# PULSARS
# AND
# PULSAR WIND NEBULAE

## Lecture 2


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# OUTLINE OF LECTURE 2

- SUMMARY OF LECTURE 1
- MHD MODELING OF NEBULAE AND THEIR RADIATION
  - 1-D MHD MODELING
  - 2-D MHD MODELING
  - VARIABILITY
- PARTICLE ACCELERATION AT THE MOST RELATIVISTIC SHOCKS IN NATURE
- OLD NEBULAE, FAST PULSARS AND THE ELECTRON-POSITRON EXCESS IN COSMIC RAYS

# SUMMARY
# OF
# LECTURE 1

# PULSARS CANNOT BE SURROUNDED BY VACUUM

- **A COROTATING MAGNETOSPHERE DEVELOPS**
- **COROTATION CANNOT EXTEND BEYON $R_{LC}$**
- **NOT ALL FIELD LINES CAN BE CLOSED**
- **PARTICLES LEAVE THE STAR ALONG OPEN FIELD LINES**

QuickTime™ and a
decompressor
are needed to see this picture.

**THE SYSTEM TRIES TO ACHIEVE $E_{//}$=0 EVERYWHERE BUT THIS IS NOT POSSIBLE WITH ONLY CHARGES FROM STAR SURFACE**

# THE WIND ZONE

$$J_{GJ} = c\rho_{GJ} = \frac{\vec{\Omega}\cdot\vec{B}}{2\pi}$$

ACTS AS SOURCE OF TOROIDAL FIELD: $B_T$ COMPARABLE TO $B_P$ AT THE LIGHT CYLINDER

AT LARGER DISTANCES FIELD LINES ARE OPEN: $B_P$ MONOPOLE LIKE

$$B_p = B_r = B_{LC}\left(\frac{R_{LC}}{r}\right)^2$$

$$B_\phi = \pm B_{LC}\left(\frac{R_{LC}}{r}\right)\sin\theta$$

TOROIDAL FIELD BECOMES DOMINANT

$$\dot{E} = \frac{c}{4\pi}4\pi R_{LC}^2\left(\vec{E}\times\vec{B}\right)_{R_{LC}} = cR_{LC}^2B_{LC}^2$$

$$\dot{E} = cB_*^2R_*^2\left(\frac{R_*^4\Omega^4}{c^4}\right)$$

~SAME AS FOR OBLIQUE DIPOLE IN VACUUM

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# PULSAR SPIN DOWN

FOR ARBITRARY INCLINATION α BETWEEN **B** AND **Ω**

$$\dot{E} = cB_*^2 R_*^2 \left(\frac{R_* \Omega}{c}\right)^4 (1+\sin^2\alpha)$$

$$\dot{E} = I\Omega\dot{\Omega} = -a\Omega^4$$

MORE GENERALLY: $\dot{\Omega} = -a\Omega^n \qquad \dot{\mathrm{E}} = I\Omega\dot{\Omega} = aI\Omega^{n+1}$

AFTER INTEGRATION $\Omega(t) = \dfrac{\Omega_0}{[1+t/\tau_0]^{1/(n-1)}} \qquad \tau_0 = \dfrac{\Omega_0^{1-n}}{a(n-1)}$

$$\Rightarrow \dot{E} = \frac{aI\Omega_0^{n+1}}{[1+t/\tau_0]^{\frac{n+1}{n-1}}}$$

n=BRAKING INDEX.
n=3 FOR A DIPOLE FIELD
AND <3 FOR OTHER CASES

DERIVING n IMPLIES MEASURING $d^2P/dt^2$
MEASURED FOR 4 PSRs ONLY: ALWAYS LESS THAN 3!!!!

# AVAILABLE POTENTIAL

$$\dot{E} \approx cB_*^2 R_*^2 \left(\frac{R_*\Omega}{c}\right)^4$$

$$\Phi = \frac{1}{2}\left(\frac{\Omega R_*}{c}\right)^2 R_* B_*$$

$$\Rightarrow \quad \Phi \approx \sqrt{\frac{\dot{E}}{c}} \quad \Rightarrow \quad E_{max} = e\Phi = 2\times 10^{15}\frac{B_{12}}{P_{100}^2} eV$$

UNSCREENED POTENTIAL $\Rightarrow$
ACCELERATION TO E»"KNEE"

- **WHERE THERE IS UNSCREENED $E_{//}$ PARTICLES ARE QUICKLY ACCELERATED TO RELATIVISTIC ENERGIES**
- **A PAIR CASCADE IS INITIATED**

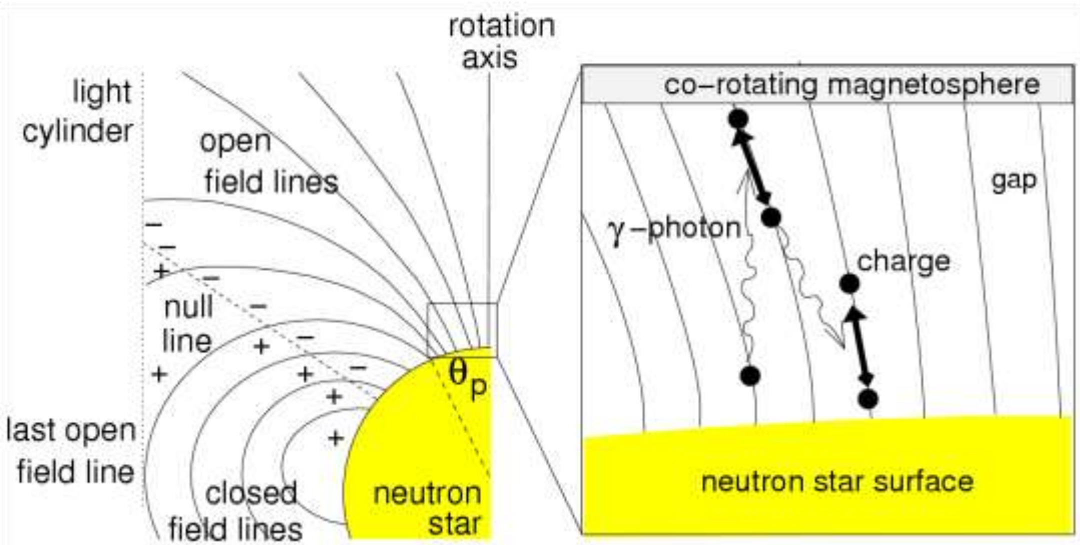
$e^-$ $\Rightarrow$ [Curvature or ICS on star X-rays] $\Rightarrow$ $\gamma$ ($E\gamma$>50 MeV) $\Rightarrow$ $\gamma + B \rightarrow e^+ + e^-$

$\gamma_{primary} \sim 10^7$ $\qquad$ $\gamma_{secondary} \sim 10^{2-3}$

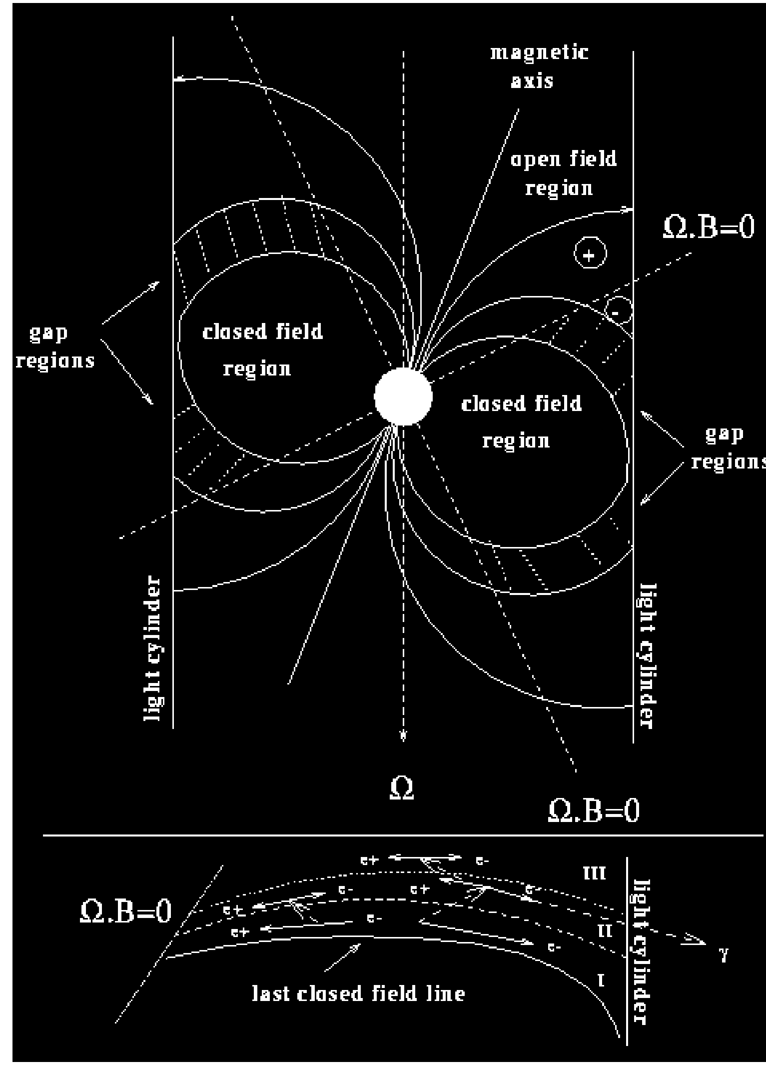
- **CASCADES OVERSHOOT $\eta_{GJ}$.**
- **BY HOW MUCH DEPENDS ON MODEL.**
- **MULTIPLICITY?**

# PAIR PRODUCTION SITES

## POLAR CAPS




## OUTER GAPS

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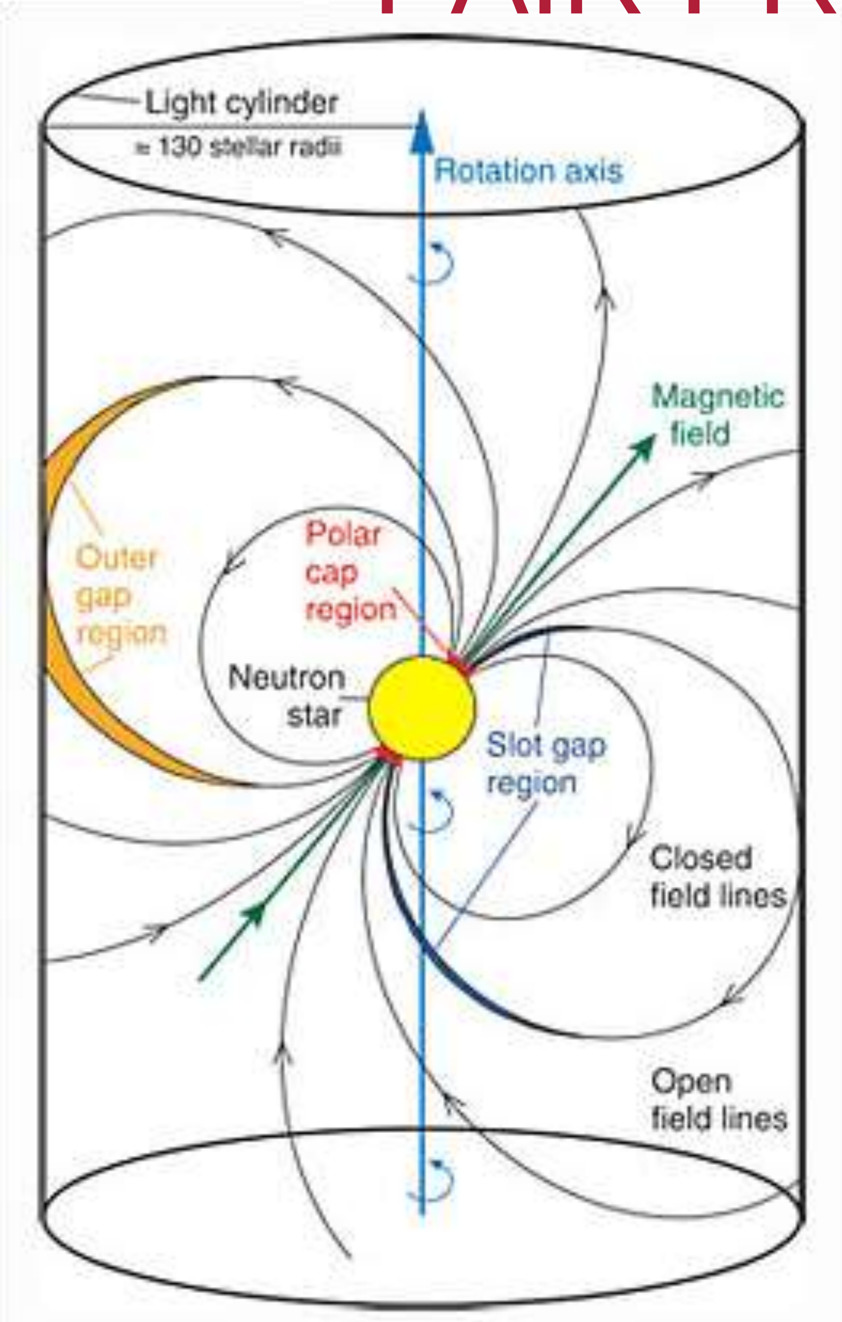
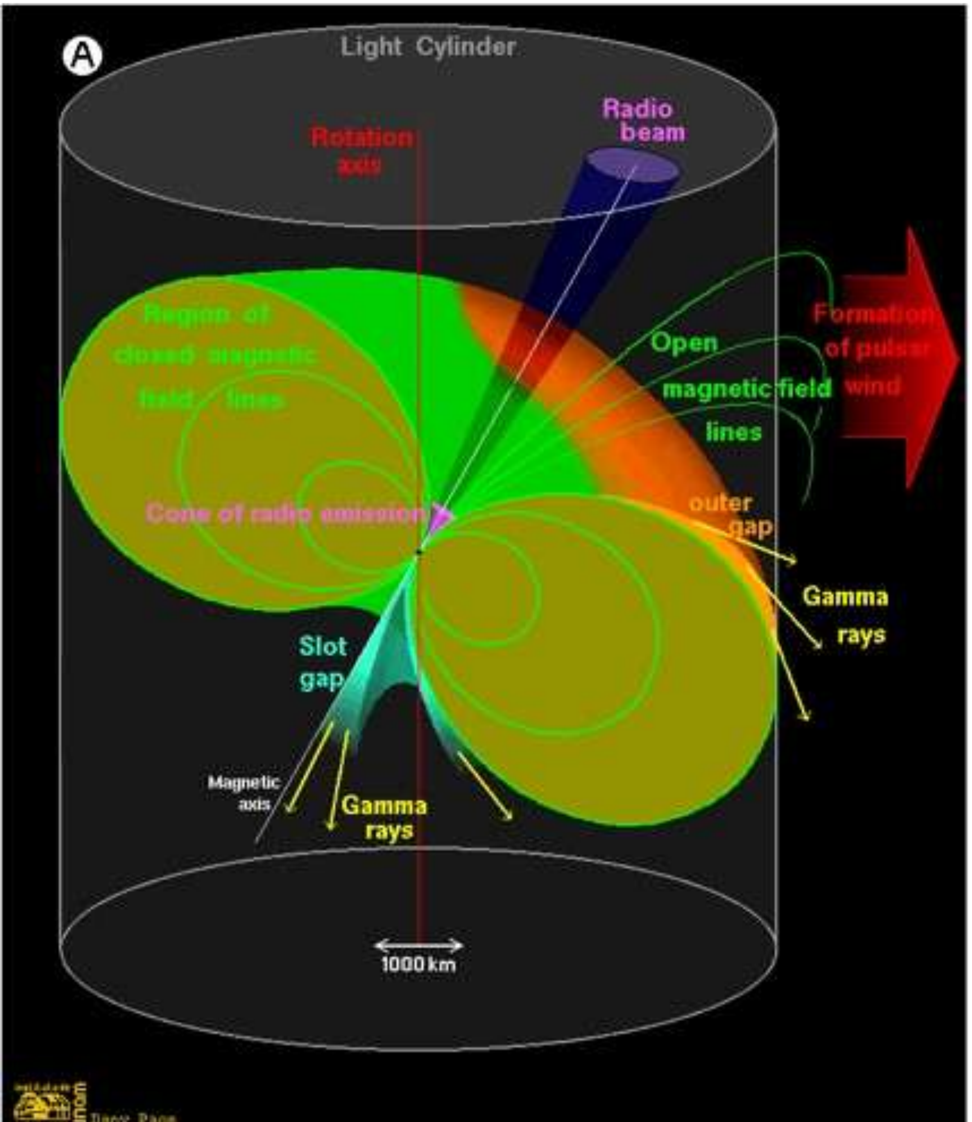
## SLOT GAPS

# PAIR PRODUCTION AND γ-RAY EMISSION

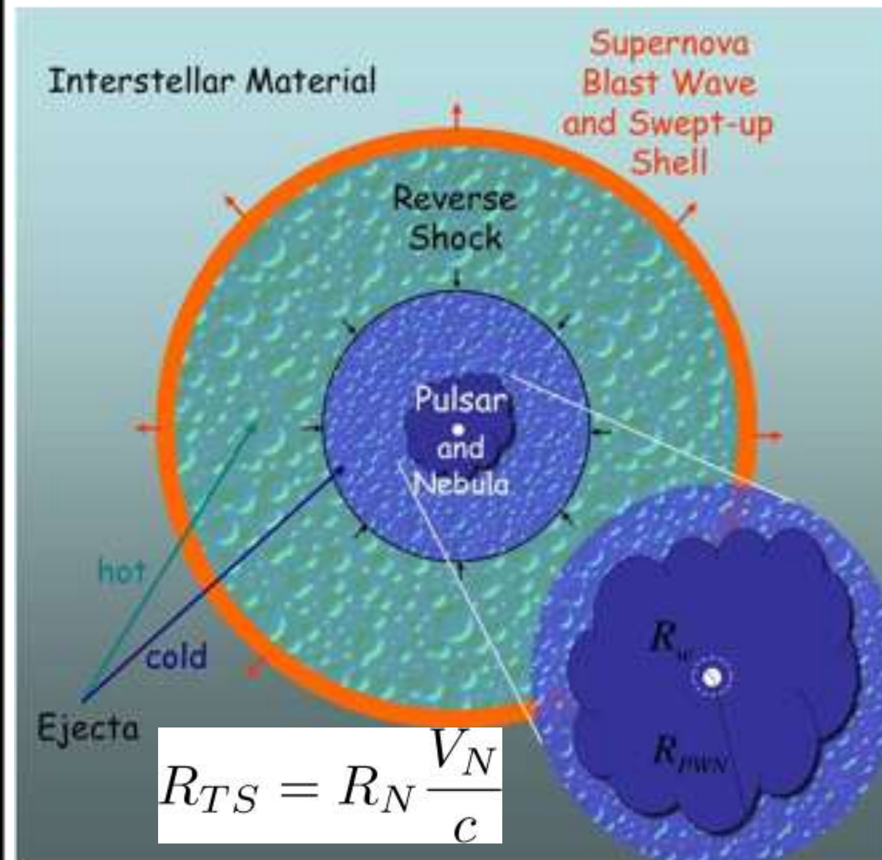



- USE γ-RAYS TO LEARN ABOUT PAIR PRODUCTION
- POLAR CAPS MODELS,THE ONES WITH CLEAREST PREDICTIONS ON MULTIPLICITY, EXCLUDED AS MAIN SOURCE OF γ-RAYS
- SLOT GAPS AND OUTER GAPS ARE HEAVILY CHALLENGED BY NEW OBSERVATIONS AND FORCE-FREE SIMULATIONS
- FORCE-FREE IS BETTER APPROX THAN VACUUM

# FOLLOW THE ENERGY




## MOST PULSAR ENERGY GOES INTO PWN




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

# THE WIND ENERGY

$$\dot{E}_R = \frac{B_0^2 R_0^6 \Omega^4}{c^3} = \int d\vec{S}\left[\frac{c}{4\pi}\vec{E}\times\vec{B} + \Gamma_{wind}\left(n_\pm m_e + n_i m_i\right)c^3\right]$$

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

WE MEASURE IT

$$\dot{N}_{GJ} \approx \pi R_0^2 \vartheta_p^2 c\left|\frac{\eta_{GJ0}}{e}\right| \approx 3\times 10^{32}\frac{\mu_{30}}{P_{100}^2}\, s^{-1}$$

DEPENDS ONLY ON MEASURED PSR PARAMETERS

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

CAN BE EVALUATED FROM PWN SYNC. EMISSION KNOWING B

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

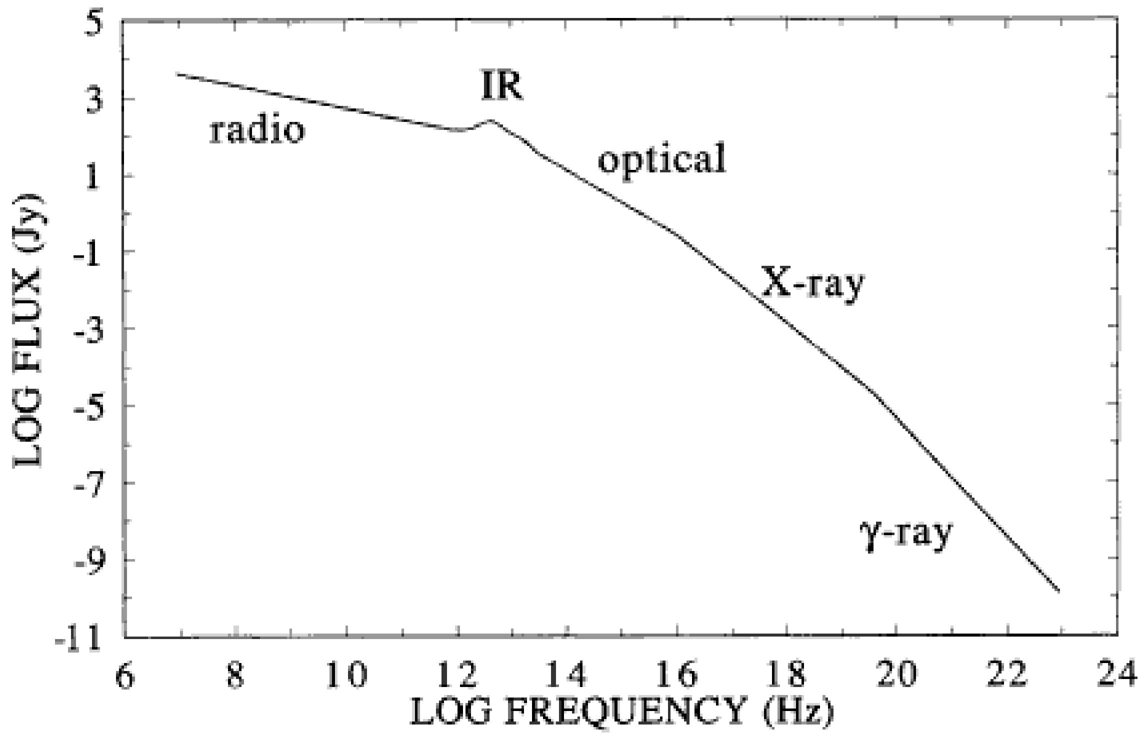
MUST BE LARGE AT LC: $\sigma \approx 10^4$-$10^6$

PROBABLY SMALL IN THE PWN

BASED ON MHD MODELING

# MAGNETIC FIELD IN NON-THERMAL SOURCES

- **EQUIPARTITION**
- **SYNCHROTRON AGE BREAK**
- **RATIO BETWEEN ICS AND SYNCHROTRON EMISSION**



# AFTER ESTIMATING MAGNETIC FIELD

**IN CRAB:** $B_{eq} \approx 300\ \mu G$

$\Downarrow$

**RADIO EMITTING PARTICLES HAVE** $\gamma \approx 10^4$

**THEIR EMISSION CORRESPONDS TO** $\dot{N} \approx 10^{40}\ s^{-1}$

$\Downarrow$

$$\boxed{\Gamma_w \approx 10^4 \qquad k \approx 10^6}$$

IONS CANNOT DOMINATE THE ENERGY

**BUT**

**X-RAY EMITTING PARTICLES IN SAME FIELD:**

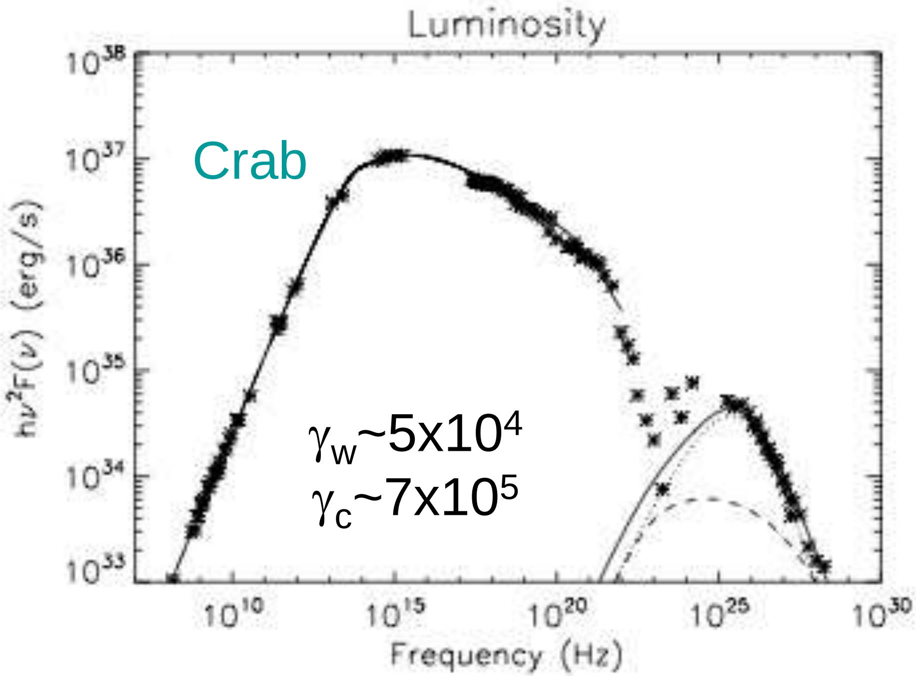
$$\boxed{\Gamma_w \approx 10^6 \qquad k \approx 10^4}$$

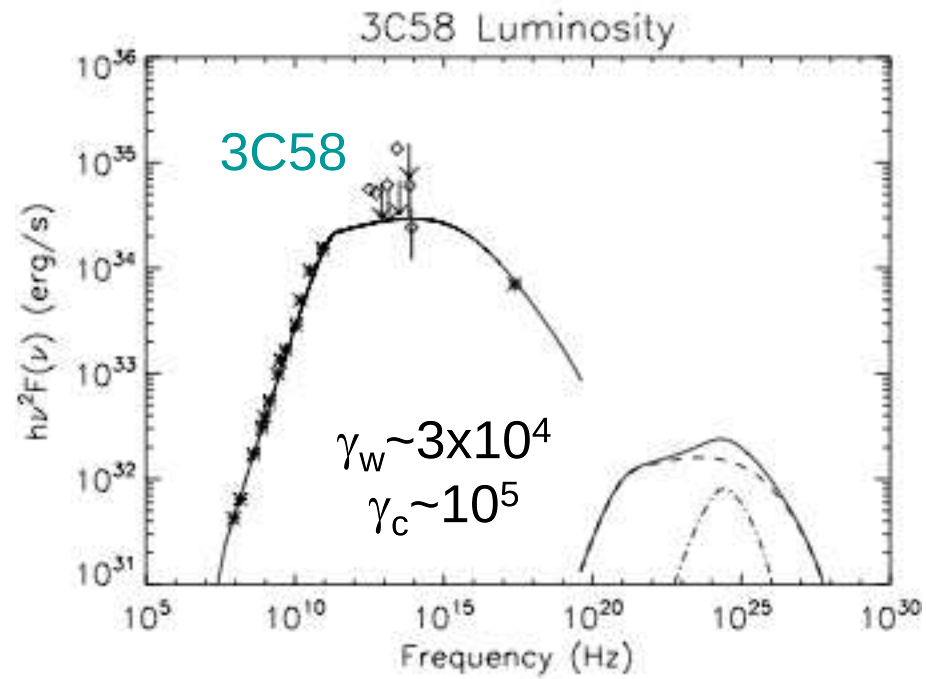
PeV IONS COULD DOMINATE THE ENERGY

# 1-ZONE MODELS FOR THE PWN EVOLUTION

**CHANGING PULSAR INPUT**

**EVOLUTION OF PARTICLES AND MAGNETIC FIELD**

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decompressor
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Bucciantini, Arons, Amato 2012

# HOW TO MAKE PROGRESS

- **1-ZONE MODELS SUGGEST HIGH MULTIPLICITIES**
- **THEY CANNOT BE CONSIDERED CONCLUSIVE:**

**ASSUMPTIONS ON WIND EVOLUTION MIGHT BE FLAWED**

- **THEY ONLY PROVIDE INFO ON AVERAGE QUANTITIES**
- **THEY DO NOT REALLY PROVIDE INFO ON $\sigma$**

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decompressor
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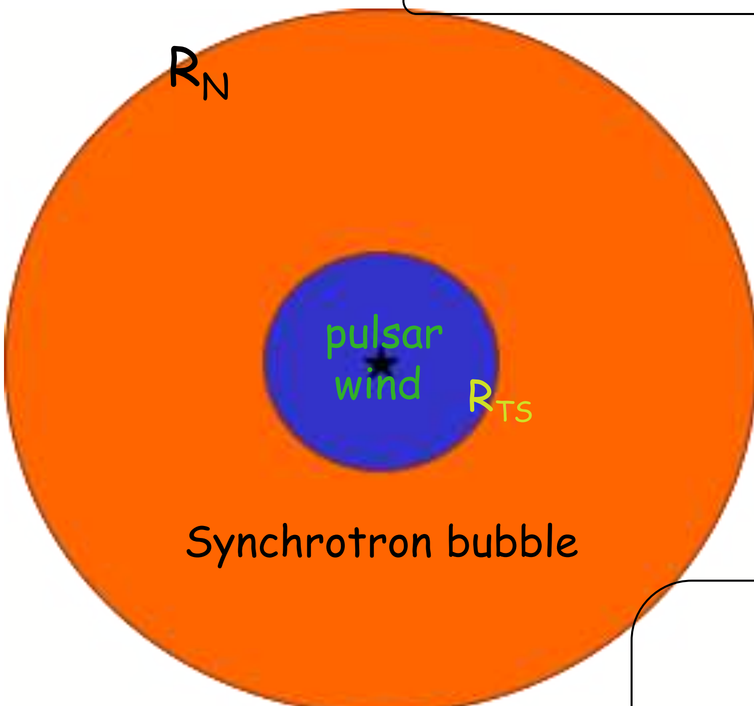
**DETAILED MHD MODELING WHEN POSSIBLE**

# MHD MODELS OF PWNe: ASSUMPTIONS

**1-D STEADY-STATE HD** (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
- STRONG PERP. REL. SHOCK
- SUBSONIC FLOW IN THE NEBULA
- PARTICLE ACCELERATION AT THE TS
- SYNCHROTRON LOSSES THEREAFTER

**MAIN FREE PARAMETERS**

- **WIND MAGNETIZATION** $\sigma = B^2/(4\pi nmc^2\Gamma^2)$
- **LORENTZ FACTOR** $\Gamma$
- **PARTICLE SPECTRAL INDEX** $\alpha$

# THE KENNEL AND CORONITI MODEL

(Kennel & Coroniti, 1984a, 1984b)

**FREE PARAMETERS**

**WIND MAGNETIZATION**

$\sigma = B^2/(4\pi n m c^2 \Gamma^2)$

**LORENTZ FACTOR** $\Gamma$

**SPECTRAL INDEX** $\alpha$

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decompressor
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YUV420 codec decompressor
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# RELATIVISTIC MHD EQUATIONS IN SPHERICAL SYMMETRY

$$\boxed{\frac{\partial}{\partial t}=0}$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\, n\, u\right)=0$$

CONSERVATION OF PARTICLE NUMBER

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{ruB}{\gamma}\right)=0$$

INDUCTION EQUATION

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(w\,u^2+p+\frac{B^2}{8\pi}\left(1+\frac{u^2}{\gamma^2}\right)\right)\right]-\frac{2p}{r}=0$$

MOMENTUM CONSERVATION

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(w\,\gamma\,u+\frac{B^2}{4\pi}\frac{u}{\gamma}\right)\right]=0$$

ENERGY CONSERVATION

# JUMP CONDITIONS AT A RELATIVISTIC SHOCK

$$(1)\quad \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 n u\right)=0 \qquad (3)\quad \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(w u^2 + p + \frac{B^2}{8\pi}\left(1+\frac{u^2}{\gamma^2}\right)\right)\right]-\frac{2p}{r}=0$$

$$(2)\quad \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{ruB}{\gamma}\right)=0 \qquad (4)\quad \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(w\gamma u + \frac{B^2}{4\pi}\frac{u}{\gamma}\right)\right]=0$$

SHOCK IS ASSUMED STEADY STATE

INTEGRATE EQUATIONS ACROSS THE SHOCK: $\Delta x \to 0$

$$n_1 u_1 = n_2 u_2 \qquad \frac{u_1 B_1}{\gamma_1}=\frac{u_2 B_2}{\gamma_2}$$

$$\boxed{\mu=\frac{w}{n}}$$

$$\mu_1 n_1 u_1^2 + p_1 + \frac{B_1^2}{8\pi}\left(1+\frac{u_1^2}{\gamma_1^2}\right)=\mu_2 n_2 u_2^2 + p_2 + \frac{B_2^2}{8\pi}\left(1+\frac{u_2^2}{\gamma_2^2}\right)$$

$$\mu_1 n_1 u_1 \gamma_1 + \frac{B_1^2}{4\pi}\frac{u_1}{\gamma_1}=\mu_2 n_2 u_2 \gamma_2 + \frac{B_2^2}{4\pi}\frac{u_2}{\gamma_2}$$

# THE SHOCK JUMP

**ASSUMPTIONS:**

- HIGHLY RELATIVISTIC SHOCK
- UPSTREAM FLUID IS COLD

$$\gamma_1 >> 1 \Rightarrow u_1 \approx \gamma_1$$

$$\frac{p_1}{n_1 m c^2} \to 0, \quad \mu_1 \to mc^2$$

$$\boxed{\sigma = \frac{B_1^2}{4\pi n_1 u_1 \gamma_1 m c^2}}$$

$$u_2^2 = \frac{1}{2}\left\{\frac{8\sigma^2 + 10\sigma + 1}{8(1+\sigma)} \pm \sqrt{\left(\frac{8\sigma^2 + 10\sigma + 1}{8(1+\sigma)}\right)^2 - \frac{\sigma^2}{2(1+\sigma)}}\right\}$$

IMPOSING POSITIVE DOWNSTREAM PRESSURE ALLOWS TO SELECT CORRECT SOLUTION

$$u_2^2 = \frac{1}{2}\left\{\frac{8\sigma^2 + 10\sigma + 1}{8(1+\sigma)} \pm \sqrt{\left(\frac{8\sigma^2 + 10\sigma + 1}{8(1+\sigma)}\right)^2 - \frac{\sigma^2}{2(1+\sigma)}}\right\} \qquad \gamma_2 = \sqrt{1 + u_2^2}$$

$$\frac{p_2}{n_1 m c^2 \gamma_1^2} = \frac{1}{4 u_2 \gamma_2}\left[1 + \sigma\left(1 - \frac{\gamma_2}{u_2}\right) - \frac{\gamma_2}{\gamma_1}\right] \qquad \frac{B_2}{B_1} = \frac{\gamma_2}{u_2}$$

# LARGE AND SMALL σ

$$u_2^2 = \frac{1}{2}\left\{\frac{8\sigma^2+10\sigma+1}{8(1+\sigma)} \pm \sqrt{\left(\frac{8\sigma^2+10\sigma+1}{8(1+\sigma)}\right)^2 - \frac{\sigma^2}{2(1+\sigma)}}\right\} \qquad \gamma_2 = \sqrt{1+u_2^2}$$

$$\frac{p_2}{n_1 mc^2\gamma_1^2} = \frac{1}{4u_2\gamma_2}\left[1+\sigma\left(1-\frac{\gamma_2}{u_2}\right)-\frac{\gamma_2}{\gamma_1}\right] \qquad \frac{B_2}{B_1} = \frac{\gamma_2}{u_2}$$

## IF B-FIELD DOMINATES DYNAMICS:

$\sigma \to \infty$

$$u_2^2 \to \sigma + \frac{1}{8} + \frac{1}{64\sigma}$$

$$\gamma_2^2 \to \sigma + \frac{9}{8} + \frac{1}{64\sigma}$$

$$\frac{p_2}{n_1 mc^2\gamma_1^2} \to \frac{1}{8\sigma} - \frac{1}{32\sigma^2}$$

$$\frac{B_2}{B_1} = \frac{N_2}{N_1} \to 1 + \frac{1}{2\sigma}$$

- FLUID DOES NOT SLOW DOWN AT SHOCK
- PRESSURE STAYS LOW (LITTLE DISSIPATION)
- B-FIELD FURTHER INCREASES EVEN IF LITTLE

$\sigma \to 0$

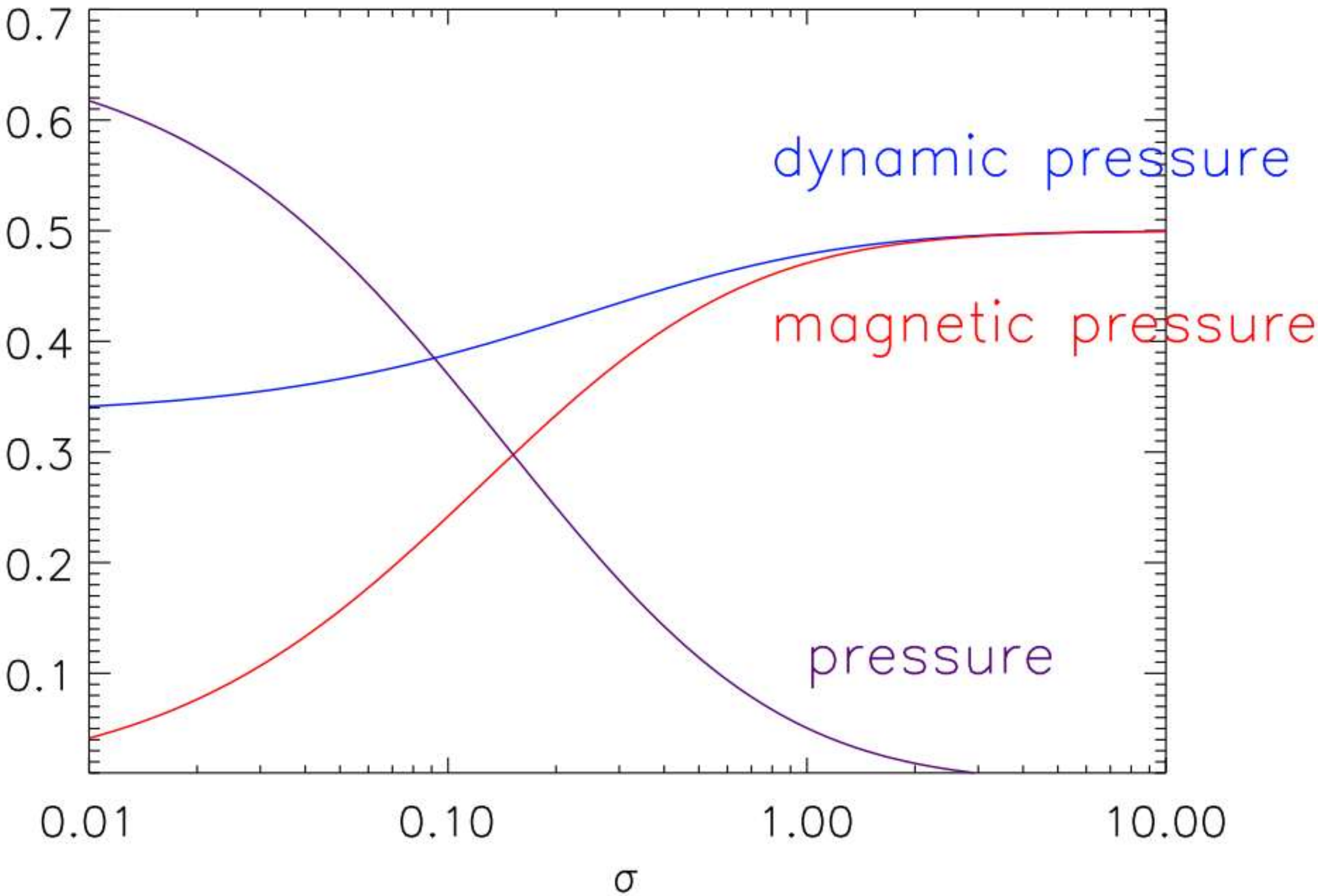
$$u_2^2 \to \frac{1+9\sigma}{8}$$

$$\gamma_2^2 \to \frac{9}{8}(1+\sigma)$$

$$\frac{p_2}{n_1 mc^2\gamma_1^2} \to \frac{2}{3}(1-7\sigma)$$

$$\frac{B_2}{B_1} = \frac{N_2}{N_1} \to 3 - 12\sigma$$

# IN FIGURES….




**QUANTITIES NORMALIZED TO UPSTREAM TOTAL ENERGY DENSITY**

# NEBULAR DYNAMICS

$$(1)\quad \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 n u\right)=0$$

$$(3)\quad \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(w u^2 + p + \frac{B^2}{8\pi}\left(1+\frac{u^2}{\gamma^2}\right)\right)\right]-\frac{2p}{r}=0$$

$$(2)\quad \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{ruB}{\gamma}\right)=0$$

$$(4)\quad \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left(w\gamma u + \frac{B^2}{4\pi}\frac{u}{\gamma}\right)\right]=0$$

$$\frac{\partial}{\partial r}\left(\frac{p}{n^\Gamma}\right)=0$$

$$\left(\mu\gamma + \frac{B^2}{4\pi n\gamma}\right)=\cos t$$

$$\mu = mc^2 + \frac{\Gamma}{\Gamma-1}\frac{p}{n}$$

$$nur^2 = n_2 u_2 r_s^2$$

$$\frac{uBr}{\gamma}=\frac{u_2 B_2 r_s}{\gamma_2}$$

$$\frac{p}{n^\Gamma}=\frac{p_2}{n_2^\Gamma}$$

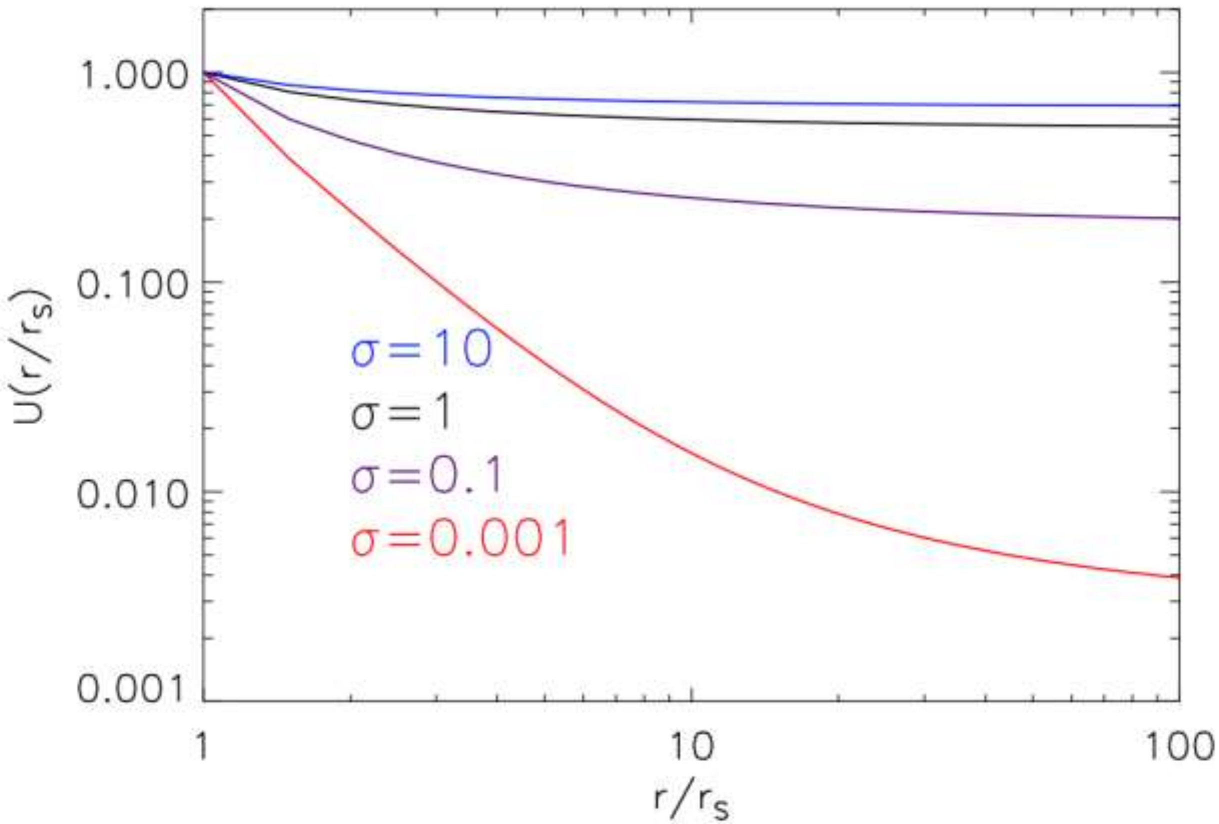
$$\gamma\left(mc^2 + \frac{\Gamma}{\Gamma-1}\frac{p}{n}+\frac{B^2}{4\pi n\gamma^2}\right)=\gamma_2\left(mc^2+\frac{\Gamma}{\Gamma-1}\frac{p_2}{n_2}+\frac{B_2{}^2}{4\pi n_2\gamma_2{}^2}\right)$$

# TERMINAL VELOCITY

$$u_\infty = \frac{\sigma}{\sqrt{1+2\sigma}}$$

$$\beta_\infty = \frac{u_\infty}{\gamma_\infty} = \frac{\sigma}{\sigma+1}$$

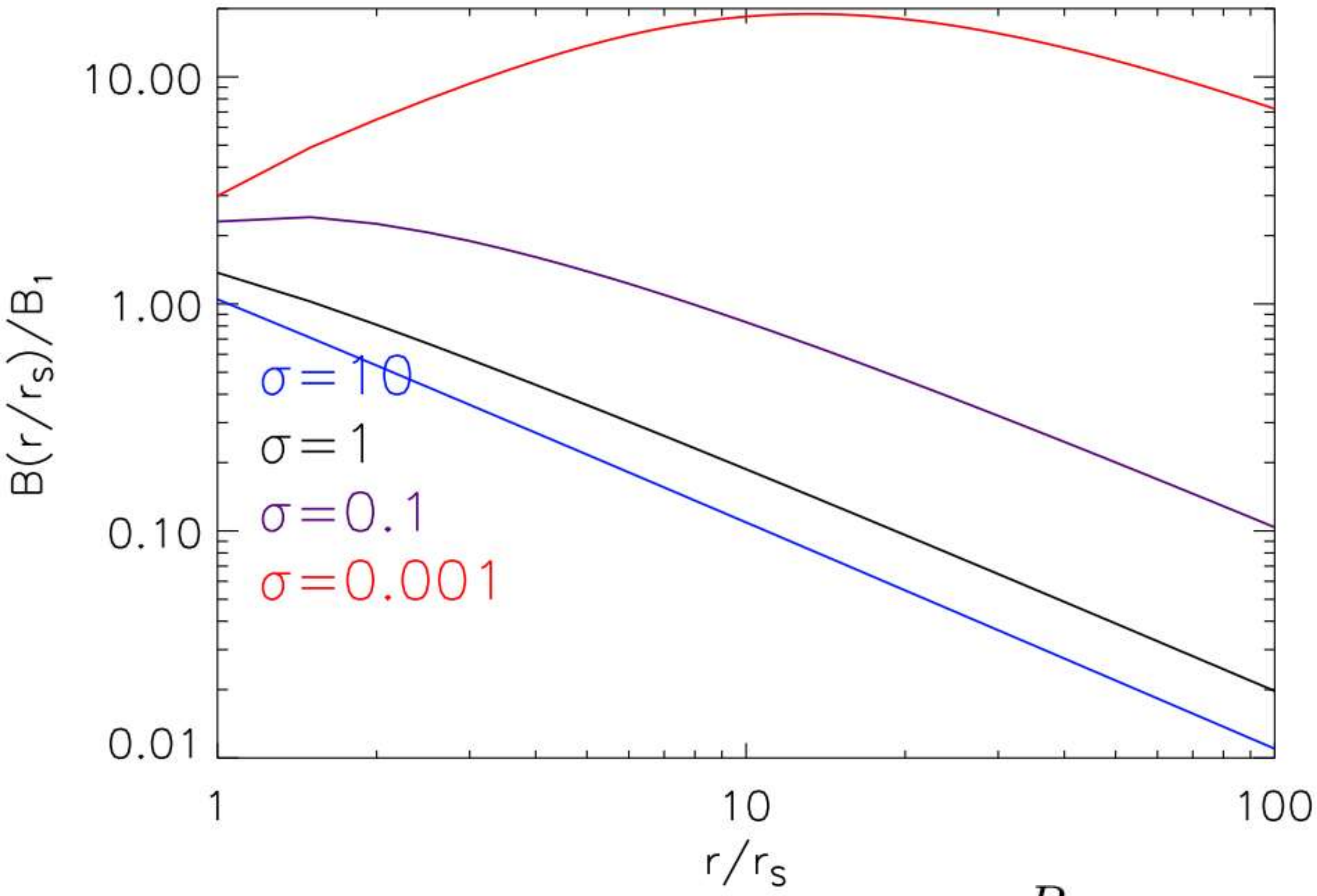
$$\begin{cases} \sigma \to \infty & \Rightarrow \quad \beta_\infty \to 1 \\ \sigma \to 0 & \Rightarrow \quad \beta_\infty \to \sigma \end{cases}$$




**FOR LARGE σ TERMINAL VELOCITY STAYS RELATIVISTIC**

**IN CRAB $v_N$=1000km/s e $\sigma = v_N/c = 0.003$**

# MAGNETIC FIELD




**FOR SMALL σ B PEAKS AT AROUND** $\frac{R_{TS}}{\sqrt{3\sigma}}$

**WHERE EQUIPARTITION IS REACHED**

# SPECTRAL EVOLUTION

INJECTION SPECTRUM AT SHOCK: $f_2(E_2) = KE_2^{-p}$

CONSERVATION OF PARTICLE NUMBER

$$4\pi r^2 cuf(E,z)dE = 4\pi r_S^2 cf_2(E_2)dE_2 \quad \Rightarrow \quad f(E,z) = \frac{1}{\mathrm{v}z^2} f_2\left[E_2(E,z)\right]\frac{\partial E_2}{\partial E}$$

$$E_2(E,z) = ?$$

$$\frac{dE}{dt} = \frac{E}{3V(t)}\frac{dV}{dt} - c_1 B^2 E^2 \quad \to \quad u\frac{dE}{dr} = Eu\frac{d}{dr}\ln n^{1/3} - \frac{c_1}{c}B^2 E^2$$

$$\frac{uBr}{\gamma} = \frac{u_2 B_2 r_s}{\gamma_2} \quad \to \quad B = \frac{B_2}{\mathrm{v}z}$$

$$nur^2 = n_2 u_2 r_s^2 \quad \to \quad n = \frac{n_2}{\mathrm{v}z^2}$$

$$f(E,z) = \frac{KE^{-p}}{\left(\mathrm{v}z^2\right)^{(2+p)/3}}\left(1 - \frac{E}{E_\infty(z)}\right)^{(p-2)}$$

**$E_\infty(z)$ MAXIMUM PARTICLE ENERGY AT ANY PLACE**

# NEBULAR SIZE

## CRITICAL FREQUENCY

$$\nu_{\infty}(z) = \frac{3}{4\pi}\left(\frac{eB_2}{mc}\right)\frac{1}{\nu z}\left(\frac{E_{\infty}(z)}{mc^2}\right)^2$$

## FORM FACTORS

$$I_{\nu}(z_{\perp}) = 2\int_{z_{\perp}}^{z_N} dz \frac{J_{\nu}(z)z}{\sqrt{\left(z^2 - z_{\perp}^2\right)}}$$

NEBULAR SIZE DECREASES WITH INCREASING OBS. FREQUENCY

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

# INTEGRATED SPECTRUM

INTEGRATED SPECTRUM SHOWS
STEEPENING DUE TO DECREASING NEBULAR VLUME WITH
INCREASING FREQUENCY

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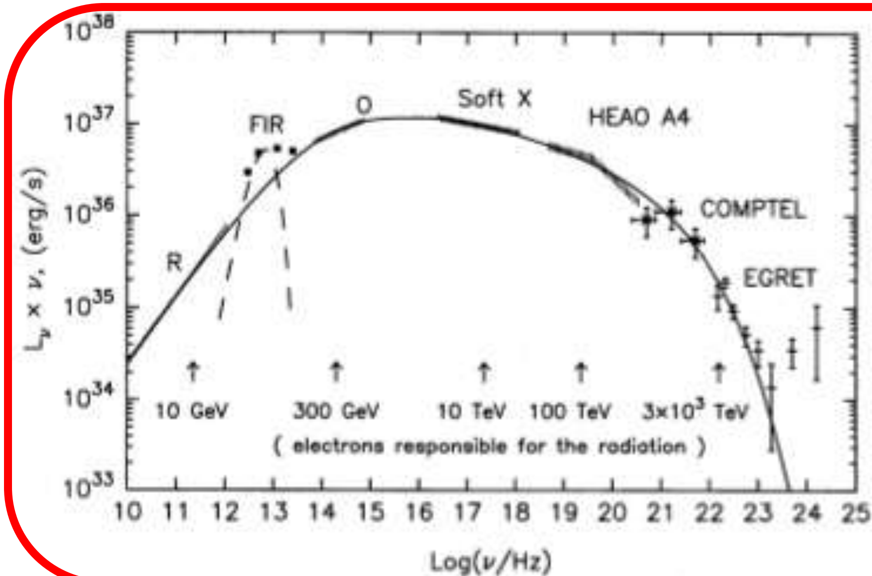
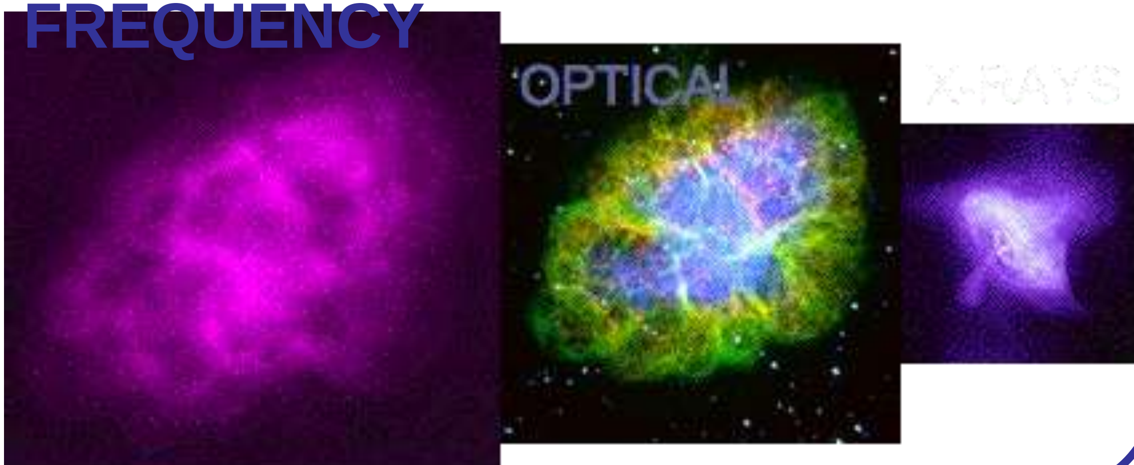
# MHD MODELS OF PWNe: PREDICTIONS



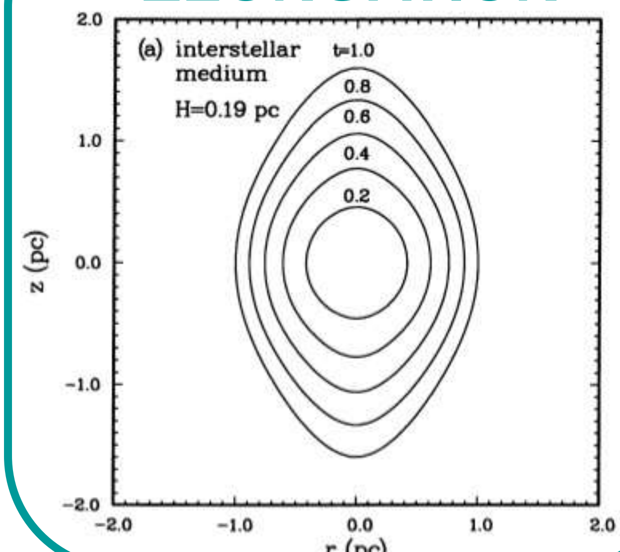

INTEGRATED EMISSION SPECTRUM FROM OPTICAL TO X-RAYS AND EVEN $\gamma$-RAYS (de Jager & Harding 92; Atoyan & Aharonian 96)

**NO EXPLANATION FOR RADIO ELECTRONS**: MAYBE PRIMORDIAL (Atoyan 99)...

## SIZE SHRINKAGE WITH 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)

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

## Wind parameters

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

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

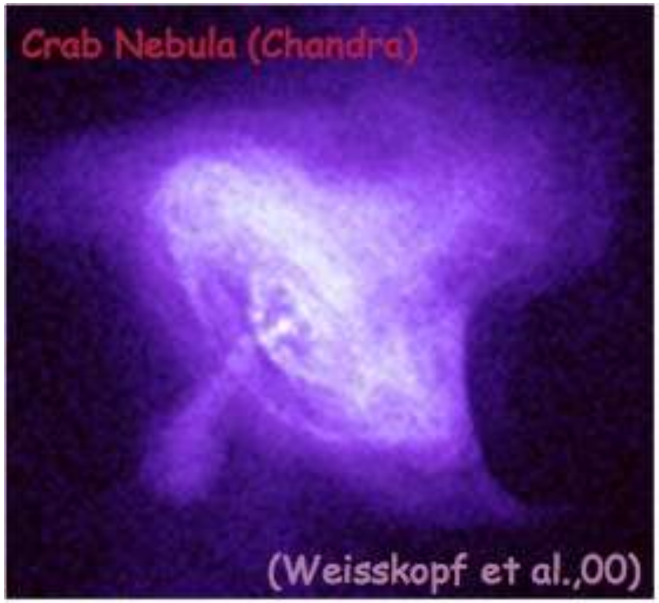
$\alpha \sim 2.2$
Just right for Fermi I

$\sigma$-paradox!

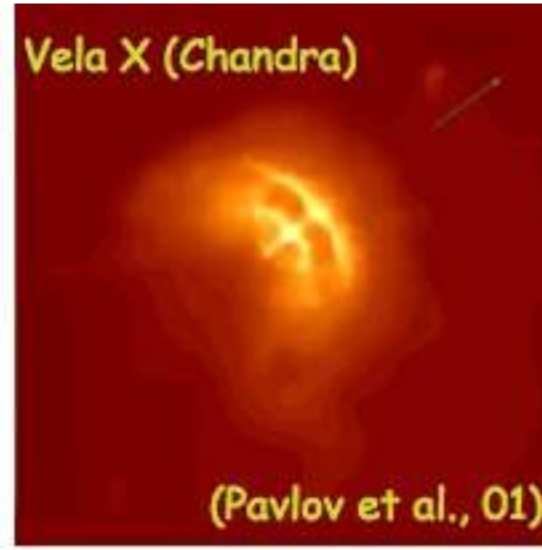
At $r \sim R_{LC}$: $\sigma \sim 10^4$ $\Gamma \sim 10^2$
(pulsar and pulsar wind theories)

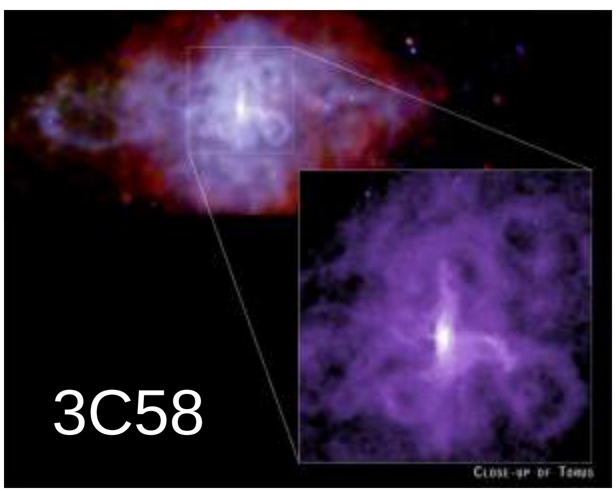
At $R_{TS}$: $\sigma \ll 1$(!?!) $\Gamma \in (10^4\text{-}10^7)$
(PWN theory and observations)

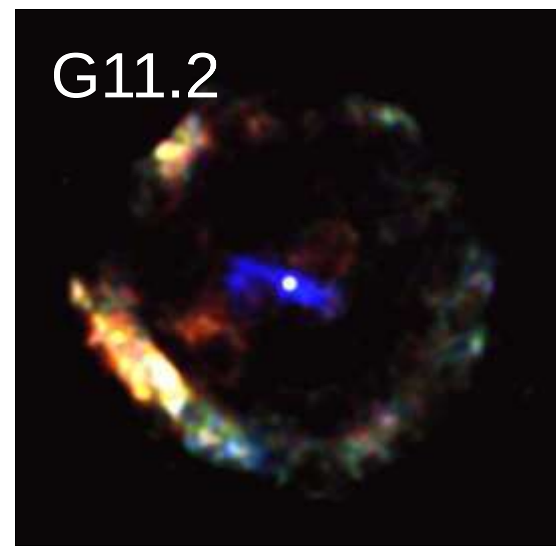
# THEN CAME CHANDRA!





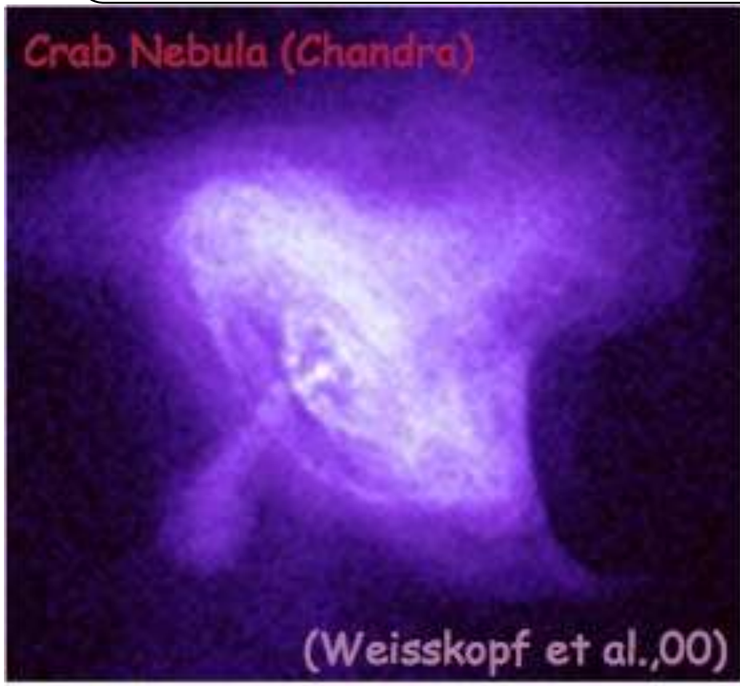


# THE PUZZLING JET IN CRAB

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

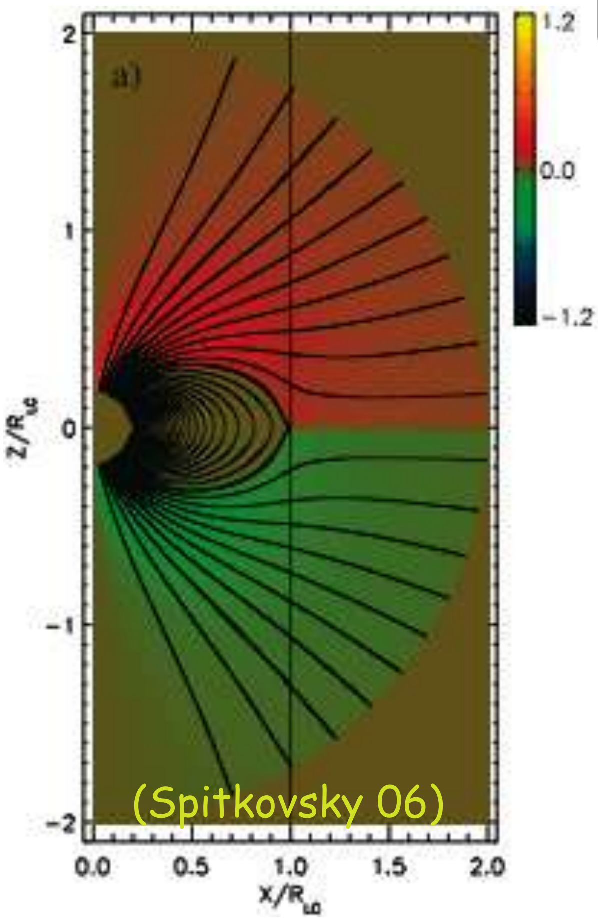
$F \propto \sin^2(\theta)$

LEADS TO OBLATE TS, CLOSER TO THE PSR AT THE POLES THAN AT THE EQUATOR

THIS IS EXACTLY WHAT WIND MODELS PREDICT!

# ANISOTROPIC WIND ENERGY FLOW

DENSE PLASMA
WE SAID….




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 ENERGY FLOWS AT LOW LATITUDES:
$F \propto \sin^2(\theta)$

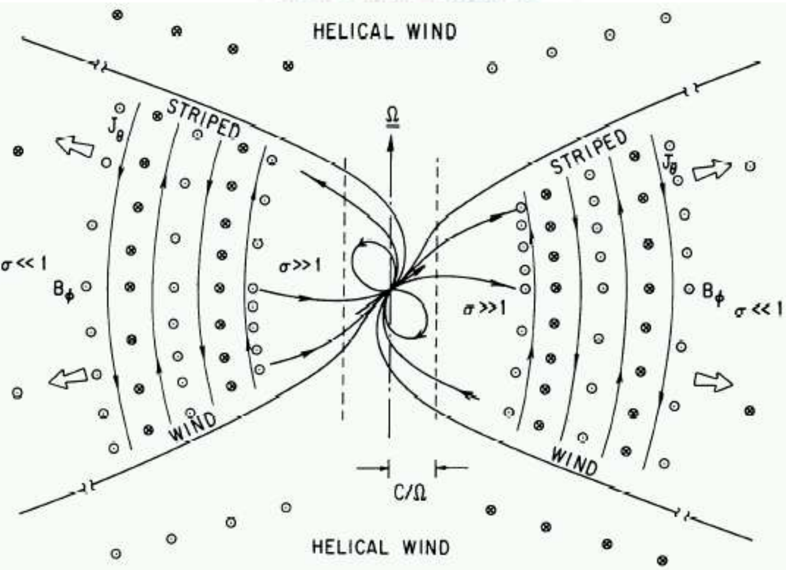
MAGNETIC FIELD COMPONENTS:
$B_r \propto 1/r^2$ $B_\phi \propto \sin(\theta)/r$

WITHIN IDEAL MHD $\sigma$ STAYS LARGE

CURRENT SHEET IN EQUATORIAL PLANE: OSCILLATING AROUND EQUATOR IN OBLIQUE CASE

ANGULAR EXTENT DEPENDS ON OBLIQUITY

# THE WIND MAGNETIZATION




LOWERING s THROUGH DISSIPATION IN THE STRIPED WIND (Coroniti 90)

DIRECT EVIDENCE OF STRIPED WIND IN BINARY PSR 0737(McLaughlin et al. 04)

PULSED $\gamma$-RAYS FROM RECONNECTION? (Kirk et al. 02)

RECENT STUDIES:

- RECONNECTION NOT FAST ENOUGH AT MINIMUM RATE (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

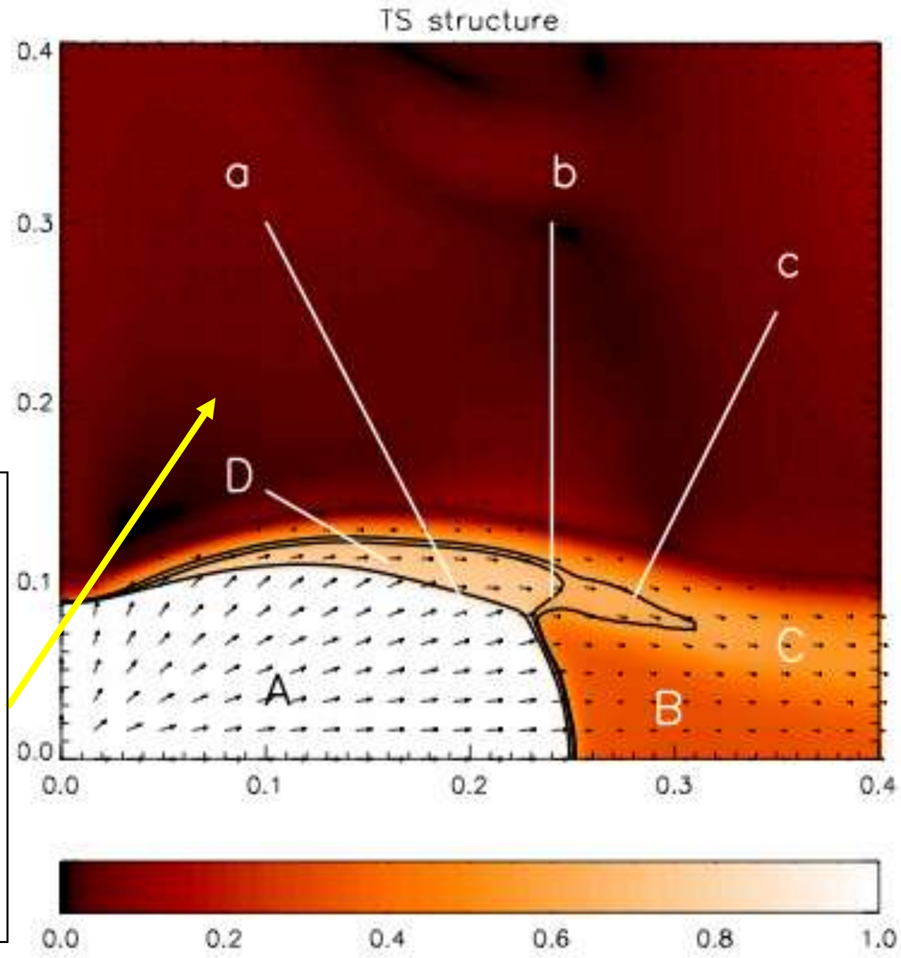
$F \propto \sin^2(\theta)$

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

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

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

A: TERMINATION SHOCK FRONT
B: RIM SHOCK
C: FMS SURFACE

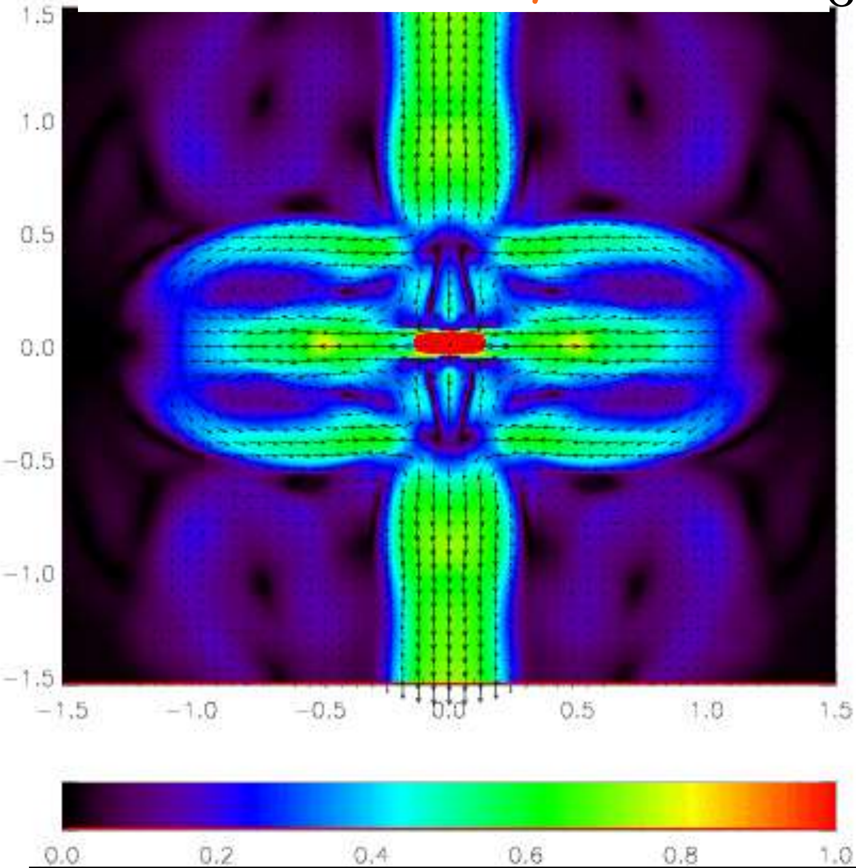


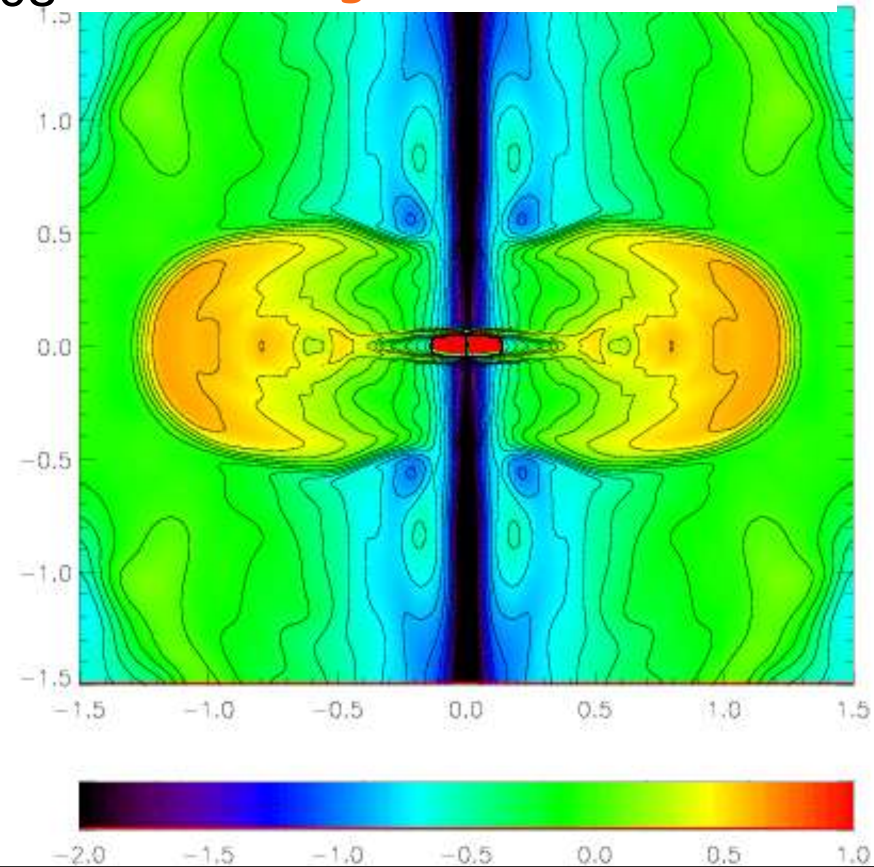
# FLOW PATTERN

Velocity

$\sigma$=0.03

Magnetization



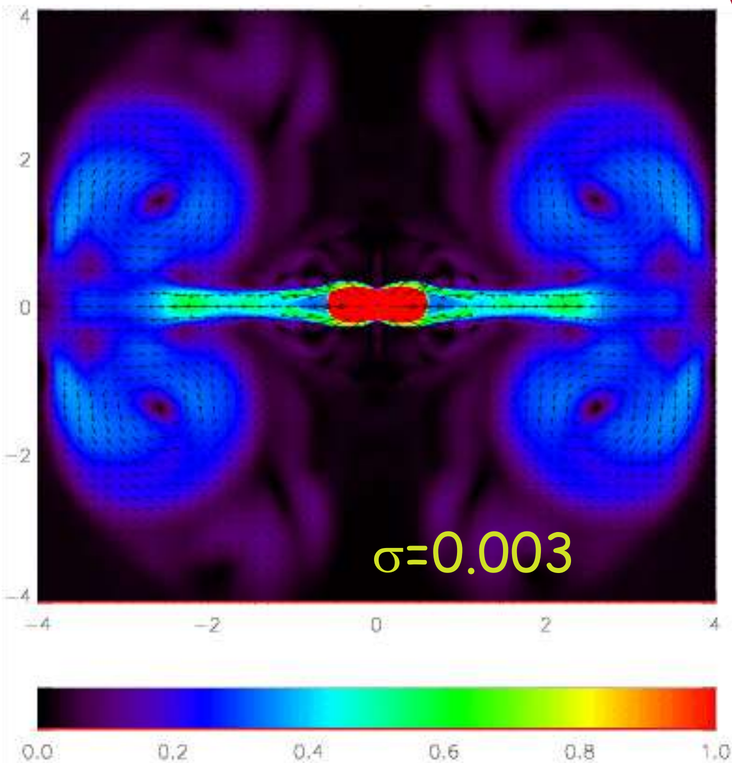



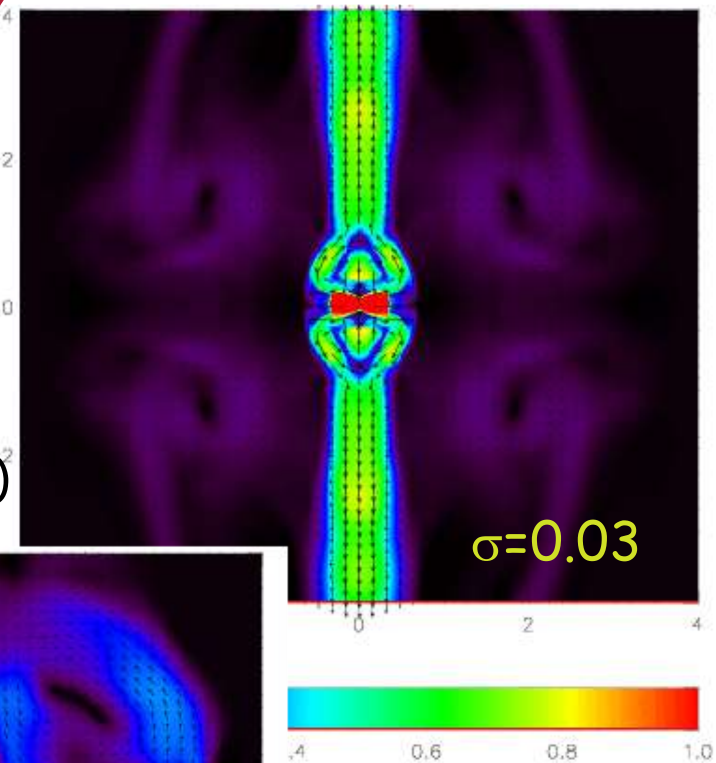

- FOR SUFFICIENTLY HIGH $\sigma$, EQUIPARTITION IS REACHED IN EQUATORIAL REGION

- EQUATORIAL FLOW IS DIVERTED TOWARDS HIGHER LATITUDES

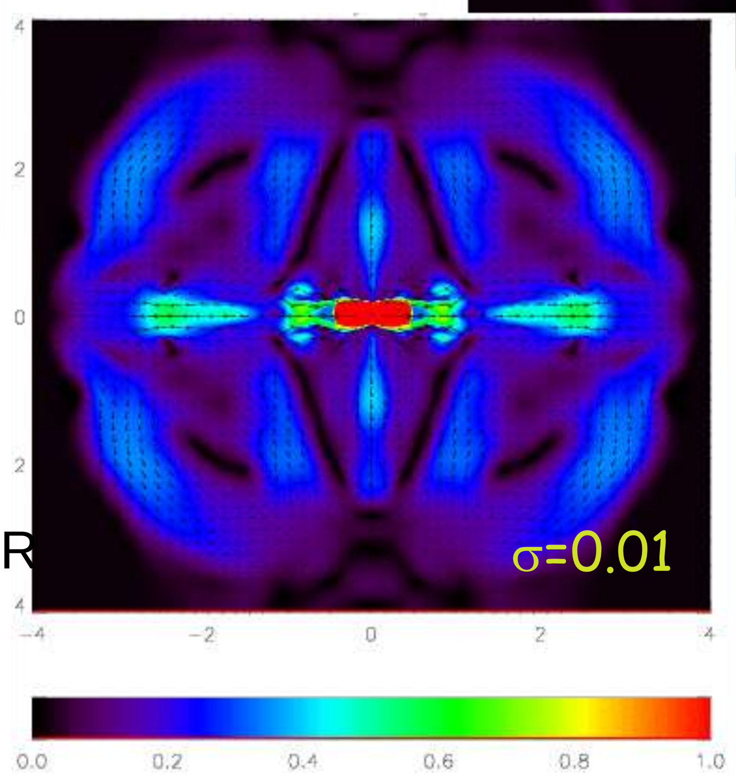
- A FAST CHANNEL MAY THEN FORM ALONG THE AXIS

# DEPENDENCE ON $\sigma$ OF FLOW VELOCITY




(Del Zanna et al 04)

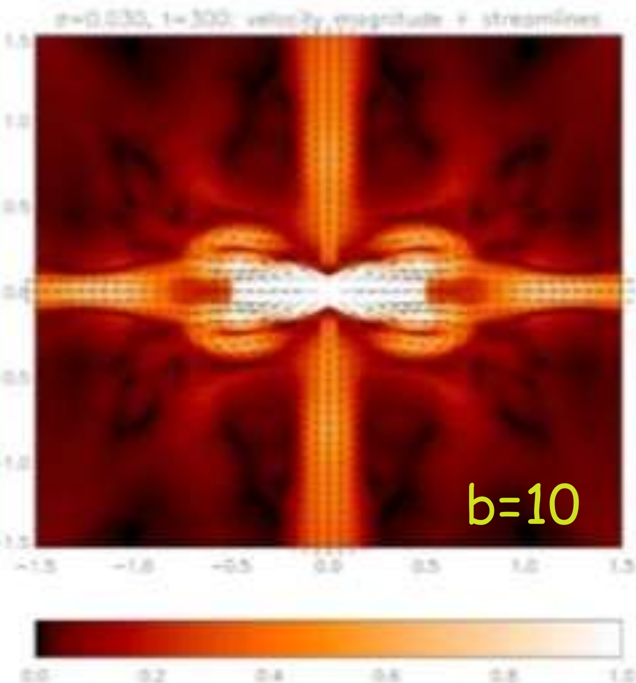


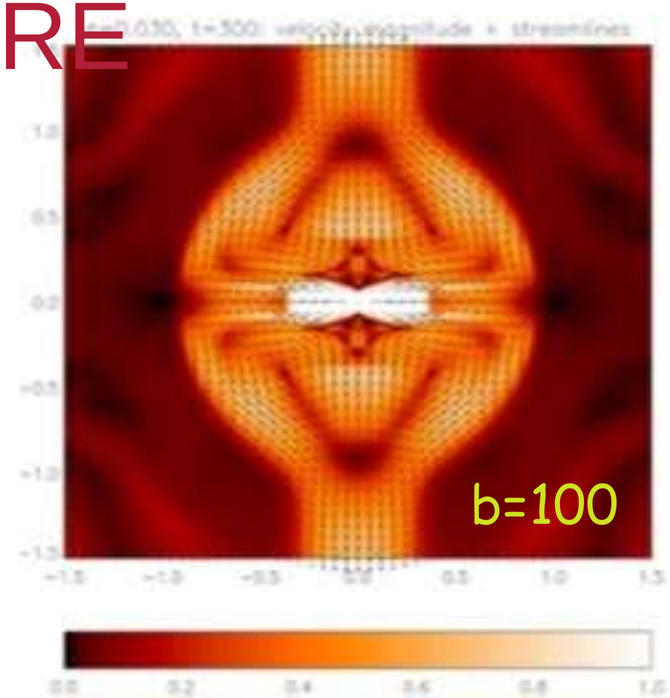

$\sigma$>0.01 REQUIRED FOR JET FORMATION

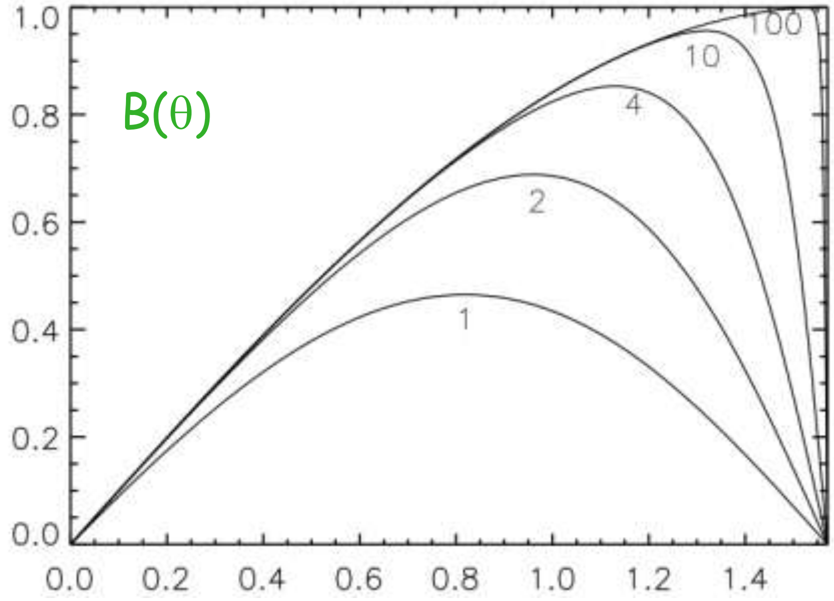
BEST FIT: FACTOR 10 LARGER THAN WITHIN 1D MHD MODELS

# DEPENDENCE ON FIELD STRUCTURE

σ=0.03



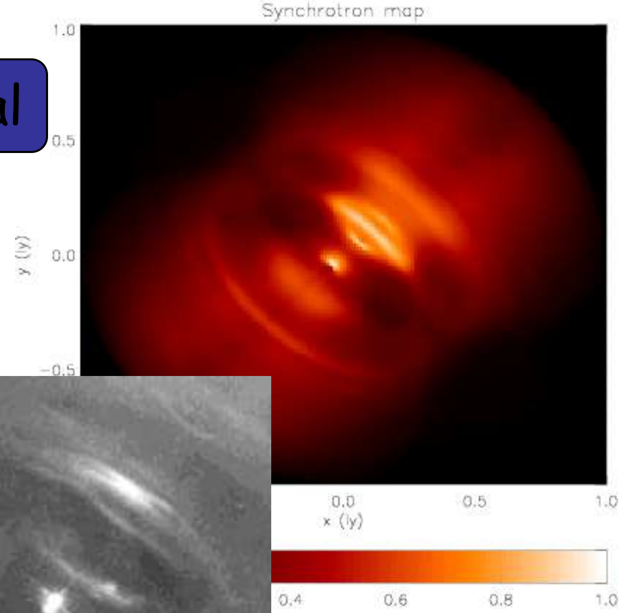



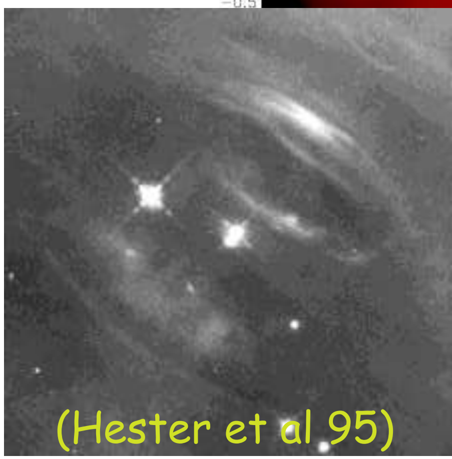




(Del Zanna et al 04)

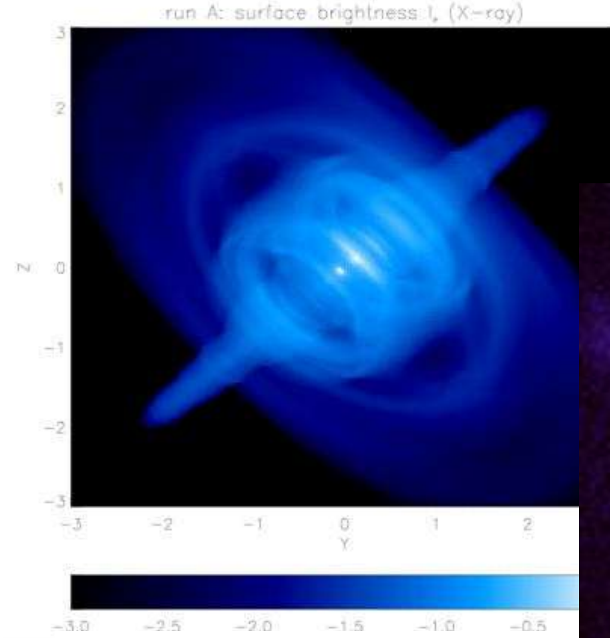
# SYNCHROTRON EMISSION MAPS

optical



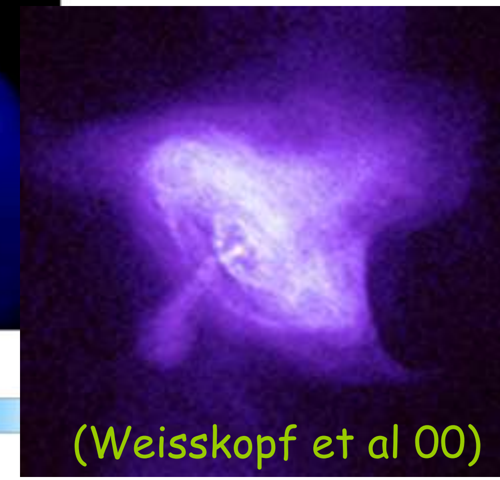



(Hester et al 95)



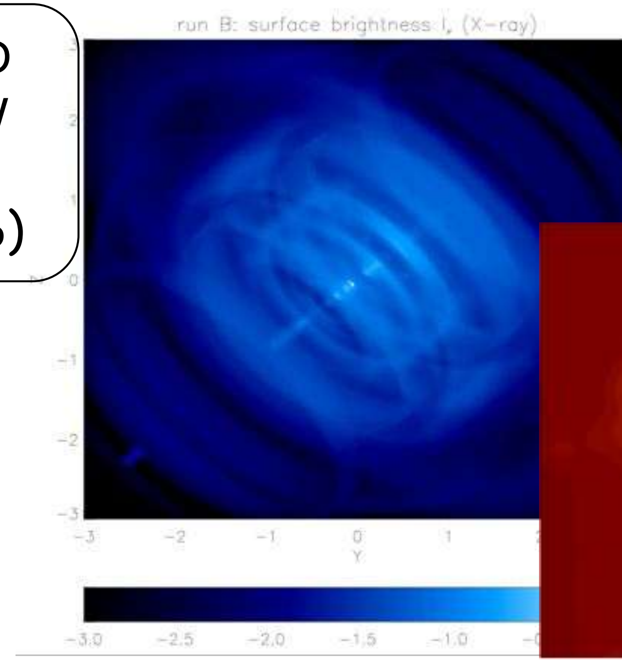

X-rays

$\sigma$=0.025, b=10

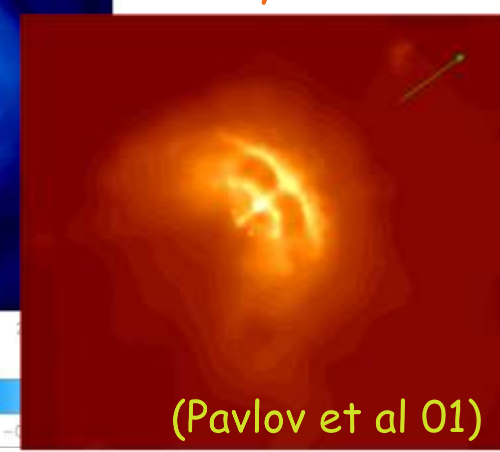


(Weisskopf et al 00)

$E_{max}$ IS EVOLVED WITH THE FLOW
$f(E) \propto E^{-\alpha}$, $E < E_{max}$
(Del Zanna et al 06)




$\sigma$=0.1, b=1

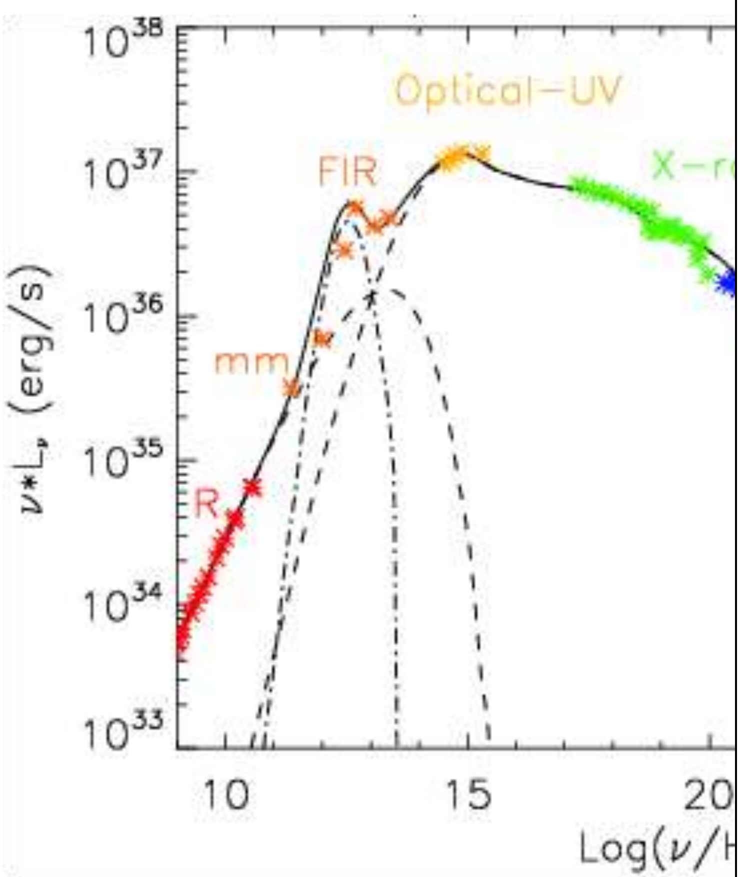


(Pavlov et al 01)

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?

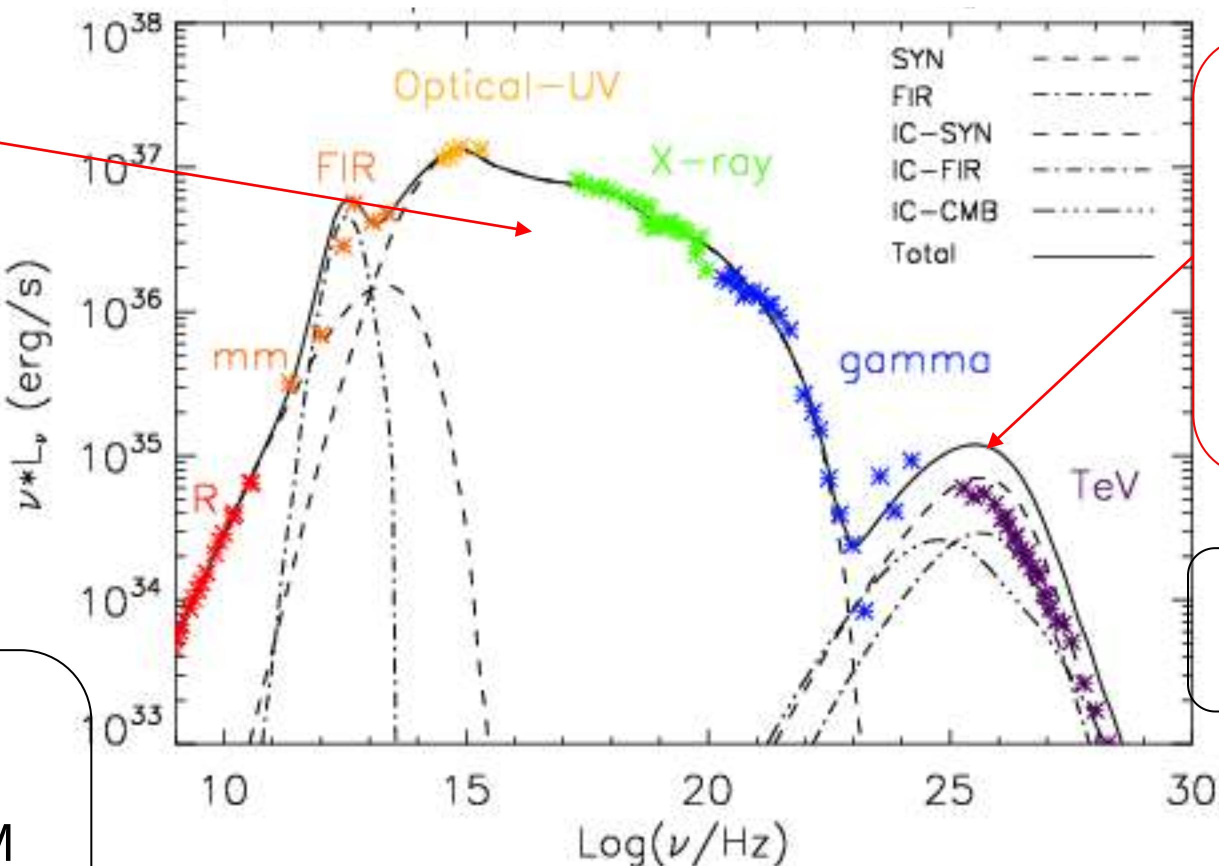
- In order to recover total flux number of particles artificially large

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

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

# γ-RAY SPECTRUM FROM CRAB

MULTIPLE CHANGES OF SLOPE!




COMPUTED ICS FLUX EXCEEDS THE DATA BY A FACTOR ~2

HIGHER σ REQUIRED?

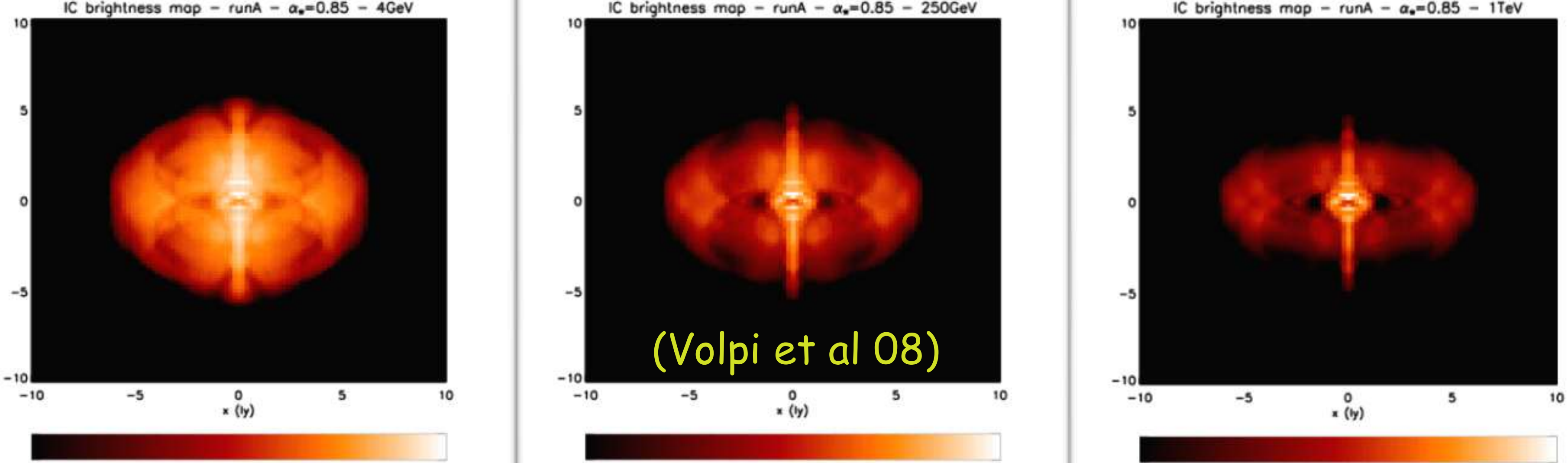
EXPLAIN ENTIRE SPECTRUM WITH SINGLE POWER-LAW AT INJECTION?

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

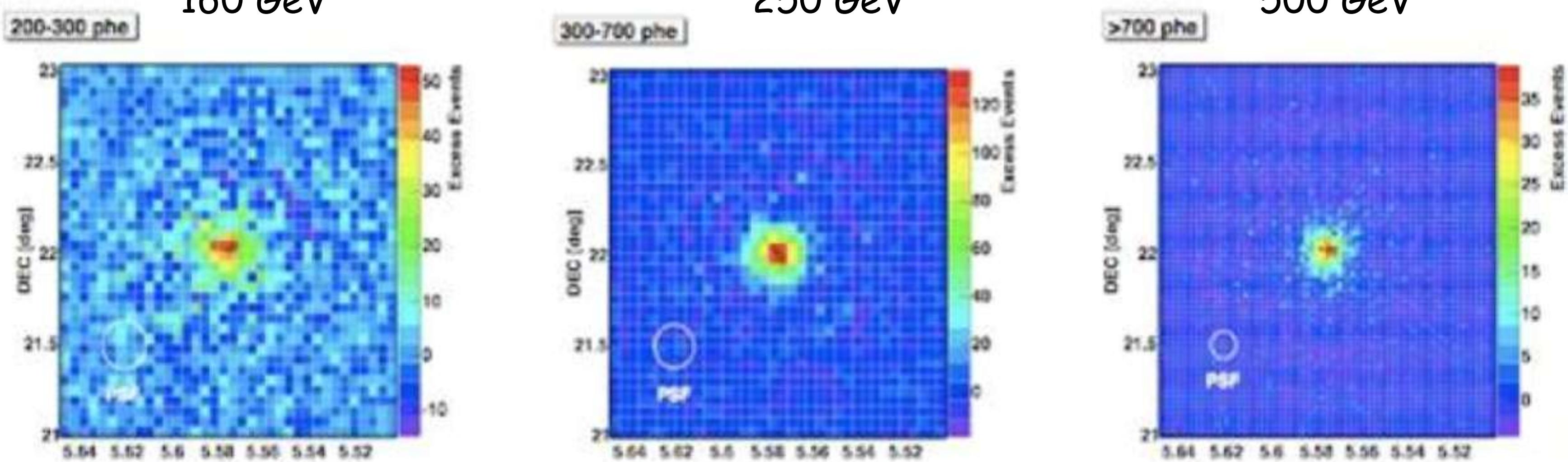
4 GeV | 250 GeV | 1 TeV




$R_N$(GeV)~$R_N$(GHz)

NO SHRINKAGE IN EQUATORIAL REGION

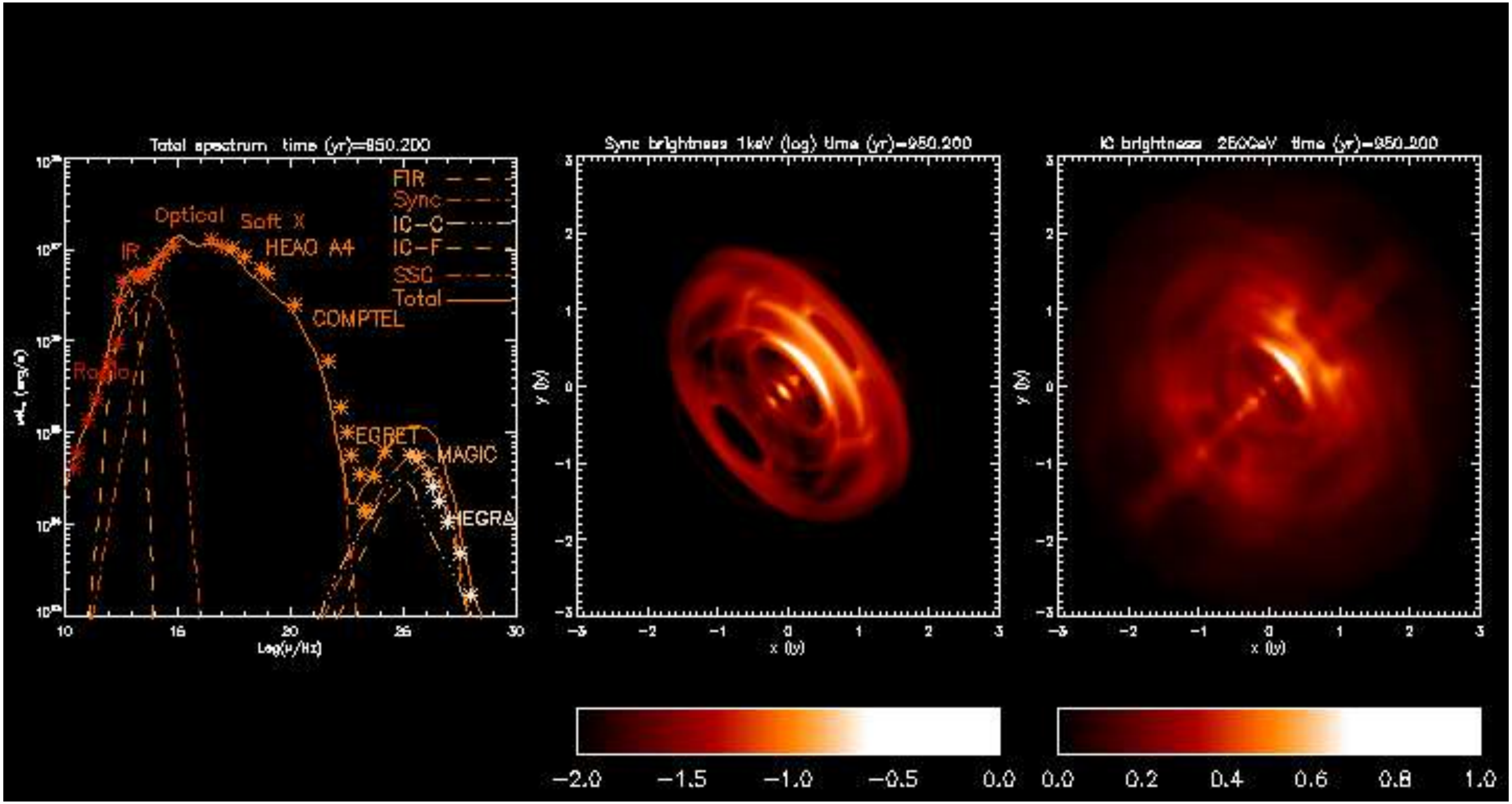
160 GeV | 250 GeV | 500 GeV




MAGIC: Albert et al 08

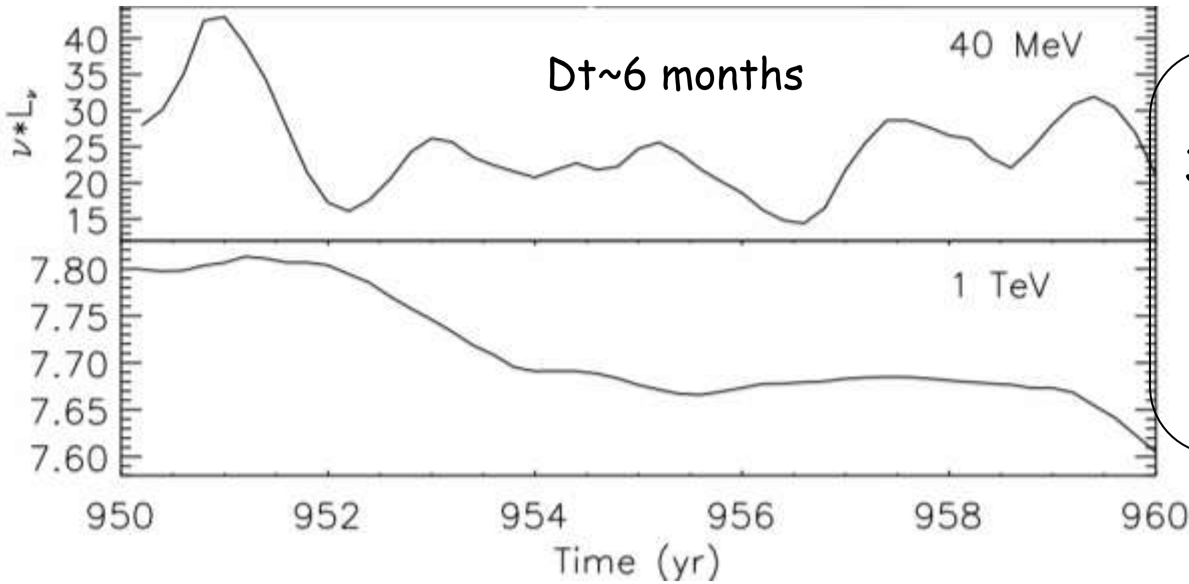
# γ-RAY VARIABILITY DUE TO MHD EFFECTS

(the movie)



# γ-RAY VARIABILITY DUE TO MHD EFFECTS

Theory




Observations

De Jager et al 96:
30% IN COMPTEL (1-150 MeV)
100% IN EGRET (70-150 MeV)
INITIALLY NOT CONFIRMED
BY FERMI (Abdo et al 09)
BUT THEN…..

**STRONG FLUX VARIATIONS IN THE SYNC CUTOFF REGION** ⇐ EMISSION DUE TO MOVING FEATURES AROUND TS

NO VARIATION (~1%) EXPECTED AT TEV ENERGIES

# X-RAY VARIABILITY IN THE INNER NEBULA

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

# VARIABLE SHOCK STRUCTURE AND THE WISPS

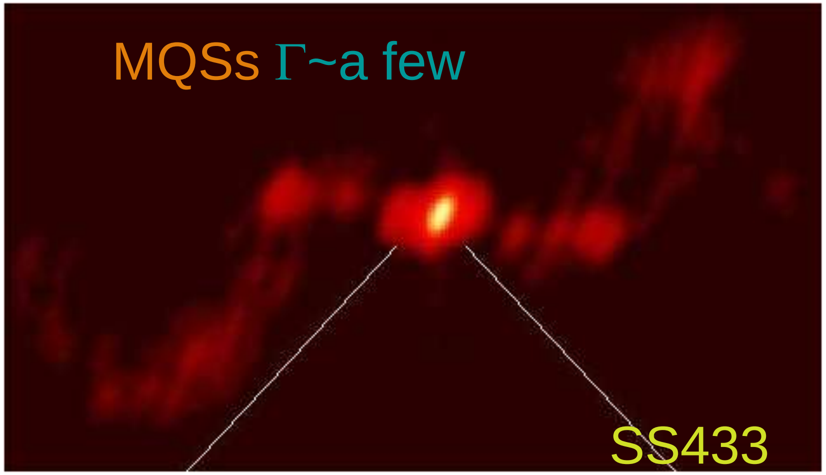
QuickTime™ and a
decompressor
are needed to see this picture.

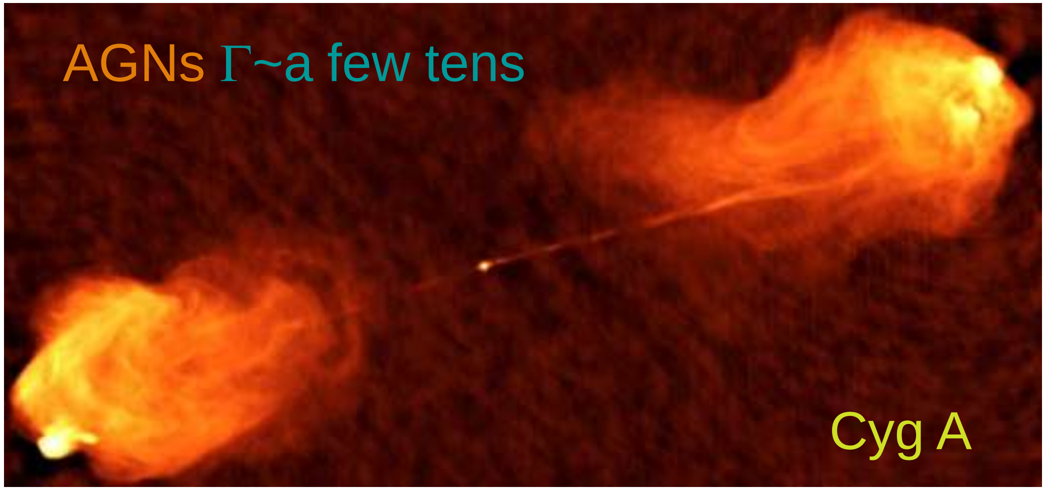
QuickTime™ and a
decompressor
are needed to see this picture.

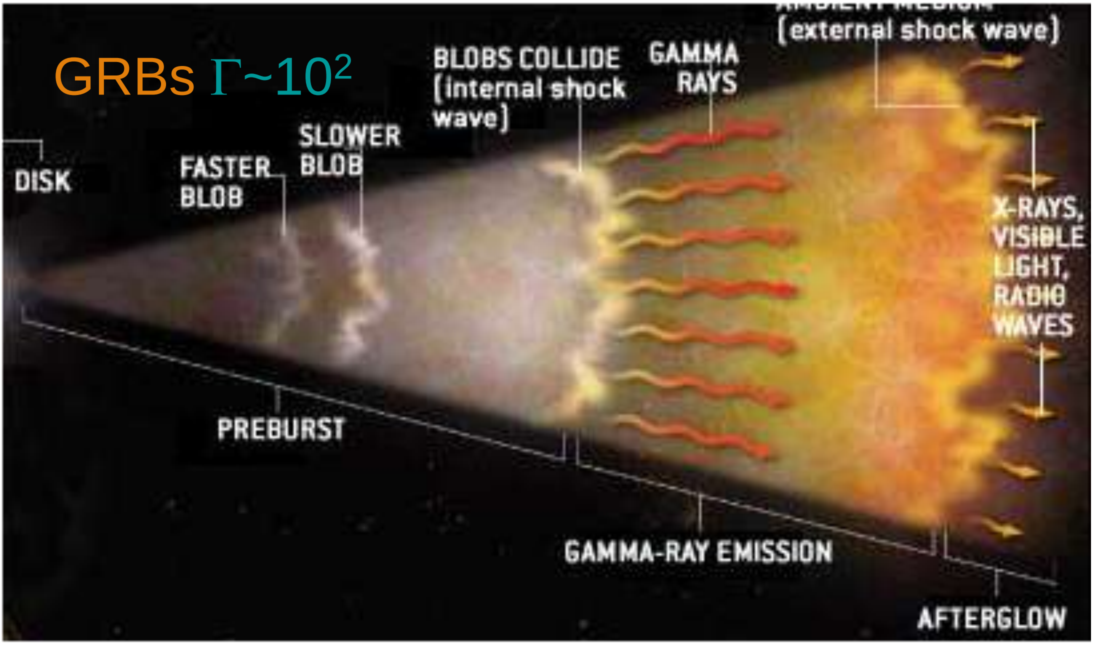
**Camus, Komissarov, Bucciantini 09**

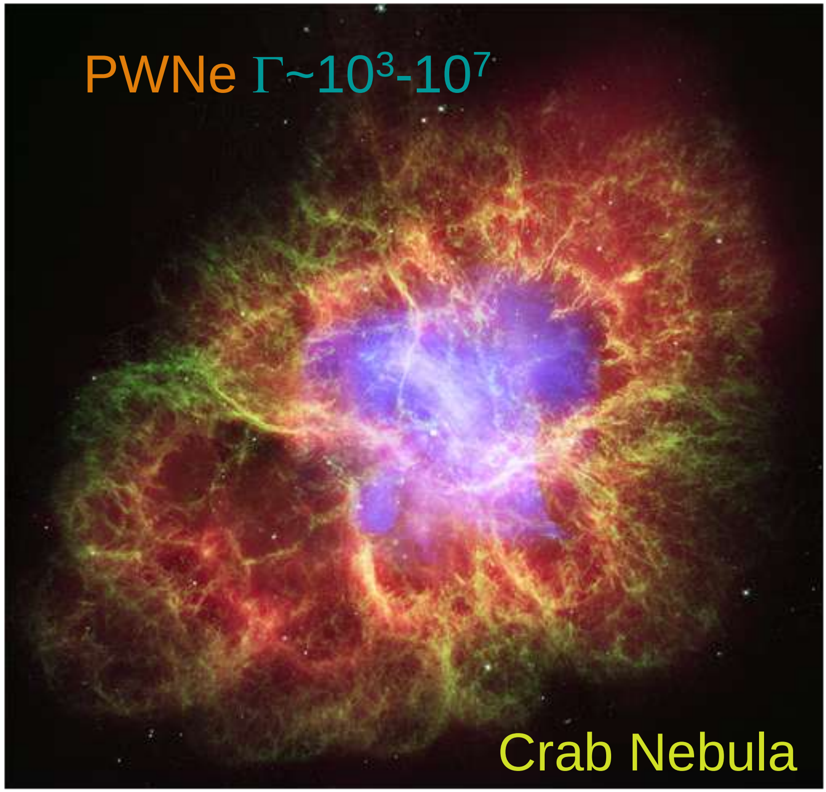
# PARTICLE ACCELERATION AT THE MOST RELATIVISTIC SHOCKS IN NATURE

# RELATIVISTIC SHOCKS IN ASTROPHYSICS



# PROPERTIES OF THE FLOW AND PARTICLE ACCELERATION

**PARTICLE ACCELERATION AT THE HIGHLY RELATIVISTIC TERMINATION SHOCK**

**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 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 ($\sigma=B^2/4\pi n\Gamma mc^2$)

GEOMETRY ($\Gamma \times \Theta(B\cdot n)$)

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 ~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 OF DSA AND SDA

-SDA NOT EFFECTIVE AT SUPERLUMINAL SHOCKS(!!) UNLESS UNREALISTICALLY HIGH TURBULENCE LEVEL (Sironi & Spitkovsky 09)

+IN WEIBEL MEDIATED (UNMAGNETIZED) $e^+$-$e^-$ SHOCKS FERMI ACCELERATION EFFECTIVE (Spitkovsky 08)

+POWER LAW INDEX OK FOR THE OPTICAL/X-RAY SPECTRUM OF CRAB (Kirk et al 00) BUT e.g. VELA SHOWS FLATTER SPECTRUM (Kargaltsev & Pavlov 09)

-SMALL FRACTION OF THE FLOW SATISFIES THE LOW MAGNETIZATION ($\sigma$<0.001) CONDITION (SEE MHD SIMULATIONS)

# DRIVEN MAGNETIC RECONNECTION

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

(Sironi & Spitkovsky 12)

# RESONANT ABSORPTION OF ION CYCLOTRON WAVES

+++++

ESTABLISHED TO EFFECTIVELY ACCELERATE BOTH $e^+$ AND $e^-$

IF

PULSAR WIND SUFFICIENTLY COLD

AND

IONS CARRY MOST OF ITS ENERGY

(Hoshino & Arons 91, Hoshino et al. 92, Amato & Arons 06, Stockem et al 12)

++++++

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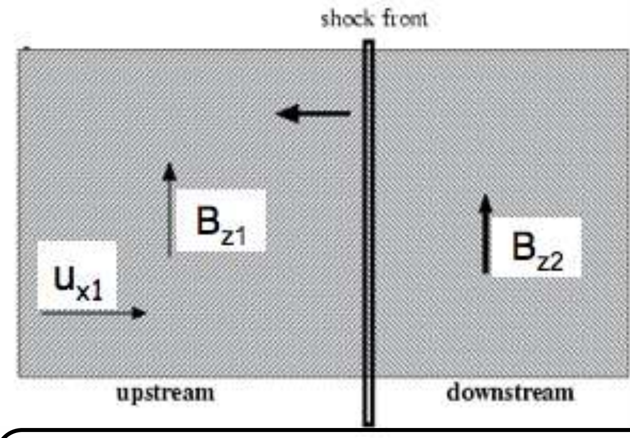
PULSAR MULTIPLICITY CANNOT BE LARGER THAN $10^4$

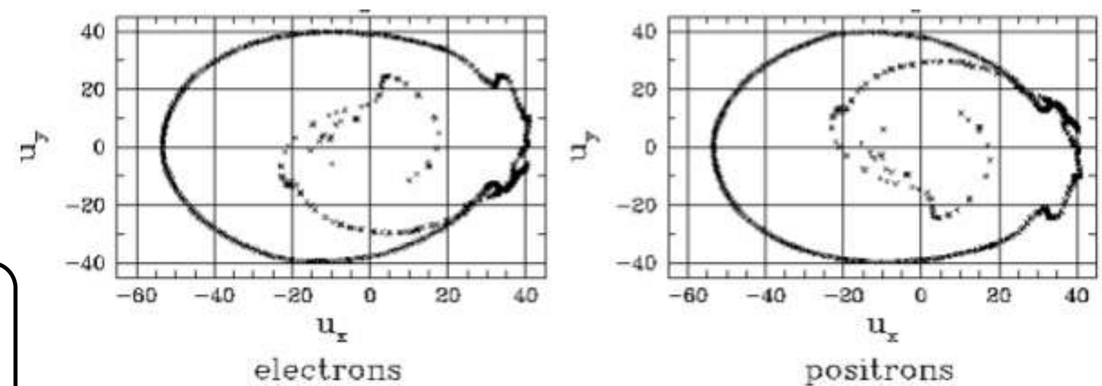
\------

# RESONANT CYCLOTRON ABSORPTION IN ION DOPED PLASMA




Magnetic reflection mediates the transition

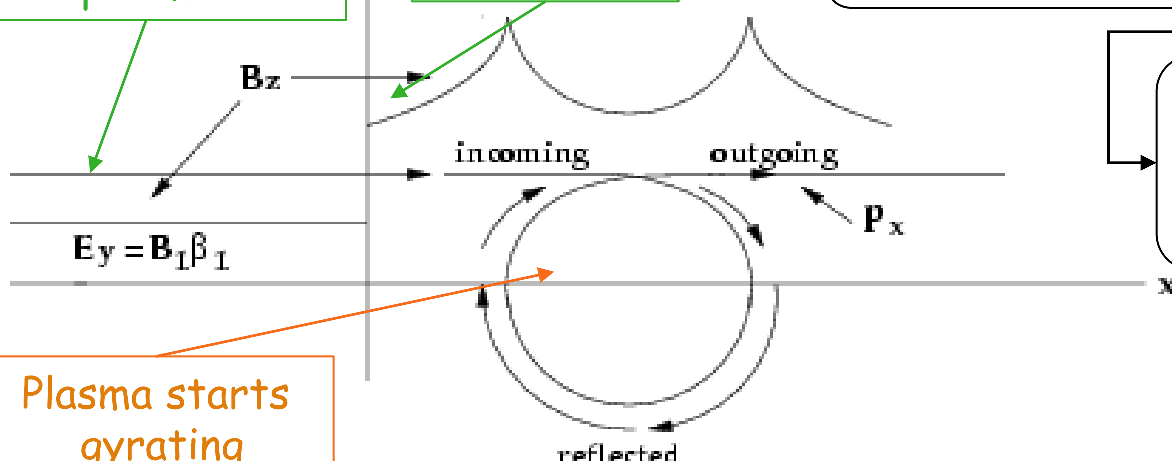
Configuration at the leading edge ~ cold ring in momentum space




Coherent gyration leads to collective emission of cyclotron waves

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

B increases

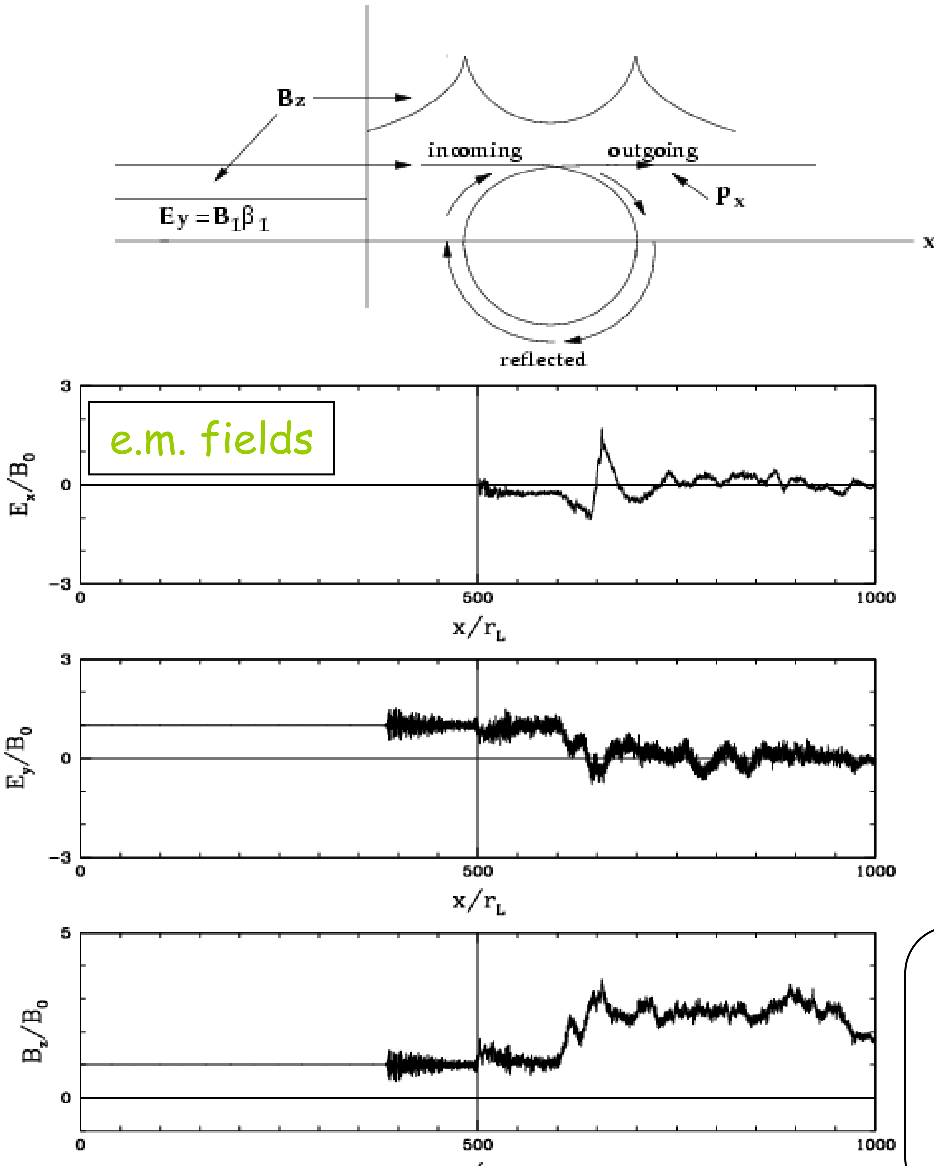


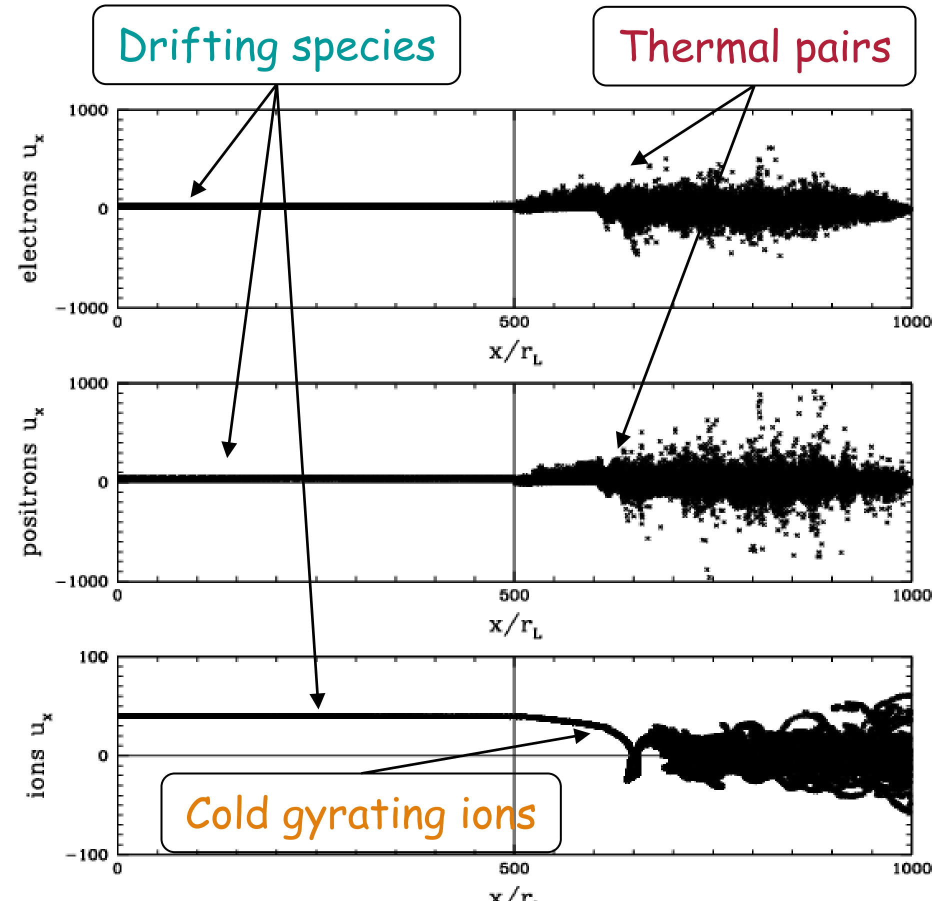

Plasma starts gyrating

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

# LEADING EDGE OF A TRANSVERSE RELATIVISTIC SHOCK IN 1D PIC



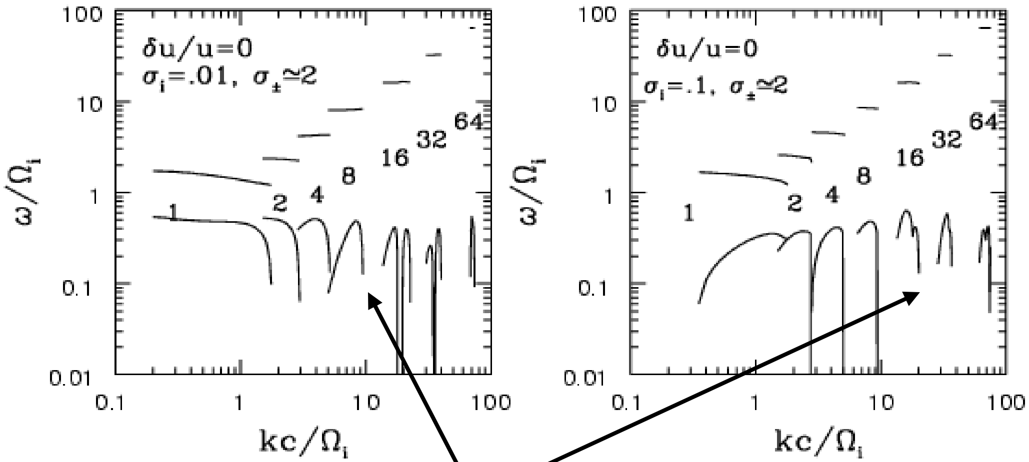




(Amato & Arons 06)

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 I




$\Omega_{ci}= m_e/m_i\Omega_{ce}$

Pairs can resonantly absorb ion radiation at $n=m_i/m_e$ and then progressively lower n down to n=1: $E_{max}= m_i/m_e\Gamma$

Growth-rate independent of n
(Hoshino & Arons 91, Amato&Arons 06)

In order to work the mechanism requires effective wave growth up to $n=m_i/m_e$

1D PIC sim. with $m_i/m_e$ up to 20 (Hoshino & Arons 91, Hoshino et al. 92)
Showed $e^+$ effectively accelerated if $U_i/U_{tot}>0.5$

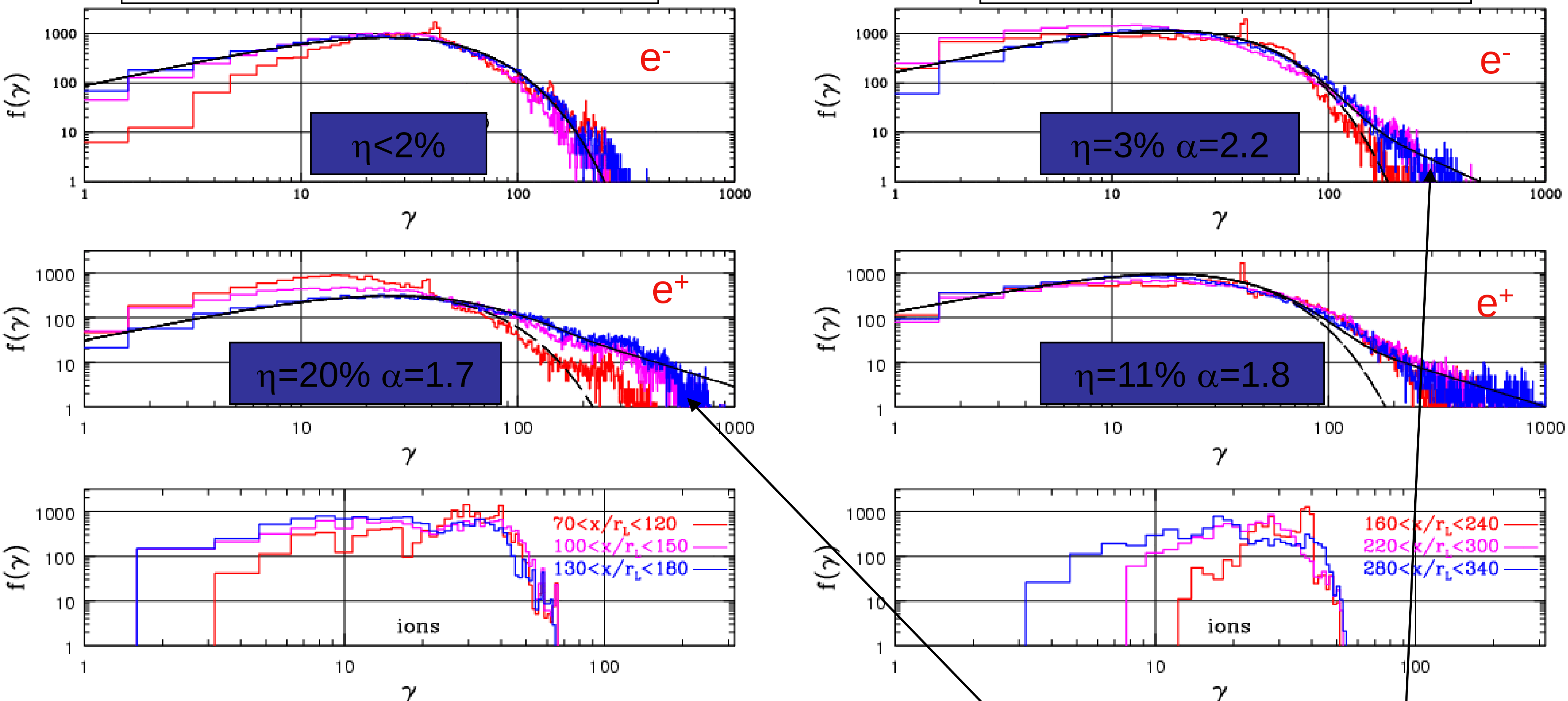
For low mass-ratios $U_i/U_{tot}>0.5$ requires large fraction of p
That makes waves circularly polarized and preferentially absorbed by $e^+$

For $m_i/m_e=100$:
polarization of waves closer to linear
Comparable acceleration of both $e^+$ and $e^-$

# POLARIZATION OF THE WAVES

$m_i/m_e$=20, $n_i/n_-$=0.4

$m_i/m_e$=40, $n_i/n_-$=0.2




Upstream flow:
Lorentz factor: Γ=40
Magnetization: $\sigma_\pm$=2

Simulation box:
$\Delta x = r_{Le}/10$
$Lx = r_{Li}x10$

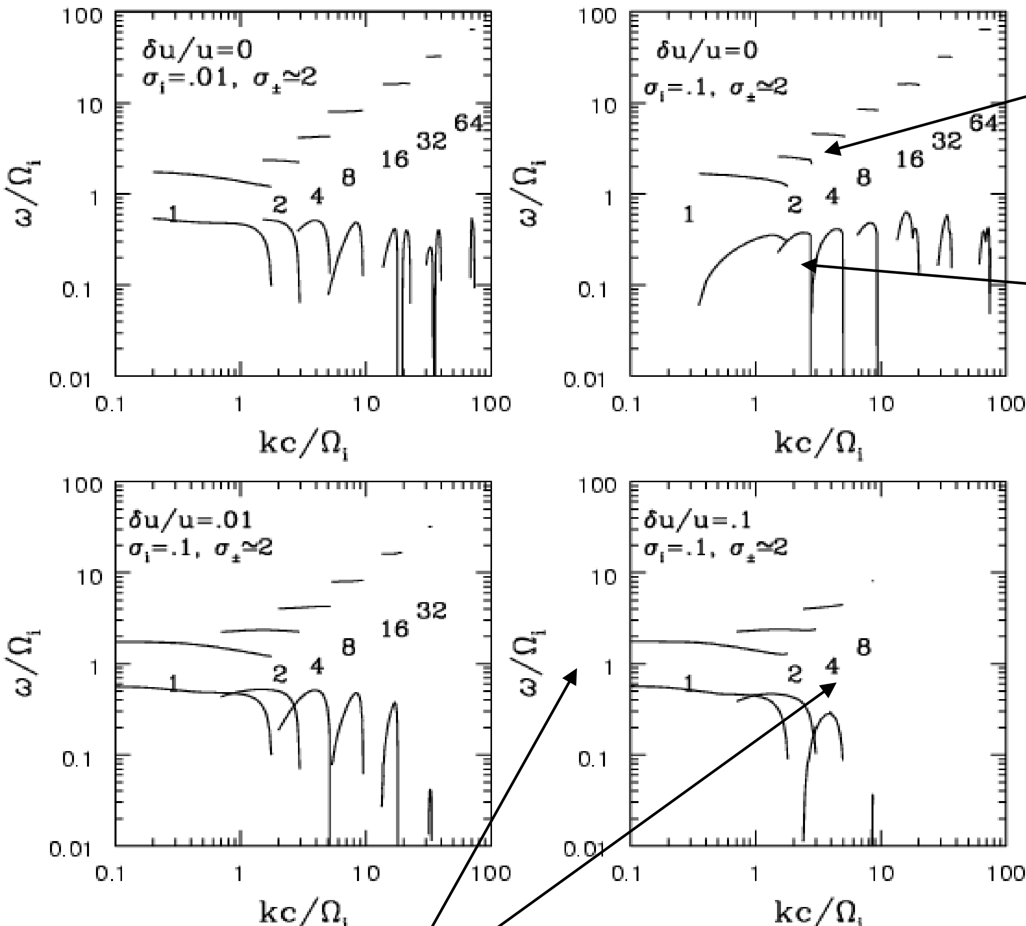
Positron tail extends to $\gamma_{max} = m_i/m_e \Gamma$

First evidence of electron acceleration

$U_i/U_{tot}$=0.7 same in both simulations

Amato&Arons 06

# SUBTLETIES OF THE RCA PROCESS II




frequency

Growth-rate

If thermal spread of the ion distribution is included

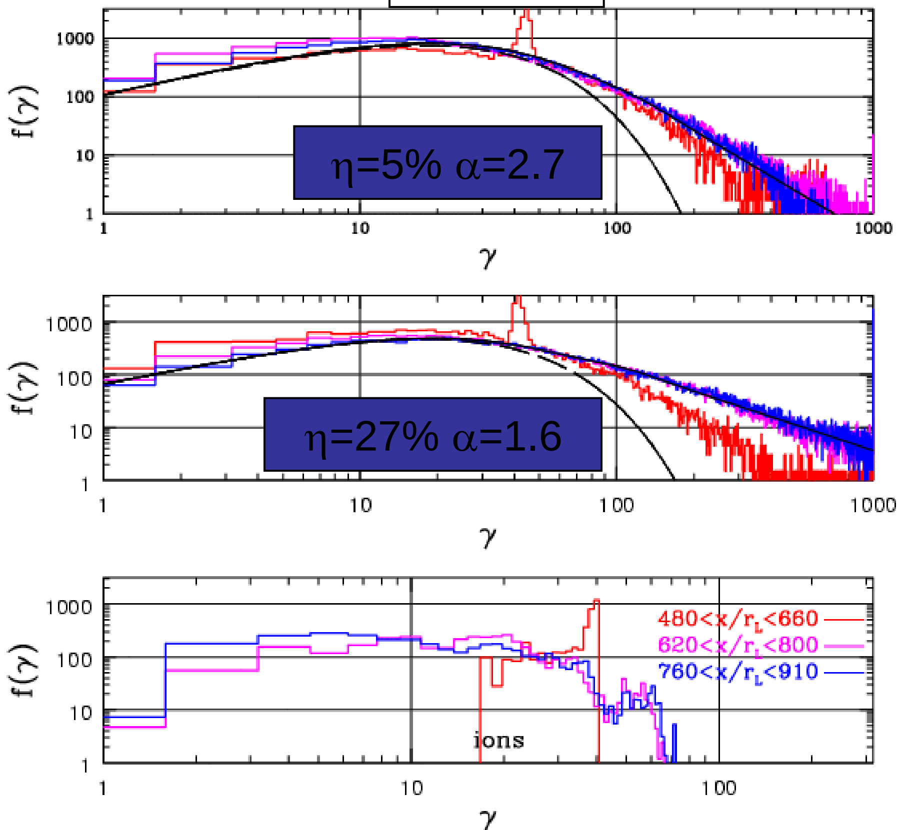
Acceleration can be suppressed

Spectrum is cut off at n~u/δu

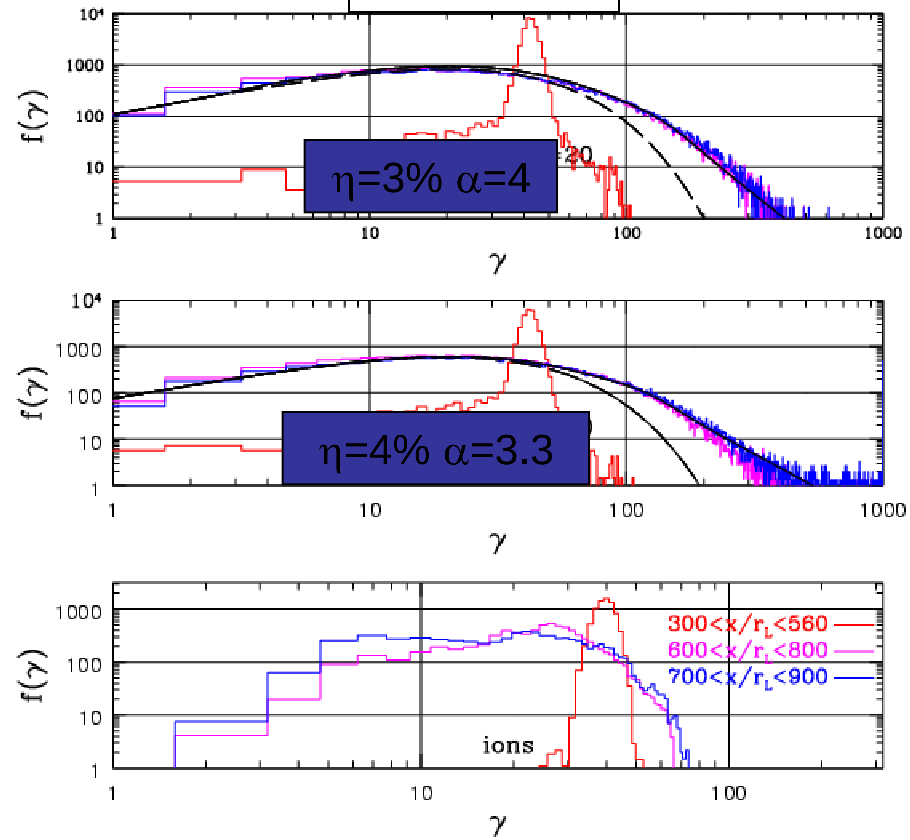
growth-rate ~ independent of n if plasma cold (Amato & Arons 06)

# EFFECTS OF THERMAL SPREAD

$\delta u/u=0$




$\delta u/u=0.1$




$n_i/n_-=0.2$ $m_i/m_e=100$
$U_i/U_{tot}=0.8$

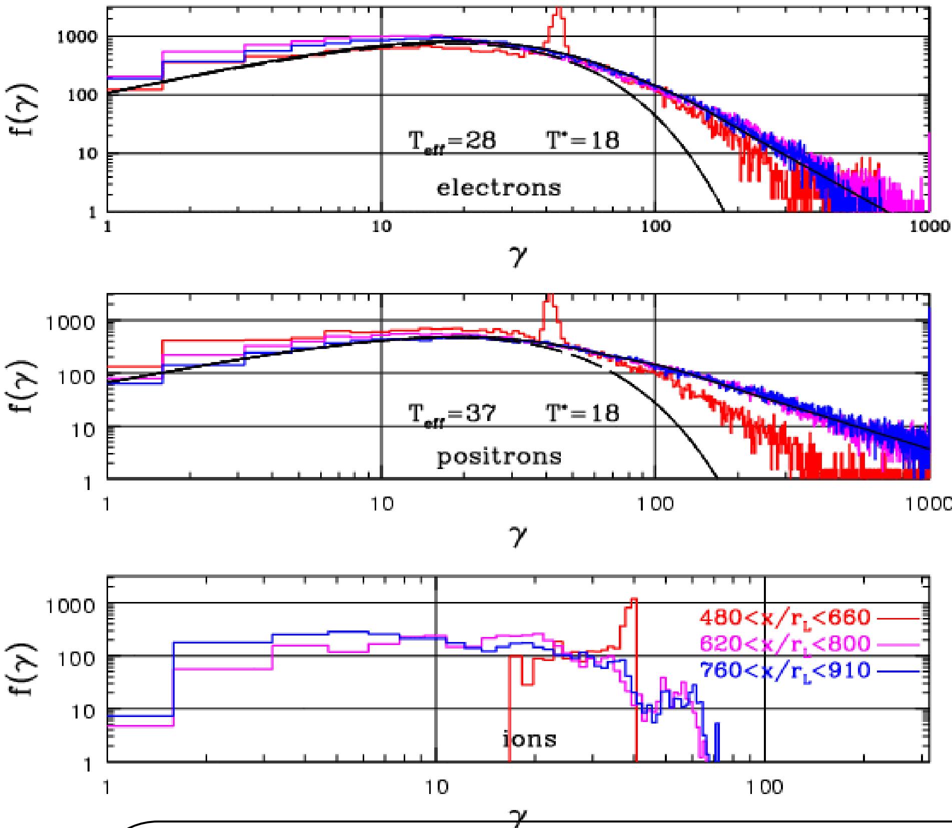
Initial particle distribution function is a gaussian of width $\delta u$

Upstream flow:
Lorentz factor: $\Gamma=40$
Magnetization: $\sigma_\pm=2$

Simulation box:
$\Delta x=r_{Le}/10$
$Lx=r_{Li}x10$

Acceleration effectively suppressed!!!

# 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
RESULTS RECENTLY CONFIRMED BY Stockem et al 12

# THINGS YOU GET FOR FREE

If $\Gamma \sim$ few x $10^6$

✓NICELY FITS WITH CORRELATION (Gotthelf 03) BETWEEN X-RAY EMISSION OF PSRs AND PWNe: EVERYTHING DEPENDS ON $u_i/u_{tot}$ AND ULTIMATELY ON ELECTRODYNAMICS OF UNDERLYING COMPACT OBJECT

✓MAXIMUM ENERGY ~ WHAT REQUIRED BY OBSERVATIONS

✓REQUIRED $(dN_i/dt) \sim 10^{34}\ s^{-1} \sim (dN_i/dt)_{GJ}$ FOR CRAB: RETURN CURRENT FOR THE PULSAR CIRCUIT

✓NATURAL EXPLANATION FOR CRAB WISPS (Gallant & Arons 94) AND THEIR VARIABILITY (Spitkovsky & Arons 04)
(ALTHOUGH ALSO DIFFERENT EXPLANATIONS WITHIN IDEAL MHD: TIME-SCALES TURN OUT TO BE THE SAME)

PUZZLE WITH K

IF MULTIPLICITY IS $10^5$-$10^6$ IONS CANNOT DOMINATE THE ENERGY

# REMINDER:LOSS-LIMITED ACCELERATION

$$t_{loss} = \frac{E}{(dE/dt)_{sync}} = \frac{6\pi}{\sigma_T}\frac{mc}{B^2\gamma}$$

$$t_{acc} = \frac{E}{(dE/dt)_{acc}} \geq \frac{m\gamma c^2}{e|\vec{E}|c} = \frac{m\gamma c}{feB} \qquad f \leq 1$$

$$t_{acc} = \eta\frac{D_B}{u^2} = \eta\frac{cr_L}{c^2} = \eta\frac{m\gamma c}{eB} \qquad \eta \geq 1$$

$$t_{acc} \leq t_{loss} \quad \Rightarrow$$

$$\gamma_{\max} = \sqrt{f\frac{6\pi e}{B\sigma_T}} \approx 1.5\times10^{10}\frac{\sqrt{f}}{\sqrt{B[100\,\mu G]}}$$

$$\varepsilon_{\max} = \frac{3h}{2}\frac{eB}{2\pi mc}\gamma_{\max}^2 = f\frac{9h}{2}\frac{e^2}{mc\sigma_T} \approx 230\, f\ MeV$$

**WHAT IS f WITHIN RCA?**

# VARIABILITY WITHIN RCA

RCA Mechanism has an intrinsic maximum energy:

$$\omega_{c\pm} \geq \omega_{ci} \quad \Rightarrow \quad \frac{1}{m_\pm \gamma_\pm} \geq \frac{1}{m_i \gamma_i} \quad \Rightarrow \quad \gamma_{\max}^{RCA} = \frac{m_i}{m_e} \Gamma_{wind} \approx 6\times 10^9 \frac{\Gamma_{wind}}{3\times 10^6}$$

Based on 1d PIC of RCA
(Amato & Arons 06)
f~.1-.5 ($\sigma$ and $E_i/E_{tot}$)
*Caveat*: in 3D?

$$\gamma_{\max}^{loss} = 1.2\times 10^{10} \sqrt{\frac{f}{B_{-4}}} \approx 2.5\times 10^9 \sqrt{\frac{f_{1/2}}{B_{-3}}}$$

Fermi steady cut-off

$$\varepsilon_{\max} \approx 100\, f_{1/2}\, MeV \approx 100\ \frac{B}{10^{-3}} \left(\frac{\gamma_{\max}}{2.5\times 10^9}\right)^2 MeV$$

$$T_{\rm var} \approx 3 \left(\frac{\varepsilon_{ph}}{100 MeV}\right)^{1/2} \left(\frac{f}{0.5}\right)^{-1} \left(\frac{B}{mG}\right)^{-3/2} days$$

$T_{var}$ and $\varepsilon_{max}$ in the ballpark…

Special relativity could help: $\varepsilon_{\max}^{obs} \approx \Gamma\, \varepsilon_{\max}^{rf}$ $\qquad T_{\rm var}^{obs} \approx \Gamma^{-1}\, T_{\rm var}^{rf}$

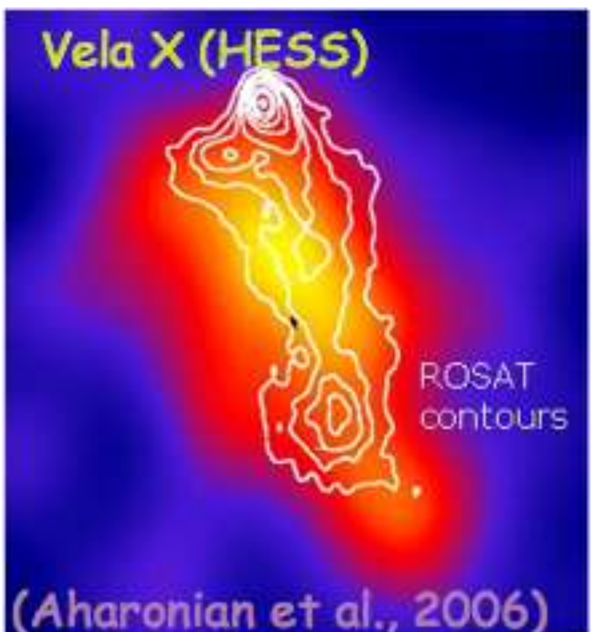
# SIGNATURES OF RELATIVISTIC PROTONS

If protons are there, they might reveal themselves through $\pi$-production (Bednarek 02; Amato et al 03)

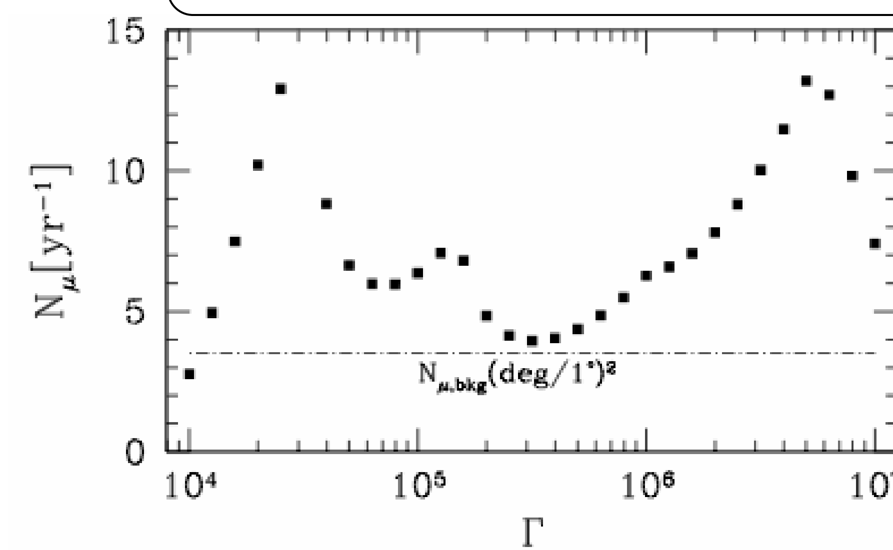
$\pi^0 \rightarrow \gamma$-rays ← $L_\pi = f_\pi L_p$ → $\pi^\pm \rightarrow e^\pm \nu$

Fluxes of all secondaries depend on $U_i/U_{tot}$, $\Gamma$ and target density

$\pi^0$ $\gamma$-rays in Vela?
(Horns et al 06)
But see also LaMassa et al 08



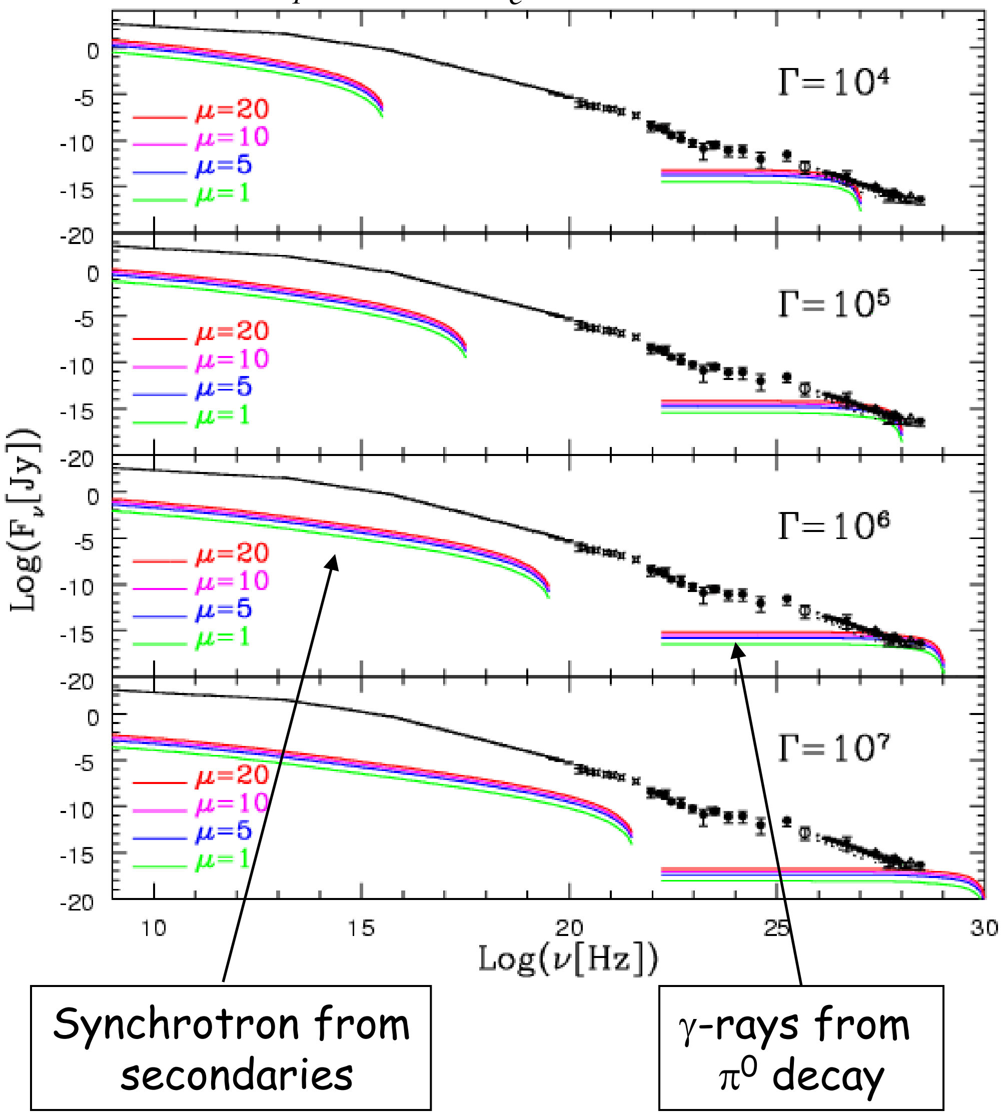

Most direct signature would be $\nu$ detection

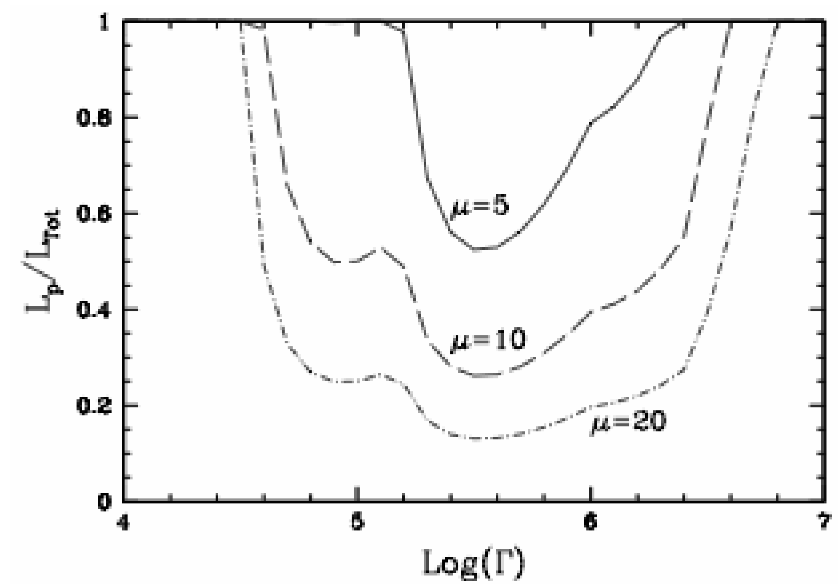



Calculations show that for Crab signal above the background if $M_{ej}$>8 $M_{sun}$

# DEPENDENCE ON CRAB WIND PARAMETERS

$$L_p = L_B = L_{e^\pm} = (1/3)L_0$$



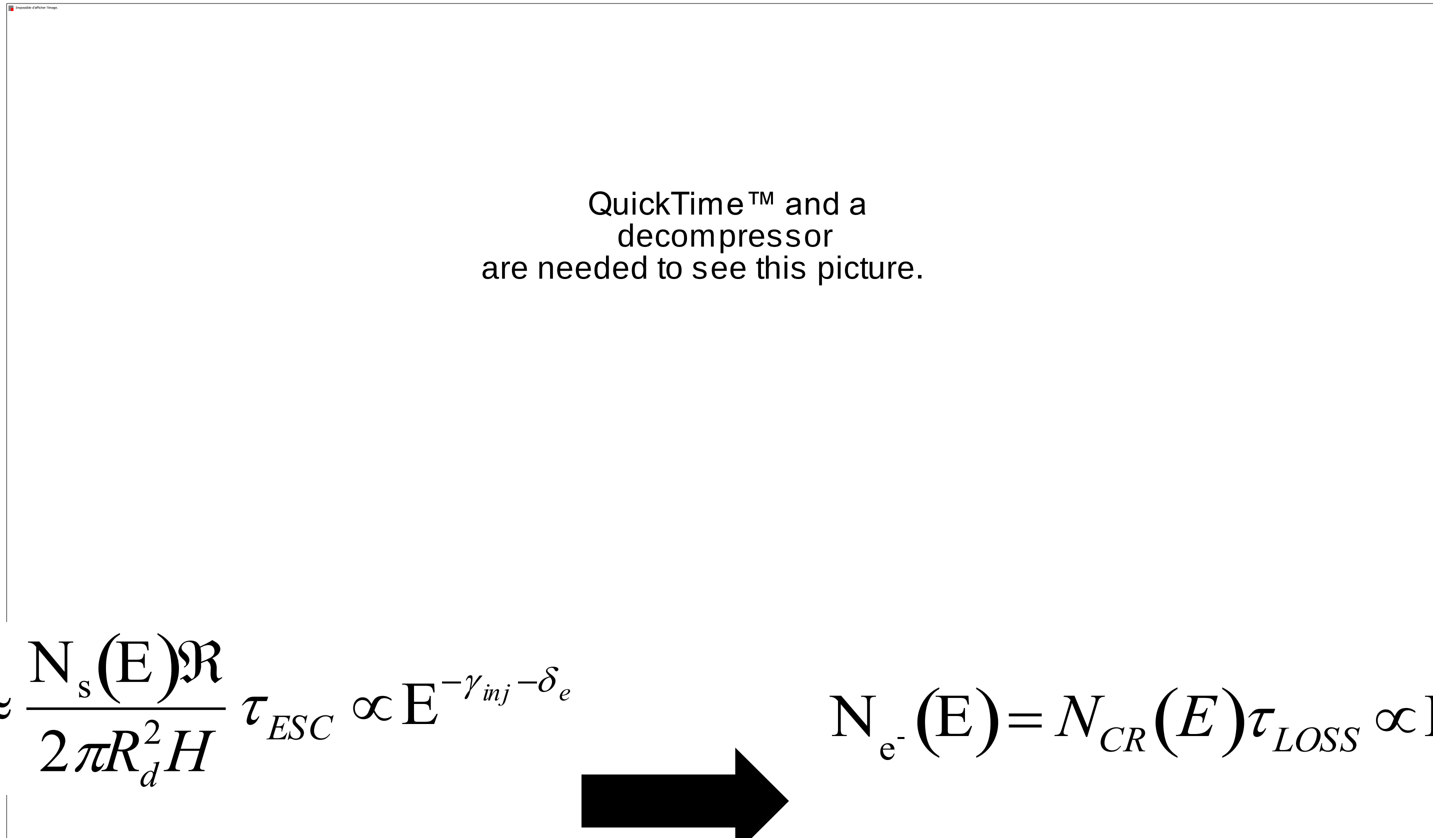




(Amato et al 03)

MORE REFINED CONSTRAINTS FROM MORE REFINED DYNAMICS AND EMISSION MODELS

# THE POSITRON “EXCESS”

Ackerman et al 11




$$N_{CR}(E) \approx \frac{N_s(E)\Re}{2\pi R_d^2 H}\tau_{ESC} \propto E^{-\gamma_{inj}-\delta_e}$$

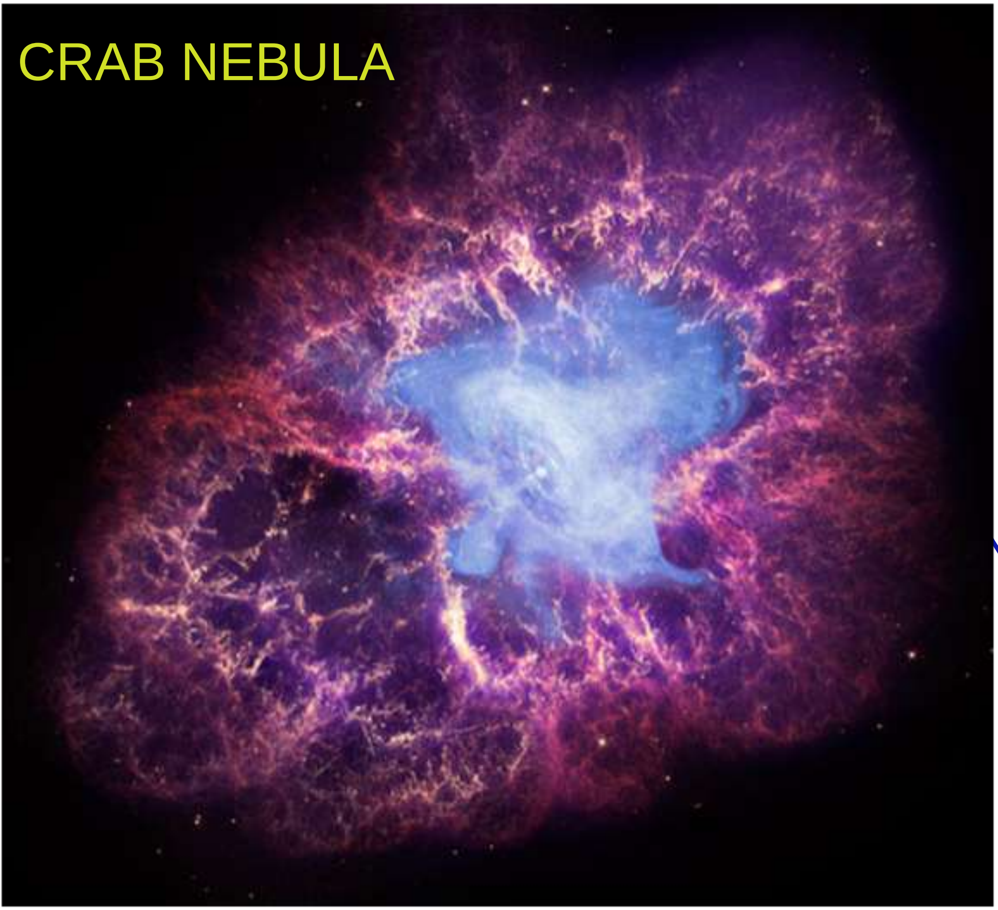
$$N_{e^-}(E) = N_{CR}(E)\tau_{LOSS} \propto E^{-\gamma_{inj}-\delta_e-1}$$

$$N_{SEC}(E) \approx N_{CR}(E)\Re_{SP}\tau_{ESC} \propto E^{-\gamma_{inj}-2\delta_e}$$

$$N_{e^+}(E) = N_{SEC}(E)\tau_{LOSS} \propto E^{-\gamma_{inj}-2\delta_e-1}$$

$$\boxed{\frac{N_{e^+}}{N_{e^-}} \propto E^{-\delta}}$$

# PULSARS AND THEIR WINDS




PULSARS ARE EXCELLENT ANTI-MATTER FACTORIES

PAIRS ARE ACCELERATED WITH

$L_{PAIRS} \approx 20\text{-}30\% L_{PSR}$

$N_{PAIRS}(E) \propto E^{-\gamma}$ $1<\gamma<1.5$ FOR $E<.1\text{-}.5$ TeV

(ALL FROM OBSERVATIONS!)

# WHAT HAPPENS TO THE PAIRS?

**THE PAIRS INSIDE THE PWN TRY TO EXPAND AGAINST THE EJECTA SUFFERING ADIABATIC+RADIATIVE LOSSES**

**WHEN THE REVERSE SHOCK OF THE BLAST WAVE REACHES THE CENTER, SOME LEVEL OF COMPRESSION MIGHT OCCUR**

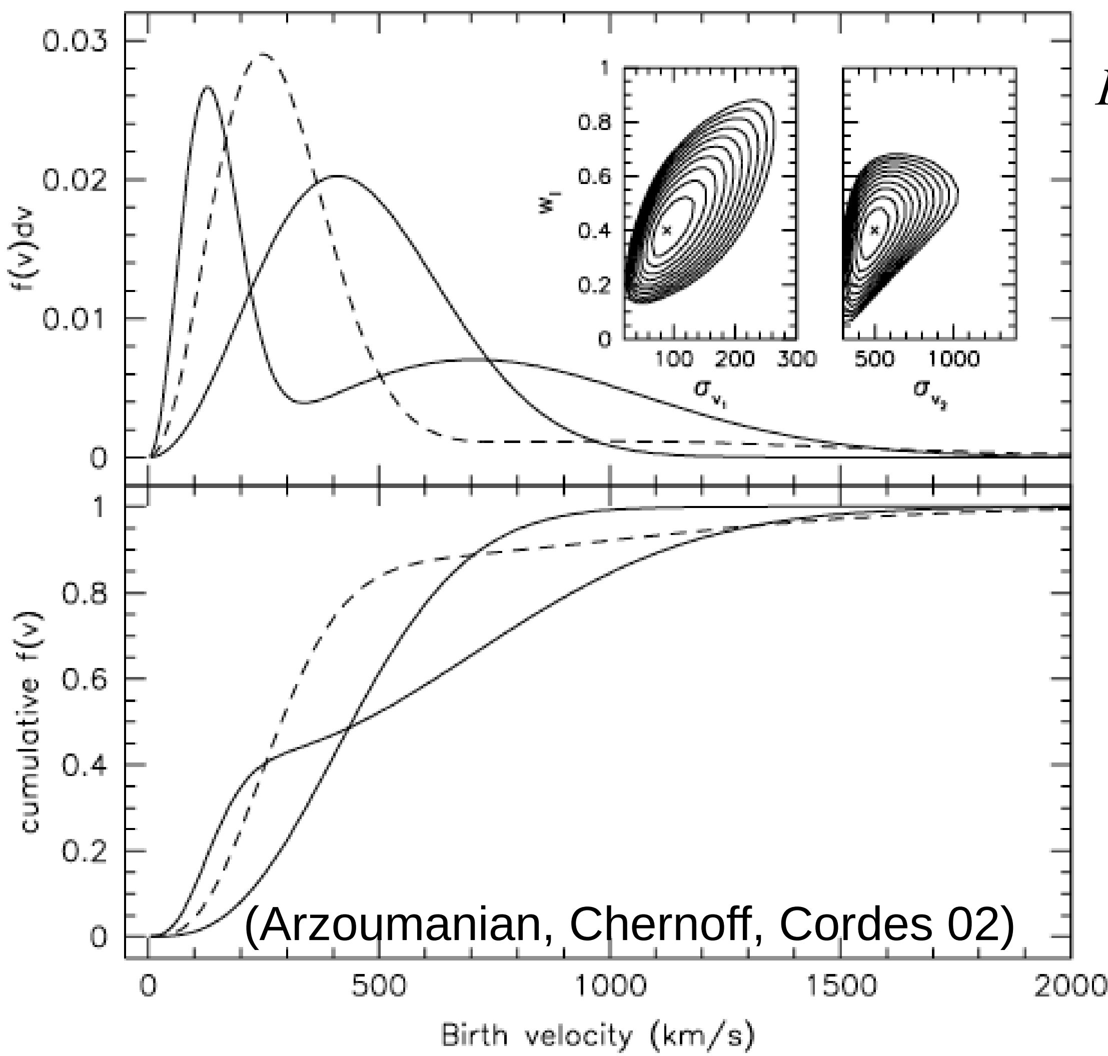
**…BUT IT COULD EVEN DISPLACE THE PWN (SEE CASE OF VELA), POSSIBLY LIBERATING SOME ELECTRONS AND POSITRONS**

**IN GENERAL HOWEVER THE ELECTRONS AND POSITRONS STAY INSIDE THE REMNANT AND KEEP LOSING ENERGY BOTH RADIATIVELY AND ADIABATICALLY**

**BUT DO WE REALLY NEED TO RETRIEVE THESE PAIRS FROM IN THERE?**

# A HIGH VELOCITY POPULATION

PEAK VELOCITY 400-500 km/s




(Arzoumanian, Chernoff, Cordes 02)

**A SIMPLE ESTIMATE:**

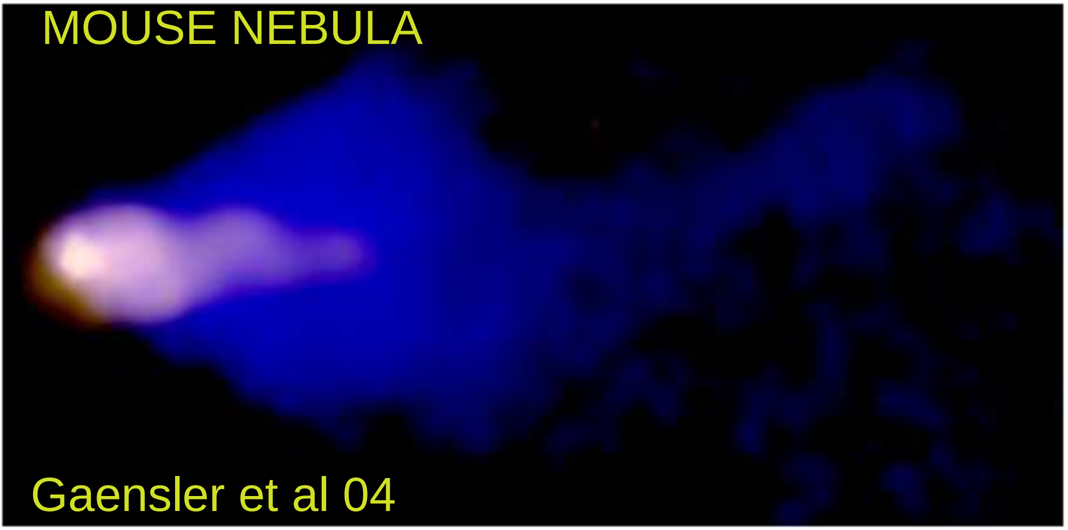
$$R_s(t) \approx R_{ST}\left(\frac{t}{T_{ST}}\right)^{2/5} \qquad \mathrm{R}_{\mathrm{NS}}(t) = V_{NS}t$$

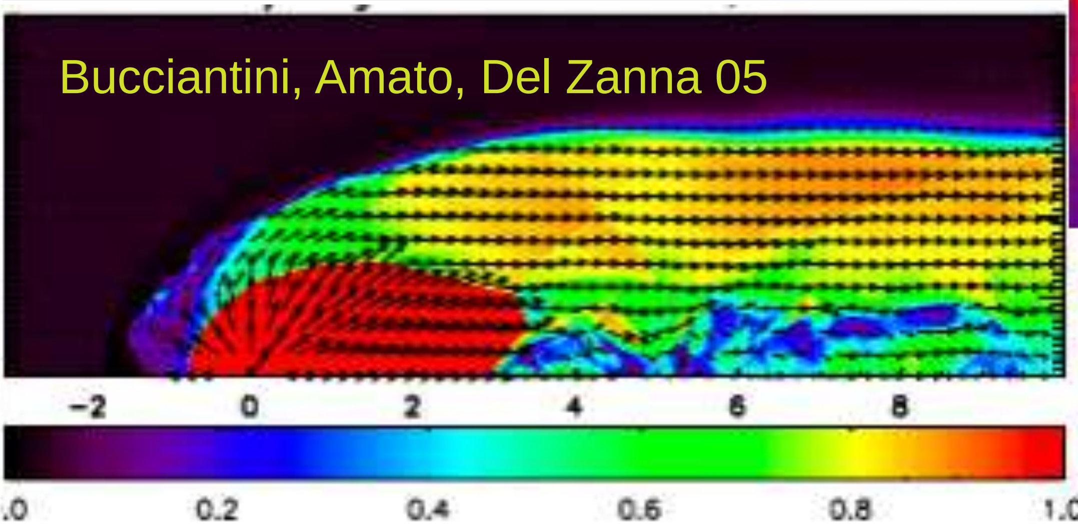
**THE NS LEAVES THE REMNANT AT**

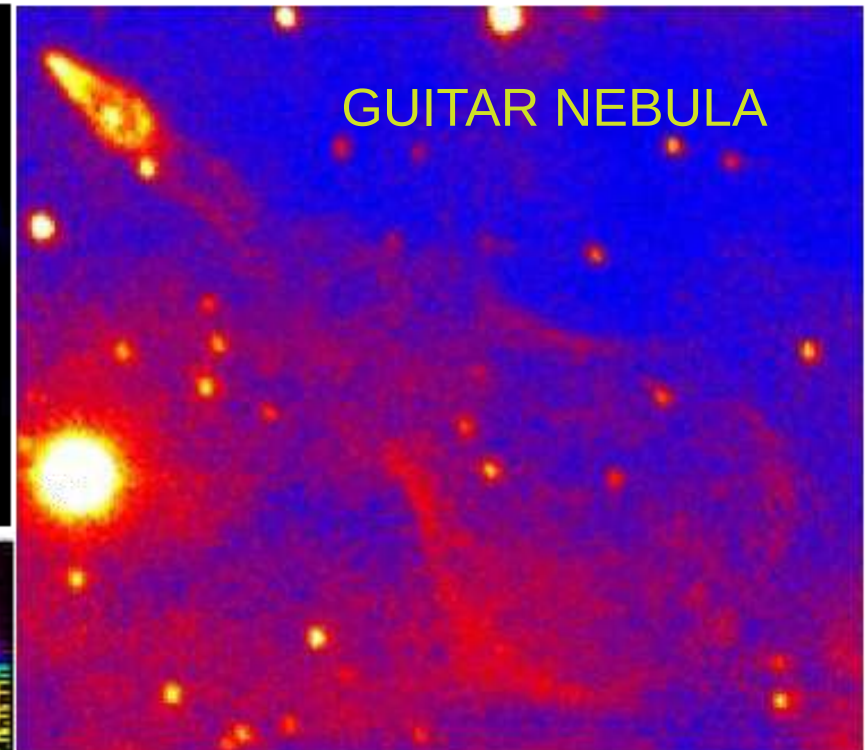
$$t \approx T_{ST}\left(\frac{R_{ST}}{T_{ST}V_{NS}}\right)^{5/3}$$

**FOR TYPICAL VALUES OF PARAMETERS THE NS LEAVES THE SNR ABOUT 40,000 years AFTER EXPLOSION**

# PULSAR BOW SHOCK NEBULAE




MAIN UNKNOWN:

HOW MUCH ENERGY IS LEFT IN PAIRS AT THIS TIME?

DEPENDS ON SPIN-DOWN: $L = I\Omega\dot{\Omega} \propto \Omega^{n+1}$

- n=3 FOR DIPOLE
- OBSERVED VALUES: ALWAYS n<3

# ENERGETICS

**THE ENERGY AVAILABLE AFTER A TIME T$_*$ WHEN THE NS IS OUTSIDE THE SNR IS**

$$E_* = E(t > T_*) = \frac{1}{2} I\Omega_0^2 \left(1 + \frac{T_*}{\tau_0}\right)^{-\frac{2}{n-1}} = E_{tot}\left(1 + \frac{T_*}{\tau_0}\right)^{-\frac{2}{n-1}}$$

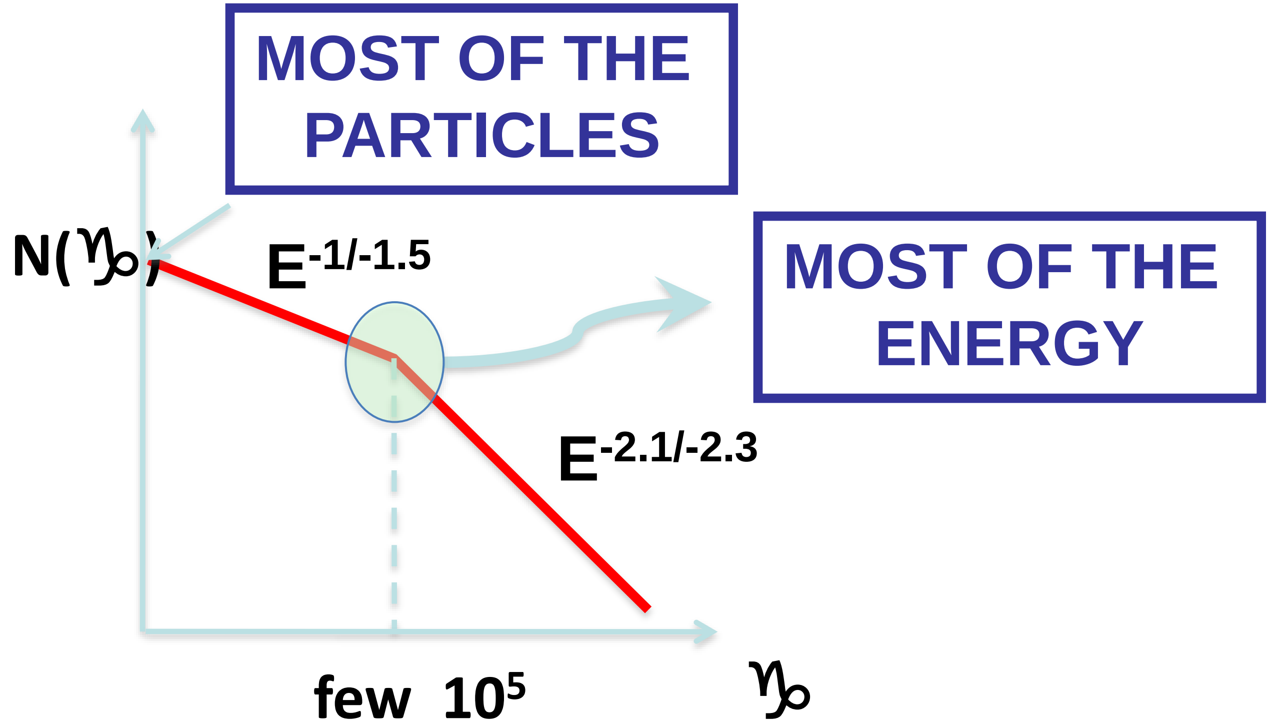
**FOR T$_*$~40,000 YEARS, ONE HAS:**

$$\frac{E_*}{E_{tot}} \approx 0.5 \qquad \text{For dipole n} = 3$$

$$\frac{E_*}{E_{tot}} \approx 0.02 \qquad \text{For n} = 2.5$$

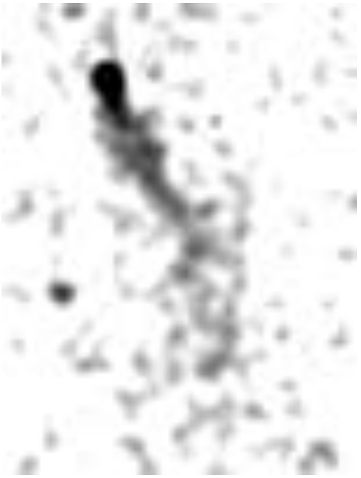
**WE WILL SEE LATER HOW THIS COMPARES WITH ENERGETIC REQUIREMENTS IMPOSED BY PAMELA RESULTS**

# INFERENCE FROM YOUNG PWNe

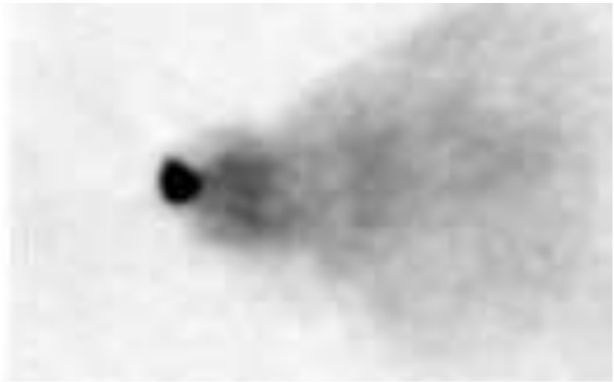


# PARTICLE SPECTRA FROM OBSERVATIONS

**IN THE TWO CASES of BSN OUTSIDE A SNR IN WHICH WE HAVE RADIO MEASUREMENTS WE INFER A SPECTRUM OF ACCELERATED PARTICLE WITH SLOPE ~-1.5**



**PSR J1509−5850**
**SLOPE RADIO: -0.26**
**SLOPE ELECTRONS: -1.52**
Ng et al. 2010



**THE MOUSE**
**SLOPE RADIO: -0.3**
**SLOPE ELECTRONS: -1.6□**

# ELECTRONS AND POSITRONS FROM PULSARS

**$e^+ + e^-$**

Blasi & Amato 11

**TOTAL**

25% EFFICIENCY

FOR n=2.5

**SNRs**

QuickTime™ and a
decompressor
are needed to see this picture.

1% EFFICIENCY

FOR n=3

**PWNe**

CONTRIBUTION FROM PULSARS MUST BE THERE AT SOME LEVEL!!!!

# SUMMARY

+THE BEST WAY TO LEARN ABOUT PSR ELECTRODYNAMICS IS BY LOOKING A PWNe

+2D AXISYMMETRIC MHD MODELS ARE VERY SUCCESSFUL AT REPRODUCING THE SPATIAL FEATURES OF THE EMISSION

+THEY ALLOW US TO CONSTRAIN THE FLOW MAGNETIZATION AT TS

+THEY CAN ALSO ACCOUNT FOR VARIABILITY IN THE INNER NEBULA ON WEEK-MONTH TIME-SCALES

+PREDICTION OF MILDLY RELATIVISTIC FLOW IN THE DOWNSTREAM ALSO HELPS WITH ACCOUNTING FOR PUZZLING FERMI CUT-OFF

-WE DO NOT UNDERSTAND HOW PARTICLES ARE ACCELERATED AT THESE EXTREME SHOCKS

-WE DO NOT HAVE A GOOD EXPLANATION FOR FLARES YET

COSMIC RAY RELATED ISSUES:

- PWNe ARE LIKELY TO BE THE PRIMARY CONTRIBUTOR TO THE CR POSITRON EXCESS
- WE STILL DO NOT KNOW WHETHER THEY CONTAIN MULTI-PEV IONS