Modeling of Pulsar Wind Nebulae

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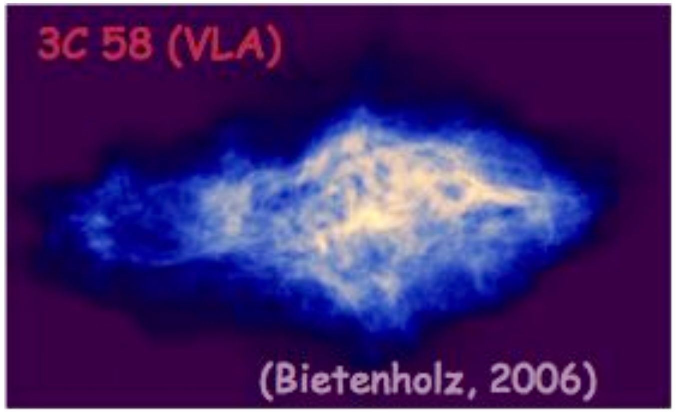
Pulsar Wind Nebulae

Why are they interesting at all?

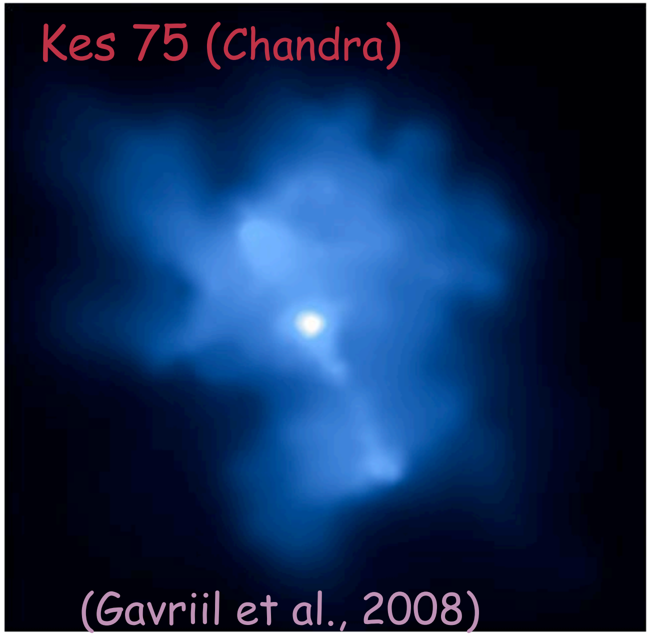

3C 58 (VLA)

(Bietenholz, 2006)

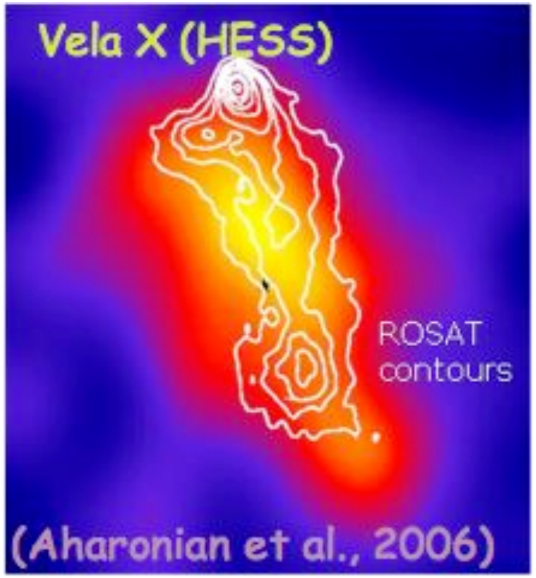
- ✓ Best probes of the physics of relativistic astrophysical plasmas
- ✓ As many positrons as electrons
- ✓ Particle acceleration at the highest speed shocks in Nature ($10^4 < \Gamma < 10^7$)
- ✓ **Direct evidence for PeV particles**


Crab Nebula (Spitzer)

(Temim et al., 2006)


Kes 75 (Chandra)

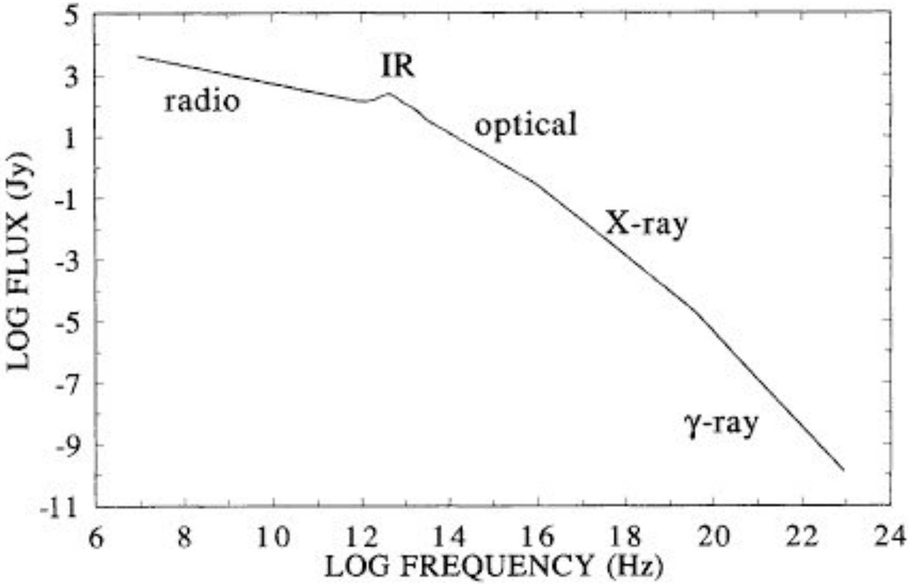
(Gavriil et al., 2008)


Vela X (HESS)

(Aharonian et al., 2006)

THE
Pulsar Wind Nebula


Combined IR, optical and X-ray data



electromagnetic braking of
fast-spinning magnetized NS

⇒

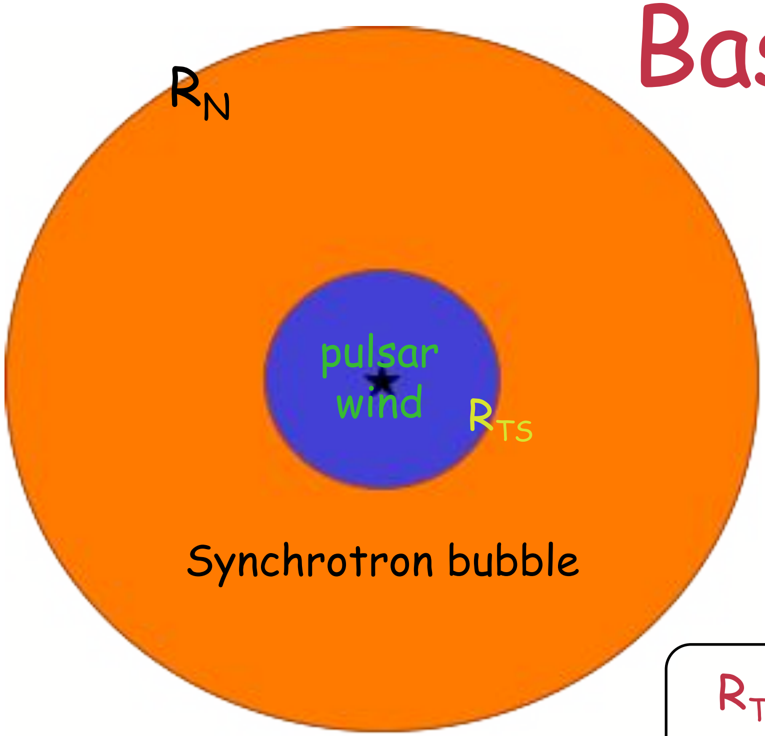
Magnetized
relativistic wind

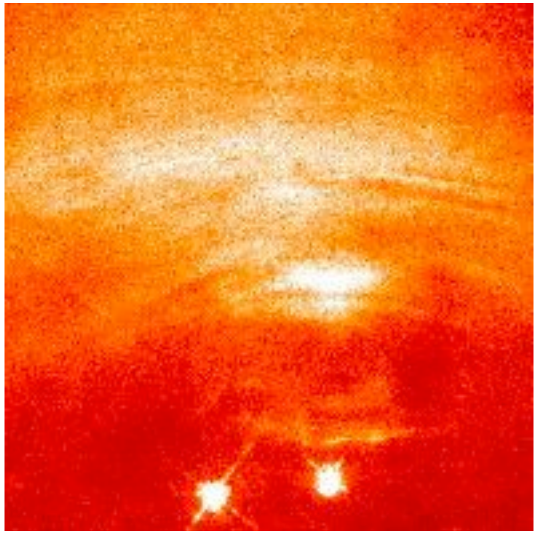
If wind is efficiently confined
by surrounding SNR

⇒

Star rotational energy *visible* as
non-thermal emission of the
magnetized relativistic plasma

Basic picture





$R_{TS} \sim R_N (V_N/c)^{1/2} \sim 10^9\text{-}10^{10}\ R_{LC}$
from pressure balance

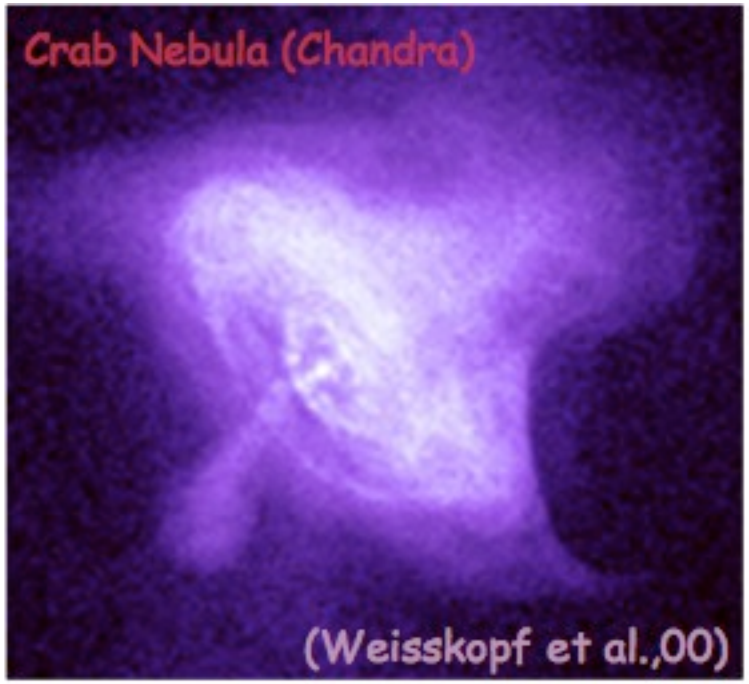
1-D and 2-D steady state or self-similar MHD models of PWNe
(Kennel & Coroniti 84; Emmering & Chevalier 87; Begelman & Li 92)

$\sigma = B^2/(4\pi nmc^2\Gamma^2) \sim V_N/c \sim 3 \times 10^{-3}$
from basic dynamics

σ-paradox

At $r \sim R_{LC}$: $\sigma \sim 10^4$ $\Gamma \sim 10^2$
(pulsar and pulsar wind theories)
At R_{TS}: $\sigma \ll 1$(!?!) $\Gamma \in (10^4\text{-}10^7)$
(PWN theory and observations)

The anisotropic wind energy flow



Split monopole solutions
(Michel 73, Bogovalov 99;
FF sim: Gruzinov 04, Spitkovsky 06;
RMHD sim: Komissarov 06, Bucciantini et al. 06)

Streamlines asymptotically radial beyond R_{LC}

Most of the energy flux is at low latitudes:
$F \propto \sin^2(\theta)$

Magnetic field components:
$B_r \propto 1/r^2$ $B_\phi \propto \sin(\theta)/r$

Within ideal MHD σ stays large

Current sheet around equatorial plane

Lowering σ in the current sheet?

- reconnection not fast enough if minimum rate assumed (Lyubarsky & Kirk 01)
- $dN/dt \sim 10^{40}\ s^{-1}$ required for Crab (Kirk & Skjaeraasen 03)
- This contrasts with PSR theory (e.g. Hibschman & Arons 01: $\kappa \sim 10^3$-$10^4 \Rightarrow dN/dt \sim 10^{38}$ for Crab) but just right for radio emitting particles

Termination Shock structure

Axisymmetric RMHD simulations of PWNe

Komissarov & Lyubarsky 03, 04
Del Zanna et al 04, 06
Bogovalov et al 05

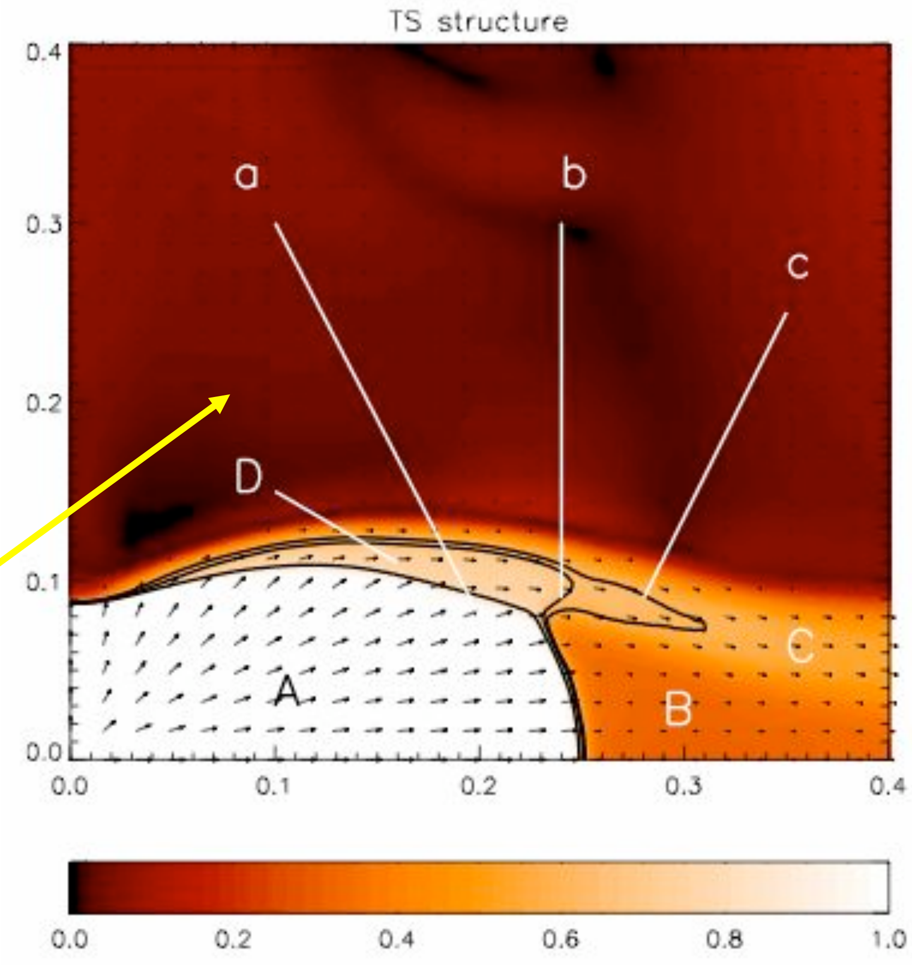
$F \propto \sin^2(\theta)$

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

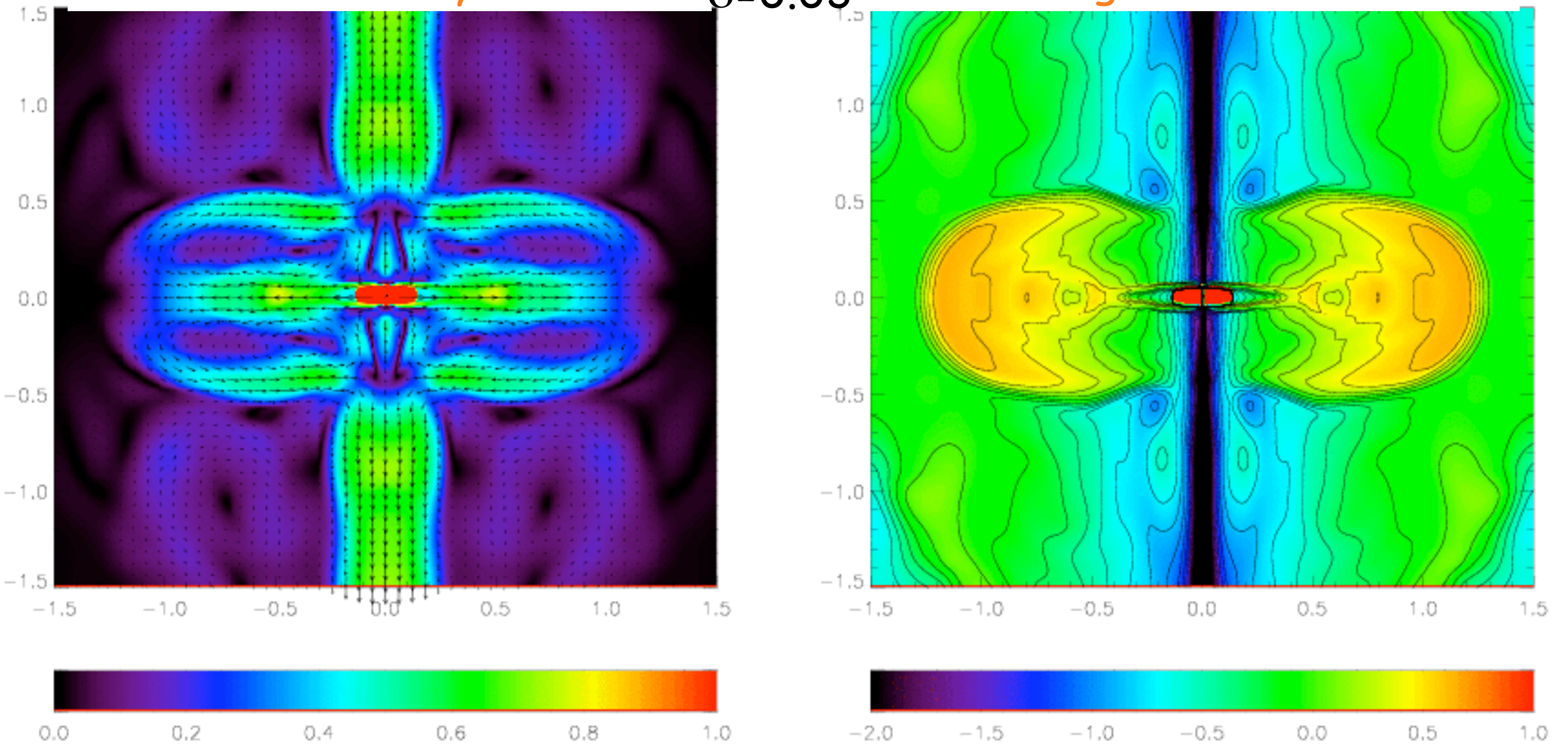
$B_\phi \propto \sin(\theta) G(\theta)$

A: ultrarelativistic PSR wind
B: subsonic equatorial outflow
C: supersonic equatorial funnel

a: termination shock front
b: rim shock
c: FMS surface



Flow pattern



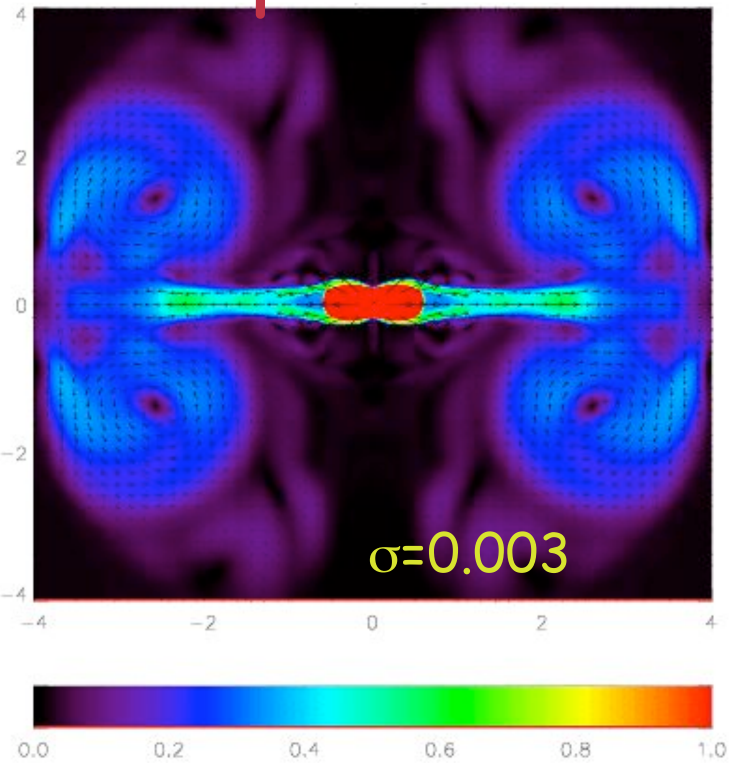
Velocity

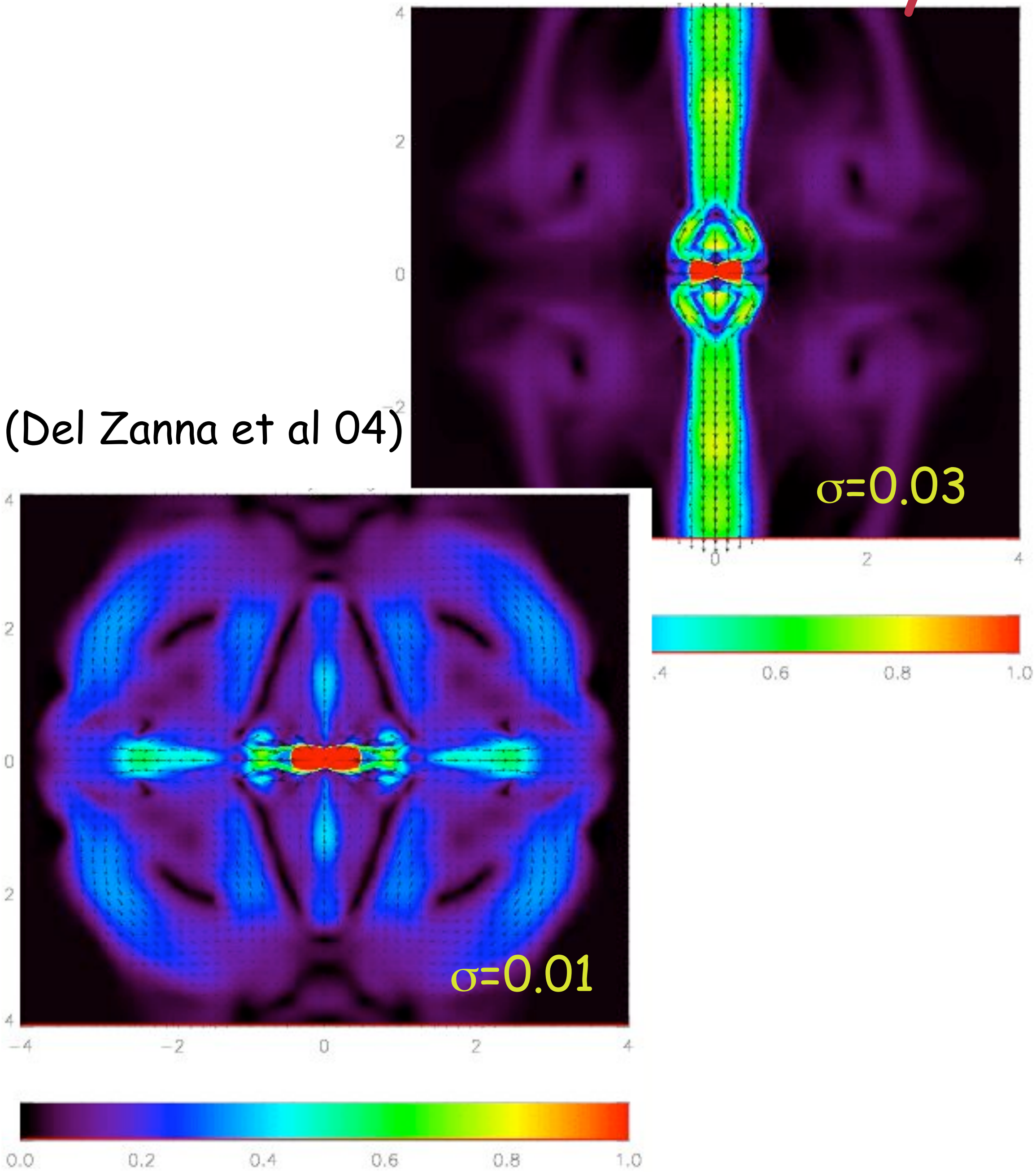
σ=0.03

Magnetization

- For sufficiently high σ, equipartition is reached in equatorial region
- Equatorial flow is diverted towards higher latitudes
- A fast channel may then form along the axis

Dependence on σ of the flow velocity



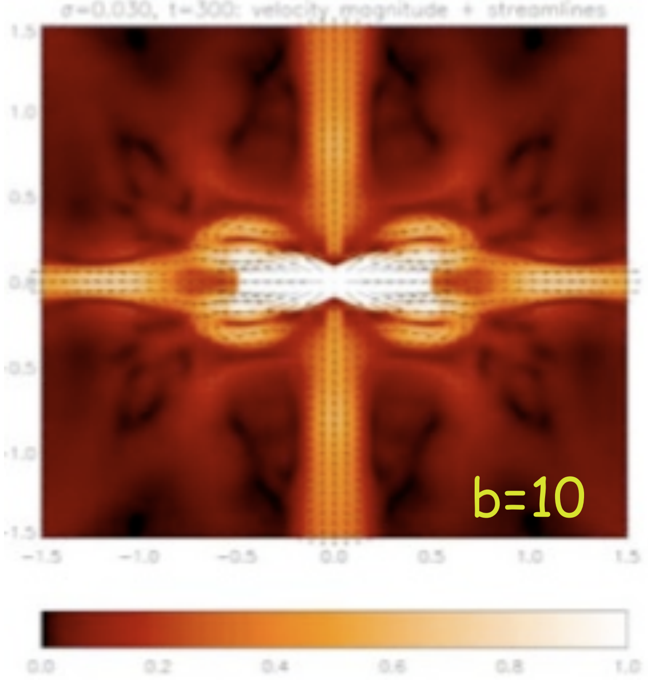


(Del Zanna et al 04)

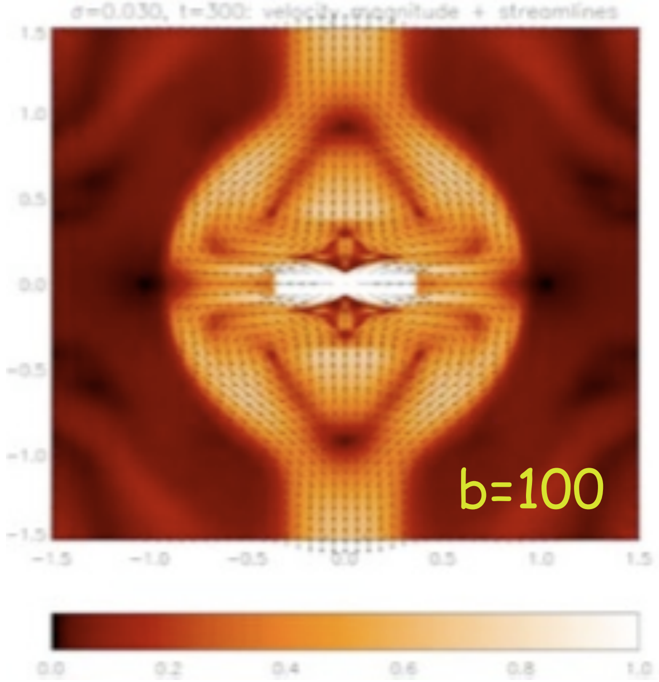
σ>0.01 required for
Jet formation

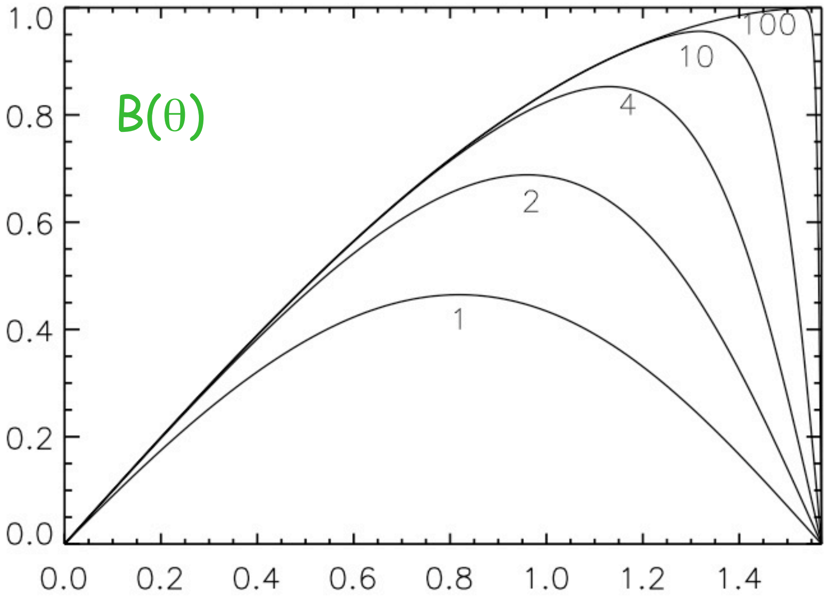
(a factor of 30 larger
than within 1D MHD
models)

Dependence on field structure



σ=0.03

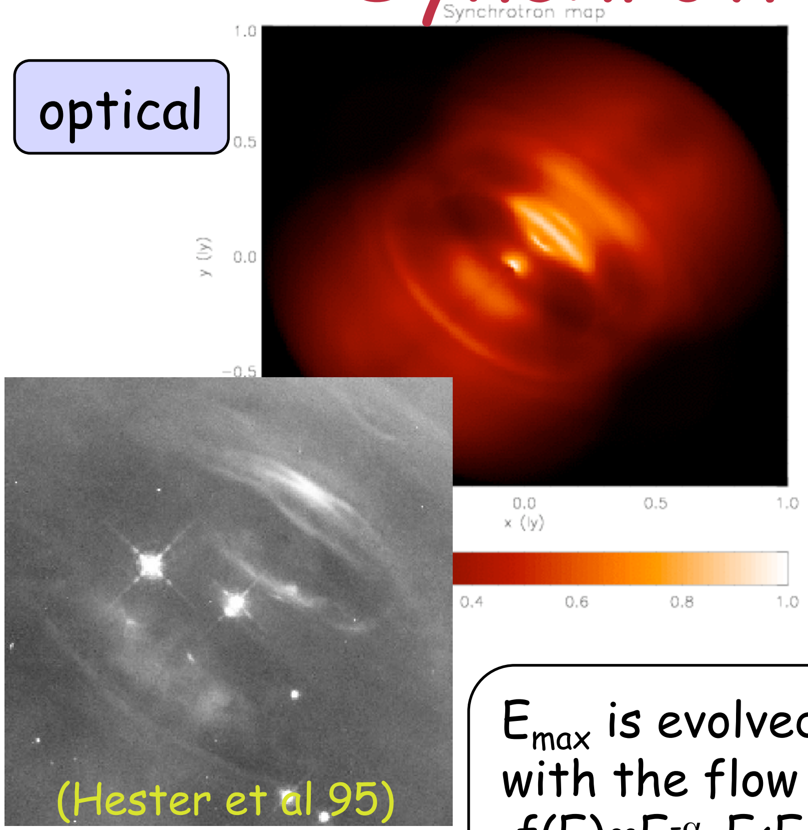




(Del Zanna et al 04)

Synchrotron Emission maps

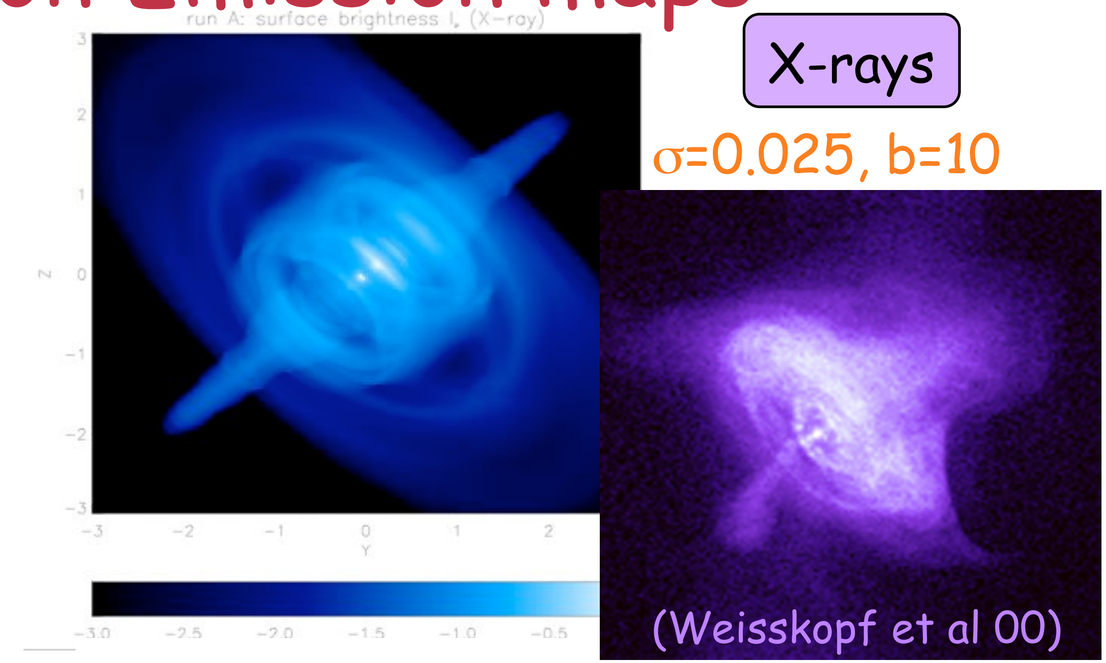
optical



(Hester et al 95)

X-rays

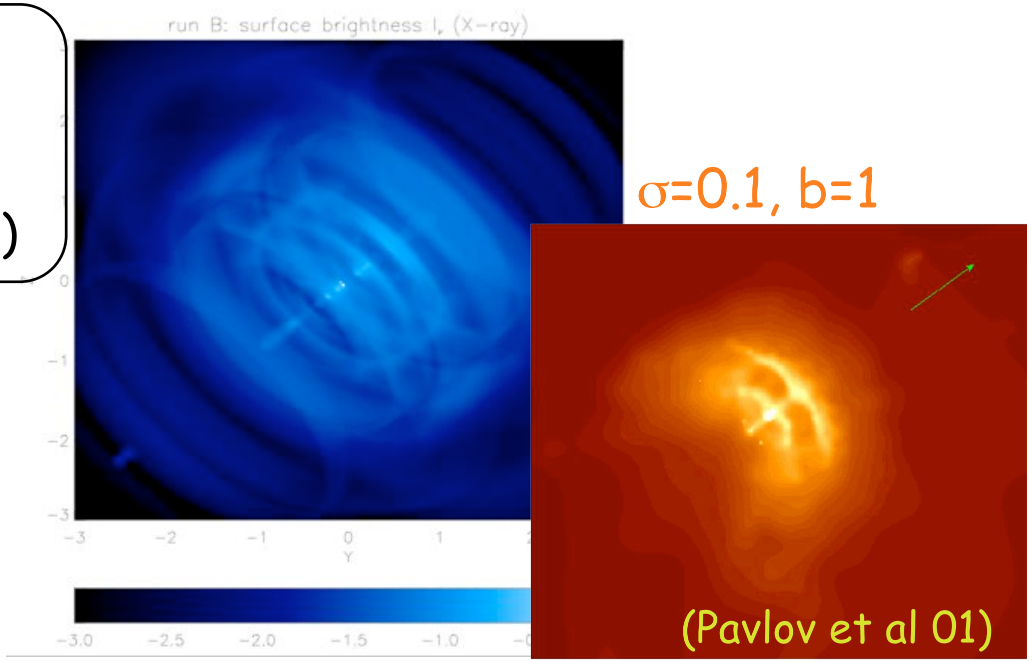
σ=0.025, b=10



(Weisskopf et al 00)

E_{max} is evolved with the flow
$f(E) \propto E^{-\alpha}$, $E<E_{max}$
(Del Zanna et al 06)

σ=0.1, b=1

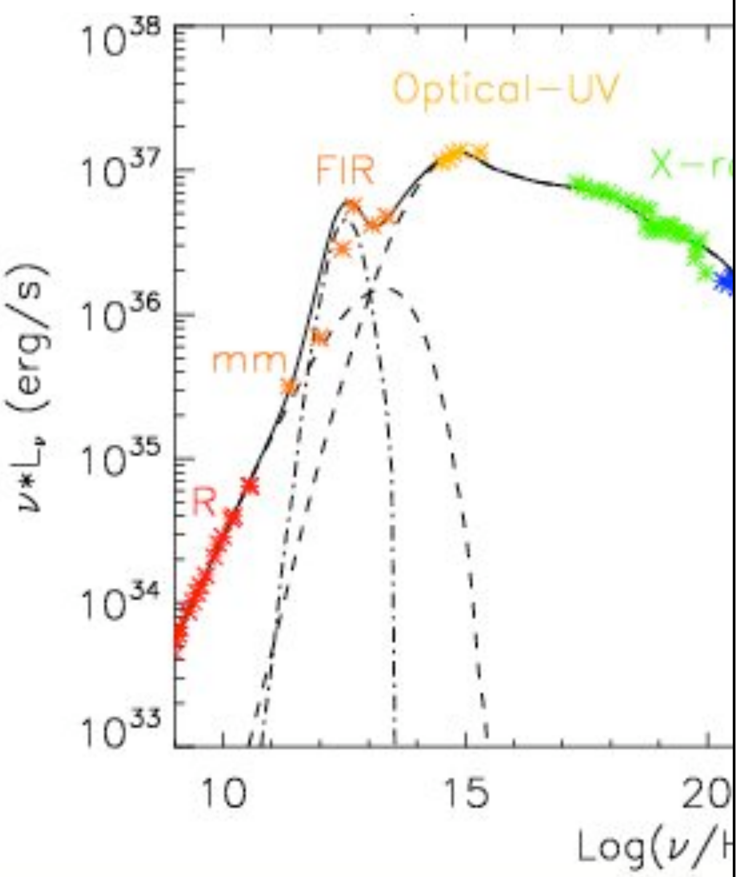


(Pavlov et al 01)

Between 3 and 15 % of the wind
Energy flows with σ<0.001

The Crab Nebula integrated emission spectrum

Quantitative fit of the spectral properties of the Crab Nebula requires injection spectrum with $\alpha=2.7$!!!! But….



- Optical spectral index maps (Veron-Cetty & Woltjer 92) suggest flatter injection spectrum: $\alpha \sim 2.2$ (but see also Kargaltsev & Pavlov 09)

- Suspicion that particles are loosing too little: average B too low?

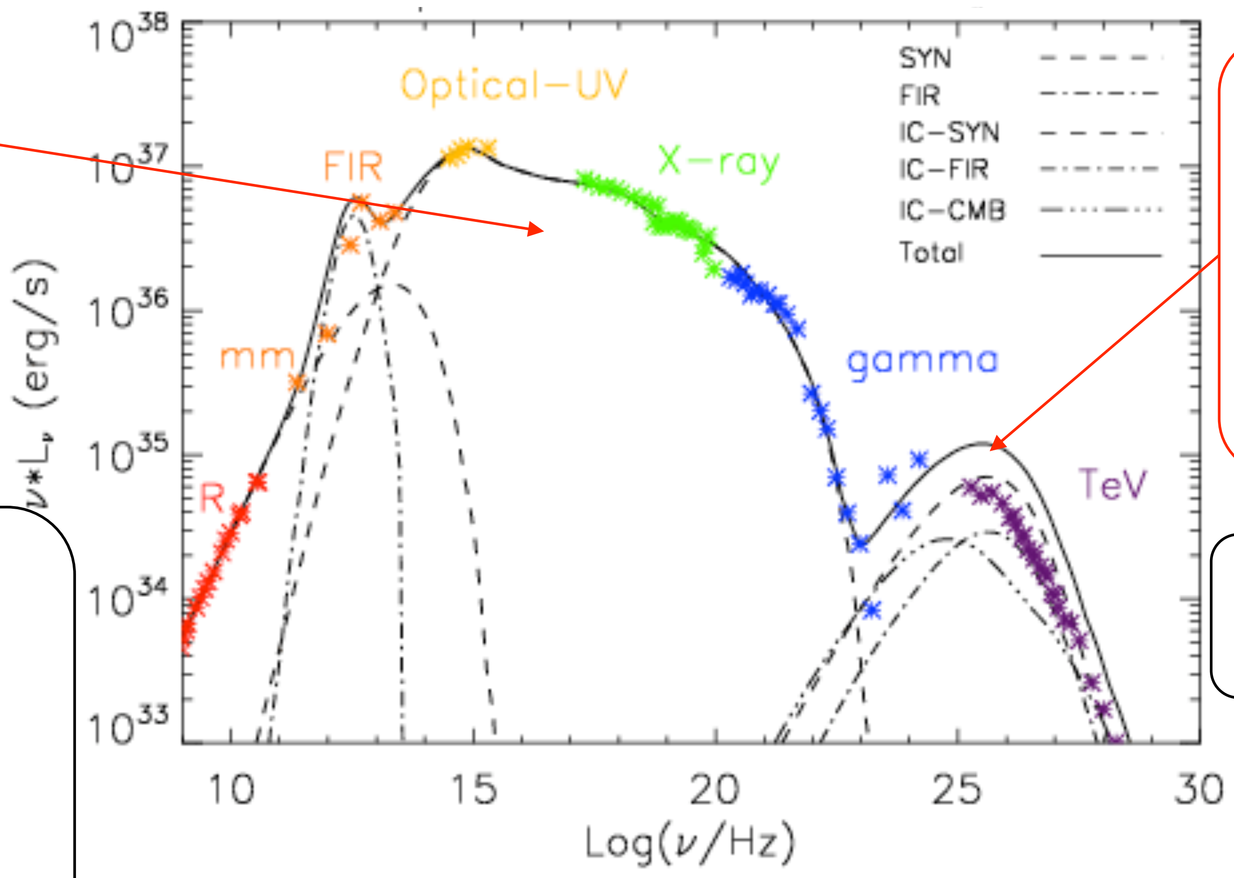
- In order to recover total flux number of particles artificially large

- Synchrotron only offers combined information on n_e and B: $L_{syn} \propto n_e B^2$

- But computation of ICS offers additional constraints: $L_{ICS} \propto n_e U_{ph}$

γ-ray spectrum from Crab

Multiple changes of slope!



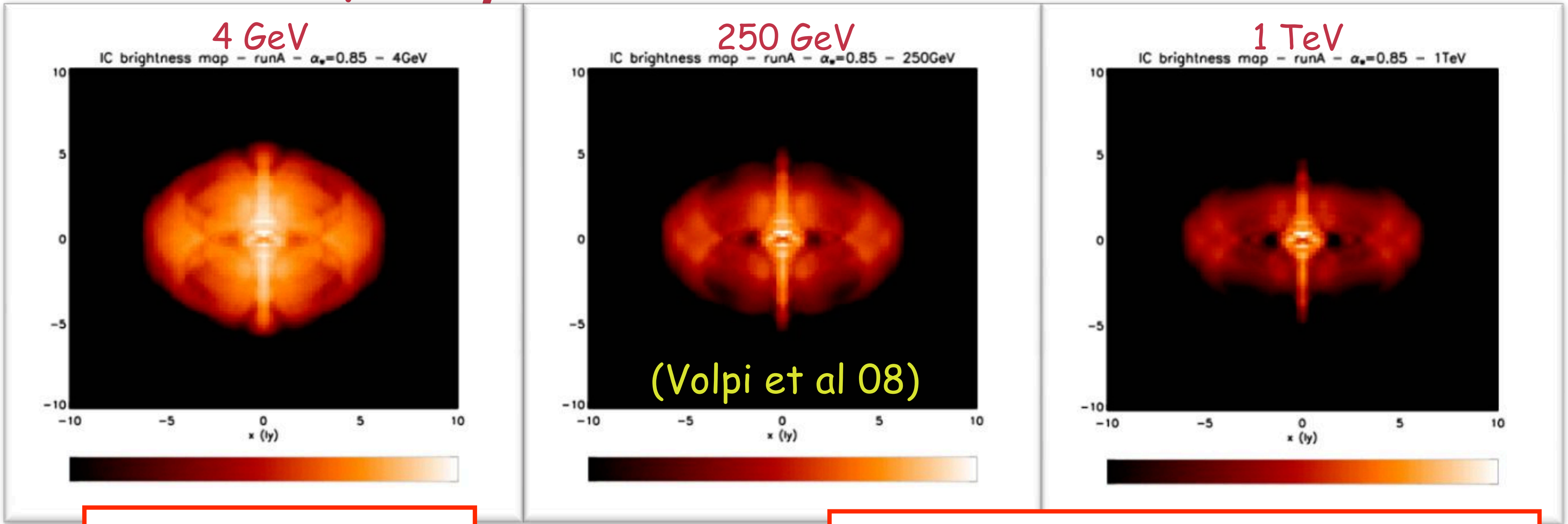
Computed ICS flux exceeds the data by a factor ~2

Higher σ required?

Explain entire spectrum with single power-law at injection?

Combined Sync+ICS diagnostic offers direct
Constraints on magnetic structure of the wind
And particle spectral index
Constraining Γ is more complicated....

γ-ray emission from Crab


4 GeV

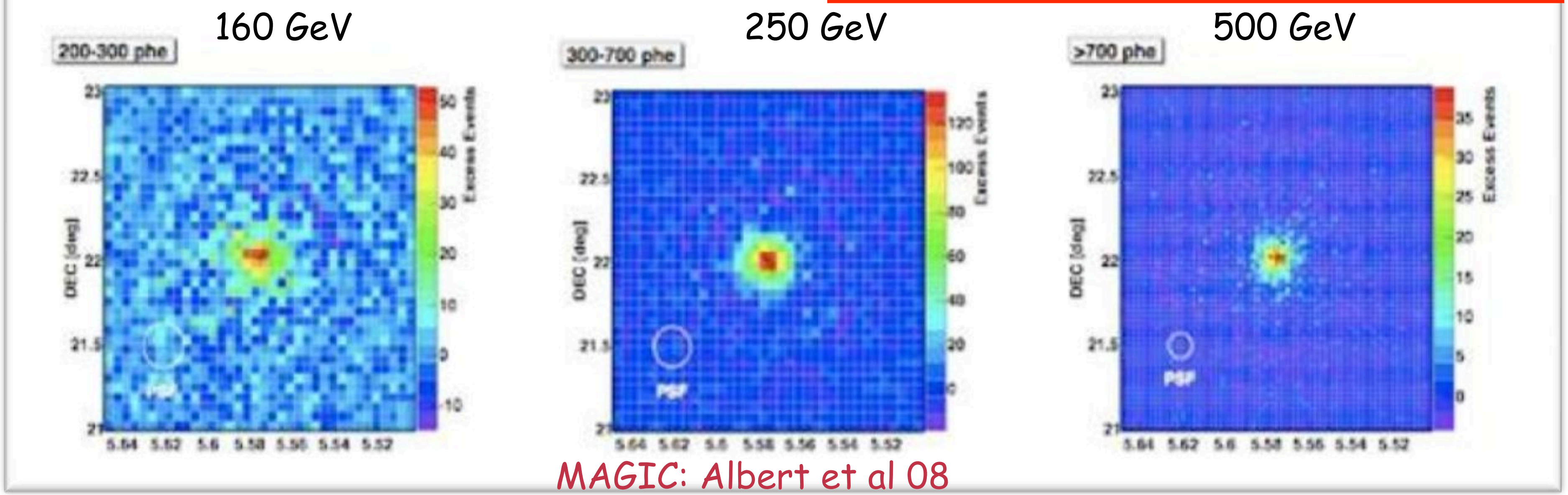
250 GeV

1 TeV

(Volpi et al 08)

$R_N(GeV) \sim R_N(GHz)$

NO shrinkage in equatorial region


160 GeV

250 GeV

500 GeV

MAGIC: Albert et al 08

Properties of the flow and particle acceleration

Particle acceleration occurs at the highly relativistic termination shock

This is a collisionless shock: transition between non-radiative (upstream) and radiative (downstream) takes place on scales too small for collisions to play a role

Self-generated electromagnetic turbulence mediates the shock transition: it must provide both the dissipation and particle acceleration mechanisms

The detailed physics and the outcome of the process strongly depend on
composition ($e^- - e^+ - p$?)
magnetization ($\sigma = B^2/4\pi n\Gamma mc^2$)
and geometry ($\Gamma \times \Theta(B \cdot n)$)
Of the flow

Particle Acceleration mechanisms

Composition: mostly pairs
Magnetization: σ>0.001 for most of the flow
Geometry: transverse

Requirements:

✓Outcome: power-law with α~2.2 for optical/X-rays α~1.5 for radio
✓Maximum energy: for Crab ~few x 10^{15} eV
(close to the available potential drop at the PSR)
✓Efficiency: for Crab ~10-20% of total L_{sd}

Proposed mechanisms:

- Fermi mechanism if/where magnetization is low enough
- Shock drift acceleration
- Acceleration associated with magnetic reconnection taking place at the shock (Lyubarsky & Liverts 08)
- Resonant cyclotron absorption in ion doped plasma (Hoshino et al 92, Amato & Arons 06)

Pros & Cons

DSA and SDA

oSDA not effective at superluminal shocks such as the pulsar wind TS unless unrealistically high turbulence level (Sironi & Spitkovsky 09)

✓In Weibel mediated e+-e$^-$ (unmagnetized) shocks Fermi acceleration operates effectively (Spitkovsky 08)

✓Power law index adequate for the optical/X-ray spectrum of Crab (Kirk et al 00) but e.g. Vela shows flatter spectrum (Kargaltsev & Pavlov 09)

oSmall fraction of the flow satisfies the low magnetization (σ<0.001) condition (see MHD simulations)

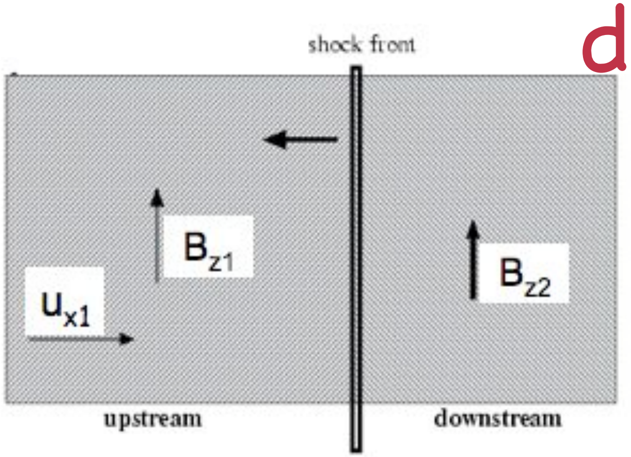
Magnetic reconnection

- Spectrum: -3 or -1? (e.g. Zenitani & Hoshino 07)
- Efficiency? Associated with X-points involving small part of the flow…
- Investigations in this context are in progress (e.g. Lyubarsky & Liverts 08)

Resonant absorption of ion cyclotron waves

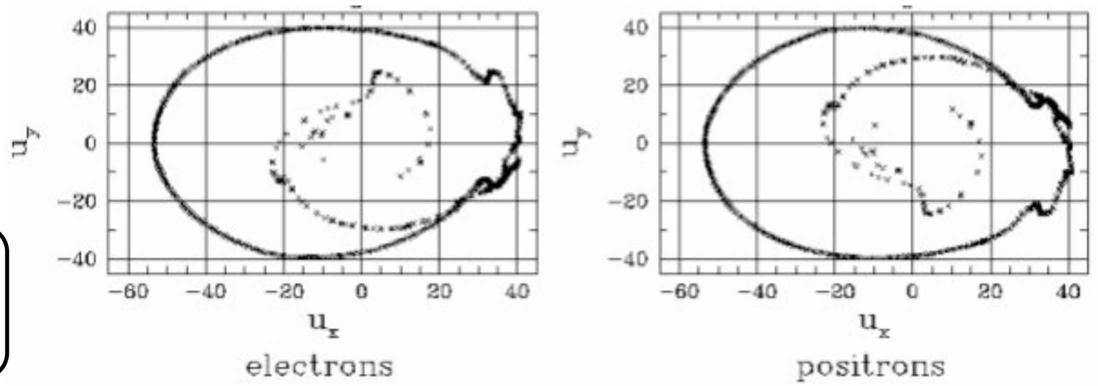
Established to effectively accelerate both e$^+$ and e$^-$ if the pulsar wind is sufficiently cold and ions carry most of its energy (Hoshino & Arons 91, Hoshino et al. 92, Amato & Arons 06)

Resonant cyclotron absorption in ion doped plasma



Magnetic reflection mediates the transition

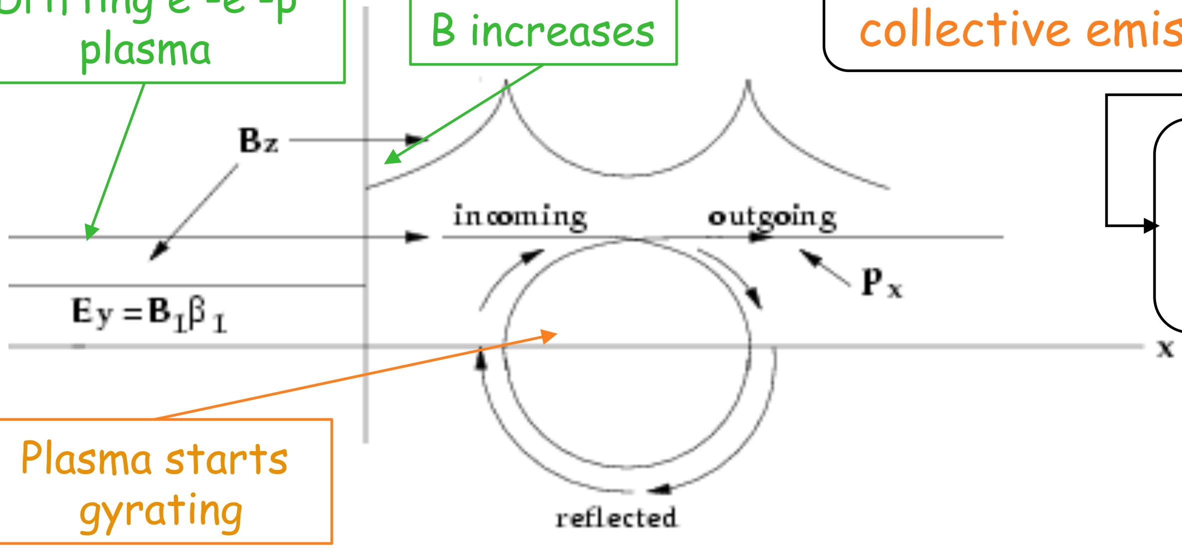
Configuration at the leading edge
~ cold ring in momentum space



Coherent gyration leads to collective emission of cyclotron waves

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

Ions take their time: m_i/m_e times longer

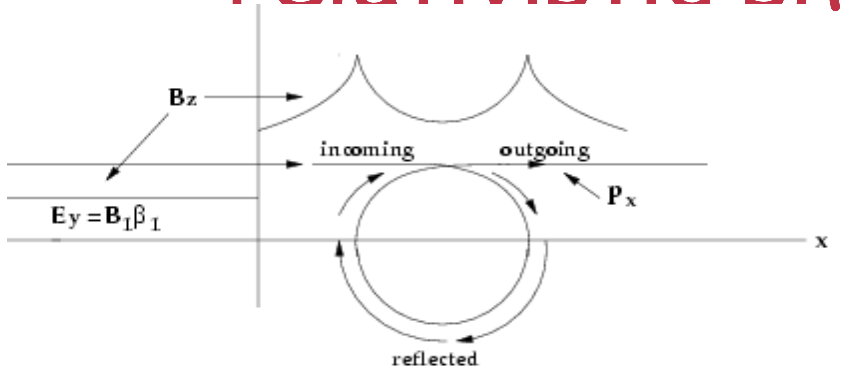


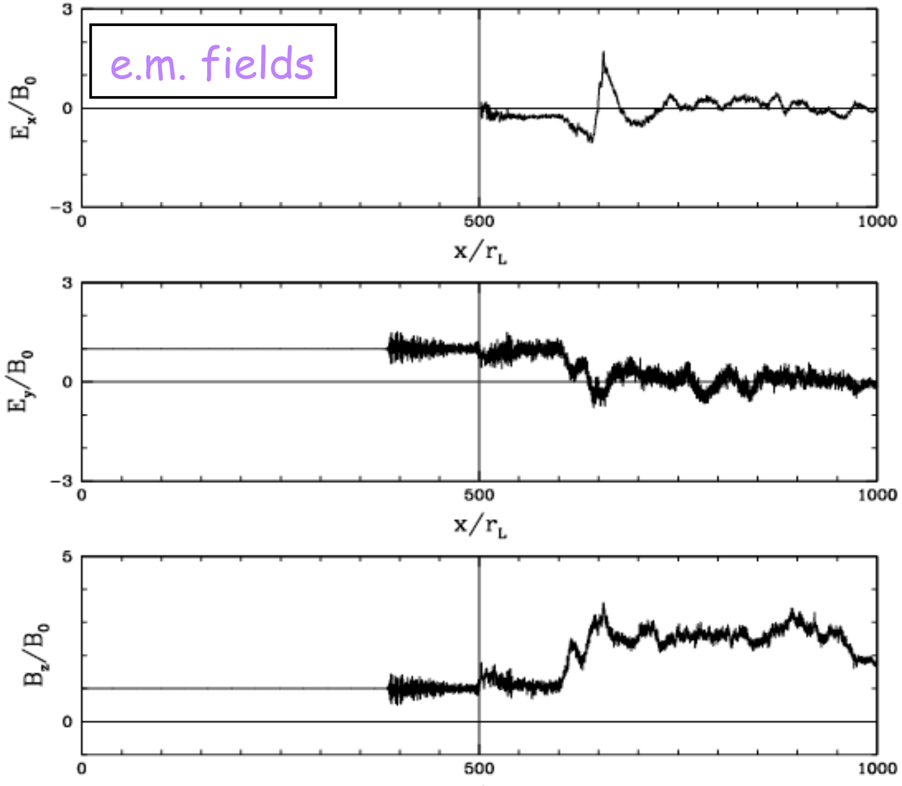
Drifting e^+-e^--p plasma

B increases

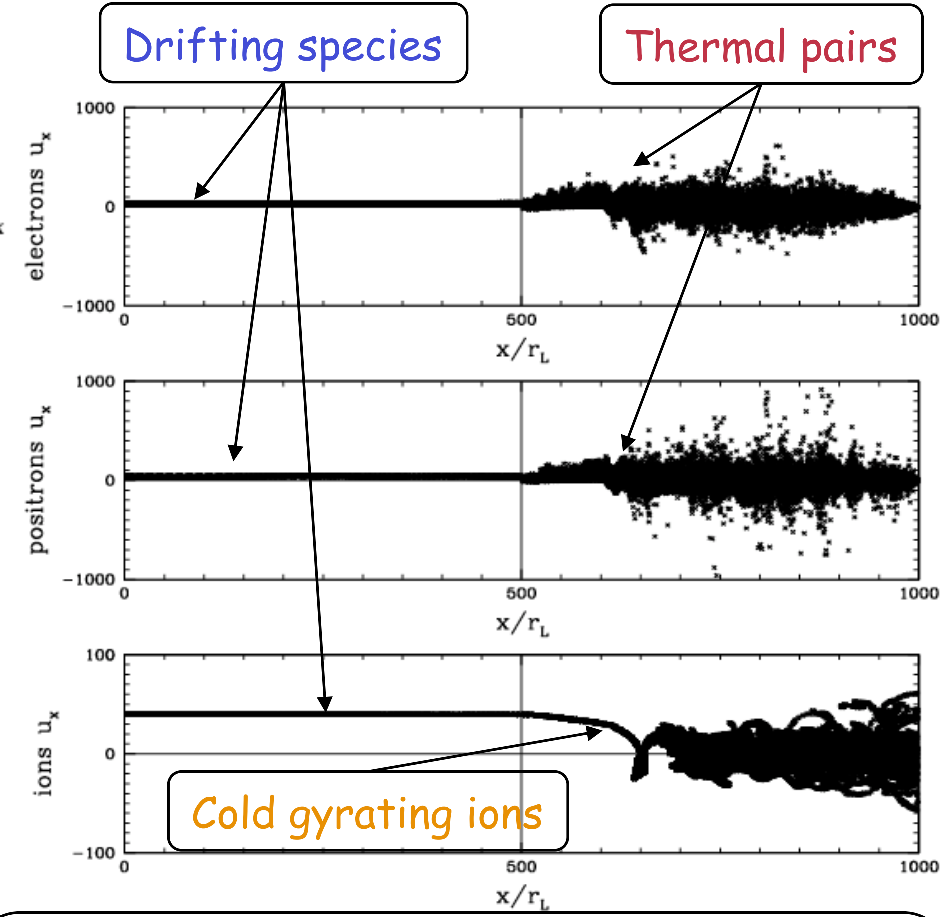
Plasma starts gyrating

Leading edge of a transverse relativistic shock in 1D PIC





e.m. fields



Drifting species

Thermal pairs

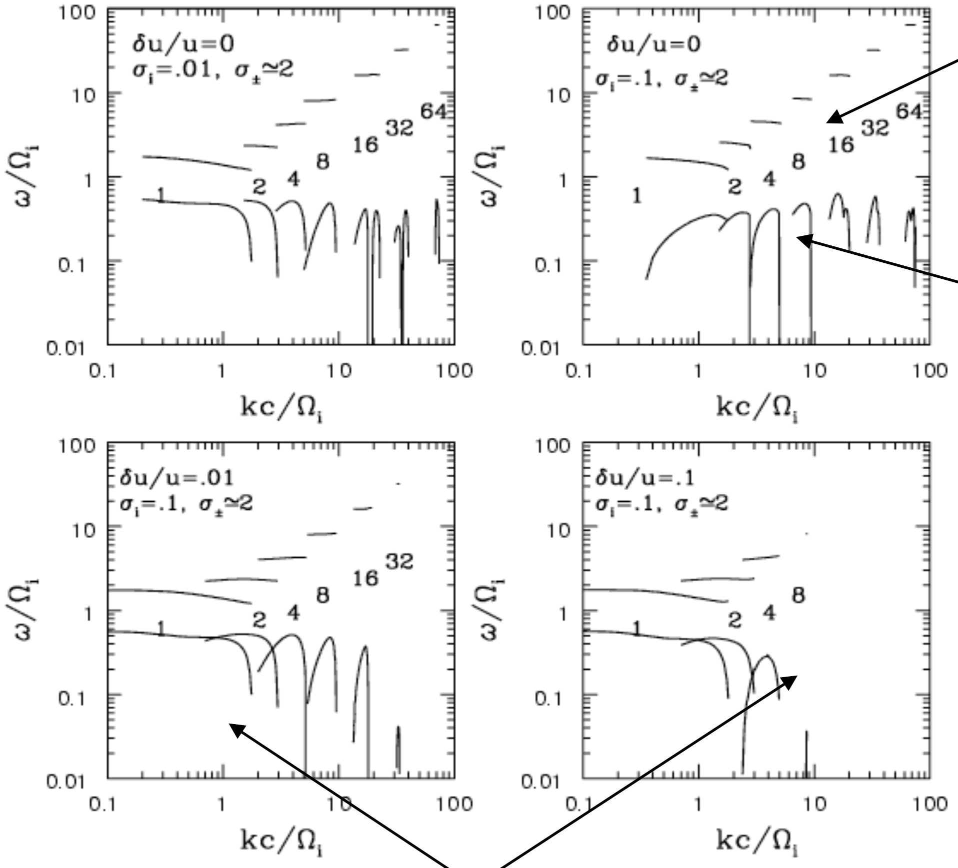
Cold gyrating ions

(Amato & Arons 06)

Pairs can resonantly absorb the ion radiation at $n=m_i/m_e$ and then progressively lower n

Effective energy transfer if $U_i/U_{tot}>0.5$

Subtleties of the RCA process



frequency

Growth-rate

Ion cyclotron frequency
$(m_e/m_i\Omega_{ce})$

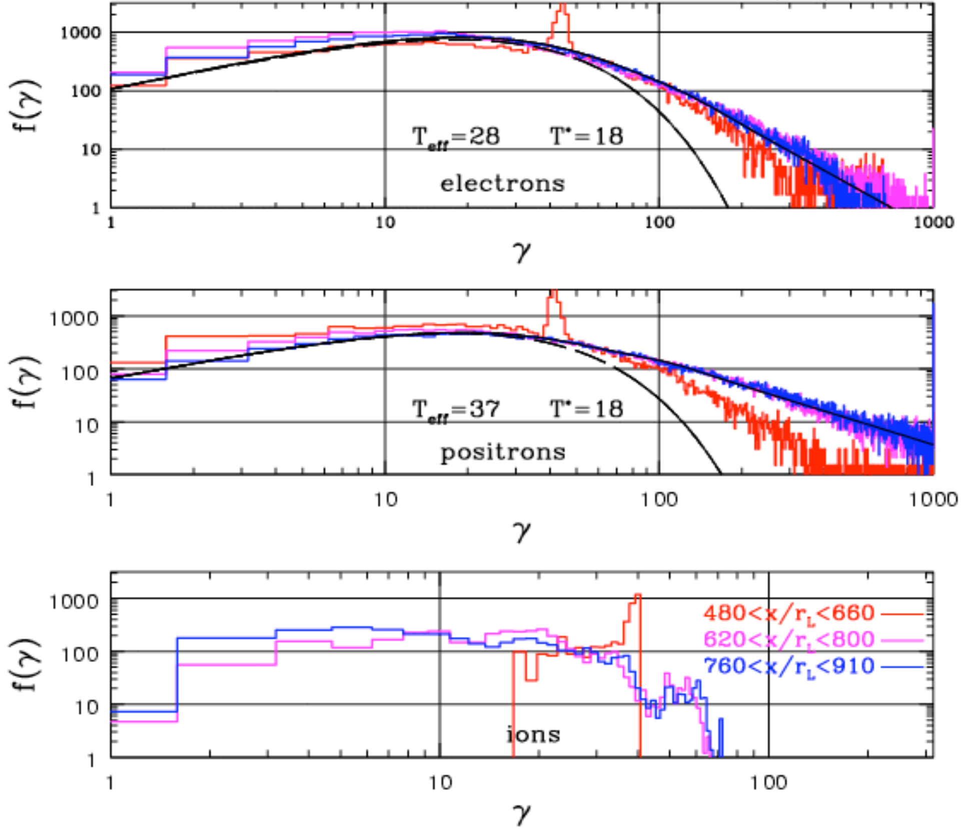
Electrons initially need
$n \sim m_i/m_e$
for resonant absorption
Then lower n

however
growth-rate ~ independent of harmonic number
(Hoshino & Arons 92)
as long as ion plasma cold
(Amato & Arons 06)

Spectrum is cut off at $n \sim u/\delta u$

In order for the process to work the pulsar wind must be really very cold $(\delta u/u < m_e/m_i)$!!!!

Particle spectra and acceleration efficiency



Acceleration efficiency:

~few% for U_i/U_{tot}~60%

~30% for U_i/U_{tot}~80%

Spectral slope:

>3 for U_i/U_{tot}~60%

<2 for U_i/U_{tot}~80%

Maximum energy:

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

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

Electron acceleration!!!

Less efficient than for positrons:

(low $m_i/m_e \Rightarrow$ large n_i/n_e to ensure U_i/U_{tot}>0.5)→elliptical polarization of the waves

Extrapolation to realistic m_i/m_e predicts same efficiency

Acceleration via RCA and related issues

✓Nicely fits with correlation (Kargaltsev & Pavlov 08; Li et al 08) between X-ray emission of PSRs and PWNe : everything depends on U_i/U_{tot} and ultimately on electrodynamics of underlying compact object

If Γ~ few x 10^6

✓Maximum energy ~ what required by observations

✓Required (dN_i/dt)~10^{34} s^{-1}~$(dN_i/dt)_{GJ}$ for Crab: return current for the pulsar circuit

✓Natural explanation for Crab wisps (Gallant & Arons 94) and their variability (Spitkovsky & Arons 04) (although maybe also different explanations within ideal MHD) (e.g. Begelman 99; Camus et al 09)

Puzzle with Γ

Radio electrons dominant by number require (dN/dt)~10^{40} s^{-1} and Γ~10^4
Preliminary studies based on 1-zone models (Bucciantini et al. in prep.) contrast with idea that they are primordial!

1-zone models for the PWN evolution

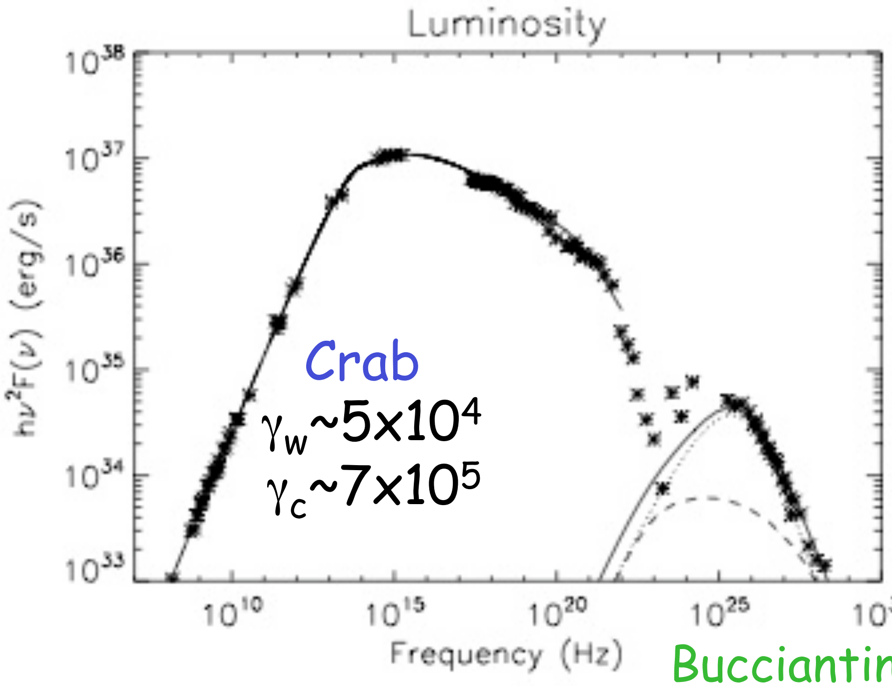
$$\dot{N}(E,t) = C_o(t)(E/\epsilon_c)^{-\gamma_1} \; for \; \epsilon_c < E < \epsilon_v$$
$$\dot{N}(E,t) = C_o(t)(E/\epsilon_c)^{-\gamma_2} \; for \; \epsilon_m < E < \epsilon_c$$

$$\eta_e L(t) = \int_{\epsilon_m}^{\epsilon_v} \dot{N}(E,t) E dE$$

$$\dot{N}(t) = \int_{\epsilon_m}^{\epsilon_v} \dot{N}(E,t) dE$$

$$N(E,t) = \int_E^{\infty} \dot{N}(E_o t_o) \frac{\partial t_o}{\partial E}(E, E_o, t) dE_o$$

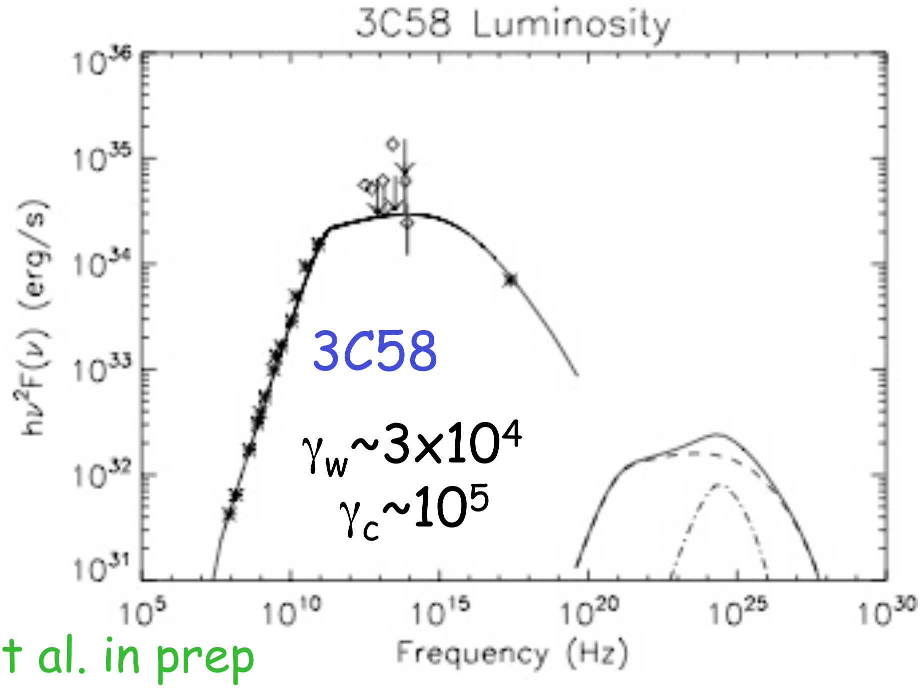
$\varepsilon_v \propto L(t)^{1/2}$ $\varepsilon_c/\varepsilon_v$=cost $\gamma_w = L(t)/(dN/dt)$



Crab

γ_w~5×10^4

γ_c~7×10^5



3C58

γ_w~3×10^4

γ_c~10^5

Bucciantini et al. in prep

Summary and Conclusions

- Nebular dynamics and emission allow to constrain σ at the termination shock
- The value of σ is low enough as to require effective magnetic dissipation
- Dissipation of magnetic energy before or at the termination shock is required
- The value of σ inferred by MHD simulations is however too large to allow efficient Fermi acceleration in a pair plasma
- A possibility is that different acceleration mechanisms operate at different latitudes
- Preliminary results from simplified modeling of the evolution of these systems suggest values of Γ as low as to rule out the best candidate (ions cannot carry most of the wind energy if Γ is below 10^6)

Where to look for answers

RMHD simulations:

- Investigation of the parameters space
- More refined model for the evolution of n(E)

- High Energy Observations

- Fermi: Emission spectrum around the synchrotron cut-off and variability
- Pion decay TeV γ-rays and neutrinos

Thank you!