PARTICLE ACCELERATION AND THE ORIGIN OF COSMIC RAYS

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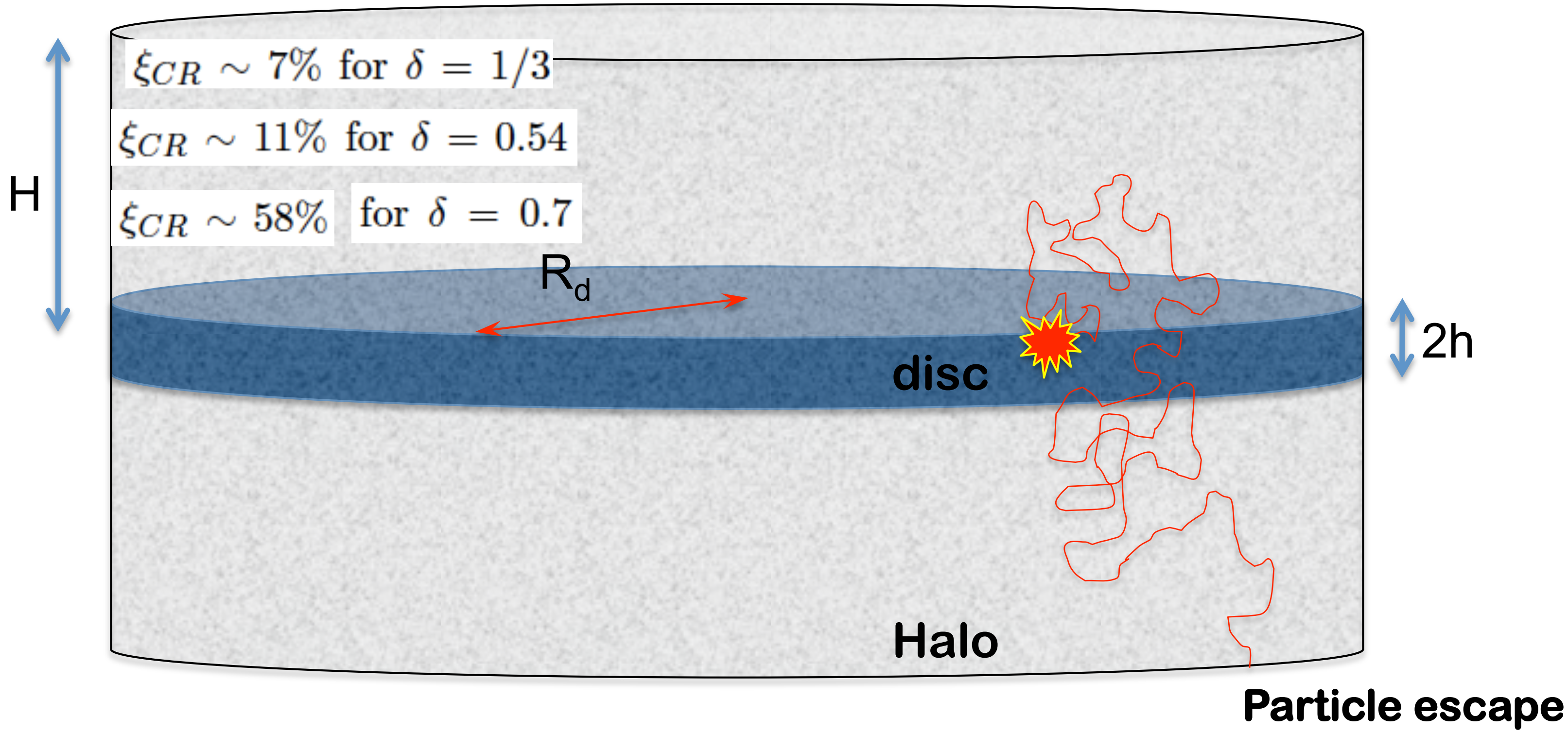
WHICH SOURCES OF COSMIC RAYS?

1. SOURCES OF PROTONS AND NUCLEI
2. …WITH MAX ENERGY FOR PROTONS AT LEAST AS HIGH 10^{15} eV
3. A THEORY EXPLAINING THE SPECTRA …
4. COMPATIBLE WITH ANISOTROPY
5. SPECTRA OF PROPAGATED NUCLEI COMPATIBLE WITH DATA (spectra, B-field, etc)
6. …THAT SATISFY MULTIFREQUENCY CONSTRAINTS (radio + X rays + gamma rays + …)

Pillars of the SNR paradigm

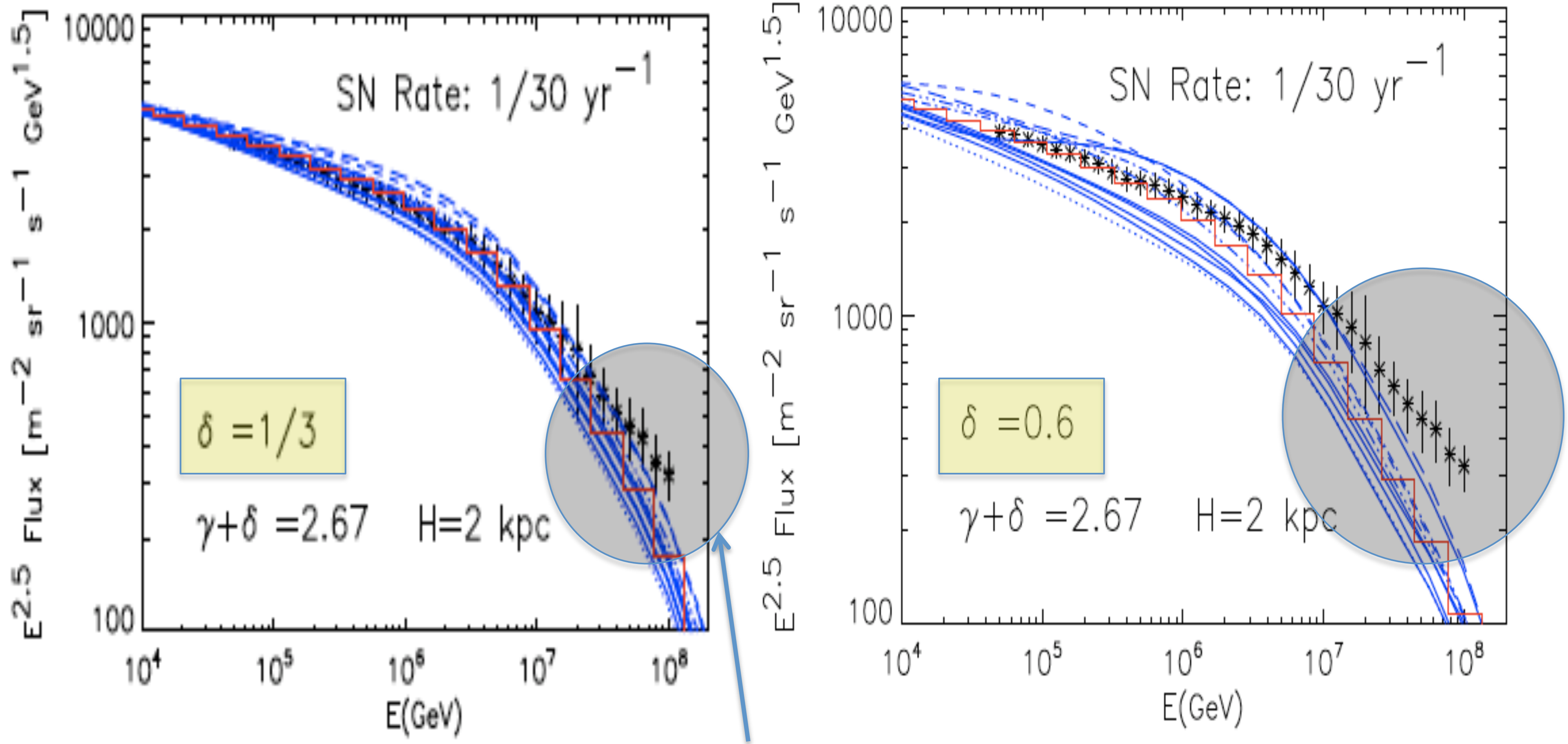


CRs IN SNR → DIFFUSIVE SHOCK ACCELERATION, Q(E)~$E^{-\gamma}$

PROPAGATION OF CRs IN THE GALAXY with D(E)~E^{δ} → n(E)~$E^{-\gamma-\delta}$

CR spectra and SNRs

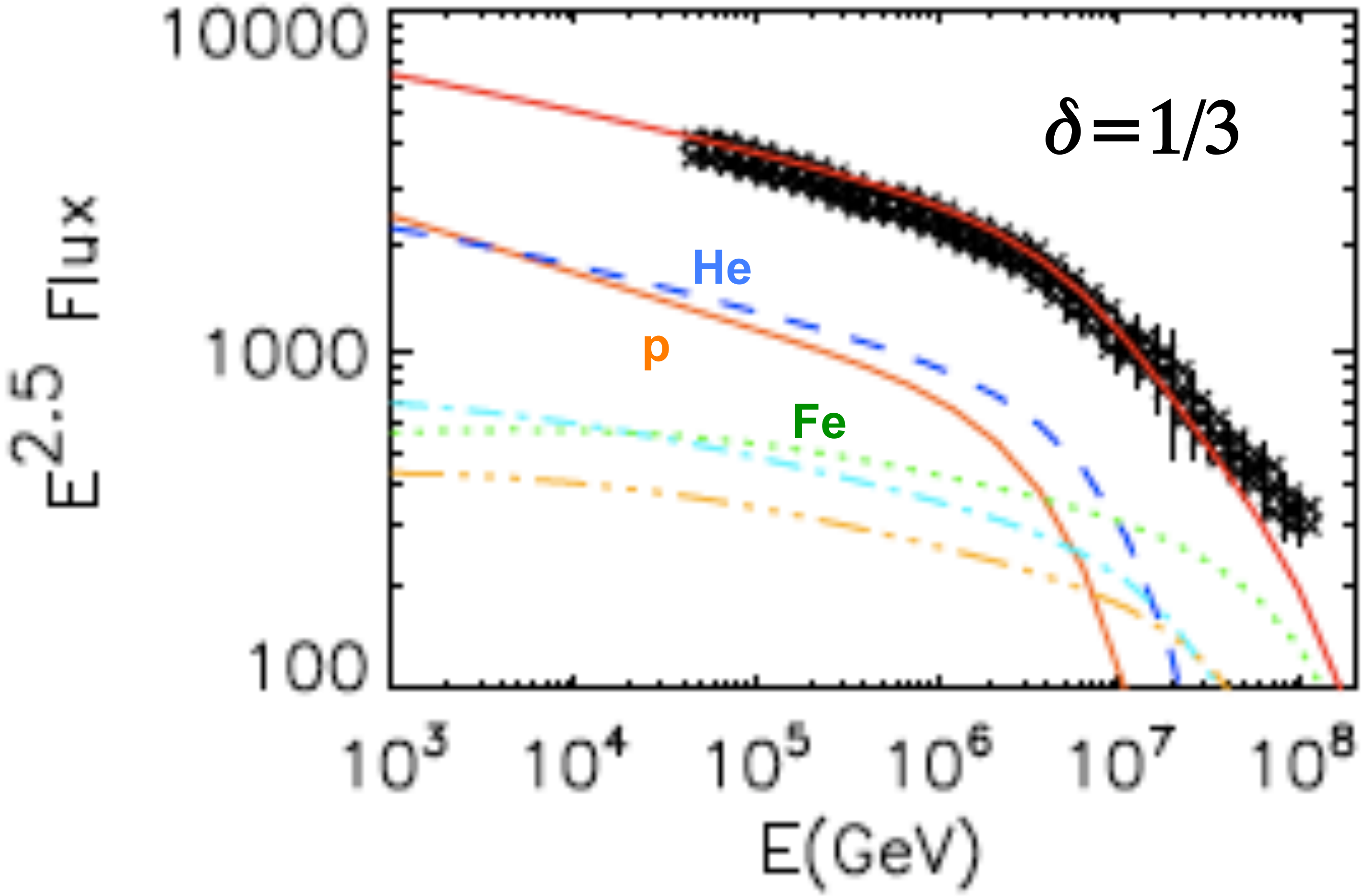
Blasi & Amato 2011



Deficit compensated by extragalactic CRs

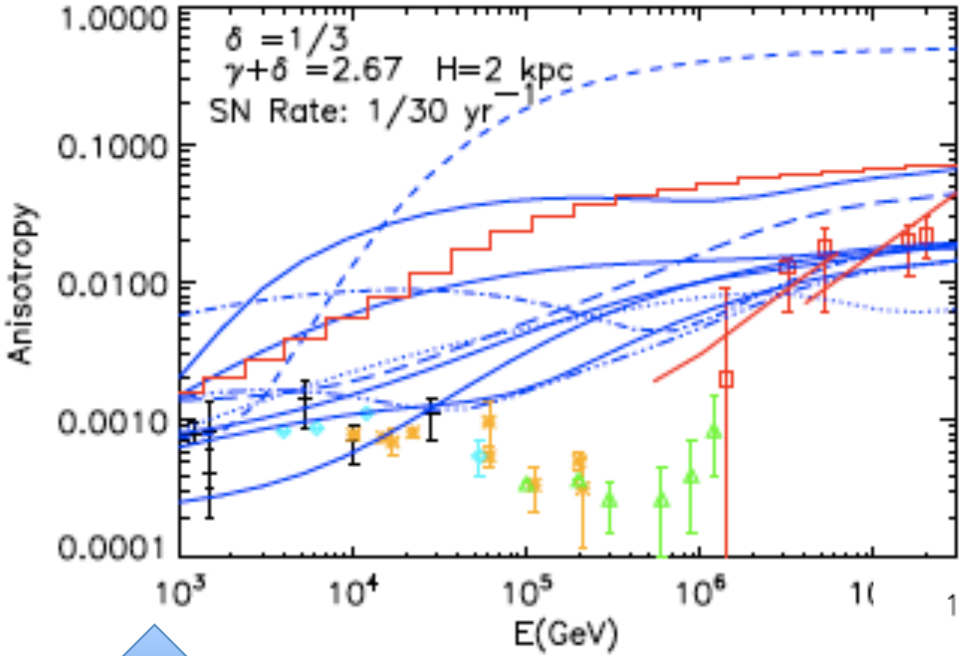
Chemicals and the KNEE

Blasi & Amato 2011



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

CR Anisotropy



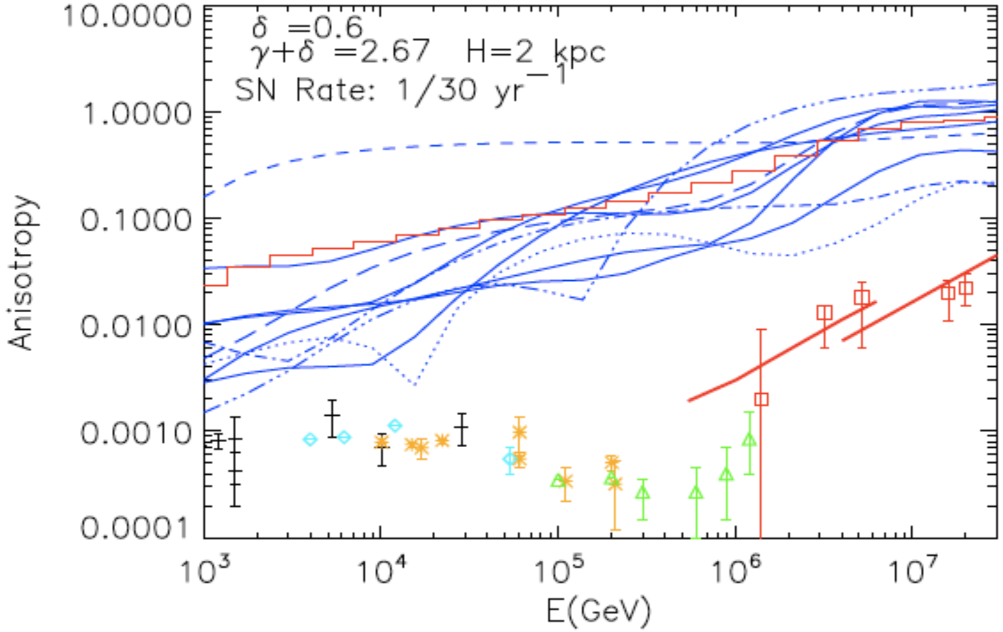
Naïve expectation:

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

proportional to E$^{\delta}$

δ=1/3

δ=0.6

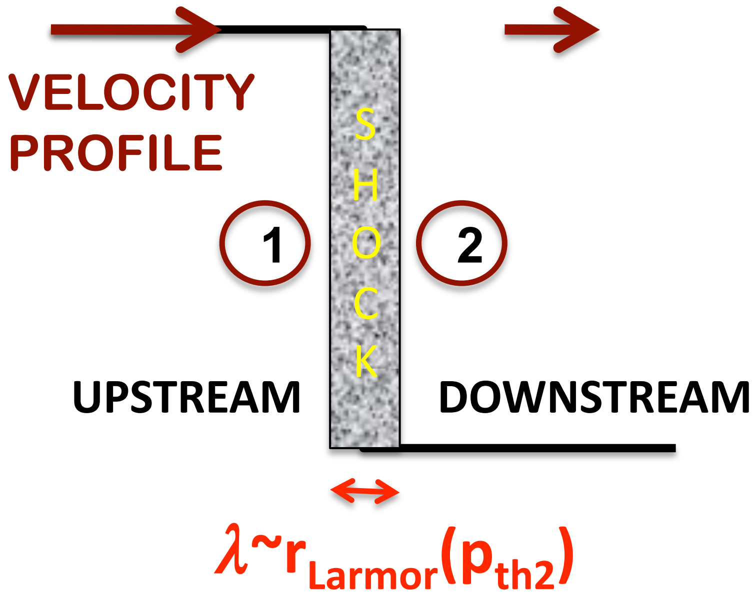


Blasi & Amato 2011

THEORY OF CR ACCELERATION IN SNRs

Diffusive Shock Acceleration

DIFFUSIVE ACCELERATION AT COLLISIONLESS NEWTONIAN SHOCKS



COLLISIONLESS → MEDIATED BY ELECTROMAGNETIC INSTABILITIES

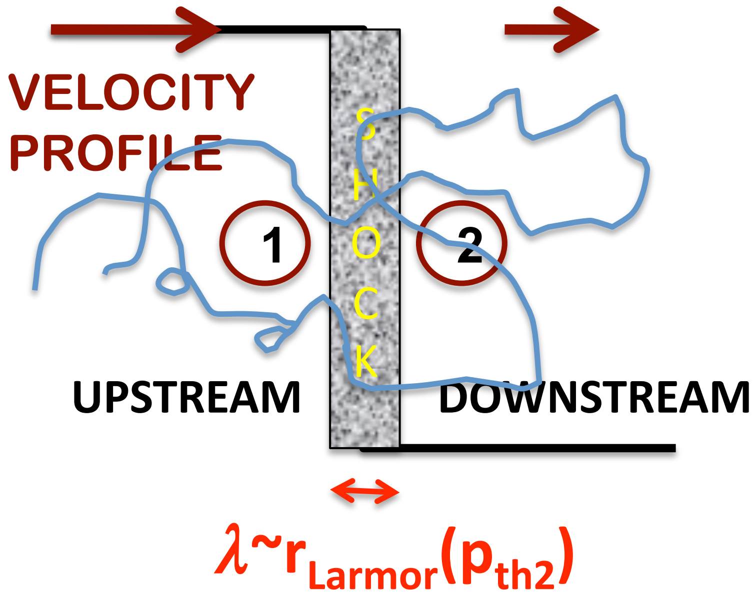
IN GENERAL ONE EXPECTS:

-Different heating for e and p

-Finite thickness of the shock

-Instabilities responsible for the shock formation also responsible for first particles reflections (injection)

DIFFUSIVE ACCELERATION AT COLLISIONLESS NEWTONIAN SHOCKS
‘test particles’



In test particle theory, all approaches lead to:

-POWER LAW SPECTRA

-SLOPE ONLY FUNCTION OF COMPRESSION

-INDEPENDENT OF D(E)

-NO CLEAR RECIPE FOR E_{MAX}

-NO DESCRIPTION OF WHY PARTICLES RETURN TO THE SHOCK (SCATTERING)

-NO DESCRIPTION OF INJECTION

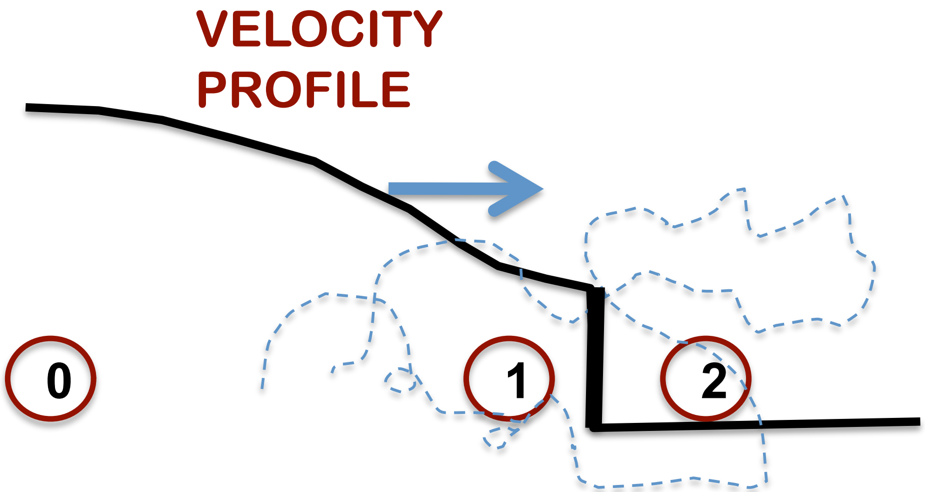
NON LINEAR THEORY

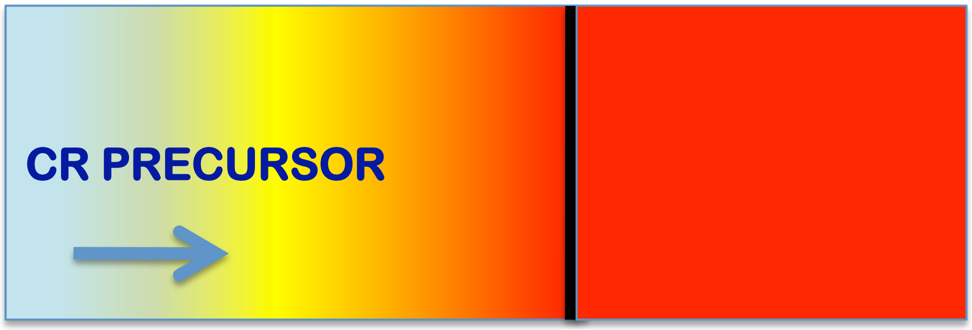
A theory of particle acceleration that allows one to describe:

1. ***Dynamical reaction of accelerated particles***
2. ***Streaming instability CR-induced B-field***
3. ***Dynamical reaction of amplified fields***
4. ***Phenomenological recipe for injection (self-regulation of the system)***
5. ***Escape of particles from boundaries (Cosmic Rays)***

DIFFUSIVE ACCELERATION AT COLLISIONLESS NEWTONIAN SHOCKS

non linear theory





SUBSHOCK

DENSITY OF ACCELERATED PARTICLES

$$\frac{\partial \rho}{\partial t} = -\frac{\partial (\rho u)}{\partial x}$$

MASS CONSERVATION

$$\frac{\partial (\rho u)}{\partial t} = -\frac{\partial}{\partial x}\left[\rho u^2 + P_{\rm g} + P_{\rm c} + P_{\rm W}\right]$$

MOMENTUM CONSERVATION

$$\frac{\partial}{\partial t}\left[\frac{1}{2}\rho u^2 + \frac{P_{\rm g}}{\gamma_{\rm g}-1}\right] = -\frac{\partial}{\partial x}\left[\frac{1}{2}\rho u^3 + \frac{\gamma_{\rm g} P_{\rm g} u}{\gamma_{\rm g}-1}\right] - u\frac{\partial}{\partial x}\left[P_{\rm c} + P_{\rm W}\right] + \Gamma E_{\rm W}$$

ENERGY CONSERVATION

$$\frac{\partial f(t,x,p)}{\partial t} + \tilde{u}(x)\frac{\partial f(t,x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(t,x,p)}{\partial x}\right] + \frac{p}{3}\frac{\partial f(t,x,p)}{\partial p}\frac{{\rm d}\tilde{u}(x)}{{\rm d}x}$$

Closing the system with waves and CR

$$u\frac{\partial P_{\mathrm{g}}}{\partial x} + \gamma_{\mathrm{g}} P_{\mathrm{g}} \frac{\mathrm{d}u}{\mathrm{d}x} = (\gamma_{\mathrm{g}} - 1)\Gamma E_{\mathrm{W}}$$

GAS PRESSURE AND WAVES

$$\frac{\partial}{\partial x}\left[\frac{1}{2}\rho u^3 + \frac{\gamma_{\mathrm{g}} P_{\mathrm{g}} u}{\gamma_{\mathrm{g}} - 1} + \frac{\gamma_{\mathrm{c}} P_{\mathrm{c}} \tilde{u}}{\gamma_{\mathrm{c}} - 1} + F_{\mathrm{W}} - \bar{D}(x)\frac{\partial E_{\mathrm{c}}}{\partial x}\right] = 0$$

$$\frac{\partial F_{\mathrm{W}}}{\partial x} = u\frac{\partial P_{\mathrm{W}}}{\partial x} + \sigma E_{\mathrm{W}} - \Gamma E_{\mathrm{W}}$$

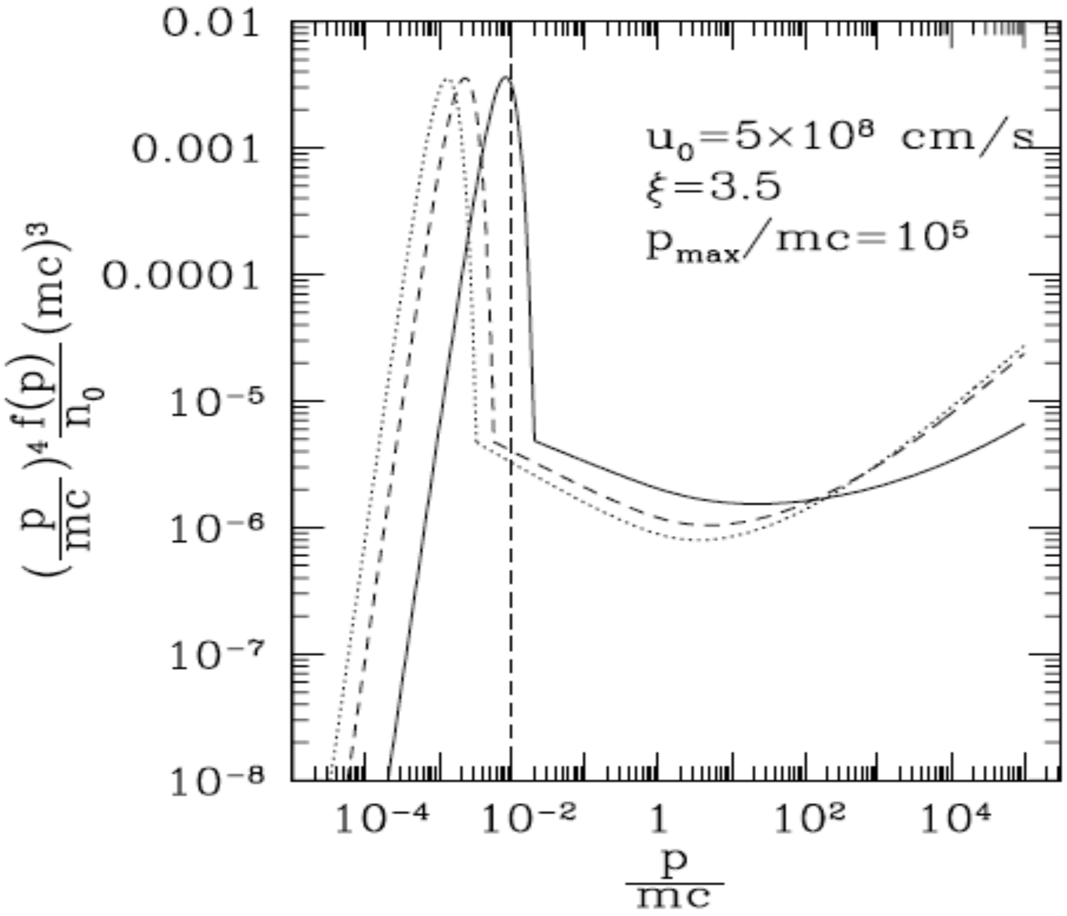
ADVECTION, GROWTH AND DAMPING OF WAVES

$$\sigma E_{\mathrm{W}} = v_{\mathrm{A}} \frac{\partial P_{\mathrm{c}}}{\partial x}$$

ONLY FOR ALFVEN WAVES!!!
AMPLIFICATION OF B-FIELD AS DUE TO CR STREAMING INSTABILITY

DIFFUSIVE ACCELERATION AT COLLISIONLESS NEWTONIAN SHOCKS

non linear theory: BASIC PREDICTIONS



COMPRESSION FACTOR BECOMES FUNCTION OF ENERGY

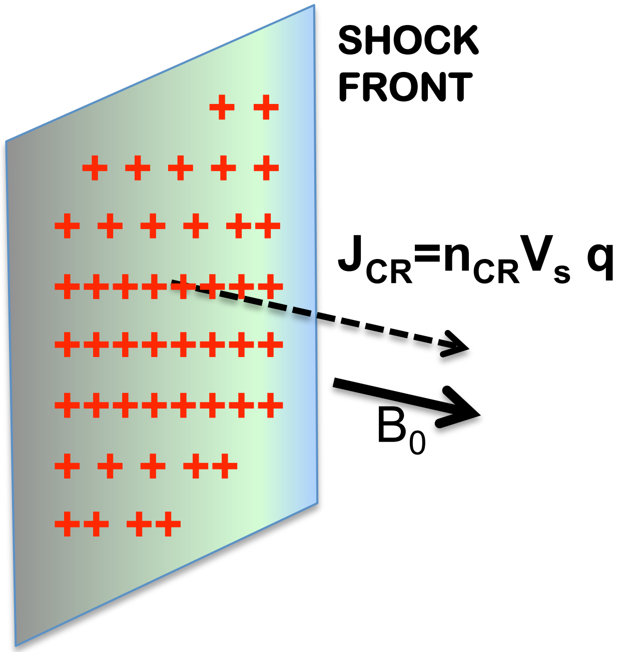
SPECTRA ARE NOT PERFECT POWER LAWS (CONCAVE)

GAS BEHIND THE SHOCK IS COOLER FOR EFFICIENT SHOCK ACCELERATION

SYSTEM SELF REGULATED

EFFICIENT GROWTH OF B-FIELD IF ACCELERATION EFFICIENT

Basics of CR streaming instability



THE UPSTREAM PLASMA REACTS TO THE UPCOMING CR CURRENT BY CREATING A RETURN CURRENT TO COMPENSATE THE POSITIVE CR CHARGE

THE SMALL INDUCED PERTURBATIONS ARE UNSTABLE (ACHTERBERG 1983, ZWEIBEL 1978, BELL 1978, BELL 2004, AMATO & PB 2009)

CR MOVE WITH THE SHOCK SPEED (>> V_A). THIS UNSTABLE SITUATION LEADS THE PLASMA TO REACT IN ORDER TO SLOW DOWN CR TO <V_A BY SCATTERING PARTICLES IN THE PERP DIRECTION (B-FIELD GROWTH)

Particle Diffusion ←→ Wave Growth

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

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

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

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

δB 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!)

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

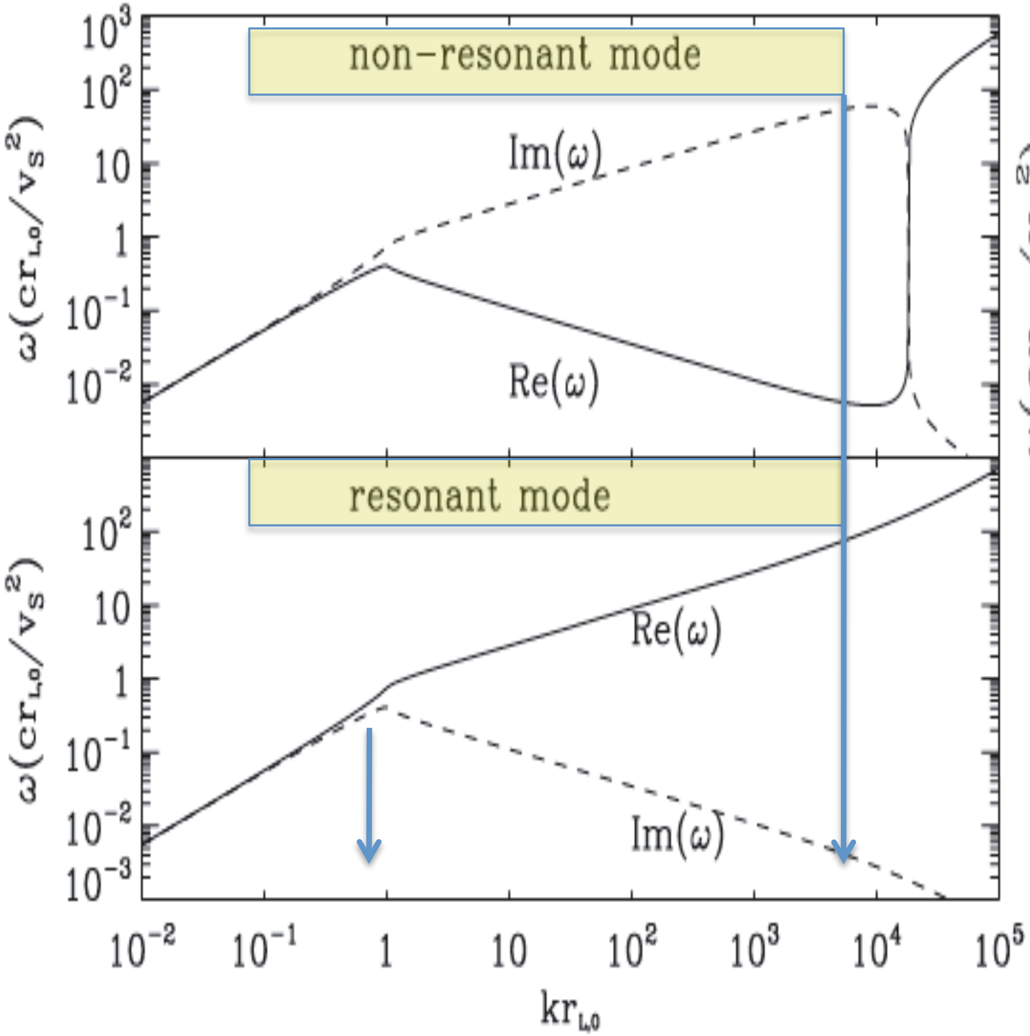
4. **VORTICITY IN THE PRECURSOR** (PB, Matthaeus, et al. 11)

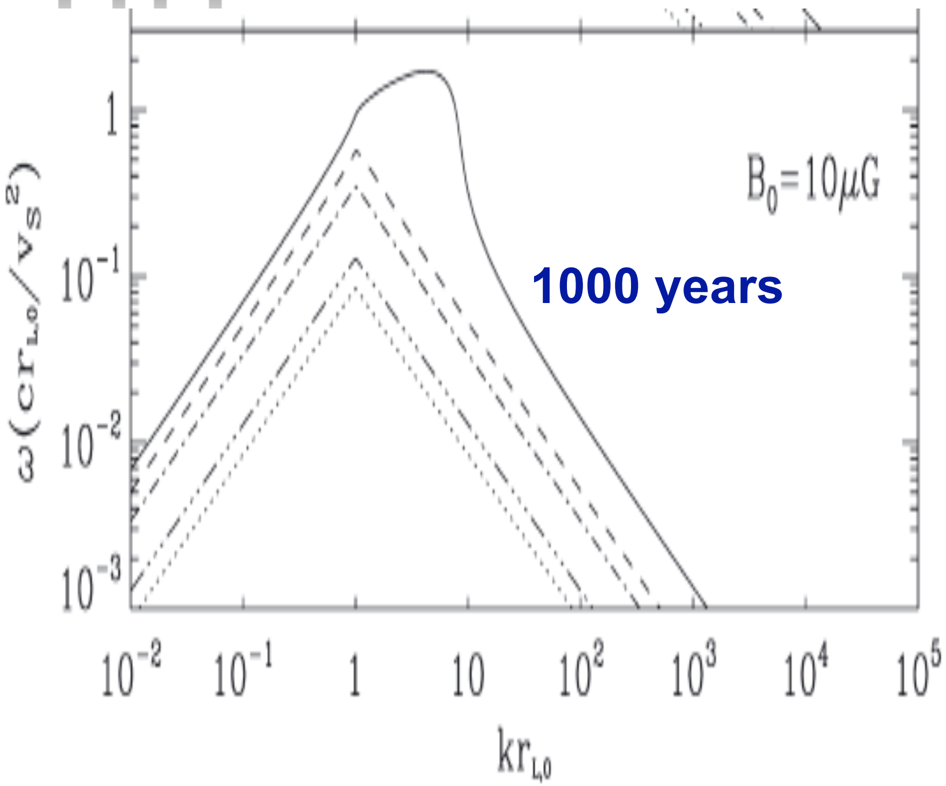
   Potentially very interesting, power on large scales

5. **FIREHOSE INSTABILITY** (Shapiro et al. 98)

   Potentially very interesting, power on large scales

GROWING MODES in CR STREAMING INSTABILITY





NON RESONANT MODES GROW FASTER BUT THEY DO NOT SCATTER PARTICLES EFFECTIVELY UNLESS FAST INVERSE CASCADE

Amato & PB 2009, Bell 2004

SATURATION OF GROWTH

Extremely uncertain. It depends on:

a) Damping (type of waves?)

b) Backreaction of fields on the CR current

c) Coupling between large and small spatial scales

A naïve extrapolation of QLT would lead to:

$$\frac{\delta B^2}{8\pi} = \frac{1}{M_A}\rho V_s^2 \xi_{CR}$$

In the resonant case, upstream (or possibly $\delta B/B \sim 1$ because resonance gets lost)

$$\frac{\delta B^2}{4\pi} = \frac{1}{2}\rho V_s^2 \xi_{CR} \frac{V_s}{c}$$

Estimated analytically from Saturation condition of non resonant Modes (Bell 2004)

X-ray rims and B-field amplification

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

The synchrotron limited thickness is:

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

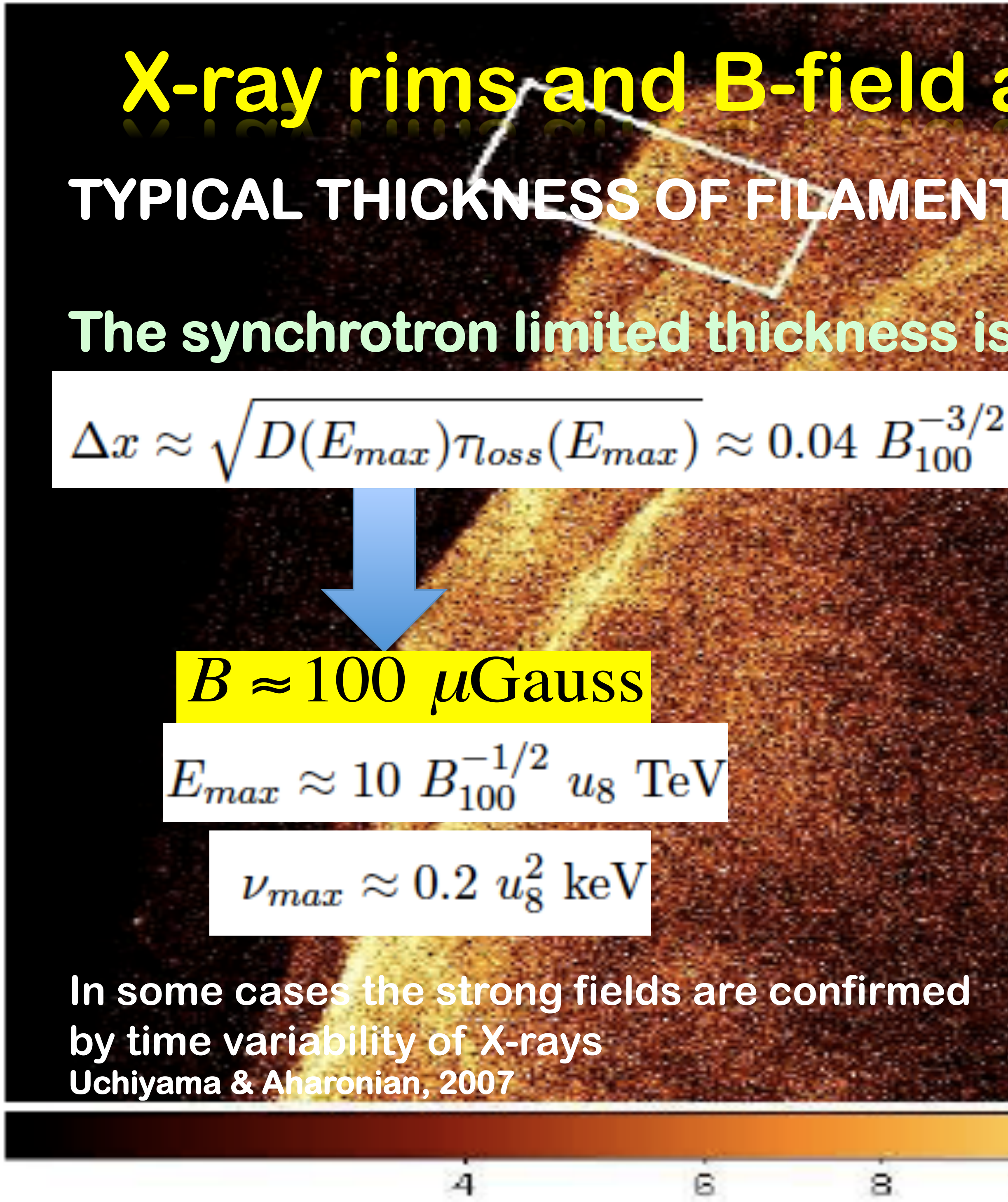
$$B \approx 100\ \mu\text{Gauss}$$

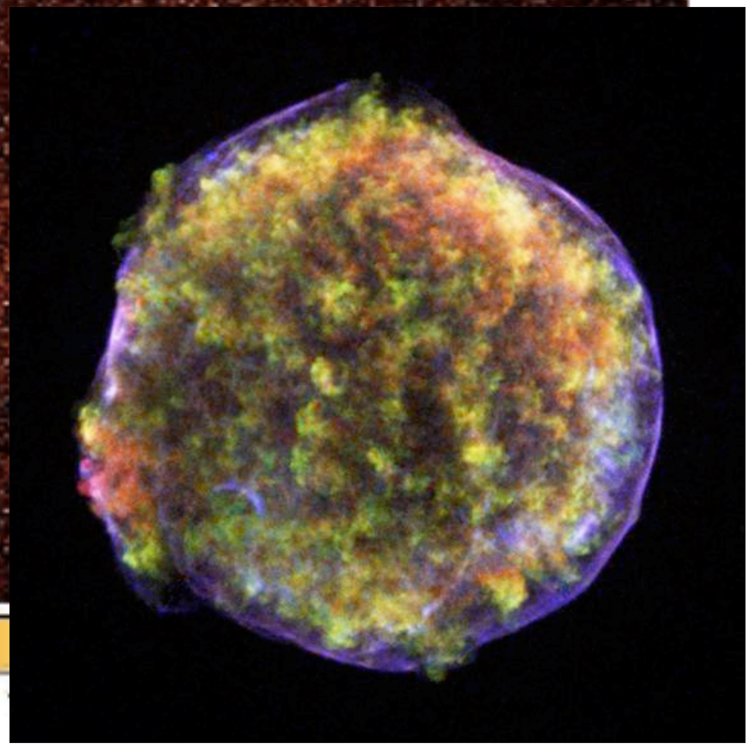
$$E_{max} \approx 10\ B_{100}^{-1/2}\ u_8\ \text{TeV}$$

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

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

Uchiyama & Aharonian, 2007





SPECTRA

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

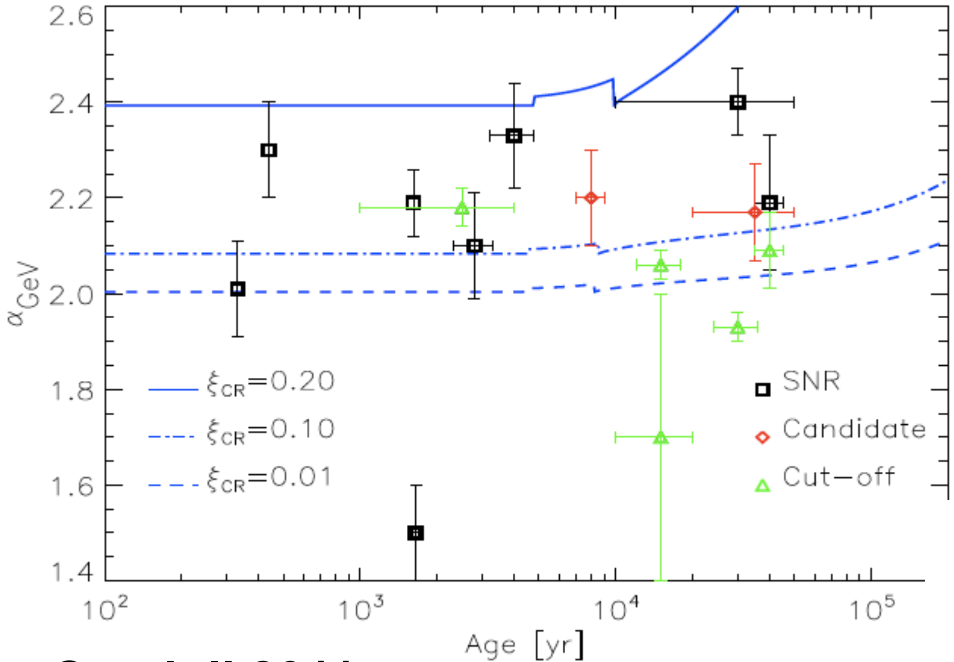
THE MAXIMUM ENERGY WITH B-FIELD AMPLIFICATION REACHS UP TO $\sim 10^{15}$ eV FOR PROTONS (Z TIMES HIGHER FOR NUCLEI)

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

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

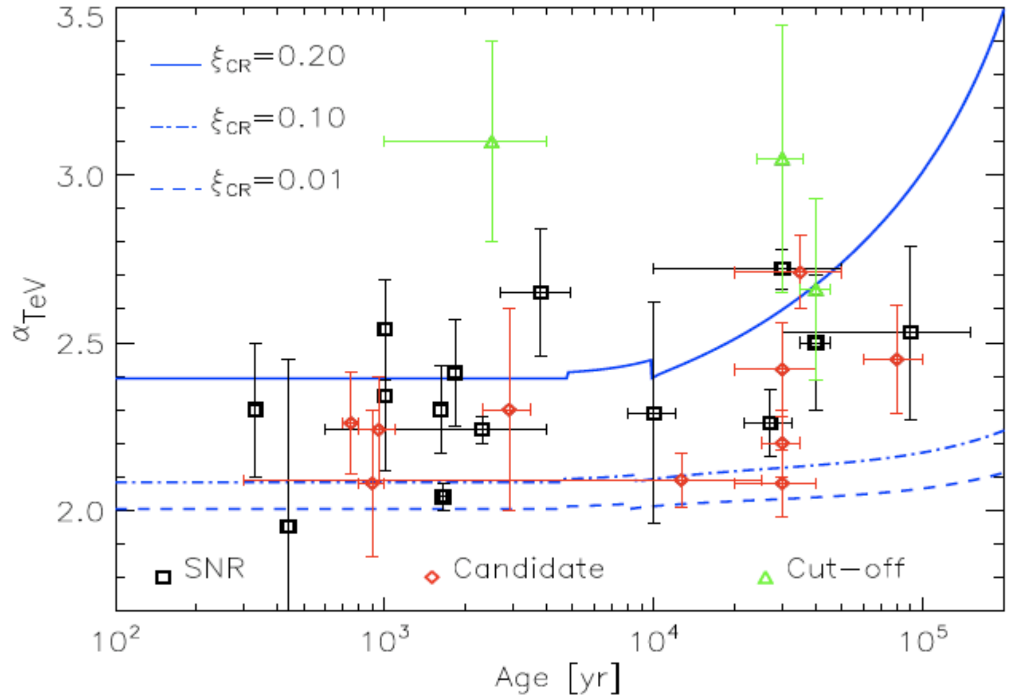
CLEARLY INCOMPATIBLE WITH LEPTONIC MODELS! BUT ALSO NOT COMPATIBLE WITH THE SIMPLEST PREDICTION OF NLDSA

TROUBLE WITH SLOPES ?



Caprioli 2011

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



BEYOND THE SIMPLEST APPROACH

1. **DYNAMICAL REACTION OF THE B-FIELD**
   $P_W = B^2/8\pi > P_{gas}$ the eq. of state becomes dominated by B and The compression factor gets smaller → steeper spectra (Caprioli, PB, Amato & Vietri 2008, 2009)

2. **SCATTERING CENTERS WITH LARGE VELOCITY**
   All but trivial (spectra depend on type and helicity of waves) but if $v_W \sim v_A(\delta B) >> v_A$, then:

$$\tilde{r} = \frac{u_1 + v_{A,1}}{u_2 + v_{A,2}} \qquad \alpha = \frac{\tilde{r}+2}{\tilde{r}-1} > 2$$

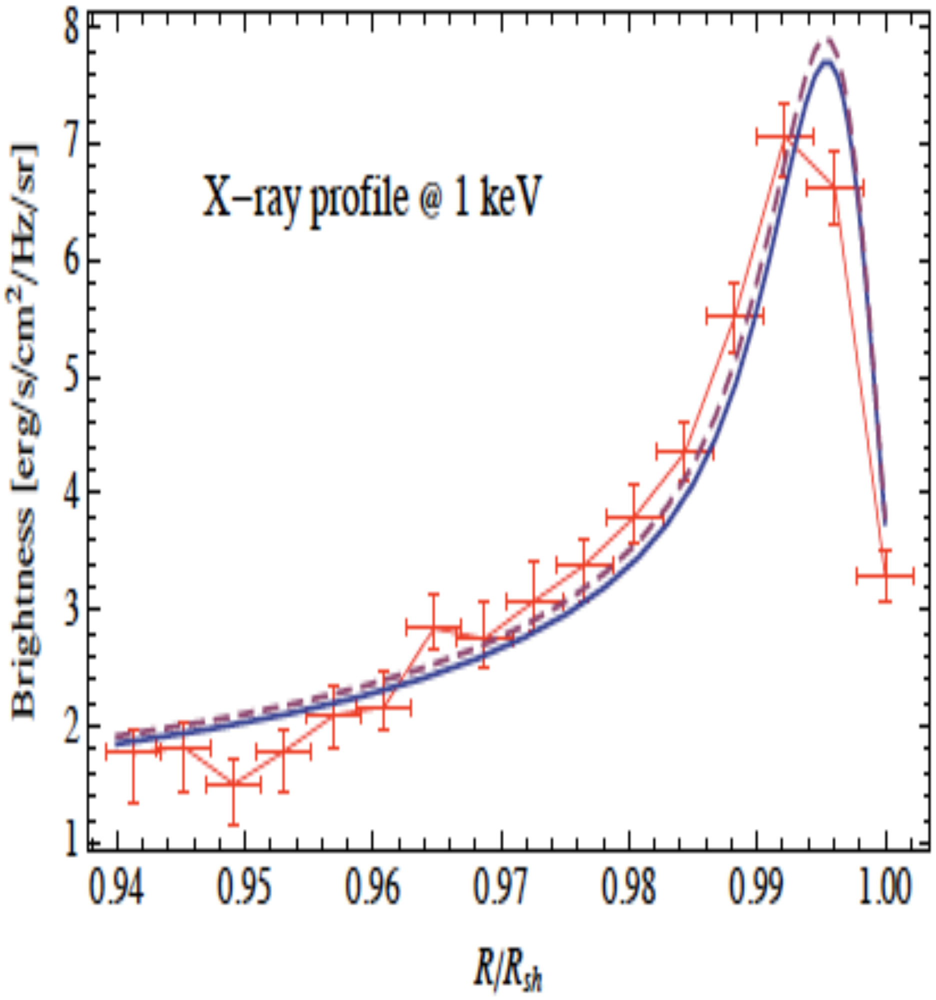
3. **ESCAPE FLUX OF CR IS DIFFERENT FROM THE SPECTRUM OF ACCELERATED PARTICLES** (CAPRIOLI, PB, AMATO 2009)

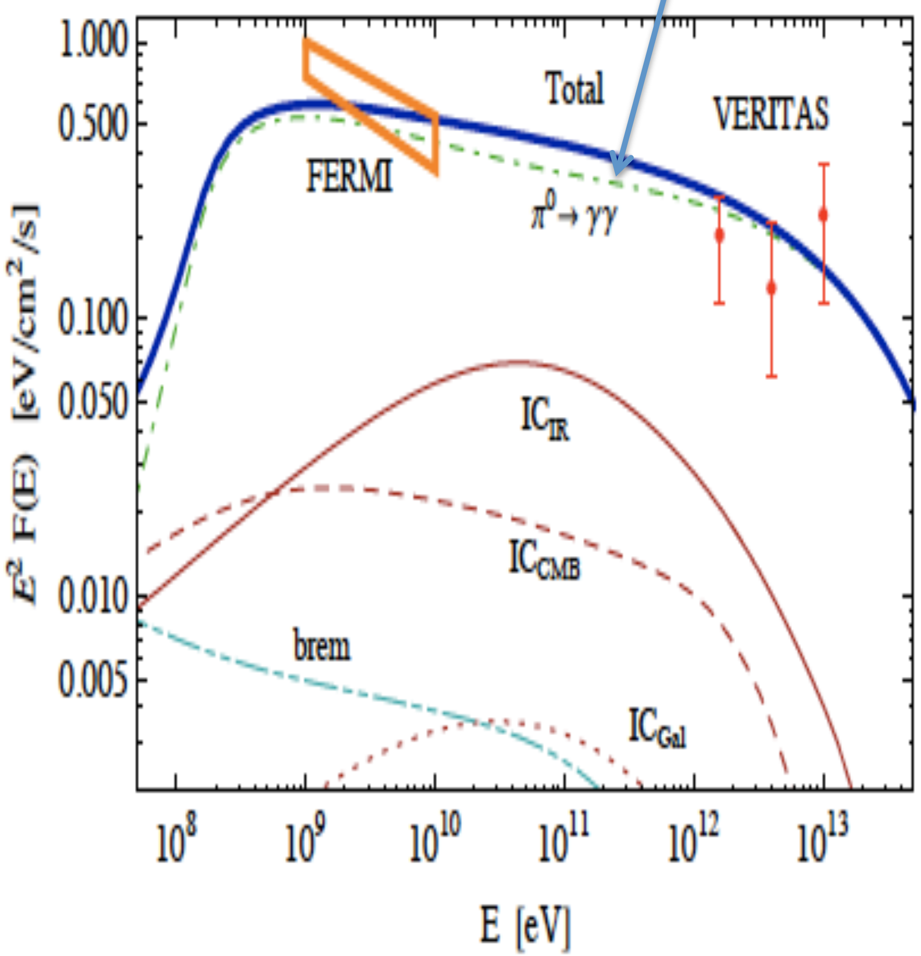
4. **PRESENCE OF NEUTRALS**
   Charge exchange with ions leads to weakening of the shock Strength (PB et al. 2011)

The case of Tycho

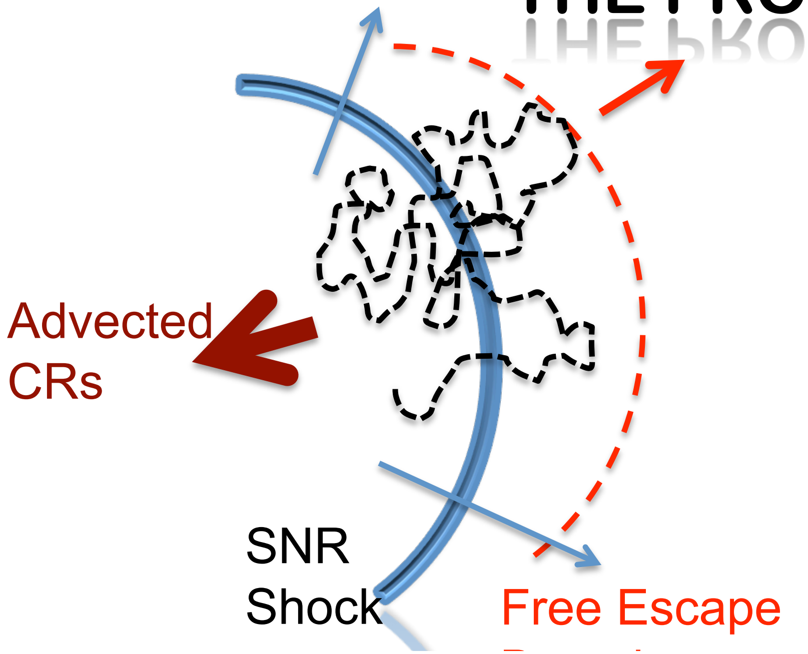
Morlino&Caprioli 2011

STEEP SPECTRUM BASICALLY IMPOSSIBLE TO EXPLAIN WITH LEPTONS



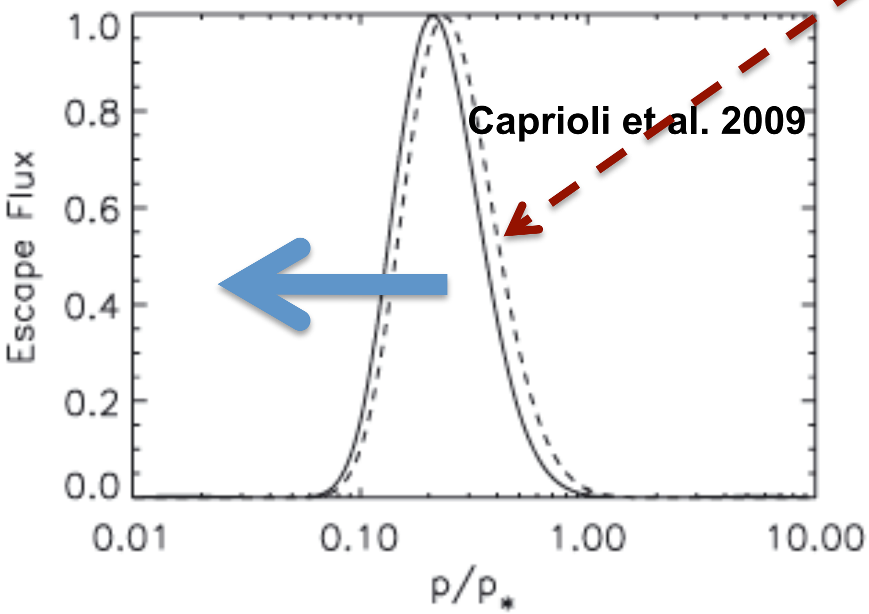


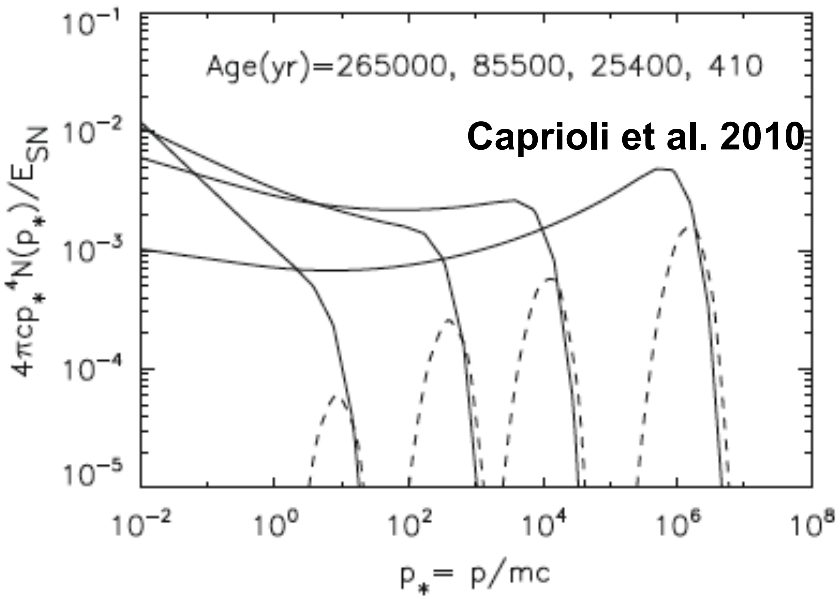
HOW DO ACCELERATED PARTICLES BECOME CRs? THE PROBLEM OF ESCAPE



The escape flux can be calculated using the transport equation IF one assumes a free escape boundary surface (DURING ST 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 MC

Collisionless shock only involves the small fraction of Ions (low density)

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

MC 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

-Escape physics

What about electrons?

Despite being the easiest to be ‘seen’, no clear understanding of their origin

High E electrons accelerated at about the same time of radiation (X-rays, Gamma rays), but radio electrons ‘feel’ the whole evolution of the SNR

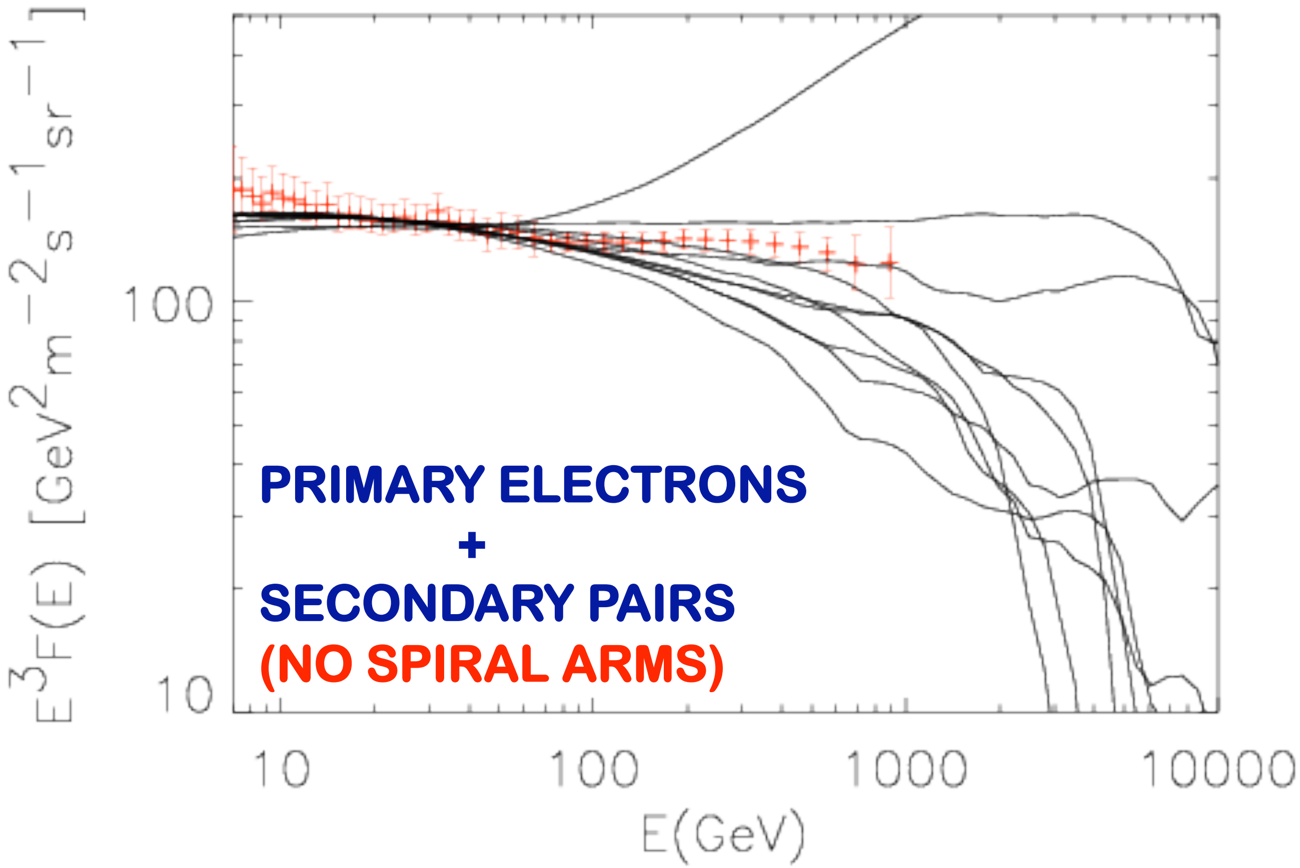
The e/p ratio at low energies (negligible E-losses) hard to predict – low energy electrons could mainly originate at late times

Important contribution to electrons from ionization of partially ionized atoms during their acceleration (Morlino 2009)

Unfortunately the spectrum of electrons at E~10-100 GeV is affected in a Substantial way by the intervention of a different source of leptons, as shown by the rising positron fraction (spectrum of leptons not useful to infer the Injection spectrum at the CR sources)

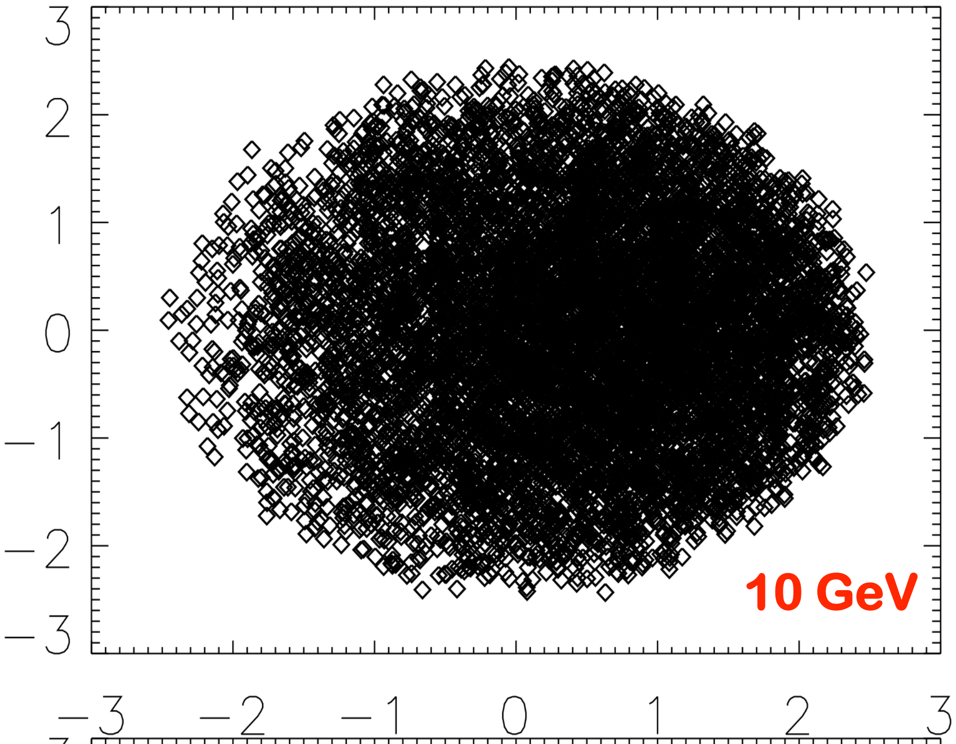
Injection of electrons still very problematic (in collisionless shocks dominated by protons, at zero order they should not even cross the shock and be Injected)

What is the electron spectrum?

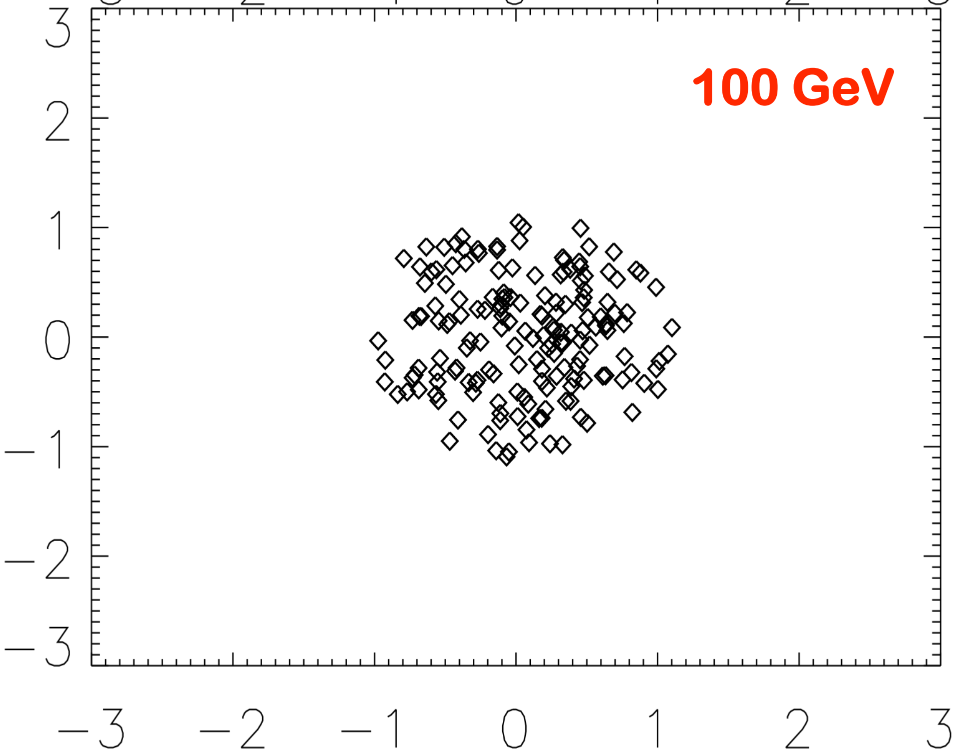


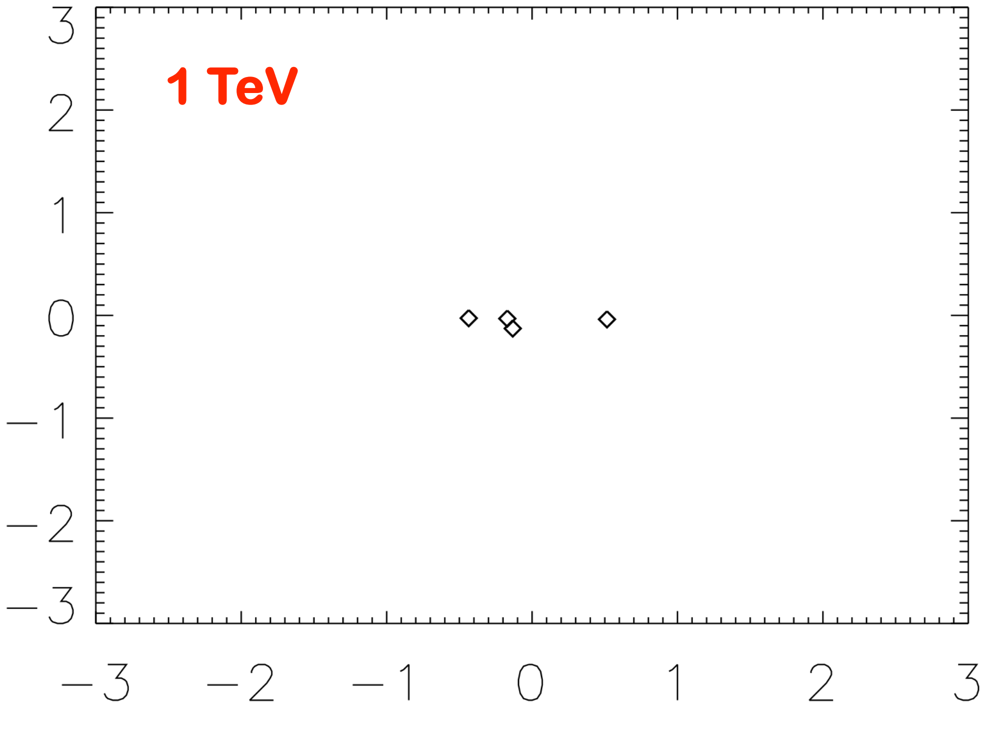
PB & Amato 2011

NUMBER OF ELECTRON SOURCES CONTRIBUTING AT GIVEN ENERGIES



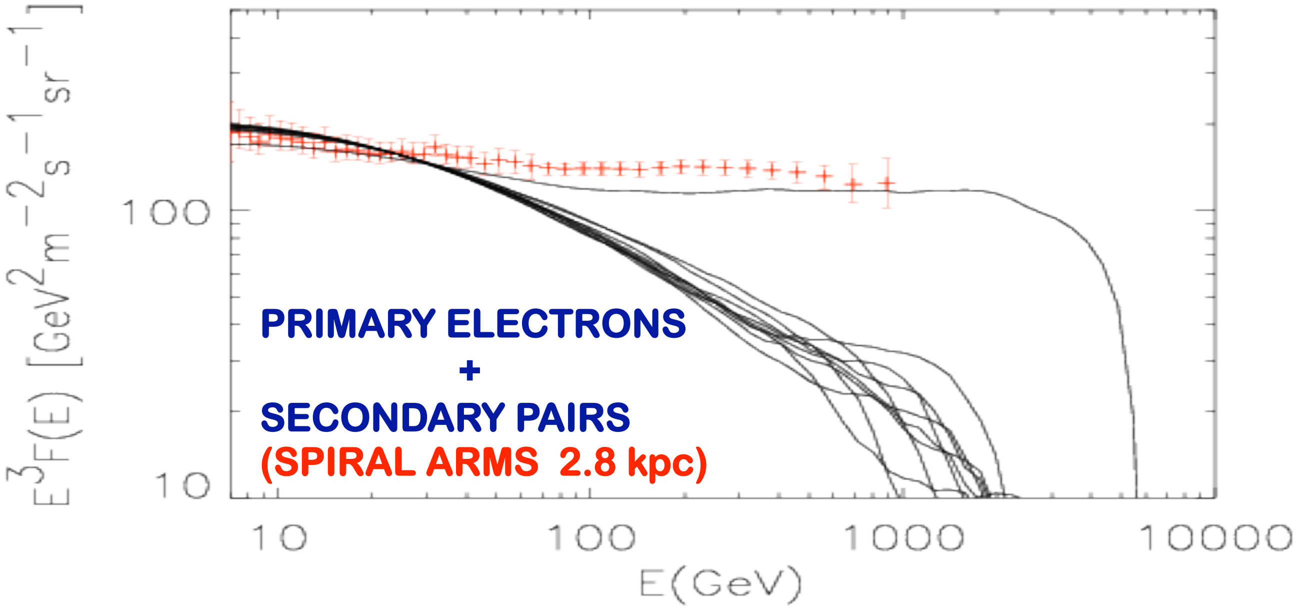
PB & Amato 2010



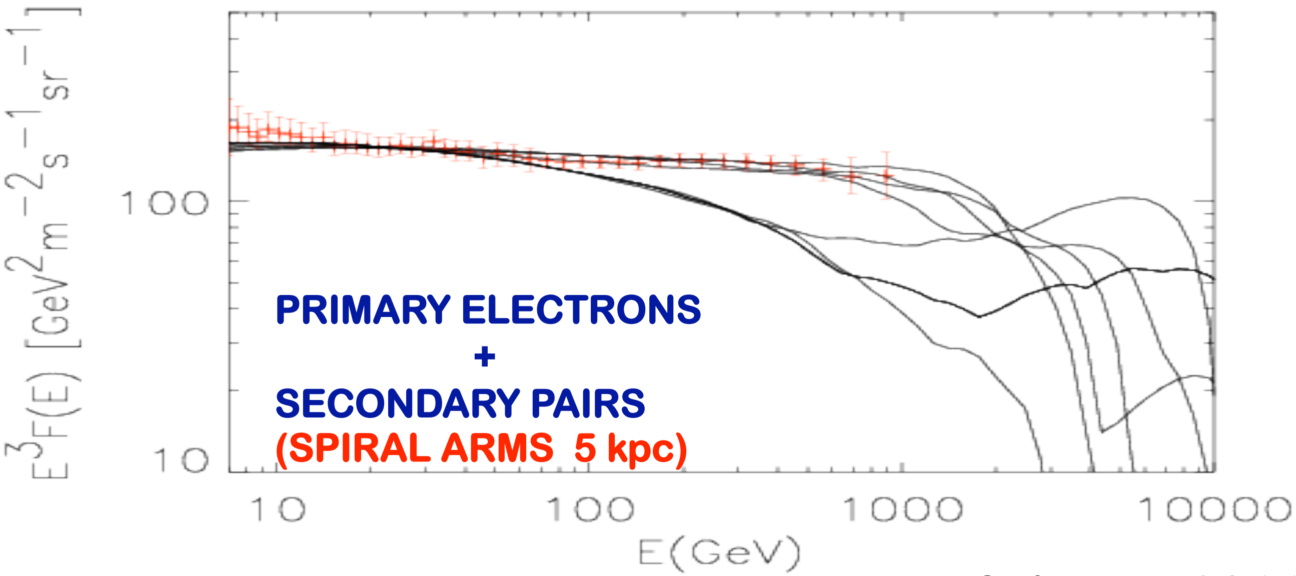


The effect of spiral arms

TIGHT
SPIRAL

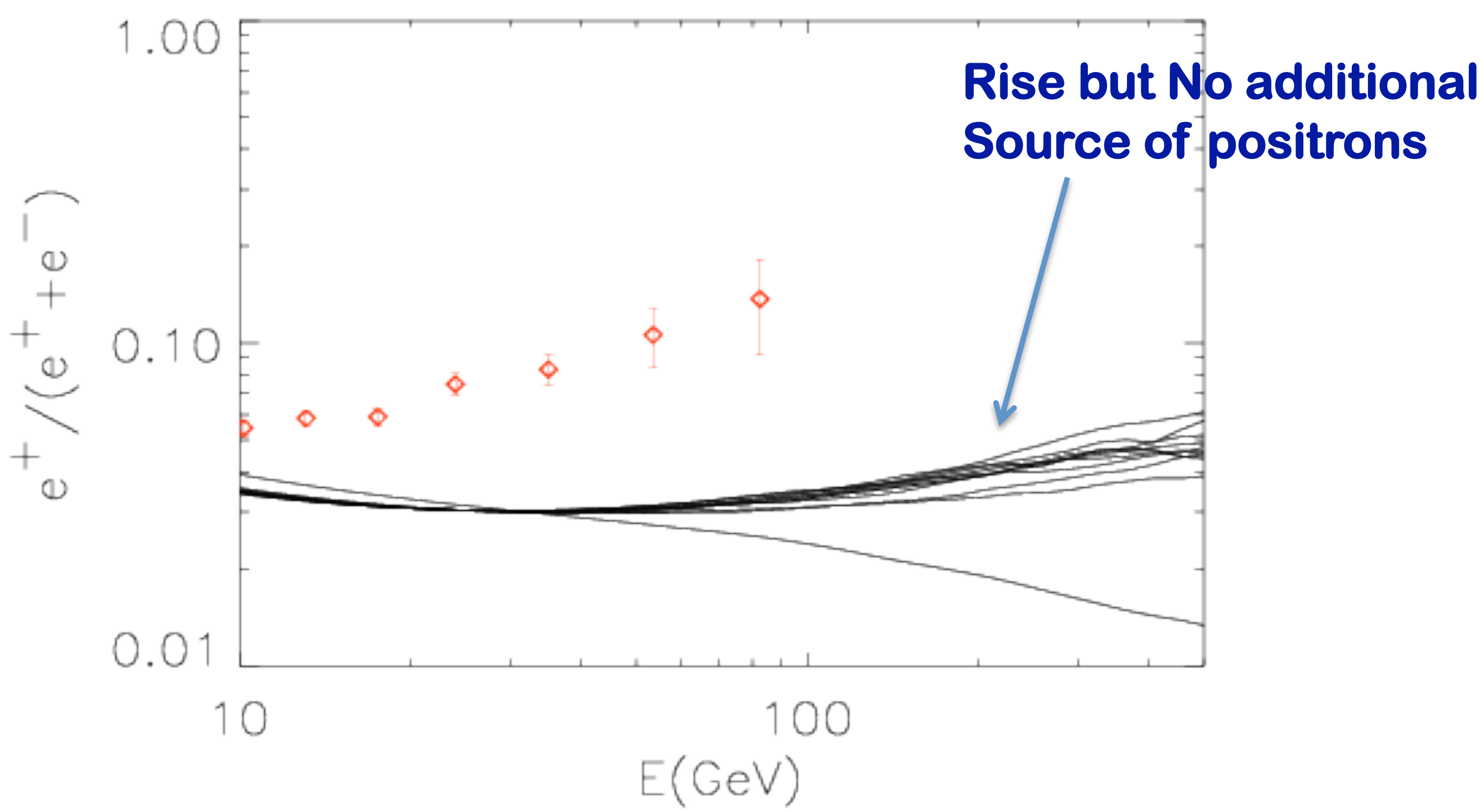


BROAD
SPIRAL



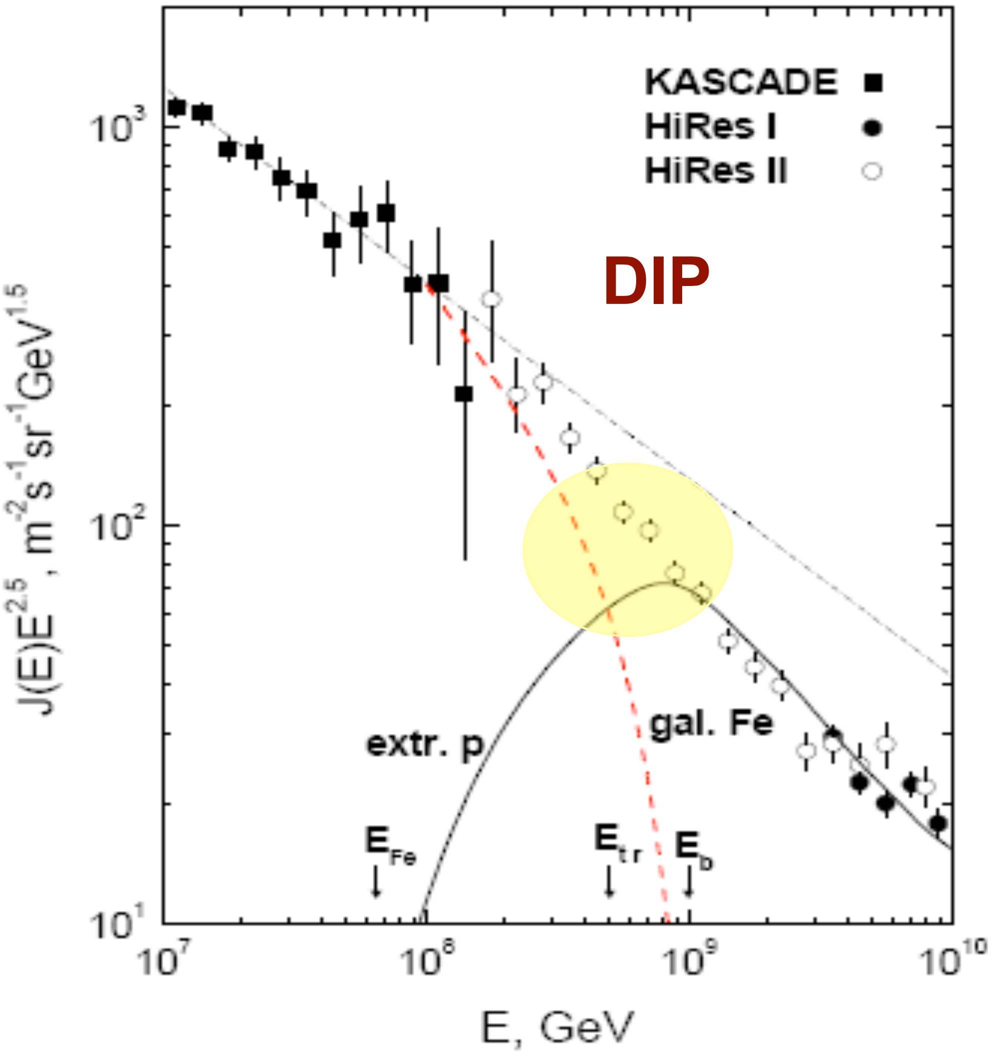
PB & Amato 2011

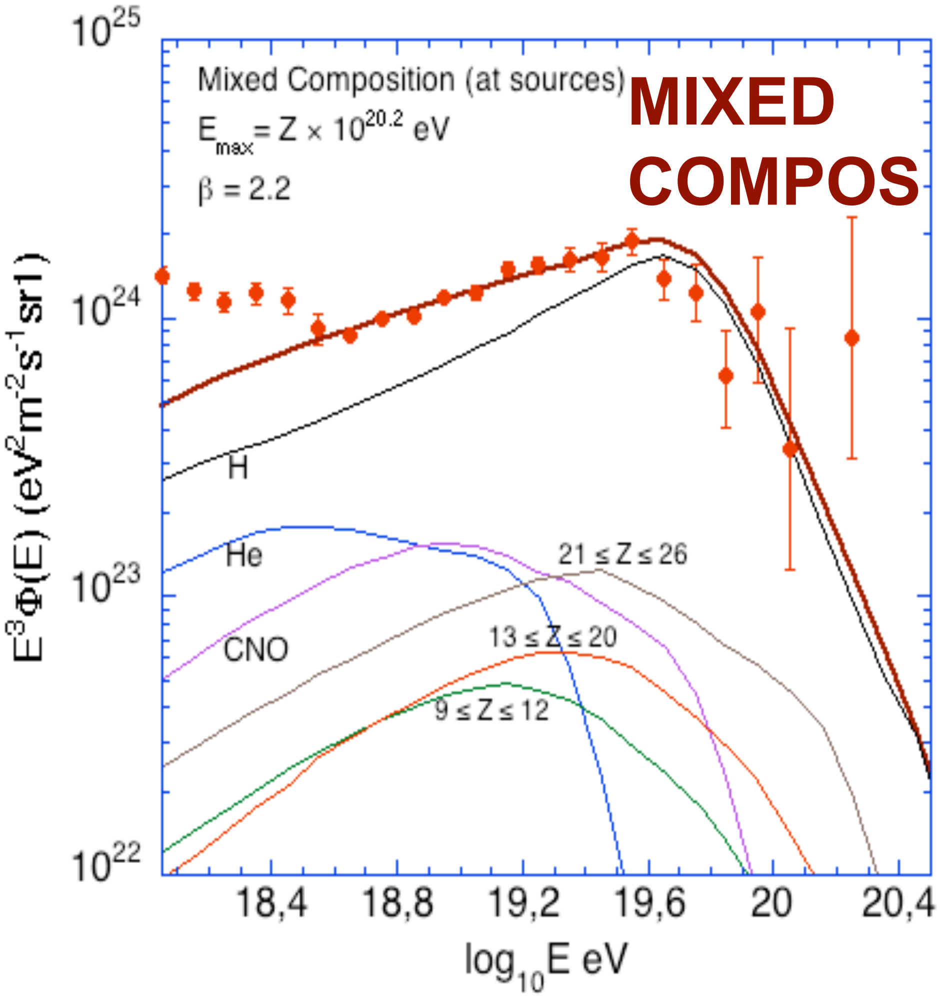
THE POSITRON FRACTION FOR THE CASE OF TIGHT SPIRAL ARMS



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

IMPLICATIONS OF THE SNR PARADIGM FOR THE TRANSITION



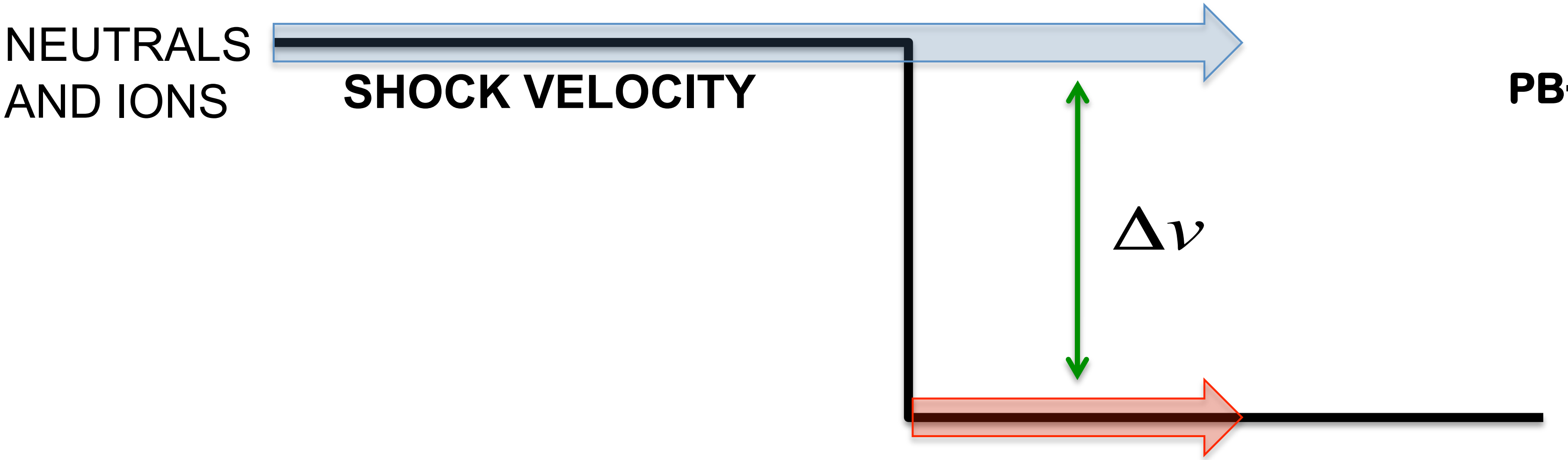


SOME RECENT PROGRESS AND POSSIBLY FUTURE DEVELOPMENTS

COLLISIONLESS SNR SHOCKS IN PARTIALLY IONIZED MEDIA:

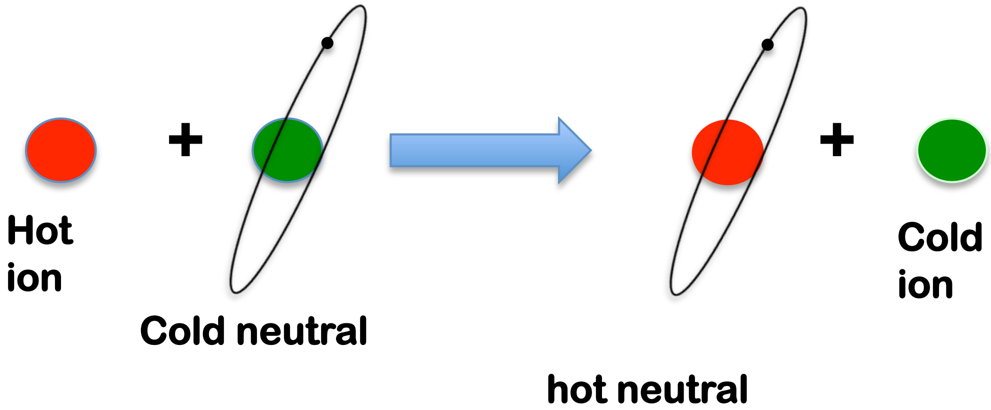
Anomalous width of Balmer lines

SUBTLE ASPECTS OF ACCELERATION AT A COLLISIONLESS SHOCK



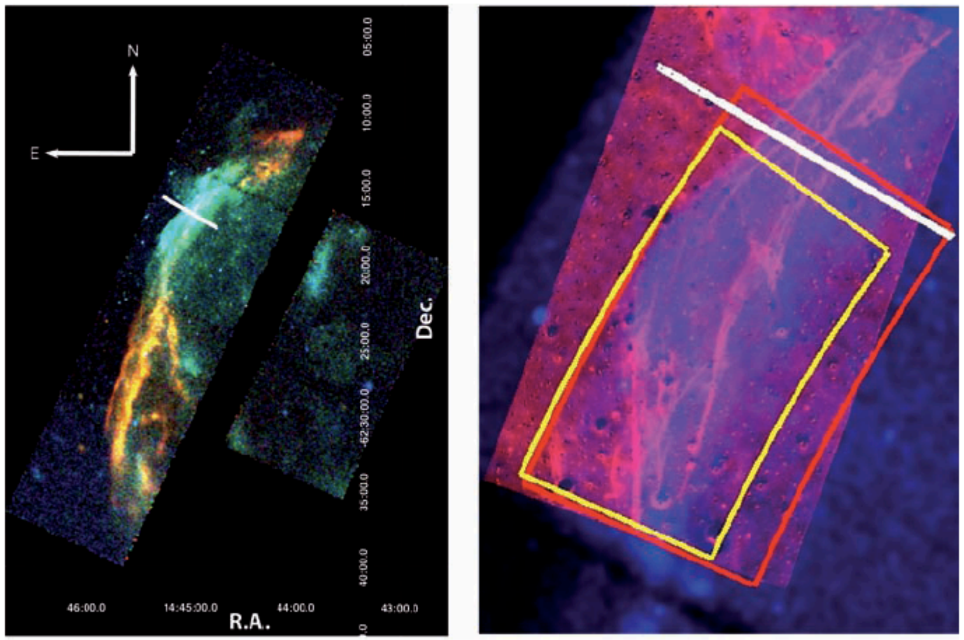
PB+, 2011

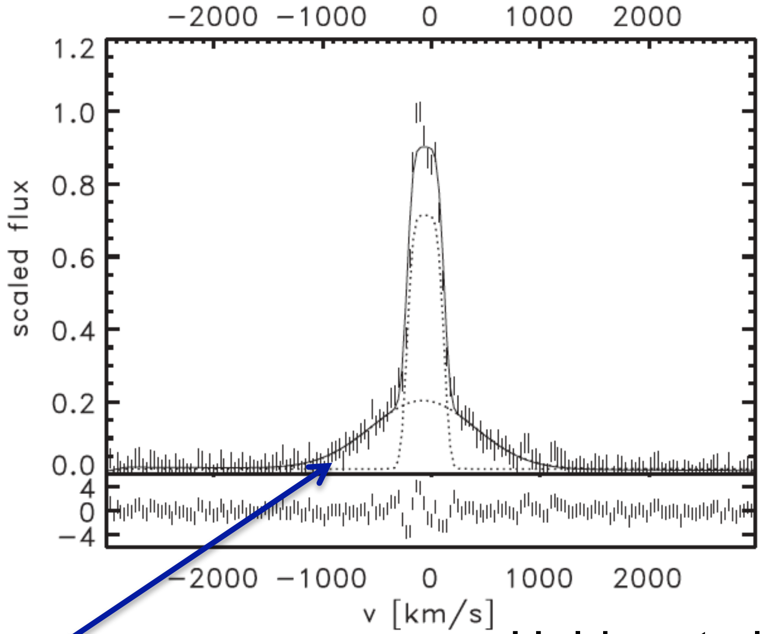
CHARGE EXCHANGE → BROAD BALMER LINE (NEUTRALS THAT MADE CHARGE EXCHANGE) REFLECTING THE TEMPERATURE OF IONS…



BUT THE LATTER AFFECTED BY EFFICIENT CR ACCELERATION

BROAD BALMER LINES NARROWER THAN FOR UNMODIFIED SHOCKS





Helder et al. 2009

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

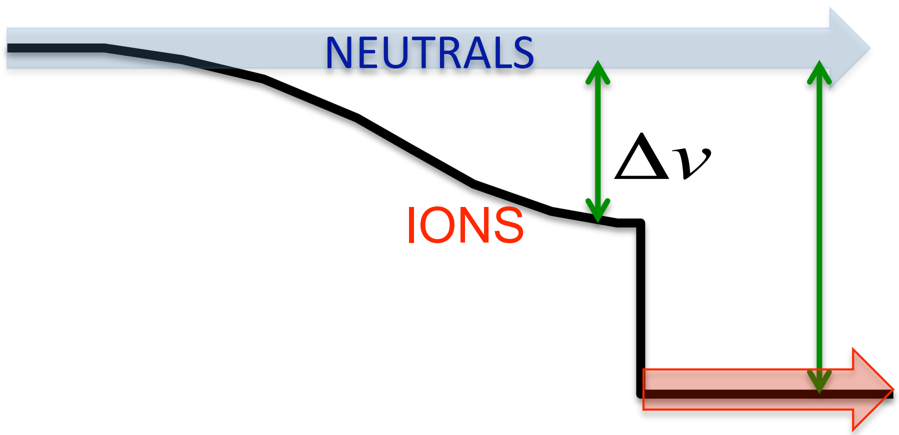
$$W_{broad} = 1100 \pm 63\, km/s \ \rightarrow\ T_2 = 2.3 \pm 0.3\, keV$$

Shock speed from proper motion

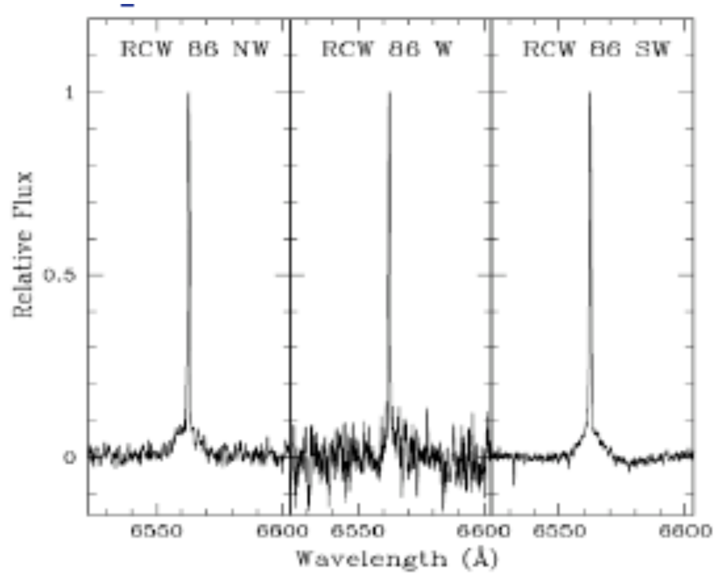
$$v_{shock} = 6000 \pm 2800\, km/s \left(\frac{d}{2.5 \pm .5\, kpc}\right)\left(\frac{\dot{\theta}_{obs}}{0.5 \pm .2''\, yr^{-1}}\right) \rightarrow T_2 = \begin{matrix} 20-150\, keV\ (no\ equilibration) \\ 12-90\, keV\ (equilibration) \end{matrix}$$

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

NARROW BALMER LINES BROADER THAN FOR UNMODIFIED SHOCKS



Sollerman et al. 2003



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

CHARGE EXCHANGE OCCURS NOW IN THE CR INDUCED PRECURSOR

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

NARROW BALMER LINE BROADER THAN FOR AN UNMODIFIED SHOCK

CONCLUSIONS

BASIC PRINCIPLES OF ACCELERATION IN SNR WELL POSED – HINT TO END OF GALACTIC CR AT ~FEW 10^{17} eV

BUT HARD TO MOVE AHEAD IN THE DETAILS (WE OBSERVE LARGE SCALES BUT THEY ARE DETERMINED BY VERY SMALL SCALES)

EFFICIENT ACCELERATION ≠ BRIGHT GAMMA OR NEUTRINO SOURCE (e.g. HIGH EFF. AND LARGE P_{MAX} FOR A SNII IN TENUOUS BUBBLE)

MAX ENERGY AT THE BEGINNING OF SEDOV: USUALLY INSIDE BUBBLE (NOT EASY TO SEE PEVATRONS UNLESS SNIa)

B-FIELD AMPLIFICATION BUT UNCLEAR DETAILS (SATURATION, SCALES – OBSERVATIONALLY HARD TO ACCESS)

STRONG EVIDENCE FOR STEEP SPECTRA (CAN'T BE LEPTONIC) ~ $E^{-2.2}$ (RECALL ESCAPE SPECTRUM ≠ ACCELERATED SPECTRUM)

BIG DEVELOPMENTS FROM BALMER DOMINATED SHOCKS AS INDICATORS OF CR ACCELERATION EFFICIENCY