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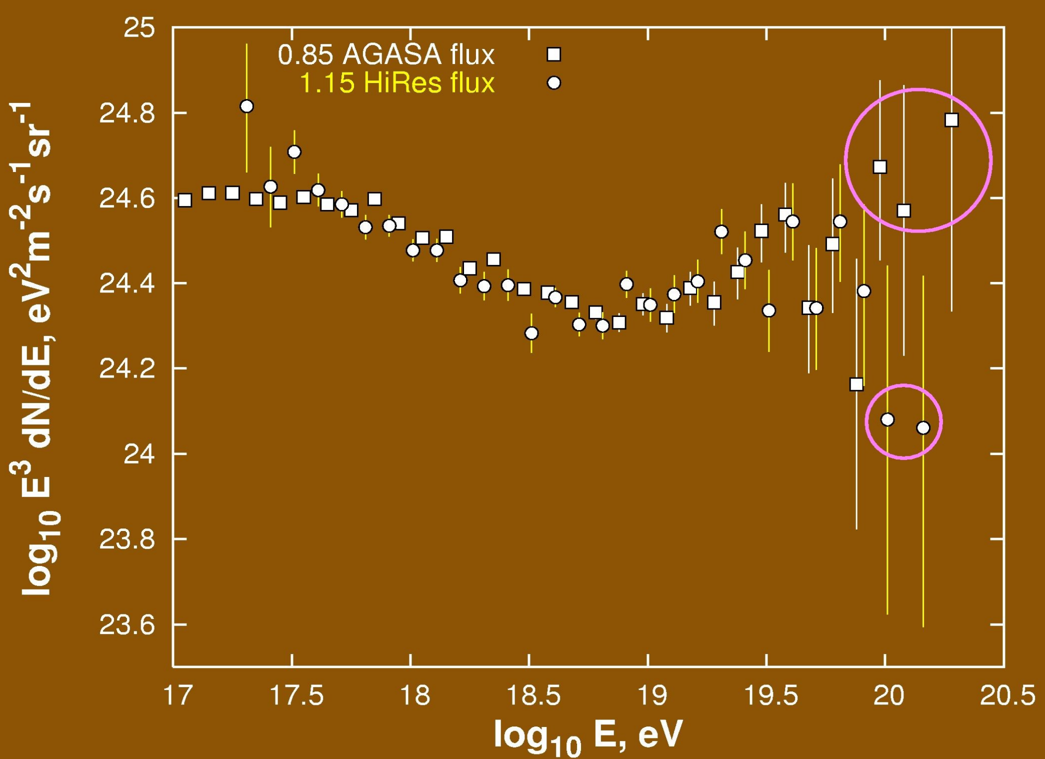
Searches for the end of the galactic cosmic ray spectrum

Todor Stanev
Bartol Research Institute
Dept of Physics and Astronomy
University of Delaware
Newark, DE19716

We discuss what other measurements and theoretical work in addition to the spectrum and composition of the cosmic rays may help to determine the end of the galactic cosmic ray spectrum. These could be the CR anisotropy that couples with the chemical composition and the detection of ultra high energy cosmogenic neutrinos.

Parts of this work are performed in collaboration with Daniel DeMarco and David Seckel..

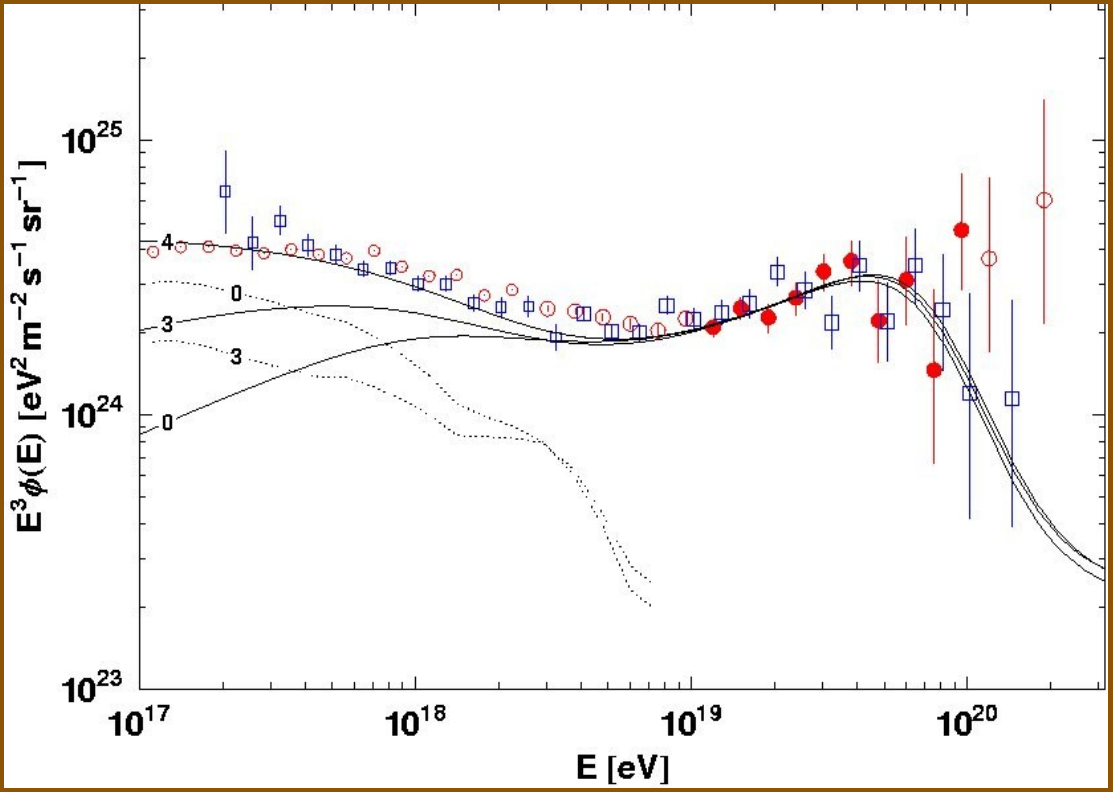
The big discussion several years ago was about the extension of the cosmic ray spectrum from the data of Agasa and HiRes. It does not excite many people now – Agasa energy estimate has come down, Auger preliminary spectrum is close to HiRes, and HiRes claims a GZK cutoff. This is not new: the UHECR spectra are not that different.



Scaled by only 15% the spectra are almost identical, except for t AGASA excess above 10^{20} eV. With the new energy assignment of Agasa the scaling factor is even smaller.

The contemporary question (at least among theorists) is different:
where is the end of the galactic cosmic ray spectrum?

We have so much freedom with the extragalactic cosmic ray spectrum that fitting the observations is easy. This is what we do:



A model spectrum is propagated in the Universe from isotropic sources to us and the result is subtracted from observations.The difference is atributed to the Galactic cosmic rays. Here is an example of such fits.

From: DeMarco and Stanev

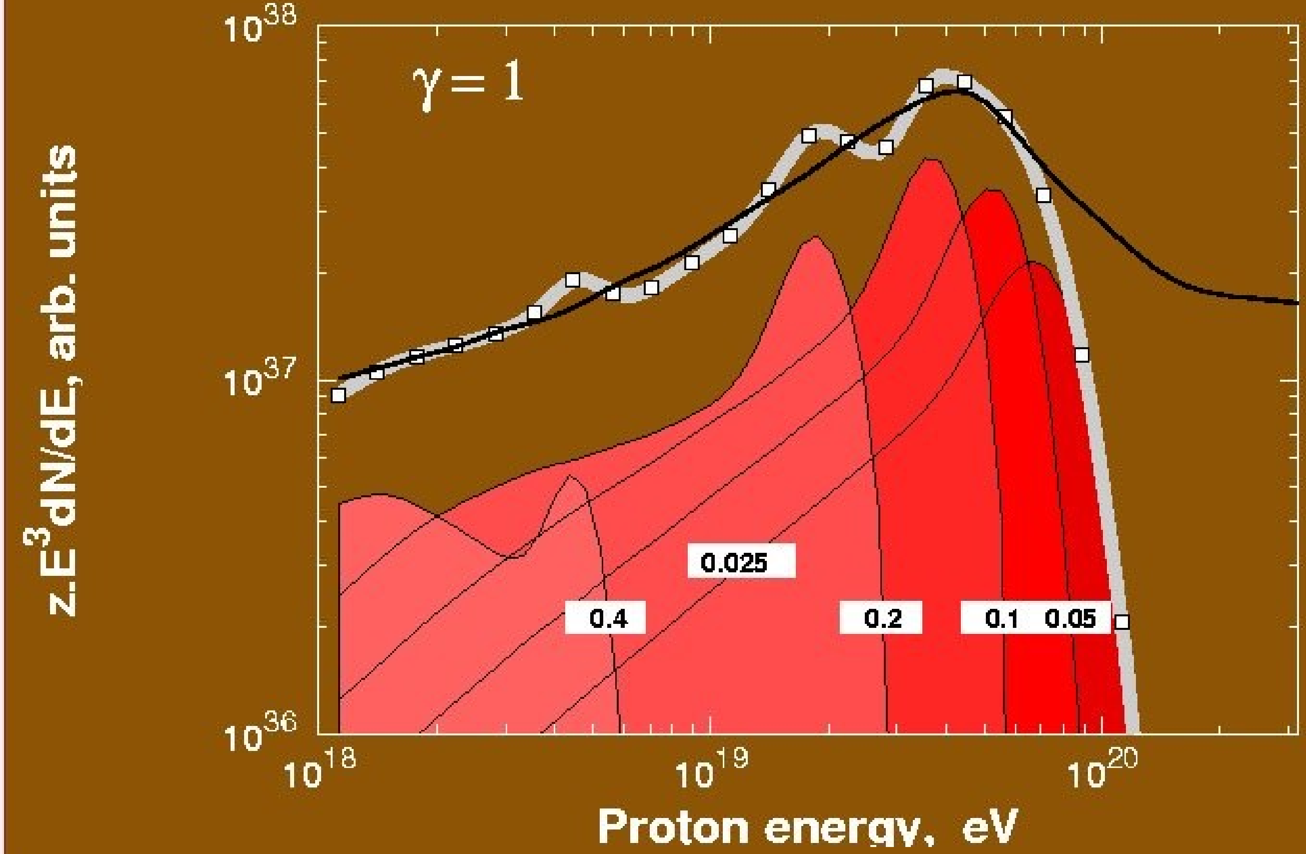
The main components of extragalactic cosmic ray spectra are:

- Acceleration spectrum

- Cosmological evolution of the cosmic ray sources, usually expressed as $(1+z)^m$, where m = 0, 3, 4

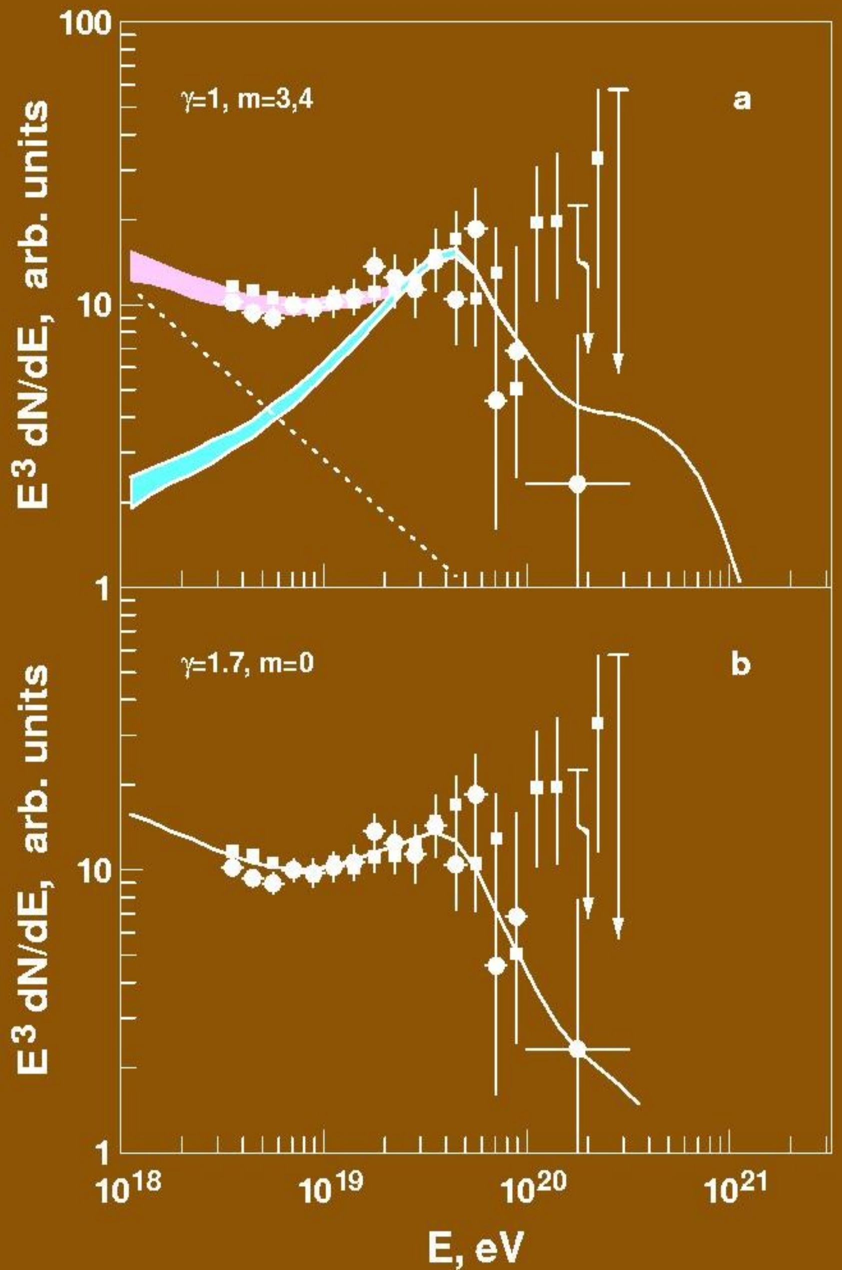
- Chemical composition of the accelerated UHECR

The change of the proton energy spectra on propagation are due to photoproduction interactions on the MBR. These are very well studied in acceleration experimens since CM energy is very low. The example below is for $m = 3$. Same spectrum is injected at different redshifts.



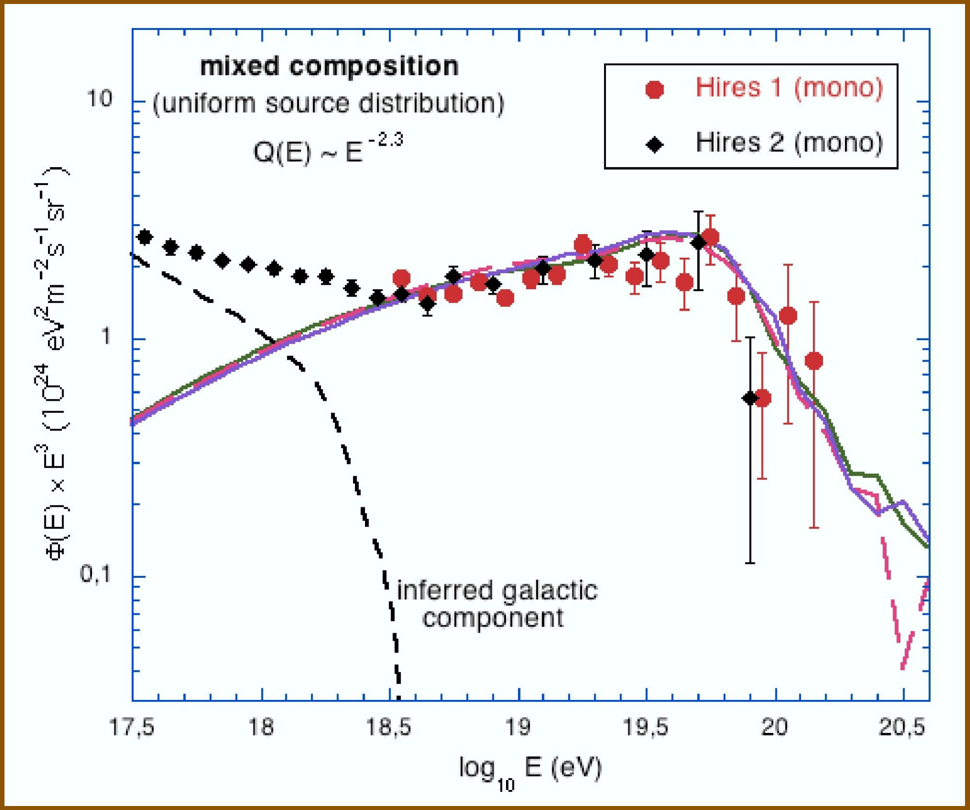
Contribution of cosmic ray sources at different redshift to the observed flux. The solid black line is the flux in case of isotropic distribution of the cosmic ray sources.

Almost everything works when only extragalactic CR are discussed:



Fit *a* is the original W&B fit using flat injection spectrum as suggested in some acceleration models. Galactic cosmic ray spectrum extends to 10 EeV

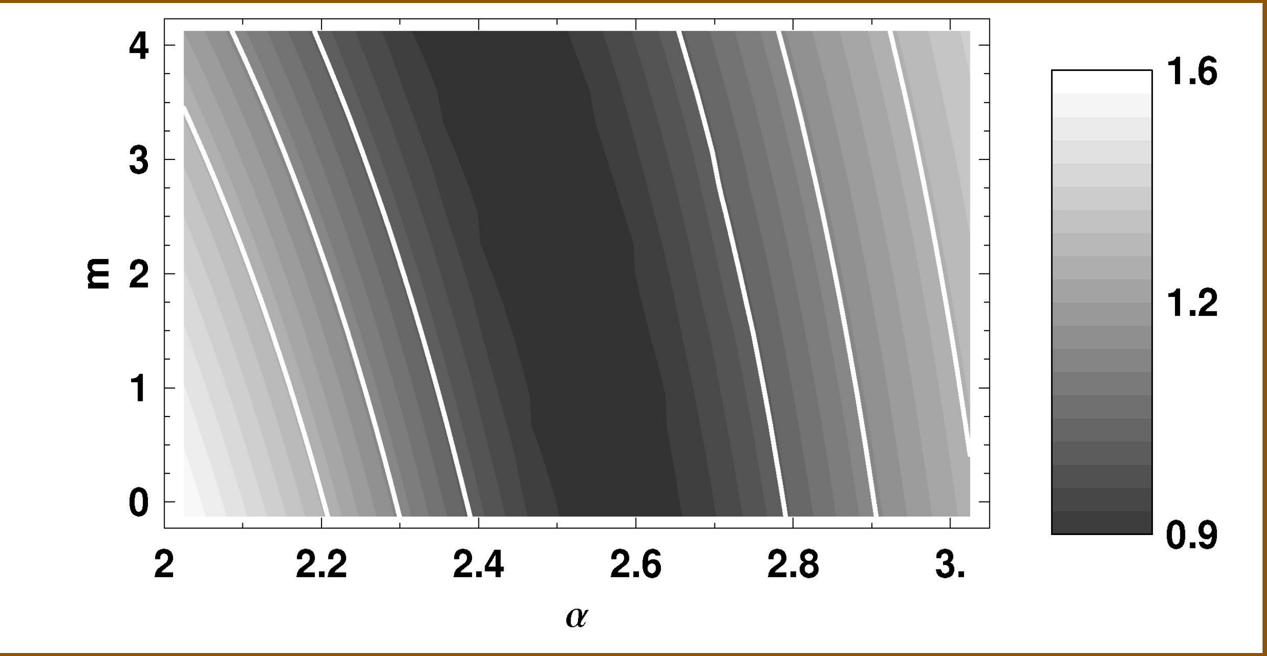
Most contemporary fits favor steeper injection spectra. Fit *b* (originally suggested by Berezinsky and co-authors) explains the obser-ved spectrum down to 1 EeV and below. The dip is caused by the pair production process. This model does not need cosmological evolu-tion of the cosmic ray sources.



From: Allard, Parizot & Olinto, 2005

Both previous fits are for proton primaries.

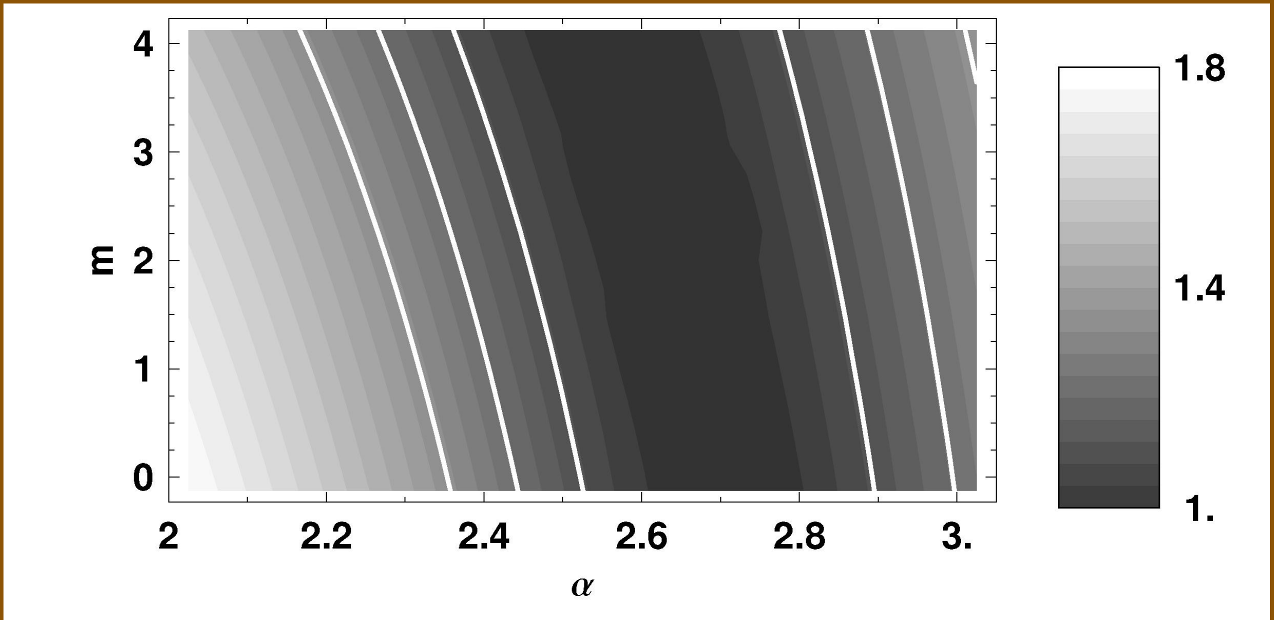
Another possibility is that extra-galactic cosmic rays have mixed composition and lose energy on propagation mostly on spallation in photon fields. This changes the story quite a bit: the dip at 10^{19} eV becomes shallower being filled with spallation nucleons. The injection spectrum for no cosmological evolution becomes flatter.



AGASA

The darker the area is the better the fit. White lines indicate 1σ errors.

Fits of the spectra above 10^{19} eV only



HiRes

Spectral fits are not exact

From: DeMarco & Stanev

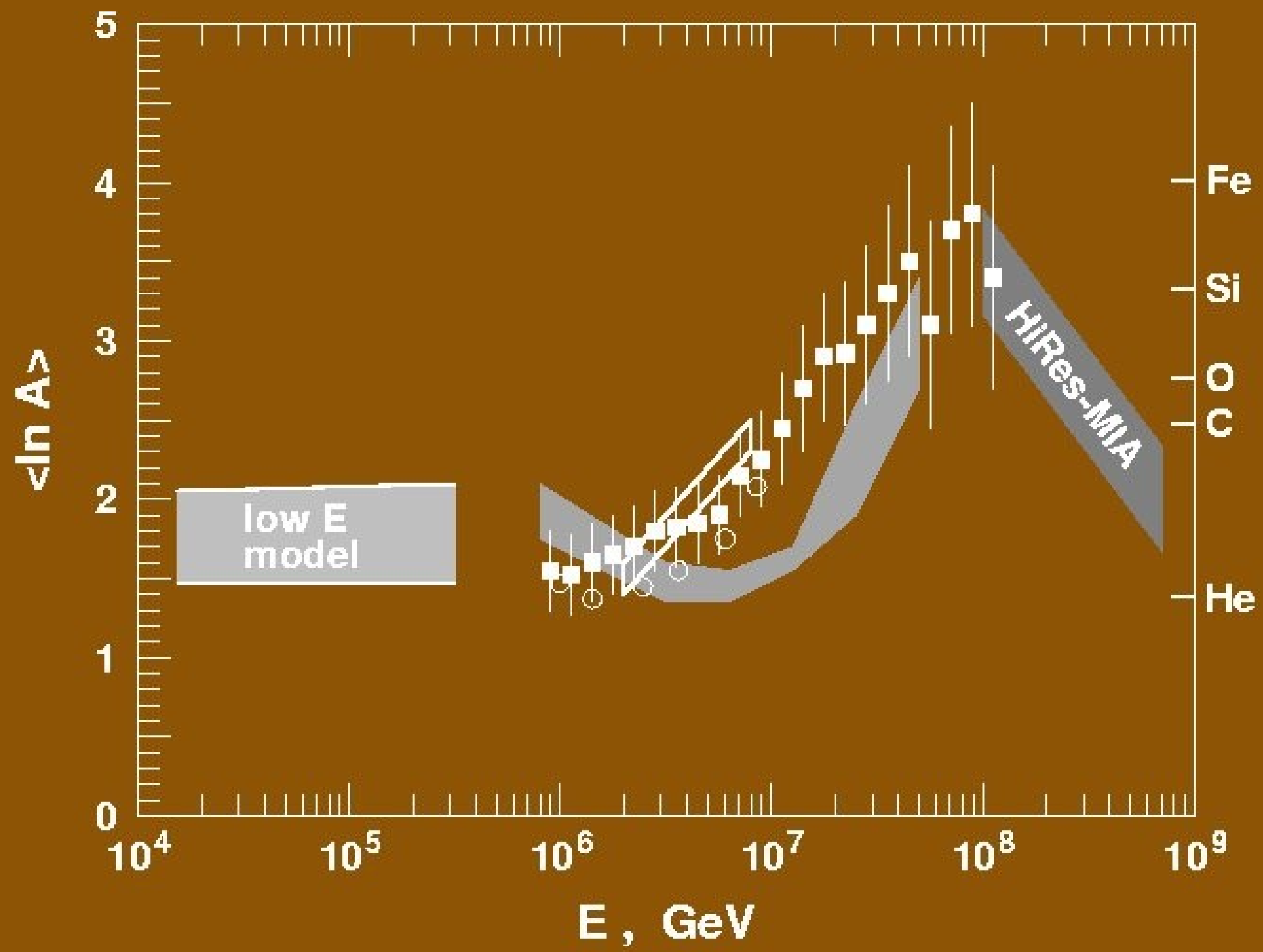
We need to use all possible inputs to solve the problems. I can think of the following related issues:

- Chemical composition – a classical approach, although if the Extragallactic CR are heavy nuclei the results are not obvious – they depend on the primary composition of extragalactic cosmic rays.

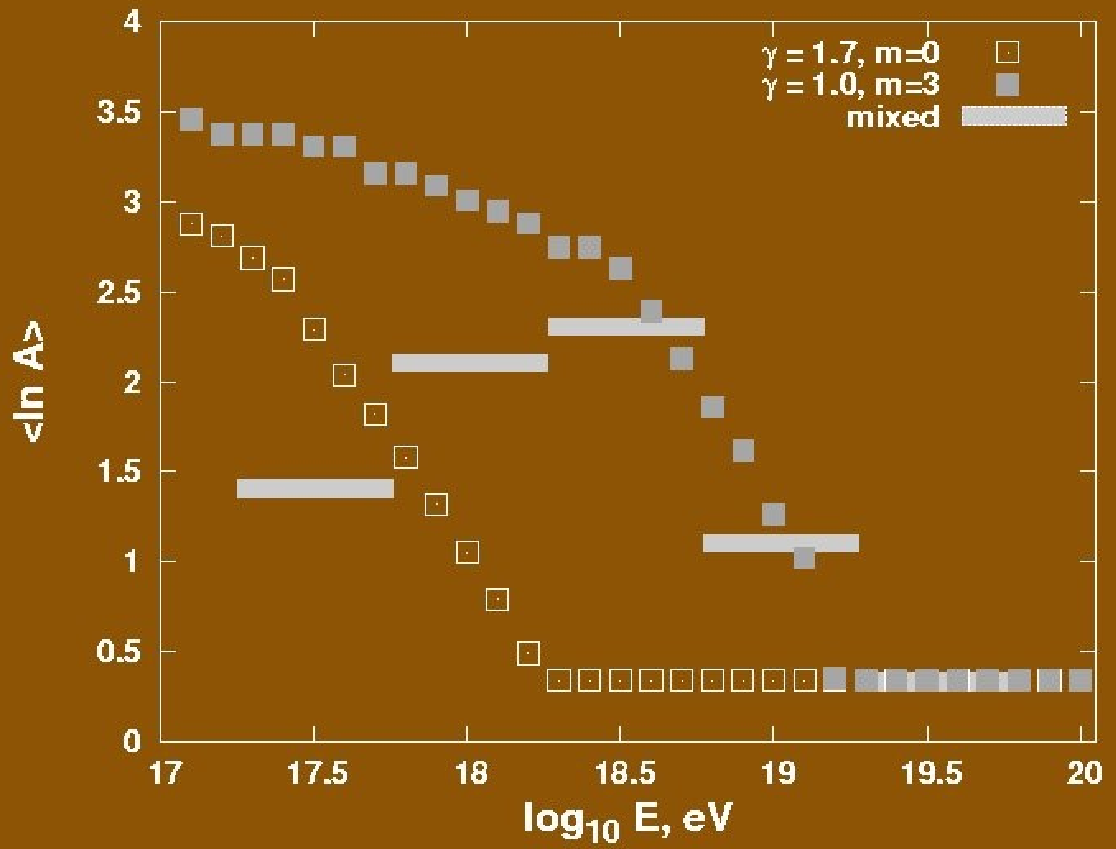
- Studies of the propagation of CR in the Galaxy:
    - containment time in the Galaxy
    - anisotropy in this energy range

- Cosmogenic neutrinos, related to the propagation of UHECR in the Universe and the cosmological evolution of their sources

What do we know about the chemical composition of the high energy cosmic rays? Here is a rough picture mostly from the data of the Kascade experiment. At higher energy we only have X_{max} data of Fly's Eye and HiRes + some Agasa analyses.

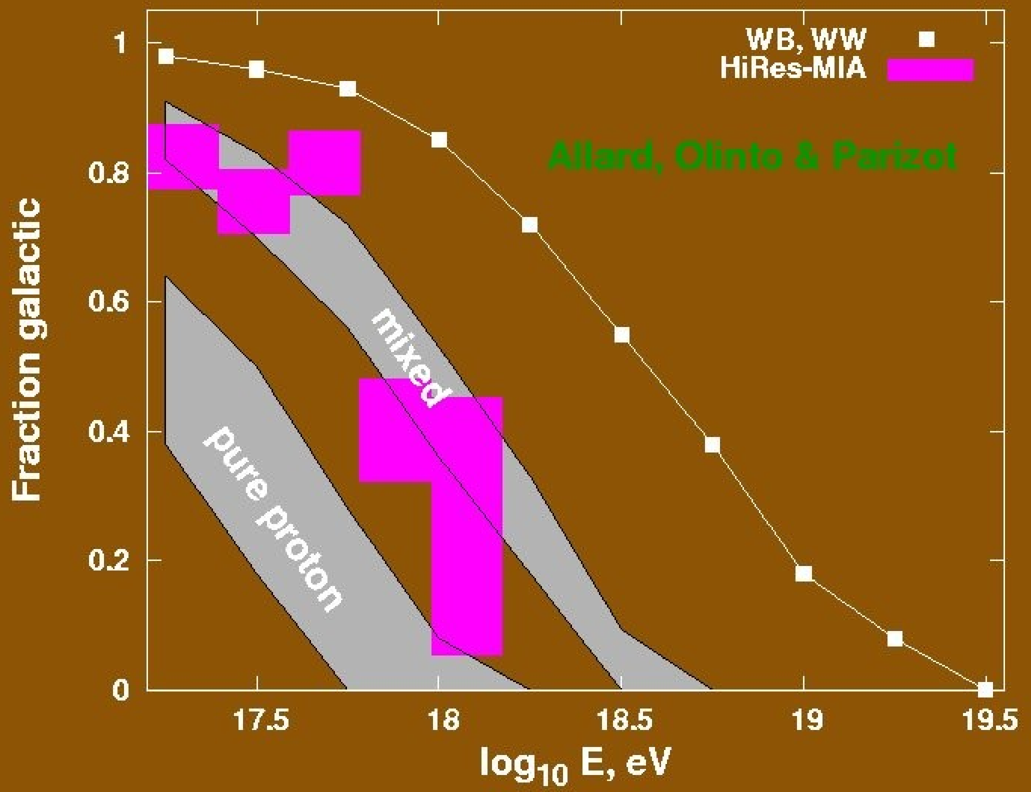


More information in the talk of Tom Gaisser.



Mixed composition <lnA> from the X_{max} graphs in the latest paper of Allard *et al* (2007) using Sibyll 2.1.

Approximate calculation of the average lnA for the two extragalactic proton models (assuming very heavy composition at 10^{17} eV) and of the mixed compositiom model of Allard et al.



These are the `error' areas from Allard *et al* for the pure proton models of WB(WW) and Berezinsky *et al* and of the mixed composition model. HiRes-MIA points are converted to mass by me using Sibyll 2.1. In this graph they seem to support the mixed composition model, but this is a matter of interpretation. They are equally compatible with the Berezinsky *et al* model.

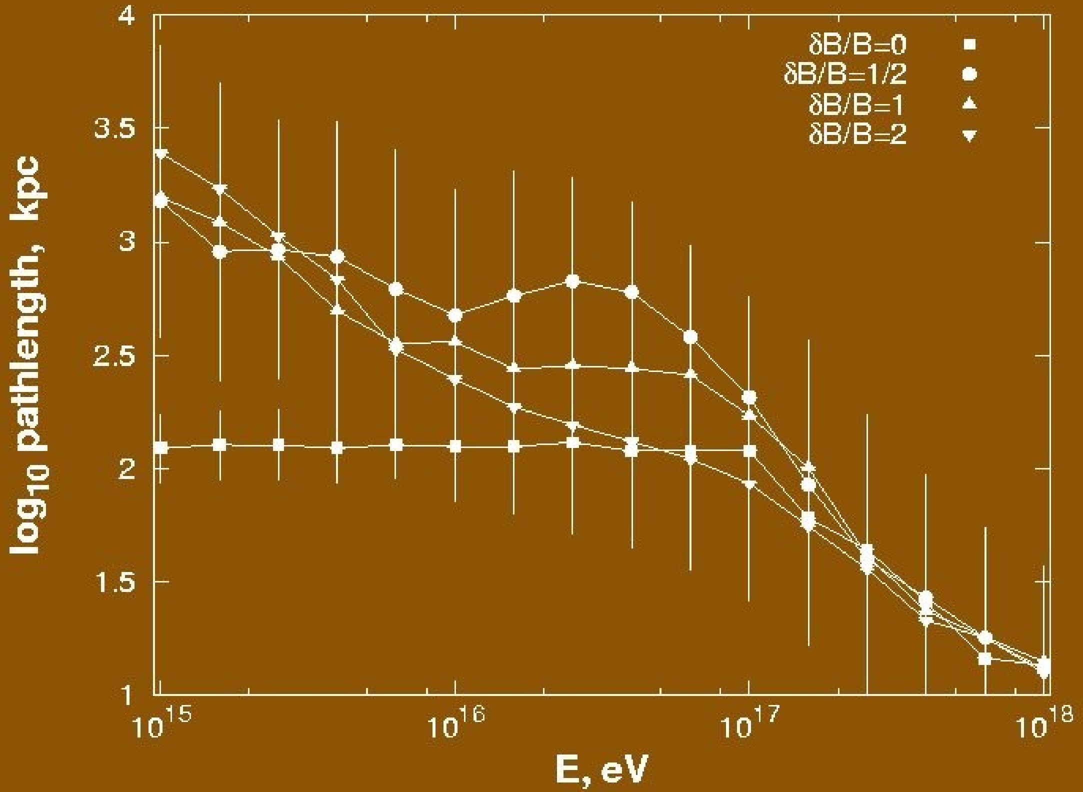
High energy cosmic rays propagation in the Galaxy.
Two numerical approaches in addition to analytical diffusion work:

- backtracking of negatively charged nucleons from the Solar system (see the talk of DeMarco on Wednesday).

- forward propagation from the sources to the Solar system or to the edge of the Galaxy. This requires knowledge of the CR source distribution.

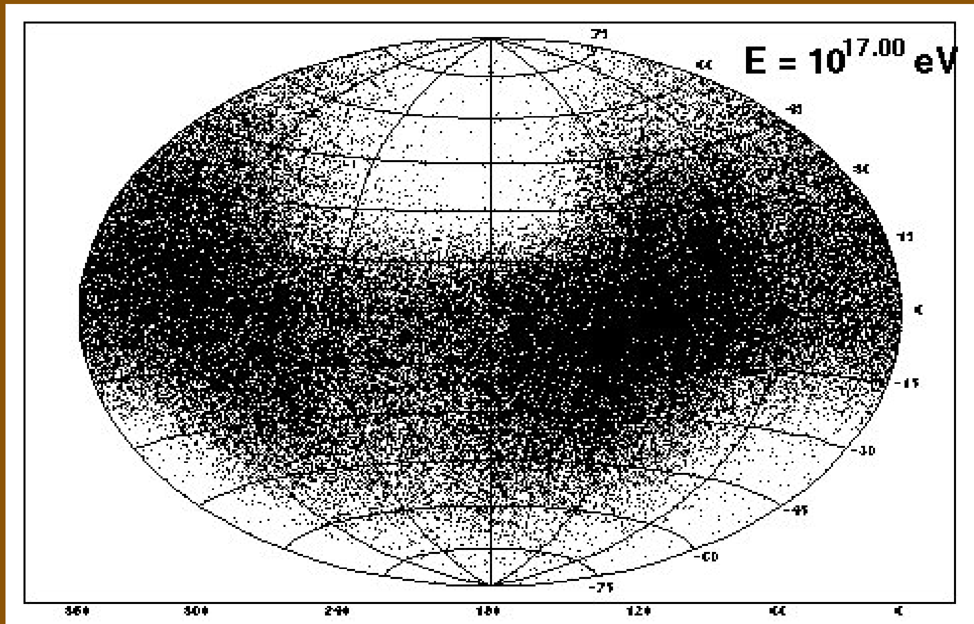
Numerical propagation work is important because of the complexity of the galactic magnetic field models.

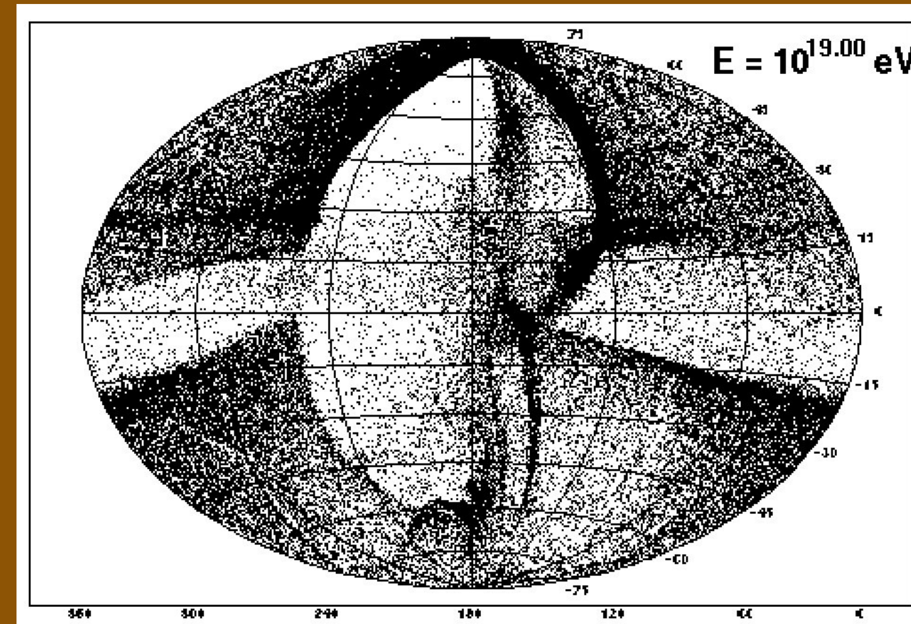
Note that there are many (not always consistent) and very complicated models of the Galactic magnetic field. We have two of the best experts at this meeting.

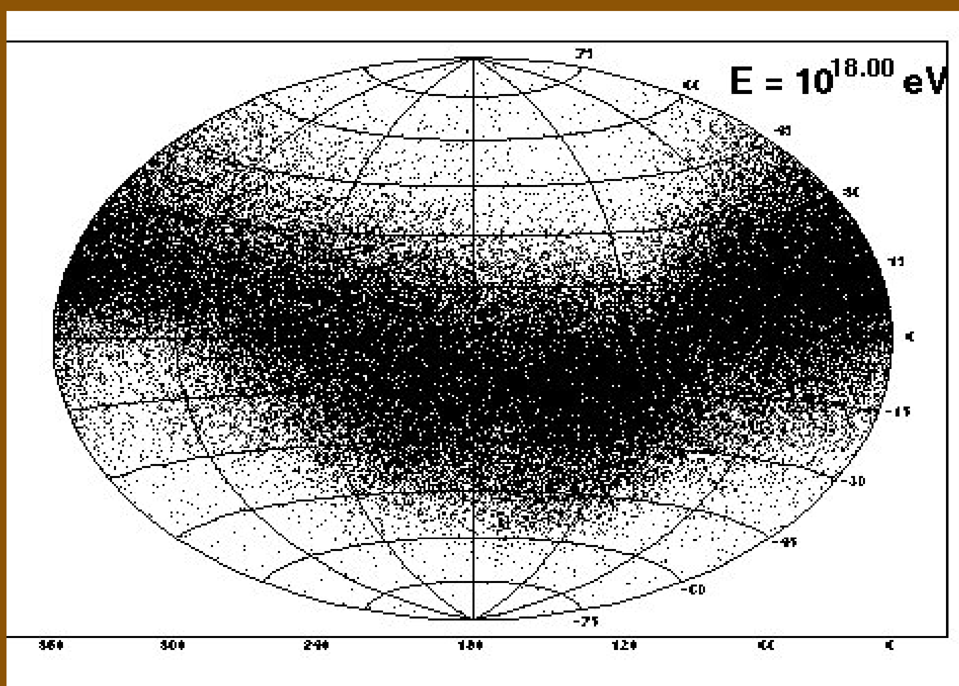


Containment time (distance) in a disk with radius 15 kpc and half height of 4 kpc for protons injected at Earth. Calculation with different values of δB/B. When the truth is established we can combine such calculations with the composition measurements and determine the acceleration spectrum of the Galactic cosmic rays.

It is not a priori obvious that results for different levels of turbulence are not compatible. The errors are not statistical – the pathlength distributions are very wide.







Exit points from the Galaxy of protons injected isotropically at the Solar system. There is no guarantee that the same fields will generate observable anisot-ropy. More data are still very important and could be useful.

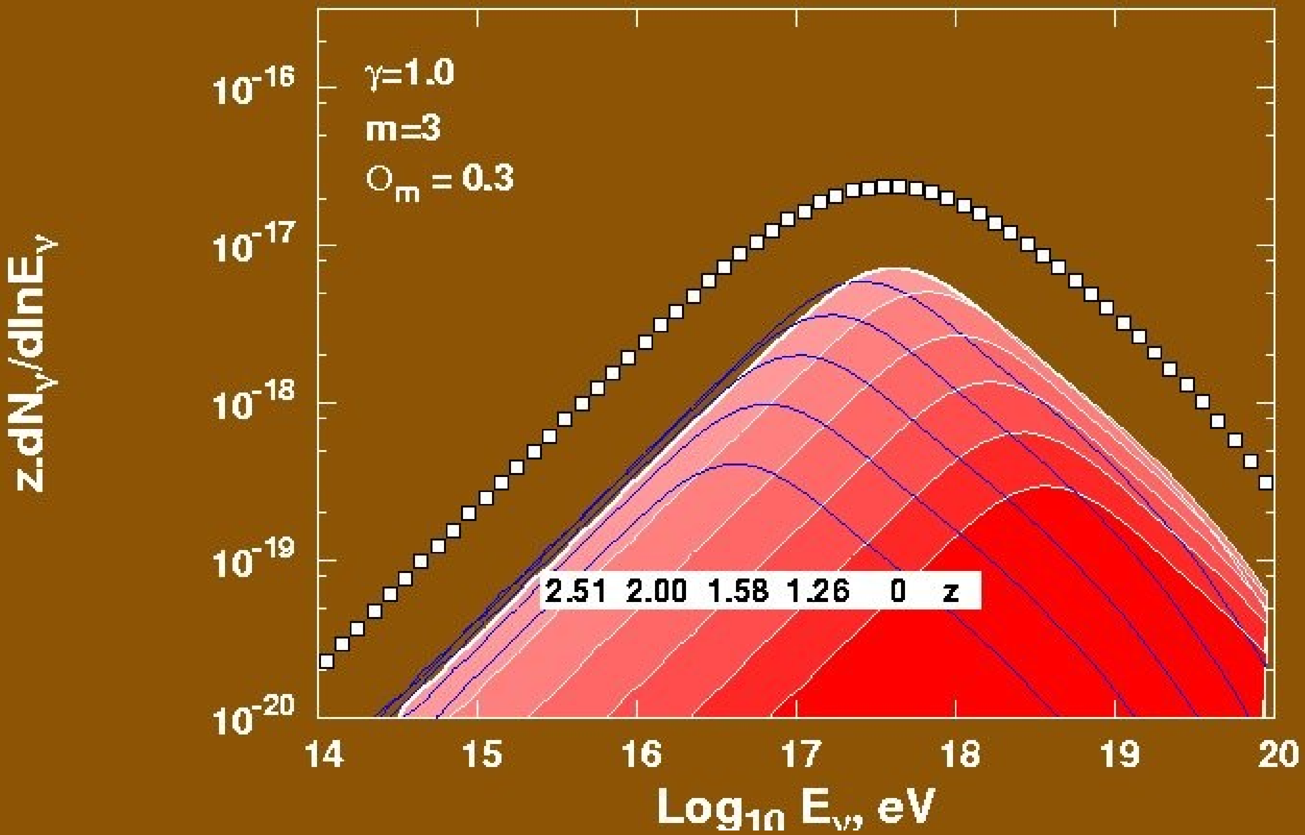
Cosmogentic neutrinos are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation 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:

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

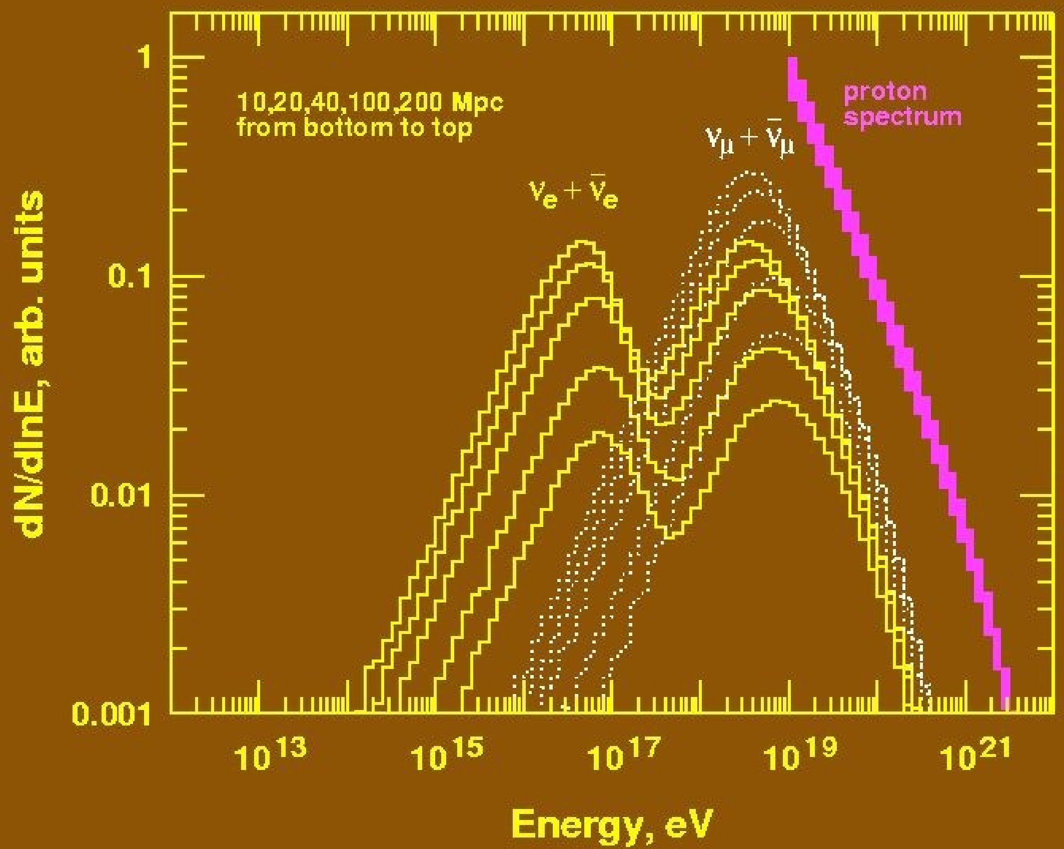
Actually the proton photoproduction threshold in the MBR is about 4.10^{19} eV. There is also production in the isotropic infrared/optical background.

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



Cosmogenic neutrinos are very sensitive to the cosmological evolution of the cosmic ray sources because of the lack of energy loss. This could be useful for establishing model for the extra-galactic cosmic rays.

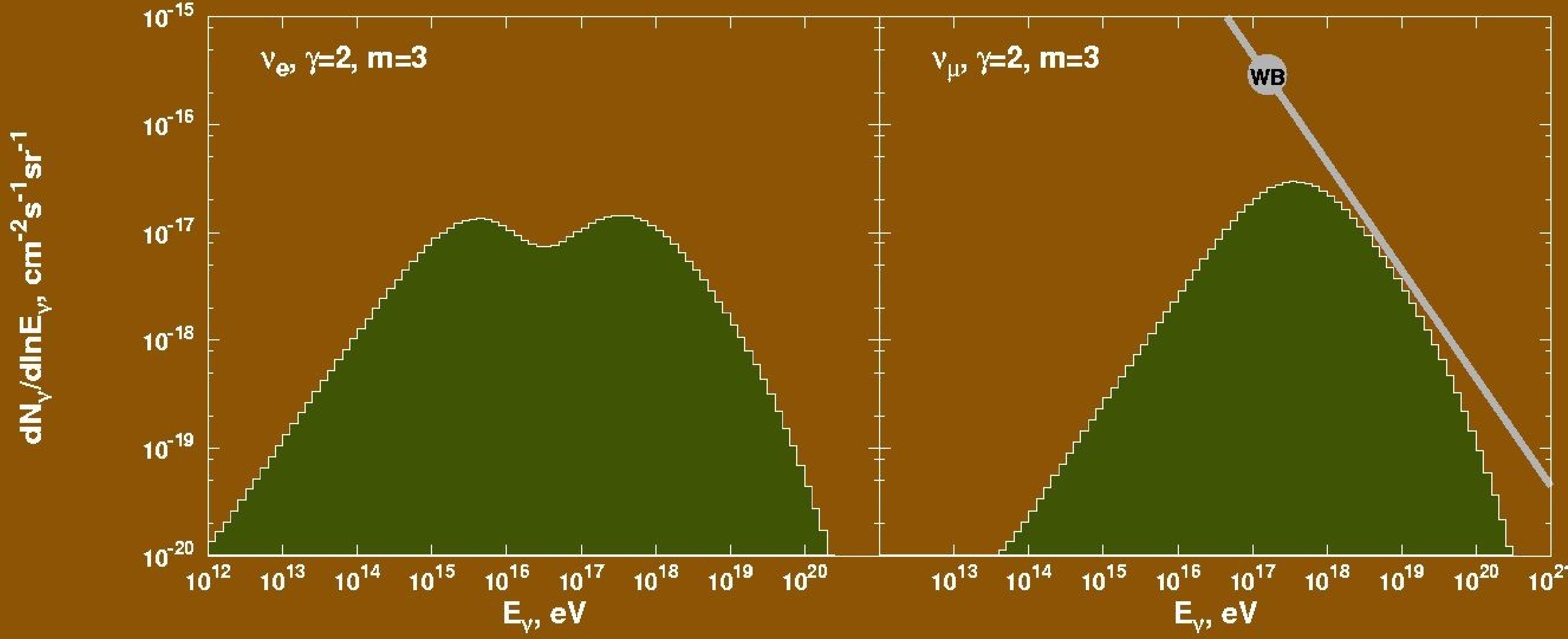
Note the logarithmic scale in redshift. Cosmological parameters are as in the cosmic ray example. The contribution increases until the source luminosity is significant (*z = 2.7 in the W&B model).* At higher redshift the production is still high because of the $(1+z)^3$ increase of the MBR density and the lower energy threshold for photoproduction.



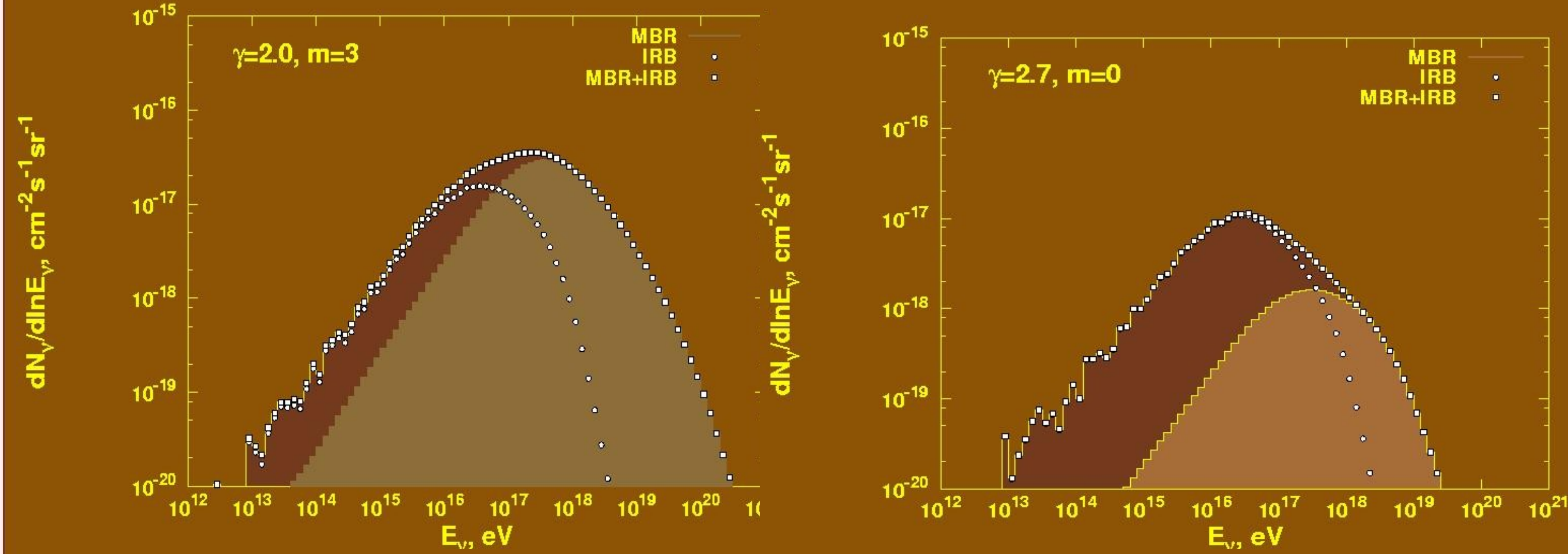
The figure shows the fluxes of electron neutrinos and antineutrinos generated by proton propagation on (bottom to top) 10, 20, 50, 100 & 200 Mpc in MBR. The top of the blue band shows the proton injection spectrum
(E^{-2} in this example).

From: Engel, Seckel & Stanev, 2001

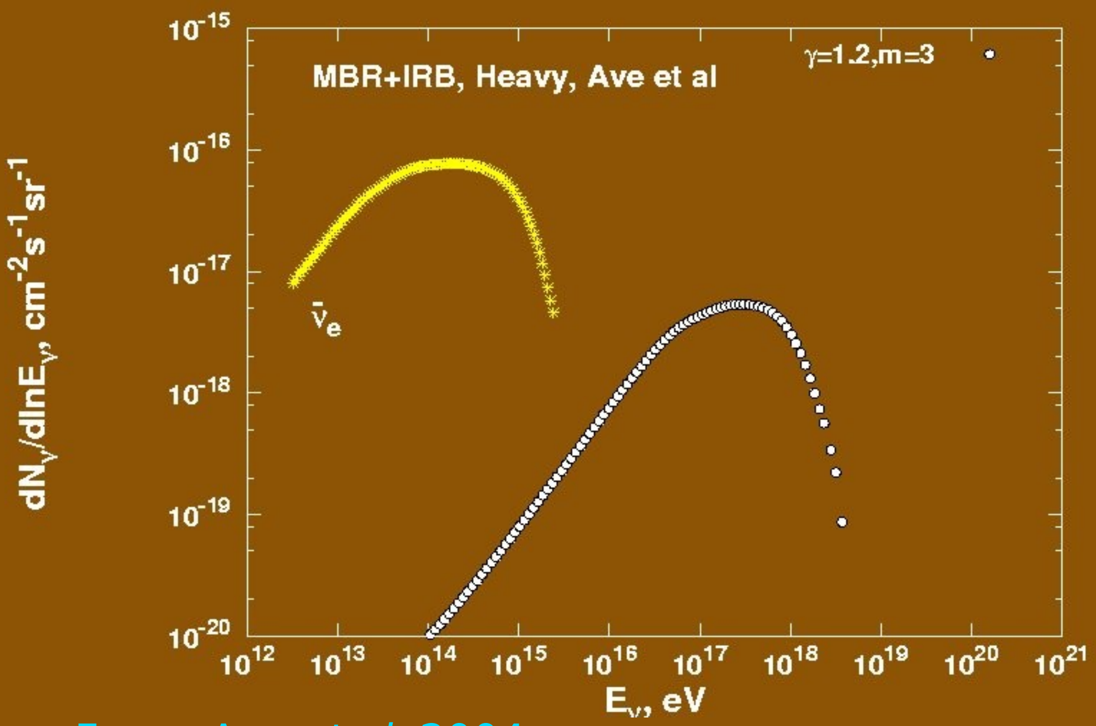
Muon neutrinos and antineutrinos are generated with a spectrum similar to the one of electron neutrinos at twice that rate. As far as neutrinos are concerned the cascade development is full after propagation on 200 Mpc. Even the highest energy protons have lost enough energy to be below threshold. We shall use these results to integrate in redshift, assuming that cosmic ray sources are homogeneously and isotropically distributed in the Universe to obtain the total flux.



Cosmogenic neutrino fluxes from proton interactions in the MBR calculated with the input that W&B used to limit the neutrino emission of optically thin cosmic ray sources. The limit is shown with the shaded *band for $(1 + z)^3$* evolution of the cosmic ray sources in $O_M = 0.3$ cosmology. Muon neutrinos are close to the limit for energies between 1 and 10 EeV, as the parent nucleons interact until they lose energy and fall below the interaction threshold which is redshift dependent.



The cosmogenic neutrino spectra generated by the two extreme models of the injection spectra of UHECR protons in case of isotropic homogeneous distribution of the cosmic ray sources. The big difference in case of `MBR only' interactions is due to the flat injection spectrum and the cosmological evolution of the sources. The interaction rate is dominated by IRB generated neutrinos in the case of steep injection spectrum. MBR neutrinos dominate the high energy end, especially in the flat injection spectrum case.



From: Ave *et al*, 2004

The muon neutrino and antineutrino flux is harder than the γ=2.7 model. The maximum flux is lower. Electron antineutrino spectrum peaks below the Glashow resonance energy.

It was shown by Hooper *et al* and Ave *et al* that heavy nuclei also generate cosmogenic neutrinos, although mostly through neutron decay. Neutrons are released in the nuclear fragmentation in interactions on universal photon fields. Photoproduction neutrinos require injection spectra that reach energies above 10^{21} eV per nucleus, so that individual nucleons of energy E/A exceed the photoproduction threshold.

Conclusions

Even with the forthcoming much more exact measurements of the UHE cosmic ray spectrum it will be difficult to distinguish Galactic from Extragalactic cosmic rays.

We better be prepared to use all of the available information.

Composition measurements are extremely important and they may be coupled with anisotropy data. Such a combination can help identify the spectral characteristics of Galactic CR and even show significant changes in the transition region.

Possible detection of cosmogenic neutrinos will limit the phase space for extragalactic CR models and thus help in solving the problem of galactic CR. Future detectors may be able to measure the energy spectrum of csmogenic neutrinos that will give more information.