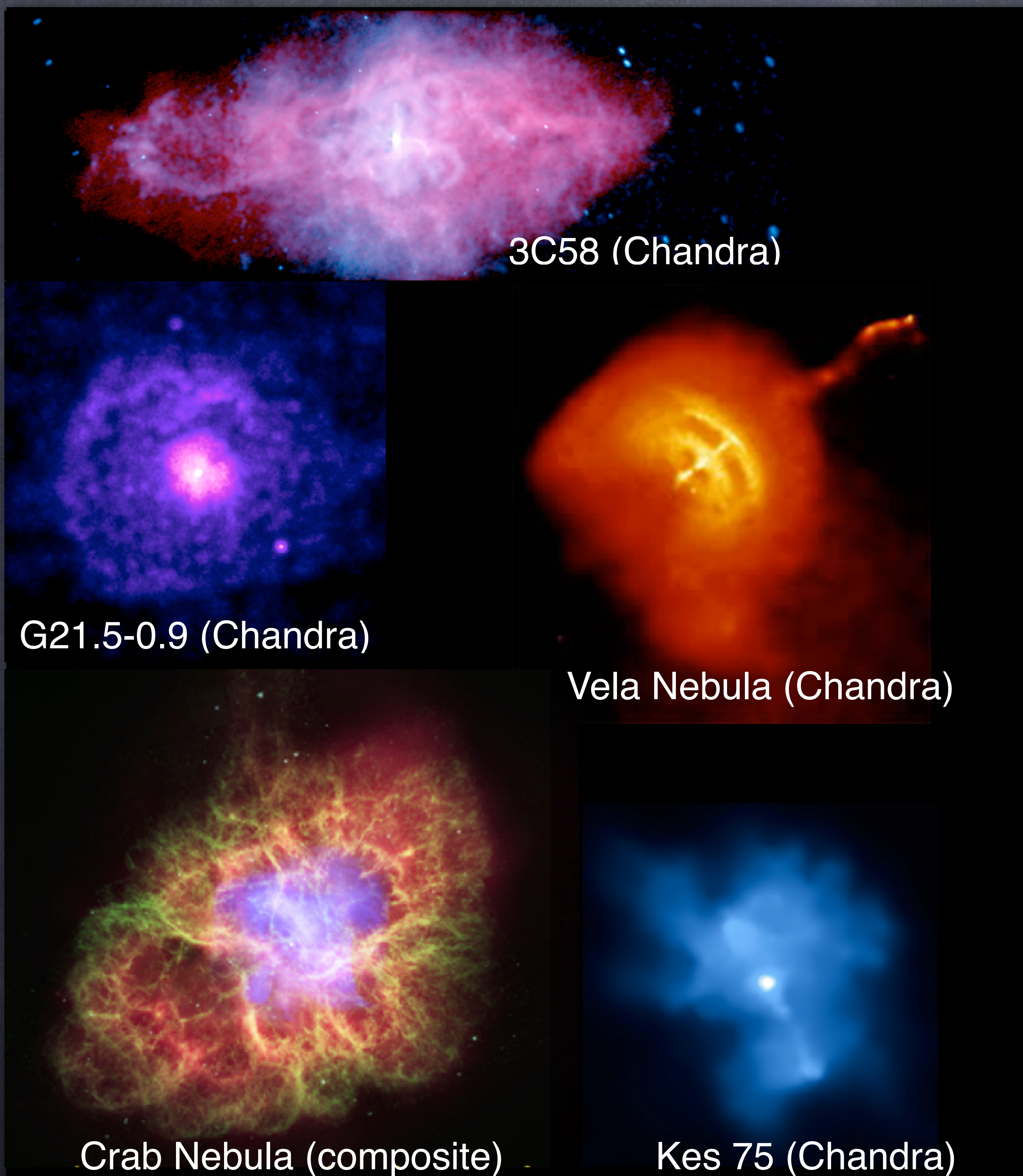
PULSAR WIND NEBULAE AS GALACTIC PEVATRON CANDIDATES

Elena Amato

INAF- Osservatorio Astrofisico di Arcetri

Firenze - Italy

PULSAR WIND NEBULAE

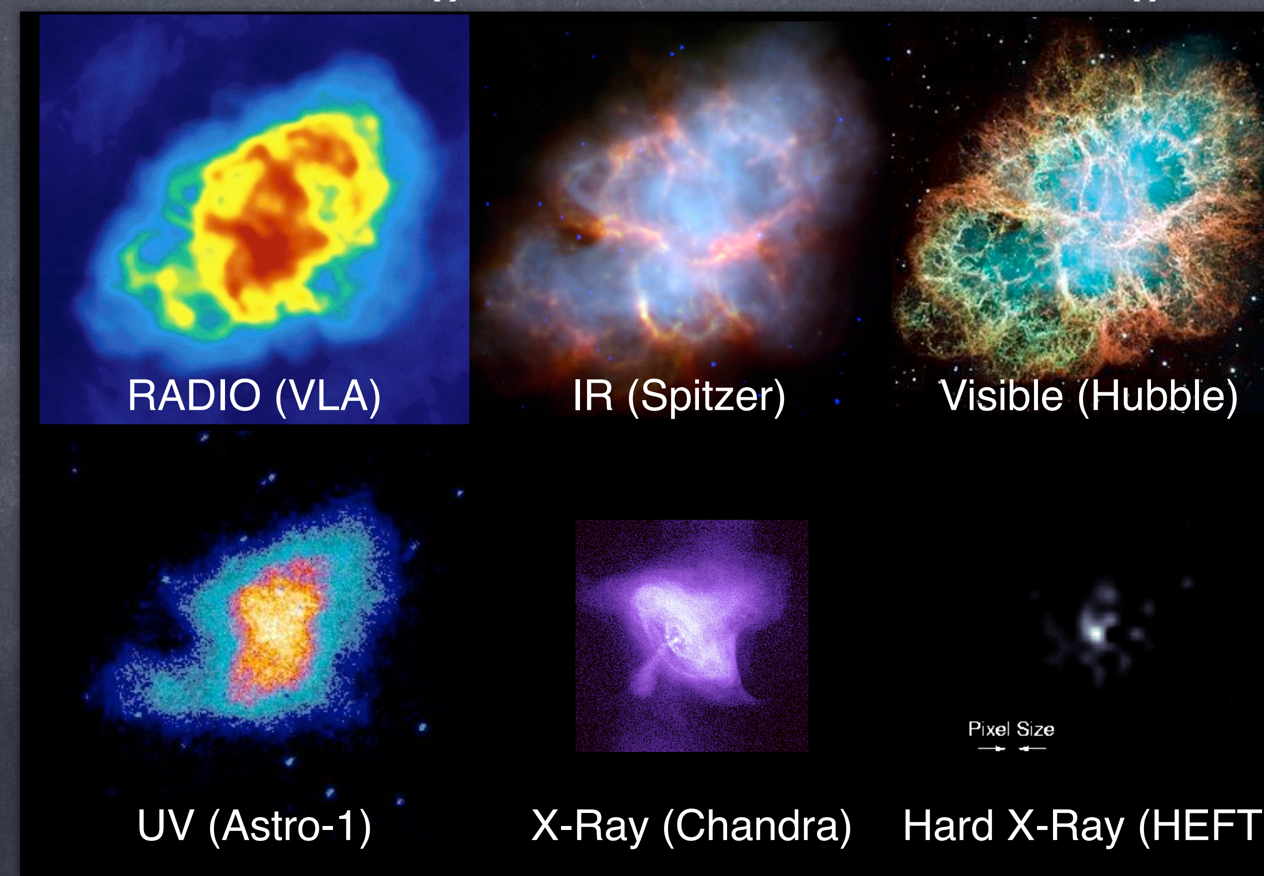


SNRs WITH

- 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



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 $(10^4 < \Gamma < 10^8)$

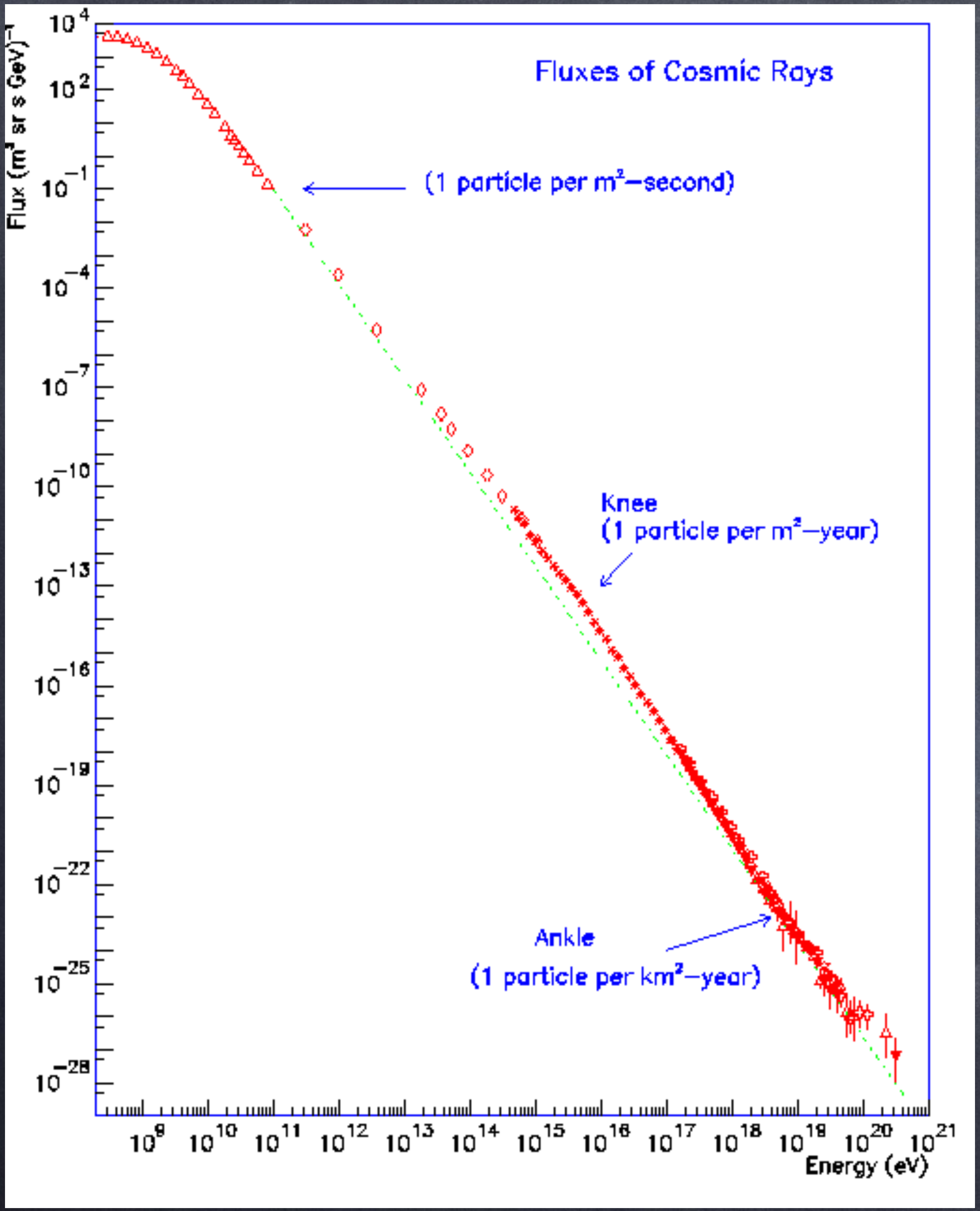
COSMIC RAY PHYSICS:

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

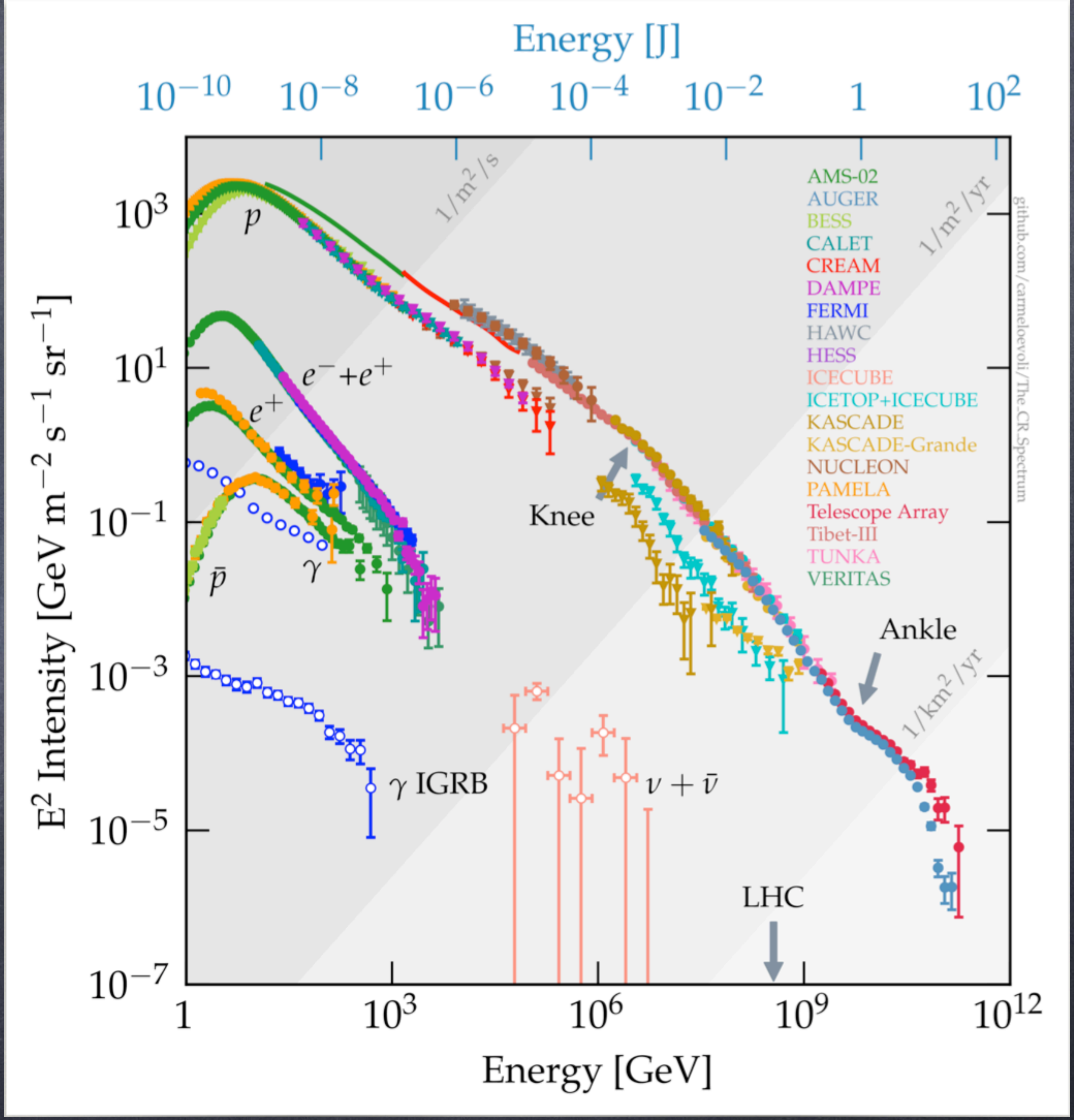
GAMMA-RAY ASTROPHYSICS:

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

COSMIC RAYS

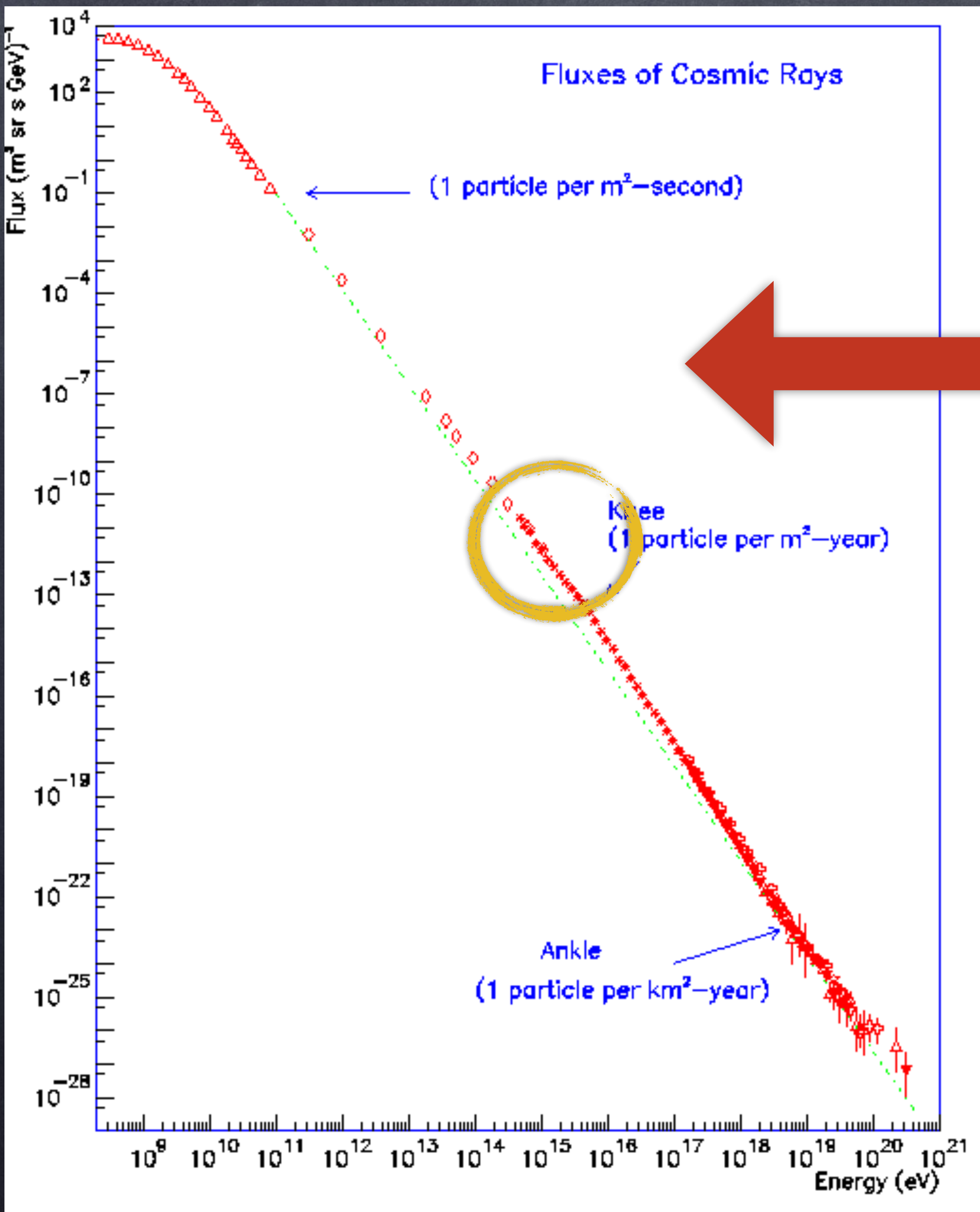


Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)



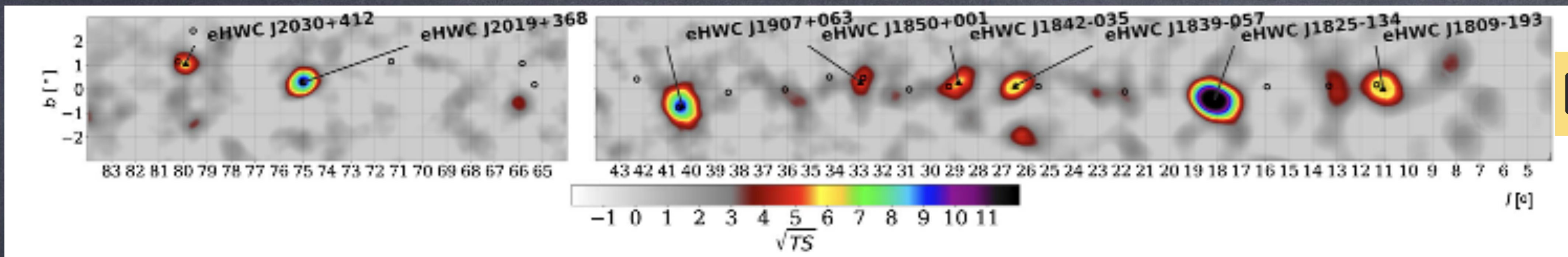
Energy [J]
E² Intensity [GeV m⁻² s⁻¹ sr⁻¹]
Energy [GeV]
AMS-02
AUGER
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP+ICECUBE
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
Telescope Array
Tibet-III
TUNKA
VERITAS
Knee
Ankle
LHC
γ IGRB
ν + ν̄
1/m²/s
1/m²/yr
1/km²/yr
github.com/carmeloevoli/The_CR_Spectrum

THE QUEST FOR PEVATRONS

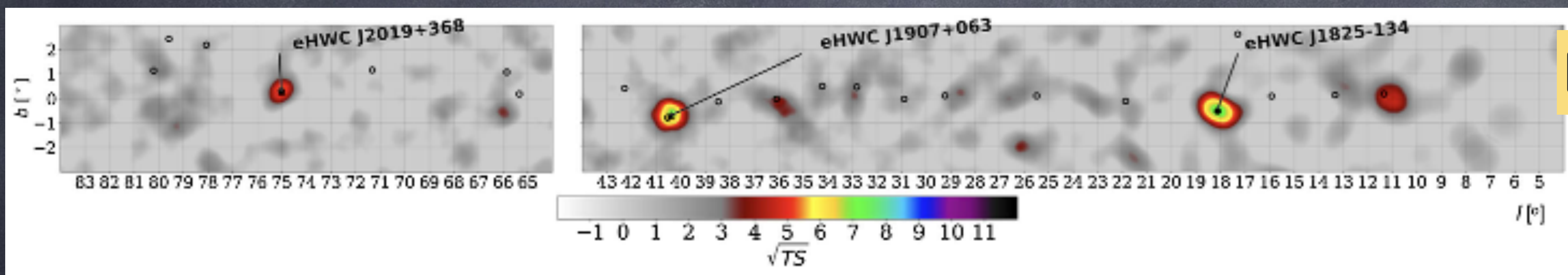


?

UHE SOURCES IN THE GALAXY



HAWC >56 TeV



HAWC >100 TeV

Abeysekara + 2020

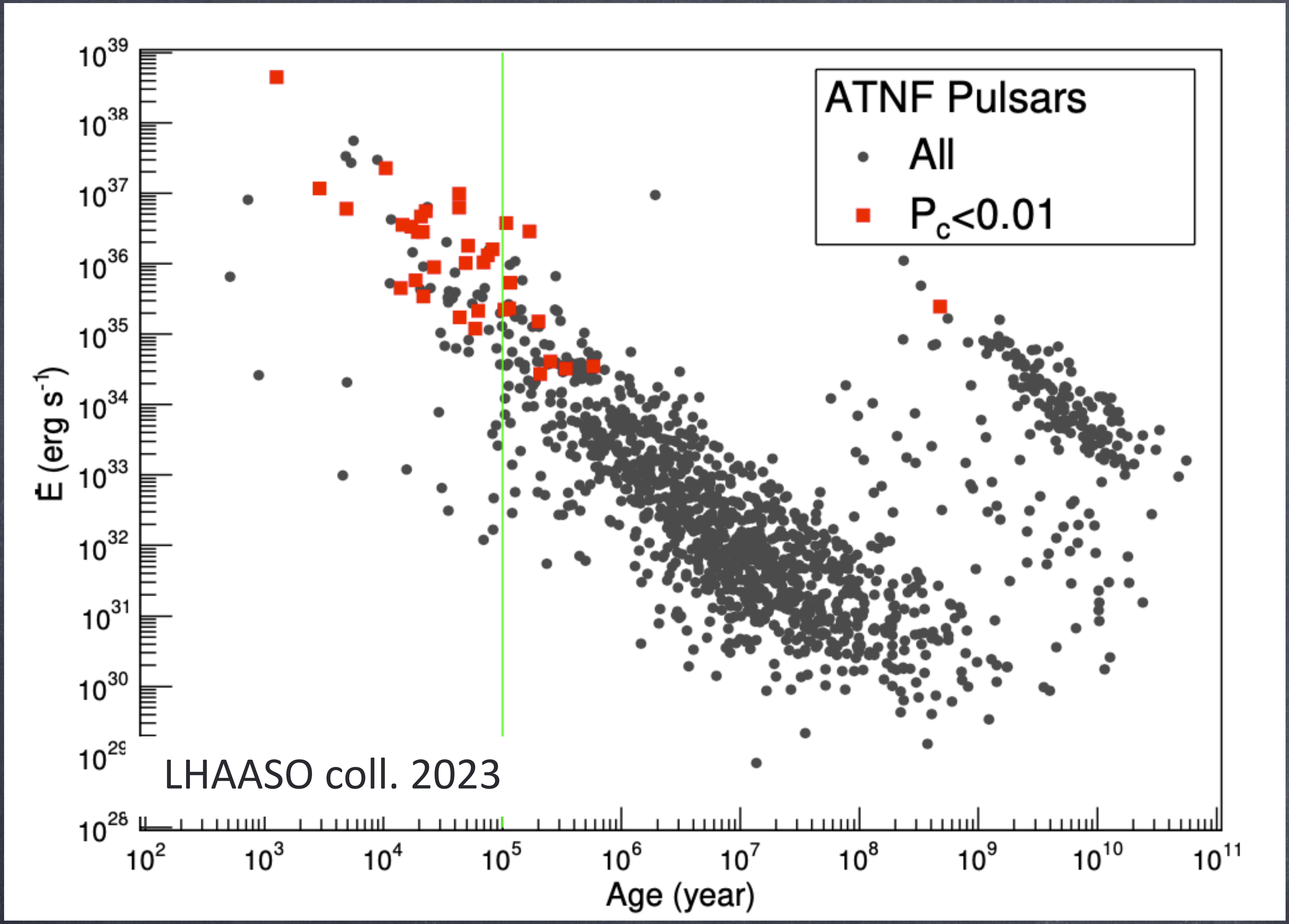
LHAASO >100 TeV

Table 1 | UHE γ-ray sources

Cao+ 2021

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)	NO PSR
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)	

PULSAR ASSOCIATIONS IN 1LHAASO

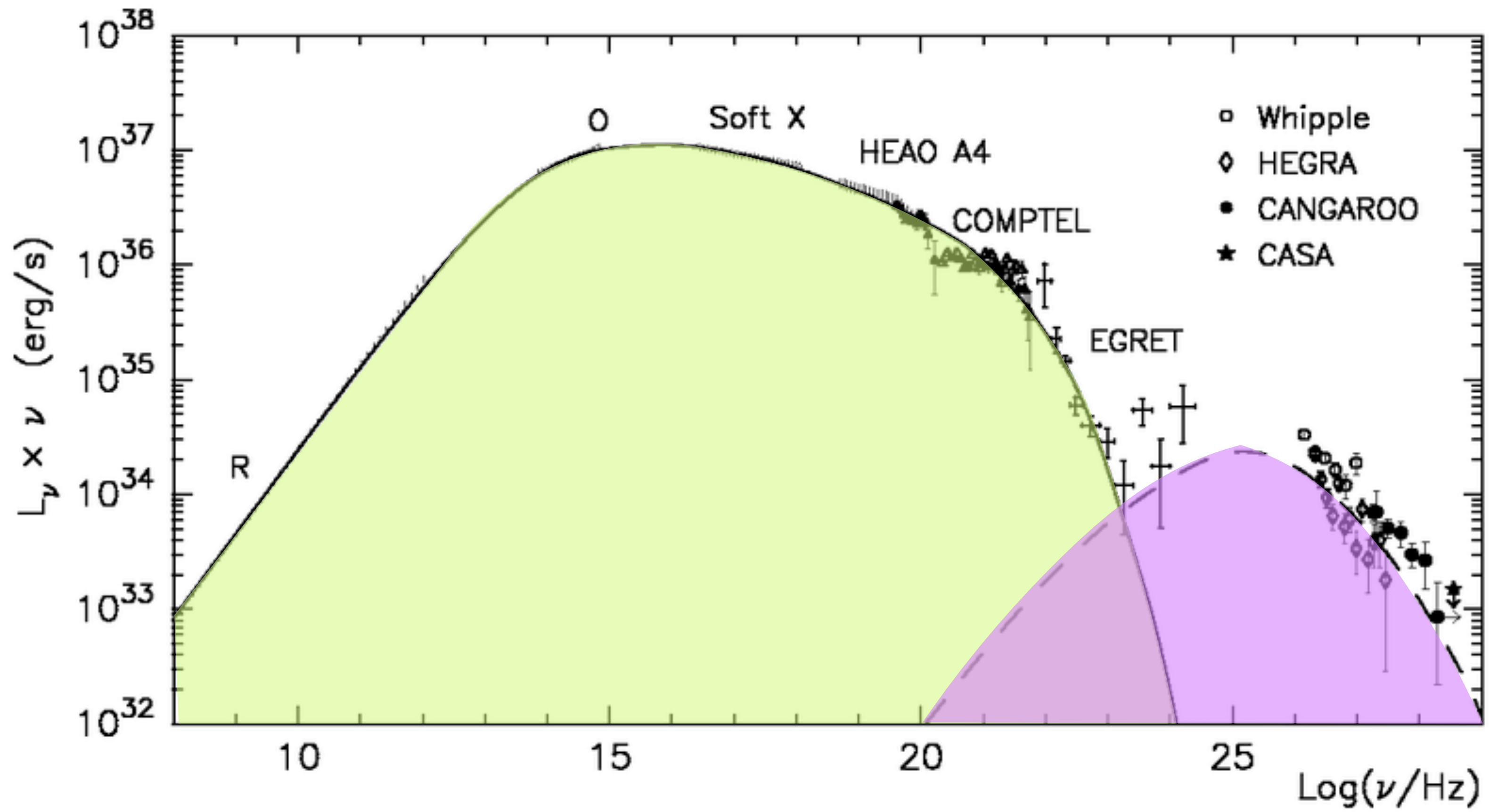


- 35 ASSOCIATIONS WITH PULSARS OUT OF 90 SOURCES
- 22 UHE OUT OF 43
- POSSIBLY THE ONLY SOURCES IN THE GALAXY ABLE TO ACCELERATE LEPTONS TO PeV ENERGIES

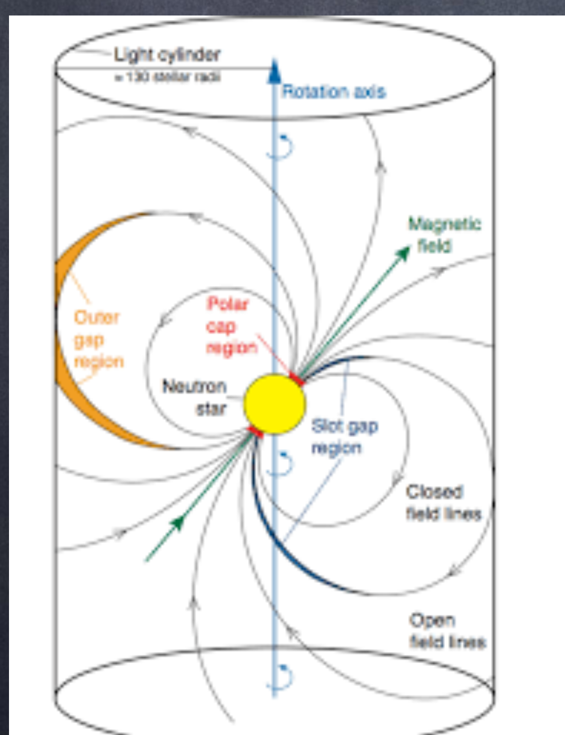
WHAT WE KNOW ABOUT PWNE

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



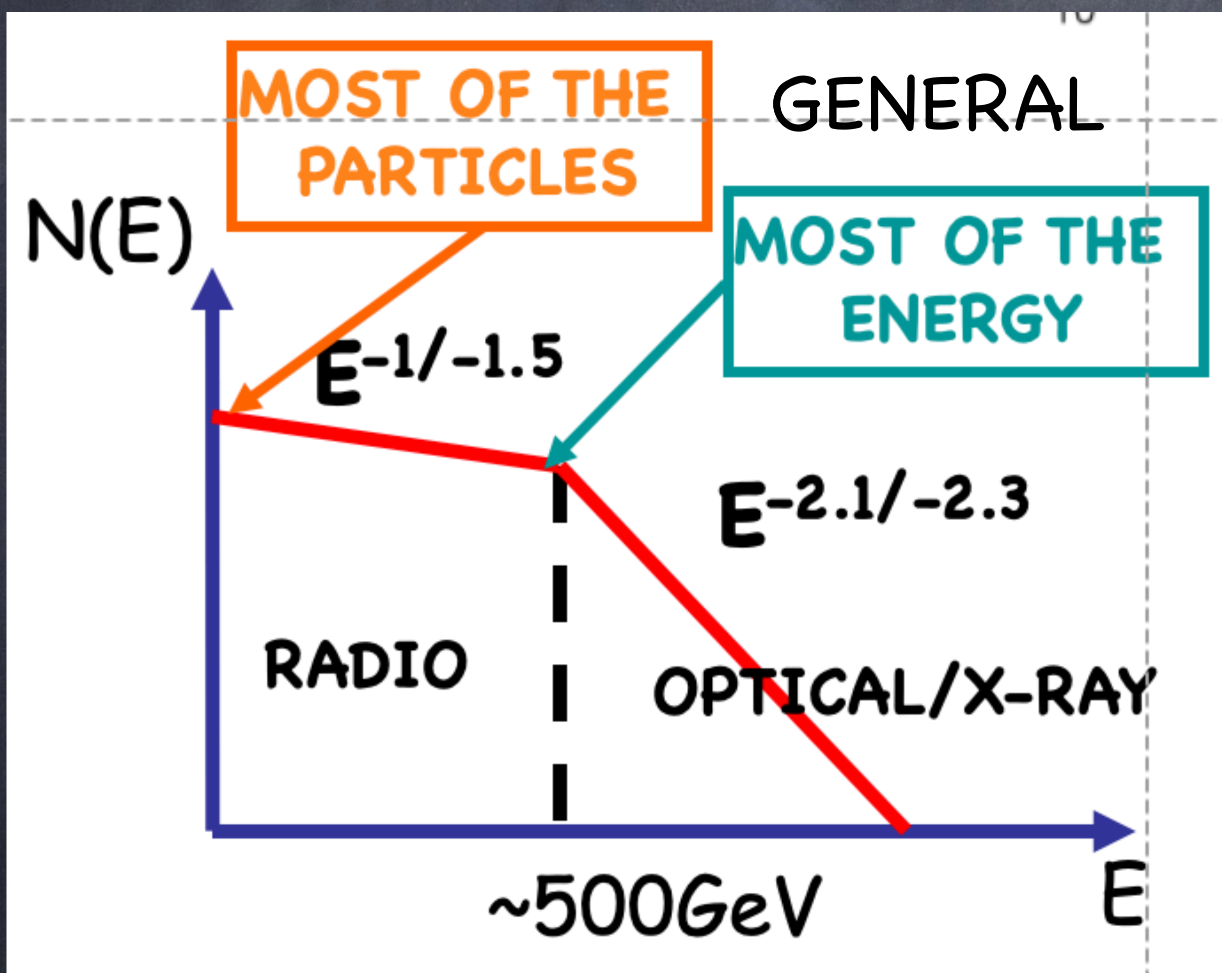
PARTICLES AND FIELD
FROM ROTATIONAL ENERGY LOST BY PULSAR

PSR IS A ROTATING MAGNET THAT
SLOWS DOWN DUE TO E.M. TORQUE

PARTICLE SPECTRUM IN YOUNG PWNe

RADIATION SPECTRUM

PARTICLE SPECTRUM

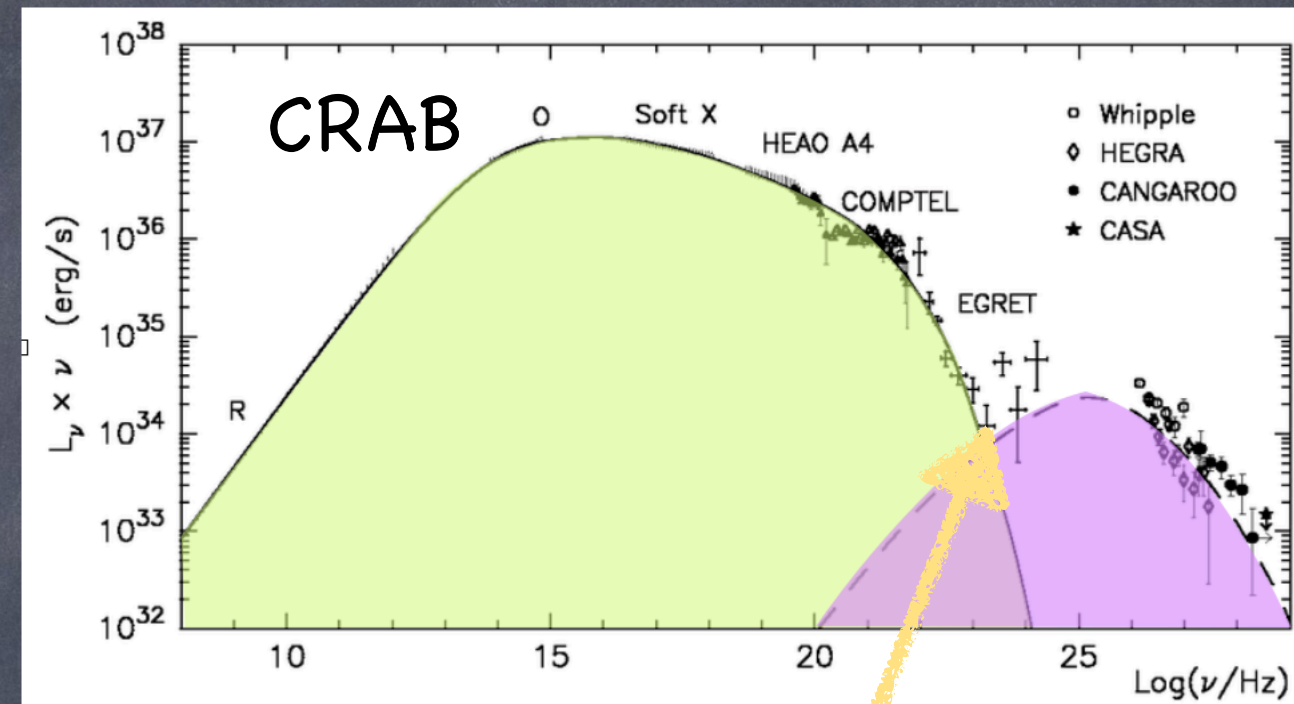


ONE ZONE MODELS

[Pacini & Salvati 1973, EA+ 2000, Bucciantini+ 2011....]

[also Fraschetti & Pohl 2017 for log-parabola injection]

[Comisso, Sobacchi & Sironi 2020 for alternative scenario]



PeV ELECTRONs

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

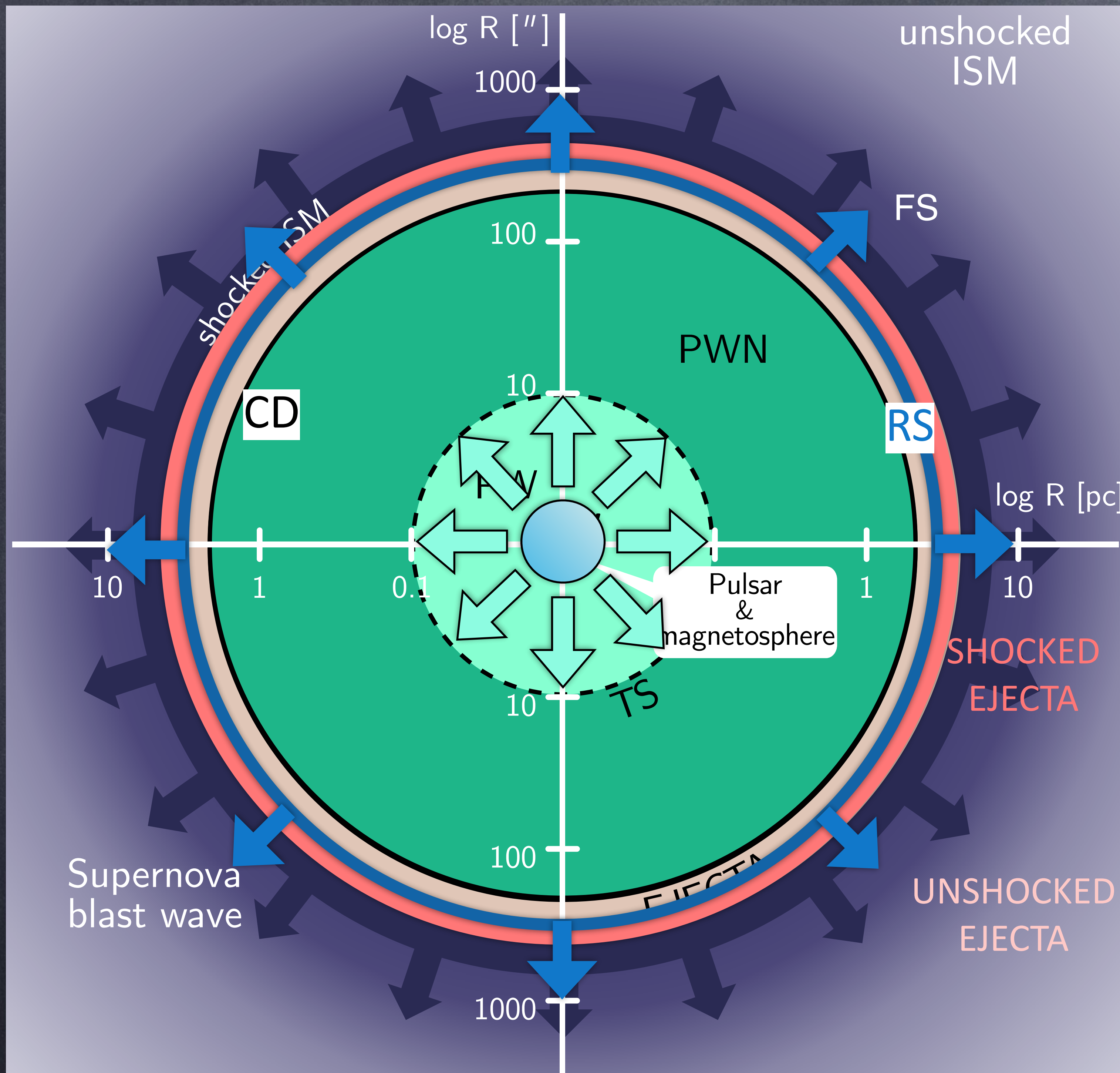
$L_{NEB} \approx 30\,\%\,\dot{E}$

EXTRAORDINARY ACCELERATOR!

POSSIBLY THE ONLY SOURCES IN THE GALAXY

ABLE TO ACCELERATE LEPTONS TO PeV ENERGIES

BASIC PICTURE FOR YOUNG SYSTEMS

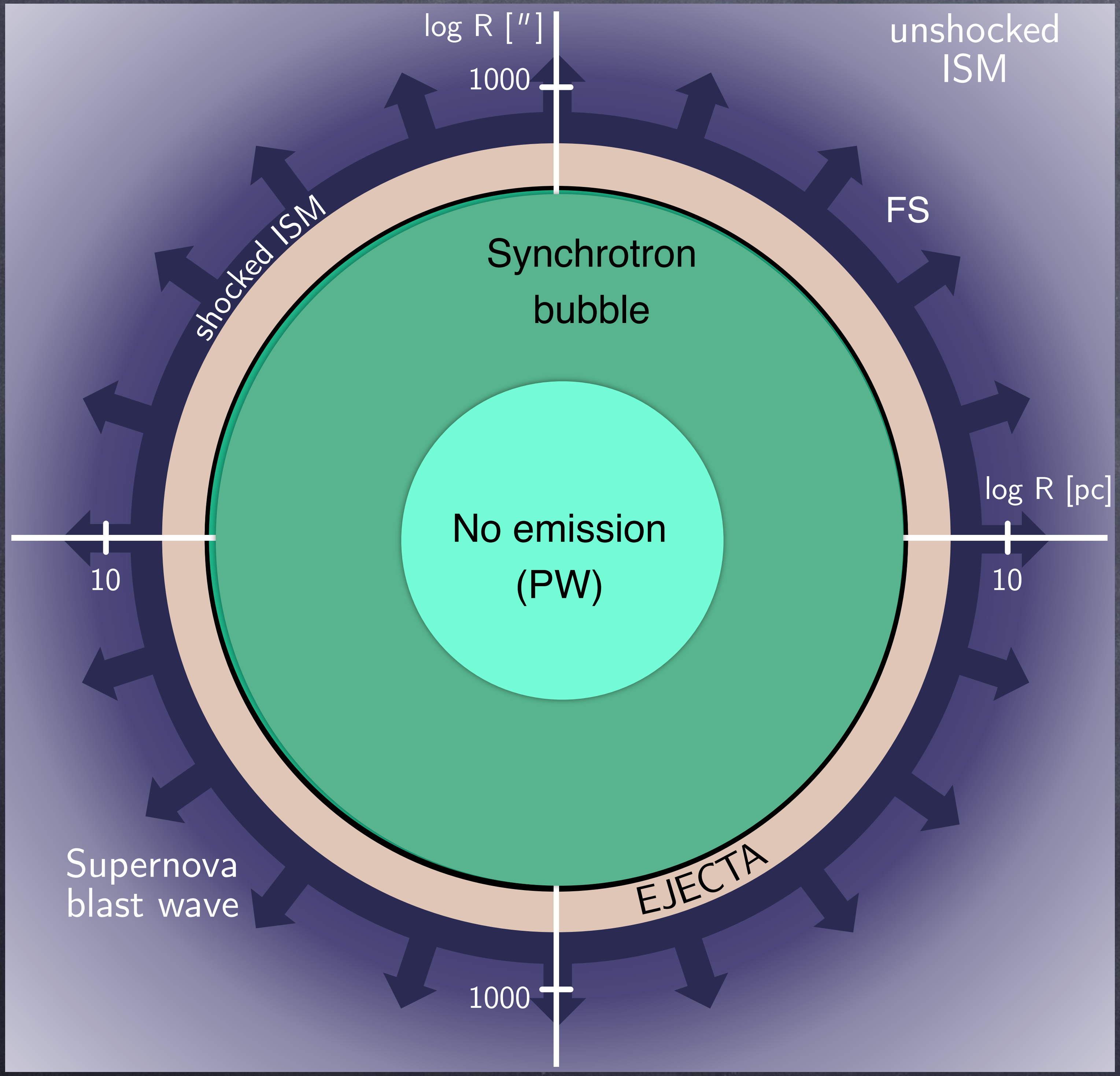


Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

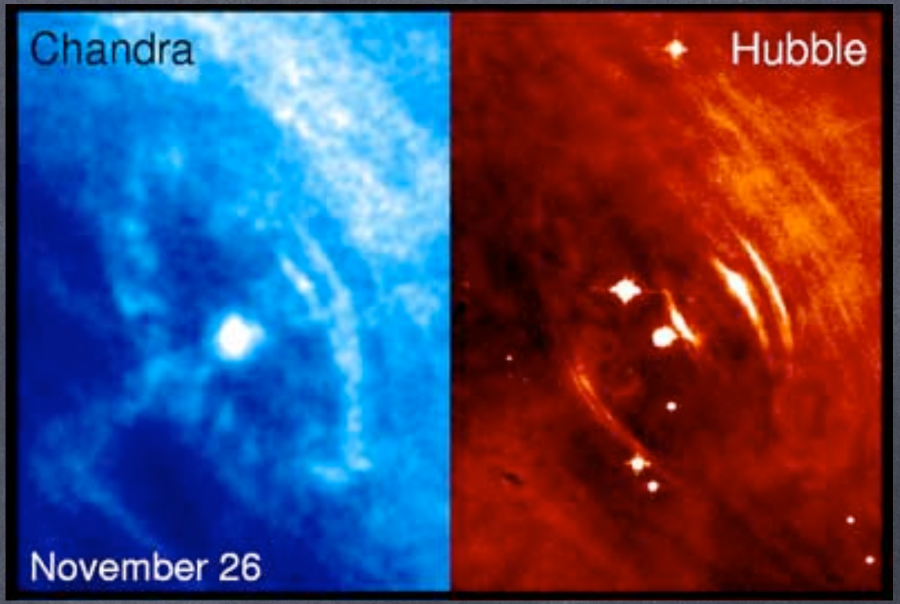
$$\frac{\dot{E}}{4\pi c R_{TS}^2} = P_{PWN} = \frac{\dot{E}\ t}{4\pi R_N^3}$$

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

BASIC PICTURE FOR YOUNG SYSTEMS



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



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

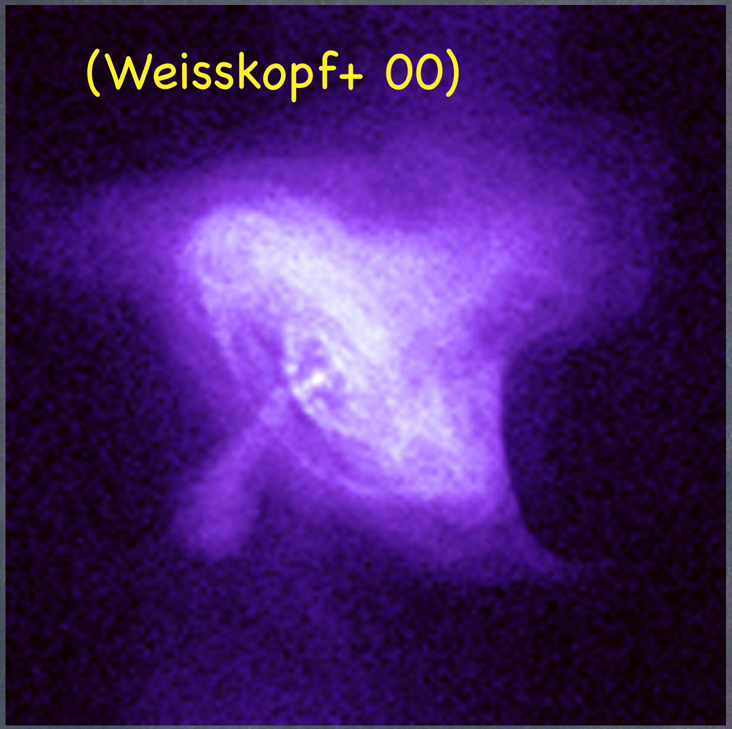
DISSIPATION AND PARTICLE ACCELERATION AT TS

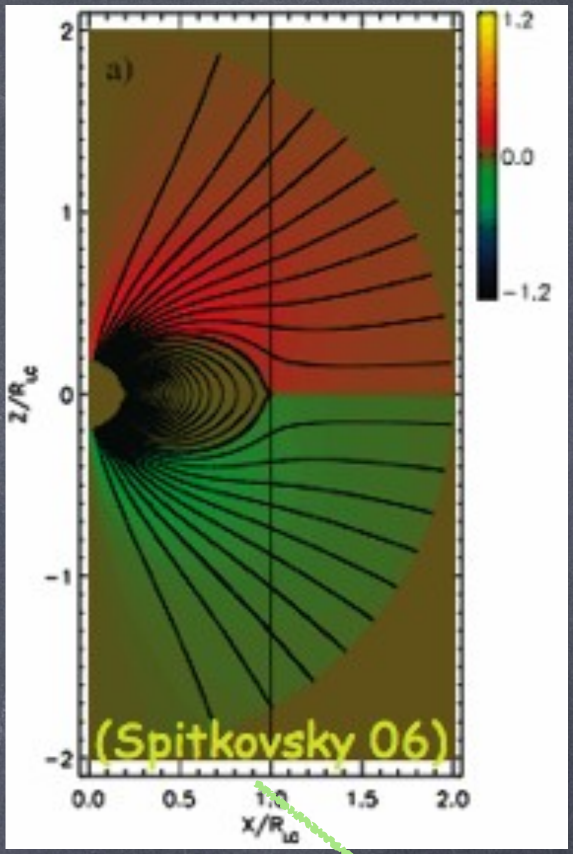
MODELING THE PSR WIND

TOTAL WIND POWER:

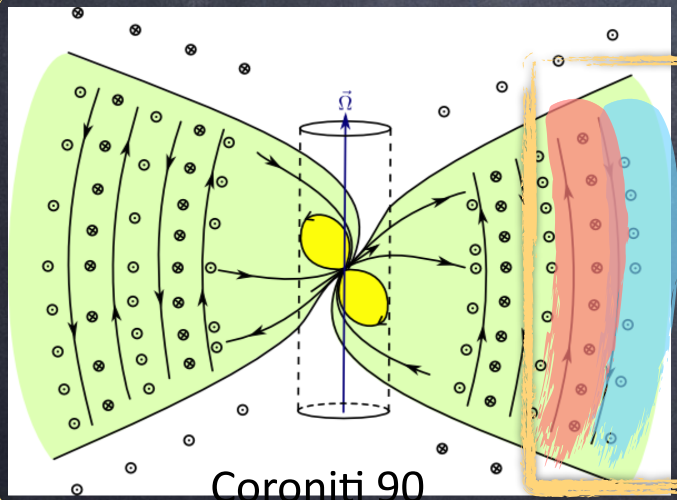
$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e}\right)(1+\sigma)$$

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



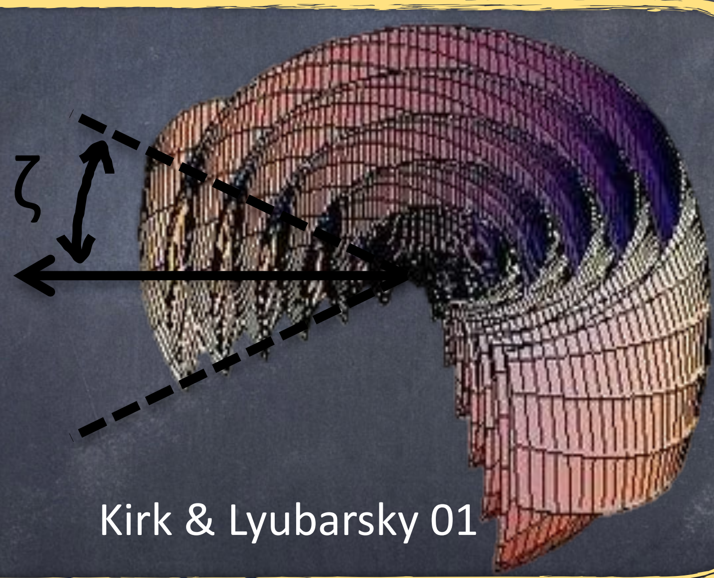


$$F(\theta) \propto \sin^2(\theta)$$


Coroniti 90

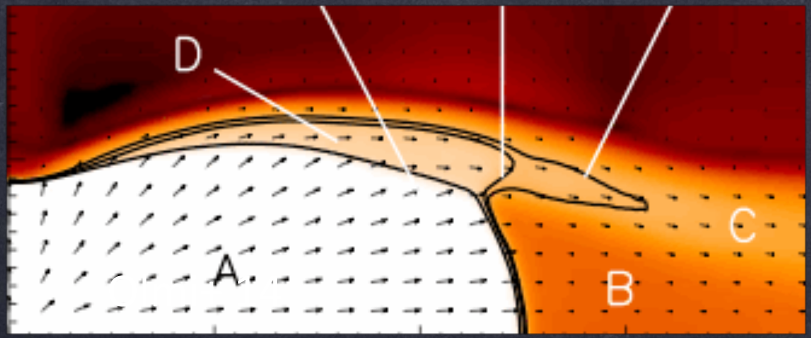
alternating stripes of opposite B polarities

dissipation in current sheet



Kirk & Lyubarsky 01

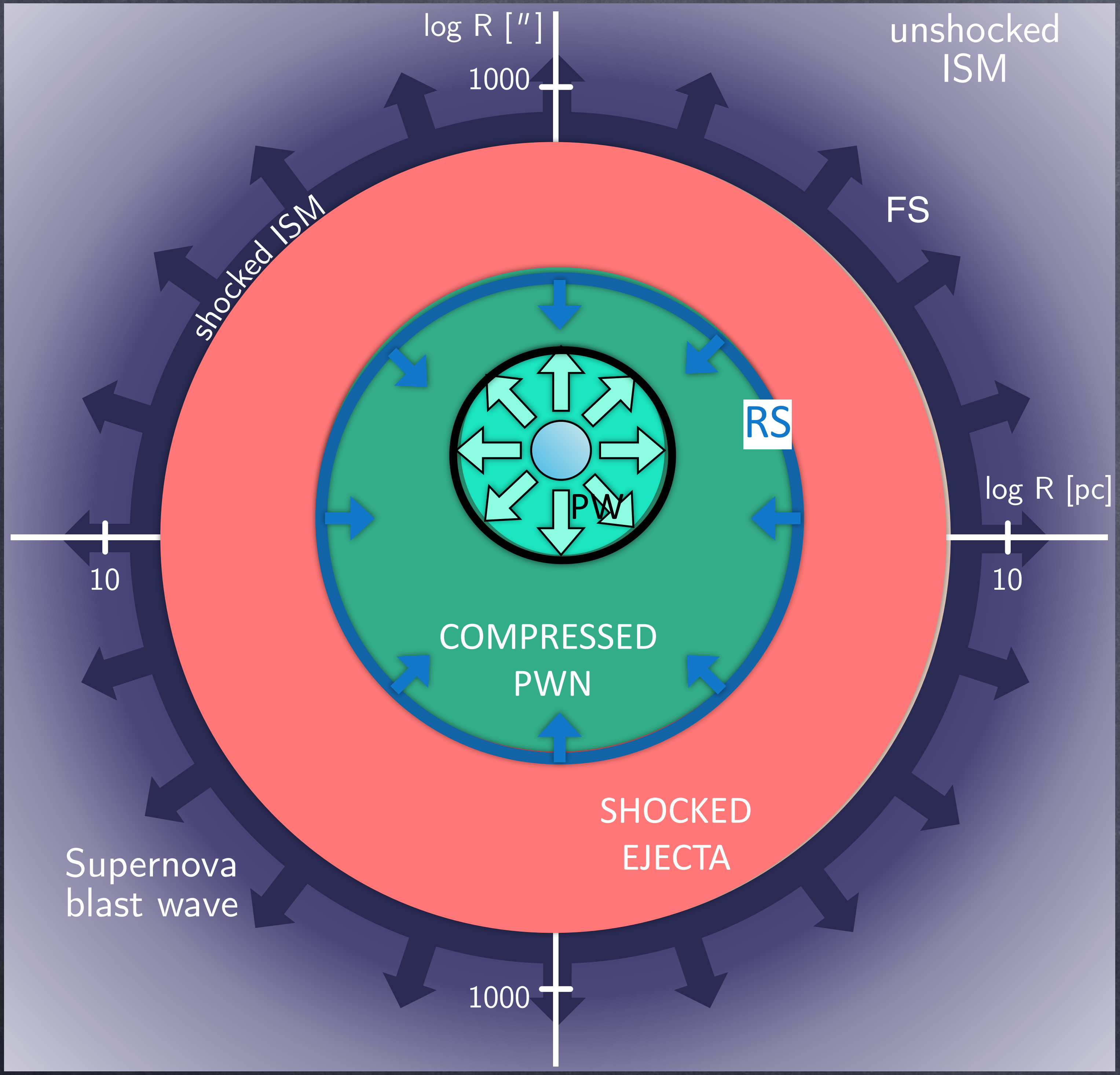
$$B(\theta) \propto \sqrt{\sigma}\ \sin\theta\ G(\theta)$$



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

[Komissarov & Lyubarsky 03,04; Del Zanna+ 04,06]

PWN EVOLUTION

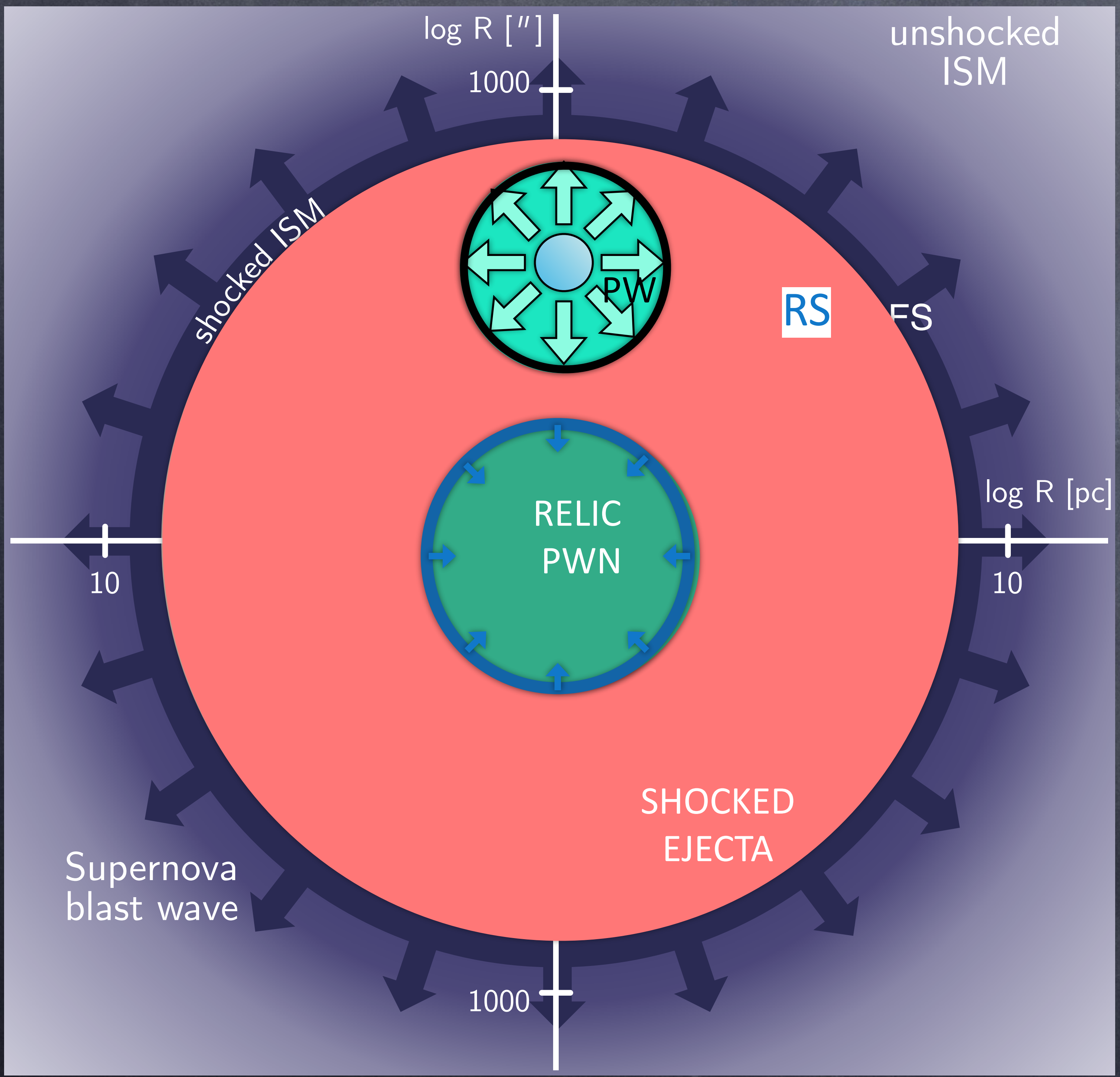


SNR EXPANSION
SLOWS DOWN
+
LARGE FRACTION OF
ALL THE PULSARS
BORN WITH
HIGH KICK VELOCITY

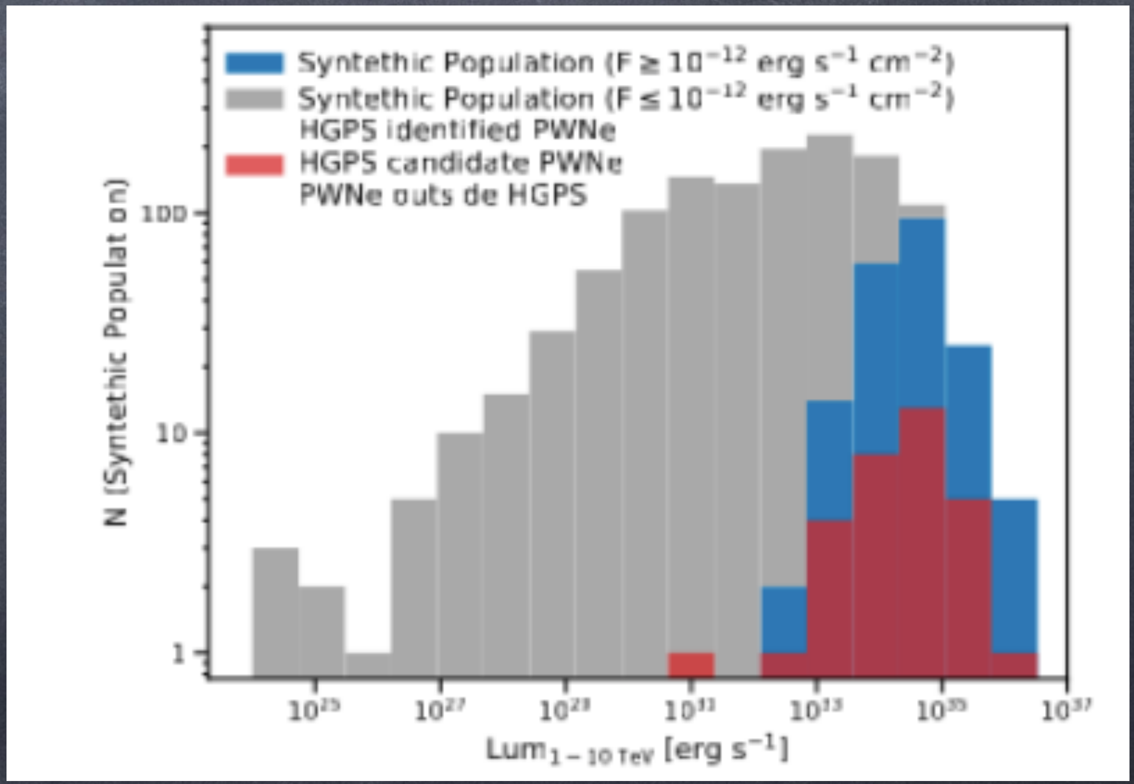
COMPRESSED PWN
OFFSET PW

REVERBERATION PHASE

RELIC NEBULAE



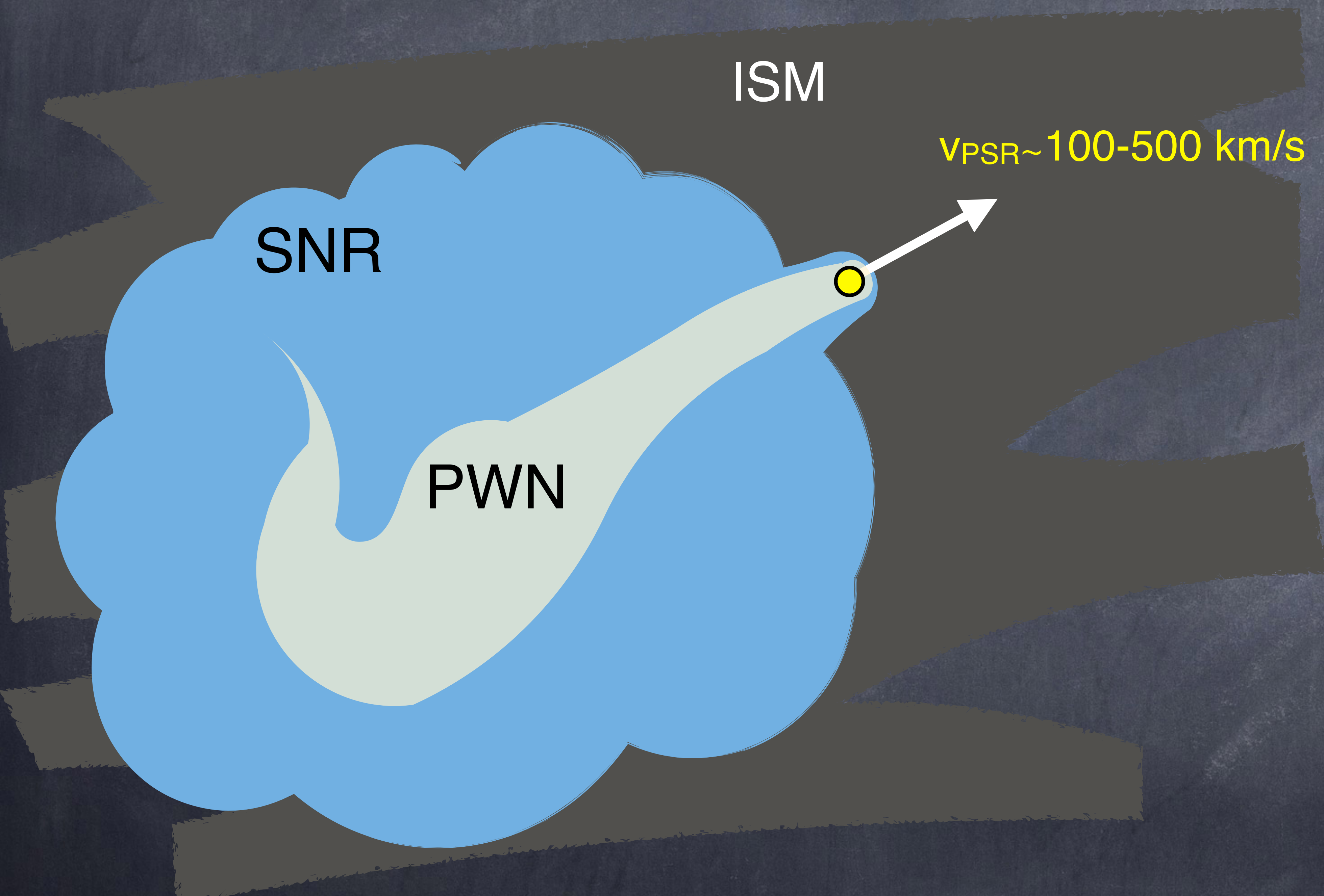
PSR MAY CROSS RS DURING COMPRESSION AND LEAVE A RELIC



[Fiori+ 22]

EVENTUALLY MOST GAMMA-RAY BRIGHT, X-RAY DIM PWNe

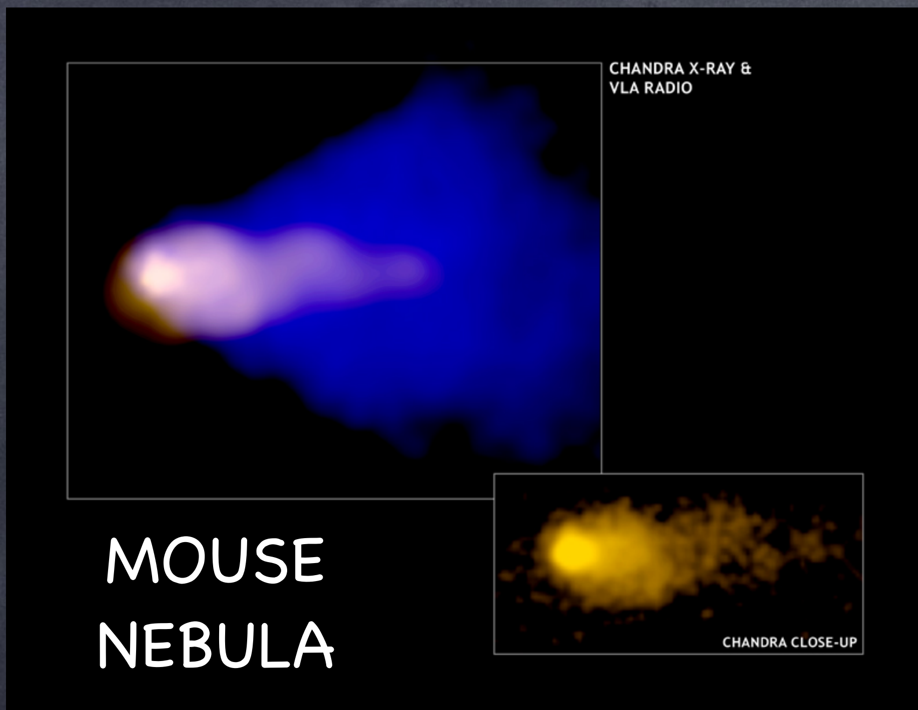
EVOLVED PWNe

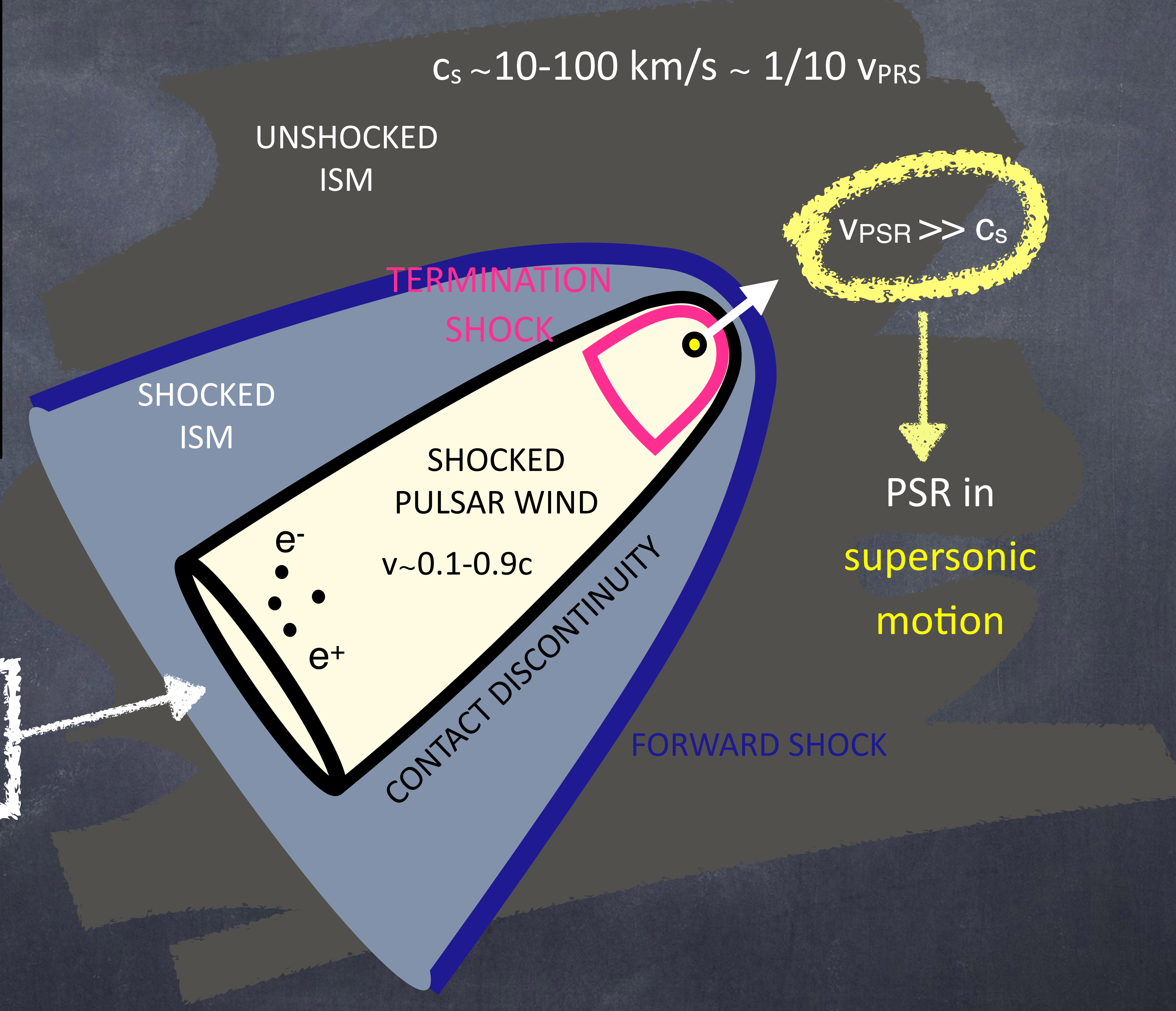


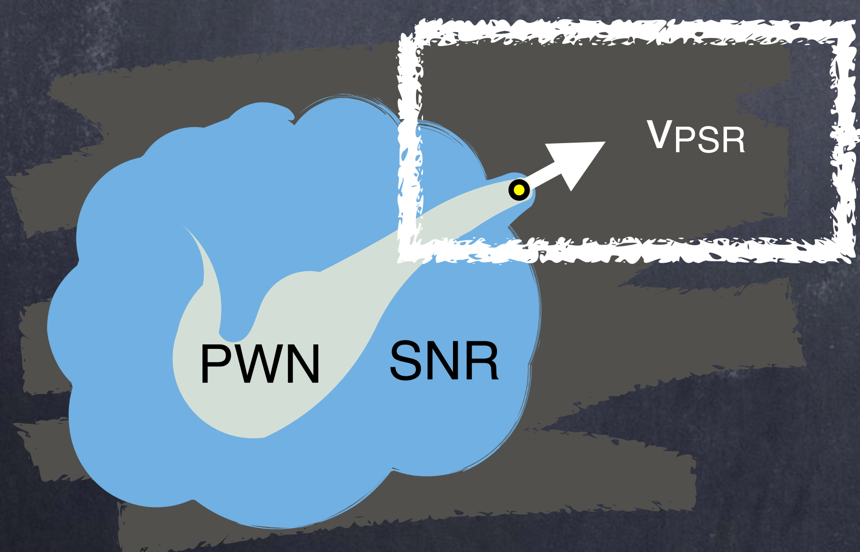
LARGE FRACTION OF ALL THE PULSARS BORN WITH HIGH KICK VELOCITY

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

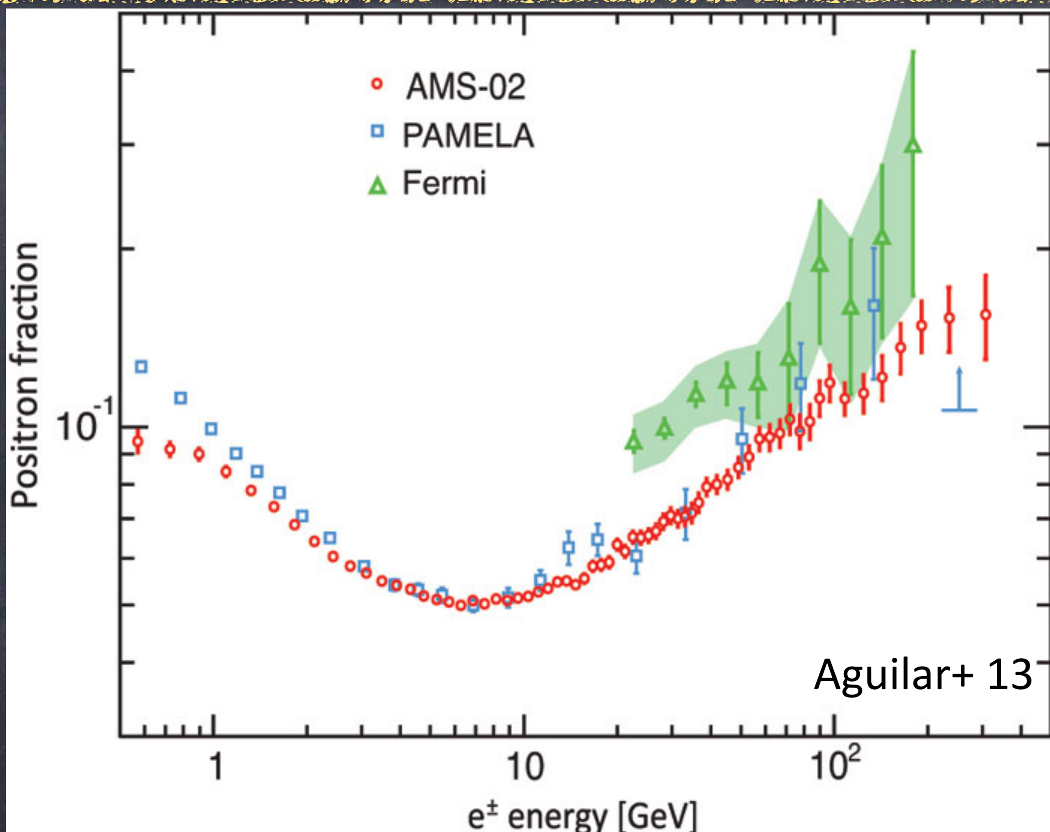
BOW SHOCK NEBULAE







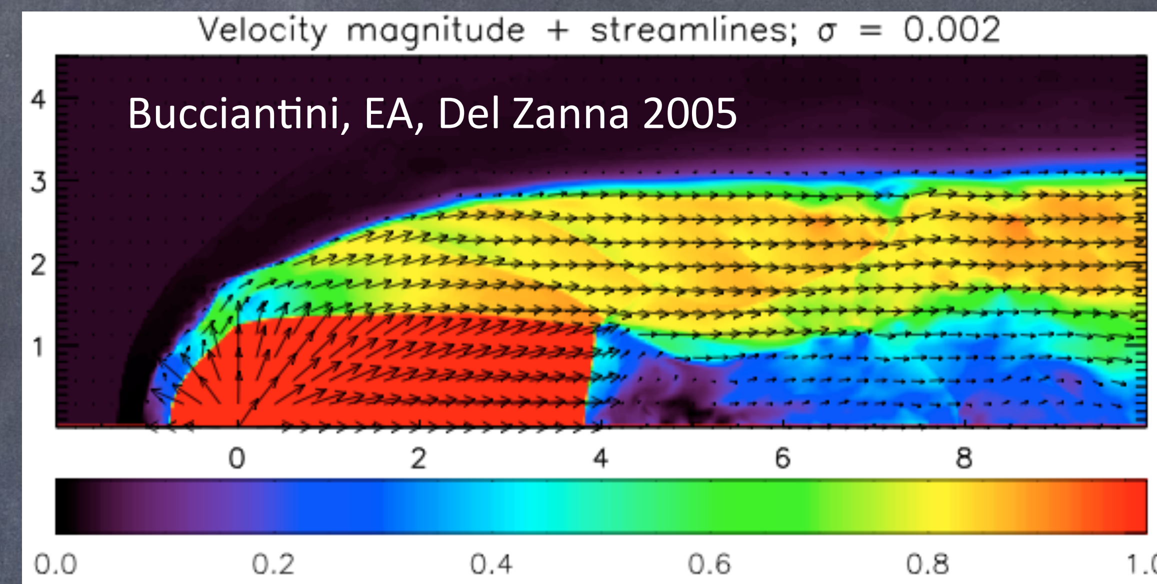
THE CR POSITRON EXCESS



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

BOW SHOCK PWNe EARLY SUGGESTED [Blasi & EA 11]

AS BEST CANDIDATES TO EXPLAIN THE EXCESS



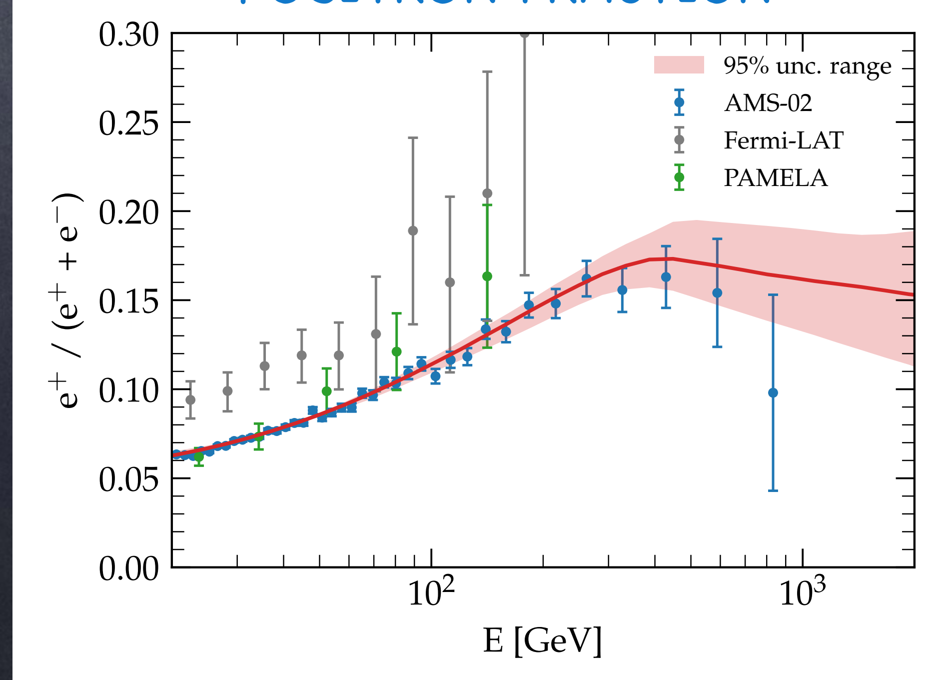
BS-PWNe INJECT $0.1\dot{E}$

AS A BROKEN

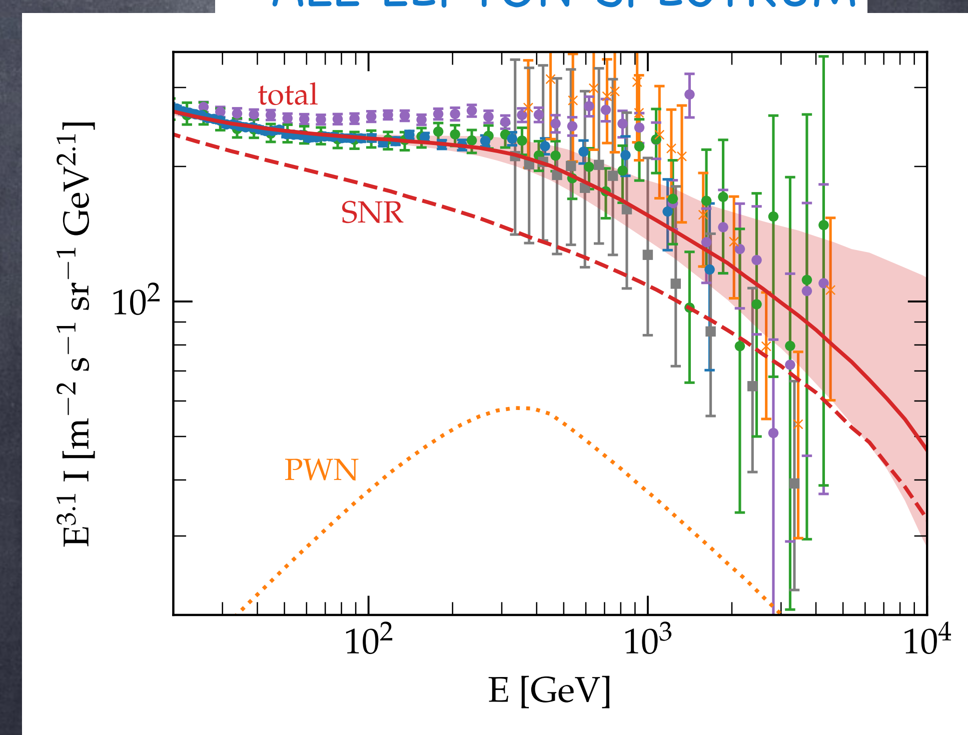
POWER-LAW OF e+-e- :

$E_B \approx 500\text{GeV}$

POSITRON FRACTION



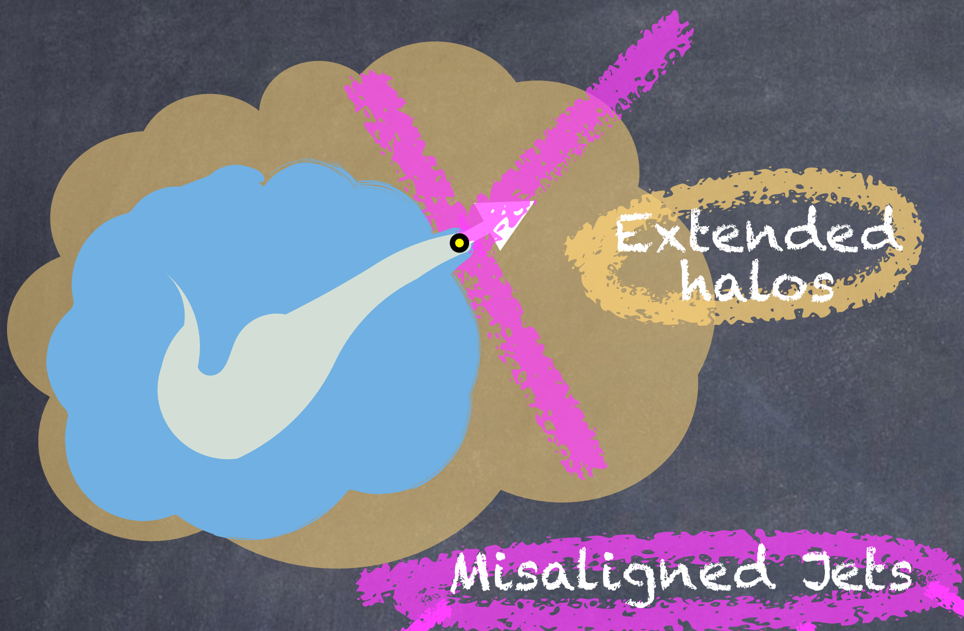
ALL LEPTON SPECTRUM



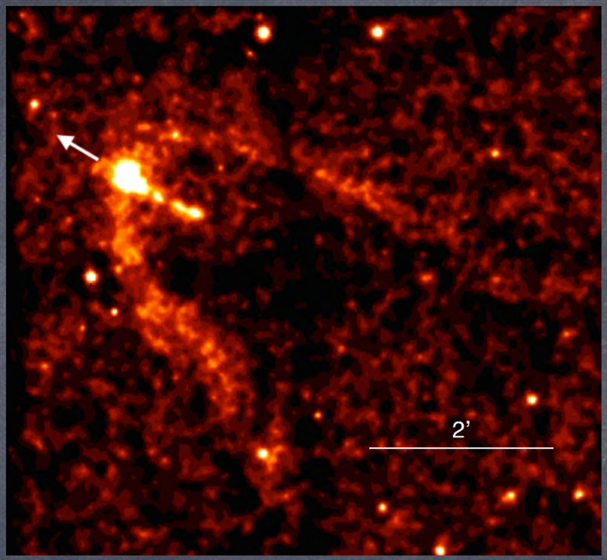
Evoli+ 21,22

EVIDENCE FOR PEV PARTICLES!

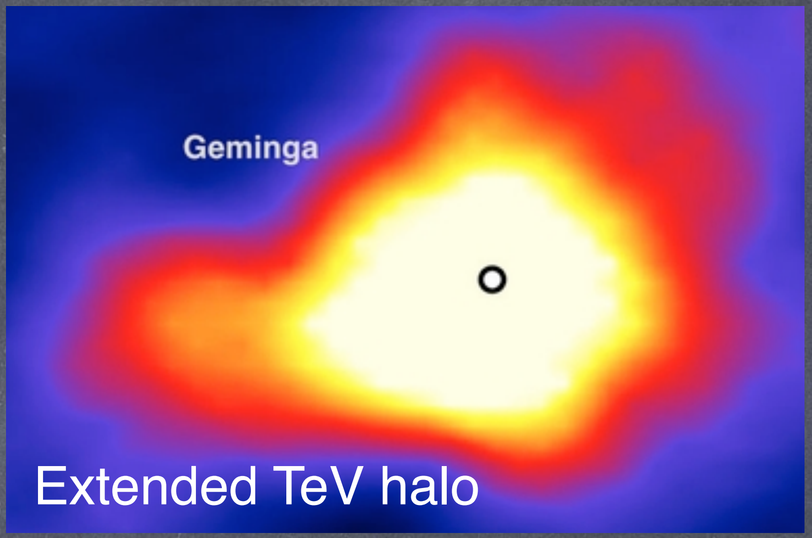
OBSERVATIONS OF JETS AND HALOES



X-ray

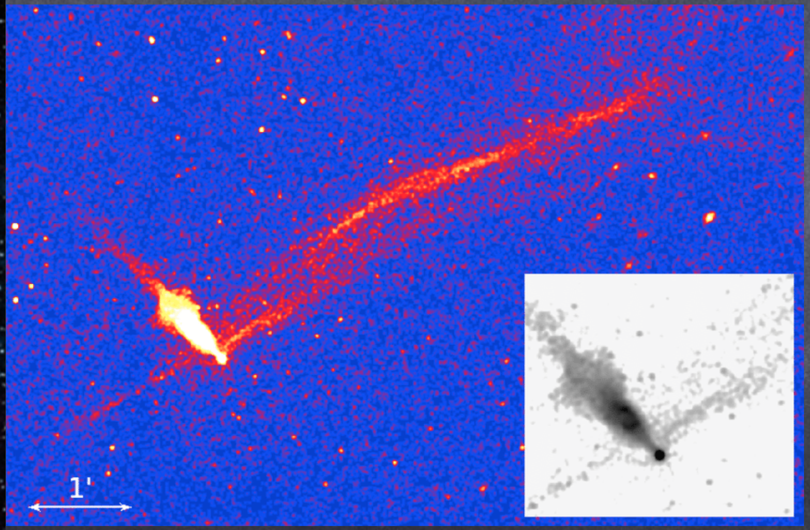


Geminga
[Posselt+ 2017]

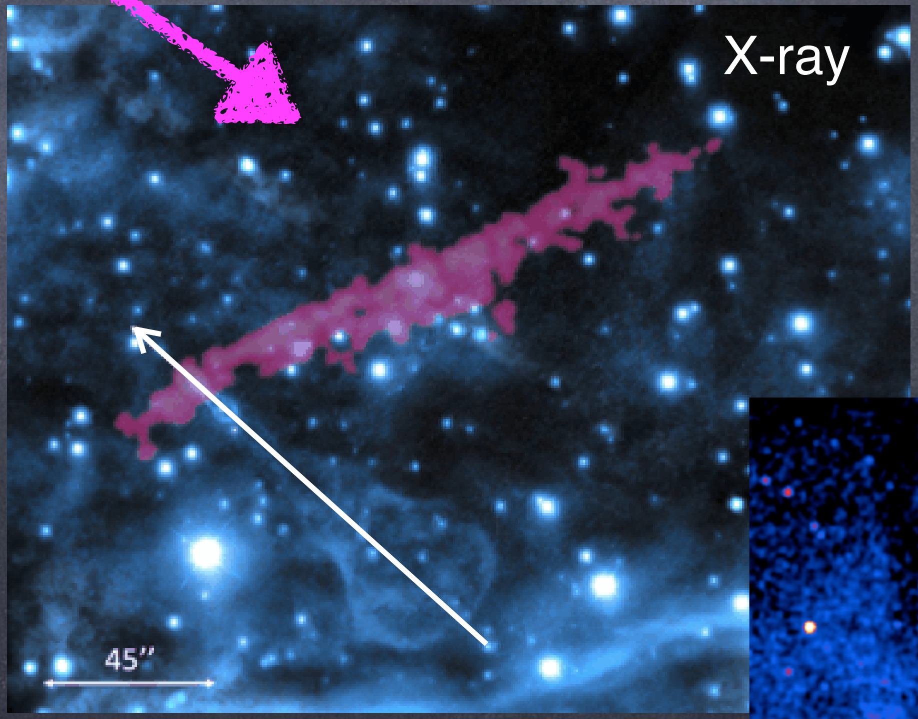


[Abeysekara+ 2017]

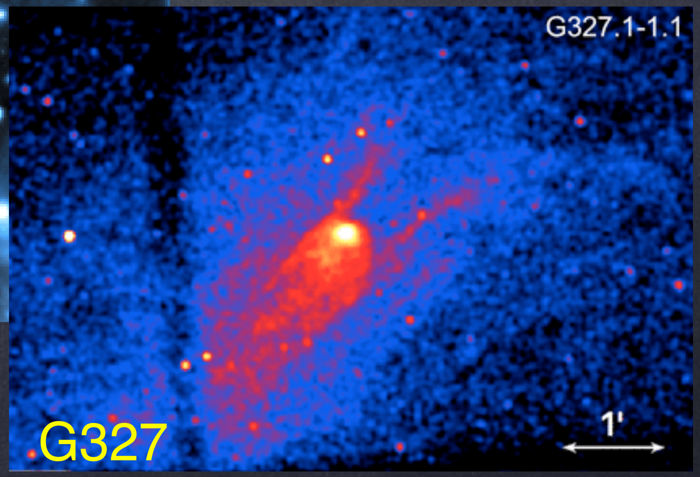
PSR J1509-5850
[Klinger+ 2016]



Lighthouse nebula
[Pavan+ 2016]



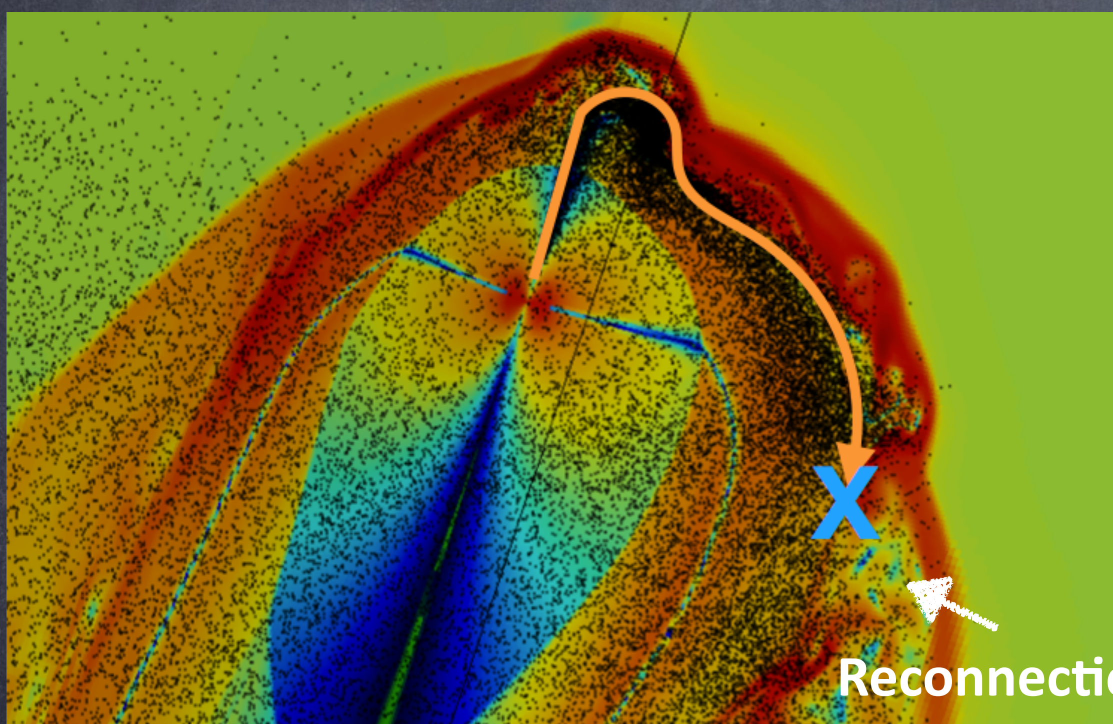
Guitar nebula
[Cordes+ 1993, Wong+ 2003]

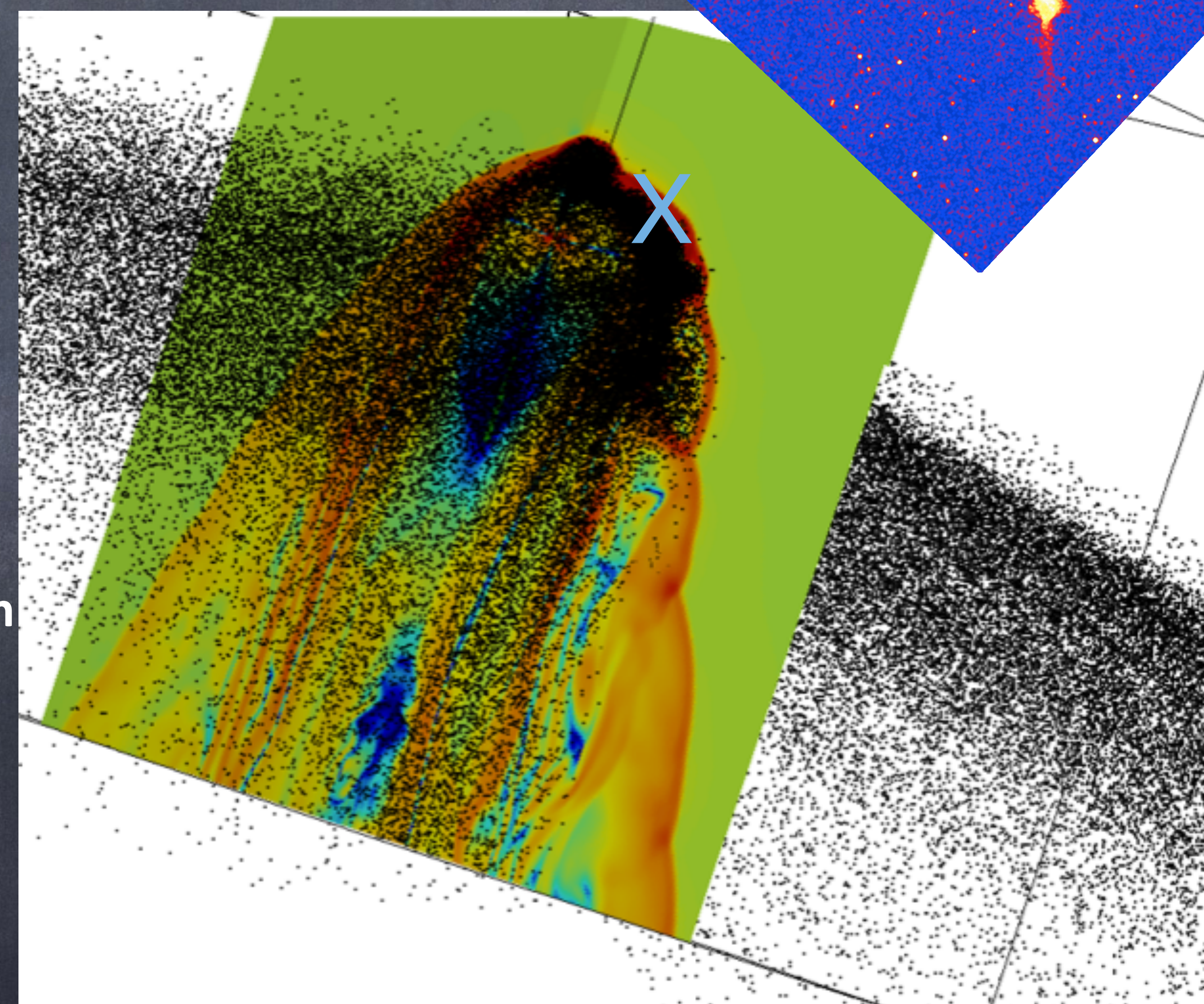


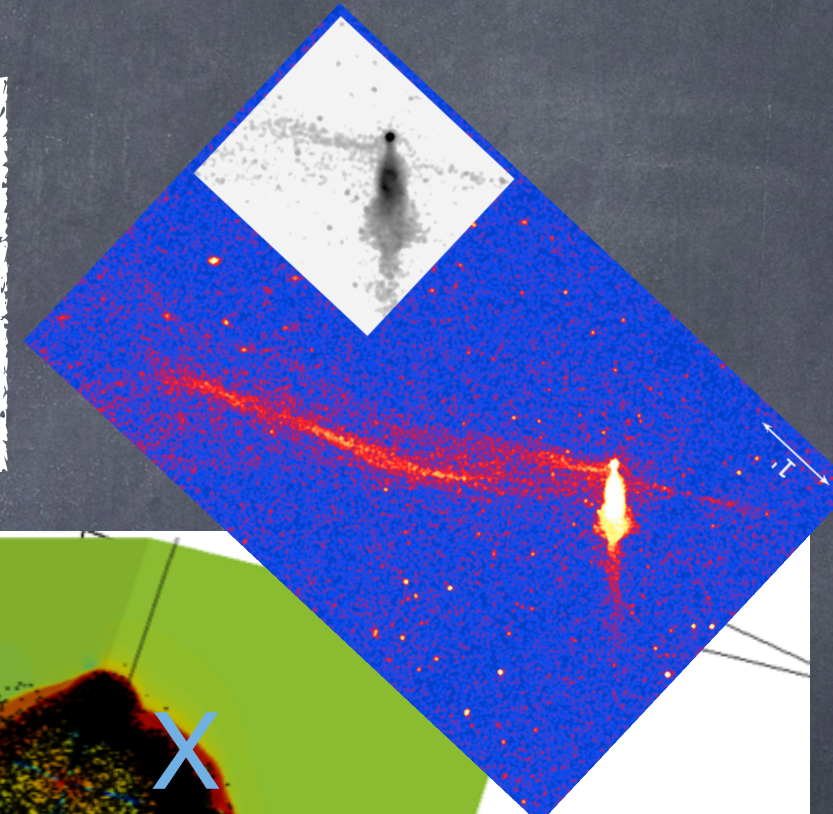
[Temim+ 2009]

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



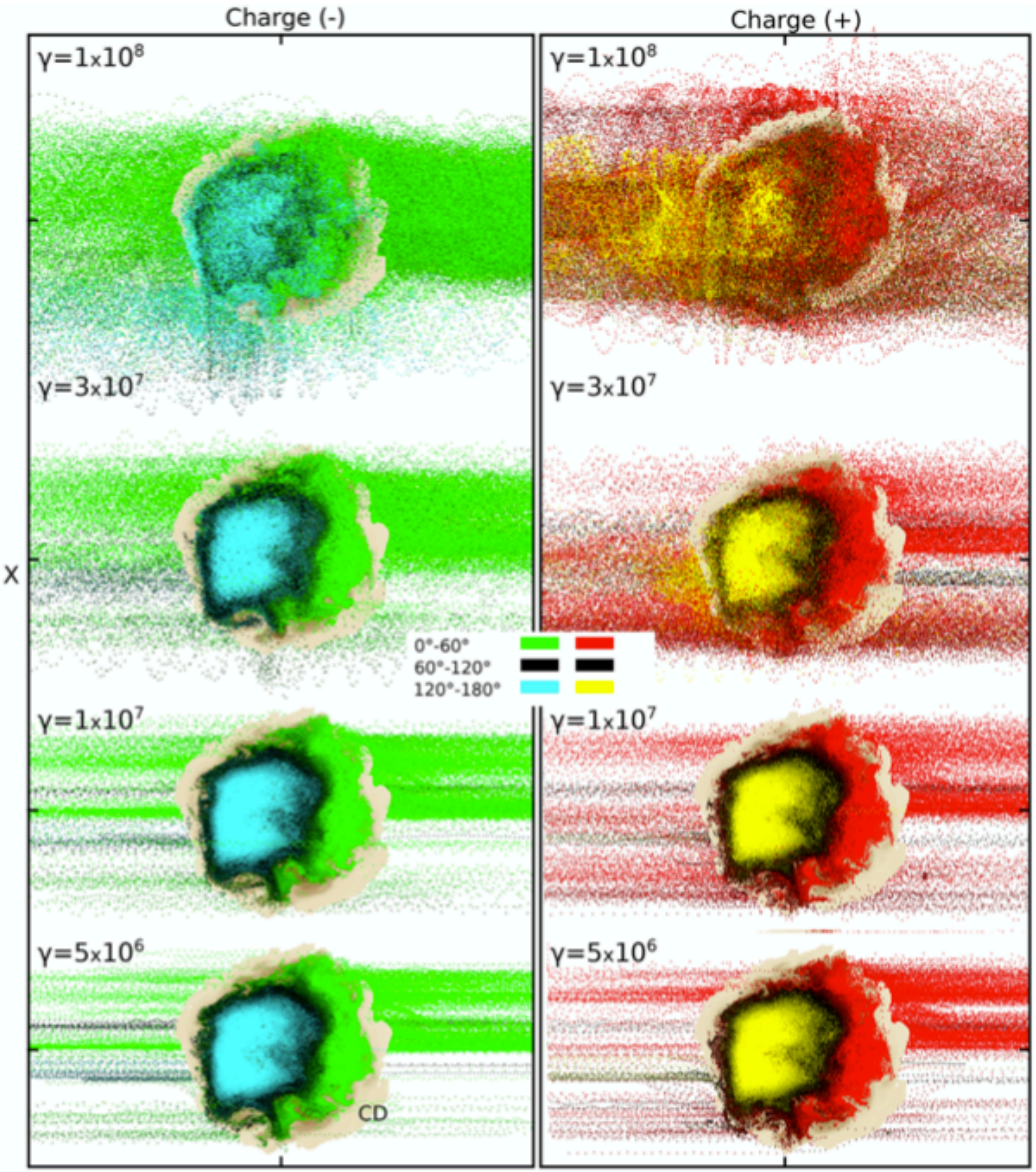




ESCAPE IS CHARGE SEPARATED!

Olmi & Bucciantini 2019

ENERGY DEPENDENCE OF THE ESCAPE



[Olmi & Bucciantini 2019b]

AT GeV ENERGIES:

- ESCAPE EXPECTED ONLY FROM THE TAIL

WITH INCREASING ENERGY:

- LARGER FRACTION OF PARTICLES
- MORE ISOTROPIC RELEASE

NOTICE THAT:

- ENERGY DEPENDENT ESCAPE PROBABILITY MAKES HALO SPECTRUM NON TRIVIAL
- ESCAPE IS CHARGE SEPARATED!
- IF LOW AMBIENT B NON RESONANT STREAMING INSTABILITY [Bell 04] POSSIBLE...

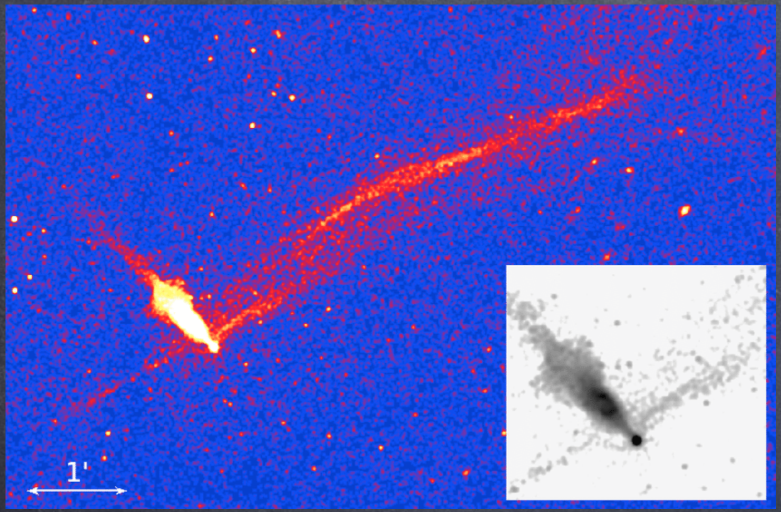
EXPLAINING JETS

EMISSION FROM PARTICLES WITH E>100 TEV!!!

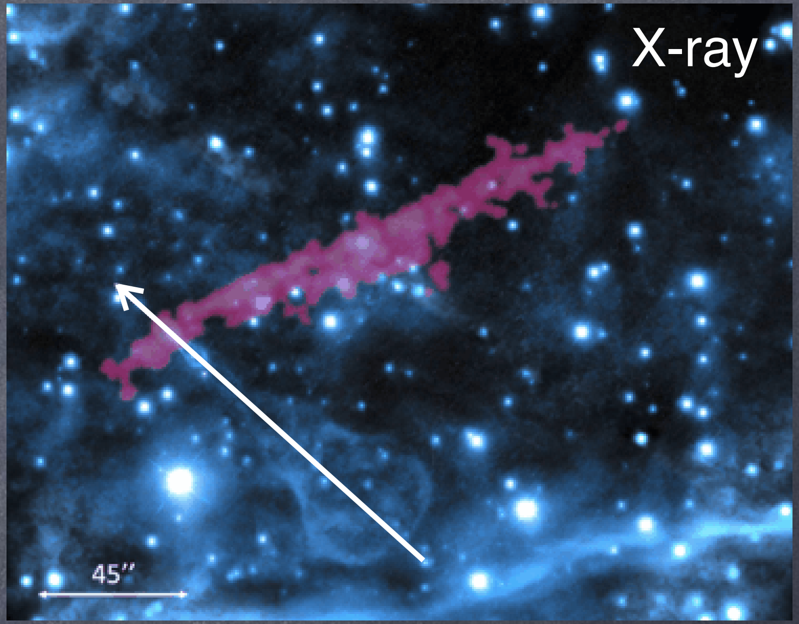
AND

DEEP IMPACT ON THE SURROUNDING MEDIUM

[Olmi, EA, Bandiera & Blasi 24]



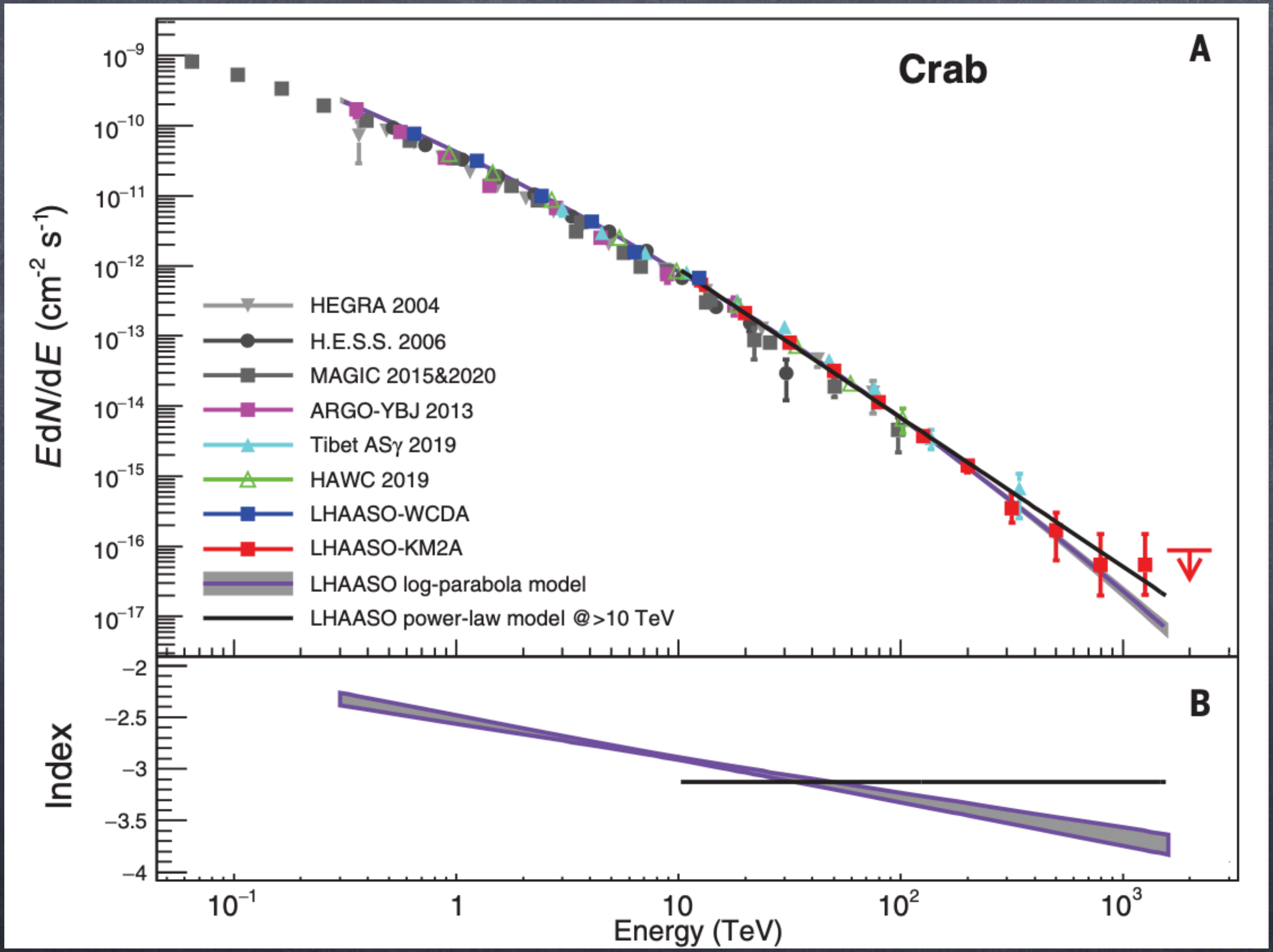
Lighthouse nebula
[Pavan+ 2016]



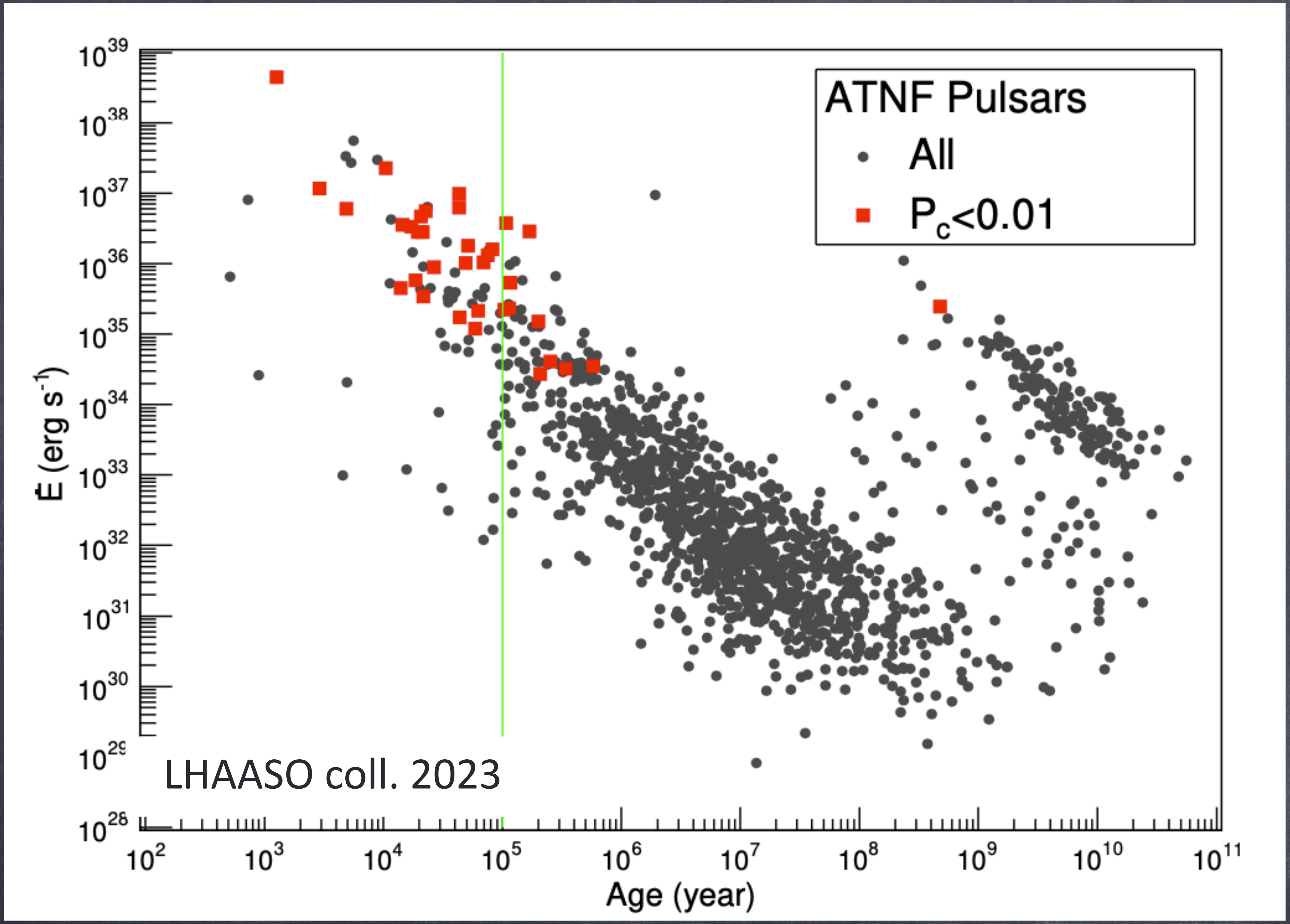
Guitar nebula
[Cordes+ 1993, Wong+ 2003]

System	$n_{\rm ISM}$ $\rm cm^{-3}$	$\gamma_{\rm MPD}$	$\gamma_{\rm esc}$	ΔB μG	ϵ $\times 10^{-3}$	R/d_0
Guitar	0.6	1.2×10^8	1.2×10^7	78	6	0.5
Lighthouse	0.07	4.0×10^9	8×10^7	26	19	2
J2030+4415	4.0	5×10^8	$\lesssim 4\times10^7\left(L_f/\rm pc\right)$	$40<\Delta B<181$	–	–

LHAASO DETECTION OF CRAB



PULSAR ASSOCIATIONS IN 1LHAASO



-35 ASSOCIATIONS WITH PULSARS OUT OF 90 SOURCES

-22 UHE OUT OF 43

-POSSIBLY THE ONLY SOURCES IN THE GALAXY ABLE TO ACCELERATE LEPTONS TO PeV ENERGIES

MAXIMUM ENERGY FOR AN ACCELERATOR

$$E_{max}^{abs} = q\Delta\Phi = q\mathcal{E}L \approx q\ \eta\ B\ L \qquad \eta = \mathcal{E}/B \sim \mathrm{v}_f/c$$

ABSOLUTE LIMIT

FINITE TIME CONSTRAINT $E_{max} \Leftarrow t_{acc}\left(E_{max}\right) = min\left[t_{age}, t_{loss}\left(E_{max}\right)\right]$

FOR DIFFUSIVE SHOCK ACCELERATION

$$t_{acc} = \frac{E}{dE/dt} = \approx \frac{D_2(E)}{\mathrm{v}_s^2}$$

BOHM LIMIT $t_{acc}(E) \approx \frac{cr_L(E)}{\mathrm{v}_s^2} = \left(\frac{c}{\mathrm{v}_s}\right)^2 \frac{E}{qBc}$

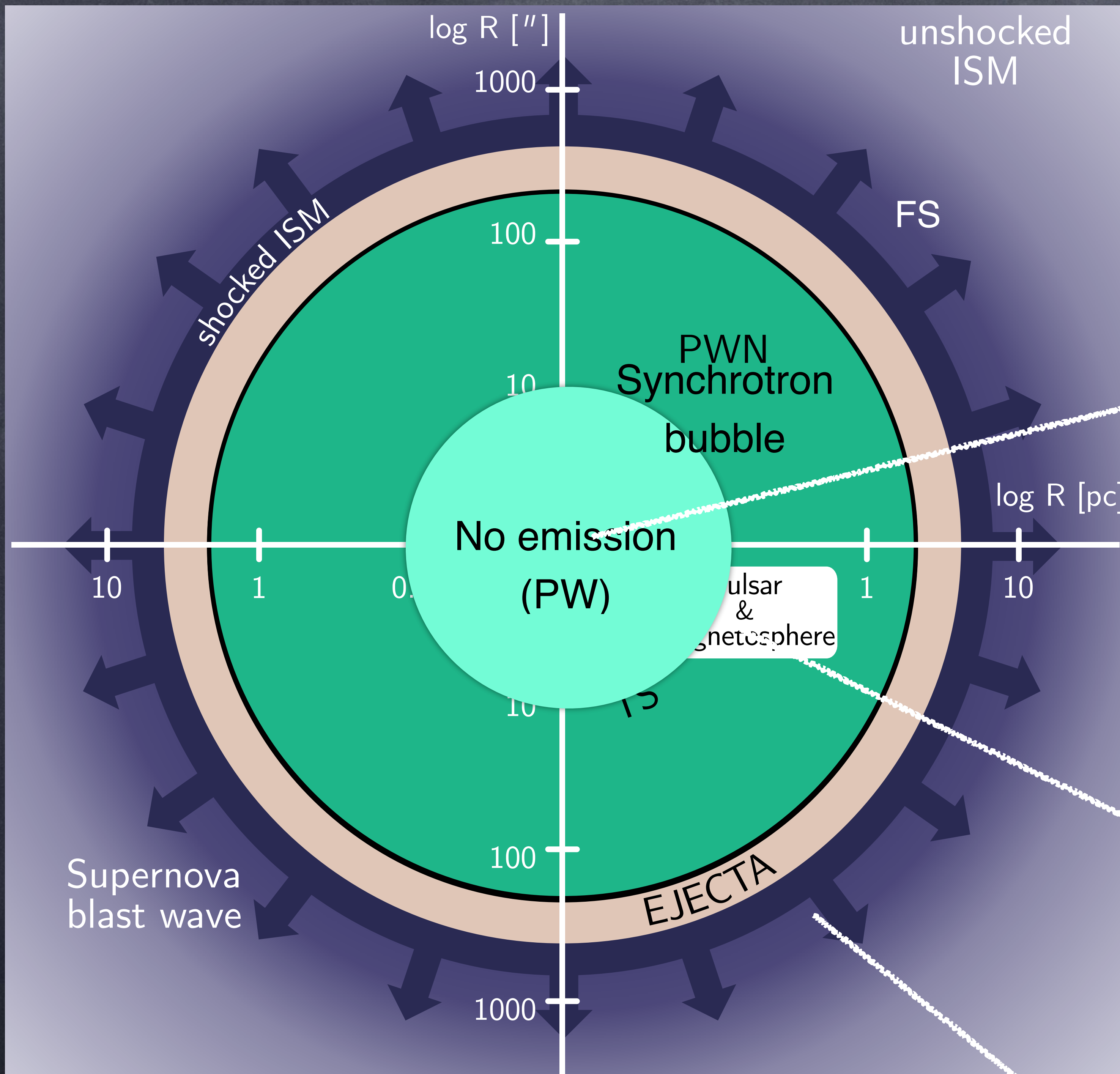
DIRECT E-FIELD ACCELERATION WITH $\mathcal{E} \approx \mathrm{v}B/c$

$$E = e\mathcal{E}ct \Rightarrow t_{acc}(E) \approx \left(\frac{c}{\mathrm{v}_f}\right) \frac{E}{qBc}$$

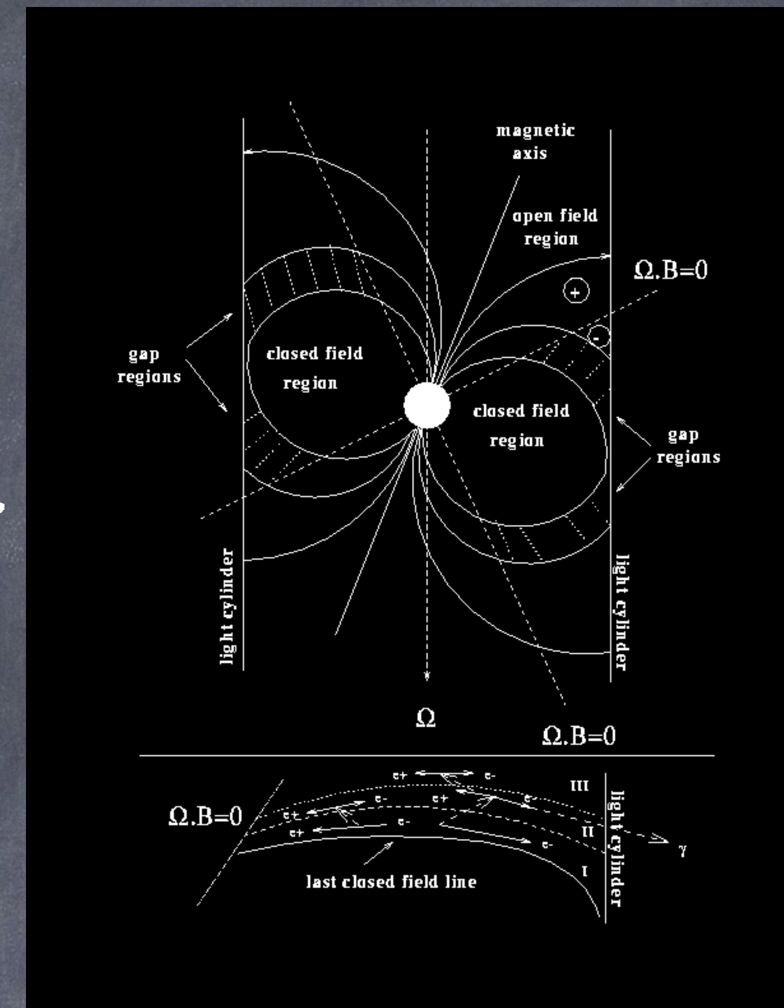
RELATIVISTIC REGIME $t_{acc}(E) \approx \frac{E}{qBc}$ ← FASTEST POSSIBLE ACCELERATION!

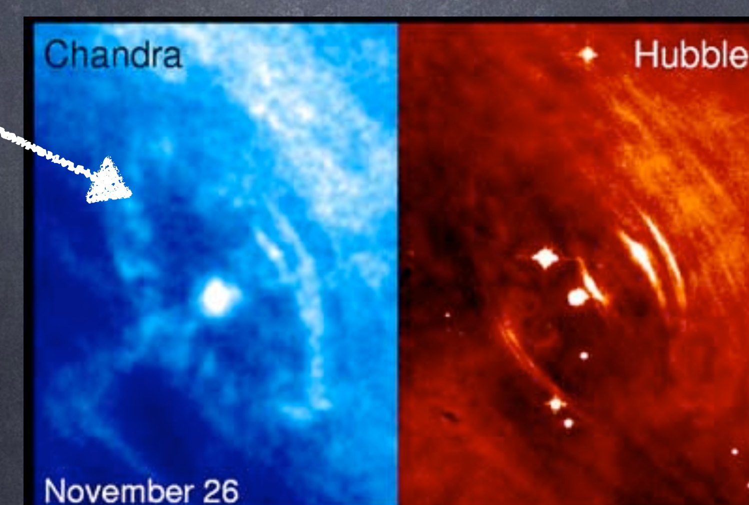
SAME AS FOR DIRECT E-FIELD ACCELERATION WITH $\mathcal{E} \approx B$

ACCELERATION SITES



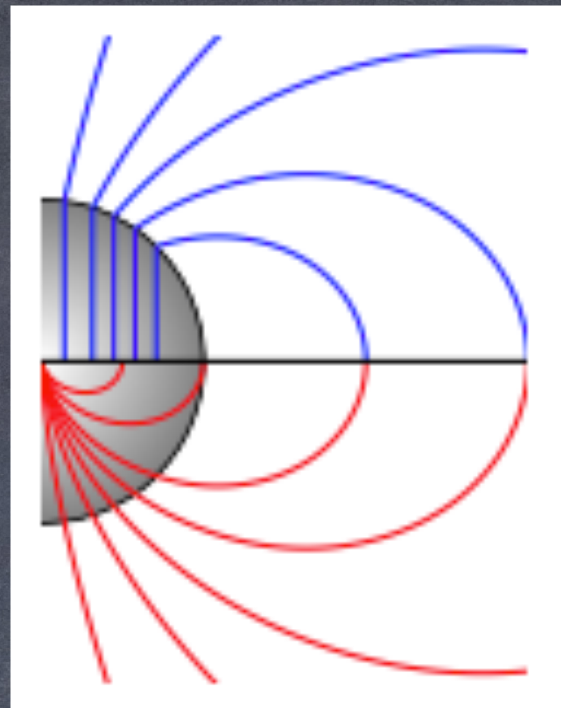
Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

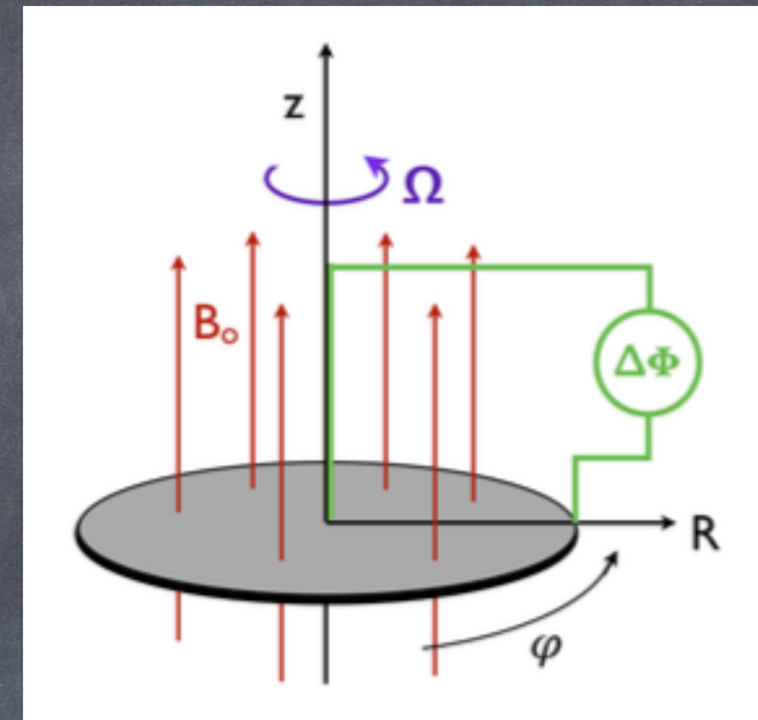




PLUS OF COURSE THE SNR SHOCK

THE PULSAR POTENTIAL DROP





CHARGE DENSITY

$$\rho_{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}\frac{1}{\left[1-\left(\frac{R}{R_L}\right)^2\sin^2\theta\right]}$$

TOTAL POTENTIAL DROP

$$\Delta\Phi^{TOT} \approx \frac{B_\star \Omega R_\star^2}{c}$$

CHARGE DENSITY

$$\rho_e^{FD} = -\frac{\Omega\ B_0}{2\pi c}$$

POTENTIAL DROP

$$\Delta\Phi^{FD} \approx B_d \frac{\Omega R_d}{c} R_d$$

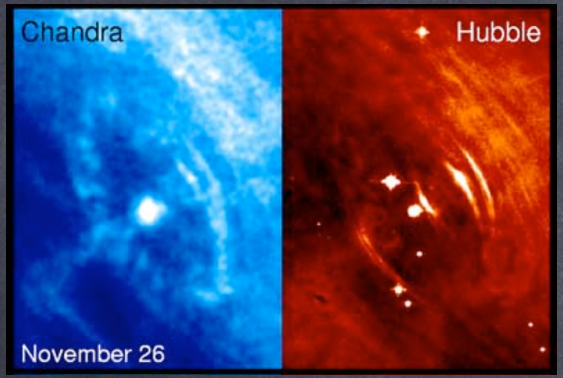
$$E_{\max} = Ze\Delta\Phi$$

PC POTENTIAL DROP

$$\Delta\Phi^{PC} \approx \frac{B_\star \Omega R_\star^2}{c}\frac{R_\star}{R_L} \approx \sqrt{\frac{\dot{E}}{c}}$$

$$E_{\max}^{\rm PSR} = 1.5\ Z\ {\rm PeV}\left(\frac{\dot{E}}{10^{36}{\rm erg/s}}\right)^{1/2}$$

MAXIMUM ENERGY IN A PWN



ACCELERATION MECHANISM UNKNOWN BUT...

IN YOUNG ENERGETIC SYSTEMS ELECTRON ACCELERATION AT THE SHOCK IS LOSS LIMITED NO MATTER THE MECHANISM

$$\boxed{t_{acc} = \frac{E}{e\eta_E Bc} < t_{loss} = \frac{6\pi(mc^2)^2}{\sigma_T c B^2 E}} \Rightarrow \boxed{E_{max} \approx 6\ PeV\ \eta_E^{1/2}\ B_{-4}^{1/2}}$$

FOR EVOLVED SYSTEMS, LOWER B-FIELD VALUES

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

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

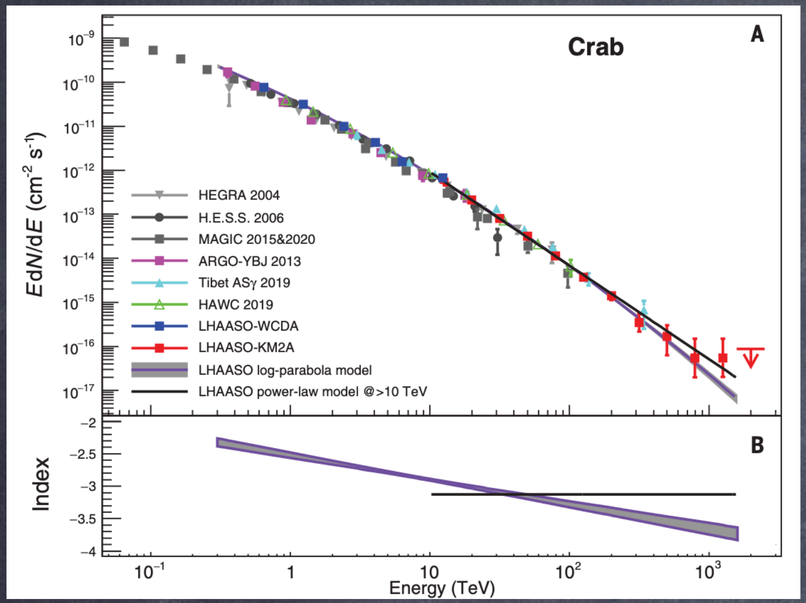
$$\frac{B_{TS}^2}{4\pi} = \xi_B \frac{\dot{E}}{4\pi R_{TS}^2 c}$$

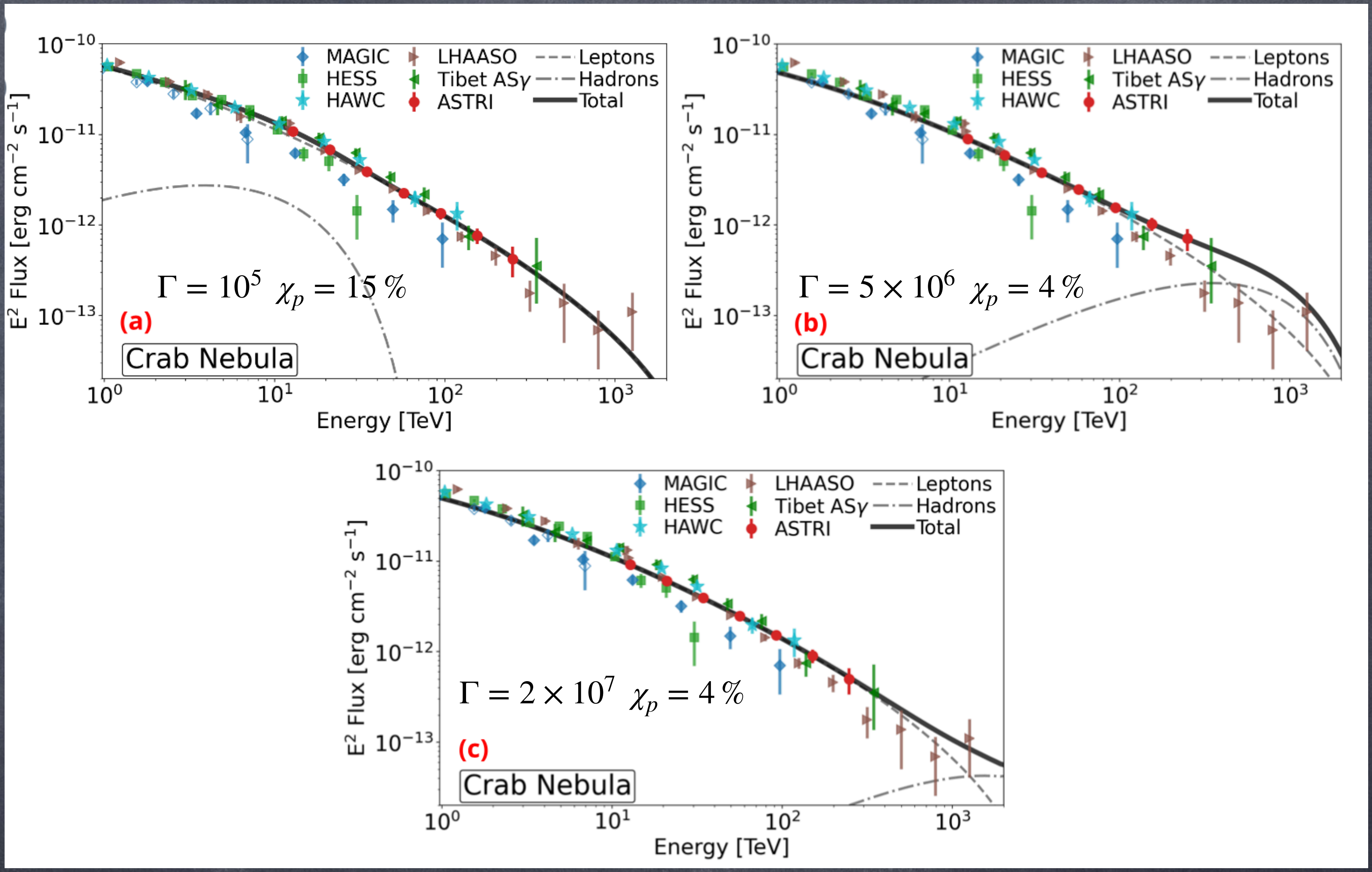
$$\Rightarrow \boxed{E_{max,abs} = e\eta_E\ \xi_B^{1/2}\sqrt{\dot{E}/c} \approx 1.8\ PeV\ \eta_E\ \xi_B^{1/2}\ \dot{E}_{36}^{1/2}}$$

RECALL $\boxed{E_{\rm max}^{\rm PSR} = 1.5\ Z\ {\rm PeV}\left(\frac{\dot{E}}{10^{36}{\rm erg/s}}\right)^{1/2}}$

IN YOUNG SYSTEMS: WE COULD SEE HADRONS...

Cao+, LHAASO Coll. 21





Vercellone+ 22

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

[EA & Arons 06; EA, Guetta, Blasi 03]

NOTE: FOR NEW BORN HIGH B PSR PARAMETERS ALSO **UHECRS** NICELY FITS COMPOSITION AND SPECTRUM AND ALSO CORRELATION WITH STARBURST GALAXIES

IONS IN PULSAR WIND?

NOTE: IN PRINCIPLE BOTH ELECTRONS AND IONS COULD BE EXTRACTED:

$$T_i \approx 3.5 \times 10^5 \text{ K} \left(\frac{B_\star}{10^{12}\text{G}}\right)^{0.73}$$

(Harding 2007)

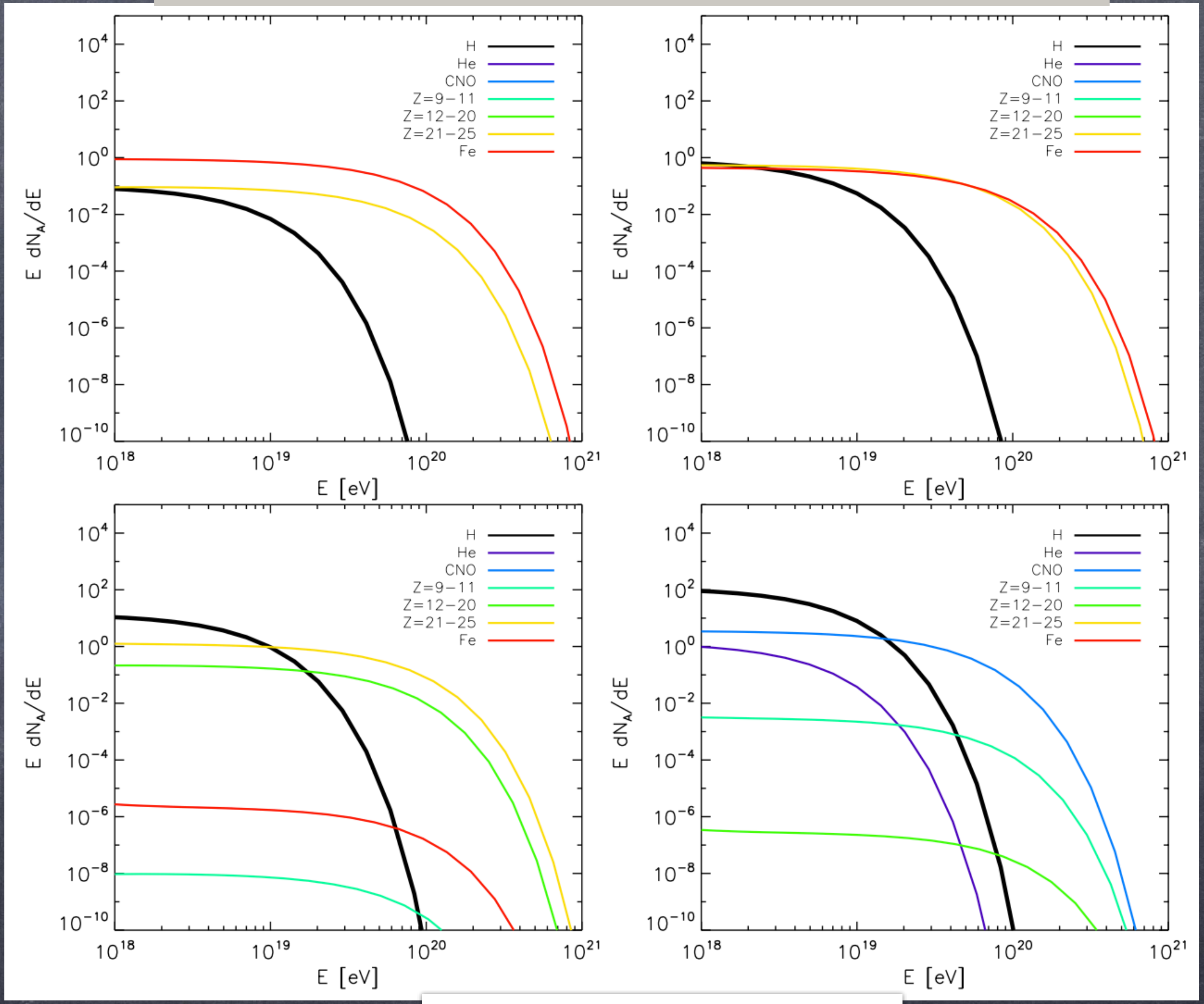
$$T_e \approx 3.6 \times 10^5 \text{ K} \left(\frac{Z}{26}\right)^{0.8} \left(\frac{B_\star}{10^{12}\text{G}}\right)^{0.4}$$

BUT $\dot{N}_i \leq \dot{N}_{GJ}$

WHILE $\dot{N}_\pm = \kappa \dot{N}_{GJ}$

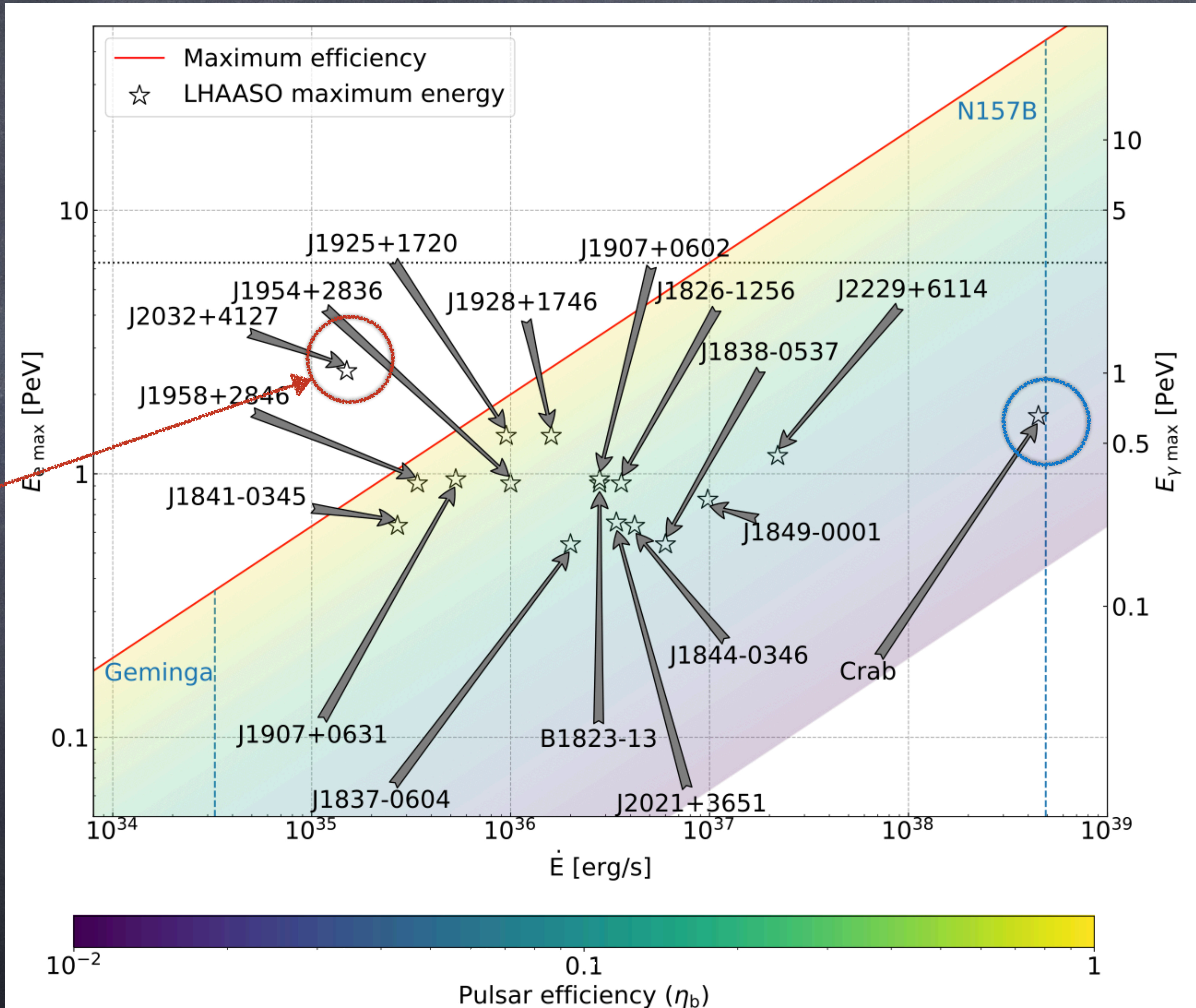
UHECRs FROM MAGNETARS

[Kotera, EA, Blasi 15]



$$T_{NS} = [1,2,5,10] \times 10^6 \ K$$

LHAASO PEVATRONS AND PWNe



CYGNUS

SUMMARY

- HUGE PROGRESS IN OUR UNDERSTANDING OF PWNe FROM MULTI-D MHD DYNAMICS AND RADIATION MODELLING

- **PARTICLE ACCELERATION MECHANISM** PROGRESSIVELY BETTER CONSTRAINED BUT **STILL UNCLEAR**

- UHE GAMMA-RAY OBSERVATIONS HIGHLIGHT THE IMPORTANCE OF UNDERSTANDING PWNe AS PARTICLE ACCELERATORS

    - ONLY FIRMLY IDENTIFIED PEVATRON IS CRAB

    - PSRs OBSERVED IN MOST OF THE UHE EMISSION FIELDS

    - PSRs LIKELY THE ONLY GALACTIC SOURCES ABLE TO PUSH LEPTONS TO PeV

    - ON THE OTHER HAND IF THEY ARE HADRONIC PSRs ARE NOT A PRIORI EXCLUDED!!!!!

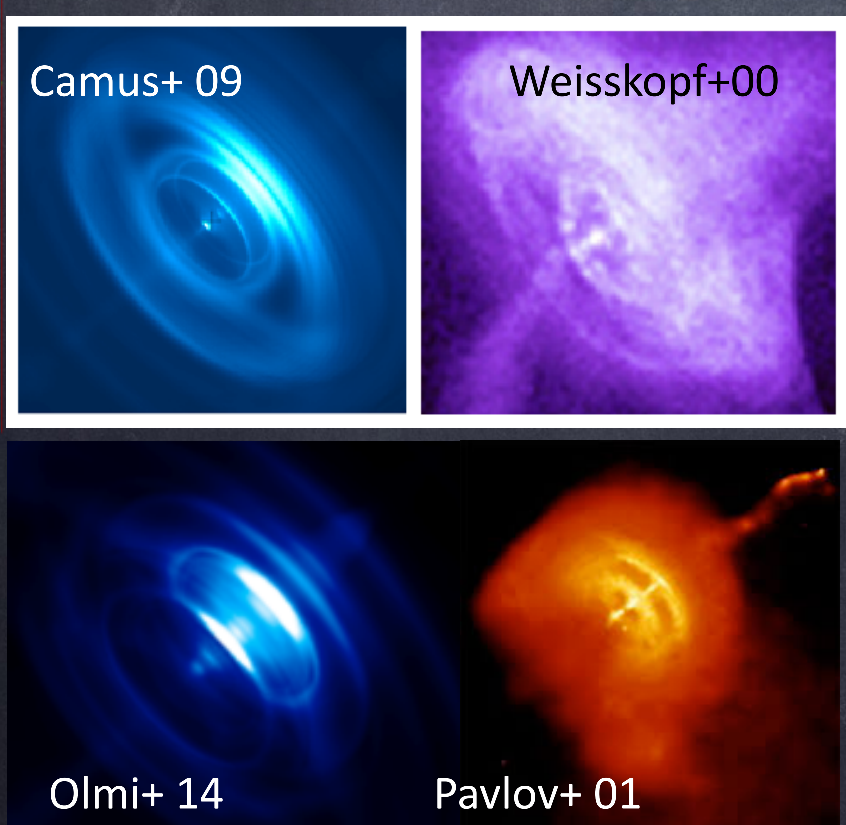
- UHE GAMMA-RAYS FROM YOUNG PWNe COULD PROVIDE FIRST EVIDENCE OF IONS IN PULSAR WINDS, WITH ENORMOUS IMPLICATIONS: NOT ONLY PULSAR PHYSICS, BUT MAYBE EVEN UHECRs...

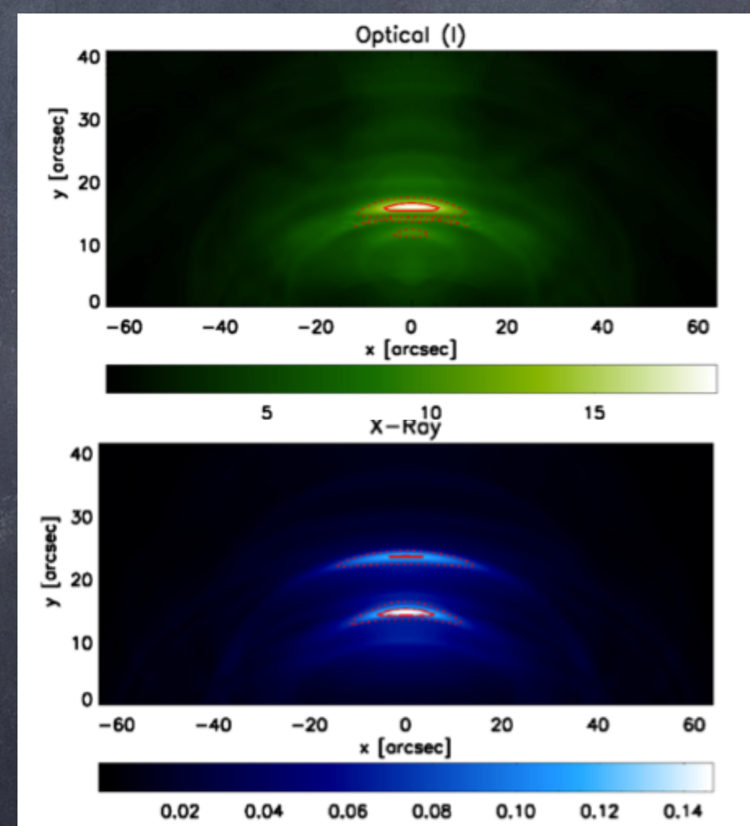
PSR WIND AND PWN DYNAMICS

- ACCELERATION MECHANISM AND PLACE DIFFERENT FOR RADIO AND X-RAY EMITTING PARTICLES
- RADIO EMITTING PARTICLES DO NOT NEED TO BE PART OF THE WIND —> MULTIPLICITY CAN BE LOW ($\kappa \sim 10^3 - 10^4$) AND WIND LORENTZ FACTOR VERY HIGH ($\Gamma \sim 10^6 - 10^7$)

MULTI-WAVELENGTH VARIABILTY

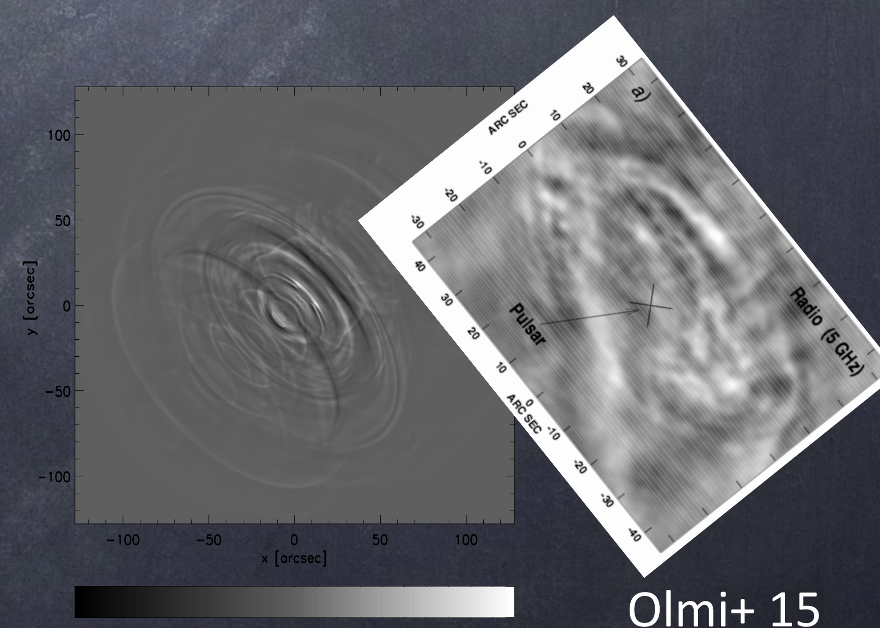
DYNAMICS AND RADIATION MODELING





Olmi+ 14

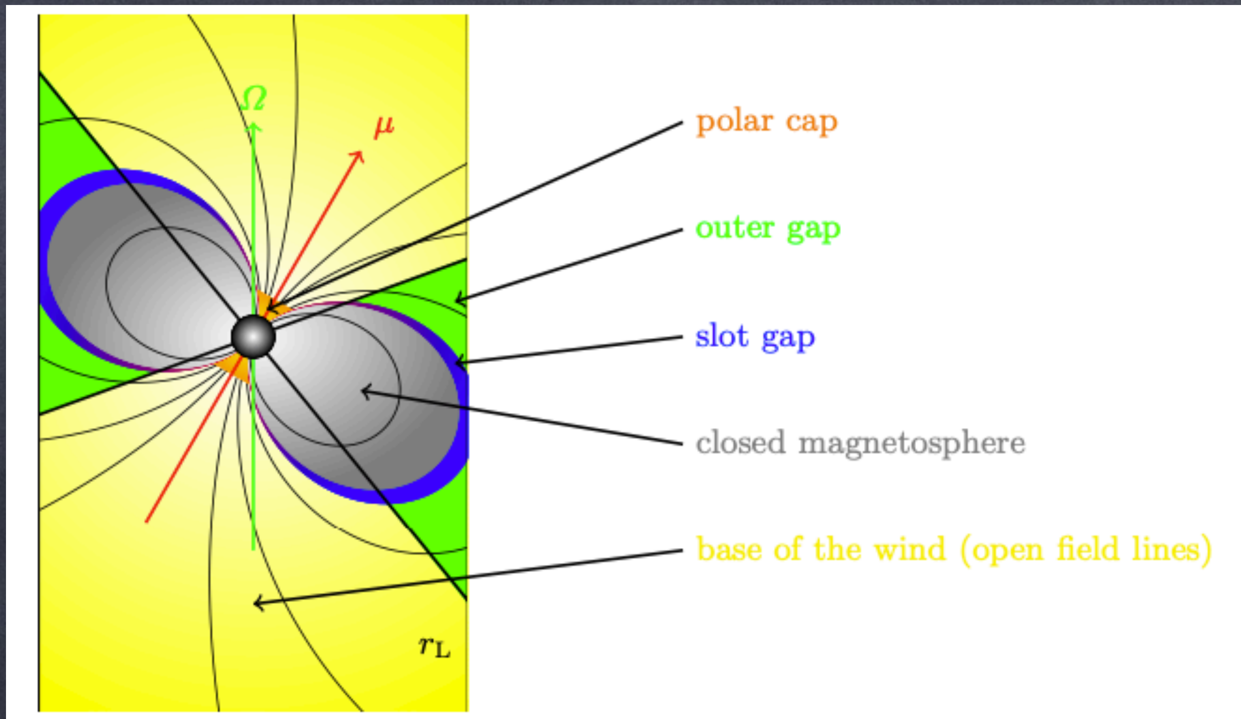
RADIO EMISSION MODELING



Olmi+ 15

[Komissarov & Lyubarsky 03,04; Del Zanna+ 04,06; Bogovalov+ 05;Camus+ 09; Volpi+ 08; Olmi+ 14,15,16;Porth+ 13,14]

THE PSR WIND



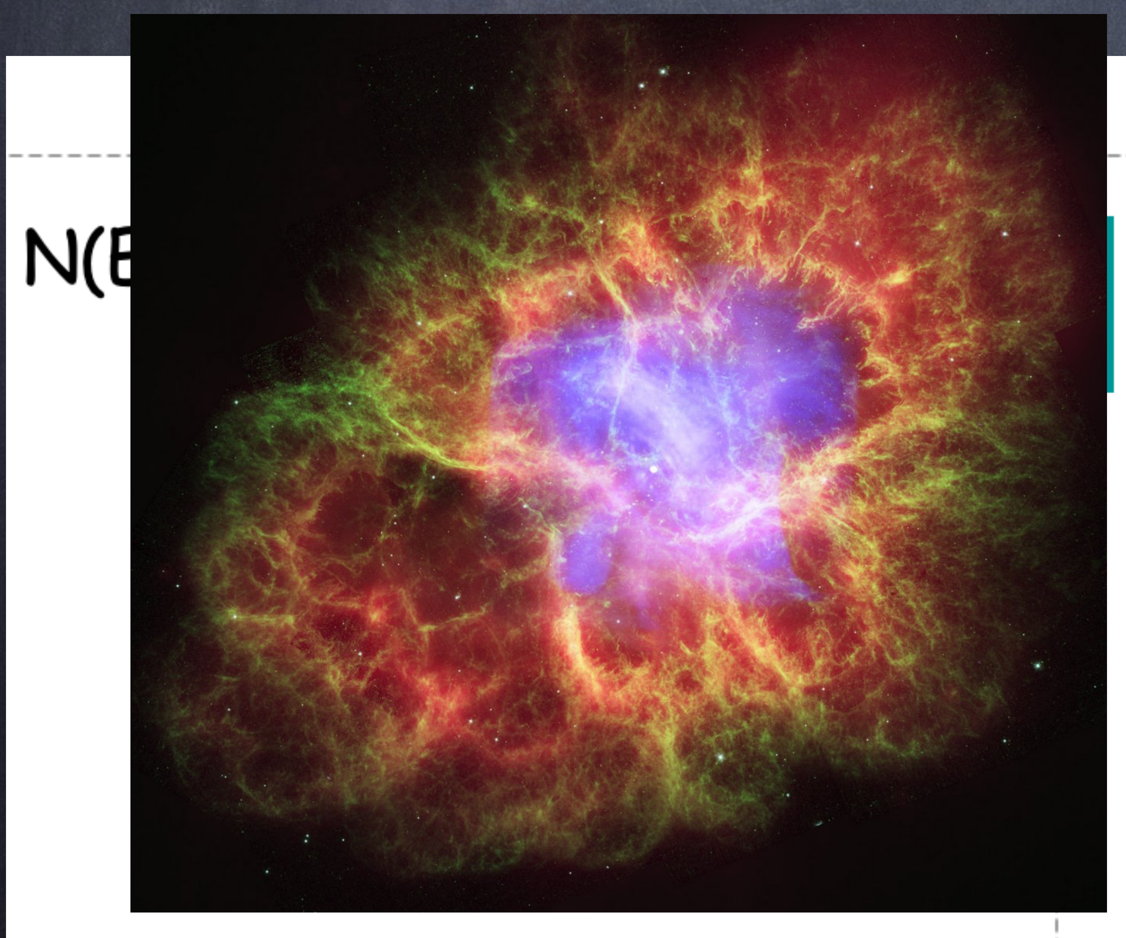
TOTAL WIND POWER:

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

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

κ, Γ AND σ UNKNOWN

$$\Gamma = \frac{e\sqrt{\dot{E}/c}}{\kappa m_e c^2 \left(1 + \frac{m_i}{\kappa m_e}\right)(1+\sigma)}$$



IF $\kappa < m_i/m_e$ IONS COULD DOMINATE ENERGY OUTFLOW AND REACH THE TERMINATION SHOCK ($\sigma \approx 1$) WITH

$$m_i \Gamma c^2 \approx e\sqrt{\dot{E}/c}$$