Ultra High Energy Cosmic Rays and Neutrinos (after Auger)

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ANCIENT HISTORY

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 indepen-dently derived the absorption of UHE protons in photoproduction interactions on the 3K background.

More problems: such detections continue, the current world statistics is around 10 events.

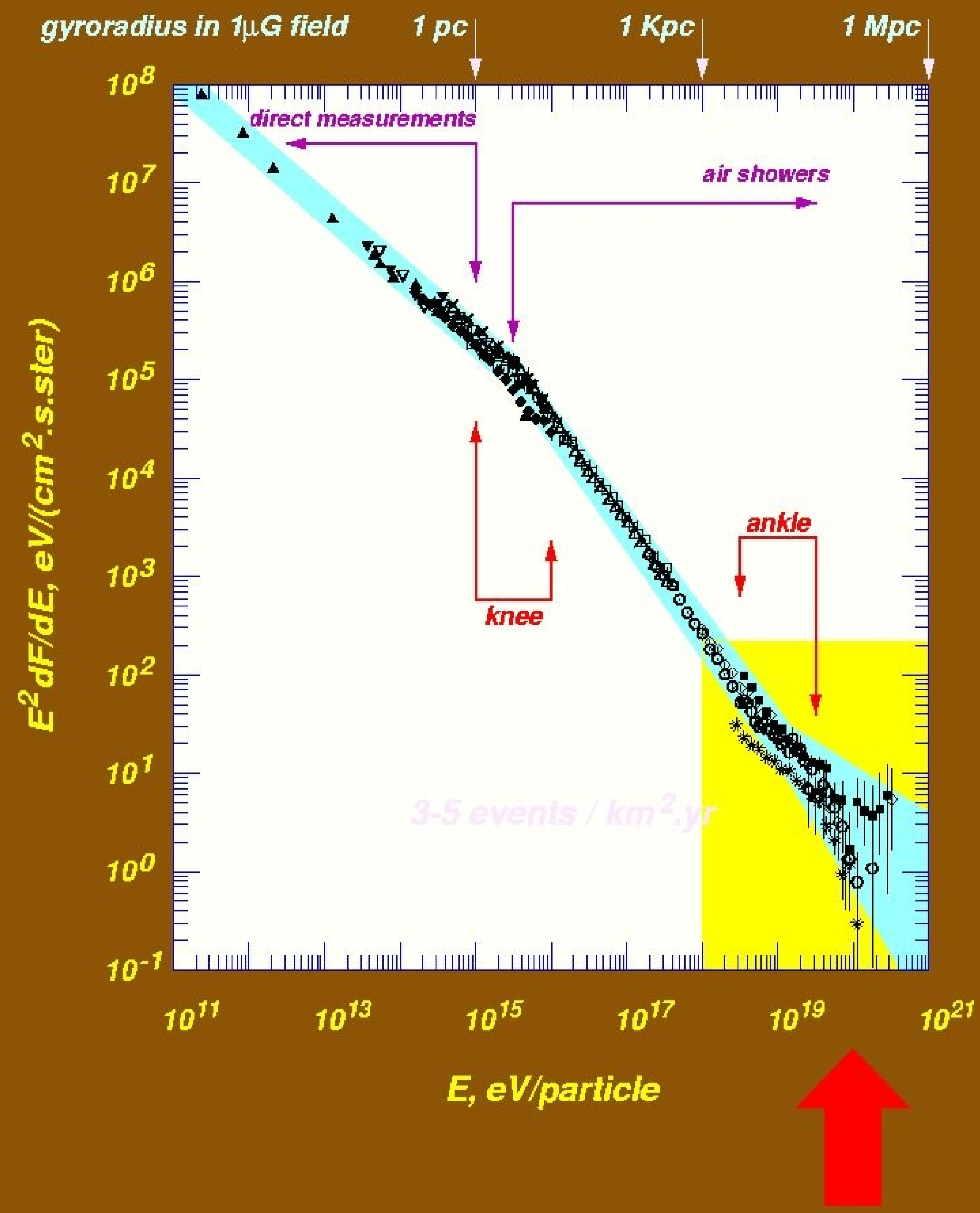
10^{20} eV =
= $2.4\text{x}10^{34}$ Hz
= $1.6\text{x}10^{8}$ erg
= 170 km/h
tennis ball

$\sqrt{s}$ equivalent is 300 TeV

These particles **should not** exist because of two sets of problems:

1) set one: production (acceleration)
2) set two: propagation

We will discuss today the topic of UHECR and UHE neutrinos in view of the latest experimental results, mostly those of the Pierre Auger observatory in Argentina. Before this discussion I want to introduce the basic problems of the UHECR propagation in the microwave background field (MBR) as a basis of many conclusions.

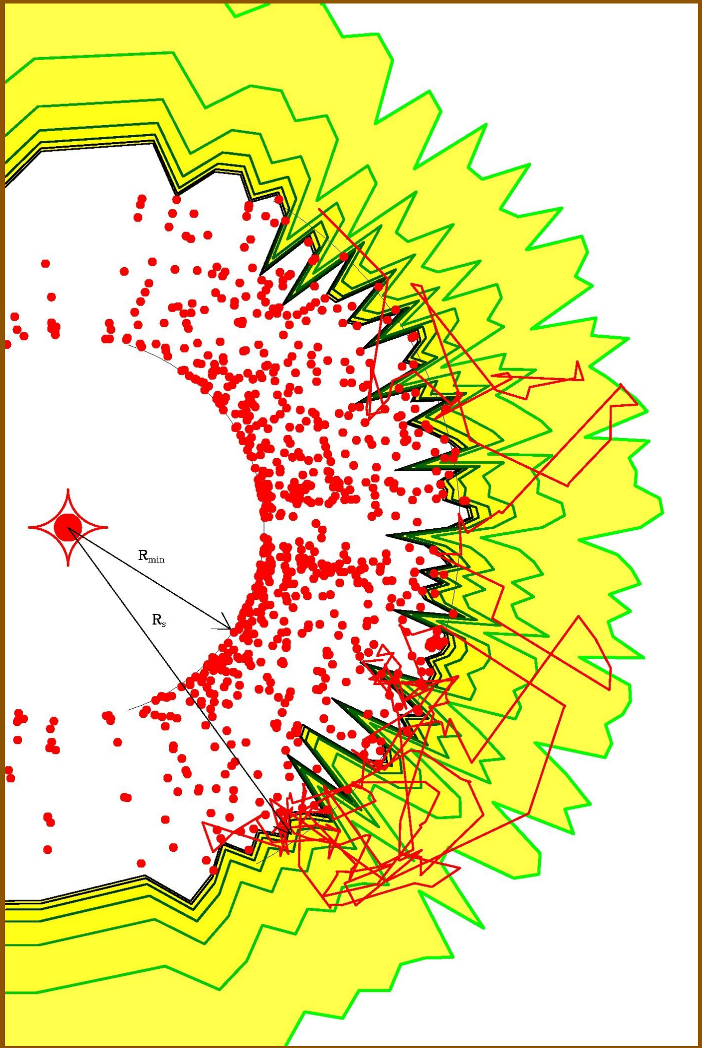


Cosmic ray energy spectrum is smooth, power law like.
It has two main features:
- the knee (A.M. Hillas' talk)
- the ankle

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, maybe also supernova remnants. (?)

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 5-10% of the kinetic energy of the SNR is converted to cosmic rays this would supply all cosmic rays in the Galaxy.

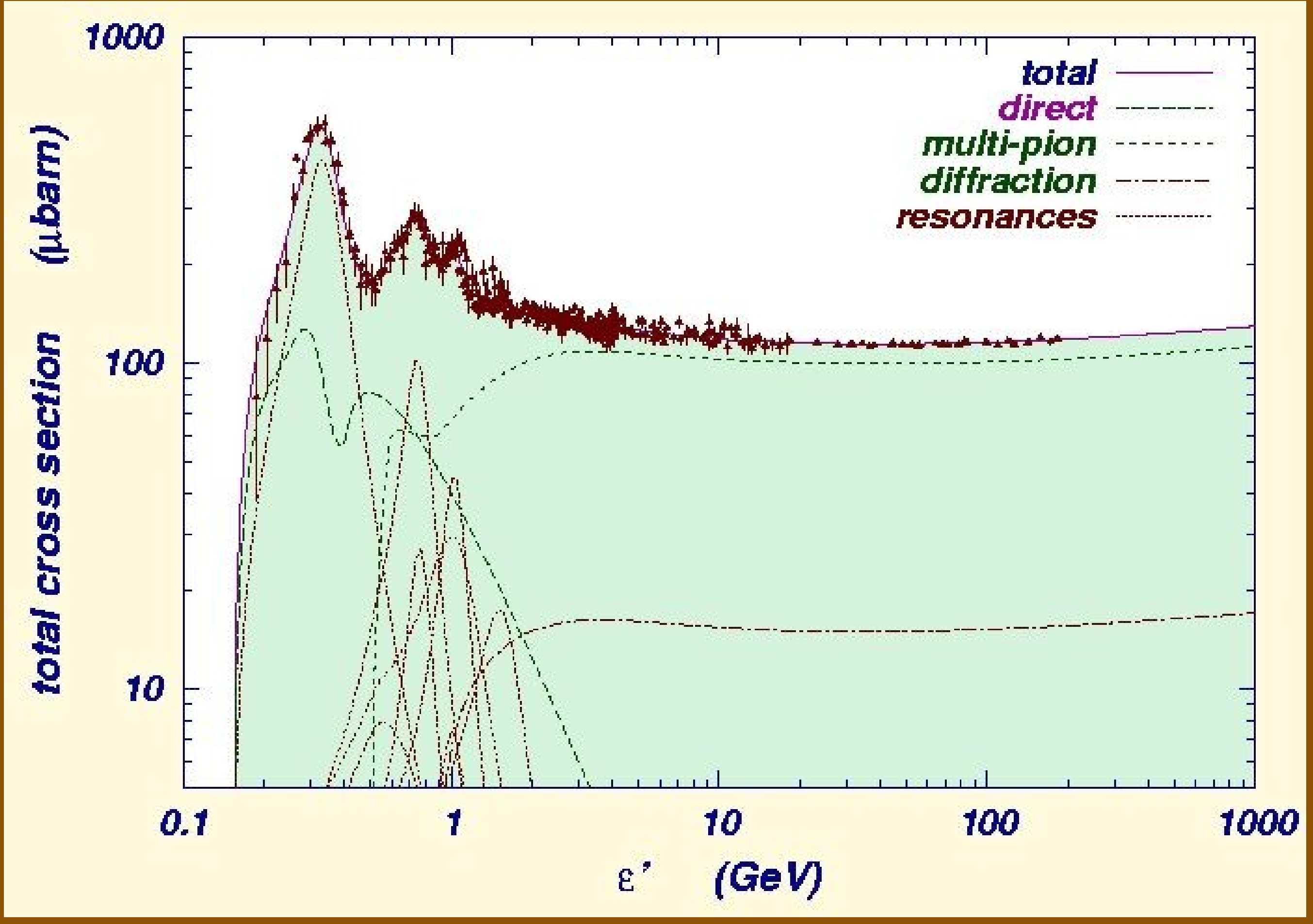
The acceleration proceeds at the shock formed by the expanding SNR envelope. Most productive time is 1000 to 10,000 years after the explosion. Shock compression ratios above 4 lead to flat power law spectra - E^{-2}. Modern calculations obtain more complicated spectra that are power laws in small energy 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.

Propagation of extragalactic cosmic rays

The spectrum of the highest energy cosmic rays is formed in their propagation from the sources to us when they interact in the photon fields of the Universe. Because we do not know what their sources are we have to assume that UHECR sources are isotropically and homogeneously distributed. The possible existence of *nearby* sources could make a significant difference.

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



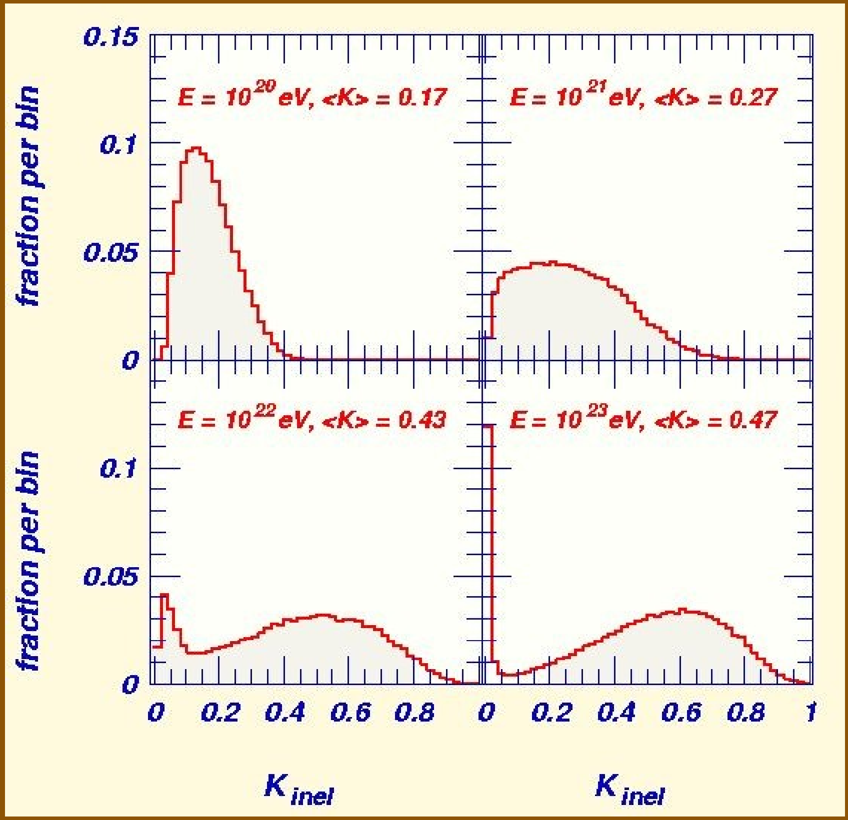
Photoproduction cross section in the mirror system, i.e. photons interacting on target protons.

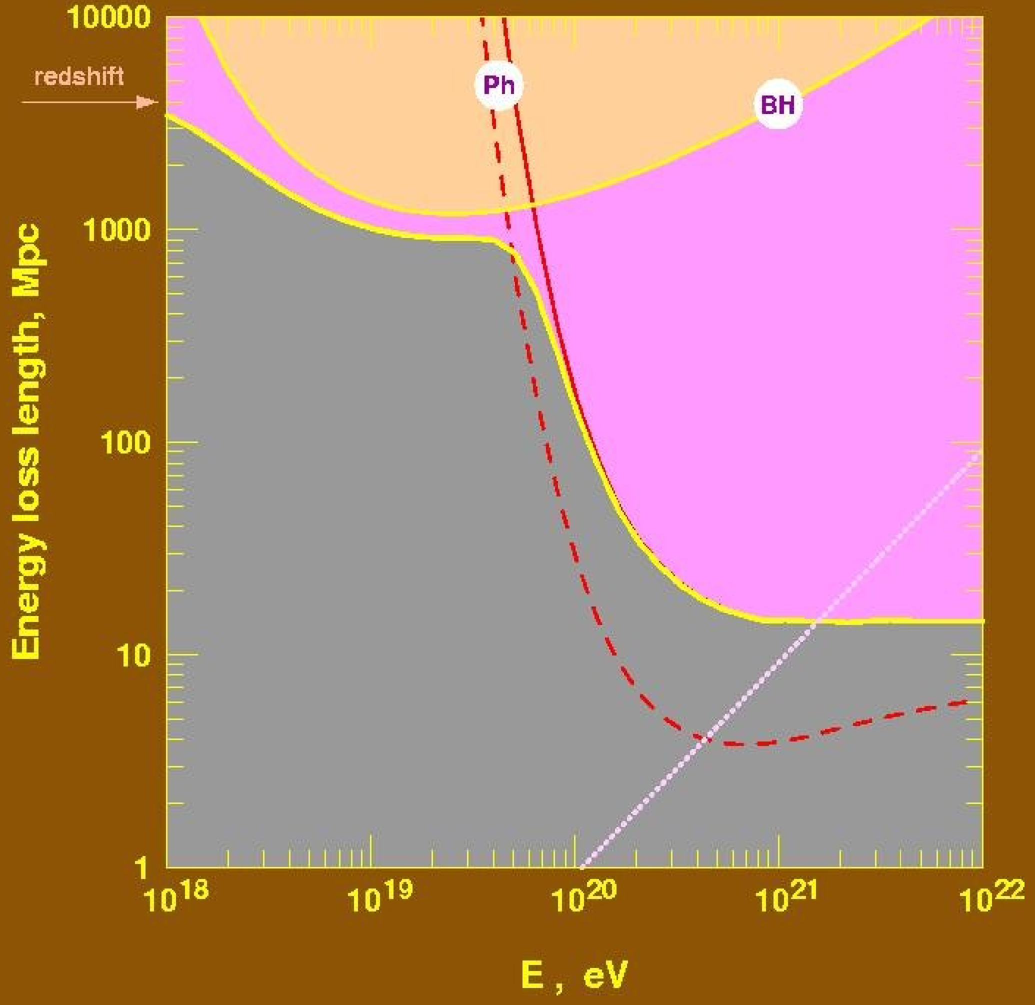
The UHE protons energy is so high that they can interact on photons from the microwave background and produce secondary pions. The threshold is when the center of mass energy exceeds the proton mass + the pion mass:

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

For the average microwave background photon the threshold is at 10^{20} eV. Averaged over the photon spectrum and direction the threshold is half of order of magnitude 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%.



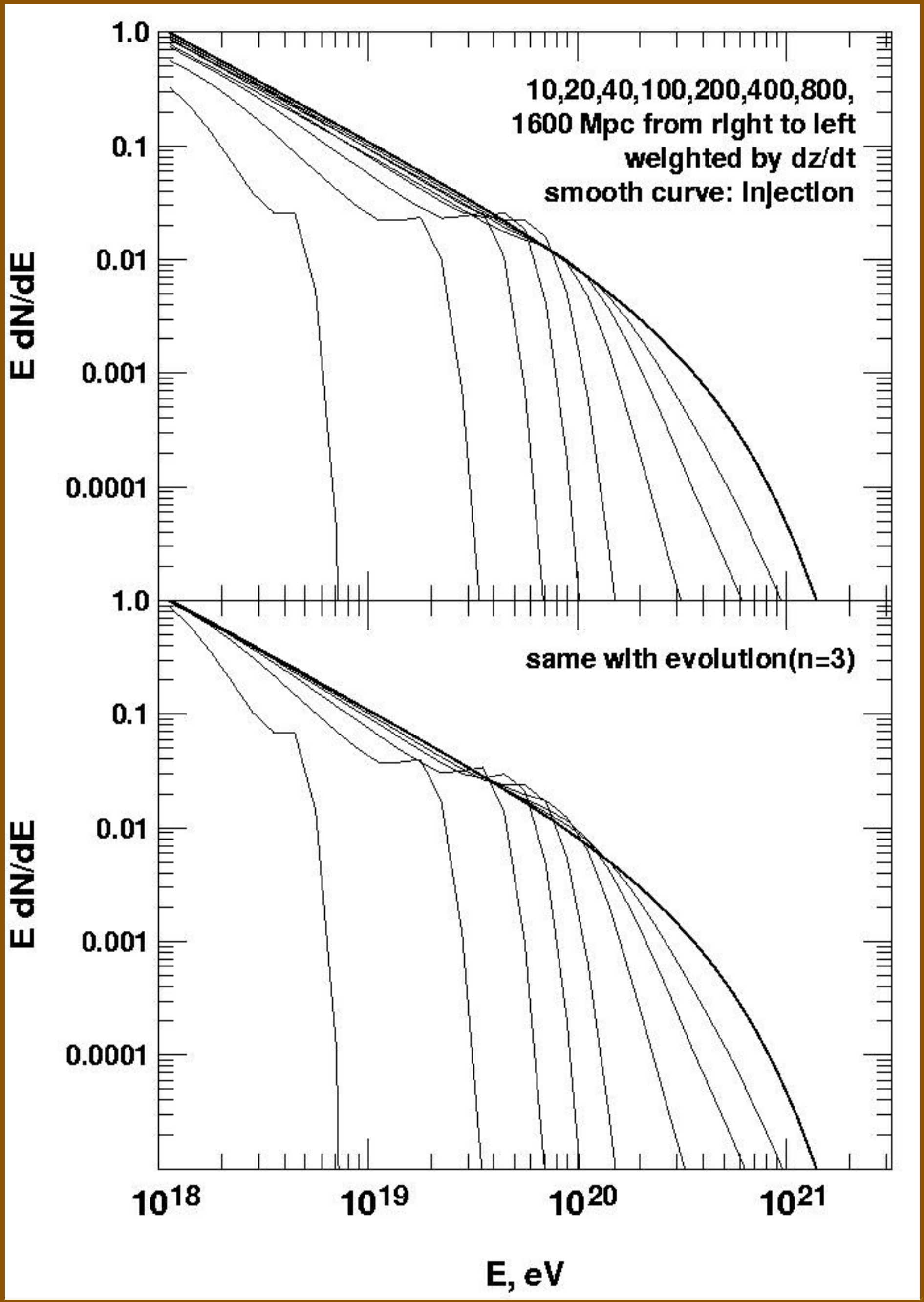


Secondary gamma rays and neutrinos (cosmogenic neutrinos) are produced on propagation.

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 production. 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.

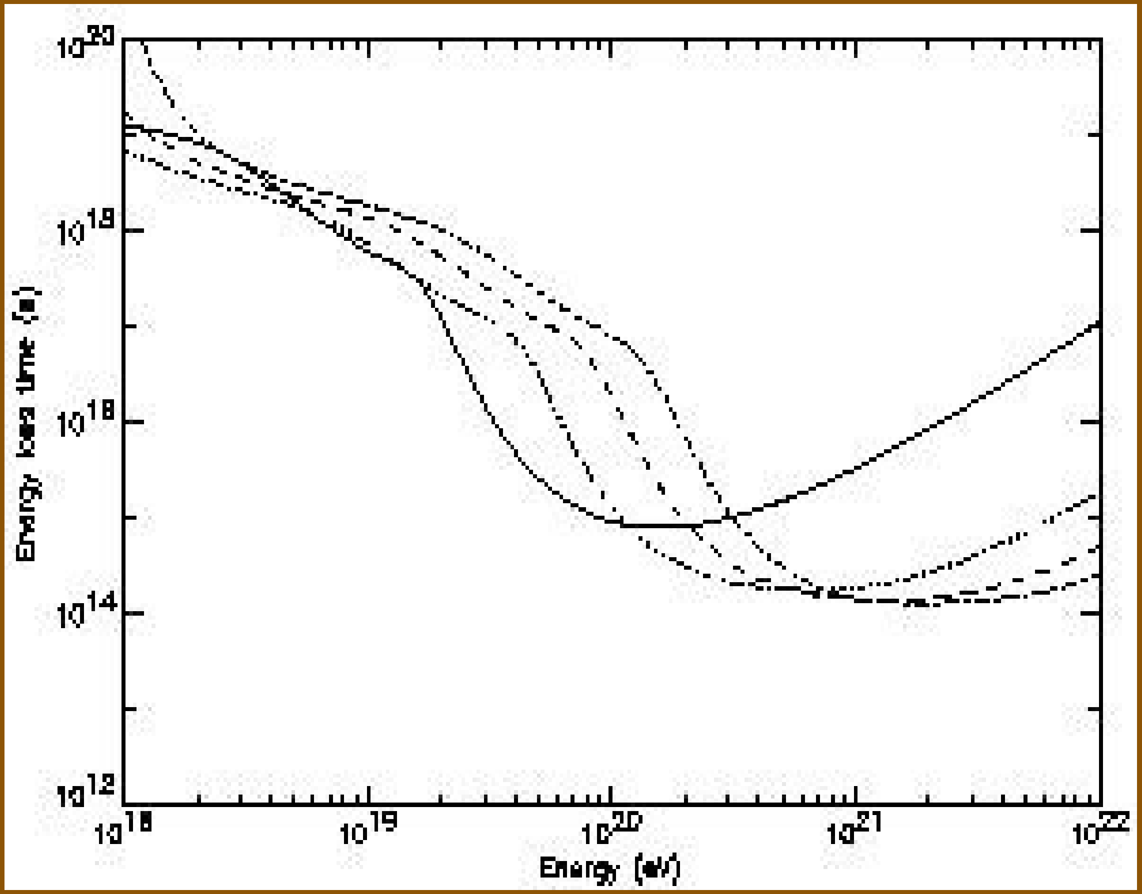


Evolution of the cosmic ray spectrum in propagation on different distances.

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 up to z = 1.7.

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.



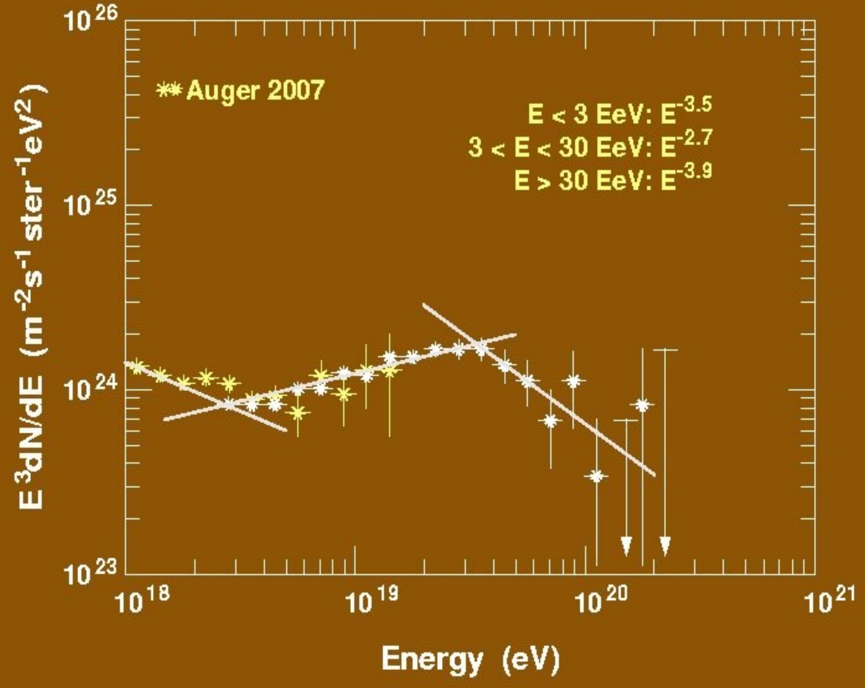
From: Bertone et al

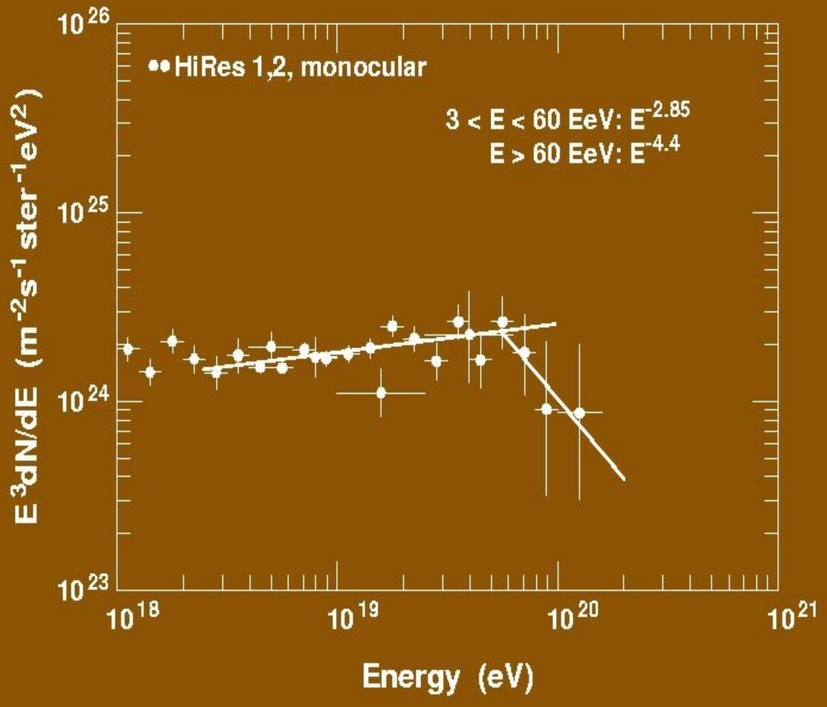
Heavy nuclei lose energy in photodisintegration on all photon fields.
A beam of heavy nuclei injected at large distance from us changes its composition in propagation. At distances larger than the energy loss distance it is a purely proton beam after the secondary neutrons decay.

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

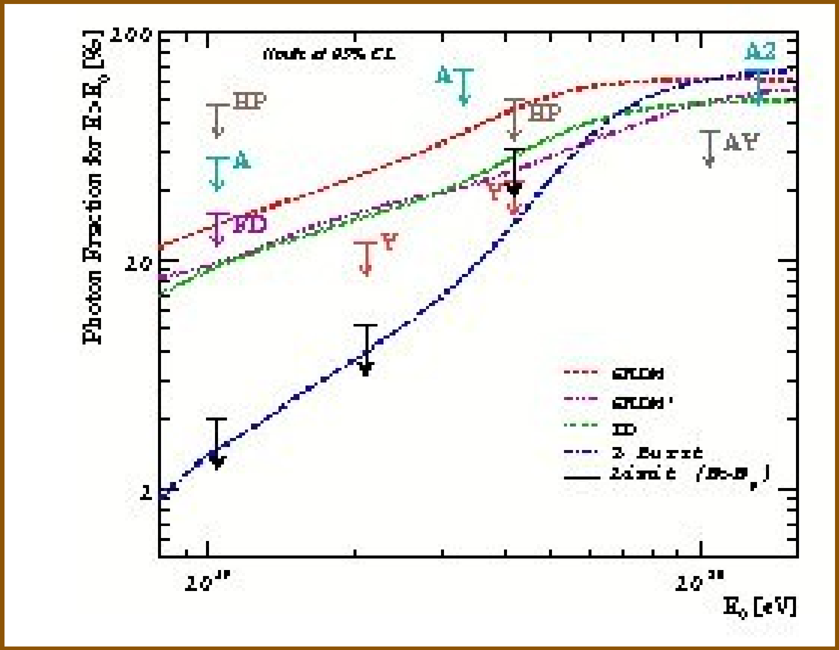
A quick summary of the Auger results:

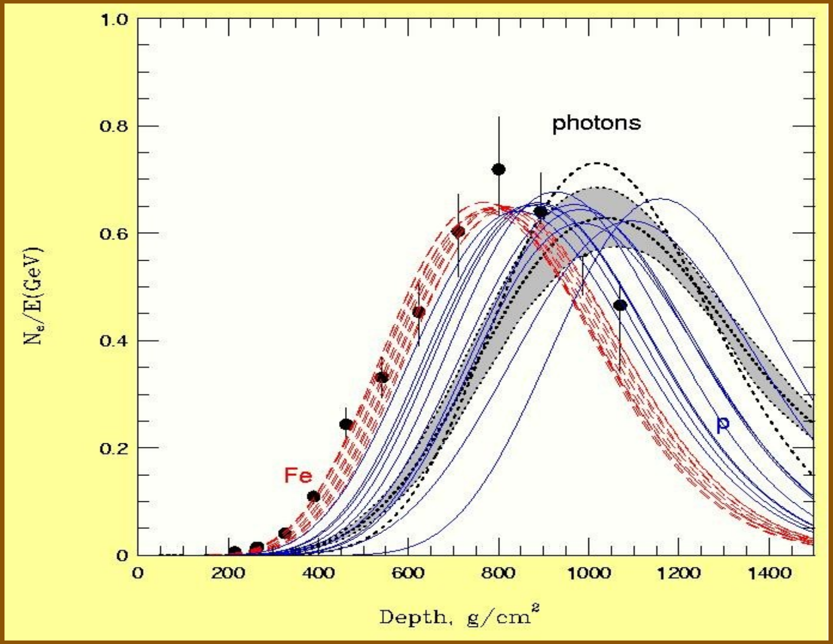
1) The Pierre Auger observatory presented in 2007 data that confirm the change of the cosmic ray spectrum above several 10^{19} eV. The HiRes Fly's Eye experiment claims the observation of the GZK cutoff. The exact shape of the Auger spectrum is somewhat different from HiRes.



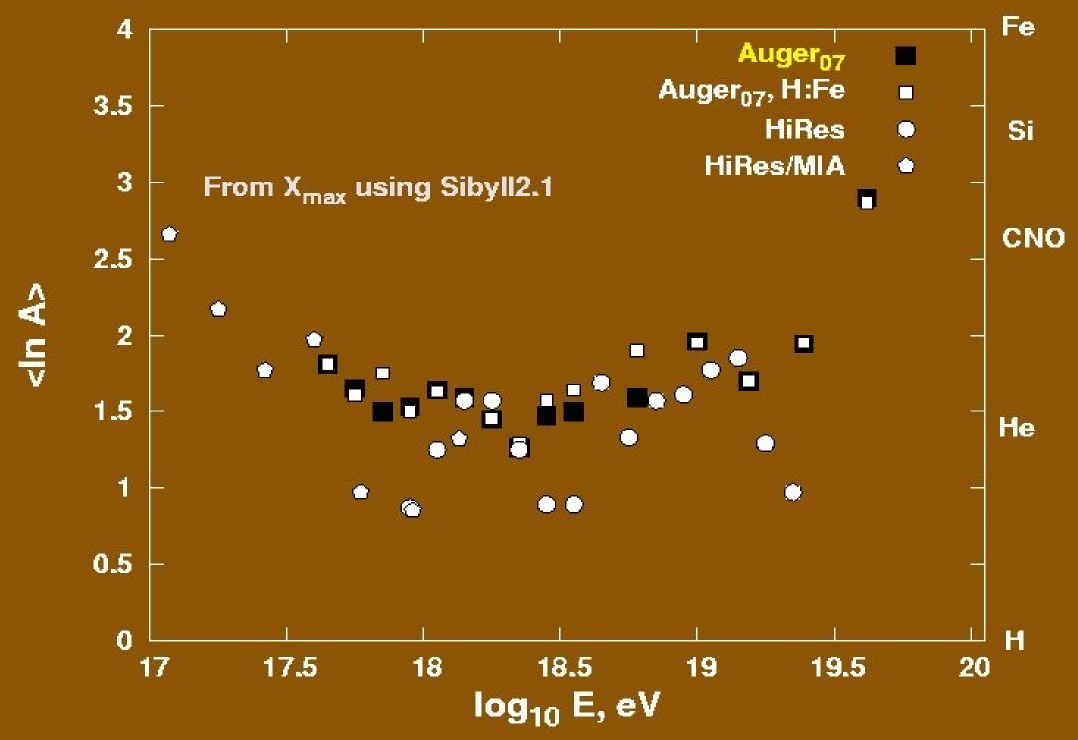


2) There is now a strong limit on the fraction of gamma rays in UHECR above 10 EeV (10^{19} eV) – 2% of all UHECR above this energy. We now believe that UHECR are charged nuclei accelerated in powerful astrophysical objects. The limits at higher energies are weaker. The conclusion is made on the basis of studies of the air shower longitudinal profile, as shown below.



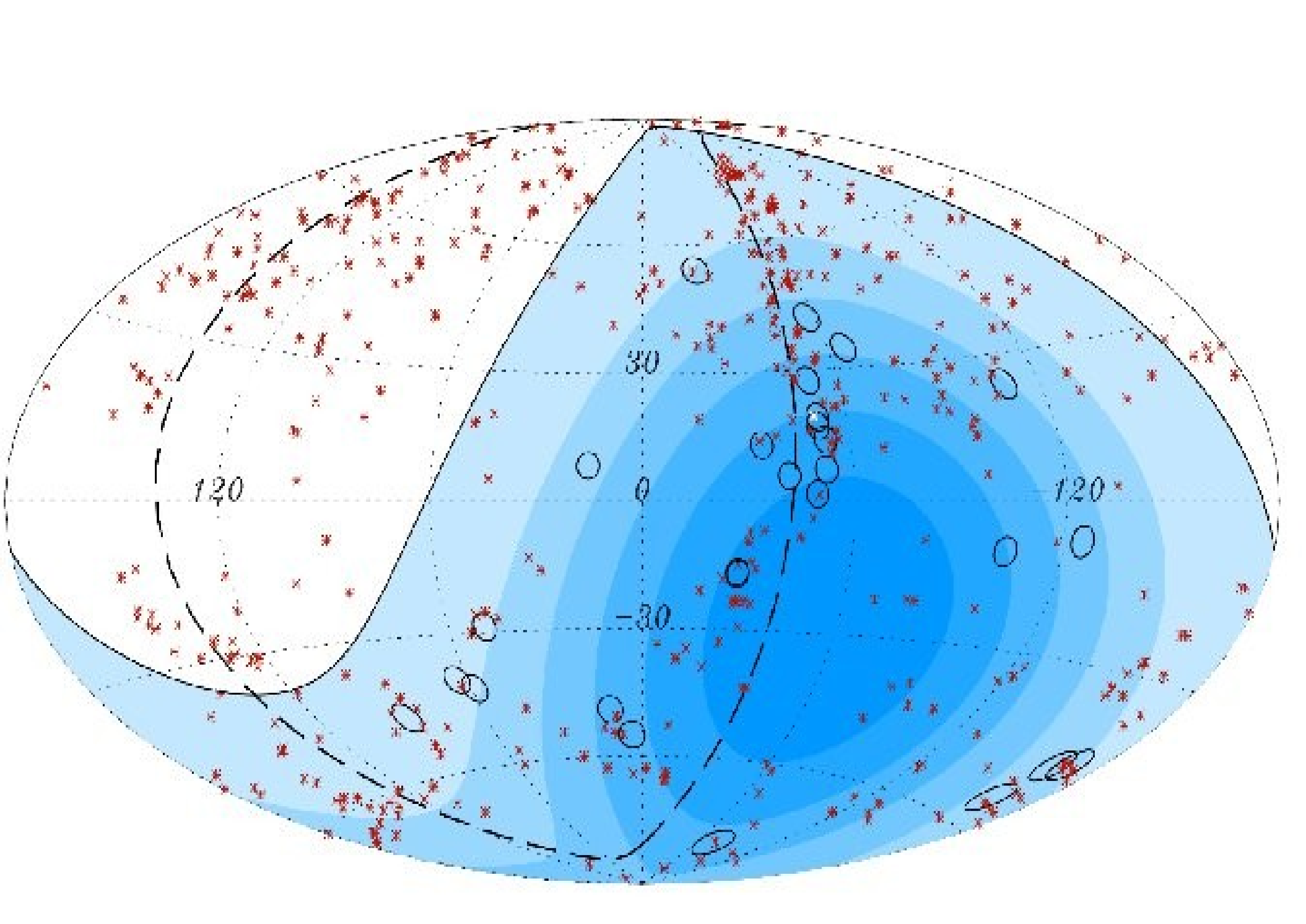


3) The composition of UHECR is not obvious. Using similar arguments (depth of maximum) the composition seems consistent with light nuclei (O ?). After some corrections of the HiRes published data (cloud coverage, etc) the composition derived is not vastly different. The model dependence is higher than that difference.



Note, however, that the current hadronic interaction models do not describe well the measured shower longitudinal behavior. Shower absorption in the atmosphere seems to be slower than predicted.

4) In November 2007 (Science) Auger reported on a correlation of their 27 highest energy events (> 57 EeV) with nearby, (distance < 75 Mpc, z < 0.0179) Active Galactic Nuclei. Most of the correlating AGN are Seyfert galaxies. There are no massive clusters of galaxies (Virgo ?) at this distance. There is a concentration of several events around CenA, nearby FRI galaxy with huge radio lobe. HiRes did not see AGN correlations of their 13 highest energy events.



The reaction to this announcement was very strong and immediate:

Question 1: Why there are no events close to Virgo when there is a large number of nearby (20 Mpc) AGN there.

Question 2: How low are extragalactic magnetic fields if the 3 degree angle corresponds only to scattering in the galactic magnetic field

Question 3: Why is the correlation seen only to distances of 75 Mpc while protons and nuclei should come from distances up to 200 Mpc.

Question 4: Why the scattering in GMF corresponds to protons while composition analysis points at medium heavy nuclei.

Many of these questions were asked by the Auger collaboration itself and were discussed in their more detailed second paper.

After Auger published the energies and directions of the 27 UHECR there were attempts for correlations with specific types of objects (more powerful AGN within 100 Mpc) that found similar correlations.

The self correlations of the Auger events suggest a relatively large number of sources (> 61 within 75 Mpc).

HiRes submitted a paper where no correlations with AGN from the same catalogue are seen for their 13 highest energy events.

In the following we will assume that UHECR detected by the Pierre Auger observatory are indeed accelerated at AGN and will follow the importance of this for the fluxes of UHE neutrinos.

Secondary particles generated in propagation

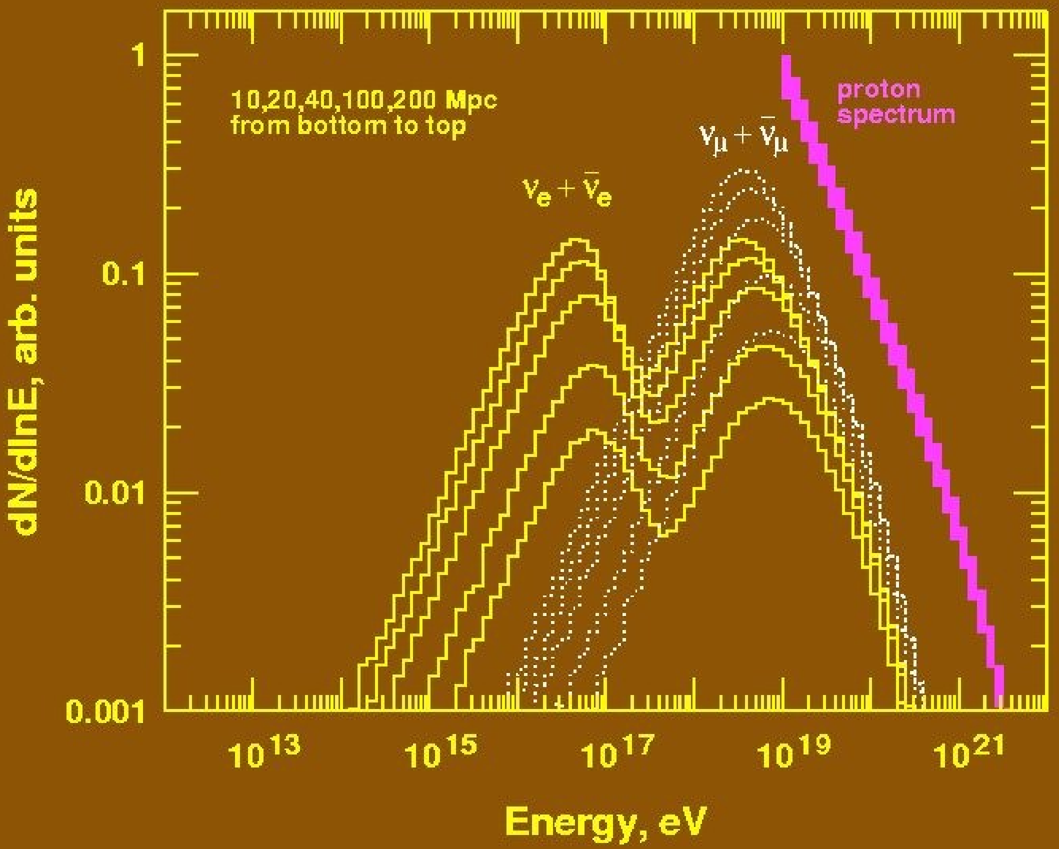
Cosmogentic neutrinos are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation and used the non-detection by Fly's Eye of neutrino induced air showers to set limits on the cosmological evolution of the cosmic rays sources.

The main difference with the processes in AGN and GRB is that the main photon target is the microwave background (2.75ºK) of much lower temperature than the photon emission of these sources. This raises the proton photoproduction threshold to very high energy:

$$E_p^{min} \simeq \frac{m_\Delta^2 - m_p^2}{2(1 - cos\theta)\varepsilon} \simeq \frac{5 \times 10^{20}}{(1 - cos\theta)} \text{ eV}$$

Actually the proton photoproduction threshold in the MBR is about 3.10^{19} eV. There is also production in the isotropic infrared/optical background.

The photoproduction energy loss of the extragalactic cosmic rays cause the GZK effect.



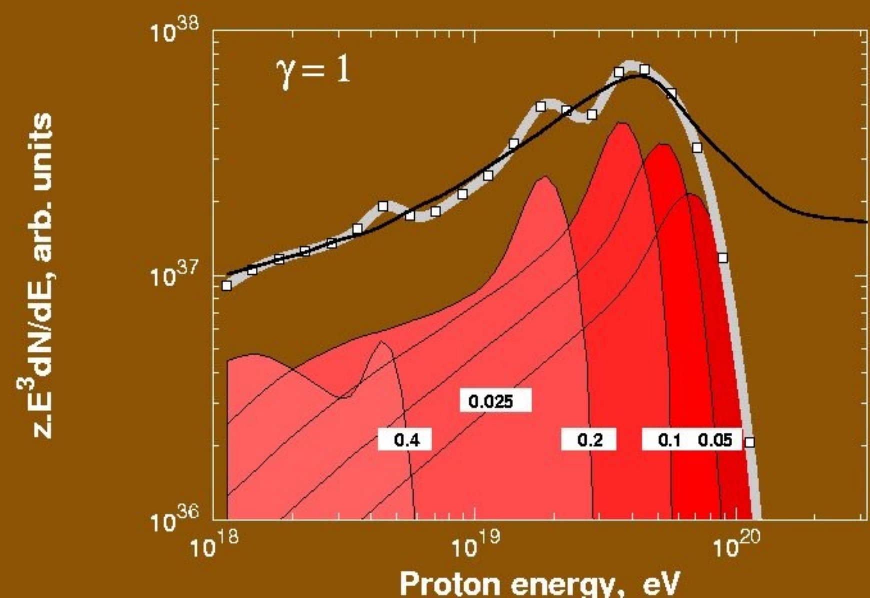
The figure shows the fluxes of electron and muon neutrinos and antineutrinos generated by proton propagation on (bottom to top) 10, 20, 50, 100 & 200 Mpc in MBR. The top of the blue band shows the proton injection spectrum
(E^{-2} in this example).

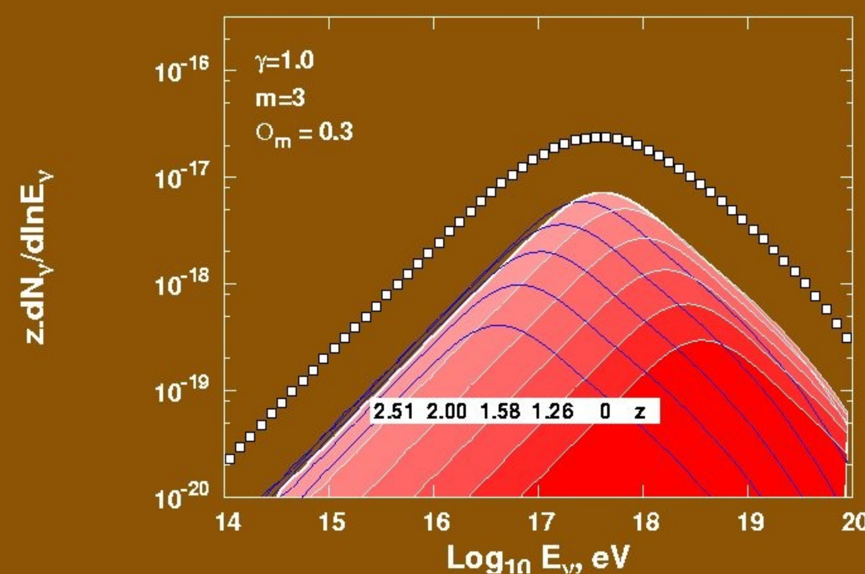
From: Engel, Seckel & Stanev, 2001

Muon neutrinos and antineutrinos are generated with a spectrum similar to the one of electron neutrinos at twice that rate. As far as neutrinos are concerned the cascade development is full after propagation on 200 Mpc. Even the highest energy protons have lost enough energy to be below threshold.
Slightly more of the proton energy loss goes to cosmogenic gamma rays generated in photoproduction and in the BH pair creation.

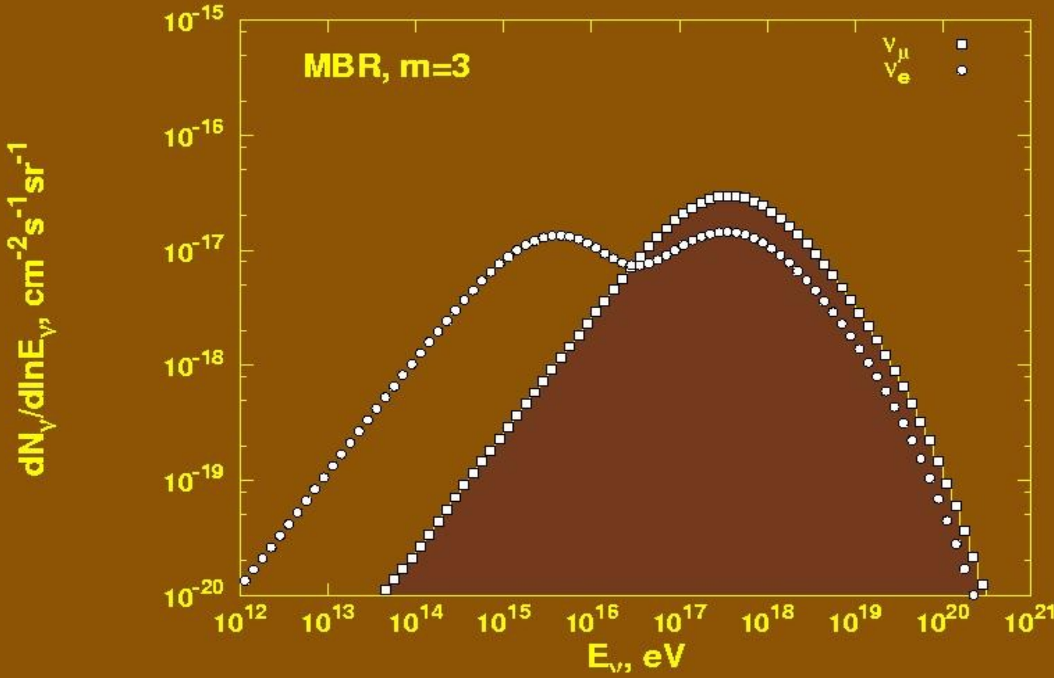
Although different spectra and cosmological evolutions of the UHECR sources fit equally well the Auger spectrum various models predict vastly different fluxes of cosmogenic (GZK) neutrinos. The inputs of a calculation are:

1) Acceleration slope of UHECR
2) Source distribution
3) Cosmological evolution of UHECR sources – 61 sources within 75 Mpc leads to source density exceeding 10^{-5} Mpc^{-3}.
4) Cosmic ray emissivity of the Universe (erg/Mpc^3/yr)

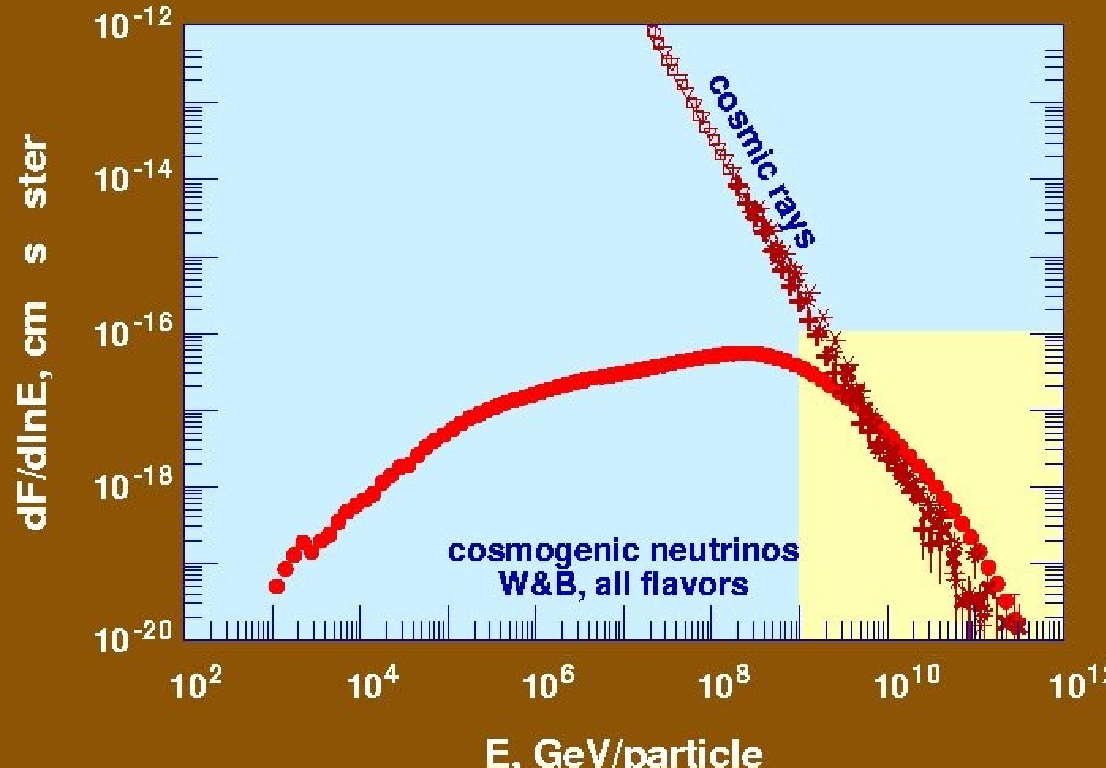




Flux of cosmogenic neutrinos created in proton interactions in MBR after integration in redshift.

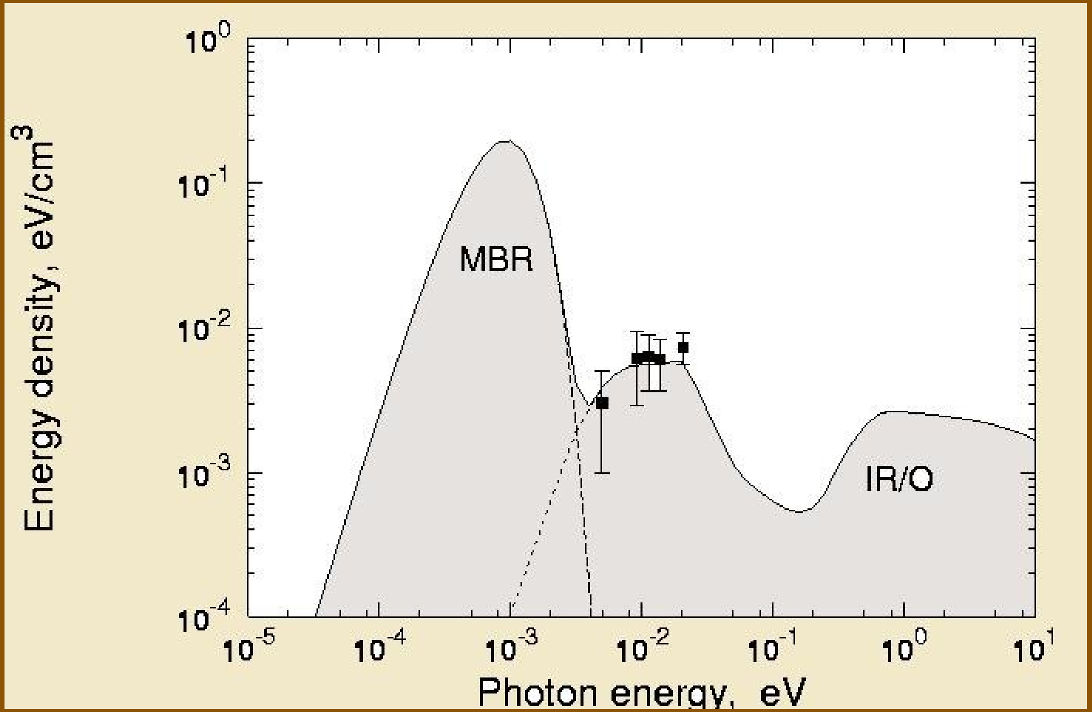


With W&B input the neutrino flux exceeds that of UHECR above 10^{18} eV.



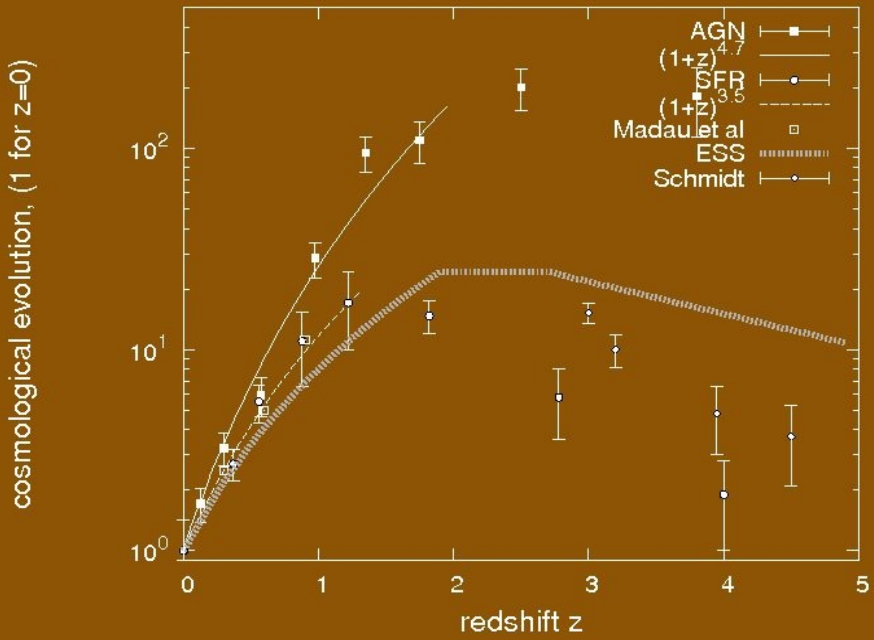
MBR is not the only universal photon field. The infrared/optical background extends over three orders of magnitude in frequency.

The number density of the IR/0 background is smaller than MBR by about 400. The photon energy is however significantly higher and lower energy protons interact in it and generate signals. The produced neutrinos are of lower energy but their flux could be significant for steeper proton spectra.

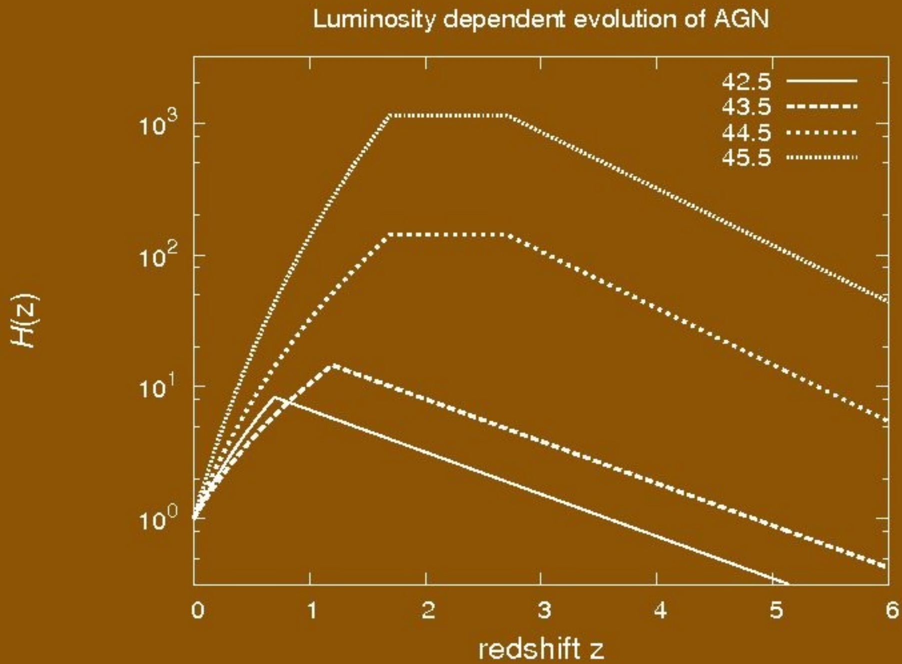


The model of Franceschini et al (2001) is compared to two sets of DIRBE data.

If the sources of UHECR are AGN the first thing we have to consider is the cosmological evolution of AGN which may be different from that of SFR.

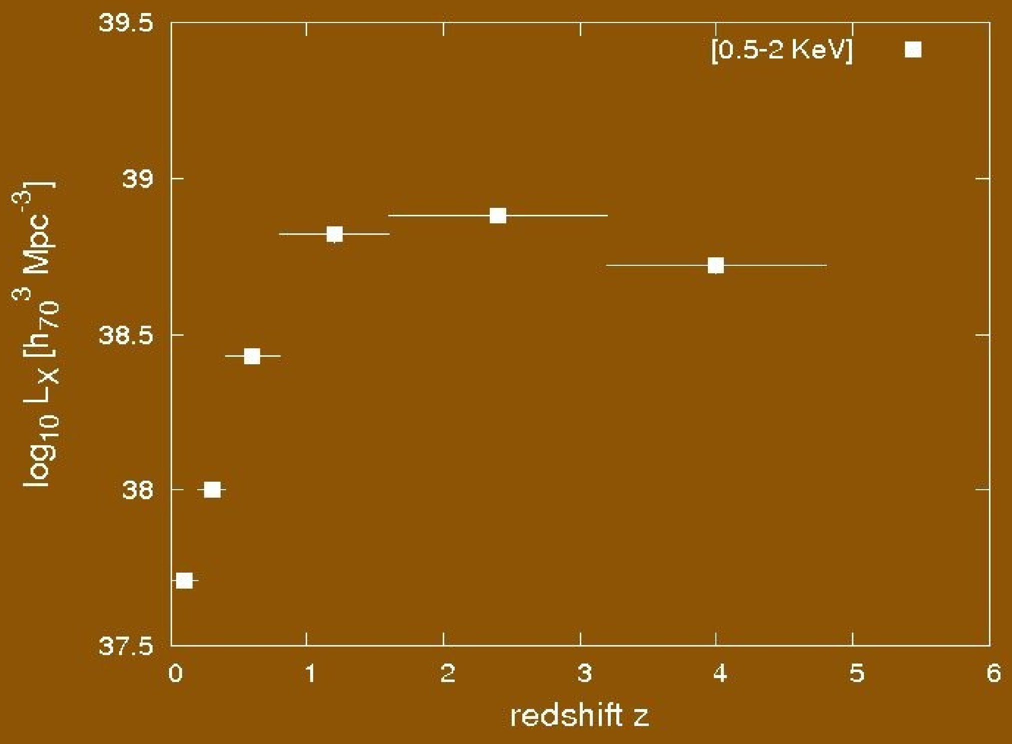


Cosmological evolution of SFR and of AGN from Rosat

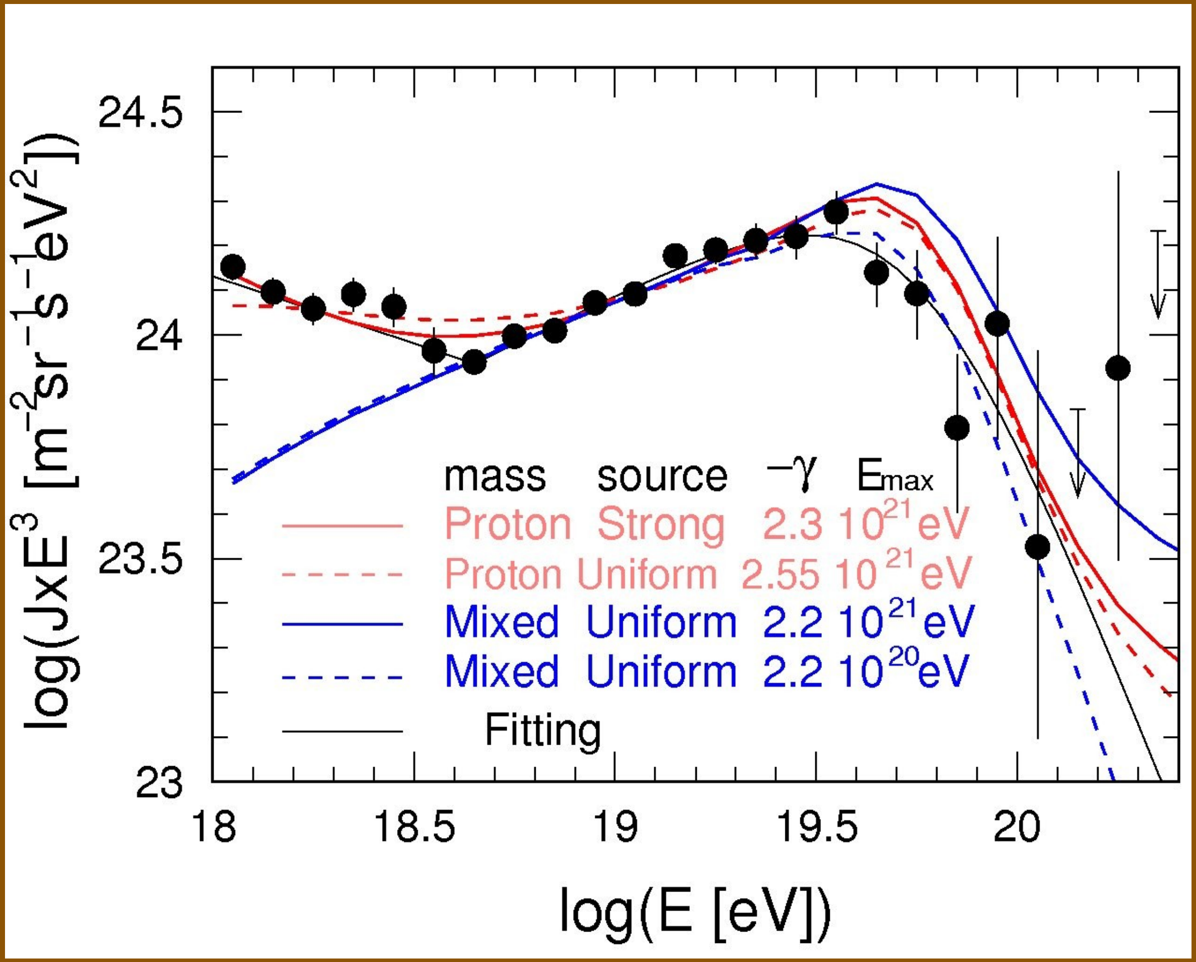


Cosmological evolution of AGN and its luminosity (X-ray, 0.5-2 KeV) dependence (Hasinger, Miyaji & Schmidt 2005)

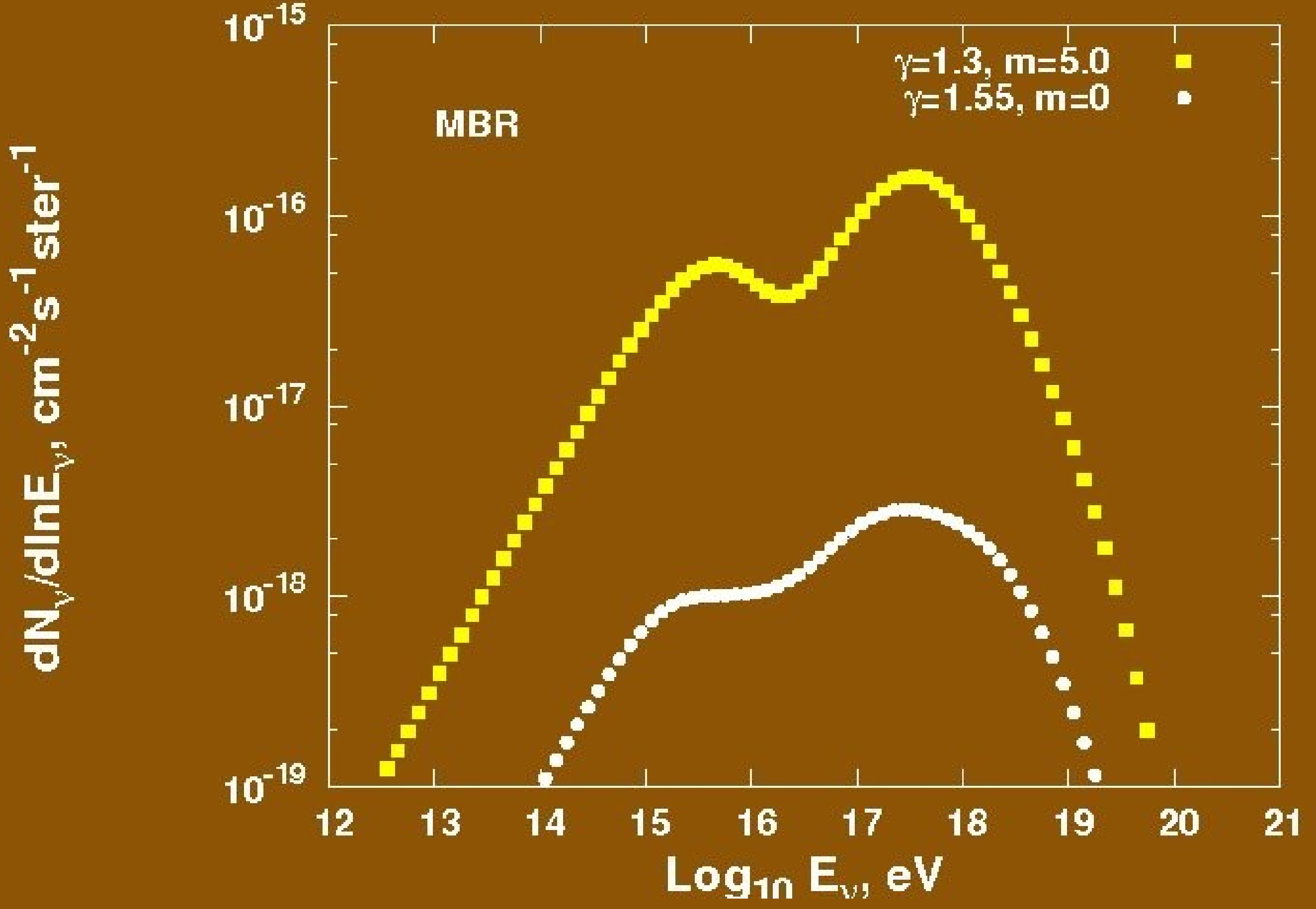
The self correlation observed by Auger requires a large number of cosmic ray sources. We can not thus assume that the most powerful AGN that are a small number are the cosmic ray sources. The average X-ray luminosity cosmological evolution is shown below it points at $(1+z)^5$ evolution. It is indeed amazing that it fits exactly one of the Auger models up to redshift exceeding 1.



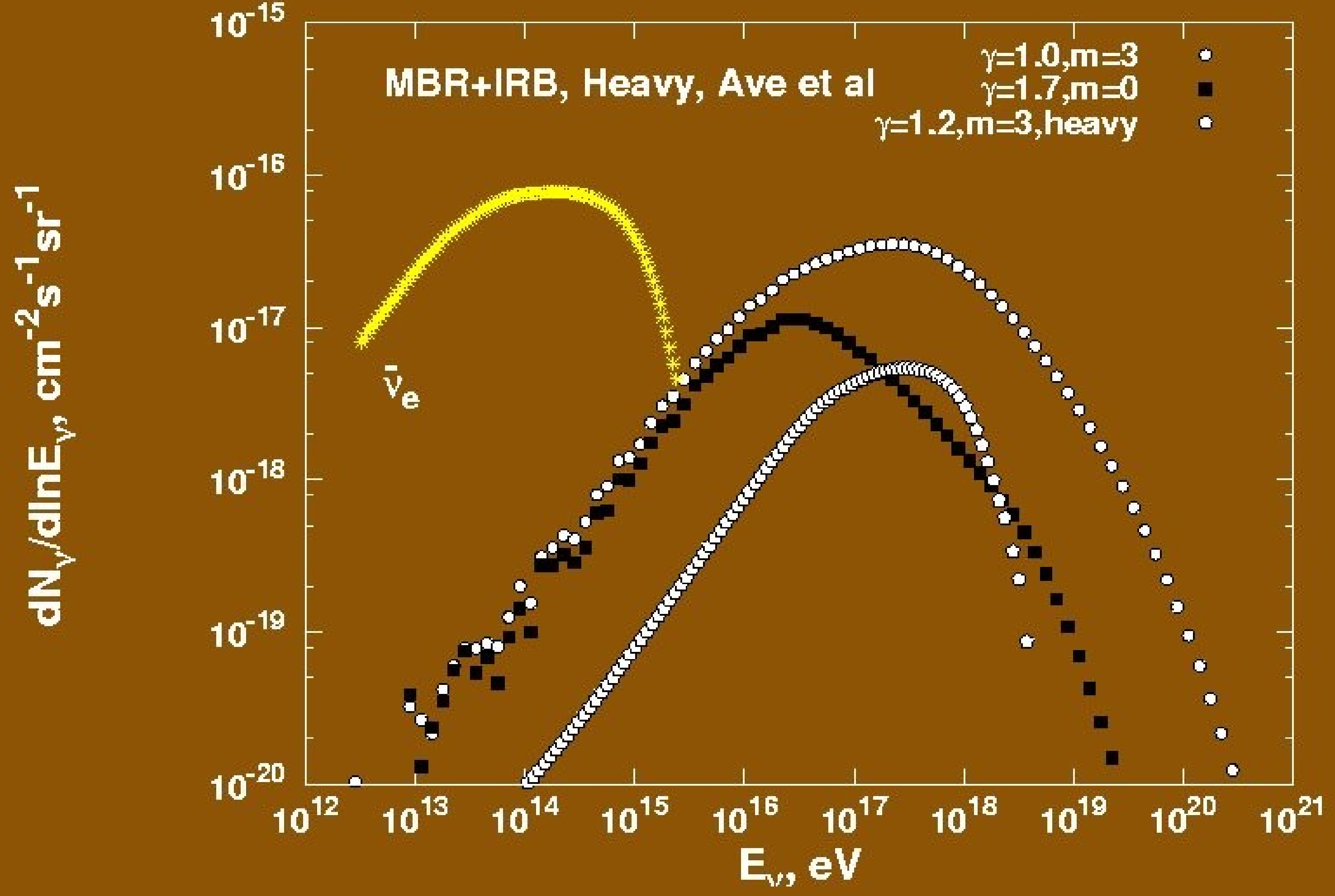
The cosmic ray spectrum measured by the Auger group can be fitted with at least threγe different models as shown below (Yamamoto for Auger): either a steep (γ=2.55) without evolution or a flatter (γ=2.3) with a strong cosmological evolution ($(1+z)^5$) if the UHECR were protons.



If they were nuclei the acceleration spectrum is still flat - γ = 2.2. We cannot distinguish between these models from the shape of the measured spectrum.



Cosmogenic neutrinos generated by the two proton models that fit well the Auger spectrum. The flux difference at 1 EeV is almost two orders of magnitude. The higher flux model is within the sensitivity of the ANITA experiment.



In the mixed composition model only the electron antineutrino flux (from neutron decay, yellow symbols) is higher than that in the proton models. The muon neutrino and antineutrino fluxes are lower.

Conclusions

Current neutrino detectors are not big enough to detect large number of cosmogenic neutrinos. (IceCube would detect O(1) neutrino per year from the higher estimated flux.) We have to rely on novel techniques that are being developed for radio detection such as ANITA.

If we detect a number of these neutrinos this will point at the cosmological evolution of the UHECR sources and may help identify the type of sources.

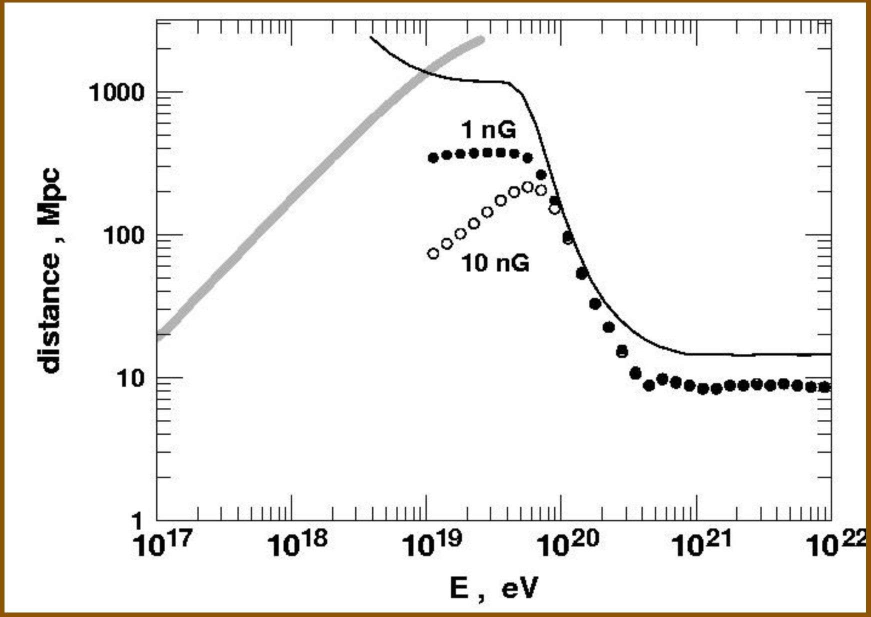
If the majority of UHECR are accelerated at nearby extragalactic systems, such as Cen A, there will practically be no neutrinos above 10^{18} to detect.

Ultrahigh energy neutrinos are deeply connected to the sources of UHE cosmic rays.

The propagation of UHECR is influenced very strongly by magnetic fields, both galactic and extragalactic.

- galactic magnetic fields deflect UHECR protons only a few degrees away from the direction of their sources. In case of heavy nuclei the deflection could be stronger, as 10^{18} V particles gyrate along the magnetic field lines.

- random extragalactic fields, if they have strengths of nG on Mpc scale, can impose a relatively small `horizon'. Protons of energy below 10^{20} eV scatter and loose energy so much that they can not reach us in Hubble time. **This may restrict the region from which this particles can reach us.**



Points are results of Monte Carlo propagation. The heavy grey line shows propagation time (analytic estimate, Achterberg) exceeding Hubble time.