Arrival Directions of Auger's Highest Energy Events

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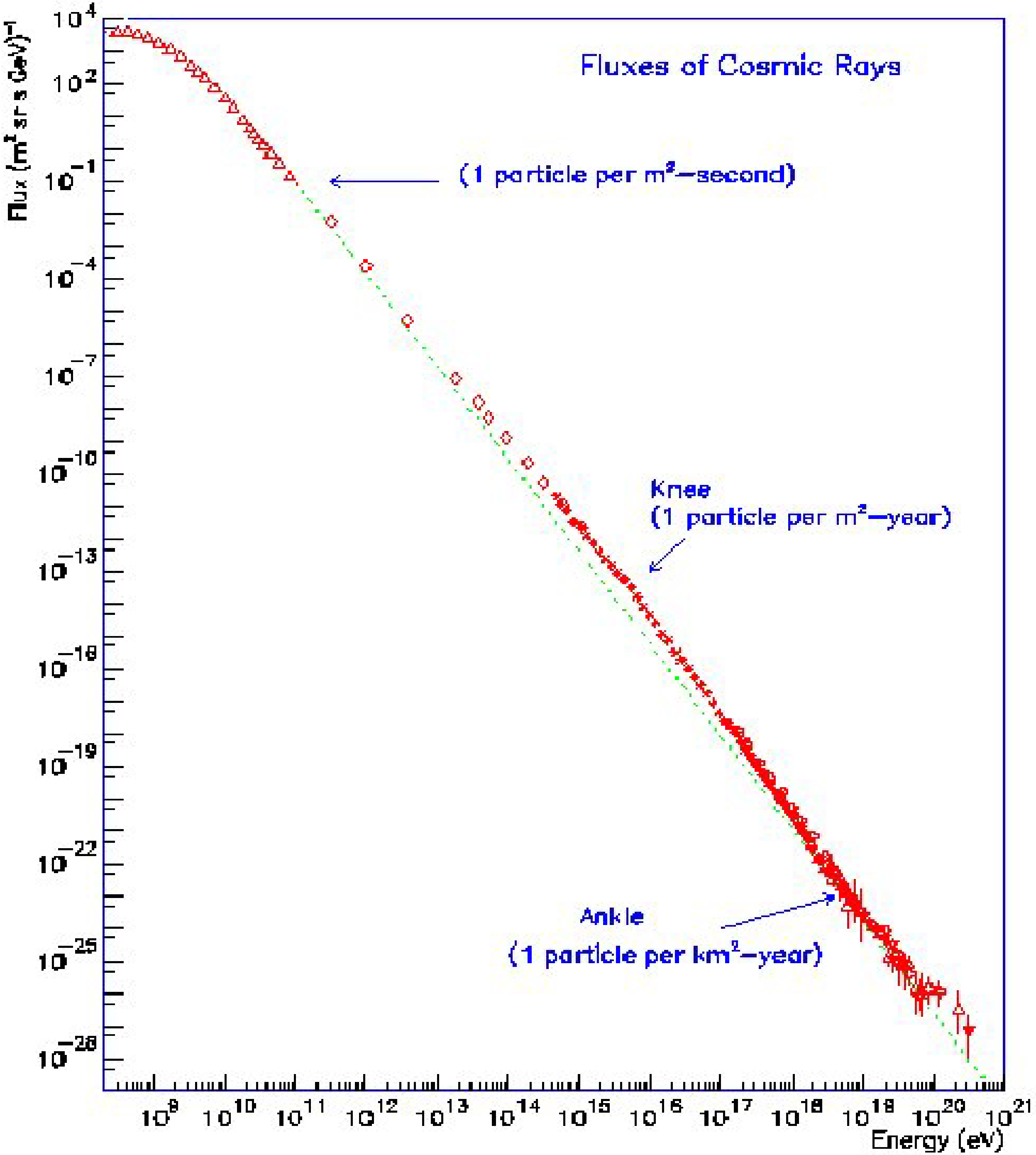
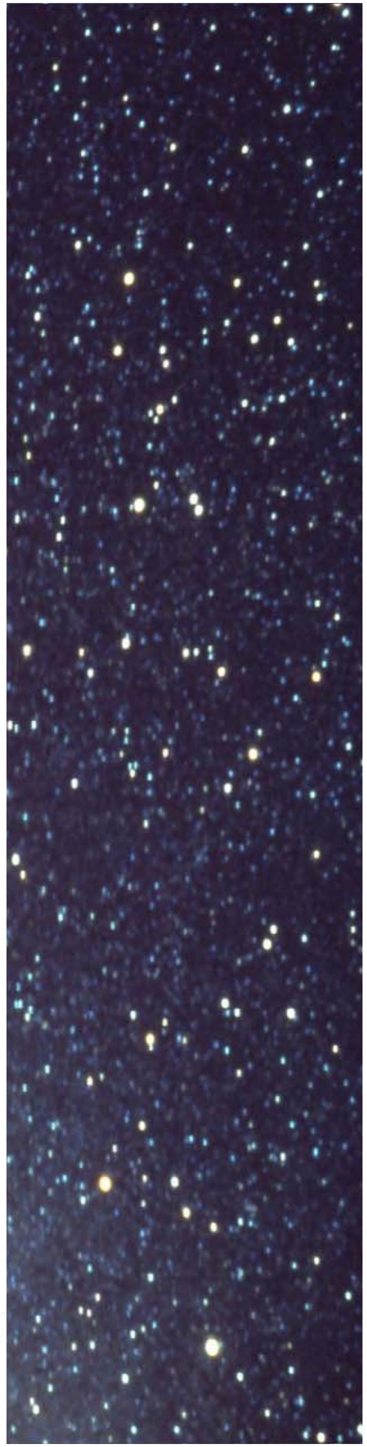
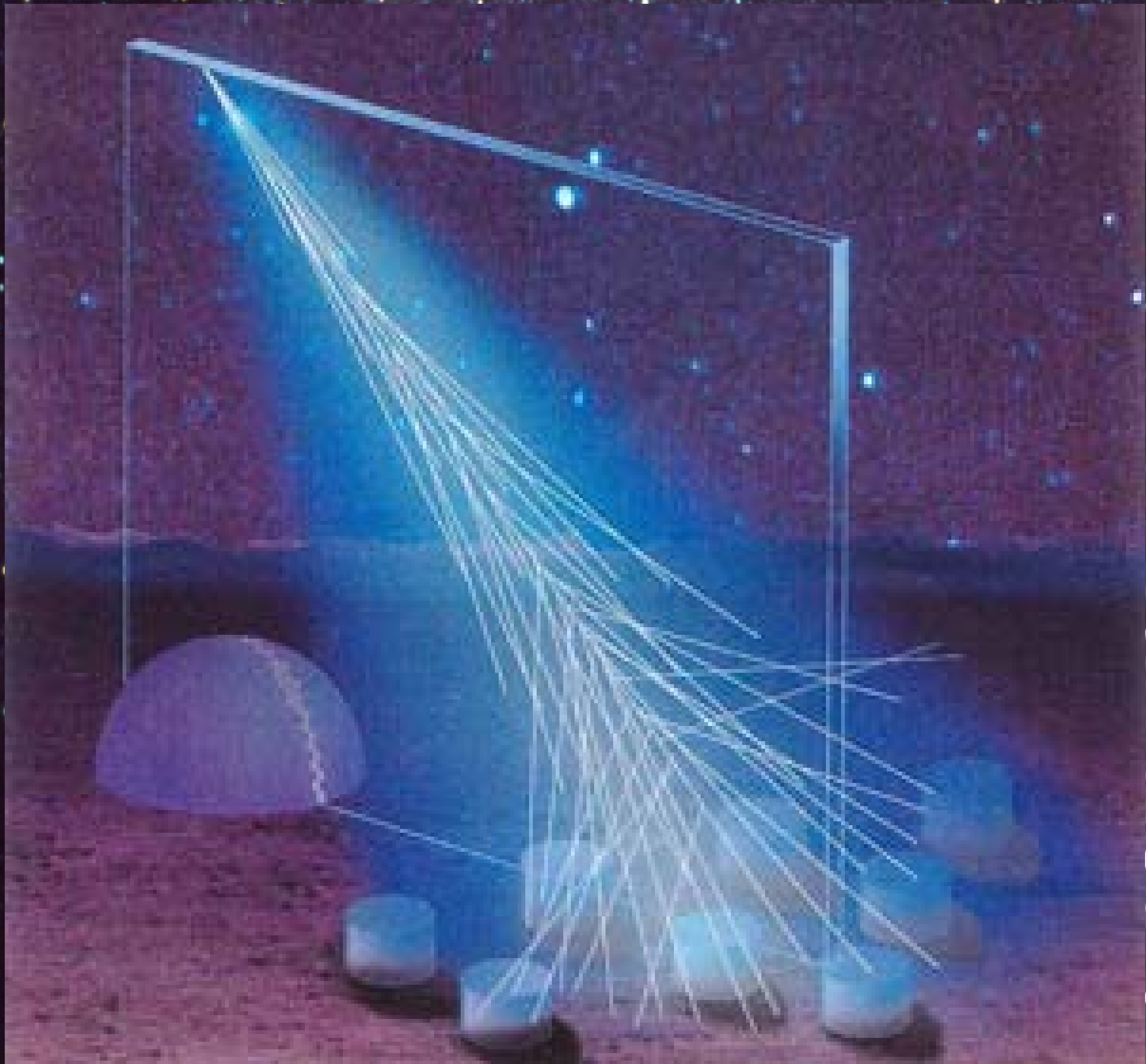


Fluxes of Cosmic Rays
(1 particle per m²—second)
Knee
(1 particle per m²—year)
Ankle
(1 particle per km²—year)
Flux (m² sr s GeV)⁻¹
Energy (eV)





<u>Observing the cascade with nitrogen fluorescence and particle detectors.</u>

We deliberately avoid the forward directed Cerenkov light.

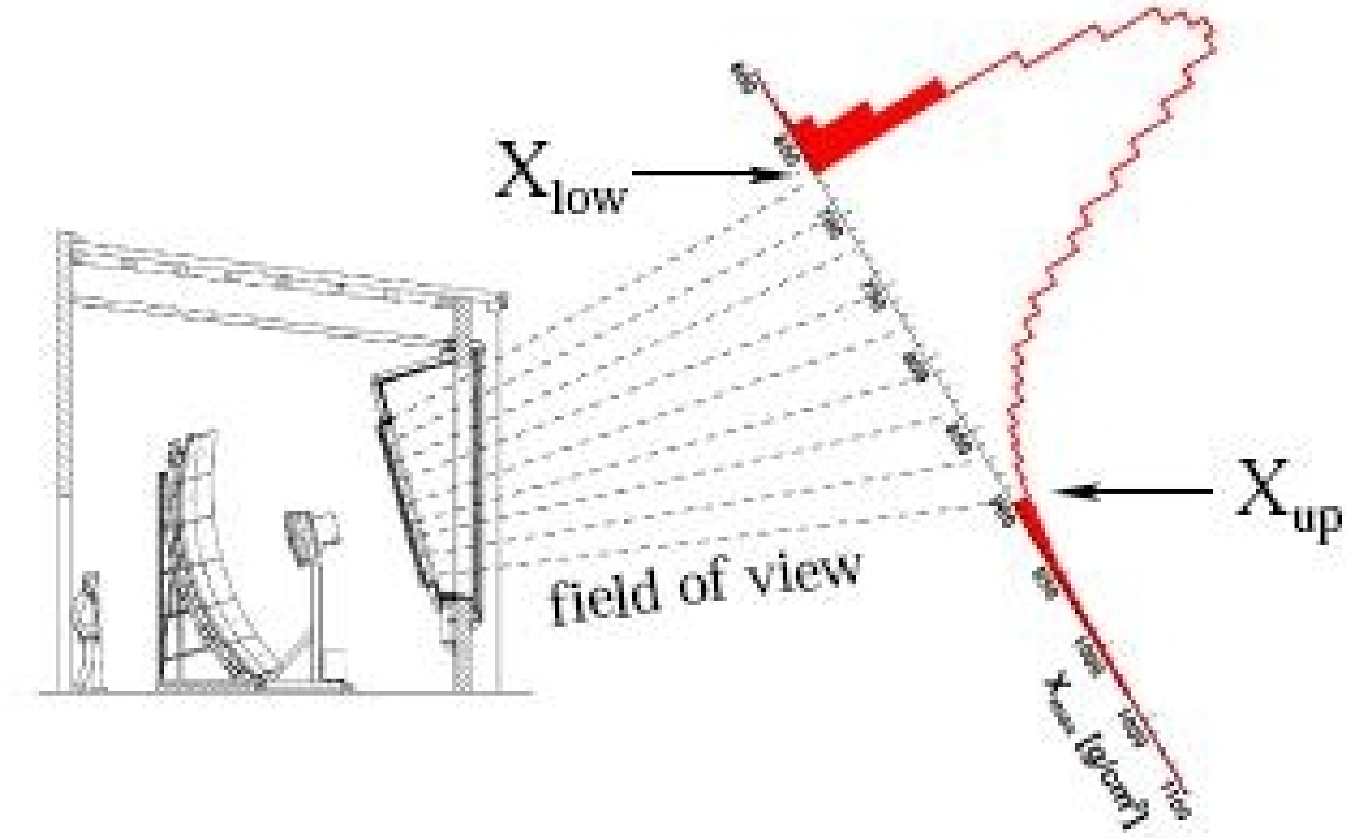


Figure 1: Illustration of the effect of the field of view of the fluorescence detector on the selected $X_{\max}$ distribution. Filled areas indicate slant depths, which are de-selected by the quality cuts.

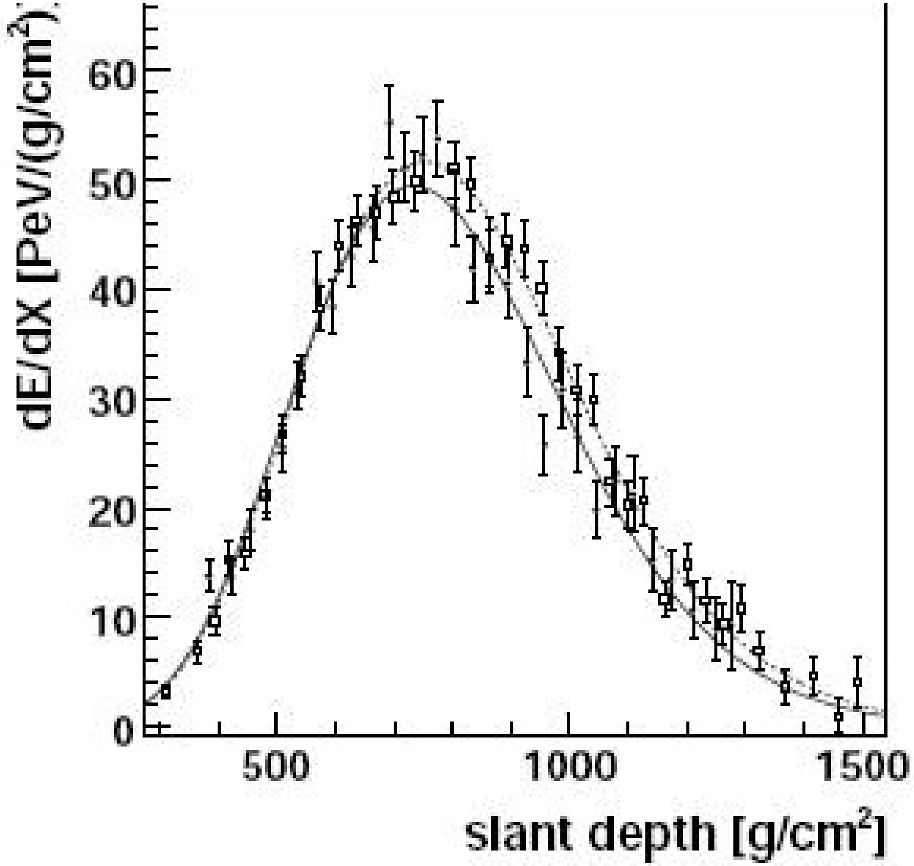


Figure 1. Example of a measured longitudinal profile, reconstructed independently by two fluorescence detectors: Los Leones (black dots, E=31±2 EeV, $X_{\rm max}$=733±18 g/cm^2) and Los Morados (open squares, E=33±2 EeV, $X_{\rm max}$=751±16 g/cm^2).

Studying composition.

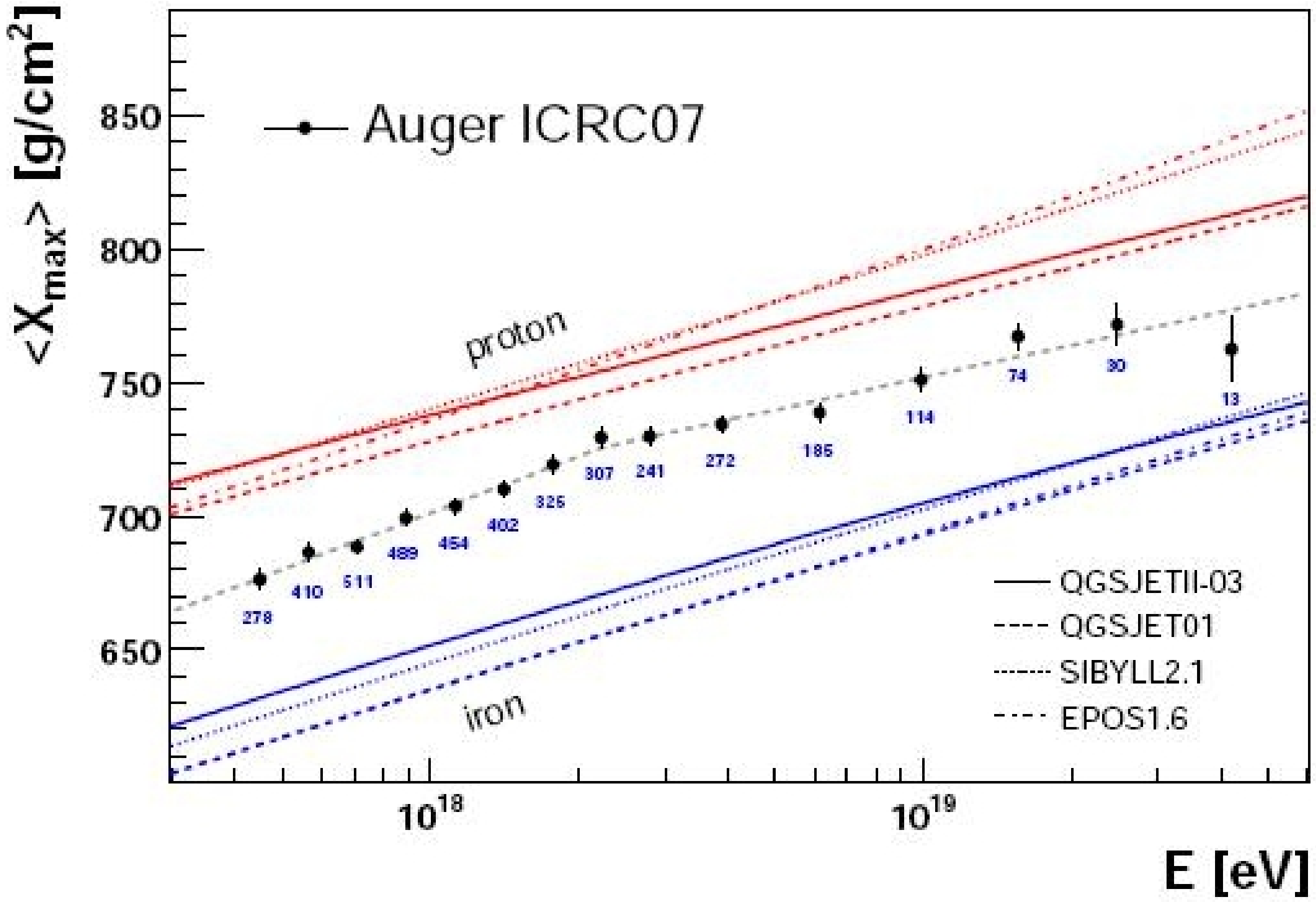
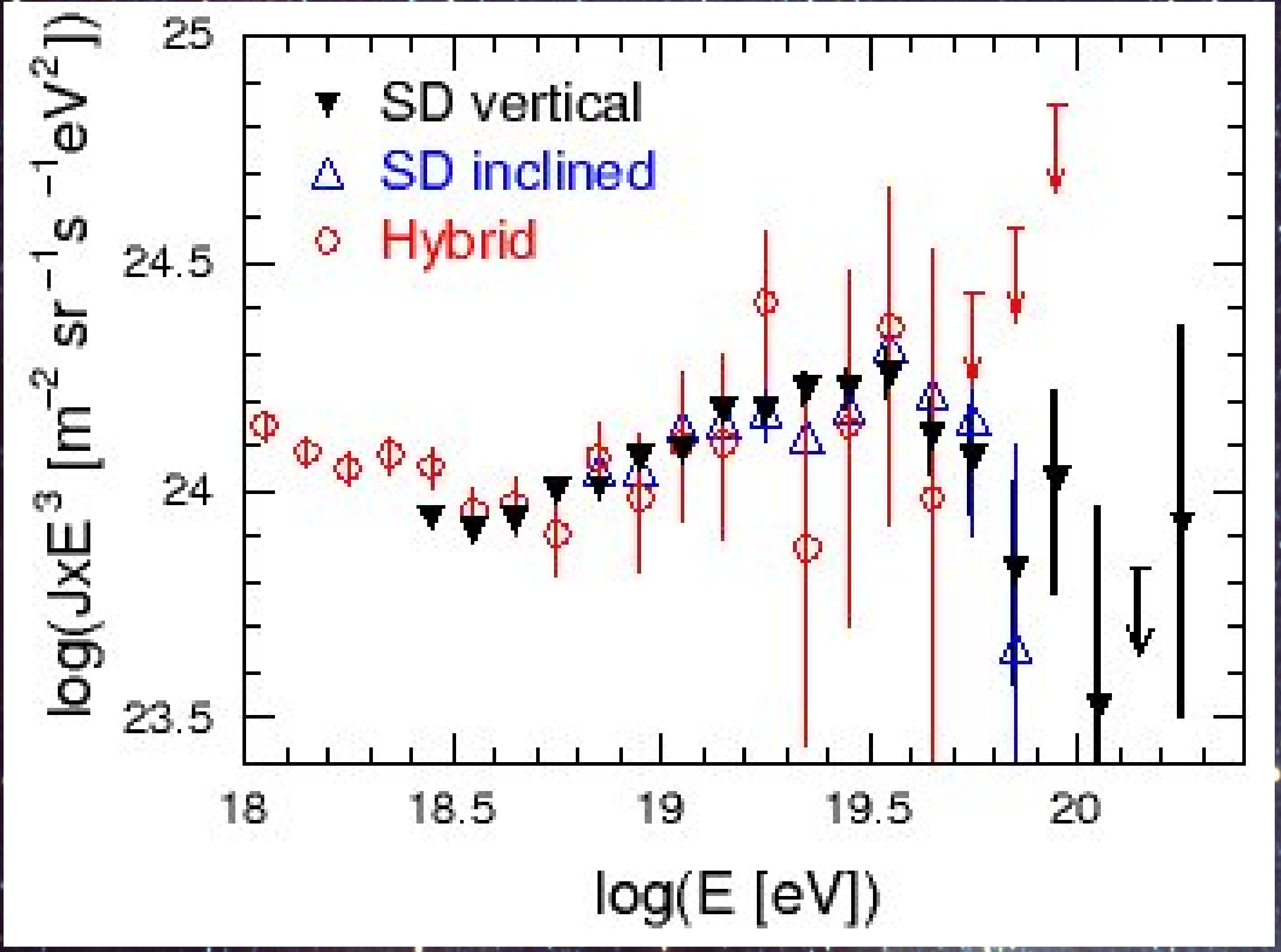
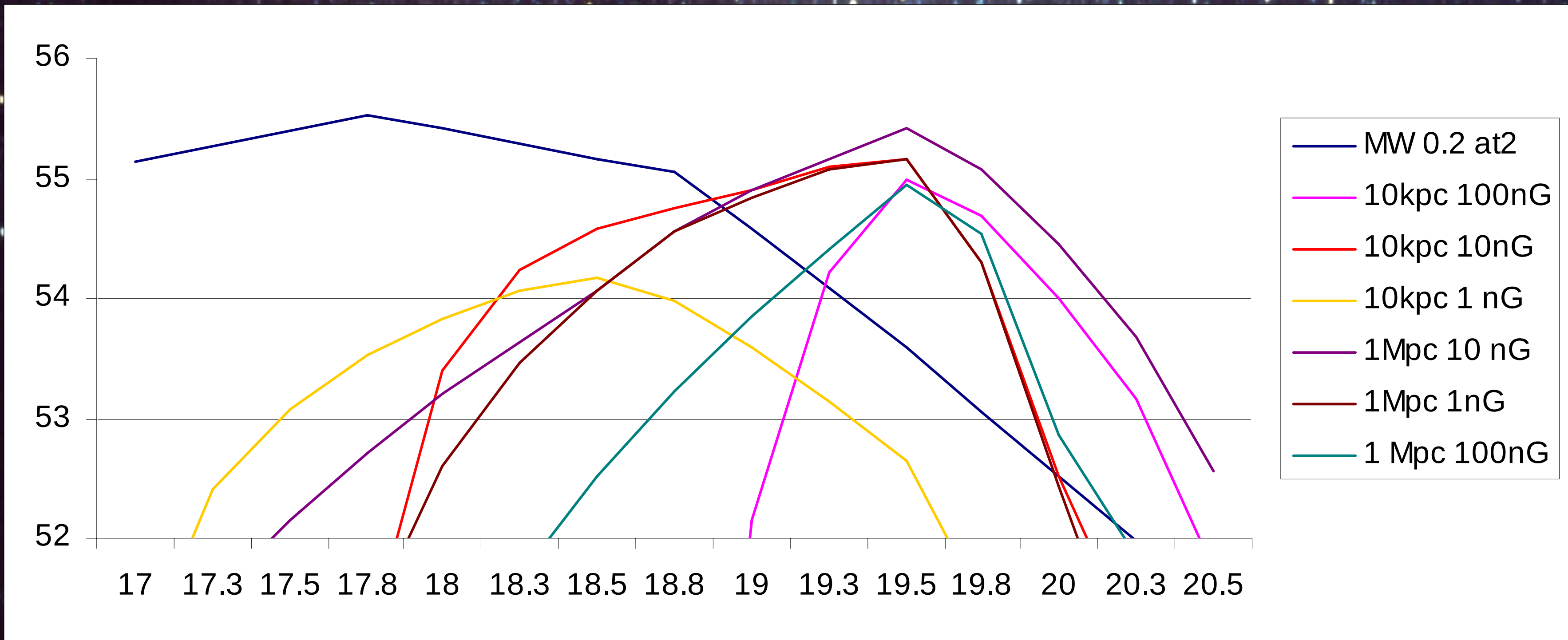


Figure 3: $\langle X_{\max} \rangle$ as a function of energy compared to predictions from hadronic interaction models. The dashed line denotes a fit with two constant elongation rates and a break-point. Event numbers are indicated below each data point.

Auger finds a spectral cut-off.



Interpreting the spectrum with a mixture of galactic (lower energy) and extra-galactic cosmic rays.



- With creative imagination one can attribute the ‘extragalactic’ flux to a locally (within 1 Mpc) trapped milky Way flux.

- But, one then has to invoke a period of cosmic ray activity 1+ million years ago.

- And a microgauss field extending over that volume.

Simple idea of a GZK spectrum depending on the source distance.

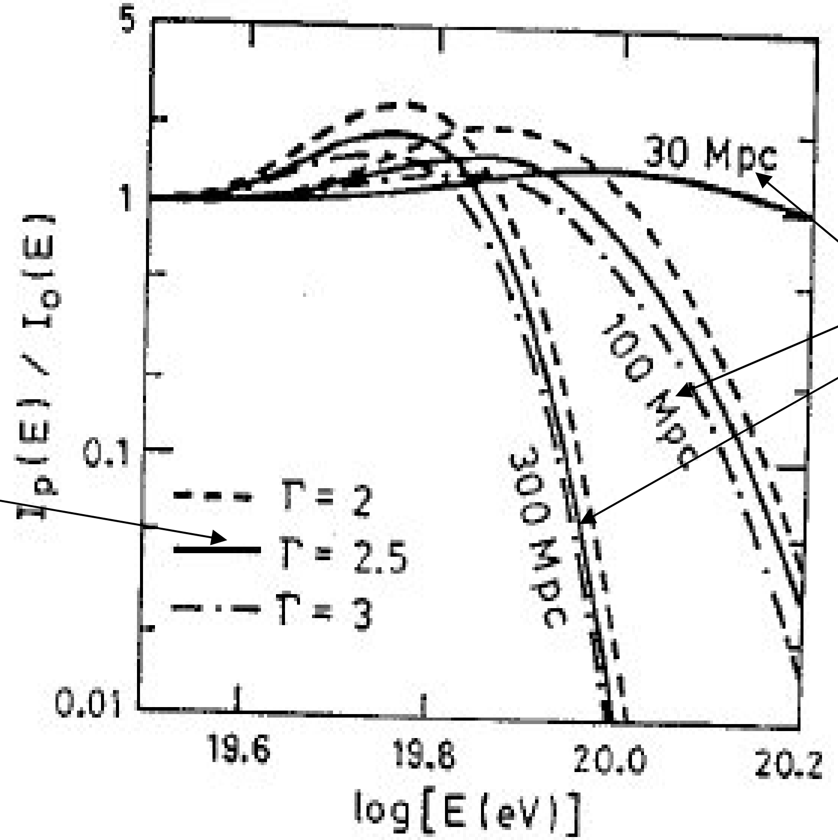


Figure 19: As figure 11. The depression of the primary proton spectrum for a number of path lengths.

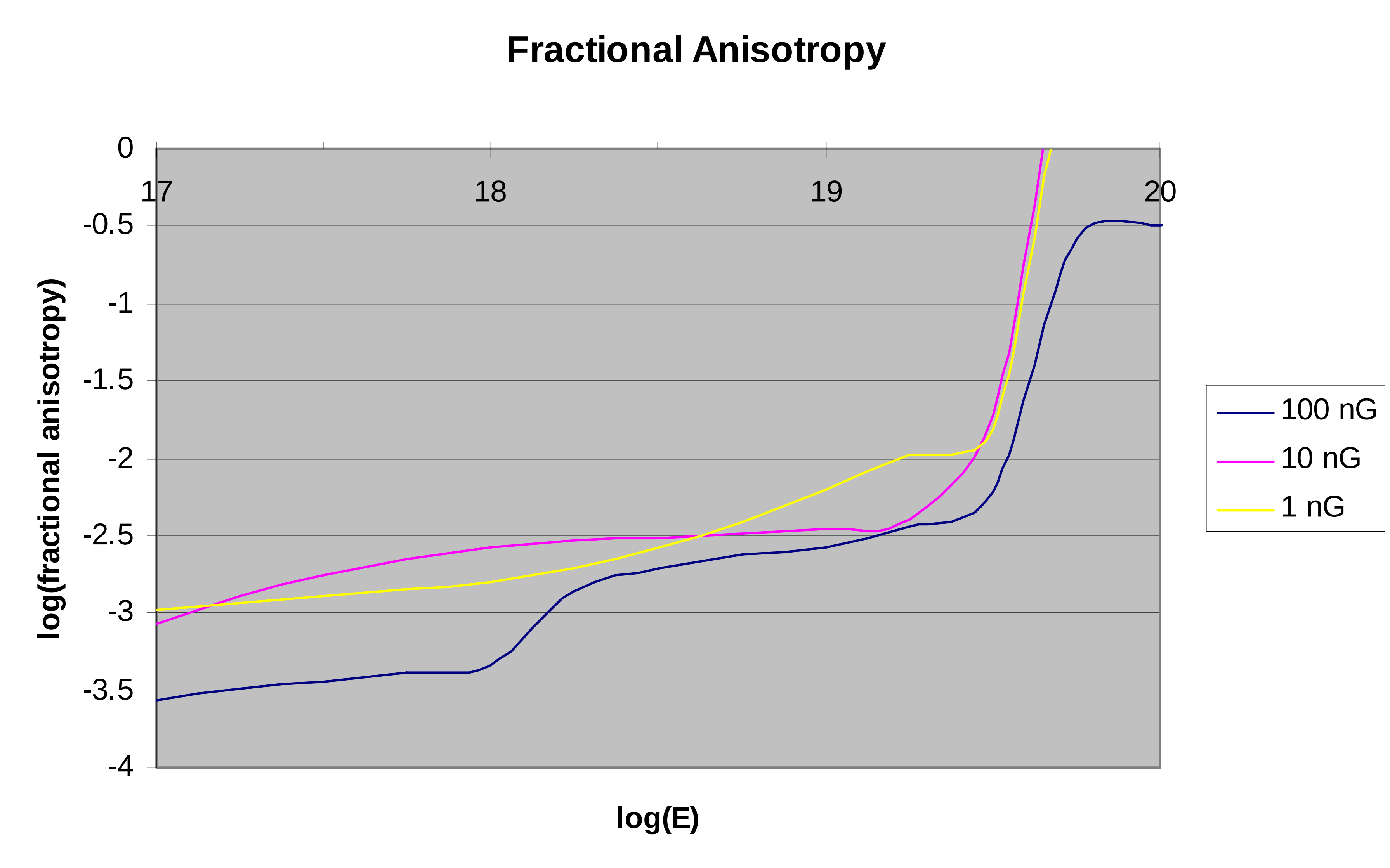
Source Differential spectral index.

(Surprisingly non-critical.)

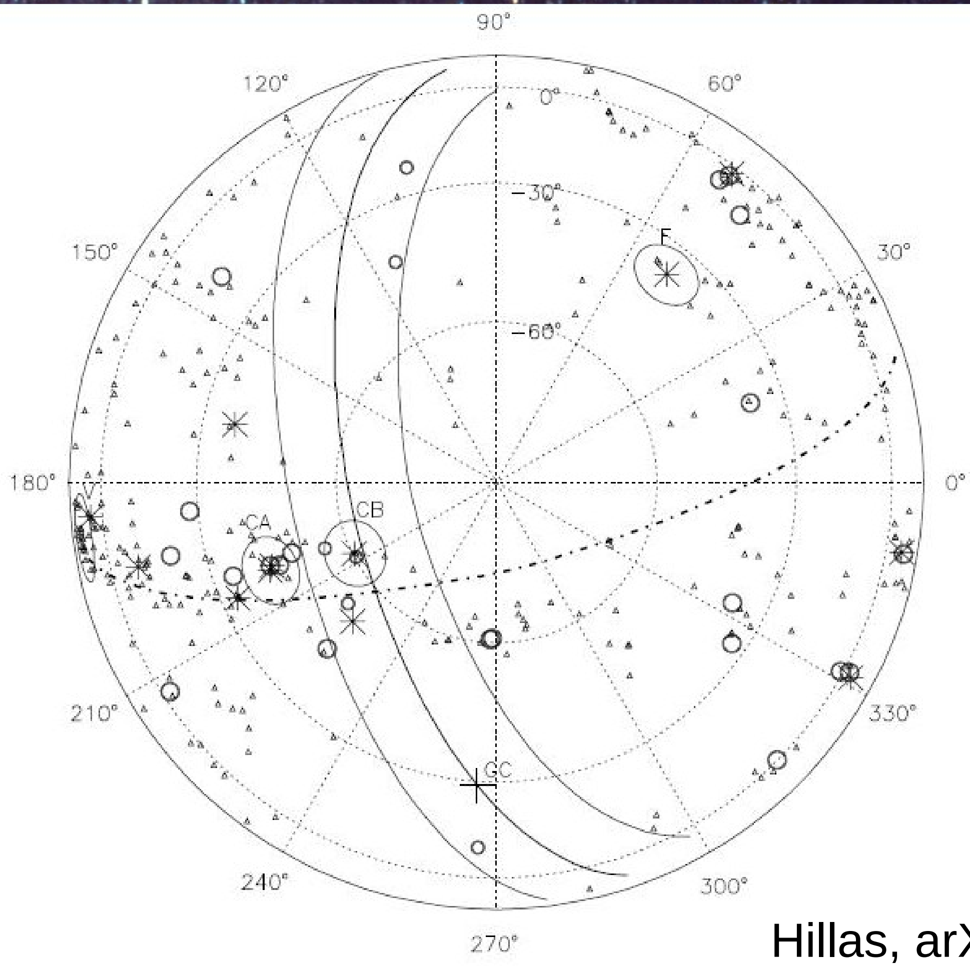
These are TIMES.

This assumes a power law source spectrum

We expect an anisotropy when the GZK effect limits the visible distance.



A uniform exposure plot of (2007 data) Auger events (circles) is NOT isotropic.



Hillas, arXiv 2009

Figure 1: The 27 arrival directions of particles above 5.7×10^{19} eV, published by Abraham et al. [1] on a uniform-exposure polar plot. The 6 particles within 12° of the galactic plane are shown as smaller circles. NB: near R.A. 268°, dec. −61° there are two cosmic rays extremely close together. The galactic plane and circles of galactic latitude ±12° are shown as full lines (GC marking the galactic centre) and the supergalactic plane as a dot-dash curve. Declination circles at 30° intervals, and radial right ascension lines, are shown dotted. Circles of 6° radius drawn around some of the strongest radio galaxies – V,Virgo A (M87), CA, Cen A, CB, Cen B and F, Fornax A – illustrate the compression of the radial scale towards the edge. (A 6° circle represents the angular distance from a source within which (at ~ 40 Mpc) most of these cosmic rays arrive according to the analyses discussed here.) Virgo A is at the centre of the Virgo cluster of galaxies. Small triangles mark the positions of 280 VCV AGNs S of declination +18°, having redshifts < 0.018. Eight-armed crosses (stars) mark the extended radio galaxies listed in [10].

Michael Hillas analysis (recent astro-ph)

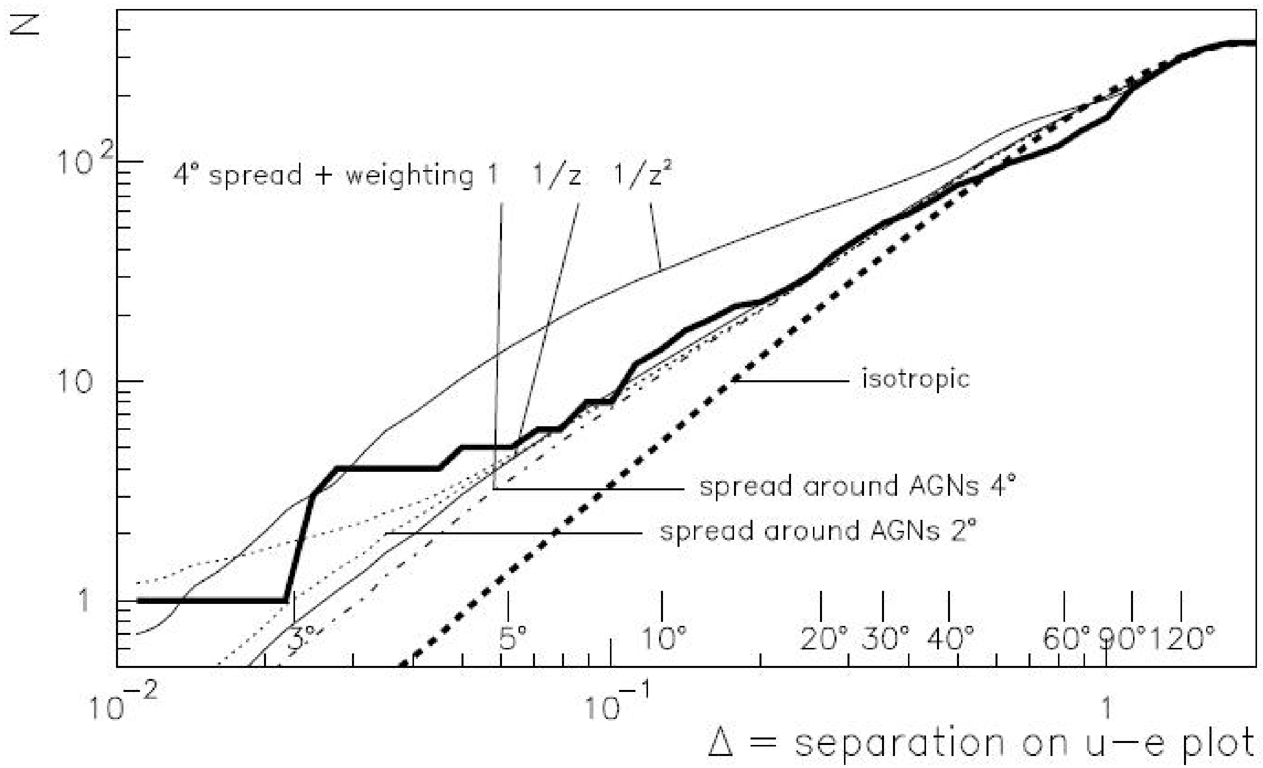


Figure 2: Cumulative number N of inter-point distances Δ on uniform-exposure plot in figure 1 for the 27 Auger cosmic-ray directions. The average separations in degrees on the sky, to which these plot-separations Δ refer, are shown just above the horizontal axis. Thick line: the observations (fig 1). Thick dashed line ("isotropic"), shows the average $N(\Delta)$ for many sets of 27 points placed randomly on the plot, simulating cosmic rays approaching the earth isotropically. Dot-dash line: average $N(\Delta)$ for many sets of 27 directions of AGNs picked from the VCV catalogue (redshifts $z< 0.018$) and given a 4° rms scatter (with refinements described in the text). Changing the scatter to 2° or 0.5° produces the variants shown by dotted lines. If a distance weighting is applied when picking AGNs, a $1/z^2$ weighting (appropriate if catalogue unbiased) moves the (4°) curve to the upper thin full line; the preferred $1/z$ weighting (see text) gives the full-line curve little different from the unweighted (dot-dash) version.

On the other hand, AGN and the highest energy cosmic rays do seem to have a correlated component.

How can this be?

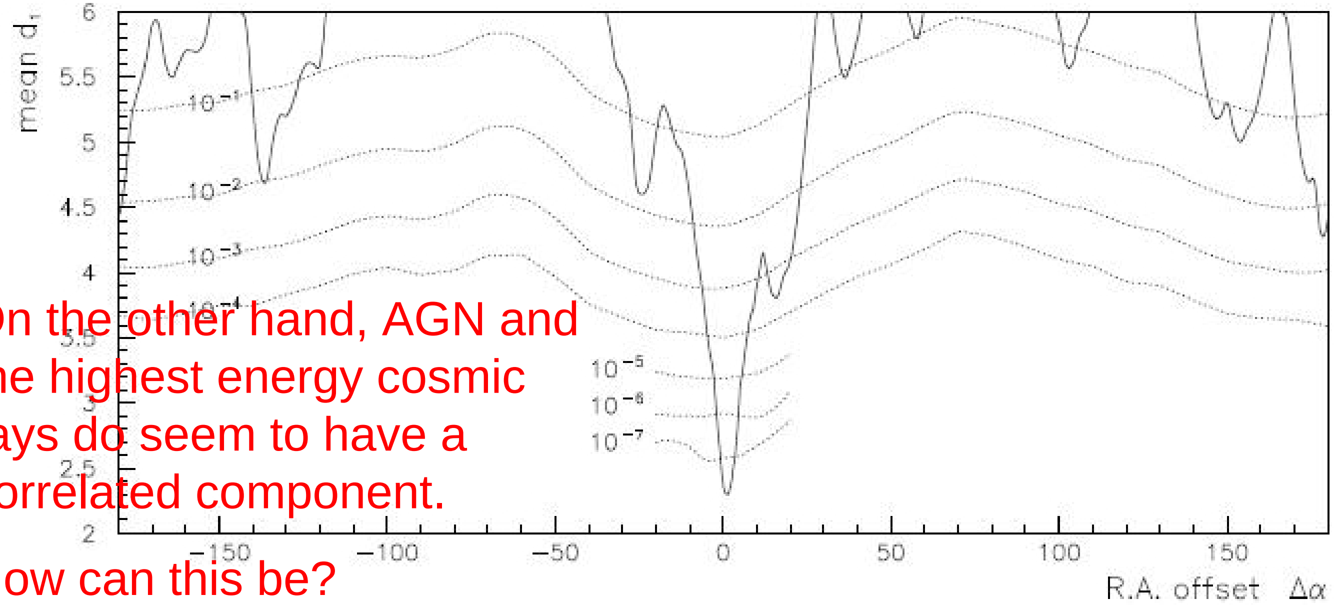


Figure 4: Right ascension resonance plot. Angular distance d_1 of cosmic ray direction from the nearest AGN (z<0.018), averaged over the Auger set of 21 cosmic ray directions ($|b_{gal}| < 12°$), plotted when the right ascension, α, of each AGN is shifted by $\Delta\alpha$. The near-horizontal dotted lines indicate the probability $P(\langle d_1 \rangle)$ of finding so small a value of $\langle d_1 \rangle$ in a set of 21 "pseudo-random" cosmic-ray directions at a specific offset position. (It varies with $\Delta\alpha$ because a 24° band almost devoid of AGNs is being shifted across the cosmic-ray pattern: only in the unshifted position does it coincide with the belt of omitted cosmic rays.) The preponderance of small distances d_1 soon disappears when the cosmic ray map and the AGN map are displaced slightly.

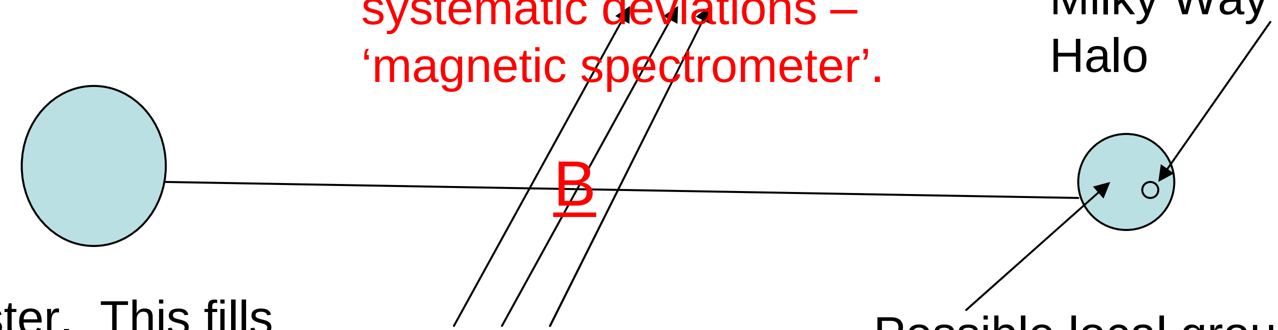
Hillas, arXiv 2009

<u>Cartoon of possible scattering field sites.</u>

Possible intergalactic or halo field.

May cause loss of flux or systematic deviations – ‘magnetic spectrometer’.

Milky Way and Halo



Source cluster. This fills with particles which are emitted from its surface. Subtends a <u>small angle</u>. May be large propagation delays.

Possible local group field. Scattering here results in <u>large deviations</u>. Could be large delays.

<u>Cluster fields</u>.

- Many galaxies are found in clusters – ‘nearby’ ones would be Virgo (which includes M87) at 20 Mpc or so, and Coma (which is five or six times more distant).
- Such clusters extend ~ megaparsecs
- Characteristically, the claim tends to be that such clusters contain ~microgauss magnetic fields.

- <u>Physics/reality check:</u>

- Radius of gyration of a 1 EeV (10^{18} eV) proton in a 1 microgauss regular field is 1 kpc.
- Of course, this scales linearly so as we saw, 100 EeV has 100 kpc.
- More highly charged nuclei (iron – 26 times) have smaller radii of gyration.
- Even Cen A is many times this distance away so retention of direction requires sub-microgauss intergalactic fields or small turbulence scales (worse for ‘iron’).

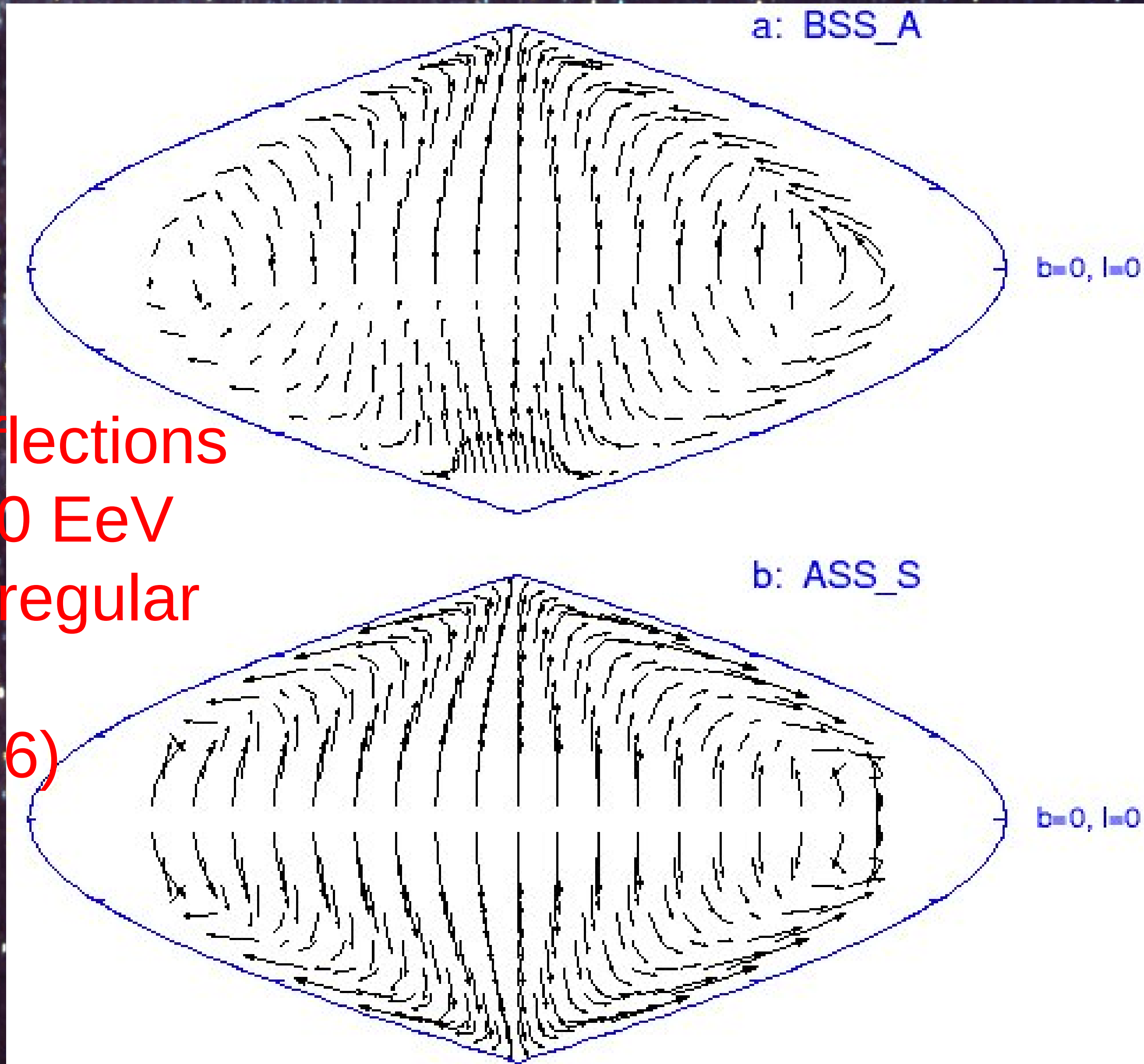
Diffusion comment:

- Diffusion is slow.
- Suppose that a source is embedded in a cluster (like M87 in Virgo). If the cluster radius is 1 Mpc and the radius of gyration is 100kpc (100 EeV, 1 micro-G), the cluster radius is ~10 gyro-radii and diffusion then gives (rough rule of thumb) 100 (10 squared) scatters to get out – a total path of 10+ Mpc. This takes a time approaching 10^8 yrs - not far from the GZK time.

The Milky Way

- What happens when a UHE extra-galactic cosmic ray approaches us from perpendicular to the galactic plane?
- There is a deflection in the galactic field (probably in the plane of the galaxy, more or less along the spiral arm) which should retain some directional information at the highest energies. At lower energies, the propagation will become diffusive and particles will be seen from all directions – possibly more along the field lines.
- We don’t yet know where high energy becomes low.

Galactic Deflections of protons 20 EeV and above (regular field).
(Stanev 1996)



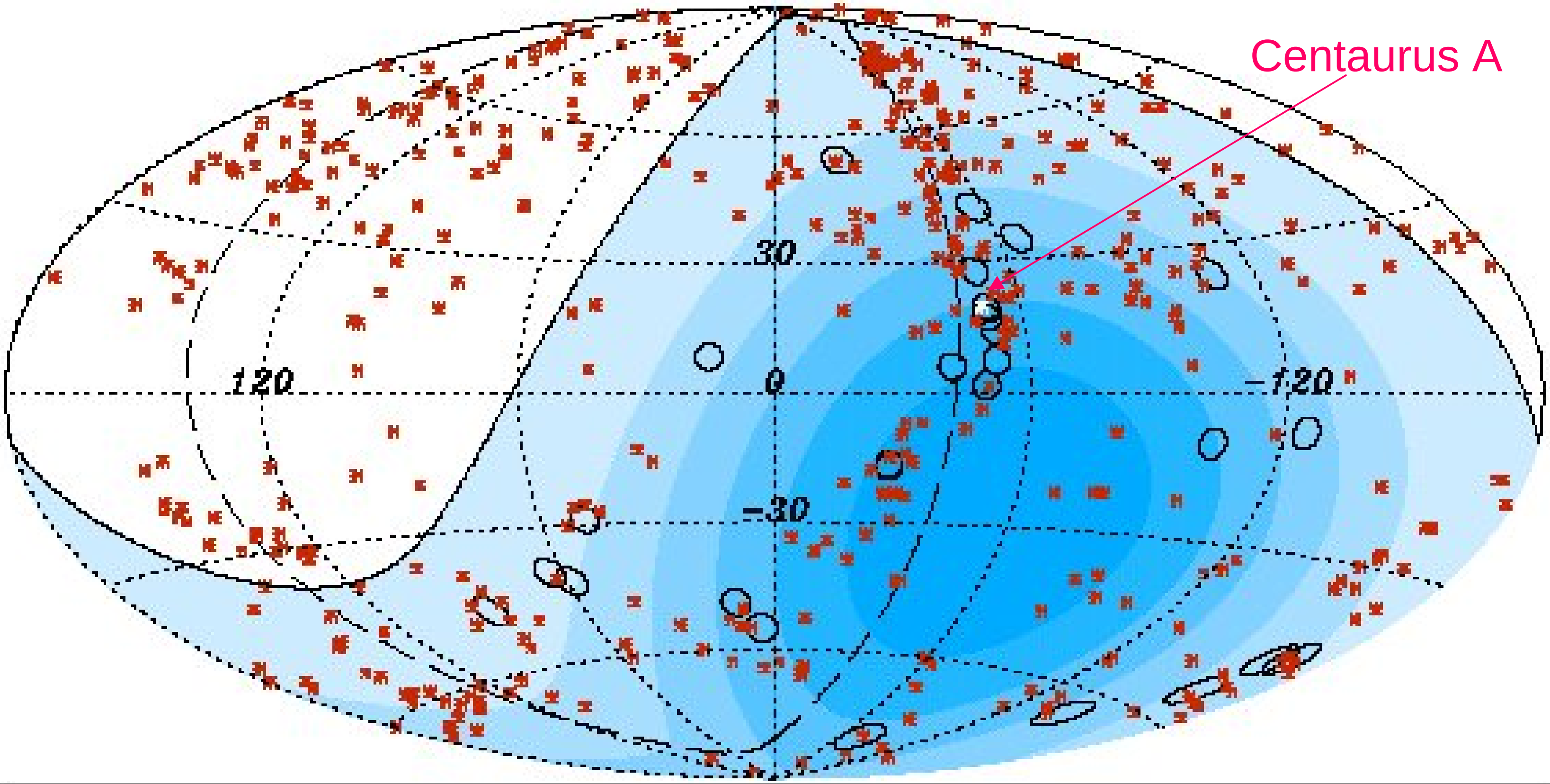


Figure 1: Aitoff projection of the celestial sphere in galactic coordinates with circles of radius 3.1° centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift $z \leq 0.018$ ($D < 75$ Mpc) from the 12^{th} edition of the catalog of quasars and active nuclei (*9*) are indicated by red asterisks. The solid line draws the border of the field of view (zenith angles smaller than 60°). Darker color indicates larger relative exposure. Each colored band has equal integrated exposure. The dashed line is, for reference, the super-galactic plane, Centaurus A, one of our closest AGN is marked in white.

2009 Auger plot (Lodz ICRC)

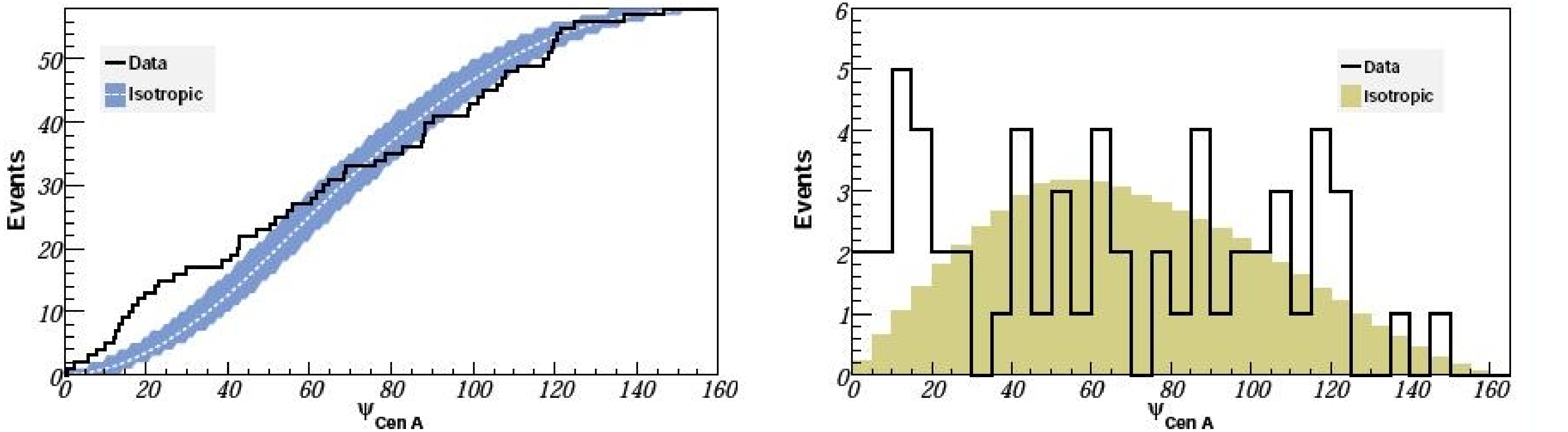


Fig. 3. *Left:* The cumulative number of events with $E \geq 55$ EeV as a function of angular distance from Cen A. The average isotropic expectation with approximate 68% confidence intervals is shaded blue. *Right:* The histogram of events as a function of angular distance from Cen A. The average isotropic expectation is shaded brown.

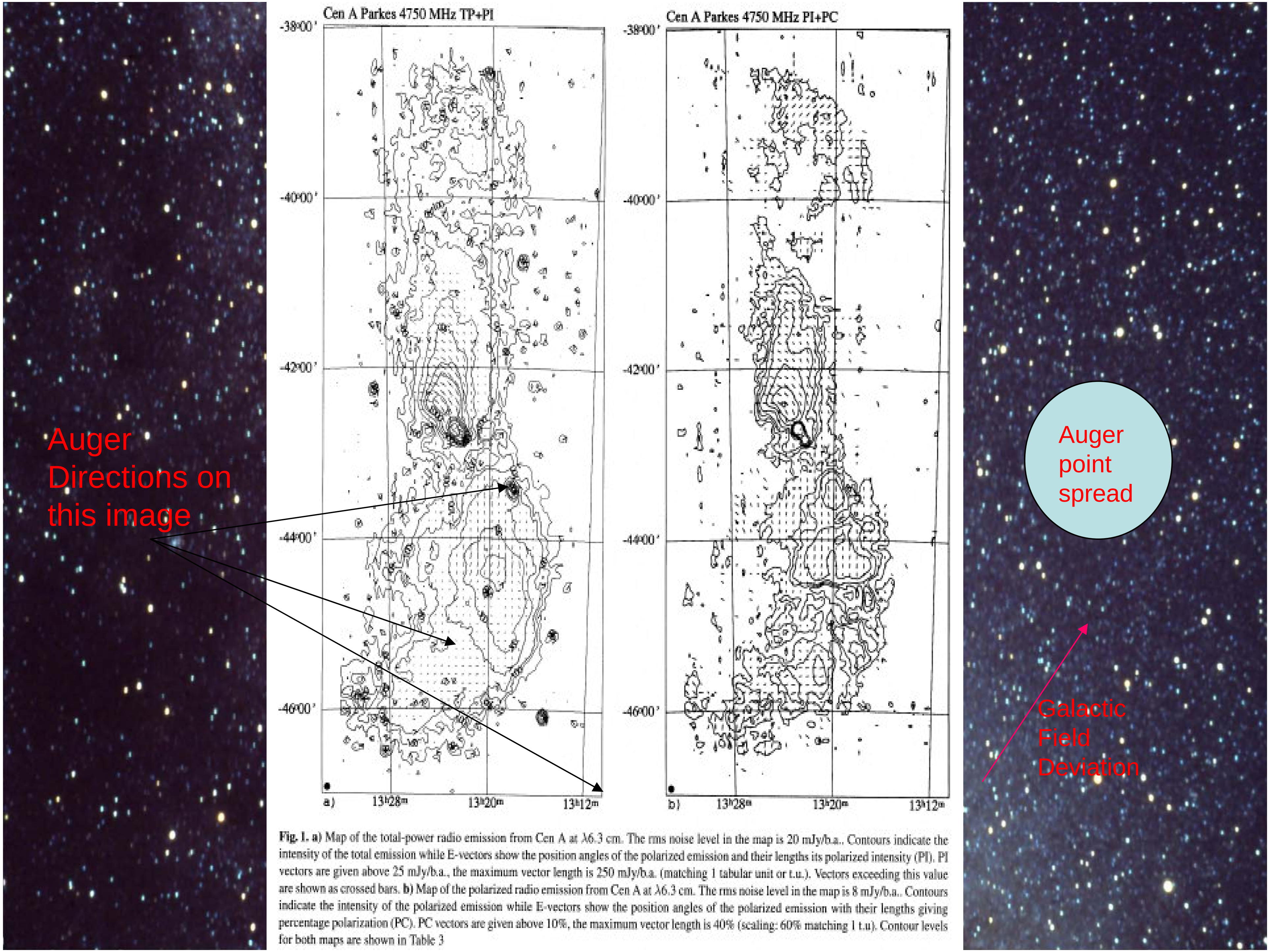
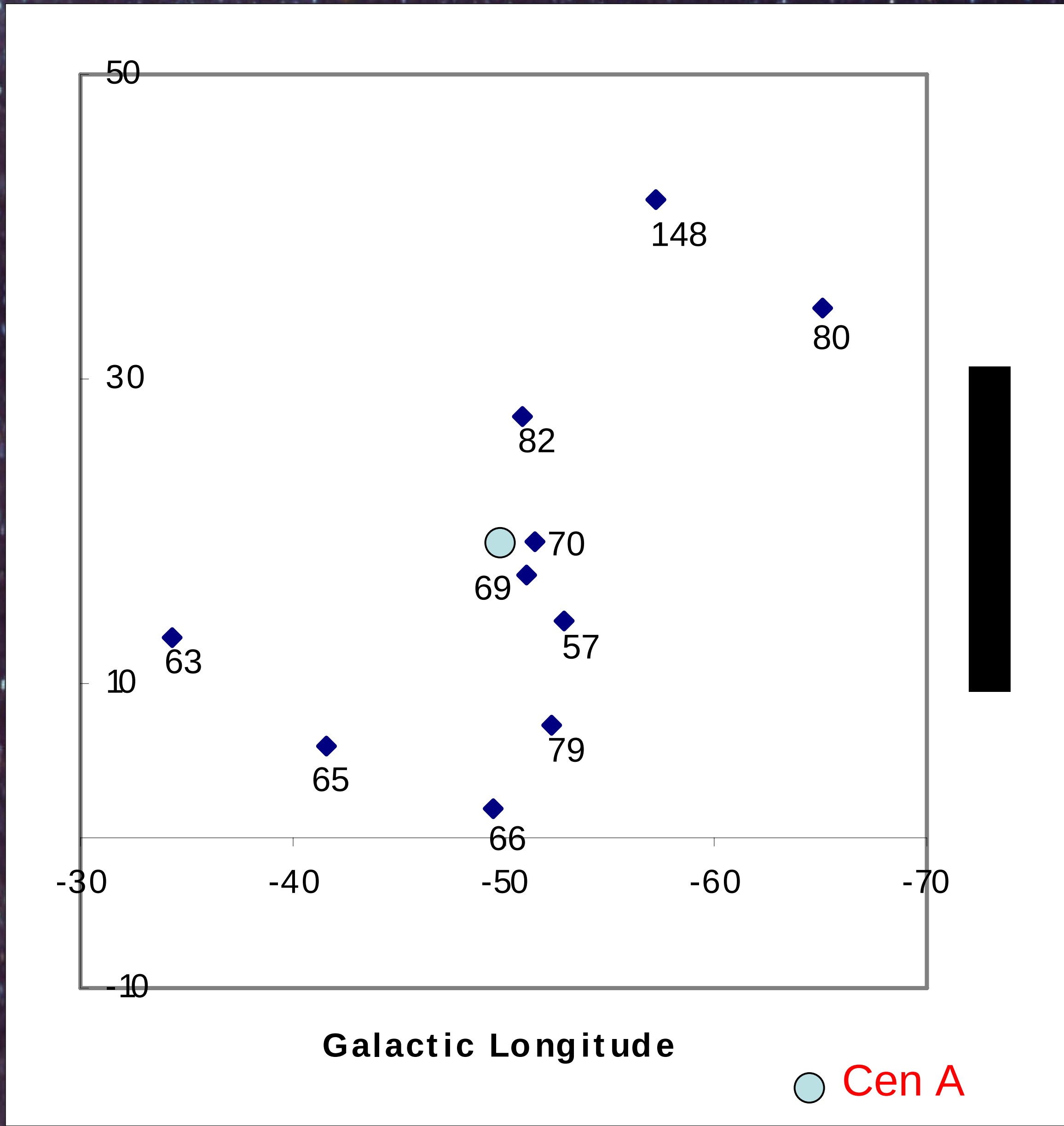


Fig. 1. a) Map of the total-power radio emission from Cen A at λ6.3 cm. The rms noise level in the map is 20 mJy/b.a.. Contours indicate the intensity of the total emission while E-vectors show the position angles of the polarized emission and their lengths its polarized intensity (PI). PI vectors are given above 25 mJy/b.a., the maximum vector length is 250 mJy/b.a. (matching 1 tabular unit or t.u.). Vectors exceeding this value are shown as crossed bars. b) Map of the polarized radio emission from Cen A at λ6.3 cm. The rms noise level in the map is 8 mJy/b.a.. Contours indicate the intensity of the polarized emission while E-vectors show the position angles of the polarized emission with their lengths giving percentage polarization (PC). PC vectors are given above 10%, the maximum vector length is 40% (scaling: 60% matching 1 t.u). Contour levels for both maps are shown in Table 3

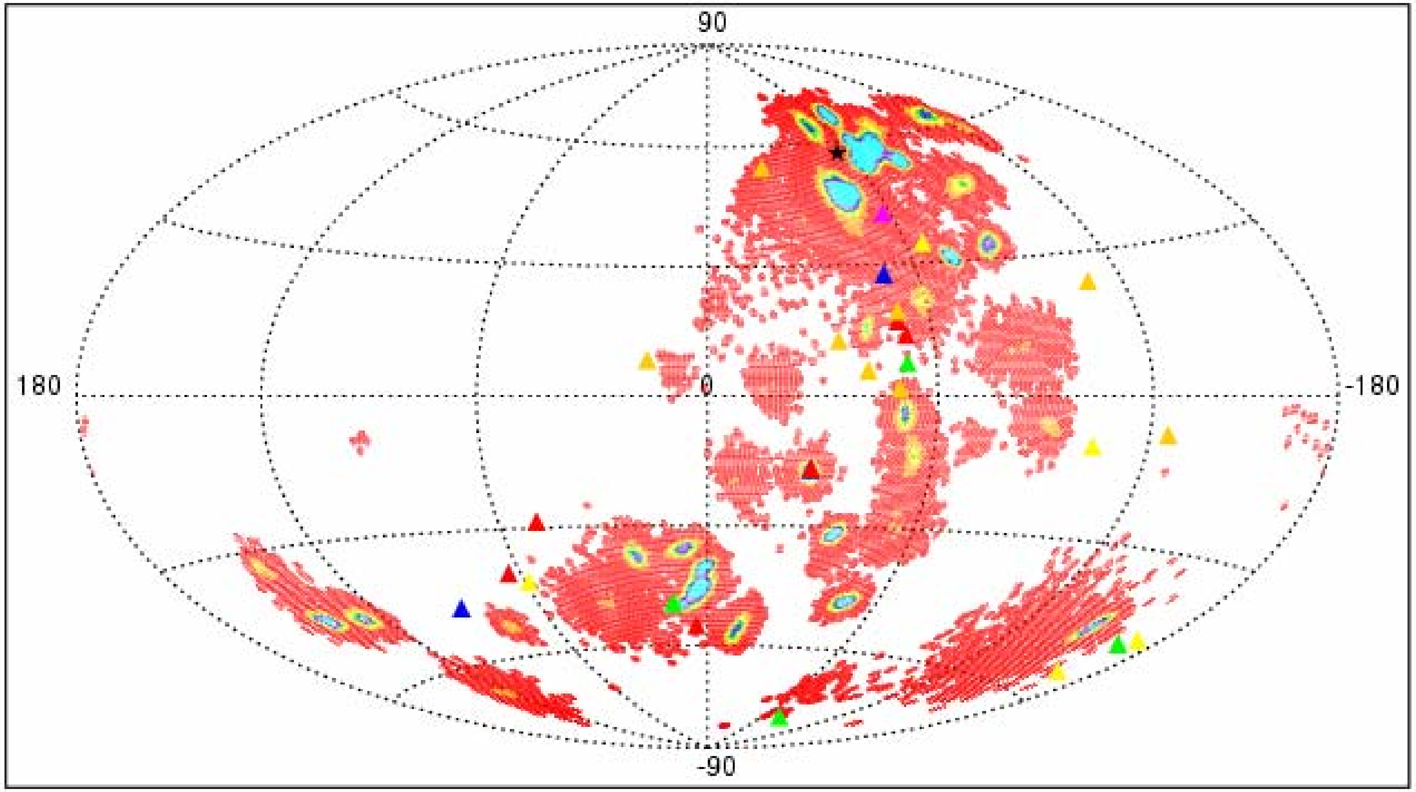
These events make up about one third of all PAO events at the highest energies – even though this is not in the area of greatest sky exposure. They arguably contribute strongly to the 2007 published excess of correlations with AGN because they are within the super-galactic plane.



- Note that the events ‘from’ Cen A do not have the most energetic events ‘on source’. We need to invoke a range of nuclear charges to reproduce this distribution.

- The 2007 Auger depth of maximum distribution suggests that those charges may be ‘heavy’. But then any ‘light’ ones would be on-source!!

- Alternatively, this peak could be transposed due to local magnetic deflection (maybe in the Milky Way field).
- Examination of the energy-direction map may support this and there could be a ‘magnetic spectrometer’ effect.
- On this assumption, we can produce a new ‘source direction’ map. (next slide)


90
180
0
-180
-90

Conclusions.

- Auger now has over 60 events at super-GZK energies
- We are trying to interpret these energy/direction data.
- Auger expects to develop a Centaurus A ‘prescription’ soon.
- We seem to be very close to being able to make more useful statements about magnetic fields in our galaxy and the local intergalactic space.