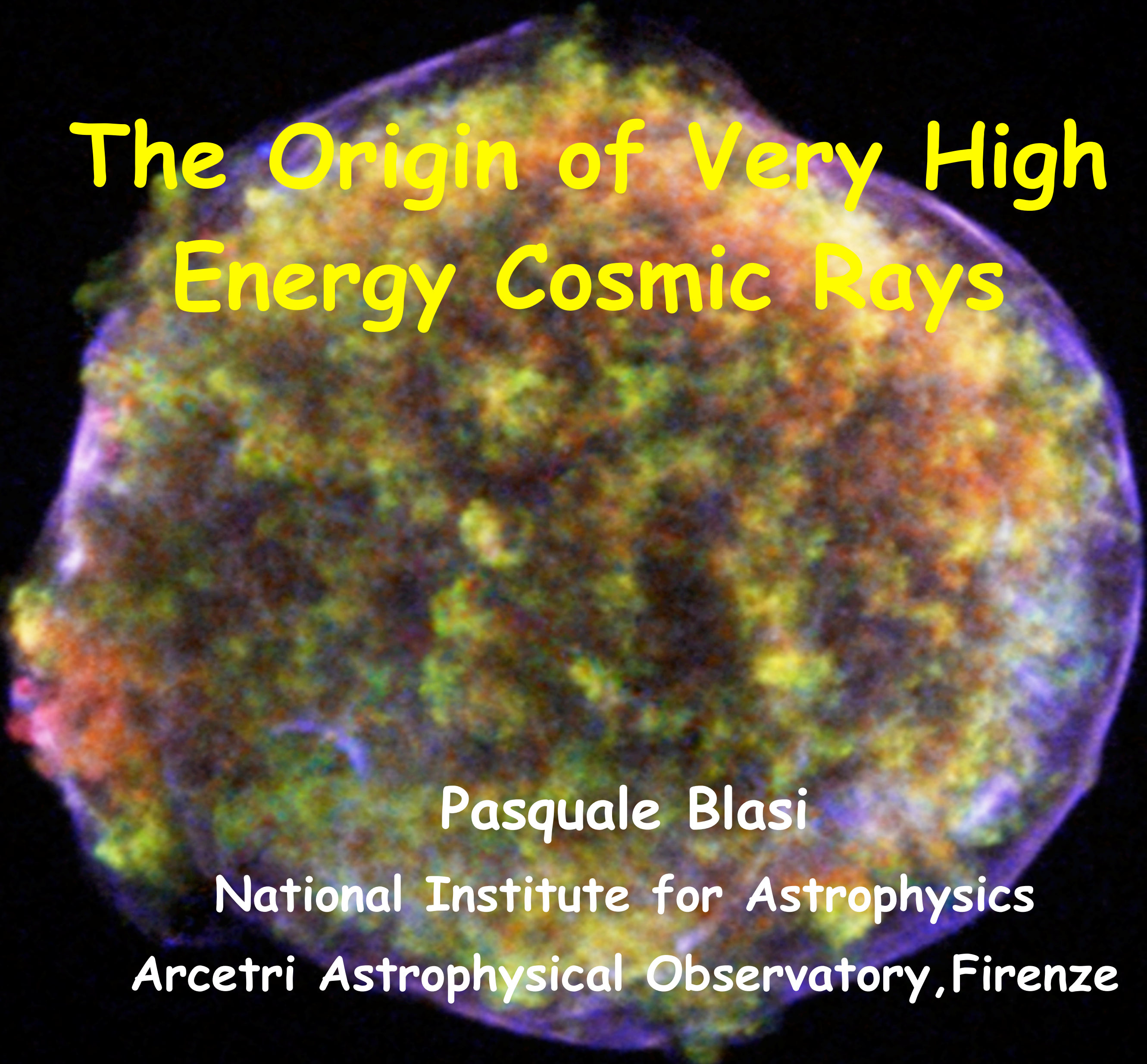
The Origin of Very High Energy Cosmic Rays



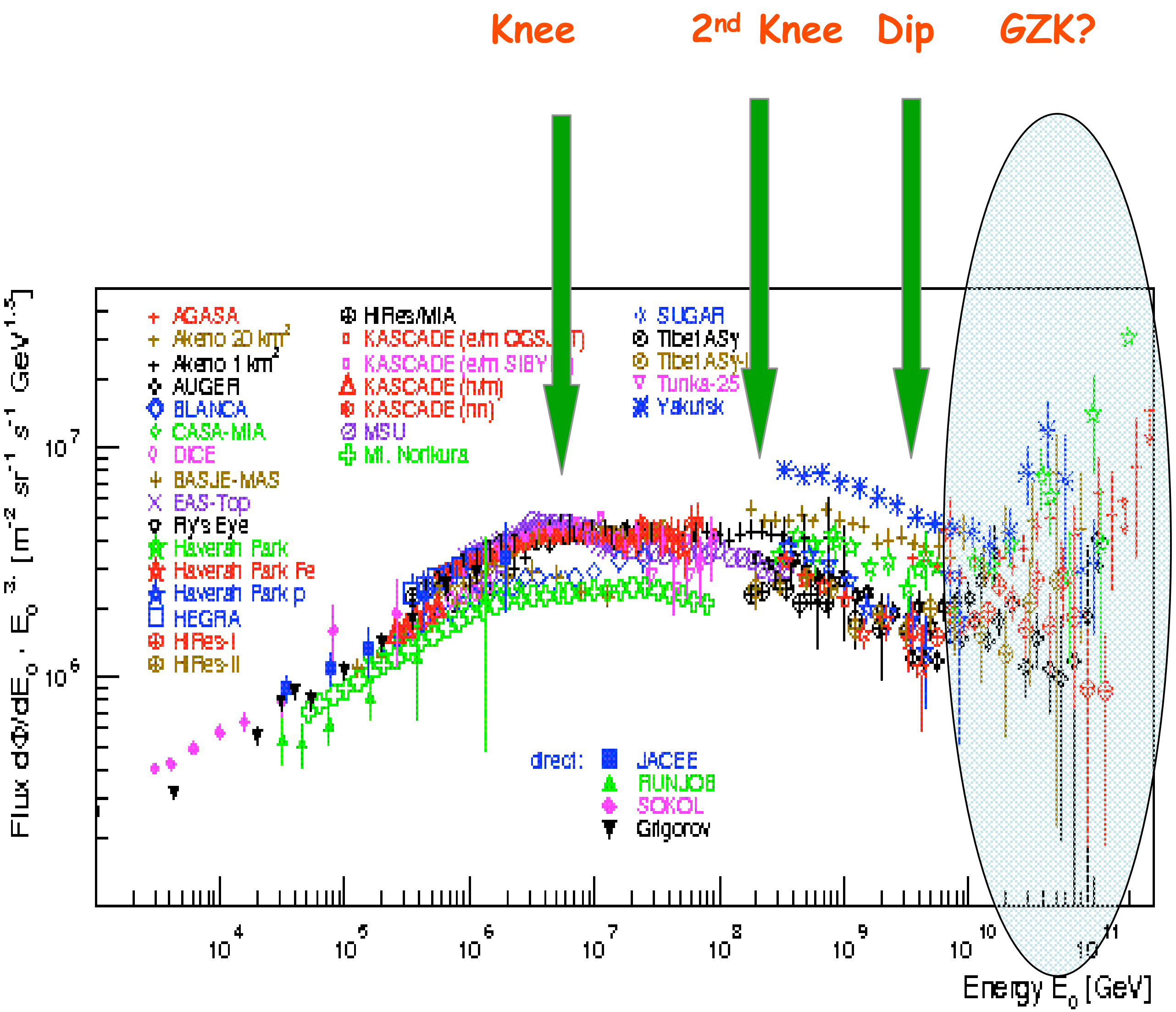
Pasquale Blasi

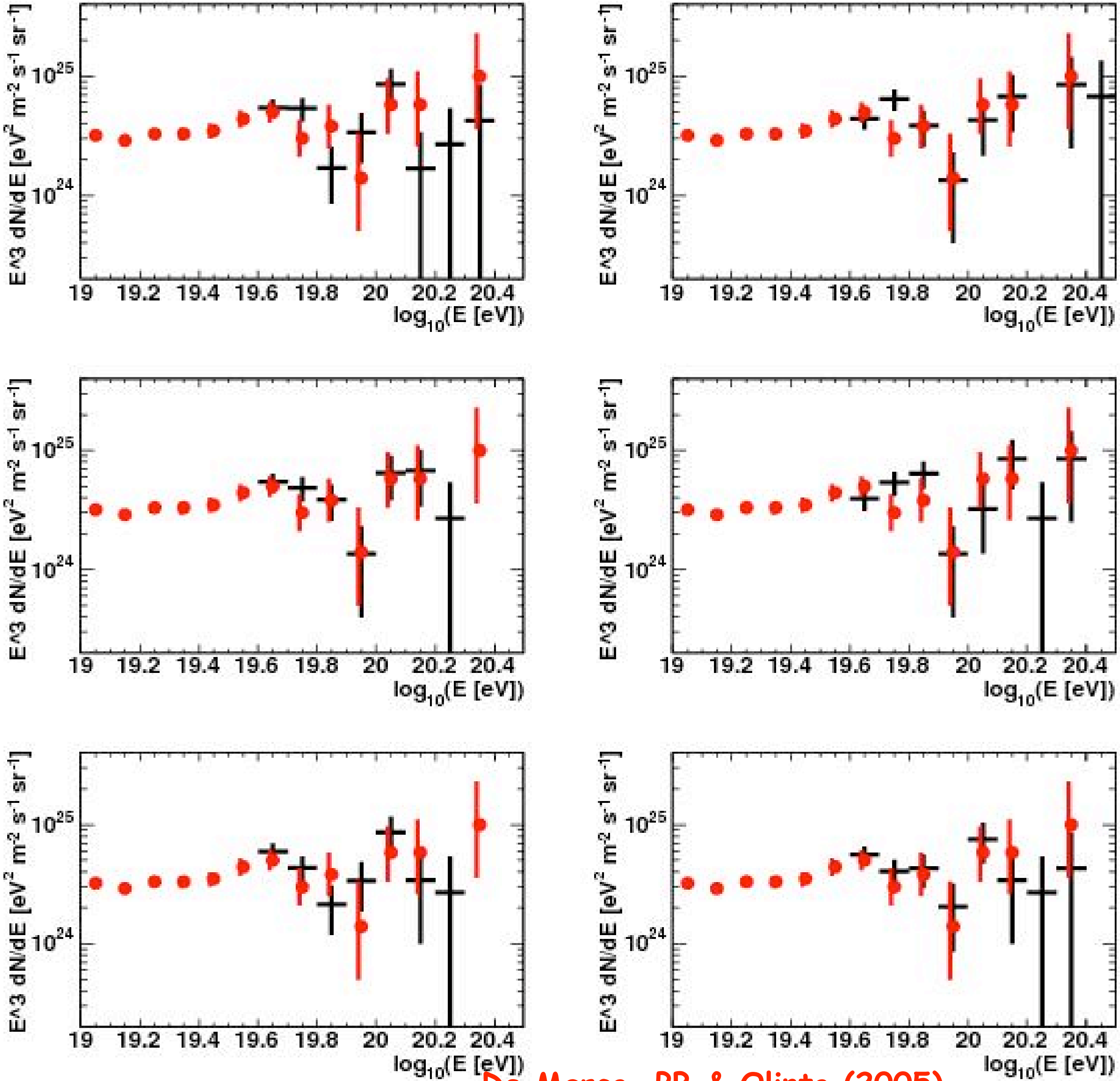
National Institute for Astrophysics

Arcetri Astrophysical Observatory, Firenze

Vulcano Workshop, May 2006

Observations – I: Spectrum





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De Marco, PB & Olinto (2005)

De Marco, PB
and Olinto 2006

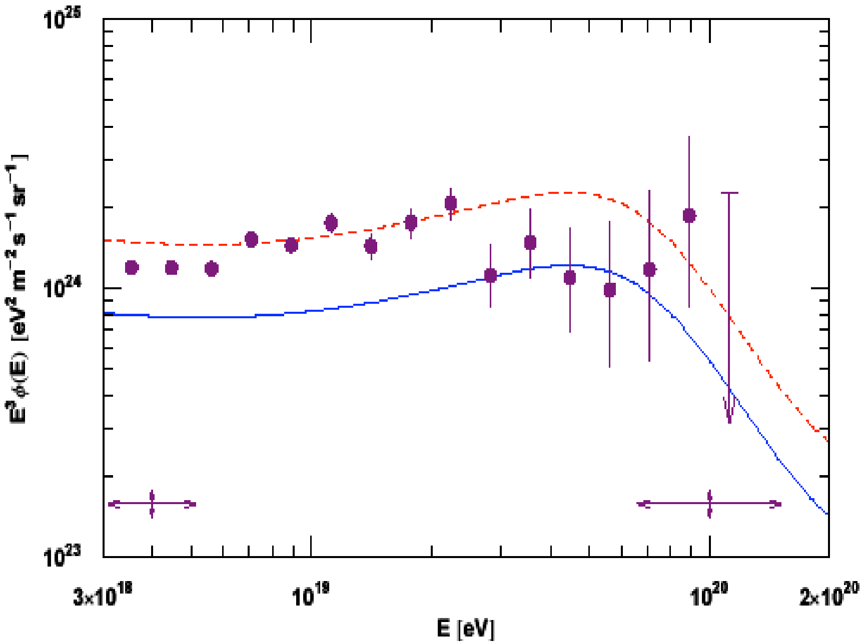
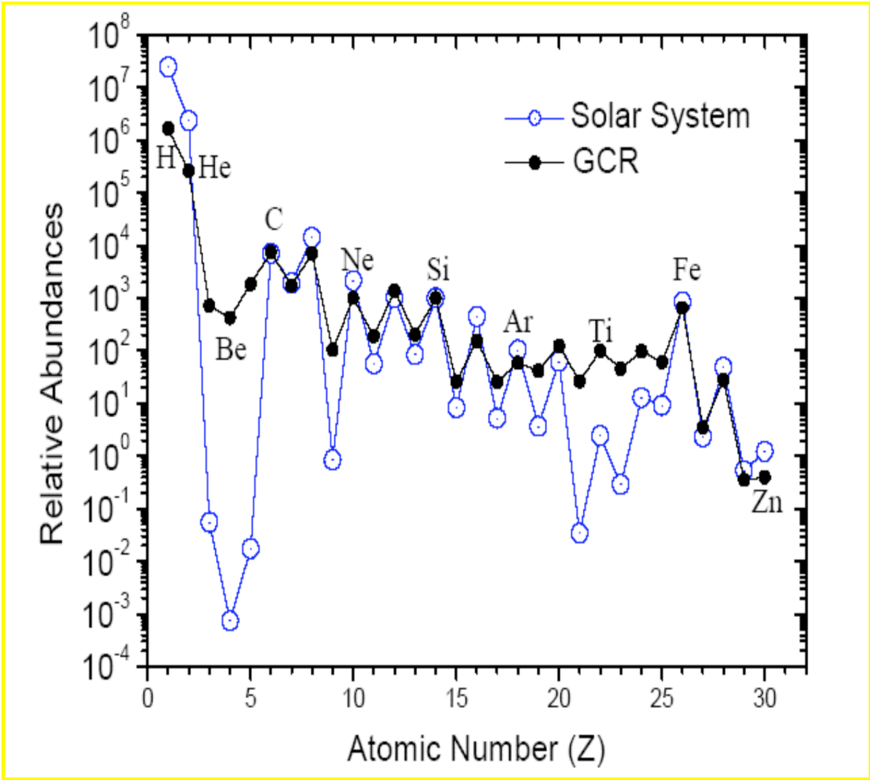


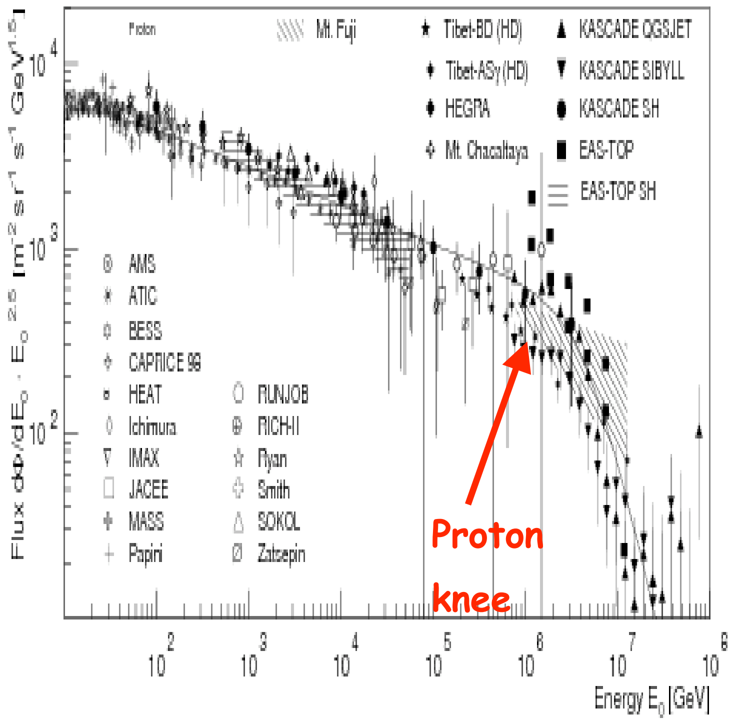
Figure 1. Data points from the Pierre Auger Observatory [24] compared with theoretical predictions normalized at different energies.

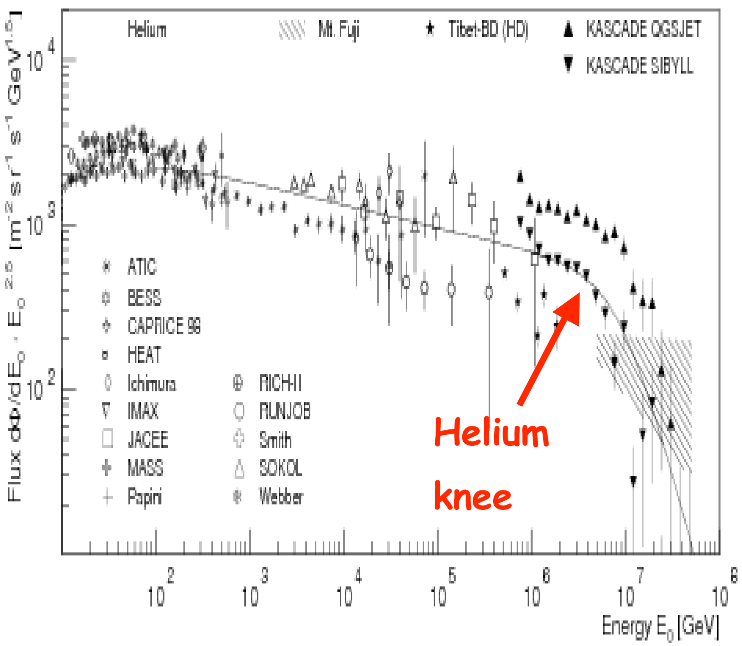
Table 2. Number of events expected with $E > 10^{20}$ eV using the normalization of the spectrum at low energy.

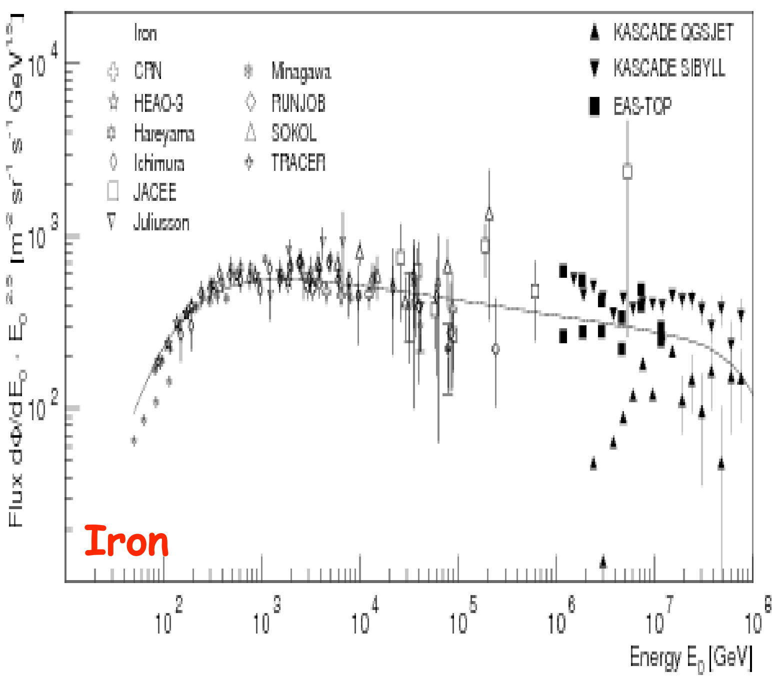
$\bar{\rho}$ (Mpc^{-3})	n_{20} / 1yr $n_{19.6} = 120$	n_{20} / 5yr $n_{19.6} = 600$	n_{20} / 10yr $n_{19.6} = 1200$	n_{20} / 15yr $n_{19.6} = 1800$
cont.	5.0 ± 2.2	25 ± 5	50 ± 7	75 ± 8
10^{-3}	4.2 ± 1.8	22 ± 5	44 ± 9	67 ± 11
10^{-4}	3.6 ± 2.0	18 ± 5	38 ± 9	58 ± 12
10^{-5}	2.5 ± 1.8	13 ± 5	24 ± 8	35 ± 10
10^{-6}	0.8 ± 1.0	3.5 ± 2.3	7.4 ± 4.2	13 ± 7

Observations
II: Chemical Composition

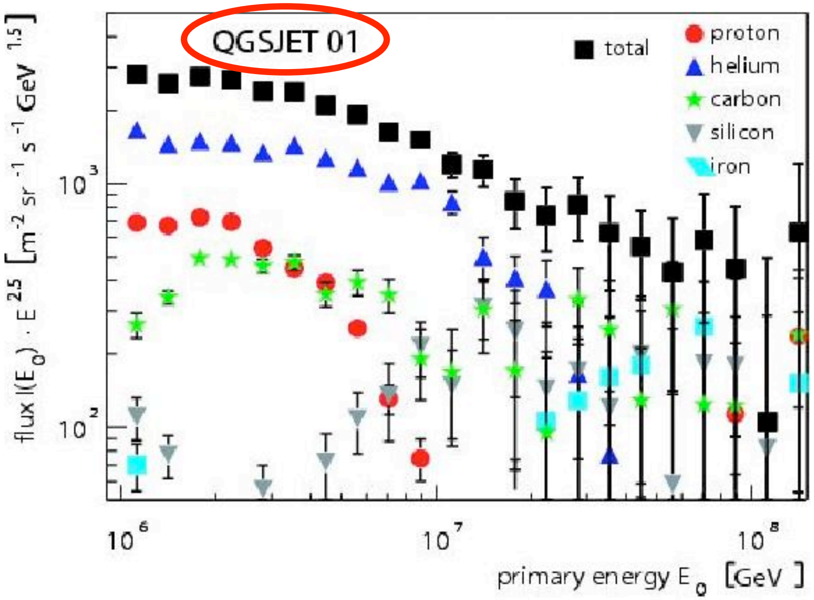

Solar System
GCR
H
He
Be
C
Ne
Si
Ar
Ti
Fe
Zn
Relative Abundances
Atomic Number (Z)

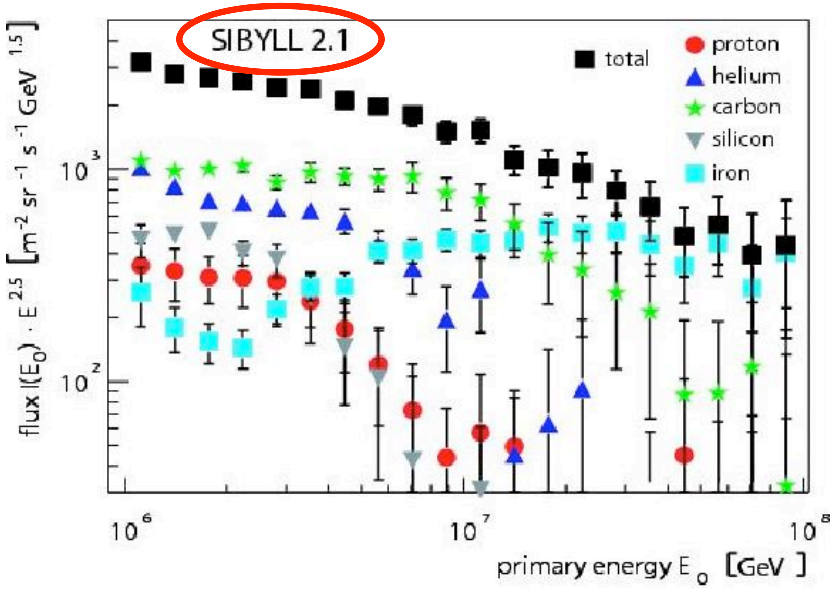

Proton
Mt. Fuji
Tibet-BD (HD)
Tibet-ASγ (HD)
HEGRA
Mt. Chacaltaya
KASCADE QGSJET
KASCADE SIBYLL
KASCADE SH
EAS-TOP
EAS-TOP SH
AMS
ATIC
BESS
CAPRICE 98
HEAT
Ichimura
IMAX
JACEE
MASS
Papini
RUNJOB
RICH-II
Ryan
Smith
SOKOL
Zatsepin
Proton knee
Flux dΦ/dE0 · E0^2.5 [m^-2 sr^-1 s^-1 GeV^1.5]
Energy E0 [GeV]

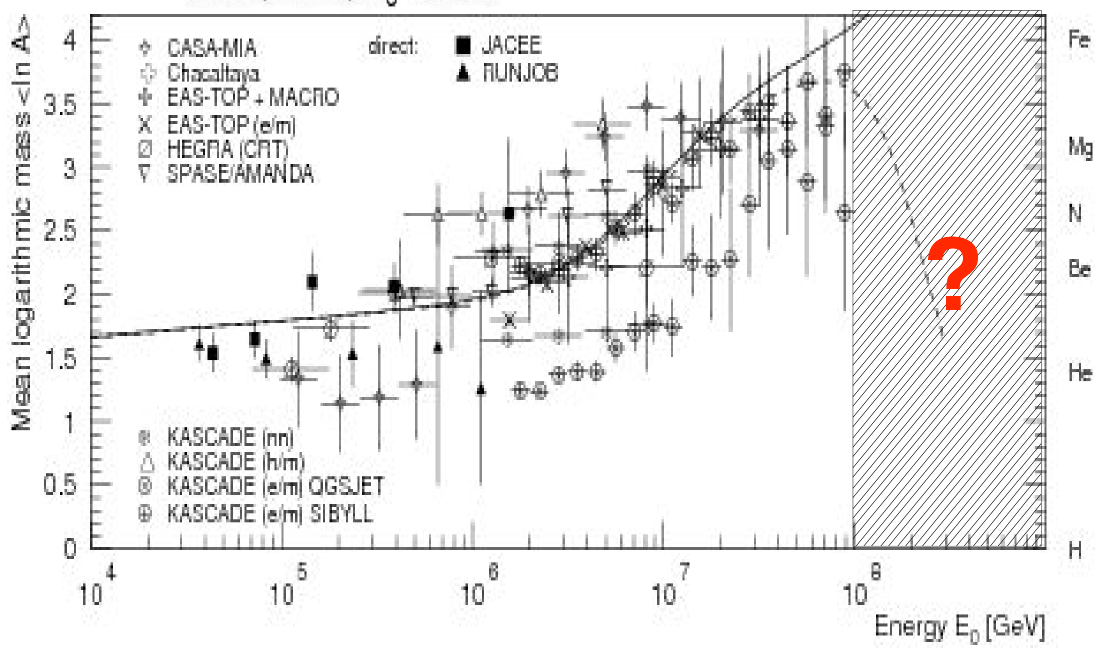

Helium
Mt. Fuji
Tibet-BD (HD)
KASCADE QGSJET
KASCADE SIBYLL
ATIC
BESS
CAPRICE 98
HEAT
Ichimura
IMAX
JACEE
MASS
Papini
RICH-II
RUNJOB
Smith
SOKOL
Webber
Helium knee
Flux dΦ/dE0 · E0^2.5 [m^-2 sr^-1 s^-1 GeV^1.5]
Energy E0 [GeV]

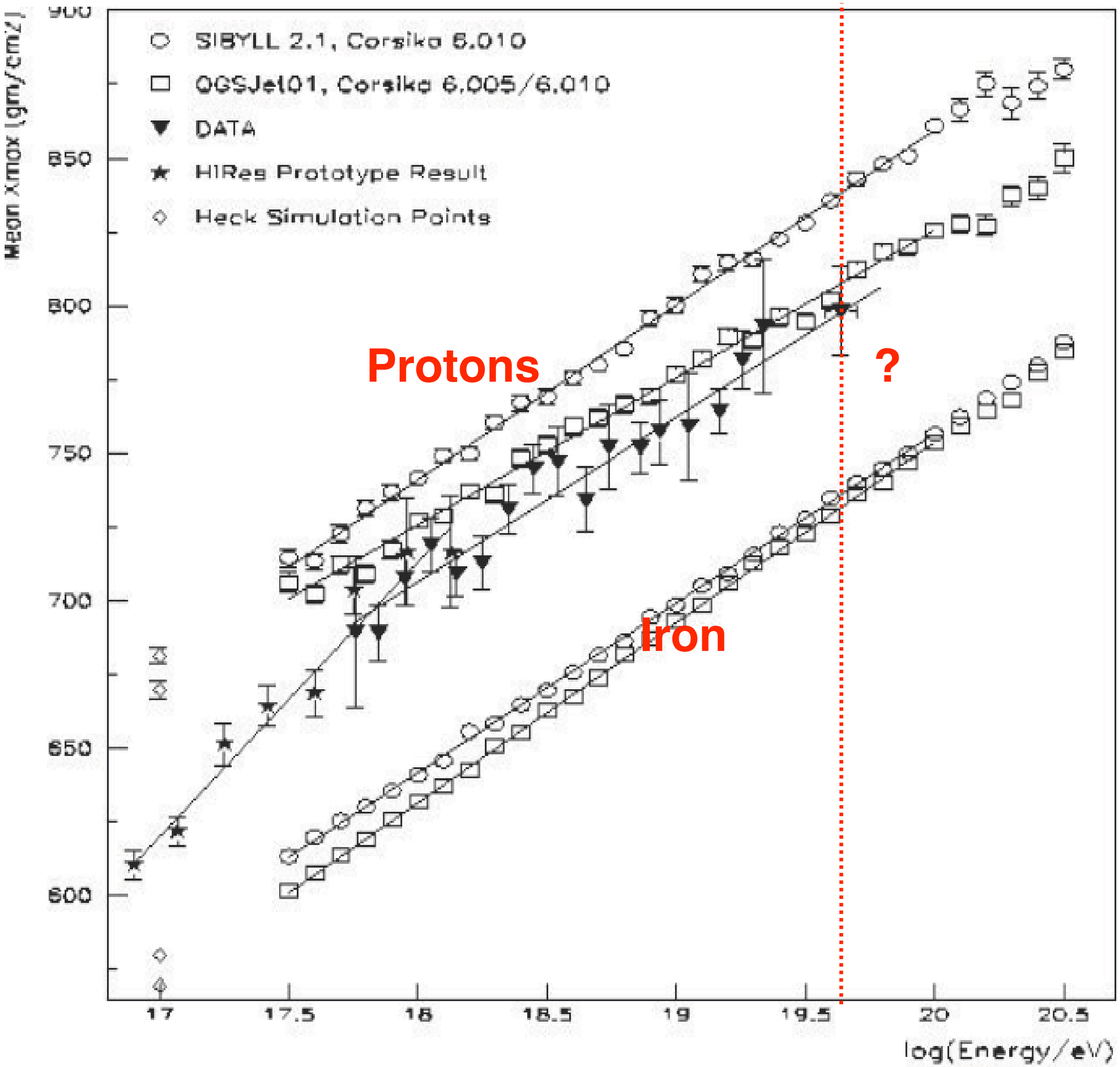

Iron
CRN
HEAO-3
Hareyama
Ichimura
JACEE
Juliusson
Minagawa
RUNJOB
SOKOL
TRACER
KASCADE QGSJET
KASCADE SIBYLL
EAS-TOP
Iron
Flux dΦ/dE0 · E0^2.5 [m^-2 sr^-1 s^-1 GeV^1.5]
Energy E0 [GeV]

A lot of uncertainties depending upon the simulations used for the interpretation of the chemical composition









Mean Xmax (gm/cm2)
900
850
800
750
700
650
600
SIBYLL 2.1, Corsika 6.010
QGSJet01, Corsika 6.005/6.010
DATA
HiRes Prototype Result
Heck Simulation Points
Protons
?
Iron
17
17.5
18
18.5
19
19.5
20
20.5
log(Energy/eV)

Observations – III: Anisotropies

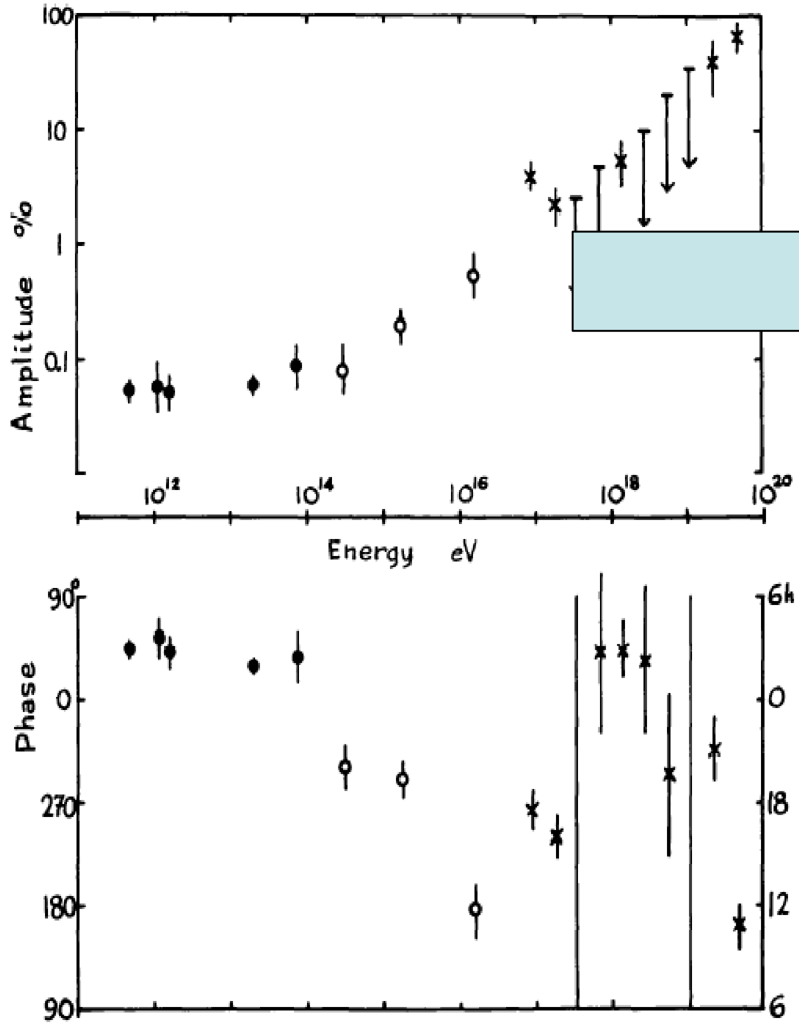
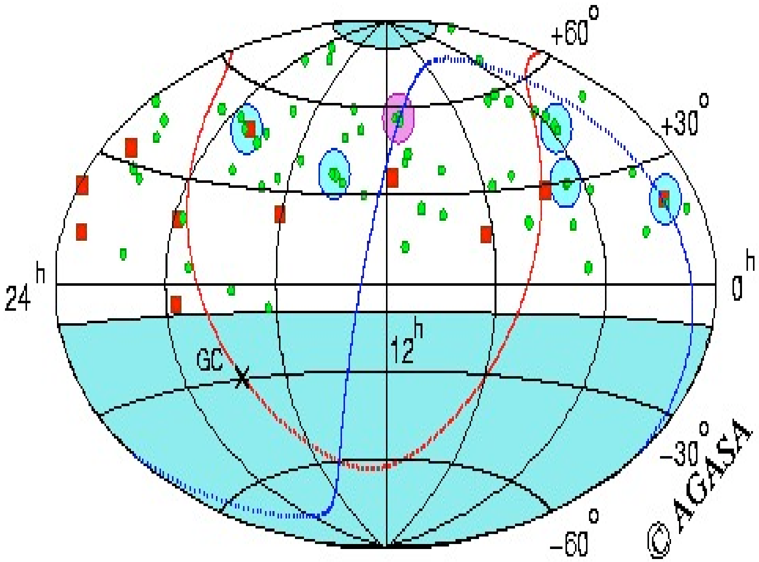


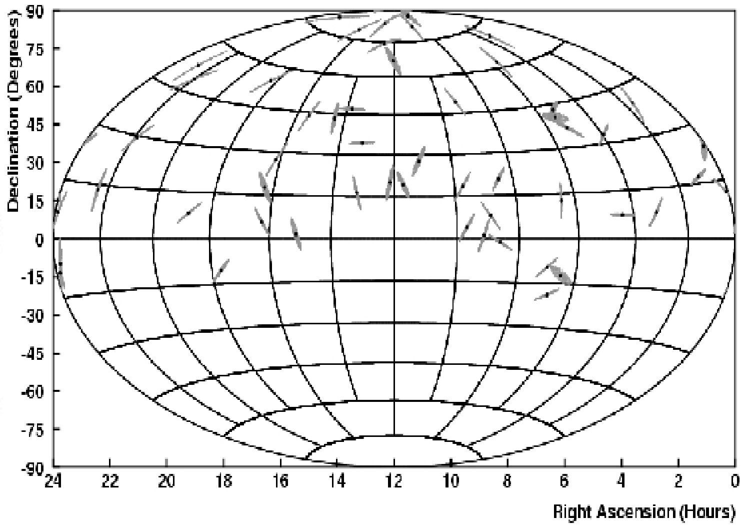
Fig. 4 Cosmic ray anisotropy

Linsley 1981

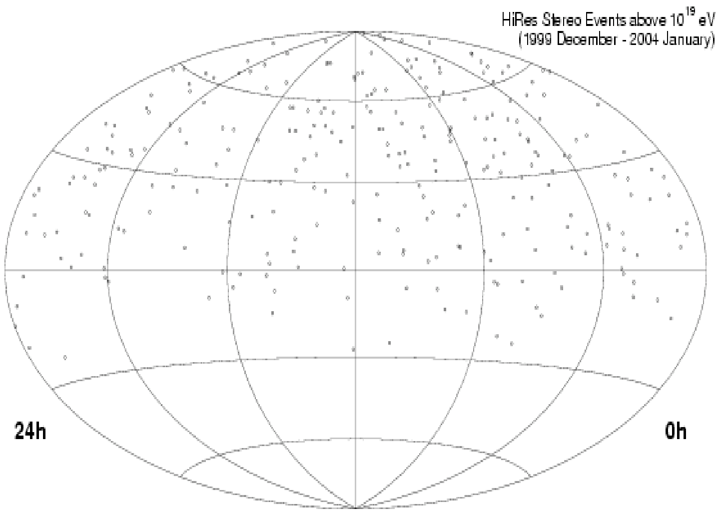
Be careful and do not get too excited

Observations – III: Anisotropy





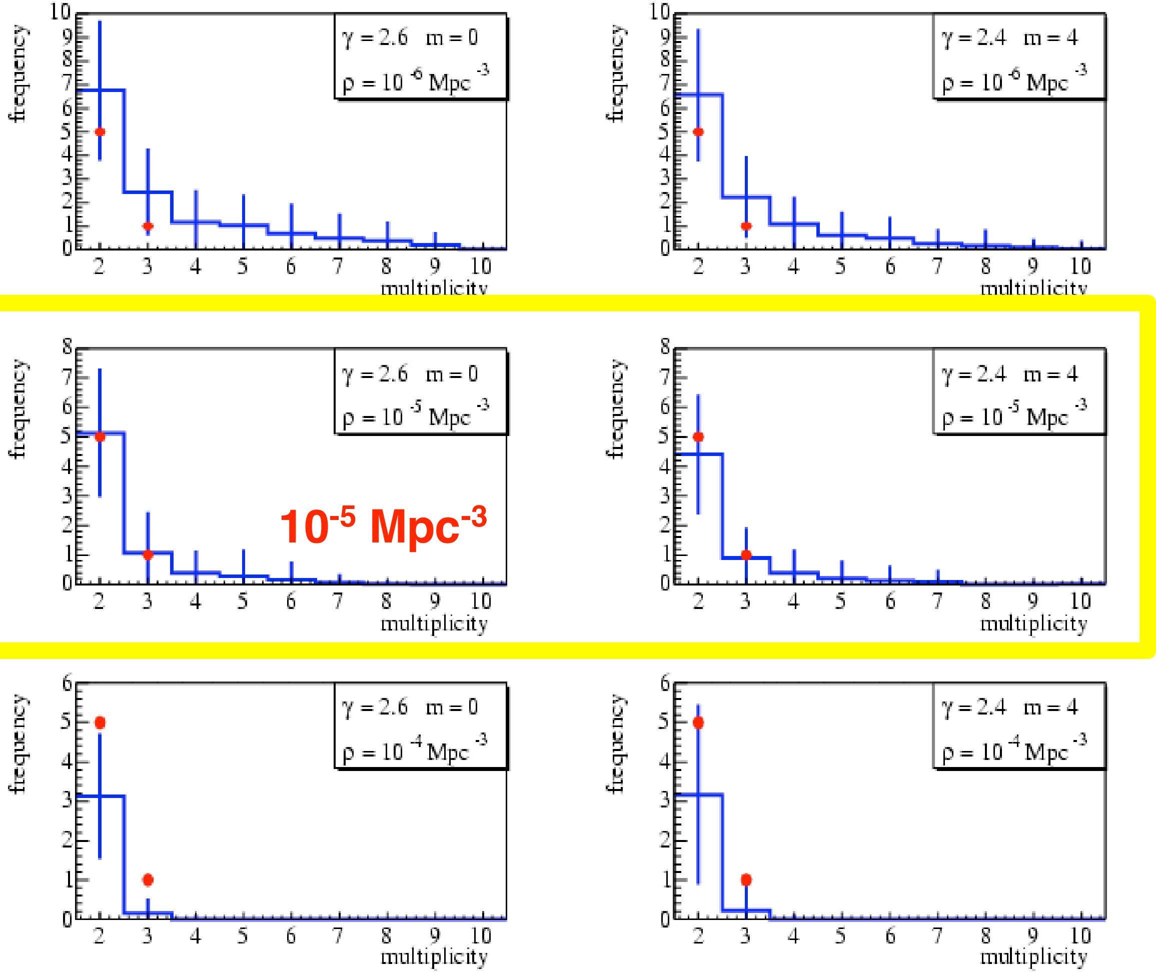
HiRes-I data with E>$10^{19.5}$ eV with mono (52 events versus 47 of AGASA) The banana-shaped error boxes are [4.9-6.1]x[0.4-1.5] degrees



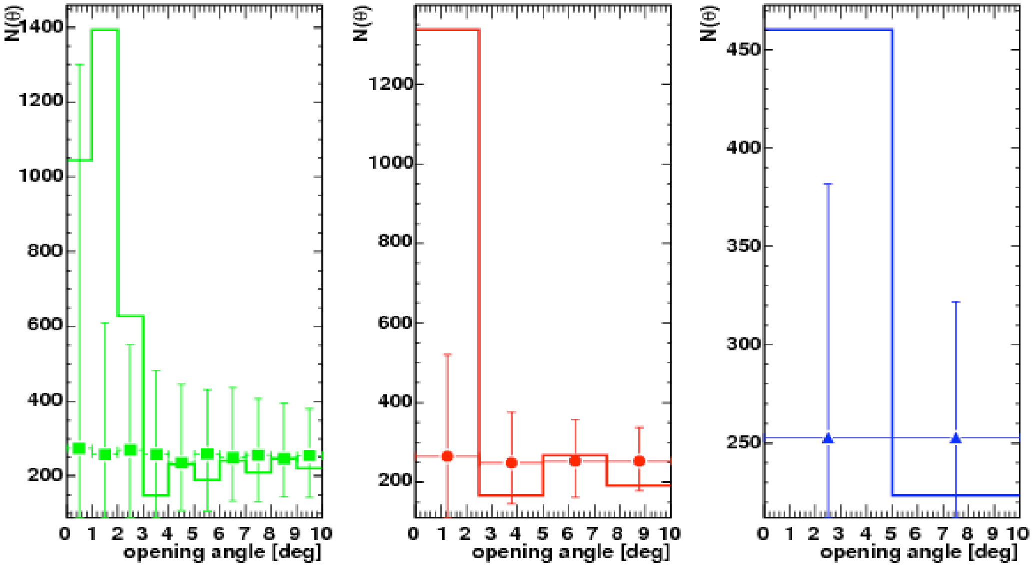
HiRes stereo data (271 events with E>10^{19} eV versus about 900 of AGASA). The error boxes are about 0.6 degrees wide.
Only 27 events above 4 10^{19} eV

Observations – III: Anisotropy

PB & De Marco 2003

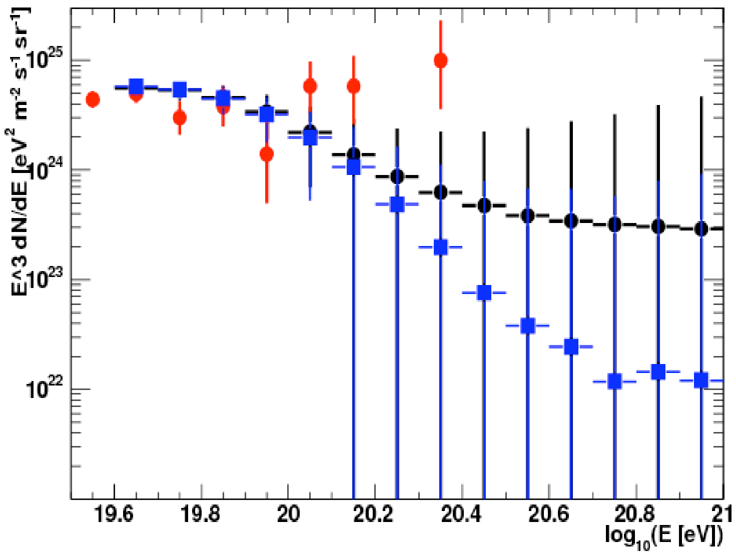


Statistical Volatility of the SSA signal



De Marco, PB & Olinto 2006

THE SSA AND THE SPECTRUM OF AGASA DO NOT APPEAR COMPATIBLE WITH EACH OTHER (5 sigma)



De Marco, PB and Olinto 2006

>4 10^{19} eV

>10^{20}eV

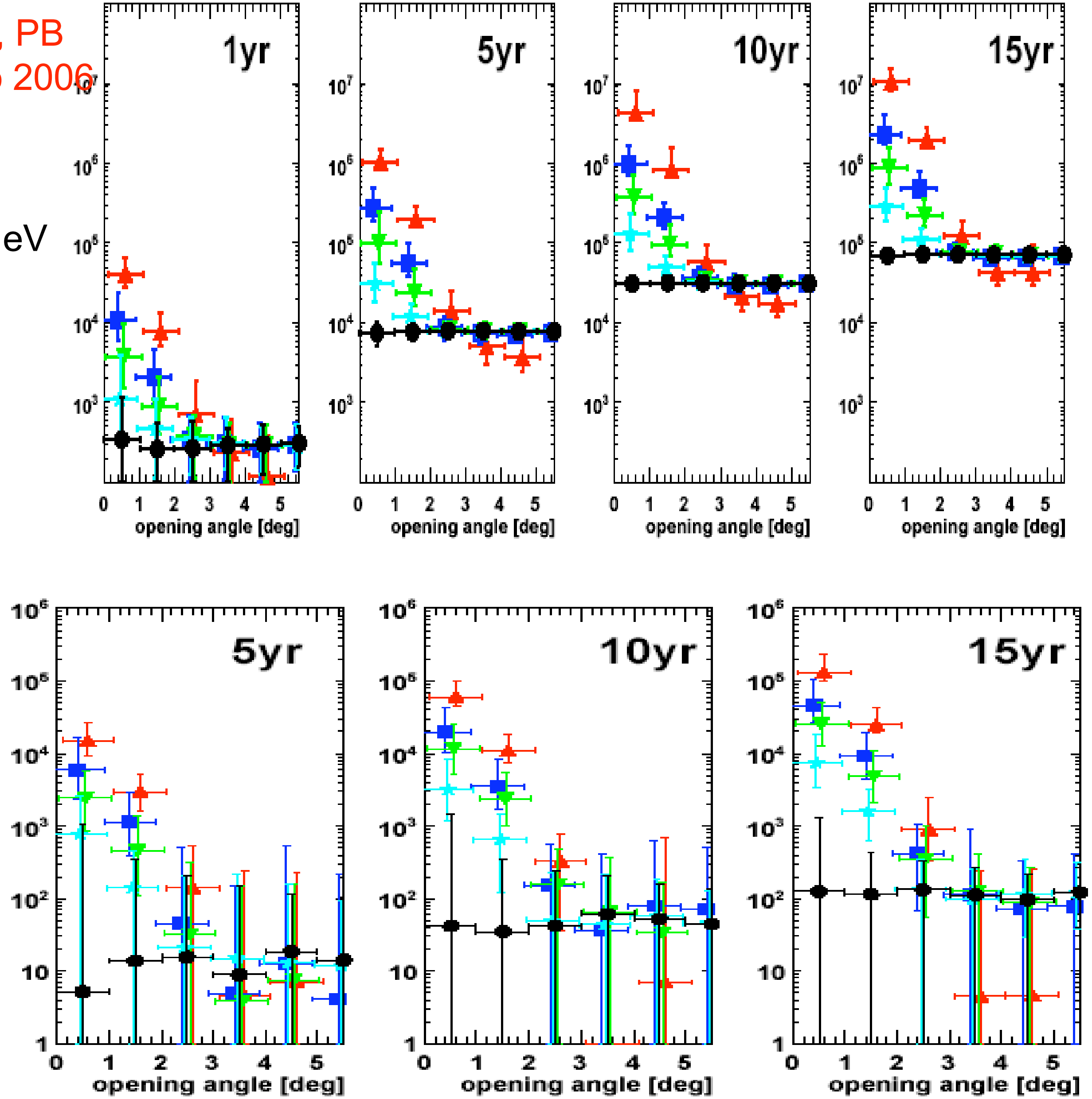


Figure 4. Two point correlation function for events above 10^{20} eV after 5, 10, and 15 years at Auger South for a continuous distribution of sources (black circles), and number densities of 10^{-3} Mpc^{-3} (cyan stars), 10^{-4} Mpc^{-3} (green downward triangles), 10^{-5} Mpc^{-3} (blue squares), and 10^{-6} Mpc^{-3} (red upward triangles). The minimum distance for the nearest source is $d_{\min}(\bar{\rho})$.

De Marco, PB
and Olinto 2006

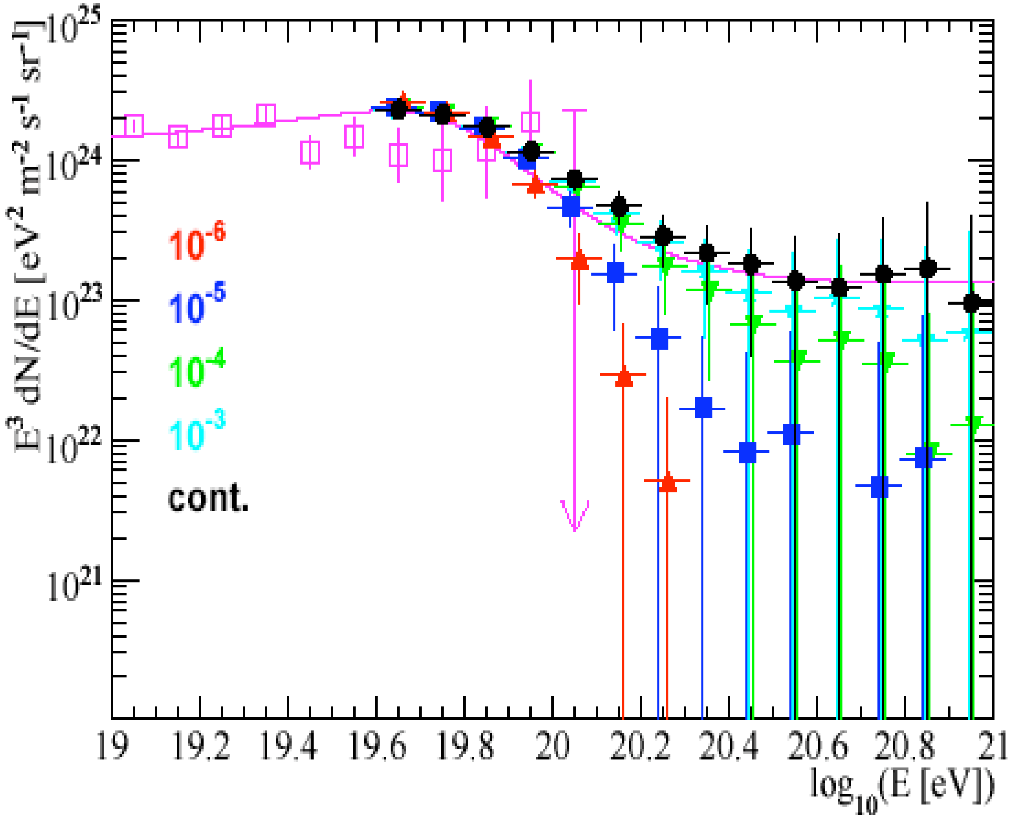


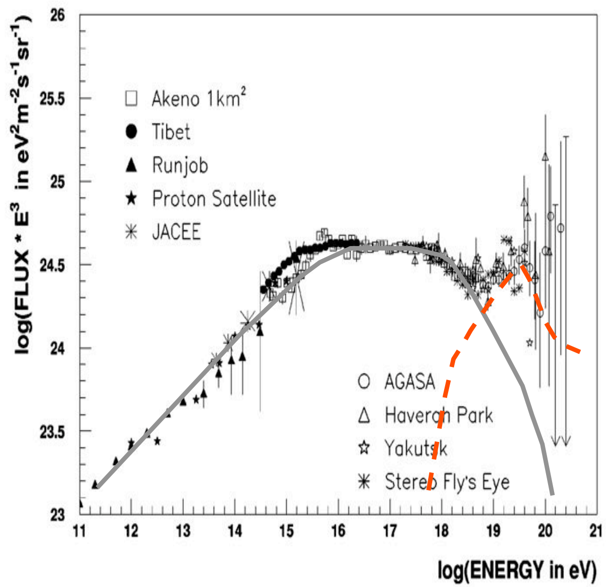
Figure 6. Energy spectrum for different source densities compared with Auger data (open squares). The sources densities are 10^{-6} Mpc^{-3} (red upward triangles); 10^{-5} Mpc^{-3} (blue squares), 10^{-4} Mpc^{-3} (green downward triangles); 10^{-3} Mpc^{-3} (cyan stars); and a continuous distribution of sources (black circles).

15 years of
Operation of
Auger South

Observations-IV:Transition from Galactic to Extragalactic CRs

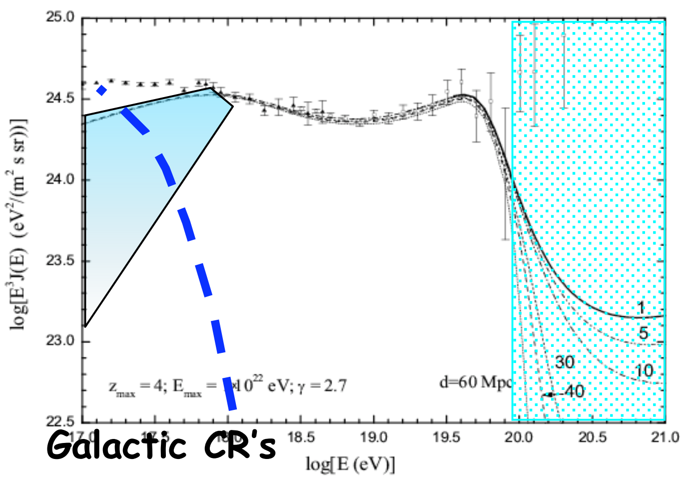
- ## Transition at the ankle

1. Injection spectrum flat enough
2. Composition allows for p+heavy
3. Very high Max energy of Galactic iron is requested (what about KASCADE?)
4. The 10% protons of Akeno @ 10^{17} eV?

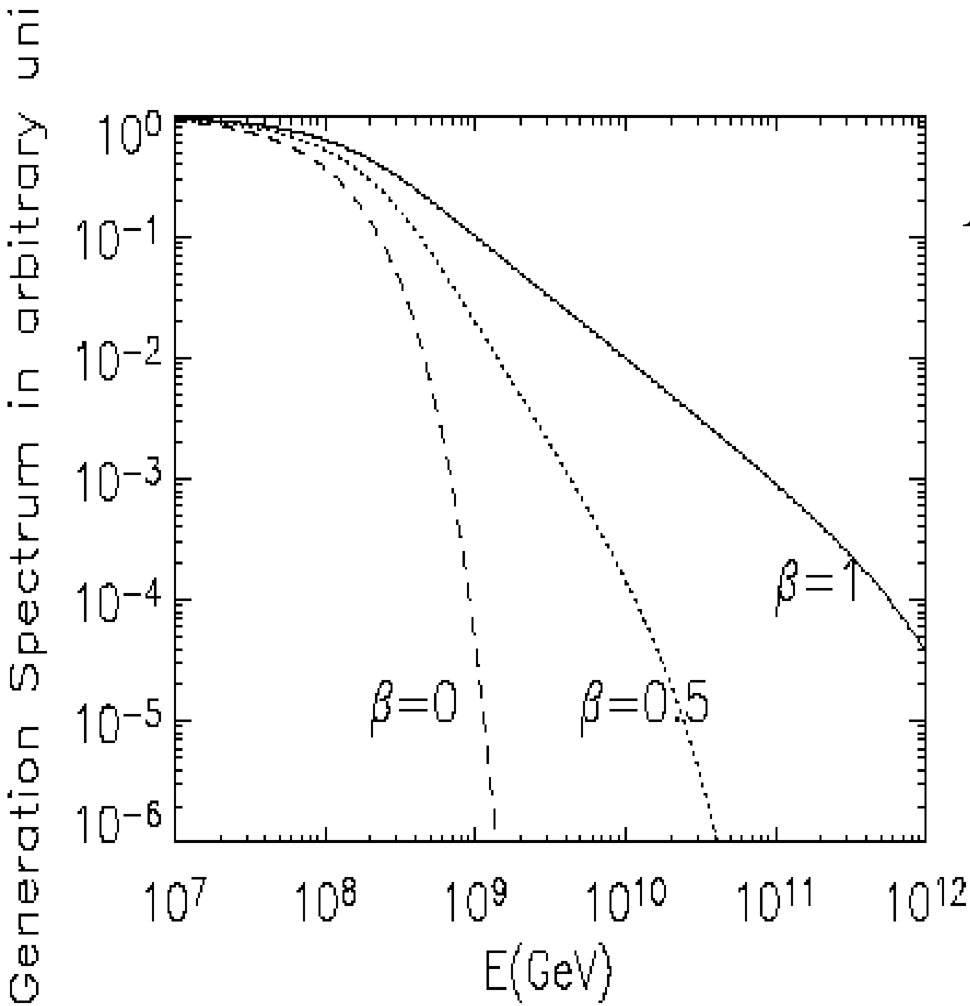


- ## Transition at the Dip

1. Pair Production -> dip
2. The 2^{nd} knee+dip is stable
3. The extragalactic component dies @ $E<10^{17.7}$ eV, OK >10% fraction of protons at ~10^{17} eV (AKENO)
4. Not >10% He allowed at the source
5. Injection spectrum very steep unless overall sources with different E_{max}



Galactic CR's (mainly Iron)

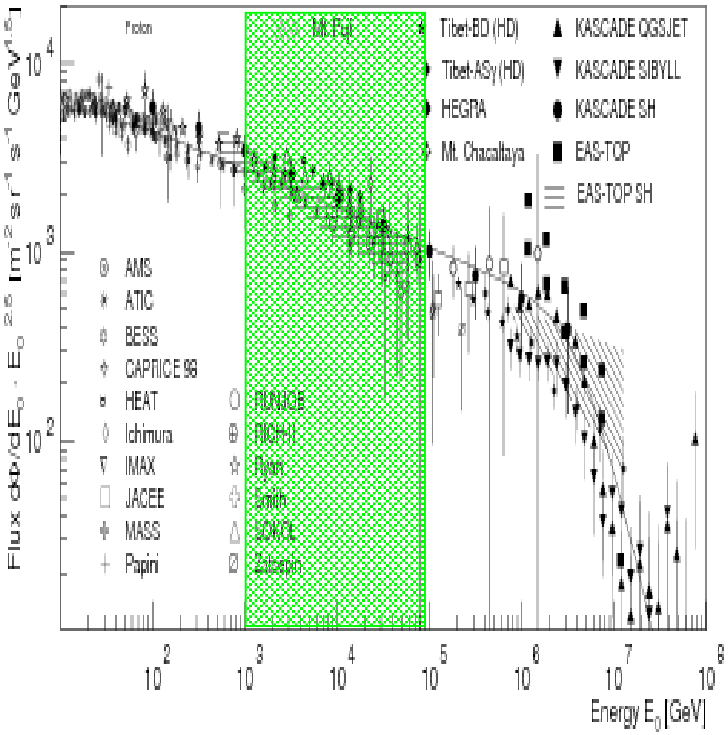


$E_{\mathbf{max}}$ **(L)** $\quad$ $\mathbf{L}^{\square}$

Kachelriess and Semikoz 2005
Aloisio, Berezinsky, PB, Grigorieva and Gazizov 2006

Some Open Problems with Acceleration of Cosmic Rays

The lesson we can learn from galactic cosmic rays…



A CRUCIAL ISSUE: the maximum energy of accelerated particles

1. The maximum energy is determined in general by the balance between the Acceleration time and the shortest between the lifetime of the shock and the loss time of particles

2. For the ISM, the diffusion coefficient derived from propagation is roughly

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

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

UP

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

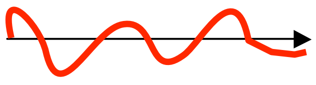
Similar numbers would be obtained for galactic sources of similar age and in similar conditions.

Particle Acceleration at Parallel Collisionless Shocks works ONLY if there is additional magnetic scattering close to the shock surface!

Pitch angle scattering and Spatial Diffusion

The Alfven waves can be imagined as small perturbations on top of a background B-field

The equation of motion of a particle in this field is



$$\vec{B} = \vec{B}_0 + \vec{B}_1$$

$$\frac{d\vec{p}}{dt} = \frac{Ze}{c}\vec{v} \times \left(\vec{B}_0 + \vec{B}_1\right)$$

In the reference frame of the waves, the momentum of the particle remains unchanged in module but changes in direction due to the perturbation:

$$\frac{d\mu}{dt} = \frac{Zev\left(1-\mu^2\right)^{1/2} B_1}{pc}\cos\left[\left(\Omega - kv\mu\right)t + \varphi\right] \qquad \Omega = ZeB_0/mc\gamma$$

$$D(p) = \frac{1}{3}v\lambda \approx \frac{1}{3}\frac{c r_L(p)}{F(p)}$$

$$F(p(k)) = k(\delta B/B)^2$$

The Diffusion coeff reduces
To the Bohm Diffusion for F(p)~1

Maximum Energy *a la* Lagage-Cesarsky

In the LC approach the lowest diffusion coefficient, namely the highest energy, can be achieved when F(p)~1 and the diffusion coefficient is Bohm-like.

$$\boxed{D(p)=\frac{1}{3}v\lambda \approx \frac{1}{3}\frac{cr_L(p)}{F(p)}}$$

$$\tau_{acc} \approx \frac{D(E)}{u^2_{shock}} = 3.3\,10^6\, E_{GeV}\, B_i^{-1}\, u_{1000}^{-2} \quad sec$$

For a life time of the source of the order of 1000 yr, we easily get

E_{max} ~ 10^{4-5} GeV

We recall that the **knee** in the CR spectrum is at **10^6 GeV** and the **ankle** at **~3 10^9 GeV**. The problem of accelerating CR's to *useful* energies remains...

BUT what generates the necessary turbulence anyway?

Wave growth **HERE IS THE CRUCIAL PART!**

$$\boxed{\frac{\partial F}{\partial t}+u\frac{\partial F}{\partial x}=\sigma F-\Gamma F}$$

Bell 1978

Wave damping

Standard calculation of the Streaming Instability (Achterberg 1983)

$$\frac{c^2 k^2}{\omega^2} = 1 + \chi^{R,L}$$

$$\chi^{R,L} = \frac{4\pi^2 e^2}{\omega} \int dp \int d\mu \, \frac{p^2 (1-\mu^2) v(p)}{\omega \pm \Omega' - v\mu k} \left[\frac{\partial f}{\partial p} + \frac{1}{p} \left(\frac{kv}{\omega} - \mu \right) \frac{\partial f}{\partial \mu} \right]$$

There is a mode with an imaginary part of the frequency: CR's excite Alfven Waves resonantly and the growth rate is found to be:

$$\Gamma = v_A \frac{\partial P_{CR}}{\partial z}$$

Maximum Level of Turbulent Self- Generated Field

$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial x} = \acute{o}F$$

Stationarity

$$u\frac{\partial F}{\partial z} = v_A \frac{\partial P_{CR}}{\partial z}$$

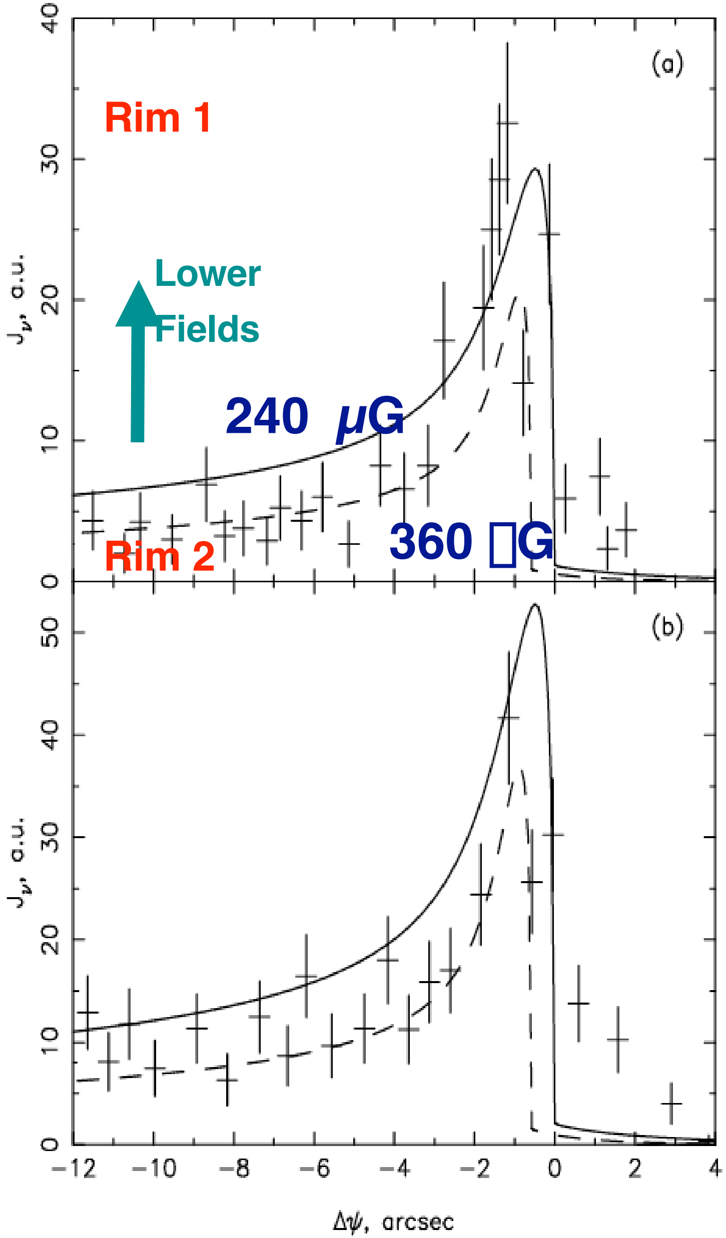
Integrating

$$\frac{\square B^2}{B_0^2} = 2M_A \frac{P_{CR}}{\square u^2} >> 1$$

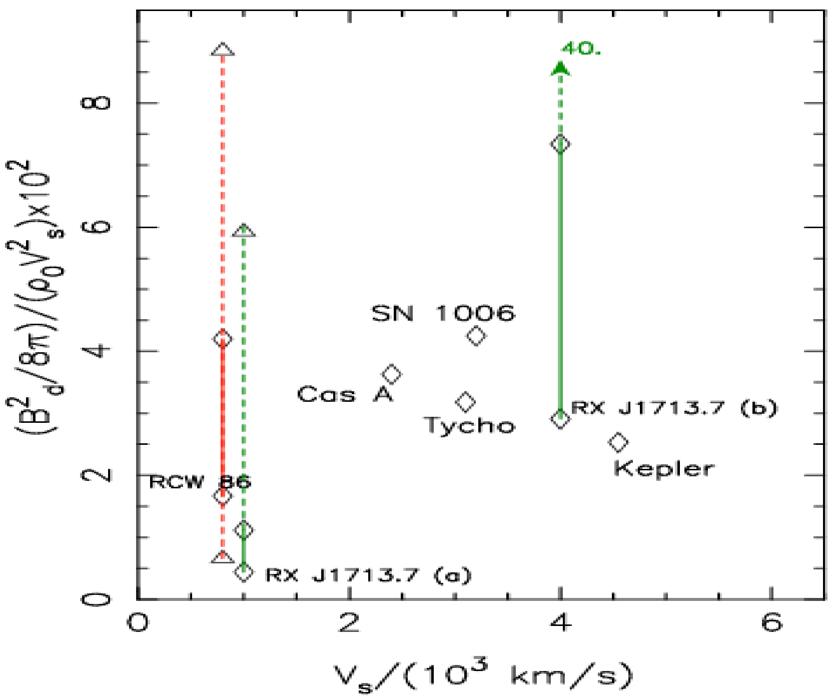
Breaking of Linear Theory…

For typical parameters of a SNR one has _B/B~20.

Possible Observational Evidence for Amplified Magnetic Fields



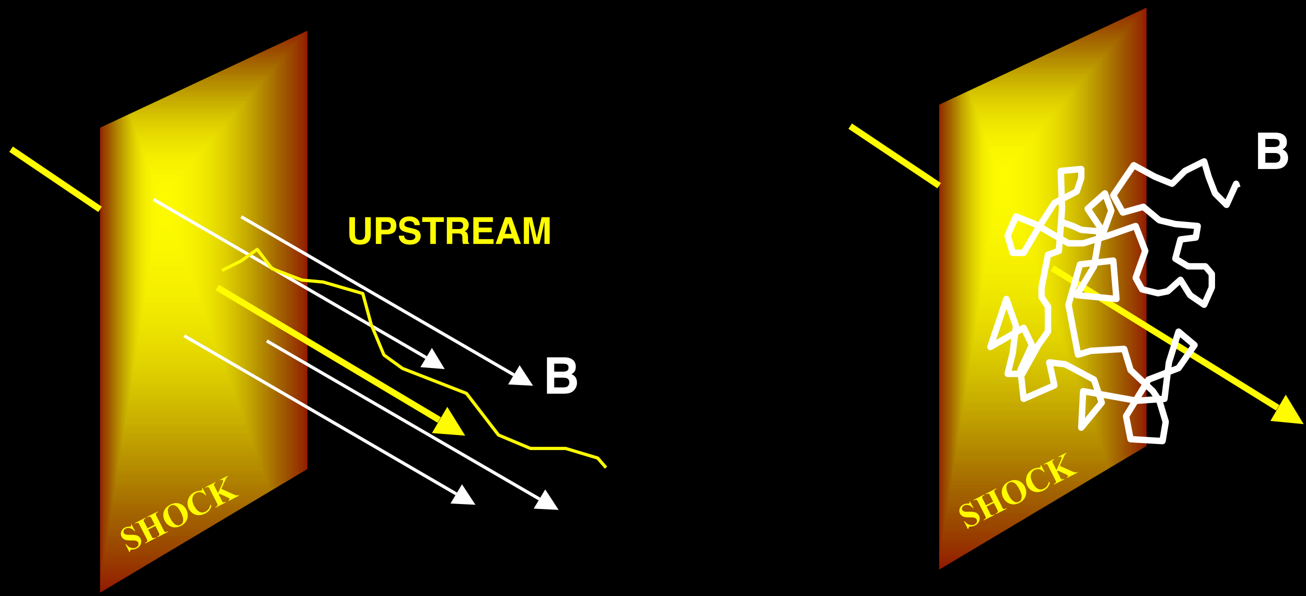
Volk, Berezhko & Ksenofontov (2005)



Add to all this, the enourmous Predictions of Non-linear Diffusive Shock Acceleration!!!

1. Curved spectra
2. Heating suppression downstream
3. B-field amplification

NON LINEAR AMPLIFICATION OF THE UPSTREAM MAGNETIC FIELD Revisited

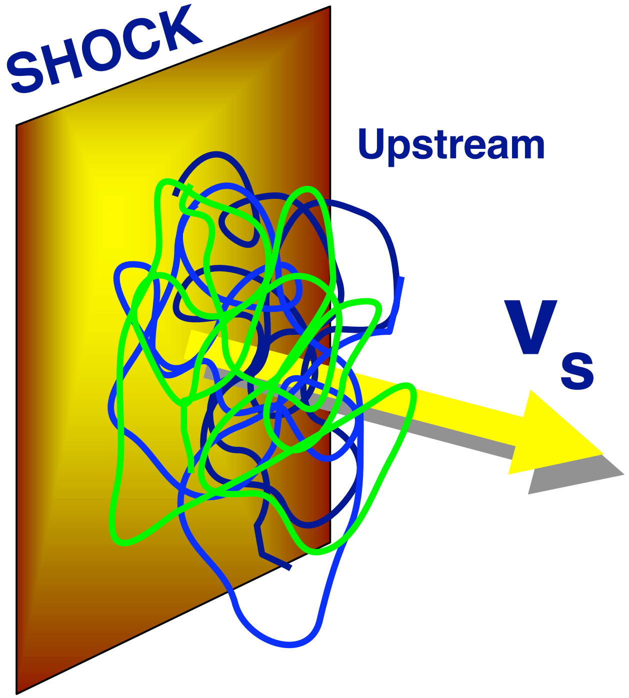


Some recent investigations suggest that the generation of waves upstream of the shock may enhance the value of the magnetic field not only up to the ambient medium field but in fact up to

Lucek & Bell 2003
Bell 2004

$$\delta B^2 \propto (v_s / c) P_{CR} \propto (v_s / c) \rho u^2$$

Generation of Magnetic Turbulence near Collisionless Shocks



Assumption: all accelerated particles are protons

In the Reference frame of the UPSTREAM FLUID, the accelerated particles look as an incoming current:

$$\vec{J}_{CR} = n_{CR} e \vec{v}_s$$

The plasma is forced by the high conductivity to remain quasi-neutral, which produces a return current such that the total current is

$$\vec{J}_{tot} = \vec{J}_{CR} + \vec{J}_{ret}$$

The total current must satisfy the Maxwell Equation

$$\nabla \times \vec{B} = \frac{4\pi}{c}\left[\vec{J}_{CR} + \vec{J}_{ret}\right] \quad \Rightarrow \quad \boxed{\vec{J}_{ret} = \frac{c}{4\pi}\nabla \times \vec{B} - \vec{J}_{CR}}$$

Clearly at the zero order $J_{ret} = J_{CR}$

Next job: write the equation of motion of the fluid, which now feels a force:

$$\vec{F} = \vec{J}_{ret} \times \vec{B}$$

$$\rho\frac{\partial \vec{u}}{\partial t} = -\nabla P + \vec{J}_{ret} \times \vec{B} \quad \Rightarrow \quad \boxed{\rho\frac{\partial \vec{u}}{\partial t} = -\nabla P - \frac{c}{4\pi}\vec{B} \times \left(\nabla \times \vec{B}\right) - \vec{J}_{CR} \times \vec{B}}$$

In addition we have the Equation for conservation of mass

$$\boxed{\frac{\partial \tilde{n}}{\partial t} = -\nabla \cdot \left(\tilde{n}\vec{u}\right)}$$

and the induction equation:

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \qquad \boxed{\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B}\right)}$$

SUMMARIZING:

$$\tilde{n}\frac{\partial \vec{u}}{\partial t} = -\nabla P - \frac{c}{4\pi}\vec{B} \times \left(\nabla \times \vec{B}\right) - \vec{J}_{CR} \times \vec{B}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left(\vec{u} \times \vec{B}\right)$$

$$\frac{\partial \tilde{n}}{\partial t} = -\nabla \cdot \left(\tilde{n}\vec{u}\right)$$

Linearization of these eqs in Fourier Space leads to 7 eqs. For 8 unknowns.

In order to close the system we Need a relation between the Perturbed CR current and the Other quantities

Perturbations of the VLASOV EQUATION give the missing equations which defines

The conductivity _ (Complex Number)

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} + \dot{\vec{p}} \cdot \frac{\partial f}{\partial \vec{p}} = 0 \qquad \square \vec{J}_{CR} = \square \frac{J_{CR}}{B_0} \square \vec{B}$$

Many pages later one gets the DISPERSION RELATION for the allowed perturbations.

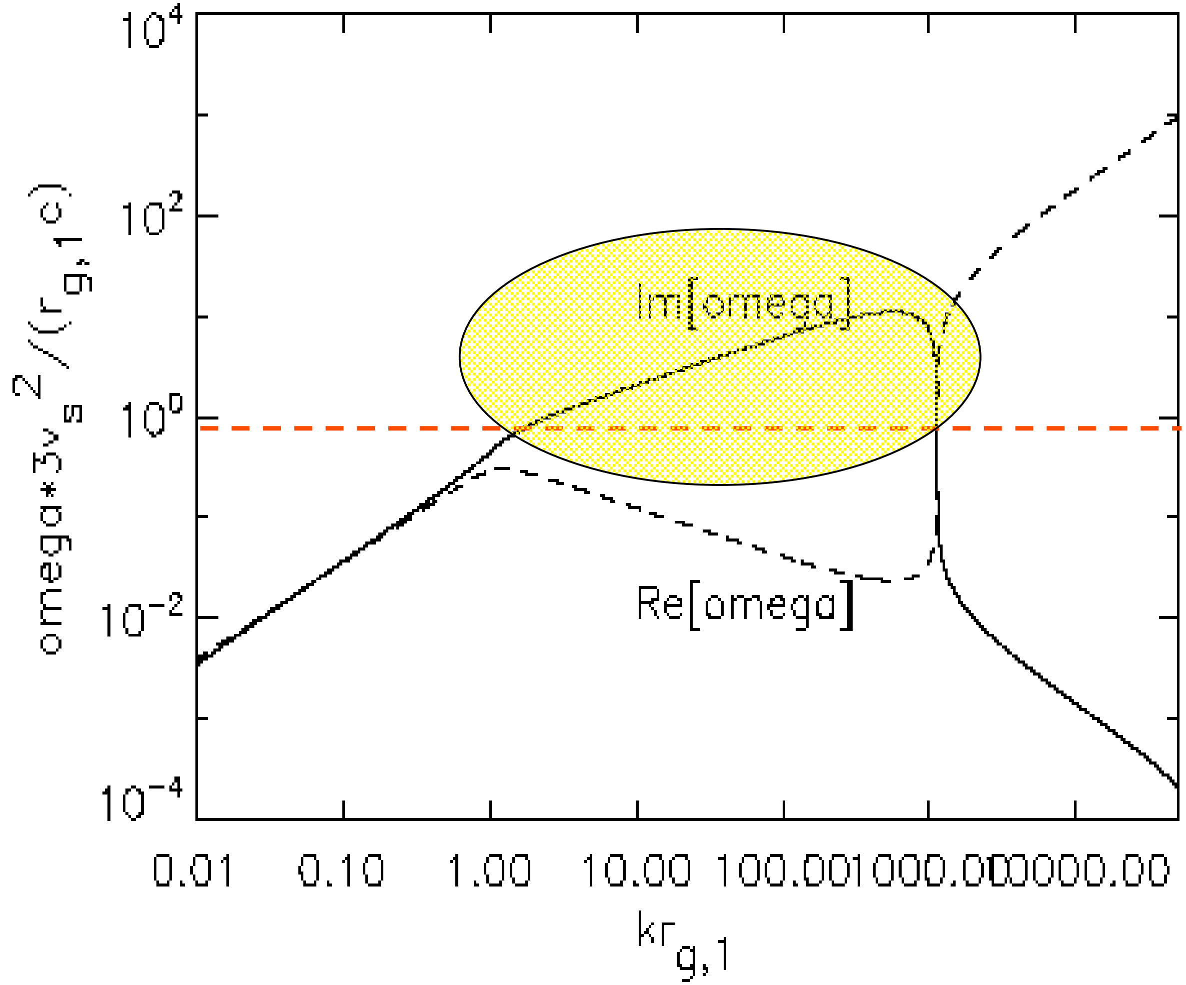
$$\omega^2 - k^2 v_A^2 = \pm \frac{J_{CR} k B_0}{\rho_0 c} (1 \square \square)$$

There is a purely growing Non Alfvenic, Non Resonant, CR driven mode if $k\ v_A < \__0^2$

$$\omega_0^2 = \frac{J_{CR} k B_0}{\rho_0 c} (1 \square \sigma)$$

Bell 2004

Re(_) and Im(_) as functions of k



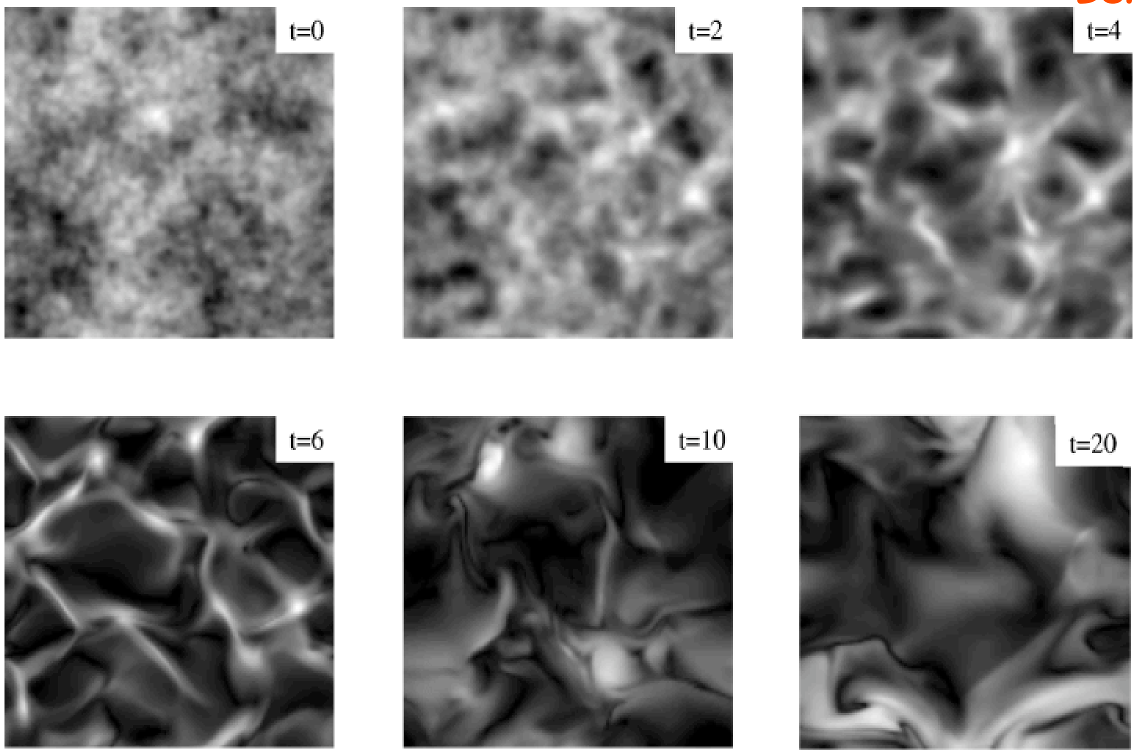
Saturation of the Growth

The growth of the mode is expected when the return current (namely the driving term) vanishes:

$$\vec{J}_{ret} = \frac{c}{4\pi} \nabla \times \vec{B} - \vec{J}_{CR} \quad \Rightarrow \quad \boxed{\nabla \times \delta\vec{B} \approx \frac{4\pi}{c} \vec{J}_{CR}}$$

Hybrid Simulations (PIC+MHD) used to follow the field Amplification when the linear theory starts to fail

Bell 2004



$$\frac{äB^2}{B_0^2} = M_A^2 \frac{u}{c} \frac{P_{CR}}{ñu^2}$$

For typical parameters of a SNR we get _B/B~300

General lesson to be learned

The level of magnetic turbulence which is relevant for the acceleration of particles is usually the self-generated one, which may correspond to _B/B>>1 and correspondingly larger maximum energies. THIS IS TRUE FOR ALL ACCELERATORS and should be kept in mind in producing Hillas-like plots.

In the vicinity of the accelerator the dynamical reaction of the accelerated particles may not be negligible!

Peculiar Aspects of Particle Acceleration at relativistic shocks

$$\tilde{a}_1 \hat{a}_1 n_1 = \tilde{a}_2 \hat{a}_2 n_2$$

$$\tilde{a}_1^2 \hat{a}_1 \left(\mathring{a}_1 + p_1\right) = \tilde{a}_2^2 \hat{a}_2 \left(\mathring{a}_2 + p_2\right)$$

$$\tilde{a}_1^2 \hat{a}_1^2 \left(\mathring{a}_1 + p_1\right) + p_1 = \tilde{a}_2^2 \hat{a}_2^2 \left(\mathring{a}_2 + p_2\right) + p_2$$

Taub's relations

we

$$\frac{B_1^2}{4\partial} << \left(\mathring{a}_1 + p_1\right)$$

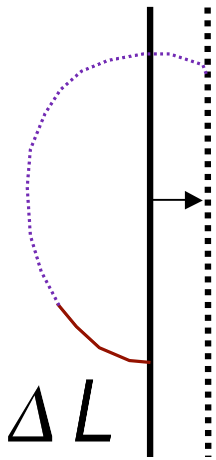
No equipartition

$$\tilde{a}_1 >> 1$$

ultrarelativistic

$$p_1 = 0$$

pressureless

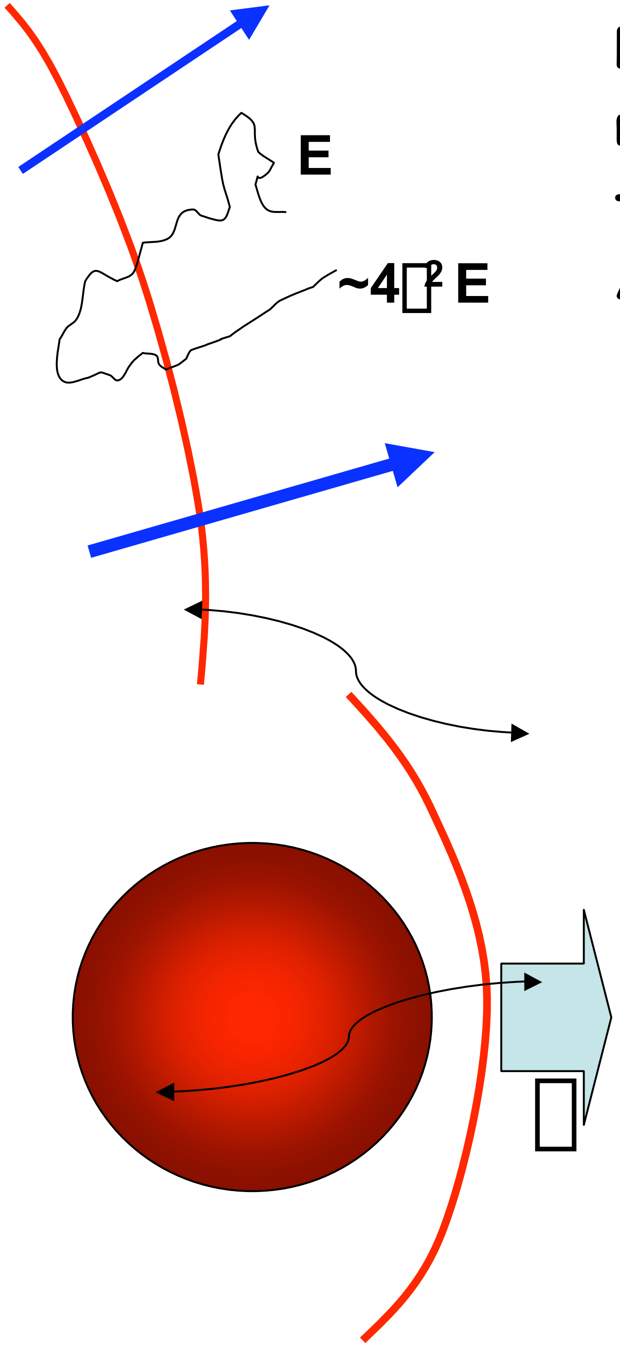


$$\hat{o}_{larmor} = \frac{2\partial r_B}{c}$$

$$\ddot{A}L / r_B \,\square\, 2\partial / 3 > 1$$

For a homogeneous magnetic field downstream NO PARTICLE is expected to return back to the shock.

The turbulent structure of the B-field is crucial!



Reflection at the relativistic mirror works ONLY at the first interaction.
After that

$$\Delta E / E \approx 2$$

1. IF THE MAGNETIC FIELD IS ONLY INSIDE THE PLASMOID, WHY DON'T THEY EXPAND UNDER THE EFFECT OF MAGNETIC PRESSURE? (REPULSION OF MAGNETIC FIELD LINES)
2. WHY DON'T THEY FORM COLLISIONLESS BOW SHOCKS, WELL KNOWN TO BE FORMED FOR INSTANCE AROUND PWNae?
3. HOW CAN PARTICLES CROSS THE CONTACT REGION BEHIND THE BOW SHOCK AND BE ACCELERATED? Suprathermal particles needed!?

Universal or non-universal…

Most calculations of particle acceleration at relativistic shocks lead to the so-called UNIVERSAL SPECTRUM

$$f(p) \propto p^{-\sigma} \qquad \sigma \approx 2.2 - 2.3 \quad \text{for } \gamma >> 1$$

This important result is obtained by solving the same equation:

$$\gamma(u+\mu)\frac{\partial f}{\partial z} = \frac{\partial}{\partial \mu}\left[(1-\mu^2)D_{\mu\mu}\frac{\partial f}{\partial \mu}\right]$$

ASSUMPTIONS: the scattering is diffusive and in the so-called Small Pitch Angle Scattering (SPAS) regime ($D_{\mu\mu}$ is constant ONLY for the isotropic case)

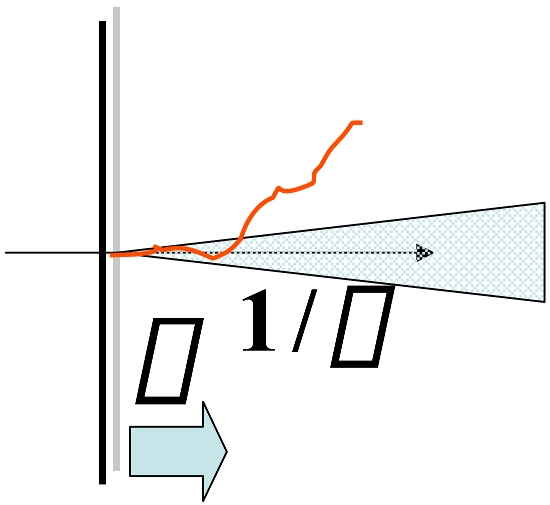
The transport equation in the most general case is

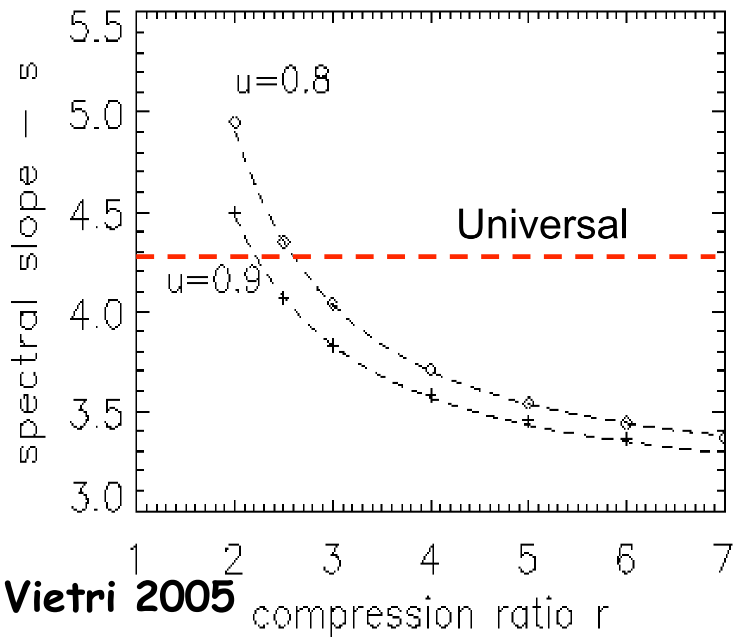
$$\tilde{a}(u+\grave{\imath})\frac{\partial f}{\partial z} = \square d(\grave{\imath})f(\grave{\imath}) + \square w(\grave{\imath}, \grave{\imath}')f(\grave{\imath}')$$

Vietri 2003
PB & Vietri 2005

Arbitrary Scattering

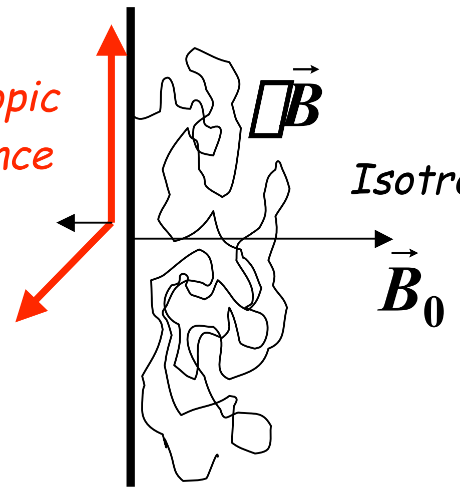
For instance, in the case of Large Angle Scattering:





Blasi & Vietri 2005

More non-universality…



Again, one ends up again in a situation of quasi-coherent perpendicular Field downstream: PARTICLES DO NOT RETURN _ SPECTRUM STEEPENS

Caveat: what if the field upstream does not have a coherence length? (e.g. Scale invariant spectrum 1/k)

CONCLUSIONS

- A lot of indirect evidence is accumulating in favor of SNRs being sources of CRs in the Galaxy, up to 5 10^{17} eV…but no iron solid proof
- The transition between Gal to Extra-Gal CRs takes place either at the second knee or at the ankle (very important for the origin of UHECRs; crucial the composition)
- Acceleration at shock fronts presents us with exciting new developments and challenges to reach high E_{max}
- The spectrum of UHECRs is being investigated by Auger…just some patience is needed. It would be precious to gather information about the composition in the transition region
- UHECRs are still orphans…may be something even bigger than Auger will be needed to "see" the sources