High energy neutrinos: sources and fluxes

Todor Stanev, Bartol Research Institute
University of Delaware, Newark, DE 19716, USA

What can one learn by observing neutrinos rather than photons of various energy ? The question is even more important now after the great success of HESS and the upcoming data of Magic.

Photons of any energy are absorbed in propagation through the Universe:
Optical photons are absorbed in matter.
PeV gamma rays on the microwave background.
TeV gamma rays – with the infrared and optical background.
Only neutrinos can come to us from invisible astrophysical objects surrounded by clouds and from the edge of the Universe.

The ratio of nucleons to electrons in the Solar system is about 100. It may be similar everywhere.
Detection of neutrinos will establish the role of nucleons and of hadronic processes in the dynamics of astrophysical systems.

We shall discuss astrophysical neutrinos of energy above 1 TeV - above the background of atmospheric neutrinos. Atmospheric neutrinos are generated in interactions of cosmic rays in the atmos-phere. They are the products of meson and pion decays, i.e.

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \longrightarrow \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$

And the same for charged kaons. Neutral kaons also contribute in a more complicated way.

The energy spectrum of the atmospheric neutrinos is determined by the spectrum of the cosmic rays that generate them, modified by the meson and muon decay probability. Neutrinos from meson decays thus have spectrum steeper than cosmic rays by one power of E, while those from muon decay are steeper by two powers of the neutrino energy.

We assume that in astrophysical environments all mesons and muons decay and the primary cosmic ray spectra will only be modified by energy loss especially of muons.

Astrophysical neutrinos can be produced by two processes:

- nucleon interactions $pp \rightarrow pp(np, nn) + n_1\pi^{\pm} + n_2\pi^0 + n_3K^{\pm} n_4K^0 + \ldots$
  same that generate the atmospheric neutrinos

- photonuclear interactions of very high energy protons, which at threshold generate only one pion $p\gamma \rightarrow p(n) + \pi^0(\pi^+)$
  but at higher energy the secondaries are similar to those in pp interactions $p\gamma \rightarrow p(n) + n^1\pi^{\pm} + n^2\pi^0 + \ldots$

Photoproduction interactions have a cross section smaller than the pp interaction by a factor of 100. They are thus important in environments where the target photon density is much higher than the matter density. This is the typical environment of all powerful astrophysical systems.

The traditional view is that pp interactions are more important in the environment of our Galaxy, while photoproduction is mostly responsible for the neutrino production in extragalactic sources. This view is currently being modified.

Guarantied sources of astrophysical neutrinos:

- the Sun. Cosmic rays of high energy reach the Sun and interact inside it, the same way they do in the atmosphere. Since a large fraction of the solar atmosphere is very tenuous, mesons and muons decay and generate neutrinos. GeV neutrinos penetrate through the Sun with small losses. Neutrinos that can be detected at Earth are generated in cosmic ray interactions on the opposite side of the Sun.

- the Galactic plane. EGRET has measured the diffuse gamma ray flux coming from the Galactic plane. At least a fraction of this flux is generated by neutral pion decay and will be accompanied by neutrinos from charged pion and muon decays. Unfortunatelly it is not possible to predict exactly what is the corresponding neutrino flux because the detected gamma rays can be fitted equally well with models dominated by hadronic or by electro-magnetic processes. With its higher angular resolution HESS has identified some of the sources EGRET coulod not see.

Potential Galactic neutrino sources include:

- supernova remnants
- powerful binary systems
- microquasars
- associations like Cygnus-OB2
- the Galactic center

We shall briefly discuss supernova remnants and binary systems.

Cygnus-OB2 is a cluster of at least 2700 young hot stars and many supernova remnants. It is likely that it is a region where cosmic rays are actively accelerated and magnetically contained.

Microquasars have a structure similar to the active galactic nuclei, but are much smaller and less powerful. The mechanism of neutrino production could be the same as in AGN, which we will discuss later. Contemporary models predict between a fraction of event to several events per year in IceCube.

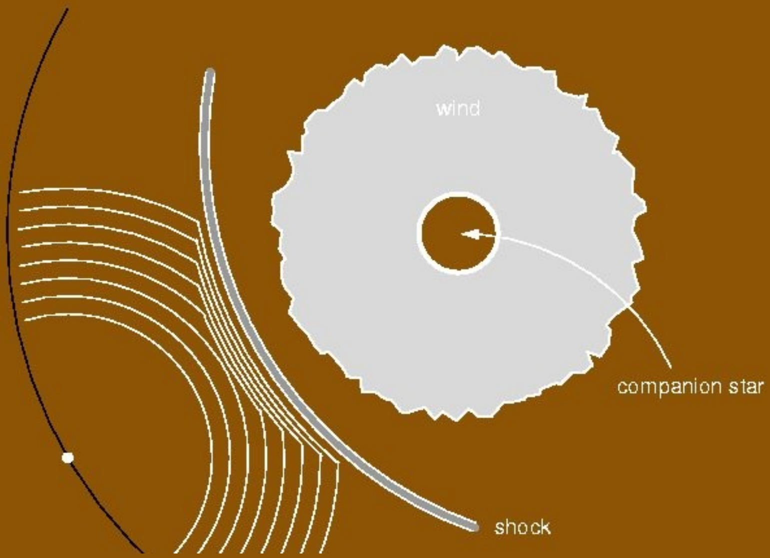
With its great power at other wavelengths SGR A East could be also a neutrino factory – D.Grasso's talk here

Neutrino production at supernova remnants

For hadronic interactions to dominate over electromagnetic processes in supernova remnants, the matter density should exceed 100.
This is likely if there is a dense molecular cloud in the vicinity of the supernova remnant as is the case of RJX1713.7-3946. Since in *pp* interactions the ratio of charged to neutral pions is 2, the neutrino flux is roughly of the same order as the gamma ray flux. The exact ratio depends on the spectrum of the accelerated protons.

Powerful extragalactic supernova explosions can also be observed. Waxman&Meszaros discuss collapsar neutrinos in M82 and NGC253. They predict 1.5 muon neutrinos in IceCube from slow jet hypernovae. Diffuse flux is low but individual events can be detected in coincidence.

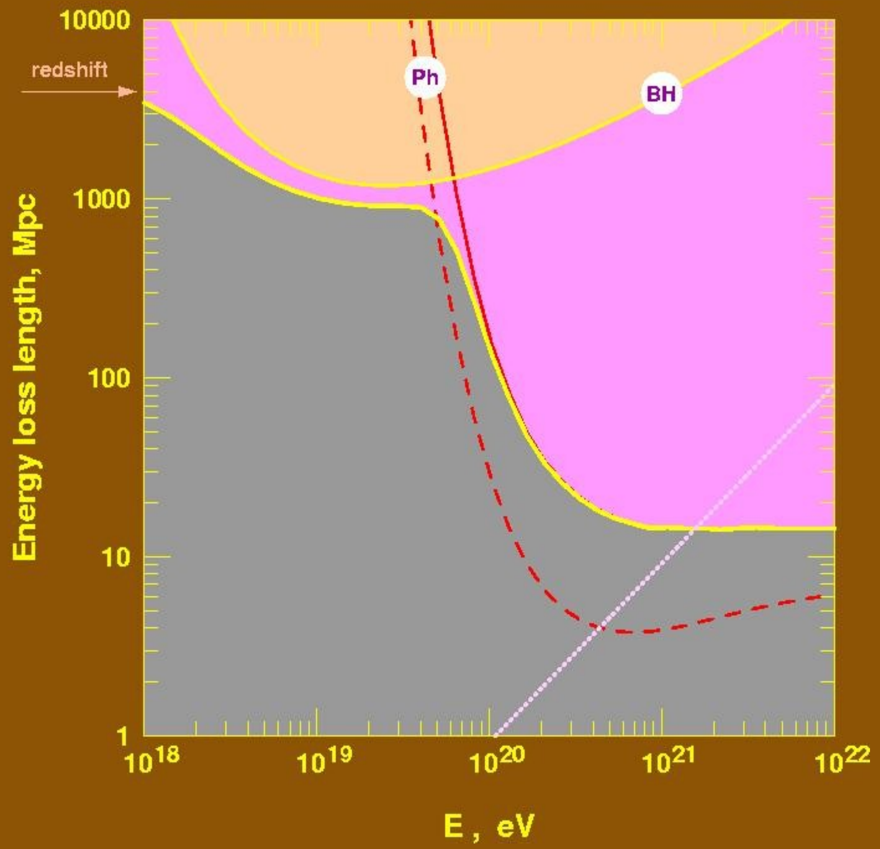
Binary systems



The interaction between the compact object (neutron star or a black hole) and the companion star creates a complicated system that includes many shocks. Such formations have been observed. Cosmic rays accelerated at the shocks can interact with matter of the stellar wind or with the accretion disk of the compact object.

The first models for the production of astrophysical neutrinos were inspired by reports for the observation of PeV gamma rays from the direction of the binary system Cygnus X-3. Models were created by Berezinsky et al and by Eichler & Vestrandt. These were the first more detailed models for gamma ray and neutrino production at astrophysical systems. Some contemporary models predict 3-5 muon neutrino events in IceCube per year from powerful binary systems with output of 4.10^{34} erg/s in cosmic rays.

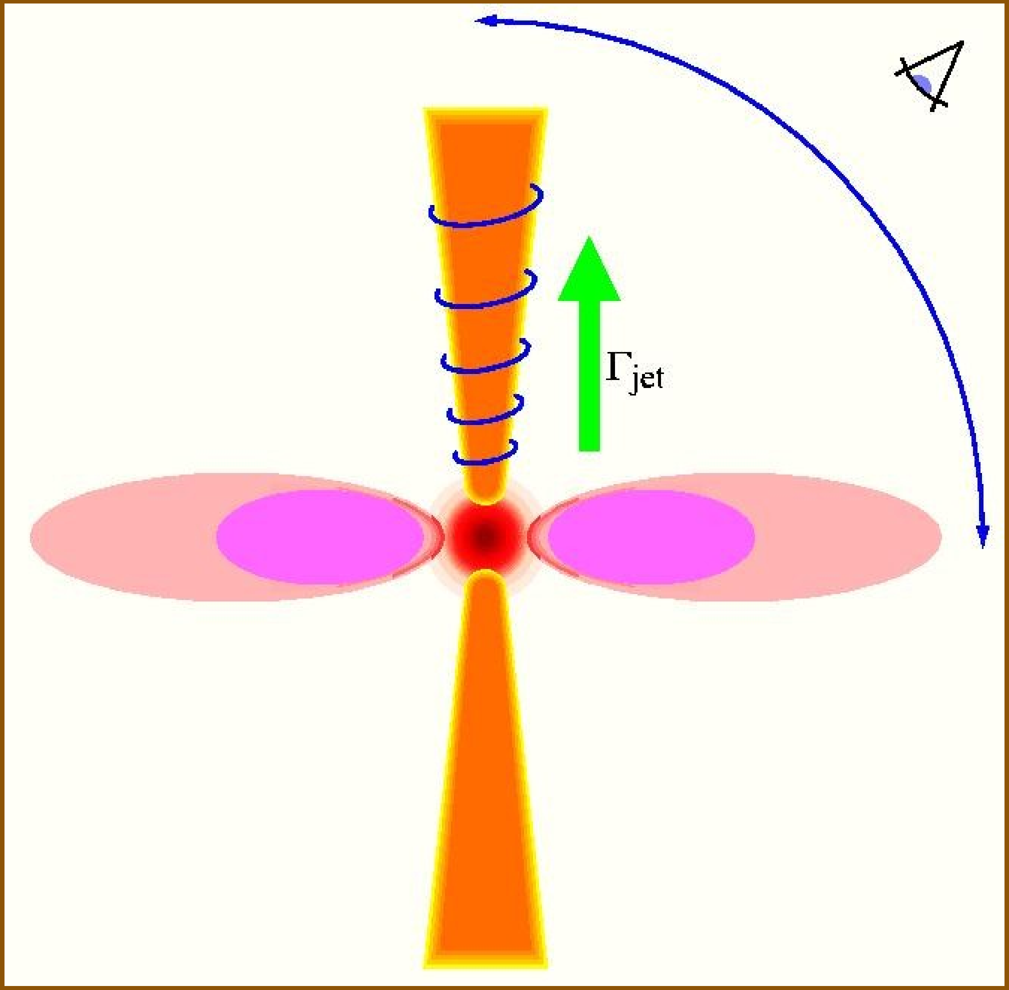
Proton photoproduction processes



The graph shows the interaction length (dashed) and the energy loss length of protons in the microwave background. In thermal backgrounds of higher energy the curves slide to the left to lower proton energy. The threshold would be below 10^{14} eV for keV photons. The energy dependence of the interaction length is determined by the seed photon spectrum (SED).

The energy loss length is higher than the interaction length by 2 (at high CM energy) to 5 (at low CM energy.

The yellow region on top refers to the BH pair production process $p\gamma \rightarrow e^+e^-$ analogues to the pair production in the nucleus field. In higher energy thermal fields the loss length scales down.

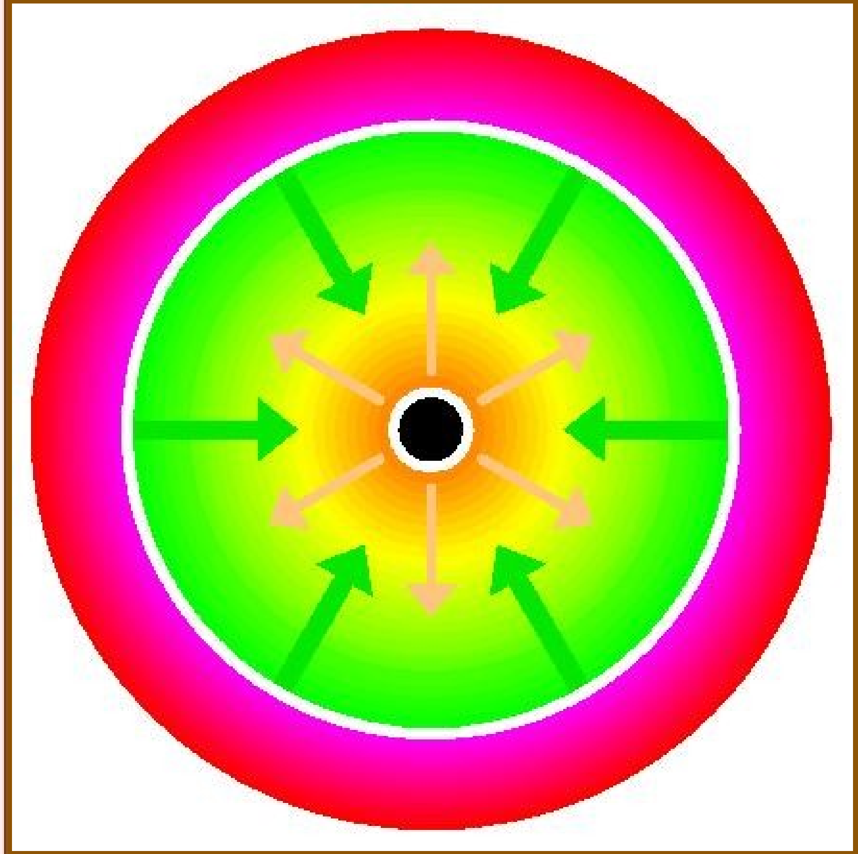


Active galactic nuclei (AGN) are powerful superluminal systems consisting of
- central engine, a massive black black hole
- accretion disk
- jets

The theory states that all AGN have the same structure, and the observed differences are caused by the viewing angle. Only the jet emission is seen when the observer looks into the jet opening angle. The luminosity of the jet depends on the Doppler factor as D^4. Lorentz factors as high as 10 have been observed.

The radiation of the disk is observed when the AGN is viewed from the side.

AGNs are the first astrophysical systems suggested as a source of very high energy neutrinos. (Ginzburg)



Close to the central black hole the accretion flow becomes spherical.
A shock is formed by the ram pressure of the black hole radiation. One can use the AGN brightness to estimate the radiation energy density:

$$U_{rad} \sim 2 \times 10^6 \, erg/s \times \frac{1}{L_{45}} \times \left(\frac{30}{x_1}\right)$$

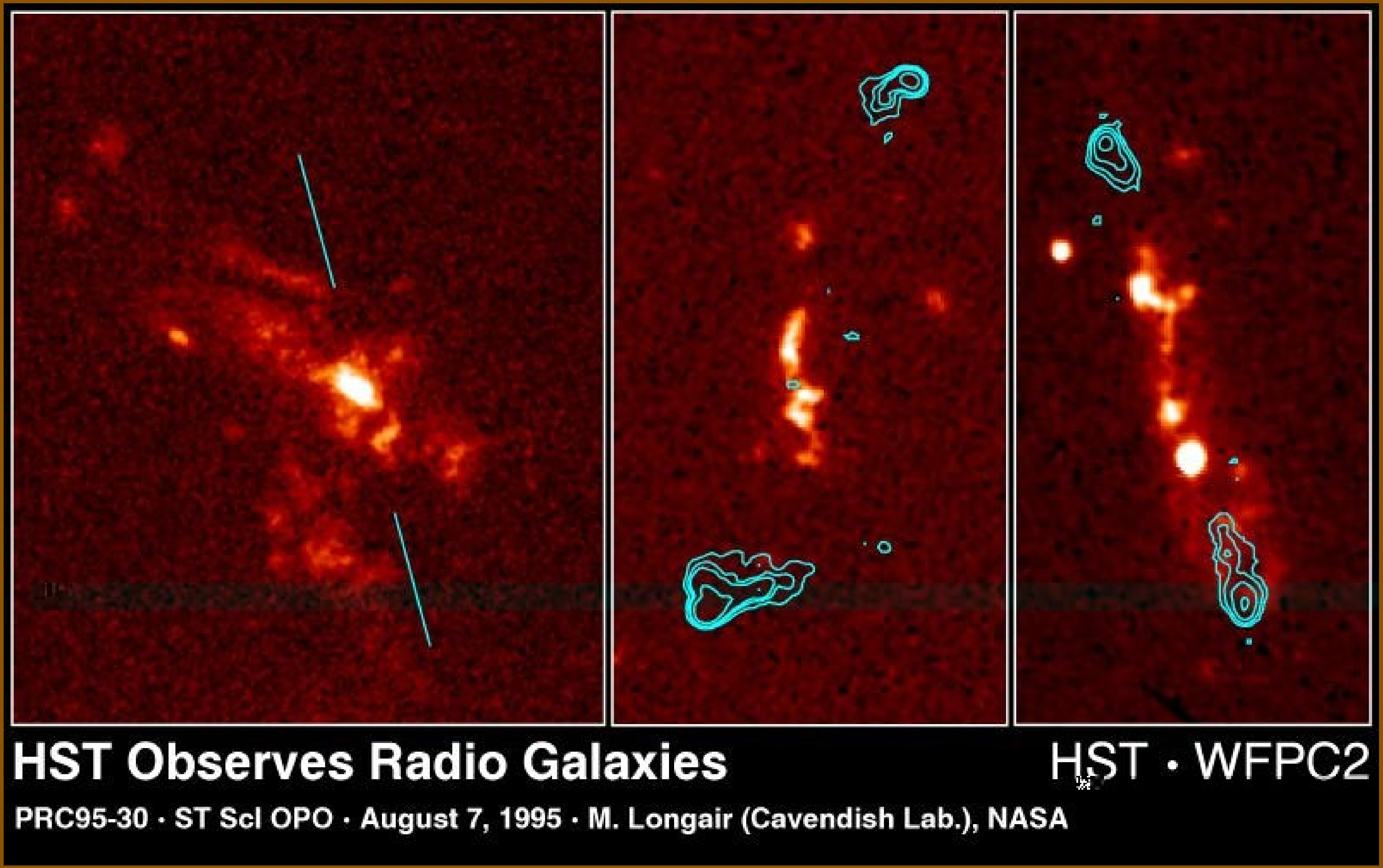
One can also use the average photon energy and the accretion power necessary to support L_{BH} to estimate the density of protons and photons at the shock. Photon density is significantly higher: $n_p/n_{ph} \simeq 2.5 \times 10^{-13} x_1^{3/2} T/Q$

The minimum proton energy in photoproduction is

$$E_p^{min} \simeq \frac{m_\Delta^2 - m_p^2}{2\epsilon}$$

about 10^7 GeV for interactions on optical and UV photons.

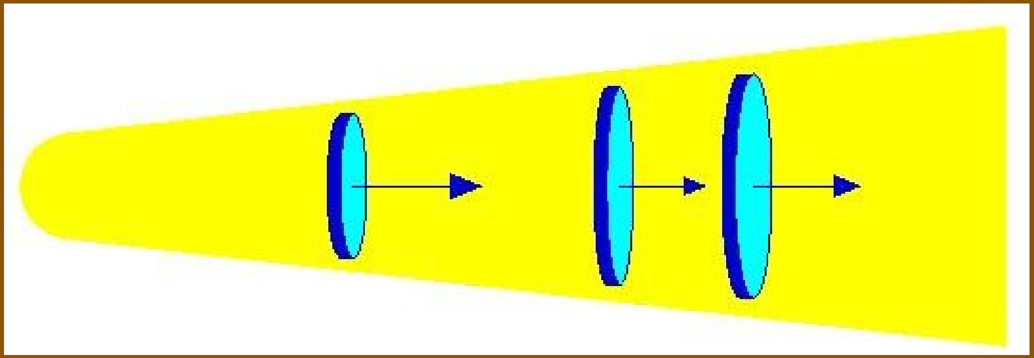
The energy loss of the protons will be in photoproduction interactions.
The problem with the existing models (SDSS,P&S) is that they are somewhat arbitrarily normalized.



While the central region of AGN is never directly visible, the AGN jets are observed very well. Here is a comparison between Hubble telescope images and radio observations. Models are much more primitive.

Neutrino production in AGN jets: several important problems:

- where and how are protons accelerated ?
- how are the neutrinos generated ?



The jets start at about the inner edge of the accretion disk. The general idea is that hot plasma is pushed out by the central engine and is contained inside the jet by magnetic fields, which are strong enough to accelerate protons to high energy. One possibility is that the chunks of matter are moving at different velocities and the acceleration is stronger when they start overtaking each other. Another option is acceleration at the jet termination shock as in Rachen&Biermann.

The accelerated protons interact on photon fields that may be internal or external. Internal fields could be produced by synchrotron radiation by electrons (or protons). External fields could be the re-scattered light from the emission of the accretion disk. These two hypotheses generate different energy spectra of the target photons. External targets are somewhat thermalized UV photons, while the synchrotron radiation has a typical spectrum extending to high energy.

All particles generated in the jet are boosted with the Lorentz factor of the jet. A particle of energy E in the jet frame appers of energy ΓE to an observer looking at a small angle to the jet axis. The apparent luminosity could be increased by Γ^4. The general rule is $I(\nu) = \Gamma^3 I^0 (\nu/\Gamma)$.

TeV gamma ray emission has been detected from several AGN jets (see F. Aharonian et al). This emission is however very well explained without the involvement of protons and hadronic processes. Purely electromagnetic scenarios, such as the synchrotron-self Compton model, predict well not only the gamma ray flux, but also multi wave-length observations.

There are also hadronic models for the production of TeV gamma rays. The main problem of these is the very fast variability of the TeV gamma ray fluxes observed. Protons have to be accelerated to very high energy to photoproduce and this takes relatively long time. On the other hand electromagnetic models can not generate gamma rays to arbitrarily high energy – there is the danger of gamma ray absorbtion on the photon target. A possible discovery of 50 TeV or higher energy gamma rays may be a proof for the hadronic origin of these particles.

Neutrinos from gamma rays bursts (GRB).

Production of neutrinos in GRB is due to the same processes as in AGN jets. The big difference is that GRBs are explosions that are not repeated and that the Lorentz factors of GRB jets are higher than 100. Waxman & Bahcall look at the GRB photon spectrum measured by the BATSE detector at the Compton GRO. On the average it could be fit with two power laws ($\varepsilon^{-\beta}$) with β=1 below about 1 MeV and β=2 above 1 MeV. If protons are accelerated on a power law spectrum E^{-2} at shocks insidethe GRB jets and are isotropic in the jet frame, they would generate a neutrino spectrum also with a brake. The brake energy in the neutrino spectrum will be 100 TeV for GRB with Lorentz factor of 300. Neutrinos of lower energy would have 1/E spectrum, which at 100 TeV will become one power of E steeper. At still higher energy the spectrum will become even steeper because of adiabatic losses of the parent muons.

Later more sophisticated models distinguish between different GRBs that are more suitable for neutrino and optical emission. Slow GRB may be neutrino oriented (HHA,WDA). Failed GRB (jet stagnates before leaving the massive object) can be only observed in neutrinos.

Flavor ratio of the astrophysical neutrinos

If all mesons and muons decay with their production energy the flavor ratio of the generated neutrinos would be $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ and will oscillate on propagation to us to a flavor ratio 1 : 1 : 1. This will certainly decrease the number of muon tracks, but will not necessarily decrease the observability of the sources.

If, however, the magnetic fields at the source are very high, and muons lose energy on synchrotron radiation before decay, then tha production flavor ratio could be close to 0 : 1 : 0, i.e. only muon neutrinos from the meson decay, and will after propagation convert to 1/3 : 1/3 : 1/3. This will not change the flavor ratio at arrival, but will incorrectly indicate a lower cosmic ray luminosity at source.

Astrophysical neutrino sources produce also an isotropic neutrino background that is due to unresolved sources.
Powerful systems were more numerous and more powerful at higher redshifts. This luminosity evolution (observed mostly in SFR) is usually presented as

$$\rho(L_x, z) = R_0^3 \frac{g(z)}{f(z)} \rho_0 \left(\frac{L_x}{f(z)} \right)$$

where g(z) is the number densi ty of the systems as a function of redshift and f(z) is the luminosity evolution of individual systems.

The spectra of the neutrino signals can be estimated by an integral over redshift of the cosmological emission of the sources:

$$\frac{dI}{dE} = \frac{1}{4\pi} \frac{c}{H_0} \frac{1}{ER_0^3} \int dL_x \int_0^{z_{max}} dz\, \rho(L_x, z) \mathcal{F}(z) \frac{dL}{dE} \left[E(1+z), L_x\right]$$

, where *F*(z) is the matrix element, determined by the cosmological model. In the Einstein-de Sitter model it is $z^{-5/2}$, and has a more complicated form in other models. The physical meaning is that it relates the redshift with the duration of the injection, i.e. It represents *dt/dz.* The redshift dependence of the signals is thus much lower than that of the sources.

The flux of extragalactic neutrinos can be related to the flux of UHECR if UHECR are also of extragalactic origin

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_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 :

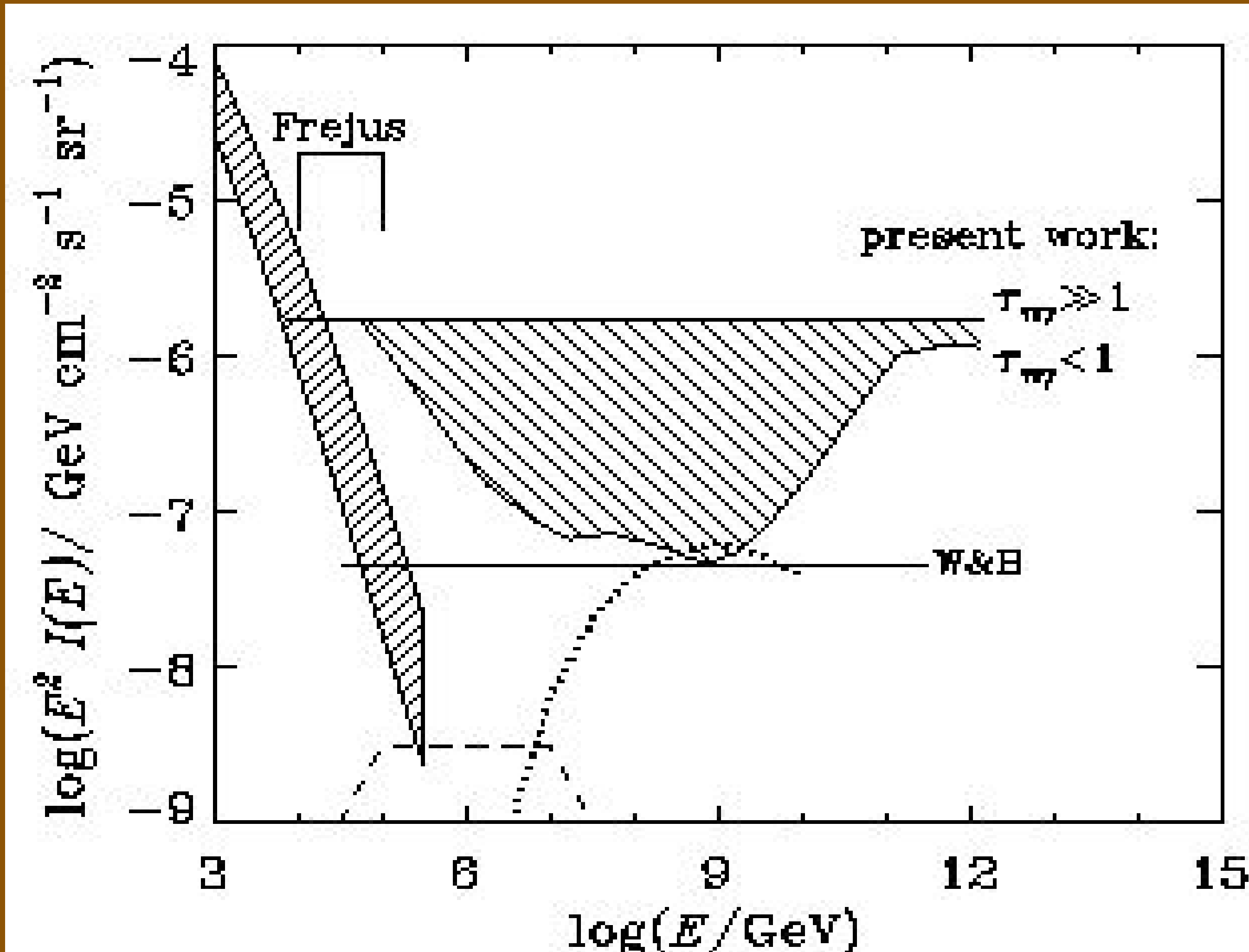
Waxman&Bahcall have not accounted for:

- 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 ~ 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.



From Mannheim, Protheroe & Rachenn

The first published relation between extragalactic cosmic rays and diffuse neutrinos is by Waxman&Bahcall. It is represented here by the lower solid line. 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.

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 and 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.

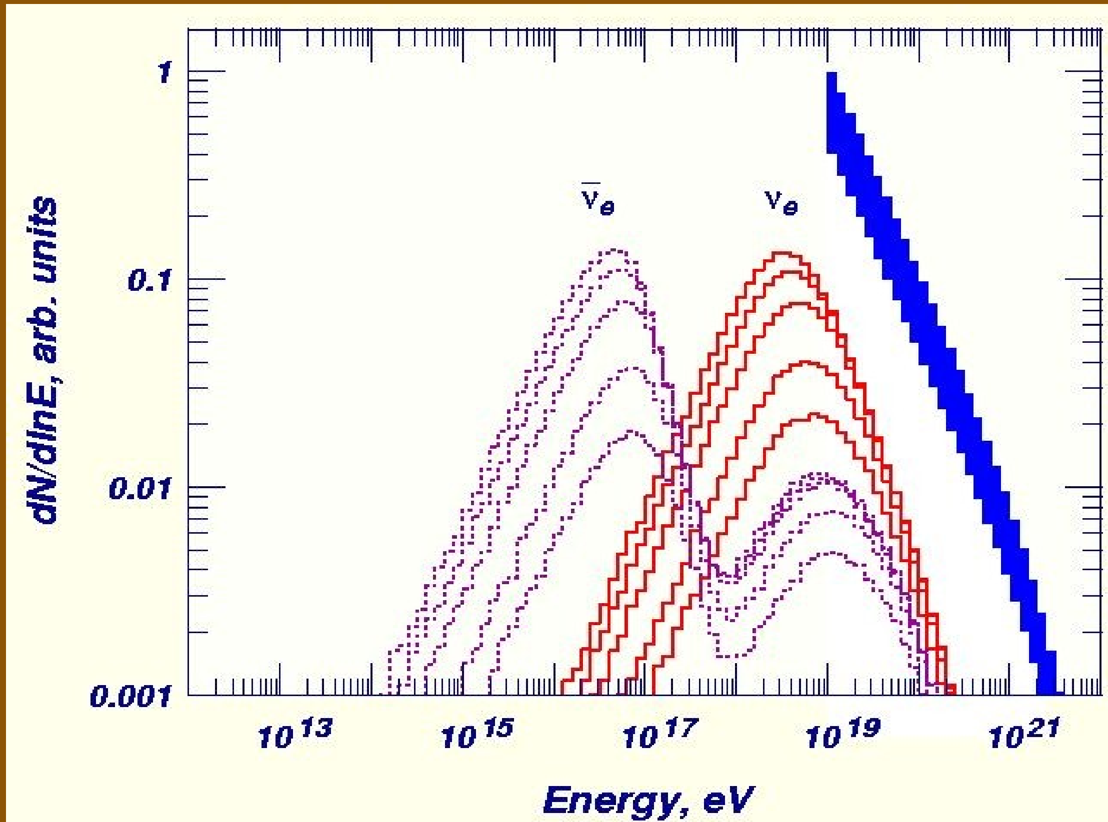
The main difference with the processes in AGN and GRB is that the photon target is the microwave background (2.75ºK) of much lower temperature than the photon emission of these sources. This raises the proton photoproduction threshold to very high energy:

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

Actually the proton photo-production threshold is about 4.10^{19} eV.

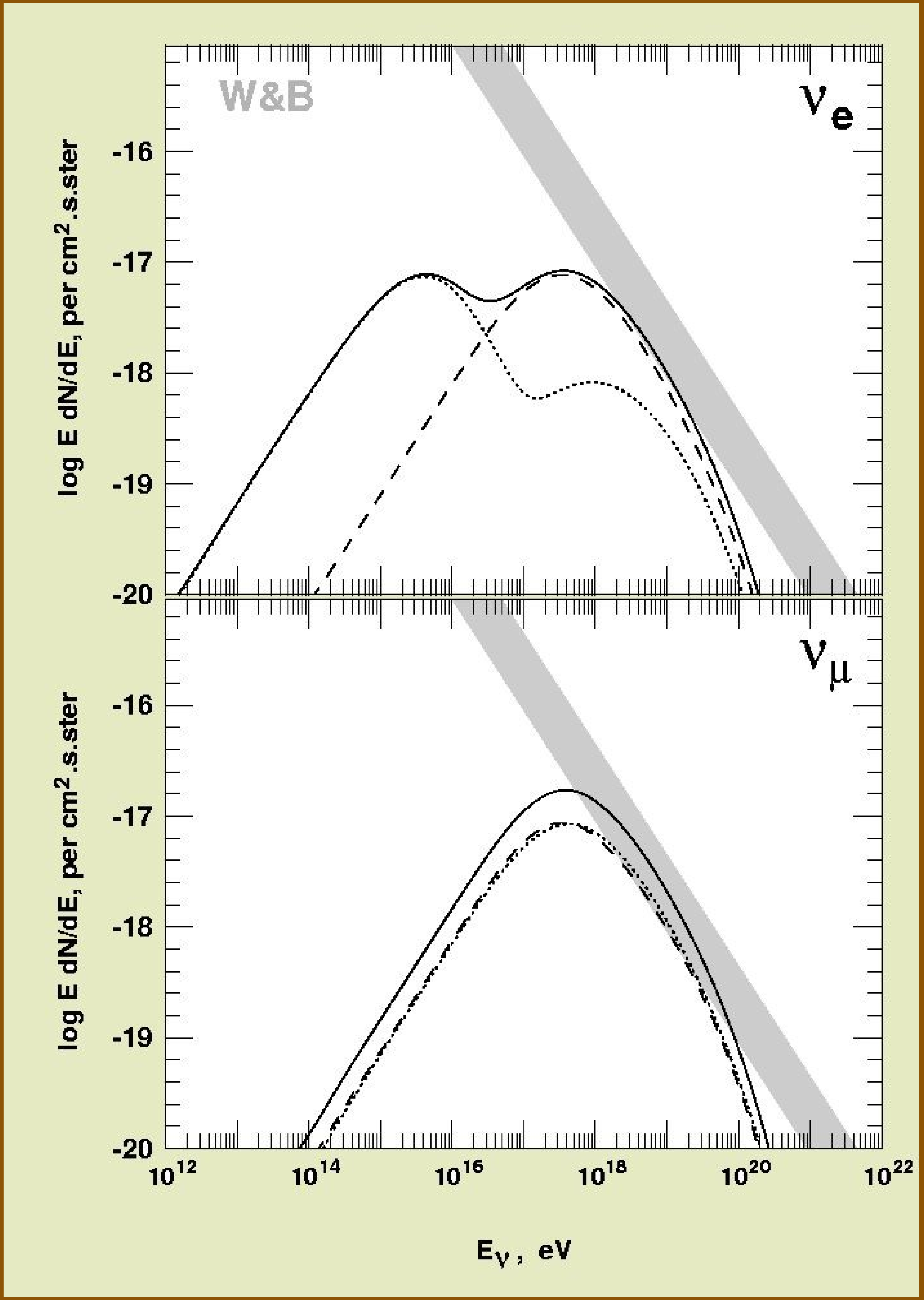
The photoproduction energy losses of the extragalctic cosmic rays cause the GZK effect – an absorption feature in their spectrum.

Heavy nuclei also generate cosmogenic neutrinos on propagation. Energy spectra are different – less higher energy neutrinos and more electron antineutrinos from neutron decay.



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 use of O_M increases the fluxes by a factor ot 2.

Astrophysical and cosmological parameters that are important for the production of cosmogenic neutrinos:

Cosmic ray luminosity and injection spectrum. Waxman&Bahcall use E^{-2} and 4. 5 10^{44} erg/Mpc^3/yr at energy above 10^{19} eV

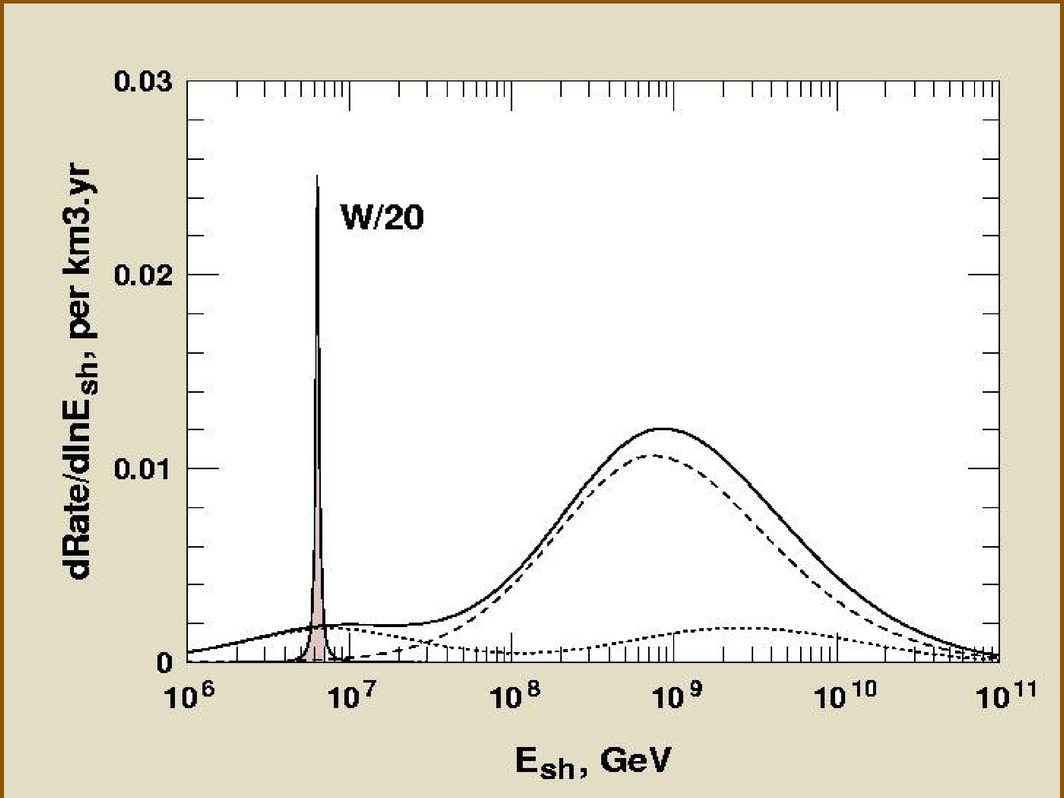
Maximum proton energy at injection (acceleration)

Cosmological evolution of the cosmic ray sources Waxman\&Bahcall use $L(z) = (1 + z)^3$

Cosmological model. The transition from $O_M = 1$ to $O_L = 0.7$, $O_M = 0.3$ increases the fluxes at the peak by about 1.7.

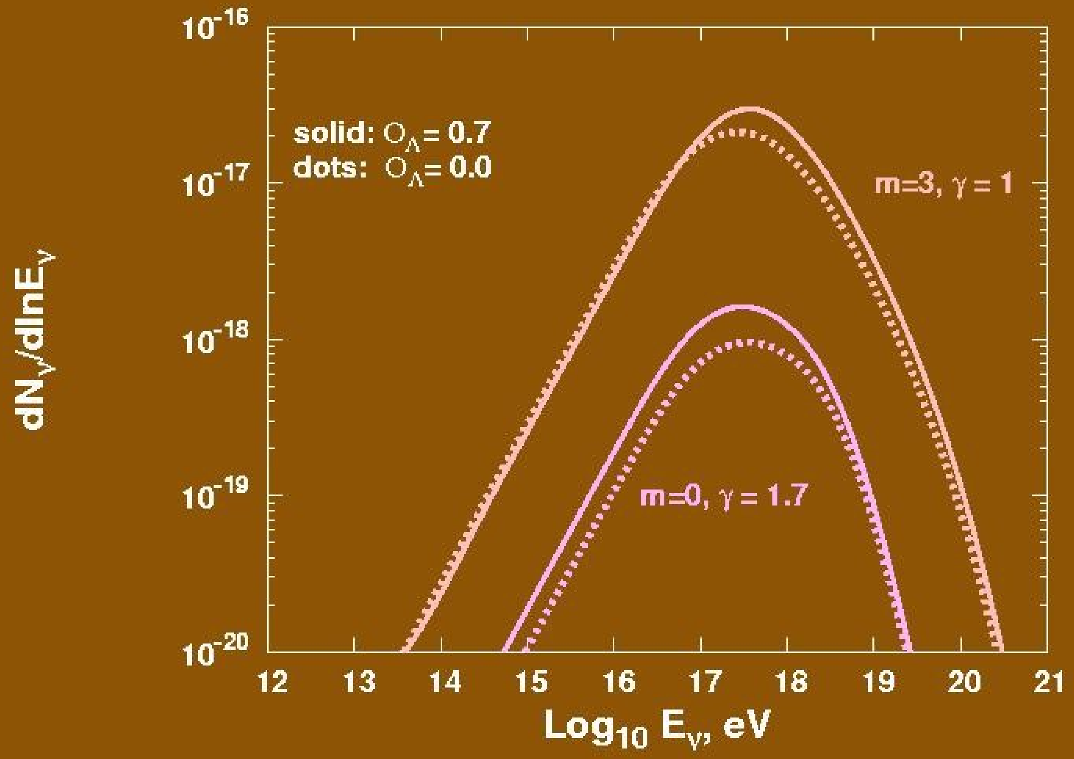
The cosmological evolution of the MBR is obvious, and does not create problems in the integration up to $z = 8$.

These neutrino fluxes are very sensitive to the same parameters that describe the fluxes of the highest energy cosmic rays !



The reason for which low energy thresholds do not affect the event rate is shown on left for electron neutrino CC interactions and the `standard' n=3, E^{-2} model. Because of the low cross section and flux low energy neutrinos contribute almost nothing to the event rate. The Glashow resonance is too narrow to be observed (giving about 0.03 events), at least with the detectors we can imagine now. Note that these are interactions inside a km^3 volume of ice.

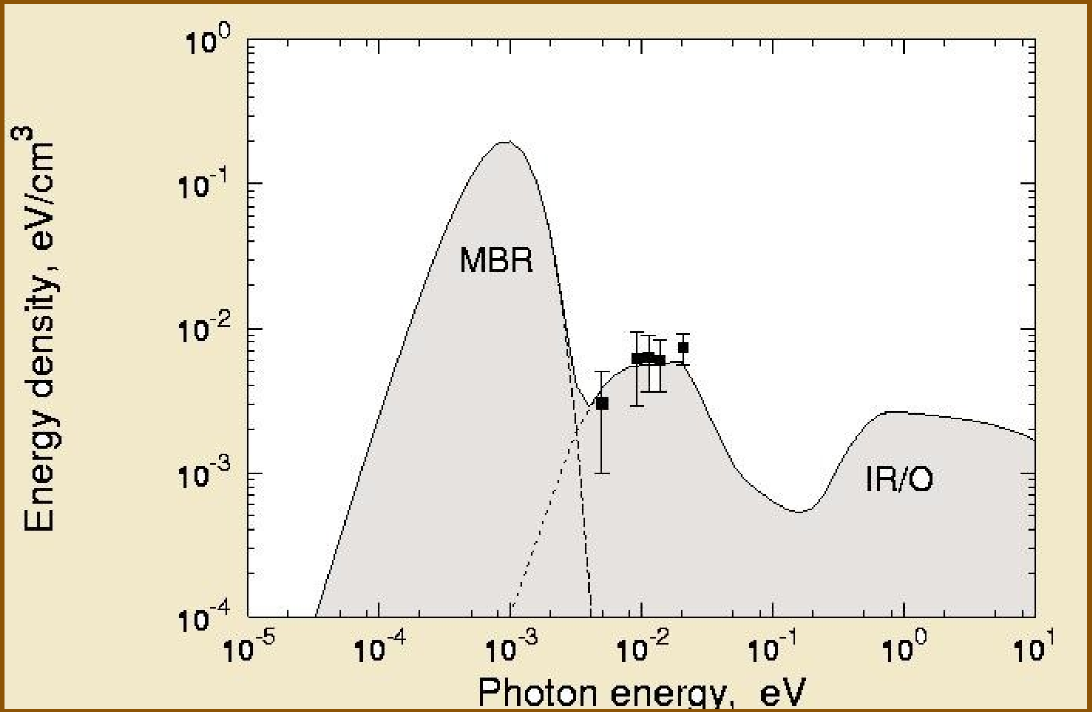
Almost the total event rate is from downgoing neutrinos, since the Earth is opaque for neutrinos of energy above 10^7 GeV. This should not be a problem for neutrino telescopes such as IceCube and Antares – there is practically no background for underwater/underice showers of energy above 1 PeV. Other detection methods, radio and acoustical are being developed now.



Cosmogenic neutrinos and the sources of the highest energy cosmic rays.

These are the fluxes of cosmogenic neutrinos generated by the two `extreme' fits of the UHE cosmic rays spectrum with primary protons (W&B vs Berezinsky et al).
The shape of the neutrino spectrum depends a little on the cosmic rays 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.

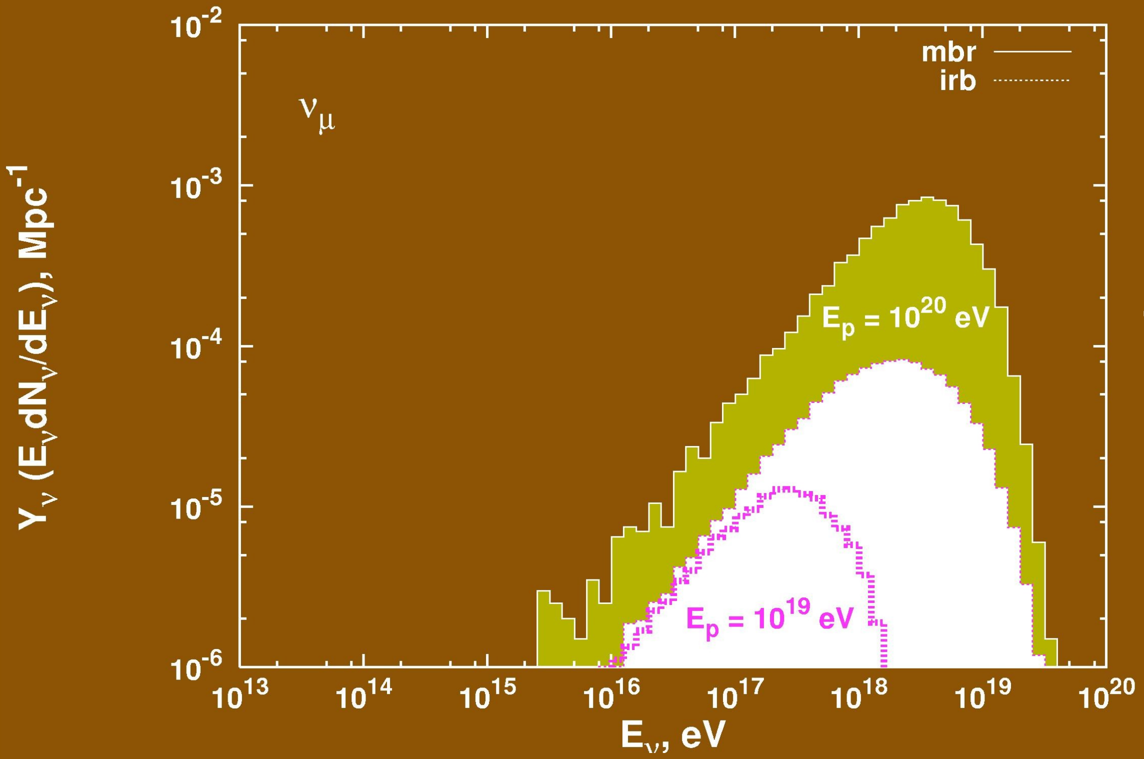
MBR is not the only universal photon field. The infrared/optical background extends over three orders of magnitude in frequency.



The model of Franceschini et al (2001) is compared to two sets of DIRBE data.

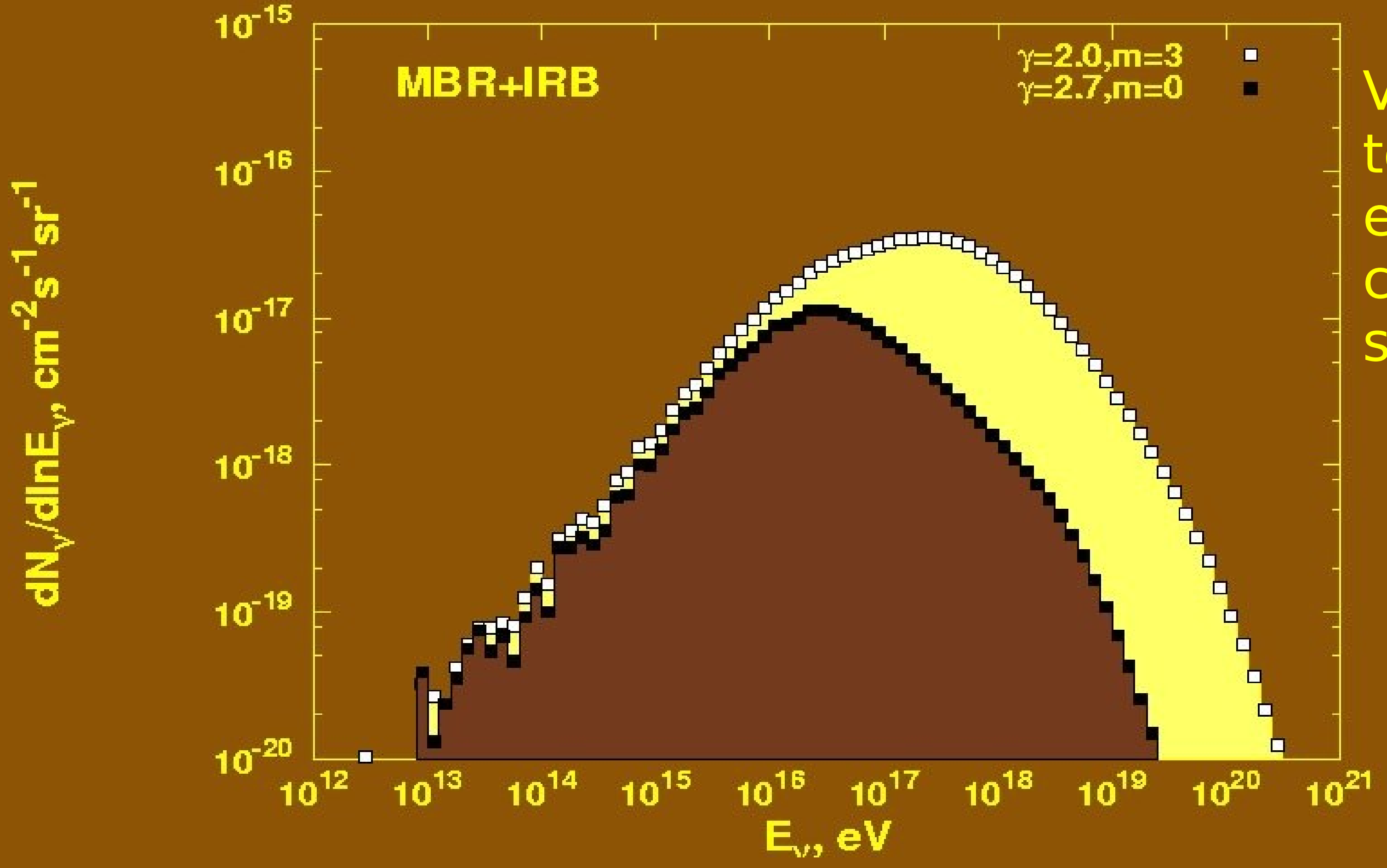
Bad news is that photon spectra are almost constant in E^2dN/dE, i.e. the number density decreases with photon energy.

The number density of the IR/0 background is smaller than MBR by about 250. In addition its large energy range decreases #/eV even more. IR/O background has been measured after subtraction of the point sources and has been estimated from the absorption of extragalactic TeV gamma-rays (Stecker & others). The wavelengths that affect TeV gamma-rays are mostly in the `near' infrared, and the `far' IR is generally less restricted. We now attempt to see if the addition of a small IR&O photon field affects the cosmogenic neutrino fluxes.



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. 10^{18} eV protons also interact in IRB. Lower energy protons interact in UV (Allard et al)

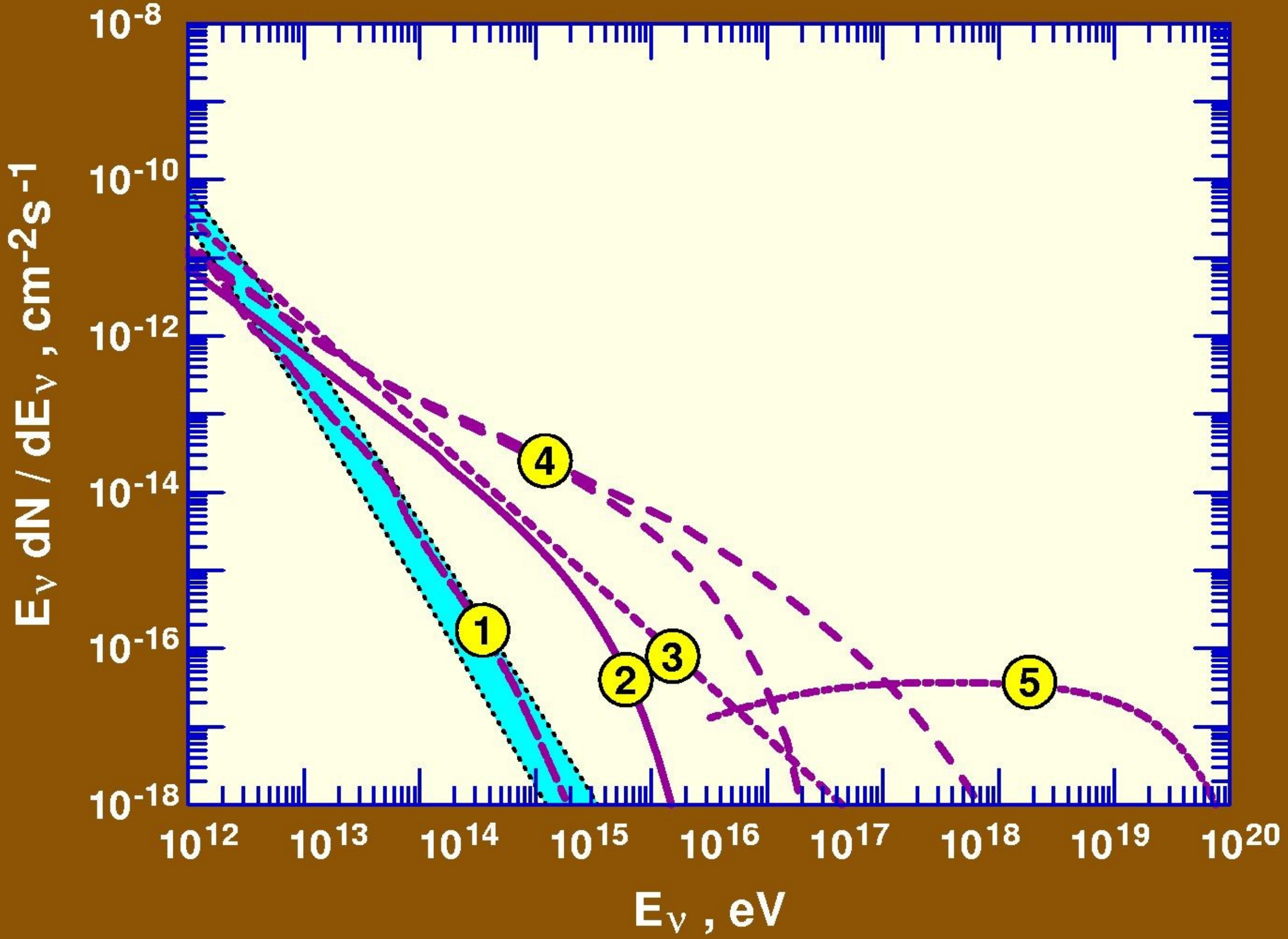
The yields peak at the same neutrino energy, but the IR target generates a wider neutrino spectrum, because of its own spectra extension.



Very sensitive to cosmological evolution of the cosmic ray sources.

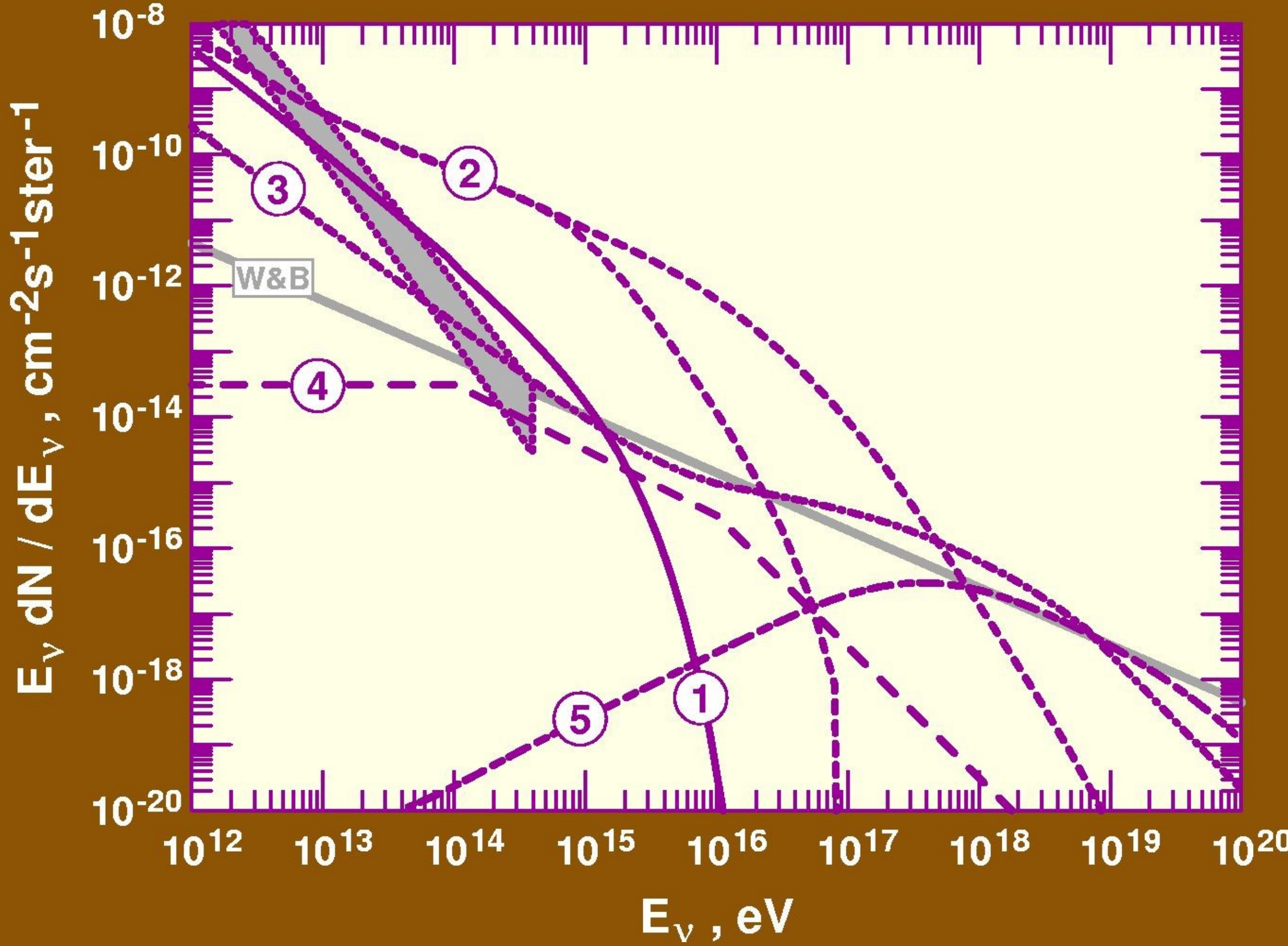
Cosmogenic neutrino fluxes from interactions on the microwave and in the infrared background for flat (left) and relatively steep cosmic ray flux.

Note: the M&S infrared background does not give maximum cosmogenic neutrino flux. Other IR models can generateup to up to 50% more neutrinos.



a sample of models for neutrino production at different sources.

1. cosmic ray interactions in the Sun.
2. SNR IC443 if detected gamma rays are hadronic
3. Mrk 501 outburst if detected gamma rays are hadronic
4. core of 3C273 (P&J)
5. jet of 3C279 (Mannheim) *pp* interactions could be added



predictions of diffuse neutrino fluxes. W&B limit shown with a gray line.

1. central region of our Galaxy normalized to EGRET observa
2. from cores of AGN (does not have to obey W&B)
3. Mannheim's proton blazar (including *pp* collisions)
4. gamma ray bursts (W&B model)
5. cosmogenic neutrinos

Summary:

With the development of the theory of the high energy neutrino astrophysics we find more systems that are potential sources of astrophysical neutrinos. These include extragalactic, as well as galactic sources.

Individual sources are not very strong – we expect not more than several events per km^3.yr from the most powerful ones. Coincidental observations at different wavelengths would be very attractive - GRBs?

There must also be a relatively strong isotropic background, that contains neutrinos of energy exceeding the atmospheric flux. More work is needed to determine exactly the extend of the atmospheric neutrino spectrum by prompt neutrinos from higher flavor decays.. Because of absorption in the Earth most of the signal would be from downgoing neutrinos.