Ultra High Energy Cosmic Rays

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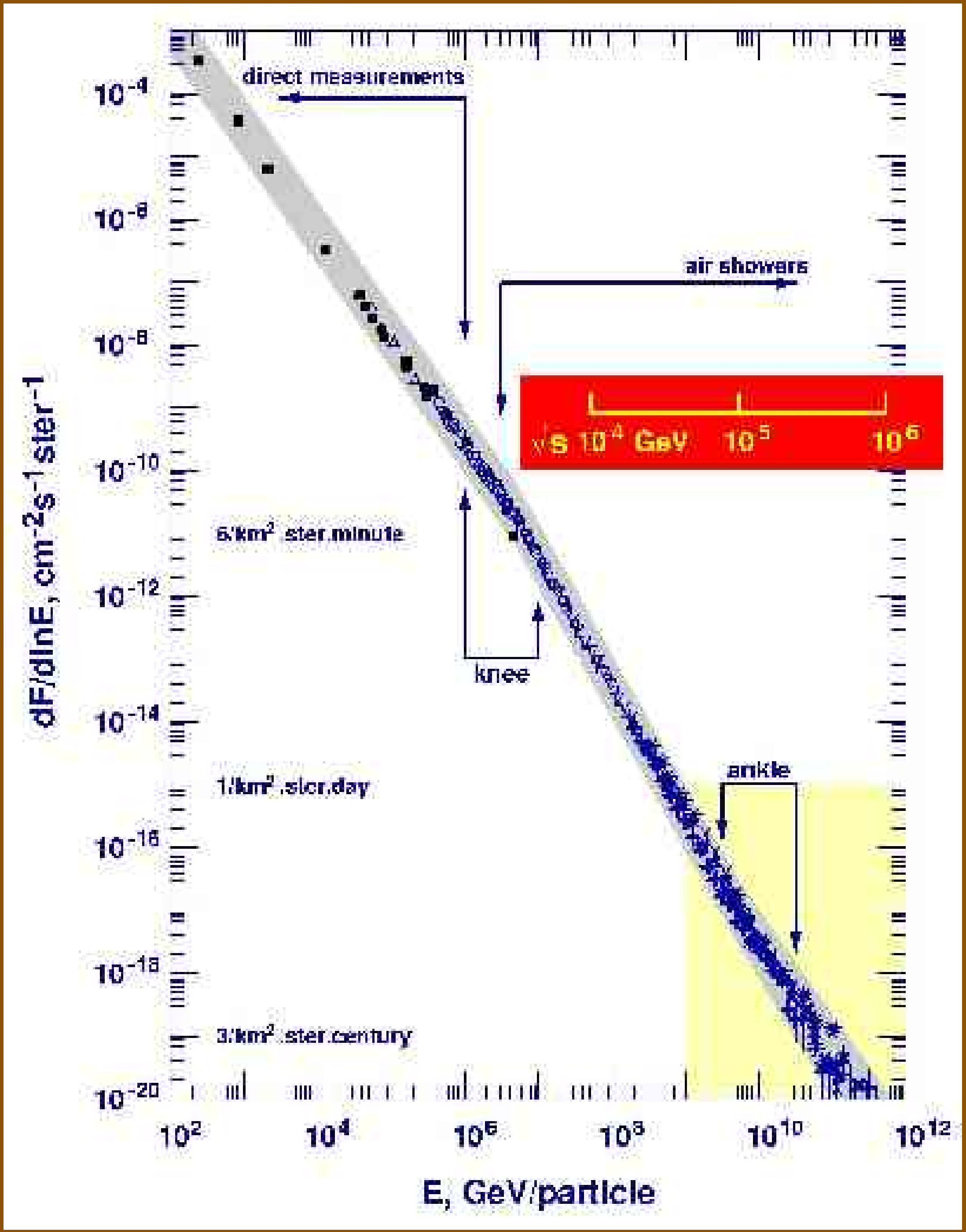
John Linsley (PRL 10 (1963) 146) reports on the detection in Vulcano Ranch of an air shower of energy above 10^{20} eV.

Problem: the microwave background radiation is *discovered* in 1965. Greisen and Zatseping&Kuzmin independently derived the absorption of UHE protons in photoproduction interactions on the 3K background.

More problems: such detections continue, the current world statistics is between 10 and 20 events.

10^{20} eV = $2.4\text{x}10^{34}$ Hz
= $1.6\text{x}10^{8}$ erg
= 170 km/h tennis ball

$\sqrt{s}$ equivalent is $3\text{x}10^{5}$ GeV



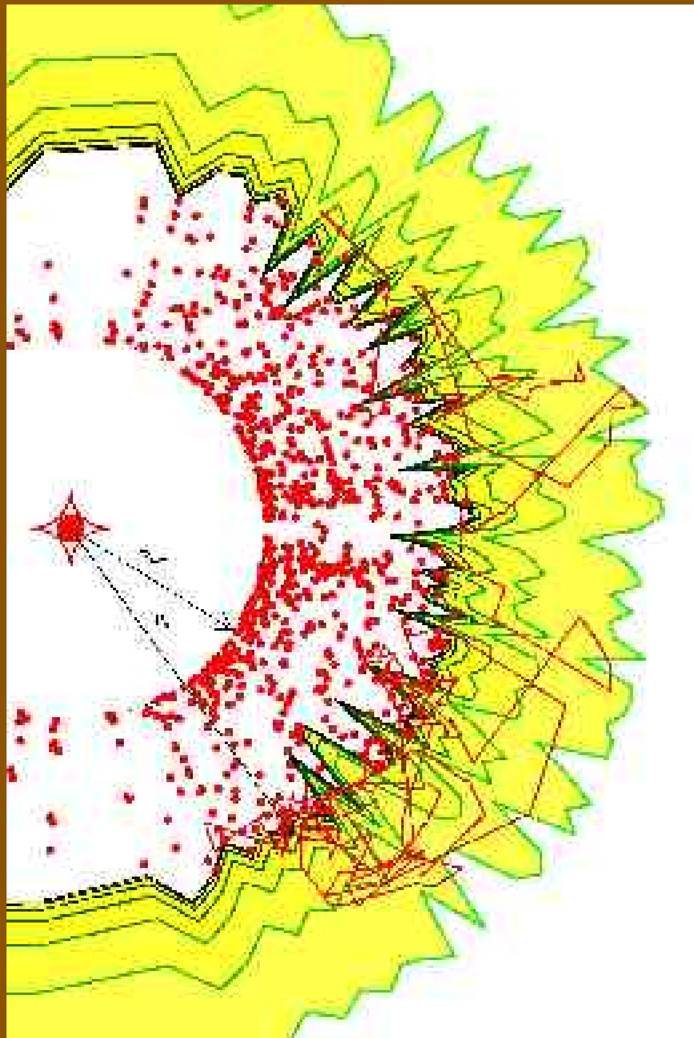
Cosmic ray energy spectrum is smooth, power law like.
It has two main features:

- the knee
- the ankle

The standard theory is that cosmic rays below the knee are accelerated at common (?) galactic sources, most likely supernova remnants.

Cosmic rays above the knee are accelerated at unknown galactic sources.

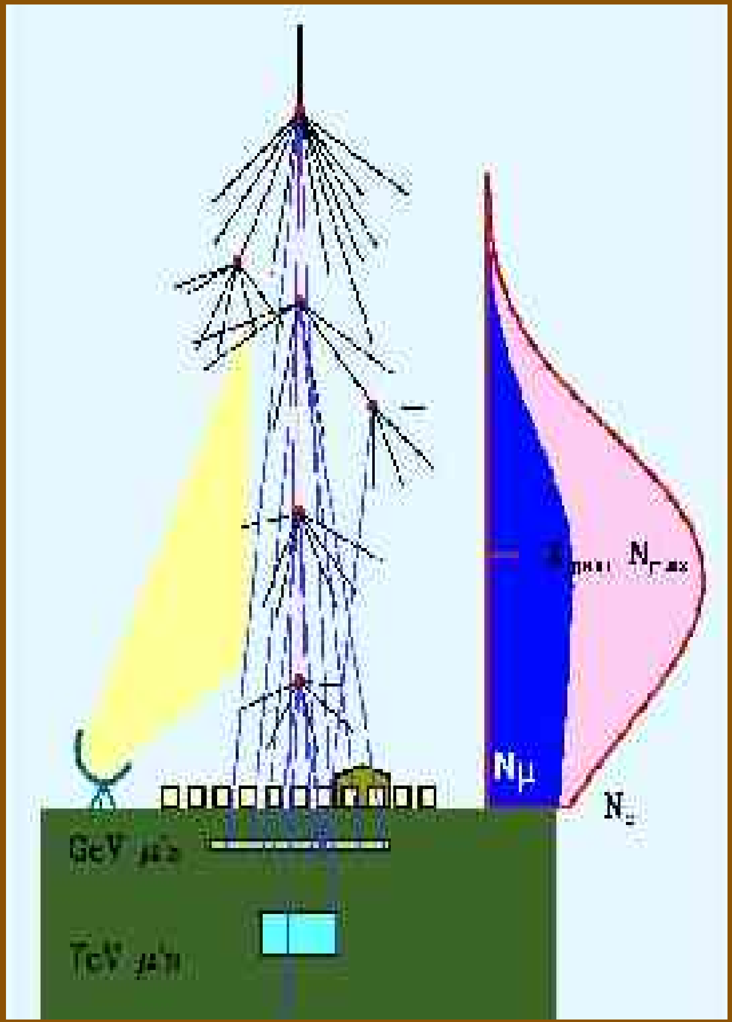
Cosmic rays above the ankle have to be extragalactic, if they are also charged nuclei. Galactic magnetic fields are not strong enough to contain such particles - their gyroradii are larger than the Galaxy.



Ginzburg&Syrovatskii have identified supernova remnants (SNR) as possible sites of cosmic ray acceleration. If only 5% of the kinetic energy of the SNR is converted to cosmic rays this would supply all cosmic rays in the Galaxy.

The acceleration proceeds at the shock formed by the expanding SNR envelope. Most productive time is 1000 to 10000 years after the explosion. Shock compression ratios above 4 lead to flat power law spectra. Modern calculations obtain more complicated spectra that are power laws in small energy ranges.

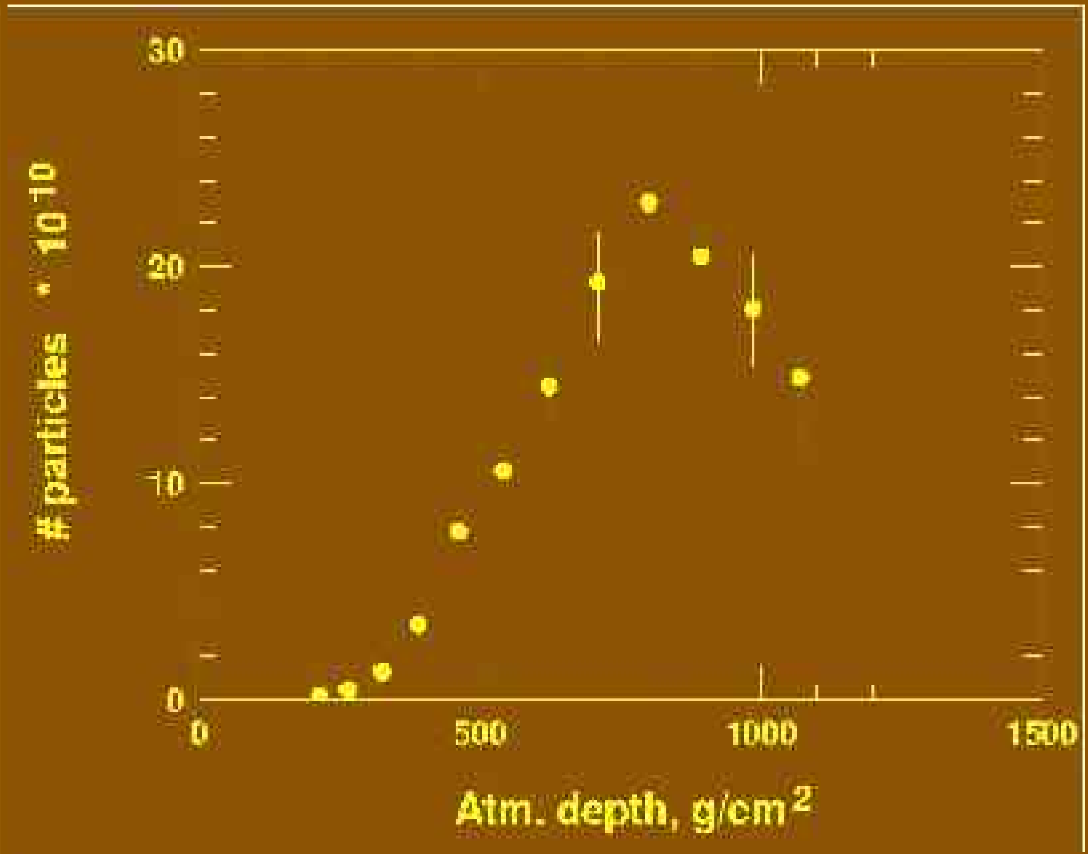
The maximum acceleration energy is between 100 and 5,000 TeV in different estimates. It could be higher when the remnant expands in highly magnetized pre-supernova wind. Heavier nuclei reach Z times the maximum energy.



There are two different rechniques for air shower observations: shower arrays and optical detectors that observe the fluorescent or Cherenkov light emitted by shower charged particles.

The shower arrays detect in coincidence the electromagnetic, muonic and hadronic components of the shower at the observation level. They need a hadronic interaction model to convert to primary energy and mass.

Optical detectors observe the development of the electromagnetic component of the air showers above about one tenth of maximum. The energy conversion is theoretically much easier.

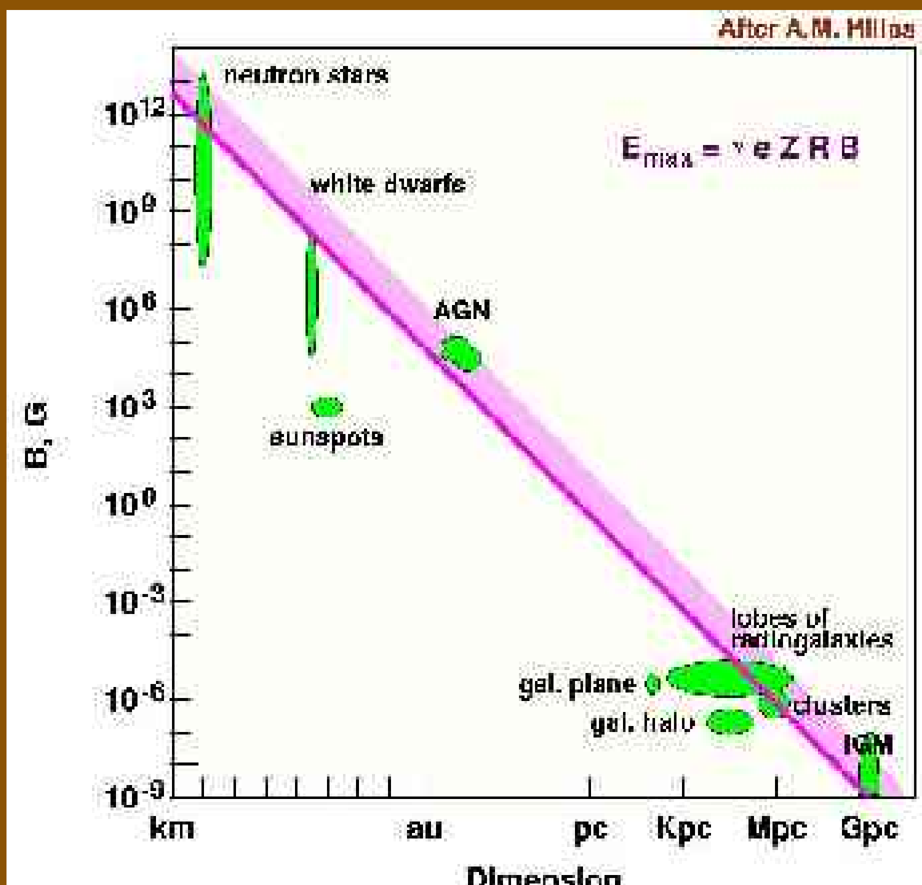


The highest energy shower was detected with the fluorescent technique by the Fly's Eye. The energy estimate is $3x10^{20}$ eV. The number of charged particles at shower max is $2x10^{11}$. The error is not likely to exceed 40%. All contemporary hadronic interaction models give 1.4-1.6 GeV per charged particle at shower maximum.

All giant shower arrays have detected super-GZK showers: Volcano Ranch, Sydney, Haverah Park, Yakutsk, and AGASA. AGASA has the highest exposure and claims 11 events above 10^{20} eV. There are currently strong arguments about the shape of the cosmic ray spectrum at these ultra high energies.

What could be the origin of these particles ?

In analogy with the lower energies one is tempted to think that they come from acceleration sites associated with powerfull astrophysical objects. How many such objects exist in the Universe ?



Michael Hillas generated this famous graph 20 years ago. It shows the dimensional upper limit for acceleration to 10^{20} eV. The upper edge is for protons and lower one - for iron nuclei. The observed magnetic field values and dimensions of astrophysical objects are indicated. There is a handful of objects that could do it with an efficiency of 1.

Possible astrophysical sources:

Shocks from structure formation: 1 nG fields on 50 Mpc distance needed for 10^{20} eV protons. Energy loss may be much too large.

Clusters of galaxies: μG fields observed on 500 kpc scales. Still the acceleration is too slow and energy losses may prevail.

Radiogalaxies: 10 μG fields on 100 kpc scale possible in *red spots* of FRII type galaxies. Since these are jet termination shocks there will be no adiabatic losses.

AGN jets: the jet Lorentz factor (10) decreases the energy requirements. There should be adiabatic loss.

GRB: the extreme case of jet acceleration. The Lorentz factors of GRB are assumed to be between 100 & 1,000. Isotropic luminosity is 10^{53-54} ergs. Suggestion first made when directions of two powerful GRB coincide with most energetic UHECR.

Colliding galaxies: 20 μG fields possible on 30 kpc scales. Very strong shocks are observed.

Quiet black holes: Such objects could exists within 50 Mpc of the Galaxy. 10^9 $M_\odot$ black hole could accelerate up to 10^{20} eV.

Pulsars: Not shock acceleration. Charged particles are accelerated in the strong electrostatic potential drop. Characteristic 1/E energy spectrum. UHECR should be iron nuclei.

In all astrophysical acceleration scenarios UHECR are charged nuclei. It is possible that only neutrons from higher energy nucleon interactions could leave the source. Many of them would decay to protons. This is the biggest difference with `top-down' models.

Top-down models: the observed cosmic rays are not accelerated, they are products of the decay of massive X-particles.

Topological defects: Monopoles were first suggested. UHECR emitted during monopole annihilation. Ordinary cosmic strings emit X-particles from their cusps and when they intersect. Superconductiong strings emit when their electric current reaches a critical value. Various more complicated scenarios.

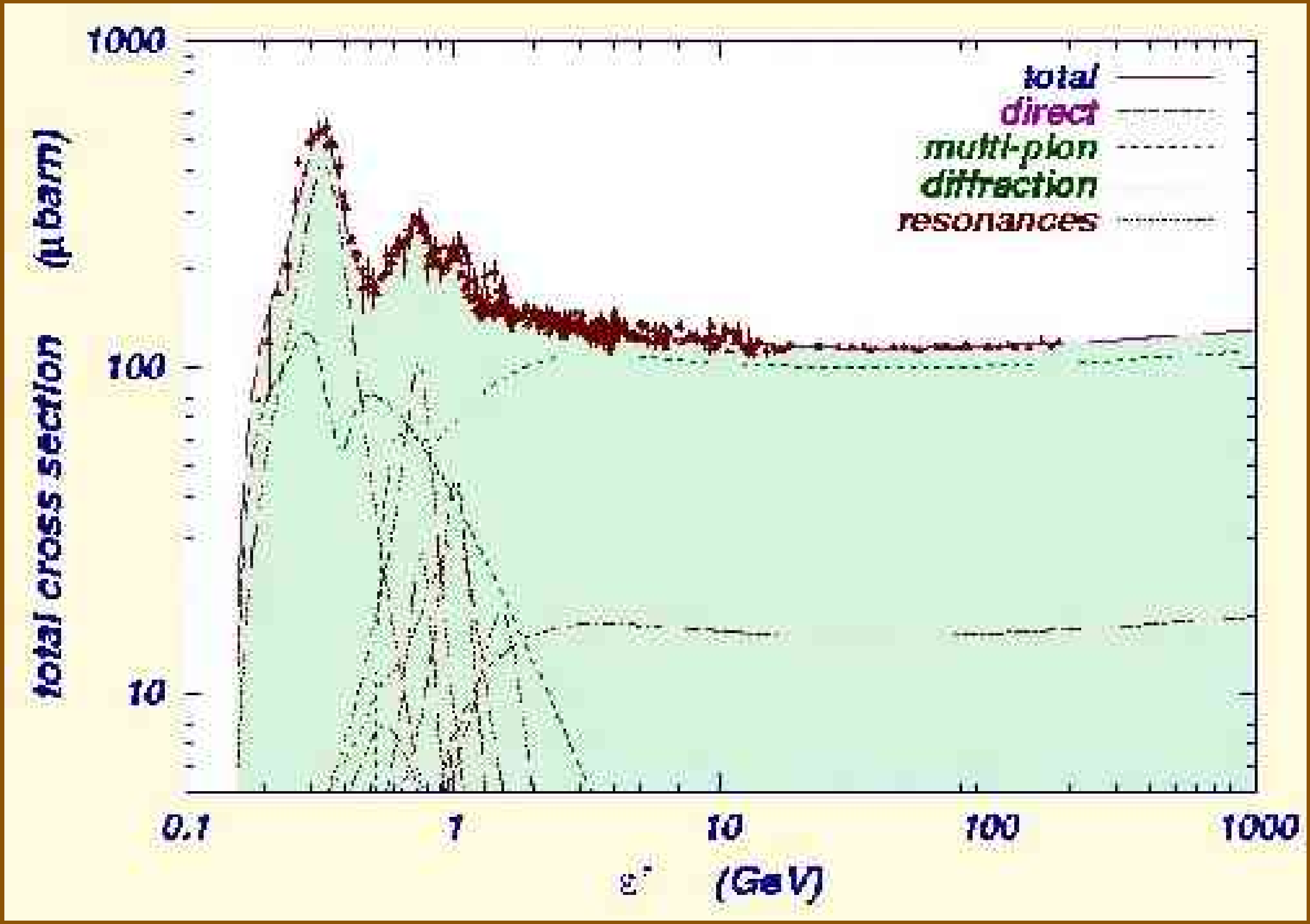
Decay of quasi stable X-particles produced in the early Universe: Must have lifetime comparable to Hubble time. Small fraction of cold dark matter.

UHECR have to be either gamma rays or neutrinos – from the fraction of nucleons and mesons in decay. The energy spectrum is flatter than acceleration spectra – $E^{-3/4}$. M_X can be restricted by observed isotropic GeV gamma ray flux to below 10^{23} eV.

Hybrid scenarios:

Z-burst: Ultrahigh energy neutrinos (of unknown origin) interact on massive relic neutrinos that are gravitationally attracted in our cosmological neighbourhood. The secondary Z_0 decay to generate UHECR. To have the resonant cross section neutrinos have to have energy $4x10^{21}$ eV/m_ν.

The main energy loss process of the ultra high energy protons in the Universe is photoproduction interactions in the microwave background. The photoprocustion cross section is very well measured in accelerator experiments.

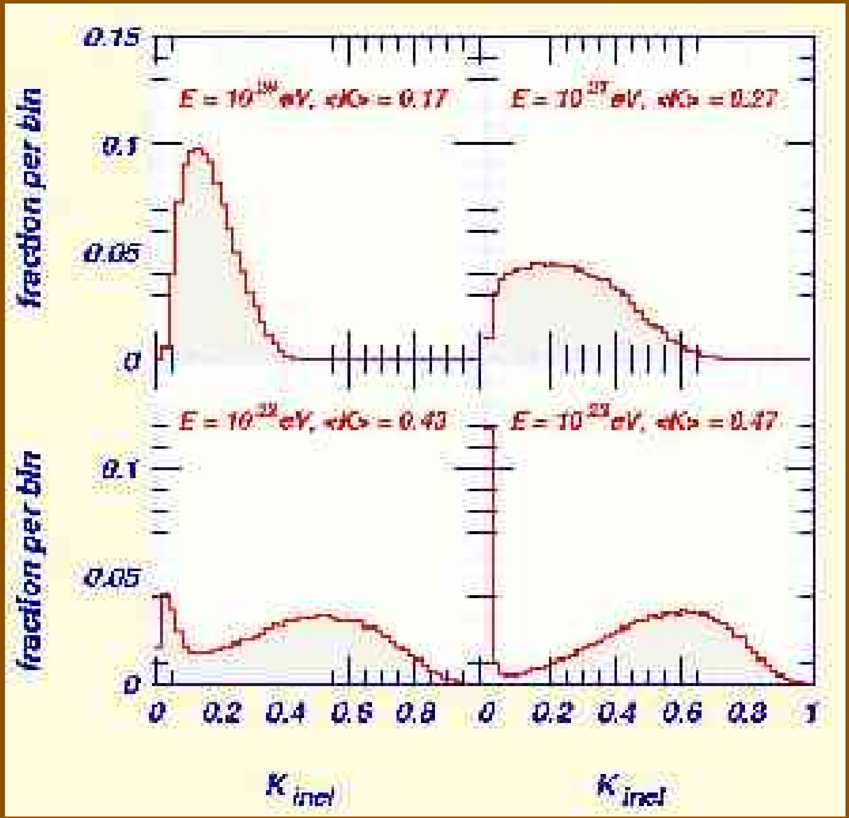


Photoproduction cross section in the mirror system, i.e. photons interacting on target protons.

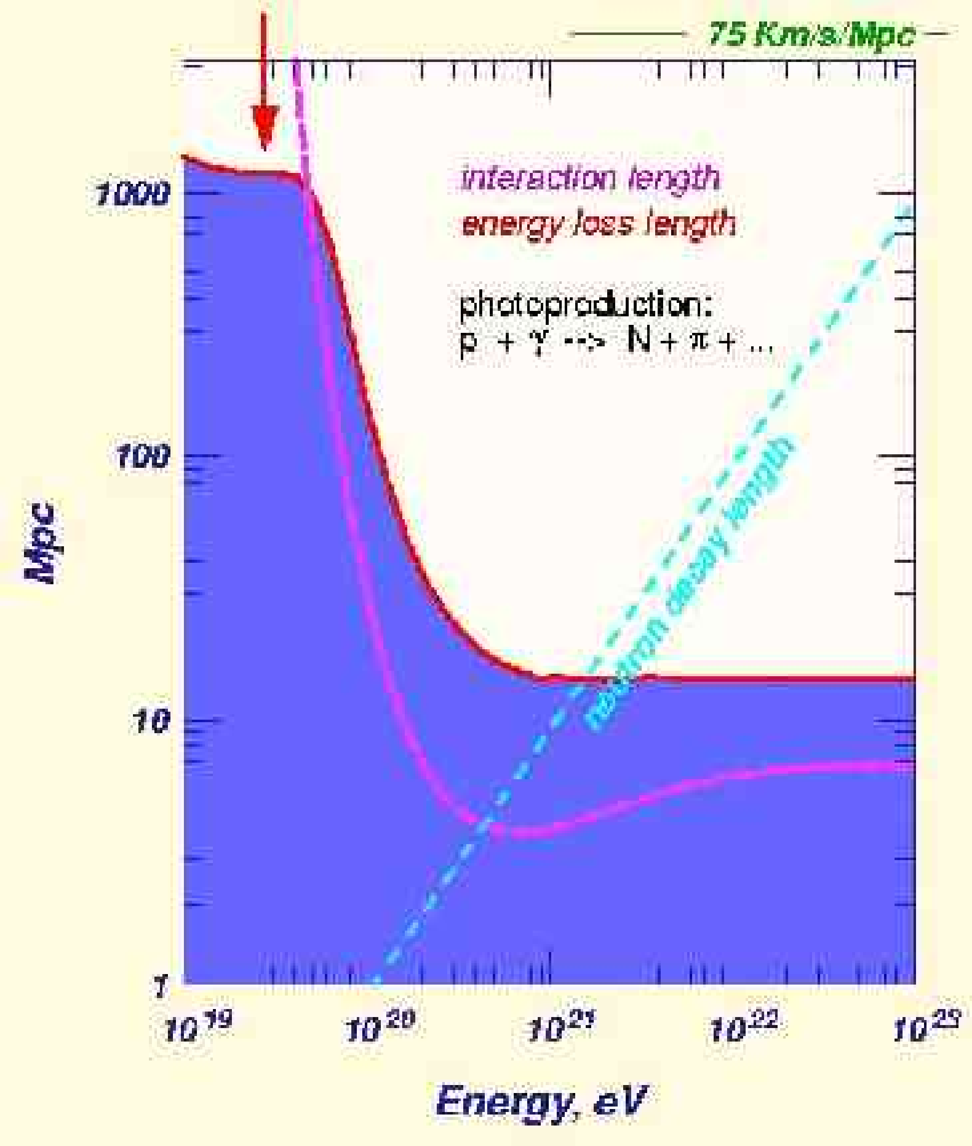
The UHE protons energy is so high that they can interact on photons from the microwave background and produce secondary pions. The threshold is when the center of mass energy exceeds the proton mass + the pion mass:

$$E\varepsilon(1-\cos\theta) > (m_p+m_\pi)^2$$

For the average microwave background photon the threshold is at 10^{20} eV. Averaged over the photon spectrum and direction the threshold is a factor of 2 lower.



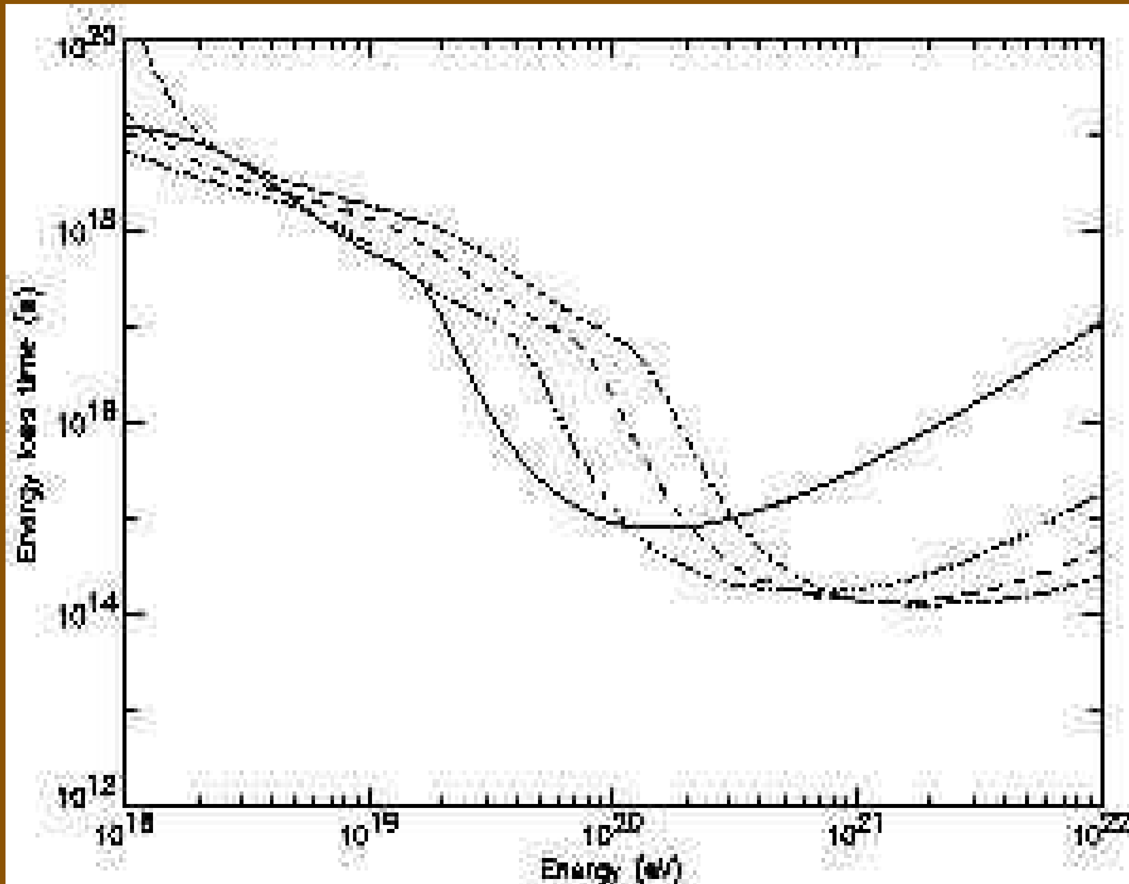
The inelasticity of the proton in these interactions is important energy dependent parameter. At threshold protons lose less than 20% of their energy. At very high energy the loss can reach 50%.



The energy loss length of protons in the microwave background is about 14 Mpc above 4×10^{20} eV, about a factor of 4 above the proton interaction length. The arow in the left upper side of the graph shows the energy loss length in the BH electron-positron pair produ-ction. The proton energy loss is the ratio of electron to proton mass. The cross section is high.

The mark at 4,000 Mpc shows the energy loss to the expansion of the Universe for H_0=75 km/Mpc/s.

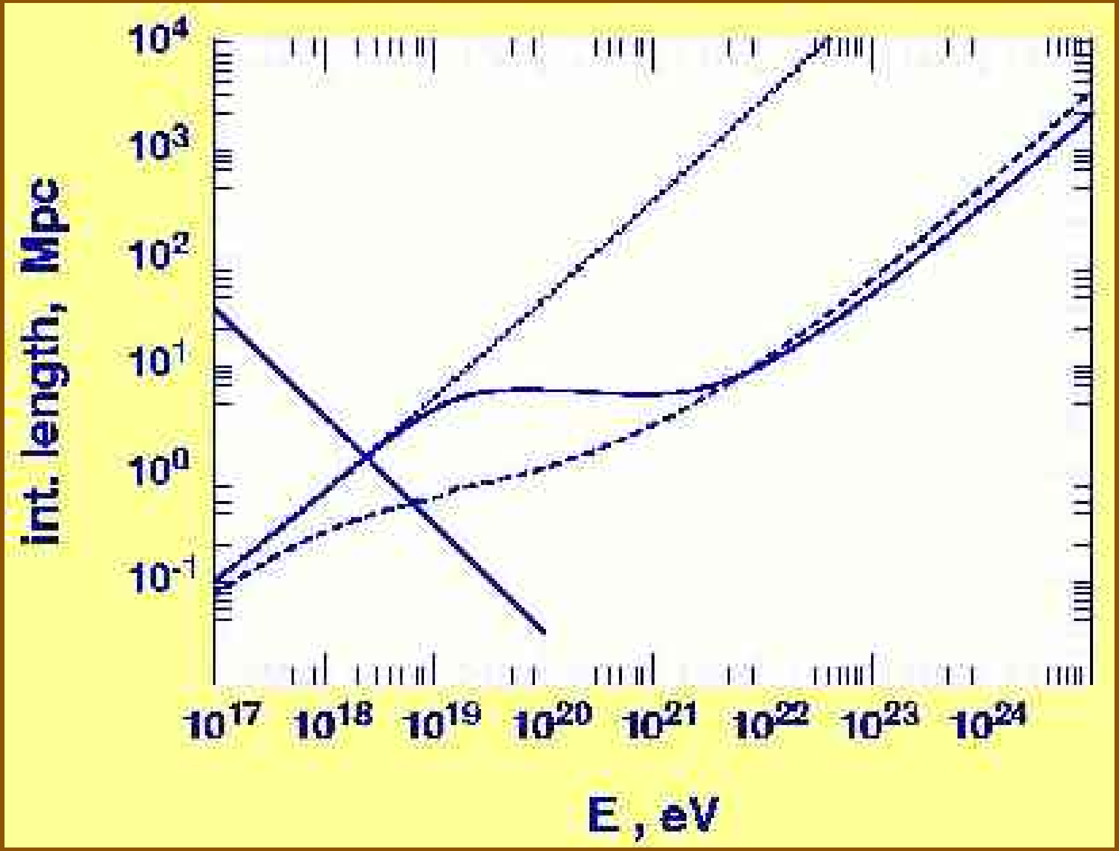
Neutron decay length is also shown with dashed line.



From: Bertone et al

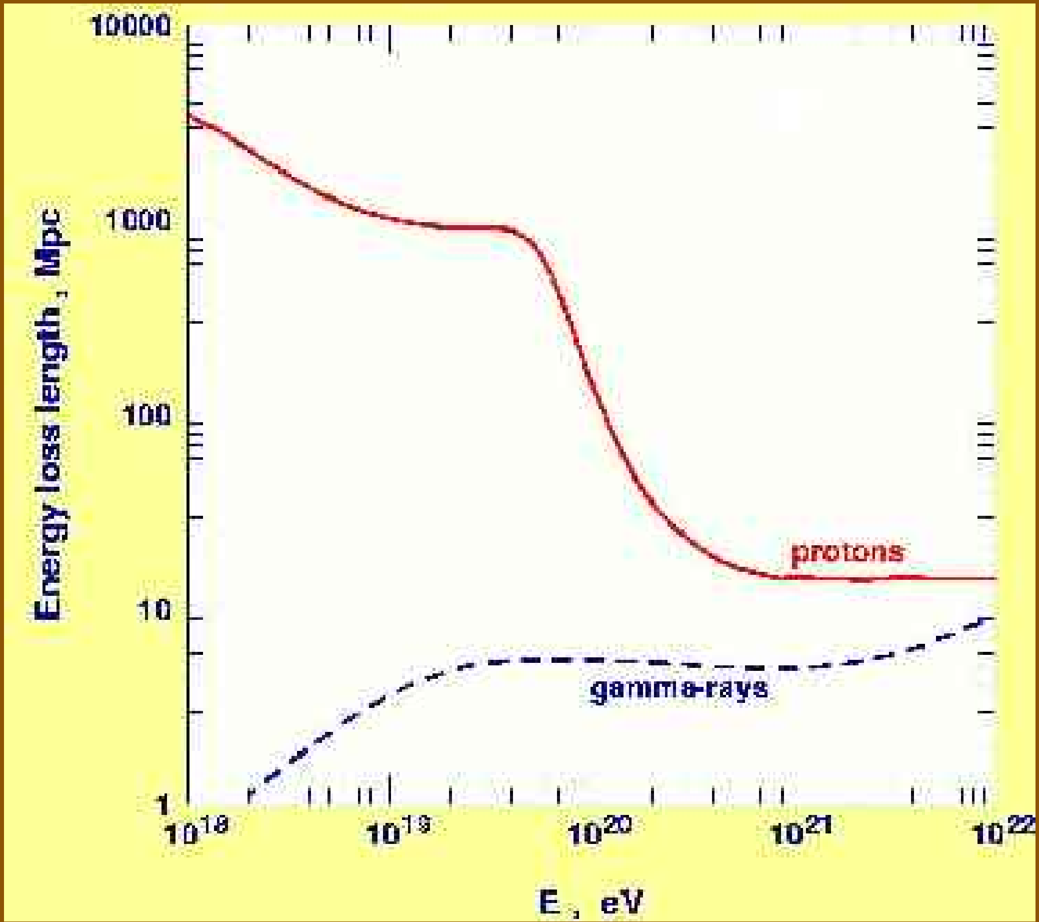
Heavy nuclei lose energy in photodisintegration on all photon fields. A beam of heavy nuclei injected at large distance from us changes its composition in propagation. At distances larger than the energy loss distance it is a purely proton beam after the secondary neutrons decay.

Energy loss time for He, C, Si, and Fe nuclei.
(1 Mpc = 10^{14} s)



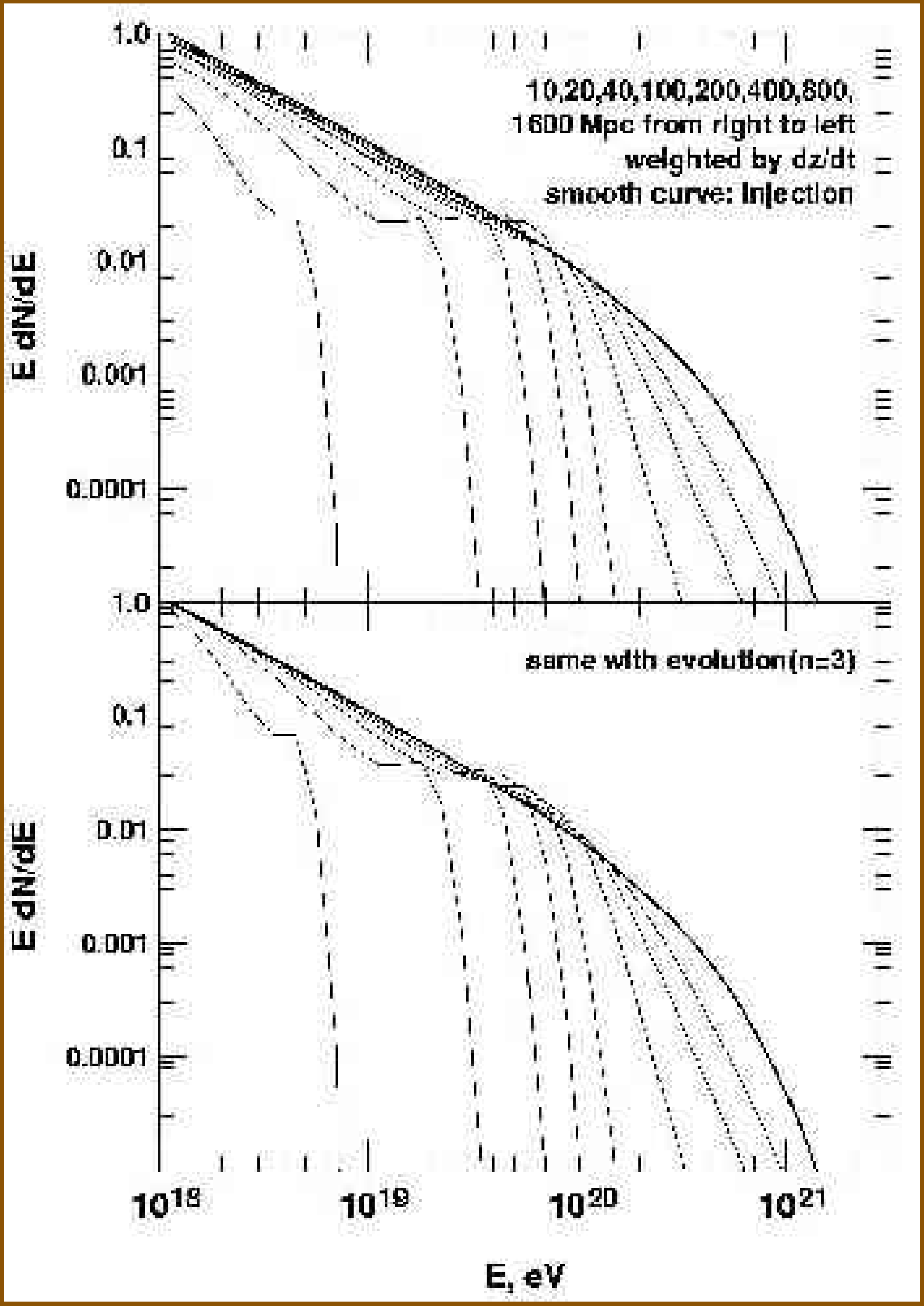
The gamma ray energy losses in the microwave background are also significant. The dotted line shows the pair production mean free path on the microwave background. Very important is the radio background which is very uncertain. It is included and shown for one model with the solid line. The photon interaction length is limited to below 120 Mpc by the double pair production process. The IC m.f.p is shown with a dashed line that includes the radio background. IC is very much a forward process at these energies.

Magnetic fields are very important for the possible electromagnetic cascade process. The straight line shows the electron energy loss length in 1 nG fields. If the magnetic fields are not significantly lower the electron energy will be downgraded by synchrotron radiation very fast.



Mostly because of the uncertainties in the MHz radio background and the magnetic field strength, there are arguments about the gamma ray energy loss length.
The estimate here uses B&P radio background and 1 nG magnetic field.

It is obvious, though, that GZK gamma rays, as well as GZK protons, can not travel far. They have to be generated at 2 to 3 energy loss lengths to minimize the (already severe) energy requirements to the sources. There very few potential sources at distance less than 50 Mpc from the Galaxy.

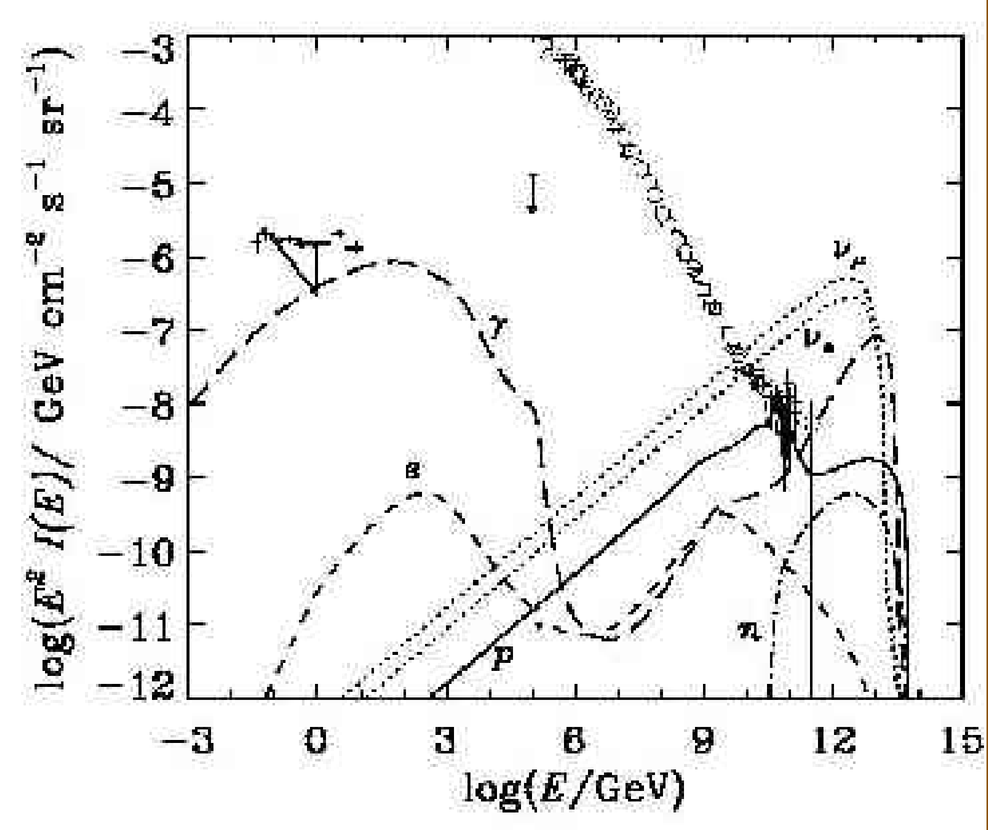


Evolution of the cosmic ray spectrum in propagation on different distances.

The solid line shows the injection spectrum.

The top panel is without cosmological evolution of the cosmic ray sources and the lower one is with $(1+z)^3$ evolution.

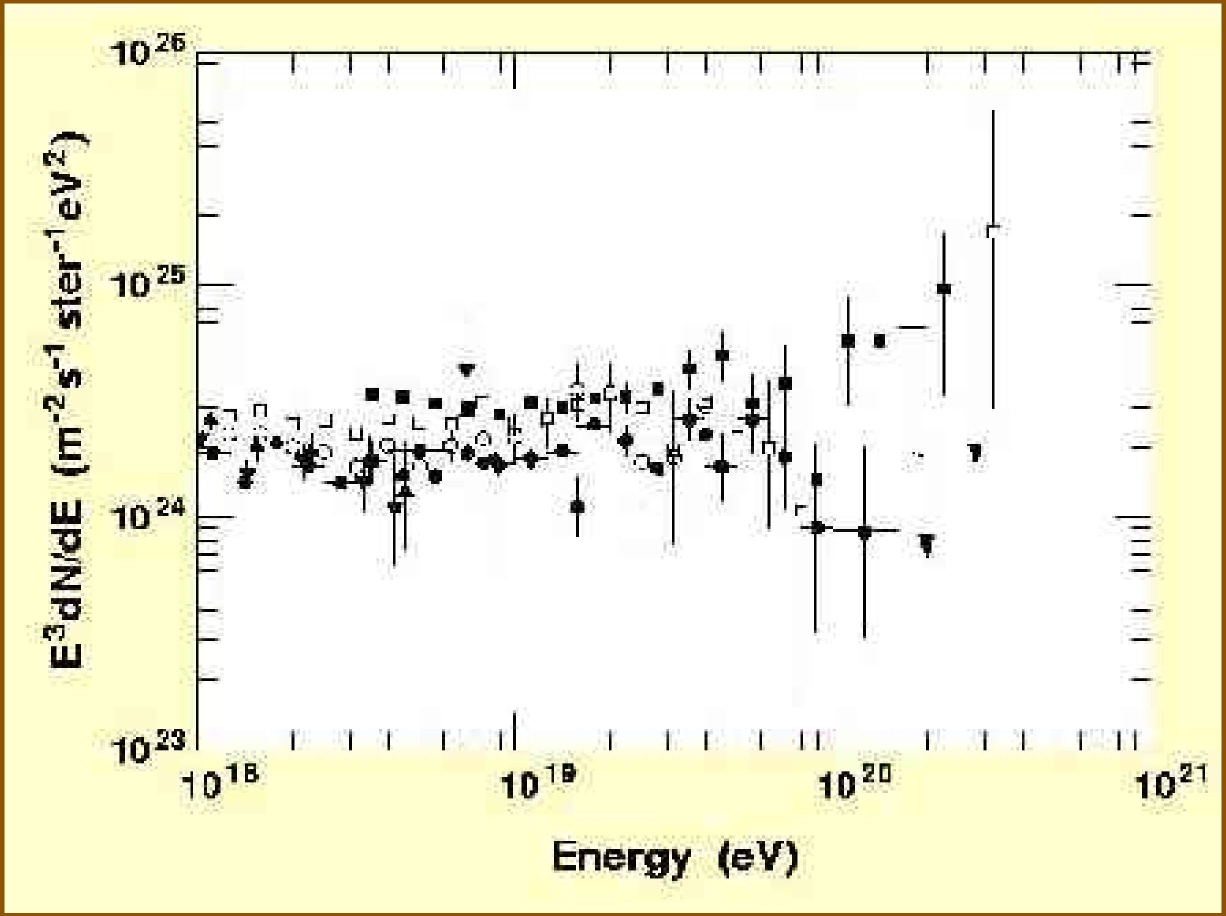
There is a pile-up of protons just below 10^{20} eV. Integration over source distance will produce the expected energy distribution for homogeneous isotropic source distribution.



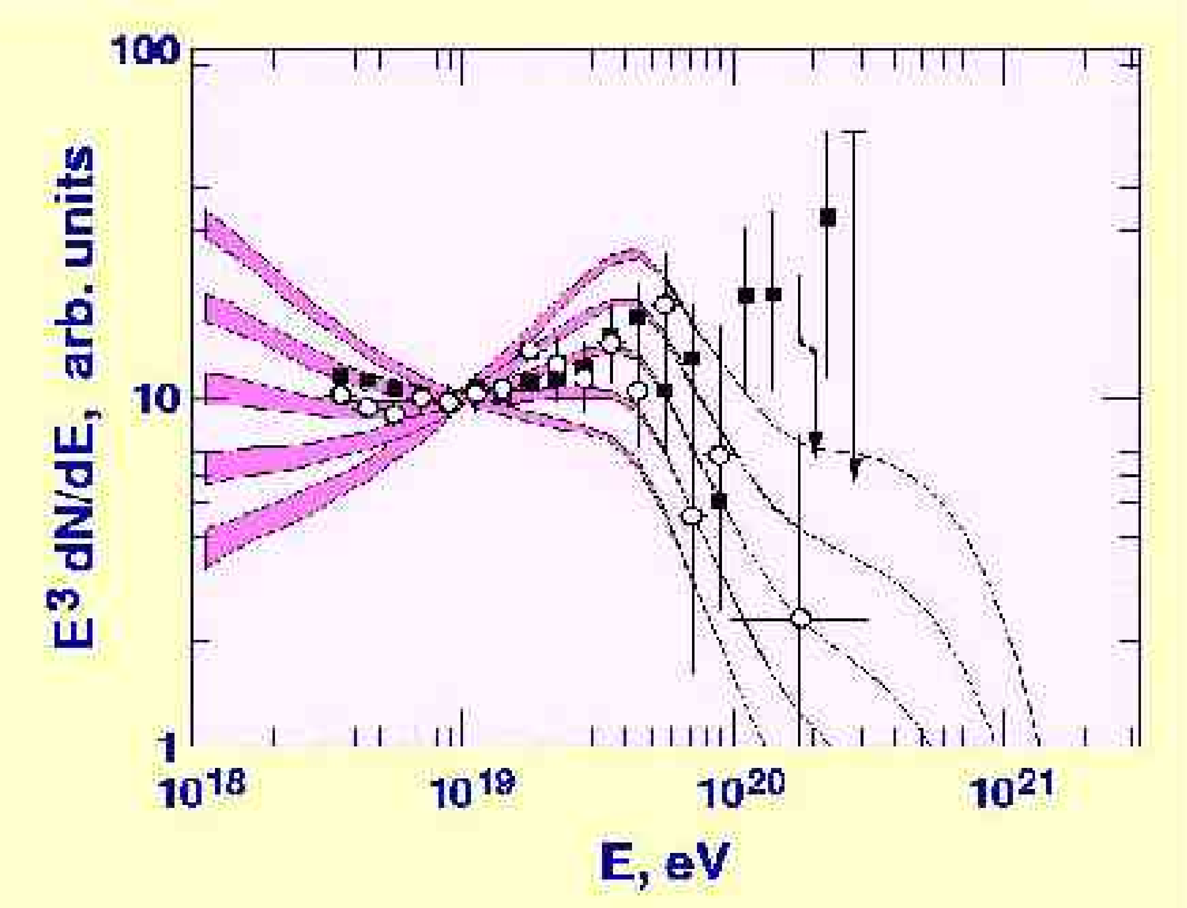
From: Protheroe&Stanev (1996)

While the proton spectra integrated over redshift always maintain power law shape, the photon spectra after propagation have very complicated shape. There is a minimum due to the interactions in the microwave background. Top-down models can be restricted with the amount of GeV gamma rays, as done here for X-particle mass of 10^{16} GeV and 1 nG magnetic field.

Experimental data: The spectra measured by several experiments have absolute normalization different by 40%. Note that the differential flux is multiplied by E^3 to emphasize the shape of the spectrum. The results are obtained with the same hadronic interaction model.



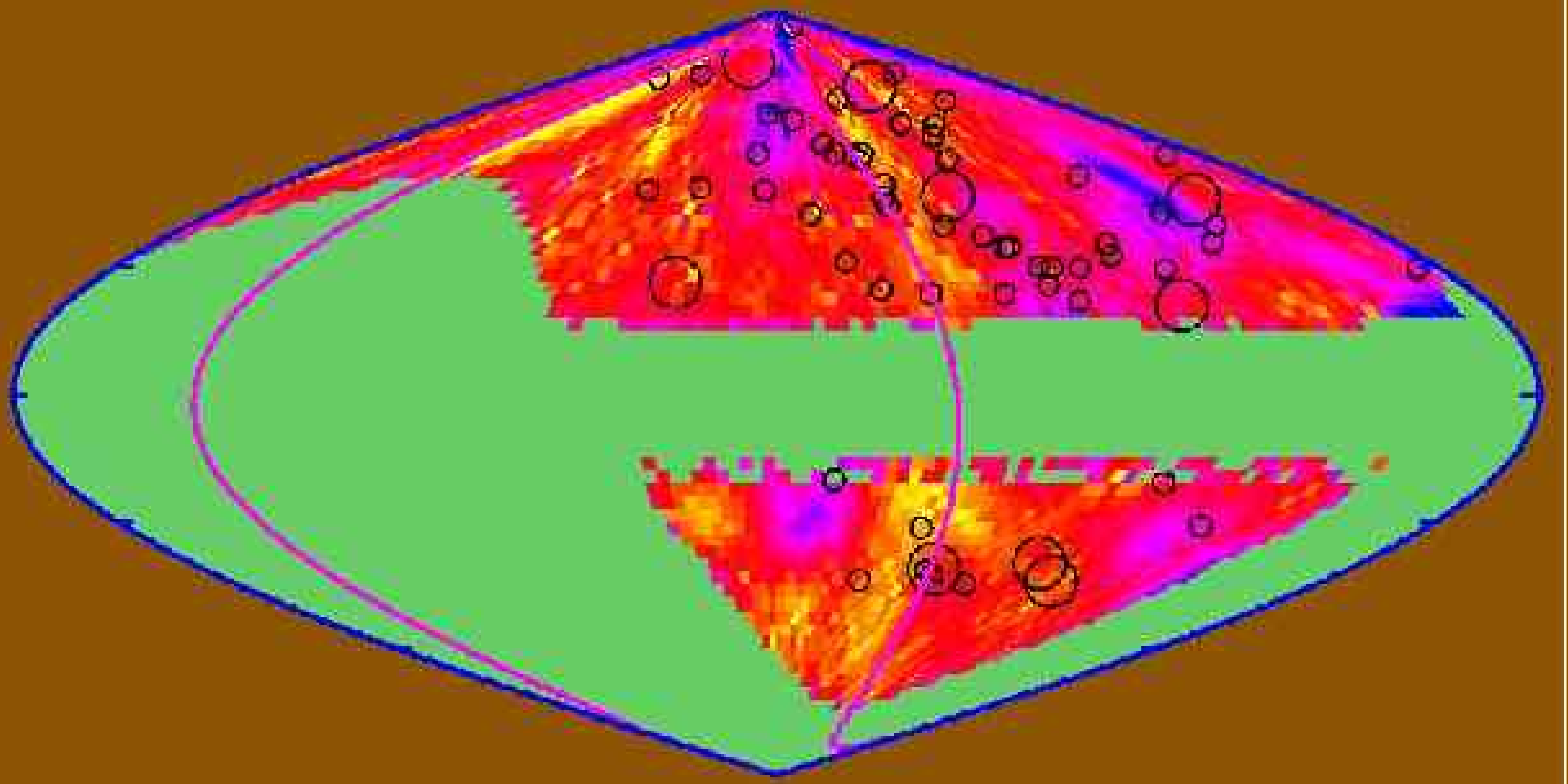
The AGASA and HiRes experiments have the highest current statistics around the GZK cut-off. AGASA shows no cut-off, while HiRes does.



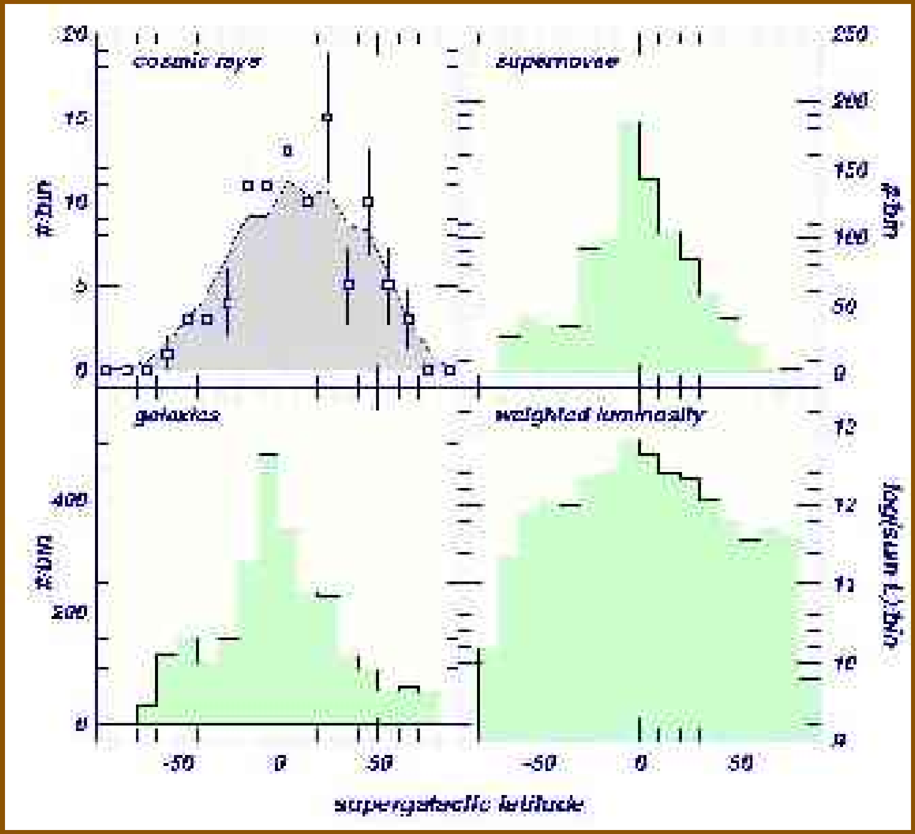
Differences are not that bad if data is normalized at some energy as done here at 10^{19} eV. The big difference is only at super-GZK energy where AGASA claims 11 events and HiRes only 2 events.

The lines are predictions for isotropic homogeneous source distribution of sources with different injection spectra with indices 2.00 (bottom at low energy), 2.25, 2.50, 2.75 and 3.00 and two source cosmological evolution models with n=3,4.

Fits favor 2.50 power law injection spectra.

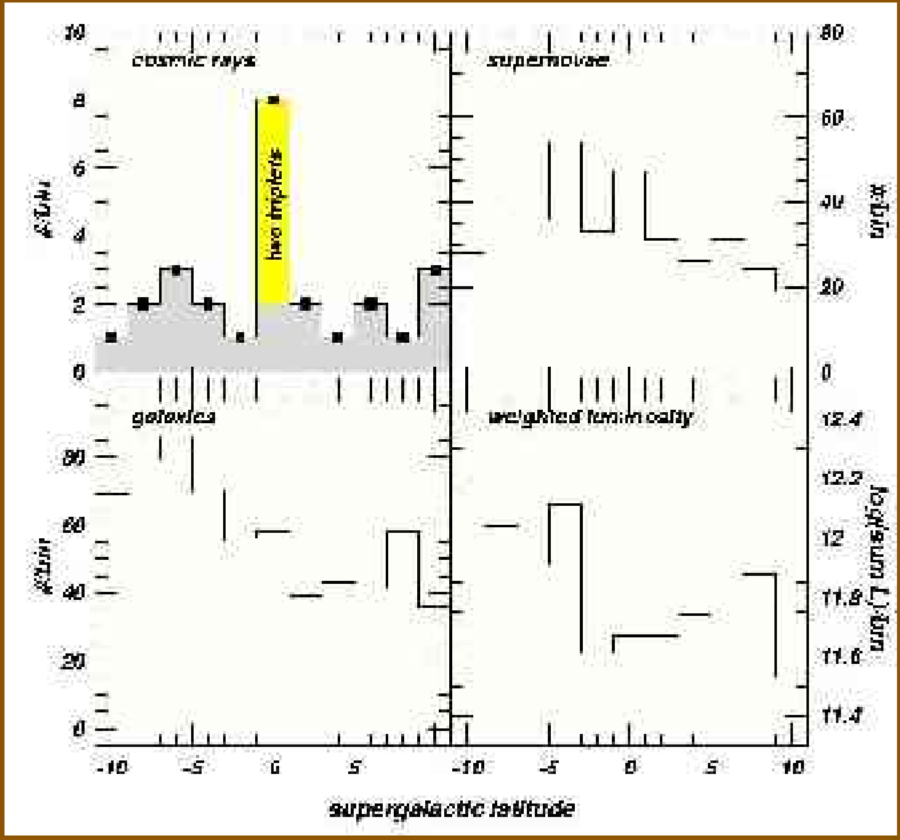


The arrival directions of cosmic rays of energy exceeding 4×10^{19} eV are plotted together with the weighted luminosity of galaxies within redshift of 0.05 that are withoin the field of view of the giant air shower arrays. There is no HiRes data in this graph. The purple line indicates the supergalactic plane.

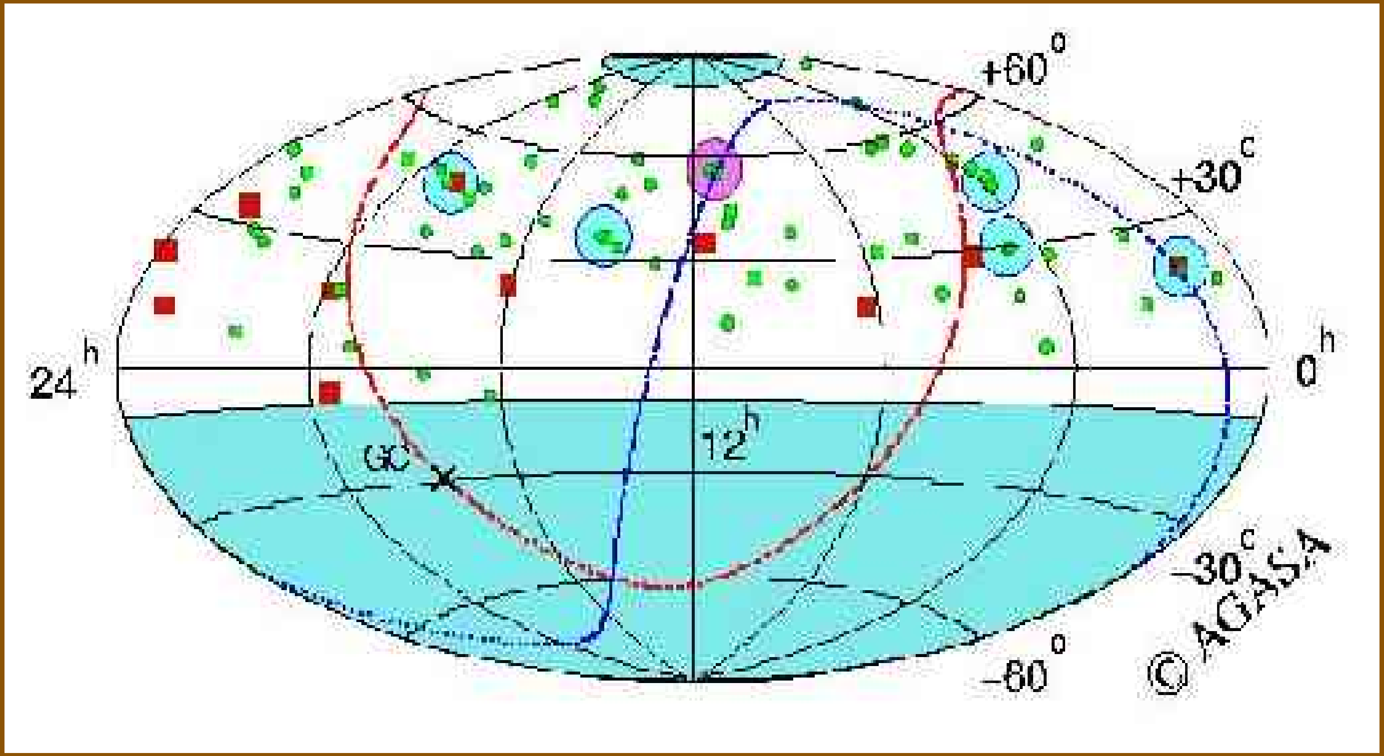


UHECR seem to be almost isotropic on the large angle scale – their arrival angle distribution matches the detector positions.

On small scales (1 degree), however, AGASA UHECR apper to be anisotropic, on a chance coincidence level of 1%.

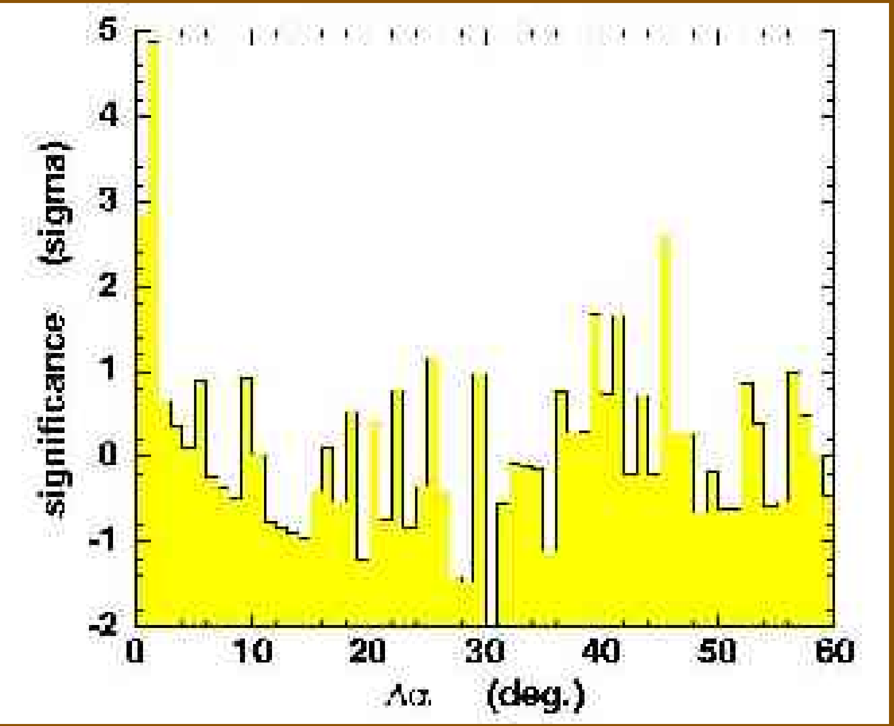


NOT confirmed by HiRes



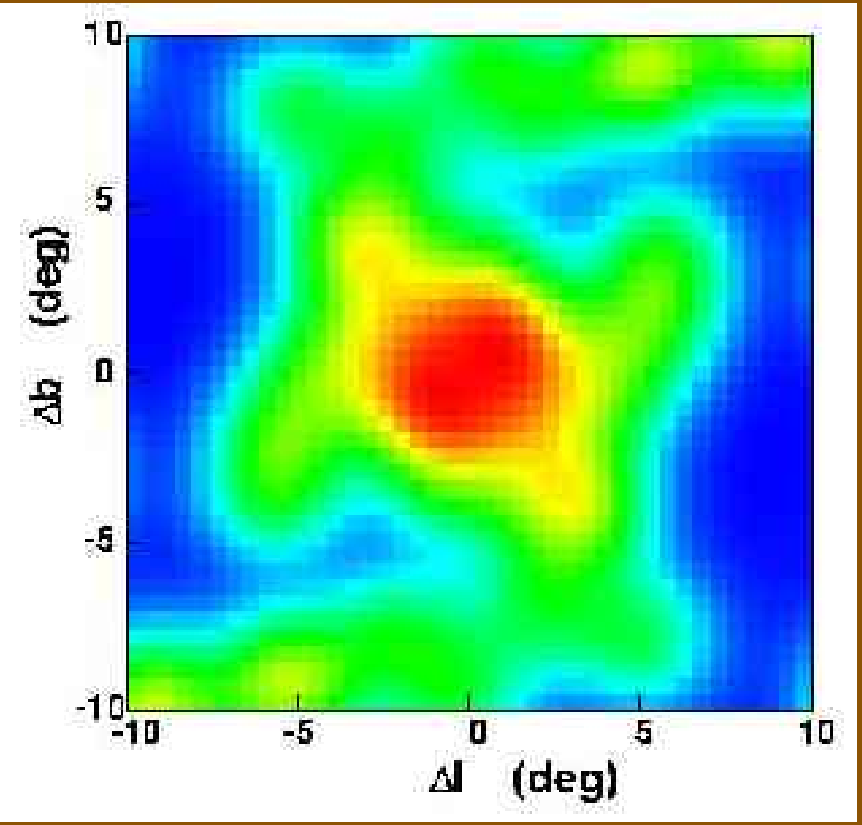
The small scale anisotropy in the AGASA data is due to the existence of 6 doublets and a triplet within the angular sensitivity of the detector. Haverah Park data forms two more clusters with the AGASA events without increasing the statistical signigicance.

Not confirmed by HiRes. Their own analysis of the AGASA clustering finds a small statistical significance.



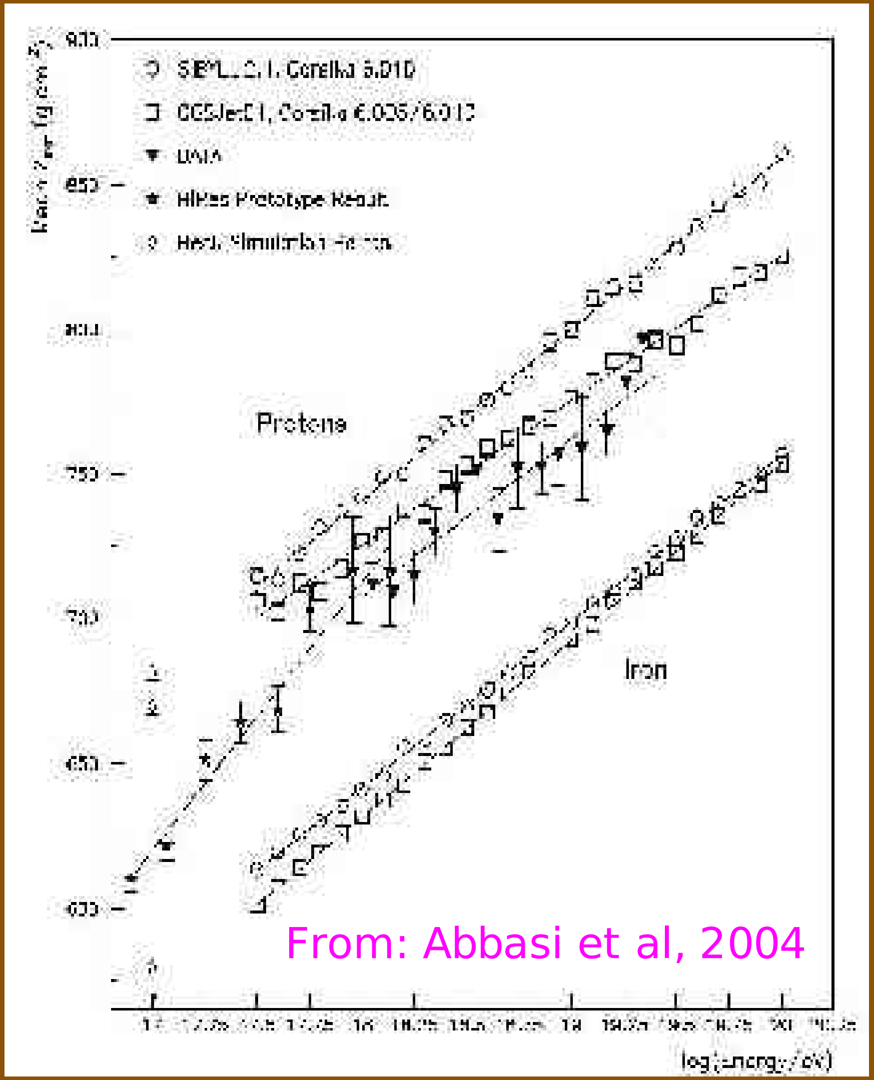
From: Alvarez-Muniz et al.

AGASA data set shows a very significance in the self correlation of the arrival direction of the events above $4x10^{19}$ eV. Shown is the distribution of the angle between all event pairs in the data set. Isotropic distribution would give a horizonthal line.



This is a two dimensional self correlation of the event sample in galactic longitude and latitude. The statistical significance is difficult to estimate. The AGASA group notices that the general shape is similar to one generated by deflection of UHECR in the *h* component of the galactic field.

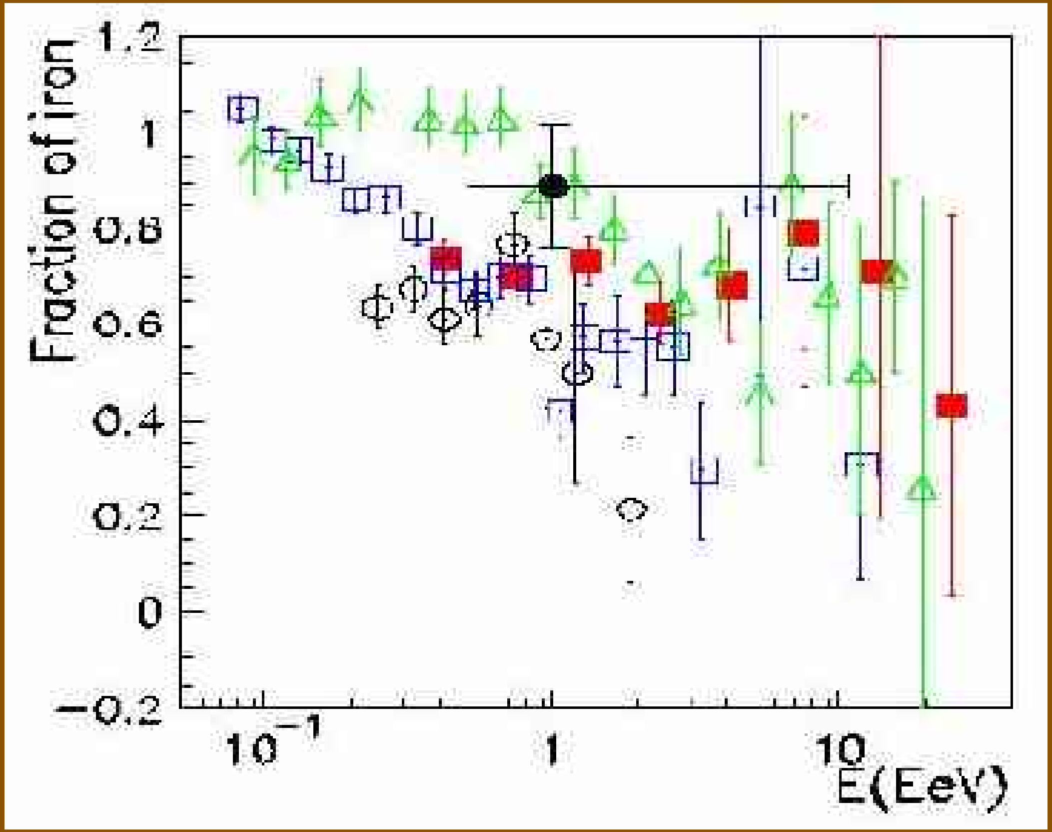
Several analyses have attempted to estimate the number of UHECR sources that would generate this type of anisotropy. There should be more sources than events if the observed effects are not statistical fluctuations.



From: Abbasi et al, 2004

The HiRes expriment derives the UHECR mass composition by statistical studies of the depth of shower maximum X_{max}. Comparisons to Monte Carlo resilts show a transition form heavy nuclei to protons when approaching 10^{18} eV. This would be a transition from galactic to extragalactic CR origin. The composition does not seem to change much after that. AGASA measures CR composition by the shower muon content and does not detect such drastic change.

Note the uncertainty due to hadronic interaction models. It would grow if other interaction models were included.

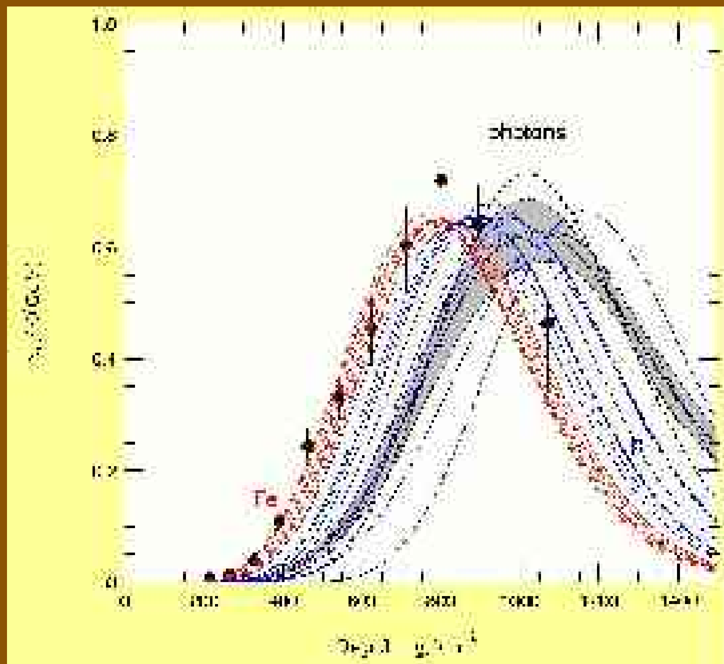


From: M.T. Dova et al

Qualitatively all experiments observe decreasing fraction of iron in the UHE cosmic rays. Quantitatively the differences are huge. There is no data on the cosmic ray composition at energies approaching 10^{20} eV – the statistic is much too small.

Comparison of some of the results on the UHECR composition. Results are presented in terms of the fraction of Fe nuclei as a function of the particle energy. Current cosmic ray experiments can not have higher accuracy in terms of the type of the primary nucleus. Even in such rough analysis the differences between various experiments are big. Triangles show the results of Fly's Eye that indicated a transition from galactic to extragalactic origin. Squares indicate the results of AGASA, and circles – of Haverah Park, which do not see changing composition aroune 10^{18} eV.

Nuclei or gamma rays ?



The longitudinal profile of the highest energy shower is compared to sets of 10 proton and iron initiated showers + gamma ray showers. Most likely origin is intermediate primary nucleus. The profile does not indicate gamma ray origin.
Shower arrays like AGASA assign gamma ray origin to showers with small muon/electron ratio.
Havera Park has studied gamma ray content by the shower absorption with zenith angle.

AGASA and Havera Park have limited the gamma ray content to no more than 40-50% of the total UHECR flux. These limits do not extend beyond $10^{19.5}$ eV. There is no serious indication for the origin of the super-GZK events.

The current experimental results are contradictory:

	AGASA	HiRes
are there super GZK events ?	Many	Few
large scale isotropy ?	Yes	Yes
small scale isotropy ?	No	Yes

The flux differences could be caused by inaccurate estimates of the experimental exposure.

The contradiction in the arrival distribution of the events is more difficult to understand – it may be related to the different detection methods.

Derived astrophysical parameters

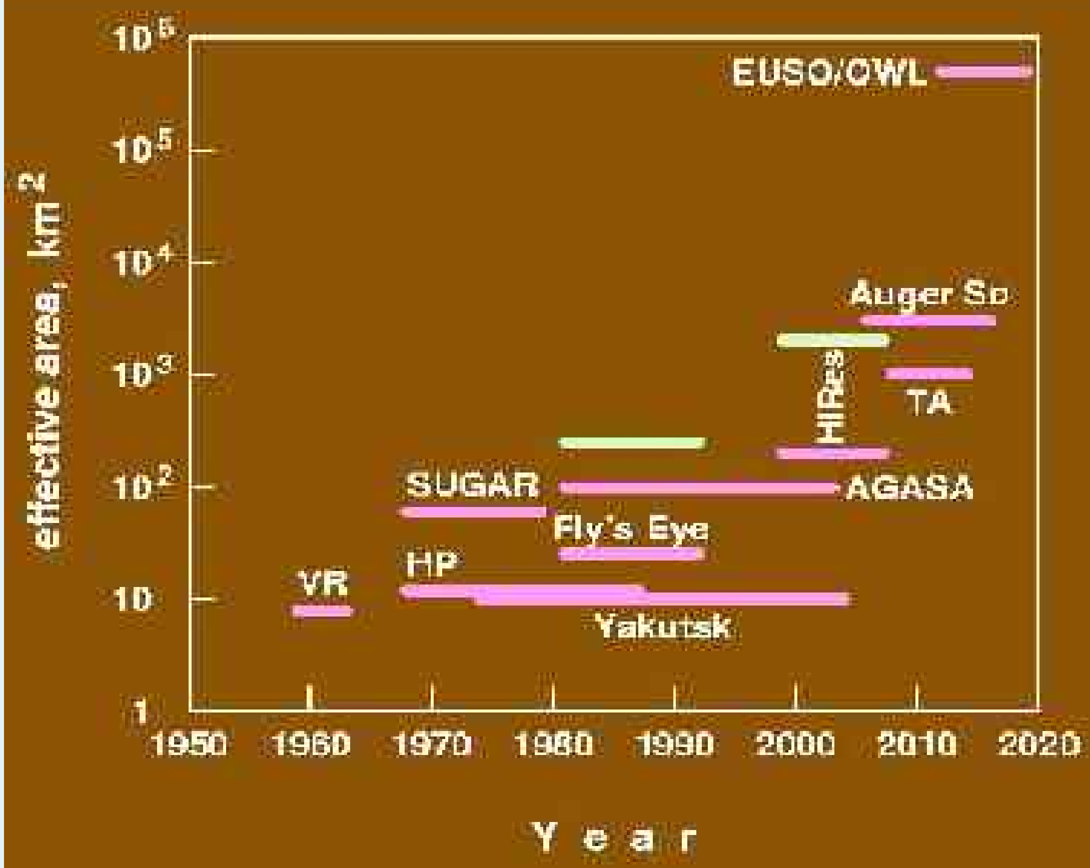
UHECR source luminosity: 4.5×10^{44} erg/Mpc^3/yr between 10^{19}-10^{21} eV for $\alpha=2$ spectrum (W&B) to 4×10^{46} (same units) for $\alpha=2.7$ (BGG). Strong dependence on spectral index and the minimum acceleration energy.

UHECR source density: 10^{-5} Mpc^{-3} $\pm$ order of magnitude: from the clustering of AGASA data set.

UHECR source distribution:

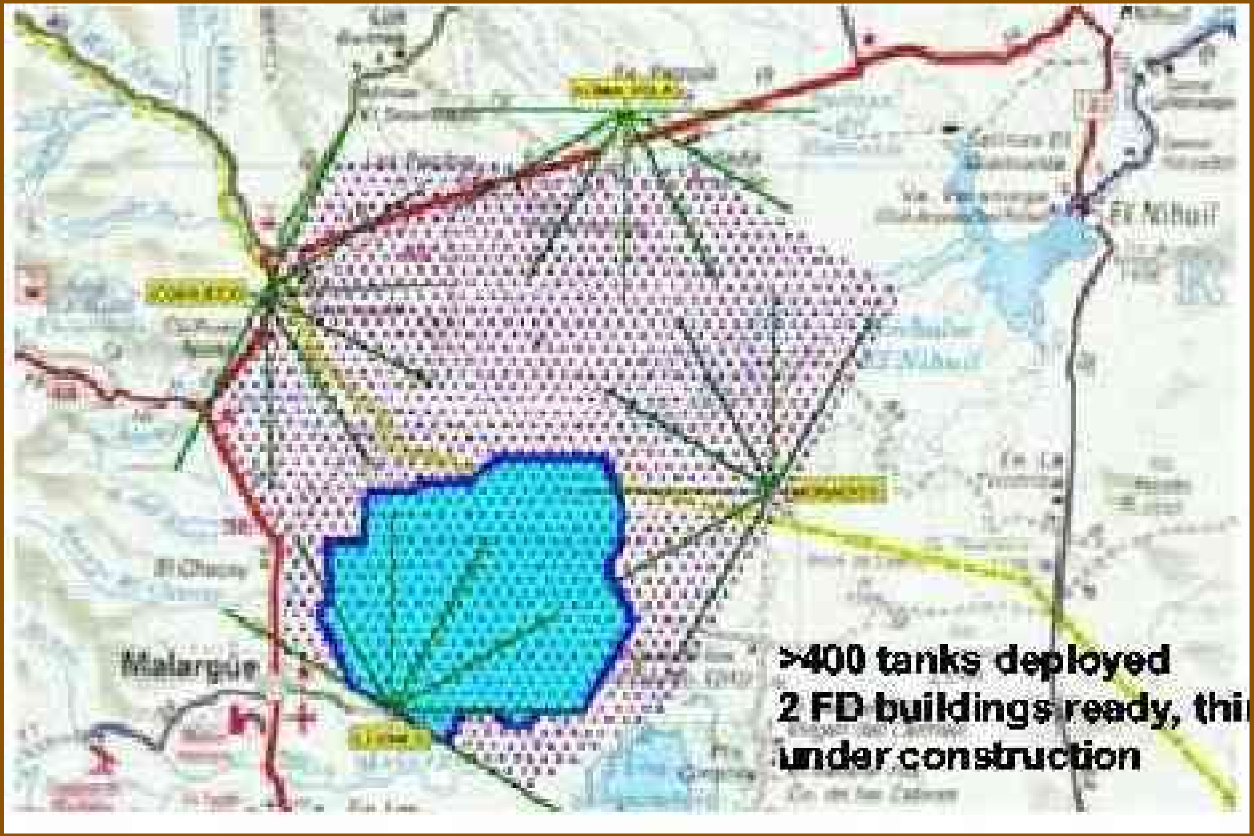
- isotropic homogeneous + local source + galactic CR
- isotropic homogeneous + top-down + galactic CR
  (no local or top-down sources needed for HiRes)

UHECR source cosmological evolution: depends on injection spectrum. Steep spectra require weak cosmological evolution.



Note that Fly's Eye and HiRes are marked twice due to their 10% lifetime. Contemporary experiments have shorter duration due to their larger effective areas. EUSO@Owl are proposed satellite experi-mets that are to observe shower flourescent light from space. EUSO was cancelled last month because of uncertainties of the ISS duration.

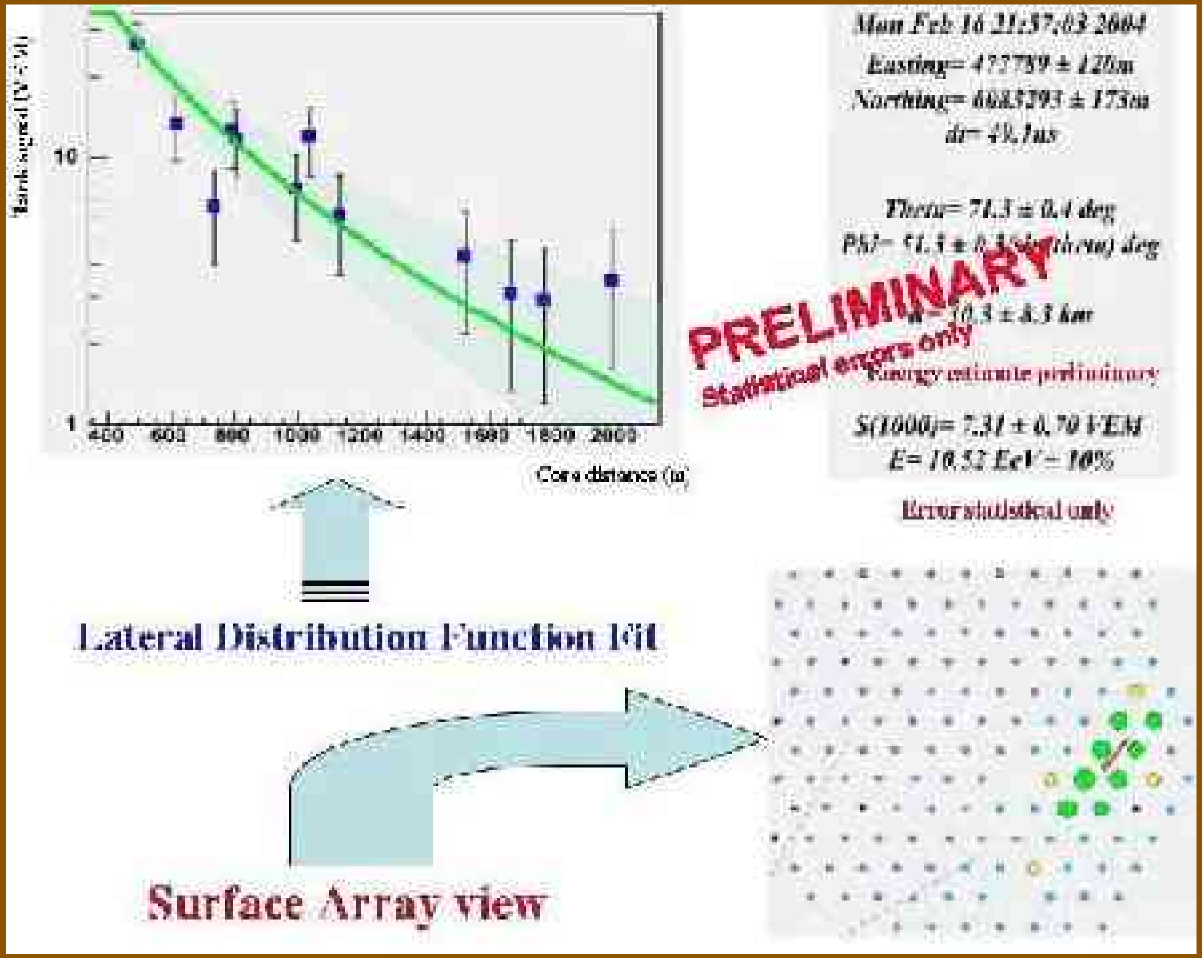
SUGAR is a novel experiment that was ahead of the technology needed for its success. Haverah Park brought the first scientific results on UHECR. Fly's Eye was the first fluorescent experiment that gave very valuable results on UHECR composition. AGASA dominated the world data sample before HiRes became opera-tional. It still has the largest event sample at 10^{19} eV, as the HiRes acceptance is energy dependent. Telescope Array is already funded by Japan and is to be built in Utah.



From: Tiina Suomijarvi

Water Cherenkov tanks are more sensitive to the shower front as photons pair produce in them. Their effective area does not change much with zenit angle.

The Southern Auger observatory is being built in Argentina. The 3,000 km^2 array, consisting of 10 m^2 water Cherenkov tanks is surrounded by four fluorescent detectors. Auger is the first *hybrid* detector that combines the two observational techniques. The shower array will be efficient almost 100%, and 10% of the time UHECR will be observed simultaneously by the optical detectors and the surface array. This should resolve the differences between AGASA and HiRes.



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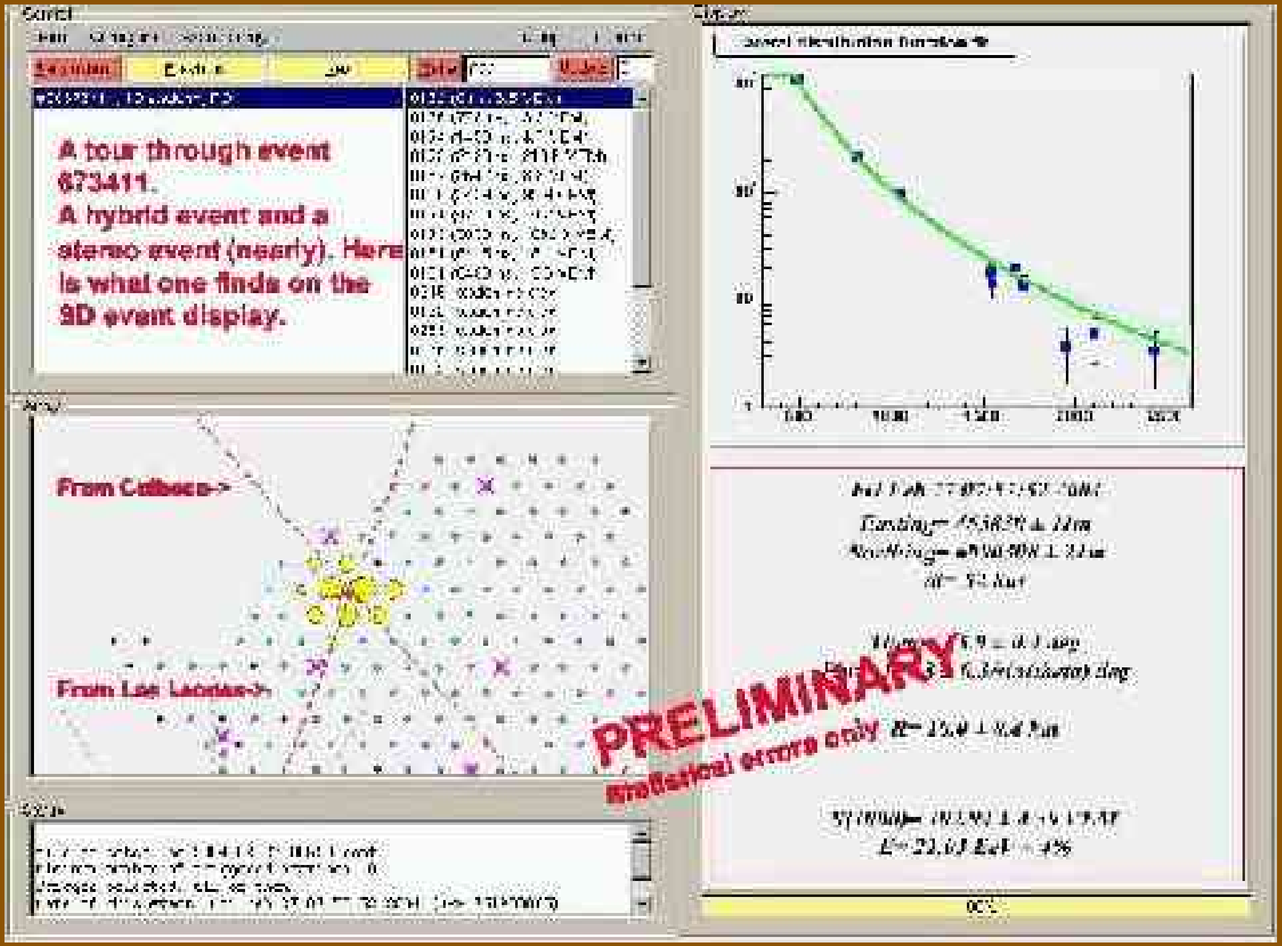
'Typical' 10^{19} eV shower observed by Auger.



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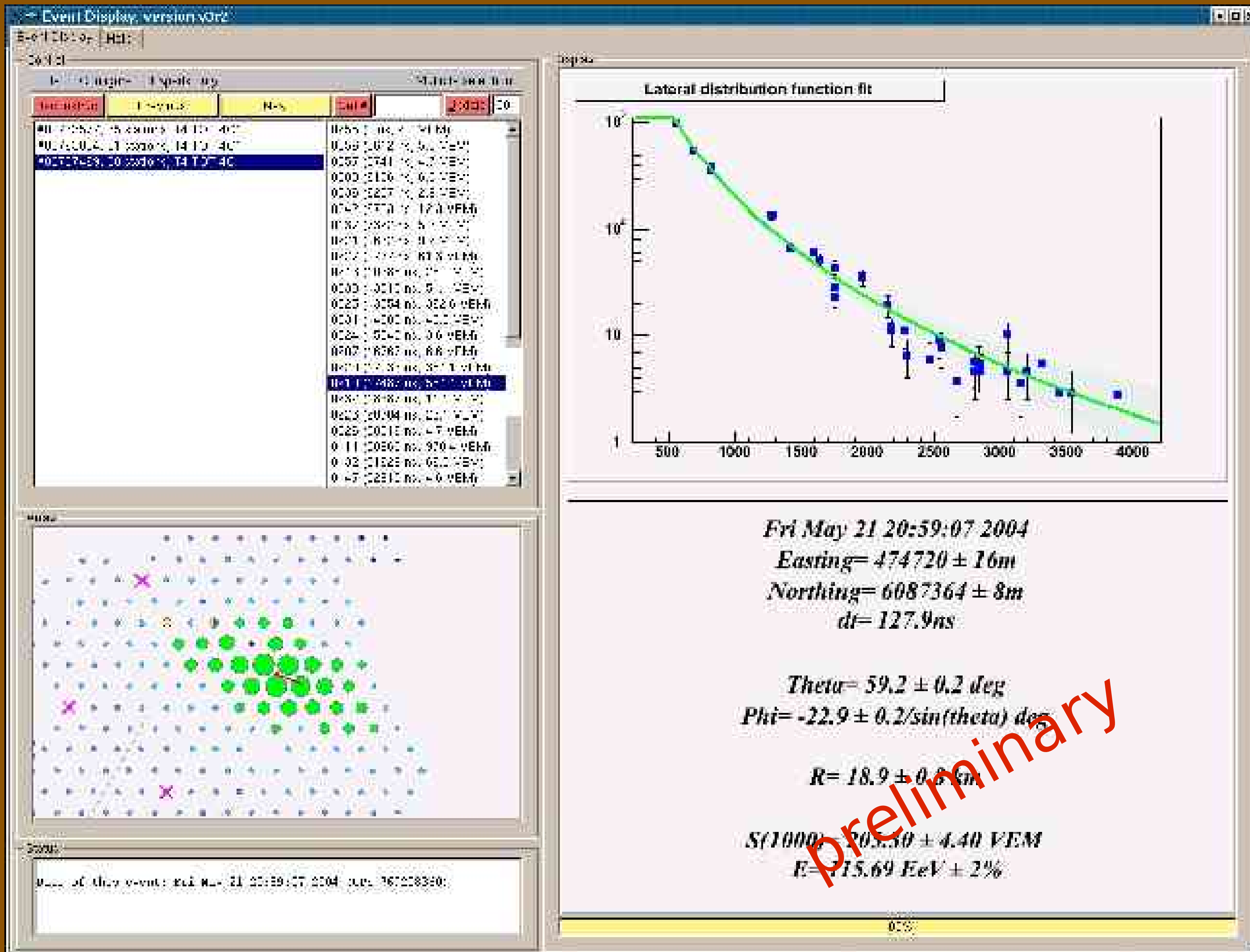
Hybrid observation of a shower with 9 tanks hit and two fluorescent detector traces.



From: Tiina Suomijarvi

Cosmic rays of energy above 10^{20} eV exist, but their flux is unknown.

Very few astrophysical objects can accelerate charged nuclei to such energy in shock acceleration processes.

Protons and heavier nuclei lose energy in propagation in photoproduction (photodisintegration) on MBR and other photon fields. The sources have thus to be within tens of Mpc from our Galaxy.

The other possibiity are `top-down' scenarios where these particles are generated in the decay of ultraheavy X-particles, which could be emitted by cosmic strings or are long lived remnants of the early Universe.

The current experimental data are not able to give us good indication on the type of these UHECR and their arrival direction distributions.

New third (and fourth) giant air shower experiments are being built and designed. They will increase the data sample by orders of magnitude and help understanding the nature and sources of these exceptional events.