PARTICLE ACCELERATION IN SUPERNOVA REMNANTS

AND

THE ORIGIN OF COSMIC RAYS

Pasquale Blasi

INAF/Arcetri Astrophysical Observatory

AGILE MEETING – April 16-17, 2012

WHICH QUESTIONS TO ANSWER TO?

ARE CRs ACCELERATED IN SNRs WITH AN EFFICIENCY AND SPECTRAL SHAPE COMPATIBLE WITH B/C AND WITH ANISOTROPY ?

ARE THE EXISTING GAMMA RAY OBSERVATIONS (AND THE WHOLE MULTI-■ SHEBANG) UNDERSTOOD IN TERMS OF KNOWN PHYSICS OF PARTICLE ACCELERATION?

DO WE SEE (and CAN WE SEE) EVIDENCE FOR CR ACCELERATION UP TO THE KNEE (IN PROTONS)?

WHAT IS THE CHEMICAL COMPOSITION AT THE SOURCE AND AT EARTH?

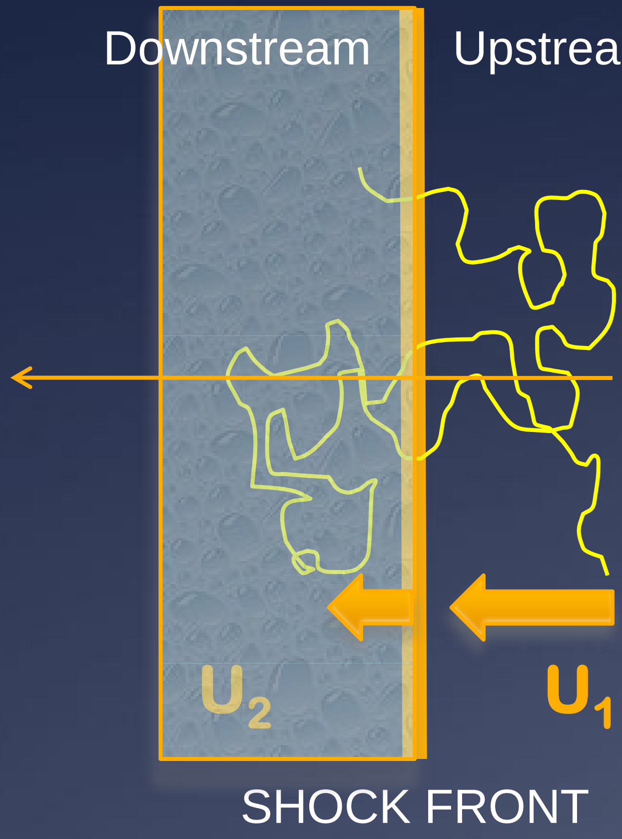
WHERE DO GALACTIC CRs END?

THEORY OF CR ACCELERATION IN SNRs

Diffusive Shock Acceleration

Berekhko, Ellison, Voelk; end of nineties +
PB 2002, 2004, Amato & PB 2005, 2006, Caprioli +, 2007-2011, Morlino + 2007-2012

First order FERMI ACCELERATION
Test particle theory



DIFFUSION OF CHARGED PARTICLES BACK AND FORTH THROUGH THE SHOCK LEADS TO

$$\frac{\Delta E}{E} = \frac{4}{3}(U_1 - U_2)$$

PARTICLES ARE ACCELERATED TO A POWER LAW SPECTRUM

THE SLOPE OF THE SPECTRUM ONLY DEPENDS ON THE COMPRESSION

NOT ON THE DIFFUSION COEFFICIENT

FOR STRONG SHOCKS: E^{-2}

NON LINEAR THEORY

A theory of particle acceleration that allows one to describe:

1. ***Dynamical reaction of accelerated particles***

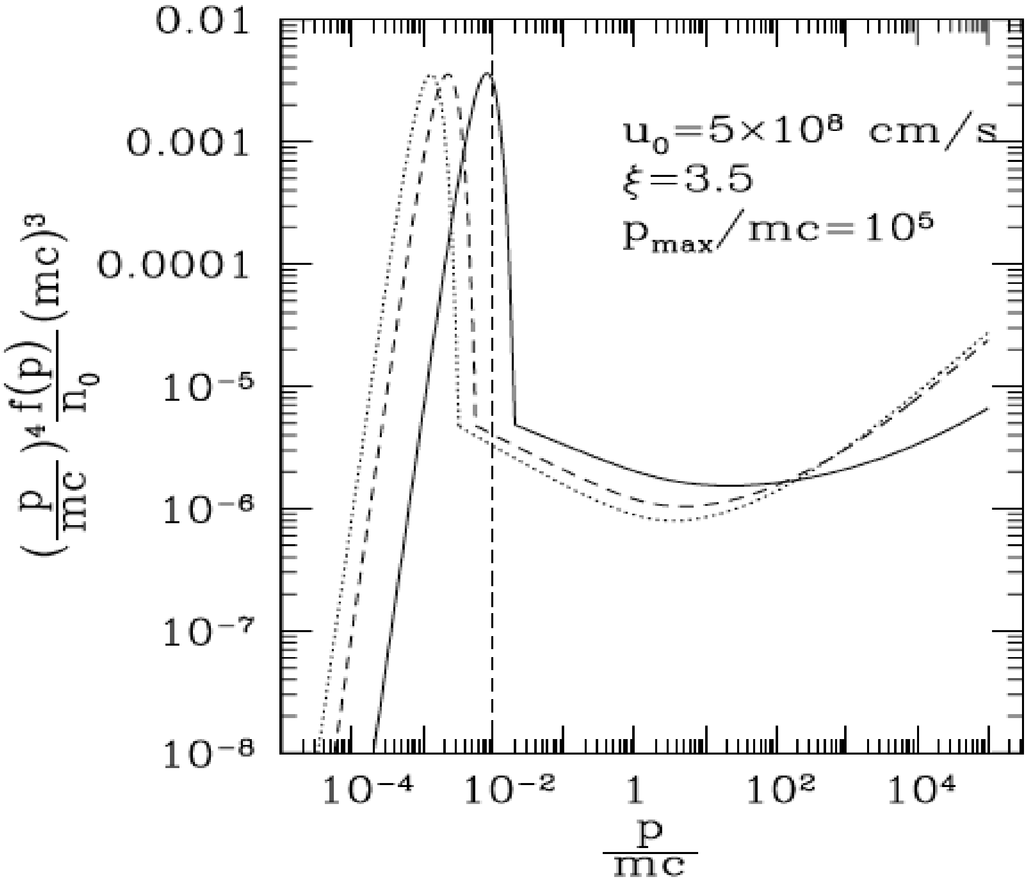
2. ***CR-induced B-field and their reaction***

3. ***Recipe for injection (self-regulation)***

4. ***Escape of particles (Cosmic Rays)***

DIFFUSIVE ACCELERATION AT COLLISIONLESS NEWTONIAN SHOCKS

non linear theory: BASIC PHYSICAL ASPECTS



COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY

SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)

GAS BEHIND THE SHOCK IS COOLER FOR EFFICIENT SHOCK ACCELERATION

SYSTEM SELF REGULATED

EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT

Particle Diffusion ←→ Wave Growth: STREAMING INSTABILITY

$$n_{CR} m v_D \rightarrow n_{CR} m V_A \Rightarrow \frac{dP_{CR}}{dt} = \frac{n_{CR} m (v_D - V_A)}{\tau}$$

$$\frac{dP_w}{dt} = \gamma_W \frac{\delta B^2}{8\pi} \frac{1}{V_A}$$

$$\gamma_W = \sqrt{2} \frac{n_{CR}}{n_{gas}} \frac{v_D - V_A}{V_A} \Omega_{cyc}$$

GROWTH RATE

In the ISM this is ~10^{-3} yr^{-1} but close to a shock front the growth can be much larger!!!

$$\gamma_W \simeq \sqrt{2}\, \xi_{CR} \left(\frac{V_s}{c}\right)^2 \frac{V_s}{V_A} \Omega_{cyc} \sim \mathcal{O}(seconds^{-1})$$

≏B IS AMPLIFIED BY PARTICLES

MAGNETIC FIELD AMPLIFICATION

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

Particles are accelerated because there is High magnetic field in the acceleration region

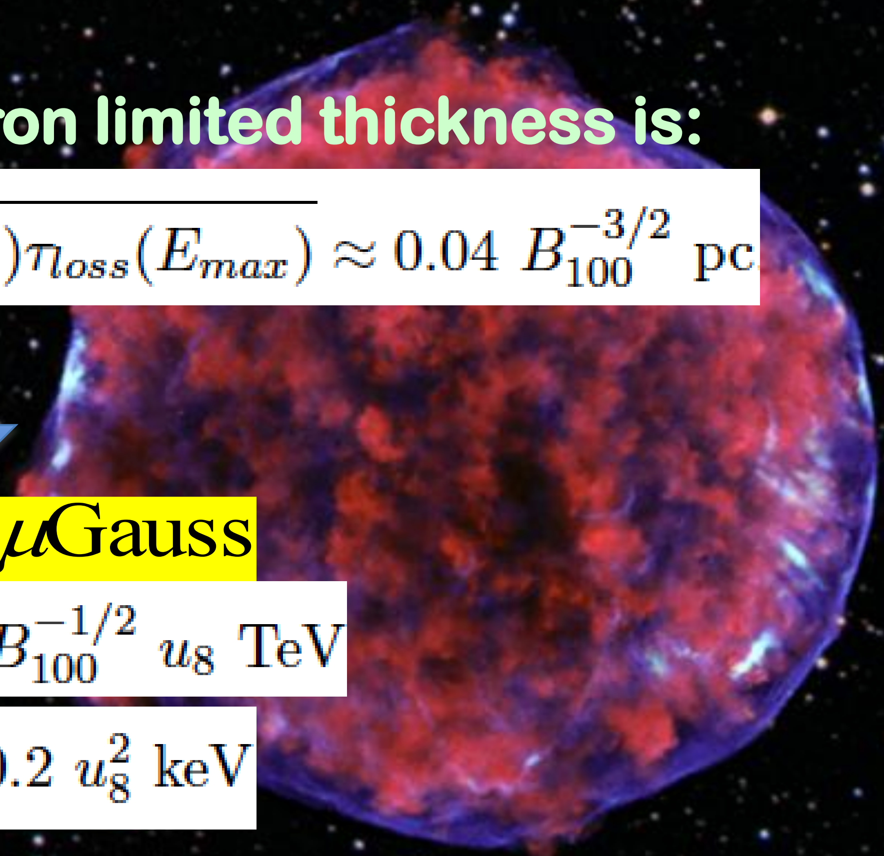
High magnetic field is present because particles are accelerated efficiently

Without this non-linear process, no acceleration of CR to High energies (and especially not to the knee!)

X-ray rims and B-field amplification

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

The synchrotron limited thickness is:



$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \text{pc}$$

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

$$E_{max} \approx 10\ B_{100}^{-1/2}\ u_8\ \text{TeV}$$

$$\nu_{max} \approx 0.2\ u_8^2\ \text{keV}$$

In some cases the strong fields are confirmed by time variability of X-rays

Uchiyama & Aharonian, 2007

TROUBLE WITH SPECTRA

THE SPECTRA OF ACCELERATED PARTICLES ARE IN GENERAL CONCAVE AND FLATTER THAN E^{-2} AT HIGH ENERGY

THE MAXIMUM ENERGY WITH B-FIELD AMPLIFICATION MAY REACH UP TO ~10^{15} eV FOR PROTONS (Z TIMES HIGHER FOR NUCLEI)

THESE SPECTRA SHOULD REFLECT IN THE GAMMA RAY SPECTRA (IF DUE TO PP SCATTERING) AND NEUTRINO SPECTRA

BUT THE OBSERVED SPECTRA OF GAMMAS ARE TYPICALLY ~ $E^{-2.3}$

OFTEN INCOMPATIBLE WITH LEPTONIC MODELS! BUT ALSO NOT COMPATIBLE WITH THE SIMPLEST PREDICTION OF NLDSA

THE EFFECT OF THE WAVE SPEED?

One should remember that the compression factor that counts in shock acceleration is not that of fluid velocity, but that of the scattering centers velocity

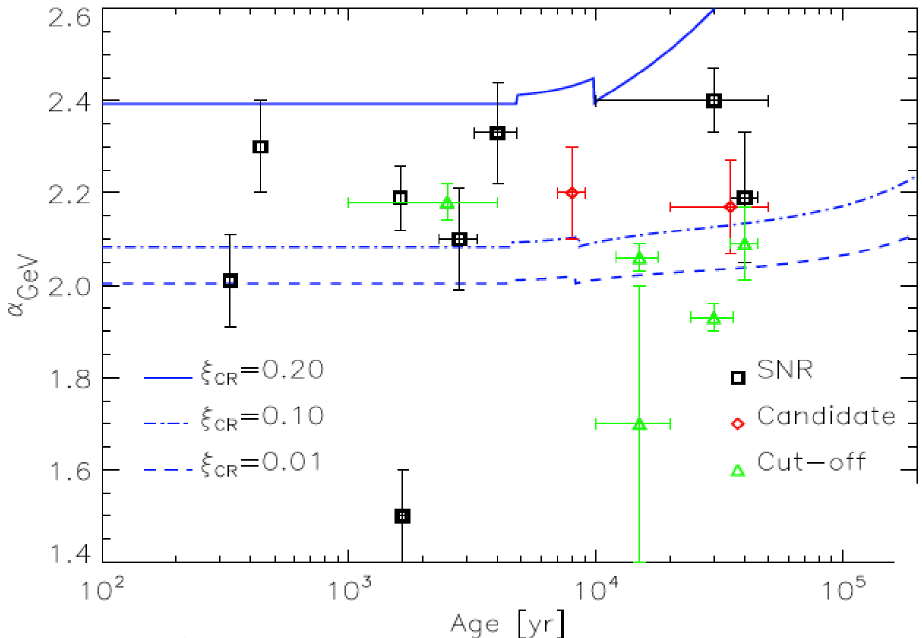
$$r = \frac{u_1}{u_2} \rightarrow \tilde{r} = \frac{u_1 + v_{A,1}}{u_2 + v_{A,2}}$$

When the magnetic field is amplified the Alfven speed is not well defined and one may argue that it should be calculated in the amplified field (it depends on helicity!):

$$\tilde{r} = r\left(1 - \frac{1}{M_{A,1}}\right) = \frac{\gamma_{\rm eff}+1}{\gamma_{\rm eff}-1+2/M_s^2}\left[1 - \frac{\xi_{cr}(2-\xi_{cr})}{2(1-\xi_{cr})^{5/2}}\right] \qquad \gamma_{\rm eff} = \frac{1}{3}\frac{5+3\xi_{cr}}{1+\xi_{cr}}$$

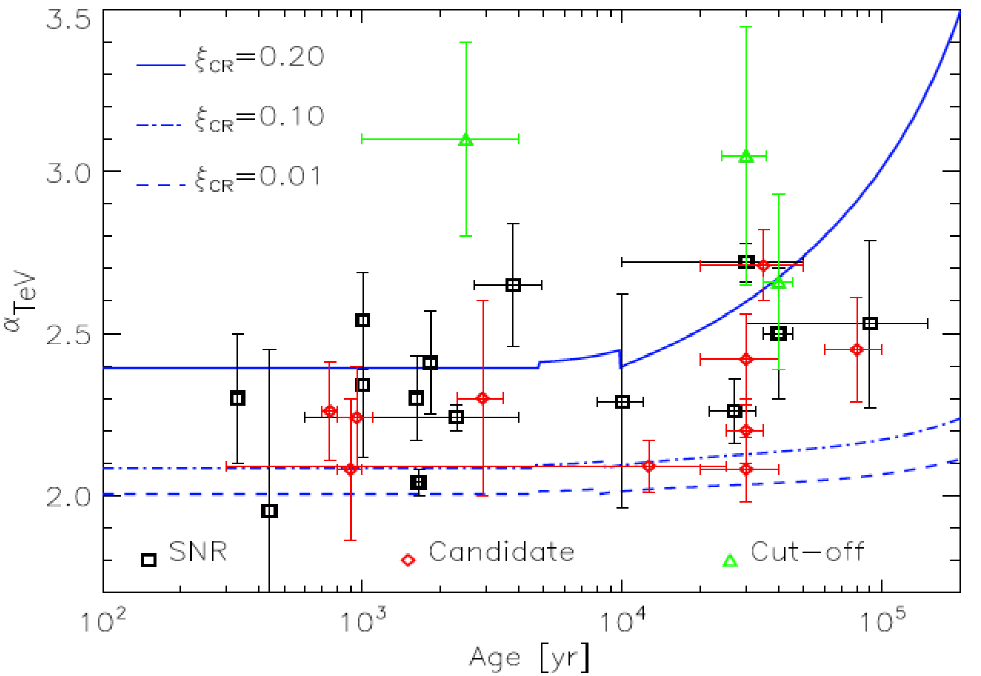
THIS EFFECT MAY LEAD TO STEEPER SPECTRA WHEN ACCELERATION IS EFFICIENT (BUT VERY MODEL DEPENDENT…could lead to opposite effect depending on wave helicity)

TROUBLE WITH SLOPES ?

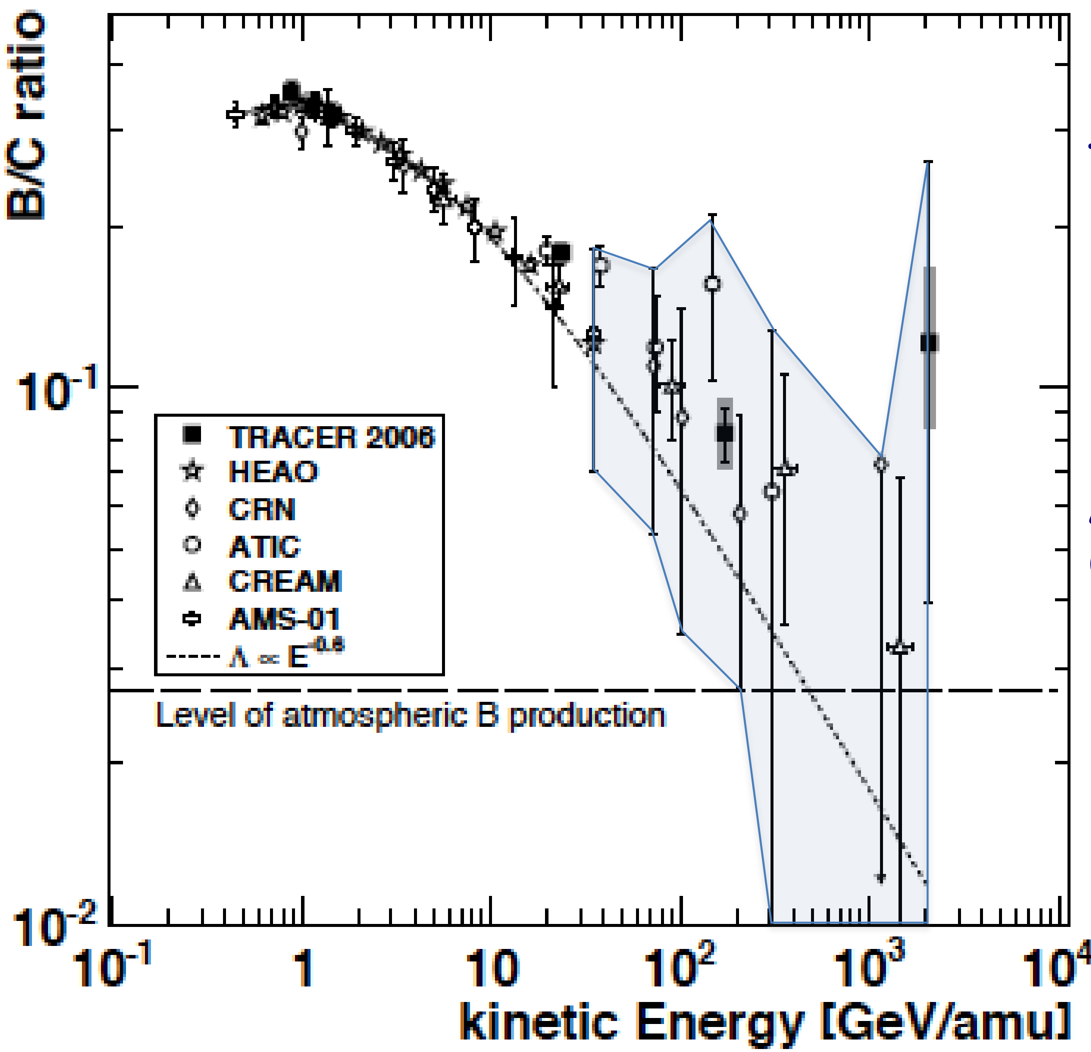


VERY SURPRISING TO SEE THAT THE REQUIRED ACCELERATION EFFIC. ARE HIGH BUT THE SPECTRA ARE STEEP

Caprioli 2011



IMPLICATIONS FOR CR PROPAGATION



Adapted from Obermeier et al. 2011

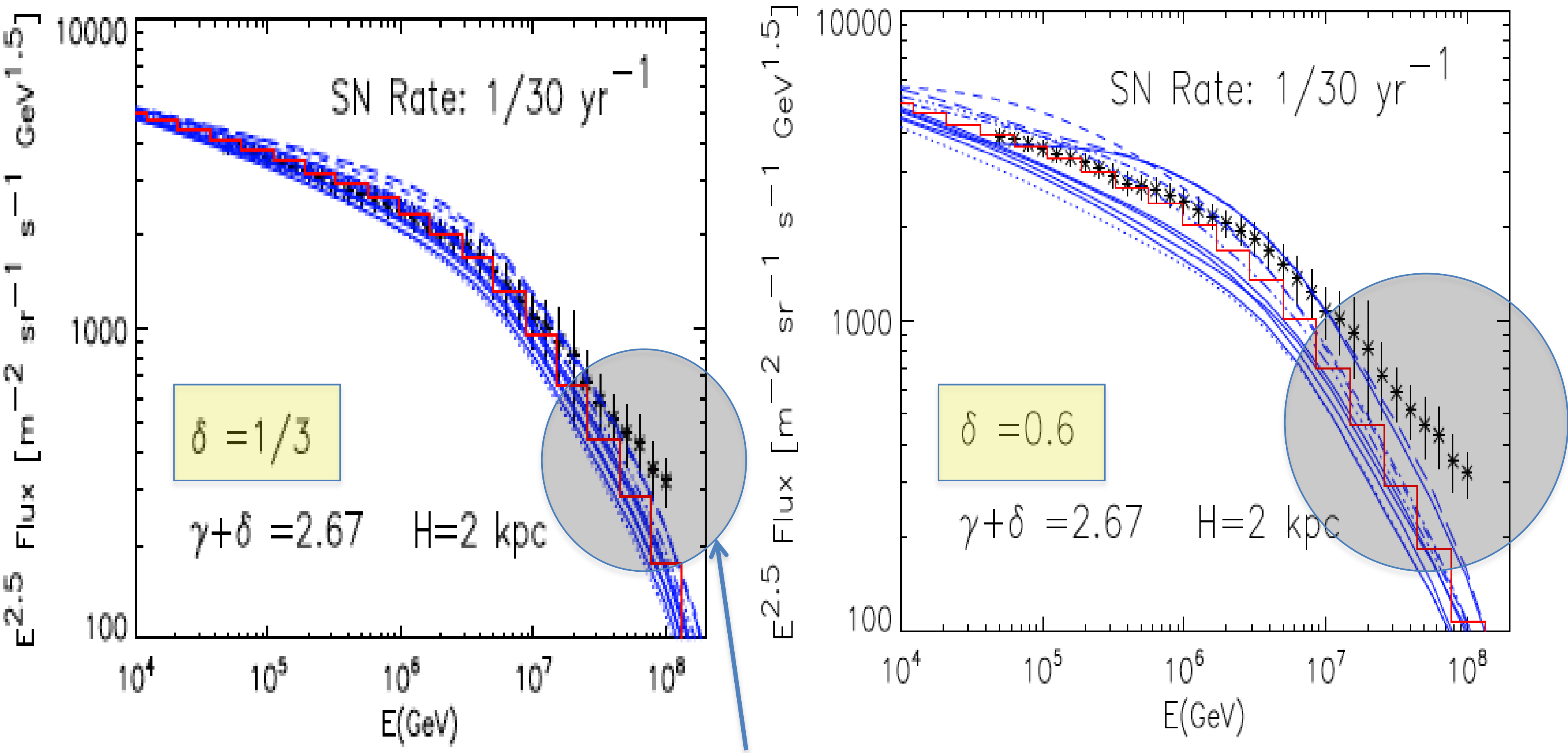
IN PRINCIPLE B/C ~ 1/D(E) IN THE HIGH RIGIDITY REGIME

BUT UNCERTAINTIES ARE STILL LARGE

NOT EASY TO DISCRIMINATE AMONG DIFFERENT DIFFUSION COEFFICIENTS

CR spectra and SNRs

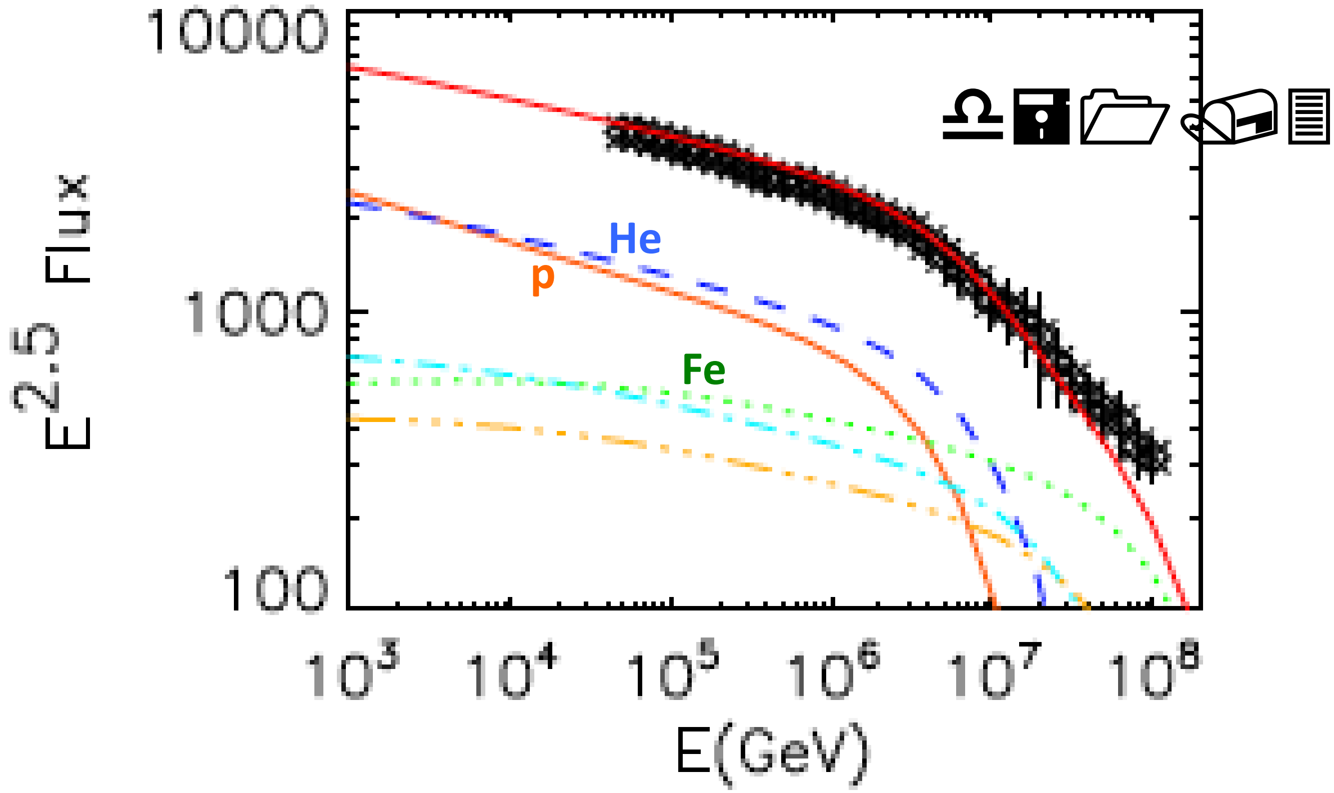
Blasi & Amato 2011



Deficit compensated
by extragalactic CRs

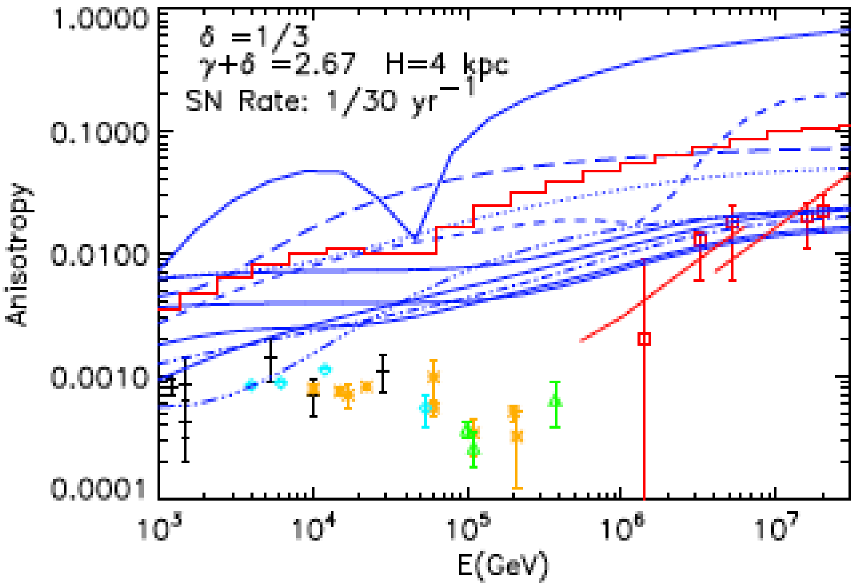
Hardening of Helium?

Blasi & Amato 2011



ONLY FOR ♎=1/3 SPECTRUM OF He HARDER THAN SPECTRUM OF PROTONS AS A RESULT OF MODEST SPALLATION

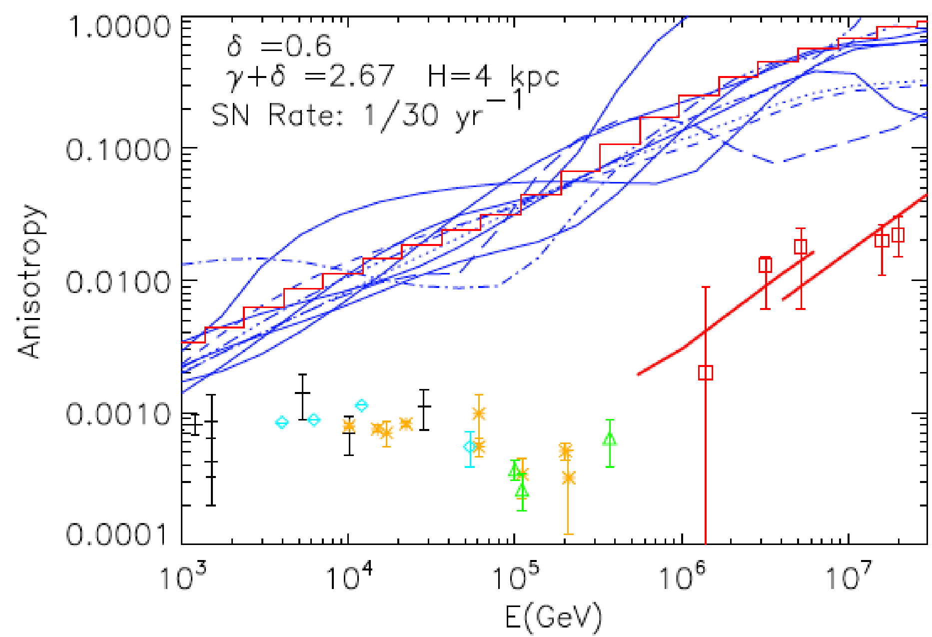
Large Scale CR Anisotropy



Naïve expectation:

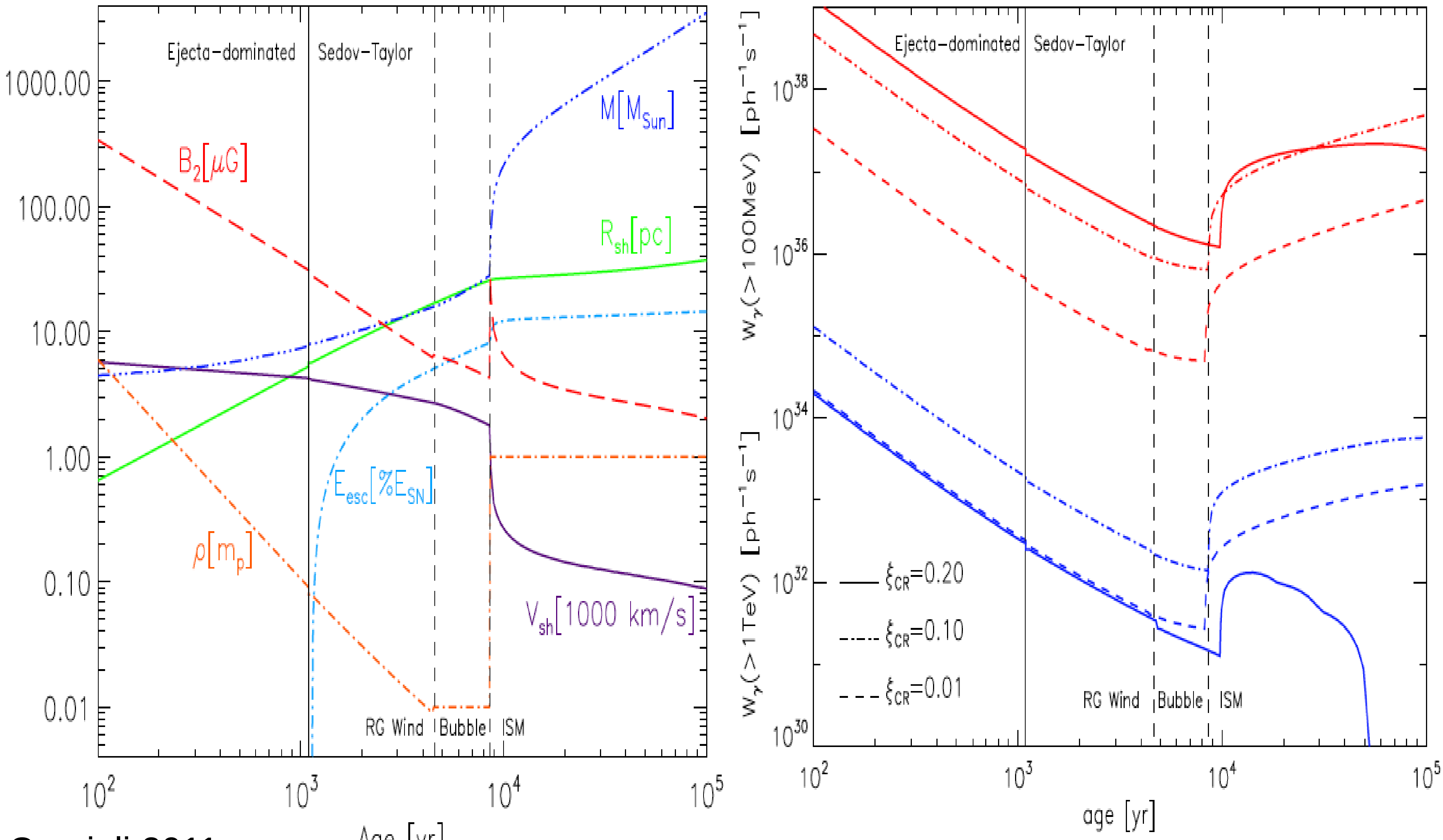
$$\delta_A = \frac{3}{2^{3/2}} \frac{1}{\pi^{1/2}} \frac{D(E)}{Hc}$$

proportional to E^{Ω}



Blasi & Amato 2011

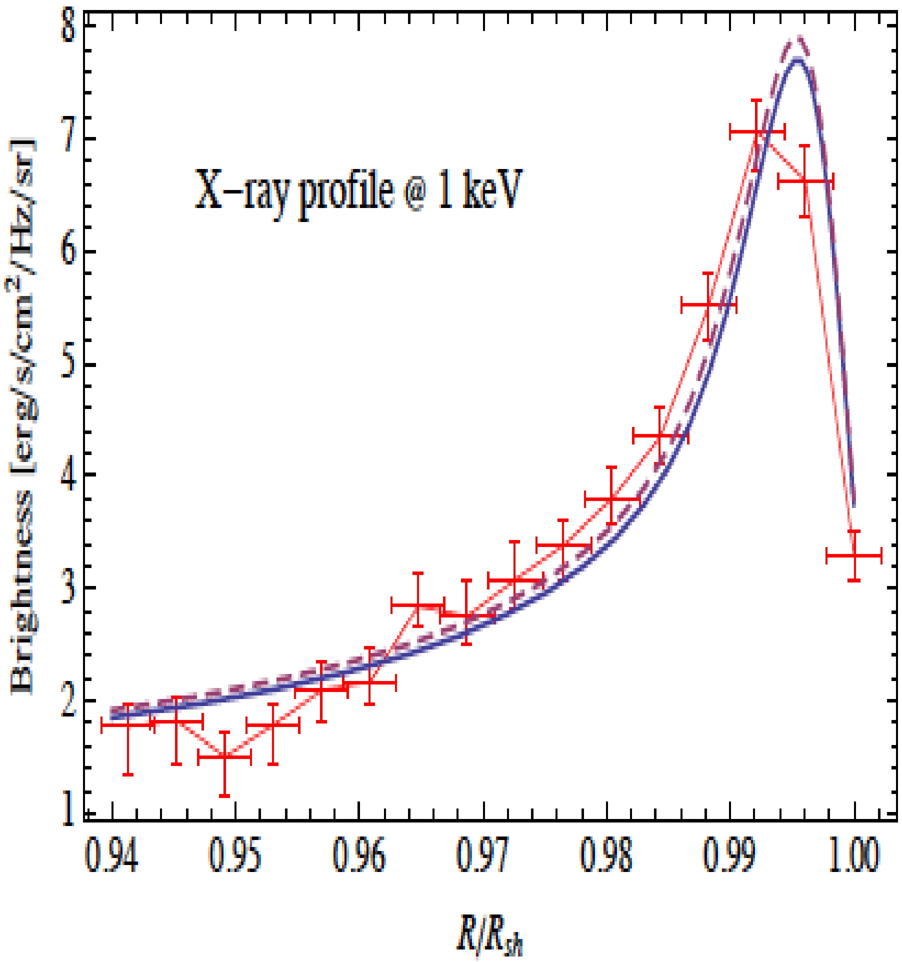
TEMPORAL EVOLUTION



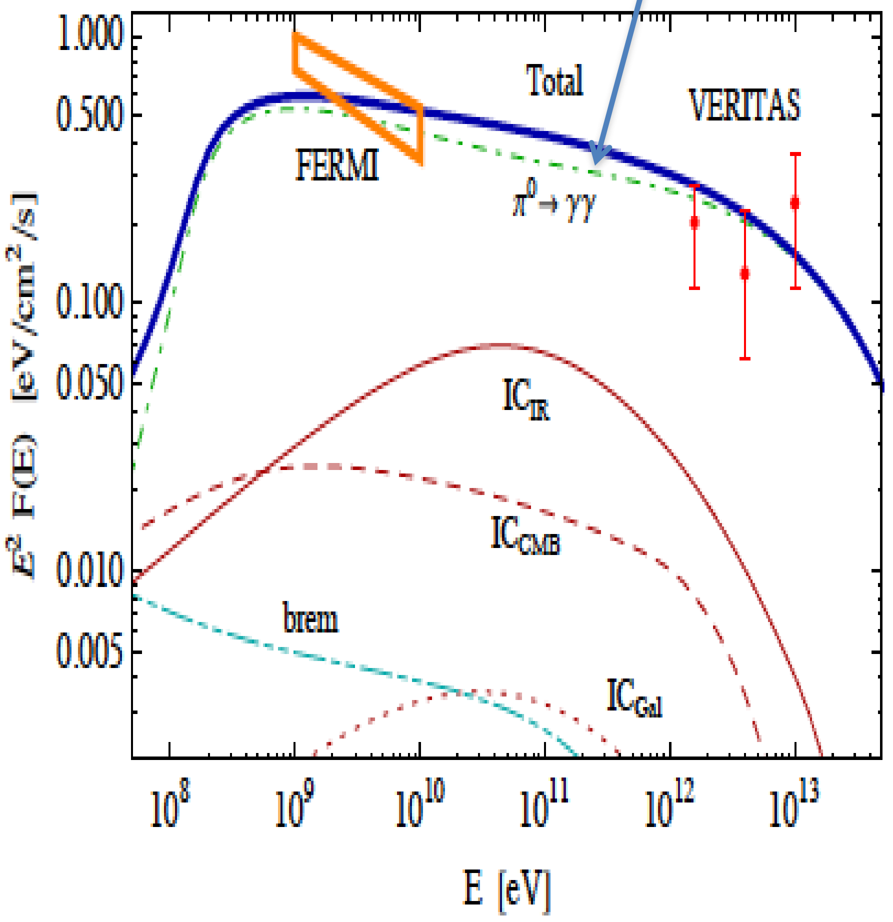
Caprioli 2011

The prototypical case of Tycho

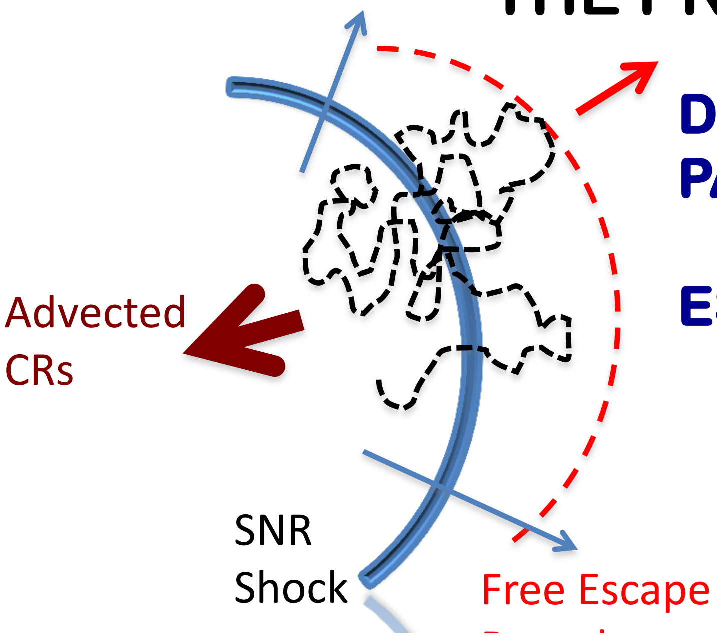
Morlino&Caprioli 2011



STEEP SPECTRUM BASICALLY IMPOSSIBLE TO EXPLAIN WITH LEPTONS



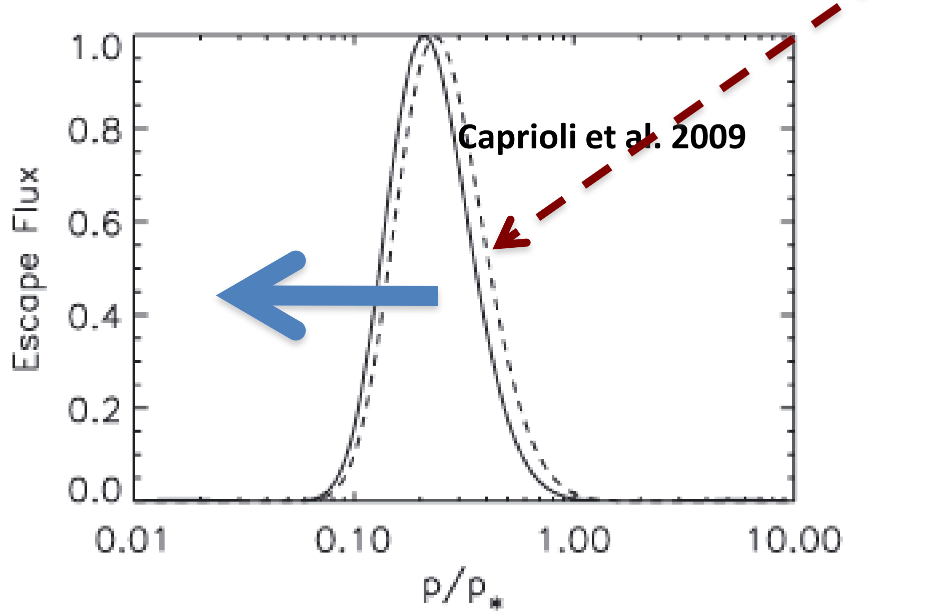
HOW DO ACCELERATED PARTICLES BECOME CRs? THE PROBLEM OF ESCAPE

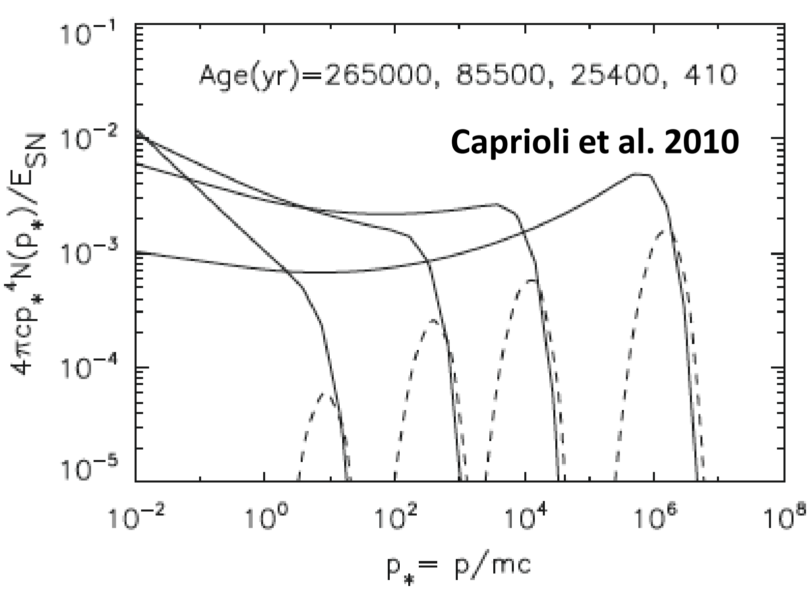


DURING THE EJECTA DOMINATED PHASE PARTICLES ARE ADVECTED WITH PLASMA

ESCAPE OCCURS DURING SEDOV PHASE

$$\Phi_{esc}(E,x) = D(E)\left(\frac{\partial f(E,x)}{\partial x}\right)_{x=x_{fe}}$$





CR ESCAPE AND CLOUDS

TWO SCENARIOS:

SNR SHOCK ENTERS THE MOLECULAR CLOUD

Collisionless shock only involves ions (very low density)

Ion-neutral density kills waves→low E_{max}

Rate of damping $\Gamma_{ion-n} = \frac{1}{2} < n_H \sigma > \approx 4.2 \times 10^{-9} T_4^{0.4} n_1 \quad s^{-1}$

Remember: D(E)=(1/3) c r_L / F(k) and here F(k)→0 in clouds

MOLECULAR CLOUD IS ILLUMINATED BY CR FROM SNR

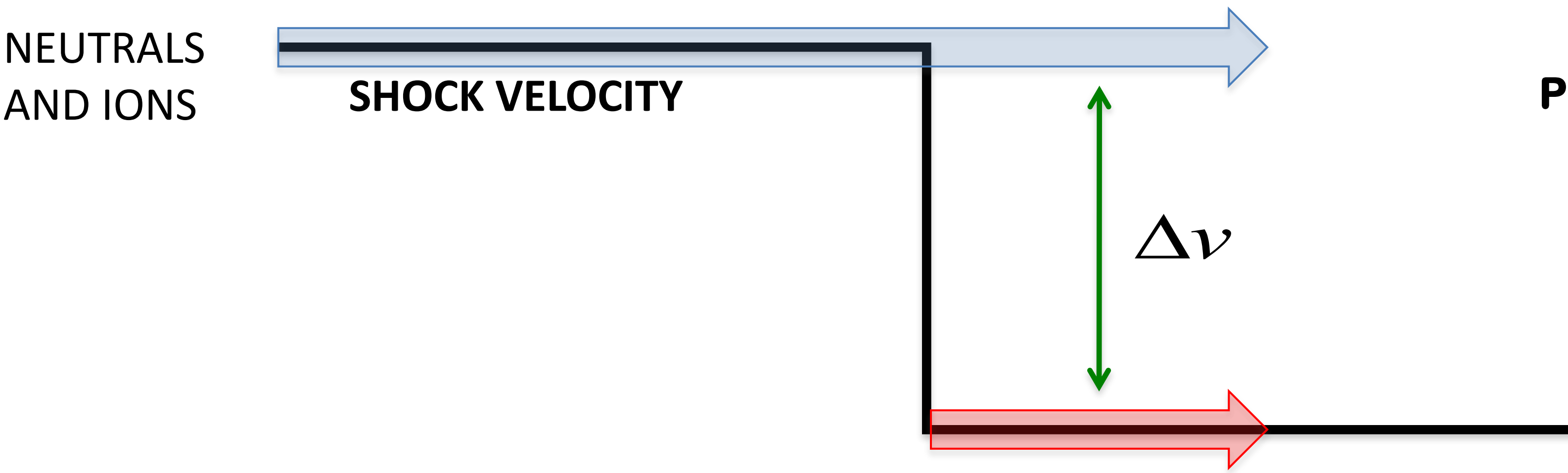
The MC only acts as a target for pp. Gamma ray flux depends on

- -Age of SNR
- -Diffusion coefficient around the SNR (LIKELY SELF GENERATED IF CR DENSITY DOMINATED BY LOCAL SNR)
- -Escape physics

SOME NEW WAYS TO MEASURE THE CR ACCELERATION EFFICIENCY IN SUPERNOVA REMNANTS

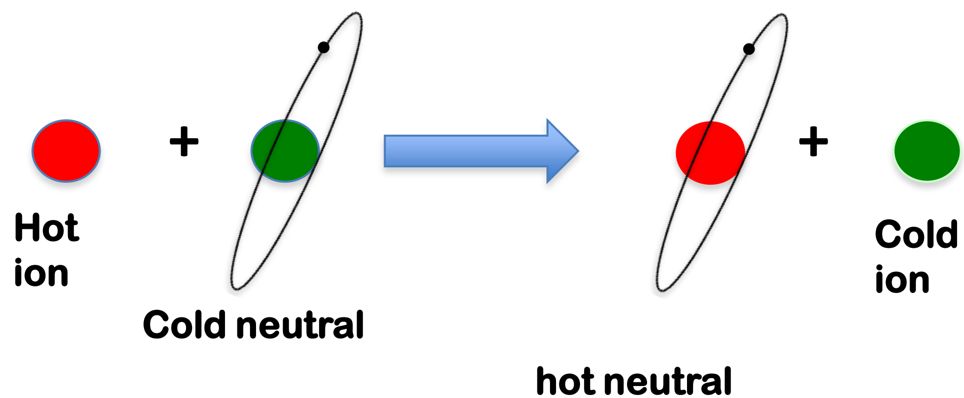
COLLISIONLESS SNR SHOCKS IN PARTIALLY IONIZED MEDIA

SUBTLE ASPECTS OF ACCELERATION AT A COLLISIONLESS SHOCK



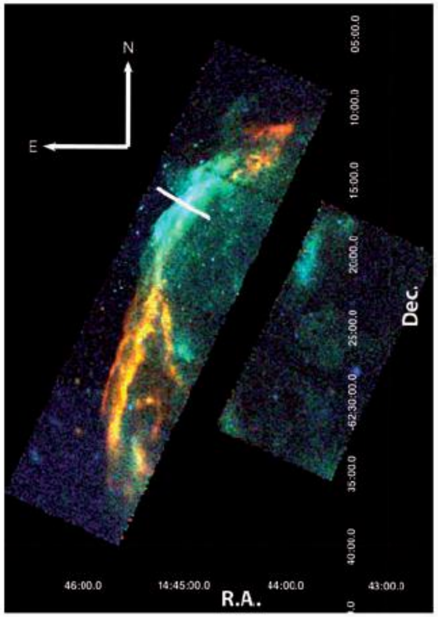
PB+, 2012

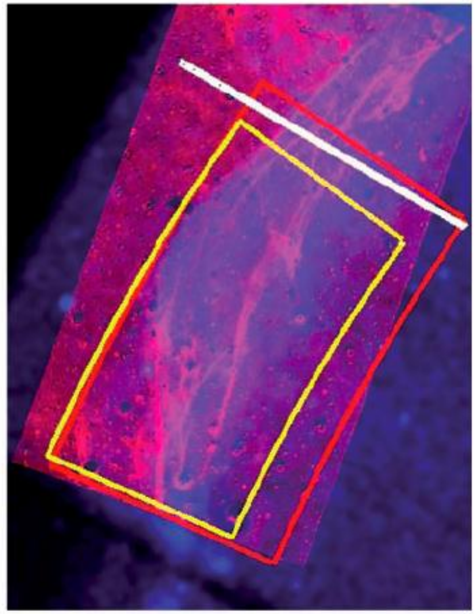
CHARGE EXCHANGE → BROAD BALMER LINE (NEUTRALS THAT MADE CHARGE EXCHANGE) REFLECTING THE TEMPERATURE OF IONS…

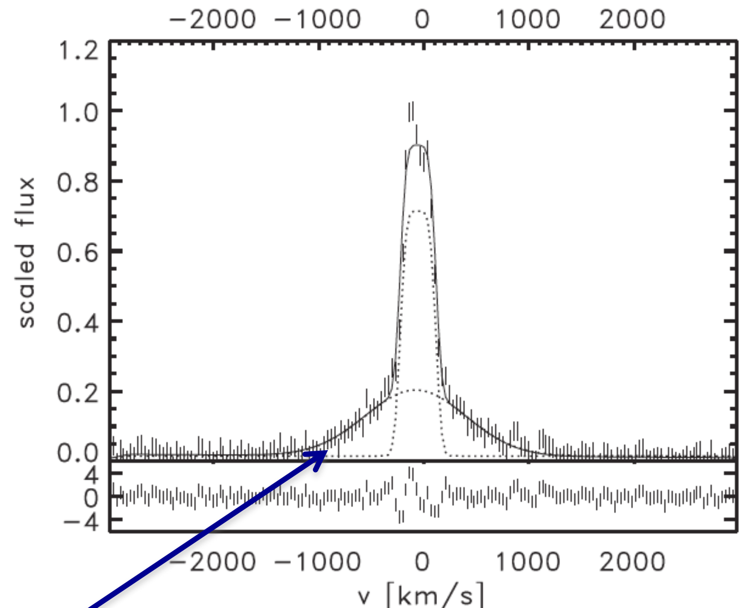


BUT THE LATTER AFFECTED BY EFFICIENT CR ACCELERATION

BROAD BALMER LINES NARROWER THAN FOR UNMODIFIED SHOCKS







Helder et al. 2009

$$W_{broad} = \sqrt{8 \ln 2 \frac{kT_2}{m}} \approx 1.02\ \mathrm{v_{sh}}$$

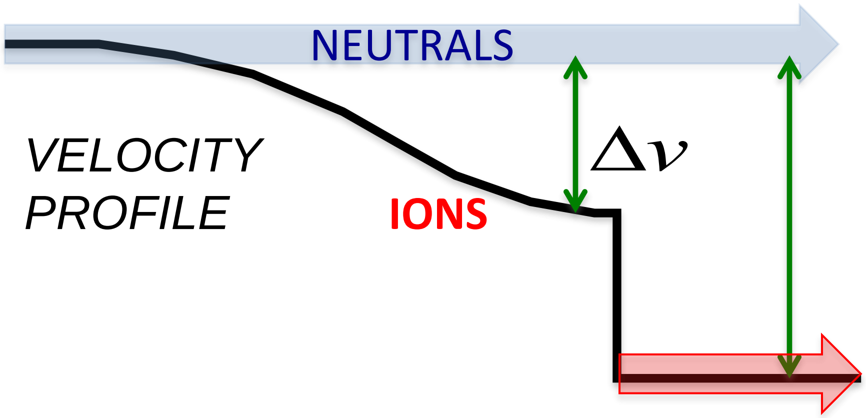
$$W_{broad} = 1100 \pm 63\, km/s \rightarrow T_2 = 2.3 \pm 0.3\, keV$$

Shock speed from proper motion

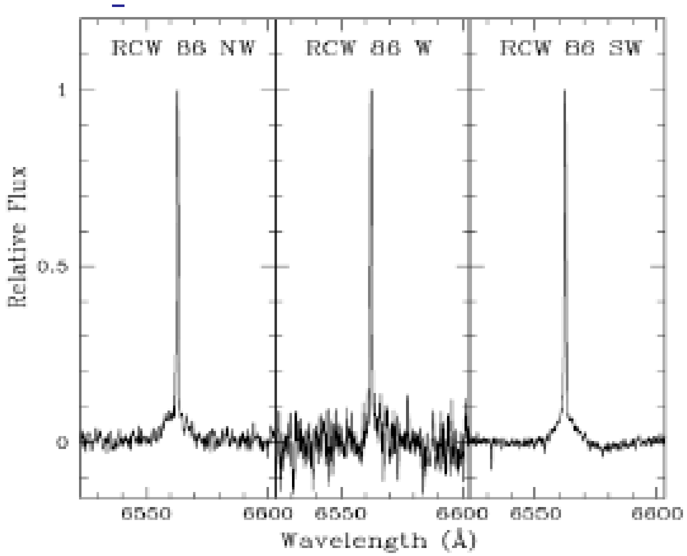
$$v_{shock} = 6000 \pm 2800\, km/s \left(\frac{d}{2.5 \pm .5 kpc} \right) \left(\frac{\dot{\theta}_{obs}}{0.5 \pm .2'' yr^{-1}} \right) \rightarrow T_2 = \begin{matrix} 20-150\, keV\, (no\, equilibration) \\ 12-90\, keV\, (equilibration) \end{matrix}$$

INFERRED EFFICIENCY of CR ACCELERATION 50-60% !!! (BUT model dependent)

NARROW BALMER LINES BROADER THAN FOR UNMODIFIED SHOCKS



Sollerman et al. 2003



$$W_{broad} = \sqrt{8 \ln 2 \frac{kT_0}{m}} \approx 21 \text{ km/s} \left(\frac{T_0}{10^4 K} \right)^{1/2}$$

$$W_n \sim 30-50\, km/s \rightarrow T \sim 2-6\, 10^4 K$$

CHARGE EXCHANGE OCCURS NOW IN THE CR INDUCED PRECURSOR

↓

NARROW BALMER LINE BROADER THAN FOR AN UNMODIFIED SHOCK

The neutral return flux

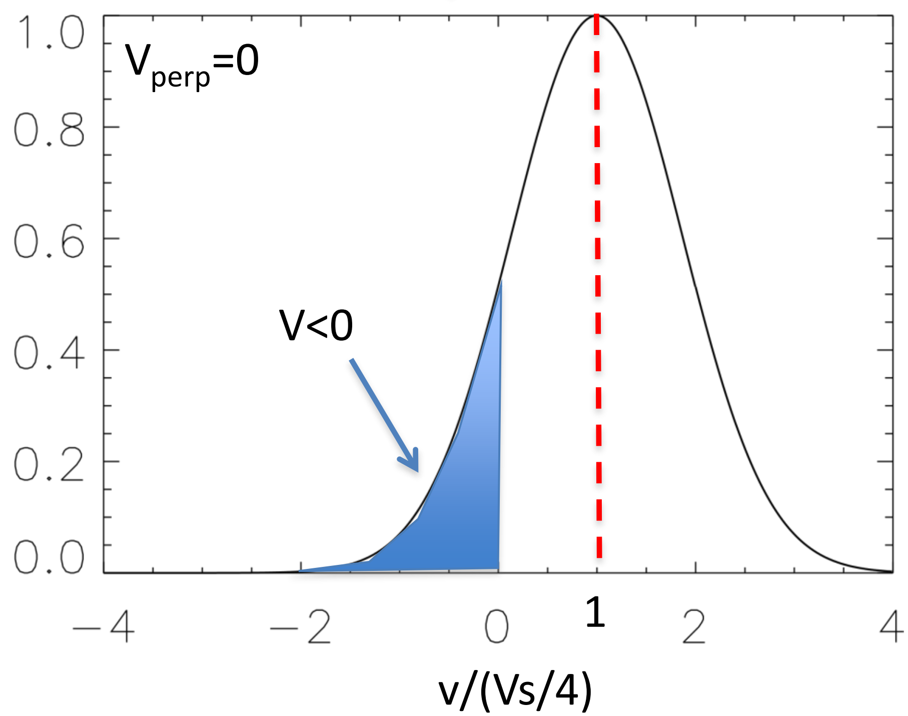
NEUTRALS
AND IONS

Blasi + 2012

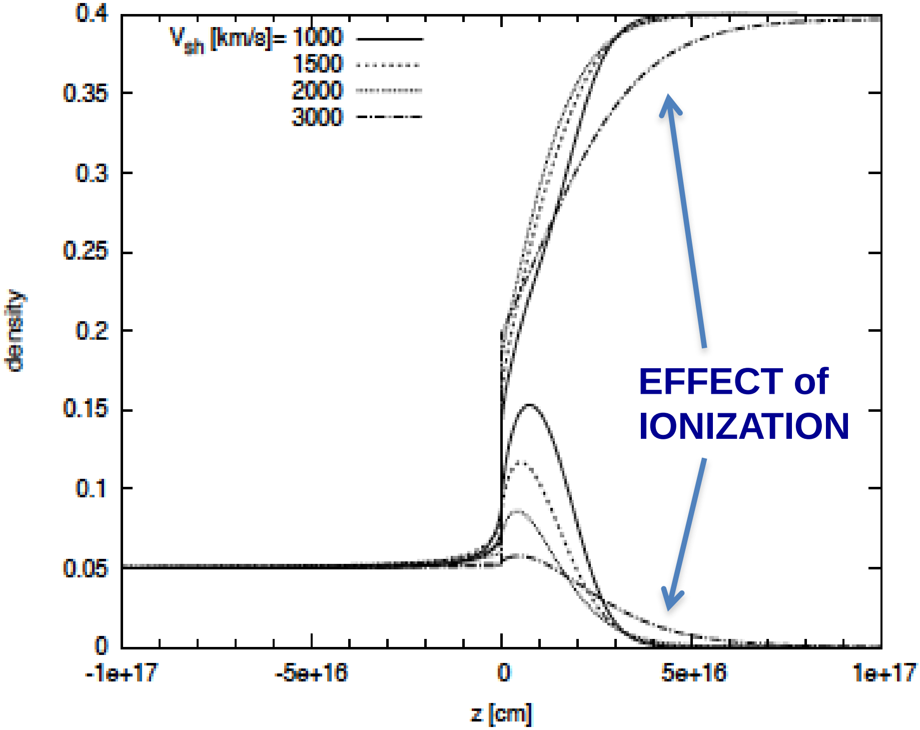
arXiv:1202.3080

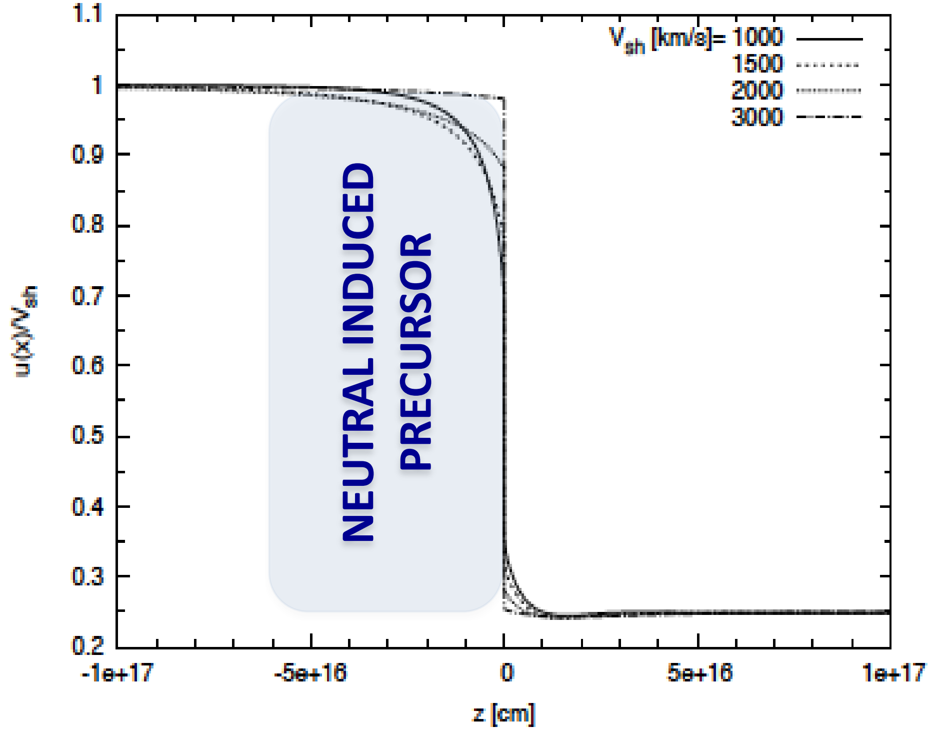
A NEUTRAL ATOM CAN CHARGE EXCHANGE WITH AN ION WITH V<0, THEREBY GIVING RISE TO A NEUTRAL WHICH IS NOW FREE TO RETURN UPSTREAM

THIS NEUTRAL RETURN FLUX LEADS TO ENERGY AND MOMENTUM DEPOSITION UPSTREAM OF THE SHOCK!



SHOCK MODIFIED BY THE NEUTRAL RETURN FLUX



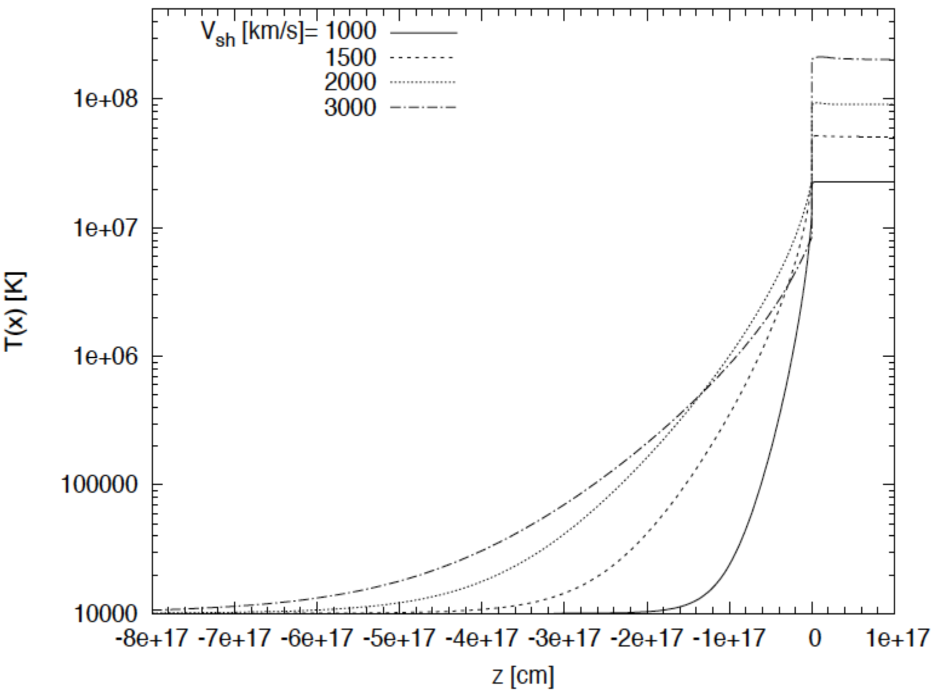


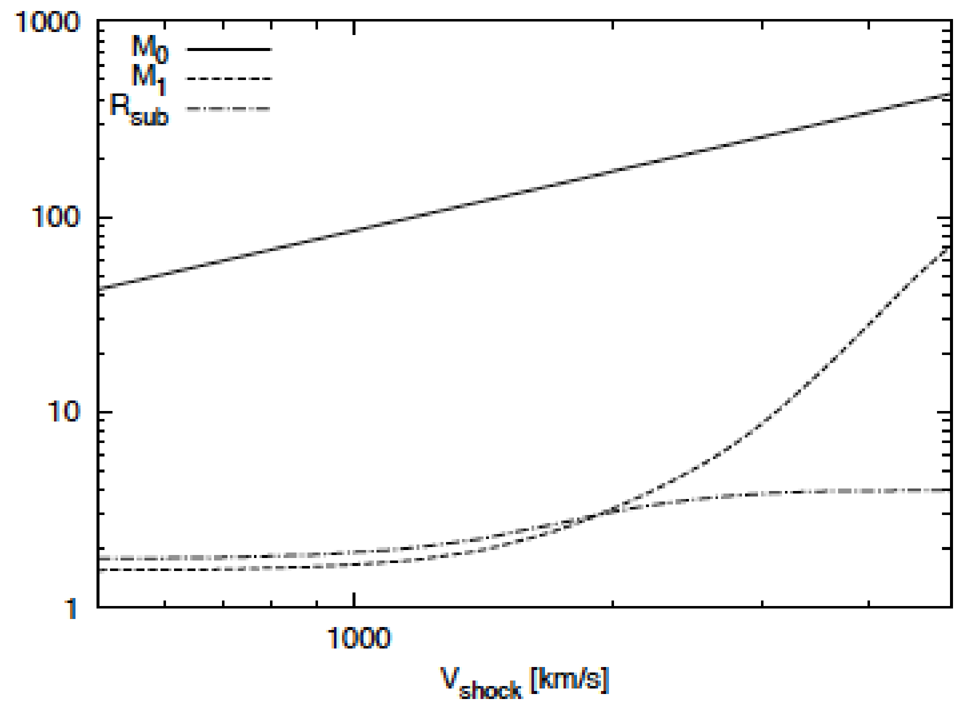
PB+2012

arXiv:1202.3080

NEUTRAL INDUCED PRECURSOR

PB+2012 arXiv:1202.3080

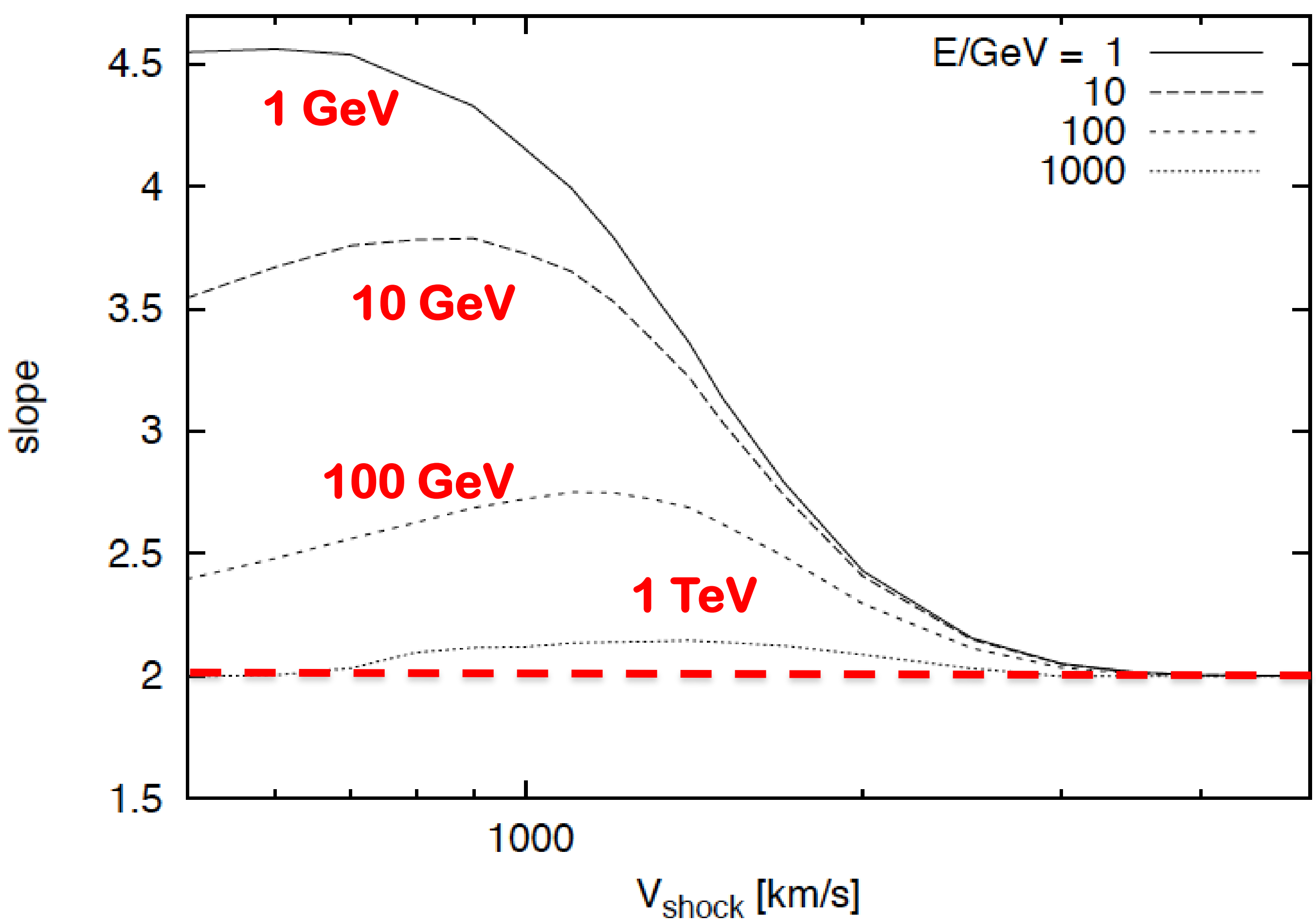




EVEN FOR A STRONG SHOCK (M>>1) THE EFFECTIVE MACH NUMBER OF THE PLASMA IS DRAMATICALLY REDUCED DUE TO THE ACTION OF THE NEUTRAL RETURN FLUX

ACCELERATION OF TEST PARTICLES

PB+ 2012 arXiv:1202.3080



CONCLUSIONS

THE SN PARADIGM EXPLAINS THE GENERAL OBSERVATIONAL PICTURE OF THE ORIGIN OF COSMIC RAYS

BUT MISSING PIECES: STEEP SPECTRA, ANISOTROPY, SPECTRAL FEATURES IN THE NUCLEAR SPECTRA

MAGNETIC FIELD AMPLIFICATION INDUCED BY CR IS NOW ONE OF THE HOT TOPICS IN EXPLAINING X-RAY MORPHOLOGY AND REACH THE KNEE

THE KNEE CAN BE EXPLAINED REASONABLY WELL IN TERMS OF CHANGE OF CHEMICAL COMPOSITION, BUT TRANSITION WELL BELOW THE ANKLE

PRESENCE OF NEUTRALS EXTREMELY IMPORTANT DIAGNOSTIC TOOL FOR CR ACCELERATION AS WELL AS POSSIBLE CAUSE FOR SPECTRAL STEEPENING