# (UHE) neutrinos: the key to ultra-high energy cosmic rays

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We present an analysis of the relation of the flux of cosmogenic neutrinos and the injection spectra of cosmic rays. The flux of cosmogenic neutrinos is very closely related to the cosmological evolution of the cosmic ray sources. We also discuss UHE proton interactions in the infrared backgound.

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

The flux of extragalactic neutrinos can be connected to the UHECR flux if UHECR are also of extragalactic origin as was done by Waxman &Bahcalll. They derived the neutrino flux that would correspond to interactions of all highest energy cosmic rays and set a ***limit*** on the flux of high energy astrophysical neutrinos.

WAXMAN&BAHCALL NEUTRINO LIMIT
(derived from the flux of the UHE cosmic rays)

$\frac{dN_{CR}}{dE} \propto E^{-2}$ in $10^{19} - 10^{21}$eV range

$\dot{\varepsilon} \sim 5 \times 10^{44}$ erg Mpc$^{-3}$yr$^{-1}$

$E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{t_H}{4} \varepsilon E^2 \frac{d\bar{N}}{dE}$

$\varepsilon < 1$ is assumed energy independent

$E_\nu$ assumed 1/20 of $E_p$

$I_{max}$ is achieved for $\varepsilon = 1$

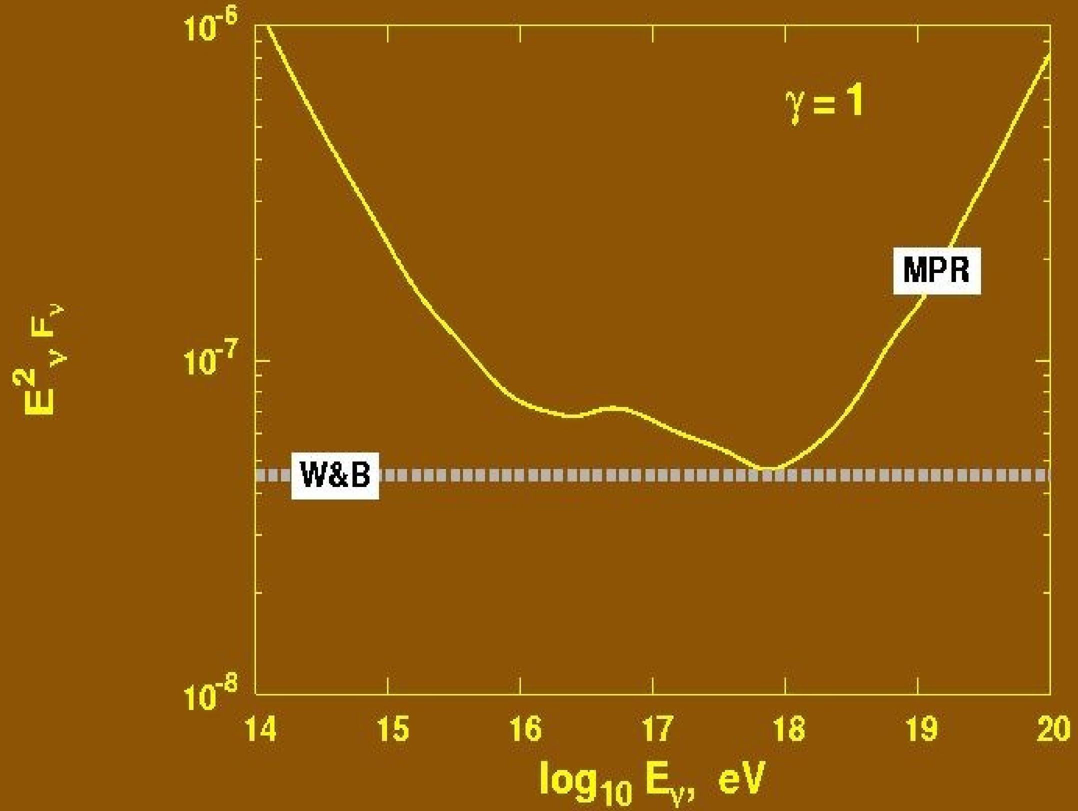
$I_{max} \simeq \frac{t_H}{4} \xi_Z \frac{c}{4\pi} E^2 \frac{d\dot{N}}{dE}$

$\simeq 1.5 \times 10^{-8} \xi_Z$ GeV.cm$^{-2}$s$^{-1}$sr$^{-1}$, i.e.

$E_\nu^2 \Phi(\nu_\mu + \bar{\nu}_\mu) = \varepsilon \times I_{max}$

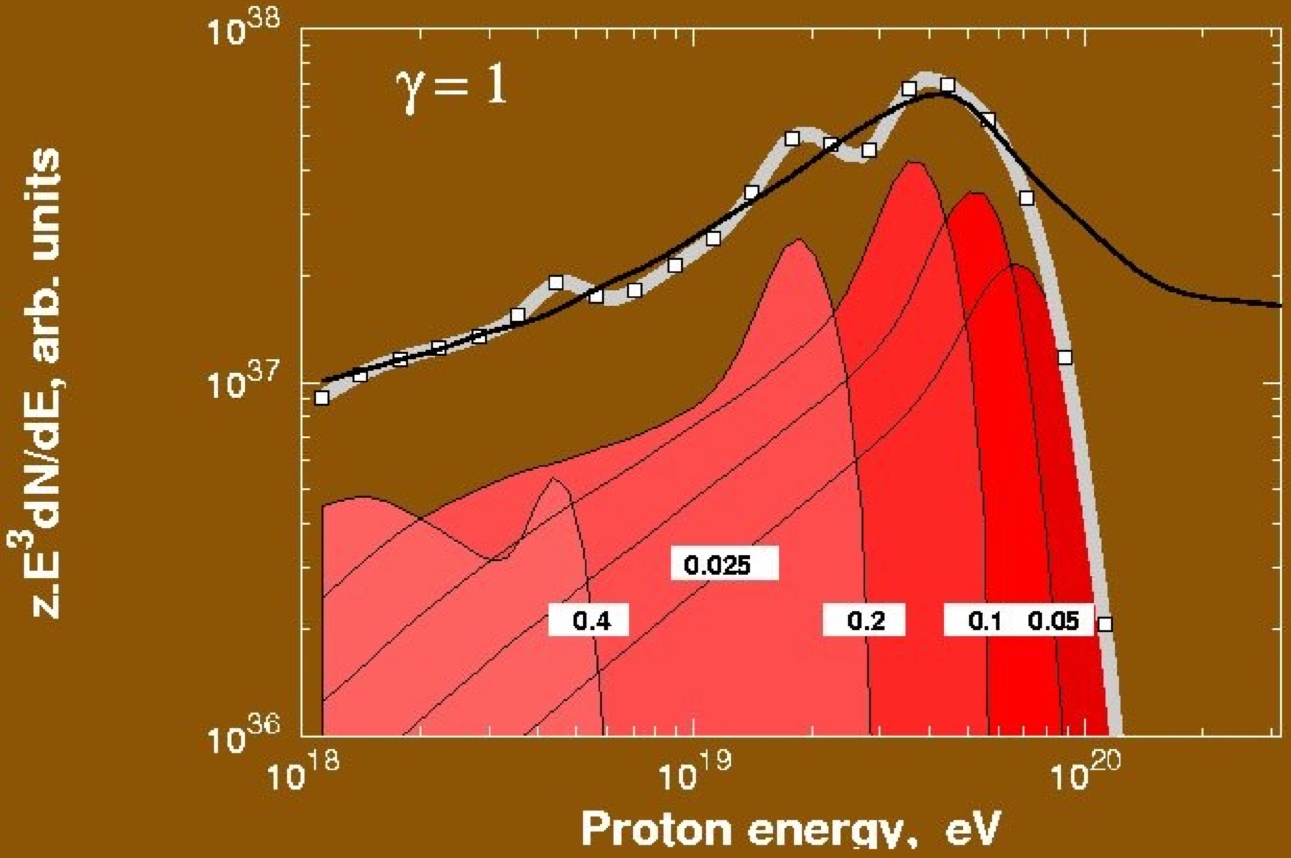
The *limit* was criticized by MPR, who made corrections to it.
It is, though, a nice straight line which is useful as a standard to which we can compare the more precise model calculations.

Waxman & Bahcall thus made the first direct connection between extragalactic cosmic rays and astrophysical neutrinos.

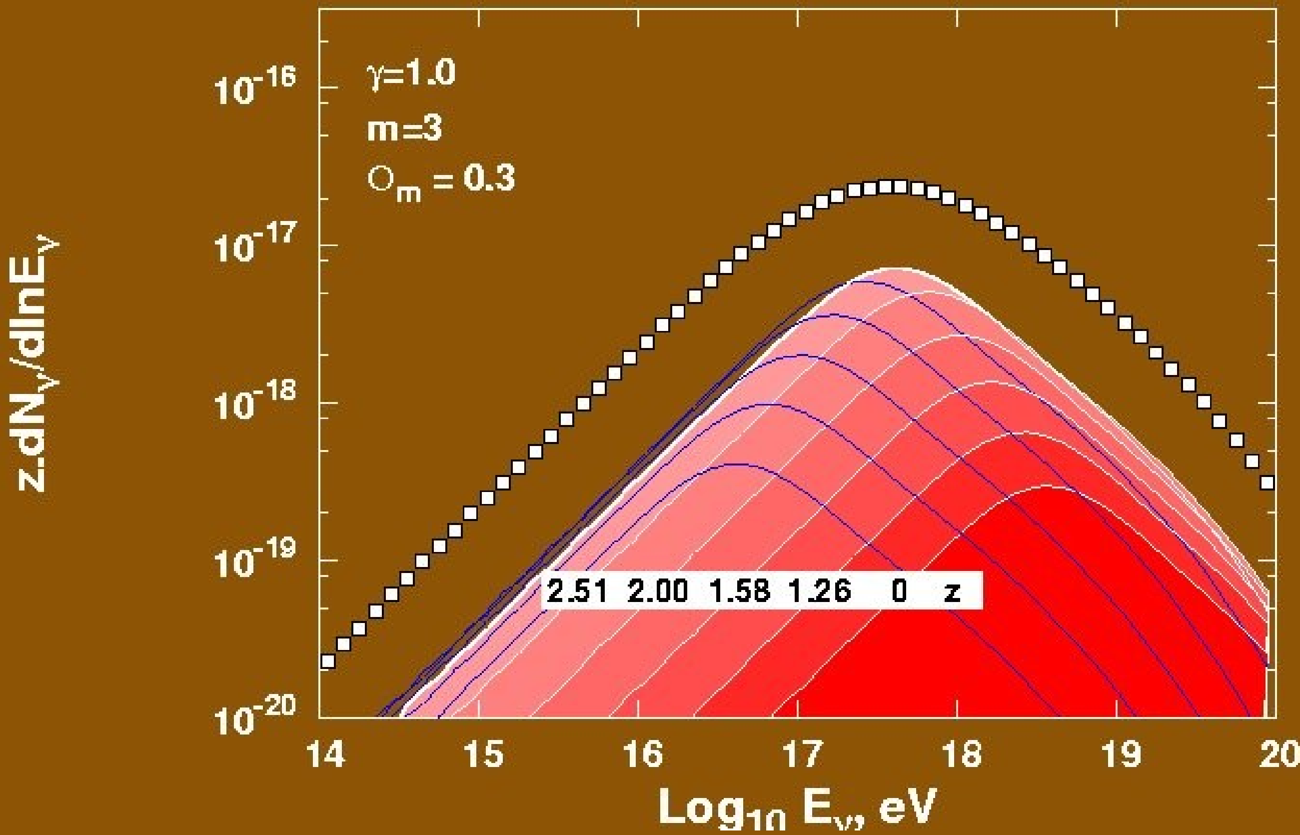



The two limits agree well only at one energy, which is related to the normalization at $10^{19}$ eV of the cosmic ray luminosity. The discreapancy at lower energy is due to the uncertainty in the contribution of extragalactic cosmic rays to the observed flux. At higher energy the problems is in the different ` horizons' for protons (and nuclei) and for neutrinos.

The difference in the two estimates of the upper bound of the extra-galactic neutrino flux at high energy (> $10^{19}$ eV) is that neutrinos produced at large distance (high redshift *z)* contribute to the local flux of extragalactic neutrinos while cosmic rays accelerated at the same redshift do not, because of energy loss.




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.




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

Note the logarithmic scale in redshift. Cosmological parameters are exactly the same for both calculations. The contribution increases until the source luminosity is significant (*$z$ = 2.7 in the Waxman&Bahcall model).* It declines exponentially at higher redshift but the production is still high because of the $(1+z)^3$ increase of the MBR density and the lower energy threshold for photoproduction.

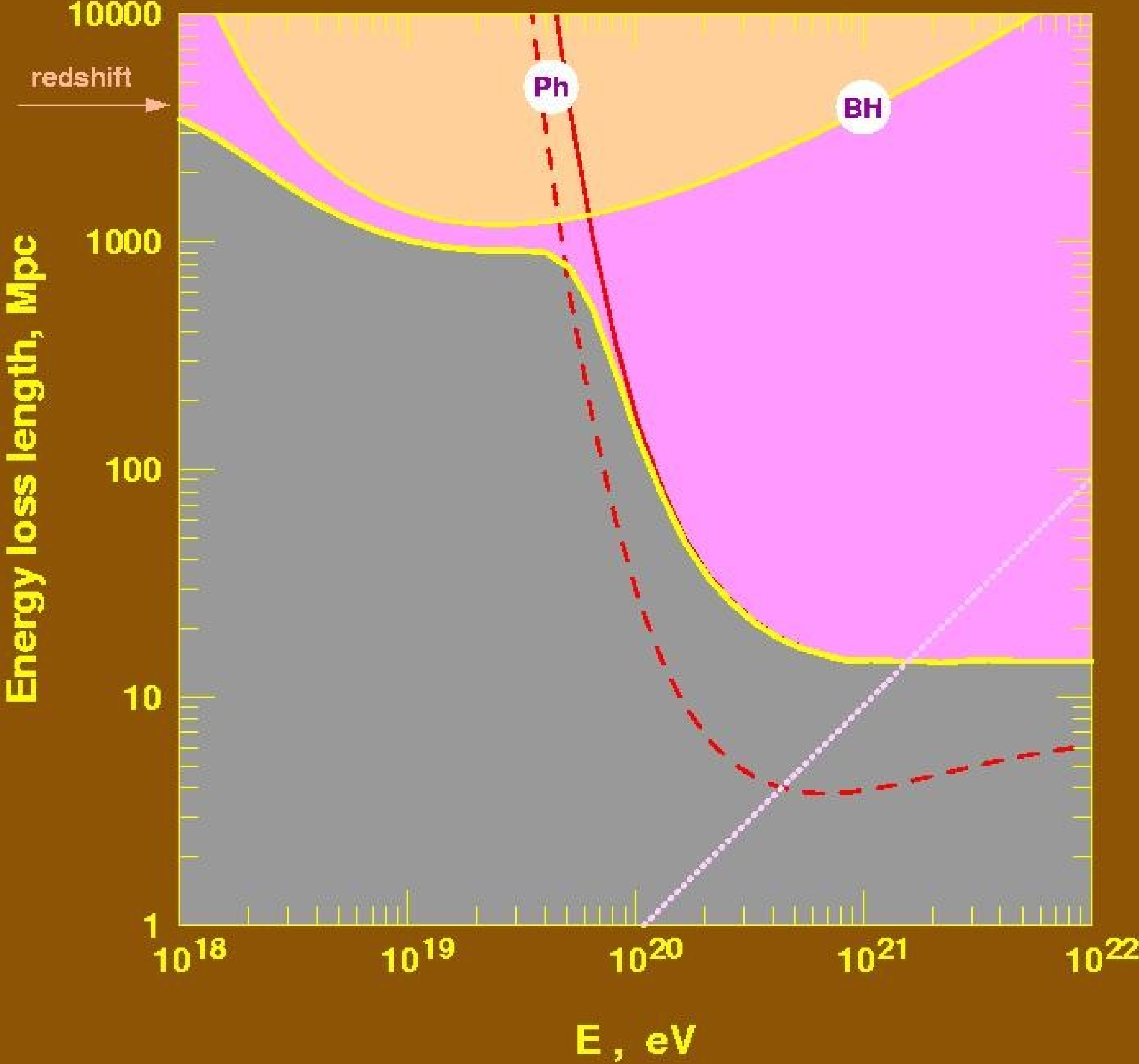
Cosmogentic neutrinos are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation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

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

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

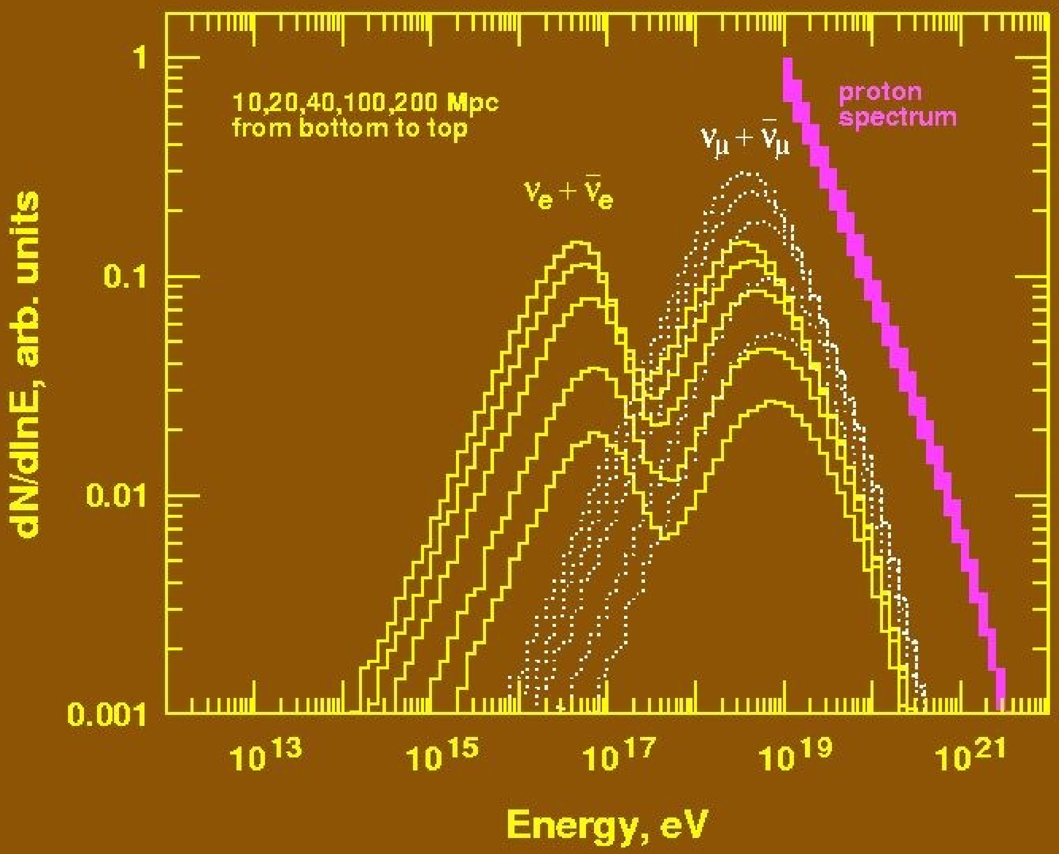
The photoproduction energy losses of the extragalctic cosmic rays cause the GZK effect – an absorption feature in their spectrum.




The 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.

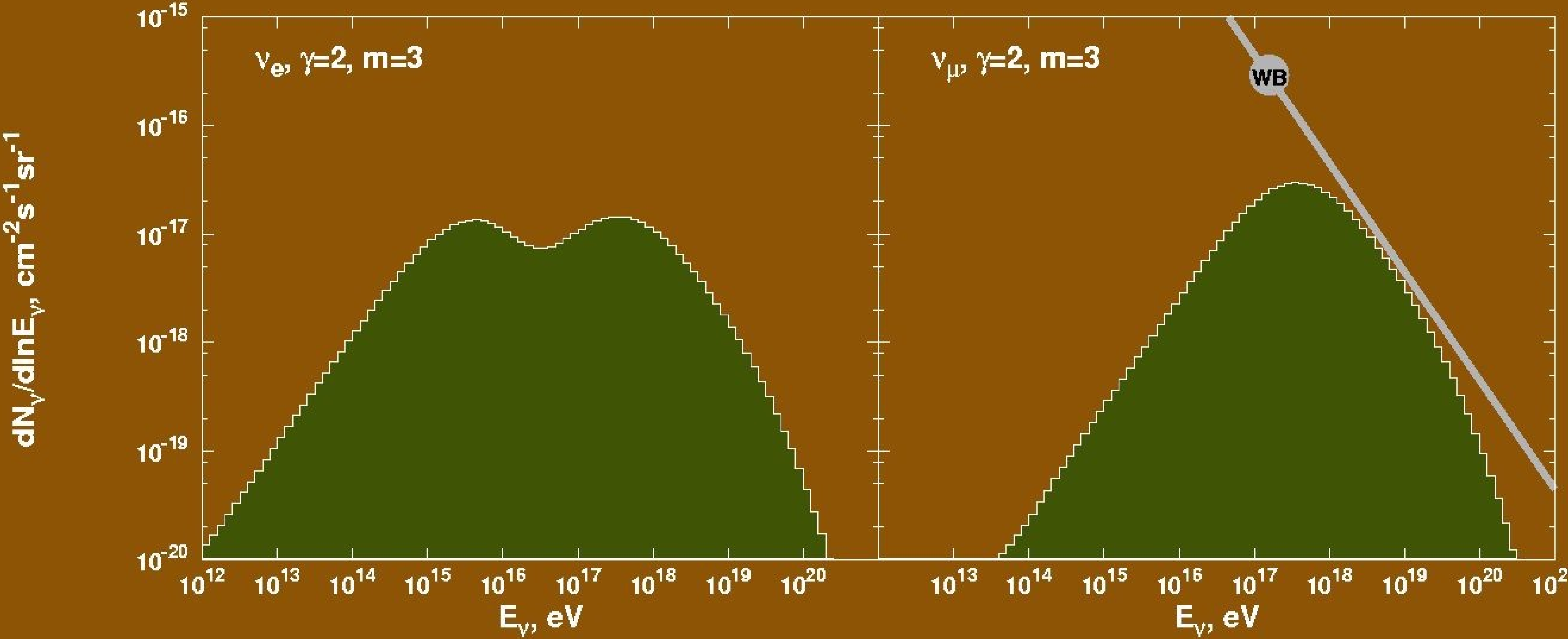
The dip at 10 EeV was predicted by Berezinsky & Grigorieva.




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.




Cosmogenic neutrino fluxes 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.

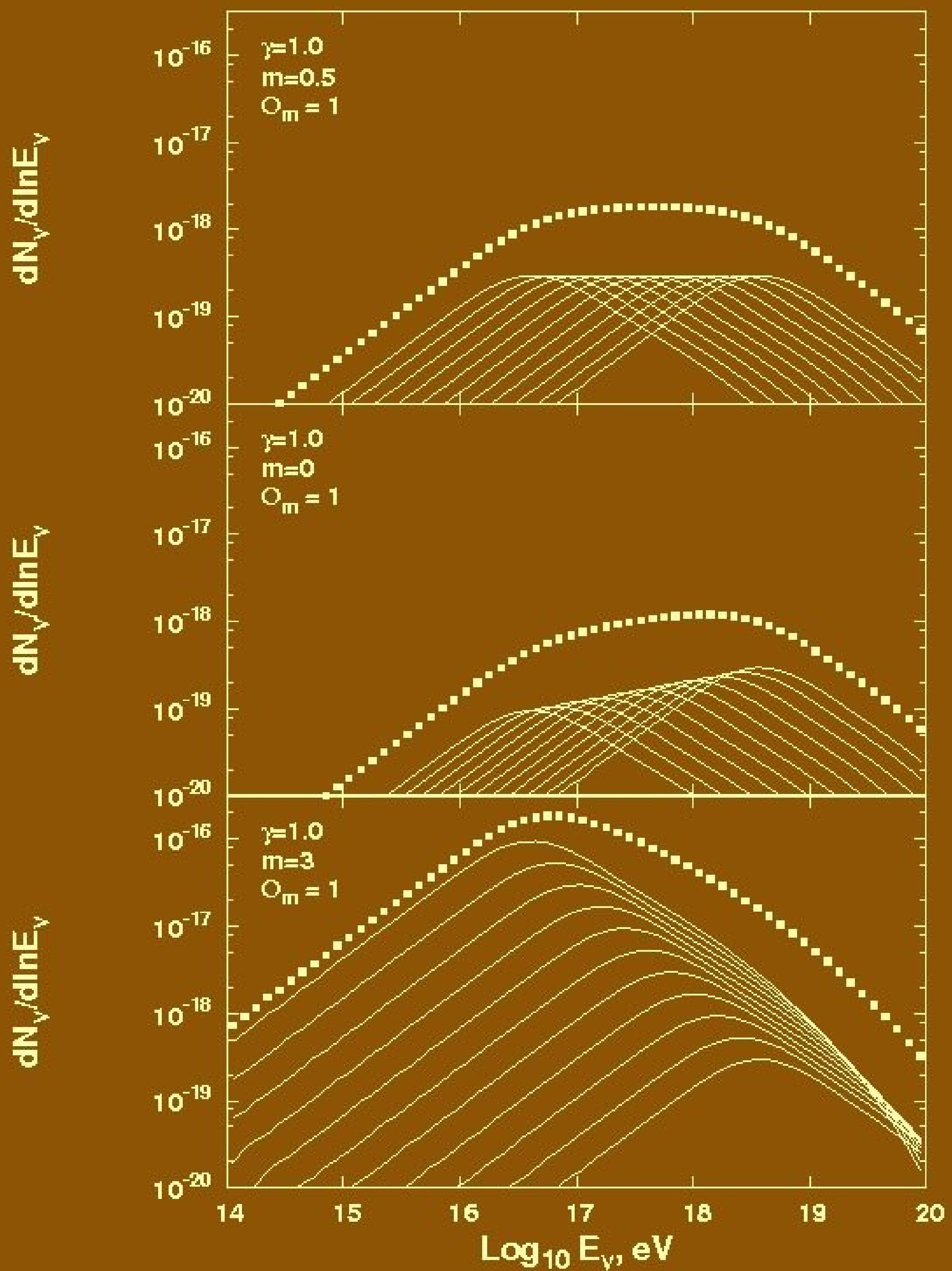
The flux of cosmogemic neutrinos at *z=0* and which is due to the cosmological evolution of cosmic ray activity can be written as

$$E_\nu \frac{d\Phi}{dE_\nu}(E_\nu) = \frac{c}{4\pi} \int dt\, d\epsilon_p \frac{d\Gamma}{d\epsilon_p} E_\nu \frac{dy}{dE_\nu}(E_\nu, \epsilon_p, t)$$

The influence of the cosmological evolution becomes much more visible if this equation is rewritten in terms of *ln q = ln(1+m)* The equation then becomes (SS)

$$E_\nu \frac{d\Phi}{dE_\nu}(E_\nu) = \frac{A}{4\pi H_0} \int_0^{q_{max}} d(\ln q)\, q^{(m+\gamma-\frac{5}{2})} E_\nu \frac{dY_{0\gamma}}{dE_\nu}(q^2 E_\nu)$$

It tells that the contribution is weighted by the sum of the cosmological evolution parameter and the index of the cosmic ray energy spectrum γ.




Illustrative examples using $\Omega_M = 1$ and cosmological evolution to z=10.

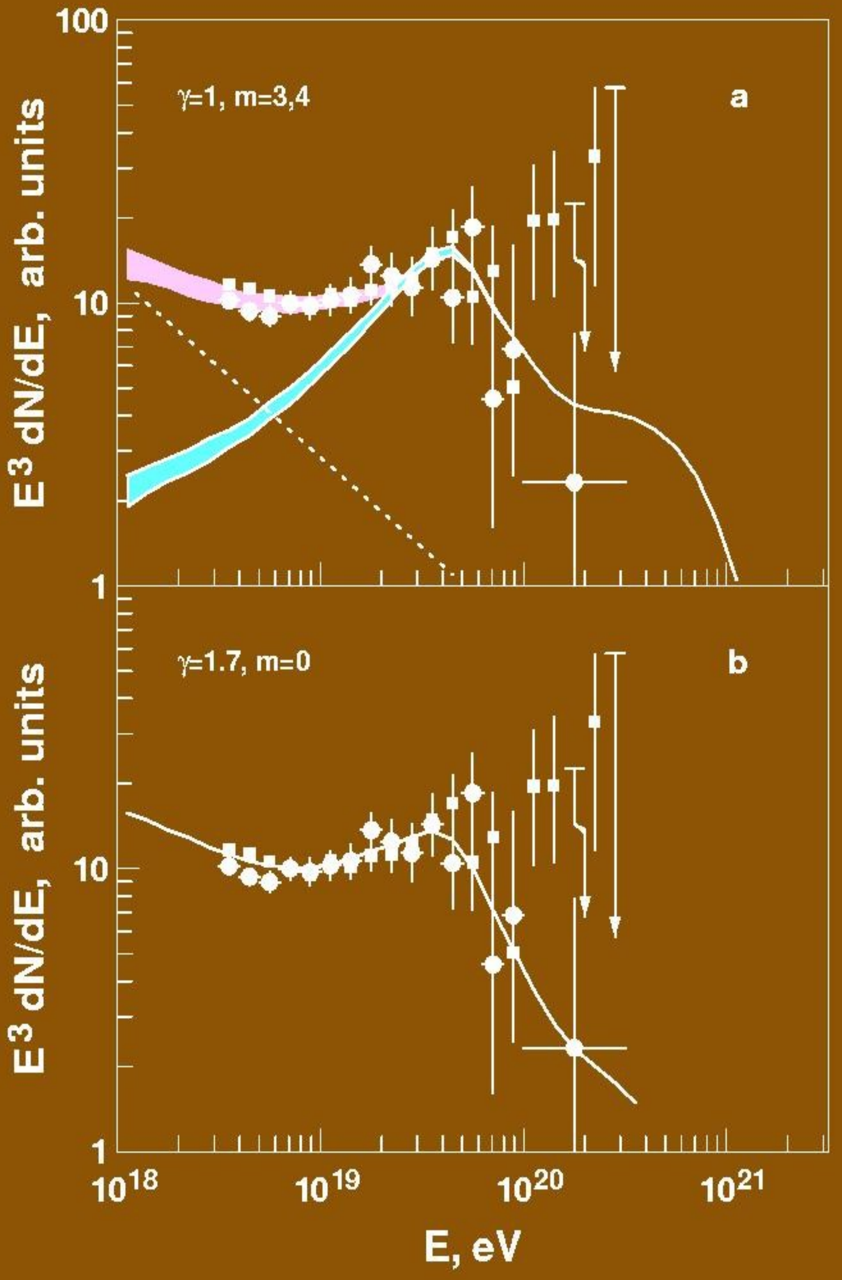
equal contribution

decreasing contribution

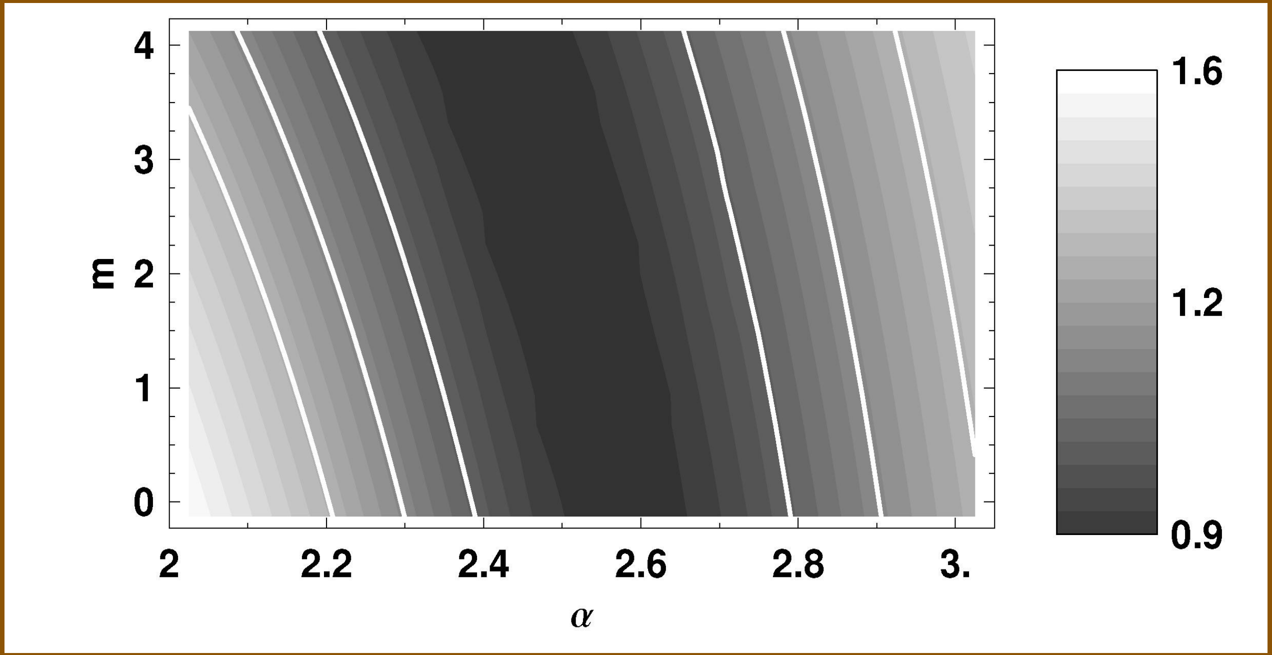
increasing contribution

From: Seckel & Stanev, 2005

We do not know what the cosmological evolution of the cosmic ray sources is. We even do not know what the cosmic ray spectrum at injection (acceleration) is. Fit *a* is the original W&B fit using flat injection spectrum as suggested in acceleration models. Galactic cosmic ray spectrum extends to 10 EeV



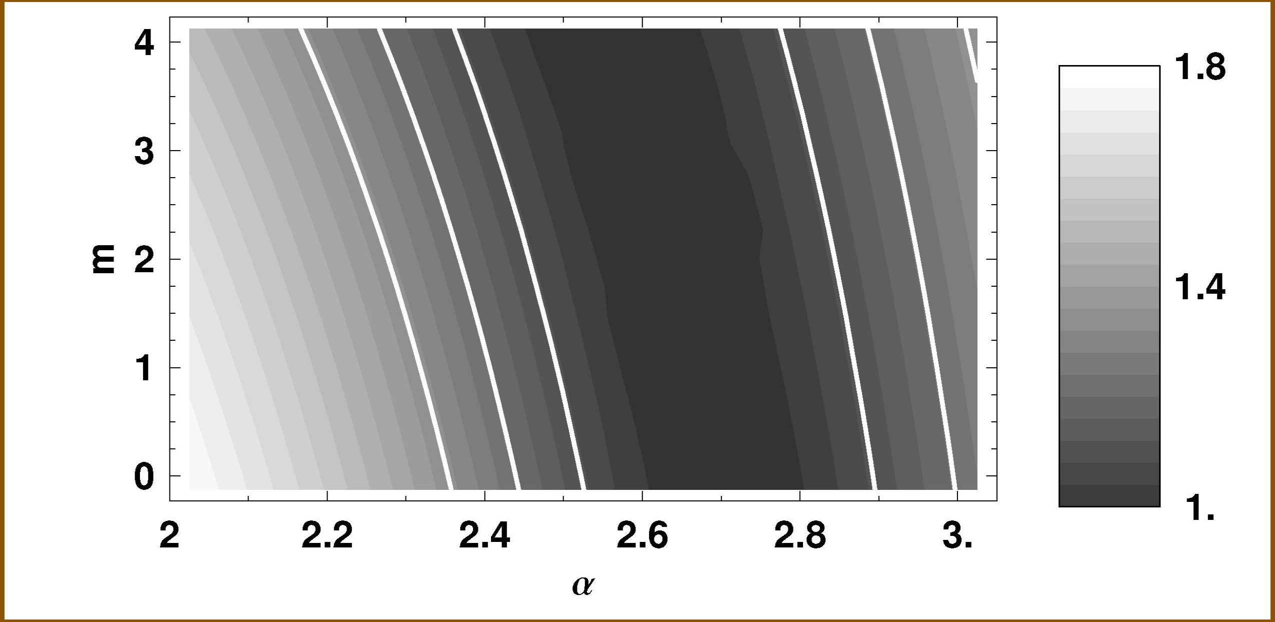

Most contemporary fits favour steeper injection spectra. Fit *b* (originally suggested by Berezinsky and co- authors) explains the observed spectrum down to 1 EeV and below. The dip is caused by the pair production process. This model does not need cosmological evolution of the cosmic ray sources.




AGASA

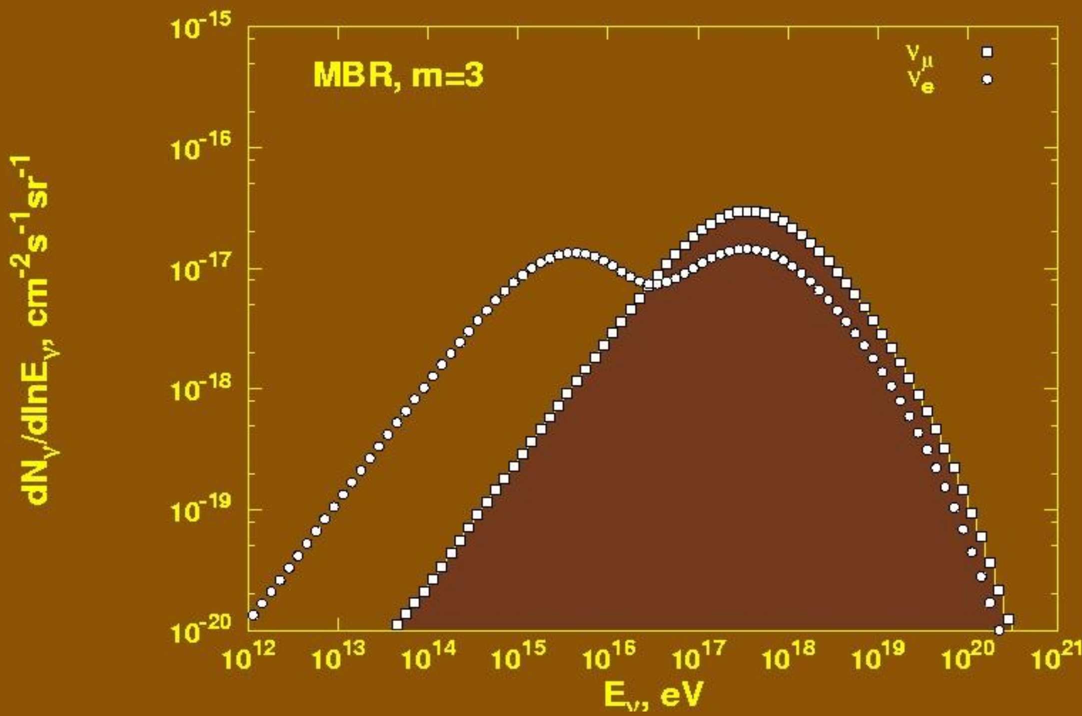
The darker the area is the better the fit. White lines indicate 1σ errors.

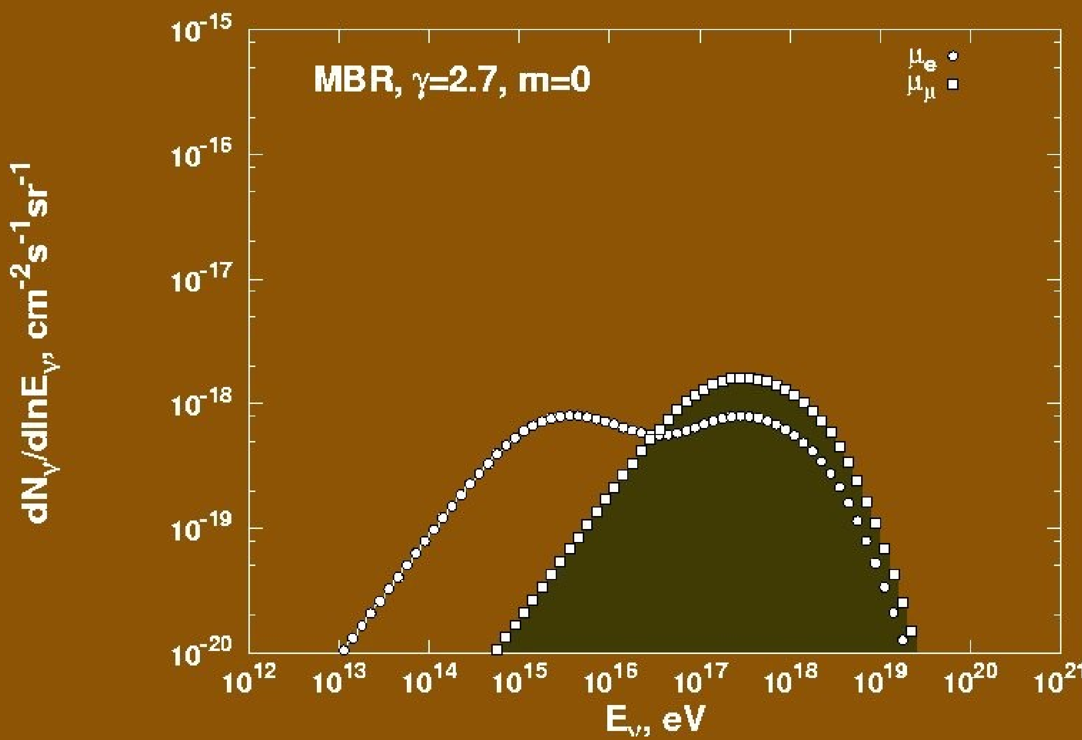
Fits of the spectra above $10^{19}$ eV <u>only</u>




HiRes

From: DeMarco & Stanev



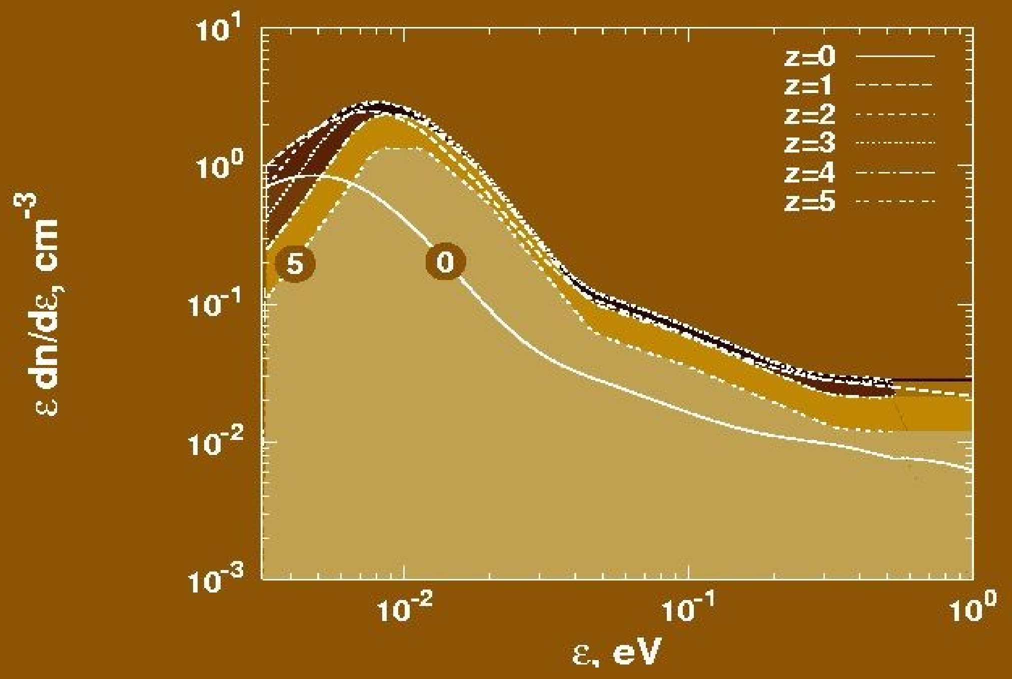




In the case of flat injection spectrum cosmogenic neutrino production is much higher for two reasons:

- there are more protons above the interaction threshold for the same CR luminosity of the sources.
- flat injection spectra do require strong cosmological evolution of the cosmic ray sources to fit observations, while steep injection spectra do not need it.

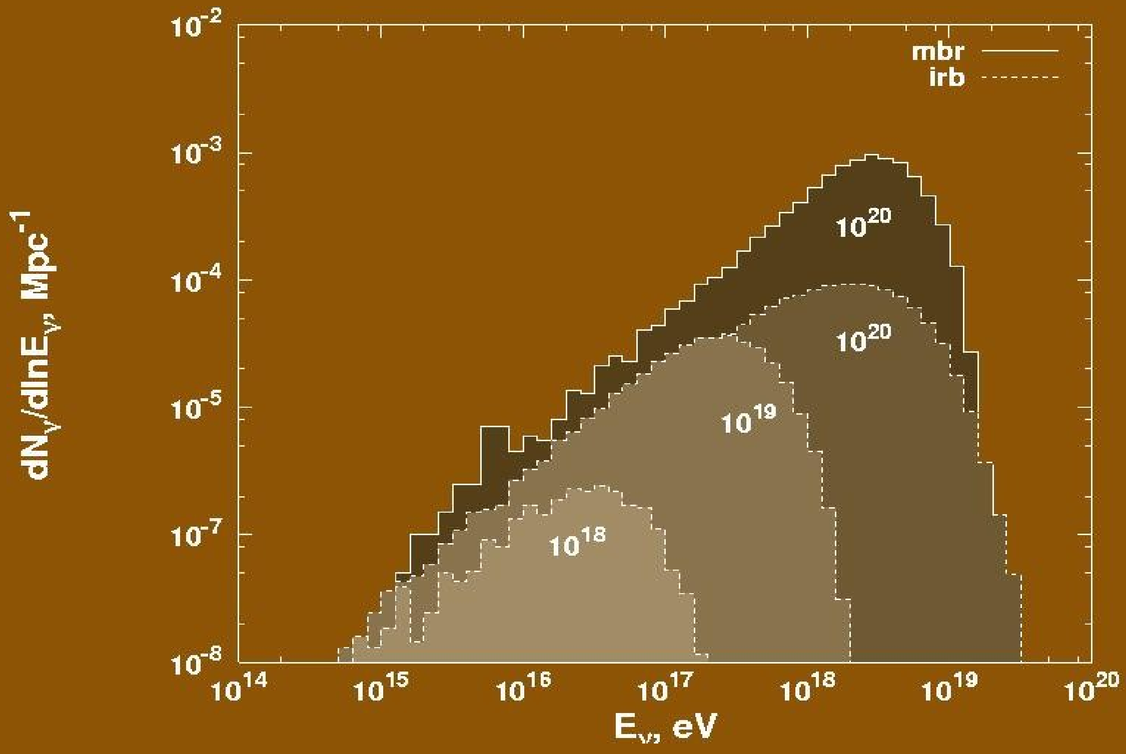
The difference between these two predictions in production of cosmogenic neutrinos is 1 ½ orders of magnitude.

**NOT THE END OF THE STORY:** The microwave background is NOT the only universal photon field. The universal infrared background occupies the energy range between MBR and the optical/ UV one. The near infrared has also been derived from multi- TeV gamma ray observations. The far infrared is being observed by infrared missions, the most current one is the Spitzer Space Telescope.



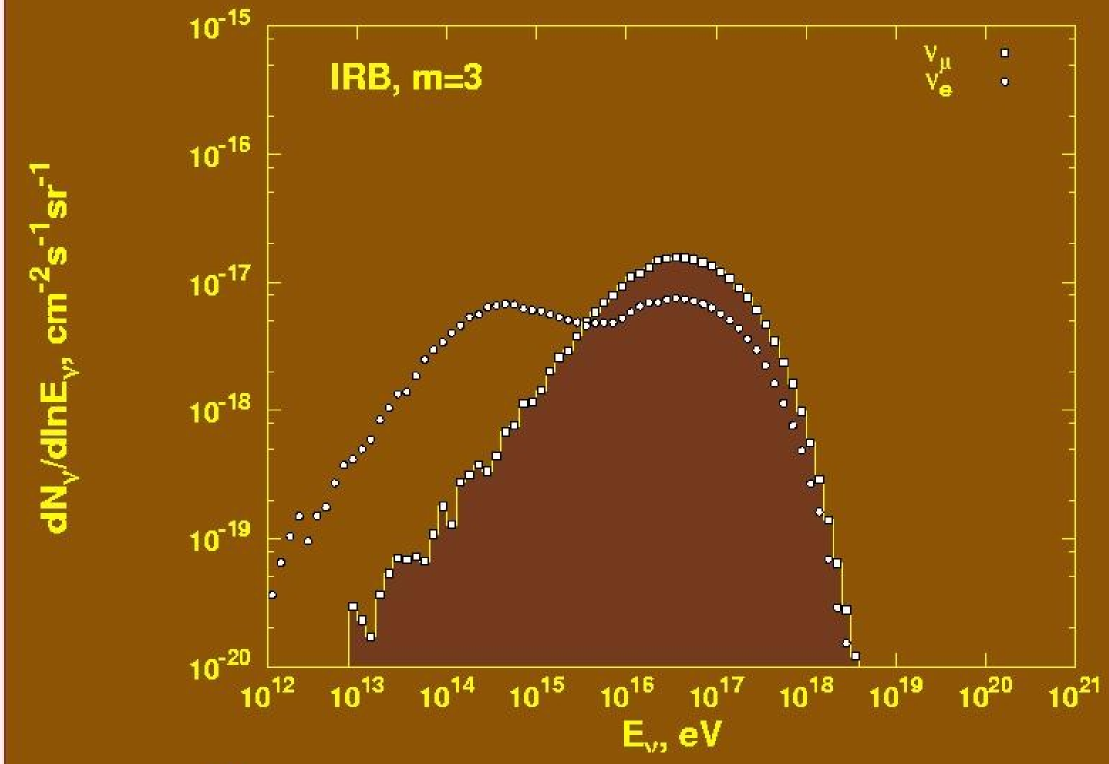

The current density of the IR background is about 1 $cm^{-3}$. Its energy is much higher than MBR and lower energy cosmic rays interact in it.

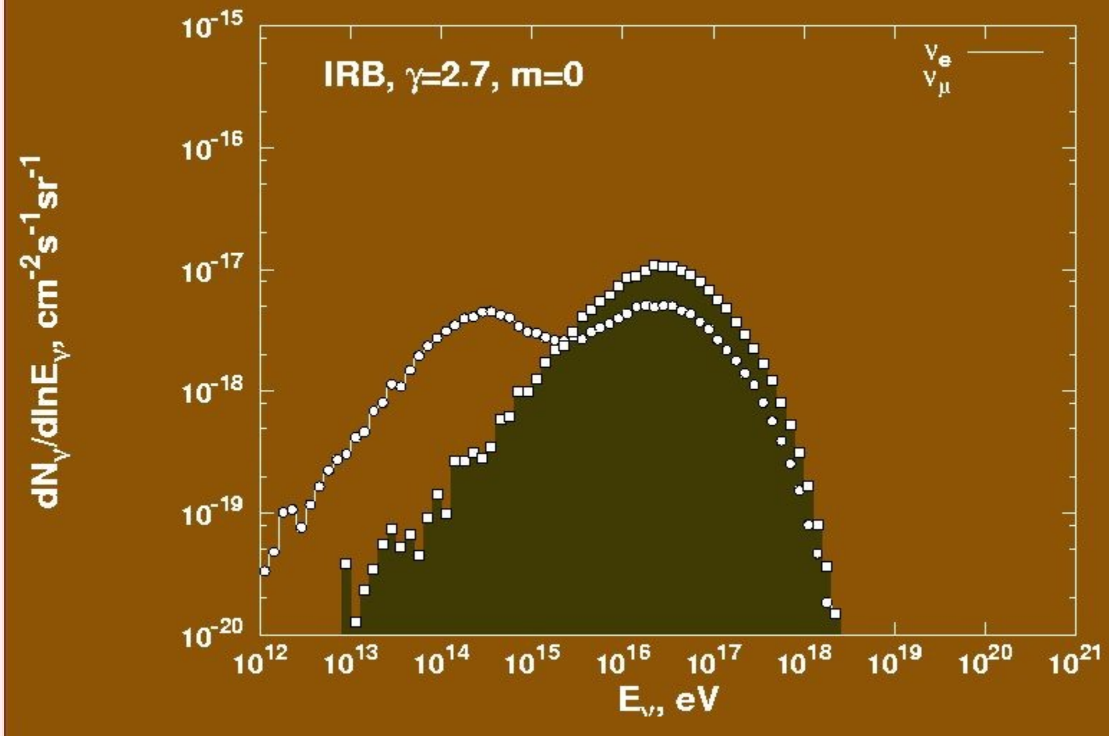
The graph on the left also shows IRB cosmological evolution in the model of Malkan&Stecker.



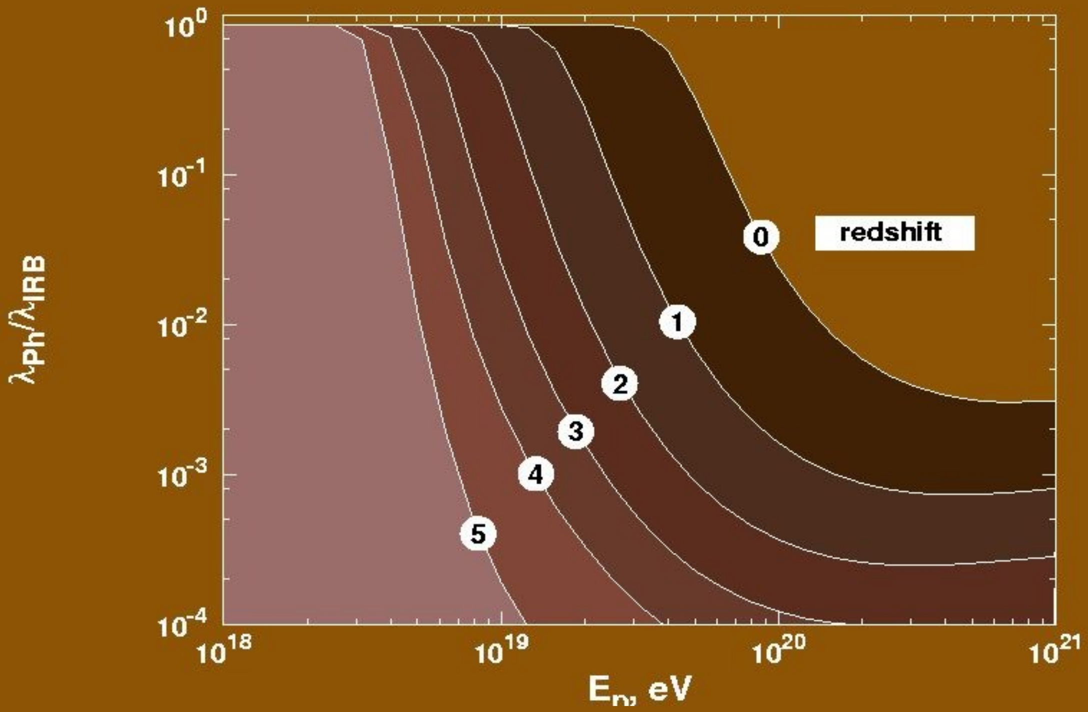

Yield of muon neutrinos from proton propagation on distance of 1 Mpc.

At $10^{20}$ eV the neutrino yield in the infrared background is smaller by about one and a half orders of magnitude only because of the higher target energy. $10^{19}$ eV protons do not interact in the MBR, while even $10^{18}$ eV ones interact in the IRB. These yields have to be scaled up by factors of at least 10 and 100 because of the increasing number of protons in the cosmic rays. Scaling is much stronger for steep injection spectra.



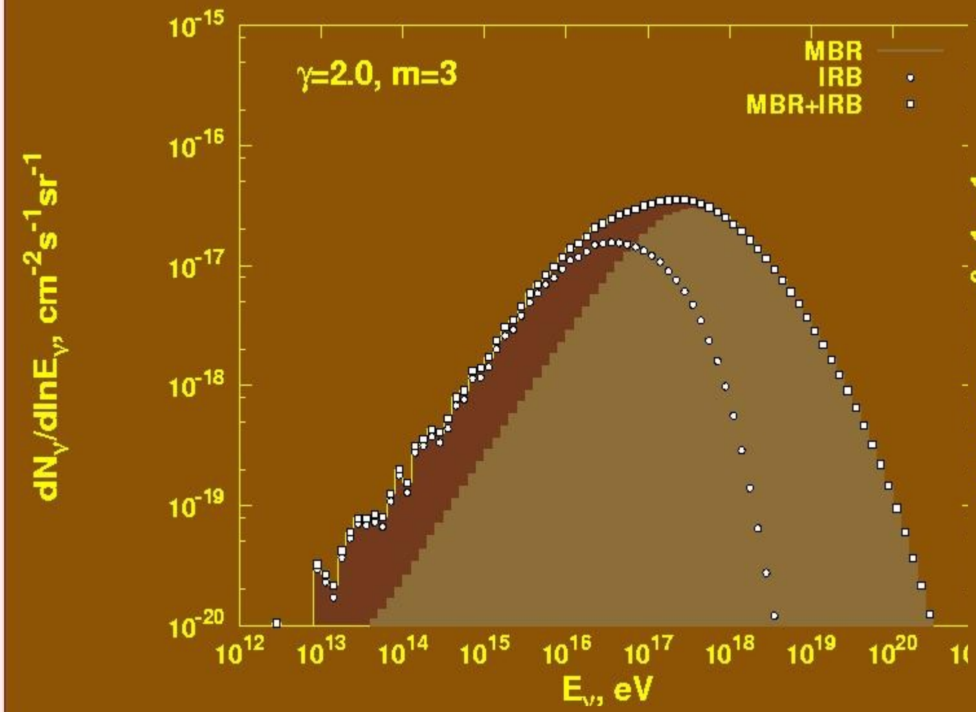



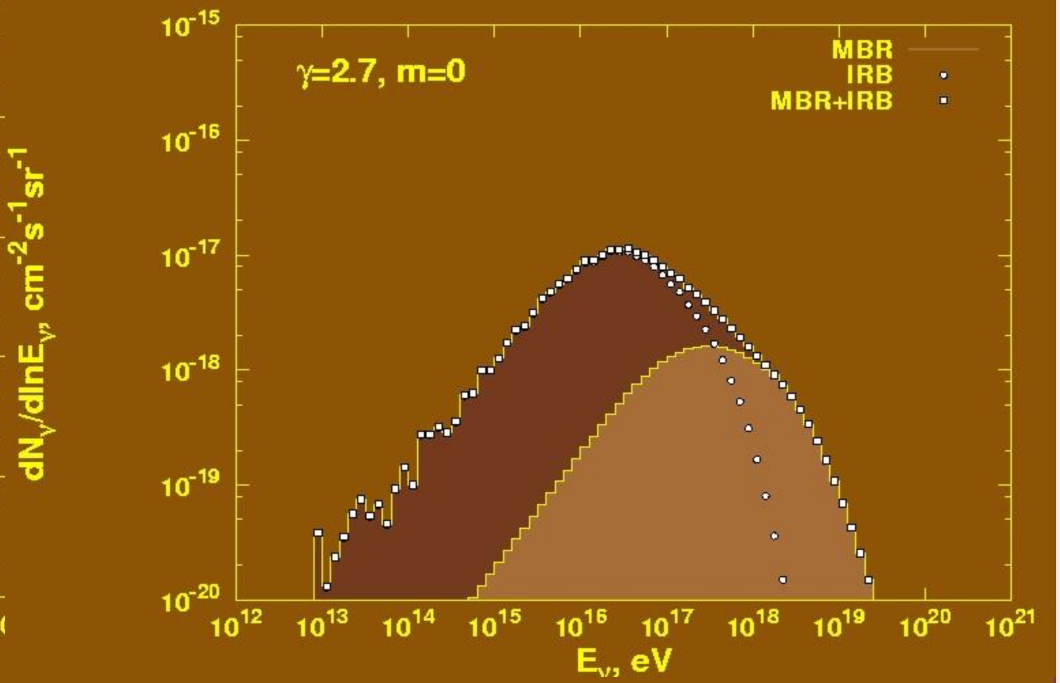

In the case of interactions in the IRB the difference between different cosmological evolutions can be compensated by the larger number of interacting protons. In case of m= 3 the difference was a factor 30 for MBR target – it is now only about a factor of 2. The neutrino energy distribution is somewhat narrower as high *z* contributions are not weighted heavier.




At redshift 0 interactions in IRB dominate to $3.10^{19}$ eV. This energy range decreases with redshift because of the stronger cosmological evolution of MBR.

To add the contributions from MBR and IRB one can either perform a calculation in the total background at different redshifts or (as done here) weight the two fluxes with the interaction lengths in the two backgrounds as a function of redshift.

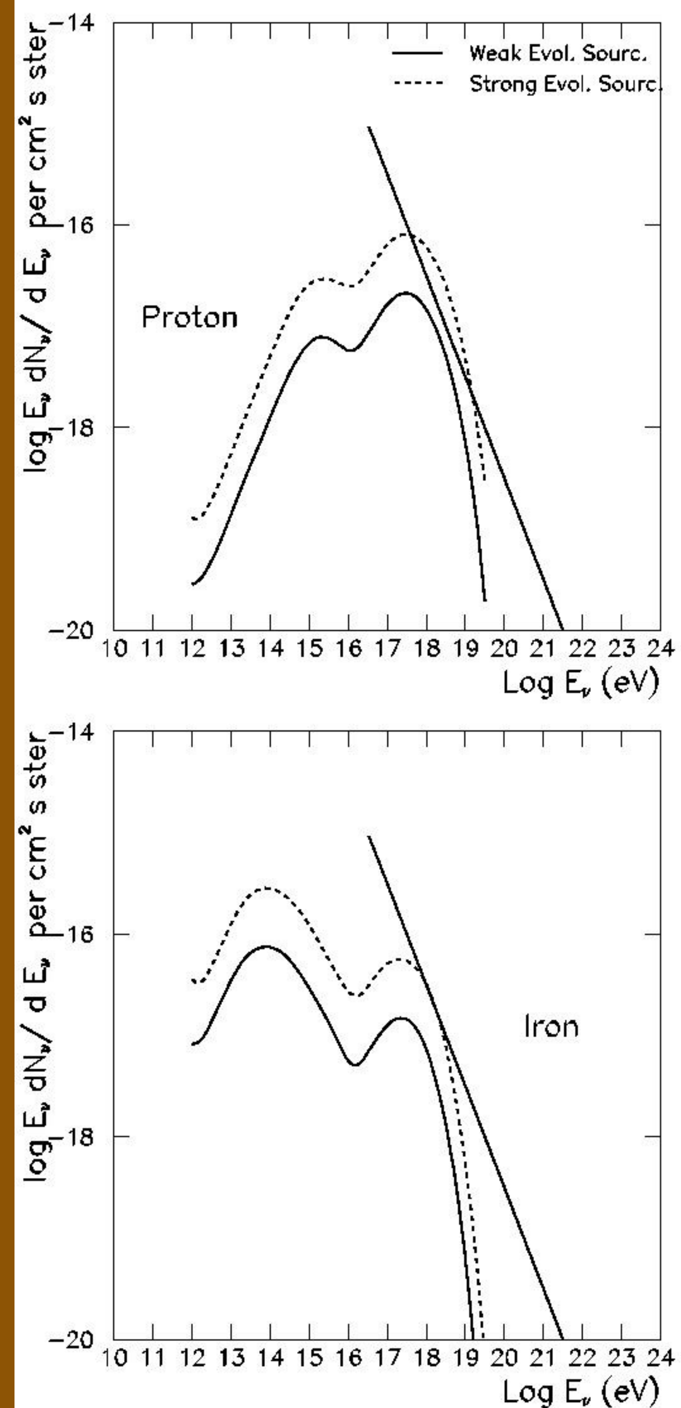



The cosmogenic neutrino spectra generated by the two extreme models of the injection spectra of UHECR protons in case of isotropic homogeneous distribution of the cosmic ray sources. The big difference in case of ` MBR only' interactions is somewhat compensated by the interactions in IRB. The interaction 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.

## WHAT 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

Even with the forthcoming much more exact measurements of the UHE cosmic ray spectrum it will be difficult to reconstruct the acceleration spectra of these particles and define better their sources.  A measurement of the cosmogenic neutrinos will reveal the cosmological evolution of the  sources, and thus eliminate one of the unknown parameters. The informaton carried by neutrinos reflects much better the cosmological history of cosmic rays than they do themselves.

Cosmic ray interactions in the IRB compensate to certain extent for the lack of evolution in the steep injection spectrum models. Steep spectra with evolution will, however, increase the cosmogenic neutrino fluxes even more.