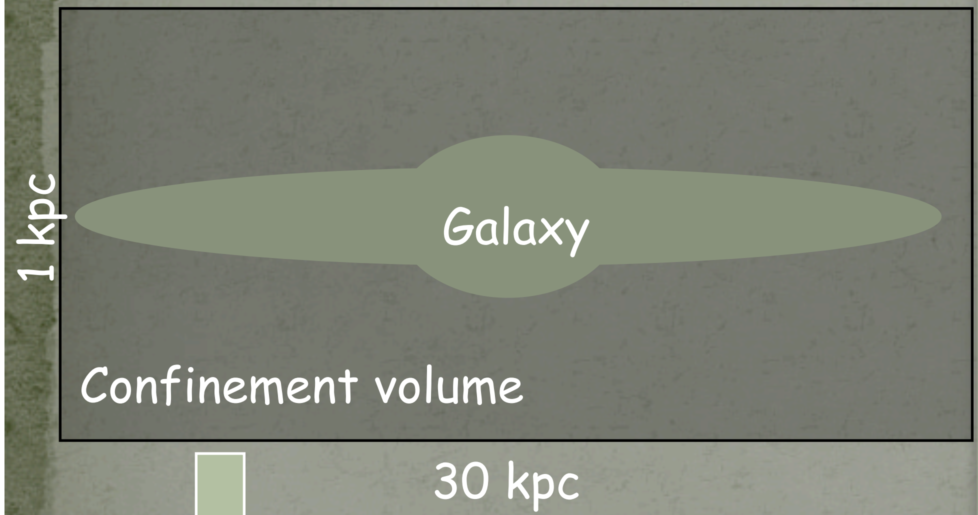
ON THE ORIGIN OF LEPTONS AND HADRONS IN THE COSMIC RADIATION

PASQUALE BLASI

INAF/Osservatorio Astrofisico di Arcetri, Firenze, ITALY

SUPERNOVA PARADIGM: I-ENERGETICS

$$\omega_{CR} = 0.5 eV cm^{-3}$$



$$V_{conf} = \pi R^2 h = 2 \times 10^{67} \text{ cm}^3$$

$$W_{CR} = \omega_{CR} V_{conf} \approx 2 \times 10^{55} \text{ erg}$$

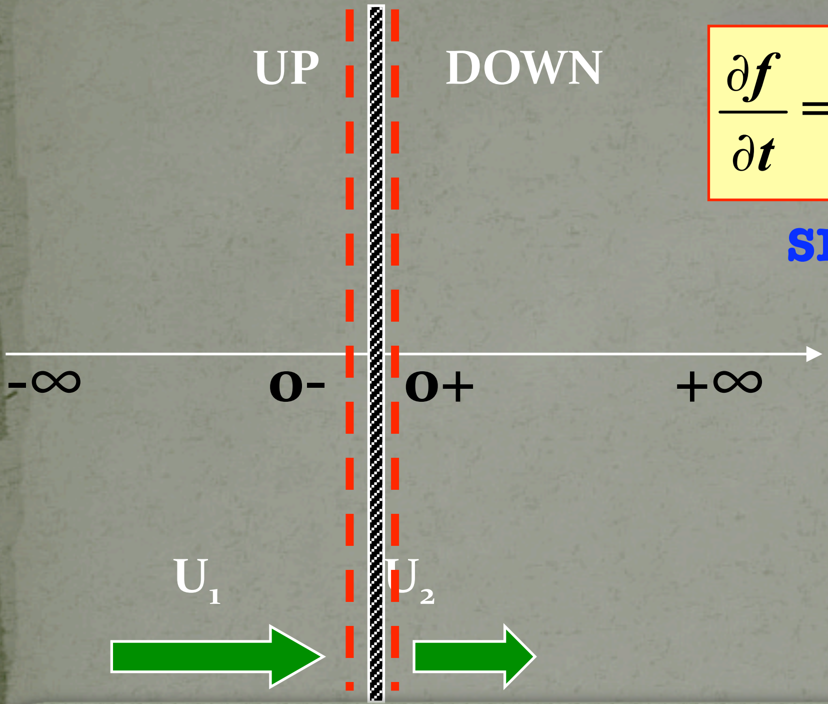
$$L_{CR} \approx \frac{W_{CR}}{\tau_{conf}} \approx 5 \times 10^{40} \text{ erg s}^{-1}$$

$$L_{SN} = R_{SN} E_{kin} \approx 3 \times 10^{41} \text{ erg s}^{-1}$$

REQUIRED EFFICIENCY

10-20 %

SUPERNOVA PARADIGM: II-Energy conversion

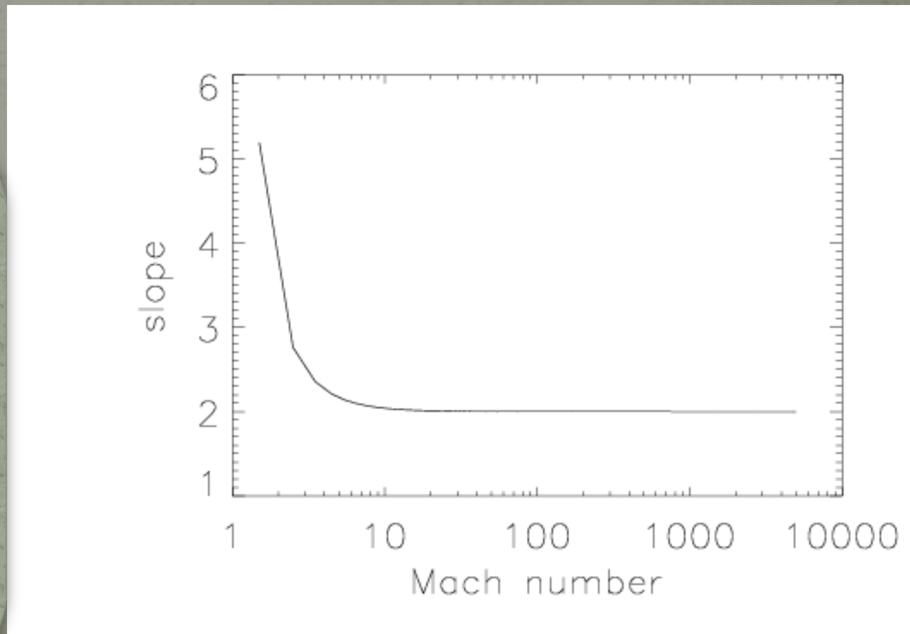


$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f}{\partial p} + Q(x,p,t)$$

SPECTRUM

$$N(E) \propto \left(\frac{E}{E_0}\right)^{-\gamma} \qquad \gamma = \frac{R+2}{R-1}$$

R COMPRESSION FACTOR



1. Power law spectrum
2. Slope only F(R)
3. No dependence on diffusion
4. For strong shocks slope ~2
5. No absolute normalization

MAXIMUM ENERGY

ACCELERATION TIME

$$\tau_{acc} = \frac{3}{U_1 - U_2}\left[\frac{D_1(E)}{U_1} + \frac{D_2(E)}{U_2}\right]$$

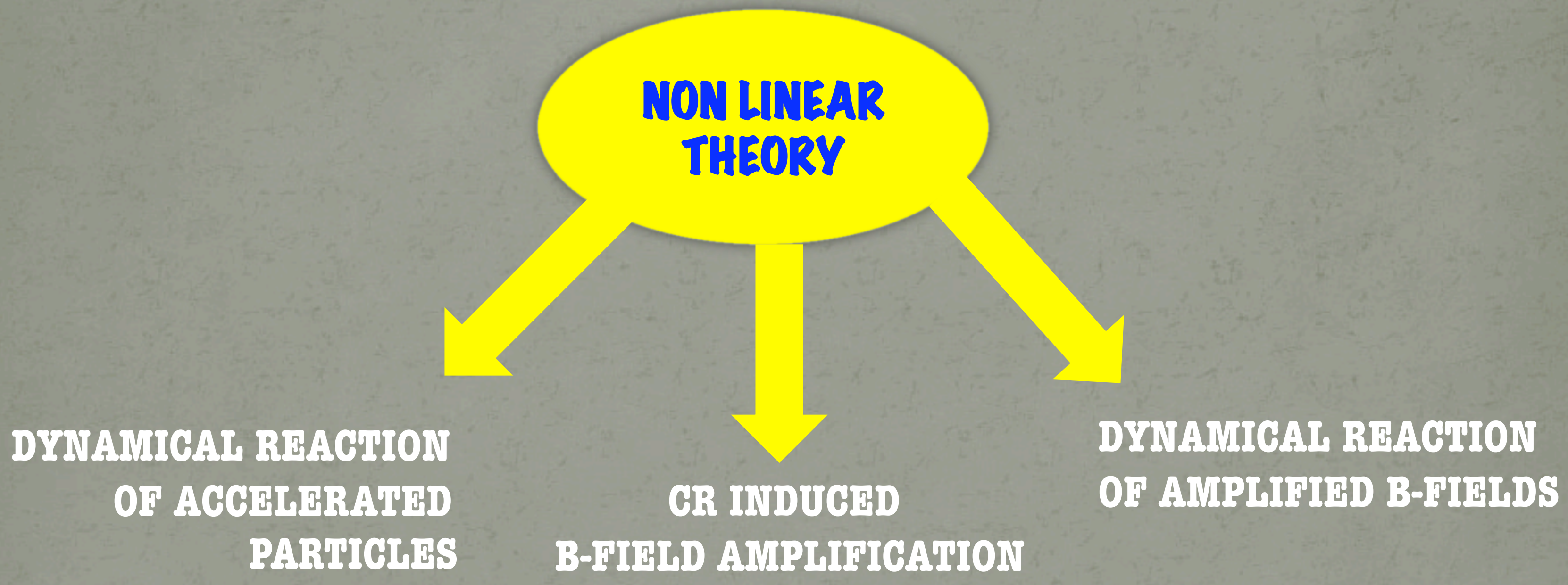
What if we use the ISM diffusion coefficient inferred from B/C?

$$\tau_{acc} \approx \tau_{age} \quad \longrightarrow \quad E_{max} \sim 1\text{-}100 \text{ GeV}$$

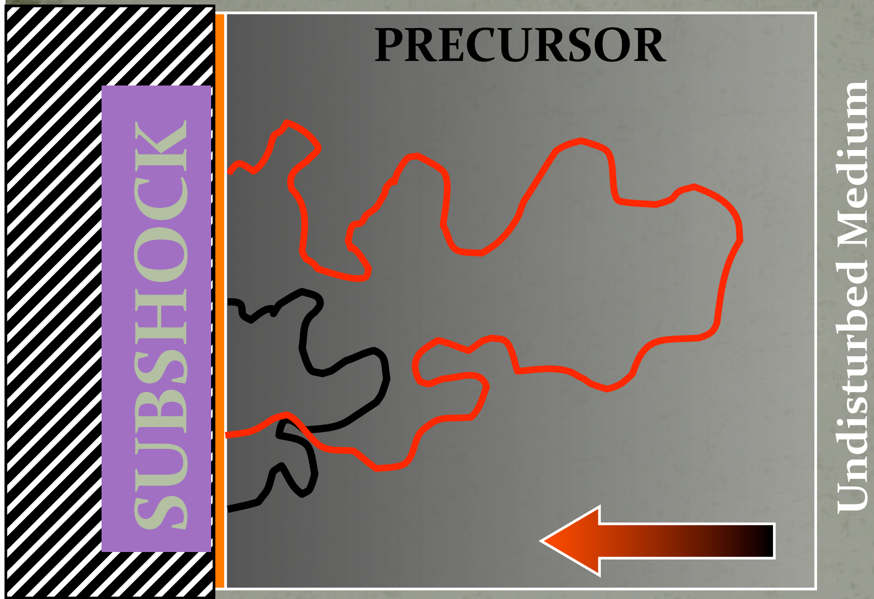
IF DIFFUSIVE SHOCK ACCELERATION IS THE CONVERSION MECHANISM IN SNR, IT MUST BE COMPLETED WITH SOME PROCESS THAT ALLOWS TO REACH PeV ENERGIES

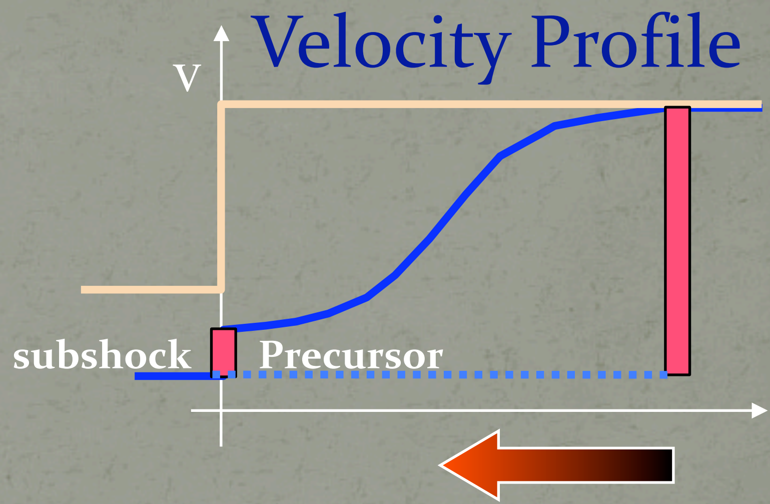
BEYOND TEST PARTICLES: *Non linear DSA*

Berezhko & Voelk, PB, Amato & PB, Ellison et al…



DYNAMICAL REACTION



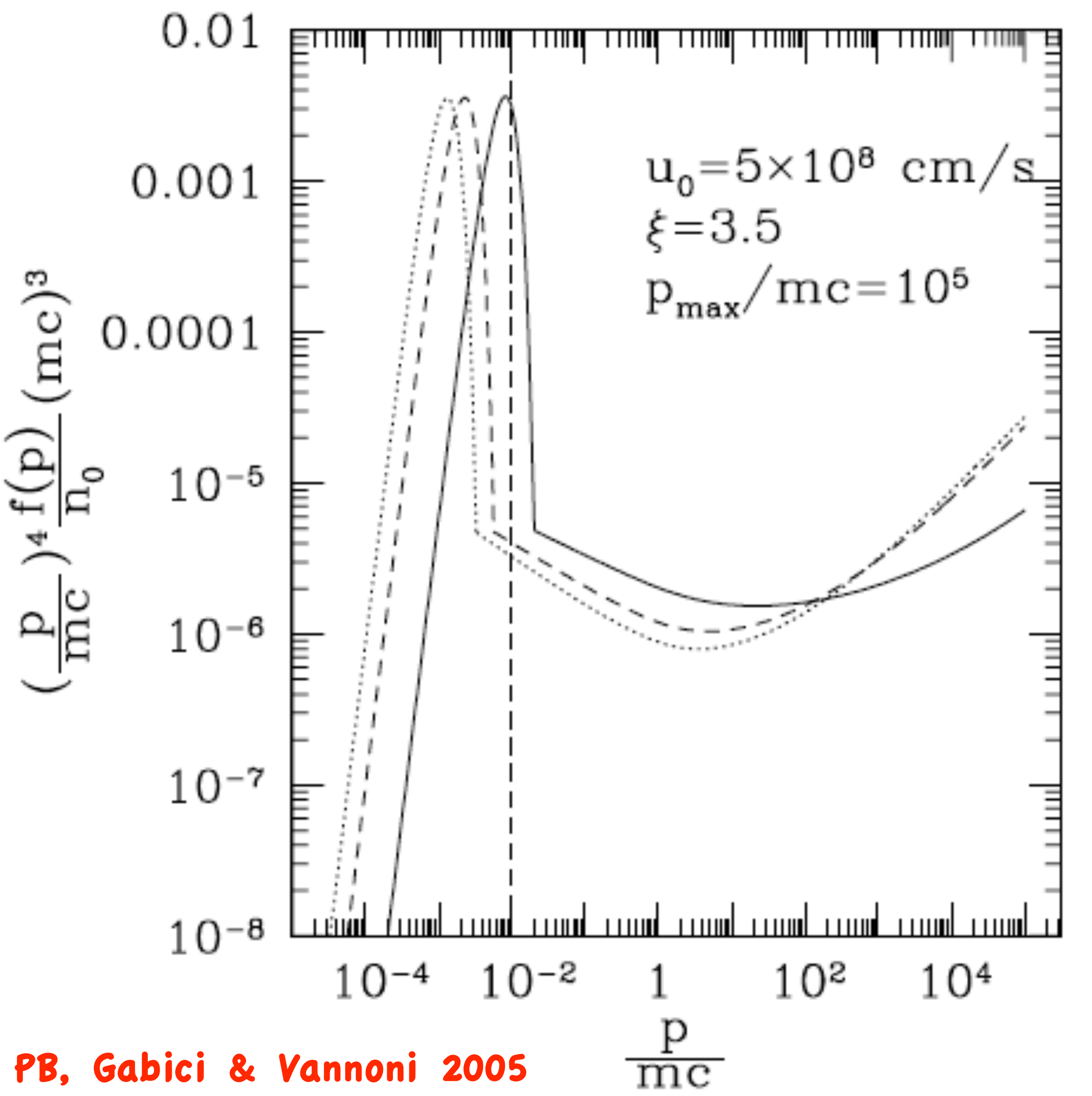


CR TRANSPORT EQUATION

+

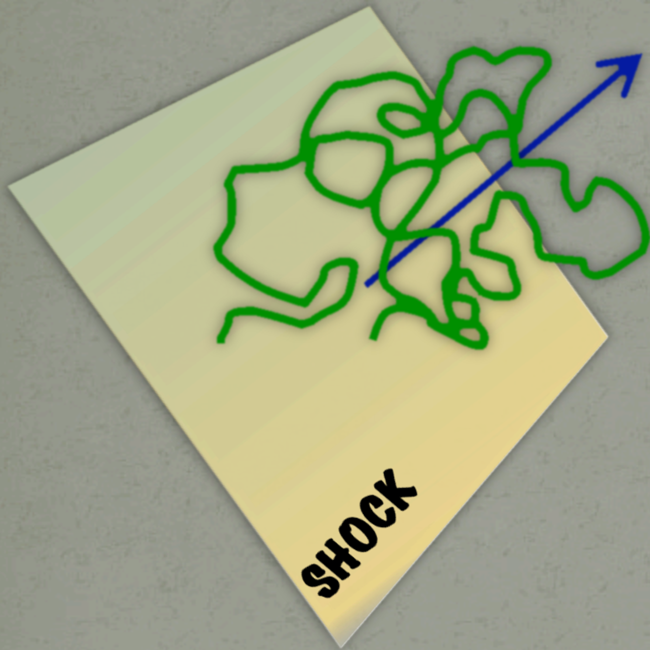
MASS, MOMENTUM, ENERGY CONSERVATION EQUATIONS

1. NO POWER LAW SPECTRA
2. HIGH ACCEL. EFFICIENCY
3. REDUCED HEATING
4. ESCAPE FLUX



PB, Gabici & Vannoni 2005

MAGNETIC FIELD AMPLIFICATION



SMALL PERTURBATIONS IN THE LOCAL B-FIELD CAN BE AMPLIFIED BY THE SUPER-ALFVENIC STREAMING OF THE ACCELERATED PARTICLES

$$\tau = \frac{1}{\Omega(\delta B / B)^2}$$

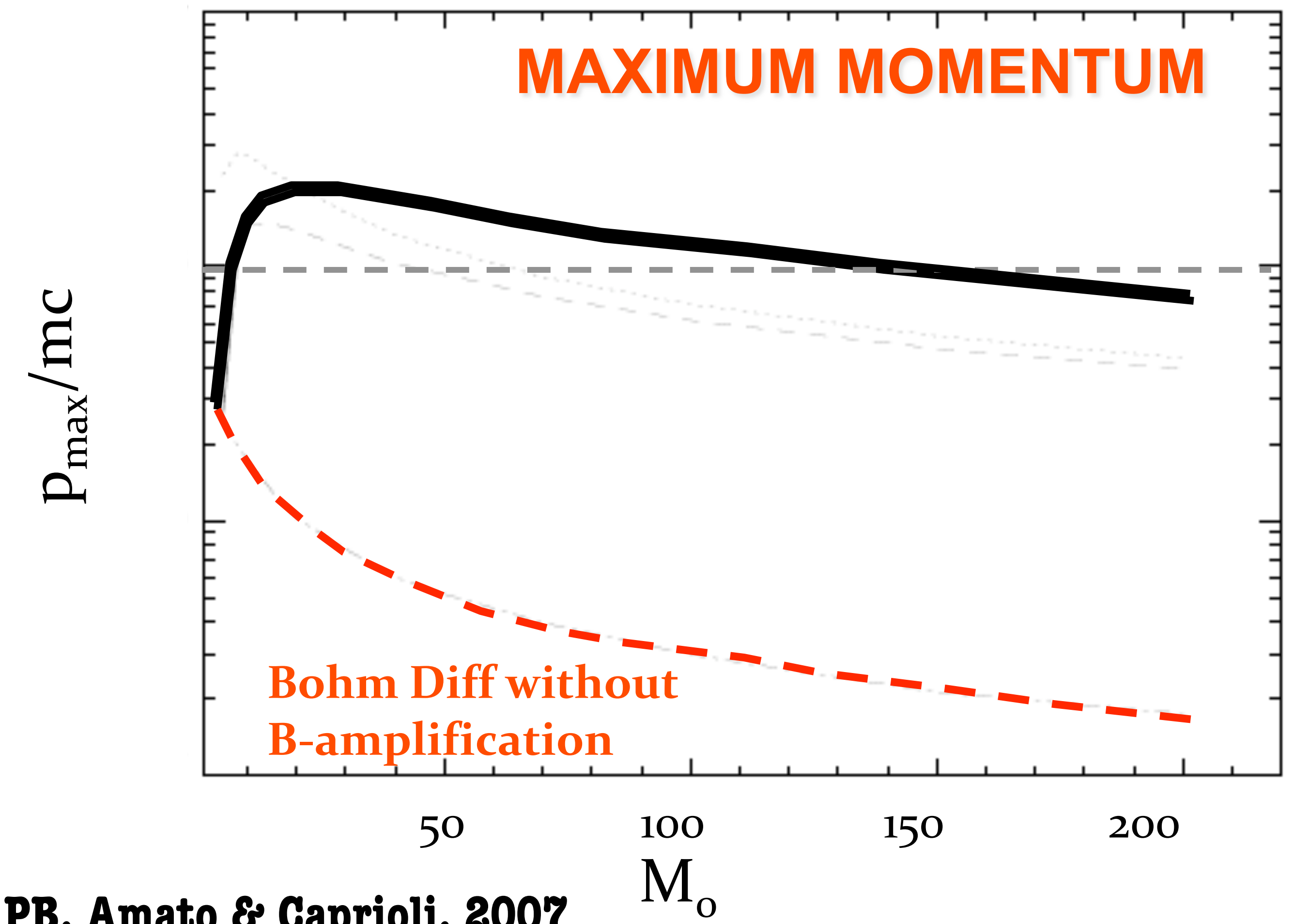
$$\frac{dP_{CR}}{dt} = \frac{n_{CR} m_p \gamma_{CR} (v_S - v_A)}{\tau}$$

$$\frac{dP_W}{dt} = \Gamma_W \frac{\delta B^2}{4\pi v_A}$$

$$\Gamma_W = \frac{n_{CR}}{n} \left(\frac{v_S - v_A}{v_A} \right) \Omega_{cyc}$$

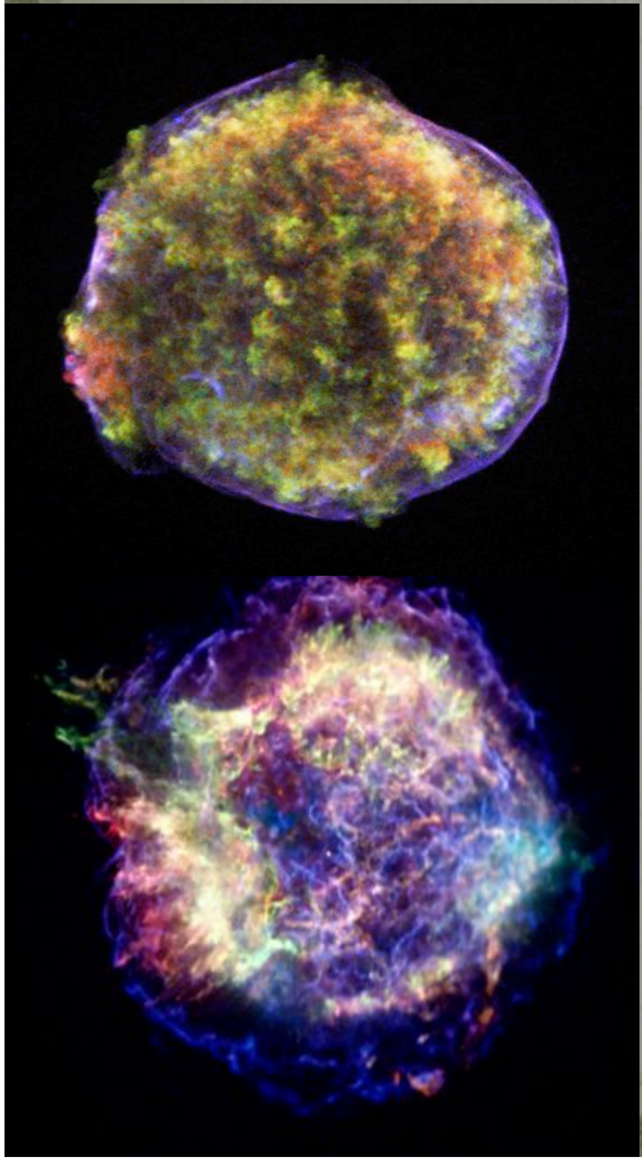
GROWTH RATE

WHY IS IT INTERESTING:
I. Reaching the knee?



PB, Amato & Caprioli, 2007

WHY IS IT INTERESTING:
II. Large B observed?



TYPICAL THICKNESS OF FILAMENTS:
10^{-2} -10^{-3} pc

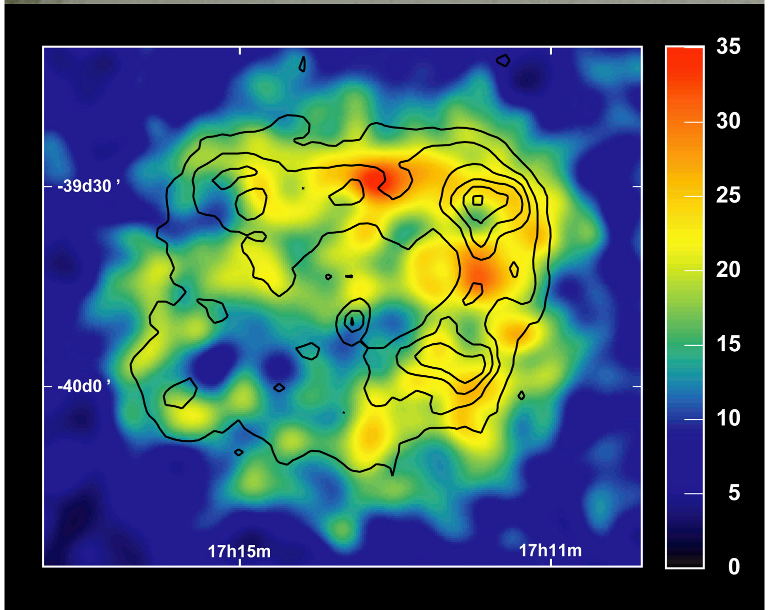
The synchrotron limited thickness is:

$$\Delta x = \sqrt{4D(E)\tau_{syn}(E)} \approx 4\,pc\ \mathrm{B}_{\mu}^{-3/2}$$

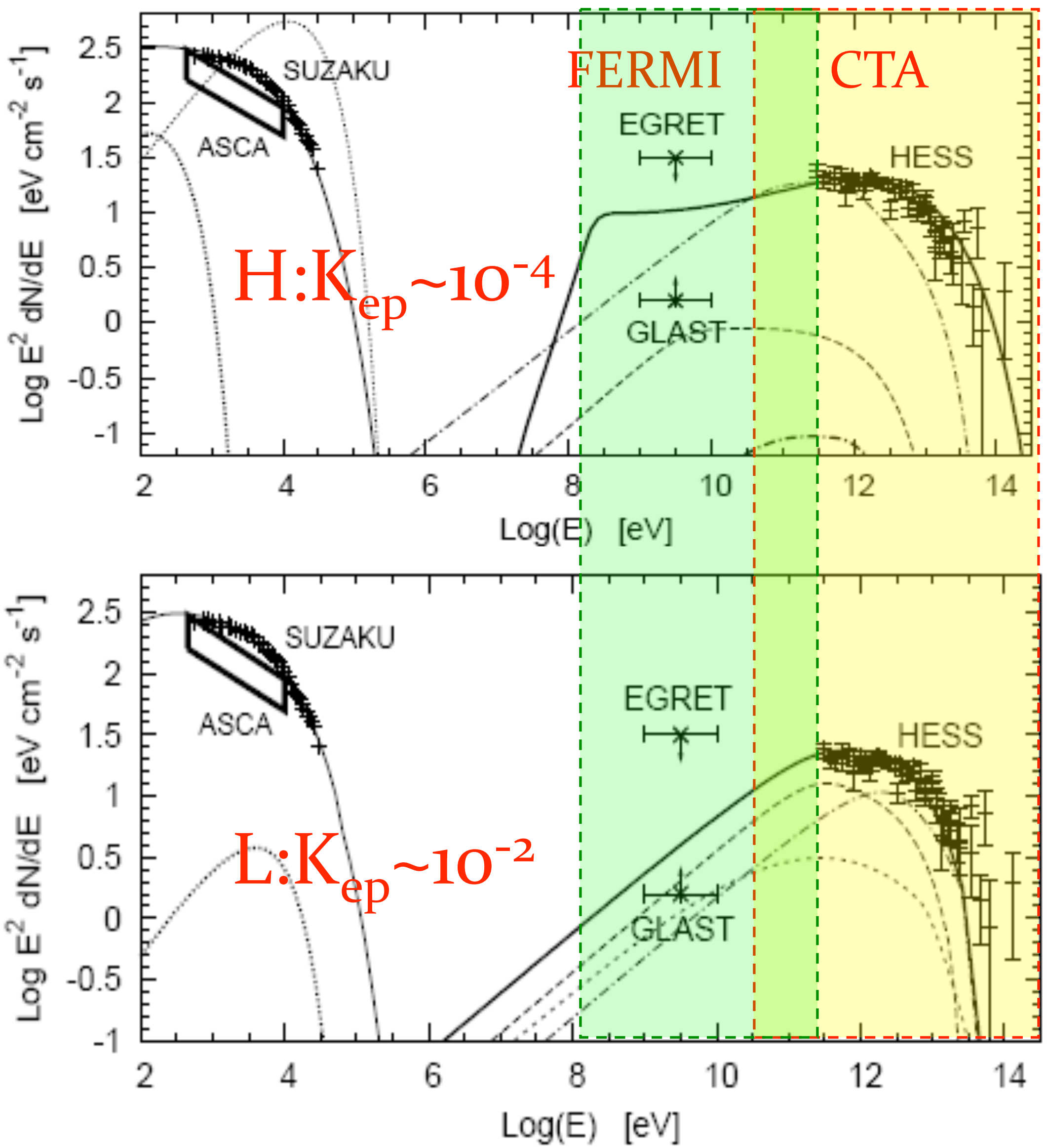
$$B \approx 100\ \mu\mathrm{Gauss}$$

COMPATIBLE WITH ESTIMATE FROM VARIABILITY
(Uchiyama et al. 2007)

PHENOMENOLOGY OF INDIVIDUAL SNR



Aharonian et al. 2007



Morlino, Amato & PB 2009

CRs versus ACCELERATED PARTICLES

WHAT IS THE SPECTRUM OF CR AT EARTH?

ESCAPE TOWARDS UPSTREAM

ESCAPE FROM DOWNSTREAM AFTER ADIABATIC LOSSES

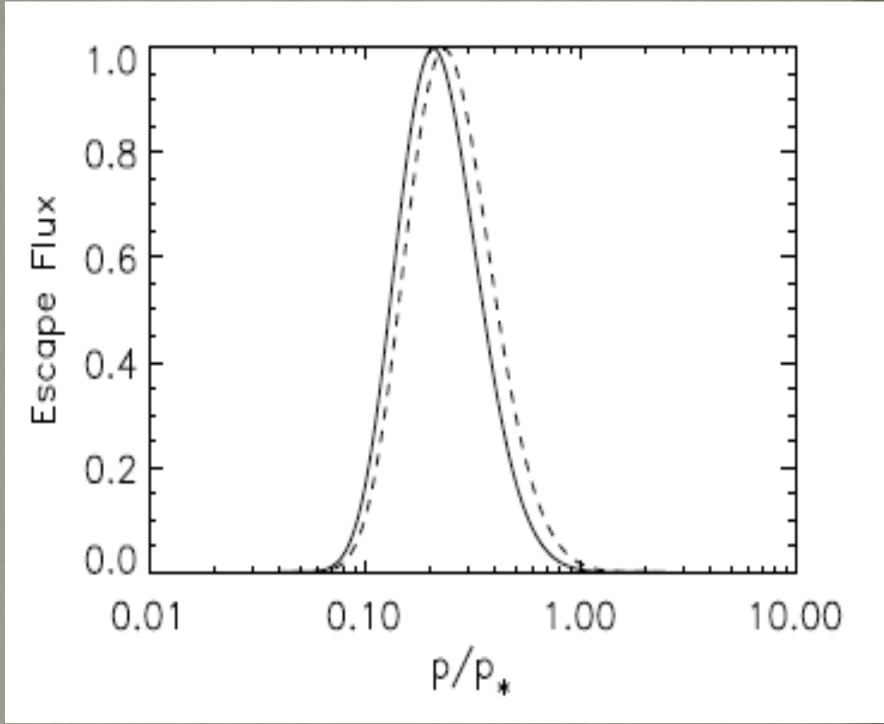
Caprioli, PB & Amato 2009

ESCAPE FLUX WITH TIME

$$E_{MAX}(t) \propto \xi_c(t)\, t^{-1/2}$$

$$R_{sh}(t) = 2.7 \times 10^{19}\,\mathrm{cm} \left(\frac{E_{51}}{n_1}\right)^{1/5} t_{kyr}^{2/5}$$

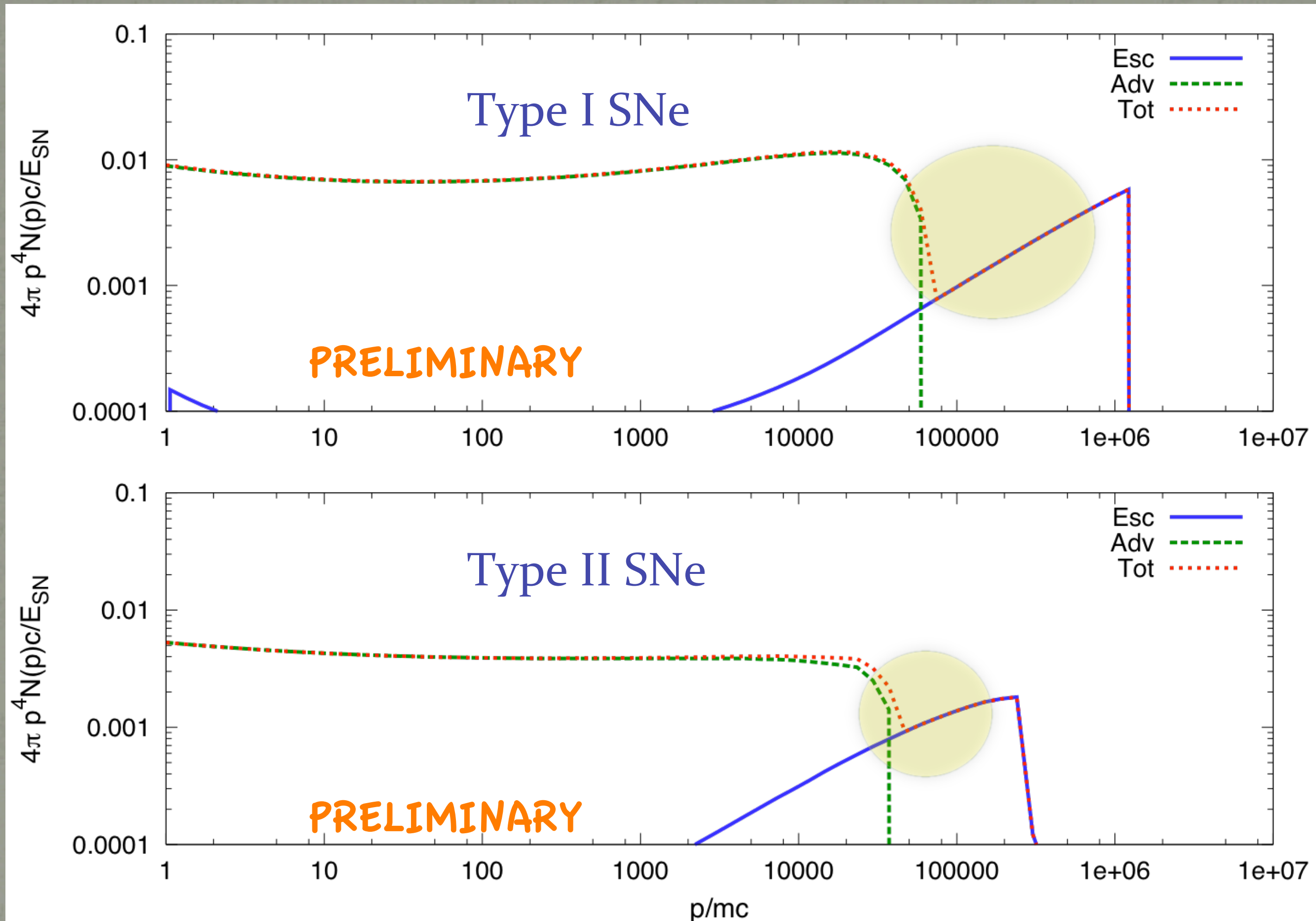
$$V_{sh}(t) = 4.7 \times 10^{8}\,\mathrm{cm/s} \left(\frac{E_{51}}{n_1}\right)^{1/5} t_{kyr}^{-3/5}$$



$$\mathrm{EQ(E)dE} \approx \mathrm{F_{esc}(t)}\ \ \frac{1}{2}\rho \mathrm{V_s^3}\ \ 4\pi \mathrm{R_{sh}^2}\ \ \frac{\mathrm{dE_{max}}}{\mathrm{dt}}\mathrm{dE} \propto\ \ \mathrm{t^{1/2}\,dE} \propto\ \ \mathrm{E^{-1}\,dE}$$

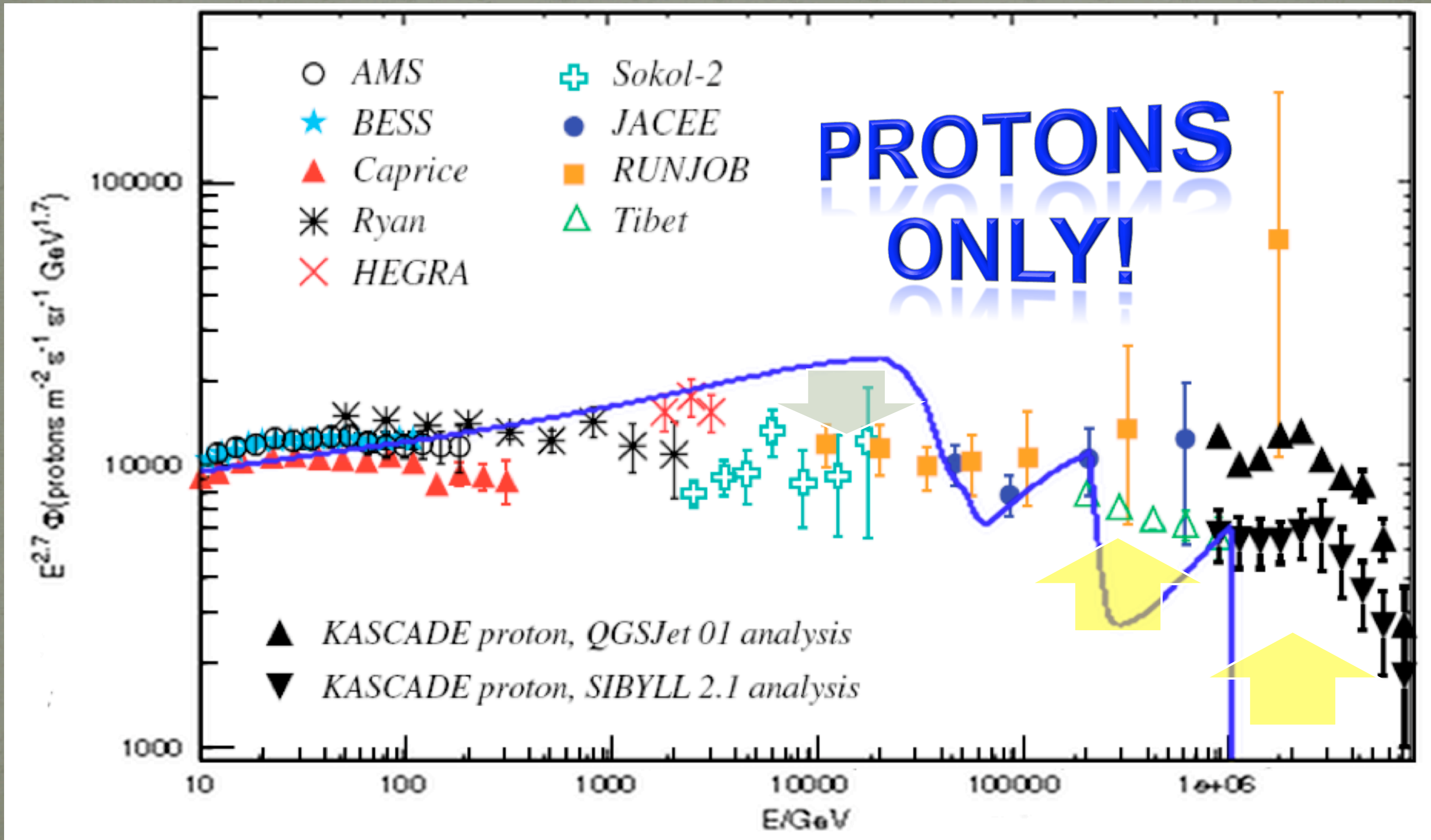
E^{-2} WITH NO CONNECTION WITH THE INTRINSIC SPECTRUM!!!

PROTON SPECTRUM AT EARTH



Caprioli, PB & Amato 2009

PROTONS AT EARTH



ELECTRONS

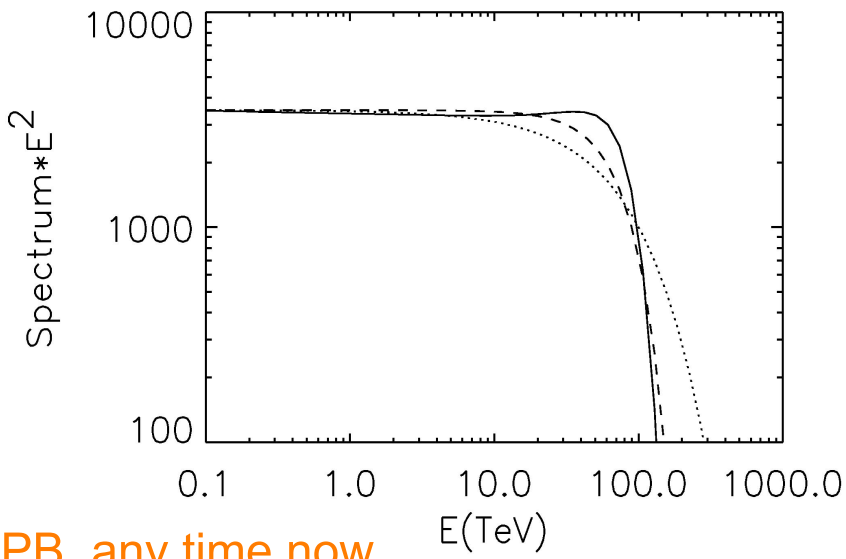
1. COMPLICATED BY ENERGY LOSSES (ESPECIALLY CLOSE TO E_{max})

2. PILE UPS MAY BE PRODUCED BY LOSSES

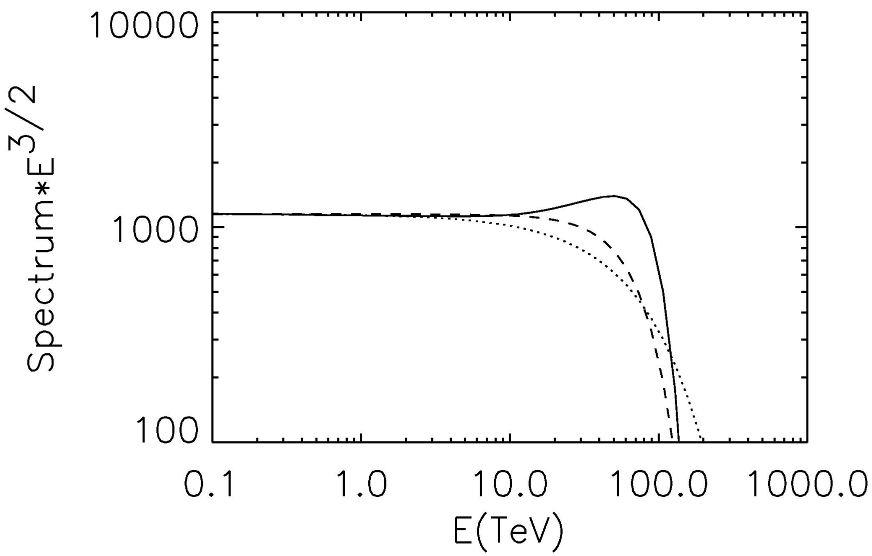
3. INJECTION NOT UNDERSTOOD AT ALL (THIS IS THE NATURE OF THE K_{ep} USUALLY USED)

4. PROPAGATION (LEAKY BOX VS DISC)

SPECTRA AT INJECTION



PB, any time now



THE SHAPE OF THE CUTOFF DEPENDS ON THE DIFFUSION COEFFICIENT

FOR BOHM DIFFUSION THE CUTOFF IS $EXP[-(E/E_{MAX})^2]$

ELECTRONS AFTER PROPAGATION

LET US ASSUME THAT LOSSES DOMINATE

$$n(E) = Q(E)\tau_{loss}(E) \sim E^{-\gamma-1}$$

$$n(E) = \frac{Q(E)\tau_{loss}(E)}{\sqrt{4D(E)\tau_{loss}(E)}} \sim E^{-\gamma-1-\frac{1}{2}(\delta-1)}$$

PRIMARY PROTONS:

$$n_{CR}(E) = N_{CR}(E)\ R\ \tau_{esc}(E) \propto E^{-\gamma} E^{-\delta}$$

PRIMARY ELECTRONS:

$$n_e(E) = N_e(E)\ R\ \mathrm{Min}\left[\tau_{esc}(E), \tau_{loss}(E)\right] \propto E^{-\gamma_e} E^{-\beta}$$

b= d for diffusion

b=1 for losses

SECONDARY POSITRONS INJECTION:

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

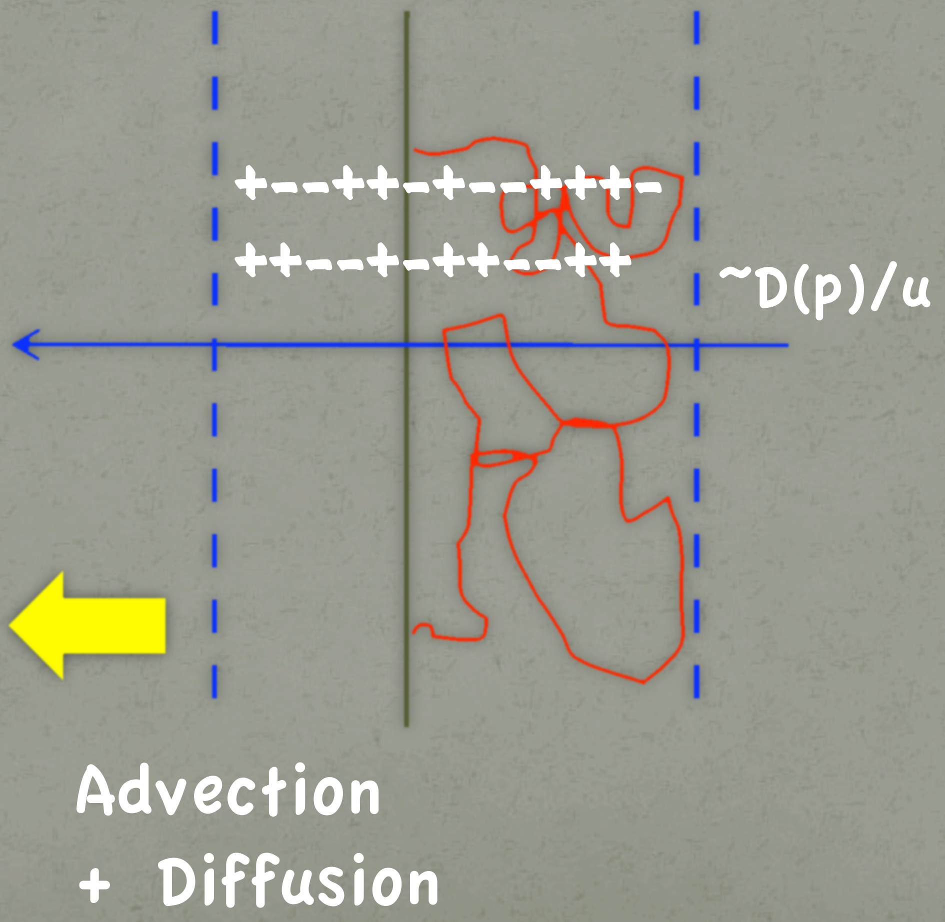
SECONDARY POSITRONS EQUILIBRIUM:

$$n_+(E) = q_+(E)\ \mathrm{Min}\left[\tau_{esc}(E), \tau_{loss}(E)\right] \propto E^{-\gamma-\delta-\beta}$$

$$\frac{n_+}{n_e} \propto E^{-(\gamma-\gamma_e)-\delta}$$

CHARGED SECONDARY PARTICLES IN THE SOURCES

PB 2009



CHARGED SECONDARY PARTICLES

THE EQUATION DESCRIBING ANY CHARGED PARTICLE IN THE SHOCK REGION IS:

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

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^{-g+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

SOLUTION AT x

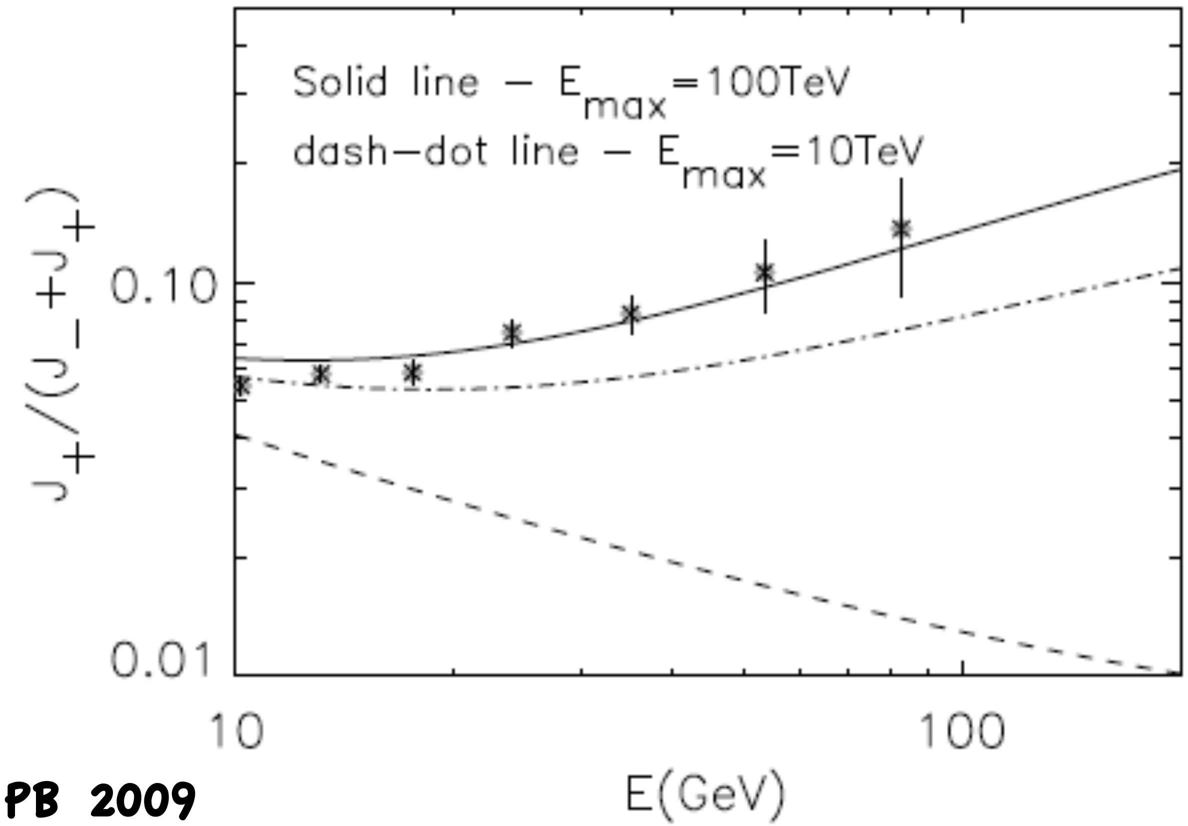
AT A GENERIC LOCATION X DOWNSTREAM OF THE SHOCK, THE SOLUTION CAN ONLY BE:

$$f_\pm(x,p) = f_{\pm,0}(p) + \frac{Q_2}{u_2}\, x \qquad 0 \le x \le u_2 \tau_{SN}$$

ACCELERATION TERM

STANDARD TERM, THE SAME AS FOR GAMMAS

THE POSITRON "EXCESS"



PB 2009

THE PARAMETERS

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

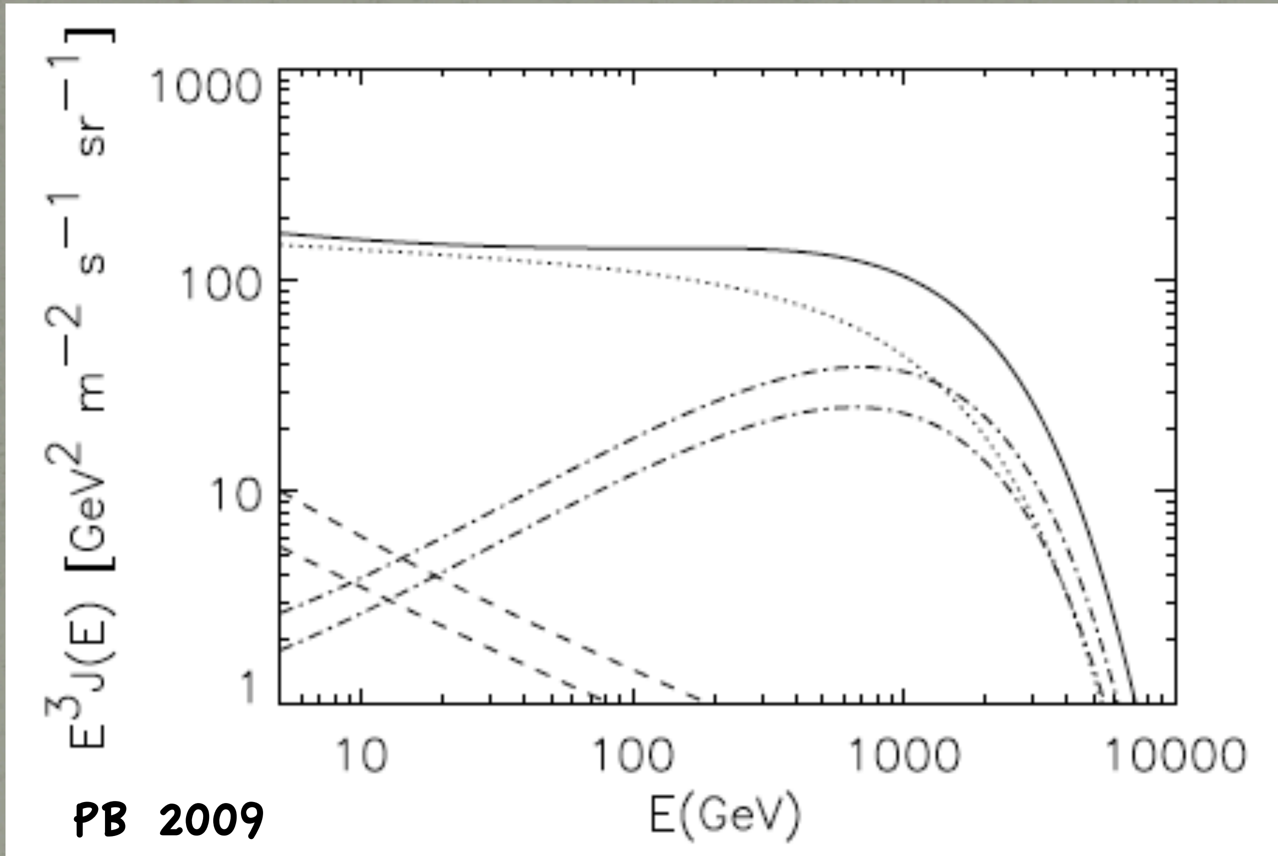
TYPICAL VALUES REQUIRED ARE

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

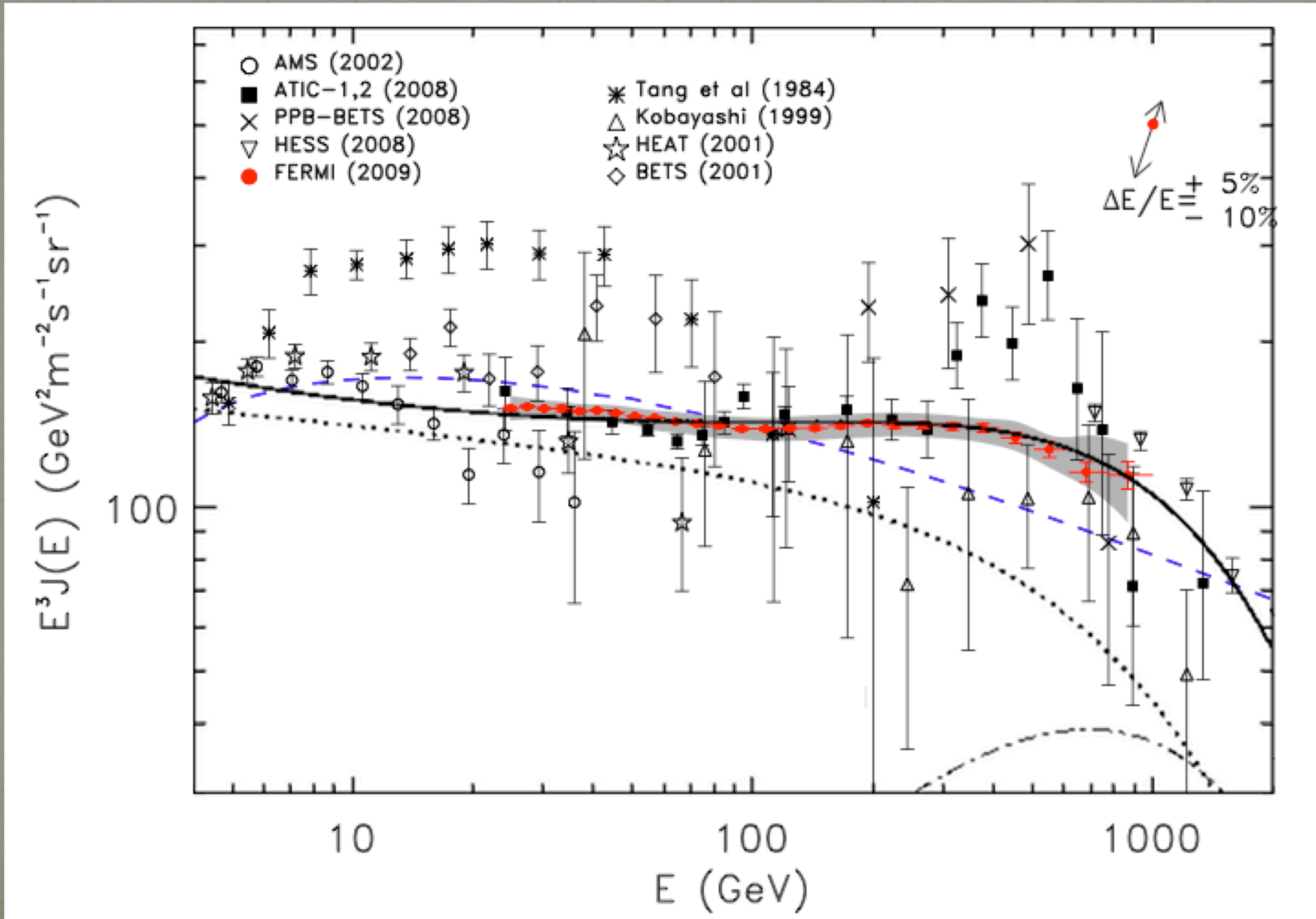
THESE MAY BE SUITABLE FOR AN OLD SN-I OR A SN-II OUTSIDE THE BUBBLE CREATED BY THE WIND OF THE PRE-SN STAR

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

THE ELECTRON SPECTRUM



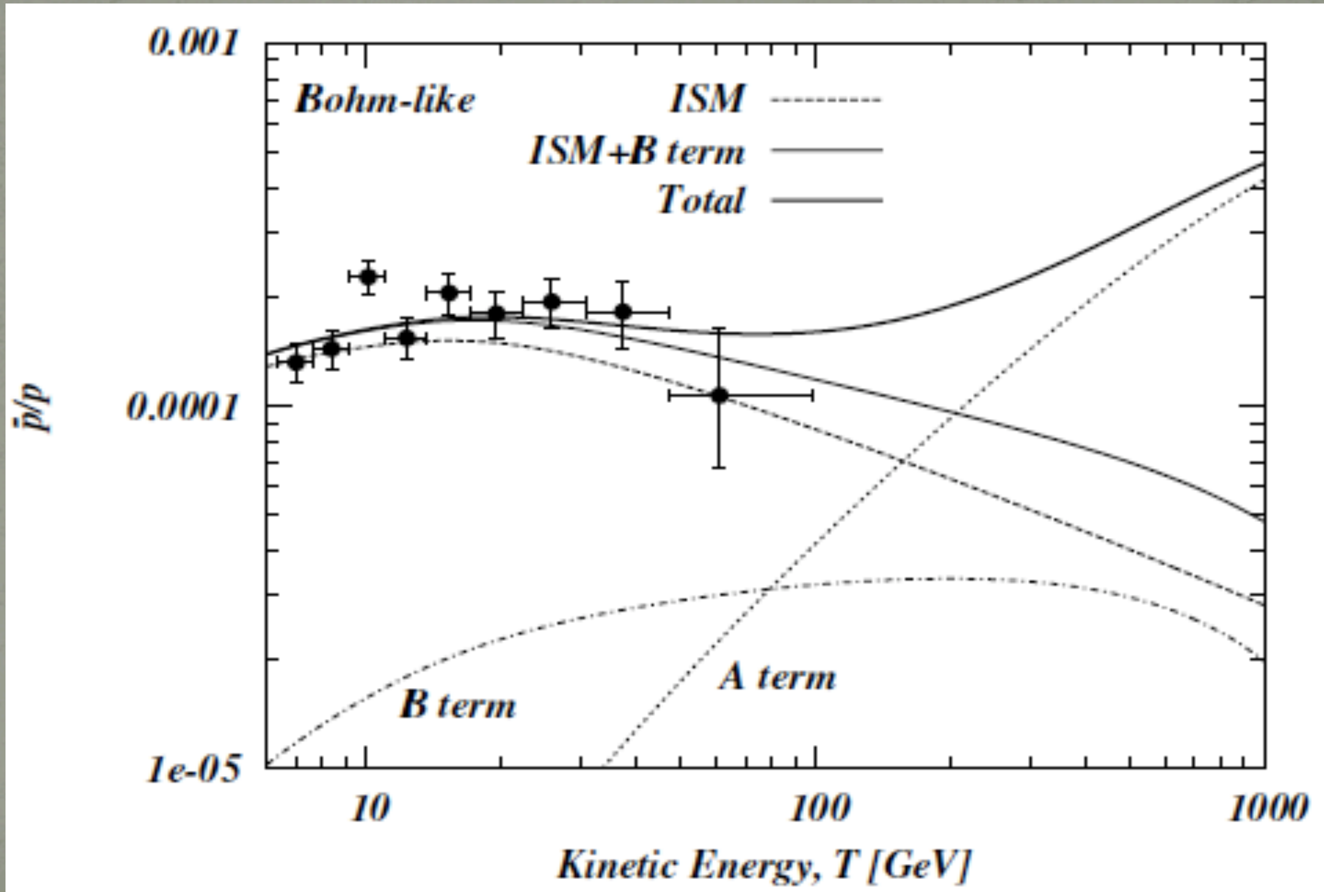
THE ELECTRON SPECTRUM



ANTIPROTONS

PB & Serpico (2009)

SIMPLER CALCULATIONS BECAUSE NO ENERGY LOSSES:



CONCLUSIONS

1. IN ORDER TO REPRODUCE THE CR SPECTRUM, NUCLEI ARE CRUCIAL
2. ACCELERATION UP TO THE KNEE IS UNDERSTOOD IF B IS AMPLIFIED
3. FOR ELECTRONS THERE ARE MORE UNCERTAINTIES BOTH ON ACCELERATION AND PROPAGATION
4. POSITRONS ARE MAINLY DIFFUSE SECONDARIES IN THE ISM AT ENERGIES BELOW 10 GeV
5. BUT AT HIGHER ENERGIES THE CONTRIBUTION OF SOURCES MAY DOMINATE
6. THE SPECTRUM OF $e^{-}+e^{+}$ AT HIGH ENERGY CAN BE DOMINATED BY SECONDARY $e^{-}+e^{+}$ FROM SOURCES