

PULSAR WIND NEBULAE:  
A CLASS OF EXTRAORDINARY  
COSMIC ACCELERATORS

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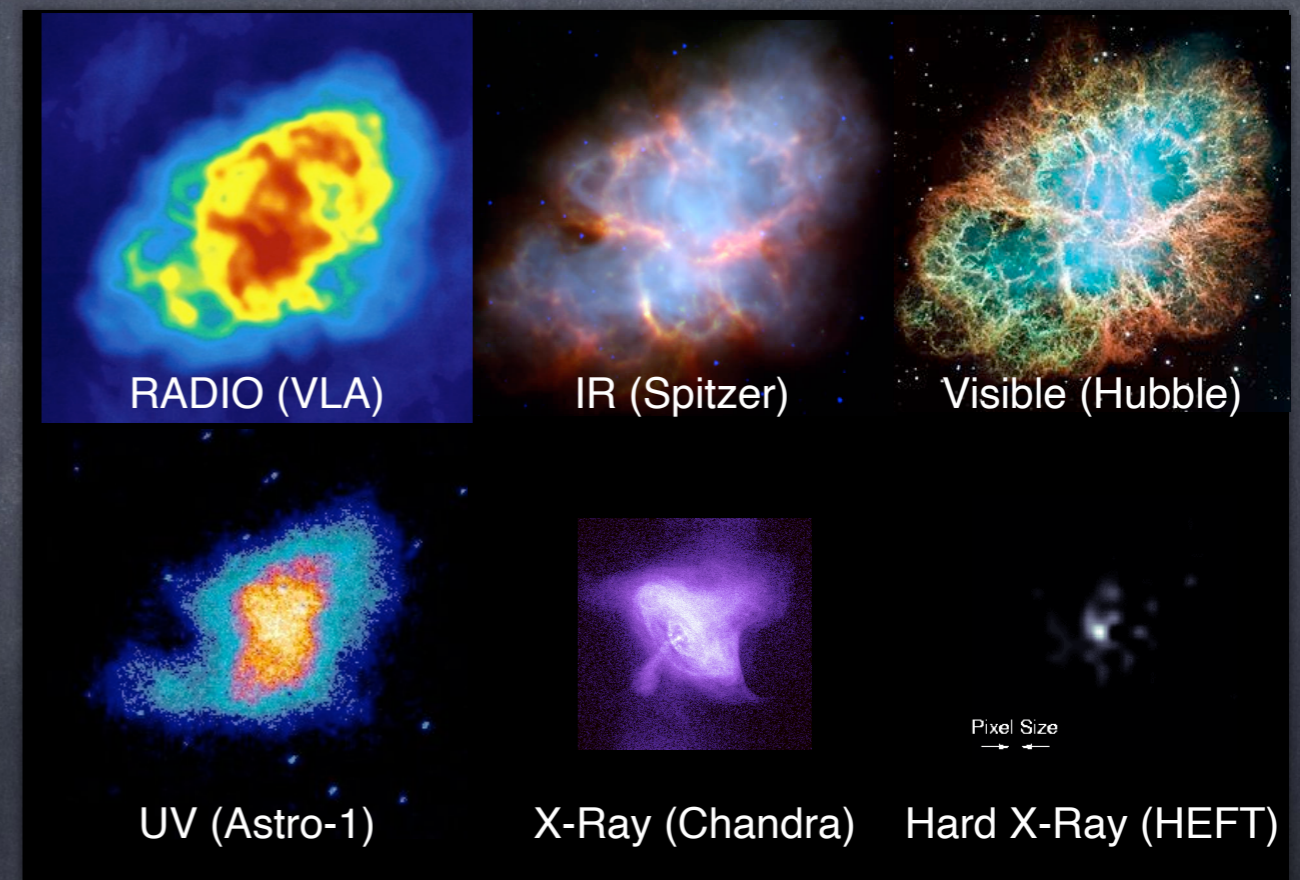
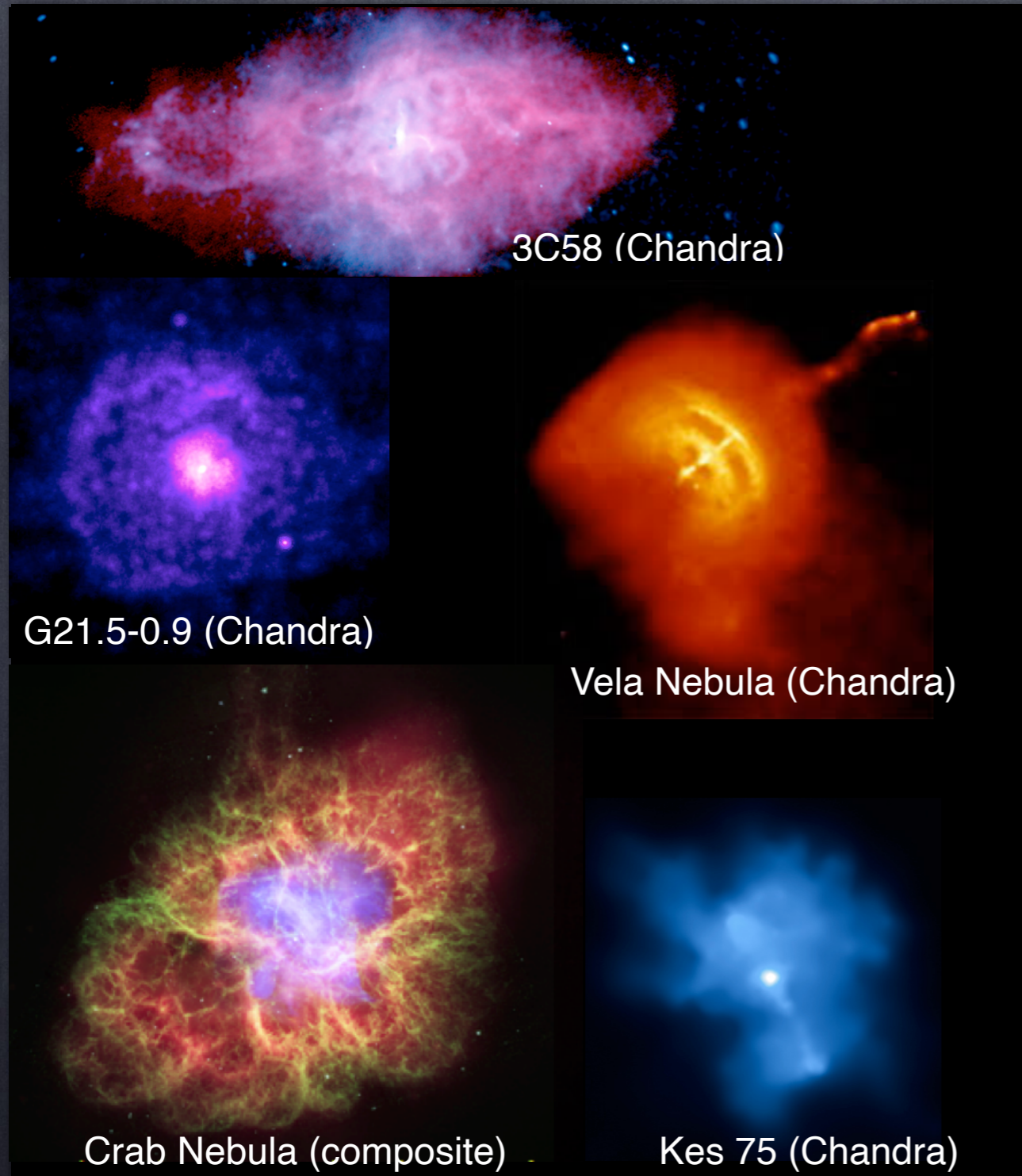
# PULSAR WIND NEBULAE

## SNRs WITH

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

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

Multi-wavelength emission and size shrinkage



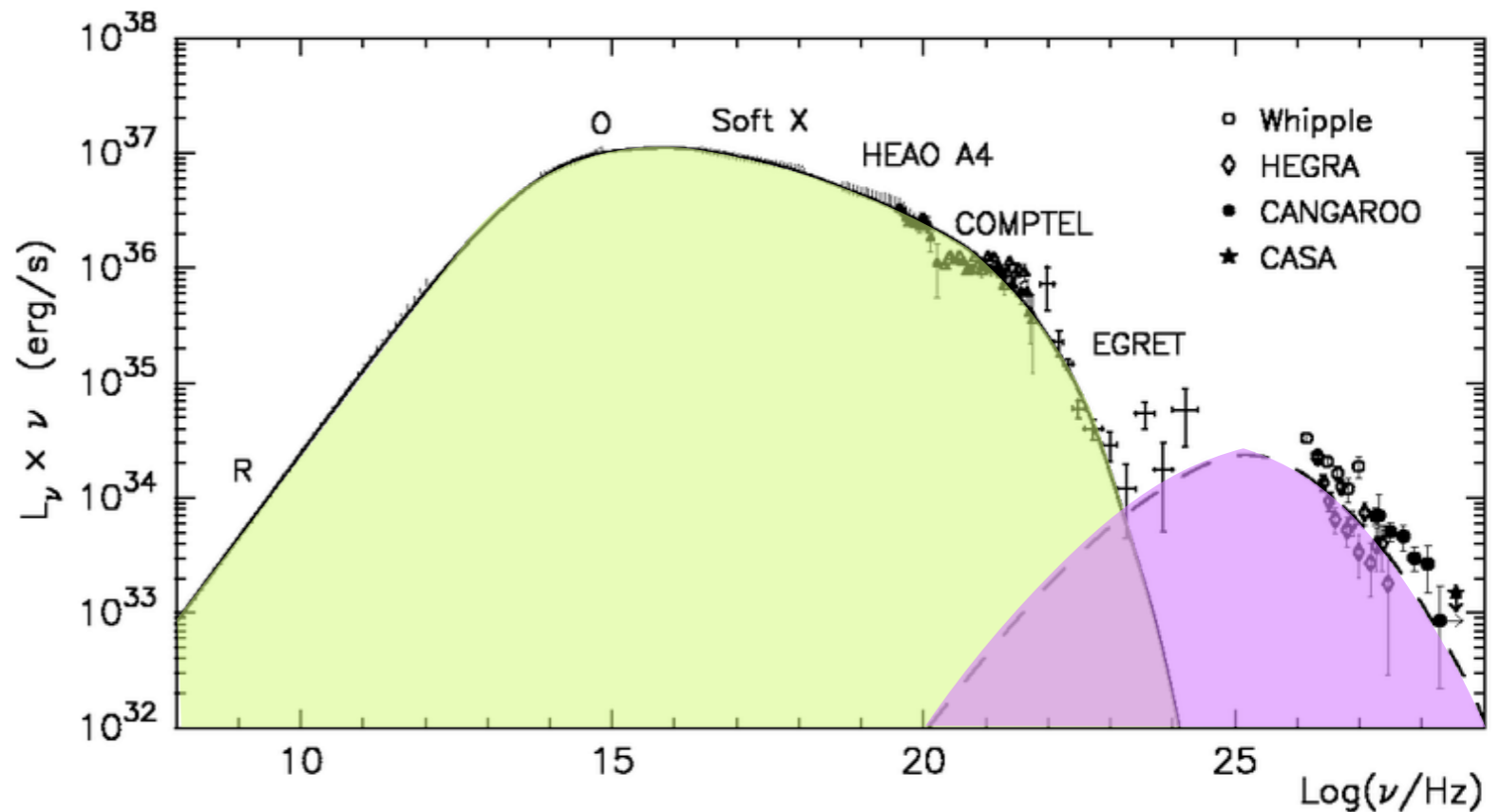
Jet-torus morphology in X-rays

# THE CRAB NEBULA

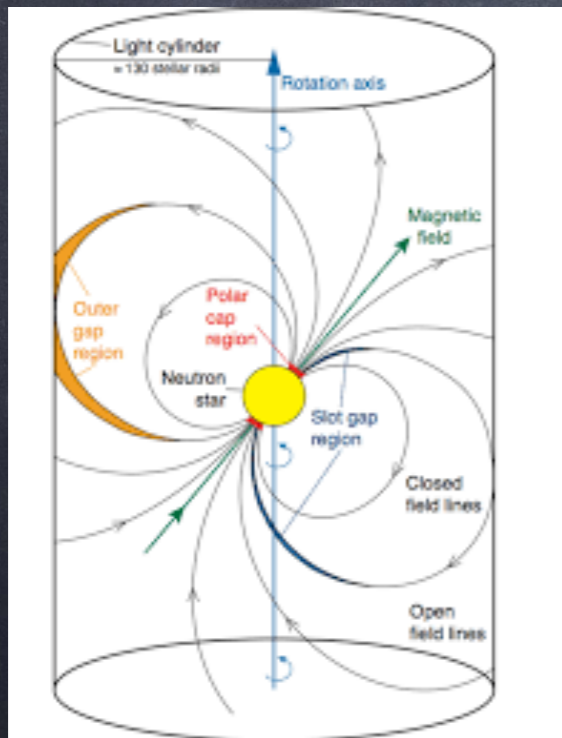
## BROAD BAND NON-THERMAL SPECTRUM



CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]



synchrotron radiation by relativistic particles in the nebular B field  
 Inverse Compton scattering with local photon 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:

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

## PLASMA PHYSICS:

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

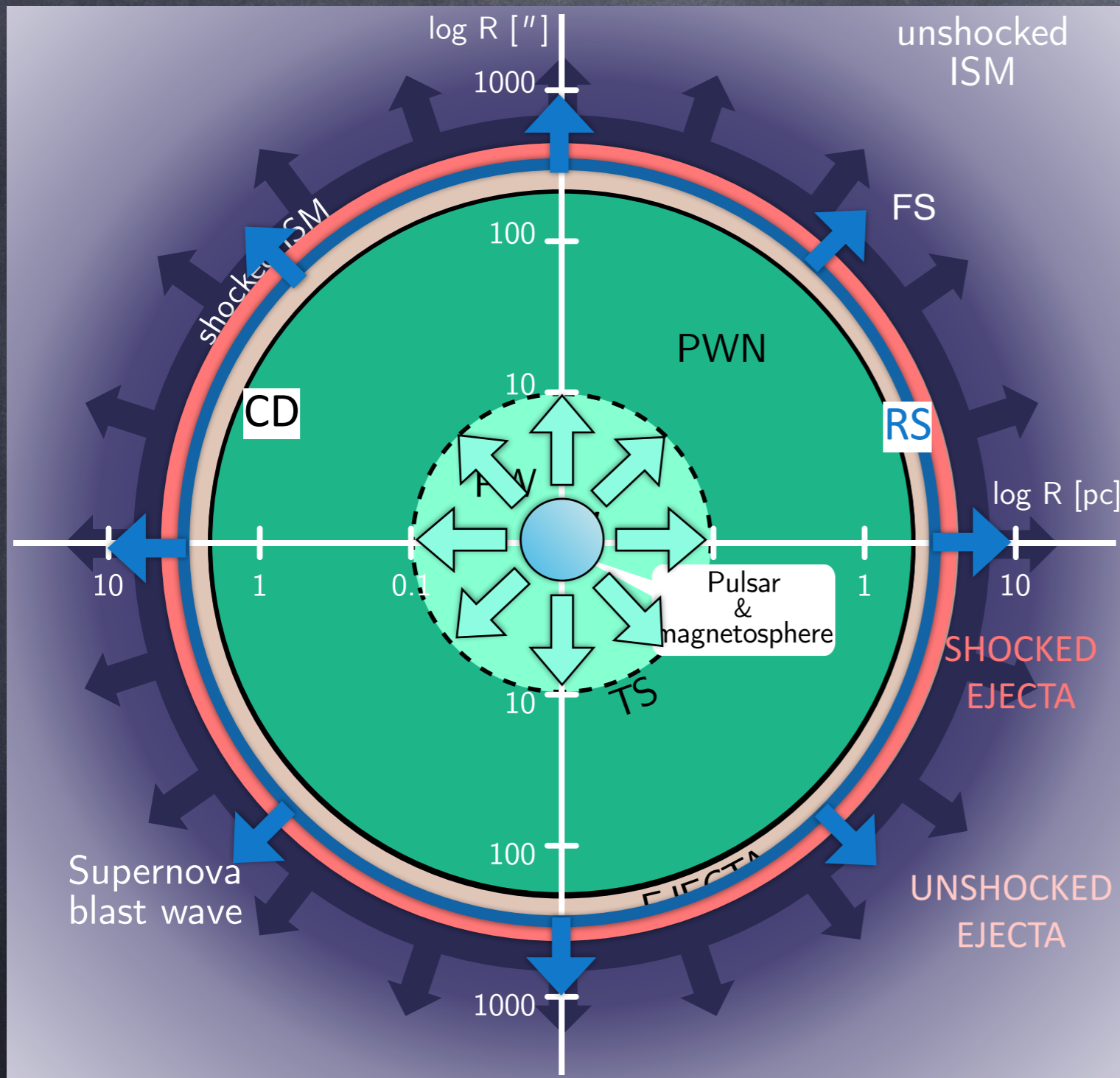
## COSMIC RAY PHYSICS:

- 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



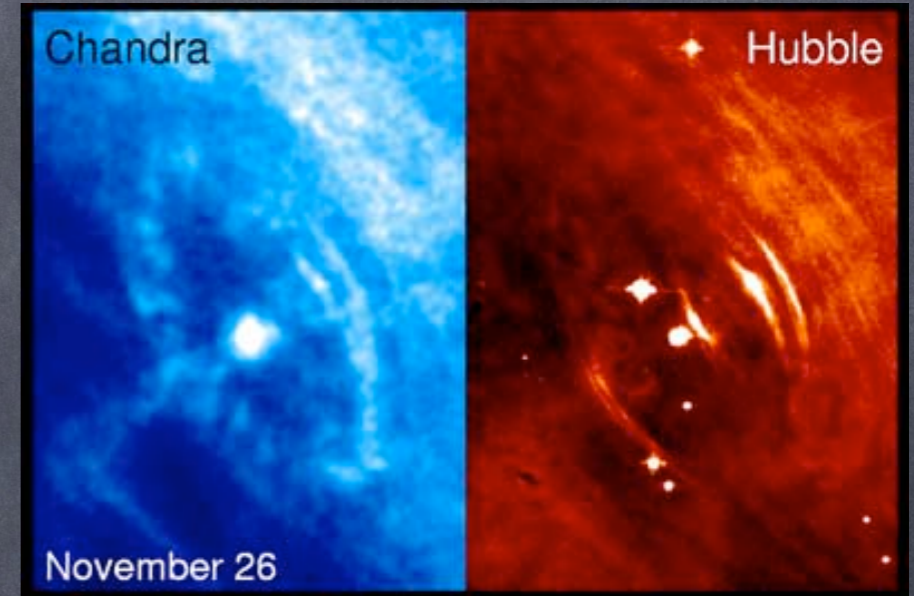
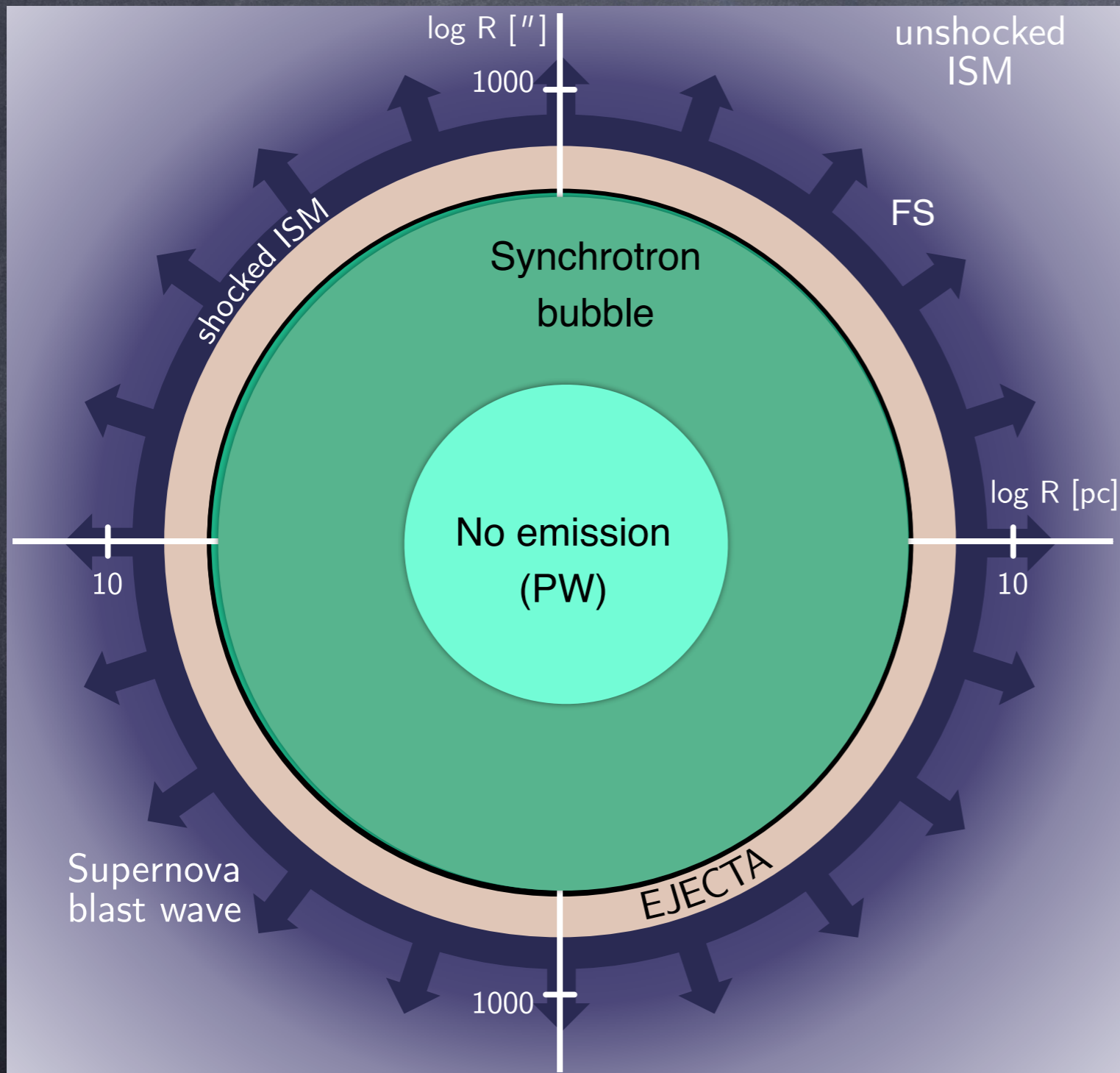
$$\frac{\dot{E}}{4\pi c R_{TS}^2} = P_{PWN} = \frac{\dot{E} t}{4\pi R_N^3}$$



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

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

# BASIC PICTURE FOR YOUNG SYSTEMS

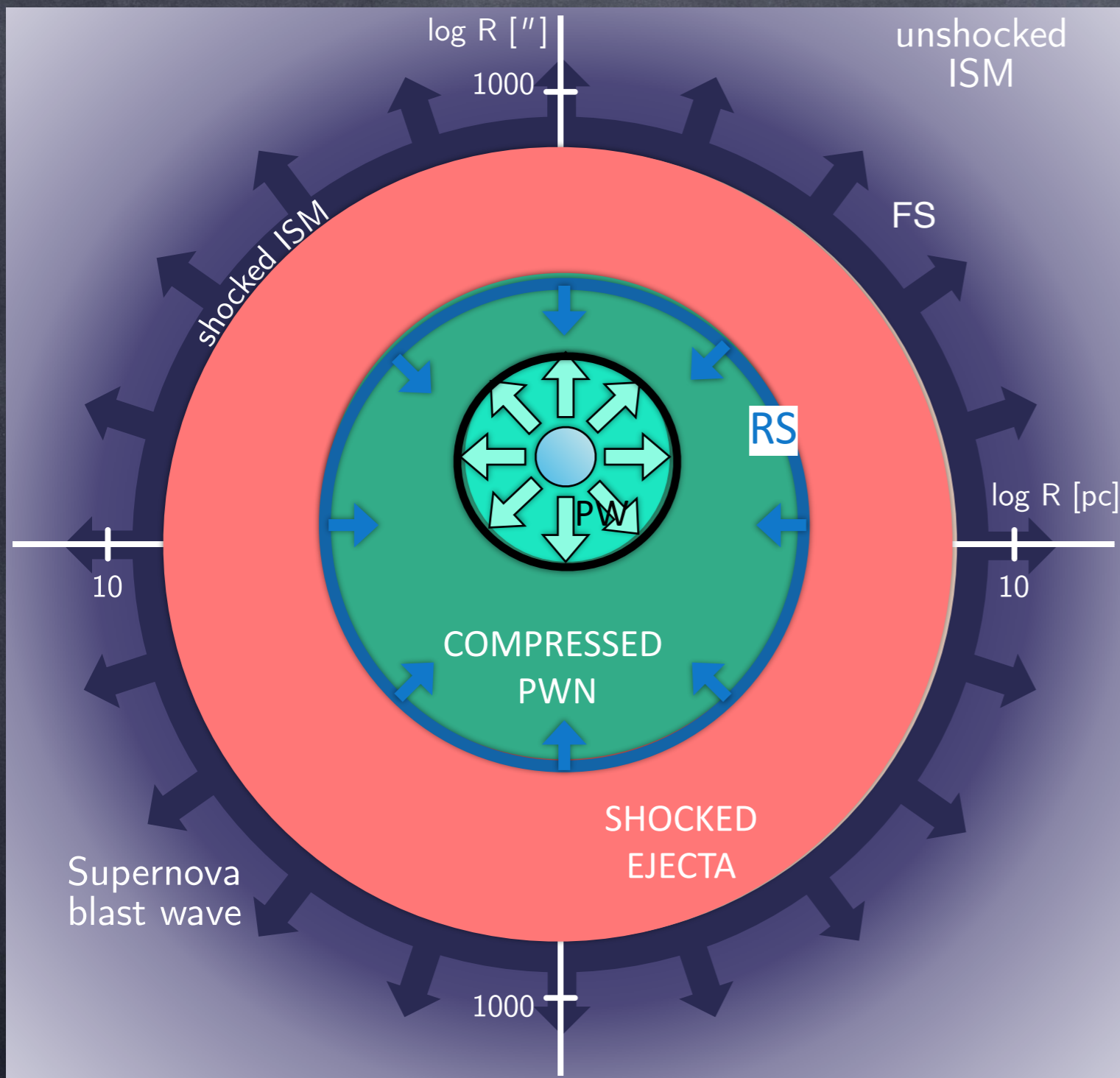


$$R_{TS} = \left( \frac{v_N}{c} \right)^{1/2} R_N$$

DISSIPATION AND  
PARTICLE  
ACCELERATION AT TS

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

# PWN EVOLUTION



SNR EXPANSION

SLOWS DOWN

+

LARGE FRACTION OF  
ALL THE PULSARS

BORN WITH

HIGH KICK VELOCITY



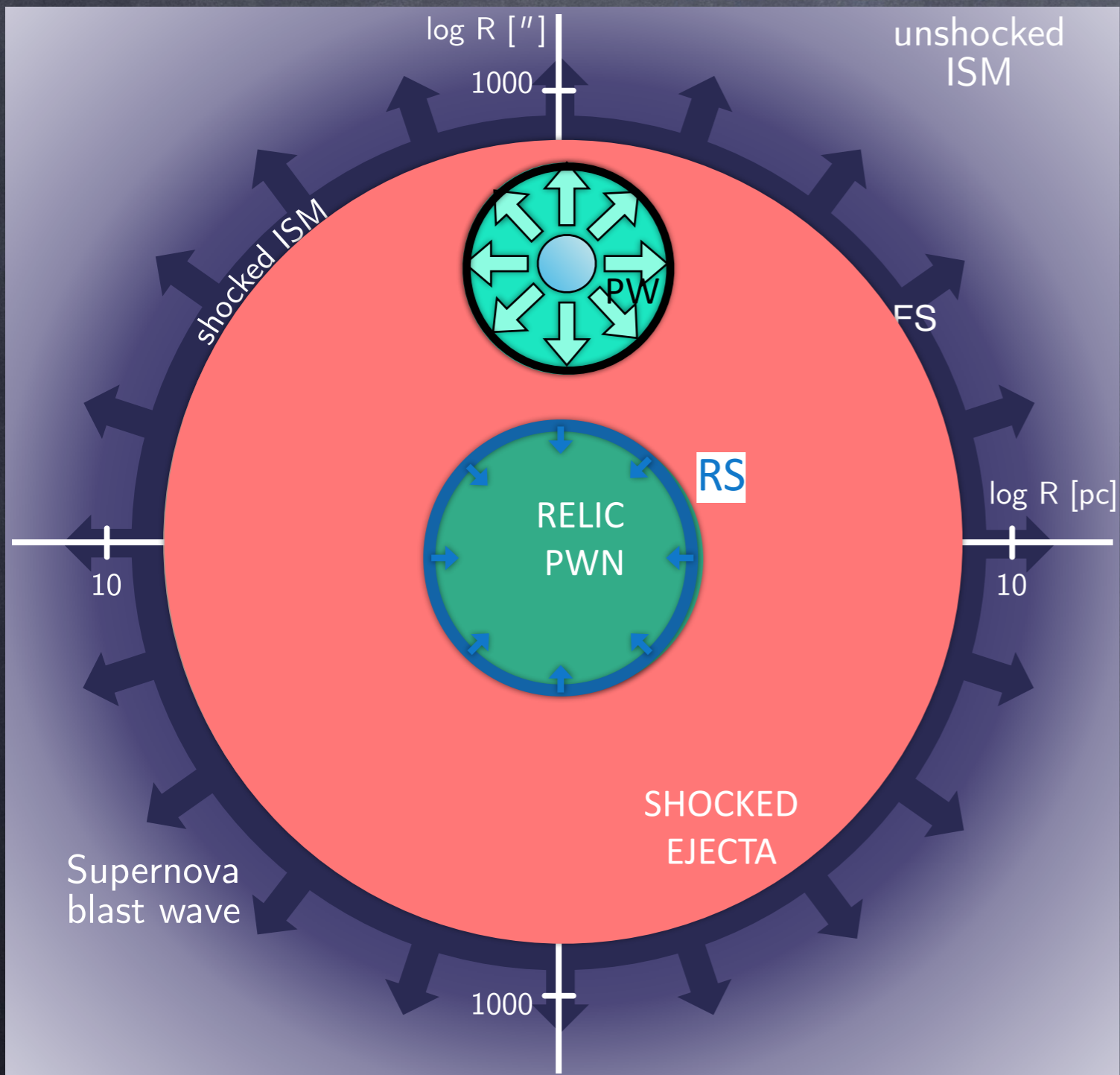
COMPRESSED PWN  
OFFSET PW



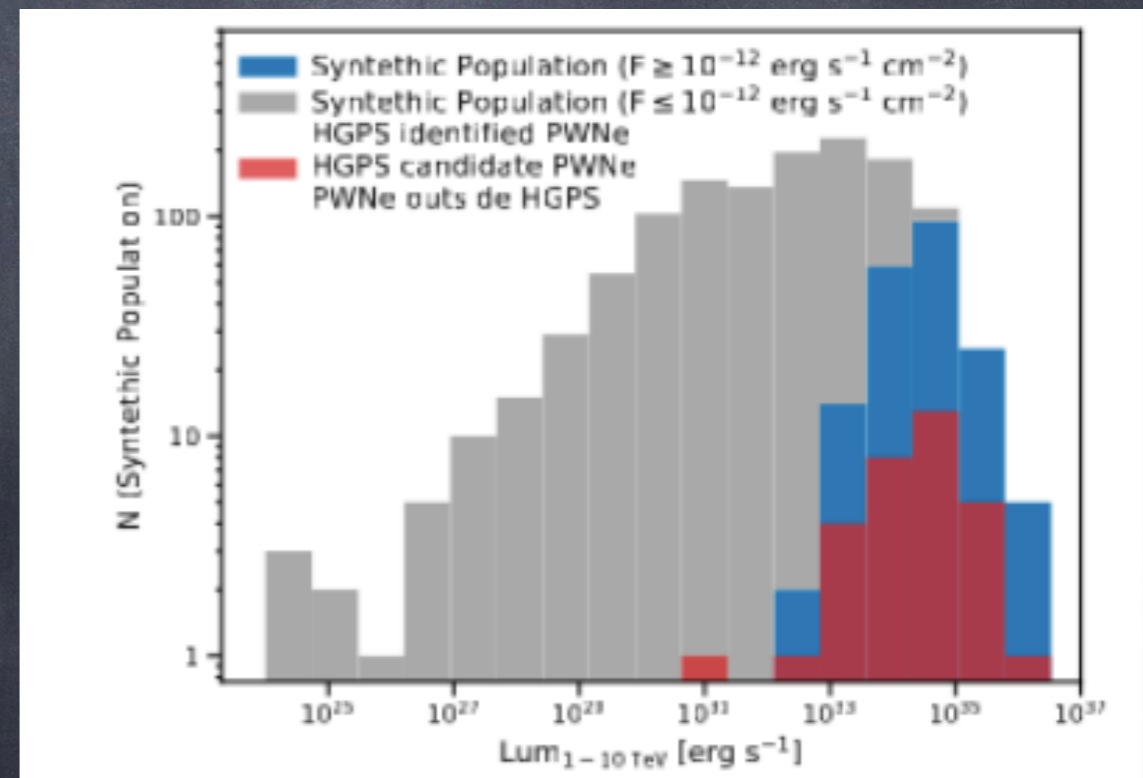
REVERBERATION PHASE

# RELIC NEBULAE

PSR MAY CROSS RS DURING COMPRESSION  
AND LEAVE A RELIC

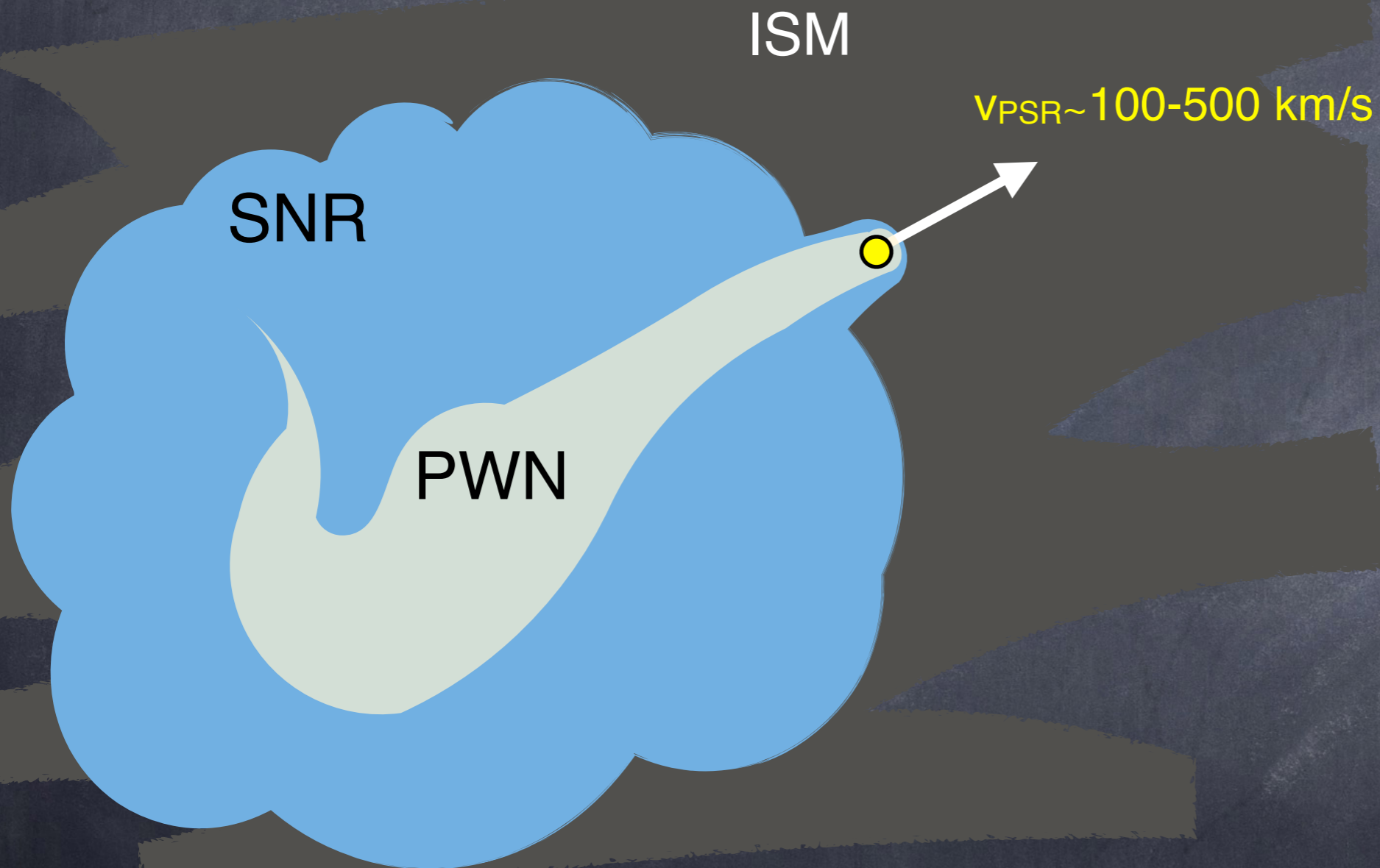


EVENTUALLY  
MOST GAMMA-RAY BRIGHT  
X-RAY DIM PWNe  
[Fiori+ 2022]





# EVOLVED PWNe

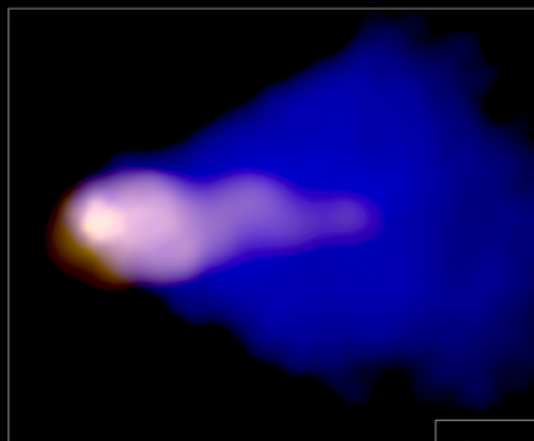


LARGE FRACTION OF  
ALL THE PULSARS  
BORN WITH  
HIGH KICK VELOCITY



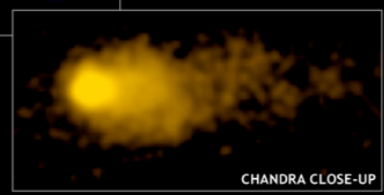
THEY LEAVE THE SNR  
ON TIMESCALES  
FEW  $\times 10^4 - 10^5$  YR

# BOW SHOCK NEBULAE



CHANDRA X-RAY & VLA RADIO

MOUSE NEBULA



CHANDRA CLOSE-UP

$$c_s \sim 10-100 \text{ km/s} \sim 1/10 v_{\text{PSR}}$$

UNSHOCKED ISM

SHOCKED ISM

SHOCKED PULSAR WIND  
 $v \sim 0.1-0.9c$

$e^-$   
 $e^+$

CONTACT DISCONTINUITY

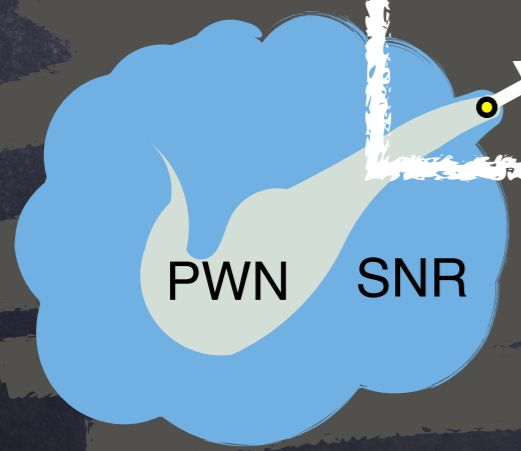
TERMINATION SHOCK

FORWARD SHOCK



$$v_{\text{PSR}} \gg c_s$$

PSR in  
supersonic  
motion

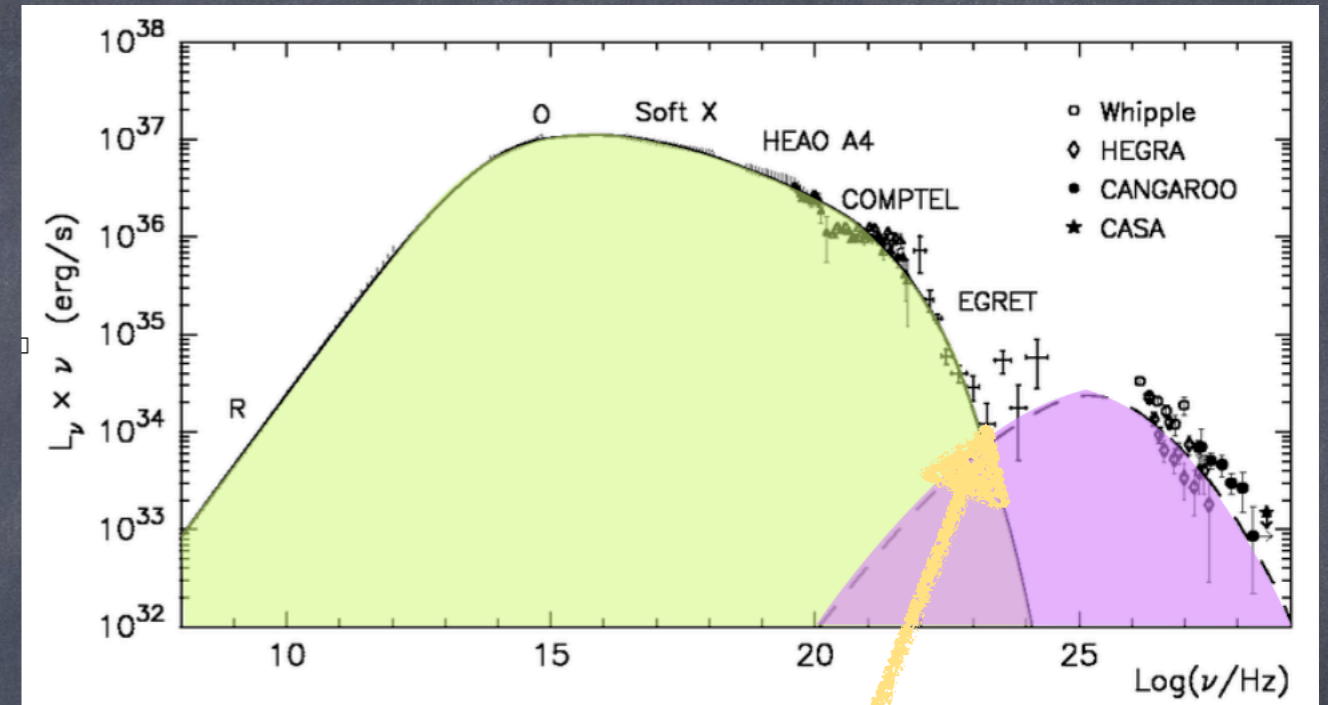
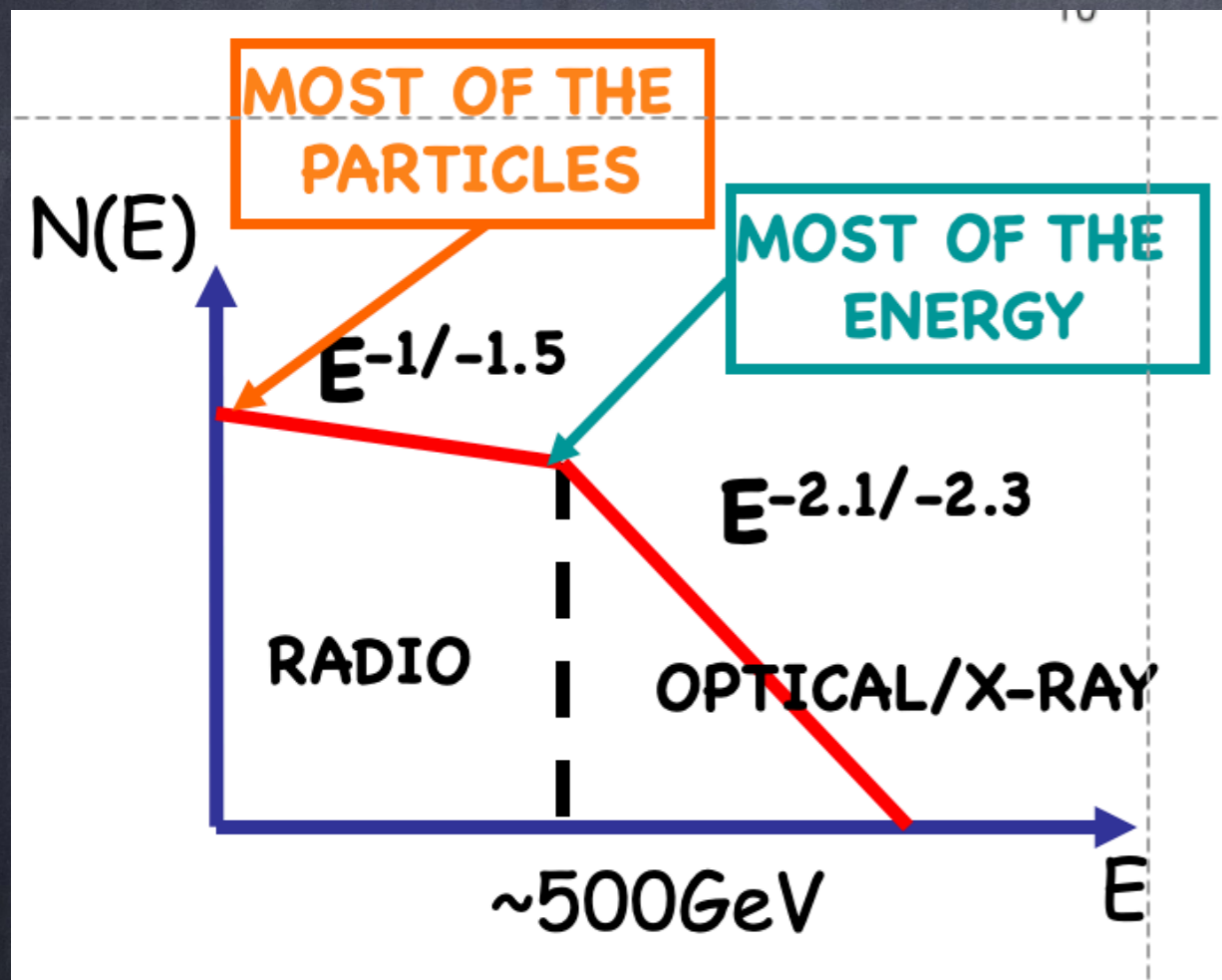


PWN

SNR

$v_{\text{PSR}}$

# EMITTING PARTICLES



**PeV ELECTRONS**

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

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

**EXTRAORDINARY ACCELERATOR!**

## ONE ZONE MODELS

[Pacini & Salvati 1973, EA+ 2000, Bucciantini+ 2011....]  
 (also Fraschetti & Pohl 2017 for log-parabola injection)

# OPEN QUESTIONS

## WHAT WE KNOW:

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

- 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?  $\kappa$ ?)

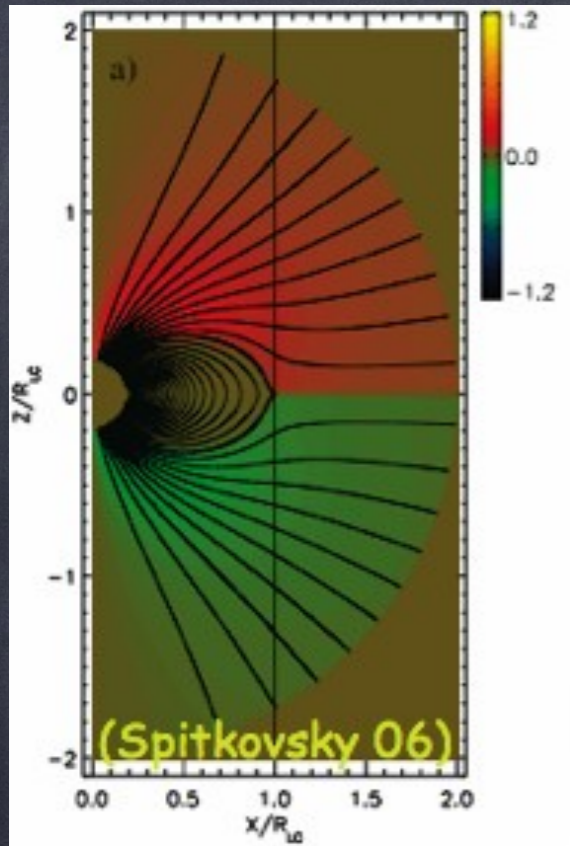
WIND MAGNETIZATION ( $\sigma$ ?)

IN PRINCIPLE BOTH  
DEPEND  
ON LOCATION

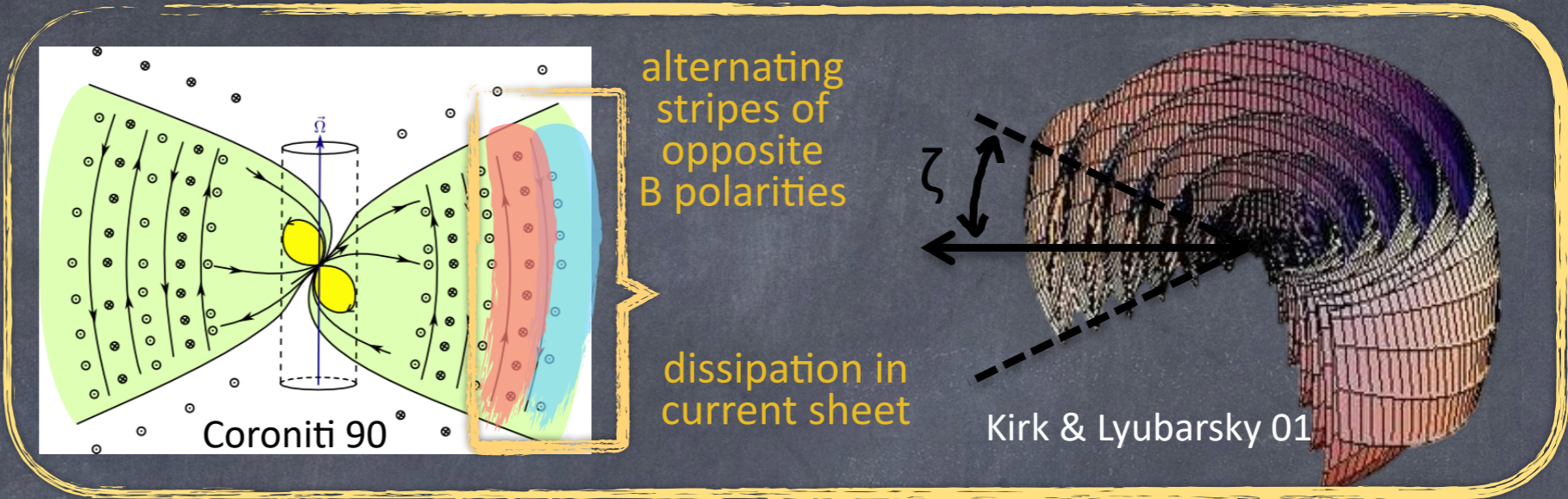


- HOW PARTICLES EVENTUALLY ESCAPE

# THE PSR WIND



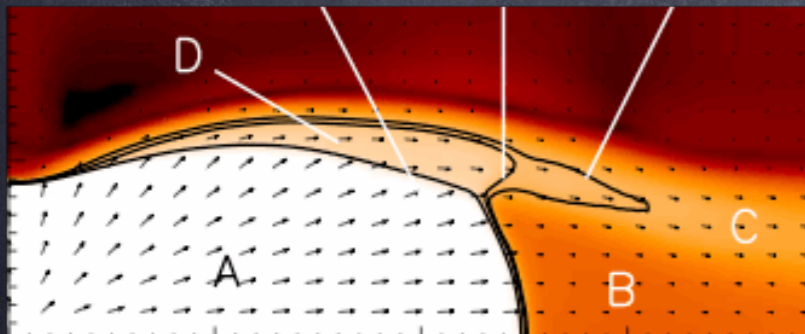
$$F(\theta) \propto \sin^2(\theta)$$



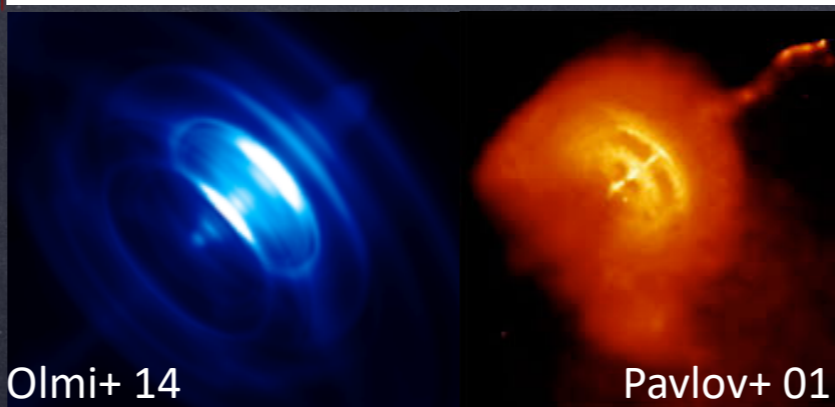
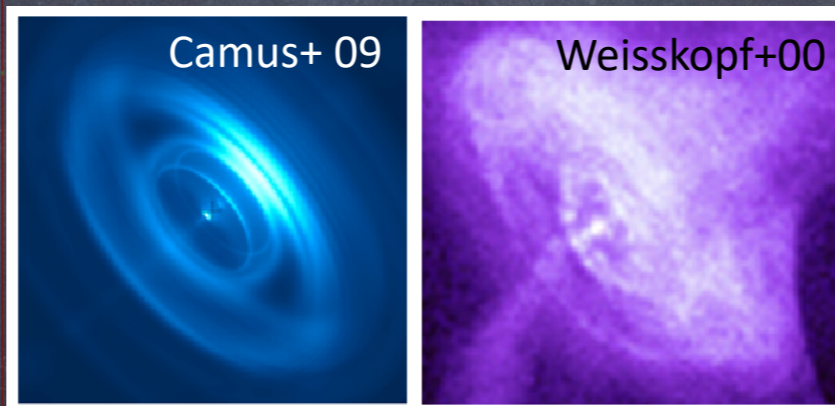
$$B(\theta) \propto \sqrt{\sigma} \sin \theta G(\theta)$$

## DYNAMICS AND RADIATION MODELING

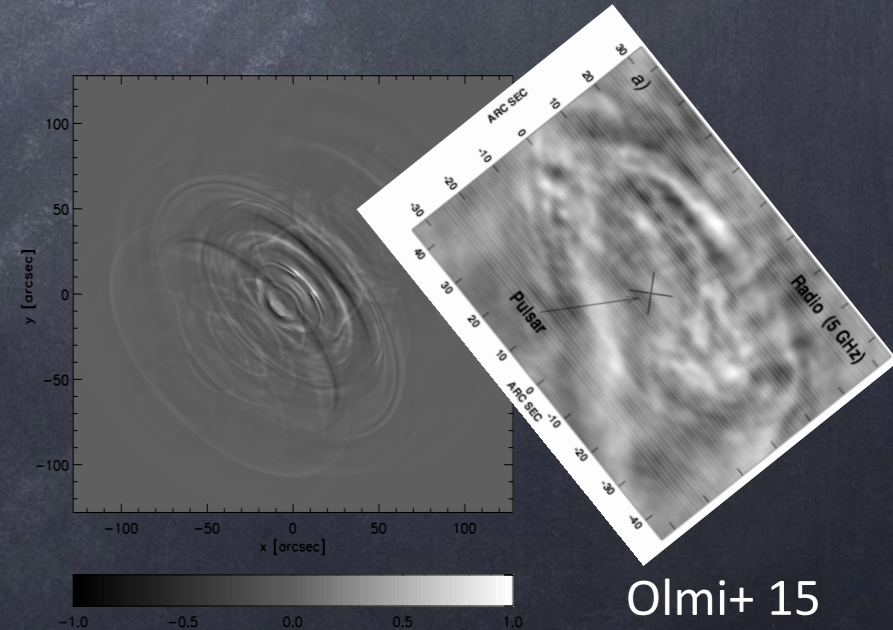
### TERMINATION SHOCK



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

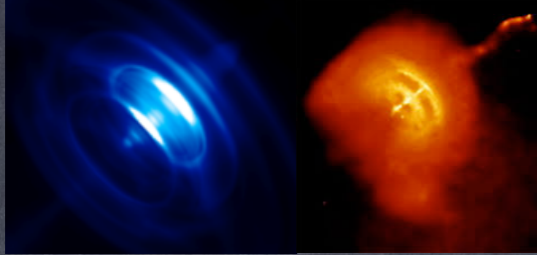


### MULTI-WAVELENGTH VARIABILITY



# CONSTRAINTS ON ACCELERATION MECHANISMS

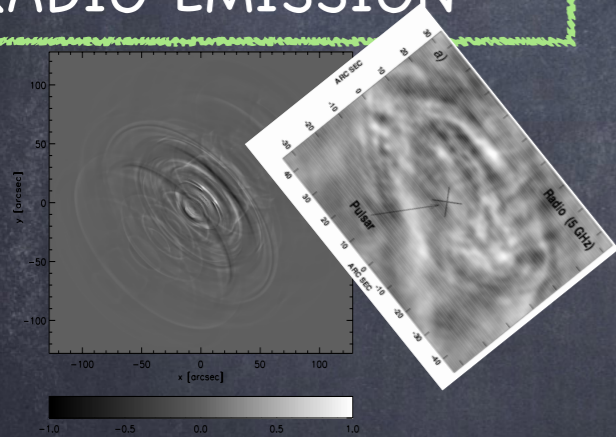
NEBULAR DYNAMICS AND HIGH ENERGY EMISSION PROPERTIES



$$\sigma_{avg} \gtrsim 1$$

TOO LARGE FOR FERMION ACCELERATION  
[Sironi & Spitkovsky 09,11]  
BUT TURBULENCE MIGHT HELP  
[Lemoine 17, Giacinti & Kirk 18, Cerutti & Giacinti 20]

MODELLING OF RADIO EMISSION



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

AND

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

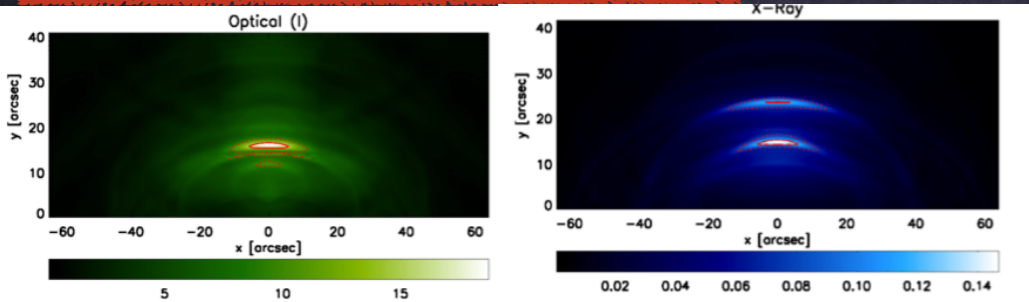
VIABLE

ION CYCLOTRON VIABLE  
[Hoshino+92, EA & Arons 06]

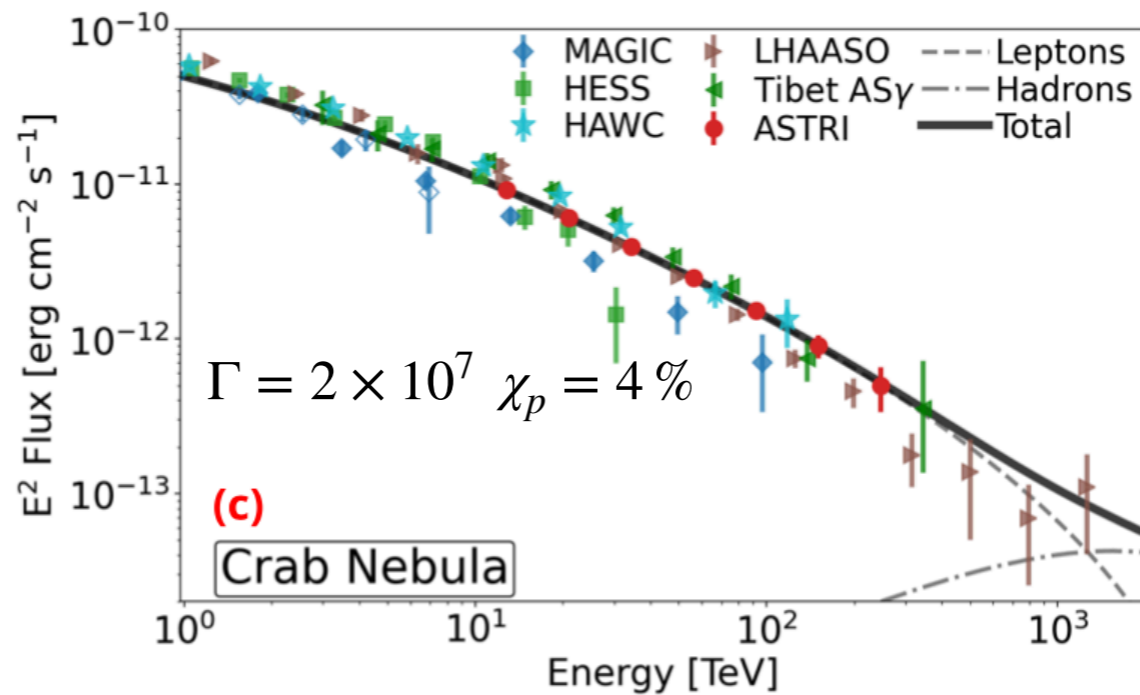
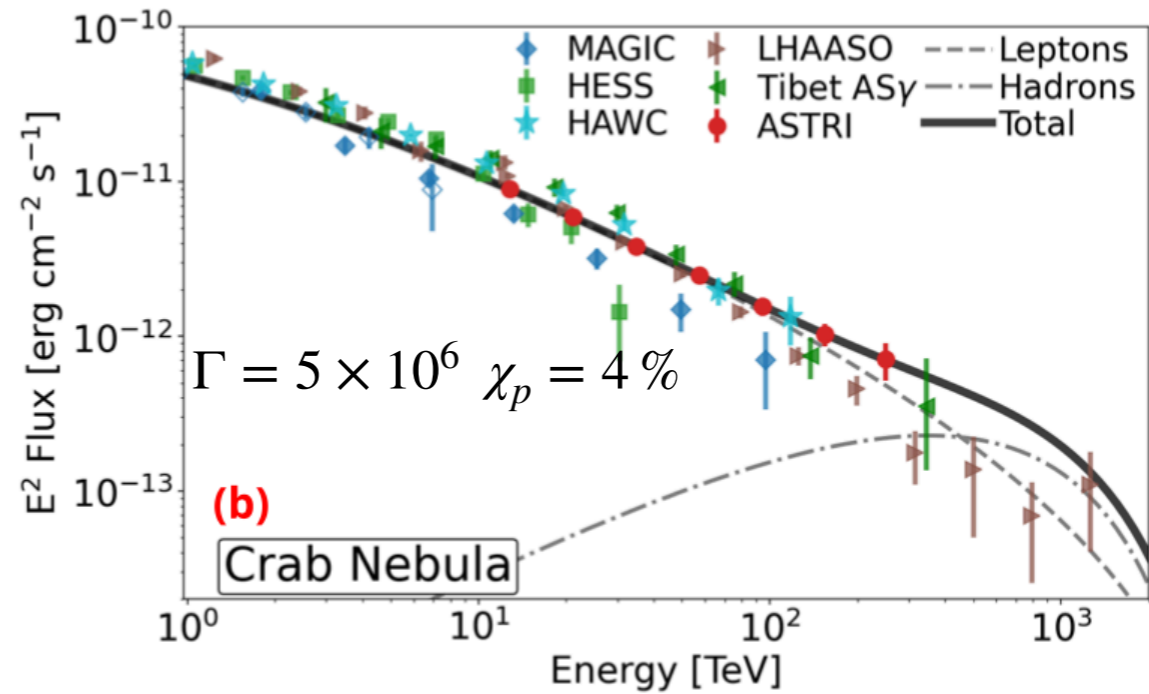
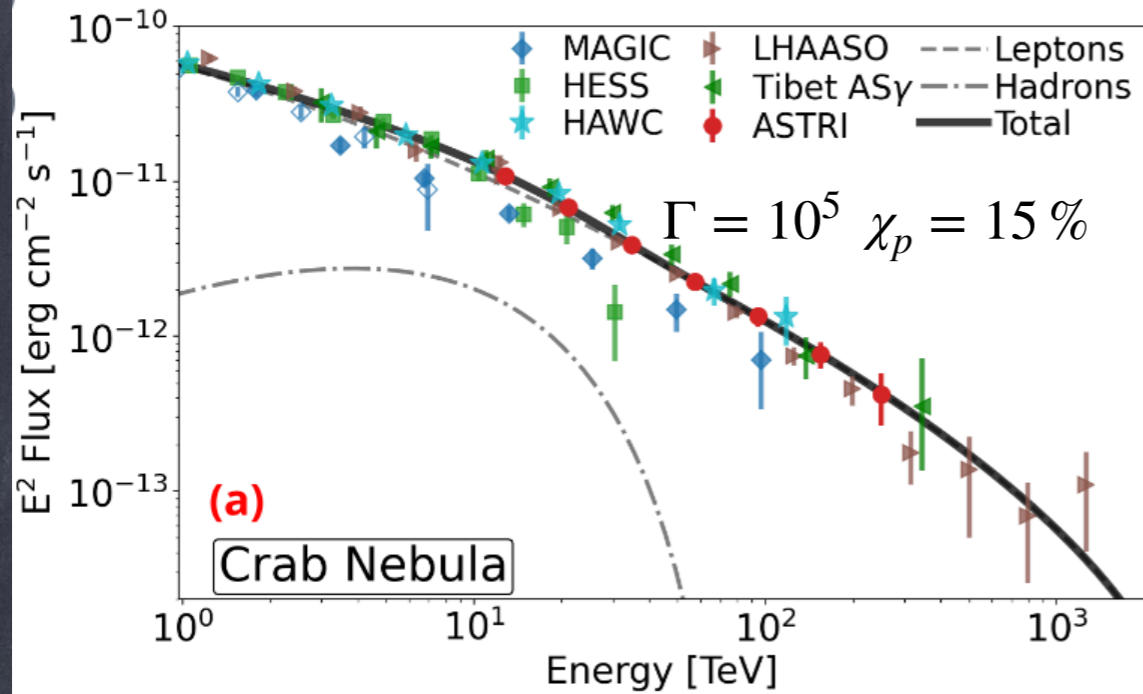
MULTIFREQUENCY VARIABILITY OF INNER NEBULA

HIGH ENERGY PARTICLES FROM EQUATORIAL REGION  
LOWER ENERGY ELSEWHERE

LOW ENERGY FROM TURBULENT ACCELERATION IN THE NEBULA?  
[Comisso+ 2020]



# HADRONS IN CRAB?



Vercellone + submitted

$$Q_p(E) \propto \delta(E - m_p c^2 \Gamma)$$

(EA & Arons 06; EA, Guetta, Blasi 03)

PWINE AS  
PEVATRONS



# GALACTIC PEVATRONS

## 12 SOURCES DETECTED BY LHAASO ABOVE 100 TeV

Table 1 | UHE  $\gamma$ -ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV ( $\times\sigma$ )	$E_{\max}$ (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	$0.88 \pm 0.11$	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	$0.42 \pm 0.16$	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	$0.21 \pm 0.05$	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	$0.35 \pm 0.07$	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	$0.44 \pm 0.05$	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	$0.42 \pm 0.03$	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	$0.27 \pm 0.02$	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	$1.42 \pm 0.13$	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	$0.43 \pm 0.05$	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	$0.57 \pm 0.19$	1.05(0.16)

Cao+ 2021

PeV PROTONS OR ELECTRONS?

THE CRAB NEBULA IS THE ONLY ESTABLISHED PEVATRON IN THE GALAXY

ALL SOURCES HAVE A PSR IN THE FIELD...

# MAXIMUM ENERGY IN A PWN

IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LOSS LIMITED

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



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

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

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

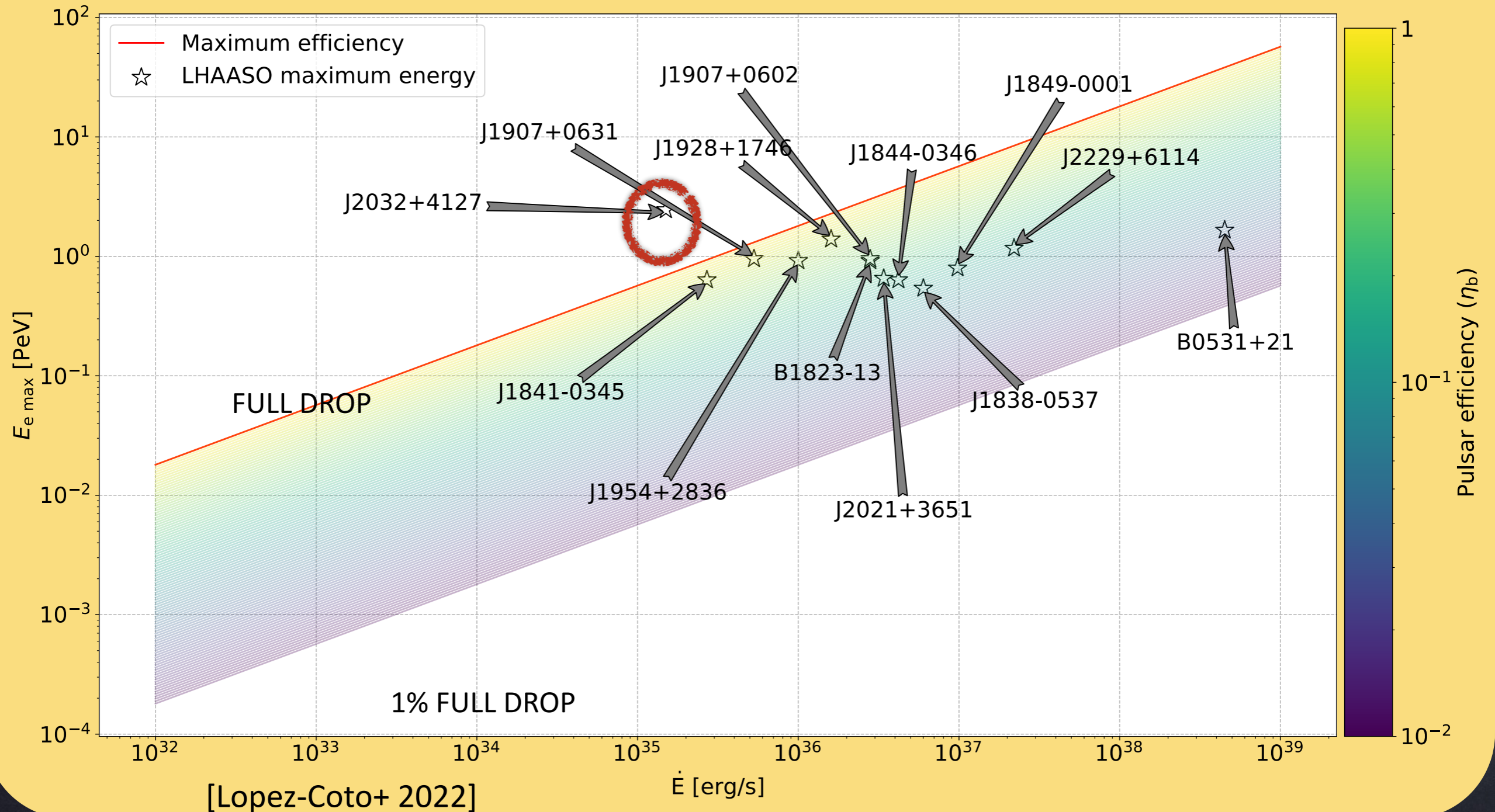


$$\frac{B_{TS}^2}{4\pi} = \xi_B \frac{\dot{E}}{4\pi R_{TS}^2 c}$$

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

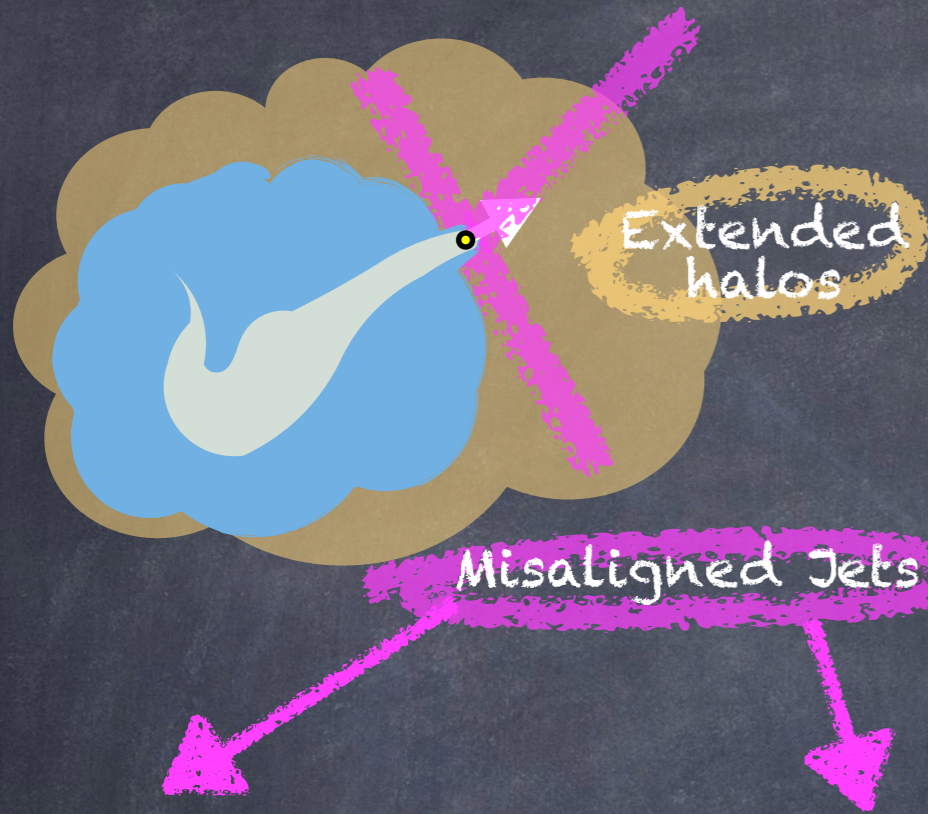
# LHAASO PEVATRONS AND PWNe

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

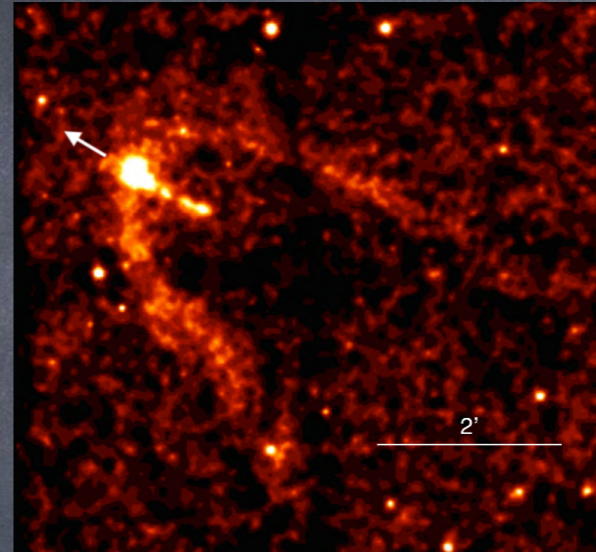


EVOLVED SYSTEMS  
AND  
PARTICLE ESCAPE

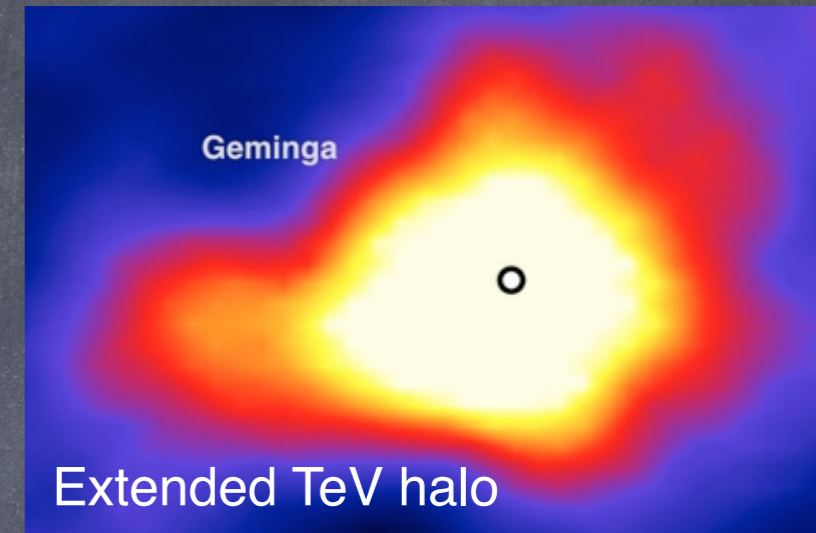
# OBSERVATIONS: JETS AND HALOES



X-ray



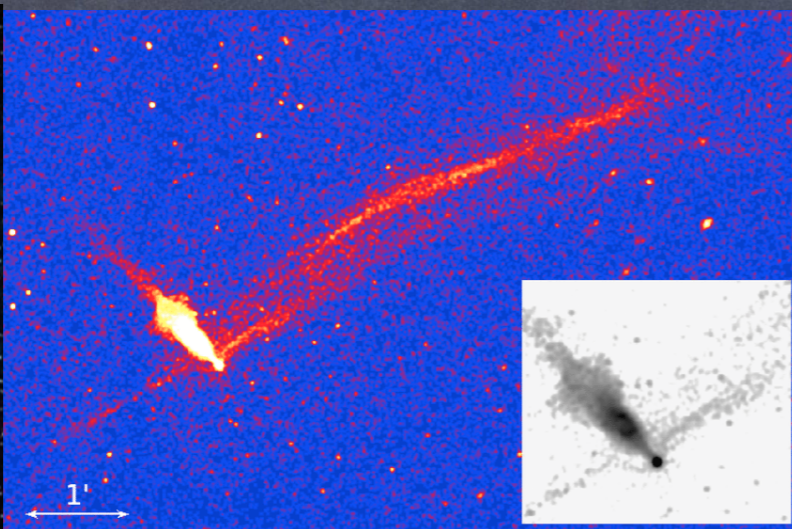
Geminga  
[Posselt+ 2017]



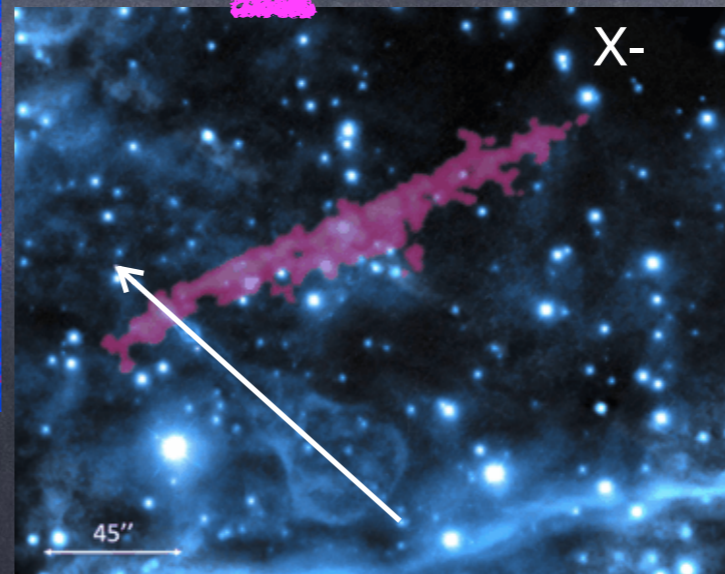
Extended TeV halo  
[Abeysekara+ 2017]



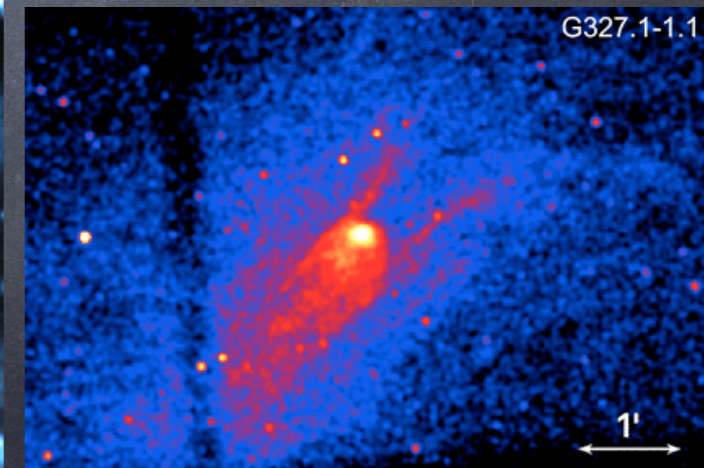
PSR J1509-5850  
[Klinger+ 2016]



Lighthouse nebula  
[Pavan+ 2016]

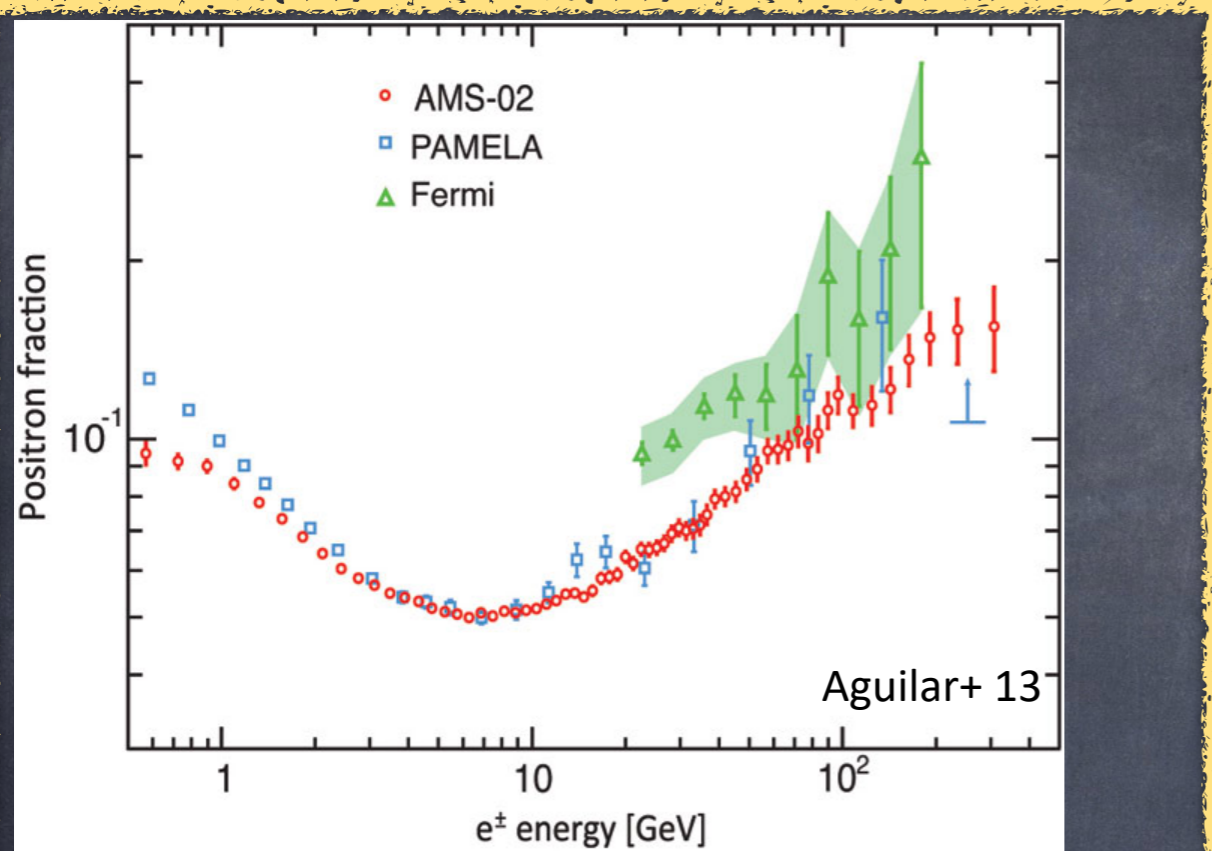


Guitar nebula  
[Cordes+ 1993, Wong+ 2003]



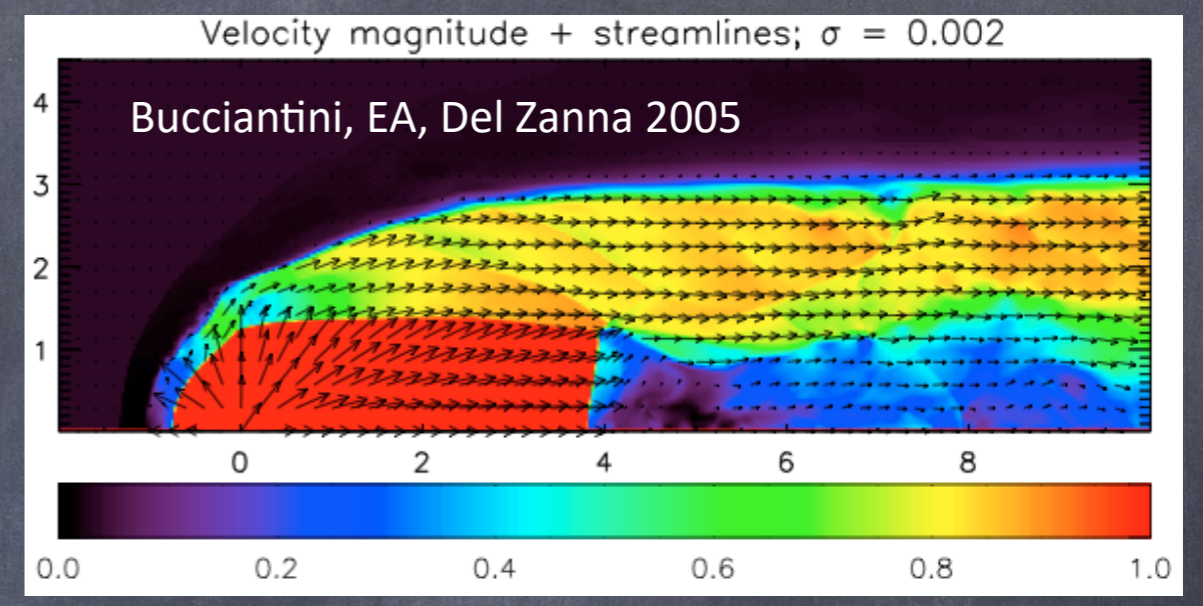
G327  
[Temim+ 2009]

# THE CR POSITRON EXCESS

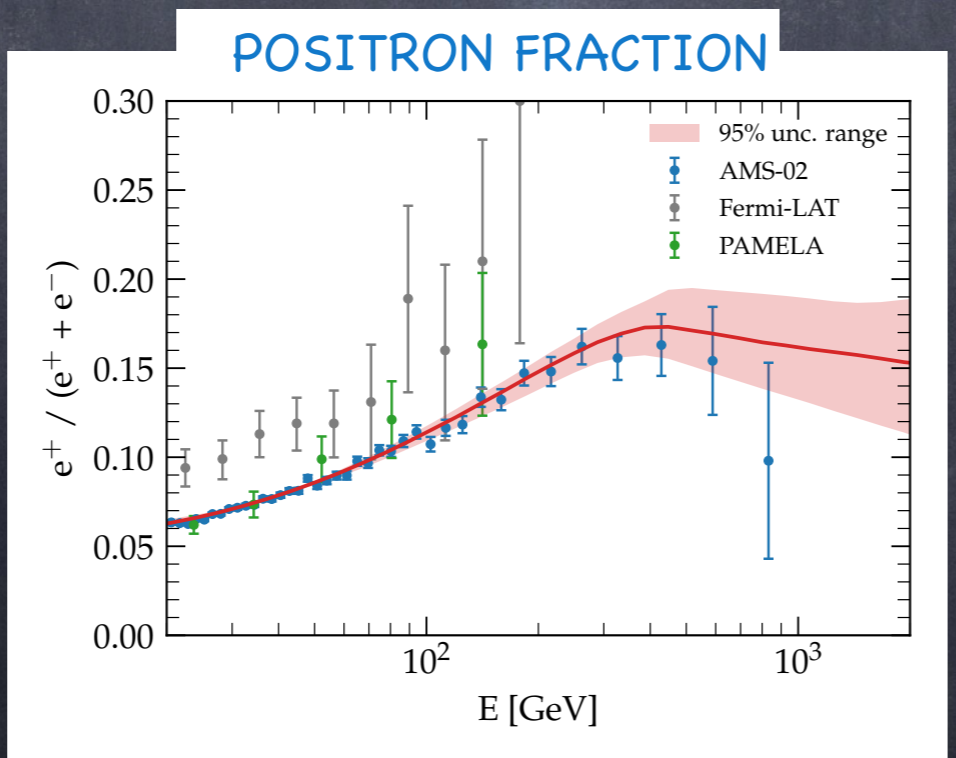


IF  $e^+$  ONLY SECONDARY:  $\frac{\Phi_{e^+}}{\Phi_{e^+} + \Phi_{e^-}} \propto E^{-\delta}$

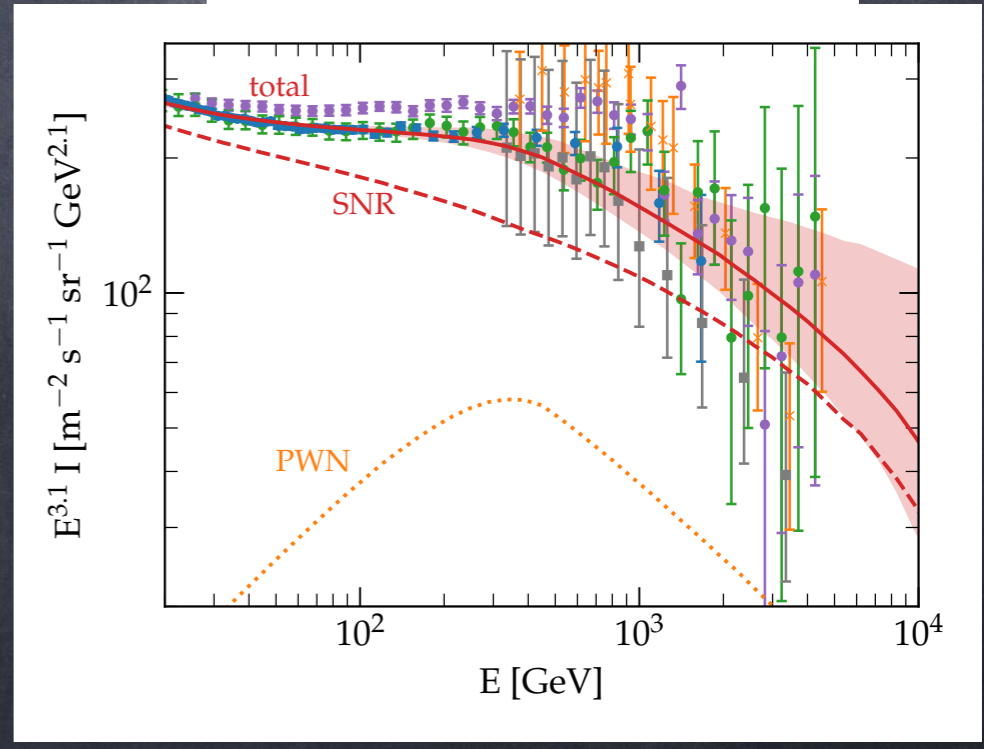
BOW SHOCK PWNe EARLY SUGGESTED [Blasi & EA 11]  
AS BEST CANDIDATES TO EXPLAIN THE EXCESS



BS-PWNe INJECT  $0.1\dot{E}$   
AS A BROKEN  
POWER-LAW OF  $e^+e^-$  :  
 $E_B \approx 500\text{GeV}$

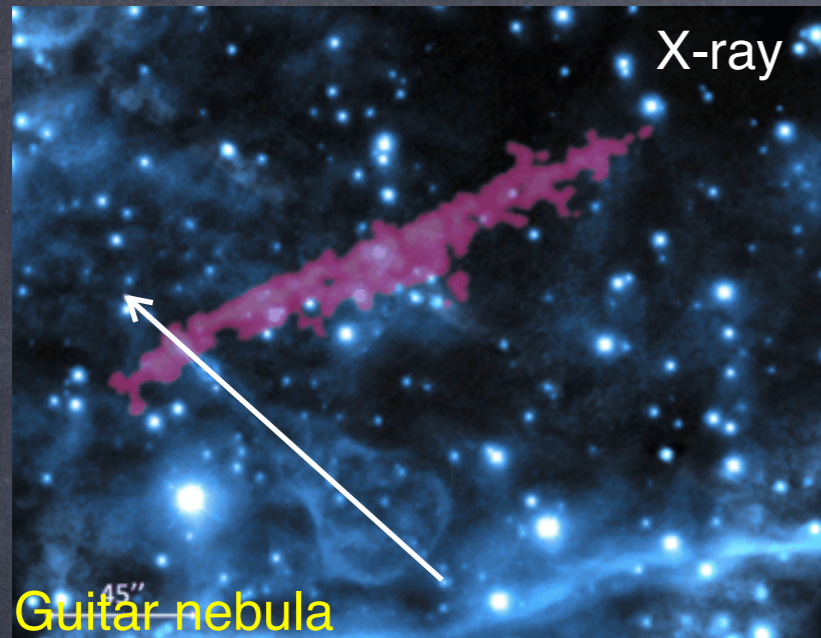


## ALL LEPTON SPECTRUM



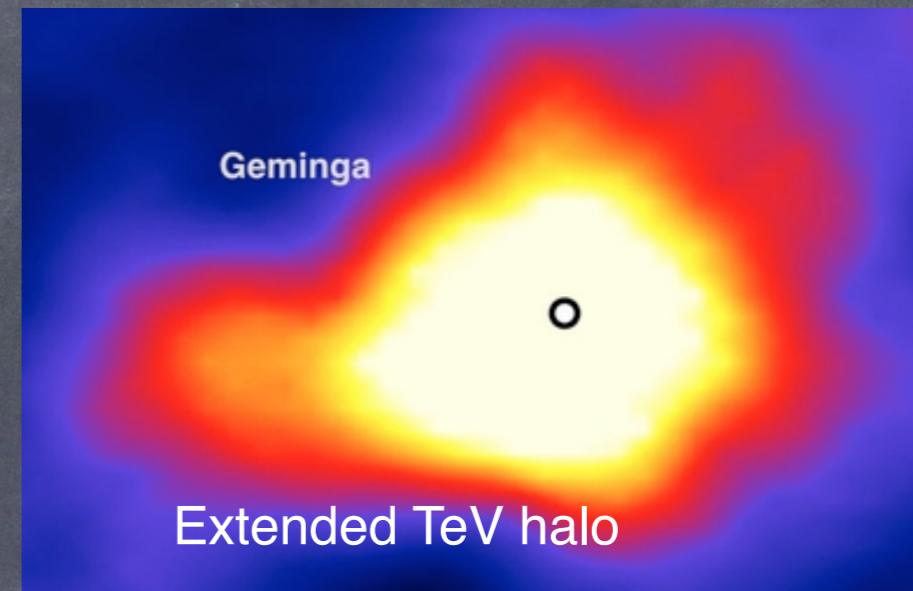
Evoli+ 21,22

# INTERPRETATION: JETS AND HALOES



[Cordes+ 1993, Wong+ 2003]

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

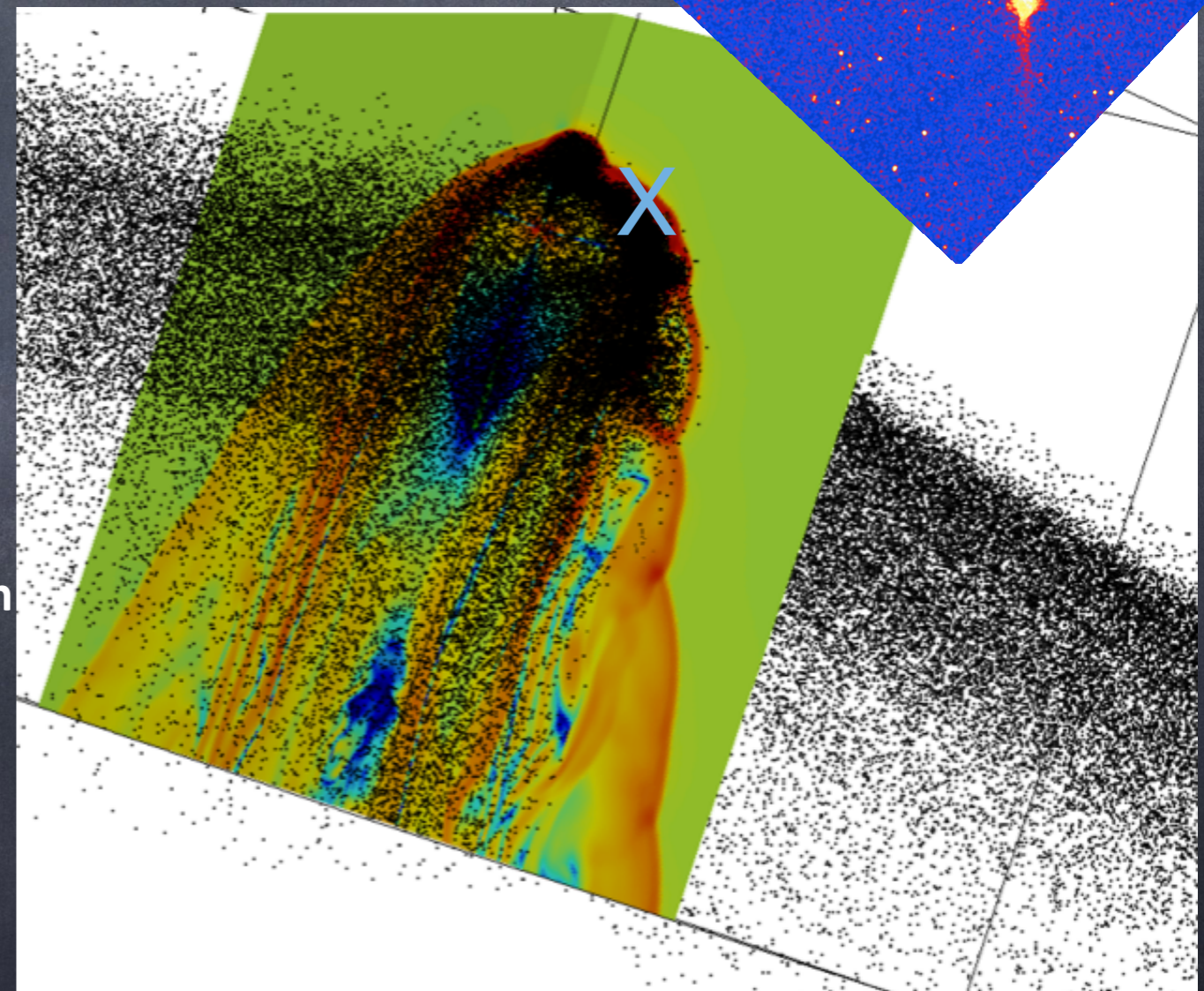
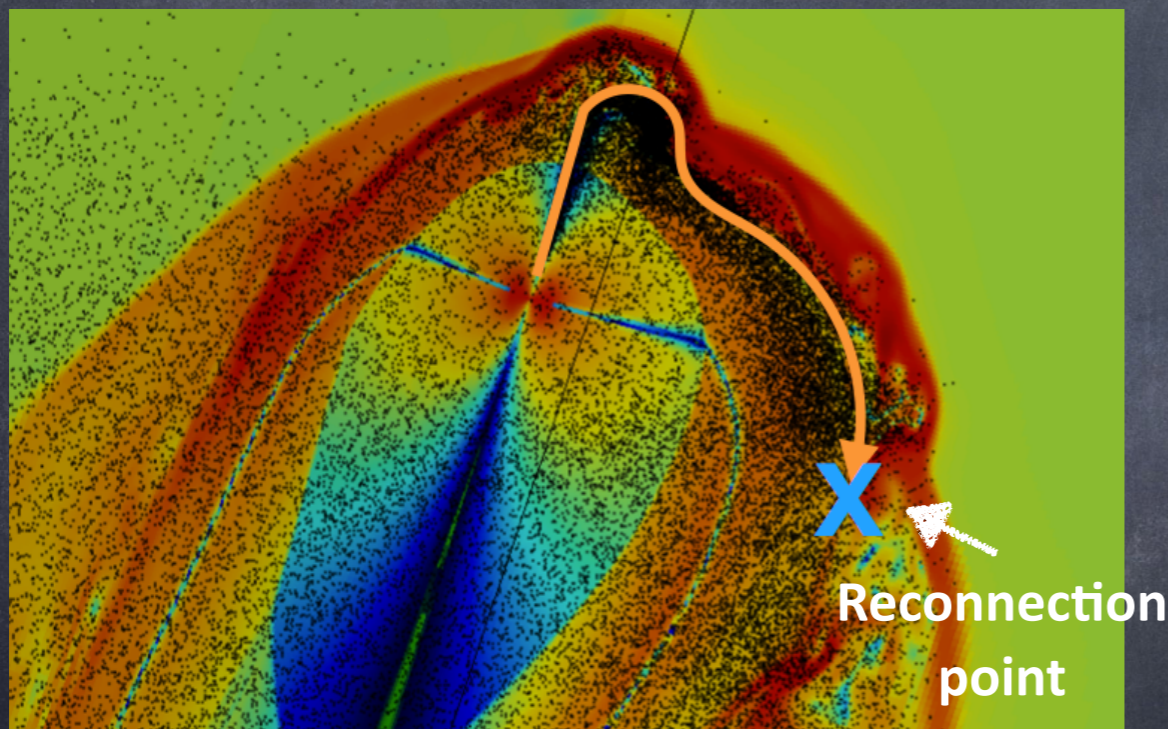
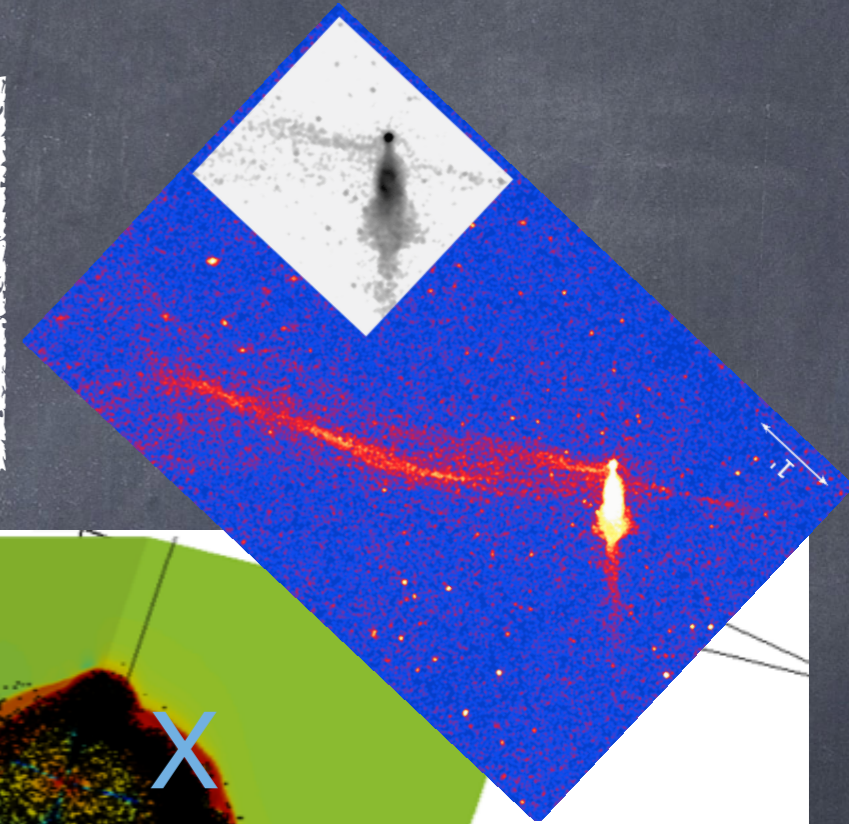


[Abeysekara+ 2017]

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

# PARTICLE ESCAPE FROM BOW SHOCK PWNe

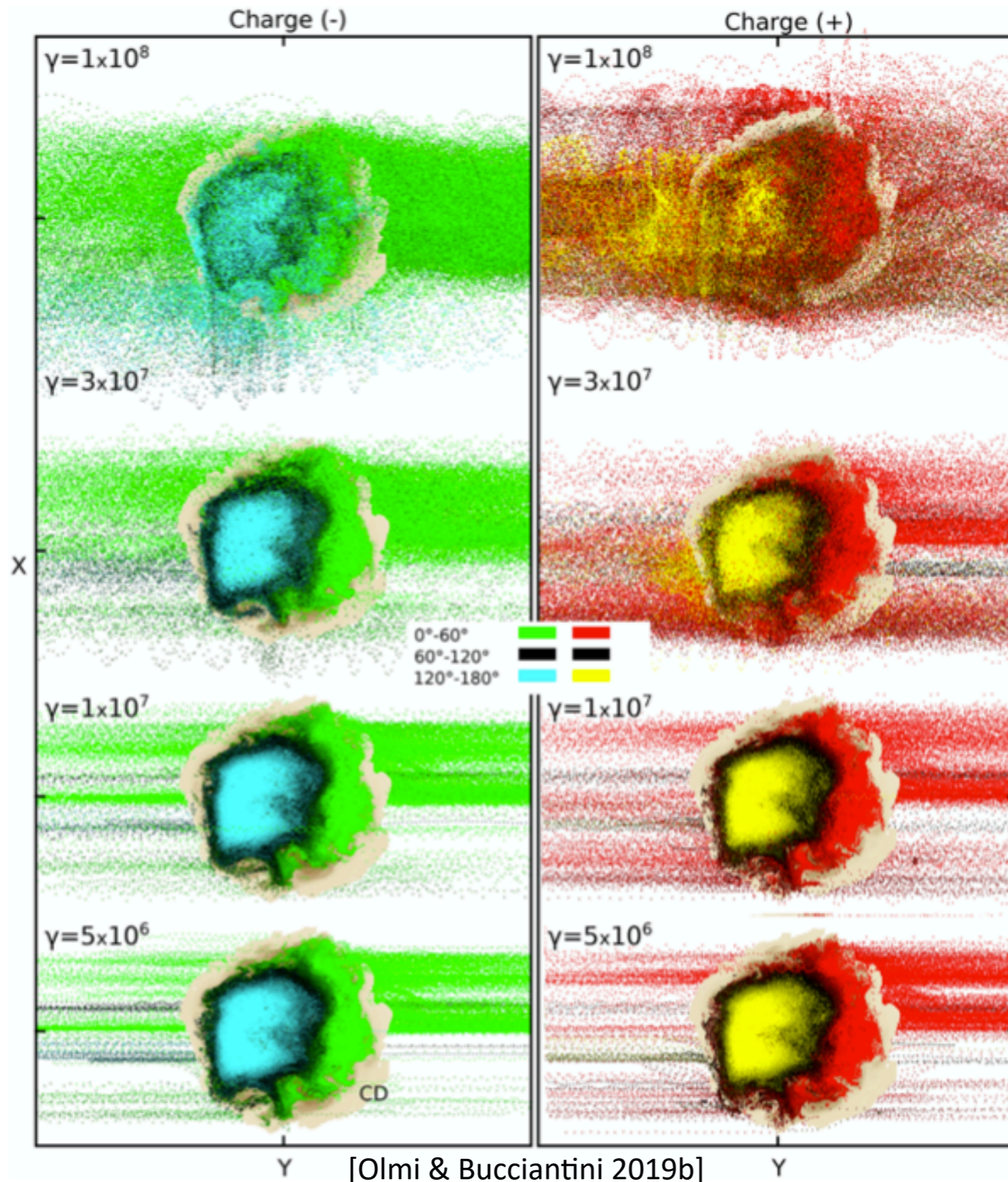
HIGH ENERGY PARTICLES  
INJECTED CLOSE TO THE POLAR AXIS  
STREAM OUT FROM RECONNECTION POINT AND  
FORM JETS IN THE ISM B-FIELD



Olmi & Bucciantini 2019b



# ENERGY DEPENDENCE OF THE ESCAPE



## 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...

# SUMMARY AND CONCLUSIONS

- HUGE PROGRESS IN OUR UNDERSTANDING OF PWNe FROM MULTI-D MHD DYNAMICS AND RADIATION MODELLING
- PARTICLE ACCELERATION MECHANISM PROGRESSIVELY BETTER CONSTRAINED BUT STILL UNCLEAR
- IN THE MEANTIME PWNe KEEP SURPRISING US AS EXTRAORDINARY ACCELERATORS:
  - THE CRAB NEBULA IS THE ONLY ASSESSED LEPTONIC PEVATRON SO FAR
  - ALSO A HADRONIC PEVATRON?
  - LHAASO SUGGESTS MORE PEVATRON PWNe
  - EVOLVED SYSTEMS SEEM TO ACCELERATE PARTICLES TO FULL POTENTIAL DROP
- PWNe AS CR SOURCES:
  - PWNe STILL THE MOST LIKELY CR POSITRON SOURCES ABOVE  $\sim 30$  GeV
  - THEIR SPECTRUM ALSO NATURALLY ACCOUNTS FOR BREAK IN CR ALL-LEPTON SPECTRUM
- PWNe AND CR TRANSPORT
  - STILL UNCLEAR HOW WIDESPREAD TeV HALOES SHOULD BE
    - ISOTROPIC PARTICLE ESCAPE ONLY AT THE HIGHEST ENERGIES
    - ESCAPING PARTICLES CARRY ELECTRIC CURRENT THAT MAY AMPLIFY B-TURBULENCE

