

# Absorption and production of high energy particles in the infrared background

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We discuss the role of the infrared&optical background radiation in two important processes in ultra high energy astrophysics – the propagation of TeV gamma ray fluxes in the Universe and the interactions and secondary particle production of ultra high energy cosmic rays.

We consider the photon background as a target for particle interactions, not as an important feature of any astrophysical system. The most important target for particle interactions, that was considered first, is the microwave background (MBR). MBR dominates all photon fields in almost any location.

There are three important processes:

- for gamma rays:
  - gamma gamma to electron-positron pairs
  - inverse Compton scattering – electrons hit ambient photons and transfer their energy to them
- for UHE protons
  - photoproduction

Since the center of mass energy has to exceed the produced particle mass (electron-positron pair or a pion) there are high energy thresholds:

$10^{14}$  eV for gamma gamma to electron positron pair, and  $3 \cdot 10^{19}$  for photoproduction

At first the infrared background looks like an insignificant target: MBR density is higher than  $400 \text{ cm}^{-3}$  while the IR/O density is of order of 1. On the other hand IR&O is of significantly higher energy – optical radiation has a critical energy of 1 eV. The interaction thresholds then come down by about two orders of magnitude – order of 1 TeV for gamma-gamma and below  $10^{18}$  eV for photoproduction.

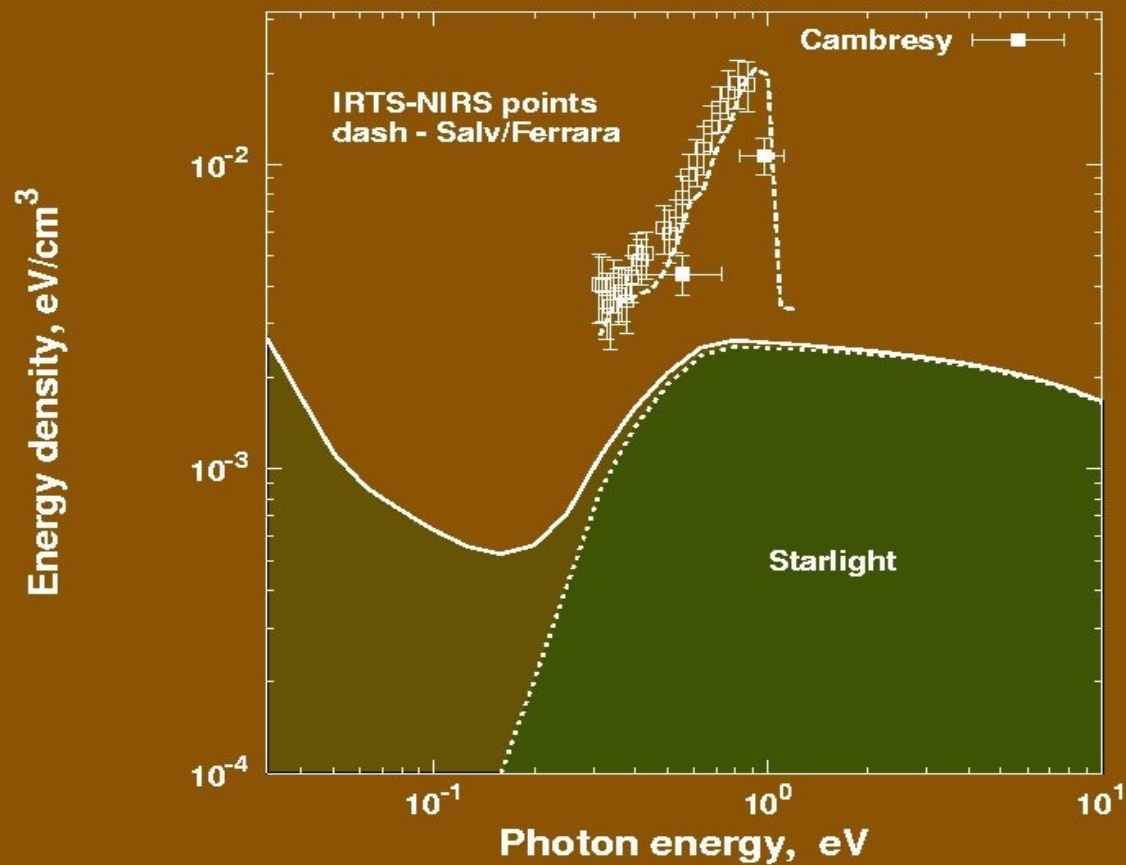
Since all particles accelerated or boosted in astrophysical environments have steep energy spectra the decrease in interaction thresholds have definite importance. Interactions on the infrared background (IRB) involve many more particles than those in the MBR. On the other hand the mean free path is much longer because of the smaller target density.

My personal interest in the IR background has increased because a couple events:

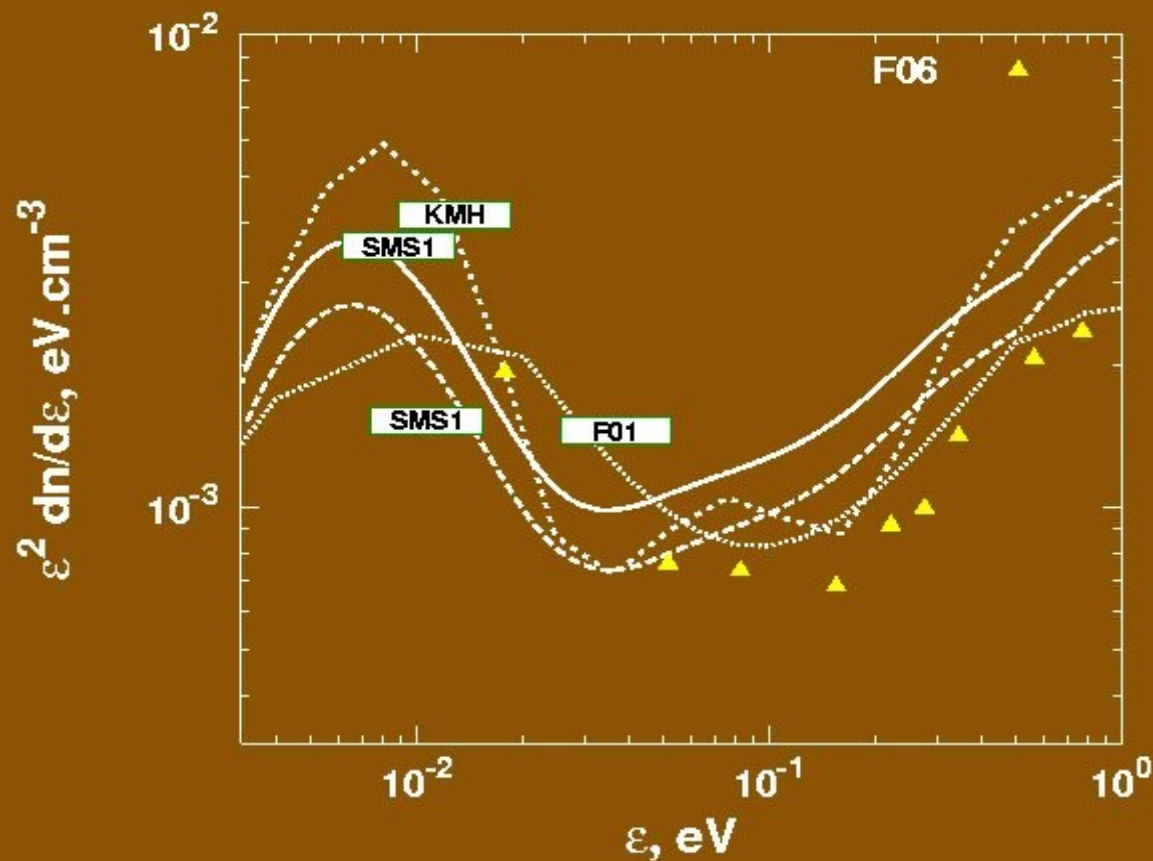
- HESS detected distant TeV gamma ray sources at very large distance – up to redshift of 0.18
- A Japanese instrument (NIRS) with very fine energy resolution claims a high peak in the 1  $\mu\text{m}$  range.

HESS used the detection to dismiss its existence and the realization that proton interactions in the IRB can generate a large number of *cosmogenic* neutrinos.

I will discuss the gamma ray absorption and cascading as well the production of cosmogenic neutrinos in the propagation of ultra high energy cosmic rays (UHECR) in the Universe.

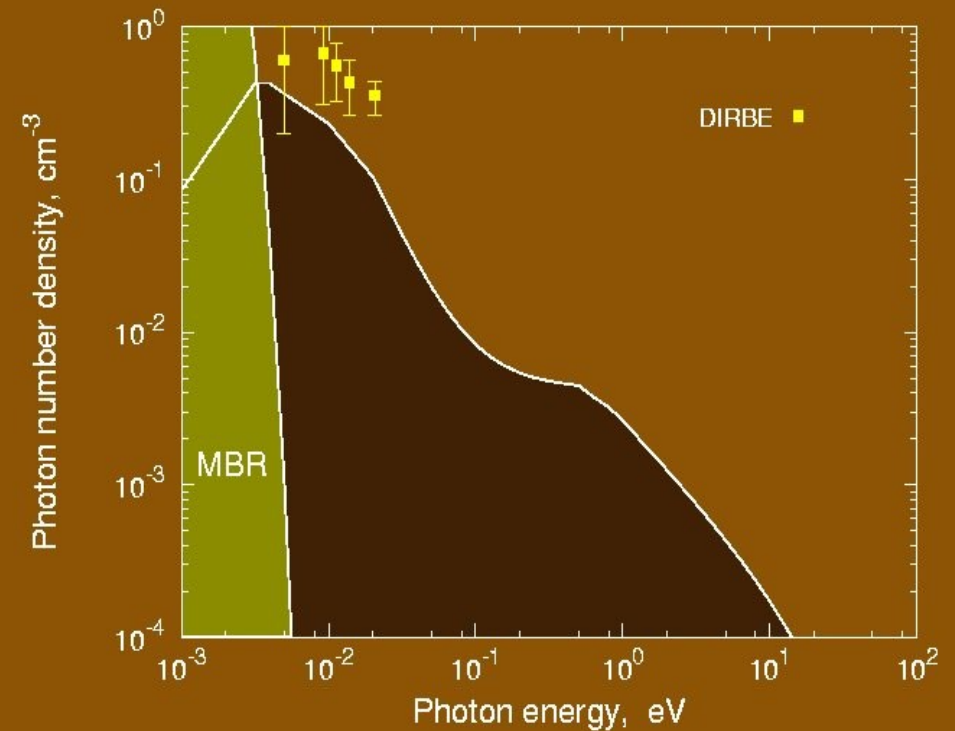
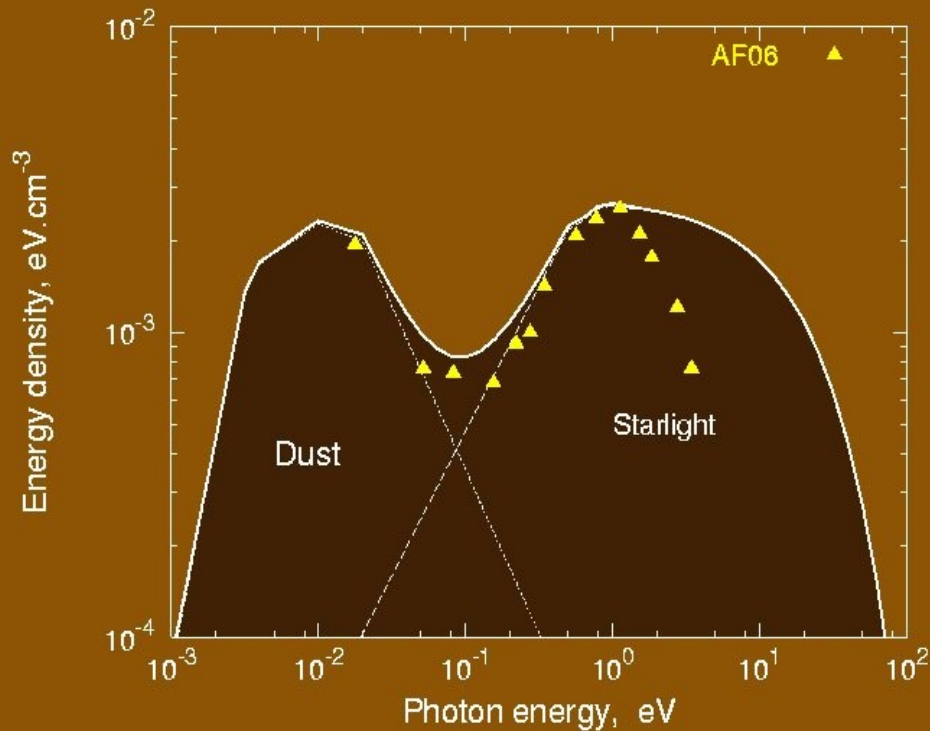


These are the NIRS observations that are dismissed by most of the experts who are convinced that it is due to incorrect subtraction of the background radiation



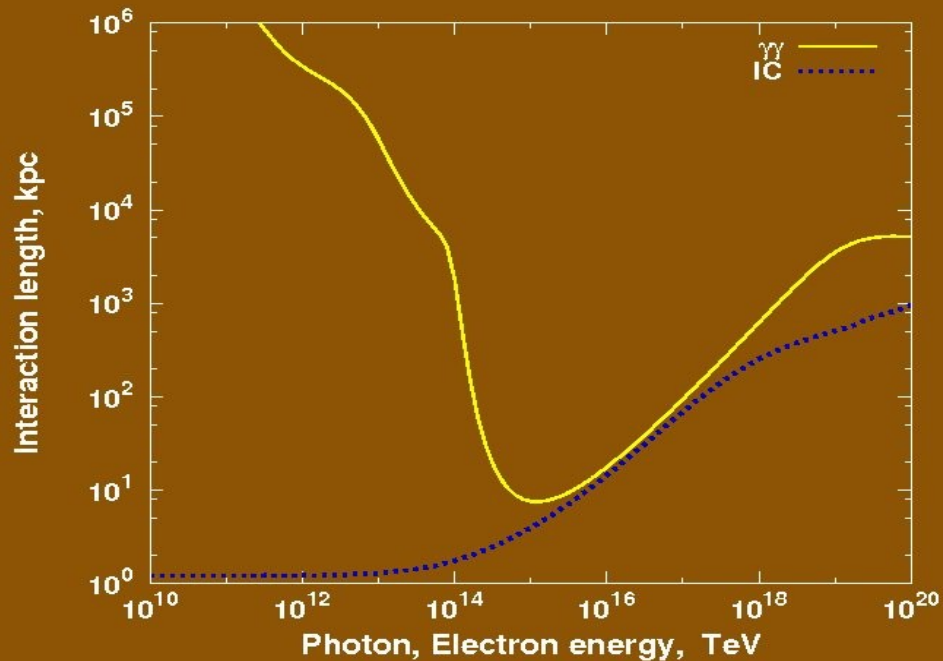
*Please do not blame Alberto Franceschini for models labeled with F. These are my own interpretations of what was published.*

Here is a collection of different models of the infrared background. Models include the emission from different types of galaxies and their cosmological evolution. The left hand peak is from light that has re-scattered in dust.



The usual way of presenting any photon field is as shown in the previous graph and in the left hand one – in terms of energy density per  $\text{cm}^3$ . We, however, use the photon field as a target and are interested in number density, as shown in the right hand graph. The distribution then peaks at the smallest energy, i.e. In the far infrared. The MBR number density is shown for comparison. There is no need to go to lower IRB density – MBR dominates.

# GAMMA RAY ABSORPTION



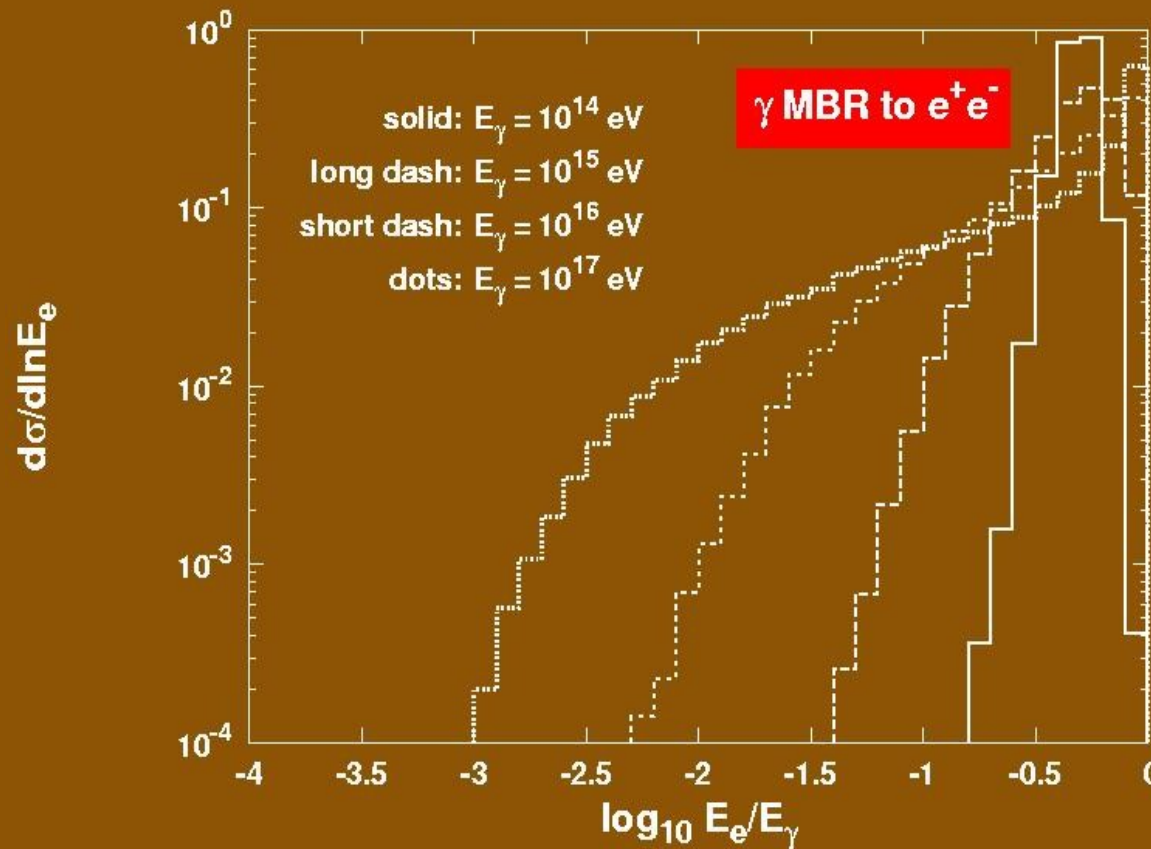
The graph shows the mean free path for gamma rays and electrons (IC) in the MBR+IRB field. TeV gamma rays interact and produce electron pairs. The flux is absorbed exponentially as  $\exp(-X/\Lambda)$  where  $X$  is the distance to the source.

The fate of the gamma rays after the pair production is not obvious, it depends on the magnetic field value in the region. Inverse Compton scattering is very fast at that energy. The newly produced electrons boost ambient photons and these may still reach the observer. In case of strong magnetic field the electron energy is quickly transferred to GeV gamma rays.



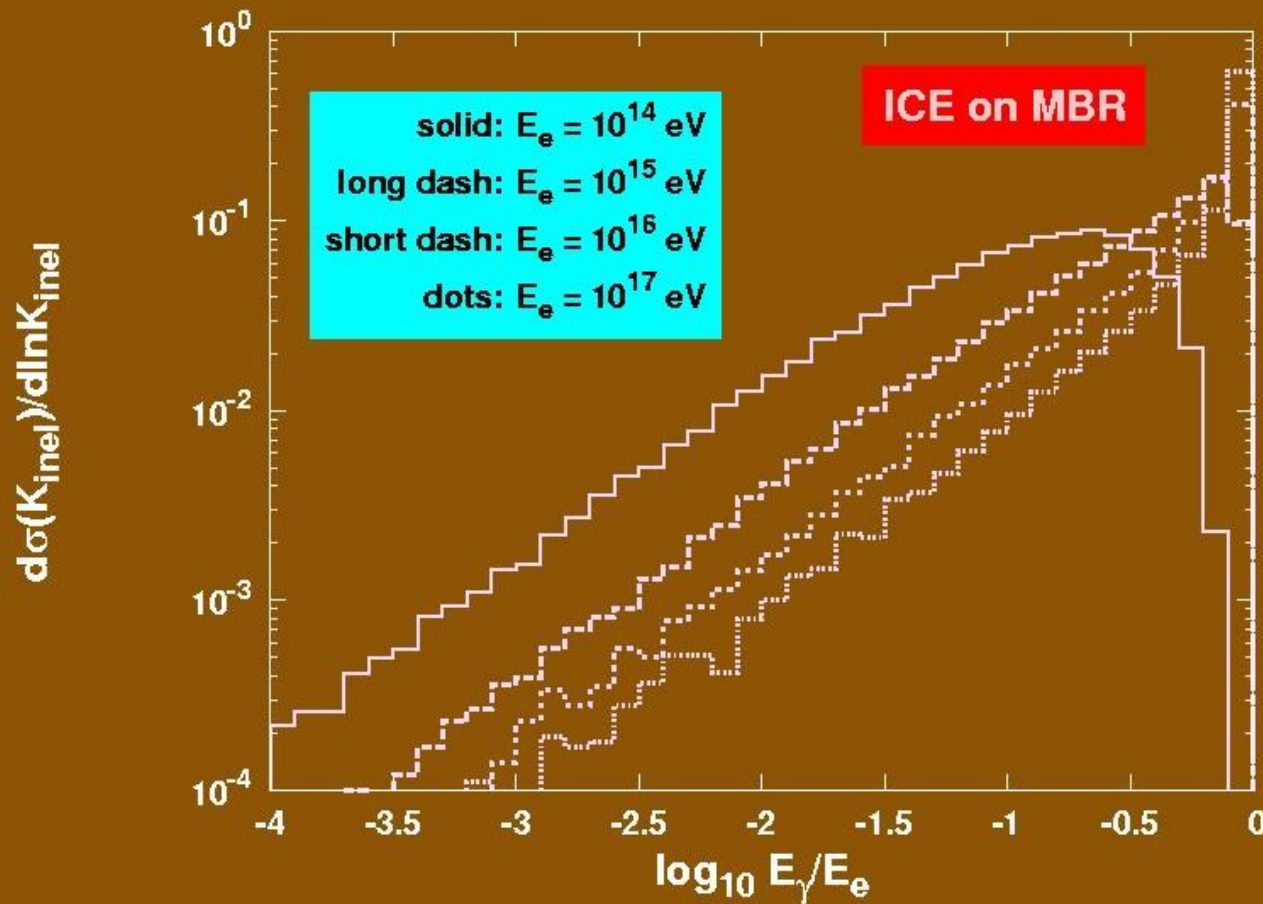
## gamma-gamma collisions

Energies of the secondary electrons as a function of the primary gamma ray in interactions with the cosmic microwave background.



Similarly to the inverse Compton scattering the energy of the secondary electrons become closer to that of the primary gamma ray. At high center of mass energy only the high energy secondary is important and the energy downgrading is quite slow. This process is often sped up by the synchrotron radiation of the newly created electrons.

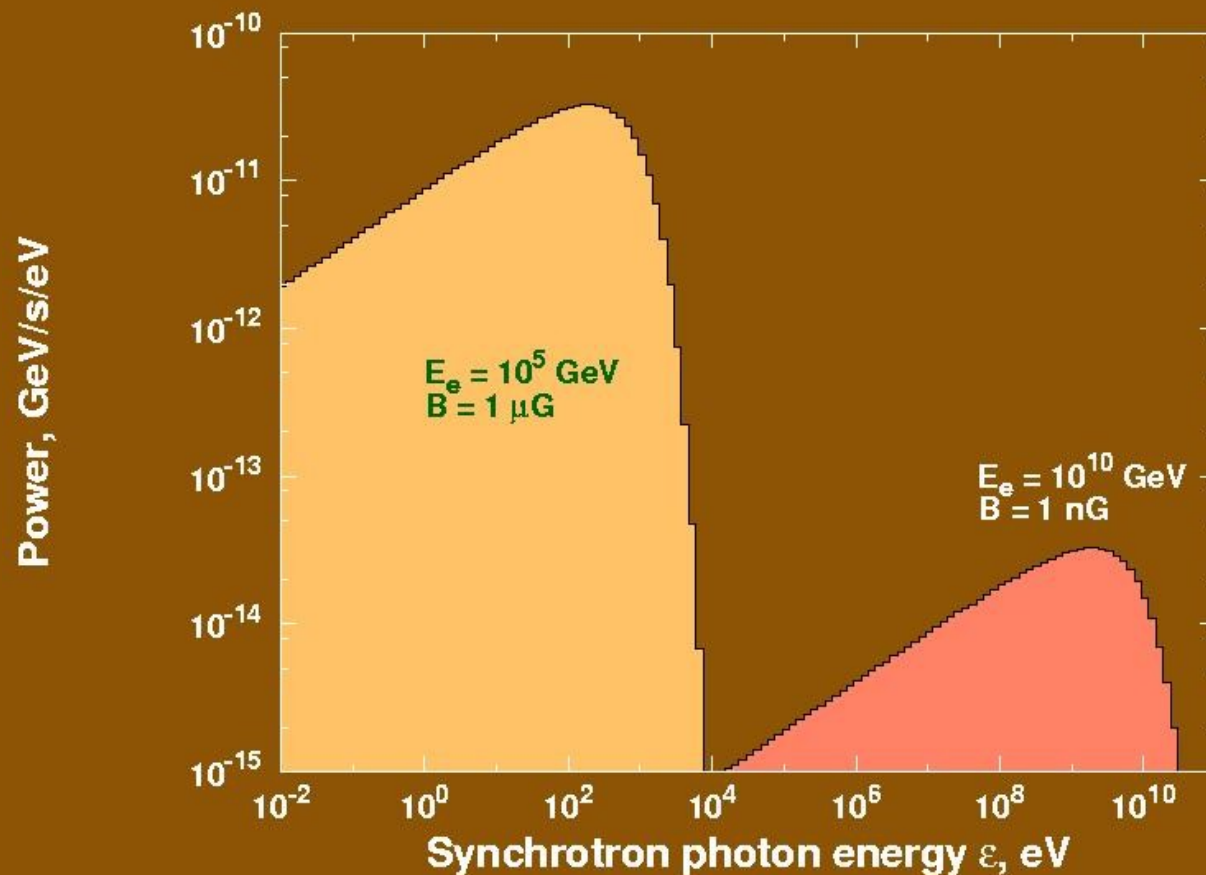
## Example: electron interactions in MBR.



Increase of the inelasticity in Inverse Compton effect with the electron energy. The dotted histogram is for  $10^{17}$  eV electrons. For higher frequency photon fields the effect would come to much lower electron energy.

## Synchrotron radiation

The energy loss of a  $10^{19}$  eV electron in 1 nG field is  $10^4$  times higher than that of a  $10^{14}$  eV electron in 1  $\mu$ G field but the critical frequency is higher by  $10^7$ .



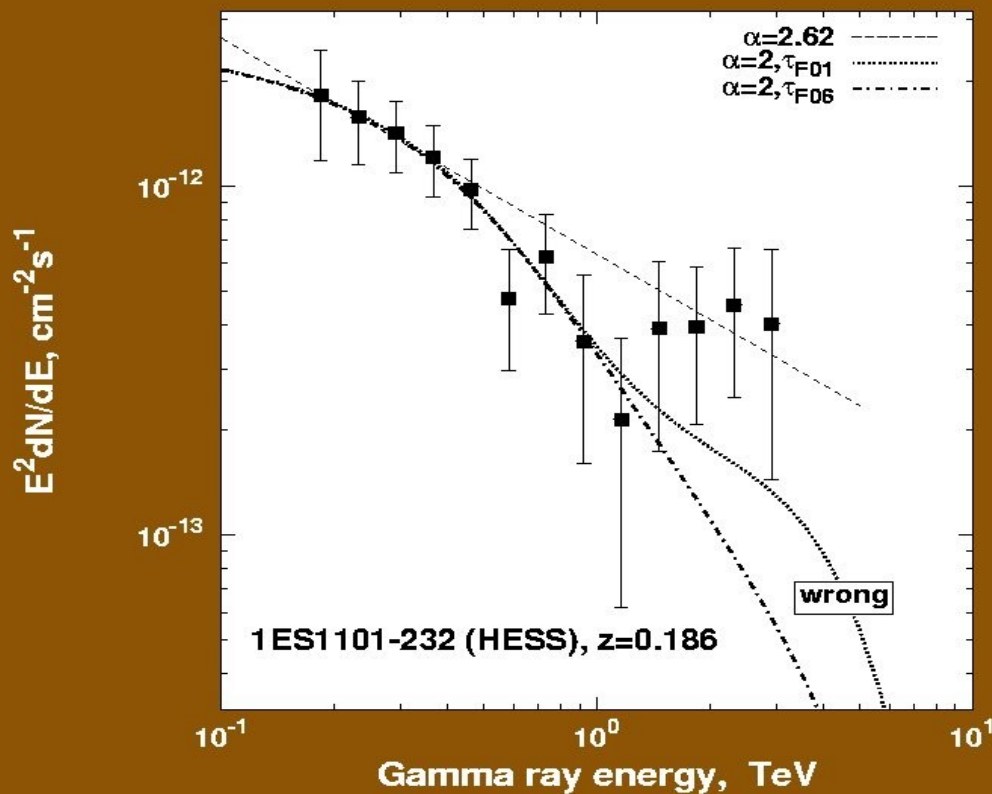
After averaging over the pitch angle the electron energy loss

$$-\frac{dE}{dt} = 3.79 \times 10^{-9} \left( \frac{B}{\text{gauss}} \right)^2 \left( \frac{E_e}{\text{GeV}} \right)^2 \text{ GeV/s}$$

The emissions

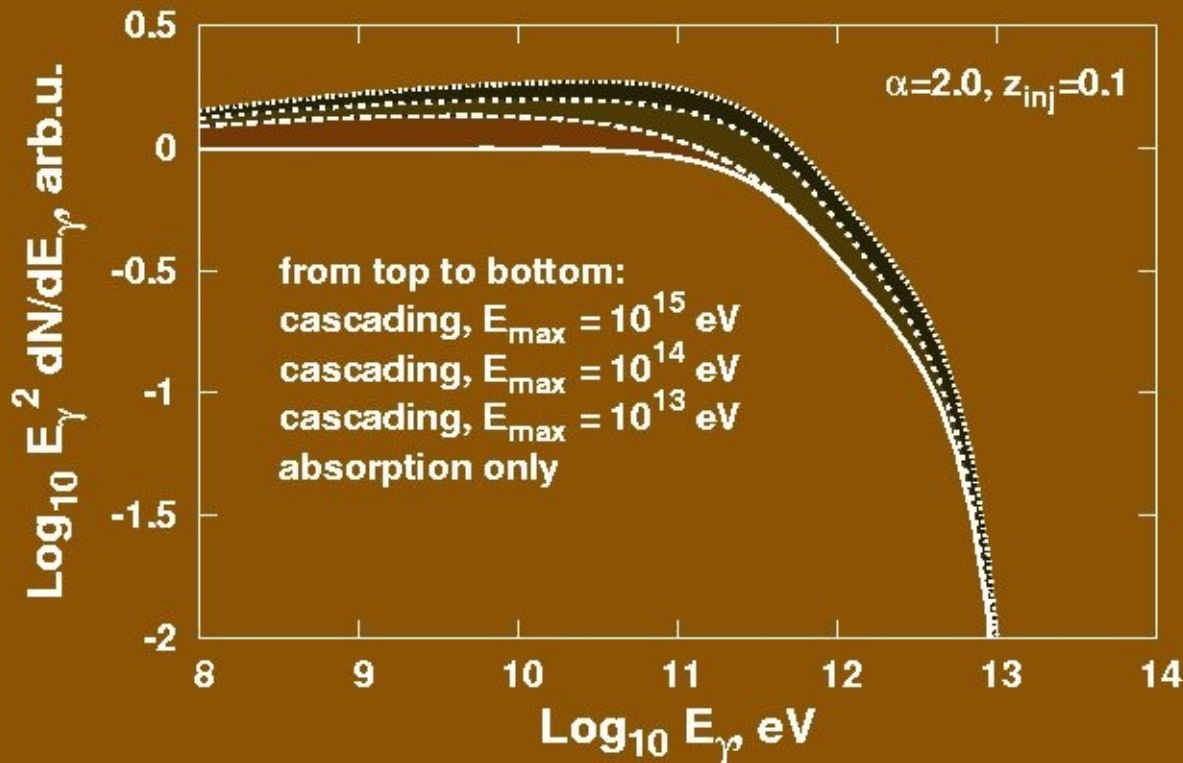
$$\nu_c = 0.0665 \left( \frac{B}{\text{G}} \right) \left( \frac{E_e}{\text{GeV}} \right)^2 \text{ eV}$$

spectrum depends on the critical frequency i.e. the higher the electron energy is, the harder the synchrotron emission is. Photon number peaks at  $0.29 \nu_c$ .

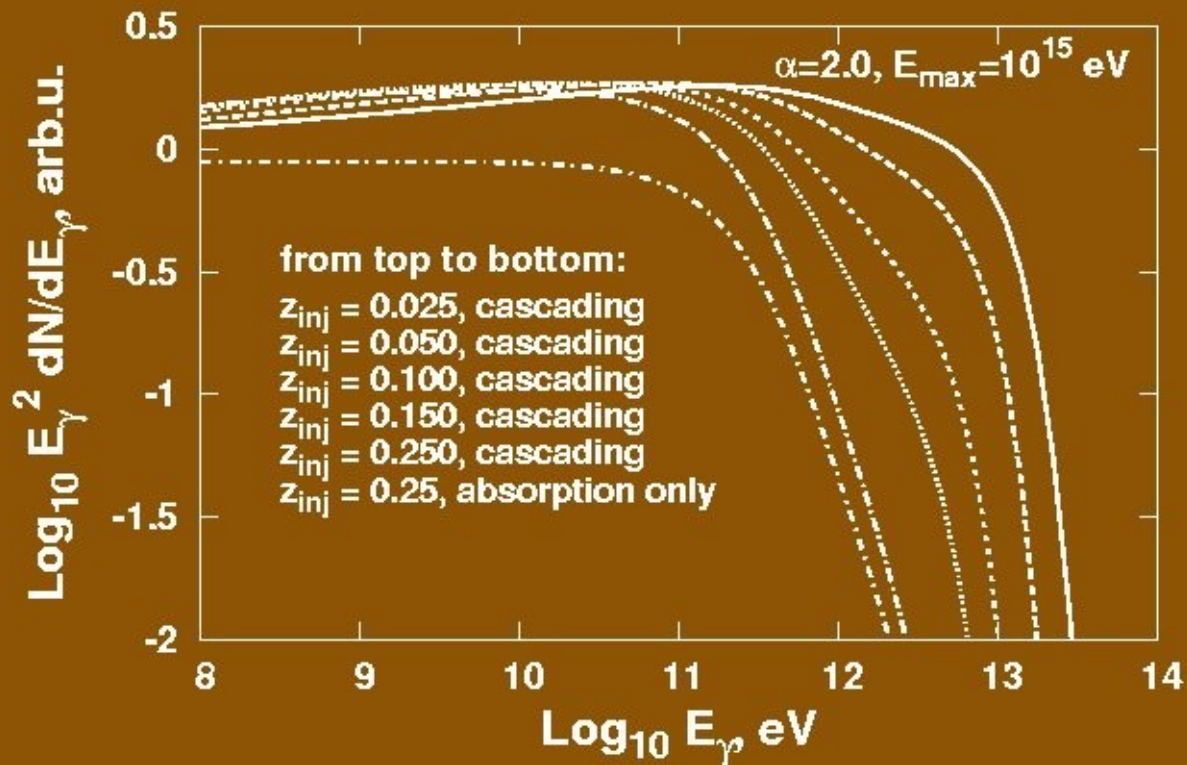


The model labeled 'wrong' was the first one I tried. It has too low middle IR and possibly too high far IR. It gives that strange absorption curve at 2-3 TeV.

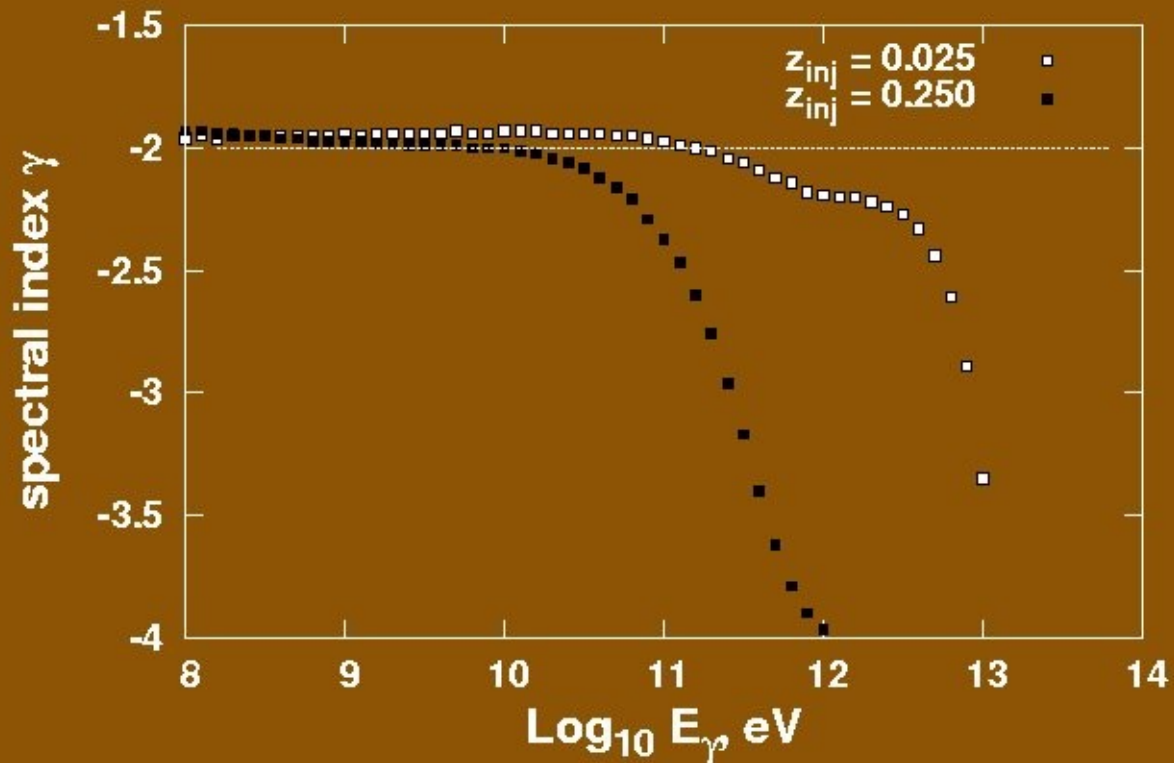
Absorption of TeV gamma rays on the large distance to the source – the dot-dash line is for the correct model. The median line is for an incorrect model of mine that had too low mid-IR. The straight line is for a fit with  $\alpha = 2.62$ . The four highest energy points may be a fluctuation, but they lead the mind to gamma-electron cascading.



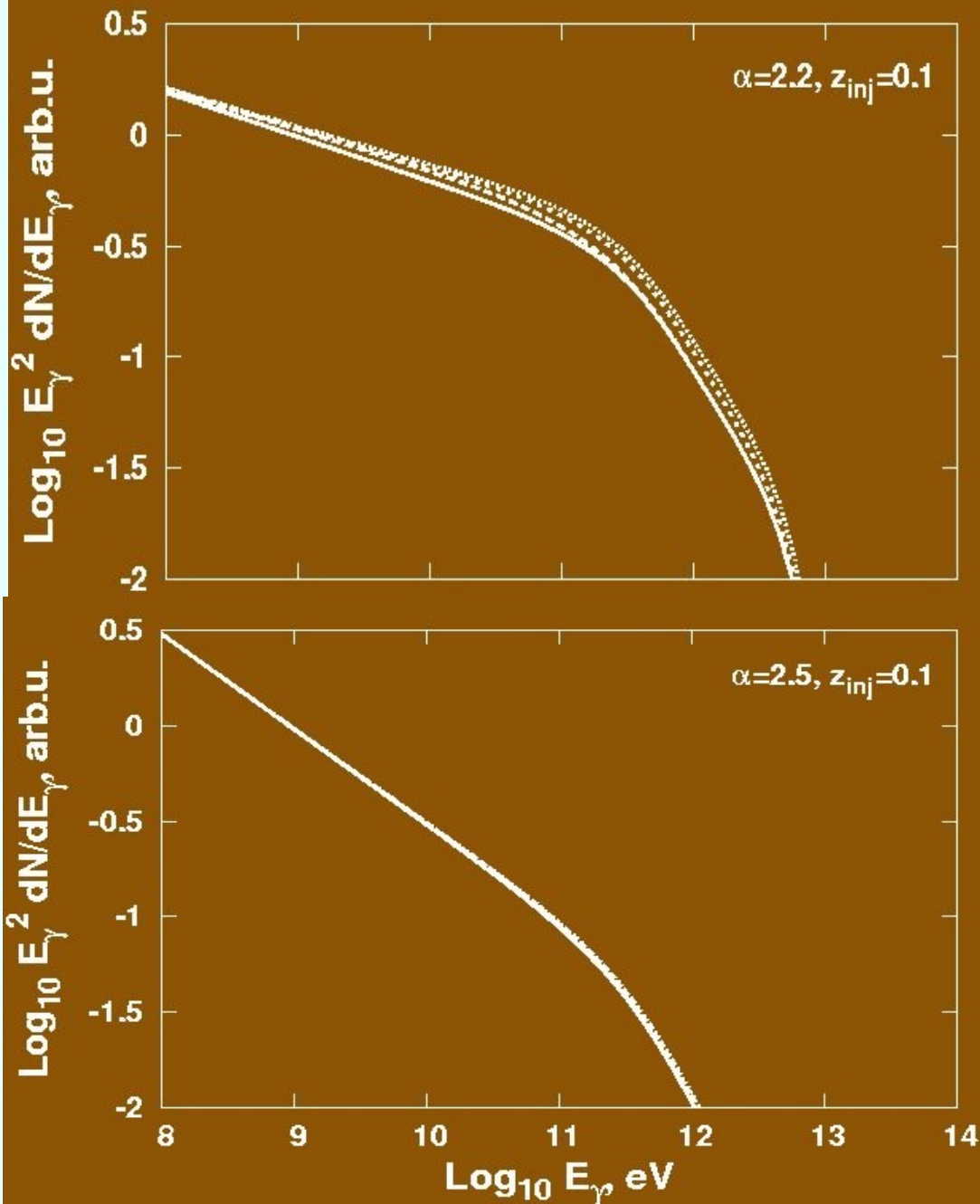
Cascading is only possible in the absence of strong magnetic field and depends mostly on two parameters: maximum gamma ray energy  $E_{max}$  at production and the distance to the source. The maximum energy has to be higher than 10 TeV, but significant cascading happens when the gamma rays interact in the MBR. The calculation shown is in the absence of magnetic fields. Redshift of 0.1 is roughly a distance of 400 Mpc.



Dependence on the distance to the source for maximum energy of 1,000 TeV. Notice the negative correlation between the maximum energy at observation and the distance to the source. For very large distances ( $z = 0.25$  in this case) the difference between cascading and absorption is only a flux increase by a factor of 2 and a change of slope below 10 TeV.



The figure shows the change of slope as a function of the gamma ray energy in propagation on the minimum and the maximum distance from the previous graph. In certain energy ranges the slope is flatter, but at high energy it is always steeper than the injection one.



Cascading can only be important for flat injection (acceleration) spectra. It is negligible for  $\alpha = 2.2$  and is totally unobservable for steeper spectra.

Since there are now very distant gamma ray sources cascading should be used for a better analysis of the sources. In case of success it could be also measure of the average magnetic field in the line of sight if the observed spectrum is flatter than any possible model.

SSC models cascading to be performed in the future



**Cosmogenic 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 Berezhinsky & 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.

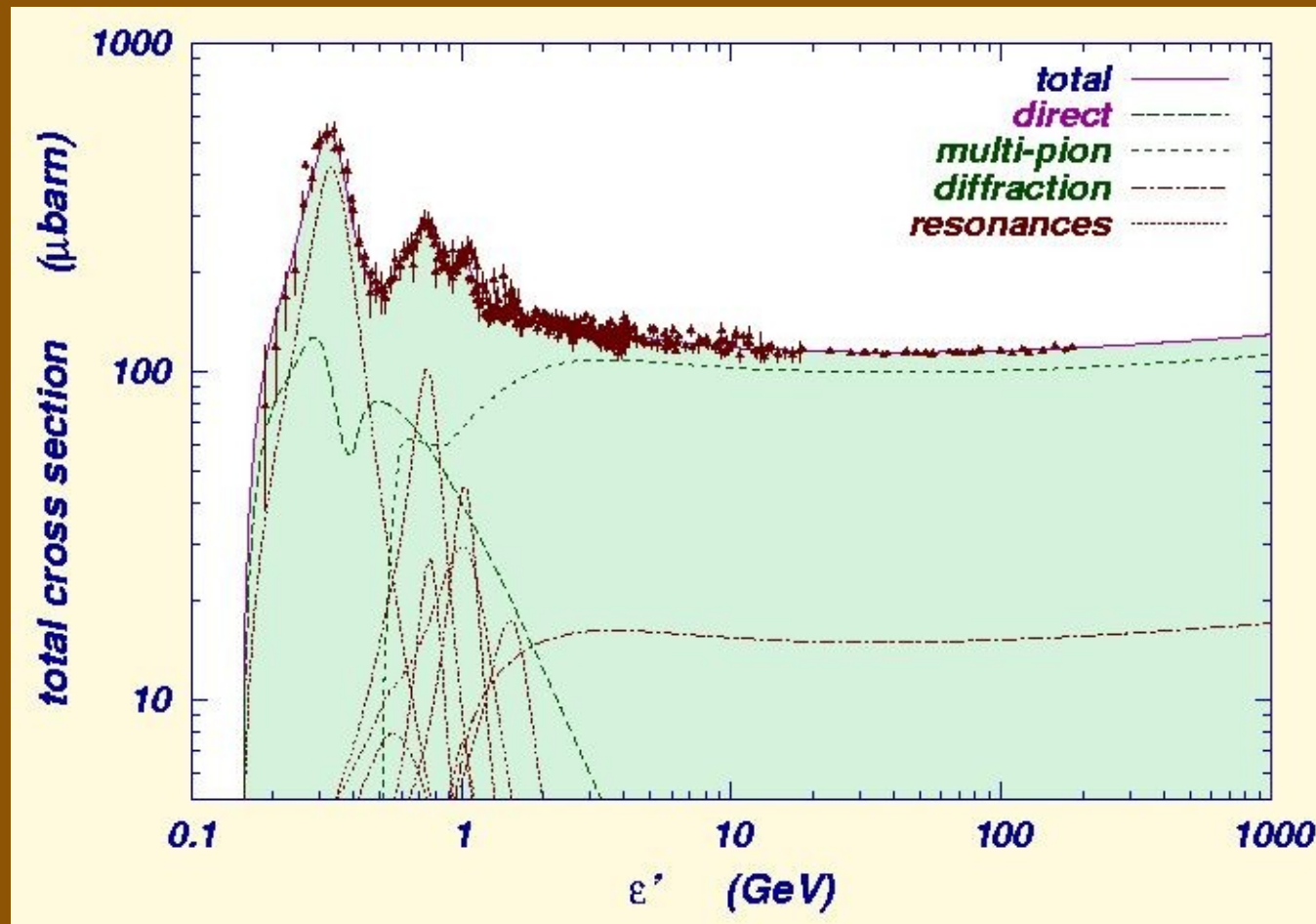
The main difference with the processes in AGN and GRB is that the photon target is the microwave background (2.75°K) of much lower temperature than the photon emission of these sources. This raises the proton photoproduction threshold to very high energy:

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

Actually the proton photoproduction threshold in MBR is about  $3 \cdot 10^{19}$  eV.

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

The main energy loss process of the ultra high energy protons in the Universe is photoproduction interactions in the microwave background. The photoproduction cross section is very well measured in accelerator experiments.



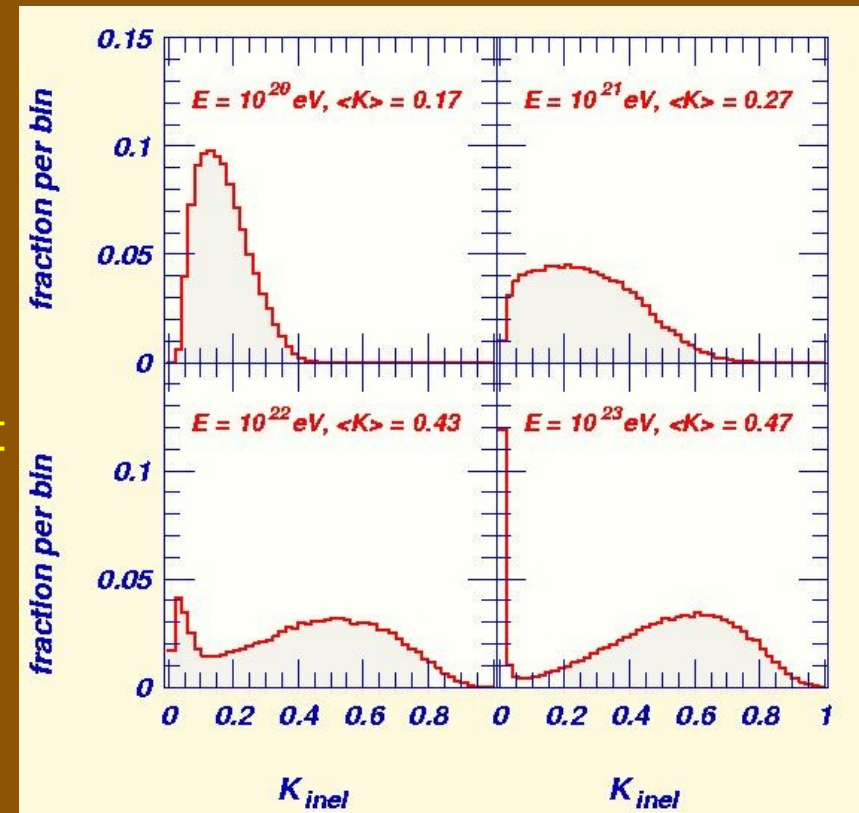
Photoproduction cross section in the mirror system, i.e. photons interacting on target protons.

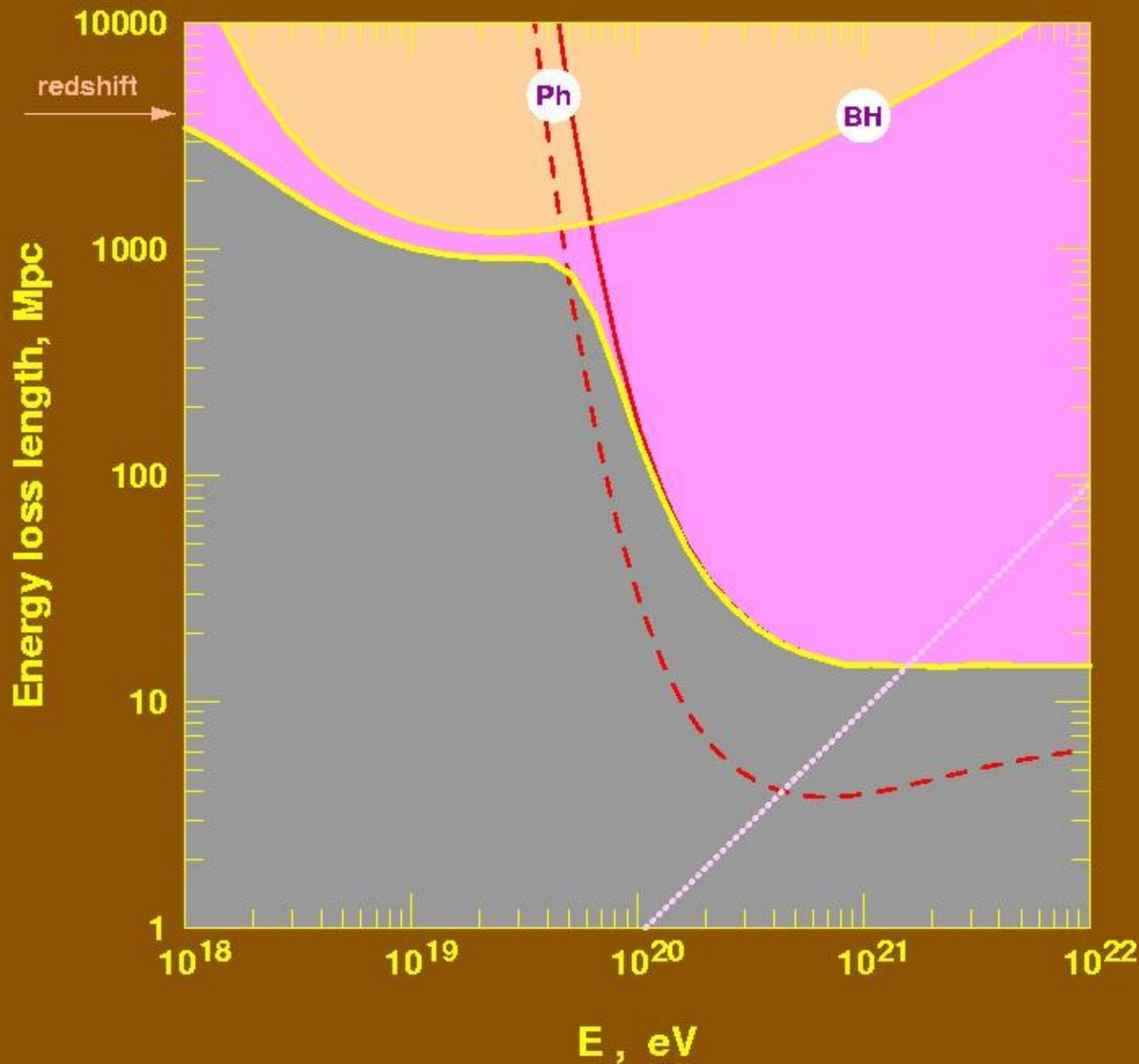
The UHE protons energy is so high that they can interact on photons from the microwave background and produce secondary pions. The threshold is when the center of mass energy exceeds the proton mass + the pion mass:

$$E\varepsilon(1-\cos\theta) > (m_p+m_\pi)^2$$

For the average microwave background photon the threshold is at  $10^{20}$  eV. Averaged over the photon spectrum and direction the threshold is a factor of 2 lower.

The inelasticity of the proton in these interactions is important energy dependent parameter. At threshold protons lose less than 20% of their energy. At very high energy the loss can reach 50%.

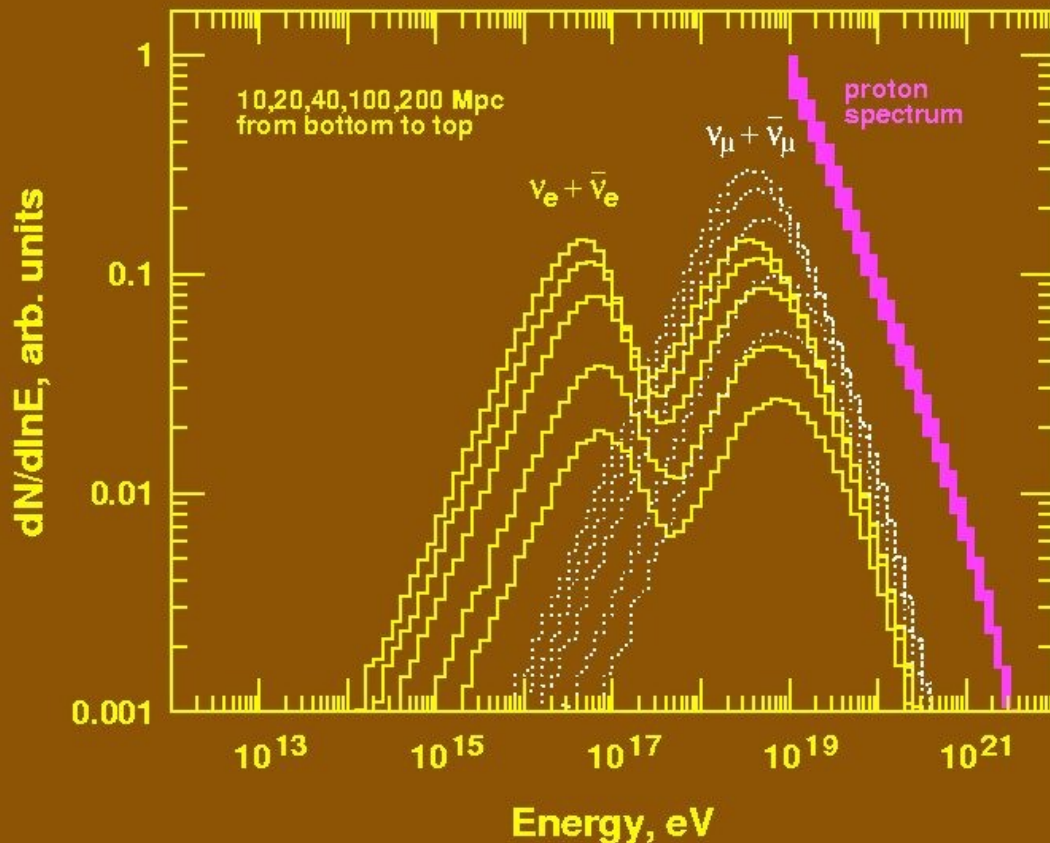




The energy loss scale of high energy protons in the microwave background.

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 Berezhinsky & Grigorieva. IRB is difficult to notice.



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).

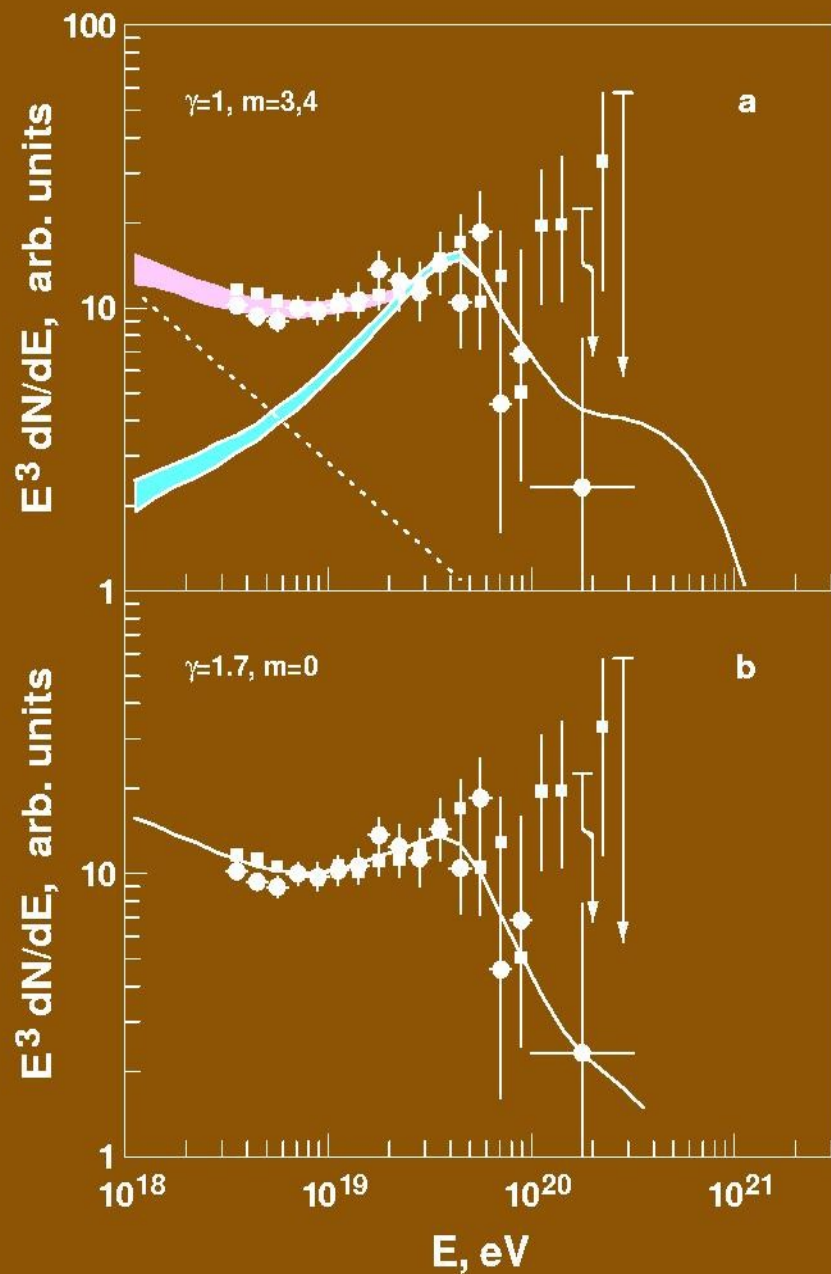
From: Engel, Seckel & Stanev, 2001

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.

The exact flux and shape of the energy spectrum of the cosmogenic neutrinos depends heavily on the UHECR luminosity in the Universe and on the cosmological evolution of the cosmic ray sources. There are two opposite models: Waxman & Bahcall use a flat  $\alpha = 2$  injection (acceleration) spectrum, that requires strong cosmological evolution of the sources to fit the observations. Berezhinsky & Co use steep  $\alpha = 2.7$  spectrum that does not need cosmological evolution. We will use these two models and attempt to estimate the fluxes of cosmogenic neutrinos for the case that UHECR are injected in sources with uniform and homogeneous distribution in the Universe. We shall keep the UHECR flux at  $10^{19}$  eV the same in both cases.

Next slide shows how these models work for the observed UHECR spectrum.

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



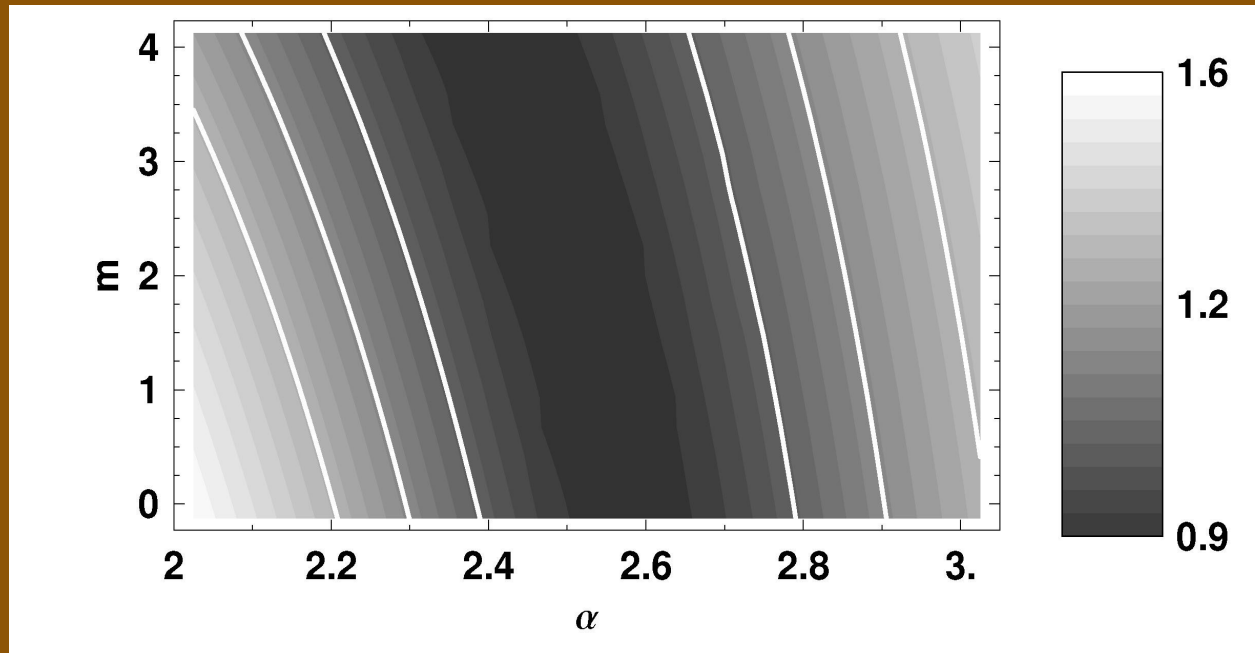
We even do not know what the cosmic ray spectrum at injection (acceleration) is. Fit *a* is the original W&B fit using flat injection spectrum as suggested in acceleration models. Galactic cosmic ray spectrum extends to 10 EeV

Most contemporary fits favour steeper injection spectra. Fit *b* (originally suggested by Berezhinsky 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.

Spectra are not very well determined.

## AGASA

The darker the area is the better the fit. White lines indicate  $1\sigma$  errors.

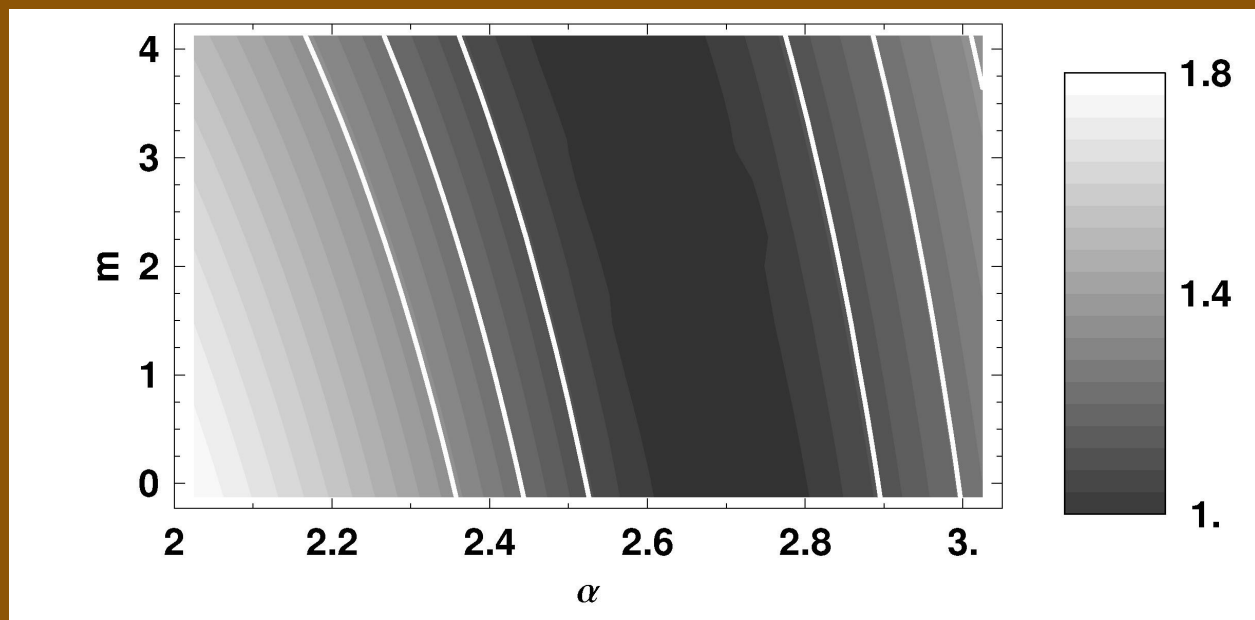


Fits of the spectra above  $10^{19}$  eV only

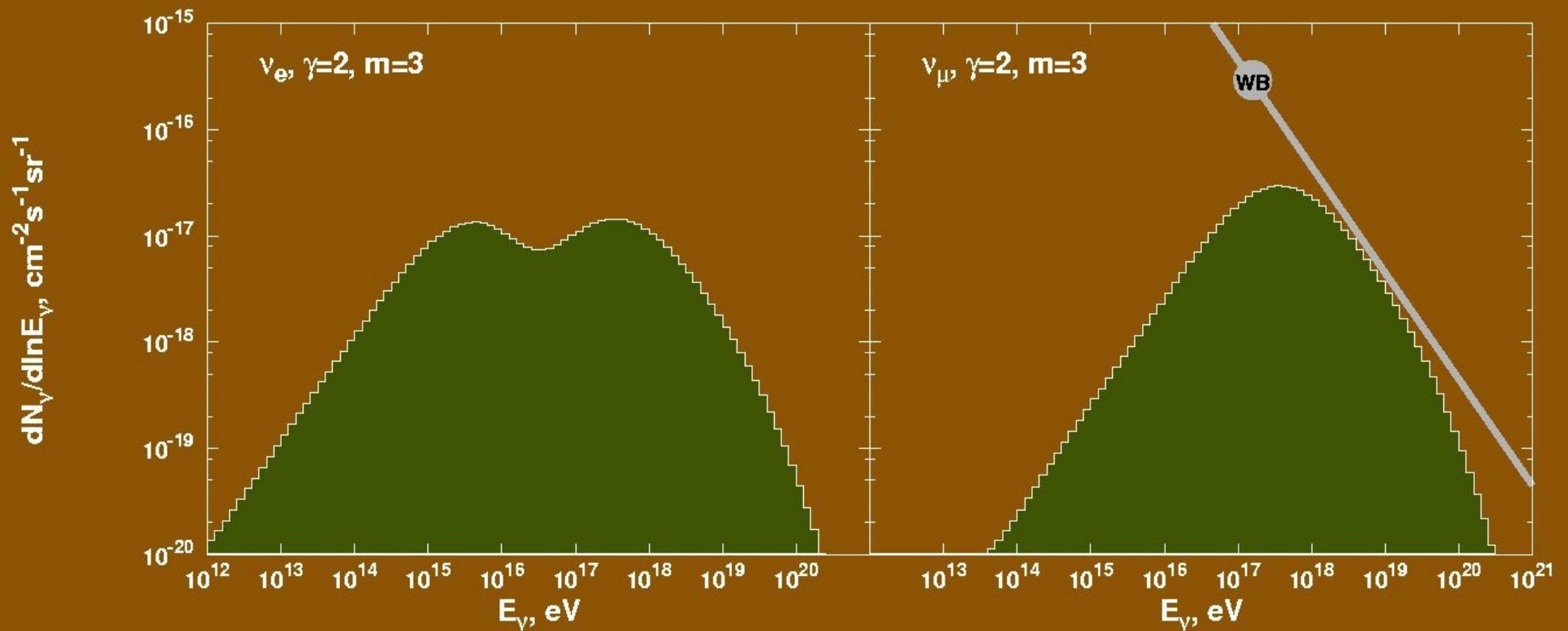
## HiRes

Note Berezhinsky et al and HiRes fit down to 1 EeV.

From: DeMarco & Stanev







From: Engel, Seckel & Stanev, 2001

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.

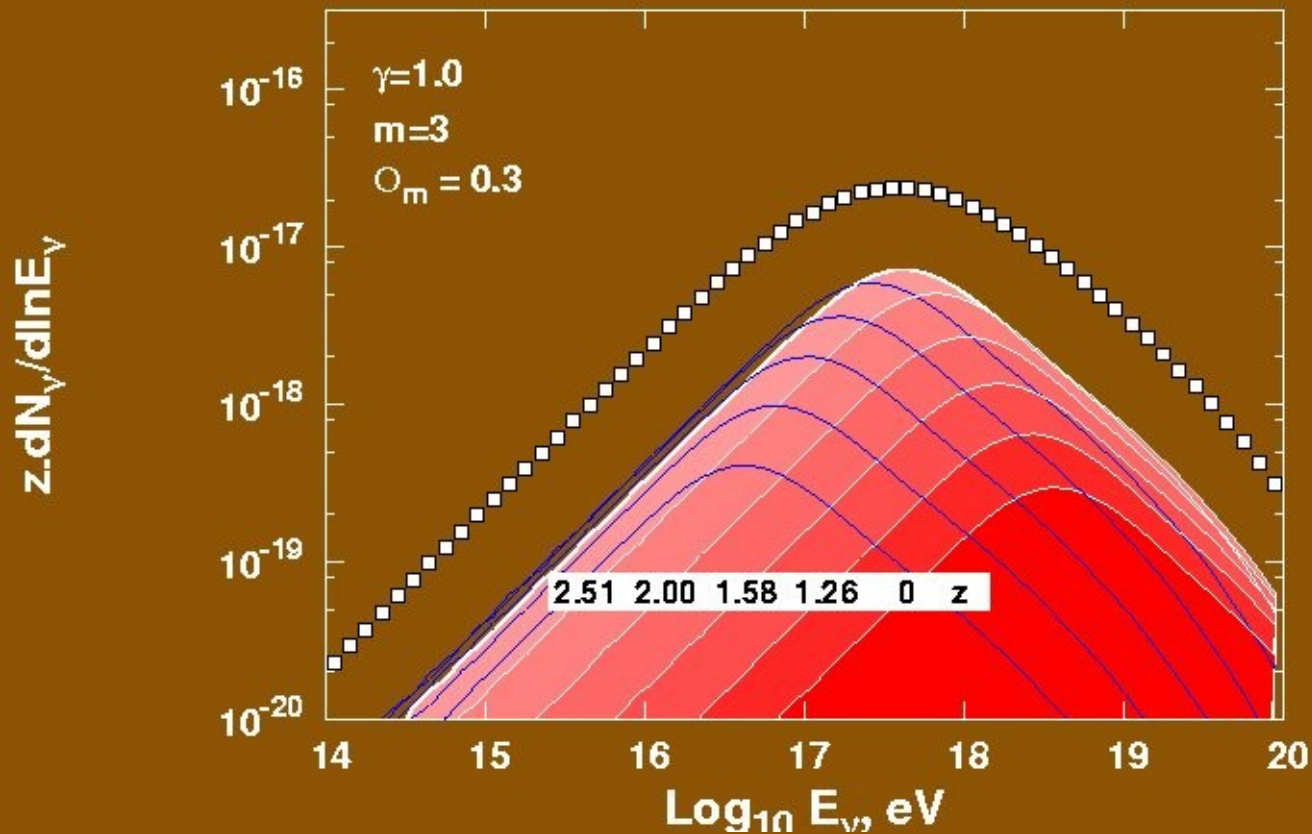
The flux of cosmogenic neutrinos at  $z=0$  and which is due to the cosmological evolution of cosmic ray activity can be written as

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

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)

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

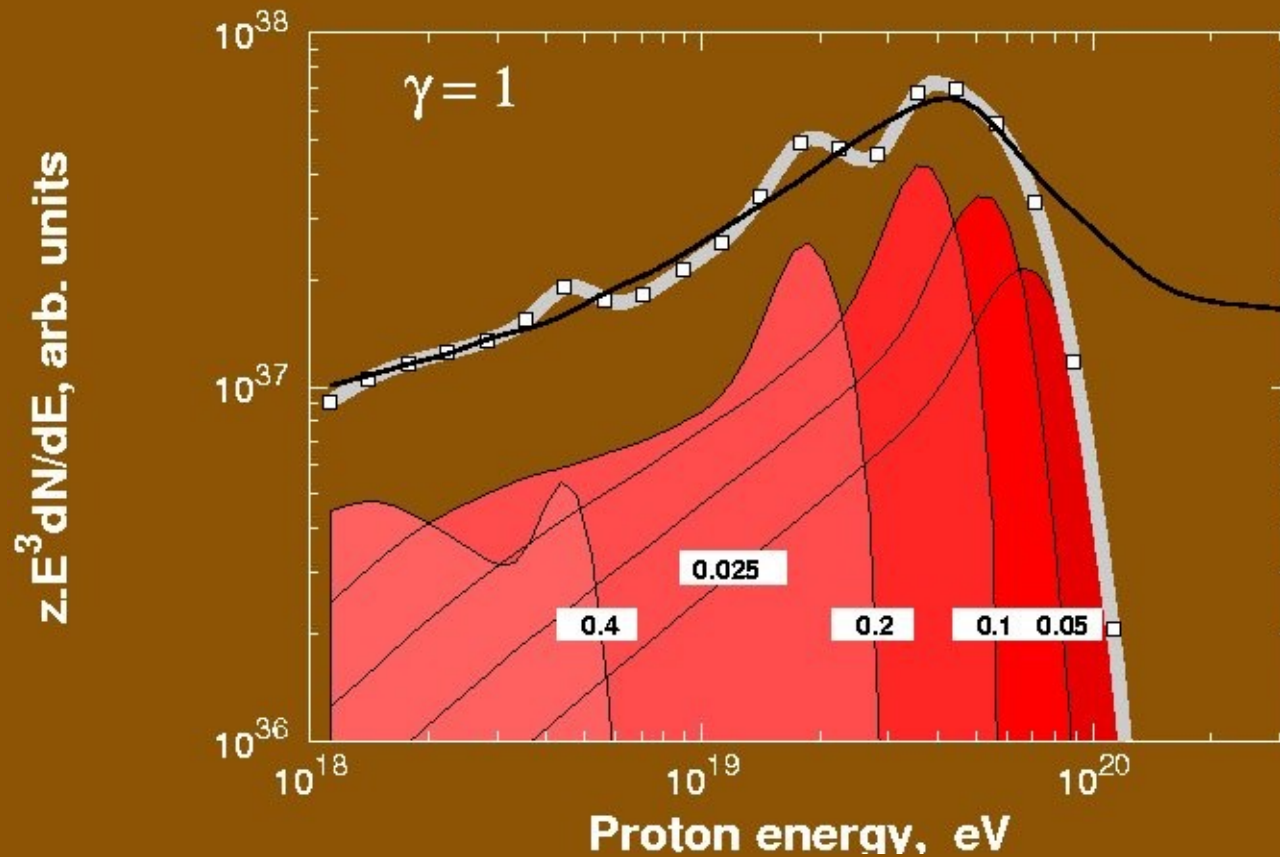
It tells that the contribution is weighted by the sum of the cosmological evolution parameter and the index of the cosmic ray energy spectrum  $\gamma$ . ( $q = 1+z$ )



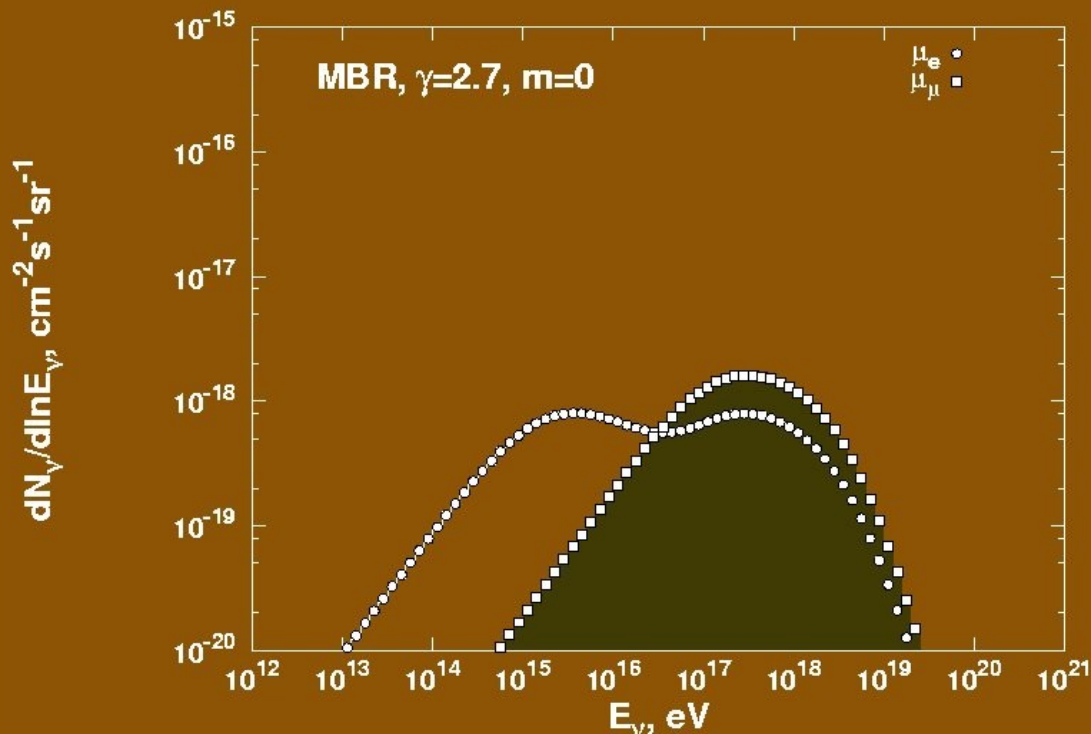
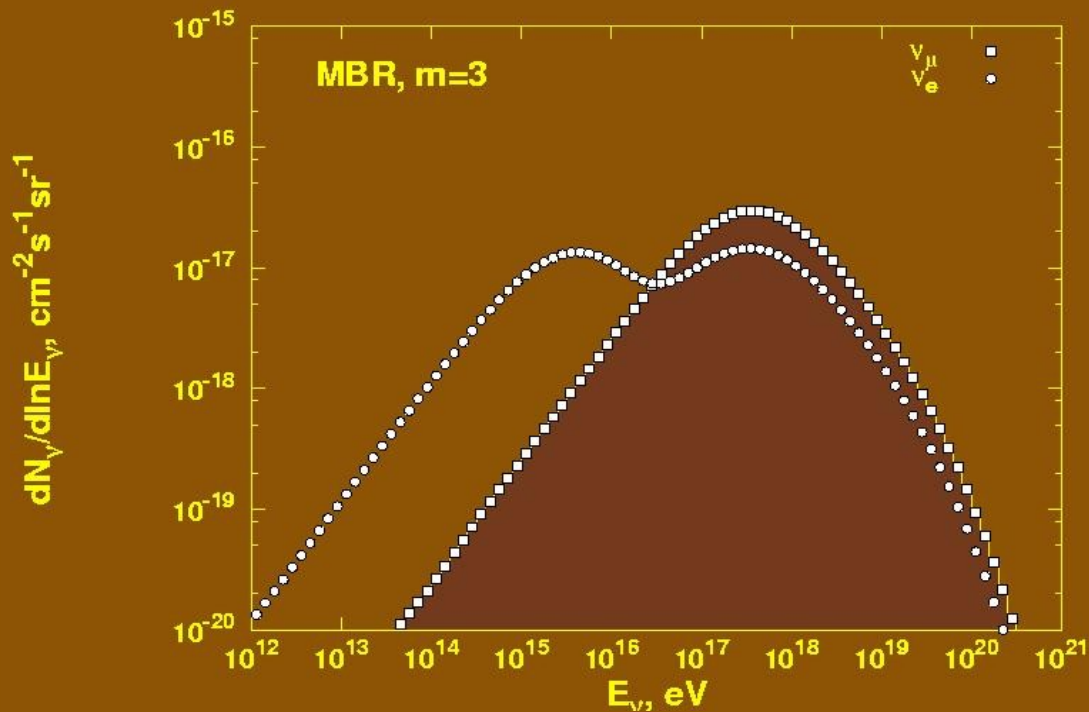
Neutrinos generated by protons in interactions on the MBR at different redshifts as marked in the figure.

Note the logarithmic scale in redshift. 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.

High energy cosmic rays ( $>10^{19}$  eV) emitted at high redshift do not contribute to the observed flux because of strong energy loss. This is major difference between neutrinos and nucleons. The maximum acceleration energy in the example below is  $10^{21.5}$  eV.



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.

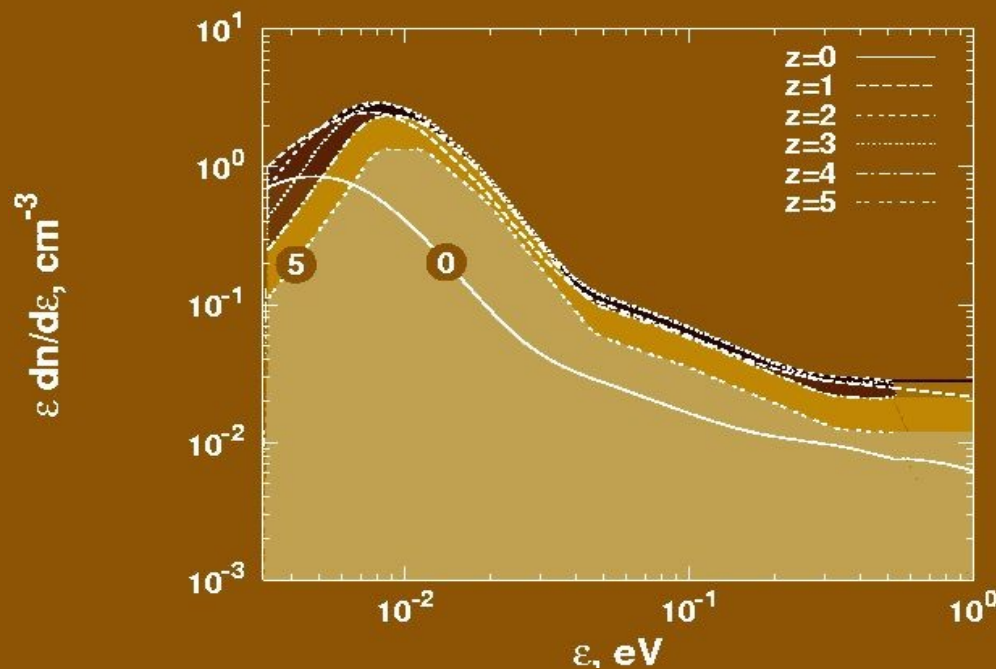


In the case of flat injection spectrum cosmogenic neutrino production is much higher for two reasons:

- 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 1/2 orders of magnitude.

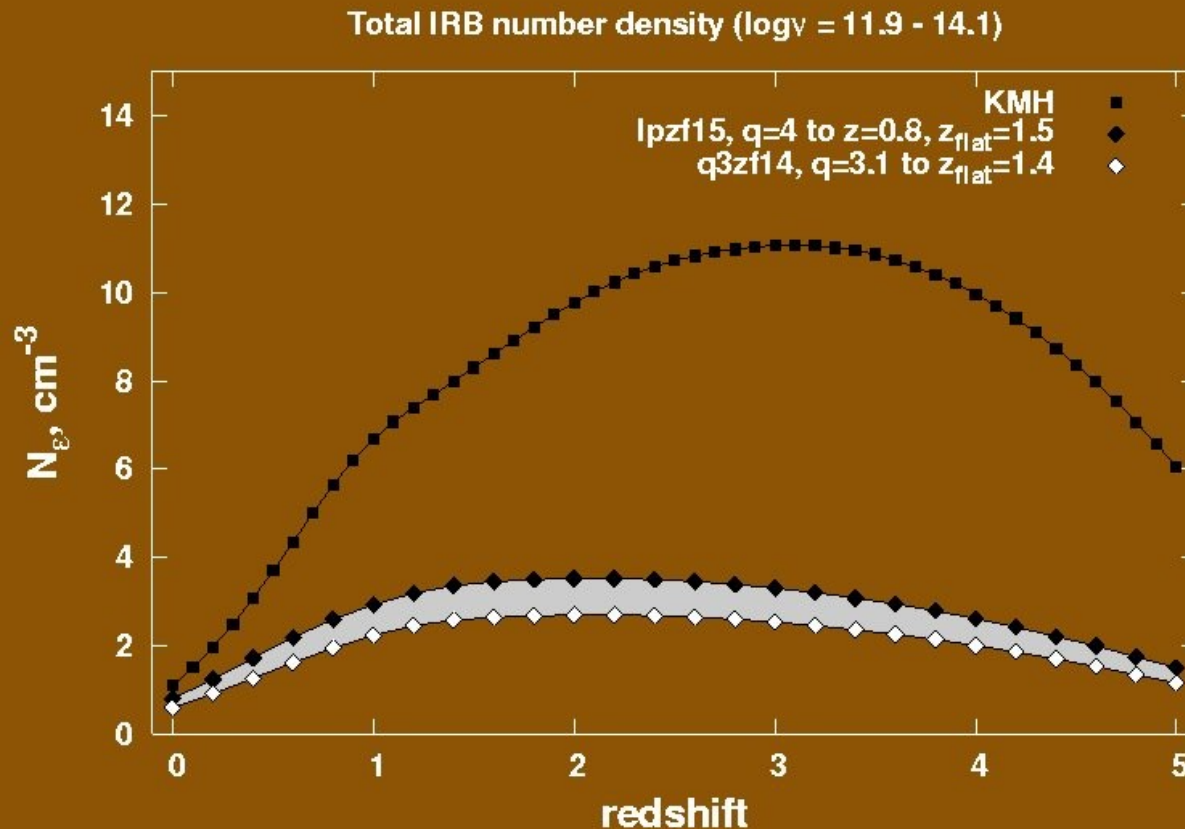
**NOT THE END OF THE STORY:** The microwave background is NOT the only universal photon field. The universal infrared background occupies the energy range between MBR and the optical/UV one. The near infrared has also been derived from multi-TeV gamma ray observations. The far infrared is being observed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



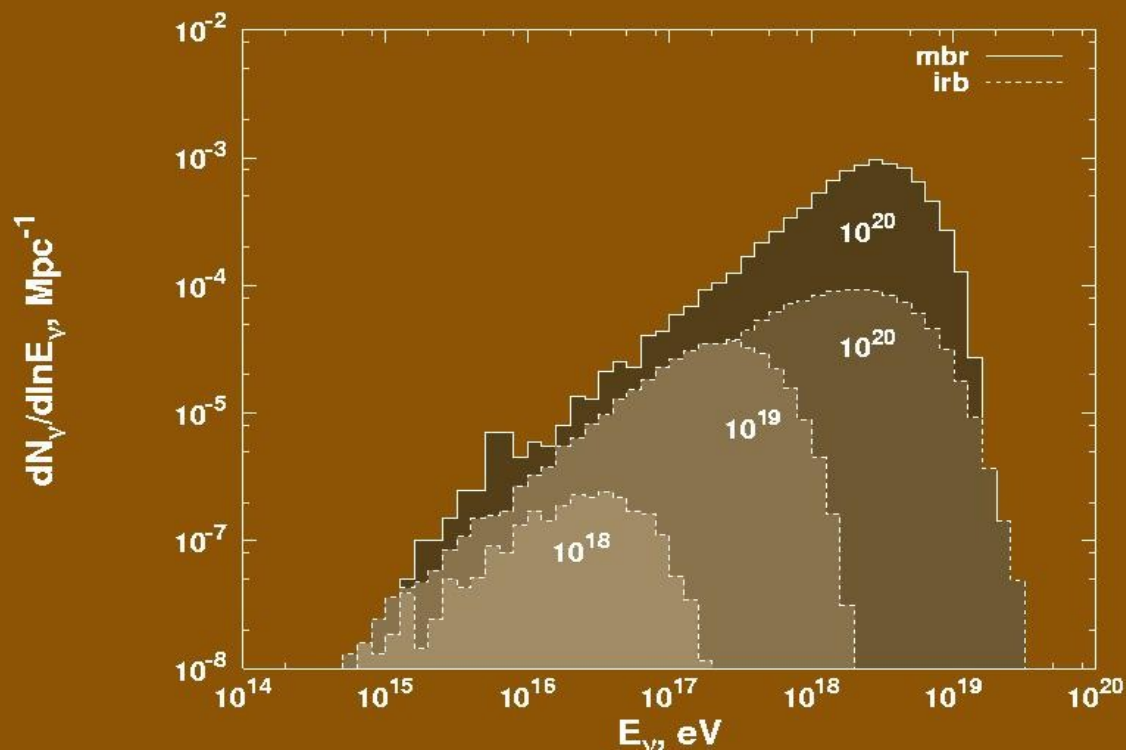
The current density of the IR background is about  $1 \text{ cm}^{-3}$ . Its energy is much higher than MBR and lower energy cosmic rays interact in it.

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

There seems to be a big difference (unless I read the papers incorrectly) in the cosmological evolution of IRB models that have similar number density at redshift of 0. This could strongly affect the calculation of cosmogenic neutrino fluxes.



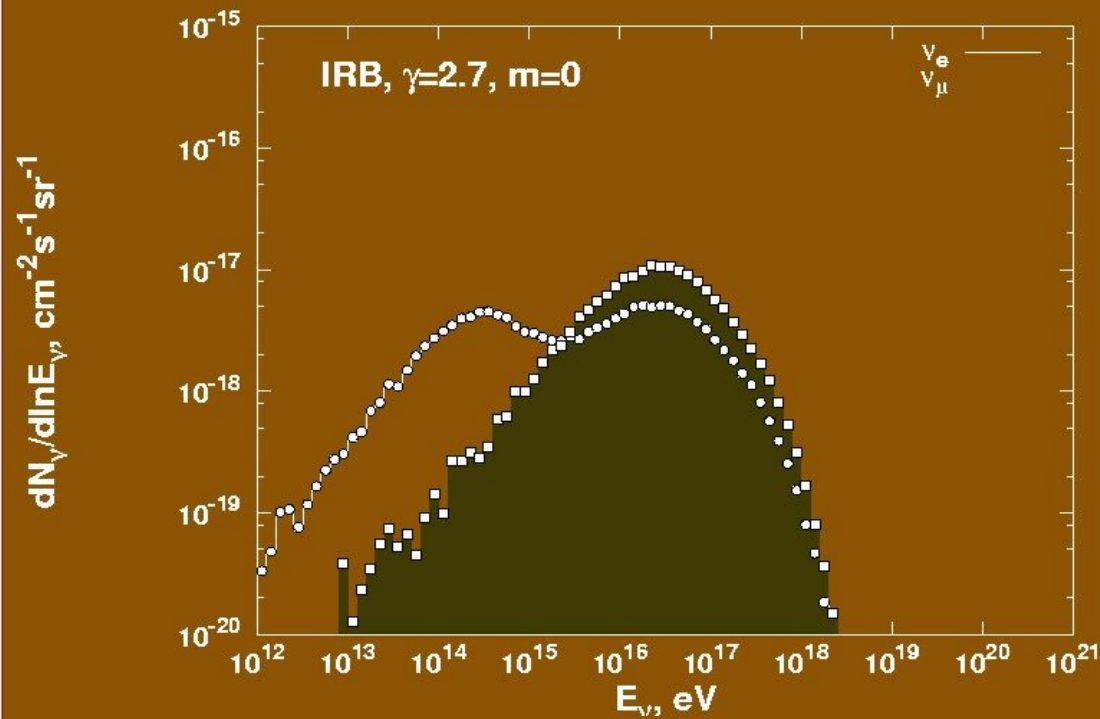
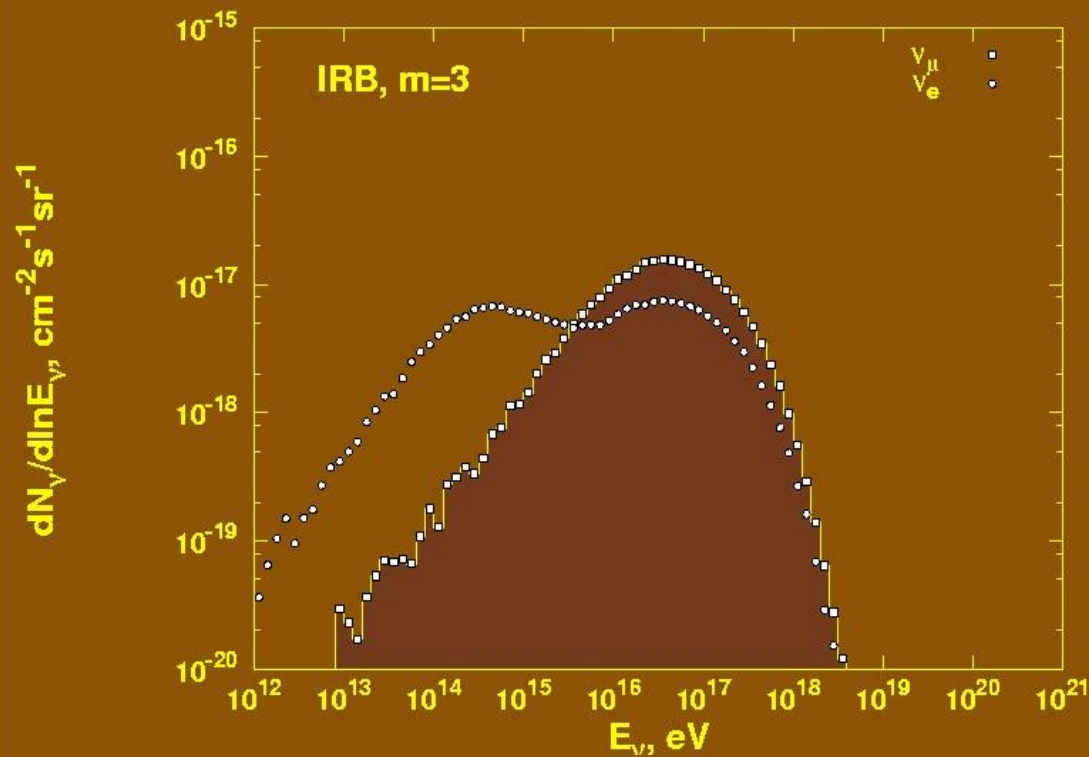
I may not have read correctly the calculation of Kneiske et al



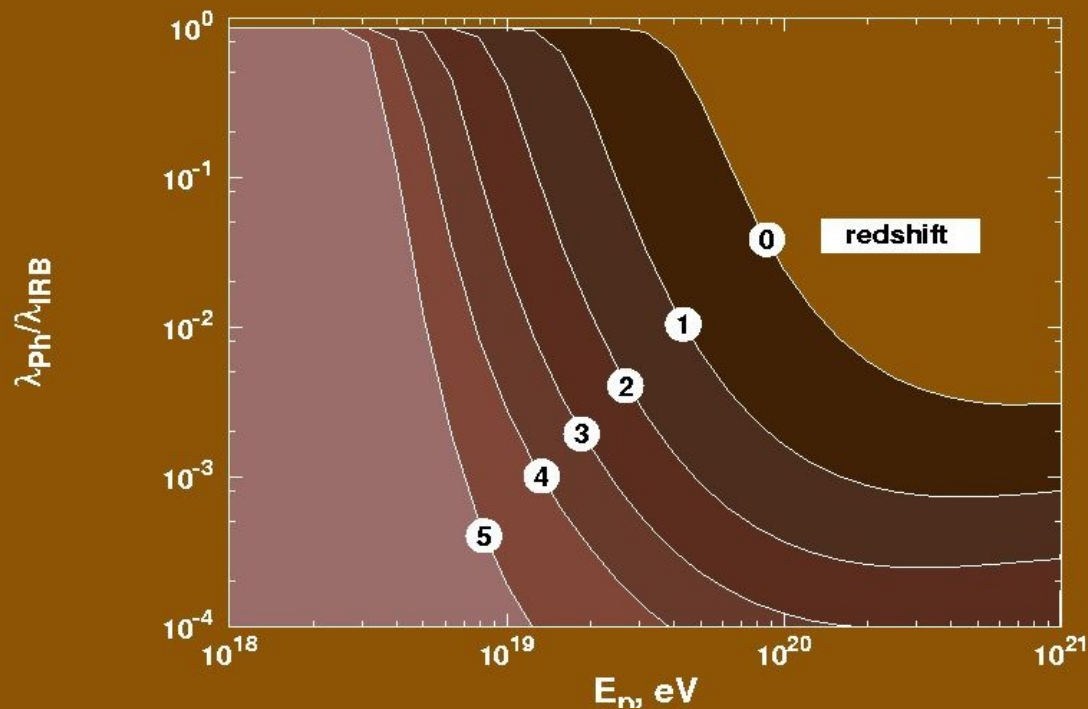
Yield of muon neutrinos from proton propagation on distance of 1 Mpc.

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.



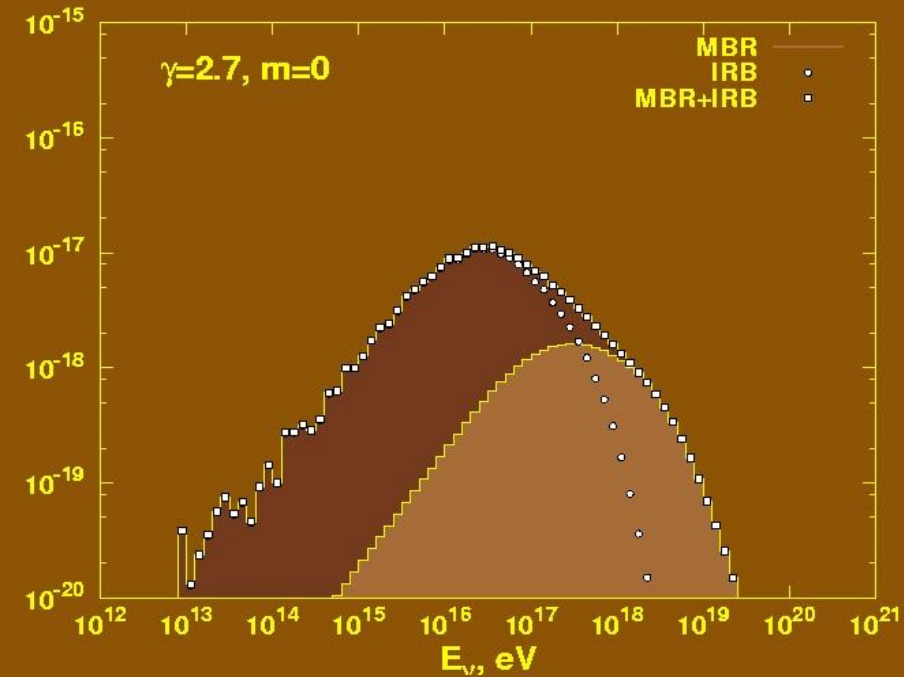
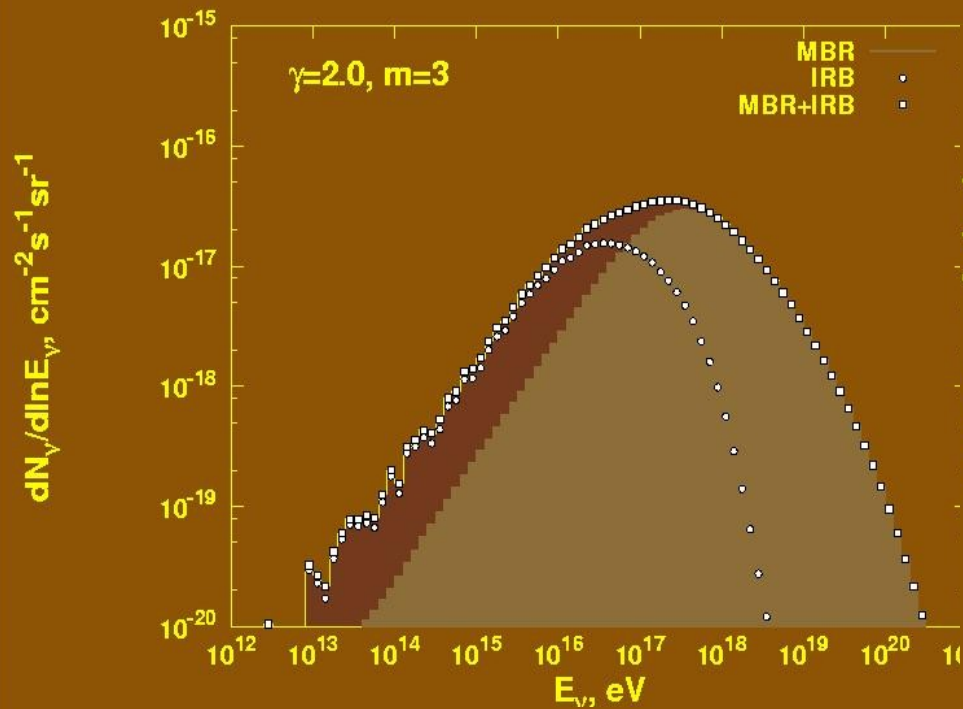


In the case of interactions in the IRB the difference between different cosmological evolutions can be compensated by the larger number of interacting protons. In case of  $m=3$  the difference was a factor 30 for MBR target – it is now only about a factor of 2. The neutrino energy distribution is somewhat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



At redshift 0 interactions in IRB dominate to  $3 \cdot 10^{19}$  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.



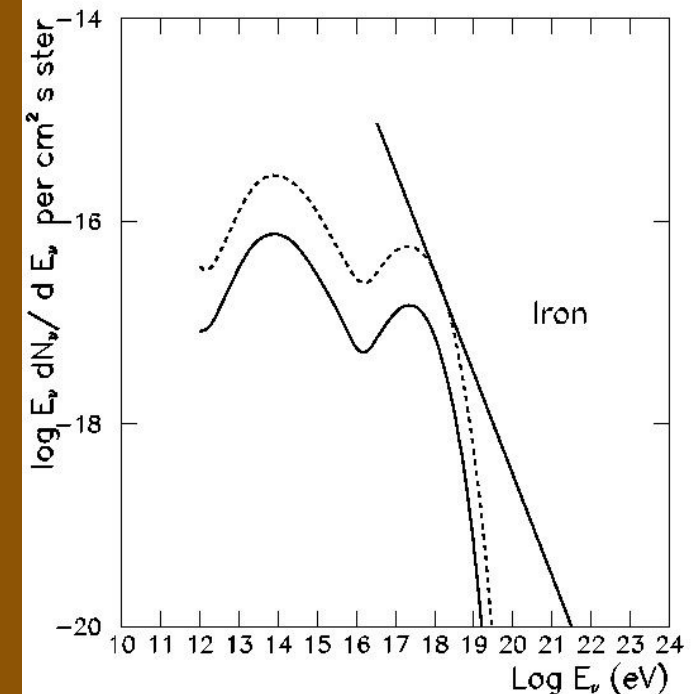
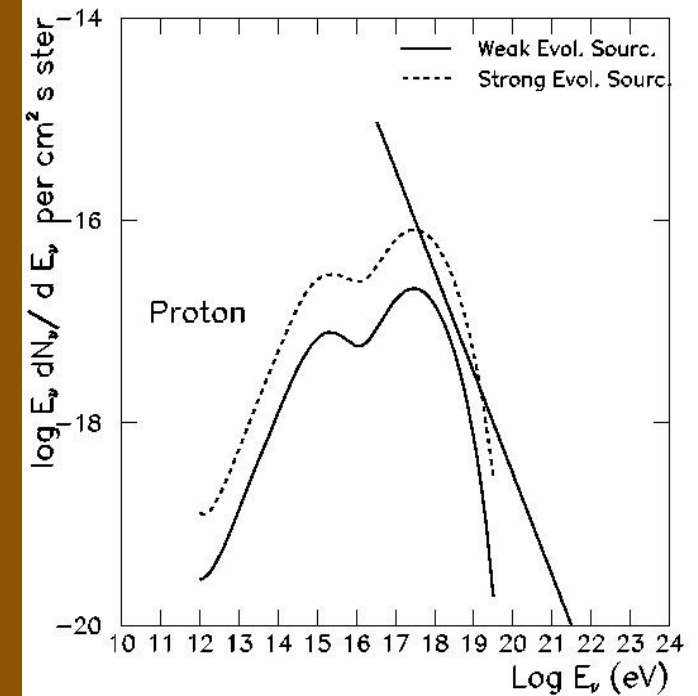
The cosmogenic neutrino spectra generated by the two extreme models of the injection spectra of UHECR protons in case of isotropic homogeneous distribution of the cosmic ray sources. The big difference in case of 'MBR only' interactions is somewhat compensated by the interactions in IRB. The interaction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

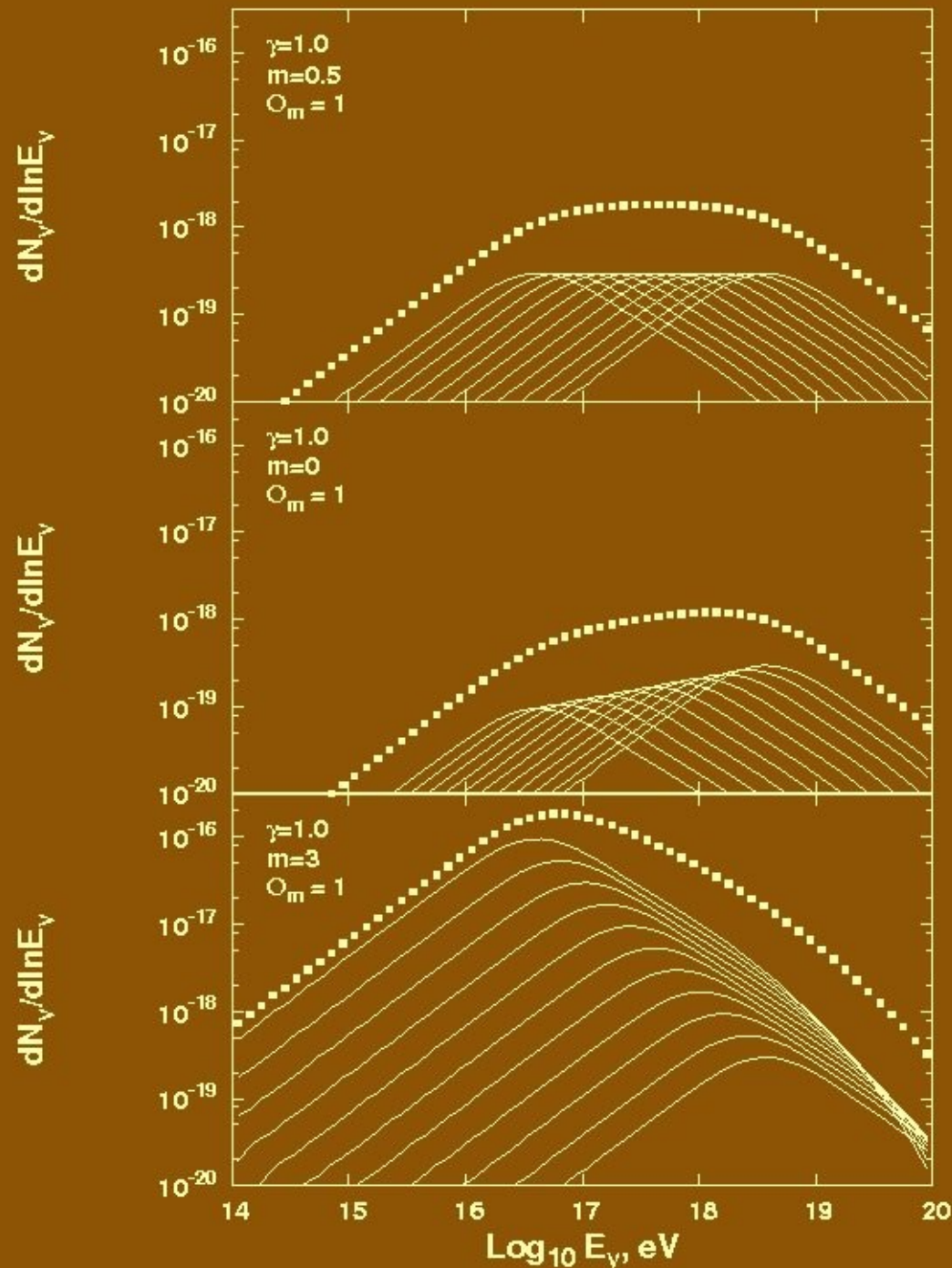


# Conclusions

The infrared background is closely related to at least two fields of the ultra high energy astrophysics that are in the process of fast development now: the TeV and higher energy gamma ray astronomy and neutrino astronomy. Its effect of the flux of UHE cosmic rays is small as the fluxes above  $10^{19}$  eV cosmic rays mostly depend on interactions in the MBR.

It is quite possible that gamma rays from distant sources with flat spectrum are affected by cascading in the IRB. We assume that cosmic rays up to highest energy are generated in extragalactic sources. The gamma rays from these sources may reach really high maximum energy.

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. Contemporary experiments (IceCube) are close to detecting them.



Illustrative examples  
 using  $\Omega_M = 1$  and cosmo-  
 logical evolution to  $z=10$ .

equal contribution

decreasing contribution

increasing contribution