

PULSAR WIND NEBULAE AS COSMIC ACCELERATORS

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WHY PWNe ARE INTERESTING

➤ **PULSAR PHYSICS:** THEY ENCLOSE MOST OF THE PULSAR SPIN-DOWN ENERGY ($L_{radio} \leq 10^{-10} E_R$, $L_\gamma \leq 10^{-2} E_R$, $L_{PWN} \geq 0.1 E_R$)

➤ **CLOSE AND BRIGHT:** BEST-SUITED LABORATORIES FOR THE PHYSICS OF RELATIVISTIC ASTROPHYSICAL PLASMAS

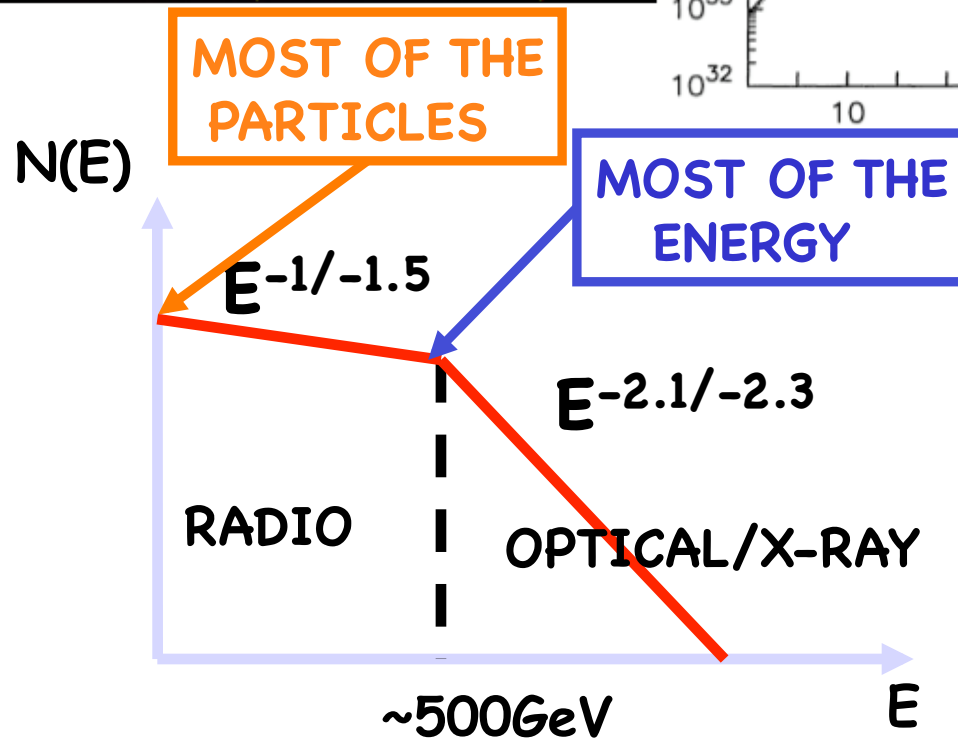
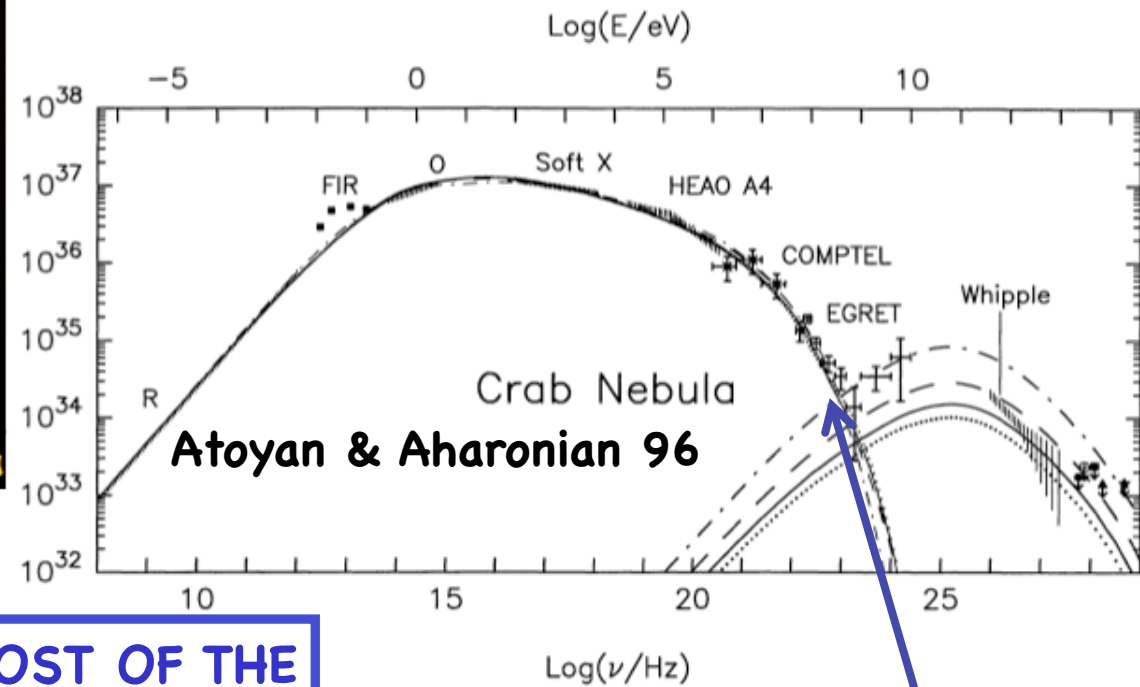
AS PARTICLE ACCELERATORS

➤ **PARTICLE ACCELERATION** AT THE HIGHEST SPEED SHOCKS IN NATURE ($10^4 < \Gamma < 10^7$)

➤ **COSMIC RAYS:** ONLY SOURCES SHOWING DIRECT EVIDENCE FOR PEV PARTICLES

➤ **ANTIMATTER STORAGE ROOMS:** AS MANY POSITRONS AS ELECTRONS (PAMELA AND AMS02 EXCESS?)

PARTICLES IN PWNe

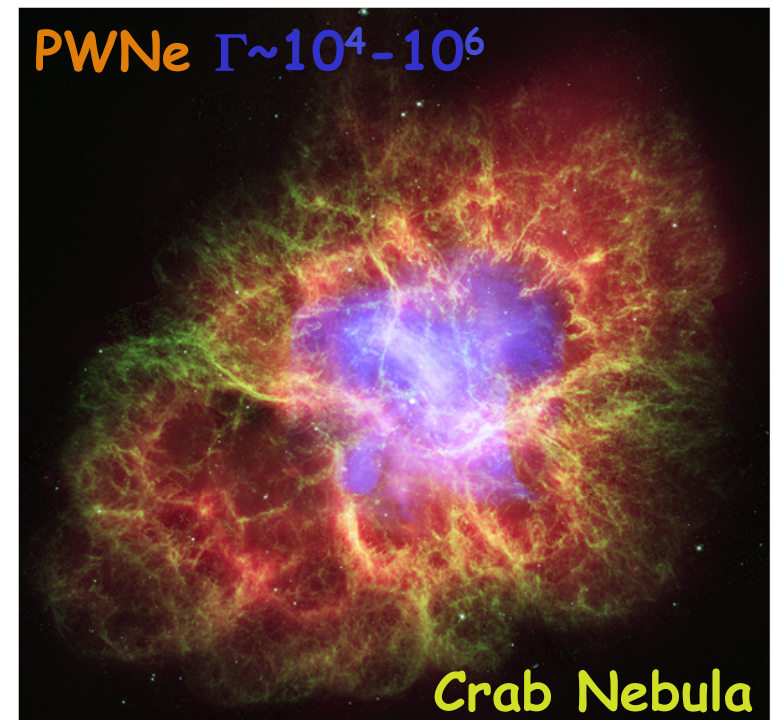
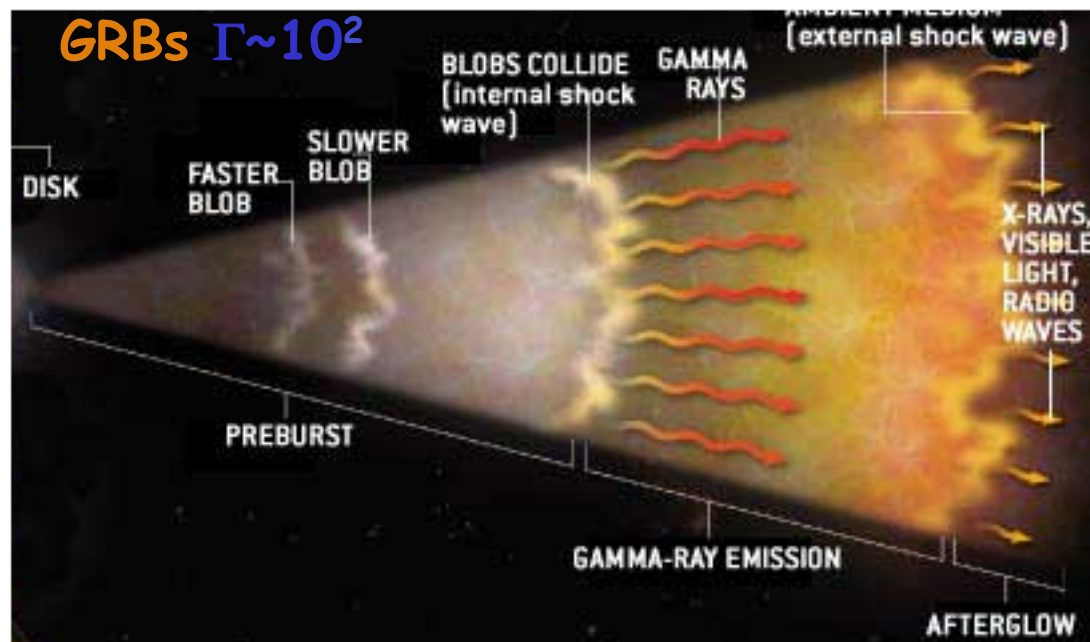
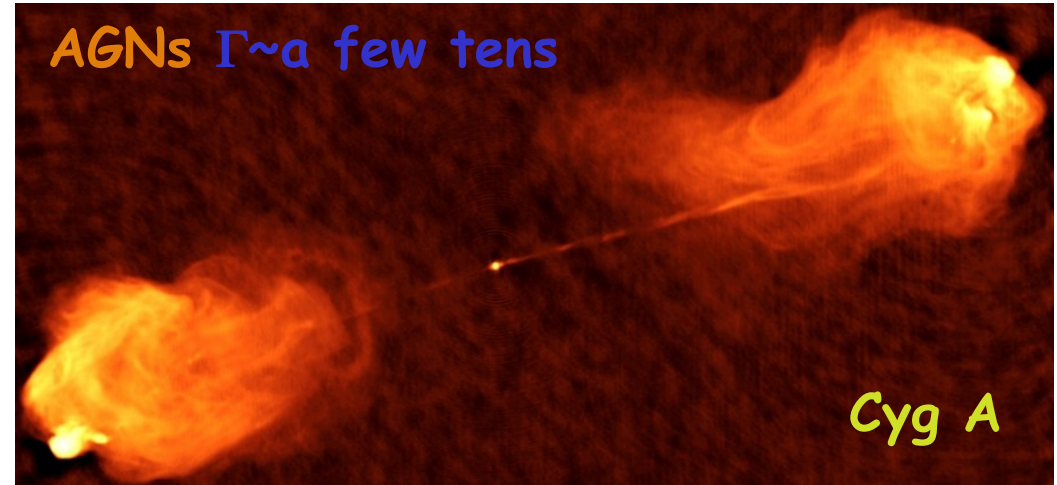
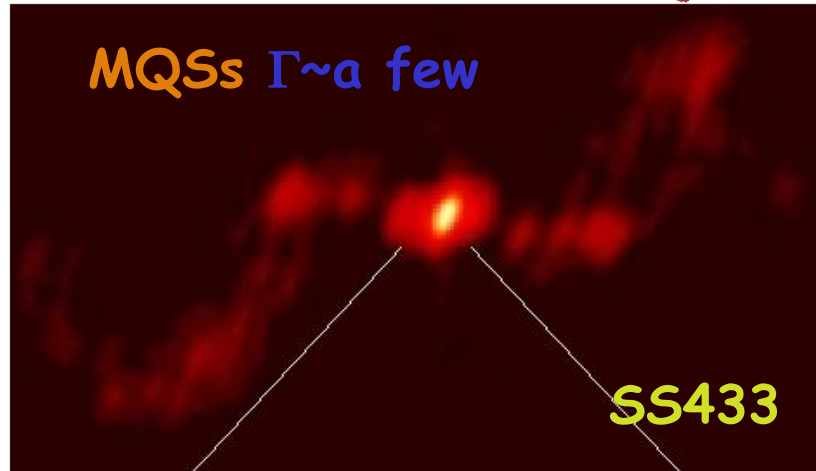


PeV ELECTRONS

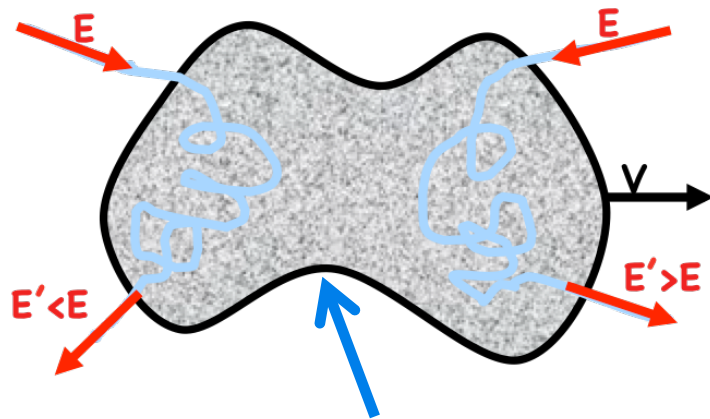
$B \approx 100 \mu\text{G}$

$L_{\text{PWN}} \approx 30\% L_{\text{PSR}}$

RELATIVISTIC SHOCKS IN ASTROPHYSICS

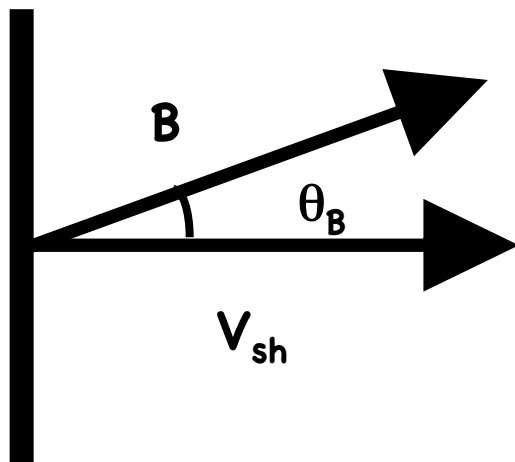
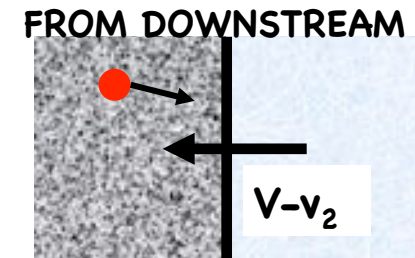
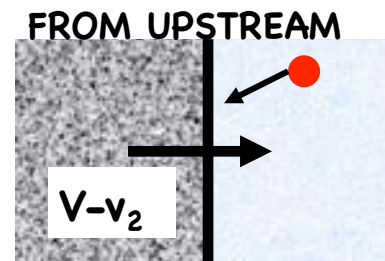
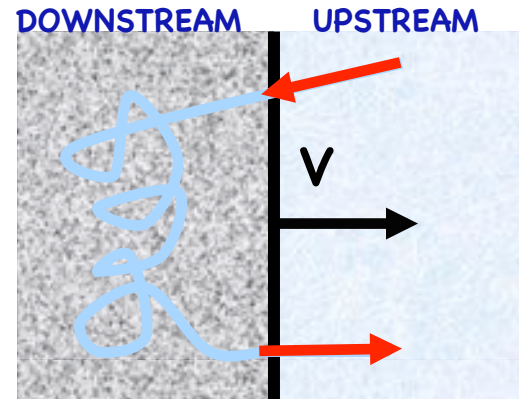


HOW ABOUT FERMI?



ENERGY GAIN $\Delta E/E \approx (V/c)^2$

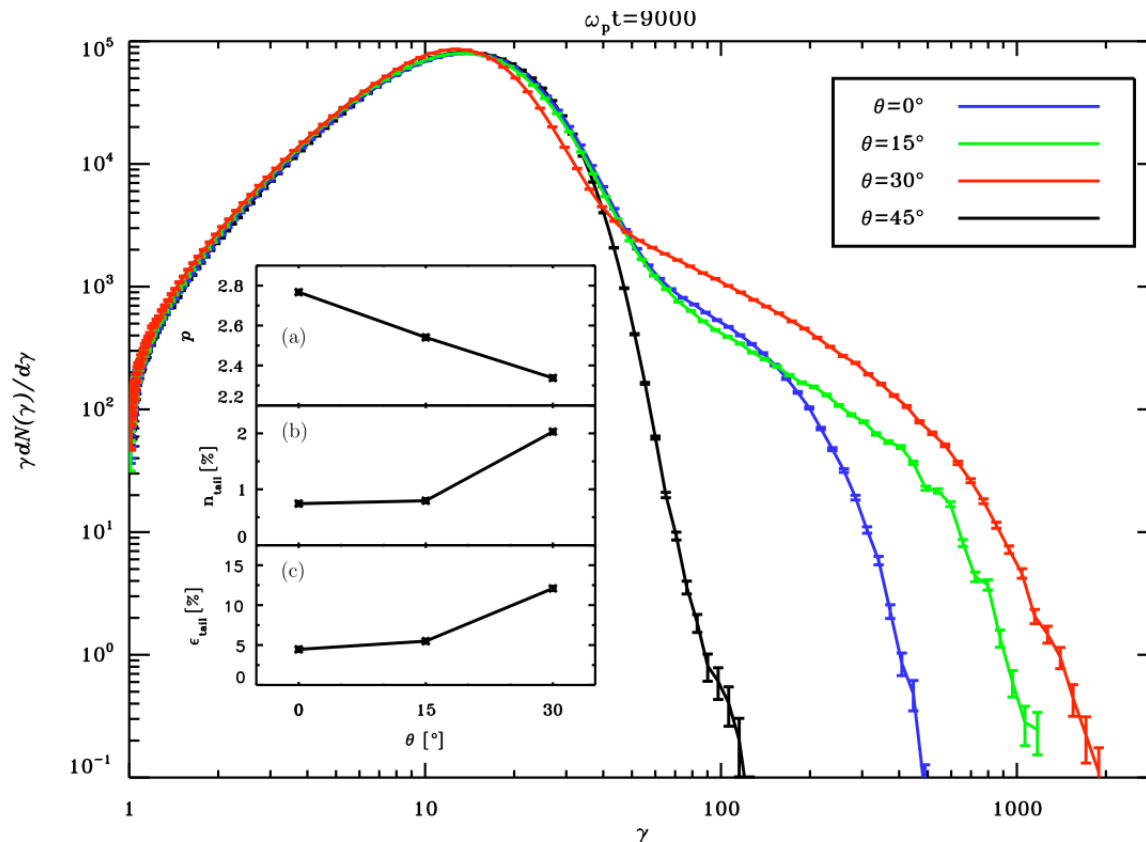
ENERGY GAIN $\Delta E/E \approx (V/c)$



- PARTICLES CAN ONLY GO BACK TO SHOCK IF $c \cos \theta > v_{sh}$
- IF B IS HIGH, PARTICLES ARE FORCED TO MOVE ALONG FIELD LINES
- THEY WILL NOT GO BACK TO THE SHOCK FROM DOWNSTREAM UNLESS $\theta_B < 1/\gamma_{sh}$

FERMI PROCESS IN PWNe?

- RIGHT SLOPE FOR OPTICAL/X-RAY PARTICLES
- VIABILITY DEPENDS ON PLASMA MAGNETIZATION



**RESULTS FROM PIC
SIMULATIONS BY**
Spitkovsky 08,
Sironi & Spitkovsky 09, 11

**EFFICIENT ACCELERATION AT UNMAGNETIZED e^-e^+
RELATIVISTIC SHOCKS**
NO ACCELERATION AT ($\sigma > 0.001$) SUPERLUMINAL SHOCKS

PROPOSED ACCELERATION MECHANISMS

FERMI MECHANISM:

- RIGHT SLOPE FOR OPTICAL/X-RAY PARTICLES
- VIABILITY DEPENDS ON PLASMA MAGNETIZATION
(Spitkovsky 08, Sironi & Spitkovsky 11,12)

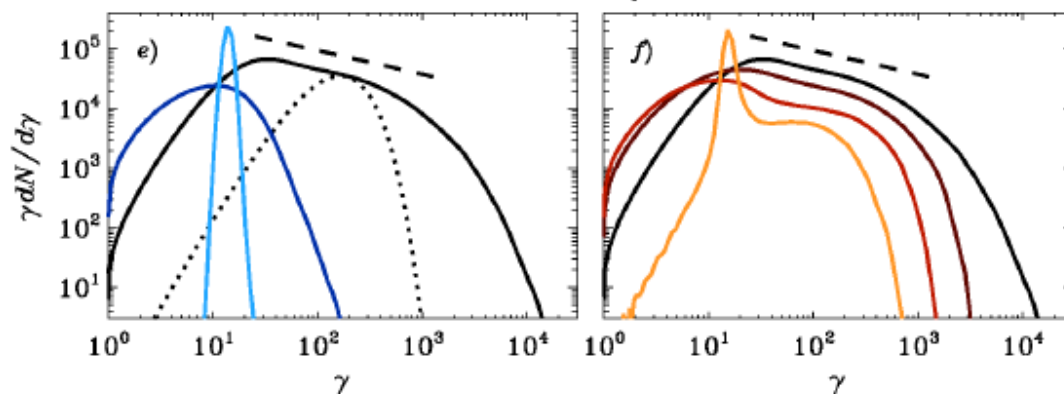
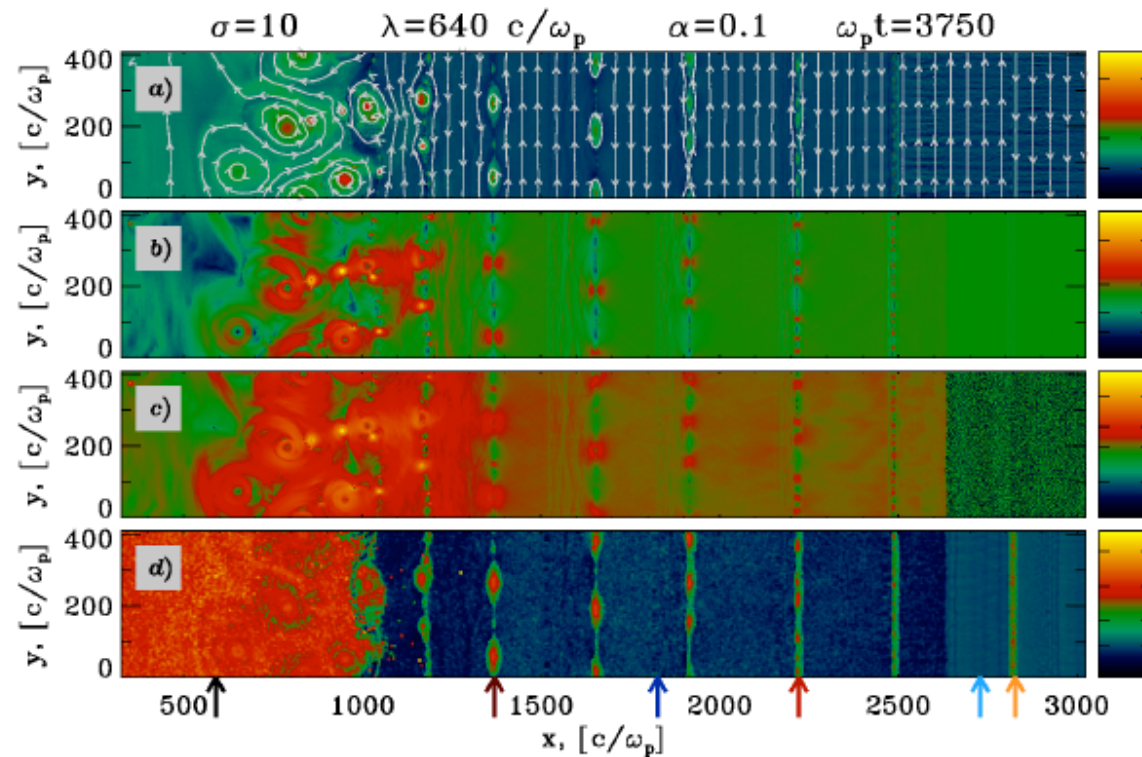
RESONANT CYCLOTRON ABSORPTION IN ION DOPED OUTFLOW:

- MAGNETIZATION IS NOT VERY IMPORTANT
 - REQUIRES IONS DOMINANCE
- PARTICLE SPECTRUM AND EFFICIENCY DEPEND ON FRACTION OF ENERGY CARRIED BY IONS (Hoshino et al 92, Amato & Arons 06, Stockem et al 12)

DRIVEN MAGNETIC RECONNECTION:

- CORRECT SLOPE FOR RADIO PARTICLES
 - REQUIRES EXTREMELY LARGE MULTIPLICITY
 - DIFFICULT TO MAKE SELF-CONSISTENT
- (Lyubarsky 03, Lyubarsky & Liverts 08, Sironi & Spitkovsky 11)

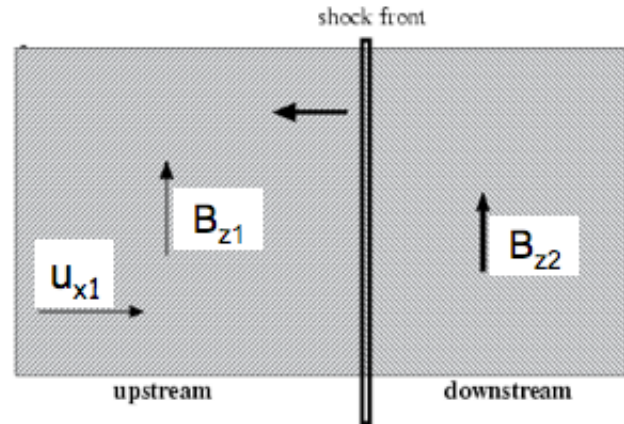
DRIVEN MAGNETIC RECONNECTION



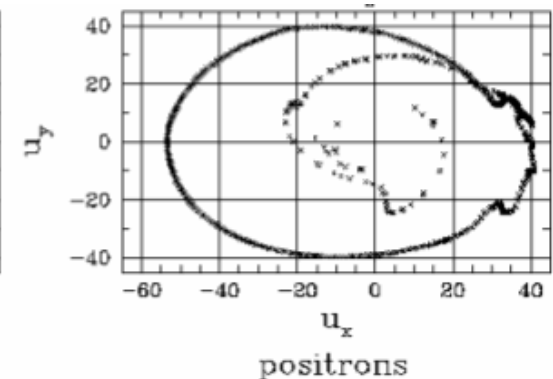
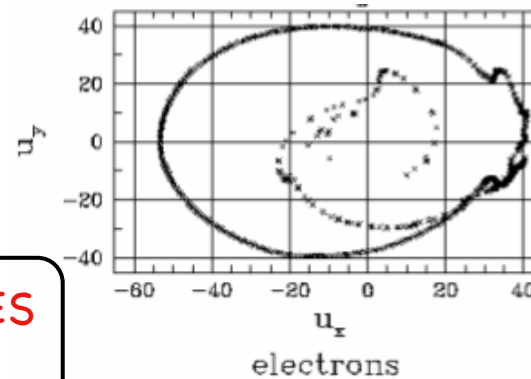
(Sironi & Spitkovsky 11)

VERY DIFFICULT
TO MAKE
SELF-CONSISTENT

RESONANT CYCLOTRON ABSORPTION IN ION DOPED PLASMA



Configuration at the leading edge
~ cold ring in momentum space



MAGNETIC REFLECTION MEDIATES
THE TRANSITION

DRIPTING e^+-e^- -p
PLASMA

B INCREASES

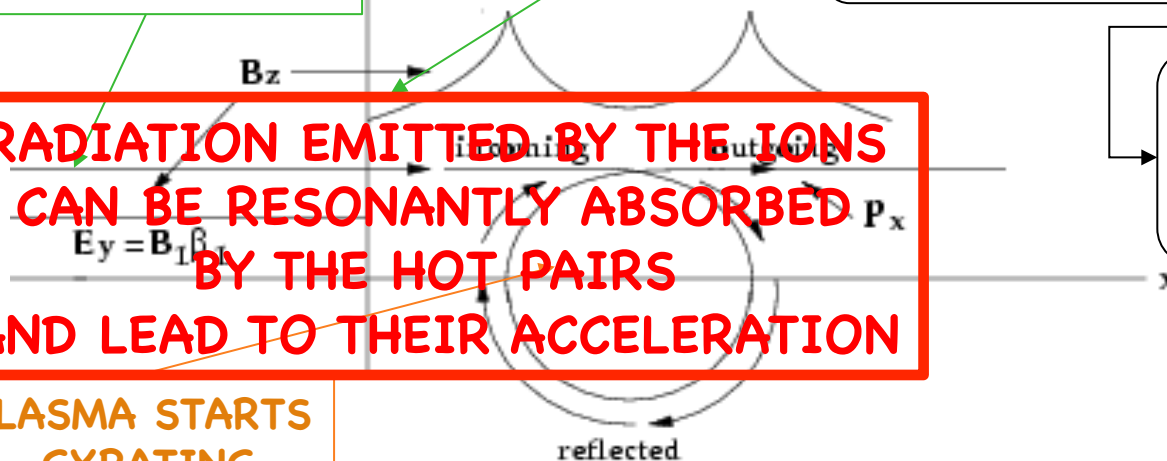
Coherent gyration leads to
collective emission of cyclotron waves

RADIATION EMITTED BY THE IONS
CAN BE RESONANTLY ABSORBED
BY THE HOT PAIRS
AND LEAD TO THEIR ACCELERATION

PLASMA STARTS
GYRATING

Pairs thermalize to
 $kT \sim m_e \Gamma c^2$ over
 $10-100 \times (1/\Omega_{ce})$

Ions take their time:
 m_i/m_e times longer

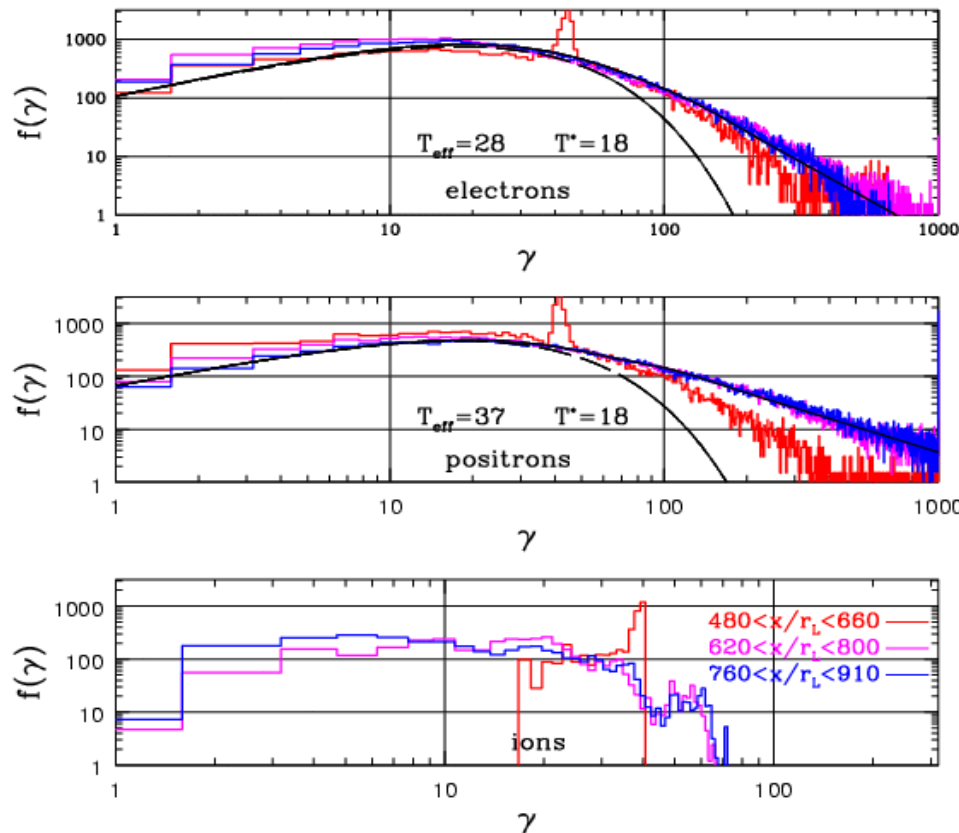


PARTICLE SPECTRA AND ACCELERATION EFFICIENCY

IF

• IONS CARRY MOST OF THE ENERGY: $\kappa < m_i/m_e$

• WIND SUFFICIENTLY COLD: $\delta u/u < m_e/m_i$



ACCELERATION EFFICIENCY:

~few% for $U_i/U_{\text{tot}} \sim 60\%$

~30% for $U_i/U_{\text{tot}} \sim 80\%$

SPECTRAL SLOPE:

>3 for $U_i/U_{\text{tot}} \sim 60\%$

<2 for $U_i/U_{\text{tot}} \sim 80\%$

MAXIMUM ENERGY:

~20% $m_i c^2 \Gamma$ for $U_i/U_{\text{tot}} \sim 60\%$

~80% $m_i c^2 \Gamma$ for $U_i/U_{\text{tot}} \sim 80\%$

RESULTS BY Amato & Arons 06
 MORE RECENTLY CONFIRMED BY Stockem et al 12

ACCELERATION MECHANISMS

FERMI MECHANISM

MAGNETIZATION

DRIVEN MAGNETIC RECONNECTION

PULSAR MULTIPLICITY

RESONANT CYCLOTRON ABSORPTION

PRESENCE OF IONS AND PULSAR MULTIPLICITY

$$\dot{E}_R = \kappa \dot{N}_{GJ} m_{\pm} c^2 \Gamma_{wind} \left(1 + \frac{\xi n_i}{\kappa m_{\pm}} \right) (1 + \sigma)$$

$\kappa = \frac{\dot{N}}{\dot{N}_{GJ}}$

MULTIPLICITY

PAIRS

IONS

MAGNETIZATION

$$\sigma = \frac{B^2}{4 \pi m_{eff} n_{eff} c^2 \Gamma_{wind}^2}$$

PULSAR WIND MAGNETIZATION

THE EXISTENCE OF A JET TORUS STRUCTURE IMPLIES $\sigma > 0.01$

(Del Zanna, Amato, Bucciantini 04, Porth et al 13, see Niccolo's talk)

ION CONTENT

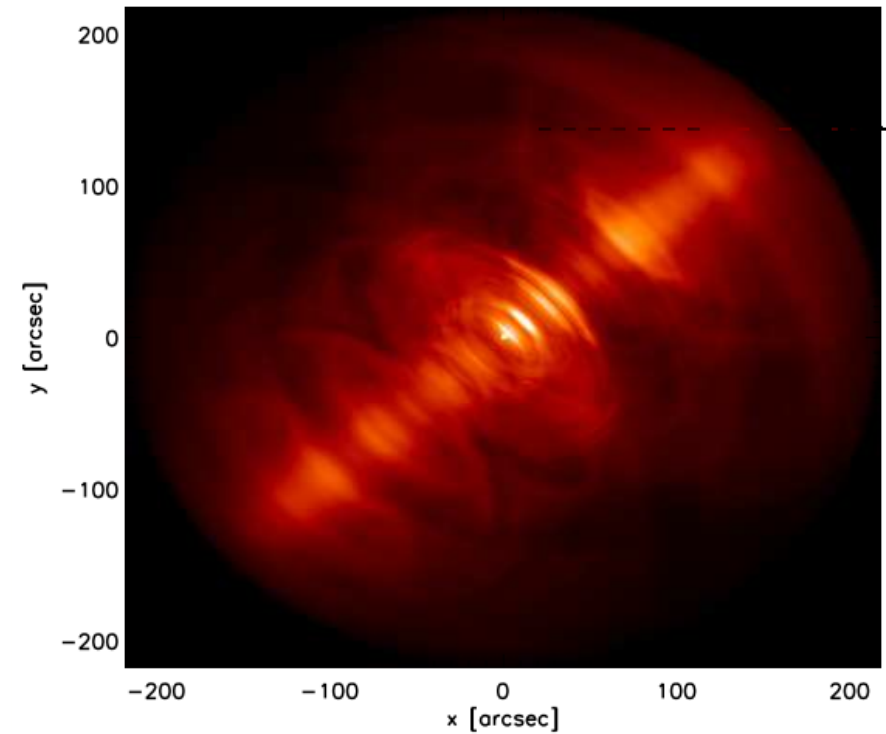
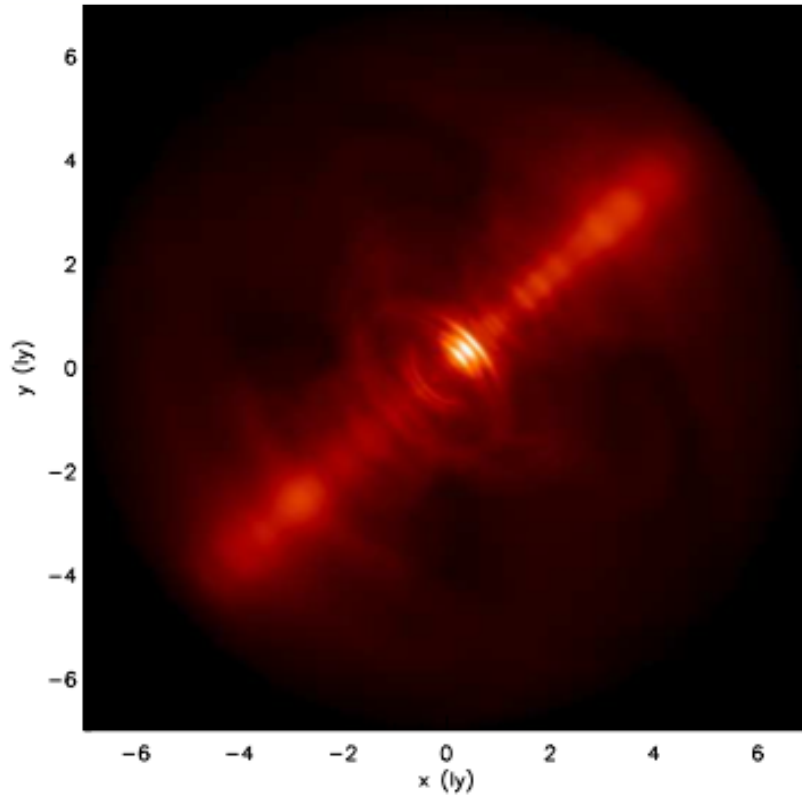
THE ONLY WAY TO PROVE FOR SURE THE PRESENCE OF VERY HIGH ENERGY IONS, ALSO INVOKED BY MODELS OF UHECRs (e.g. Kotera, Amato, Blasi 15), WOULD BE NEUTRINO DETECTION, BUT UNCERTAINTIES ON THE TARGET DENSITY AND DISTRIBUTION MAKE RELIABLE CALCULATIONS DIFFICULT (e.g. Amato, Guetta, Blasi 03)

AND MULTIPLICITY

IF RADIO PARTICLES PART OF THE PULSAR OUTFLOW: $\kappa \approx \text{few} \times 10^6$
NO ION DOMINANCE, MAYBE EFFICIENT RECONNECTION

IF ONLY OPTICAL/X-RAY PARTICLES PART OF THE FLOW: $\kappa \approx \text{few} \times 10^4$
NO RECONNECTION, MAYBE ION CYCLOTRON

RADIO EMISSION MORPHOLOGY



SHOCK ACCELERATION
+
ADVECTION

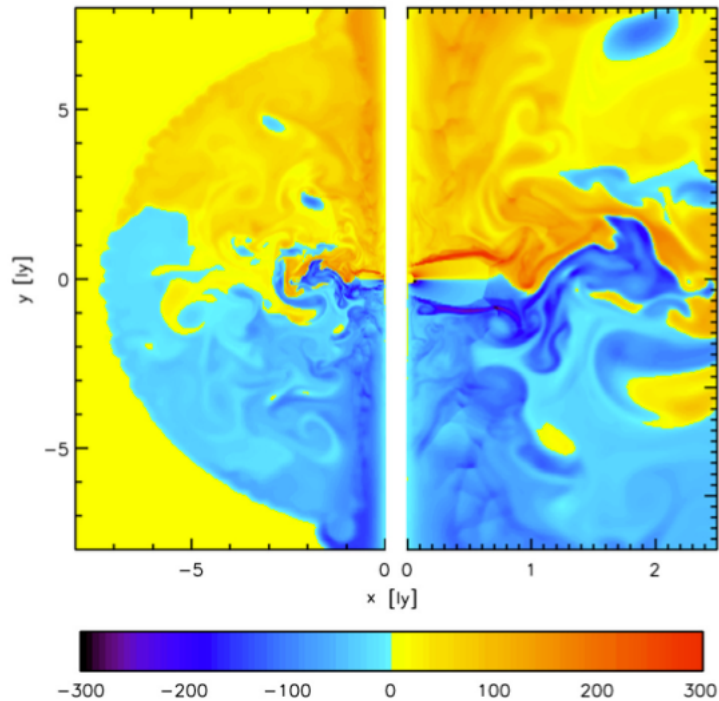
UNIFORM
INJECTION

VERY SIMILAR MAP

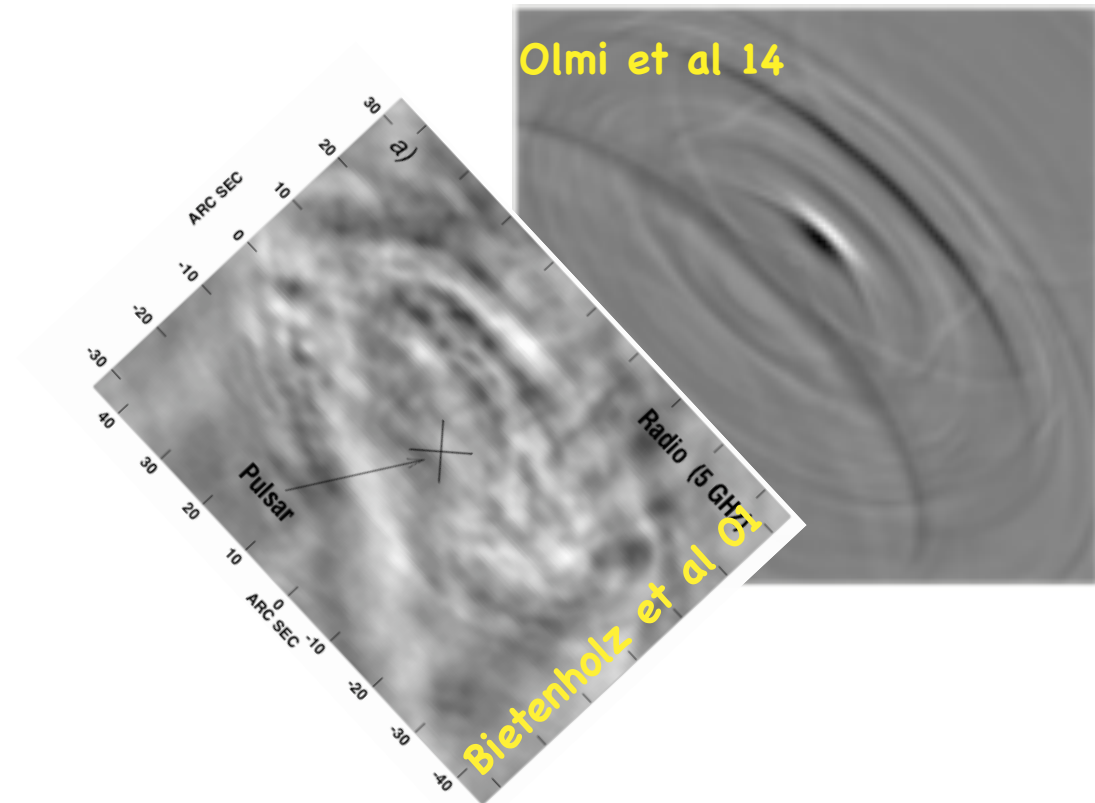
Olmi et al 14

RADIO WISPS

MAGNETIC FIELD



DIFFERENCE BETWEEN IMAGES AT
DIFFERENT TIMES



- RADIO EMISSION TRACES MAGNETIC FIELD
- RADIO WISPS EVEN FOR UNIFORM PARTICLE DISTRIBUTION

ORIGIN OF RADIO PARTICLES

$$\alpha=1.5 \quad E_{\text{MAX}} \approx 0.1-0.5 \text{ TeV} \quad 1 < E_{\text{MIN}}/mc^2 < 10^3$$

$$10^{-6} < n(\text{cm}^{-3}) < 10^{-4}$$

► PSR ORIGIN FOSSILE (Atoyan 99) WITH REACCELERATION

• NO CONSTRAINTS ON CURRENT K

• IF INJECTED AT LOW ENERGY NO VIOLATION OF ENERGY CONSTRAINTS

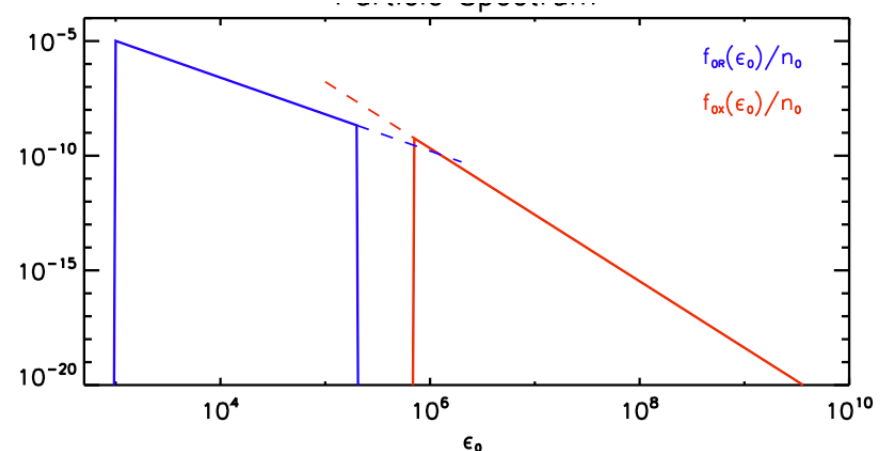
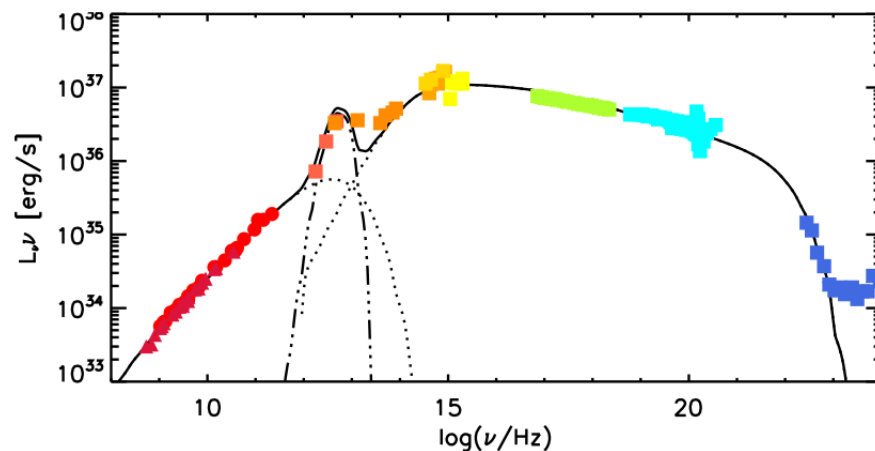
► EVAPORATION FROM THERMAL FILAMENTS (Bucciantini et al 11, Komissarov 13)

▪ ONLY e^- IN THIS CASE: NO CONTRIBUTION TO e^+ EXCESS

(PAMELA: Adriani et al 09; AMS02: Aguilar et al 13; Blasi & Amato 11)

▪ BUT BOW SHOCK PWNe (Yusef-Zadeh & Gaensler 05, Ng et al 12)....

SPECTRAL CONTINUITY



SUMMARY AND CONCLUSIONS

- PULSAR WIND NEBULAE ARE AMONG THE MOST EFFICIENT PARTICLE ACCELERATORS IN THE GALAXY:
 - THEY ARE LIKELY A MAJOR SOURCE OF CR POSITRONS
 - THEY CAN BE IN PRINCIPLE A SOURCE OF VERY HIGH ENERGY NUCLEI (see e.g. Kotera, Amato, Blasi 15)
- IN SPITE OF THIS, THEY ARE ALSO PLACES WHERE PARTICLE ACCELERATION IS UNDERSTOOD THE LEAST
- OUR UNDERSTANDING IS HAMPERED BY LACK OF KNOWLEDGE OF THREE MAIN PROPERTIES OF THE PULSAR OUTFLOW:
 - WIND MAGNETIZATION
 - PAIR MULTIPLICITY
 - WIND HADRONIC CONTENT
- DETAILED MODELLING OF THE NEBULAR EMISSION (INCLUDING TIME, SPACE AND SPECTRAL VARIABILITY) CAN HELP CONSTRAIN THE ACCELERATION PROCESS (SEE NEXT TALK) AND EVEN SHED LIGHT ON THE ELUSIVE COMPOSITION OF THE PULSAR WIND