

Status of neutrino astronomy

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Abstract. Astrophysical neutrinos can be produced in proton interactions of charged cosmic rays with ambient photon or baryonic fields. Cosmic rays are observed in balloon, satellite and air shower experiments every day, from below 10^9 eV up to macroscopic energies of 10^{21} eV. The observation of different photon fields has been done ever since, today with detections ranging from radio wavelengths up to very high-energy photons in the TeV range. The leading question for neutrino astronomers is now which sources provide a combination of efficient proton acceleration with sufficiently high photon fields or baryonic targets at the same time in order to produce a neutrino flux that is high enough to exceed the background of atmospheric neutrinos. There are only two confirmed astrophysical neutrino sources up to today: the sun and SuperNova 1987A emit and emitted neutrinos at MeV energies. The aim of large underground Cherenkov telescopes like IceCube and KM3NeT is the detection of neutrinos at energies above 100 GeV. In this paper, recent developments of neutrino flux modeling for the most promising extragalactic sources, gamma ray bursts and active galactic nuclei, are presented.

1. Introduction

The detection of cosmic radiation from space in the early 20th century was the first step of the today established idea that particles can be accelerated to ultra-high energies by cosmic accelerators [1]. Today, the cosmic ray energy spectrum ranges from below 10^9 eV up to energies larger than a joule, 10^{21} eV, see Fig. 1 (left). Still, the origin of those cosmic rays could not be identified unambiguously yet due to the scrambling of their original directions by galactic magnetic fields. High-energy neutrinos play an important role in identifying cosmic ray accelerators. Undeflected and unabsorbed, they traverse the universe and are therefore perfect messengers from the acceleration region of baryonic particles. This advantage poses a disadvantage for the detection of neutrinos, which is one of the reasons why only two neutrino source predictions could be confirmed until today: solar neutrinos and the supernova 1987A. Figure 1 shows the expected astrophysical neutrino spectrum, ranging from 10^{-3} eV energies (cosmic background neutrinos, decoupled after 1 s after the Big Bang), up to 10^{19} eV - those high-energy neutrinos connected to the highest energy cosmic rays. In this contribution, the possible production sites in astrophysical source classes are the topic of this paper. Section 2 discusses candidate sources for high-energy production. In Section 3, neutrino flux models are presented in the context of current experimental limits. Section 4 gives an outlook on future neutrino astronomy.

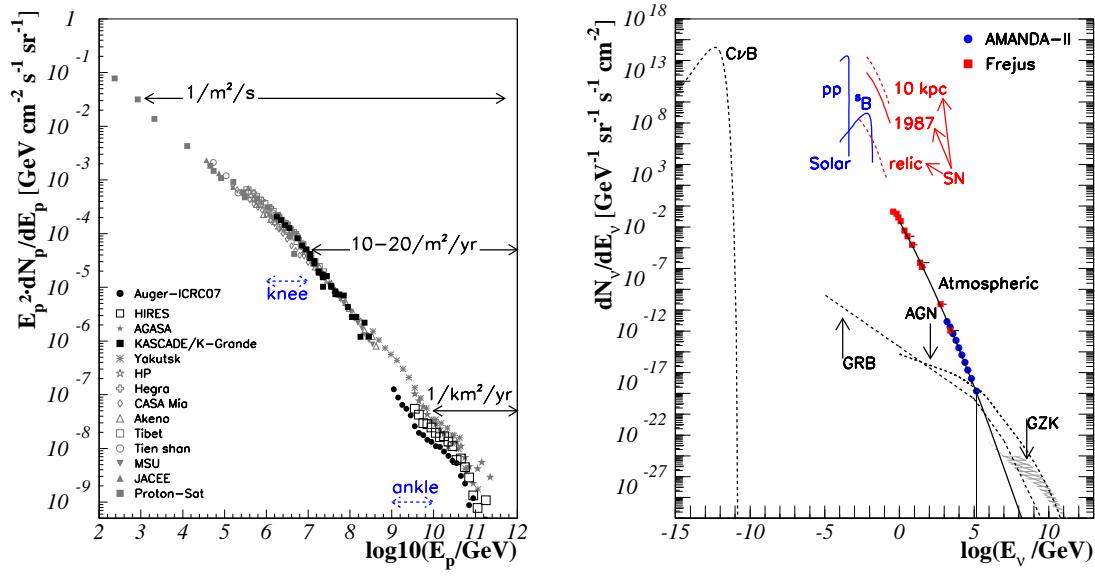


Figure 1. The measured spectrum of cosmic rays (left) and the predicted spectra of astrophysical neutrinos (right). Cosmic rays have been measured since the early 20th century, but their sources could not be identified unambiguously yet. Astrophysical neutrinos, on the other hand, are predicted from a wide range of sources, but difficult to detect. Confirmed sources (solid lines) are the sun and the supernova 1987A. See [2] and references therein.

2. Potential neutrino emitters

Neutrinos are dominantly produced in interactions of protons with ambient photon or proton fields: $p\gamma \rightarrow \Delta^+ \rightarrow p\pi^0/n\pi^+$ and $pp \rightarrow \pi^+\nu_\mu e^+\bar{\nu}_e$. The charged pions subsequently decay to produce neutrinos, $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e \bar{\nu}_\mu \nu_\mu$ and $\pi^- \rightarrow \mu^-\bar{\nu}_\mu \rightarrow e^-\bar{\nu}_e \nu_\mu \bar{\nu}_\mu$. The neutrino flavors are produced at the source in ratios $(\nu_e : \nu_\mu : \nu_\tau) = (\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = (1 : 2 : 0)$. Due to neutrino oscillations, the ratio at Earth becomes $(\nu_e : \nu_\mu : \nu_\tau) = (\bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau) = (1 : 1 : 1)$. In order to produce a significant neutrino flux, two criteria need to be fulfilled:

- (i) The kinematics must allow for the production of the Delta-resonance in the case of $p\gamma$ interactions, and for the production of the three pions in case of proton-proton interactions.
- (ii) The environment of the source needs to provide sufficient photon or proton targets, i.e. the optical depth for proton-proton or proton-photon interactions, τ_{pp} or $\tau_{p\gamma}$, needs to be close to or above unity, $\tau_{pi} = L/\lambda_{mfp} = l \cdot n_i \cdot \sigma_{pi}$, with $i = p, \gamma$. The mean free path is given as $\lambda_{mfp} = (n_i \cdot \sigma_{pi})^{-1}$ and L is the extension of the source.

In any case, the sources need to contain high-energy protons in order to have the above collisions. This means the proposed sources for cosmic ray acceleration corresponds to the predicted sources of neutrino emission. Here, two criteria have to be met to have a source class responsible for a particle flux as high as observed in the cosmic ray spectrum:

- (i) The maximum energy of the particle must be high enough. A single particle's energy is mainly determined by the product of the extension of the source, L , and the source's magnetic field, B , see [3]: $E_{\max} \approx 10^{18} \text{ eV} \cdot Z \cdot \beta_{SH} \cdot L/(1 \text{ kpc}) \cdot B/(1 \mu\text{G})$. Here, Z is the charge of the particle in units of the electron's charge. Further, β_{SH} is the velocity of the shock region, in which the particle is accelerated, in units of the speed of light.

- (ii) The non-thermal, electromagnetic luminosity of the sources is directly connected to the acceleration: it is mainly produced by accelerated electrons, emitting synchrotron radiation. If protons are present in the source, they are accelerated in the same way. Thus, the electromagnetic energy, E_{em} , must correspond to or exceed the total energy observed in cosmic rays, E_{CR} , $E_{\text{em}} \geq E_{\text{CR}}$. Here, the total electromagnetic energy release of a source class can be determined by multiplying the characteristic luminosity with the life time of the sources. To determine the total energy in cosmic rays, the total energy density measured at Earth needs to be multiplied with the expected volume of the sources producing the cosmic rays. For a detailed discussion, see e.g. [4, 2].

A list of proposed sources of cosmic rays contributing at different energies in the spectrum is given in table 1. Supernova remnants (SNRs) in the Galaxy are the best candidates for cosmic

Table 1. Possible source classes of the cosmic ray spectrum.

Source class	L_{em} [erg/s]	life time [yr]	energy range	Ref
SNR	10^{42}	1000	$10^{10} \text{ eV} < E_p < 10^{15} \text{ eV}$	[5]
SNR-wind	10^{44}	1000	$10^{10} \text{ eV} < E_p < 10^{18} \text{ eV}$	[6]
X-ray binaries	10^{38}	$10^5 - 10^6$	$10^{14} \text{ eV} < E_p < 10^{18} \text{ eV}$	[4]
Pulsars	10^{37}	10^6	$10^{14} \text{ eV} < E_p < 10^{18} \text{ eV}$	[4]
Galaxy clusters	$\sim 10^{44}$	10^7	$3 \cdot 10^{18} \text{ eV} < E_p < 10^{21} \text{ eV}$	[7]
AGN	$10^{44} - 10^{47}$	10^7	$3 \cdot 10^{18} \text{ eV} < E_p < 10^{21} \text{ eV}$	[8]
GRBs	$10^{49} - 10^{51}$	$10^{-8} - 10^{-4}$	$3 \cdot 10^{18} \text{ eV} < E_p < 10^{21} \text{ eV}$	[9, 10]

ray production below the knee of the cosmic ray spectrum, i.e. $E < 10^{15}$ eV. If a supernova does not explode into the interstellar medium, but into a dense environment ('SNR-wind'), energies up to $\sim 10^{18}$ eV can be achieved. X-ray binaries and pulsars in the Galaxy do not provide enough total energy of the cosmic ray flux below the knee. However, their maximum energy and their energy output is enough to contribute in the energy range between knee and ankle, i.e. $10^{15} \text{ eV} < E_p < 10^{18} \text{ eV}$. Above the ankle, the sources cannot be of Galactic origin¹. Extragalactic candidates providing sufficient maximum energies and total energy release are galaxy clusters, active galactic nuclei (AGN) and gamma ray bursts (GRBs).

Alternative neutrino production scenarios are usually connected with *hidden* cosmic ray sources. If an accelerator of cosmic rays lies behind dense molecular clouds, the high-energy protons interact with the hydrogen atoms in the clouds. While the protons are absorbed this way, neutrinos are produced in high numbers as described above. This process can happen on Galactic scales, when a supernova remnant or a pulsar sits behind molecular clouds, or on extragalactic scales, when an AGN jet is absorbed by dense matter.

3. Neutrino flux models

The neutrino flux of a single emitting source follows the protons in their spectral behavior. The energy spectrum, $d\Phi_\nu/dE_\nu$, is thus represented by a power law with a spectral index around $\alpha_\nu \sim 2$ and a cutoff depending on the maximum proton energy, $E_\nu^{\max} \sim E_p^{\max}/20$:

$$\frac{d\Phi_\nu}{dE_\nu} = A_\nu \cdot E_\nu^{-\alpha_\nu} \cdot \exp\left(-\frac{E_\nu}{E_\nu^{\max}}\right). \quad (1)$$

¹ At energies of above 10^{18} eV, the energy of the emitted charged particles is high enough to let the particles travel on straight lines despite Galactic magnetic field deflections. Since no such anisotropy was observed for cosmic rays above the ankle, they have to come from larger distances, i.e. they must be extragalactic.

The signal strength, A_ν , can be determined by assuming the production of neutrinos in correlation with either high-energy cosmic rays or photon emission. Depending on the model, neutrinos can for instance be connected to radio emission, because it reflects the acceleration of electrons, which in turn mirrors the protons' acceleration. Alternatively, high-energy photon emission can be accompanied by a neutrino signal: Neutral pions, originating from the same process as charged pions as described above, decay into photons at MeV-TeV energies.

The neutrino flux from a class of objects, dN_ν/dE_ν , can then be determined by folding the single source flux with the source distribution function, $dn/dL/dV$, giving the number of sources per luminosity L and per comoving volume dV :

$$\frac{dN_\nu}{dE_\nu} = \int_z \int_L dz dL \frac{d\Phi_\nu}{dE_\nu} \cdot \frac{dn}{dL dV} \cdot \frac{dV}{dz} \cdot \frac{1}{4\pi d_L^2}. \quad (2)$$

The factor $(4\pi d_L^2)^{-1}$ takes into account the decrease of the flux with the luminosity distance d_L . Here, the status of neutrino flux modeling in the context of observational astronomy is reviewed.

3.1. The progress of neutrino astronomy so far

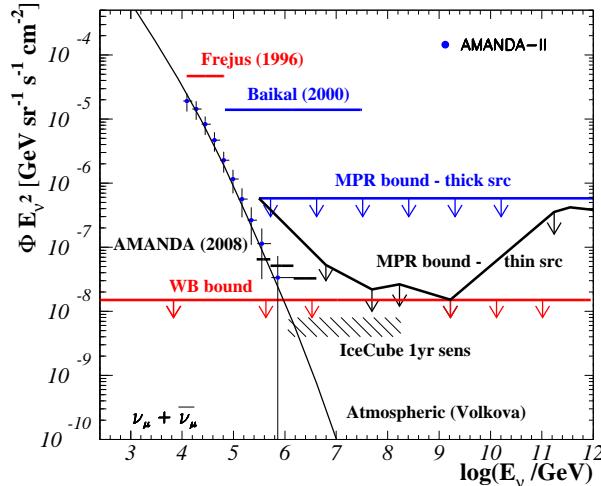


Figure 2. High-energy neutrino spectrum. Theoretical bounds: upper bound on $n\gamma$ -optically thick (uppermost, blue horizontal line) and optically thin (black, broken powerlaw line) sources [11]; E^{-2} -bound on optically thin sources (red, lower horizontal line) [10]. Experimental limits: Fréjus (1996) [12], Baikal (2000) [13], AMANDA (2008) limit and atmospheric spectrum [14]. The atmospheric prediction is given in [15]. IceCube sensitivity for 1 full year from [16].

The modeling of neutrino fluxes constantly improved throughout the years, using new pieces of information provided by cosmic ray experiments, keV-TeV photon astronomy and in particular from large volume neutrino detectors which have improved limits by several orders of magnitude over the years. Despite the lack of detected sources so far, those strict experimental limits start to exclude certain classes of sources, leaving other source classes in favor of producing high-energy neutrinos. One of the most important examples is that the correlation between X-rays and neutrinos from AGN can be excluded: the possible contribution of X-ray emitting AGN to the neutrino background was calculated by different authors [17, 18, 19]. Each of the predictions exceeds current neutrino flux limits by at least one order of magnitude, see [20].

The progress of neutrino astronomy within the past 10 years is shown in Fig. 2. Experimental limits were at a level $> 10^{-5} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ in the late 1990s and have improved by more than 2 orders of magnitude in the past 10 years. This is an important step, given the theoretical upper bounds derived in the late 1990s as well, see [10, 11], implying that sources optically thin for neutron-photon interactions cannot provide more than $\sim 10^{-6} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ and optically thick sources are restricted to $\lesssim 10^{-6} \text{--} 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, depending on the energy. Today, neutrino flux models below those two bounds can easily be explored by experiments like AMANDA, Anita, Auger and many more. Next generation neutrino telescopes like IceCube and KM3NeT will improve the sensitivities by a further factor 10 within the first year of operation.

3.2. Prospects for the near future

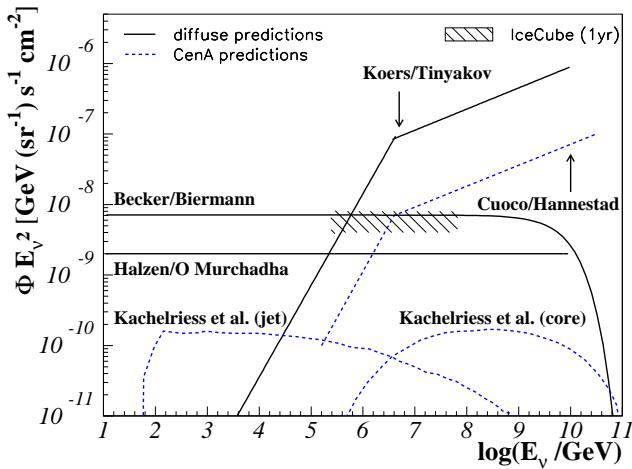


Figure 3. Predictions in connection to the hint of anisotropy in cosmic rays observed by Auger [21]. Diffuse predictions: $p\gamma$ -interactions with synchrotron photons [22]; coincident emission of neutrinos and TeV γ -rays [23]; neutrinos from the base of AGN jets [24]. Predictions for CenA: $p\gamma$ -interactions [25]; production in the AGN jet and core [26].

Many of the source classes are still unexplored due to limited experimental sensitivities. The two most interesting classes of extragalactic objects, GRBs and AGN, providing intensities in excess of IceCube's sensitivity within the first years of operation, are presented here.

- *Gamma ray bursts*

GRBs were proposed as the sources of cosmic rays above the ankle [9, 10]. Due to the high synchrotron field in those sources, they are good neutrino candidates as well [10, 27, 28]. The stacking of identified GRBs for neutrino data provides the best limit so far, see [29], reaching within a factor of a few above the classical GRB neutrino flux prediction given in [10]. A single, bright GRB can be identified with a fully operational 1 km^3 -detector like IceCube. The bright burst GRB080319b was observed by IceCube while under construction, with $\sim 1/10 \text{ km}^3$ operational volume, and ~ 0.1 expected events at a much lower background level [30]. With a full IceCube detector, between 1 – 2 events are expected.

- *Active galactic nuclei*

A variety of AGN sub-classes are proposed as potential neutrino emitters. Among the most prominent ones are TeV photon emitters, under the assumption that the TeV emission originates from π^0 -decays rather than from Inverse Compton scattering, see e.g. [11].

Another option is that those AGN responsible for the cosmic ray flux above the ankle also produce neutrinos. This implies that the cosmic ray emitters need to provide a target that absorbs part of the cosmic rays before they can escape the source, i.e. either sufficiently high photon or proton fields. Possible targets are the accretion disk's radiation field, the synchrotron field in the jet, or the torus as a baryonic target. A first hint of a correlation between the highest energy cosmic rays and a catalog of close AGN was announced by Auger [21]. This correlation can be used to estimate the neutrino flux from the same sources. Different predictions, many of them based on the assumption that the close AGN Centaurus A is one of the dominant sources, are presented in Fig. 3.

4. Outlook

Previous high-energy neutrino detectors turned helped excluding different scenarios of neutrino production so far. Future detectors like IceCube and KM3NeT will provide large enough effective volumes to explore further orders of magnitude in the neutrino energy density of different single sources or source classes.

In order to identify the sources of cosmic rays and the mechanisms producing them, multiwavelength astronomy is crucial. Each of the messengers, i.e. charged cosmic rays, radio to TeV photons, neutrinos and also gravitational waves, provide us with pieces of information. We need to have all those pieces in order to see the whole picture. The role of neutrino astronomy in this puzzle is to identify the birth place of cosmic rays.

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