Production of ultrahigh energy neutrinos in hadronic interactions in astrophysical photon fields

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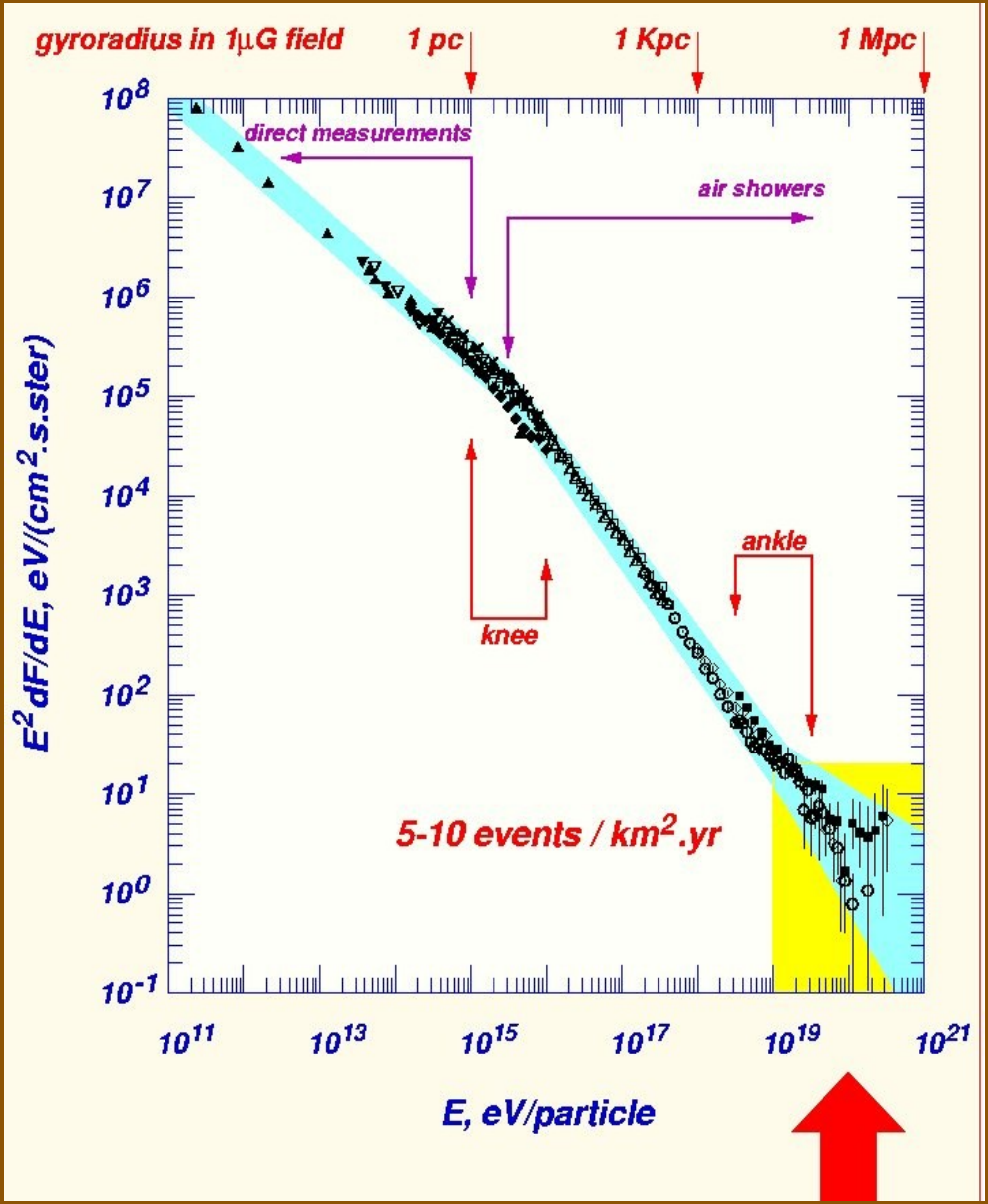
We discuss the the hadronic interactions of ultrahigh energy cosmic rays, protons and nuclei, in their propagation from their sources to us. Protons, neutrons, and nuclei interact with photons from the microwave background, as well with the infrared&optical background. One of the products of these interactions are ultrahigh energy neutrinos that are now close to a detectable level.

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

Ultrahigh energy cosmic rays



The cosmic ray spectrum extends to ultra high energies exceeding 10^{10} GeV. The number of events is small and we do not know much about them - they could be protons or nuclei or even gamma rays.
Energy estimates are also quite uncertain as detection is air shower observation. Each experiment has seen events of energy above 10^{11} eV.

We do not know what the sources of these particles are. If they were of astrophysical origin, they would be accelerated at powerful objects, such as AGN, clusters of galaxies, interacting galaxies, etc. The highest energy cosmic rays are charged nuclei, from general principles H and He. Astrophysical acceleration to such high energy is, however, very difficult - the necessary combination of magnetic fields and dimension rarely exist in the Universe.

Another option is that UHE cosmic rays are of exotic origin. They could be produced at topological defects of many kinds. In such a case they would be gamma rays (and neutrinos).

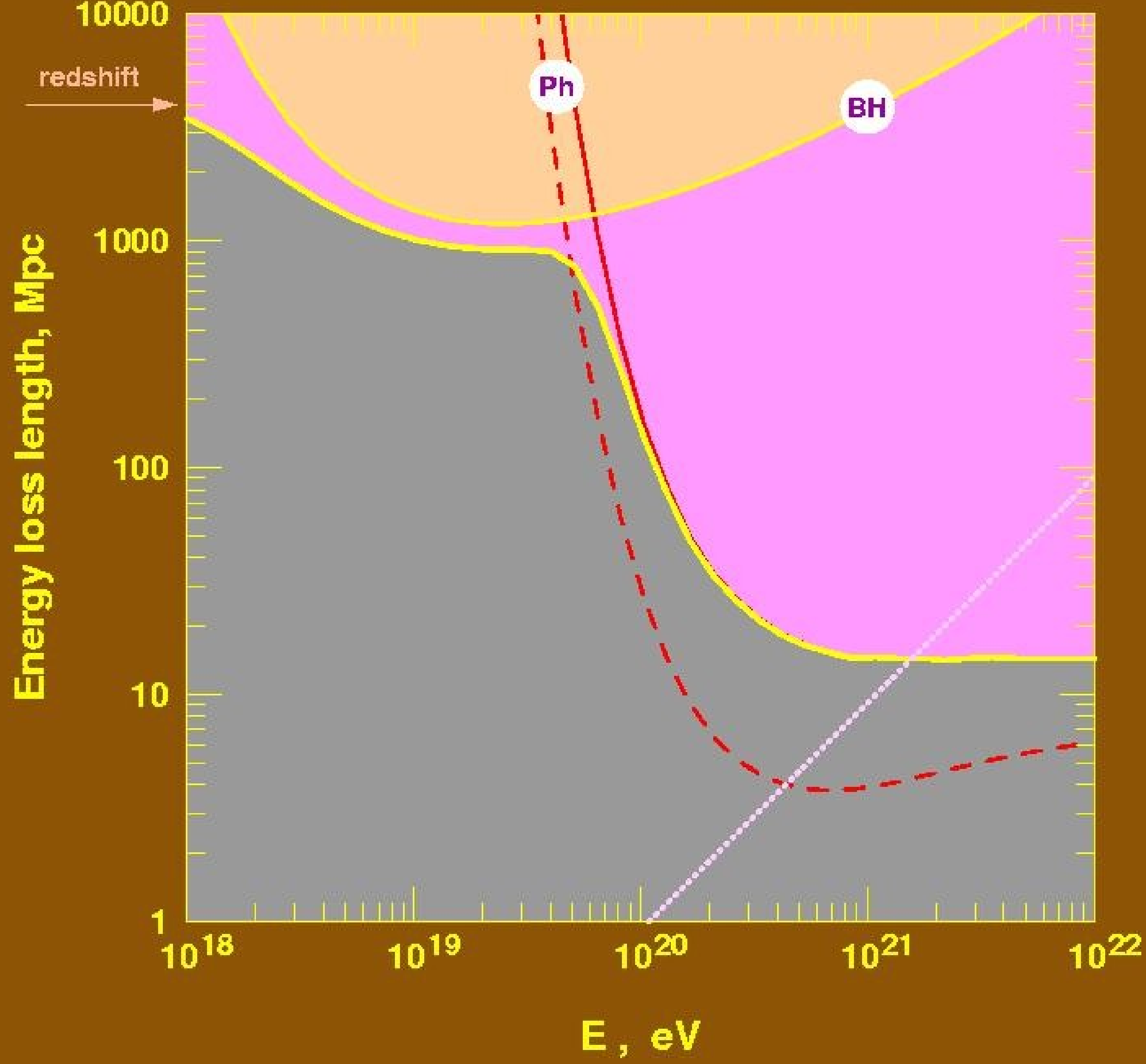
There are also hybrid scenarios such as Z-burst, where UHE neutrinos interact on primordial neutrinos.

Such events, however, should not exist. If cosmic rays are protons the cosmic ray spectrum should have an end at about $6x10^{10}$ GeV because protons lose energy in photoproduction interactions with the microwave background as pointed out independently by Greisen and by Zatsepin&Kuzmin in 1966 soon after the discovery of the 3 degree radiation.

In addition to the photoproduction interaction nuclei are fragmented at lower CMS energy and the cosmic ray spectrum would be cut off at about the same energy.

The details of the spectrum depend very much on the acceleration spectrum of these particles.

Gamma rays also have strong energy loss.



The energy loss scale of high energy protons in the microwave background.

The pile up at the approach of 100 EeV is due to the decrease of energy loss from photoproduction to BH pair creation.

The dip at 10 EeV was predicted by Berezinsky & Grigorieva.

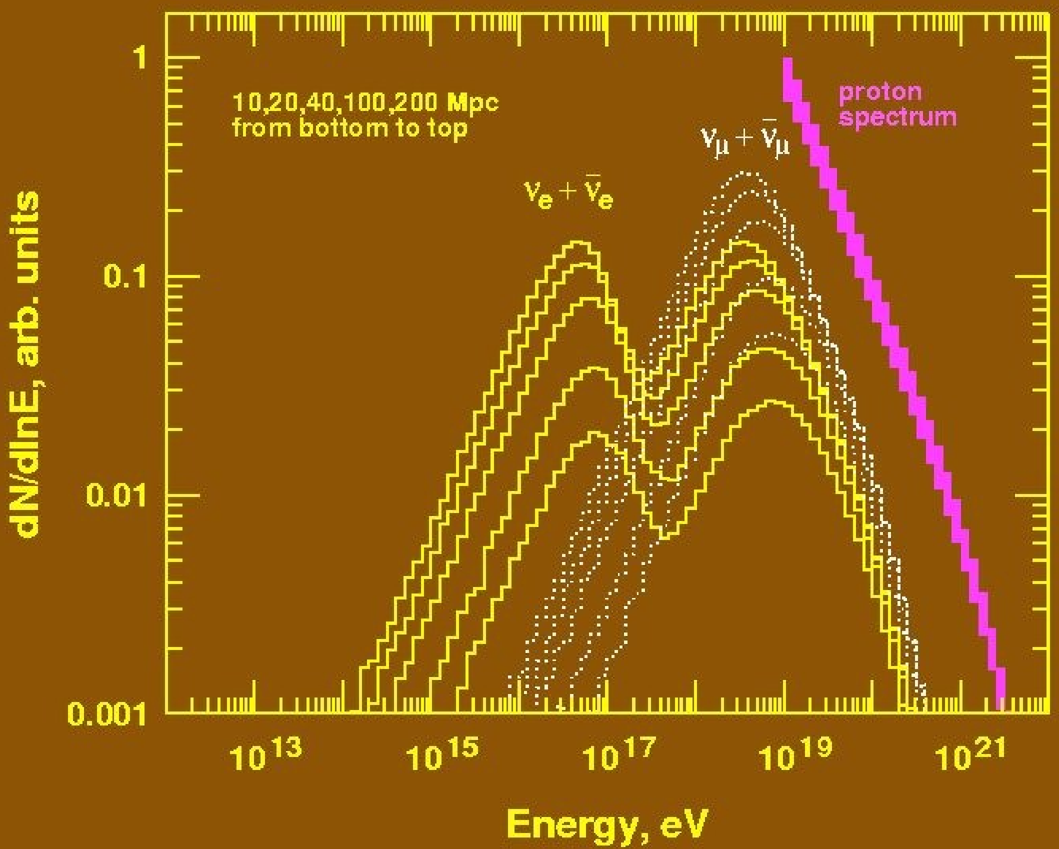
Cosmogentic neutrinos are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation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

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

Actually the proton photoproduction threshold is about 4.10^{19} eV.

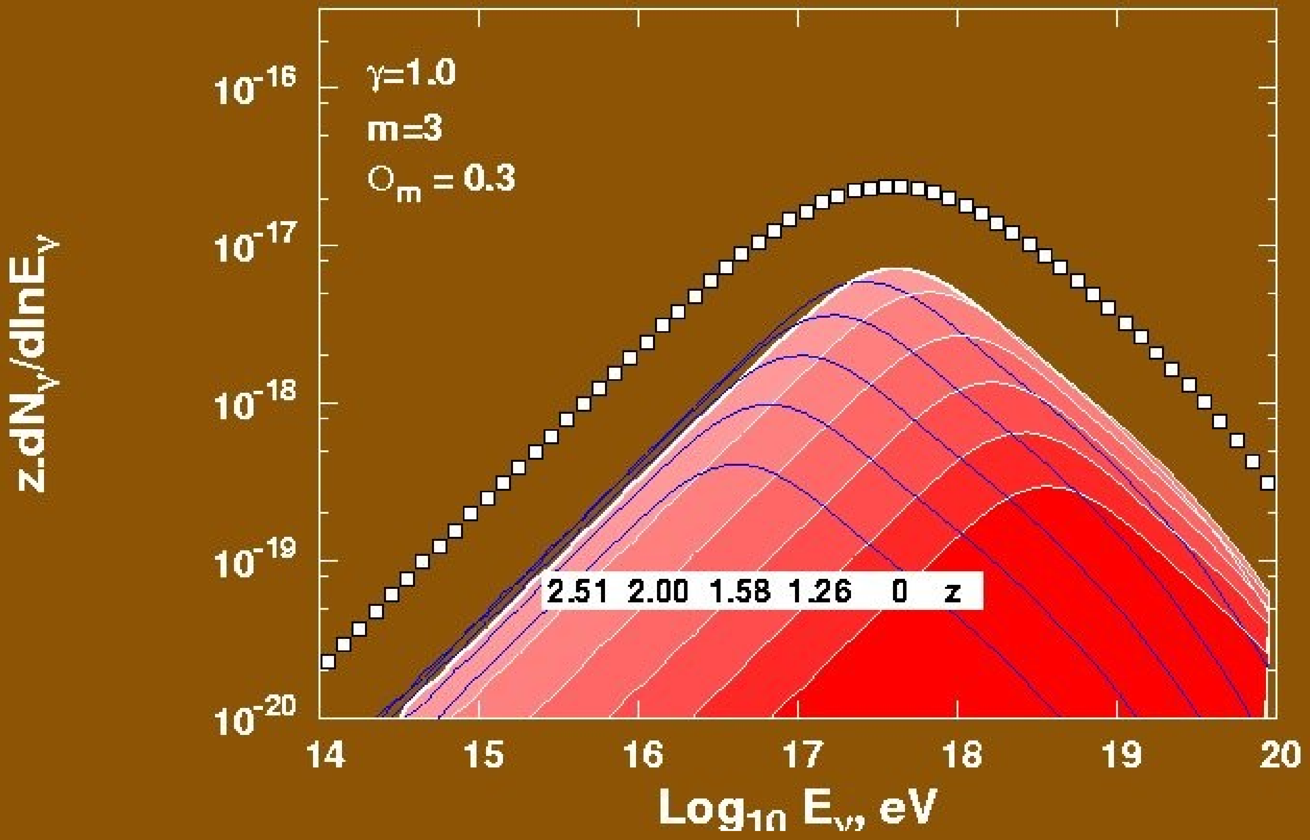
The photoproduction energy losses of the extragalctic cosmic rays cause the GZK effect – an absorption feature in their spectrum.



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

From: Engel, Seckel & Stanev, 2001

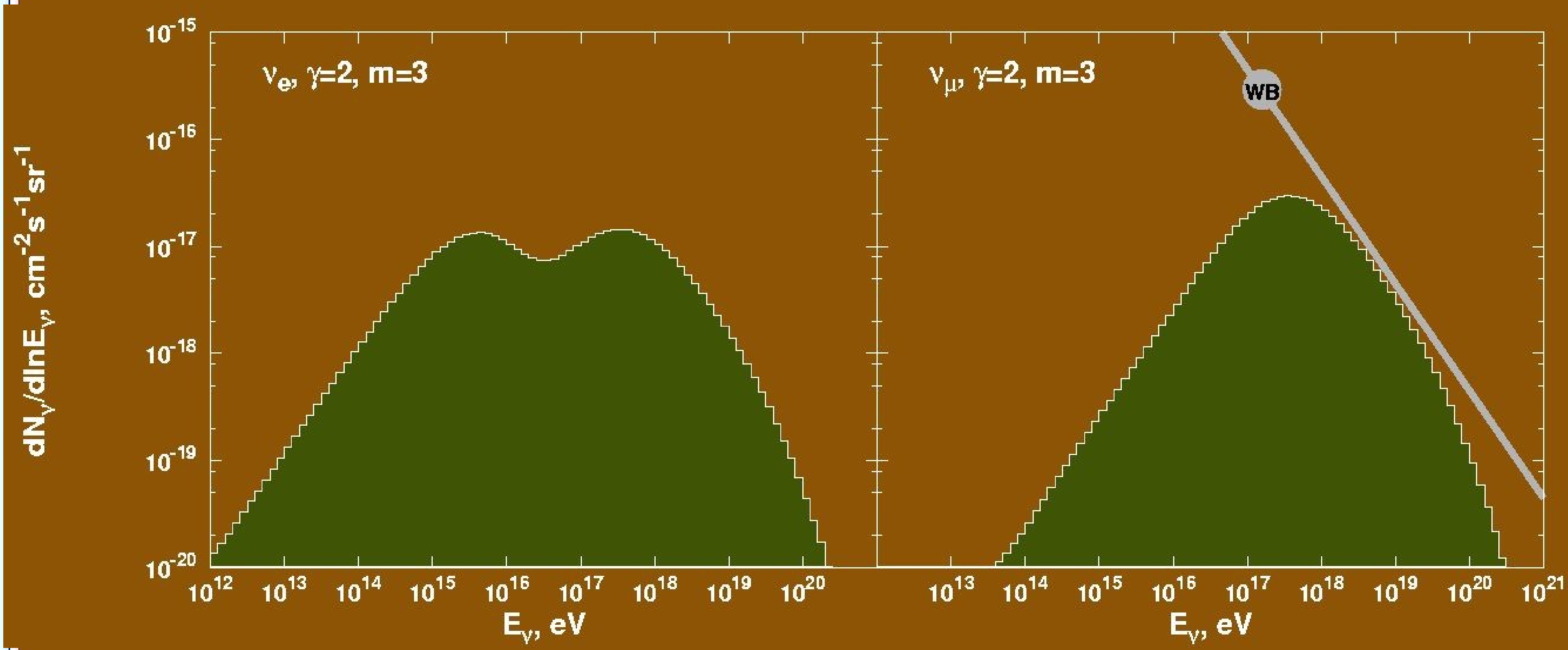
Muon neutrinos and antineutrinos are generated with a spectrum similar to the one of electron neutrinos at twice that rate. As far as neutrinos are concerned the cascade development is full after propagation on 200 Mpc. Even the highest energy protons have lost enough energy to be below threshold. We 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.



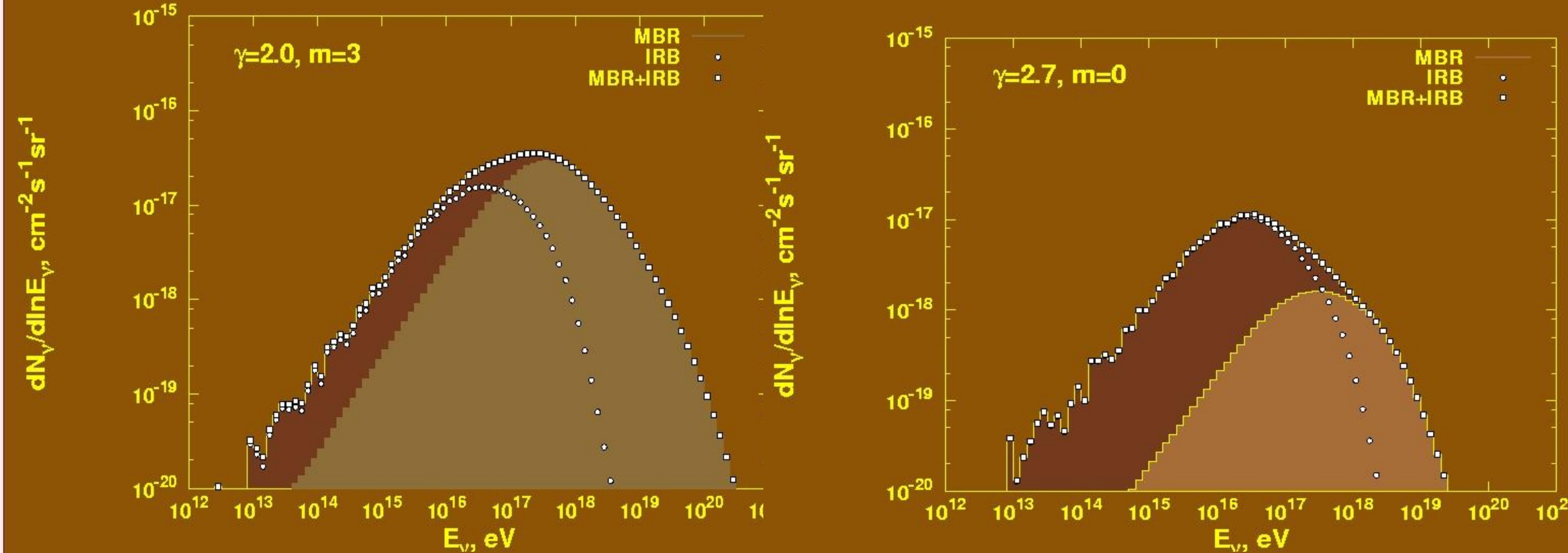
Neutrinos generated by protons in interactions on the MBR at different redshifts as marked in the figure.

Protons above 10^{19} eV can only come from redshifts smaller than 0.4.

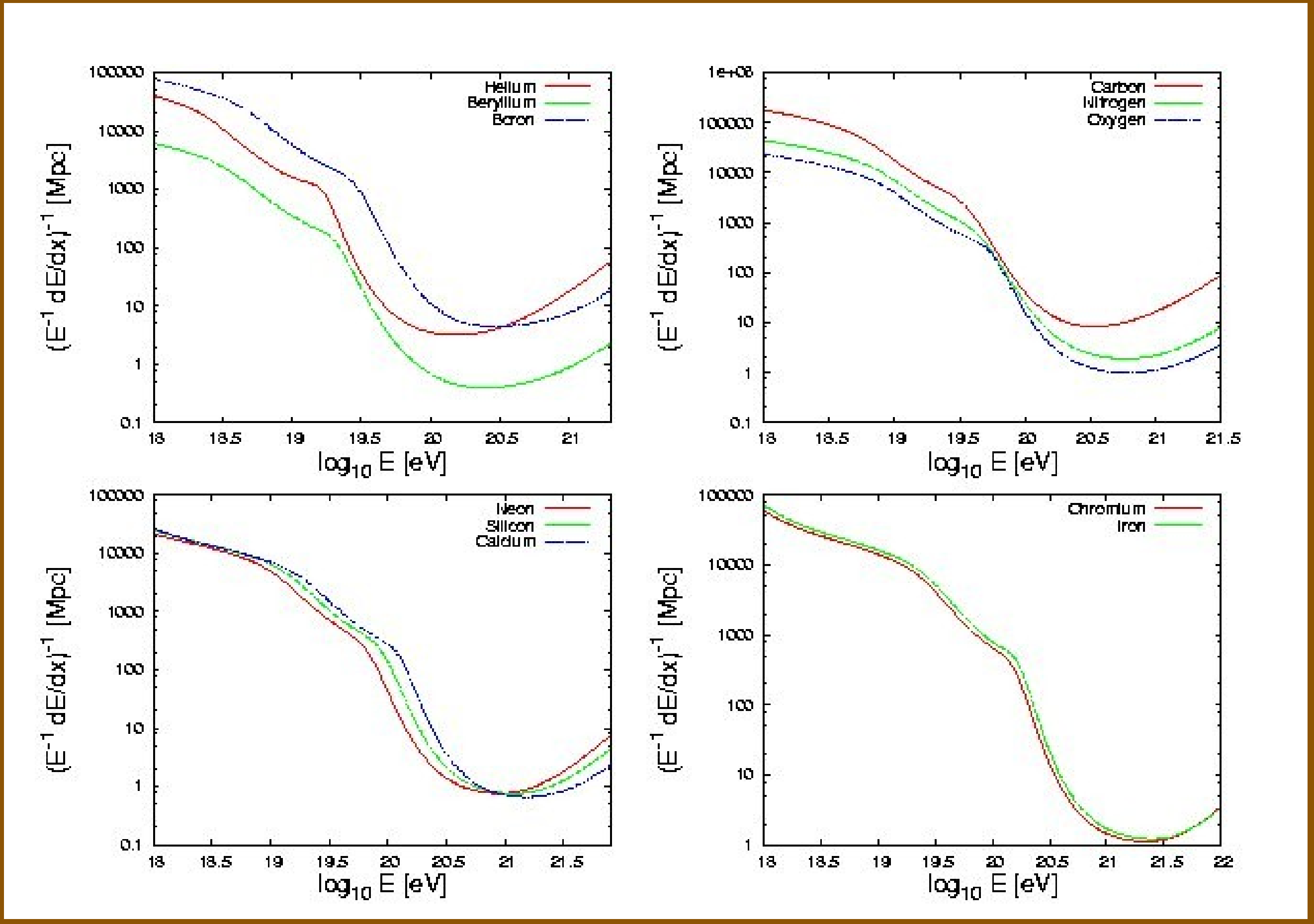
Neutrinos are the most important tracer of such interactions because of their low interaction cross section. Gamma rays quickly lose energy in pair production and inverse Compton cascades plus synchrotron loss for the participating electrons.



Cosmogenic neutrino fluxes calculated after intehration in redshift with $(1 + z)^3$ evolution of the cosmic ray sources in $O_M = 0.3$ cosmology. Note the double peaked spectrum of electron neutrinos. The low energy peak contains electron antineutrinos from neutron decay. These neutrino spectra depend strongly on the cosmic ray injection (acceleration) spectra.



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 somewhat compensated by the interactions in IRB. 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.



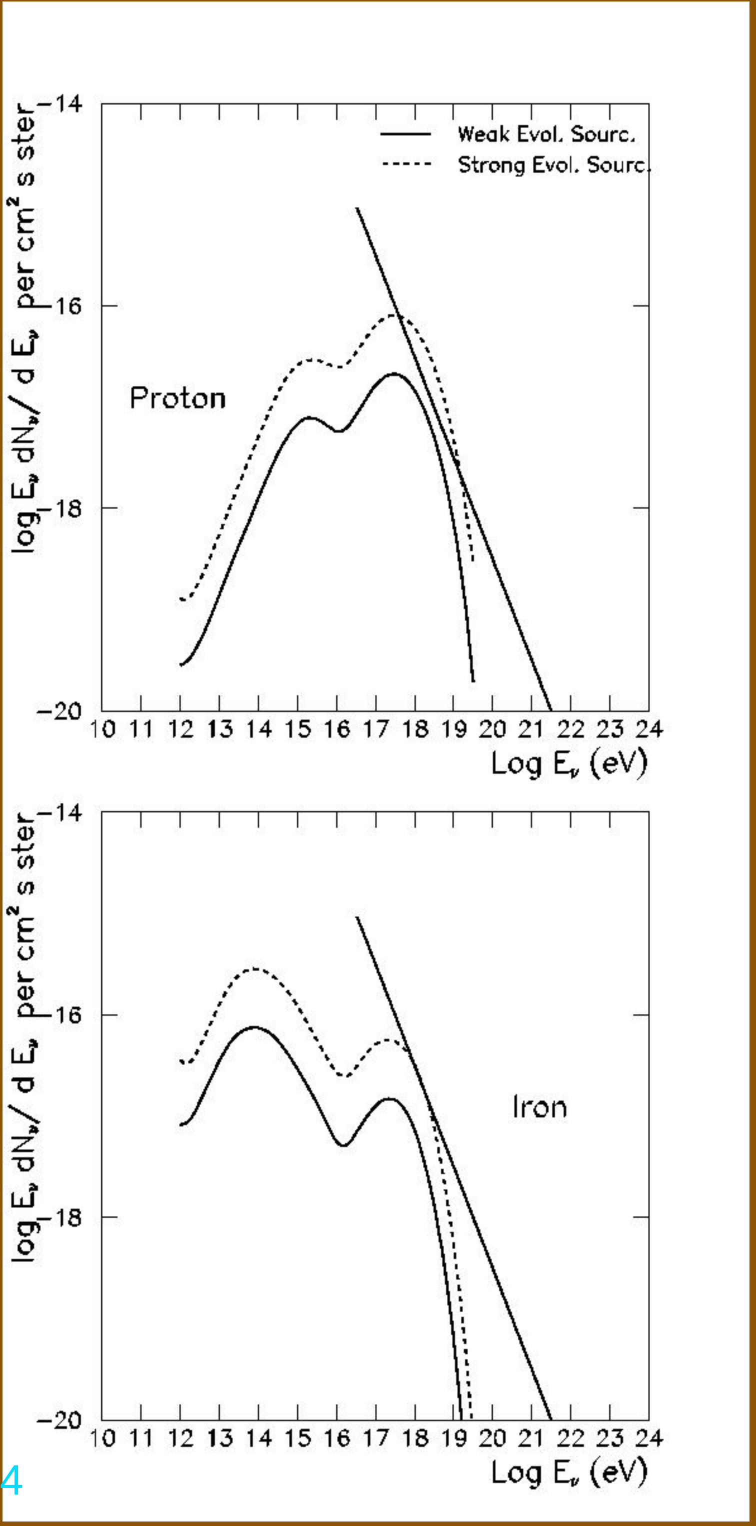
Heavy nuclei lose energy mostly through fragmentation in the photon fields.

From: Hooper, Sarkar & Taylor (2006)

Energy loss lengths for different nuclei in interactions in the microwave and infrared&optical background.

If UHE cosmic rays are not protons, rather heavy nuclei, it was shown by Hooper *et al* and Ave *et al* that heavy nuclei also generate cosmogenic neutrinos, although mostly through a different process - –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.



From: Ave *et al*, 2004

Conclusions

Ultrahigh energy neutrino fluxes are generated by the highest energy cosmic rays on propagation from their sources to us. Current (IceCube, Antares, Nestor, all in construction) and future (km3, Anita, Rice2, funded or likely to be funded) experiments should be able to detect these neutrinos.

If the fluxes of cosmogenic neutrinos are at the higher end of the predictions, they will solve many problems in UHE astrophysics: type and acceleration spectra of UHE cosmic rays, cosmological evolution of UHECR sources (and their type), even the level of the IRB in the vicinity of the sources. Nature has given us one more tool to study the highest energy particles in the Universe.