PARTICLE ACCELERATION IN SNR AND THE POSITRON EXCESS

Pasquale Blasi
INAF/Arcetri Astrophysical Observatory

OUTLINE

1. Basic aspects of particle acceleration in SNRs
2. Production of secondary particles
3. Particles that stay and particles that become CRs
4. Charged secondary particles in the acceleration region
5. The positron “excess”
6. The contribution to anti-protons

SN Type I and type II

SN Ia	SN II
Accretion induced collapse of a white Dwarf	Collapse of a massive star
It explodes in the typical ISM	Explodes in the bubble created by the wind of the pre-SN
No left-over	It leaves a pulsar

Calculations show that they contribute roughly the same to the CR flux at the Earth

BASIC ASPECTS OF PARTICLE ACCELERATION IN SNRs

1. THE MECHANISM OF ENERGY CONVERSION IS FIRST ORDER FERMI ACCELERATION AT THE SHOCK

2. ACCELERATED PARTICLES MODIFY THE SHOCK PROFILE SO TO MAKE IT EFFICIENT (NON LINEAR 1)

3. ACCELERATED PARTICLES CAN AMPLIFY LOCAL MAGNETIC FIELDS (NON LINEAR 2)

4. THE NON LINEAR EFFECTS GETS SMALLER IN LATER PHASES

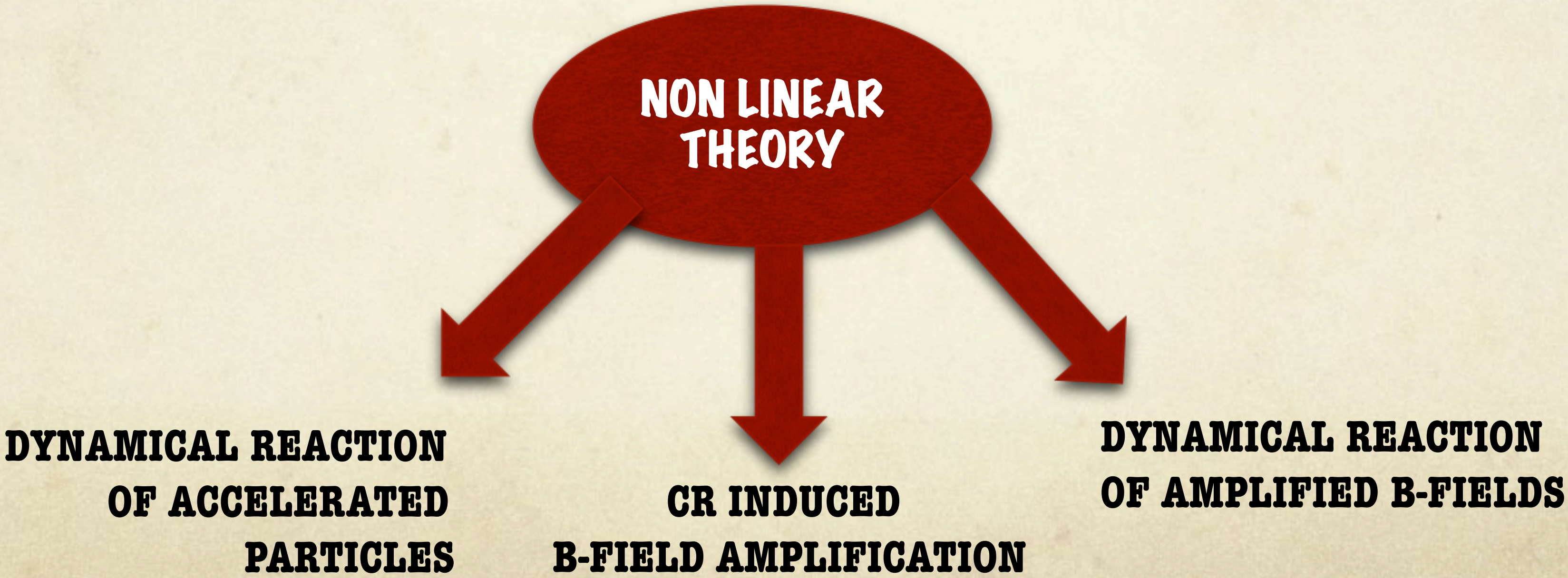
BEYOND TEST PARTICLES: Non linear DSA

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

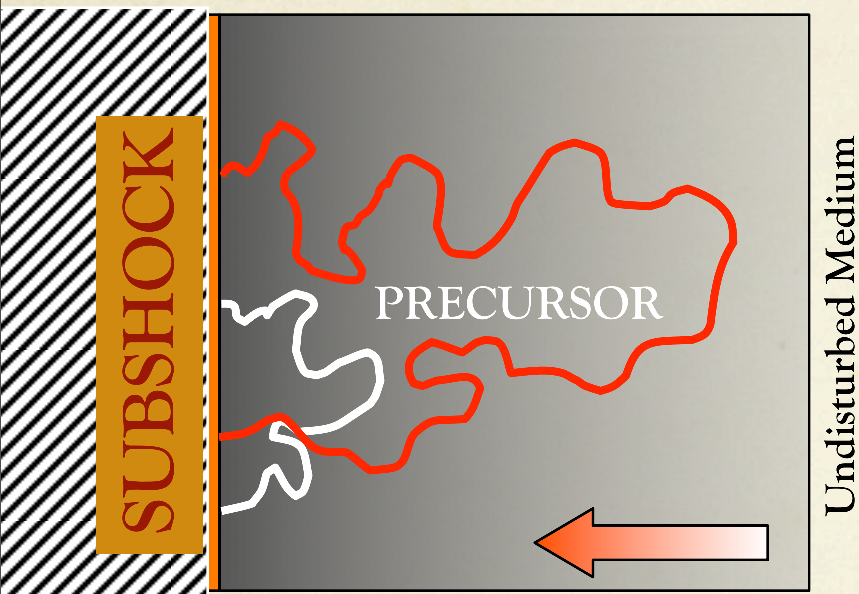
1. **TEST PARTICLE THEORY PROVIDES NO INFO ON ACCELERATION EFFICIENCY**

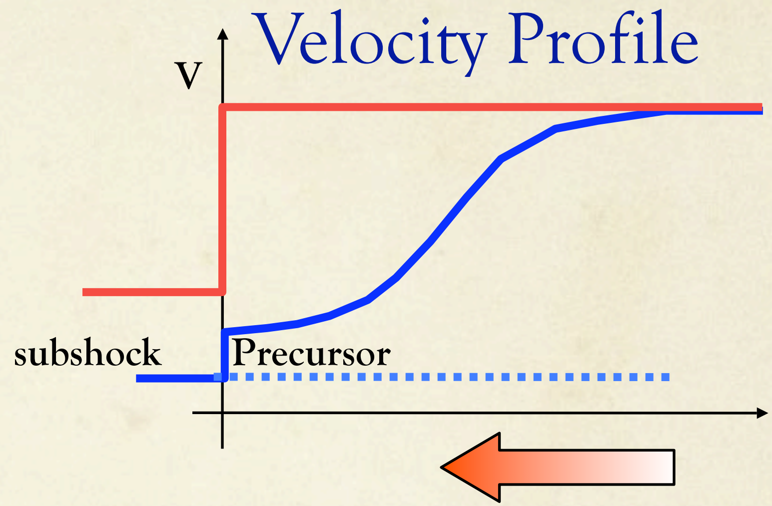
2. **THE REQUIRED EFFICIENCIES ARE SUCH THAT CR SHOULD EXERT A DYNAMICAL REACTION ON THE SYSTEM**

3. **IN TP THEORY THERE IS NO EASY WAY TO REACH THE KNEE**



DYNAMICAL REACTION





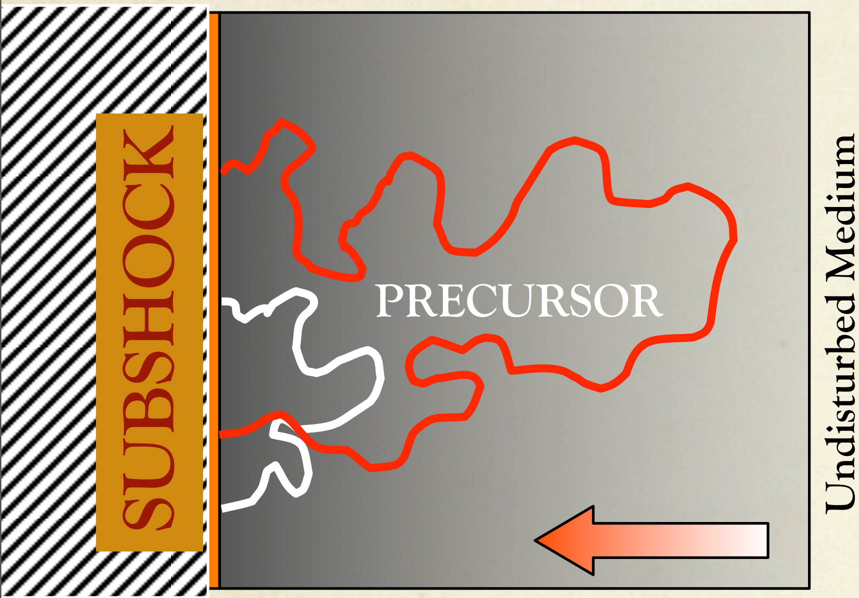
CR TRANSPORT EQUATION

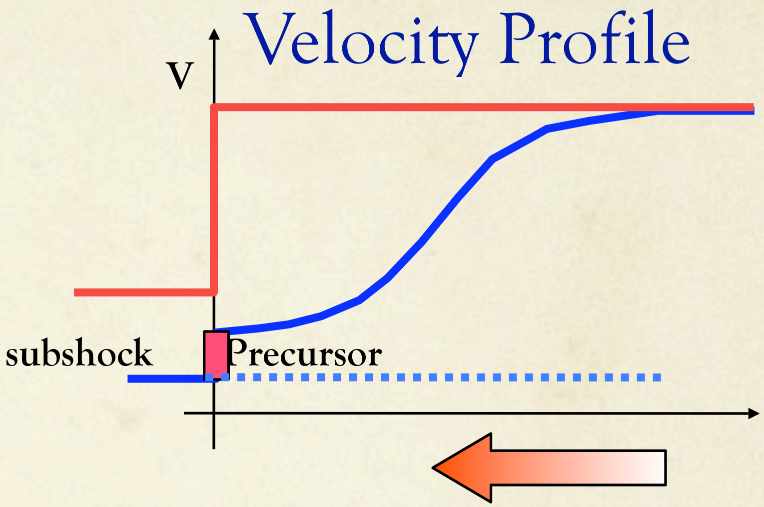
+

MASS, MOMENTUM, ENERGY CONSERVATION EQUATIONS

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

DYNAMICAL REACTION





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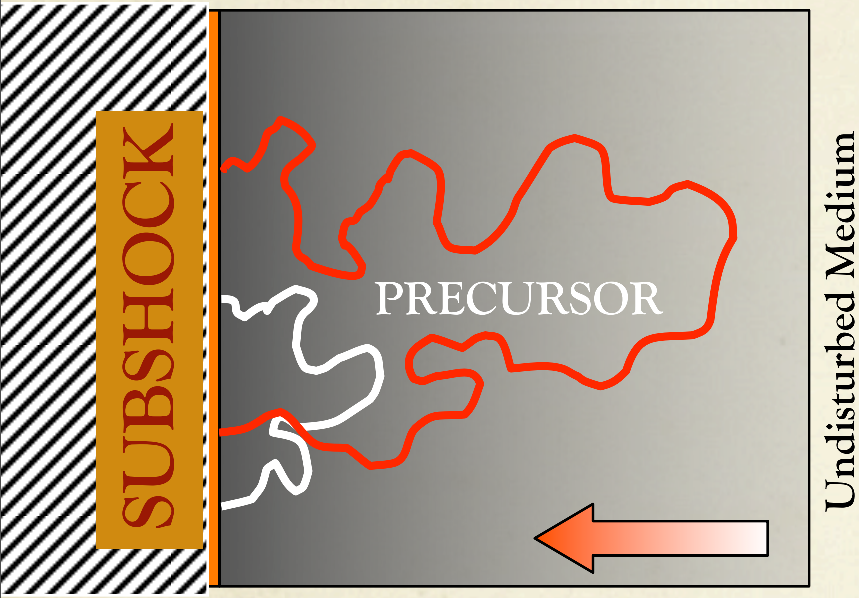

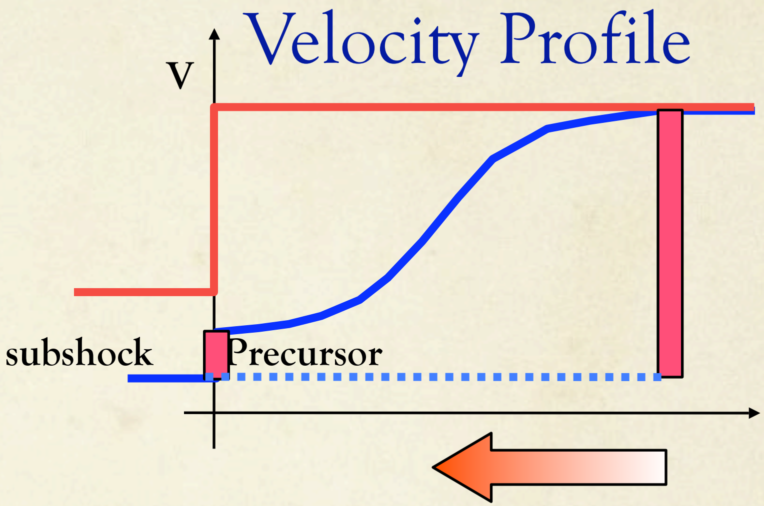

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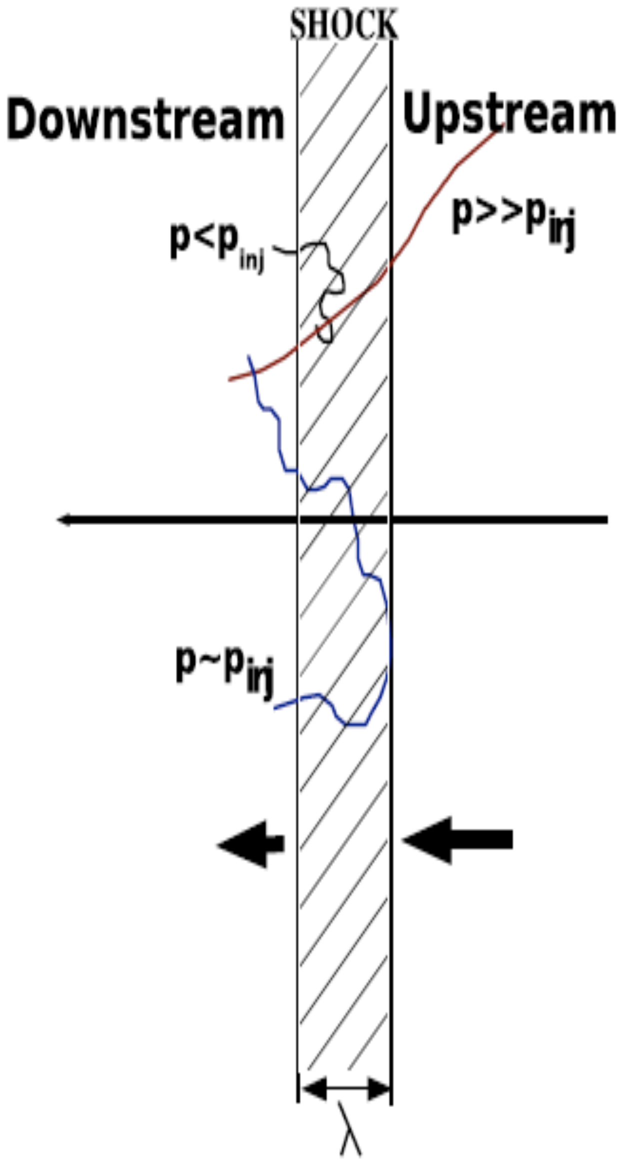
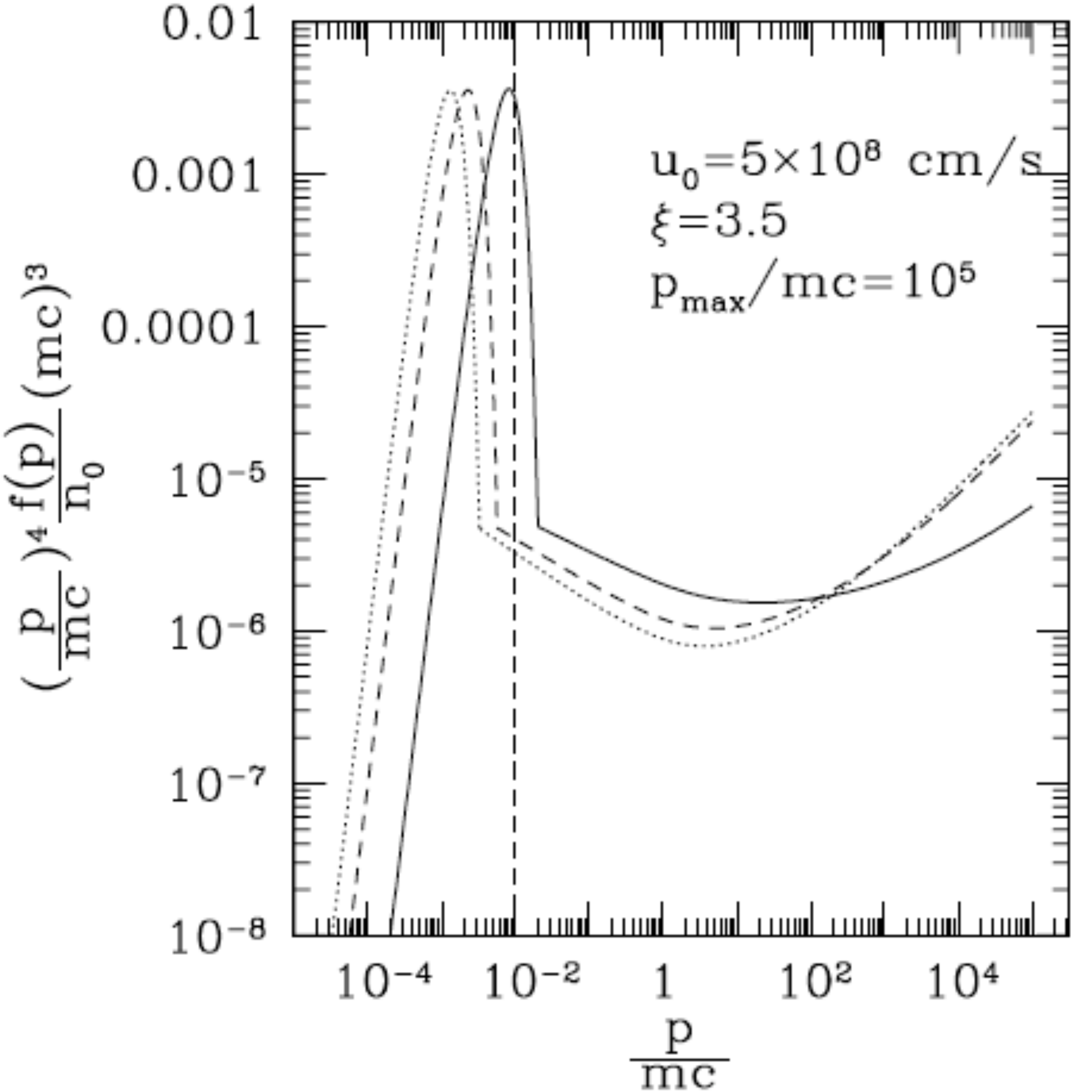
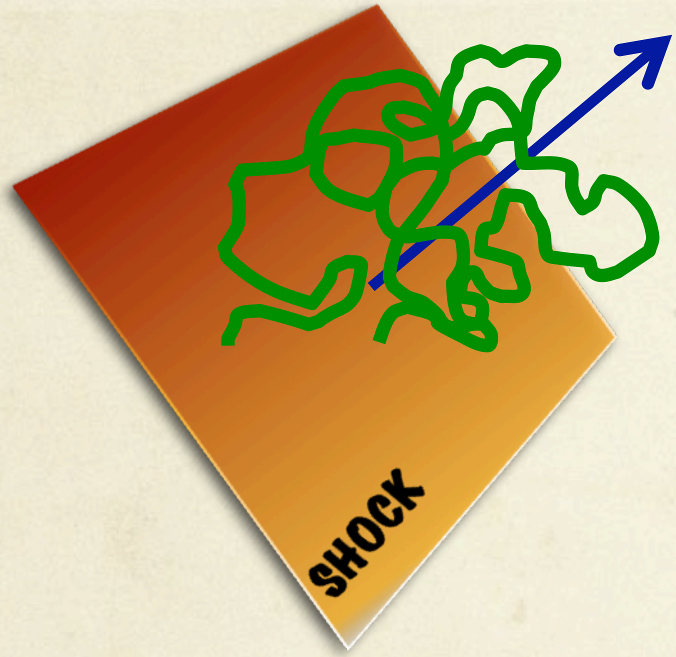




PB, Gabici & Vannoni 2005

MAGNETIC FIELD AMPLIFICATION



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

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

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

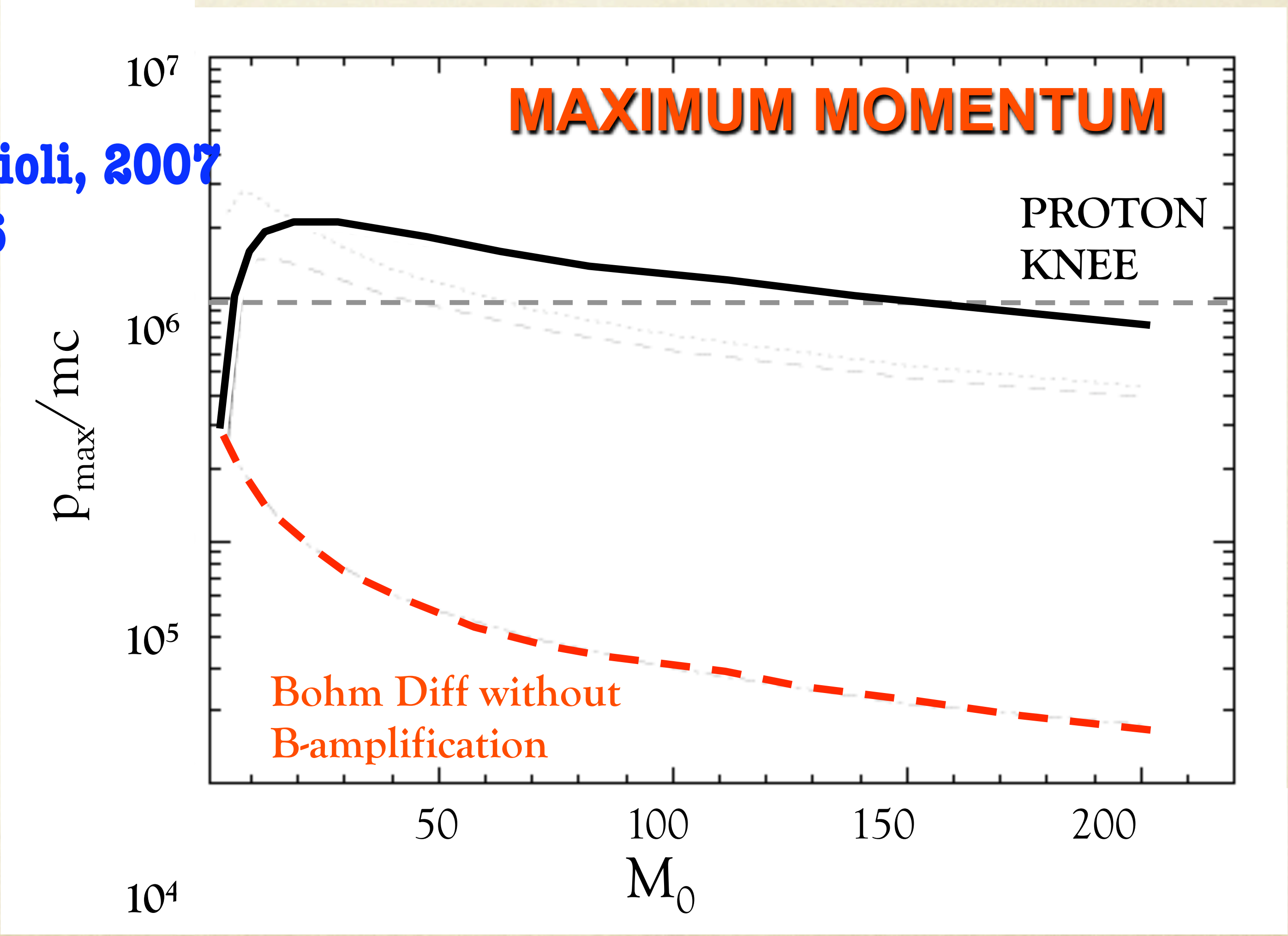
$$\frac{dP_W}{dt} = \Gamma_W \frac{\delta B^2}{4\pi v_A}$$

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

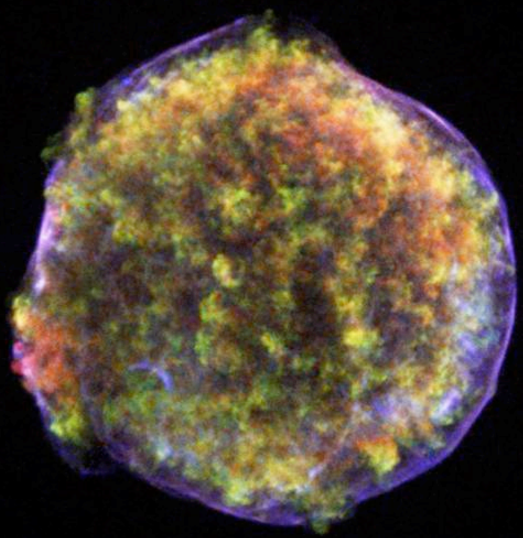
GROWTH RATE

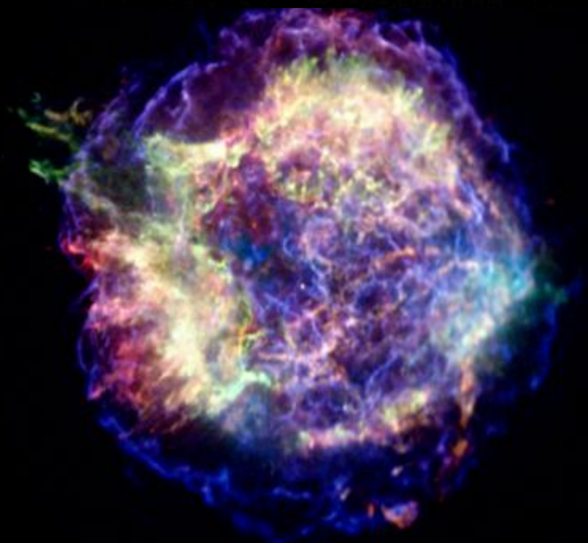
WHY IS IT INTERESTING:
I. Reaching the knee?

PB, Amato & Caprioli, 2007
Amato & PB, 2006



WHY IS IT INTERESTING: II. Large B observed?





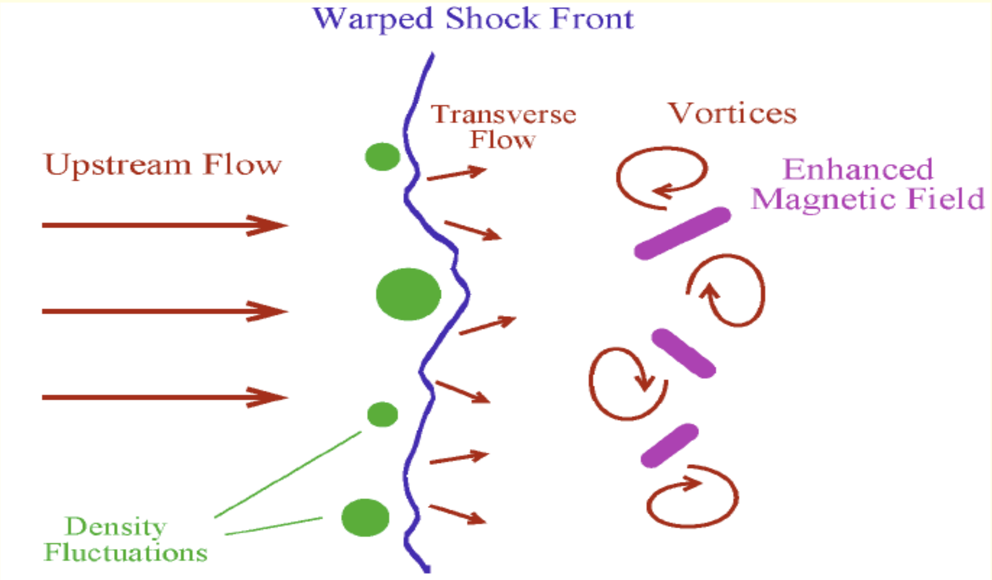
TYPICAL THICKNESS OF FILAMENTS:
10^{-2} -10^{-3} pc

The synchrotron limited thickness is:

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

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

CR INDUCED OR PLASMA INDUCED?



Giacalone & Jokipii 2007

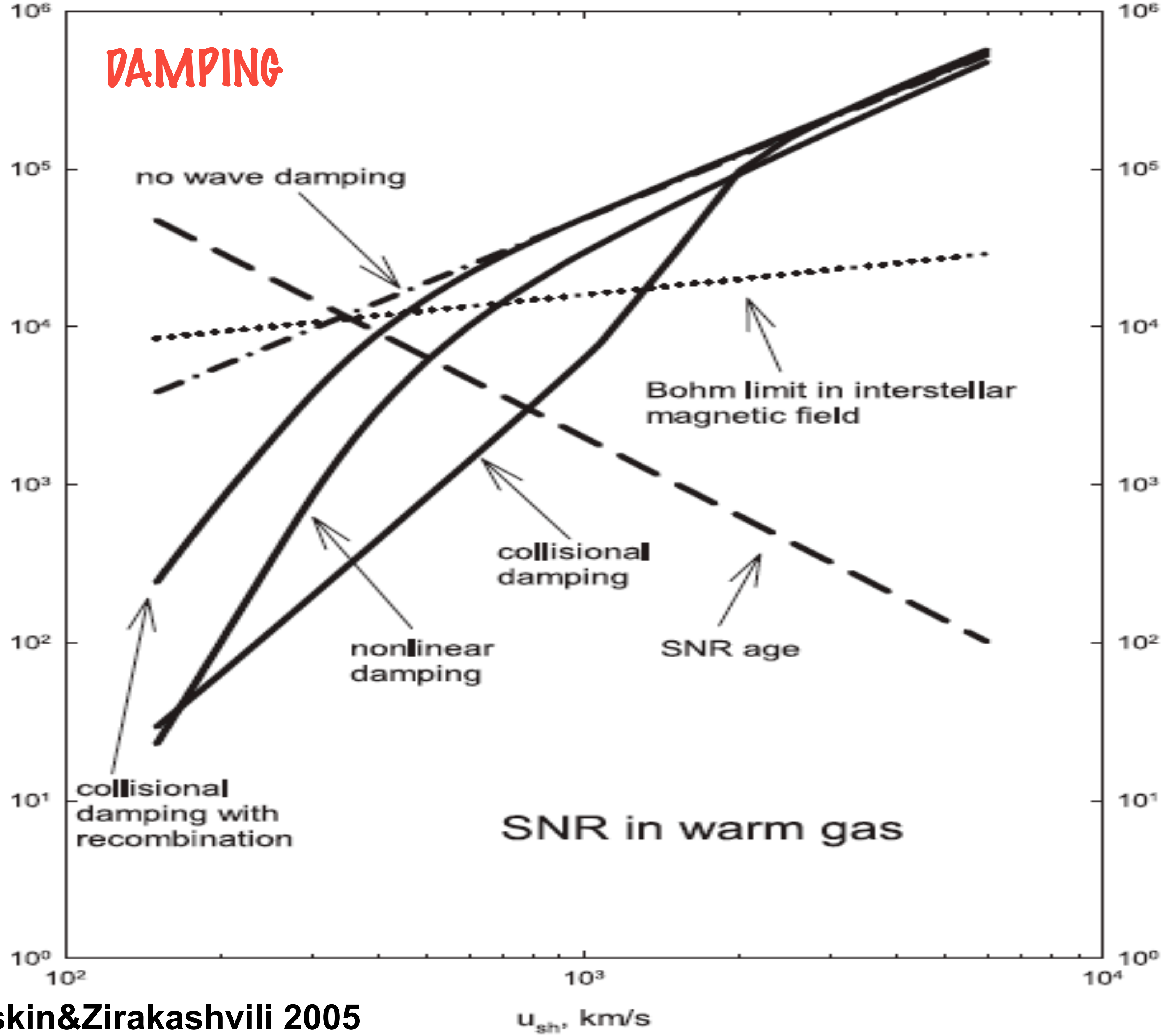
CORRUGATIONS ON THE SHOCK SURFACE, DUE TO DENSITY FLUCTUATIONS MAY INDUCE FLUID INSTABILITIES IN THE DOWNSTREAM PLASMA

CR INDUCED	PLASMA INDUCED
UPSTREAM EFFECTIVE ACCELERATION B ADVECTED	DOWNSTREAM EFFECTIVE ACC. ONLY IF QUASI PERPENDICULAR SHOCK B AMPLIFIED @ L/U

DYNAMICAL ROLE OF B

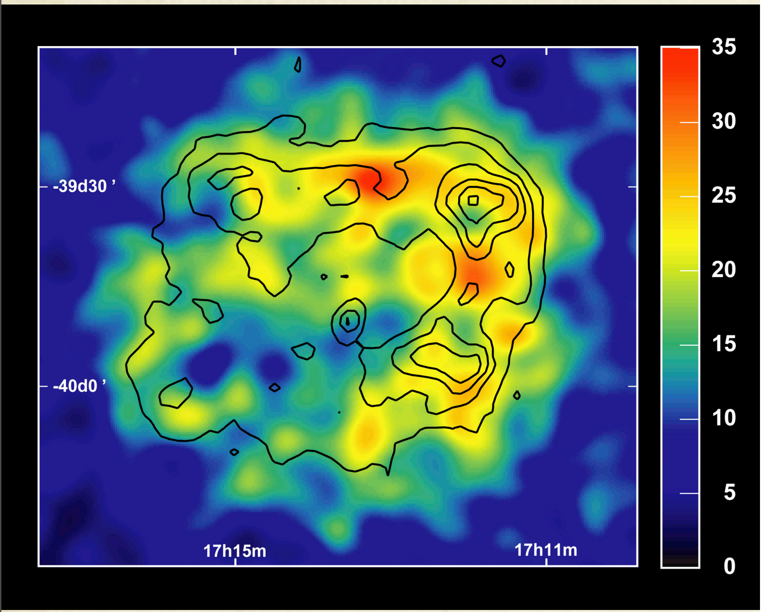
1. LARGE B INCREASE THE MAX MOMENTUM
2. HIGH MAX MOMENTUM MODIFY THE SHOCK
3. SHOCK MODIFICATION → CONCAVE SPECTRA
4. LARGE B → REDUCE MODIFICATION → LESS CONCAVE SPECTRA (Rtot~10)

DAMPING

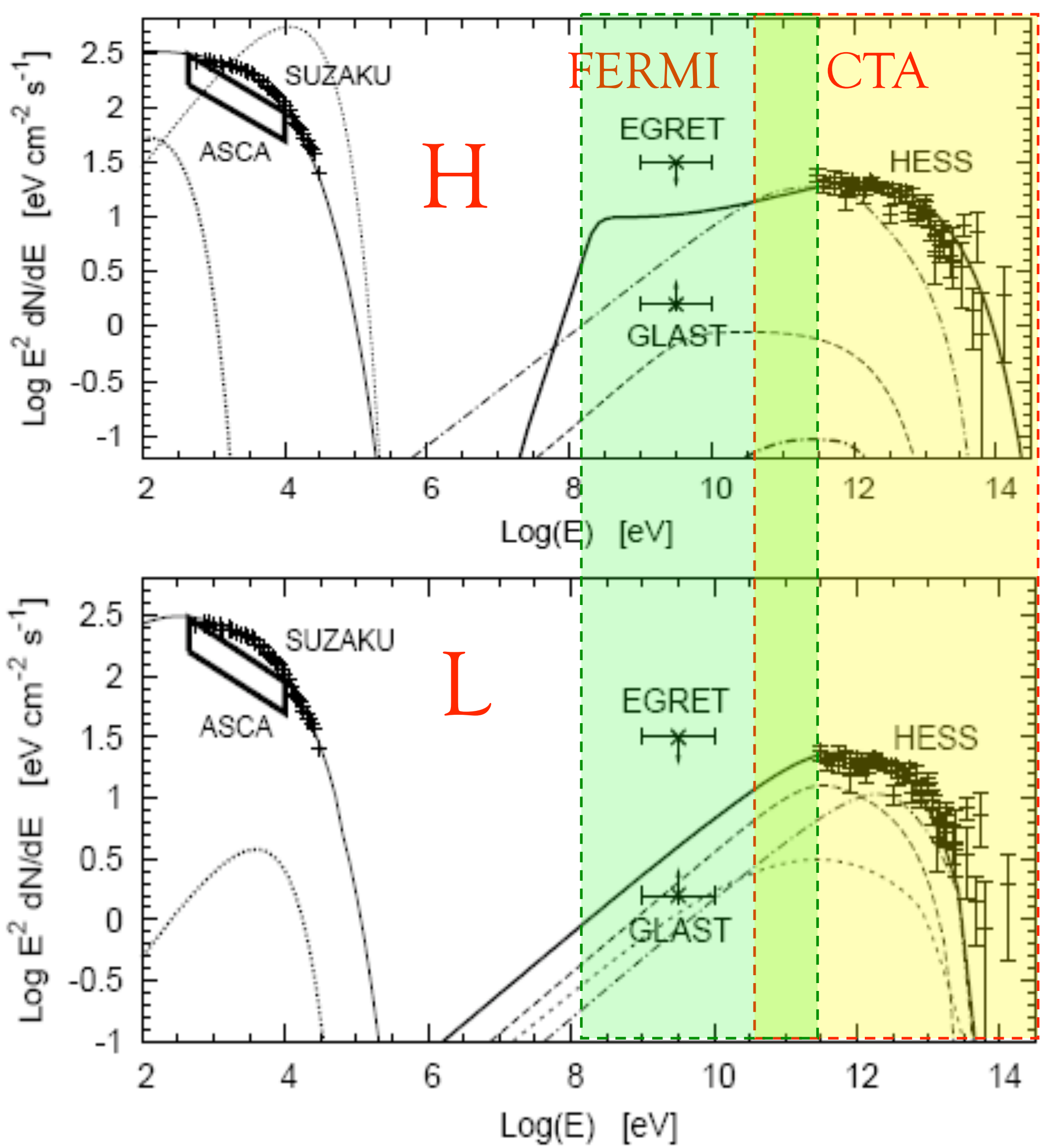


Ptuskin&Zirakashvili 2005

PHENOMENOLOGY OF INDIVIDUAL SNR



Aharonian et al. 2007



Morlino, Amato & PB 2009

CRs versus ACCELERATED PARTICLES

WHAT IS THE SPECTRUM OF CR AT EARTH?

PARTICLES ACCELERATED AT SHOCKS ARE ADVECTED TOWARDS DOWNSTREAM AND ESCAPE MUCH LATER ... THEY CANNOT CONTRIBUTE TO THE KNEE

SOME PARTICLES WITH $E \sim E_{MAX}$ CAN ESCAPE TOWARDS UPSTREAM, NAMELY TOWARDS US...

THIS PHENOMENON OF ESCAPE TOWARDS UPSTREAM BECOMES RELEVANT ONLY FOR CR MODIFIED SHOCKS

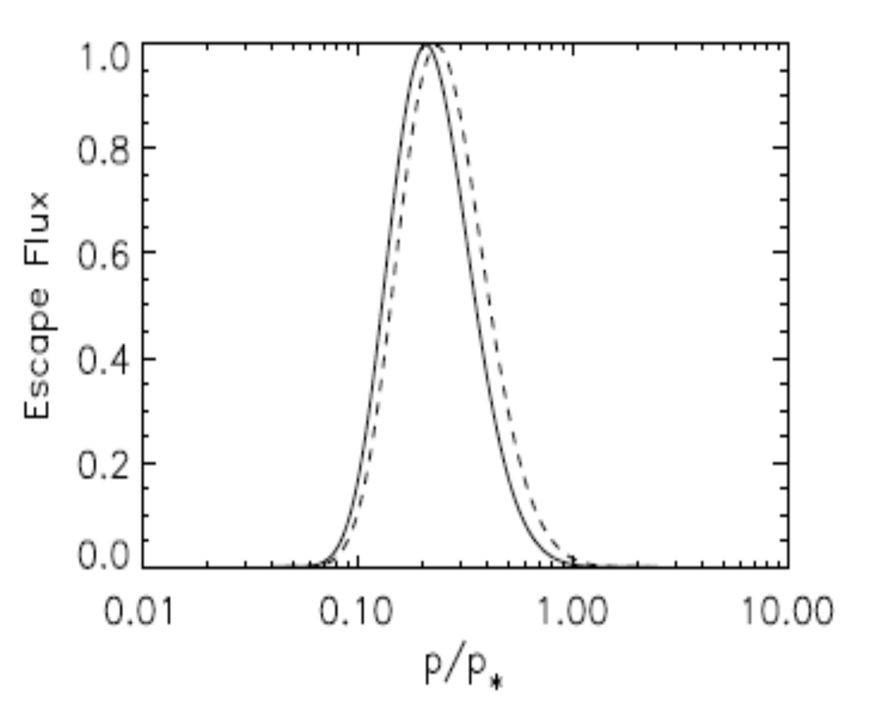
Caprioli, PB & Amato 2009

ESCAPE FLUX WITH TIME

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

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

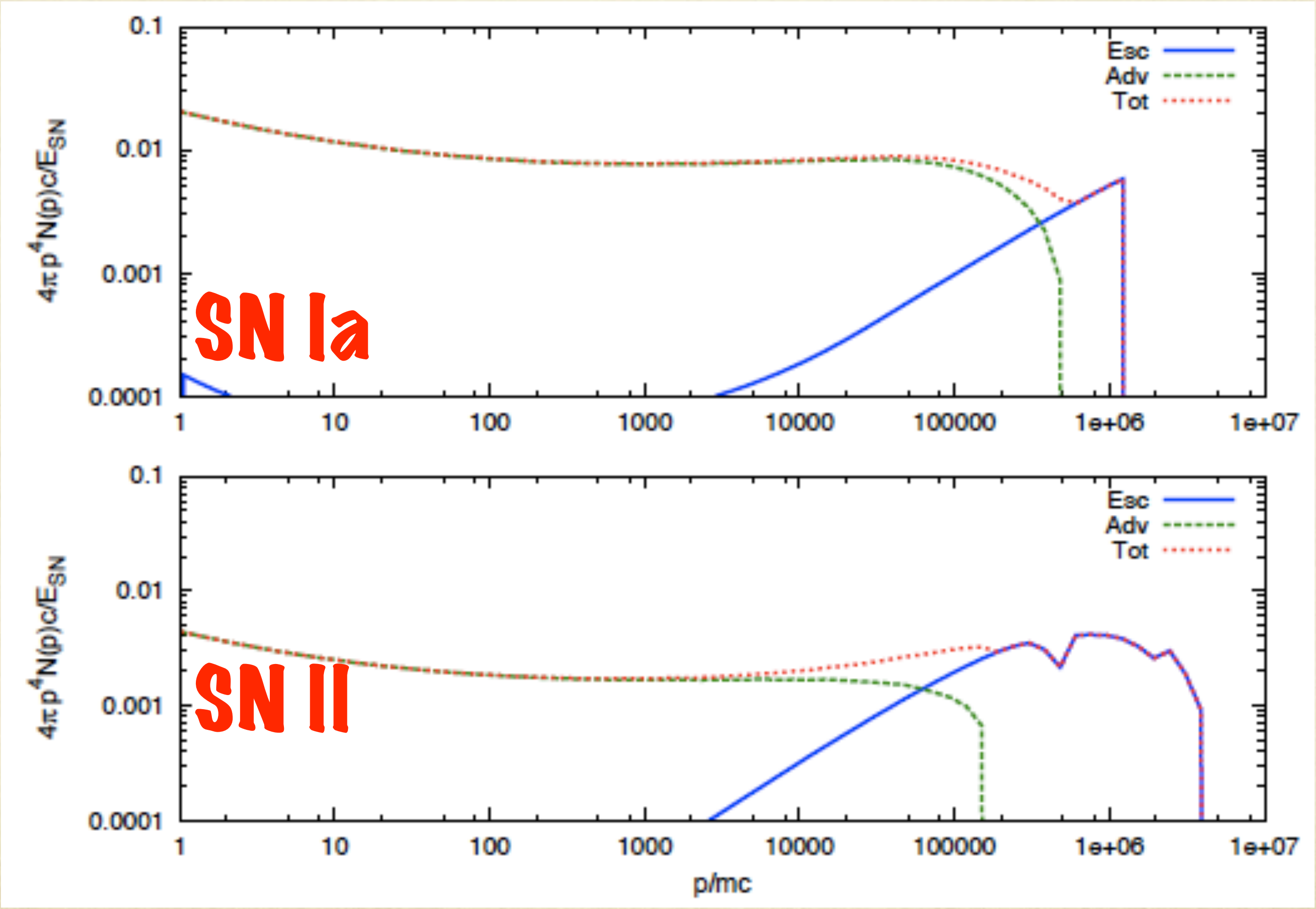
$$V_{sh}(t) = 4.7 \times 10^{8}\mathrm{cm/s}\left(\frac{E_{51}}{n_1}\right)^{1/5} t_{kyr}^{-3/5}$$



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

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

PROTON SPECTRUM AT EARTH



Caprioli, PB & Amato 2009

CONNECTION WITH THE

PRIMARY PROTONS:

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

PRIMARY ELECTRONS:

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

b= **d for diffusion**

b=**1 for losses**

SECONDARY POSITRONS INJECTION:

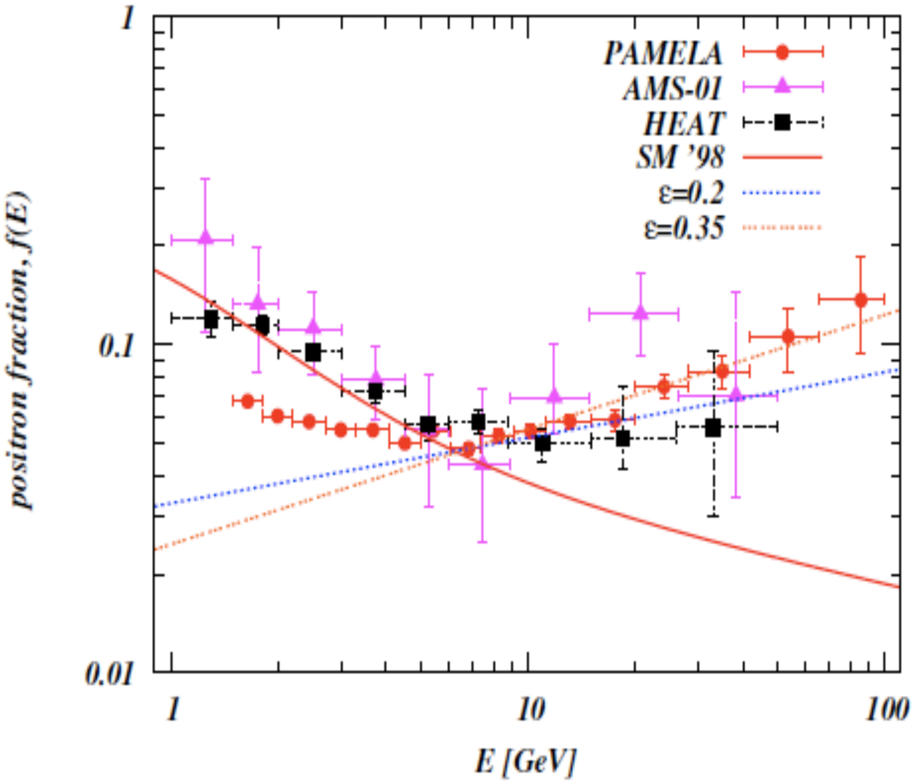
$$\mathrm{q}_+(\mathrm{E}')\mathrm{dE}' = \mathrm{n}_{\mathrm{CR}}(\mathrm{E})\mathrm{dE}\ \mathrm{n}_{\mathrm{H}}\ \sigma_{\mathrm{pp}}\ \mathrm{c} \propto \mathrm{E}^{-\gamma-\delta}$$

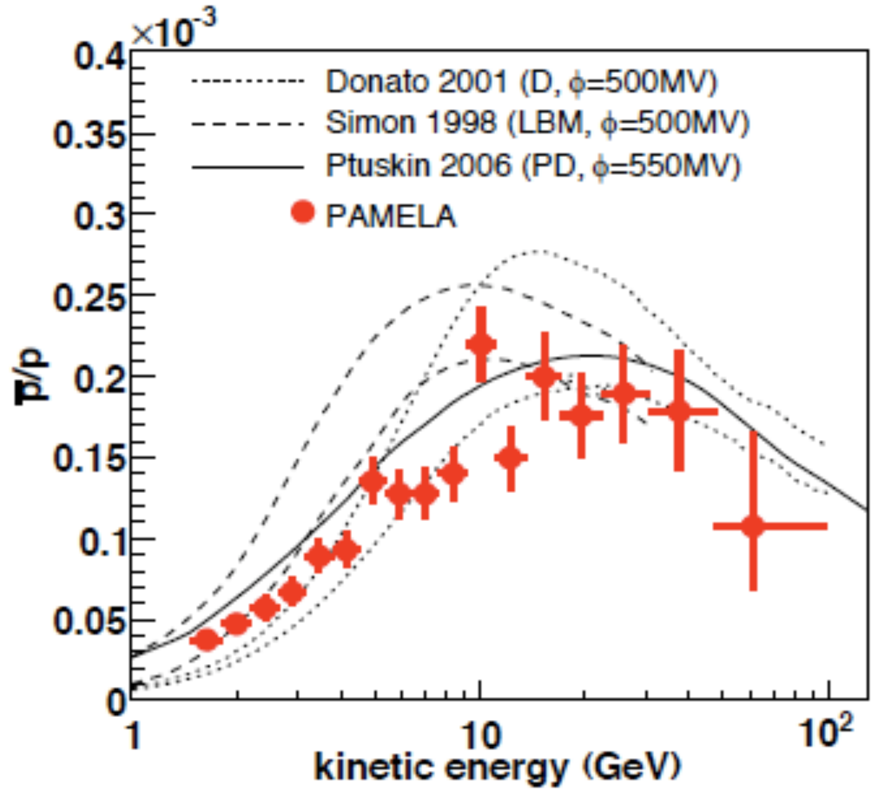
SECONDARY POSITRONS EQUILIBRIUM:

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

RATIO: $\dfrac{n_+}{n_e} \propto E^{-(\gamma-\gamma_e)-\delta}$ **MUST DECREASE**

PAMELA e^+ and Anti-p





From Serpico 2009

Adriani et al. 2008

WHAT ARE WE SEEING?

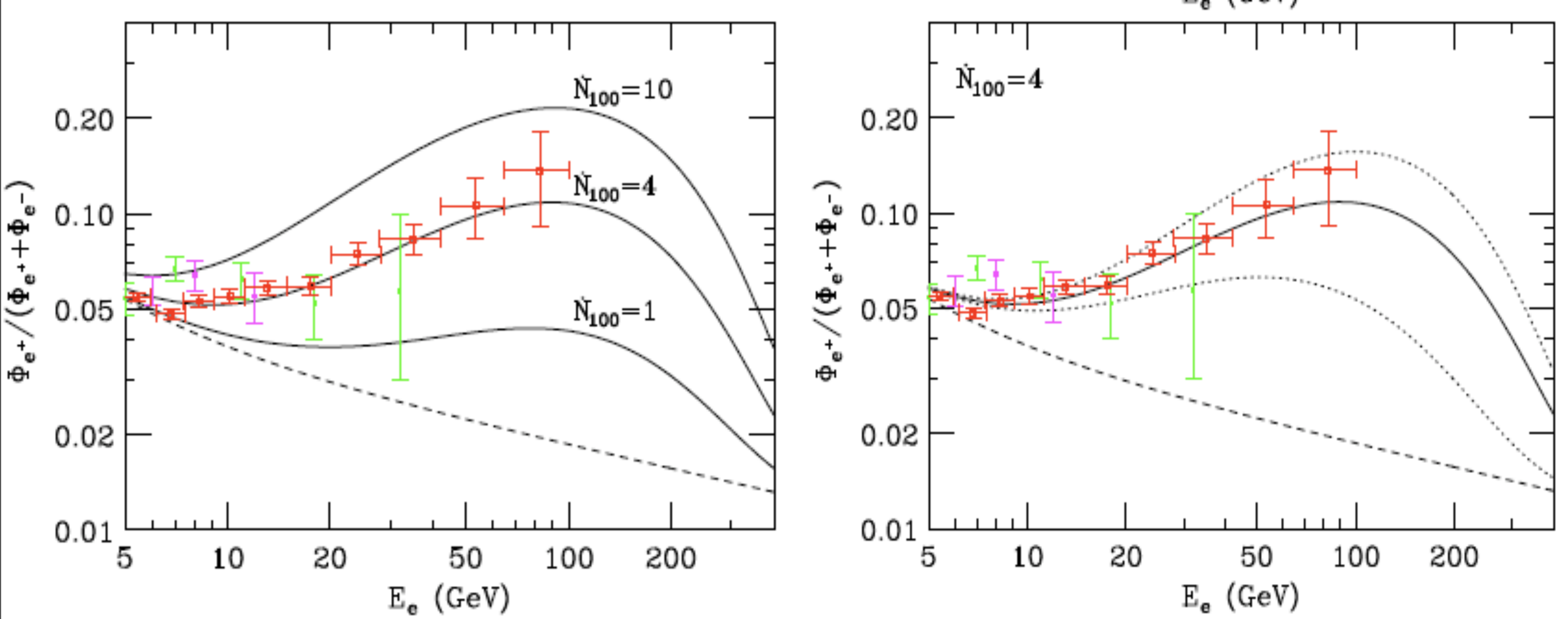
1. POSITRONS ARE LOWER THAN DETECTED BEFORE AT LOW ENERGIES
2. POSITRONS ARE IN EXCESS OF PREDICTIONS AT E>10 GeV
3. THE POSITRON FRACTION RISES WITH ENERGY
4. THE ANTIPROTONS ARE “WELL” BEHAVED

LOW ENERGY BEHAVIOUR POSSIBLY DUE TO INVERSION OF POLARITITY OF THE SOLAR MAGNETIC FIELD

THE EXCESS IS COMPATIBLE WITH PREVIOUS MEASUREMENTS

WHATEVER IT IS, IT CANNOT VIOLATE THE BOUND FROM ANTIPROTONS

PULSARS: DIFFUSE

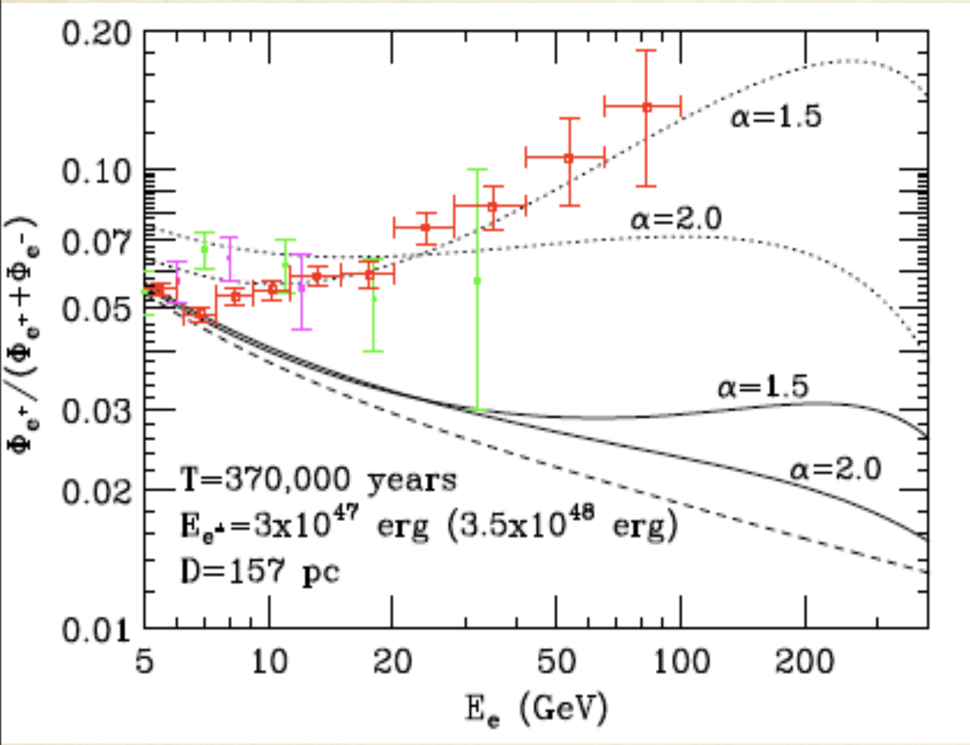


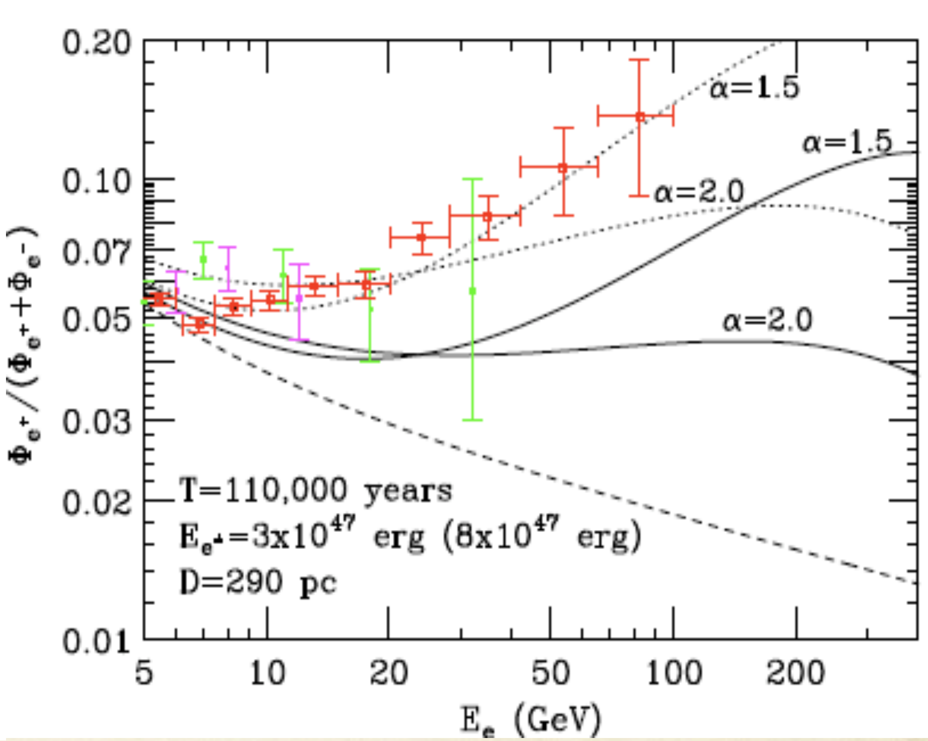
Hooper, Blasi, Serpico 2009

$$\frac{dN_e}{dE_e} \approx 8.6 \times 10^{38} \dot{N}_{100} \left(E_e/\mathrm{GeV}\right)^{-1.6} \exp\left(-E_e/80\,\mathrm{GeV}\right) \mathrm{GeV}^{-1}\,\mathrm{s}^{-1},$$

NO ANTIPROTONS

ISOLATED PULSARS



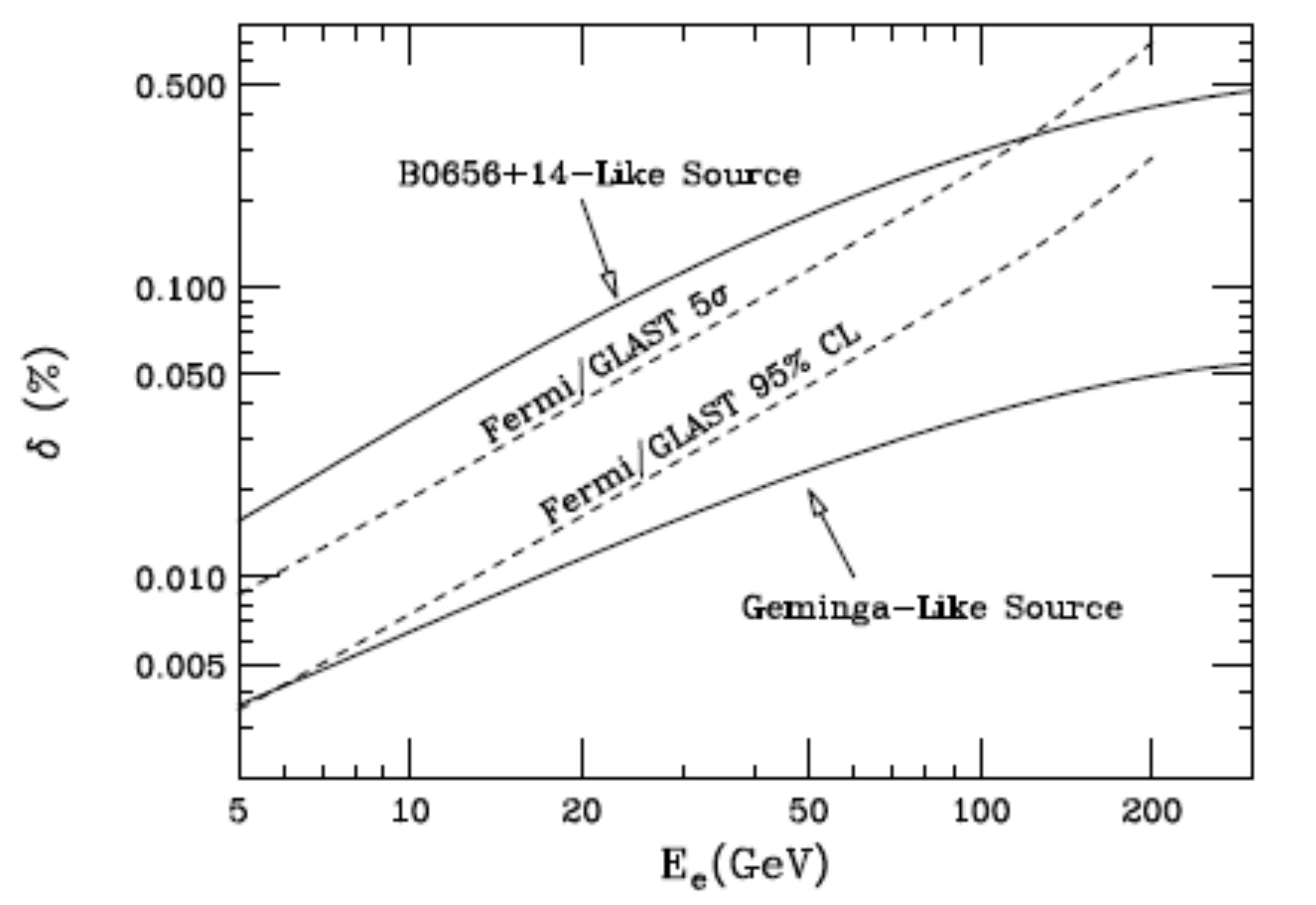


Hooper, Blasi, Serpico 2009

GEMINGA

B0656+14

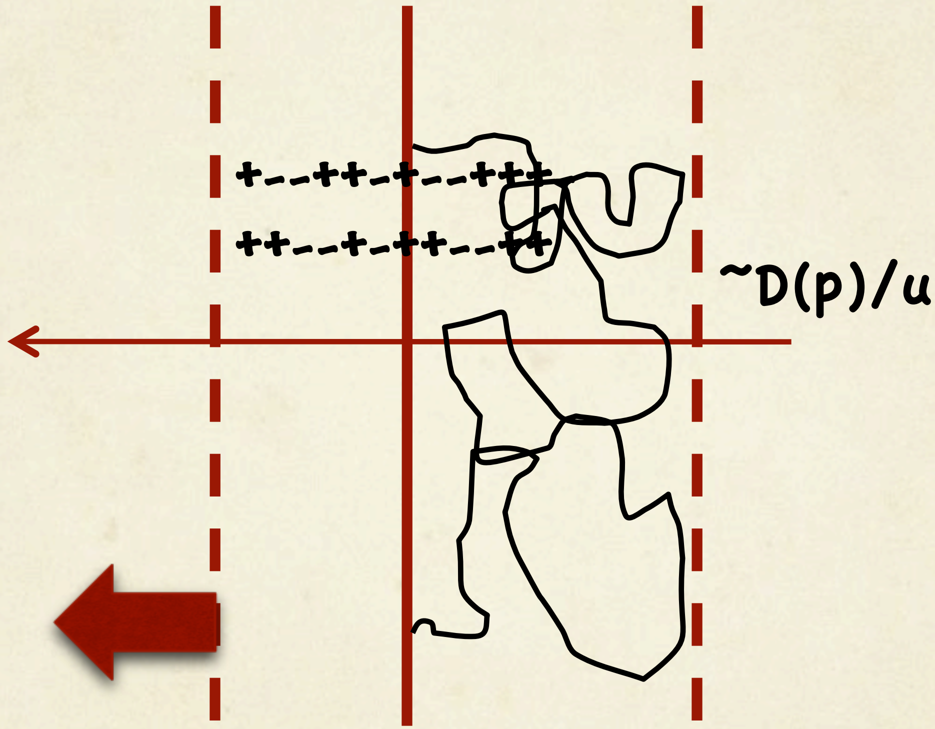
ANISOTROPY



Hooper, Blasi, Serpico 2009

CHARGED SECONDARY PARTICLES IN THE SOURCES

PB 2009



Advection

\+ Diffusion

CHARGED SECONDARY PARTICLES

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

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

ADVECTION DIFFUSION ENERGY GAIN INJECTION

$$Q_\pm(x,E) = \int dE' N_{CR}(E',x)\frac{d\sigma(E',E)}{dE'} n_{gas}(x) c$$

ONE NEEDS TO SOLVE THE TRANSPORT EQUATION BOTH FOR ACCELERATED CR AND SECONDARY PAIRS

IN THE ABSENCE OF NON LINEAR EFFECTS

$$N_{CR}(p,x) = \begin{cases} N_0(p) \exp[ux/D(p)] & \text{UPSTREAM } (x<0) \\ N_0(p) & \text{DOWNSTREAM } (x>0) \end{cases}$$

$$N_0(p) = A\, p^{-g} \qquad \gamma = \frac{3r}{r-1}$$

THE SLOPE DEPENDS ONLY ON THE COMPRESSION FACTOR r AT THE SHOCK

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

INTEGRATION OVER THE UPSTREAM REGION GIVES

$$D(p)\frac{\partial f}{\partial x}\bigg|_1 = u_1 f_0 - \int_{-\infty}^{0} dx\, \mathrm{Q}_1(x,p) \equiv u_1 f_0 - \Im_1(p)$$

INTEGRATION DOWNSTREAM:

$$D(p)\frac{\partial f}{\partial x}\bigg|_2 = D_2(p)\frac{Q_2}{u_2}$$

BOUNDARY CONDITION 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}

1. 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

SOLUTION AT x

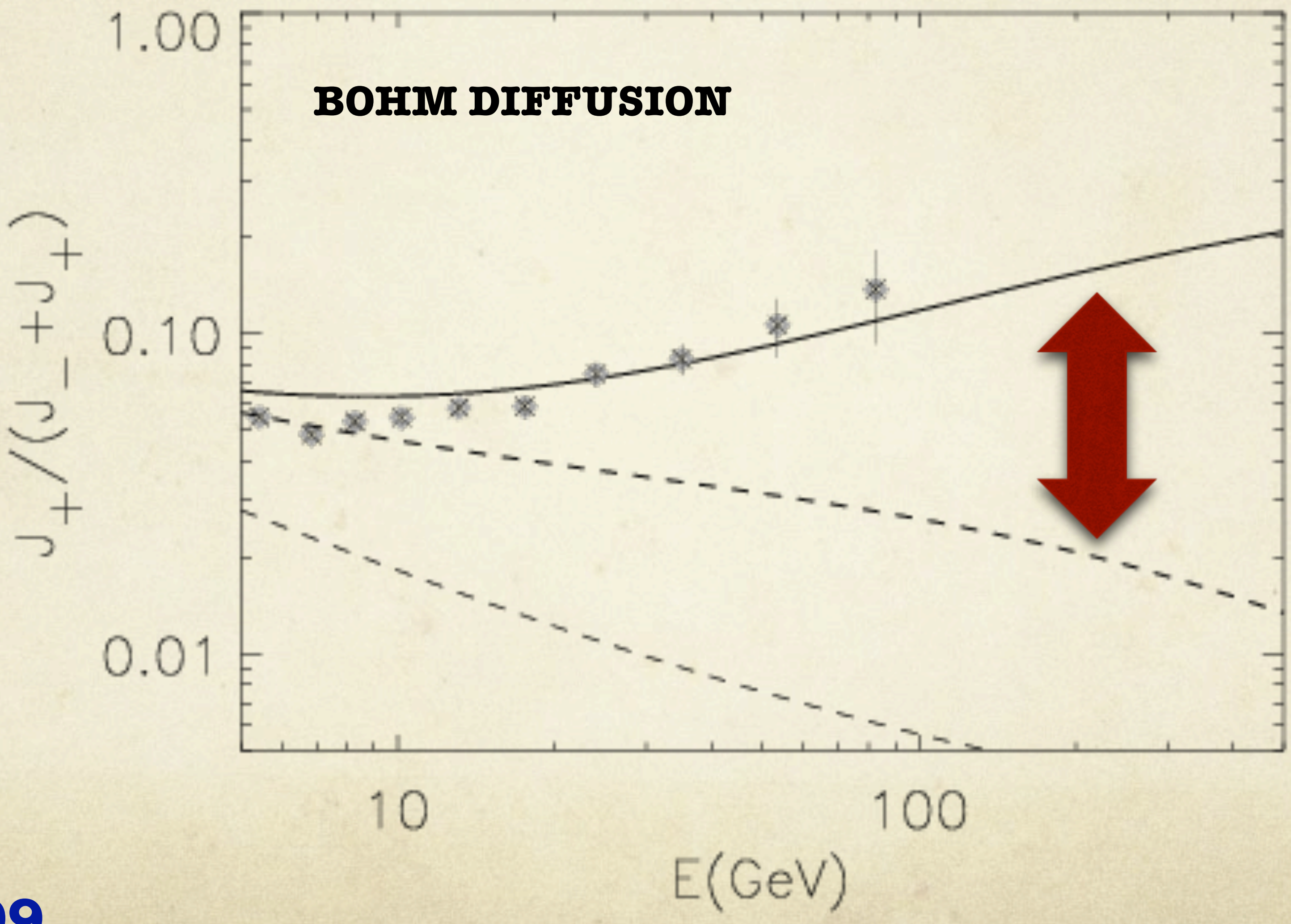
AT A GENERIC LOCATION X DOWNSTREAM OF THE SHOCK, THE SOLUTION CAN ONLY BE:

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

ACCELERATION TERM

STANDARD TERM, THE SAME AS FOR GAMMAS

THE POSITRON "EXCESS"



PB 2009

THE PARAMETERS

$$D_B(E) = K_B \frac{1}{3} r_L(E) c = 3.3\times10^{22} K_B B_\mu^{-1} E_{GeV}\ cm^2 s^{-1}$$

TYPICAL VALUES REQUIRED ARE

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

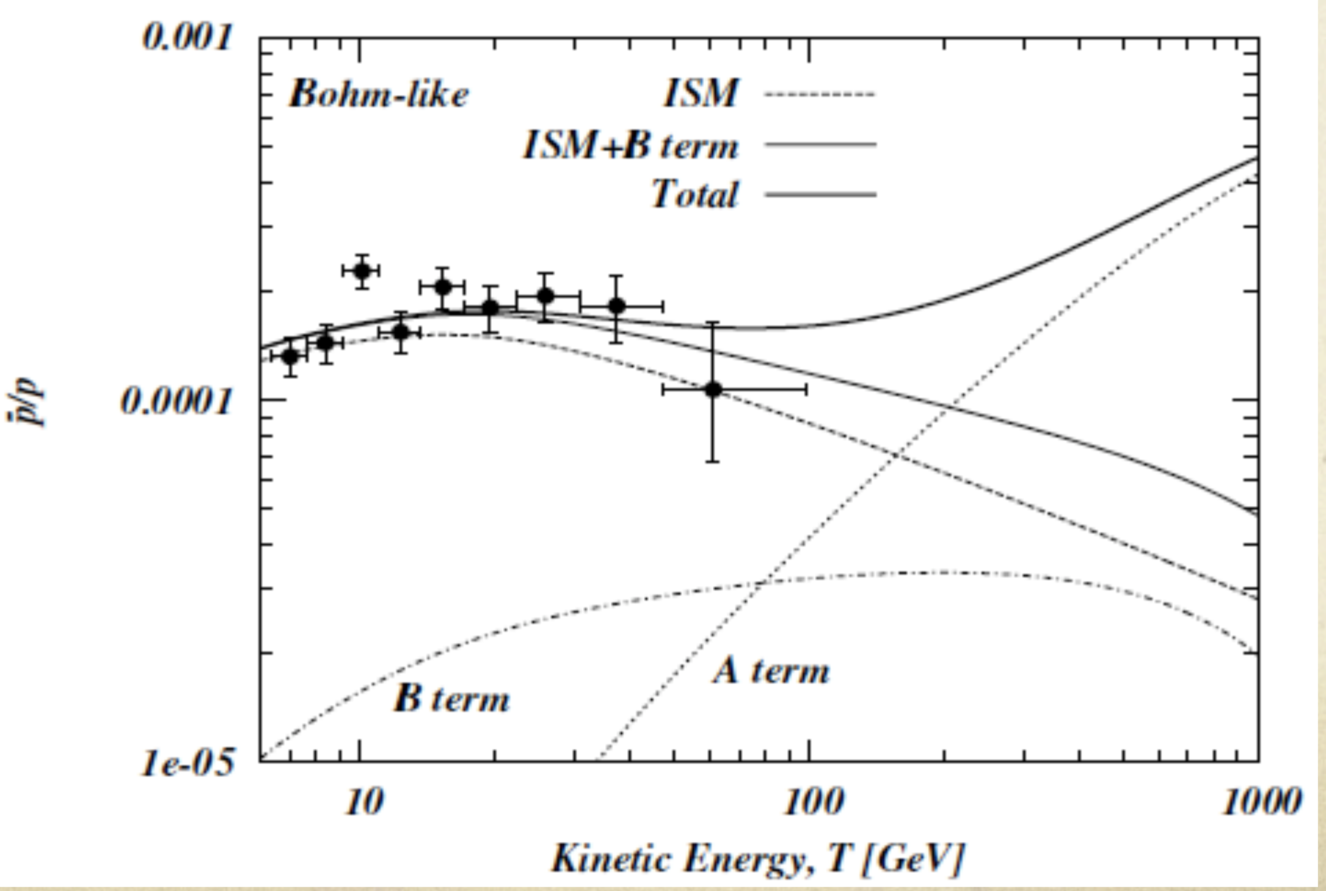
THESE ARE TYPICAL FOR AN OLD SN-I OR A SN-II OUTSIDE THE BUBBLE CREATED BY THE WIND OF THE PRE-SN STAR

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

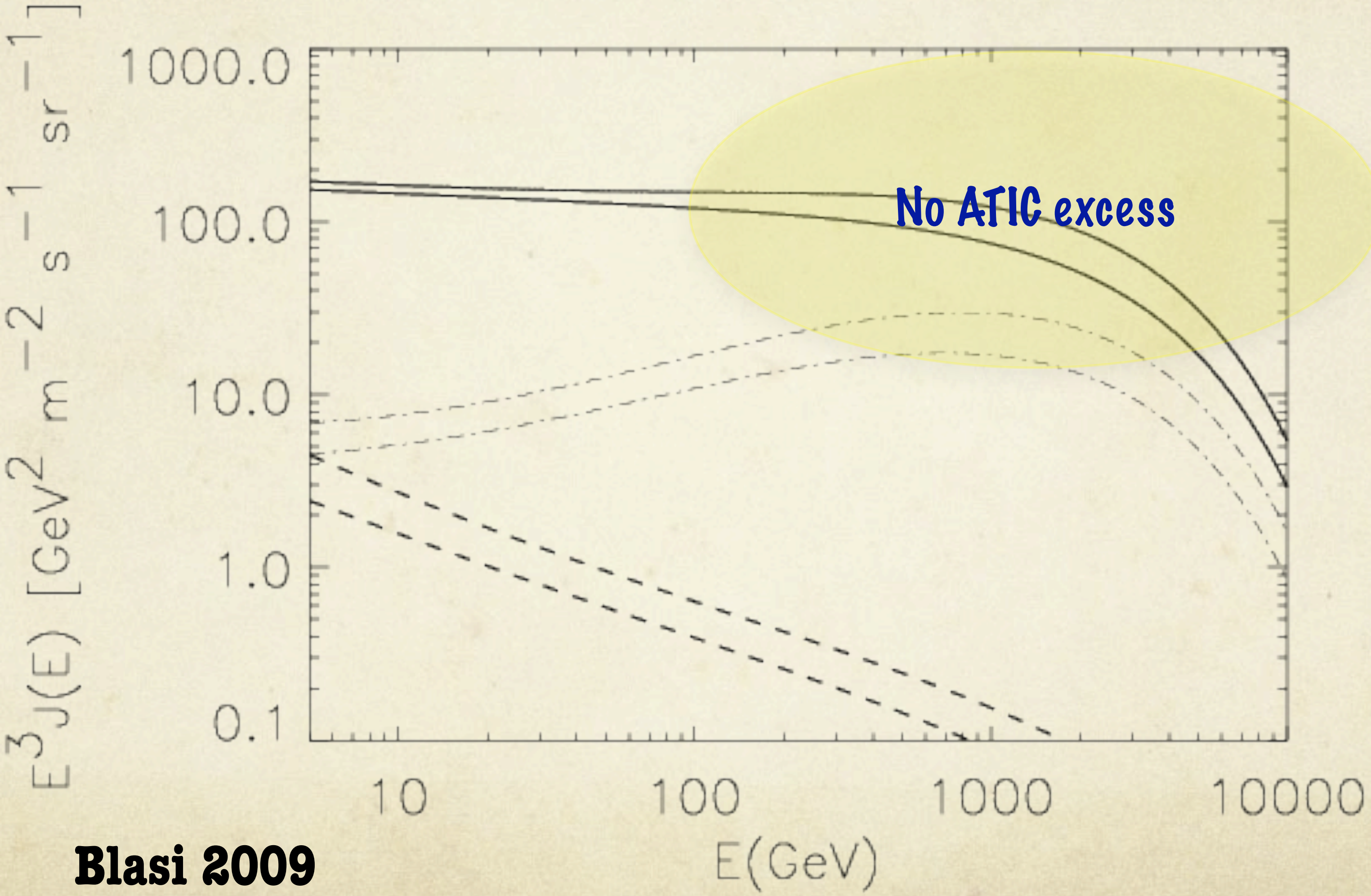
ANTIPROTONS

PB & Serpico (2009)

SIMPLER CALCULATIONS BECAUSE NO ENERGY LOSSES:



ELECTRONS (e- and e+)



Blasi 2009

NOTES AND DISCUSSION

MECHANISM FOR RISING POSITRON FRACTION

EVEN THE CONSTANT TERM CAN BE IMPORTANT (THOUGH NOT RISING BUT FLAT)

SOME SNR CAN BE CLOSE TO VERY DENSE CLOUDS WHICH ADDS TO THEIR ROLE AS SOURCES OF SEC'S

BUT BIG UNCERTAINTY DUE TO THE

1) RELATIVE ROLE OF ADVECTED AND ESCAPING
2) TEMPORAL EVOLUTION

AT PRESENT THESE PROBLEMS ARE NOT SOLVED EVEN FOR STANDARD CR

IMPLICATIONS FOR DARK MATTER DETECTION

Both pulsars and CR-induced effects lead to rather well justified predictions, despite astrophysical uncertainties

Until we understand these effects no claim for dark matter Discovery may be possible, within the realm of Science at least

Pulsars by themselves may contribute appreciably to the positron Flux (without providing antiprotons)

SNRs can explain the excess (with a related antiproton signal) and even without the rising part they would spoil the dark matter signal