Galactic sources: connection between gamma-rays and neutrinos

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We have suspected for a long time that gamma-rays and neutrinos will be generated by cosmic ray interactions at the cosmic ray acceleration sites.
One such classical calculation is the SNR gamma-ray production paper of Drury, Aharonian & Völk. For a flat ($\gamma = 1.1$) the gamma-ray flux is:

$$F(> E_\gamma = 10^{-10} \chi \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-1.1} \left(\frac{\theta E_{SN}}{10^{51}\,\mathrm{erg}}\right) \left(\frac{d}{1\,\mathrm{kpc}}\right)^{-1} n_1\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

For a SNR with n_1 =1, θ = 0.2 and χ =1 (no gamma ray absorption) the flux would be

$$F(> E_\gamma) \; = \; 10^{-11} \left(\frac{E_\gamma}{\mathrm{TeV}} \right) \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

Neutrino fluxes generated by pion decay are about one half of the gamma ray fluxes.

$$\phi_\nu \; = \; \phi_\gamma (1 - r_\pi)^{(\alpha - 1)}$$

where r_π is the squared ratio of the muon to pion masses, i.e. the coefficient is 0.45. For neutrinos generated by kaons this coefficient is close to 1 because of the large mass of the kaons and the different decay kinematics. Since the K/π ratio increases with energy one expects that the gamma-ray and neutrino fluxes become closer at high energy.

So the first question when we search for galactic neutrino sources is *"Where are the galactic cosmic rays accelerated"* Our standard theory tells us the most likely acceleration is in Supernova Remnants (SNR) about 1000 yrs after the supernova explosion. There are now some doubts, after the great advantages in the TeV gamma-ray astronomy - see the recent Nature paper by Yousaf Butt.

Butt favors more distributed acceleration in super bubbles or in the whole Galaxy. Multiple supernovae explode in super bubbles and create multiple shocks where cosmic rays could be accelerated. The acceleration sites would not then be point sources, generating rather a diffuse flux of gamma-rays and neutrinos. The lack of cosmic ray anisotropy may suggest that the process is distributed in the whole Galaxy and its halo, including the termination shock of the galactic wind.

Talking about galactic neutrino sources we will be mostly interested in the sources of TeV gamma-rays. At lower energy the atmospheric neutrinos dominate and thus the neutrino telescopes, such as Amanda, IceCube, Antares and KM3NeT, are designed for the detection of neutrinos above 1 TeV.

The reason is that atmospheric neutrinos have a very steep energy spectrum approaching $E^{-3.5}$ in this range while the galactic sources would generate much flatter spectra matching the spectrum of the accelerated cosmic rays, $E^{-2.0/-2.5}$ or so.

Neutrino observatories become better at high energy in angular resolution and energy estimate.

Gamma rays can be produced in several different processes:

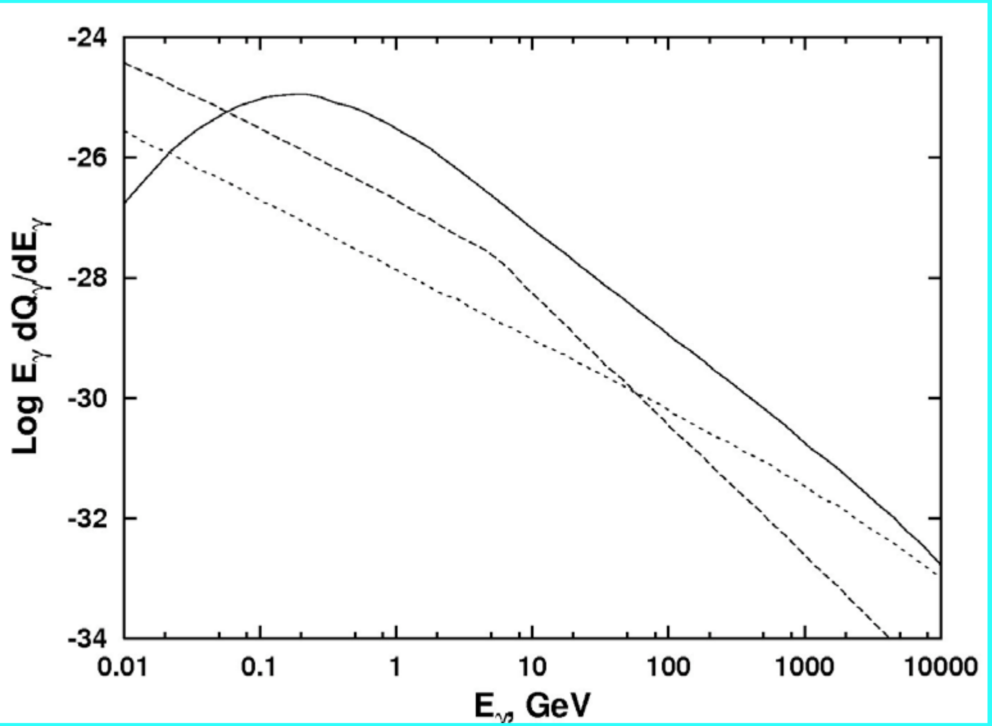
- -- cosmic ray interactions on matter plus neutral mesons decay
- -- bremsstrahlung of high energy electrons
- -- inverse Compton scattering of high energy electrons with MBR photons or local photon fields

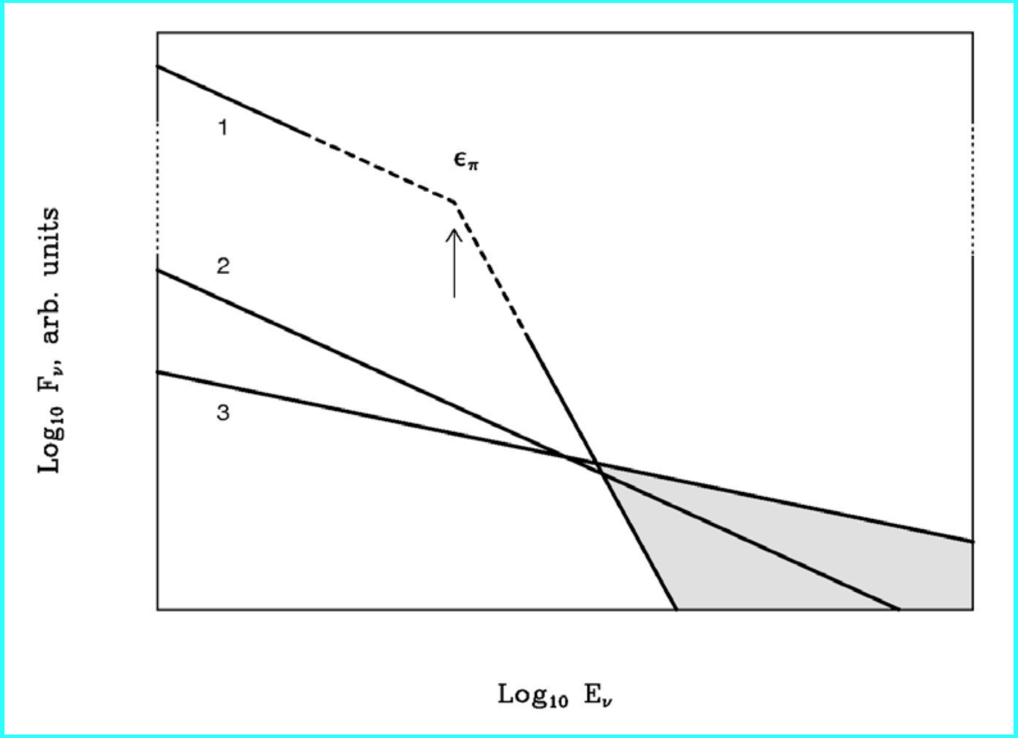
High energy gamma rays are absorbed in $\gamma\gamma$ interactions that generate electron positron pairs.

How can we distinguish between these three processes? Only the first one will produce neutrinos in the charged mesons decay chain.

Most of the information is in the energy spectrum of gamma ray source as shown in the figure below for diffuse galactic gamma rays. The π^0 gamma rays peak at ½ of the neutral pion mass and follow the cosmic ray spectrum after that. Bremsstahlung photons follow the electron acceleration spectrum.

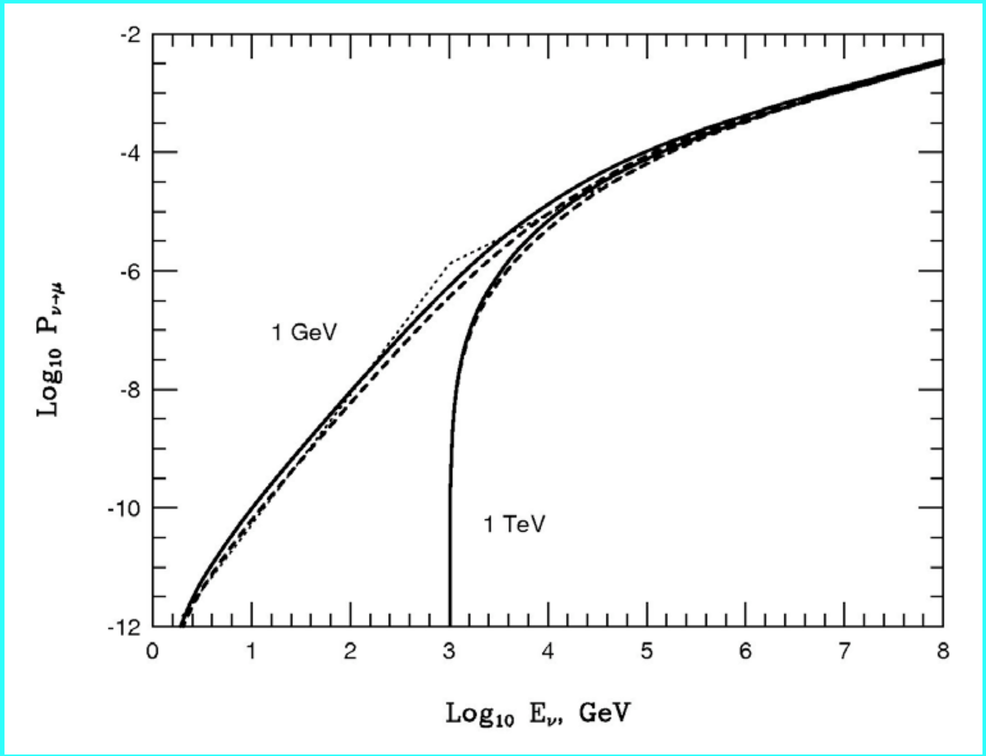
Inverse Compton gamma rays have a flatter spectrum until the process is in deep Klein-Nishina regime with very low cross section, i.e. the process can not produce gamma rays above ~20 TeV.





Cosmic neutrinos are bound to have flatter spectra than atmospheric neutrinos because high energy pions do not decay in the atmosphere, they rather interact and do not generate neutrinos.

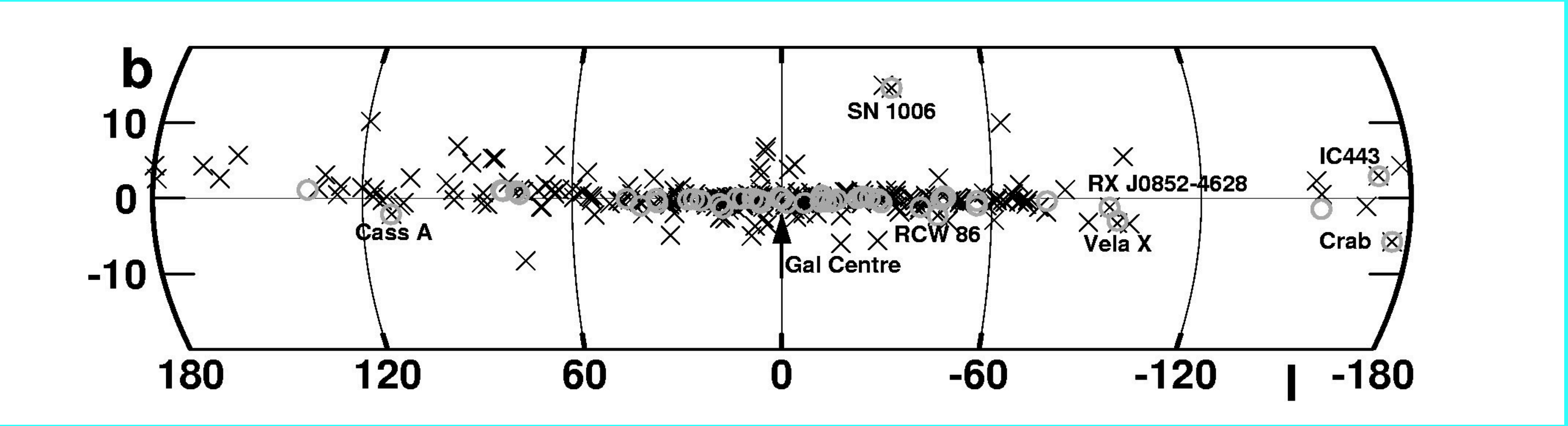
Schematic presentation of the energy spectra of
atmospheric neutrinos
diffuse galactic neutrinos
cosmic ray source neutrinos



Principles of neutrino detection: detection of upward going neutrino induced muons. At depth of 1.5 km.w.e., the ratio of the down going muons to upward going muons is 10^6 .

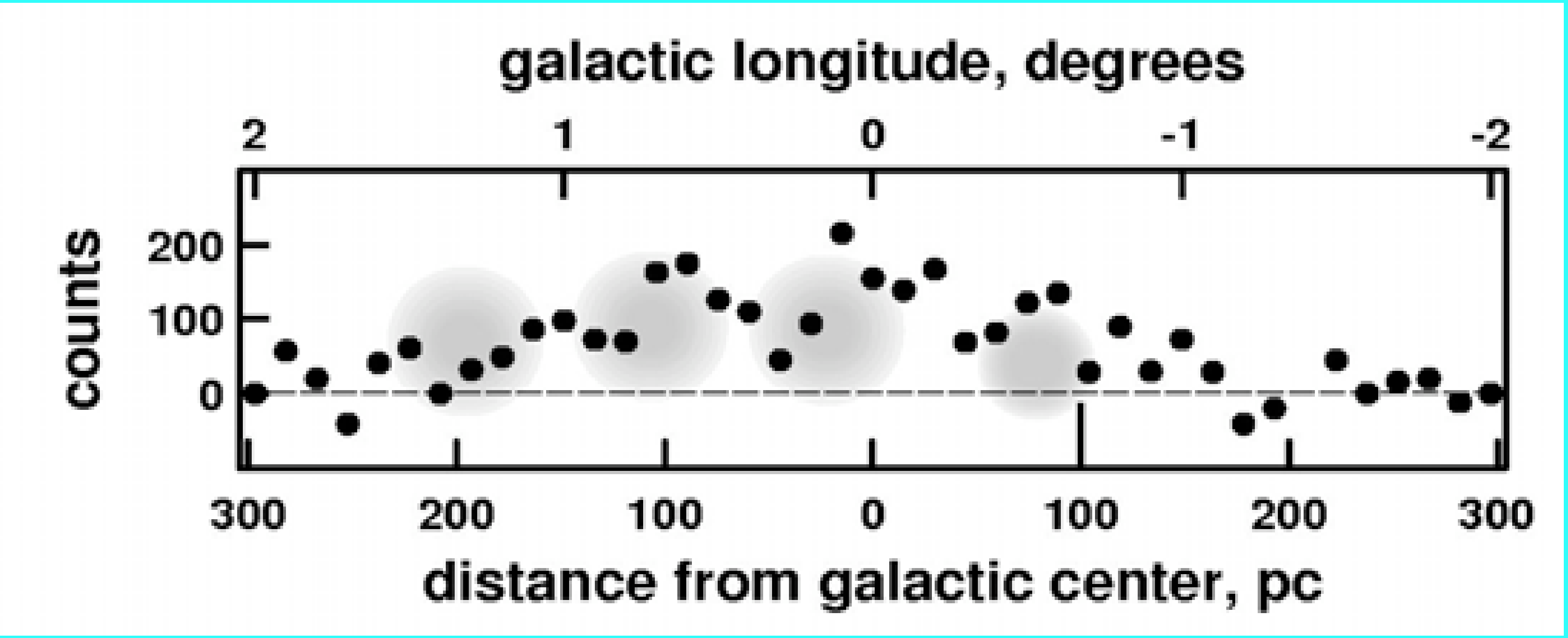
Probability that a muon neutrino of given energy would generate a muon of energy 1 GeV and 1 TeV.

Galactic TeV gamma ray sources



The positions of the TeV galactic sources from *TeVCat* compared to the locations of SNR from D.A. Green's catalog. There are a few coincidences (which are marked with the SNR name) but the majority of SNR are not TeV gamma-ray sources.

The reason may be obvious from the observation of HESS of the Galactic ridge.



Gamma- rays seem to come from cosmic ray interactions of nearby molecular clouds. The idea is that cosmic rays have been accelerated some time ago (10^4 yrs) in the galactic center and have propagated to three out of four clouds to interact and produce gamma-rays. TeV and GeV gamma-rays may not coincide (CR propagation).

What are the possible acceleration sites of galactic cosmic rays. The are at least three types of candidates:

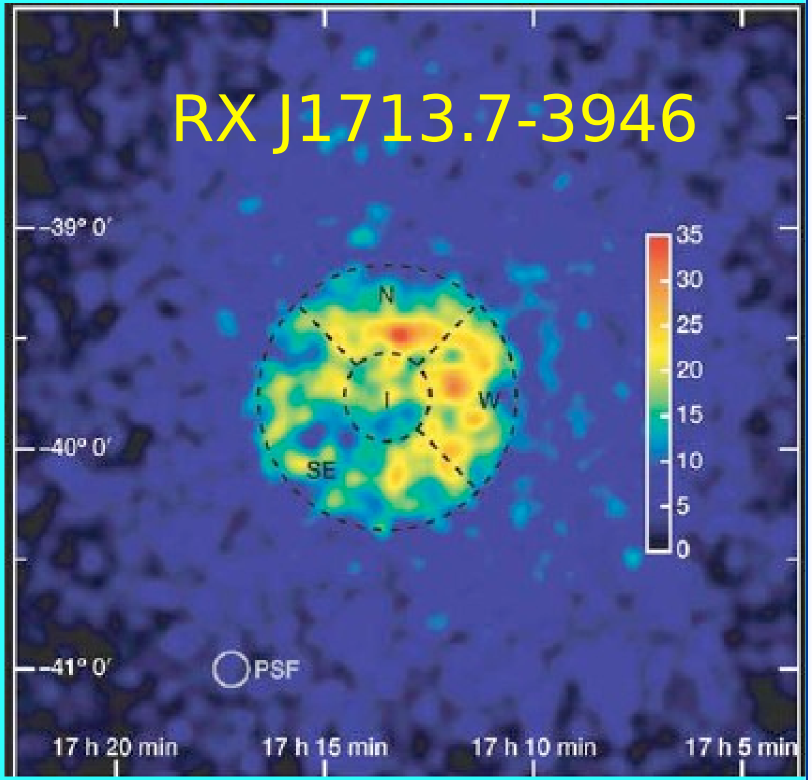
1. Supernova remnants (SNR)
2. Pulsar wind nebulae (PWN)
3. X-ray binary systems (BIN)

Let's look at a couple of examples among the sources of TeV gamma-rays.

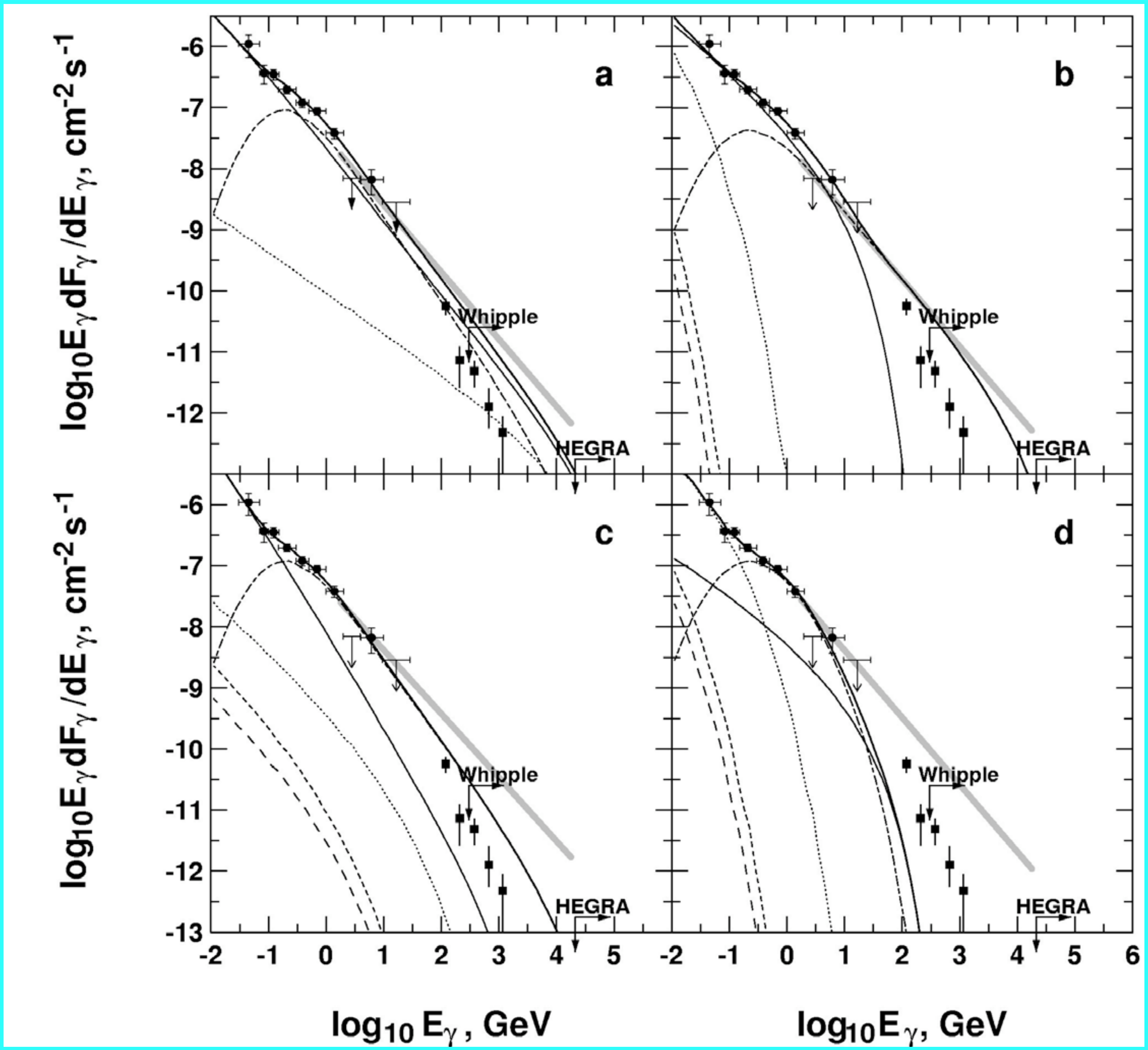
Supernova remnants:

RX J1713.7-3946	1 Crab	0.2 kpc	?
RX J0852.0-46.22 (Vela Jr)	0.66	2 kpc?	$\gamma = 1.2$

Two of the strongest TeV gamma-ray sources detected by HESS. The gamma-ray flux between 0.5 and 10 TeV is $\sim 10^{-10}$ erg/(cm^2 s), i.e. The differential flux at 1 TeV is $2.4\ 10^{-11}\ E^{-2.2}\ cm^{-2}\ s^{-1}$



One expects 3-6 >TeV neutrinos from Vela Jr and 2-3 neutrinos from RX J1713.7-3946 in KM3NeT. (Kiestler & Beacom)



IC443

detected by EGRET (see the old models) and by MAGIC.

D. Torres at all explain the two different spectra with two clouds at different distances

Pulsar wind nebulae

These are also very powerful gamma-ray sources, see the Crab and Vela pulsars, for example. The emission from these sources is usually interpreted as perfectly electromagnetic – inverse Compton scattering on MBR or synchrotron photons from energetic electrons.

The electron energy in such a case should reach 100 TeV, so if cosmic rays are also accelerated, they should have higher maximum energy because of their lower energy loss. Some authors suggest significant number of nuclei in pulsar winds.

1 Crab (HESS definition) $2.83 \; 10^{-11} \; cm^{-2} \; s^{-1} \; TeV^{-1}$ *at 1 TeV*

--> 2.7 > 1 TeV neutrinos in IceCube (K&B)

X-ray binary systems

LS 5039	HESS	0.03 Crab
LS I +61303	Magic	0.16 Crab

Such sources maybe very strong neutrino sources as the detected TeV gamma-rays may have been absorbed at the source in the very strong photon field. Neutrino fluxes in such a case would be much stronger than the gamma-ray fluxes.

In addition, the fast cooling of energetic electrons in the strong photon field of these sources supports hadronic origin of the detected TeV gamma-rays.

Unidentified sources

There is a large number of TeV sources that do not have a counterpart in any other wavelength. They still generate TeV gamma-rays so they could also produce neutrinos or belong to one of the previous classes. Those very close to the galactic plane could be just dense molecular clouds in the vicinity of a cosmic ray accelerator.

Estimates of the neutrino flux from these objects are difficult but one would have 1-2 events per year in km3 telescopes when these sources are stacked.

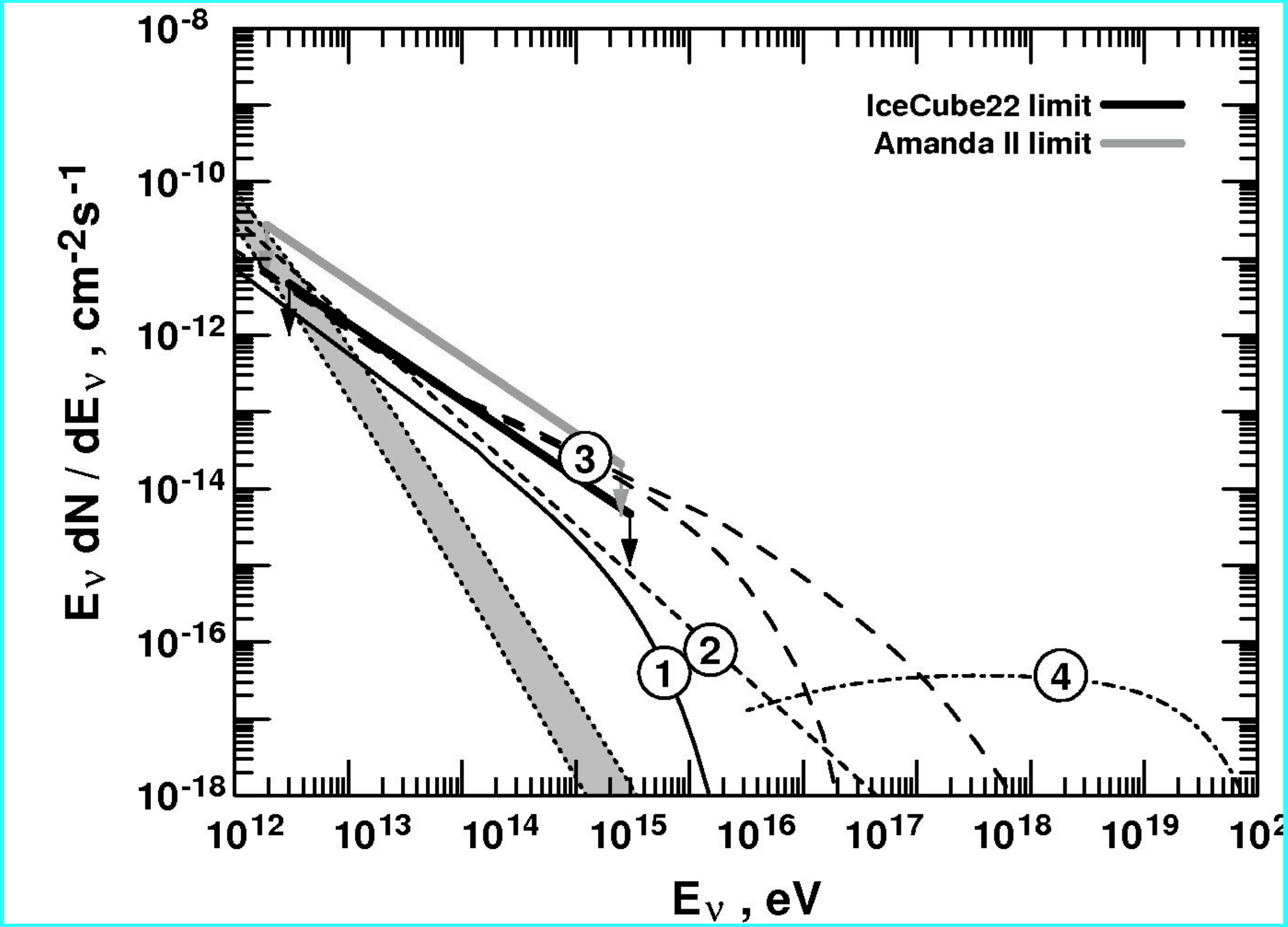
Galactic gamma ray sources

Source type	α_ν	#*	neutrinos above 1 TeV/5yr	
			source	atmospheric
SNR	1.7 - 2.5	6	27	173
PWN	1.0 - 2.7	12	68	122
BIN	1.6 - 2.7	2	1.3	9
UnID	1.3 - 2.4	6	23	63

* HESS sources

(from Kappes *et al*, 2007)

These are theoretical estimates, i.e. neutrino flux times neutrino cross section times muon production probability. There is no account for detector efficiency.



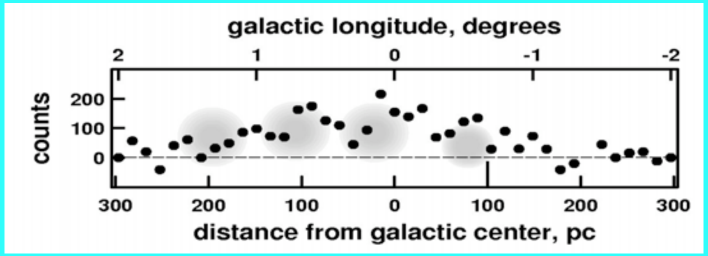
Source 1 is the only galactic neutrino source - IC443 most favorable fit of EGRET data – high maximum energy.

Note that the detector efficiency is accounted for in these limits,

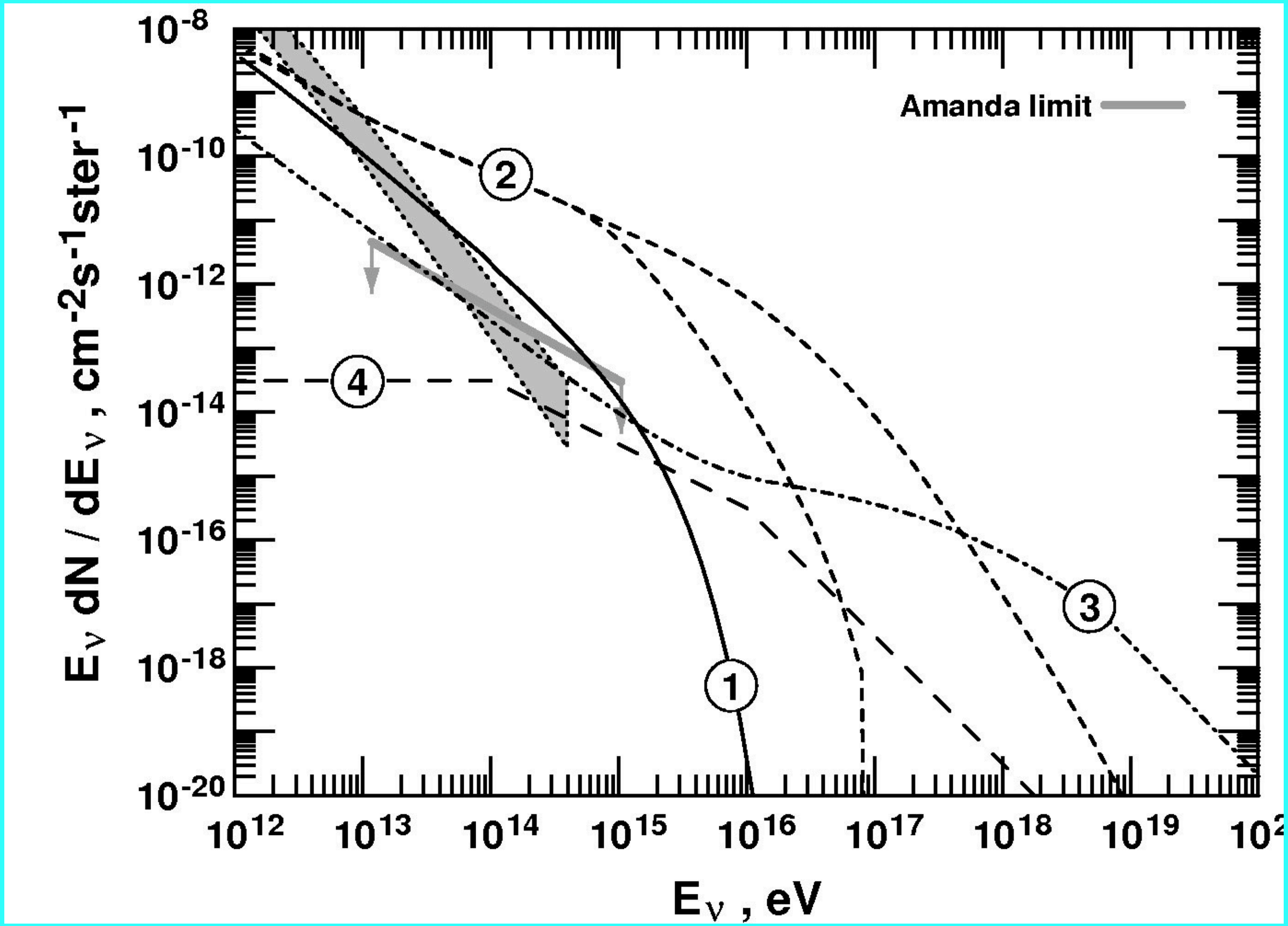
Some of the potential sources from the previous page (RX J's SNR) would also be above the IceCube limit.

Diffuse emission

The only realistic example for now is the galactic center ridge. About 3 neutrinos above 1 TeV expected from the same region of the sky for 5 years.

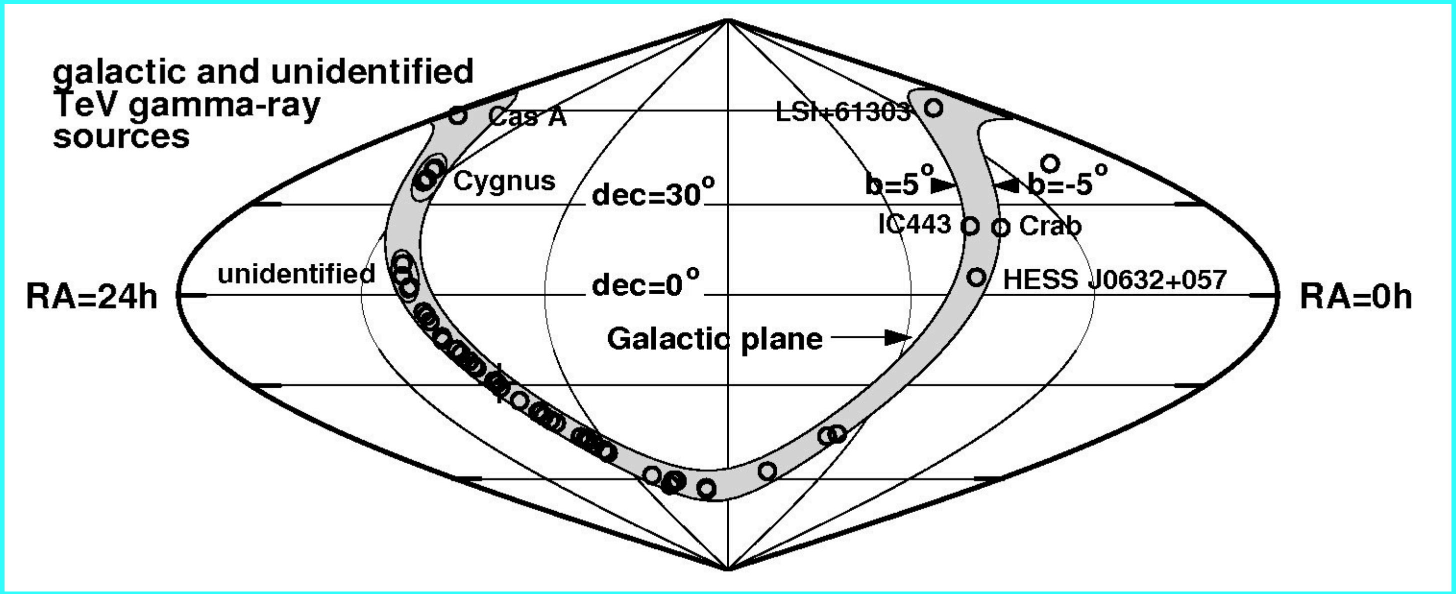


It is not obvious what is a diffuse neutrino emission - in case of gamma-rays the known sources are subtracted. From all sources in the galactic plane one expects 120 neutrinos above 1 TeV over a background of 400.

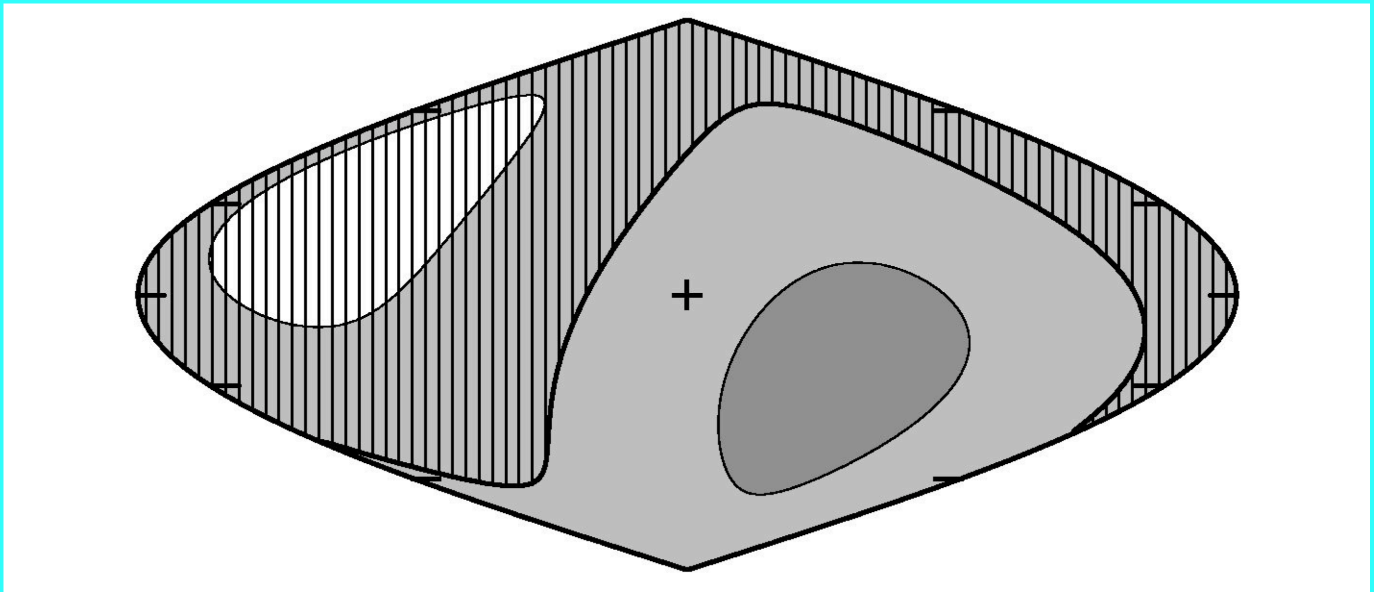


Curve 1 is for neutrinos from the central galactic plane which is not visible by Amanda. There is practically no limit in this direction.

Location of the neutrino telescope



The limits of Amanda and IceCube are for sources in the Northern hemisphere. Most of the sources are, however, in the Southern hemisphere, over the head of HESS. These can be observed by KM3NeT in upward going neutrino produced muons.



The fields of view in galactic coordinates of IceCube (stripes) and KM3NeT, which never sees the white area and always sees the dark area in the galactic South.

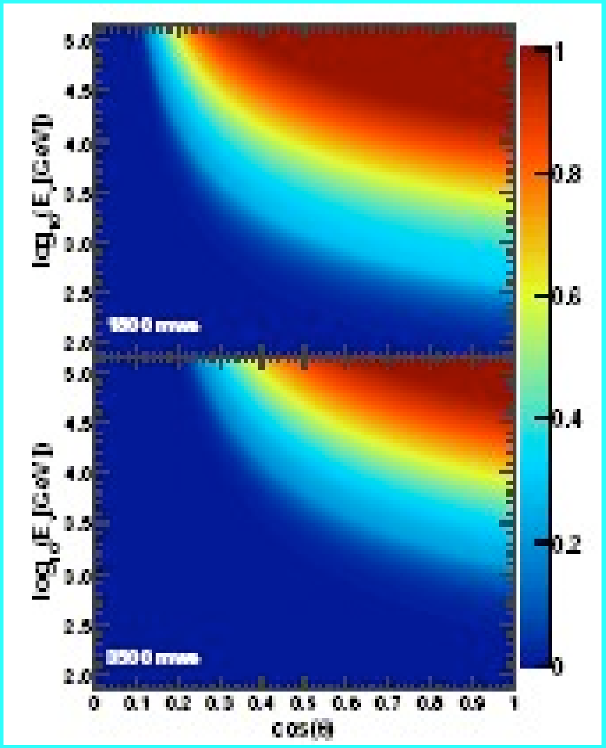
There is obviously **need** to measure down going neutrinos. There are some ideas how this could be done. Only neutrinos that interact inside the detector can be distinguished from atmospheric muons.

One should then measure the energy spectrum of these events and compare with the expected spectrum of atmospheric neutrinos (as a function of the zenith angle).

After that one could analyze the *extra* high energy neutrino events and even search for sources from the arrival direction distribution.

This is not an easy job but it has to be done if we want neutrino telescopes to observe the whole sky and double their statistics.

A different interesting idea was recently published by Schönert *et al* – vetoing the atmospheric neutrinos by the acompaning muon from pion decay. (High energy muons do not stop and decay in the atmosphere. The veto power has energy dependence. The veto power approaches 1 for vertical neutrinos at about 10 TeV. At higher zenith angles the veto is achieved at higher energy and is not possible for horizontal ones.



Veto power as a function of the neutrino energy and zenith angle from Phys Rev D79:043009 (2009) at two depths (km.w.e.)

CONCLUSIONS

The fast development of TeV gamma ray astronomy and the fast growing number of sources gives us some information about the possible galactic neutrino sources.

There are still large uncertainties: the same way not all expected gamma ray sources are indeed such sources, the gamma ray sources may not be neutrino sources. Many of them could have pure electromagnetic origin - PWN for example.

We should patiently continue observing the sky and continue improving the neutrino telescopes and their analysis procedures. Todays effective areas of the neutrino telescopes are way below a square kilometer.