Astrophysical Origin of the Positron Excess in Cosmic Rays

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Sources of astrophysical positrons

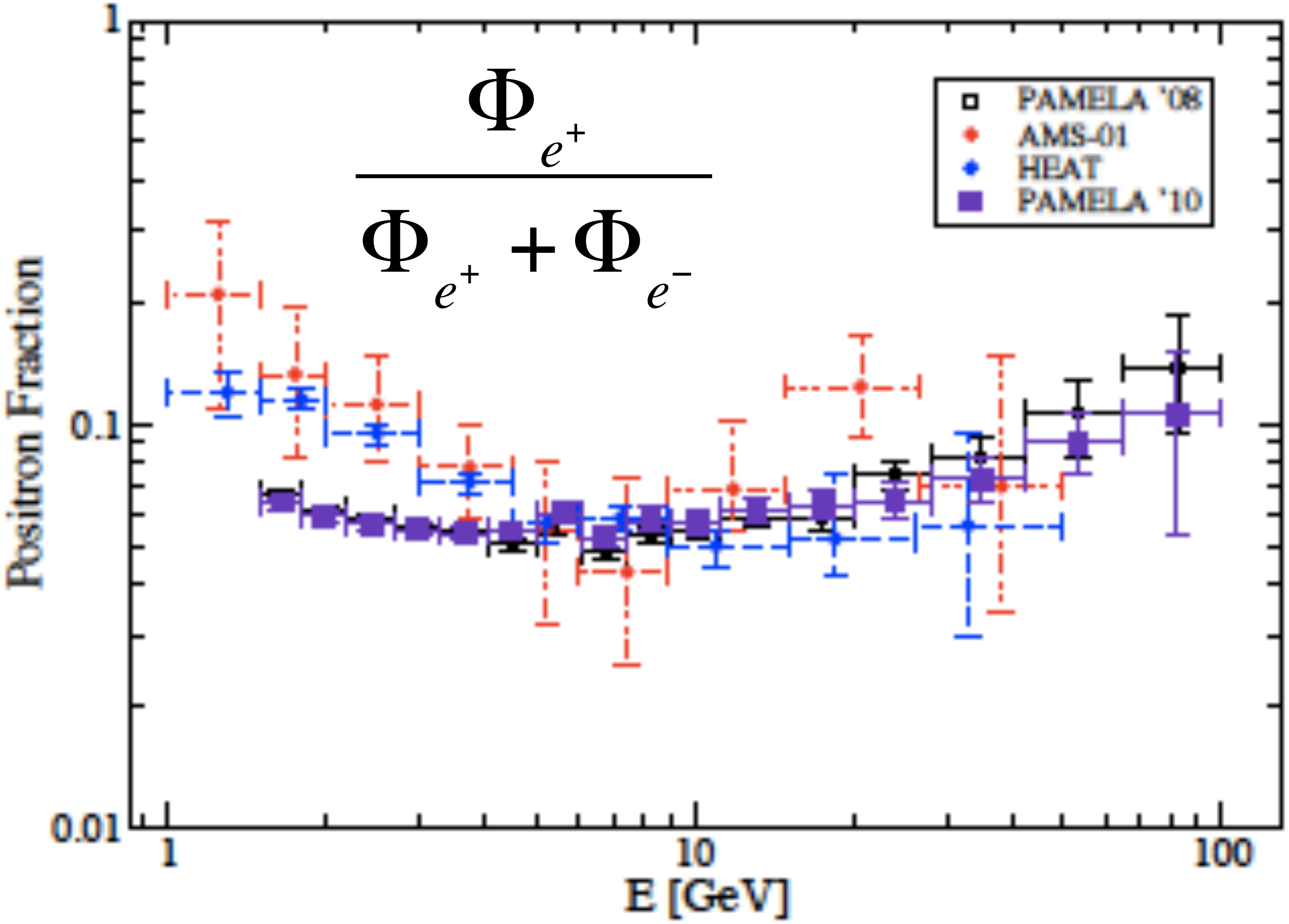
Radioactive Decays (e.g. in SNRs)

Secondary products of hadronic interactions

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

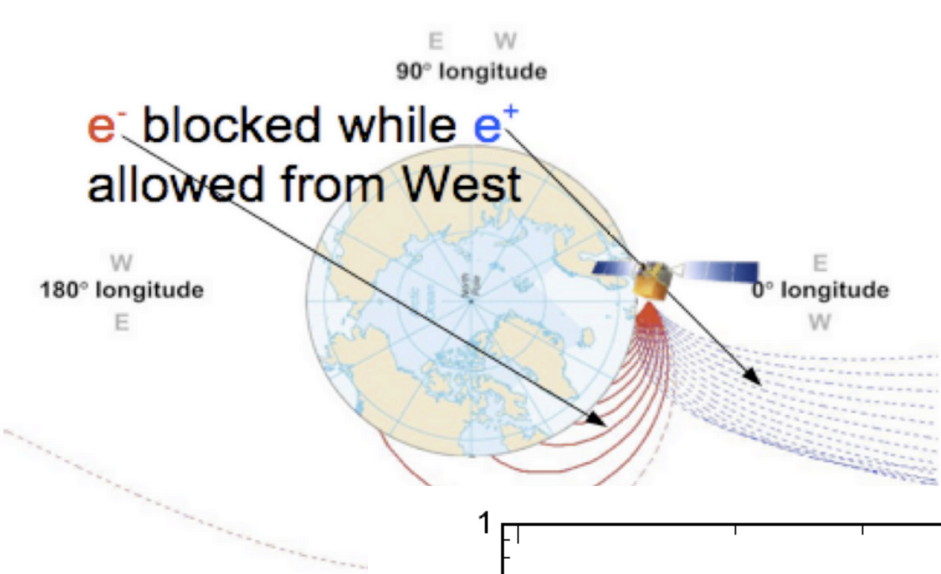
Pulsar magnetospheres (cascade multiplication in Intense magnetic fields)

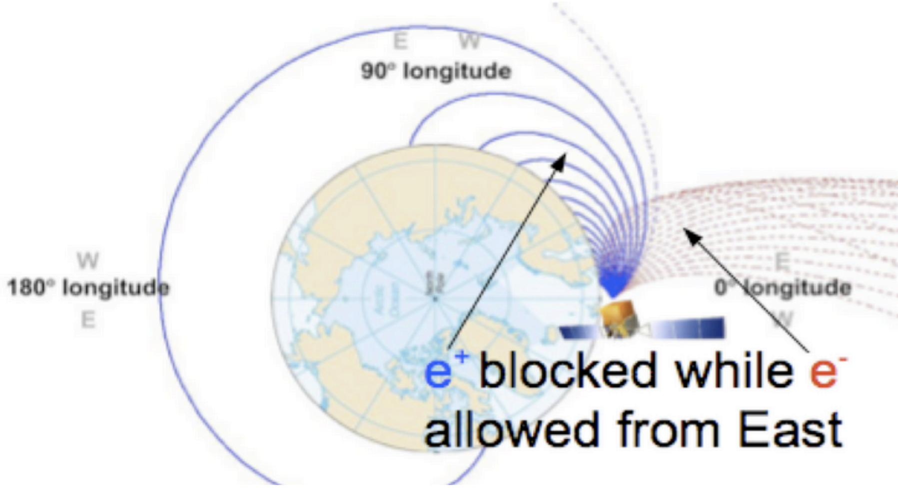
The Positron Ratio

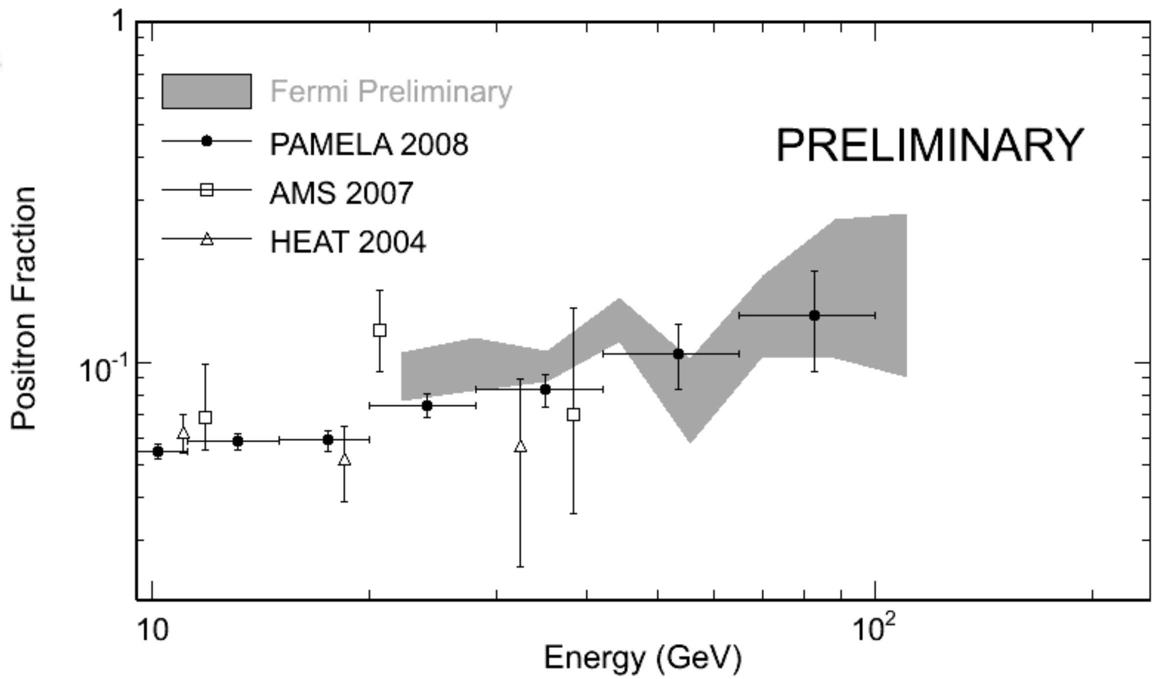


Serpico 2011

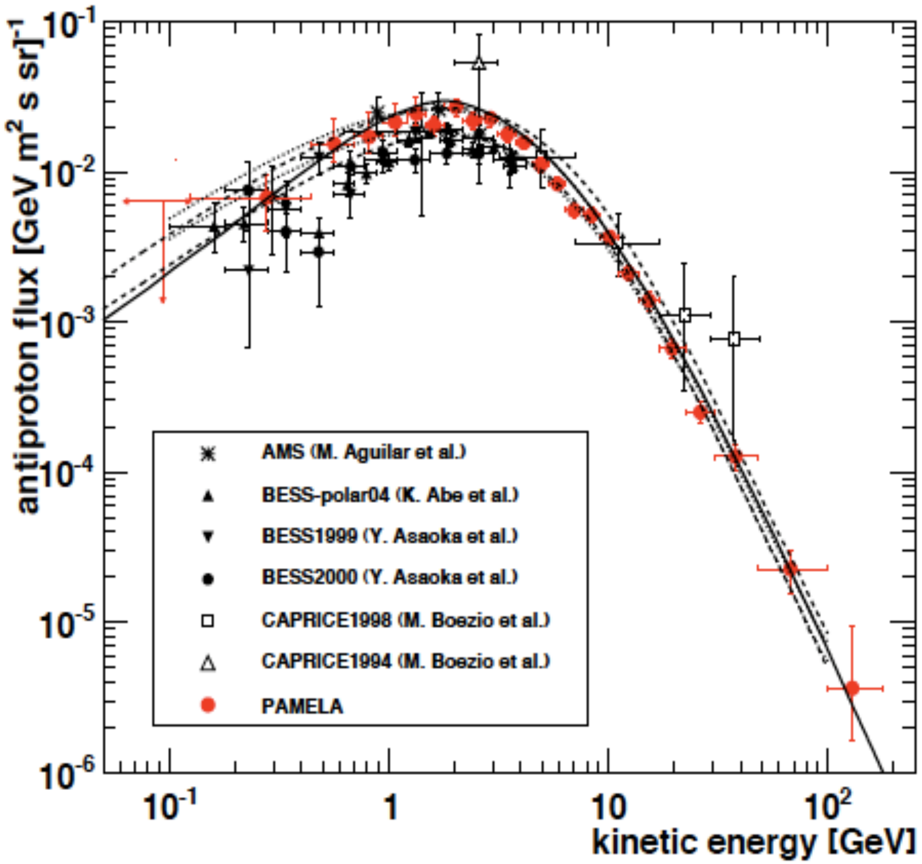
RISING POSITRON FRACTION WITH FERMI-LAT

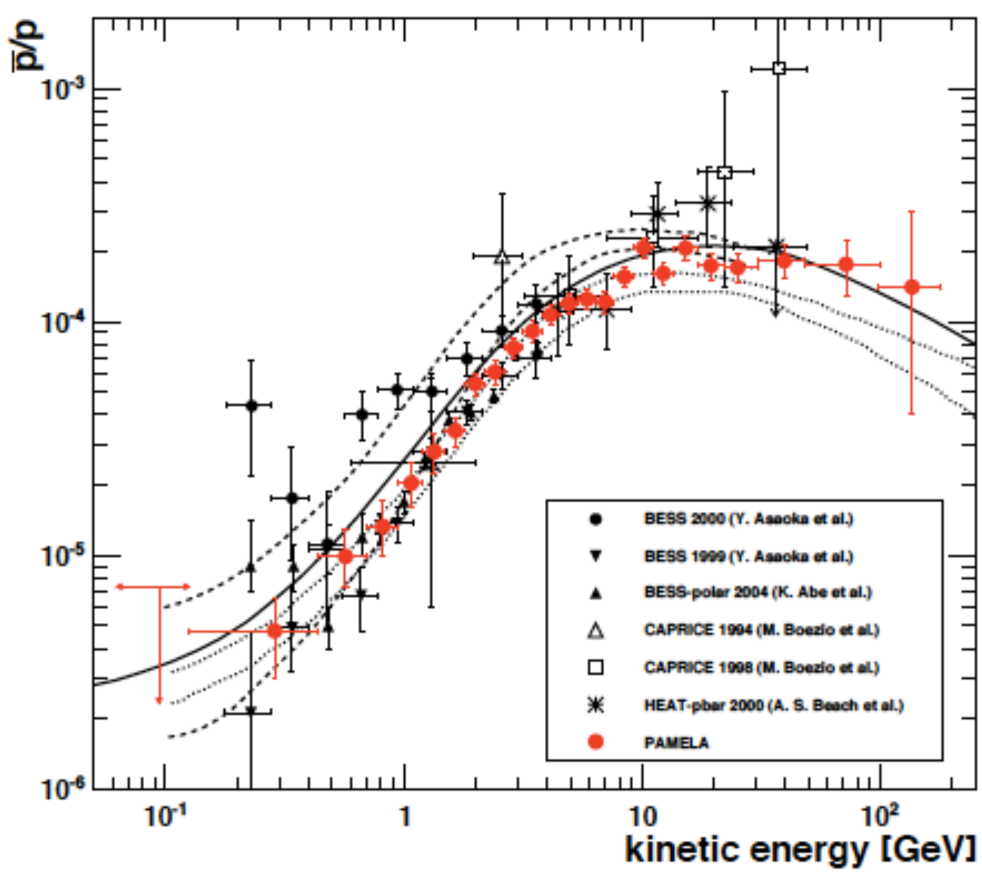






Antiprotons





Adriani 2010, 2011

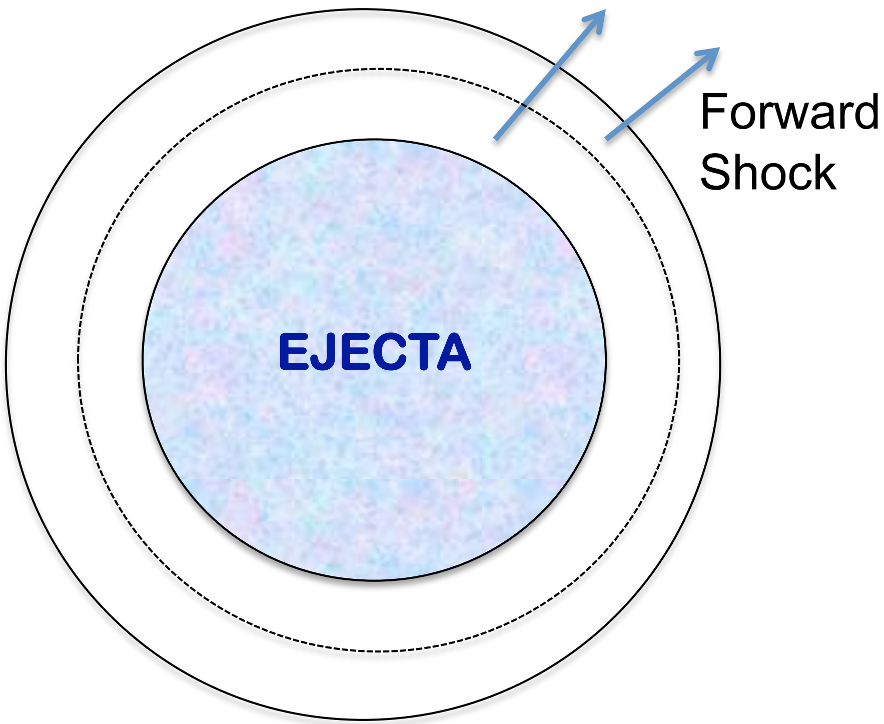
Radioactive decays in SN explosions

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

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

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

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

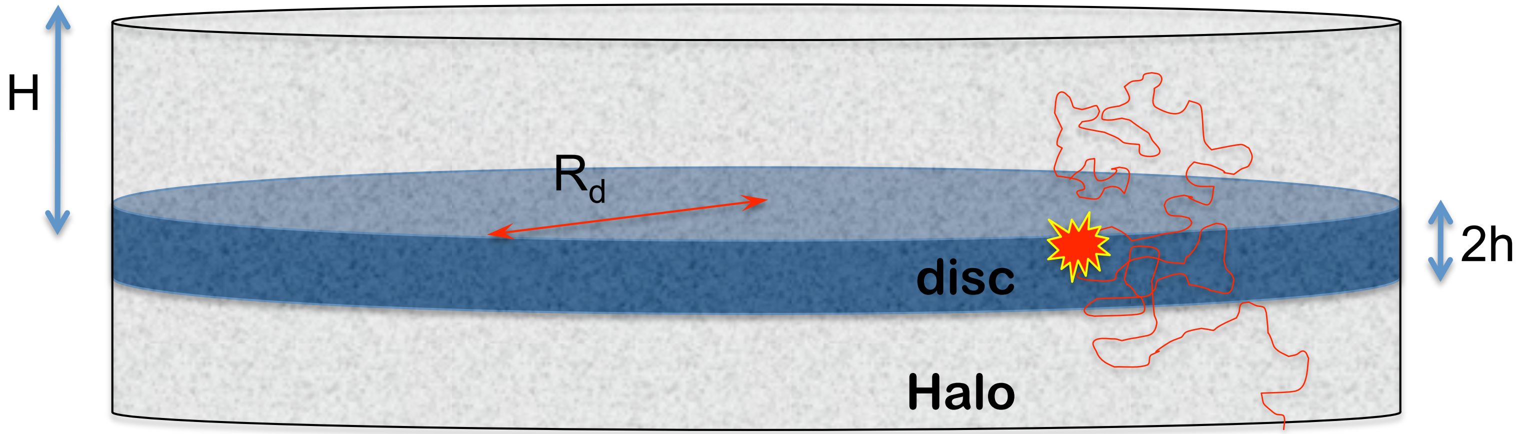


LOW ENERGY POSITRONS

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

Implications

A rising positron fraction requires:

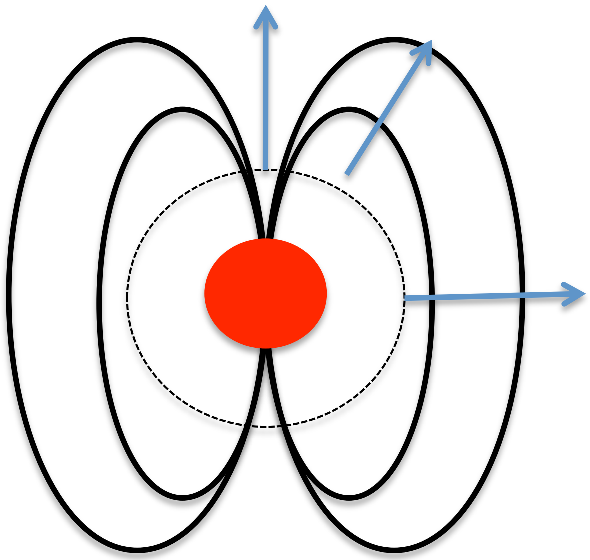
1. An additional component of positrons with spectrum flatter than CR primary electrons

2. A diffusion coefficient with a weird energy dependence (BUT this should reflect in the CR spectrum as well)

3. Subtleties of Propagation

Subtle aspects of shock acceleration

Biermann et al. 2009



A CORE COLLAPSE SN CAN TAKE PLACE IN THE MAGNETIZED PRESUPERNOVA WIND

IN THE REGIONS WHERE THE SHOCK IS QUASI-PARALLEL THE SPECTRUM MAY BE SOMEWHAT FLATTER THAN IN THE REGIONS WHERE THE SHOCK IS QUASI-PERPENDICULAR

PARALLEL SHOCK → slope 2 small solid angle (THIS CONTRIBUTION DOMINATES AT HIGH E)

PERP SHOCK → slope 7/3 larger solid angle

Pros and Cons

INTERACTIONS ARE ASSUMED TO TAKE PLACE INSIDE THE SOURCE REGION, BUT UNDER WHICH CONDITIONS IS THIS SATISFIED?

CONCLUSION ON SPECTRUM BASED ON ASSUMPTIONS ON MODELING RAPID CONVECTION THROUGH AN ENERGY INDEPENDENT DIFFUSION COEFFICIENT (IN GENERAL THIS IS NOT THE CASE)

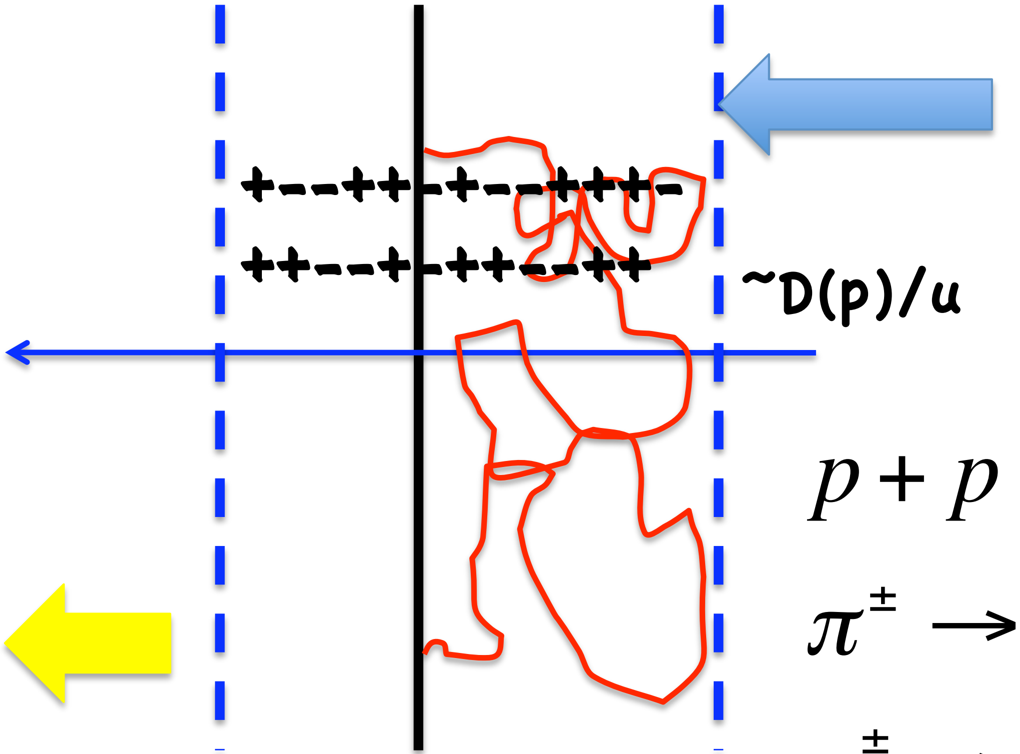
EVEN IN THE PARALLEL CASE ONE CAN LIST MANY REASONS WHY THE SPECTRUM OF ACCELERATED PARTICLES CAN DEPART FROM THE USUALLY QUOTED E^{-2} (finite speed of scattering centers, non linear effects)

THE GENERAL POINT THAT A SUBDOMINANT COMPONENT OF CR WITH A SLIGHTLY FLATTER SPECTRUM CAN DO THE GAME IS VALID
AND TELLS US ABOUT HOW WEAK IS THE "STANDARD MODEL" WITH WHICH WE ARE COMPARING THE DATA

Secondary Positrons from Sources

PB 2009; PB & Serpico 2009; Alhers et al. 2009

PB 2009



Advection
+ Diffusion

$$p + p \longrightarrow \pi^{\pm} + X$$

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}$$

$$\mu^{\pm} \longrightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

CHARGED SECONDARY PARTICLES

THE EQUATION DESCRIBING ANY CHARGED PARTICLE IN THE SHOCK REGION IS THE DIFFUSION-CONVECTION EQUATION:

$$u\frac{\partial f_\pm}{\partial x} = D(p)\frac{\partial^2 f_\pm}{\partial x^2} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f_\pm}{\partial p} + Q_\pm(x,p)$$

AT THE SHOCK

$$p\frac{\partial f_{\pm,0}}{\partial p} = -\gamma f_{\pm,0} + \gamma\frac{D_1(p)}{u_1^2}\left(\frac{1}{\xi} + r^2\right)$$

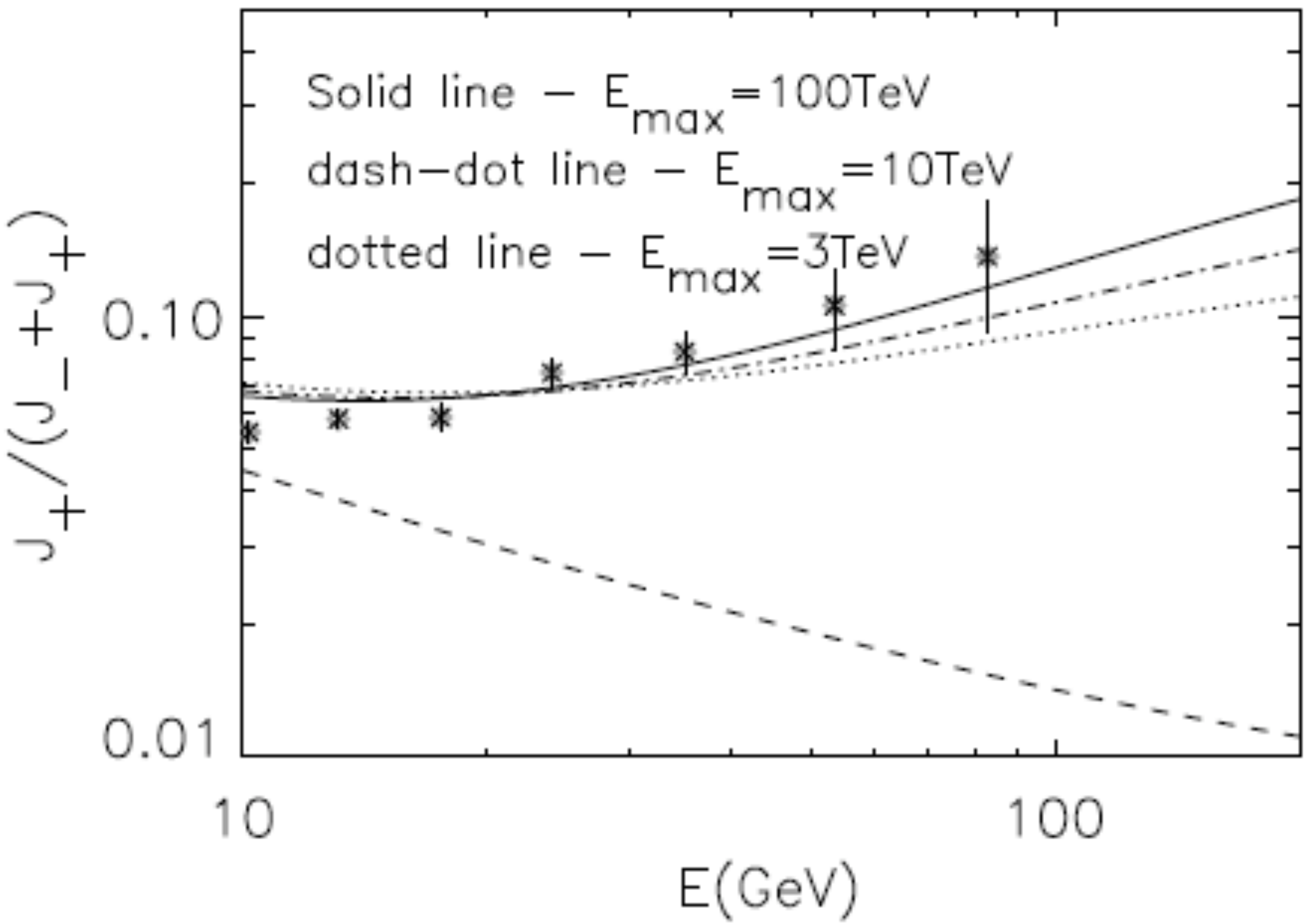
$$\xi \approx 0.05$$

SOLUTION AT THE SHOCK

$$f_{\pm,0}(p) = \gamma\left(\frac{1}{\xi} + r^2\right)\int_0^p \frac{dp'}{p'}\left(\frac{p'}{p}\right)^{\gamma} \frac{D_1(p')}{u_1^2} Q_1(p')$$

1. In terms of momentum dependence this scales as D(p)Q(p)~$p^{-\gamma+1}$
2. The coefficient in front expresses the re-energization of the secondary particles by the shock (CONSERVES PARTICLE NUMBER BUT INCREASES THE En/Part)
3. Of course the final f is cut off at the same momentum as that of the parent protons

THE POSITRON "EXCESS"



PB 2009

THE PARAMETERS

$$D_B(E) = K_B \frac{1}{3} r_L(E) c = 3.3\times 10^{22} K_B B_\mu^{-1} E_{GeV}\ cm^2 s^{-1}$$

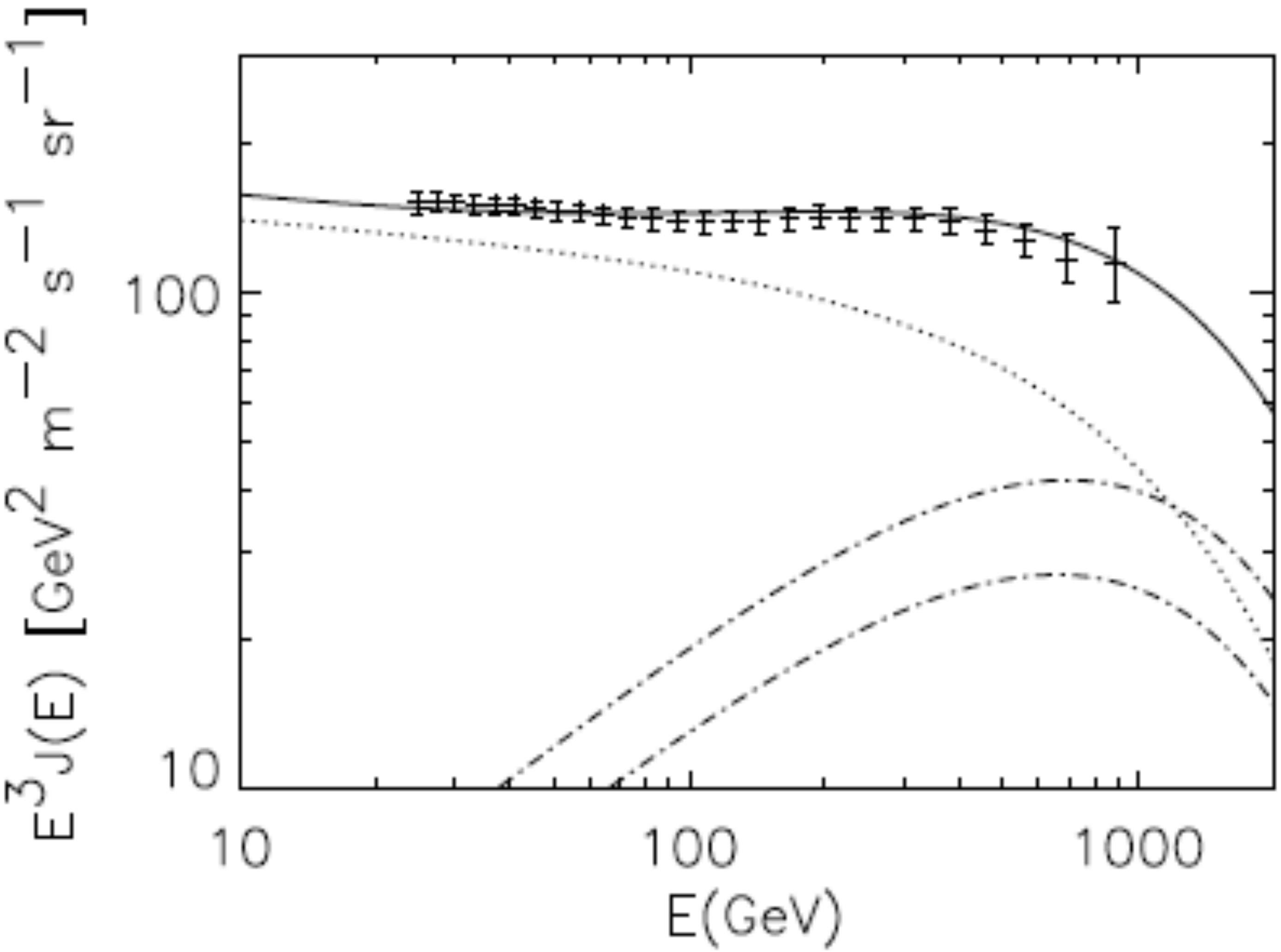
TYPICAL VALUES REQUIRED ARE

$K_B \approx 10 - 20$ $B_\mu \approx 1$ $u_1 \approx 500 - 1000 km/s$ $n \approx 1 - 3\ cm^{-3}$

THESE MAY BE SUITABLE FOR AN OLD SN-I OR A SN-II OUTSIDE THE BUBBLE CREATED BY THE WIND OF THE PRE-SN STAR

THE BULK OF CR ARE ACCELERATED DURING THIS PHASE WHICH IS THE ONE THAT LASTS THE MOST...

THE ELECTRON SPECTRUM

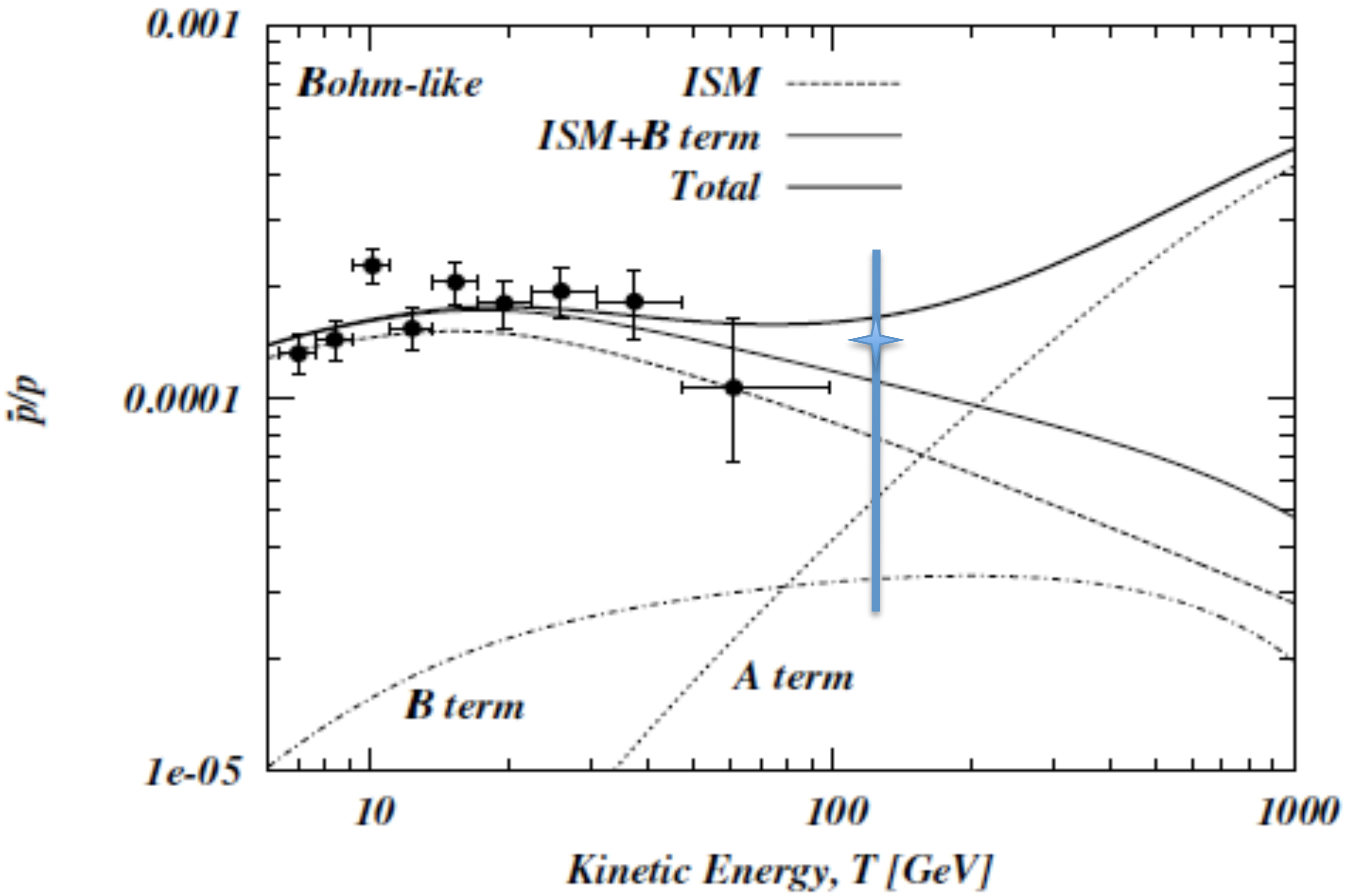


PB 2009

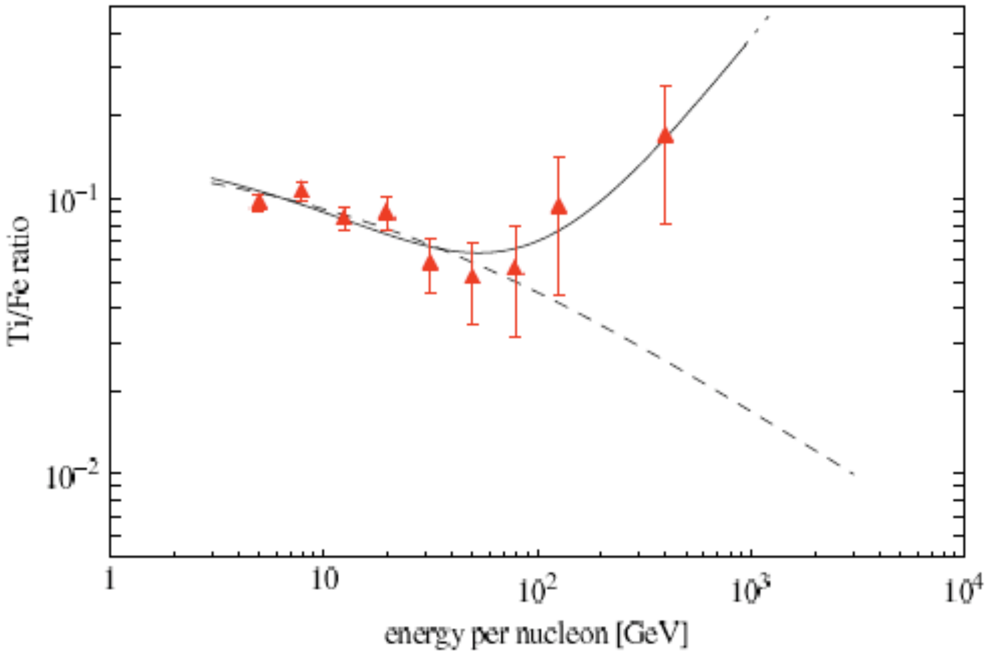
ANTIPROTONS

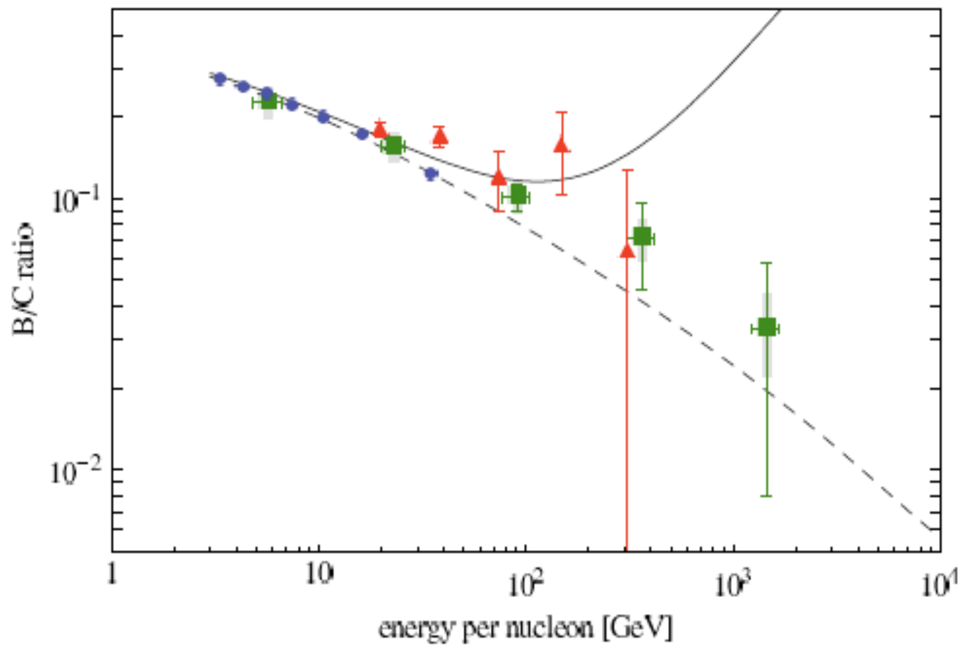
PB & Serpico (2009)

SIMPLER CALCULATIONS BECAUSE NO ENERGY LOSSES:



SECONDARY NUCLEI



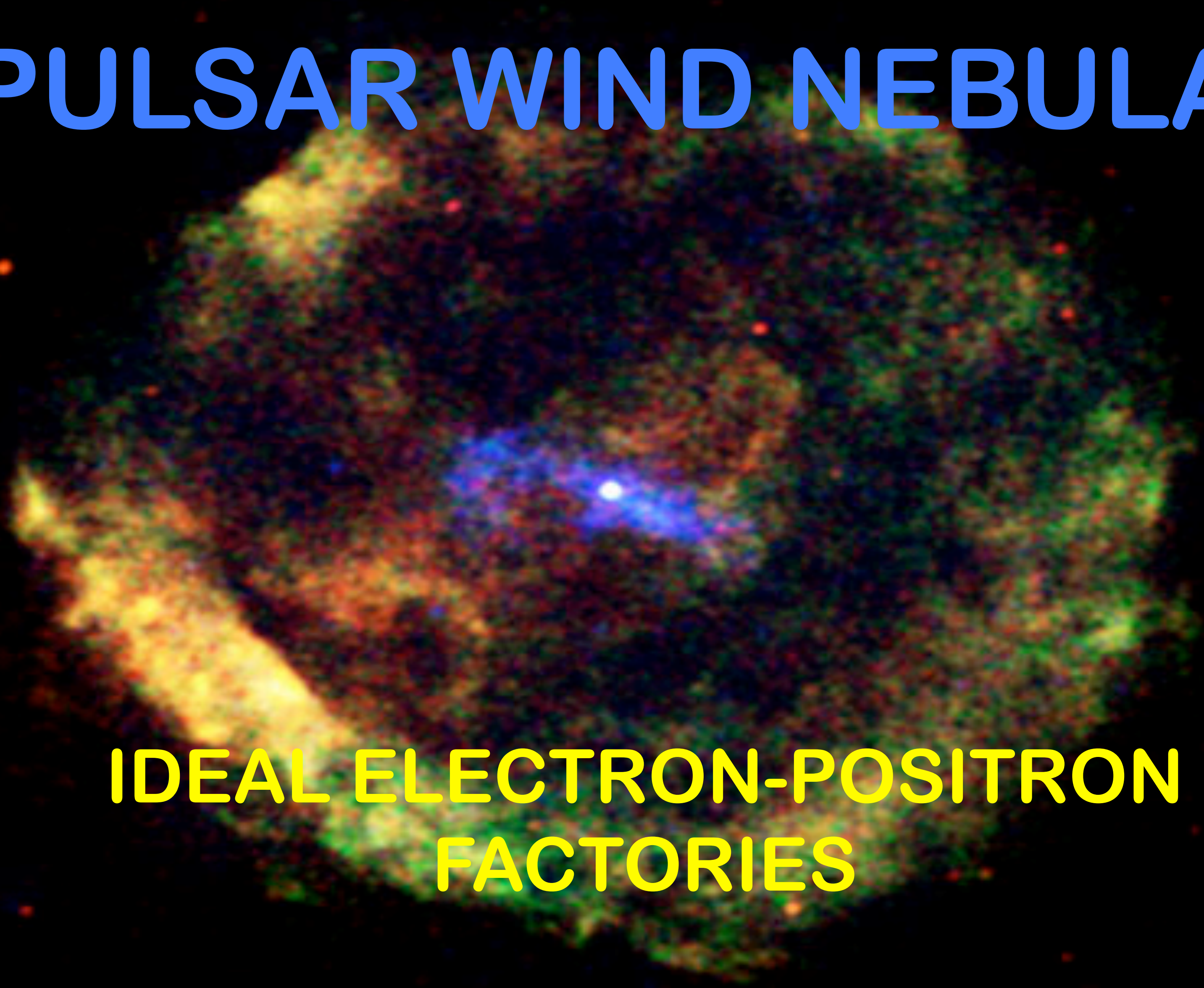


Ti/Fe

B/C

Mertsch & Sarkar 2009

PULSAR WIND NEBULAE

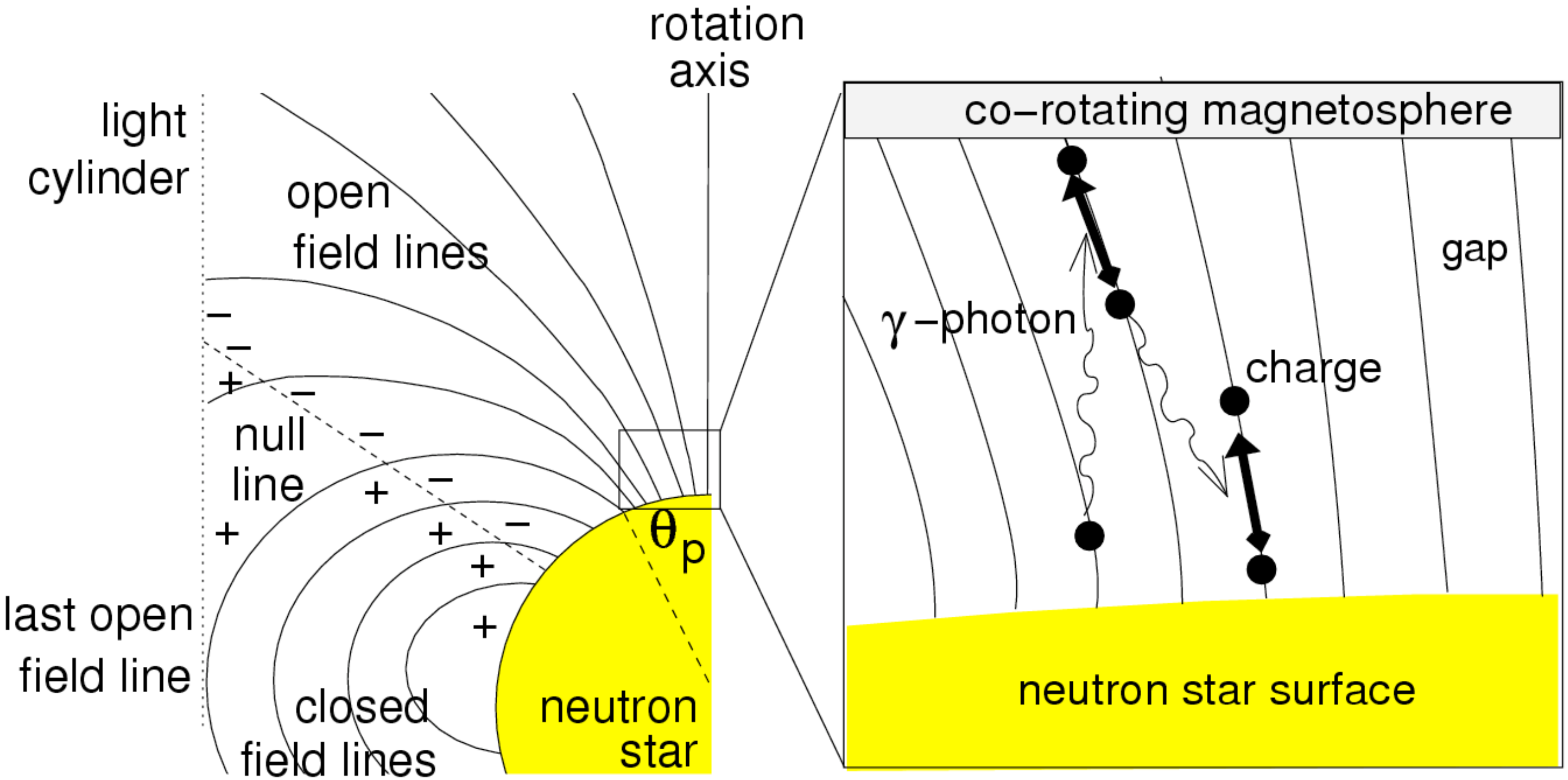


IDEAL ELECTRON-POSITRON FACTORIES

Papers by: Hooper, PB & Serpico, 2008; Grasso et al. 2009; PB & Amato 2010, 2011

Pulsar wind launching

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



PULSAR SPIN DOWN

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

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

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

n is the braking index

It equals 3 for a dipole field and <3 for other cases

THE DIPOLE CASE

DIPOLE (n=3)

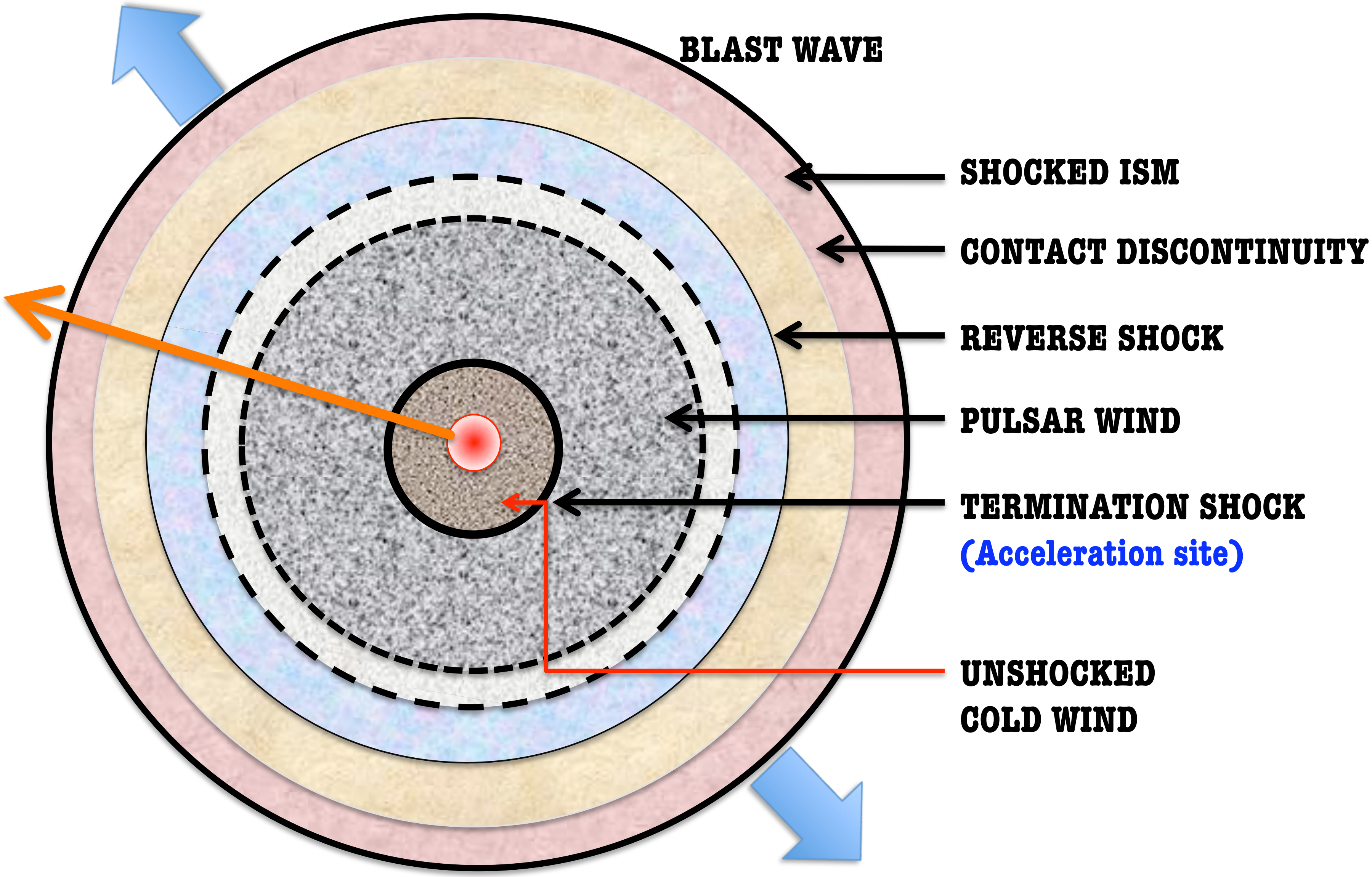
$$\dot{E} = \frac{B^2 R^6 \Omega^4}{6c^3} = 10^{39}\, B_{12}^2 R_{10}^6 P_{10}^4\, erg/s$$

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

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

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



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 λ the spectrum of accelerated particles is inferred to be a broken power law with slope ~1-1.5 at $\gamma<10^5$ and ~2.3 at $\gamma>10^5$

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 on an Electron within a SNR

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

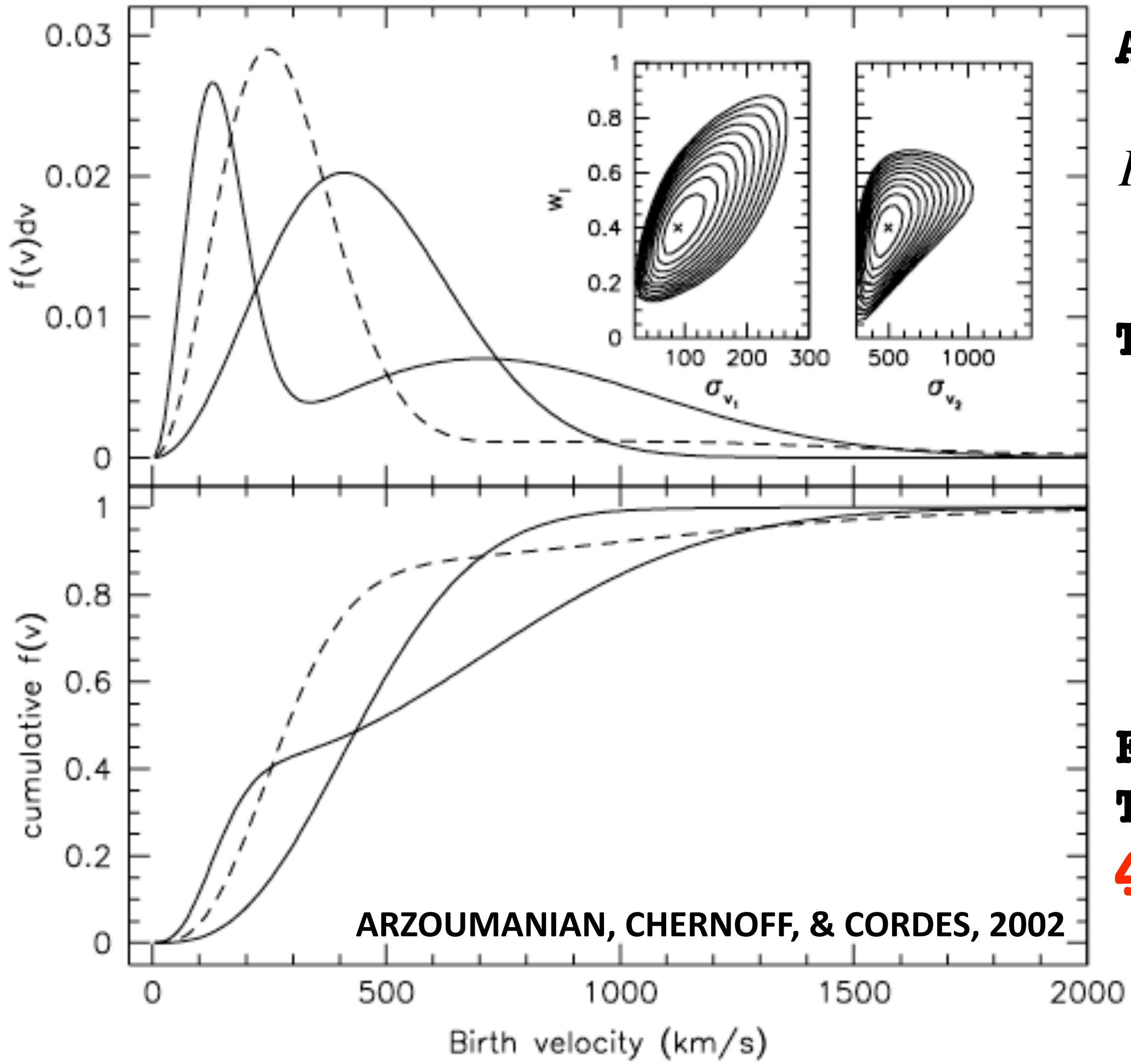
When the reverse shock of the blast wave reaches the center, some level of compression might occur

…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:

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

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

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:

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

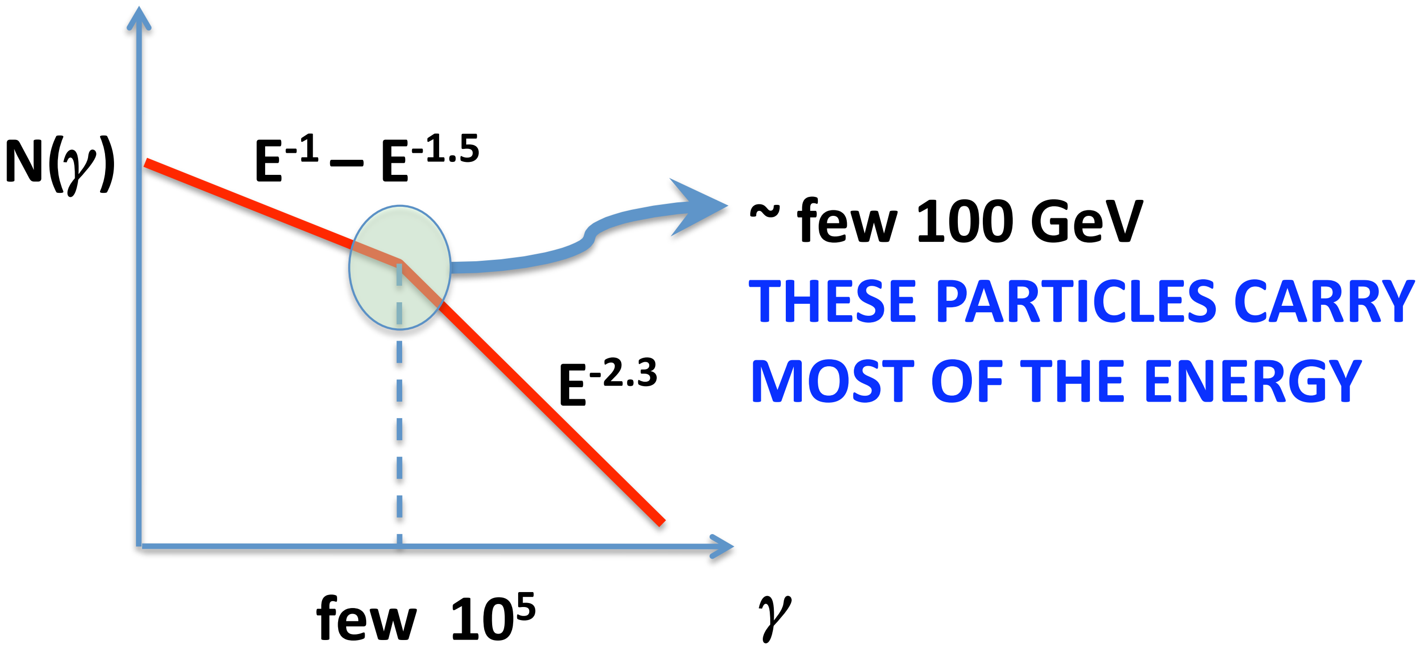
$$\frac{E_*}{E_{tot}} \approx 0.02 \qquad \text{For n} = 2.5$$

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

SPECTRA OF PWN IN PLERIONS

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)

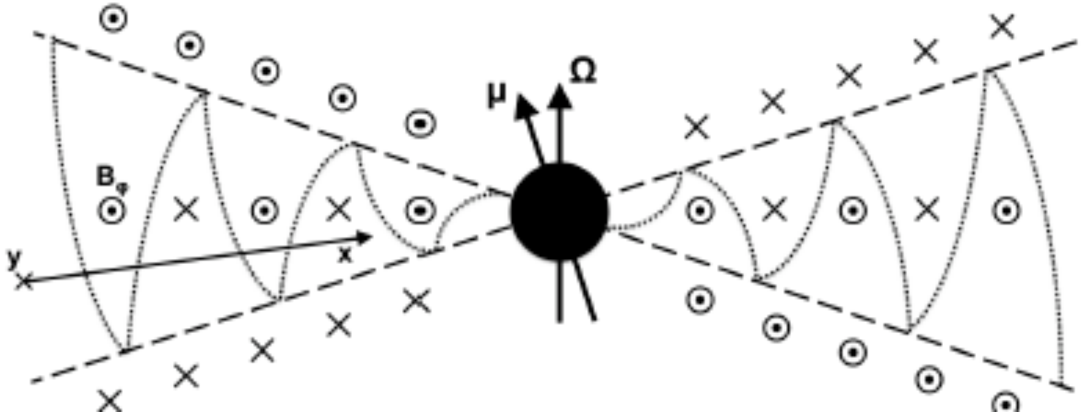
-Quasi-universal low E spectrum??? hard
-intrinsic spectral break?
-thermal component?

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 $E^{-2.5}$)

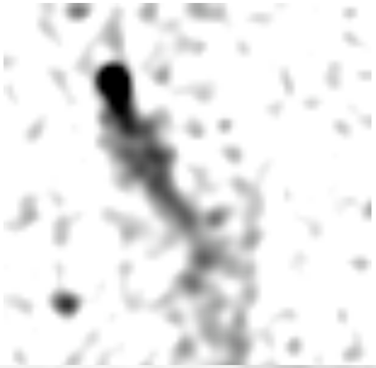
IT WORKS IN THE EQUATORIAL PLACE

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

Spectra in bow shock nebulae

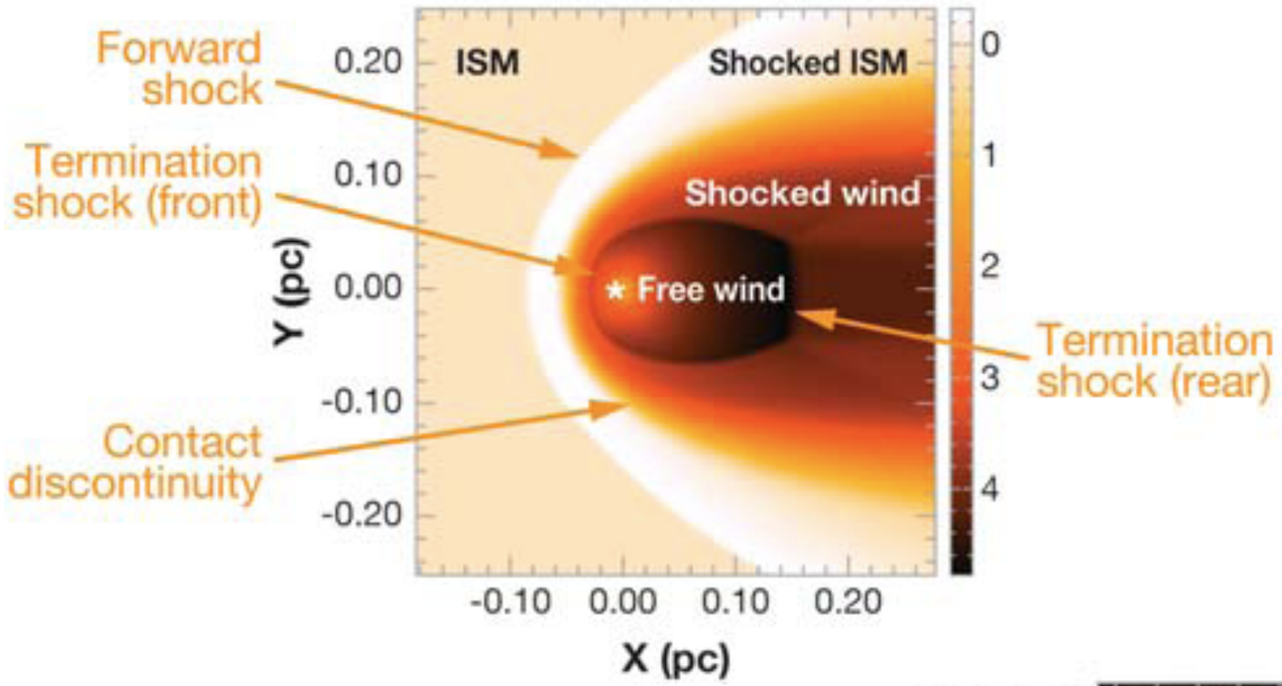
Still spinning after escaping the SNR

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

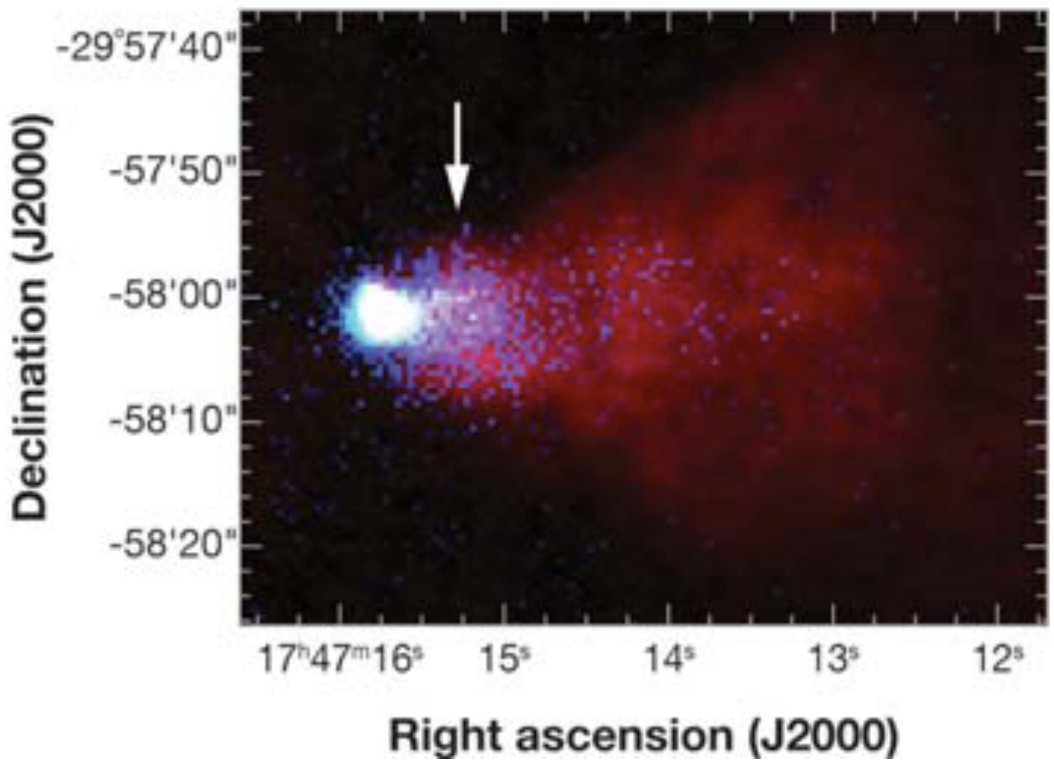


PSR J1509–5850
Slope radio: -0.26
Slope Electrons: -1.52
Ng et al. 2010

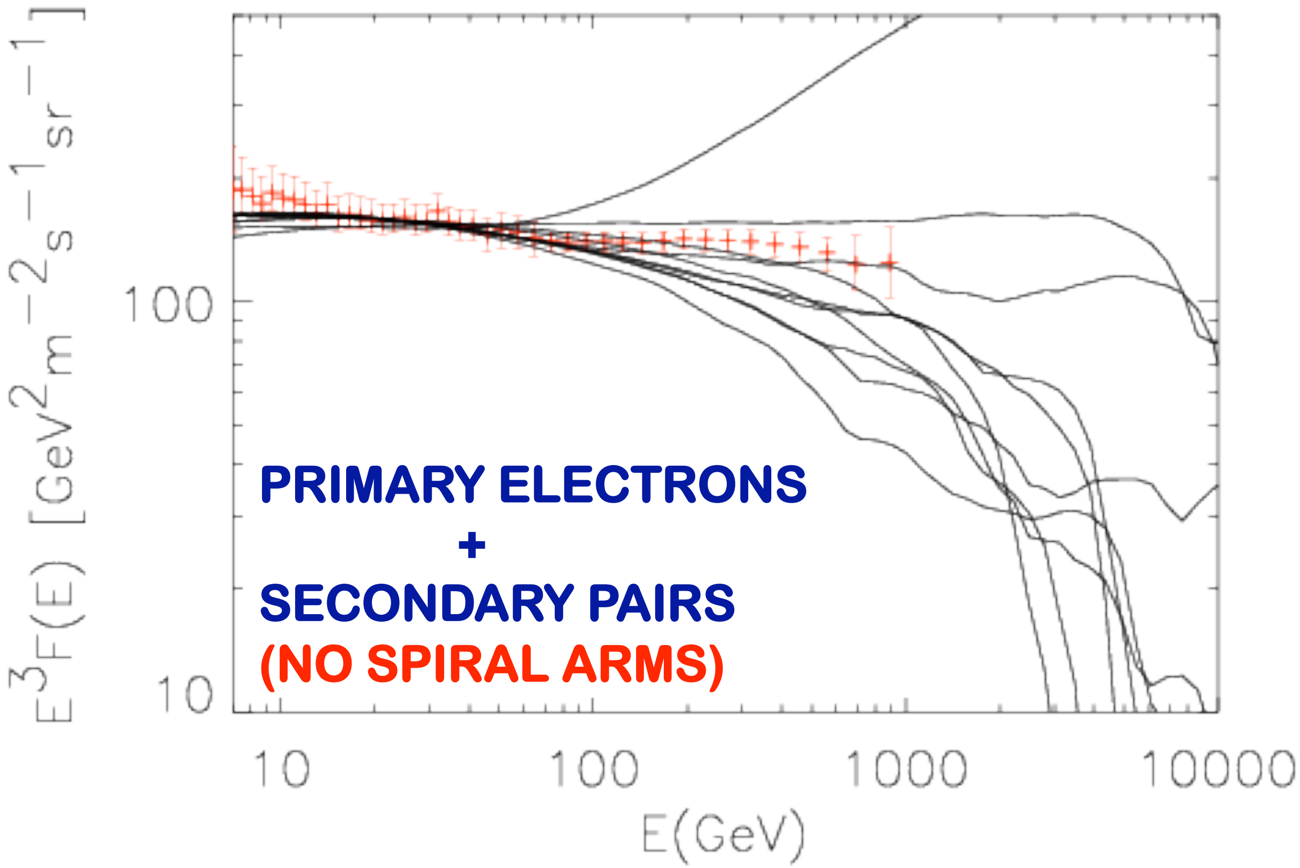
The Mouse
Slope radio: -0.3
Slope Electrons: -1.6
Gaensler et al. 2004



Slane & Gaensler 2006

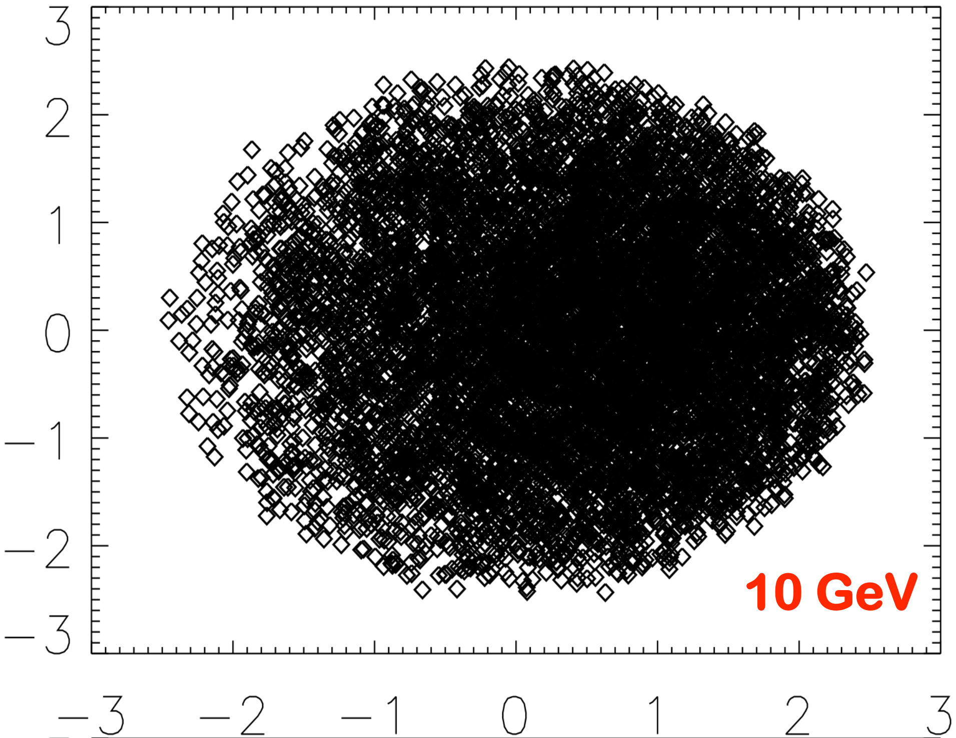


Excess with respect to what?

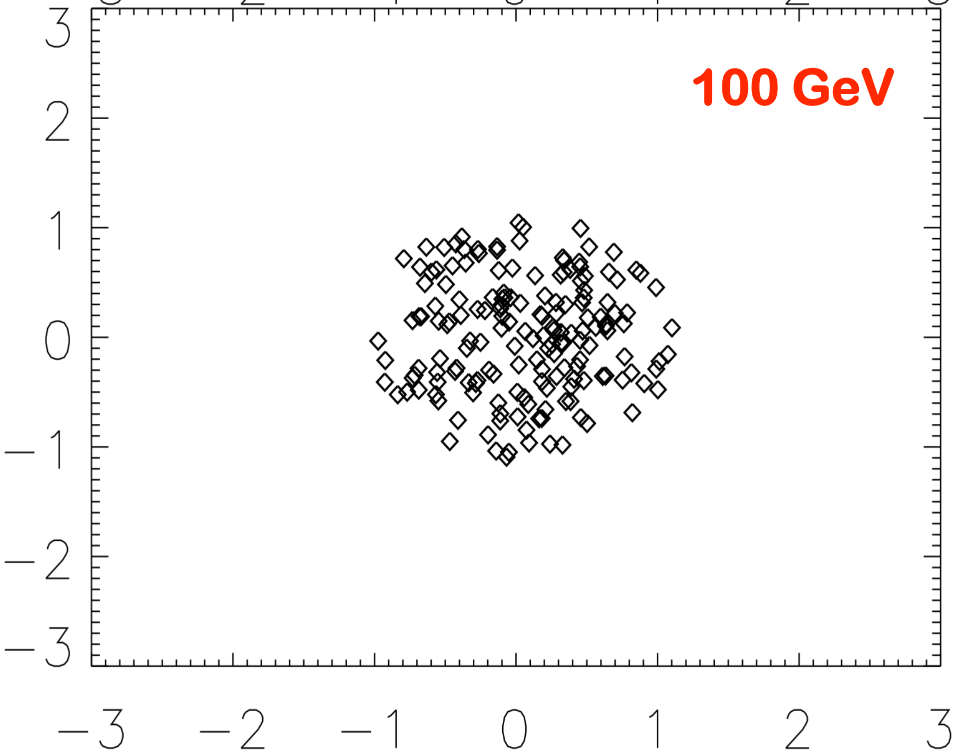


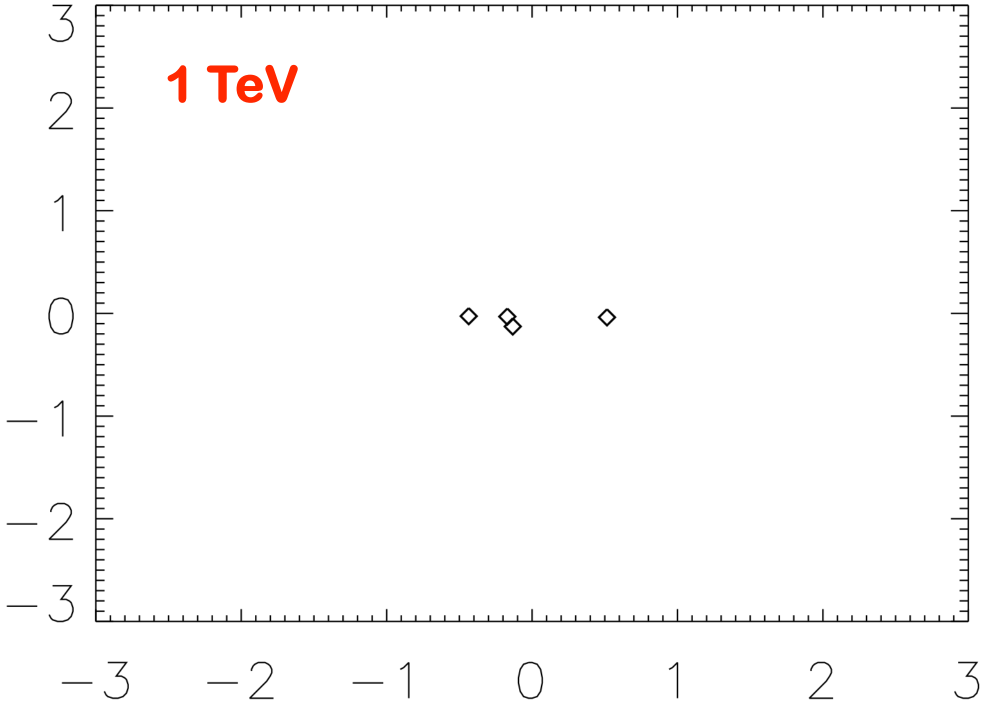
PB & Amato 2011

NUMBER OF ELECTRON SOURCES CONTRIBUTING AT GIVEN ENERGIES



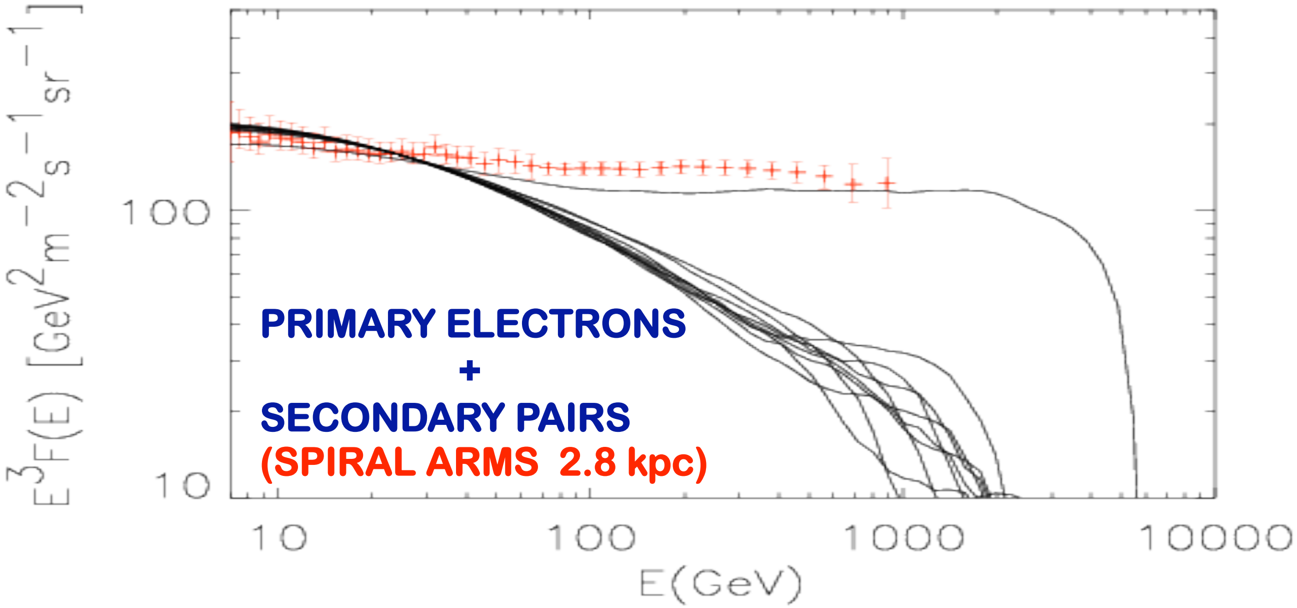
PB & Amato 2010



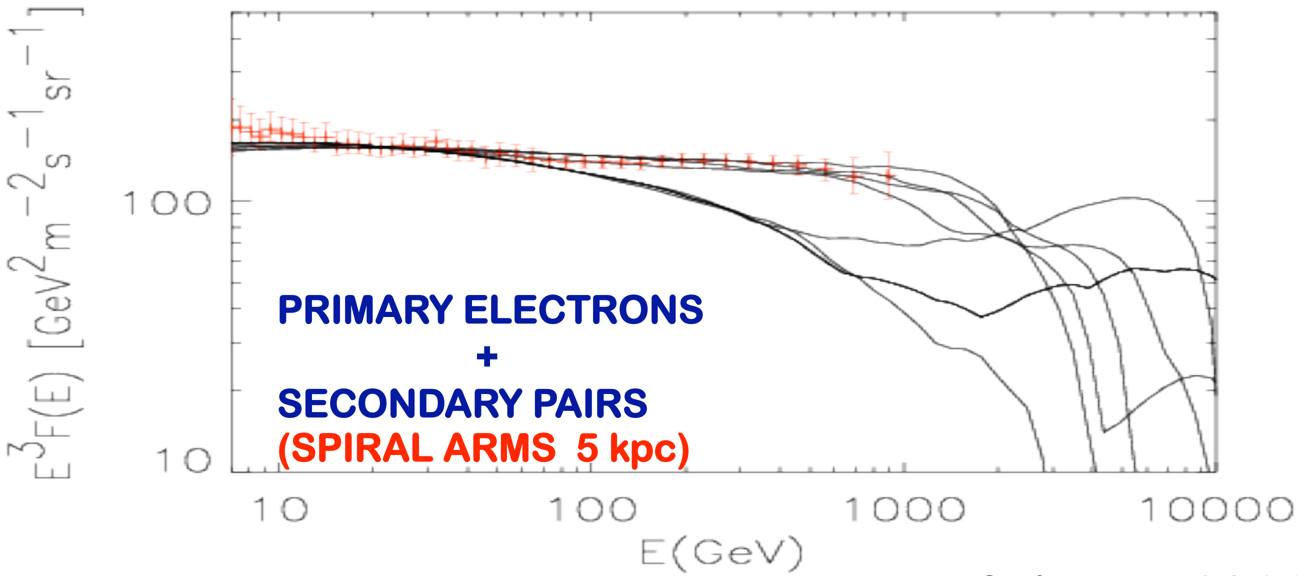


The effect of spiral arms

TIGHT SPIRAL

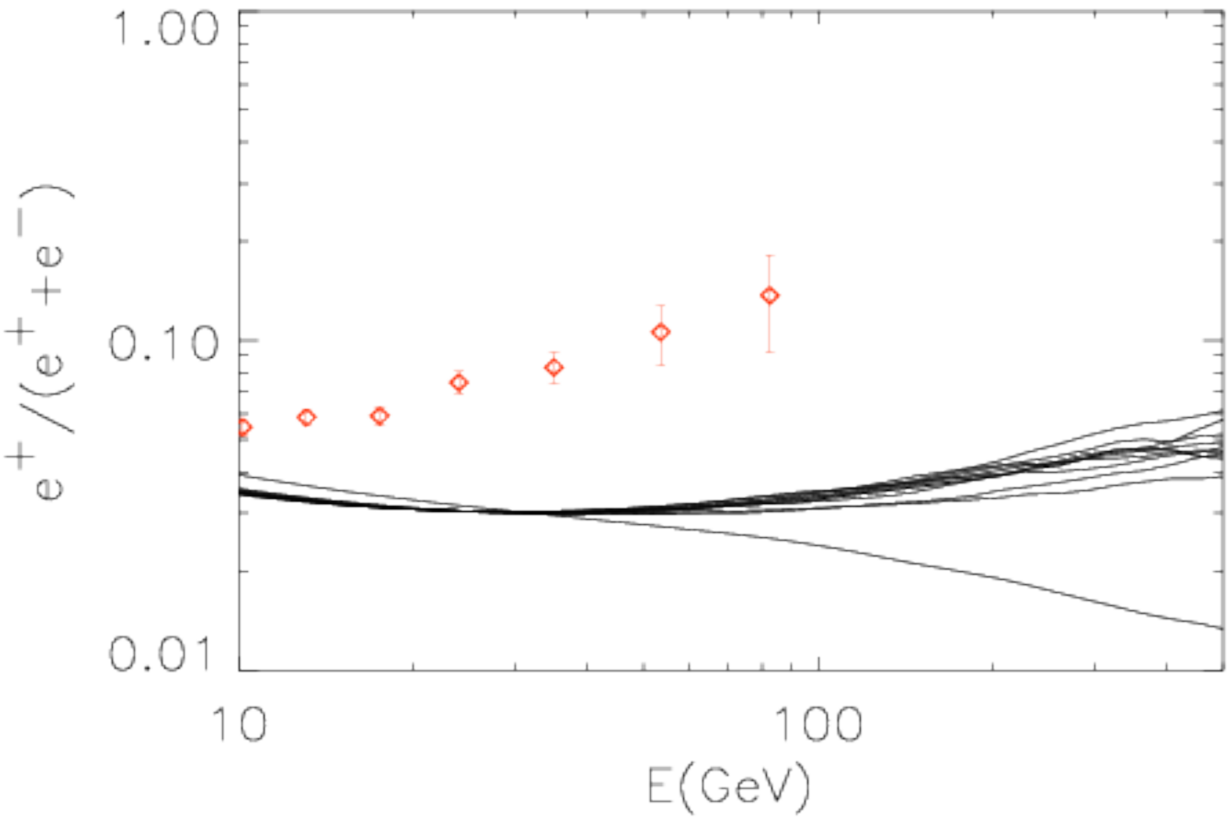


BROAD SPIRAL



PB & Amato 2011

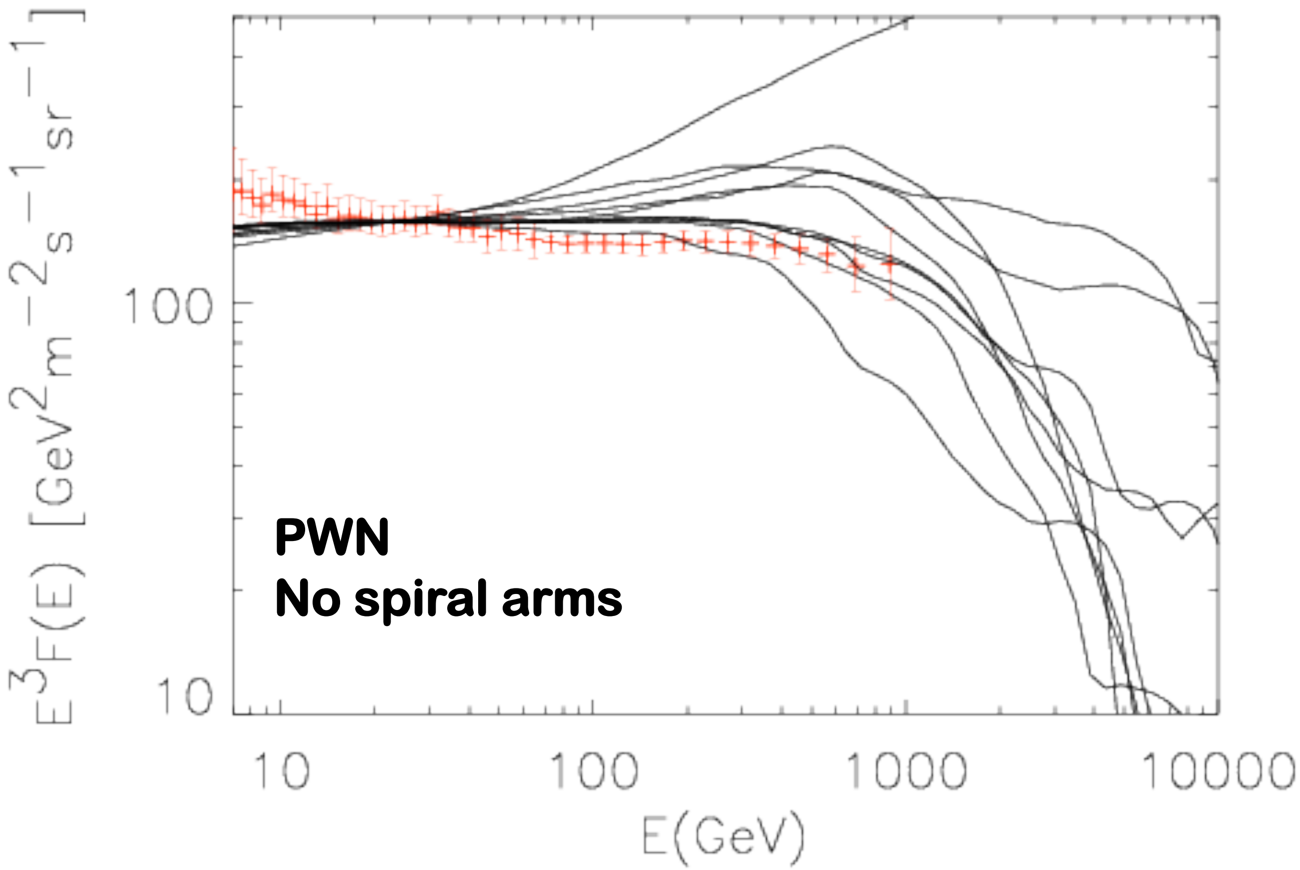
THE POSITRON FRACTION FOR THE CASE OF TIGHT SPIRAL ARMS

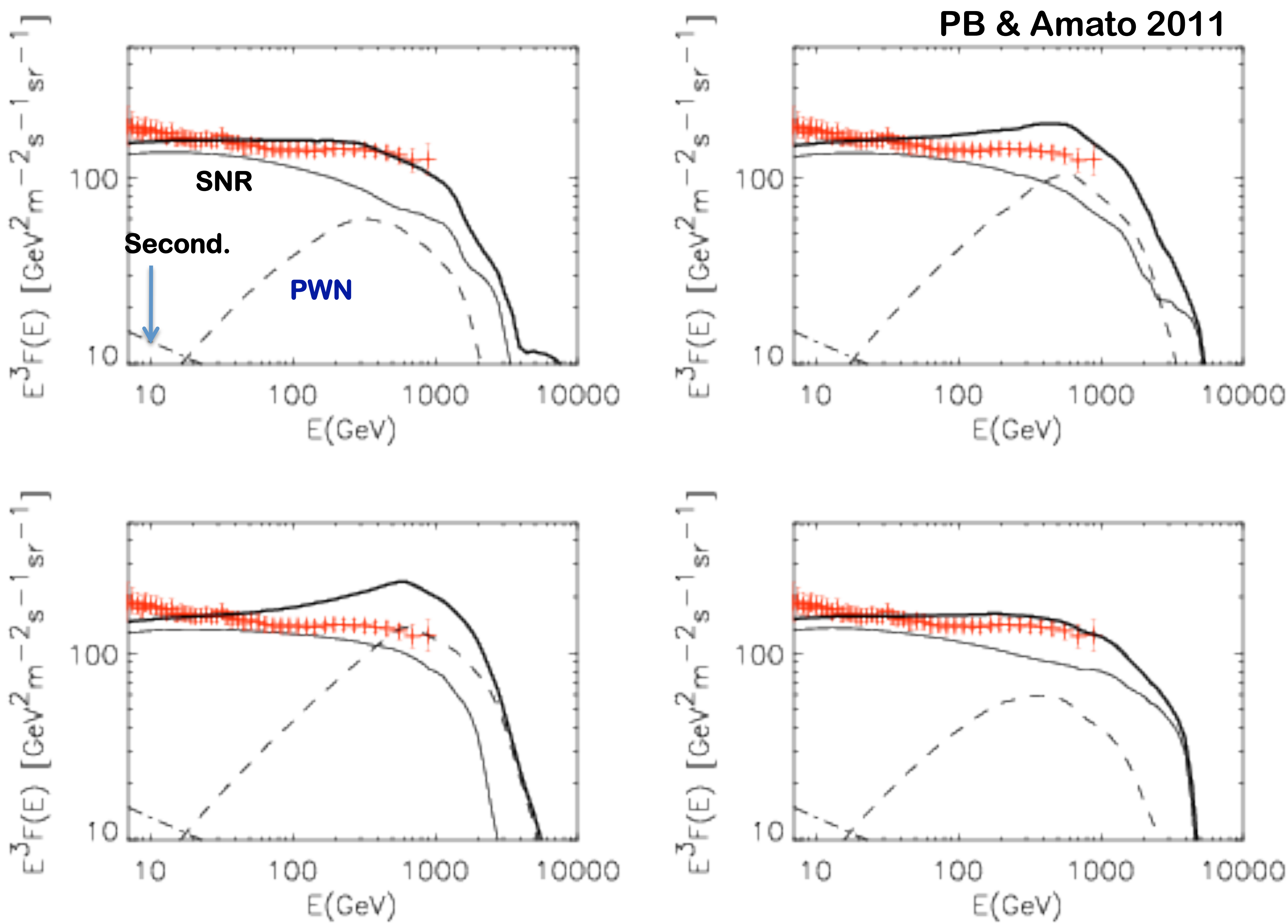


THIS SITUATION IS REMINISCENT OF THE PROPAGATION EFFECTS SUGGESTED BY Shaviv et al. 2009, but somewhat at odds with recent Fermi-LAT electron data

Positrons from PWNe

PB & Amato 2011

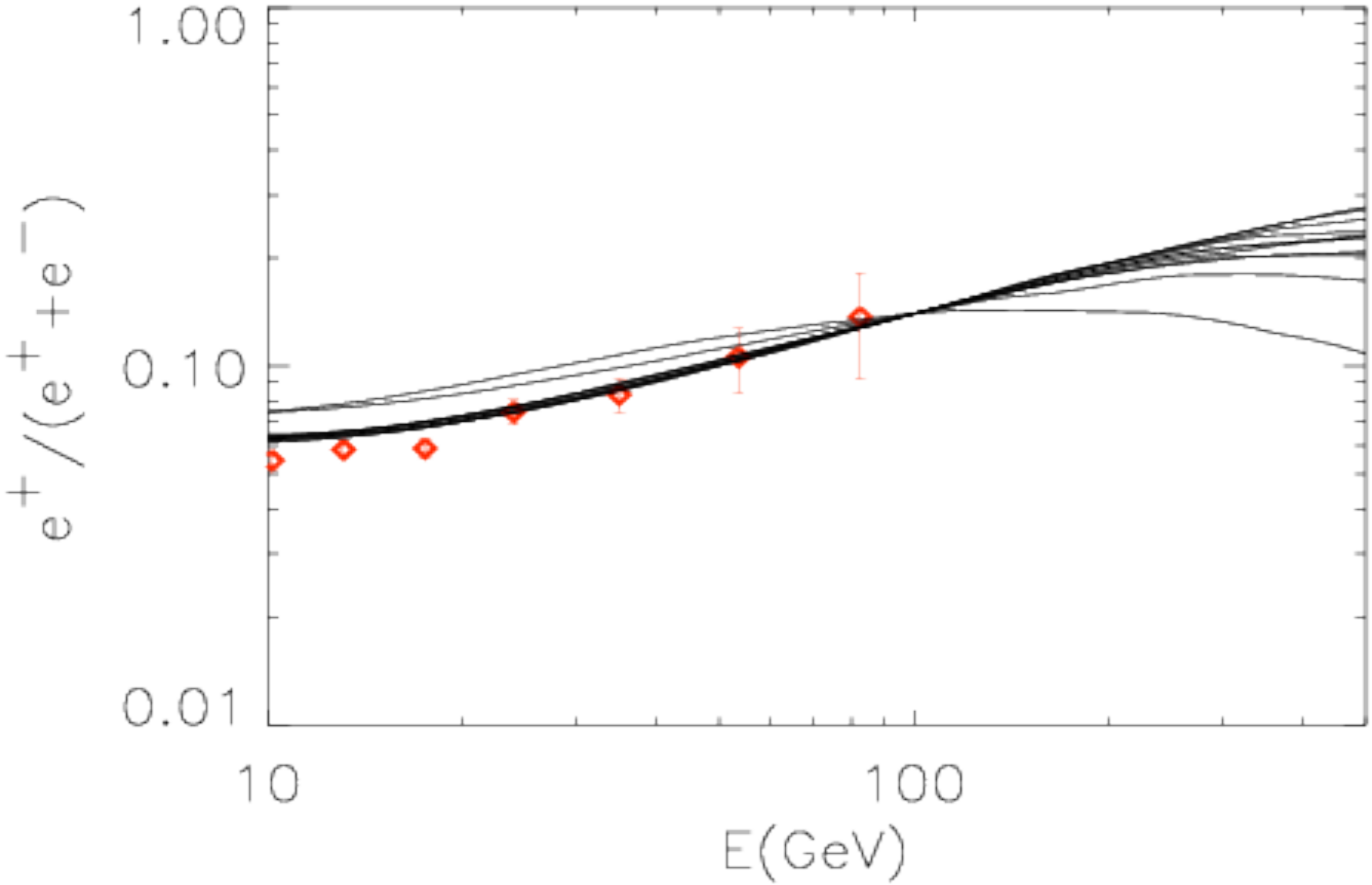




PB & Amato 2011
SNR
Second.
PWN
$E^3F(E)$ [GeV^{2}m^{-2}s^{-1}sr^{-1}]
E(GeV)

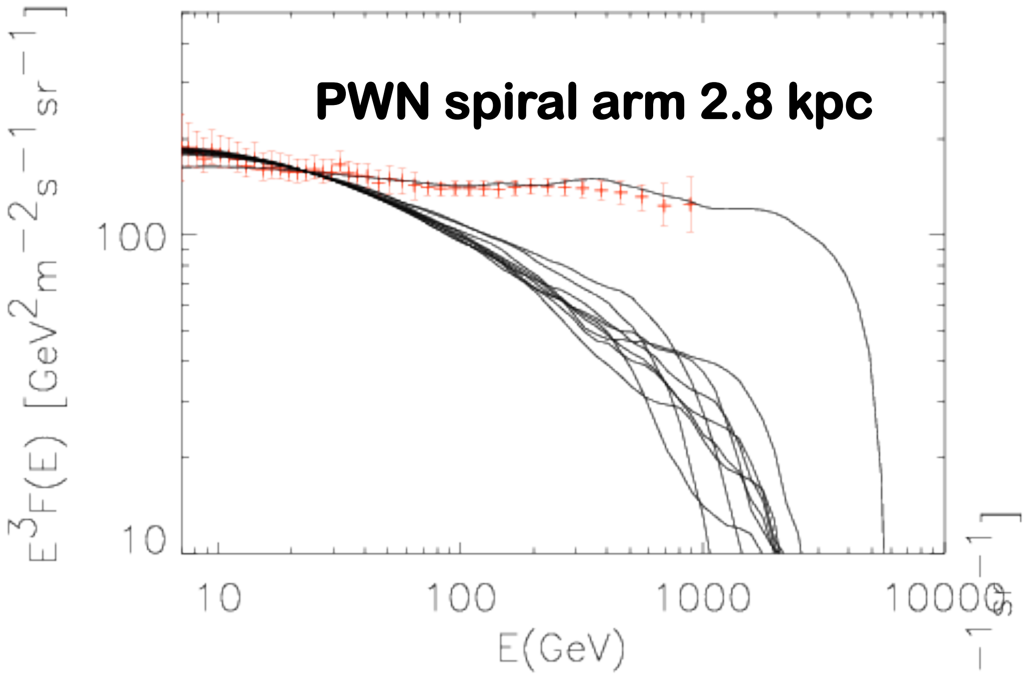
THE POSITRON FRACTION

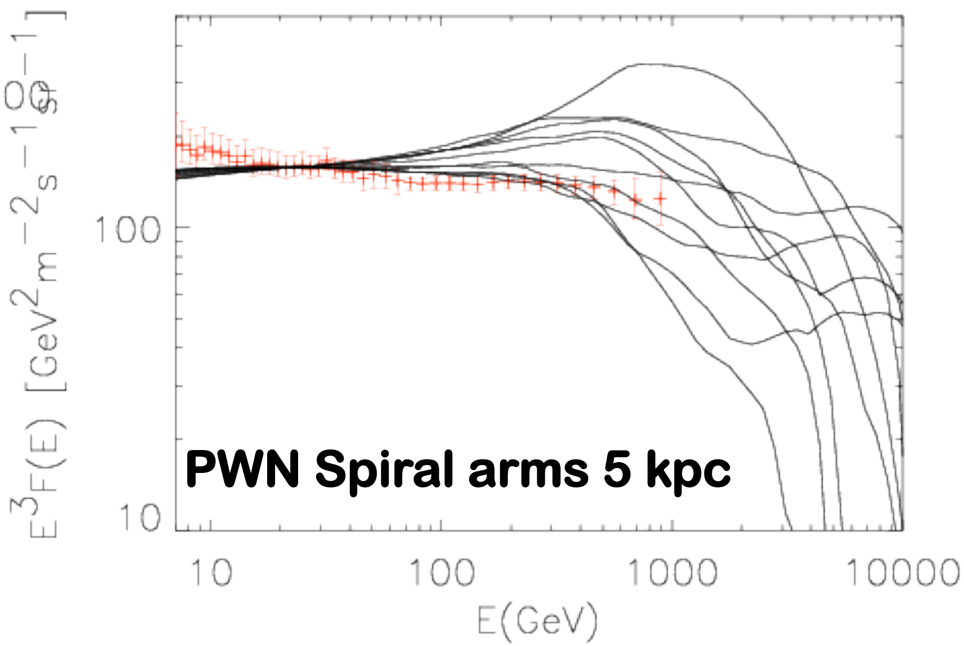
PB & Amato 2011



Positrons from PWNe

PB & Amato 2011





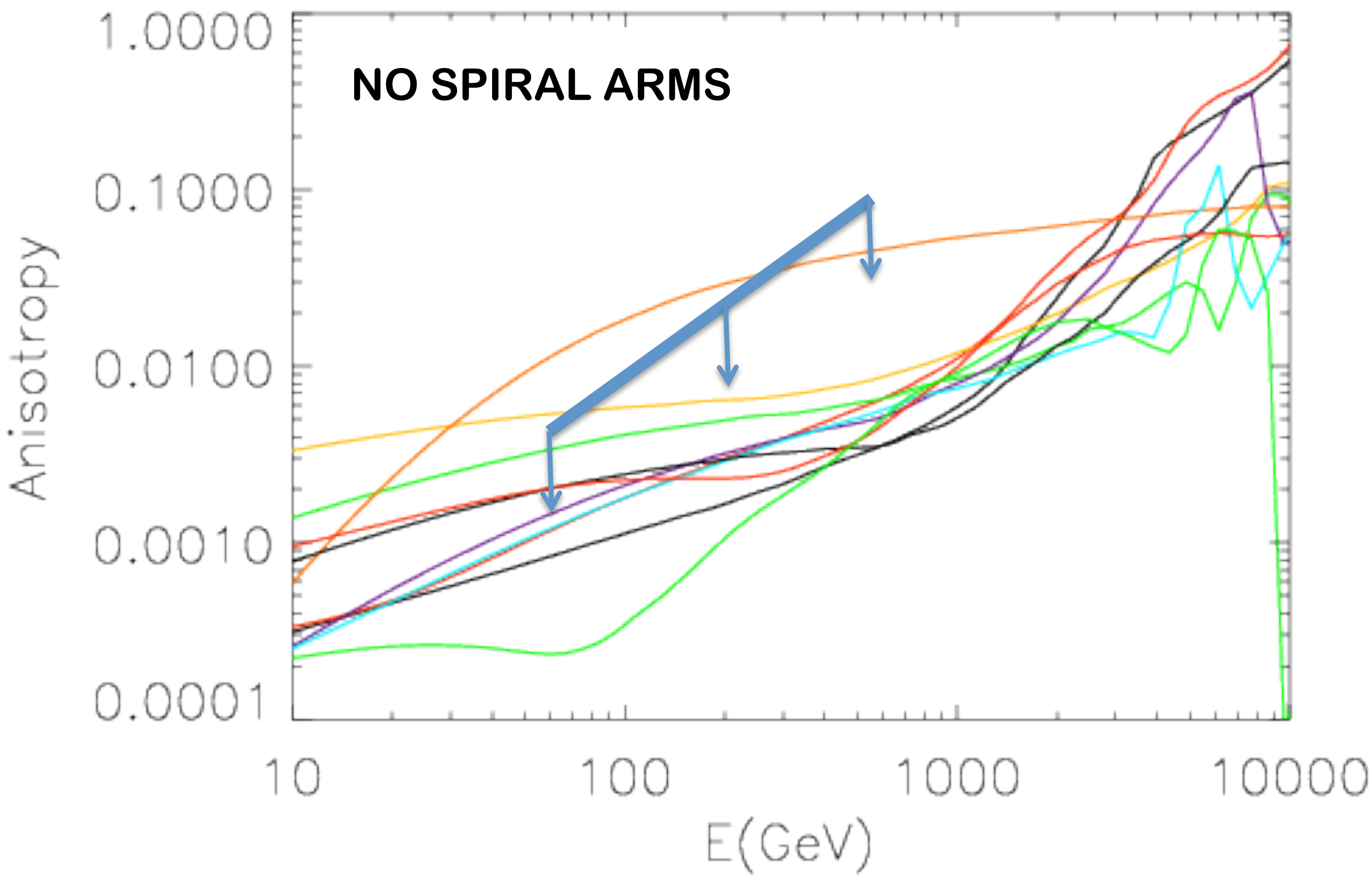
ENERGETICS

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

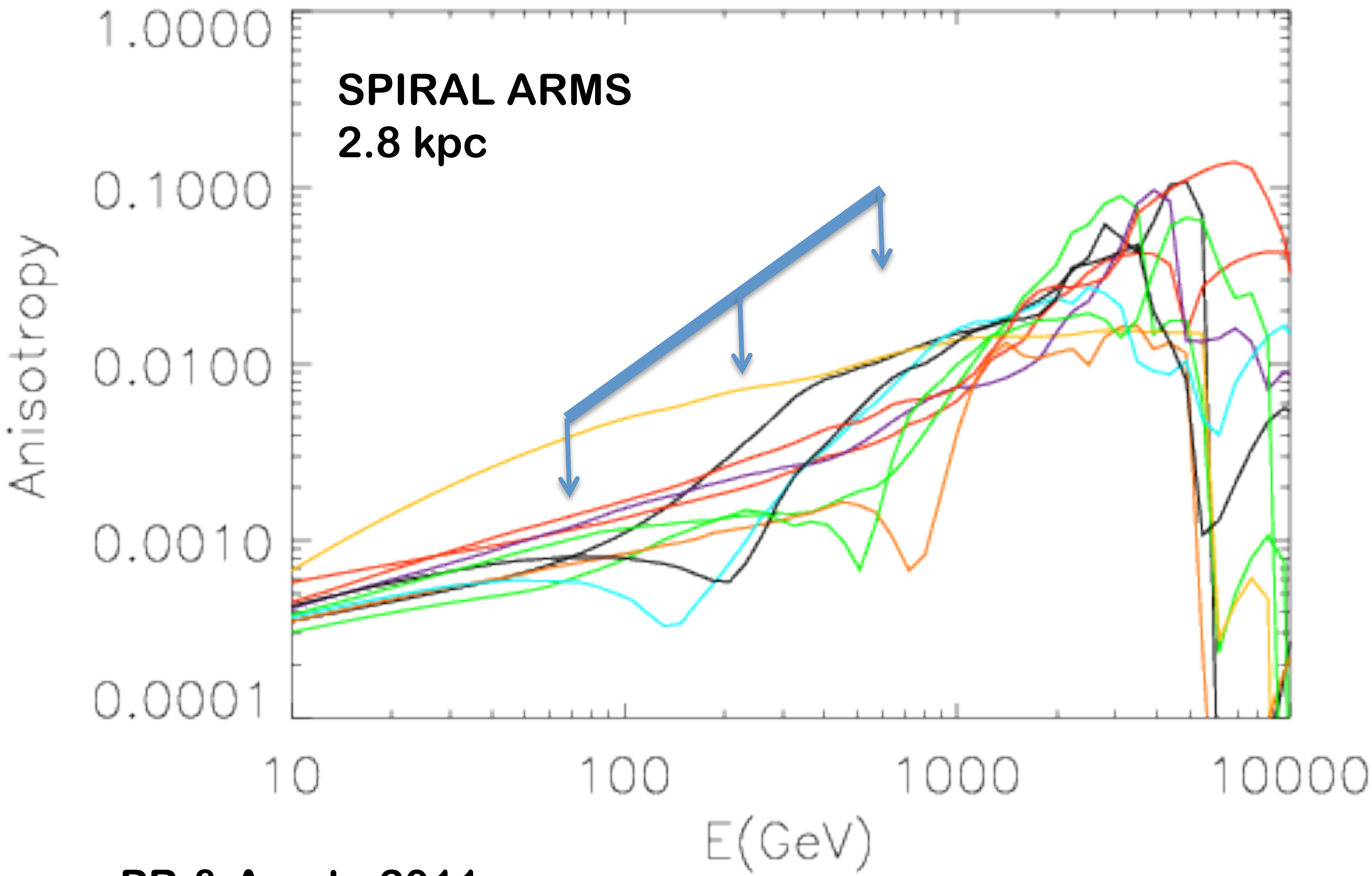
IN THE DIPOLE CASE ONE MIGHT WANDER WHERE ARE ALL THE POSITRONS GOING?

Anisotropy



PB & Amato 2011

Anisotropy



PB & Amato 2011

SUMMARY (1)

BACKGROUND FLUX OF e^-+e^+ STRONGLY DEPENDENT UPON THE SOURCE REALIZATION

EXCESS COULD BE DUE TO SECONDARY PRODUCTION IN SOURCES (OLD SNR) BUT

- PECULIAR CHOICE OF PARAMETERS
- POSSIBLE PROBLEM WITH SECONDARY/PRIMARY RATIO (we will see)

SNR IN MAGNETIZED WIND COULD PRODUCE A SUBDOMINANT COMPONENT OF CR WITH FLATTER SPECTRUM

- ASSUMPTION OF SECONDARY PRODUCTION INSIDE THE SOURCE TO BE CHECKED
- CONCLUSION ON SPECTRA MODEL DEPENDENT

POSSIBILITY OF PROPAGATION EFFECTS RATHER HARD TO REALIZE DUE TO THE FERMI-LAT ELECTRON SPECTRUM

SUMMARY (2)

PULSAR WINDS ARE PERFECT POSITRON SOURCES

- ENERGY LEFT AFTER ESCAPING THE REMNANT (BOW SHOCK NEBULA) ENOUGH TO POWER THE POSITRON EXCESS
- SPECTRA INFERRED FROM OBSERVATIONS WORK FINE, THOUGH NOT UNDERSTOOD

DATA ARE EXPECTED TO IMPROVE SOON WITH AMS-02 TO CONFIRM THAT THE POSITRON EXCESS IS AS PRONOUNCED AS SHOWN BY PAMELA

AS A GENERAL COMMENT: LET US BE CAREFUL TO GET TOO EXCITED ABOUT SPECTRAL FEATURES (POSITRONS, NUCLEI, …): SOME OF THESE FEATURES ALSO APPEAR DUE TO FLUCTUATIONS IN THE SOURCE ACTIVITY OR LOCATIONS

THERE IS A LOT OF WORK TO BE DONE BEFORE WE ACTUALLY FIGURE OUT THE DETAILS OF CR PROPAGATION AND ACCELERATION… EXCESSES SHOULD BE COMPARED WITH HOW WELL WE UNDERSTAND SUCH DETAILS