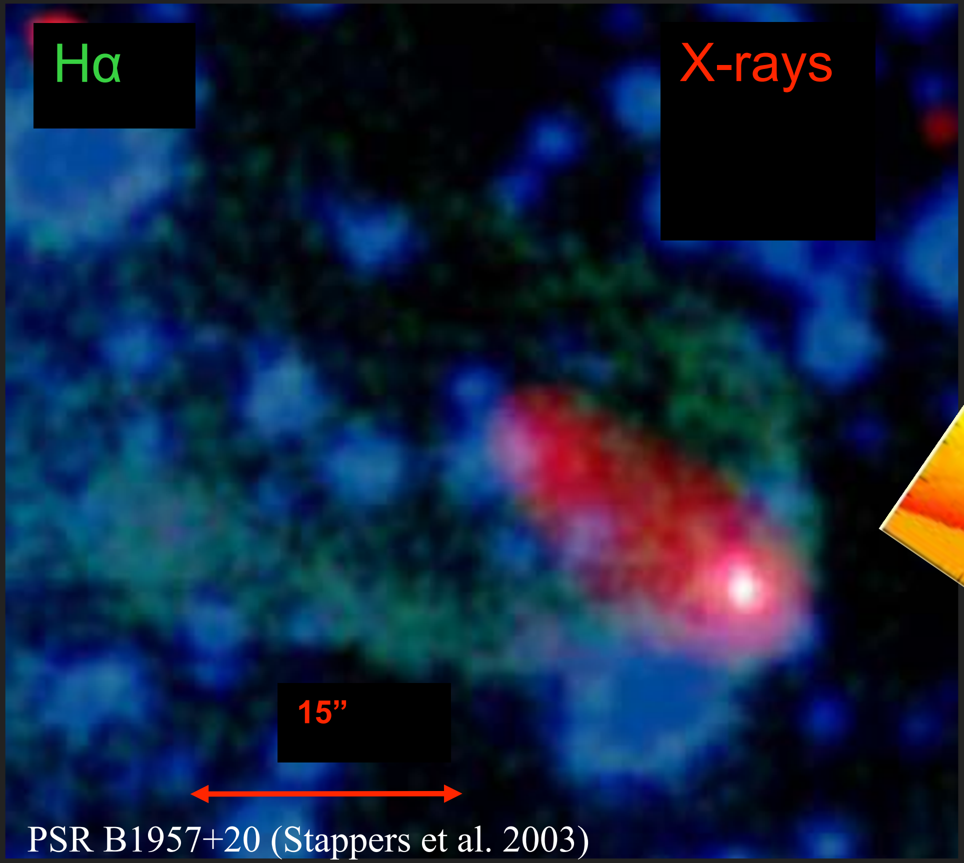


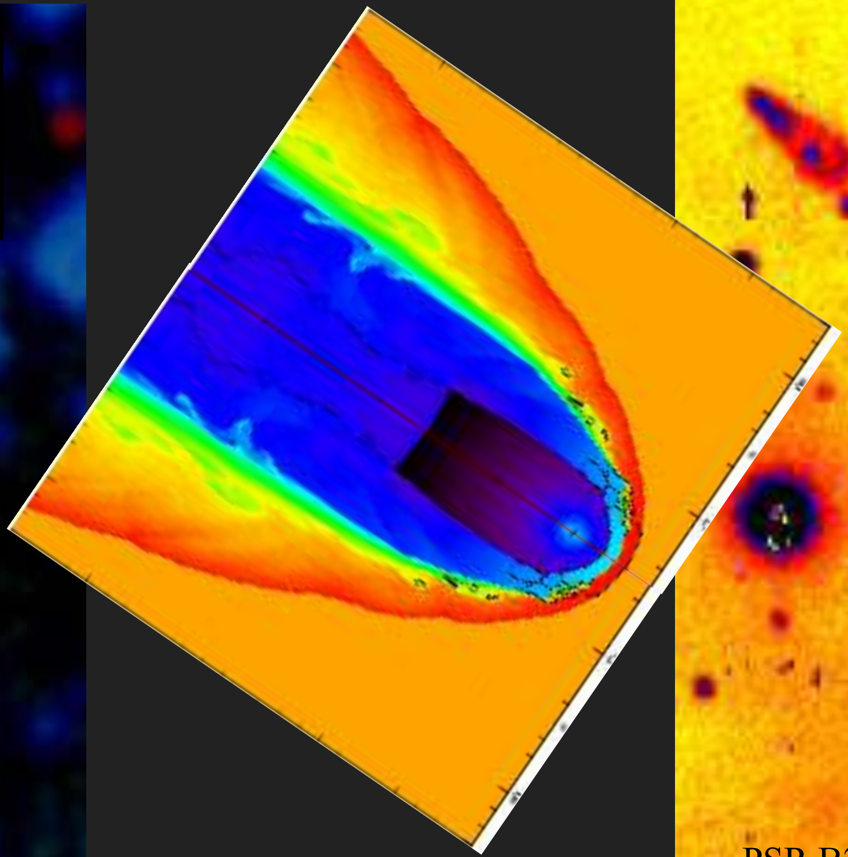



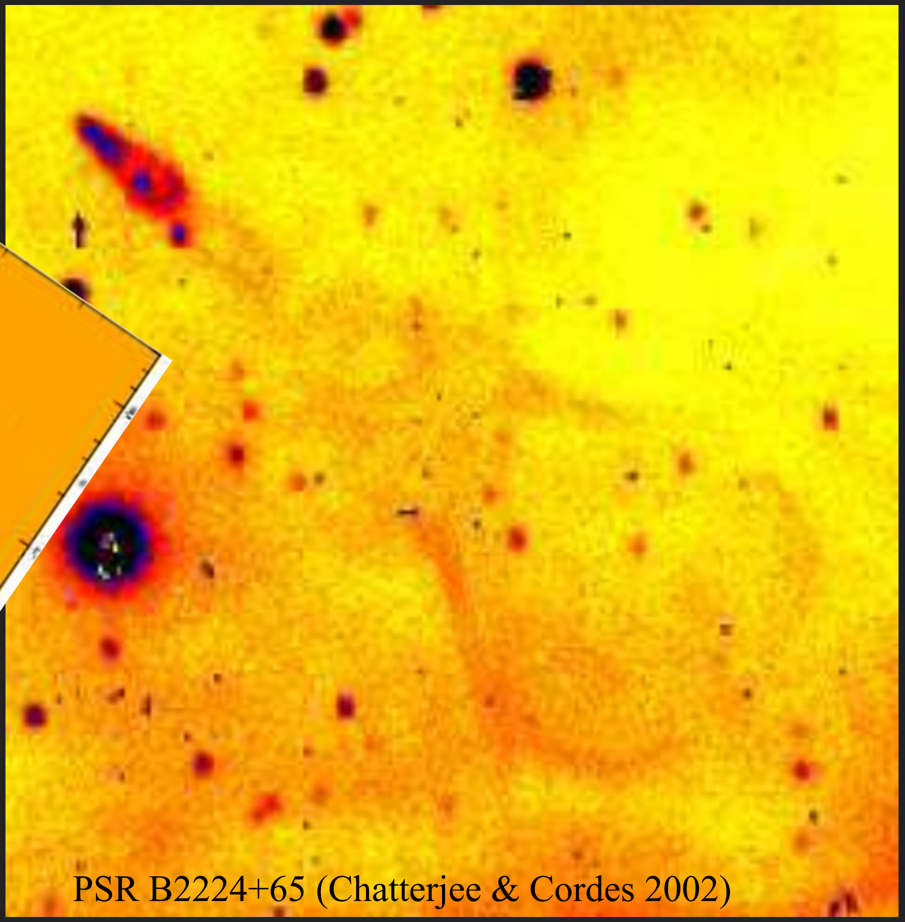
# BOW SHOCK PWNE

**MOST PULSARS KICK VELOCITY IS SUPERSONIC IN ISM**

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



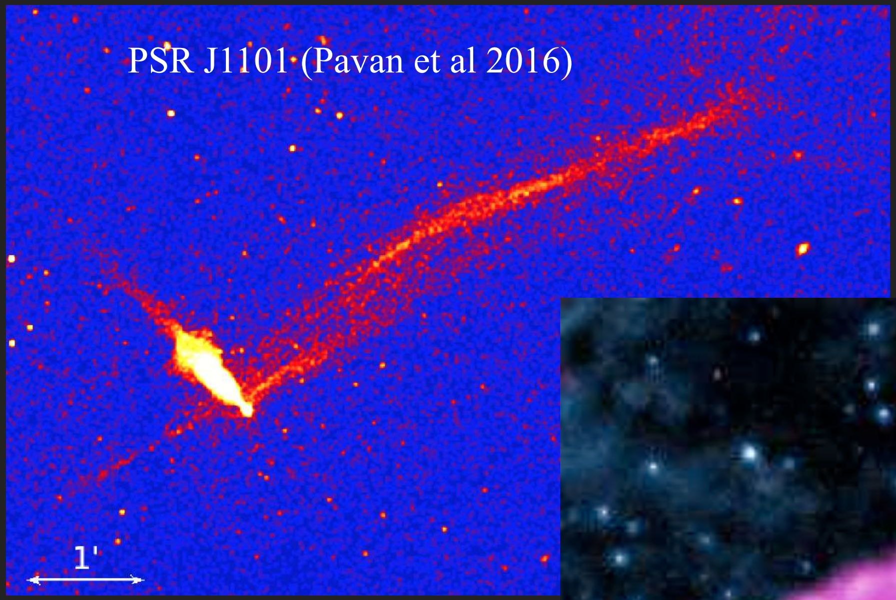





# PAIR ESCAPE

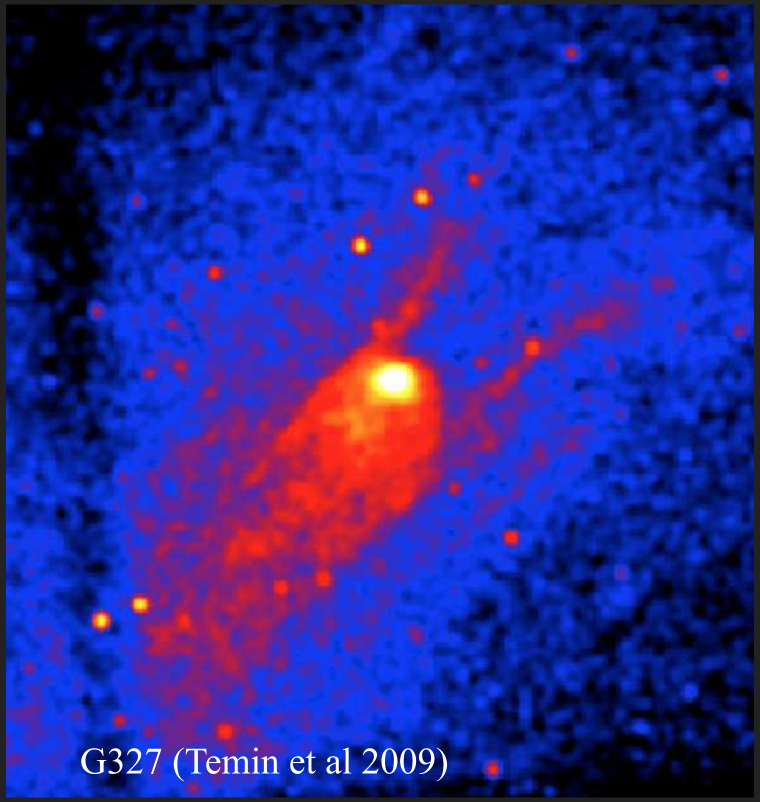
The are BS PWNe where the X-ray "tail" is where it should not be!

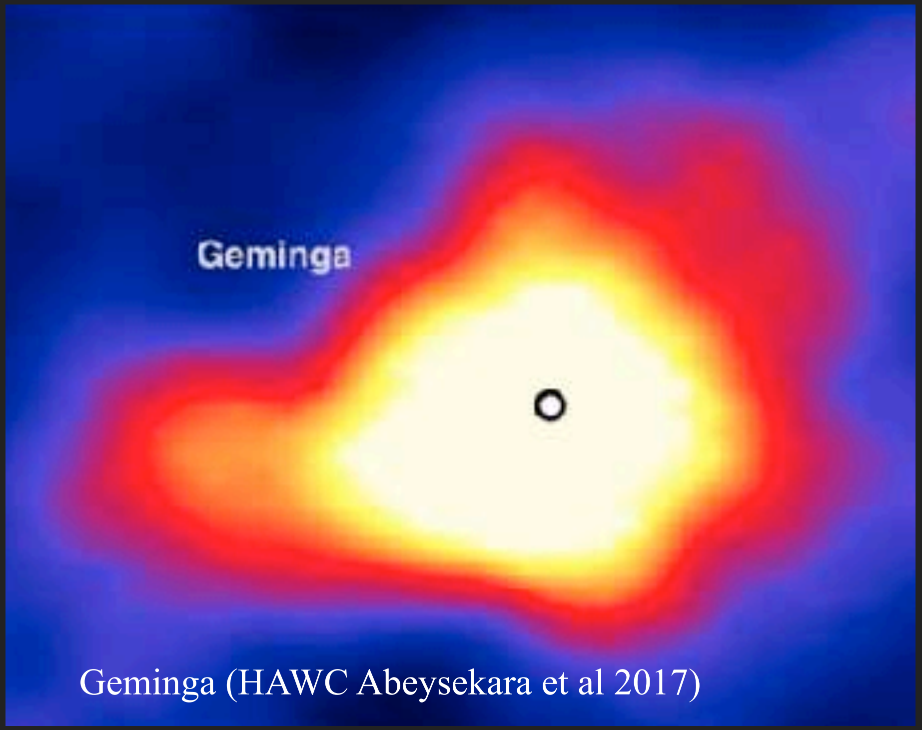
The particles in these features are ~ PSR voltage



PSR J1101 (Pavan et al 2016)

Guitar (Wong et al 2003)


G327 (Temin et al 2009)

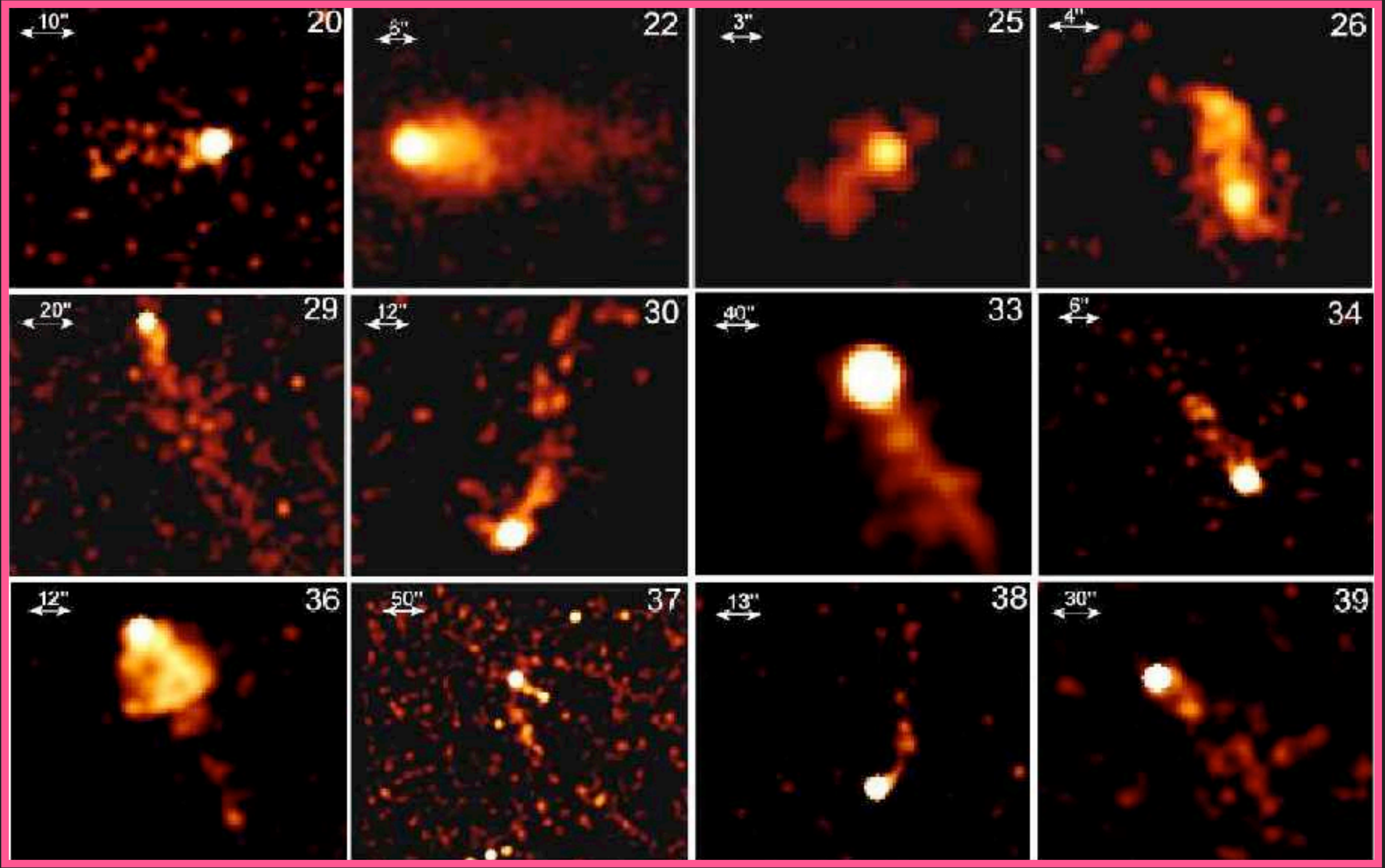


Geminga (HAWC Abeysekara et al 2017)

TeV halo suggest strong diffusion

# BOW-TAILS IN X-RAY

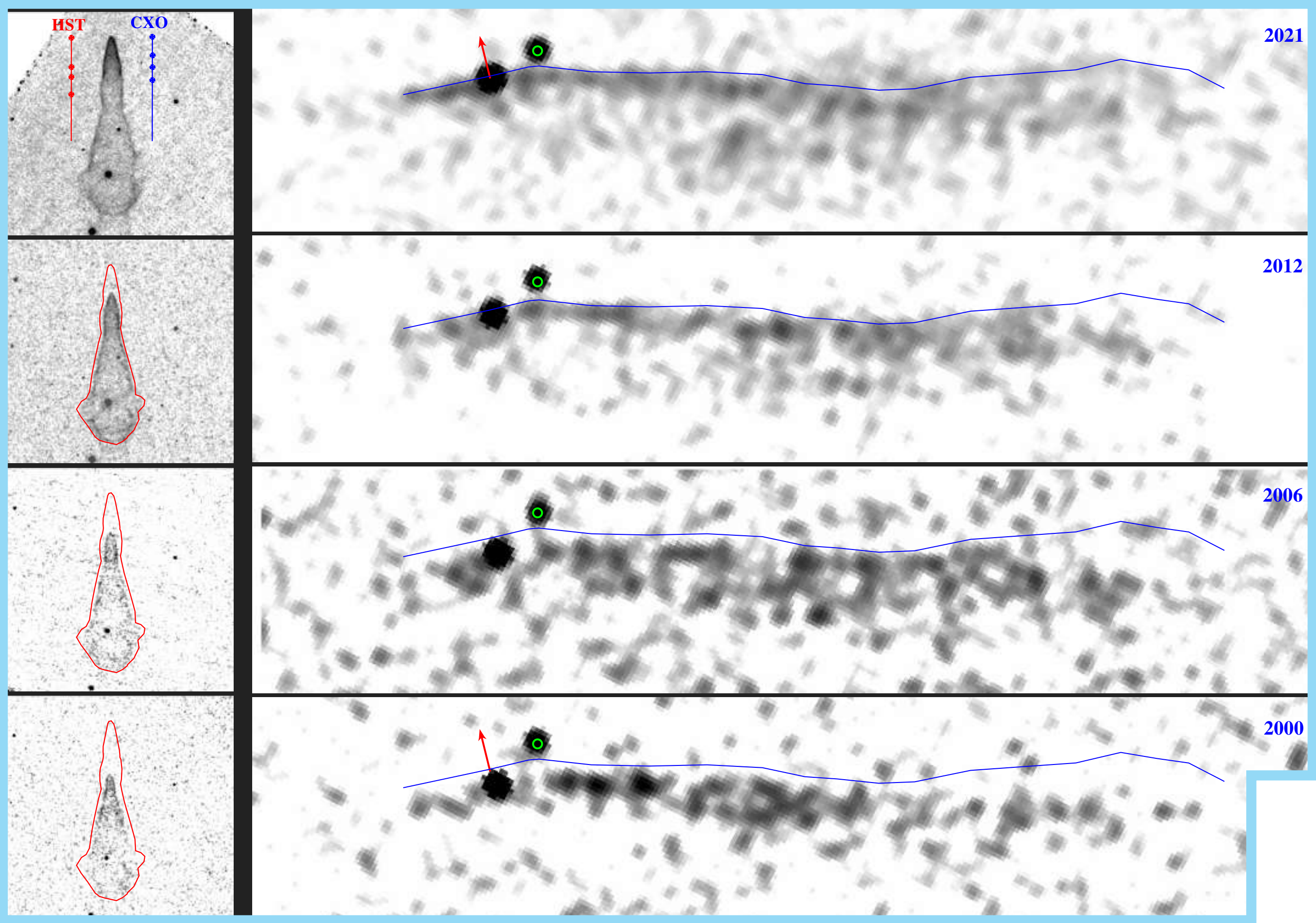
Kargaltsev & Pavlov 2008



# GUITAR NEBULA

De Vries et al 2022

22 YEARS OF GUITAR



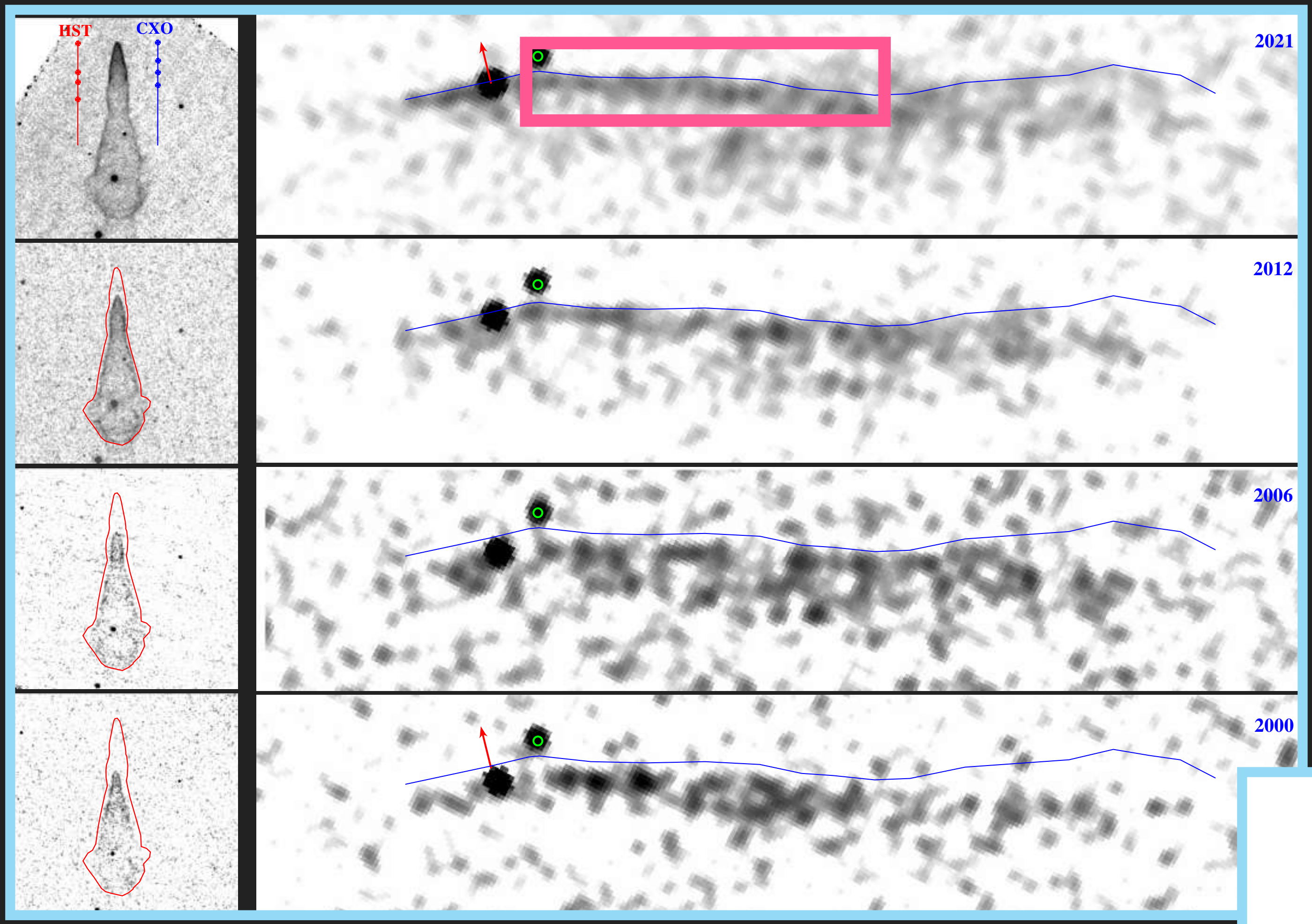

| Region | Counts | $\Gamma$ | $f_{-15}$[b] | $\chi^2$/DoF | $B_{eq}$ [$\mu G$] |
|---|---|---|---|---|---|
| Inner | $214 \pm 17$ | $1.31 \pm 0.16$ | 9.9 | 29.3/27 | 13 |
| Middle | $209 \pm 17$ | $1.37 \pm 0.17$ | 10.2 | 24.3/24 | 14 |
| Outer | $489 \pm 32$ | $1.58 \pm 0.15$ | 24.1 | 53.2/48 | 8 |
| CF | $86 \pm 11$ | $1.71 \pm 0.30$ | 3.5 | 23.8/24 | 17 |
| Leading | $273 \pm 19$ | $1.39 \pm 0.14$ | 13.6 | 22.7/33 | 19 |
| Trailing | $154 \pm 16$ | $1.60 \pm 0.20$ | 7.1 | 30.5/30 | 17 |
| Remnant | $174 \pm 19$ | $1.40 \pm 0.27$ | 7.2 | 38.0/33 | 9 |

[a] $N_H$ fixed at $2.7 \times 10^{21}\mathrm{cm}^{-2}$.
[b] $0.5 - 7\,\mathrm{keV}$ unabsorbed fluxes in units of $10^{-15}\mathrm{erg\,cm^{-2}s^{-1}}$.

# GUITAR NEBULA

De Vries et al 2022

22 YEARS OF GUITAR




NO EVIDENCE OF COOLING IN THE INNER REGION

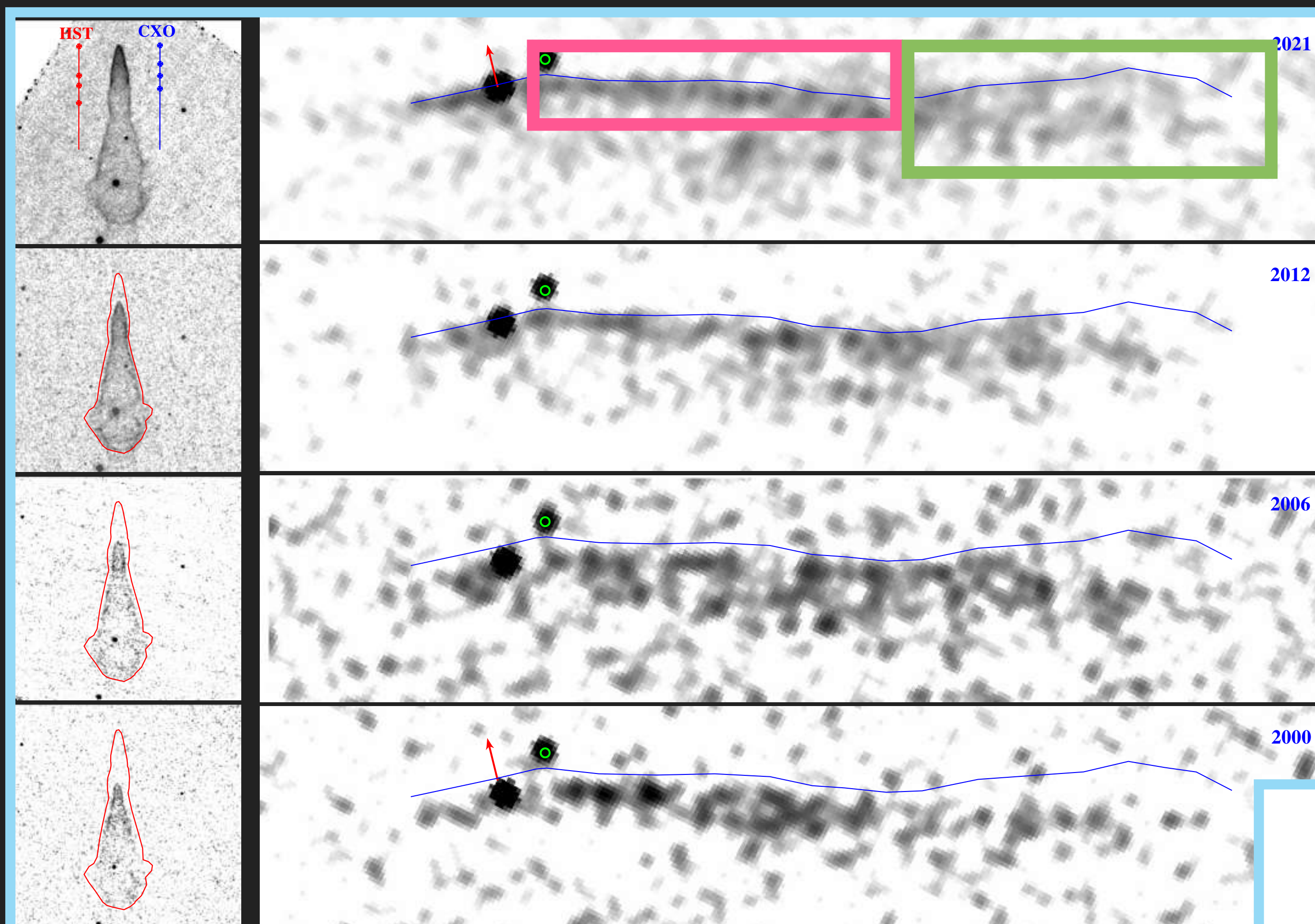
| Region | Counts | $\Gamma$ | $f_{-15}$ [b] | $\chi^2$/DoF | $B_{eq}$ [$\mu G$] |
|---|---|---|---|---|---|
| Inner | $214 \pm 17$ | $1.31 \pm 0.16$ | 9.9 | 29.3/27 | 13 |
| Middle | $209 \pm 17$ | $1.37 \pm 0.17$ | 10.2 | 24.3/24 | 14 |
| Outer | $489 \pm 32$ | $1.58 \pm 0.15$ | 24.1 | 53.2/48 | 8 |
| CF | $86 \pm 11$ | $1.71 \pm 0.30$ | 3.5 | 23.8/24 | 17 |
| Leading | $273 \pm 19$ | $1.39 \pm 0.14$ | 13.6 | 22.7/33 | 19 |
| Trailing | $154 \pm 16$ | $1.60 \pm 0.20$ | 7.1 | 30.5/30 | 17 |
| Remnant | $174 \pm 19$ | $1.40 \pm 0.27$ | 7.2 | 38.0/33 | 9 |

[a] $N_H$ fixed at $2.7 \times 10^{21}\,\mathrm{cm}^{-2}$.
[b] $0.5 - 7\,\mathrm{keV}$ unabsorbed fluxes in units of $10^{-15}\,\mathrm{erg\,cm^{-2}s^{-1}}$.

# GUITAR NEBULA

De Vries et al 2022

22 YEARS OF GUITAR




NO EVIDENCE OF COOLING IN THE INNER REGION

SOME COOLING IN THE OUTER REGION ?

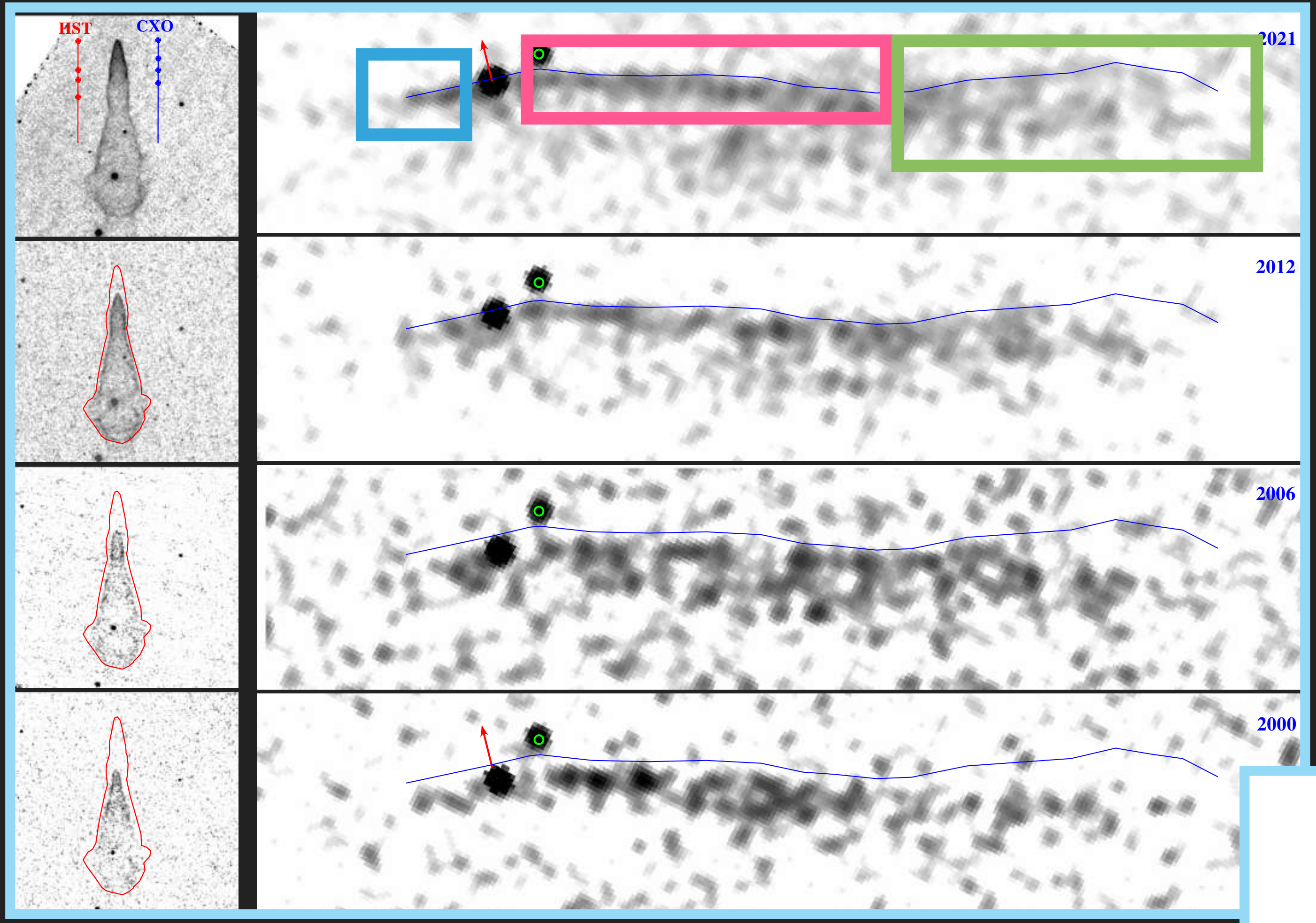
| Region | Counts | $\Gamma$ | $f_{-15}$ [b] | $\chi^2$/DoF | $B_{eq}$ [$\mu G$] |
|---|---|---|---|---|---|
| Inner | $214 \pm 17$ | $1.31 \pm 0.16$ | 9.9 | 29.3/27 | 13 |
| Middle | $209 \pm 17$ | $1.37 \pm 0.17$ | 10.2 | 24.3/24 | 14 |
| Outer | $489 \pm 32$ | $1.58 \pm 0.15$ | 24.1 | 53.2/48 | 8 |
| CF | $86 \pm 11$ | $1.71 \pm 0.30$ | 3.5 | 23.8/24 | 17 |
| Leading | $273 \pm 19$ | $1.39 \pm 0.14$ | 13.6 | 22.7/33 | 19 |
| Trailing | $154 \pm 16$ | $1.60 \pm 0.20$ | 7.1 | 30.5/30 | 17 |
| Remnant | $174 \pm 19$ | $1.40 \pm 0.27$ | 7.2 | 38.0/33 | 9 |

[a] $N_H$ fixed at $2.7 \times 10^{21}\mathrm{cm}^{-2}$.
[b] $0.5 - 7\,\mathrm{keV}$ unabsorbed fluxes in units of $10^{-15}\mathrm{erg\,cm^{-2}s^{-1}}$.

# GUITAR NEBULA

De Vries et al 2022

22 YEARS OF GUITAR




NO EVIDENCE OF COOLING IN THE INNER REGION

SOME COOLING IN THE OUTER REGION ?

MUCH STEEPER SPECTRUM IN THE COUNTER JET

| Region | Counts | $\Gamma$ | $f_{-15}$[b] | $\chi^2$/DoF | $B_{eq}$ [$\mu G$] |
|---|---|---|---|---|---|
| Inner | $214 \pm 17$ | $1.31 \pm 0.16$ | 9.9 | 29.3/27 | 13 |
| Middle | $209 \pm 17$ | $1.37 \pm 0.17$ | 10.2 | 24.3/24 | 14 |
| Outer | $489 \pm 32$ | $1.58 \pm 0.15$ | 24.1 | 53.2/48 | 8 |
| CF | $86 \pm 11$ | $1.71 \pm 0.30$ | 3.5 | 23.8/24 | 17 |
| Leading | $273 \pm 19$ | $1.39 \pm 0.14$ | 13.6 | 22.7/33 | 19 |
| Trailing | $154 \pm 16$ | $1.60 \pm 0.20$ | 7.1 | 30.5/30 | 17 |
| Remnant | $174 \pm 19$ | $1.40 \pm 0.27$ | 7.2 | 38.0/33 | 9 |

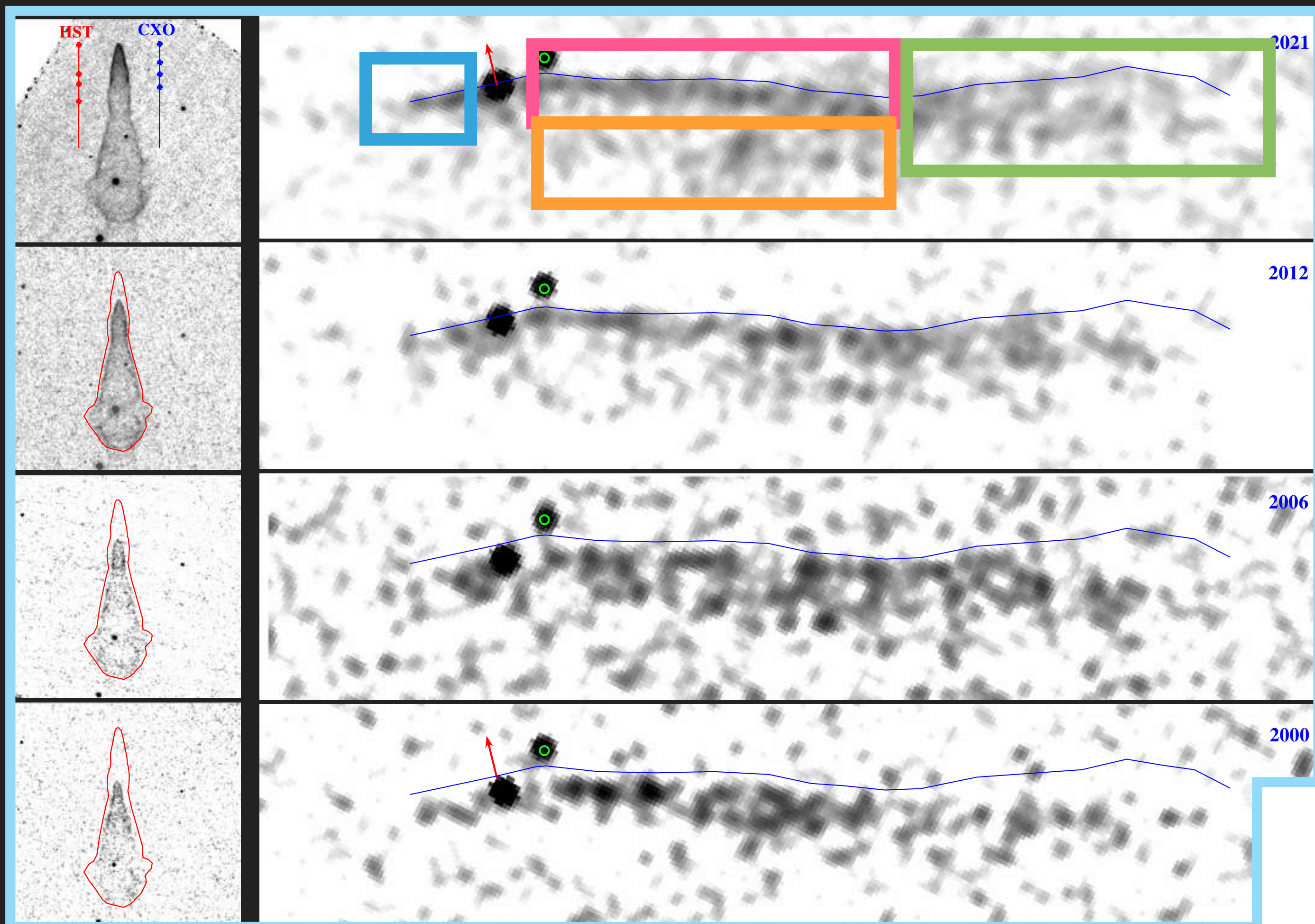
[a] $N_H$ fixed at $2.7 \times 10^{21} \mathrm{cm}^{-2}$.

[b] $0.5 - 7\,\mathrm{keV}$ unabsorbed fluxes in units of $10^{-15} \mathrm{erg\,cm^{-2}s^{-1}}$.

# GUITAR NEBULA

De Vries et al 2022

22 YEARS OF GUITAR




NO EVIDENCE OF COOLING IN THE INNER REGION

SOME COOLING IN THE OUTER REGION ?

MUCH STEEPER SPECTRUM IN THE COUNTER JET

COOLING IN THE TRAILING

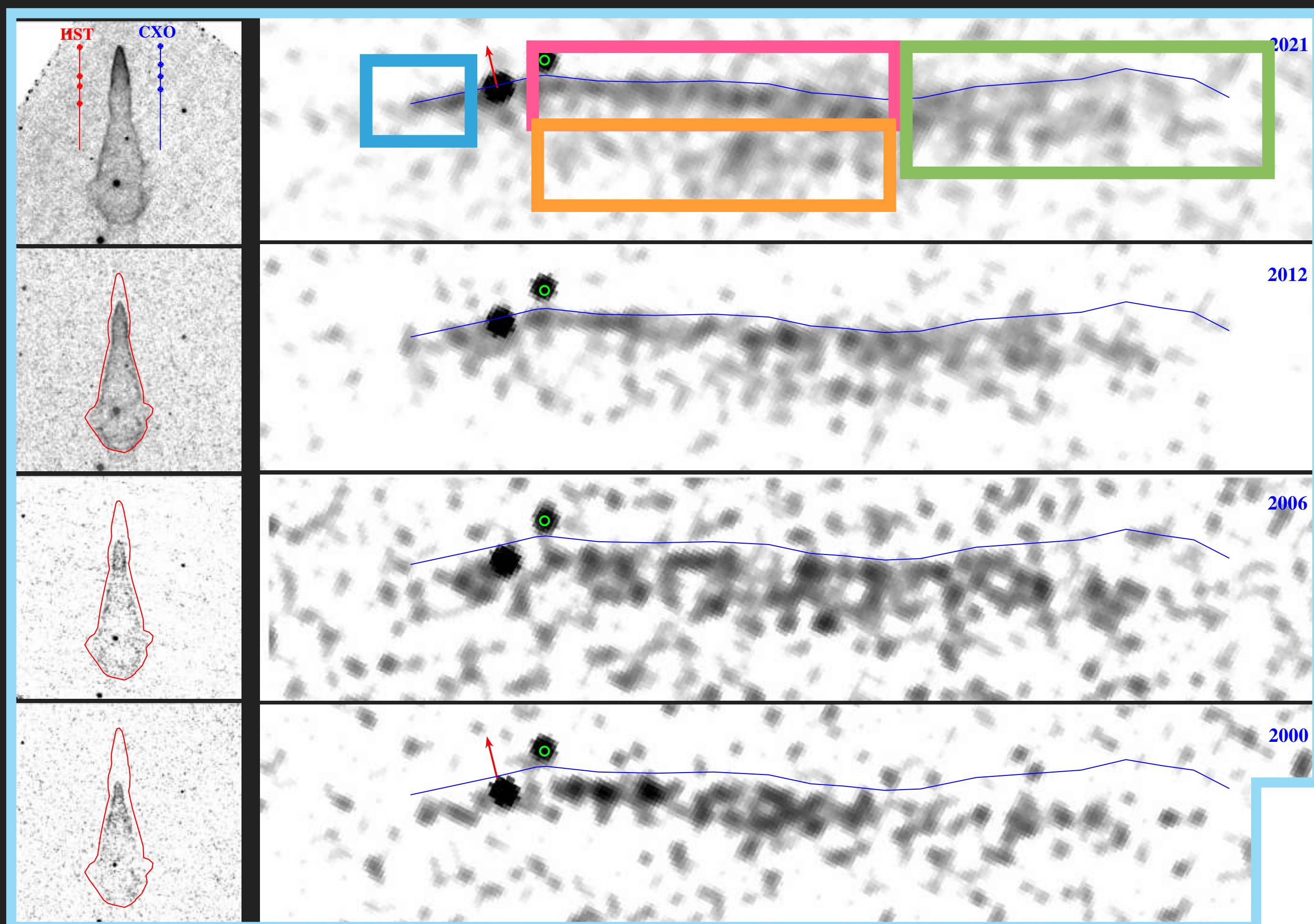
| Region | Counts | $\Gamma$ | $f_{-15}$[b] | $\chi^2$/DoF | $B_{eq}$ $[\mu G]$ |
|---|---|---|---|---|---|
| Inner | $214 \pm 17$ | $1.31 \pm 0.16$ | 9.9 | 29.3/27 | 13 |
| Middle | $209 \pm 17$ | $1.37 \pm 0.17$ | 10.2 | 24.3/24 | 14 |
| Outer | $489 \pm 32$ | $1.58 \pm 0.15$ | 24.1 | 53.2/48 | 8 |
| CF | $86 \pm 11$ | $1.71 \pm 0.30$ | 3.5 | 23.8/24 | 17 |
| Leading | $273 \pm 19$ | $1.39 \pm 0.14$ | 13.6 | 22.7/33 | 19 |
| Trailing | $154 \pm 16$ | $1.60 \pm 0.20$ | 7.1 | 30.5/30 | 17 |
| Remnant | $174 \pm 19$ | $1.40 \pm 0.27$ | 7.2 | 38.0/33 | 9 |

[a] $N_H$ fixed at $2.7 \times 10^{21} \mathrm{cm}^{-2}$.
[b] $0.5 - 7\,\mathrm{keV}$ unabsorbed fluxes in units of $10^{-15} \mathrm{erg\,cm}^{-2} \mathrm{s}^{-1}$.

# GUITAR NEBULA

De Vries et al 2022

**22 YEARS OF GUITAR**




**NO EVIDENCE OF COOLING IN THE INNER REGION**

**SOME COOLING IN THE OUTER REGION ?**

**MUCH STEEPER SPECTRUM IN THE COUNTER JET**

**COOLING IN THE TRAILING**

EQ (1)

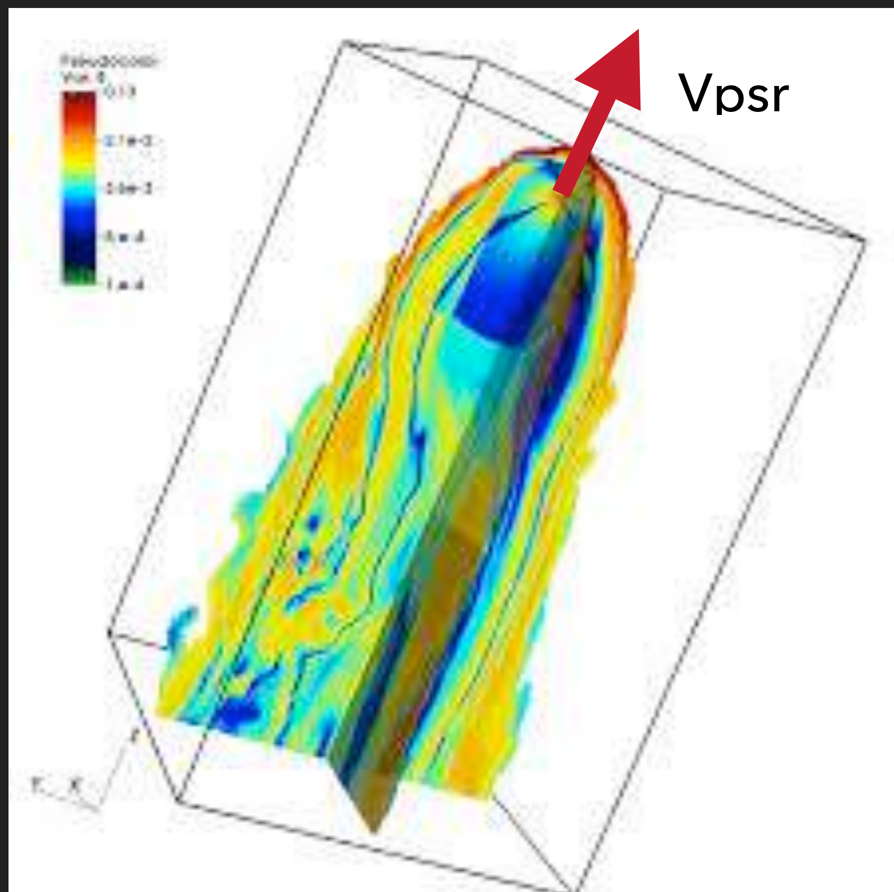
$$\Delta B \simeq 62\,\mu\mathrm{G} \left(\frac{\rho_{ISM}}{m_p\,\mathrm{cm}^{-3}}\right)^{1/4} \left(\frac{\gamma_{esc}}{10^7}\right)^{1/2} \left(\frac{L_f}{1\,\mathrm{pc}}\right)^{-1/2}$$

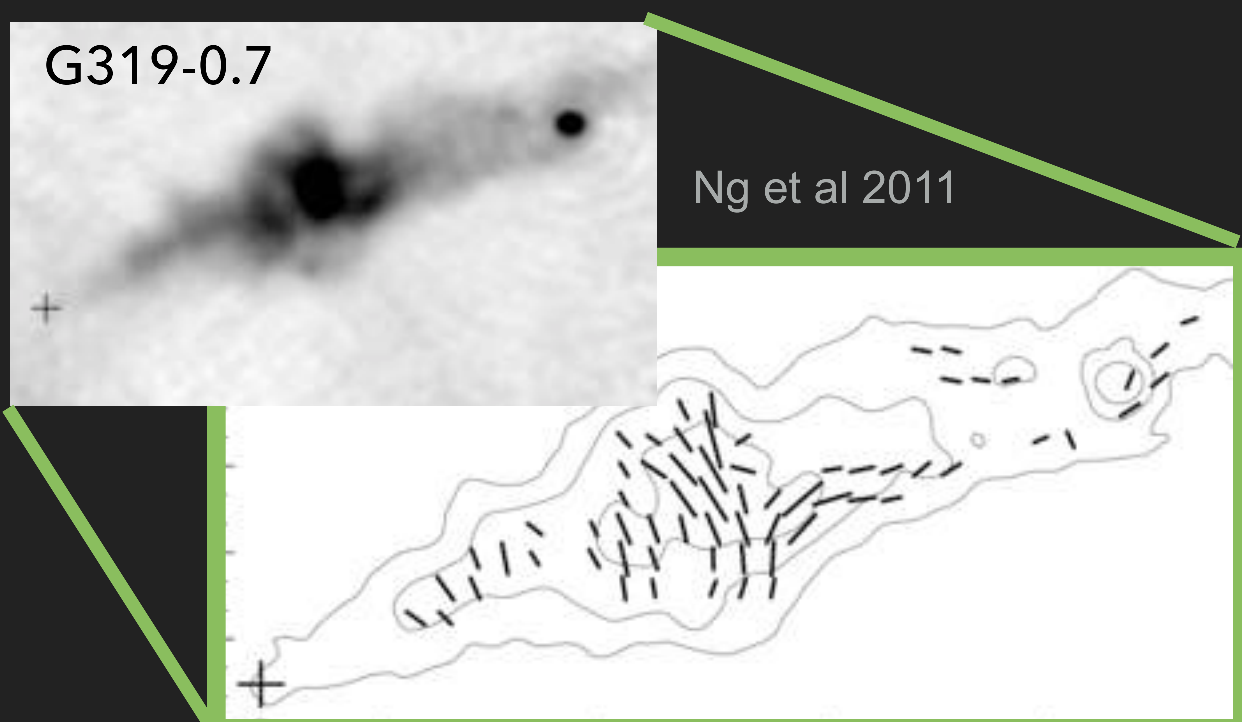
Olmi et al 2024

| Region | Counts | $\Gamma$ | $f_{-15}$ [b] | $\chi^2$/DoF | $B_{eq}$ [$\mu G$] |
|---|---|---|---|---|---|
| Inner | $214 \pm 17$ | $1.31 \pm 0.16$ | 9.9 | 29.3/27 | 13 |
| Middle | $209 \pm 17$ | $1.37 \pm 0.17$ | 10.2 | 24.3/24 | 14 |
| Outer | $489 \pm 32$ | $1.58 \pm 0.15$ | 24.1 | 53.2/48 | 8 |
| CF | $86 \pm 11$ | $1.71 \pm 0.30$ | 3.5 | 23.8/24 | 17 |
| Leading | $273 \pm 19$ | $1.39 \pm 0.14$ | 13.6 | 22.7/33 | 19 |
| Trailing | $154 \pm 16$ | $1.60 \pm 0.20$ | 7.1 | 30.5/30 | 17 |
| Remnant | $174 \pm 19$ | $1.40 \pm 0.27$ | 7.2 | 38.0/33 | 9 |

[a] $N_H$ fixed at $2.7 \times 10^{21}\,\mathrm{cm}^{-2}$.
[b] $0.5 - 7\,\mathrm{keV}$ unabsorbed fluxes in units of $10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$.

# BOW SHOCK PWNE: THEORY VS REALITY



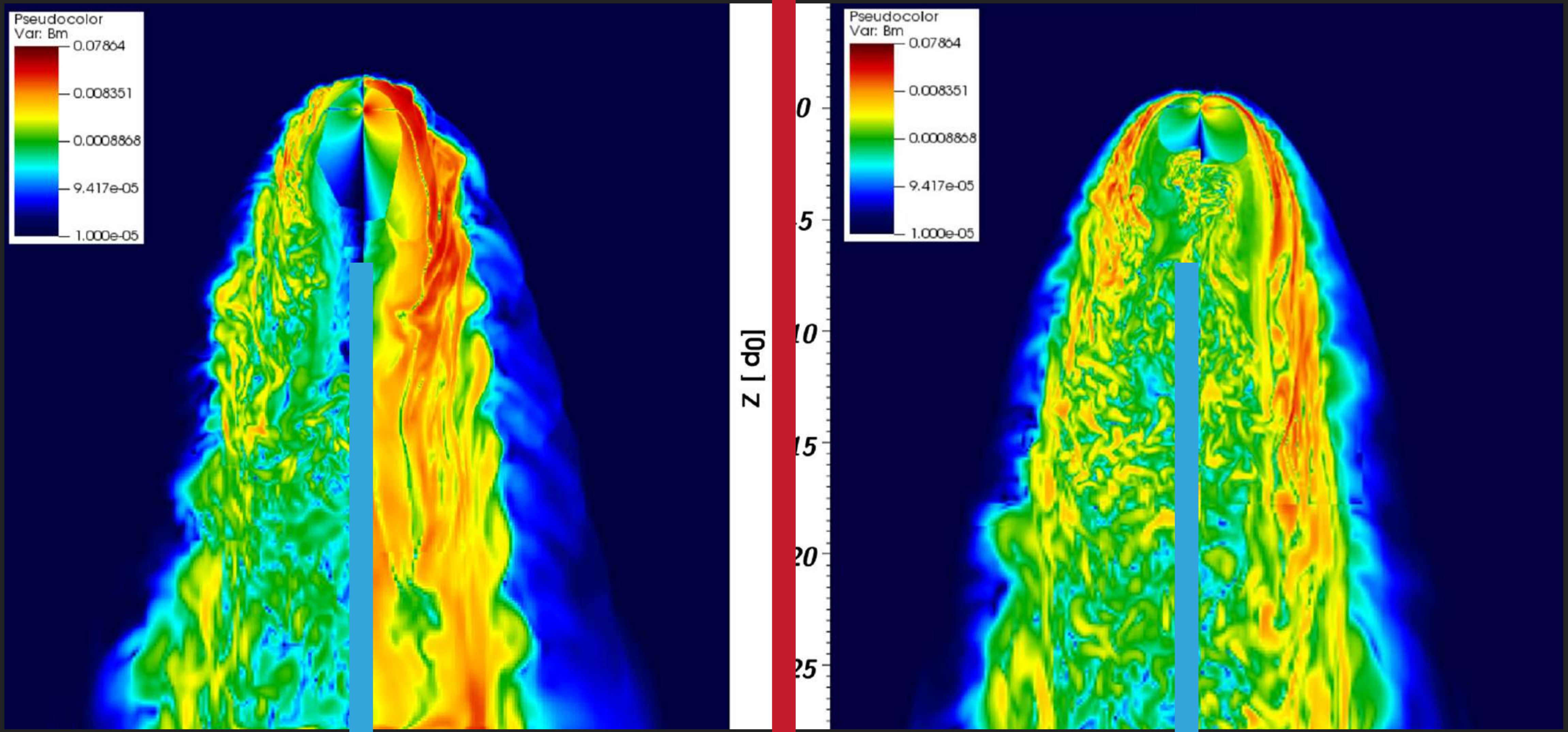

Ng et al 2011


Ng et al 2012

# BOW SHOCK PWNE: INTERNAL TURBULENCE

Isotropic Wind

Anisotropic Wind



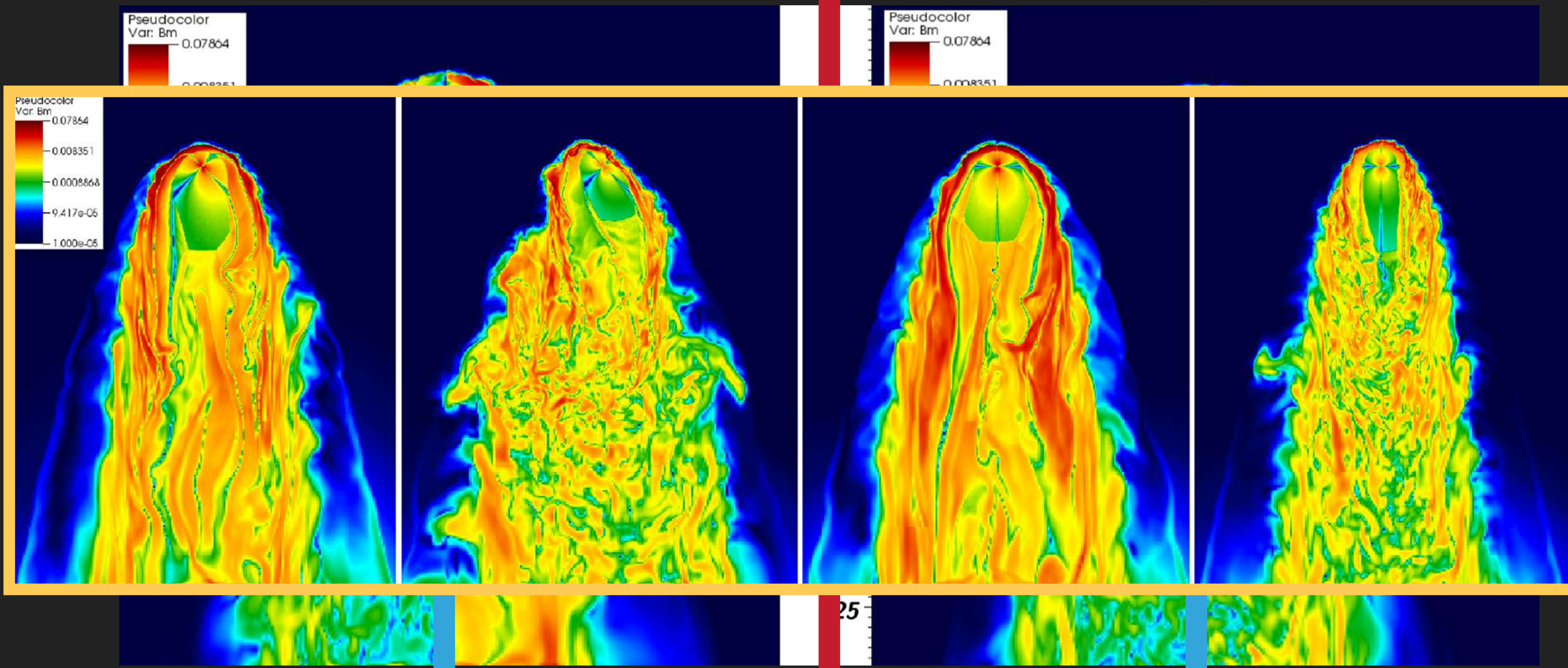

Low Mag | High Mag

Low Mag | High Mag

# BOW SHOCK PWNE: INTERNAL TURBULENCE

Isotropic Wind

Anisotropic Wind



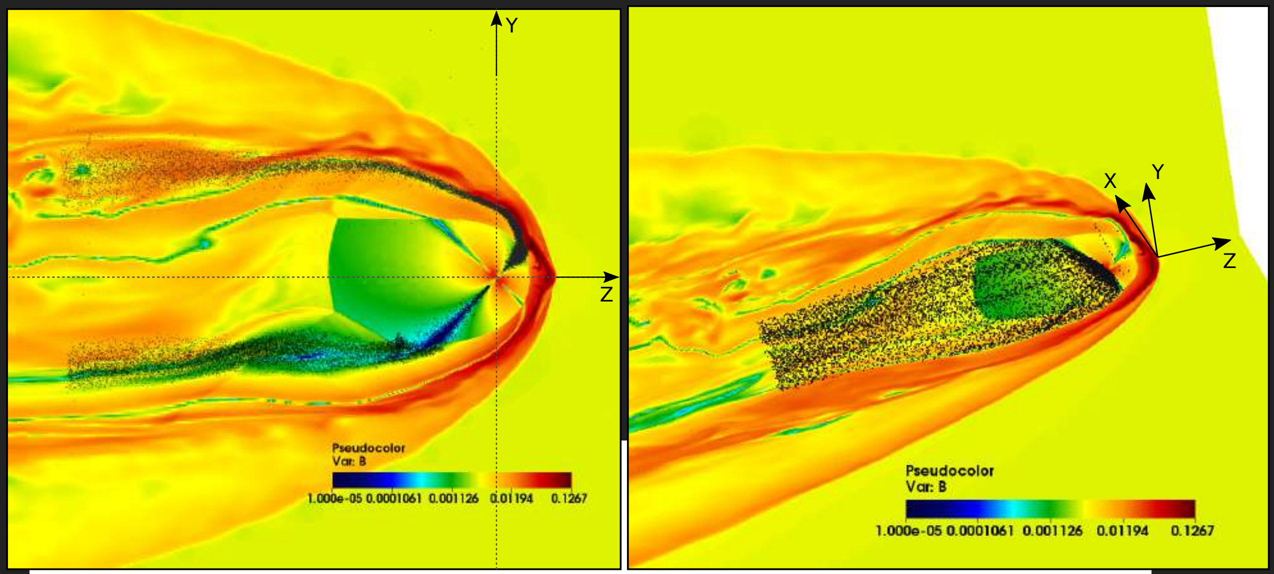

Low Mag

High Mag

Low Mag

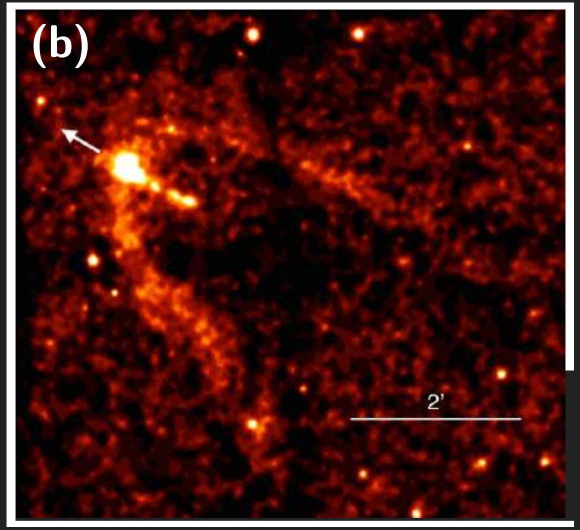
High Mag

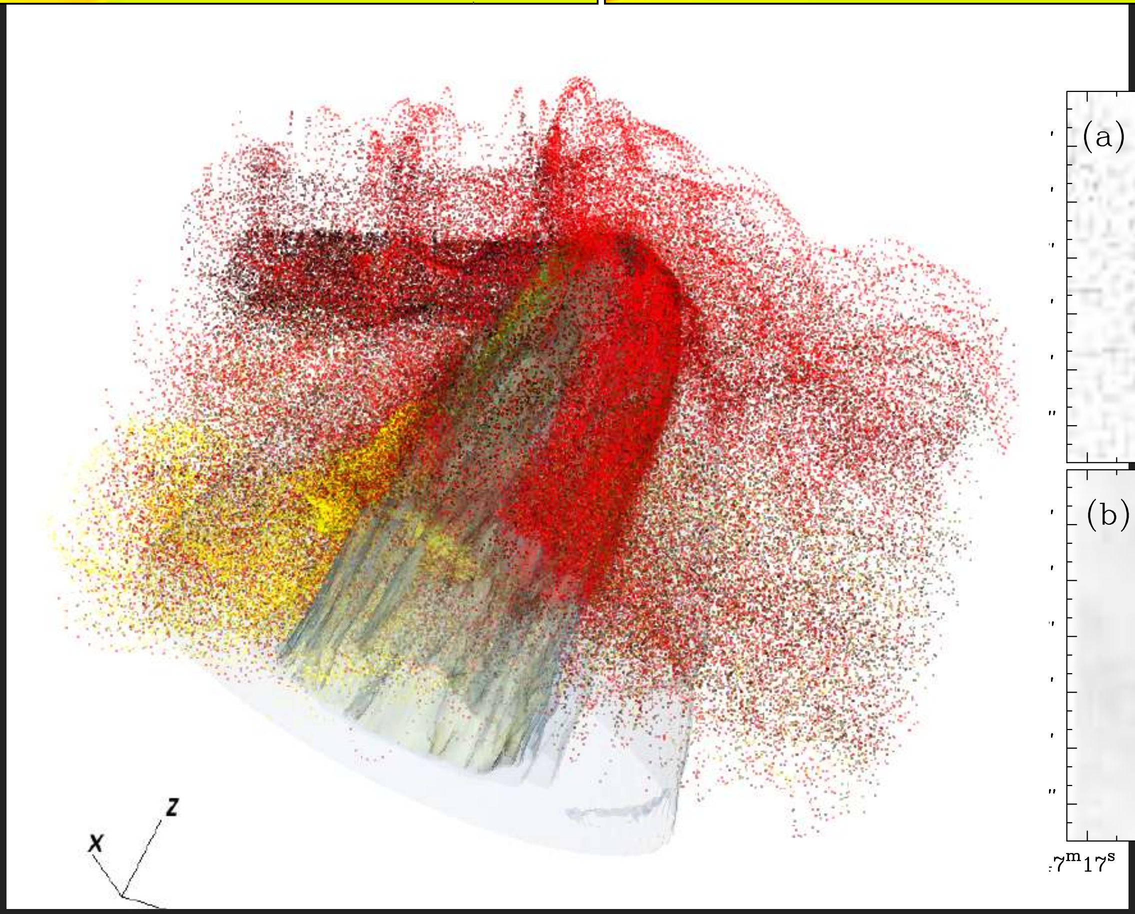
# PAIR ESCAPE IN MHD MODELS

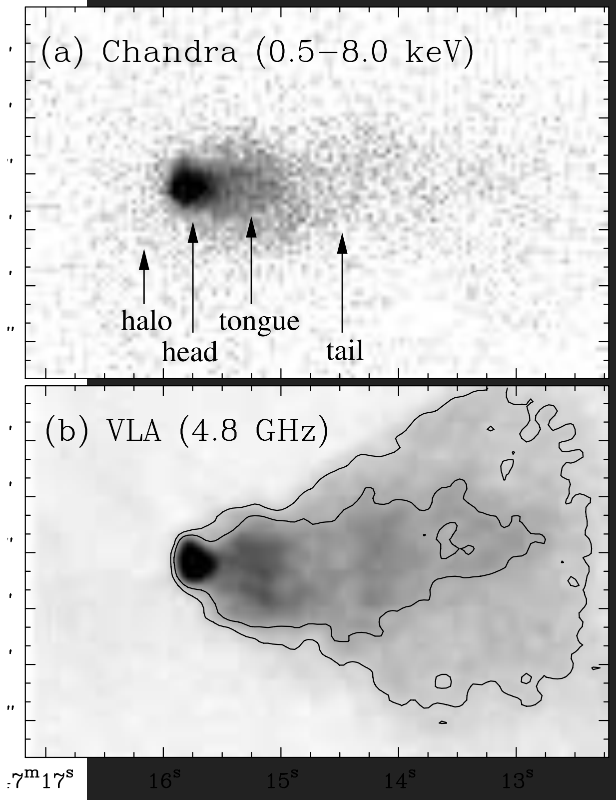



LOW ENERGY PARTICLES REMAIN CONFINED IN CURRENTS

GEMINGA HARD TAILS



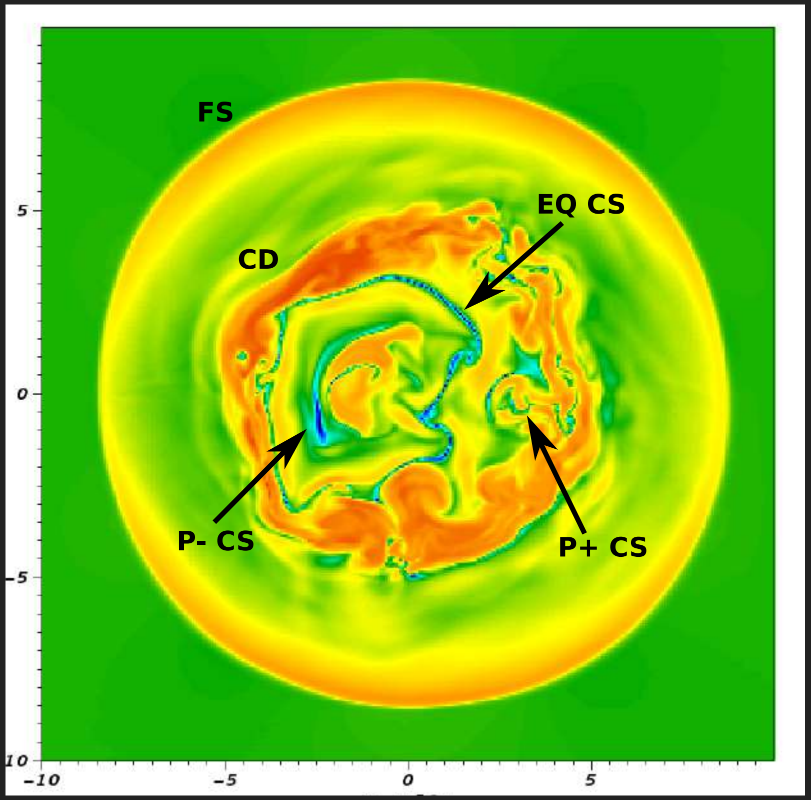




VERY HIGH ENERGY PARTICLES CAN ALSO DIFFUSE AHEAD

MAUSE X-RAY HALO

# PAIR ESCAPE IN MHD MODELS



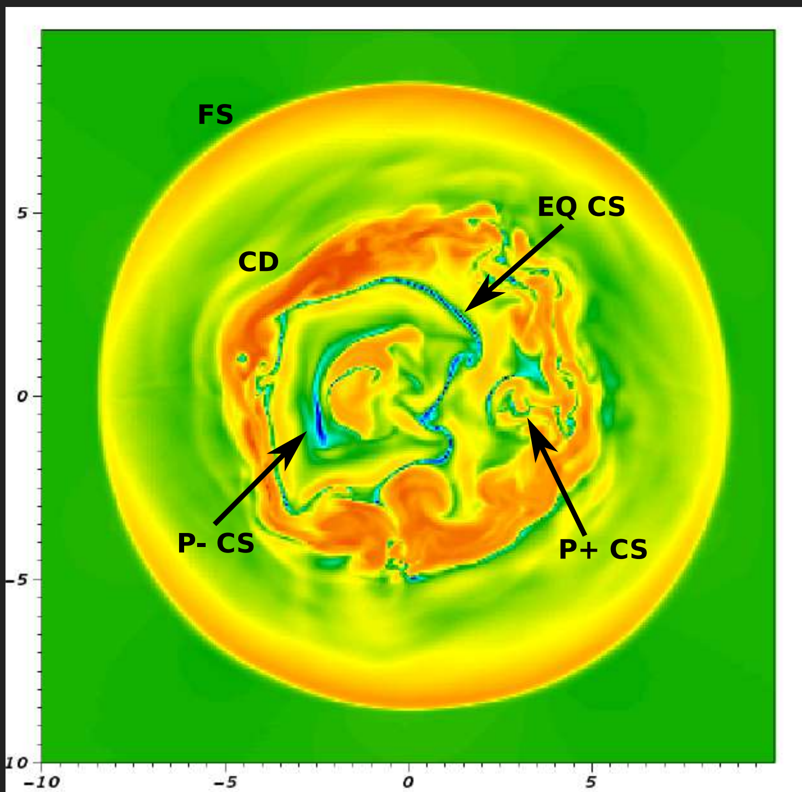

Olmi & Bucciantini 2019

**ESCAPE ASSOCIATED TO RECONNECTION SITES AT THE MAGNETOPAUSE**

**STRONG ENERGY DEPENDENCE**

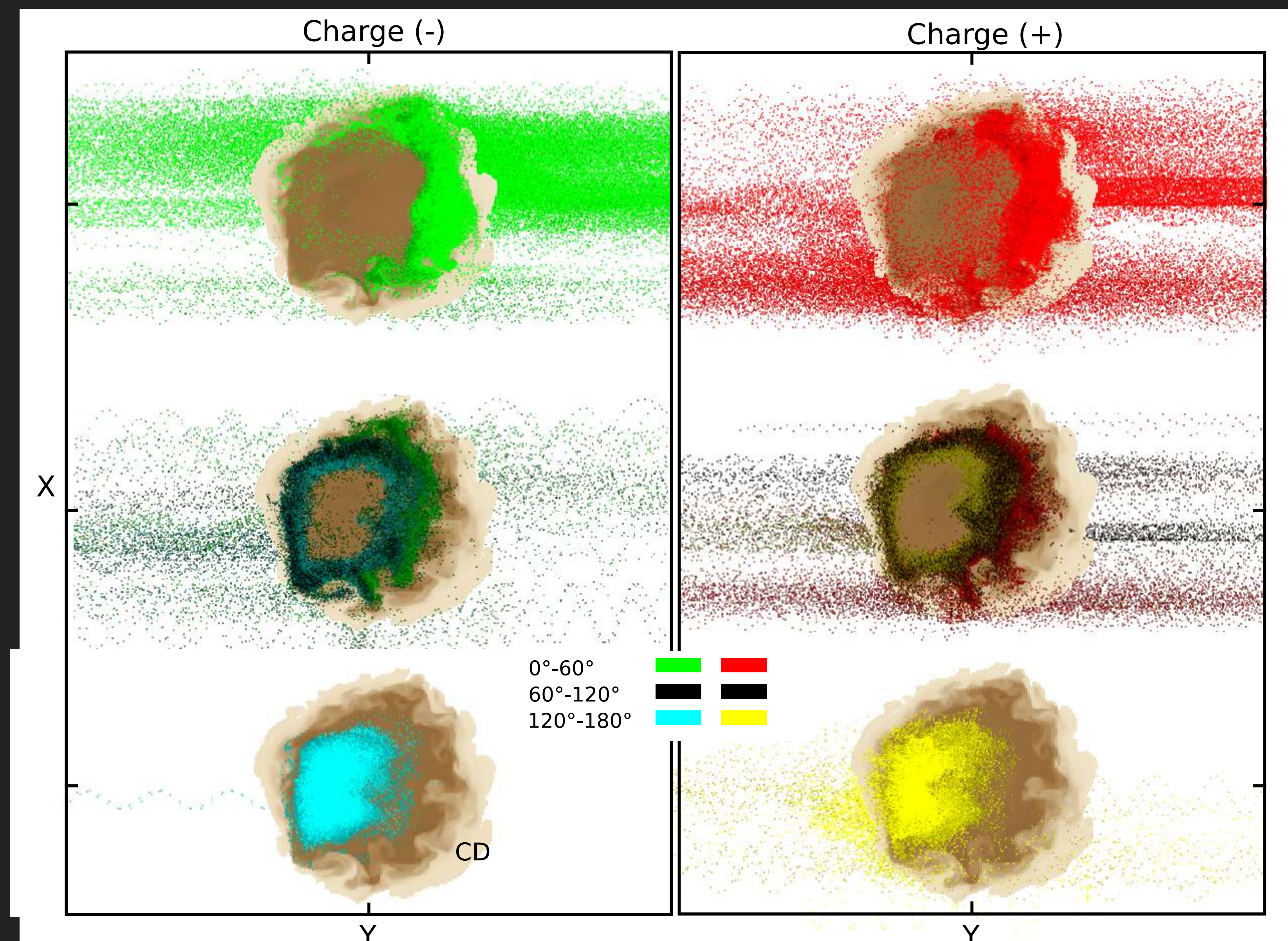
**TURBULENCE IN THE TAIL DEPENDENT ON INTERACTION GEOMETRY**

# PAIR ESCAPE IN MHD MODELS




Olmi & Bucciantini 2019

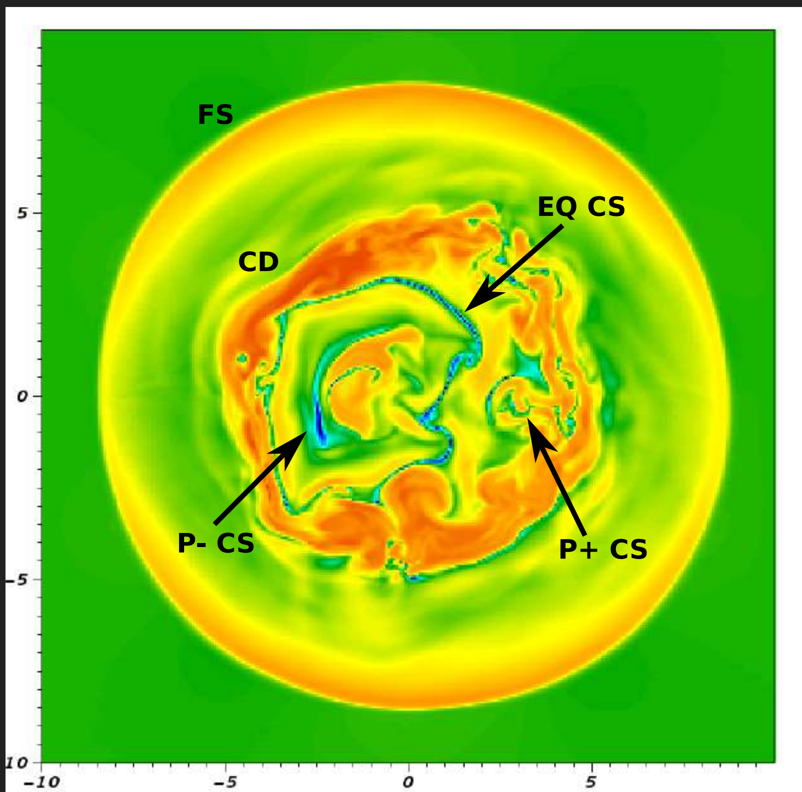
## TURBULENCE IN THE TAIL DEPENDENT ON INTERACTION GEOMETRY




**ESCAPE ASSOCIATED TO RECONNECTION SITES AT THE MAGNETOPAUSE**

**STRONG ENERGY DEPENDENCE**

# PAIR ESCAPE IN MHD MODELS

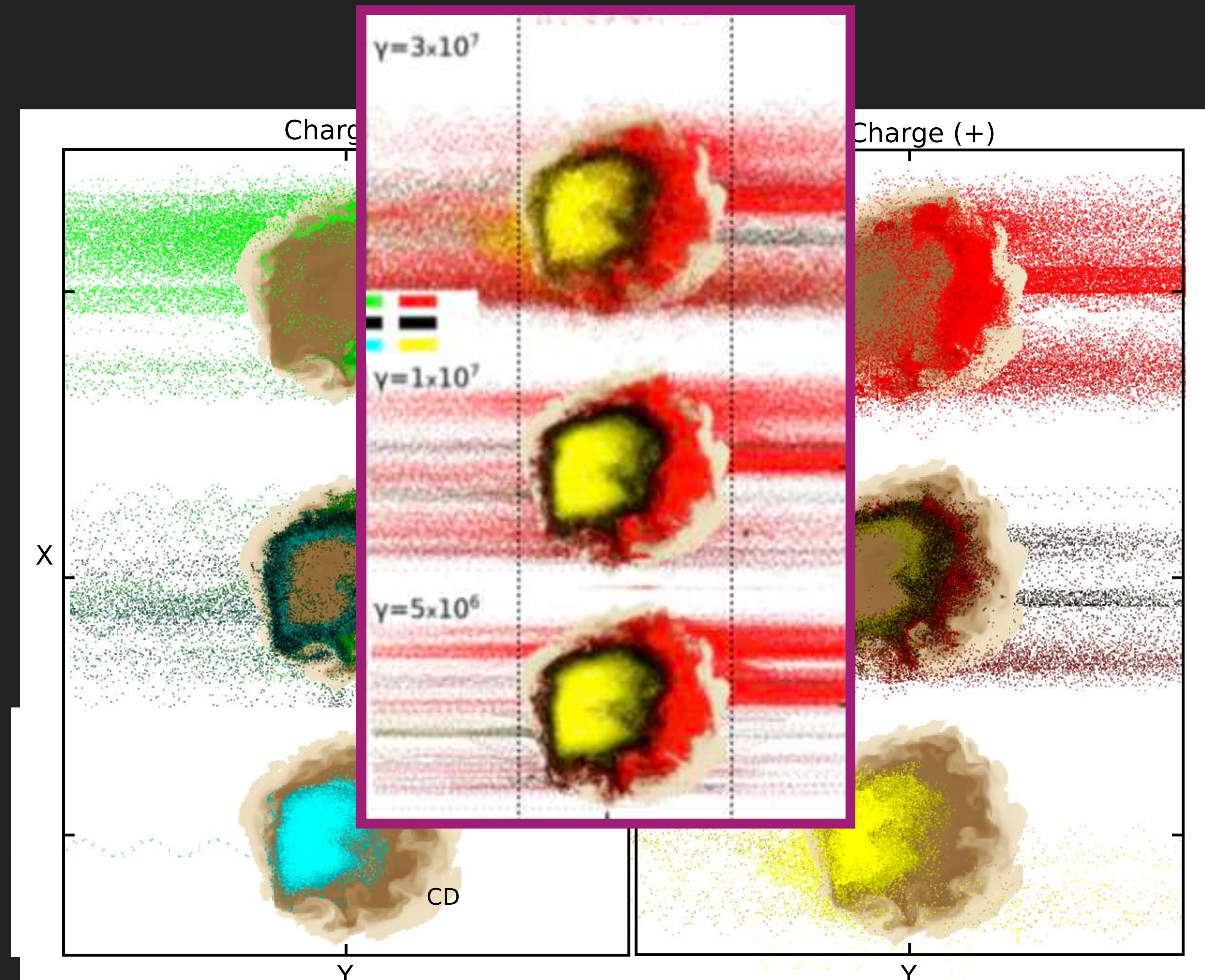



Olmi & Bucciantini 2019

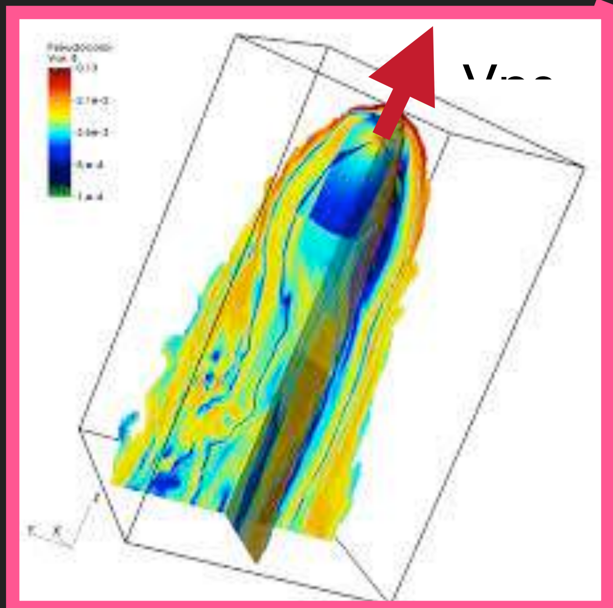
**ESCAPE ASSOCIATED TO RECONNECTION SITES AT THE MAGNETOPAUSE**

**STRONG ENERGY DEPENDENCE**

## TURBULENCE IN THE TAIL DEPENDENT ON INTERACTION GEOMETRY

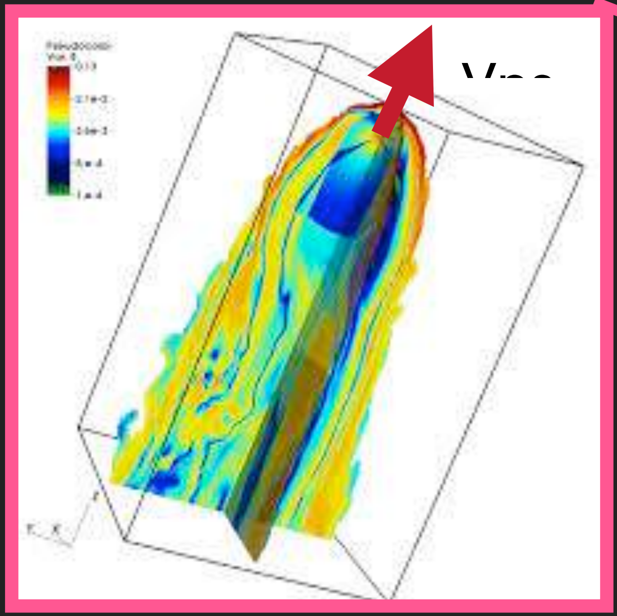


# HEAD VS TAIL ESCAPE



BOW-SHOCK $E_{MAX}$ ~ 0.1 PSR VOLTAGE

# HEAD VS TAIL ESCAPE



BOW-SHOCK $E_{MAX}$ ~ 0.1 PSR VOLTAGE

ESCAPE FROM THE HEAD
0.1 - 1.0 $E_{MAX}$

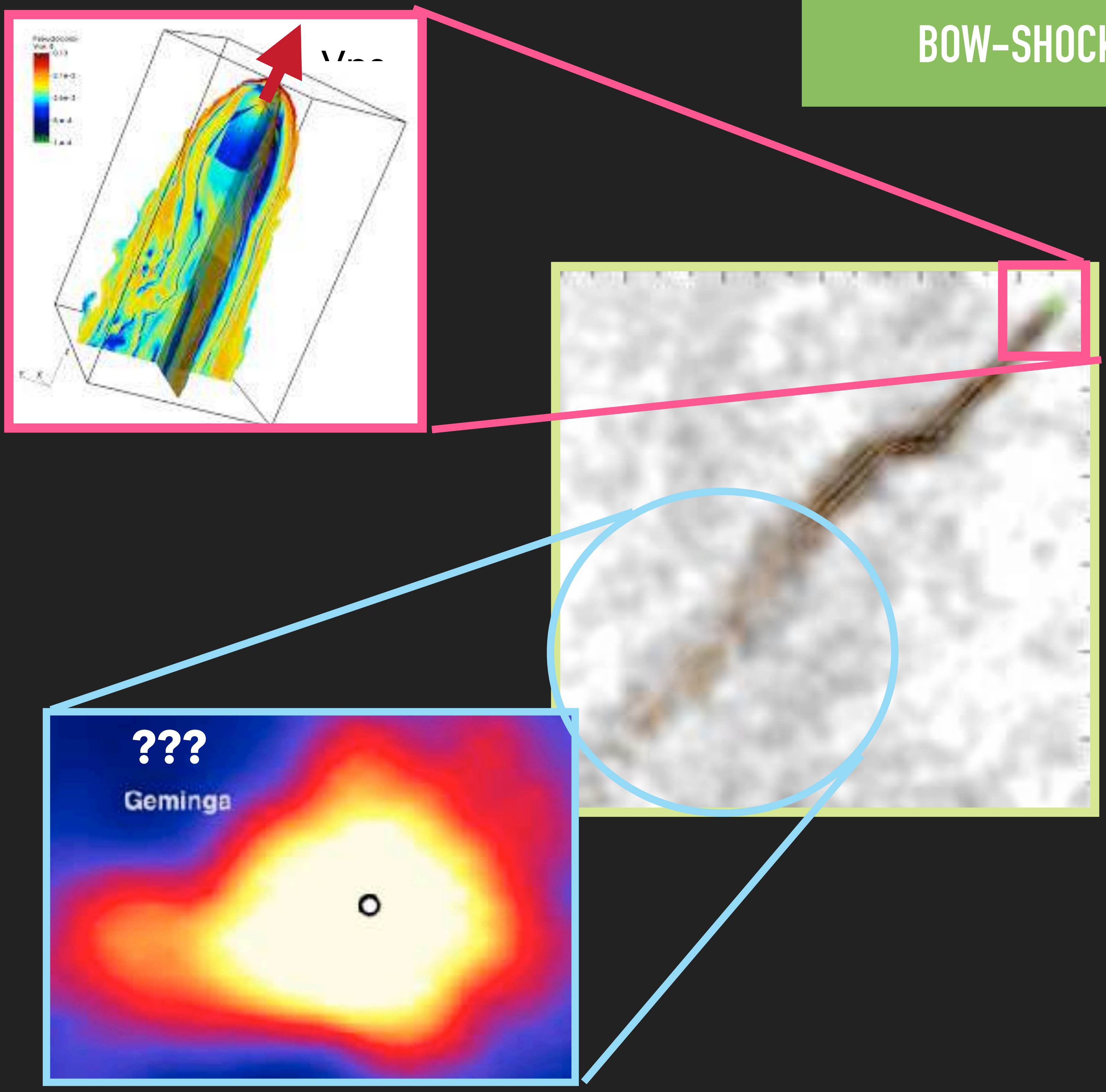
ALMOST MONOCHROMATIC
PARTICLE INJECTION
LOW EFFICIENCY

# HEAD VS TAIL ESCAPE

BOW-SHOCK $E_{MAX} \sim 0.1$ PSR VOLTAGE

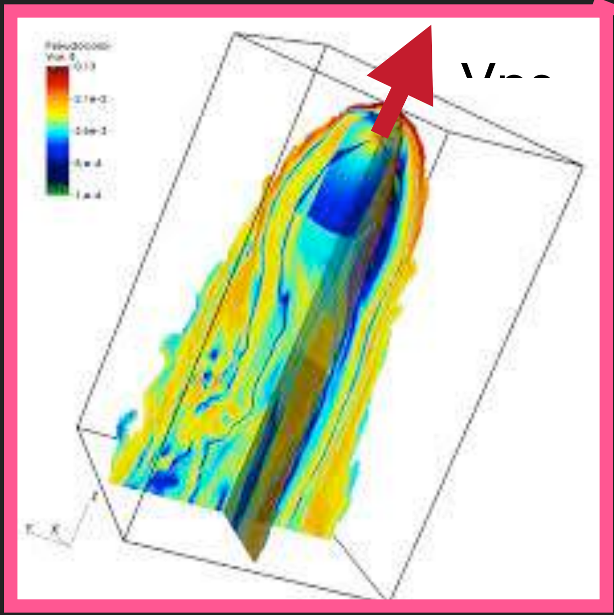
ESCAPE FROM THE HEAD
$0.1 - 1.0\ E_{MAX}$

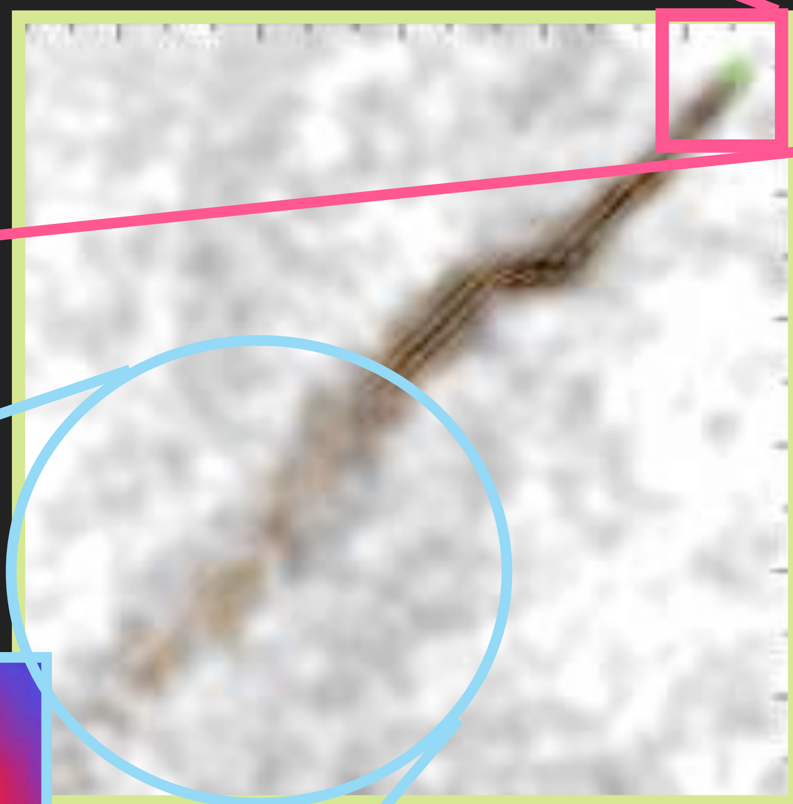
ALMOST MONOCHROMATIC
PARTICLE INJECTION
LOW EFFICIENCY



# HEAD VS TAIL ESCAPE

BOW-SHOCK $E_{MAX}$ ~ 0.1 PSR VOLTAGE





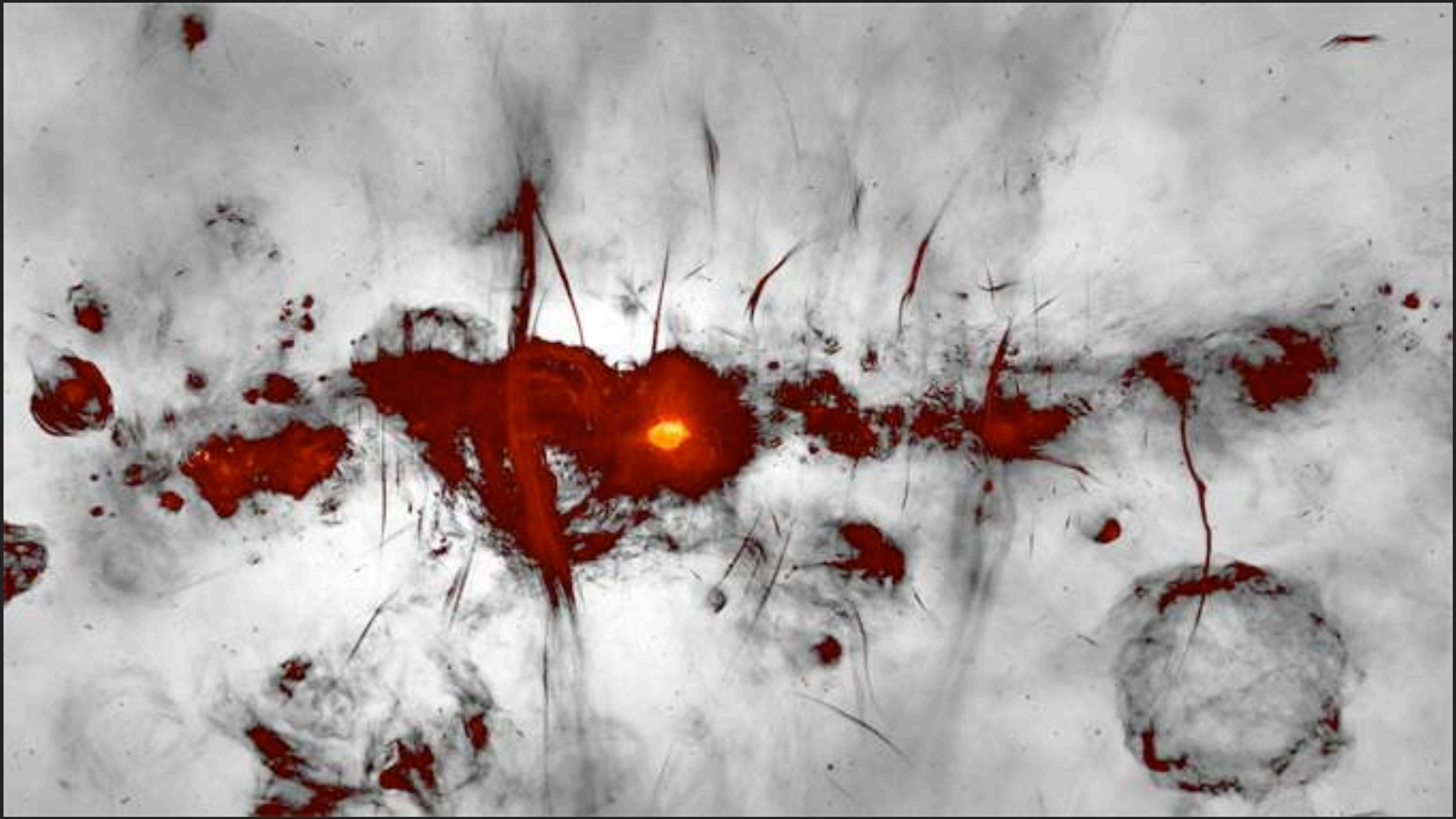
ESCAPE FROM THE HEAD
0.1 - 1.0 $E_{MAX}$

ALMOST MONOCHROMATIC
PARTICLE INJECTION
LOW EFFICIENCY

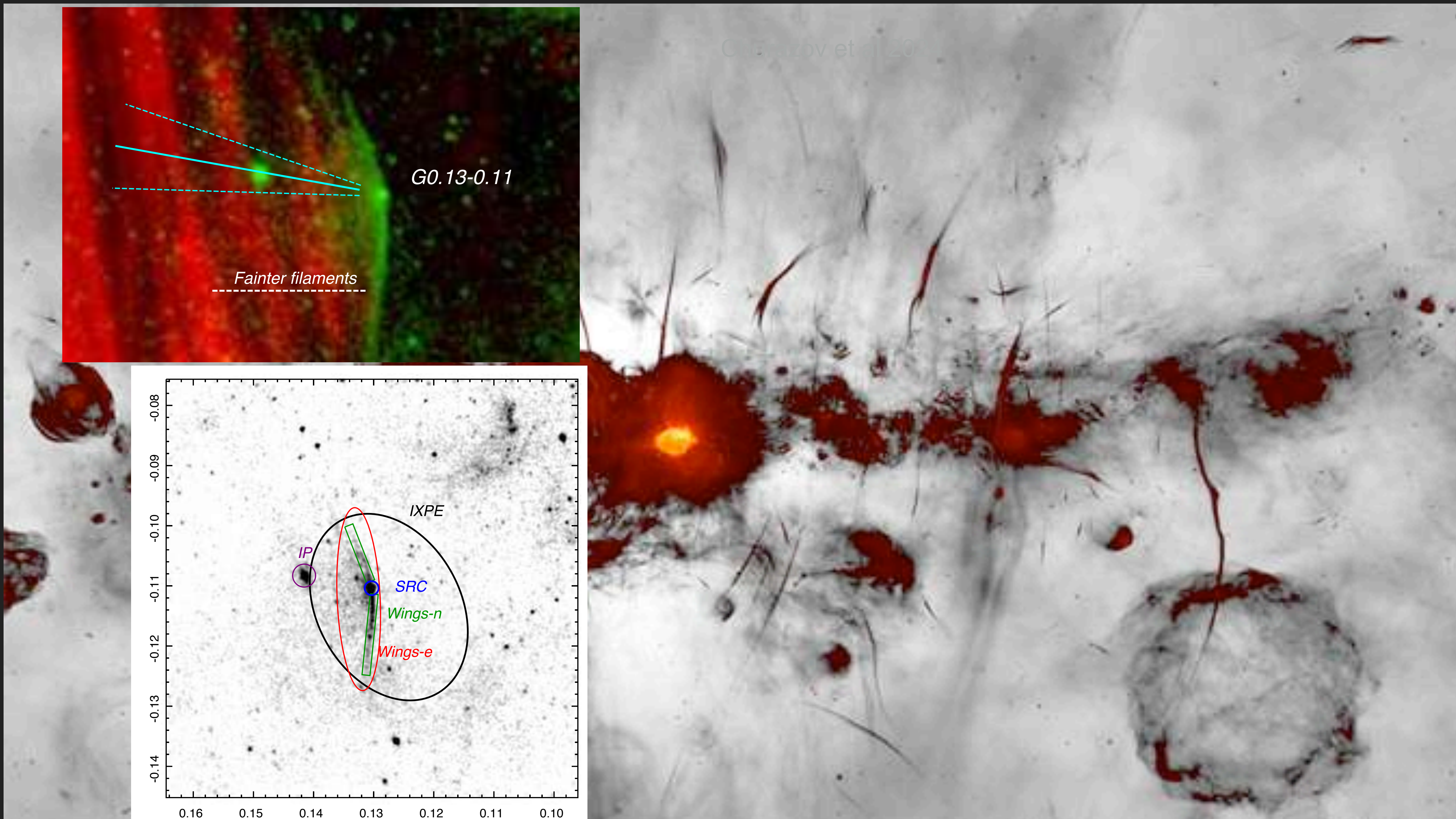
INJECTION REFLECTS PWN
ACCELERATION
HIGH EFFICIENCY


ESCAPE FROM THE TAIL
< 0.1 $E_{MAX}$

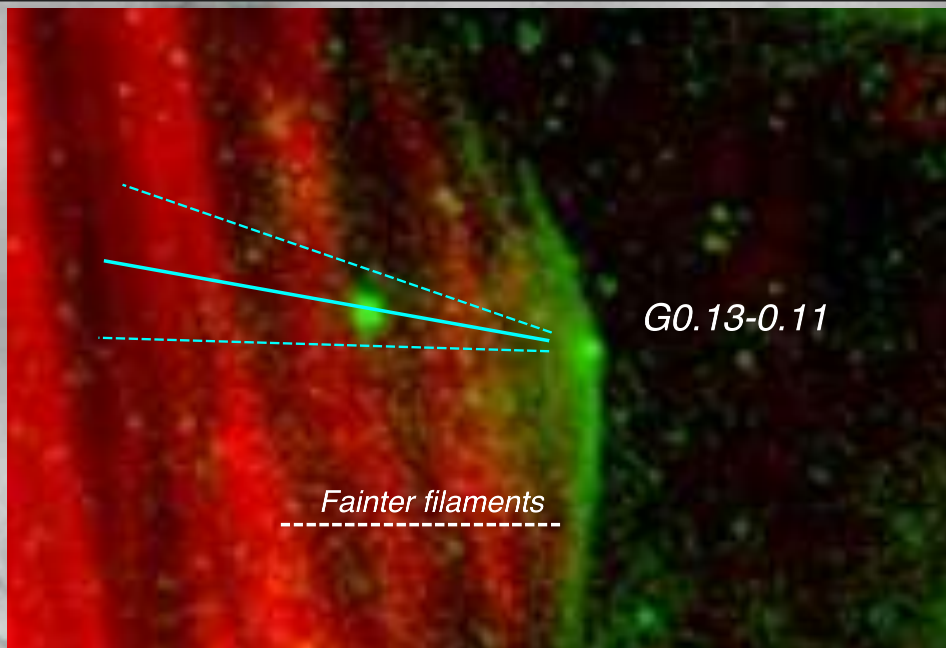
# IXPE – X-RAY POLARIMETRY – G 0.13-0.11

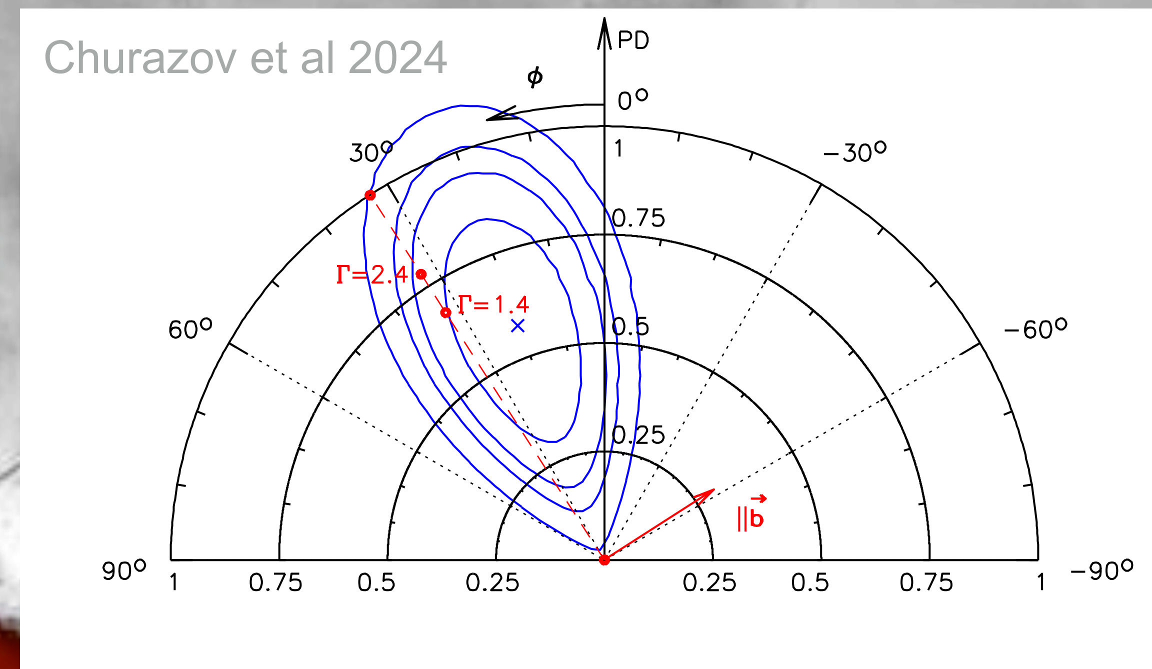


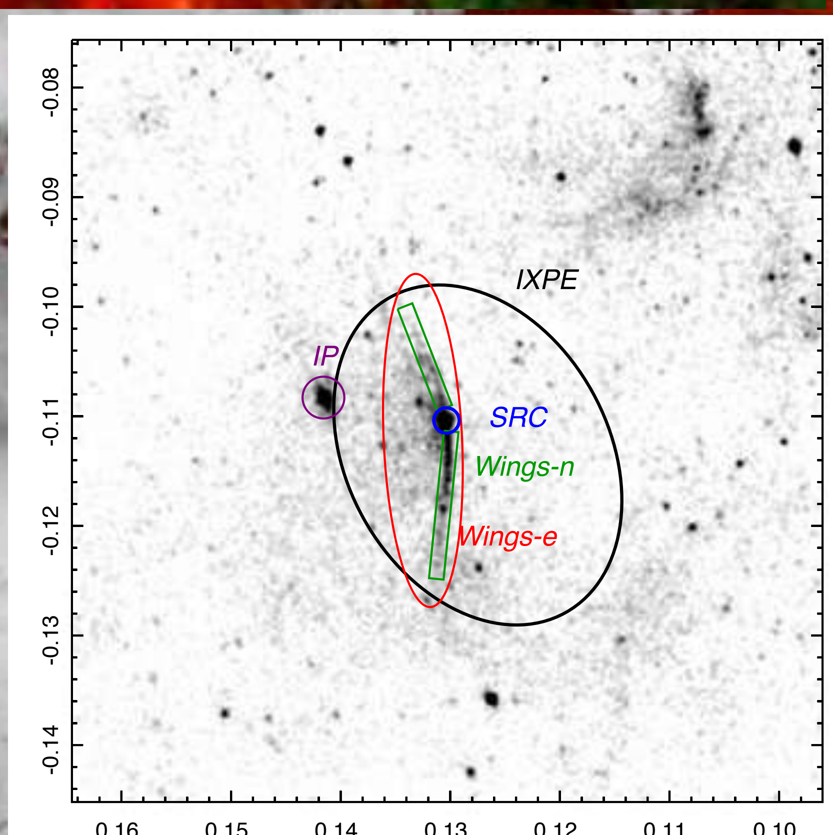
# IXPE – X-RAY POLARIMETRY – G 0.13-0.11



# IXPE – X-RAY POLARIMETRY – G 0.13-0.11



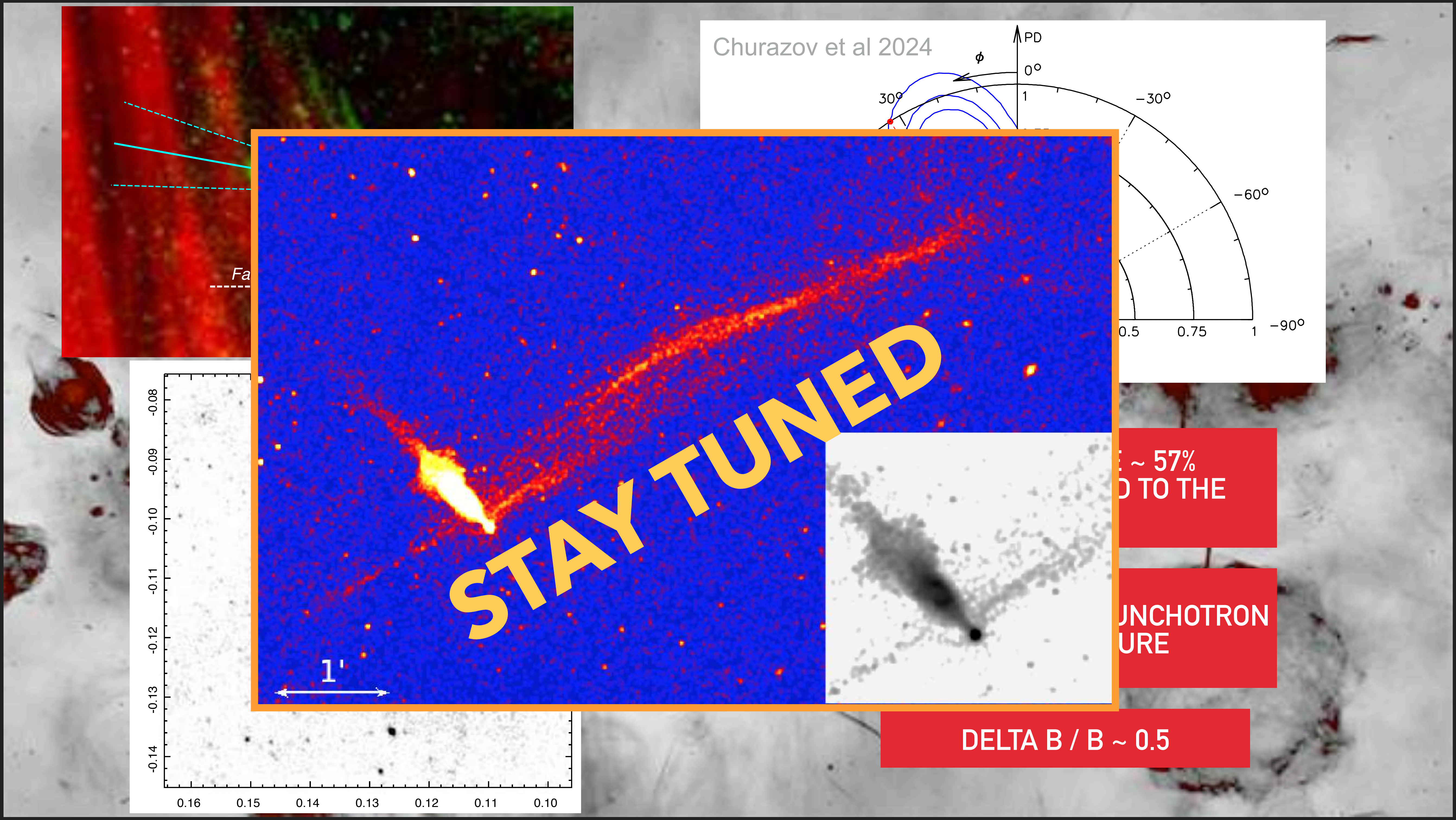




POLARIZATION DEGREE ~ 57%
MAGNETIC FIELD ALIGNED TO THE FEAATURE

CLEAR EVIDENCE FOR THE SUNCHOTRON ORIGIN OF THIS FEATURE

DELTA B / B ~ 0.5

# IXPE – X-RAY POLARIMETRY – G 0.13-0.11



# CONCLUSIONS

## CURRENT CANONICAL PICTURE WELL ESTABLISHED

# CONCLUSIONS

CURRENT CANONICAL PICTURE WELL ESTABLISHED

PWNE WILL BE MAIN SOURCE OF GAMMA RAY SKY

LIKELY TO DOMINATE THE PEVATRONS

PSR/PWN PROBABLY THE MAIN  ANTIMATTER FACTORIES

# CONCLUSIONS

CURRENT CANONICAL PICTURE WELL ESTABLISHED

PWNE WILL BE MAIN SOURCE OF GAMMA RAY SKY

LIKELY TO DOMINATE THE PEVATRONS

PSR/PWN PROBABLY THE MAIN  ANTIMATTER FACTORIES

NO CLEAR IDENTIFICATION FOR THE ACCELERATION MECHANISM

NO CLEAR INDICATION FOR THE ORIGIN OF THE OBSERVED DIVERSITY

# CONCLUSIONS

CURRENT CANONICAL PICTURE WELL ESTABLISHED

PWNE WILL BE MAIN SOURCE OF GAMMA RAY SKY

LIKELY TO DOMINATE THE PEVATRONS

PSR/PWN PROBABLY THE MAIN  ANTIMATTER FACTORIES

NO CLEAR IDENTIFICATION FOR THE ACCELERATION MECHANISM

NO CLEAR INDICATION FOR THE ORIGIN OF THE OBSERVED DIVERSITY

OLD SYSTEMS ARE POORLY CONSTRAINED

BOW SHOCK PWNE LIKELY GOOD INJECTOR OF PAIRS

# CONCLUSIONS

CURRENT CANONICAL PICTURE WELL ESTABLISHED

PWNE WILL BE MAIN SOURCE OF GAMMA RAY SKY

LIKELY TO DOMINATE THE PEVATRONS

PSR/PWN PROBABLY THE MAIN  ANTIMATTER FACTORIES

NO CLEAR IDENTIFICATION FOR THE ACCELERATION MECHANISM

NO CLEAR INDICATION FOR THE ORIGIN OF THE OBSERVED DIVERSITY

OLD SYSTEMS ARE POORLY CONSTRAINED

BOW SHOCK PWNE LIKELY GOOD INJECTOR OF PAIRS

ESCAPE FROM OLDER BUT CONFINED SYSTEMS IS UNLIKELY

JET FEATURES DEPEND ON BOW SHOCK HEAD CONDITIONS

NON UNIFORM BOW SHOCK TAIL DYNAMICS