PULSAR WIND NEBULAE: A CLASS OF EXTRAORDINARY COSMIC ACCELERATORS

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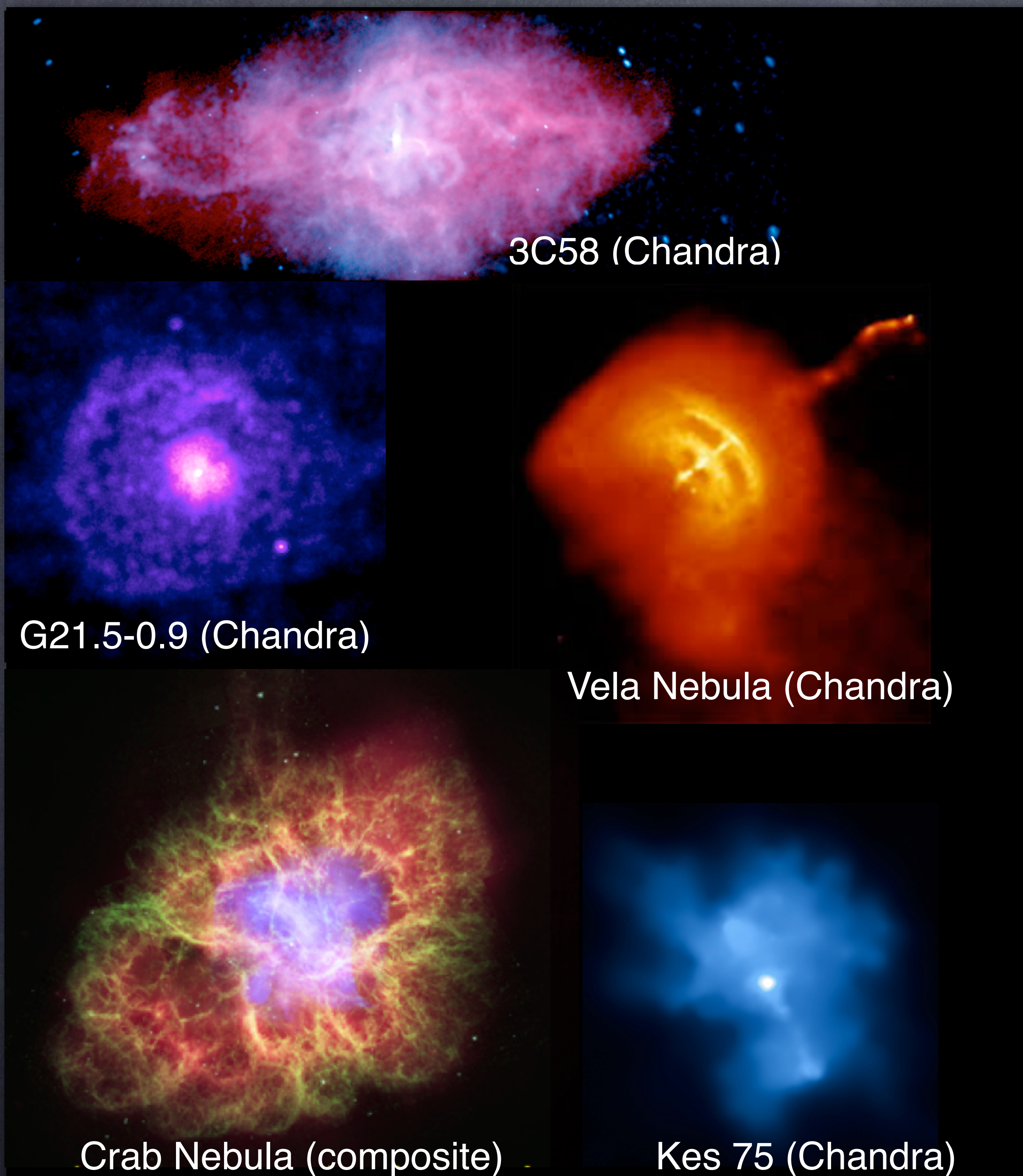
PULSAR WIND NEBULAE

SNRs WITH

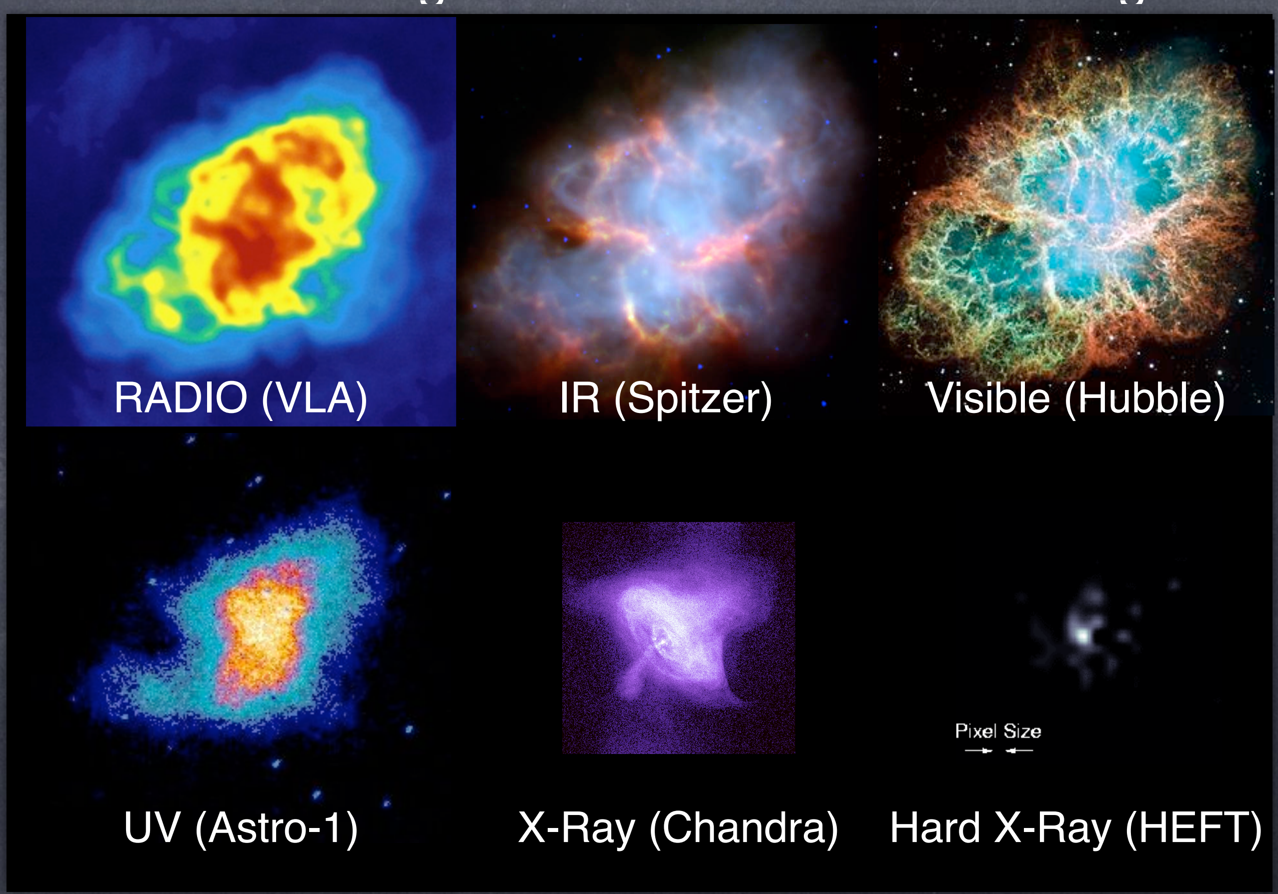
- CENTER FILLED MORPHOLOGY
- BROAD NON THERMAL SPECTRUM
- FLAT RADIO SPECTRUM

$$F_\nu \propto \nu^{-\alpha}, \quad \alpha < 0.5$$



Jet-torus morphology in X-rays

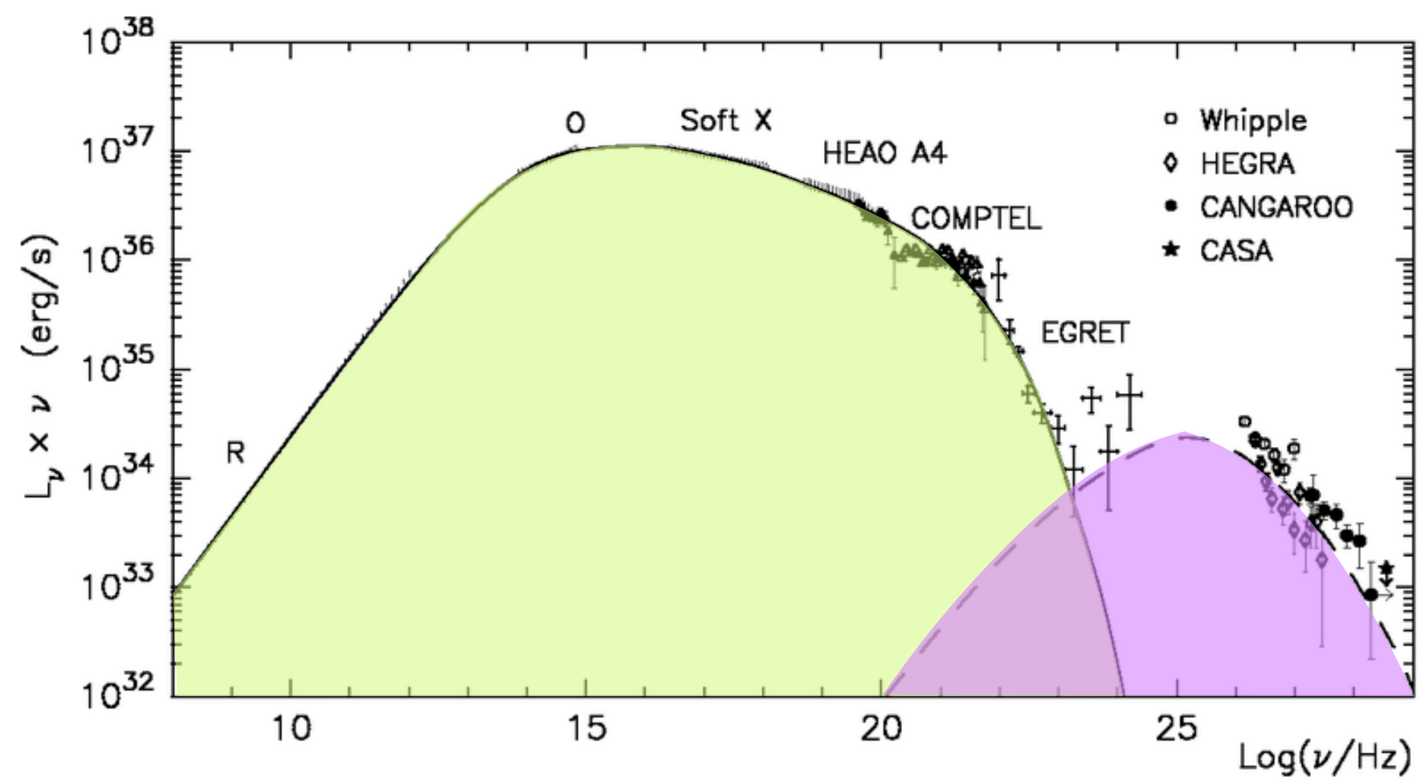
Multi-wavelength emission and size shrinkage



THE CRAB NEBULA

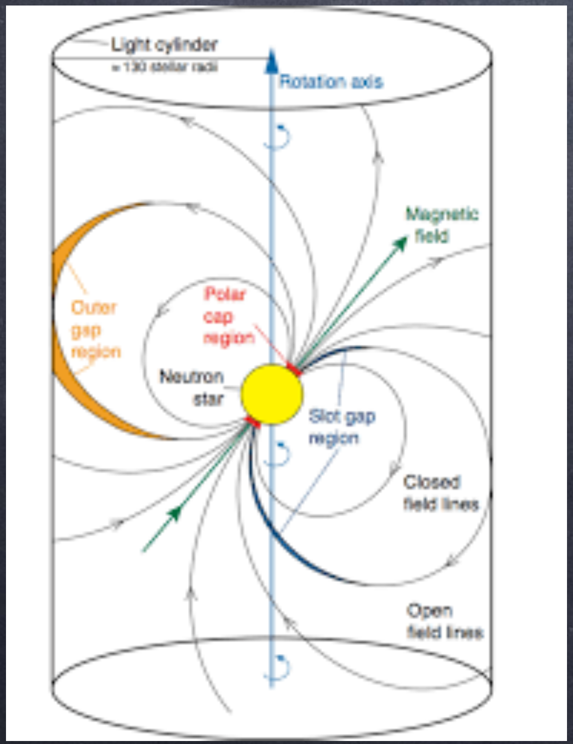
BROAD BAND NON-THERMAL SPECTRUM

CRAB NEBULA spectrum [adapted from Atoyan & Aharonian



synchrotron radiation by relativistic particles in the nebular B field

PARTICLES AND FIELD
FROM ROTATIONAL ENERGY LOST BY PULSAR



PSR IS A ROTATING MAGNET THAT SLOWS DOWN
DUE TO E.M. TORQUE [Pacini 1969]

WHY PWNe ARE INTERESTING

PULSAR PHYSICS:

$$L_{\rm radio} \lesssim 10^{-10}\dot{E}_{\rm PSR}, \quad L_\gamma \lesssim 10^{-2}\dot{E}_{\rm PSR}, \qquad L_{\rm PWN} \geq 0.1\dot{E}_{\rm PSR}$$

PLASMA PHYSICS:

- CLOSEST AND BEST STUDIED RELATIVISTIC PLASMAS
- PARTICLE ACCELERATION AT THE MOST RELATIVISTIC SHOCKS IN NATURE ($10^4 < \Gamma < 10^8$)

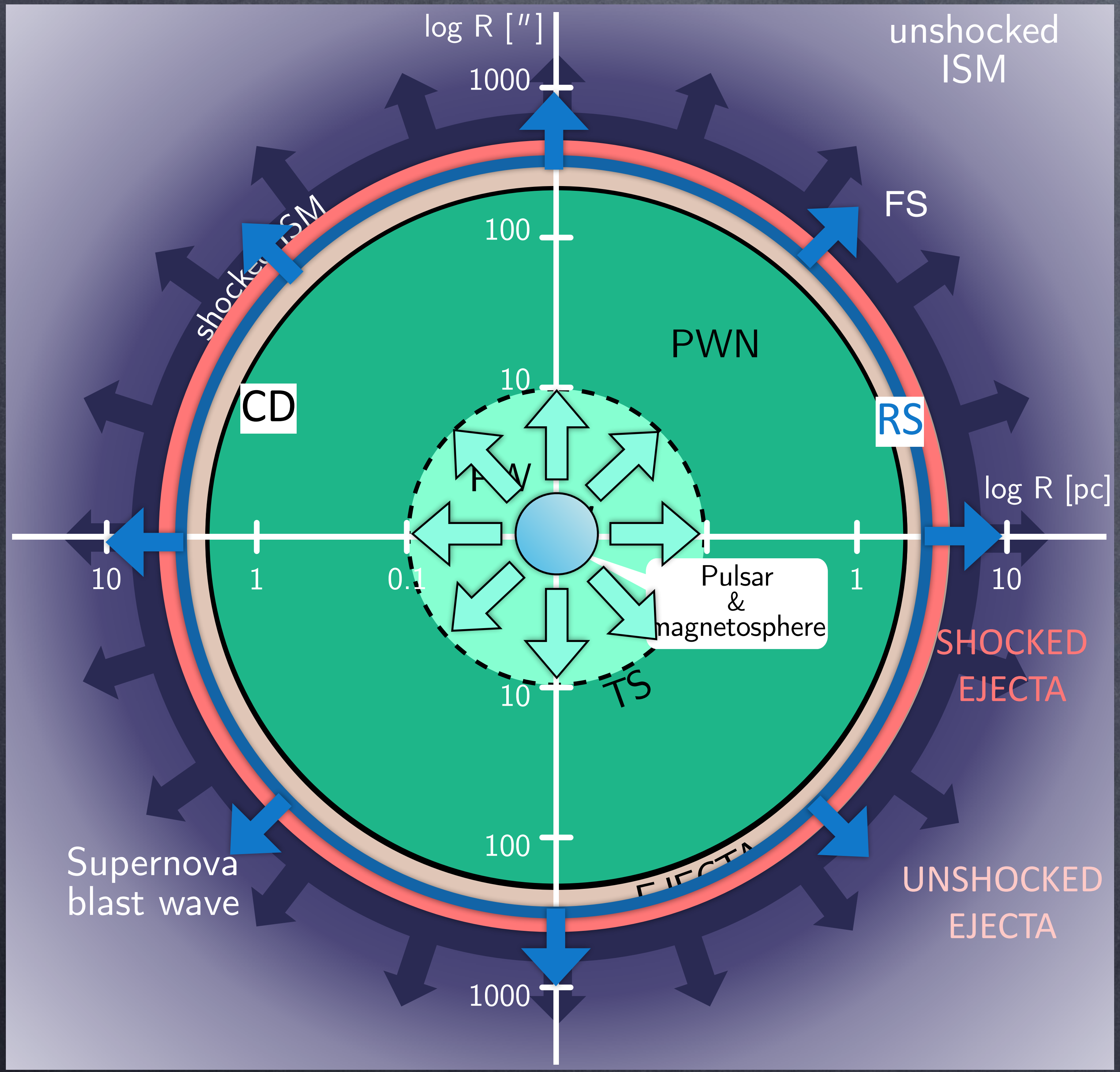
COSMIC RAY PHYSICS:

- ONLY SOURCES WITH DIRECT EVIDENCE OF PeV PARTICLES
- LIKELY MAIN CONTRIBUTORS OF CR POSITRONS

GAMMA-RAY ASTROPHYSICS:

- MOST NUMEROUS CLASS OF GALACTIC SOURCES
- EXTENDED TeV HALOES
- LEPTONIC (AT LEAST) PEVATRONS

BASIC PICTURE FOR YOUNG SYSTEMS

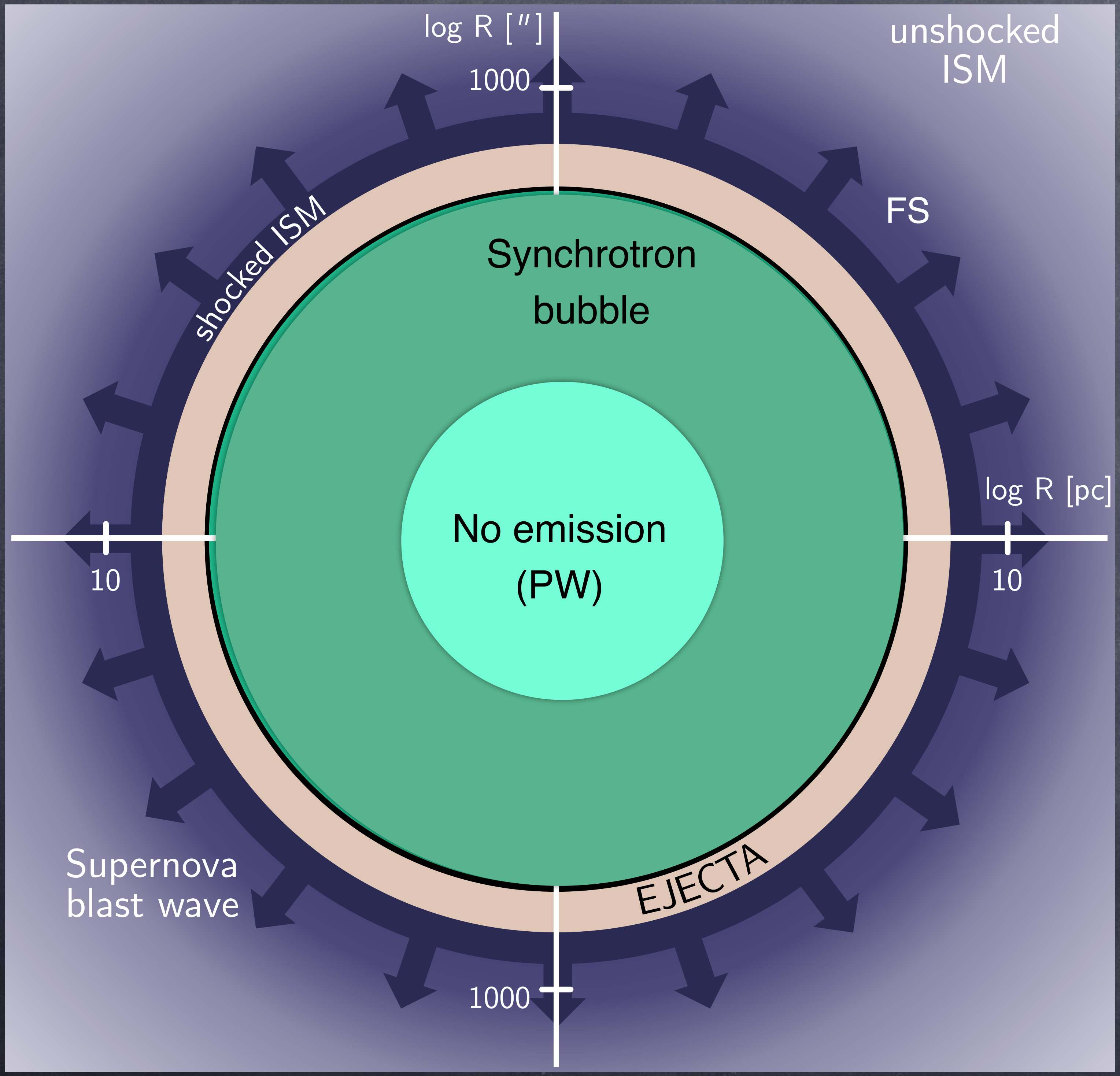


Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

$$\frac{\dot{E}}{4\pi c R_{TS}^2} = P_{PWN} = \frac{\dot{E}\ t}{4\pi R_N^3}$$

$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

BASIC PICTURE FOR YOUNG SYSTEMS



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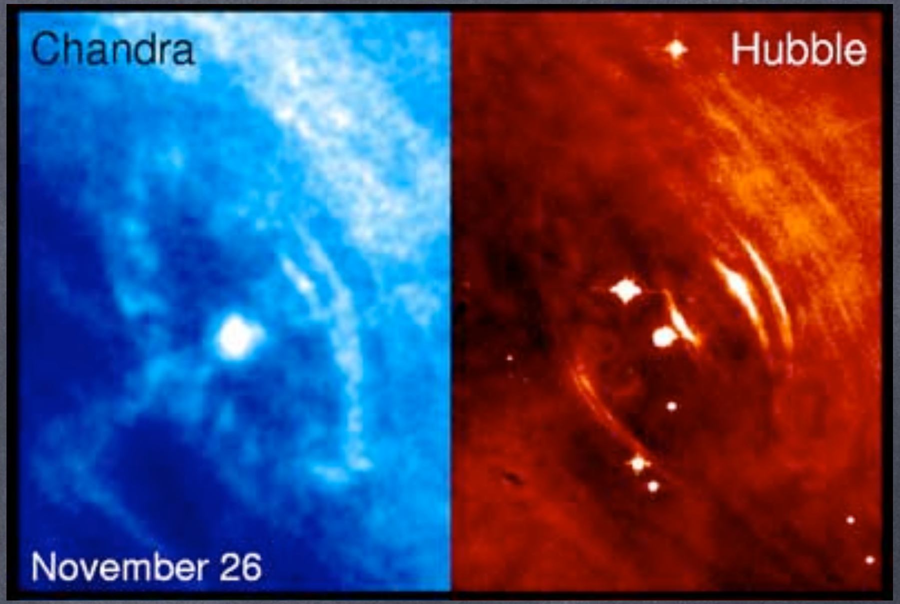
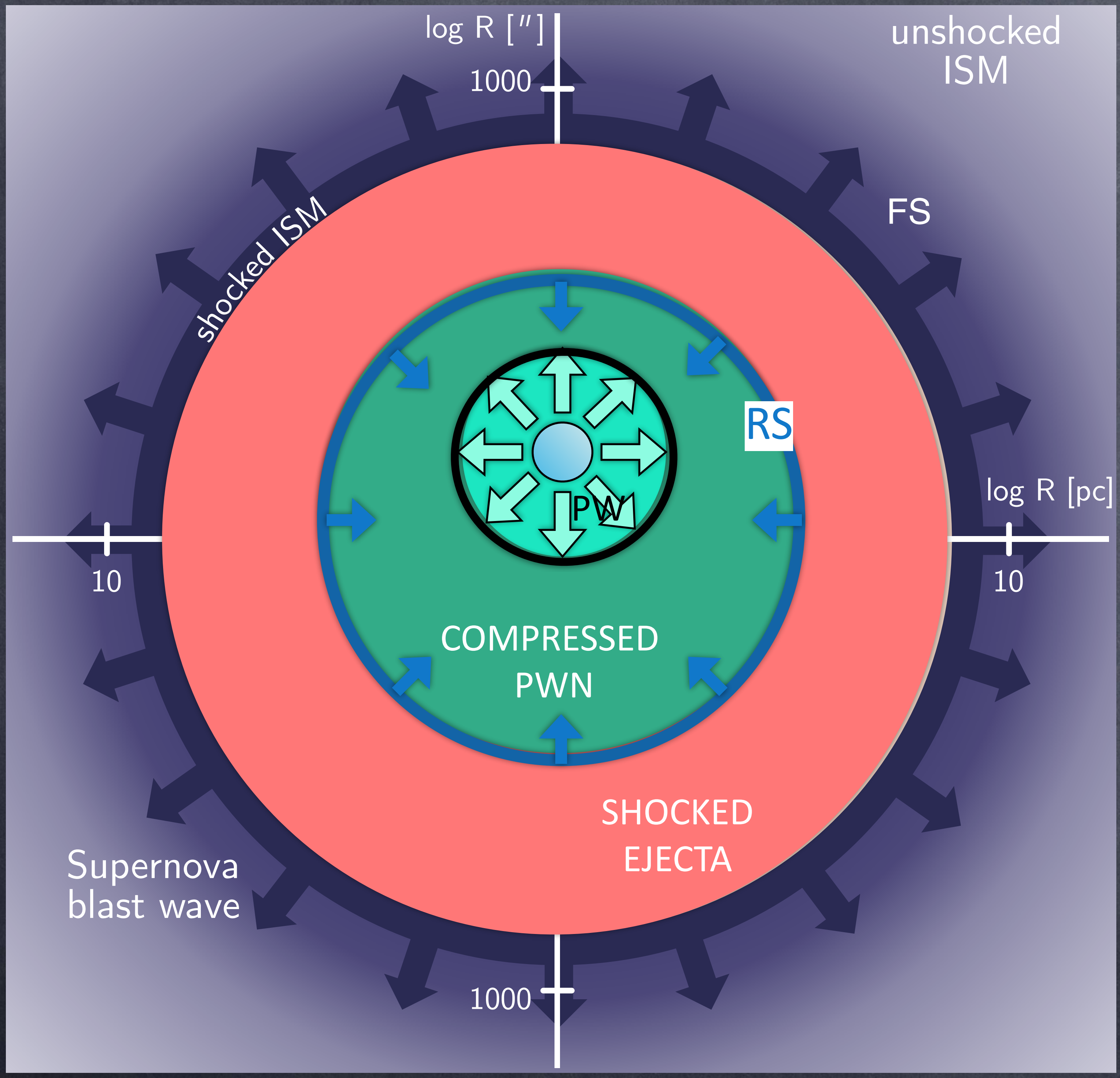


$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

DISSIPATION AND PARTICLE ACCELERATION AT TS

PWN EVOLUTION



SNR EXPANSION SLOWS DOWN

+

LARGE FRACTION OF ALL THE PULSARS BORN WITH HIGH KICK VELOCITY

↓

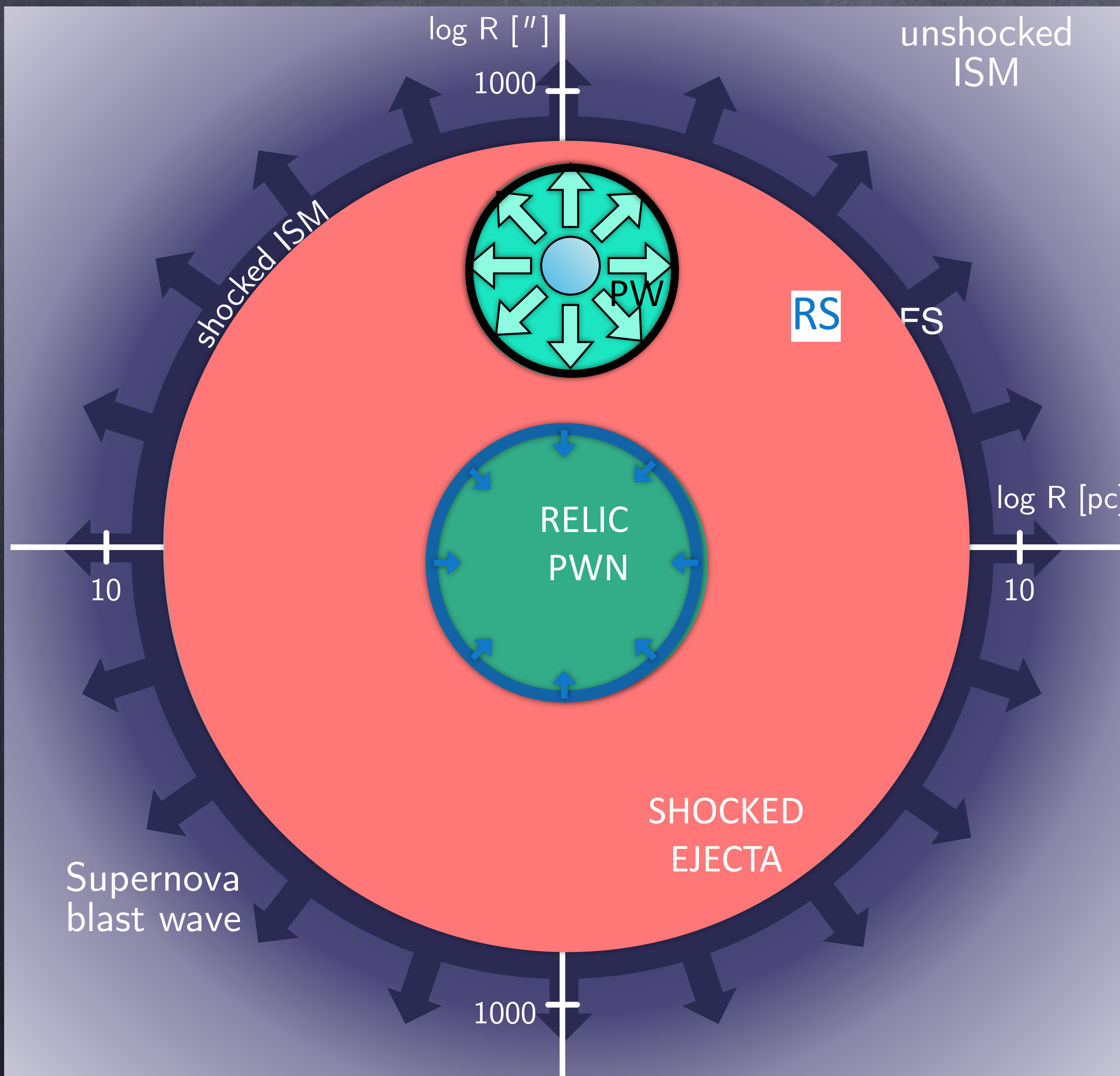
COMPRESSED PWN
OFFSET PW

↓

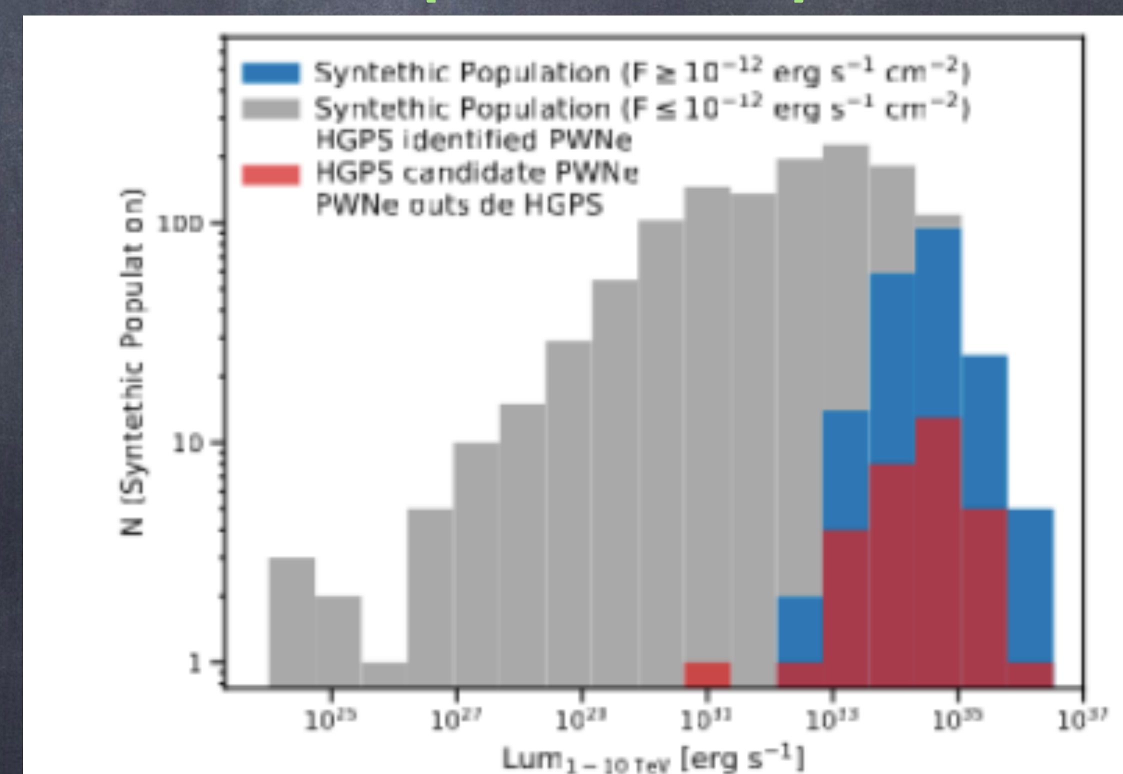
REVERBERATION PHASE

RELIC NEBULAE

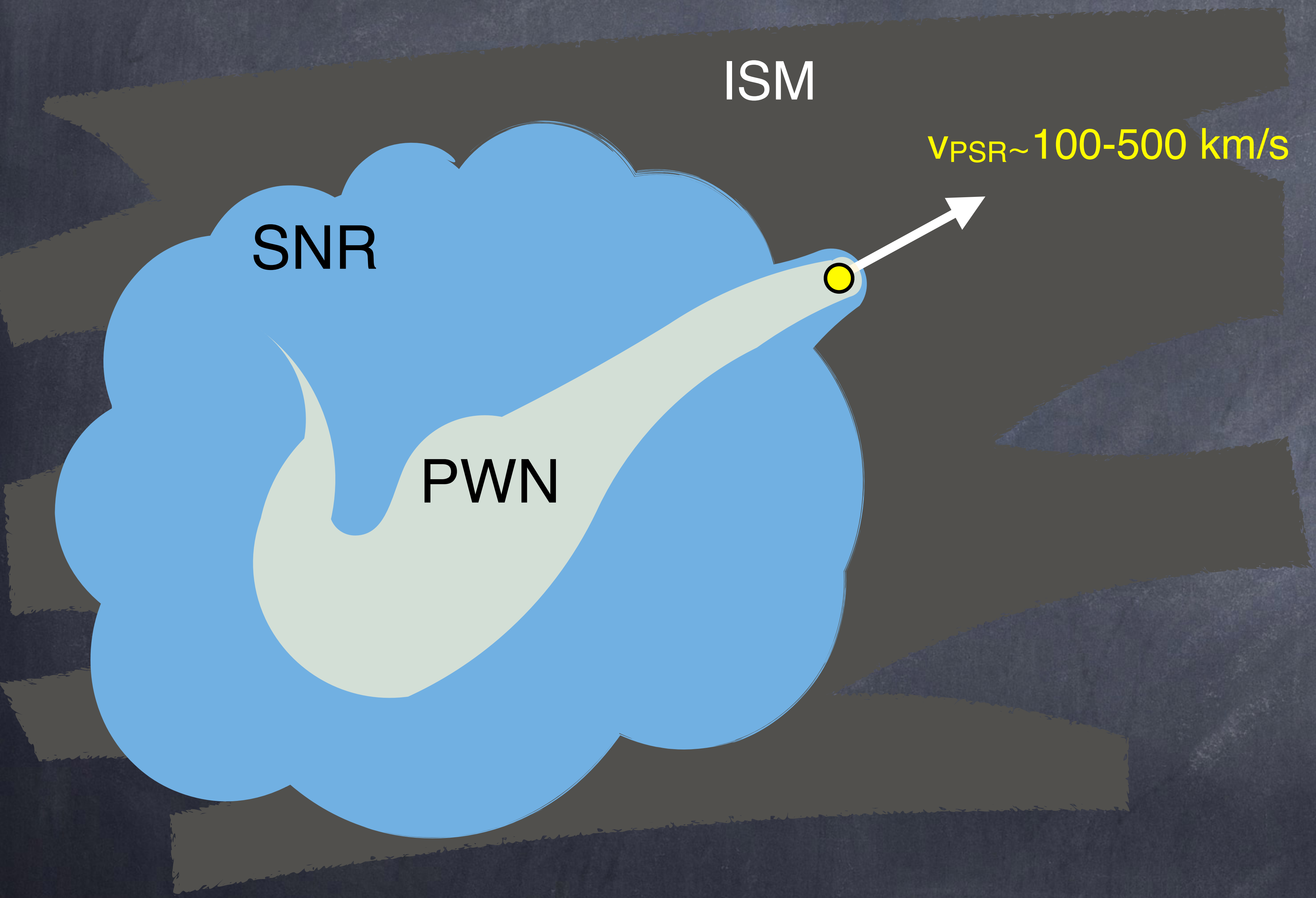
PSR MAY CROSS RS DURING COMPRESSION
AND LEAVE A RELIC



EVENTUALLY
MOST GAMMA-RAY BRIGHT
X-RAY DIM PWNe
[Fiori+ submitted]



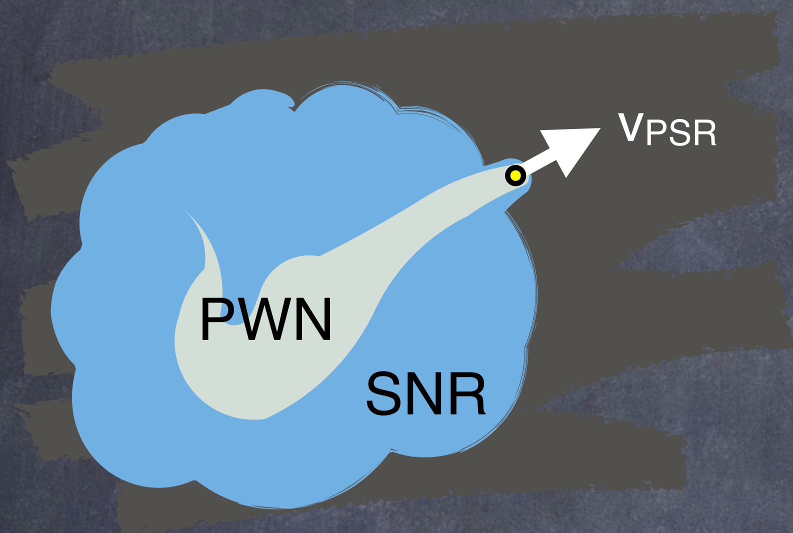
EVOLVED PWNe

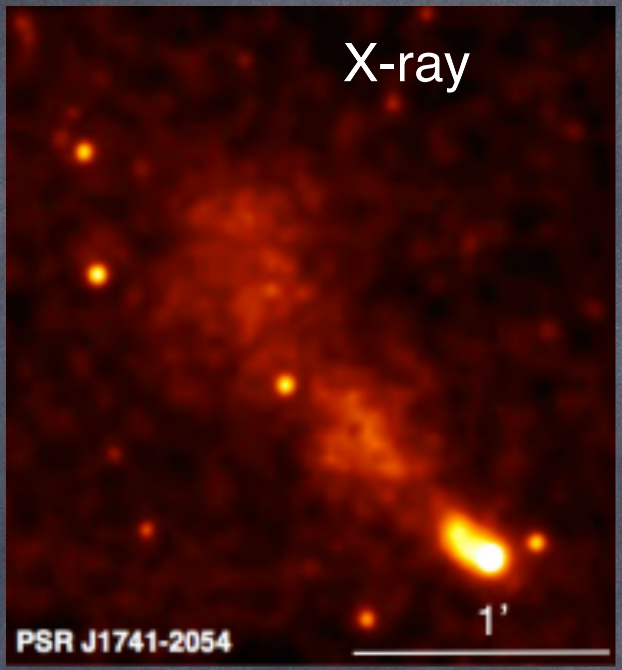


LARGE FRACTION OF ALL THE PULSARS BORN WITH HIGH KICK VELOCITY

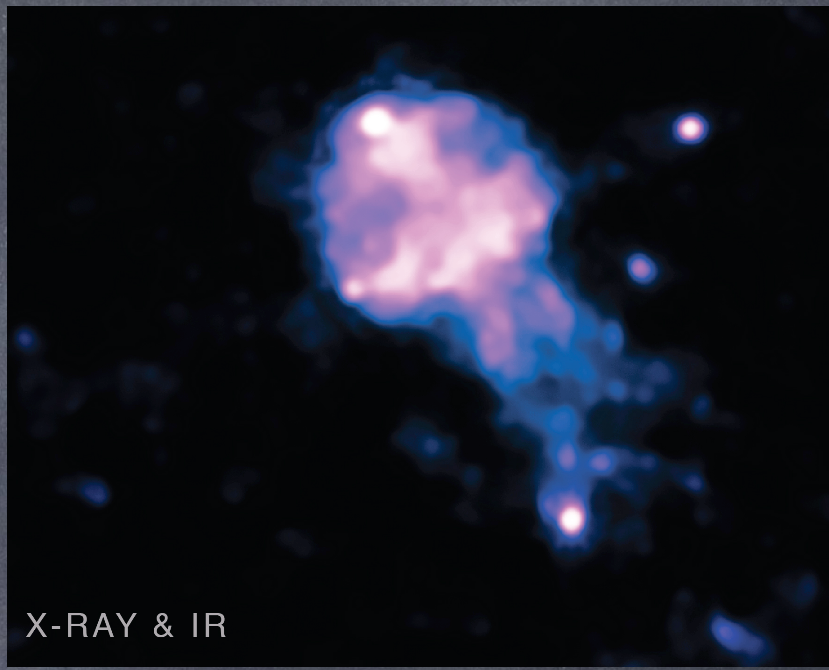
THEY LEAVE THE SNR ON TIMESCALES FEW X 10^4 – 10^5 YR

OBSERVATIONS: COMETARY NEBULAE

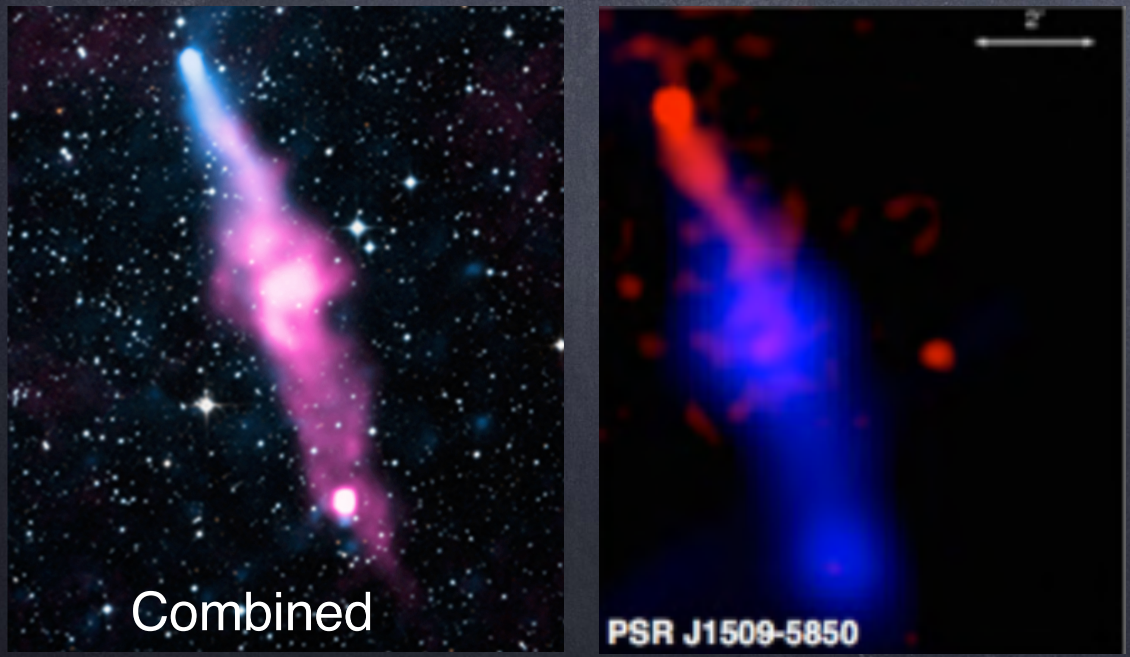




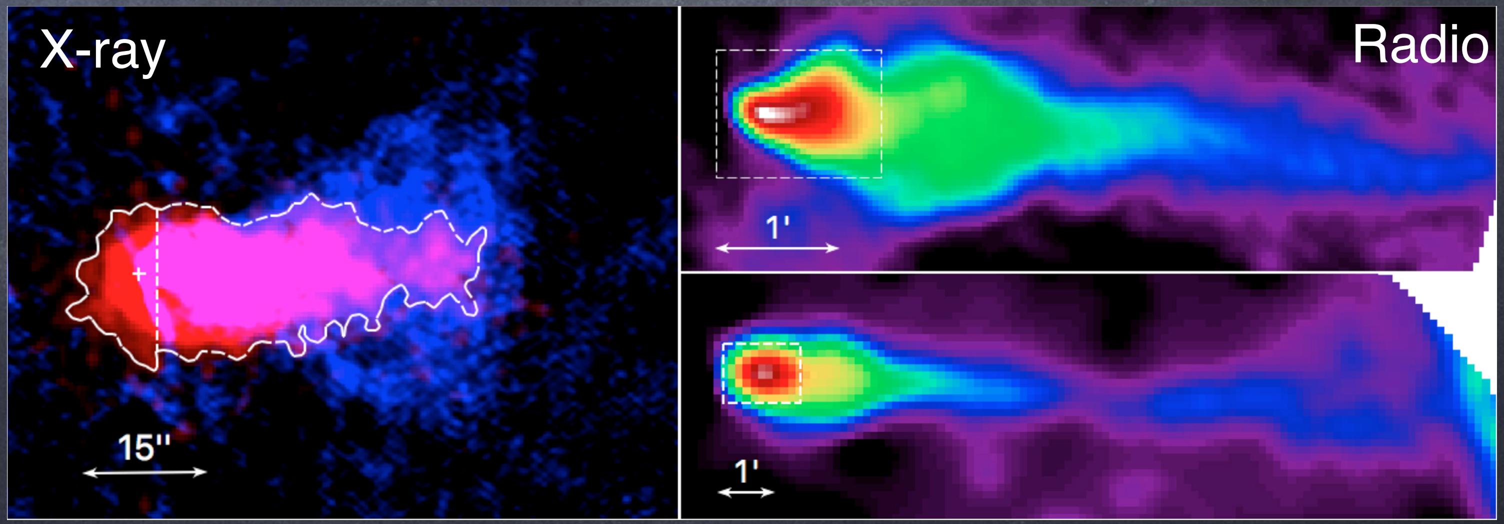
PSR J1741-2054
[Kargaltsev et al. 2016]



B0355+54
[Emre et al. 2005]

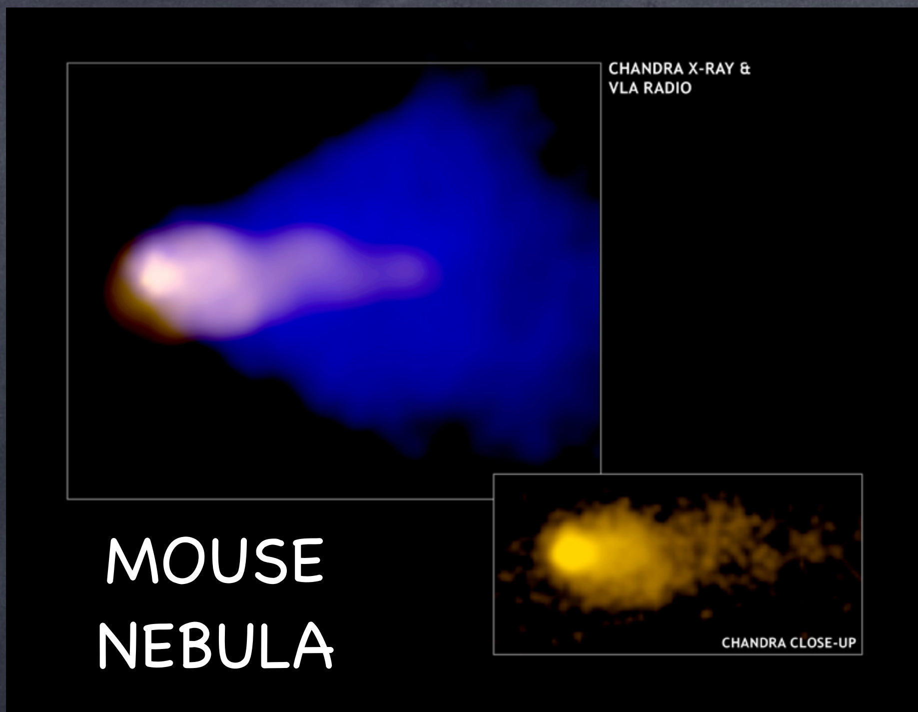


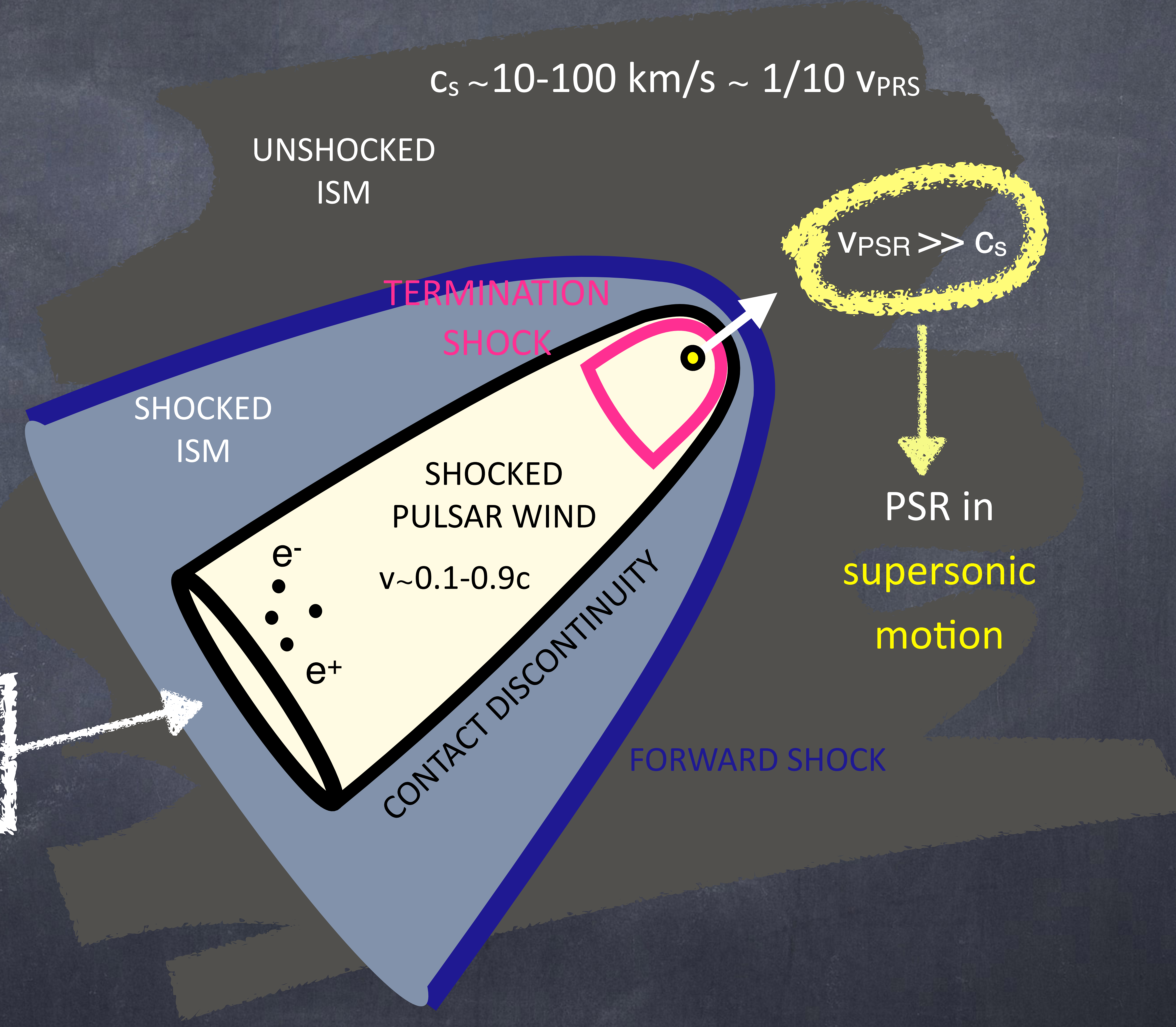
PSR J1509-5850
[Hui & Becker 2007, Klinger et al. 2016]

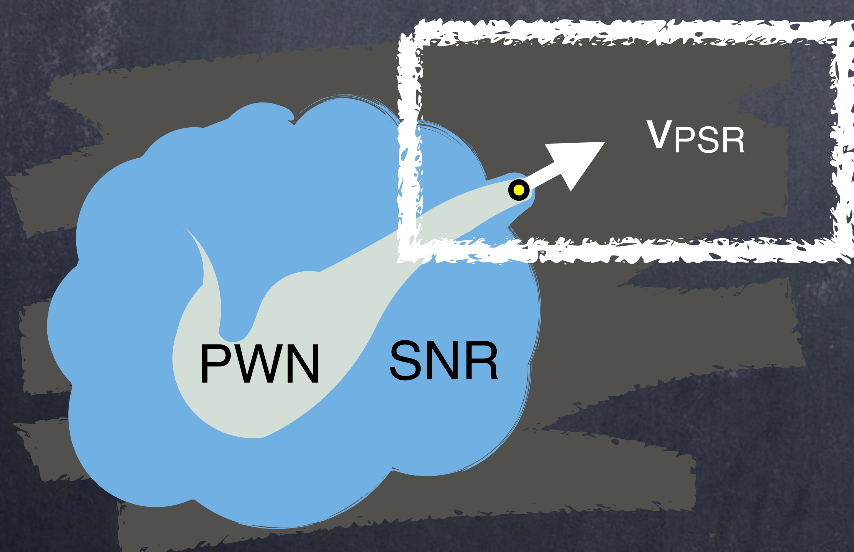


Mouse PWN
[Yusef-Zadeh & Bally 1987, Yusef-Zadeh & Gaensler 2005, Klinger et al. 2018]

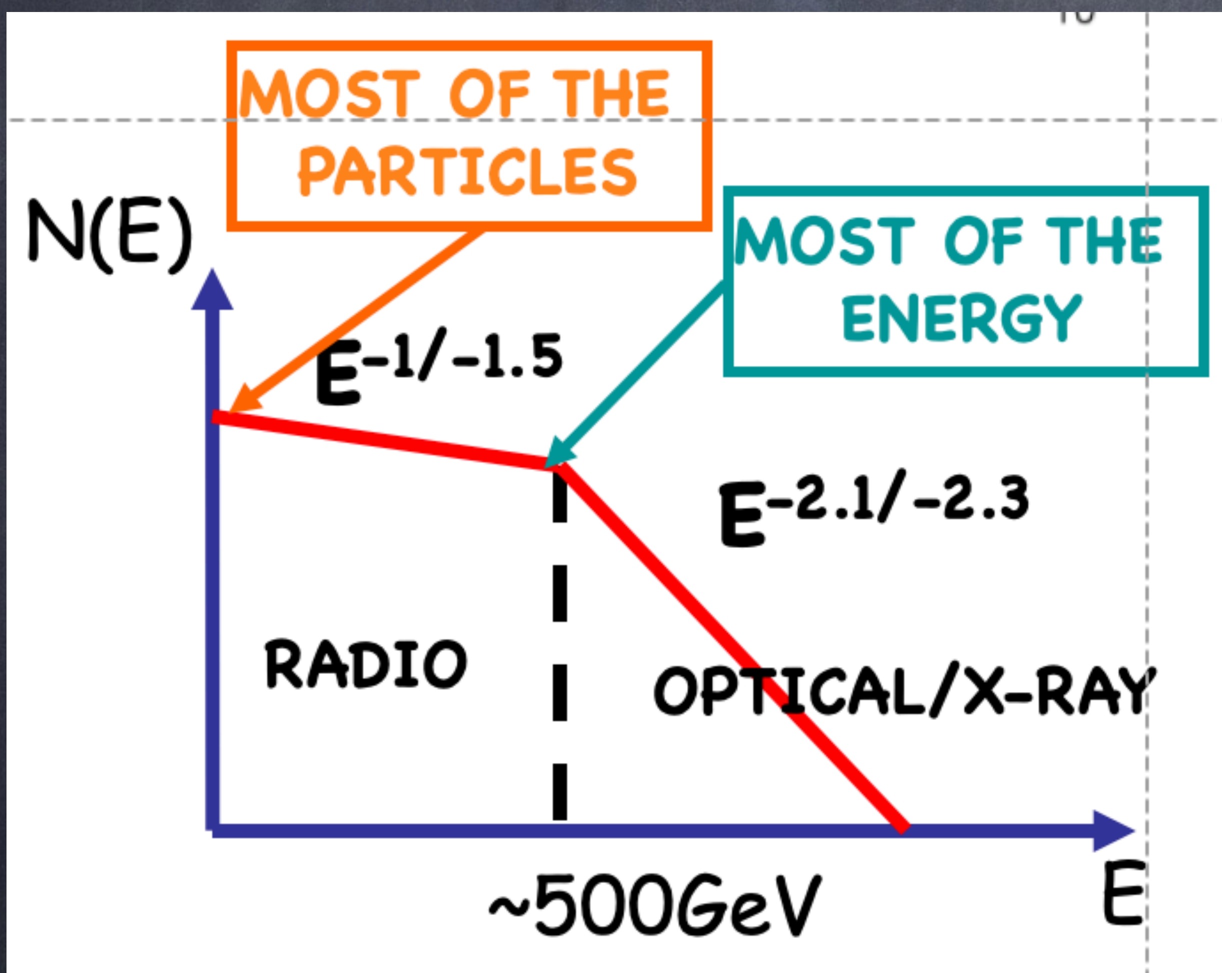
BOW SHOCK NEBULAE



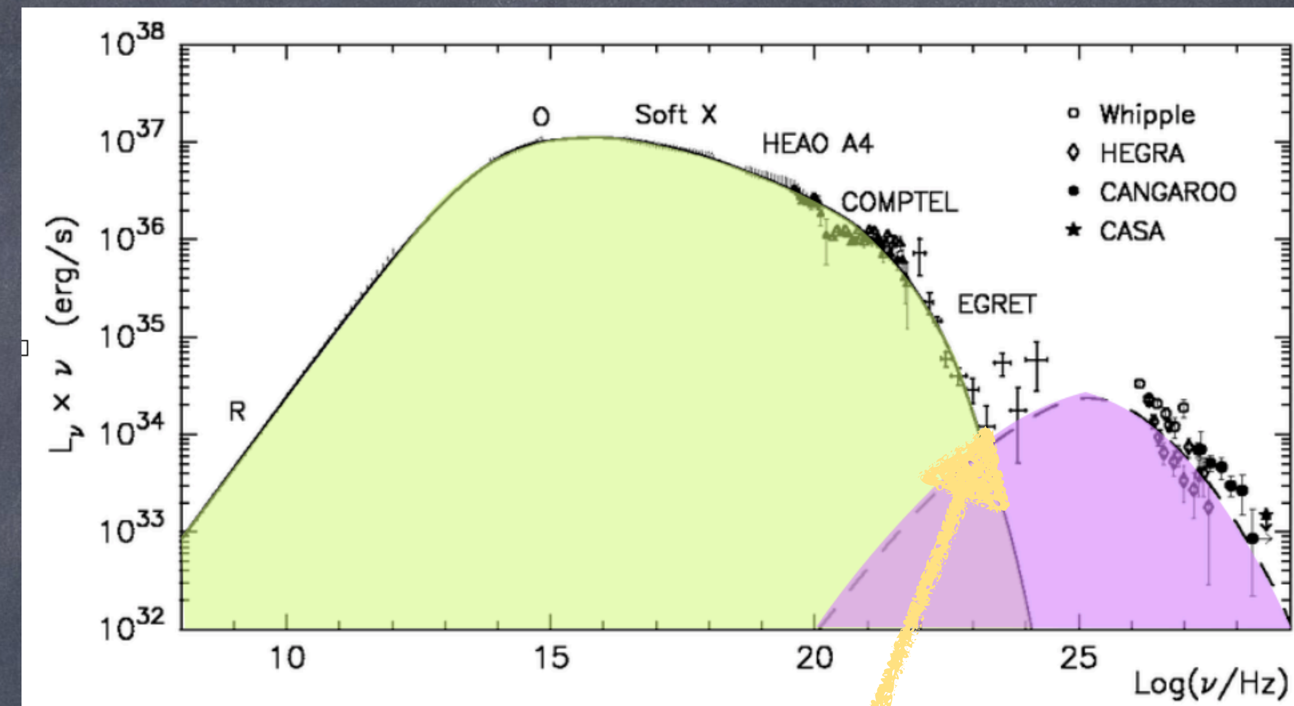




EMITTING PARTICLES



ONE ZONE MODELS
(Pacini & Salvati 1973, EA+ 2000, Bucciantini+ 2011….)
(also Fraschetti & Pohl 2017 for log-parabola injection)



PeV ELECTRONs

$B_{NEB} \approx 100\ \mu G$

$L_{NEB} \approx 30\,\%\,\dot{E}$

EXTRAORDINARY ACCELERATOR!

OPEN QUESTIONS

WHAT WE KNOW:

- MOST EFFICIENT ACCELERATORS IN NATURE $\epsilon_{\rm acc} \lesssim 30\,\%$

- ENERGY FLUX THAT LEAVES THE PSR

$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e} \right) (1 + \sigma)$$

$$\sigma = \frac{B^2}{4\pi\ n_\pm\ m_e\ c^2\ \Gamma^2}$$

WE DO NOT KNOW:

- WHAT THE ACCELERATION MECHANISM(S) IS (ARE)

POSSIBILITIES DEPEND ON

WIND COMPOSITION (IONS? κ?)

WIND MAGNETIZATION (σ?)

IN PRINCIPLE BOTH DEPEND ON LOCATION

- HOW PARTICLES EVENTUALLY ESCAPE

PARTICLE ACCELERATION MECHANISMS (BEST STUDIED)

FERMI MECHANISM

✓EFFICIENT AT UNMAGNETIZED e^+-e^- RELATIVISTIC SHOCKS [Spitkovsky 08]

- NO ACCELERATION AT σ>0.001 SUPERLUMINAL SHOCKS [Sironi & Spitkovsky 09, 11]
- TOO SLOW TO GUARANTEE MAXIMUM ENERGY OBSERVED IN CRAB [Pelletier+ 17]

✓POSSIBLY EFFICIENT AT HIGHLY TURBULENT MODERATELY MAGNETIZED SHOCKS [Lemoine 17, Giacinti & Kirk 18, Cerutti & Giacinti 20]

✓RIGHT SPECTRUM FOR X-RAYS

DRIVEN MAGNETIC RECONNECTION:

✓BROAD AND HARD PARTICLE SPECTRA IF $\sigma \gtrsim 30$ AND $\kappa > 10^8$ [Sironi & Spitkovsky 11b]

- FOR THIS LARGE κ WIND LIKELY TO DISSIPATE BEFORE SHOCK [Kirk & Skjeraasen 03]

RESONANT CYCLOTRON ABSORPTION:

✓SPECTRA AND ACCELERATION EFFICIENCY DEPEND ON ENERGY FRACTION IN IONS: U_i/U_{TOT}=0.8-0.6, γ=1.5-3, ε_{ACC}=0.3-0.03 [Hoshino+ 92, EA & Arons 06; Stockem+ 12]

✓HIGHER σ IMPLIES FASTER ACCELERATION

- NO ACCELERATION IF $\kappa > m_i/m_e$

PARTICLE ACCELERATION MECHANISMS: SUMMARY OF REQUIREMENTS

FERMI MECHANISM → MAGNETIZATION: REQUIRES LOW

HOWEVER SEE VARIANTS

DRIVEN MAGNETIC RECONNECTION → MAGNETIZATION: REQUIRES HIGH

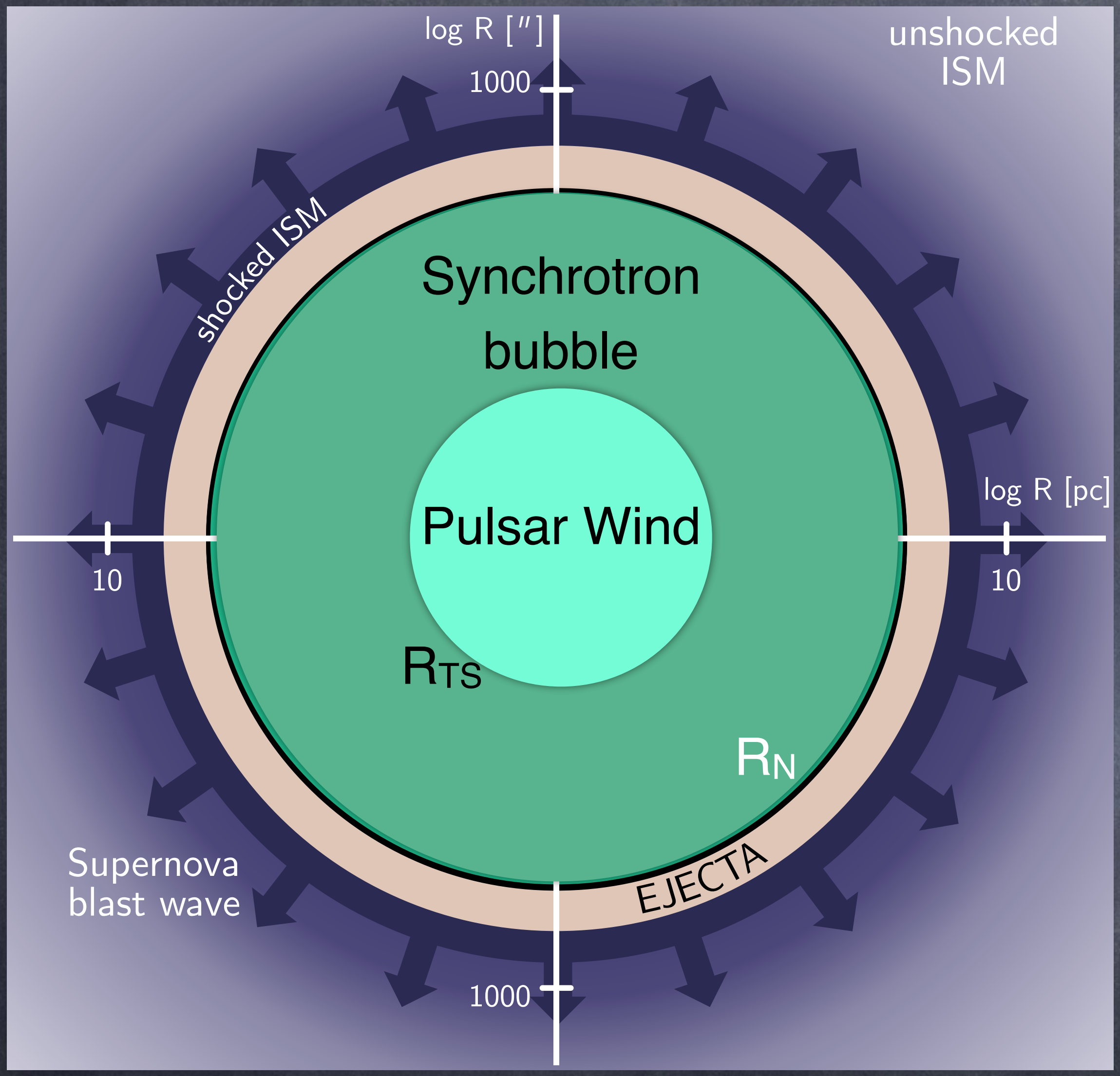
DRIVEN MAGNETIC RECONNECTION → PLASMA MULTIPLICITY: REQUIRES HIGH

ION CYCLOTRON ABSORPTION IN ION DOPED PLASMA → PLASMA MULTIPLICITY: REQUIRES LOW

CONSTRAINING THE WIND MAGNETIZATION

1D/2D STATIC MODELS OF PWNE

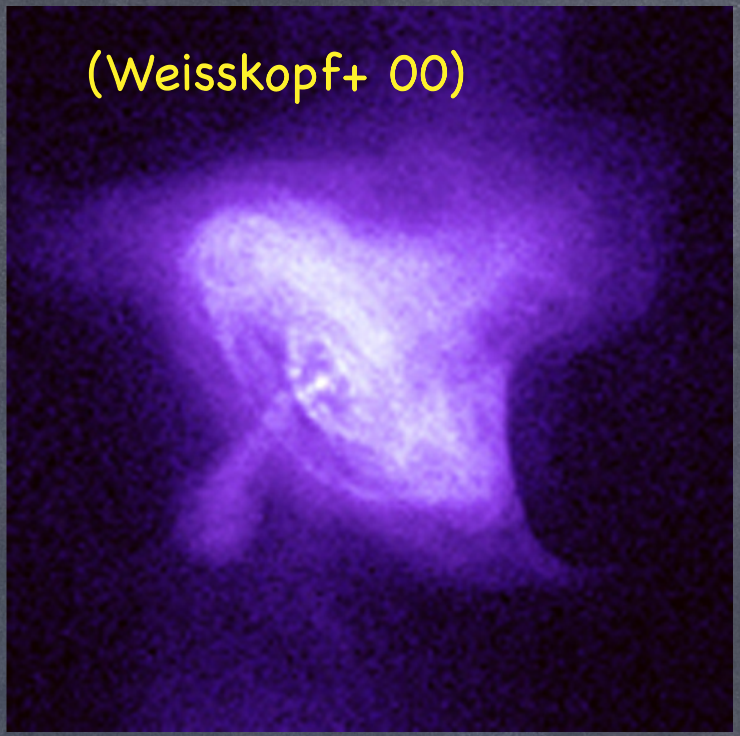
[Rees & Gunn 1974, Kennel & Coroniti 1984, Emmering & Chevalier 1987, Begelman & Li 1992]



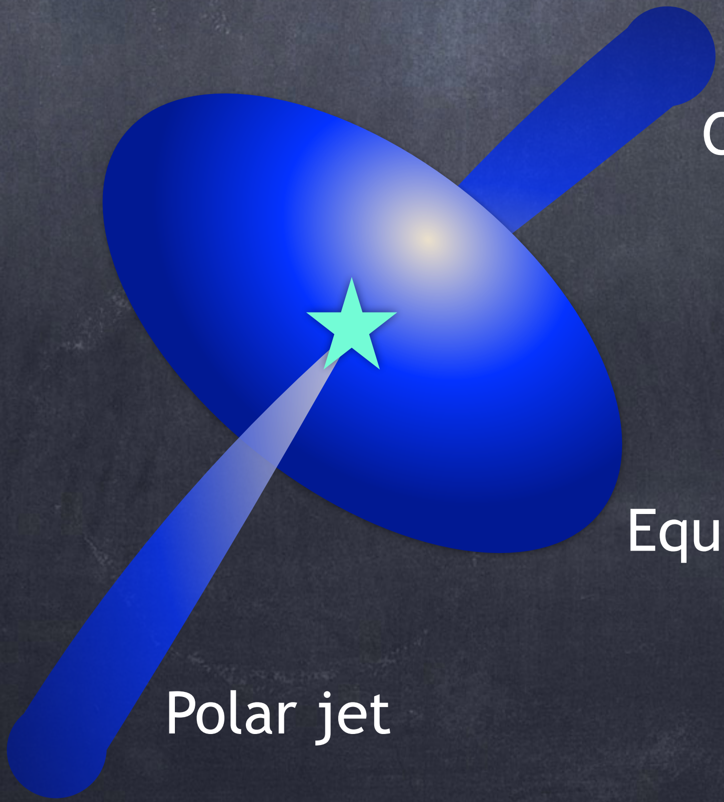
- particle spectral index(es) → $\boxed{\gamma = 2.3}$
- wind Lorentz factor → $\boxed{\Gamma = 3 \times 10^6}$
- wind magnetization → $\boxed{\sigma = v_N/c \approx 3 \times 10^{-3}}$

FROM DYNAMICS AND RADIATION MODELING OF OPTICAL /X-RAY EMISSION

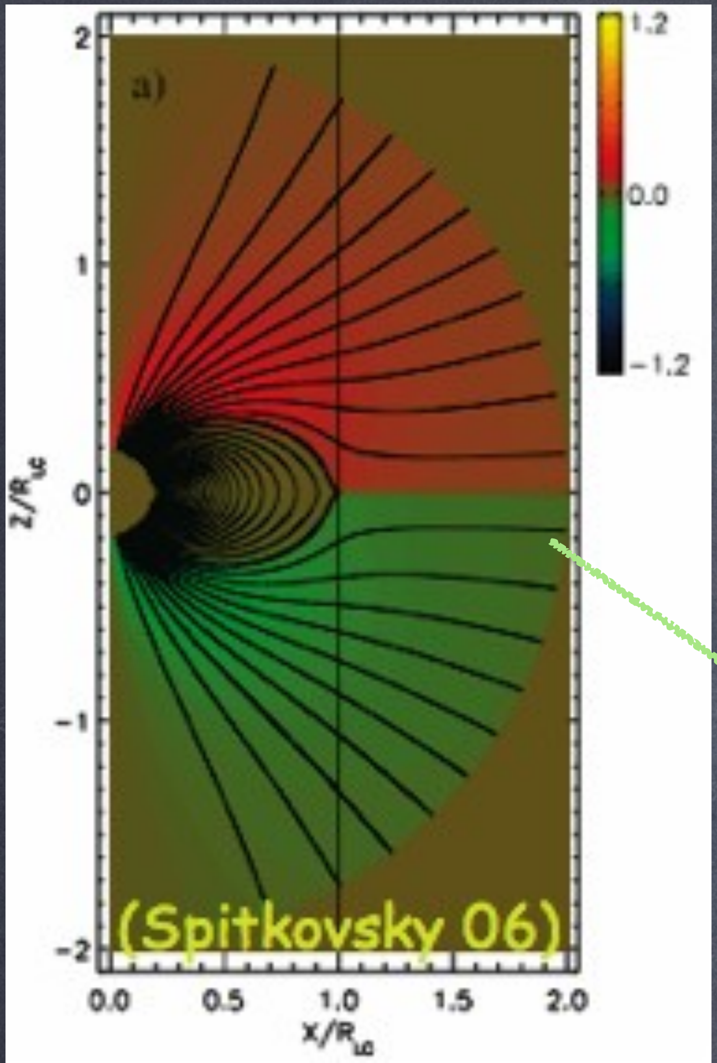
CHANDRA'S VIEW OF PWNE



Jet-torus morphology of inner nebula



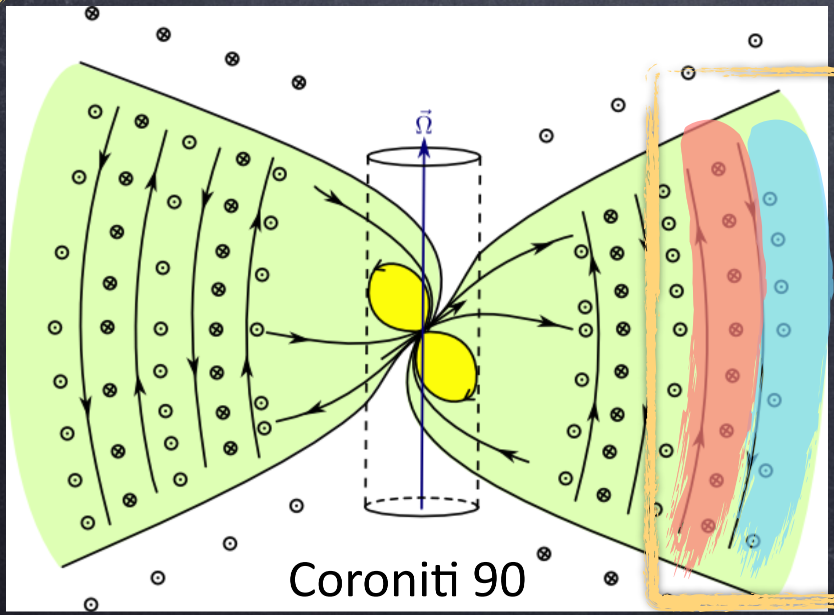
THE ANISOTROPIC PULSAR WIND



Komissarov & Lyubarsky 03, 04; Del Zanna+ 04, 06; Bogovalov+ 05
Camus+ 09; Volpi+ 08; Olmi+ 14, 15

$$\boxed{F(\theta) \propto \sin^2(\theta)}$$

$$\boxed{B(\theta) \propto \sqrt{\sigma}\ \sin\theta\ G(\theta)}$$

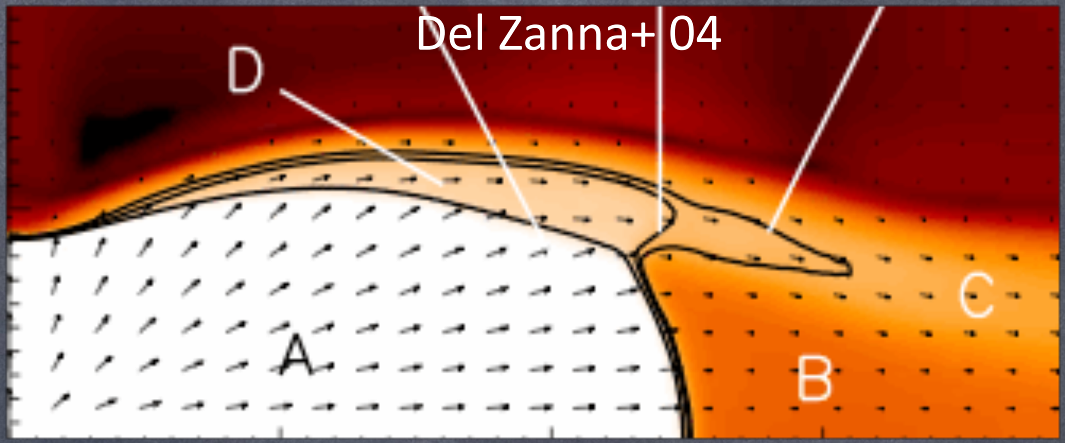


alternating stripes of opposite B polarities

dissipation in current sheet

2D MHD NUMERICAL MODELING: RINGS AND TORII

A: ULTRARELATIVISTIC WIND
B: SUBSONIC OUTFLOW
C: SUPERSONIC FUNNEL



$$F(\theta) \propto \sin^2(\theta)$$

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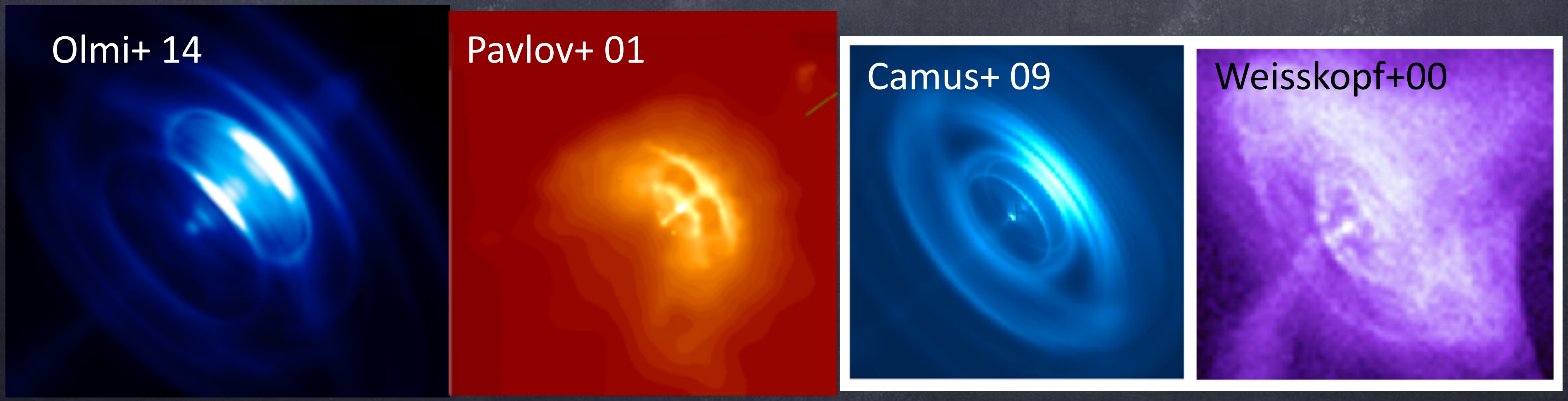
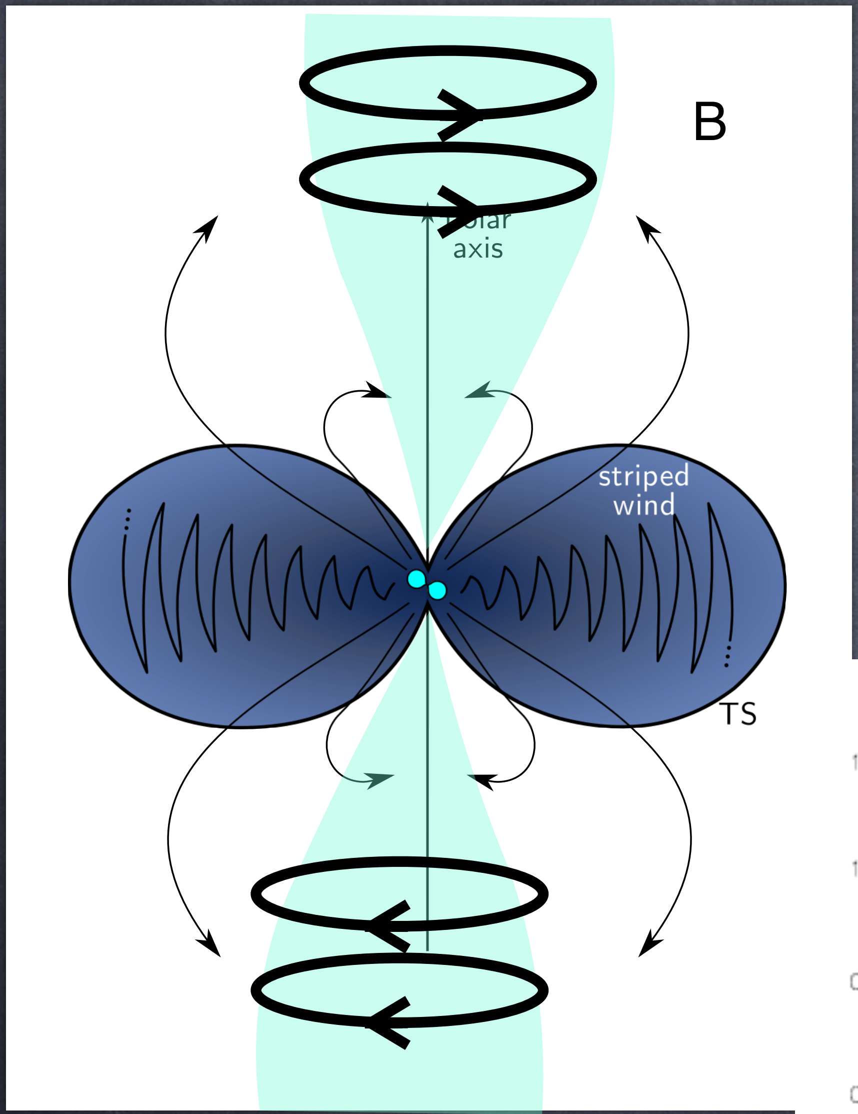
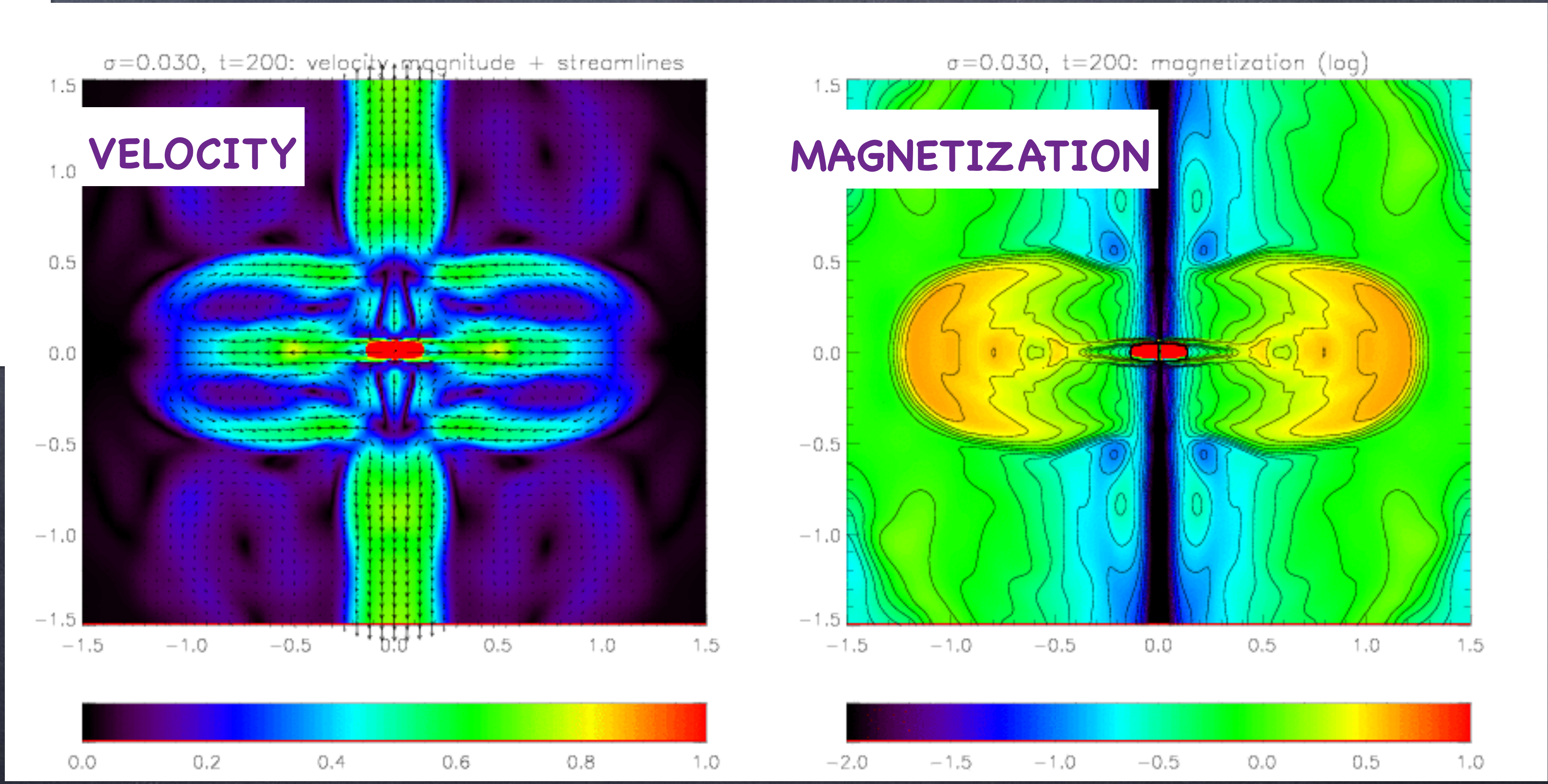


2D MHD NUMERICAL MODELING: JETS



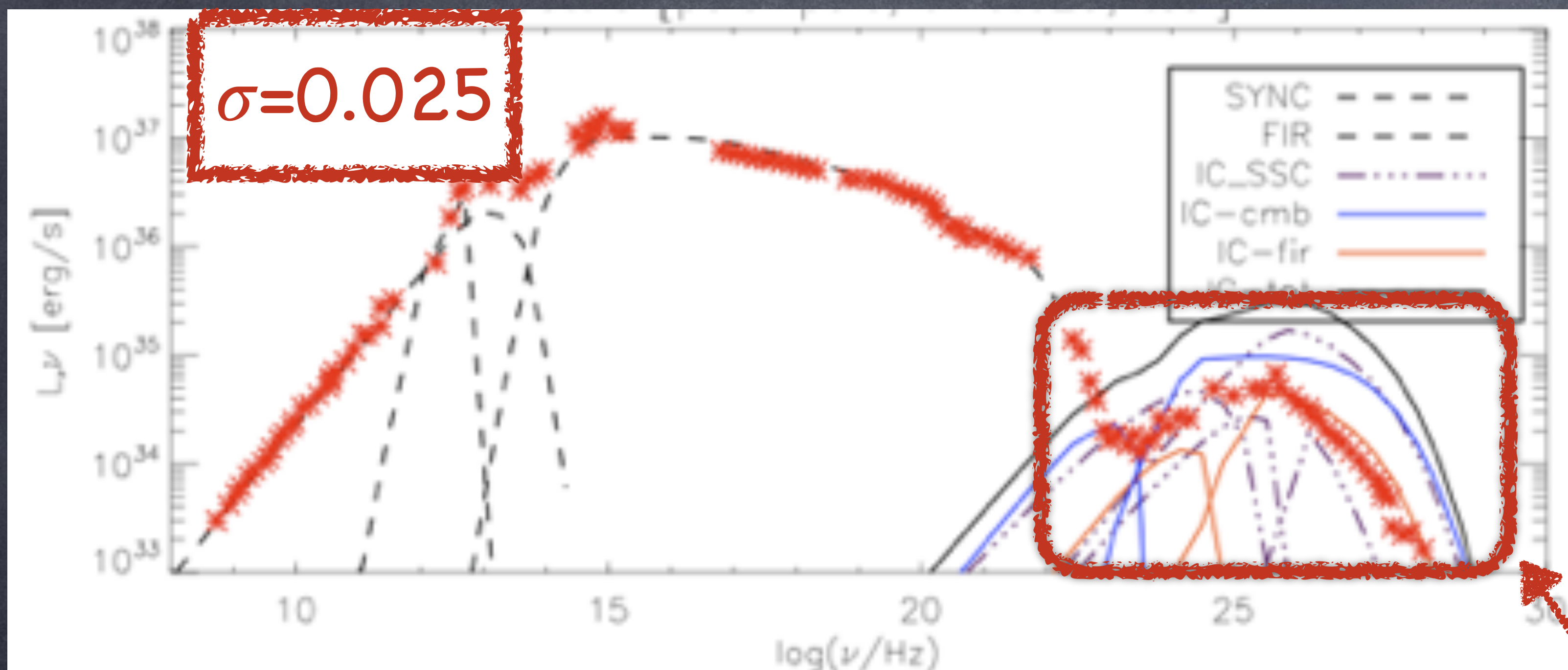
IN 2D JETS REQUIRE σ>0.03

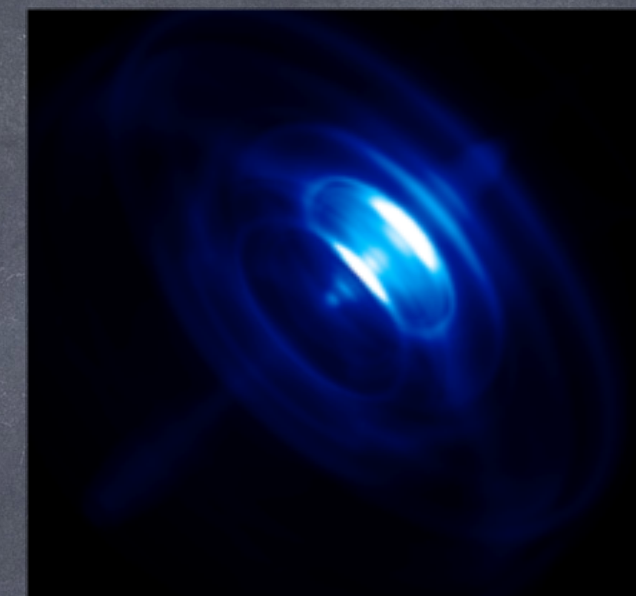


EQUIPARTITION NEEDED FOR JET FORMATION

Del Zanna, EA, Bucciantini 04, 06

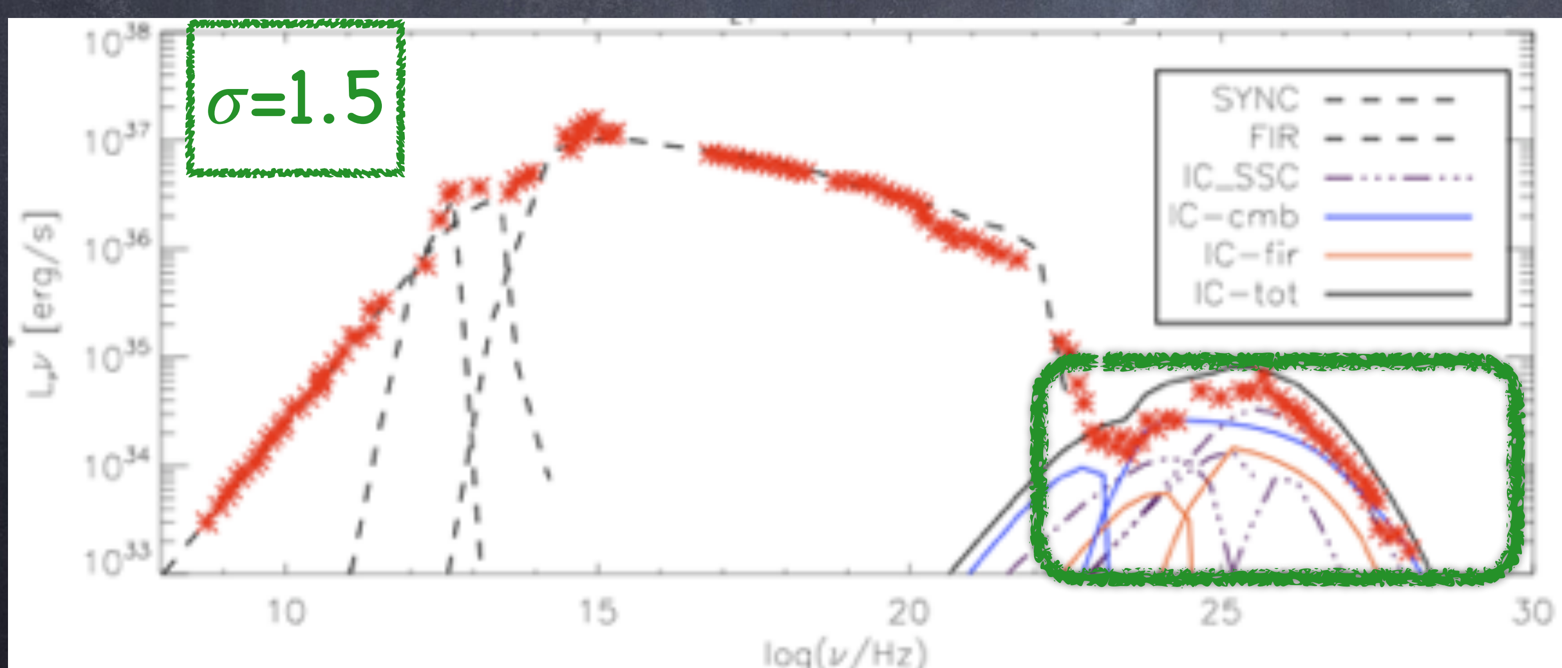
BEHIND PRETTY PICTURES

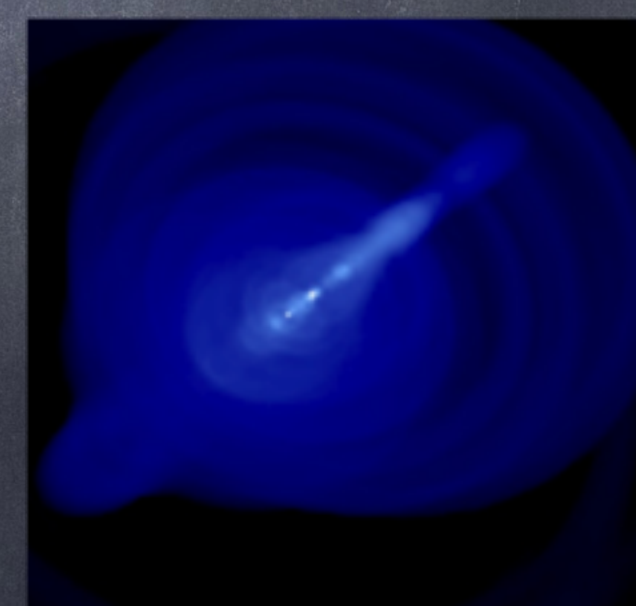




$B_{sim} \approx 10^{-5}\ G$

Volpi+ 08, Olmi+14



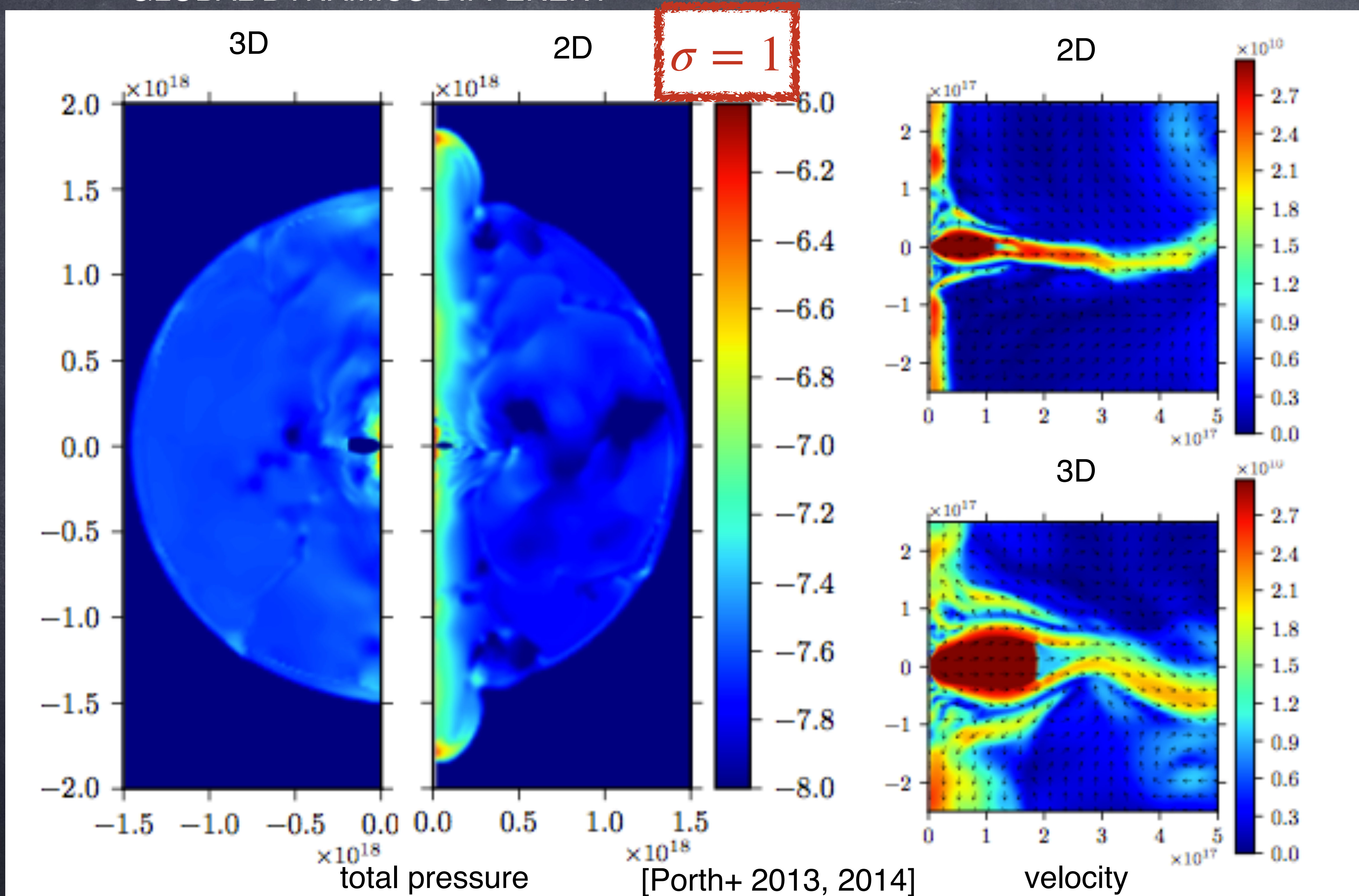


$B_{obs} \approx 10^{-4}\ G$

3D RMHD SIMULATIONS

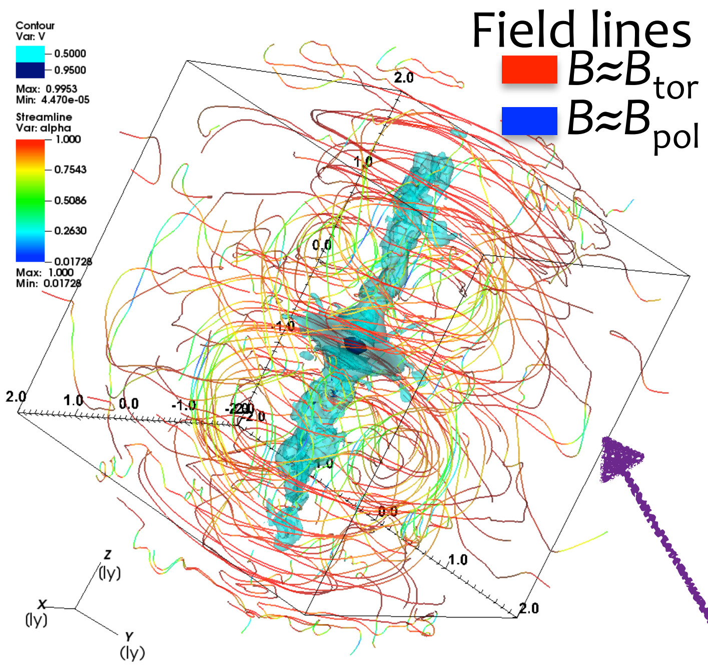
GLOBAL DYNAMICS DIFFERENT

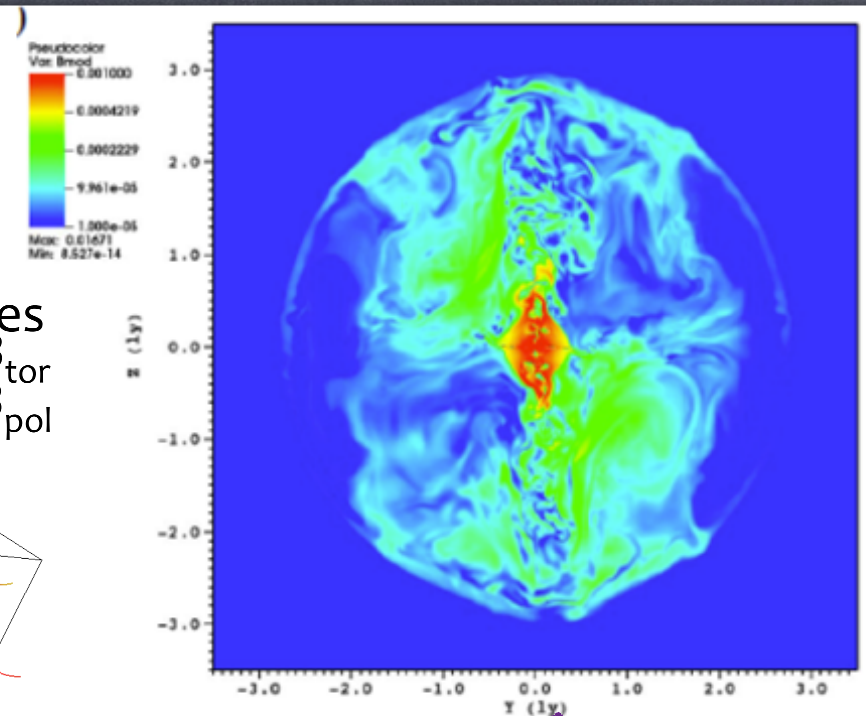
INNER DYNAMICS SIMILAR



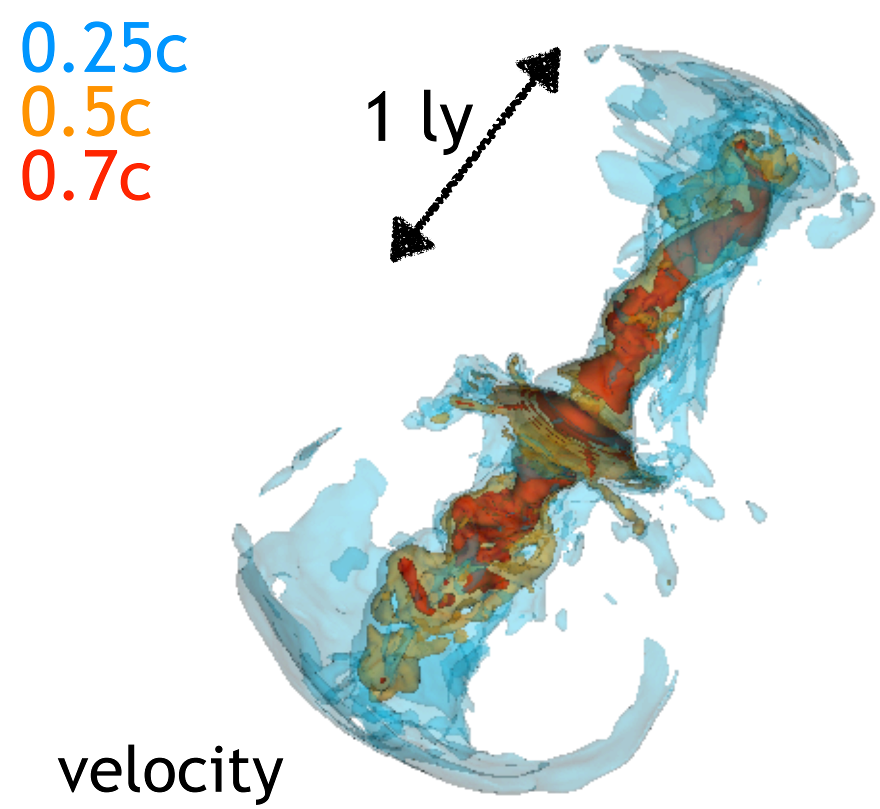
EARLY SUGGESTION (Begelman 98): KINKS REDUCE HOOP STRESS WITH LITTLE DISSIPATION

LONGER 3D RMHD SIMULATIONS

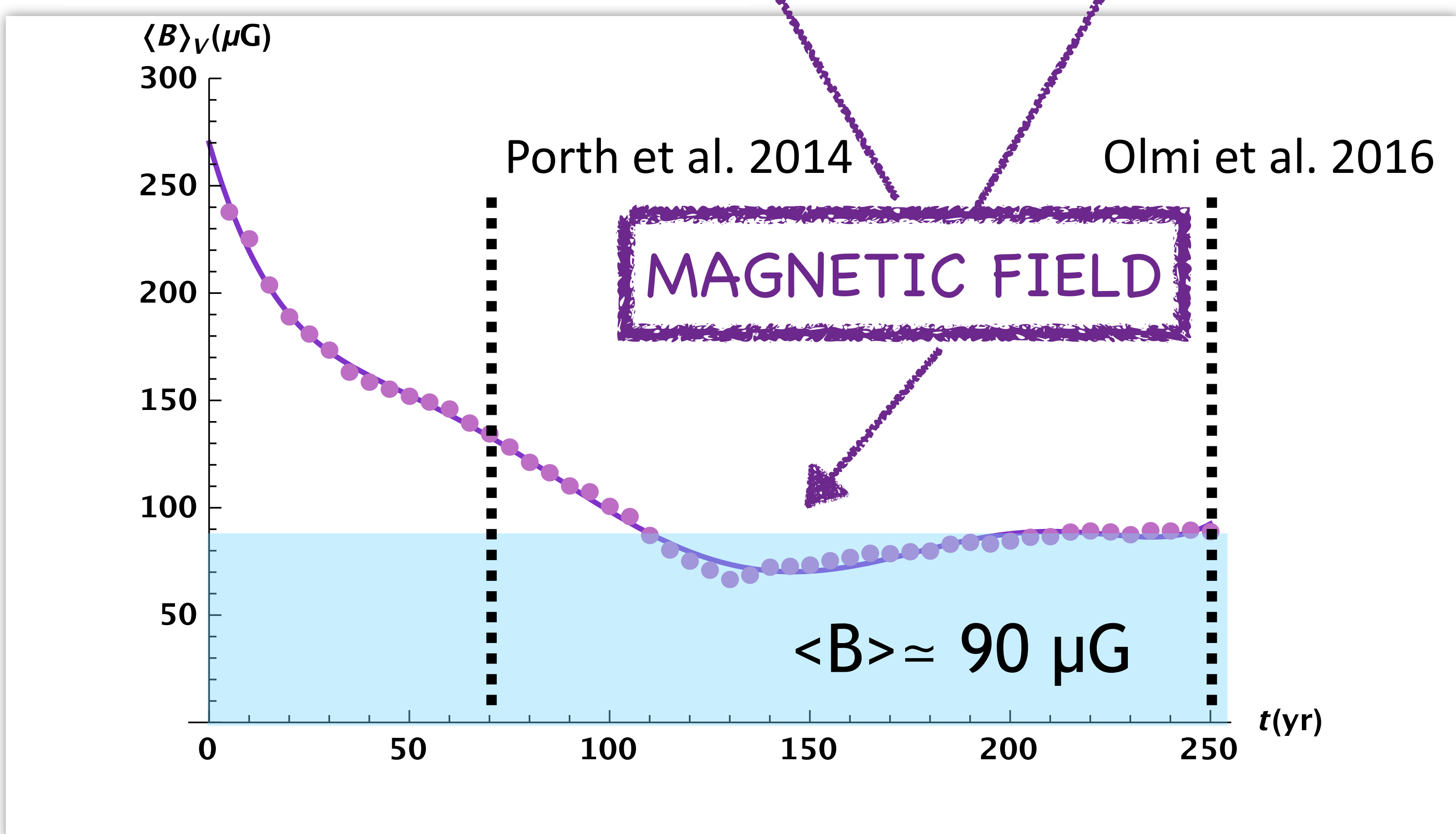




SELF SIMILAR PHASE FULLY REACHED



MAGNETIC FIELD



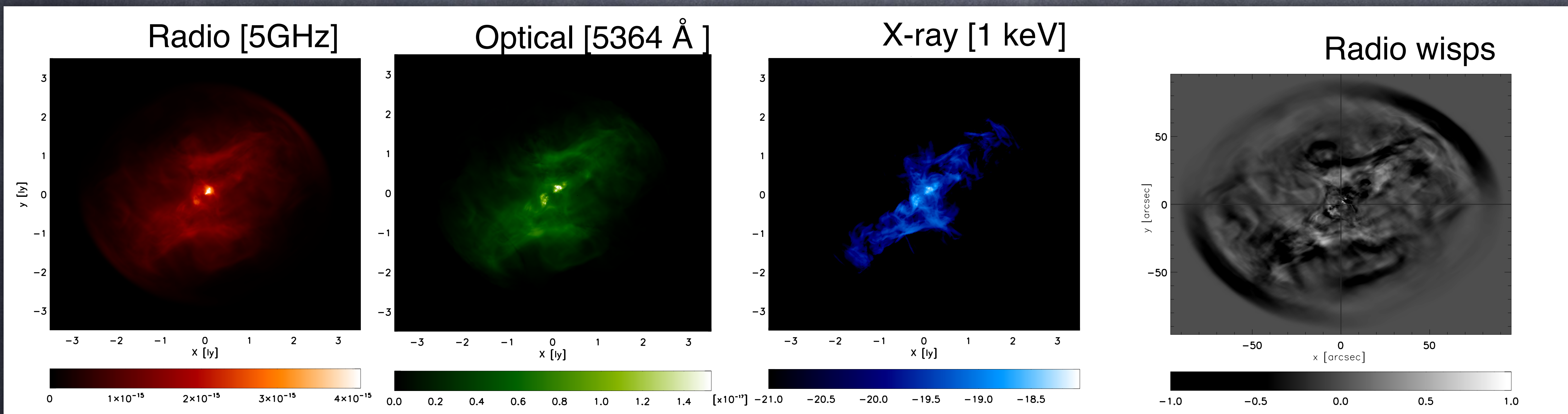
$\boxed{\sigma = 1.5}$

ALL IS SOLVED?

✓ SHRINKAGE AND WISPS VARIABILITY OK

- NO BRIGHT X-RAY TORUS

Olmi+ 16



...NOT YET...

AVERAGE FIELD STILL TOO LOW

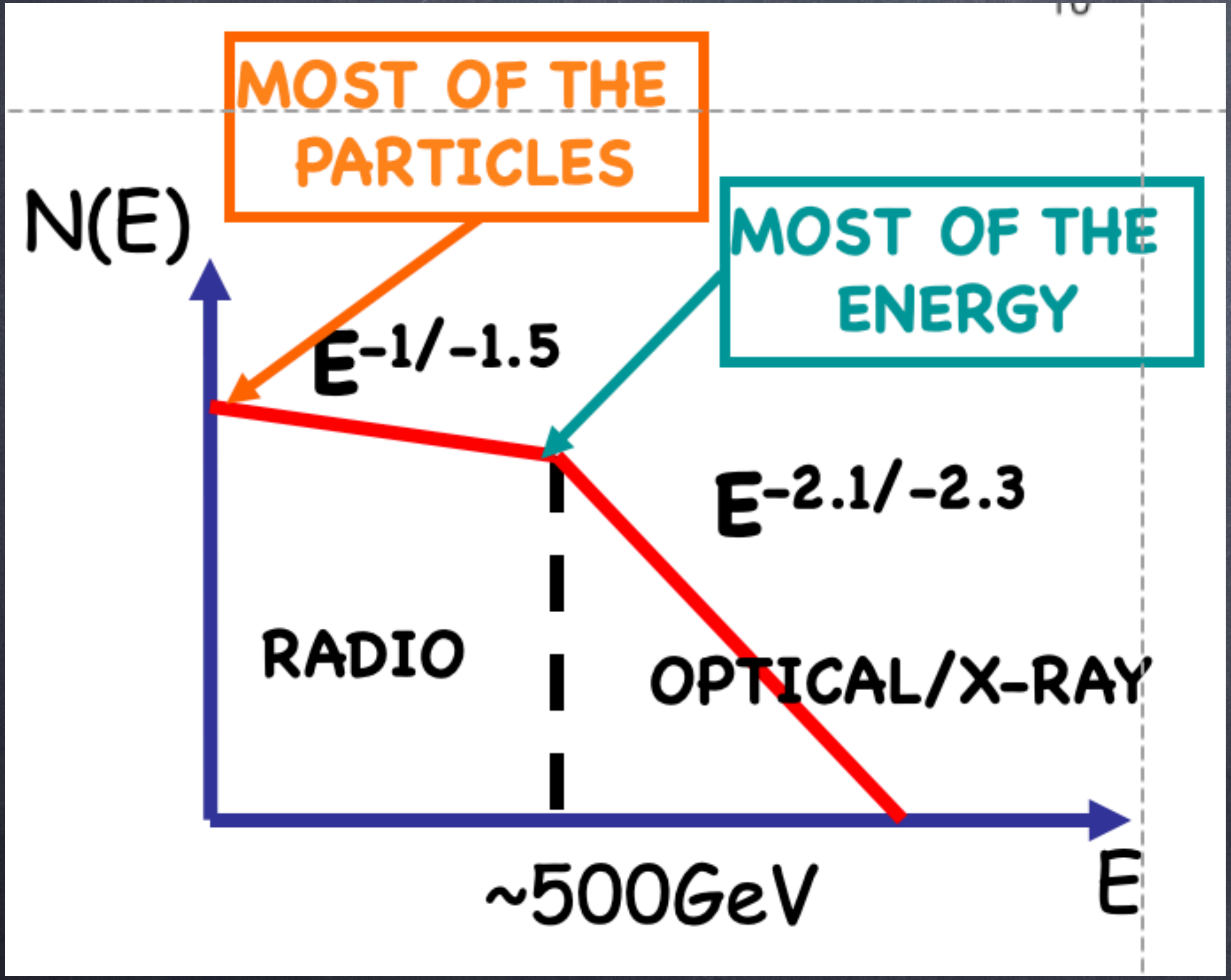
- ARTIFICIAL STEEPENING OF X-RAY PARTICLE SPECTRUM STILL NEEDED
- IC SPECTRUM STILL OVERESTIMATED

EVEN HIGHER σ NEEDED ON AVERAGE

DIFFERENT LOCATIONS OF PARTICLE ACCELERATION?

CONSTRAINING THE PULSAR MULTIPLICITY

κ IS CONSTRAINED BY RADIO EMITTING PARTICLES



RADIO EMITTING PARTICLES HAVE LONG LIFETIMES: DO NOT NEED TO BE PART OF THE FLOW

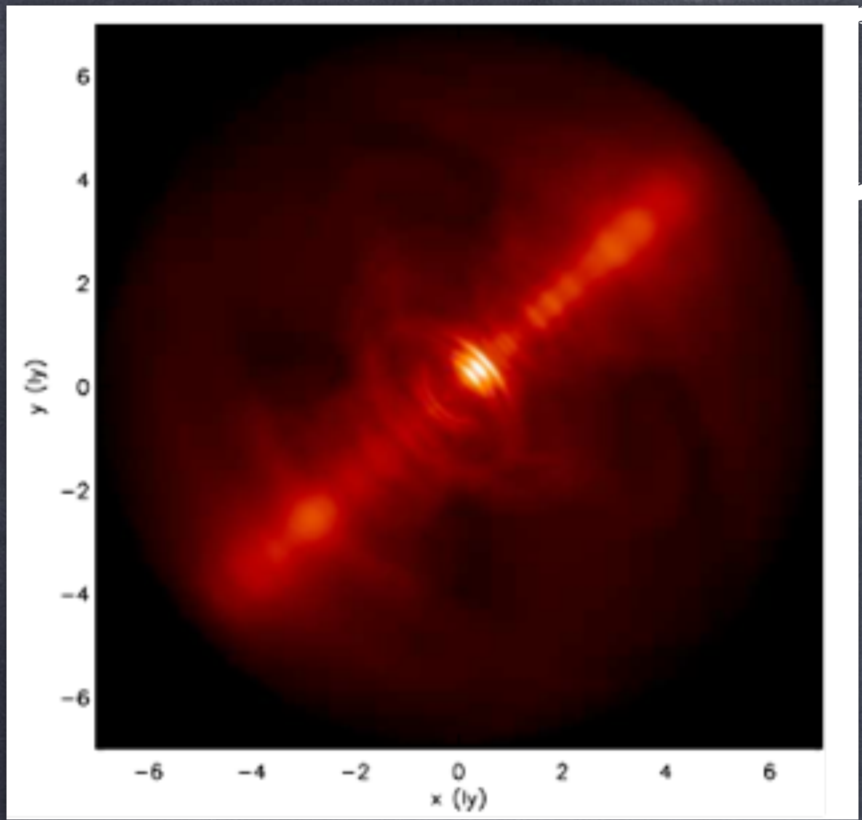
IF PART OF THE FLOW

$\kappa \approx 10^6$ $\Gamma \approx 10^4$

OTHERWISE

$\kappa \approx 10^3\text{–}10^4$ $\Gamma \approx 10^6\text{–}10^7$

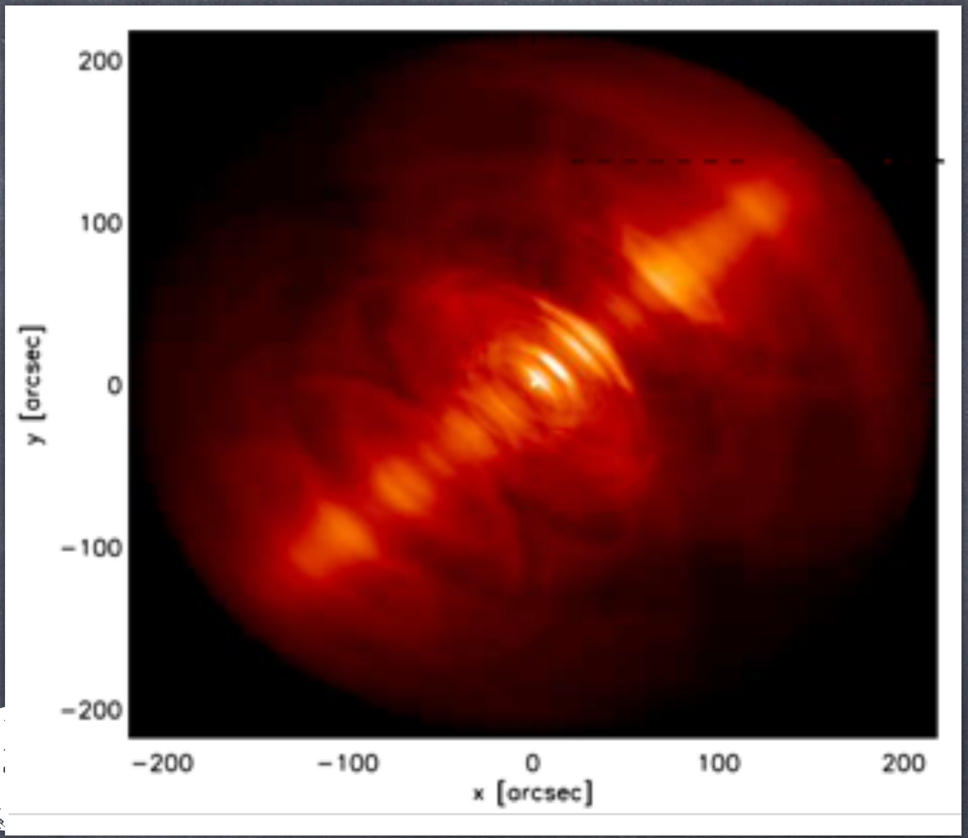
RADIO EMISSION

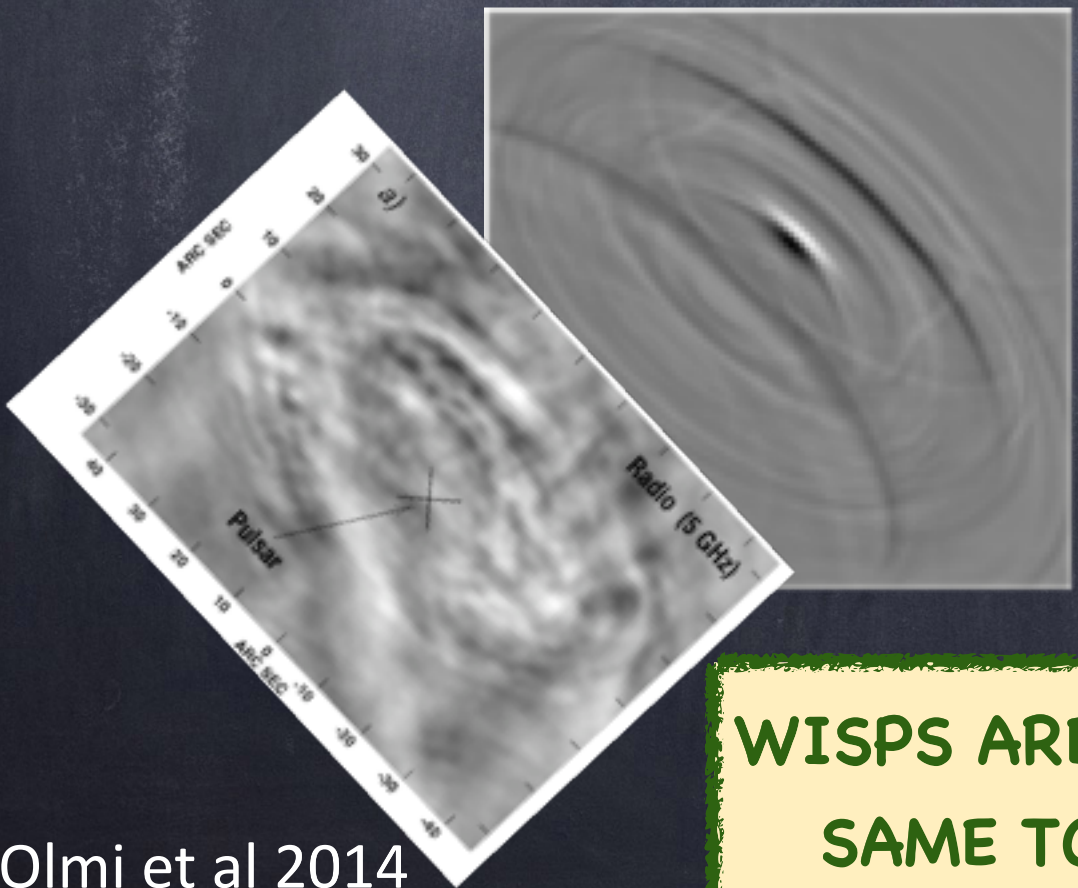


SHOCK ACCELERATION & ADVECTION

EMISSION MAPS CANNOT DISTINGUISH

UNIFORM INJECTION





Olmi et al 2014

WISPS ARE THE SAME TOO

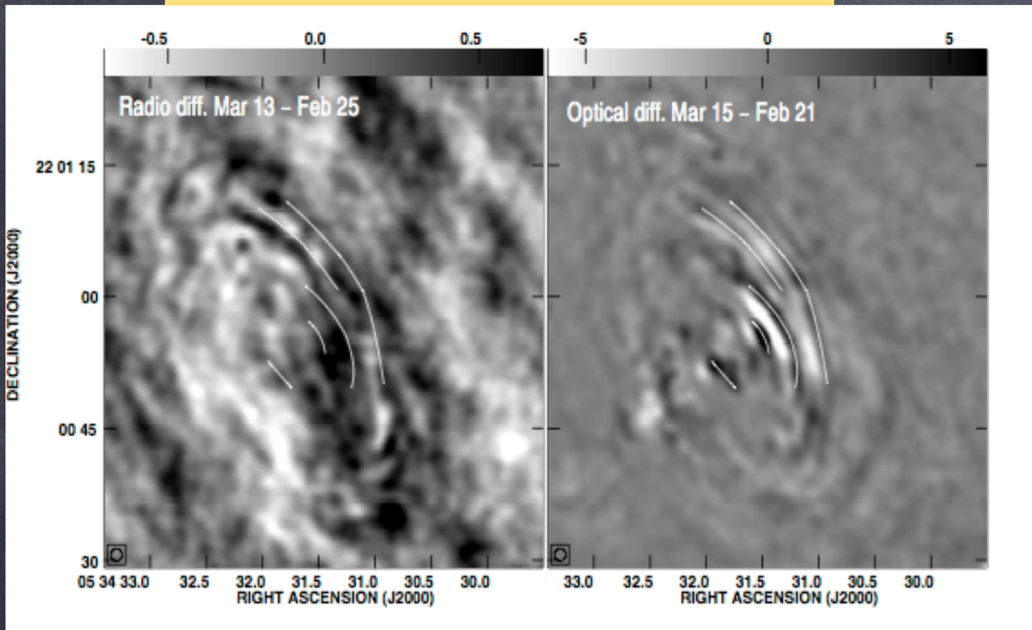
RADIO PARTICLES DO NOT NEED TO BE CURRENTLY ACCELERATED AT THE SHOCK

$\kappa \sim 10^3$–10^4 IS VIABLE

CONSTRAINING THE LOCATIONS OF PARTICLE ACCELERATION

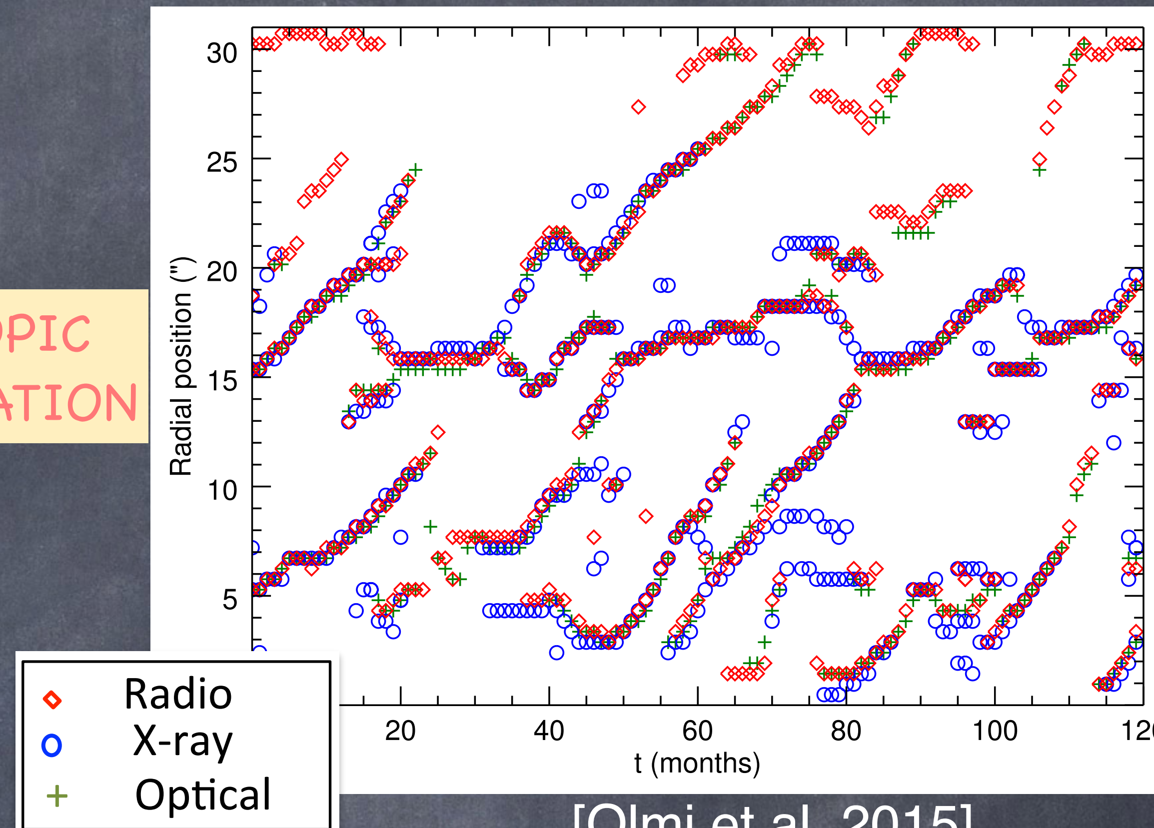
HINTS ON LOCATIONS OF PARTICLE ACCELERATION

RADIO VS OPTICAL WISPS



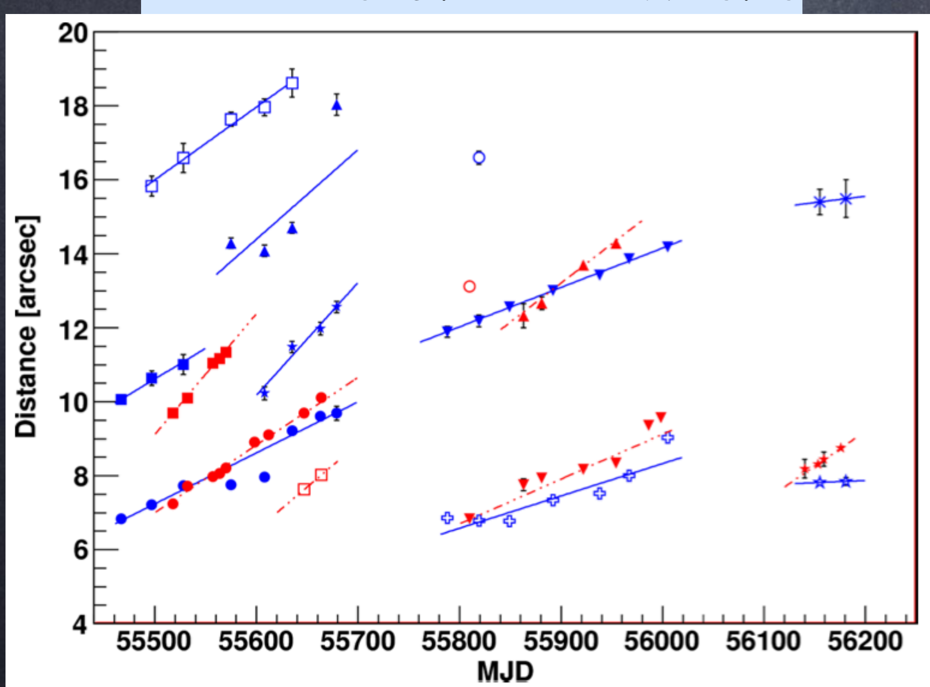
[Bietenholtz et al. 2004]

ISOTROPIC ACCELERATION

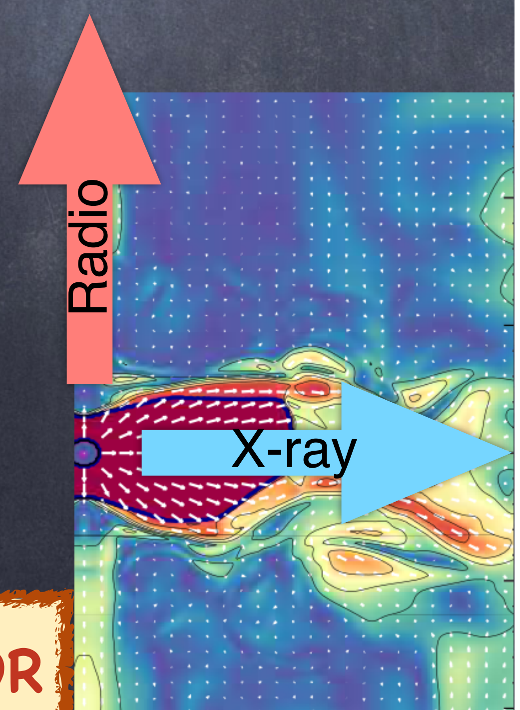


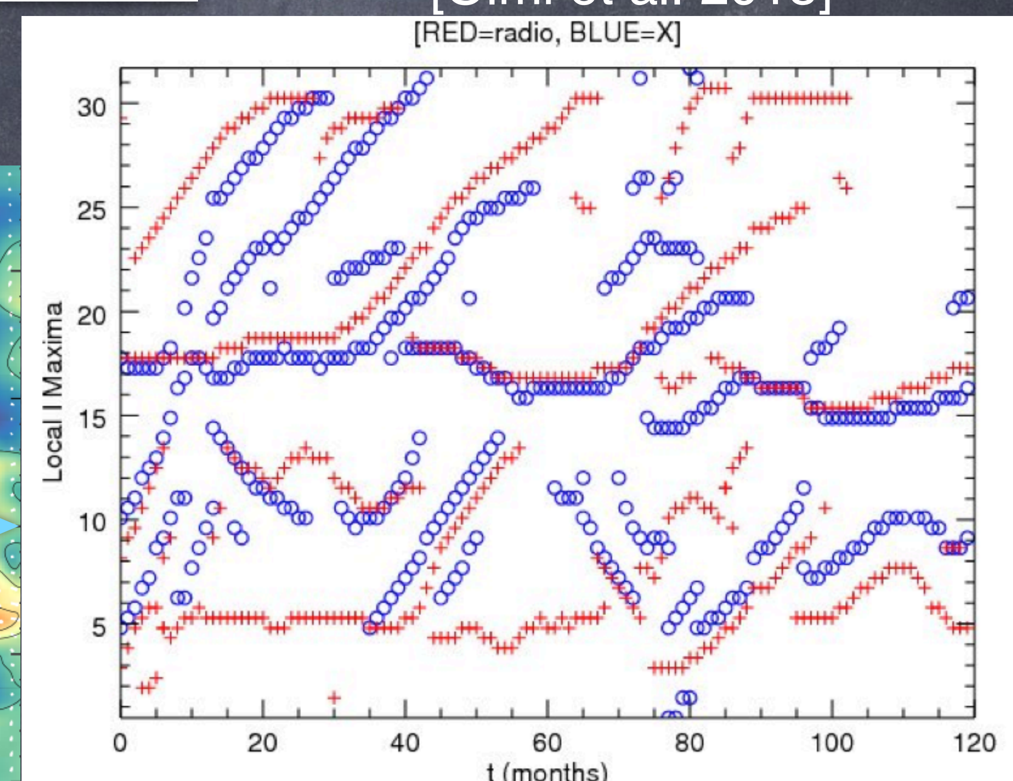
[Olmi et al. 2015]

X-RAY VS OPTICAL WISPS



[Schweizer et al. 2013]





X-RAY EMITTERS FROM EQUATOR

LOWER ENERGY ANYWHERE

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?

PWNe AS PEVATRONS

MAXIMUM ENERGY IN A PWN

IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LOSS LIMITED

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

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

STRICT LIMIT FROM THE PSR POTENTIAL DROP $\Phi_{PSR} = \sqrt{\dot{E}/c}$

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

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

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

LEPTONIC OR HADRONIC PEVATRONS?

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)

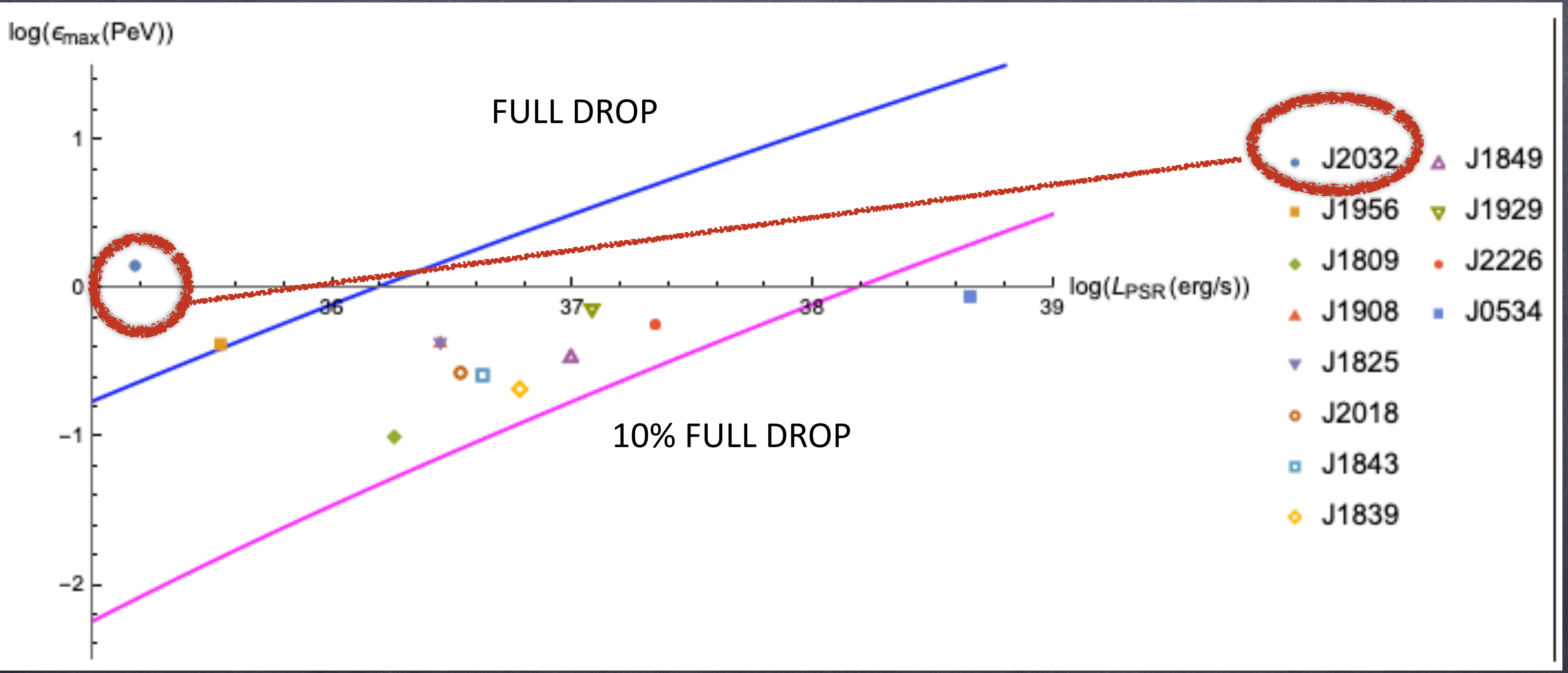
Cao+ 2021

PeV PROTONS OR ELECTRONS?

ALL SOURCES HAVE A PSR IN THE FIELD BUT….

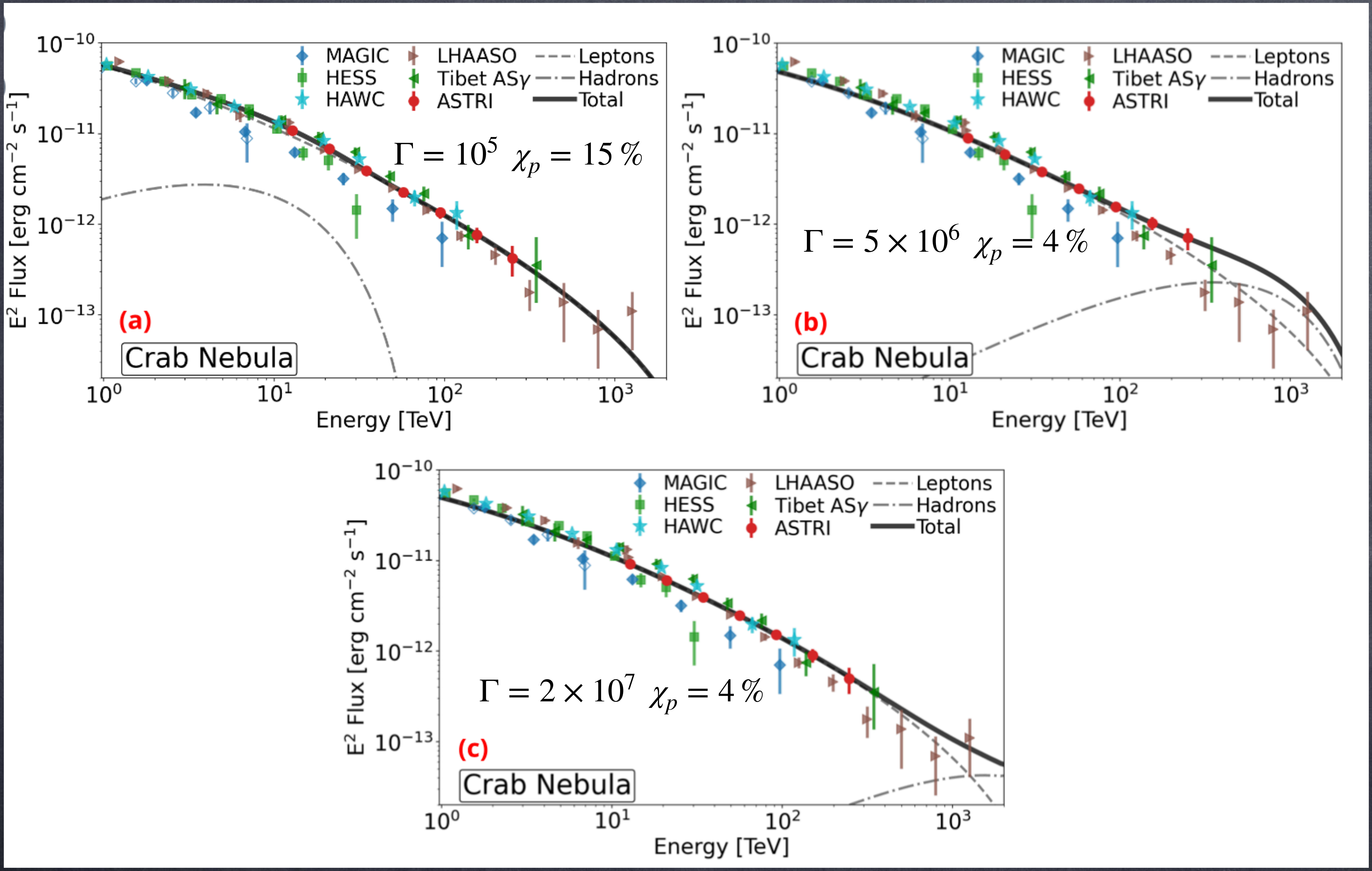
LHAASO PEVATRONS AND PWNe

MAXIMUM ELECTRON ENERGY AS A FUNCTION OF PSR POTENTIAL DROP AND LHAASO SOURCES



[Lopez-Coto+ in prep]

HADRONS IN CRAB?

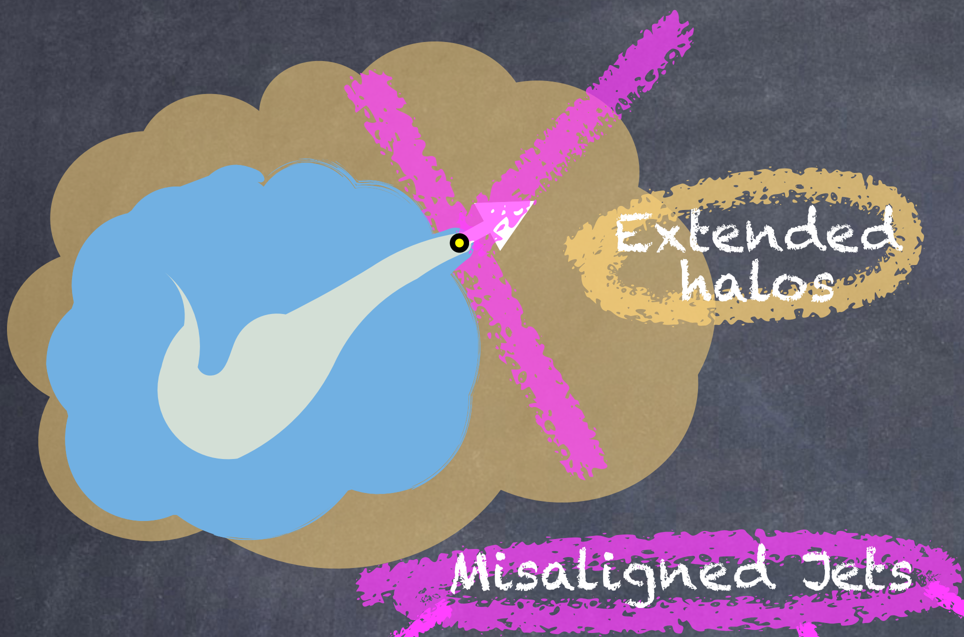


Fiori, EA + in prep.

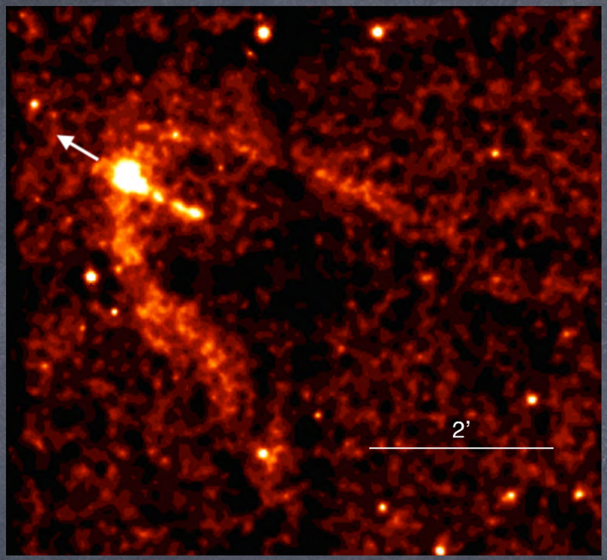
$$Q_p(E) \propto \delta(E - m_p c^2 \Gamma)$$ (EA & Arons 06; EA, Guetta, Blasi 03)

EVOLVED SYSTEMS AND PARTICLE ESCAPE

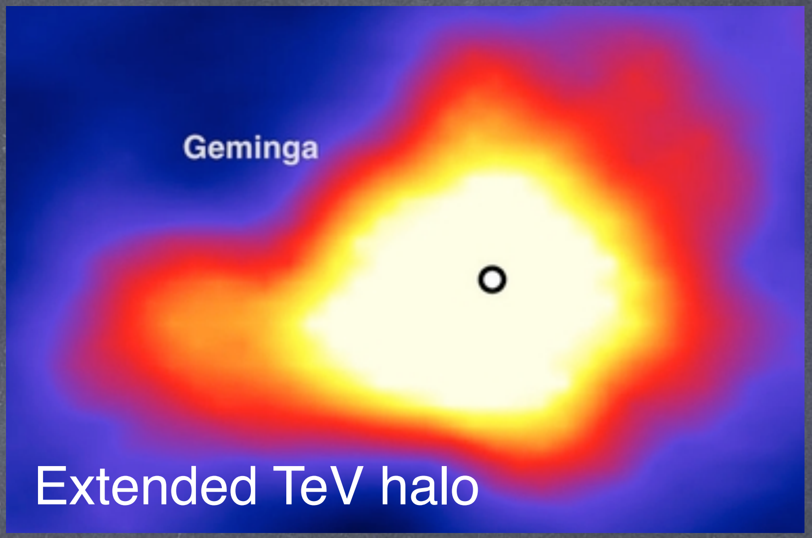
OBSERVATIONS: JETS AND HALOES



X-ray

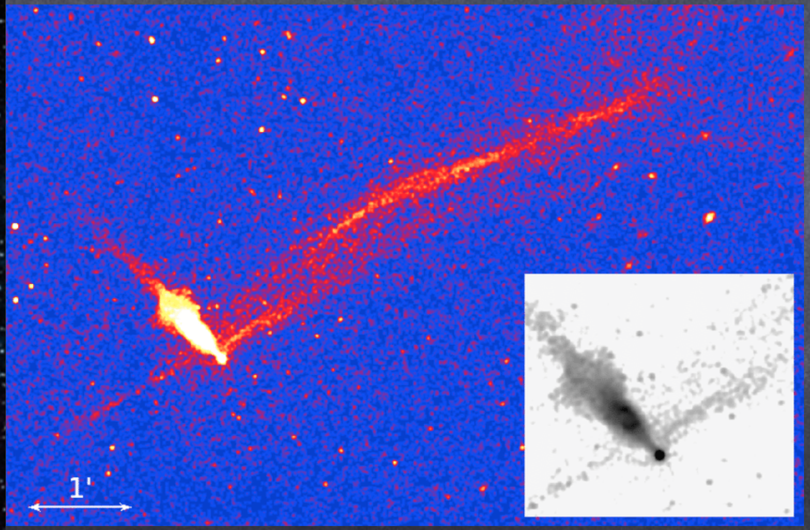


Geminga
[Posselt+ 2017]

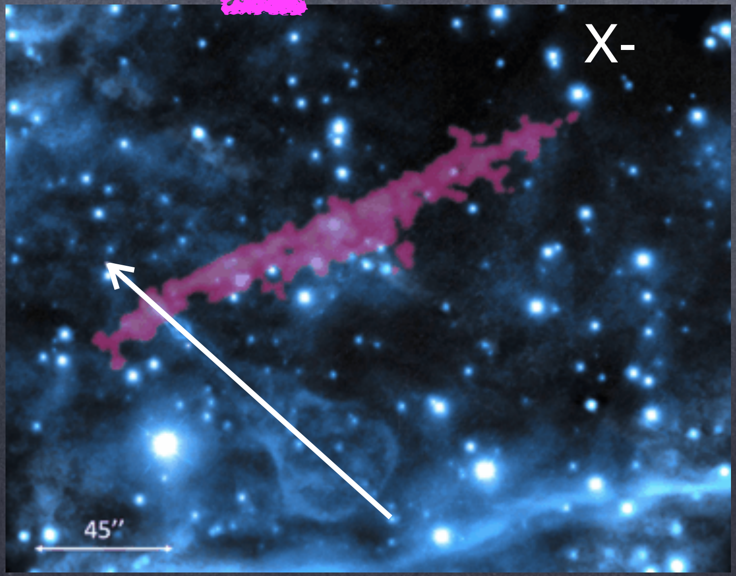


[Abeysekara+ 2017]

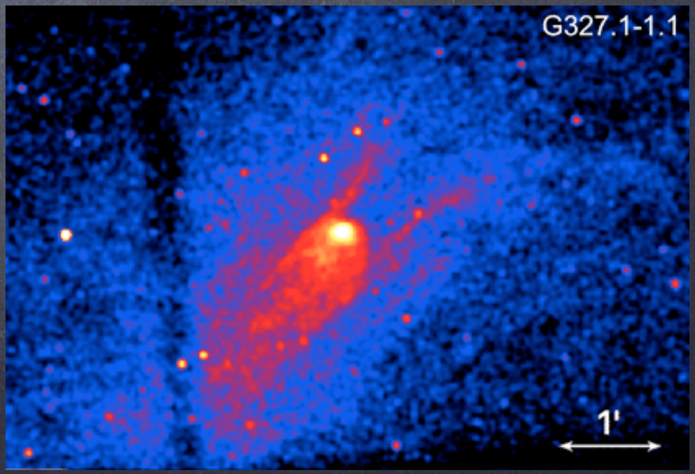
PSR J1509-5850
[Klinger+ 2016]



Lighthouse nebula
[Pavan+ 2016]

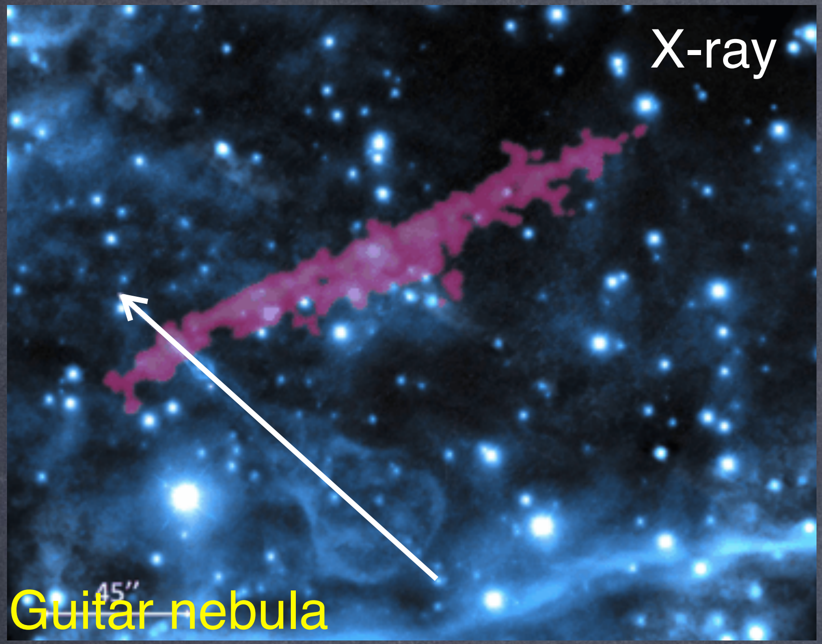


Guitar nebula
[Cordes+ 1993, Wong+ 2003]

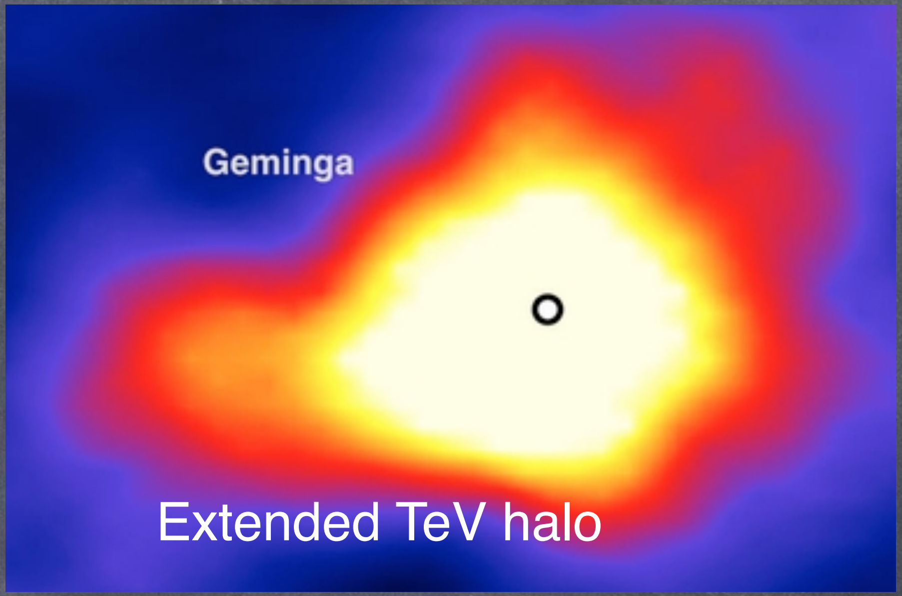


G327
[Temim+ 2009]

INTERPRETATION: JETS AND HALOES



[Cordes+ 1993, Wong+ 2003]

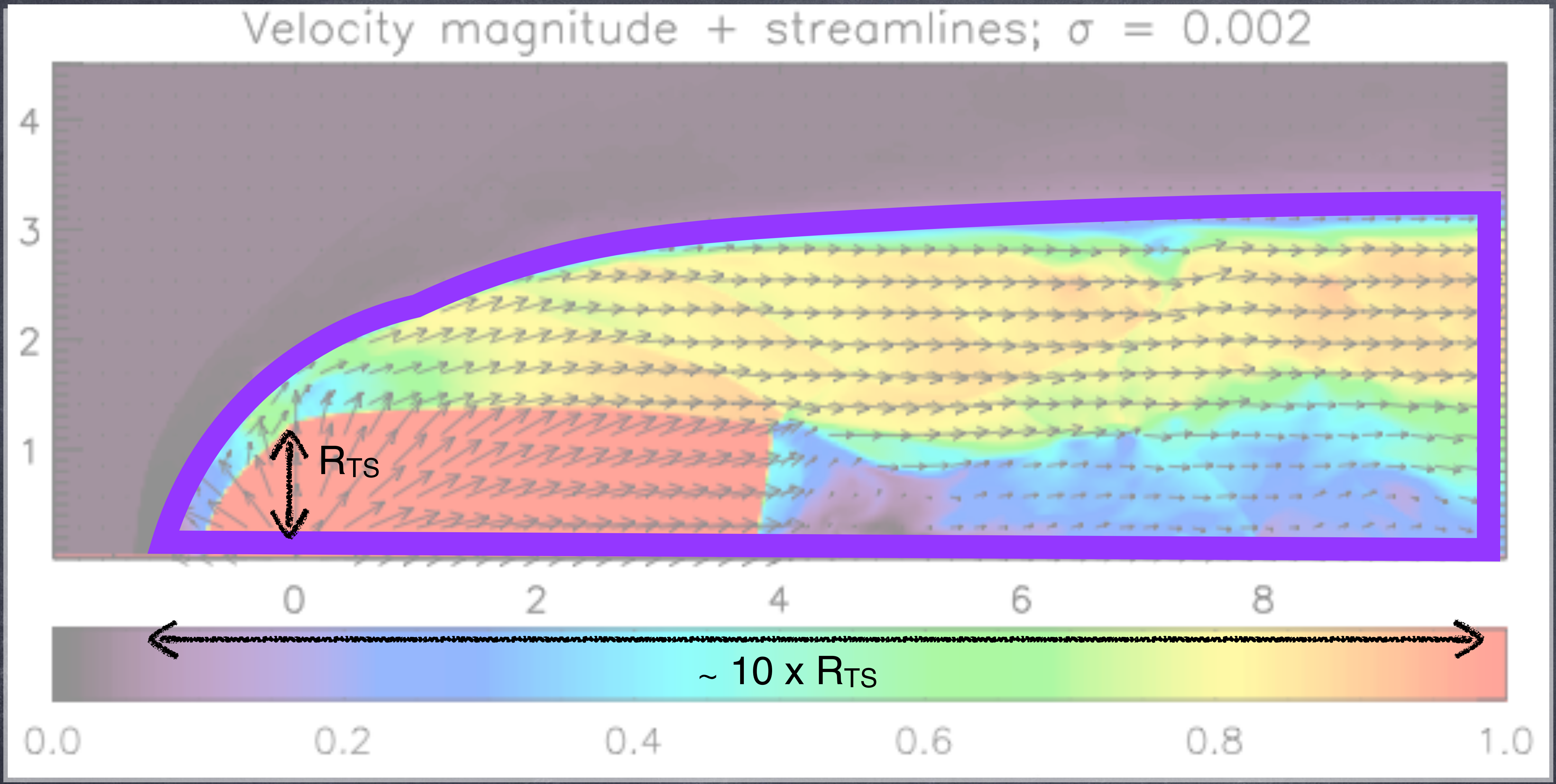


[Abeysekara+ 2017]

JETS CONSISTENT WITH
SYNCHROTRON EMISSION
OF PARTICLES WITH $E \approx e\Phi_{\rm PSR}$
IN A FEW X $10\mu G$ MAGNETIC FIELD
[Bandiera 2008]

HALOS CONSISTENT WITH
ICS EMISSION
OF PARTICLES WITH $E \approx e\Phi_{\rm PSR}$
IN A $\approx \mu G$ MAGNETIC FIELD
AND $D \approx 10^{-2} D_{gal}$
[Abeysekara+ 2017, Lopez-Coto & Giacinti 2018, Lopez-Coto + 2021]

2D RMHD MODELS OF BS PWNE



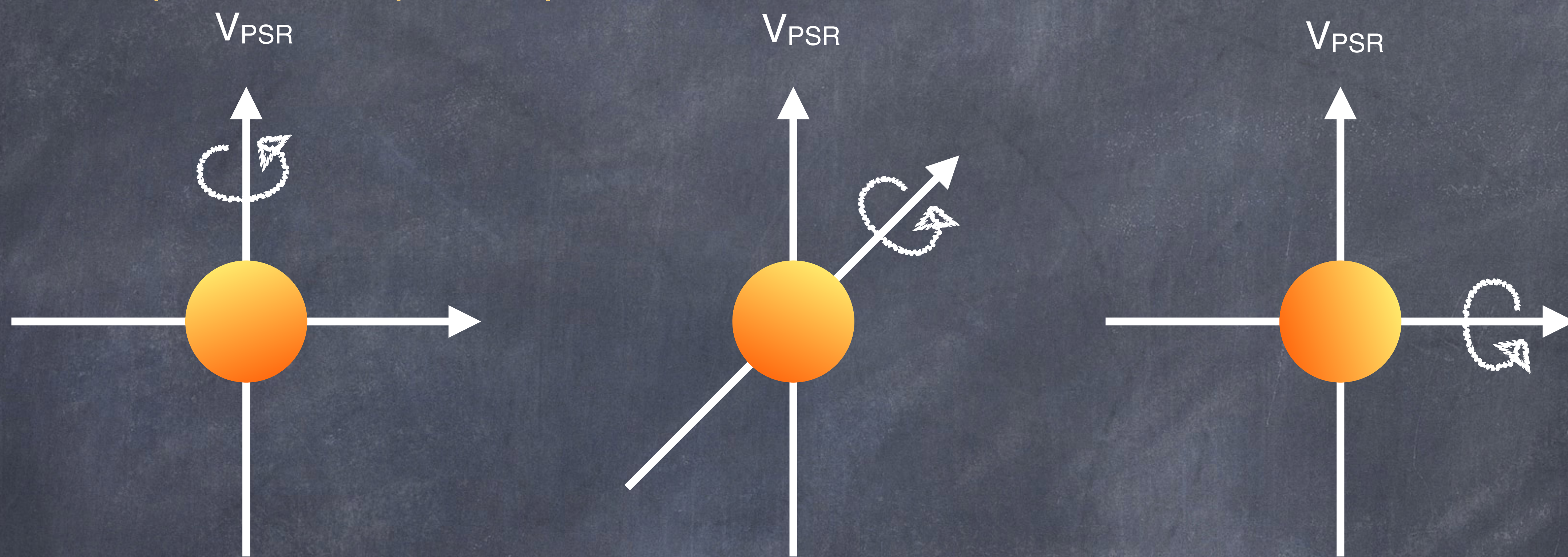
Bucciantini, EA, Del Zanna 2005

FORMATION OF BOW SHOCK, TS DEFORMATION, CYLINDRICAL TAIL WITH MILDLY RELATIVISTIC OUTFLOW IN THE TAIL

3D MHD MODELS OF BSPWNe

PARAMETERS OF THE PULSAR WIND

Inclination of the spin-axis and pulsar speed:



Spin-axis aligned with pulsar motion Φ_M=0°

Φ_M=45°

Φ_M=90°

Anisotropy in the energy flux: $F(\psi) \propto 1 + \alpha \sin^2 \psi$

ψ colatitude from the spin-axis

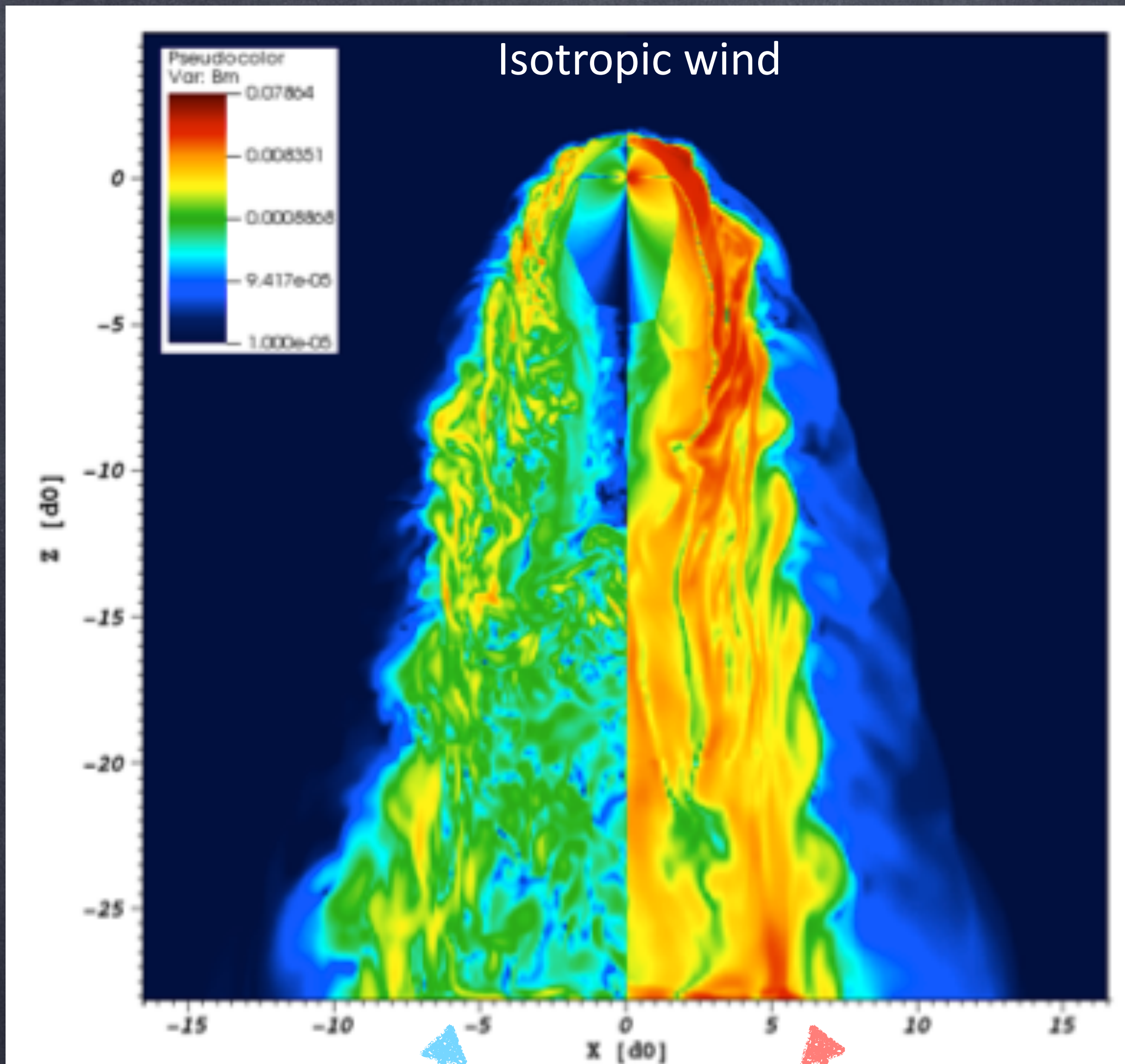
ISOTROPIC case (α=0)

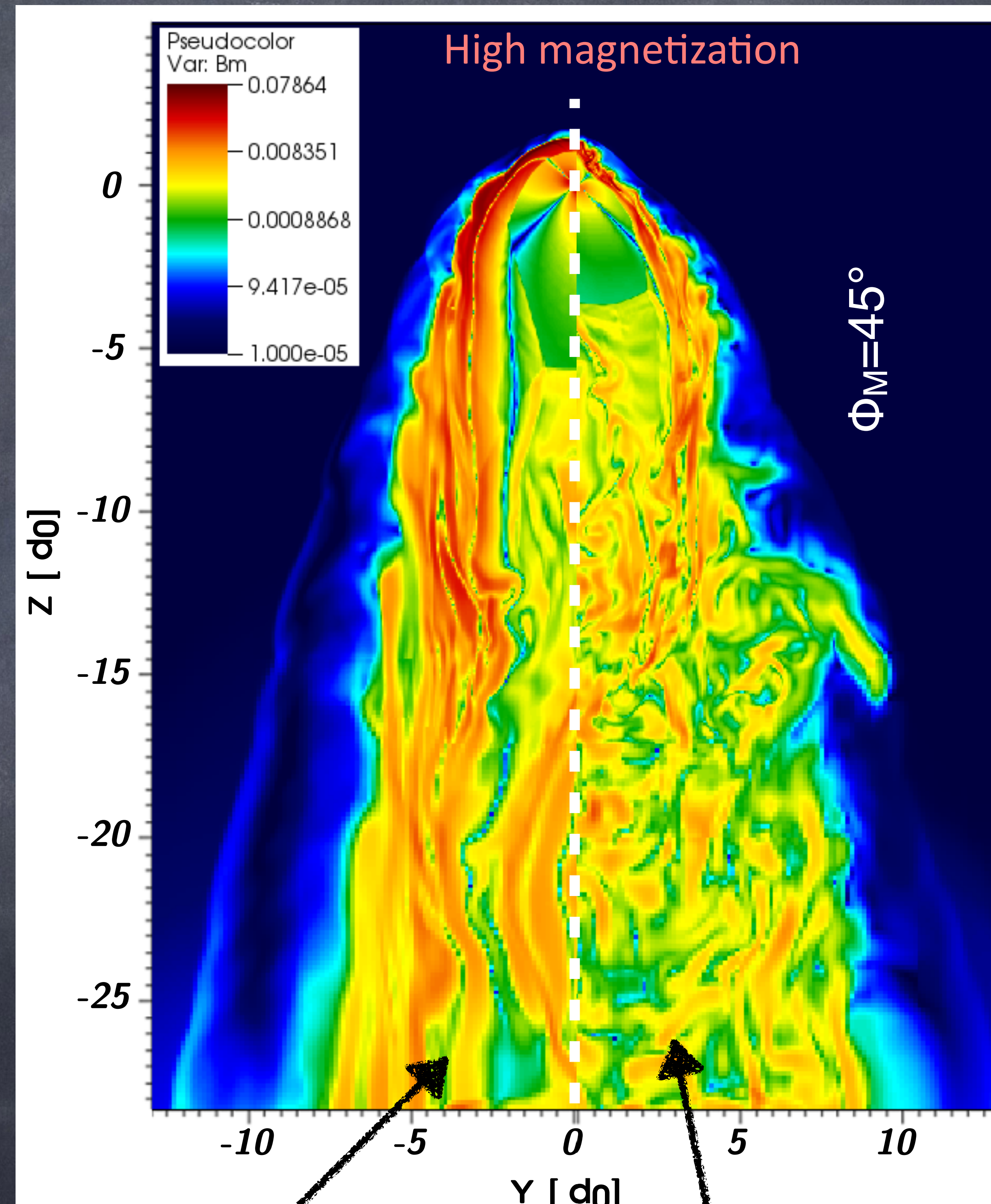
ANISOTROPIC case ($\alpha \neq 0$)

Wind magnetization: $0.01 \lesssim \sigma \lesssim 1$

3D RMHD SIMULATIONS OF BSPWNe

[Olmi & Bucciantini 2019]





Low magnetization

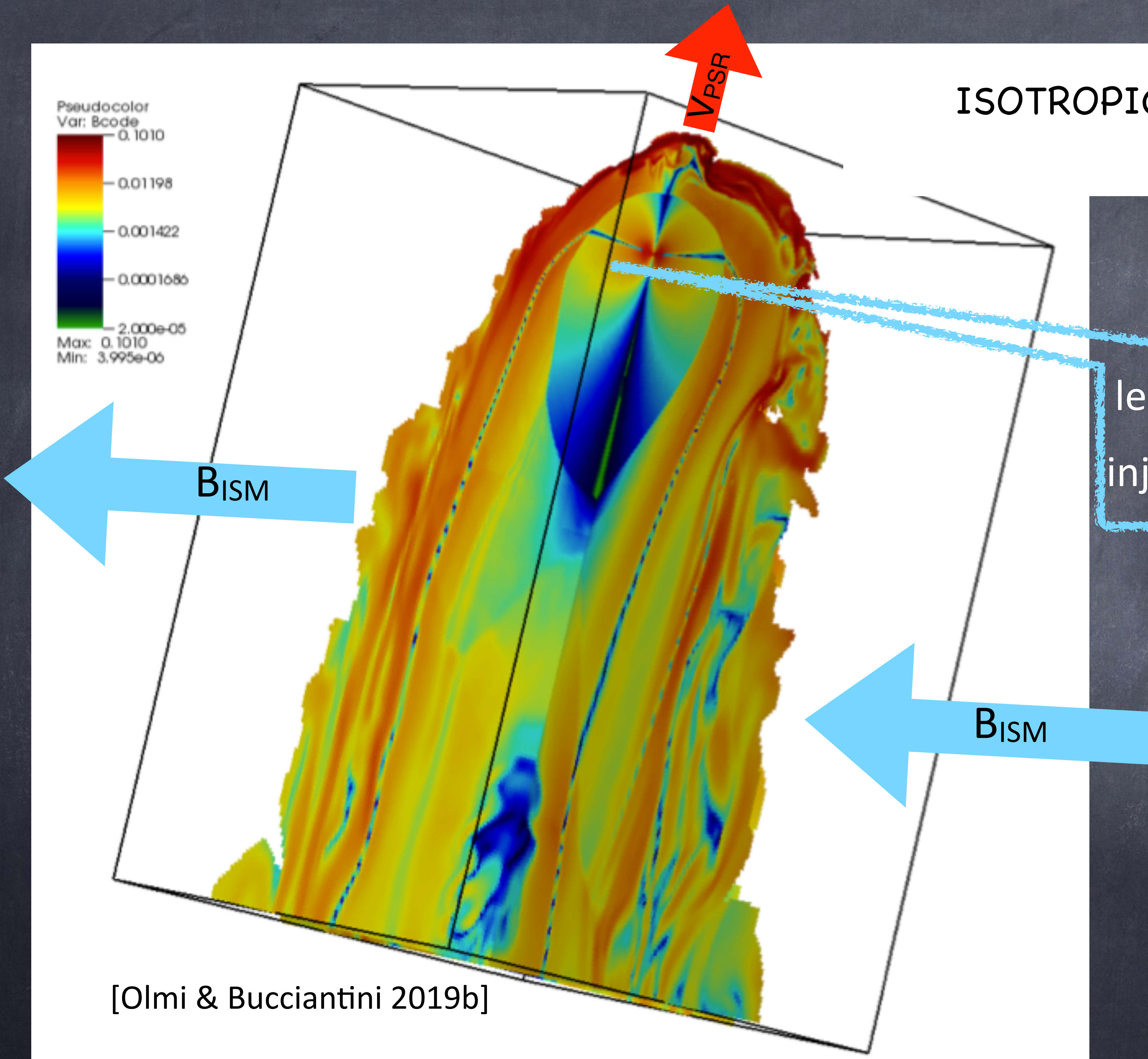
High magnetization

Isotropic wind

Anisotropic wind

PARTICLE ESCAPE FROM BSPWN

ISOTROPIC WIND MODEL
σ=1

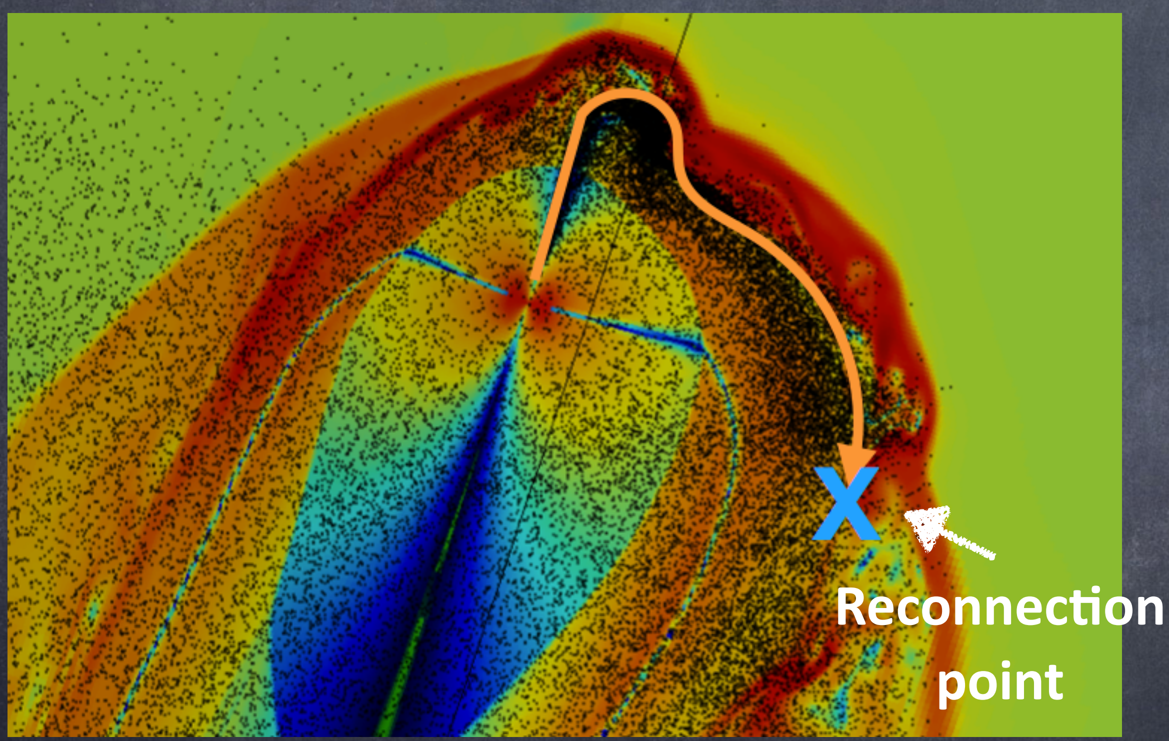


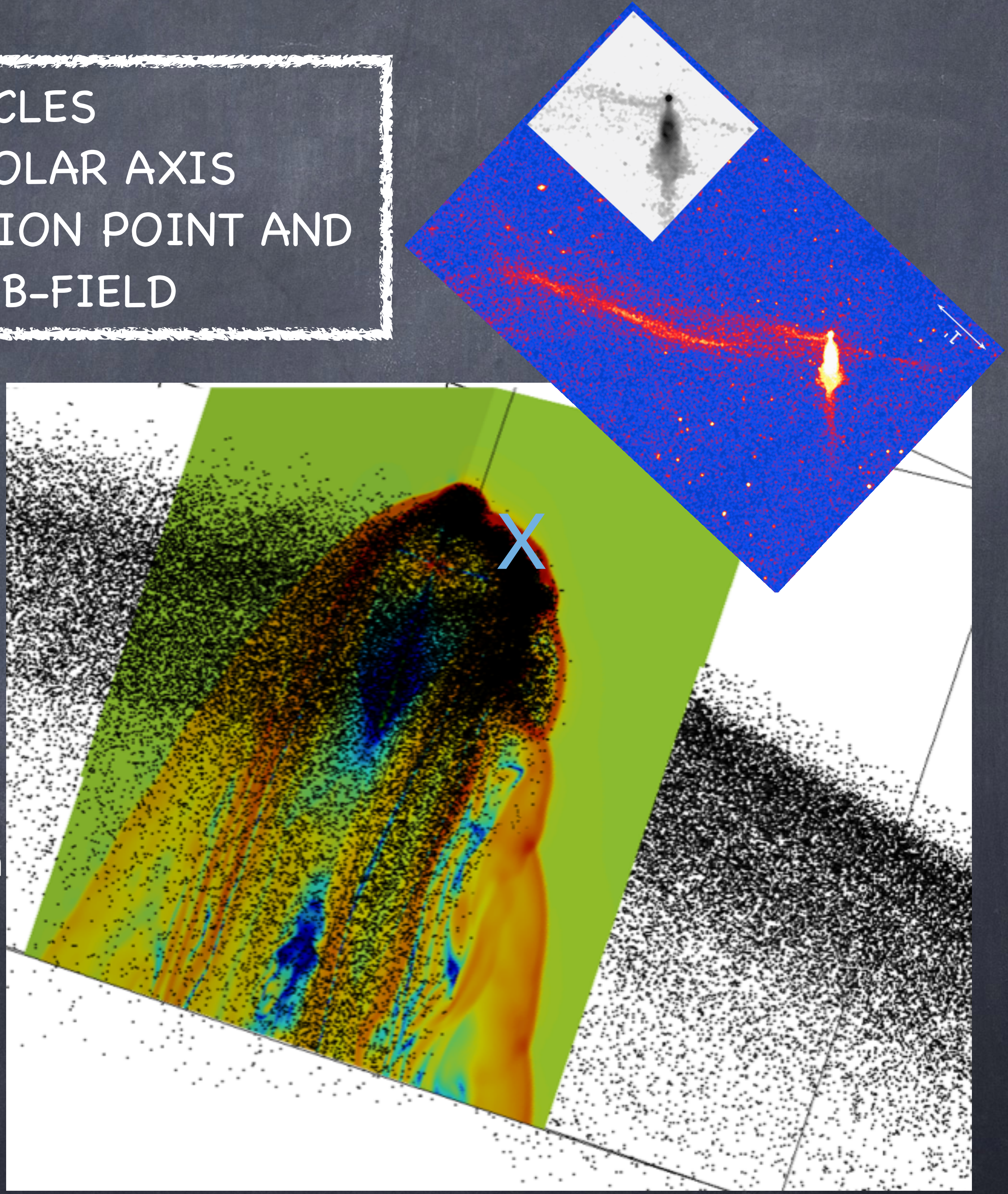
leptons with $\gamma=3\text{x}10^7$ injected into the wind

[Olmi & Bucciantini 2019b]

PARTICLE ESCAPE FROM BOW SHOCK PWNe

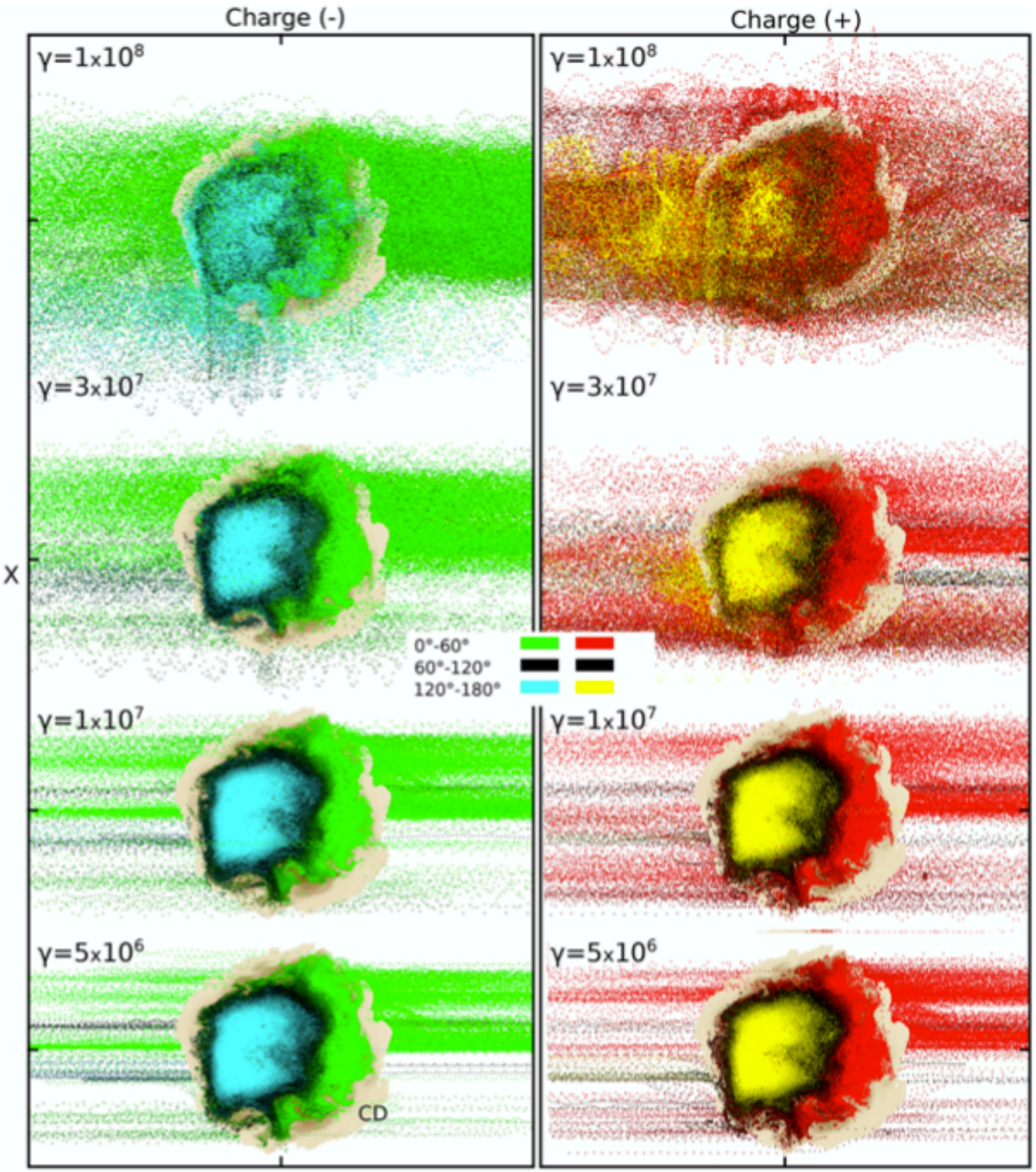
HIGH ENERGY PARTICLES
INJECTED CLOSE TO THE POLAR AXIS
STREAM OUT FROM RECONNECTION POINT AND
FORM JETS IN THE ISM B-FIELD





Olmi & Bucciantini 2019b

ENERGY DEPENDENCE OF THE ESCAPE



[Olmi & Bucciantini 2019b]

WITH INCREASING ENERGY:

- LARGER FRACTION OF PARTICLES
- MORE ISOTROPIC RELEASE

AT GeV ENERGIES:

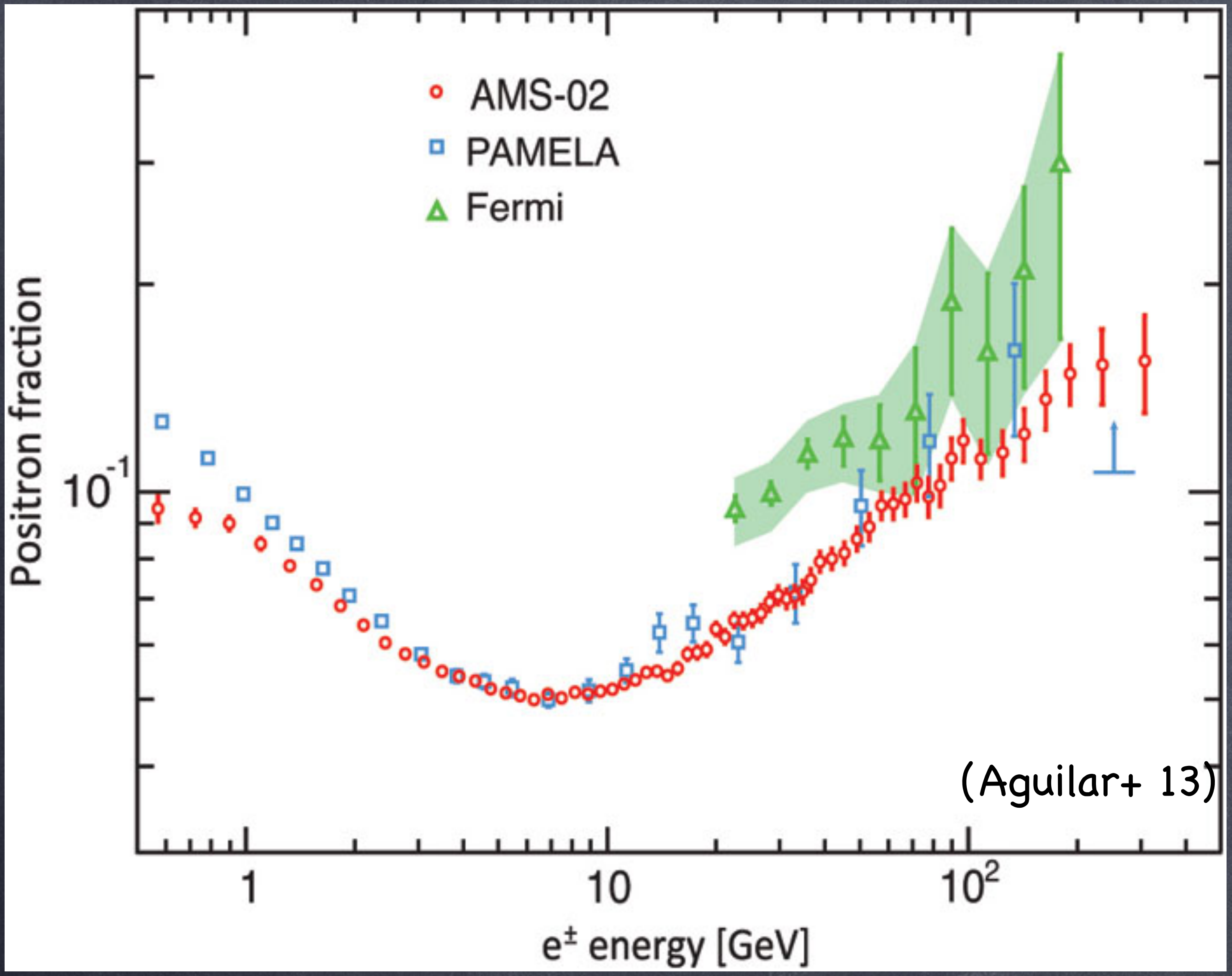
- ESCAPE EXPECTED ONLY FROM THE TAIL

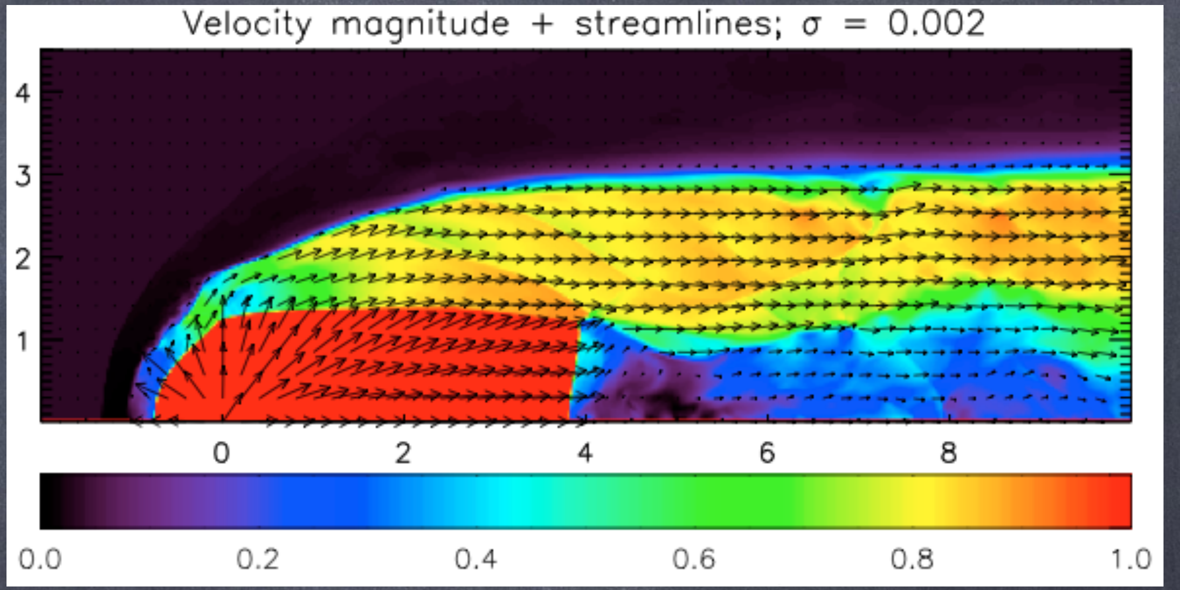
NOTICE THAT:

- ENERGY DEPENDENT ESCAPE PROBABILITY MAKES HALO SPECTRUM NON TRIVIAL
- ESCAPE IS CHARGE SEPARATED!
- IF LOW AMBIENT B BELL INSTABILITY POSSIBLE...

PWNe AS CR SOURCES

THE POSITRON EXCESS

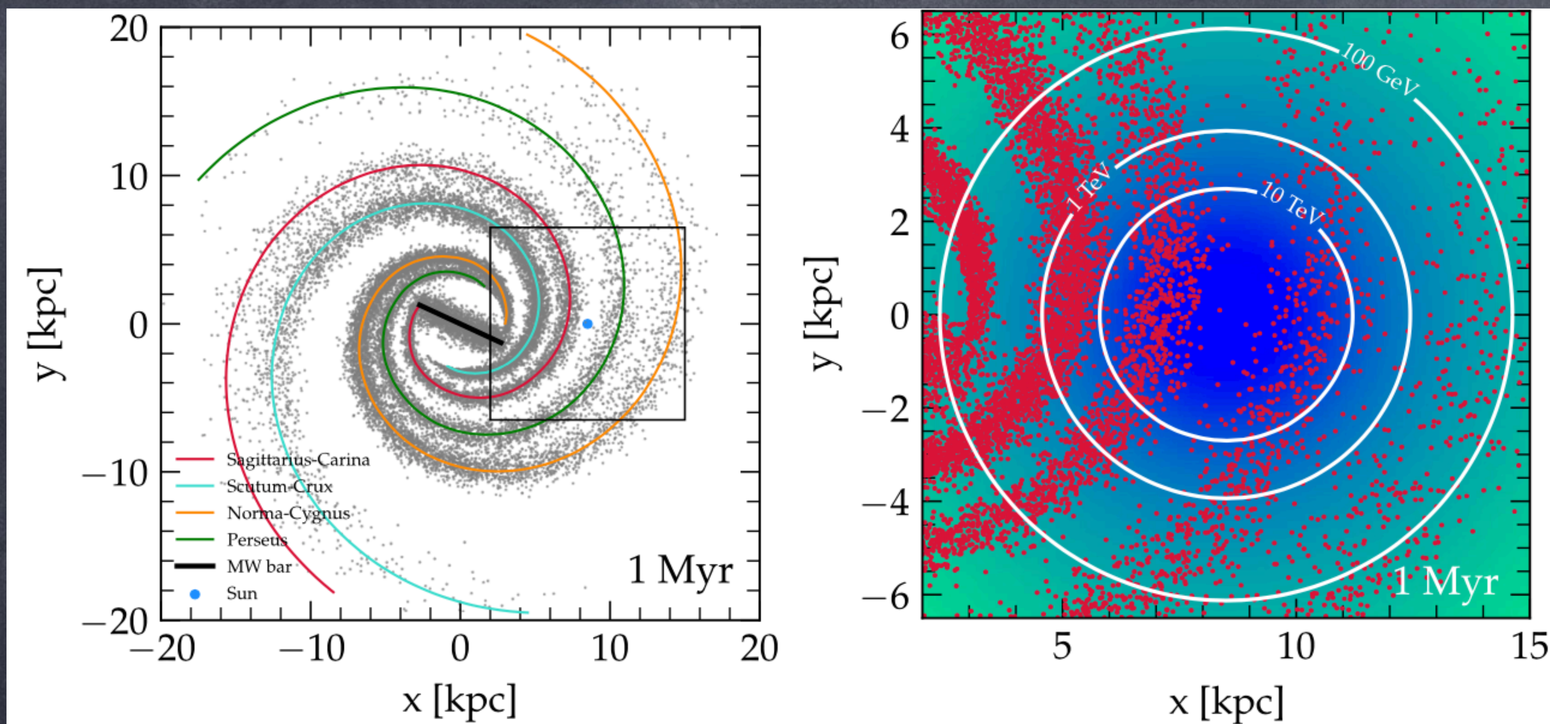




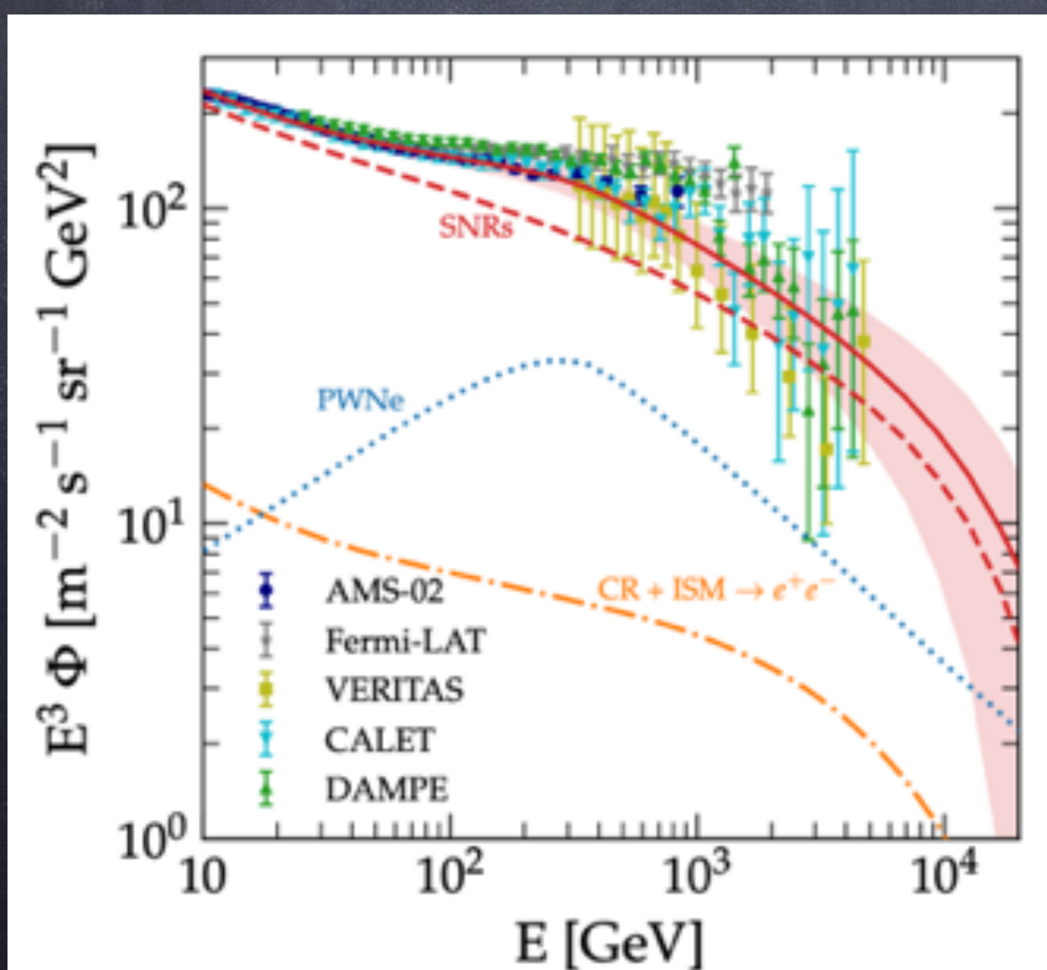
Bucciantini, EA, Del Zanna 2005

- IF POSITRONS ONLY SECONDARY, FRACTION SHOULD DECREASE WITH INCREASING ENERGY
- BOW SHOCK PWNe EARLY SUGGESTED AS BEST CANDIDATES TO EXPLAIN THE EXCESS [e.g. Blasi & EA 11]

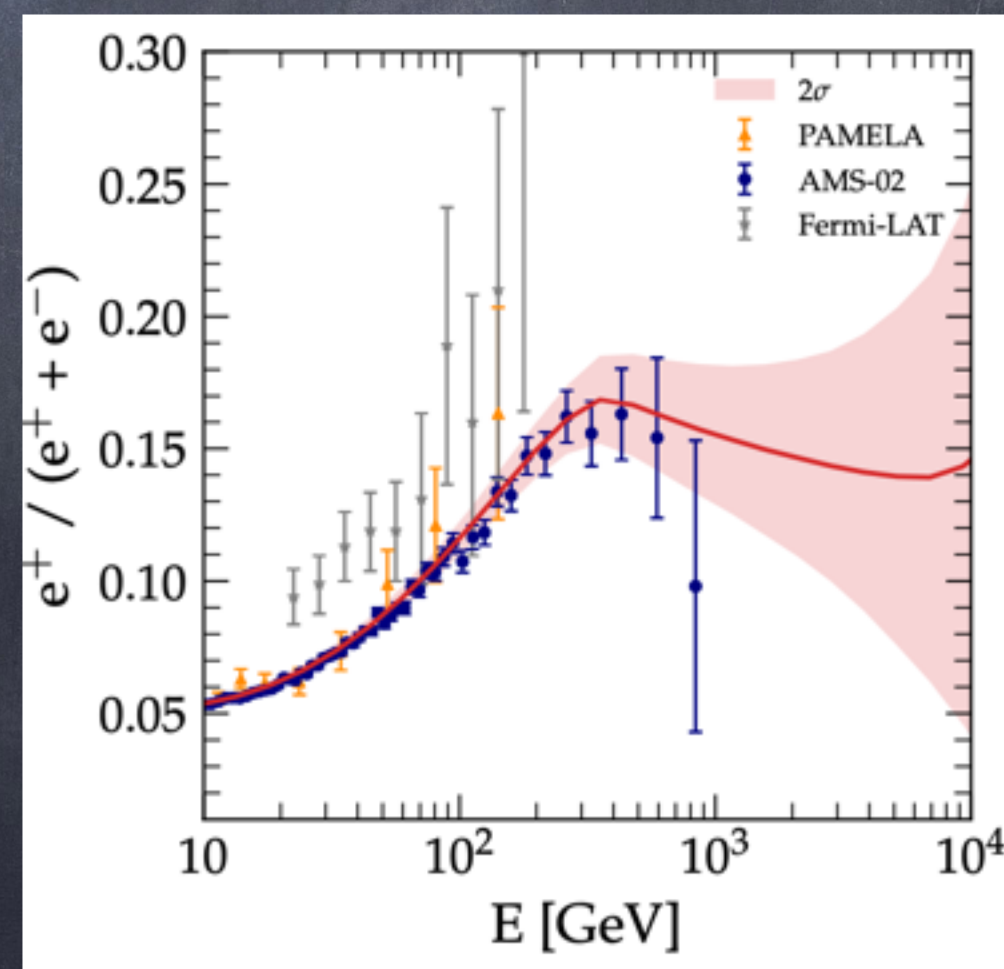
CR POSITRONS FROM PWNe



- PSR PARAMETERS ACCORDING TO Faucher-Giguere & Kaspi 06
- BROKEN POWER-LAW SPECTRUM STEEPENING AT ~500 GeV
- PROPAGATION PARAMETERS THAT FIT ALL AVAILABLE DATA



Evoli+ 21



SUMMARY AND CONCLUSIONS

- 3D MHD SIMULATIONS REQUIRE σ> A FEW TO REPRODUCE SPETRUM AND MORPHOLOGY
- FERMI MECHANISM PROBLEMATIC, THOUGH SHOCK CORRUGATION MIGHT HELP
- DRIVEN MAGNETIC RECONNECTION DIFFICULT TO MAKE SELF-CONSISTENT, BUT MAGNETIC RECONNECTION IN HIGH TURBULENT PLASMA…
- RADIO PARTICLES DO NOT NEED TO BE PART OF THE FLOW AND SPECTRUM CAN RESULT FROM ACCELERATION IN HIGH σ TURBULENCE [Comisso+ 2020]
- MULTIPLICITY CAN BE SMALL ENOUGH FOR ION CYCLOTRON… BUT ARE THERE SUFFICIENT IONS?
- CRAB IS A LEPTONIC PEVATRON, BUT IS IT ALSO A HADRONIC PEVATRON?
- EVOLVED SYSTEMS MAY ACCELERATE PARTICLES TO FULL POTENTIAL DROP AND THEY SEEM TO DO IT
- MOST LHAASO SOURCES COULD INDEED BE PWNe
- ISOTROPIC PARTICLE ESCAPE EFFICIENT ONLY AT THE HIGHEST ENERGIES
- ESCAPING PARTICLES CARRY ELECTRIC CURRENT, POSSIBLY IMPORTANT TO EXPLAIN HALOES…
- PWNe STILL THE MOST LIKELY CR POSITRON SOURCES ABOVE ~30 GeV