PULSAR WIND NEBULAE: A REVIEW

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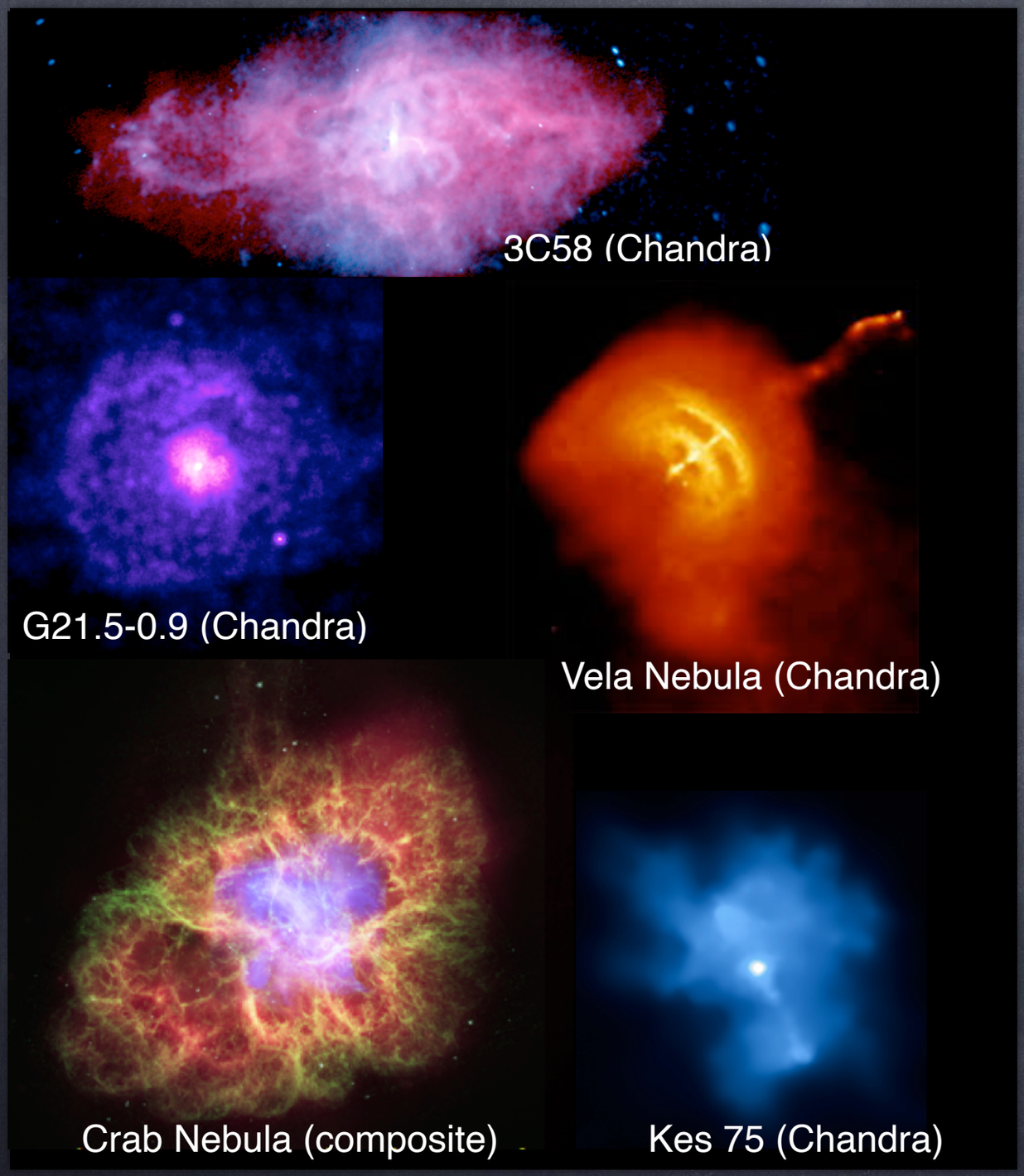
PULSAR WIND NEBULAE



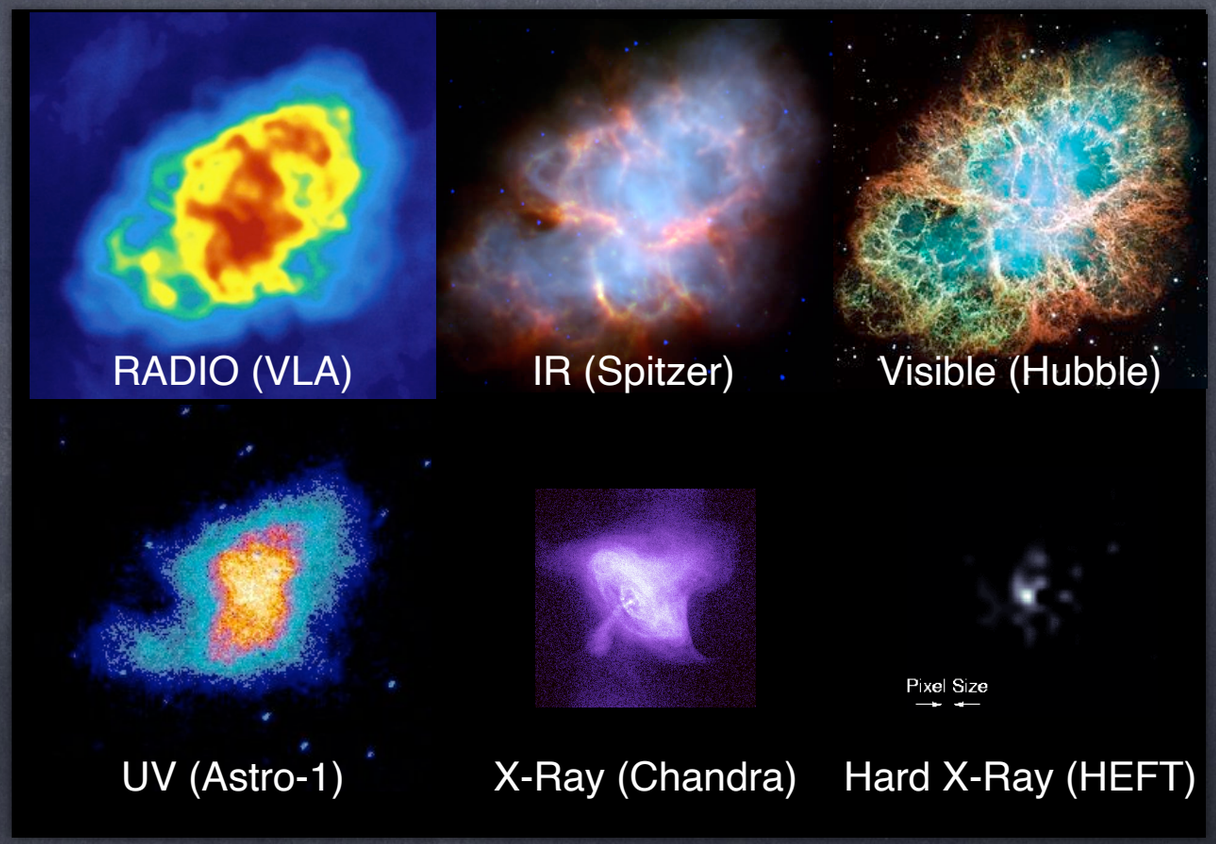
Jet-torus morphology in X-rays

SNRs WITH

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

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

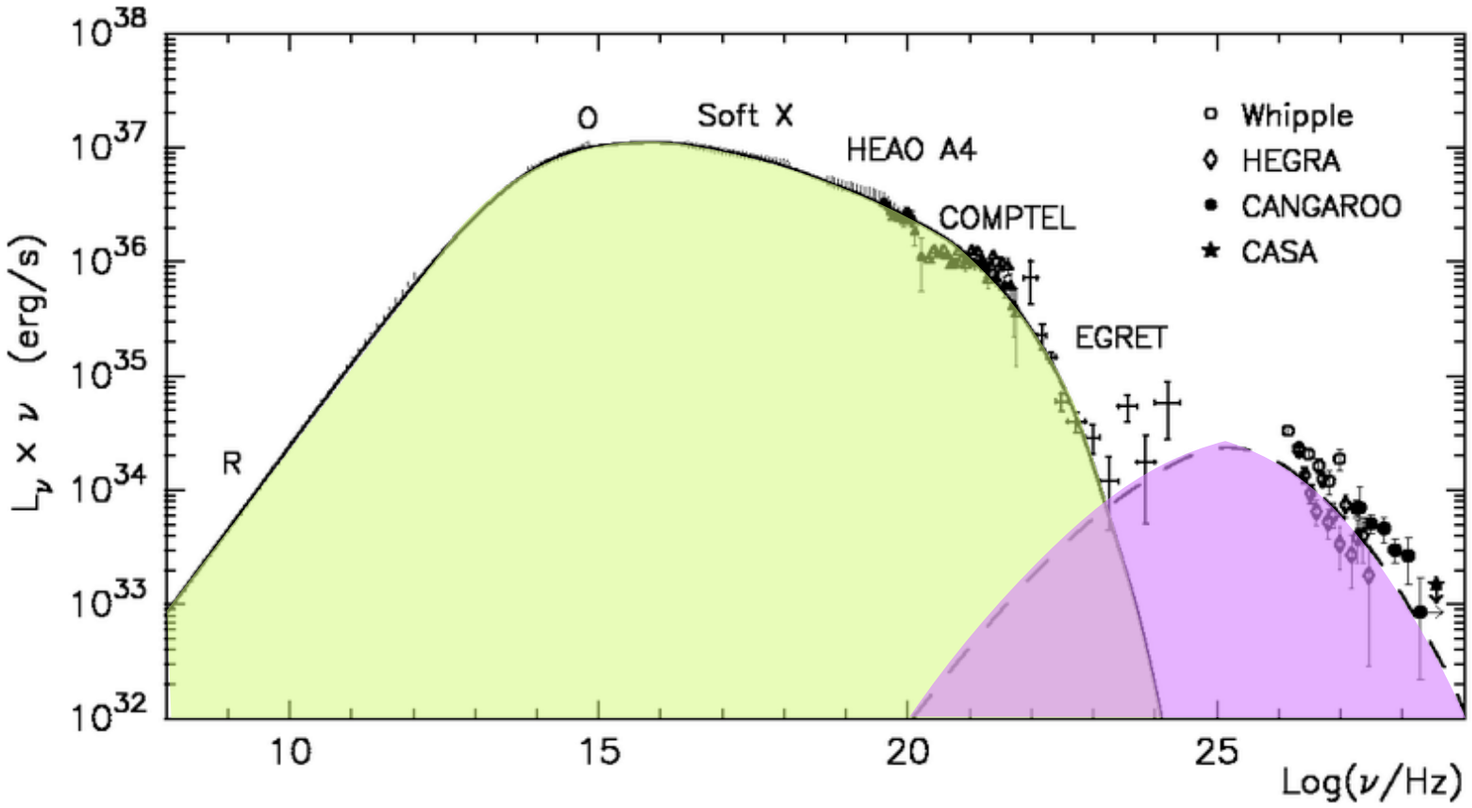
Multi-wavelength emission and size shrinkage



THE CRAB NEBULA

BROAD BAND NON-THERMAL SPECTRUM

CRAB NEBULA spectrum [adapted from Atoyan & Aharonian 1996]

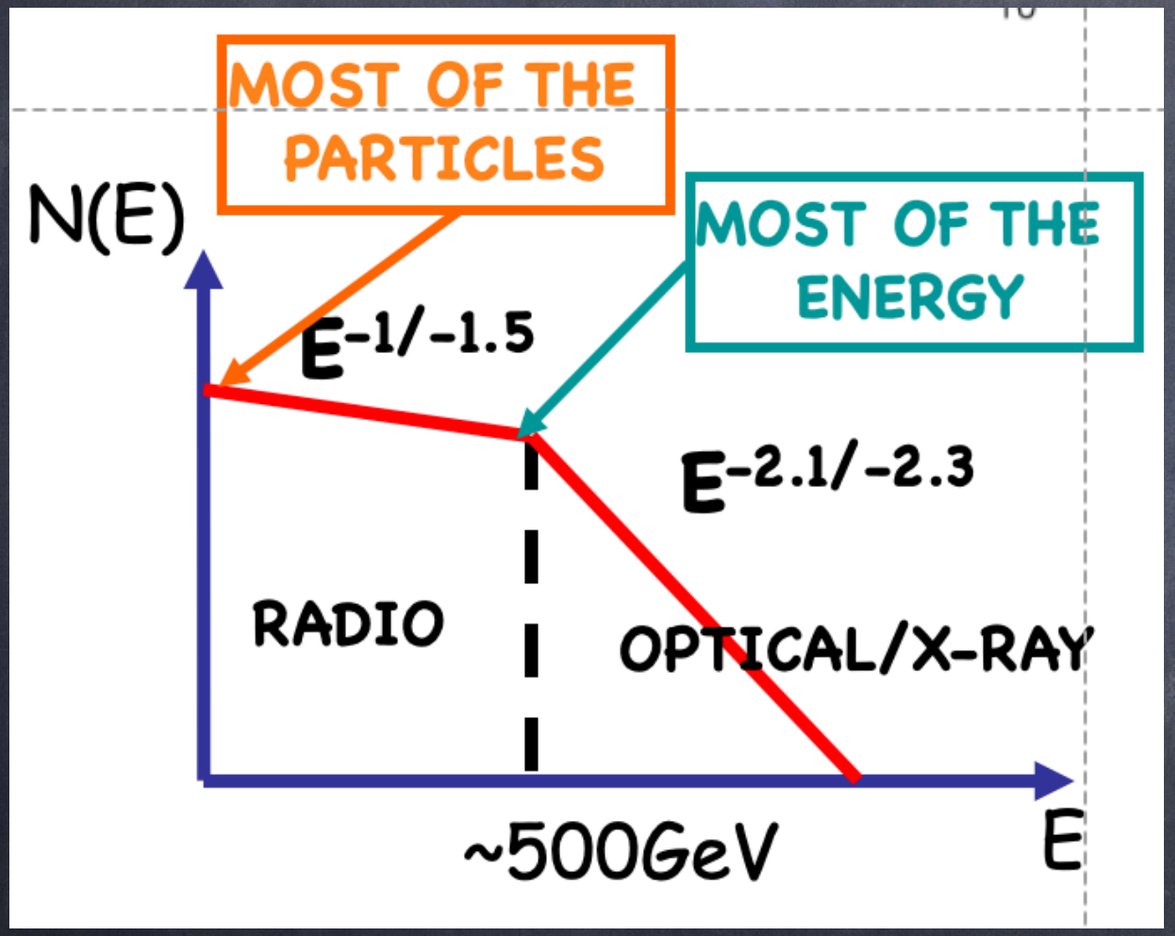


synchrotron radiation by relativistic particles in the nebular B field

Inverse Compton scattering with local photon field

PARTICLES AND FIELD
FROM ROTATIONAL ENERGY LOST BY PULSAR

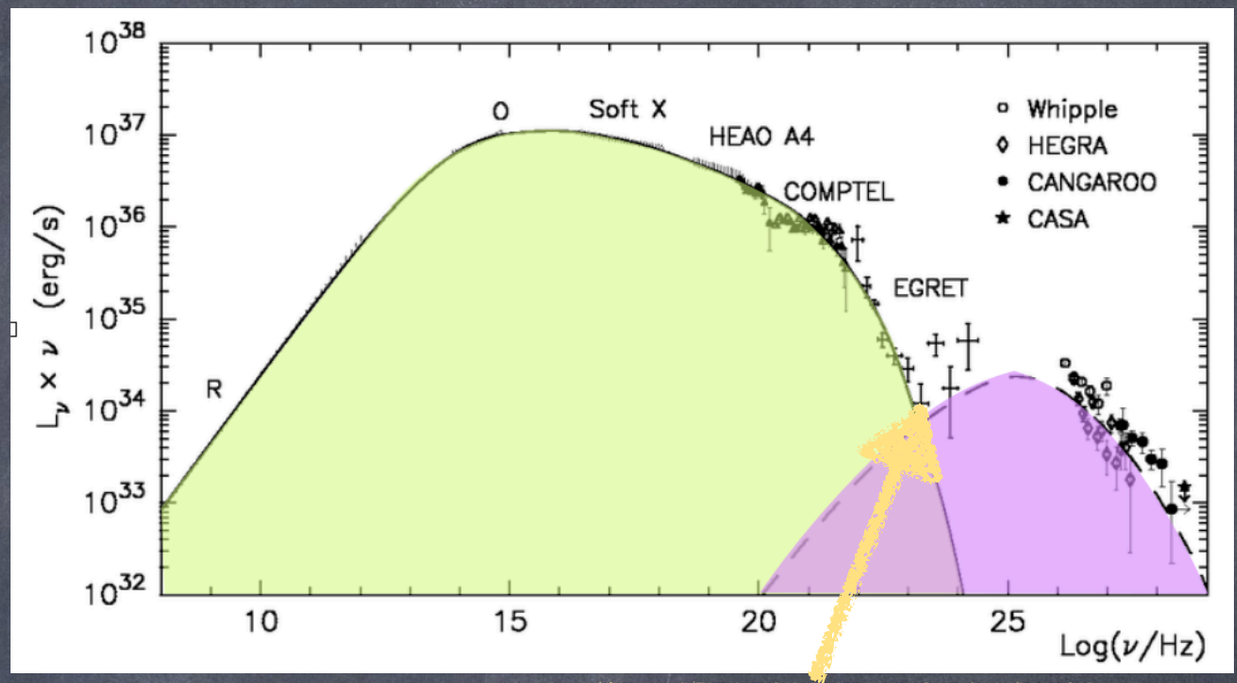
EMITTING PARTICLES



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

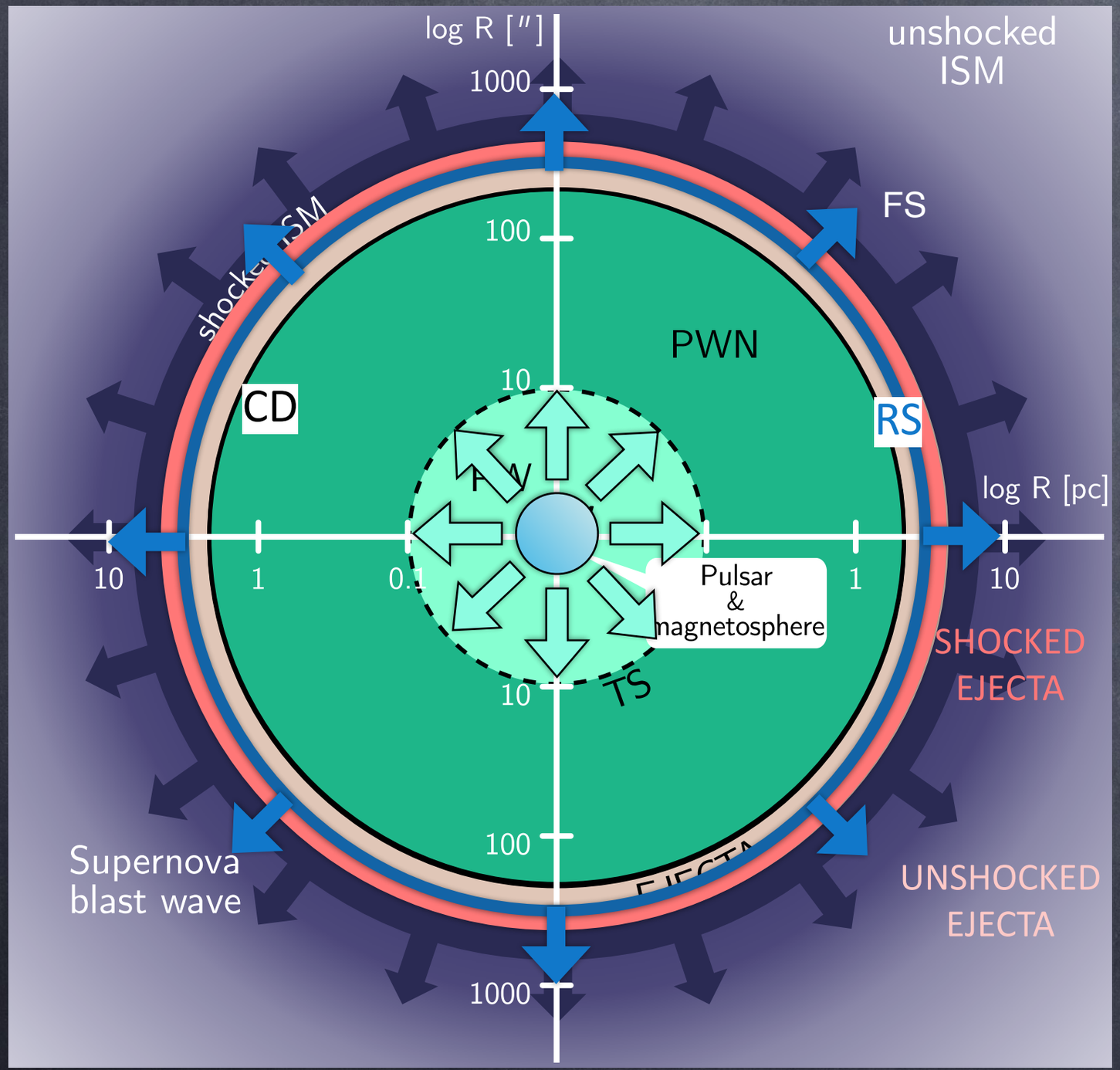
WIND COMPOSITION (IONS? κ?)

WIND MAGNETIZATION (σ?)

IN PRINCIPLE BOTH DEPEND ON LOCATION

- HOW PARTICLES EVENTUALLY ESCAPE

BASIC PICTURE FOR YOUNG SYSTEMS

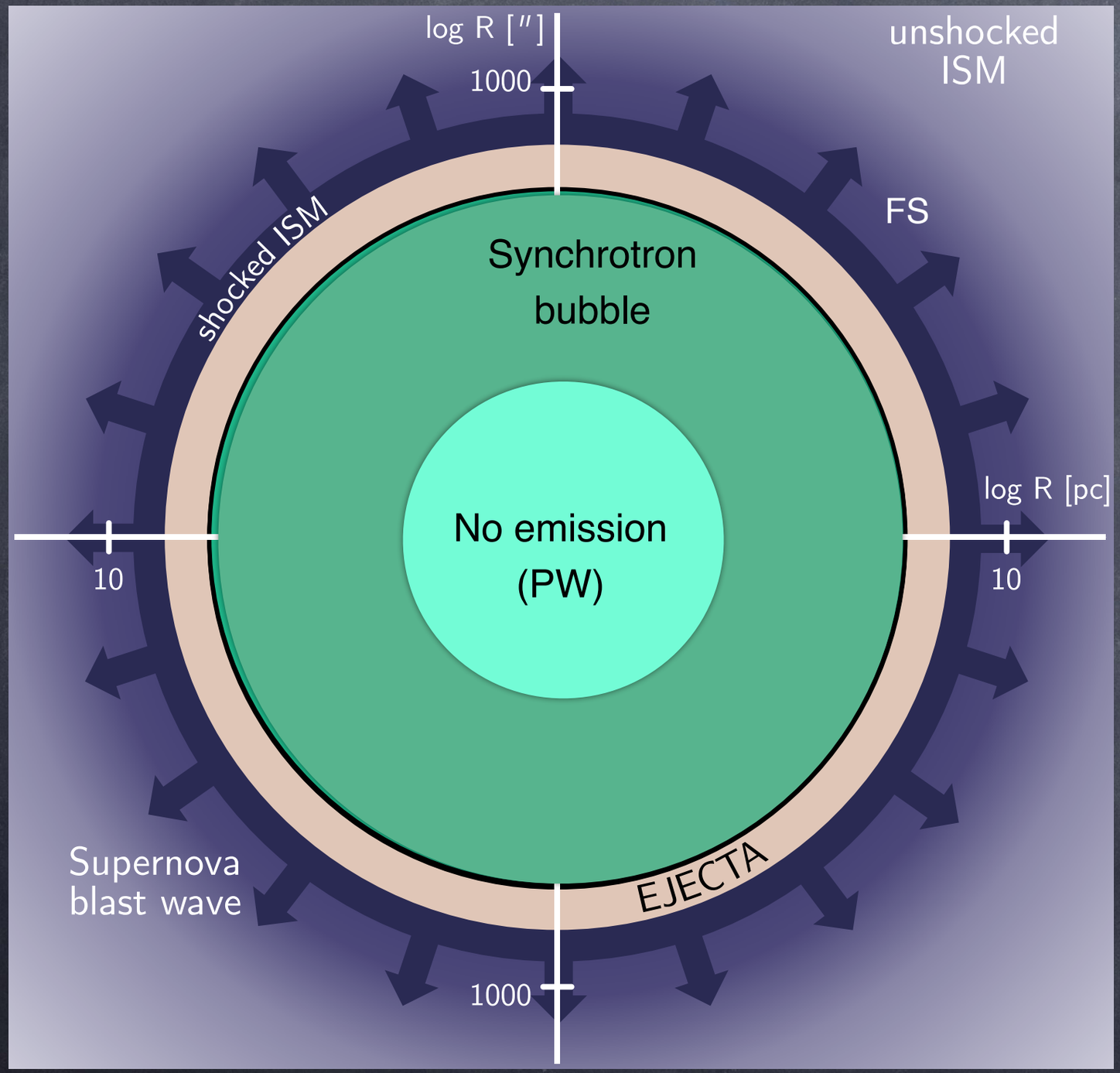


Adapted from Kennel & Coroniti 1984
[Del Zanna & Olmi 2017]

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

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

BASIC PICTURE FOR YOUNG SYSTEMS



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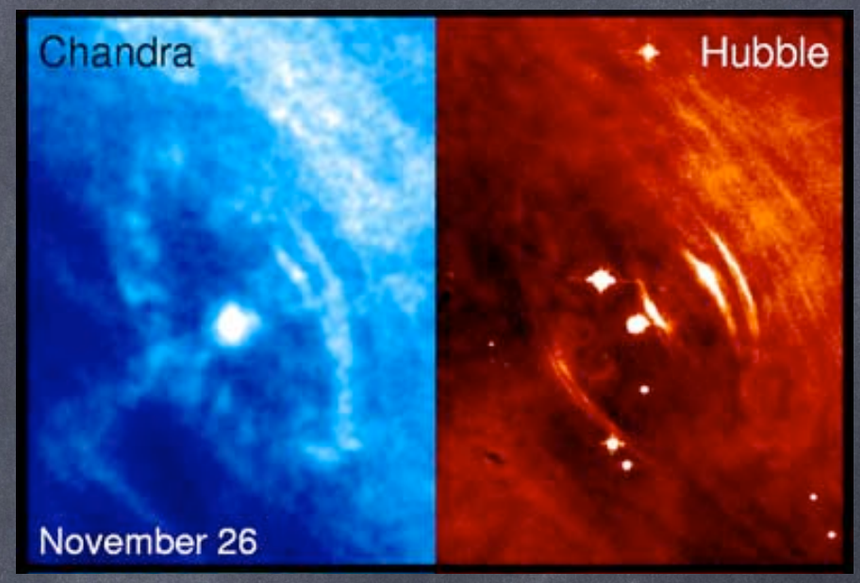
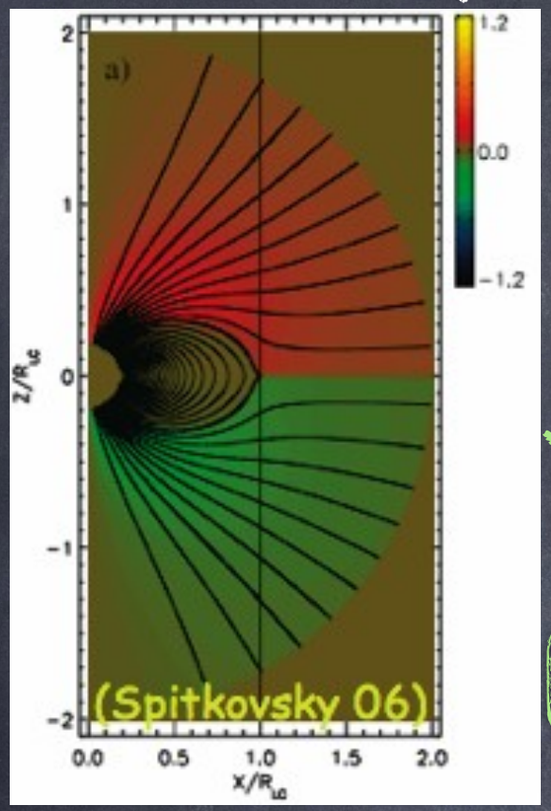


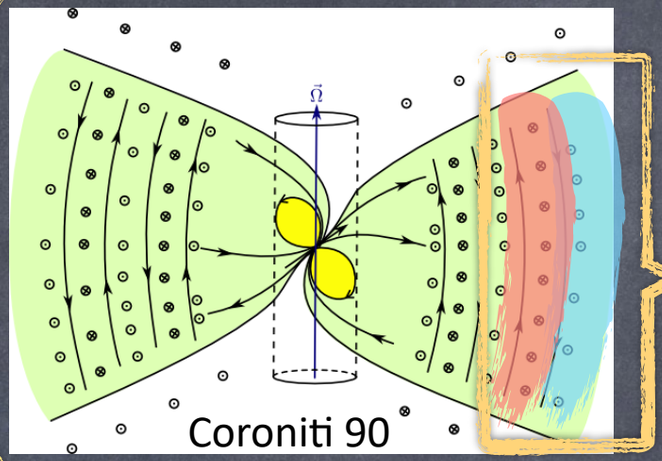
$$R_{TS} = \left(\frac{v_N}{c}\right)^{1/2} R_N$$

DISSIPATION AND PARTICLE ACCELERATION AT TS

PSR WIND AND PWN DYNAMICS

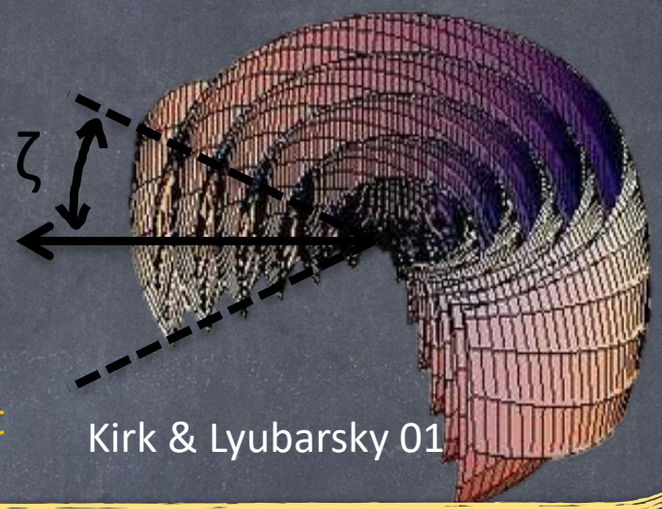


$$F(\theta) \propto \sin^2(\theta)$$



alternating stripes of opposite B polarities

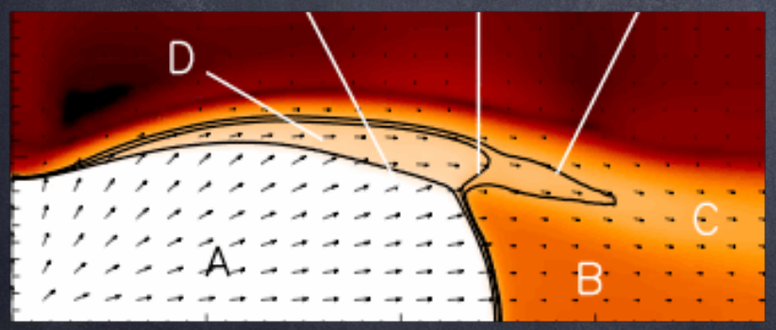
dissipation in current sheet



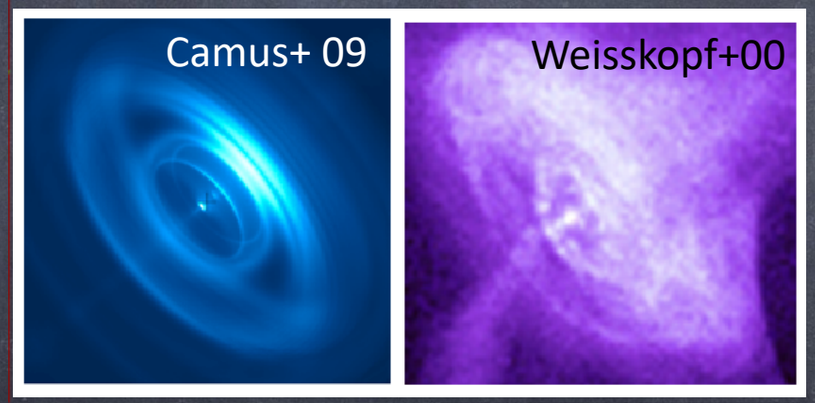
$$B(\theta) \propto \sqrt{\sigma}\ \sin\theta\ G(\theta)$$

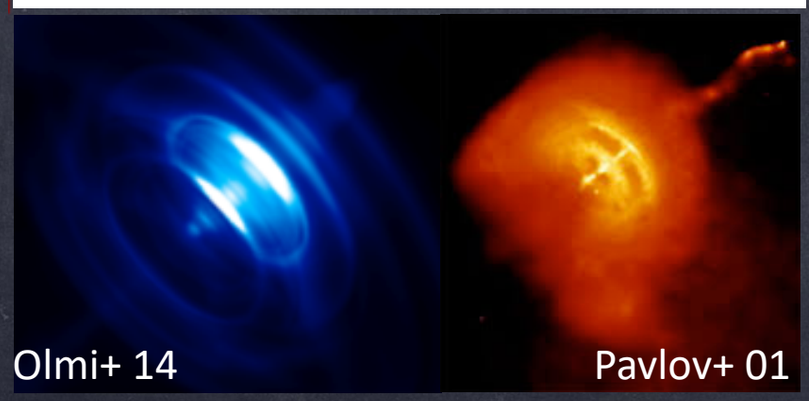
DYNAMICS AND RADIATION MODELING

TERMINATION SHOCK

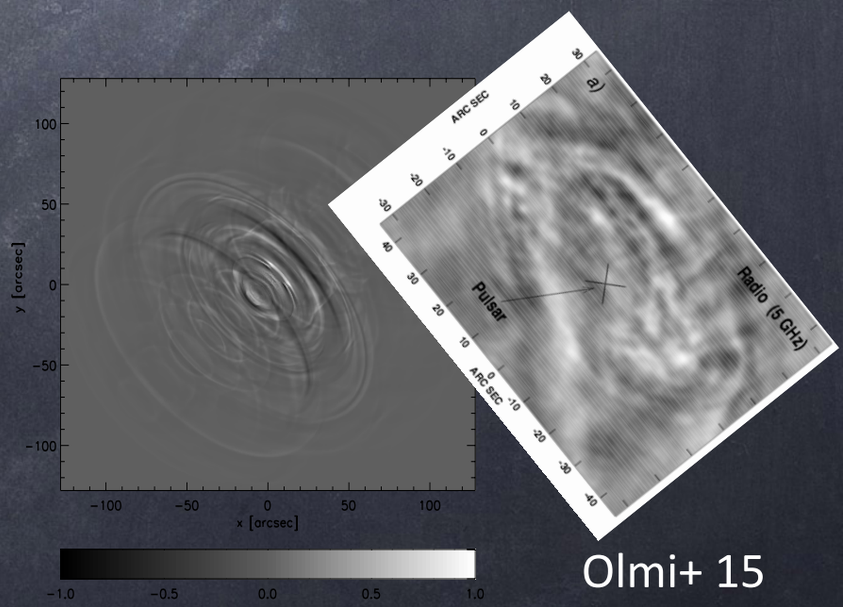


A: ULTRARELATIVISTIC WIND
B: SUBSONIC OUTFLOW
C: SUPERSONIC FUNNEL



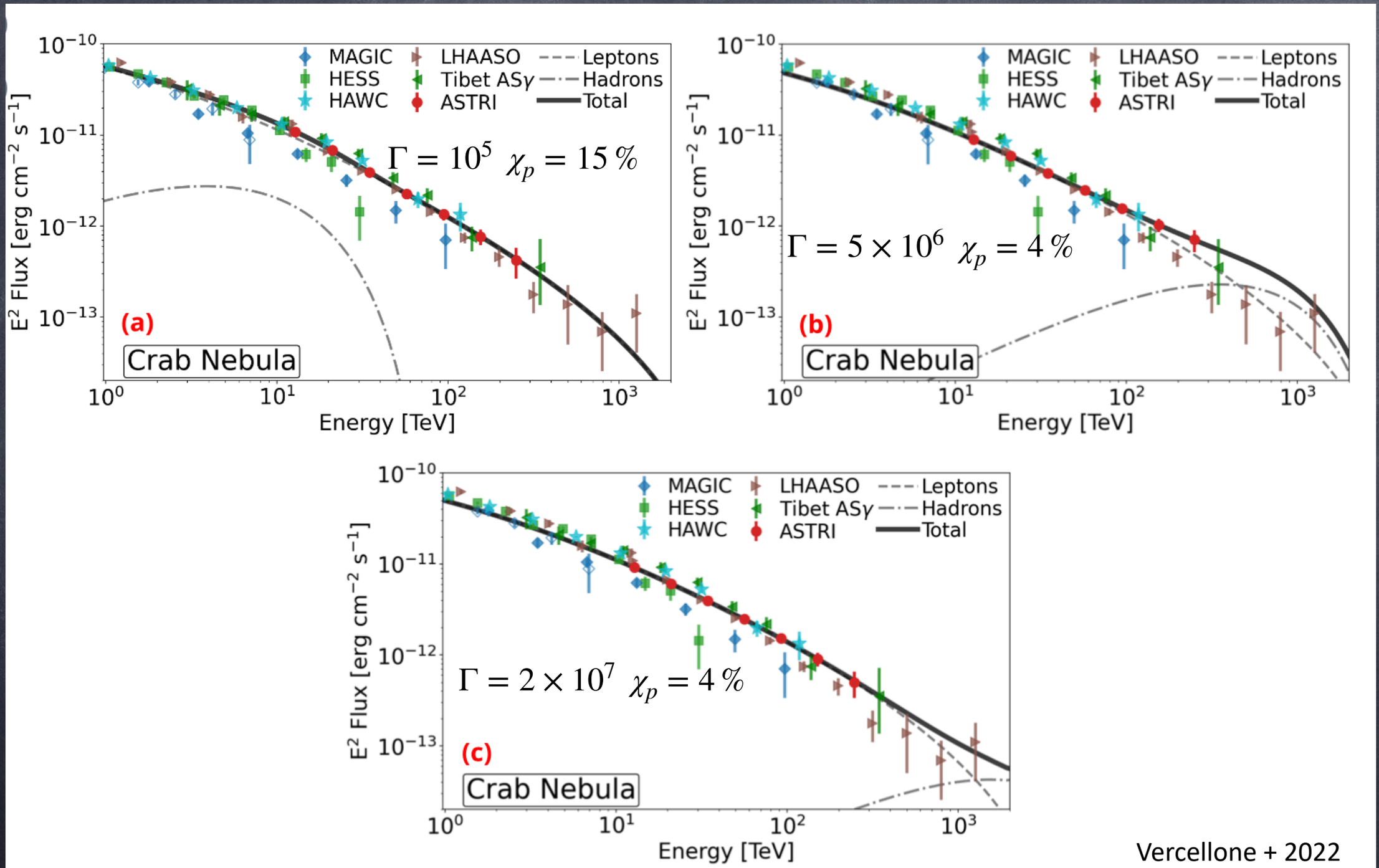


MULTI-WAVELENGTH VARIABILTY



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

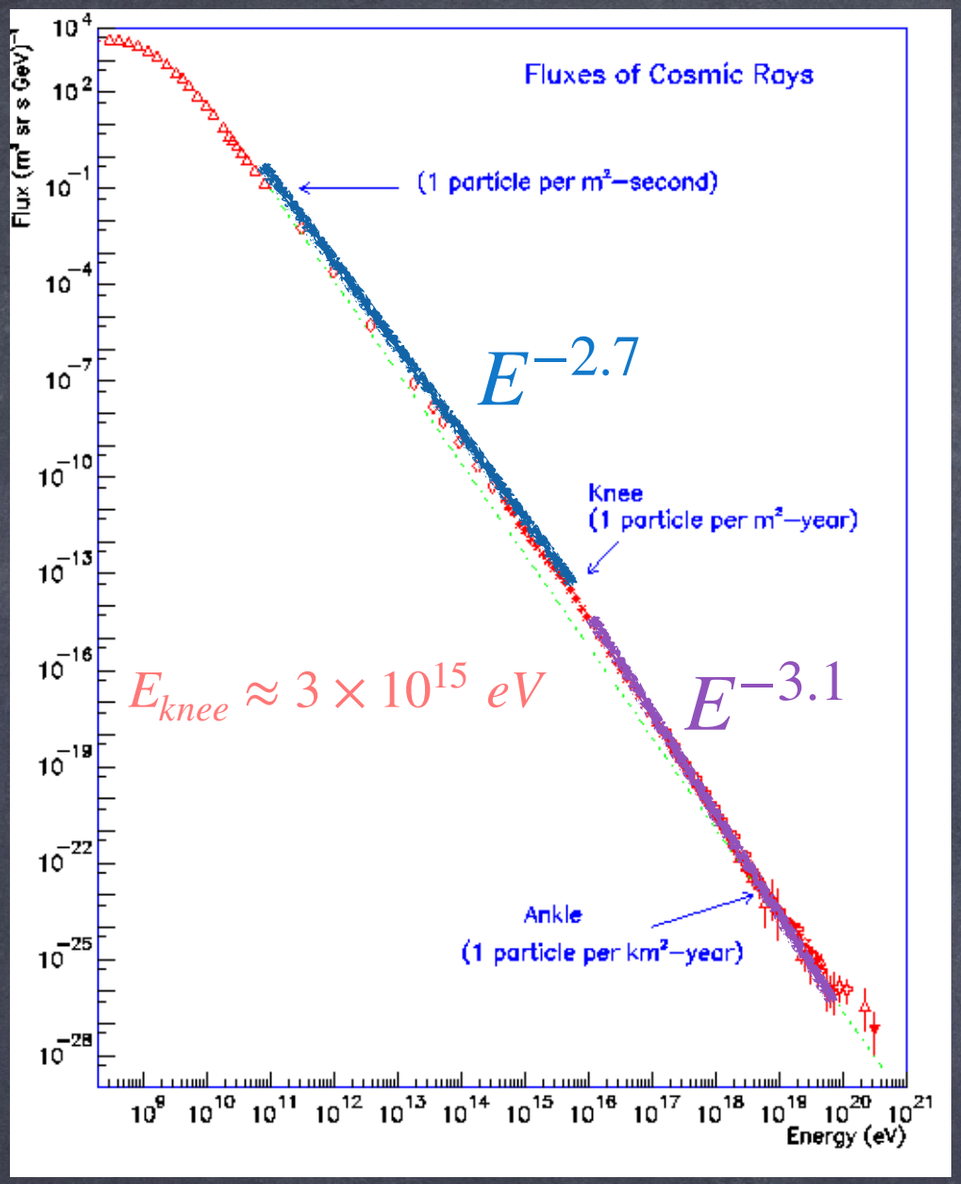
HADRONS IN CRAB?



Vercellone + 2022

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

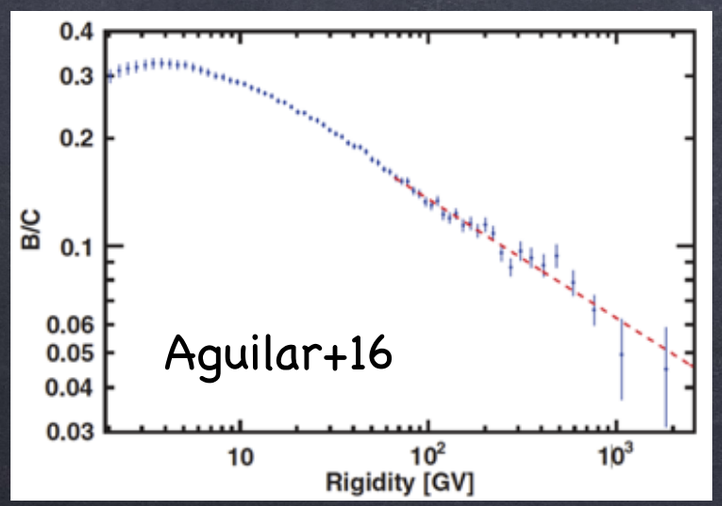
PWNe AND COSMIC RAYS

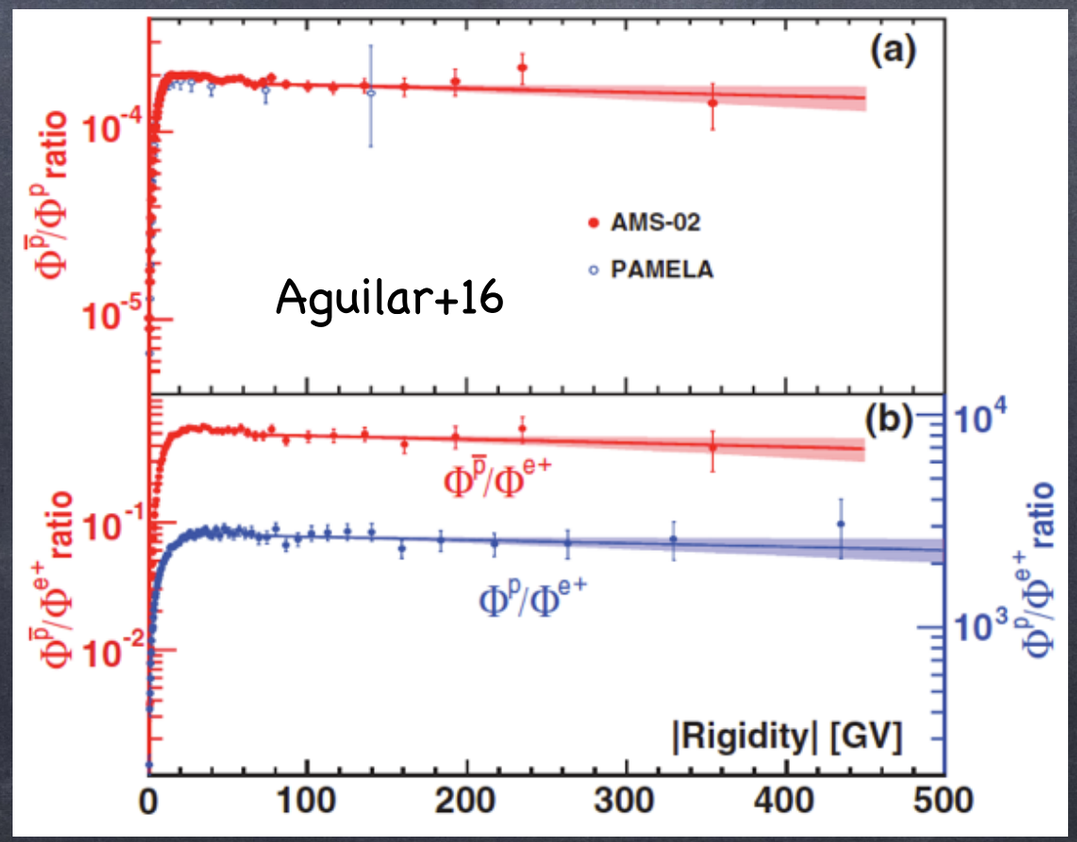


98% PROTONS AND NUCLEI
- 87% PROTONS
- 12% He
- 1% HEAVIER NUCLEI

2% ELECTRONS

0.1% ANTIMATTER
(POSITRONS AND ANTI-PROTONS)





UHECRs FROM MAGNETARS

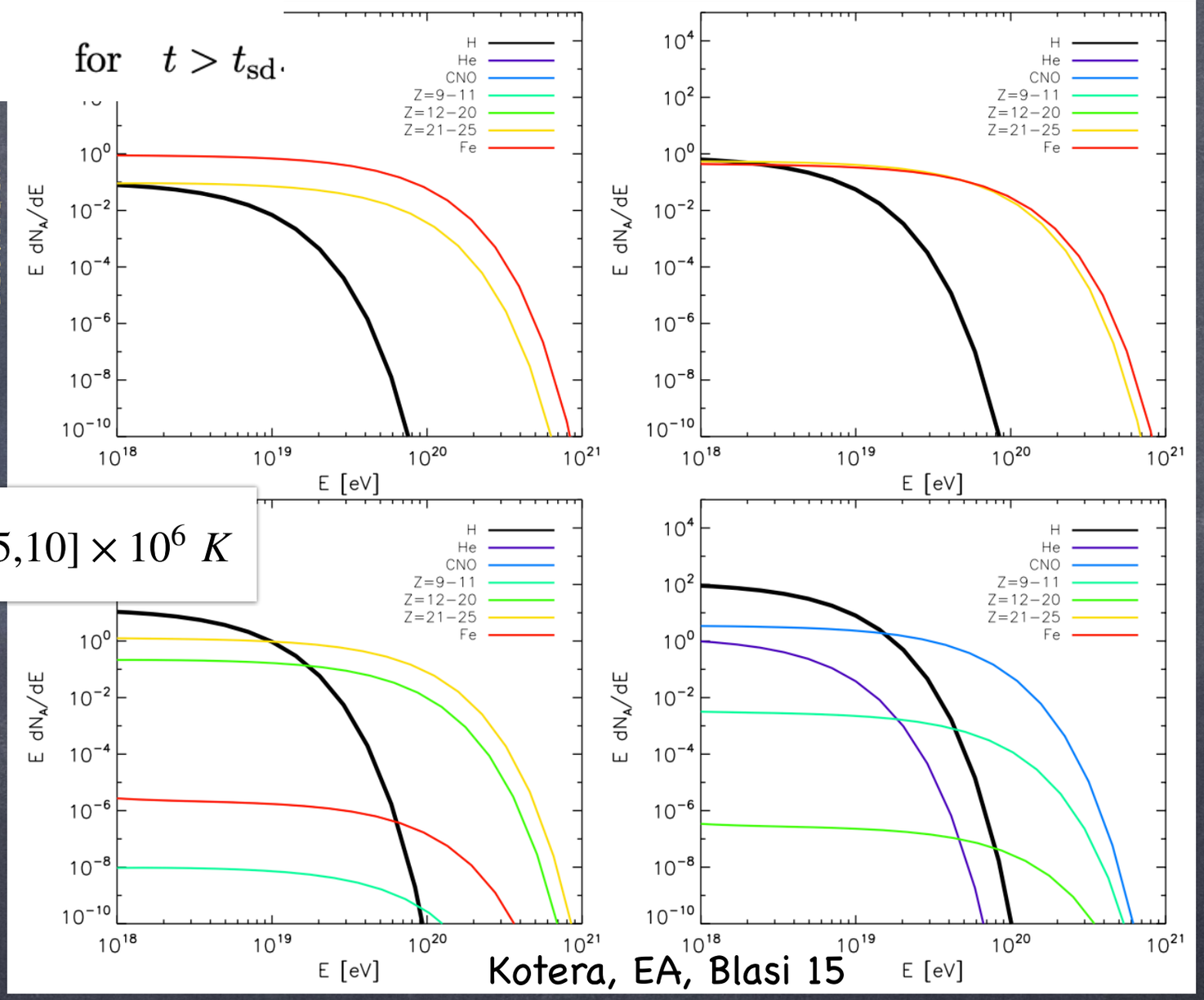
$$E_{\rm CR}(t) = E_0\ (1+t/t_{\rm sd})^{-1}$$
$$\sim 1.2\times10^{20}\,{\rm eV}\,\eta A_{56}\kappa_4 I_{45} B_{13}^{-1} R_{\star,6}^{-3}\, t_{7.5}{}^{-1}$$

for $t > t_{\rm sd}$.

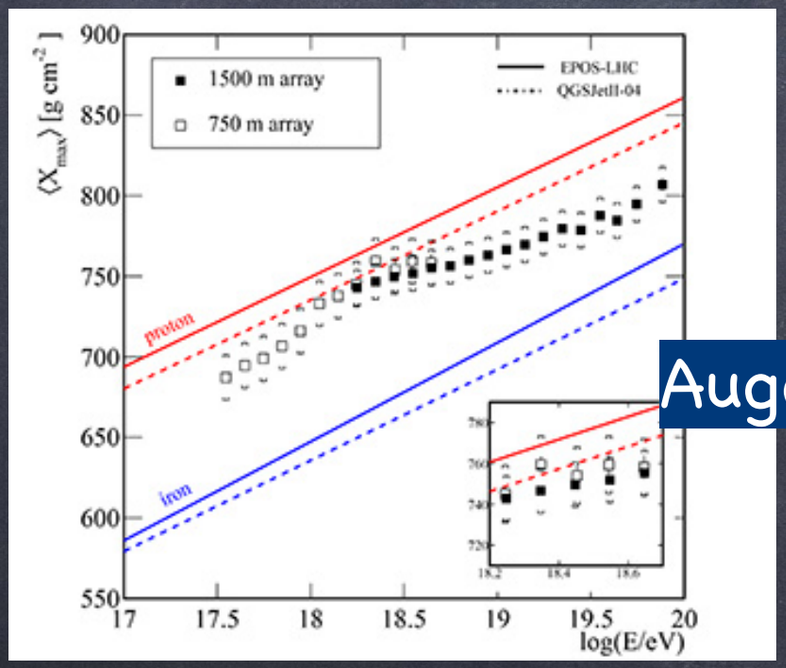
$$\frac{{\rm d}N_{\rm CR}}{{\rm d}E} = \int_0^\infty {\rm d}t \dot{N}_{\rm GJ}(t)\delta\left(E - E_{\rm CR}(t)\right) = \frac{\dot{N}_{\rm GJ}(0) t_{\rm sd}}{E}$$

$$t_{\rm sd} = \frac{9Ic^3P_{\rm i}^2}{8\pi^2B^2R^6} \sim 3.1\times10^7\,{\rm s}\, I_{45} B_{13}^{-2} R_{\star,6}^{-6} P_{\rm i,-3}^2$$

$$T_{NS} = [1,2,5,10]\times10^6\ K$$



Kotera, EA, Blasi 15



Auger 20

PWNe AS PeVATRONS

DETECTED PEVATRONS: LEPTONS OR HADRONS?

12 SOURCES DETECTED BY LHAASO ABOVE 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)	Cygnus
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)	G106.3+2.7

PeV ELECTRONS REQUIRE SUFFICIENT DROP AND $v_{flow} \sim c$

ALL SOURCES BUT ONE HAVE 1+ PSR IN THE FIELD….

MAXIMUM ENERGY IN A PWN

$$|\vec{E}| = \eta_E |\vec{B}| \qquad \eta_E \approx v_{flow}/c$$

IN YOUNG ENERGETIC SYSTEMS ACCELERATION IS LOSS LIMITED

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

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

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

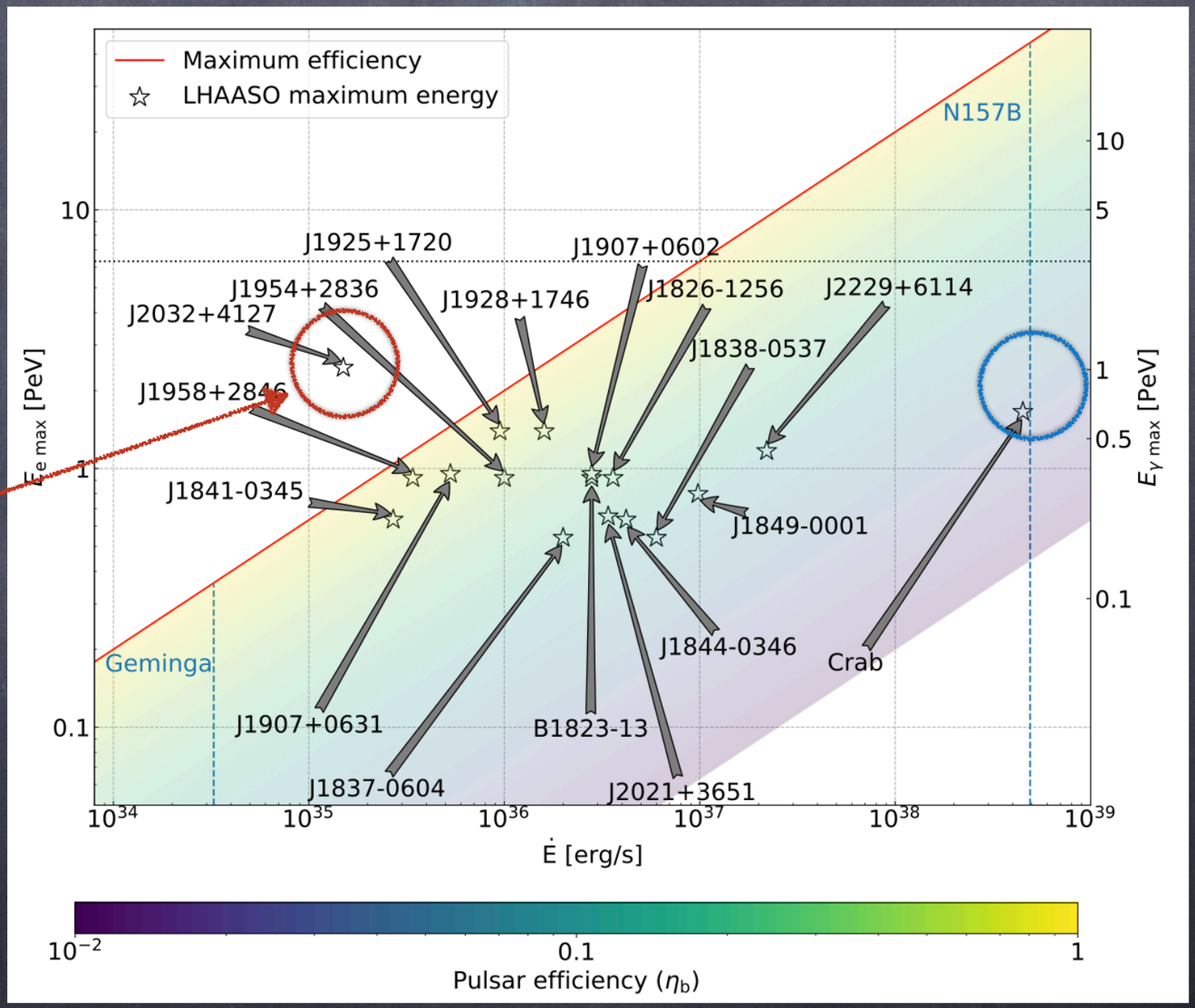
$$\frac{B_{TS}^2}{4\pi} = \eta_B \frac{\dot{E}}{4\pi R_{TS}^2 c}$$

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

LHAASO PEVATRONS AND PWNe

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

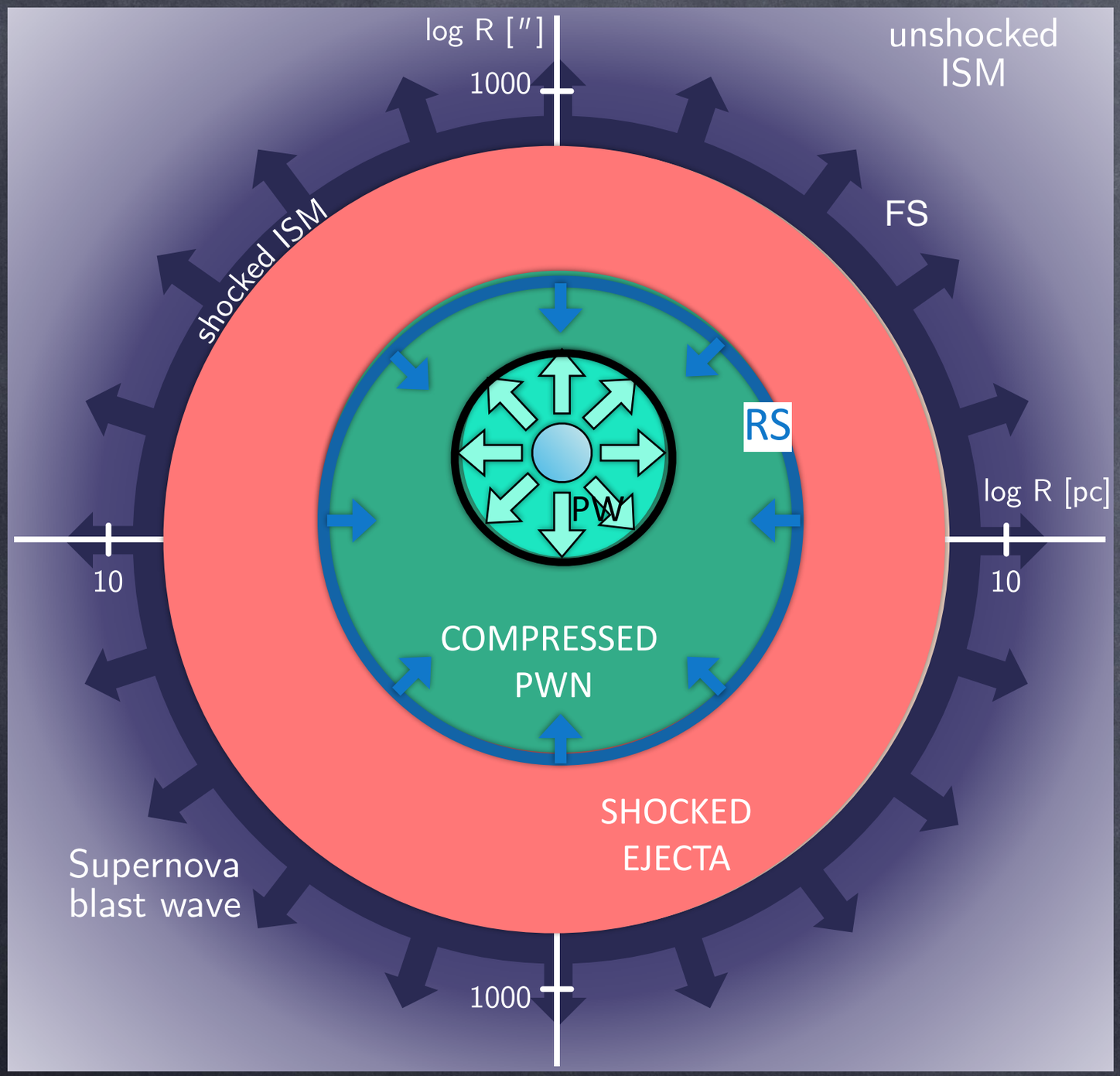
CYGNUS



de Ona Wilhelmi + 2022

EVOLVED PULSAR WIND NEBULAE

PWN EVOLUTION



SNR EXPANSION

SLOWS DOWN

+

LARGE FRACTION OF

ALL THE PULSARS

BORN WITH

HIGH KICK VELOCITY

↓

COMPRESSED PWN

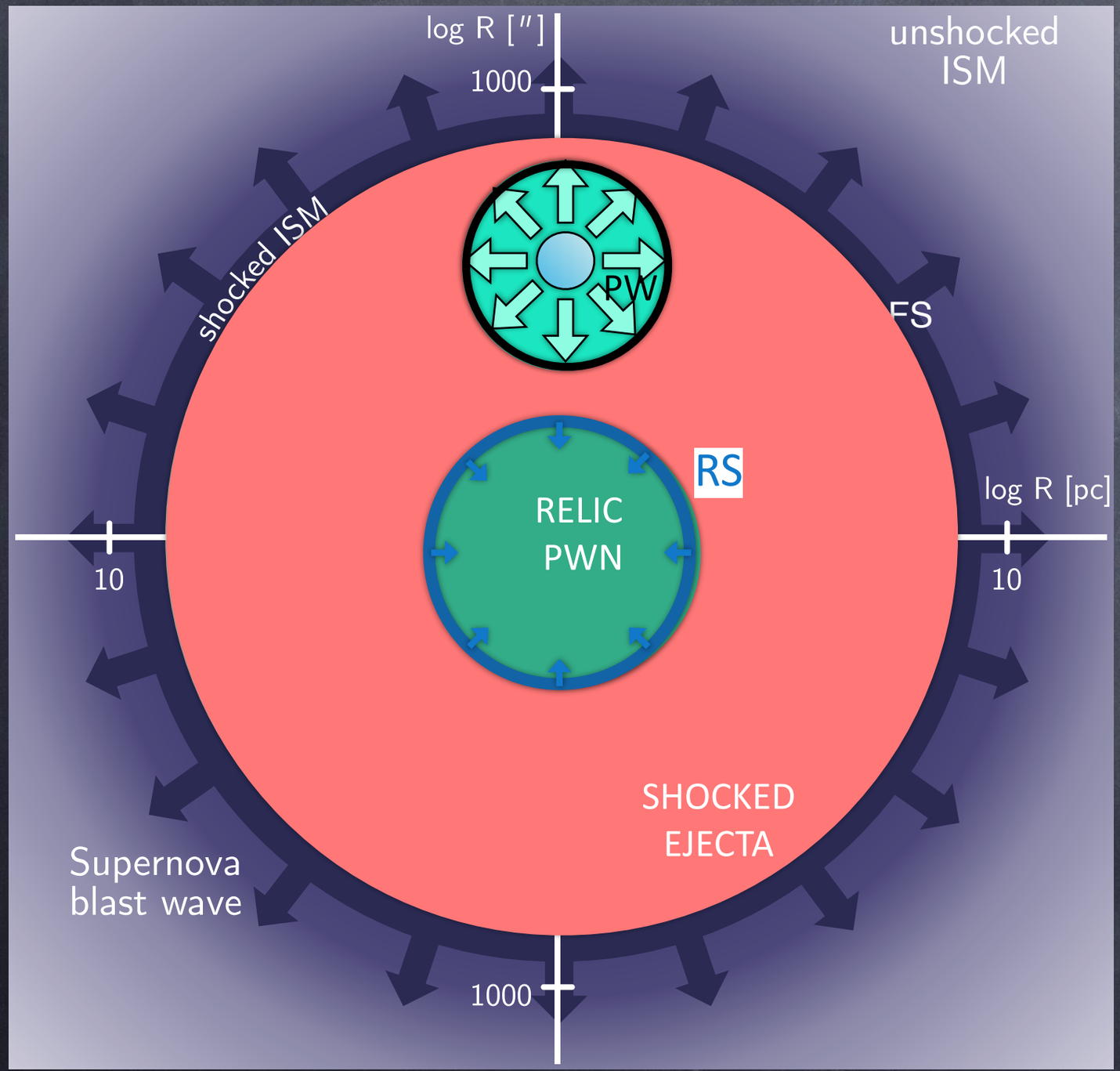
OFFSET PW

↓

REVERBERATION PHASE

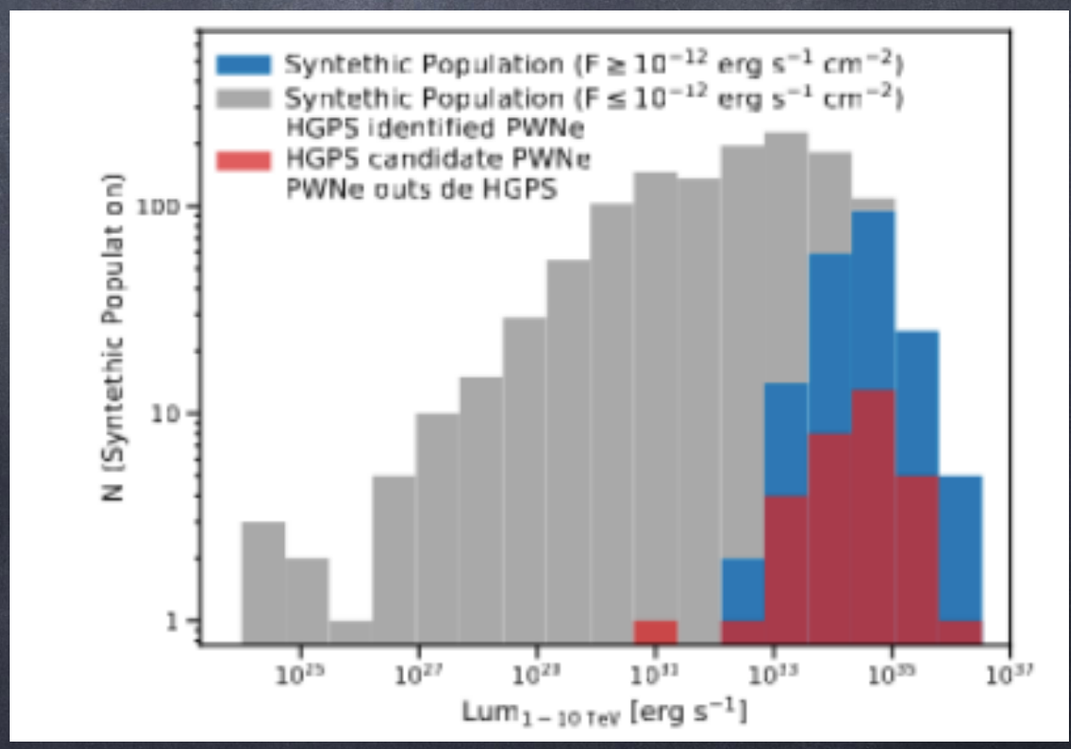
RELIC NEBULAE

PSR MAY CROSS RS DURING COMPRESSION AND LEAVE A RELIC

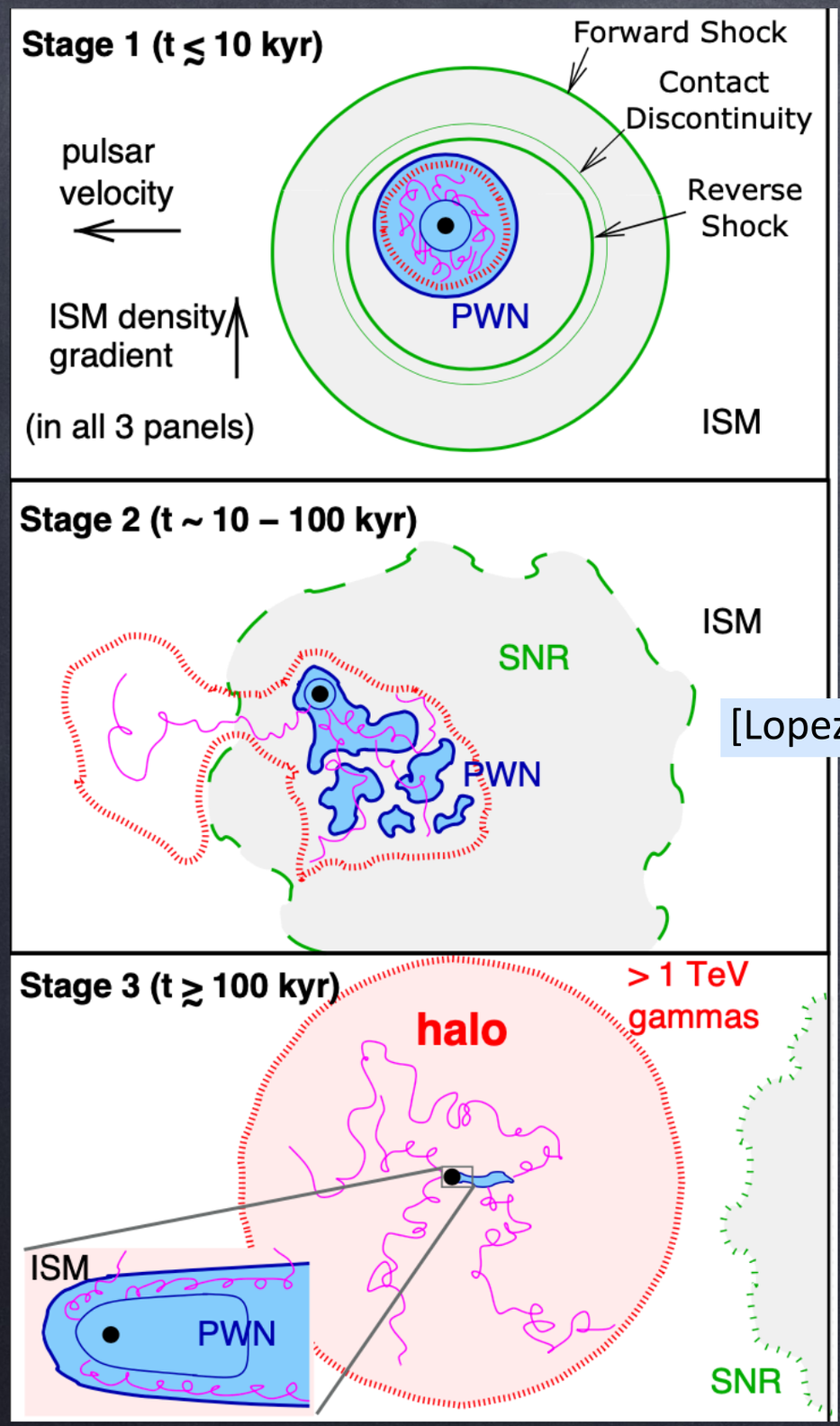


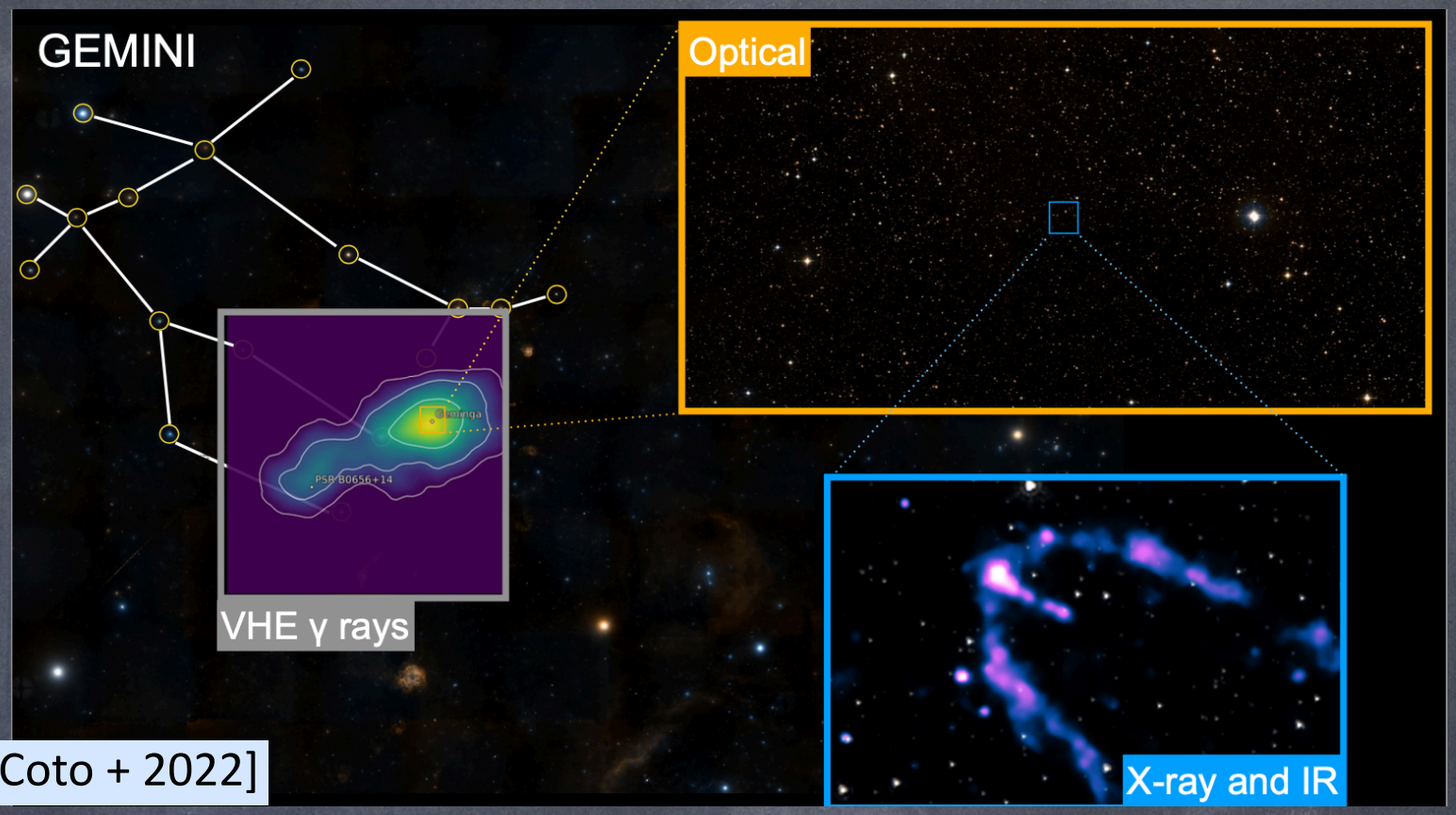
EVENTUALLY MOST GAMMA-RAY BRIGHT X-RAY DIM PWNe

[Fiori+ 2022]

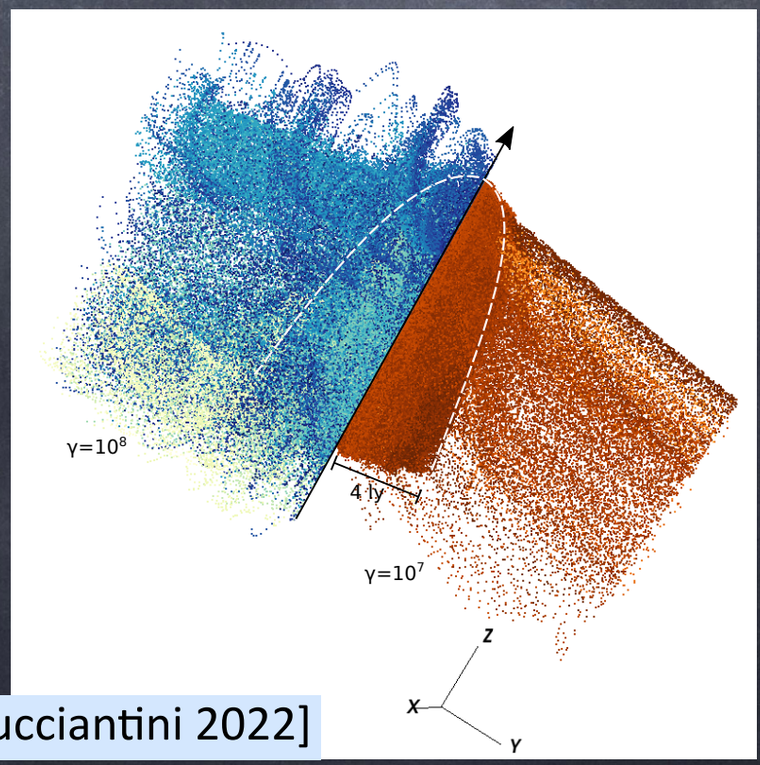


BOW SHOCK NEBULAE: POSITRONS, JETS AND HALOES



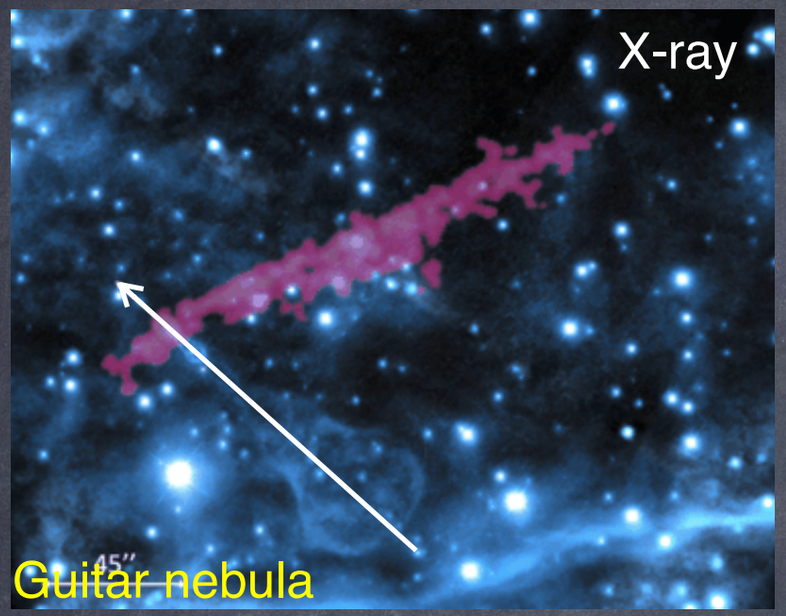


[Lopez-Coto + 2022]



[Olmi&Bucciantini 2022]

JETS AND HALOES



[Cordes+ 1993, Wong+ 2003]

JETS CONSISTENT WITH

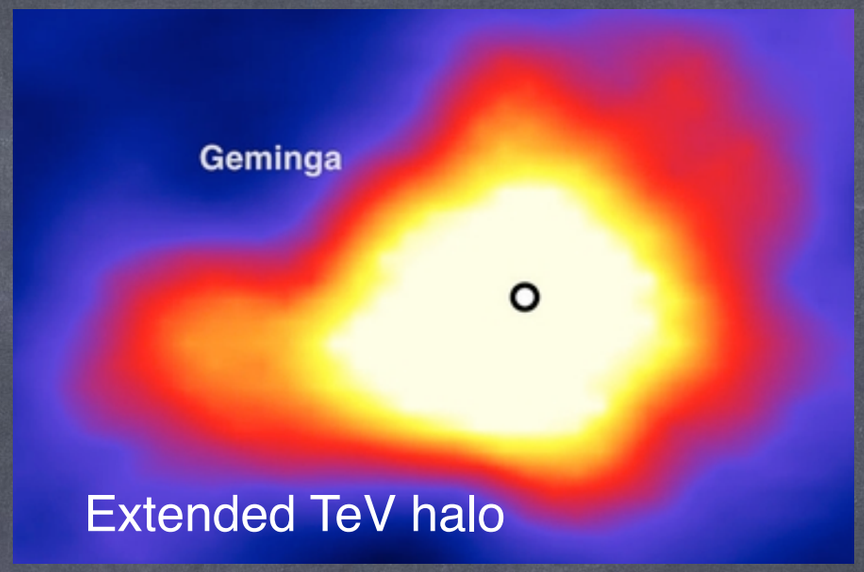
SYNCHROTRON EMISSION

OF PARTICLES WITH $E \approx e\Phi_{\rm PSR}$

IN A FEW X $10\mu G$ MAGNETIC FIELD

[Bandiera 2008]

[Pavan+2016, de Vries & Romani 2022,.....]



[Abeysekara+ 2017]

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]

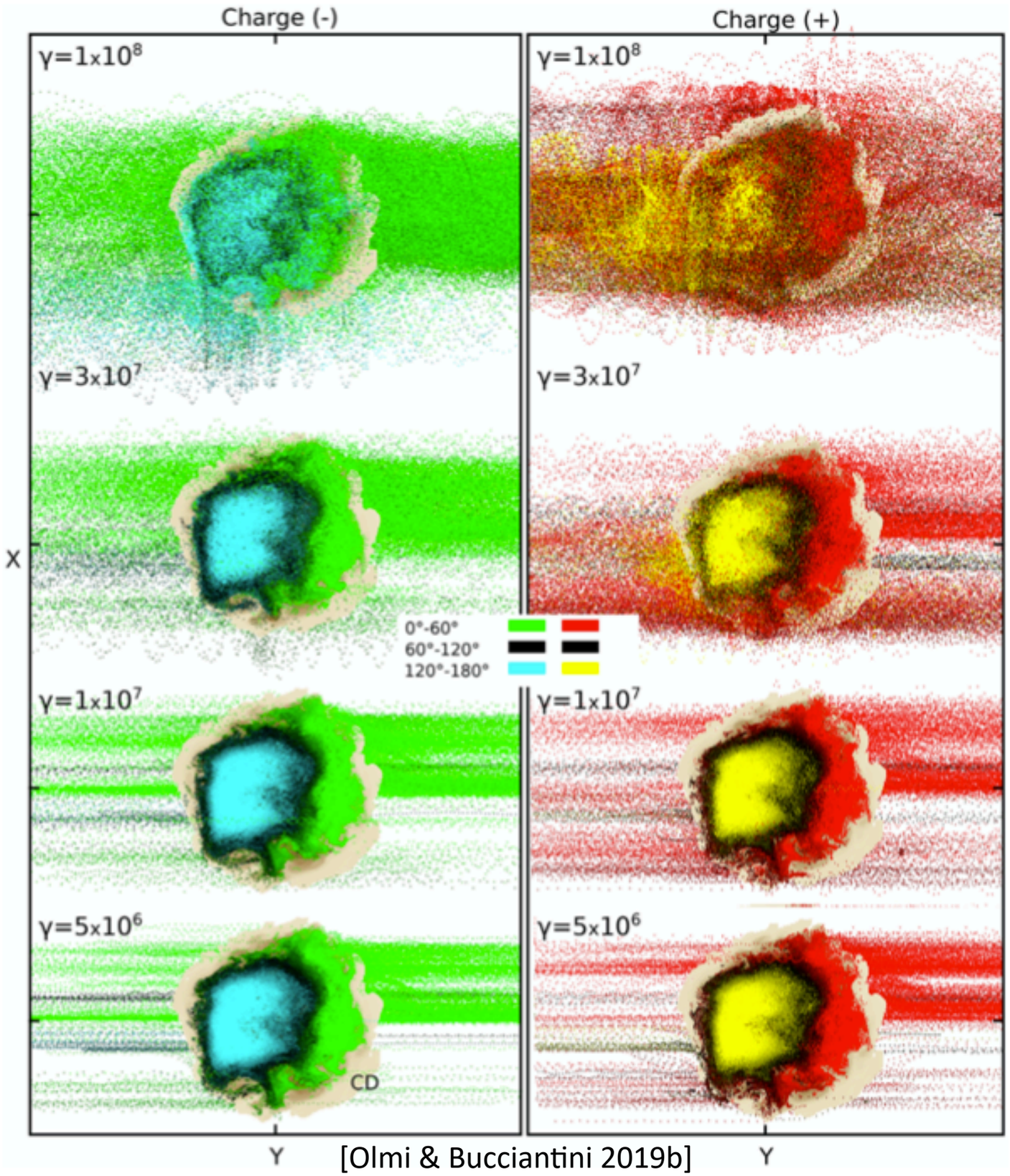
BUT ALSO ALTERNATIVE PROPOSALS

[e.g. Recchia+2021]

MAGNETIC FIELD AMPLIFICATION BY ESCAPIMG PARTICLES?

[Evoli, Linden, Morlino 18, Linden +22]

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

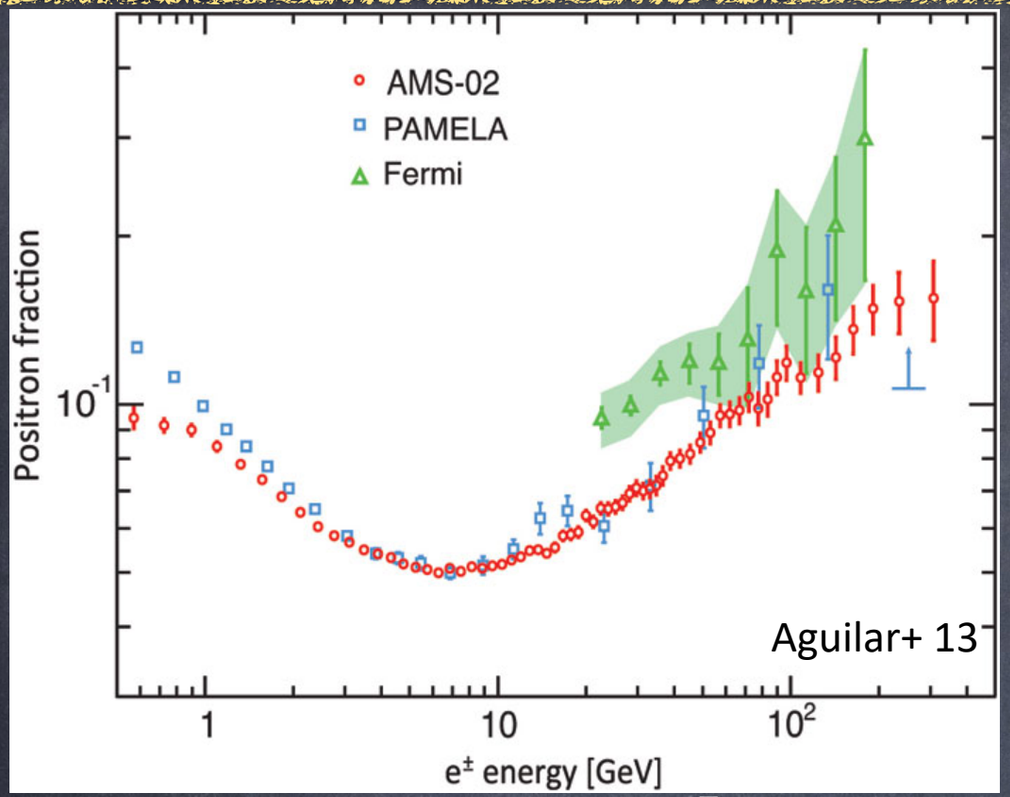
NOTICE THAT:

- ENERGY DEPENDENT ESCAPE PROBABILITY MAKES HALO SPECTRUM NON TRIVIAL

- ESCAPE IS CHARGE SEPARATED!

- IF LOW AMBIENT B BELL INSTABILITY POSSIBLE…

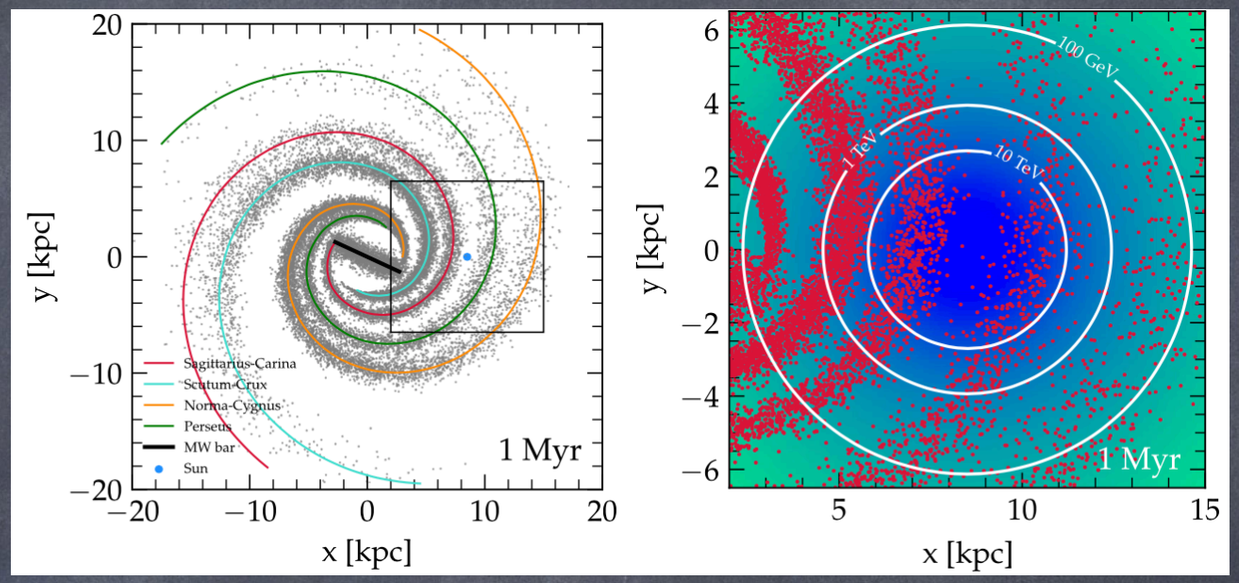
THE CR POSITRON EXCESS



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

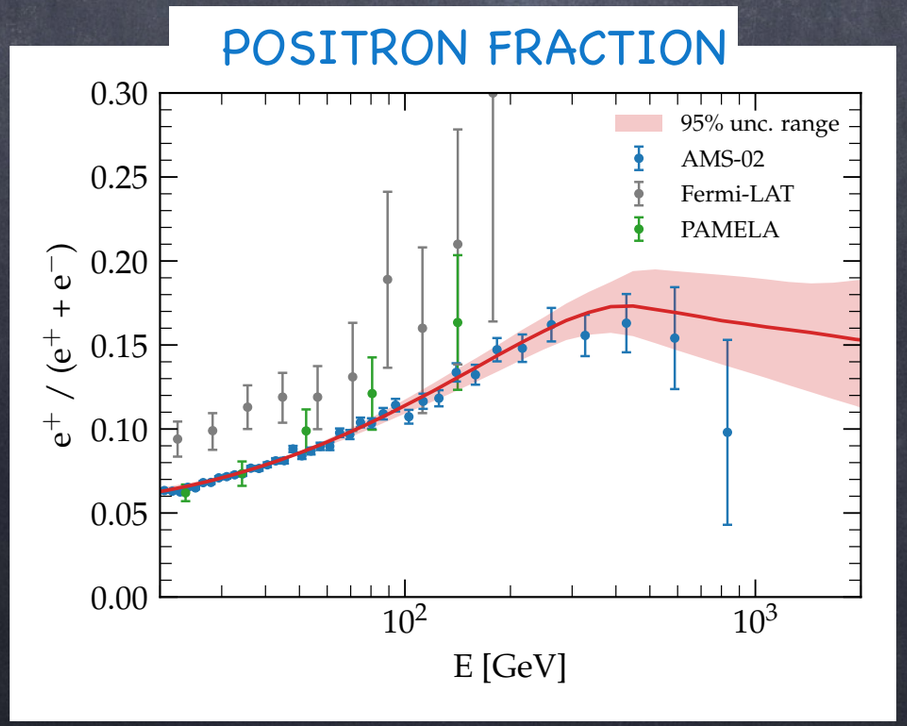
BOW SHOCK PWNe EARLY SUGGESTED [Blasi & EA 11]

AS BEST CANDIDATES TO EXPLAIN THE EXCESS

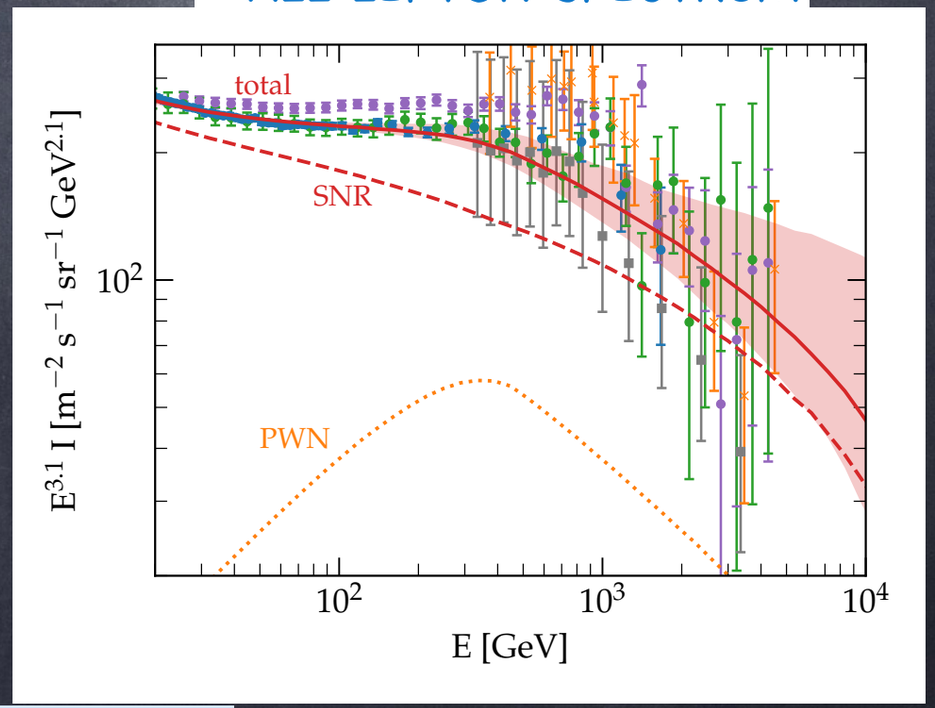


BS-PWNe INJECT $0.1\dot{E}$ AS A BROKEN POWER-LAW OF e^+-e^- : $E_B \approx 500\text{GeV}$

POSITRON FRACTION



ALL LEPTON SPECTRUM



Evoli+ 21,22

SUMMARY

- IN THE LAST DECADE, PWNe HAVE ENTERED THE REALM OF POTENTIAL CR SOURCES

- ONLY FIRMLY IDENTIIED PEVATRON IS CRAB, A PWN

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

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

- EVIDENCE FOR HADRONS IN PULSAR WINDS WOULD HAVE ENORMOUS IMPLICATIONS: NOT ONLY PULSAR PHYSICS, BUT MAYBE EVEN UHECRs...

- UNDERSTANDING HALO ESSENTIAL FOR CR TRANSPORT AND TO UNDERSTAND THE ORIGIN OF COSMIC LEPTONS

- FIRST QUESTION TO ANSWER IS HOW WIDESPREAD THEY ARE AND AT WHAT ENERGIES THEY SHOW