COSMIC RAYS AND NEUTRINOS FROM PeV TO GZK ENERGIES

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Trying to understand High Energy Cosmic Rays:

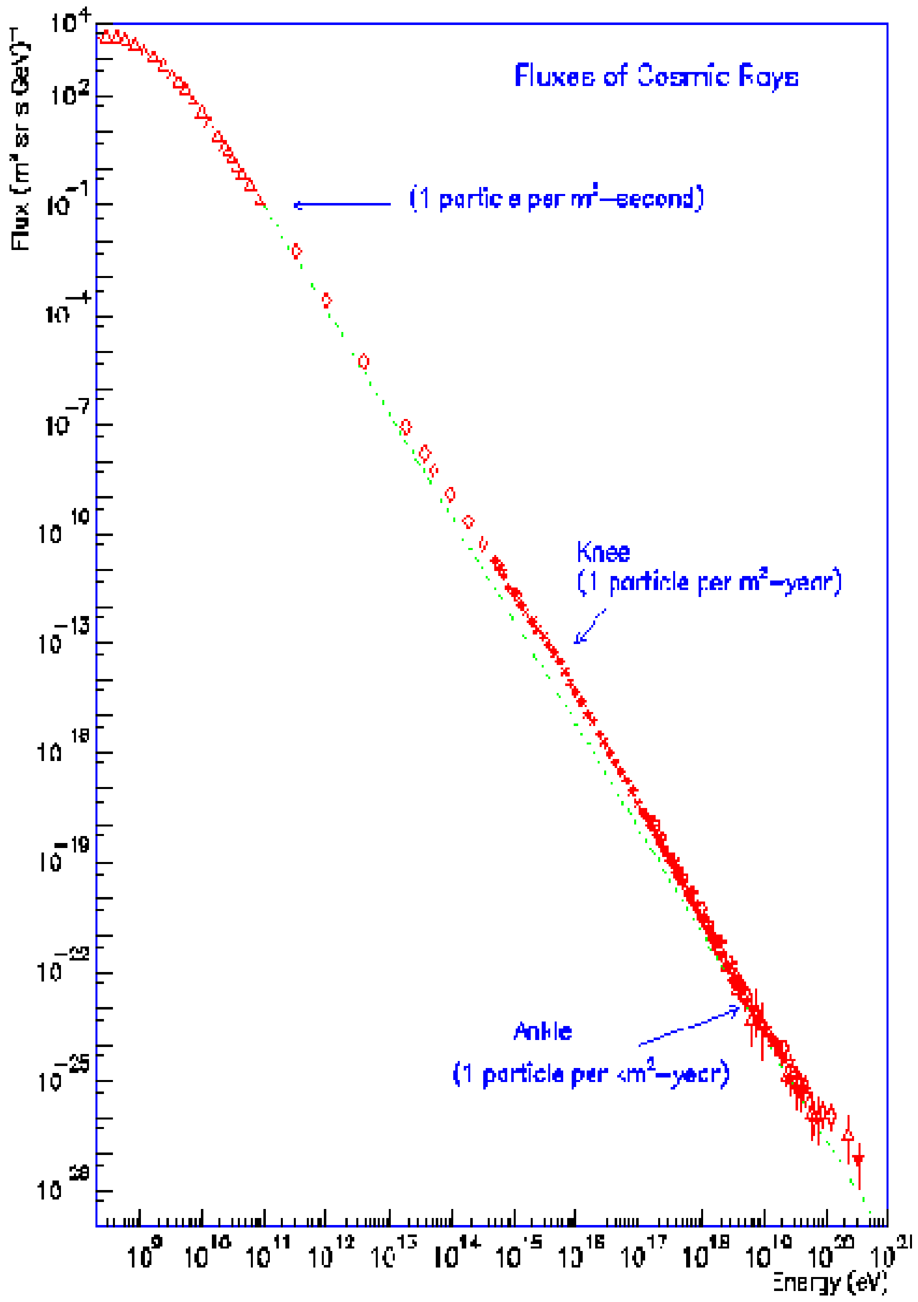
Cosmic Ray observables:

Spectrum, anisotropies, composition

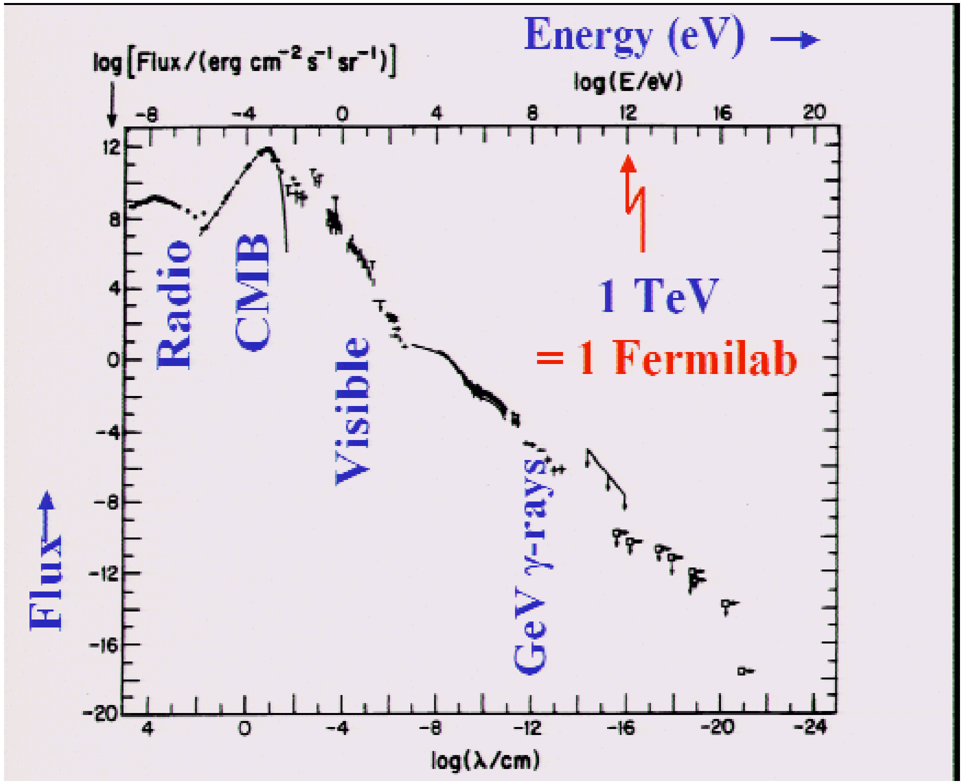
Cosmic Ray challenges:

to understand the shape of the spectrum, the anisotropies, the composition, the sources, the propagation, ...

CR SPECTRUM

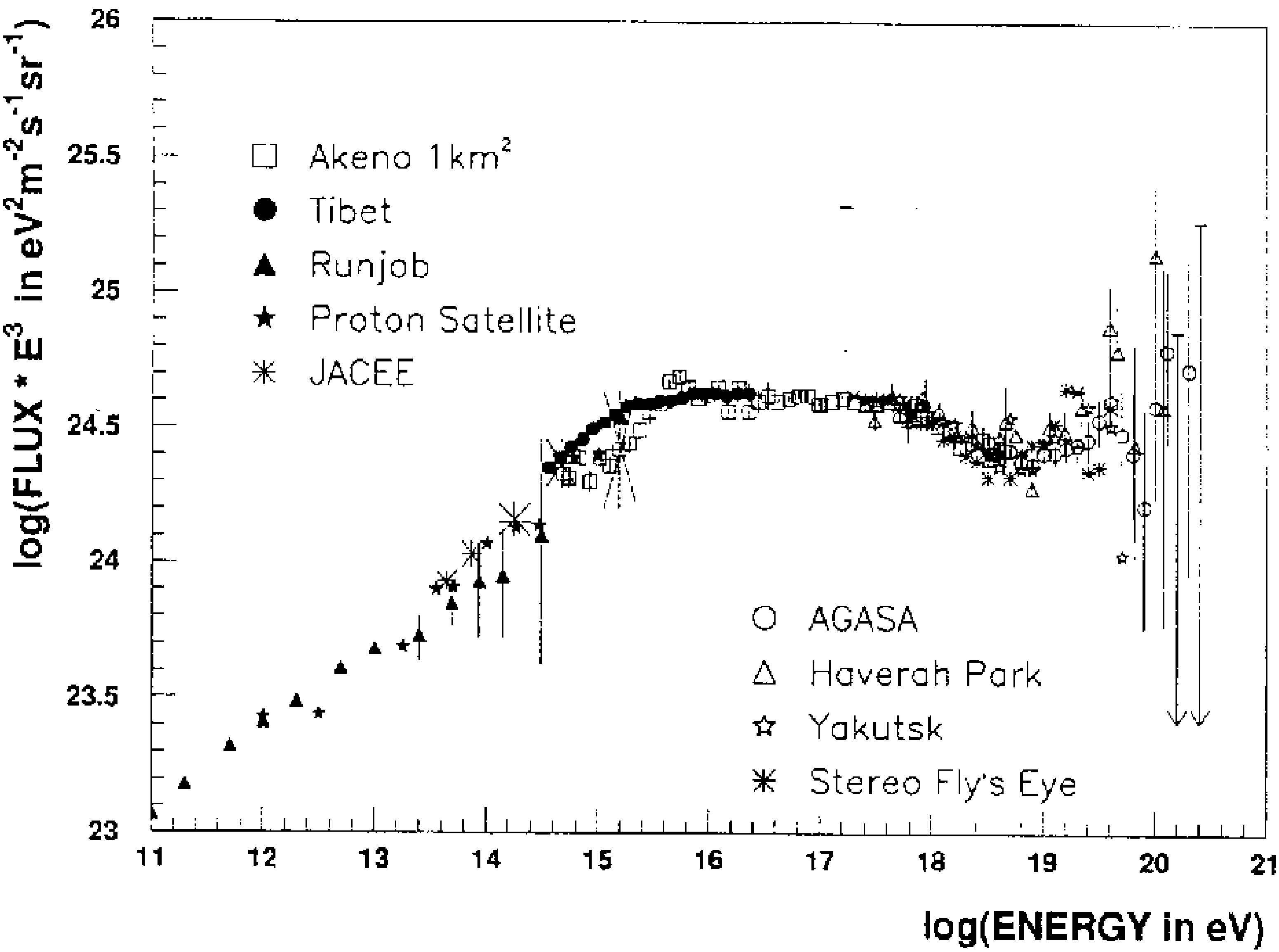


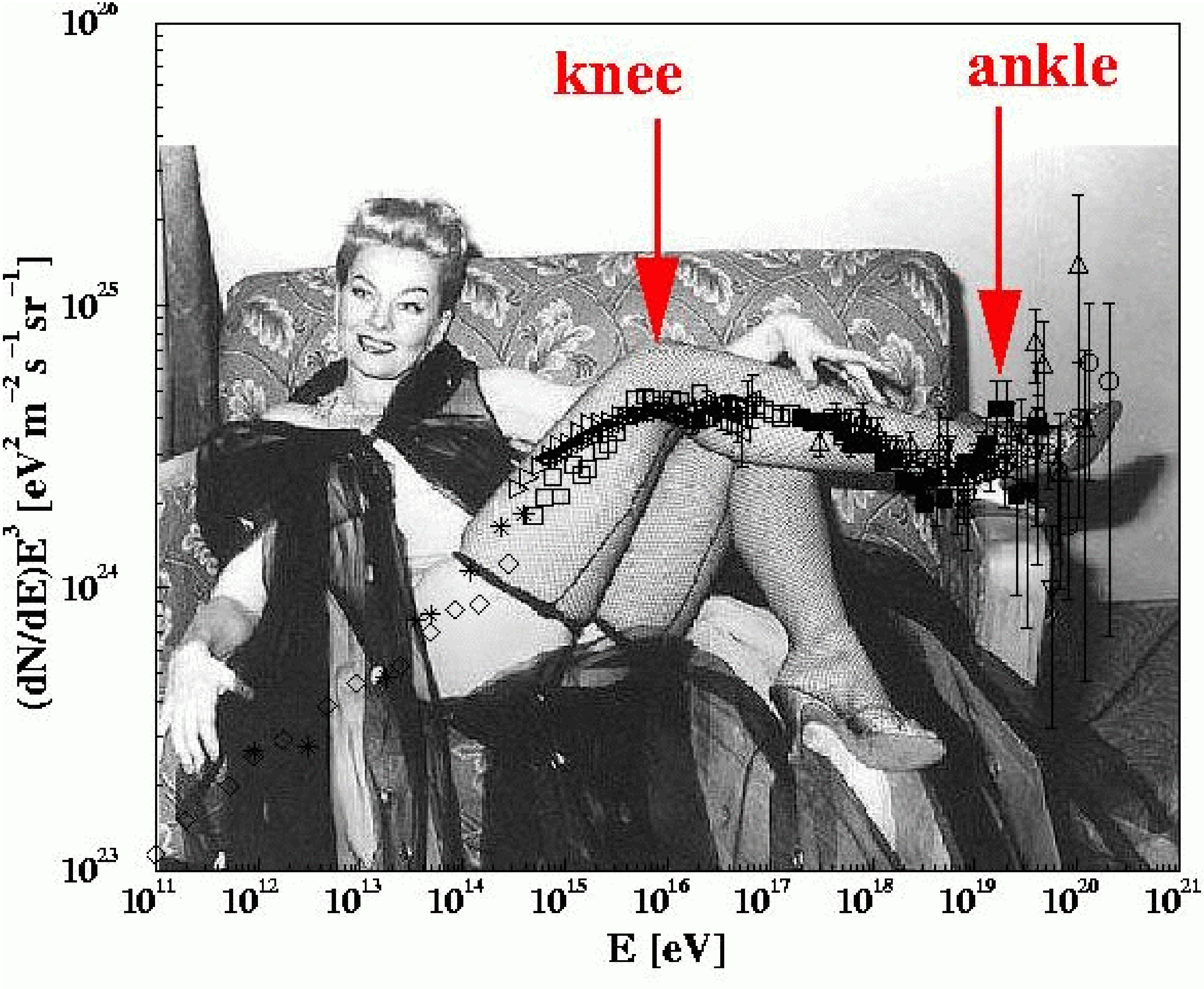
Very different from γ one



CR spectrum x E^3

M. Nagano and A. A. Watson: Ultrahigh-energy cosmic rays




knee
ankle
(dN/dE)E^3 [eV^2 m^-2 s^-1 sr^-1]
10^26
10^25
10^24
10^23
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
E [eV]

What is the origin of the knee? ($E_{knee}=3x10^{15}$ eV)

Heavy nuclei disintegrate in sources with high UV γ fluxes (e.g. nucleus A → A nucleons of $E_n = E/A$)

composition should become lighter above E_{knee}

Less efficient acceleration in the sources (e.g. parallel shocks → perpendicular shocks)

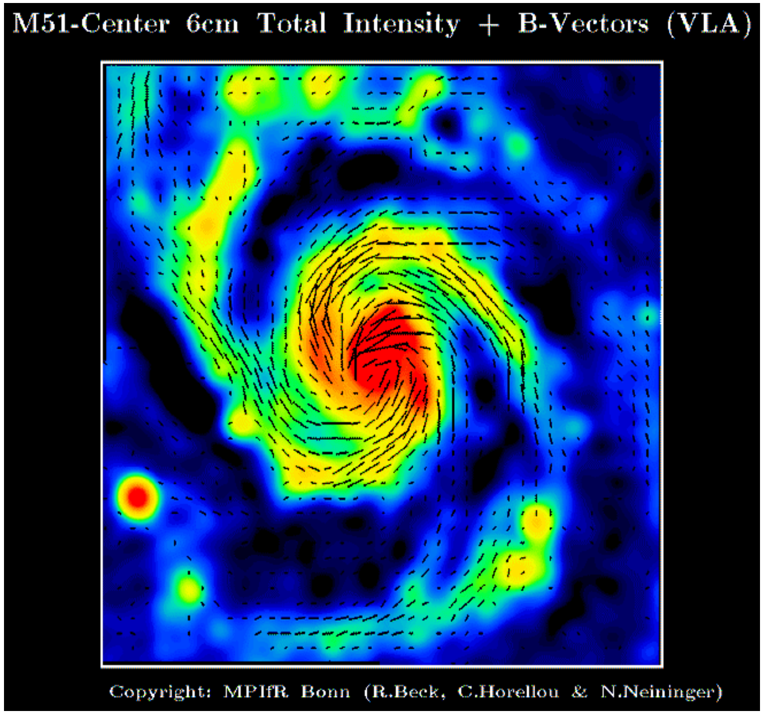
Limit of acceleration: $E_{max} \sim Z\, E_{knee}$

for rigidity dependent effects: composition should become heavier above E_{knee}

More efficient escape from Galaxy

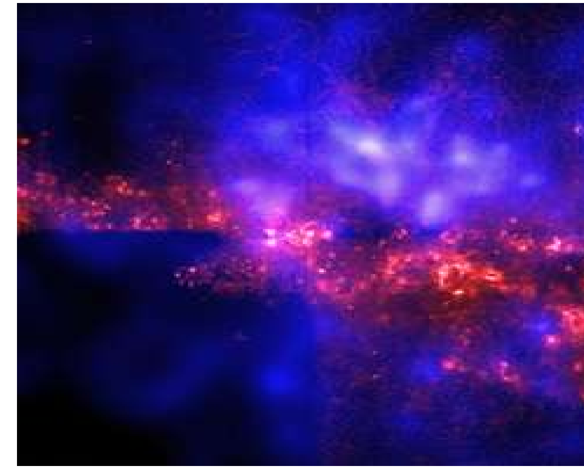
If due to changes in the escape mechanism, expect correlation between changes in spectrum and the behavior of the anisotropies

Galactic magnetic fields

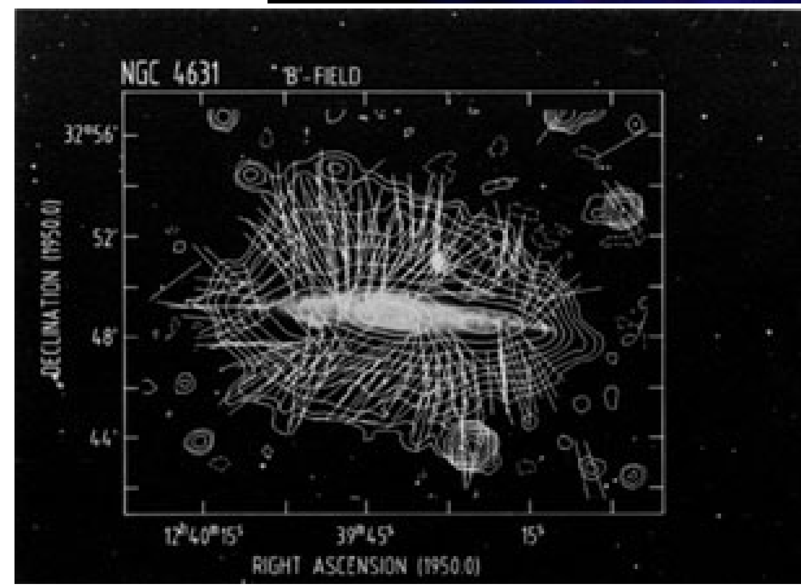


M51

Regular B field follows spiral arms



NGC 4631



Radio signal from magnetic halo (z_h~few kpc)

Faraday rotation → field reversals between arms. Locally B_0 = 2 - 3 μG

Random turbulent component, B_{rms} = few μG,

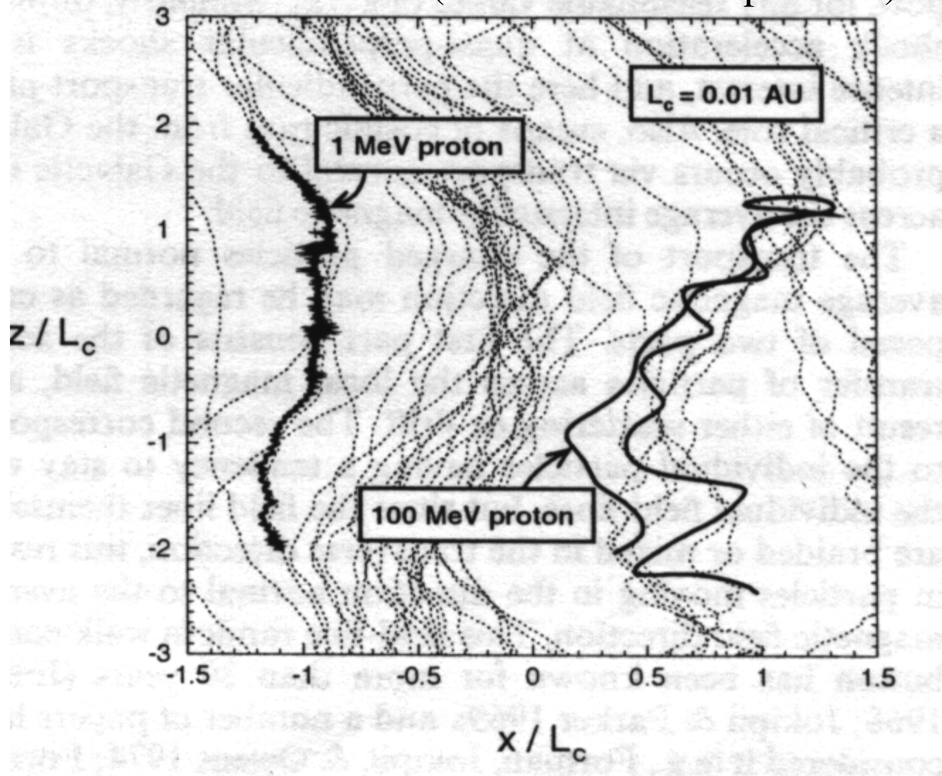
with Kolmogorov spectrum dE/dk ~ $k^{-5/3}$, with L_{max} ~ 100 pc

The level of turbulence is high: $\sigma^2 \equiv B_r^2 / B_0^2 \simeq 1$

In regular field, CRs have helical trajectories, with

$$V_{\|} = V \cdot \cos\theta$$ **(θ: pitch angle)**

(Giacalone & Jokipii 1999)



Larmor radius:

$$r_L = \frac{p_\perp c}{ZeB_0} \simeq \frac{E/Z}{10^{15} eV} \frac{\mu G}{B_0} pc$$

But for E/Z < 10^{17} eV they scatter off magnetic field irregularities with scale ~ r_L, they make a random walk and diffuse:

$$D_{\|} = \frac{\langle \Delta x_{\|}^2 \rangle}{2\Delta t} = \frac{c}{3}\lambda_{\|}$$

with

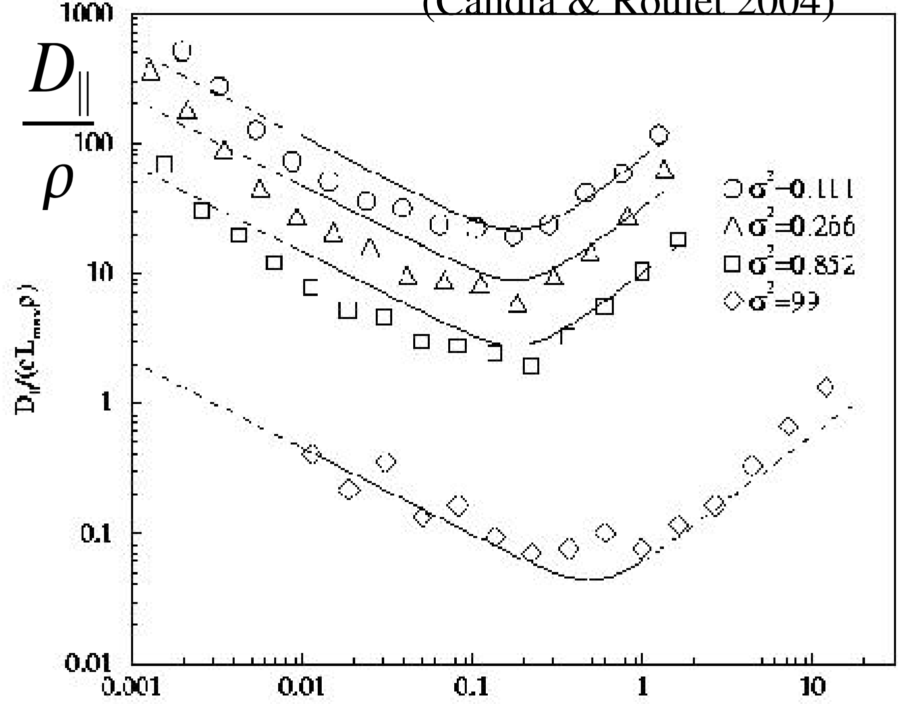
$$\lambda_{\|} \propto \frac{r_L}{dE_{rand}/d\ln k} \propto E^{1/3}$$

pitch angle scattering length

Diffusion coefficients can be obtained numerically → need to follow particle trajectories to obtain decorrelation times

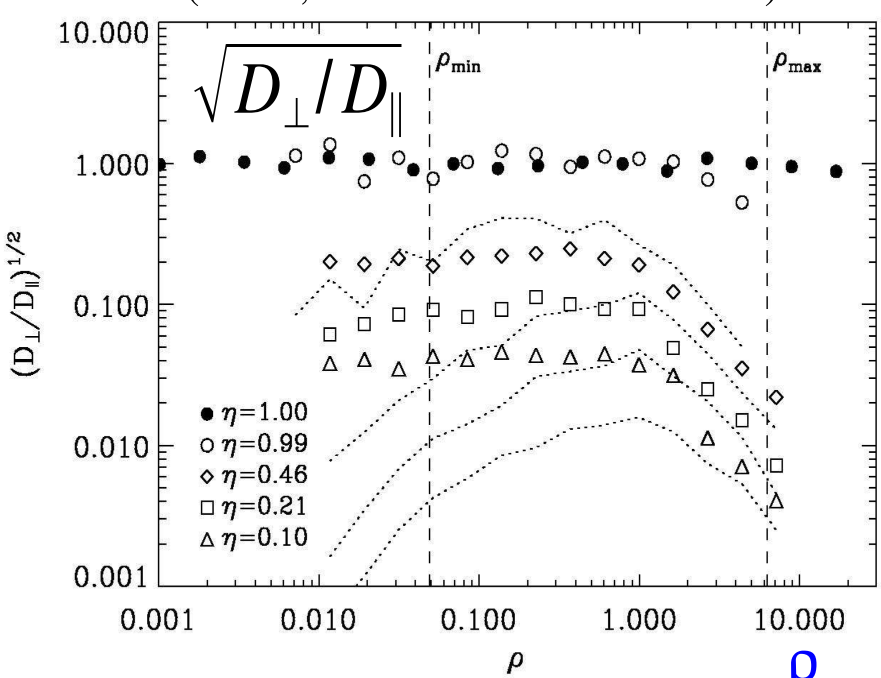
$$D_{\parallel} \simeq 5\times10^{30}\frac{cm^2}{s}\,\frac{\rho^{1/3}}{\sigma^2} \qquad (\rho<0.3)$$

(Candia & Roulet 2004)



$$\rho \equiv \frac{r_L}{L_{max}/2\pi} \simeq \frac{E/Z}{3\times10^{16}eV}\,\frac{\mu G}{|B_0|}\,\frac{100\,pc}{L_{max}}$$

(Casse, Lemoine & Pelletier 2002)



Diffusion ⊥ to B_0 much slower:

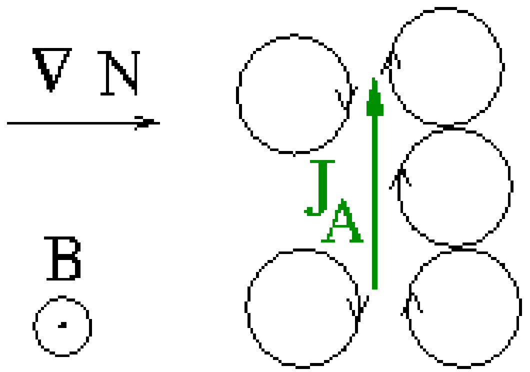
it arises from pitch angle scattering and, mostly, from wandering of field lines

$$D_{\perp} \simeq 0.025\,D_{\parallel}(\sigma^2)^{1.4} \propto E^{1/3}$$

Antisymmetric (Hall) diffusion: drift

In the presence of gradients of the CR density, there is macroscopic drift

$$J_A = D_A \frac{B}{|B|} \times \nabla N$$



$$D_A \simeq \frac{r_L c}{3} \simeq 5 \times 10^{29} \frac{cm^2}{s} \rho \propto E$$

$$D_A \simeq D_\perp \; for \; \rho \simeq 0.1 \left(\sigma^2\right)^{0.6}$$

$$i.e. \; for \; E/Z \sim 10^{16} eV$$

Ptuskin et al. 1993
Candia, Epele, Mollerach, ER

The CR distribution in the Galaxy follows from:

$$\nabla \cdot J_D = Q$$

with

$$J_{Di} = -D_{ij} \nabla_j N$$

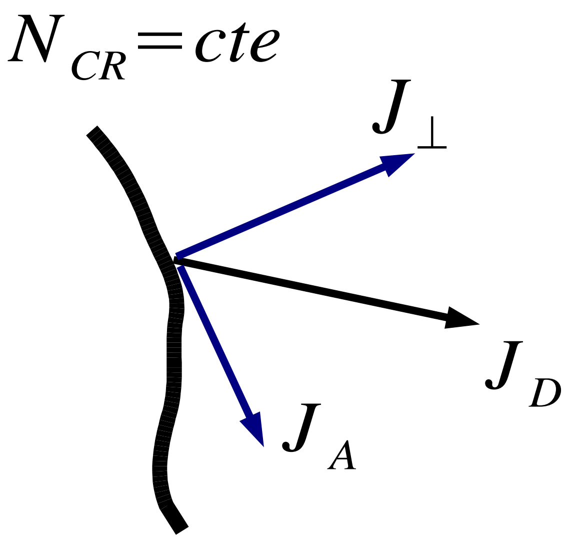
The diffusion tensor is

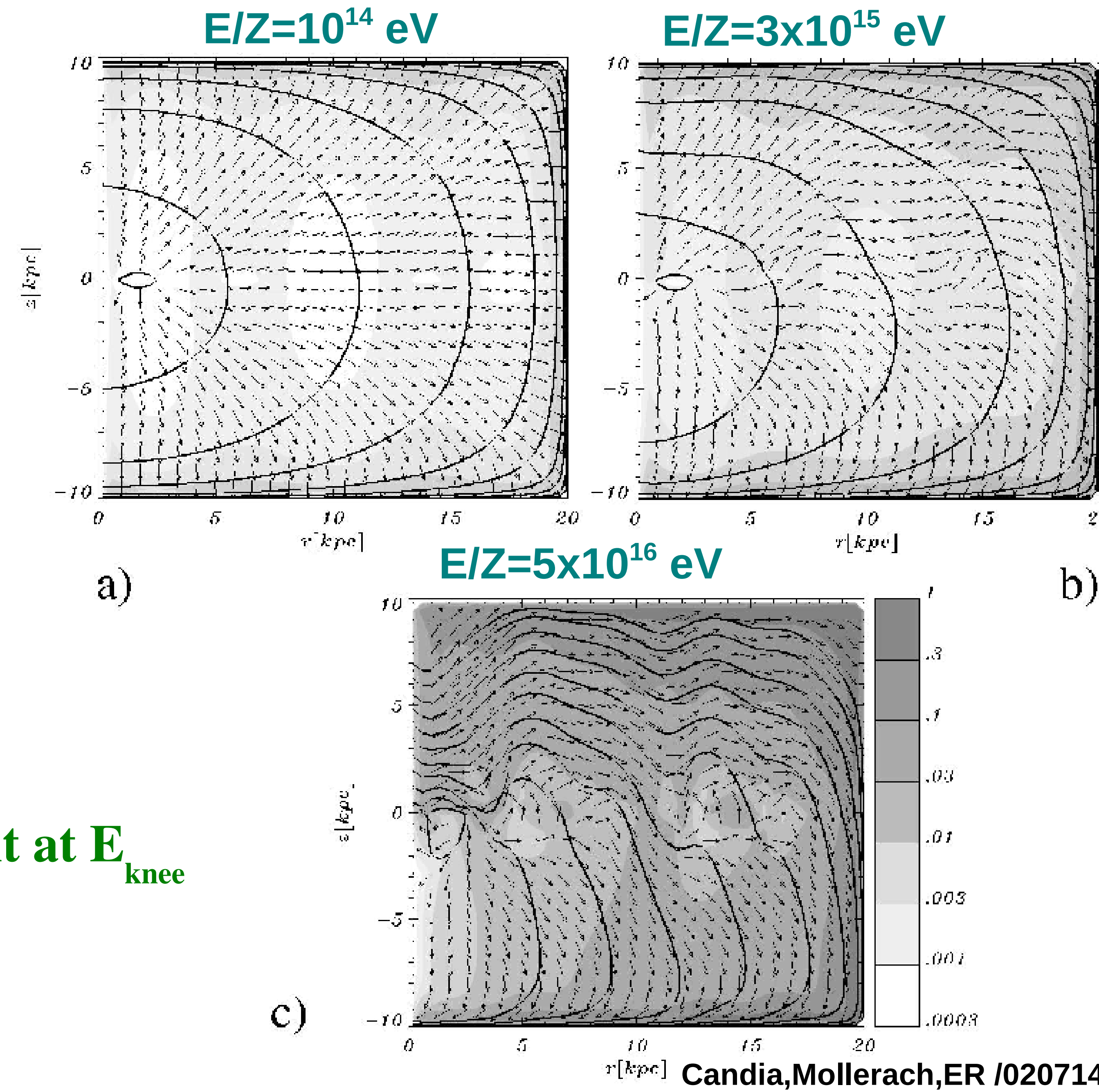
$$D_{ij} = \begin{pmatrix} D_\perp & D_A & 0 \\ -D_A & D_\perp & 0 \\ 0 & 0 & D_\parallel \end{pmatrix}$$

for B || z

For cylindrical symmetry and azymuthal B_0 field, $D_\parallel$ plays no role

$$J_D \simeq -D_\perp \nabla N + D_A \frac{B_0}{|B_0|} \times \nabla N$$





Drifts become relevant at E_{knee}

Candia,Mollerach,ER /0207143

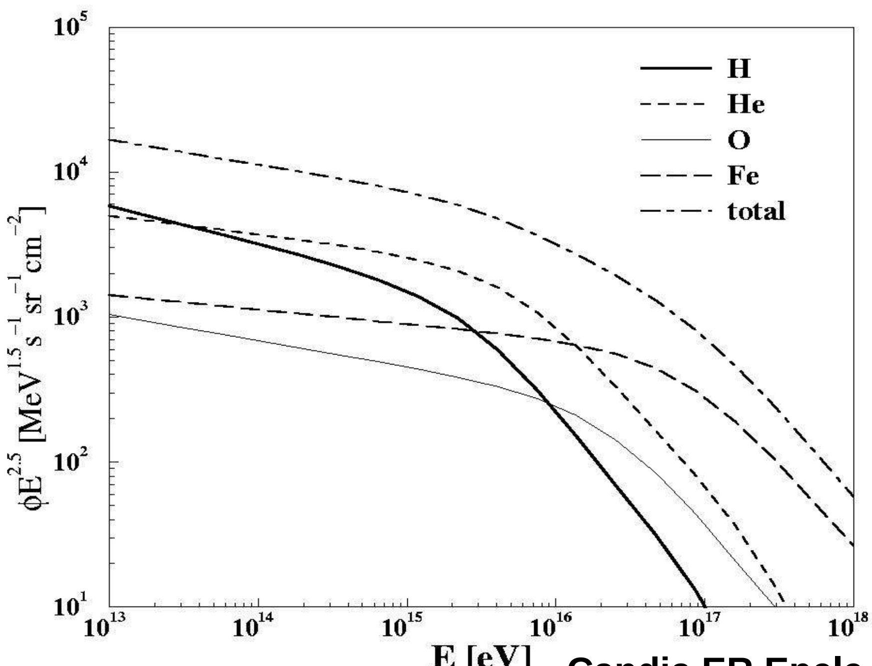
For E/Z ○ ✢④⑦❾❾, escape dominated by transverse diffusion $\tau_e \propto D_\perp^{-1} \propto E^{-1/3}$

the observed spectrum is $\frac{dN_{CR}}{dE} \propto \tau_e \frac{dN_s}{dE} \propto E^{-\alpha_s - 1/3}$ **a source spectral index** $\alpha_s \sim$ **2.3 is required**

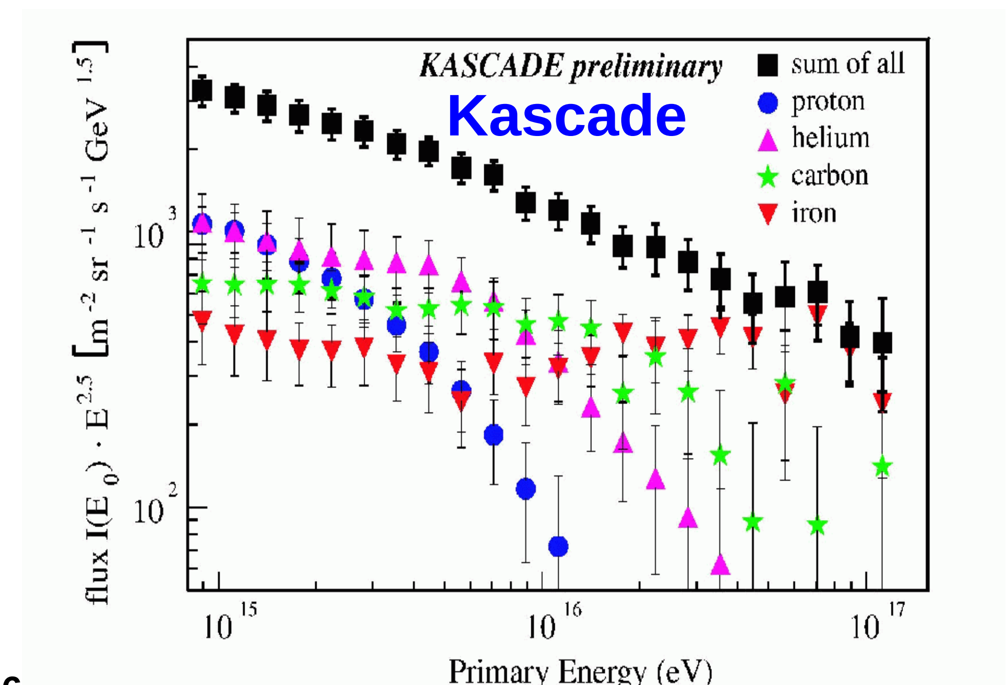
For E/Z > E_{knee}, escape dominated by drifts, $\tau_e \propto D_A^{-1} \propto E^{-1}$

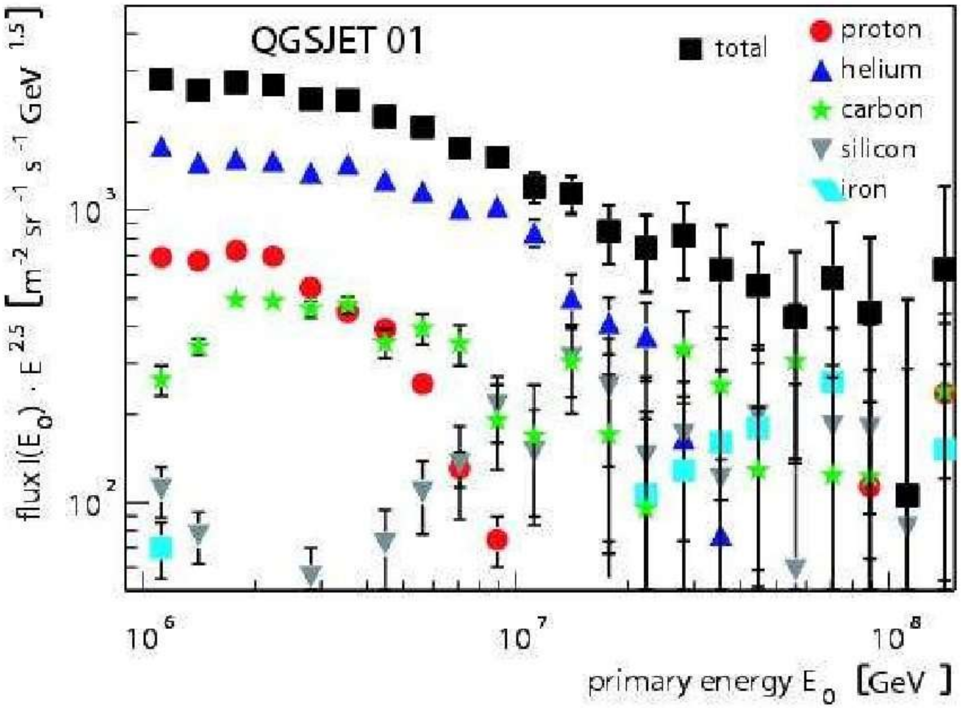
$$dN_Z / dE \propto E^{-\alpha_s - 1} \sim E^{-3.3}$$ → $\Delta\alpha \sim 2/3$

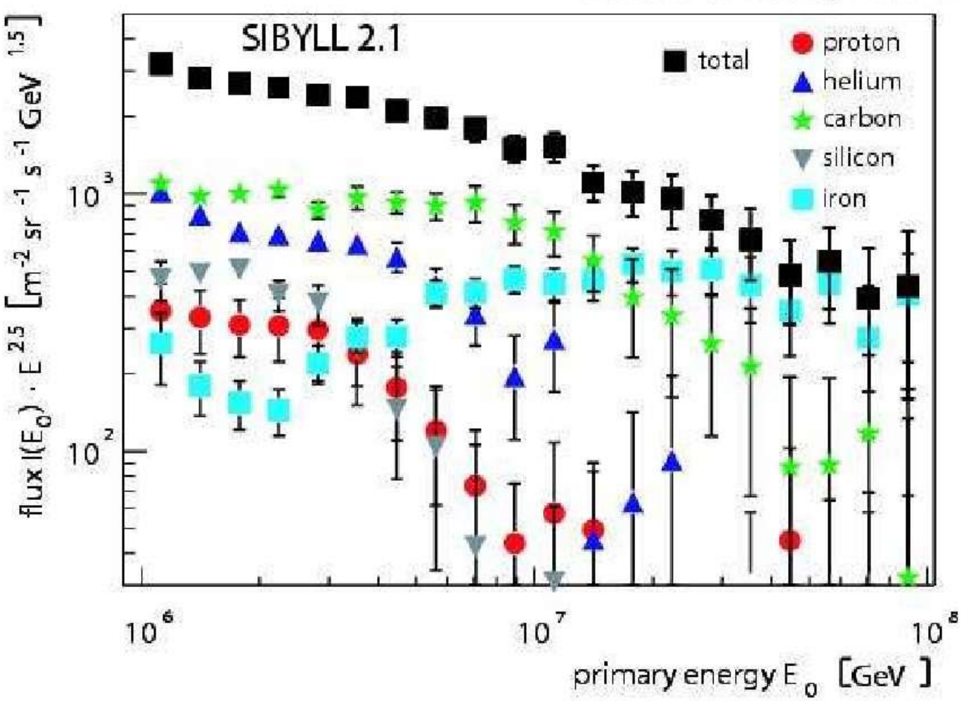
A rigidity dependent break in the observed spectra results without requiring any break in the source spectra



Candia,ER,Epele /0206336



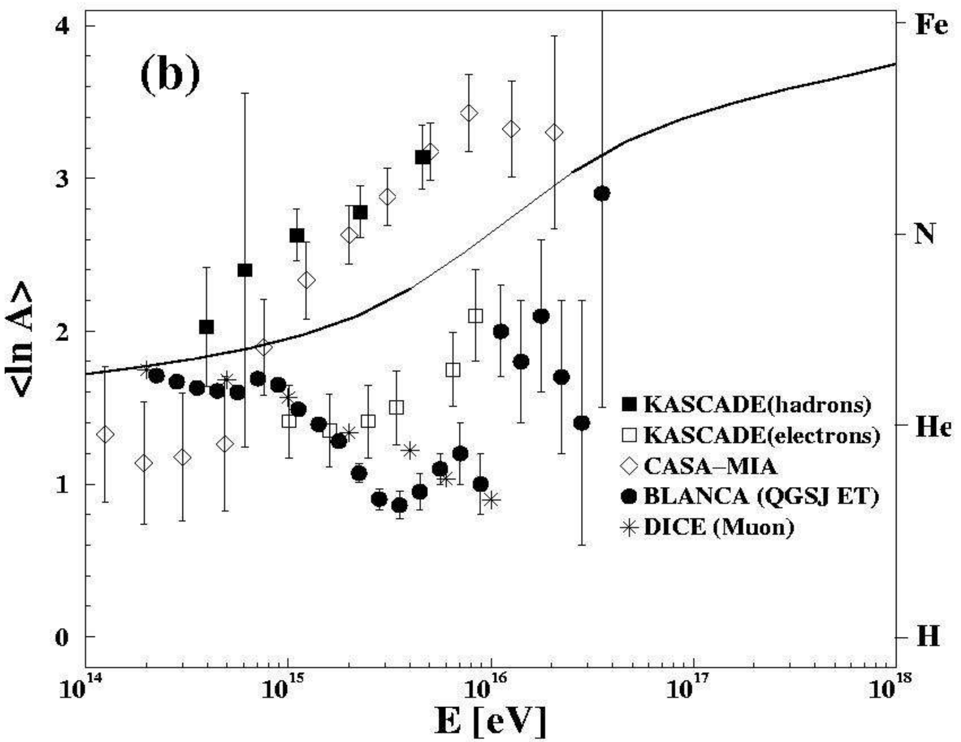




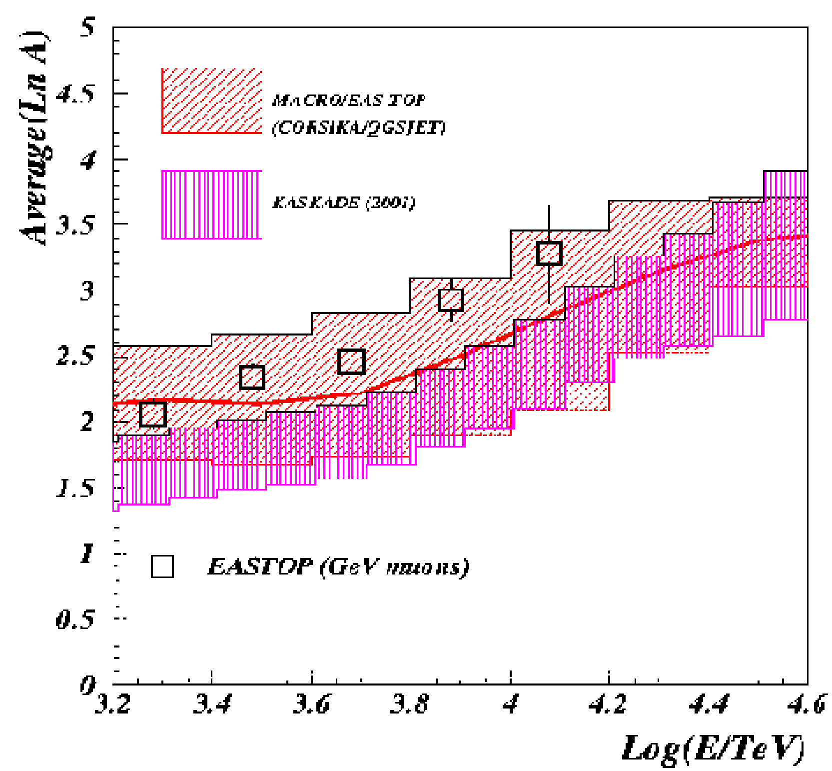
details depend on hadronic model adopted

The composition becomes heavier

Candia,ER,Epele/0206336



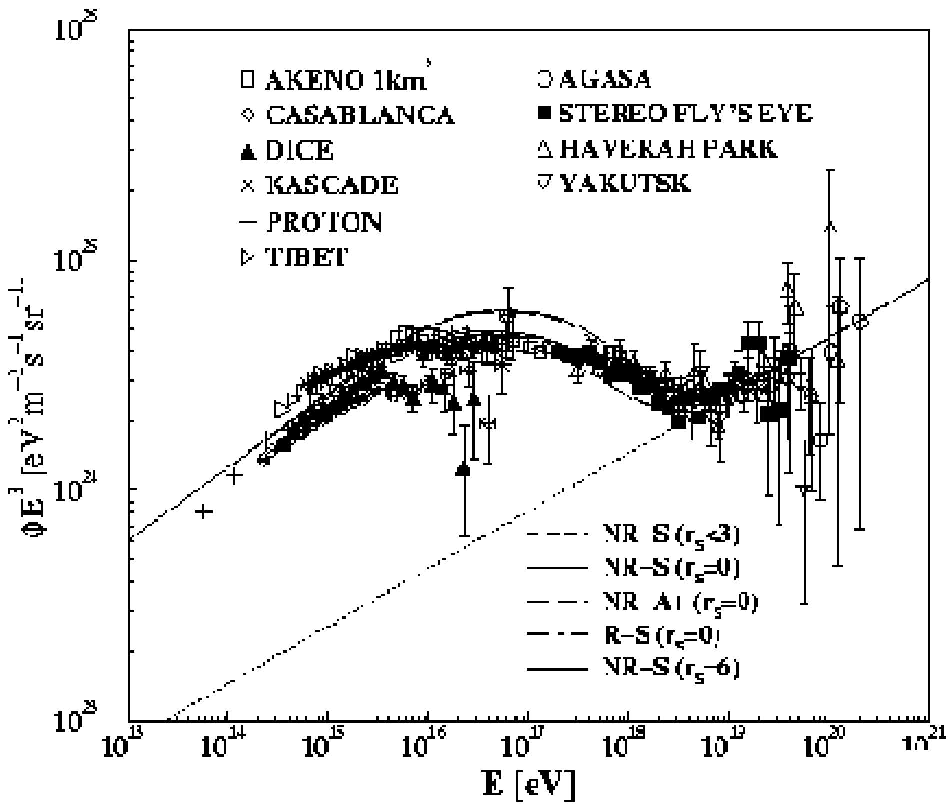
MACRO – Eas Top **/0305325**



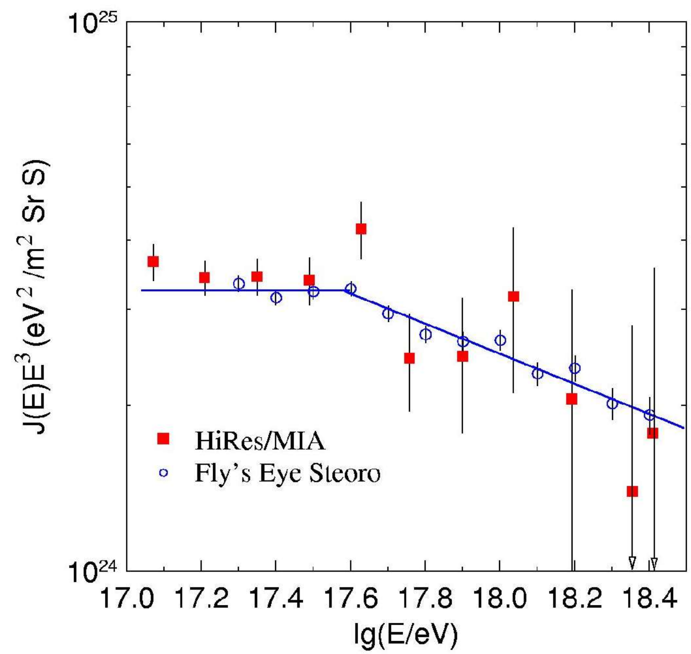
$$\Delta\alpha = 0.7 \pm 0.4$$

(see also SPASE/AMANDA)

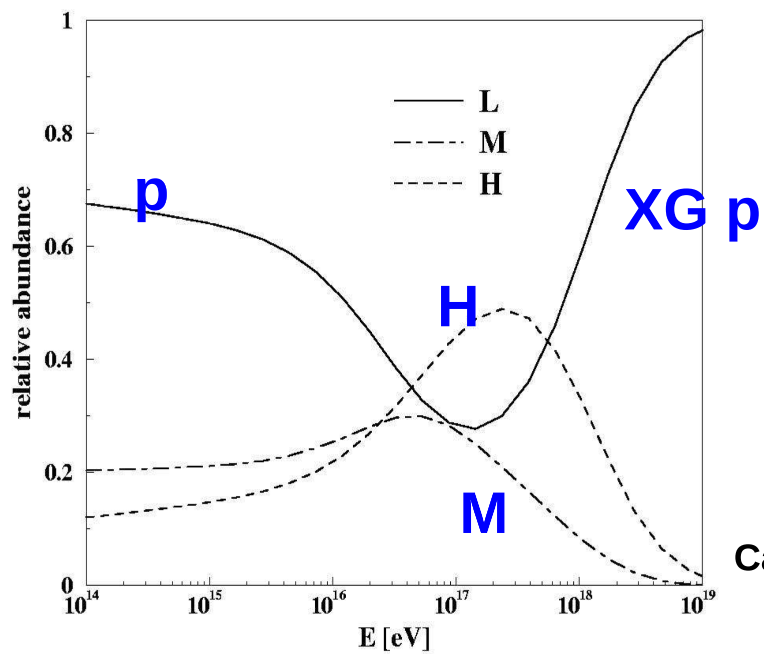
The second knee results from drift of Fe component



HiRes-MIA



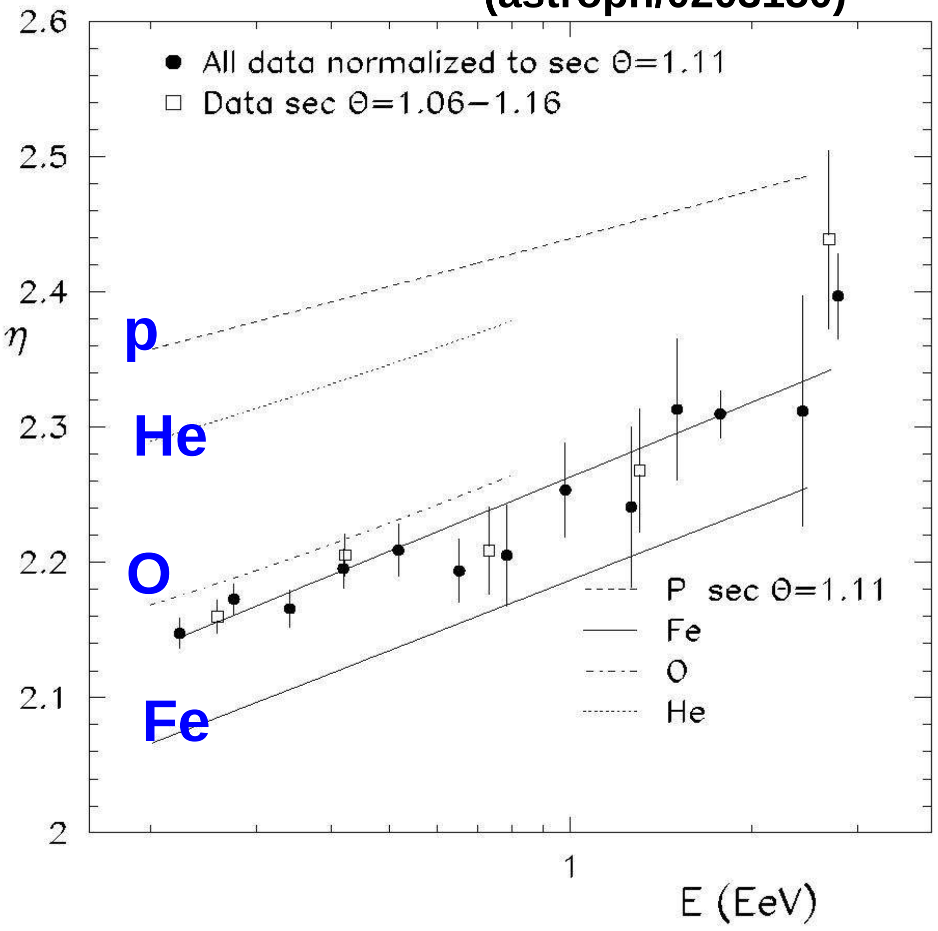
Heavy elements predominant around the second knee



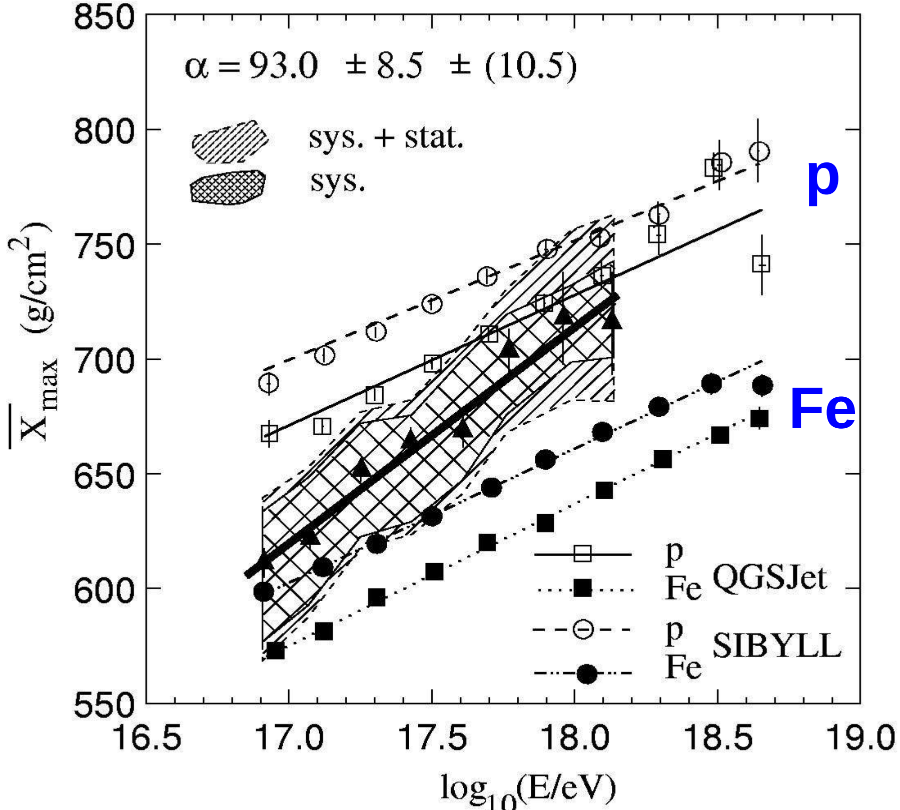
Candia,Mollerach,ER /0207143

This is consistent with measurements by Haverah Park (and AGASA) using the lateral distribution of the showers

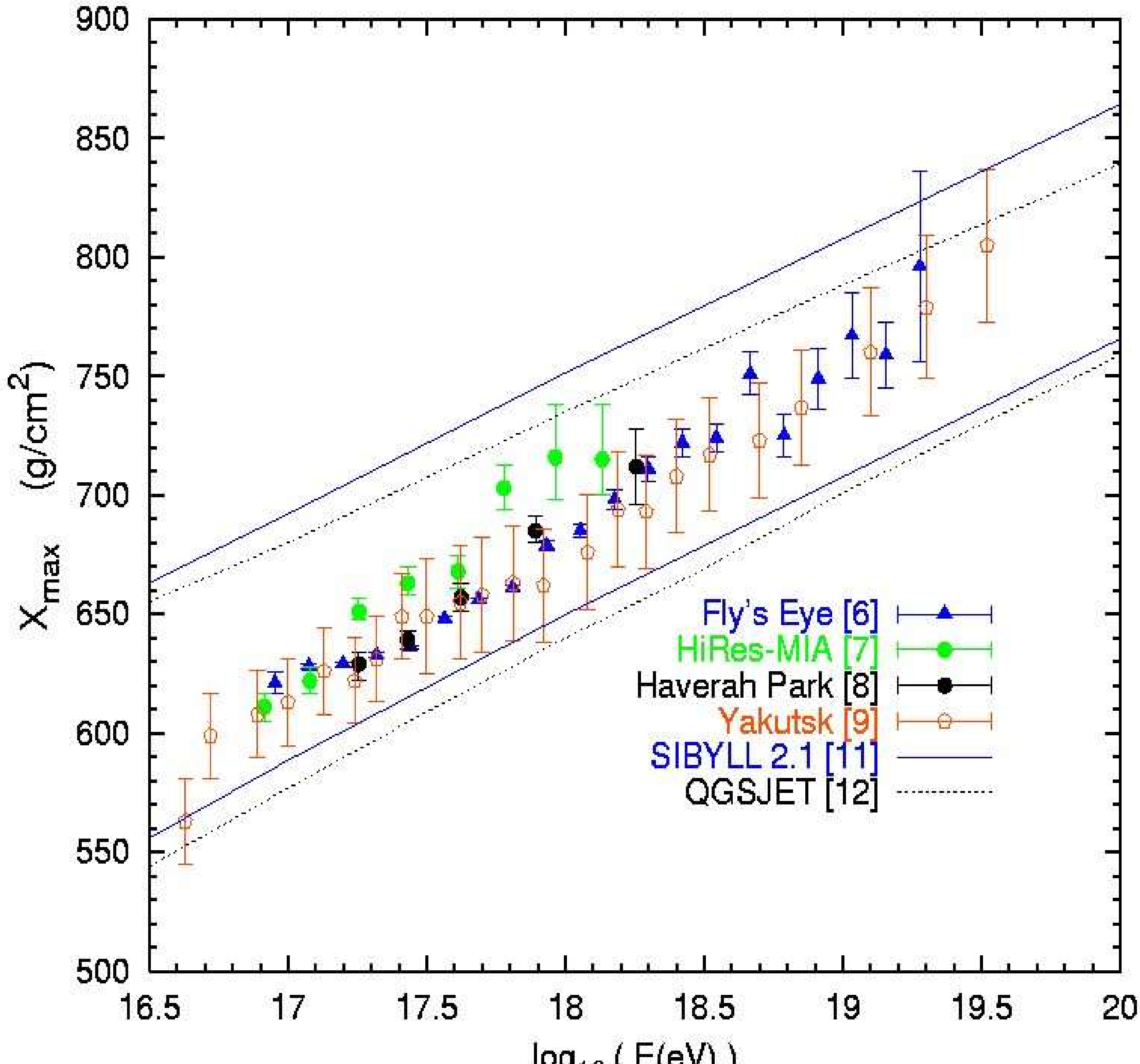
(astroph/0203150)



but not much with the composition measured by HiRes through X_{max}



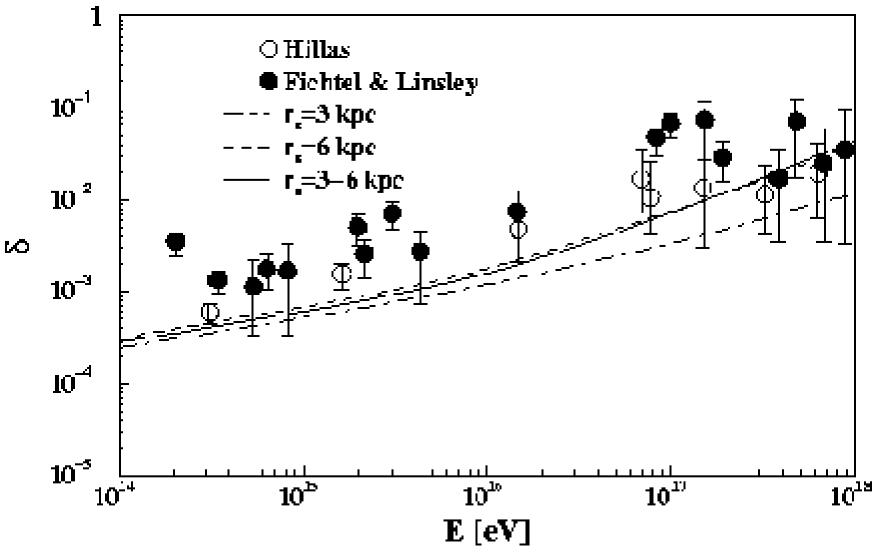
(astroph/0010652)



900
850
800
750
700
650
600
550
500
X_{max} (g/cm^2)
16.5
17
17.5
18
18.5
19
19.5
20
$\log_{10}$ (E(eV))
Fly's Eye [6]
HiRes-MIA [7]
Haverah Park [8]
Yakutsk [9]
SIBYLL 2.1 [11]
QGSJET [12]

Also anisotropies grow due to drifts

Candia,Mollerach,ER /0302082



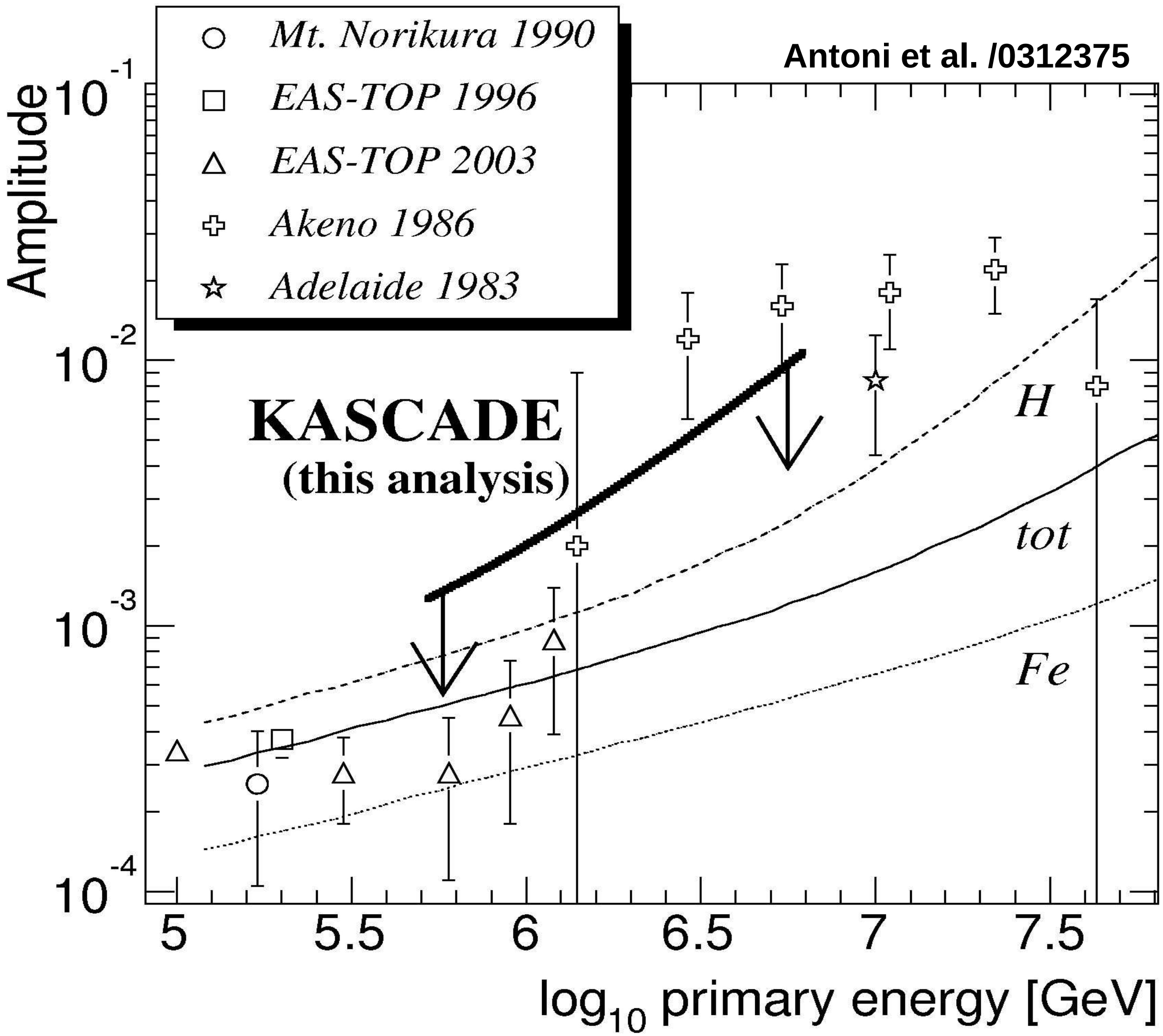
amplitude of first harmonic in right ascension

$$\delta_i = \frac{3 J_i^D}{c N_i} \quad \textbf{with} \quad \delta = \sum_i f_i \delta_i$$

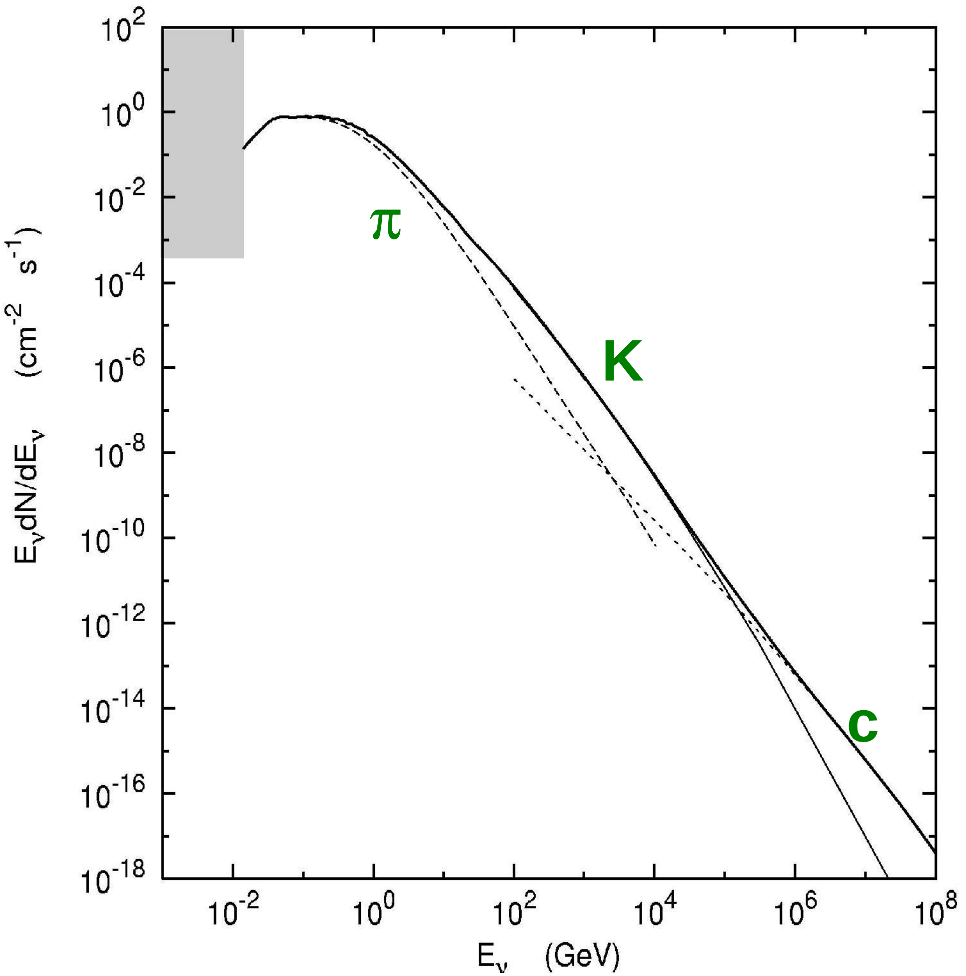
each δ_i grows as E, but overall $\delta \sim E^{1/3}$

It would be interesting to measure individual δ_i (Kascade?)

KASCADE RESULTS:



High energy atmospheric neutrinos



decay length $L = \gamma c \tau$

$$L_\pi \simeq 6\ km\,(E_\pi / 100\ GeV)$$

$$L_K \simeq 7.5\ km\,(E_K / TeV)$$

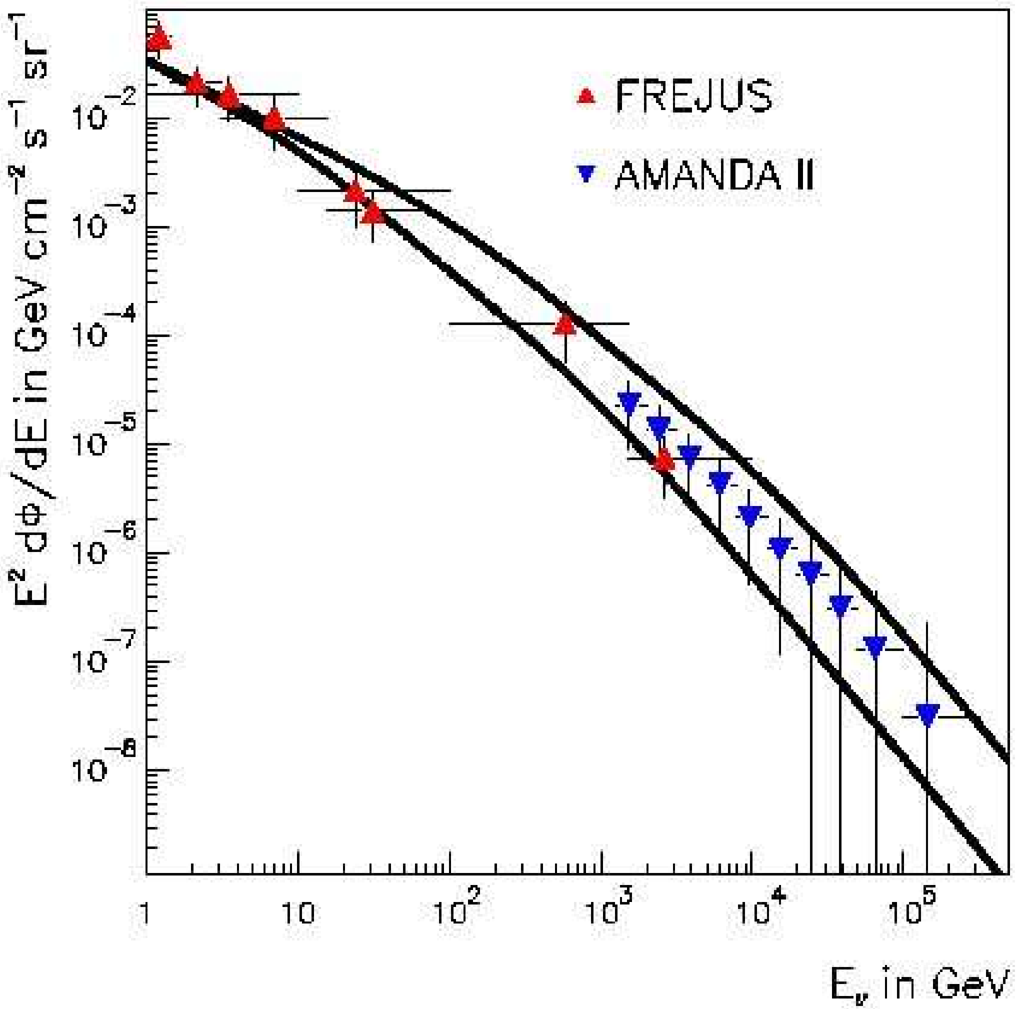
$$L_D \simeq 2\ km\,(E_D / 10\ PeV)$$

Atmospheric νs mainly from pion decays at low energies,

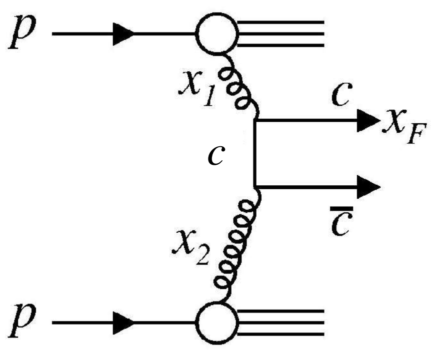
but above 100 GeV pions are stopped before decay ⇒ kaons become the main source,

but above ~10^{14} eV prompt charm decays dominate

AMANDA results



Prompt charm production

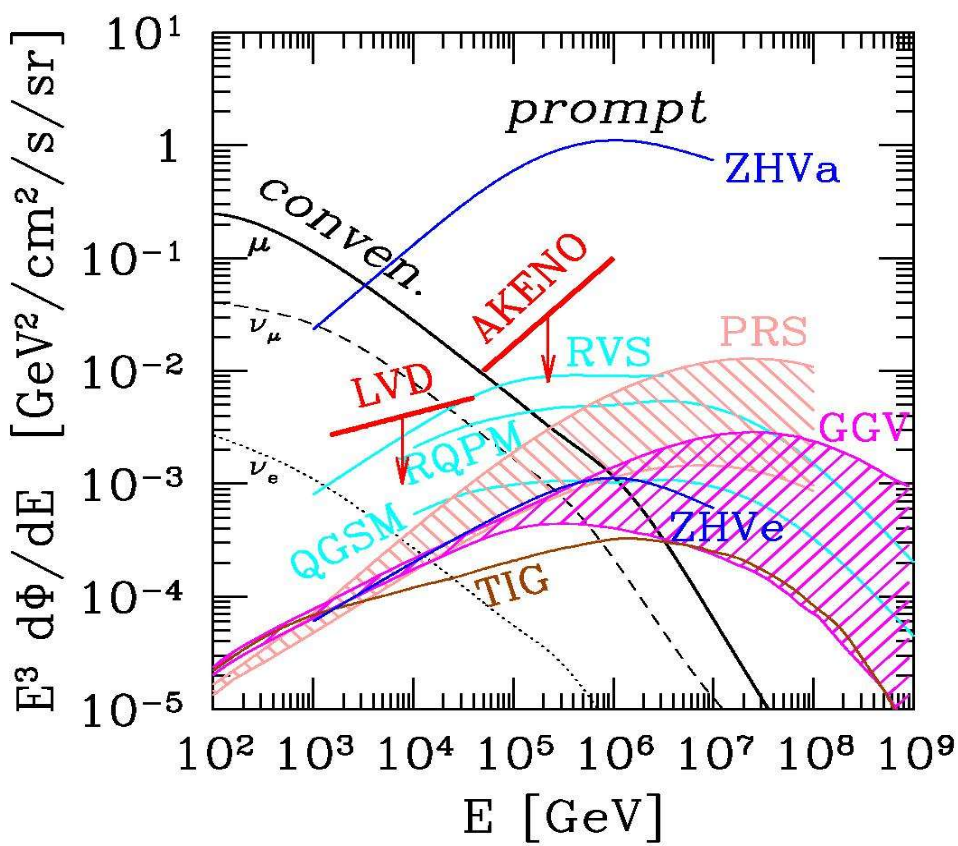


sample gluon density distribution at $x_2 \simeq \frac{M_{cc}^2}{2\, x_F\, s}$

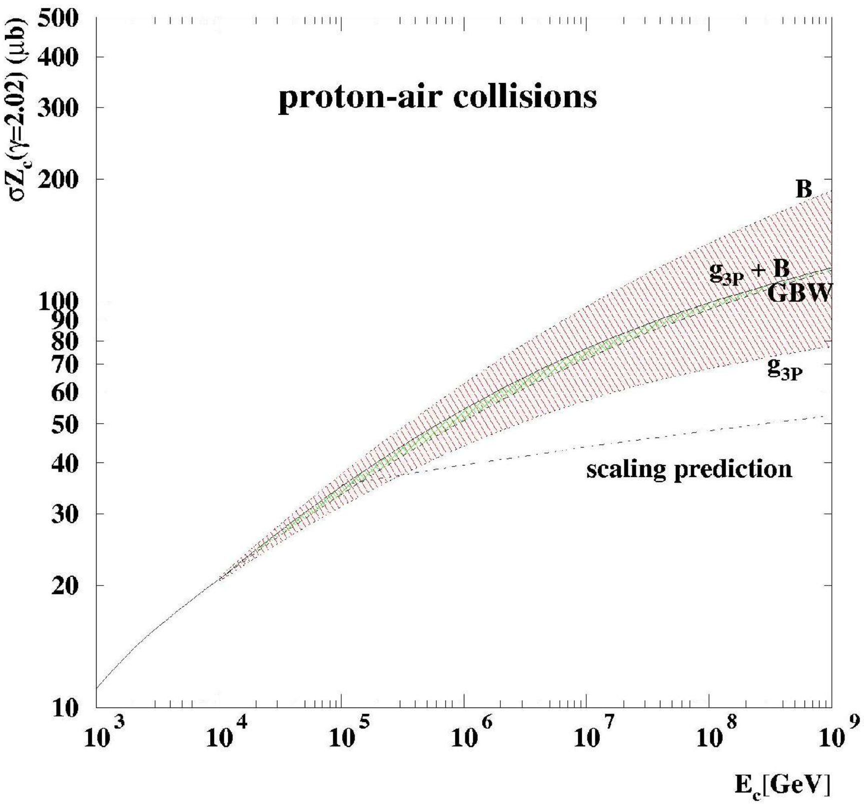
$\Rightarrow x_2 < 10^{-5}$ for $E > 10^{15}$ eV

need to extrapolate from measured values

also requires to include NLO processes



Martin et al. /0302140

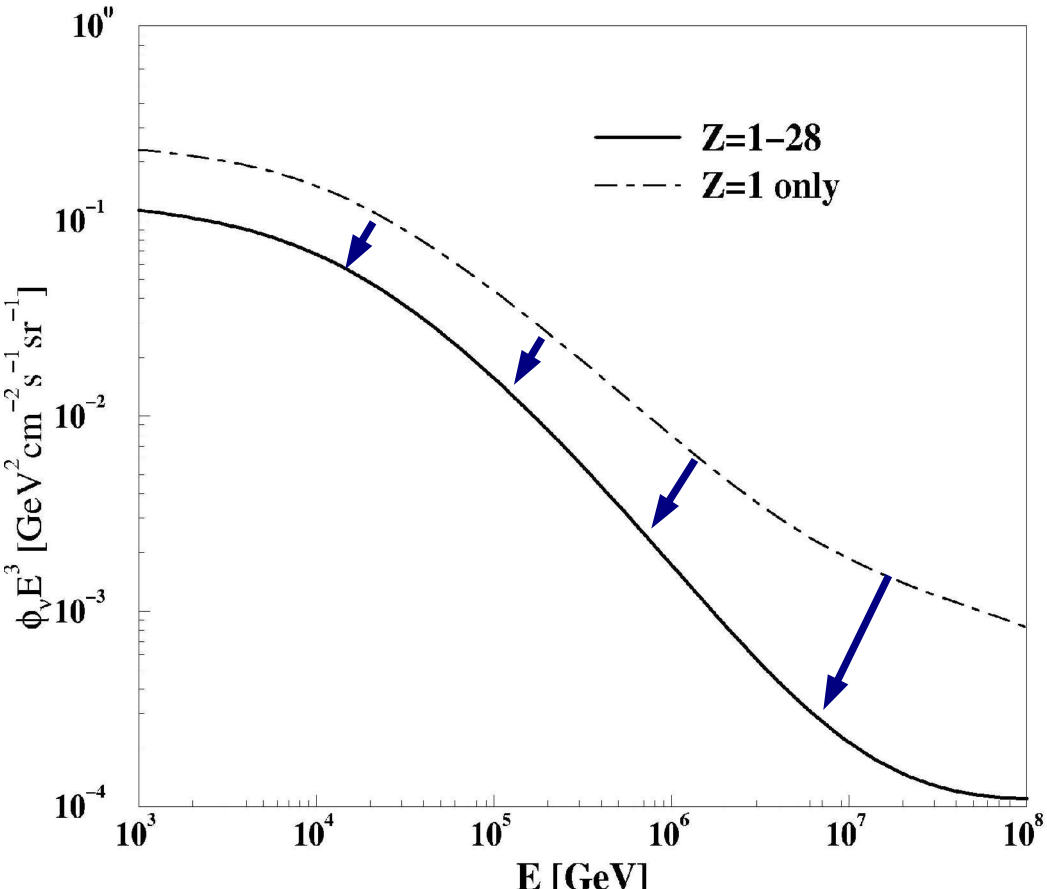


(see also Pasquali, Reno, Sarcevic)

But for rigidity dependent scenarios for the knee, the composition becomes predominantly heavy above E_{knee}

CR nuclei of mass A behaves as A nucleons of energy E/A

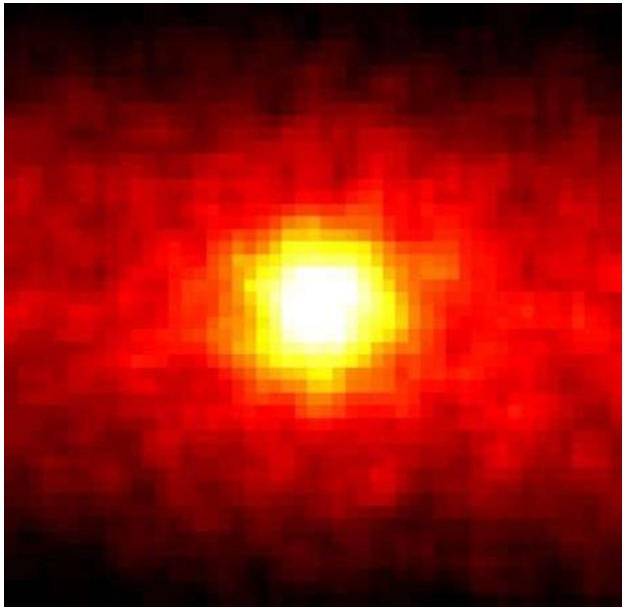
$\Rightarrow$ neutrinos are produced with much lower energies, and due to steep spectrum, they become strongly suppressed



Candia, ER /0306632

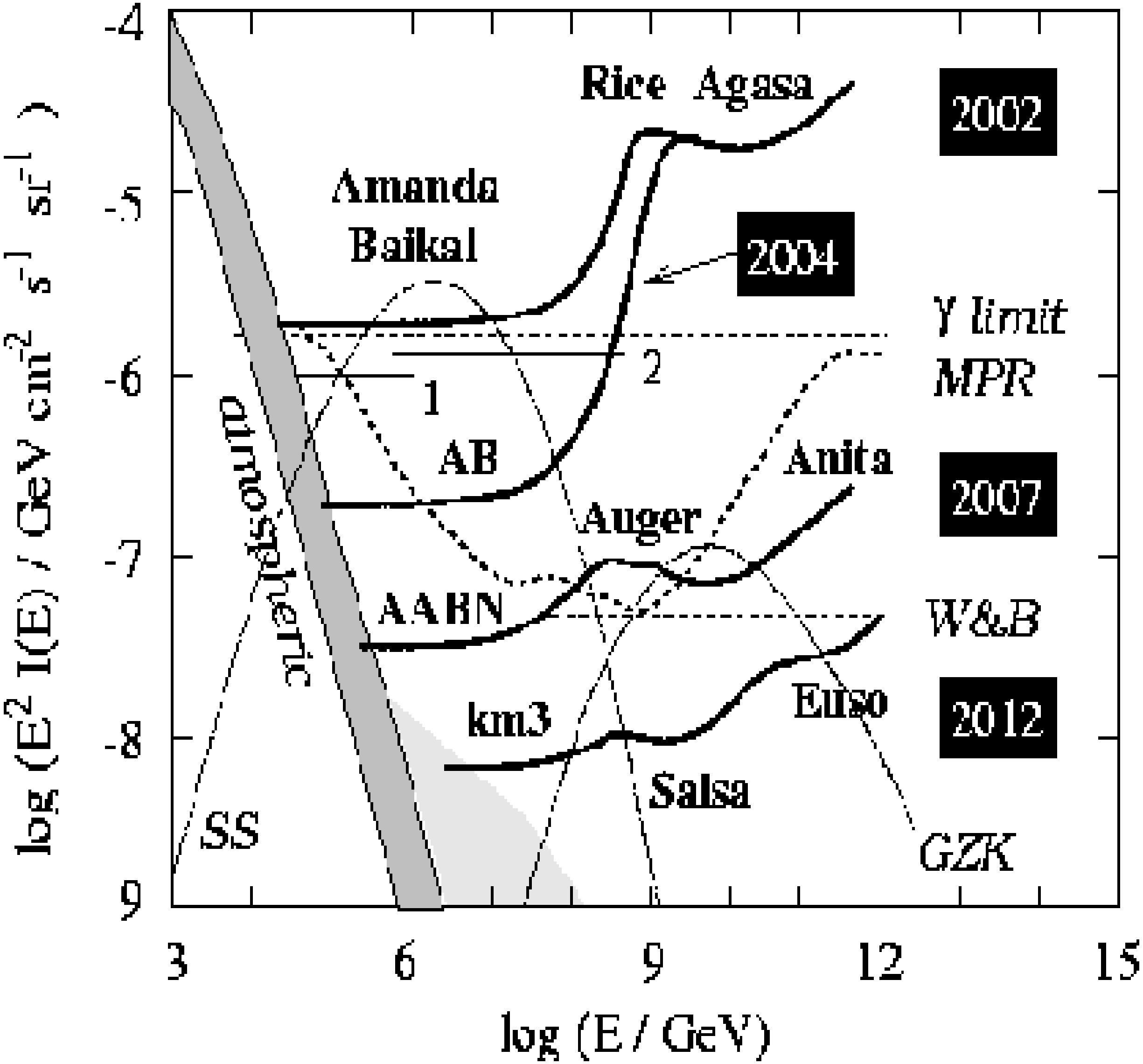
Something similar happens to the ν's produced by CR interactions in the Galactic ISM

Neutrino astronomy



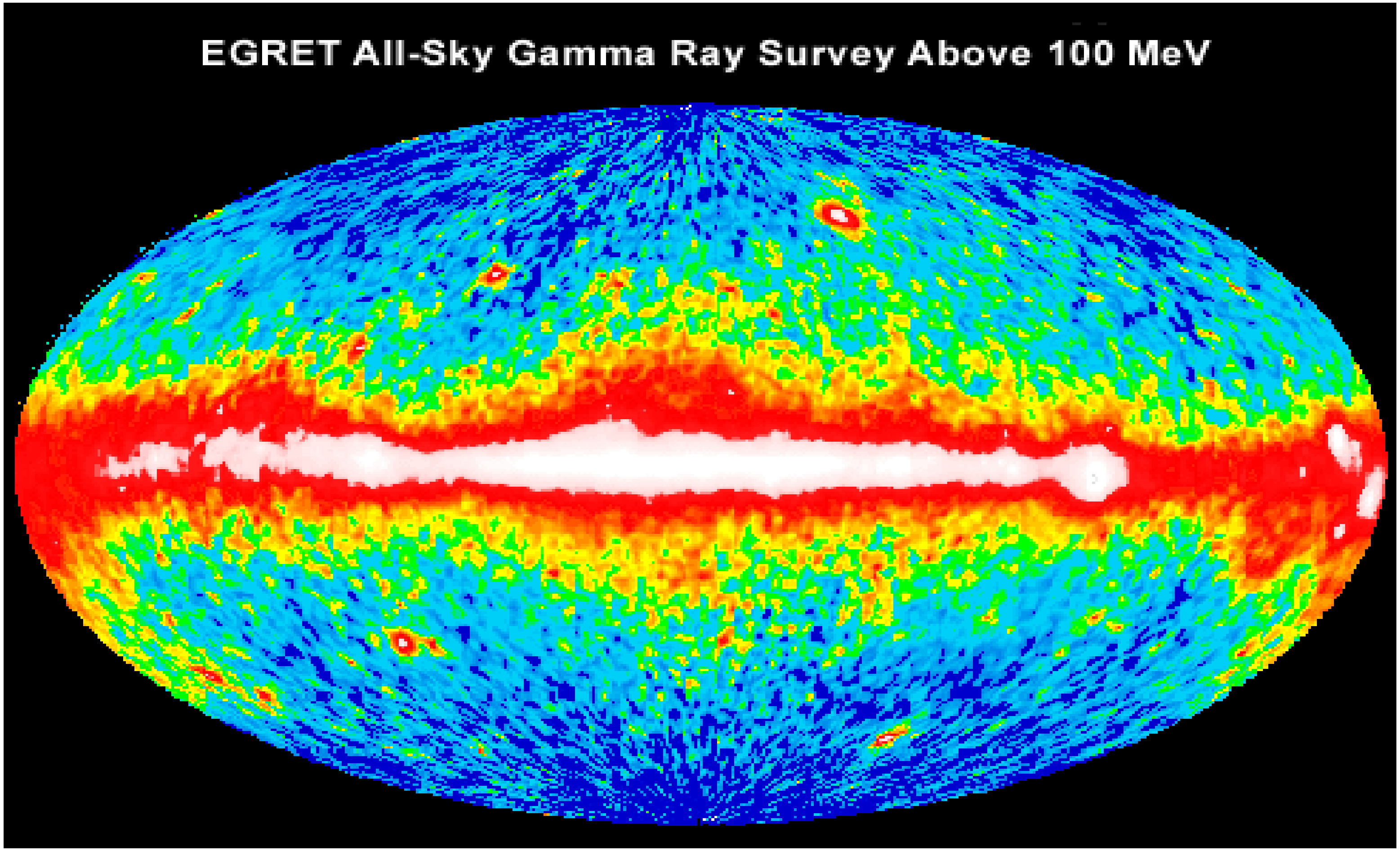
Sun seen in ν's

Carr



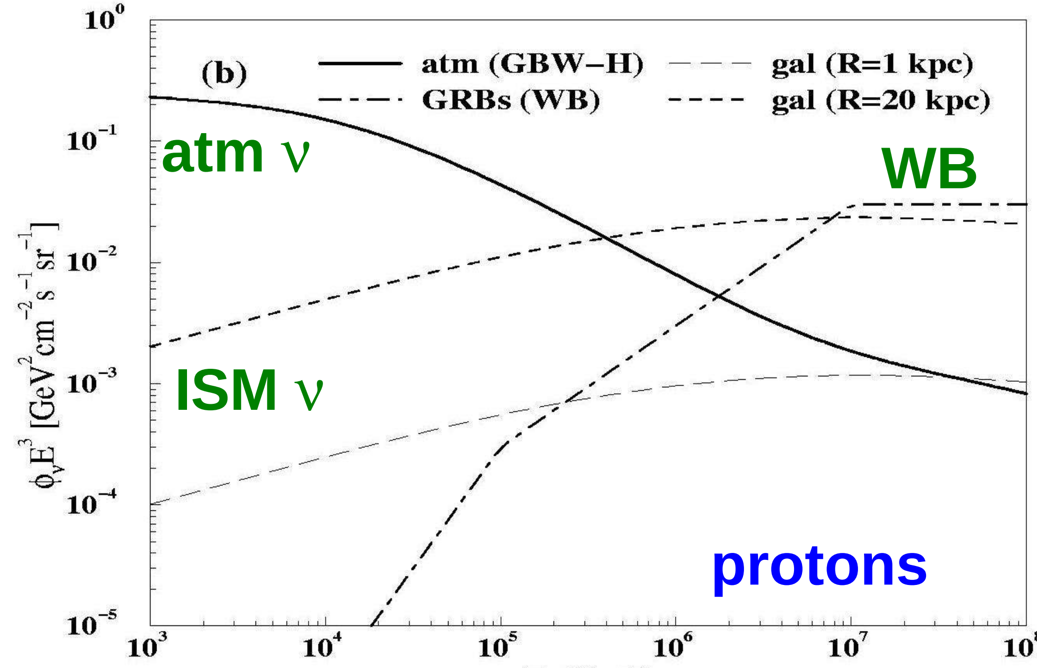
diffuse ν fluxes

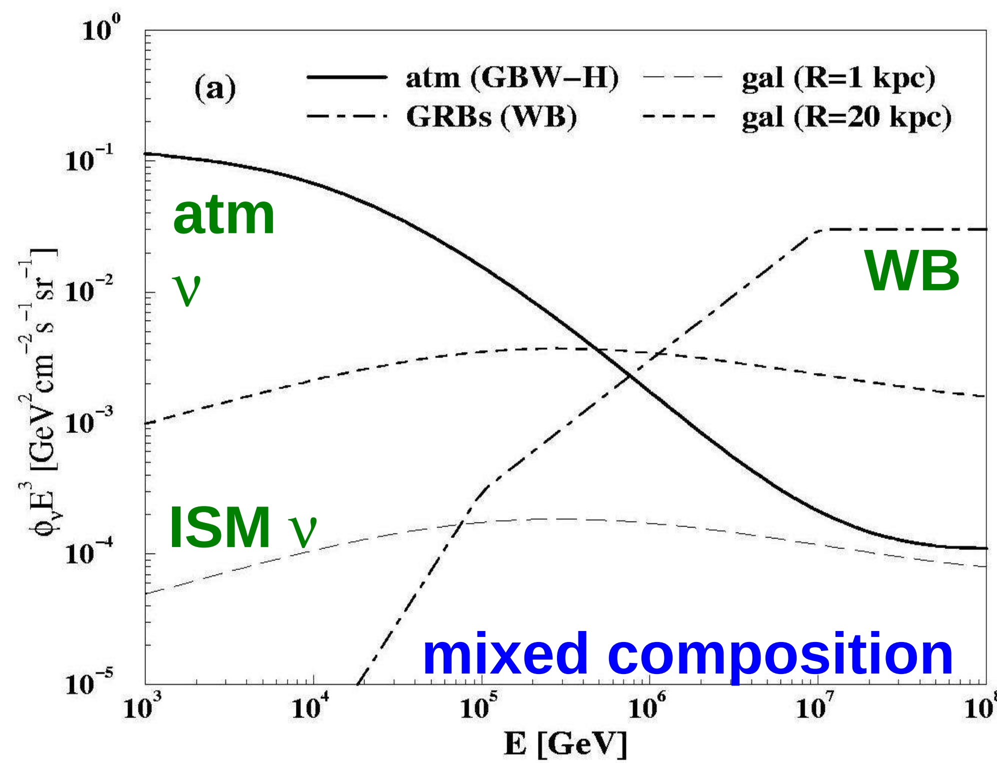
Sky seen in γ's



Something similar should be seen in ν's

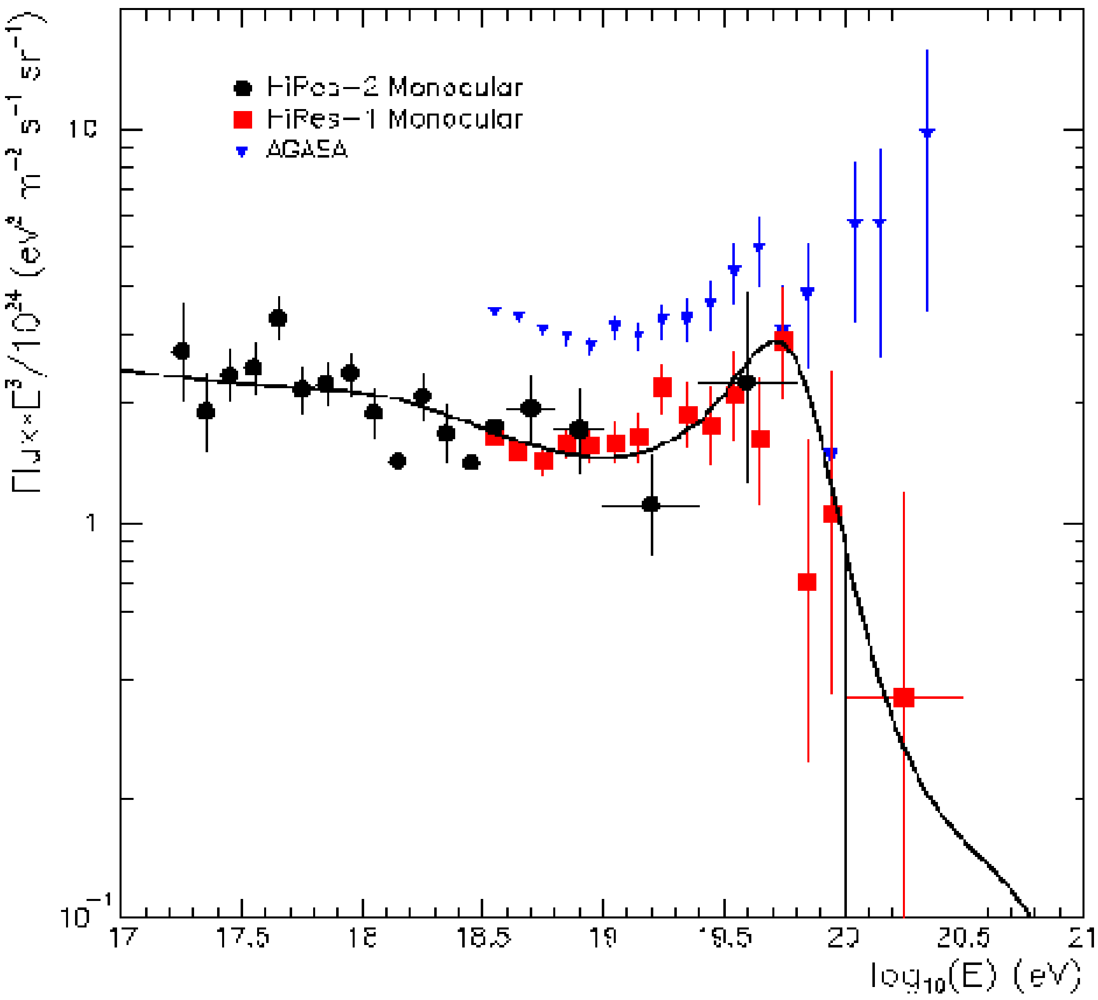
This heavy composition of rigidity dependent scenarios results into a reduced background for the detection of diffuse astrophysical fluxes, such as those from GRBs





Candia, ER /0306632

IS THERE A GZK CUTOFF?



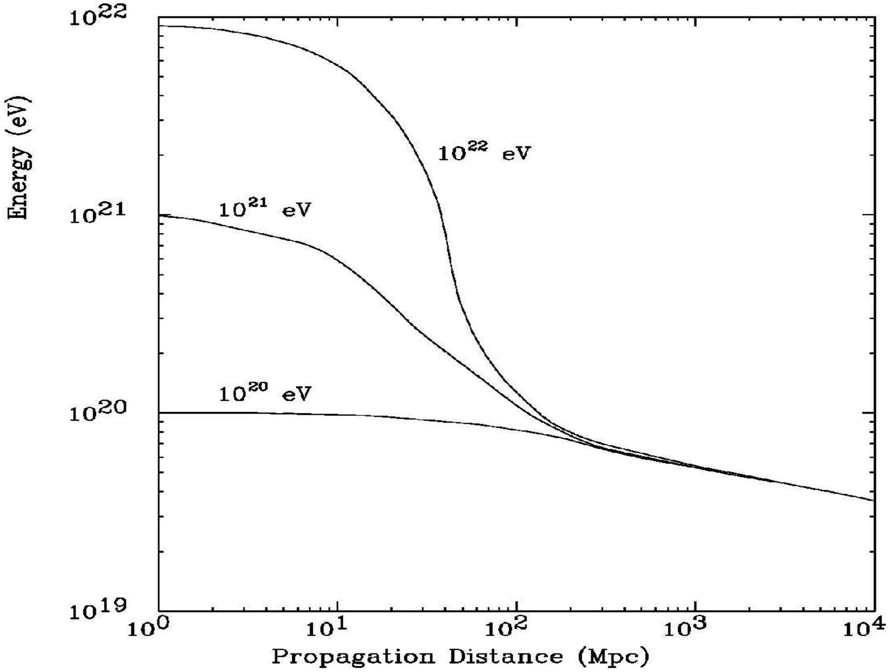
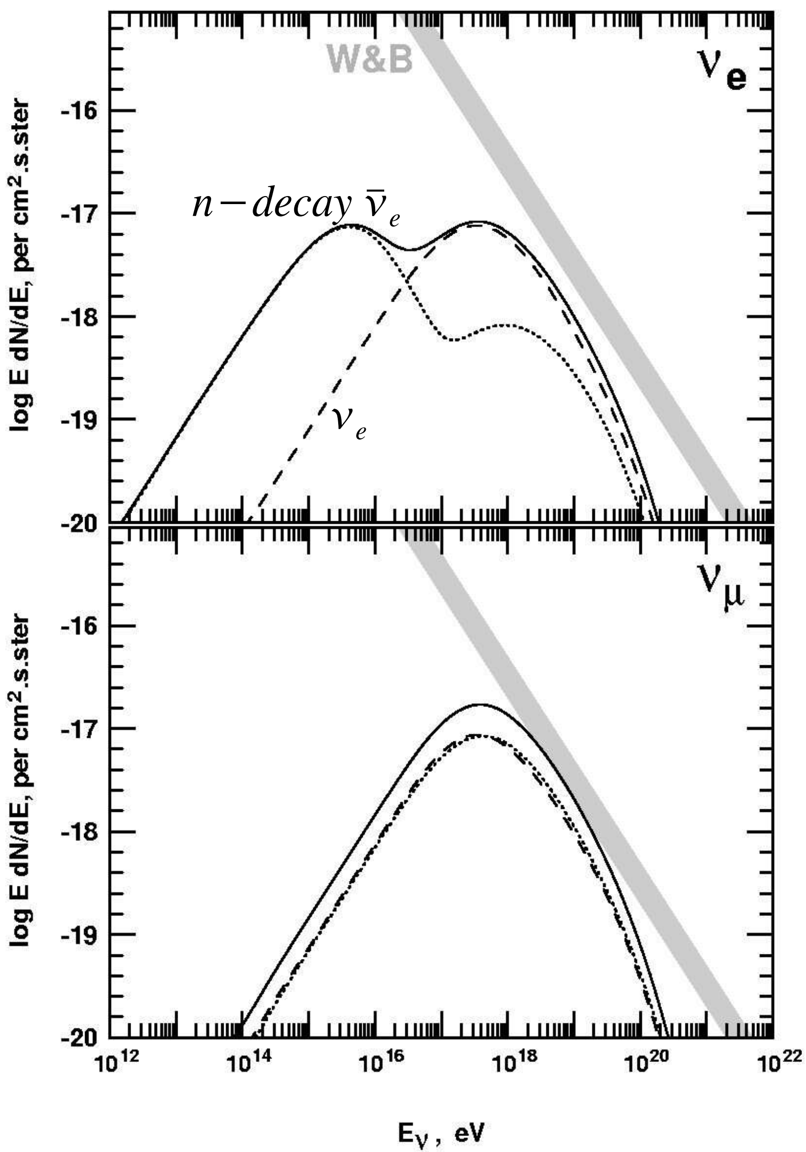


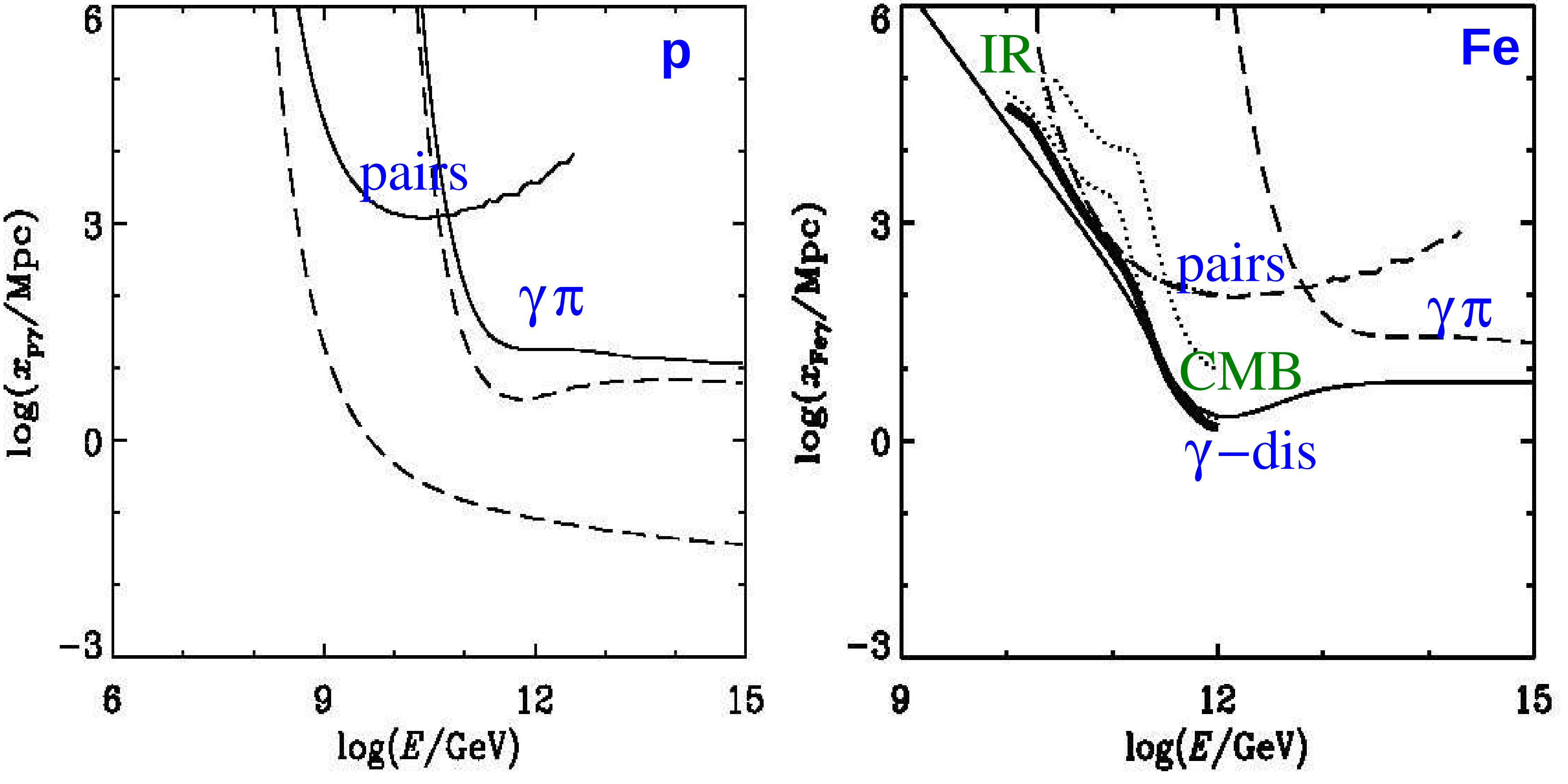
Photo-pion production attenuates protons and produces neutrinos!

Engel, Seckel, Stanev 2001

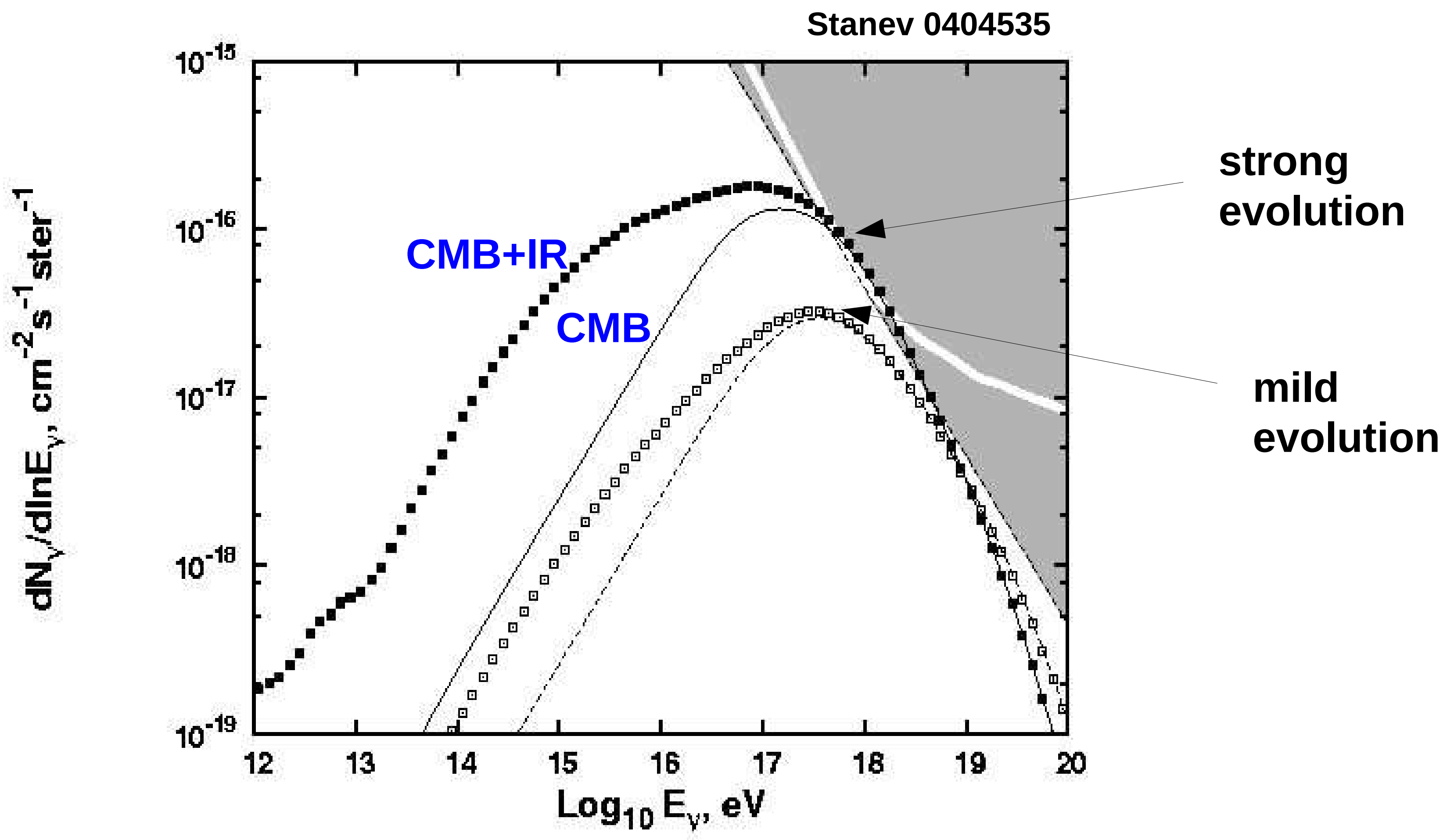


Proton (and Fe) energy loss-time

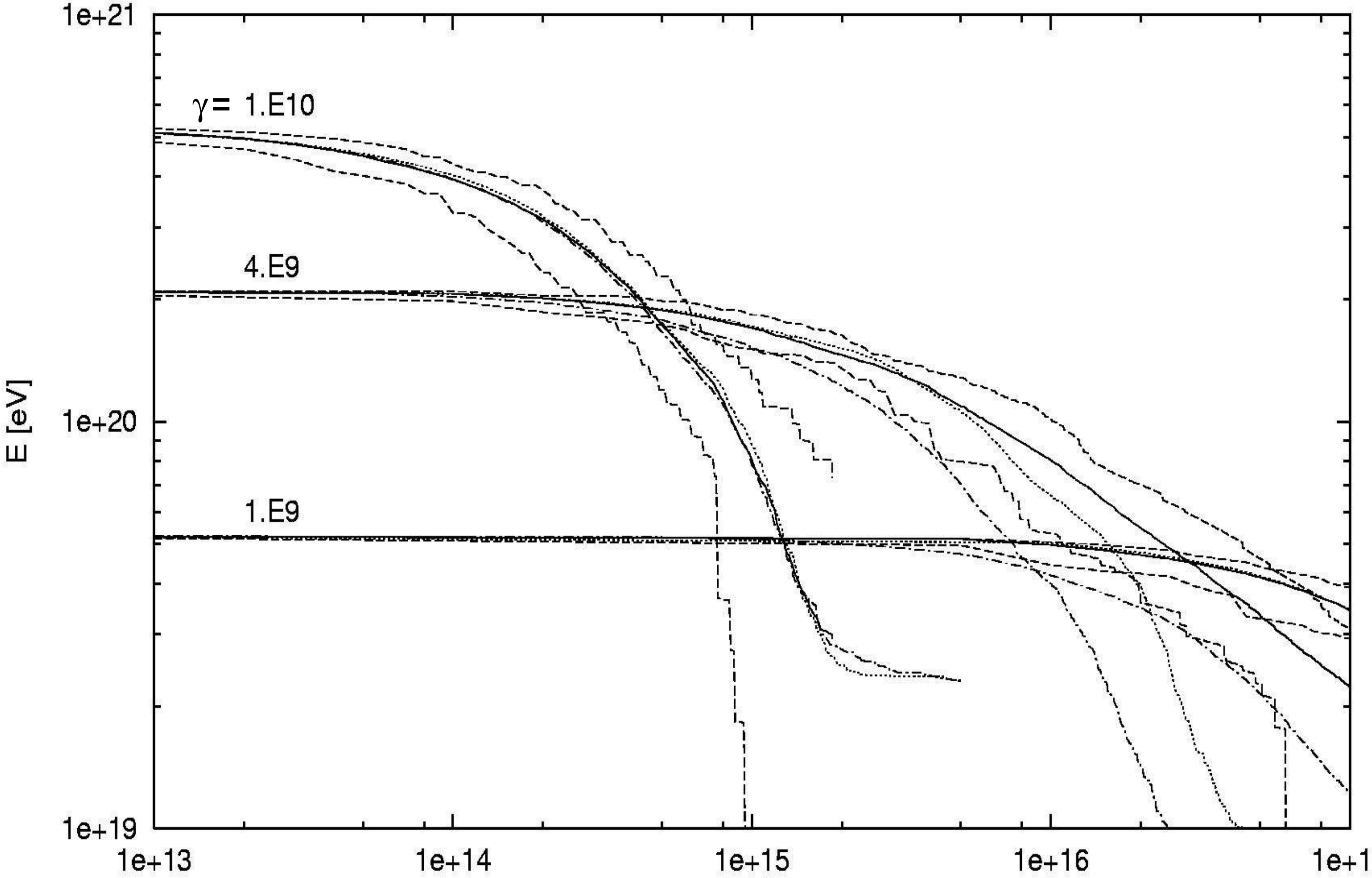
Protheroe



Also IR background adds to the neutrinos from proton photo-pion



What if UHECR composition is heavy? (at least at the source)



1 Mpc

1 Gpc

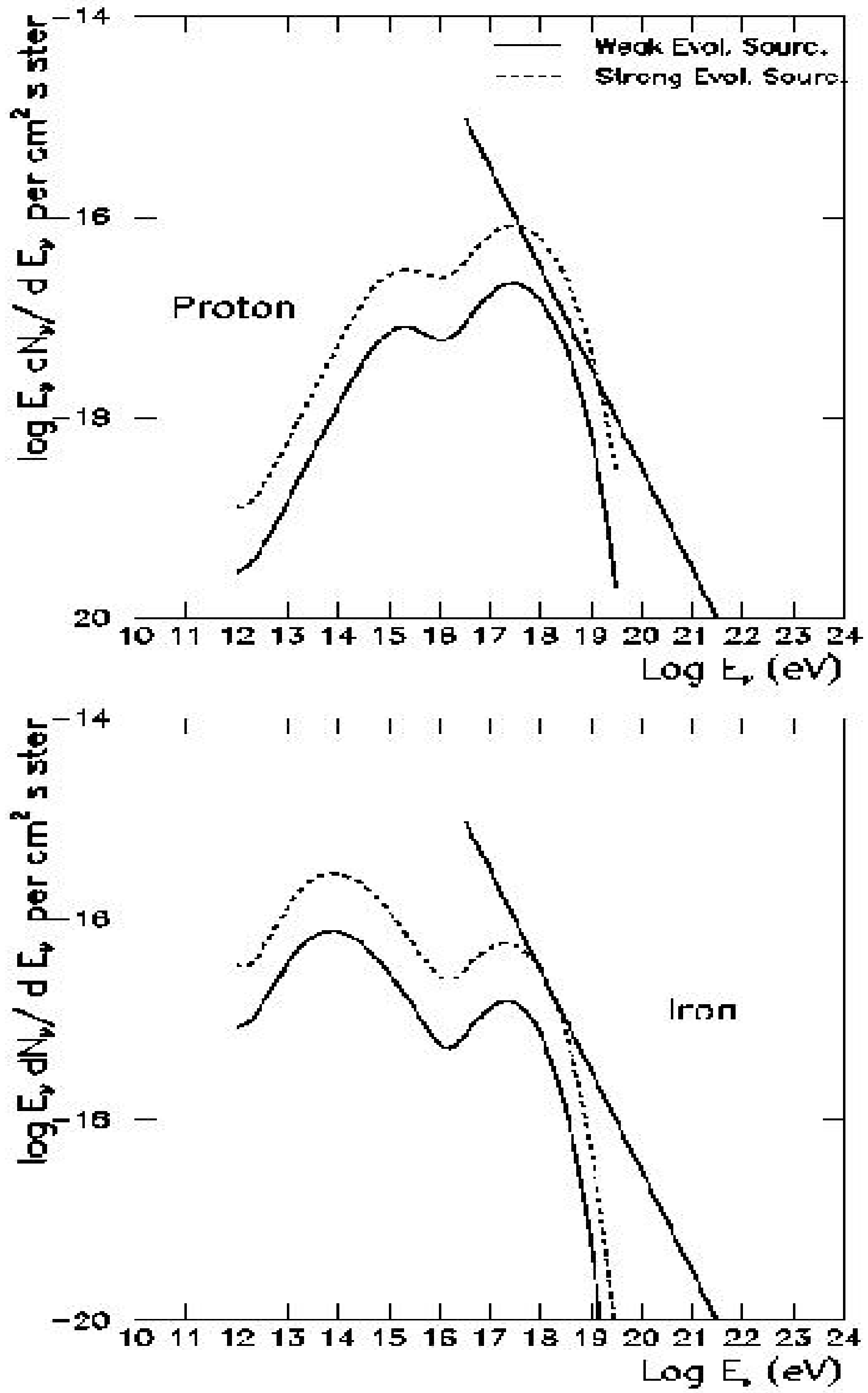
Epele, Roulet 9808104

Ave et al. 0409316
(see also Hooper et al.)

But photodisintegration produces only low energy (10^{14} eV) from n-decay.
To have high energy neutrinos from Fe photopion production need E > 5 10^{21} eV

This heavy composition is at the source, above 10^{20} eV we should see mostly protons

Due to oscillations, flavor distribution becomes 1:1:1



ON FLAVOR RATIOS:

Beam dump neutrinos: $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

oscillations for $L > 10\, E\,[EeV]\, pc$ $\rightarrow \nu_e : \nu_\mu : \nu_\tau = 1:1:1$

What if flavor content different?
e.g.:
muons stopped before decay (strong source B fields) $0:1:0 \rightarrow 0.5:1:1$

ν_e **from n-decay** $1:0:0 \rightarrow 3:1:1$

if neutrinos decay in flight $\left(\nu_{2,3} \rightarrow \nu_1 + \phi\right)$

$$1:2:0 \rightarrow U_{e1}^2 : U_{\mu 1}^2 : U_{\tau 1}^2 \sim 5:1:1 \;\left(U_{e3} \simeq 0\right)$$

for inverted hierarchy $\left(\nu_{1,2} \rightarrow \nu_3 + \phi\right)$

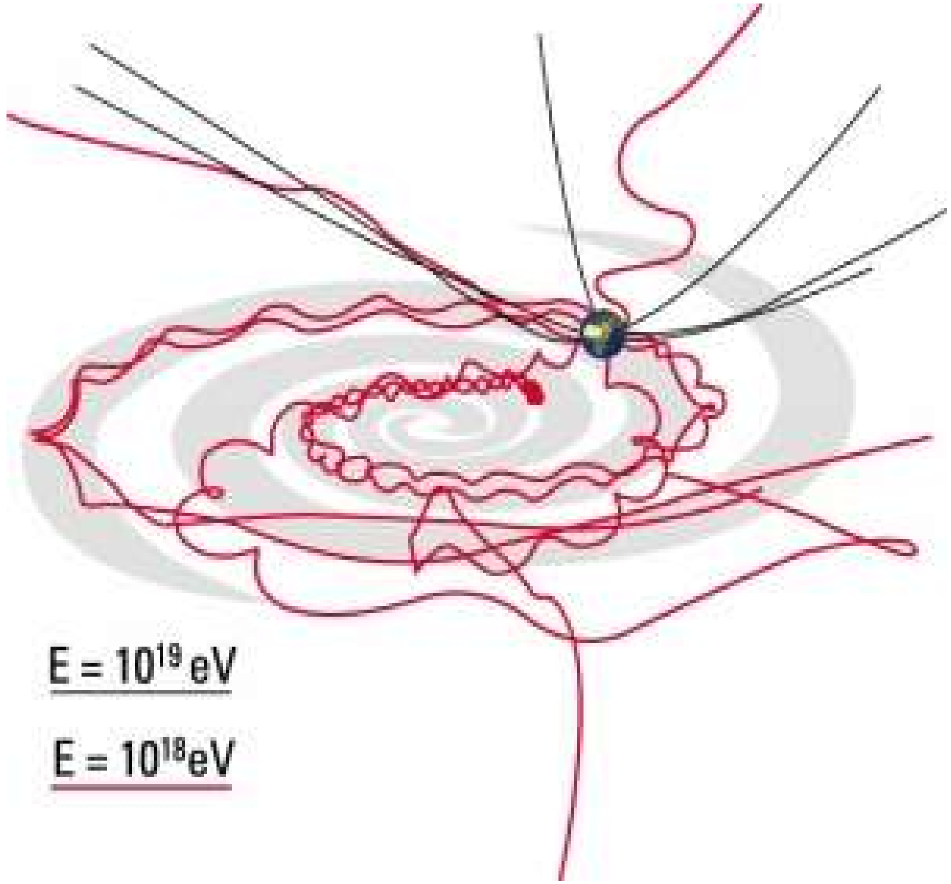
$$1:2:0 \rightarrow U_{e3}^2 : U_{\mu 3}^2 : U_{\tau 3}^2 \sim 0:1:1 \;\left(U_{e3} \simeq 0\right)$$

if Ue3 $\neq$ 0, also depends on CPV phase δ

(see Pakvasa 0412371)

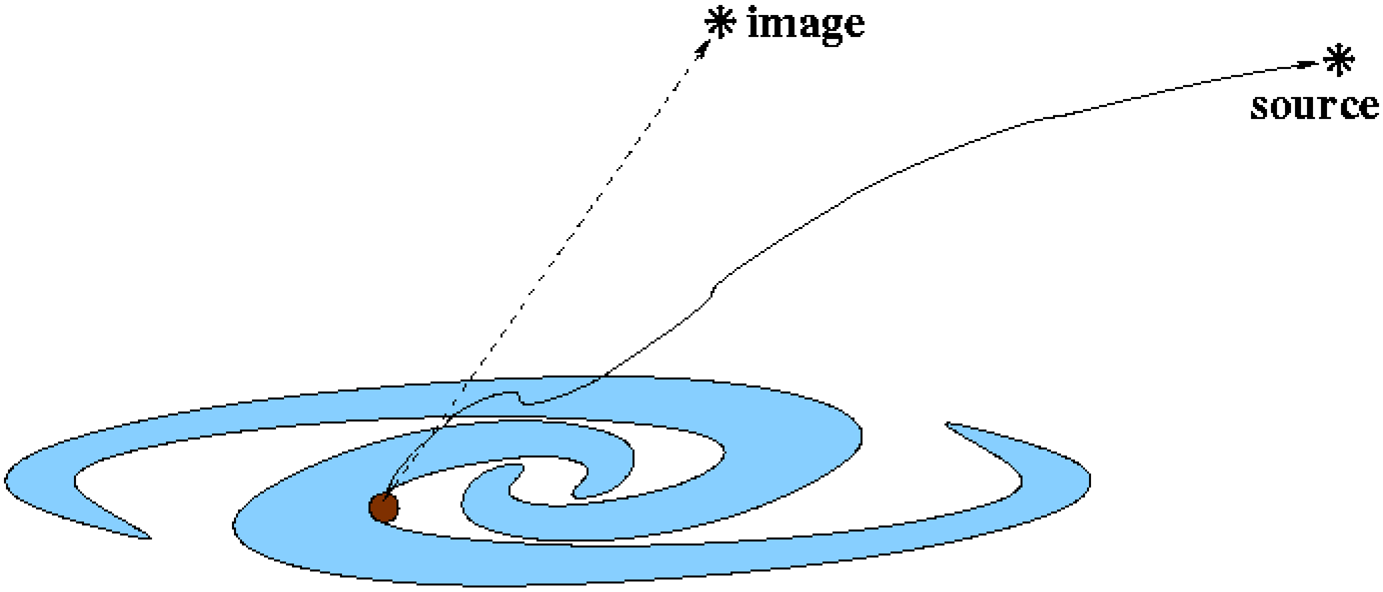
UHECR propagation in Galactic magnetic fields

(with Harari and Mollerach)
9906309,0001084,0202362,0205448,0404304



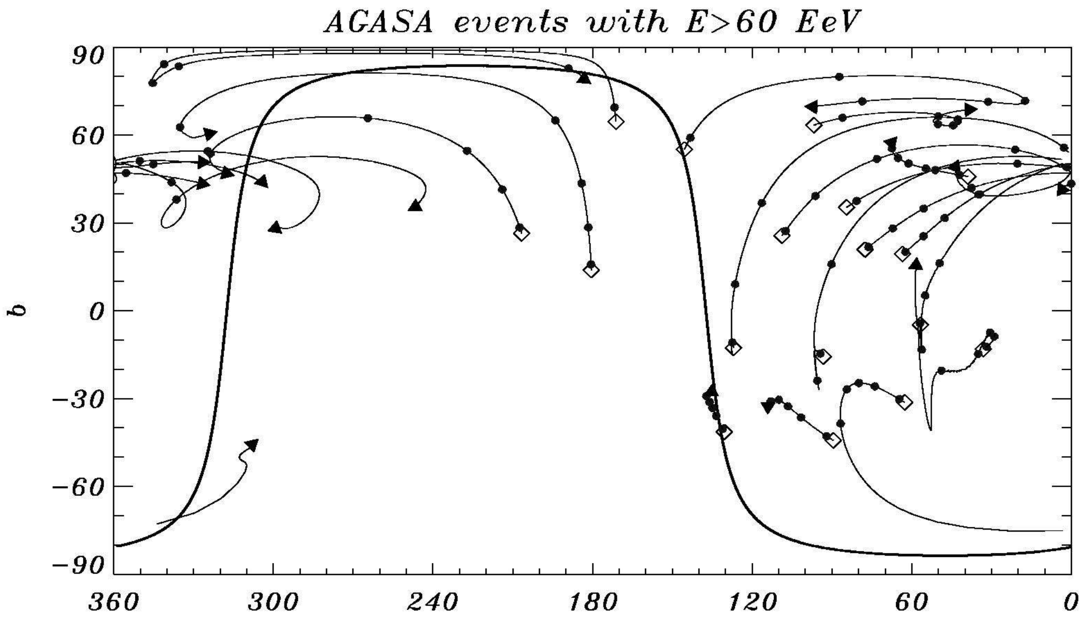
It is only for E/Z >10^{19} eV that trajectories become straight and astronomy becomes possible

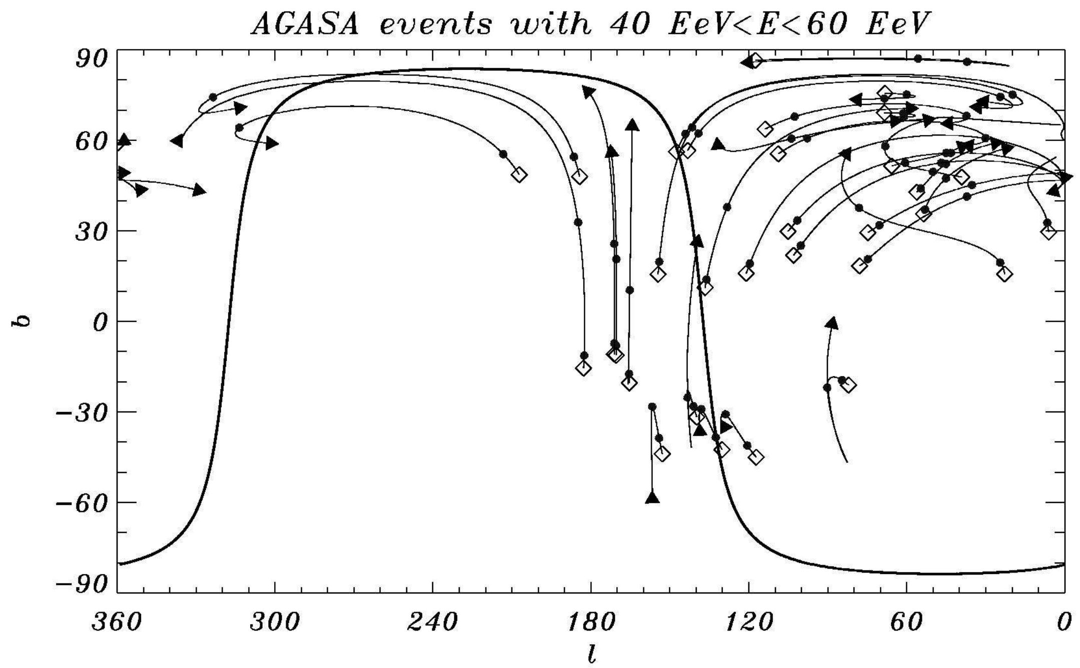
If Galactic B field (and composition) were known, one could correct the arrival direction to search for the source

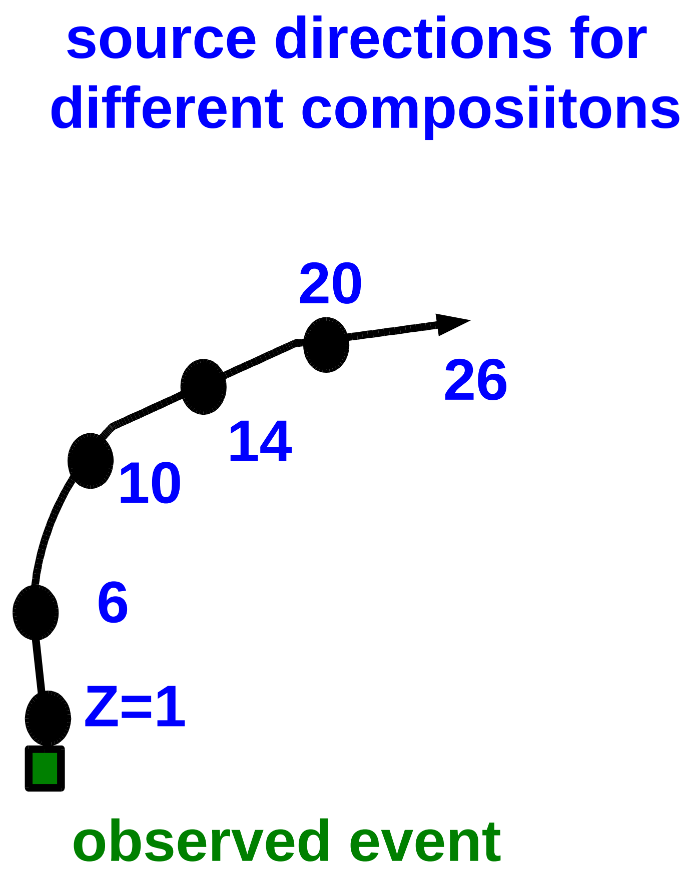


Need to 'backtrack antiprotons' (antinuclei)

AGASA events



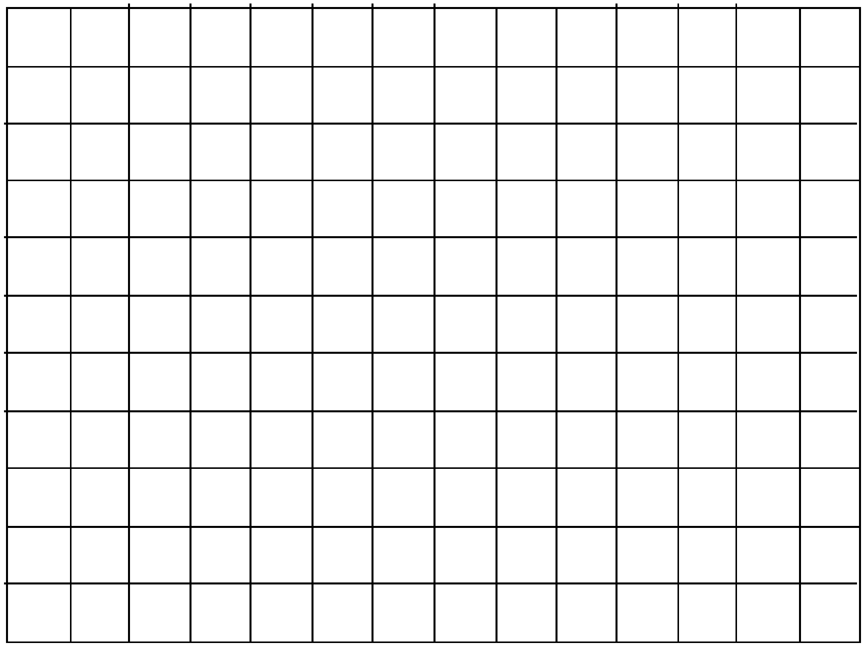




And multiple images can appear

Sky as seen on Earth

b



l

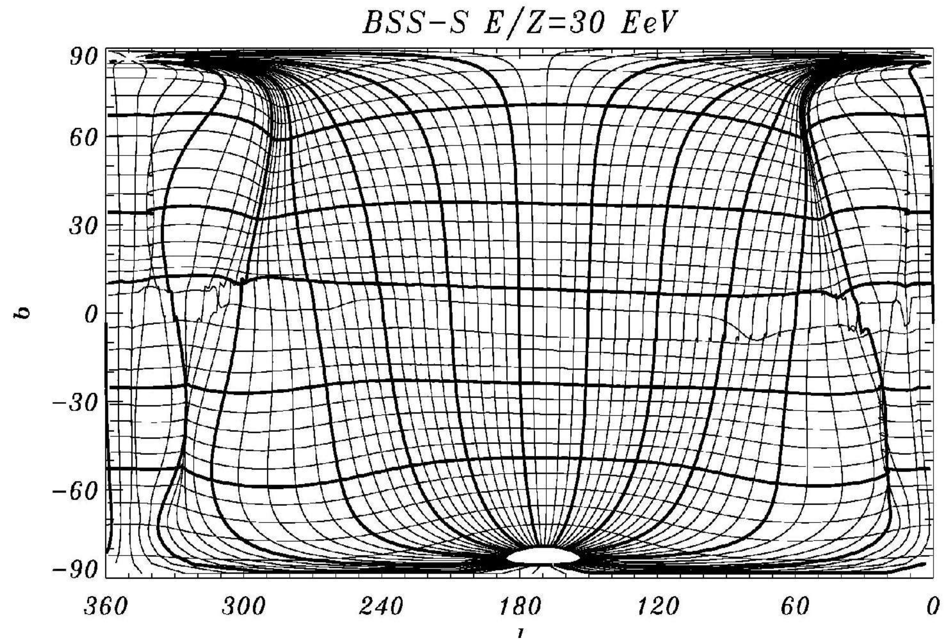
For every fold, two new images are present

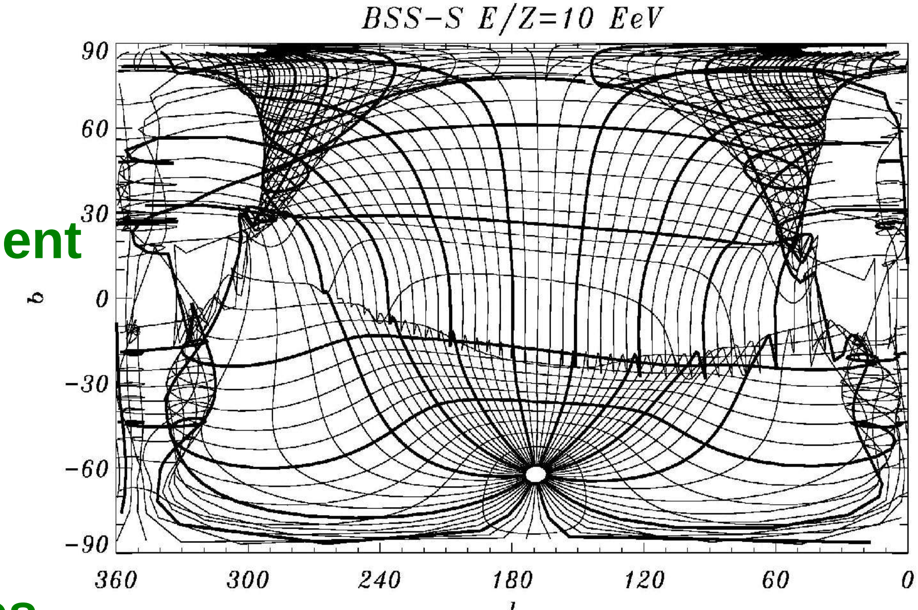
sky stretching ⟶ demagnification

sky compression ⟶ magnification

at folds (caustics) magnification diverges

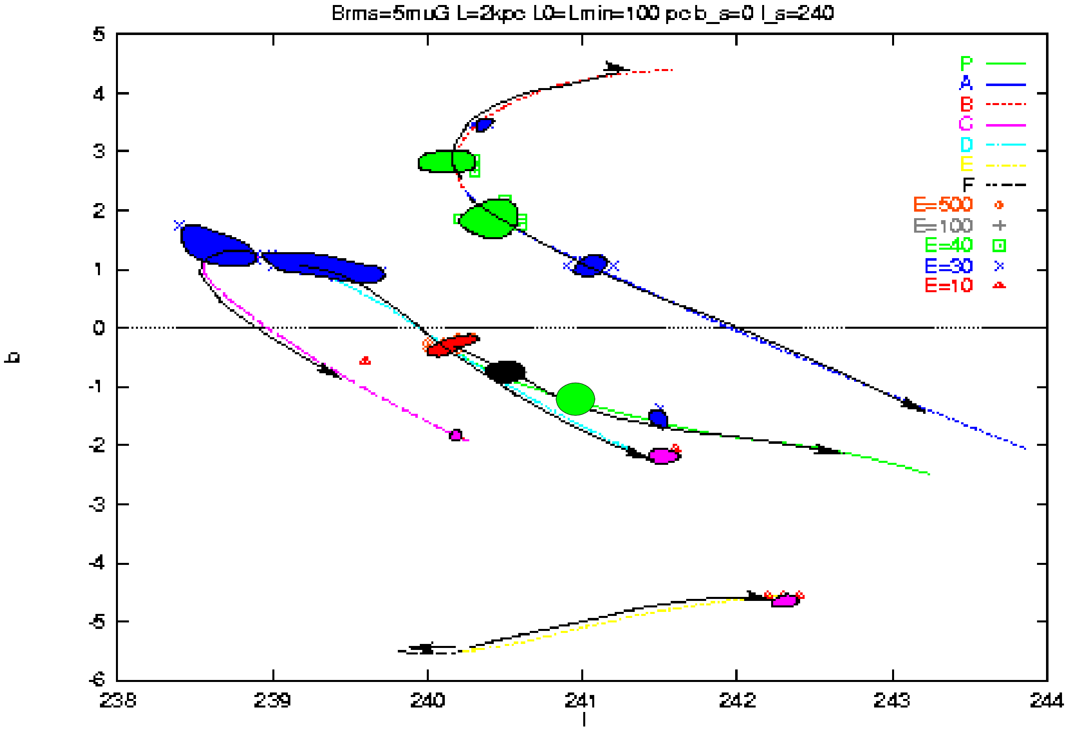
Sky projected into the halo





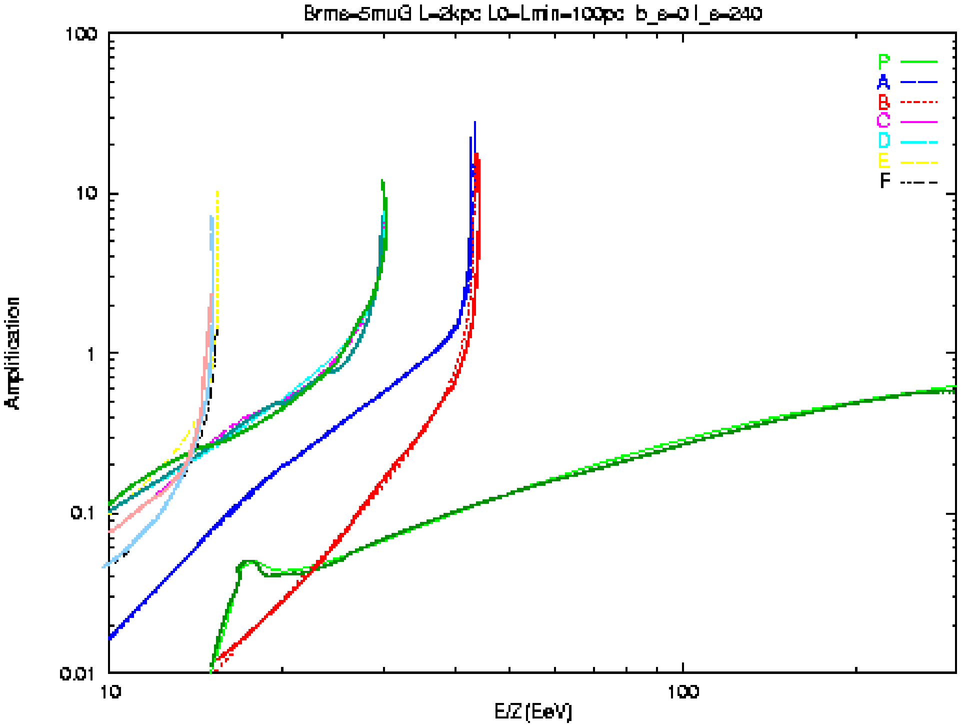
example:

images



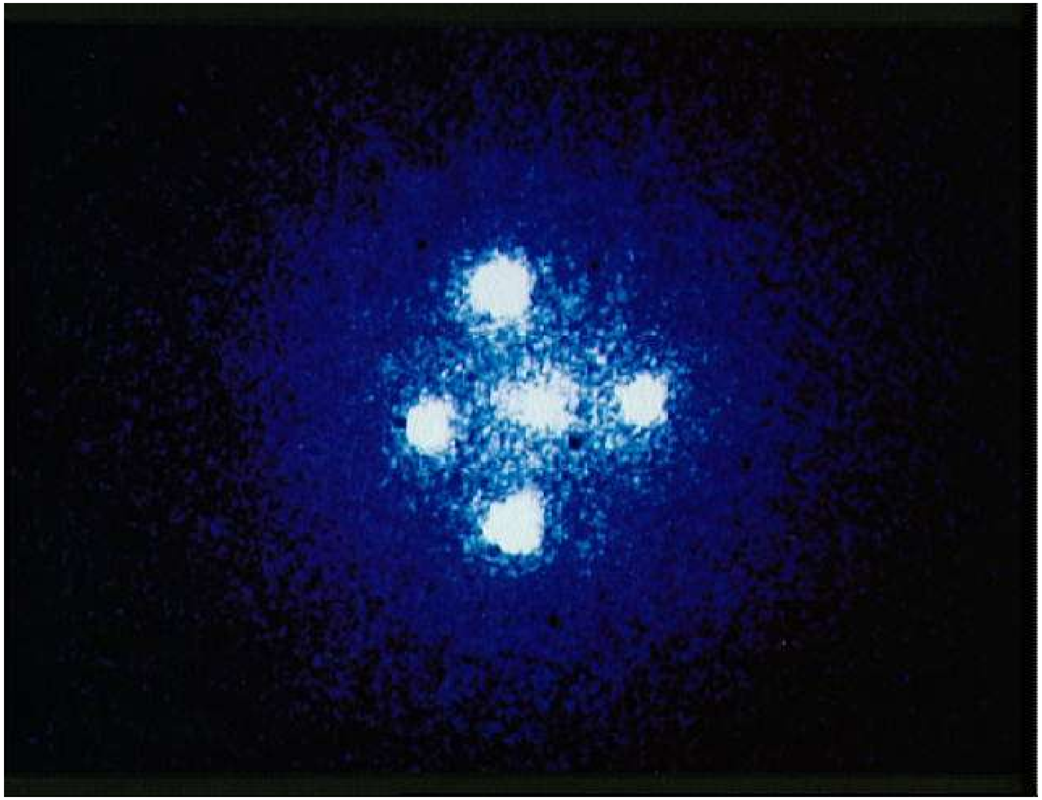
5×10^{20}, 10^{20}, 4×10^{19}, 3×10^{19}, 10^{19}

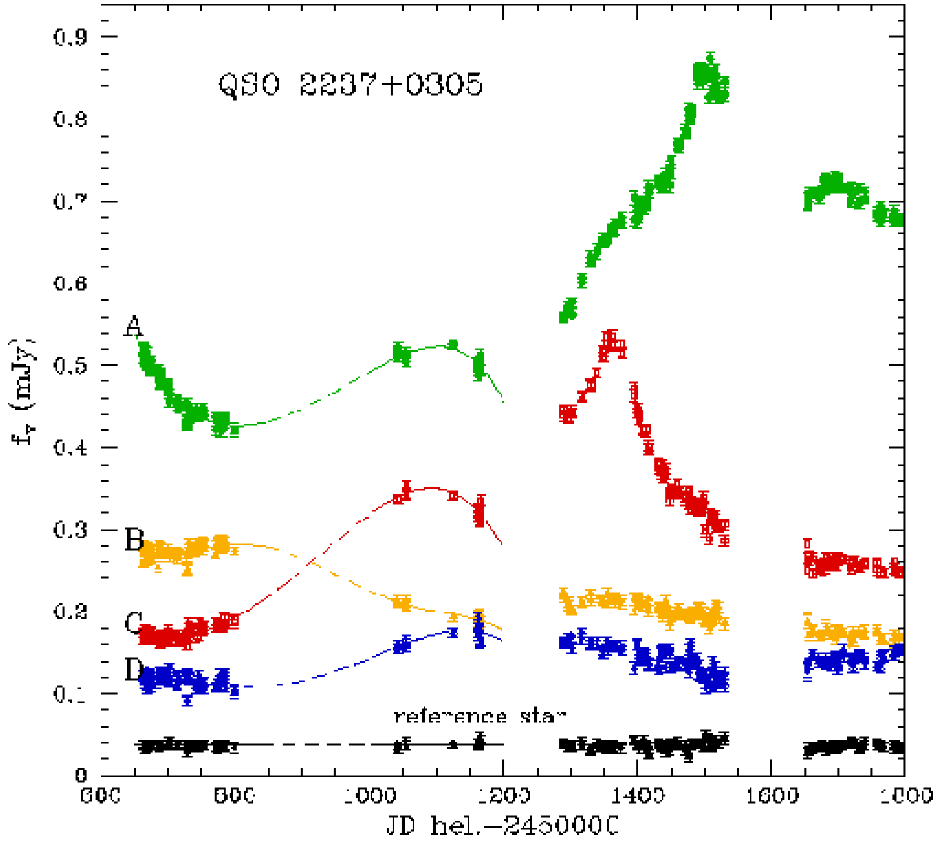
magnification



this is similar to

(Ogle)





Einstein's cross

log E

Cluster	Exp.	Date	Log E
Triplet #1	HP	810105	19.99
	AG	931203	20.33
	AG	951029	19.71
Triplet #2	AG	920801	19.74
	AG	950126	19.89
	AG	980404	19.73
Doublet #1	AG	910420	19.64
	AG	940706	20.03
Doublet #2	AG	860105	19.74
	AG	951115	19.69
Doublet #3	HP	860315	19.71
	AG	960513	19.68
Doublet #4	HP	720525	19.65
	YK	911201	19.62
Doublet #5	VR	610319	19.73
	HP	850313	19.62
Doublet #6	HP	661008	19.67
	YK	750317	19.67
Doublet #7	HP	740228	19.86
	AG	980330	19.84
Doublet #8	HP	760206	19.62
	HP	850313	19.62

(Uchihori et al.: AGASA, Yakutsk, HP, V. Ranch)

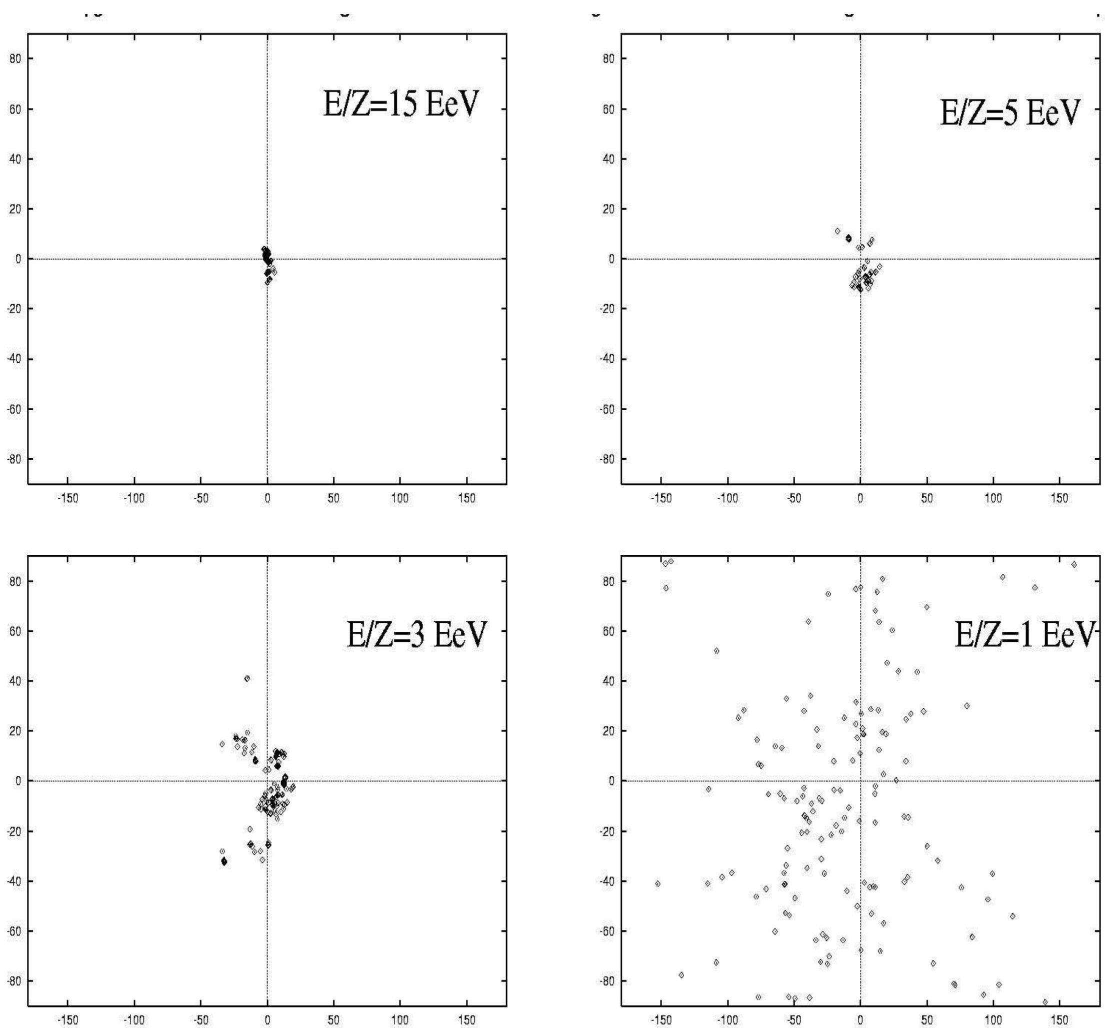
Magnification peaks due to the appearance of new images of a source lead to clustering of events both in angle and in energy, as seems to be suggested by the data

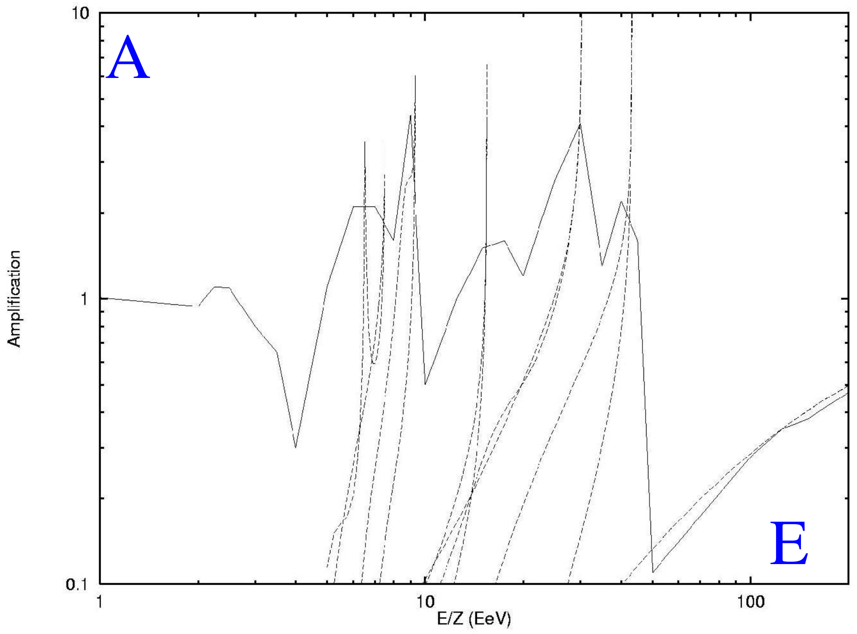
a quantitative analysis with AGASA events above 4×10^{19} eV shows that clustering in energy is significant

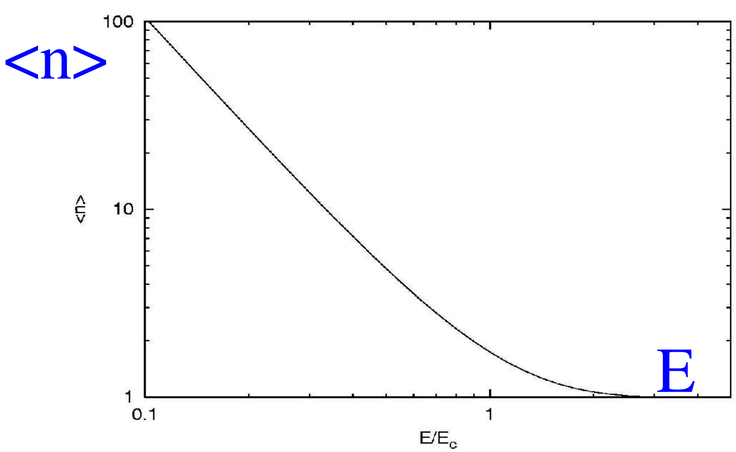
but statistics still very poor $\rightarrow$ need AUGER

Doing UHECR astronomy immersed in Galactic B fields is like doing optical astronomy putting a telescope at the bottom of a swimmingpool

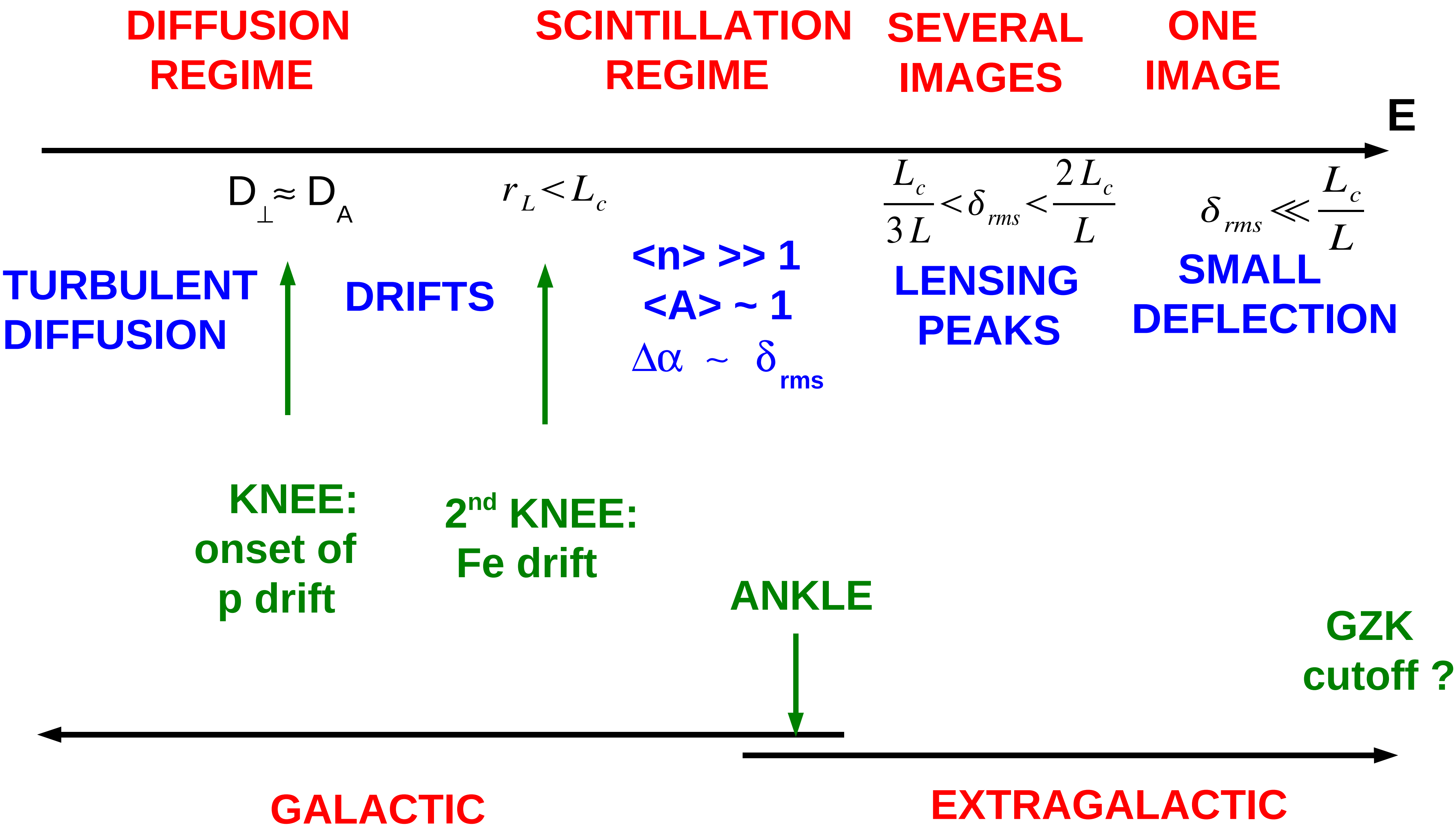
The scintillation regime







A regime is reached with a large number of images, spread over $\Delta\alpha \sim \delta_{rms}$ and with <A>~1 (like twinkling stars)



DIFFUSION REGIME
SCINTILLATION REGIME
SEVERAL IMAGES
ONE IMAGE
E
$D_\perp \approx D_A$
$r_L < L_c$
$\frac{L_c}{3L} < \delta_{rms} < \frac{2L_c}{L}$
$\delta_{rms} \ll \frac{L_c}{L}$
TURBULENT DIFFUSION
DRIFTS
<n> >> 1
<A> ~ 1
$\Delta\alpha \sim \delta_{rms}$
LENSING PEAKS
SMALL DEFLECTION
KNEE: onset of p drift
2nd KNEE: Fe drift
ANKLE
GZK cutoff ?
GALACTIC
EXTRAGALACTIC

many answers will come from AUGER, which is growing at Malargue