Cosmogenic Neutrinos

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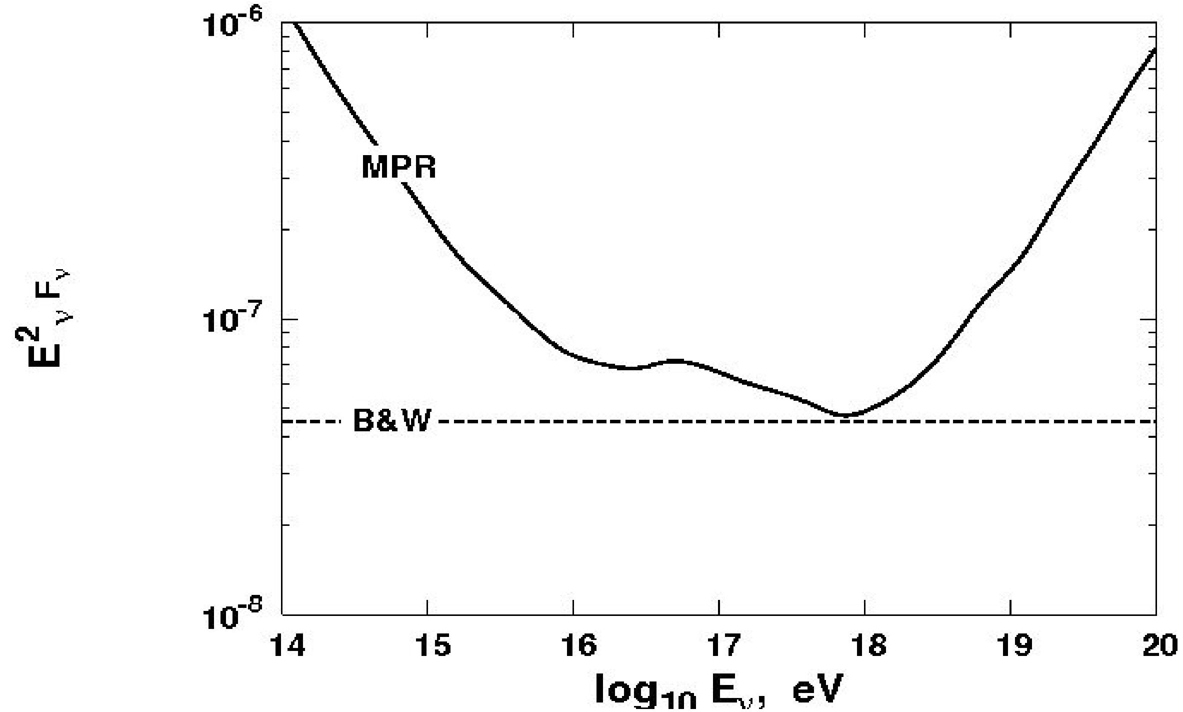
The detection of *cosmogenic neutrinos* or other types of astrophysical neutrinos will indicate the beginning of experimental neutrino astronomy. It will, however strongly affect the study of the high energy cosmic rays. Detection of high energy astrophysical neutrinos will identify the sources of high energy cosmic rays and the interpretation of the spectrum and composition of the ultrahigh energy cosmic rays. Currently the two active detectors, the Auger Observatory in Argentina and the Telescope Array in Utah, USA, do not agree in their analysis of the chemical composition, which is essential for the prediction of expected astrophysical neutrino fluxes.

Neutrino telescopes workshop, Venezia, March 2013

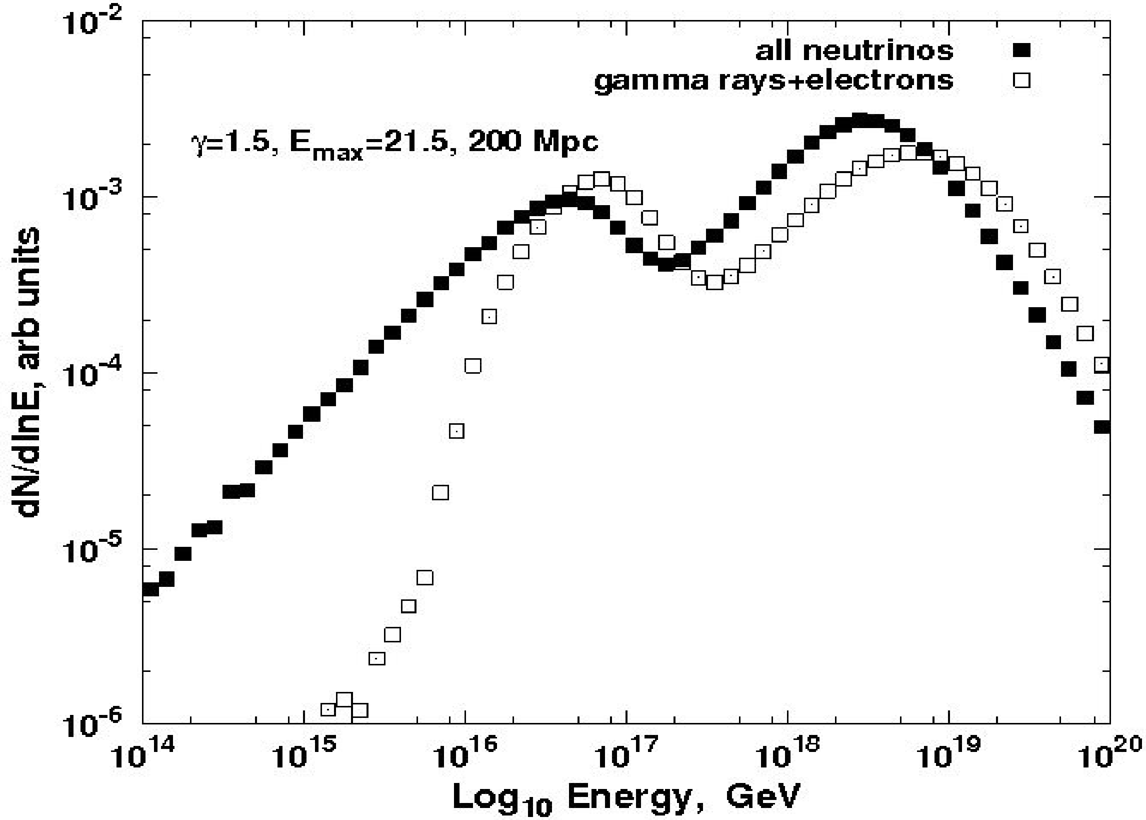


Very high energy neutrinos have always been predicted to come from the sources of UHE cosmic rays, as first stated by Waxman and Bahcall more than 10 years ago. The W&B Limit was challenged but nobody doubts the relation between cosmic ray sources and astrophysical neutrinos. We show the upper limits of W&B and of Manheim, Protheroe & Rachen. These are neutrinos generated in the the UHECR sources.

Cosmogentic neutrinos are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed in 1969 by Berezinsky&Zatsepin and in 1973 independently by Stecker.
Often called GZK neutrinos these should be called BZS neutrinos.
In 1983 Hill & Schramm did a calculation and used the non-detection by Fly's Eye of neutrino induced air showers to set limits on the cosmological evolution of the CR 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:

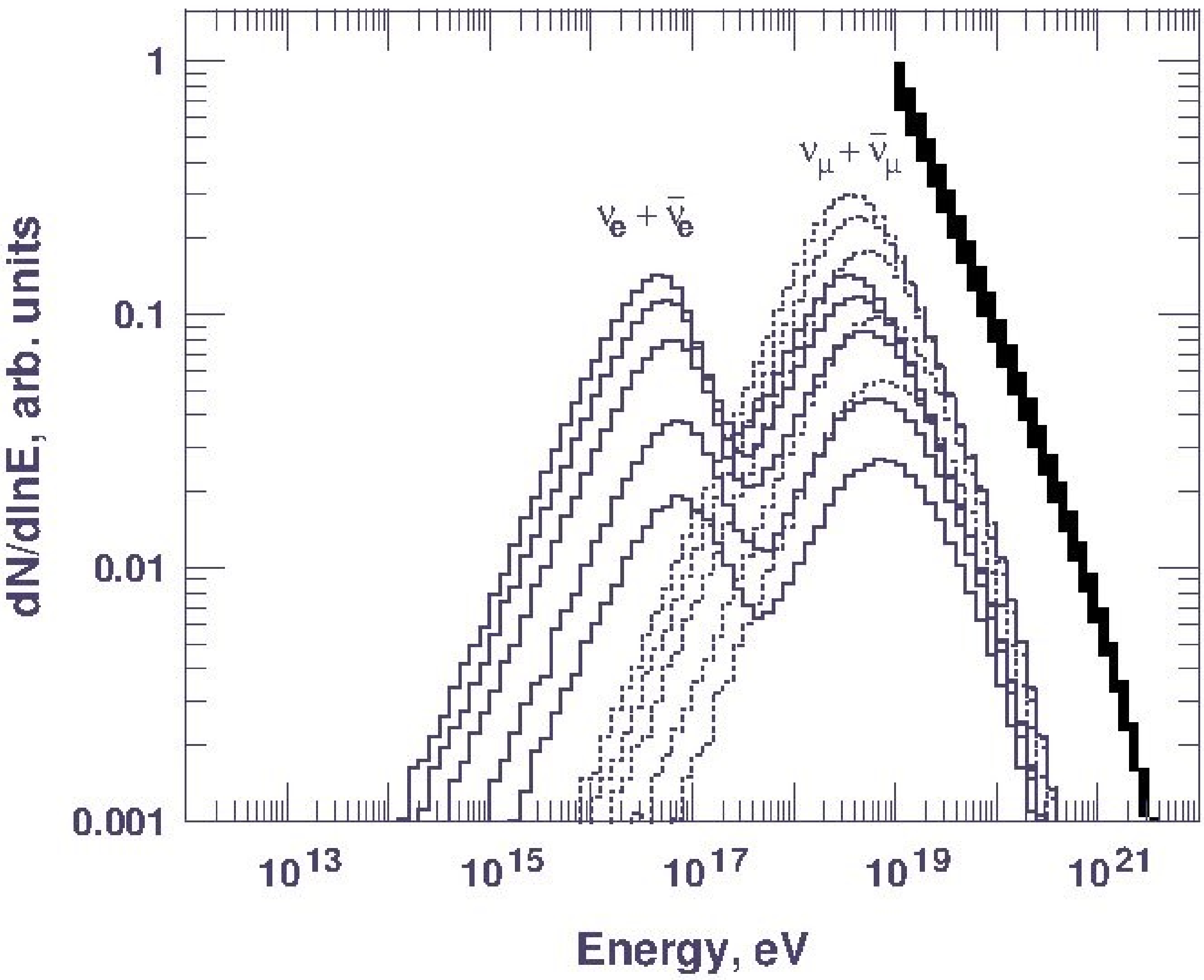
$$E_p^{min} \simeq \frac{m_\Delta^2 - m_p^2}{2(1 - cos\theta)\varepsilon} \simeq \frac{5 \times 10^{20}}{(1 - cos\theta)} \text{ eV}$$

Actually the proton phortoproduction theshold in the CMB is about 3.10^{19} eV. There is also production in the isotropic infrared/optical background.



When nucleons interact In photon fields they produce mesons that decay to gamma rays and neutrinos. There are thus *cosmogenic neutrinos* and *cosmogenic gamma rays*.

Cosmogenic gamma rays have higher energy at production: one neutral pion decays in two gamma rays while a charged pion decays into three neutrinos + e. For the same reason the neutrino flux is higher. It is difficult, though, to use the γ-ray background to limit the neutrino flux because of the extragalactic magnetic fields, although the Fermi satellite results have been used for that purpose.



Production of neutrinos in proton propagation on distances from 10 Mpc to 200 Mpc. Note the increase of the electron neutrino production. Dashed lines indicate muon neutrinos and anti-neutrinos.

The peak at 10^{18} eV corresponds to neutrinos from meson decay. Its exact position depends on the cosmic ray energy spectrum and the maximum acceleration energy. The lower energy peak is of electron anti-neutrinos from neutron decay.

The important astrophysical parameters for the shape and magnitude of the cosmogenic neutrino fluxes are:

Emissivity of UHECR sources

Maximum acceleration energy

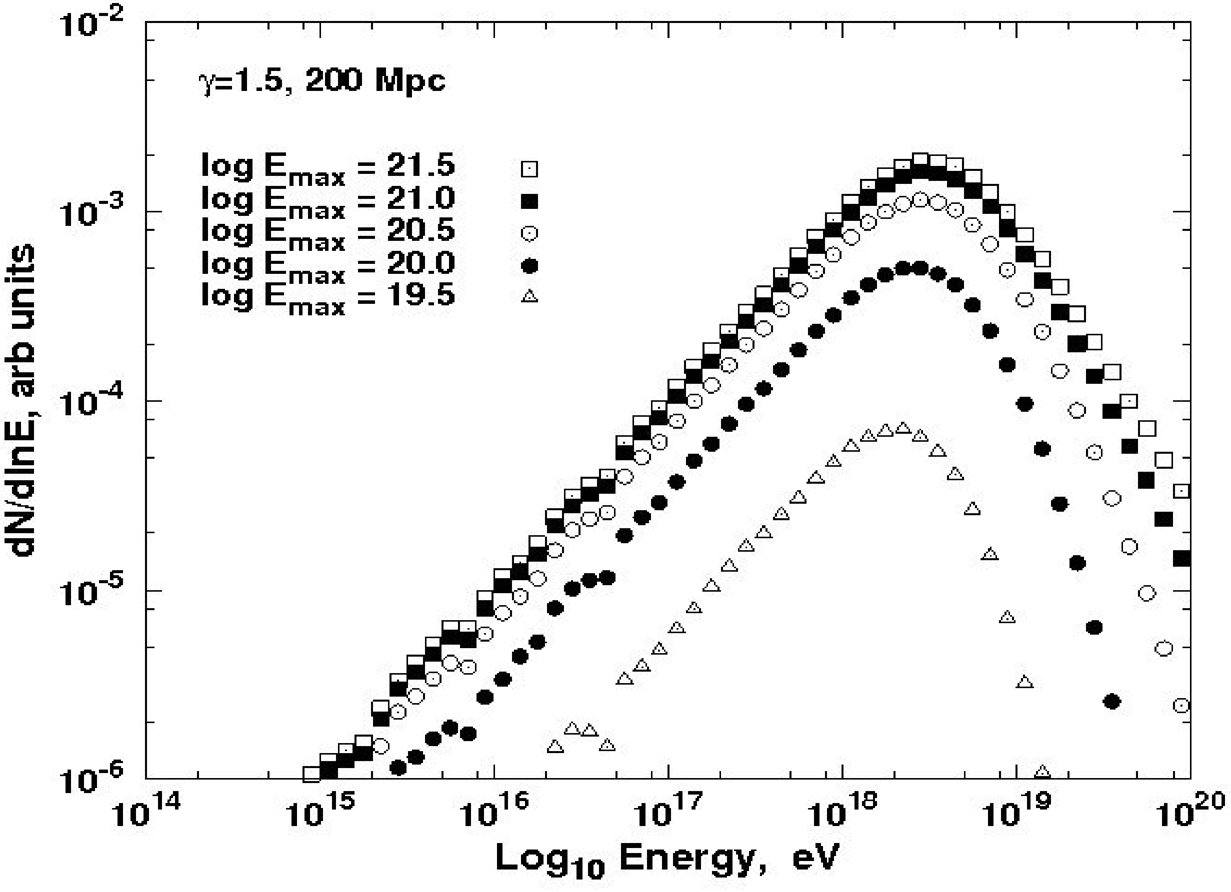
Energy spectrum at acceleration

Cosmological evolution of the UHECR sources

Composition of UHECR at acceleration

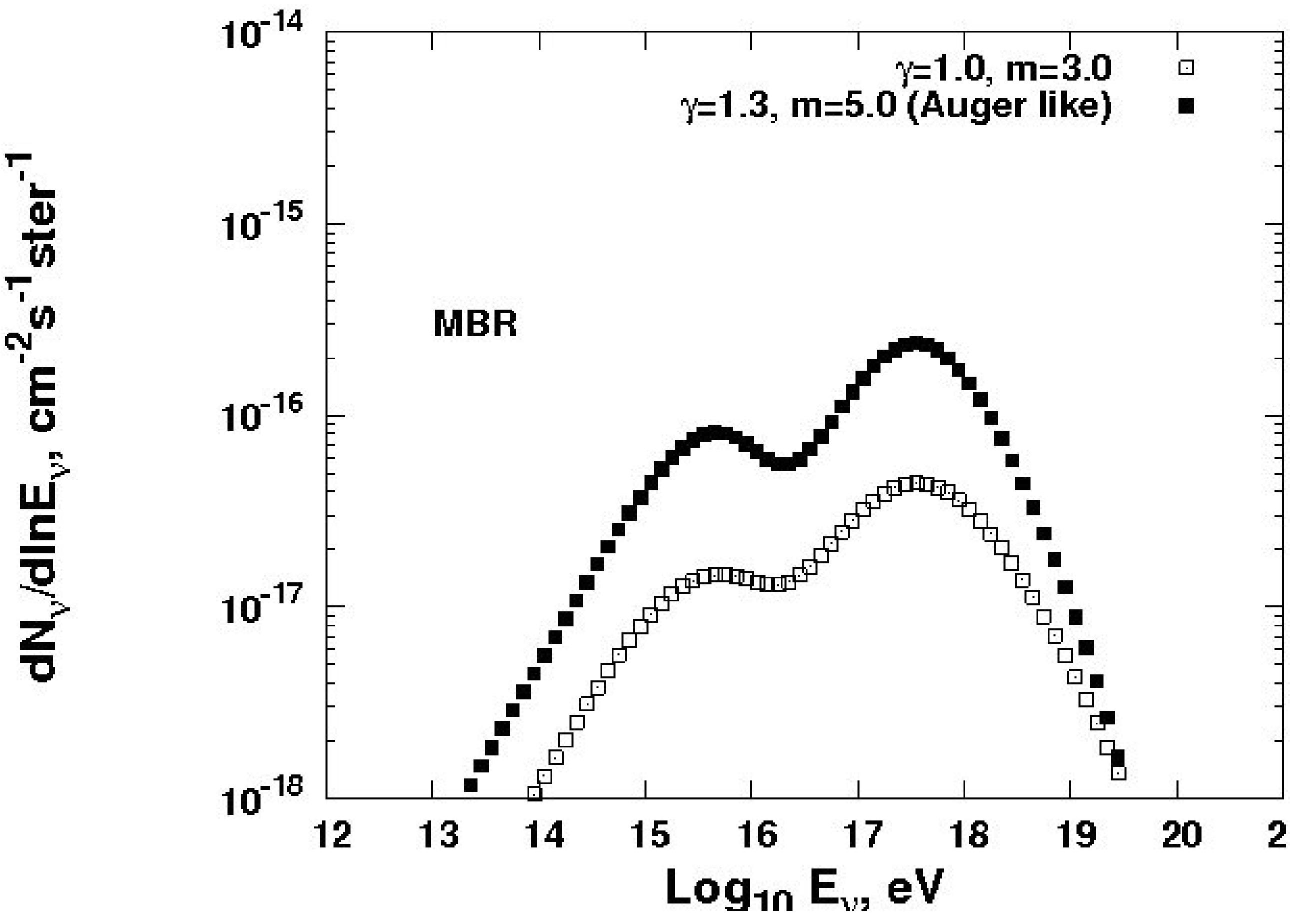
Distribution of these sources in the Universe

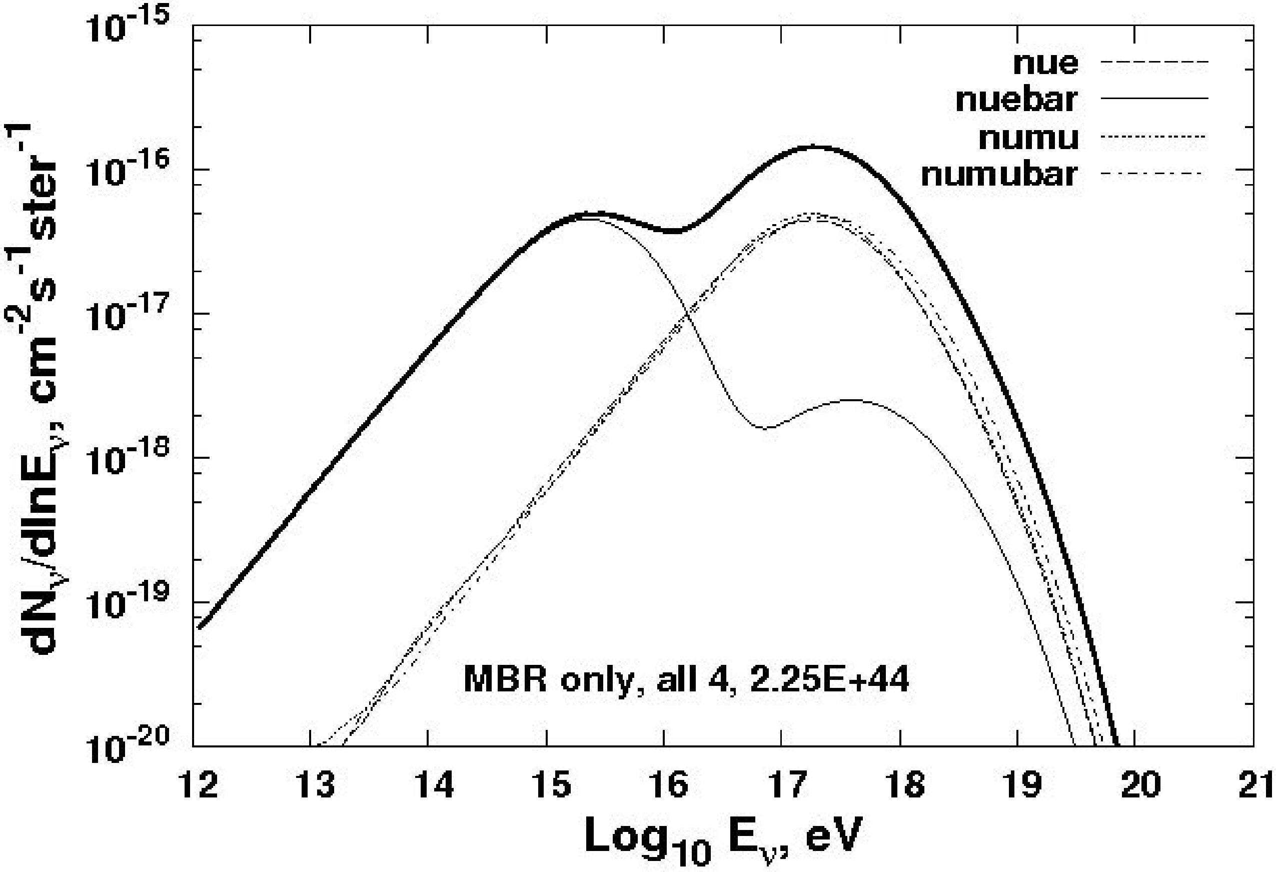
Most of these parameters are correlated with each other



The maximum acceleration energy of the UHE protons is one of the most important astrophysical parameters for the estimate of the cosmogenic neutrino flux. If the maximum acceleration energy *per nucleon* is below 10^{20} eV the total flux is very low. Only muon neutrinos and antineutrinos shown here.

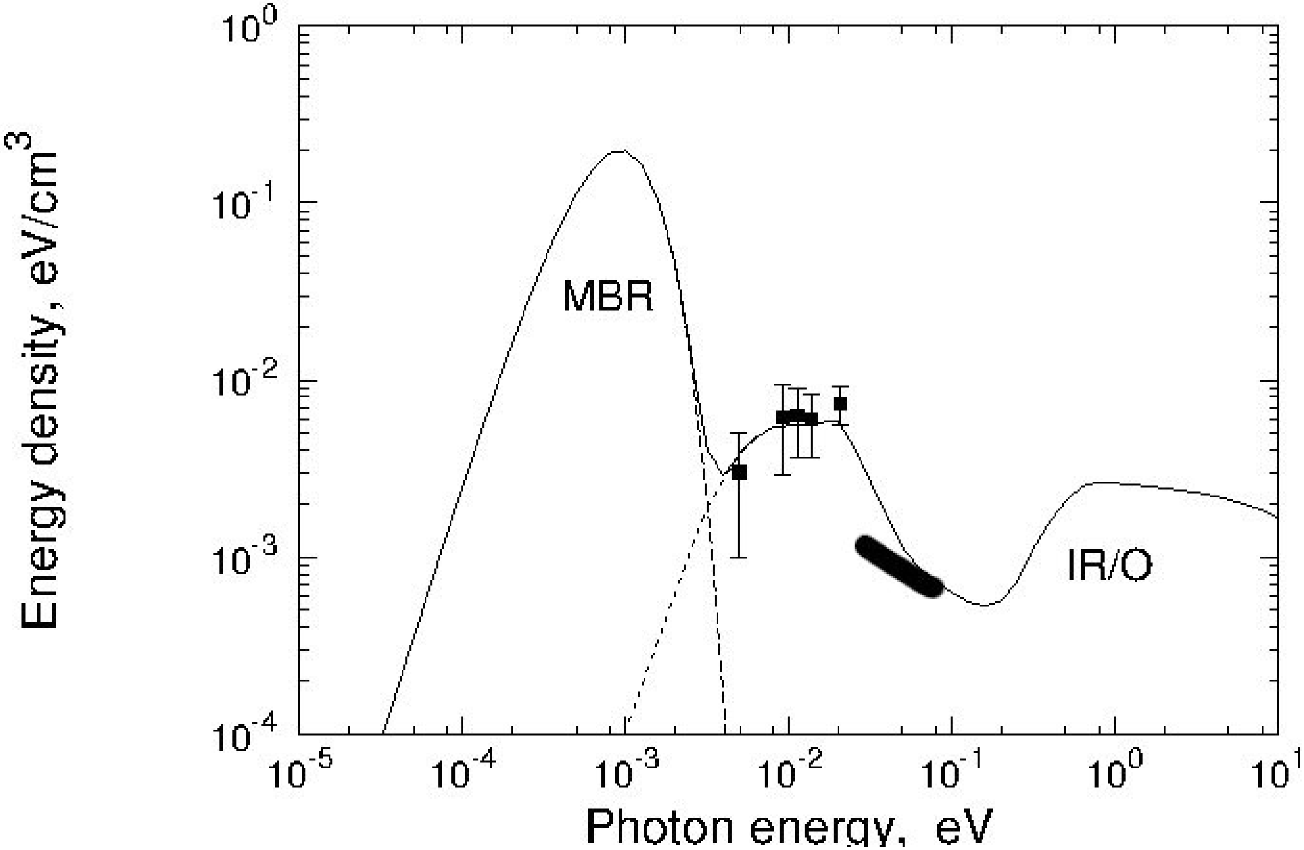
What can we expect after the current measurements of the UHECR flux? We can use some of the `proton' fits of the Auger spectrum. The emissivity of the UHECR sources is corrected (it is a linear effect, a coefficient). We use now ½ of the emissivity of W&B, which is too high since it corresponds to the AGASA energy spectrum.



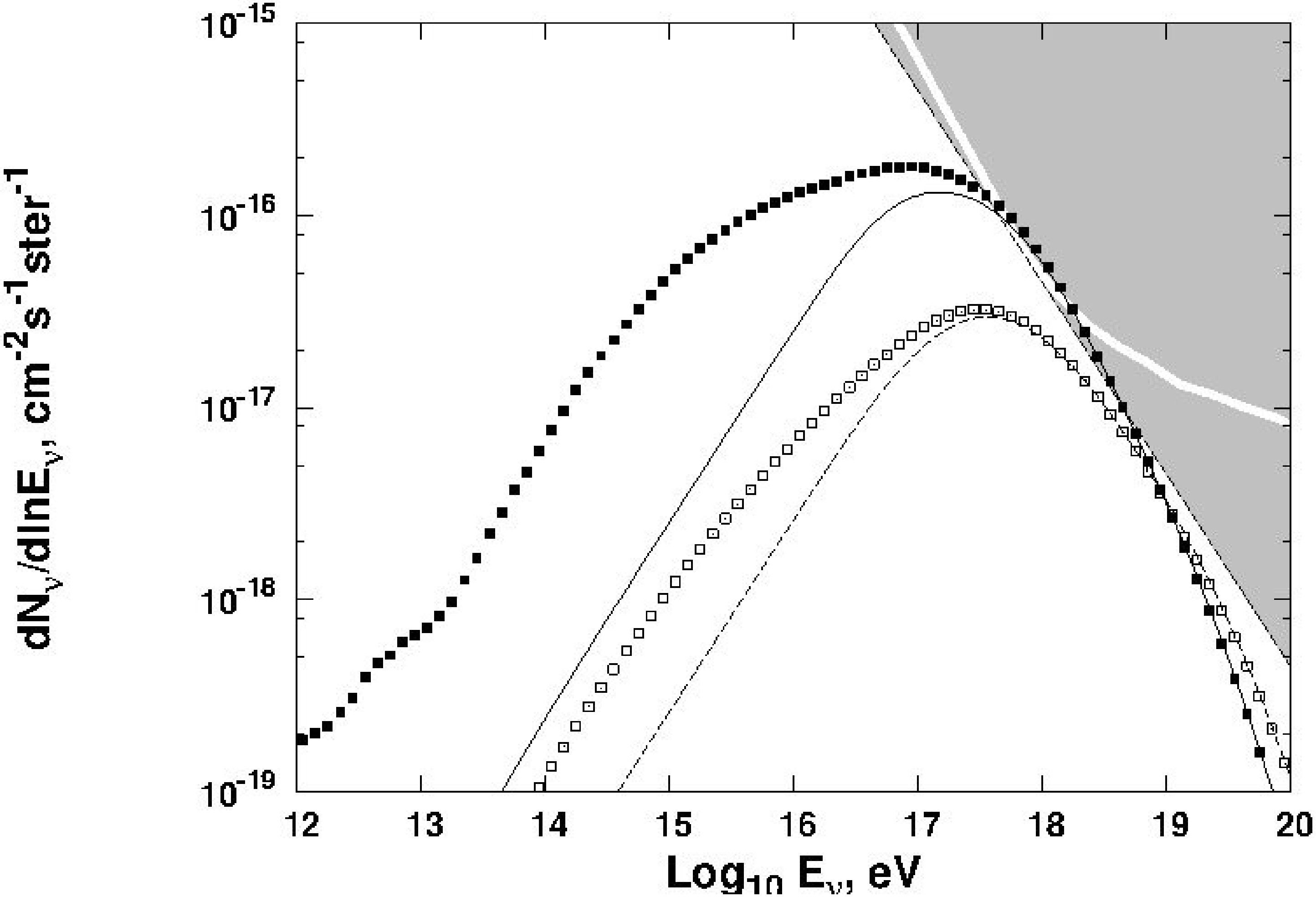


Emissivity corrected to fit the contemporary UHECR spectra

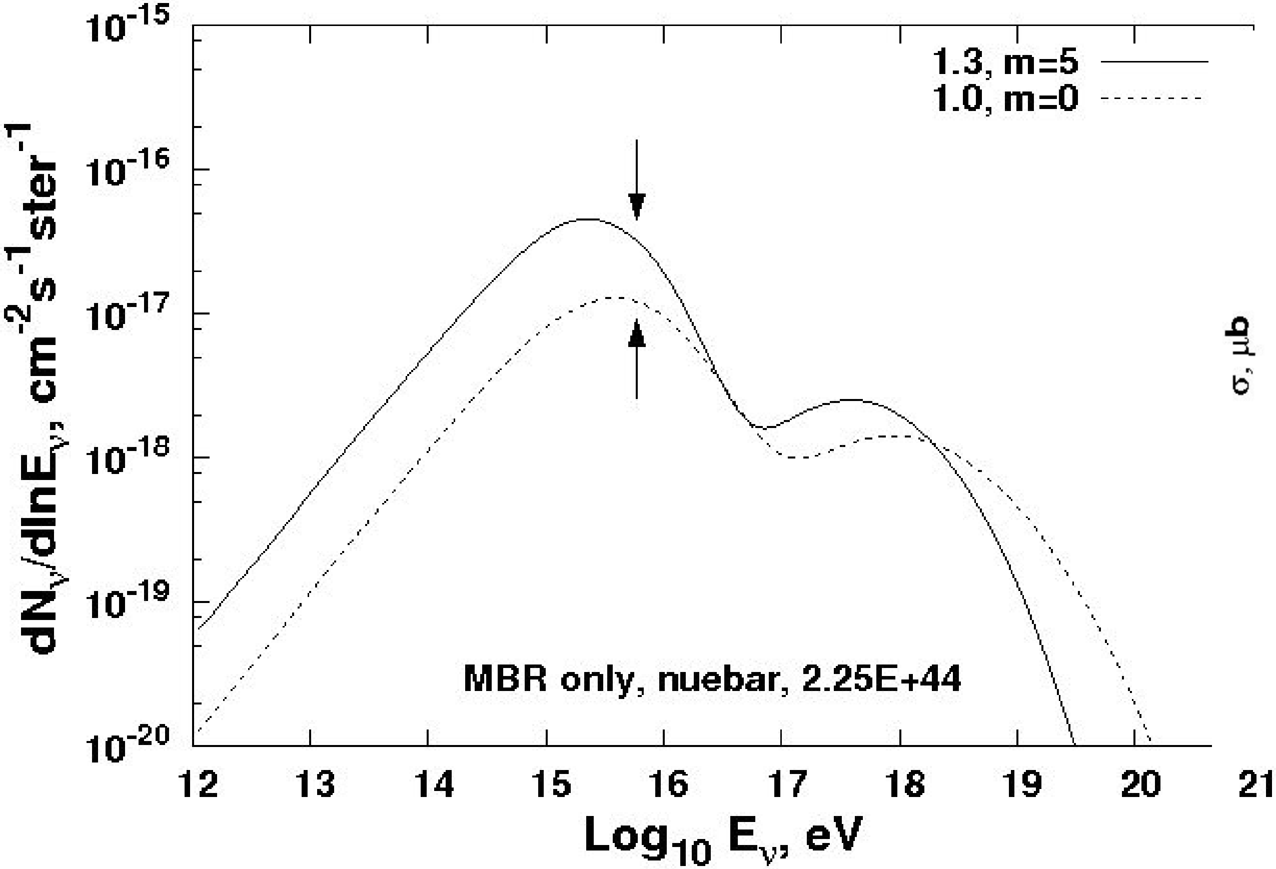
Different neutrino flavors in a standard cosmogenic neutrino calculation. Electron antineutrinos are result of neutron decay. Have in mind that these neutrinos are generated very far away and at arrival at Earth the composition is bound to be close to 1:1:1.

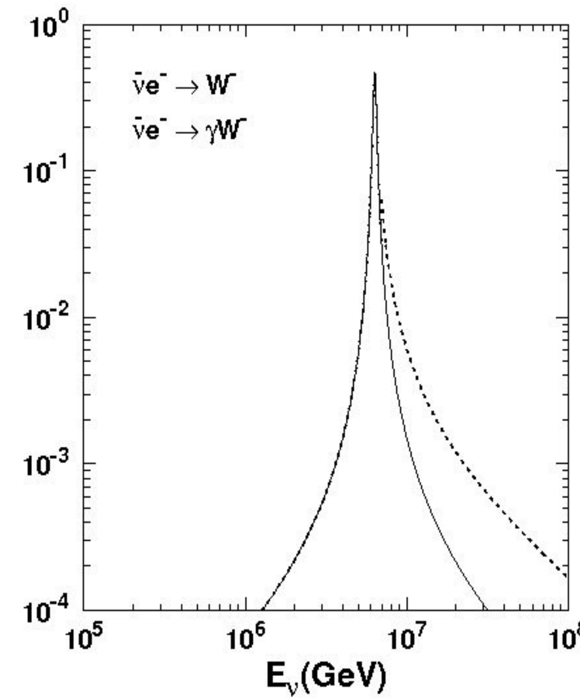


CMB is not the only universal photon field in the Universe. The infrared and optical background (EBL) is much more energetic although its number density is significantly lower: about $1/cm^3$ vs $430/cm^3$. This means that lower energy protons can photoproduce in EBL and with the steep CR spectrum this could be a big effect.



It also means that steeper proton spectra generate more neutrinos in EBL than flatter ones. The figure shows the muon neutrinos generated in CMB and EBL by proton spectra with $\gamma = 2$ and 2.5 for the same total emissivity of high energy protons.





The highest possible cross section is at the Glashow resonance: $\bar{\nu}_e + e^- = W^-$ Some of the decay products of the W^- would generate showers in a big detector. The resonance is however narrow and high rate is not expected.

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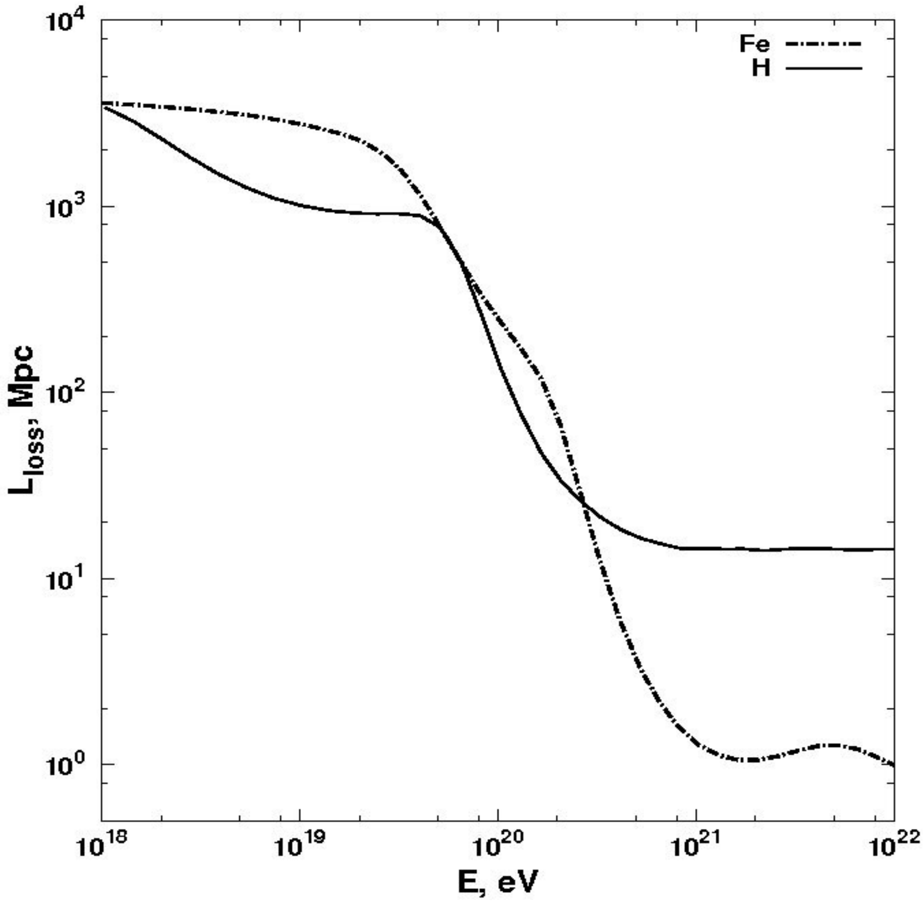
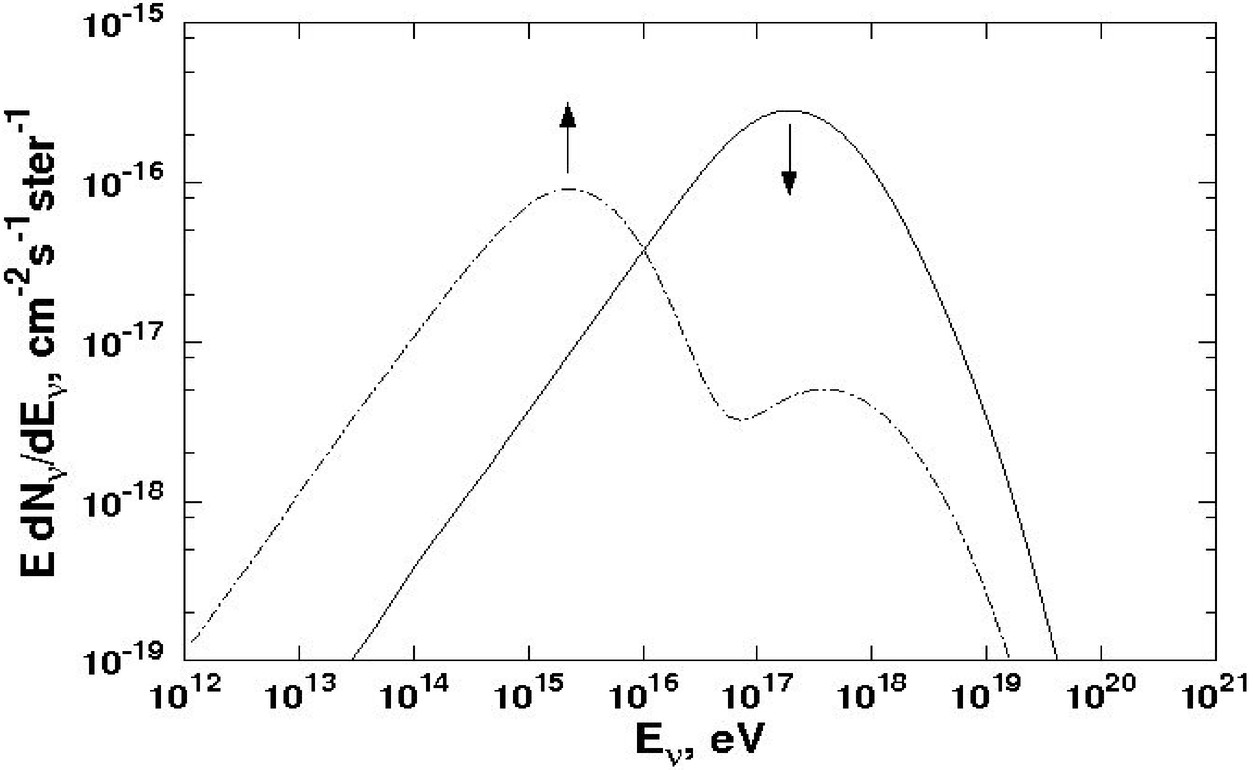


We do know the chemical composition of the highest energy cosmic rays.

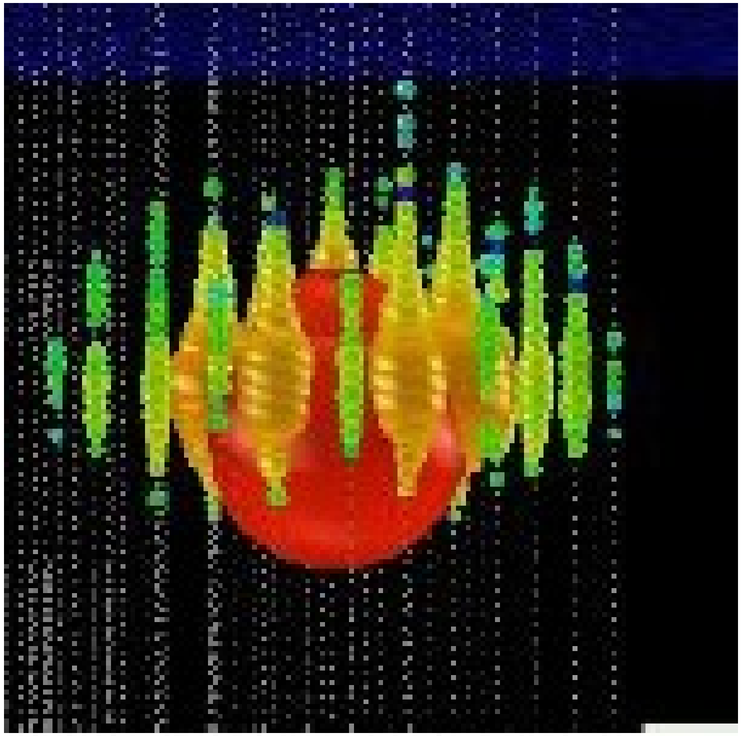
The depth of shower maxima of the HiRes and TA experiments suggest very light (H+He) UHECR composition while Auger measures an increasingly heavier composition at hery high energy

The energy loss length of Fe is close to that of protons but the main neutrino production is from neutron decay → mostly electron antineutrinos are created. Only when the energy per nucleon exceeds the threshold energy of 30 EeV other neutrino types are created.

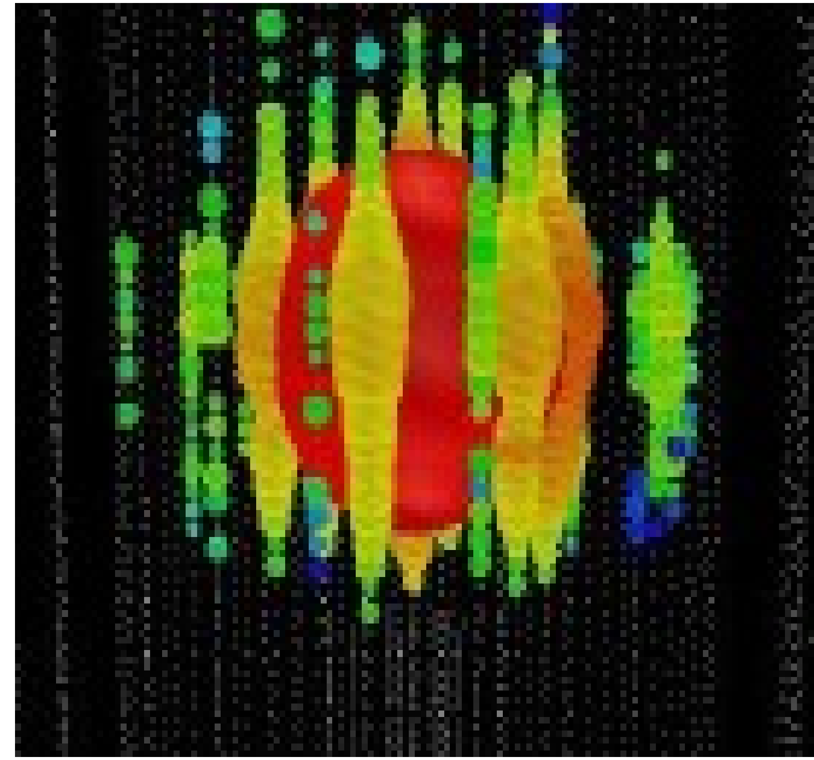


The general rule is that heavy composition would increase the flux of electron antineutrinos and decrease all others.

The heavier the UHE cosmic ray composition is, the higher is the flux of electron antineutrinos and the lower is the flux of all other flavors. Detection of the Glashow resonance would support heavy composition while the detection of 10^{18} eV neutrinos would support proton composition of UHECR.



312 DOMs



354 DOMs

Two neutrino events of energy above 10^{15} eV detected by IceCube (in 615.9 days) were reported on Neutrino 2012 by **Aya Ishihara**. The first thought was that these events are produced by electron antineutrinos generating the Glashow resonance. We will now examine if these events could come from cosmogenic neutrino. (See also the talk of A. Karle.)

These processes are:

Glashow resonance and W^- decay
(three lepton channels (10.5% each) plus q-qbar

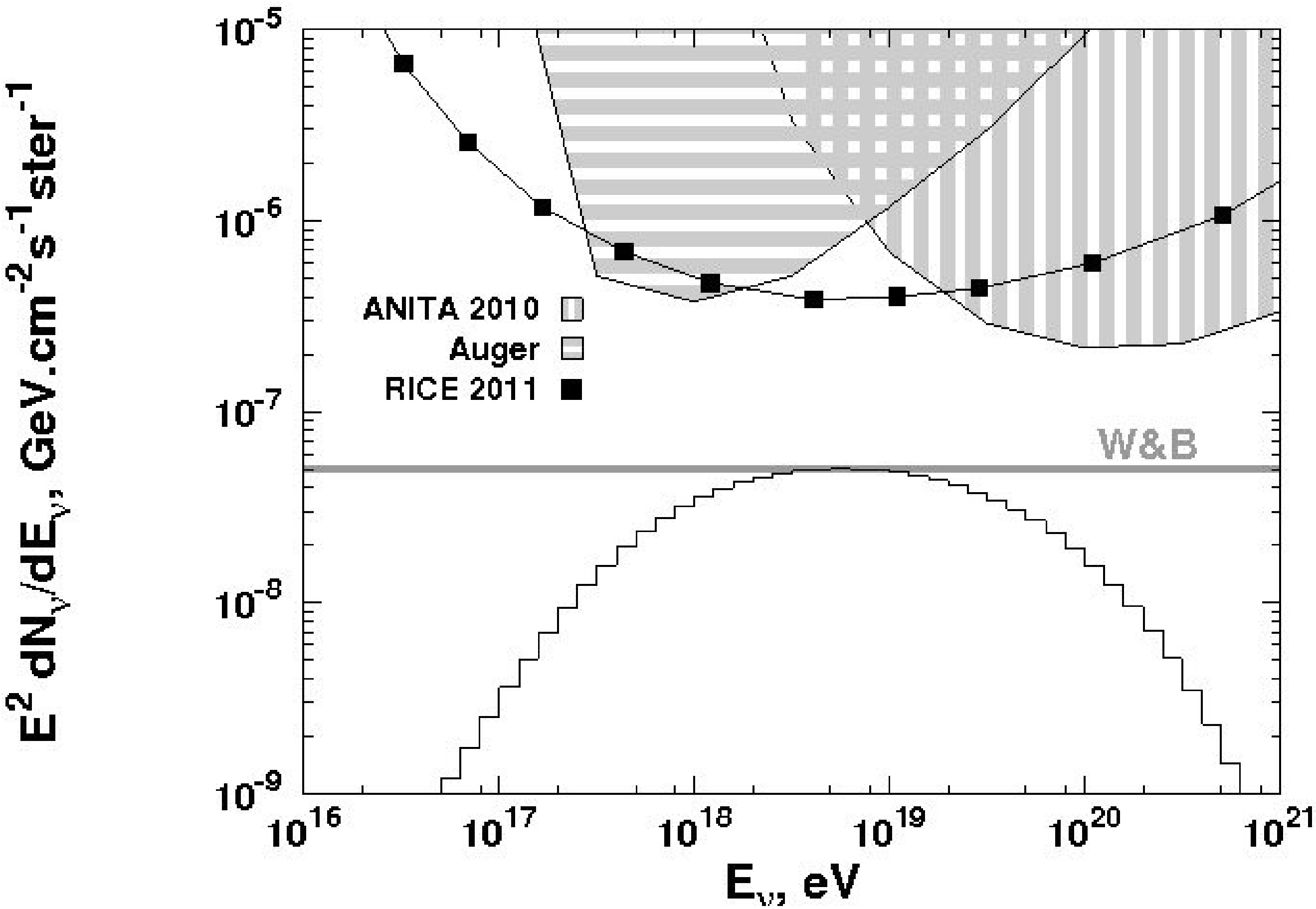
Electron neutrino with energy above 1 PeV interaction
(the total neutrino energy in the cascade)

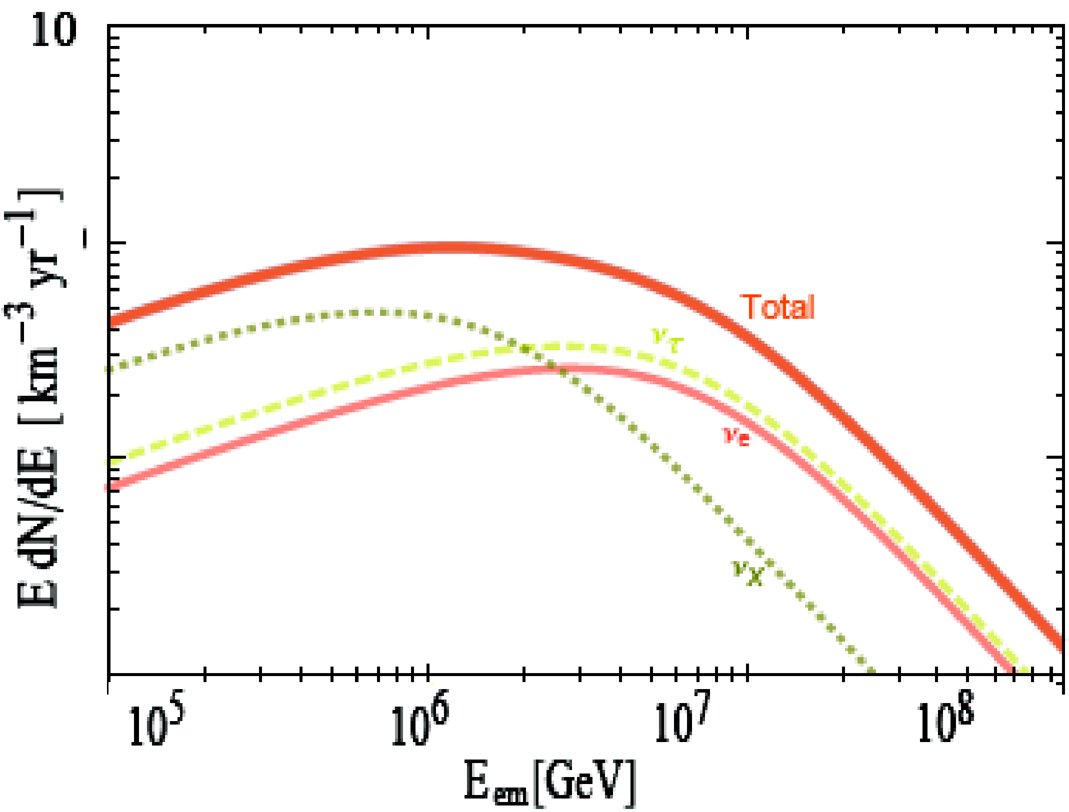
Tau neutrino with energy above 1 PeV interaction
(assume the tau track not visible)

Neutral current interaction of any neutrino type
(average inelasticity about 0.26 above 1 PeV but with considerably wide distribution: leads on the average to several PeV neutrino energy)

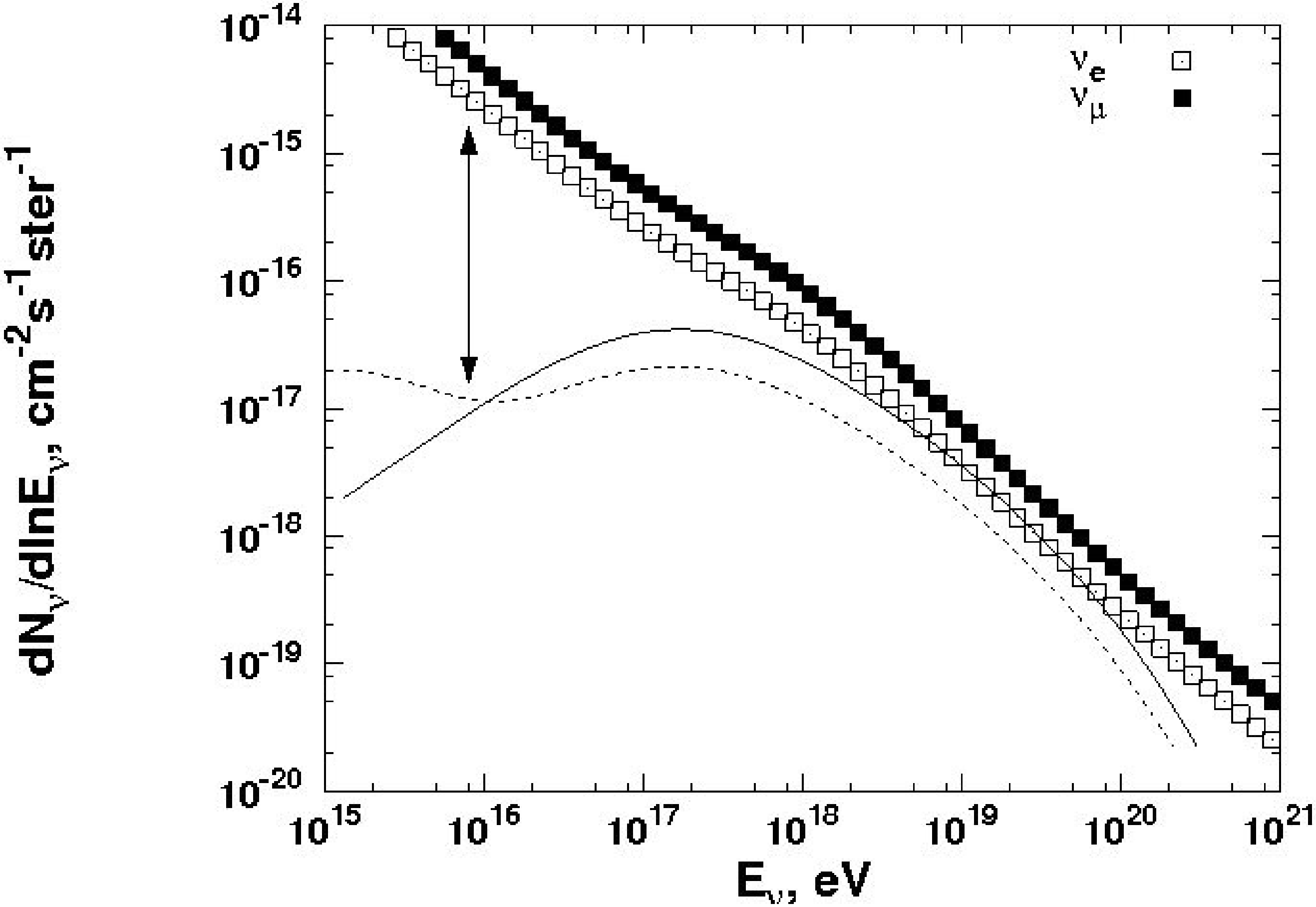
The responsible neutrinos could be either extraterrestrial or atmospheric with a strong prompt (charm) contribution

Current limits on the flux of high energy cosmogenic neutrinos. Note it is plotted as E^2F so W&B limit is a straight line. IceCube has a lower limit at lower energy.





Accounting for all these possibilities and normalizing the neutrino fluxes to two shower events we can generate the following extraterrestrial neutrino fluxes using 1:1:1 flavor ratio. Have in mind that atmospheric neutrino cascade events are much more rare than muon events (0.08).



Comparison of the W&B limit + cosmogenic neutrinos to only cosmogenic neutrinos.

It is easier to believe that the two PeV neutrino events in IceCube were generated at some of the cosmic ray sources rather than by UHECRs in propagation. The Glashow resonance cascades would have been of higher energy.