ASTROPARTICLE THEORY

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New Insights into High Energy Cosmic Rays

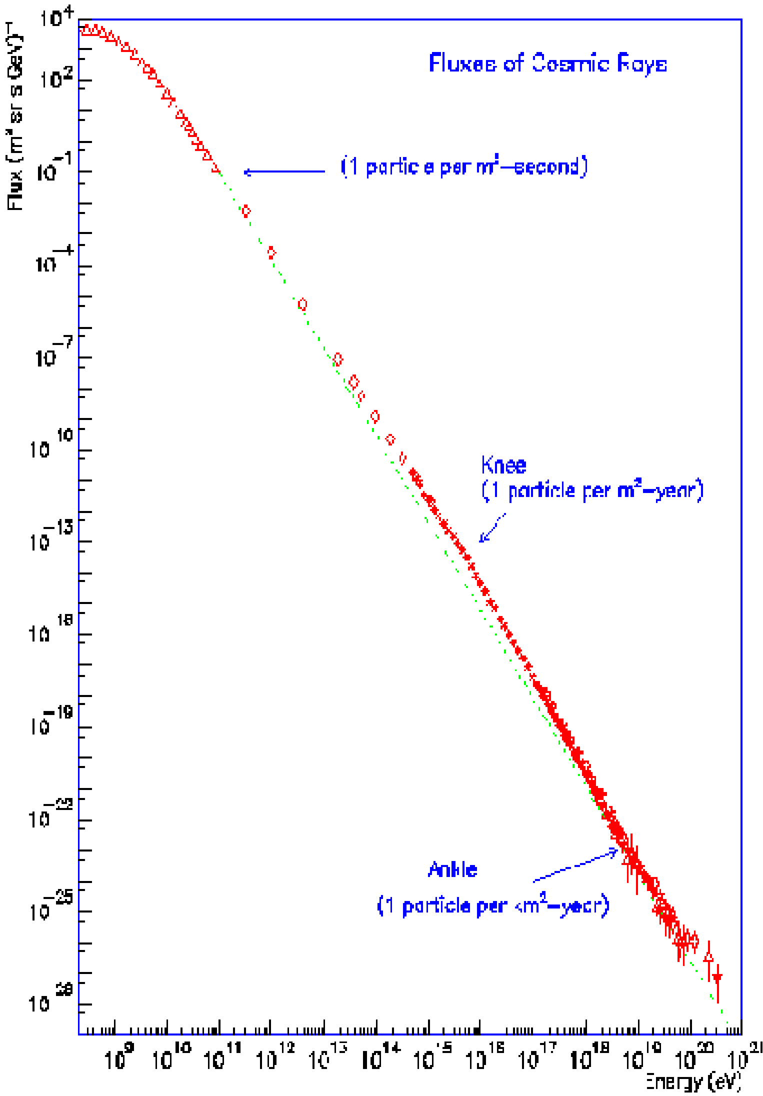
Cosmic Ray observables:

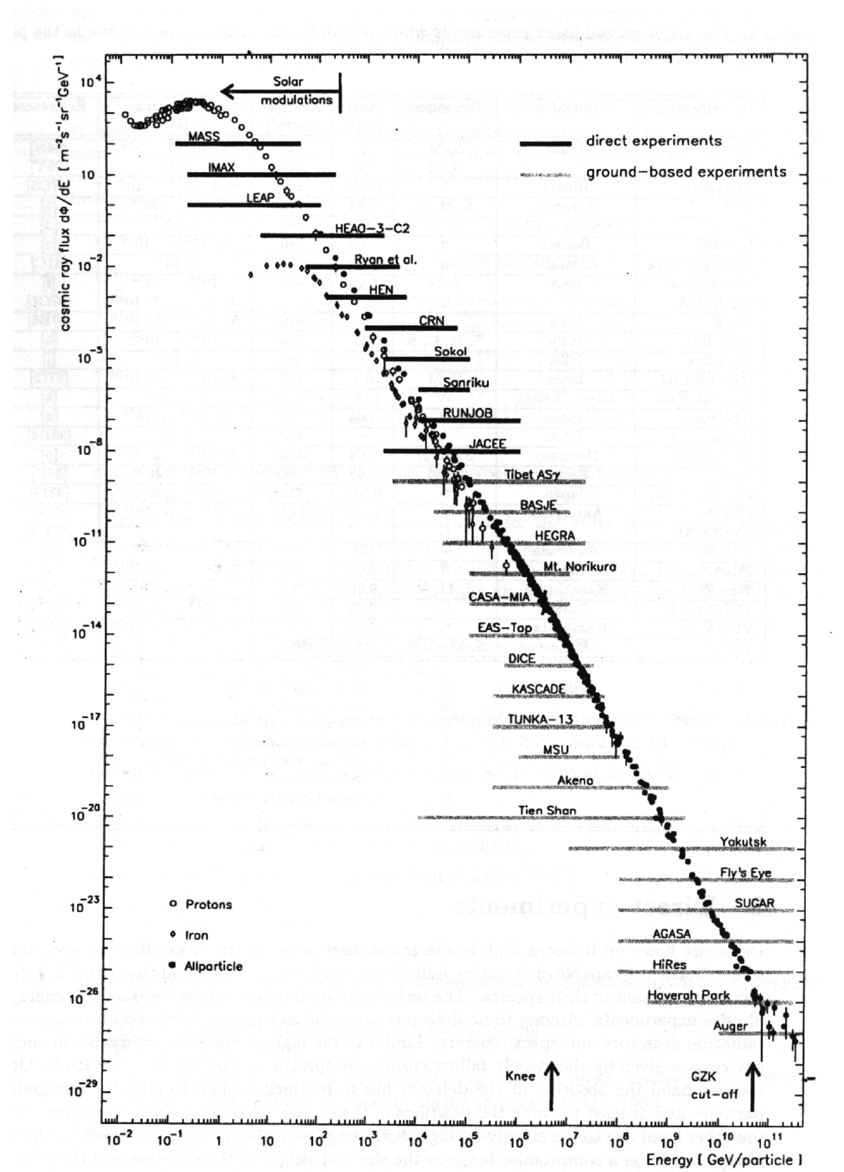
Spectrum, anisotropies, composition

Cosmic Ray challenges:

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

CR SPECTRUM and Experiments



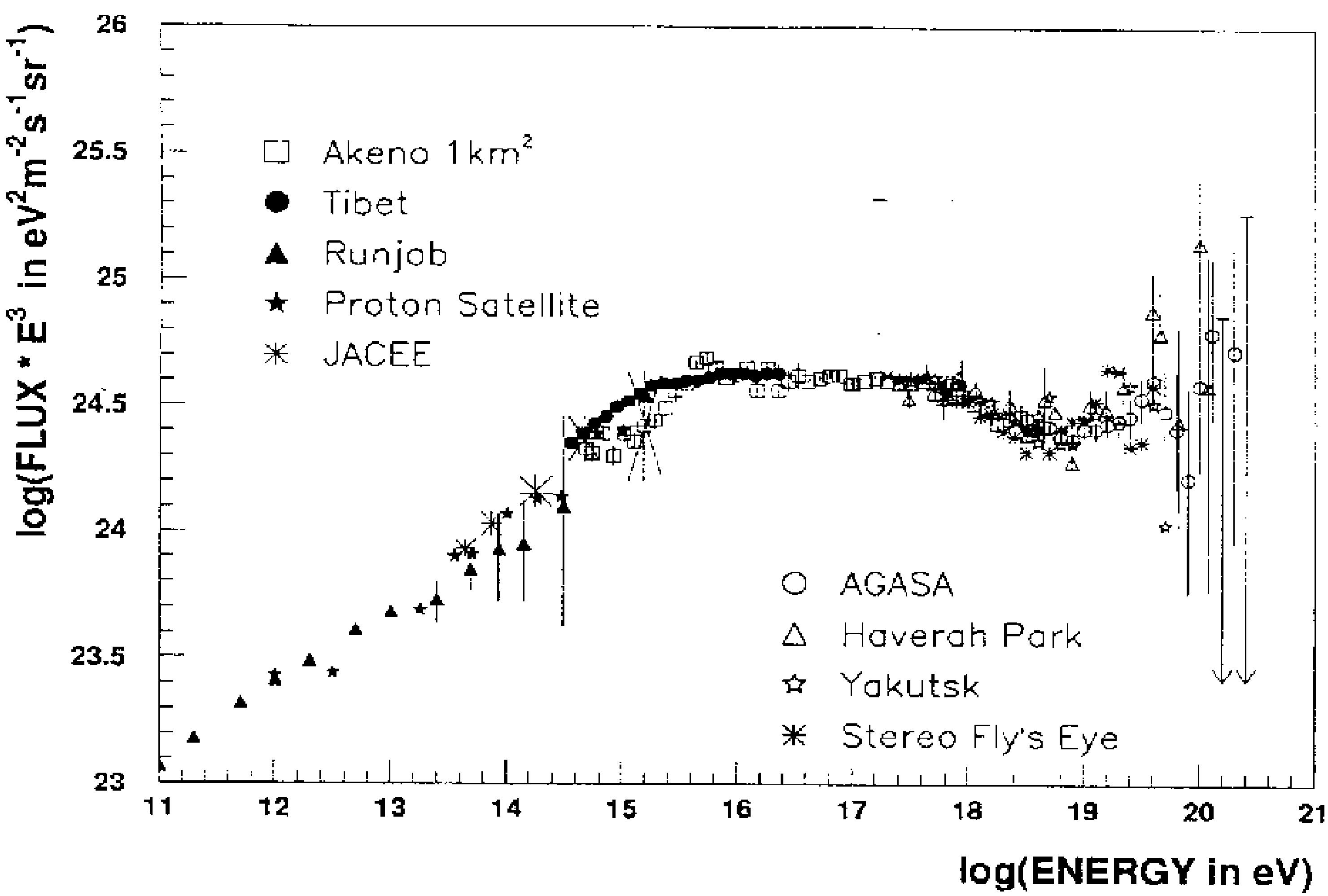


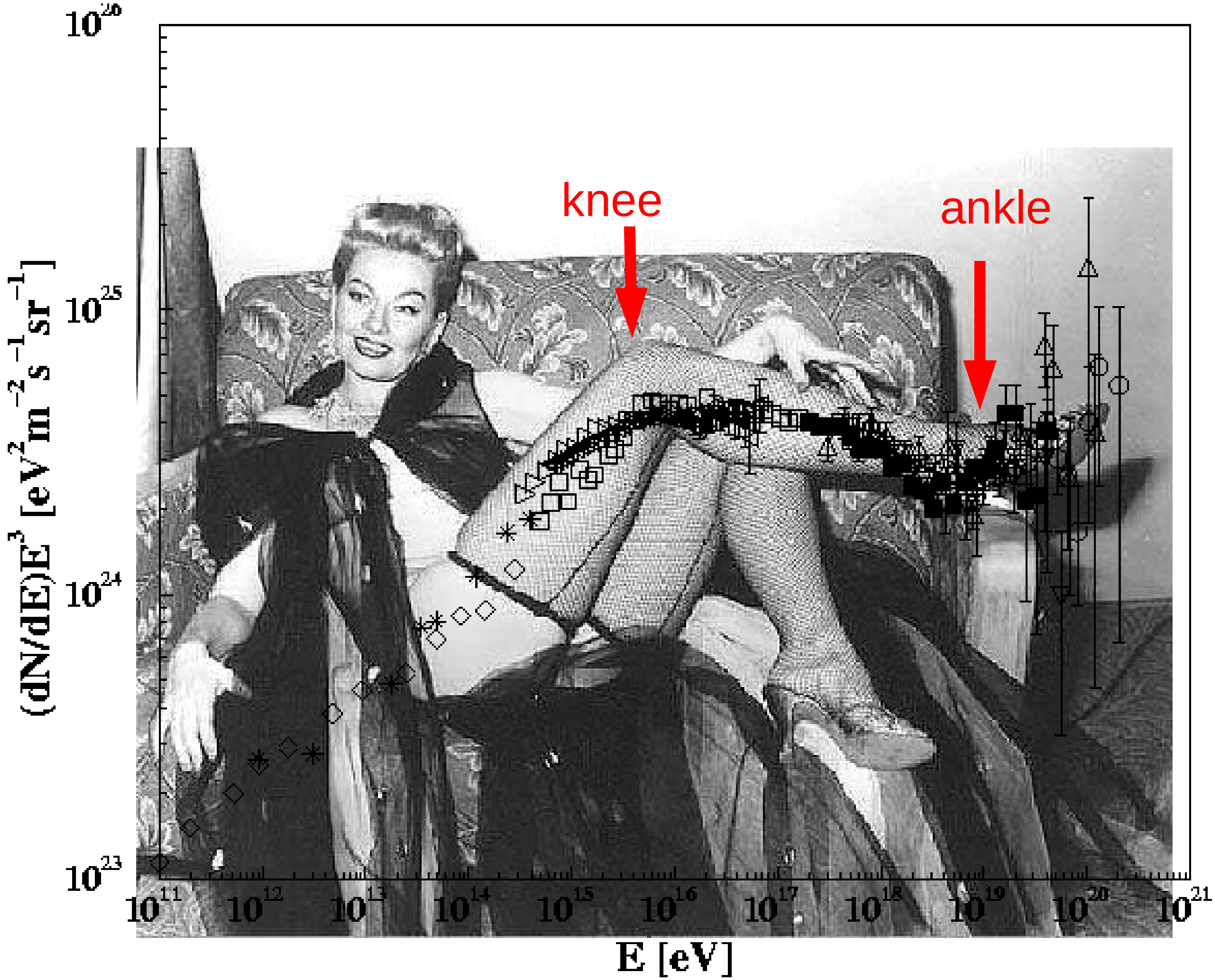
Balloons satellites

Air showers

CR spectrum x E^3

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





knee
ankle
10^{26}
10^{25}
10^{24}
10^{23}
(dN/dE)E^3 [eV^{2}m^{-2}s^{-1}sr^{-1}]
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}

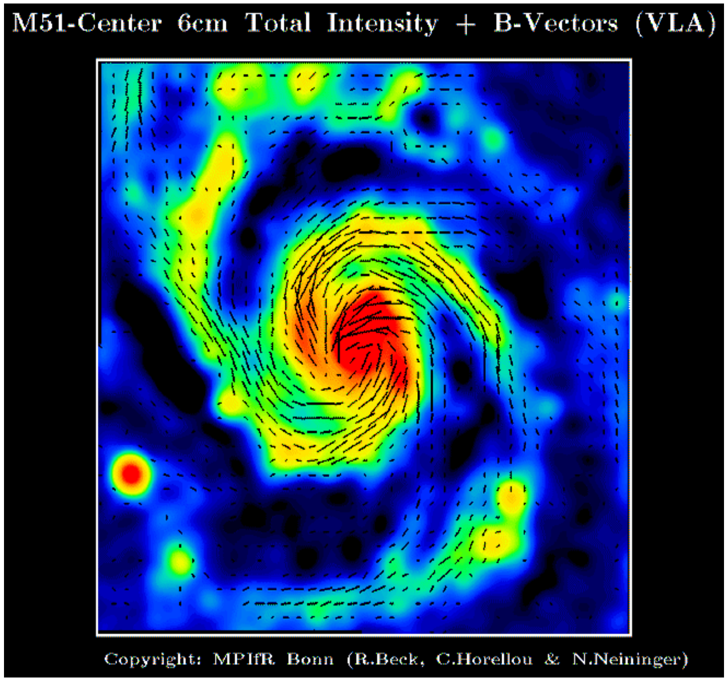
Less efficient acceleration in the sources
(e.g. parallel shocks --> perpendicular shocks)

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

More efficient escape from Galaxy
for rigidity dependent effects: composition should become heavier above E_{knee}

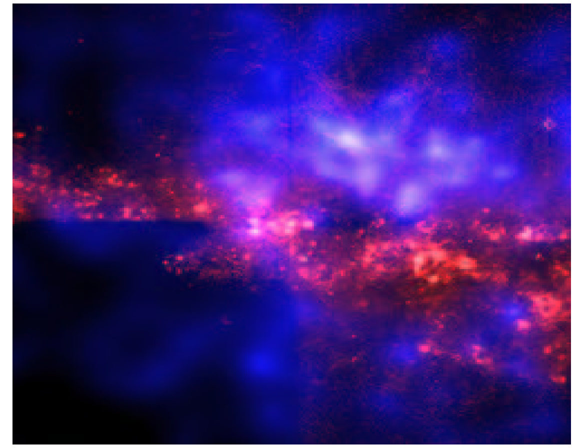
If due to changes in the escape mechanism, expect correlation between changes in spectrum and the behavior of the anisotropies

Galactic magnetic fields

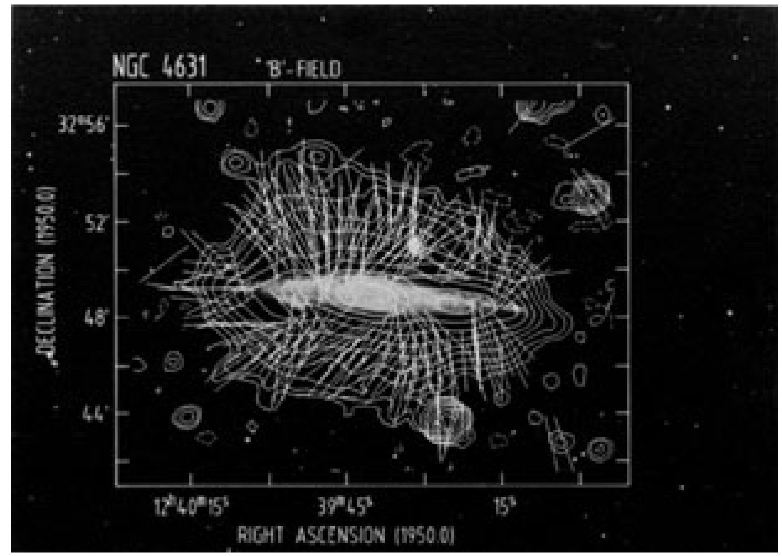


M51

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,

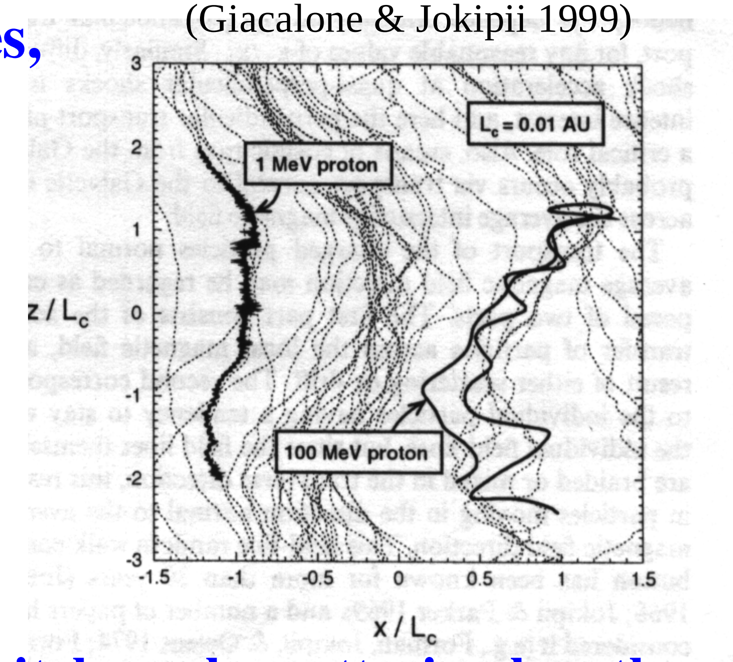
with Kolmogorov spectrum dE/dk ~ $k^{-5/3}$, with L_{max} ~ 100 pc

The level of turbulence is high:

$$\eta \equiv \frac{B_r^2}{B_0^2 + B_r^2} \simeq 0.5 \div 1$$

In regular field, CRs have helical trajectories,
with $V_{parallel} = V \cdot \cos\theta$ **(θ: pitch angle)**

(Giacalone & Jokipii 1999)



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

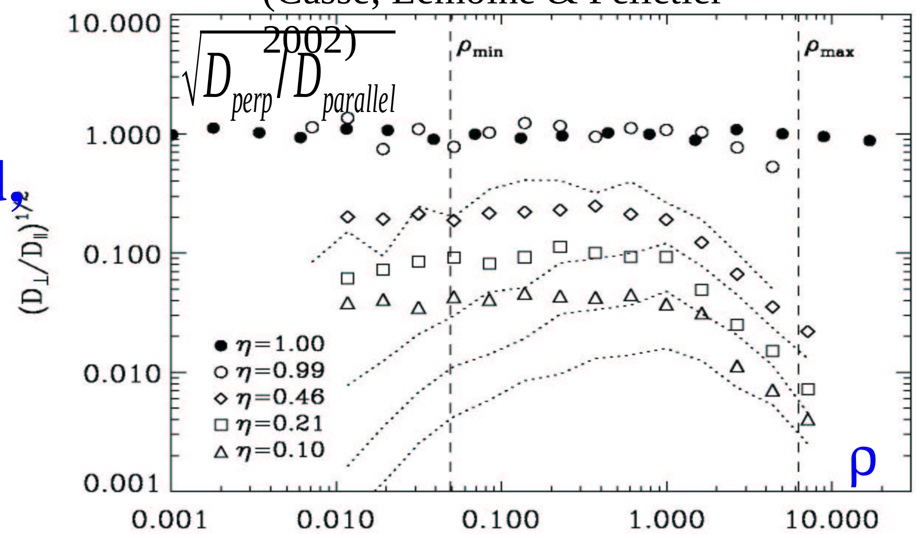
But for E/Z<10^{17} eV they scatter off magnetic field irregularities with scale ~ r_L, they make a random walk and diffuse:

$$D_{parallel} = \frac{\langle \Delta x^2_{parallel} \rangle}{2\Delta t} = \frac{c}{3} \lambda_{parallel}$$ **with** $$\lambda_{parallel} \propto \frac{r_L}{dE_{rand}/d\ln k} \propto E^{1/3}$$ **: pitch angle scattering length**

Diffusion ⊥ to B_0 much slower:
it arises from pitch angle scattering and, mostly, from wandering of field lines
=> need to follow trajectories to obtain decorrelation times

$$D_{perp} = \frac{\langle \Delta x^2_{perp} \rangle}{2\Delta t} \propto E^{1/3}$$

(Casse, Lemoine & Pelletier 2002)

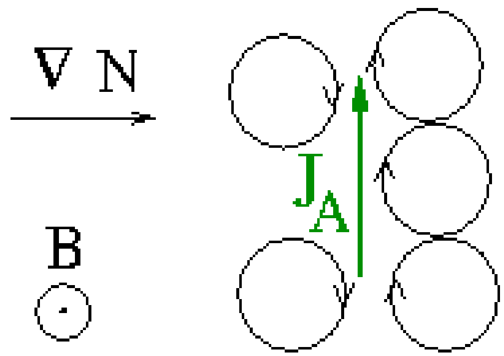


$$\rho \equiv \frac{r_L}{L_{max}/2\pi} \simeq \frac{E/Z}{3\times 10^{16}\, eV} \frac{\mu G}{|B_0|} \frac{100\, pc}{L_{max}}$$

Antisymmetric (Hall) diffusion: drift

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

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



$$D_A = \frac{r_L c}{3} \frac{1}{1+(r_L/\lambda_{perp})^2} \simeq \frac{r_L c}{3} \propto E$$

$$D_A \simeq D_{perp} \ for\ E \sim 10^{16}\, eV \quad (r_L \simeq L_{max}/2\pi)$$

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

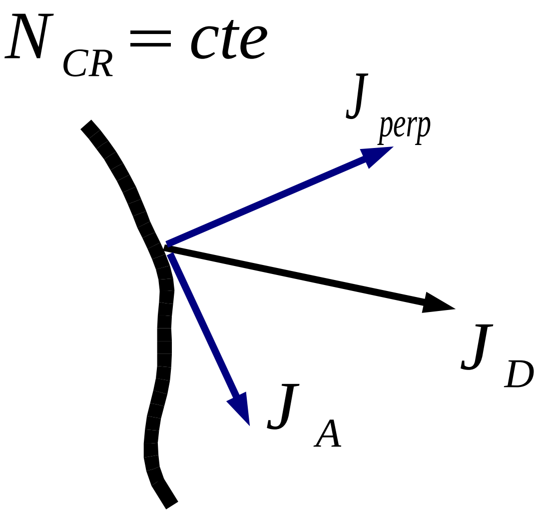
$$D_{ij} = \begin{pmatrix} D_{perp} & D_A & 0 \\ -D_A & D_{perp} & 0 \\ 0 & 0 & D_{parallel} \end{pmatrix}$$

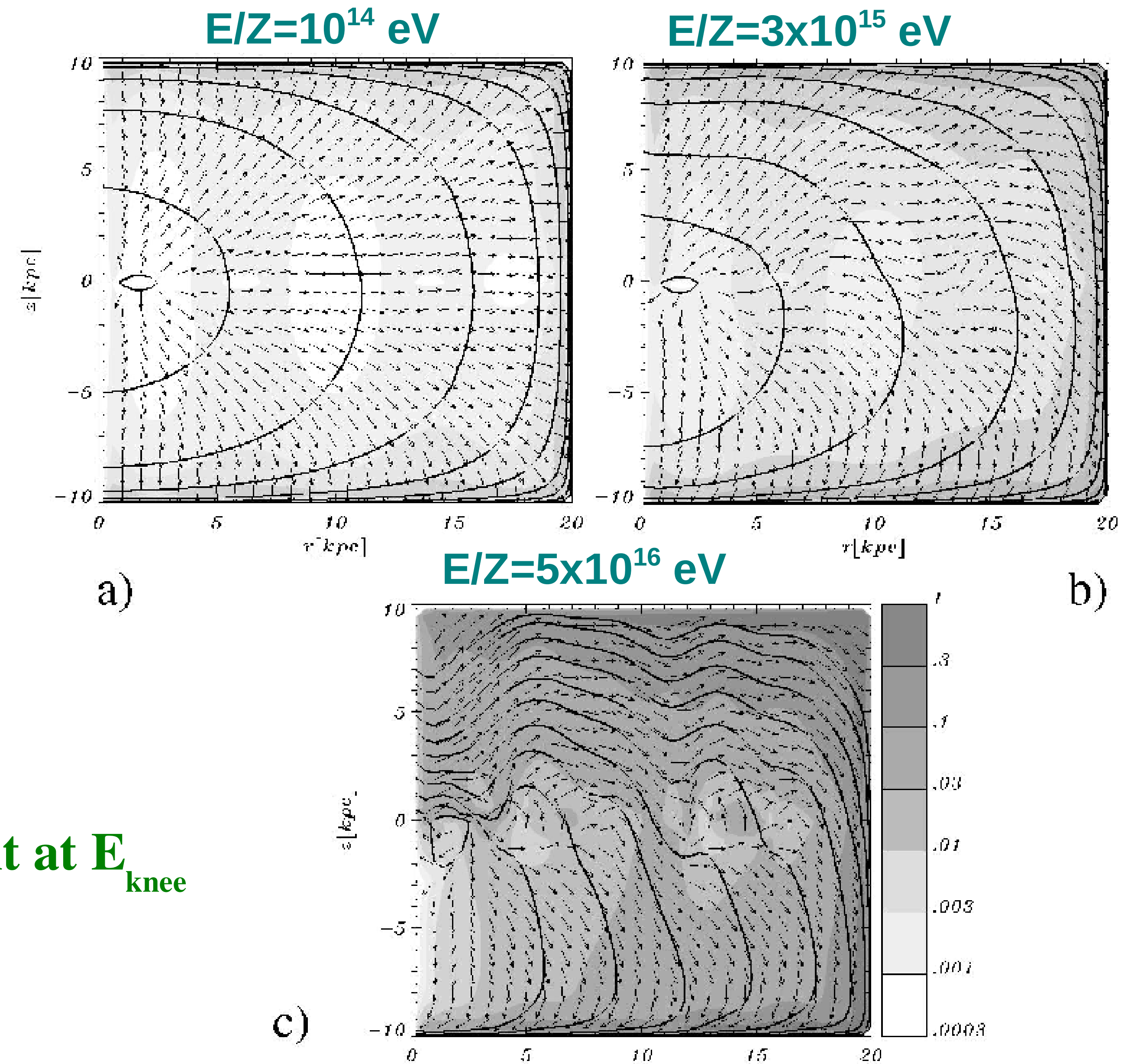
for B || z

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

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<<10^{16} eV, escape dominated by transverse diffusion $\tau_e \propto D_{perp}^{-1} \propto E^{-1/3}$

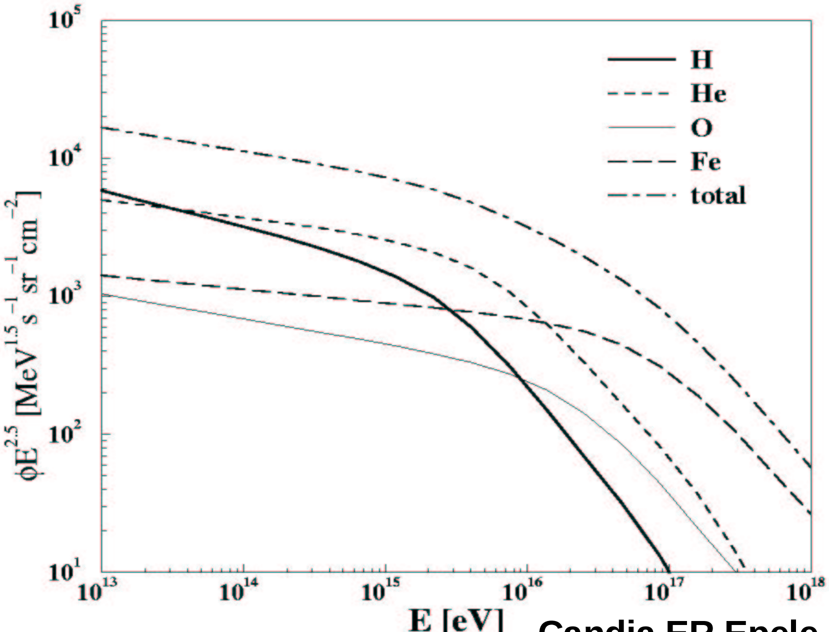
the observed spectrum is $\frac{dN_{CR}}{dE} \propto \tau_e \frac{dN_s}{dE} \propto E^{-\alpha_s - 1/3}$ **a source spectral index α_s ~ 2.3 is required**

For E/Z>10^{16} eV, escape dominated by drifts, $\tau_e \propto D_A^{-1} \propto E^{-1}$

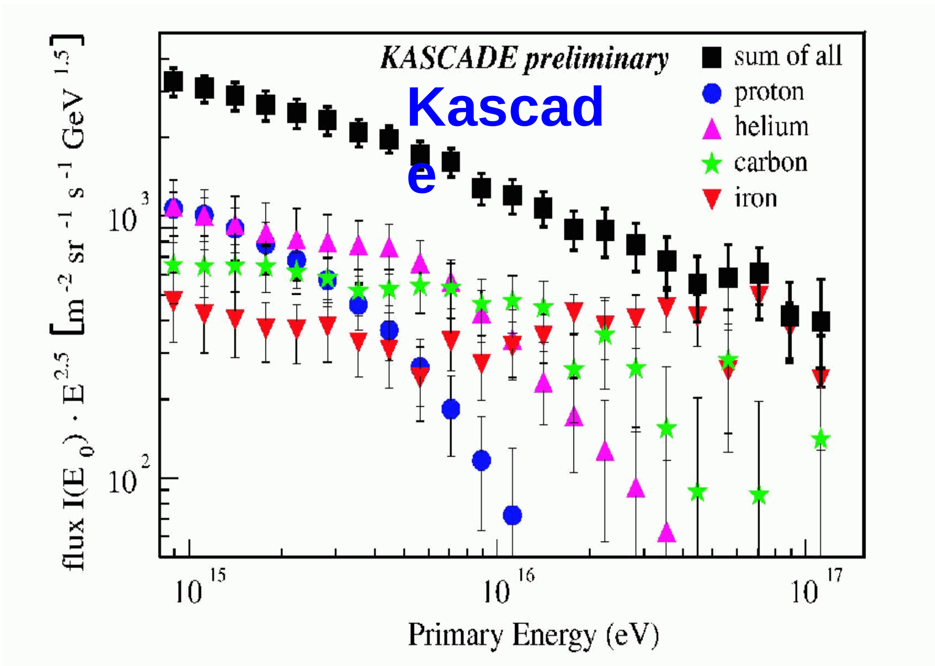
$$dN_Z / dE \propto E^{-\alpha_s - 1} \sim E^{-3.3}$$

=> Δα ~ 2/3

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

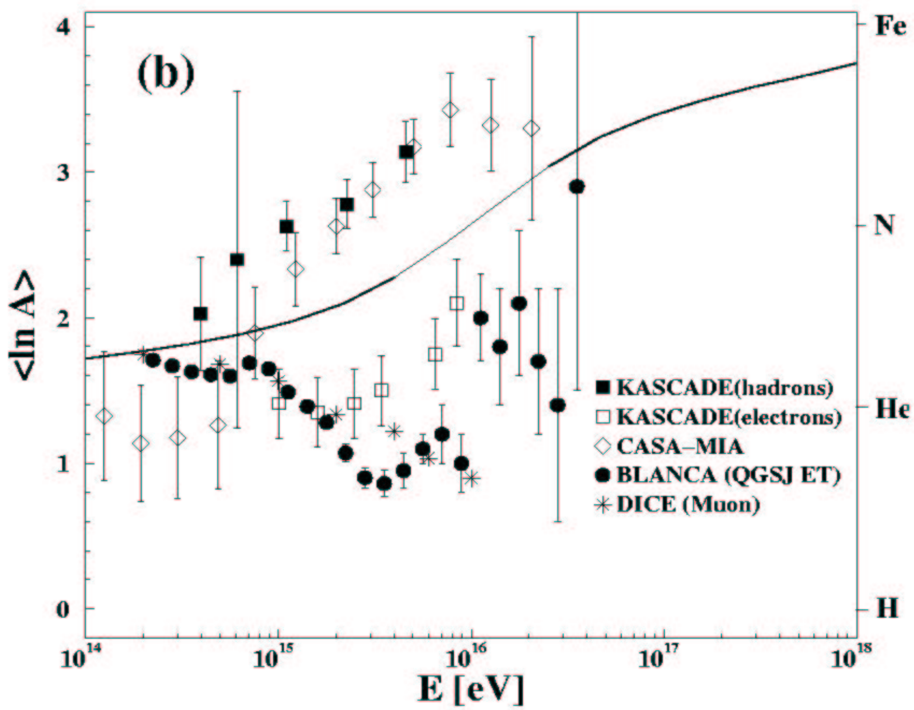


Candia,ER,Epele /0206336

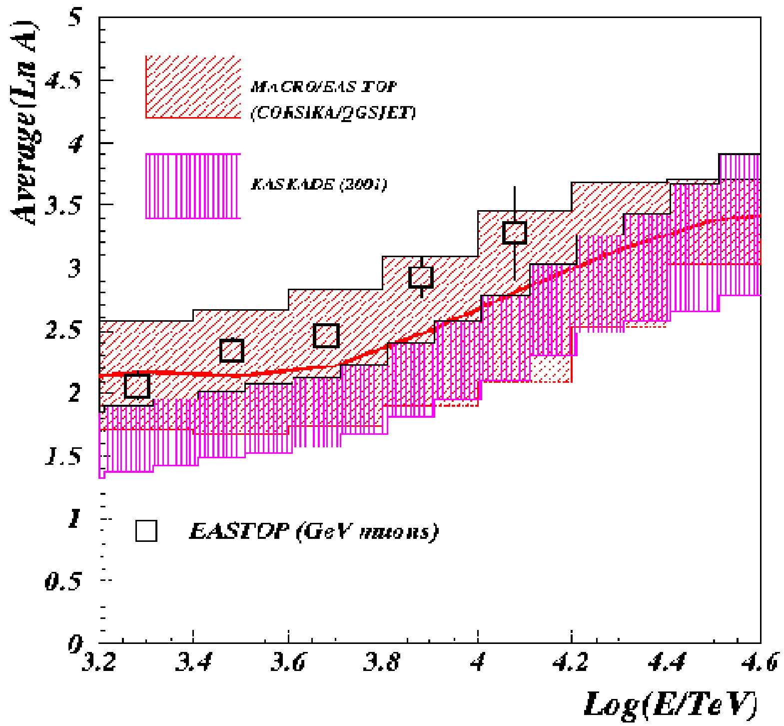


The composition becomes heavier

Candia,ER,Epele/0206336

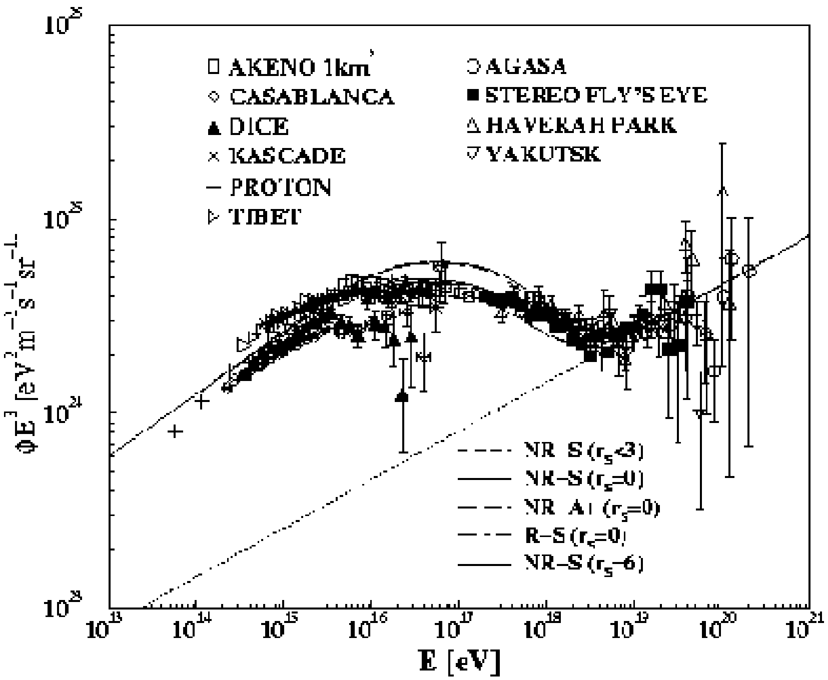


MACRO – Eas Top /0305325

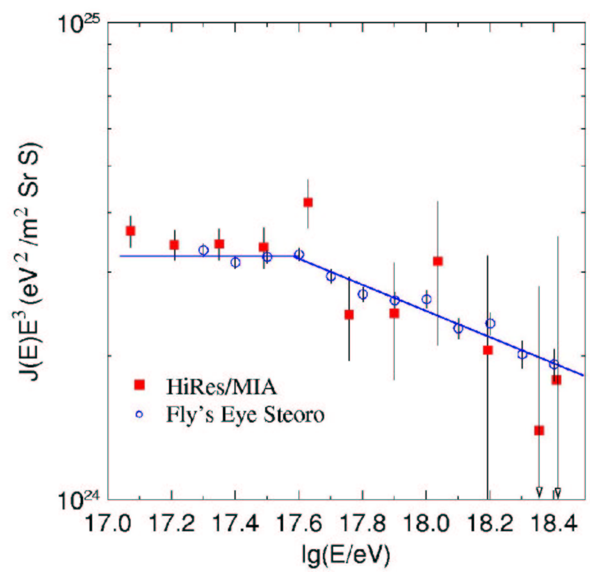


$$\Delta\alpha = 0.7 \pm 0.4$$

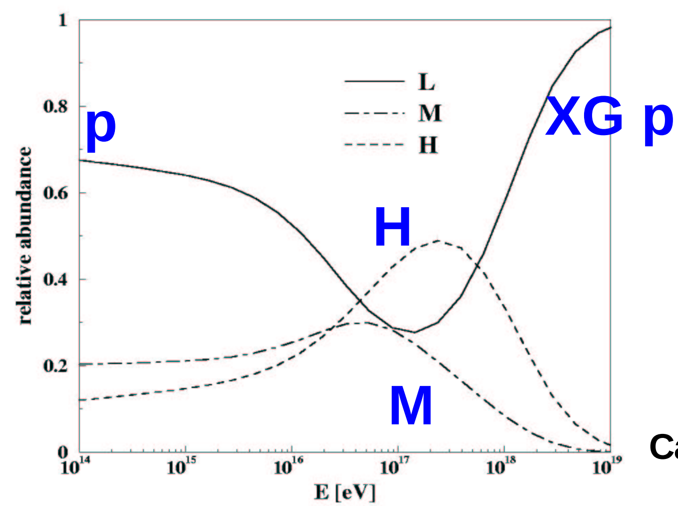
The second knee results from drift of Fe component



HiRes-MIA



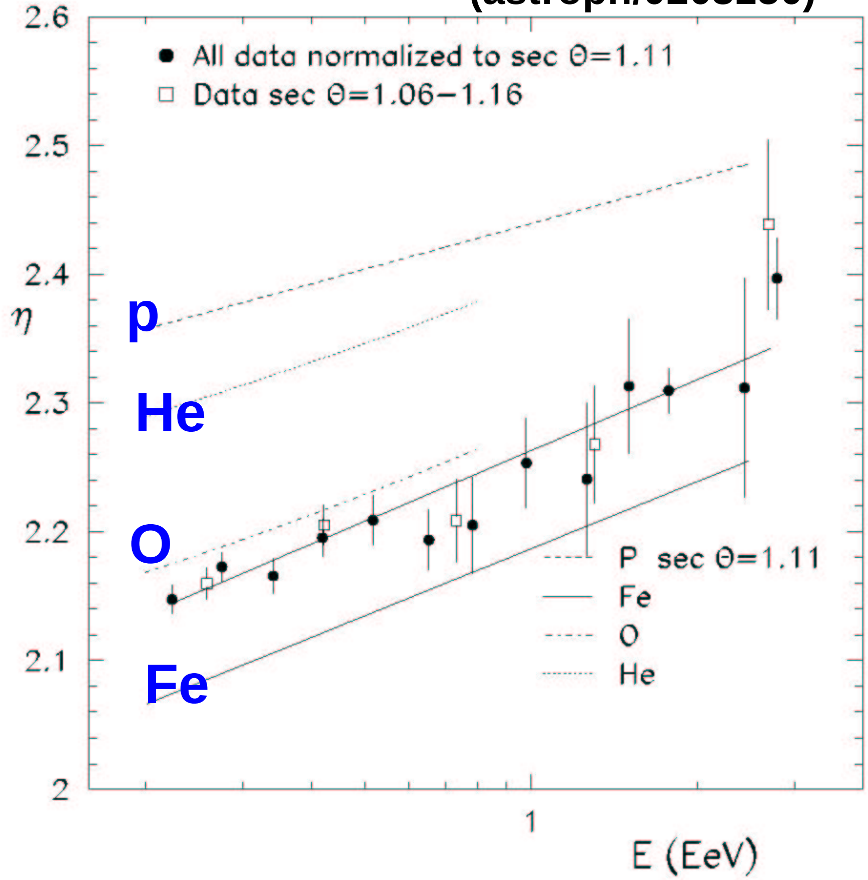
Heavy elements predominant around the second knee



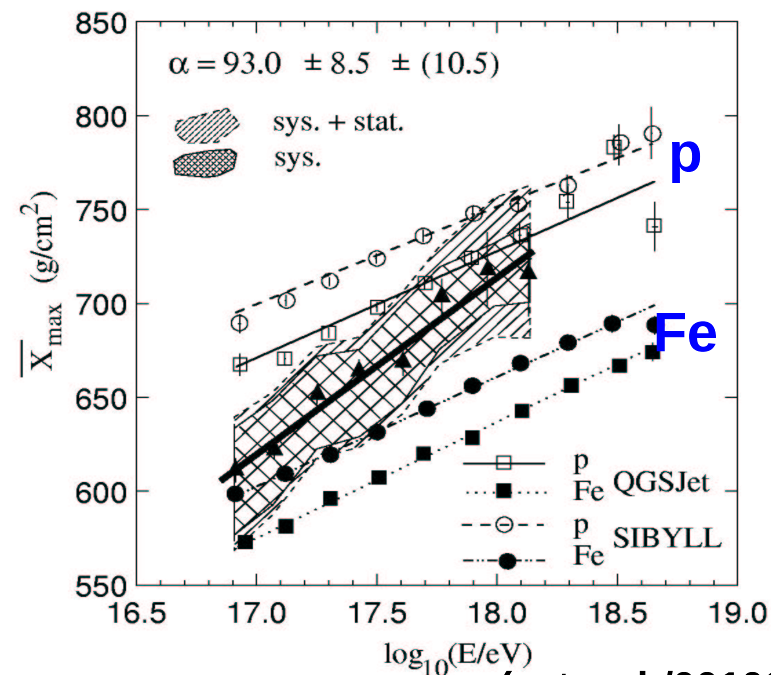
Candia,Mollerach,ER /0207143

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

(astroph/0203150)



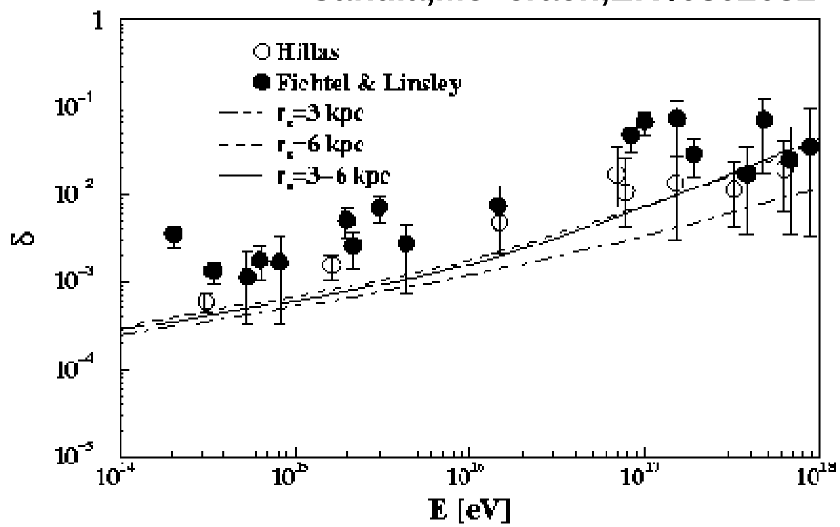
but not much with the composition measured by HiRes



(astroph/0010652)

Also anisotropies grow due to drifts

Candia,Mollerach,ER /0302082



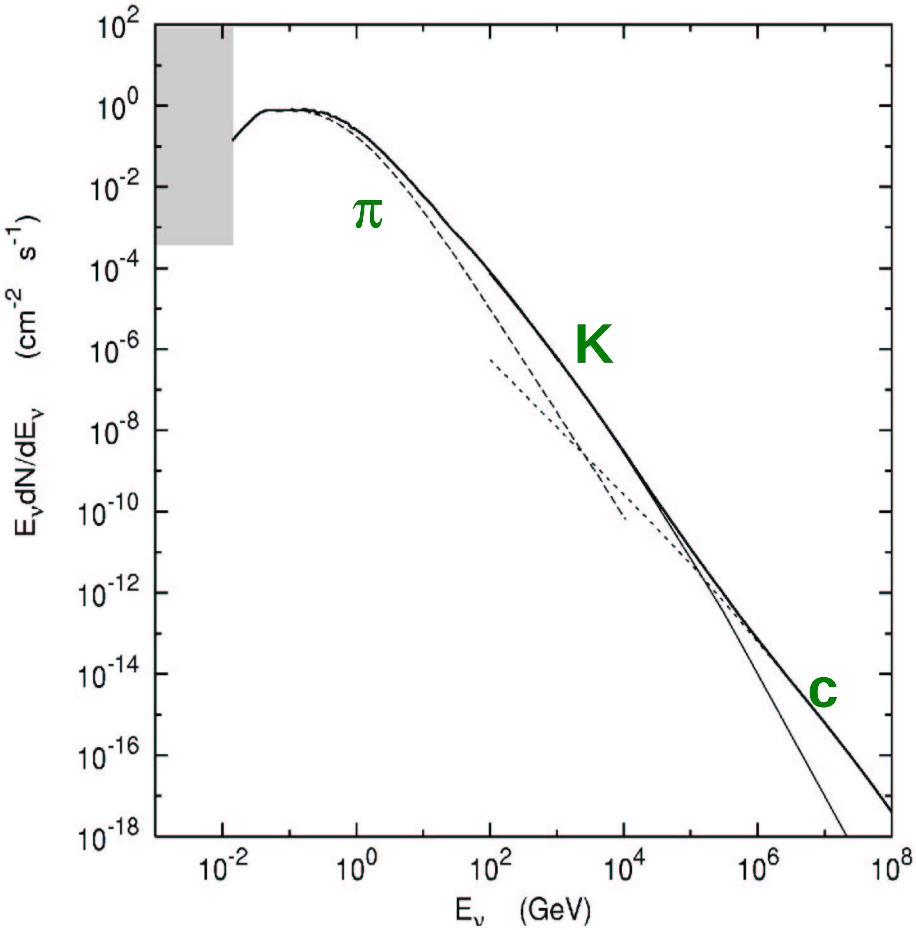
amplitude of first harmonic in right ascension

$$\delta_i = \frac{3J_i^D}{cN_i} \qquad \textbf{with} \qquad \delta = \sum_i f_i \delta_i$$

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

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

High energy atmospheric neutrinos



decay length $L = \gamma\, c\, \tau$

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

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

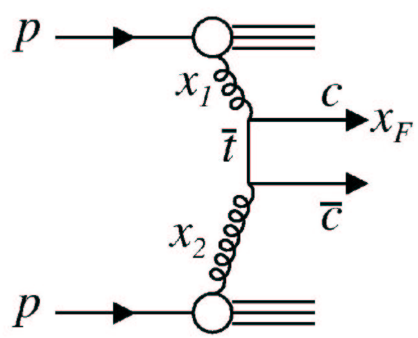
$$L_D \simeq 2\ km\,(E_D / 10\ PeV)$$

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

Prompt charm production

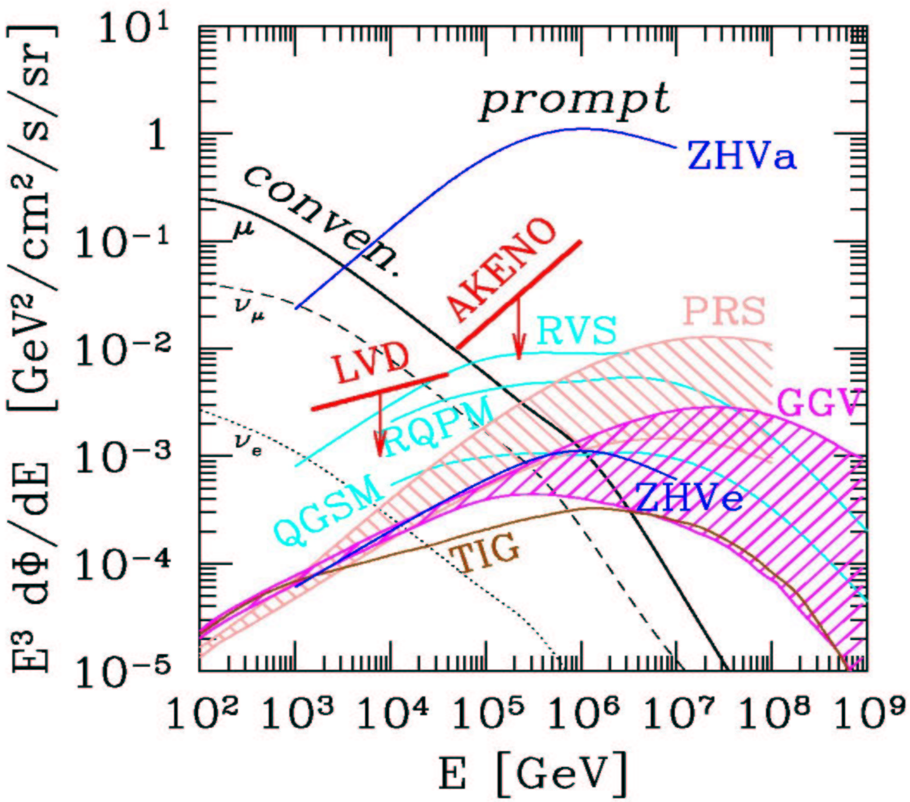


sample gluon density distribution at $x_2 \simeq \frac{M_{cc}^2}{2x_F s}$

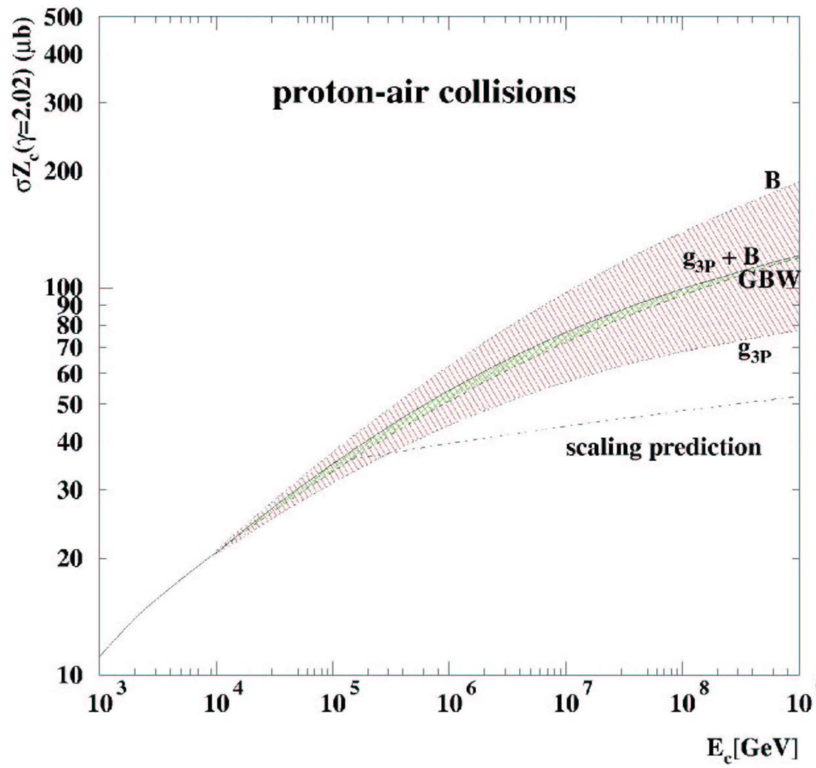
=> $x_2 < 10^{-5}$ for $E>10^{15}$ eV

need to extrapolate from measured values

also requires to include NLO processes



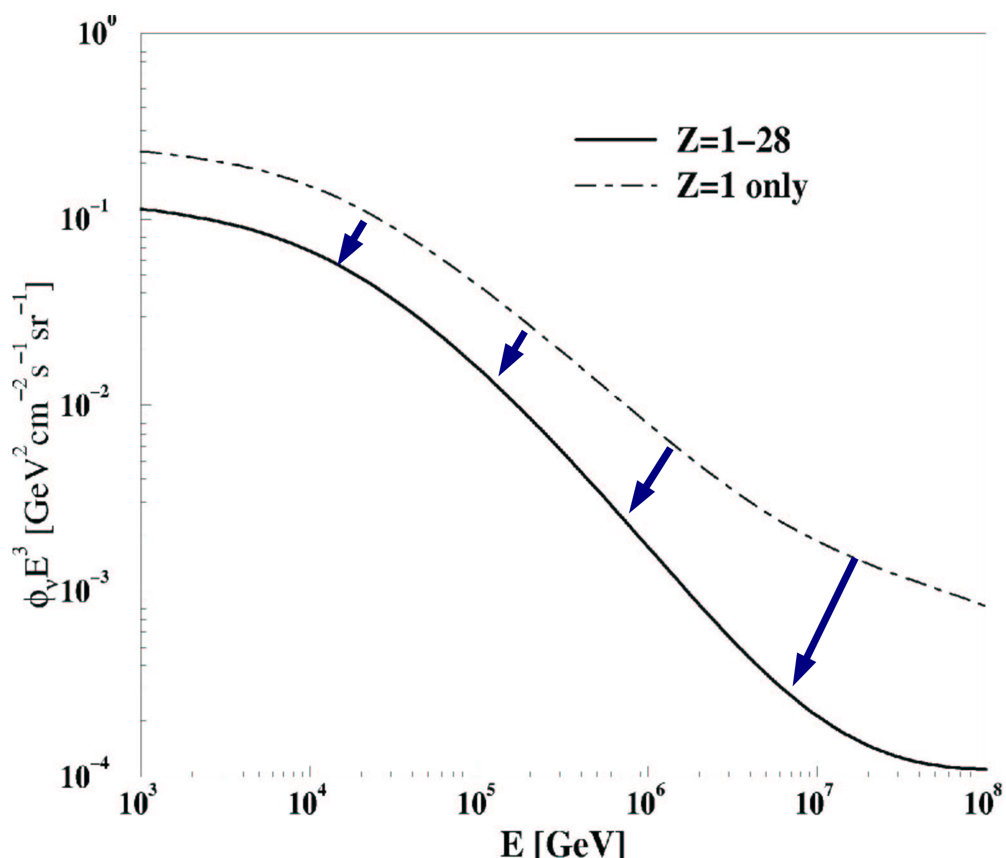
Martin et al. /0302140



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

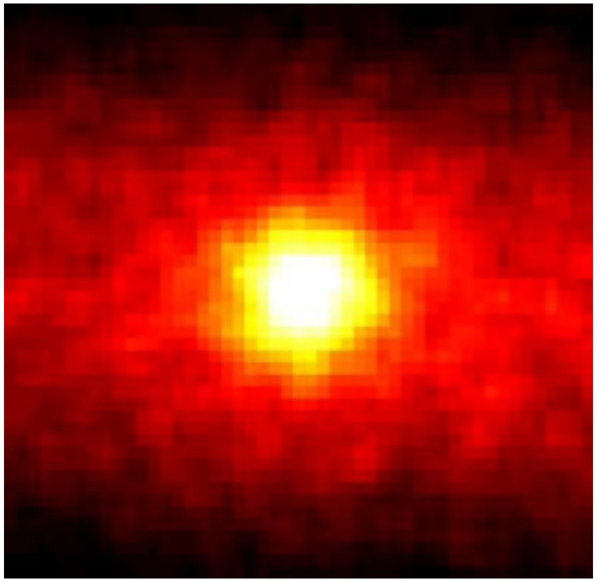
=> neutrinos are produced with much lower energies, and due to steep spectrum, they become strongly suppressed



Candia, ER /0306632

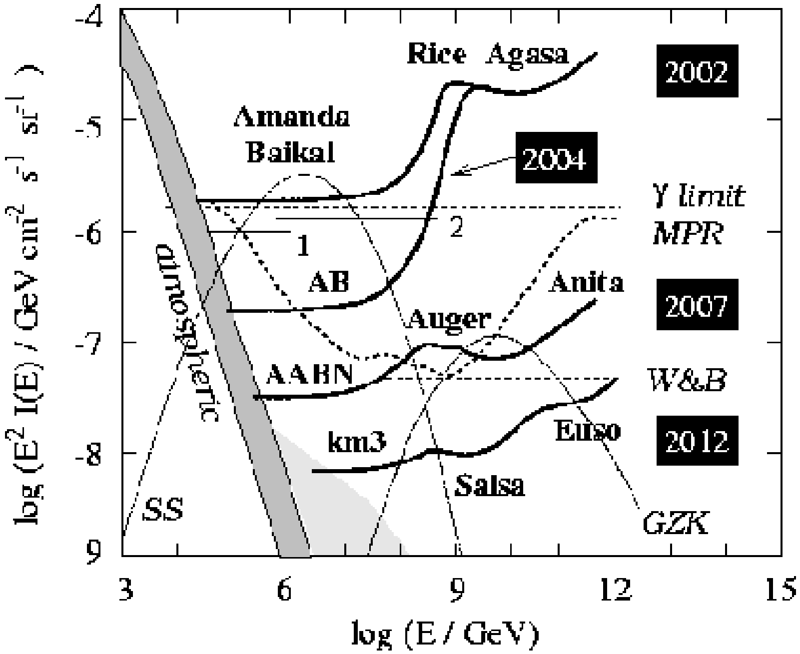
Something similar happens to the ν's produced by CR interactions in the Galactic ISM

Neutrino astronomy



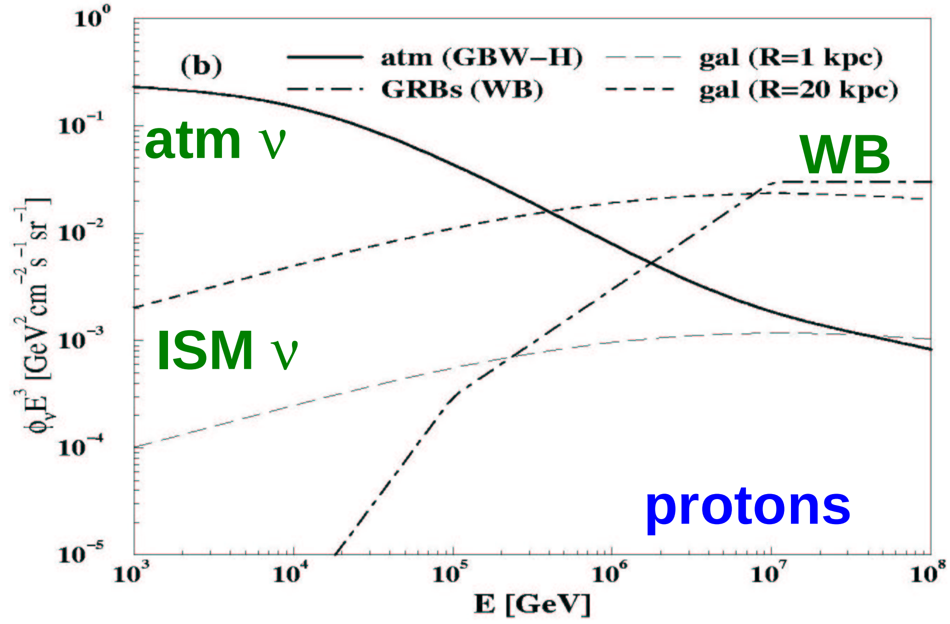
Sun seen in ν's

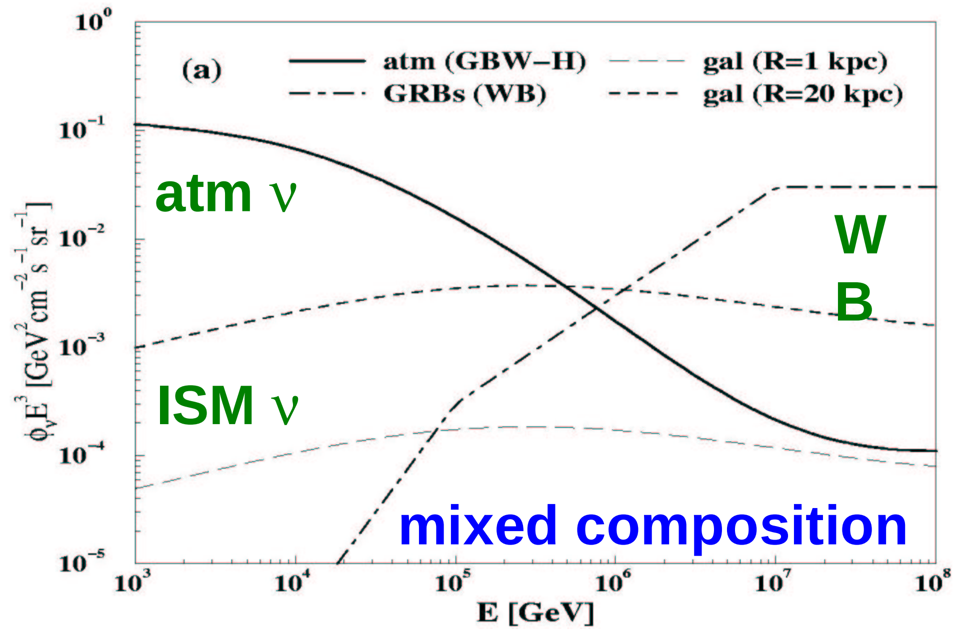
Carr



diffuse ν fluxes

This results into a reduced background for the detection of diffuse astrophysical fluxes, such as those from GRBs

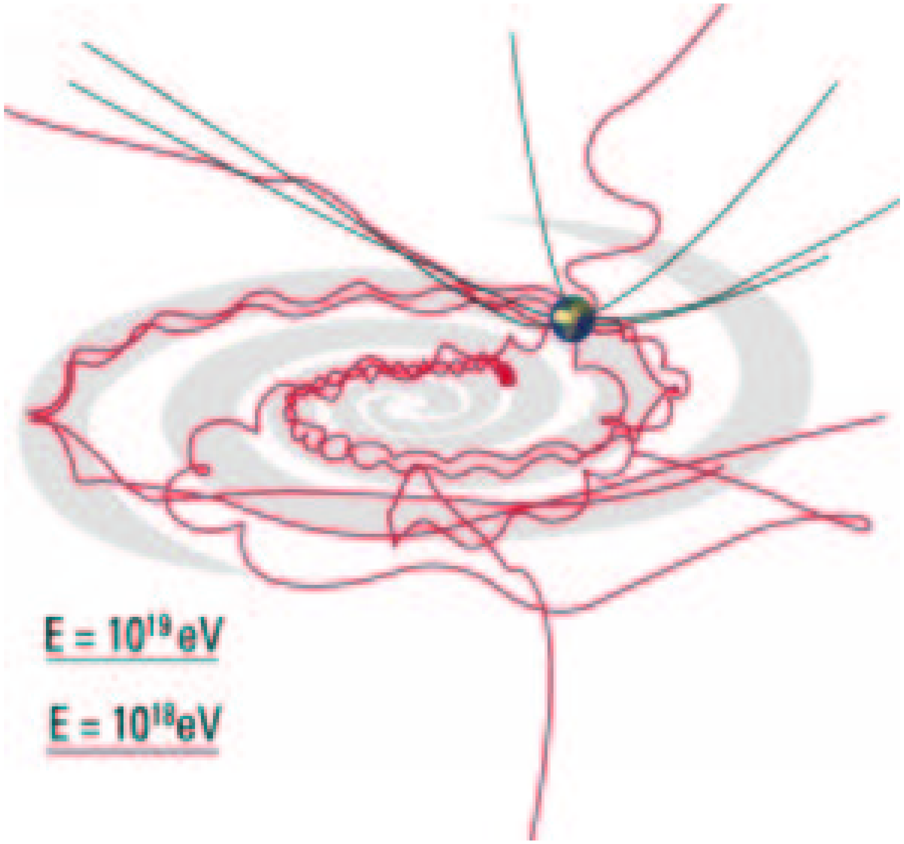




Candia, ER /0306632

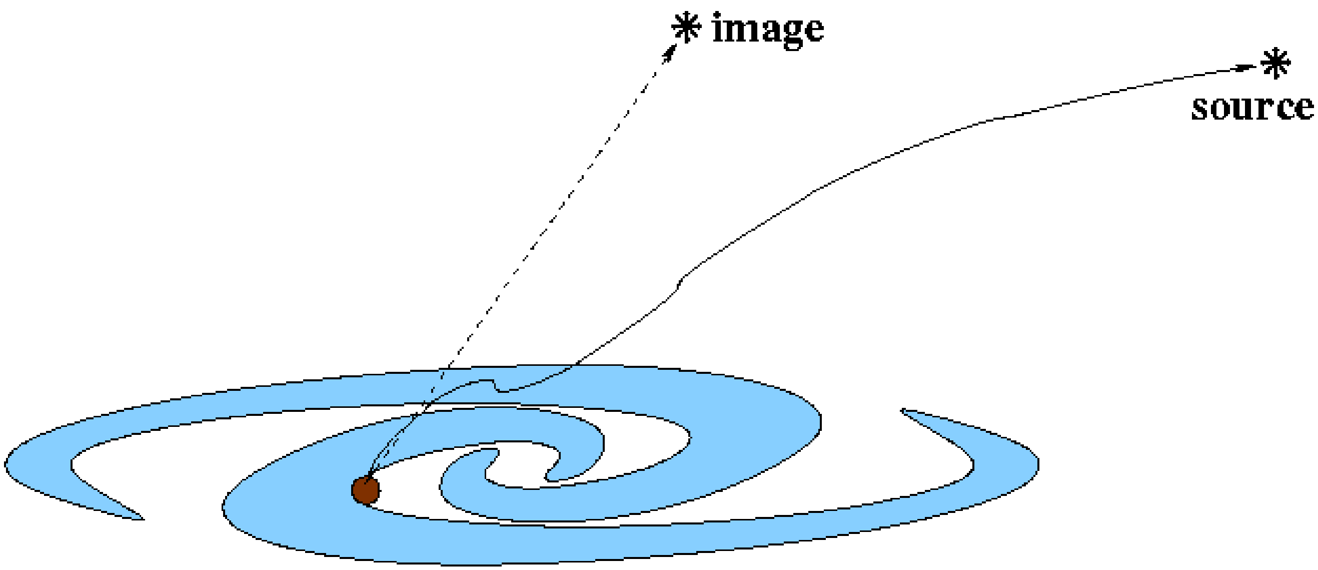
UHECR propagation in Galactic magnetic fields

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



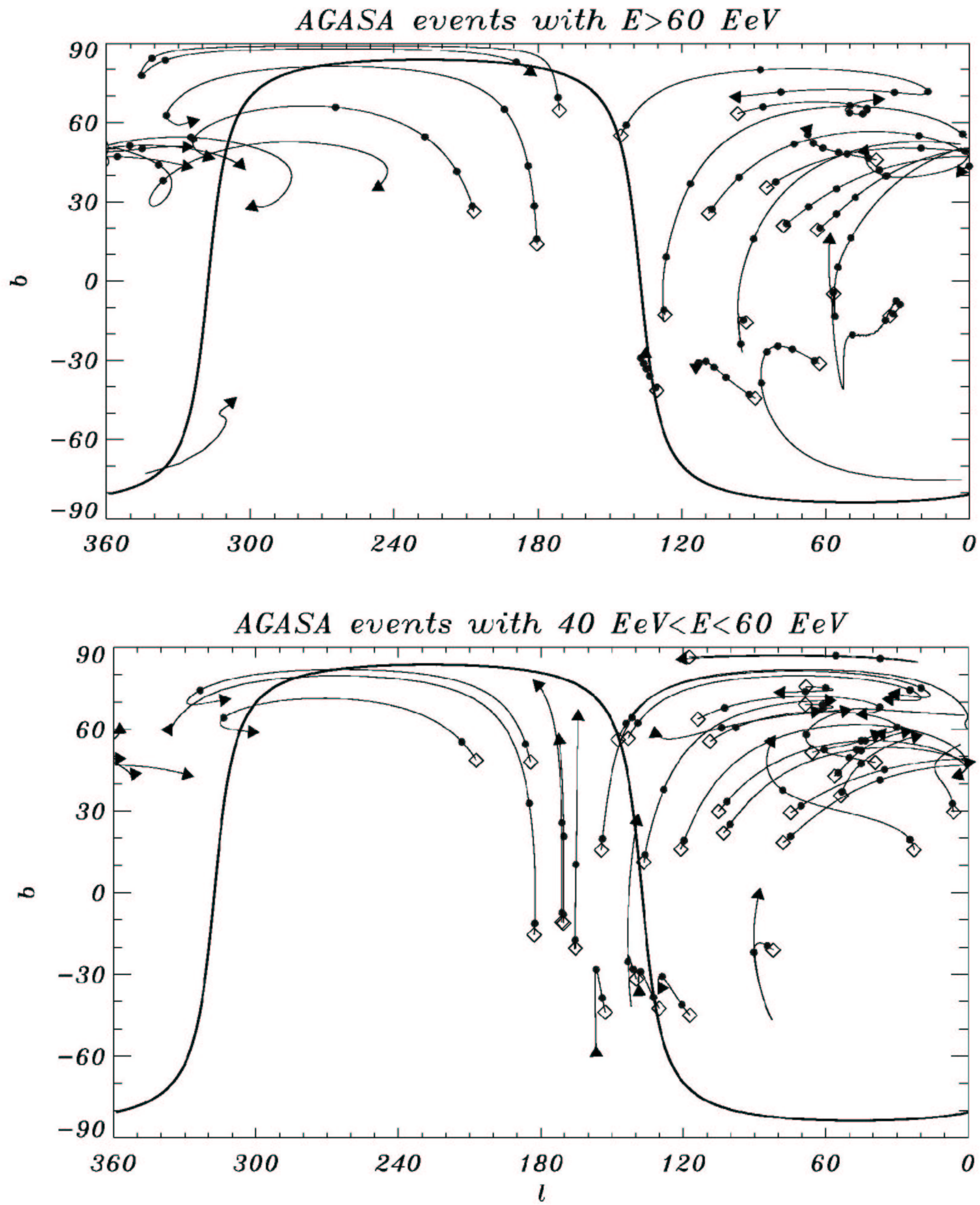
It is only for E/Z>10^{19} eV that trajectories become straight and astronomy becomes possible

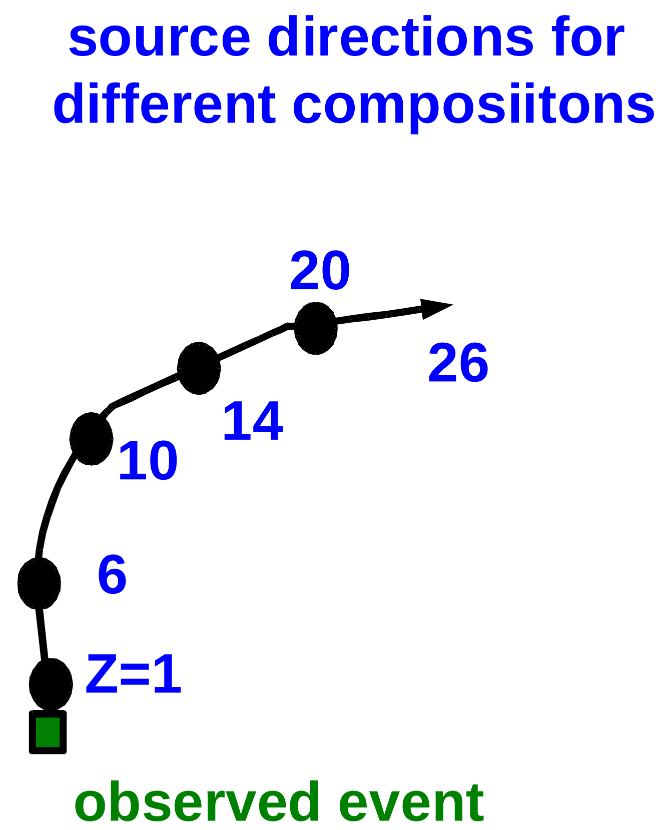
If Galactic B field (and composition) were known, one could correct the arrival direction to search for the source



Need to 'backtrack antiprotons' (antinuclei)

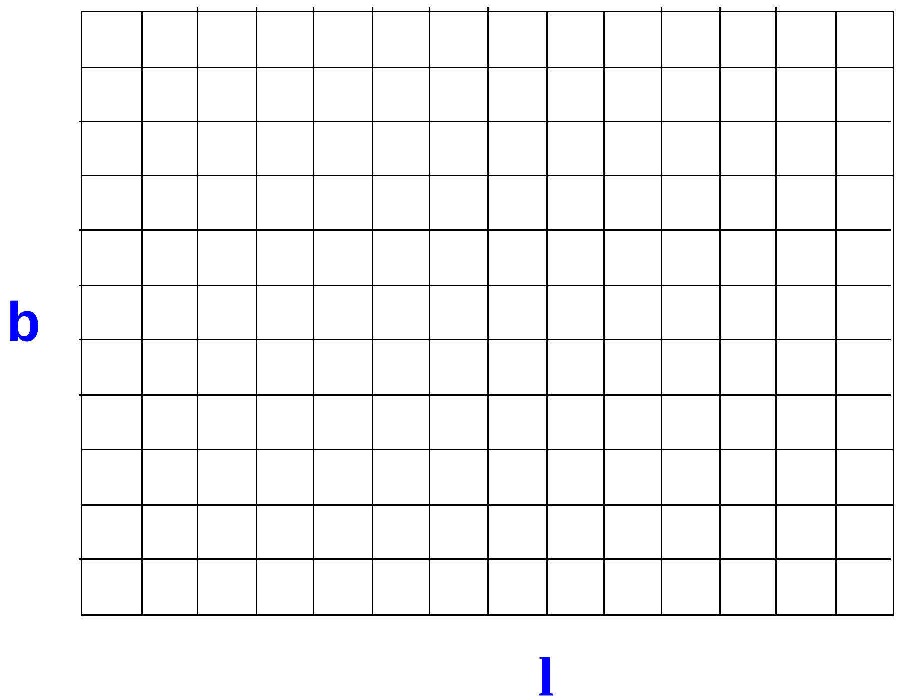
AGASA events



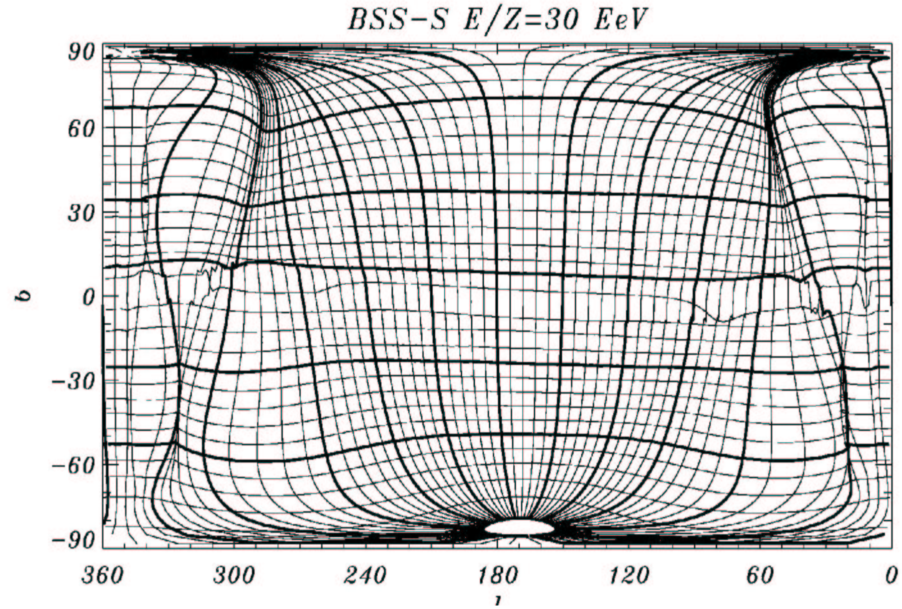


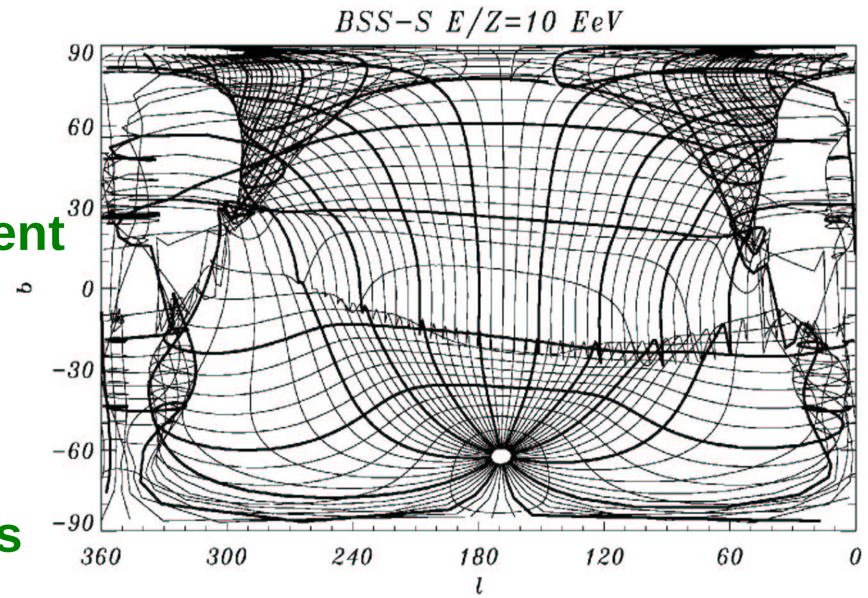
And multiple images can appear

Sky as seen on Earth



Sky projected into the halo





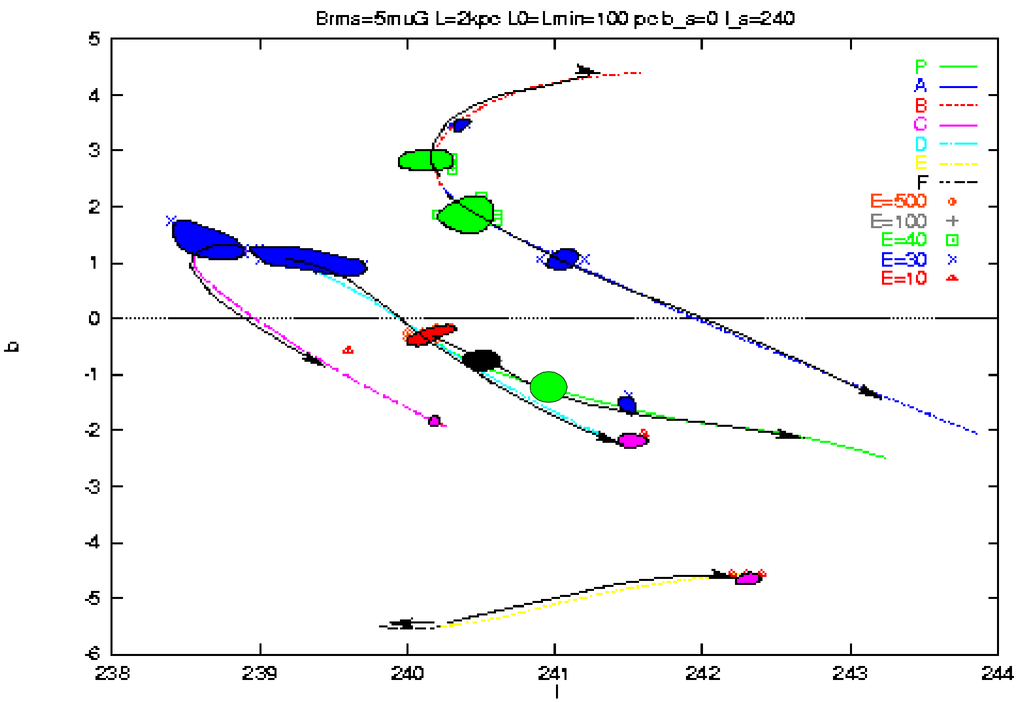
For every fold, two new images are present

sky stretching -> demagnification
sky compression -> magnification

at folds (caustics) magnification diverges

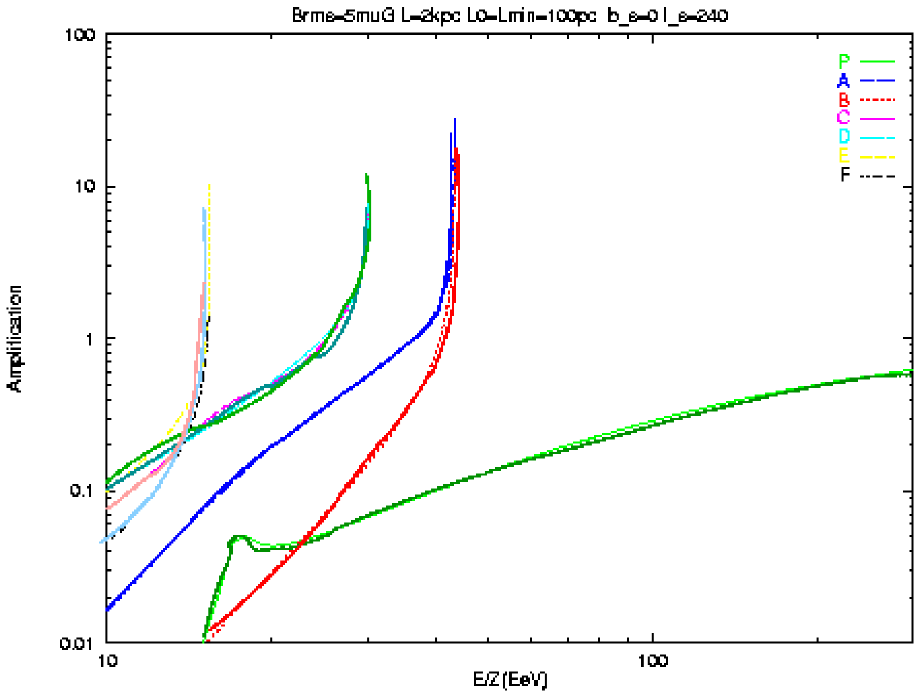
example:

images



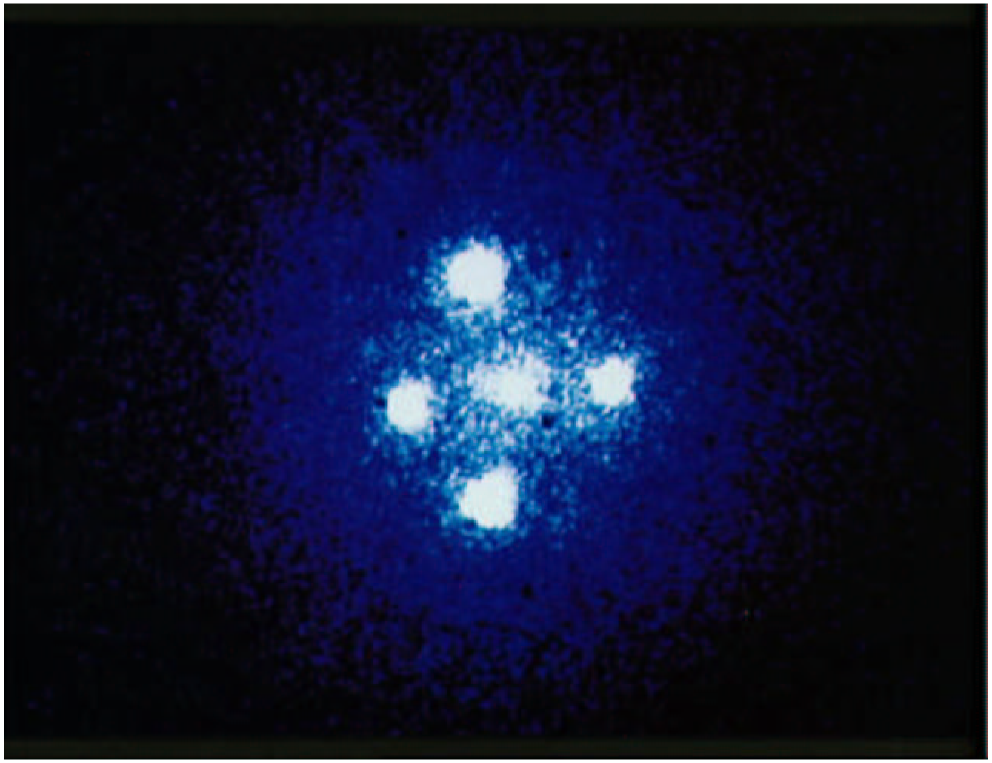
$5x10^{20}$, 10^{20}, $4x10^{19}$, $3x10^{19}$, 10^{19}

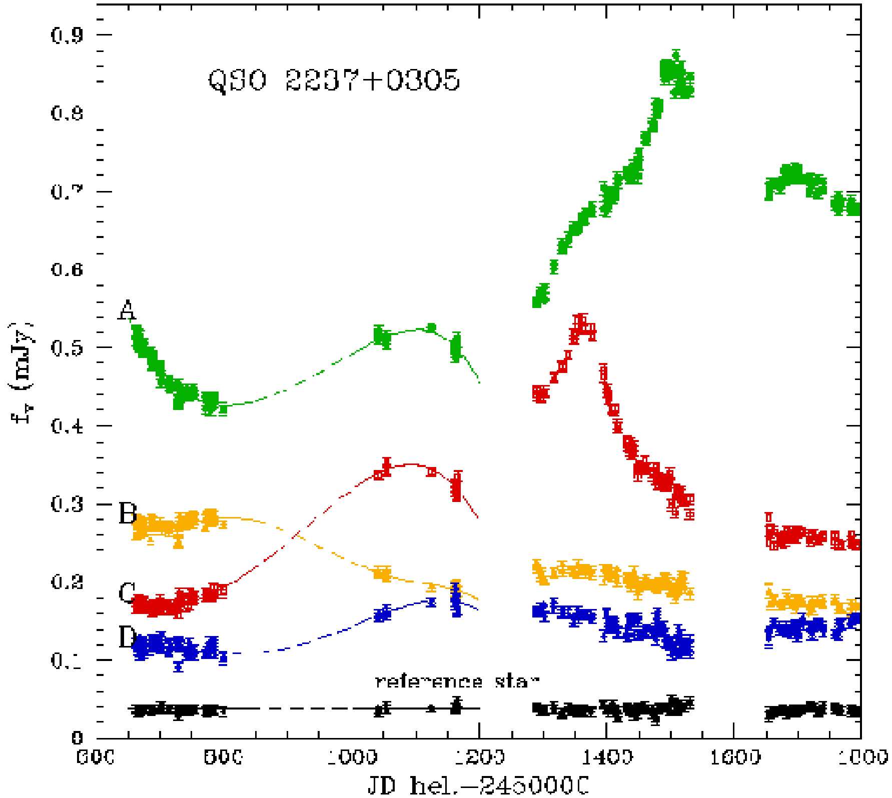
magnification



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)

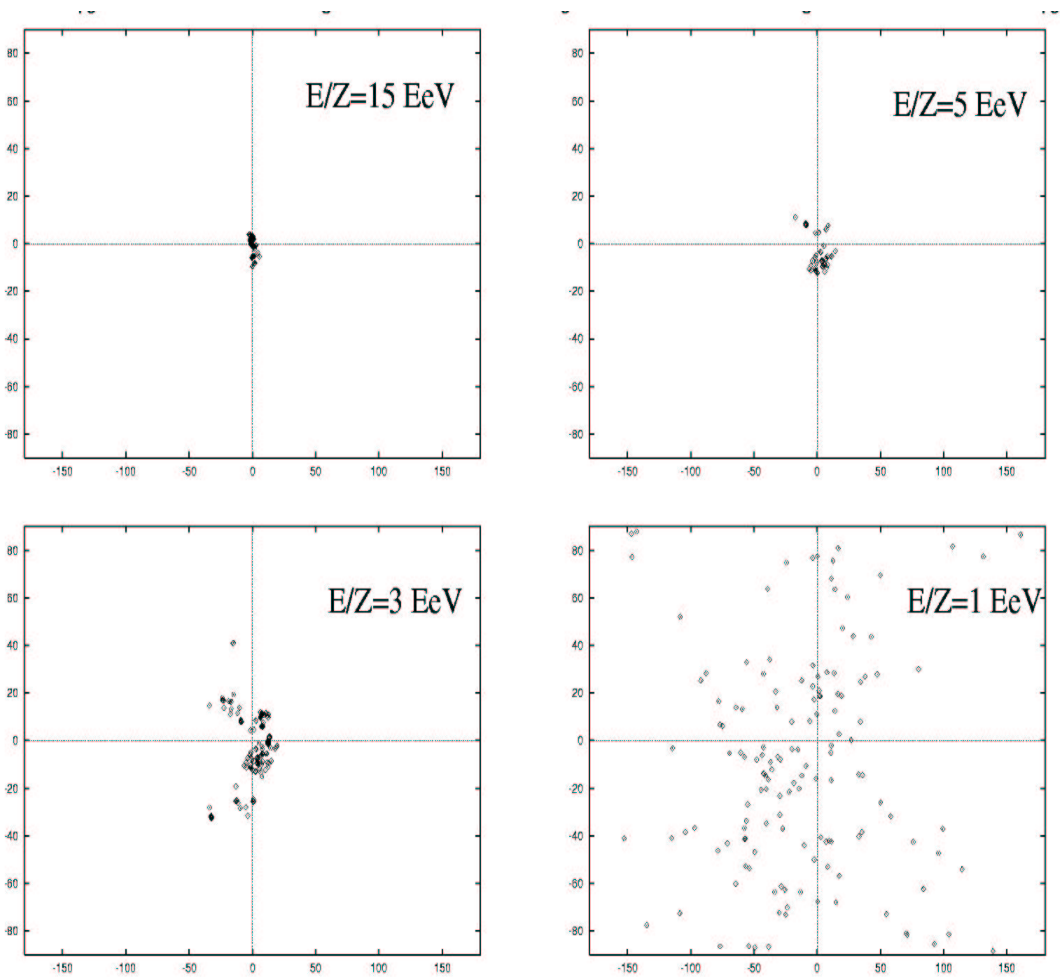
Magnification peaks due to the appearance of new images of a source lead to clustering of events both in angle and in energy, as seems to be suggested by the data

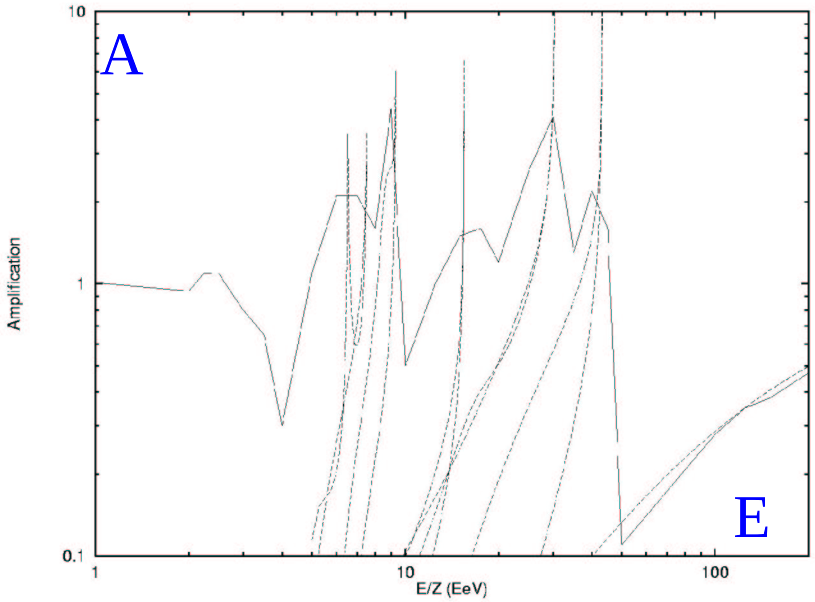
a quantitative analysis with AGASA events above $4x10^{19}$ eV shows that clustering in energy is significant

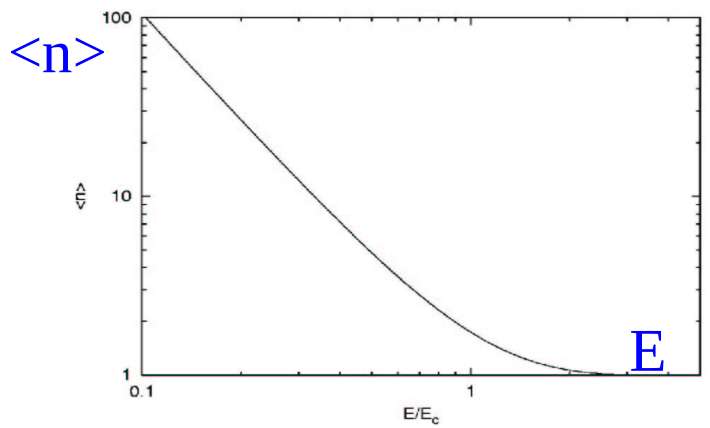
but statistics still very poor => need AUGER

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

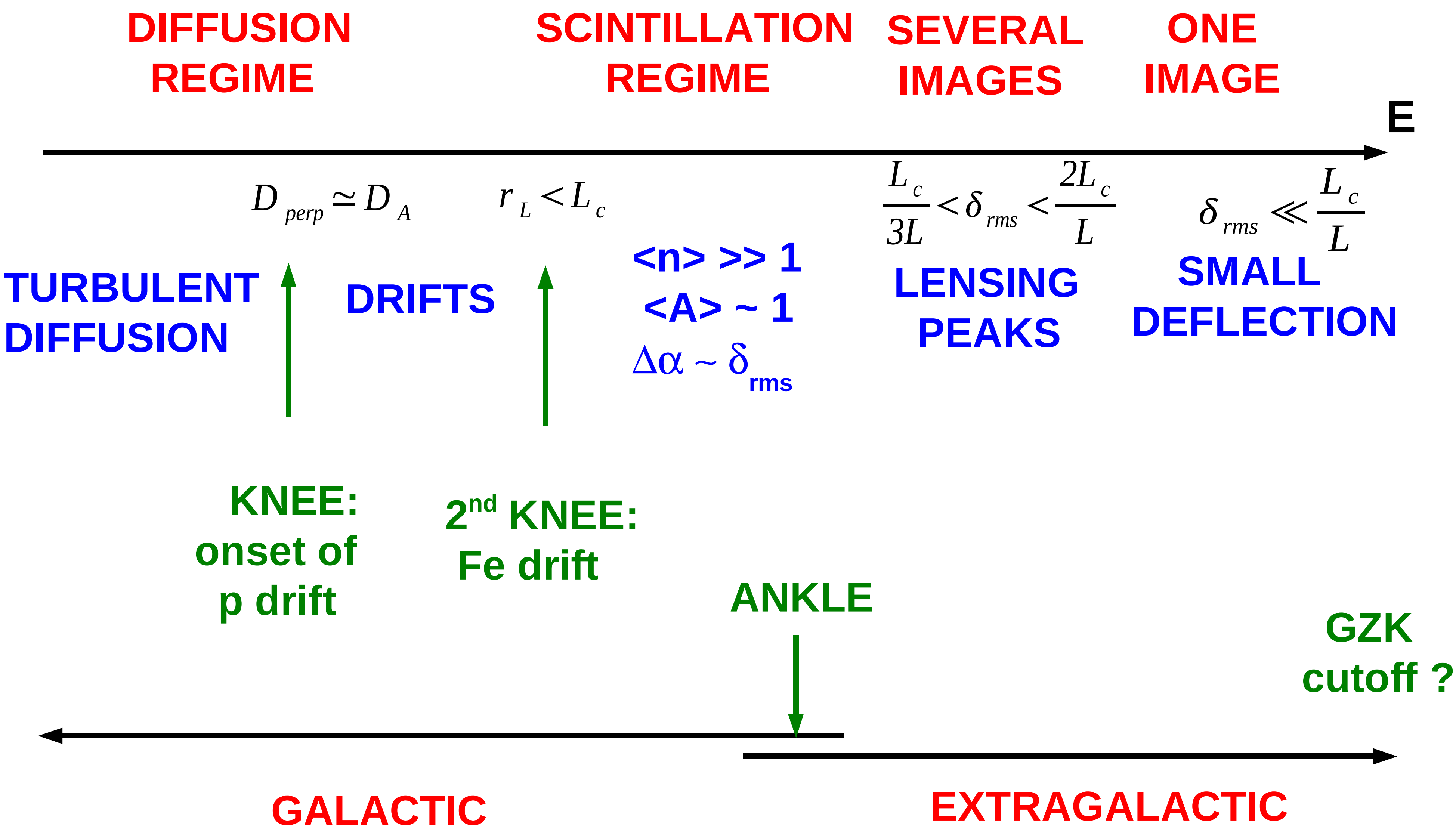
The scintillation regime



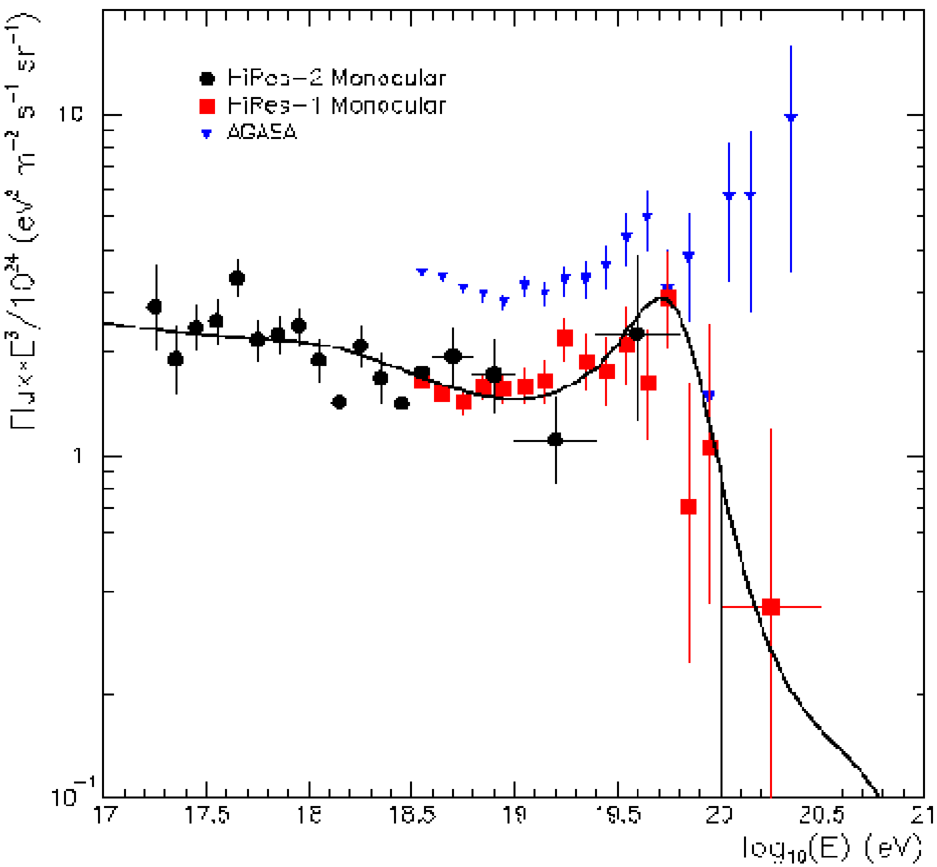




A regime is reached with a large number of images, spread over $\Delta\alpha \sim \delta_{rms}$ and with <A>~1 (like twinkling stars)


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

GZK or no GZK?



HiRes-2 Monocular
HiRes-1 Monocular
AGASA
Flux*E^3/10^24 (eV^2 m^-2 s^-1 sr^-1)
10
1
10^-1
17
17.5
18
18.5
19
19.5
20
20.5
21
log10(E) (eV)

many answers will come from AUGER, which is being built at Malargue