ORIGIN OF GALACTIC COSMIC RAYS

PASQUALE BLASI

INAF/Arcetri Astrophysical Observatory, Firenze &

GSSI/Gran Sasso Science Institute, L'Aquila

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DO WE HAVE A STANDARD MODEL?

THE MAIN GUIDANCE FROM DATA HAS COME FROM:

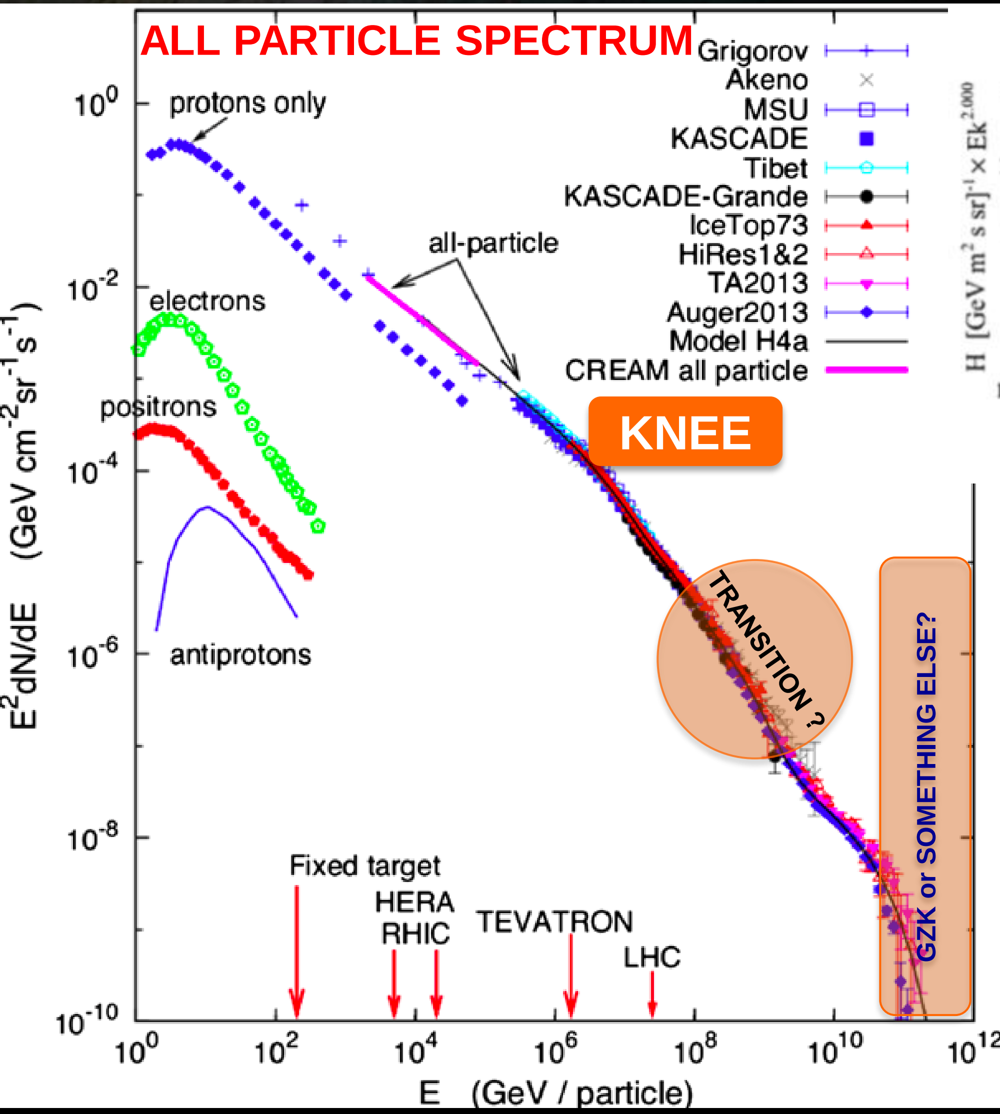
- PROTON KNEE AT ~ THE ALL-PARTICLE KNEE
- B/C RATIO (and other secondary/primary ratios)

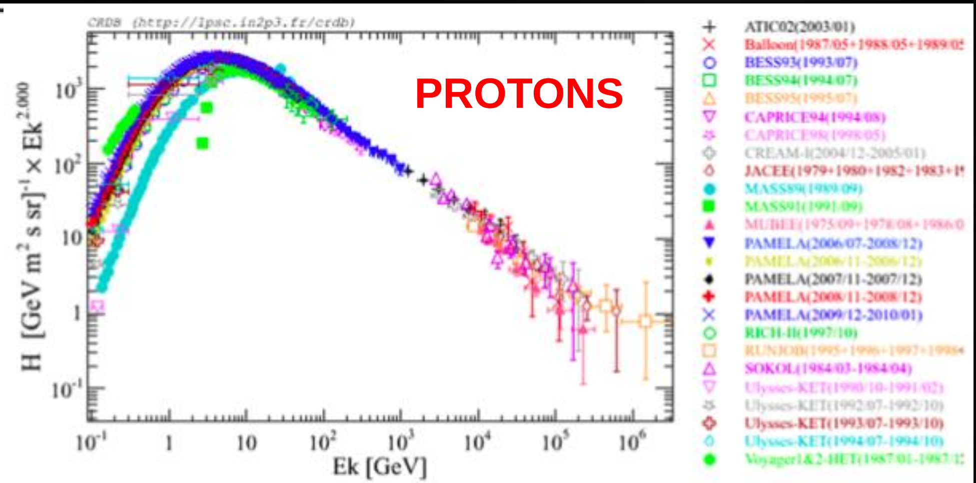
THE MOST *'STANDARD' MODEL* WE HAVE CONSISTS OF TWO PIECES:

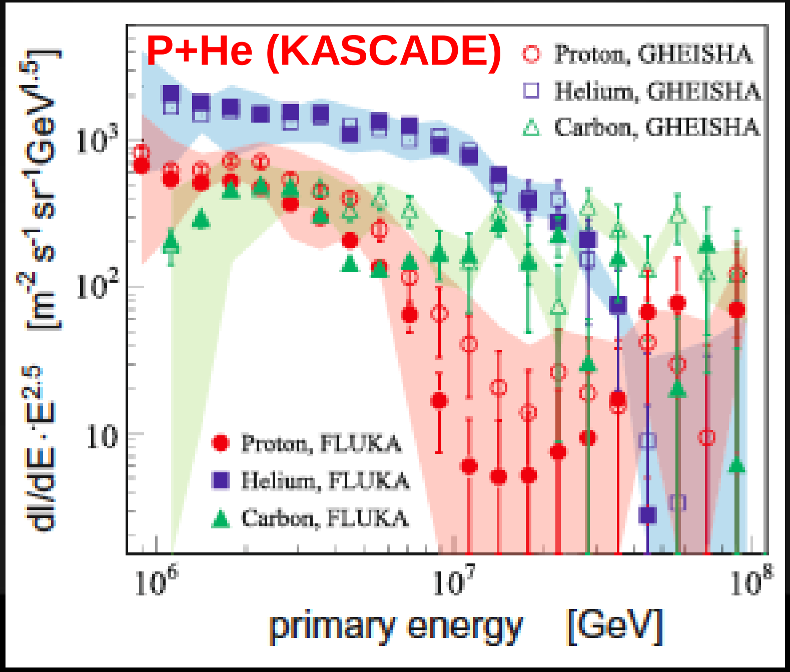
1. Particles propagate diffusively in the Galaxy, which should explain the secondary/primary ratios and unstable isotopes + diffuse bkgnds.

1. Particles are accelerated in supernova remnants (SNRs) through Diffusive Shock Acceleration

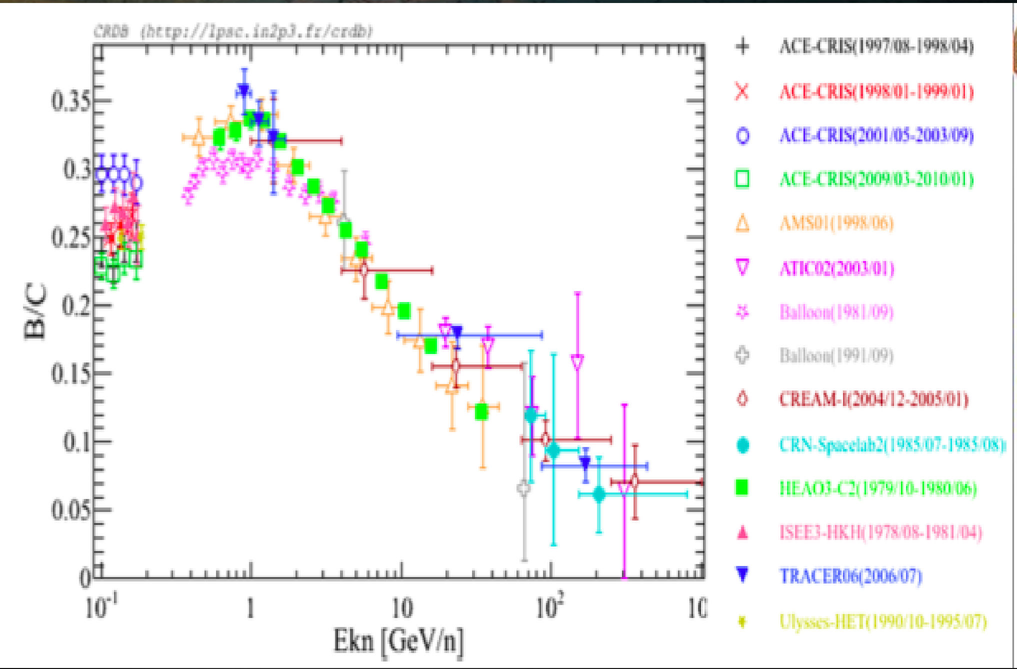
SPECTRA

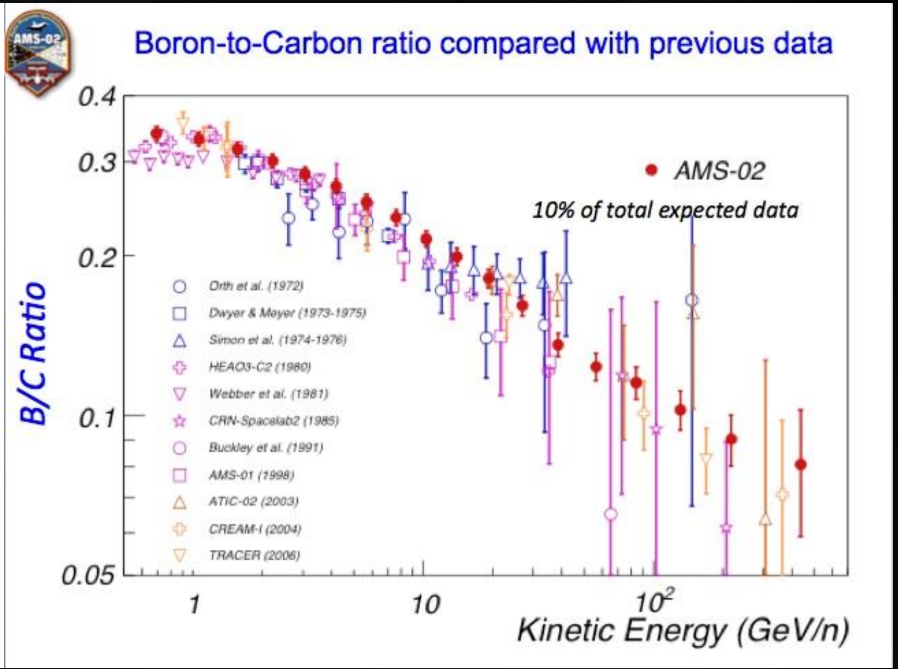

ALL PARTICLE SPECTRUM
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
protons only
all-particle
electrons
positrons
antiprotons
KNEE
TRANSITION ?
GZK or SOMETHING ELSE?
Fixed target
HERA
RHIC
TEVATRON
LHC
E^2dN/dE (GeV cm^{-2}sr^{-1}s^{-1})
E (GeV / particle)


PROTONS
H [GeV m^2 s sr]$^{-1}$ × Ek$^{2.000}$
Ek [GeV]


P+He (KASCADE)
Proton, GHEISHA
Helium, GHEISHA
Carbon, GHEISHA
Proton, FLUKA
Helium, FLUKA
Carbon, FLUKA
dI/dE · E$^{2.5}$ [m^{-2} s^{-1}sr^{-1}GeV$^{1.5}$]
primary energy [GeV]

B/C RATIO





THE DECREASE OF B/C WITH Energy/nucleon IS THE BEST SIGN OF A RIGIDITY DEPENDENT GRAMMAGE TRAVERSED BY COSMIC RAYS ON THEIR WAY OUT OF THE GALAXY

$$\frac{\Phi_B(E)}{\Phi_C(E)} \propto X(E) \propto \frac{1}{D(E)} \sim E^{-\delta}$$

For relativistic E

HOW STANDARD IS THE STANDARD MODEL OF TRANSPORT?

EVEN COMPLEX COMPUTATION CODES SUCH AS GALPROP ADOPT IMPORTANT SIMPLIFICATIONS… RELAXING THESE ASSUMPTIONS → CORRECTIONS AT THE ZERO ORDER … PROBLEM IS THAT SOME OF THESE COMPLICATIONS ARE DIFFICULT IN PRINCIPLE, NOT ONLY IN IMPLEMENTATION!

SEVERAL COMPLICATIONS:

1. *DIFFUSION COEFFICIENT NON SPATIALLY CONSTANT*
2. *ANISOTROPIC DIFFUSION (PARALLEL vs PERPENDICULAR)*
3. *EFFECT OF SELF-GENERATION OF WAVES INDUCED BY CR*
4. *DAMPING OF WAVES AND ITS EFFECTS ON CR PROPAGATION*
5. *CASCADING OF MODES IN WAVENUMBER SPACE*

EACH ONE OF THESE PHYSICAL MECHANISMS CHANGES THE PREDICTED SPECTRA AND ANISOTROPIES IN A SUBSTANTIAL WAY but there are questions of principle that make it difficult to address them

NON SEPARABLE D(E,z)

THE STANDARD RULE OF THUMB THAT

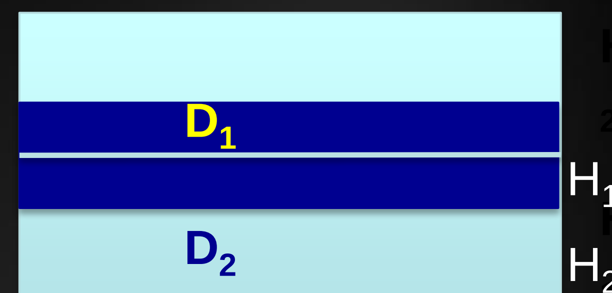
n(E)~Q(E) ⧫(E) ~ Q(E)/D(E)~E⊡♑⊡♎

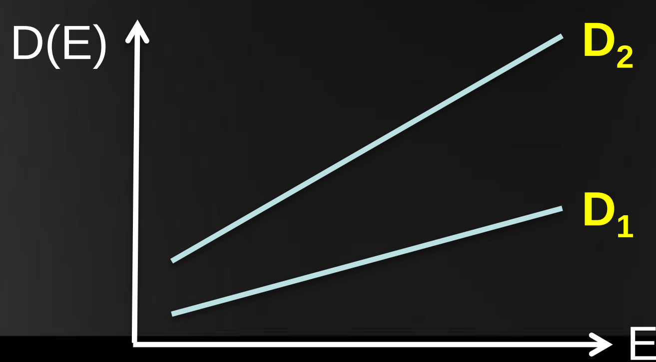
IS ONLY VALID FOR SPATIALLY CONSTANT DIFFUSION OR FOR SEPARABLE D(E,z)=F(E)G(z)

EASIEST INSTANCE OF NON-SEPARABILITY:

$$D(E,z) = D_1(p) = K_1 \left(\frac{E}{E_0}\right)^{\delta_1} \qquad for\ |z| < H_1$$

$$D(E,z) = D_2(p) = K_2 \left(\frac{E}{E_0}\right)^{\delta_2} \qquad for\ H_1 < |z| < H_2$$





NON SEPARABLE D(E,z)

THE SIMPLEST FORM OF THE TRANSPORT EQUATION CAN BE WRITTEN AS:

$$-\frac{\partial}{\partial z}\left[D(p,z)\frac{\partial f}{\partial z}\right] = q(p,z)$$

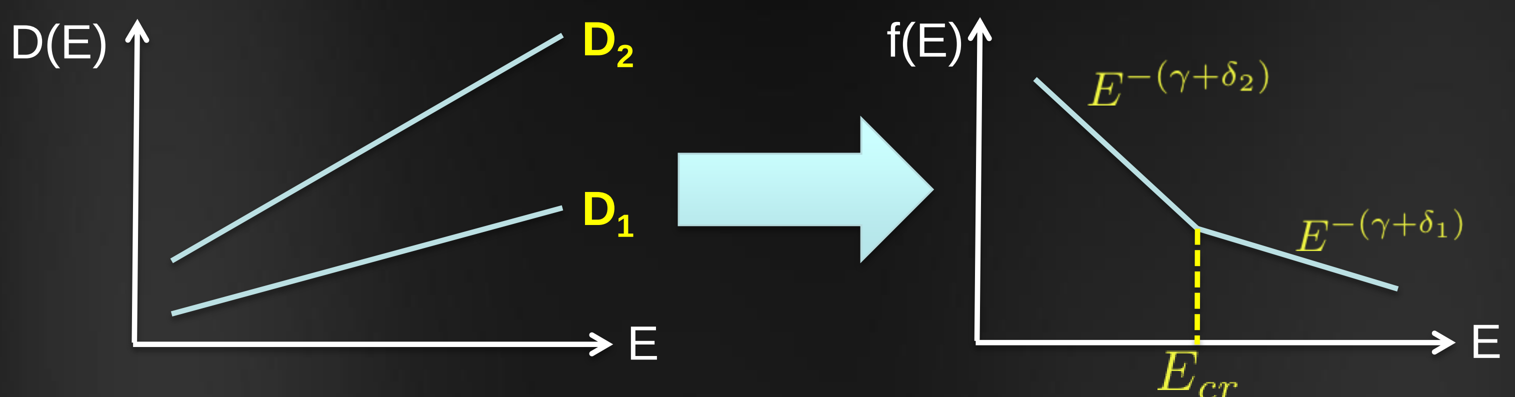
$$q(p,z) = 2hq_0(p)\delta(z)$$

$$q_0(p) = \frac{N(p)\mathcal{R}}{2h\pi R_d^2}$$

WHERE THE CR DENSITY IN THE DISC IS (*e.g. Dogiel 2001, Tomassetti 2012****):***

$$f_0(p) = \frac{N(p)\mathcal{R}}{2\pi R_d^2}\left[\frac{H_1}{D_1} + \frac{H_2-H_1}{D_2}\right] \propto \begin{cases} E^{-\gamma-\delta_2} & E \ll E_{cr} \\ E^{-\gamma-\delta_1} & E \gg E_{cr} \end{cases}$$

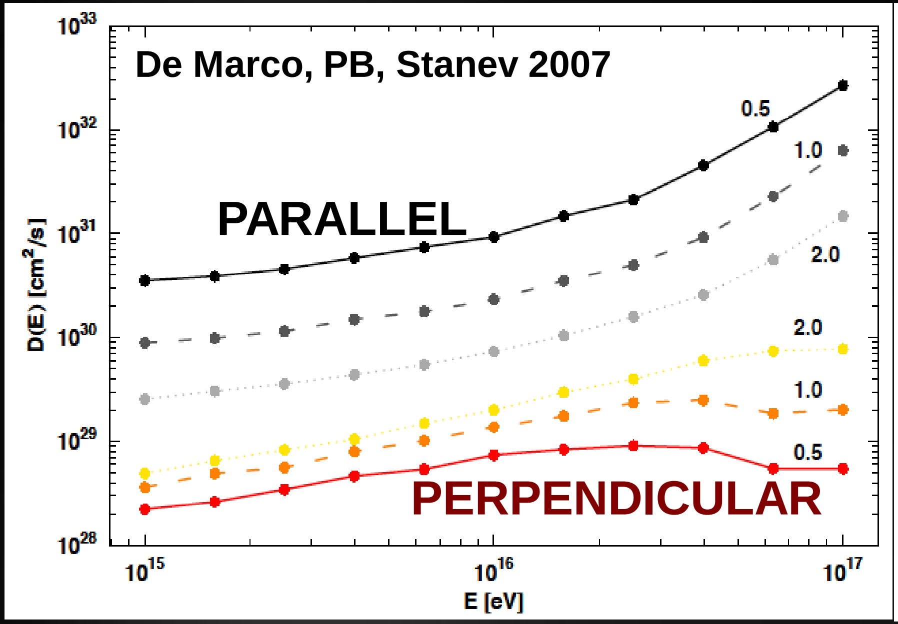
$$E_{cr} = \left[\frac{K_1}{K_2}\frac{H_2-H_1}{H_1}\right]^{\frac{1}{\delta_2-\delta_1}}$$

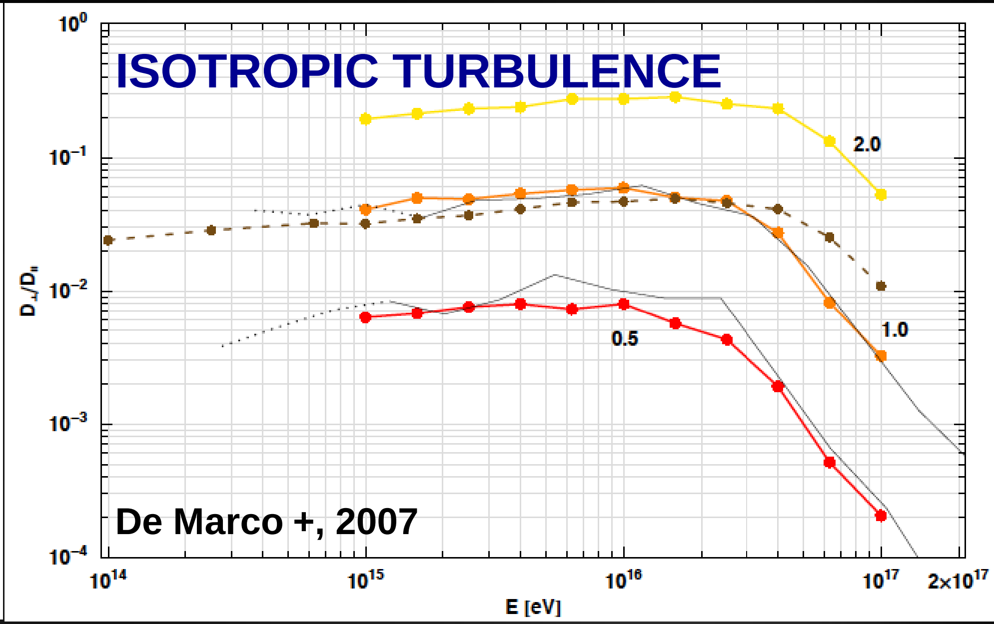


ANISOTROPIC DIFFUSION

EVEN FOR ISOTROPIC TURBULENCE, DIFFUSION IS NOT ISOTROPIC

$$D_{\parallel} \neq D_{\perp}$$





NUMERICAL SIMULATIONS OF PARTICLE PROPAGATION IN ISOTROPIC TURBULENCE SHOW THAT

1) EVEN FOR ♎B/B~1, $D_{par} > D_{perp}$

2) PAR AND PERP D(E) HAVE DIFFERENT ENERGY DEPENDENCES

SOME POINTS …

1. THE PARALLEL AND PERPENDICULAR D(E) IN GENERAL HAVE DIFFERENT ENERGY DEPENDENCES (ONE MAY DOMINATE UPON THE OTHER AT DIFFERENT ENERGIES)

2. SINCE GAS IS IN THE SPIRAL ARMS AND NOT MUCH OUTSIDE (INCLUDING THE HALO) THE GRAMMAGE IS HEAVILY AFFECTED BY PARALLEL vs PERPENDICULAR TRANSPORT

3. IN THIS SENSE, WE DO NOT KNOW WHETHER THE B/C IS SHOWING US THE PARALLEL OR THE PERPENDICULAR TRANSPORT MODE (SAME FOR ANISOTROPY)

1. MAIN UNCERTAINTY: DEVELOPMENT OF THE TURBULENT CASCADE WHICH DEVELOPS MAINLY PERP TO B_0 THEREBY SUPPRESSING THE RESONANCE (though in the solar system this effect is much less than expected from theoretical arguments)

AN OLD PROBLEM … *Ion-Neutral Damping*

Kulsrud & Cesarsky (1971)

$$\Gamma_D(k) = \frac{\nu}{2}, \qquad k > \frac{\nu}{v_A}\left(1 + \frac{n_i}{n_H}\right) = k_*$$

$$\Gamma_D(k) = \frac{k^2 v_A^2}{2\nu\left(1+\frac{n_i}{n_H}\right)}, \qquad k < \frac{\nu}{v_A}\left(1 + \frac{n_i}{n_H}\right)$$

$$\nu \approx 8.4 \times 10^{-9} \left(\frac{n_H}{1\ \mathrm{cm}^{-3}}\right) \left(\frac{T}{10^4 K}\right)^{0.4}\ s^{-1}$$

ION-NEUTRAL DAMPING IS EFFECTIVE FOR LARGE WAVENUMBER NAMELY FOR LOW PARTICLE MOMENTUM (IN TERMS OF RESONANT SCATTERING).

FOR V_A=20 km/s and $n_i \ll n_H$: $k_* \approx \frac{\nu}{v_A} \approx 4 \times 10^{-15}\ cm^{-1}$

$$r_L \sim 1/k_* \rightarrow E_* \sim 75 GeV$$

PARTICLES SHOULD NOT DIFFUSE IN THE INNER kpc FROM THE DISC OF THE GALAXY !!!

EFFECTIVE SPATIAL SEGREGATION (MOLECULAR CLOUDS?) IS REQUIRED IN ORDER TO ALLOW FOR DIFFUSION IN THE GALACTIC DISC

CR INDUCED SCATTERING

ENSAMBLES OF CHARGED PARTICLES WITH SUPERALFVENIC VELOCITY INDUCE STREAMING INSTABILITY ON k ~ 1/LARMOR RADIUS

IN THE CONTEXT OF CR PROPAGATION IN THE GALAXY, THIS WAS FIRST DISCUSSED BY Skilling (1975). Holmes (1975) DISCUSSED THE RELATIVE IMPORTANCE OF GROWTH AND DAMPING OF THE WAVES RESPONSIBLE FOR CR SCATTERING

COSMIC RAYS MAY PLAY AN ACTIVE ROLE IN THEIR OWN DIFFUSIVE PROPAGATION

THE PRESSURE OF CR CAN FIGHT AGAINST GRAVITY AND LAUNCH WINDS BY USING THE WAVES THEY GENERATE → TRANSPORT CHANGES

THE ROLE OF CR ON THEIR OWN TRANSPORT

THE GROWTH RATE OF THE UNSTABLE MODES INDUCED BY CR IS PROPORTIONAL TO THEIR SPATIAL GRADIENT

$$\Gamma_{CR} = \frac{16\pi^2}{3} \frac{v_A}{B_0^2 \mathcal{F}(k_{res})} \left[p^4 v(p) \frac{\partial f}{\partial z} \right]_{p_{res}(k)}$$

WHERE THE DISTRIBUTION FUNCTION OF CR IS FOUND FROM THE DIFFUSION EQUATION WITH:

$$D(p) \approx \frac{1}{3} r_L v(p) \frac{1}{\mathcal{F}(k_{res})} \qquad k_{res}(p) = 1/r_L(p)$$

$$\Gamma_{CR}(k) = \frac{\tau_A}{\tau_{diff}(p)} \Omega_{cyc} \frac{n_{CR}(>p_{res})}{n_i} \qquad \tau_A = \frac{H}{v_A} \qquad \tau_{diff} = \frac{H^2}{D(p)}$$

$$\Gamma_{CR}(k) \approx 2 \times 10^{-10} \left(\frac{E}{5GeV} \right)^{-1.2} \; s^{-1}$$

CR TRANSPORT IN SELF-GENERATED WAVES

PB, Amato & Serpico 2012, Aloisio & PB 2013

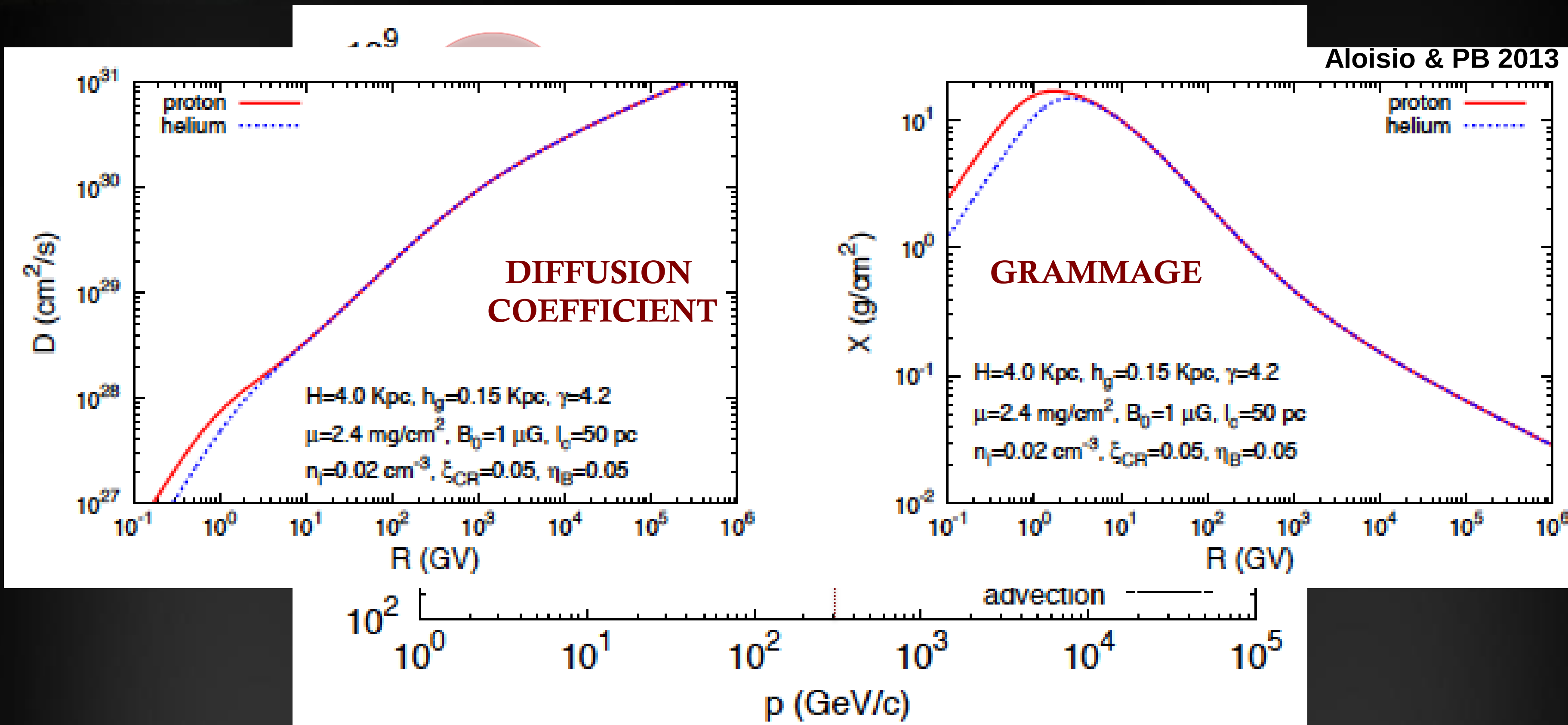
$$-\frac{\partial}{\partial z}\left[D_\alpha(E)\frac{\partial f_\alpha}{\partial z}\right] + v_A\frac{\partial f_\alpha}{\partial z} + \frac{f_\alpha}{\tau_{sp,\alpha}} - \frac{dv_A}{dz}\frac{p}{3}\frac{\partial f_\alpha}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}f_\alpha\right)_{ion}\right] = q_{inj}(p) + \sum_{\alpha'>\alpha}\frac{f_{\alpha'}}{\tau_{sp,\alpha'\to\alpha}}$$

α DENOTES THE TYPE OF NUCLEUS (BOTH PRIMARIES AND SECONDARIES ARE INCLUDED)

$$\frac{\partial}{\partial k}\left[D_{kk}\frac{\partial W}{\partial k}\right] + \Gamma_{CR} W = q_W(k)$$

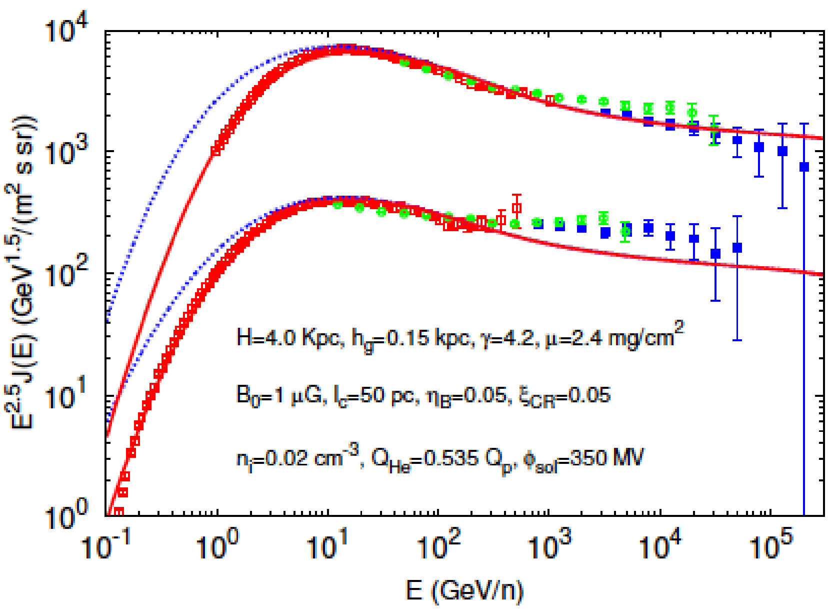
TRANSPORT EQUATION FOR WAVES

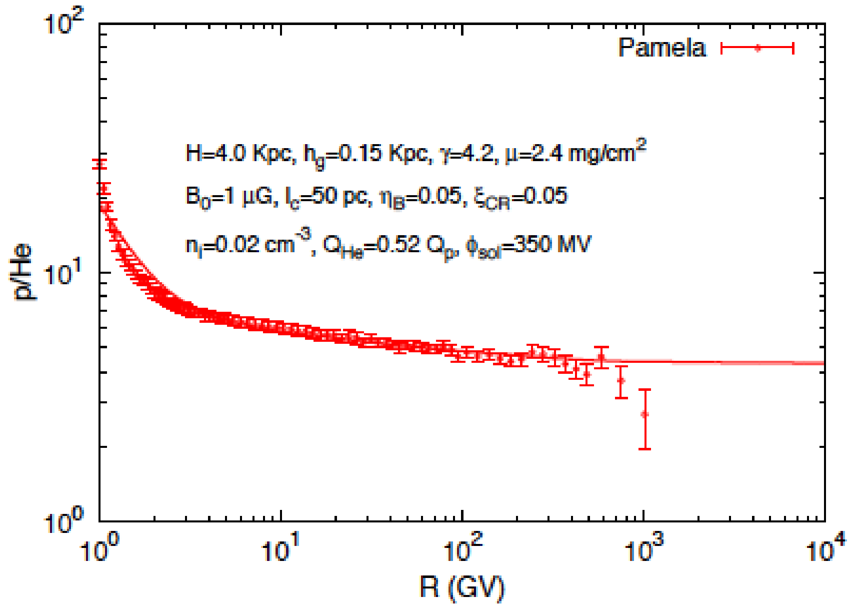
GENERAL TRENDS, D(E), X(E)

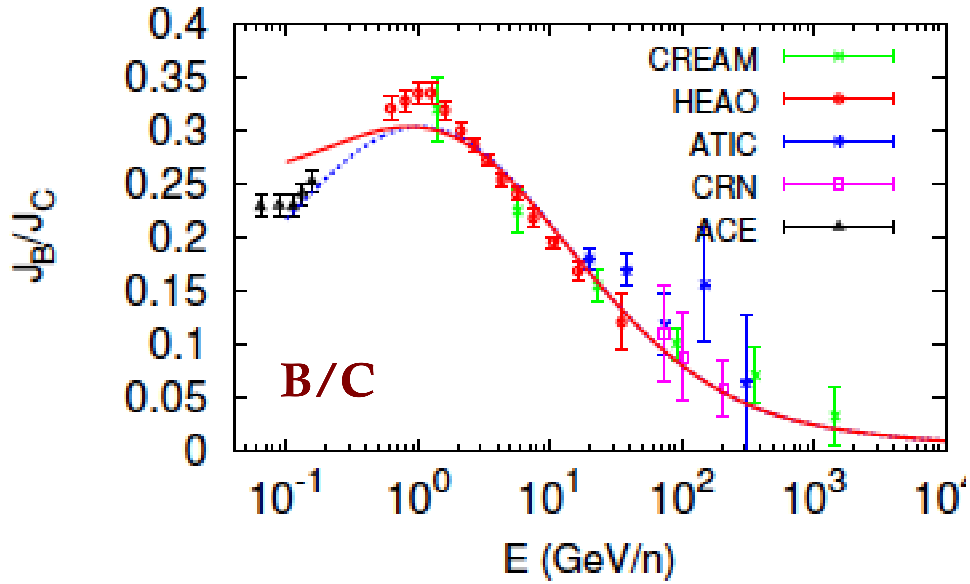


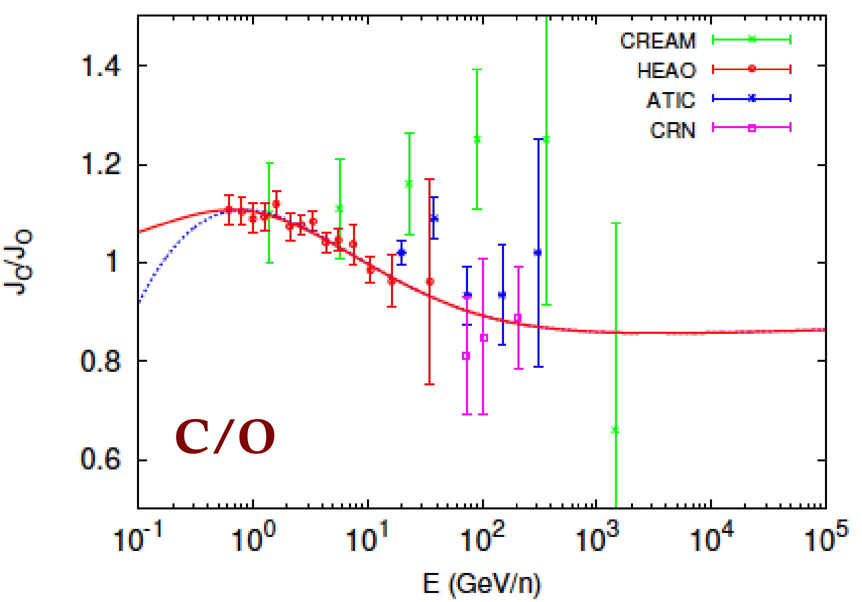
Aloisio & PB 2013

MAIN IMPLICATIONS

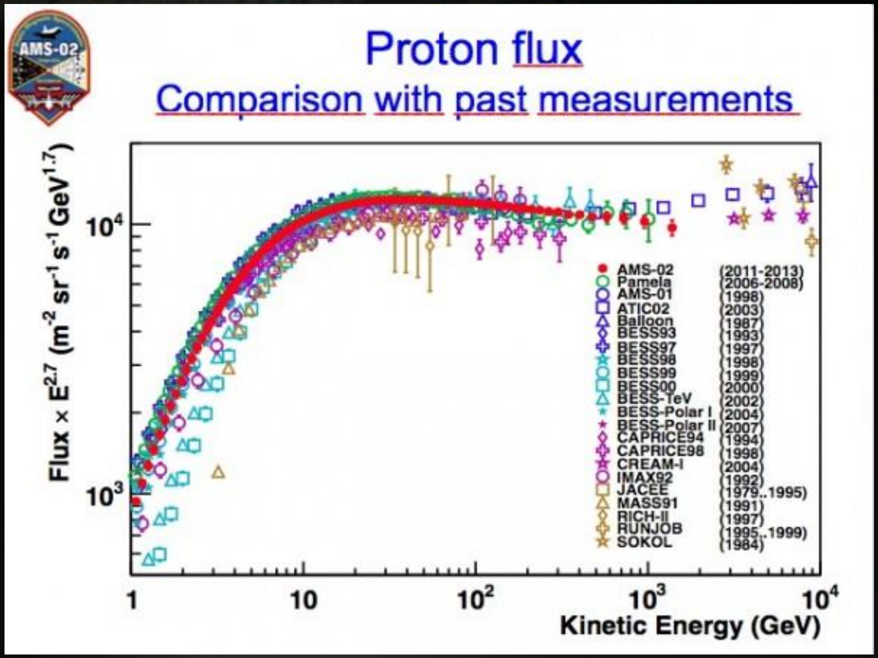


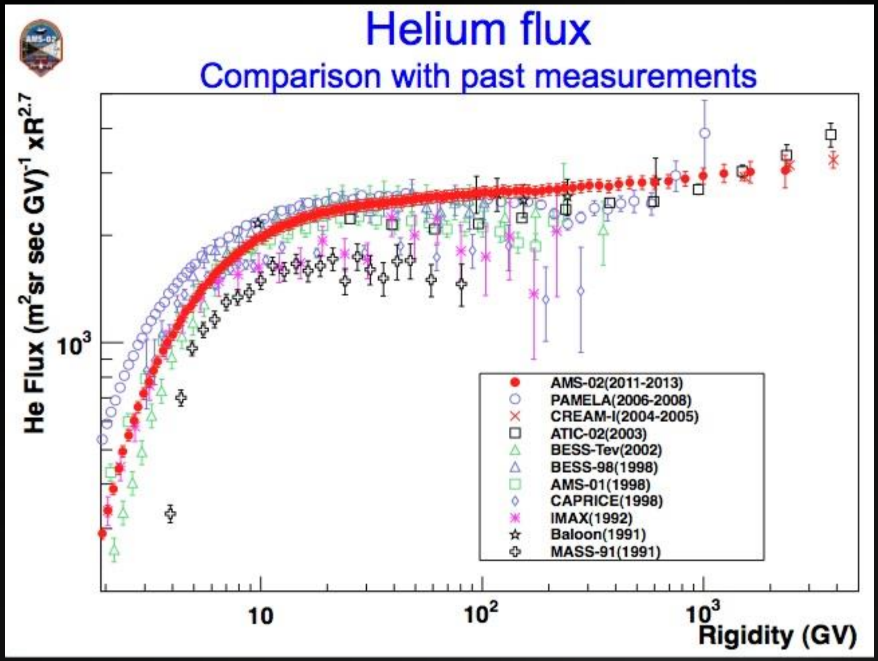






NO BREAKS IN AMS-02 (?)





1. APPARENTLY NO SIGN OF SPECTRAL BREAKS
2. OVERALL SPECTRAL STRUCTURE RATHER DIFFERENT
3. ALL AGREE THAT He SPECTRUM IS HARDER THAN H SPECTRUM
4. BUT NORMALIZATION OF FLUXES IN GOOD AGREEMENT WITH CREAM
   (shouldn’t there be a change of slope after all?)

CR INDUCED GALACTIC WINDS

CR PRESSURE GRADIENTS ACT AS A FORCE AGAINST GRAVITY

THIS CAN LAUNCH WINDS FROM THE GALACTIC DISC (Breitschwerdt+1991,1993)

THIS MAY PROFOUNDLY CHANGE THE DYNAMICS OF THE GALAXY AS WELL AS THE TRANSPORT OF GALACTIC CR (Zirakashvili+ 1996).

ADVECTION vs DIFFUSION:

$$\frac{r_b^2}{D(p)} = \frac{r_b}{u_w} \rightarrow r_b \sim p^{\delta/2}$$

assuming $u_w \sim r$

WHERE NOW DELTA IS A FUNCTION OF THE INJECTION SPECTRUM (SELF-GENERATION)

IT FOLLOWS THAT:

$$N(p) = Q(p)\frac{r_b}{D(p)} \sim p^{-\gamma-\delta(\gamma)/2}$$

HOW STANDARD IS THE STANDARD MODEL OF CR ACCELERATION?

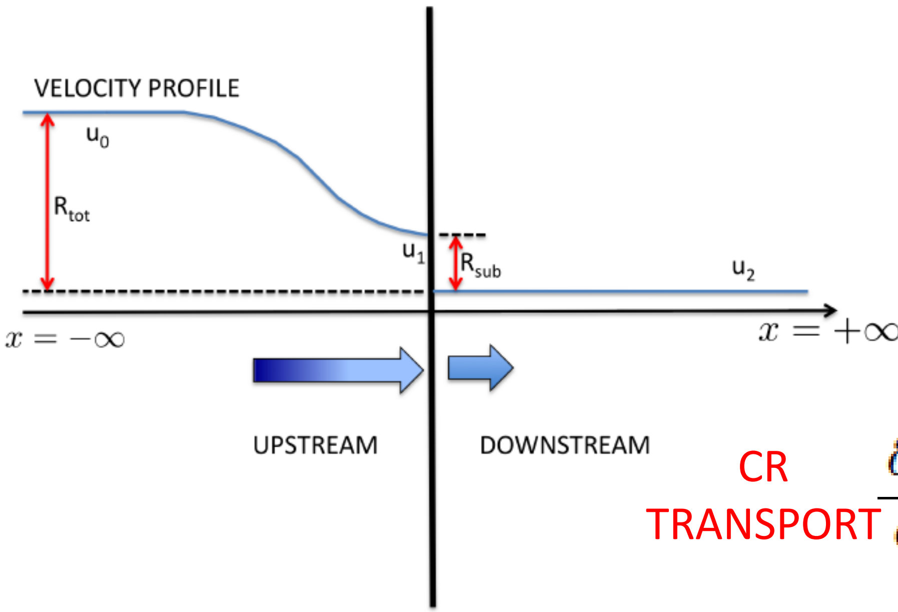
CR ACCELERATION EFFICIENCIES OF 10-20% → **NON LINEAR DSA**

MAXIMUM ENERGIES → **MAGNETIC FIELD AMPLIFICATION**, MOST LIKELY DUE TO ACCELERATED PARTICLES (ADDITIONAL NON LINEARITY)

SPECTRUM AT THE EARTH ← A RATHER COMPLEX SUPERPOSITION OF PARTICLES ADVECTED DOWNSTREAM AND **ESCAPING FLUX**

BUT THERE ARE NUMEROUS ASPECTS OF DSA THAT GO WAY BEYOND THIS *QUASI-STANDARD* PICTURE…

ACCELERATION AT SNR SHOCKS



MASS
$$\frac{\partial}{\partial z}(\rho u) = 0$$

MOMENTUM
$$\frac{\partial}{\partial z}\left(\rho u^2 + P_g + P_c\right) = 0$$

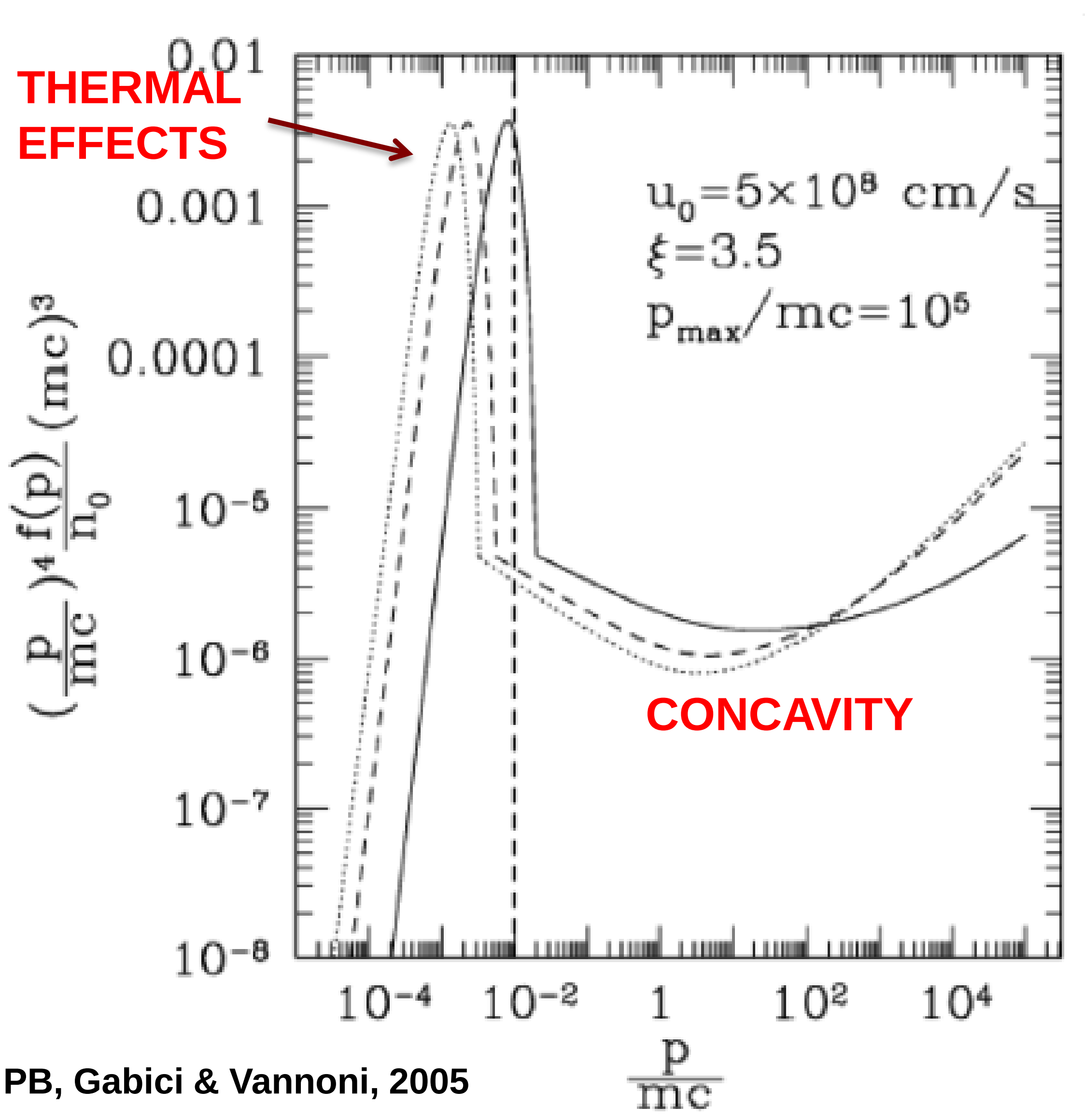
ENERGY
$$\frac{\partial}{\partial z}\left(\frac{1}{2}\rho u^3 + \frac{\gamma_g}{\gamma_g - 1} u P_g\right) = -u\frac{\partial P_c}{\partial z}.$$

CR TRANSPORT
$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \frac{1}{3}\frac{du}{dz}p\frac{\partial f}{\partial p} + Q$$

TWO MAIN IMPLICATIONS:

1. **CONCAVE SPECTRA**
2. **MODIFIED SHOCK HEATING**

EFFECTS OF NLDSA



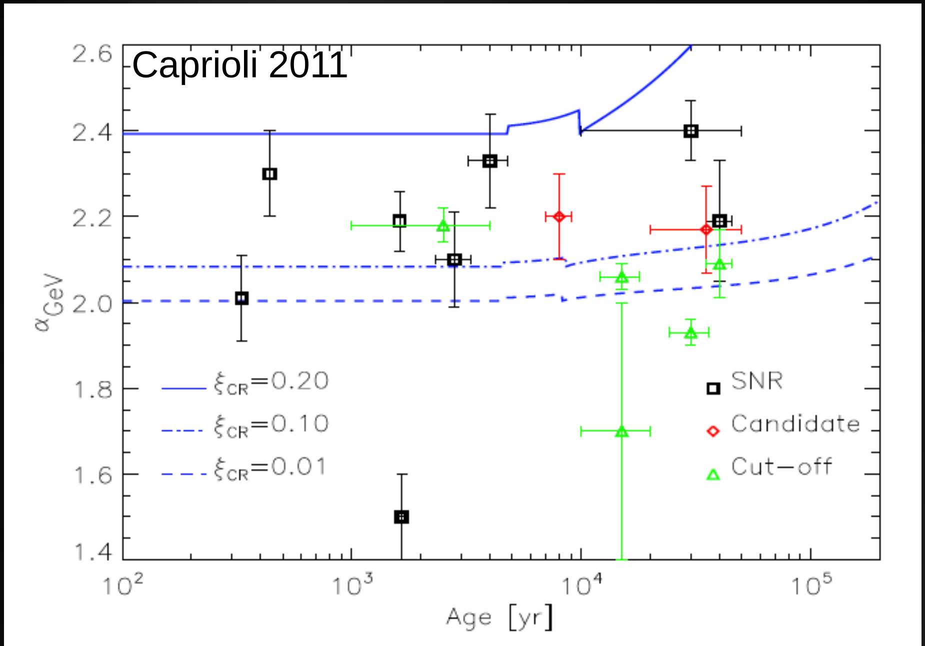
PB, Gabici & Vannoni, 2005

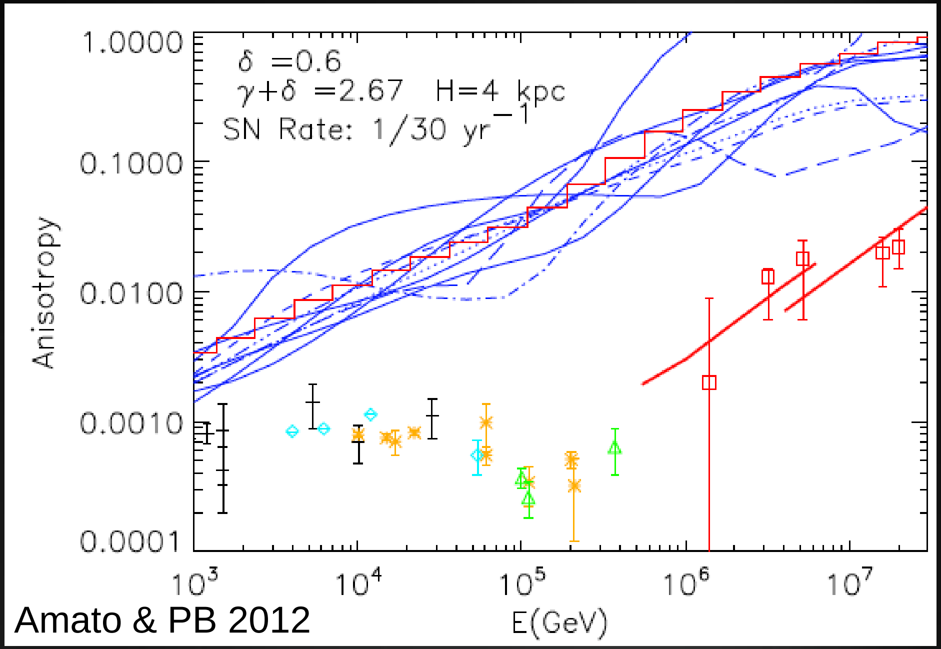
PROBLEMS WITH PREDICTED SPECTRA

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 (THE REQUIRED D(E) HAS TO SCALE AS $E^{0.75}$)***
2) ***GAMMA RAY SPECTRA FROM SELECTED SNRS***





ANTHROPOCENTRIC ANISOTROPY ?

THE ANISOTROPY THAT WE CALCULATE IS A GLOBAL QUANTITY, BUT IS IT WHAT WE MEASURE AT THE EARTH?

FLUXES OF CR ARE MORE SOLID, BUT ANISOTROPY IS AFFECTED BY LOCAL PHENOMENA (Zirakashvili 2005):

$$\delta_{inside} \simeq \frac{D_{inside}}{D_{outside}} \delta_{outside} \ll \delta_{outside}$$

BOTH LARGE SCALE AND SMALL SCALE CR ANISOTROPIES MIGHT BE AFFECTED BY LOCAL, PECULIAR CONDITIONS

DISAPPOINTING, BUT POSSIBLE…

HARD He SPECTRUM

THE ONLY VIABLE EXPLANATION OF THE HARDER He SPECTRUM SO FAR IS BASED ON THE INJECTION MODEL OF Malkov et al. 2012.

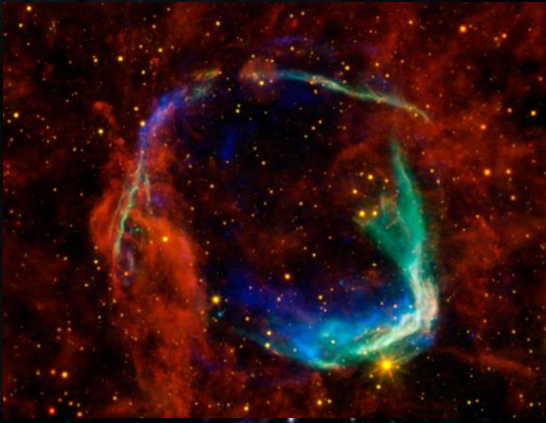
THE PREFERENTIAL INJECTION OF He^{2+} IS DUE TO ITS LARGER LARMOR RADIUS, BUT THEN IT IS REQUIRED TO DECREASE WITH M_A

INDEPENDENT OF THIS MODEL PROVIDING OR NOT THE CORRECT INTERPRETATION OF THE DATA, IT GIVES US A FLAVOR OF HOW MUCH OUR 'STANDARD MODEL' IS SENSITIVE TO POORLY KNOWN ASPECTS OF THE MICROPHYSICS

THIS IS, IN A WAY, A RECENT FINDING, DUE TO THE FACT THAT THE EFFECTS WE ARE SEARCHING FOR ARE AT THE SAME LEVEL OF EXPERIMENTAL SYSTEMATICS…

MAGNETIC FIELD AMPLIFICATION

TYPICAL SIZE OF THE FILAMENTS ~ 10^{-2} parsec



The emission in the filaments is non-thermal synchrotron of the highest energy electrons in the accelerator

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

Comparison with the observed thickness leads to an estimate for the local field

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

MAGNETIC FIELD AMPLIFICATION AND P_{MAX}

THE EVIDENCE FOR B-FIELD AMPLIFICATION IS CRUCIAL FOR AT LEAST TWO REASONS:

✦ *IN THE ABSENCE OF THIS PHENOMENON THE MAXIMUM ENERGY OF ACCELERATED PARTICLES IS ~1-10 GeV ONLY*

✦ *MAGNETIC FIELD AMPLIFICATION HAS LONG BEEN EXPECTED AS A BY-PRODUCT OF CR ACCELERATION (STREAMING INSTABILITY)*

IN THE BOHM ASSUMPTION FOR THE TURBULENT COMPONENT:

$$D(E) = \frac{1}{3}\frac{pc^2}{eB_{ampl}} = 10^{27} cm^2/s \; B_{30\mu G}^{-1}\left(\frac{E}{10^{15}eV}\right)$$

$$\tau_{acc} = \frac{D(E)}{V_{sh}^2} \approx 130\left(\frac{E}{10^{15}eV}\right)\left(\frac{V_{sh}}{5000km/s}\right)^2 B_{30\mu G}^{-1}\; years$$

CLOSE TO THE TIME OF BEGINNING OF THE SEDOV PHASE…

THE QUESTION IS ‘WHETHER THE CR INDUCED INSTABILITIES GROW FAST ENOUGH TO ACHIEVE THE GOAL

A RELEVANT QUANTITY IS $\frac{n_{CR}}{n_i}\frac{v_s c}{v_A^2}$

$$\frac{n_{CR}}{n_i} < \frac{v_A}{v_s}\frac{v_A}{c}$$

WEAK CR INDUCED MODIFICATION

Alfven waves are excited, with a small imaginary part of frequency. The growth rate reads:

$$\gamma_W \approx \frac{\pi}{8}\frac{n_{CR}(p > p_{res}(k))}{n_i}\frac{v_s}{v_A}\Omega_c, \qquad p_{res}(k) = \frac{\Omega_c m_p}{k} \ \mathit{or}\ k = 1/r_L(p_{res})$$

The resonant nature of the instability limits it to ♎B/B~1

$$\frac{n_{CR}}{n_i} > \frac{v_A}{v_s}\frac{v_A}{c}$$

STRONG CR INDUCED MODIFICATION

Quasi-purely growing non resonant modes are excited (Bell 2004) together with aperiodic resonant modes with Im[◆]~Re[◆].
In the absence of additional dynamics the non resonant modes do not scatter CR effectively [$k>>1/r_L(p)$]

STRONGLY CR MODIFIED REGIME

THE MAX GROWTH RATE IS:

$$\gamma_{W,max} = k_{max} v_A \qquad k_{max} B_0 \simeq \frac{4\pi}{c} J_{CR}$$

WHERE J_{CR} IS THE CR CURRENT. IN THE PICTURE OF Schure, Bell, Reville THE RELEVANT CURRENT IS THAT OF PARTICLES THAT ATTEMPT TO ESCAPE THE ACCELERATOR AT ENERGY E

$$k_{max} r_L(E) = \xi_{CR} \frac{1}{\Lambda} \left(\frac{v_s}{v_A}\right)^2 \left(\frac{v_s}{c}\right) \gg 1$$

THE ♎B GROWS BUT ALSO CHANGES SCALE (PLASMA IS MOVED AROUND WITH FORCE ~(1/c) J_{CR} ♎B). SATURATION OCCURS WHEN

$$\Delta x \approx \frac{J_{CR}\delta B}{c\rho} \approx r_L^* = \frac{E}{e\delta B} \rightarrow \frac{\delta B}{B} \approx \frac{\xi_{CR}}{\Lambda} \frac{v_s}{c} \left(\frac{v_s}{v_A}\right)^2$$

MAXIMUM ENERGY FOR A SNR IN THE ISM

THE SATURATION IS TYPICALLY REACHED WHEN $\gamma_{W,max}\, t \sim 5$, WHICH IMPLIES, EVALUATED AT THE BEGINNING OF THE SEDOV PHASE:

$$E_M = \frac{\xi_{CR} 3^{1/3}}{5\Lambda}\frac{e}{c}(4\pi\rho)^{1/6} E_{SN} M_{ej}^{-2/3} \approx 2 \times 10^5 \text{ GeV}$$

Schure et al. 2012

THIS VALUE OF **A FEW HUNDRED TeV** IS RATHER WEAKLY DEPENDENT UPON THE VALUES OF PARAMETERS

IT APPEARS UNLIKELY THAT PROTONS MAY BE ACCELERATED UP TO THE KNEE IN A SN TYPE Ia, ALTHOUGH THE PROBLEM IS BY A FACTOR ~10

MAXIMUM ENERGY FOR A SNR IN A SUPERGIANT WIND

CORE COLLAPSE SN OFTEN EXPLODE IN THE WIND OF THE GIANT PROGENITOR. THE GAS DENSITY IN THE WIND IS

$$\rho(r) = \frac{\dot{M}}{4\pi r^2 v_W}$$

THE MAX ENERGY OF ACCELERATED PARTICLES IS

$$E_M(R) = \frac{\xi_{CR} e}{5\Lambda c}\sqrt{\frac{\dot{M}}{v_W}}\, v_s^2(R) \sim t^{-2/7}$$

IN THE DENSE WIND THE SEDOV PHASE IS REACHED AT DISTANCE

$$R = M_{ej} v_W / \dot{M}$$

CHOOSING: $\dot{M} = 10^{-5} M_\odot\ \mathrm{yr}^{-1}$, $v_W = 10$ km/s and $M_{ej} = 1 M_\odot$

AND WITH A SHOCK SPEED 20000 km/s

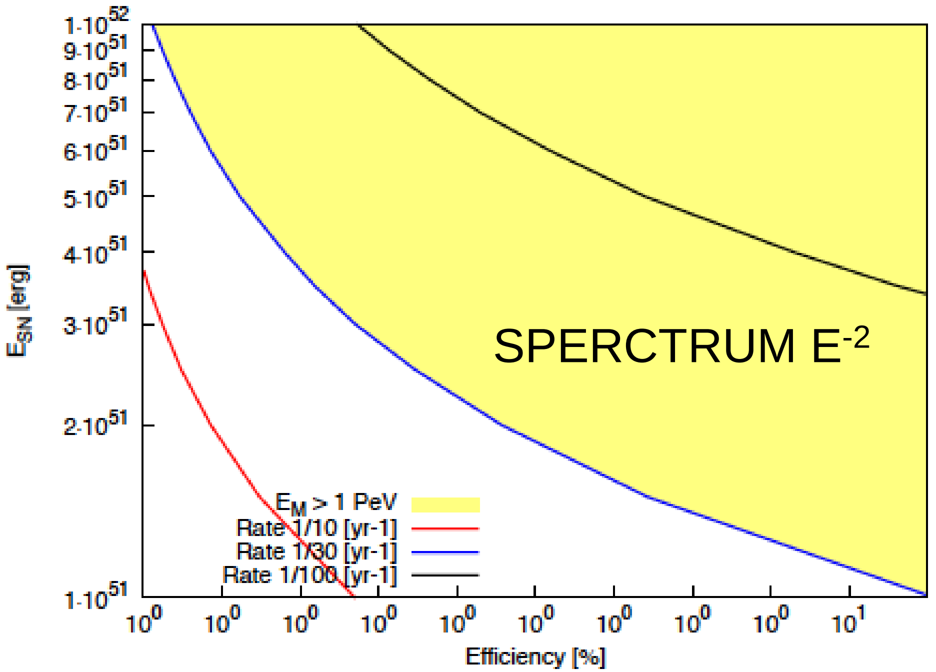
$$E_M \approx 2 \times 10^6\ \mathrm{GeV}$$

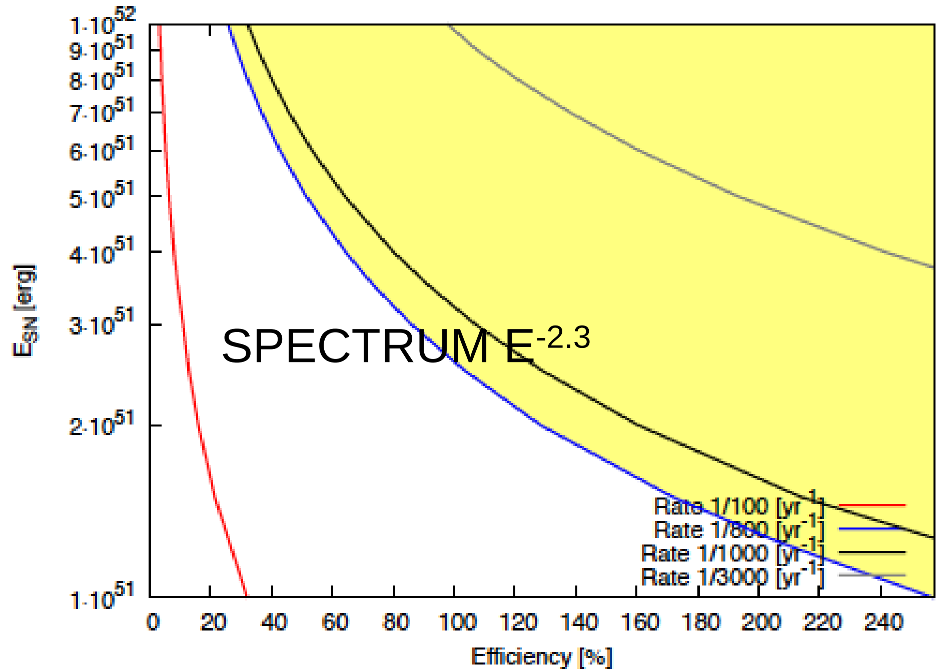
close to the knee…

CR CURRENTS AND FLUXES

(see also talk by M. Cardillo)

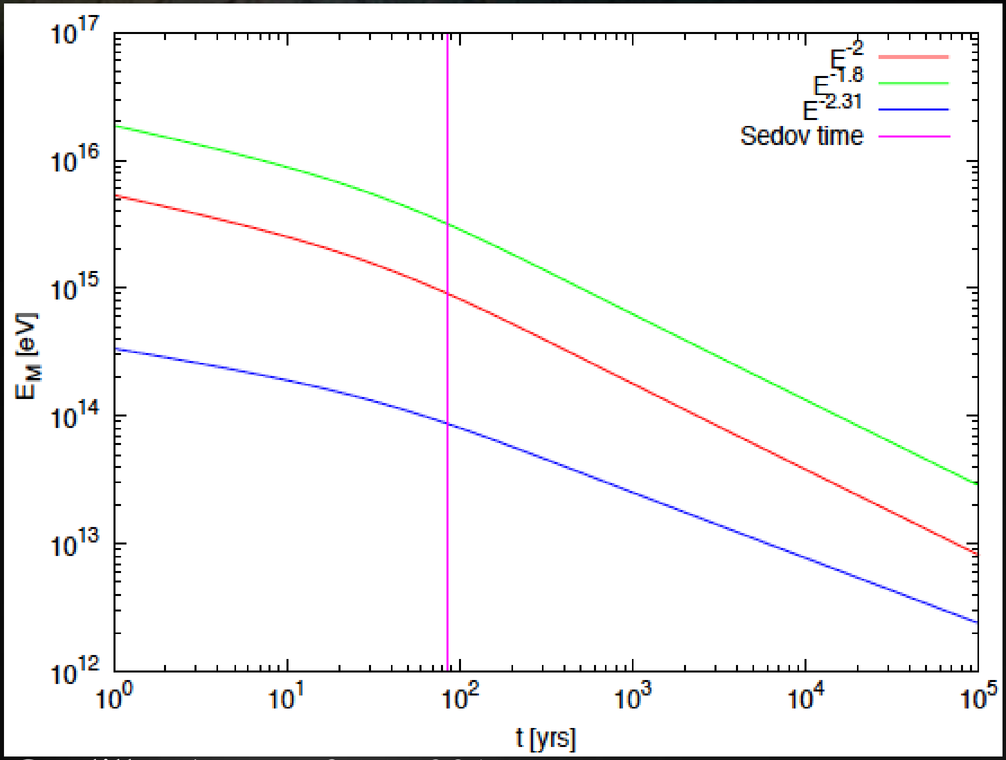
Cardillo, Amato & PB 2015





THE MAXIMUM ENERGY IS DETERMINED BY THE CR CURRENT (NAMELY BY THE ENERGETICS AND SPECTRUM) WHILE THE FLUXES AT EARTH ARE ALSO AFFECTED BY THE SN RATE

WHEN IS A SNR A PEVATRON?



Cardillo, Amato & PB 2015

THE HIGHEST ENERGIES ARE REACHED AT EARLY TIMES

IN FACT THE RELEVANT EPOCH FOR COPIOUS PARTICLES ACCELERATION AT PEV ENERGIES WOULD BE ~50 YEARS

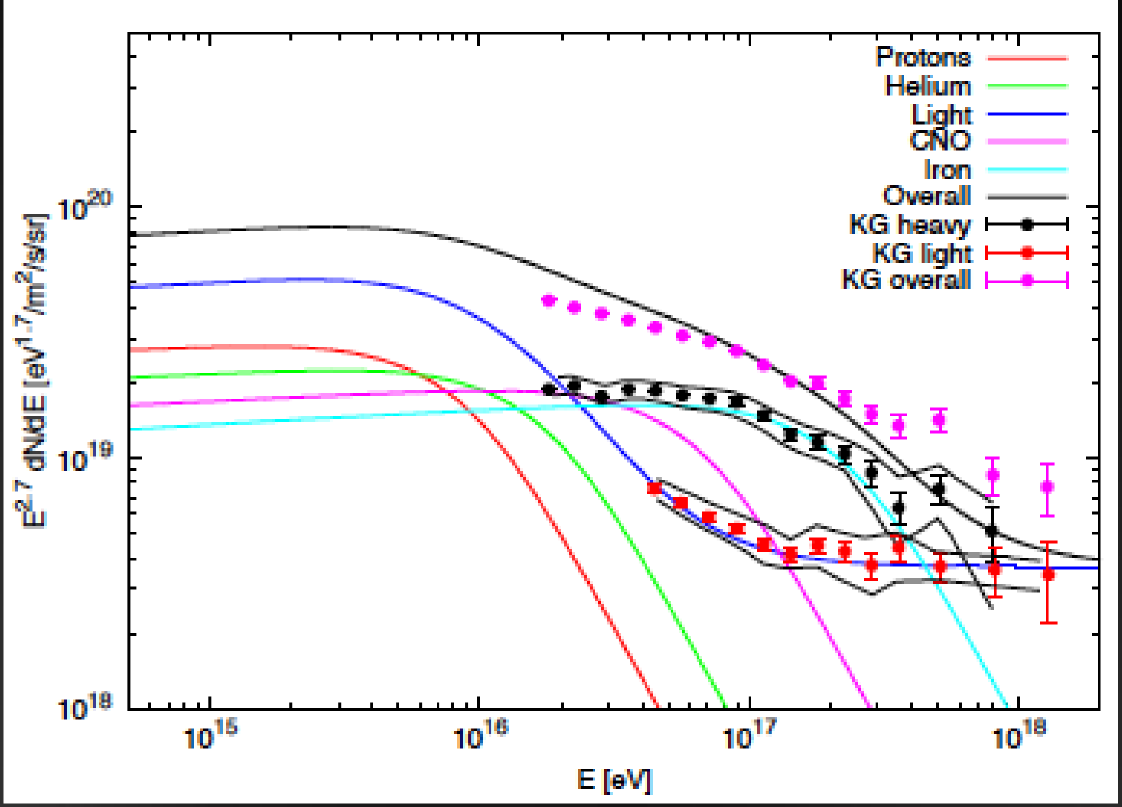
VERY HARD TO OBSERVE DIRECTLY IN OUR GALAXY

PROBABLY A BETTER CHANCE IS TO TARGET CLOUDS AROUND A SNR, BUT IT IS A MATTER OF FINE TUNING (talk by S. Gabici)

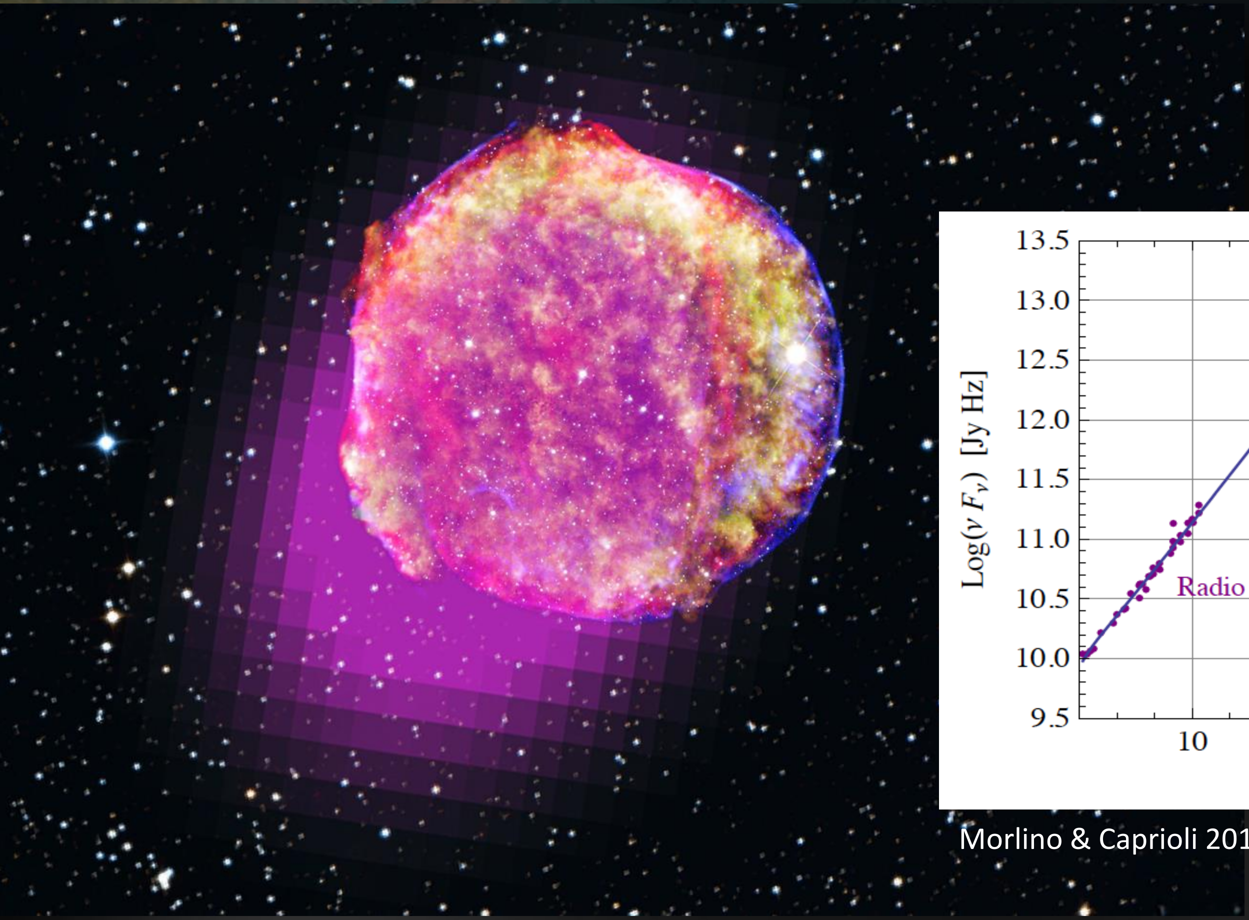
IT IS IMPORTANT TO HAVE AN OBSERVATIONAL STRATEGY FOR CTA (OBSERVING CLOUDS MAY BE SUBJECT TO MANY PROPAGATION INDUCED UNCERTAINTIES)

CR FLUXES AT THE EARTH

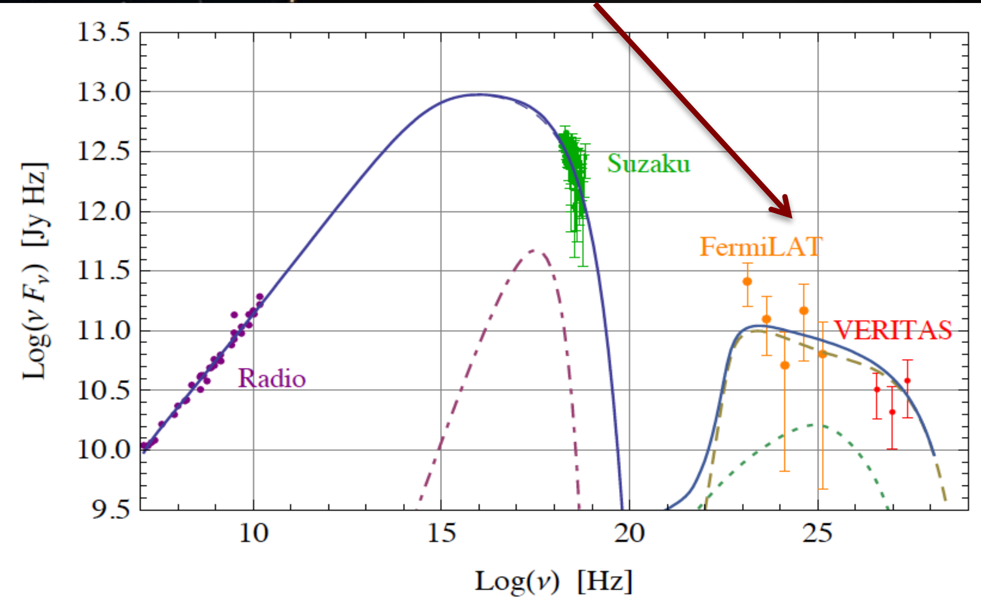
Cardillo, Amato & PB 2015



TYCHO SNR



STEEP SPECTRUM HARD TO EXPLAIN WITH LEPTONS

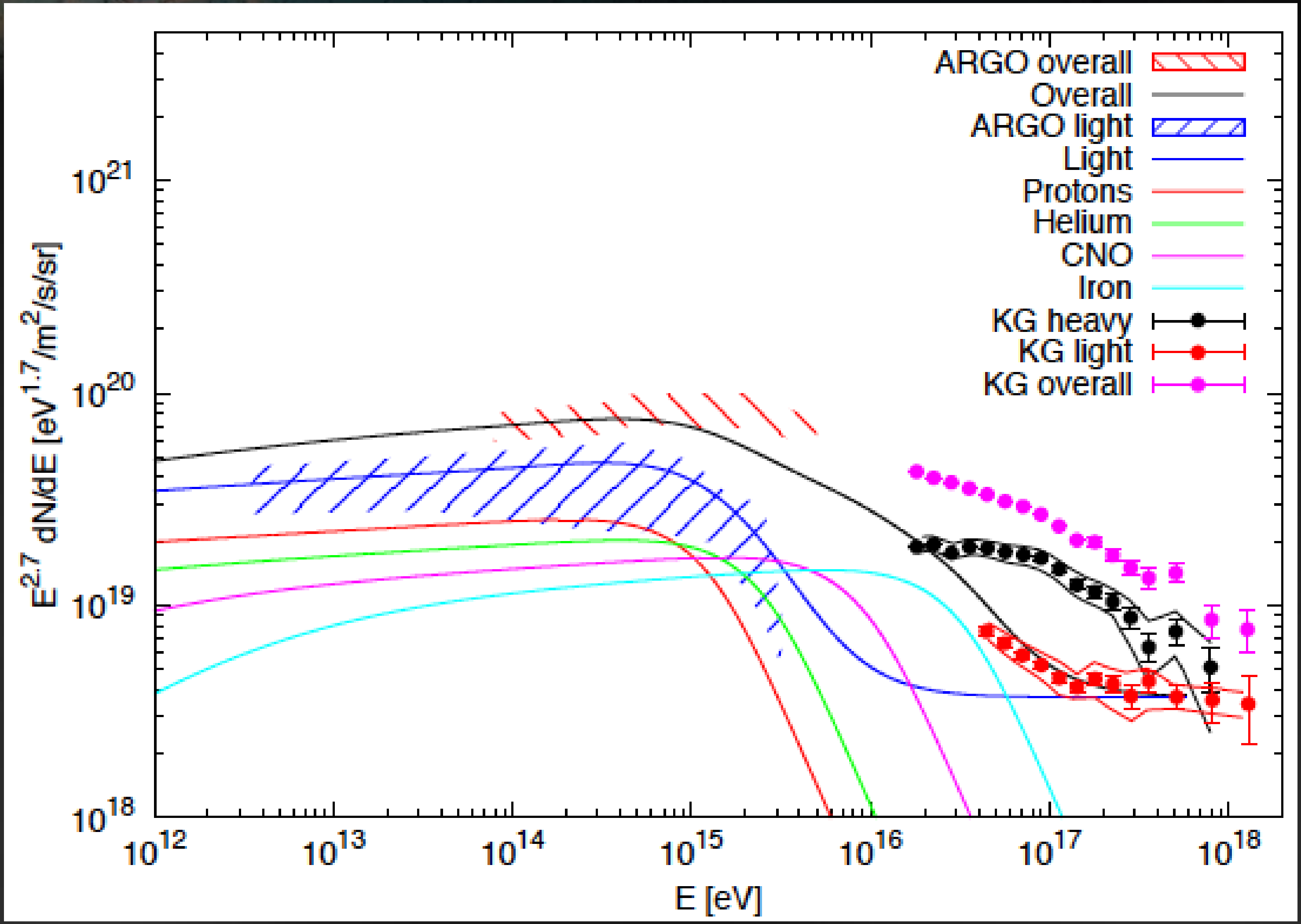


Morlino & Caprioli 2011

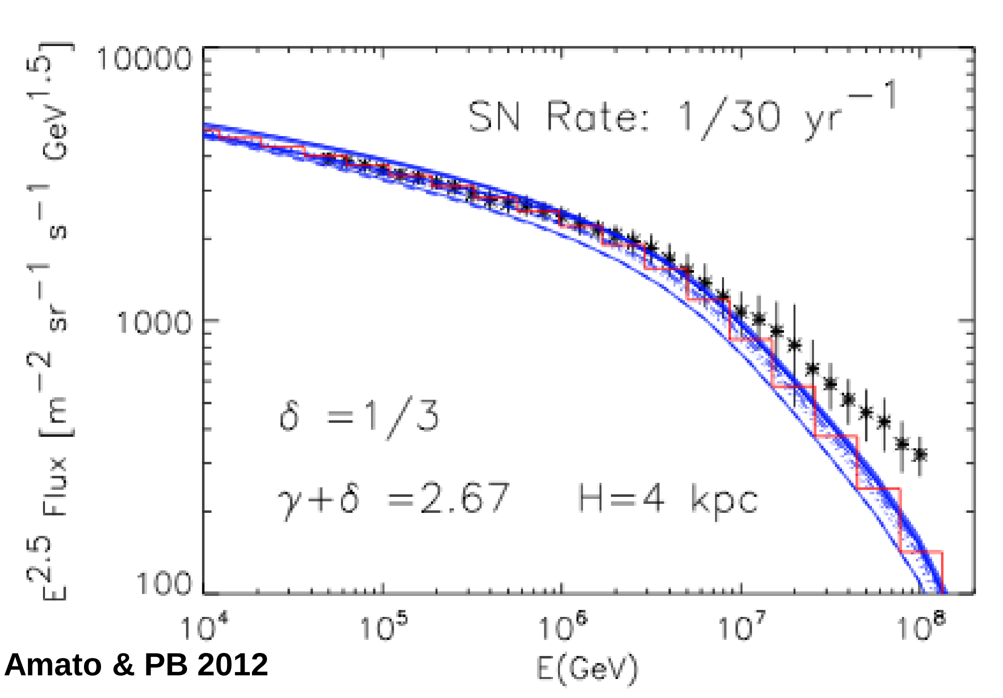
E_{max}~500 TeV

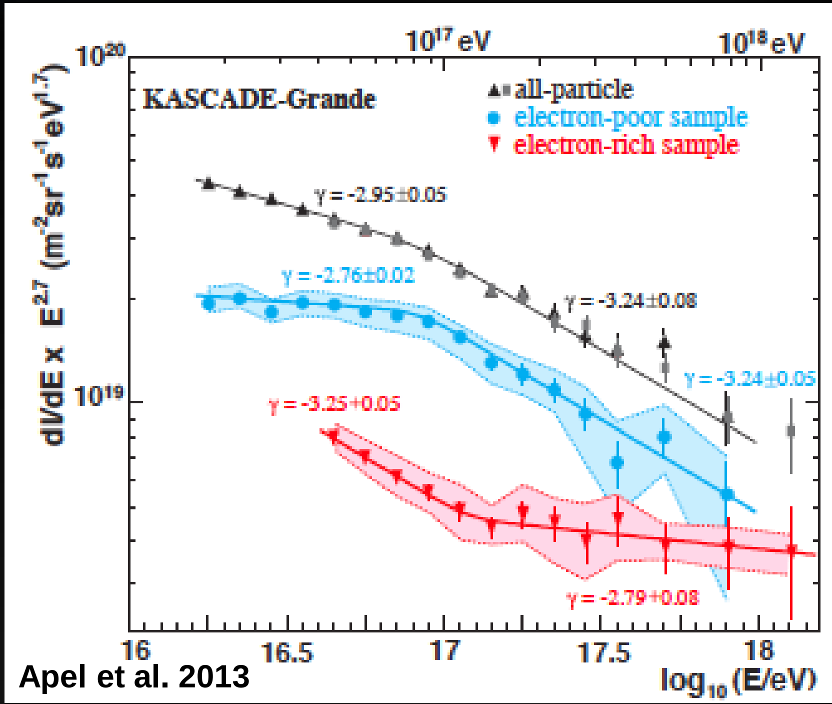
THE STEEP SPECTRUM MAY BE THE RESULT OF FINITE VELOCITY OF SCATTERING CENTERS (Caprioli et al. 2010, Ptuskin et al. 2010, Morlino & Caprioli 2011) OR MAY RESULT FROM AN INHOMOGENEOUS MEDIUM (Berezhko et al. 2013)

ARE WE LOOKING IN THE RIGHT DIRECTION?



WHERE DO GALACTIC CRs END?

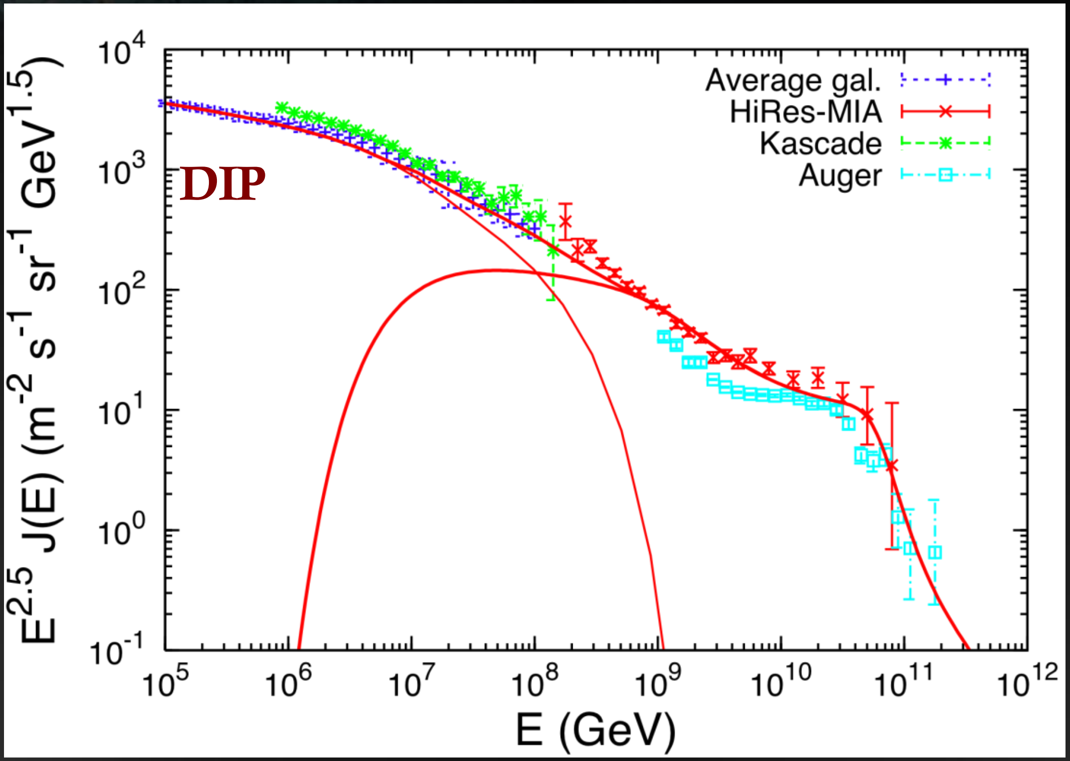




A SUPERPOSITION OF EXPONENTIAL CUTOFFS SCALING WITH Z FROM THE KNEE LEADS TO A DEFICIT AT E>10^7 GeV

KASCADE GRANDE DATA SHOW A RATHER COMPLEX IMPLEMENTATION OF THE TRANSITION REGION, WHICH IS NOT EASY TO RECONCILE WITH OBSERVATIONS OF UHECR SPECTRA AND MASS COMPOSITION

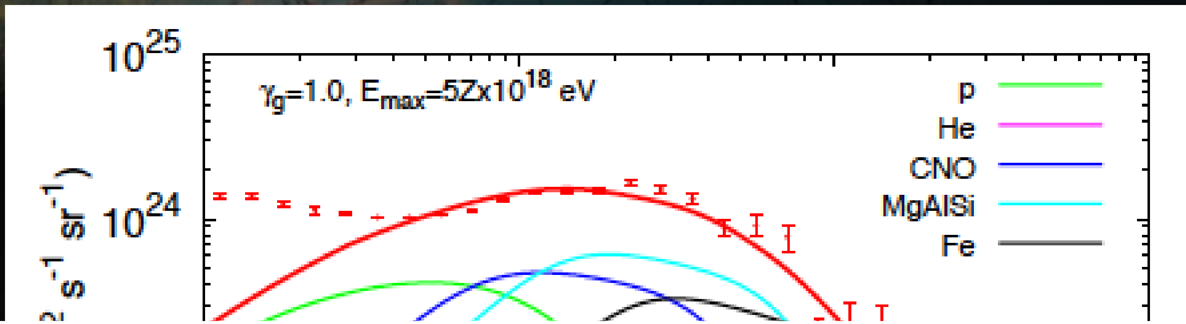
A LOOK FROM THE OTHER END…



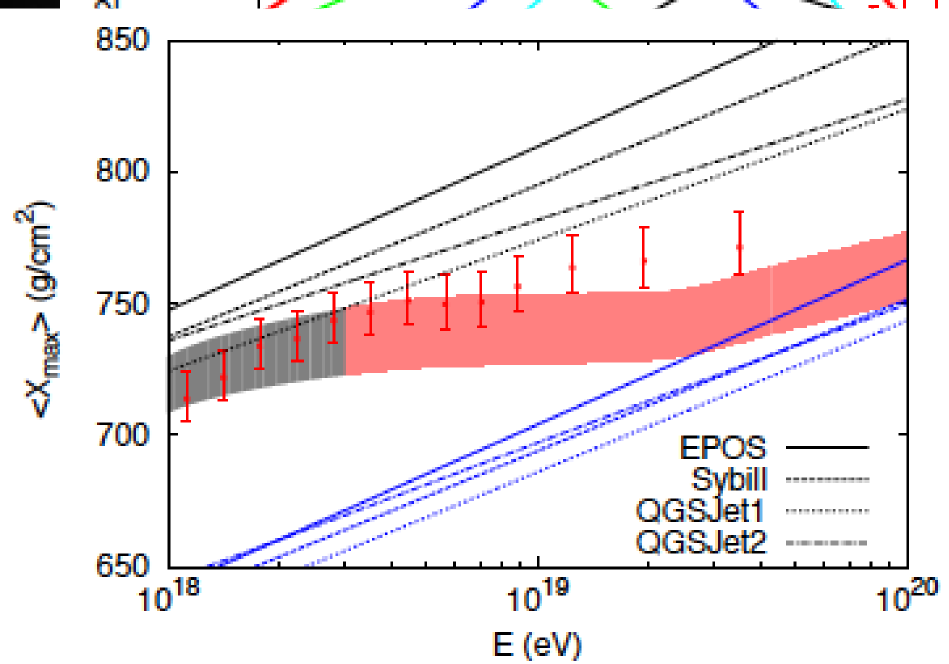
THE DIP IS THE ONLY EXPLANATION OF THE TRANSITION THAT IS COMPATIBLE WITH THE BASIC PREDICTIONS OF THE SNR PARADIGM FOR GALACTIC COSMIC RAYS

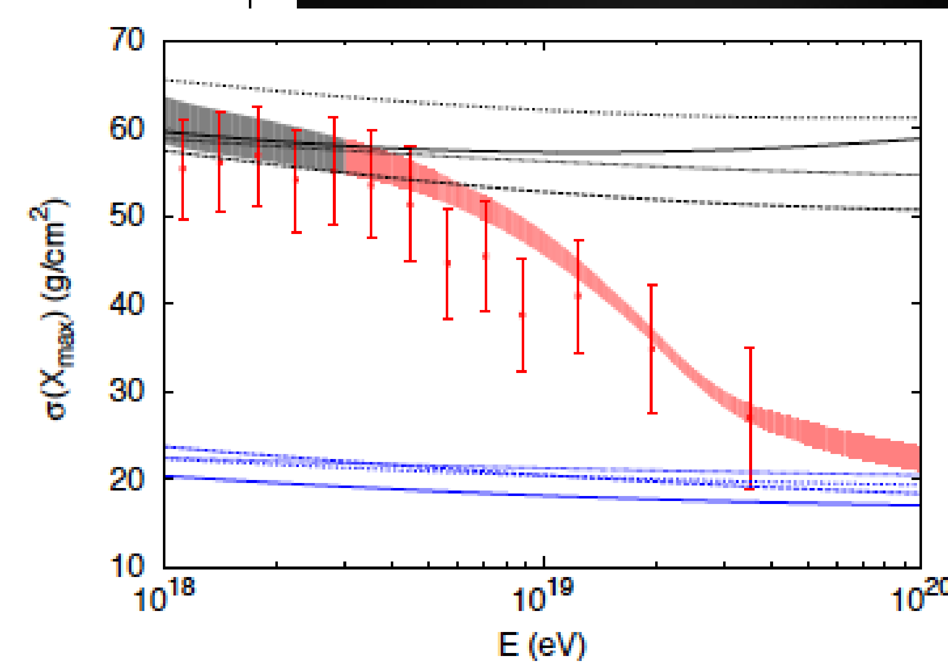
BUT IT IS INCOMPATIBLE WITH THE OBSERVED COMPOSITION

TRANSITION AND UHECR



VERY HARD INJECTION SPECTRA REQUIRED IF SOURCES GENERATE NUCLEI

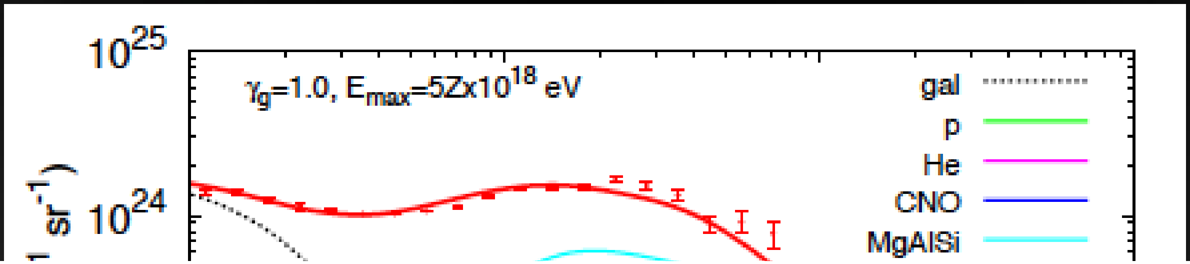


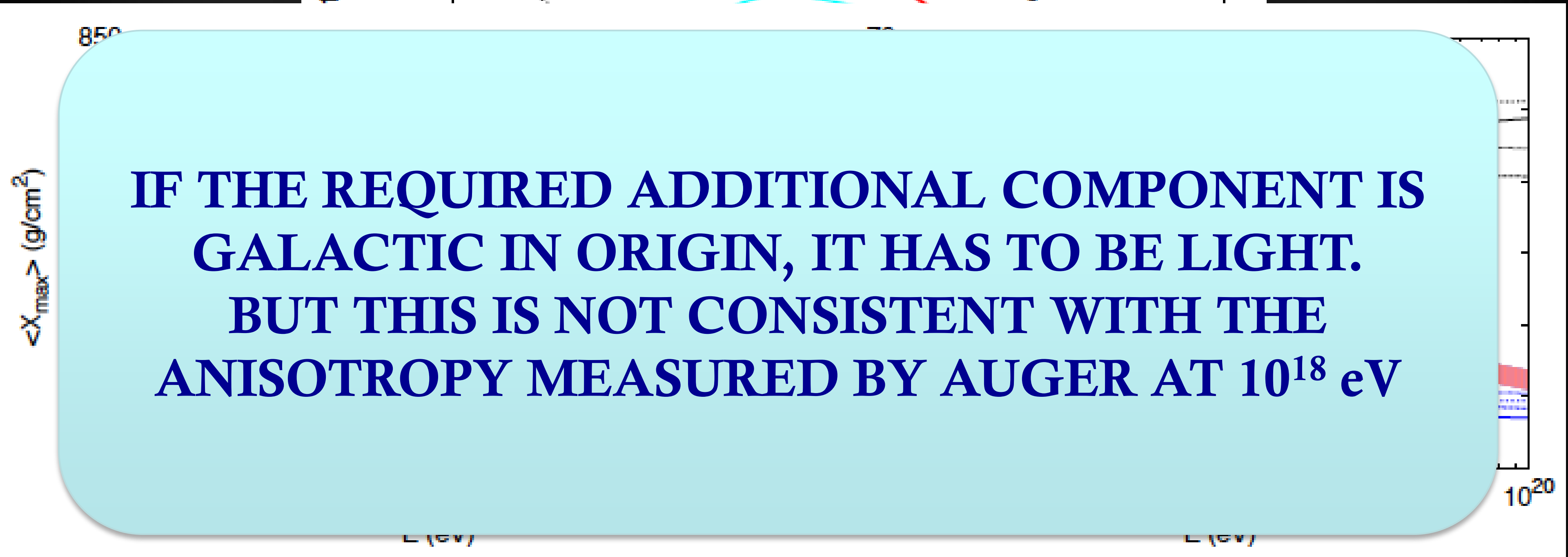


Aloisio, Berezinsky & PB 2013

TRANSITION AND UHECR

Additional Galactic Component



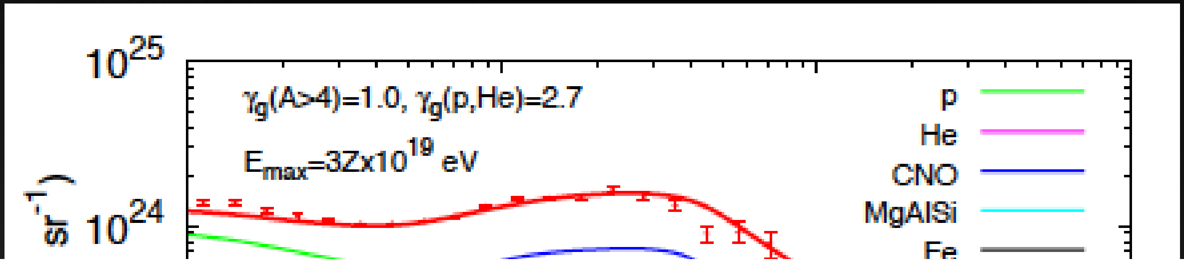


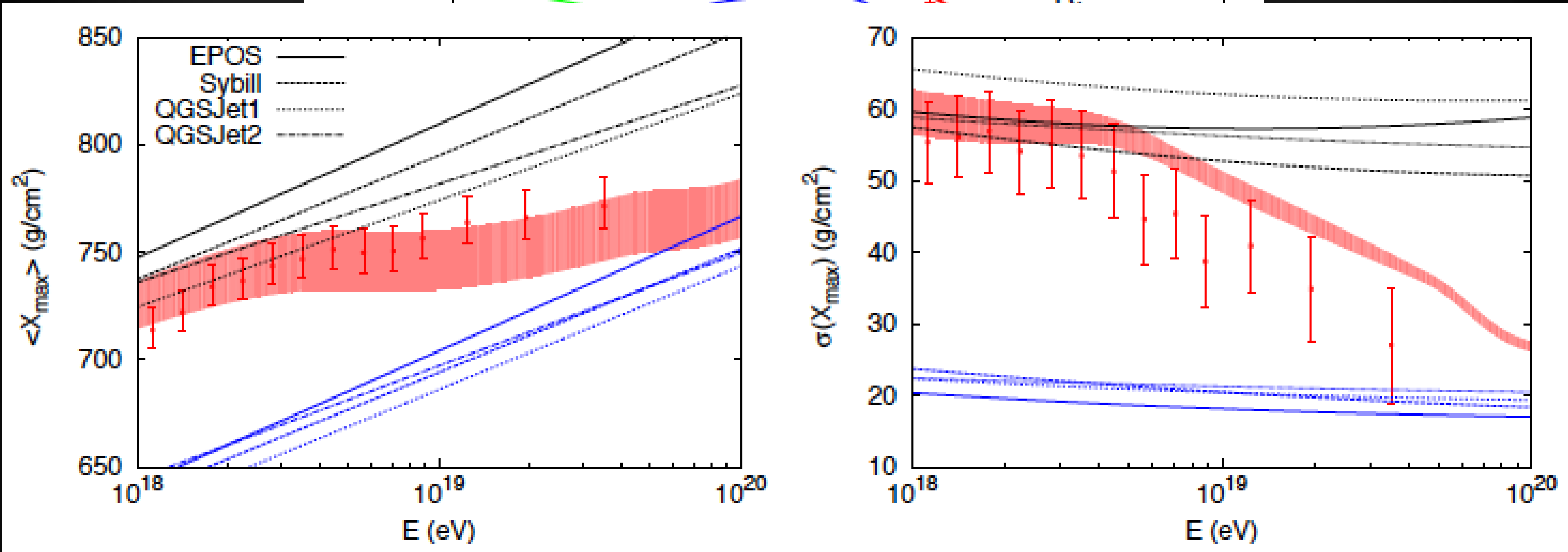
IF THE REQUIRED ADDITIONAL COMPONENT IS GALACTIC IN ORIGIN, IT HAS TO BE LIGHT. BUT THIS IS NOT CONSISTENT WITH THE ANISOTROPY MEASURED BY AUGER AT 10^{18} eV

Aloisio, Berezinsky & PB 2013

TRANSITION AND UHECR

Additional Extragalactic Component

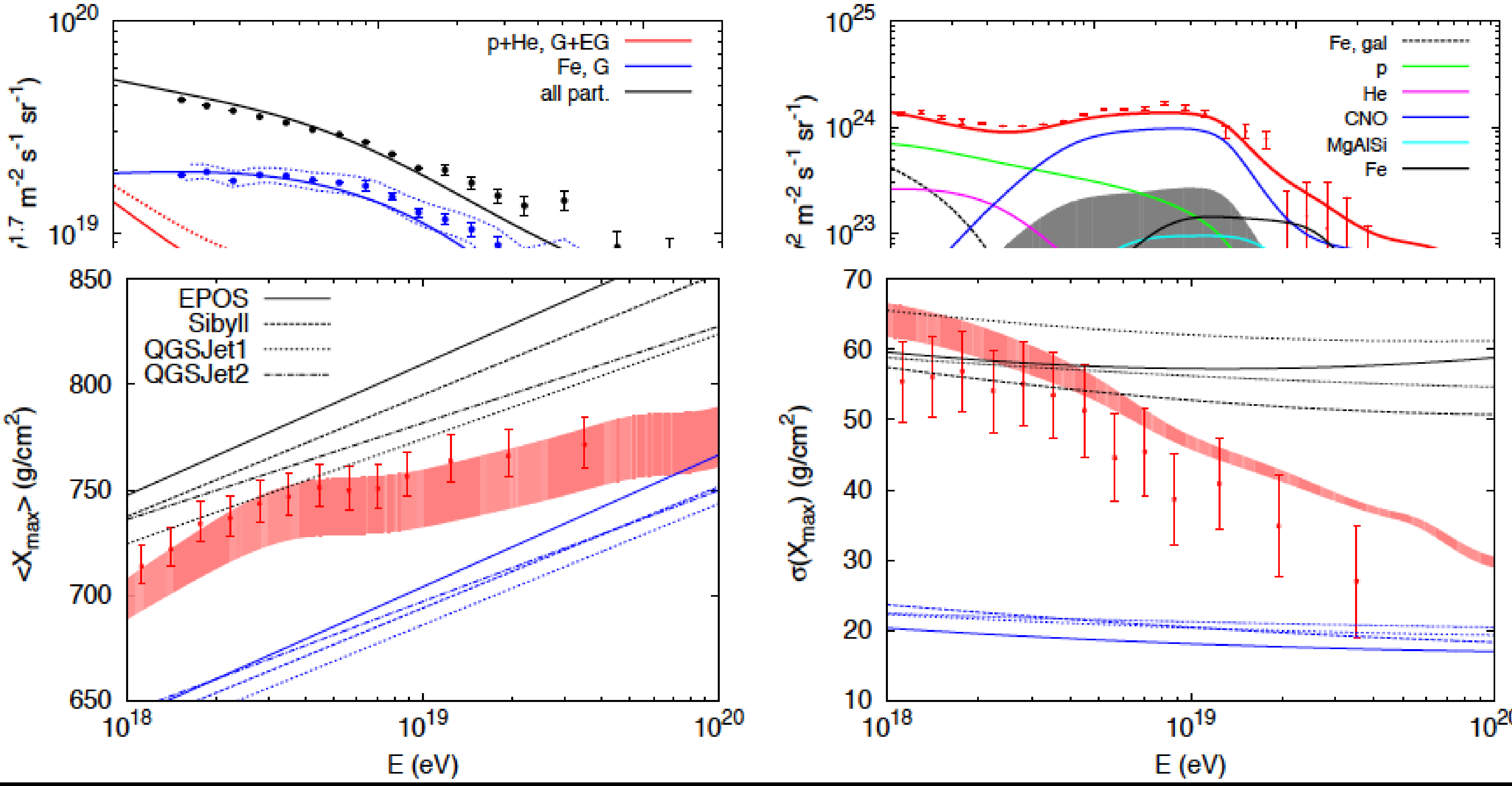




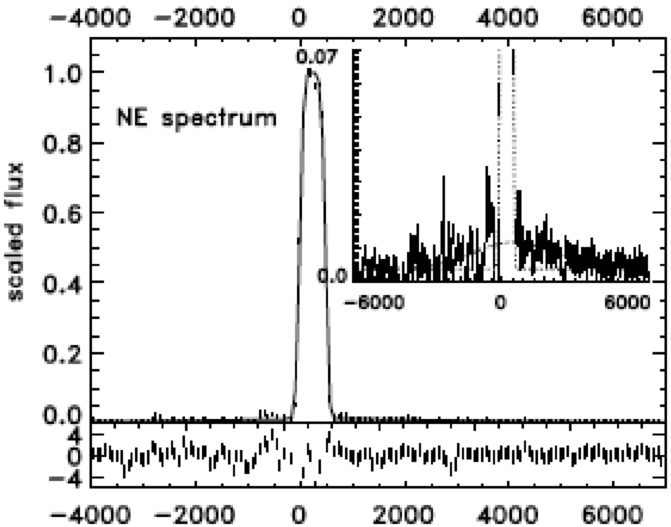
Aloisio, Berezinsky & PB 2013

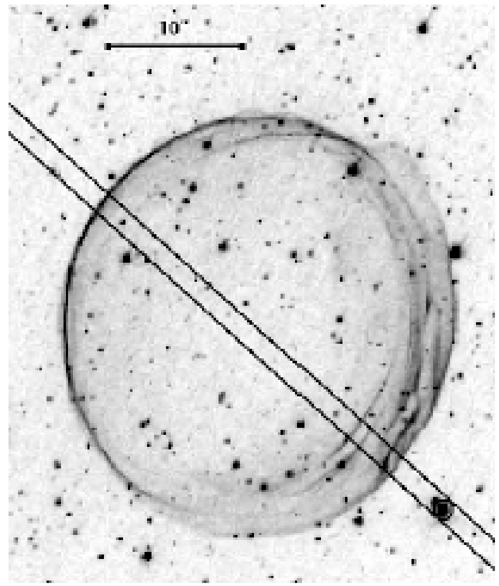
PROLIFERATION OF COMPONENTS

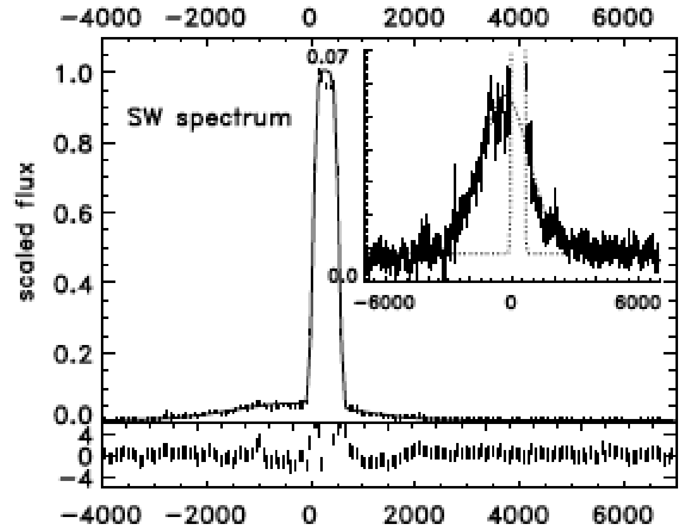
Aloisio, Berezinsky & PB 2013



OPTICAL LINES TO MEASURE CRs







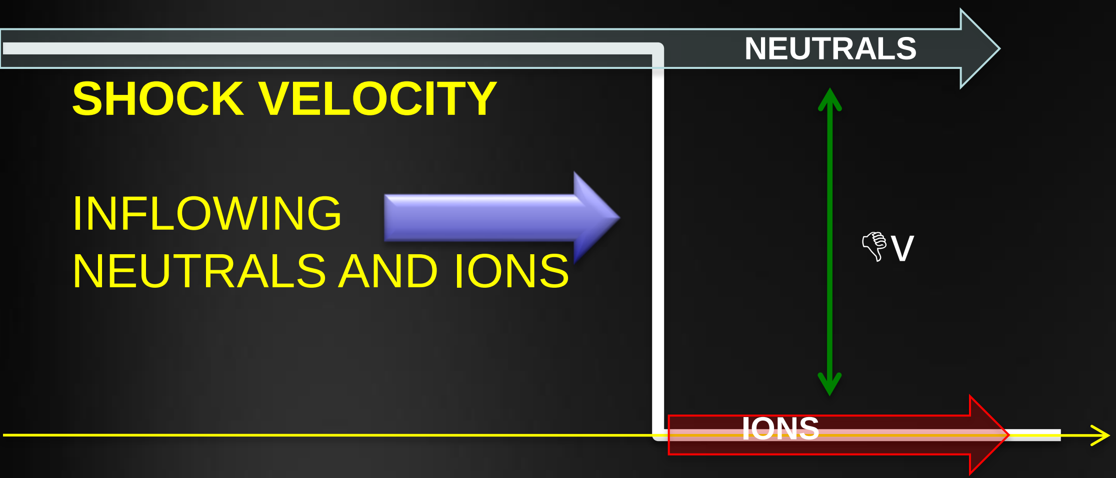
BALMER LINES AS A DIAGNOSTIC TOOL OF CR ACCELERATION IN SNR

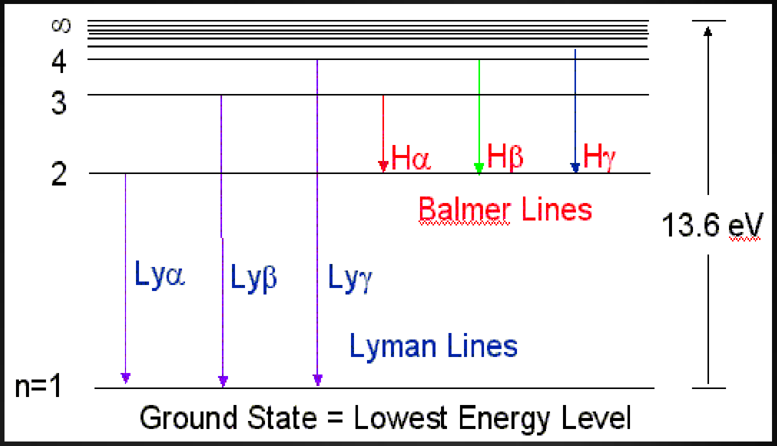
NEUTRAL HYDROGEN PLAYS AN ACTIVE ROLE IN THE SHOCK DYNAMICS AND CHANGES CR SPECTRA

OBSERVATION OF ANOMALOUS BALMER LINES

THIS FIELD IS STILL YOUNG, BUT IT HAS A HUGE POTENTIAL IN TERMS OF 'MEASURING' THE AMOUNT OF COSMIC RAYS CLOSE TO SNR SHOCKS

THE PHYSICS QUESTION IS: "WHAT HAPPENS WHEN A COLLISIONLESS SHOCK CROSSES A PARTIALLY IONIZED MEDIUM?"

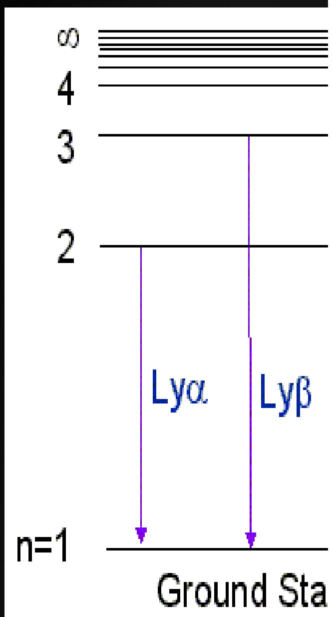


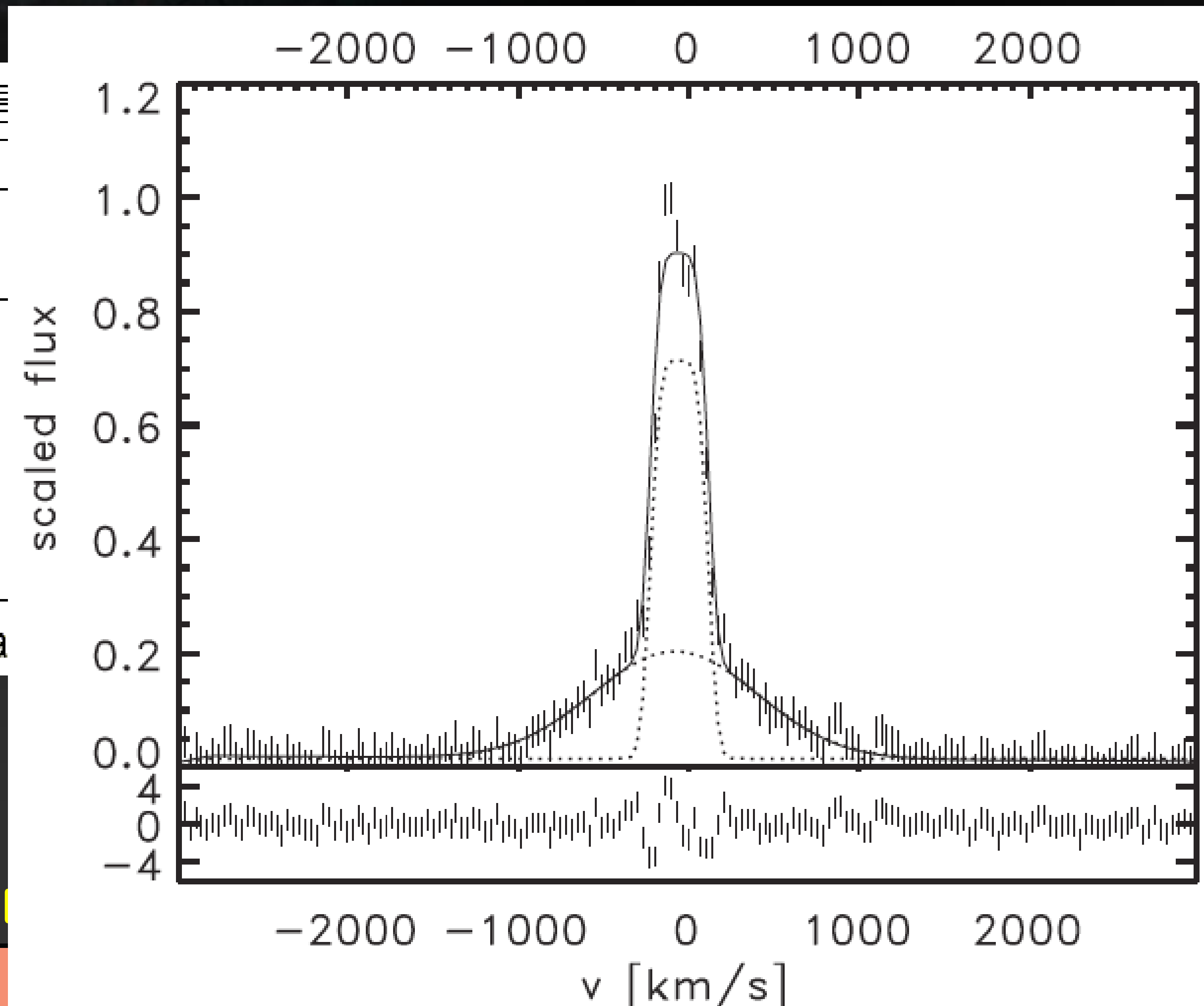


THE WIDTH OF THE BALMER LINE(S) PROVIDES POWERFUL INFORMATION ON THE IONS TEMPERATURE DOWNSTREAM OF THE SHOCK → CR CALORIMETRY !!!

BASIC PHYSICS OF BALMER SHOCKS

[Chevalier & Raymond (1978); Chevalier et al. (1980)]





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TO n=2

S BEFORE
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BALMER

R CHARGE
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THE WIDTH ... T THE ION
TEMPERATU...

$W_{narrow} \propto \sqrt{T_0}$

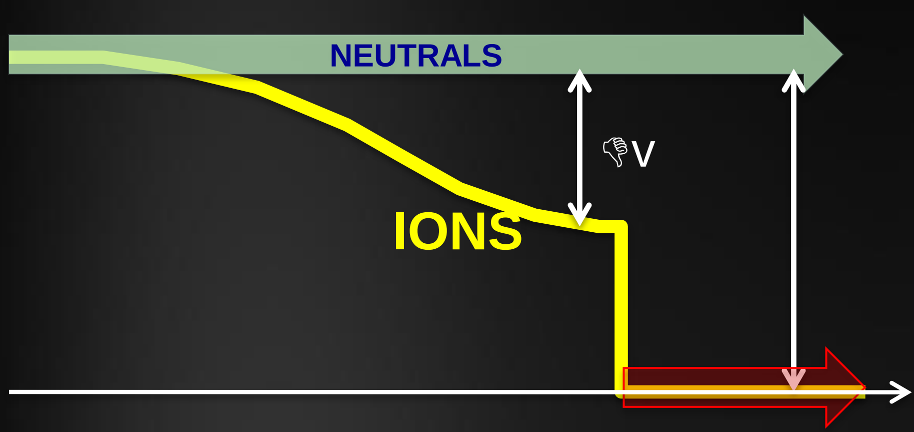
$W_{broad} \propto \sqrt{T_2} \sim v_{sh}$

ANOMALOUS H♋ LINE WIDTHS

IN THE PRESENCE OF PARTICLE ACCELERATION TWO THINGS HAPPEN:

LOWER TEMPERATURE DOWNSTREAM

A PRECURSOR APPEARS UPSTREAM



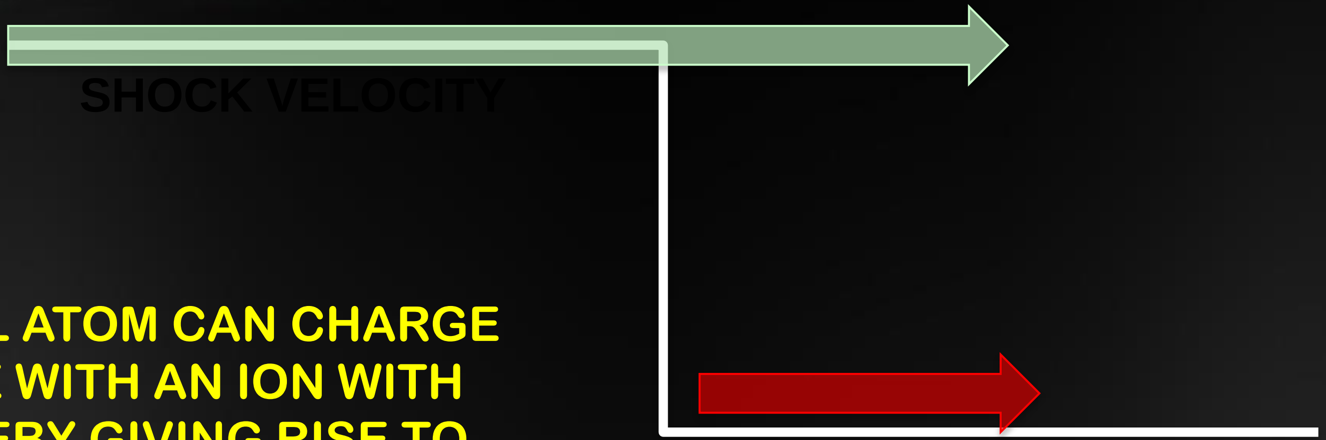
BROAD BALMER LINE GETS NARROWER

NARROW BALMER LINE GETS BROADER

NEUTRAL RETURN FLUX

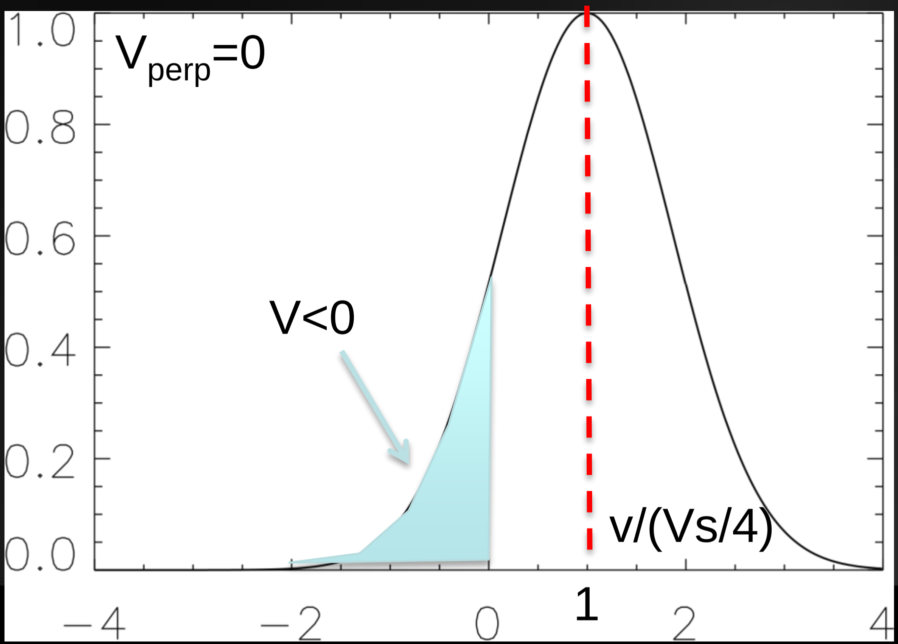
PB et al. 2012

NEUTRALS
AND IONS



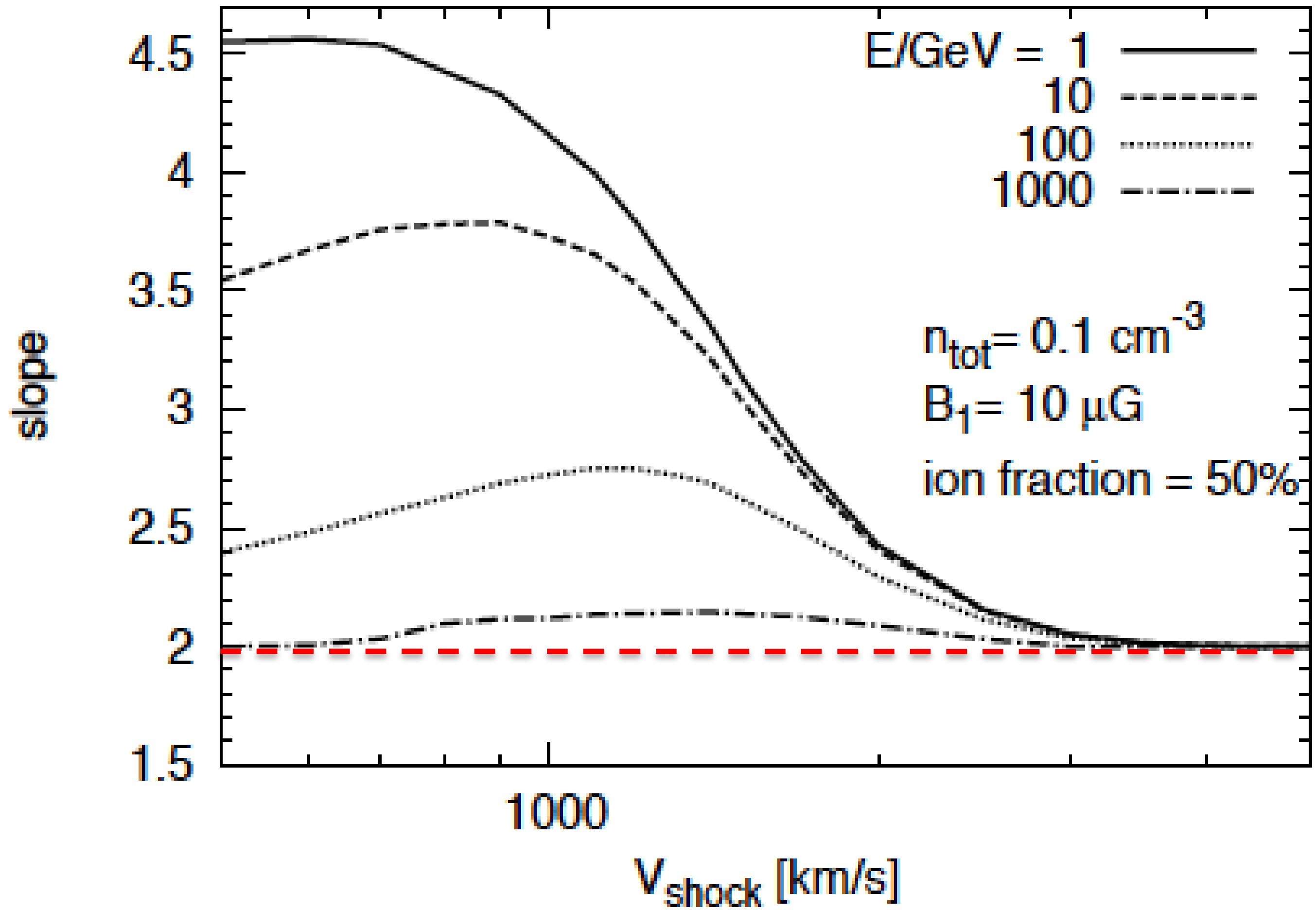
A NEUTRAL ATOM CAN CHARGE EXCHANGE WITH AN ION WITH V<0, THEREBY GIVING RISE TO A NEUTRAL WHICH IS NOW FREE TO RETURN UPSTREAM

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



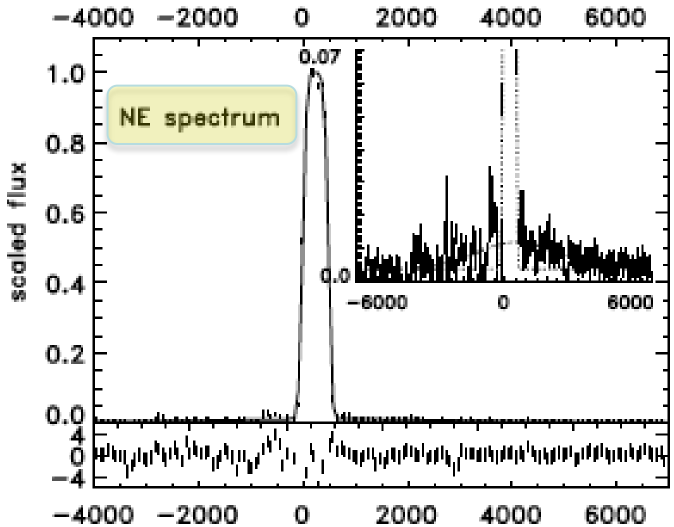
ACCELERATION OF TEST PARTICLES

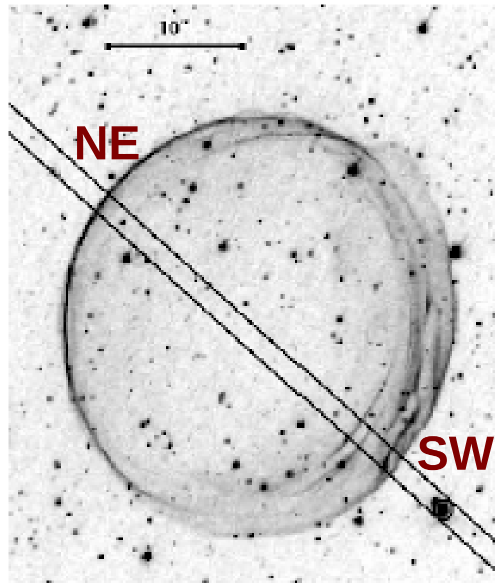
PB+ 2012

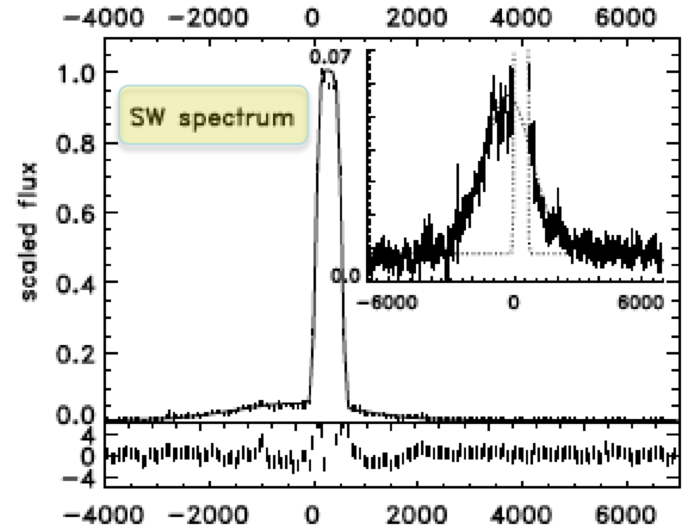


SNR 0509-67.5

Helder et al. 2009

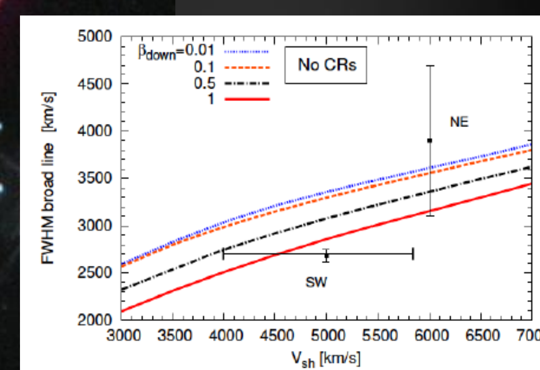




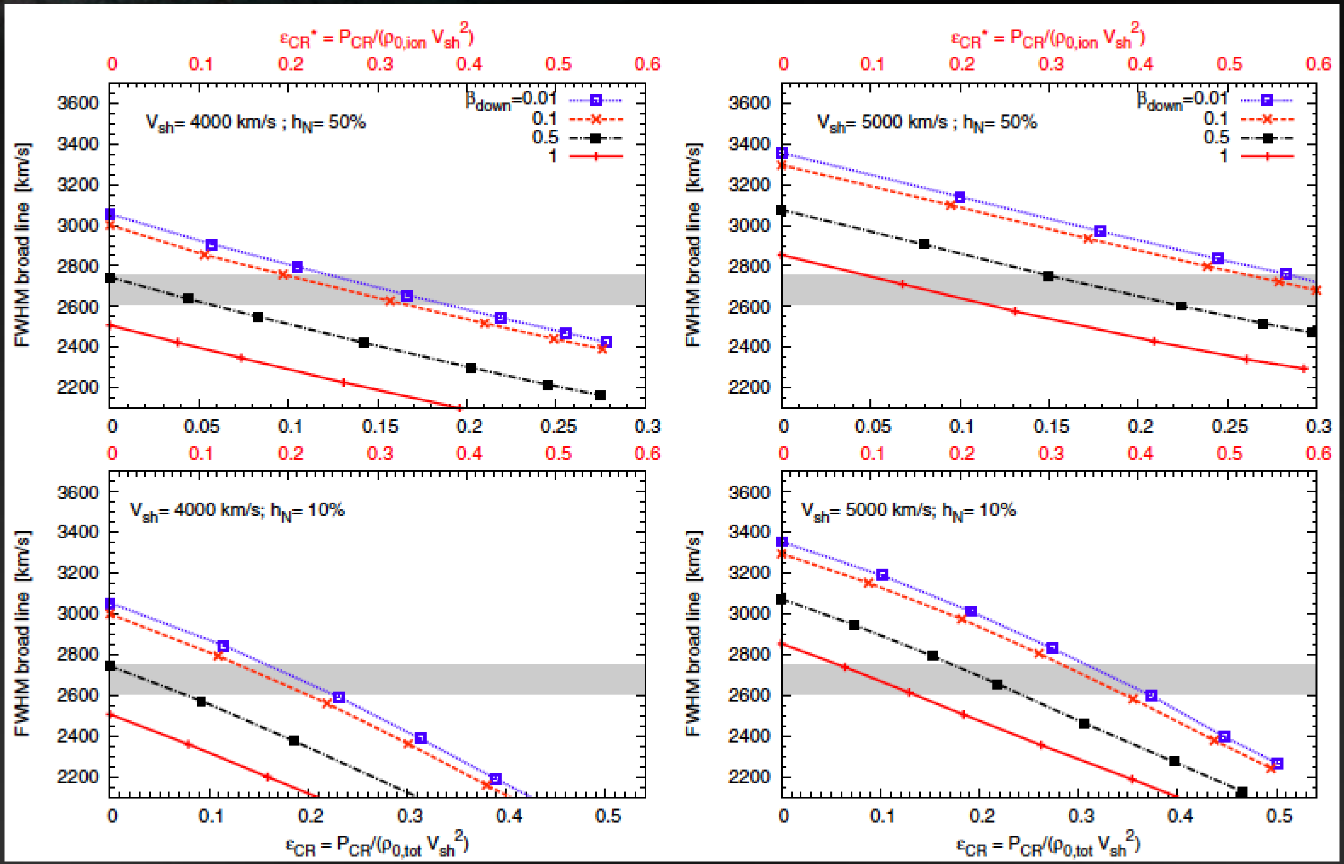


DISTANCE WELL KNOWN (LMC): **50±1 kpc**

Morlino et al. 2013



SNR 0509-67.5



Morlino et al. 2013

FOR SHOCK VELOCITY ~5000 km/s A LOWER LIMIT OF 5-10% TO THE CR ACCELERATION EFFICIENCY CAN BE IMPOSED

SUMMARY

WE HAVE A STANDARD MODEL OF CR ORIGIN ONLY TO THE EXTENT THAT WE DO NOT LOOK CLOSE ENOUGH

SEVERAL ASPECTS OF CR TRANSPORT ARE NOT UNDERSTOOD (ESSENCE OF DIFFUSION, ESCAPE FROM THE GALAXY,…)

NLDSA PROVIDES A MACROSCOPIC DESCRIPTION OF ACCELERATION BUT SEVERAL MICROPHYSICAL ASPECTS ARE NOT CLEAR (SPECTRA SHOULD BE STEEPER, MAGNETIC FIELD AMPLIFICATION, MAX ENERGY, …)

THE UNCERTAINTIES OF MAX ENERGY LEAD TO A LARGE UNCERTAINTY ON THE TRANSITION FROM GALACTIC TO EXTRAGALACTIC CR

DATA FROM KASCAGE-GRANDE AND AUGER DID NOT HELP REDUCING THIS UNCERTAINTY (LOTS OF ADDITIONAL COMPONENTS)

NEW AVENUES TO LOOK AT SNR SHOCKS AS CR ACCELERATORS USING BALMER LINES AND TAKING INTO ACCOUNT THE PRESENCE OF NEUTRALS