Lecture 4:
Positrons, Pulsars and PWN

Pasquale Blasi

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- SITUATION WITH THE OBSERVATION OF THE POSITRON RATIO
- PULSARS AND PWN AS ACCELERATORS AND STORAGE ROOMS OF POSITRONS
- BOW SHOCK NEBULAE AS THE POSITRON KEEPERS
- POSITRON PROPAGATION

Sources of astrophysical positrons

Radioactive Decays (e.g. in SNRs)

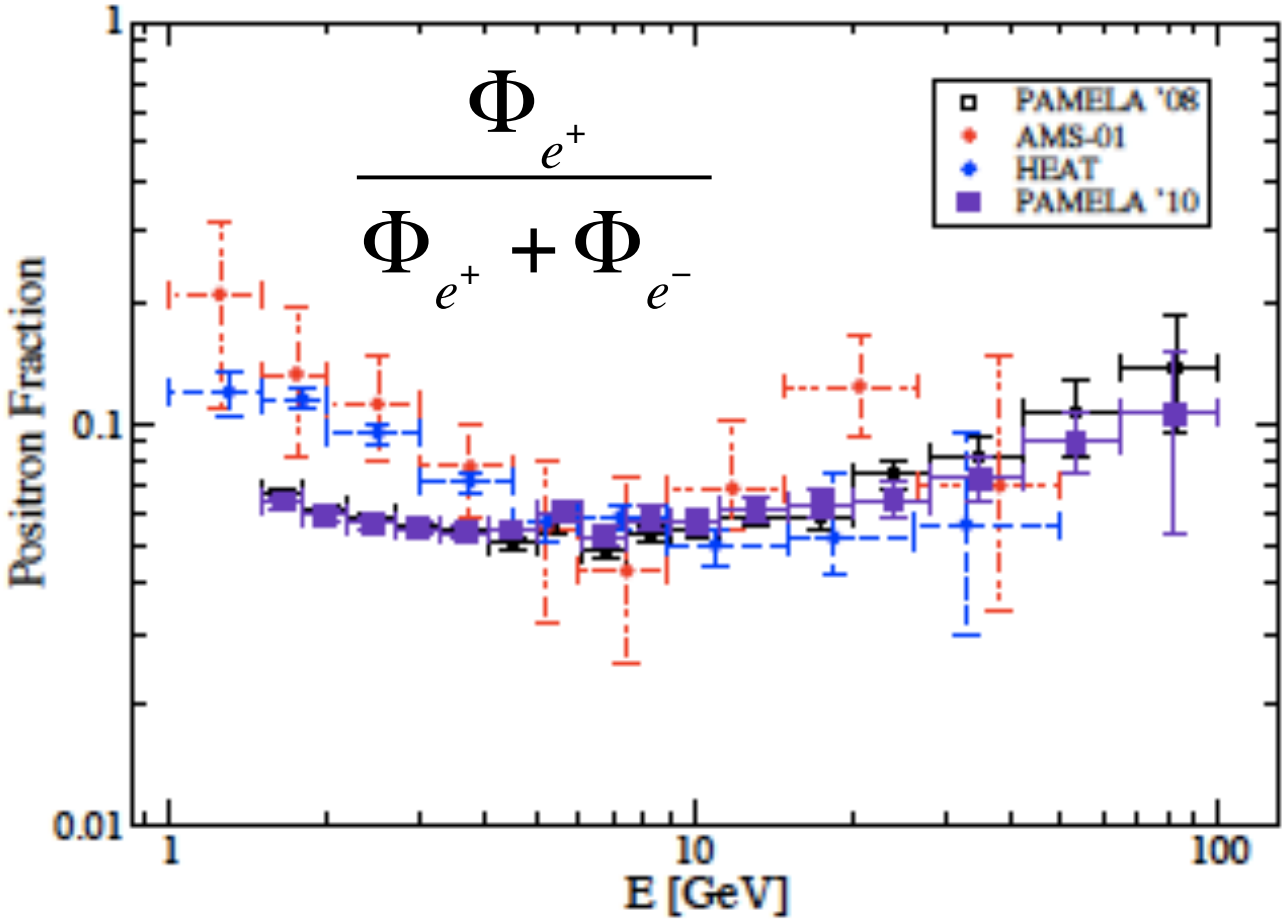
Secondary products of hadronic interactions

Electron-positron pair creation ($g + g \rightarrow e^+ + e^-$)

Pulsar magnetospheres (cascade multiplication in Intense magnetic fields)

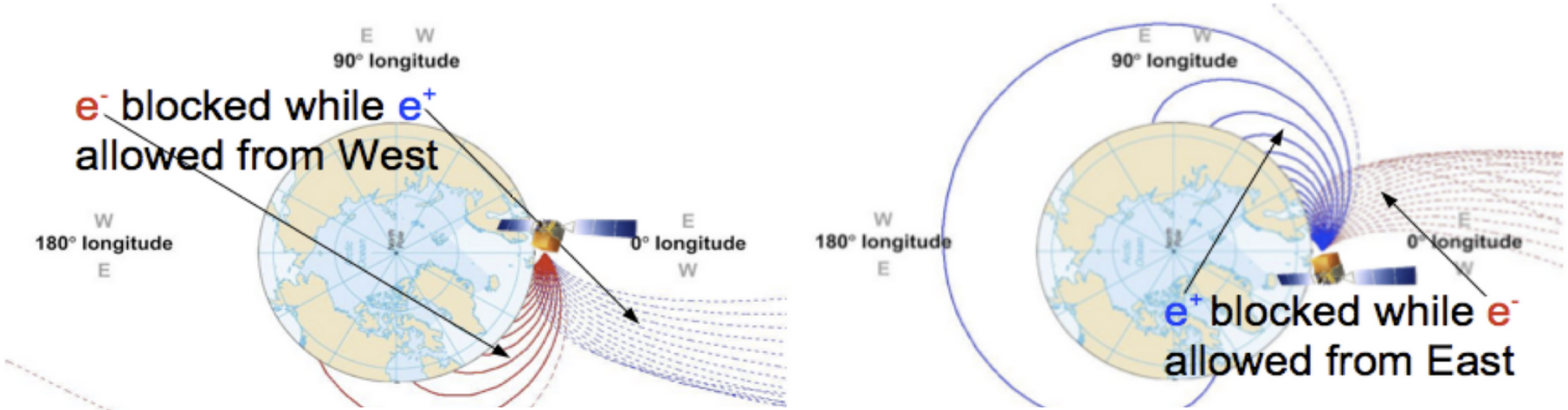
Dark Matter Annihilation?

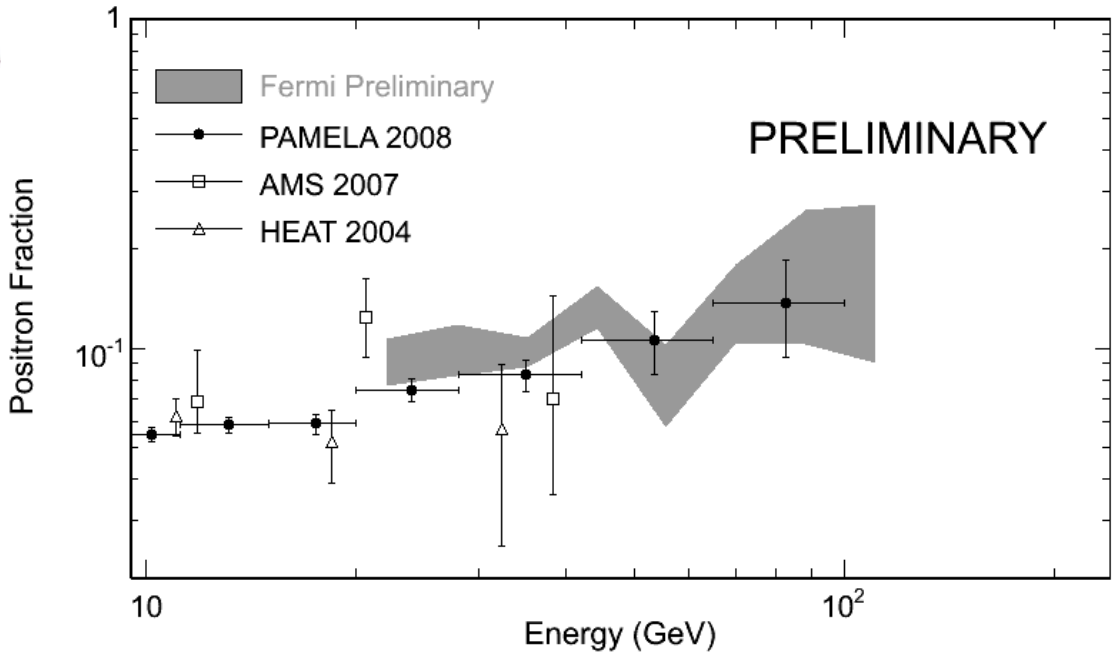
The Positron Ratio



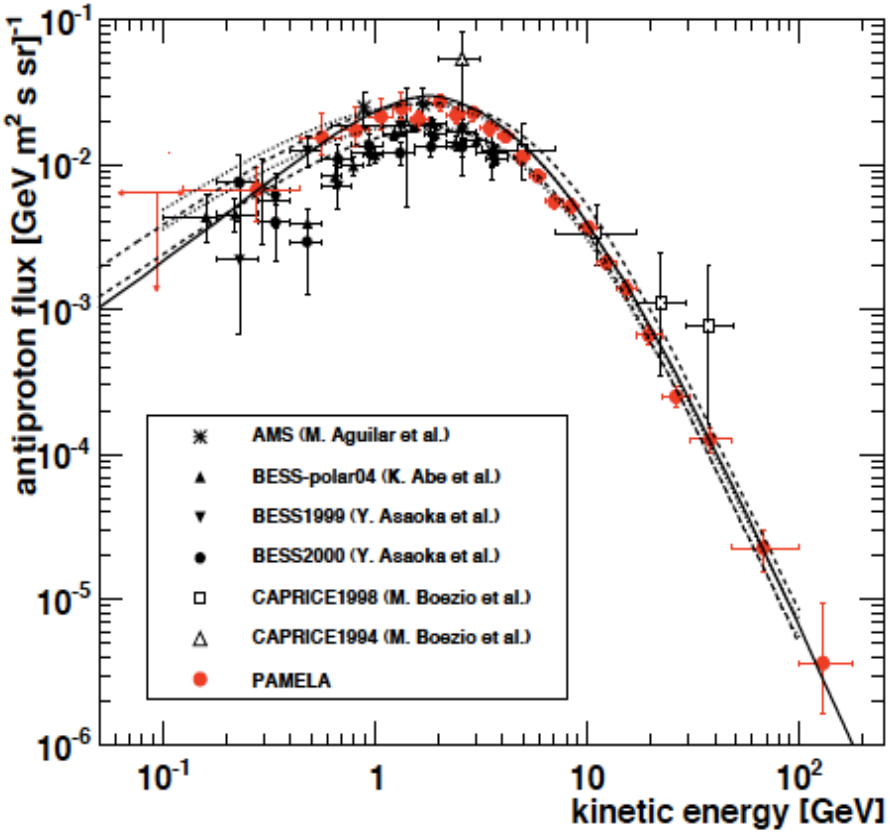
Serpico 2011

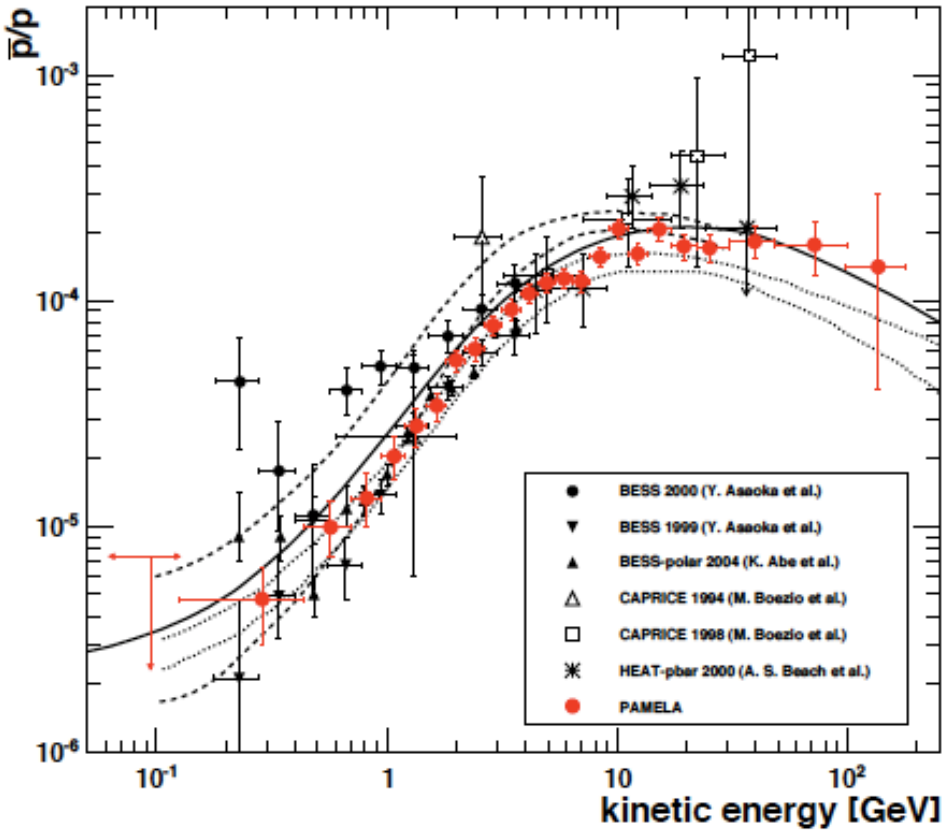
RISING POSITRON FRACTION WITH FERMI-LAT





Antiprotons

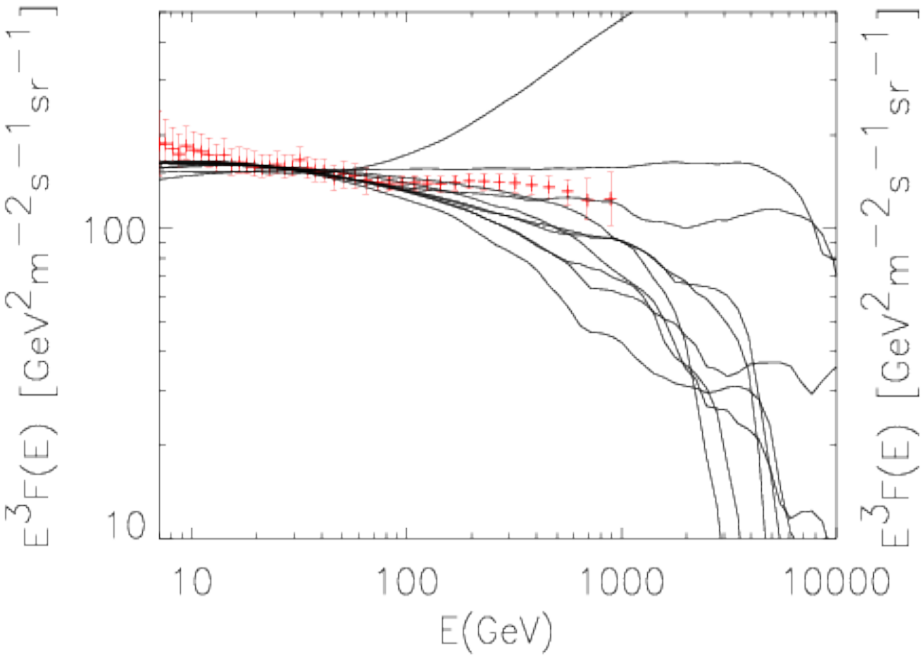




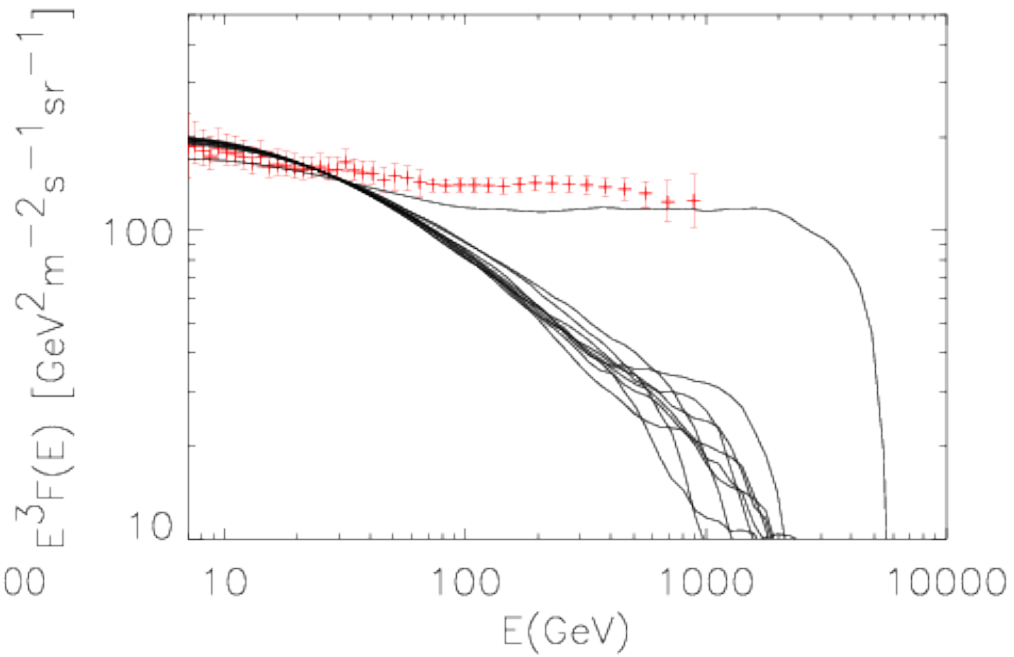
Adriani 2010, 2011

EXCESS WITH RESPECT TO WHAT?

a note of caution

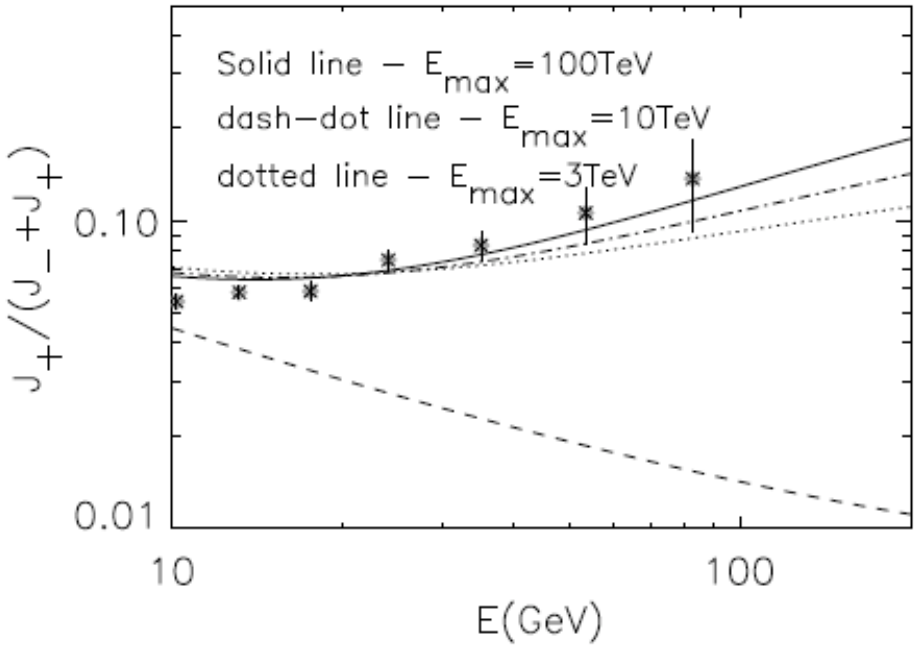


PRIMARY ELECTRONS
+
SECONDARY PAIRS
(NO SPIRAL ARMS)

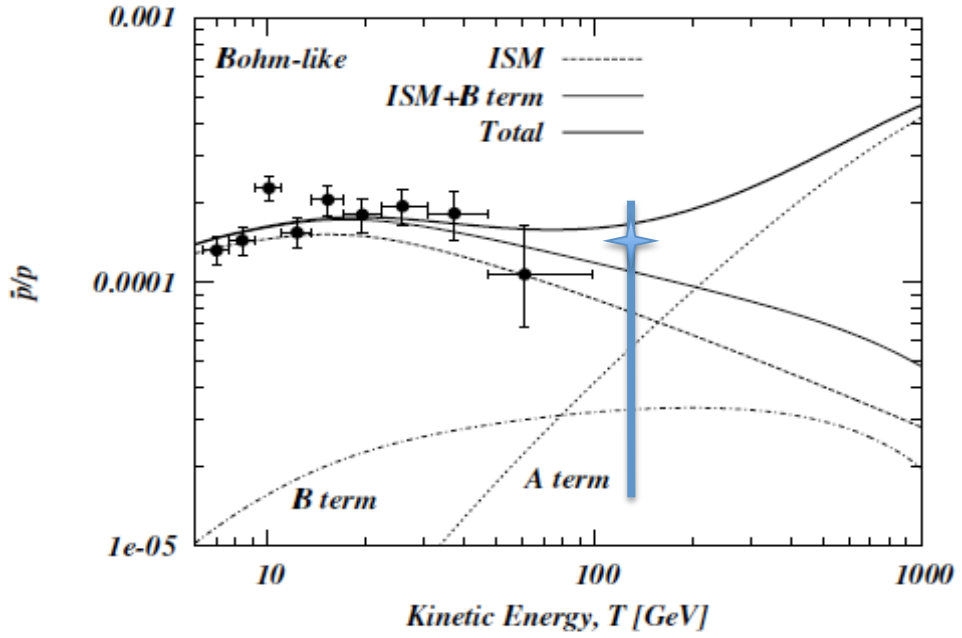


PRIMARY ELECTRONS
+
SECONDARY PAIRS
(TIGHT SPIRAL ARMS)

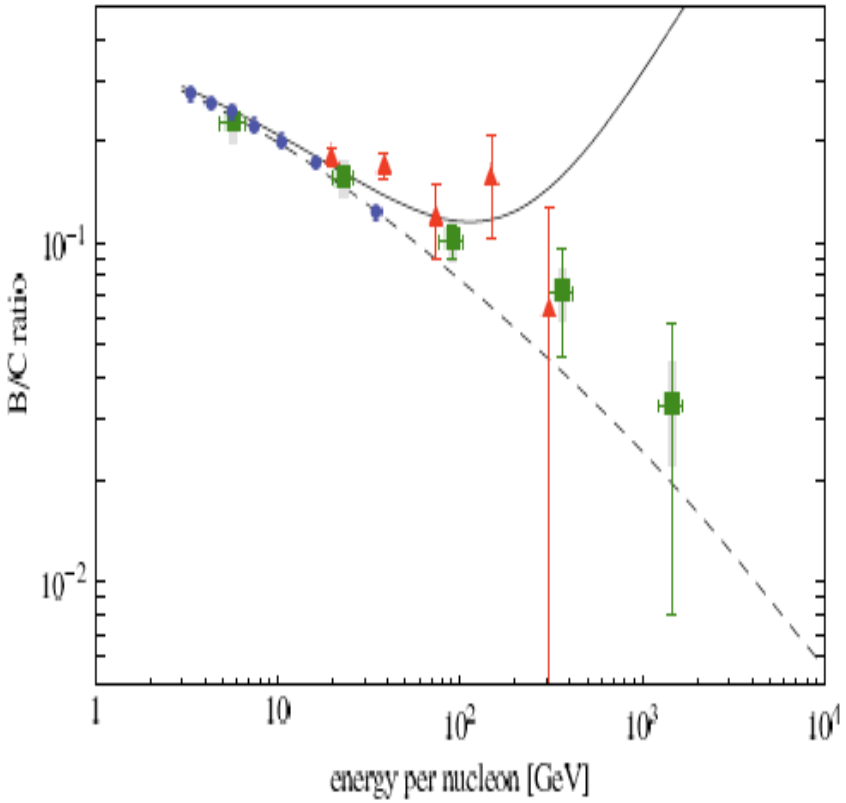
ANTIPROTONS and B/C POWERFUL TOOLS TO DISCRIMINATE



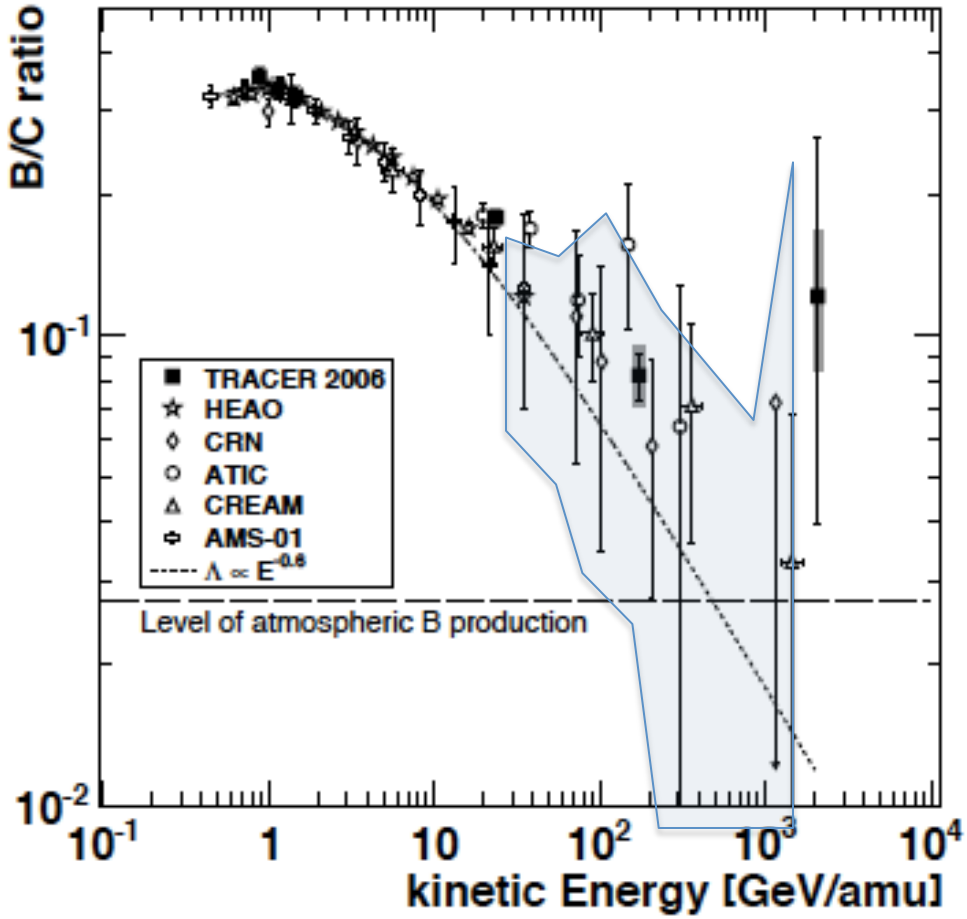
PB 2009



PB & Serpico 2009



Mertsch & Sarkar 2009



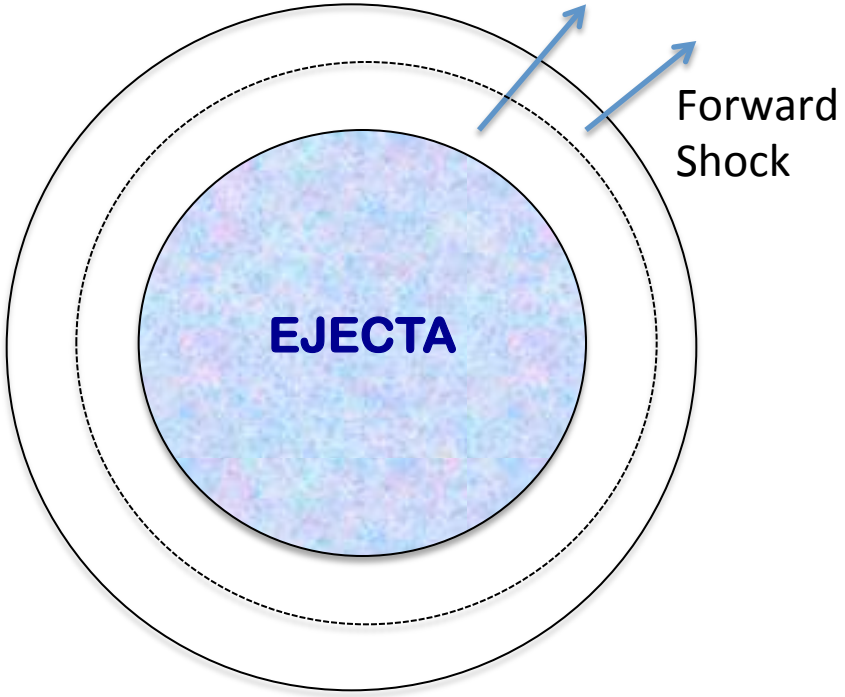
Radioactive decays in SN explosions

$$^{56}Ni \Rightarrow {}^{56}Co \Rightarrow {}^{56}Fe + e^{+} + \gamma$$

$$^{44}Ti \Rightarrow {}^{44}Sc + e^{-} \Rightarrow {}^{44}Ca + e^{+} + e^{-}$$

$T_{1/2,\,Ni}$=6.1 days $T_{1/2,Co}$=77 days

$T_{1/2,Ti}$=63 years

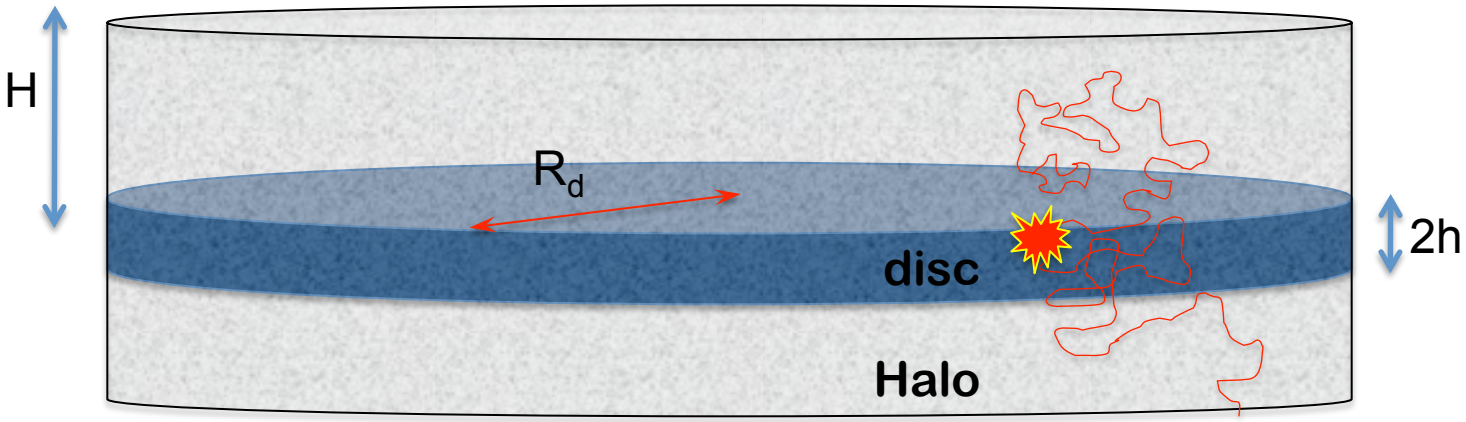


LOW ENERGY POSITRONS

CONFINED IN THE EJECTA

EVEN IF ACCELERATED AT THE REVERSE SHOCK → SPECTRUM THE SAME AS COSMIC RAYS

Secondary positrons (1)



PRIMARY COSMIC RAY SPECTRUM AT EARTH

$$n_{CR}(E) = \frac{N(E)\mathcal{R}}{2\pi R_d^2}\frac{H}{D(E)} \equiv \frac{N(E)\mathcal{R}}{2H\pi R_d^2}\frac{H^2}{D(E)} \propto E^{-\gamma-\delta}$$

SPECTRUM OF PRIMARY ELECTRONS AT EARTH

$$n_e(E) \approx \frac{N(E)\Re\tau_{loss}(E)}{\sqrt{D(E)\tau_{loss}(E)}} \propto E^{-\gamma-1/2-\delta/2}$$

IF ENERGY LOSSES ARE DOMINANT UPON DIFFUSION (TYPICALLY E>10 GeV

Secondary positrons (2)

INJECTION RATE OF SECONDARY POSITRONS

$$q_{e^+}(E')dE' = n_{CR}(E)dE\, n_H\, \sigma_{pp}\, c \propto E^{-\gamma-\delta}$$

EQUILIBRIUM SPECTRUM OF SECONDARY POSITRONS (AND ELECTRONS) AT EARTH

$$n_{e^+}(E) \approx \frac{q_{e^+}(E)\tau_{loss}(E)}{\sqrt{D(E)\tau_{loss}(E)}} \propto E^{-\gamma-1/2-3\delta/2}$$

POSITRON FRACTION

$$\frac{\Phi_{e^+}}{\Phi_{e^+}+\Phi_{e^-}} \approx \frac{\Phi_{e^+}}{\Phi_{e^-}} \propto E^{-\delta}$$

MONOTONICALLY DECREASING FUNCTION OF ENERGY

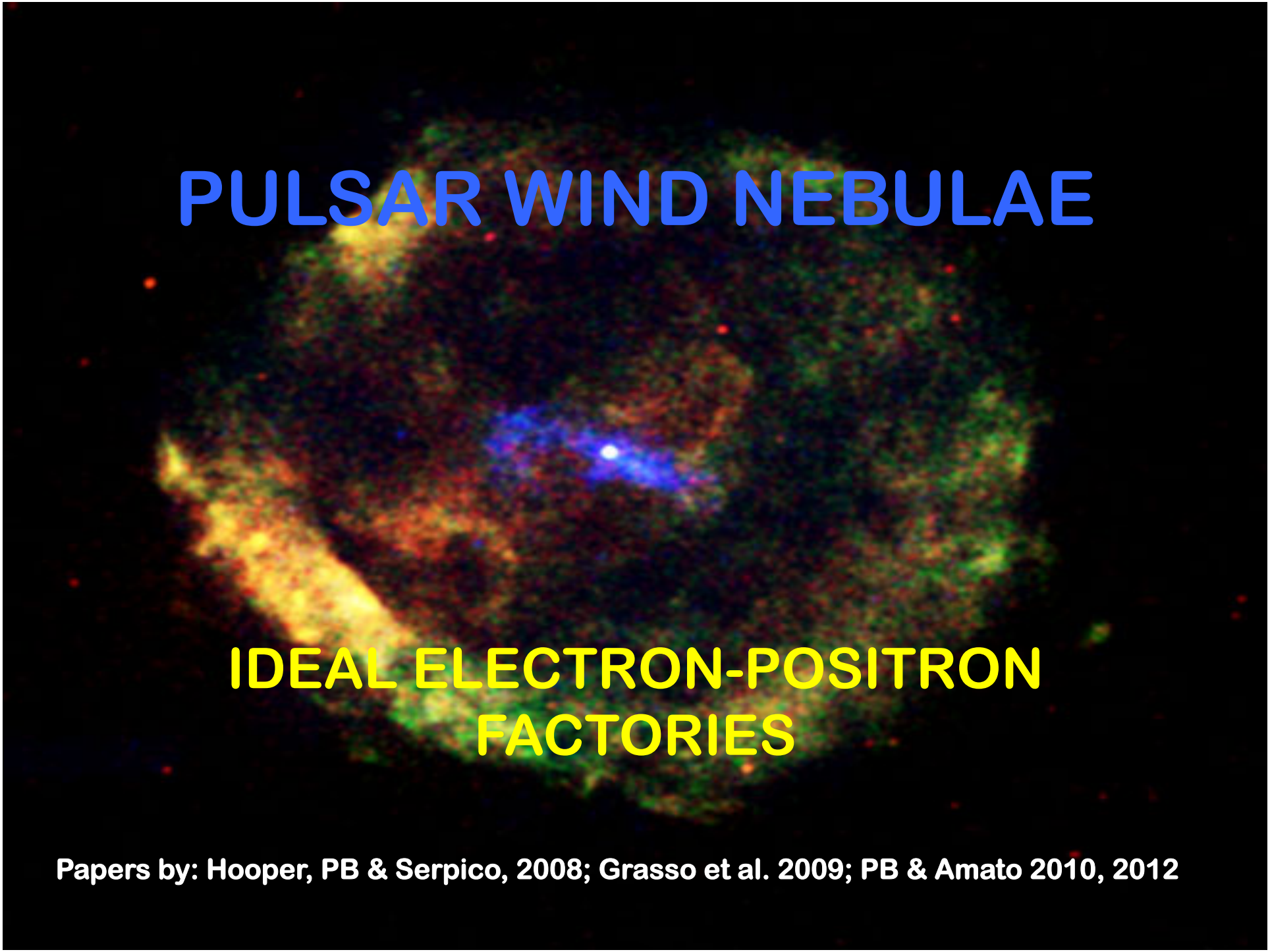
DARK MATTER as source of positrons

DARK MATTER ANNIHILATIONS MAY LEAD TO PRODUCTION OF ELECTRON POSITRON PAIRS DUE TO HADRONIZATION OF Q-Qbar PAIRS WITH PRODUCTION AND DECAY OF CHARGED PIONS.

IT IS EASY TO SHOW THAT IN ORDER TO EXPLAIN THE OBSERVED POSITRON RATIO, THE DARK MATTER CANDIDATE MUST SATISFY SOME RATHER ARTIFICIAL CONDITIONS:

1. THE BOOSTING FACTOR ASSOCIATED WITH THE DM ANNIHILATION (SUBSTRACTURES) MUST LARGELY EXCEED THE ONE OBTAINED IN NUMERICAL SIMULATIONS OF LARGE SCALE STRUCTURE FORMATION
2. THE CROSS SECTION NEED TO BE MUCH LARGER THAN FOR NORMAL WIMPS (POSSIBLY DUE TO A SOMMERFELD ENHANCEMENT)
3. IN ORDER TO AVOID OVERPRODUCTION OF ANTIPROTONS ONE HAS TO REQUIRE THAT THE DM PARTICLE IS LEPTOPHILIC

ALL THESE CONDITIONS APPEAR TO BE TOO MUCH *ad hoc* TO ADDRESS ONE SINGLE ISSUE



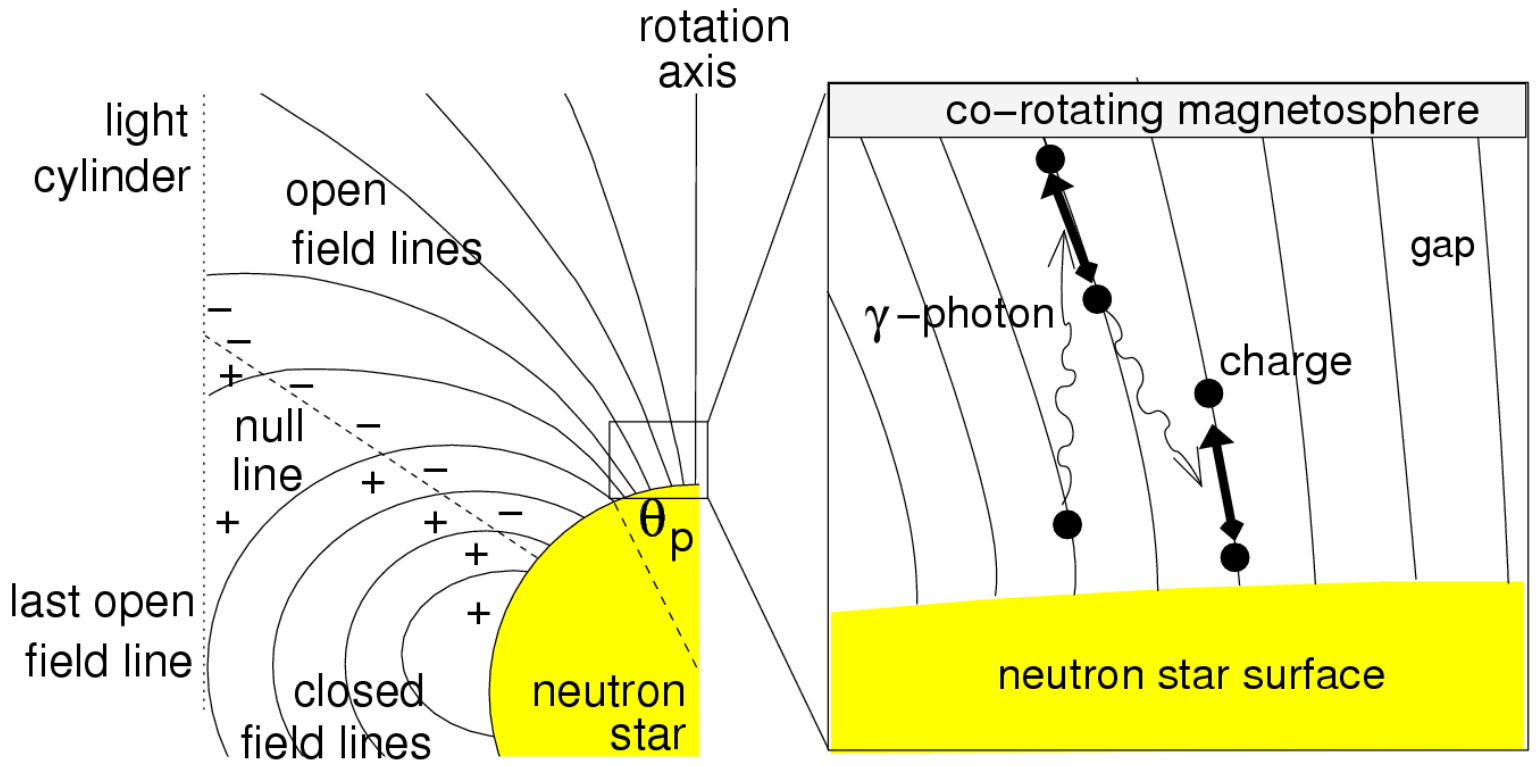
PULSAR WIND NEBULAE

IDEAL ELECTRON-POSITRON FACTORIES

Papers by: Hooper, PB & Serpico, 2008; Grasso et al. 2009; PB & Amato 2010, 2012

Pulsar wind launching

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



Pulsar magnetosphere

Electrons are stripped off the surface of the neutron star because of the strong electric field and drift along the direction of the magnetic field.

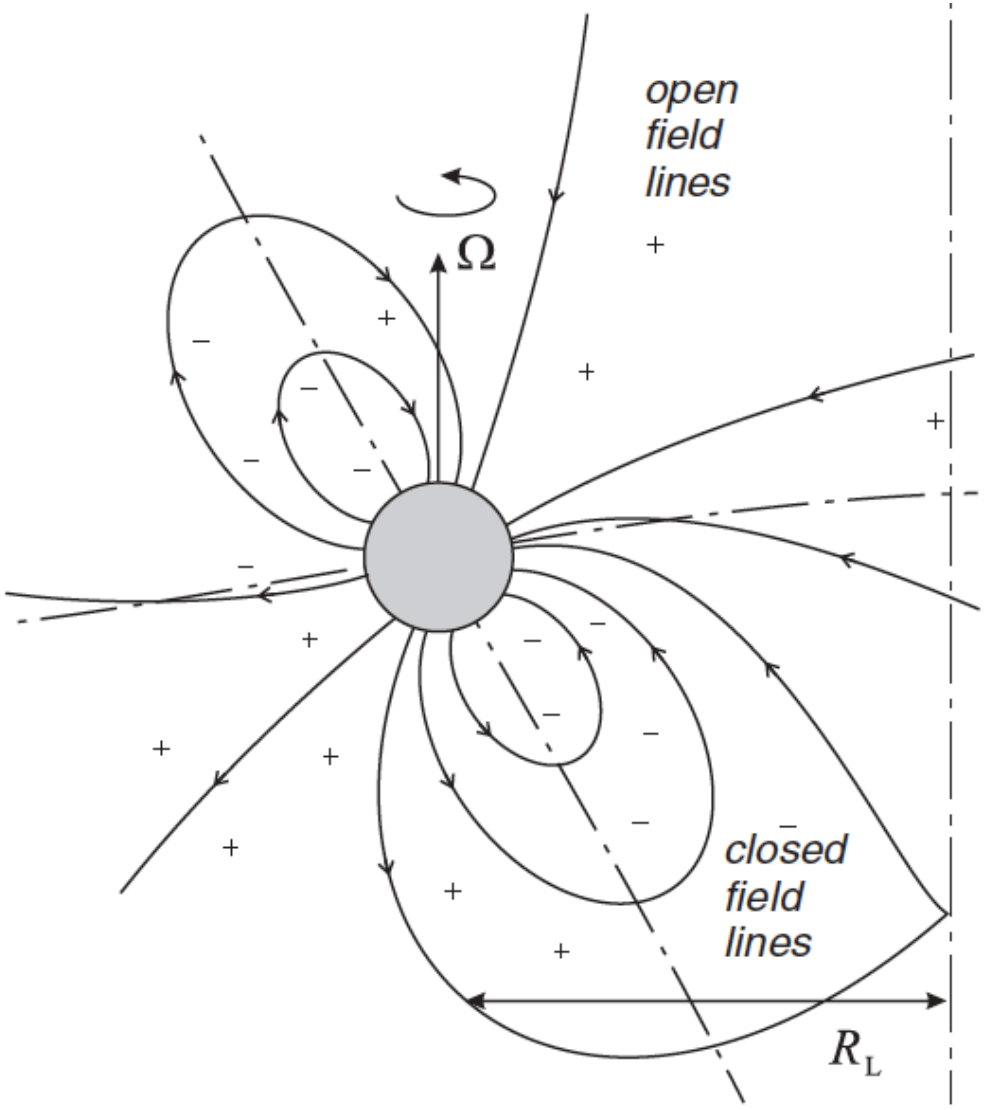
Any perpendicular momentum is rapidly dissipated through synchrotron emission

The combination of curvature radiation, pair production on the virtual photons of the magnetic field and ICS off the thermal photons leads to populate the magnetosphere with 10^4-10^6 pairs for each electron extracted from the surface.

The actual charge density is however fixed at the Goldreich-Julian value:

$$\rho_{\rm GJ} = \frac{1}{4\pi}\mathrm{div}\mathbf{E} \approx -\frac{\mathbf{\Omega}\cdot\mathbf{B}}{2\pi c}$$

MORE ON THE MAGNETOSPHERE

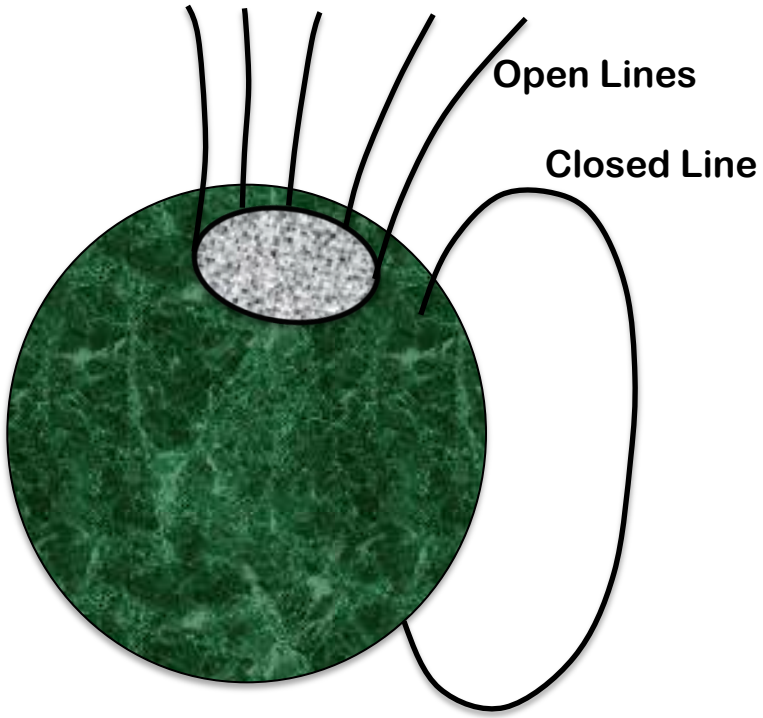


THE MAGNETOSPHERE, FILLED WITH ELECTRON-POSITRON PAIRS IS FORCED TO COROTATE WITH THE STAR, AT LEAST OUT TO THE POINT WHERE THE CO-ROTATION SPEED EQUALS THE SPEED OF LIGHT. THIS IS CALLED THE LIGHT CYLINDER:

$$R_L = \frac{c}{\Omega}$$

INTERESTINGLY ENOUGH, ALL PROPERTIES OF THE PWN ARE MAPPED INTO PROPERTIES OF THE LIGHT CYLINDER

MAGNETIC FIELD



WIND REGION

MAGNETIC FIELD STRENGTH SCALES AS $1/r^3$ IN THE DIPOLE REGION AND AS $1/r$ IN THE WIND REGION

LOCATION OF GAPS

MUCH DISCUSSION IS GOING ON IN RECENT TIMES ABOUT THE LOCATION OF THE GAPS (SEE TALKS BY M. Weisskopf AND N. Otte)

FERMI AND MAGIC RECENT DATA SUGGEST THAT THE GAP MUST BE DISTANT FROM THE STAR'S SURFACE IN ORDER TO ACCOMODATE THE HIGH ENERGY PART (BUT EVEN IN THIS CASE THERE IS THE PROBLEM WITH THE POWER LAW TAIL)

BUT THE GAP CLOSE TO THE POLAR REGION CANNOT BE AVOIDED, BECAUSE IN THE END YOU NEED TO STRIP THE ELECTRONS OFF THE SURFACE OF THE STAR IN ORDER TO INITIATE THE CASCADE THAT POPULATES THE MAGNETOSPHERE

SO THE PROBLEM IS OF WHERE IS THE REST OF THE GAP (OUTER GAP, DISTRIBUTED GAPS)

PULSAR SPIN DOWN

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

$$\Omega(t) = \frac{\Omega_0}{\left[1 + t/\tau_0\right]^{1/(n-1)}} \qquad \tau_0 = \frac{\Omega_0^{1-n}}{a(n-1)}$$

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

n is the braking index.
n=3 for a dipole field
and <3 for other cases

THE DIPOLE CASE

DIPOLE (n=3)

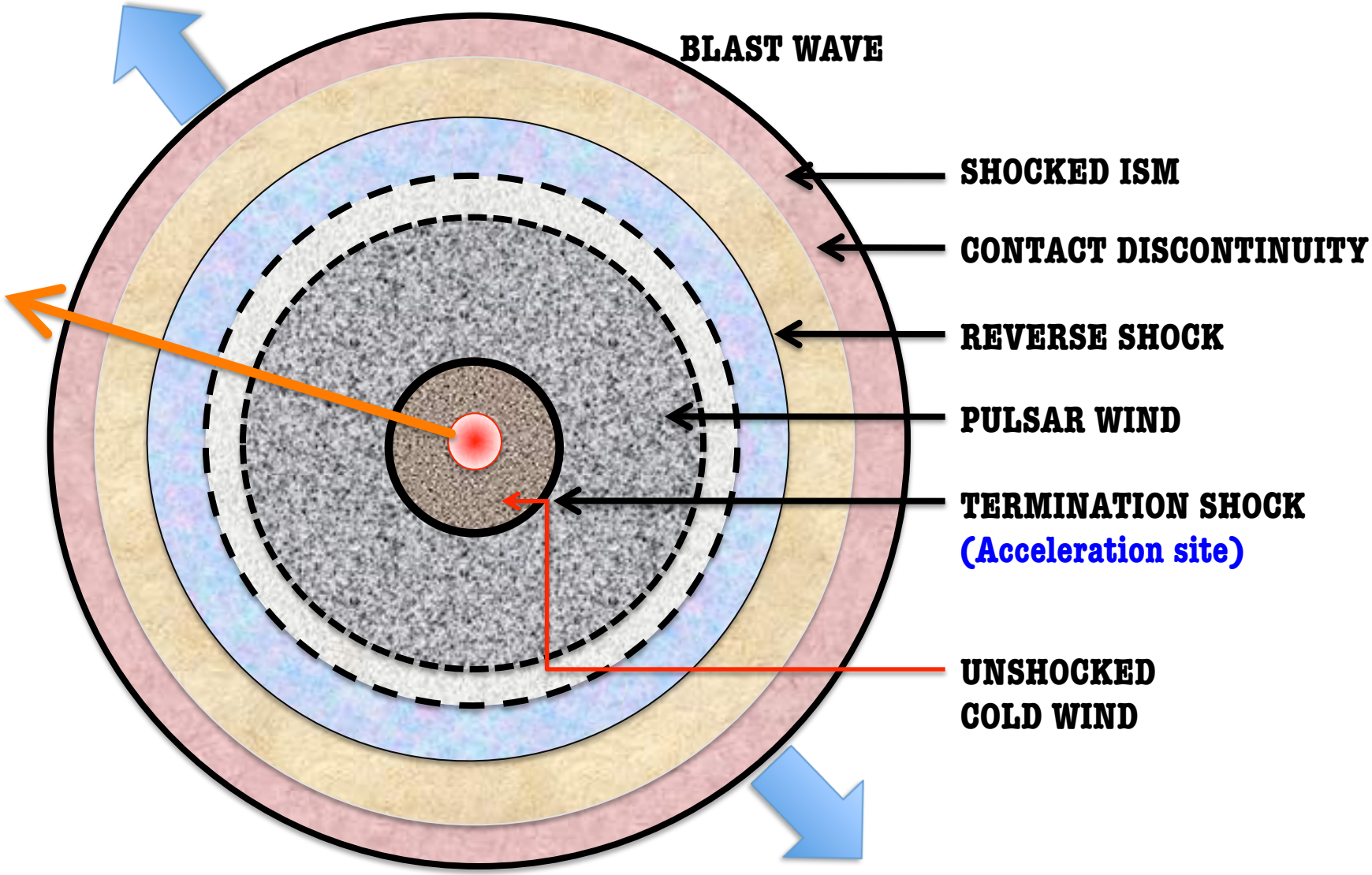
$$\dot{E} = \frac{B^2 R^6 \Omega^4}{6c^3} = 10^{39}\, B_{12}^2 R_{10}^6 P_{10}^4 erg/s$$

$$\tau_0 = 5300\, B_{12}^{-2} M_s R_{12}^{-4} P_{10}^{-2} yr$$

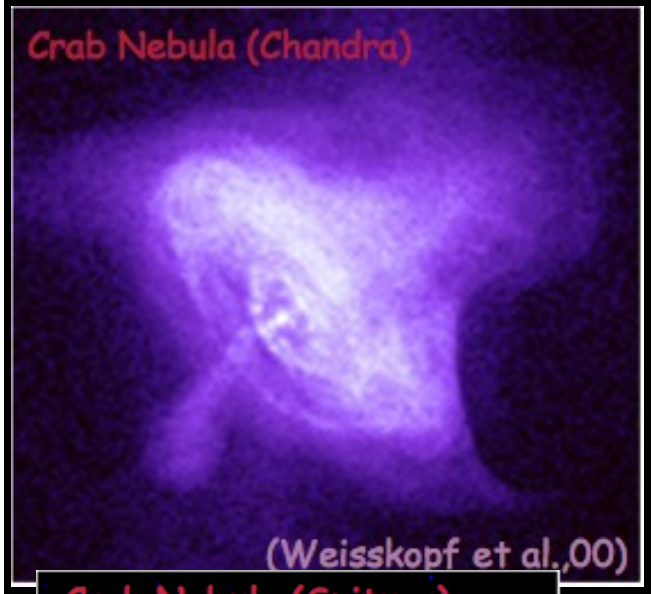
$$\dot{E}\tau_0 \approx 10^{50}\, erg$$

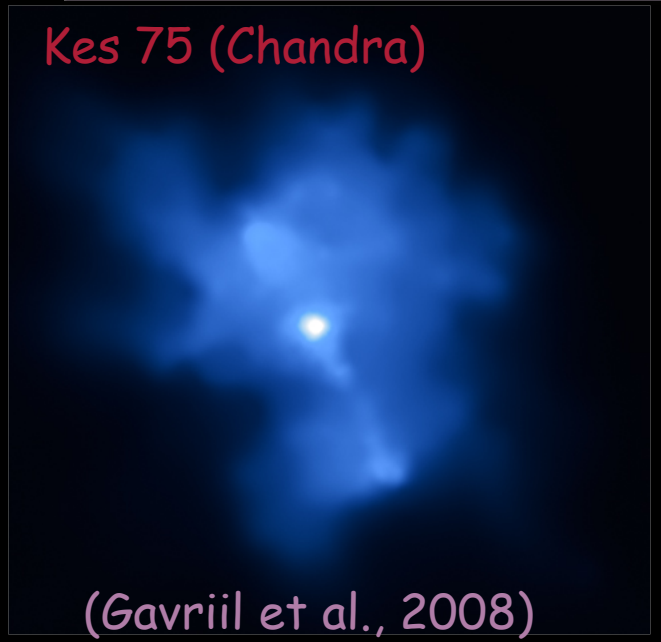
IN ALL CASES IN WHICH n CAN BE MEASURED (USING P, Pdot and Pdotdot) ONE FINDS n<3 (n=1.4 for Vela, 2.5 for Crab, 2.8 for B1509058)

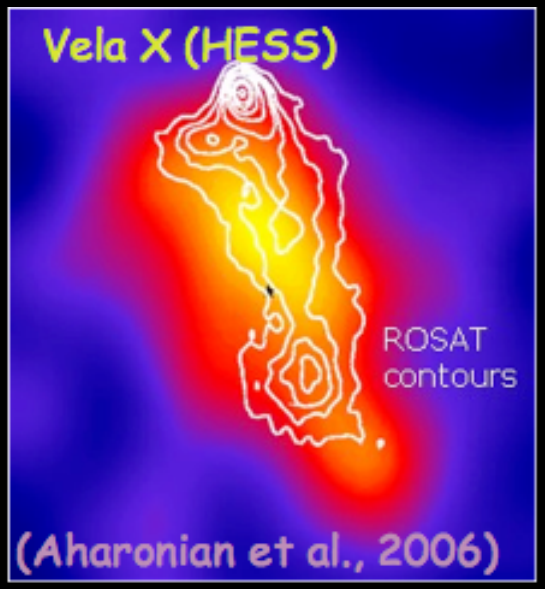
A SCHEMATIC VIEW OF A PWN



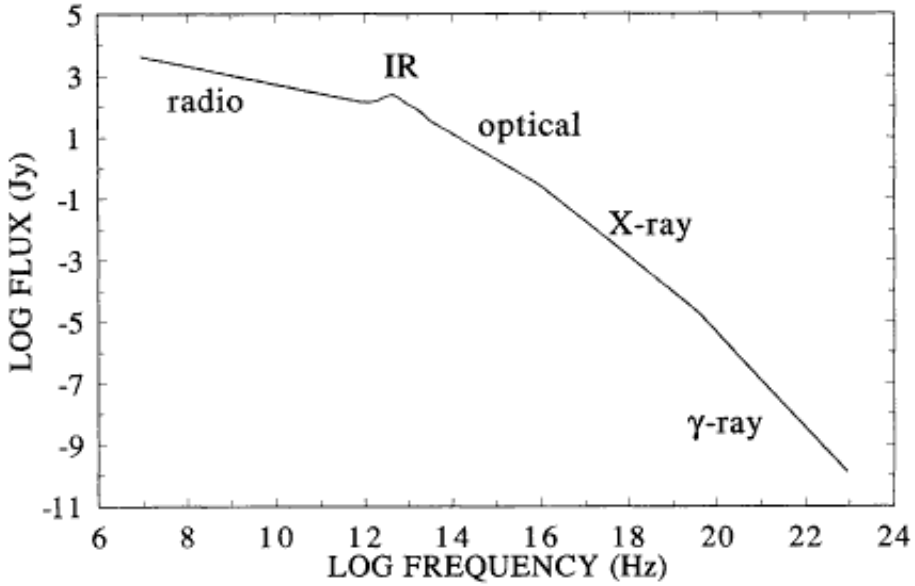
COMPLEX MORPHOLOGIES







THE STEREOTYPICAL PWN



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

That a fast rotating Neutron Star could be the powering engine of the Crab was suggested before Pulsar discovery by Franco Pacini in 1967.

THE TERMINATION SHOCK

THE RADIUS OF THE TERMINATION SHOCK CAN BE DERIVED FROM THE PRESSURE BALANCE BETWEEN THE RELATIVISTIC WIND AND THE NON-RELATIVISTIC NEBULA: $R_{TS} \sim R_N (V_N/C)^{1/2} \sim 10^9\text{-}10^{10}\ R_{LC}$ (REES & GUNN 74) – HERE WE ASSUMED THAT THE MAGNETIC PRESSURE IS NEGLIGIBLE, NOT TRUE IN GENERAL – In the Crab R_{TS} ~0.1 pc

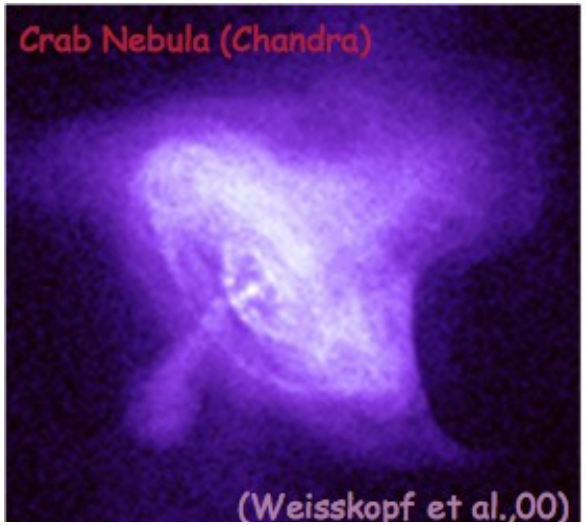
Composition: mainly pairs maybe a fraction of ions
Geometry: perpendicular where magnetized even if field not perfectly toroidal
Magnetization: $\sigma = B^2/4\pi n \Gamma mc^2 \rightarrow \sigma \sim V_N/c \ll 1$, a paradox

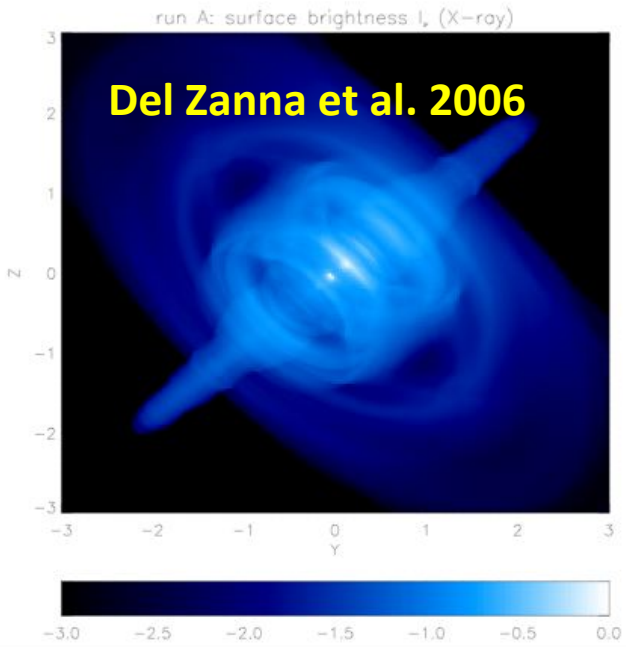
At $r \sim R_{LC}$: $\sigma \sim 10^4$ $\Gamma \sim 10^2$
(pulsar and pulsar wind theories)

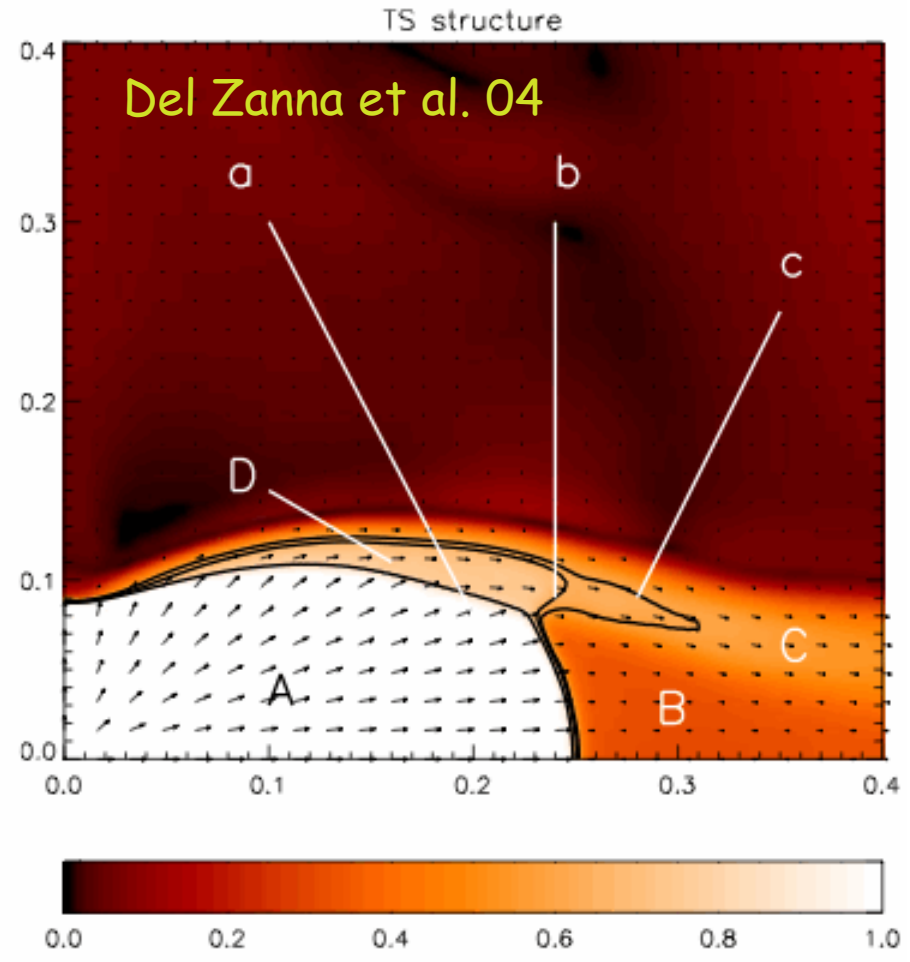
σ-paradox!

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

A more realistic structure of the termination shocks

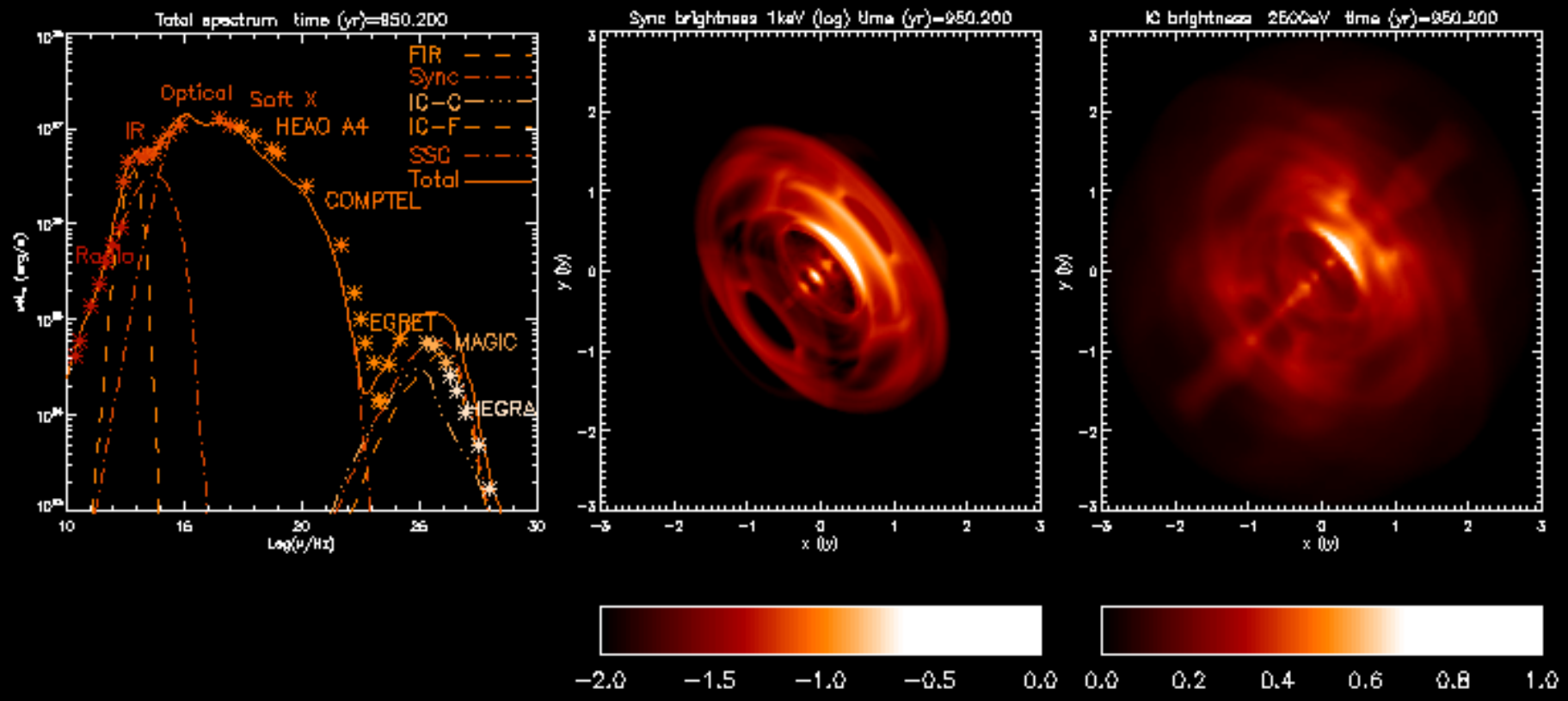




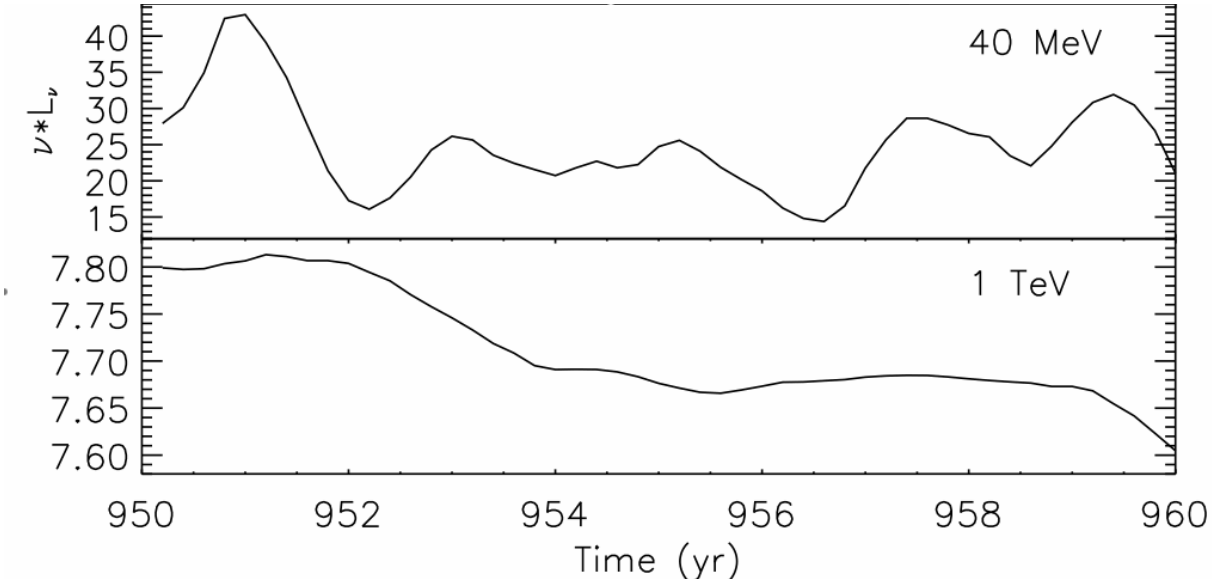


Variability in MHD models

Courtesy E. Amato



Variability in MHD models



Strong flux variations in the sync cutoff region

Emission due to moving Features around TS

No variation (~1-2%) expected at TeV energies

PWN and Escape of Pairs

A relativistic wind with Lorentz factor 10^4-10^6 is shocked at the TERMINATION SHOCK

Some fraction of the particle flux across the shock is accelerated further

From observations in the radio, X, and in some cases other I the spectrum of accelerated particles is inferred to be a broken power law with slope ~1-1.5 at $g<10^5$ and ~2.3 at $g>10^5$

BUT ALL THESE PAIRS ARE TRAPPED IN THE INNER REGION OF THE REMNANT

HOW CAN WE RETREIVE THE PAIRS AND HOW MANY OF THEM?

Life of an Electron within a SNR

The pairs inside the PWN try to expand against the ejecta → adiabatic+ radiative losses

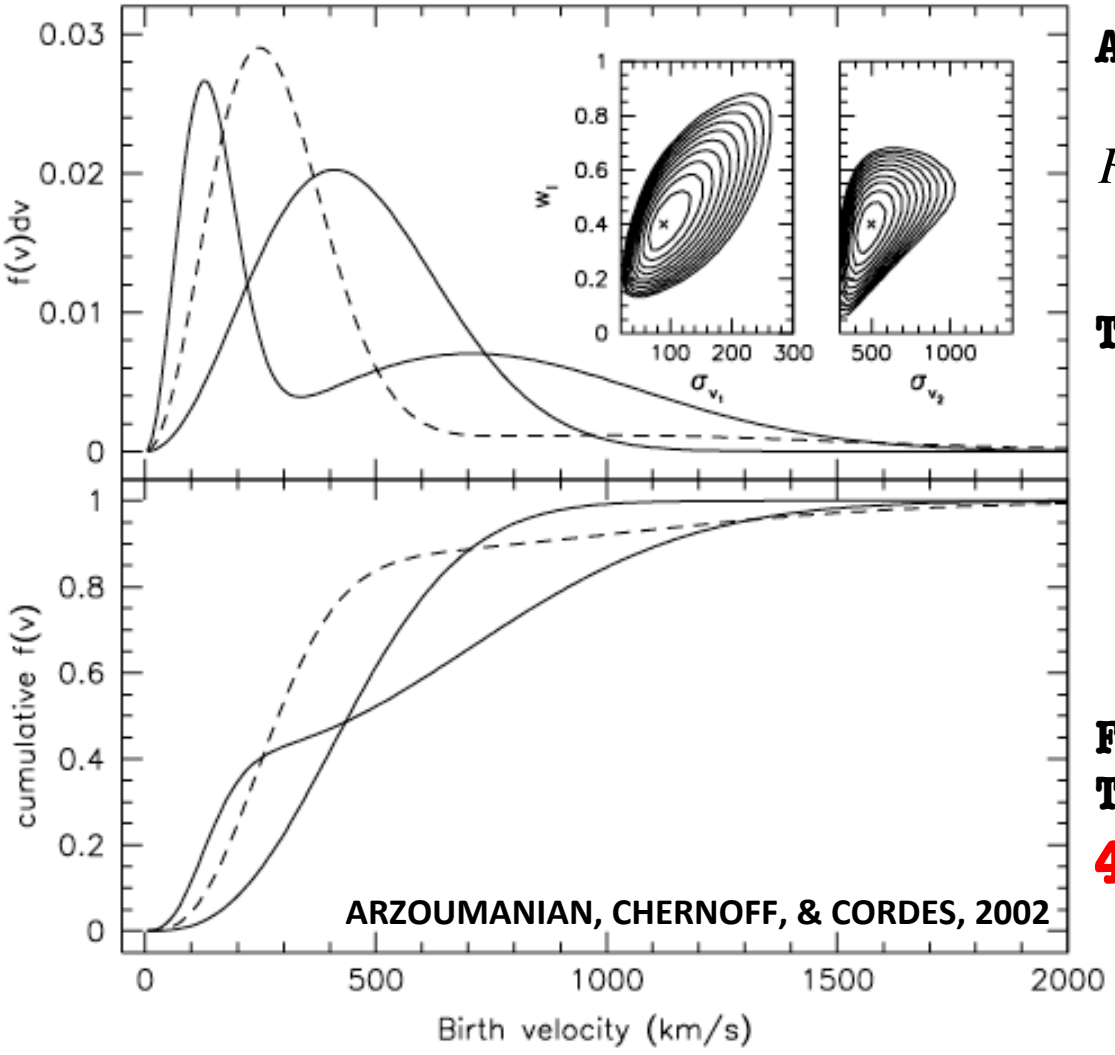
When the reverse shock of the blast wave reaches the center, some level of compression might occur

...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?

NS KICKS: ESCAPE THE REMNANT



A SIMPLE ESTIMATE:

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

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

ENERGETICS OF RUNAWAY NS

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:

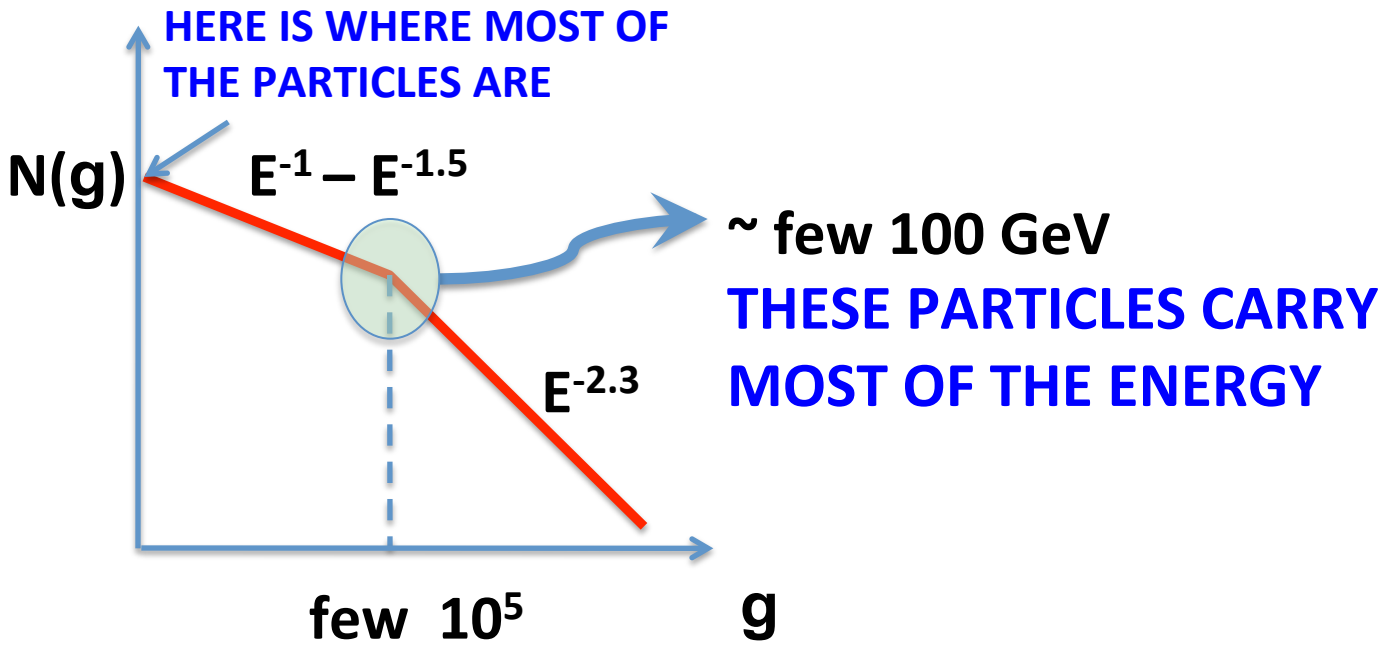
$$\frac{E_*}{E_{tot}} \approx 0.5 \qquad \text{For dipole n} = 3$$

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

We will see later how this compares with energetic requirements imposed by PAMELA results

SPECTRA OF PWN IN PLERIONS

THERE APPEARS TO BE A GENERAL TREND TO HAVE PARTICLES ACCELERATED AT THE TERMINATION SHOCK WITH A SPECTRUM REPRESENTED BY A BROKEN POWER LAW (Not understood!)



SPECTRA OF PWN IN PLERIONS: Acceleration processes

SHOCK ACCELERATION

-slope OK @ high E
-but hard to do @ perpendicular relativistic shocks
-low energy spectrum too hard and not easy to accommodate
-where is the thermal component anyway?

CYCLOTRON ABSORPTION (Amato & Arons 2003)

-quasi-universal low E spectrum??? hard
-intrinsic spectral break?
-thermal component?

RECONNECTION (Kirk & Petri)

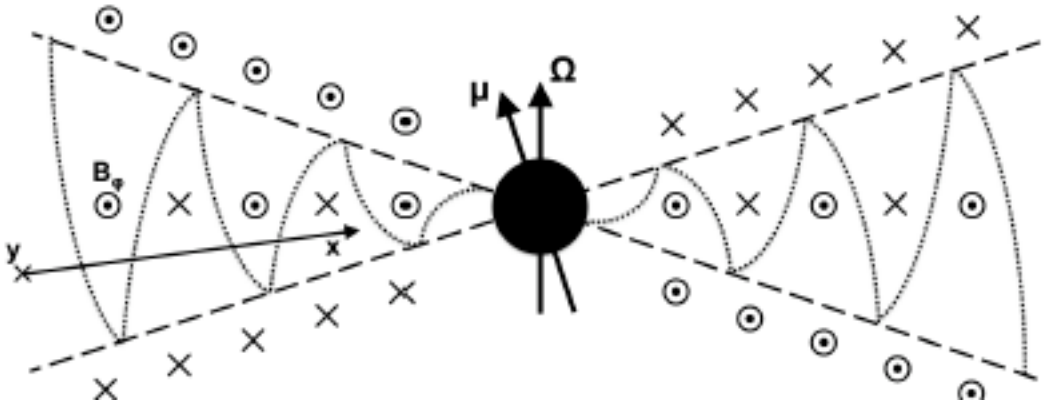
-Quasi-universal low E spectrum??? hard
-intrinsic spectral break?
-thermal component?

COMMON PROBLEMATIC ISSUES:

Multiplicity of pairs (too) high and worse for low E_{min}
Absence of thermal component

Shock driven reconnection

Sironi & Spitkovsky 2011



SHOCK DRIVEN RECONNECTION → FLAT SPECTRUM $E^{-1.5}$

PARTICLES ARE INJECTED IN A KIND OF FERMI ACCELERATION DUE TO DESTRUCTION OF FIELD TOPOLOGY CAUSED BY RECONNECTION (HIGH ENERGY $E^{-2.5}$)

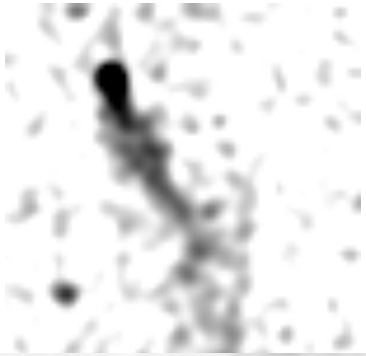
IT WORKS IN THE EQUATORIAL PLANE

IT REQUIRES PAIR MULTIPLICITY OF ORDER 10^8 – MUCH HIGHER THAN THEORETICALLY EXPECTED

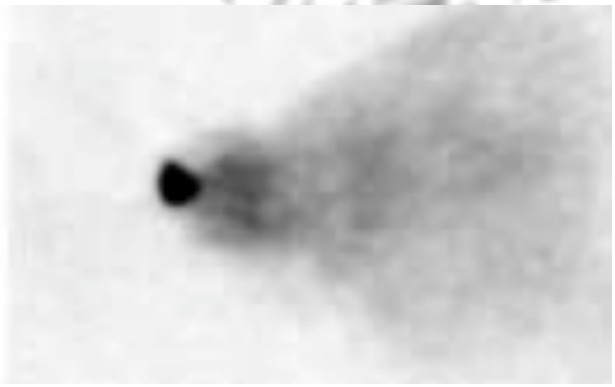
Spectra in bow shock nebulae

Still spinning after escaping the SNR

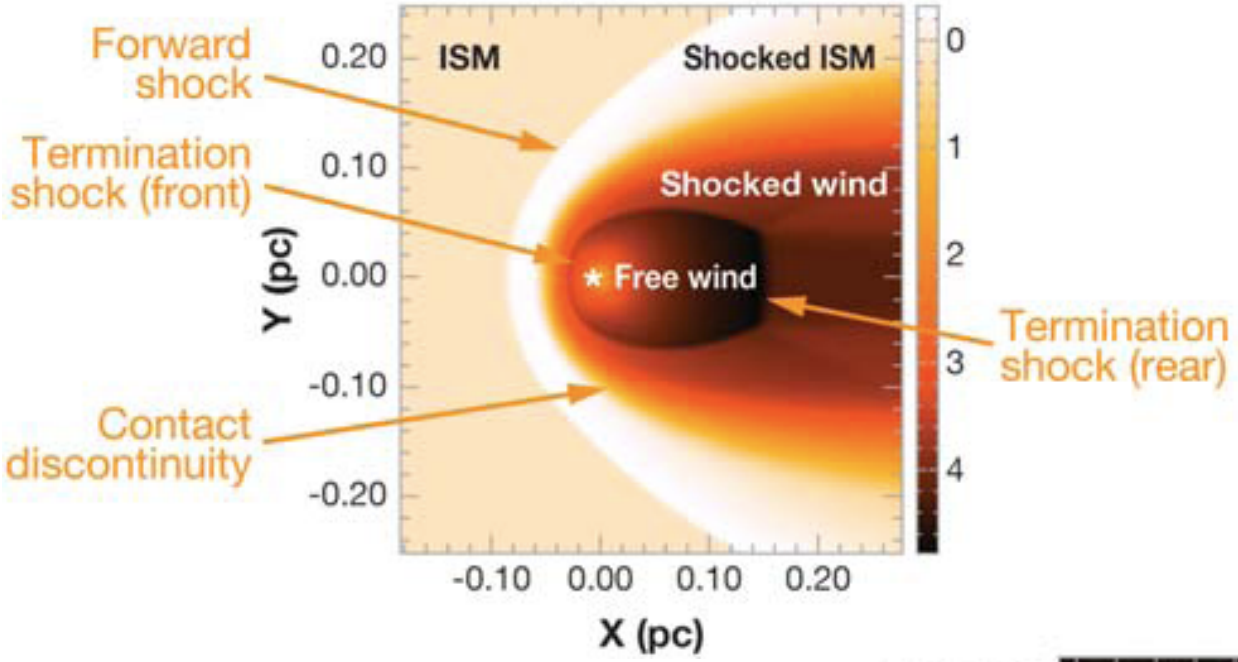
IN THE TWO CASES of BSN OUTSIDE A SNR IN WHICH WE HAVE RADIO MEASUREMENTS WE INFER A SPECTRUM OF ACCELERATED PARTICLES WITH SLOPE ~-1.5



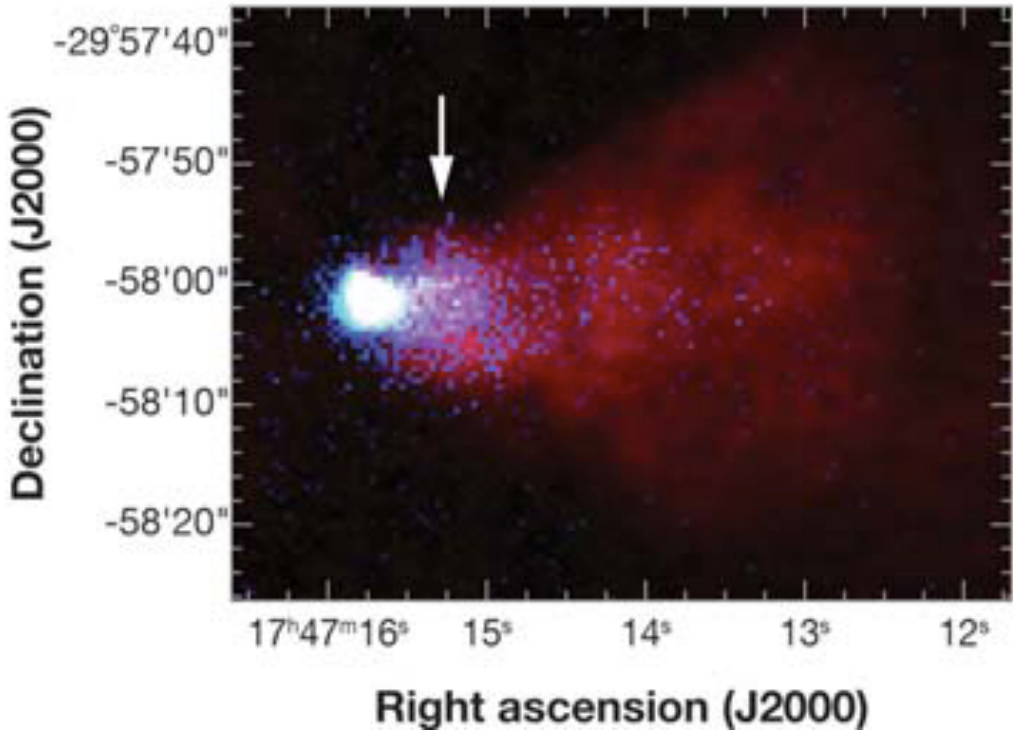
PSR J1509–5850
Slope radio: -0.26
Slope Electrons: -1.52
Ng et al. 2010



The Mouse
Slope radio: -0.3
Slope Electrons: -1.6
Gaensler et al. 2004

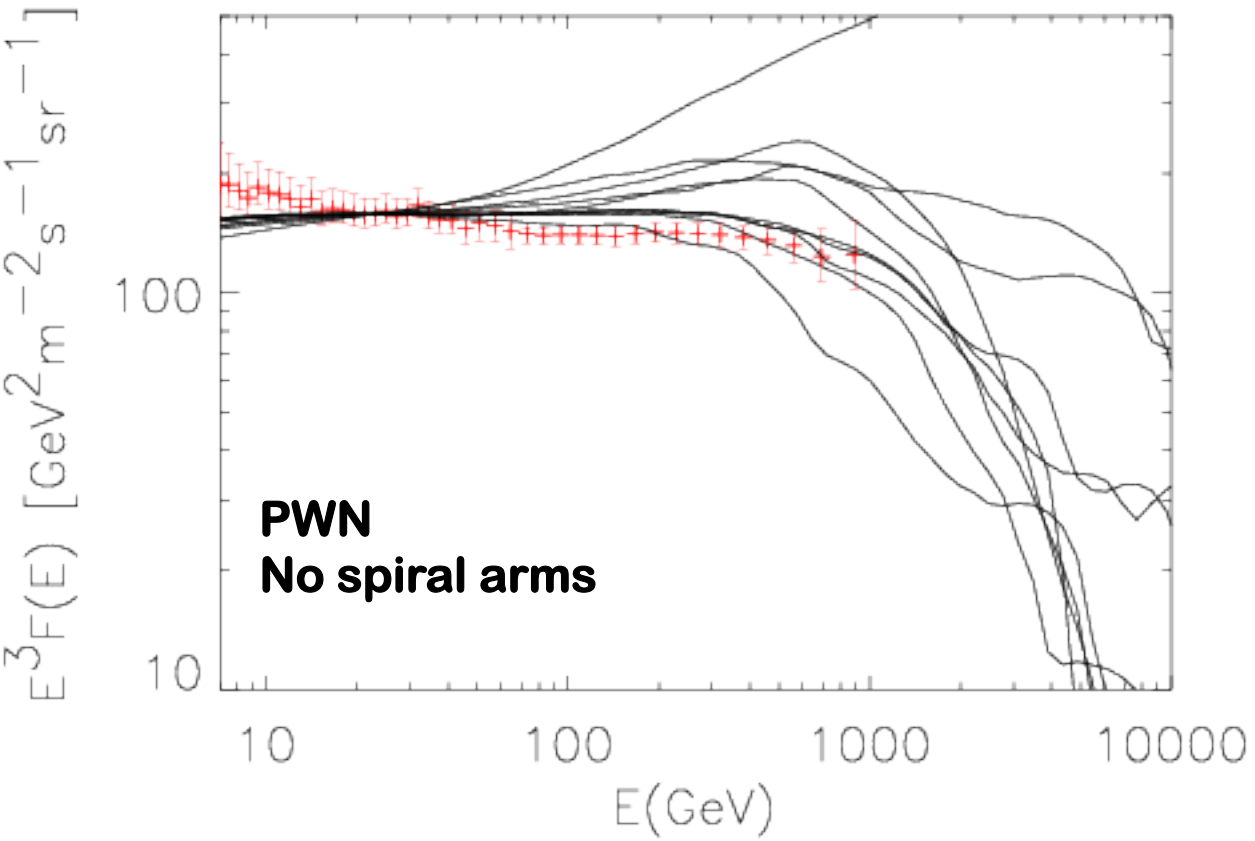


Slane & Gaensler 2006

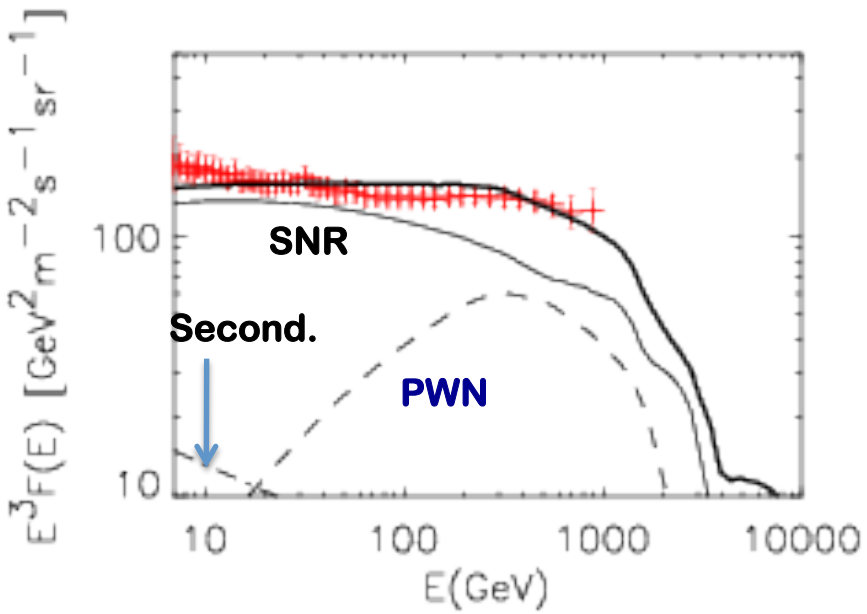


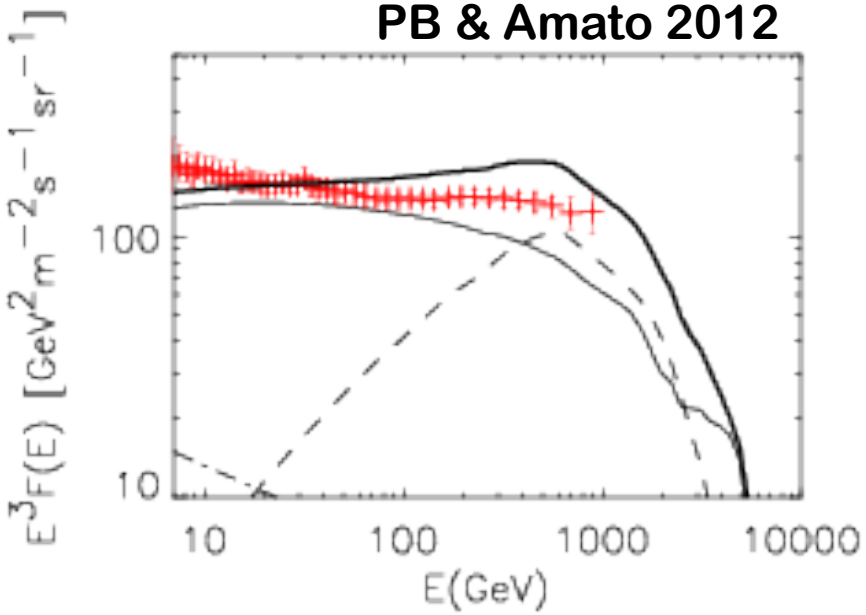
Positrons from PWNe

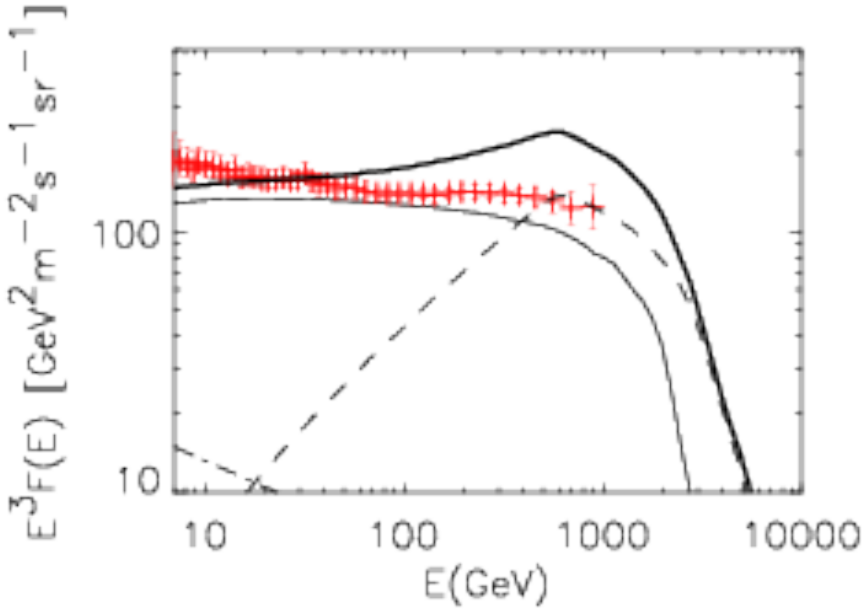
PB & Amato 2011

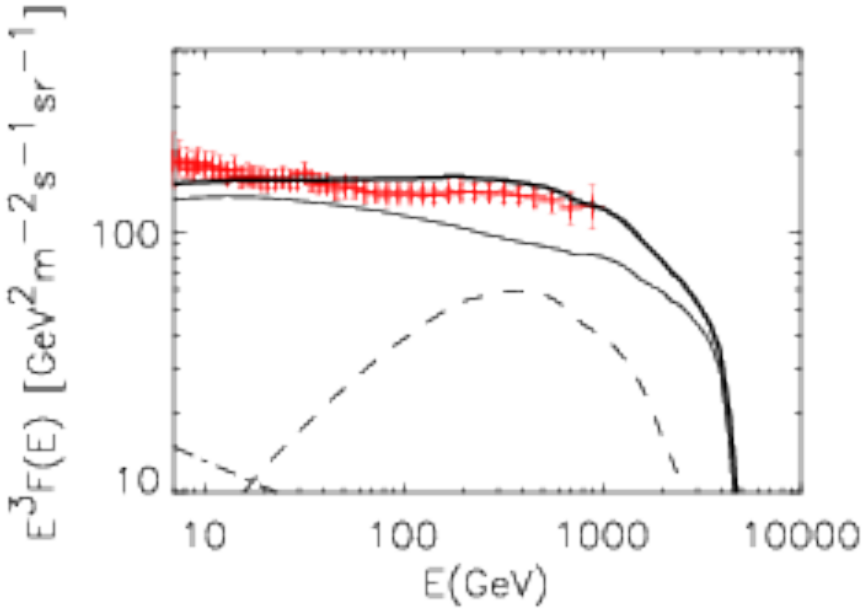


PB & Amato 2012



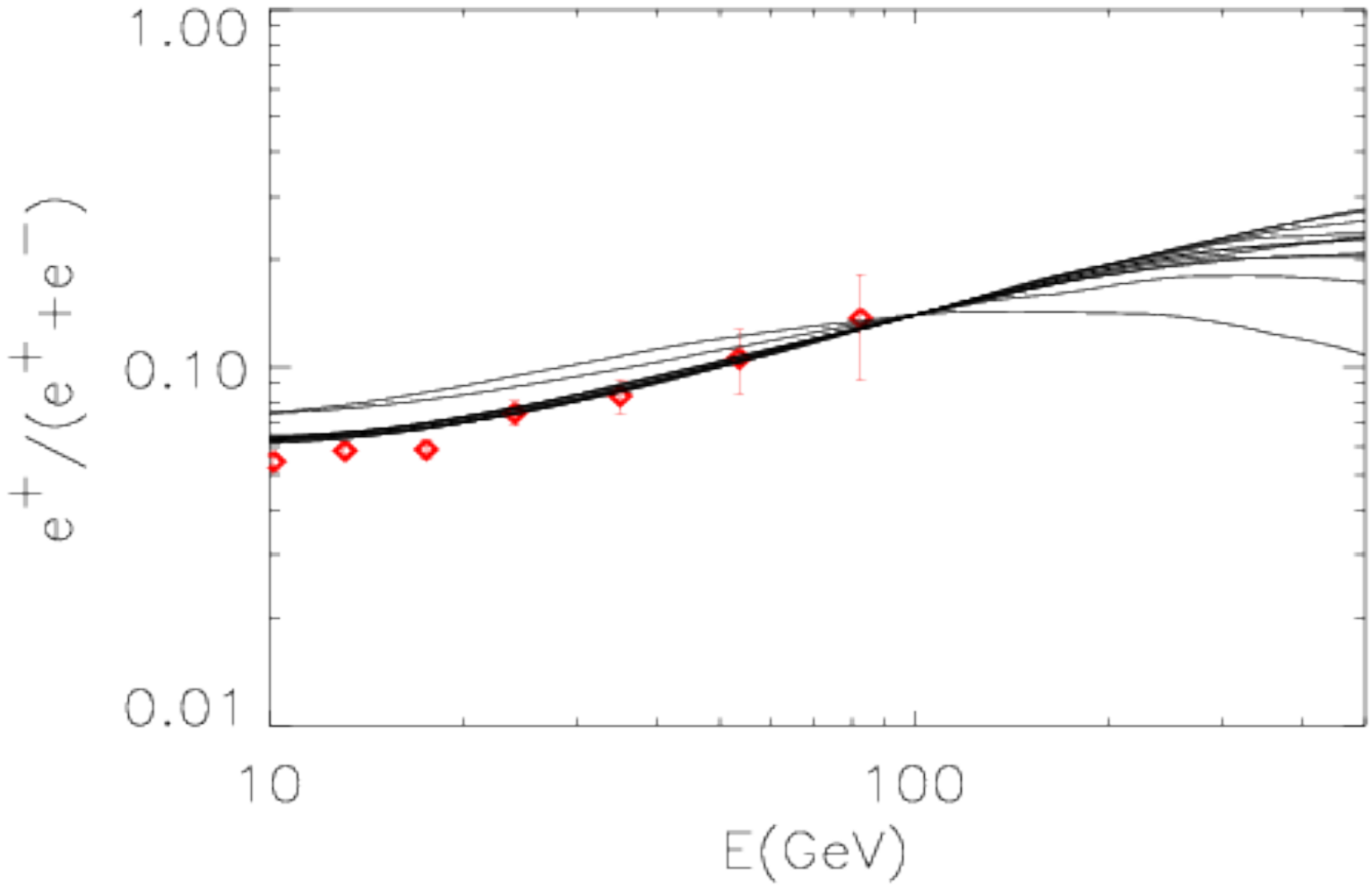






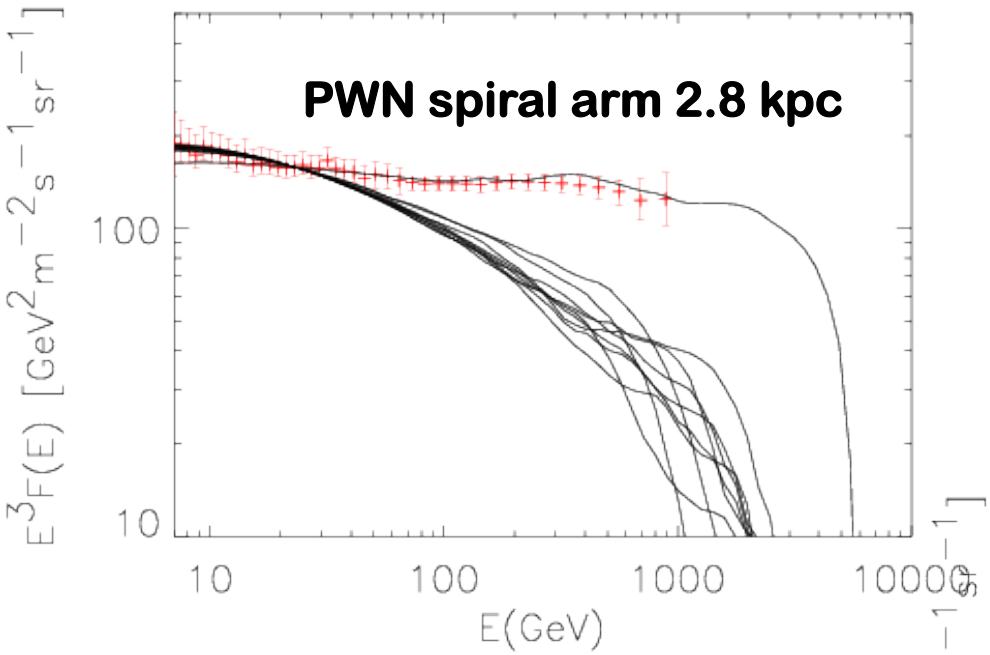
THE POSITRON FRACTION

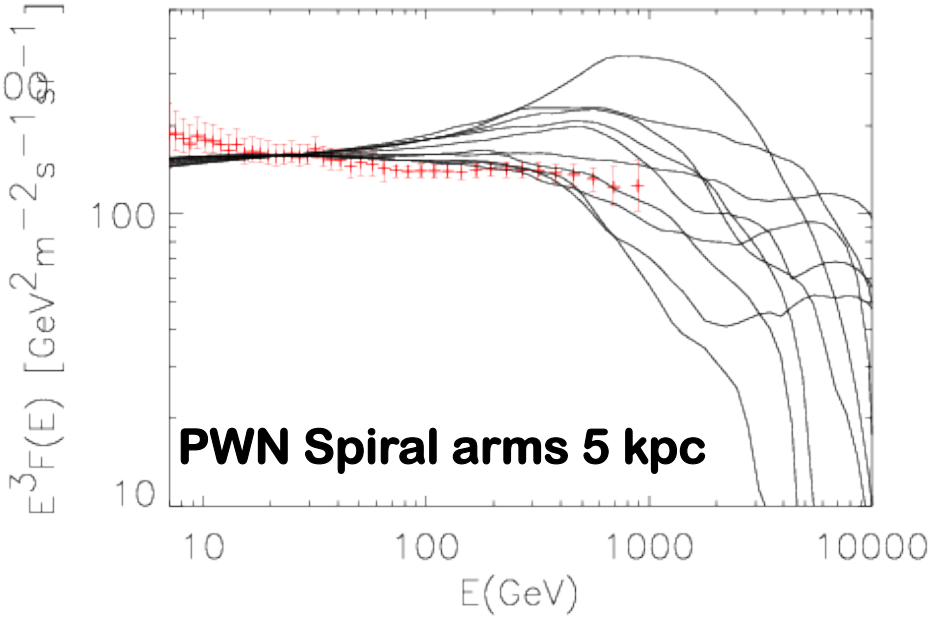
PB & Amato 2012



Positrons from PWNe + spiral arms

PB & Amato 2012





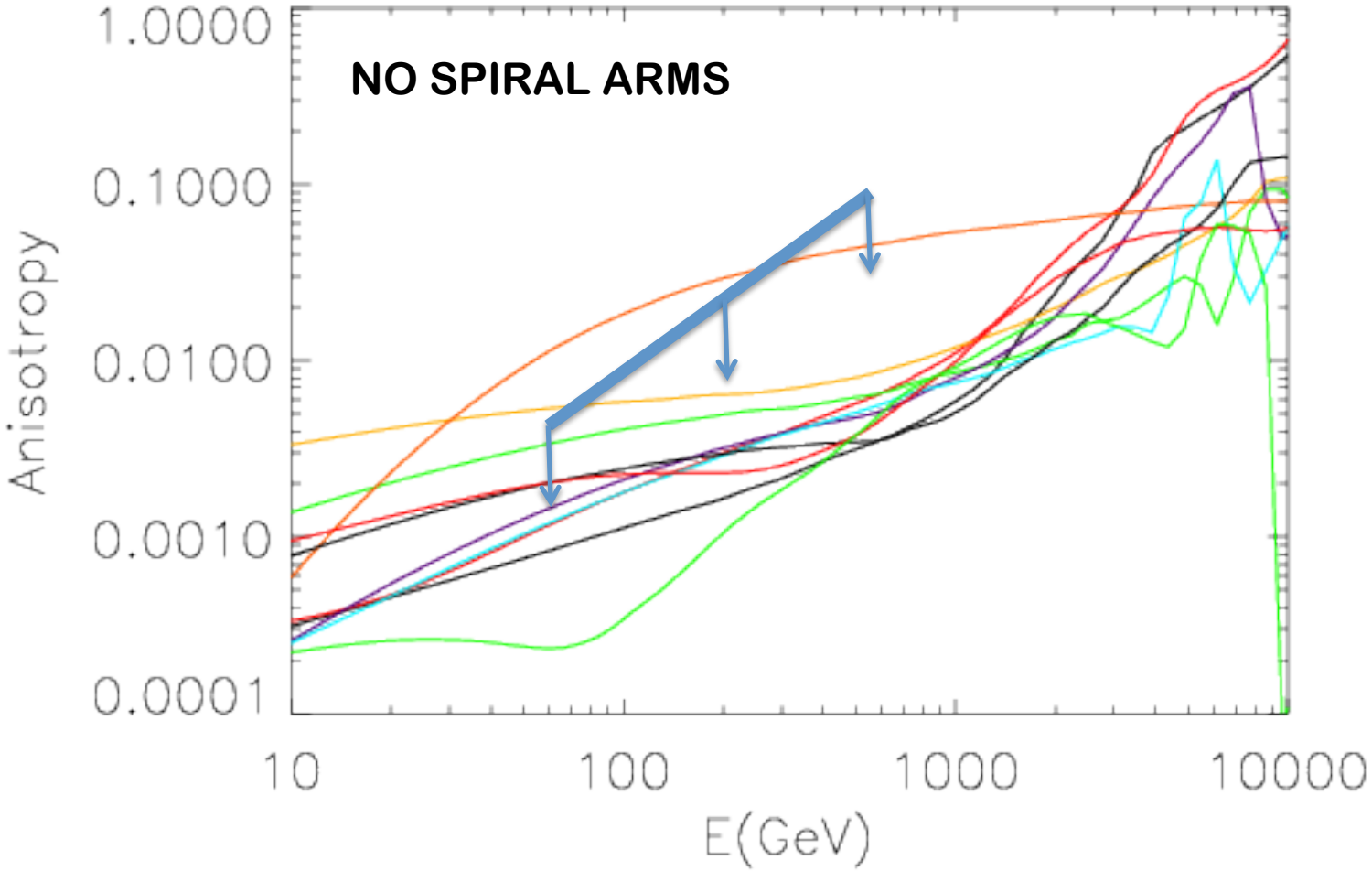
ENERGETICS

ROUGHLY 50% OF THE ENERGY IN THE PULSAR ROTATION LEFT AFTER THE PULSAR ESCAPES THE REMNANT IS SUFFICIENT TO POWER THE POSITRON EXCESS

THIS FRACTION IS EVEN SMALLER FOR DIPOLE SPIN DOWN

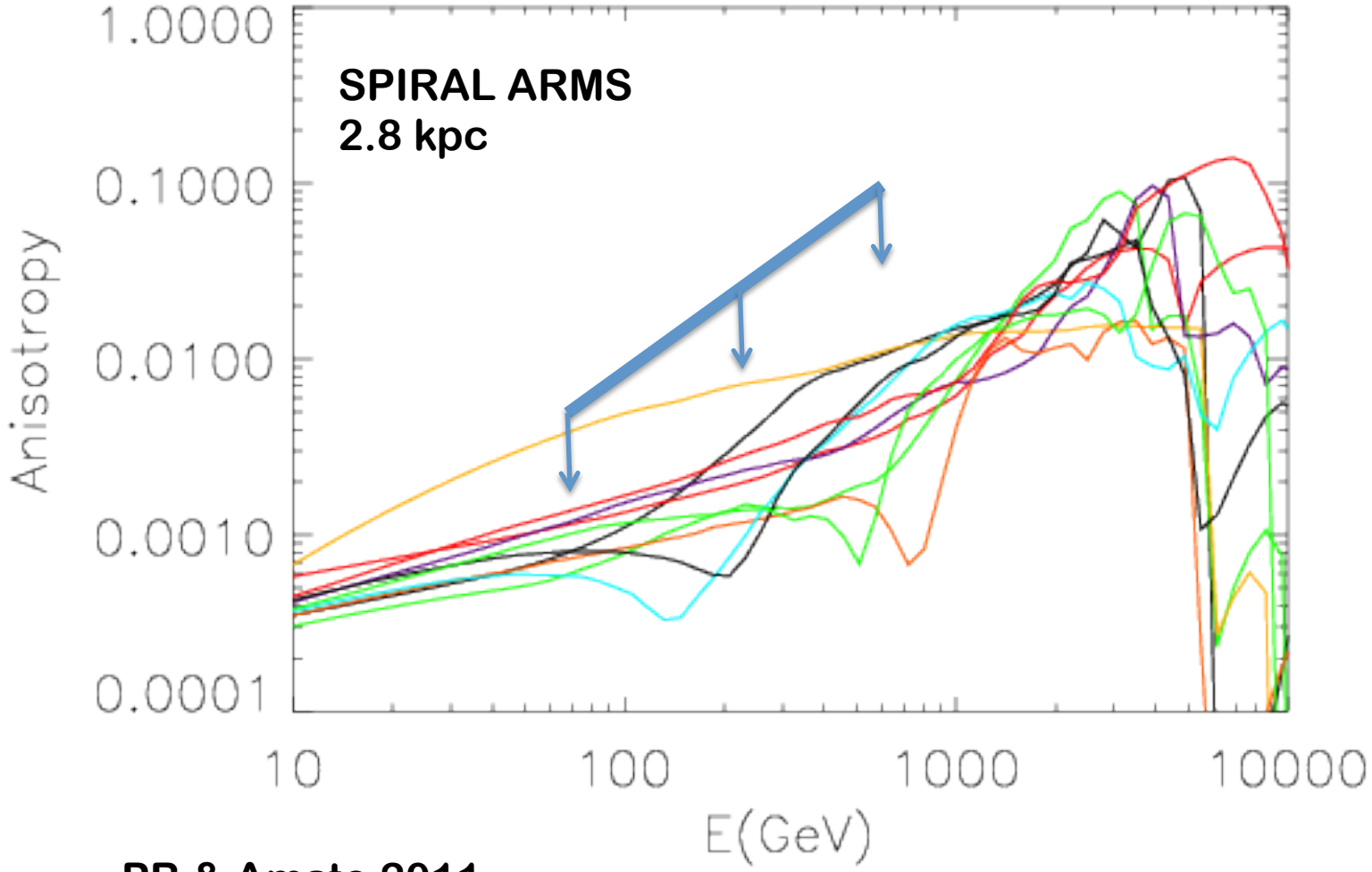
IN THE DIPOLE CASE ONE MIGHT WANDER WHERE ARE ALL THE POSITRONS GOING?

Anisotropy



PB & Amato 2011

Anisotropy



PB & Amato 2011