High energy neutrinos and cosmic rays

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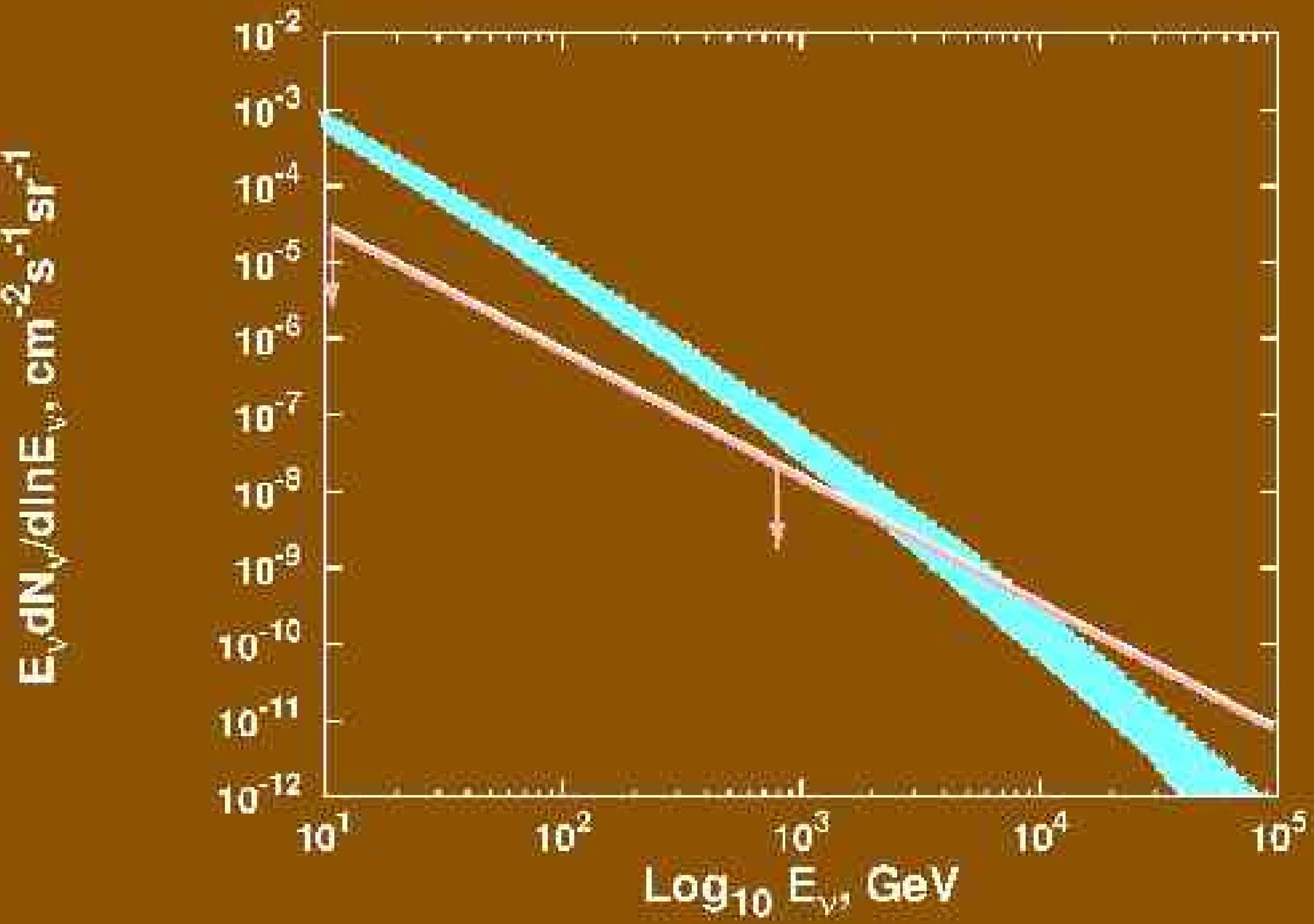
We present an analysis of the relation of the flux of cosmogenic neutrinos and the injection spectra of cosmic rays. The flux of cosmogenic neutrinos is very closely related to the cosmological evolution of the cosmic ray sources. This research is a continuation of the work started here at Fermilab 20 years ago by Cris Hill & David Schramm. We also discuss UHE proton interactions on the infrared backgound.

This work is performed in collaboration with Daniel DeMarco, David Seckel and Floyd Stecker.



When we do not know what else to do the cosmic ray spectrum can be used to figure out what the neut-rino expectations are.

The straight line with arrows shows the neutrino spectrum generated by galactic cosmic rays if every 1/100'th cosmic ray interacted on galactic matter. This would correspond to cosmic rays spending 7×10^5 years in density n=1, i.e. in the Gallactic disk.

The flux of extragalactic neutrinos can be connected to the UHECR flux in UHECR are also of extragalactic origin as 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

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

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

$\epsilon < 1$ is assumed energy independent

E_ν assumed 1/20 of E_p

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

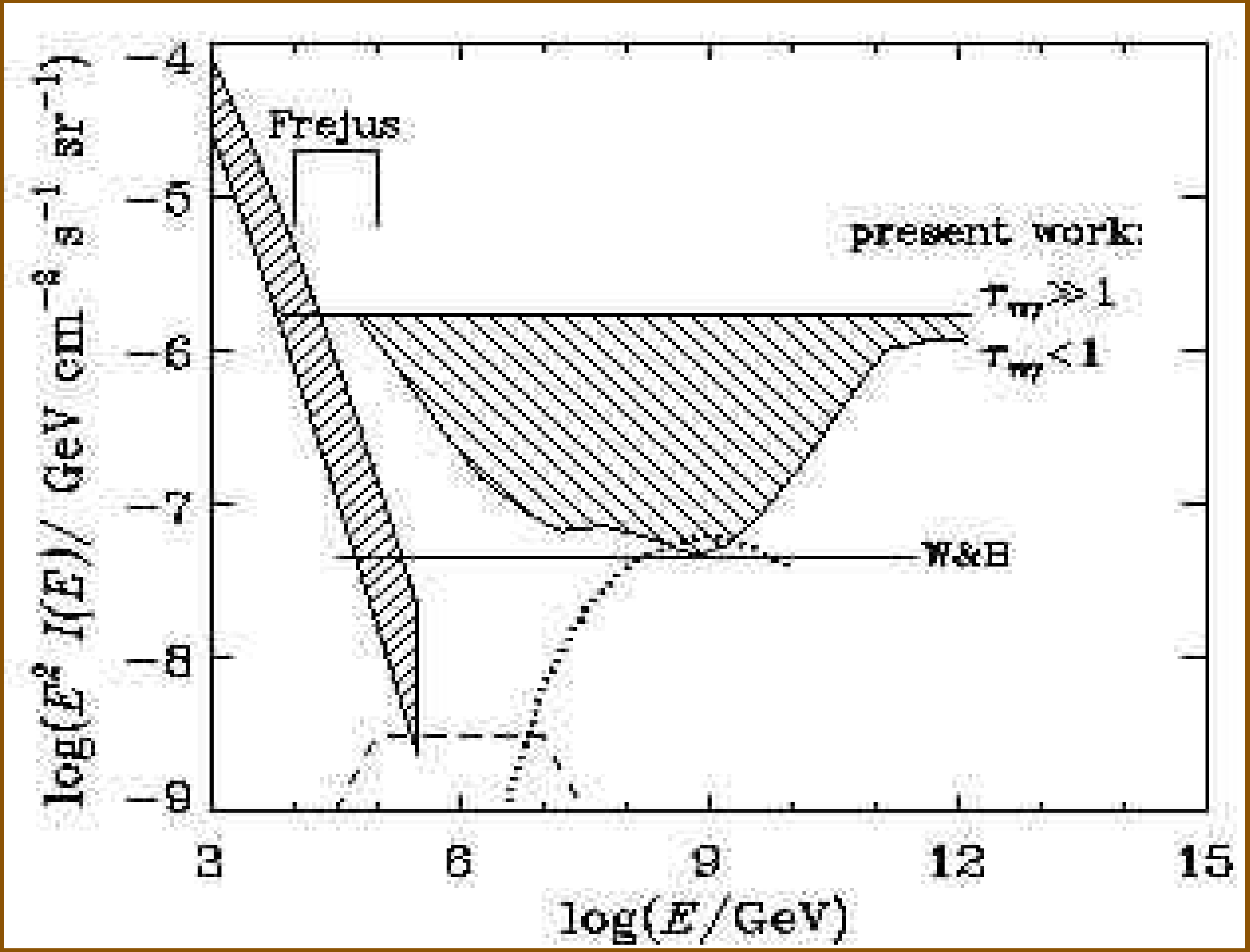
$I_{max} \simeq \frac{t_H}{4} \xi_Z \frac{c}{4\pi} E^2 \frac{dN}{dE}$

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

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

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.



From Mannheim, Protheroe & Rachenn

The dashed line represents W&B model for neutrino production in GRB and the dotted line is Mannheim's model for neutrino production by active galactic nuclei.

We are not going to discuss neutrino production at astrophysical systems, that are subjects of the W&B limit. We will discuss the relation of cosmogentic neutrinos and the power and energy spectrum of the extragalactic cosmic rays and the cosmological evolution of their sources.

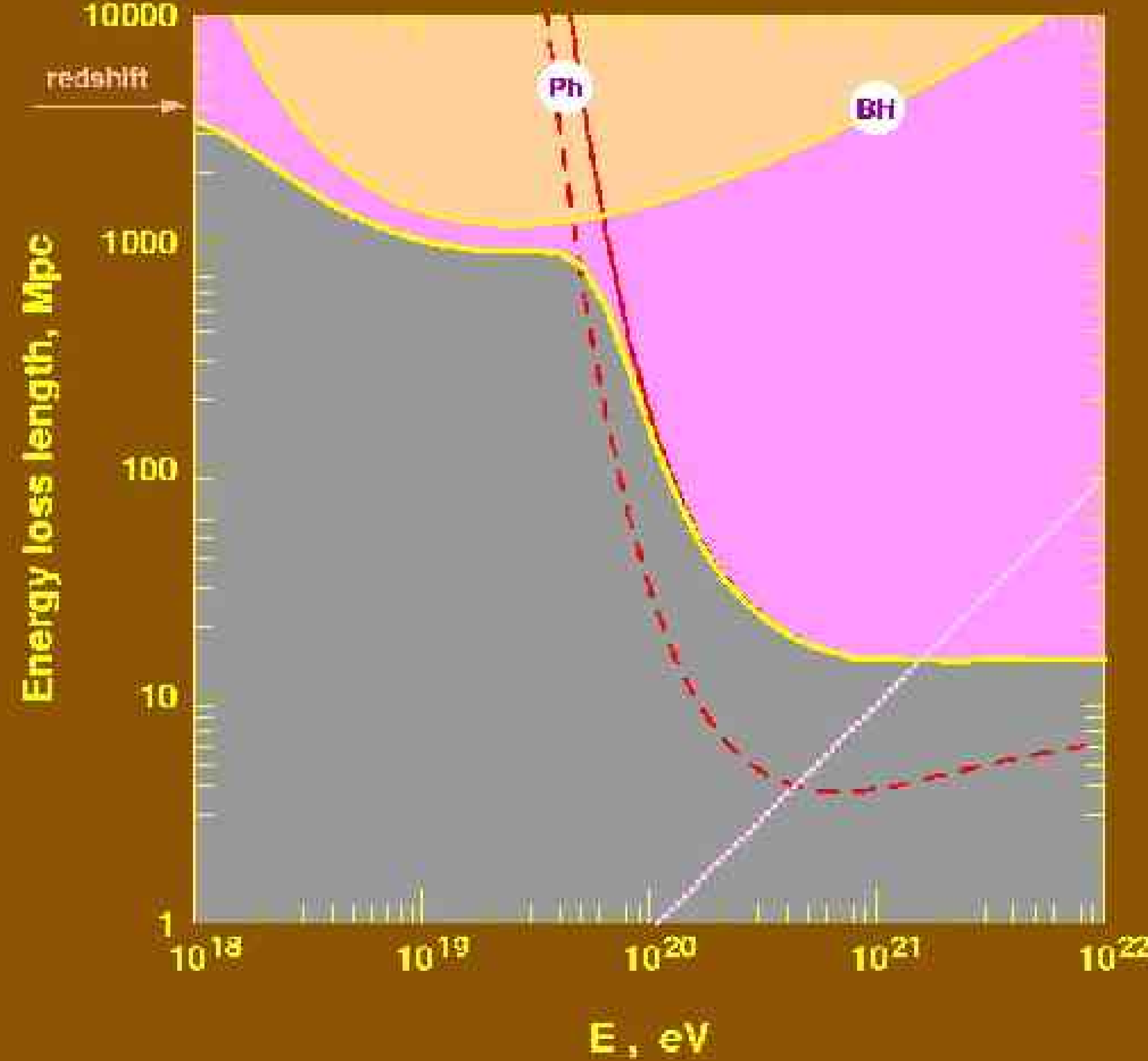
Cosmogentic neutrinos: neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation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

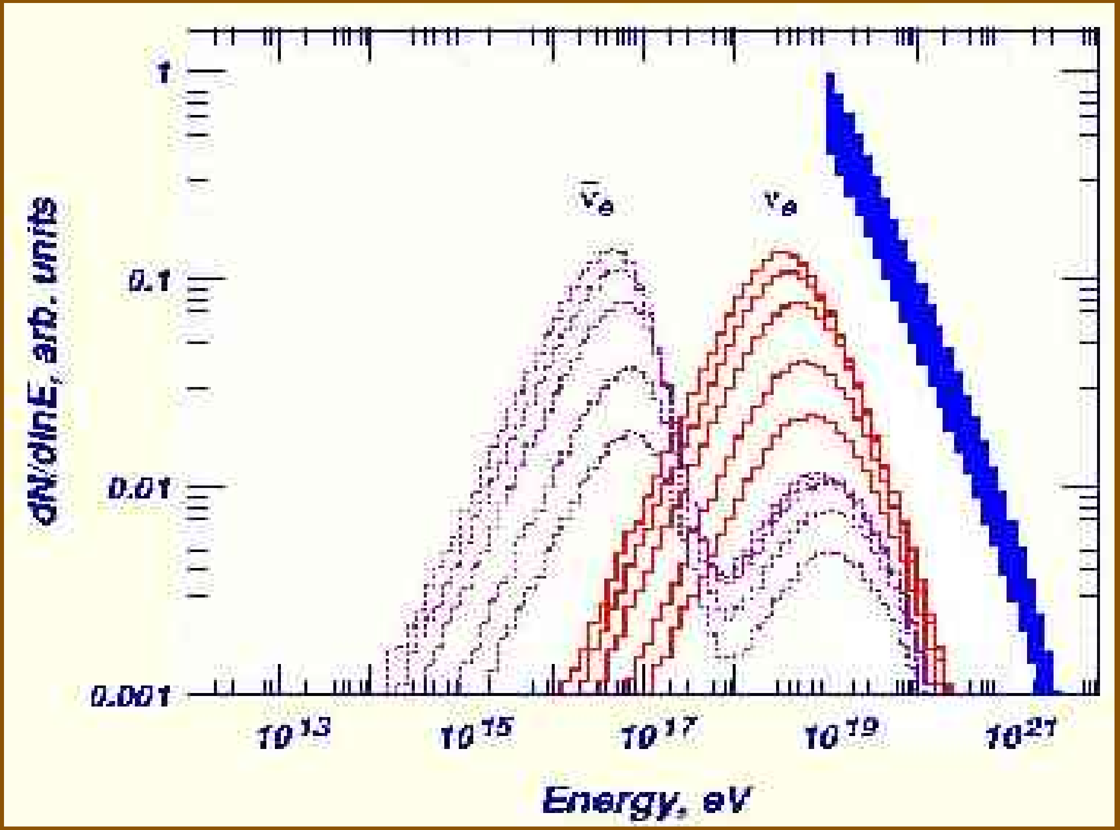
The photoproduction energy losses of the extragalctic cosmic rays cause the GZK effect – an absorption feature in their spectrum.



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

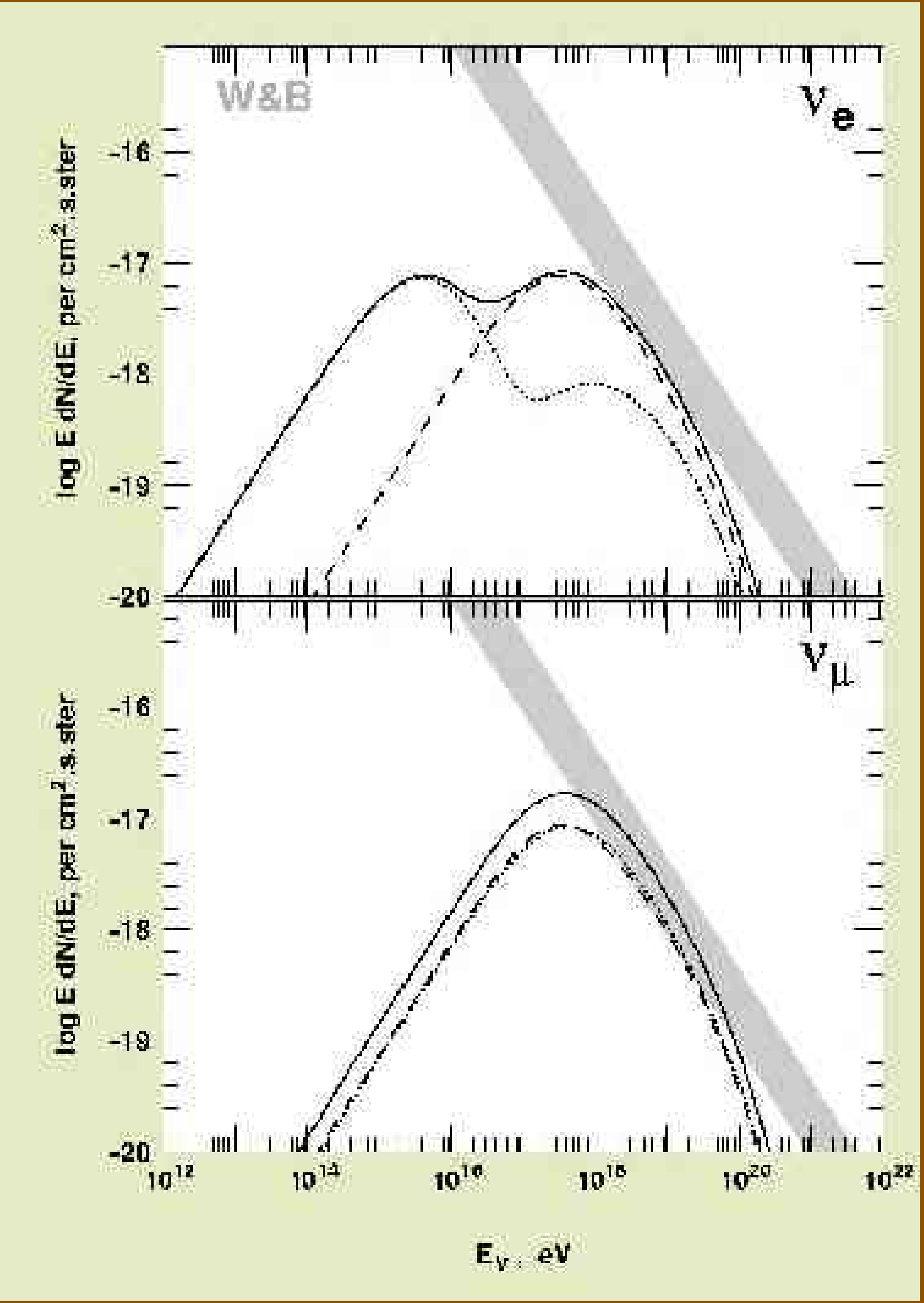
The pile up at the approach of 100 EeV is due to the decrease of energy loss from photoproduction to BH pair creation.

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



The figure shows the fluxes of electron 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).

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 strip. Its lower edge indicates no cosmological evolution of the sources, and the upper edge is for $(1 + z)^3$ evolution. (O_M = 1 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.

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

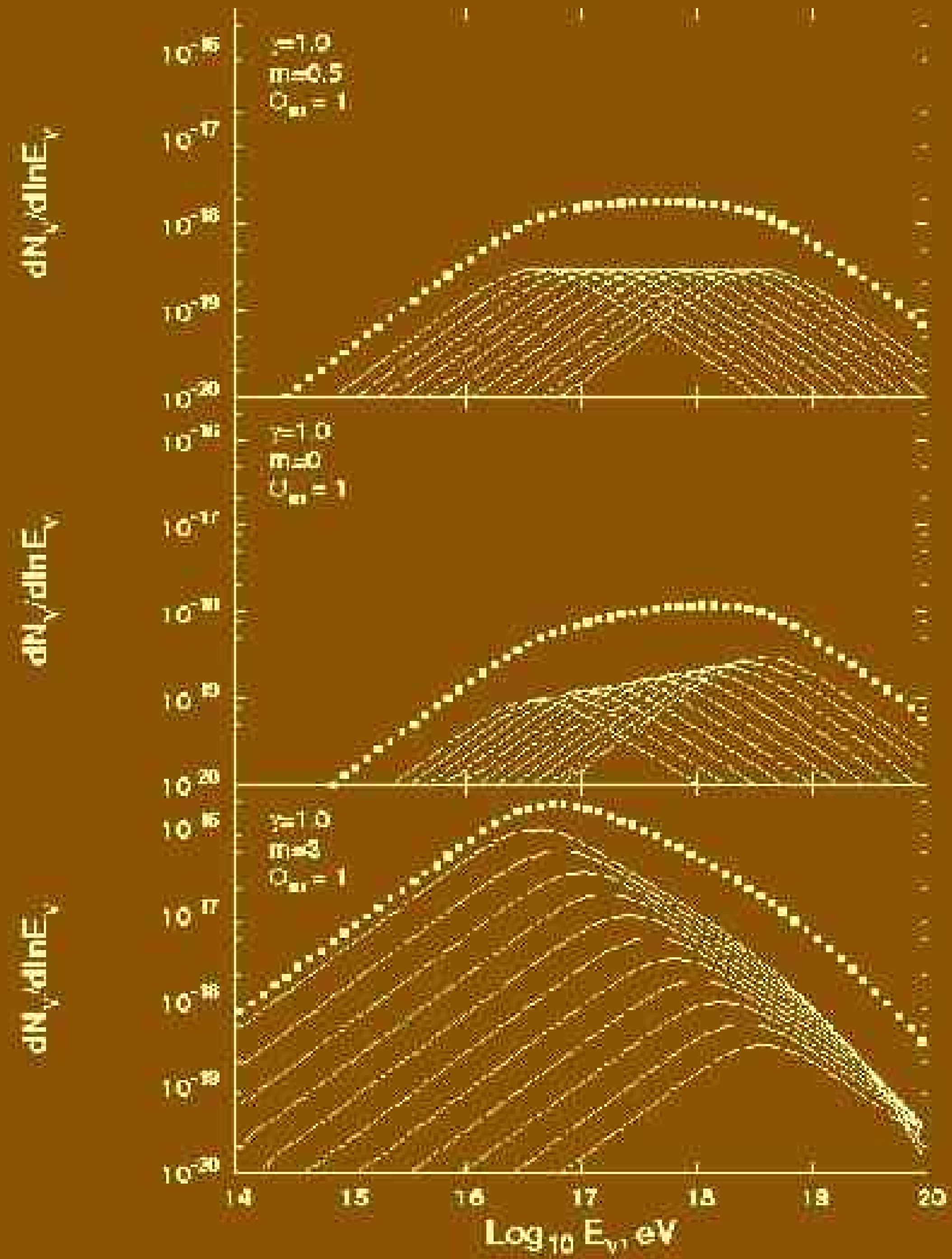
$$E_\nu \frac{d\Phi}{dE_\nu}(E_\nu) = \frac{c}{4\pi} \int dt d\epsilon_p \frac{d\Gamma}{d\epsilon_p} E_\nu \frac{dy}{dE_\nu}(E_\nu, \epsilon_p, t)$$

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)

$$E_\nu \frac{d\Phi}{dE_\nu}(E_\nu) = \frac{A}{4\pi H_0} \int_0^{q_{max}} d(\ln q) q^{(m+\gamma-\frac{8}{3})} E_\nu \frac{dY_{0\gamma}}{dE_\nu}(q^2 E_\nu)$$

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.

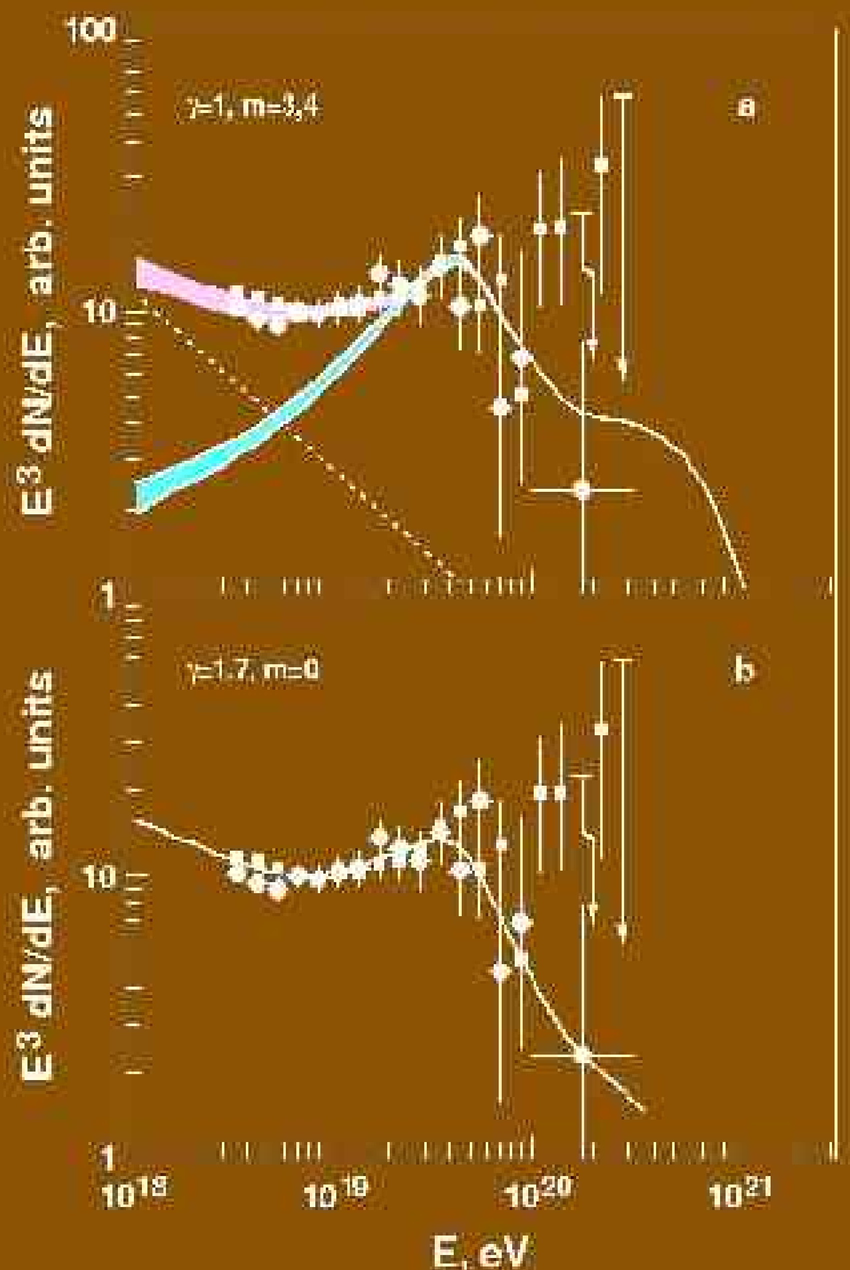


equal

decreasing

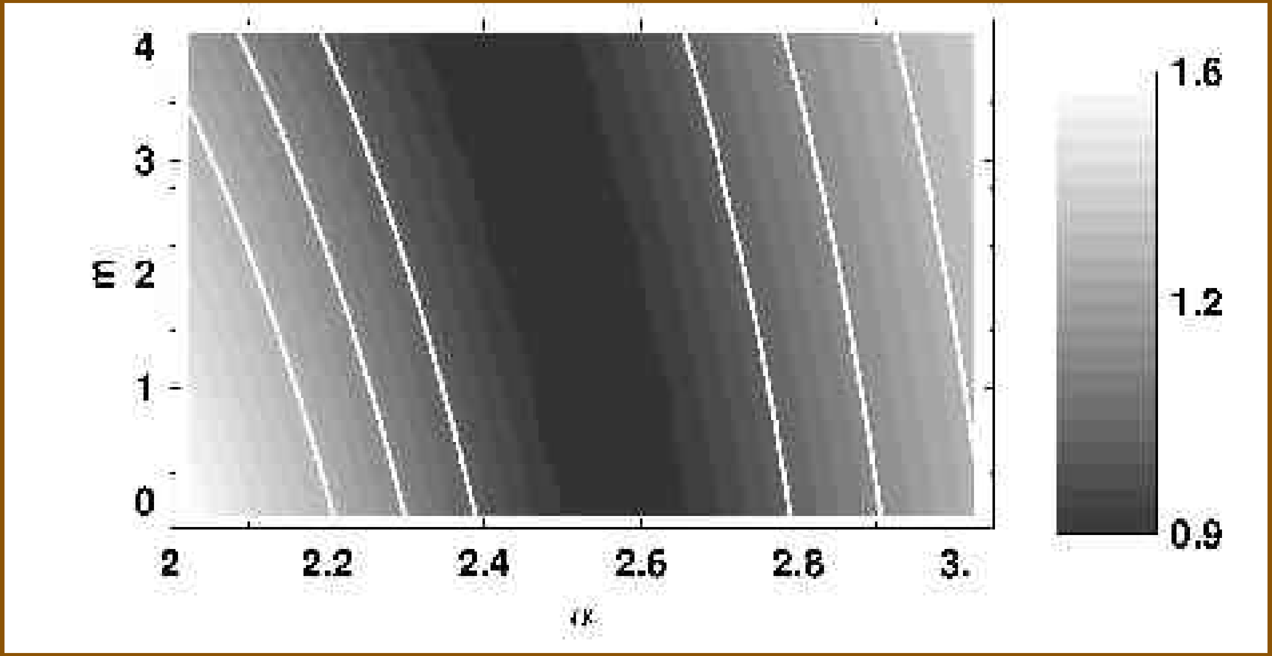
increasing

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).



Strong shocks are supposed to accelerate cosmic rays on flat spectra, but most of the current fits of the observed spectra give much steeper spectra, similar to the case *b.*

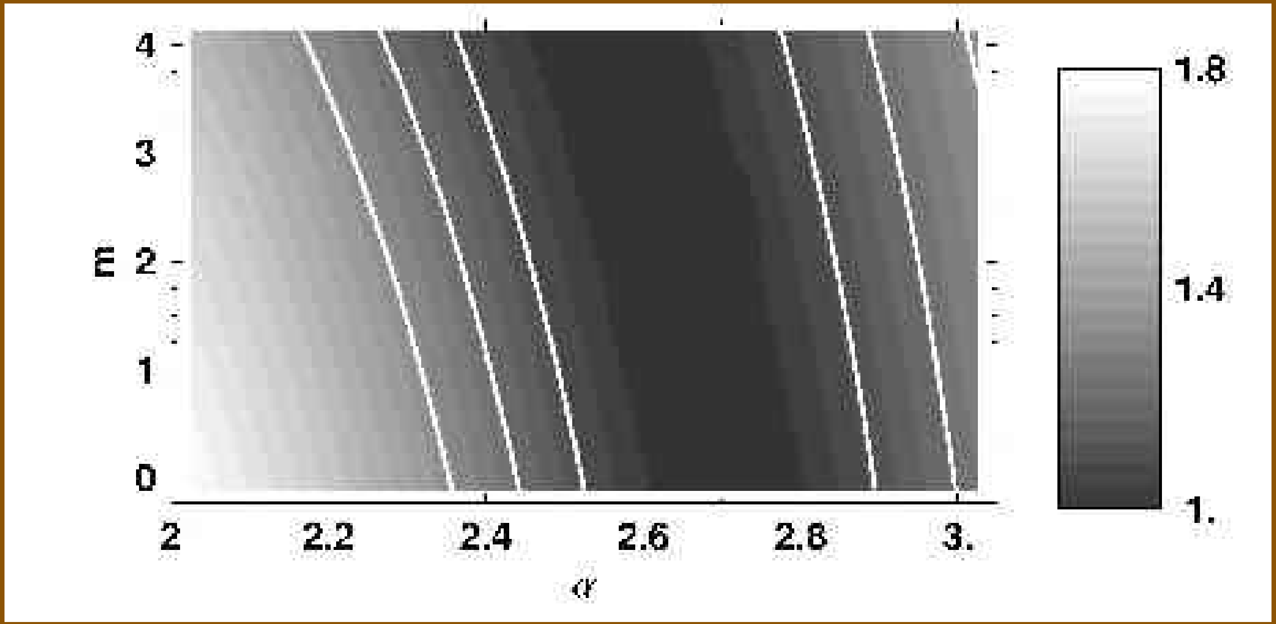
Case *a is* a fit with flat injection spectrum – galactic cosmic rays extend to 10 EeV.



AGASA

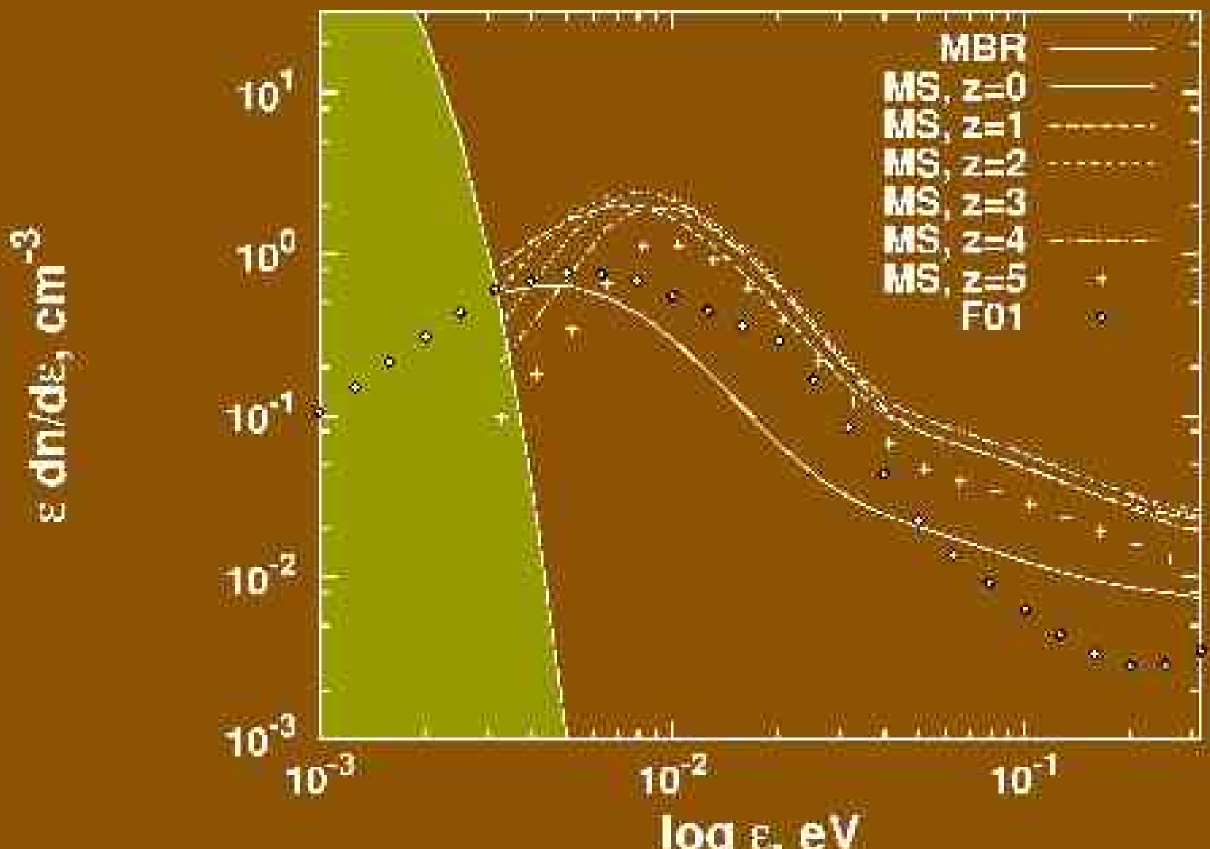
The darker the area is the better the fit. White lines indicate 1σ errors.

Fits of the spectra above 10^{19} eV

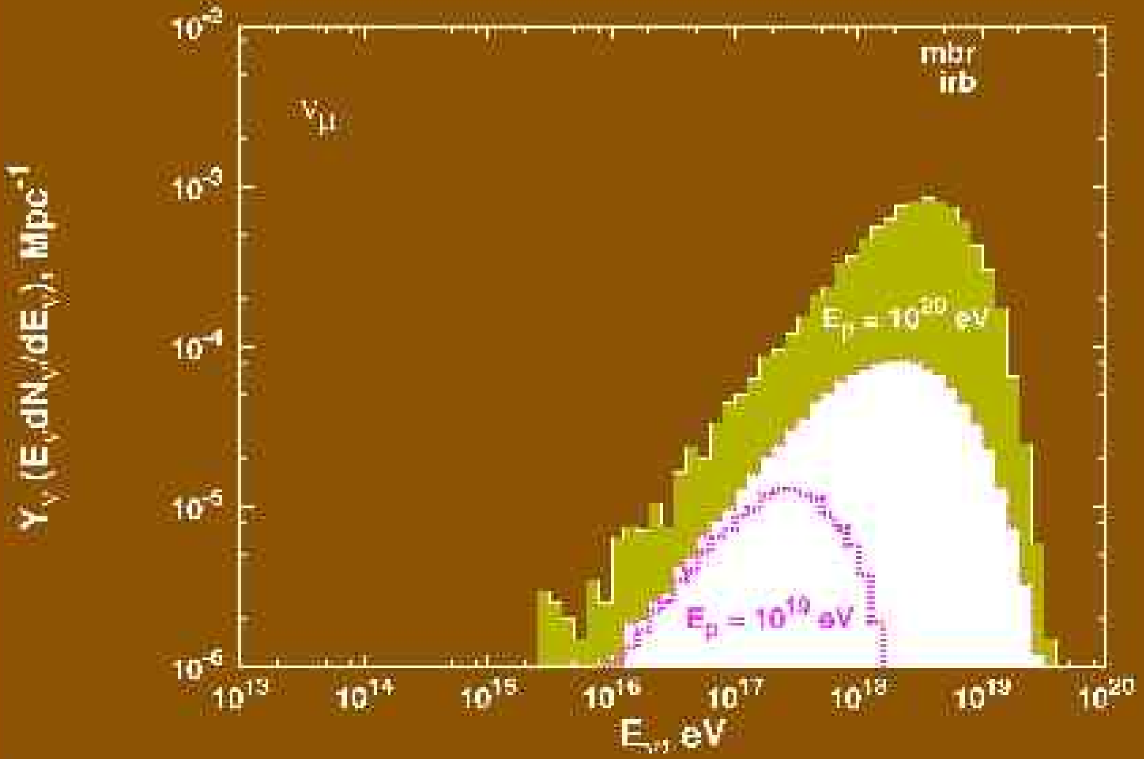


HiRes

The steeper cosmic ray spectra are, the more important are cosmic ray interactions on different photon backgrounds. The infrared spectra shown below as a function of redshift come from the new work of Malkan&Stecker.

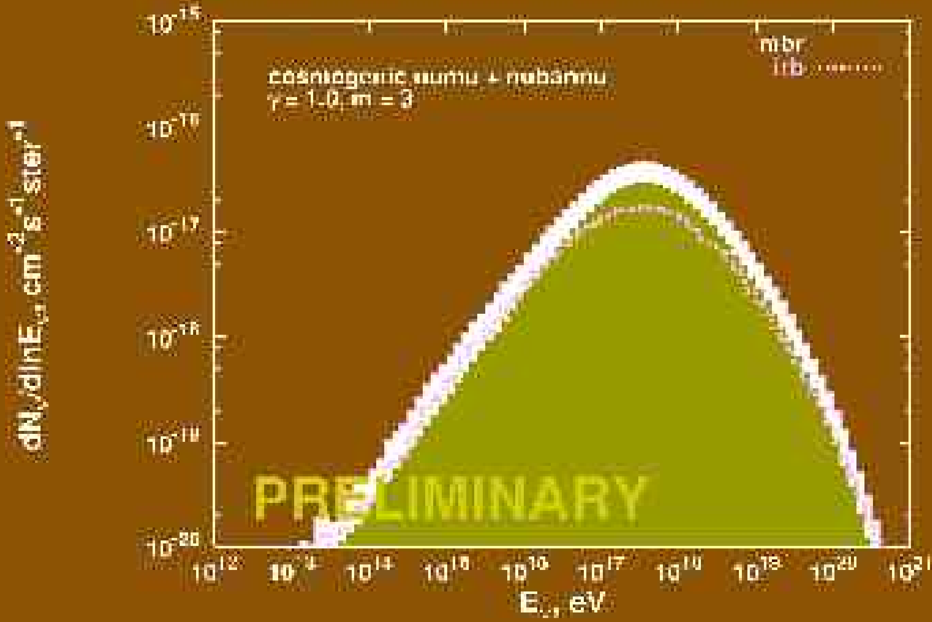


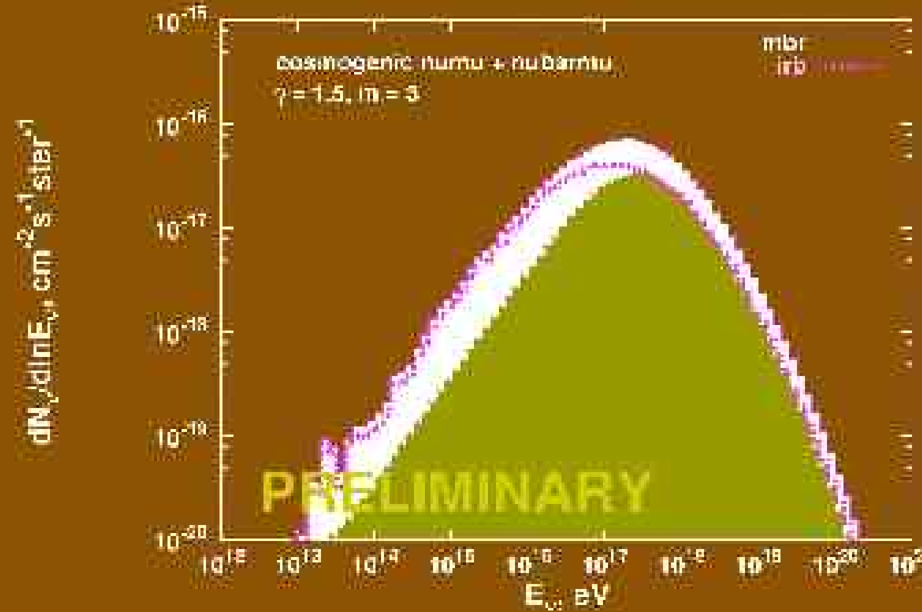
When the photon field is a target, the number density is the most important parameter.



The yields peak at the same neutrino energy, but the IR target generates a wider neutrino spectrum, because of its own spectra extension.

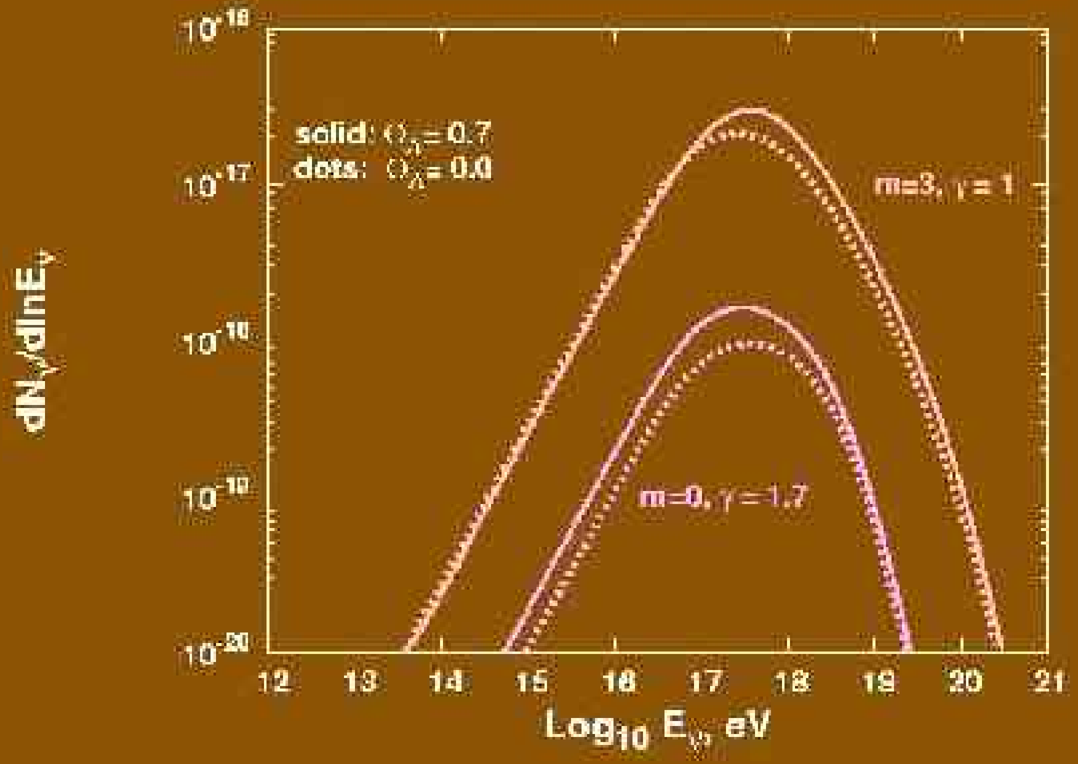
Yields per Mpc of propagation of muon neutrino production by protons of energy 10 and 100 EeV. The yields at 100 EeV are much higher on the MBR, but there are no yields for 10 EeV protons. Even for flat injection spectra the 10 EeV yields have to be scaled up by a factor of ten.





Cosmogenic neutrino fluxes from interactions on the microwave and in the infrared background for flat (left hand graph) and relatively steep cosmic ray flux – work in progress (DeMarco, Malkan, Stanev, Stecker)ote

Note: the MS infrared background does not give maximum cosmogenic neutrino flux. Other IR models could generateup to up to 50% more neutrinos.



The calculation including the infrared background will be finished this month. This one is only for MBR.

These are the fluxes of cosmogenic neutrinos generated by the two `extreme' fits of the UHE cosmic rays spectrum presented earlier. The shape of the spectra depends a little on the injection spectra, but the main difference is the cosmological evolution of the cosmic ray sources. Steep injection spectra do not require (but do not exclude) strong cosmological evolution. The currently preferred cosmological model increases the spectrum by less than a factor of 2.

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. A measurement of the cosmogenic neutrinos will reveal the cosmological evolution of the cosmic ray sources, and thus eliminate one of the unknown parameters in the fitting of the UHECR acceleration spectrum and thus help the identification of their sources. The informaton carried by neutrinos reflects much better the cosmological history of cosmic rays than they do themselves.

It is important to include all isotropic photon backgrounds in such calculations.