ACCELERATION AND TRANSPORT OF HIGH ENERGY COSMIC RAYS: A REVIEW

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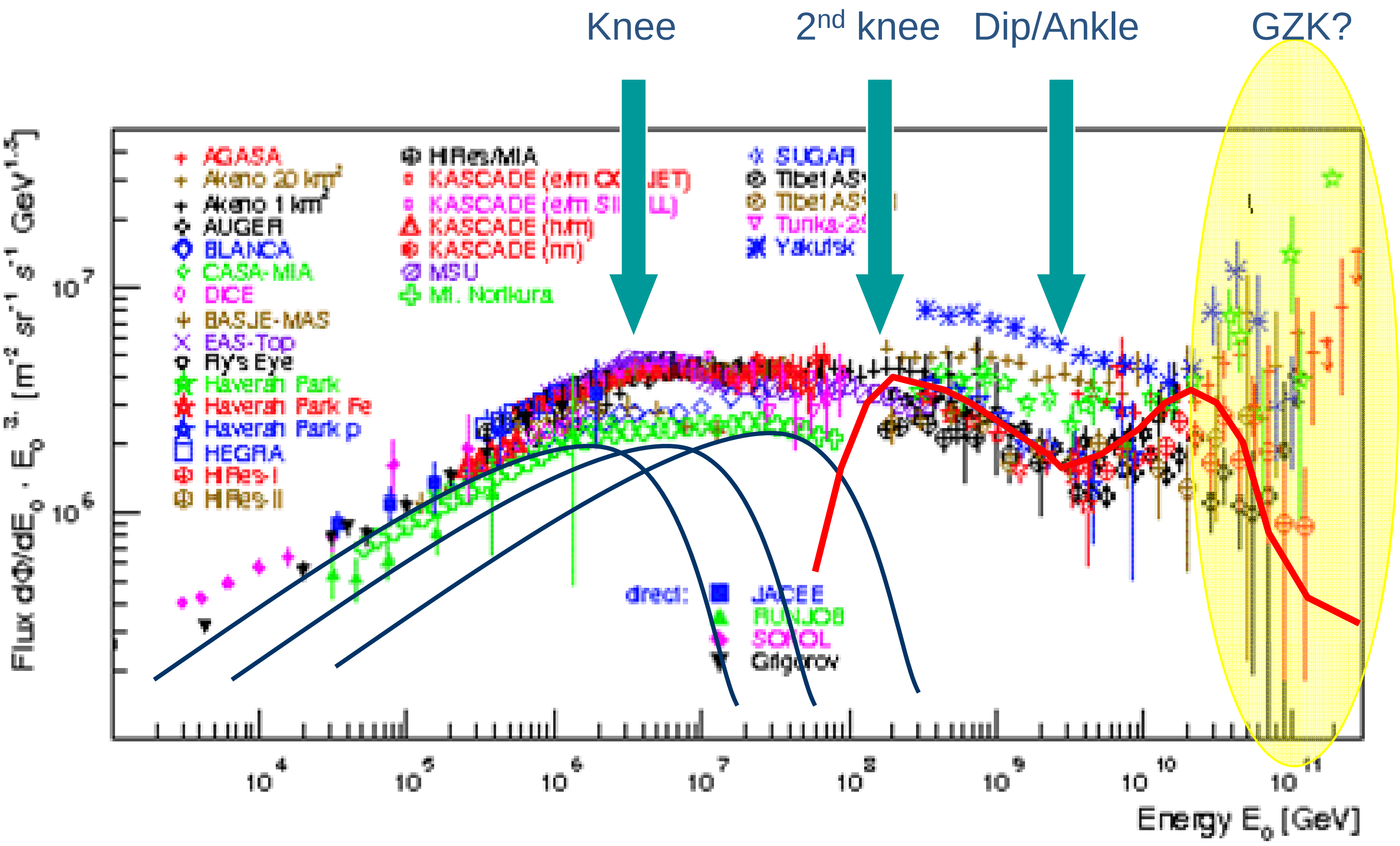
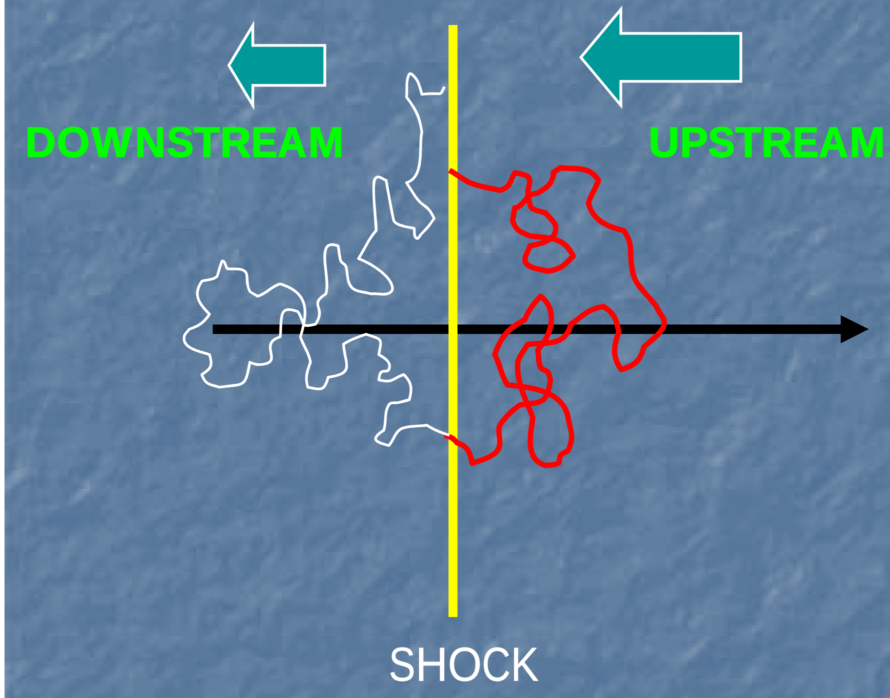
The all-particle spectrum of CR's



TEST PARTICLES THEORY OF SHOCK ACCELERATION



RETURN PROBABILITY FROM UP

$$P_{up} = 1$$

RETURN PROBABILITY FROM DOWN

$$\mathrm{P}_{\mathrm{DW}} = \left(\frac{1 - \mathrm{u}_2}{1 + \mathrm{u}_2} \right)^2 \approx 1 - 4\,\mathrm{u}_2$$

ENERGY GAIN PER CYCLE

$$\left\langle \Delta E / E \right\rangle_{cycle} = \frac{4}{3}\left(\mathrm{u}_1 - \mathrm{u}_2\right)$$

IMPLICATIONS OF T-P THEORY

- The spectrum of accelerated particles is a power law $E^{-\gamma}$ with $\gamma=(r+2)/(r-1) \to 2$ for $r \to 4$
- The spectrum is independent of the diffusion coefficient
- The spectrum is universal and independent of all details.
- What does depend on details is the maximum energy!

THE NEED FOR A NON LINEAR THEORY

- Energetic argument:

$$E_{CR} = \int dE E N(E) \propto \ln\left(E_{max}/E_{min}\right) \quad \text{can be larger than the total energy}$$

- The few particles that leave from upstream carry out energy which make the shock radiative and thereby more compressive (r>4) -> even flatter spectra

- If the pressure accumulated in CRs is large, then γ=5/3 approaches 4/3 and again the shock becomes more compressive (r>4) -> even flatter spectra

A crucial point that makes shock acceleration nonlinear

The case of SNR shocks is a useful example here:

ASSUMPTION: The diffusion coefficient experienced by particles is the same as in the ISM

$$D(E) = 3\times 10^{29} E_{GeV}^{\alpha} \qquad \alpha \approx 0.3 - 0.6$$

The ACCELERATION TIME is then

$$\tau_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right]$$

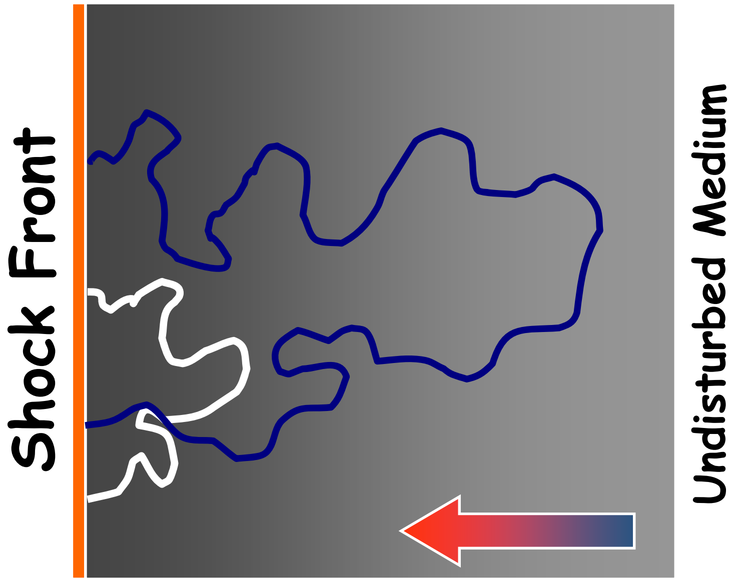
For a typical SNR the maximum energy comes out as FRACTIONS OF GeV !!!

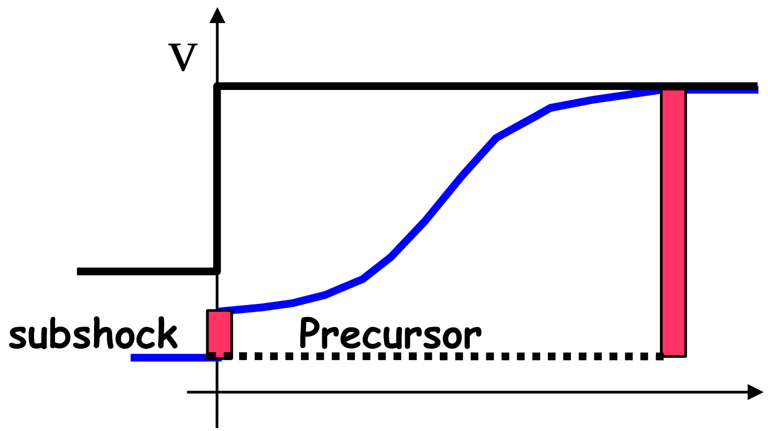
NONLINEAR SHOCK ACCELERATION IS NEEDED TO ACCOUNT FOR:

- **The dynamical reaction of the accelerated particles onto the shock structure**

- **Describe the magnetic field amplification induced by cosmic rays themselves [SELF GENERATION THROUGH COSMIC RAY INDUCED INSTABILITIES]**

The Basic Physics of Modified Shocks





$$\rho(x)\,u(x) = \rho_0\, u_0$$

Conservation of Mass

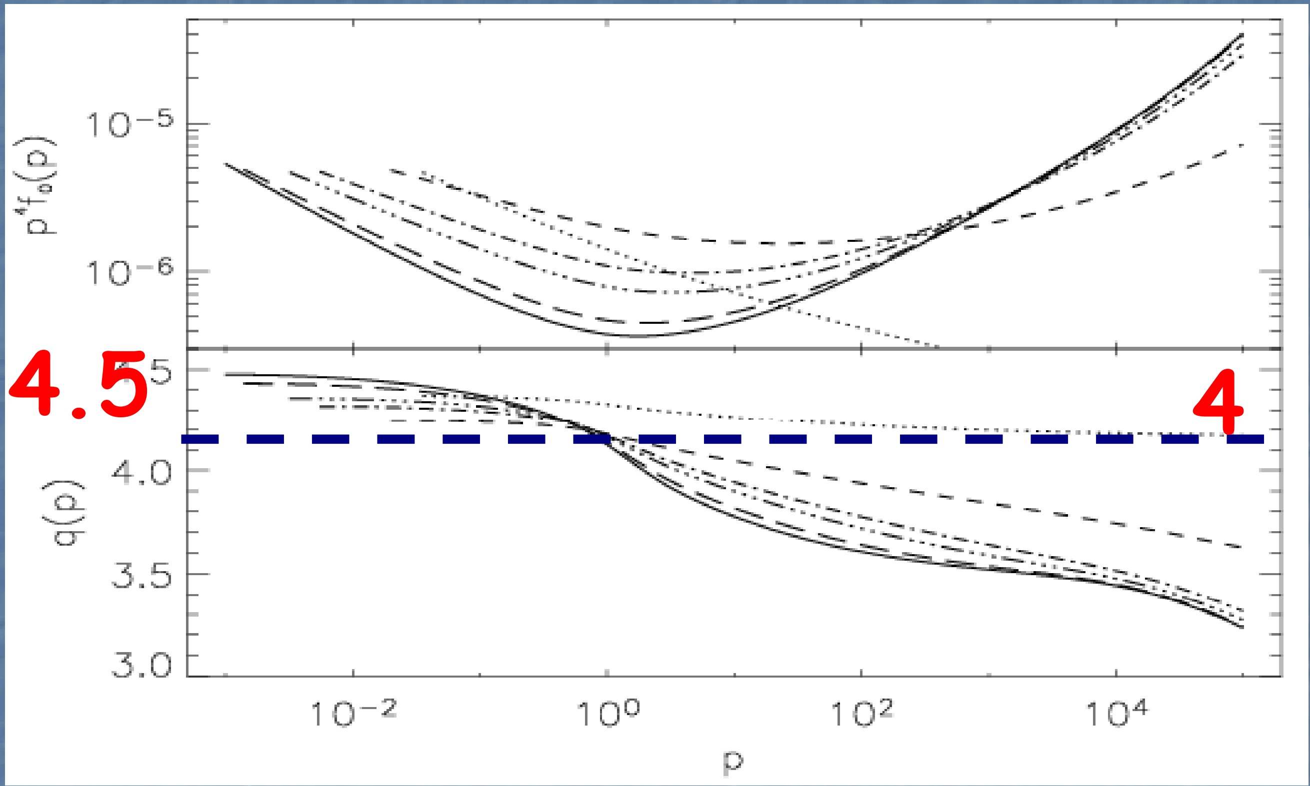
$$\rho_0 u_0^2 + P_{g,0} = \rho(x)\,u(x)^2 + P_g(x) + P_{CR}(x)$$

Conservation of Momentum

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{du}{dx}\,p\frac{\partial f}{\partial p} + Q(x,p,t)$$

Equation of Diffusion Convection for the Accelerated Particles

Spectra at Modified Shocks



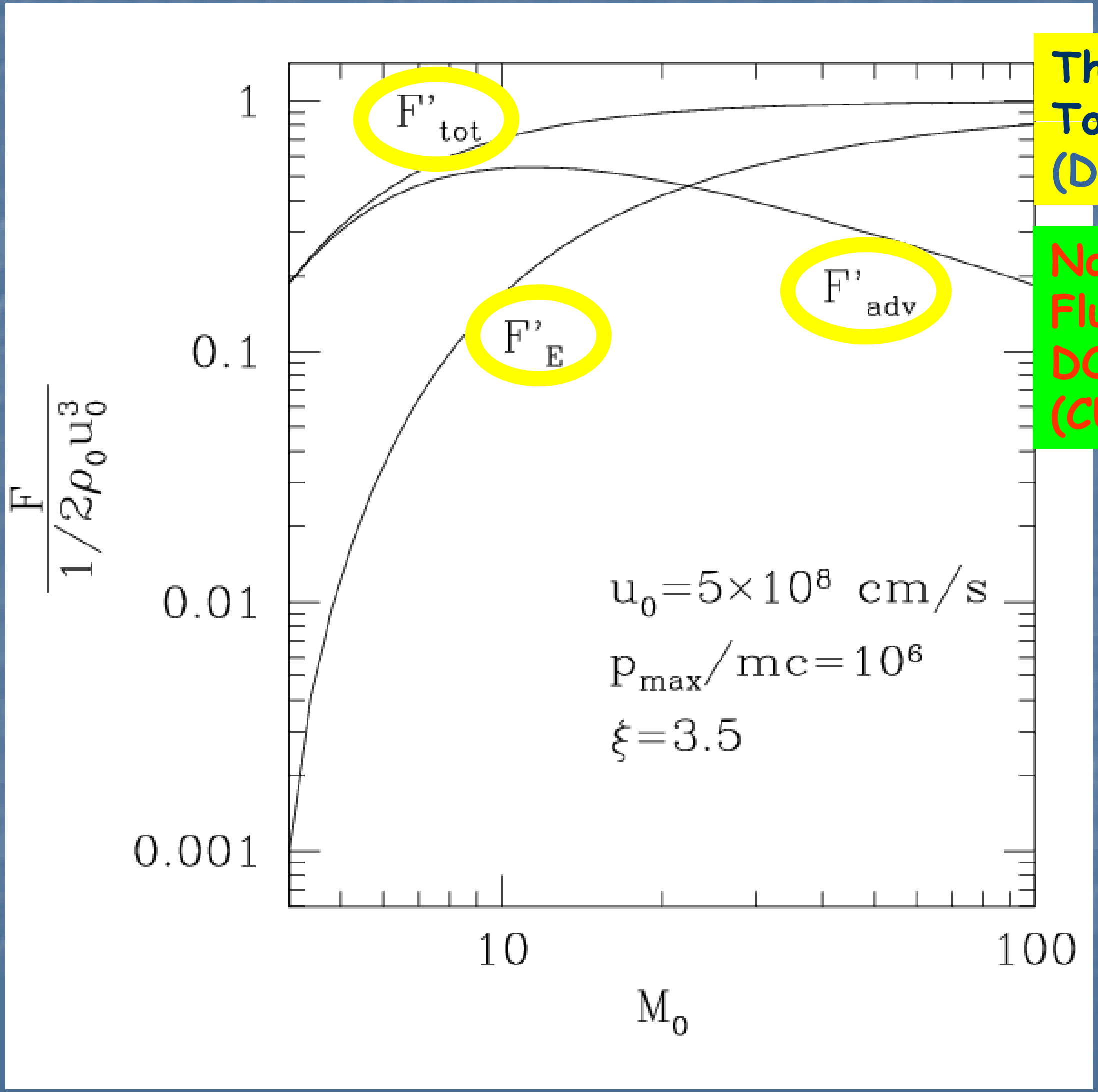
Linear Spectrum

3.2

Amato and PB (2005)

Very Flat Spectra at high energy

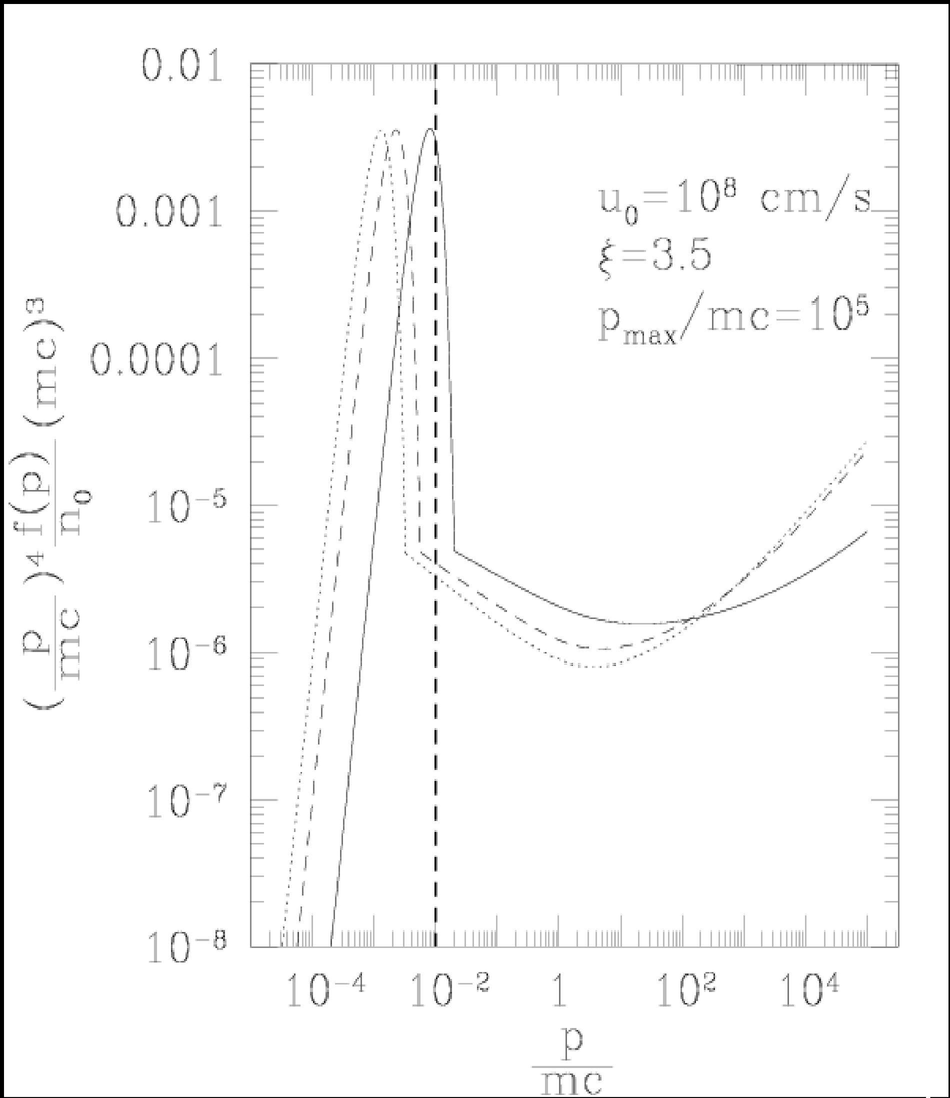
Efficiency of Acceleration (PB, Gabici & Vannoni (2005))



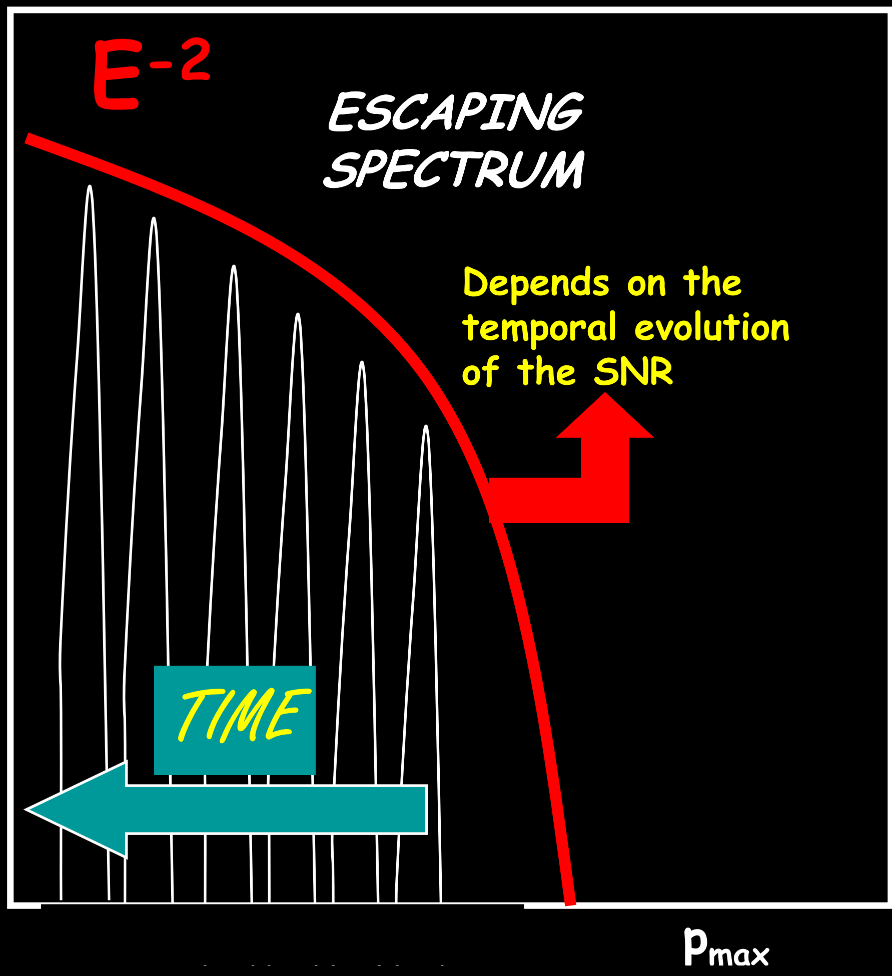
This escapes out
To UPSTREAM
(DELTA FUNCTION)

Note that only this
Flux ends up
DOWNSTREAM!!!
(CURVED SPECTRA)

Advected and escaping spectra

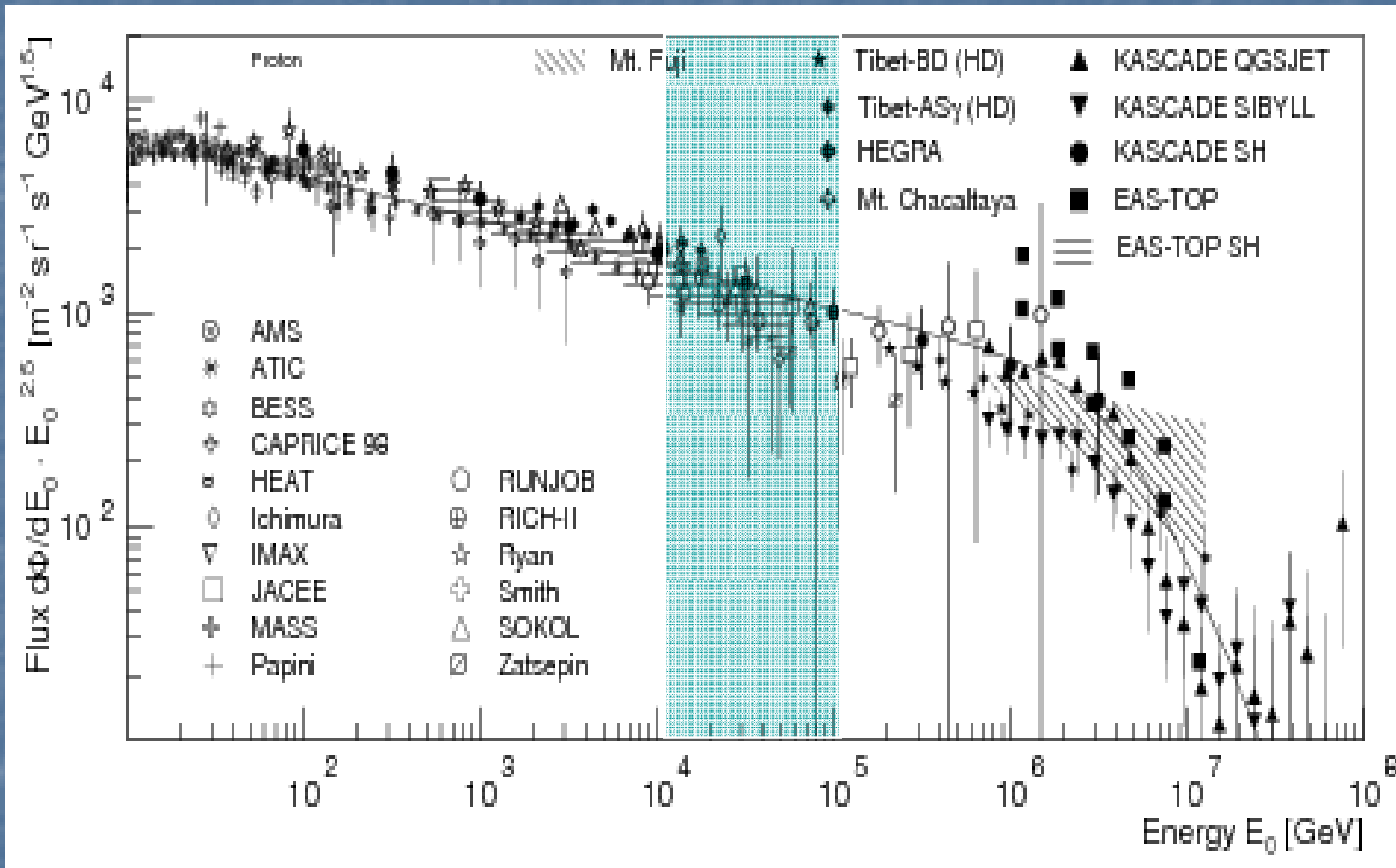


PB, Gabici and Vannoni 2005



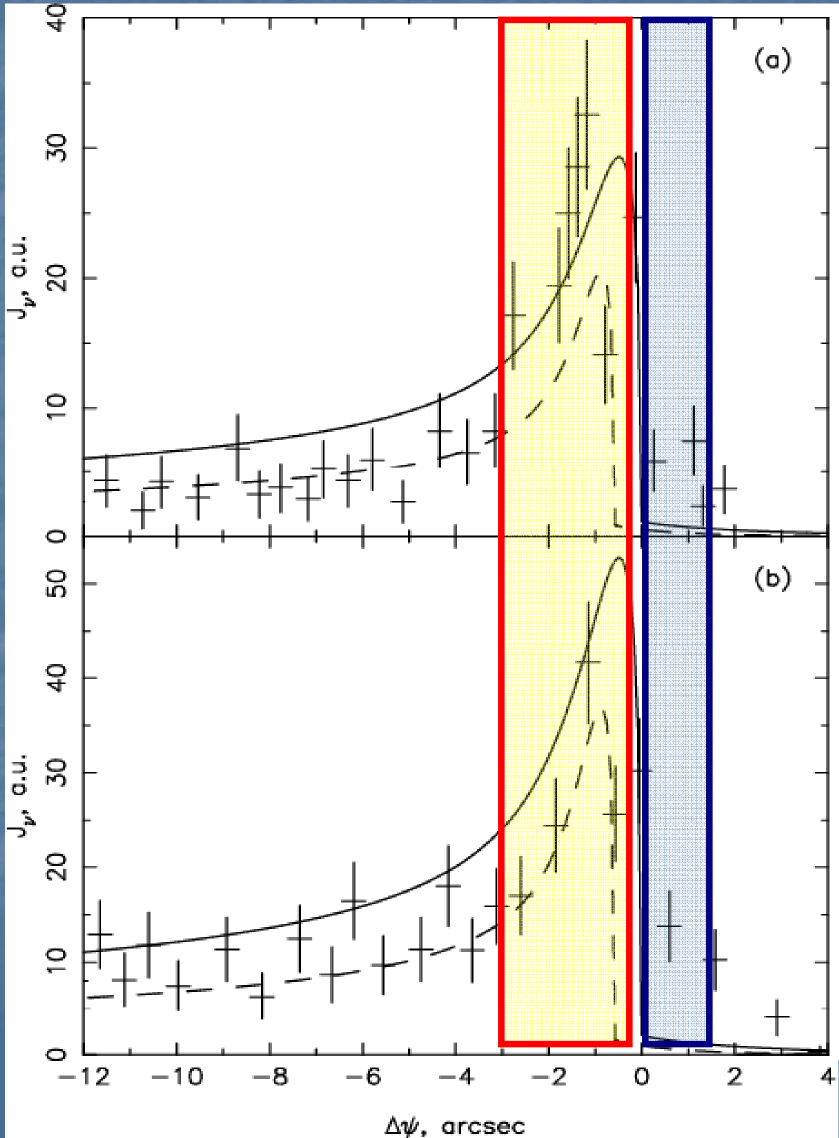
tuskin and Zirakashvili 2005

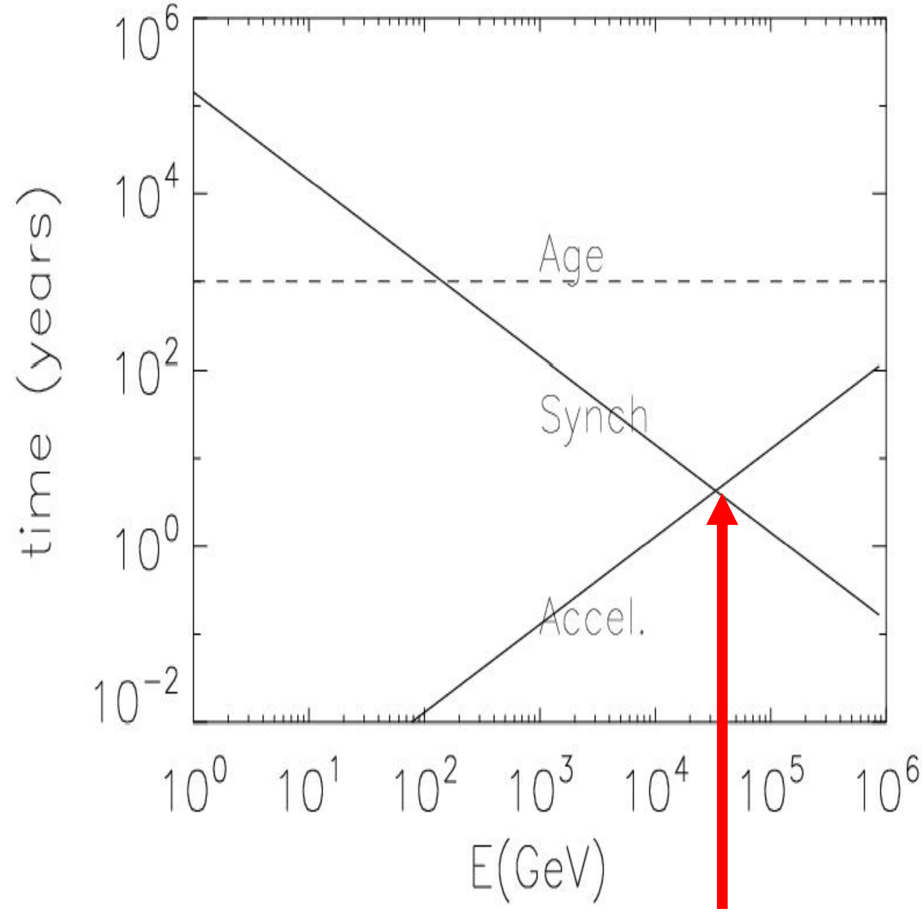
NEED FOR LARGE TURBULENT MAGNETIC FIELDS



LARGE B IS NOT ENOUGH: SCATTERING MUST OCCUR AT ROUGHLY THE BOHM RATE!!! -> STRONG TURBULENCE

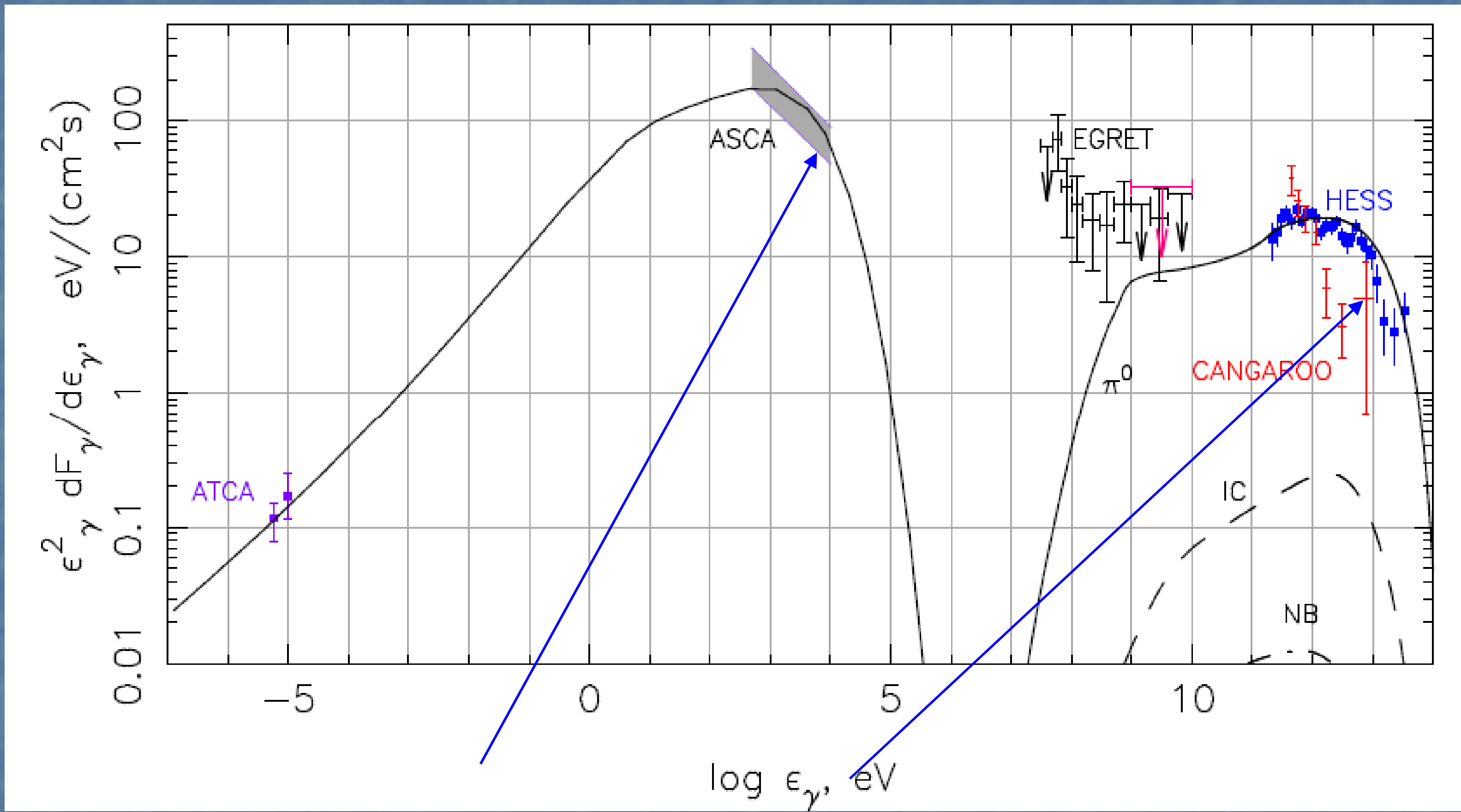
POSSIBLE EVIDENCE FOR B-FIELD AMPLIFICATION





Cutoff

Figure from Berezhko & Volk 2006



THE PHYSICS IS IN THE CUTOFFS !!!

THE PHYSICS IS IN THE CUTOFFS

- The position of the X-ray cutoff is independent of the strength of B (for Bohm diffusion)
- The way the flux goes to zero tells us about the spectrum of accelerated electrons
- The cutoff in the gammas tells us about the cutoff in the proton spectrum or in the electron spectrum

MAGNETIC FIELD AMPLIFICATION

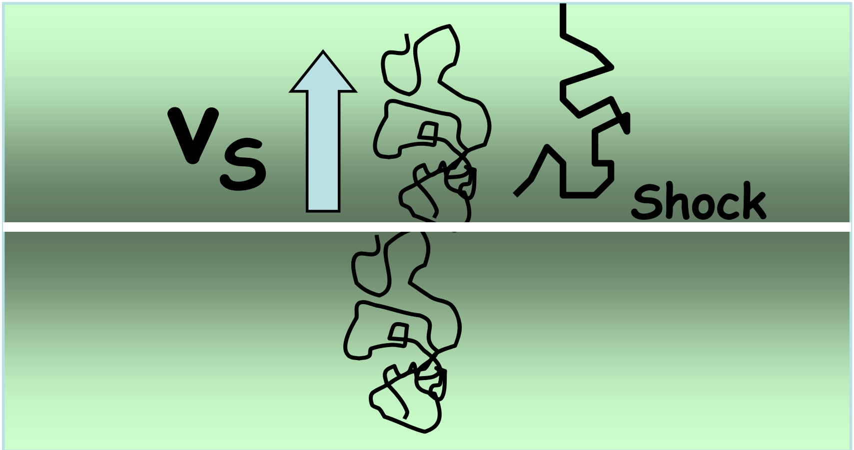
- Resonant Streaming Instability
  (Achterberg 1983, Zweibel 1978, Bell 1978)

- Non-resonant Streaming Instability
  (Bell 2004)

- Firehose Instability

- ...

BASIC ASPECTS OF B-FIELD AMPLIFICATION BY CR's



$$\frac{dP_{CR}}{dt} = \frac{n_{CR}\, m\, \Gamma_{CR}\, (v_D - v_A)}{\tau}$$

RATE OF MOMENTUM LOST BY CR

BUT THIS MUST EQUAL THE RATE OF MOMENTUM GAIN BY THE WAVES

$$\frac{dP_W}{dt} = \gamma_W \frac{\delta B^2}{8\pi} \frac{1}{v_A}$$

GROWTH RATE OF WAVES

BY REQUIRING EQUILIBRIUM:

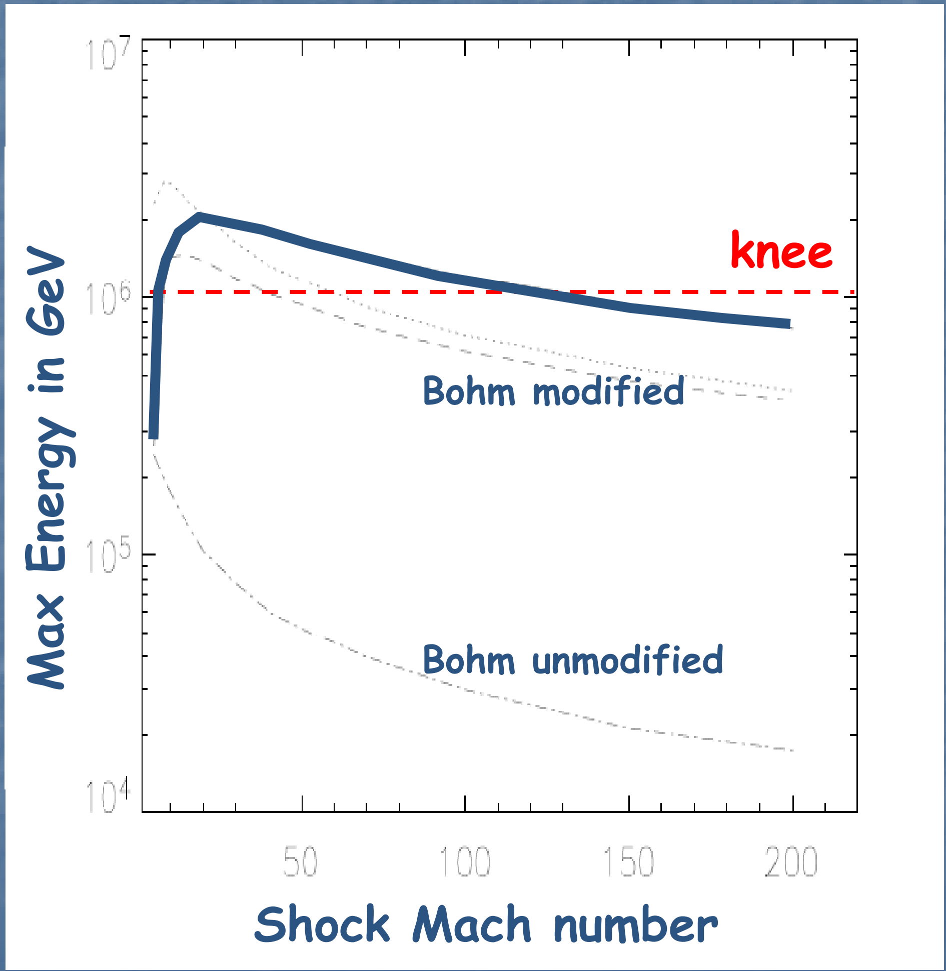
$$\gamma_W = \frac{n_{CR}}{n_{gas}} \Omega_{cyc} \left(\frac{v_D - v_A}{v_A} \right)$$

Maximum Energy in the Proton Spectrum

- 1st effect: the magnetic field is amplified thereby leading to higher Emax

- 2nd effect: the precursor slows down the upstream plasma thereby reducing the pmax

IF SNR ACCELERATE GALACTIC COSMIC RAYS WE SHOULD DETECT GAMMA RAY SPECTRA WITH CUTOFFS AROUND 10-100 TeV



PB, Amato & Caprioli 2007

RESONANT AND NON-RESONANT UNSTABLE MODES

The upstream plasma is made of :

$$f_i(p) = \frac{n_i}{p^2}\delta(p - m_i v_s)\delta(\mu + 1)$$

Cold protons

$$f_e(p) = \frac{n_e}{p^2}\delta(p - m_e v_s)\delta(\mu + 1)$$

Cold electrons

$$f_e^{cold}(p) = \frac{N_{CR}}{2p^2}\delta(p).$$

Cold isotropic electrons which
Compensate the CR charge!!!

and COSMIC RAYS:

$$f_{CR}(p) = \frac{N_{CR}}{2}g(p),$$

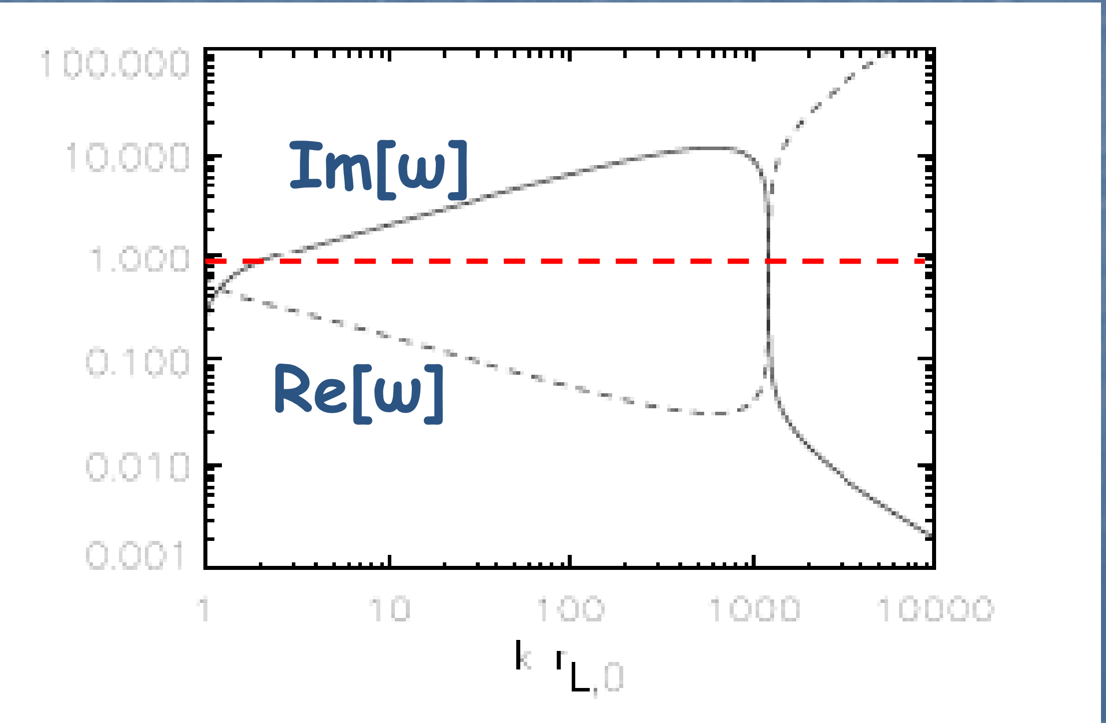
Each component is described through a Vlasov equation (collision-less plasmas):

$$\frac{\partial f_\mu}{\partial t} + (\vec{v}\cdot\vec{\nabla}) f_\mu + \frac{q_\mu}{c}[\vec{v}\times\vec{B}]_\alpha \frac{\partial f_\mu}{\partial p_\alpha} = 0$$

Perurbation of the Vlasov equations together with the Equation of conservation of charge provide a dispersion relation:

$$v_A^2 k^2 = \omega^2 \mp \frac{k v_s \Omega_i^* N_{CR}}{n_i} \left[1 \pm I_1(k) \pm i I_2(k)\right].$$

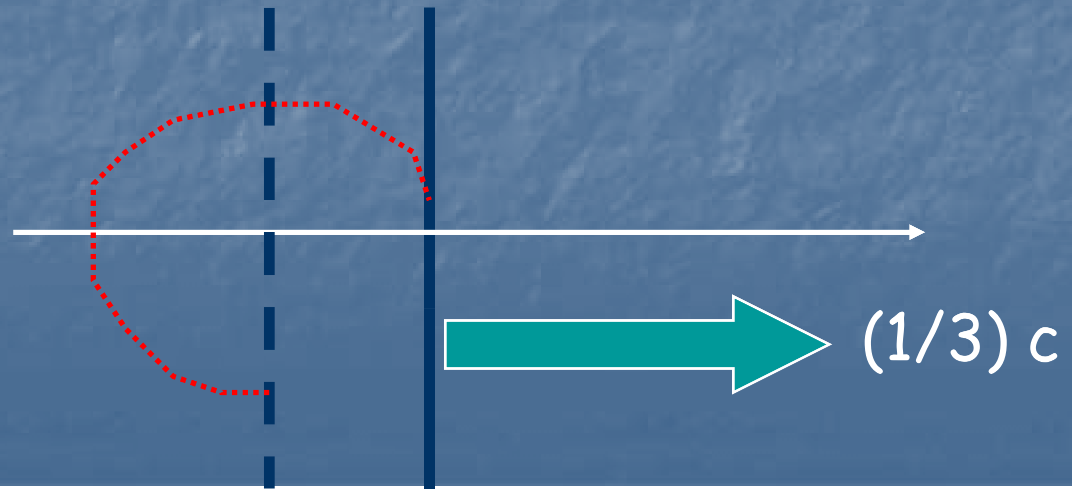
If CR acceleration is efficient ($P_{CR} \sim \rho u^2$):



Bell 2004
Blasi & Amato 2007

RELATIVISTIC SHOCKS IN 1 SLIDE

- The standard prediction in the SPAS regime is a universal spectrum $E^{-2.3}$
- BUT many violations: LAS (<2), B-field compression at the shock (>>2)
- In general, need strong turbulence.



Concluding remarks on acceleration

- Most physics concepts discussed so far are fully general: both dynamical reaction and B-field amplification are crucial in all CR accelerators: NONLINEAR EFFECTS ARE NOT CORRECTIONS. THEY ARE THE REASON WHY IT WORKS!
- We limited our discussion to non-relativistic shocks because a theory of modified relativistic shocks has not been developed yet
- If the magnetic field amplification due to streaming instability takes place, also acceleration to UHE in some sources could be made easier
- Many issues still unclear: injection, nonlinear development of turbulence, diffusion coefficient when $\delta B/B \gg 1$,…

THE TRANSITION FROM GALACTIC TO EXTRAGALACTIC COSMIC RAYS

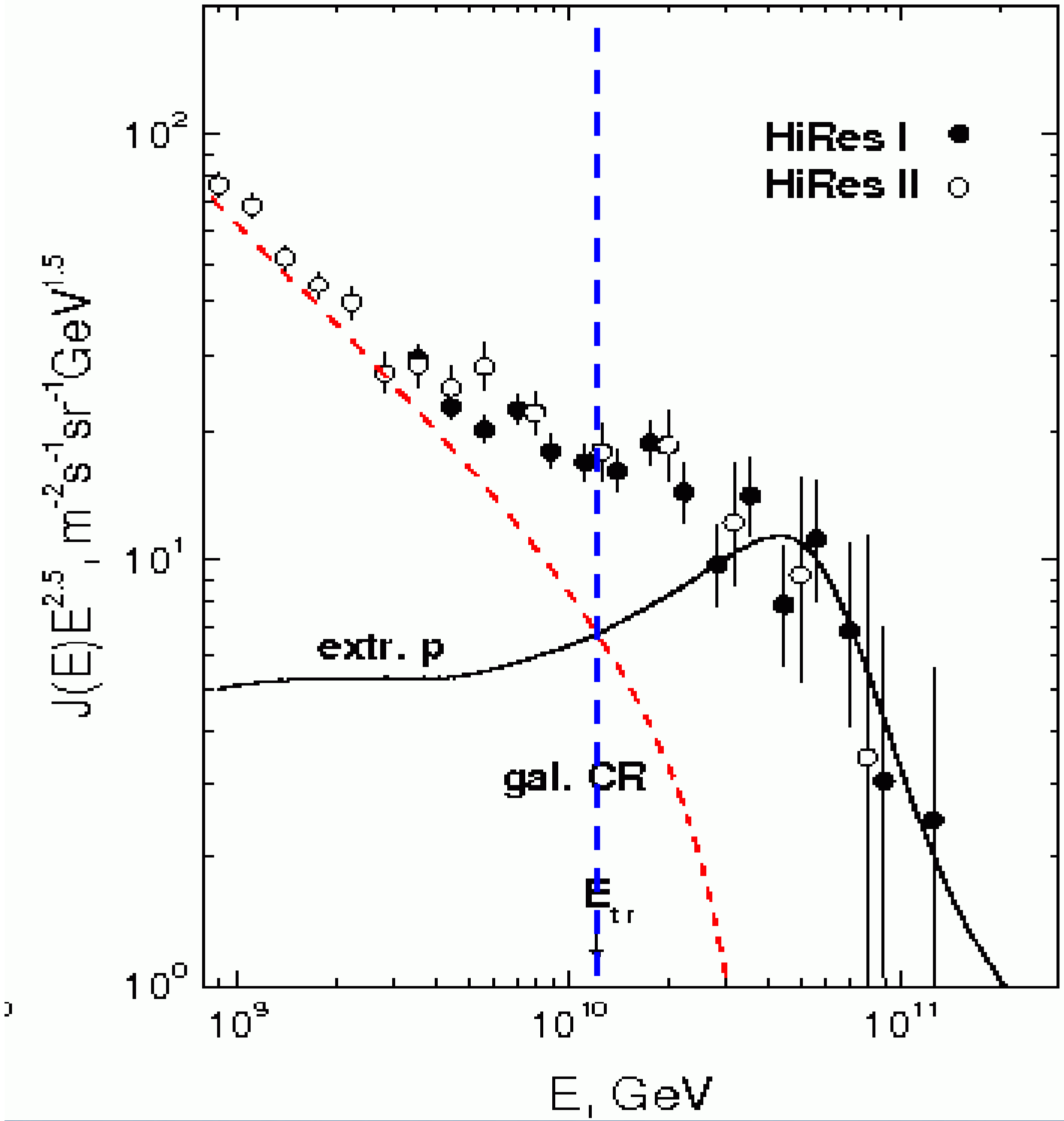
Consequences of the previous points:

- *If protons are accelerated to about the knee, and scattering is at the Bohm rate, then the knees in the other elements are at Z times the proton knee*

⇓

THE GALACTIC CR SPECTRUM MUST END SOMEWHERE AROUND 10^{17} eV

Transition at the Ankle

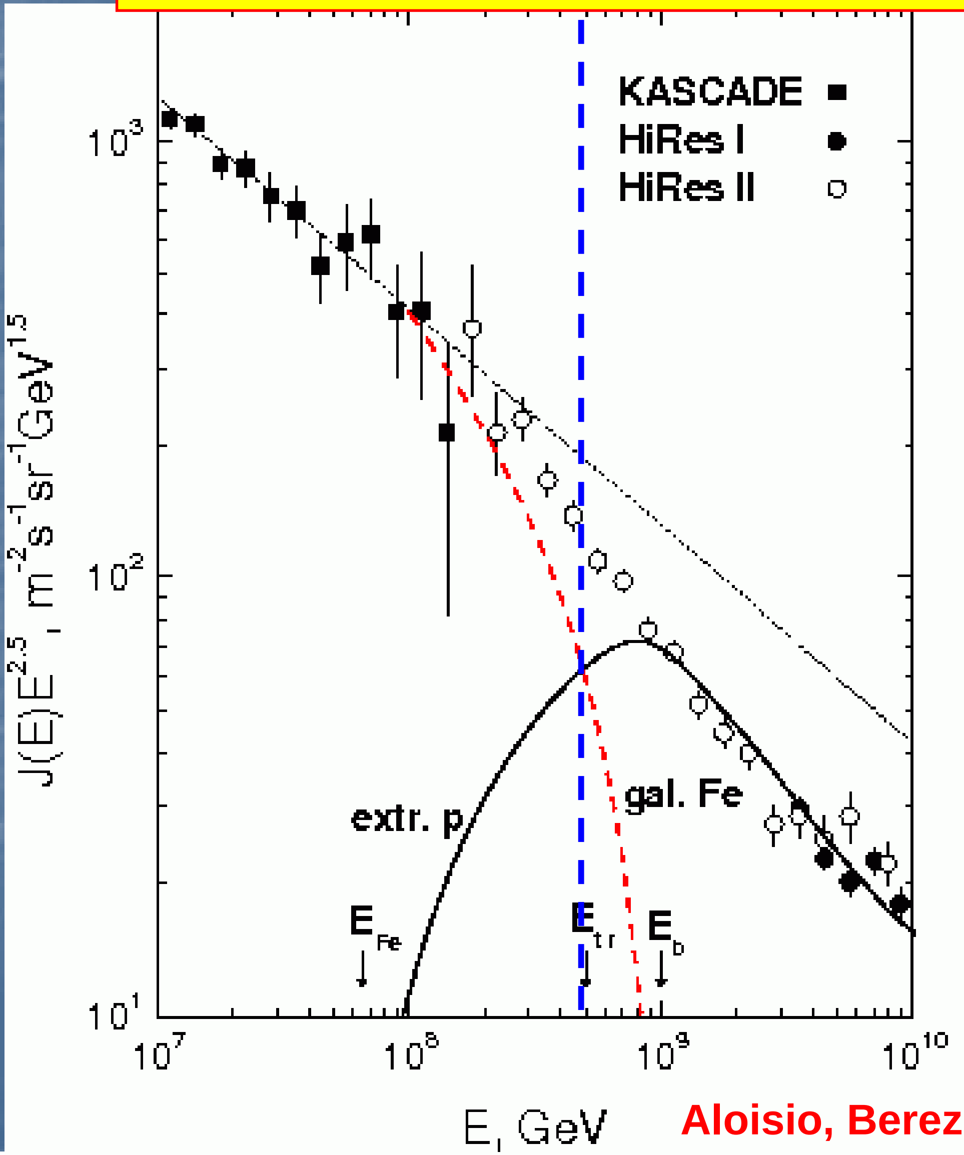


1. A steep GAL spectrum encounters a flat EX-GAL spectrum
2. The GAL spectrum should extend to >10^{19} eV and is expected to be Fe dominated
3. The chemical composition of the EX-GAL part can have heavy nuclei

Aloisio, Berezinsky, PB, Gazizov, Grigorieva, Hnatyk 2006

Transition at the Dip

A DIP IS GENERATED DUE ONLY TO PAIR PRODUCTION. ITS POSITION IS FIXED BY PARTICLE PHYSICS INTERACTIONS

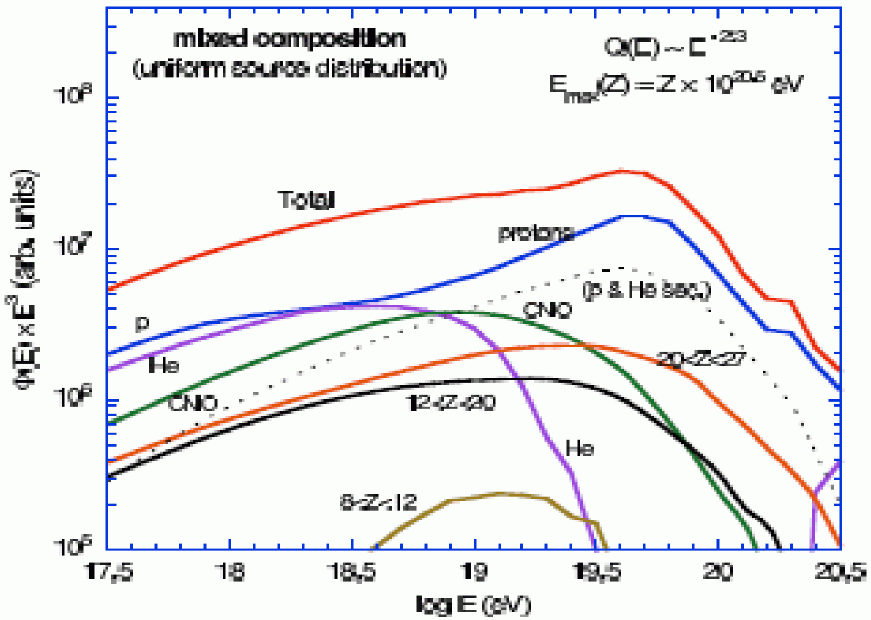


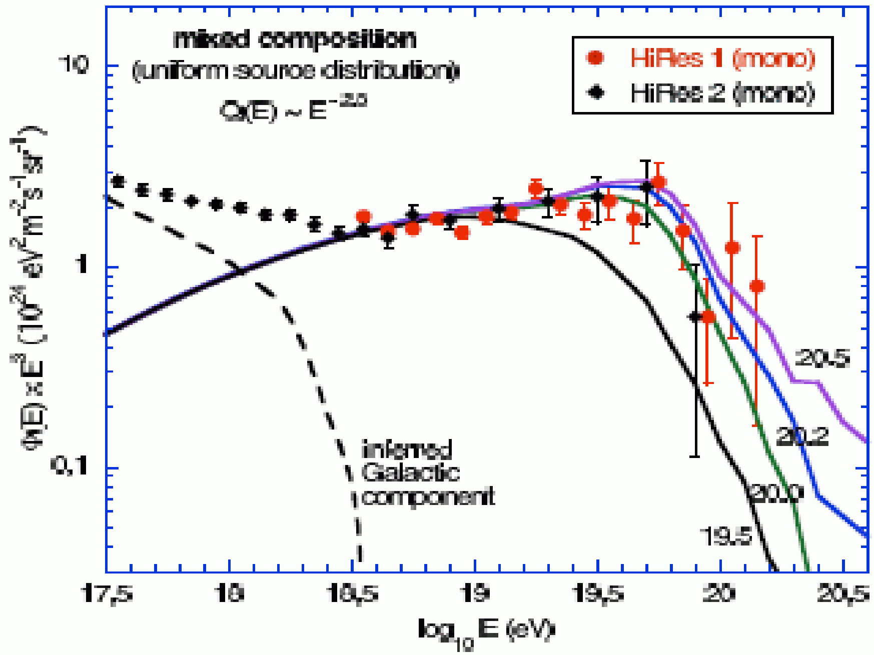
1. STILL TRUE that a STEEP GAL spectrum meets a FLAT EX-GAL spectrum (Second knee)
2. The Low energy flattening due to either pair prod. or most likely magnetic horizon
3. The GAL spectrum is expected to END at <10^{18} eV (mainly Fe)
4. The EX-GAL spectrum is predicted to be mainly protons at E>10^{18} eV (No more that 15% He allowed)
5. Steep injection spectrum unless complex injection

Aloisio, Berezinsky, PB, Gazizov, Grigorieva, Hnatyk 2006

Transition due to Mixed Composition

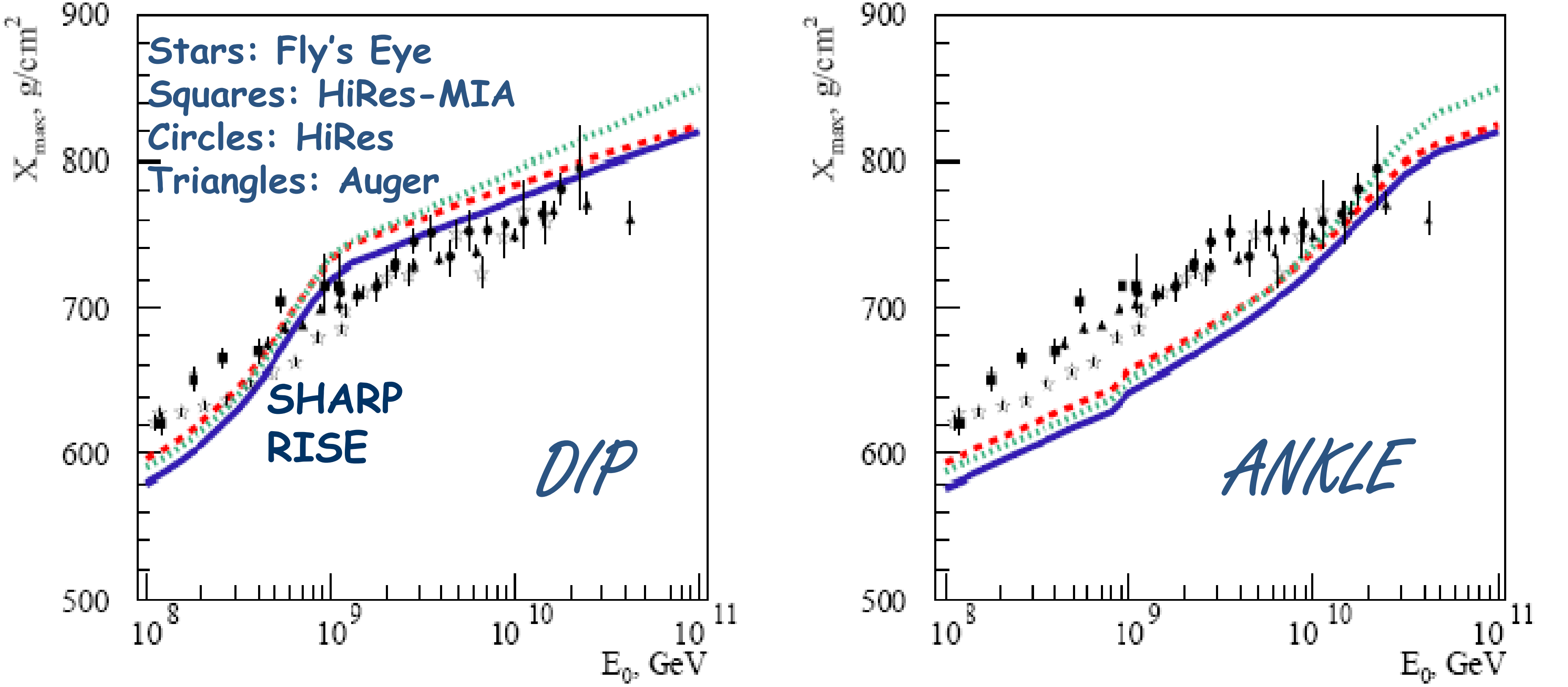
Allard et al. 2006





1. Particles at injection have an arbitrary chemical composition
2. Relatively flat spectra at injection are required
3. The inferred galactic spectrum has a cutoff at energies about the same as in the DIP scenario
4. At 10^{19} eV there is still an appreciable fraction of heavy elements
5. At 10^{20} eV, as in all other models, there are mainly protons

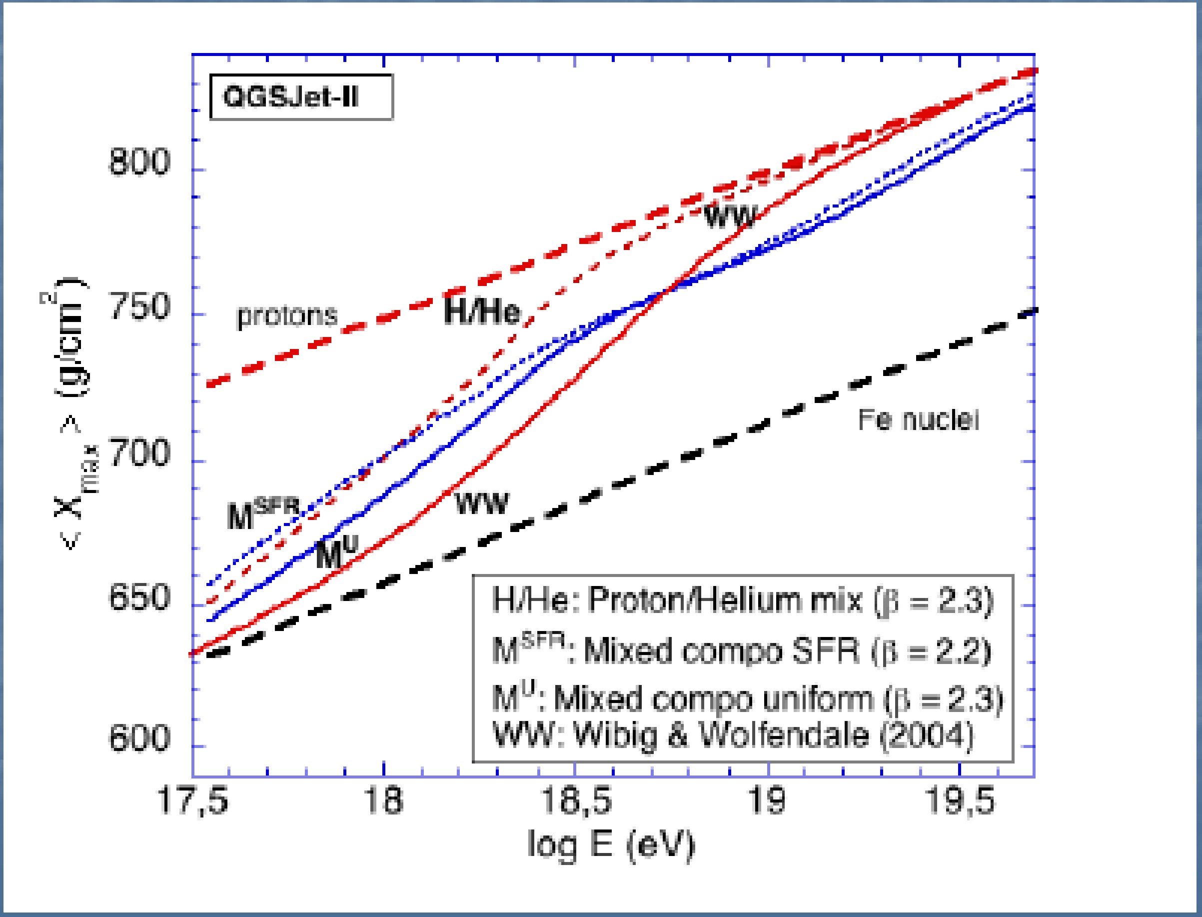
ELONGATION RATES



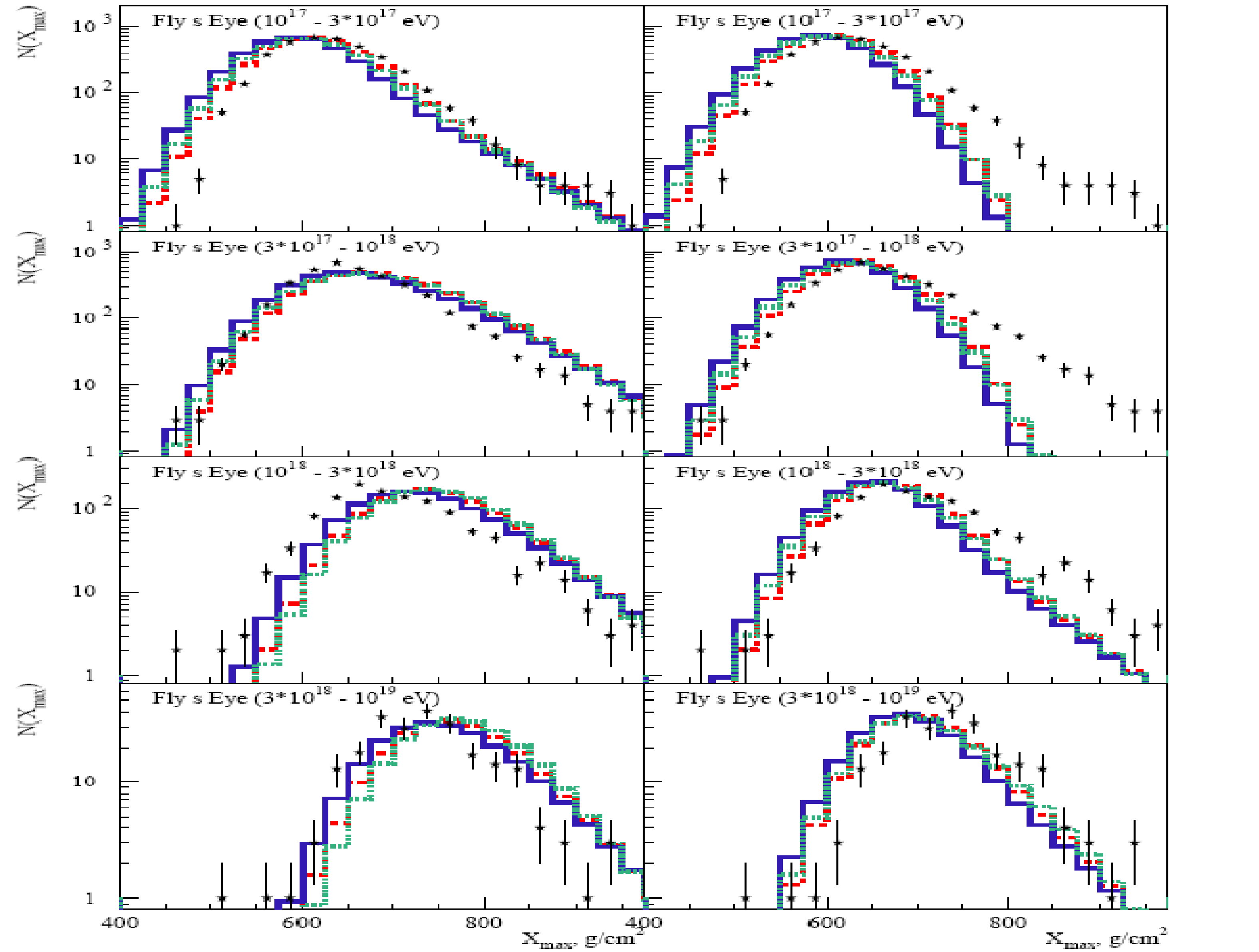
Aloisio, Berezinsky, PB and Ostapchenko, 2007

Elongation rate (Mixed Composition)

Allard et al. 2007

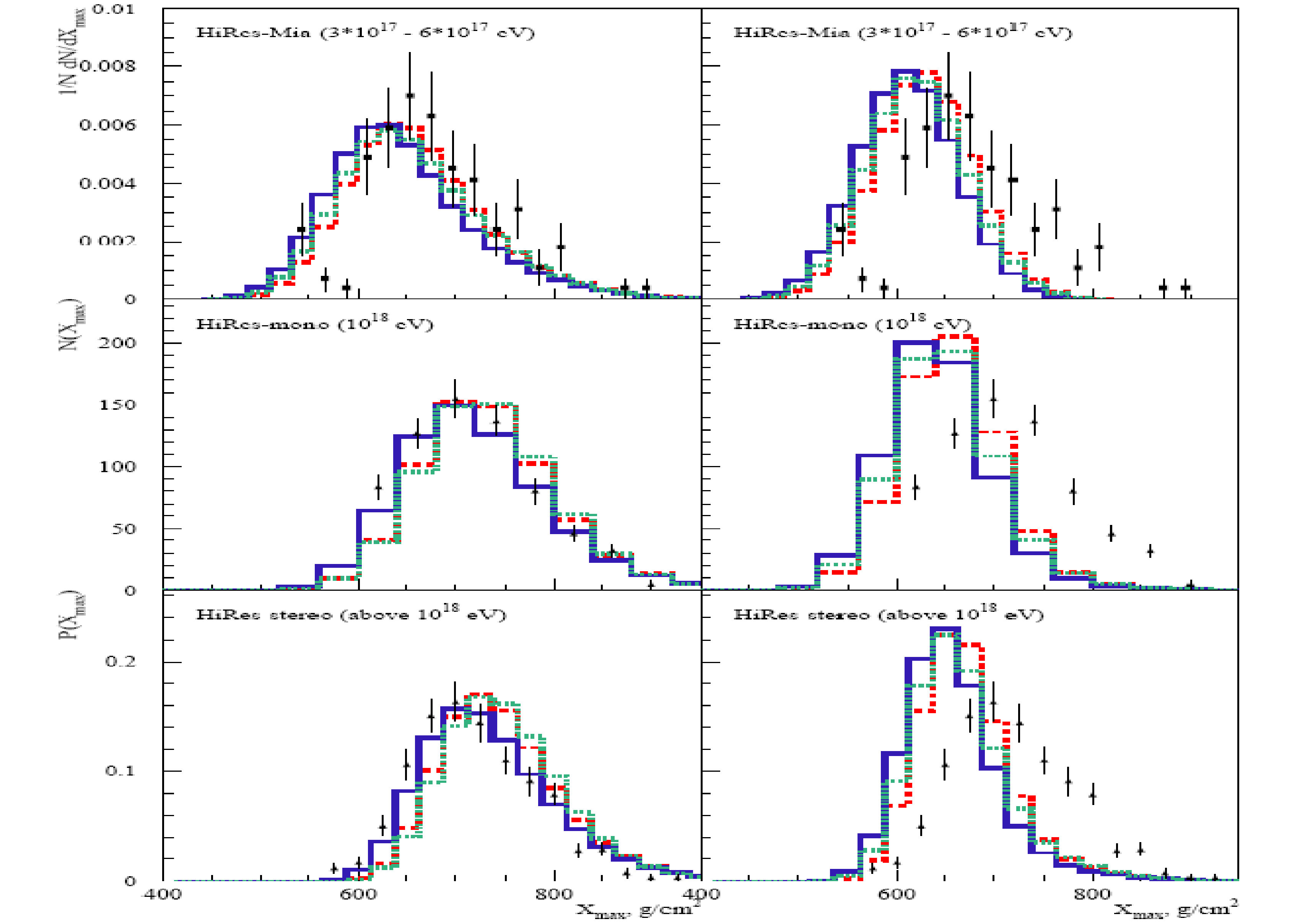


DISTRIBUTION OF X_{MAX} (Fly's Eye)



Aloisio, Berezinsky, PB and Ostapchenko, 2007

DISTRIBUTION OF X_{MAX} (HiRes-MIA)



Aloisio, Berezinsky, PB and Ostapchenko, 2007

CONCLUSIONS

- ACCELERATION BY SHOCKS IS BECOMING SELF-CONSISTENT
- THE PICTURE WE ARE GETTING FROM SNR IS THAT ACCELERATION OCCURS IN A NONLIN REGIME AND IMPLIES STRONG B AMPLIFICATION
- THE IMPLICATION IS THAT THE GALACTIC COSMIC RAY SPECTRUM SHOULD END AT A FEW 10^{17} Ev (MAINLY IRON)
- THE TRANSITION REGION IS THEREFORE UNDER DEBATE (ANKLE, DIP or MIXED?) Consistency with the standard model?
- THE CHEMICAL COMPOSITION IS THE BEST TOOL TO EXPLORE THIS PHENOMENON, BUT NO ANSWER YET