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Summer School on Particle Physics in the LHC Era

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Astroparticle Physics - IV

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Announcement

The next session of the ISCRA (International School of Cosmic Ray Astrophysics) will be in July 11-18 in the Centre for Scientific Culture in Erice, Sicily. All interested can google ISCRA (at lsu.edu) and contact me (stanev@bartol.udel.edu) or John Wefel (wefel@phunds.phys.lsu.edu) for more information.

High energy neutrinos and ultrahigh energy cosmic rays

Waxman & Bahcall attempted to use the extragalactic cosmic rays luminosity to set an upper limit on the fluxes of high energy neutrinos. Setting the limit requires assuming UHECR luminosity of the Universe, injection spectrum of UHECR and cosmological evolution of the cosmic ray sources.
W&B assumptions are

L_{UHECR} = 4.5 10^{44} erg/Mpc^3/yr above 10 EeV

injection spectral index of 2

$(1+z)^3$ cosmological evolution of the sources to z=1.8

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}

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

$\varepsilon \; < 1$ is assumed energy independent

E_ν 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.

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

MANNHEIM, PROTHEROE & RACHEN :

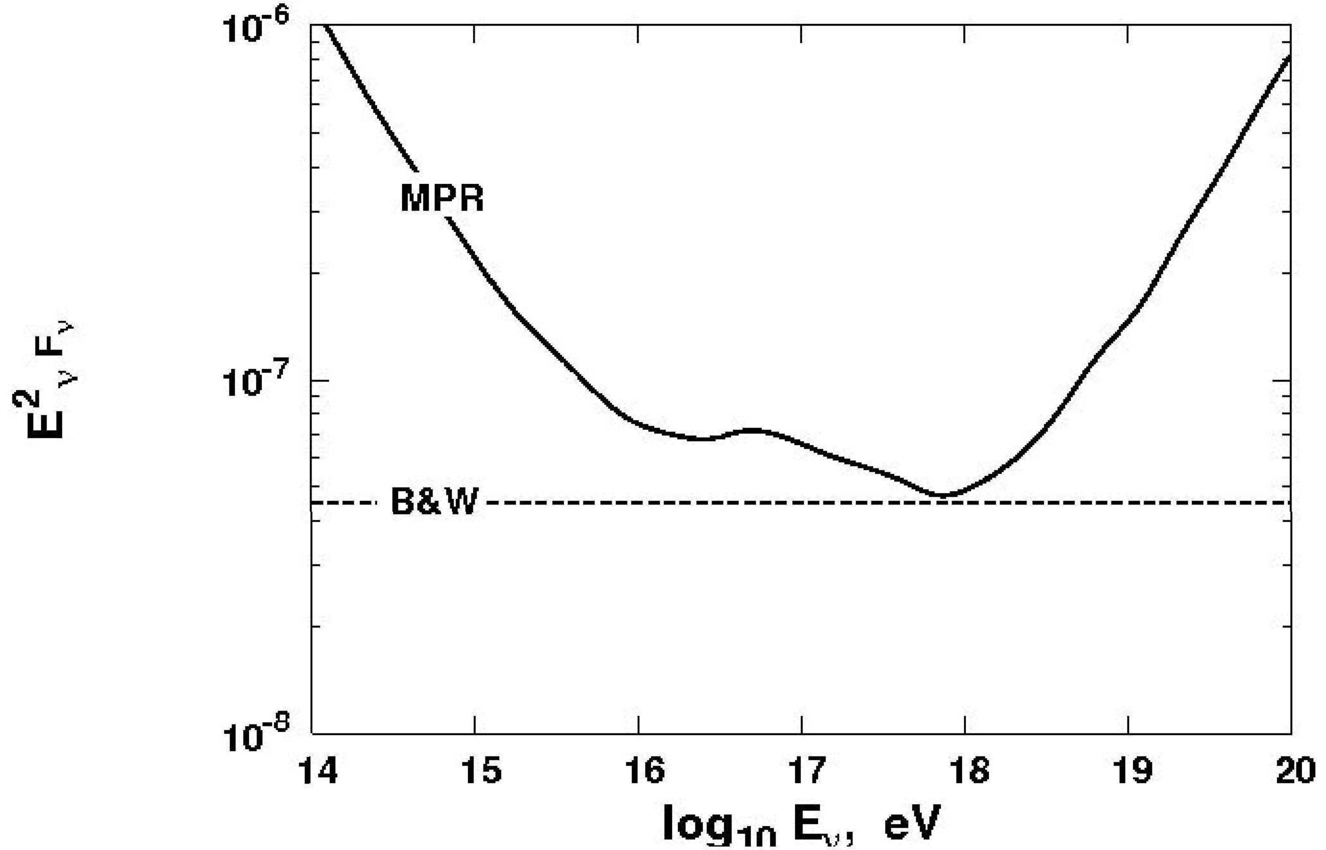
Waxman&Bahcall have not accounted for:

- the difference in the protons and neutrinos energy loss horizon: $\lambda_p^{-1} = \lambda_z^{-1} + \lambda_{p,BH}^{-1} + \lambda_{p,\pi}^{-1}$

$\lambda_{p,\pi} = (n_{bg}\langle K_p \sigma_{p\gamma}\rangle)^{-1} = (400 \times 2.5 \times 10^{-29})^{-1} = 10^{26}$ cm $\sim$ 30 Mpc, while $\lambda_\nu = \lambda_z$, which is the energy loss due to the expansion of the Universe. This distorts the account for the cosmological evolution of the proton and neutrino fluxes.

- have not accounted correctly for the actual energy spectrum of the cosmic rays (assuming E^{-2}) and have neglected the adiabatic losses for the protons possibly accelerated at gamma ray bursts.

- MP&R limit agree with W&B only at 10^{19} eV, where that latter calculation is normalized.



Comparison of the Waxman & Bahcall upper limit to that of Manheim, Protheroe & Rachen

These limits are relevant for the neutrinos generated
in the sources of UHE cosmic rays, whatever they are.

We will talk about neutrinos generated outside the sources
of cosmic rays, during the UHECR propagation to the
observer

Secondary particles generated in propagation

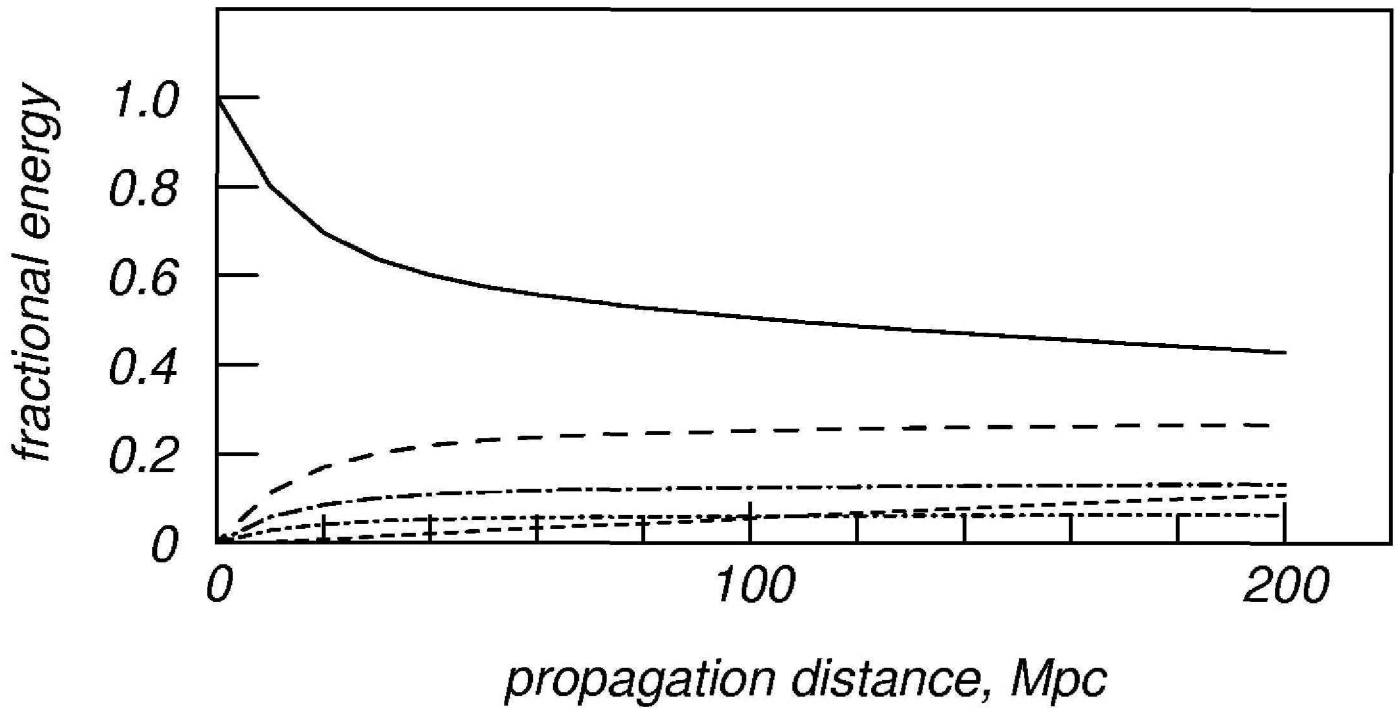
Cosmogentic neutrinos are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These neutrinos were first proposed and their flux was calculated in 1969 by Berezinsky & Zatsepin. An independent calculation was done by Stecker in 1973. In 1983 Hill & Schramm did another calculation 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 (2.75^{o}K) of much lower temperature than the photon emission of these sources. This raises the proton photoproduction threshold to very high energy:

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

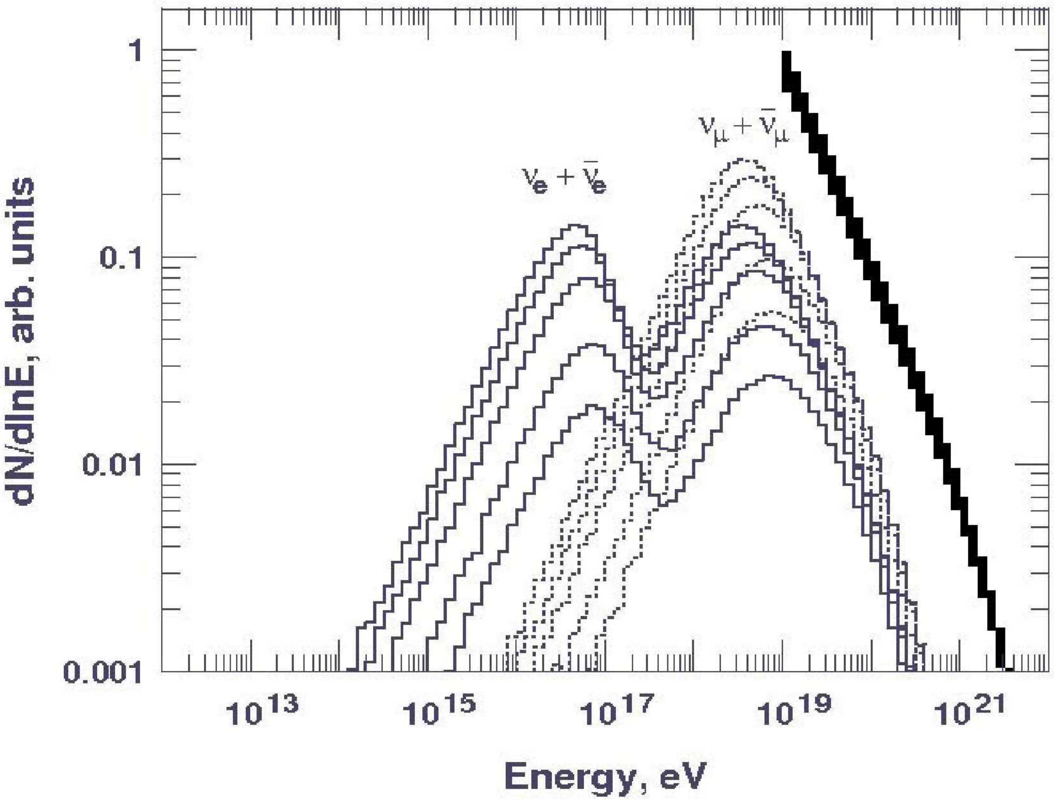
Actually the proton photoproduction threshold in the MBR is about 3.10^{19} eV. There is also production in the isotropic infrared/optical background.

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



Fraction of the initial proton energy of $10^{21.5}$ eV in different types of particles after propagation on different distances:

gamma rays from photoproduction – long dashes
gamma rays from pair production – short dashes
muon neutrinos – long dash-dots
electron neutrinos – short dash-dots



The figure shows the fluxes of electron and muon 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).

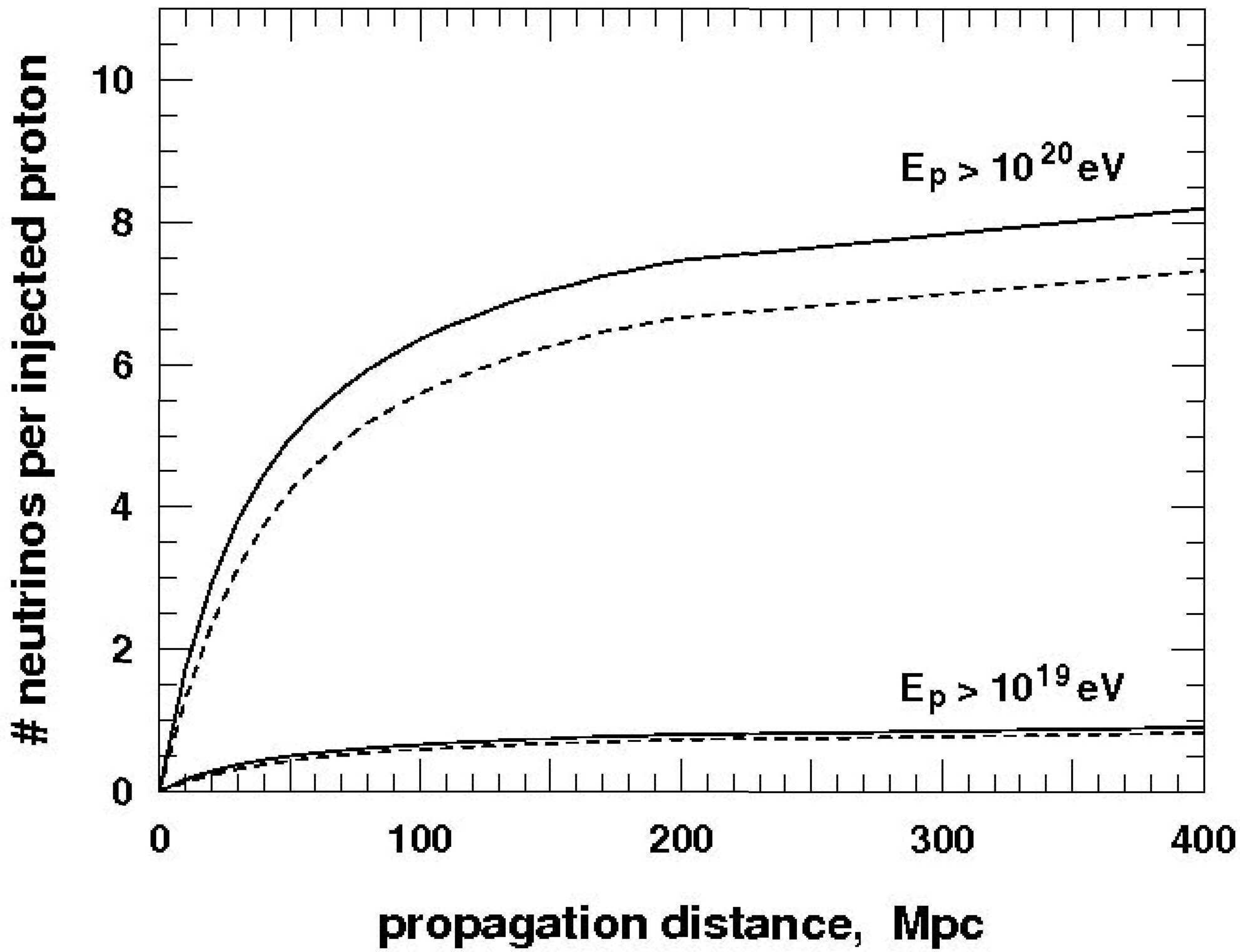
From: Engel, Seckel & Stanev, 2001

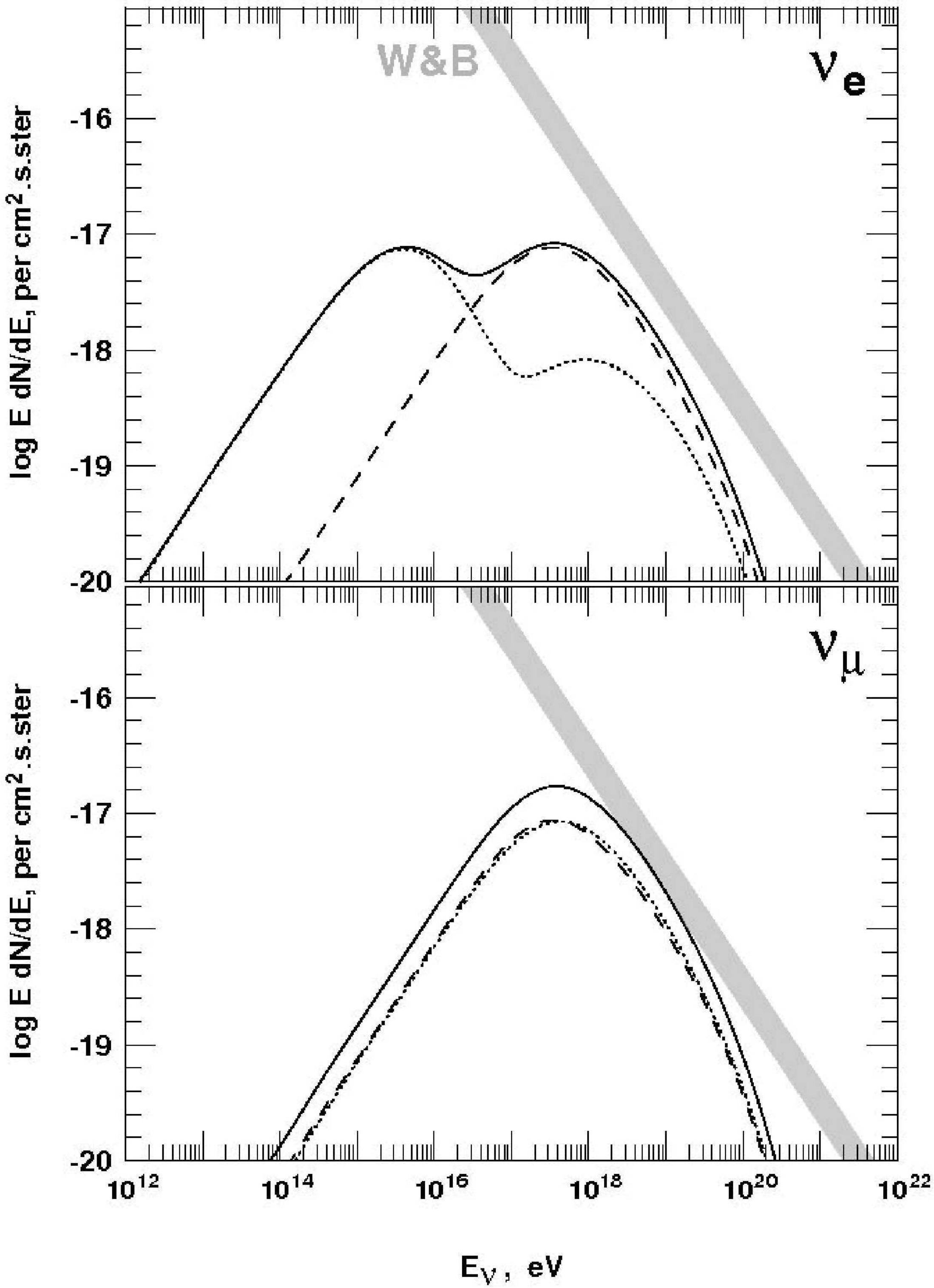
Muon neutrinos and antineutrinos are generated with a spectrum similar to the one of electron neutrinos at twice that rate. As far as neutrinos are concerned the cascade development is full after propagation on 200 Mpc. Even the highest energy protons have lost enough energy to be below threshold.

Slightly more of the proton energy loss goes to cosmogenic gamma-rays generated in photoproduction and in the BH pair creation.

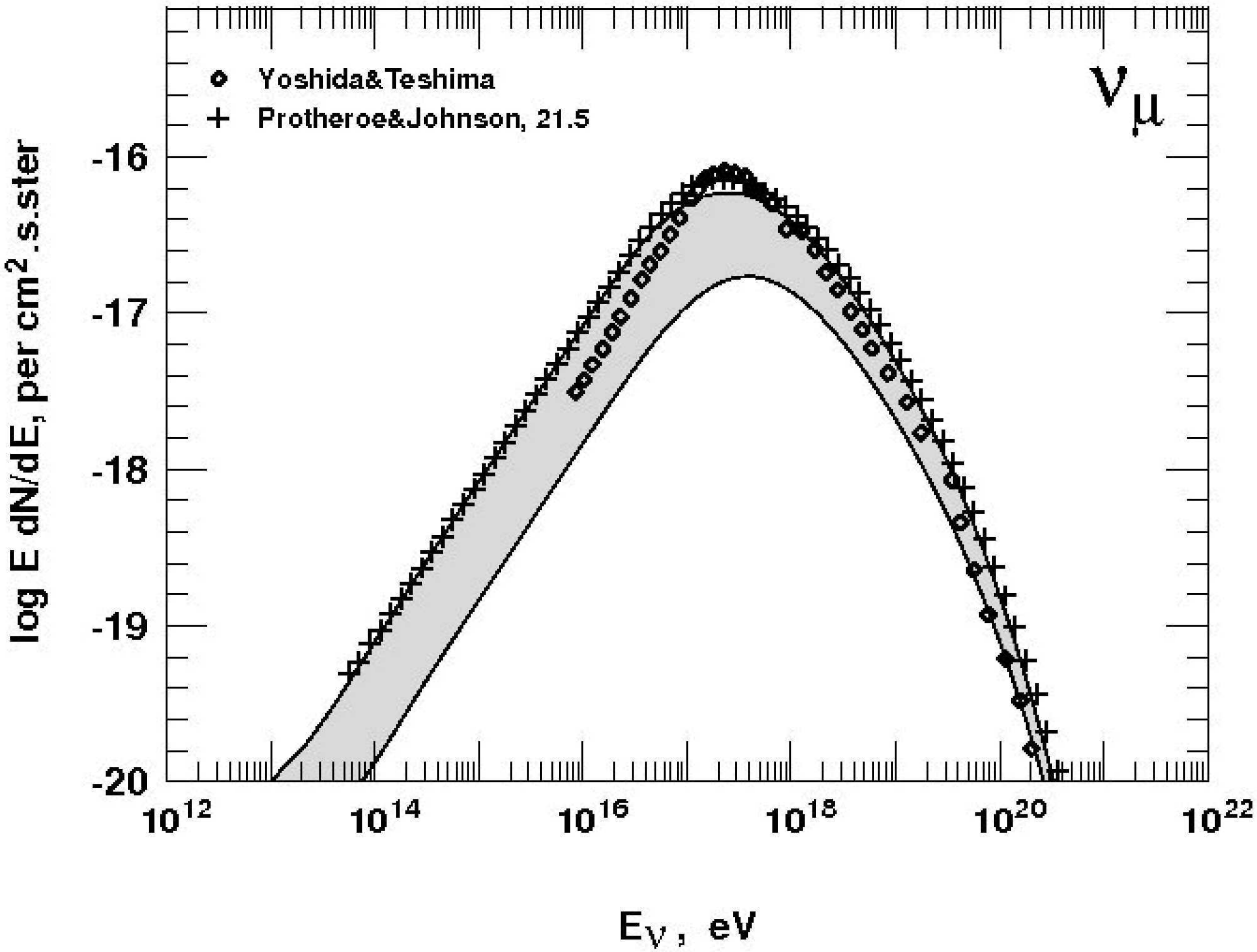
Number of neutrinos produced by protons above 100 EeV (up to 3,000 EeV) and by protons above 10 EeV. The injection spectral index is 2.

Solid: muon neutrinos
dash: electron neutrinos

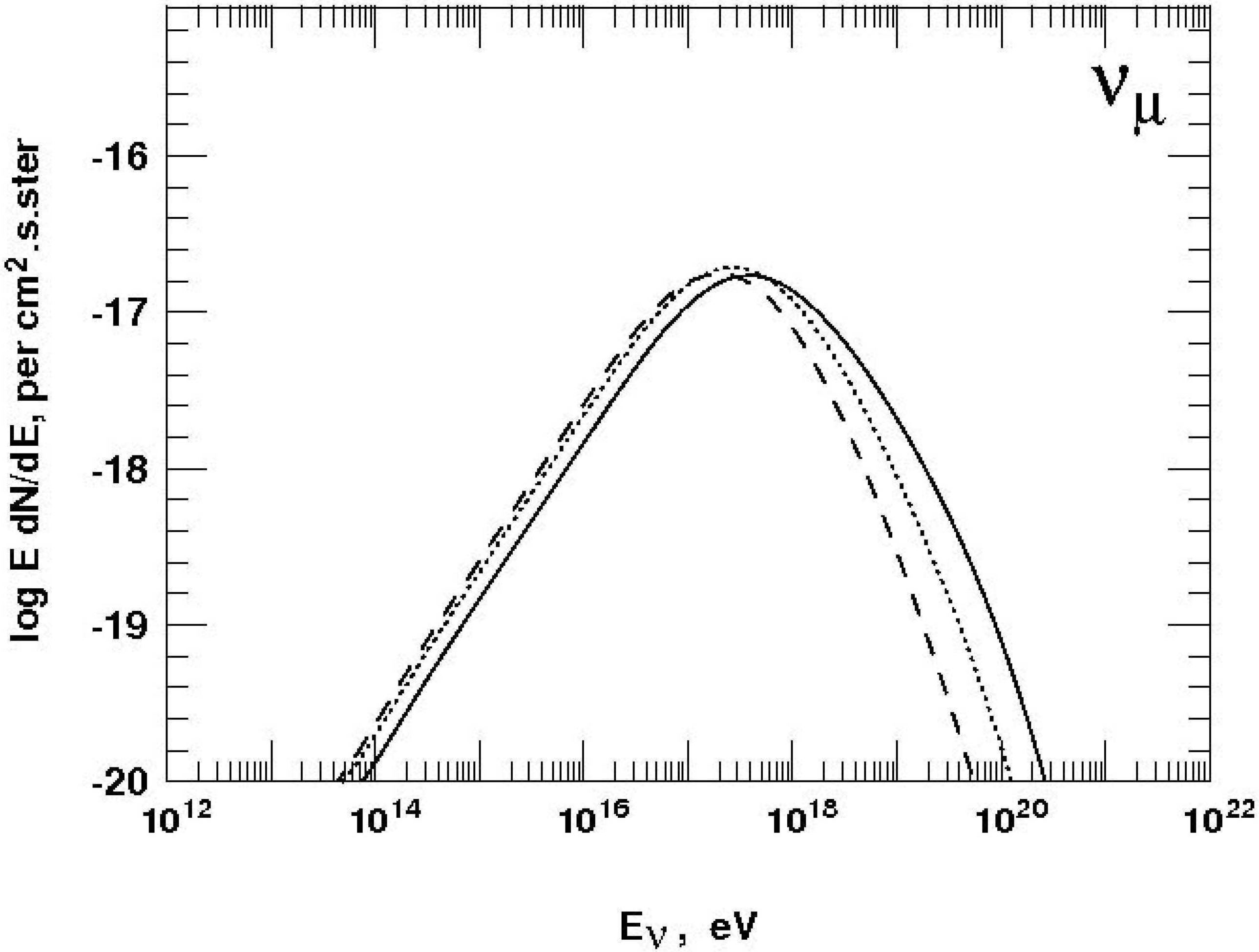




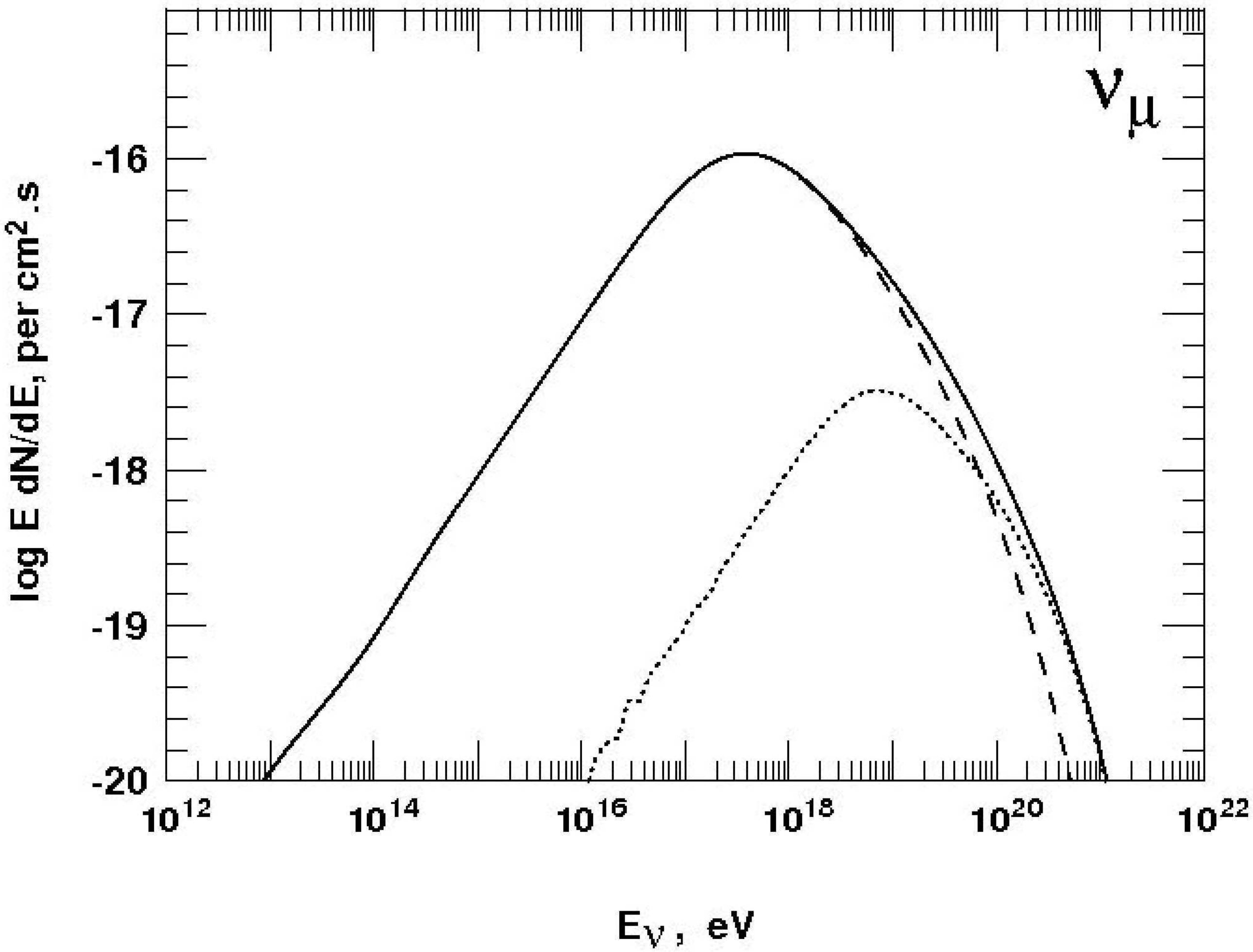
Comparison of the flux
of cosmogenic neutrinos
to the Waxman&Bahcall
upper limit with the same
astrophysical input:
UHECR luminosity
spectral index
cosmological evolution



Comparison to other calculations that use stronger cosmological evolution. The upper curve uses $(1+z)^4$. Note how important the cosmological evolution is for the flux of cosmogenic neutrinos.

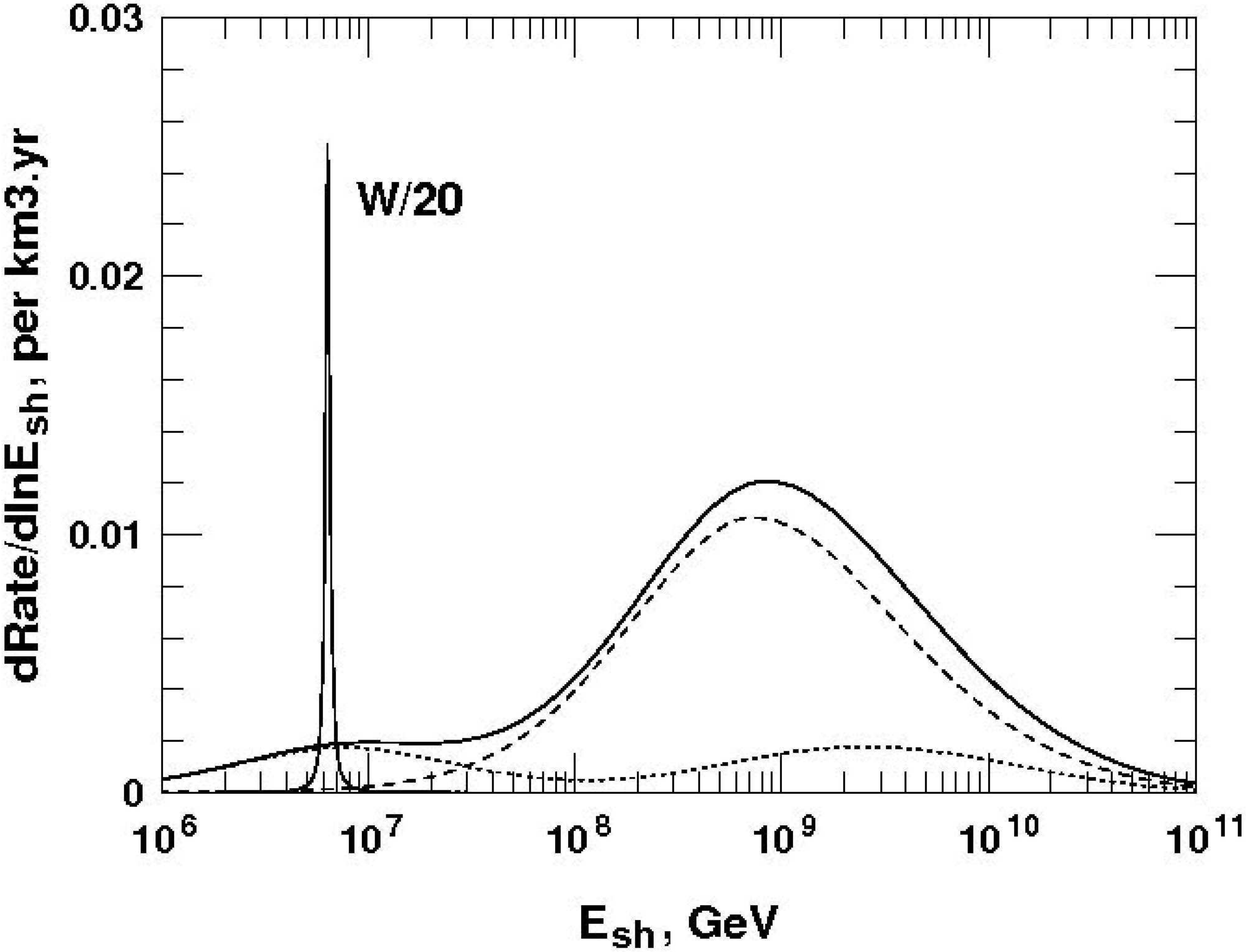


Dependence of the flux of cosmogenic neutrinos on the proton injection spectrum: from right to left 2.0, 2.5, 3.0 keeping the maximum proton energy and the luminosity the same.



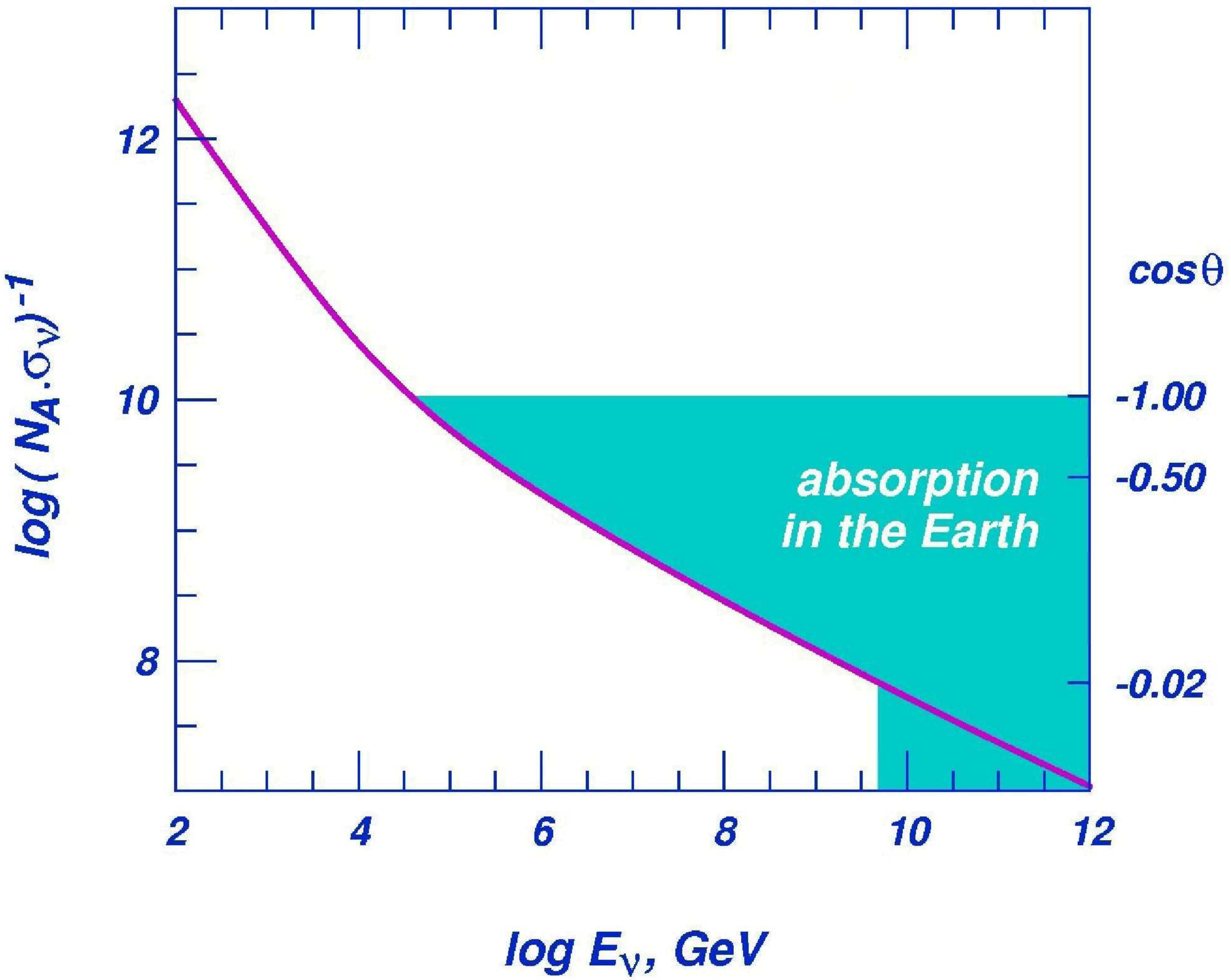
Note that neutrinos generated nearby reach the highest energies. If neutrinos come from high redshift their energy decreases by 1/(1+z).

The assumption here is that ½ of the detected UHECR are produced cosmologically nearby, at a distance of 20 Mpc - the dotted curve. Input parameters like in W&B.

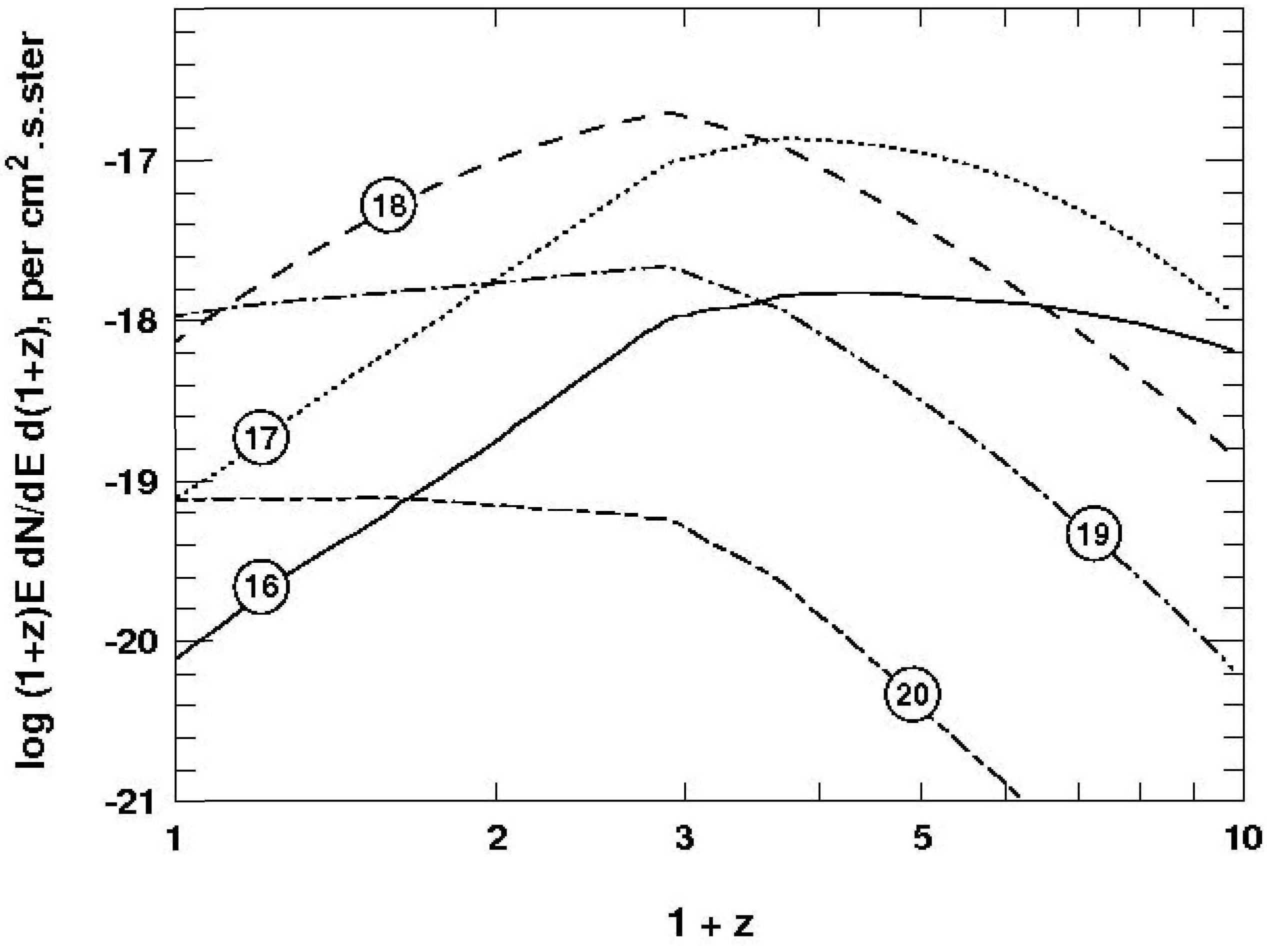


The neutrino cross section affects very strongly the interaction rate. Absorption in the Earth is included.

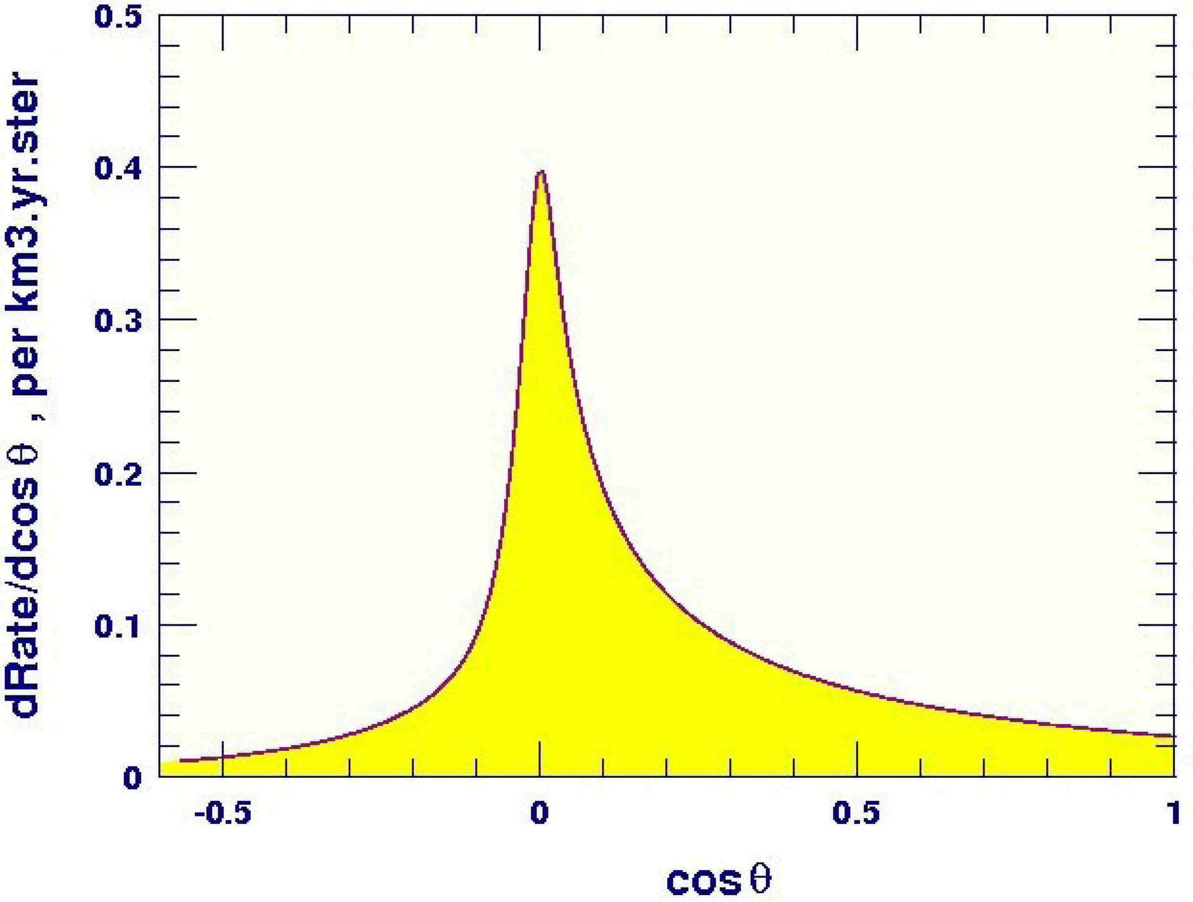
Differential rates from interactions of electron neutrinos (dash) and antineutrinos (dots). The resonant peak is from the Glashow resonance (ν_e interaction with electron). The resonance is too narrow to generate a high rate.



Neutrinos of energy above 100 TeV are absorbed in charge current interactions in the Earth when they propagate vertically upwards. 10 EeV neutrinos are absorbed crossing the Earth in any direction. There is about 10% regeneration in neutral current interactions.



cosmogenic neutrino production at different redshifts

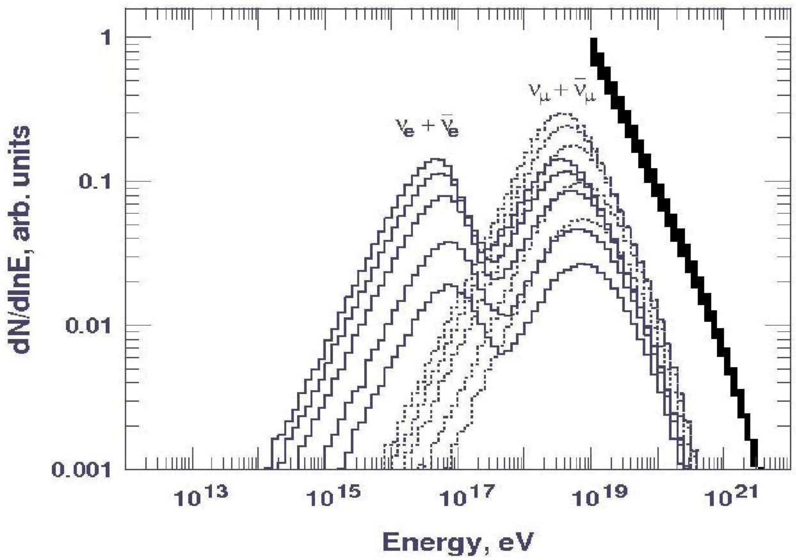


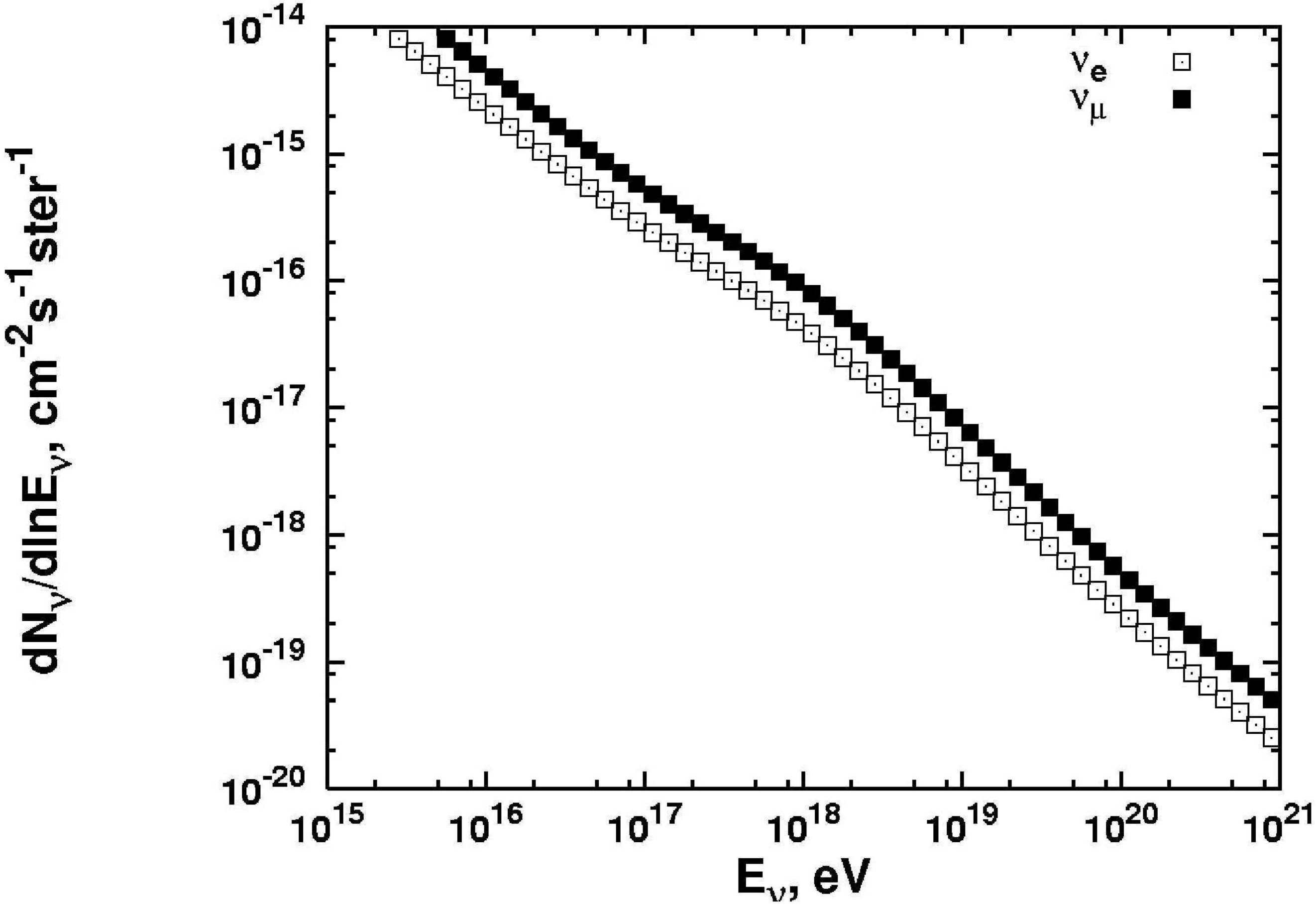
Because of the structure of the atmosphere and the shadowing of the Earth all signals are concentrated in horizontal direction. This creates uniques signatures for Auger and other surace arrays and creates the most useful geometry (tracklength) for OWL/Airwatch.

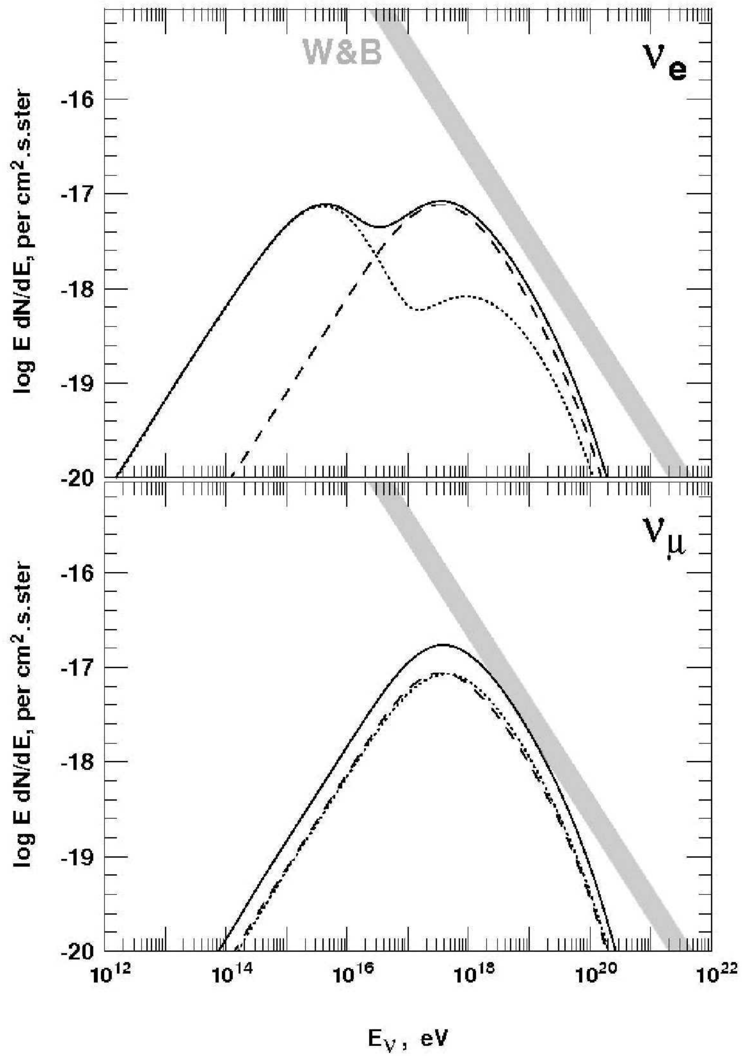
Dependence of fluxes on the cosmic ray injection spectra and the cosmological evolution of the cosmic ray sources

Expectations from the cosmic ray spectrum measured by the Auger Southern Observatory

Cosmic ray interactions in the infrared/optical background.



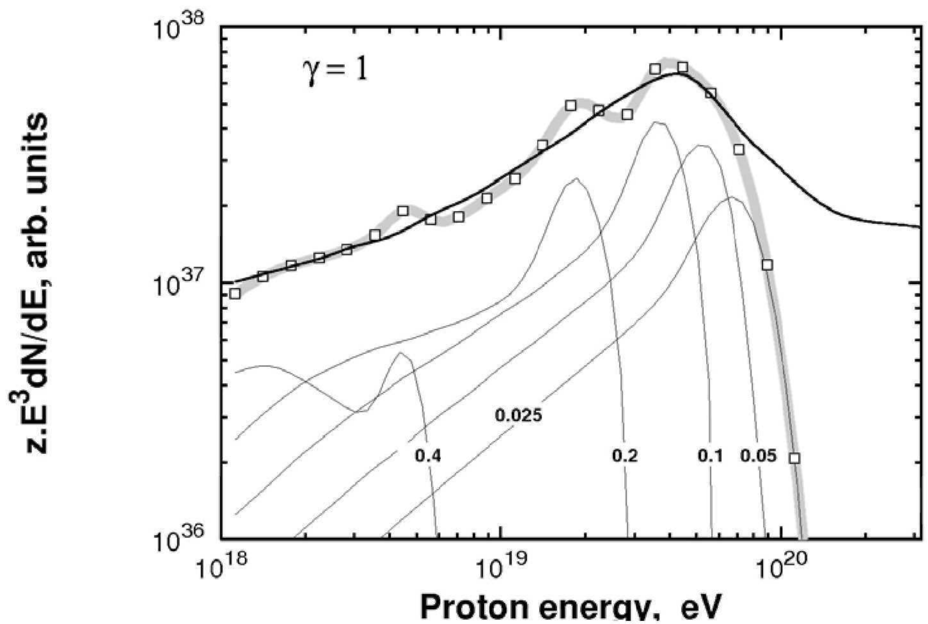


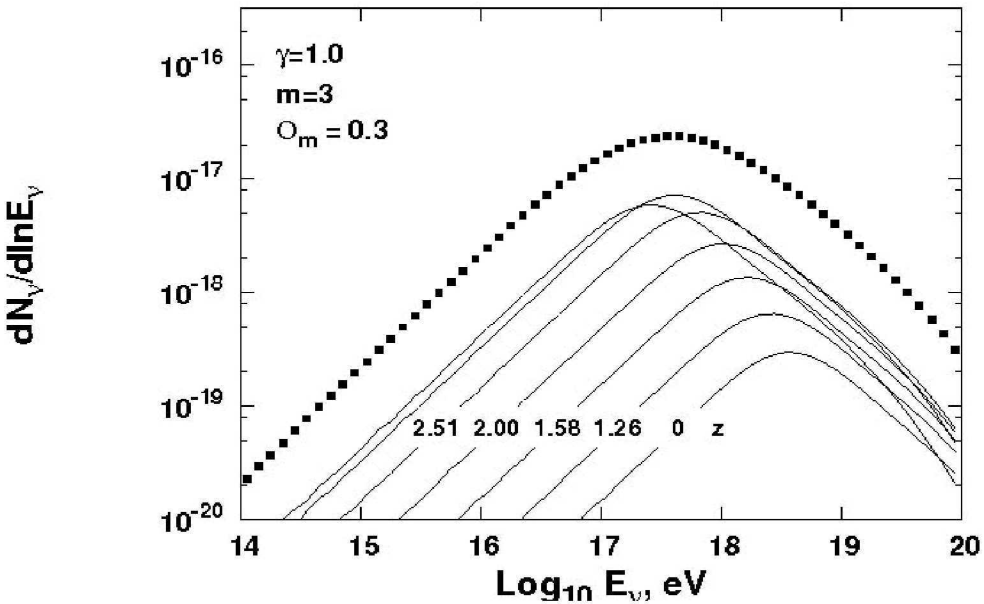


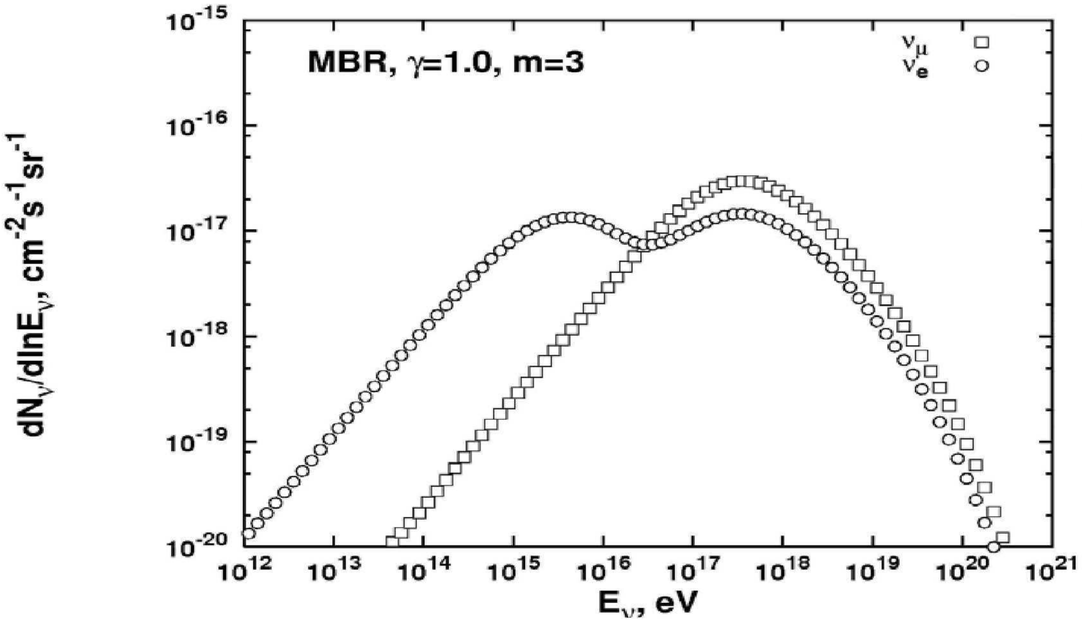
Sum of the W&B neutrino limit and cosmogenic neutrinos calculated with their astrophysical input

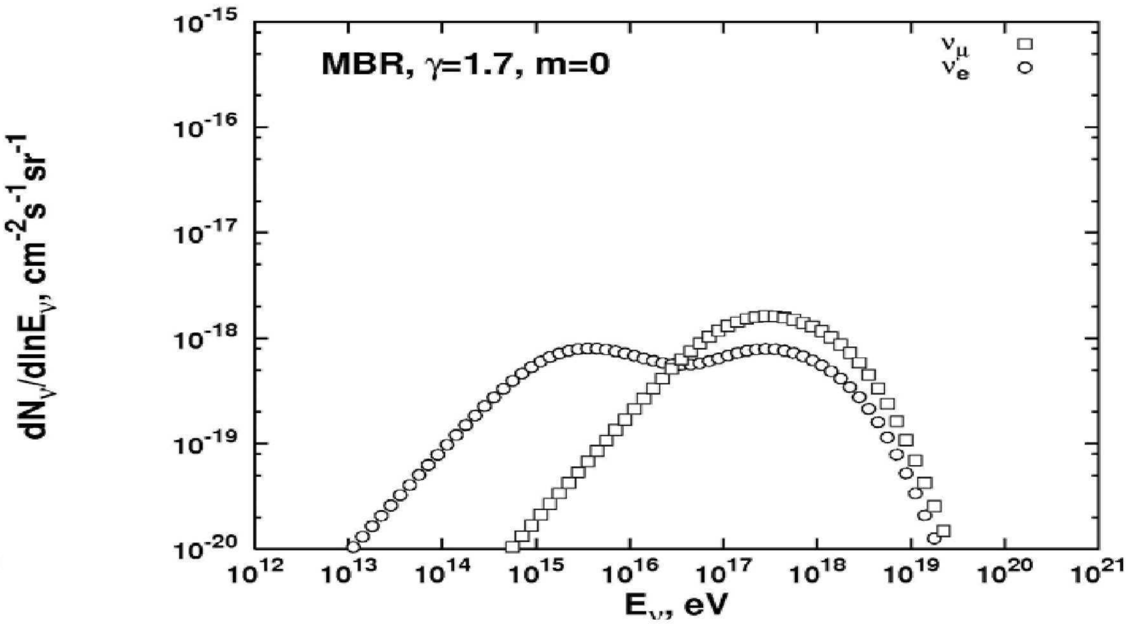
Although different spectra and cosmological evolutions of the UHECR sources fit equally well the Auger spectrum various models predict vastly different fluxes of cosmogenic (GZK) neutrinos. The inputs of a calculation are:

1) Acceleration slope of UHECR
2) Source distribution
3) Cosmological evolution of UHECR sources – 61 sources within 75 Mpc leads to source density exceeding 10^{-5} Mpc^{-3}.
4) Cosmic ray emissivity of the Universe ($erg/Mpc^3/yr$)

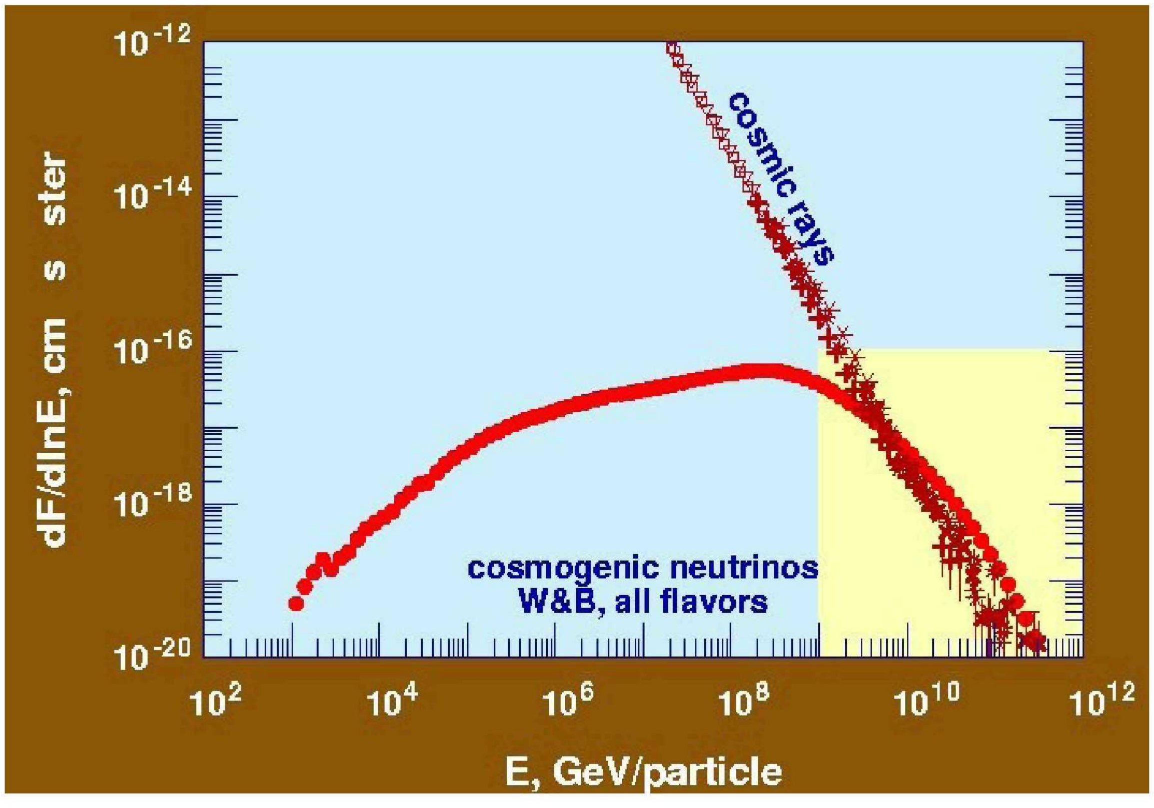








With W&B input (γ=1, m=3) the neutrino flux exceeds that of UHECR above 10^{18} eV. Neutrino cross section makes the detection much more difficult.



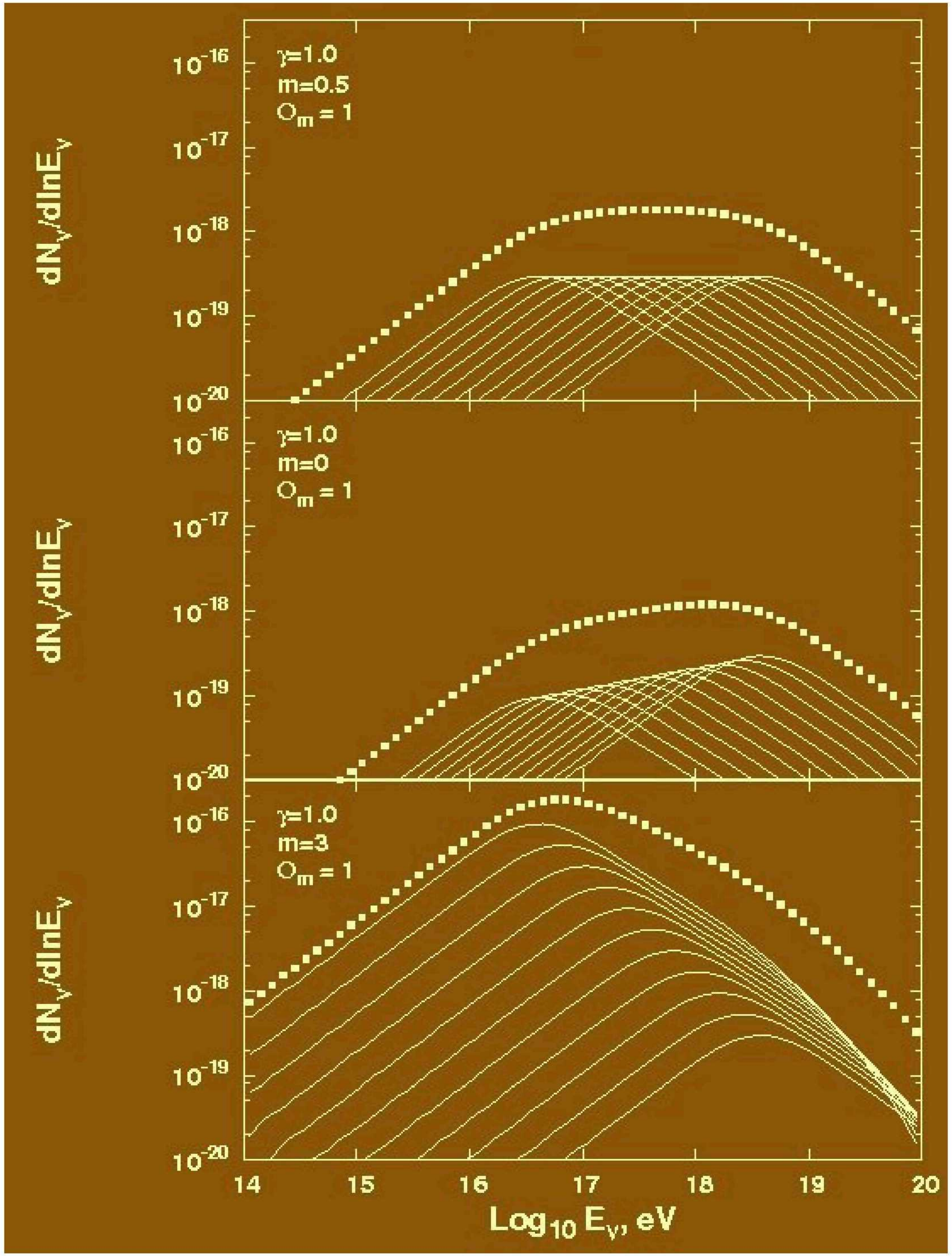
The flux of cosmogenic neutrinos at *z=0* and which is due to the cosmological evolution of cosmic ray activity can be written as

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

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)

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

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 Ω_M = 1 and cosmological evolution to z=10.

equal contribution

decreasing contribution

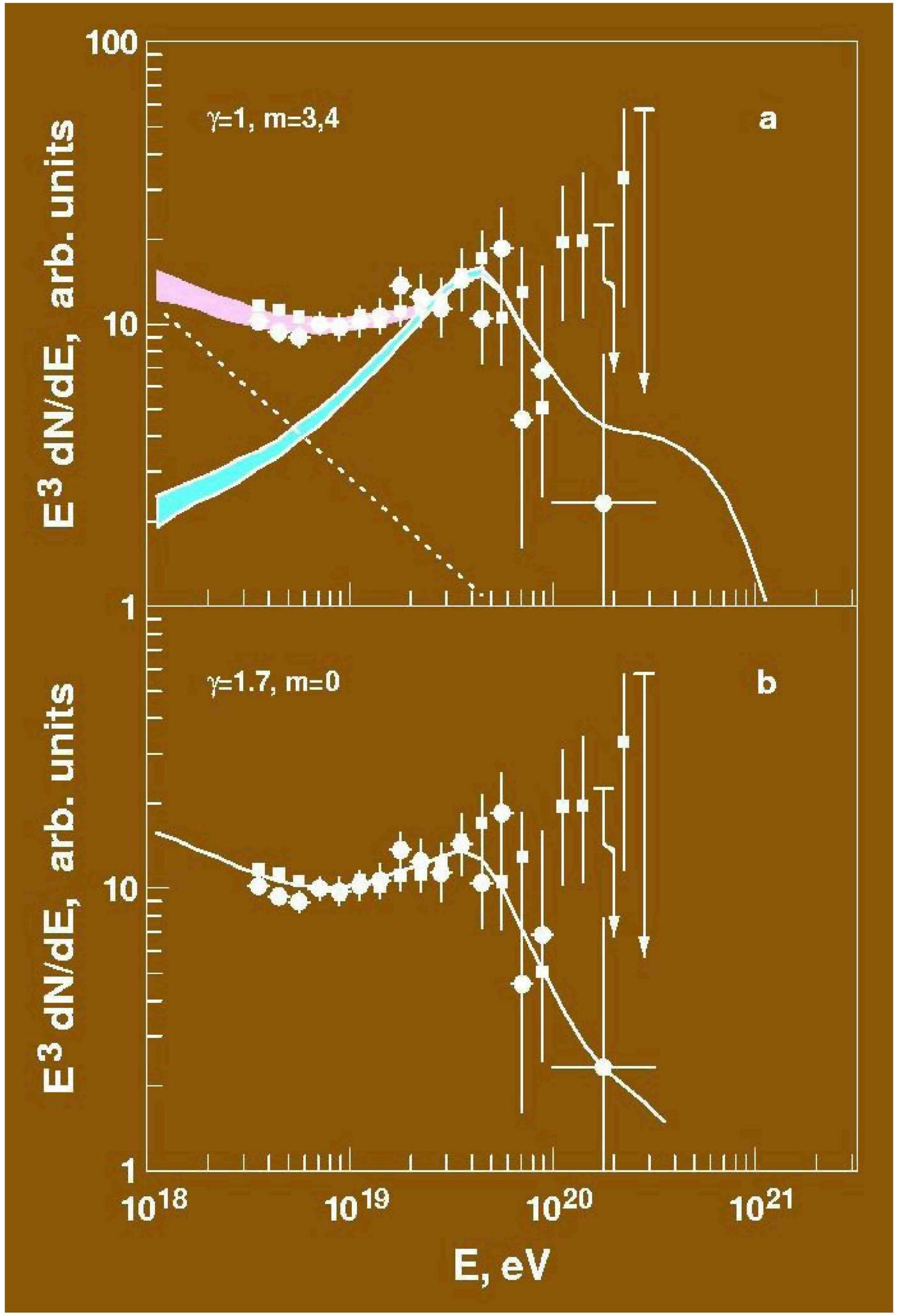
increasing contribution

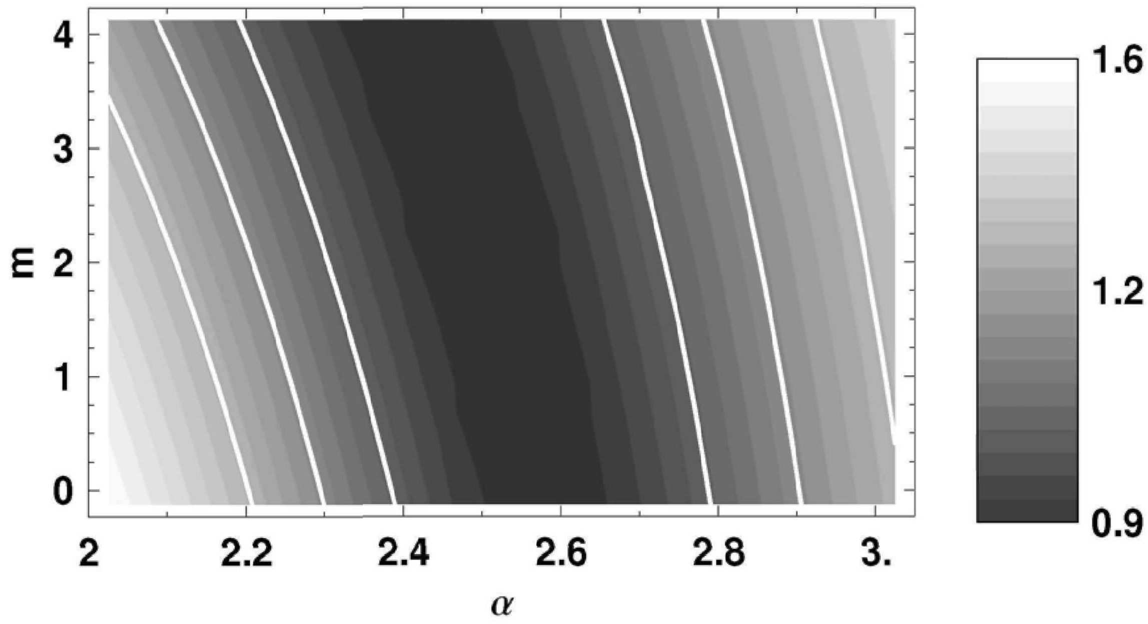
$$q^{(m + \gamma - 3/2)}$$

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 favor 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.

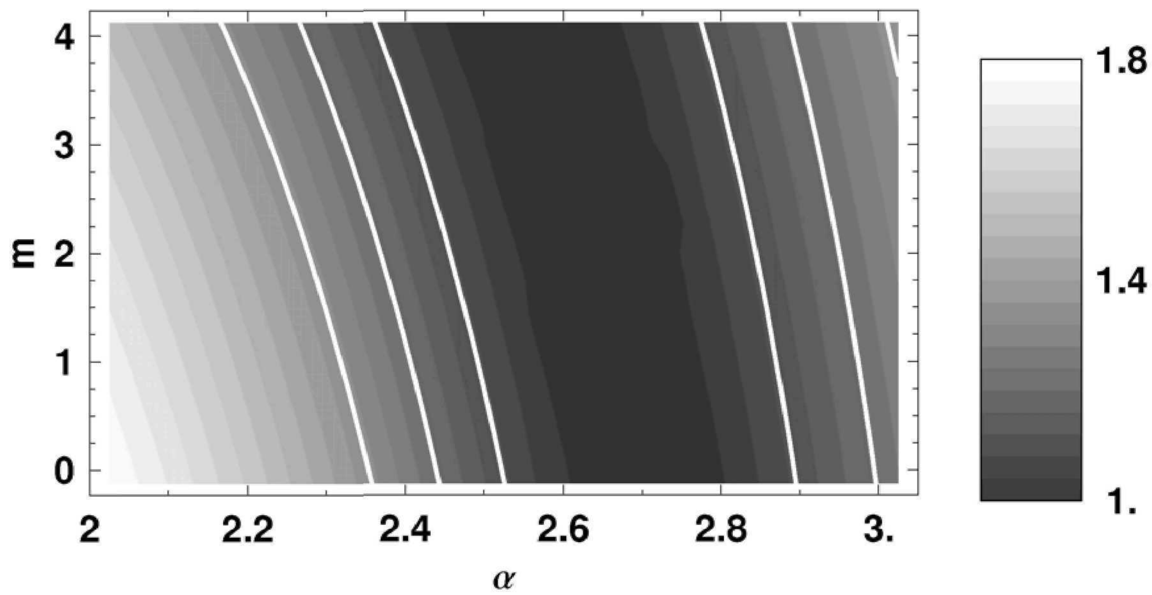




AGASA

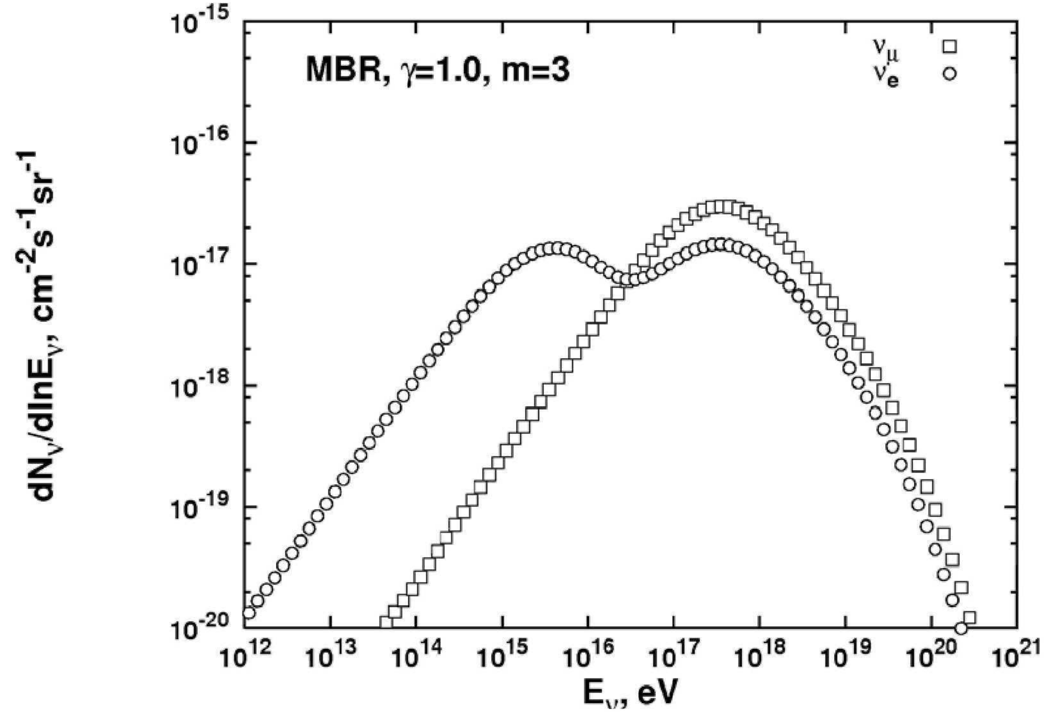
The darker the area is the better the fit. White lines indicate 1σ errors.

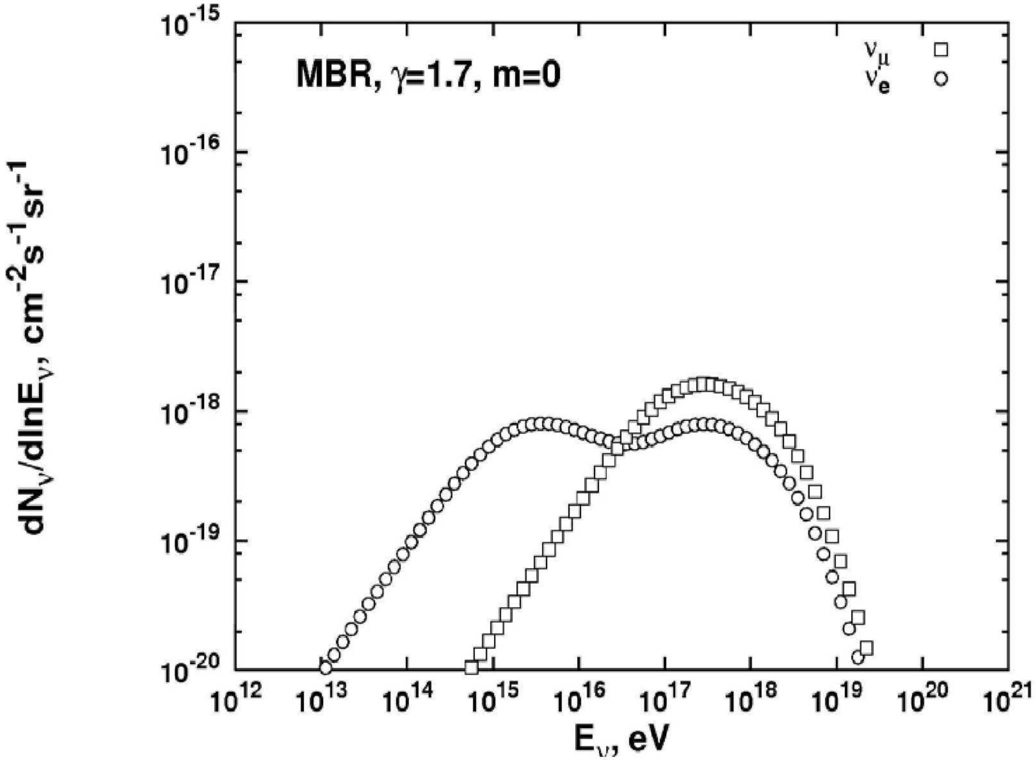
Fits of the spectra above 10^{19} eV <u>only</u>



HiRes

From: DeMarco & Stanev

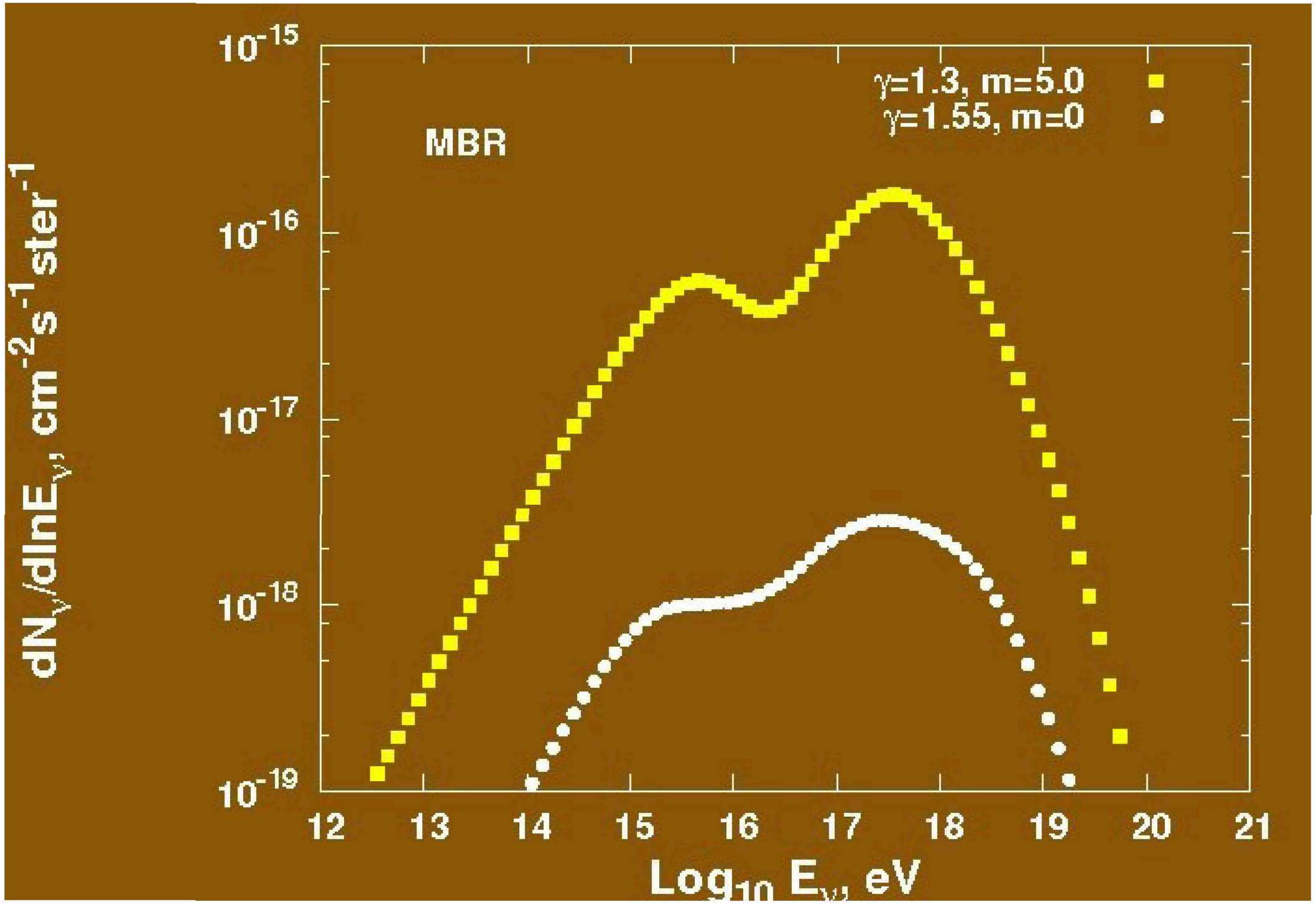




In the case of flat injection spectrum cosmogenic neutrino production is much higher for two reasons:

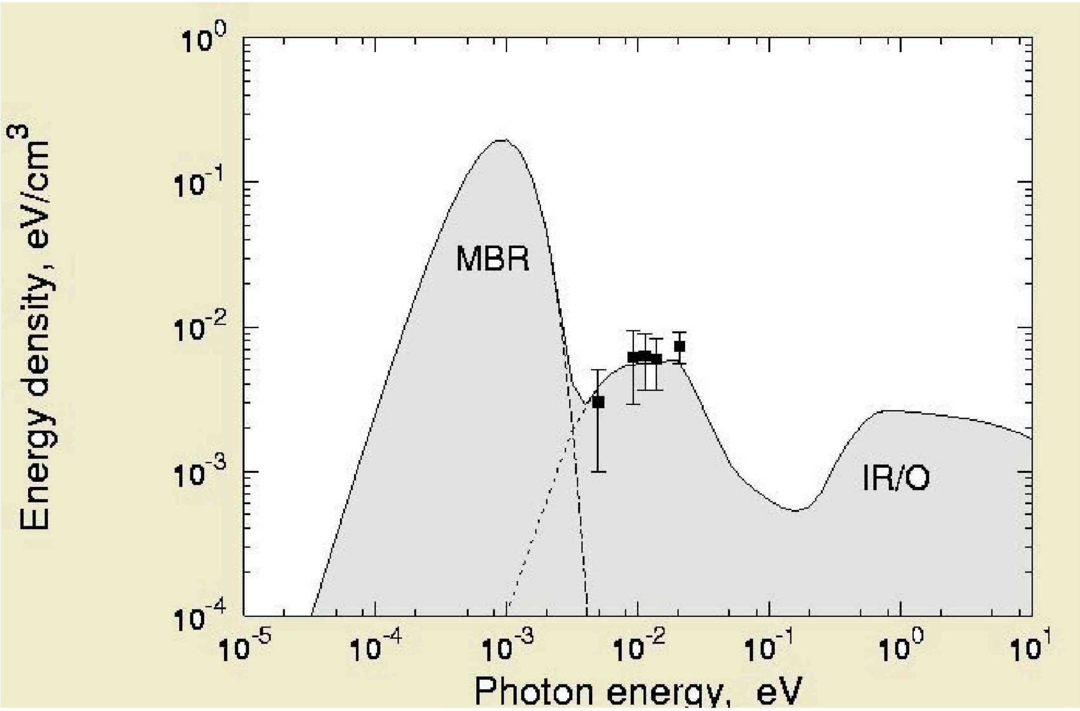
- there are more protons above the interaction threshold for the same CR luminosity of the sources.
- flat injection spectra do require strong cosmological evolution of the cosmic ray sources to fit observations, while steep injection spectra do not need it.

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

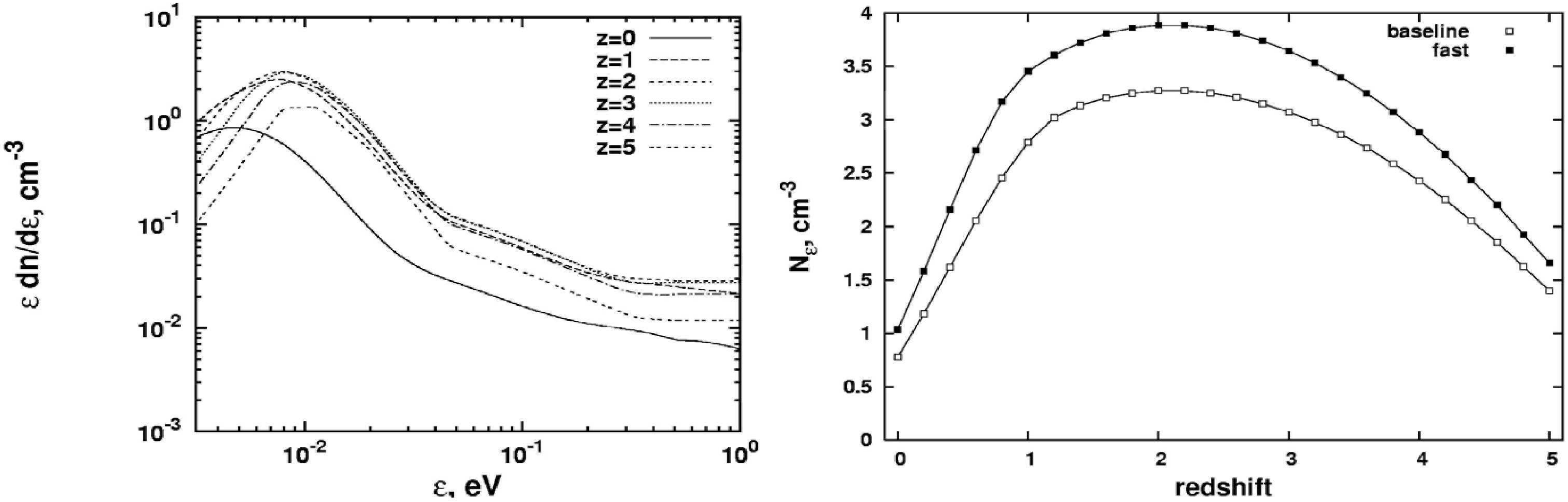


Cosmogenic neutrinos generated by the two proton models that fit well the Auger spectrum. The flux difference at 1 EeV is almost two orders of magnitude. The higher flux model is within the sensitivity of the ANITA experiment.

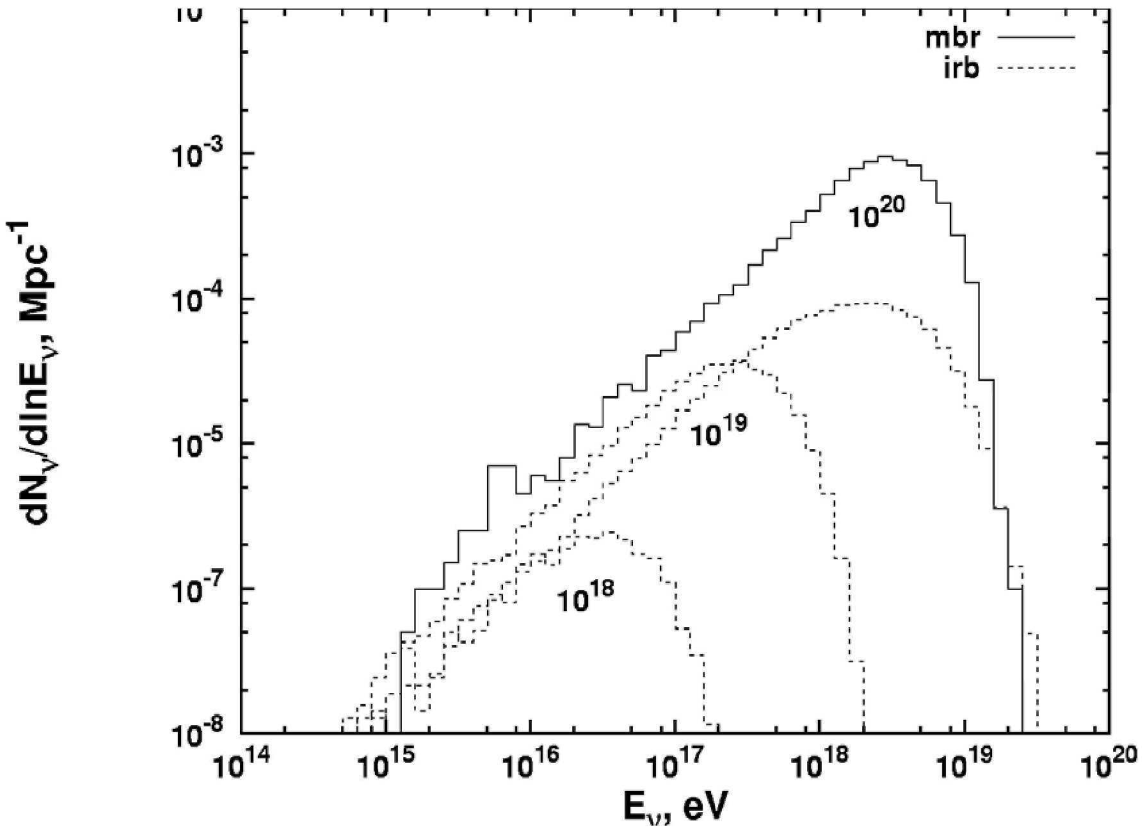
NOT THE END OF THE STORY: The microwave background is NOT the only universal photon field. The universal infrared background occupies the energy range between MBR and the optical/UV one. The near infrared has also been derived from multi-TeV gamma ray observations. The far infrared is being observed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

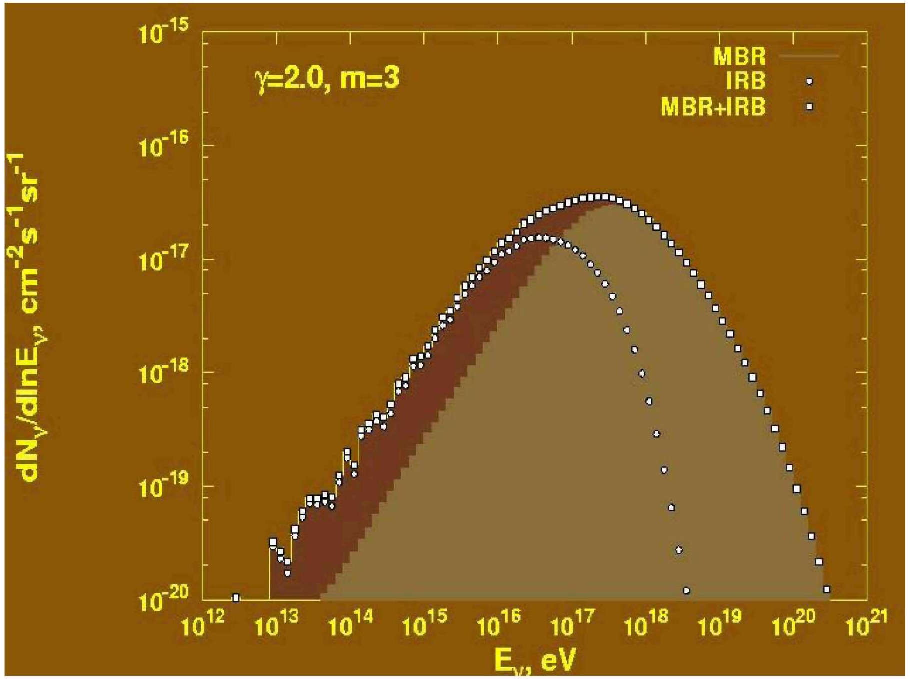


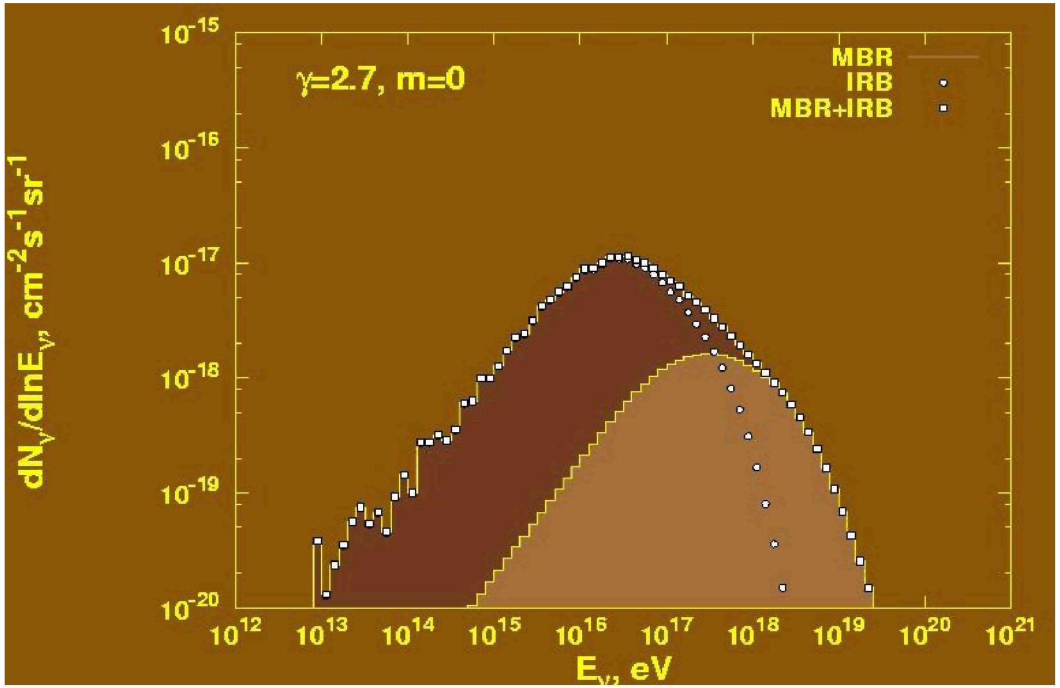
Cosmological evolution of the IR/O background number density for two different models. The cosmological evolution is much slower than the $(1+z)^3$ dependence of the microwave background.



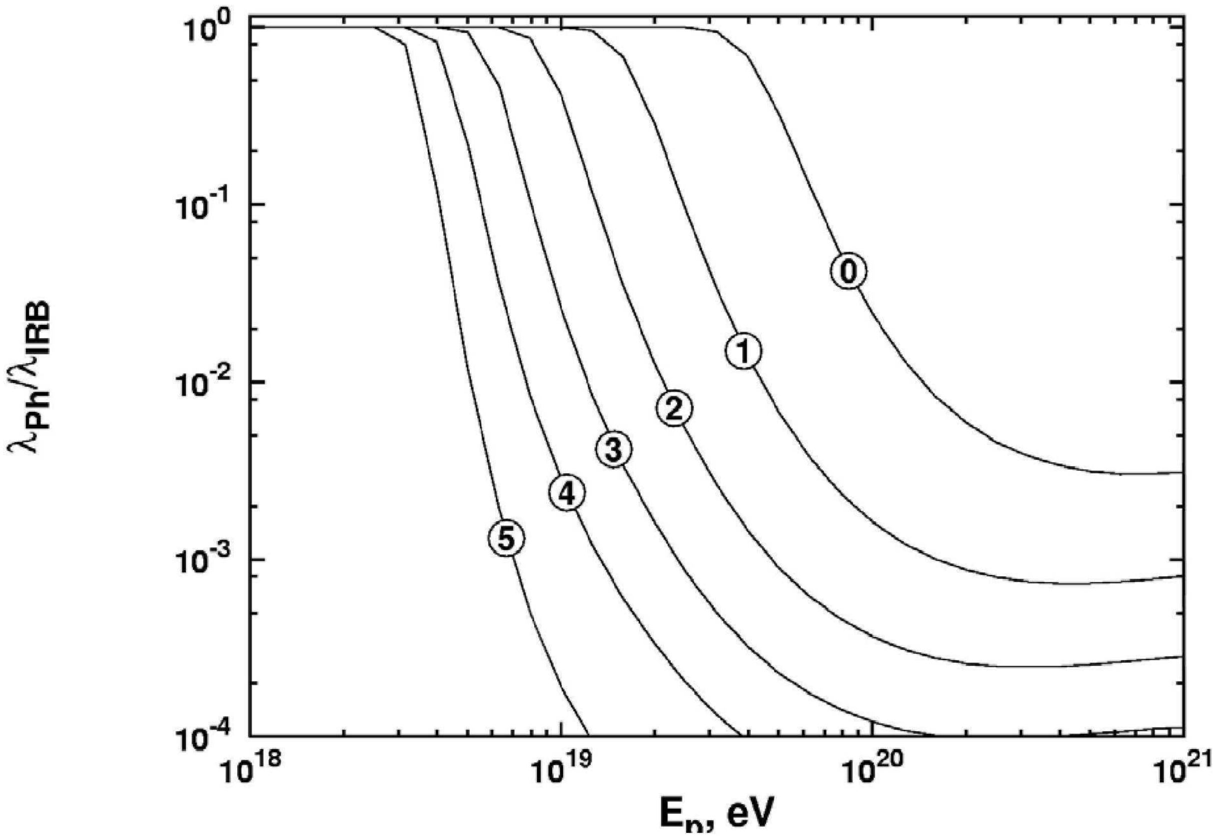
Yield of muon neutrinos from proton propagation on distance of 1 Mpc.

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.



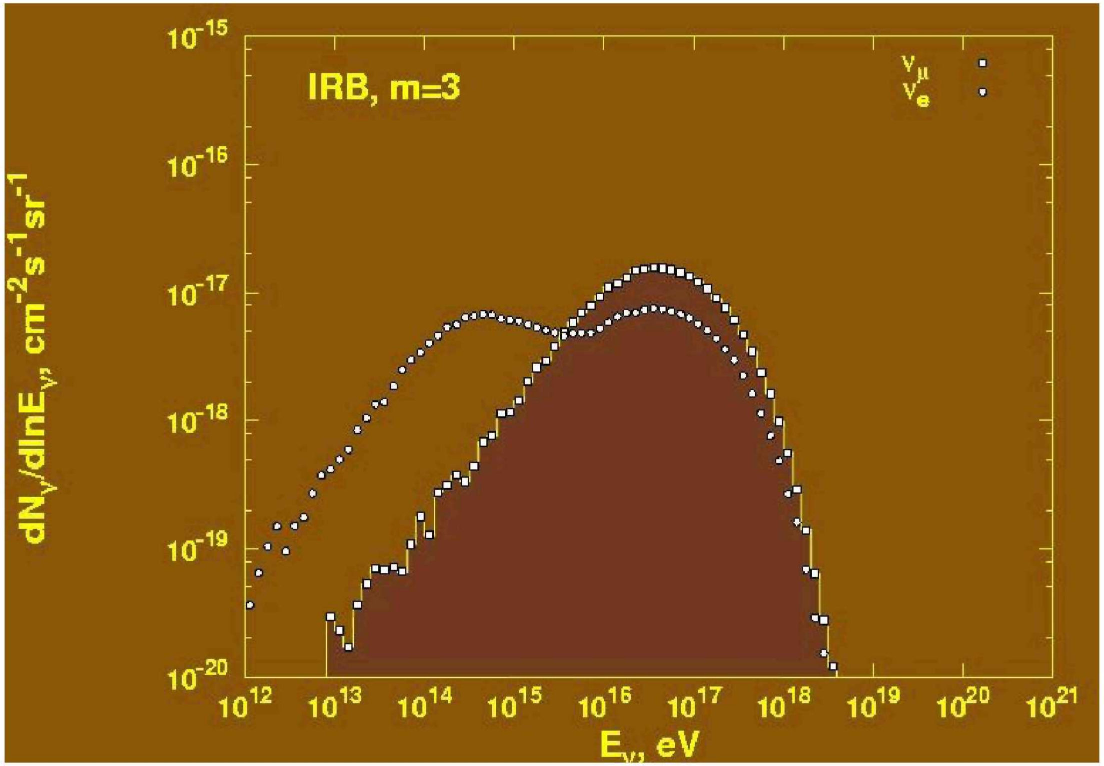


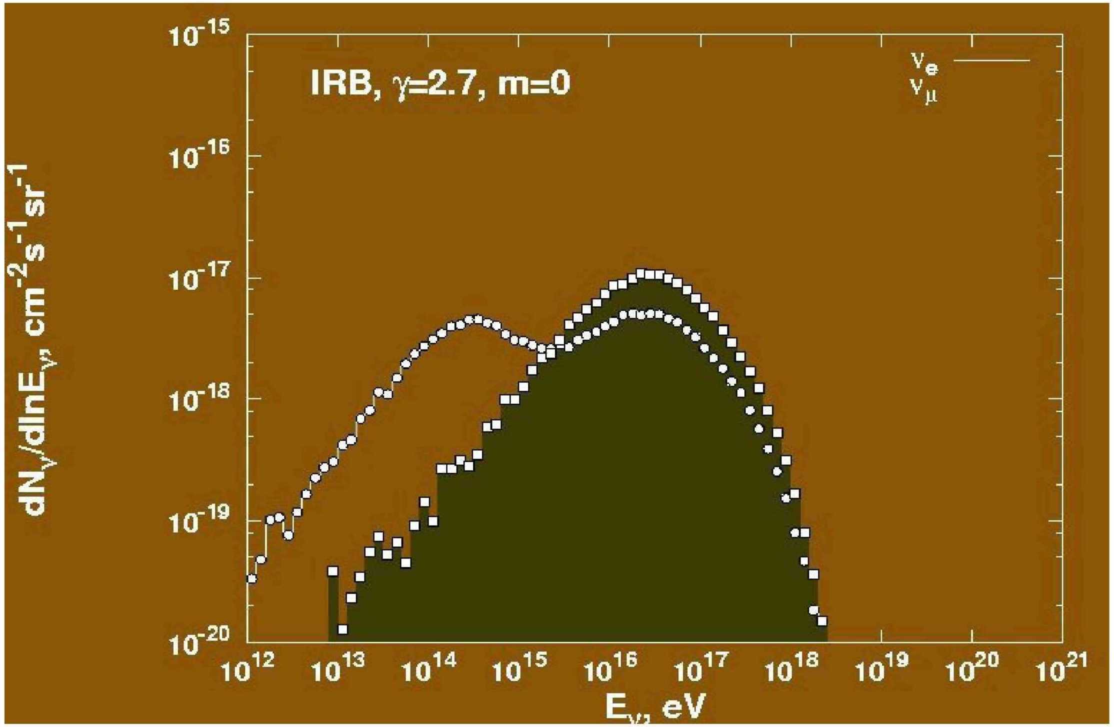
The cosmogenic neutrino spectra generated by the two extreme models of the injection spectra of UHECR protons in case of isotropic homogeneous distribution of the cosmic ray sources. The big difference in case of `MBR only' interactions is somewhat compensated by the interactions in IRB. The interaction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



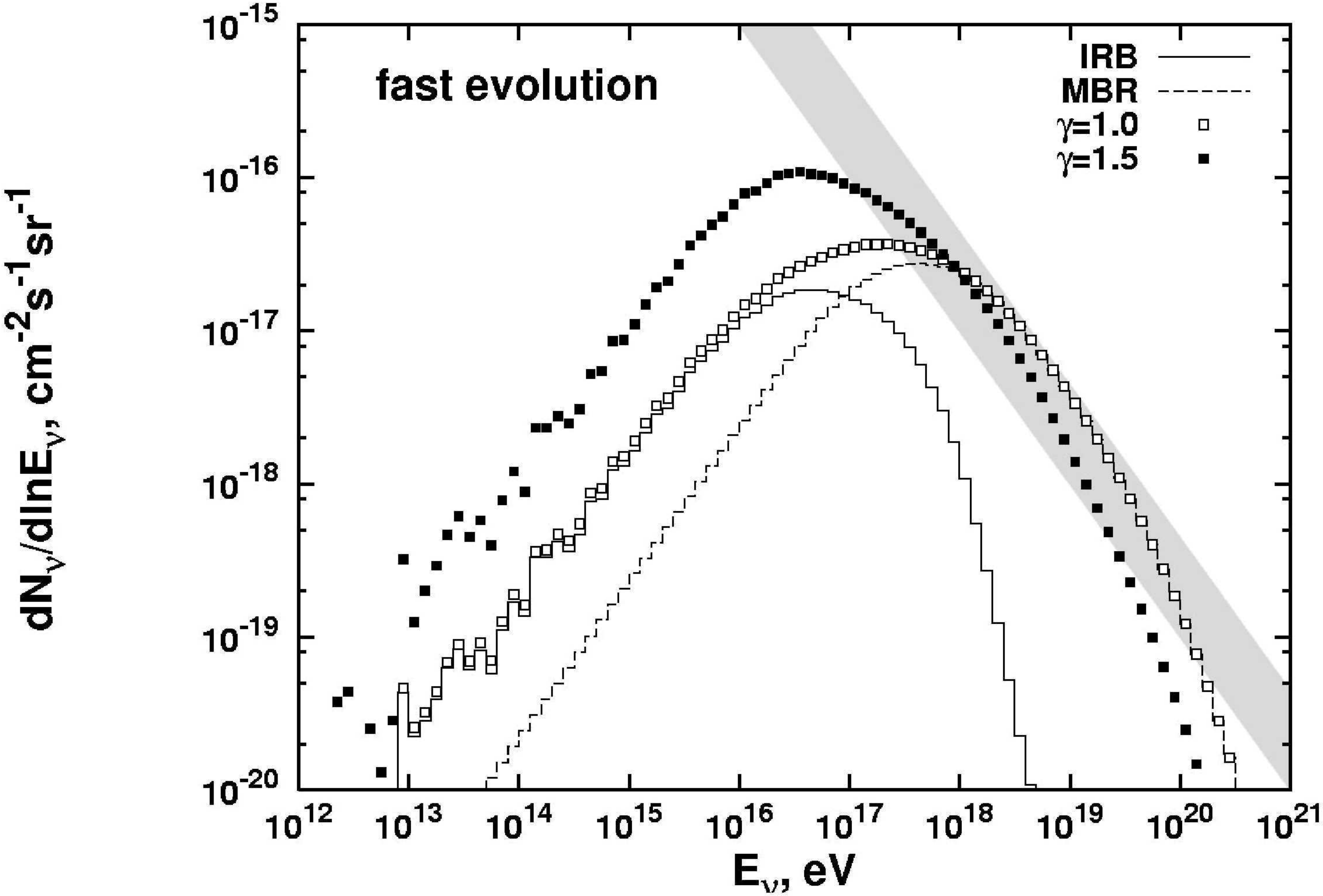
At redshift 0 interactions in IRB dominate to 3.10^{19} eV. This energy range decreases with redshift because of the stronger cosmological evolution of MBR.

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.





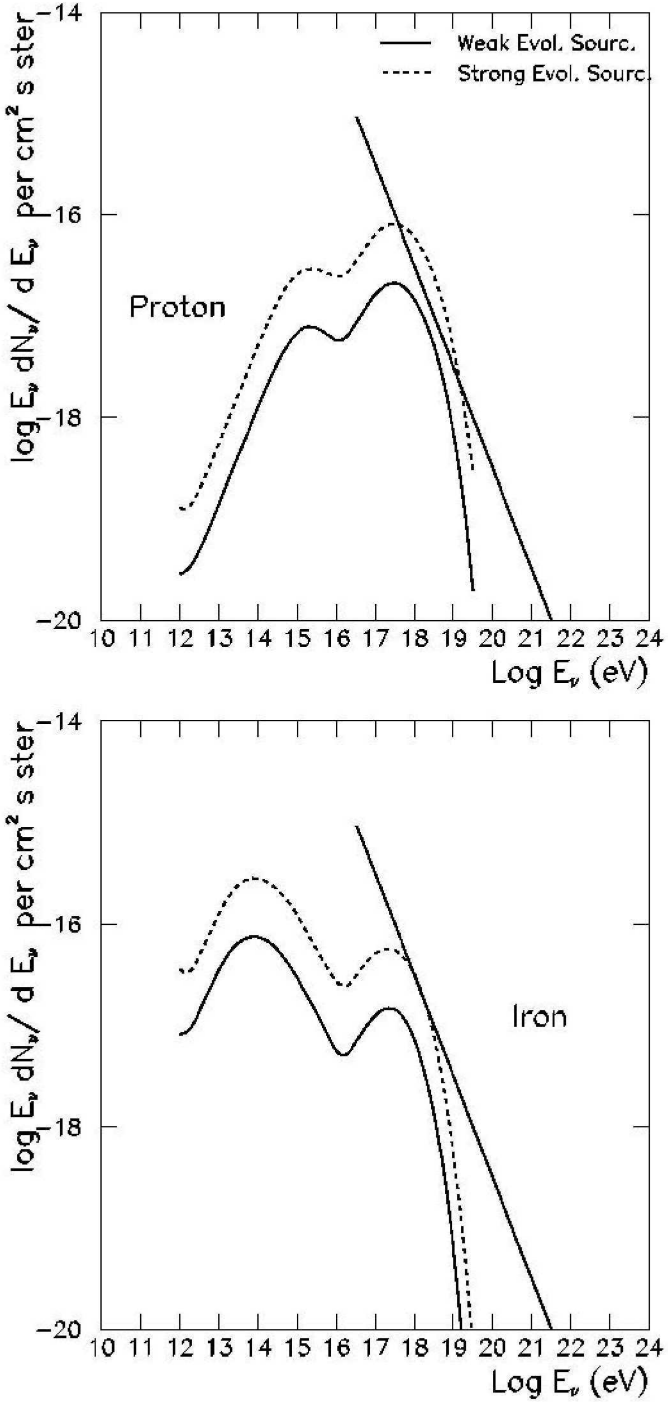
In the case of interactions in the IRB the difference between different cosmological evolutions can be compensated by the larger number of interacting protons. In case of m=3 the difference was a factor 30 for MBR target – it is now only about a factor of 2. The neutrino energy distribution is somewhat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



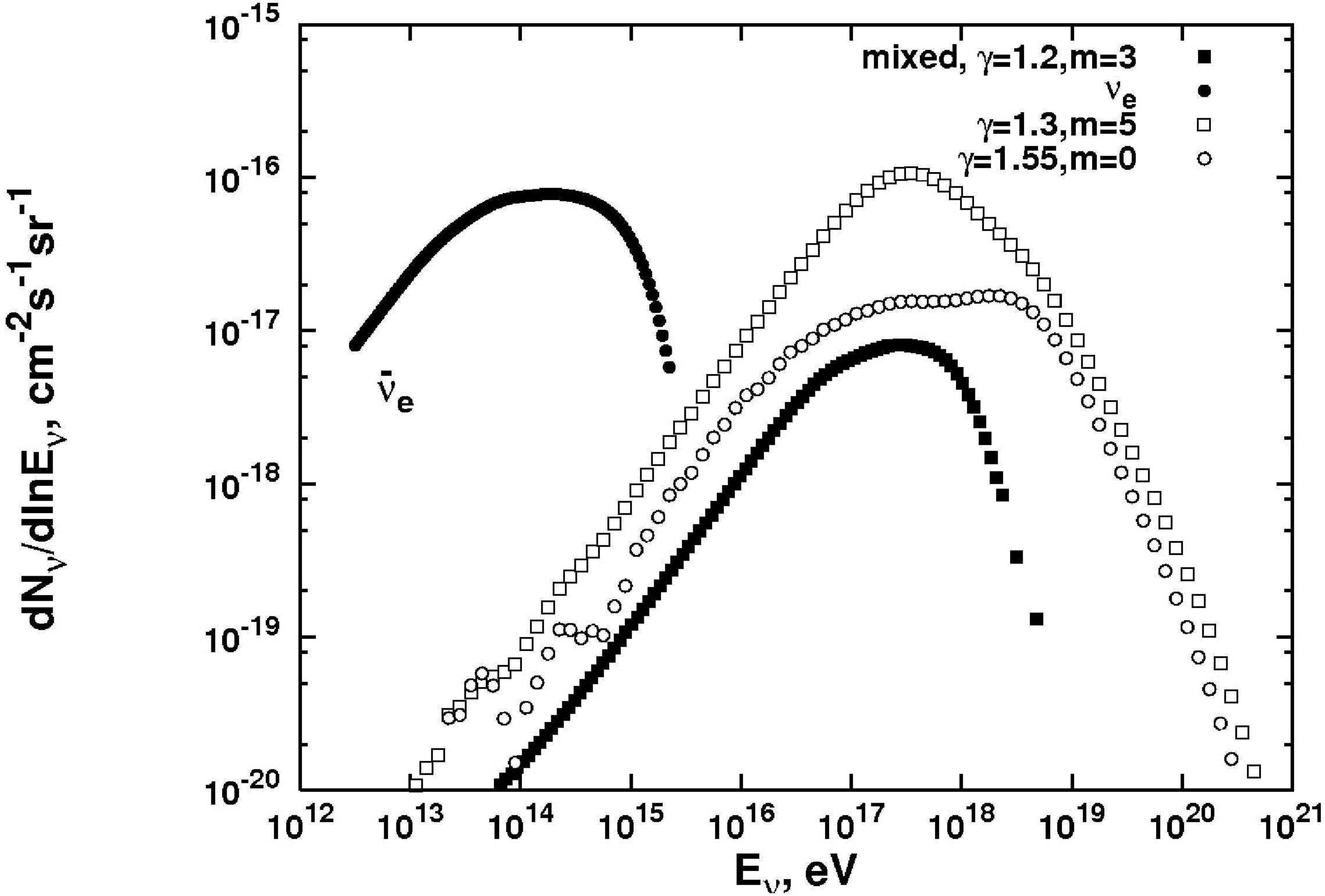
The cosmogenic neutrino flux can even grow with moderately steep injection spectrum when the interactions in the IR/O background are accounted for.

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 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



Range of cosmogenic neutrino fluxes corresponding on models that fit the Auger South cosmic ray spectrum.