PULSAR WIND NEBULAE AS GALACTIC PEVATRON CANDIDATES

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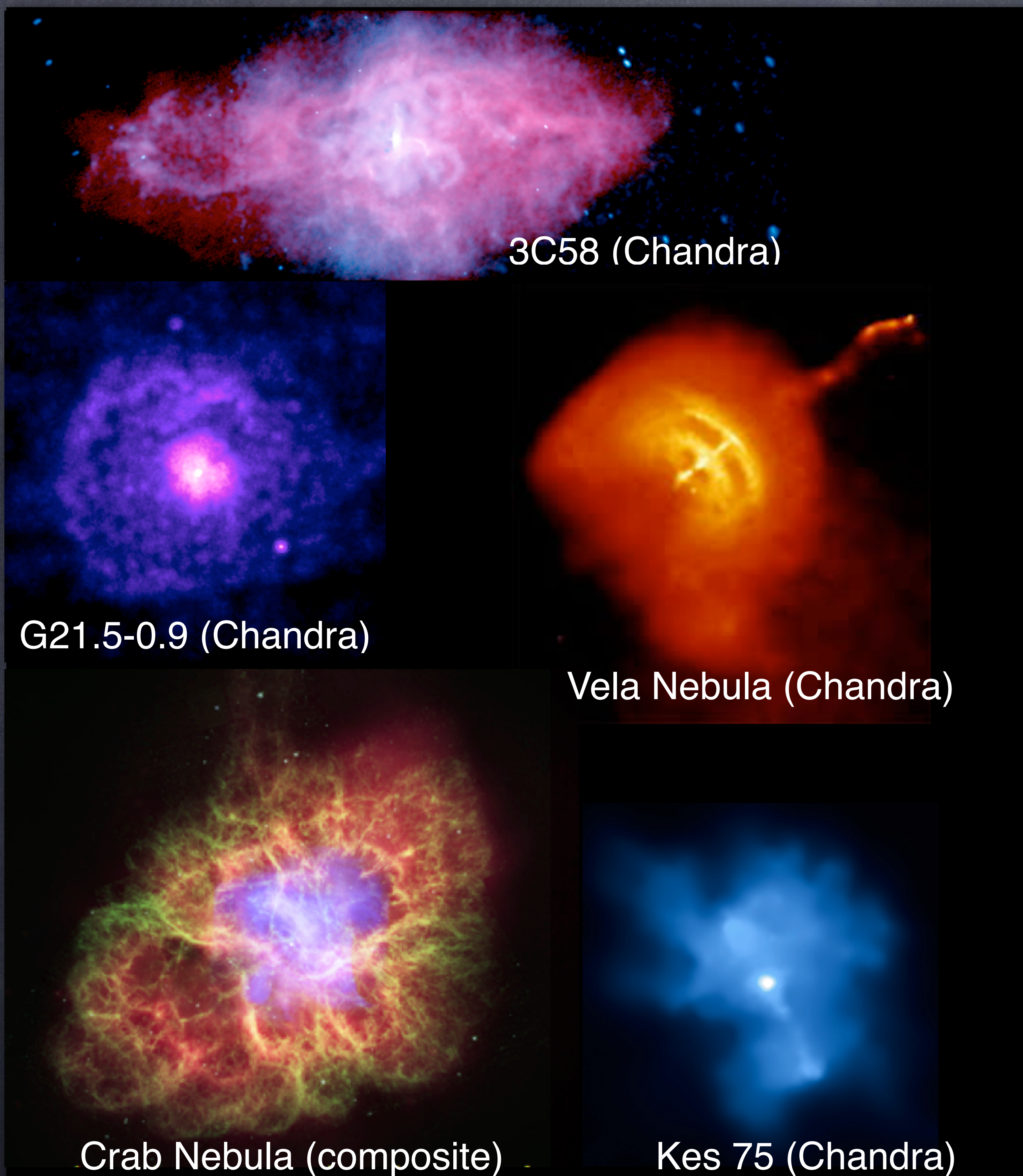
PULSAR WIND NEBULAE

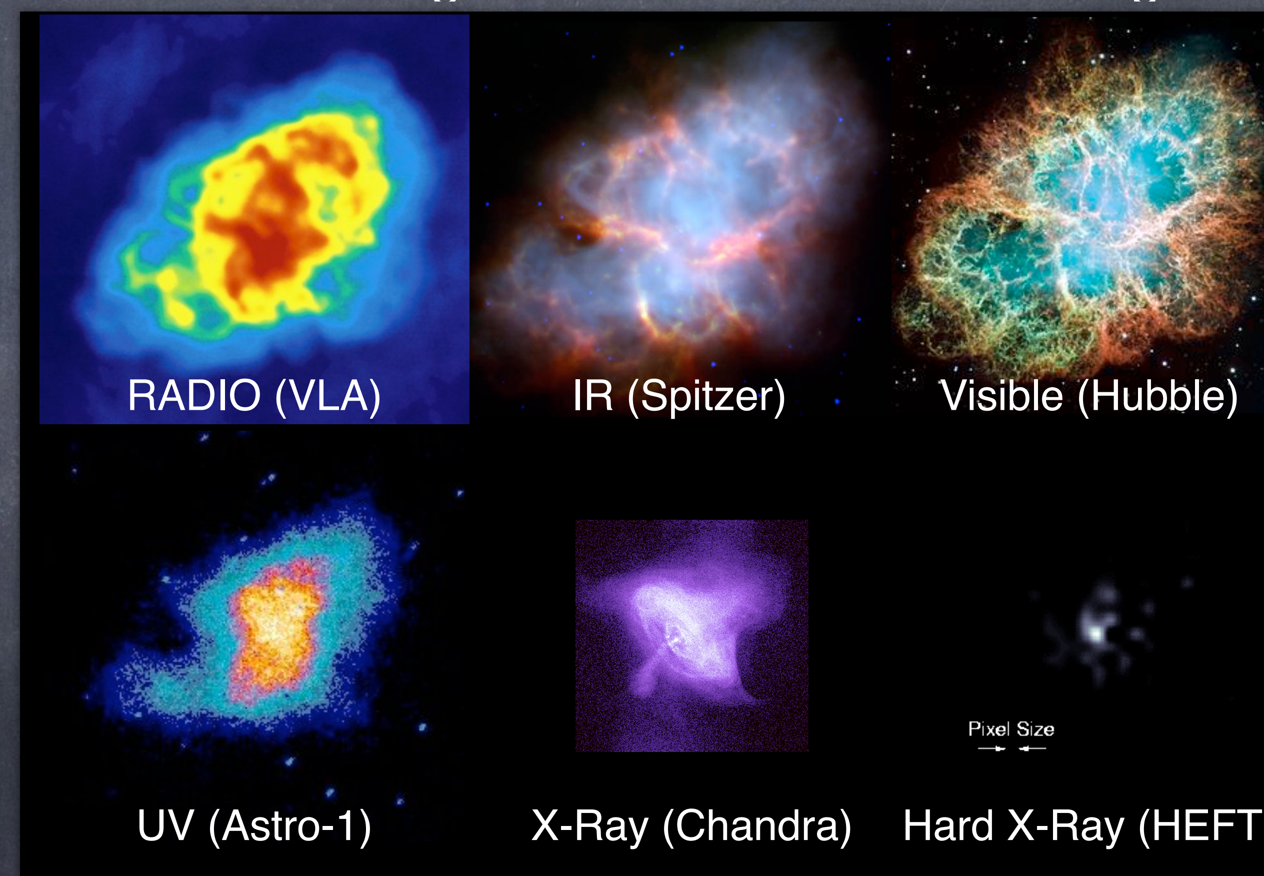


SNRs WITH

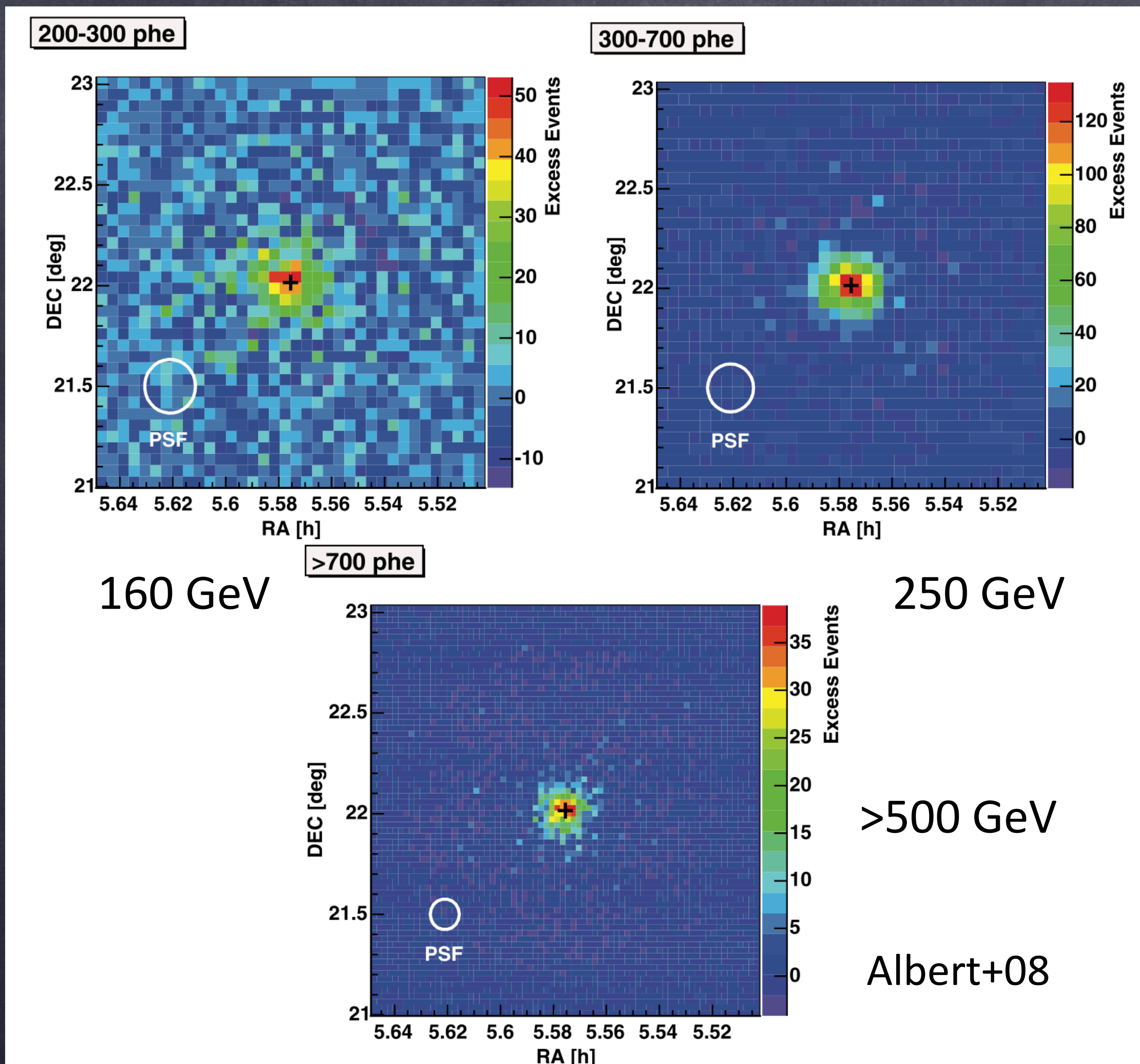
- CENTER FILLED MORPHOLOGY
- BROAD NON THERMAL SPECTRUM
- FLAT RADIO SPECTRUM

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

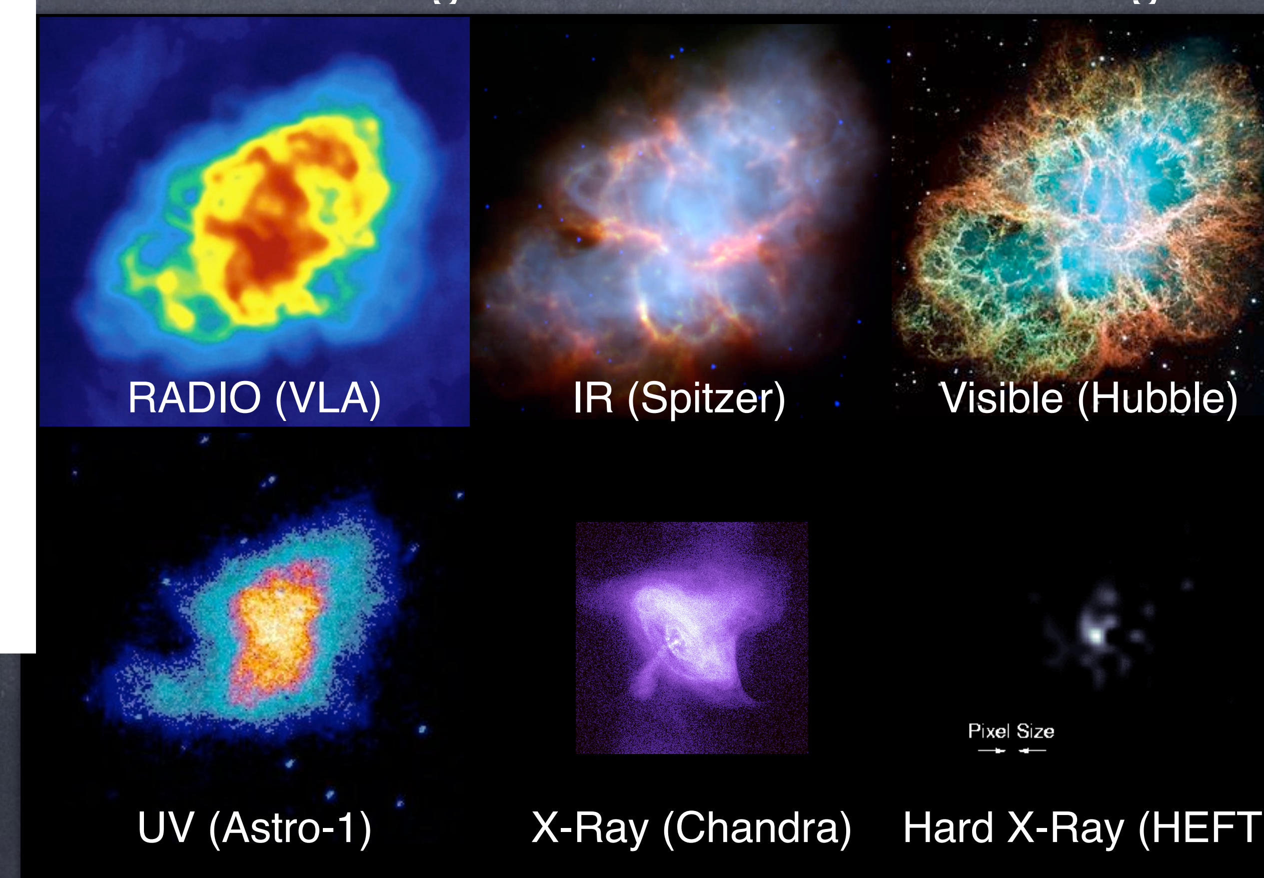
Multi-wavelength emission and size shrinkage



THE CRAB NEBULA



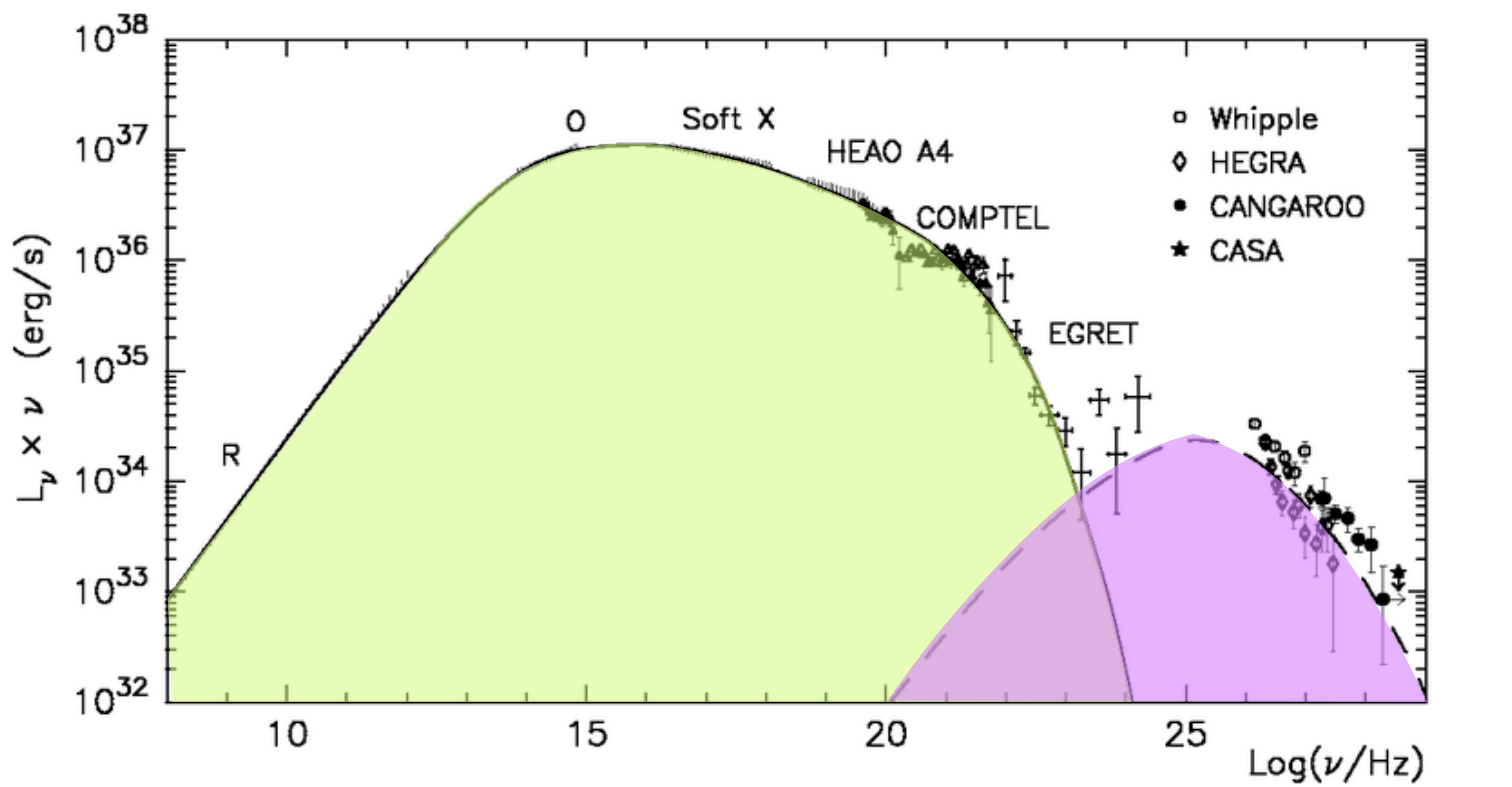
Multi-wavelength emission and size shrinkage



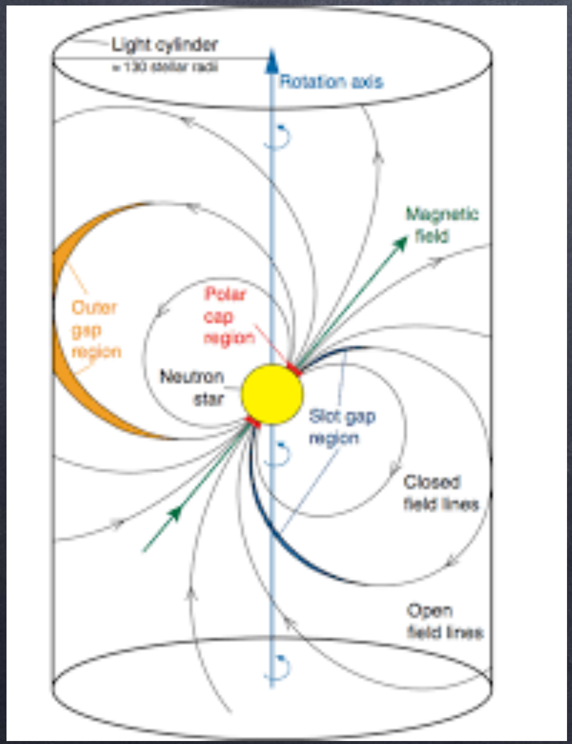
THE CRAB NEBULA

BROAD BAND NON-THERMAL SPECTRUM

CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]



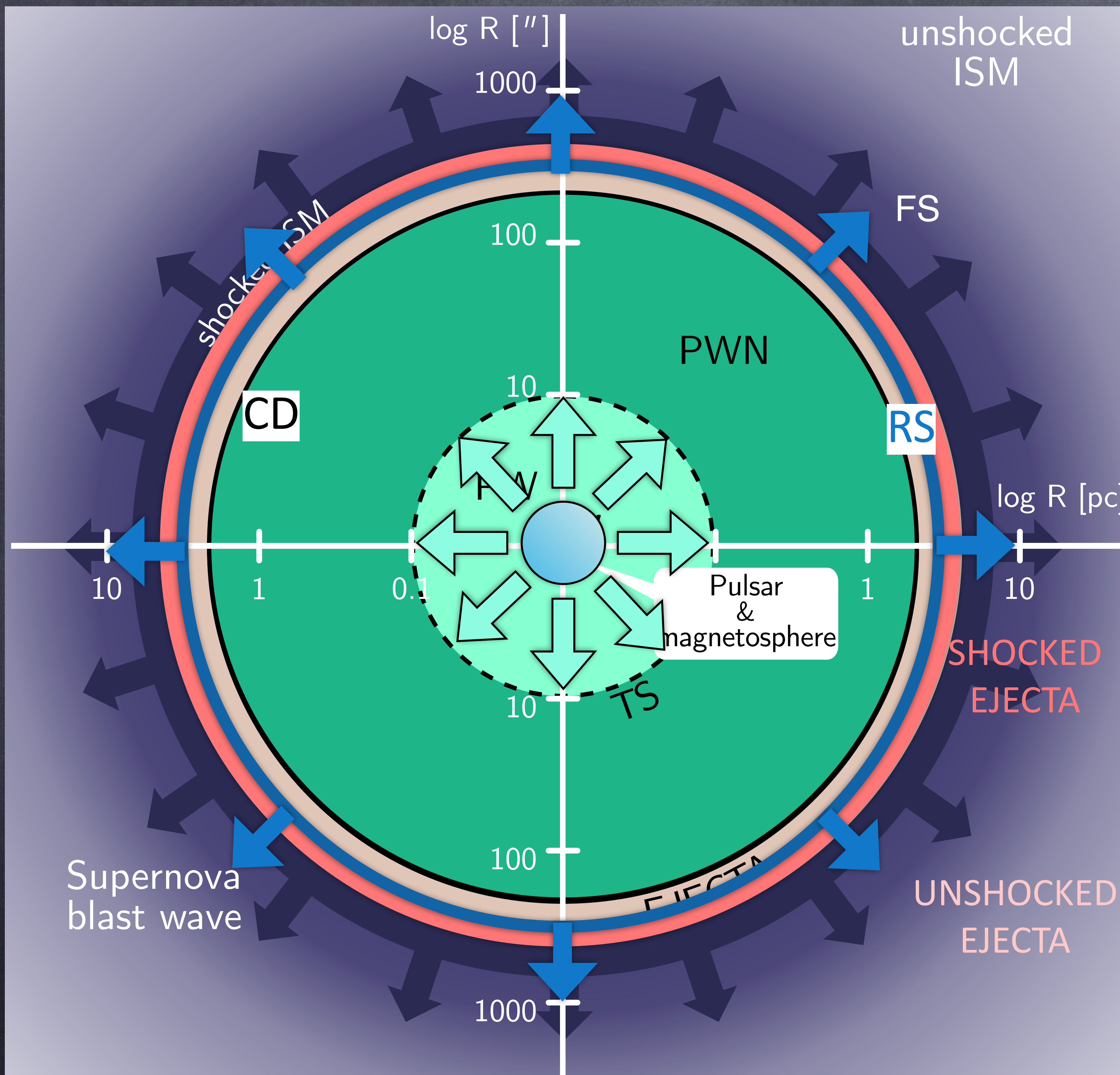
synchrotron radiation by relativistic particles in the nebular B field
Inverse Compton scattering with local photon field



PARTICLES AND FIELD
FROM ROTATIONAL ENERGY LOST BY PULSAR

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

BASIC PICTURE FOR YOUNG SYSTEMS

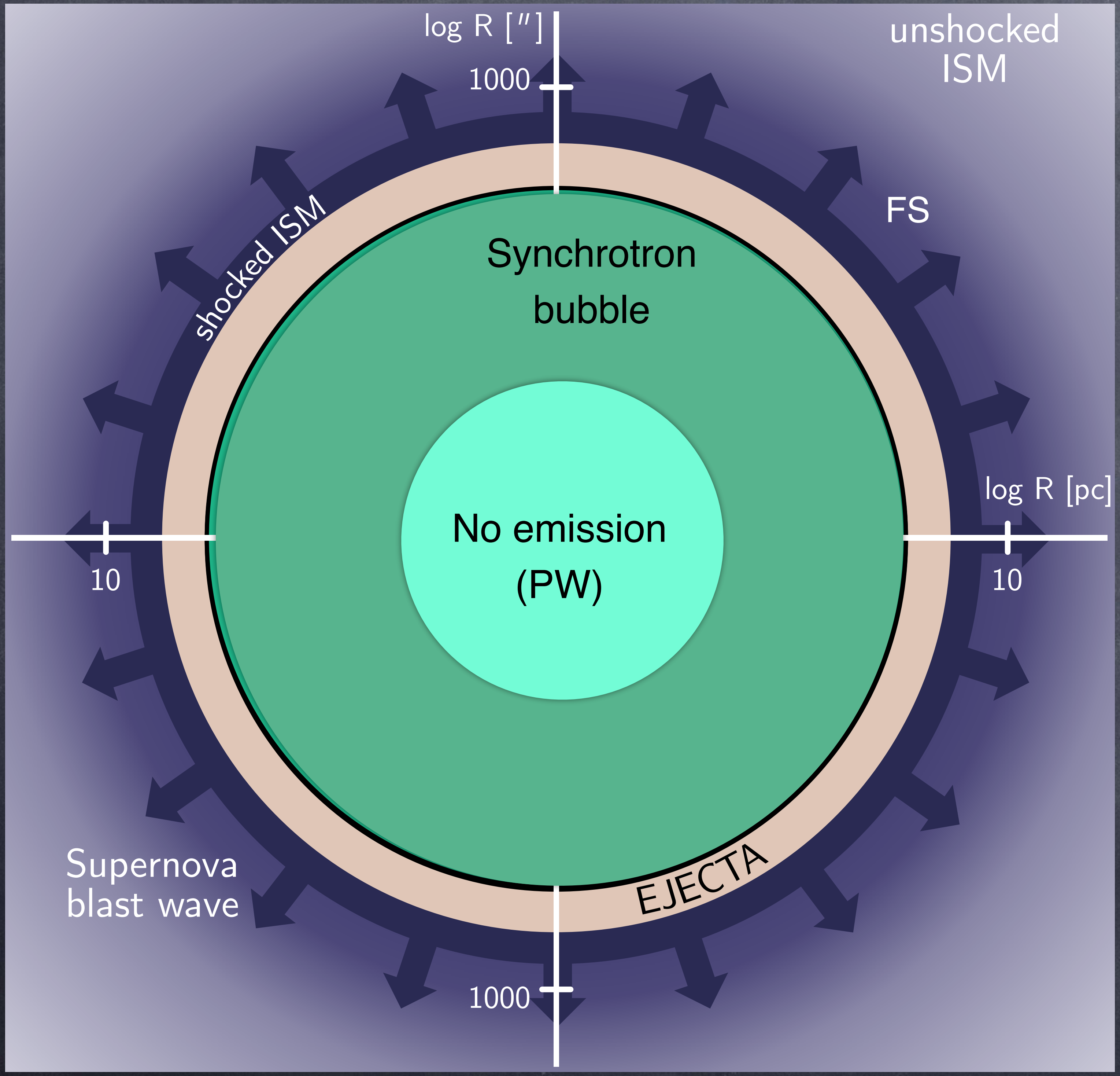


Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

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

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

BASIC PICTURE FOR YOUNG SYSTEMS



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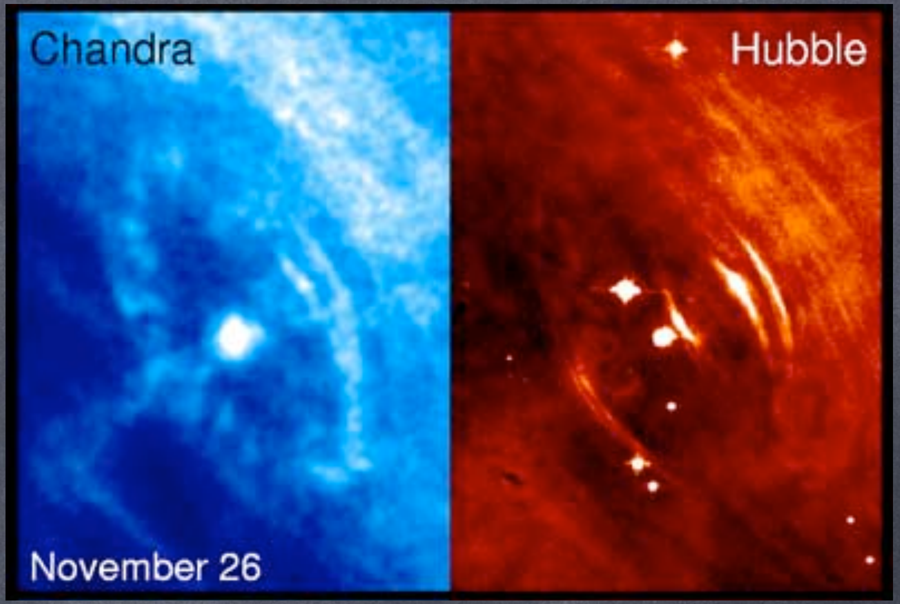
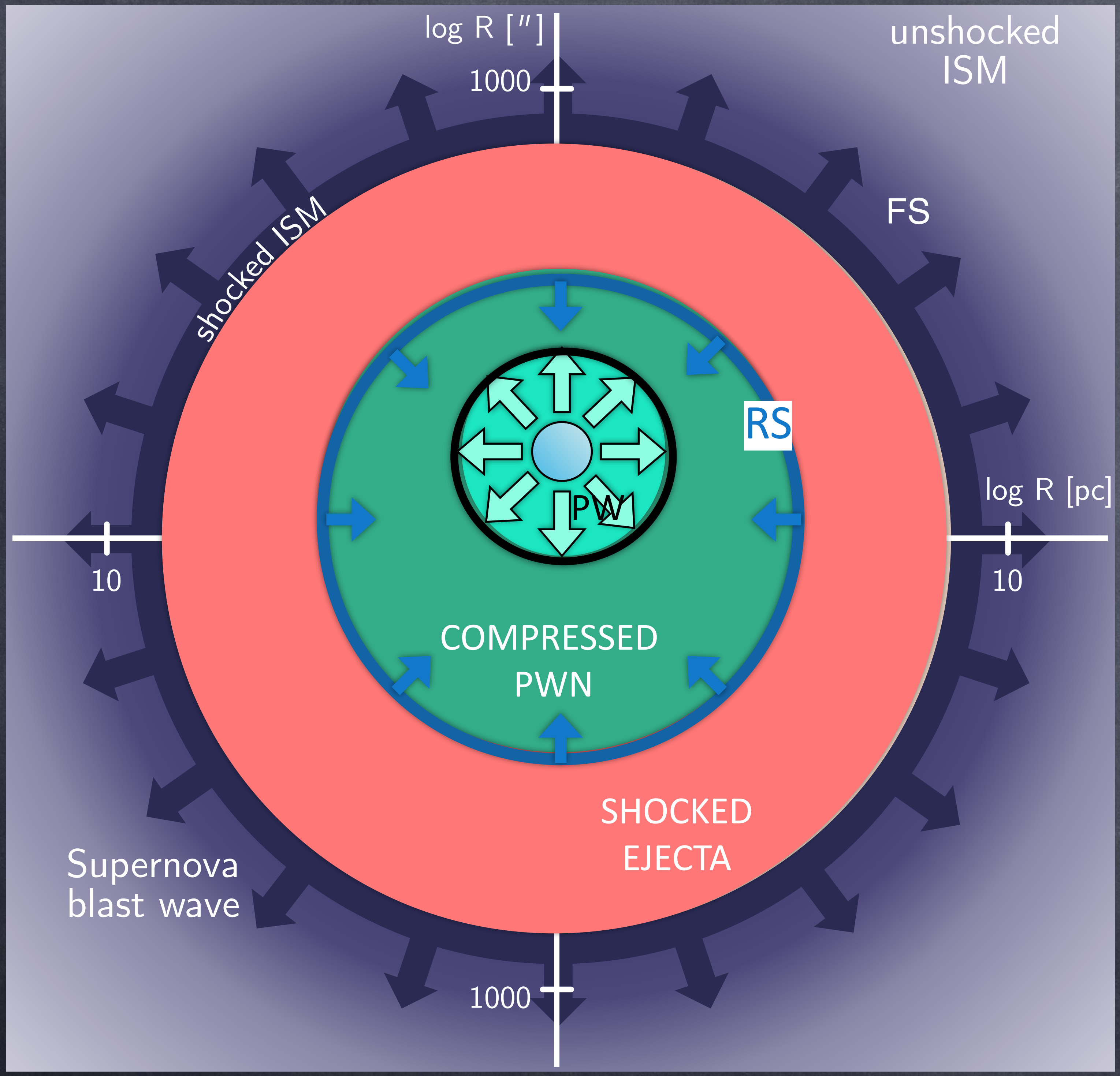


$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

DISSIPATION AND PARTICLE ACCELERATION AT TS

PWN EVOLUTION



SNR EXPANSION

SLOWS DOWN

+

LARGE FRACTION OF

ALL THE PULSARS

BORN WITH

HIGH KICK VELOCITY

↓

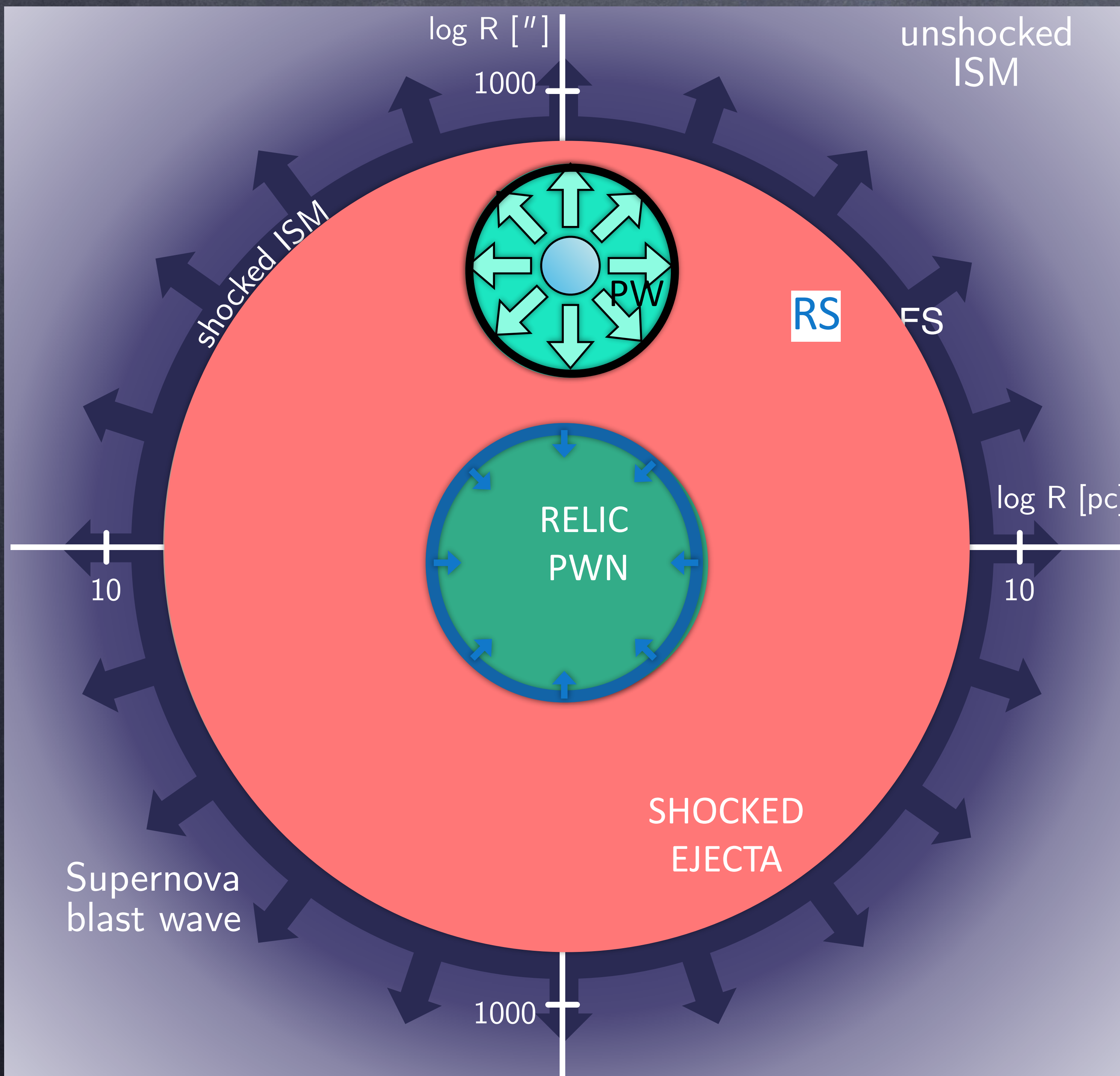
COMPRESSED PWN

OFFSET PW

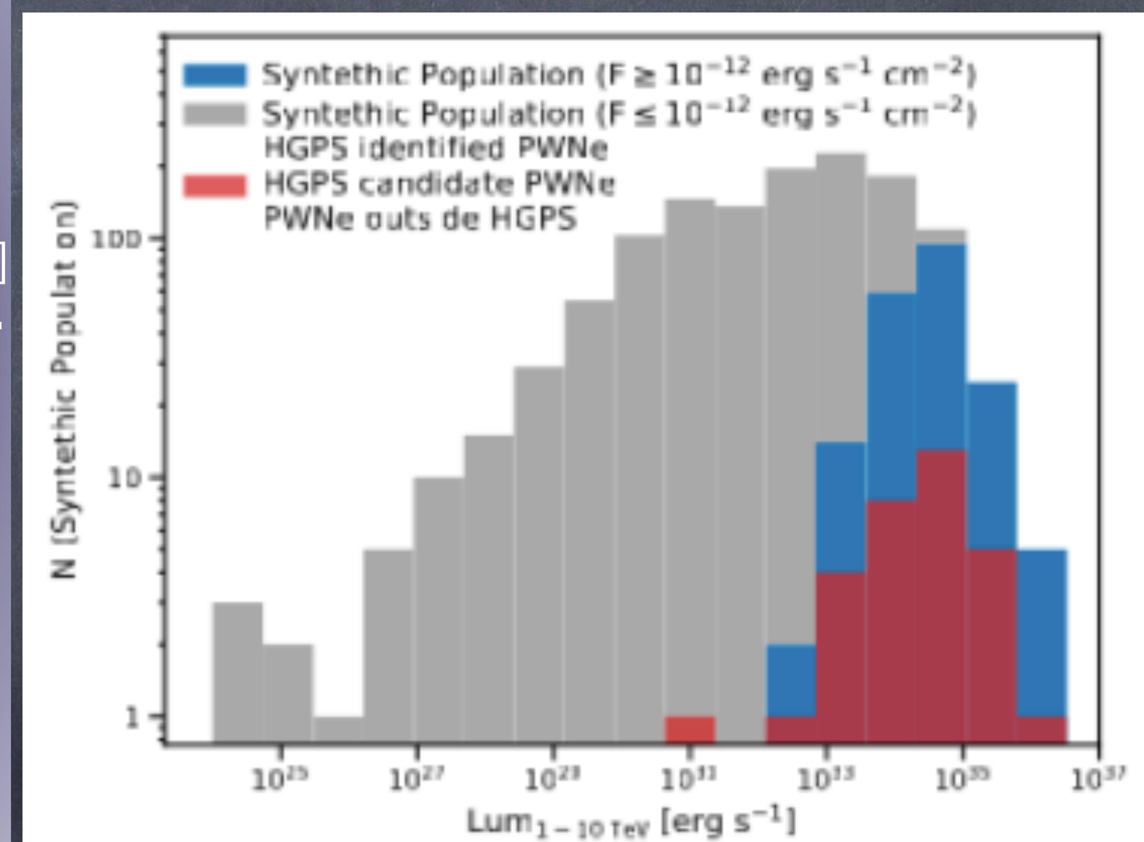
↓

REVERBERATION PHASE

RELIC NEBULAE



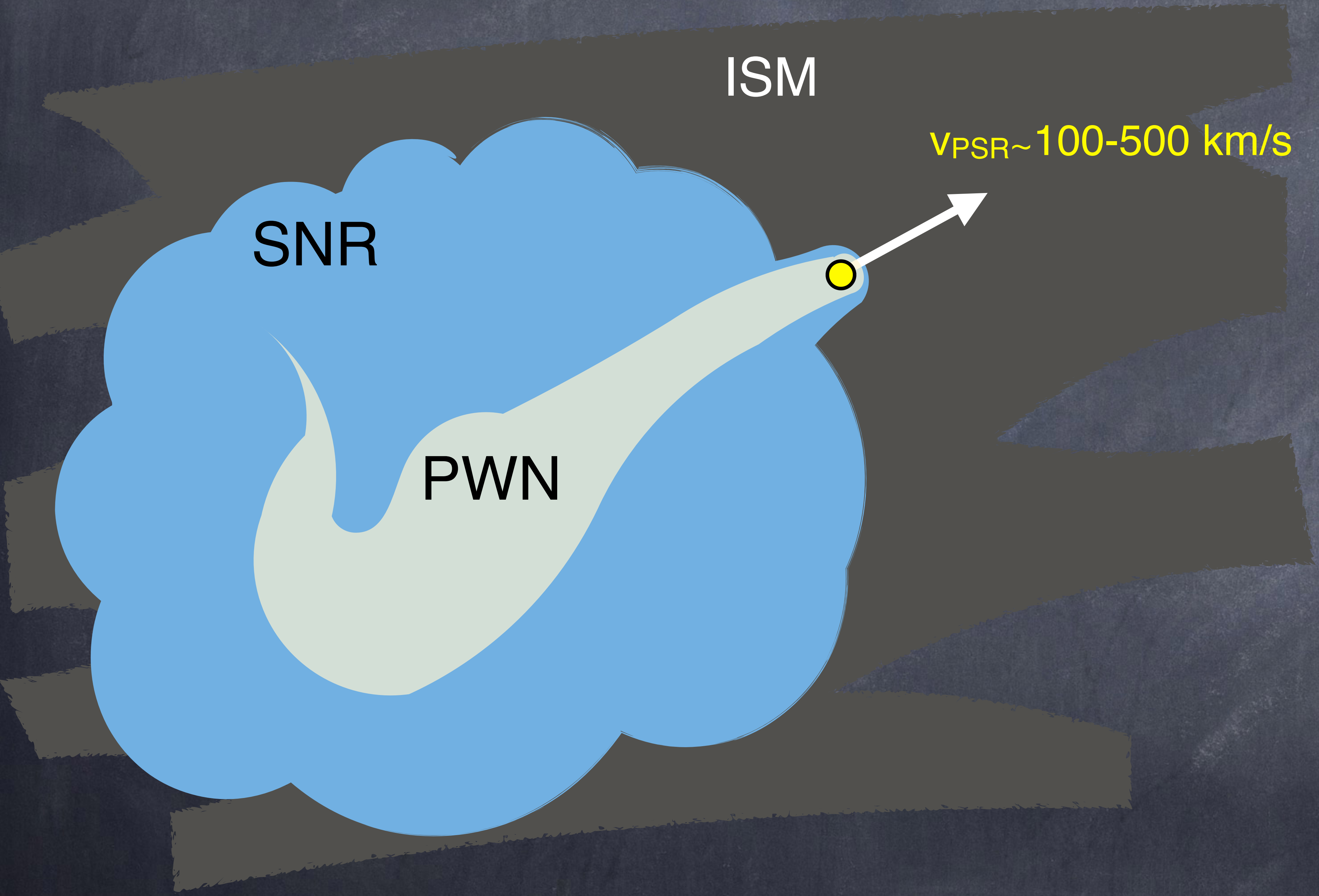
PSR MAY CROSS RS DURING COMPRESSION AND LEAVE A RELIC



[Fiori+ 22]

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

EVOLVED PWNe



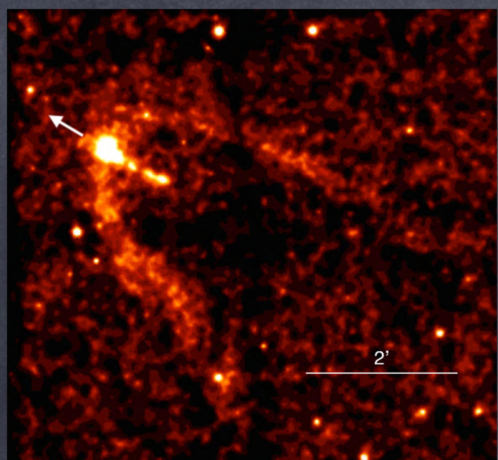
LARGE FRACTION OF ALL THE PULSARS BORN WITH HIGH KICK VELOCITY

↓

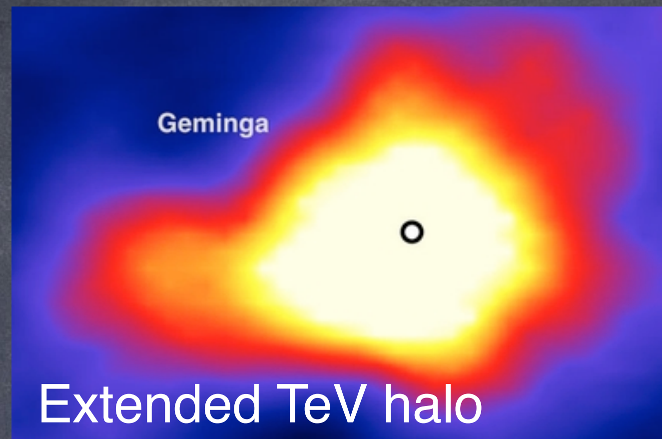
THEY LEAVE THE SNR ON TIMESCALES FEW X 10^4 – 10^5 YR

BOW SHOCK NEBULAE

X-ray

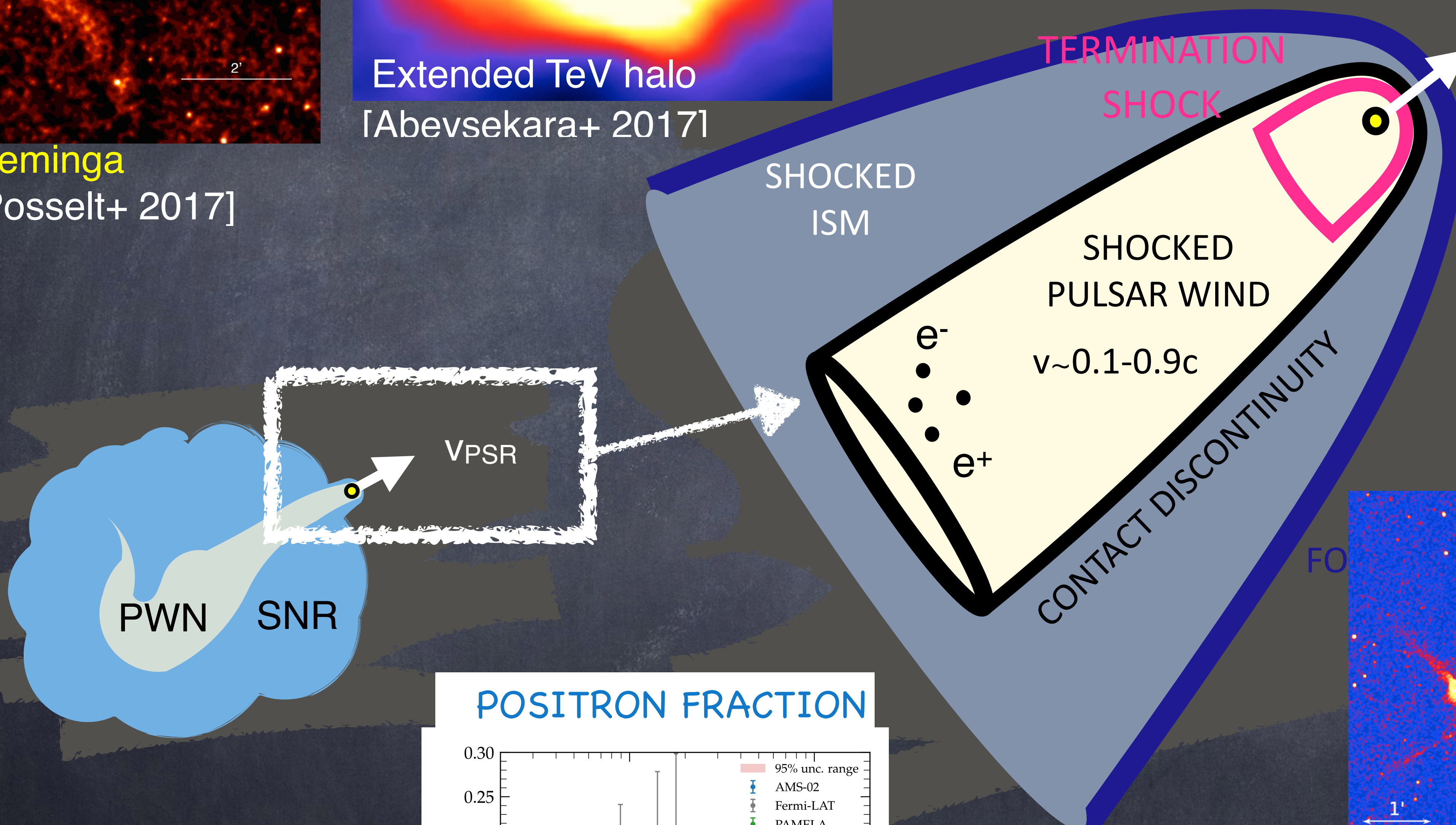


Geminga
[Posselt+ 2017]

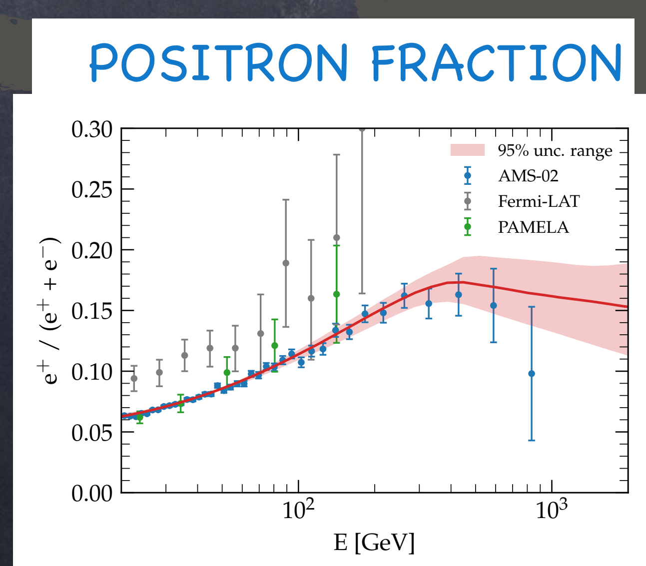


[Abeysekara+ 2017]

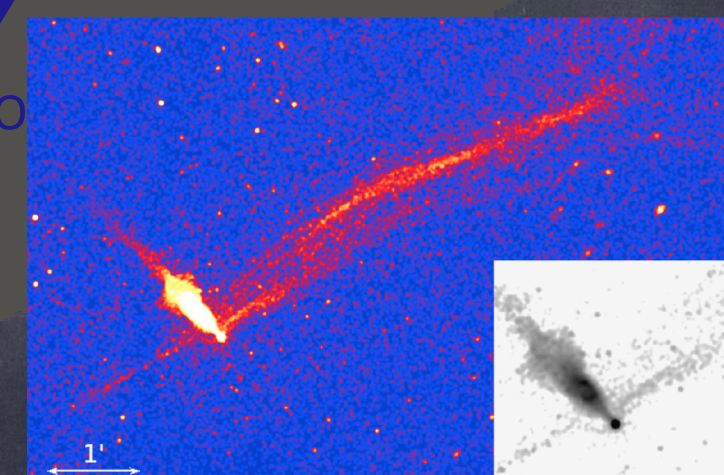
$c_s \sim$10-100 km/s ~ 1/10 v_{PRS}



PSR in supersonic motion



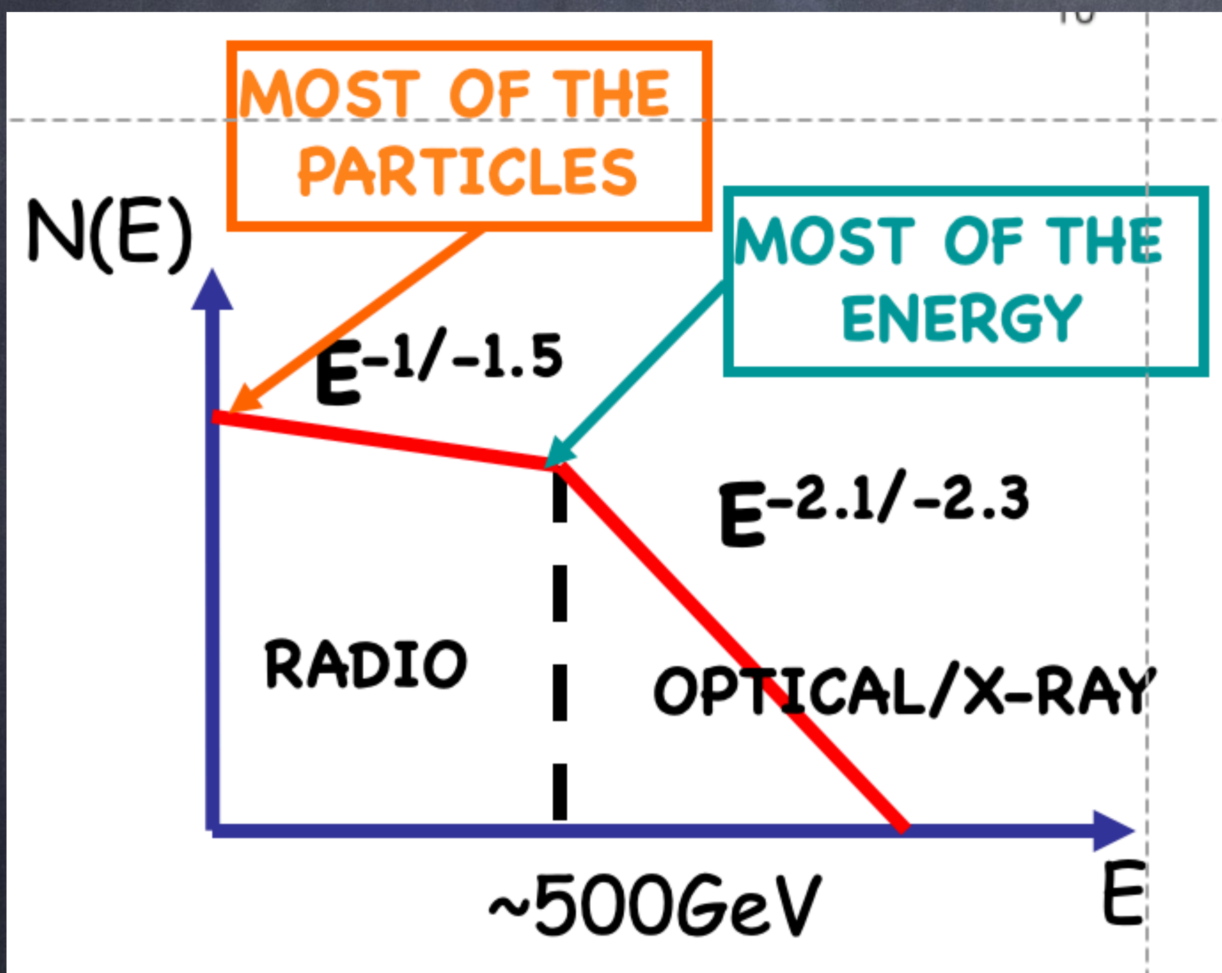
Evoli+ 21,22



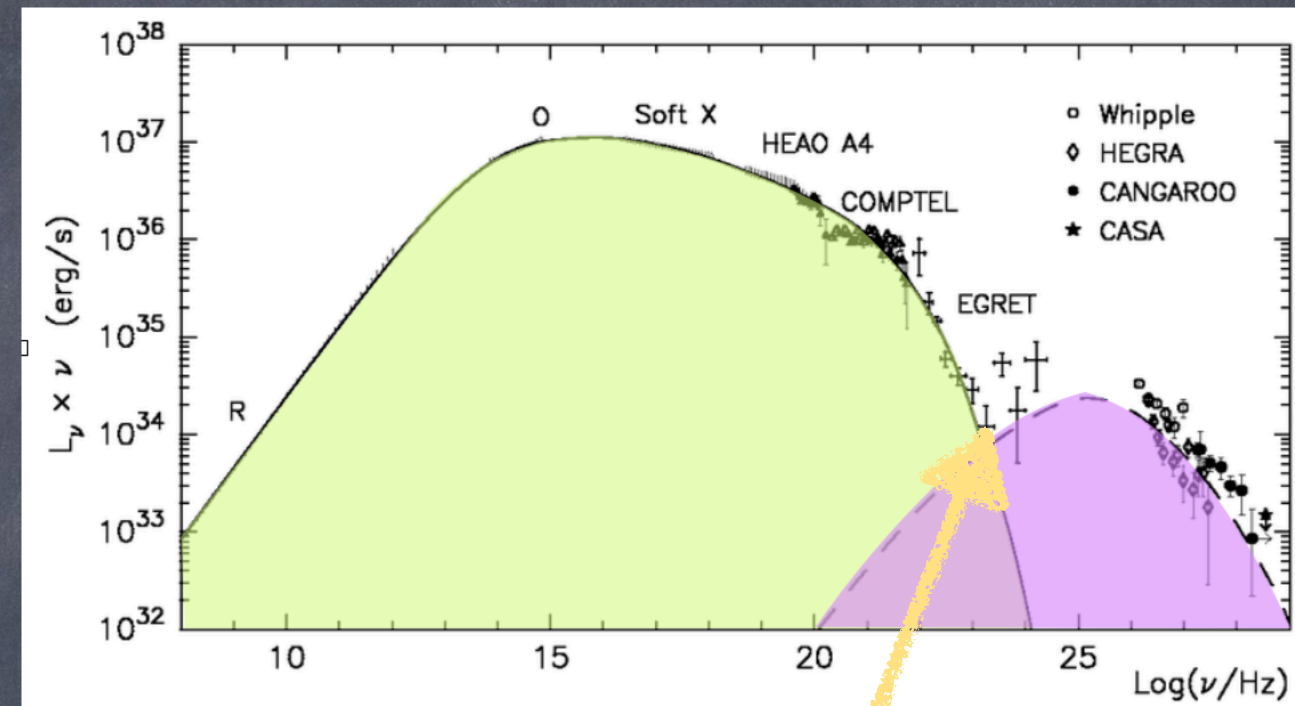
Lighthouse nebula
[Pavan+ 2016]

PARTICLE ACCELERATION IN PULSAR WIND NEBULAE

EMITTING PARTICLES



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

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 $\mathcal{E} \approx \mathrm{v}B/c$

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

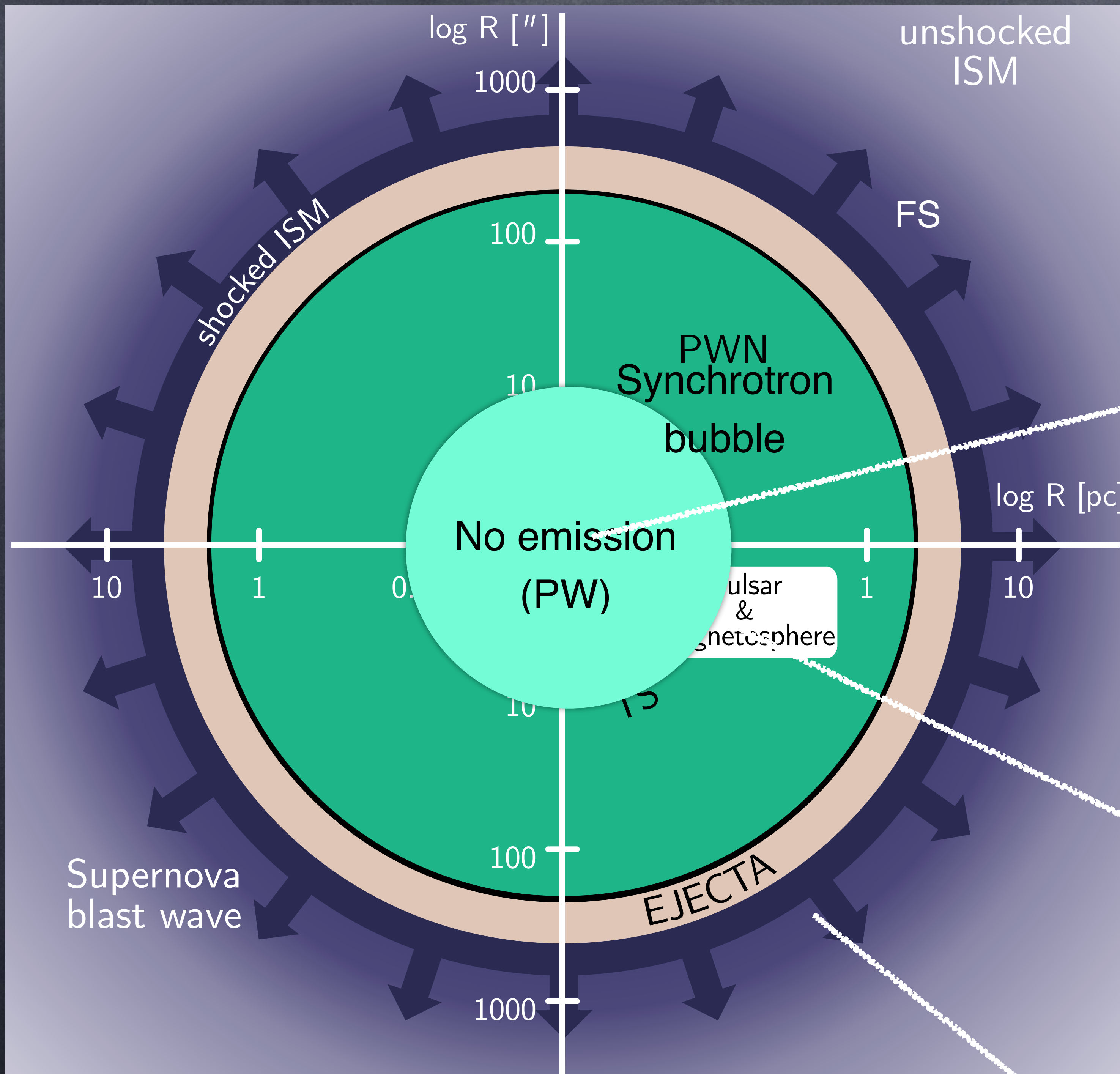
RELATIVISTIC REGIME

$$t_{acc}(E) \approx \frac{E}{qBc}$$

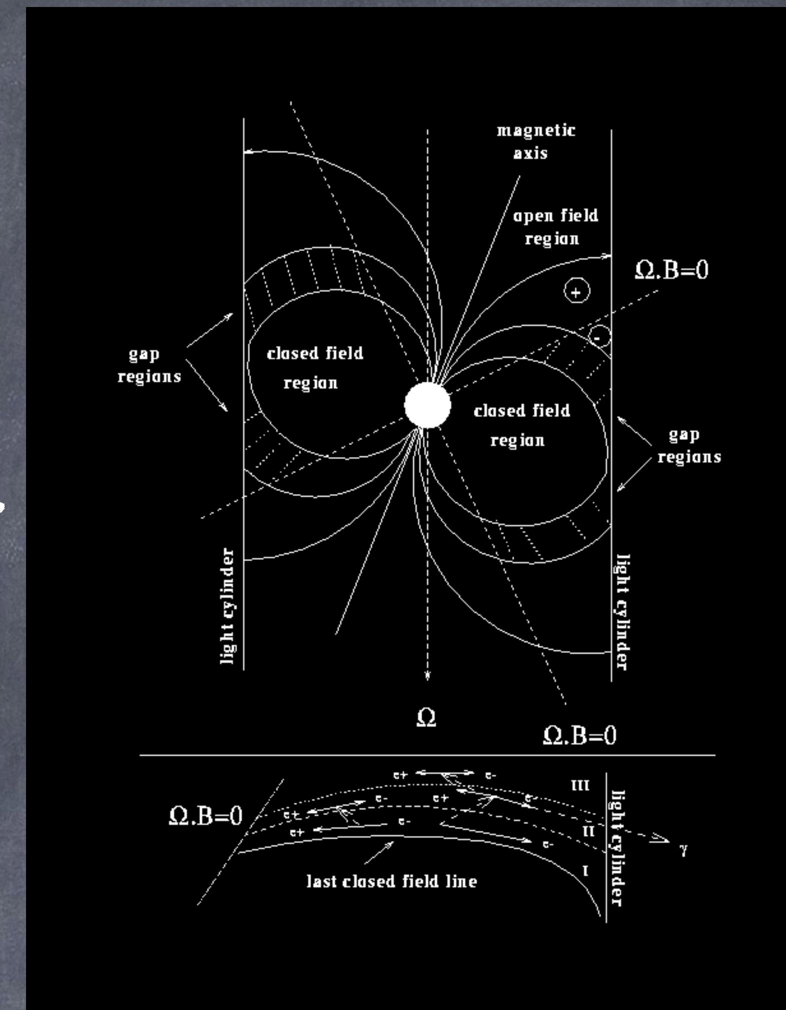
FASTEST POSSIBLE ACCELERATION!

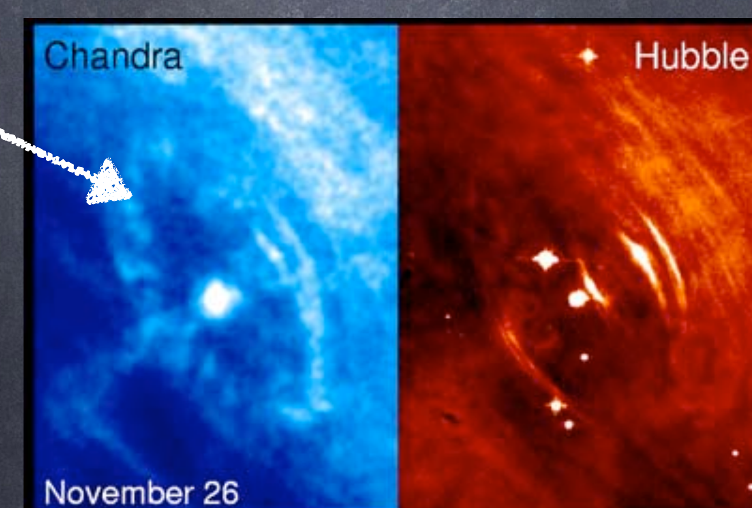
SAME AS FOR DIRECT E-FIELD ACCELERATION WITH $\mathcal{E} \approx B$

ACCELERATION SITES



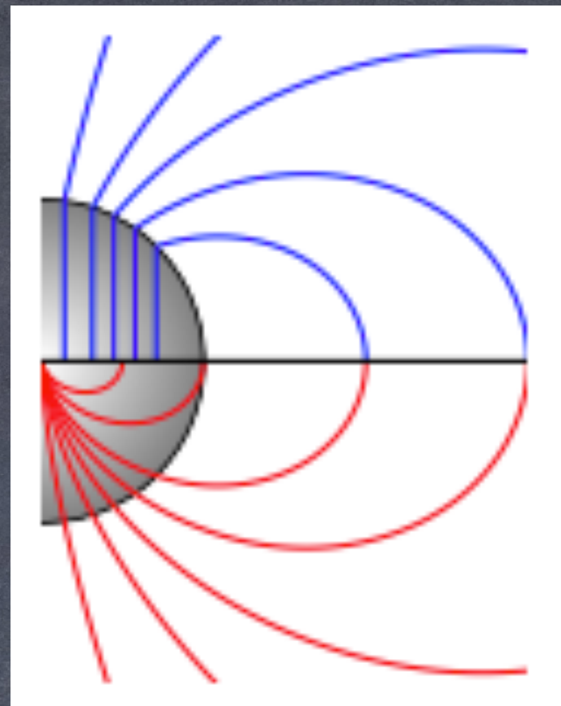
Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

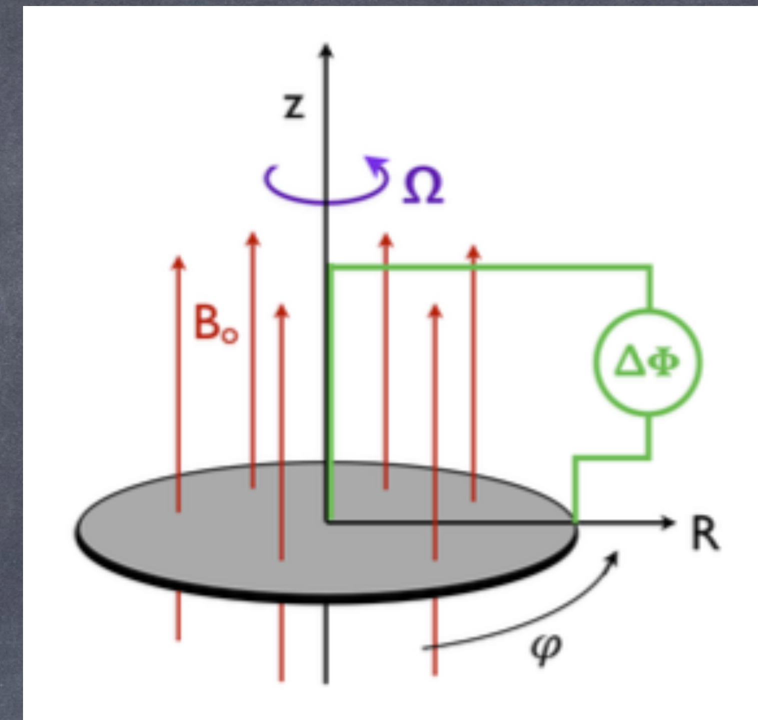




PLUS OF COURSE THE SNR SHOCK

THE PULSAR POTENTIAL DROP





CHARGE DENSITY

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

CHARGE DENSITY

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

TOTAL POTENTIAL DROP

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

POTENTIAL DROP

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

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

PC POTENTIAL DROP

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

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

THE PSR WIND

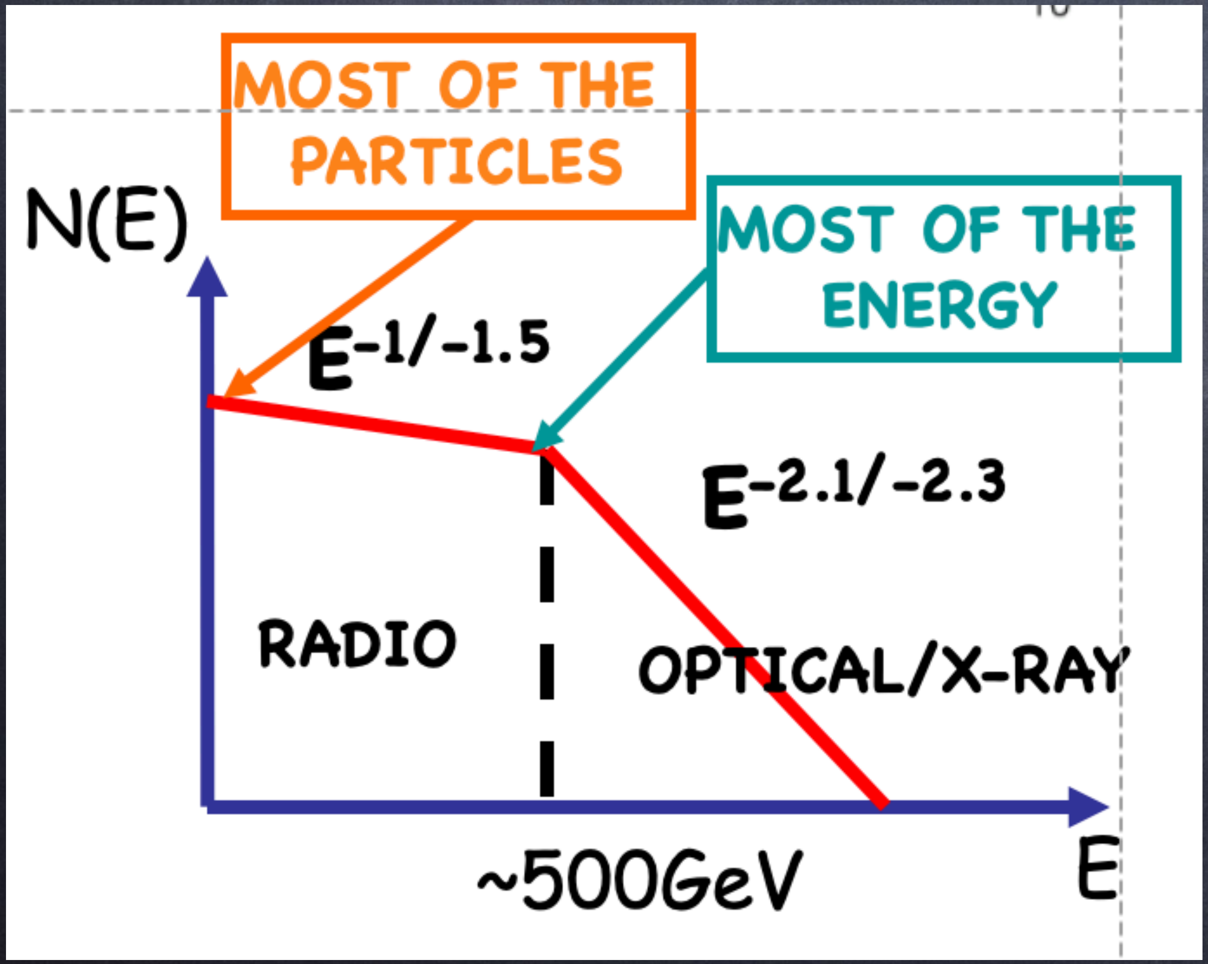
TOTAL WIND POWER:

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

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

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

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

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 07)

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

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

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

$$\kappa < m_i/m_e \Rightarrow m_i \Gamma c^2 \approx e\sqrt{\dot{E}/c}$$

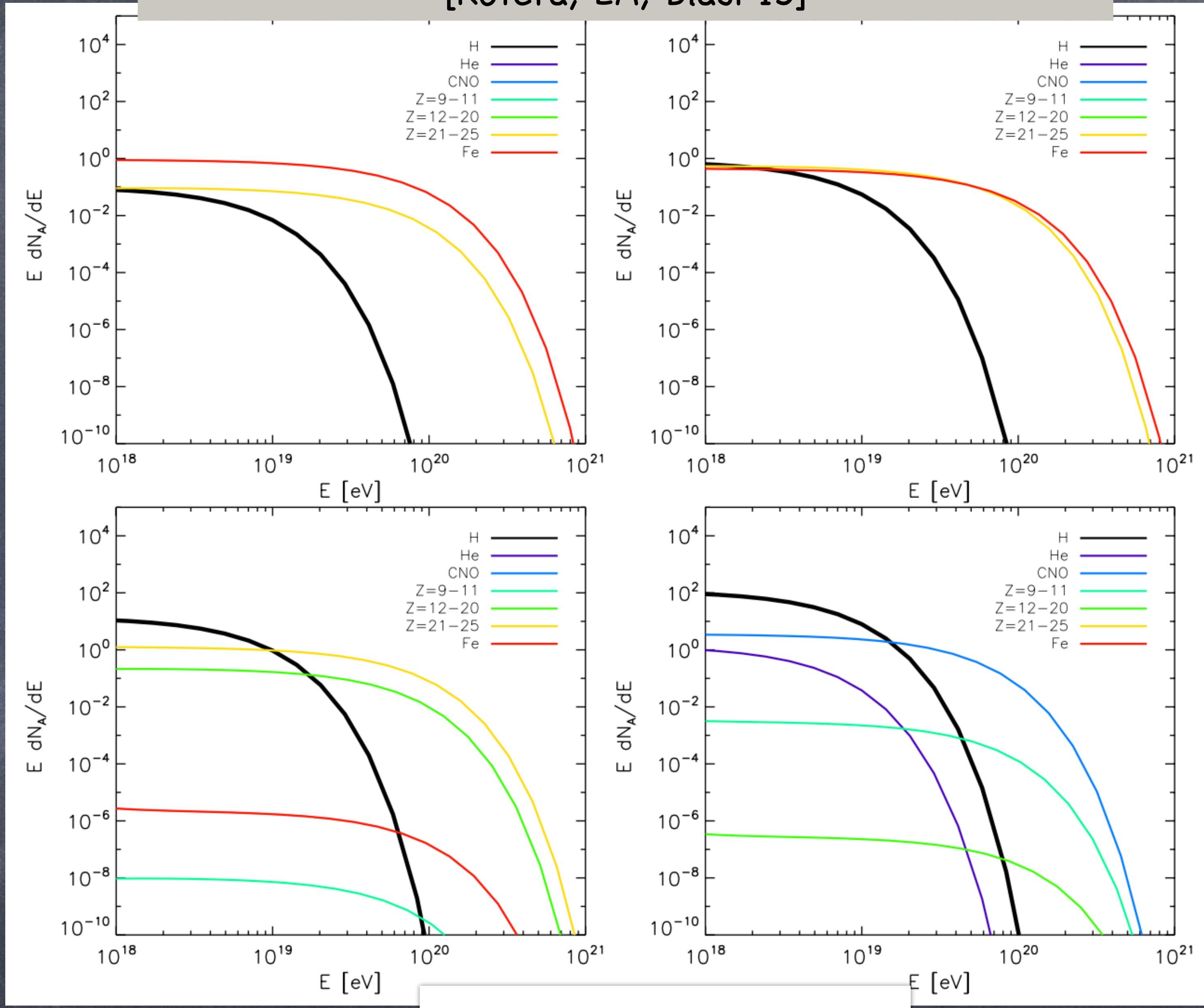
CURRENT BEST ESTIMATE FOR YOUNG PSRs

$\kappa \approx 10^3 - 10^5$

[Timokhin & Harding 19]

UHECRs FROM MAGNETARS

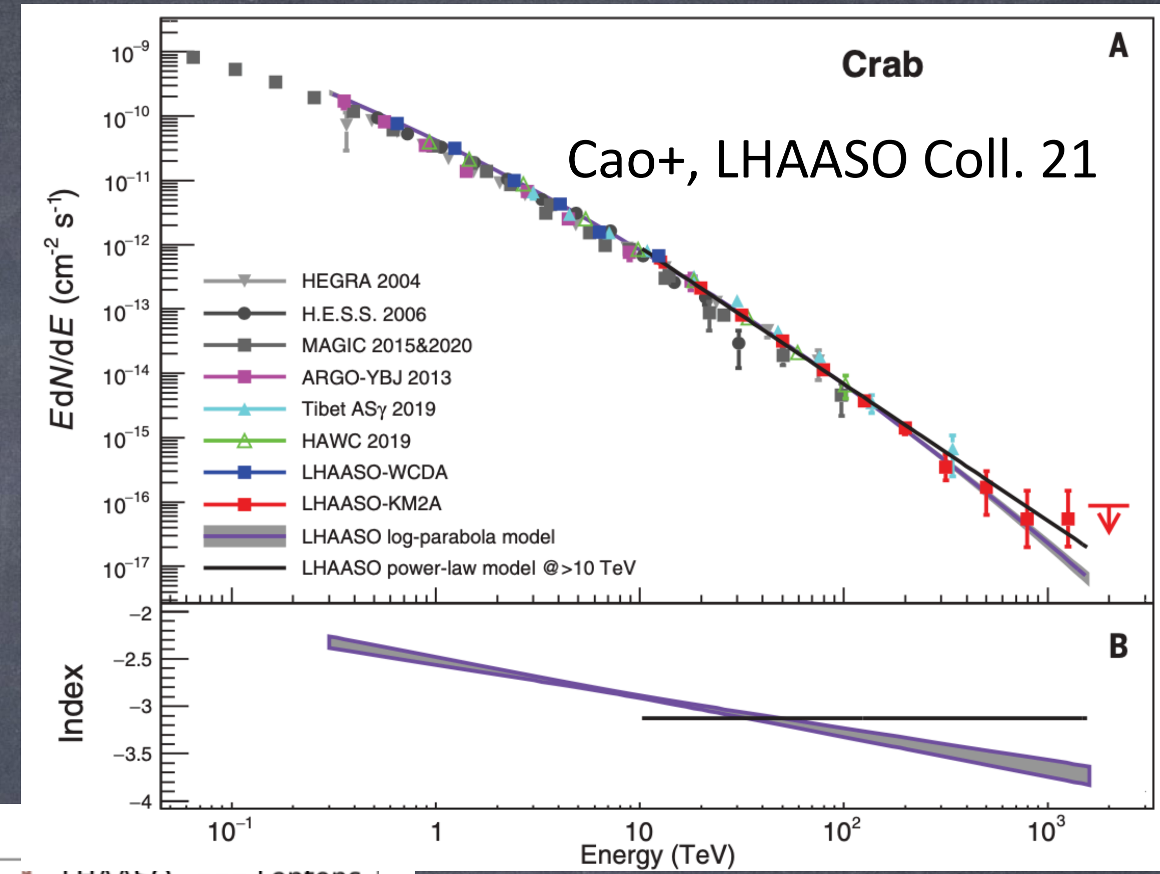
[Kotera, EA, Blasi 15]



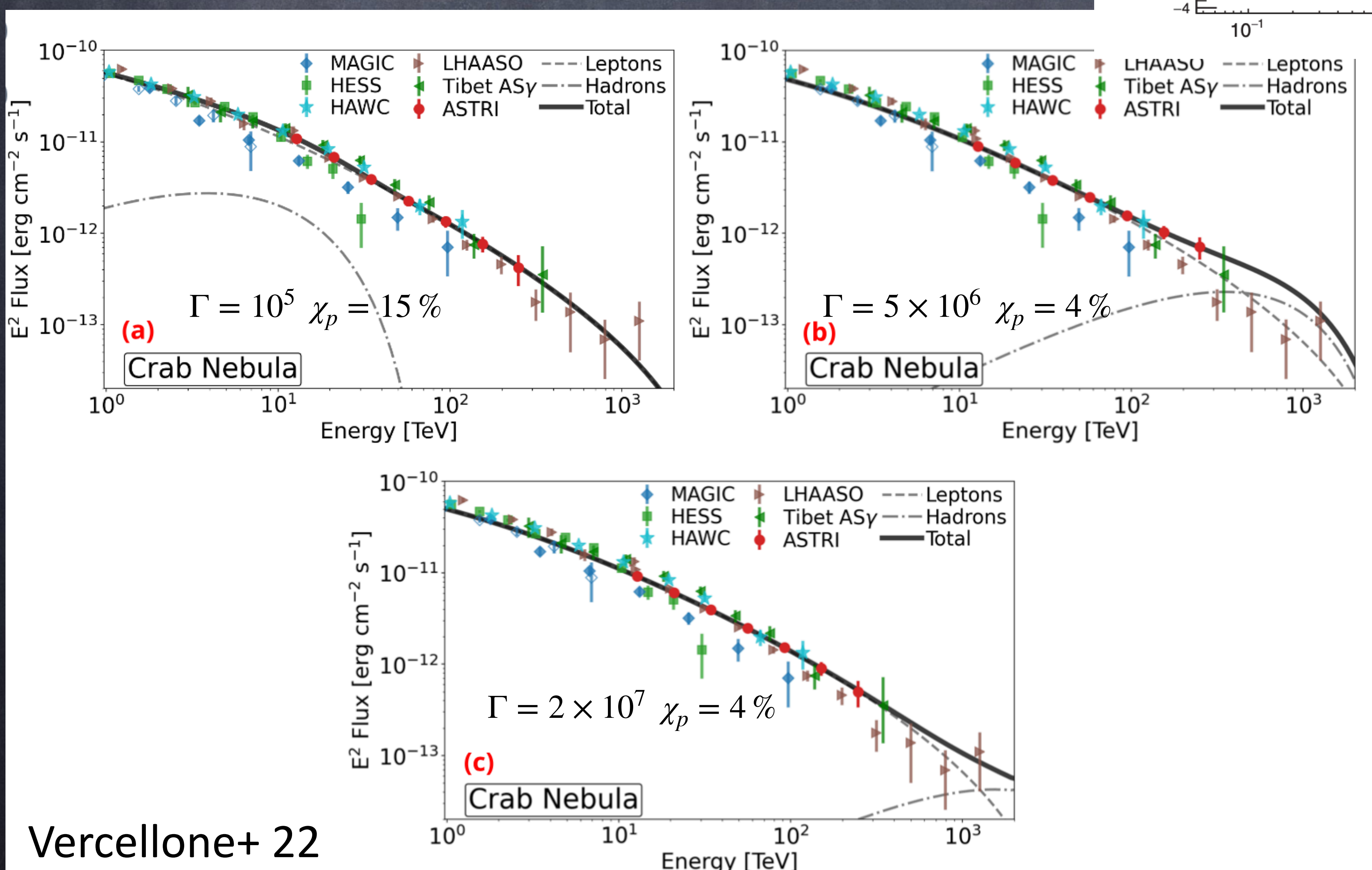
$T_{NS} = [1,2,5,10] \times 10^6 \ K$

NICELY FITS COMPOSITION, SPECTRUM AND CORRELATION WITH STARBURST GALAXIES

DIRECT EVIDENCE FOR IONS?



Cao+, LHAASO Coll. 21



Vercellone+ 22

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

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

PARTICLE ACCELERATION AT THE PWN TS

FERMI MECHANISM → MAGNETIZATION: REQUIRES LOW

HOWEVER SEE VARIANTS

DRIVEN MAGNETIC RECONNECTION → MAGNETIZATION: REQUIRES HIGH

DRIVEN MAGNETIC RECONNECTION → PLASMA MULTIPLICITY: REQUIRES HIGH

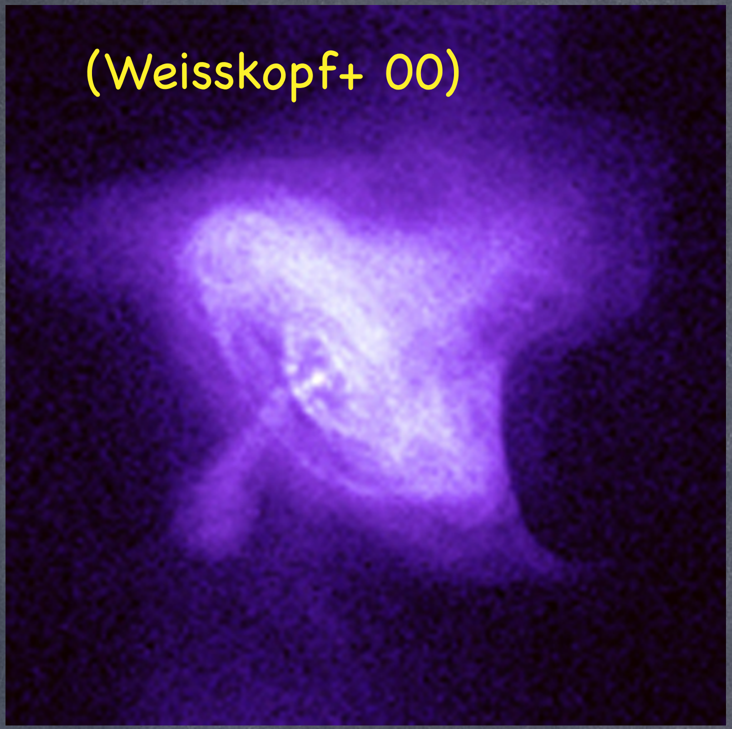
ION CYCLOTRON ABSORPTION IN ION DOPED PLASMA → PLASMA MULTIPLICITY: REQUIRES LOW

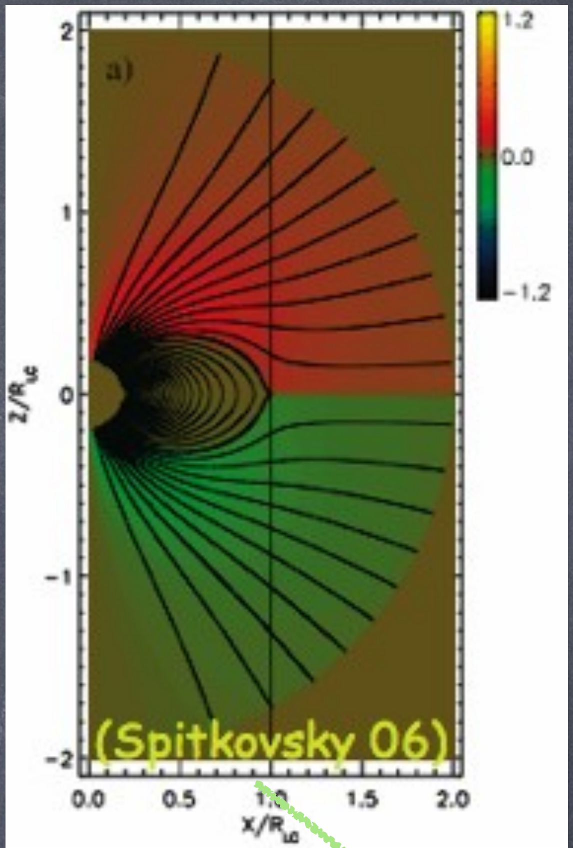
MODELING THE PSR WIND

TOTAL WIND POWER:

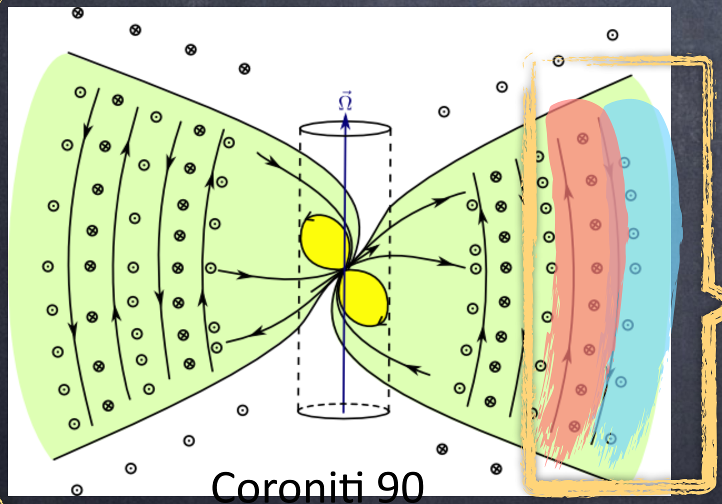
$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e}\right)(1+\sigma)$$

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



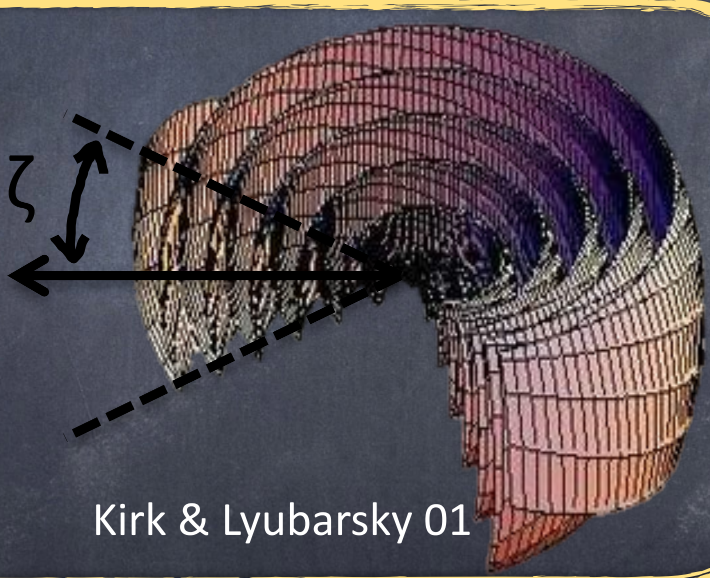


$$F(\theta) \propto \sin^2(\theta)$$

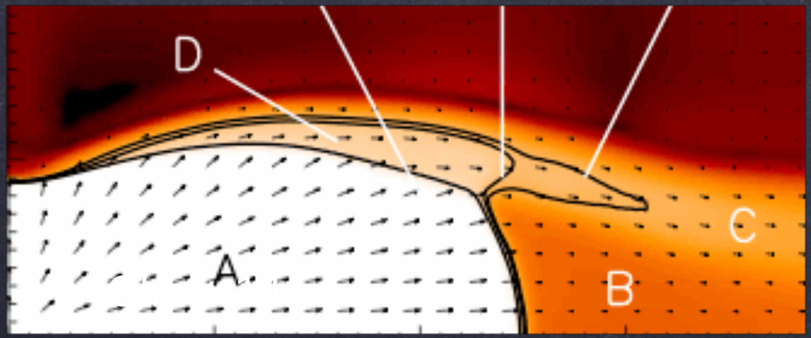


alternating stripes of opposite B polarities

dissipation in current sheet



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



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

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

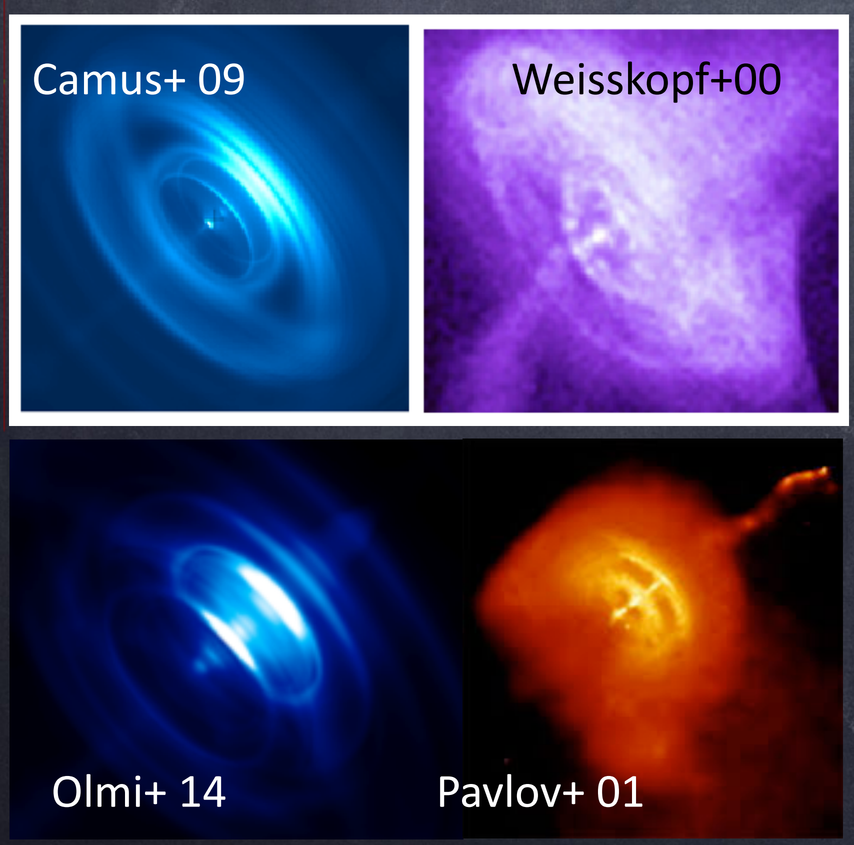
PSR WIND AND PWN DYNAMICS

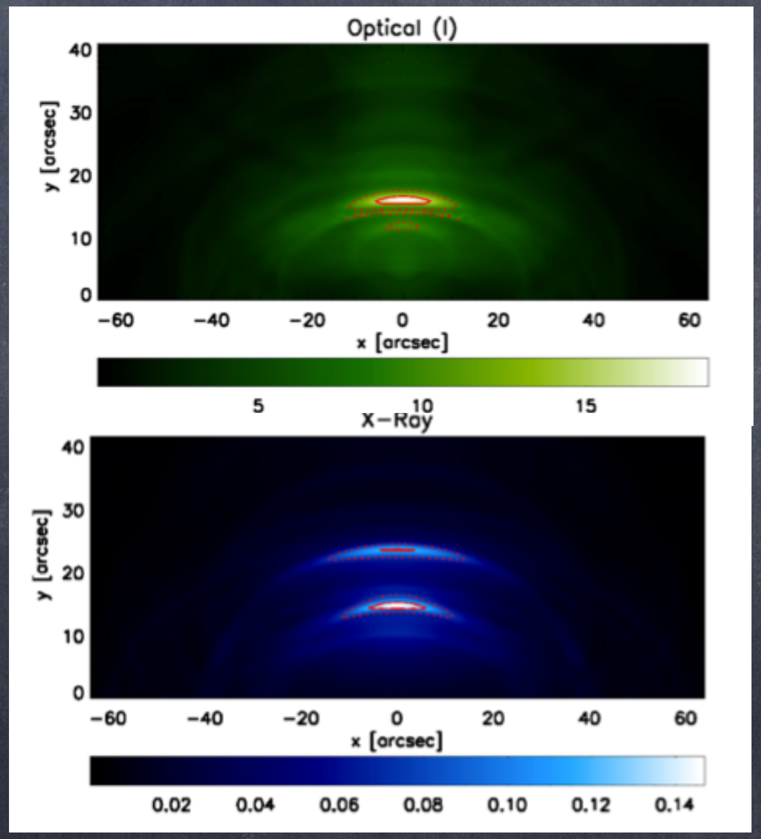
- ACCELERATION MECHANISM AND PLACE DIFFERENT FOR RADIO AND X-RAY EMITTING PARTICLES

- 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

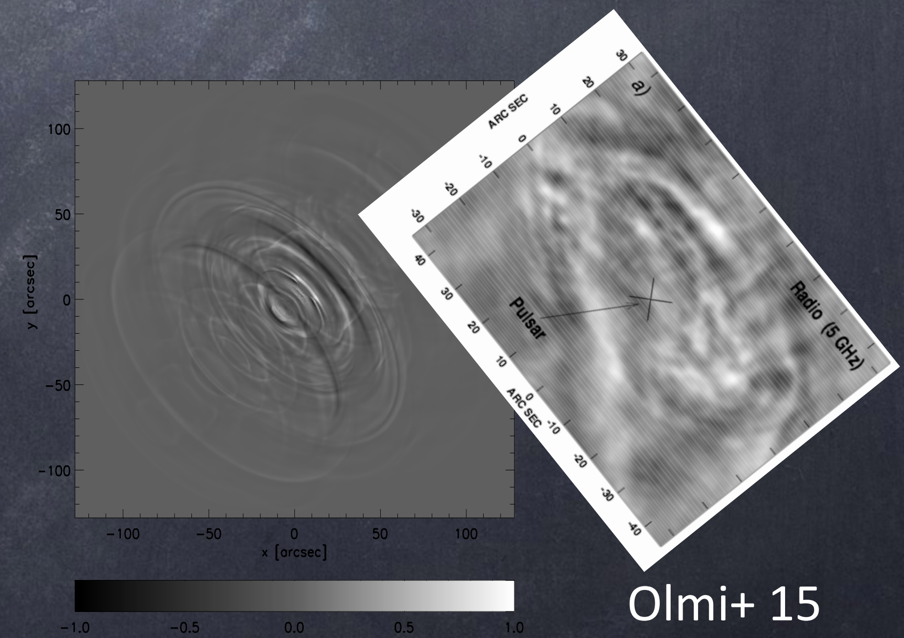
DYNAMICS AND RADIATION MODELING





Olmi+ 14

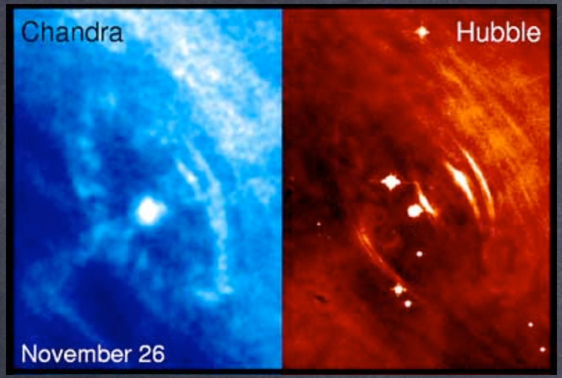
RADIO EMISSION MODELING



Olmi+ 15

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

MAXIMUM ENERGY AT THE PWN TS



ACCELERATION MECHANISM UNKNOWN BUT...

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

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

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

FOR EVOLVED SYSTEMS, LOWER B-FIELD VALUES
STRICT LIMIT FROM THE PSR POTENTIAL DROP $\Phi_{PSR} = \sqrt{\dot{E}/c}$

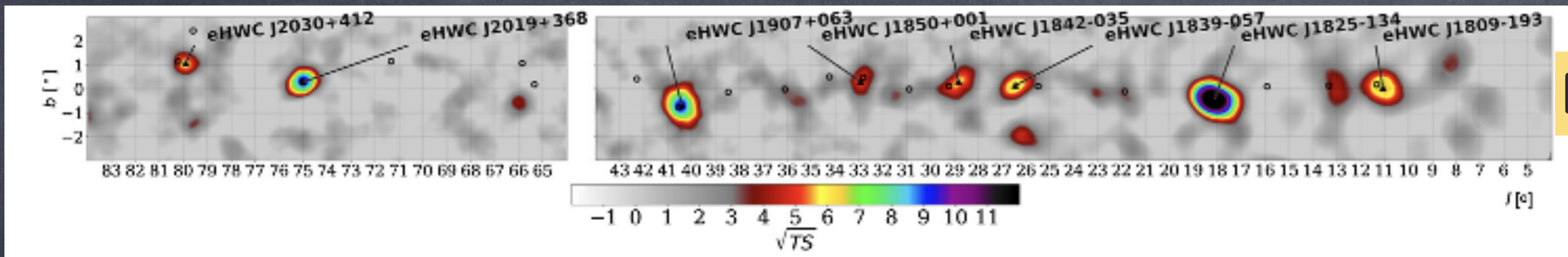
$$E_{max,abs} = e\eta_E B_{TS}\ R_{TS}$$

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

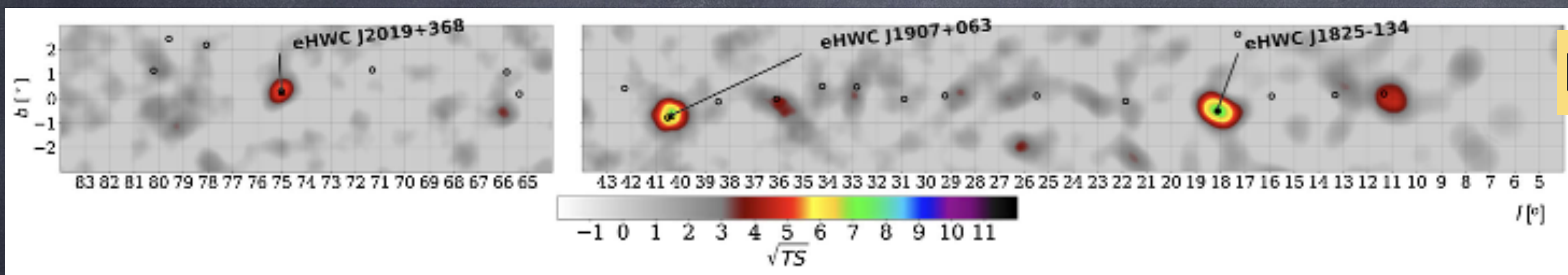
$$E_{max,abs} = e\eta_E\ \xi_B^{1/2}\sqrt{\dot{E}/c} \approx 1.8\ PeV\ \eta_E\ \xi_B^{1/2}\ \dot{E}_{36}^{1/2}$$

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

UHE SOURCES IN THE GALAXY



HAWC >56 TeV



HAWC >100 TeV

Abeysekara + 2020

LHAASO >100 TeV

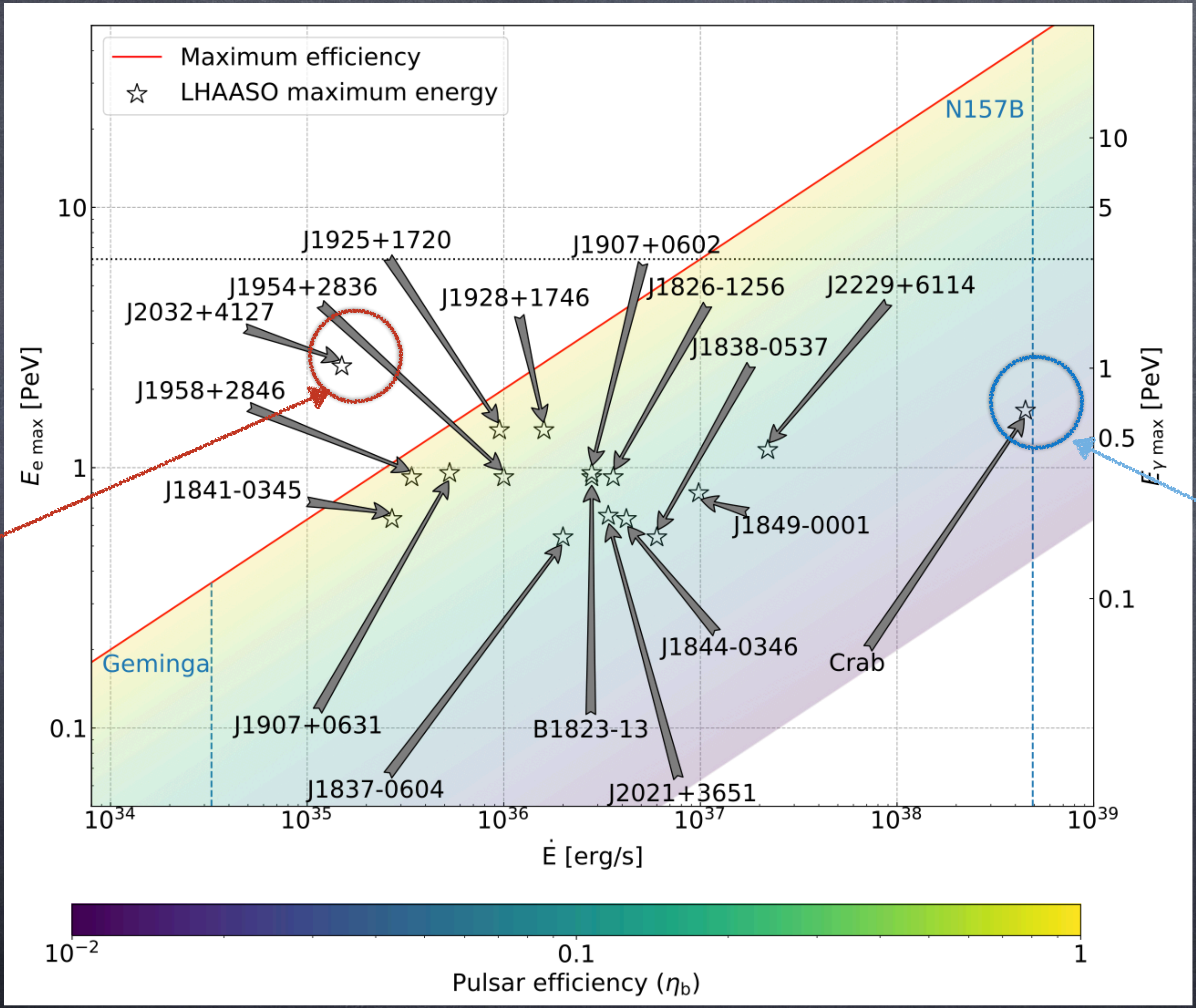
Table 1 | UHE γ-ray sources

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)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

NO PSR

LHAASO PEVATRONS AND PWNe



CYGNUS

MAXIMUM DETECTED ENERGY ABOVE AVAILABLE PSR POTENTIAL

CRAB

MAXIMUM DETECTED ENERGY WELL BELOW AVAILABLE PSR POTENTIAL

de Ona Wilhelmi + 2022

SUMMARY

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

- **PARTICLE ACCELERATION MECHANISM** AND PULSAR WIND PARAMETERS PROGRESSIVELY BETTER CONSTRAINED BUT **STILL UNSETTLED**

- 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

    - AND PROVIDE DIAGNOSTIC OF THE ACCELERATION CUT-OFF IN OLD SYSTEMS

DO WE STILL NEED VHE FOR PWNe???? ABSOLUTELY YES!!!!!!