# Pulsar Wind Nebulae and Relativistic Shocks

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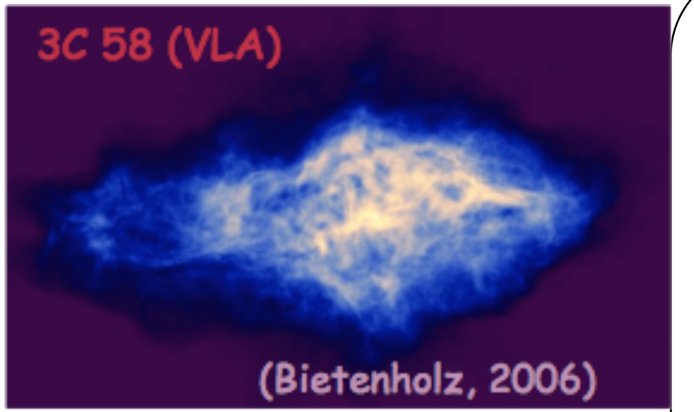
# Pulsar Wind Nebulae

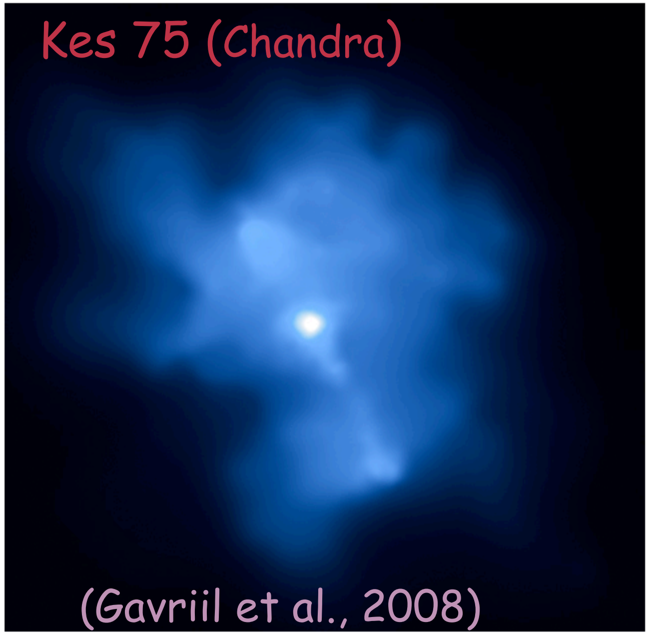


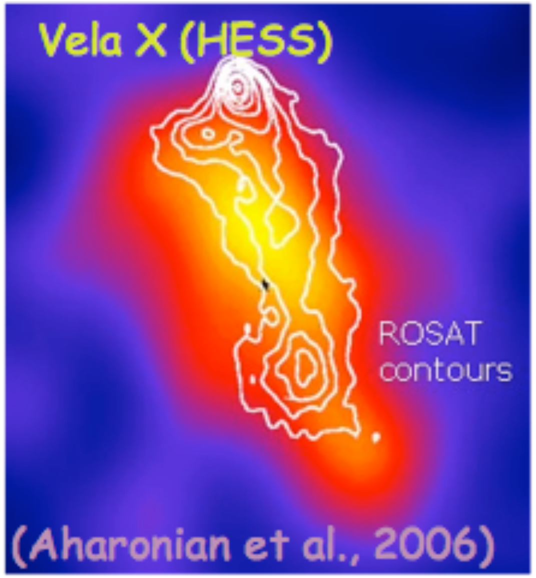

**Plerions:**

✓Supernova Remnants with a center filled morphology

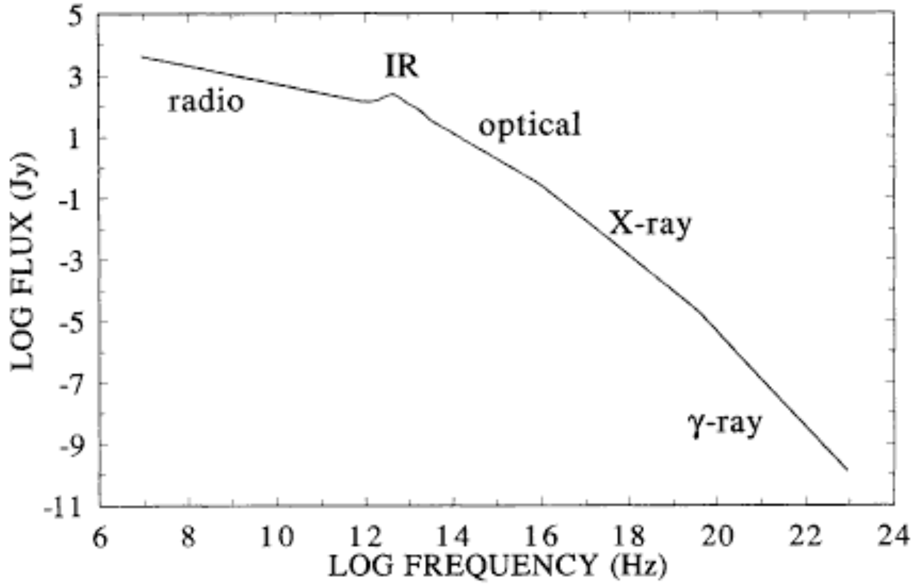
✓Flat radio spectrum ($\alpha_R$<0.5)

✓Very broad non-thermal emission spectrum (from radio to X-ray and even $\gamma$-rays) (~10 objects at TeV energies)

# THE
# Pulsar Wind Nebula

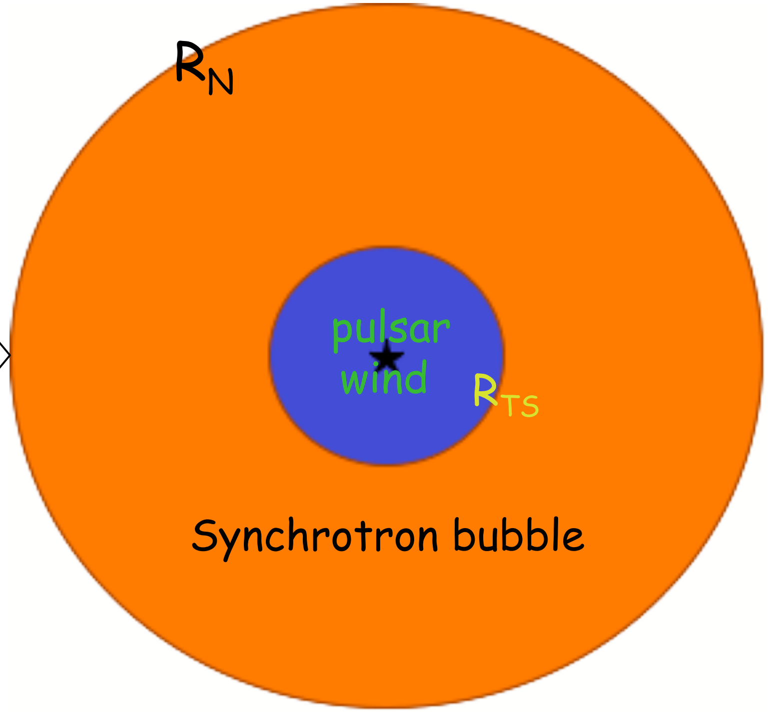

Primary emission mechanism is synchrotron radiation by relativistic particles in an *intense* (>few x 100 $B_{ISM}$) *ordered* (high degree of radio polarization) magnetic field

Source of both magnetic field and particles:
Neutron Star suggested before Pulsar discovery (Pacini 67)

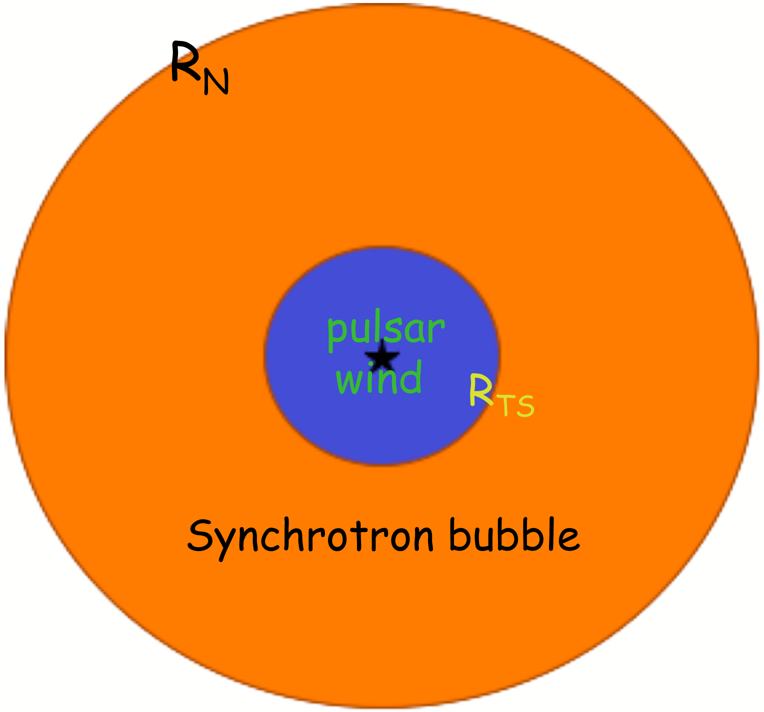
# Basic picture

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

# MHD models of PWNe




1-D steady-state hydro (Rees & Gunn 74)
1-D steady-state MHD (Kennel & Coroniti 84)
1-D self-similar MHD (Emmering & Chevalier 87)
2-D static MHD (Begelman & Li 92)

**General assumptions**

- Cold isotropic MHD wind terminates in a strong perpendicular relativistic shock
- Flow in the nebula is subsonic
- Particle acceleration at the TS
- Synchrotron losses thereafter

**Main free parameters**

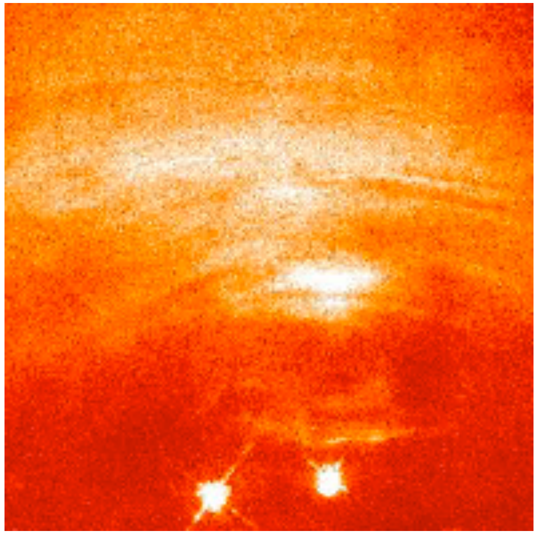
Wind magnetization $\sigma = B^2/(4\pi n m c^2 \Gamma^2)$ and Lorentz factor $\Gamma$, particle spectral index

**Predictions**

- Integrated emission spectrum from optical to X-rays and even $\gamma$-rays (e.g. de Jager & Harding 92; Atoyan & Aharonian 96)
- Size shrinkage with increasing observation frequency
- Elongation

# Basic Parameters and Questions left open

$R_{TS} \sim R_N (V_N/c)^{1/2} \sim 10^9\text{-}10^{10}\ R_{LC}$
from pressure balance
(e.g. Rees & Gunn 74)



In Crab $R_{TS}$ ~0.1 pc:
~boundary of underluminous (*cold wind*) region
~"wisps" location (variability over months)

**Wind parameters**

$\sigma \sim V_N/c \sim 3 \times 10^{-3}$
from basic dynamics

$\Gamma \sim 3\times10^6$
from radiation properties

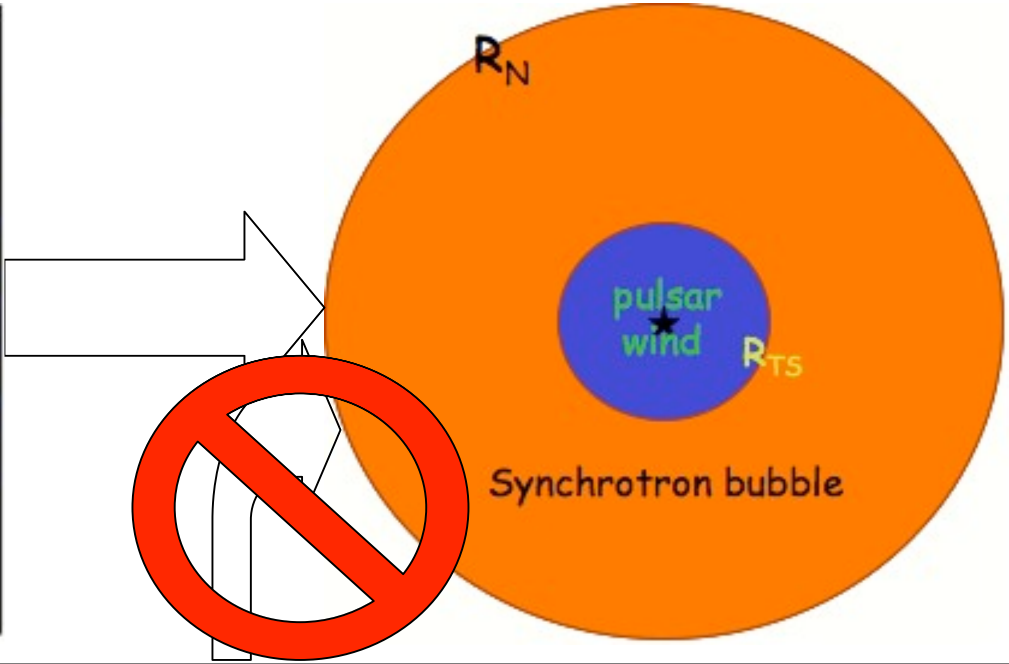
$\sigma$-paradox!

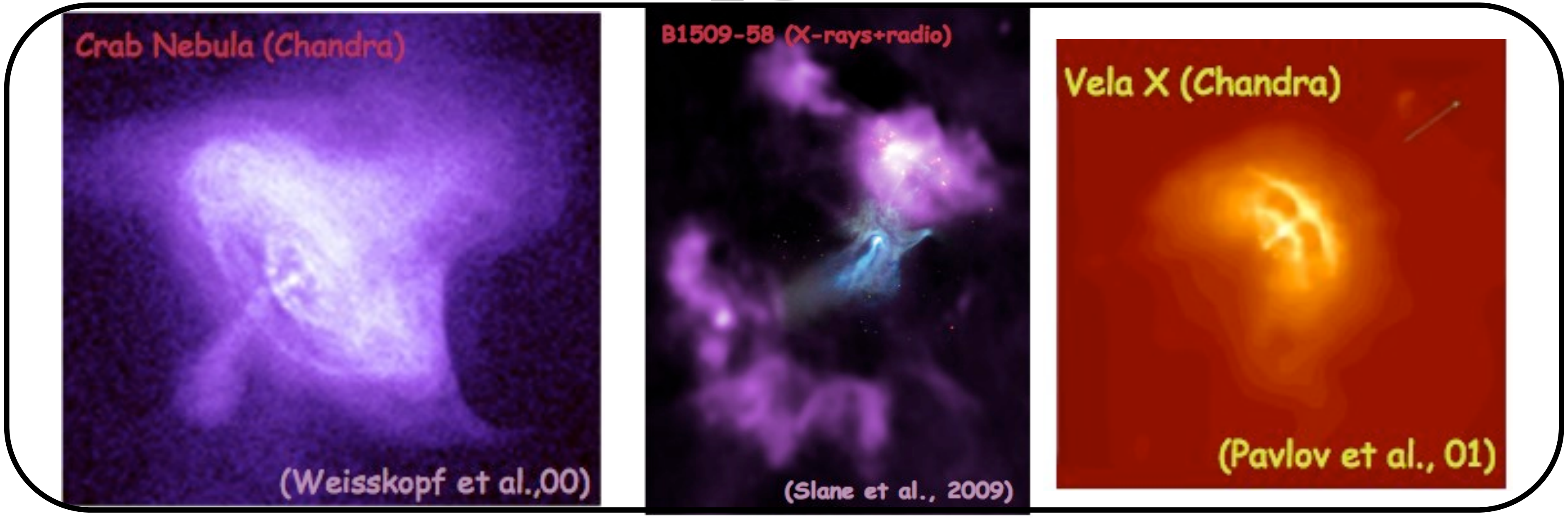
At $r \sim R_{LC}$: $\sigma \sim 10^4$ $\Gamma \sim 10^2$
(pulsar and pulsar wind theories)

At $R_{TS}$: $\sigma \ll 1$(!?!) $\Gamma \in (10^4\text{-}10^7)$
(PWN theory and observations)

No explanation for radio electrons: maybe primordial (Atoyan 99)

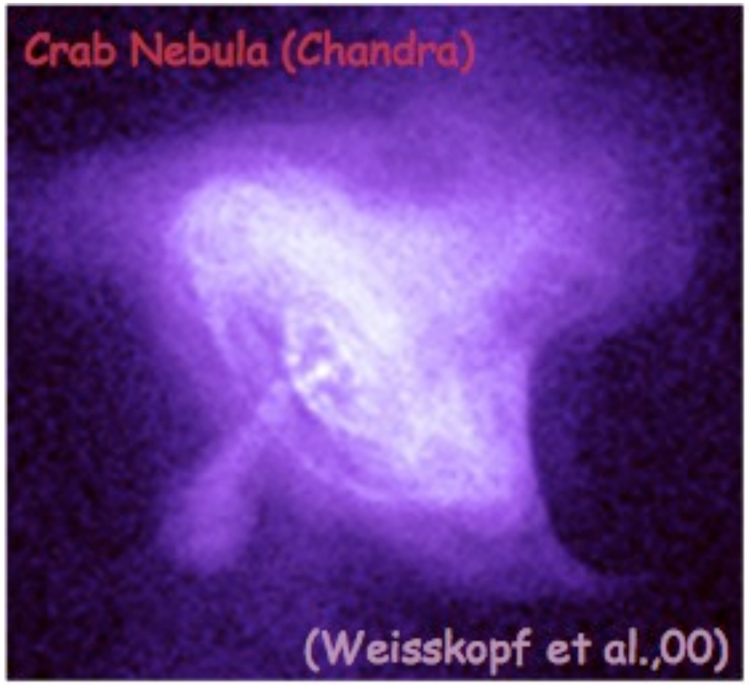
# Then came Chandra!

# The puzzling jet in Crab

Jet in Crab appeared to originate from closer to the PSR than $R_{TS}$




Magnetic collimation in relativistic flow not an option

(e.g. Lyubarsky & Eichler 01)

$$\Gamma \gg 1 \Rightarrow \quad \rho \vec{E} + \vec{j} \times \vec{B} \approx 0$$

Collimation must occur inside the nebula

(Bogovalov & Khangoulian 02; Lyubarsky 02)

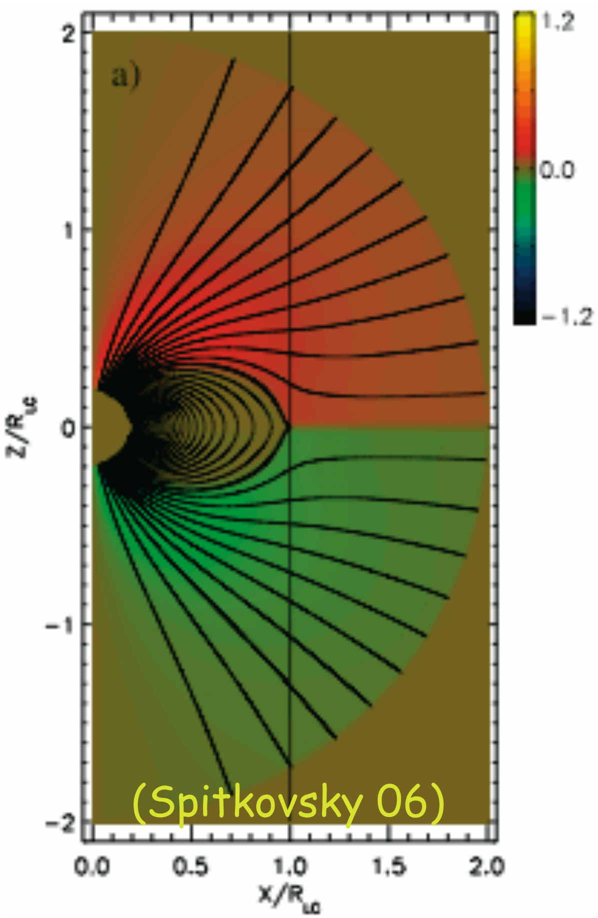
Anisotropic energy flux of the wind

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

leads to oblate TS, closer to the PSR at the poles than at the equator

**This is exactly what wind models predict!**

# The anisotropic wind energy flow




Analytic split monopole solutions
(Michel 73; Bogovalov 99)
confirmed by numerical studies in the Force Free
(Contopoulos et al 99, Gruzinov 04, Spitkovsky 06)
and RMHD regime
(Bogovalov 01, Komissarov 06, Bucciantini et al 06)

Streamlines become asymptotically radial beyond $R_{LC}$

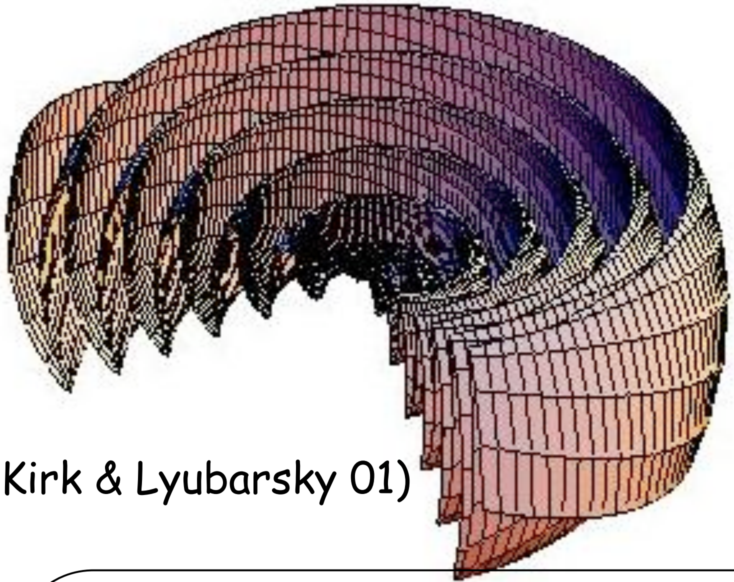
Most of the energy flux is at low latitudes:
$F \propto \sin^2(\theta)$

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

Within ideal MHD $\sigma$ stays large

Current sheet in equatorial plane:
oscillating around the equator in oblique case
angular extent depends on obliquity

# The wind magnetization



(Kirk & Lyubarsky 01)

Lowering $\sigma$ through
dissipation in the striped wind
(Coroniti 90)

Recent studies:

- 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

In 2-D MHD simulations $B \propto \sin(\theta)\ G(\theta)$
with $G(\theta)$ accounting for decreasing magnetization toward equator

# Termination Shock structure

Axisymmetric RMHD simulations of PWNe

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

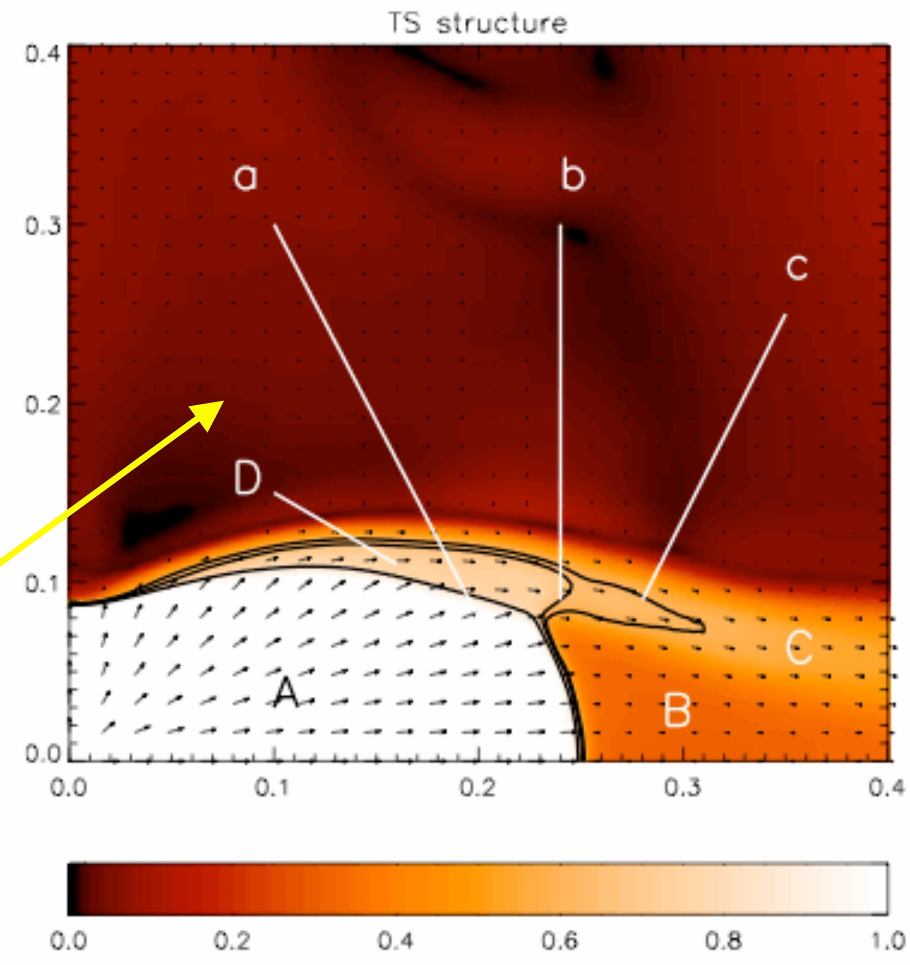
$F \propto \sin^2(\theta)$

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

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

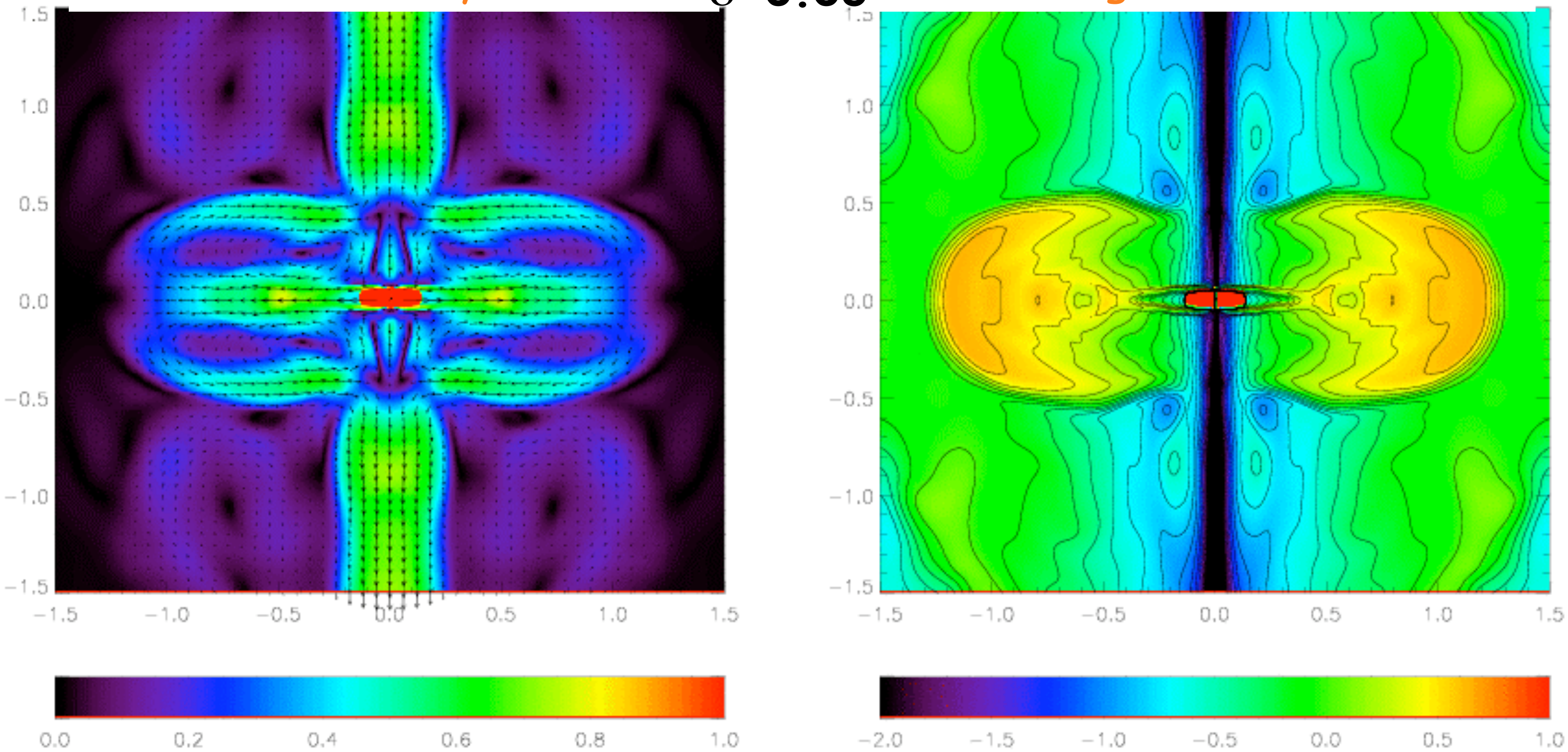
A: ultrarelativistic PSR wind
B: subsonic equatorial outflow
C: supersonic equatorial funnel

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



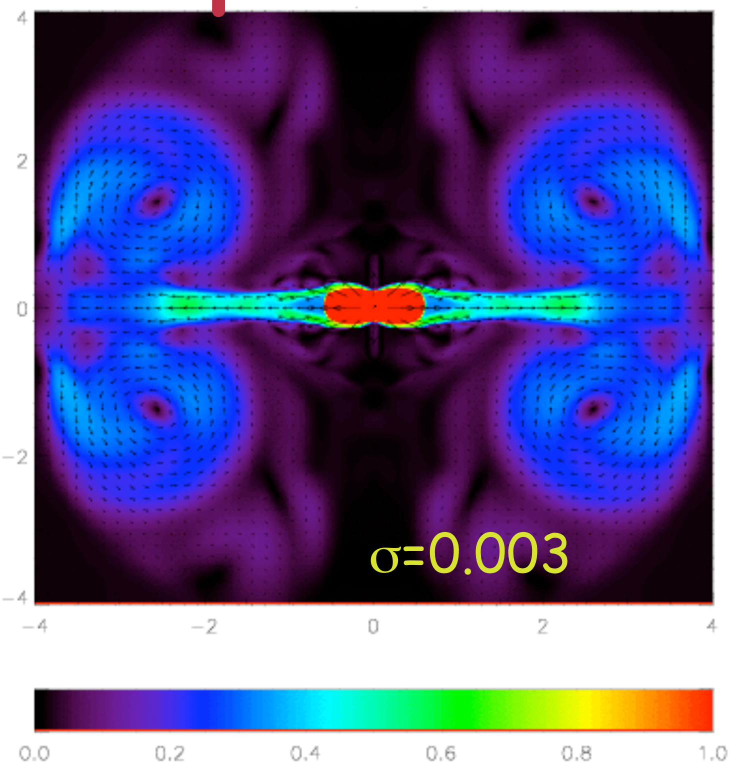
# Flow pattern

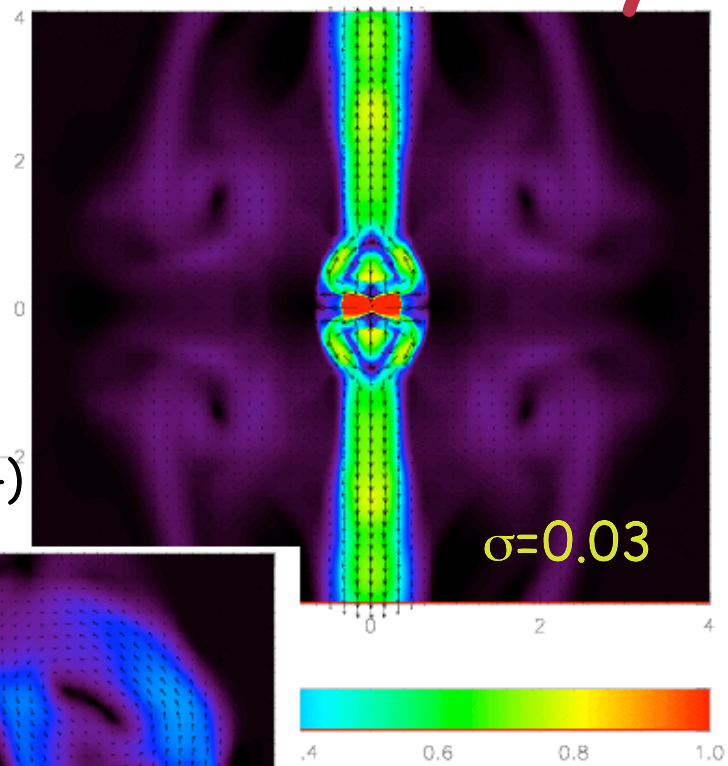
Velocity $\sigma$=0.03 Magnetization



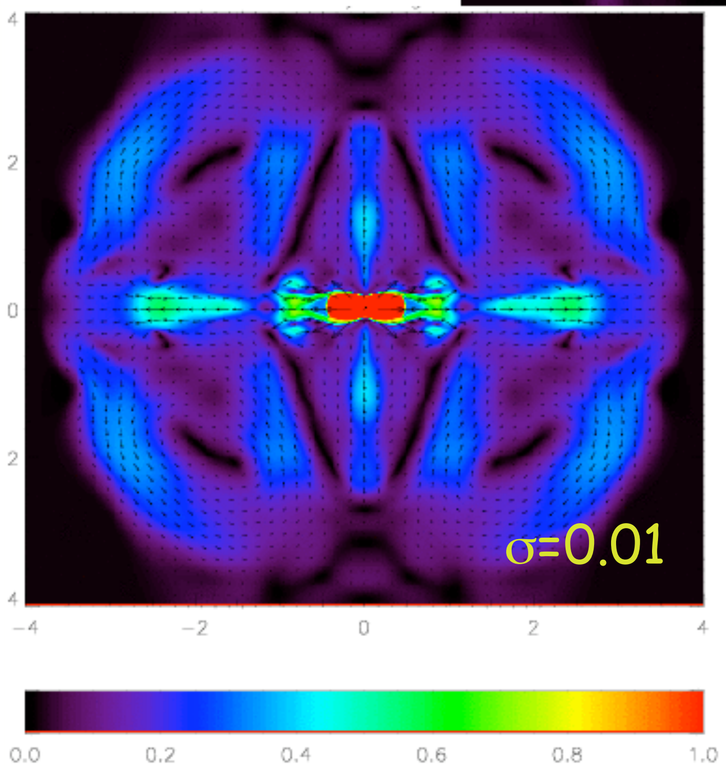

- **For sufficiently high** $\sigma$, equipartition is reached in equatorial region
- Equatorial flow is diverted towards higher latitudes
- A fast channel may then form along the axis

# Dependence on σ of the flow velocity



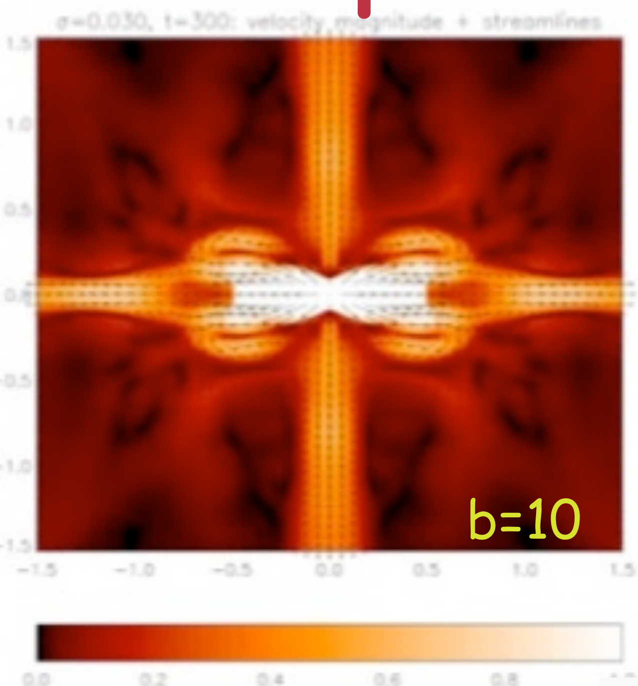

(Del Zanna et al 04)

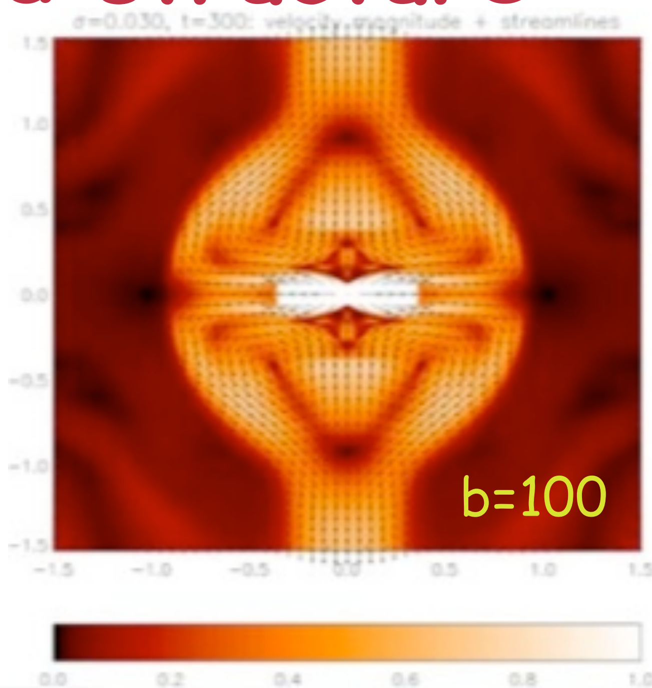



**σ>0.01 required for Jet formation**

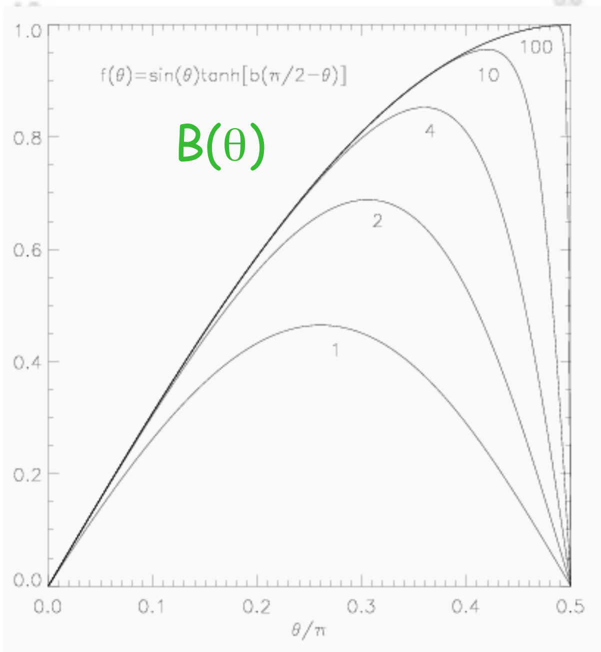
(a factor of 30 larger than within 1D MHD models)

# Dependence on field structure



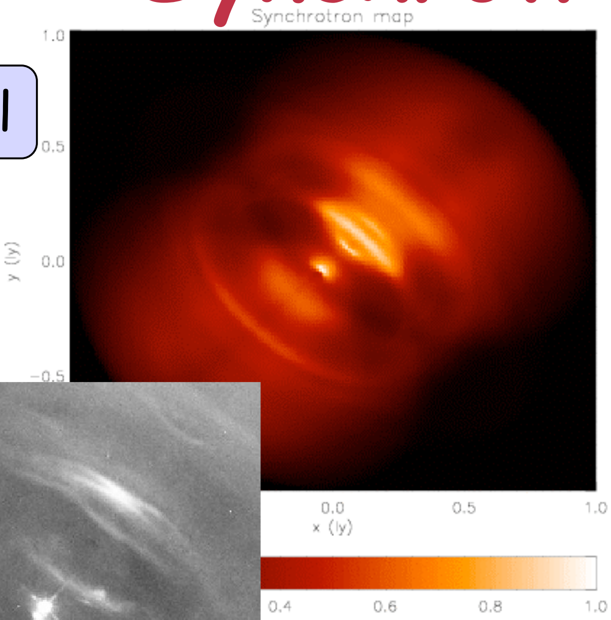



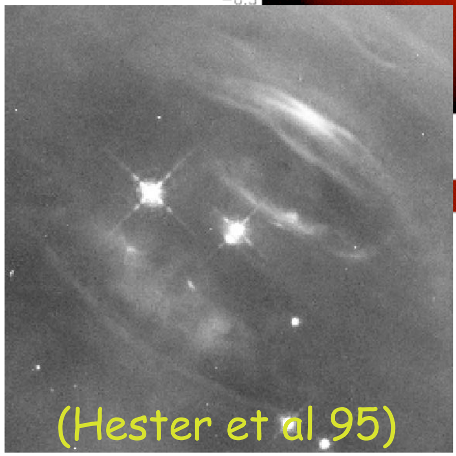

(Del Zanna et al 04)



# Synchrotron Emission maps

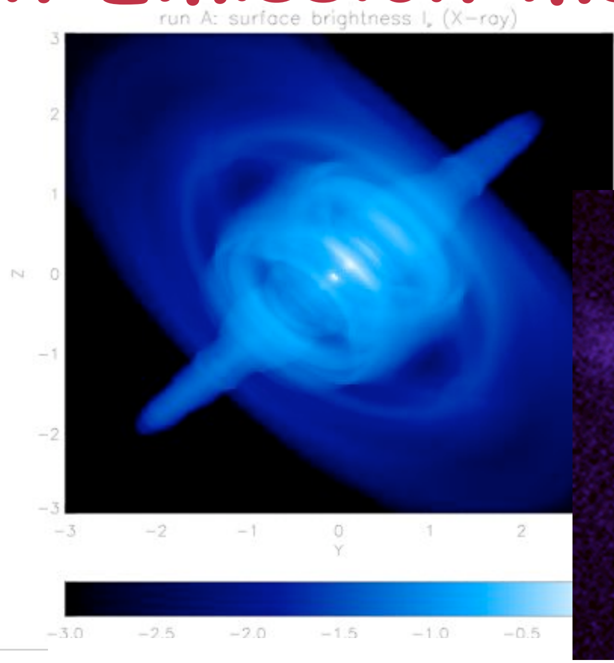
optical



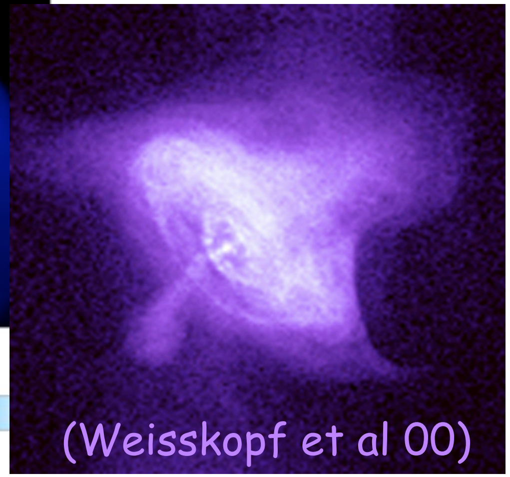



(Hester et al 95)

X-rays

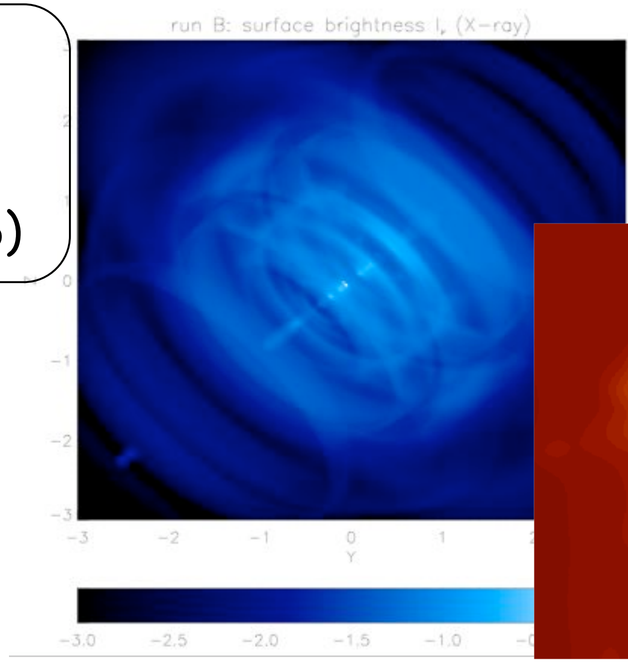



$\sigma$=0.025, b=10

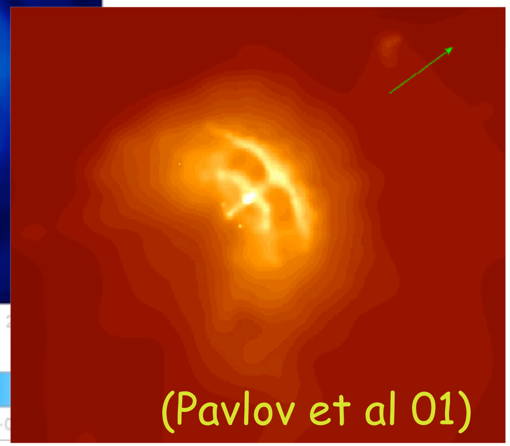


(Weisskopf et al 00)

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




$\sigma$=0.1, b=1

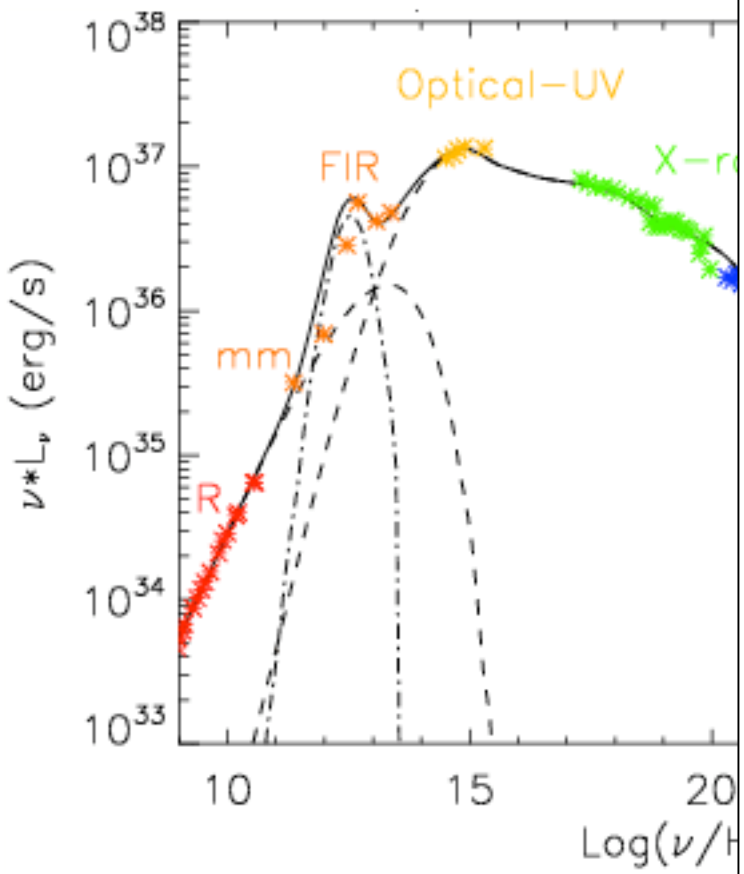


(Pavlov et al 01)

**Between 3 and 15 % of the wind**
**Energy flows with $\sigma$<0.001**

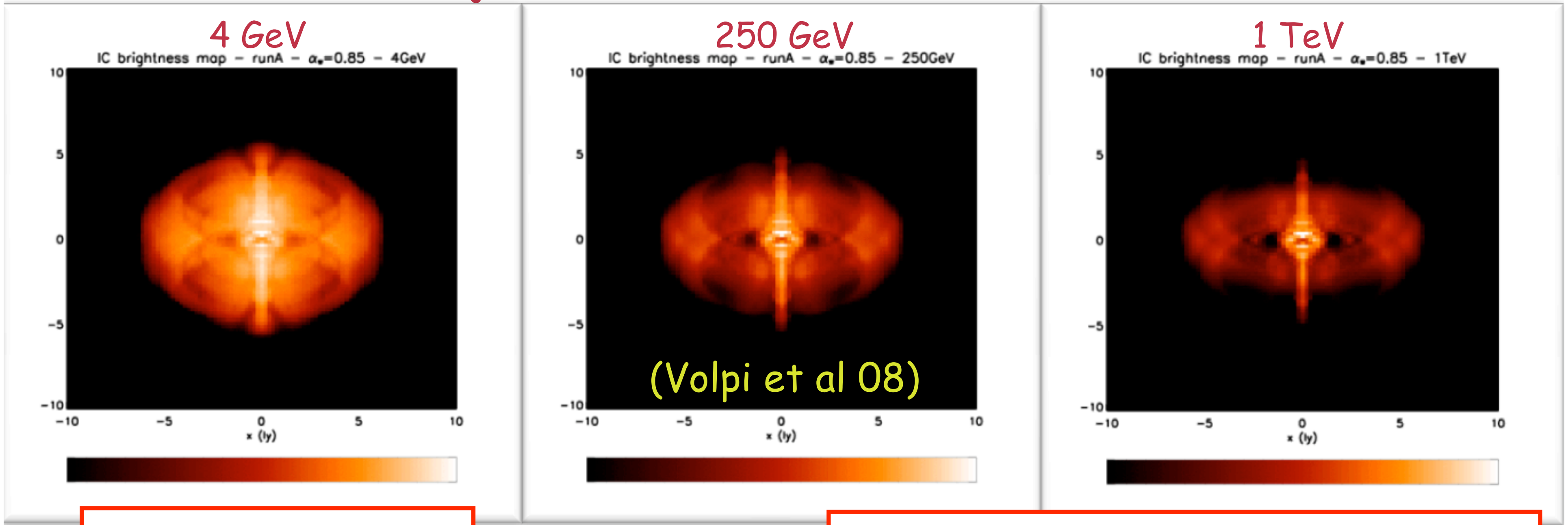
# The Crab Nebula integrated emission spectrum

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



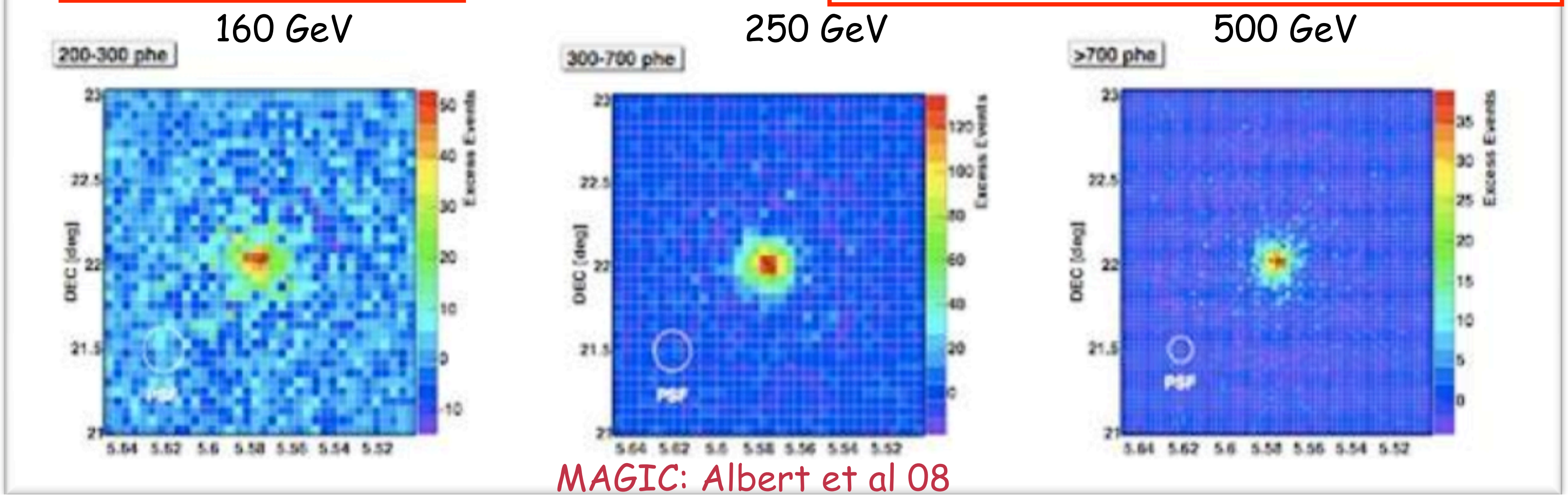

- Optical spectral index maps (Veron-Cetty & Woltjer 92) suggest flatter injection spectrum: $\alpha$~2.2 (but see also Kargaltsev & Pavlov 09)
- Suspicion that particles are loosing too little: average B too low?
- In order to recover total flux number of particles artificially large
- Synchrotron only offers combined information on $n_e$ and B: $L_{syn} \propto n_e B^2$
- But computation of ICS offers additional constraints: $L_{ICS} \propto n_e U_{ph}$

# $\gamma$-ray emission from Crab




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

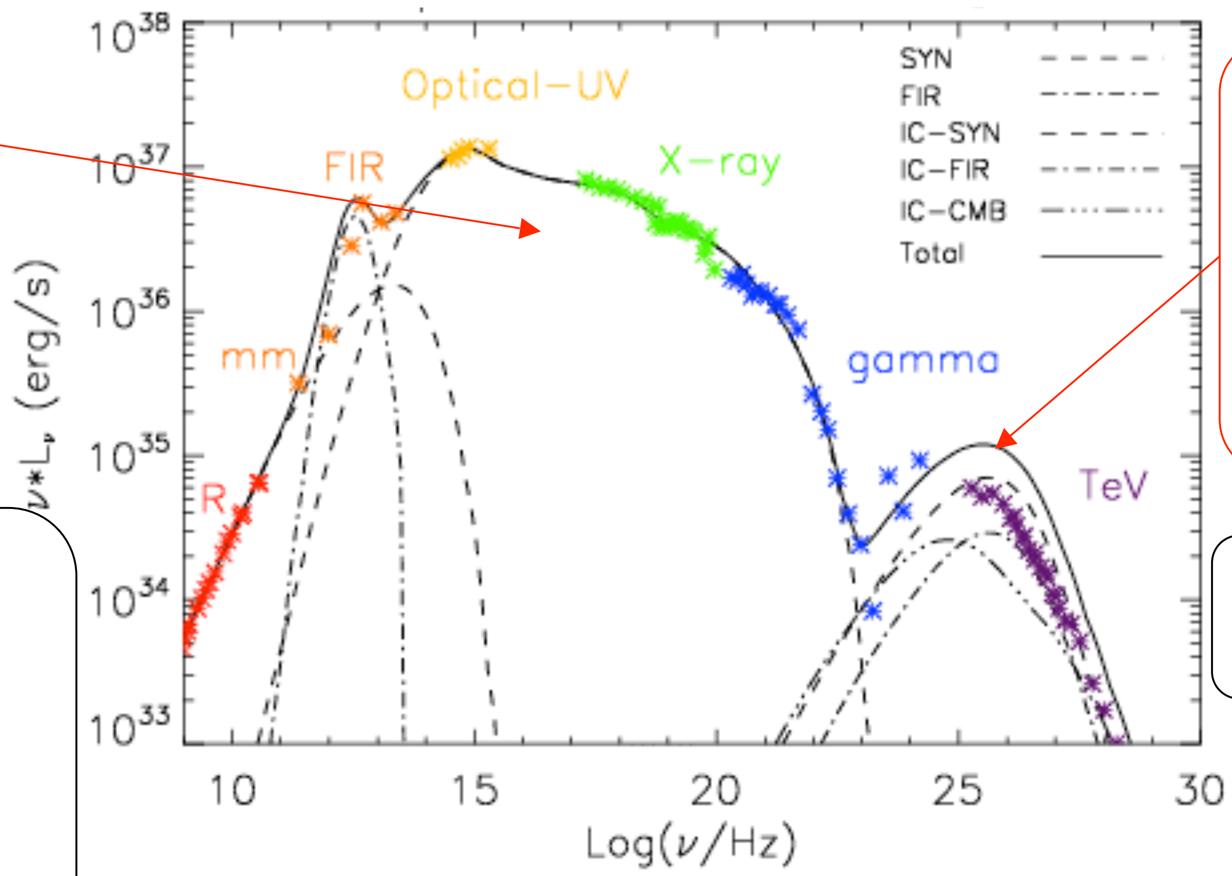
NO shrinkage in equatorial region




MAGIC: Albert et al 08

# 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….**

# 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 ($\Gamma\times\Theta(\mathbf{B}\cdot\mathbf{n})$)
Of the flow

# Particle Acceleration mechanisms

Composition: mostly pairs
Magnetization: $\sigma$>0.001 for most of the flow
Geometry: transverse

## Requirements:

✓Outcome: power-law with $\alpha$~2.2 for optical/X-rays $\alpha$~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

o SDA 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)

o Small fraction of the flow satisfies the low magnetization ($\sigma$<0.001) condition (see MHD simulations)

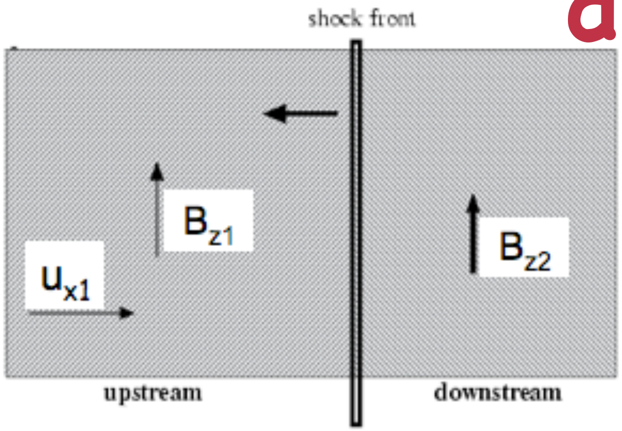
### Magnetic reconnection

- 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

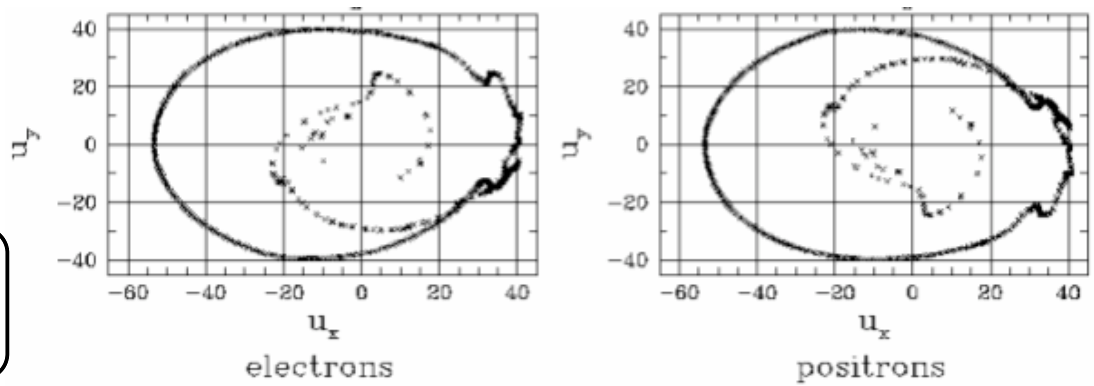
Established to effectively accelerate both $e^+$ and $e^-$ if the pulsar wind is sufficiently cold and ions carry most of its energy
(Hoshino & Arons 91, Hoshino et al. 92, Amato & Arons 06)

# Resonant cyclotron absorption in ion doped plasma




Magnetic reflection mediates the transition

Configuration at the leading edge ~ cold ring in momentum space



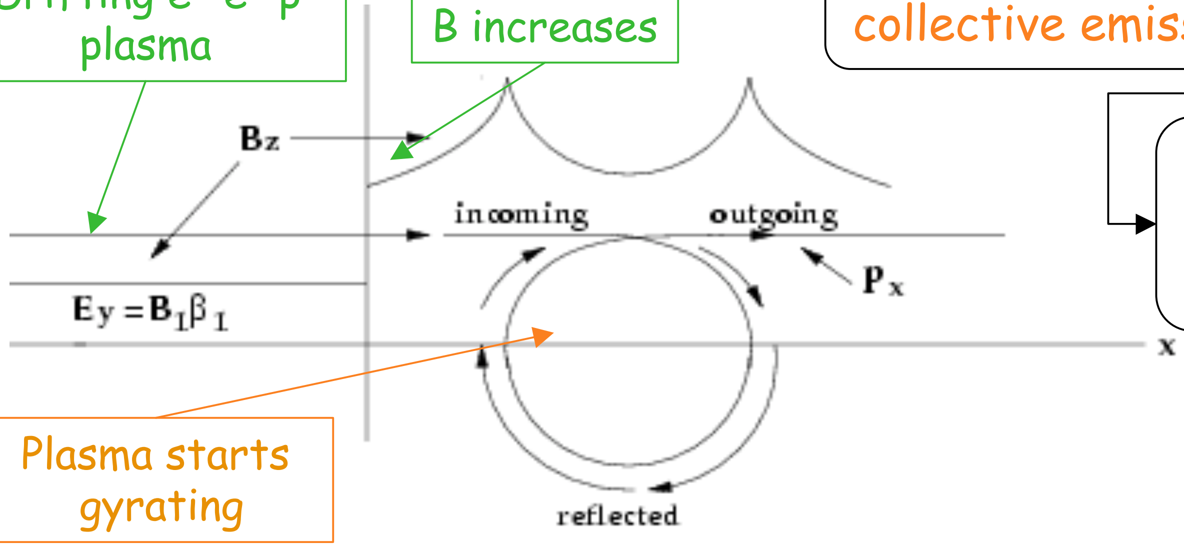

Coherent gyration leads to collective emission of cyclotron waves

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

Ions take their time: $m_i/m_e$ times longer

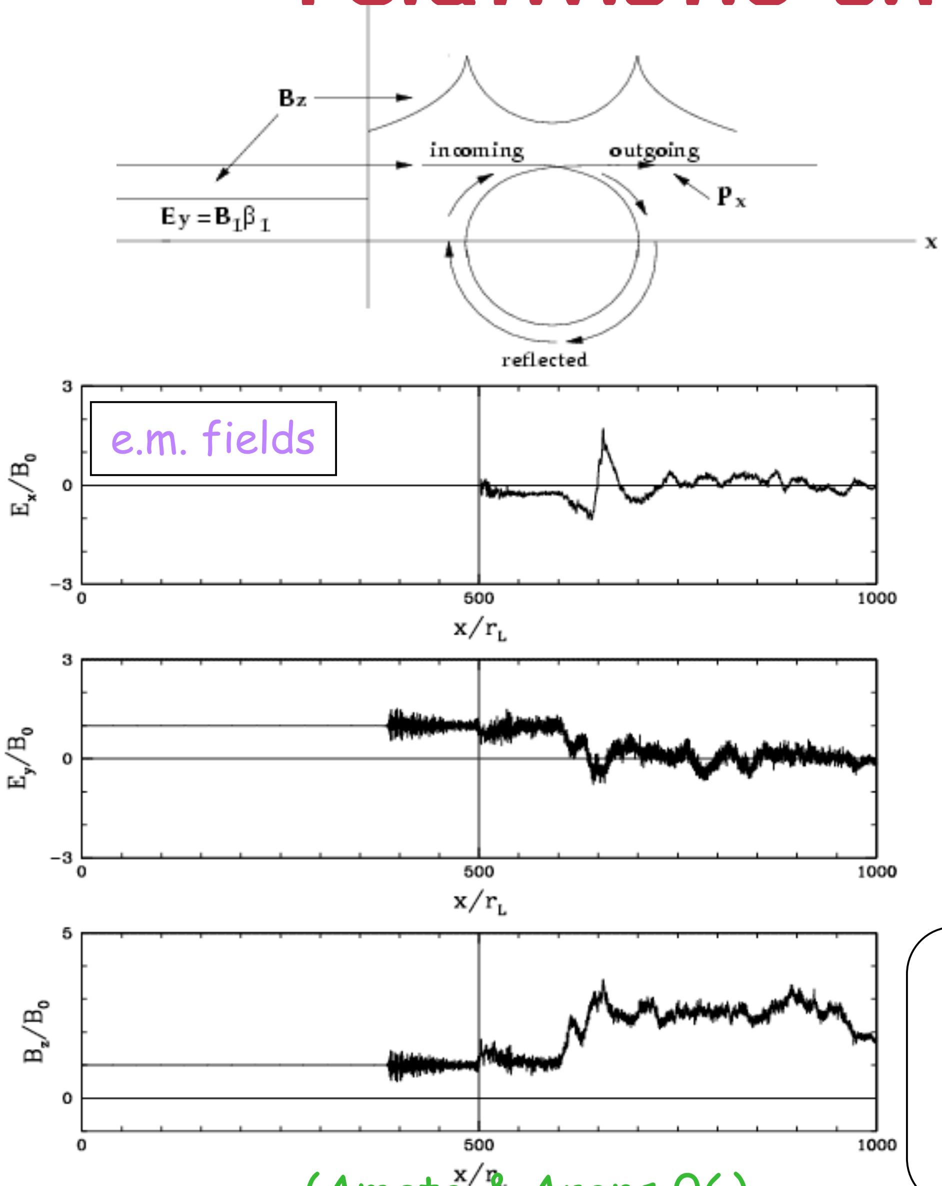
Drifting $e^+$-$e^-$-p plasma

B increases

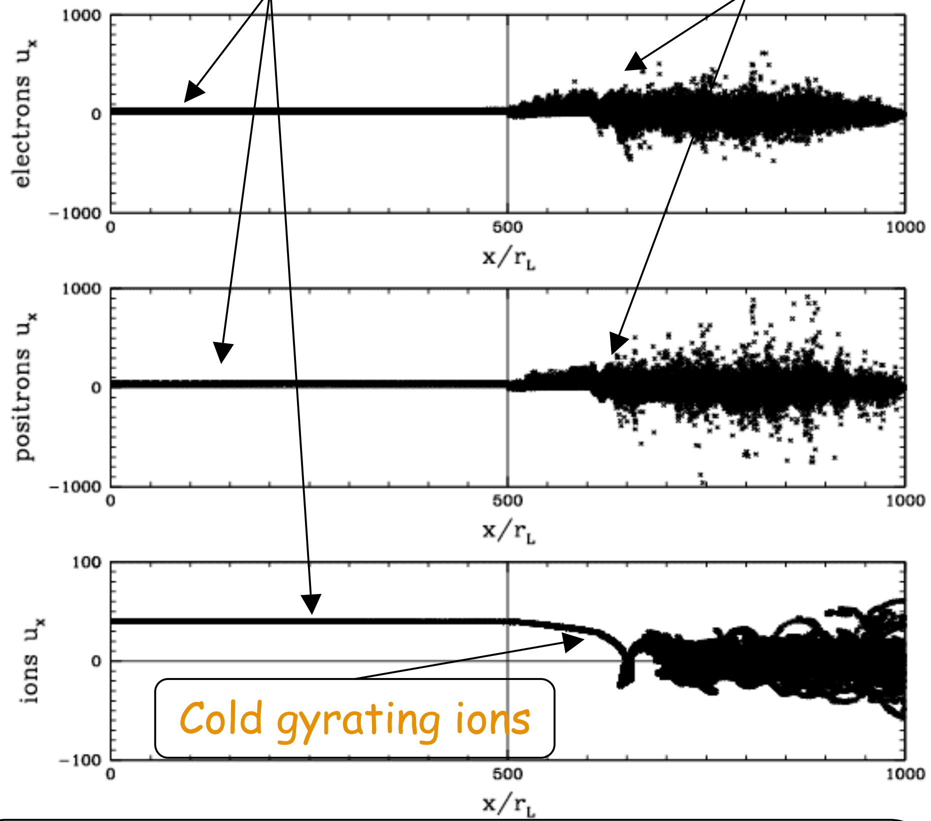



Plasma starts gyrating

# Leading edge of a transverse relativistic shock in 1D PIC




(Amato & Arons 06)




Drifting species

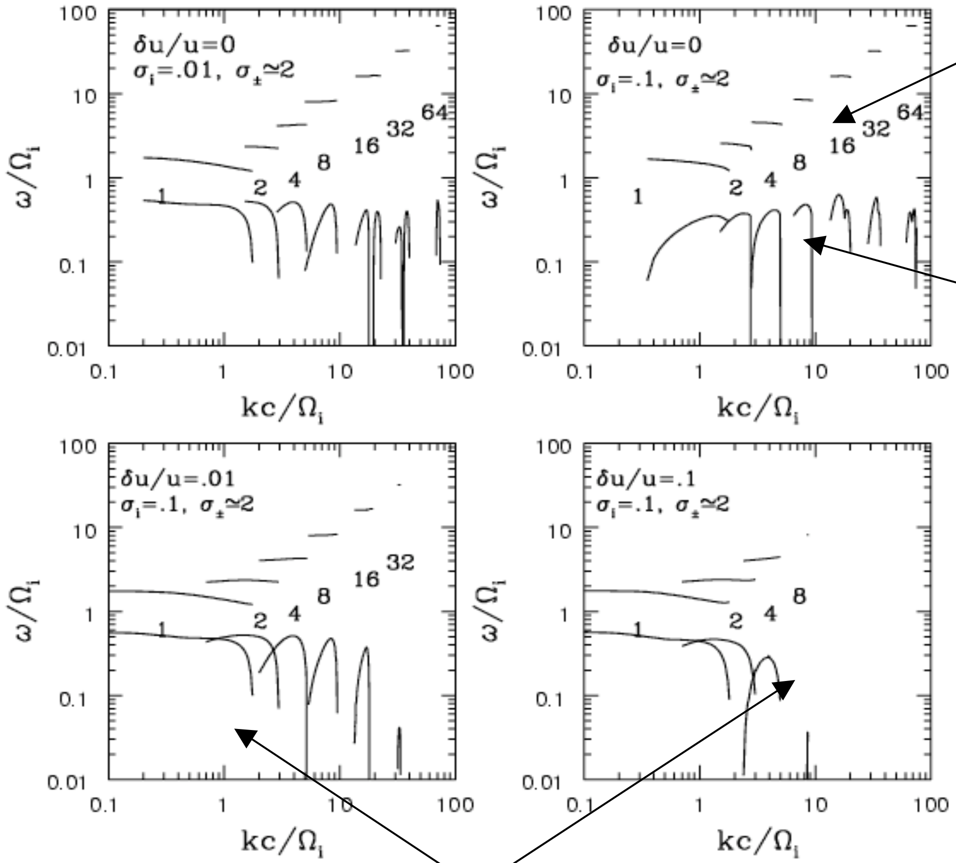
Thermal pairs

Cold gyrating ions

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

Spectrum is cut off at n~u/δu

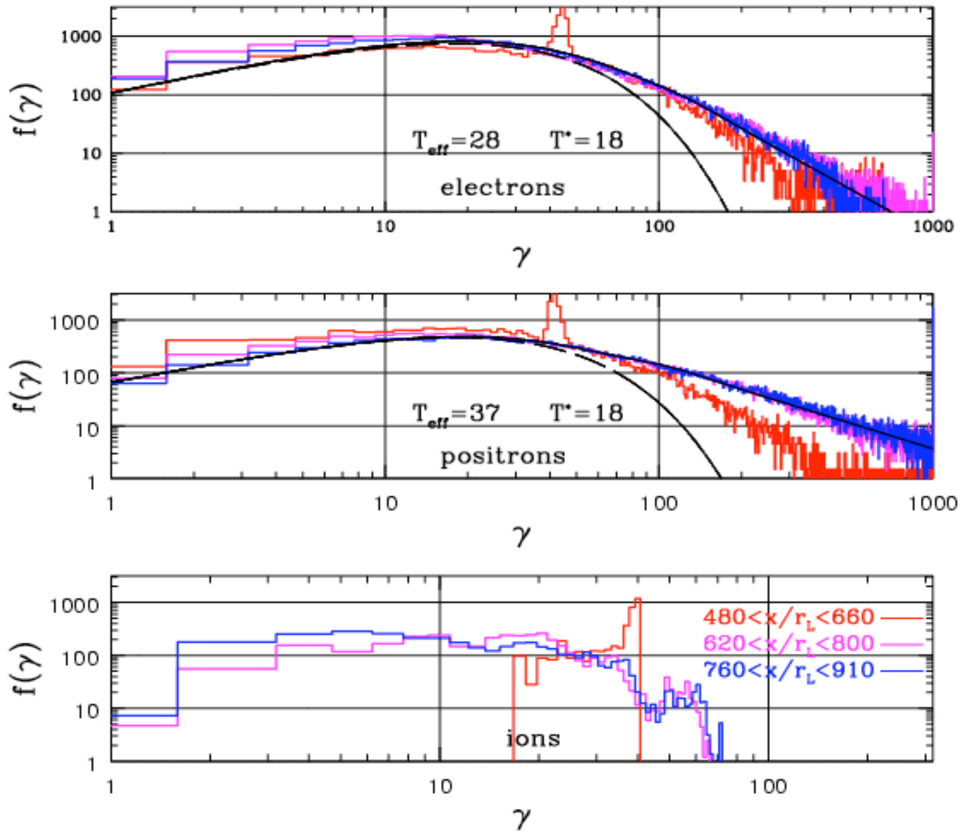
Ion cyclotron frequency
($m_e/m_i \Omega_{ce}$)

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)

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% $m_ic^2\Gamma$ for $U_i/U_{tot}$~60%

~80% $m_ic^2\Gamma$ 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 $\Gamma$~ 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; Komissarov et al 09)

**Puzzle with $\Gamma$**

Radio electrons dominant by number require $(dN/dt)$~$10^{40}$ $s^{-1}$ and $\Gamma$~$10^4$
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

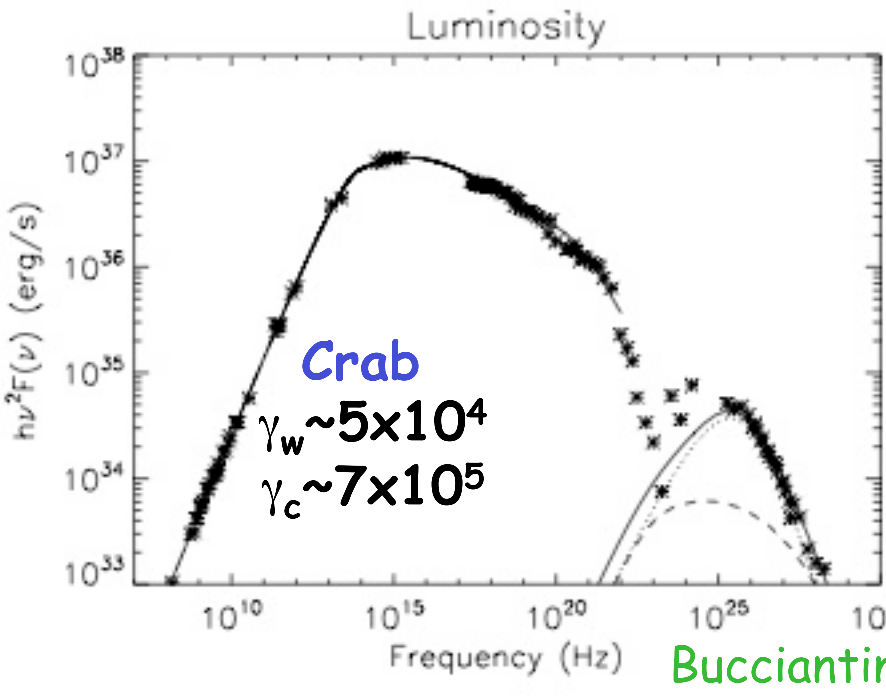
$$\dot{N}(E,t) = C_o(t)(E/\epsilon_c)^{-\gamma_1}\, for\ \epsilon_c < E < \epsilon_v$$
$$\dot{N}(E,t) = C_o(t)(E/\epsilon_c)^{-\gamma_2}\, for\ \epsilon_m < E < \epsilon_c$$

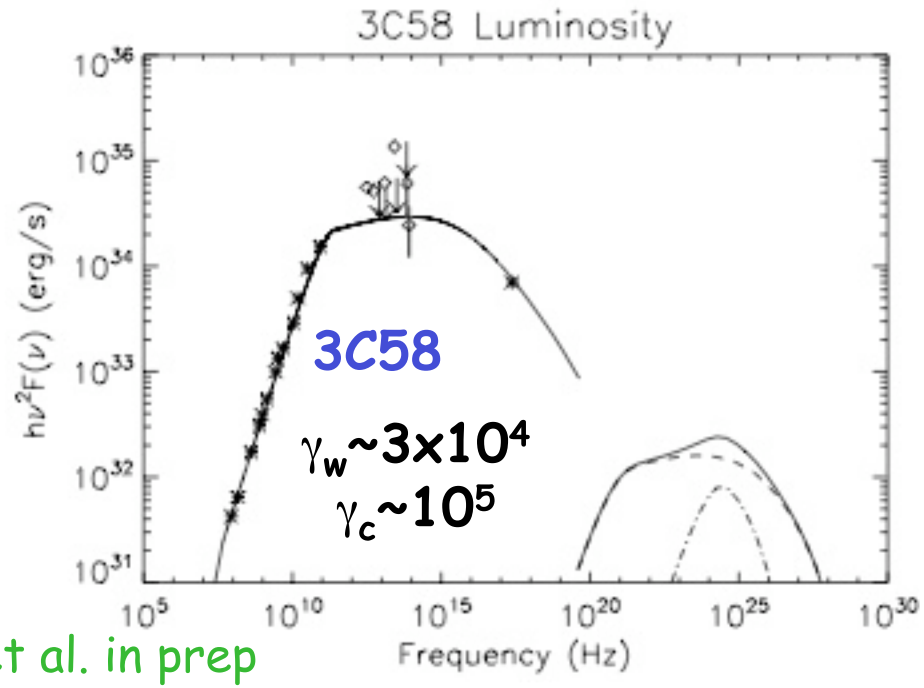
$$\eta_e L(t) = \int_{\epsilon_m}^{\epsilon_v} \dot{N}(E,t) E dE$$

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

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

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




Bucciantini et al. in prep

# Summary and Conclusions

- Nebular dynamics and emission suggest $\sigma$ not so much smaller than 1 after all
- In 2D the synchrotron spectrum seems more complicated than in the 1D picture (multiple changes of slope)
- Even possible to make the entire Crab spectrum with just one "population" of particles?... Implications for PSR theories....
- Or different acceleration mechanisms operate at different latitudes?

## Where to look for answers

RMHD simulations:

- Investigation of the parameters space
- More refined model for the evolution of n(E)
- Introduction of latitude dependence along the shock surface of n(E) (both $\sigma$ and $\Gamma$ are varying with $\theta$)
- What happens if the field is not strictly toroidal

High Energy Observations

- Fermi: Emission spectrum around the synchrotron cut-off and variability
- TeV $\gamma$-rays and neutrinos

**Thank you!**