PARTICLE ACCELERATION IN PULSAR WIND NEBULAE

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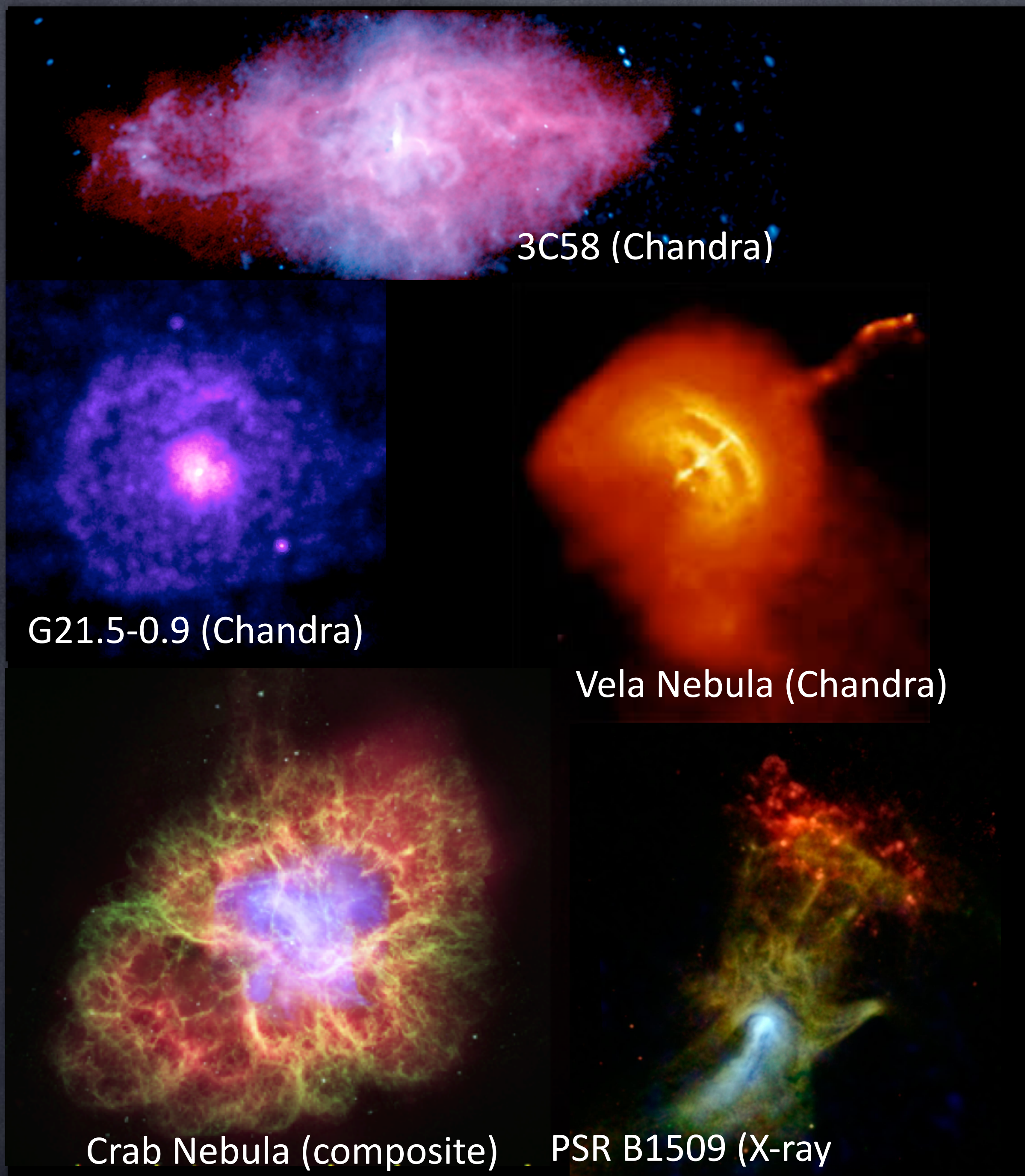
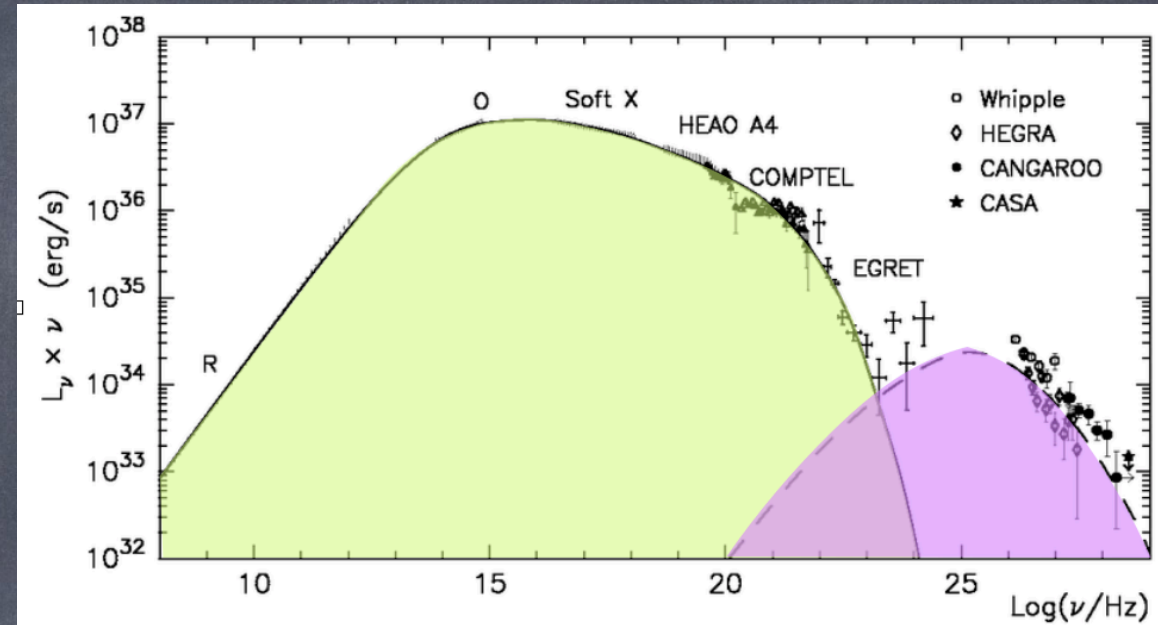
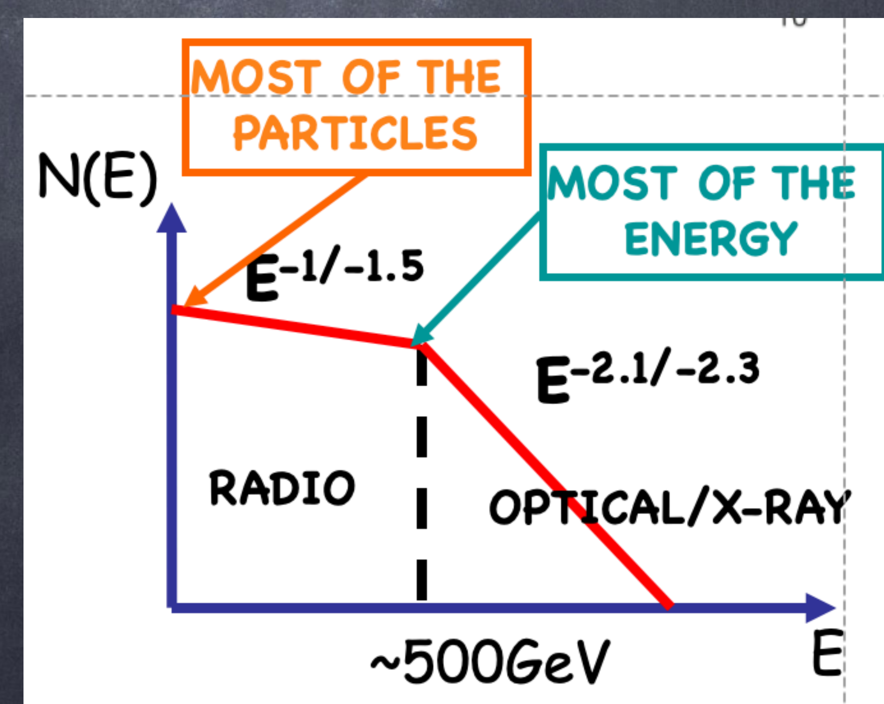
THE MOST EFFICIENT ACCELERATORS IN THE GALAXY





Crab: adapted from Atoyan & Aharonian 1996

- PEV LEPTONS
- ACCELERATION EFFICIENCY UP TO 30%

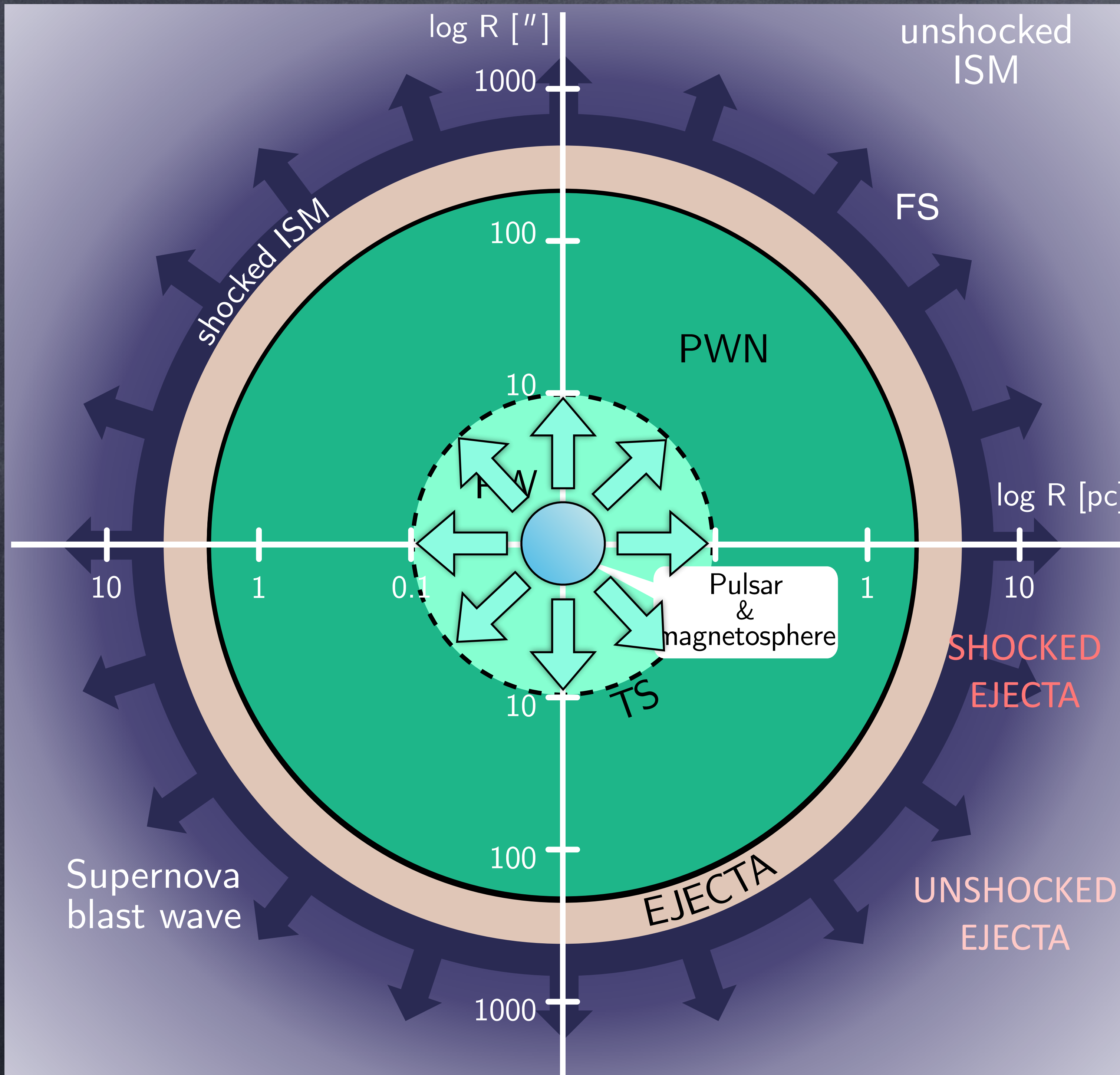


PECULIARITIES

- FLAT LOW ENERGY SPECTRUM WITH BREAK AROUND 500 GEV
- NO SIGNS OF THERMAL PARTICLES

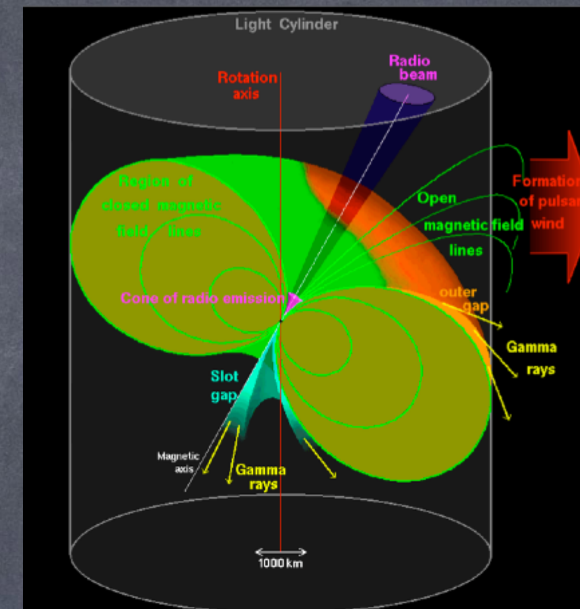
WHERE AND HOW ARE PARTICLES ACCELERATED?

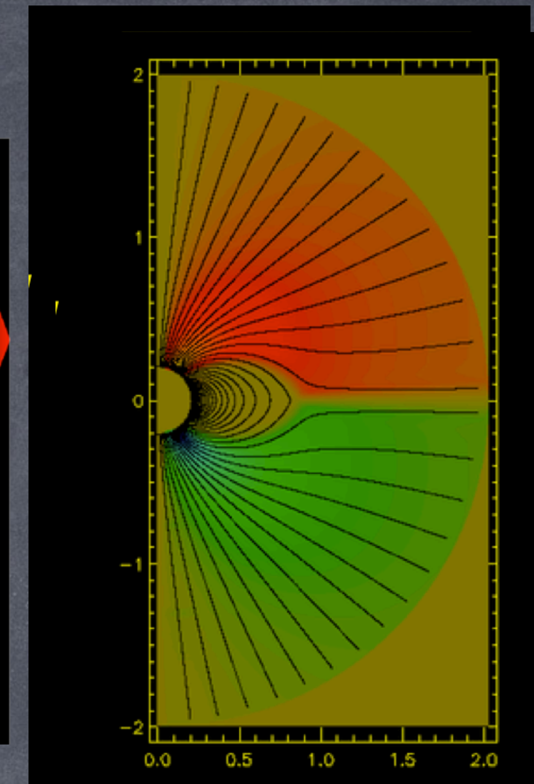
WHERE?



Adapted from Kennel & Coroniti 1984

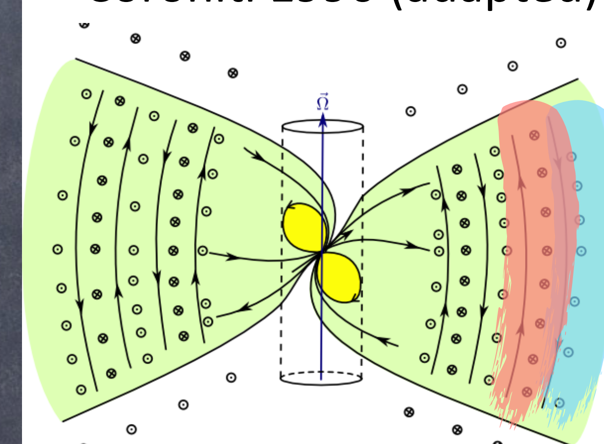
[Del Zanna & Olmi 2017]



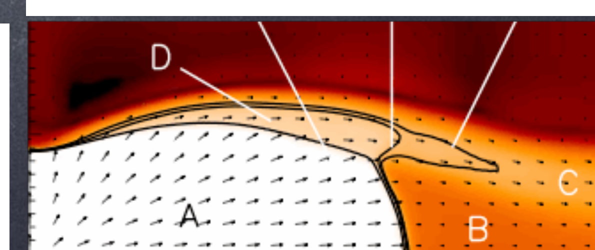


Spitkovsky 2006

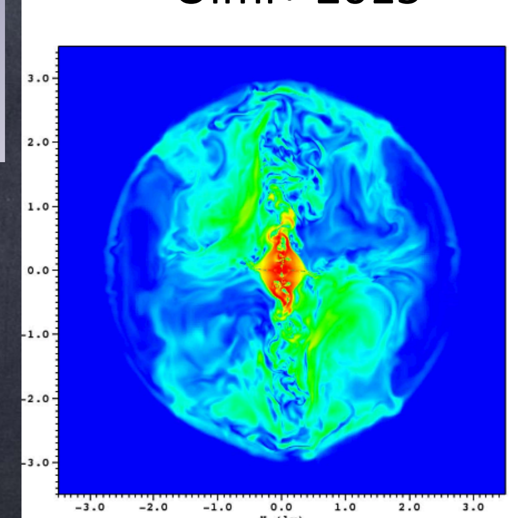
Coroniti 1990 (adapted)



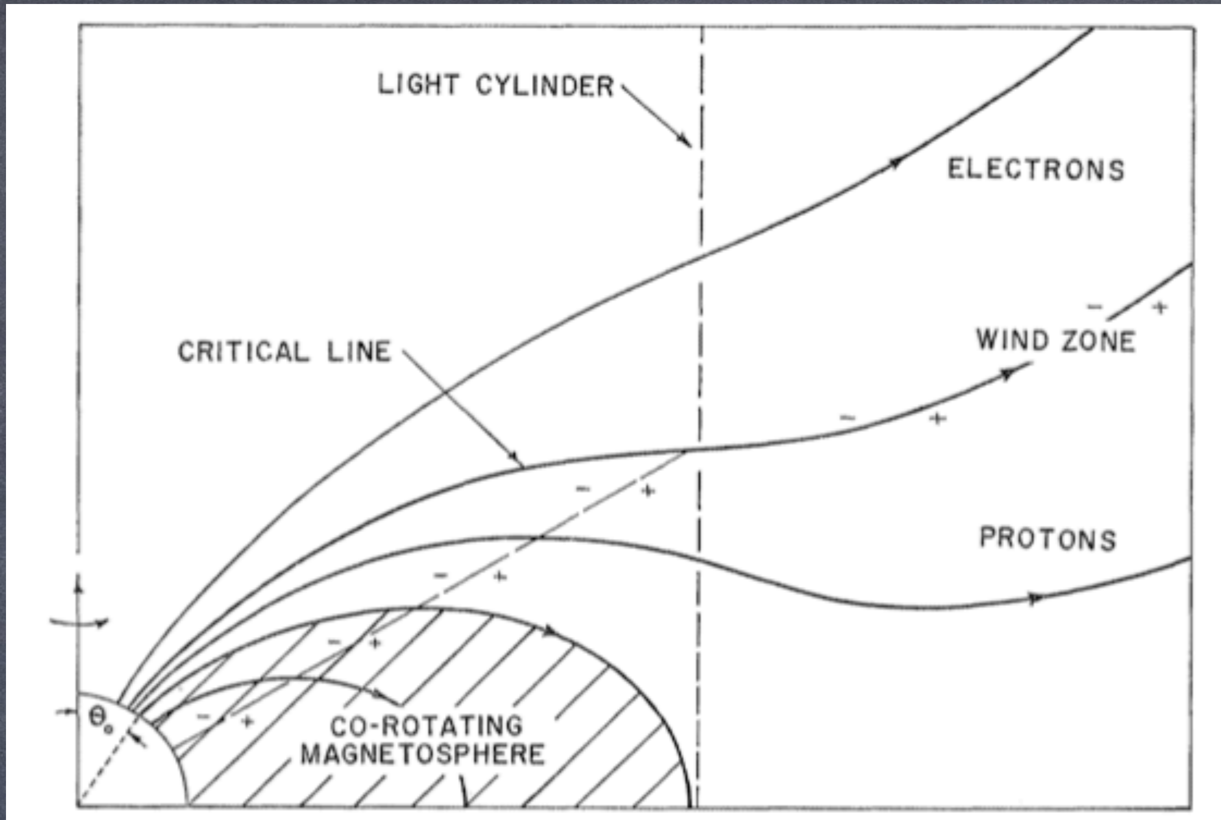
Del Zanna + 2004



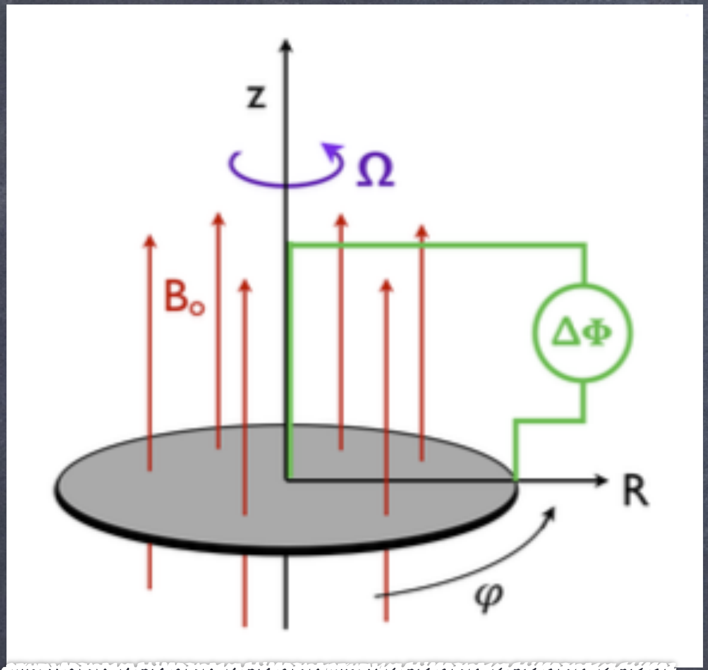
Olmi+ 2015



ABSOLUTE MAXIMUM ENERGY

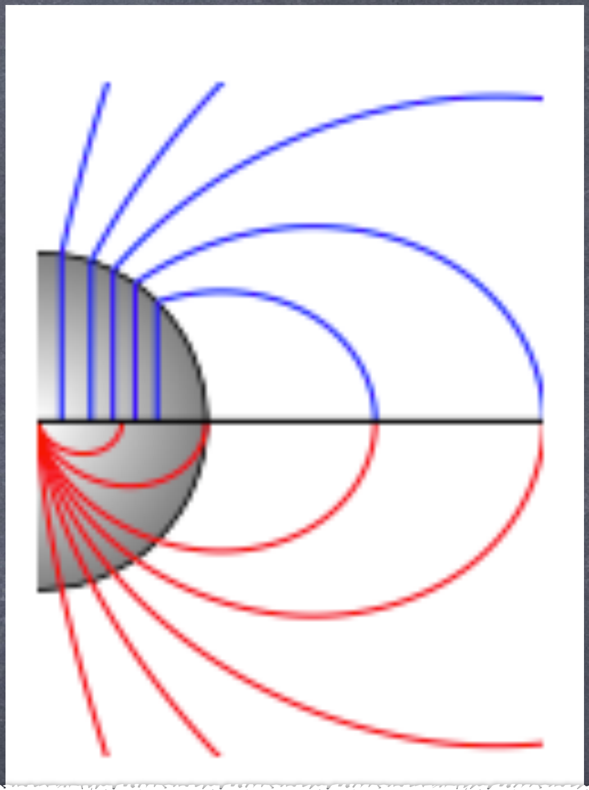


Goldreich & Julian 1969



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

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



$$\Delta\Phi_{TOT} \approx \frac{B_\star \Omega R_\star}{c} R_\star$$

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

$$E_{max} = Ze\Delta\Phi_{PC} \approx 2\ Z\ PeV\ \dot{E}_{36}^{1/2}$$

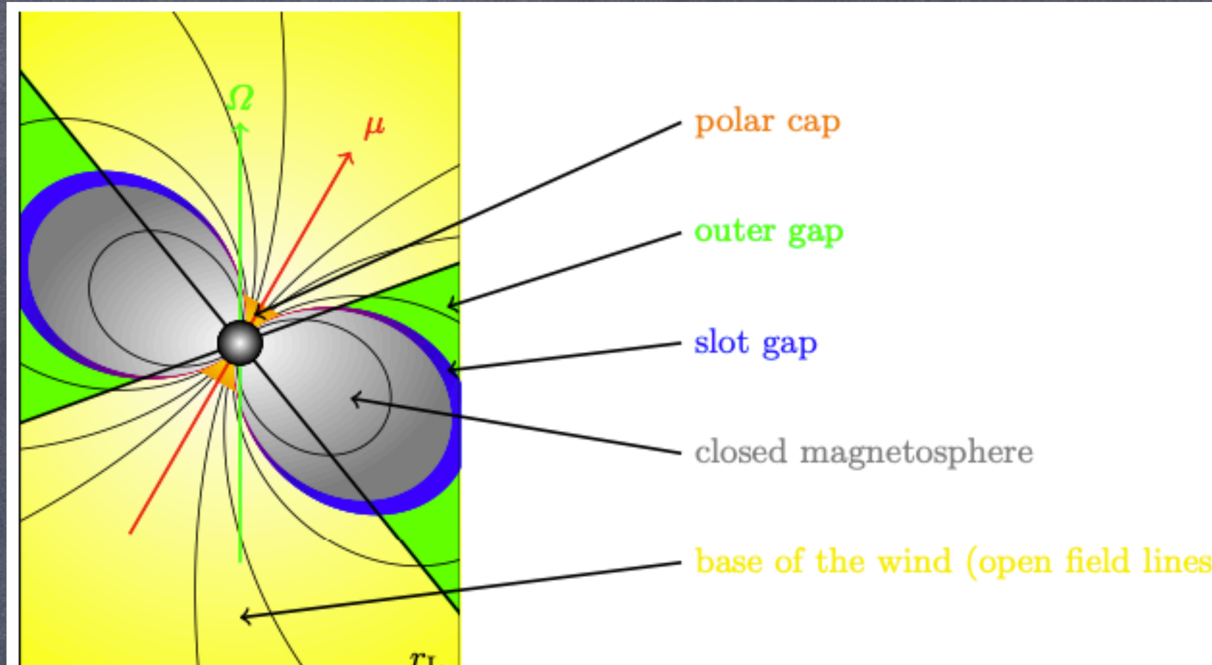
PARTICLE ACCELERATION IN PSR MAGNETOSPHERE

DIRECT E-FIELD ACCELERATION IN GAP OF SIZE ξR_L WITH POTENTIAL DIFFERENCE Φ VS CURVATURE

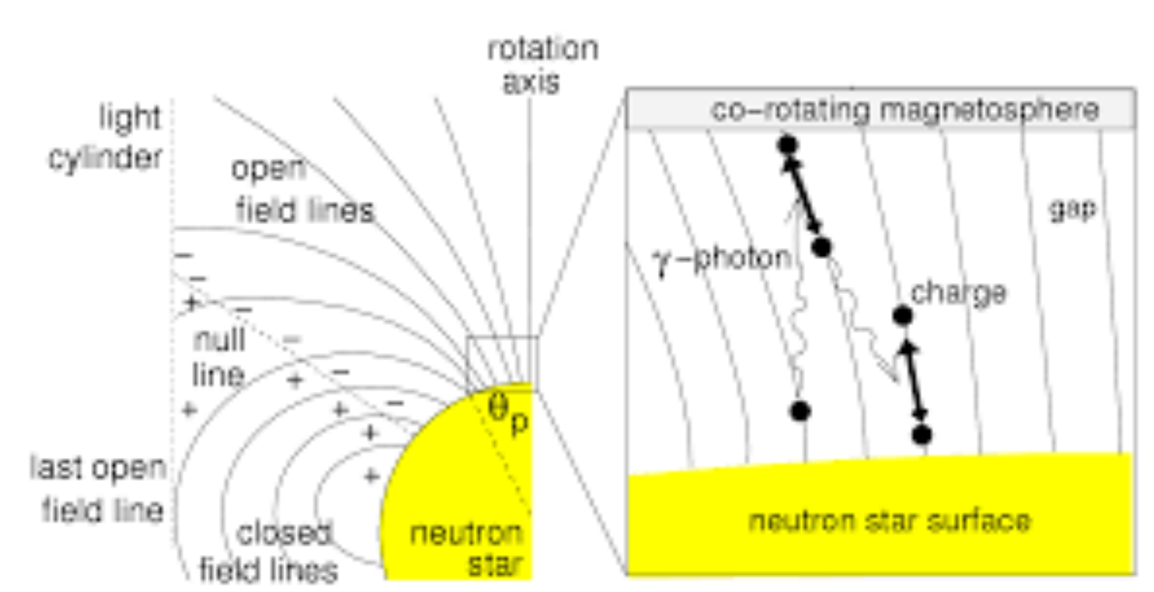
$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{Ze\Phi}{Am_{\rm p}c^2}\frac{2\pi}{\xi P} - \frac{8\pi^2}{3cP^2}\frac{Z^2e^2}{Am_{\rm p}c^2}\gamma^4$$

[Kotera, EA, Blasi 15]

$$\gamma_{\rm curv} = \left(\frac{3\pi B R_\star^3}{2ZecP\xi}\right)^{1/4} \sim 1.1\times10^8 Z_{26}^{-1/4}\xi^{-1/4}B_{13}^{1/4}P_{-3}^{-1/4}R_{\star,6}^{3/4}$$



Petri 2017



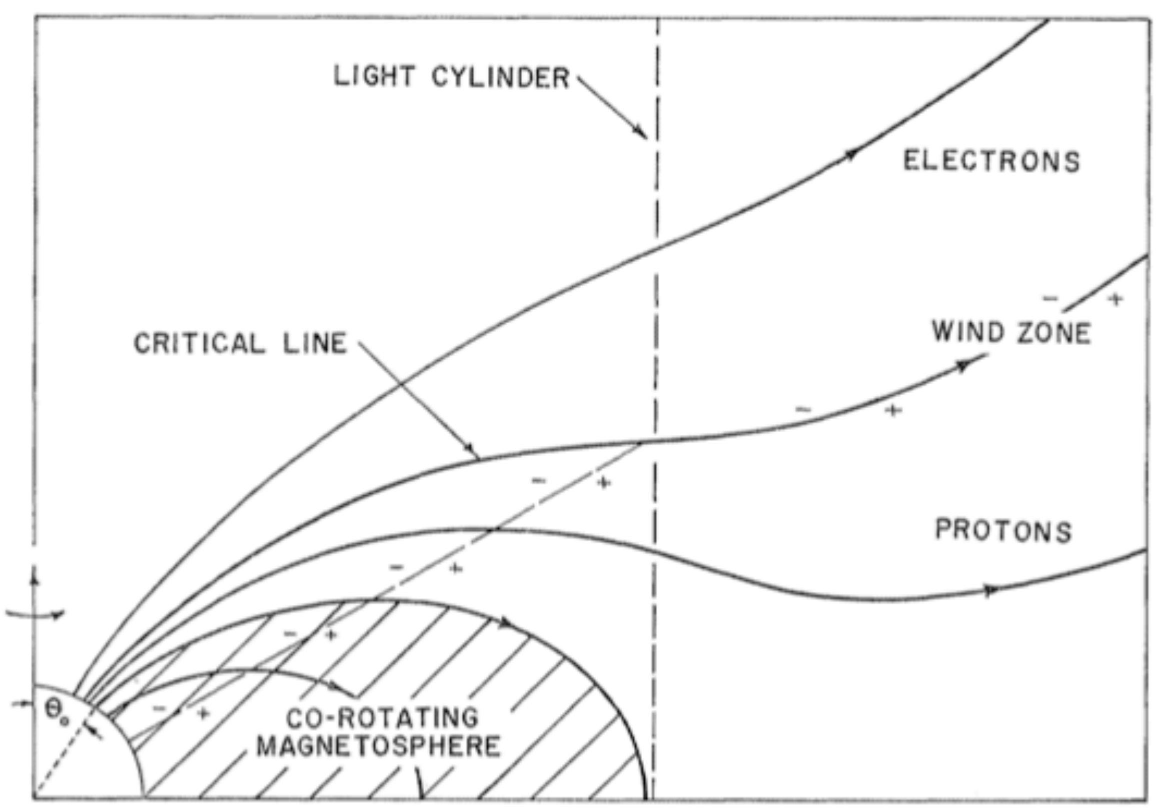
e^- ⟹ Curvature or ICS on star X-rays ⟹ γ (E_γ>50 MeV) ⟹ $\gamma + B \rightarrow e^+ + e^-$

$\gamma_{primary}$~10^7

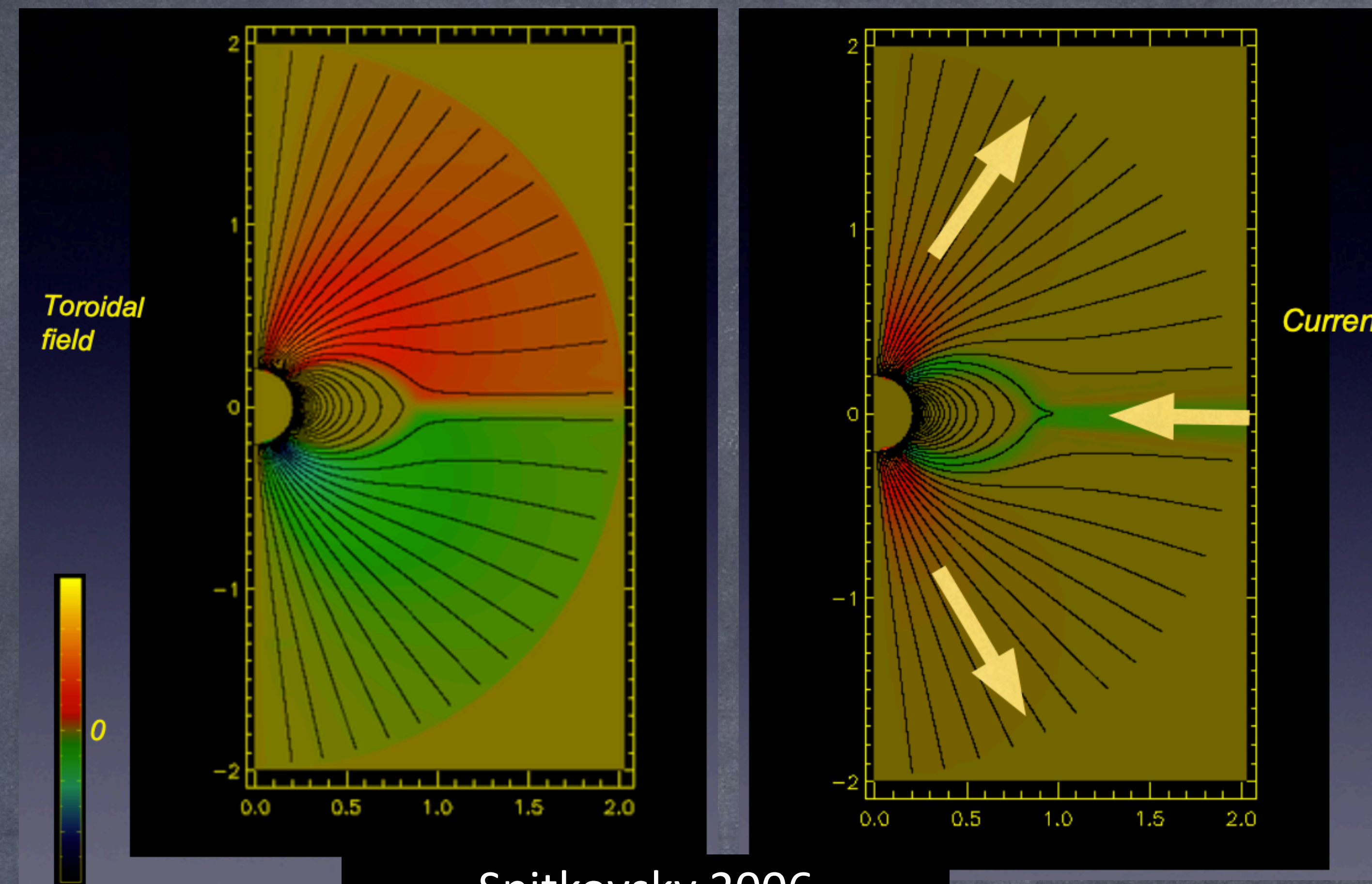
$\gamma_{secondary}$~10^{2-3}

⬇ γ-RAYS

THE PULSAR WIND



Goldreich & Julian 1969



Spitkovsky 2006

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

$$\sigma = \frac{B^2}{4\pi \; n_\pm \; m_e \; c^2 \; \Gamma^2} \qquad \dot{N}_{GJ} = \frac{\sqrt{c\dot{E}}}{e}$$

$$\gamma_\phi = 10^{11} \frac{Z}{A} B_{13} \; P_{-3}^2$$

$$\gamma_{max} \approx \Gamma = \epsilon \Gamma_\phi$$

THE SMALLER κ IS,
THE LARGER ϵ IS

UHECRs from Pulsars?

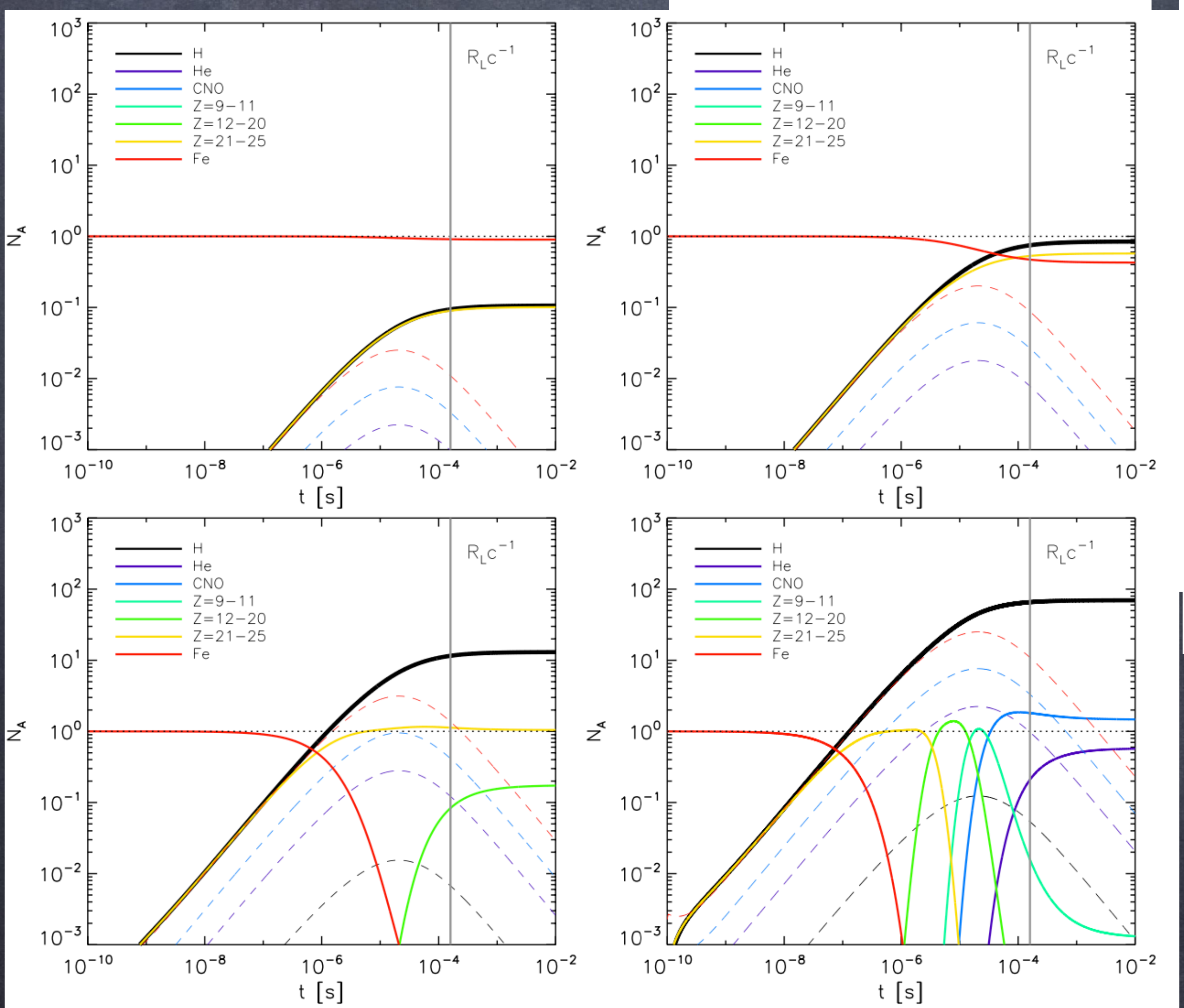
$$E_{\rm CR}(t) = E_0\,(1+t/t_{\rm sd})^{-1} \sim 1.2\times10^{20}\,{\rm eV}\,\eta A_{56}\kappa_4 I_{45} B_{13}^{-1} R_{\star,6}^{-3}\, t_{7.5}{}^{-1} \quad \text{for} \quad t > t_{\rm sd}$$

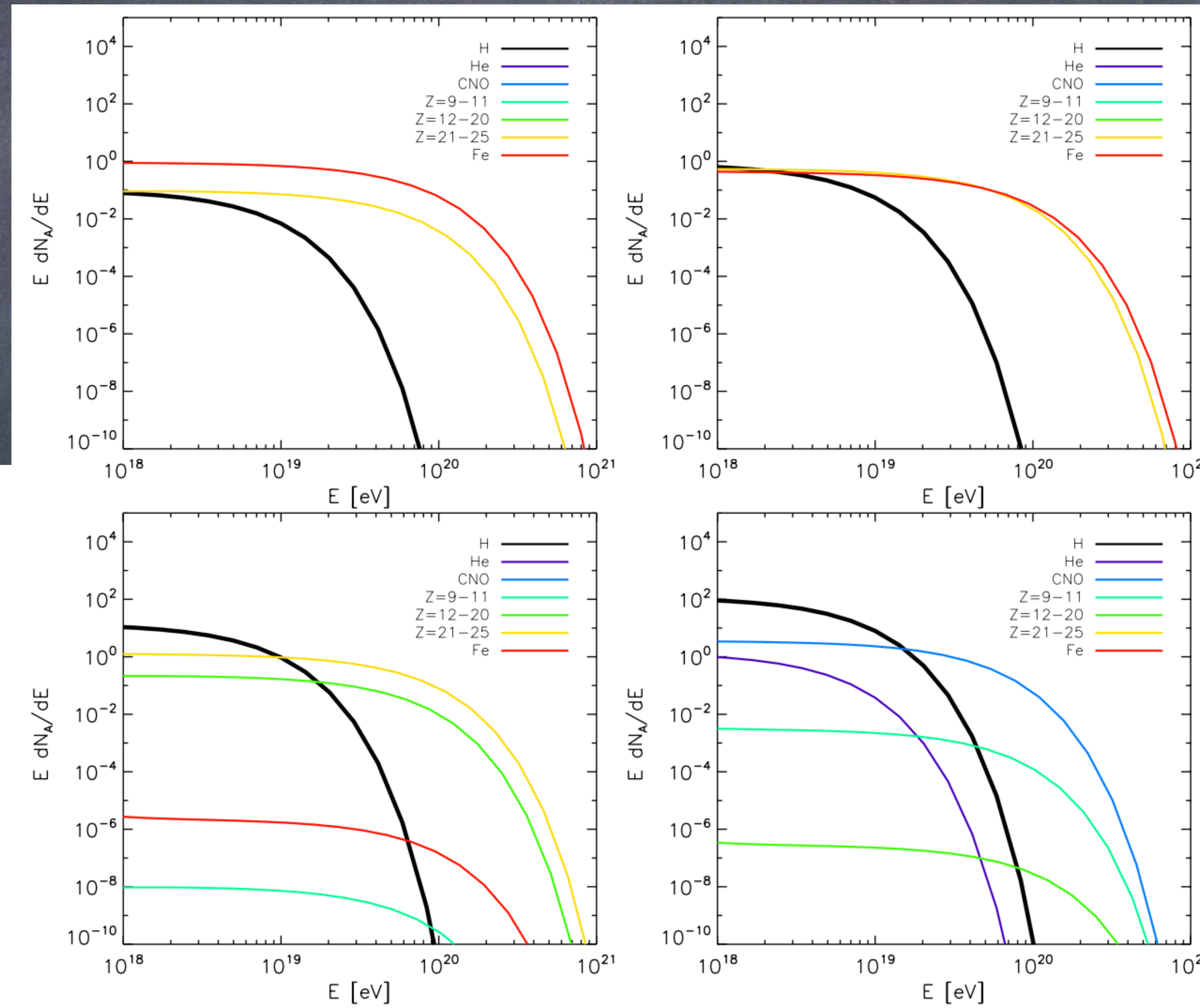
$$\frac{{\rm d}N_{\rm CR}}{{\rm d}E} = \int_0^\infty {\rm d}t\dot{N}_{\rm GJ}(t)\delta\left(E - E_{\rm CR}(t)\right) = \frac{\dot{N}_{\rm GJ}(0)t_{\rm sd}}{E}$$

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

PURE IRON EXTRACTION AND PHOTODISINTEGRATION

$$\frac{{\rm d}N_A}{{\rm d}t} + \frac{N_A}{t_A} = \frac{N_{A+1}}{t_{A+1}}$$



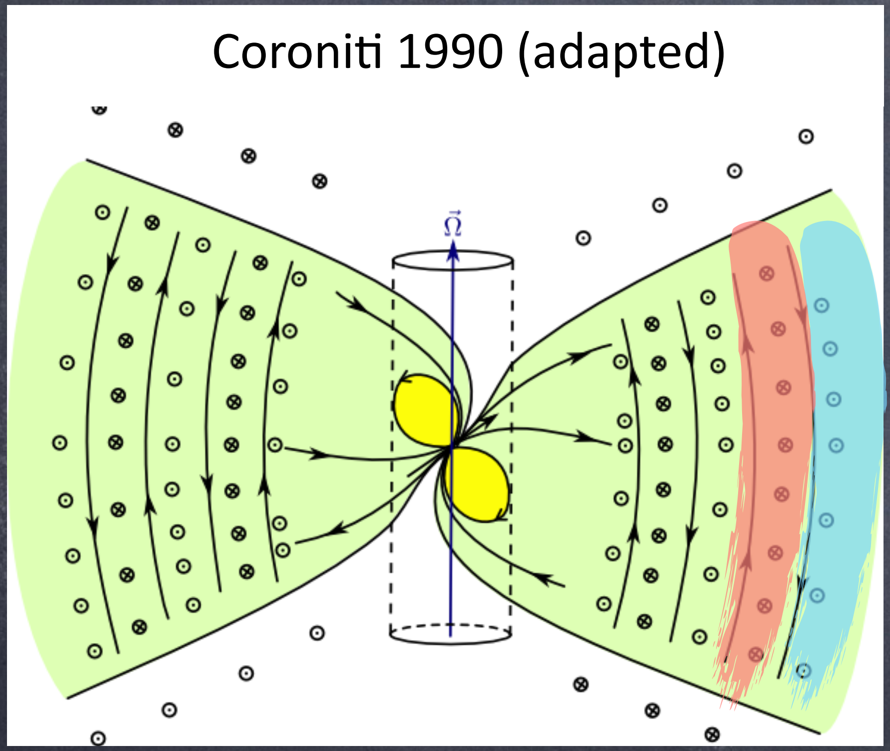


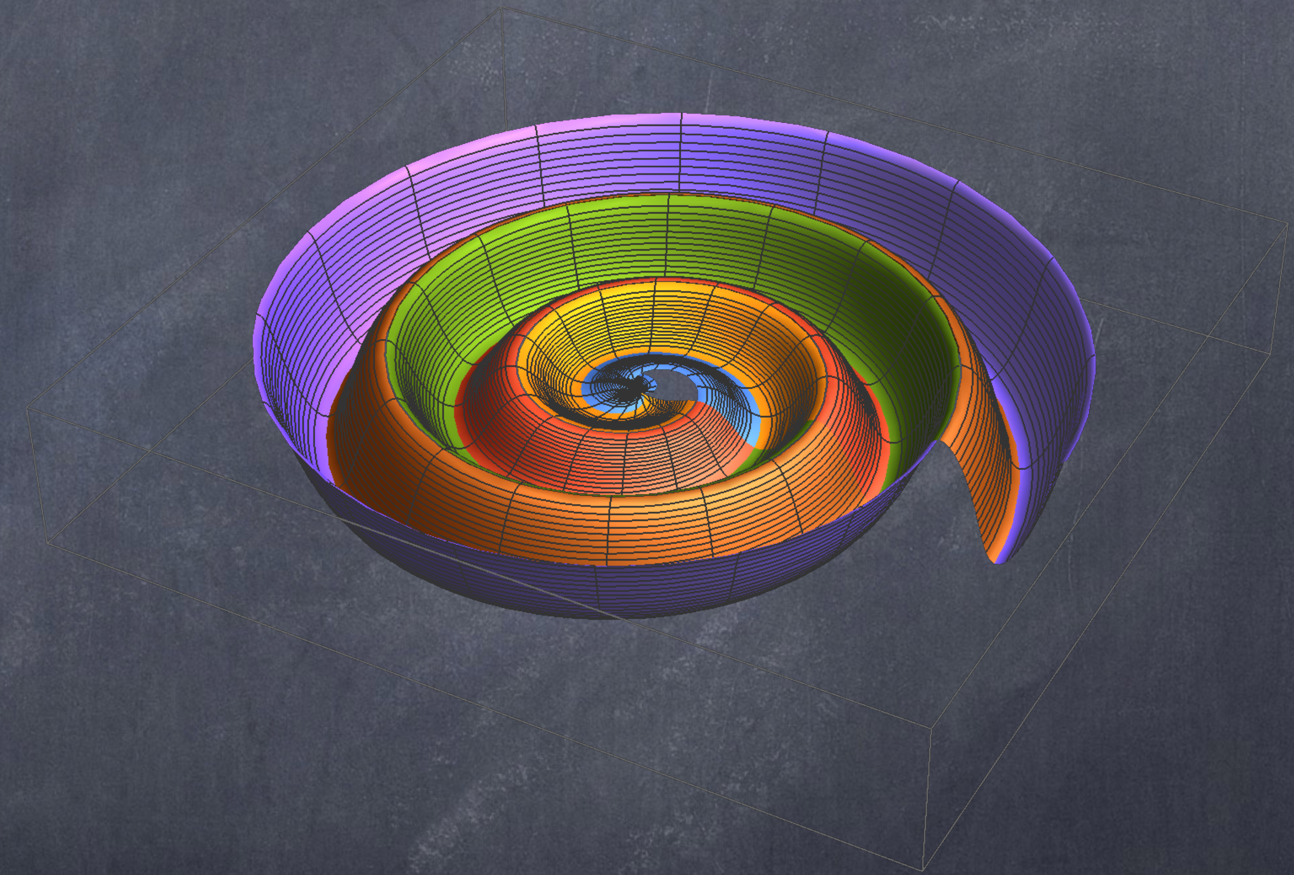
Kotera, EA, Blasi 15

ENERGY DEPENDENT COMPOSITION AND CORRELATION WITH STARBURST

[Auger coll. 2020]

PARTICLE ACCELERATION IN THE (RECONNECTING) CURRENT SHEET

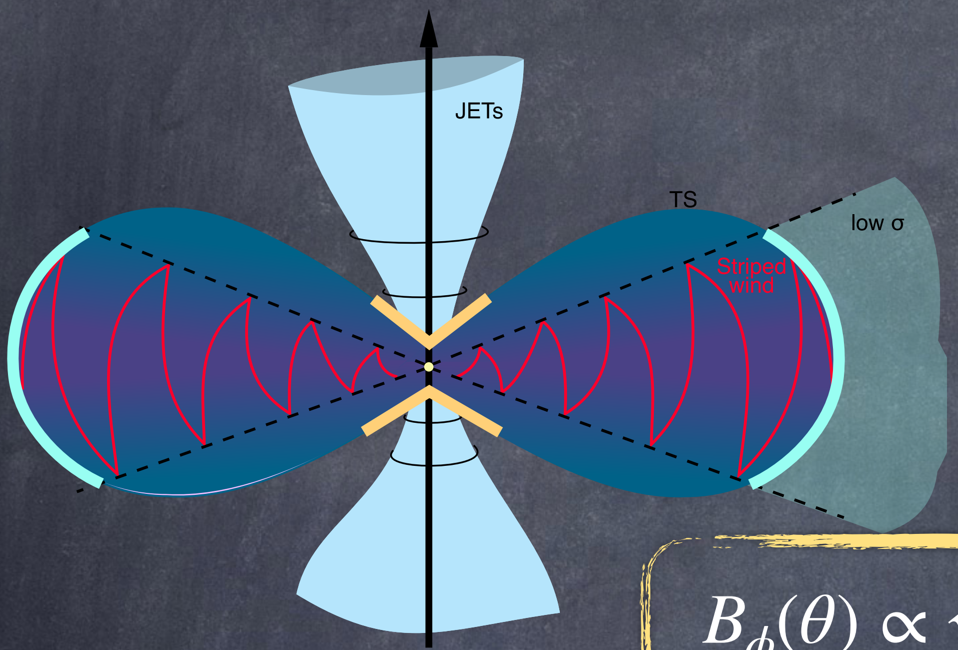




- EFFICIENT DISSIPATION BEFORE THE SHOCK REQUIRES $\kappa > 10^6$
[Kirk & Lyubarsky 2001]

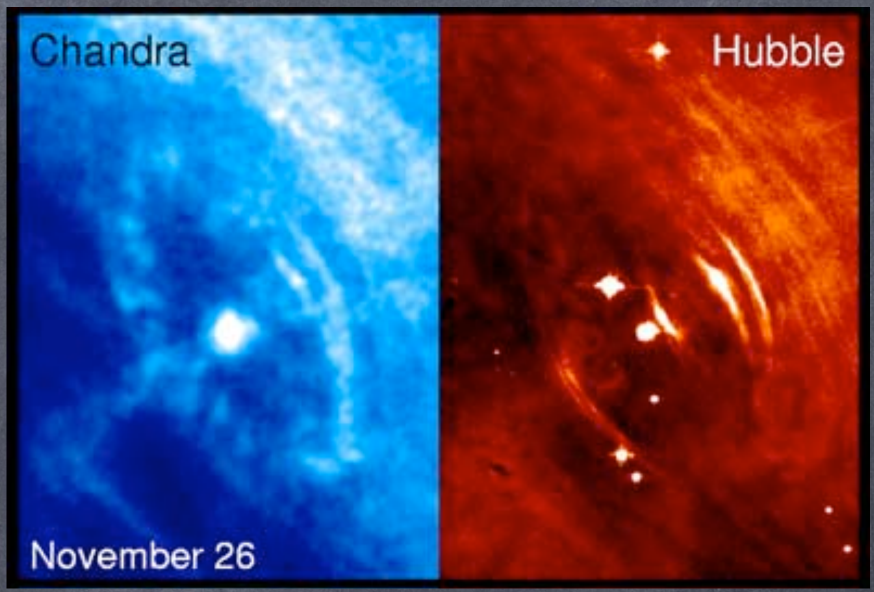
- PARTICLE ACCELERATION (LEPTONS) WOULD RESULT IN PULSED EMISSION [Kirk, Skjaeraasen & Gallant 2002]

PARTICLE ACCELERATION AT THE TERMINATION SHOCK



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

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

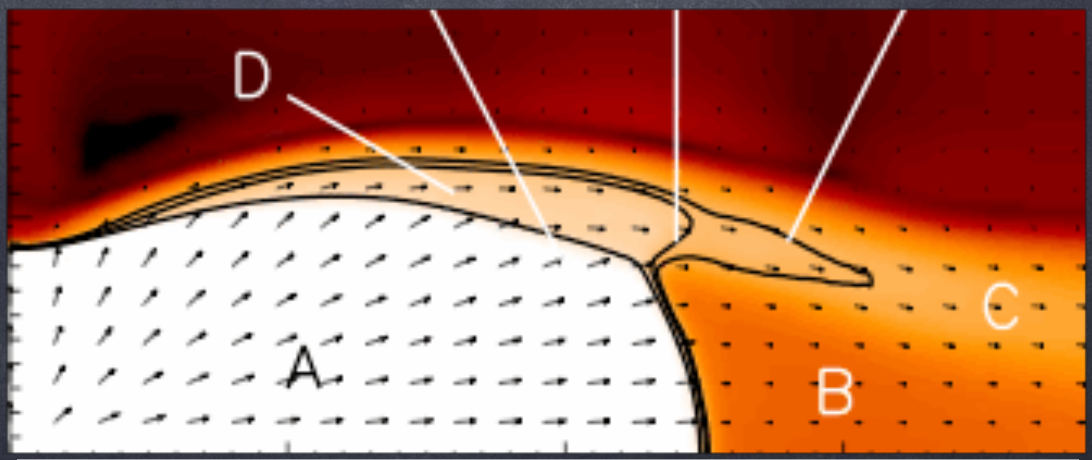


Weisskopf+ 2001

COLLISIONLESS RELATIVISTIC SHOCK

DRAMATIC DEPENDENCE ON:

- COMPOSITION
- MAGNETIZATION
- INCLINATION

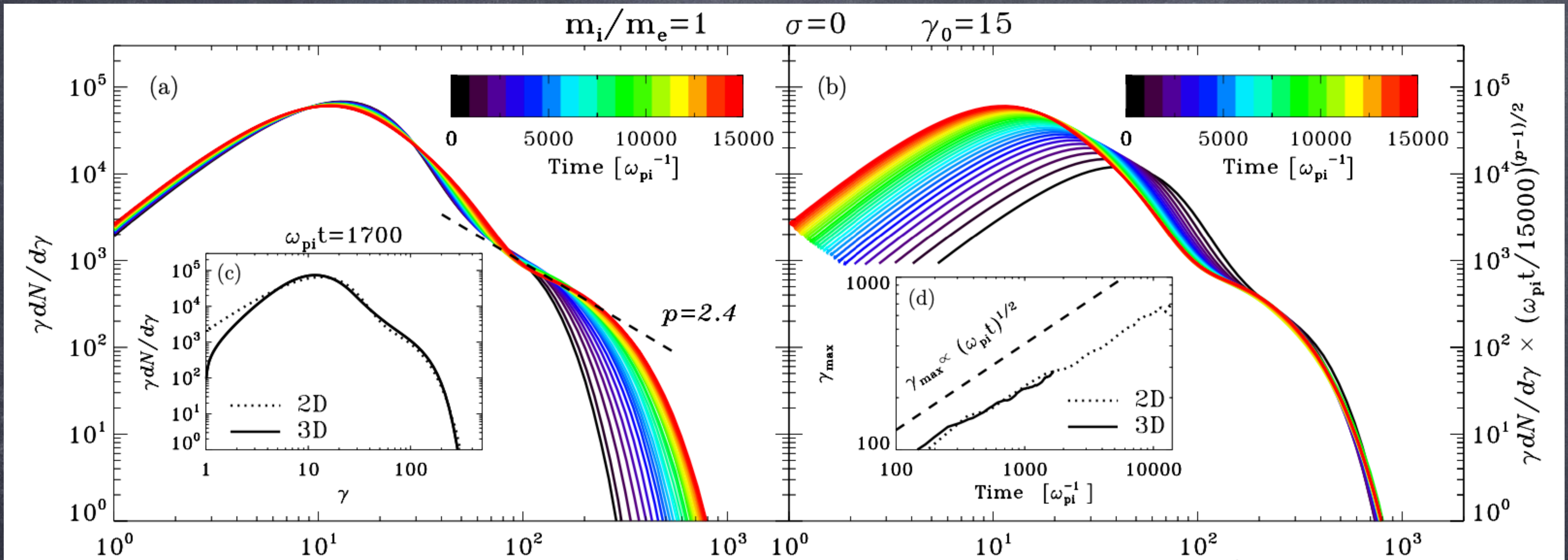


Del Zanna, EA, Bucciantini 2004

HILLAS CRITERION

$$E_{max} \approx ZeB_{TS}R_{TS}$$

FERMI ACCELERATION (RELATIVISTIC, UNMAGNETIZED, PAIRS!)



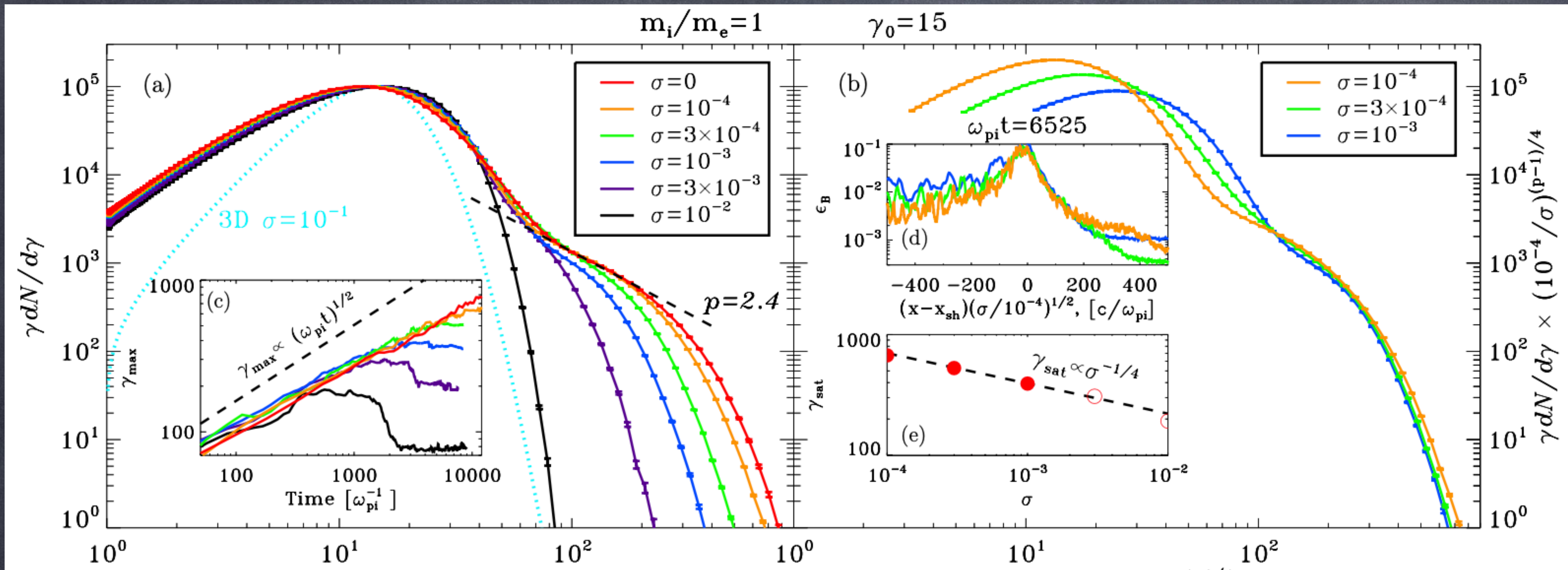
Sironi, Spitkovsky, Arons 2013

POWER-LAW DEVELOPS BUT SLOW PROCESS!

SCATTERING ON SMALL-SCALE TURBULENCE: $E_{\mathrm{MAX}} \propto t^{1/2}$

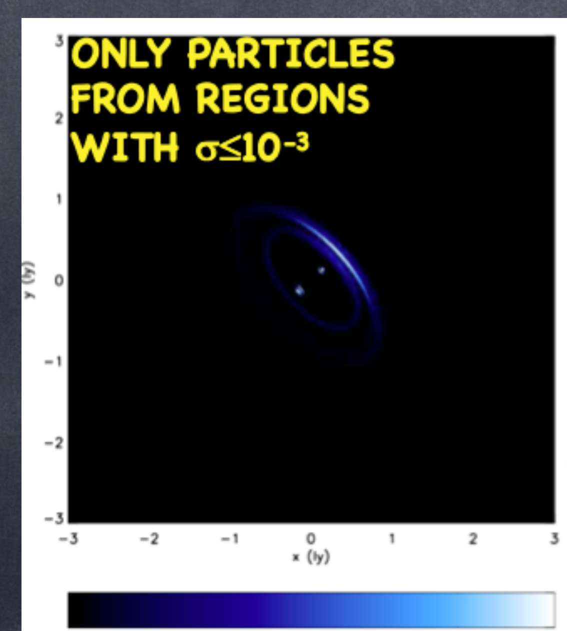
NO PeV ELECTRONS IN CRAB

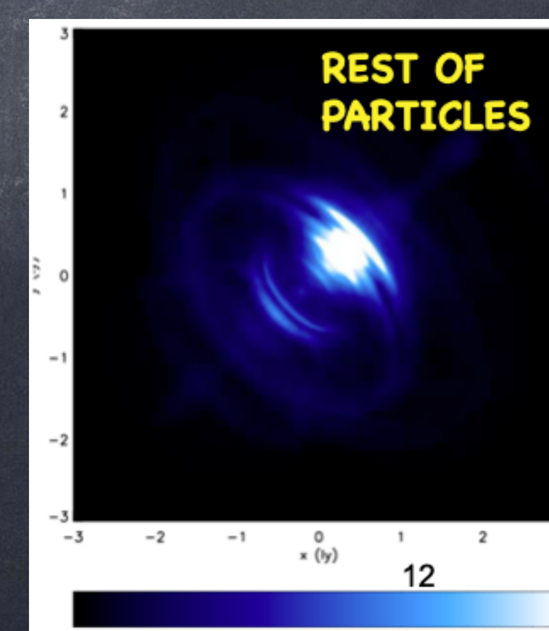
FERMI ACCELERATION (RELATIVISTIC MAGNETIZED PAIRS!)



Sironi, Spitkovsky, Arons 2013

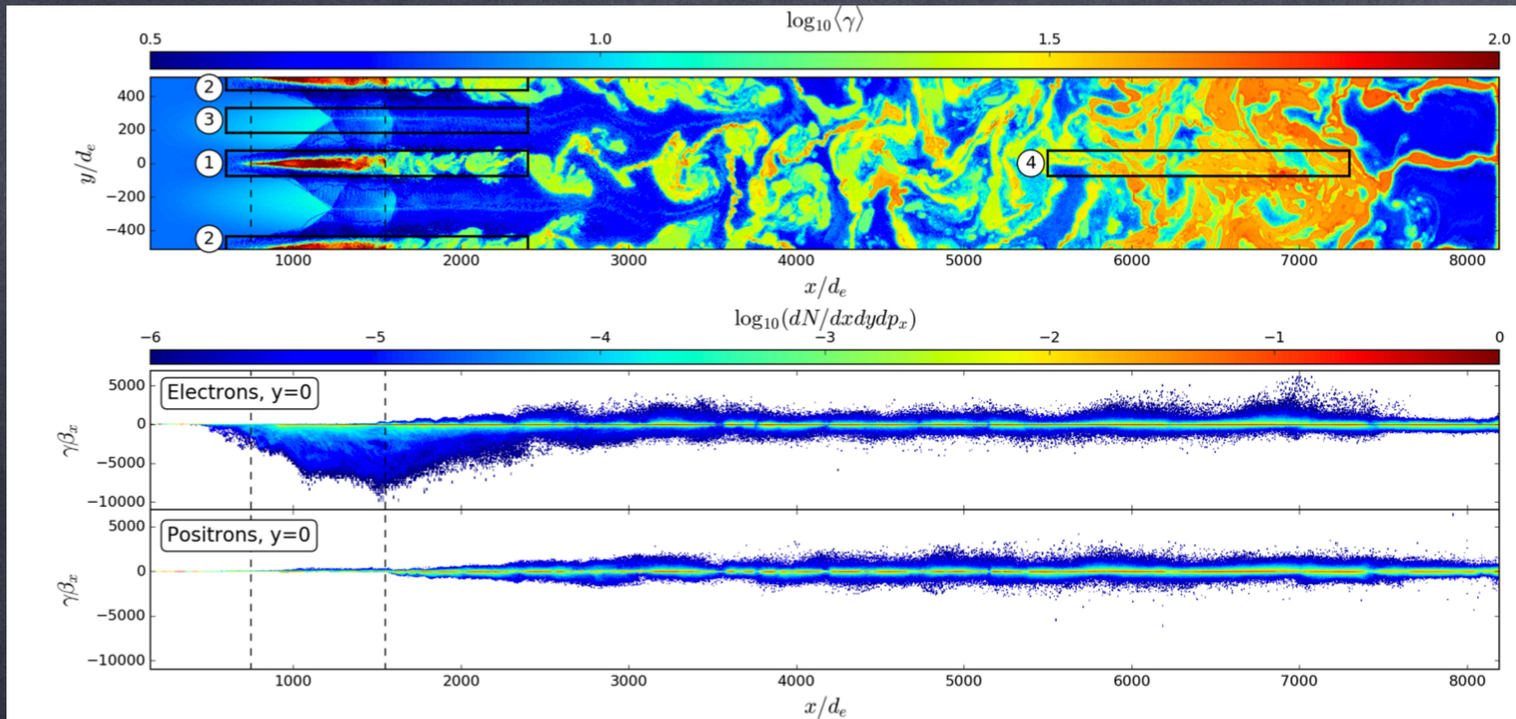
- $E_{\mathrm{MAX}} \approx \sigma^{-1/4}$
- ACCELERATION COMPLETELY SUPPRESSED FOR $\sigma > 10^{-3}$
- $\sigma > 10^{-3}$ LIKELY OVER MOST OF THE SHOCK SURFACE

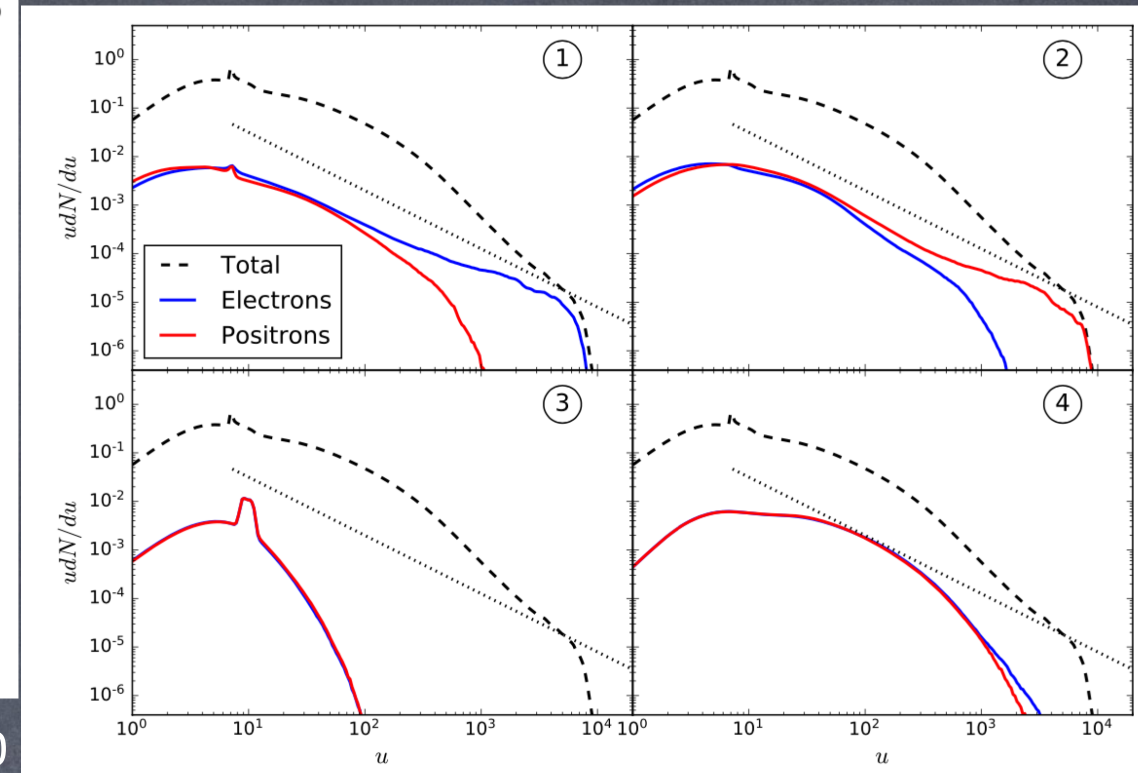




Olmi+ 2015

SHOCK ACCELERATION VARIANTS





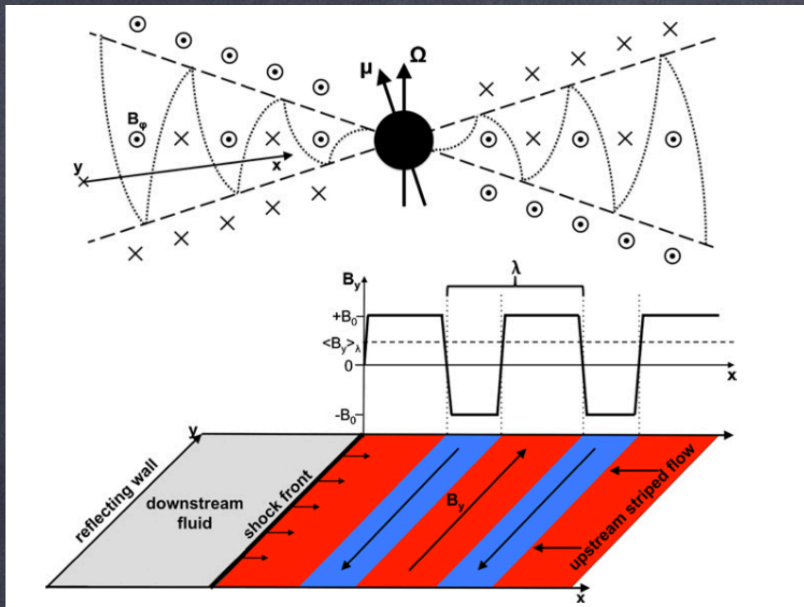
Cerutti & Giacinti 20

TURBULENT SHOCK FRONT

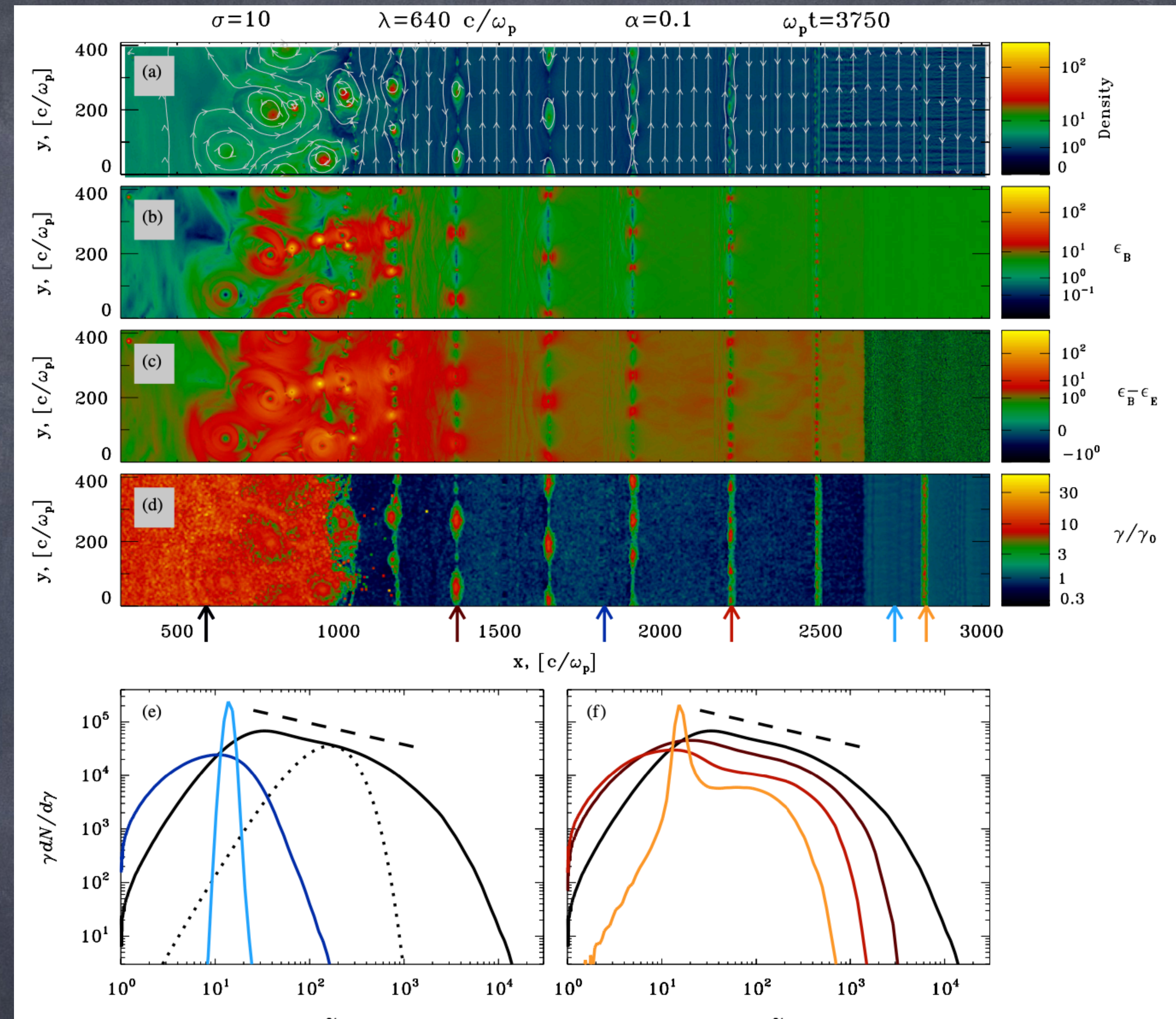
- CORRUGATED SHOCK [Lemoine 17]
- DIFFERENT TURBULENCE LEVELS AT DIFFERENT LATITUDES [Giacinti & Kirk 18]
- POSSIBLY PROVIDED BY ANISOTROPIC B- FIELD [Cerutti & Giacinti 20]
- PRODUCES HARD (STEEP) SPECTRA FOR LOW (HIGH) TURBULENCE LEVEL
- SPECTRUM HARDENS WITH INCREASING MAGNETIZATION
- INTERESTING LATITUDE DEPENDENCE OF SPECTRAL INDEX
- ACCELERATES ONE SIGN OF CHARGES PREFERENTIALLY (focus particles in current sheets)
- SPECTRUM EXTENDS TO $\Gamma\sigma_0 \leq 10^8 \leftrightarrow 100\ TeV$

IN THE END **ALWAYS** NEED HIGH TURBULENCE LEVEL AT THE RIGHT SCALES [Bell's talk]

FORCED MAGNETIC RECONNECTION

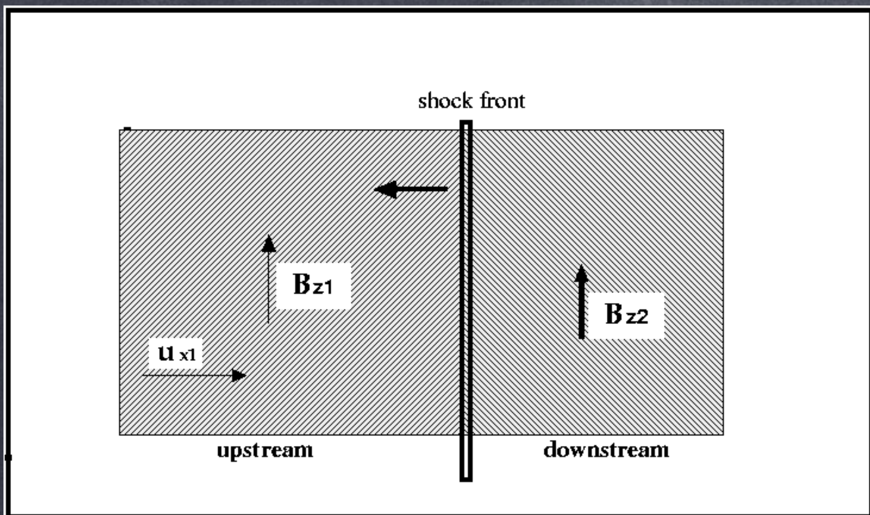


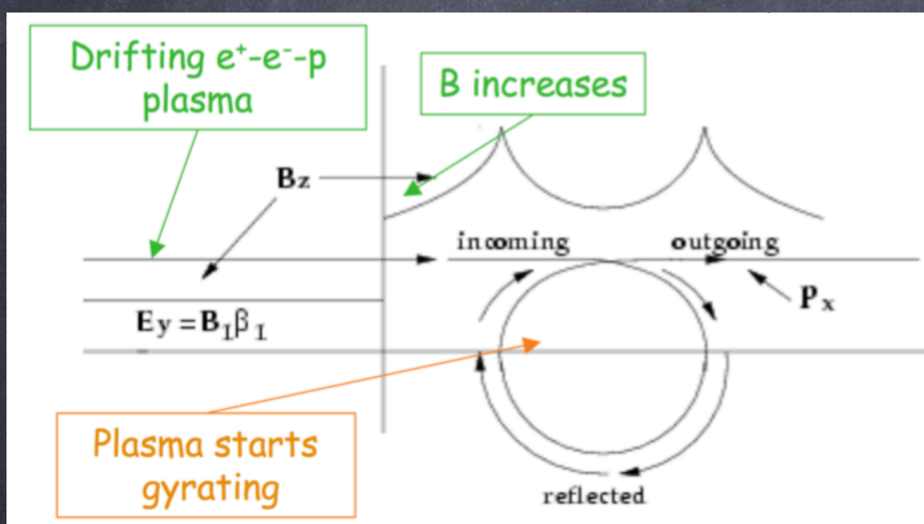
Sironi, Spitkovsky 2011



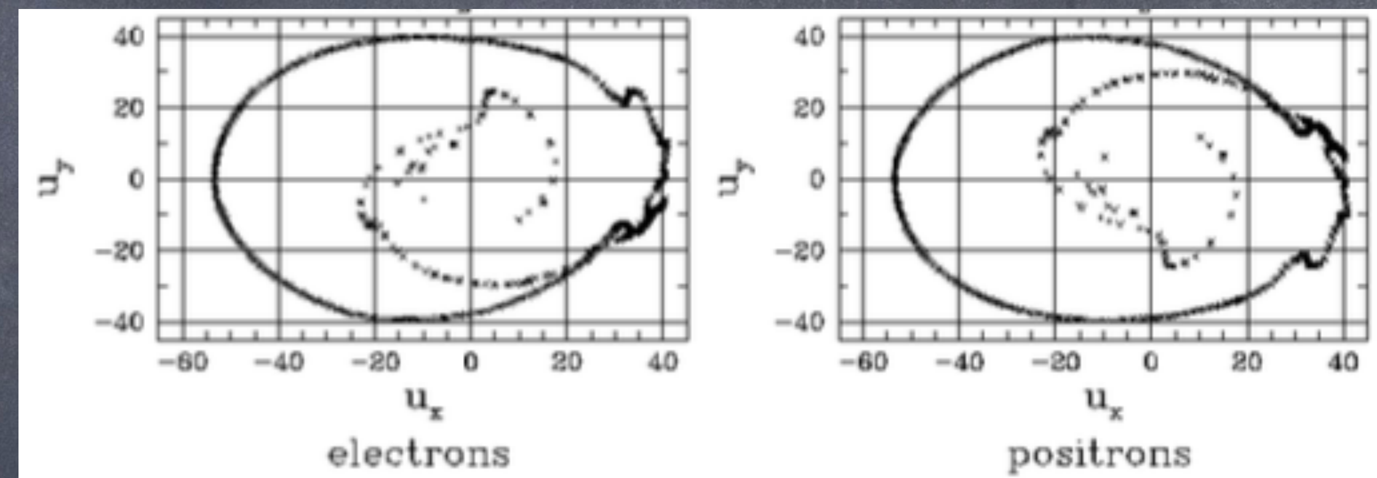
- IN PRINCIPLE VERY FLAT SPECTRA AT LOW ENERGY
- FERMI ACCELERATION IN UNMAGNETIZED PLASMA AFTERWARDS [see also Lu+ 2021]
- RESULTS DEPEND ON σ AND $\frac{\lambda}{r_L \sigma}$
- CRAB SPECTRUM WOULD REQUIRE $\sigma > 30$ AND $\kappa \approx 10^8$ (10^3 MORE THAN CURRENT PSR THEORIES CAN EXPLAIN) [e.g. Timokhin & Harding 19]
- WIND WOULD RECONNECT BEFORE SHOCK [Kirk & Kyubarsky 01]

ION CYCLOTRON ABSORPTION

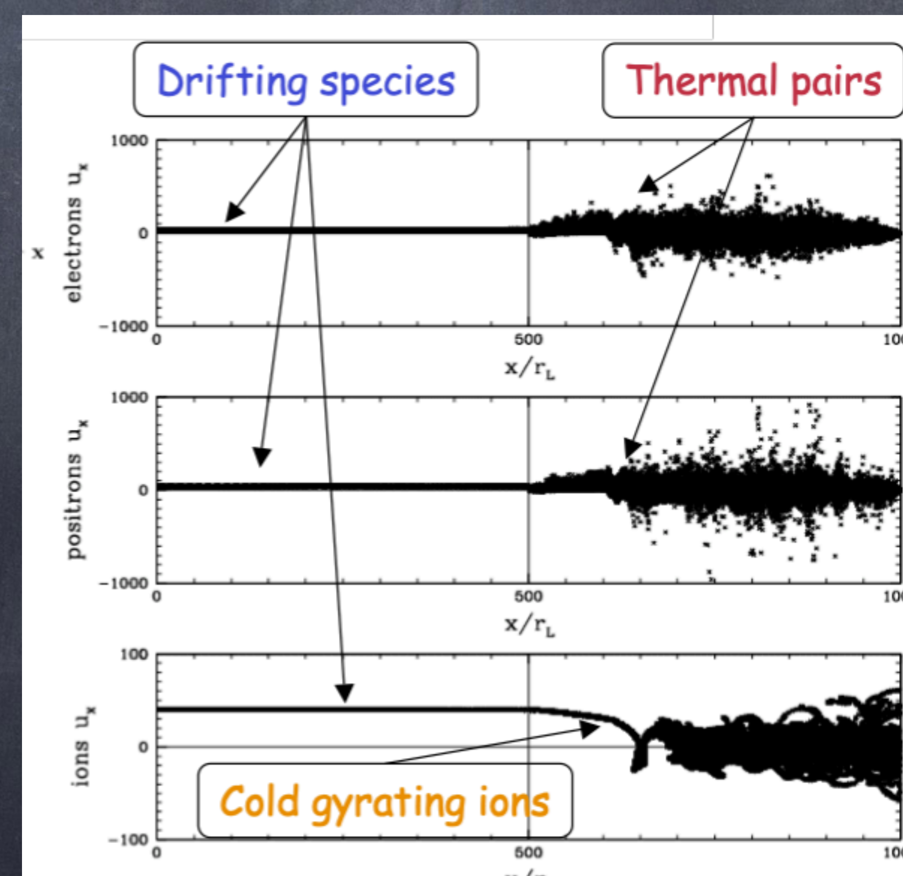




AT THE SHOCK LEADING EDGE
COLD RING IN MOMENTUM SPACE



COHERENT GYRATION LEADS TO
COLLECTIVE EMISSION OF CYCLOTRON WAVES

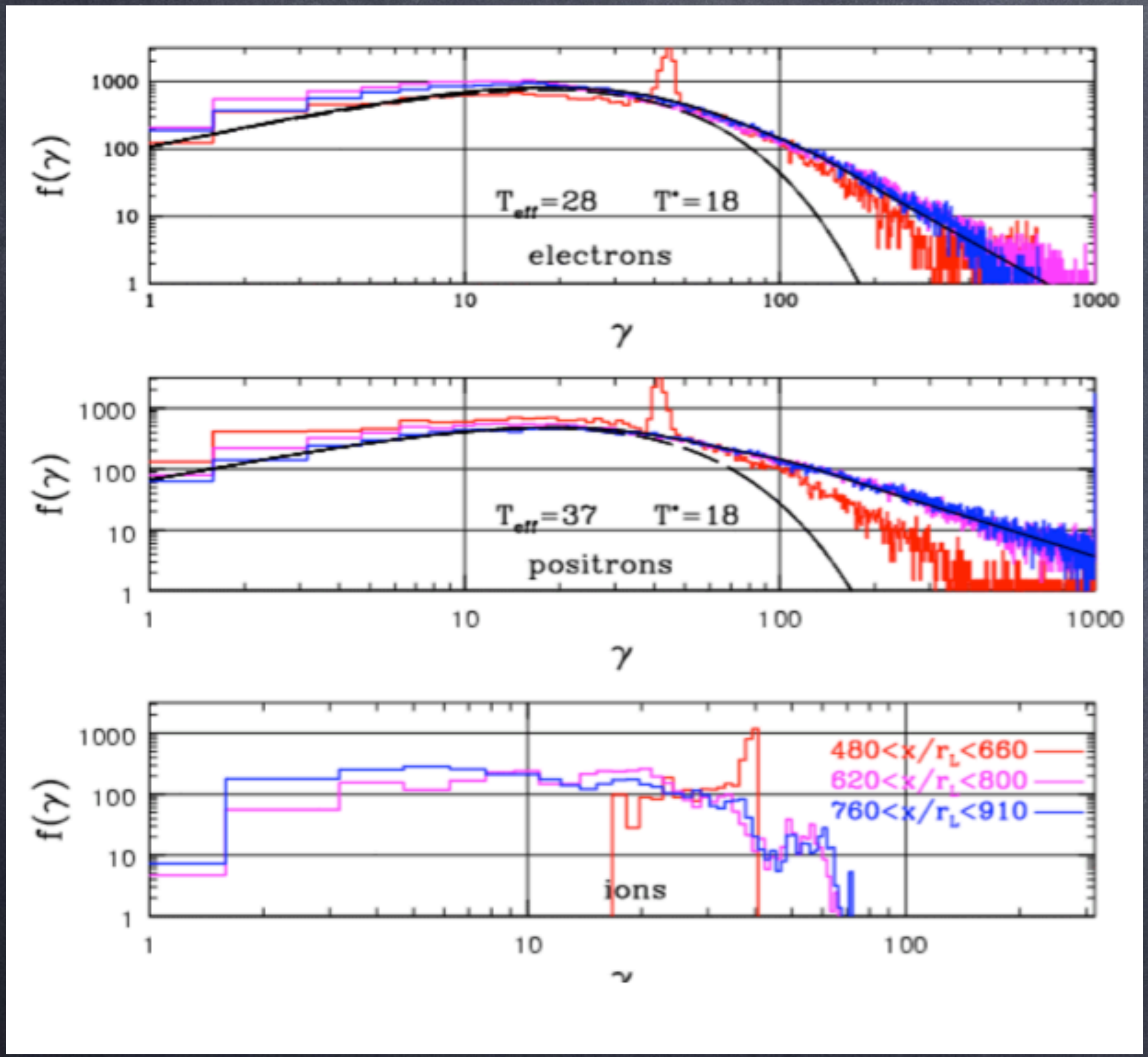


[EA & Arons 2006]

- PAIRS THERMALIZE TO OVER $10 - 100 \times (1/\Omega_{ce})$
- IONS TAKE m_i/m_e TIMES LONGER
- IF PLASMA IS COLD $\delta u/u < m_e/m_i$ ION EMIT VERY HIGH CYCLOTRON HARMONICS
- HARMONIC $n = m_i/m_e$ CAN BE RESONANTLY ABSORBED BY PAIRS

ION CYCLOTRON ACCELERATION AT SHOCK

IF
- ➡ IONS CARRY MOST OF THE ENERGY $\kappa < m_i/m_e$
- ➡ WIND SUFFICIENTLY COLD $\delta u/u < m_e/m_i$



[EA & Arons 2006]

ACCELERATION EFFICIENCY:

$U_i/U_{tot} \sim 60\,\% \Rightarrow \epsilon \sim few\,\%$

$U_i/U_{tot} \sim 80\,\% \Rightarrow \epsilon \sim 30\,\%$

SPECTRAL SLOPE:

$U_i/U_{tot} \sim 60\,\% \Rightarrow s > 3$

$U_i/U_{tot} \sim 80\,\% \Rightarrow s < 2$

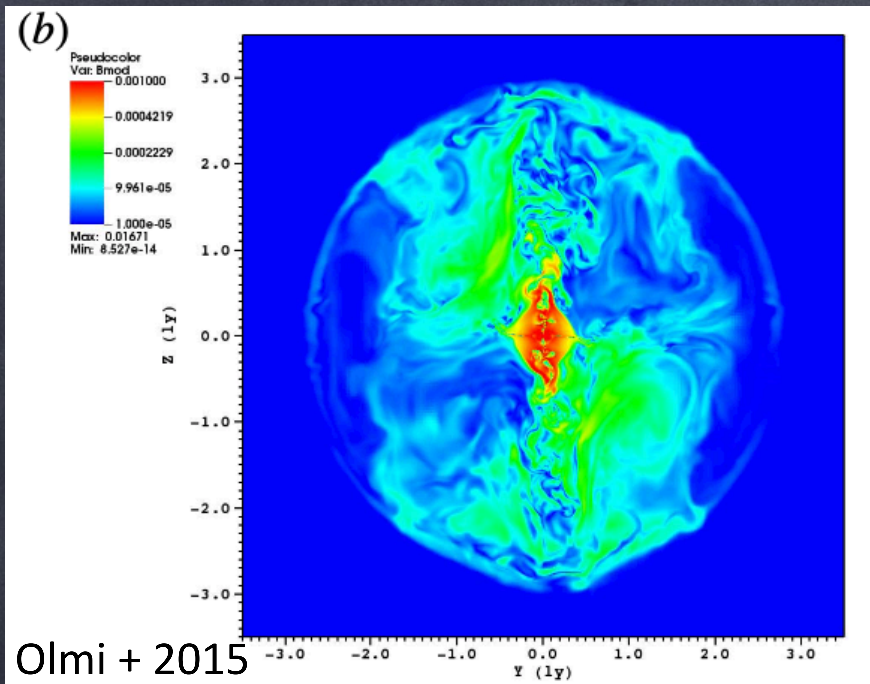
MAXIMUM ENERGY:

$U_i/U_{tot} \sim 60\,\% \Rightarrow E_{max} \sim 20\,\%\, m_i c^2 \Gamma$

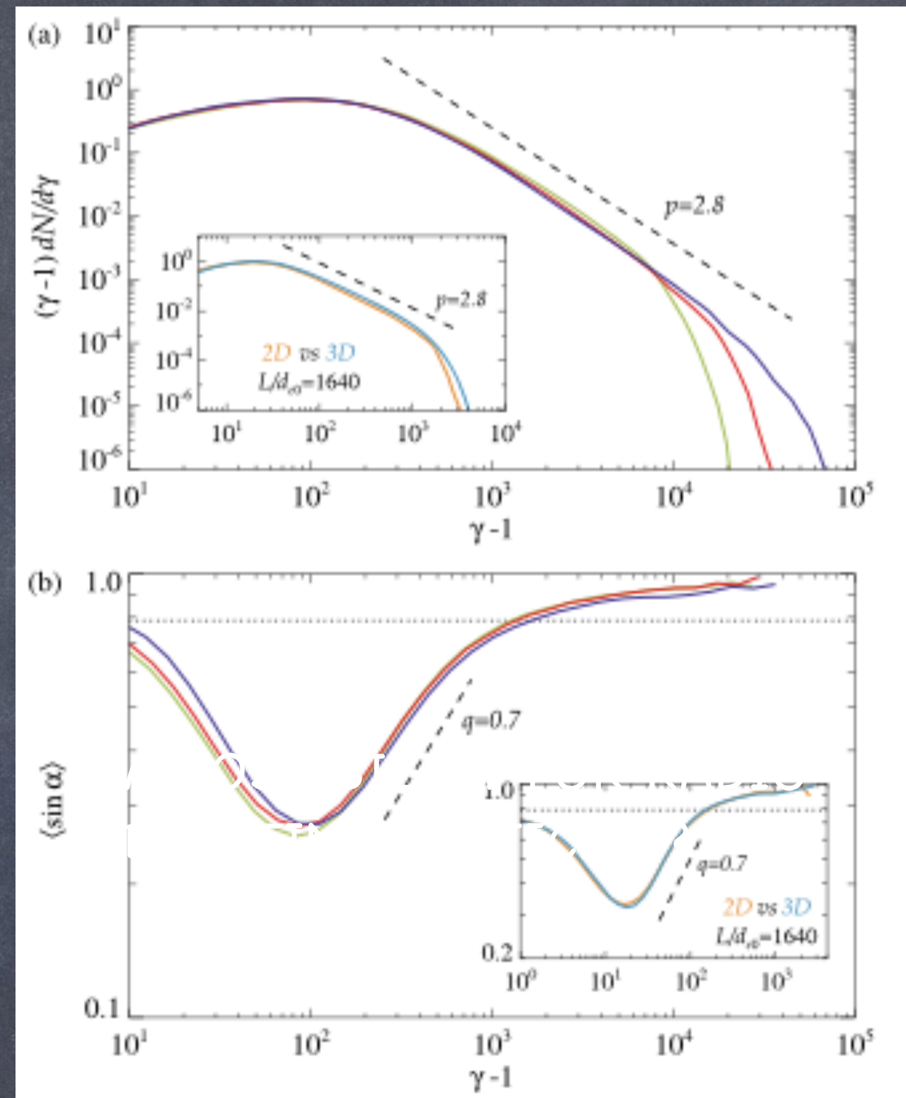
$U_i/U_{tot} \sim 80\,\% \Rightarrow E_{max} \sim 80\,\%\, m_i c^2 \Gamma$

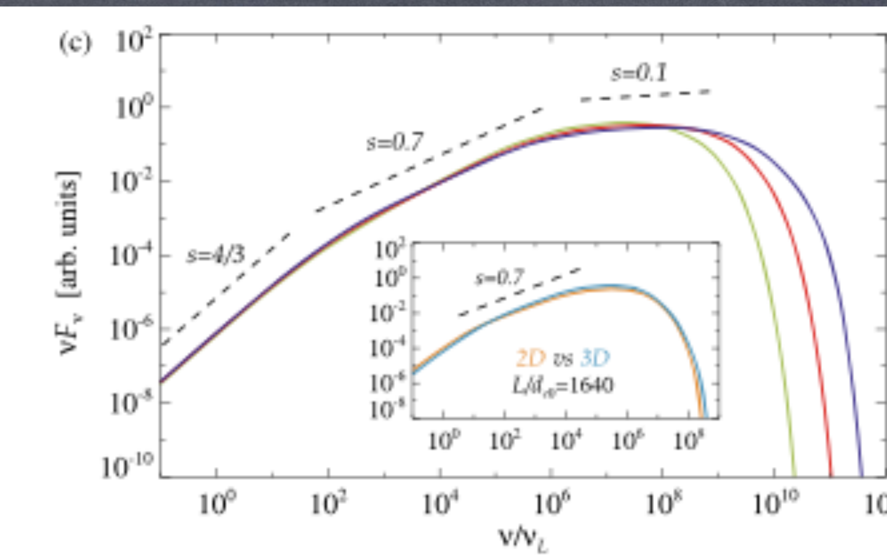
IF $\kappa \leq 10^4$ AND IONS THERE
PROCESS COULD ENSURE PeV PAIRS IN CRAB

ACCELERATION IN TURBULENCE



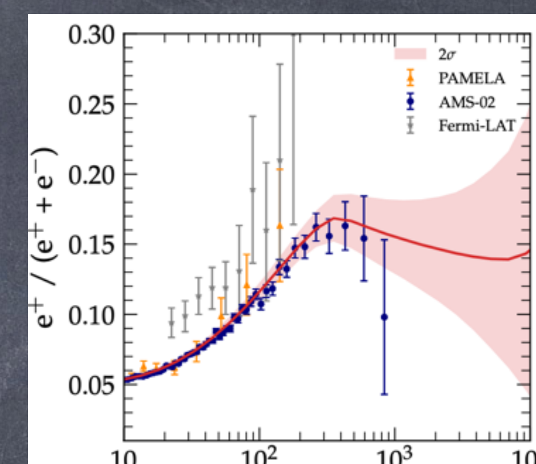
Olmi + 2015





Comisso, Sobacchi, Sironi 20

A POSSIBILITY FOR RADIO EMITTING PARTICLES?
[Olmi + 2014]



Evoli + 2021

- ➡SPECTRA TYPICALLY STEEP $s \sim -3$
- ➡LARGE ANISOTROPY AT LOW ENERGY
- ➡EVEN MORE RADIO EMITTING ELECTRONS REQUIRED? STILL HIGH MULTIPLICITY?
- ➡RESULT OF ANISOTROPY IS TO MIMIC FLAT SYNCHROTRON SPECTRUM AT LOW ENERGY

➡CONSEQUENCES ON COSMIC LEPTONS: BREAK IS ESSENTIAL [e.g. Evoli + 2021]

GROWING INTEREST AND MUCH ONGOING WORK
[Zhdankin+ 2018, 2020; Lemoine & Malkov 2020; Lemoine 2021; Comisso+ 2020, 2021, 2022; Bresci+ 2022]

LHAASO RESULTS

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)
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)

PeV PROTONS OR ELECTRONS?

ALL SOURCES BUT ONE HAVE A PSR IN THE FIELD

PSRs ARE THE ONLY POTENTIAL SOURCES OF PeV LEPTONS IN THE GALAXY

BUT...

MAXIMUM ENERGY IN A PWN

STRICT LIMIT FROM THE PSR POTENTIAL DROP

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

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

$$\frac{B_{TS}^2}{8\pi} = \xi_B \frac{\dot{E}}{4\pi R_{TS}^2 c}$$

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

APPLIES TO ALL SPECIES!

NO MATTER THE PROCESS!

$$E_{max,Crab} \approx 30\ \mathrm{PeV}$$

IN YOUNG ENERGETIC SYSTEMS ACCELERATION LIKELY LOSS LIMITED

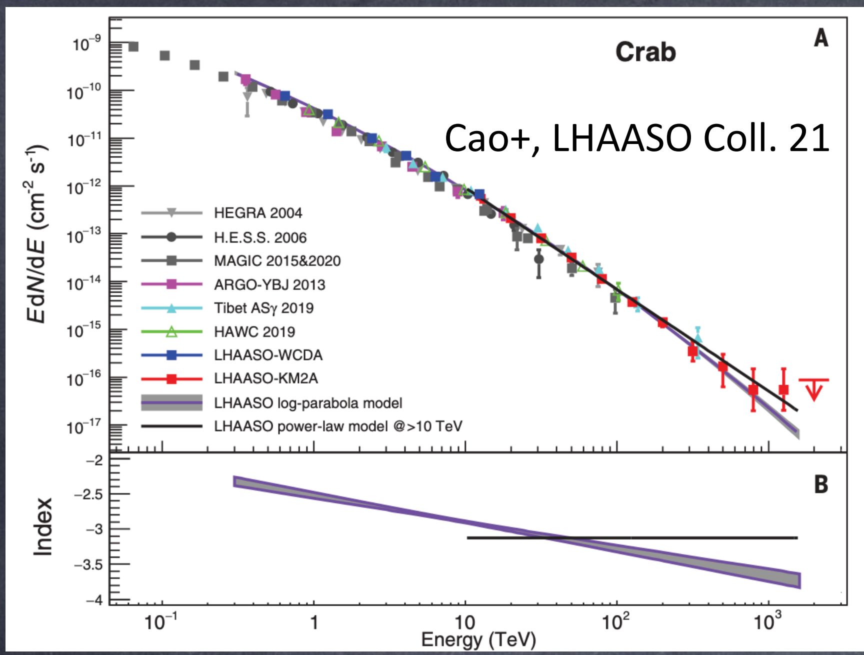
$$t_{acc} = \frac{E}{e\xi_E Bc} < t_{loss} = \frac{6\pi(mc^2)^2}{\sigma_T c B^2 E}$$

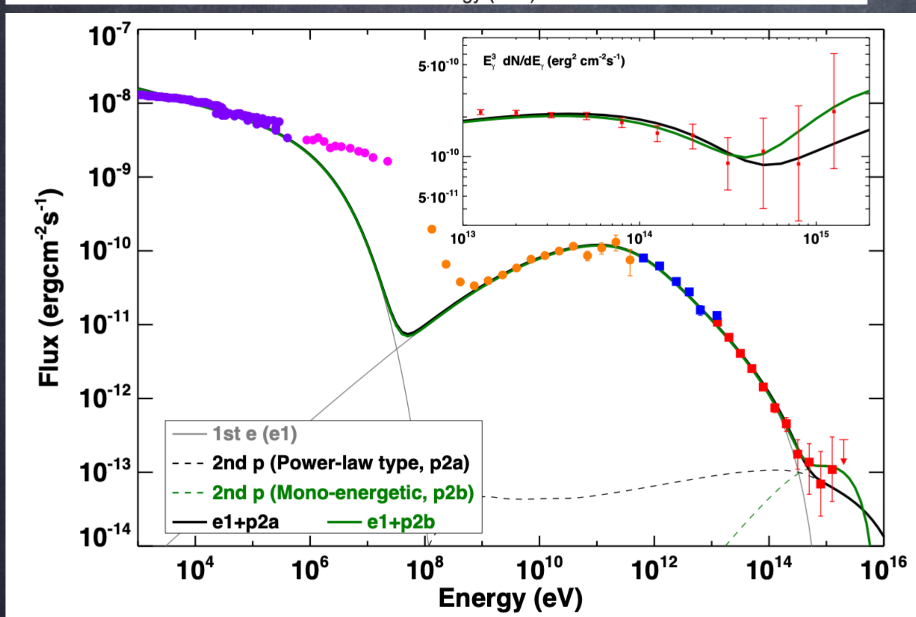
$$E_{max} \approx 6\ PeV\ \xi_E^{1/2}\ B_{-4}^{-1/2}$$

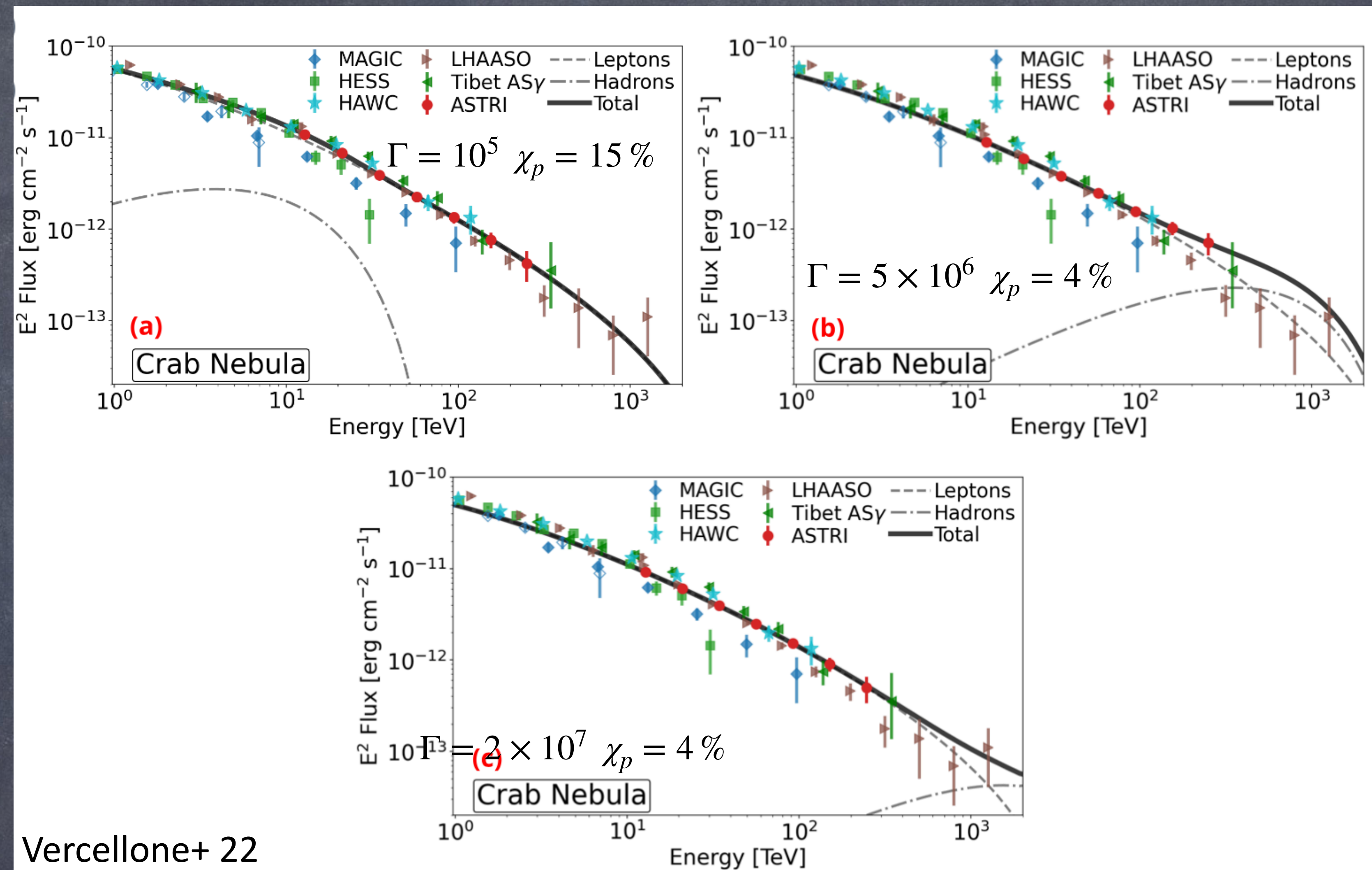
NOTICE: $E_{max}^{PSR} = \frac{c}{v_S} E_{max}^{NRS}$

EVEN FOR MAXIMALLY EFFICIENT (BOHM REGIME) SHOCK ACCELERATION

PEV GAMMA-RAYS FROM CRAB?







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

- E_{max} LARGE ENOUGH!
- PEV ELECTRONS SEEN IN FLARES BUT 10^{-2} THAN NEEDED HERE

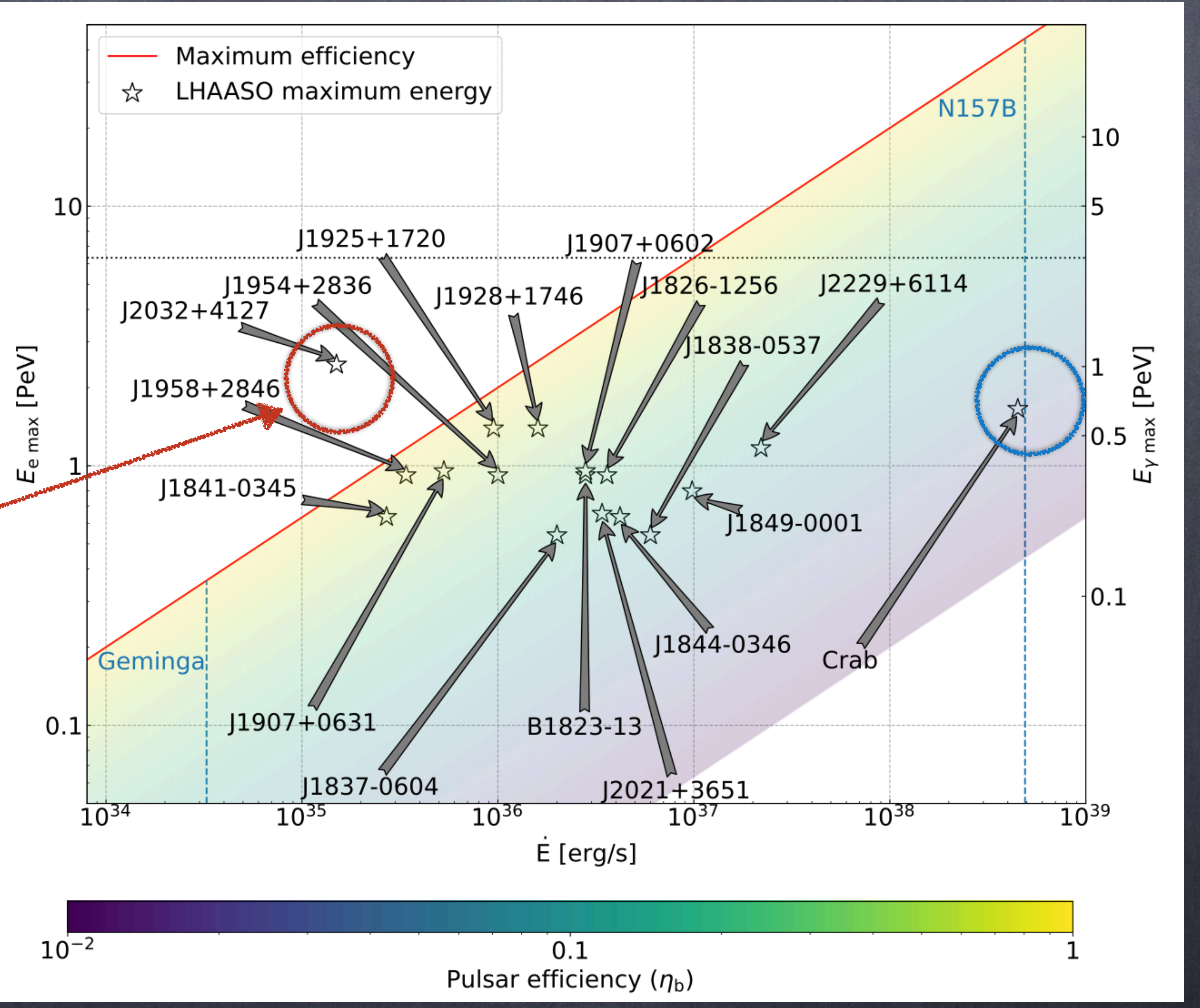
TAKE INTO ACCOUNT EVOLUTION, ALL SED, DIFFERENT MODELS FOR ESCAPE

[Fiori, EA + in prep.; see Olmi's talk]

LHAASO PEVATRONS AND PWNe

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

CYGNUS



de Ona Wilhelmi + 2022

SUMMARY AND CONCLUSIONS

- MECHANISM(S) RESPONSIBLE FOR PARTICLE ACCELERATION IN PWNe STILL NOT KNOWN BUT INCREASINGLY WELL CONSTRAINED FROM DIFFERENT SIDES

- VHE AND UHE GAMMA-RAY OBSERVATIONS PROVIDE NEW POWERFUL PROBE:
  - TEST MAXIMUM ENERGY
  - POTENTIAL TO CONSTRAIN THE PRESENCE OF IONS IN PULSAR WINDS

- WHATEVER THE MECHANISM: THE POLAR CAP POTENTIAL DROP OFFERS AN ABSOLUTE LIMIT FOR THE MAXIMUM ENERGY
  - USEFUL TOOL, IN THE WAIT FOR ASTRI AND CTA, TO POSSIBLY EXCLUDE LEPTONIC NATURE OF LHAASO PEVATRONS

- NEW QUESTION: PWNE AS HADRONIC PEVATRONS?