ORIGIN OF GALACTIC COSMIC RAYS

PASQUALE BLASI
INAF/ARCETRI ASTROPHYSICAL OBSERVATORY

Scineghe 2012, Lecce 19-22/06/2012

GENERAL TERMS

IT IS NOT ONE PROBLEM ANY MORE, BUT A WEB OF PROBLEMS INVOLVING ASTRONOMY, PARTICLE PHYSICS, PLASMA PHYSICS … :

1) **ACCELERATION (source dependent)**
2) **PROPAGATION**
3) **IN BOTH CASES ORIGIN OF THE SCATTERING CENTERS (LOTS OF PHYSICS HERE) - (this is tightly connected with anisotropy)**
4) **ESCAPE: FROM ACCELERATED PARTICLES TO COSMIC RAYS**
5) **ORIGIN OF THE KNEE**
6) **TRANSITION TO EXTRA-GALACTIC COSMIC RAYS**
7) **UHECR ARE ALL ANOTHER BALL GAME**

EVEN FROM THE OBSERVATIONAL POINT OF VIEW THERE ARE A VARIETY OF PHENOMENA THAT ARE USED TO ‘SEE’ CR AND THE RADIATION THEY PRODUCE.

THE SUPERNOVA REMNANT PARADIGM

The Historical Paradigm that Supernova Remnants (SNRs) are responsible for the acceleration of the bulk of Galactic CRs is globally in good shape.

The part of the paradigm that has been developed best is the acceleration part

CR originate through First Order Fermi Acceleration at the forward (and possibly at the reverse) shock of the SNR blast wave

For the acceleration efficiencies required to explain the fluxes (5-20%), non-linear effects cannot be ignored

A well established non-linear version of the Diffusive Shock Acceleration (DSA) Theory has been developed by many authors (Berezhko, Voelk, Ellison, PB+)

ENERGETICS INVOLVED

THE DENSITY OF CR IN THE EASIEST SCENARIO IS SIMPLY:

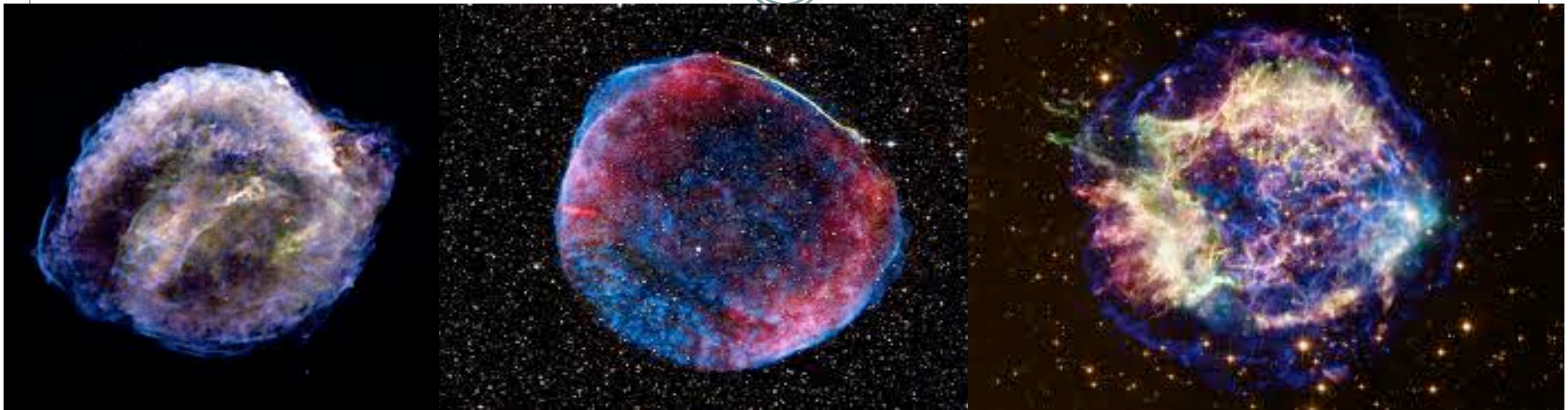
$$n_{CR}(E) = \frac{N(E)\mathcal{R}}{2\pi R_d^2}\frac{H}{D(E)} \equiv \frac{N(E)\mathcal{R}}{2H\pi R_d^2}\frac{H^2}{D(E)}$$

RATE OF SN PER UNIT TIME PER UNIT VOLUME — **CONFINEMENT TIME**

THE TYPICAL EFFICIENCY OF 5-10% FOR THE PARADIGM TO WORK DERIVES FROM THE 'MEASUREMENT' OF THE CONFINEMENT TIME AS INFERRED FROM B/C AND ^{10}Be.

THIS MEASUREMENT IS, IN TURN, THE ONLY WAY TO INFER THE DIFFUSION PROPERTIES OF THE ISM

SUPERNOVA SHOCKS

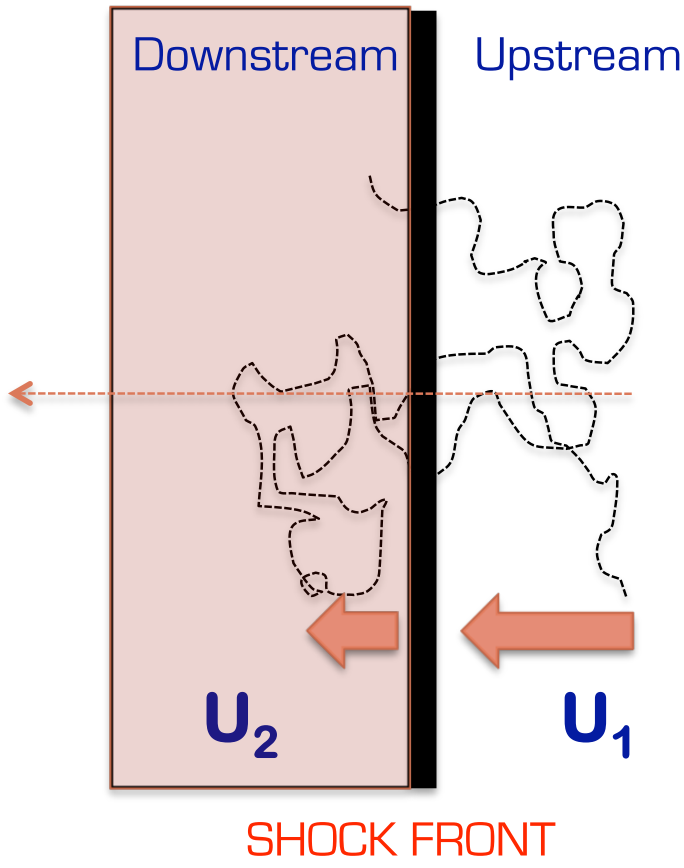


FREE EXPANSION VELOCITY: $V_s = \sqrt{\frac{2E_{ej}}{M_{ej}}} = 10^9\ E_{51}^{1/2}\ M_{ej,\Theta}^{-1/2}\ \text{cm/s}$

THE EXPANSION SPEED DROPS DOWN DURING THE SEDOV-TAYLOR PHASE, BUT THE MACH NUMBER IS ~100

A STRONG SHOCK WAVE DEVELOPS

The 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

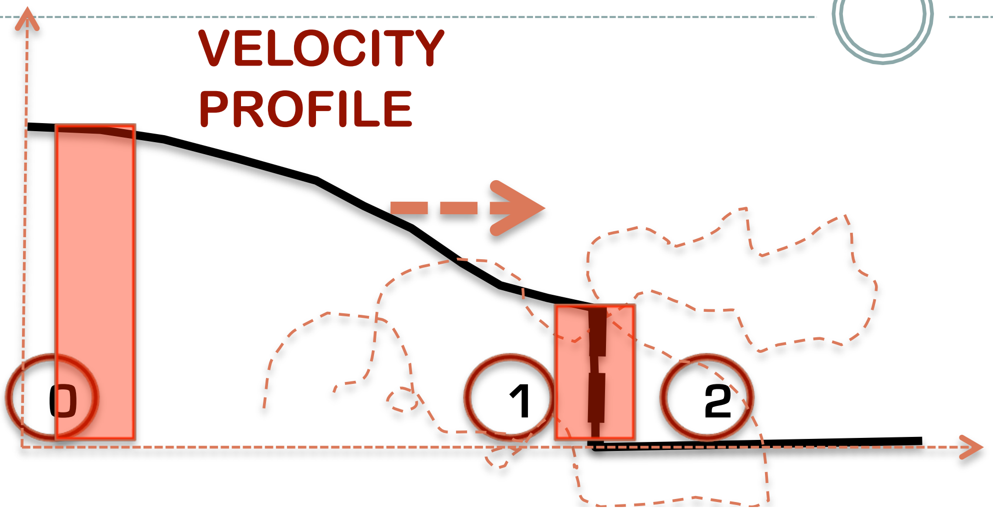
FOR STRONG SHOCKS: E^{-2}

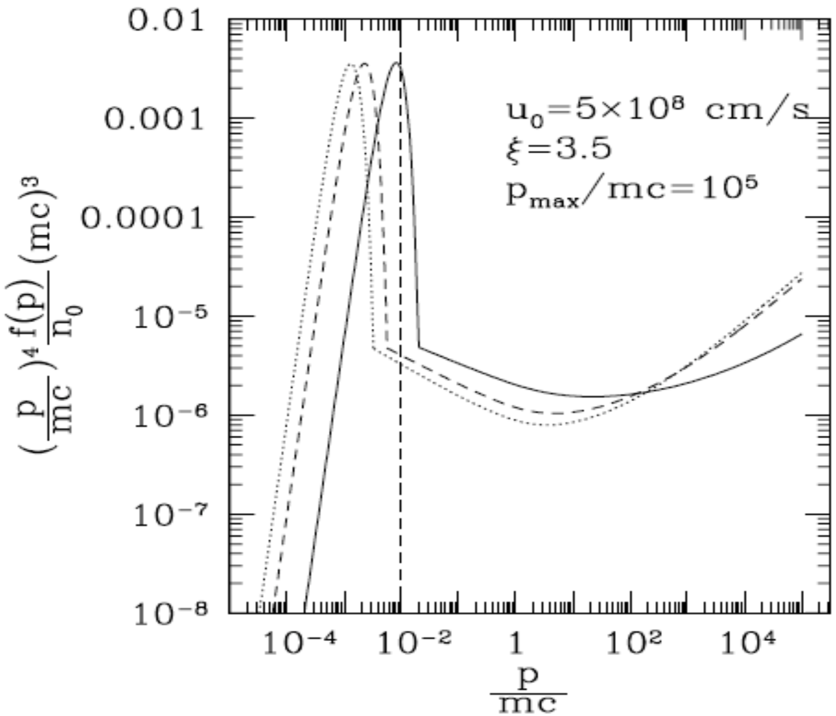
NON LINEAR THEORY

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)**

BASIC PREDICTIONS





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

MAGNETIC FIELD AMPLIFICATION

CR streaming with the shock leads to growth of waves. The general idea is simple to explain:

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

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

and assuming equilibrium:

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

And for parameters typical of SNR shocks:

$$\gamma_W \simeq \sqrt{2}\, \xi_{CR} \left(\frac{V_s}{c}\right)^2 \frac{V_s}{V_A} \Omega_{cyc} \sim \mathcal{O}(10^{-4}\ seconds^{-1})$$

X-ray rims and B-field amplification

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

The synchrotron limited thickness is:

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

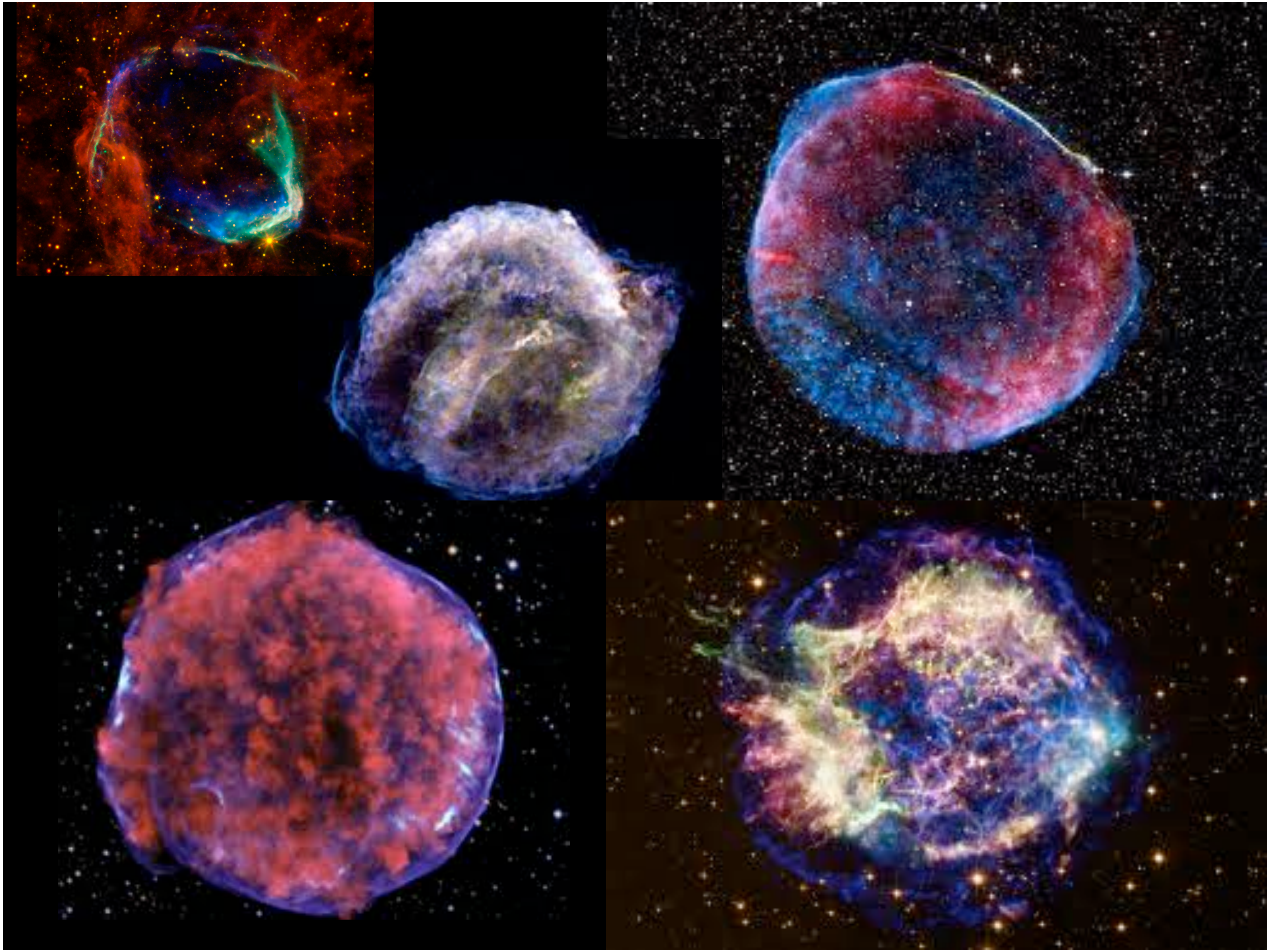
$$B \approx 100\ \mu\mathrm{Gauss}$$

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

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

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

Uchiyama & Aharonian, 2007



…BUT MAGNETIC FIELD CAN BE AMPLIFIED BY

1. **RESONANT STREAMING** (Bell 78, Achterberg 83, Zweibel 78)
   Fast generation, fast scattering … saturation?

2. **NON RESONANT STREAMING** (Bell 04, Amato & PB 09)
   Probably more efficient generation rate but inefficient scattering

3. **SHOCK CORRUGATION (DOWNSTREAM)** Giacalone & Jokipii 07
   Not CR induced!
   It happens downstream only, it does not help with particle acceleration unless perpendicular shock

4. **VORTICITY IN THE PRECURSOR** (PB, Matthaeus, et al. 12; Drury & Downes, 2012)
   Potentially very interesting, power on large scales

5. **FIREHOSE INSTABILITY** (Shapiro et al. 98)
   Potentially very interesting, power on large scales

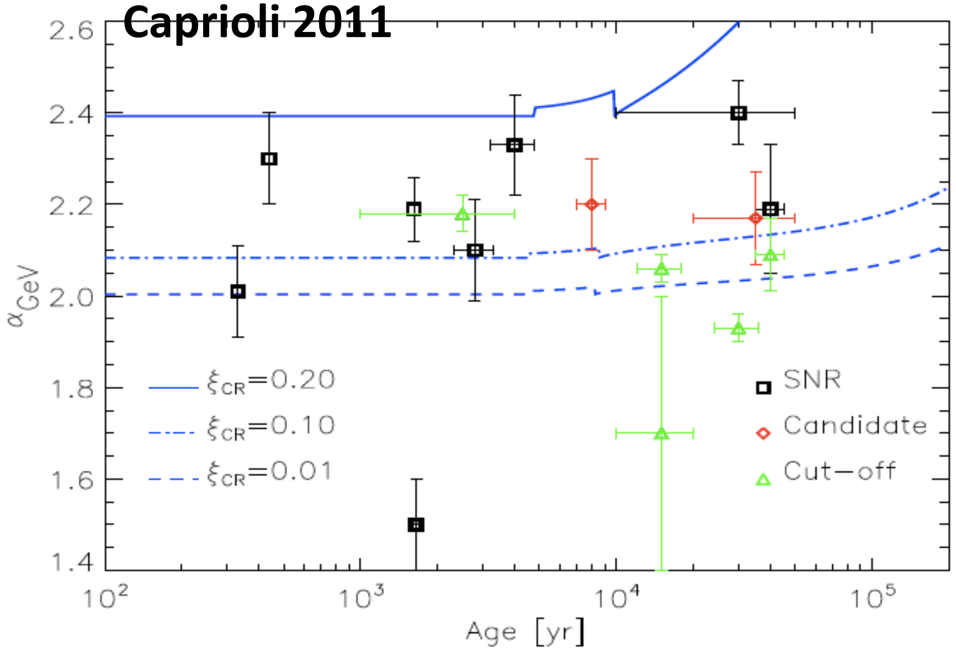
Problematic Aspects I: Spectra

The non linear theory of DSA (as well as the test particle theory) all predict CR spectra close to E^{-2} and even harder than E^{-2} at E>10 GeV

This finding does not sit well with:

1) **CR Anisotropy**
2) **Gamma Ray Spectra from selected SNRs**

Caprioli 2011



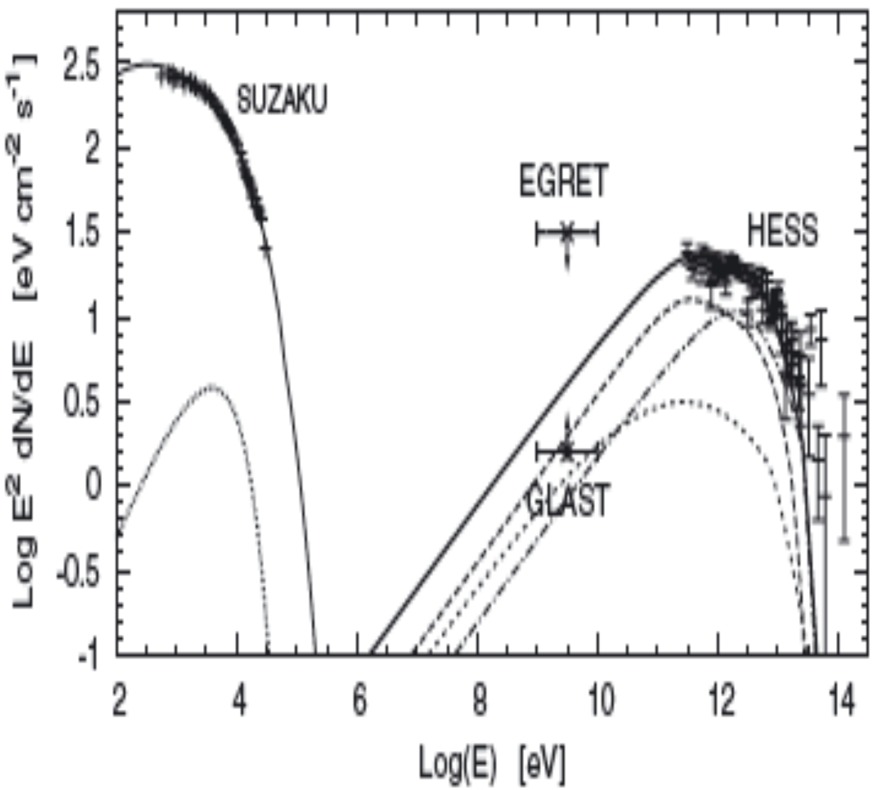
THE PROBLEM WITH ANISOTROPY IS CONNECTED WITH THE FACT THAT:

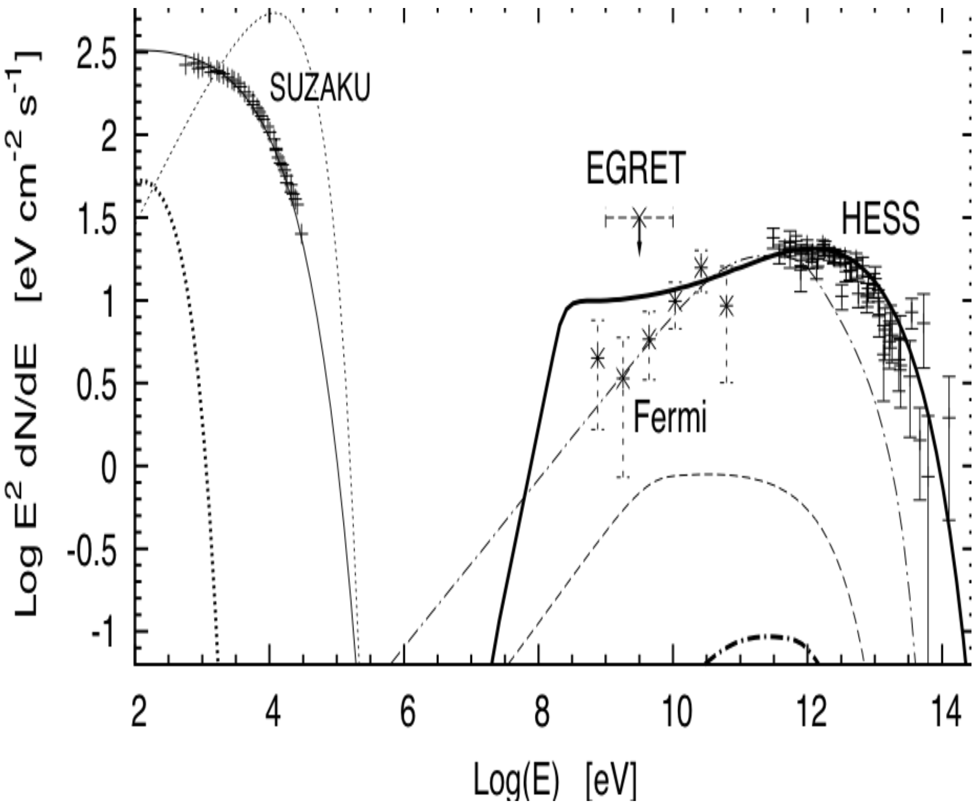
$\gamma+\delta = 2.7 \rightarrow \delta=0.6-0.7$

WHILE THE ISSUES WITH THE GAMMA RAY SPECTRA IS ILLUSTRATED ON THE SIDE

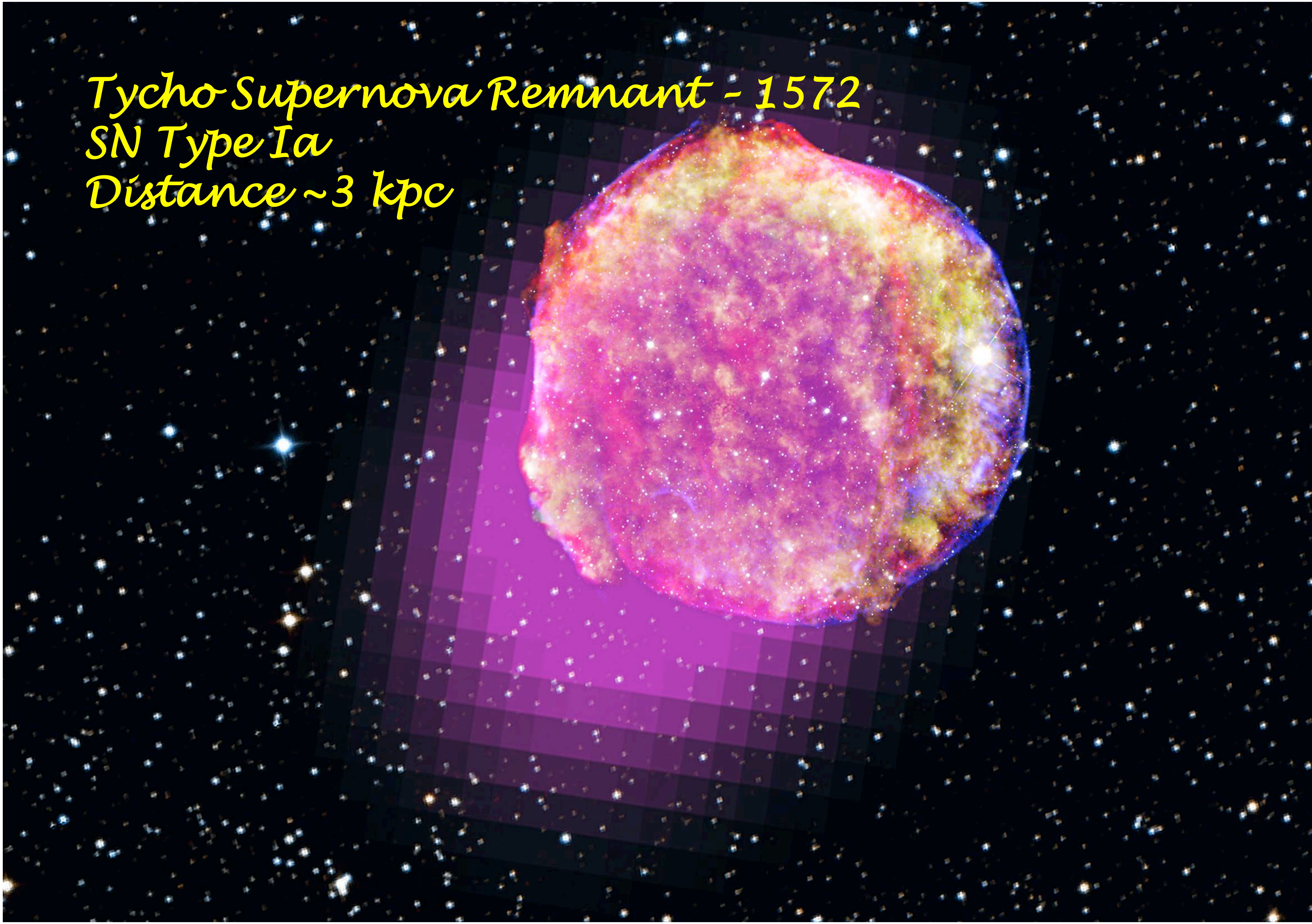
THE CASE OF RX J1713

Morlino et al. 2009



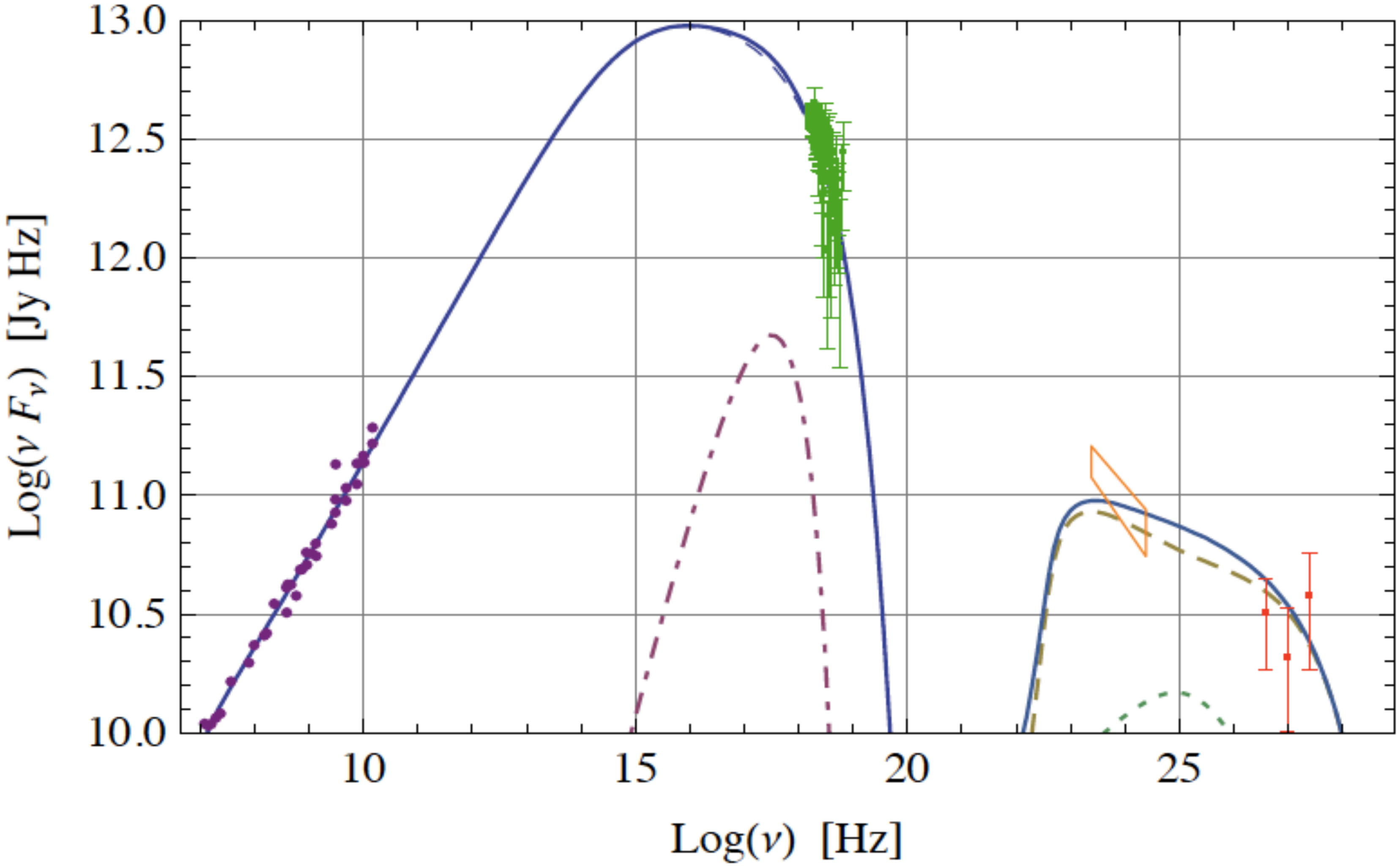


Morlino, Amato & PB 2009


Tycho Supernova Remnant - 1572
SN Type Ia
Distance ~3 kpc

THE CASE OF TYCHO

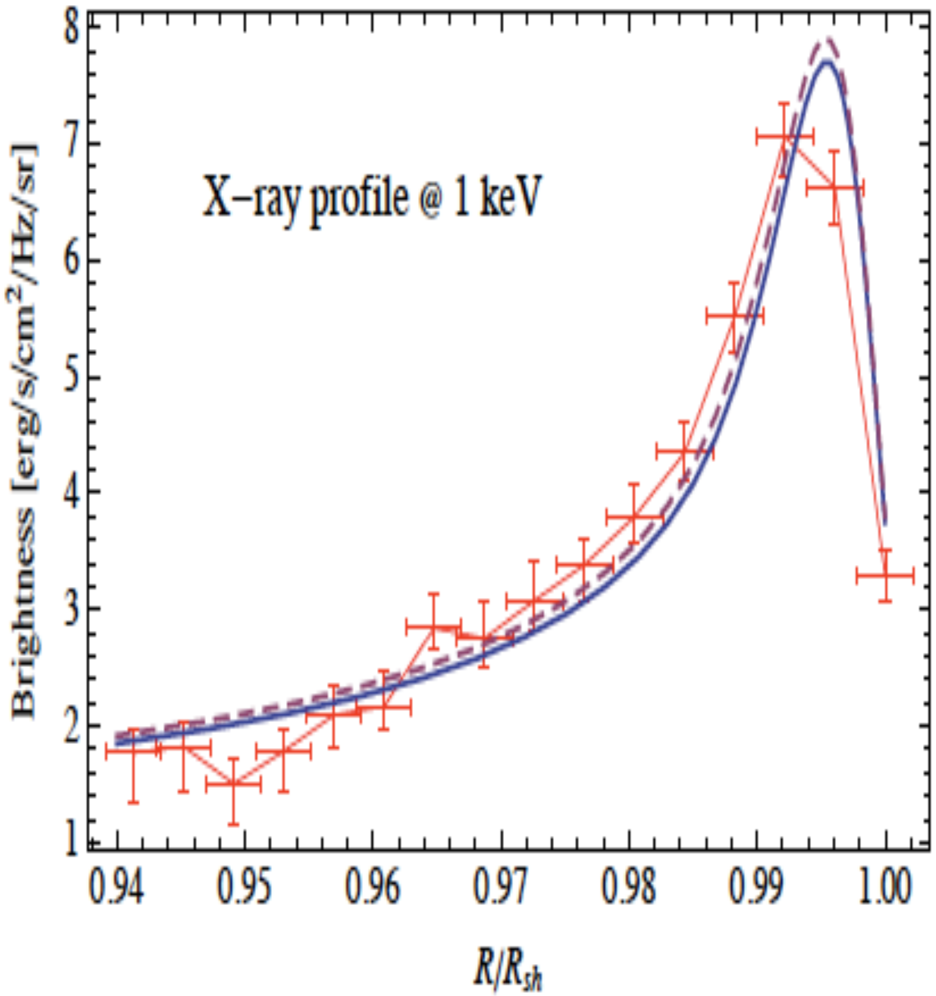
Morlino&Caprioli 2011

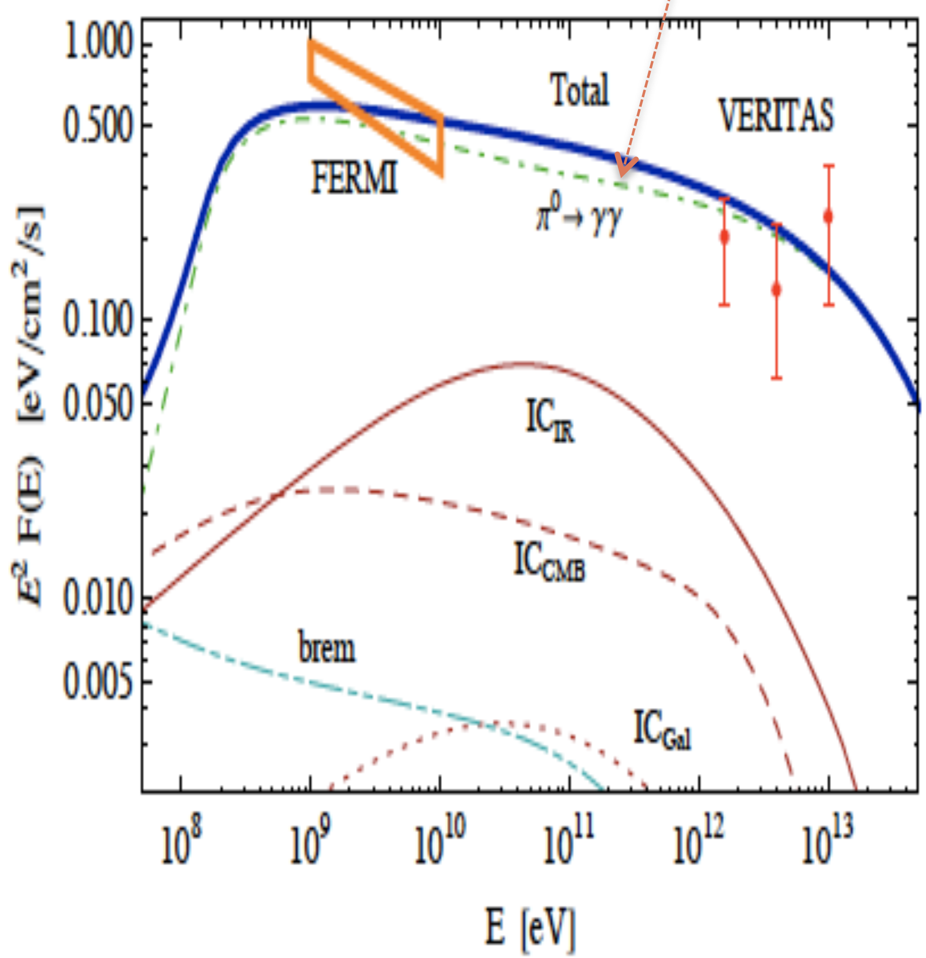


THE CASE OF TYCHO

Morlino&Caprioli 2011

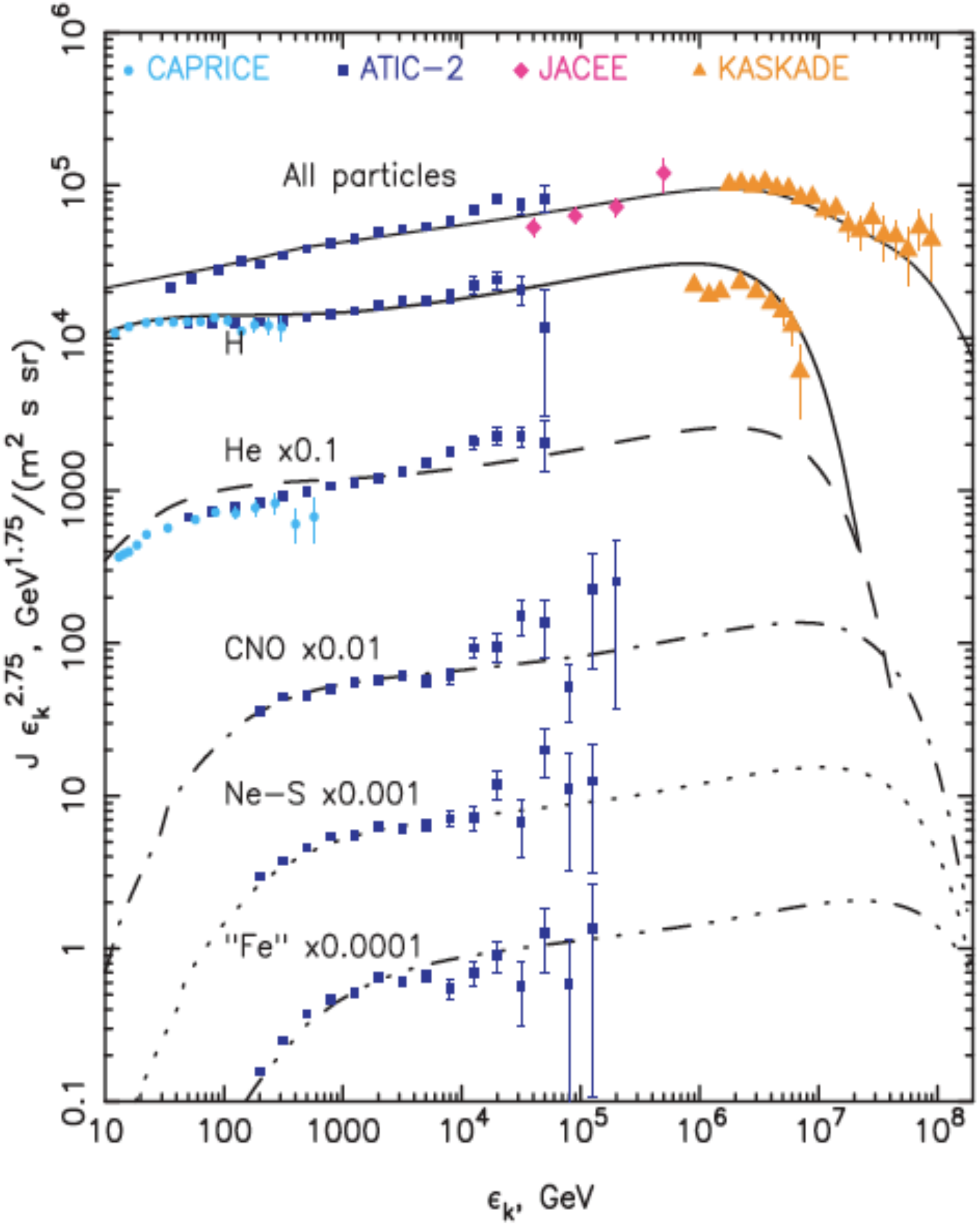
STEEP SPECTRUM BASICALLY IMPOSSIBLE TO EXPLAIN WITH LEPTONS

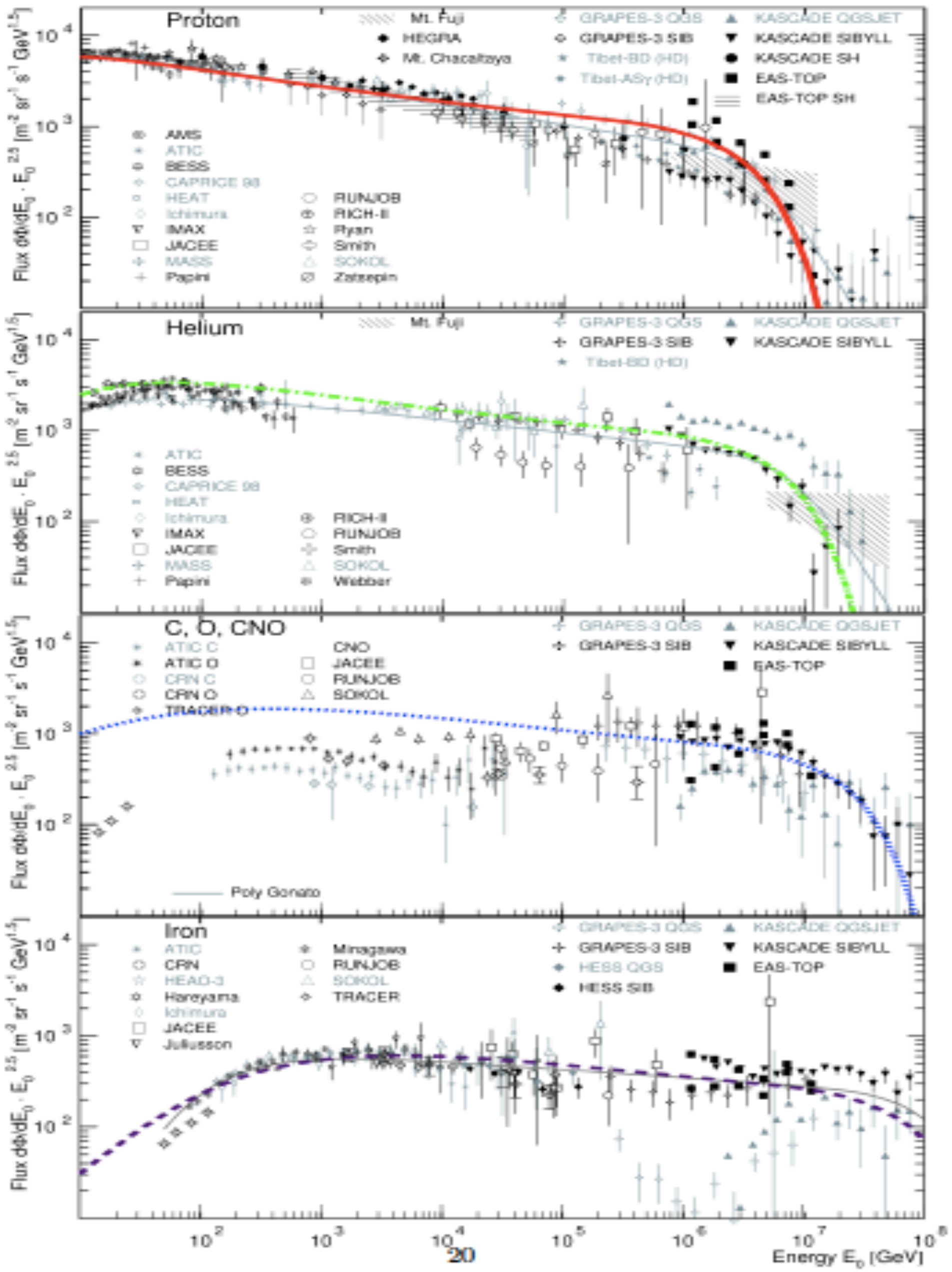




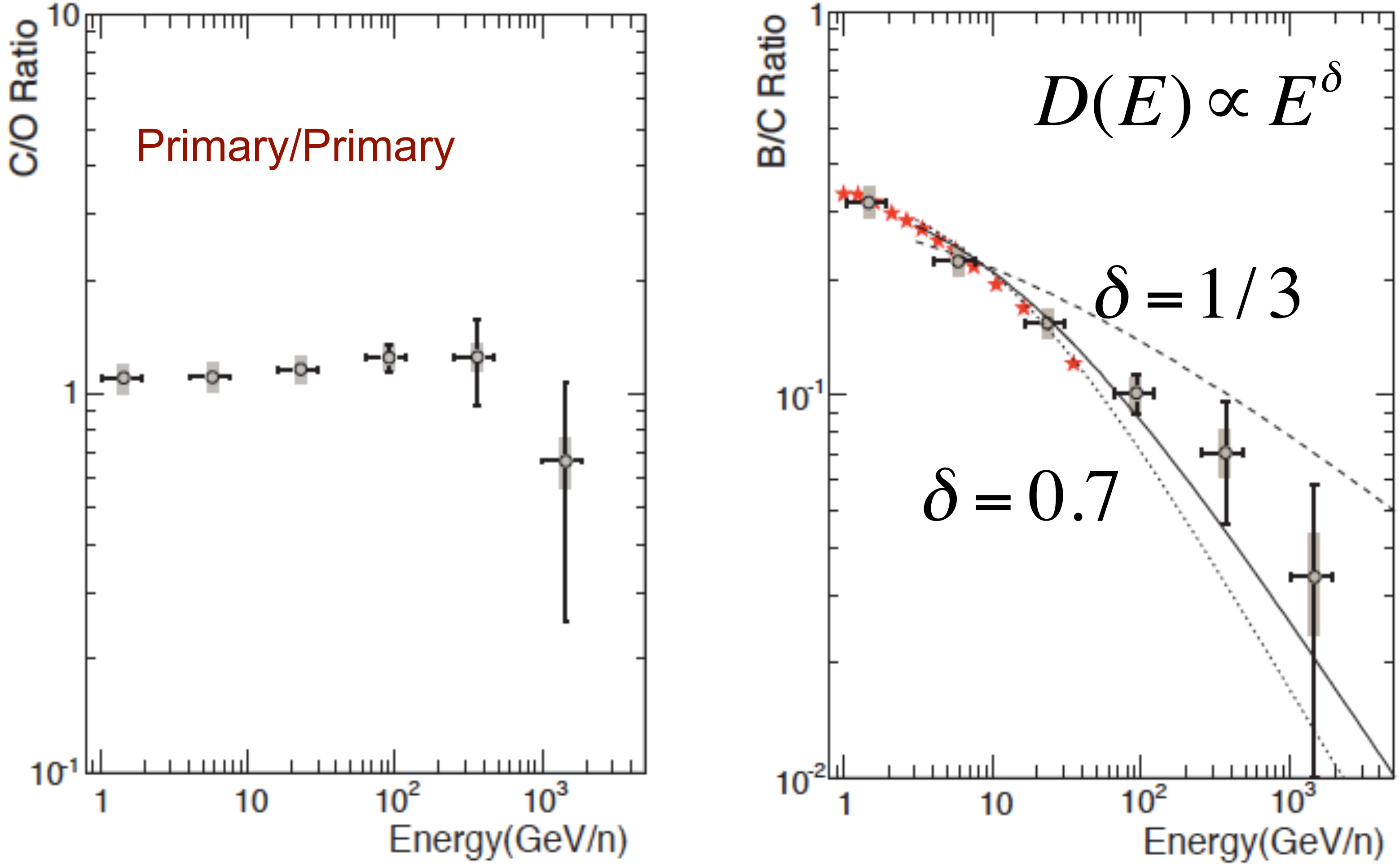
Berezhko & Voelk (2007): D(E) ~ $E^{0.75}$

Caprioli, PB & Amato (2010) and Ptuskin, Zirakashvili & Seo (2010): D(E)~$E^{0.54}$ due to the effect of velocity of Scattering centers

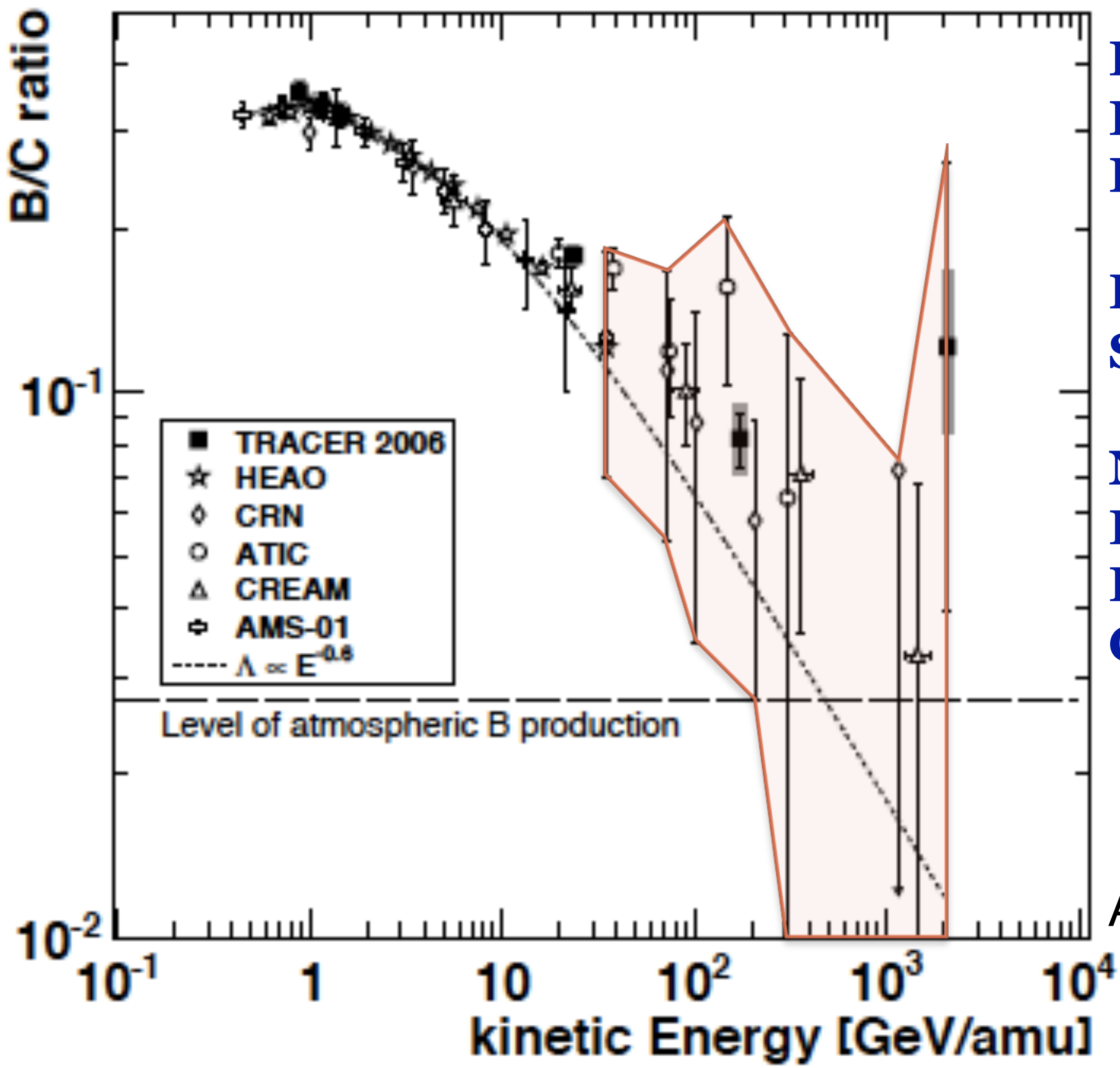




Secondary/Primary ratios



THE B/C RATIO AS A DIFFUSION INDICATOR



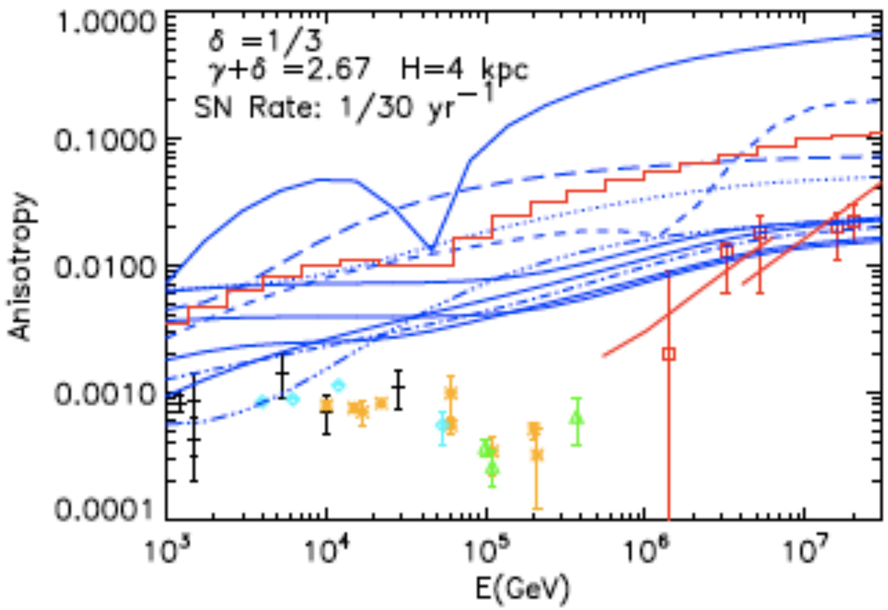
IN PRINCIPLE B/C ~ 1/D(E) IN THE HIGH RIGIDITY REGIME

BUT UNCERTAINTIES ARE STILL LARGE

NOT EASY TO DISCRIMINATE AMONG DIFFERENT DIFFUSION COEFFICIENTS

Adapted from Obermeier et al. 2011

PROBLEMATIC ASPECTS II: LARGE SCALE CR ANISOTROPY



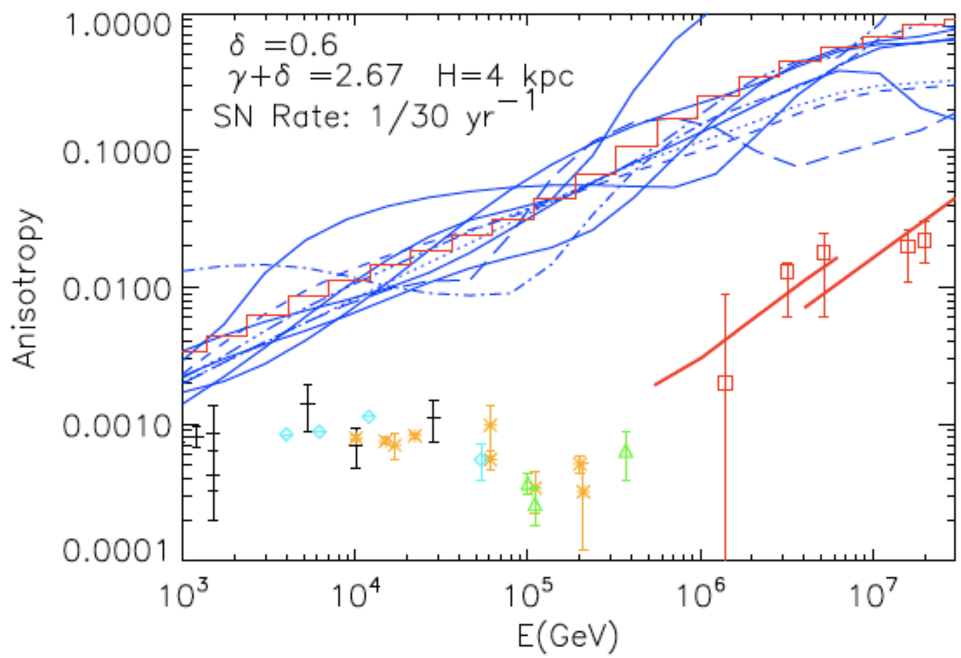
$\delta=1/3$

Naïve expectation:

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

proportional to E^{δ}

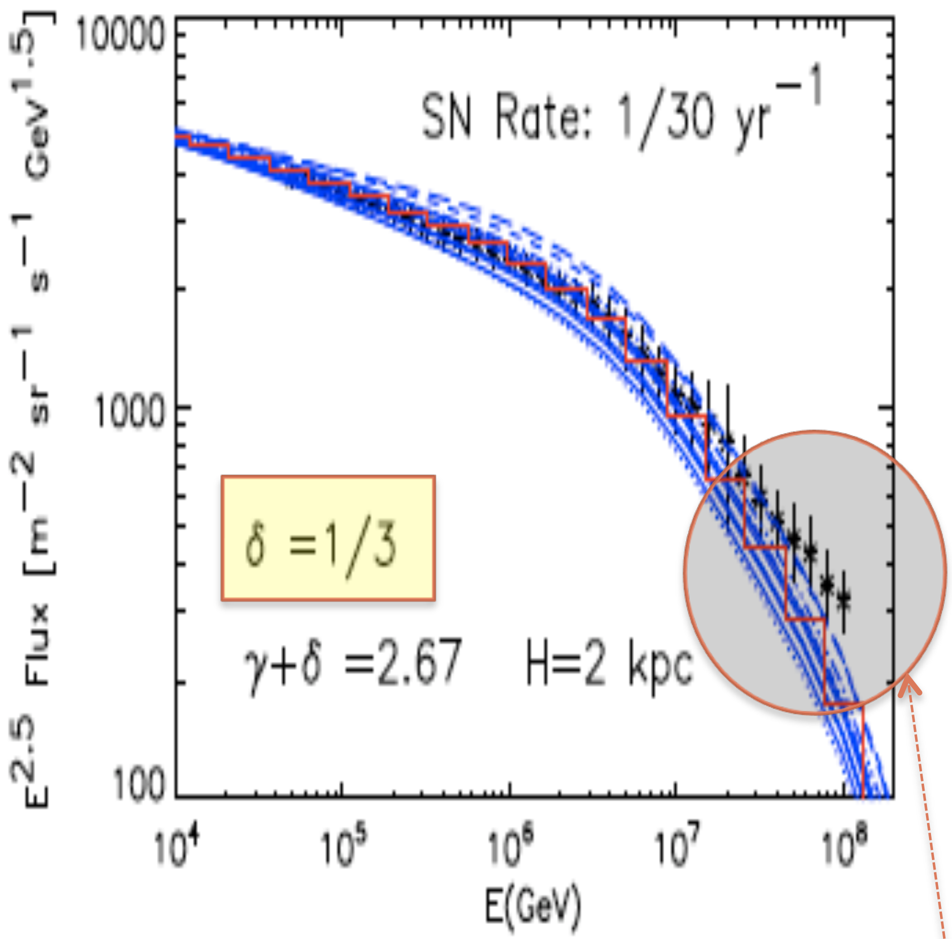
$\delta=0.6$

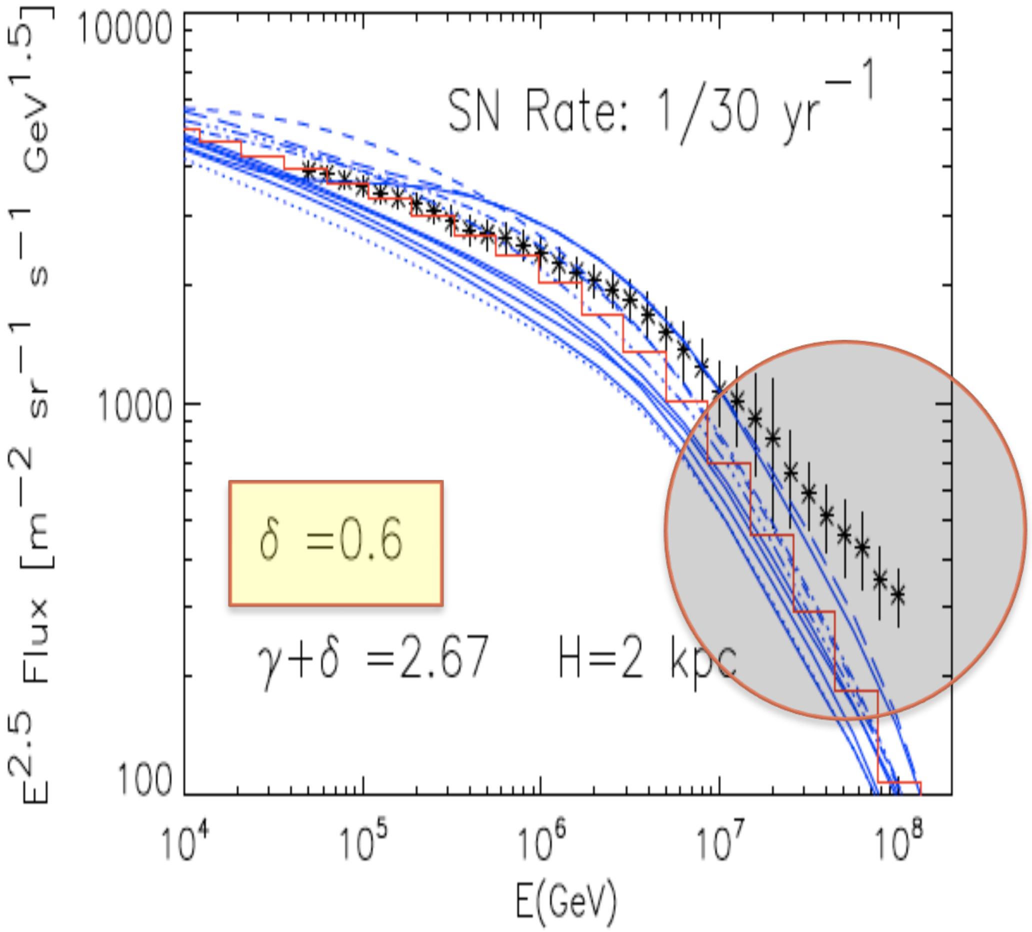


PB & Amato 2011 (see also Wolfendale, Erlykin)

CR SPECTRA AND RANDOM NATURE OF SNR

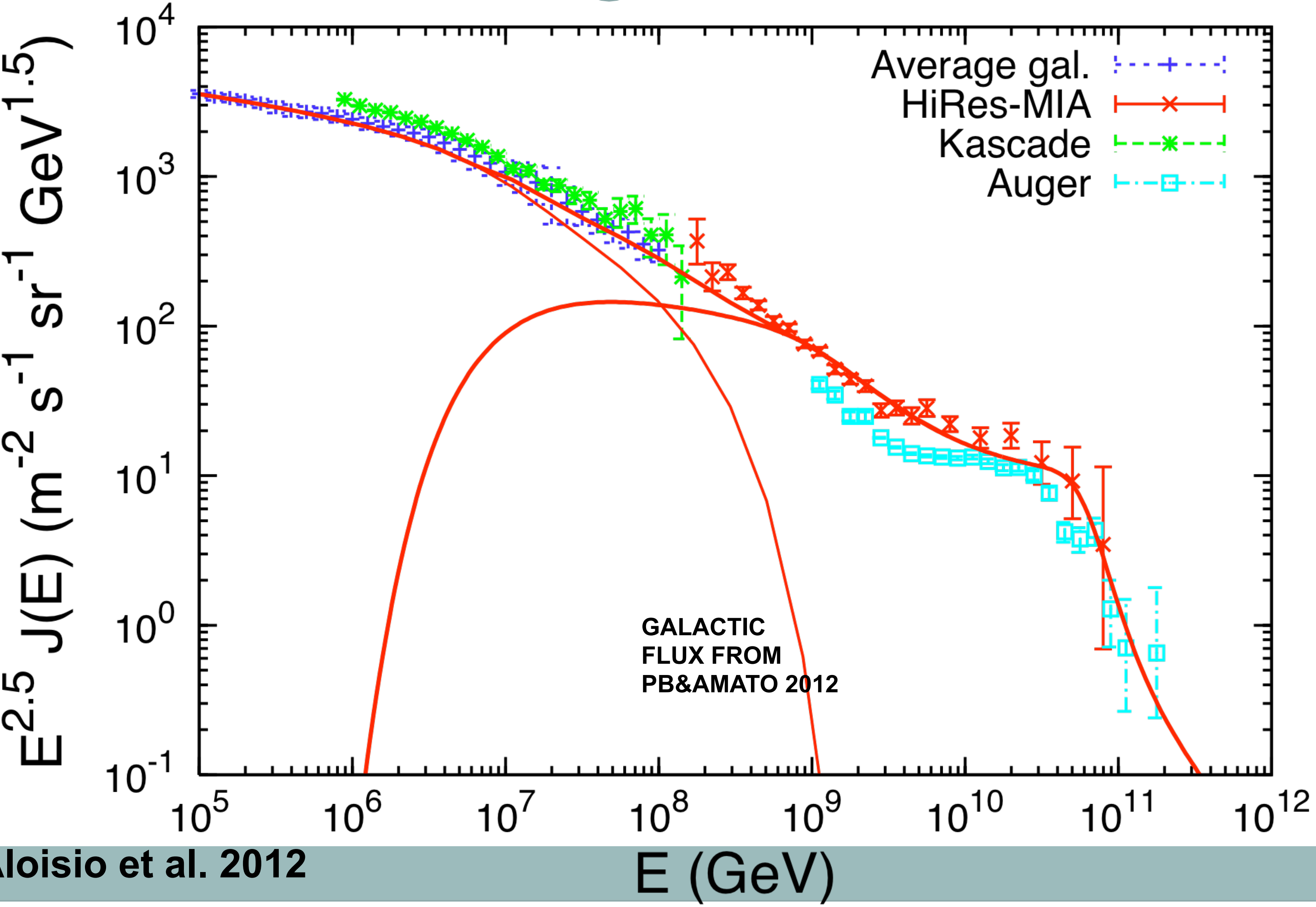
PB & Amato 2011





Deficit compensated
by extragalactic CRs?

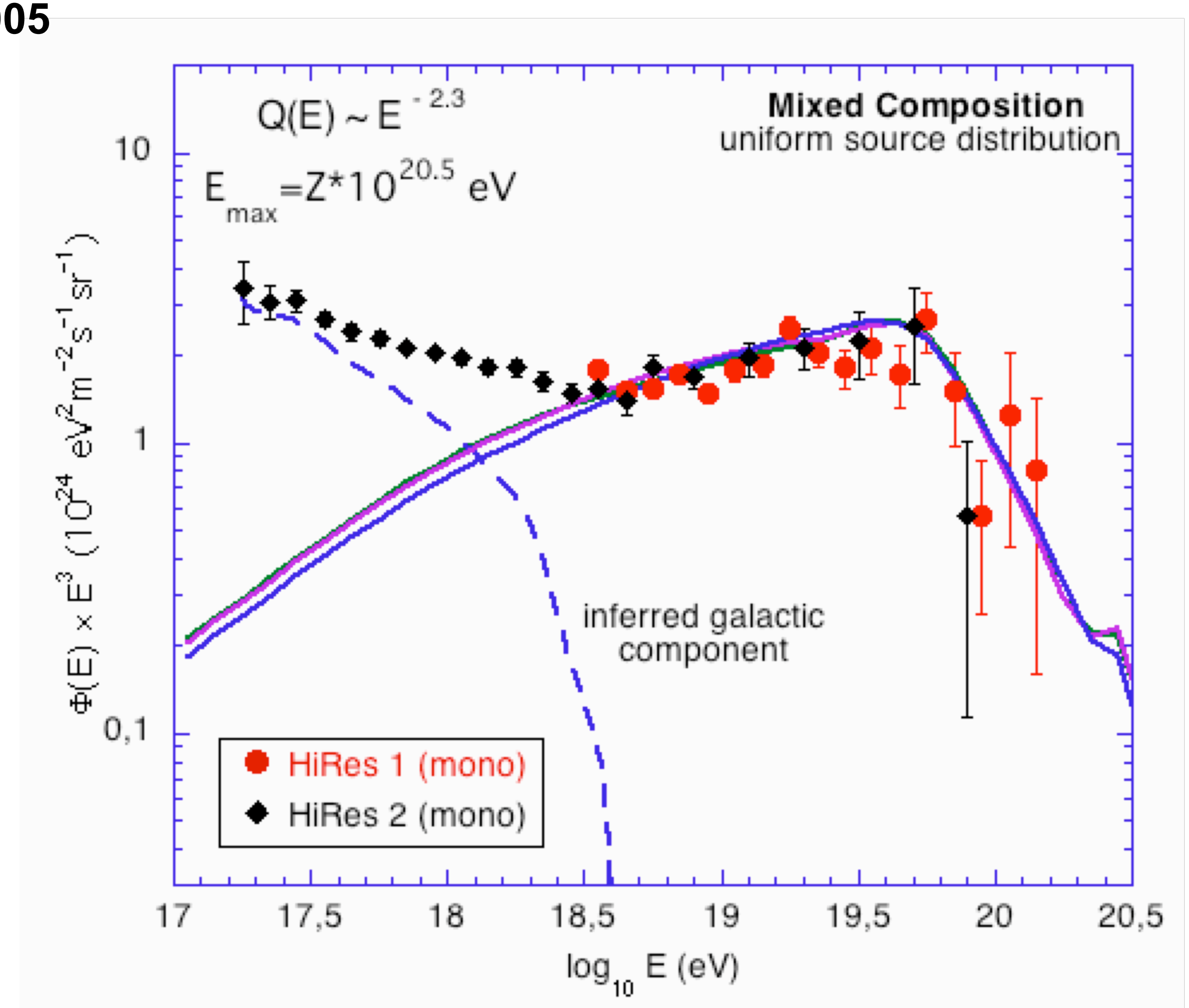
THE TRANSITION REGION - DIP



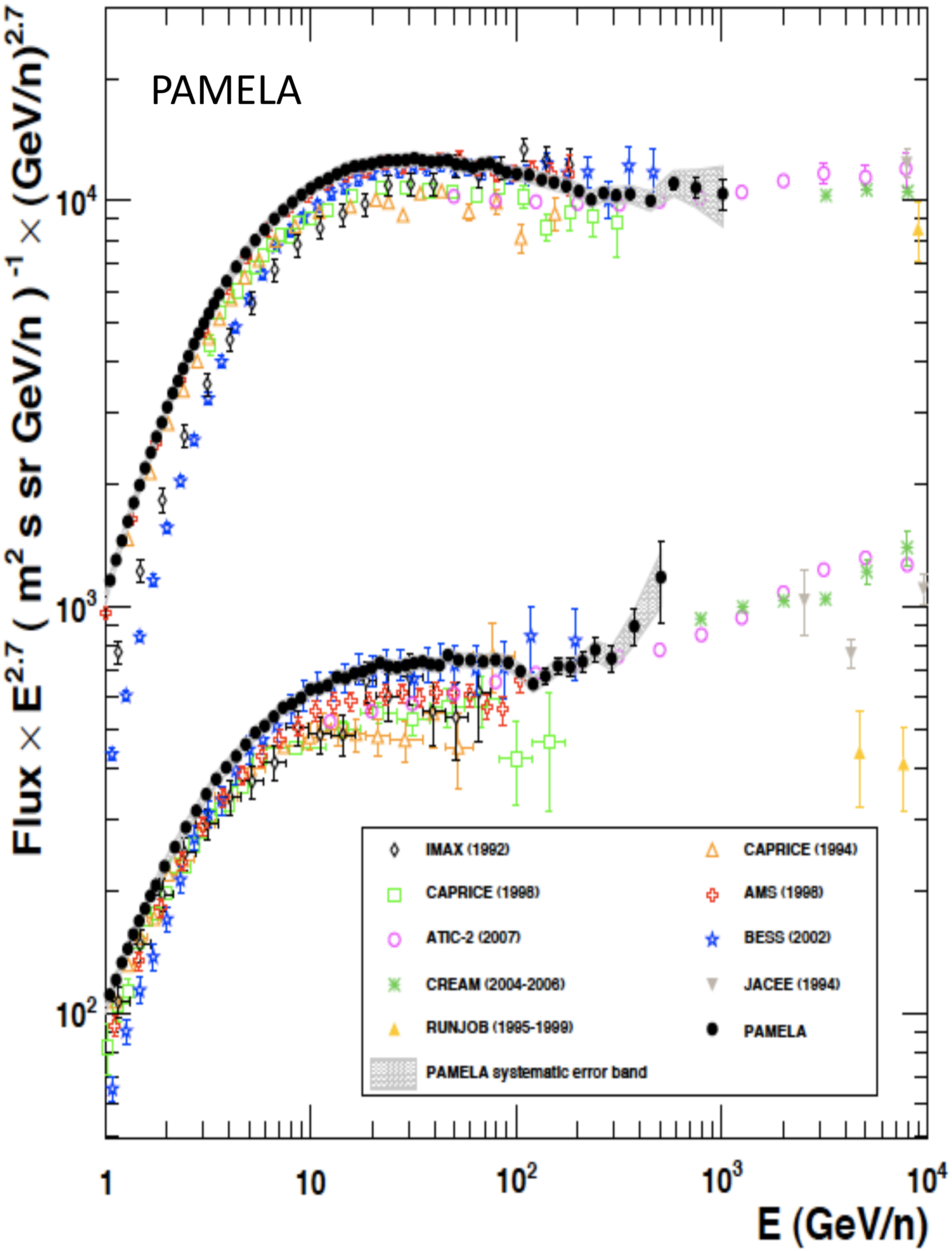
Aloisio et al. 2012

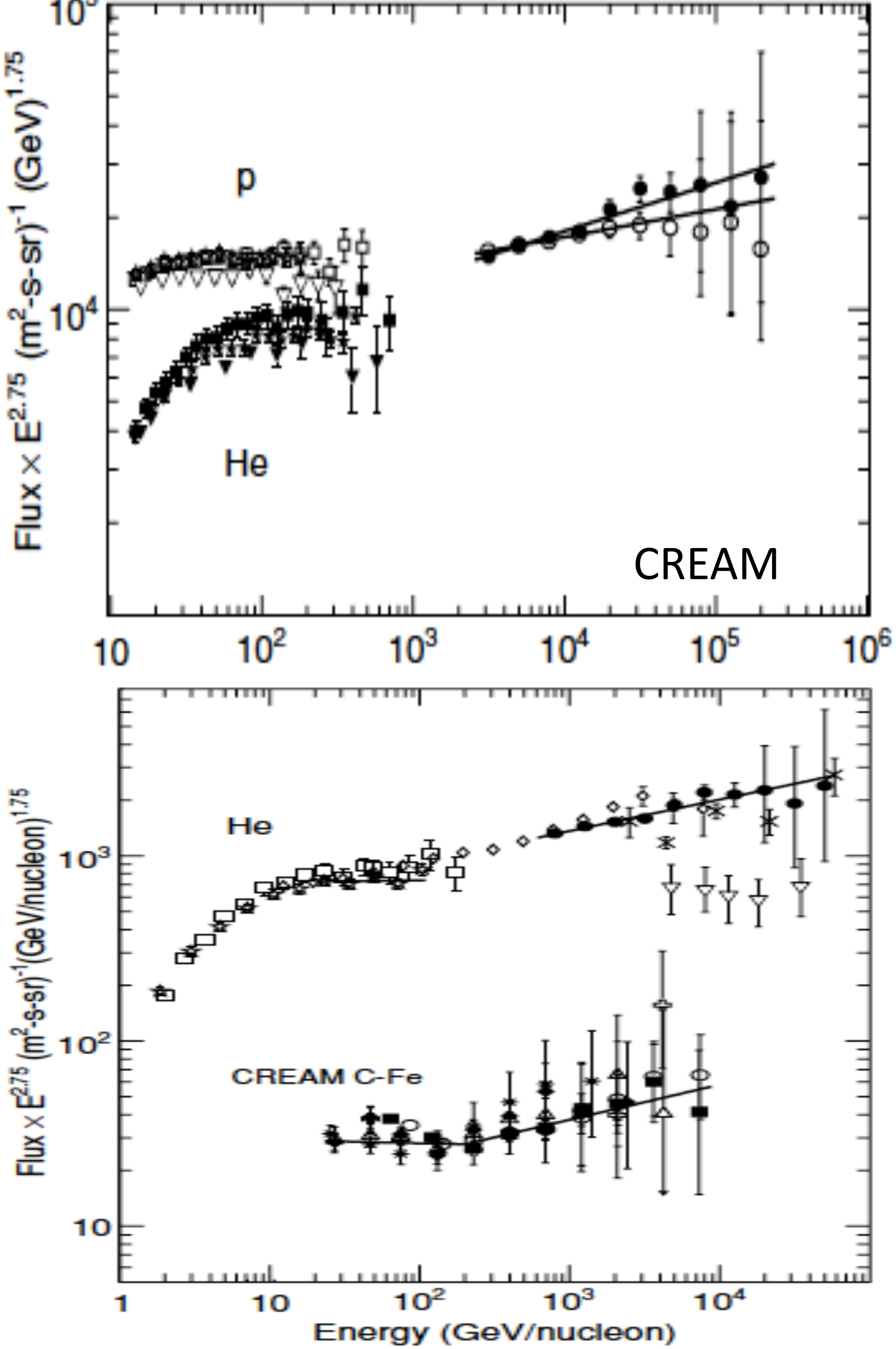
TRANSITION REGION – MIXED COMPOSITION

Allard et al. 2005

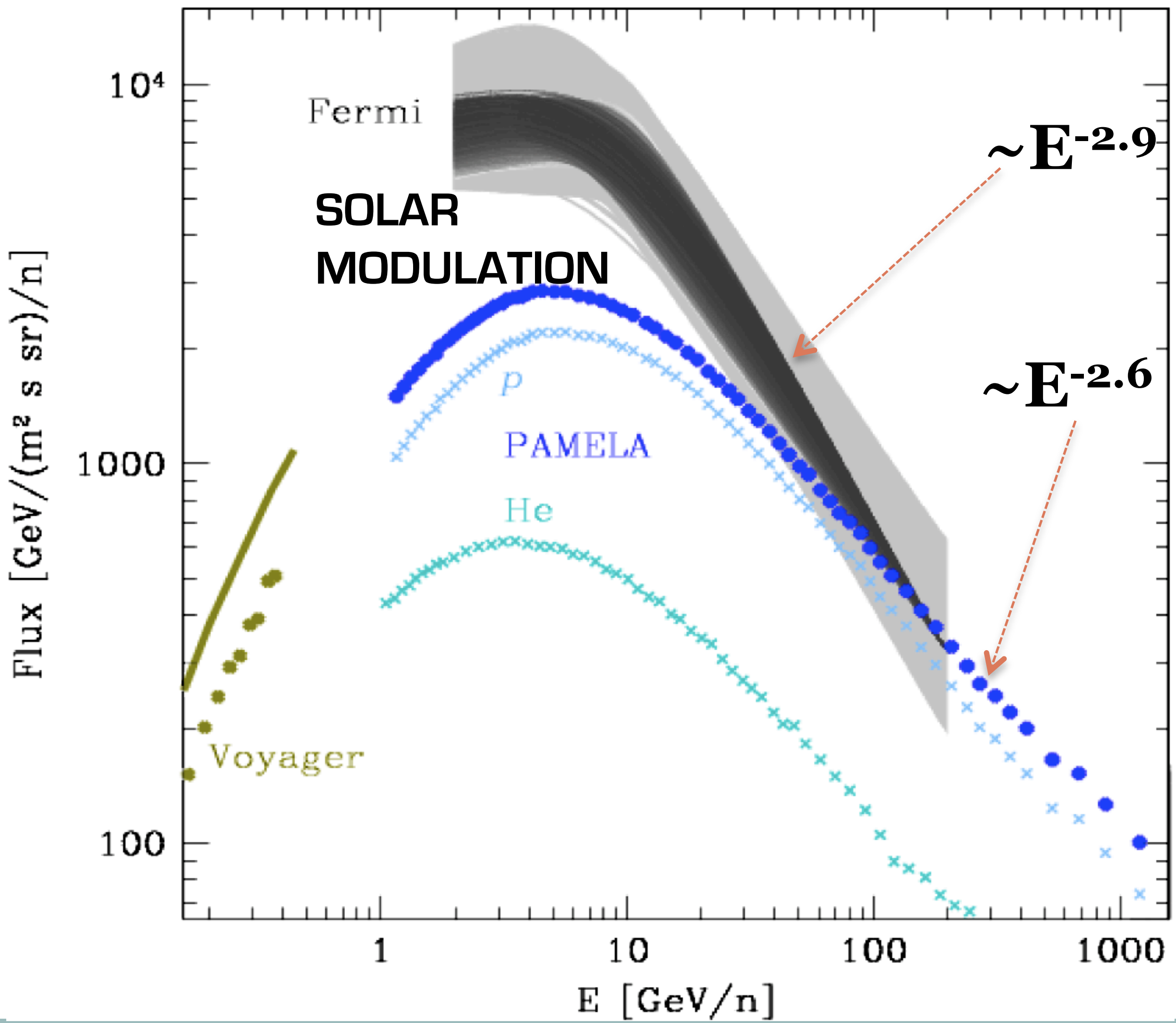


SOMETHING NEW IN PROPAGATION OF GALACTIC COSMIC RAYS?


PAMELA
Flux × E^2.7 (m^2 s sr GeV/n)^-1 × (GeV/n)^2.7
E (GeV/n)
IMAX (1992)
CAPRICE (1994)
CAPRICE (1998)
AMS (1998)
ATIC-2 (2007)
BESS (2002)
CREAM (2004-2006)
JACEE (1994)
RUNJOB (1995-1999)
PAMELA
PAMELA systematic error band

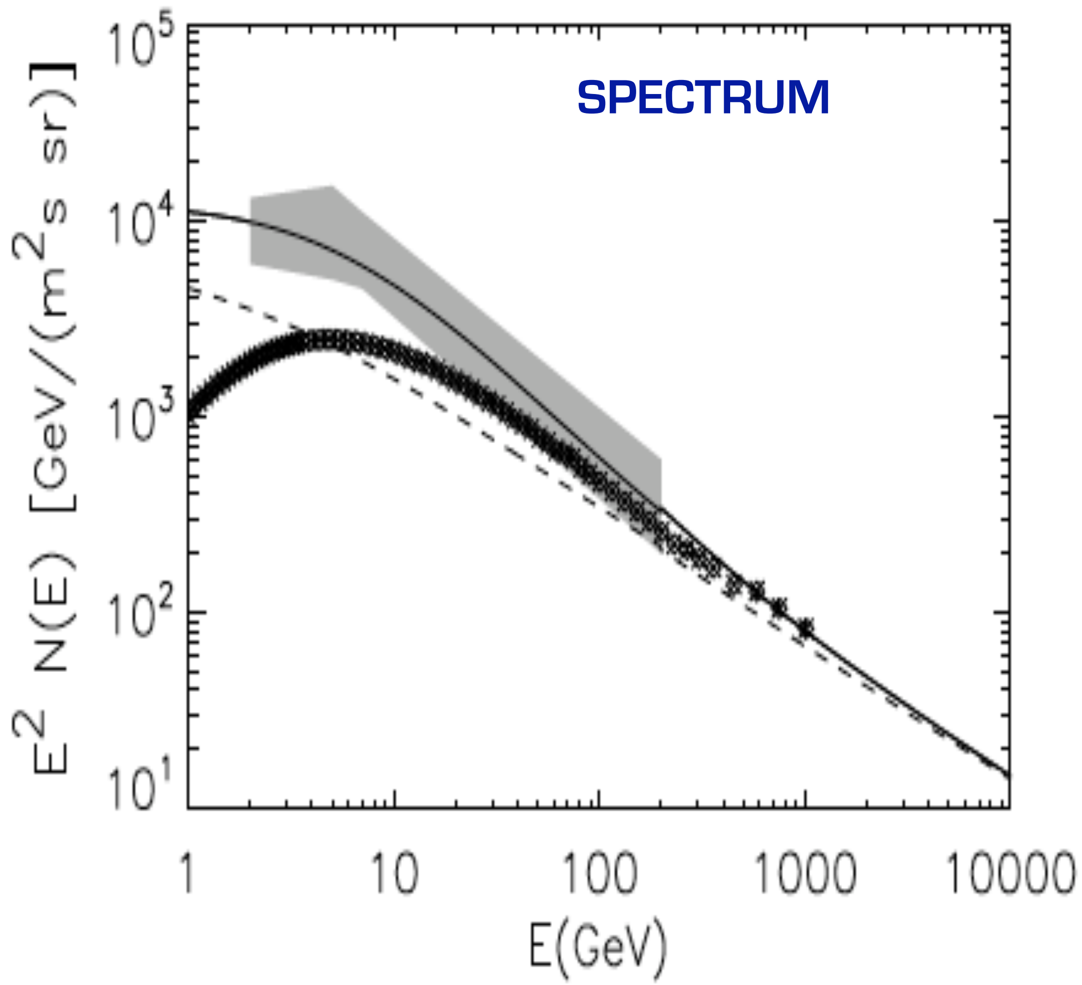

p
He
CREAM
Flux × E^2.75 (m^2-s-sr)^-1 (GeV)^1.75
He
CREAM C-Fe
Flux × E^2.75 (m^2-s-sr)^-1 (GeV/nucleon)^1.75
Energy (GeV/nucleon)

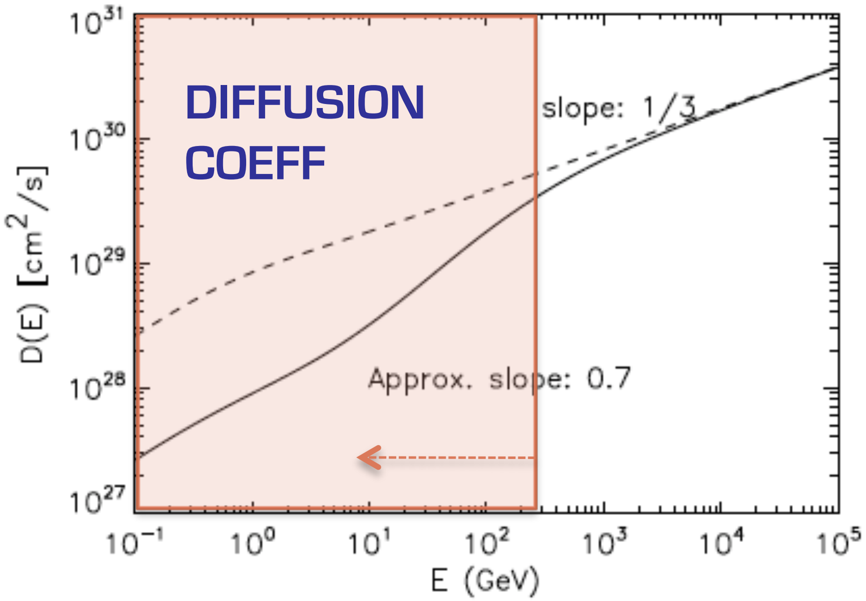
CLOUDS IN THE GOULD BELT

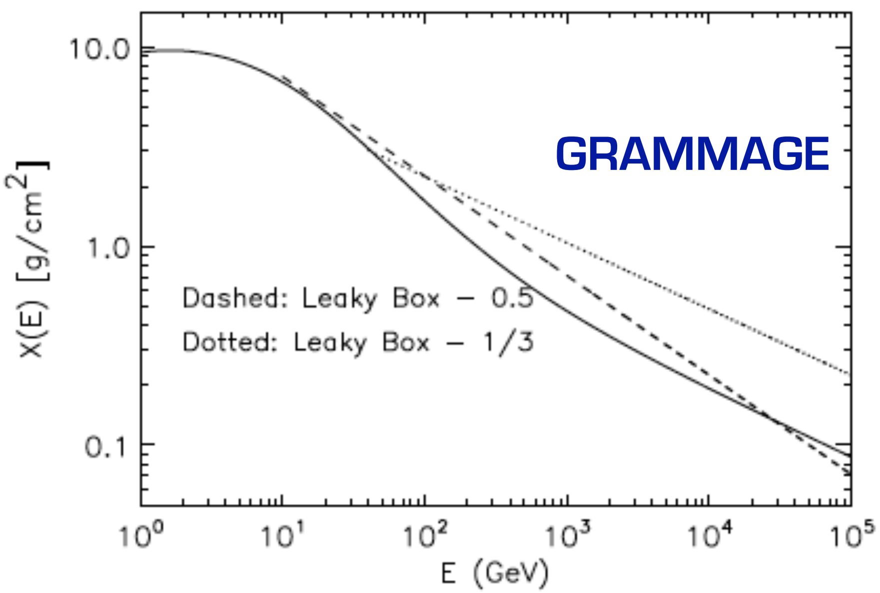


Neronov, Semikoz, Taylor 2012

A POSSIBLE EXPLANATION



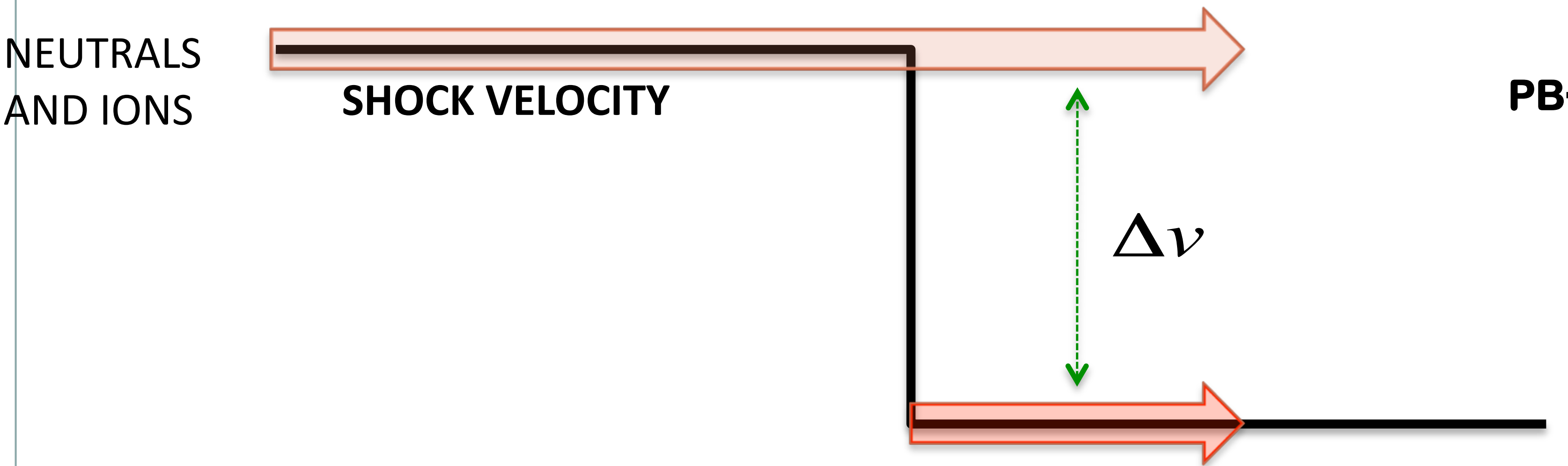




PB, Amato & Serpico 2012

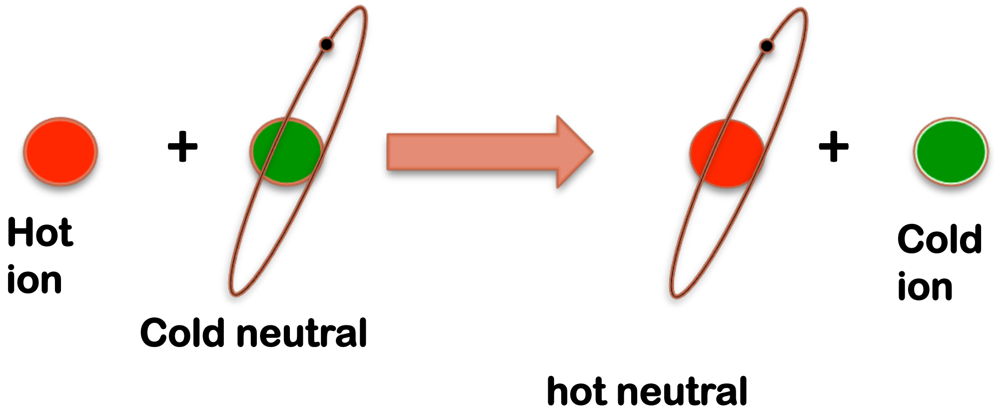

SOME NEW DIRECTIONS
COLLISIONLESS SNR SHOCKS IN PARTIALLY IONIZED MEDIA
LOOKING FOR COSMIC RAYS WITH OPTICAL TELESCOPES

NEUTRALS IN COLLISIONLESS SHOCK



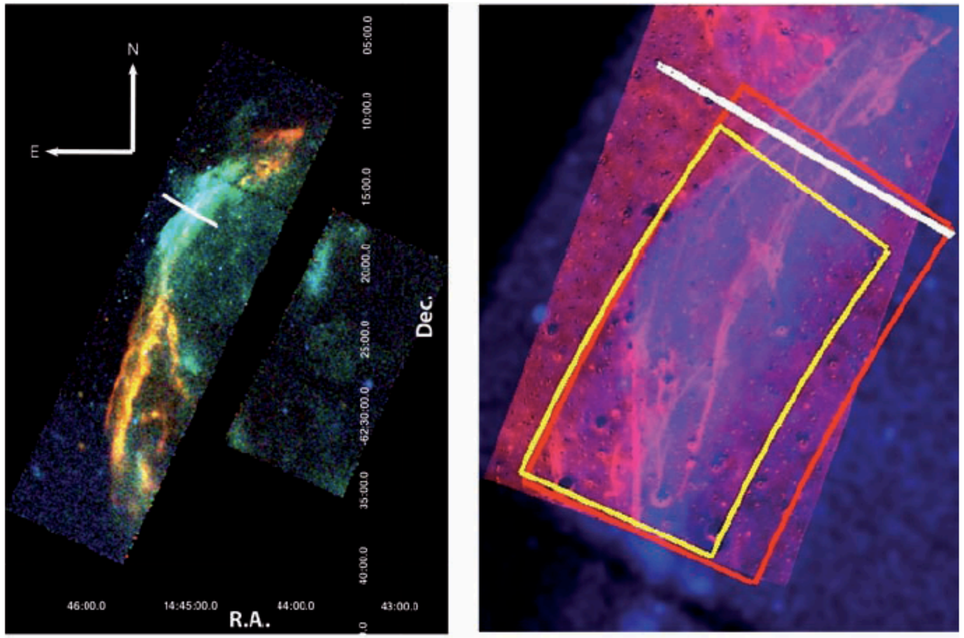
PB+, 2011

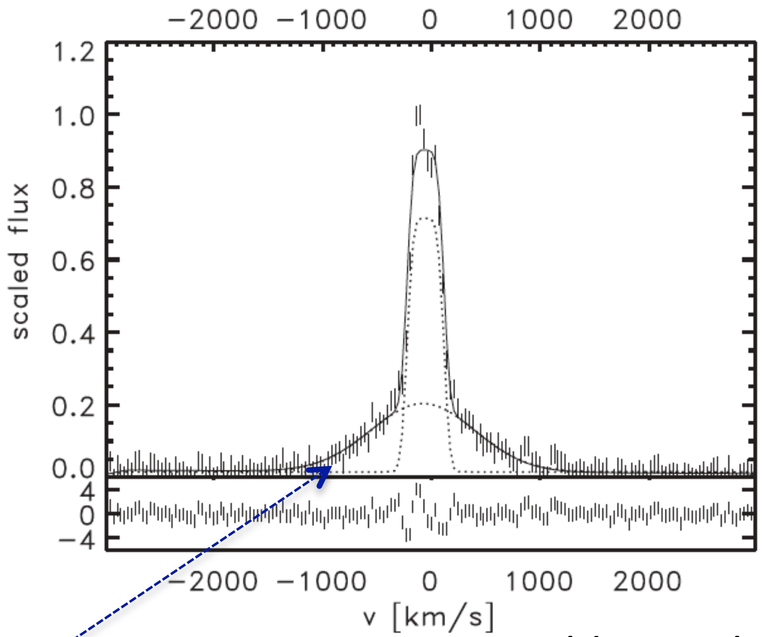
CHARGE EXCHANGE → BROAD BALMER LINE (NEUTRALS THAT MADE CHARGE EXCHANGE) REFLECTING THE TEMPERATURE OF IONS…



BUT THE LATTER AFFECTED BY EFFICIENT CR ACCELERATION

BROAD BALMER LINES NARROWER THAN FOR UNMODIFIED SHOCKS





Helder et al. 2009

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

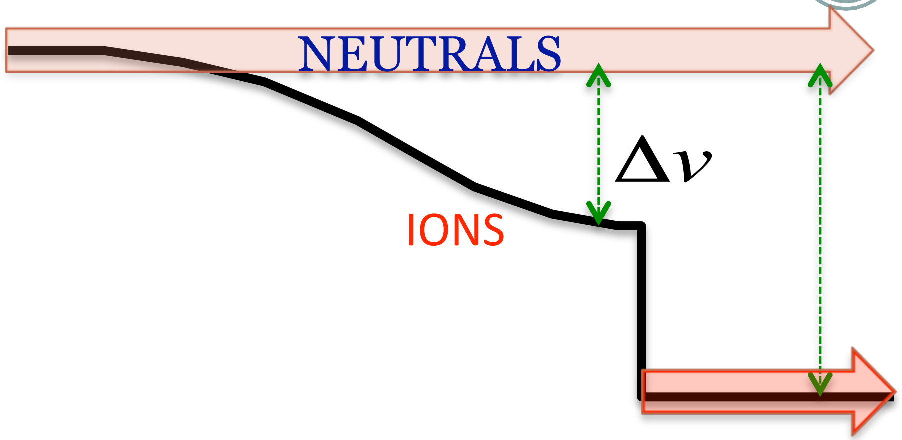
$$W_{broad} = 1100 \pm 63\,km/s \rightarrow T_2 = 2.3 \pm 0.3\,keV$$

Shock speed from proper motion

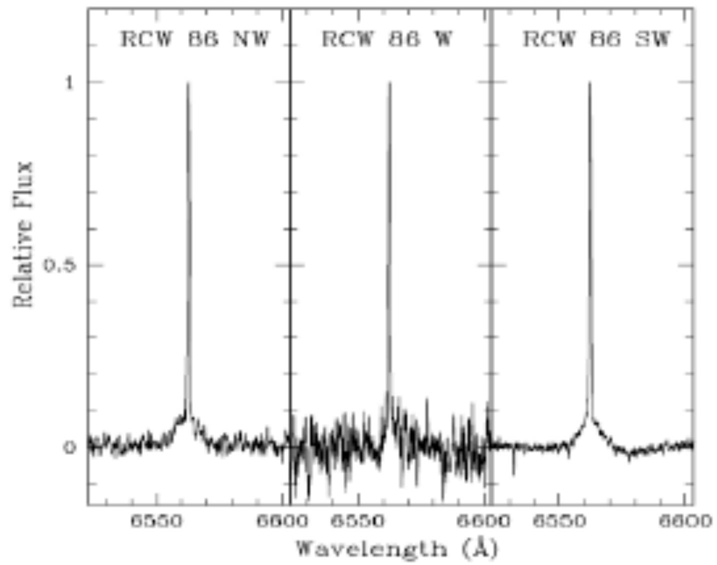
$$v_{shock} = 6000 \pm 2800\,km/s \left(\frac{d}{2.5 \pm .5\,kpc}\right)\left(\frac{\dot{\theta}_{obs}}{0.5 \pm .2''\,yr^{-1}}\right) \rightarrow T_2 = \begin{matrix} 20-150\,keV\ (no\ equilibration) \\ 12-90\,keV\ (equilibration) \end{matrix}$$

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

NARROW BALMER LINES BROADER THAN FOR UNMODIFIED SHOCKS



Sollerman et al. 2003



CHARGE EXCHANGE OCCURS NOW IN THE CR INDUCED PRECURSOR

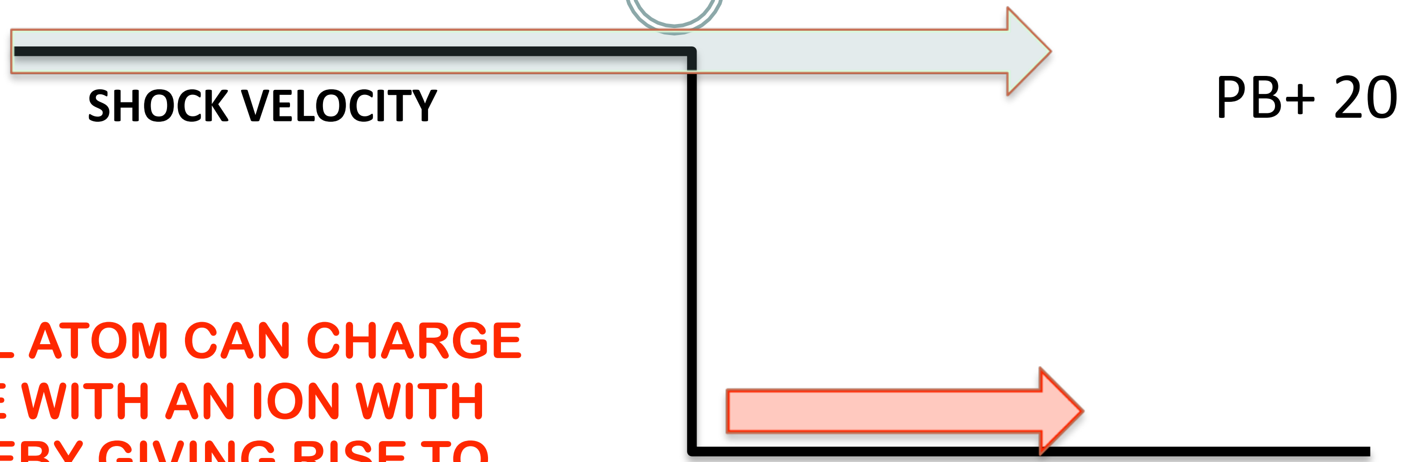
$$W_{broad} = \sqrt{8\ln 2 \frac{kT_0}{m}} \approx 21\ \text{km/s} \left(\frac{T_0}{10^4 K}\right)^{1/2}$$

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

NARROW BALMER LINE BROADER THAN FOR AN UNMODIFIED SHOCK

THE NEUTRAL RETURN FLUX

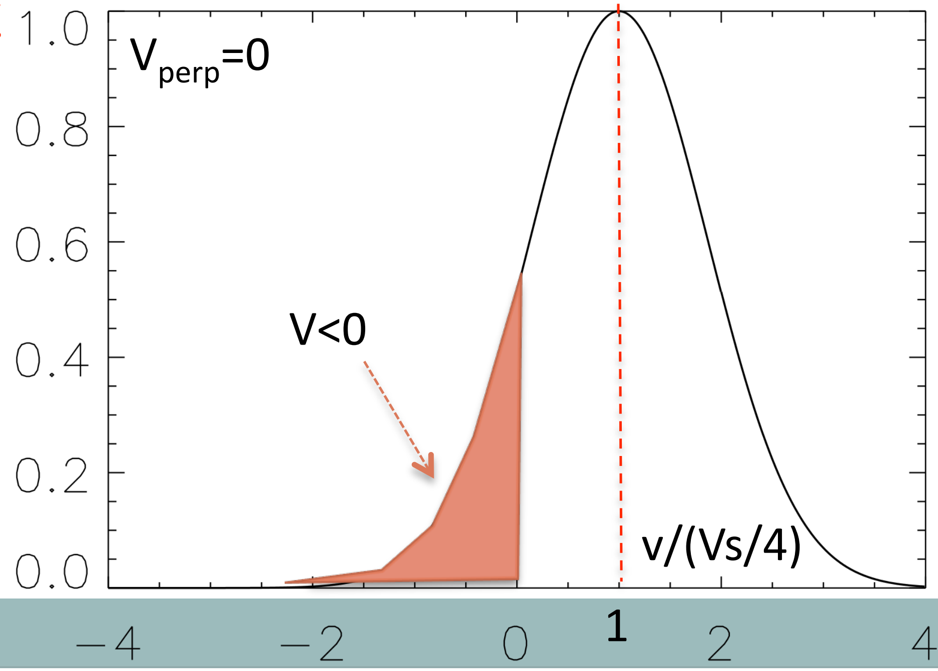
NEUTRALS
AND IONS



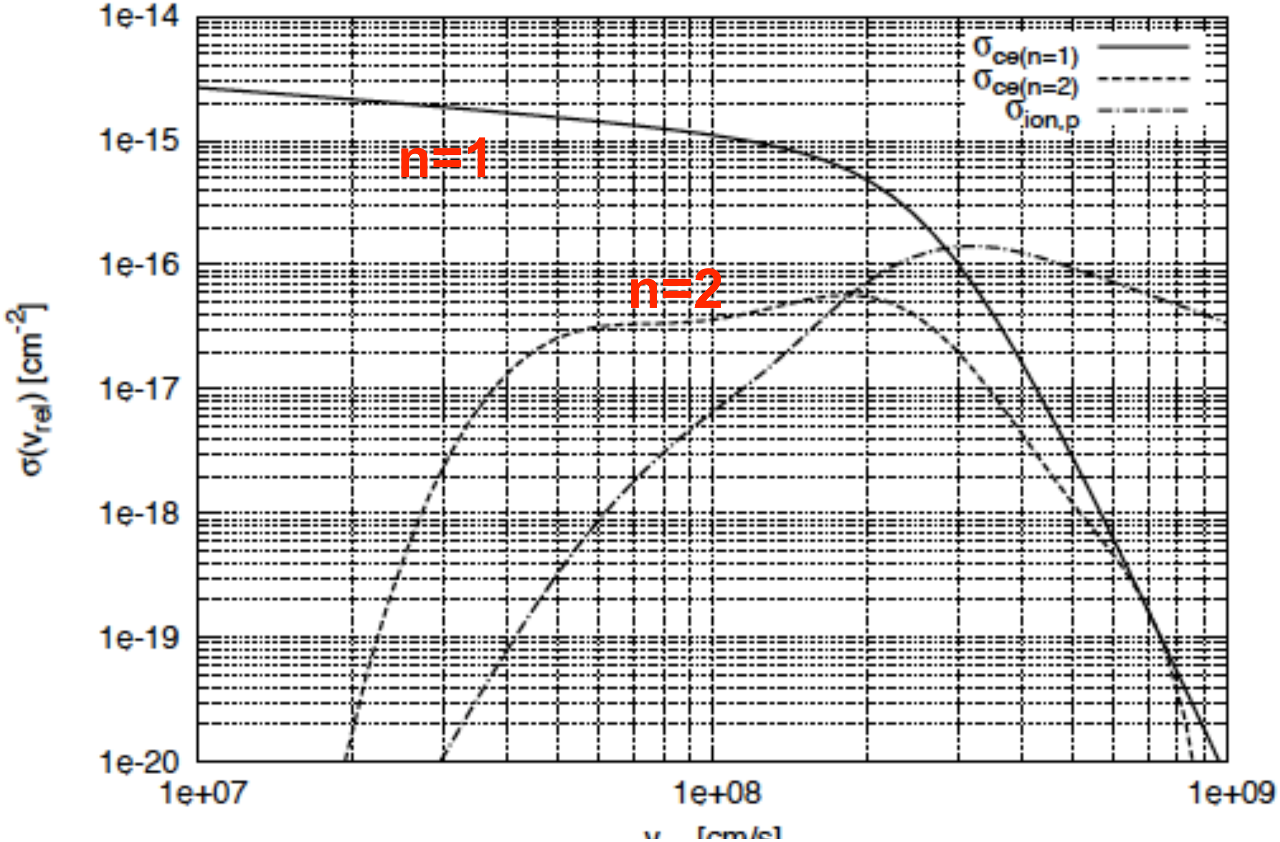
PB+ 2012

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!



RELEVANT CROSS SECTIONS

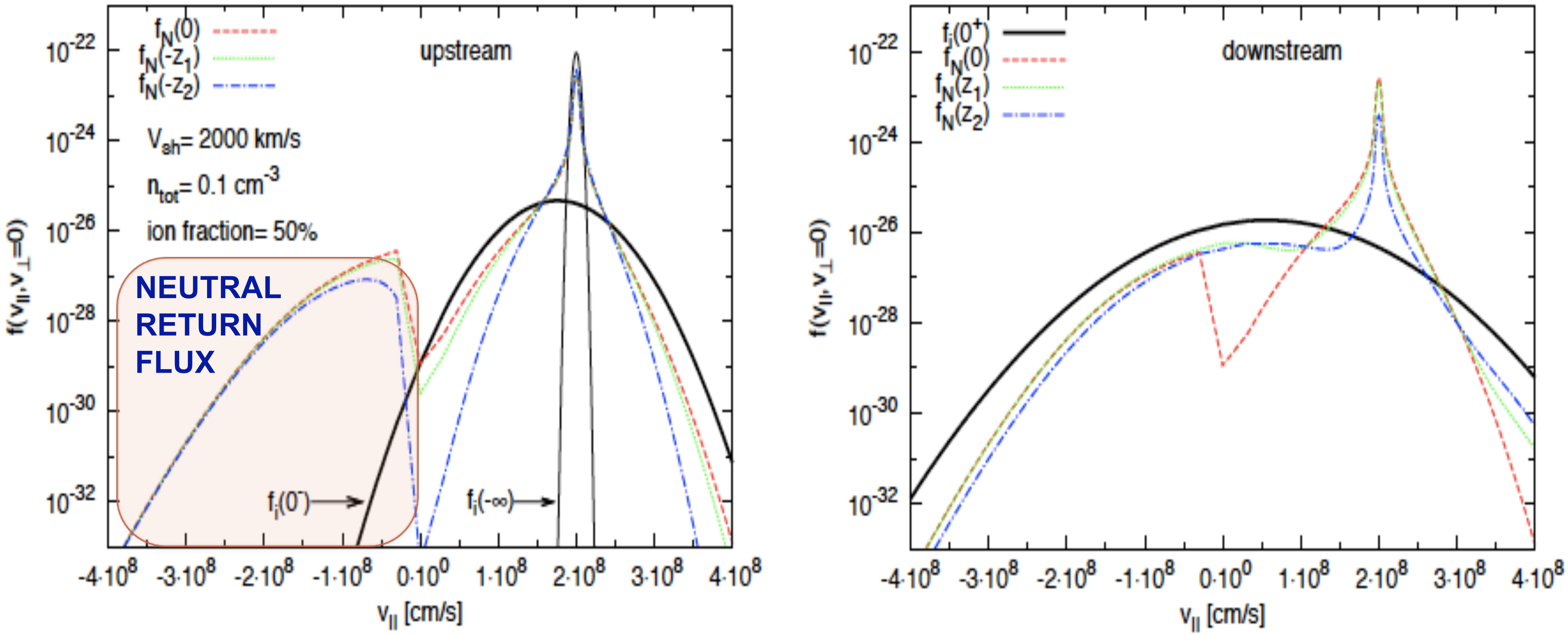


PB+ 2012

$$\sigma_{ce} = \sum_{n=1}^{\infty} \sigma_{ce,n} \approx \sigma_{ce,1} + \sigma_{ce,2} \sum_{n=2}^{\infty} (2/n)^3$$

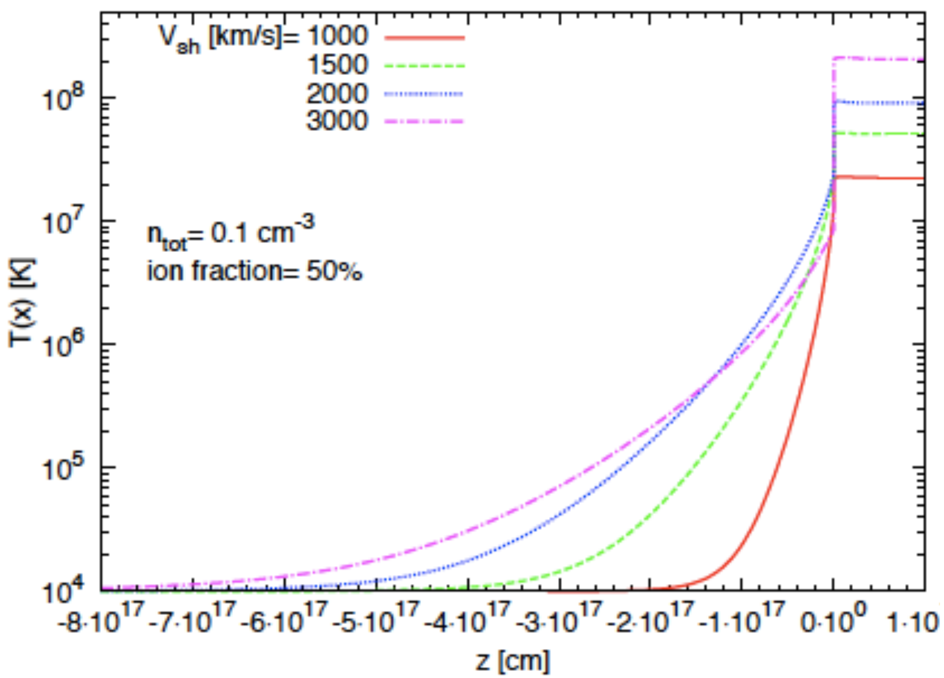
PARTIAL FUNCTIONS IN PHASE SPACE

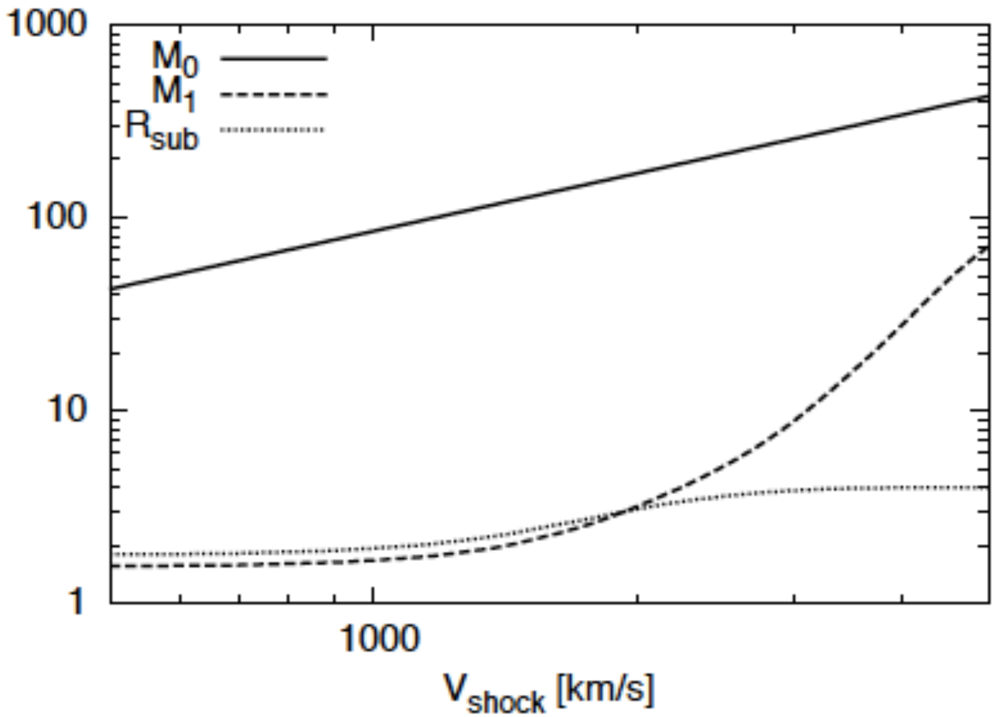
PB+ 2012



THE DISTRIBUTION FUNCTIONS OF NEUTRALS ARE NOT MAXWELLIAN IN SHAPE BUT APPROACH SUCH SHAPE AT DOWNSTREAM INFINITY

NEUTRAL INDUCED PRECURSOR



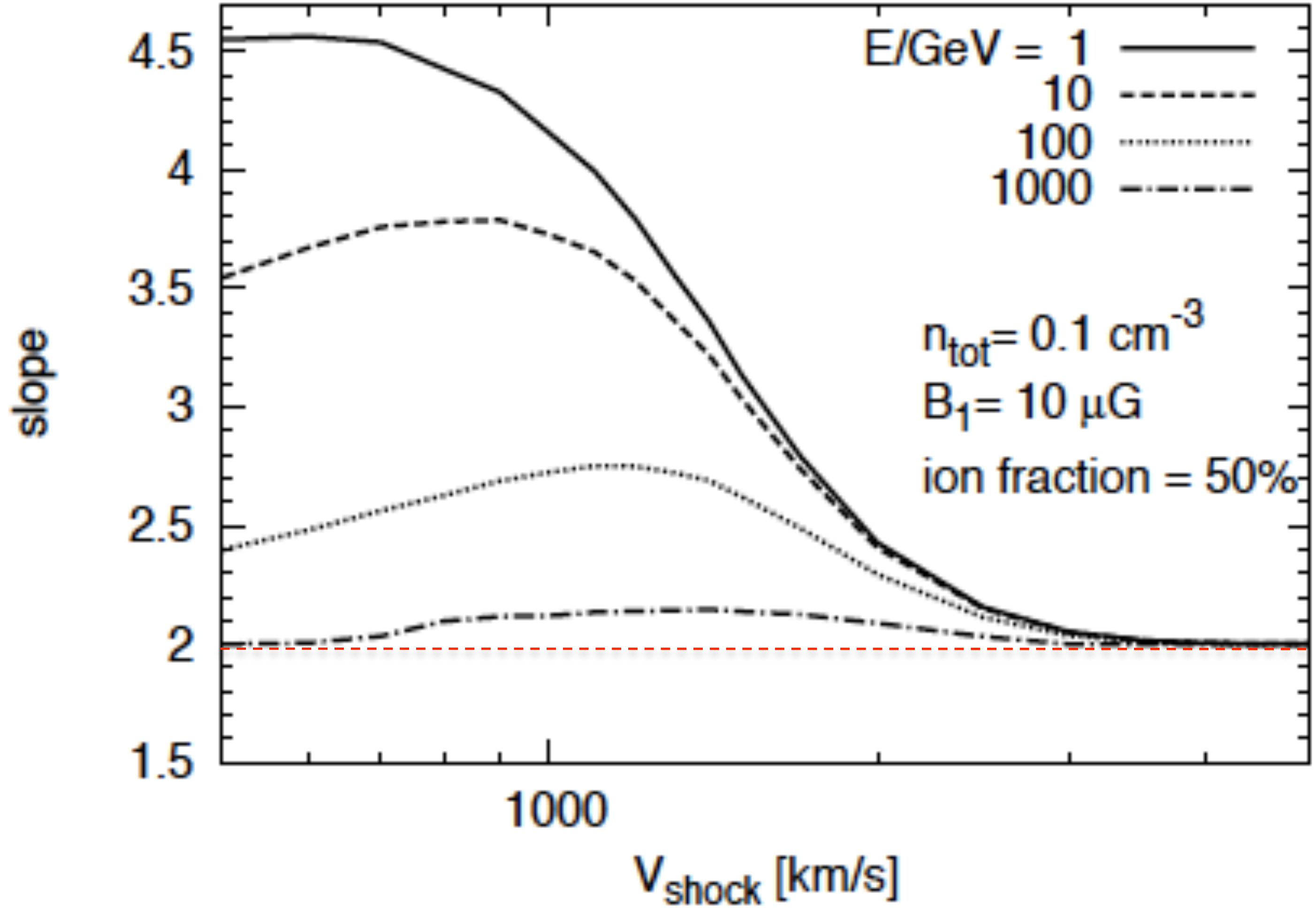


PB+ 2012

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



Epilogue

From "COSMIC RAYS", by Bruno Rossi, 1964

The last pages of this book are written in August, 1962. A few days ago it was the fiftieth anniversary of Hess's flight, with which my story began. The half century covered by this story has been a revolutionary period for science. And cosmic rays, as I have tried

It is particularly appropriate at this time to pause and look back on the history of cosmic rays, not so much because the fiftieth anniversary of their discovery calls for some sort of celebration, but because, curiously enough, the anniversary comes at a critical moment for cosmic-ray physicists, if not for cosmic-ray physics itself. The interest in cosmic rays is certainly not waning; on the contrary, it is steadily growing. But cosmic-ray research has

the solution of their problems. It is quite possible that future historians of science will close the chapter on cosmic rays with the fiftieth anniversary of Hess's discovery. However, they will undoubtedly note that in renouncing its individuality and merging with the main stream of science, cosmic-ray research continued to perform a vital role in advancing man's understanding of the physical world.