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Astroparticle Physics - III

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Ultrahigh Energy Cosmic Rays: Propagation Calculations and Contemporary Data

Propagation of UHECR protons

Propagation of UHE nuclei

Propagation of UHE gamma rays

Contemporary data from the Southern Auger Observatory and the HiRes detector

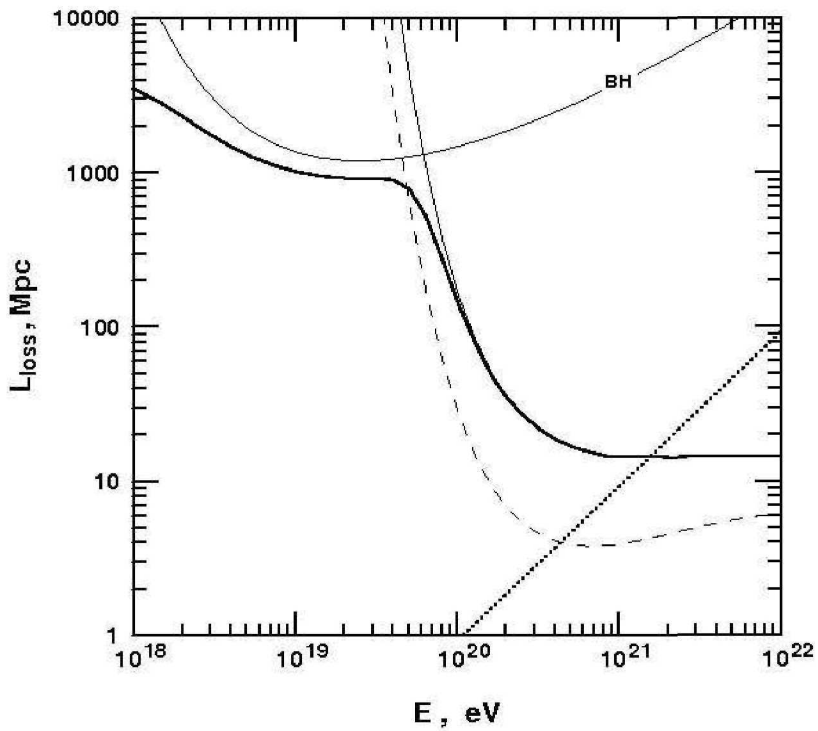
Propagation of UHE protons in MBR

photoproduction mean free path

$$\lambda_{p\gamma}^{-1}(E_p) = \frac{1}{8E_p^2}\int_{\epsilon_{thr}}^{\infty} d\epsilon \frac{n(\epsilon)}{\epsilon^2}\int_{s_{min}}^{s_{max}} ds(s-m_p^2)\sigma_{p\gamma}(s)\ .$$

$$s = m_p^2 + 2E_p\epsilon(1-\beta_p\cos\theta)$$

$$\epsilon_{thr} = \frac{s_{min}-m_p^2}{4E_p}$$



$$L_{loss} = \frac{E_p}{dE_p/dx} = \frac{\lambda_{p\gamma}(E_p)}{K_{inel}(E_p)}$$

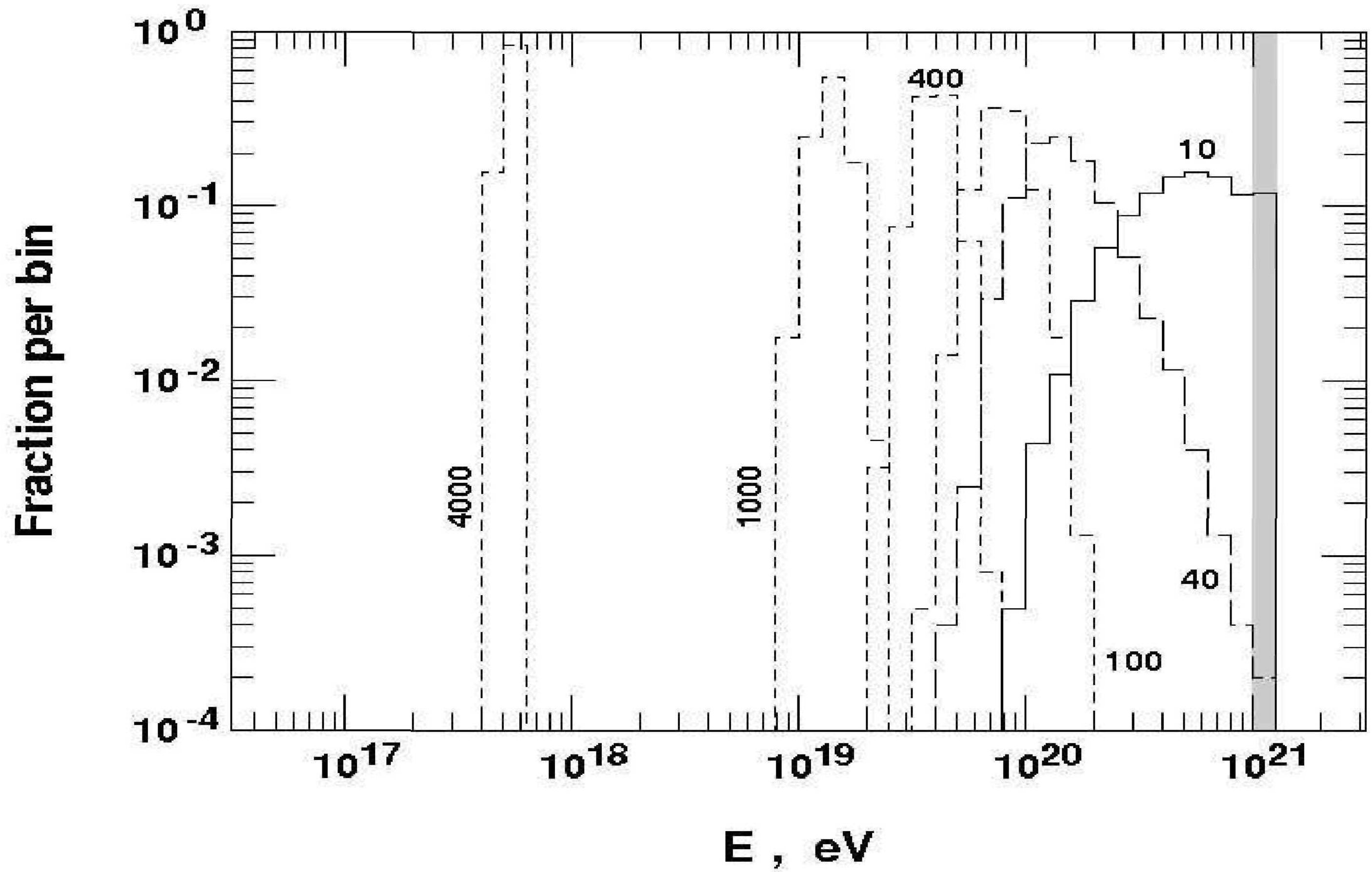
$$L_{loss}(E_p, z) = (1+z)^{-3} L_{loss}[(1+z)E_p, z=0]$$

for photoproduction and pair production and

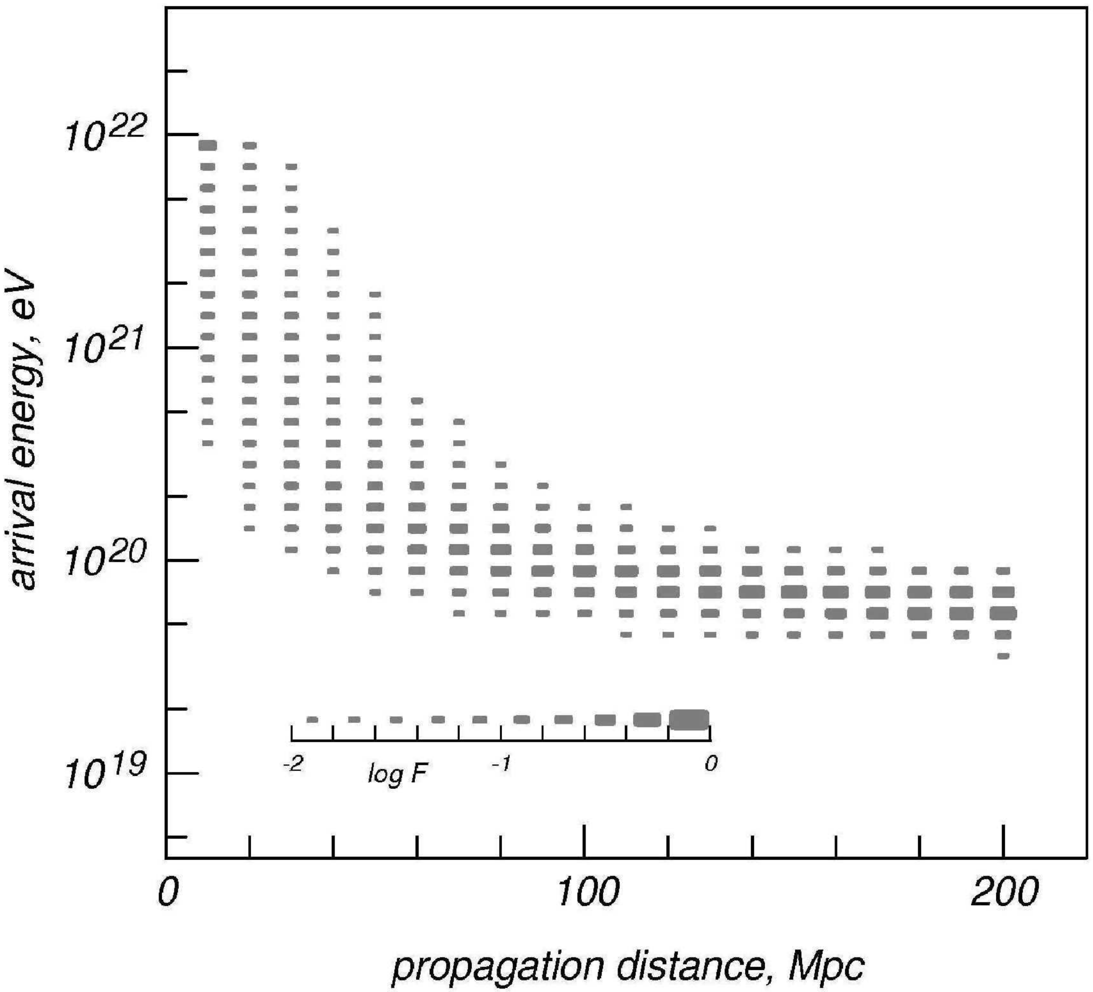
$$L_{loss}^{ad}(z=0) = \frac{c}{H_0} \simeq 4,000 \,\mathrm{Mpc}$$

$$L_{loss}^{ad}(z) = L_{loss}^{ad}(z=0)(1+z)^{-3/2}$$

for adiabatic loss with H_0 = 75 km/s/Mpc.
A better value should be 71-72.



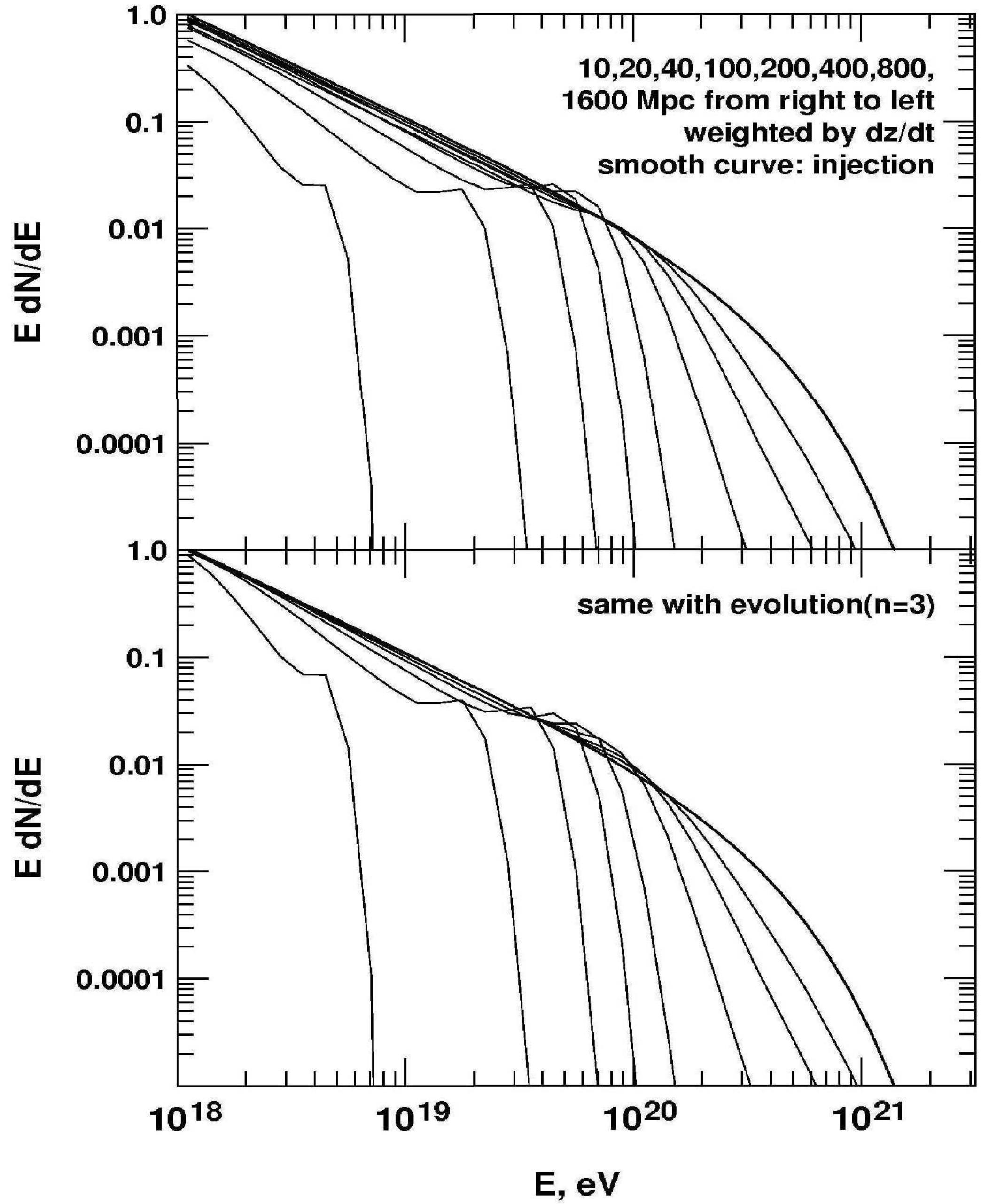
Protons of energy 10^{21} eV are injected in MBR and are propagated at different distances. The graph shows the energy distribution at arrival. The propagation code simulates the fluctuations in energy loss in photoproduction interactions.



Protons of energy 10^{22} eV (btw 21.9 and 22) are injected and propagated in the microwave background radiation.

Fluctuations are huge at very high proton energy and start decreasing when pair production and adiabatic losses dominate. Higher energy particles lose more energy and energy distributions become tight.

Formation of the proton energy spectrum at propagation



The injection spectrum is E^{-2} with an exponential cutoff in this example. Note the formation of a bump after propagation on 40-100 Mpc.

The upper graph is without cosmological evolution of the cosmic ray sources, the lower one is with evolution. In the latter the bump is slightly higher.

To obtain the observed spectrum on has to integrate over distance (time).

Other possible inputs: cosmic ray luminosity

cosmic rays injection luminosity

TKG: $\rho_{CR} = 2 \times 10^{-19}$ erg/cm ^{3}

$$\frac{\rho_{CR}}{\tau_{CR}} = \frac{5.8 \times 10^{54}\ \mathrm{erg/Mpc^3}}{10^{10}\ \mathrm{yrs}}$$

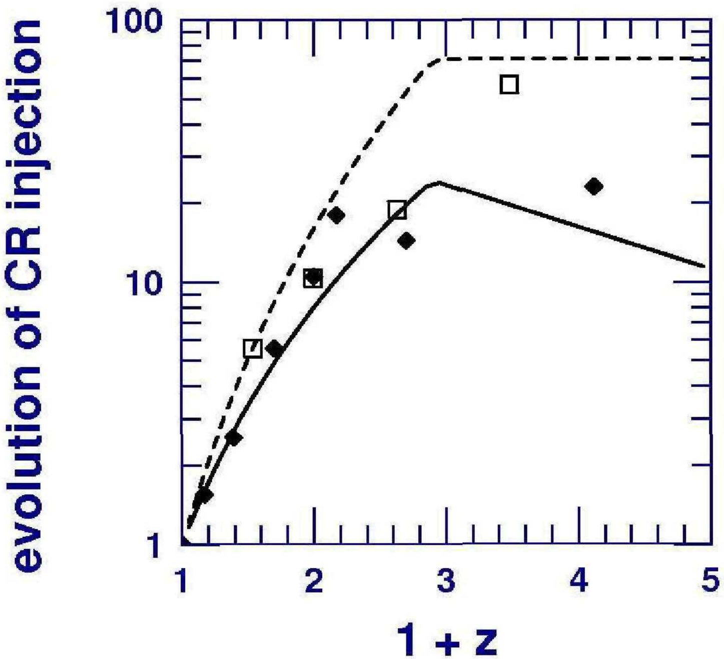
$$L_{CR}^{EG} = 5.8 \times 10^{44}\ \mathrm{erg/Mpc^3/yr}$$

a fraction of this luminosity is in particles above 10^{19}eV, depending on injection spectrum and acceleration model.

Note this is extremely conservative since it uses Hubble time, while cosmic rays above 10^{19}eV only travel 300 to 400 Mpc

Waxman&Bahcall use 4.5×10^{44}erg/Mpc^3 /yr for cosmic rays above 10^{19}eV, maybe still a bit low for sources imbedded in high magnetic fields.

cosmological evolution of CR injection

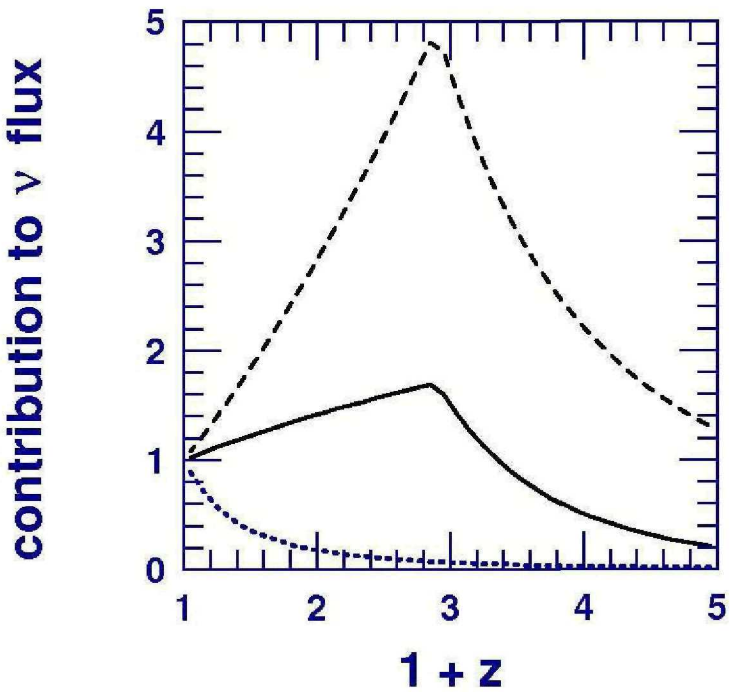


diamonds - SFR (Madau et al)

boxes - GRB (Fenimore&Ramirez-Ruiz)

$(1 + z)^n$ up to z_{max} then either flat or declining with z

The effect on the observed spectra is much lower because of the decrease of the injection time with redshift – $(1 + z)^{-5/2}$ for Einstein-DeSitter cosmology ($\Omega_M = 1$).



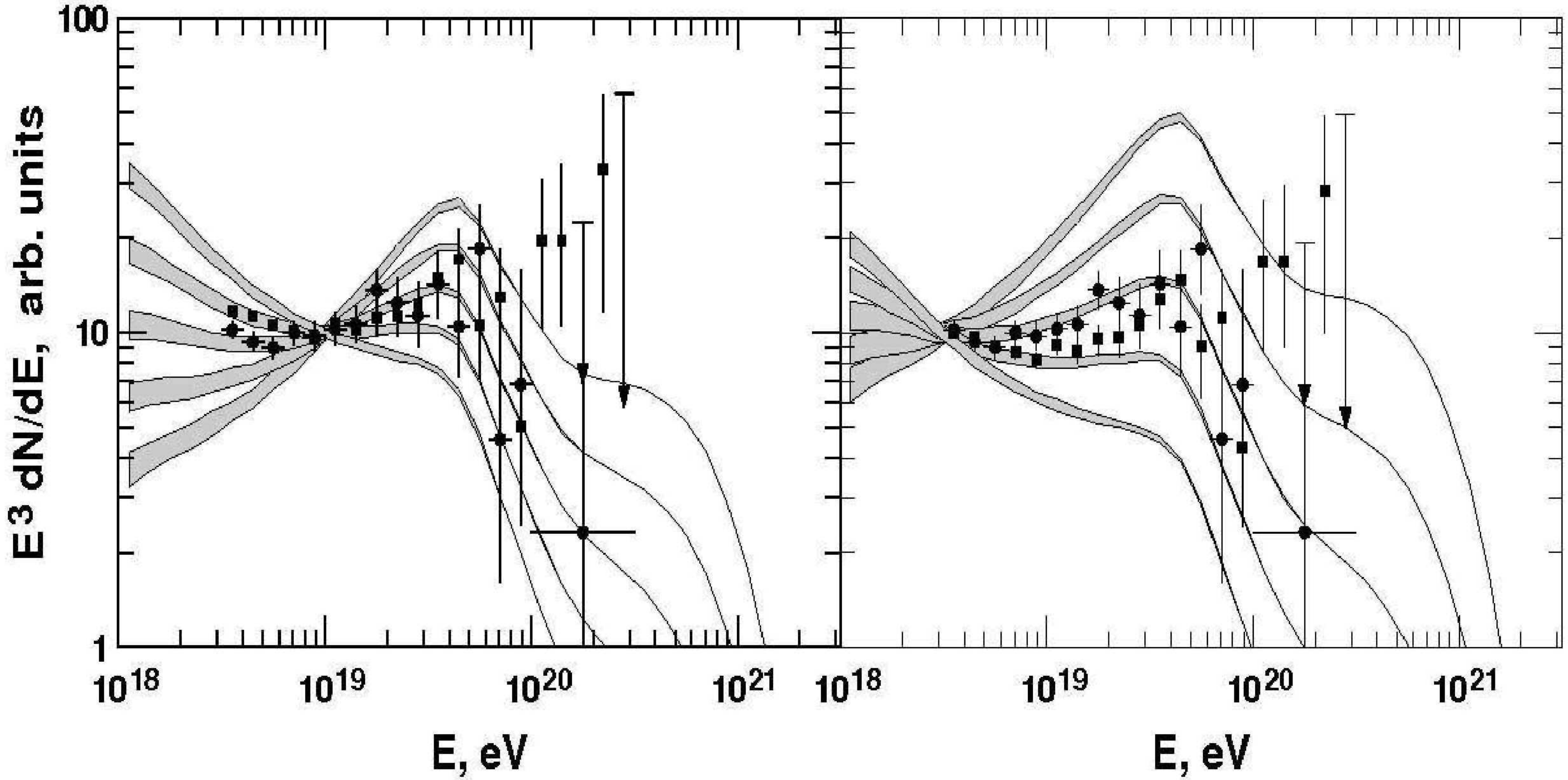
In the more general case (Λ term cosmology) the relation is

$$\frac{dt}{dz} = \frac{1}{H_0(1+z)}\left[\Omega_M(1+z)^3 + \Omega_\Lambda + (1-\Omega_M-\Omega_\Lambda)(1+z)^2\right]^{-1/2}$$

In contemporary cosmological models $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ which represents the dark energy causing the faster expansion of the Universe.

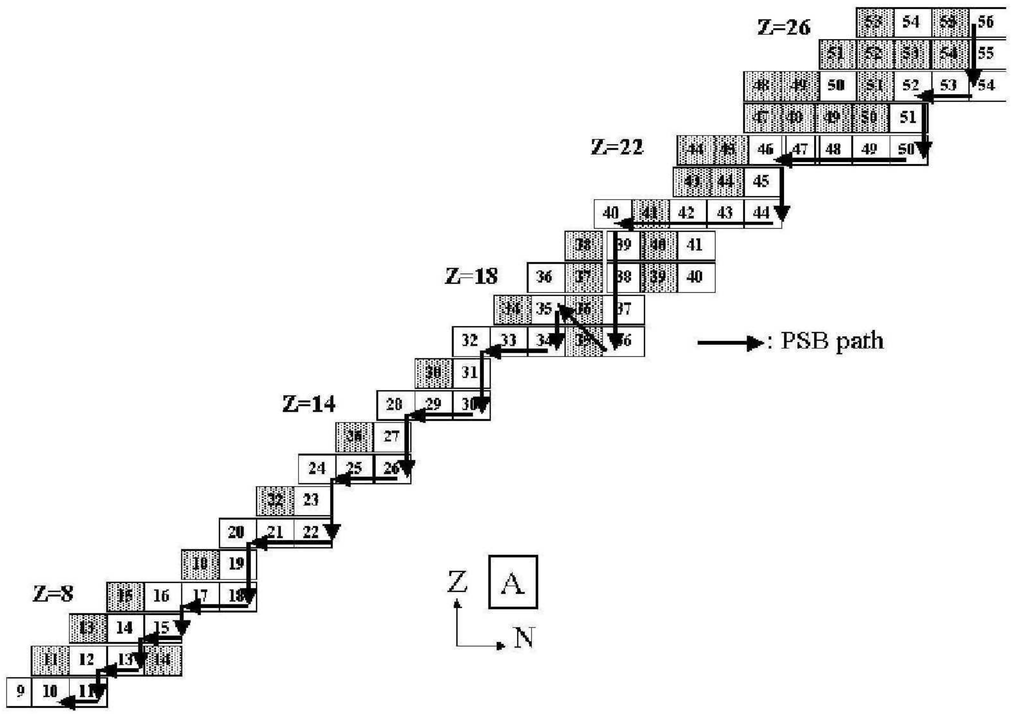
The cosmological evolution of the UHECR sources is not very important for the highest energy cosmic rays have such large energy loss that they can only come from cosmologically nearby objects with redshifts smaller than 0.05.

Fitting the observed cosmic ray spectra with protons requires the use of injection spectrum with index steeper than 2.5.



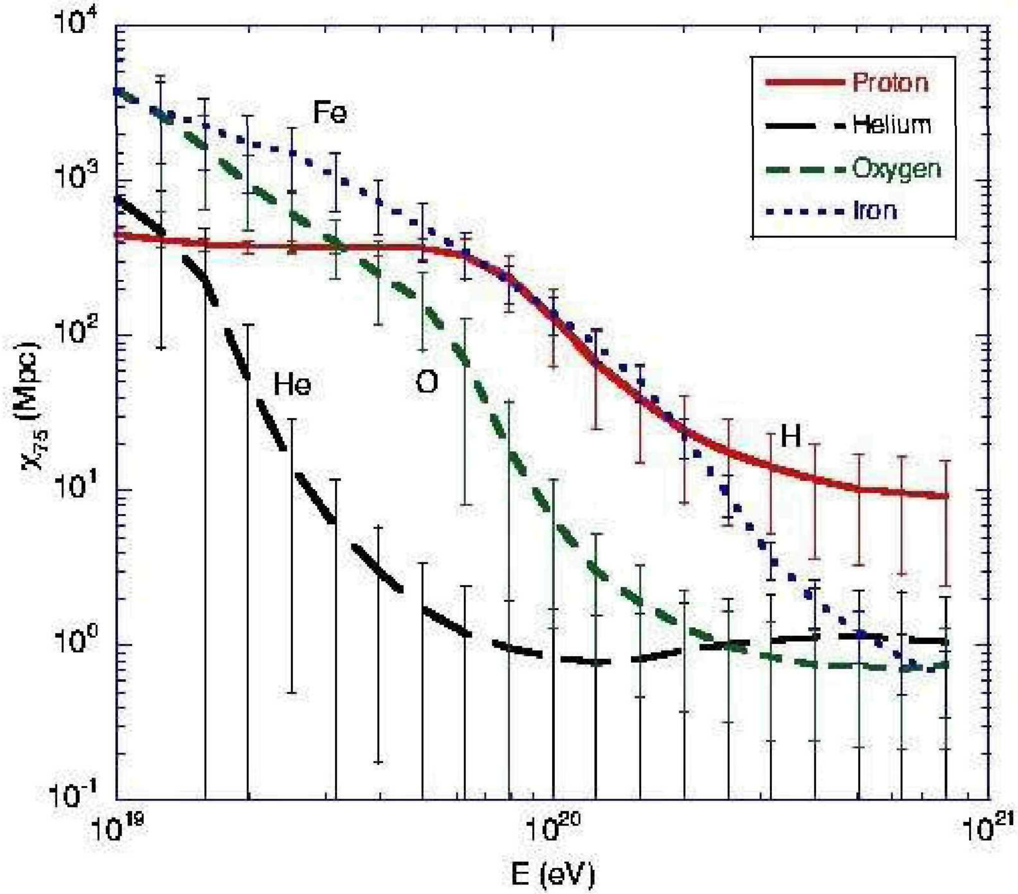
Agasa and HiRes spectra versus a calculation of proton primaries after propagation

Propagation of UHECR nuclei: one needs to know a lot about nuclear fragmentation.

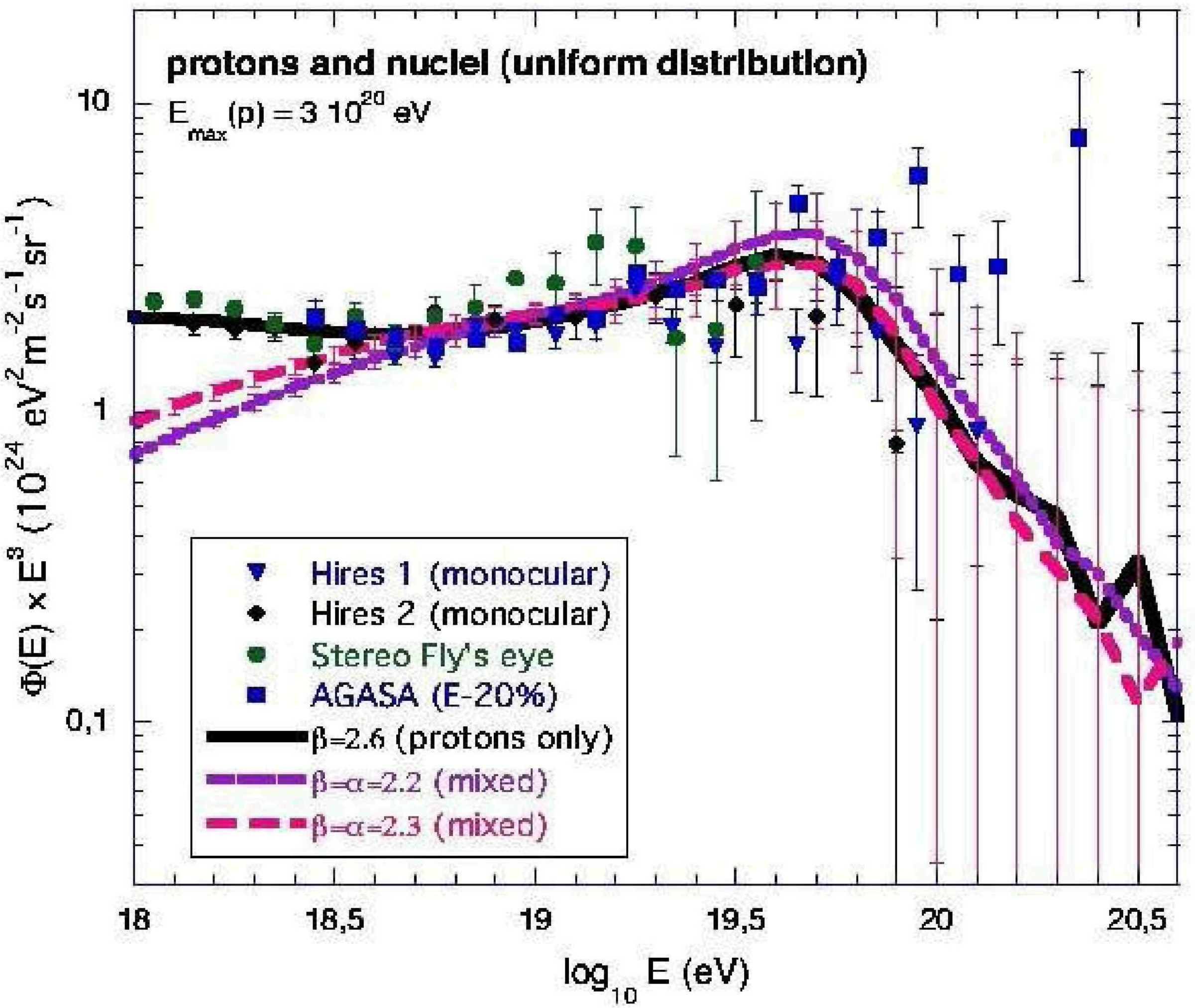


From: Khan et al

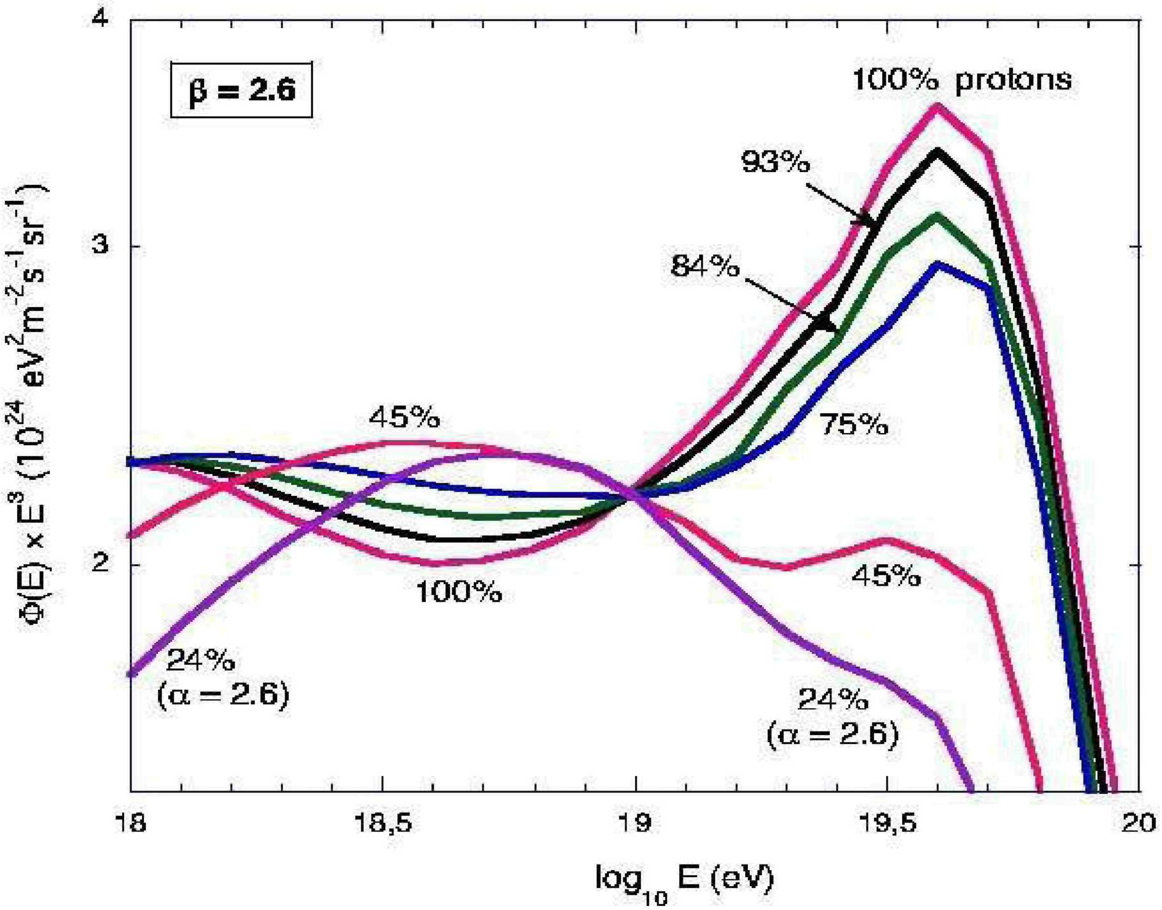
Results from the propagation calculation of Allard et al. Vertical lines show the fluctuations from the simulation of the photodisintegration.



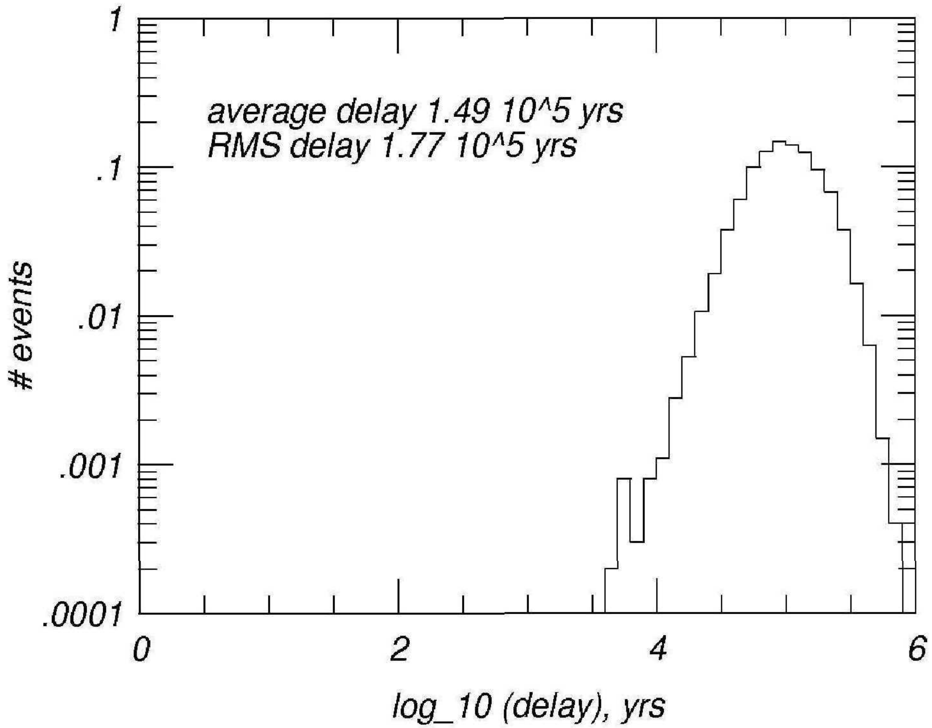
Fits of the observed cosmic ray spectrum with heavy nuclei accelerated and the cosmic ray sources. Source composition is as the galactic chemical composition at 1 GeV. (Allard, Parizot and Olinto)



Composition of the observed UHECR if the source composition is the same as galactic cosmic rays at 1 GeV. Spectral index is 2.6. (Allard, Parizot and Olinto)

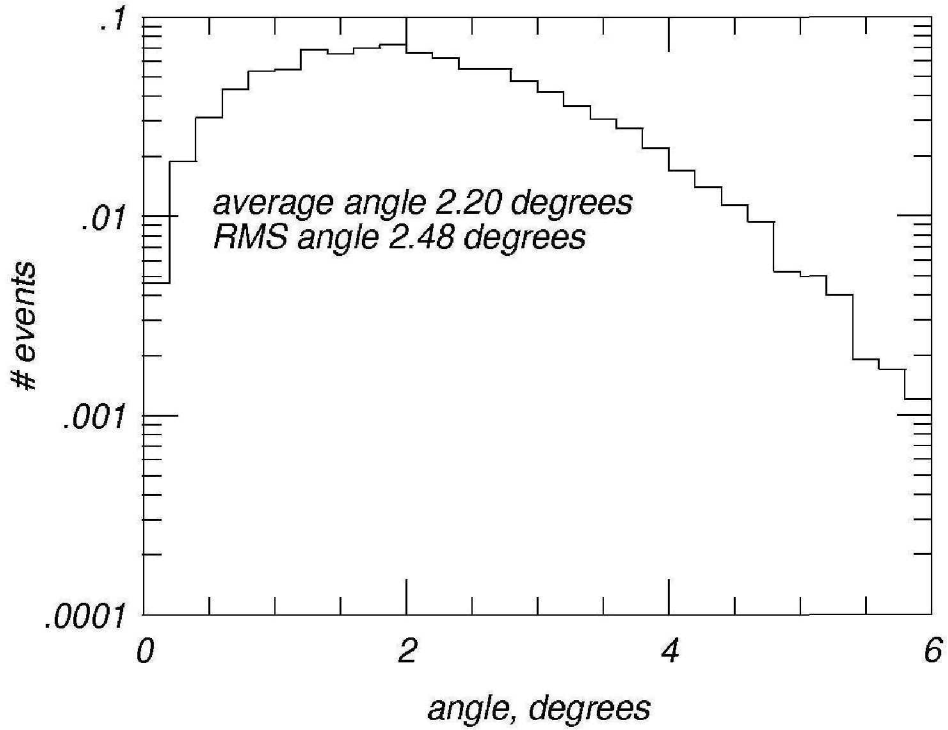


Importance of the extragalactic magnetic fields. Propagation of 100 EeV protons on a distance of 100 Mpc in 1 nG field. Effect will be Z times stronger for heavier nuclei.

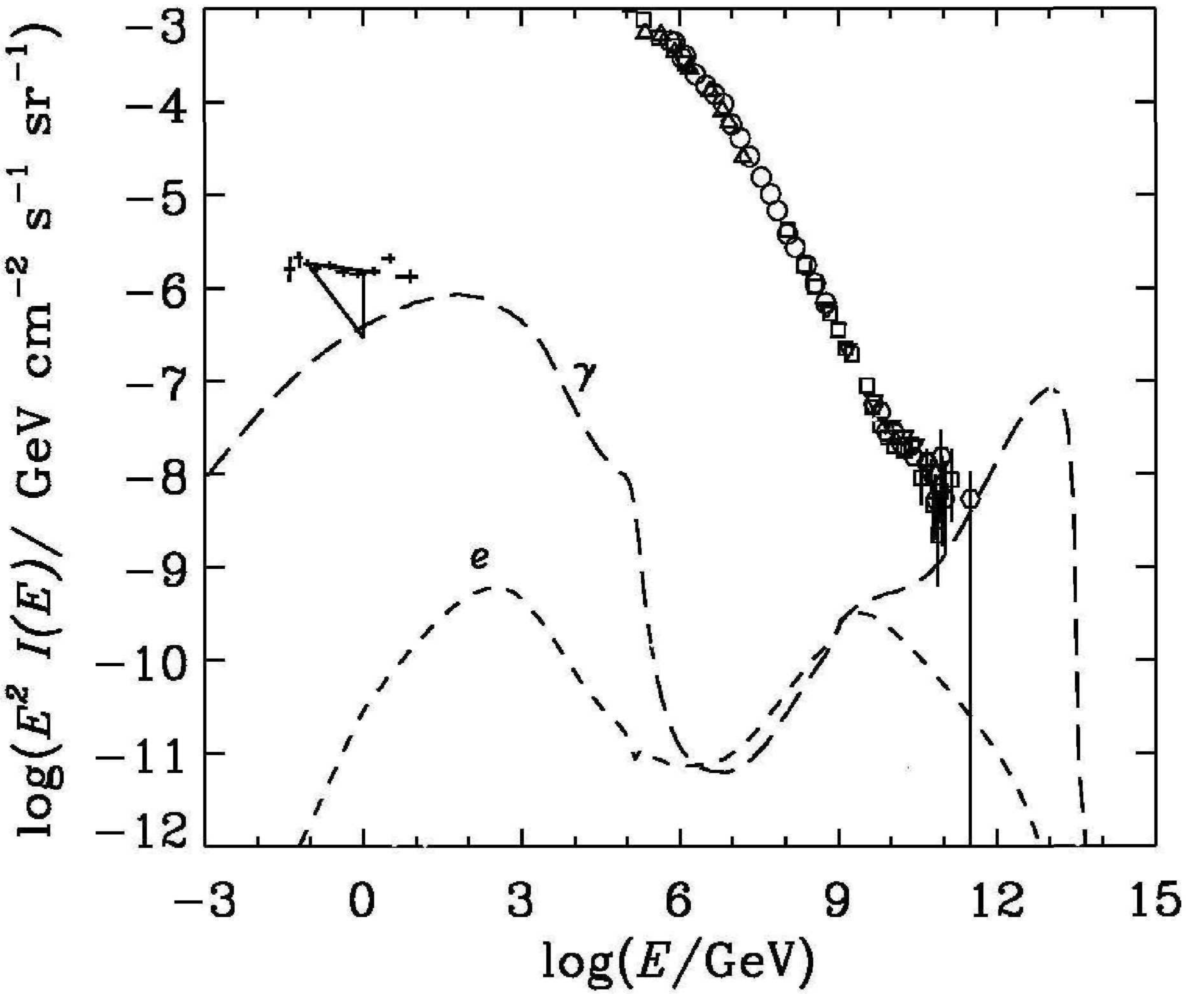


Time delay

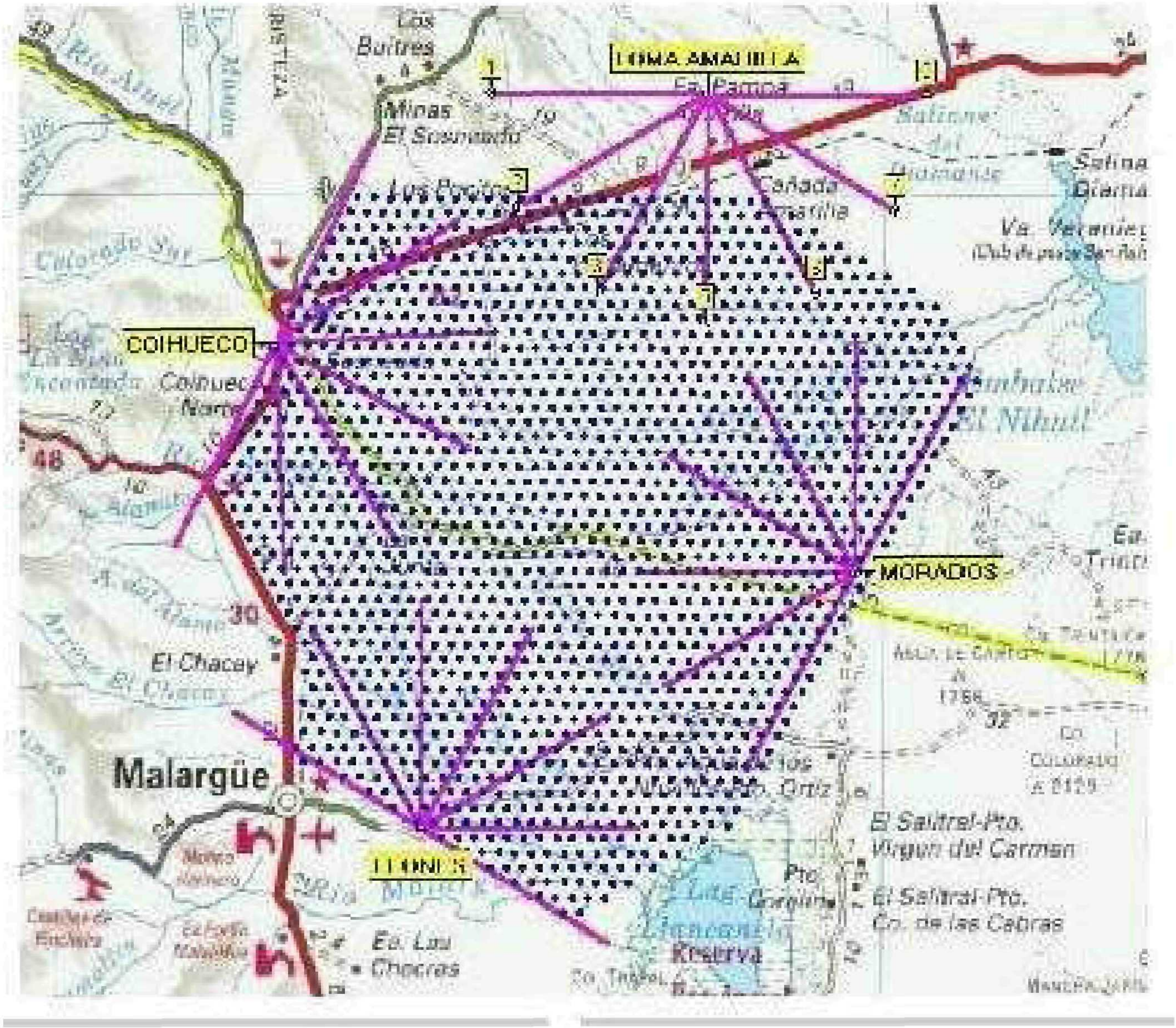
Scattering angle

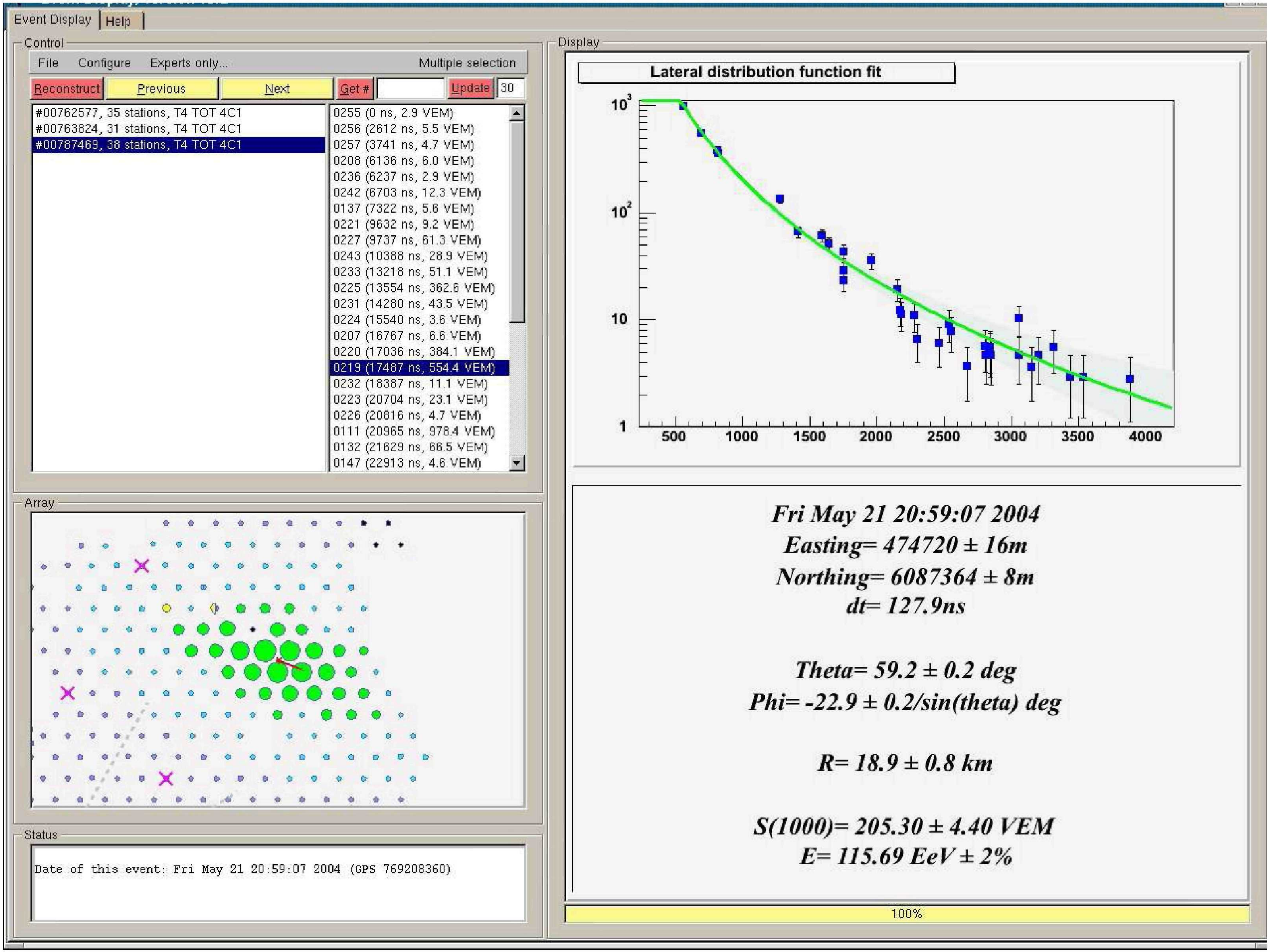


Propagation of UHE gamma rays. The gamma rays are injected with energy $10^{12.5}$ GeV. The highest pair production cross section is at 3 PeV which causes the dip at that energy. At lower energy the gamma rays interact on the infrared background radiation.



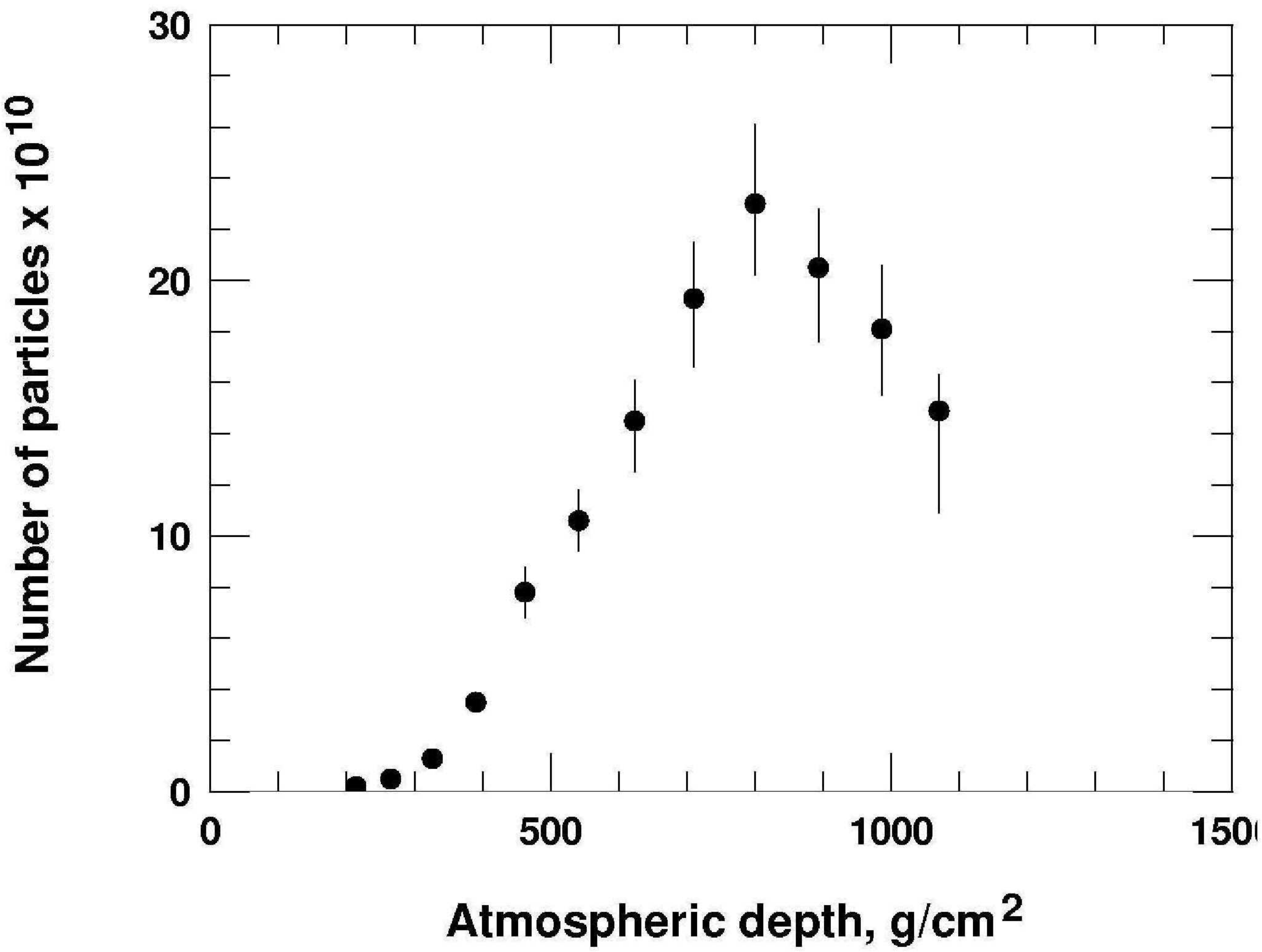
The Southern Auger Observatory





Event Display
Help
Control
File
Configure
Experts only...
Multiple selection
Reconstruct
Previous
Next
Get #
Update
30
#00762577, 35 stations, T4 TOT 4C1
#00763824, 31 stations, T4 TOT 4C1
#00787469, 38 stations, T4 TOT 4C1
0255 (0 ns, 2.9 VEM)
0256 (2612 ns, 5.5 VEM)
0257 (3741 ns, 4.7 VEM)
0208 (6136 ns, 6.0 VEM)
0236 (6237 ns, 2.9 VEM)
0242 (6703 ns, 12.3 VEM)
0137 (7322 ns, 5.6 VEM)
0221 (9632 ns, 9.2 VEM)
0227 (9737 ns, 61.3 VEM)
0243 (10388 ns, 28.9 VEM)
0233 (13218 ns, 51.1 VEM)
0225 (13554 ns, 362.6 VEM)
0231 (14280 ns, 43.5 VEM)
0224 (15540 ns, 3.6 VEM)
0207 (16767 ns, 6.6 VEM)
0220 (17036 ns, 384.1 VEM)
0219 (17487 ns, 554.4 VEM)
0232 (18387 ns, 11.1 VEM)
0223 (20704 ns, 23.1 VEM)
0226 (20816 ns, 4.7 VEM)
0111 (20965 ns, 978.4 VEM)
0132 (21629 ns, 66.5 VEM)
0147 (22913 ns, 4.6 VEM)
Array
Status
Date of this event: Fri May 21 20:59:07 2004 (GPS 769208360)
Display
Lateral distribution function fit
10^3
10^2
10
1
500
1000
1500
2000
2500
3000
3500
4000
Fri May 21 20:59:07 2004
Easting= 474720 ± 16m
Northing= 6087364 ± 8m
dt= 127.9ns
Theta= 59.2 ± 0.2 deg
Phi= -22.9 ± 0.2/sin(theta) deg
R= 18.9 ± 0.8 km
S(1000)= 205.30 ± 4.40 VEM
E= 115.69 EeV ± 2%
100%

While Auger observes both the air shower signals at ground and the shower profile, HiRes consisted only of fluorescent detectors. As a reminder we show here the profile of the highest energy shower seen by the Fly's Eye. Showers of heavy nuclei will have maxima and lower atmospheric depth, gamma ray showers would penetrate deeper.



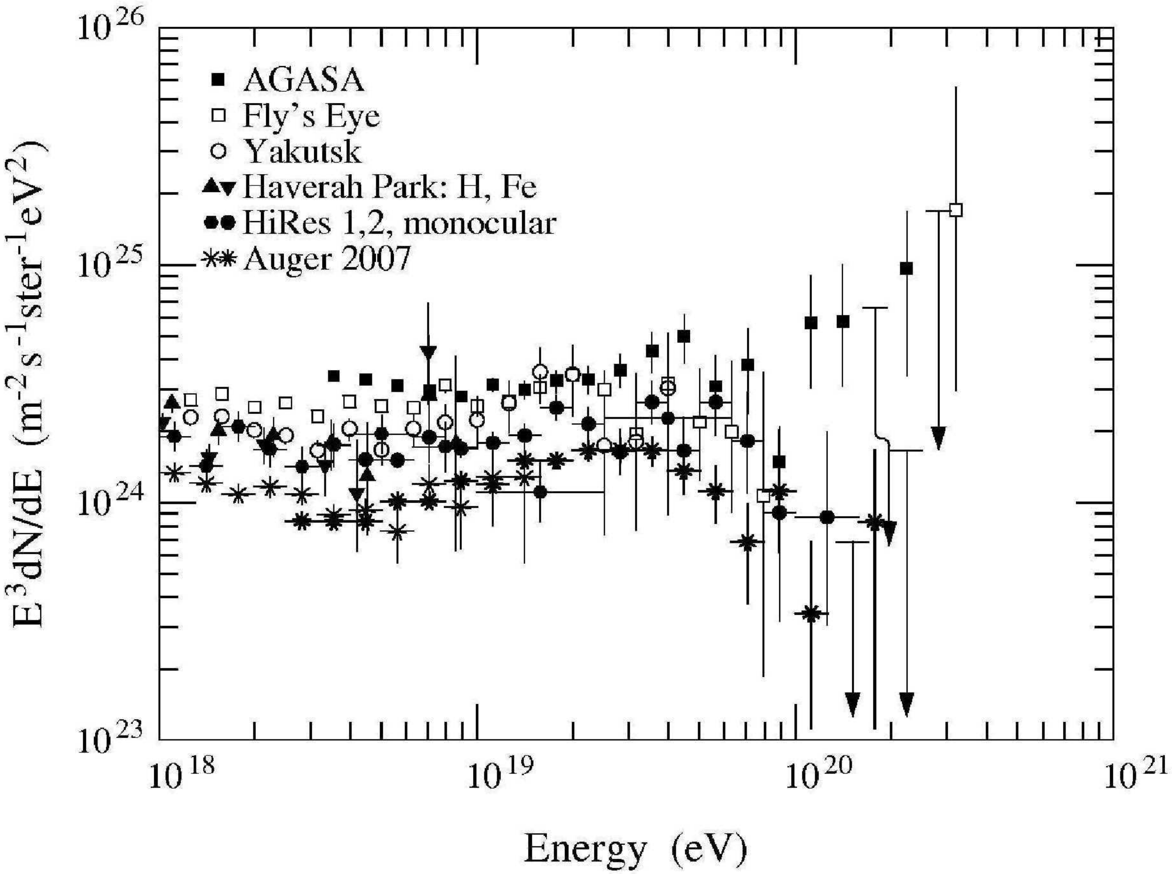
The biggest excitement in 2007-08 came from the field of the ultrahigh energy cosmic rays (UHECR): from the results of Auger and HiRes.

These two detectors proved that UHECR are charged nuclei by observing the GZK effect, the steep change of the cosmic ray spectrum at about $10^{19.7}$ eV which is due to interactions with the photon fields of the Universe, mostly with the MBR. Apart from this statement the two groups do not agree on much else.

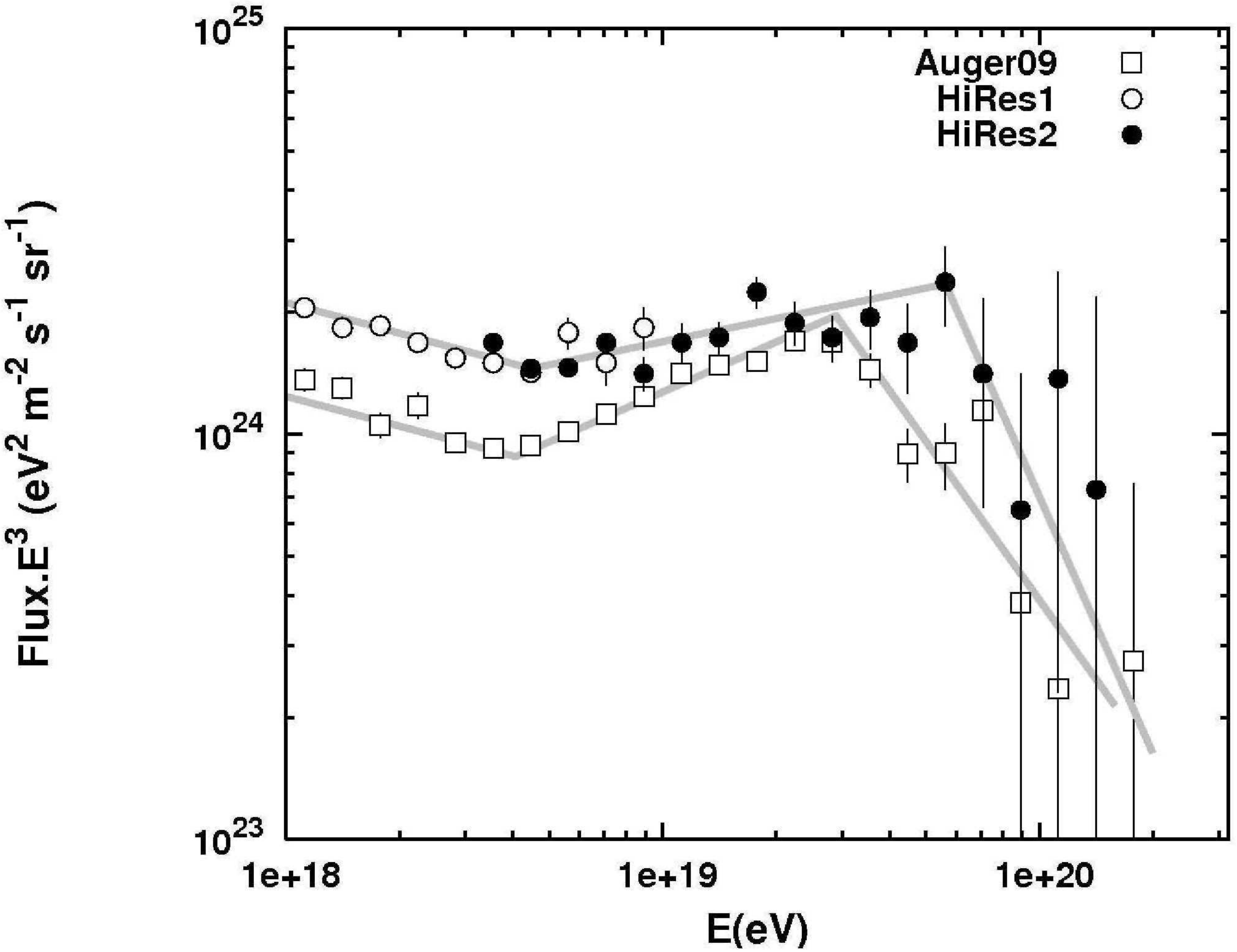
Let us go through some of the arguments. Do not forget that most arguments were raised by the experimental groups themselves.

Ultrahigh Energy cosmic ray spectrum:

with the exception of the AGASA events (note that there is a re-analysis of AGASA, not shown) above 10^{20} eV all other measurements show approximately the same spectral shape.



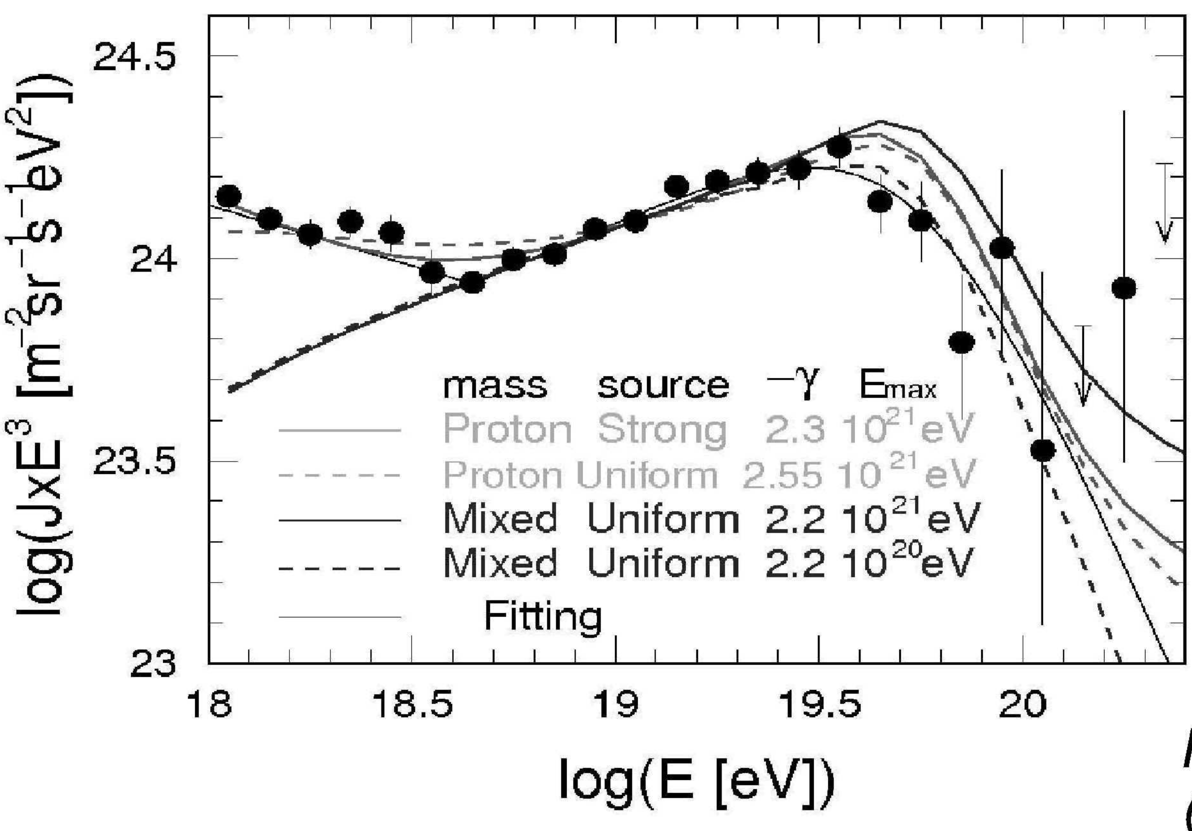
The highest energy events of AGASA inspired the top-down models for UHECR production.



The spectra of HiRes and Auger as published in Phys. Rev. Lett. last year. Both measurements claim a confirmation of the GZK feature.
The differences are small but lead to different interpretations.

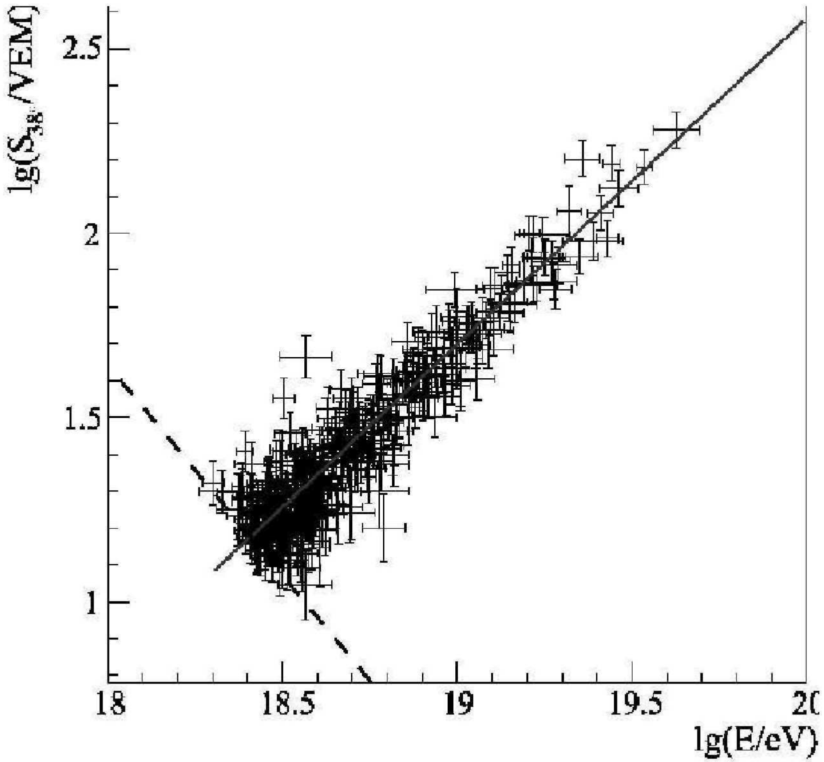
The HiRes spectrum has a slope of 2.8 between log10(E) of 18.65 and 19.75 with a steepening to 5.1 at higher energy. Auger has a flatter slope of 2.69 between log10(E) of 18.6 to 19.6 with a steepening to 4.2. The 2009 spectrum with much higher statistics confirms the earlier result.

The HiRes spectrum is fully consistent with the model of Berezinsky et al (protons, $\gamma = 1.7$, no cosmological evolution) while the Auger spectrum is well fit by several different models, some involving mixed composition at the sources. Proton models include ($\gamma = 1.55$, no evolution) and ($\gamma = 1.30$, $(1+z)^5$ evolution)



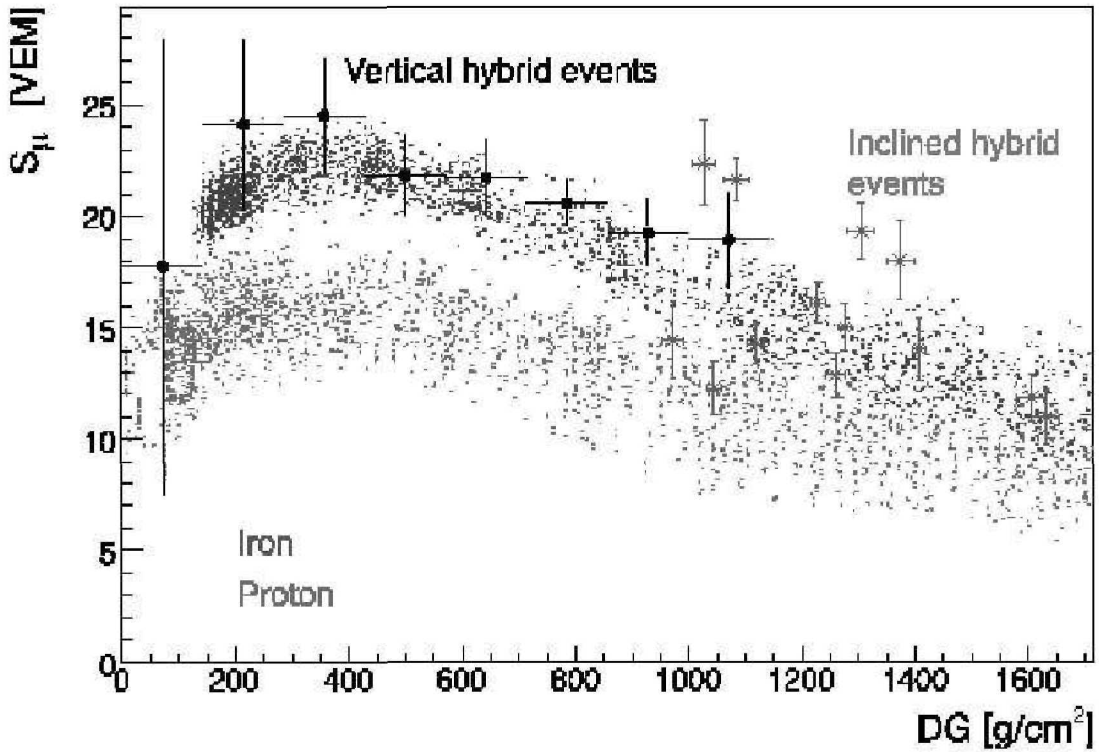
From: Yamamoto et a (Auger Collaboration)l

HiRes uses the integral of the shower longitudinal profile and accounts for the *invisible* (non EM) energy.
Auger uses S(1000) scaled to the fluorescent energy as $E_{FD} = 1.5\ 10^{17}$ eV $S(1000)^{1.08}$. The two energy estimates should be the same and they are not.
Note: the Auger aperture is fixed by the size of the surface array, HiRes aperture comes from MonteCarlo.



Problem
Why are the energy assignments different when they should be identical?

From: M. Roth for the Auger collaboration



From: R. Engel for the Auger collaboration.

Not everything is fine for Auger either. When the MonteCarlo EM component is subtracted from S(1000) the fraction of the muon component is much higher than predicted by interaction models.

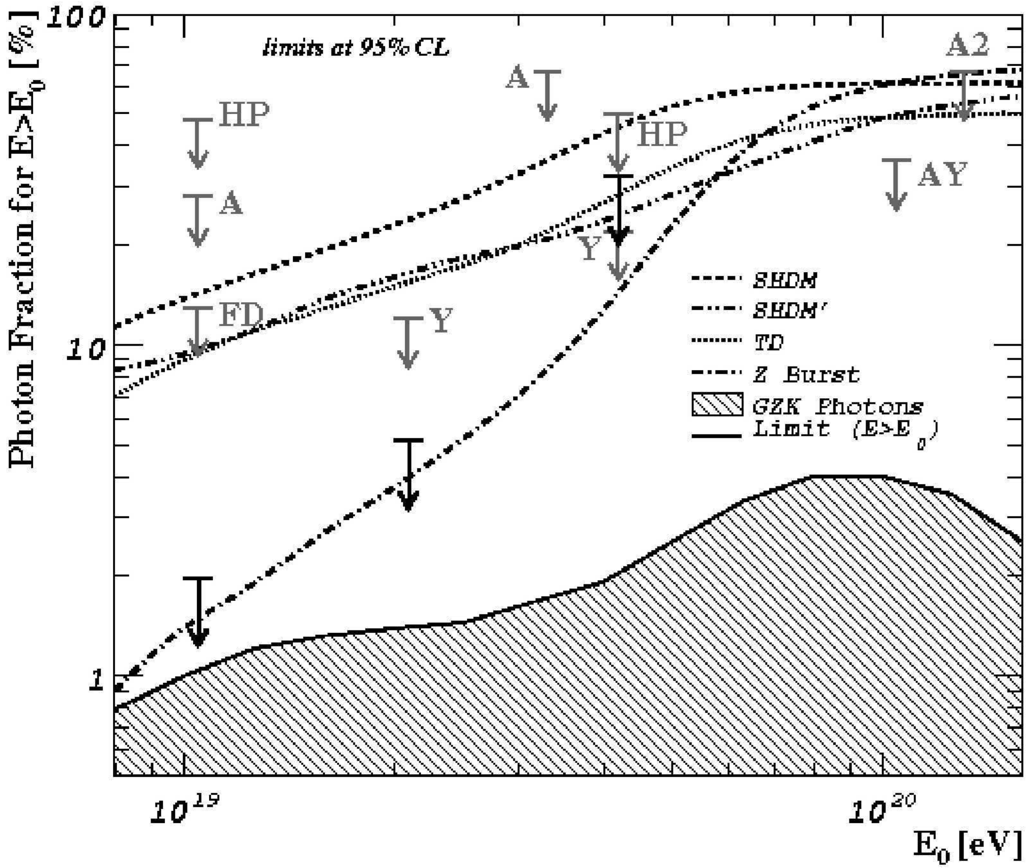
Is there a problem with the hadronic interaction models that are used for the giant air shower analysis?

UHECR composition is measured by the depth of shower maximum X_{max}.

$<X_{max}>$ is sensitive to the mass of the primary cosmic ray:

$$<X_{max}> = D_{10}\,[\ln(E/E_0) - <\ln A>] + X_{max}(E_0),$$

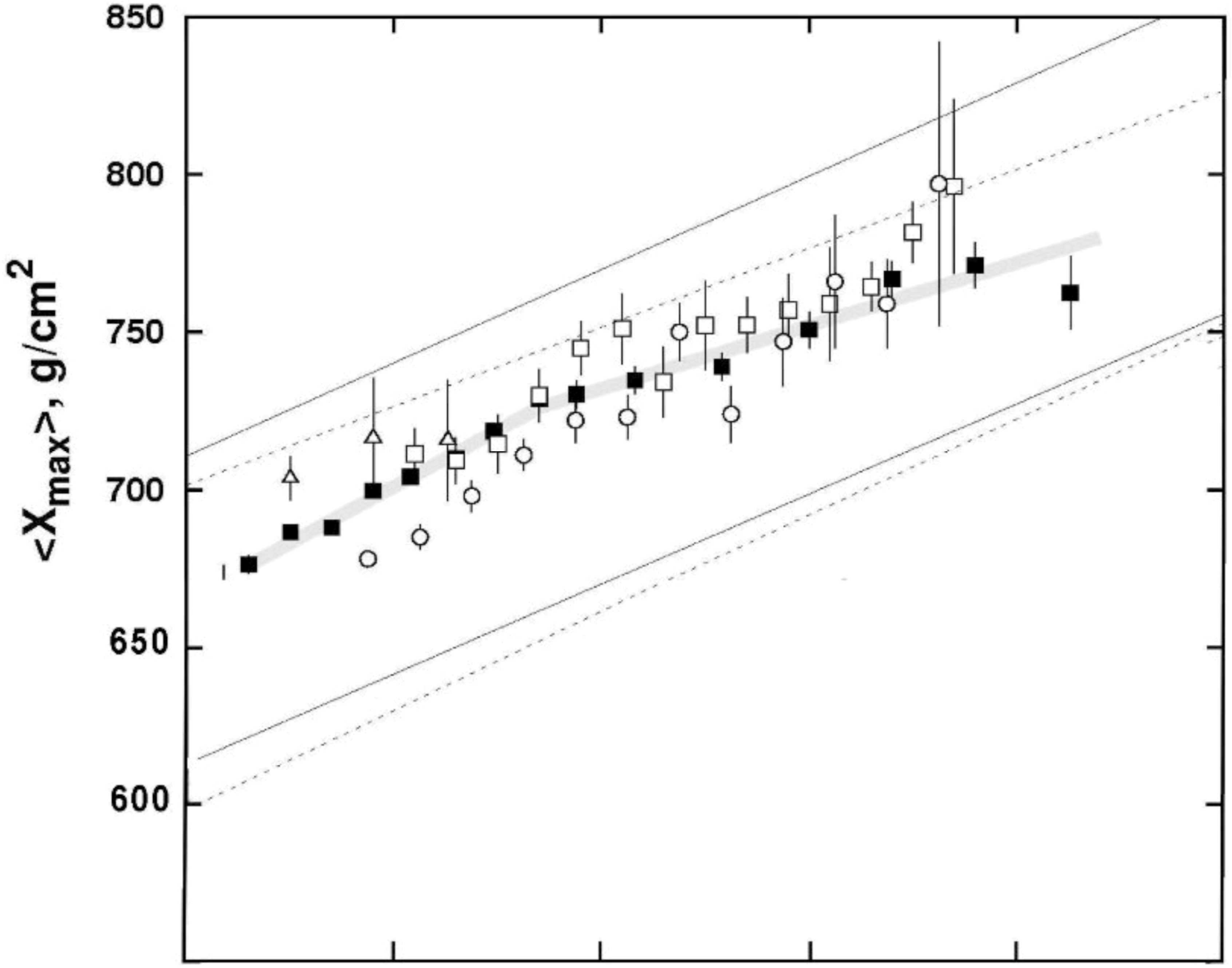
where the *elongation rate* D_{10} is $dX_{max}/d(\log_{10} E)$ and $X_{max}(E_0)$ is the depth of maximum of proton showers of that energy. The common wisdom is that extragalactic cosmic rays should be H and He nuclei in a standard 9:1 ratio and one should see much lighter cosmic ray composition in the transition of galactic to extragalactic cosmic rays. This would show up as an elongation rate significantly bigger than D_{10} of the hadronic interaction model.



From: Abraham et al (Auger collaboration) Astropart. Phys. 29:243 (2008).

From the properties of the detected showers Auger did limit the fraction of gamma-rays.

The big achievement of the Auger collaboration is the setting a 2% limit on the gamma-ray fraction in UHECR at energies above 10^{19} eV, much lower than any other attempt.

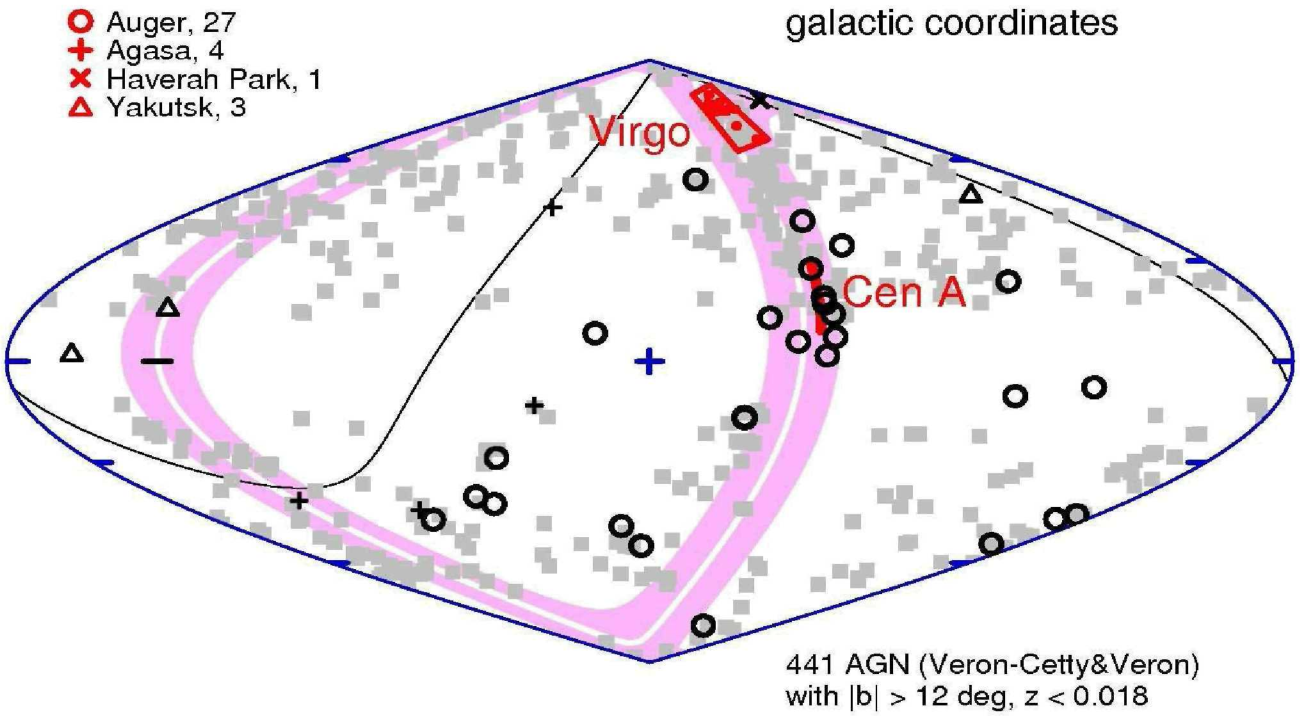


The Fly's Eye, HiRes-MIA and HiRes data show very light cosmic ray composition.

The Auger elongation rate is, however, not constant – it is 71 g/cm^2 up to $10^{18.35}$ eV and decreases to 40 g/cm^2 at higher energy.

This indicates a 'lightening' of the composition up to that energy and a transition to heavier composition at higher energy.

Cosmic ray astronomy



The Auger Observatory reported a correlation of their highest energy events (E>57 EeV) with AGN from the Vèron-Cetty and Vèron catalog at redshifts less than 0.018. The search angle around the UHECR direction is 3.2 degrees. The HiRes does not see this correlation or any anisotropy.

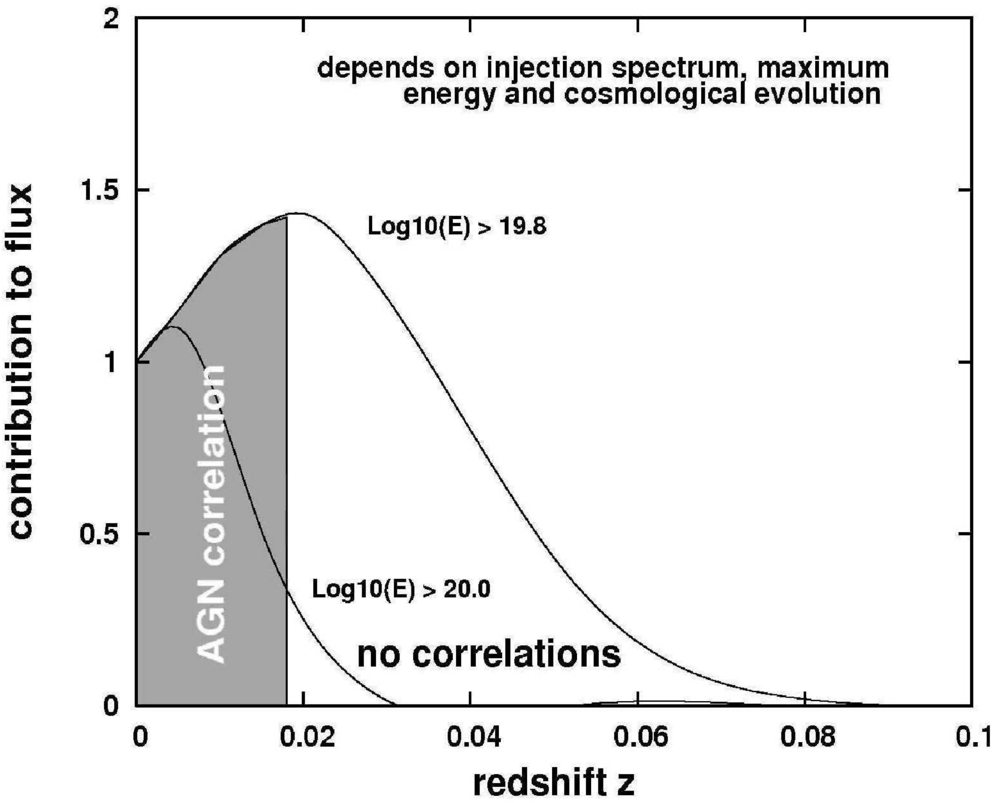
The discovery of anisotropy, if confirmed, is very important. All the questions, including that of the energy assignment, define another problem

Problem: What do we know about the sources of the highest energy particles in the Universe? What are the galactic and extragalactic magnetic fields that UHECR propagate from their sources to us?

Ultrahigh energy cosmic ray astronomy can answer many questions related to the general conditions of extragalactic space that are very difficult to study with the classical astronomical devices and means. The main problem here is the low UHECR statistics. After HiRes and Auger we expect not more than 0.2 UHECR per 1,000 km^2.sr.yr.

Auger did not claim that the AGN are the sources of the UHECR. Sources may correlate with AGN, the anisotropy is the important discovery. There were still many questions.

1) *Why these particular low luminosity AGN?*
2) *Why there are no UHECR close to the Virgo cluster?*
3) *What is going on in Cen A?*
4) *Why 3.2 degrees angle?*
5) *Why only redshifts to 0.018?*



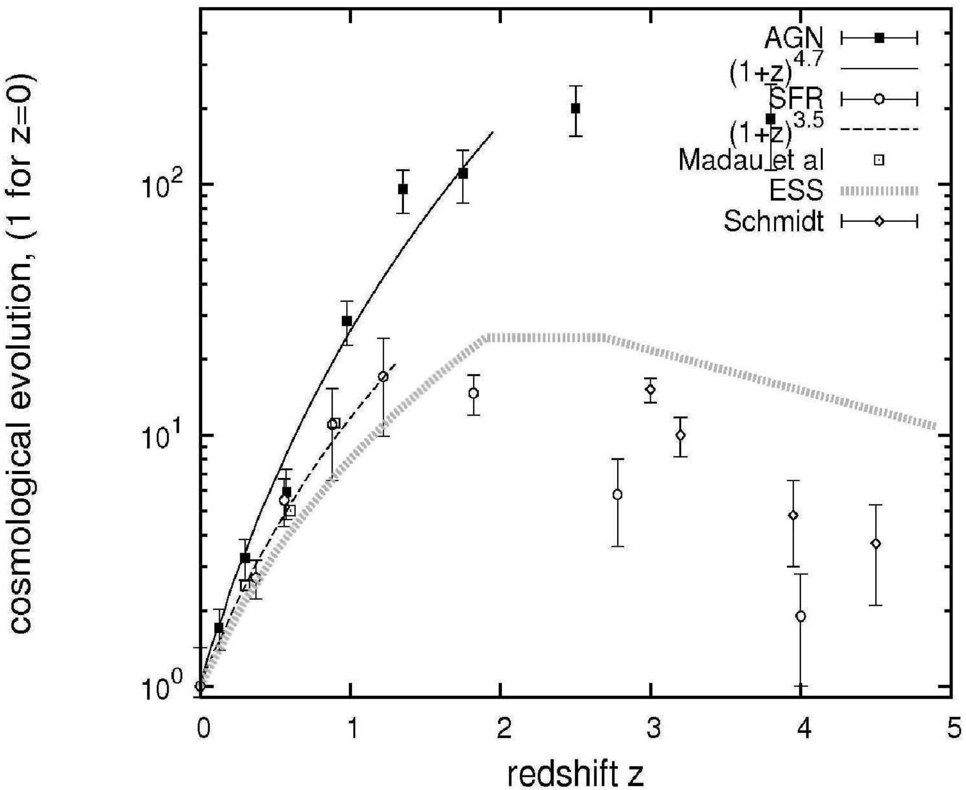
3.2 degrees scattering suggests protons, while X_{max} indicates heavier nuclei.

If these are protons, why z<0.018 when more distant objects should contribute. Is the energy assigment correct?

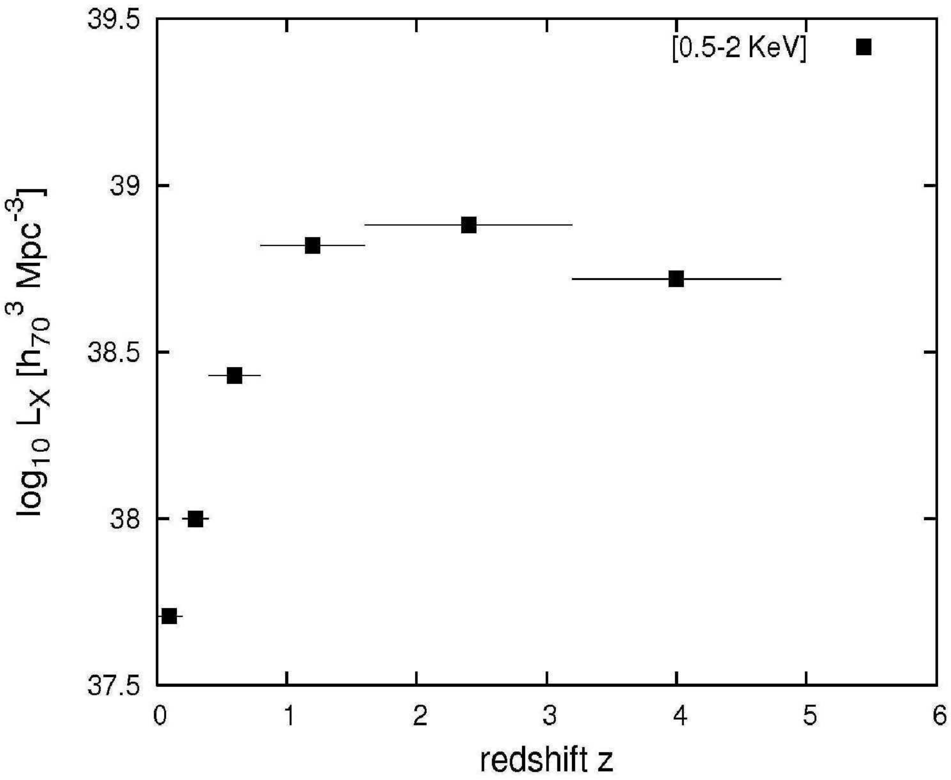
In 2009 the Auger Southern Observatory has increased its statistics by a factor more than 2. The correlation with VC-V AGN catalog has decreased: 18 of the 27 highest energy events used to correlate with AGN. Now the number is 26 out of 58, i.e. only 8 out of 31 new events.

The main confirmation of anisotropy is now the large number of events around the Cen A radio galaxy. Many other analyses show that there is anisotropy at about 3σ level.

The correlation with AGN also raised interesting questions about the cosmological evolution of the UHECR sources. It is the cosmological evolution of star forming regions (SFR) that is studied the best. AGN, however, may have faster cosmological evolution if the observations in infrared give identical results to these in soft X-rays.



The lower data sets are from observations of SFR, while the faster evolving points are AGN observations of ROSAT in 0.5-2 KeV X-rays. The evolution is close to $(1+z)^5$.



Cosmological evolution of the 0.5-2 KeV X-ray flux emitted by all AGN - $(1+z)^5$ evolution to $z=2$

UHE cosmic rays and UHE neutrinos

Such an interpretation of the Auger energy spectrum is extremely important for the production of secondary signals in propagation – gamma-rays and neutrinos. We will discuss the relevant neutrino fluxes in the next lecture.