CANDIDATE PEVATRONS: PULSAR WIND NEBULAE

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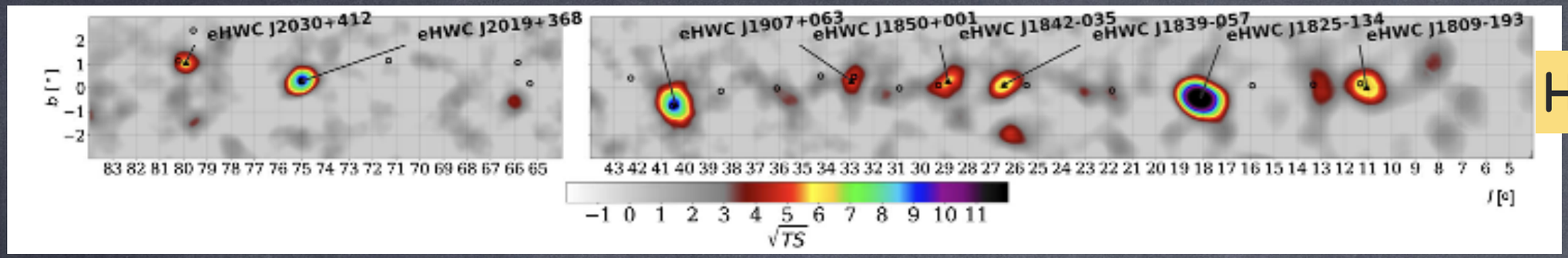
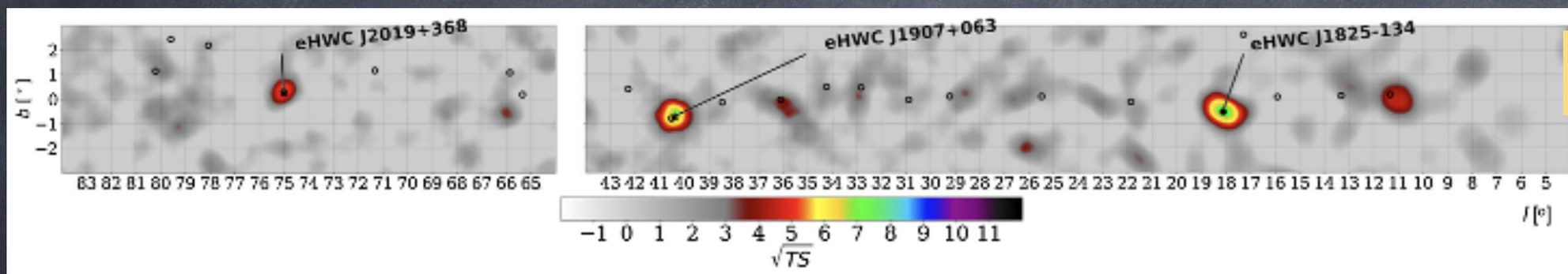
UHE SOURCES IN THE GALAXY



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	$0.26\ ^{+0.16}_{-0.10}$	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	$0.71\ ^{+0.16}_{-0.07}$	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

THE QUESTION:

ARE THESE THE SOURCES OF CRs AT THE KNEE?

IF SO:

A. THE SPECTRUM OF EMITTING PARTICLES MUST EXTEND BEYOND PeV WITHOUT A CUTOFF

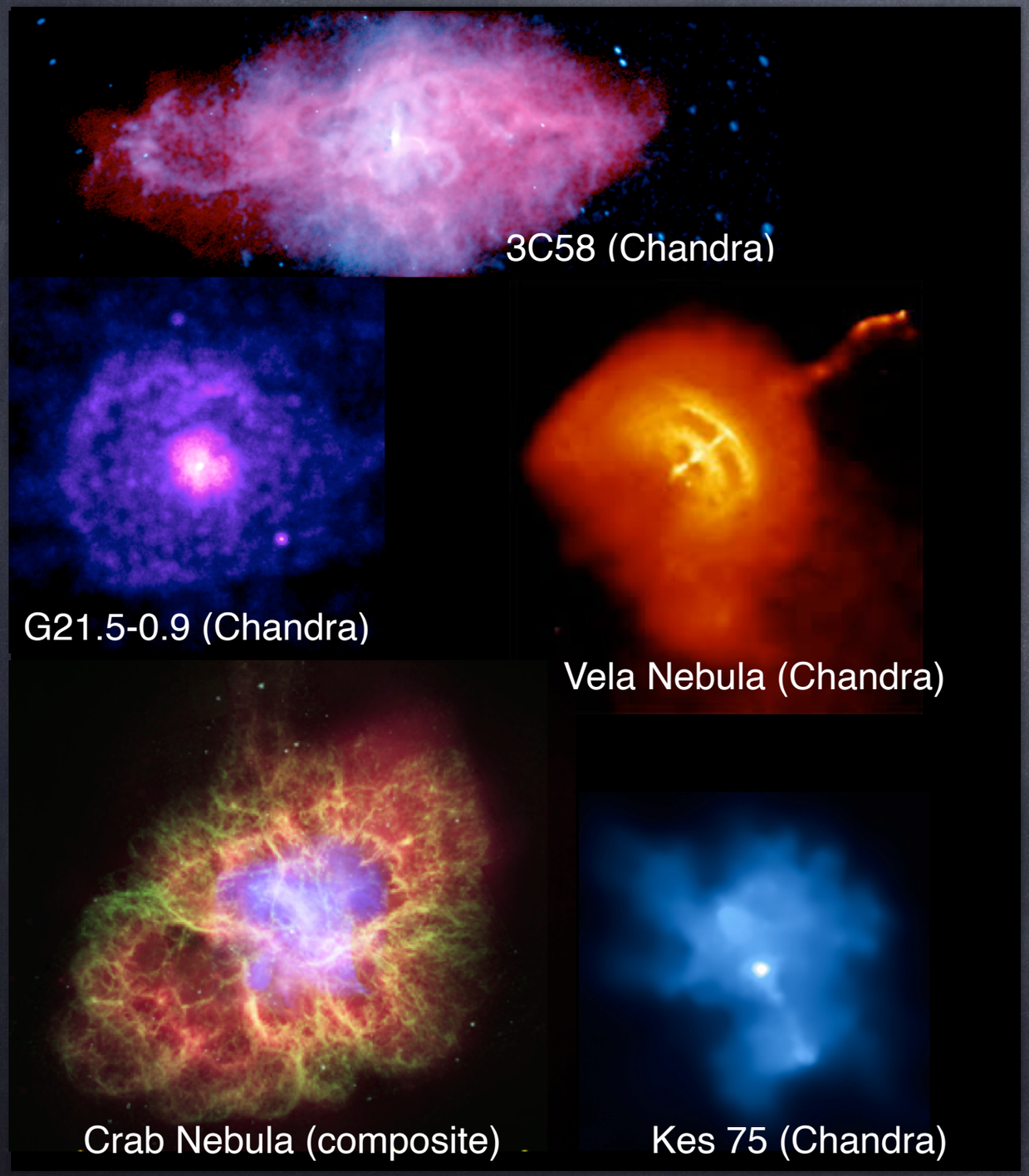
B. EMITTING PARTICLES MUST BE HADRONS

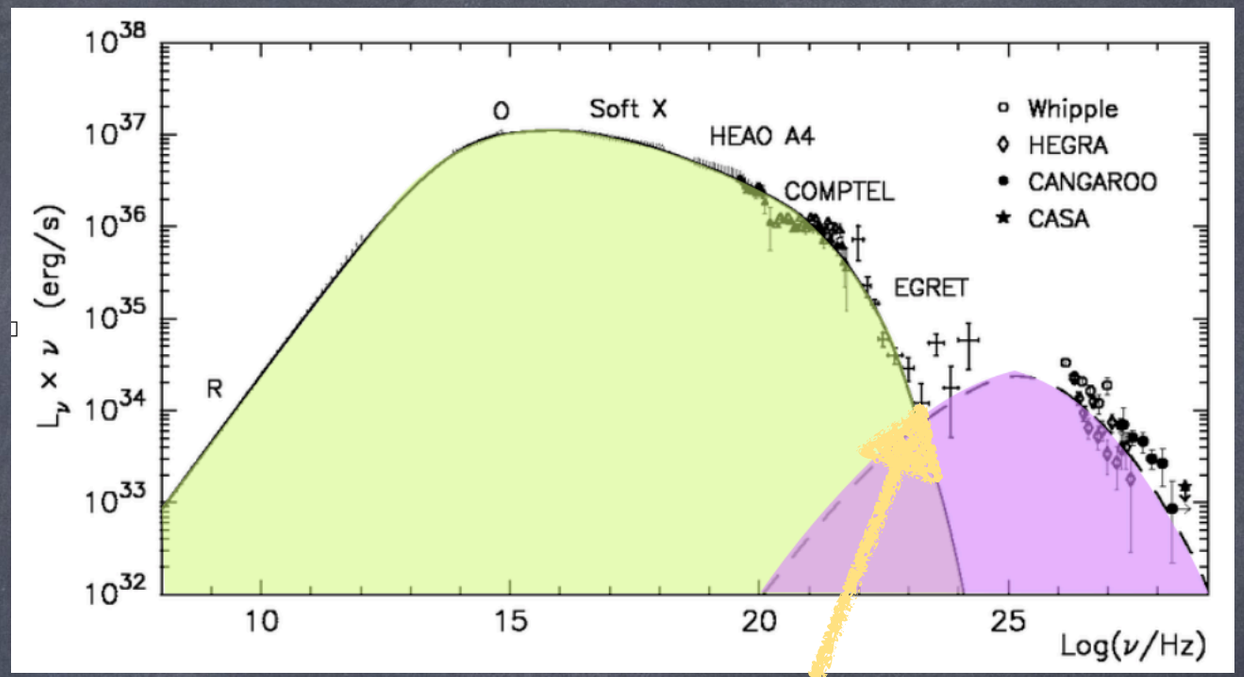
TESTING A REQUIRES GOOD SPECTRA AND GOOD STATISTICAL METHODS FOR FITTING (e.g. Anguner et al in prep)

TESTING B REQUIRES EXCLUDING LEPTONS BY PHYSICALLY MOTIVATED MODELLING

PULSARS AND THEIR NEBULAE

OBSERVATIONALLY: THE ONLY SOURCES WITH DIRECT EVIDENCE OF PeV LEPTONS

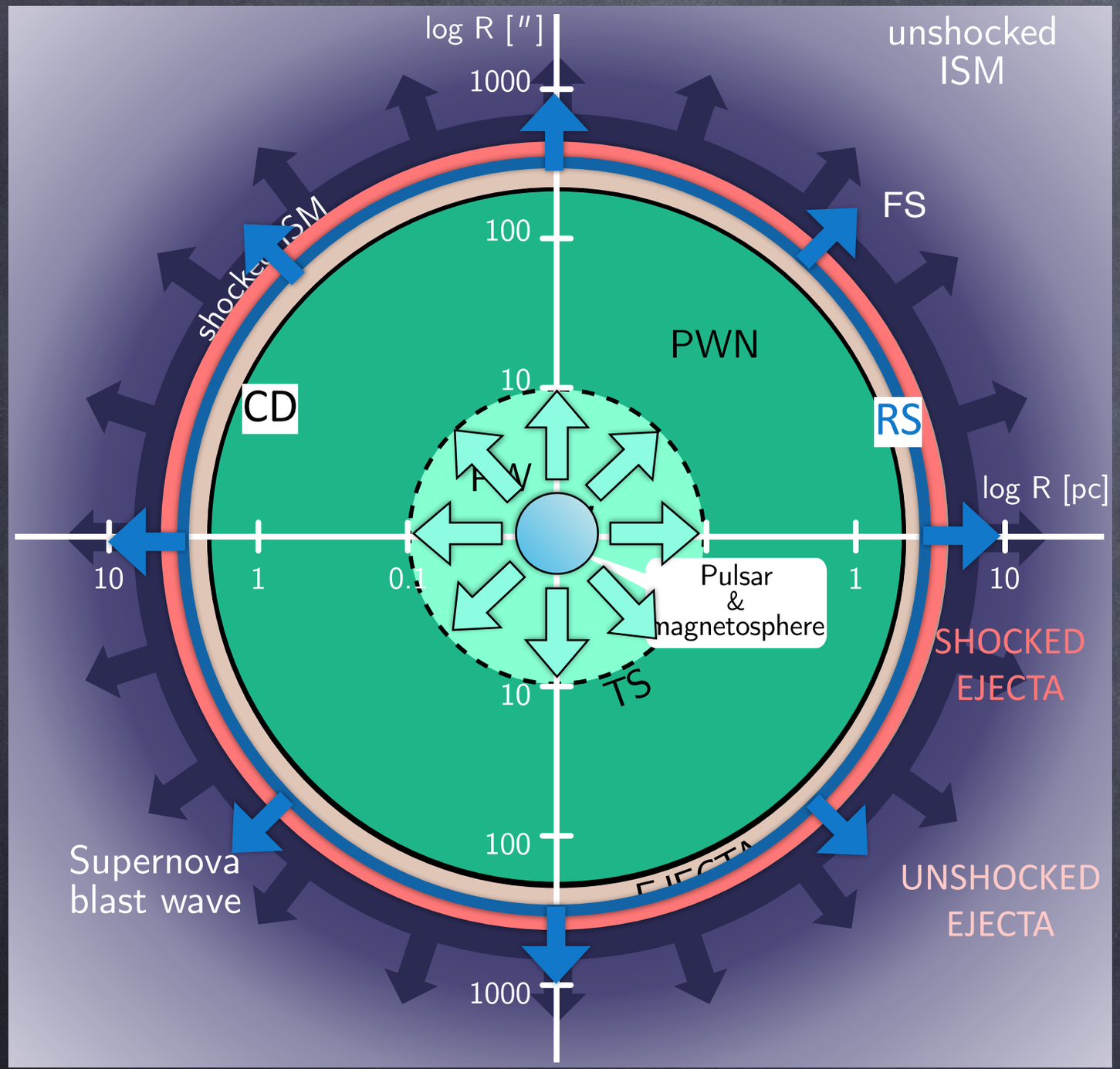




PeV ELECTRONs

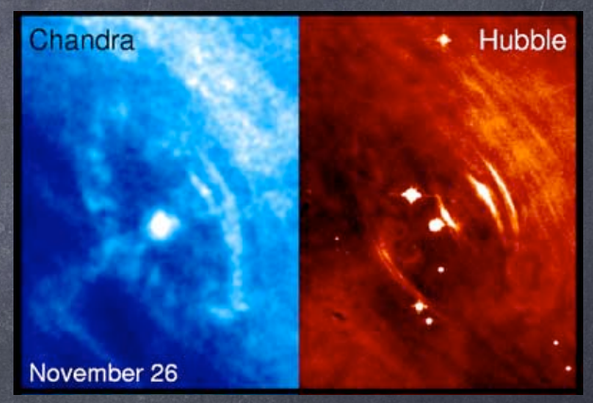
IN THEORY, ABOUT THE ONLY SOURCES IN THE GALAXY ABLE TO ACCELERATE LEPTONS TO PeV ENERGIES
(although... see Vieu et al 23)

BASIC PICTURE FOR YOUNG SYSTEMS



Adapted from Kennel & Coroniti 1984

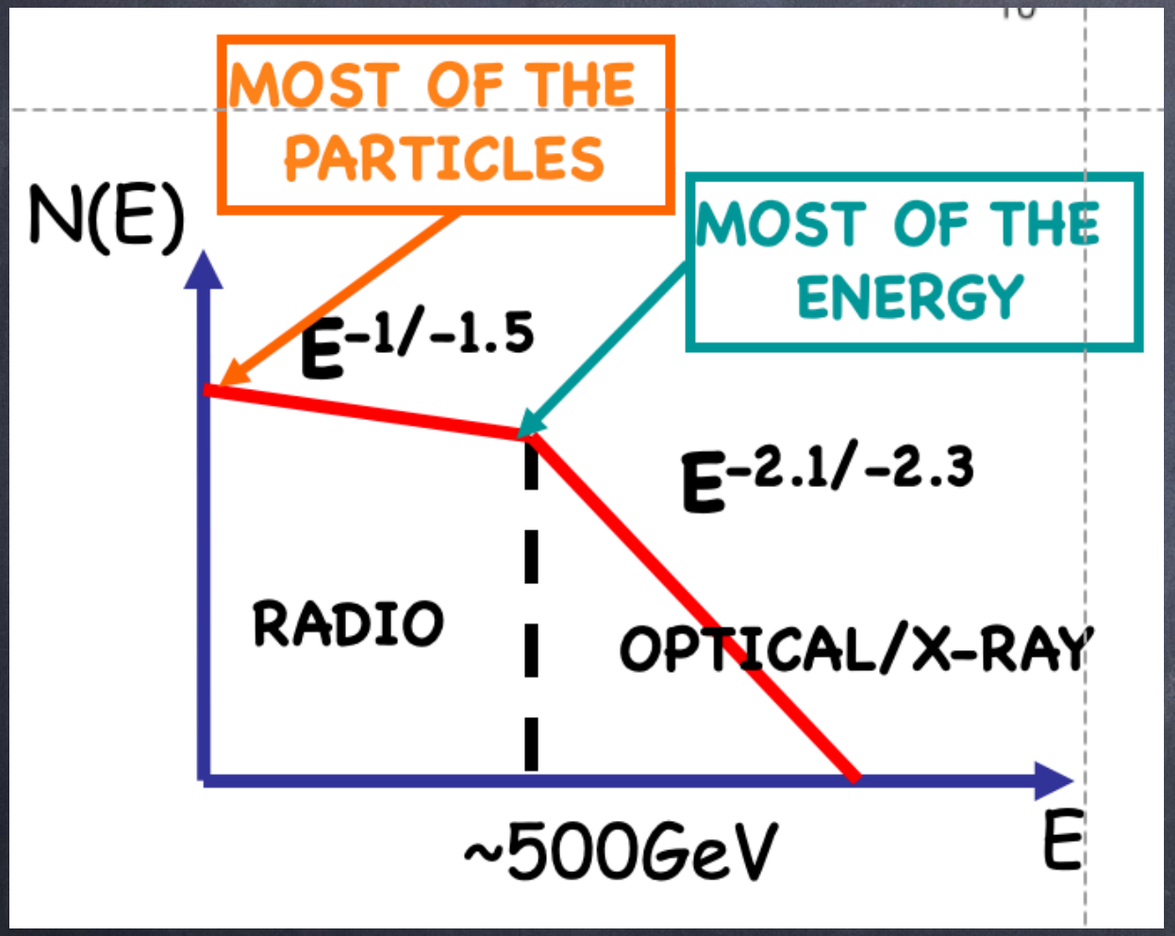
[Del Zanna & Olmi 2017]



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

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

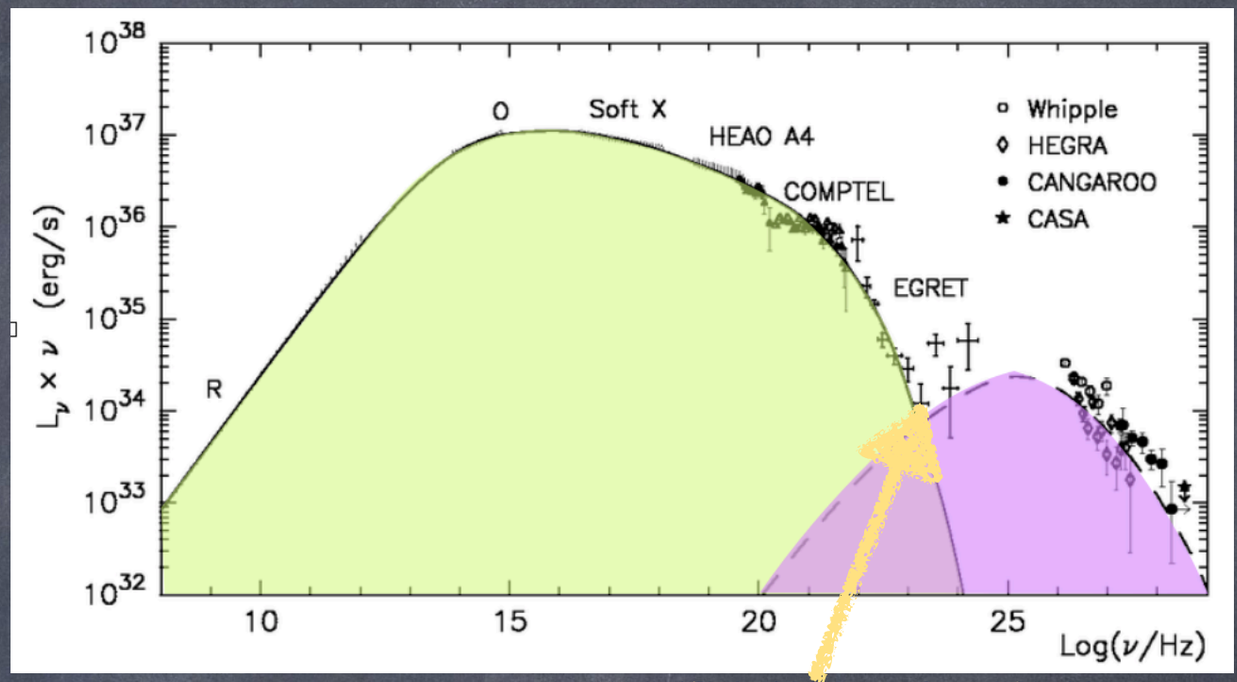
EMITTING PARTICLES



ONE ZONE MODELS

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

(also Fraschetti & Pohl 2017 for log-parabola injection)



PeV ELECTRONs

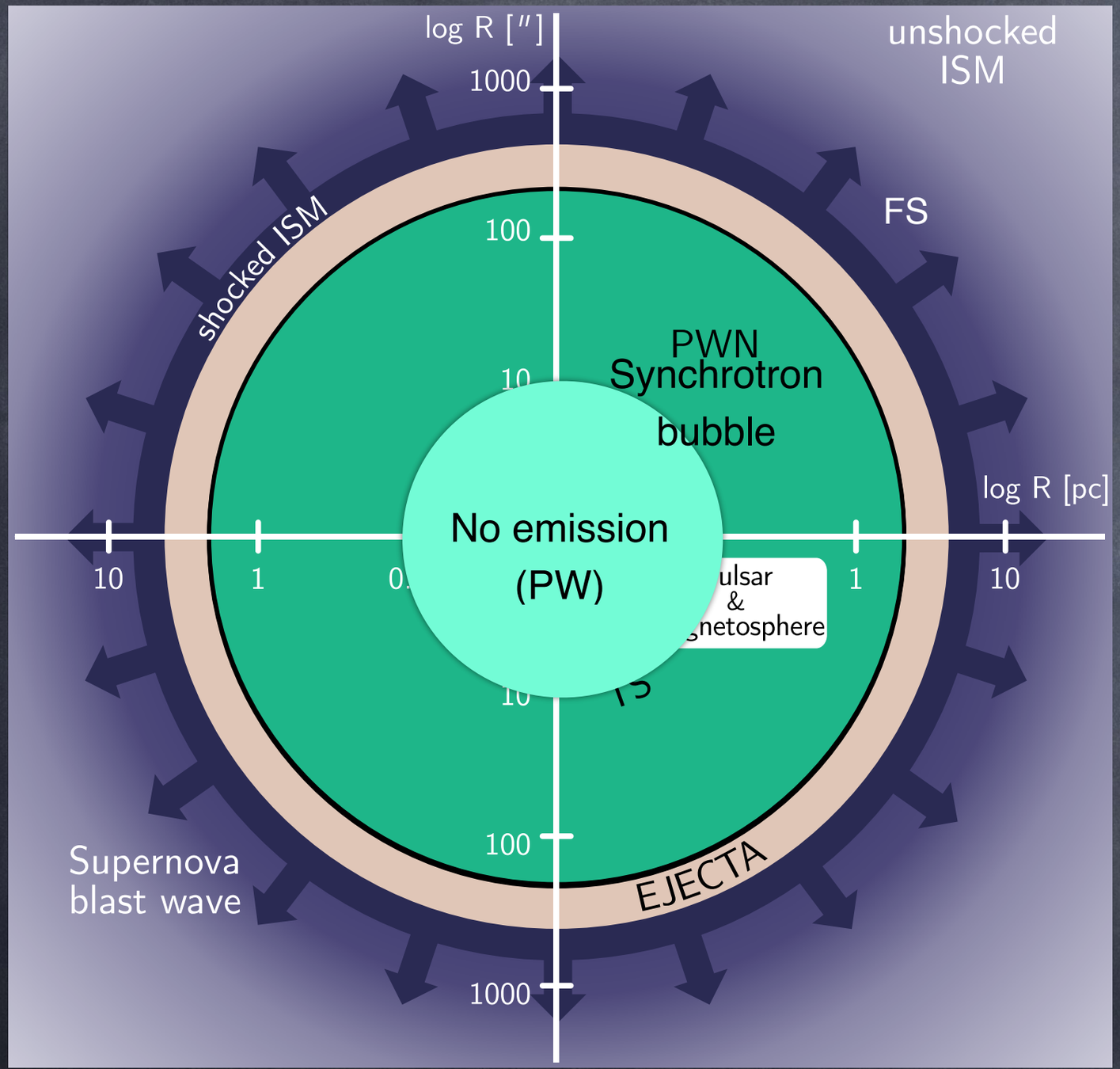
$B_{NEB} \approx 100\ \mu G$

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

EXTRAORDINARY ACCELERATOR!

BUT NO CLUE HOW IT WORKS….

ACCELERATION SITES



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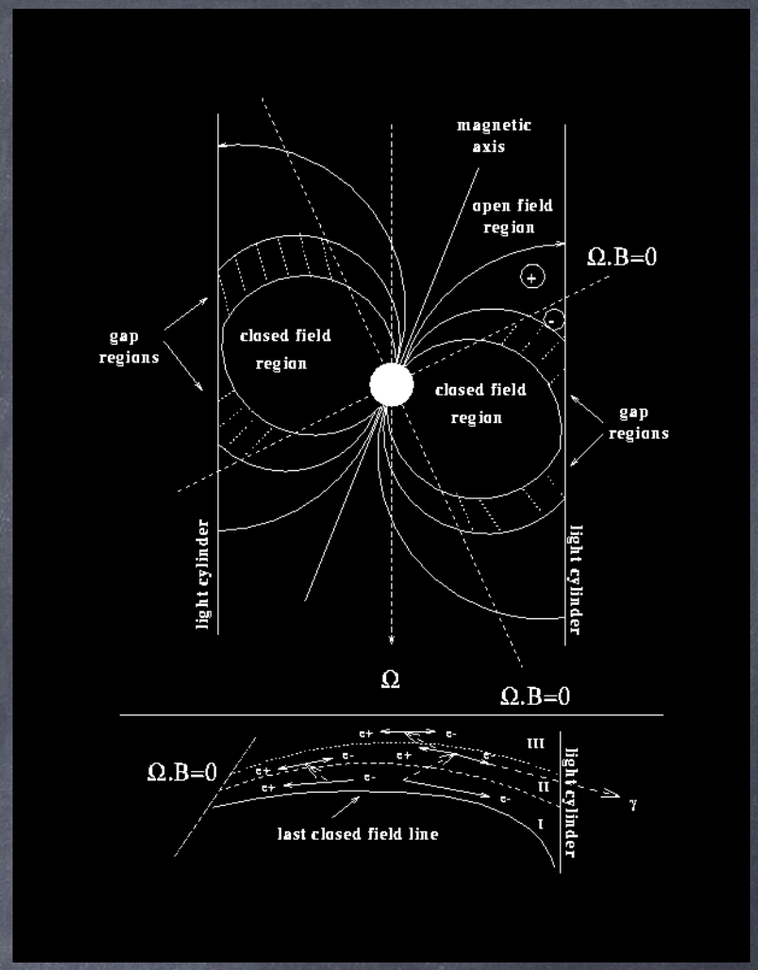
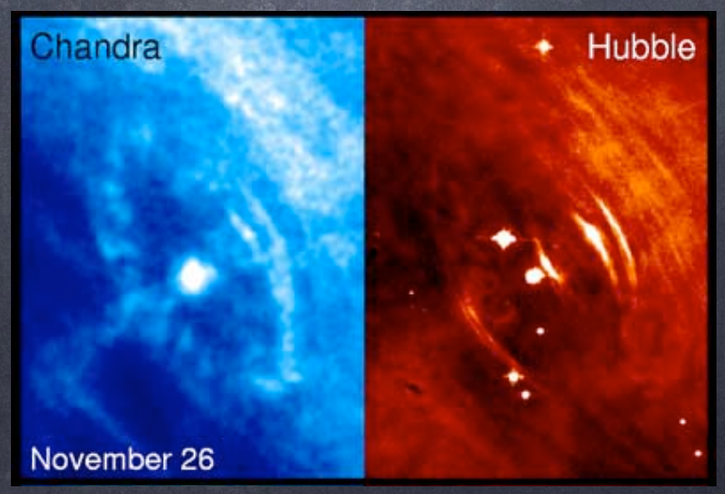
[Del Zanna & Olmi 2017]





PLUS OF COURSE THE SNR SHOCK

MAXIMUM ENERGY FOR AN ACCELERATOR

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

ABSOLUTE LIMIT

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

FOR DIFFUSIVE SHOCK ACCELERATION

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

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

DIRECT E-FIELD ACCELERATION WITH $\mathscr{E} \approx \mathrm{v_f} B/c$

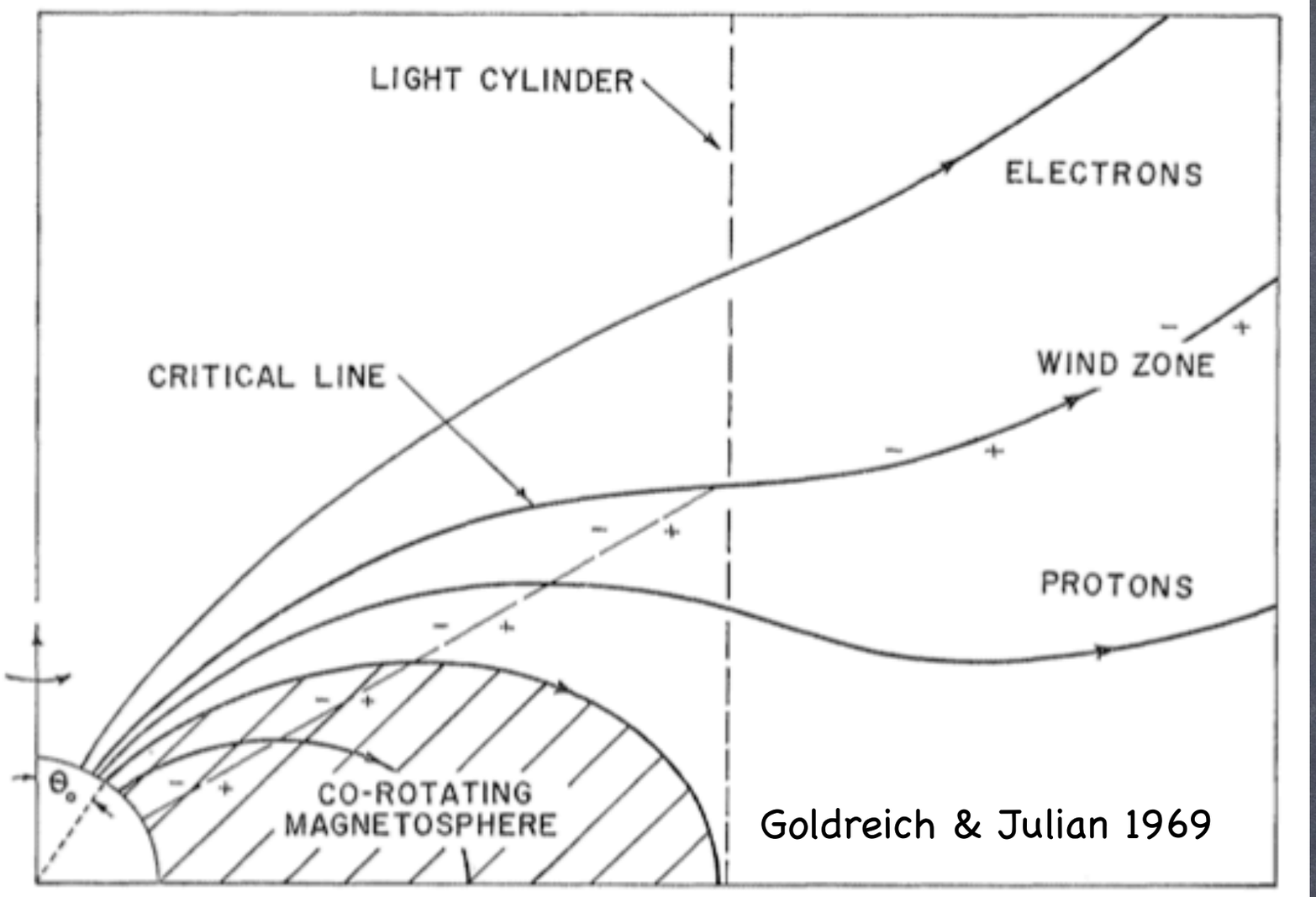
$$E = q\mathscr{E}ct \quad \rightarrow \quad t_{acc}(E) \approx \left(\frac{c}{\mathrm{v}_f}\right)\frac{E}{qBc}$$

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

FASTEST POSSIBLE ACCELERATION!

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

THE PULSAR MAGNETOSPHERE



Goldreich & Julian 1969

STAR DEVELOPS COROTATING MAGNETOSPHERE

$$\vec{E} = -\frac{\Omega R \sin\theta}{c}\underline{\mathbf{e}}_{\phi} \wedge \vec{B}$$

THROUGHOUT COROTATION REGION

COROTATION ONLY POSSIBLE UNTIL $v < c$

LAST CLOSED FIELD LINE DEFINES **POLAR CAP**

$$\theta_{pc} = \sqrt{\frac{R_\star}{R_L}}$$

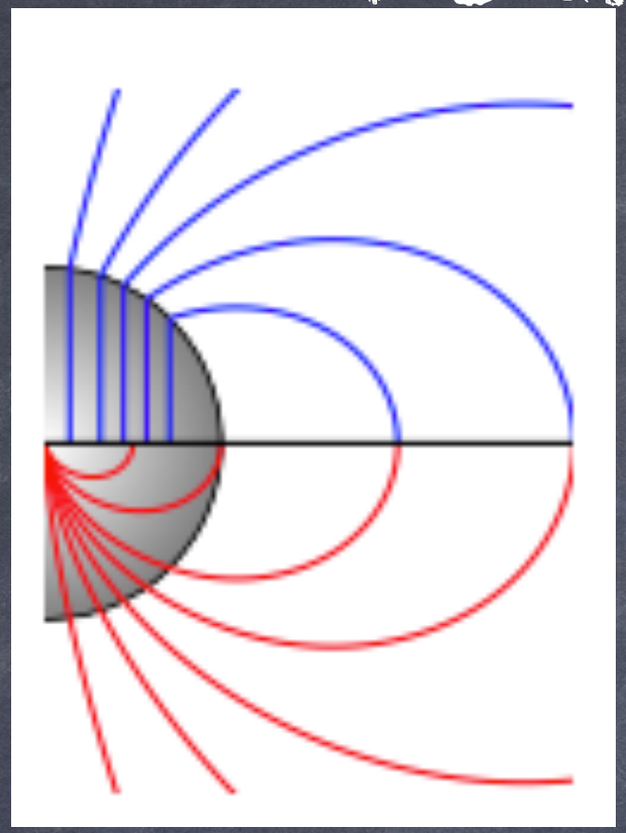
LIGHT CYLINDER

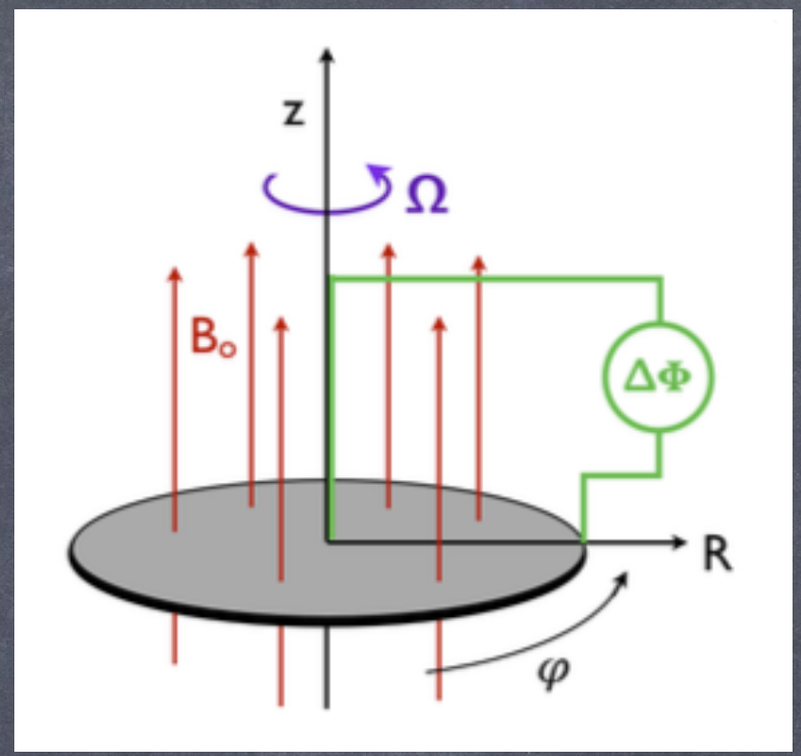
$$R_L = \frac{c}{\Omega} = 5 \times 10^8 P_{100}\ \mathrm{cm}$$

THE STAR SPINS DOWN BY WIND EMISSION

$$\dot{E} \approx \frac{B_\star^2 R_\star^6 \Omega^4}{c^3} = I\Omega\dot{\Omega}$$

PULSAR ELECTRODYNAMICS





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

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

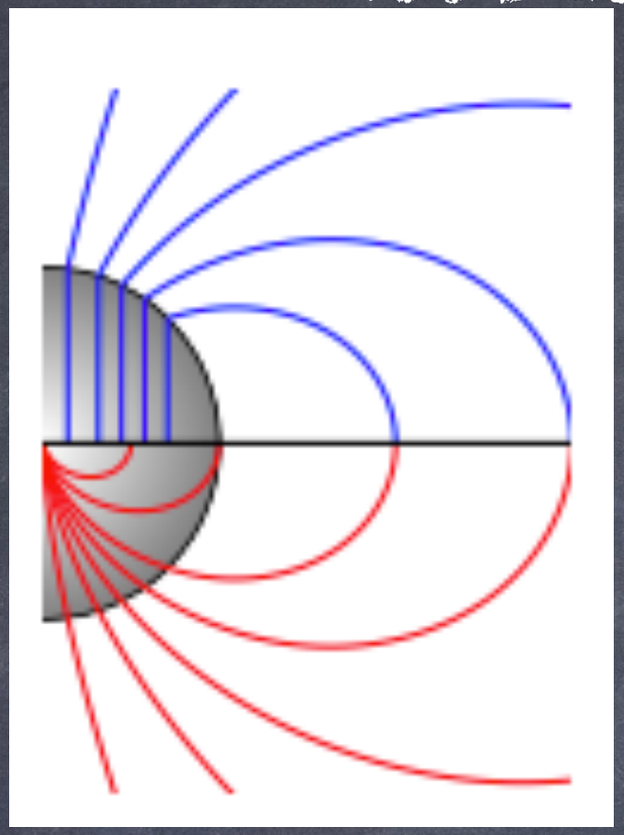
CHARGE DENSITY

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

POTENTIAL DROP

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

ABSOLUTE LIMIT ON MAXIMUM ENERGY



PC POTENTIAL DROP

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

remember $\dot{E} \approx \dfrac{B_\star^2\ R_\star^6 \Omega^4}{c^3}$

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

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

$$E_{\max} = Ze\sqrt{\dot{E}/c}$$

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

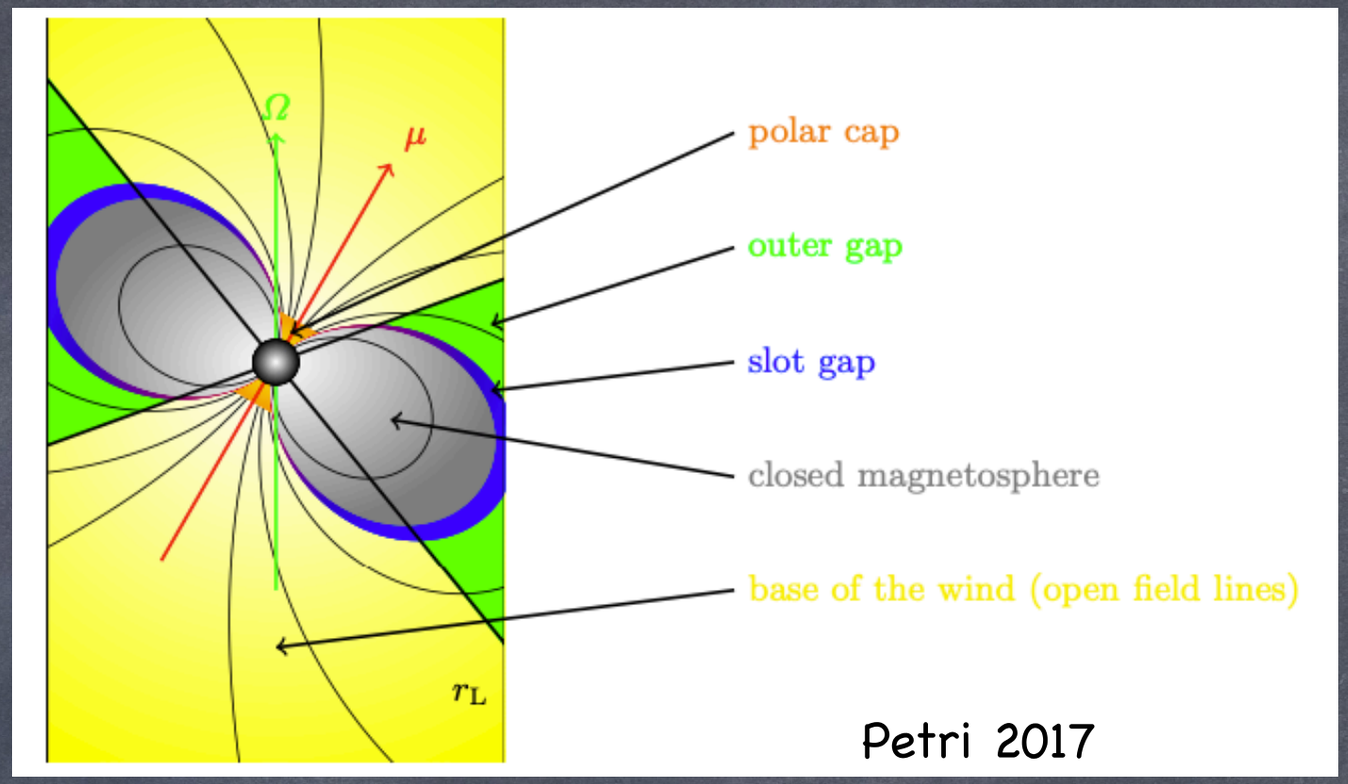
PAIR PRODUCTION AND PULSAR MULTIPLICITY

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)

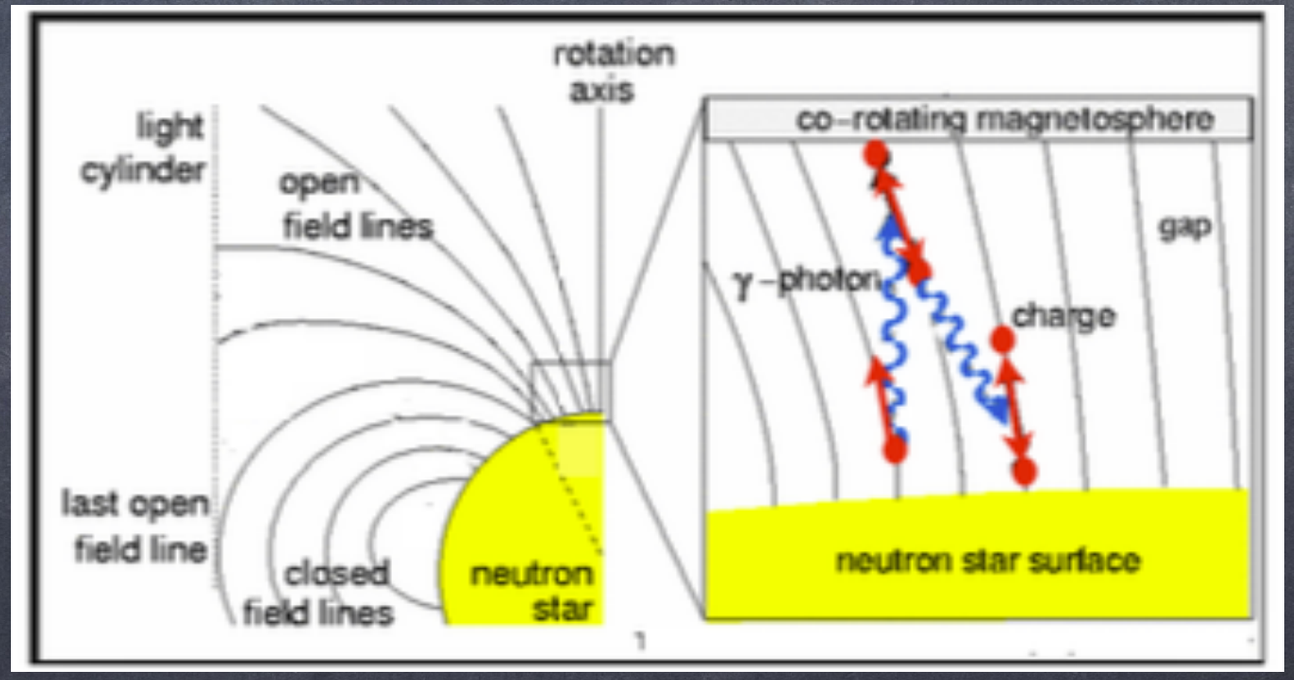
$$T_e \approx 3.6 \times 10^5 \text{ K} \left(\frac{Z}{26} \right)^{0.8} \left(\frac{B_\star}{10^{12}\text{G}} \right)^{0.4}$$



TOTAL WIND POWER:

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

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

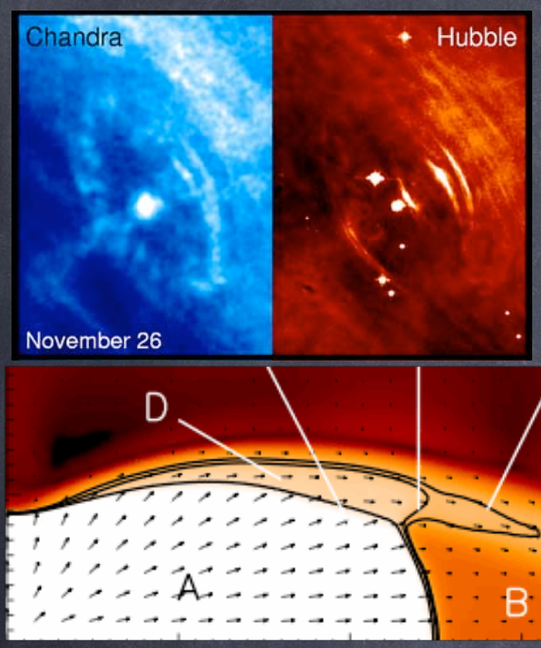


IF $\kappa < m_i/m_e$ IONS COULD DOMINATE ENERGY OUTFLOW AND EXPLAIN ACCELERATION [EA & Arons 06]

CURRENT BEST ESTIMATE OF κ FOR CRAB LIKE PSRs [TIimokhin & Harding 19]:

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

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

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

FOR EVOLVED SYSTEMS, LOWER B-FIELD VALUES
STRICT LIMIT FROM THE PSR POTENTIAL DROP

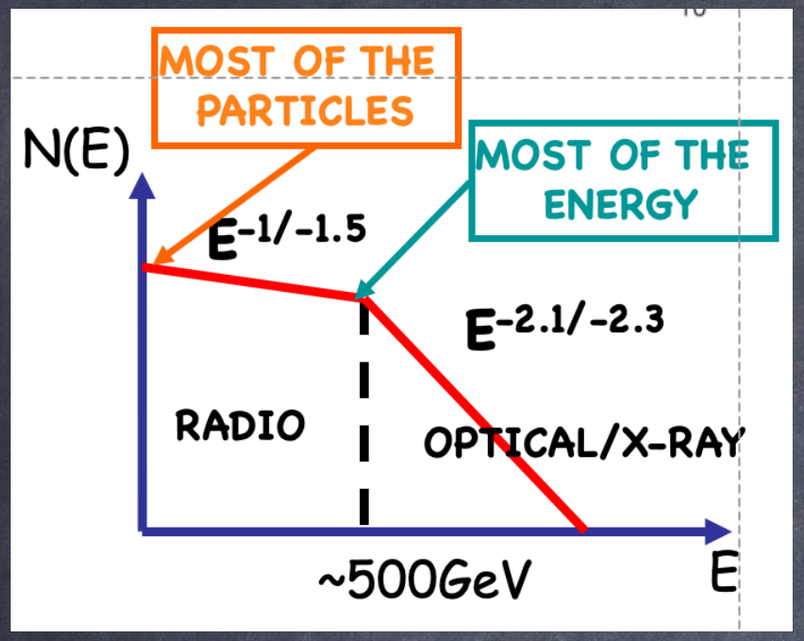
$$E_{max,abs} = e\eta_E B_{TS}\ R_{TS}$$

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

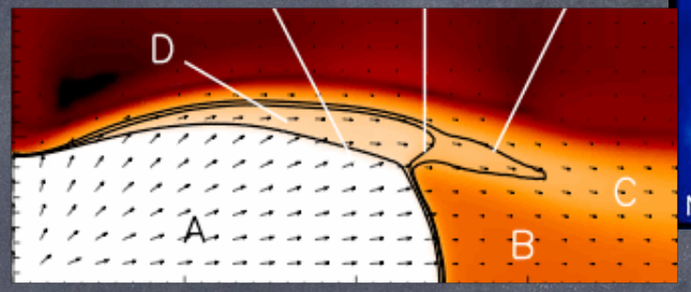
$$\Phi_{PSR} = \sqrt{\dot{E}/c}$$

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

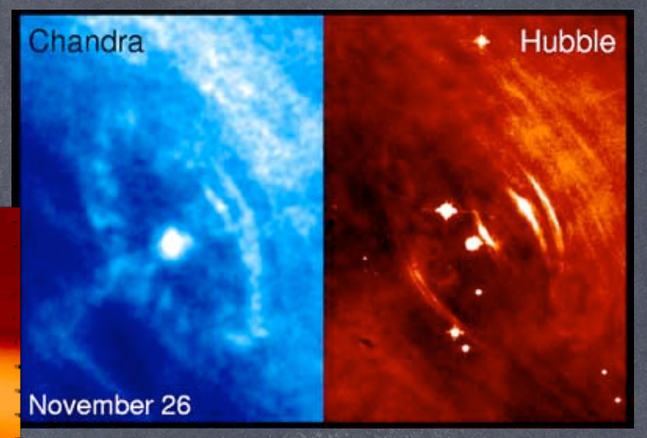
PARTICLE ACCELERATION MECHANISMS



[Amato & Olmi 22]



Del Zanna, Amato, Bucciantini 04



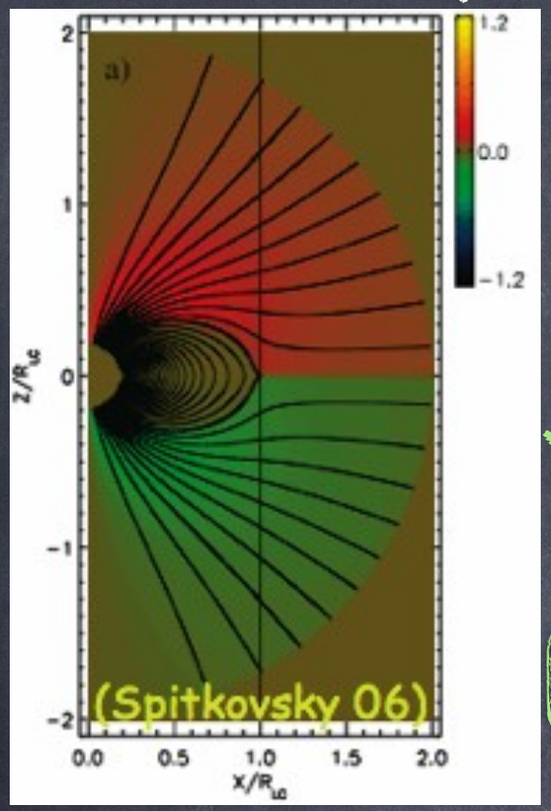
FERMI MECHANISM → MAGNETIZATION: REQUIRES LOW ← HOWEVER SEE VARIANTS

DRIVEN MAGNETIC RECONNECTION → MAGNETIZATION: REQUIRES HIGH

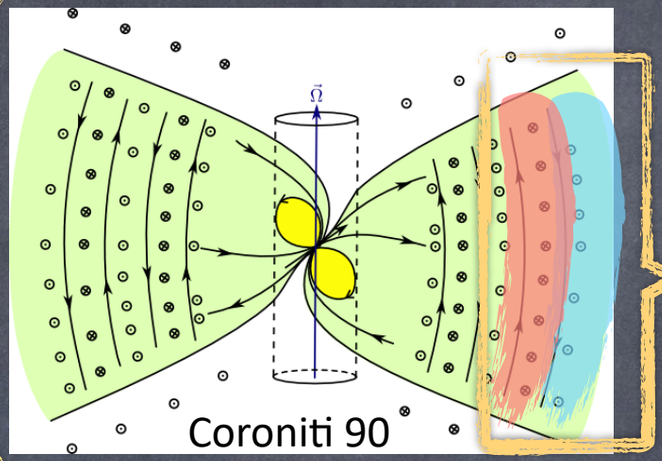
DRIVEN MAGNETIC RECONNECTION → PLASMA MULTIPLICITY: REQUIRES HIGH

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

PSR WIND AND PWN DYNAMICS

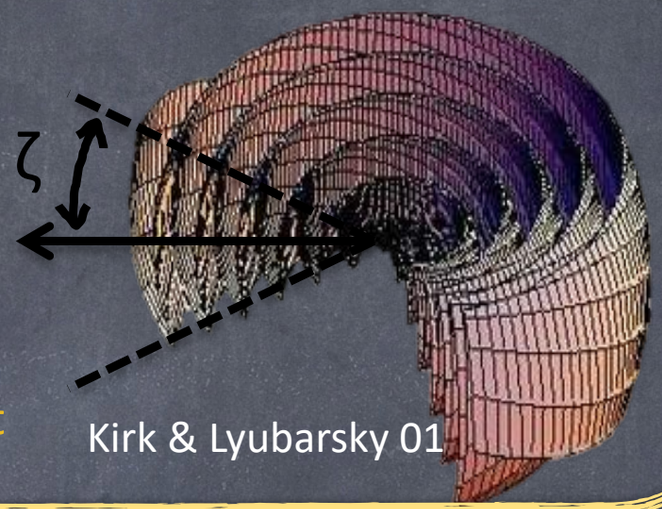


$$F(\theta) \propto \sin^2(\theta)$$



alternating stripes of opposite B polarities

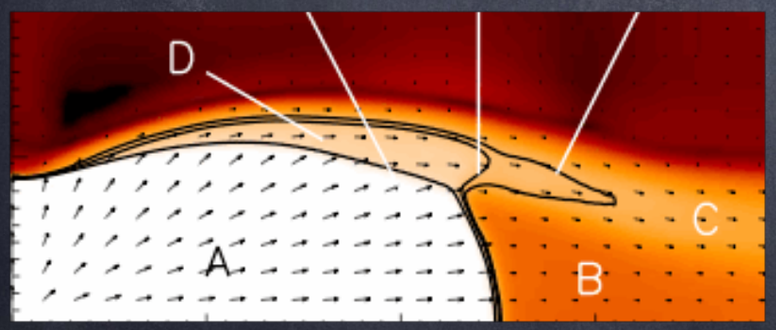
dissipation in current sheet



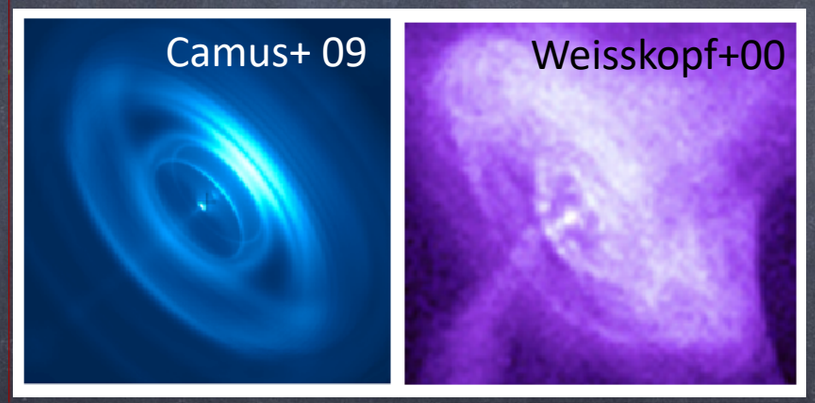
$$B(\theta) \propto \sqrt{\sigma}\ \sin\theta\ G(\theta)$$

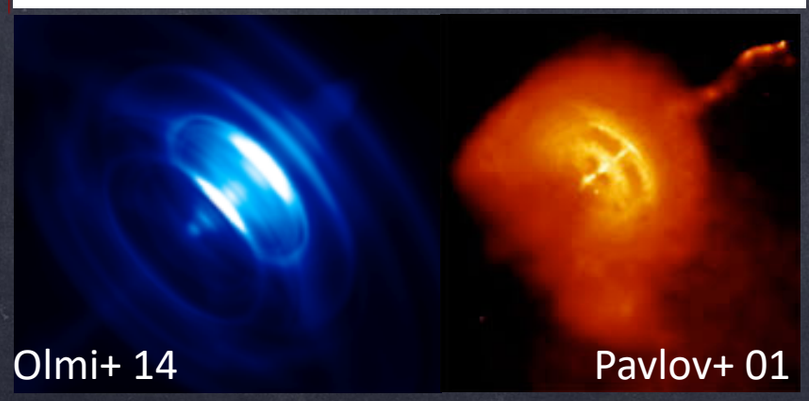
DYNAMICS AND RADIATION MODELING

TERMINATION SHOCK

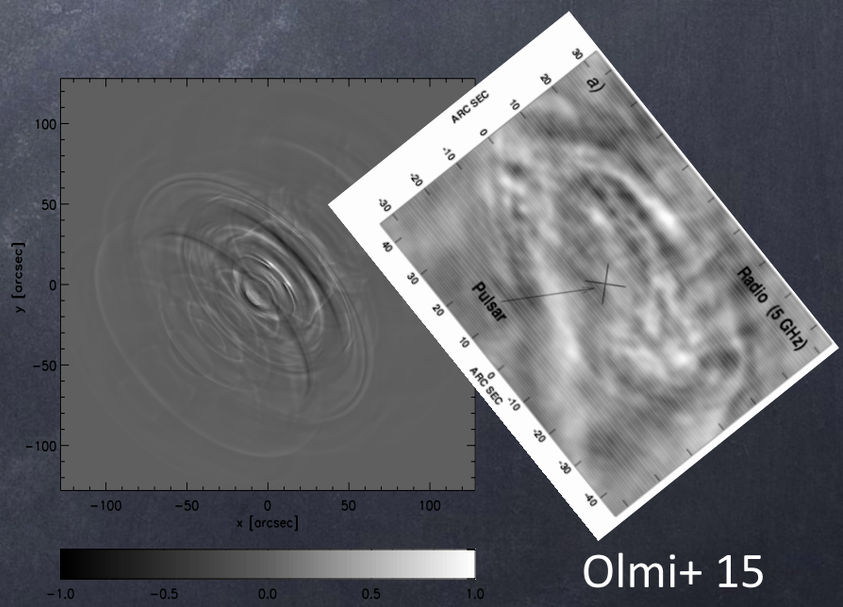


A: ULTRARELATIVISTIC WIND
B: SUBSONIC OUTFLOW
C: SUPERSONIC FUNNEL





MULTI-WAVELENGTH VARIABILTY



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

CONCLUSIONS FROM MULTI-D MHD MODELLING

A. AVERAGE MAGNETIZATION AT THE SHOCK TOO HIGH FOR FERMI PROCESS

B. X-RAY EMITTING PARTICLES NEED TO BE ACCELERATED IN THE EQUATORIAL REGION OF THE TS

C. RADIO EMITTING PARTICLES DO NOT NEED TO BE PART OF THE WIND

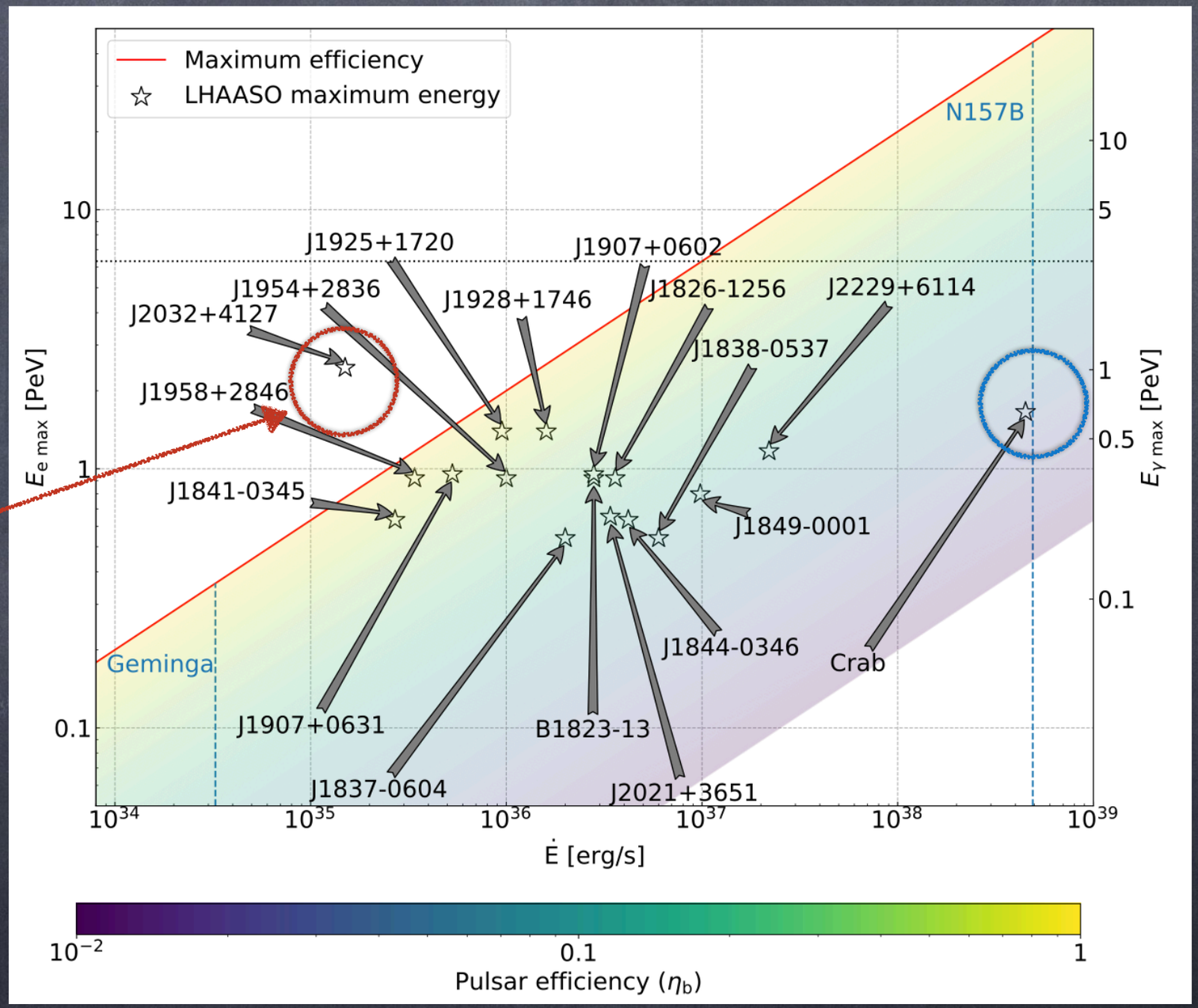
D. THE ACCELERATION SITES OF X-RAY AND RADIO EMITTING PARTICLES CANNOT BE PERFECTLY COINCIDENT

LHAASO PEVATRONS AND PWNe

de Ona Wilhelmi + 2022

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

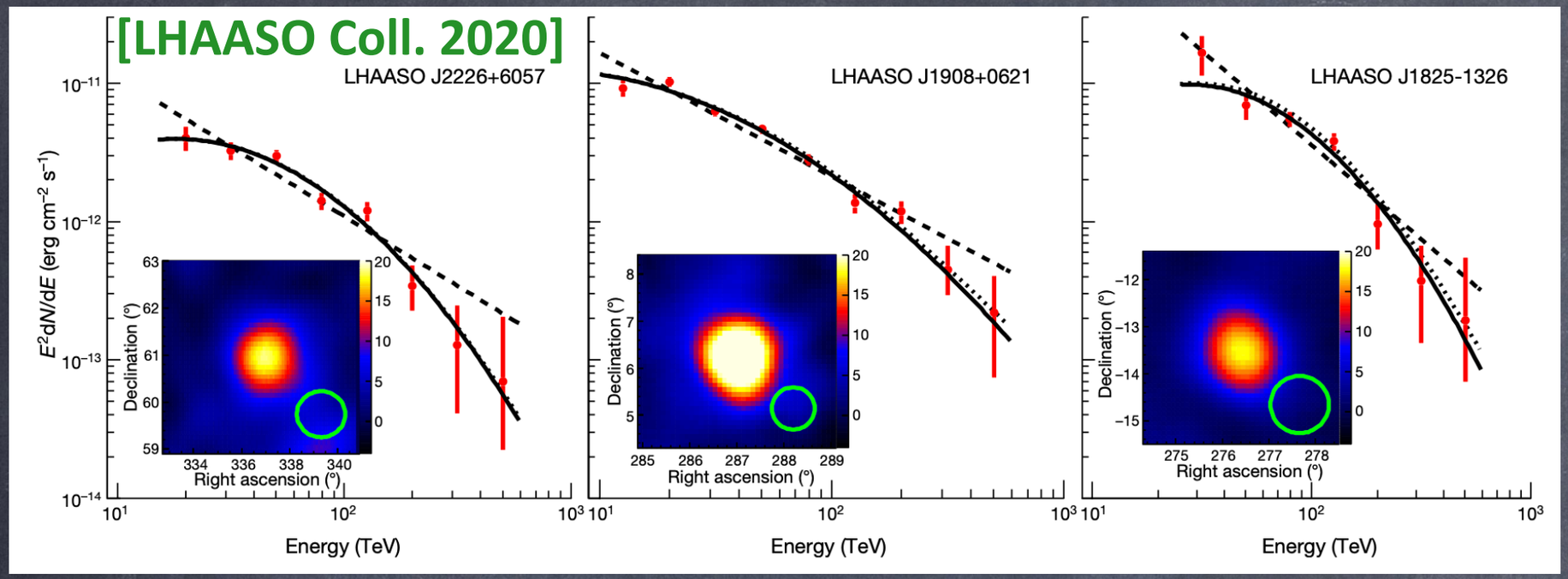
CYGNUS

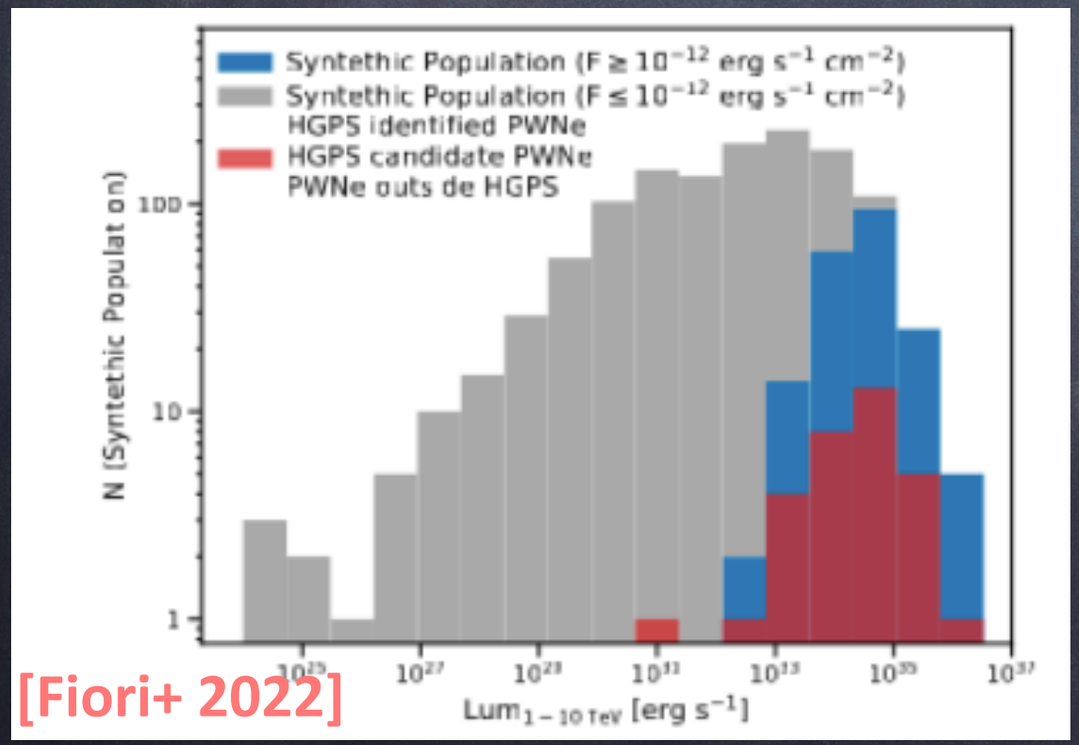


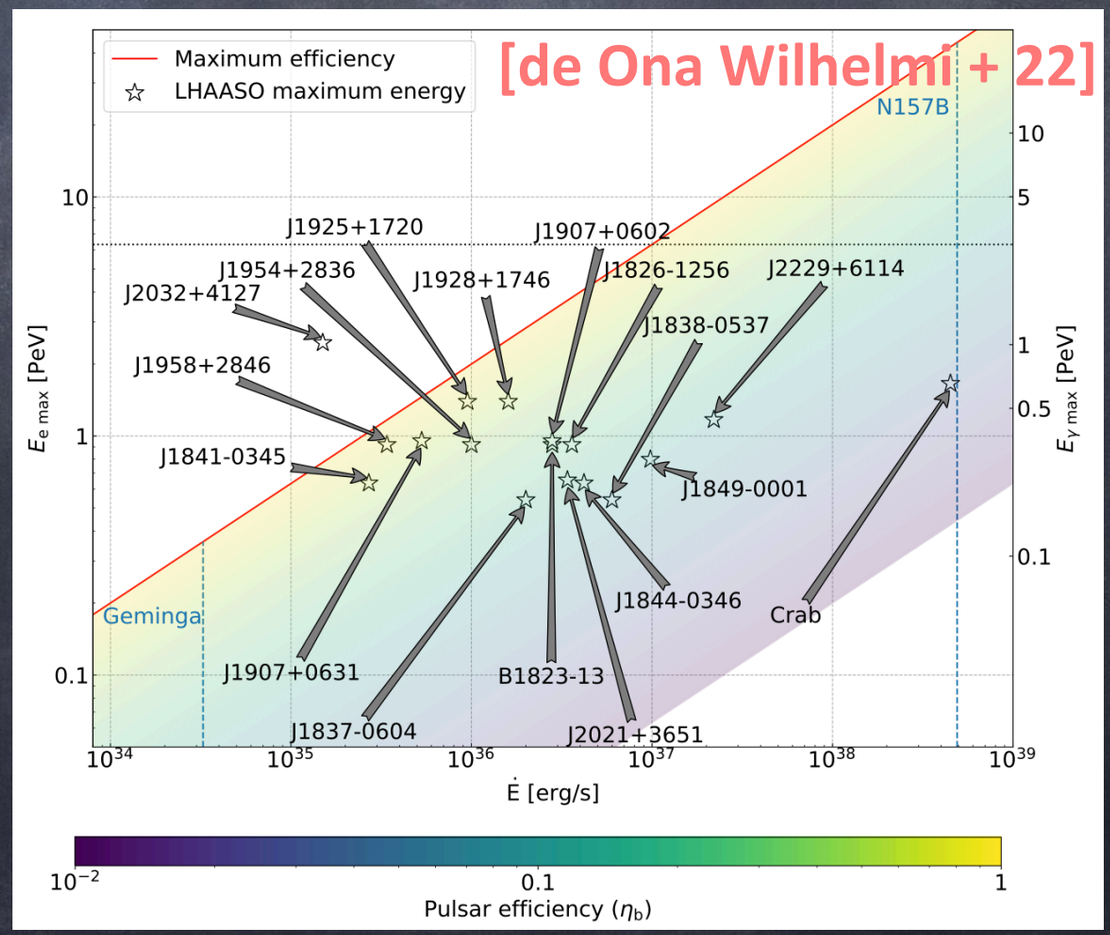
$$E_{e,max} = e\eta_E\ \xi_B^{1/2}\sqrt{\dot{E}/c} \approx 1.8\ PeV\ \eta_E\ \xi_B^{1/2}\ \dot{E}_{36}^{1/2}$$

WHAT WE CAN LEARN FROM UHE GAMMA-RAYS

IN EVOLVED SYSTEMS: STUDY INTRINSIC ACCELERATON CUT-OFF



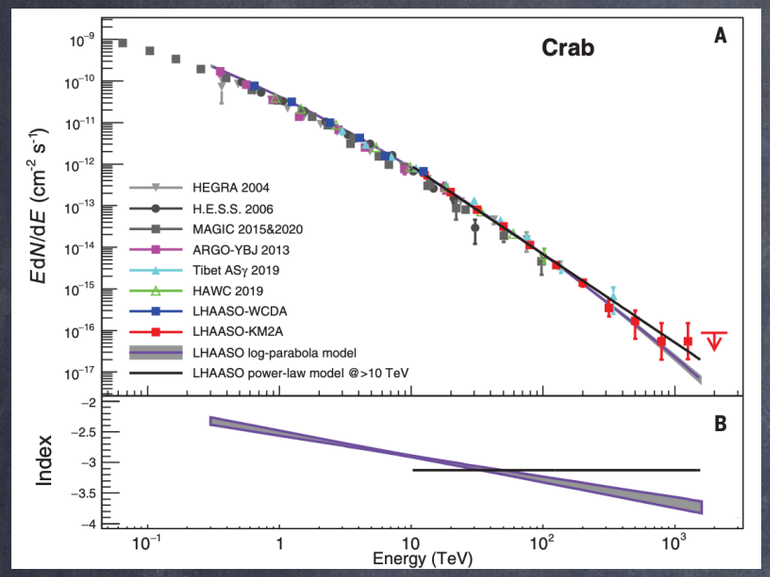




REMEMBER: FASTEST POSSIBLE t_{acc}

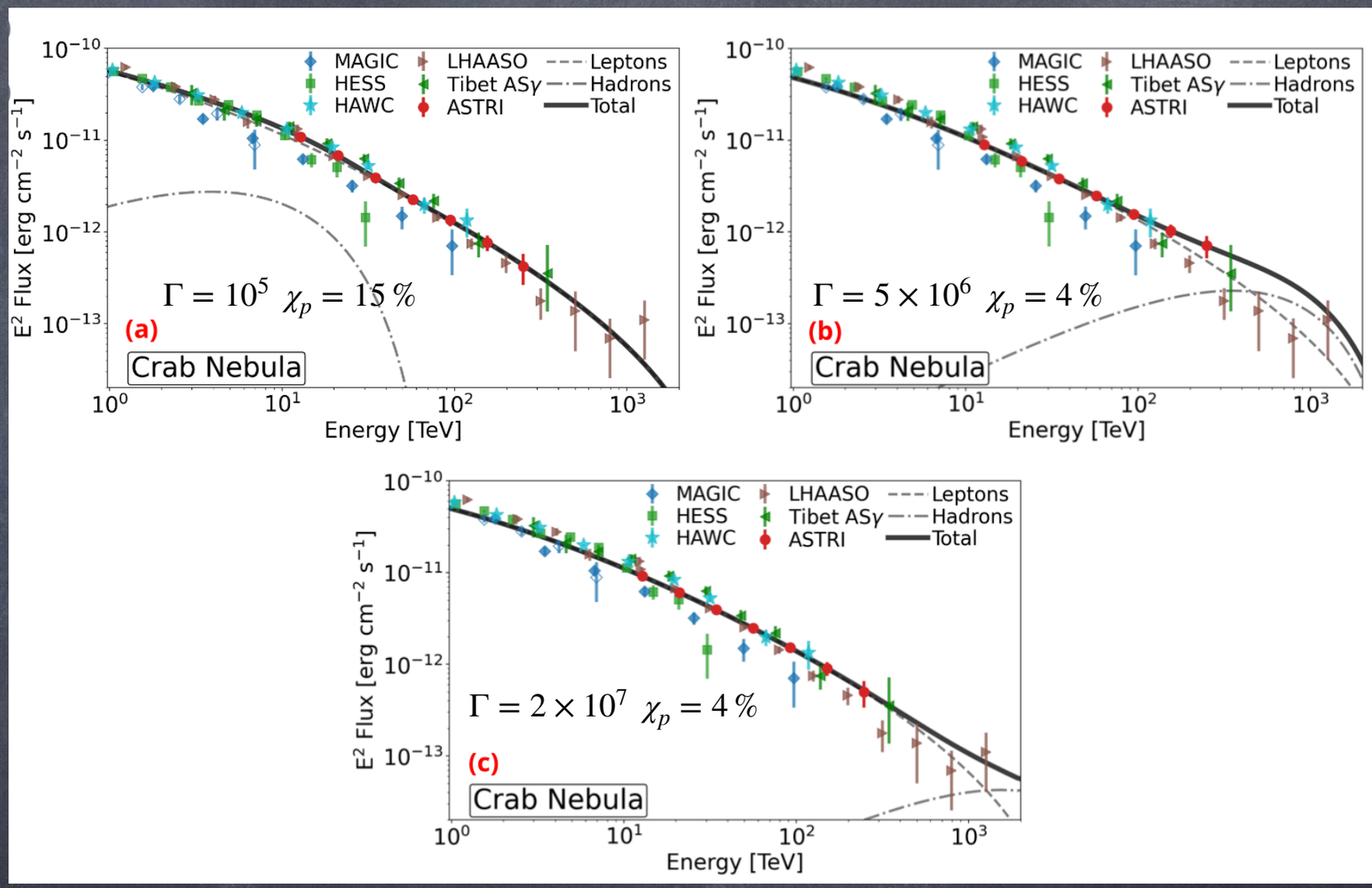
IN YOUNG SYSTEMS: WE COULD SEE HADRONS...

Cao+, LHAASO Coll. 21



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

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



Vercellone+ 22; Fiori+ in prep.

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

SUMMARY

- ONLY FIRMLY IDENTIFIED PEVATRON SO FAR IS CRAB, A PWN

- IF LHAASO PEVATRONS ARE LEPTONIC, THEN PULSARS ARE LIKELY THE ONLY CANDIDATES IN THE GALAXY

- ON THE OTHER HAND IF THEY ARE HADRONIC PULSARS 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...

- SINCE PWNe ARE THE FASTEST ACCELERATORS IN THE GALAXY, IN EVOLVED SYSTEMS UNIQUE OPPORTUNITY TO SEE INTRINSIC CUT-OFF OF THE ACCELERATION MECHANISM!

- KEY TO UNVEIL THE NATURE OF DETECTED PEVATRONS IS ANGULAR RESOLUTION: ASTRI OFFERS UNIQUE OPPORTUNITY!

- THEN ALSO HALOES AND CR POSITRONS...