# KILOMETER-SCALE HIGH ENERGY NEUTRINO OBSERVATORIES

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ABSTRACT

We review the rationale for building kilometer-scale high energy neutrino detectors: the kilometer-scale is connected, in an essentially model-independent way, to the observed flux from the (unknown) sources of high energy cosmic rays. A similar analysis based on the flux of TeV-energy gamma rays from supernova remnants and active galaxies confirms this conclusion. The scientific reach of future kilometer-scale neutrino observatories does not only derive from their increased telescope area, but also from their superior performance as particle detectors compared to first-generation detectors; most importantly, they have the capability to measure neutrino energy and identify neutrino flavors.

## 1. Neutrino Astronomy 2001

Suggestions to use a large volume of water for high-energy neutrino astronomy were made as early as the 1960s[1)]. In this case, a muon neutrino ($\nu_\mu$) interacts with a hydrogen or oxygen nucleus in the water and produces a muon travelling in nearly the same direction as the neutrino. The blue Čerenkov light emitted along the muon's ~km-long trajectory is detected by strings of photomultiplier tubes deployed deep below the surface. DUMAND, a pioneering project located off the coast of Hawaii, demonstrated that muons could be detected by this technique[2)], but the planned detector was never realized. A detector composed of about ninety photomultiplier tubes (or optical modules) located deep in Lake Baikal was the first to demonstrate the detection of neutrino-induced muons in natural water[3)]. The European collaborations ANTARES[4)] and NESTOR[5)] plan to deploy large-area detectors in the Mediterranean Sea within the next few years. The NEMO Collaboration is conducting a site study for a future kilometer-scale detector in the Mediterranean[6)].

The AMANDA experiment, situated at the U.S. Amundsen-Scott South Pole Station, has strikingly demonstrated the merits of natural ice as a Čerenkov detector medium[7,8)]. In 1996, AMANDA was able to observe atmospheric neutrino candidates using only 80 eight-inch photomultiplier tubes[7)]. With 1997 data and 302 optical modules instrumenting approximately 6000 tons of ice, AMANDA extracted several hundred atmospheric neutrino events. AMANDA was the first neutrino telescope with an effective area in excess of 10,000 square meters for TeV muons. In January 2000, AMANDA-II was completed. It consists of 19 string with a total of 677 OMs arranged in concentric circles, with the ten strings from AMANDA forming the central core of the new detector. AMANDA-II has been calibrated and neutrinos have been detected. Several technologies were deployed to evaluate their utility and readiness for future expansion to larger systems. AMANDA has met the key challenge of neutrino astronomy: it has developed a reliable, expandable, and affordable technology for deploying a kilometer-scale neutrino detector named IceCube.

AMANDA/IceCube and the detectors to be located in the Mediterranean Sea will be complementary in several respects. First and foremost, they will cover different portions of the sky. (From its location at the South Pole, IceCube observes the northern sky.) Because of the different properties of Antarctic ice and ocean water — ice scatters light more but absorbs it less — IceCube should have better energy resolution and a larger effective area for neutrino detection, while the deep sea detectors should have better pointing resolution. Finally, one of the key challenges in neutrino astronomy has been the ability to deploy and maintain optical modules far below the surface; here, too, ice and ocean are essentially different.

## 2. The Science Case

The construction of neutrino telescopes is overwhelmingly motivated by their discovery potential which covers astronomy, astrophysics, cosmology and particle physics. From this point of view, one has to design an instrument with the best angular and energy resolution, and the largest possible effective telescope area, because the science goals are so varied:

- searching for the source(s) of the cosmic rays
- searching for steady and variable sources of high energy neutrinos, e.g. Active Galactic Nuclei (AGN) or Supernova Remnants (SNR);
- searching for high energy neutrinos from transient sources like Gamma Ray Bursts (GRB) or Supernova bursts;
- searching for neutrinos from the decay of superheavy cosmological remmants or topological defects;
- searching for Weakly Interacting Massive Particles (WIMPs), which may constitute dark matter;
- searching for magnetic monopoles and other exotic particles like strange quark matter;
- monitoring our Galaxy for MeV neutrinos from supernova explosions and operation within the worldwide triangulation network;
- searching for unexpected phenomena.

Where the size of the detector is concerned, the observed fluxes of cosmic rays and gamma rays set the scale of a neutrino telescope. With minimal model-dependence, one can indeed anticipate the very high energy cosmic neutrino fluxes by scaling to the observed energy density in high energy cosmic rays, or to the measured fluxes of nonthermal high energy gamma rays. The basic assumption in calculating the expected neutrino fluxes is that some fraction of cosmic rays will interact in their sources to produce neutrinos.

Although they are not yet identified, the sources of the highest energy cosmic radiation very likely involve extremely dense regions with exceptional gravitational forces such as supermassive black holes, collapse of massive stars and mergers of black holes and neutron stars. With black holes, accretion and intense radiation fields as ingredients, some fraction of the accelerated particles will produce pions in hadronic collisions with ambient gas and/or by photoproduction on the intense radiation fields near the black hole(s). In either case, the neutral pions decay to photons, while charged pions include neutrinos among their decay products with spectra related to the observed gamma-ray spectra. Estimates based on this relationship show that a kilometer-scale detector is needed to observe neutrino signals from the source(s) of the highest energy cosmic rays and from known classes of high energy astrophysical sources which produce the highest energy gamma rays.

Other scientific missions of a neutrino telescope impose requirements on the instruments beyond large size, such as good angular and energy resolution, and the capability to distinguish neutrino flavors, opening the possibility to measure neutrino oscillation over cosmic baselines. Electron and tau-neutrinos are identified by the electromagnetic showers they initiate in interactions inside or near the detector.

Energy resolution is anticipated to be 25% in the logarithm of the energy for muons, possibly better. The detectors should definitely be able to determine energy to better than an order of magnitude, sufficient for the separation of high energy neutrino signals from atmospheric neutrinos with energies below 100 TeV. The energy response for showers is linear, and expected to be better than 20%. With good energy measurement one can separate interesting high energy events from the background of lower energy atmospheric neutrinos (and muons). The instrument can thus identify neutrinos with energies in excess of 100 TeV over $4\pi$ solid angle, and not just in the lower hemisphere where they are identified by their penetration of the Earth, as is the case with first-generation detectors. This is of primary importance because neutrinos of 100 TeV energy and higher are efficiently absorbed by the Earth. The observed events are dominated by neutrinos interacting in the ice, water or atmosphere *above* the detector and near the horizon where the atmosphere alone represents a target density for converting neutrinos of $36\,\mathrm{kg/cm^2}$. The frequency of down-going near-horizon events exceeds the rate of conventional up-going neutrinos by over an order of magnitude in typical models.

In what follows we will first describe the intimate relationship between neutrino and observed cosmic ray and gamma-ray fluxes. It forms the rationale for commissioning kilometer-size neutrino detectors. Subsequently, we will discuss their capability to identify the showers initiated by electron- and tau-neutrinos. The discussions, though more general, will, from now on, refer to the architecture and performance of

IceCube. It is at this time the only proposed instrument with a definite design.

## 3. Why 1 km$^2$ ?

### *3.1. The Highest Energy Cosmic Rays: Energy Considerations*

Models for the origin of the highest energy cosmic rays typically predict associated neutrino fluxes. A requirement on the sources is that they must provide sufficient power to supply the observed energy in the galactic or extragalactic component of the cosmic radiation. The assumption that comparable amounts of energy go into high-energy neutrinos allows an estimate of the corresponding neutrino signal that is independent of the specific nature of the source, but which depends only on their distribution in the universe. The following analysis is due to Gaisser[9)].

In the case of galactic cosmic rays, the energy flux carried by neutrinos is much lower than that carried by the parent cosmic rays because the charged particles are trapped locally as they propagate diffusively in the turbulent galactic magnetic fields. Thus an observer inside the galaxy has several chances to see a given cosmic ray particle, but only one chance to see a neutrino that passes directly out of the galaxy. Nevertheless, there is a chance that some nearby galactic sources could be visible in neutrinos in a kilometer-scale detector. Examples will be discussed in the next section.

For a cosmological distribution of sources, on the other hand, the energy flux in neutrinos can be comparable to the observed energy flux in cosmic rays, or even somewhat larger, depending on how the sources have evolved over cosmological time scales — provided that the fraction of accelerated protons that interact near the source is large. One natural scenario that gives comparable energy in neutrinos and cosmic rays occurs when protons remain trapped in the acceleration region until they suffer inelastic collisions, while secondary neutrons escape and decay to become cosmic-ray protons. It is generally believed that sources of the highest energy cosmic rays are indeed extragalactic, or at least not confined to the plane of the galaxy. There is some evidence for a transition from one particle population to another somewhere above $10^{18}$ eV, as well as for a trend from heavy toward lighter composition. Measurements of the cosmic-ray spectrum above $10^{17}$ eV are summarized in Fig. 1.

We now wish to estimate the neutrino signal expected if the energy in neutrinos is comparable to the energy in the extragalactic component of the cosmic radiation. The first step is to determine what fraction of the observed spectrum is the extra-galactic component. It is generally assumed that the acceleration processes produce a power-law spectrum $\propto E^{-\alpha}$ with differential index $\alpha = 2.0$ or slightly higher[10,11)]. But the measured spectrum has an index close to $\alpha = 3$. As an example, the lower heavy line in Fig. 1 shows a spectrum with $\alpha = 2$ and an exponential cutoff at $5 \times 10^{19}$ eV to represent the Greissen-Kuzmin-Zatsepin (GKZ) effect. At super GKZ energies the interaction length of cosmic rays in the microwave background is $\sim 50\,$Mpc. They

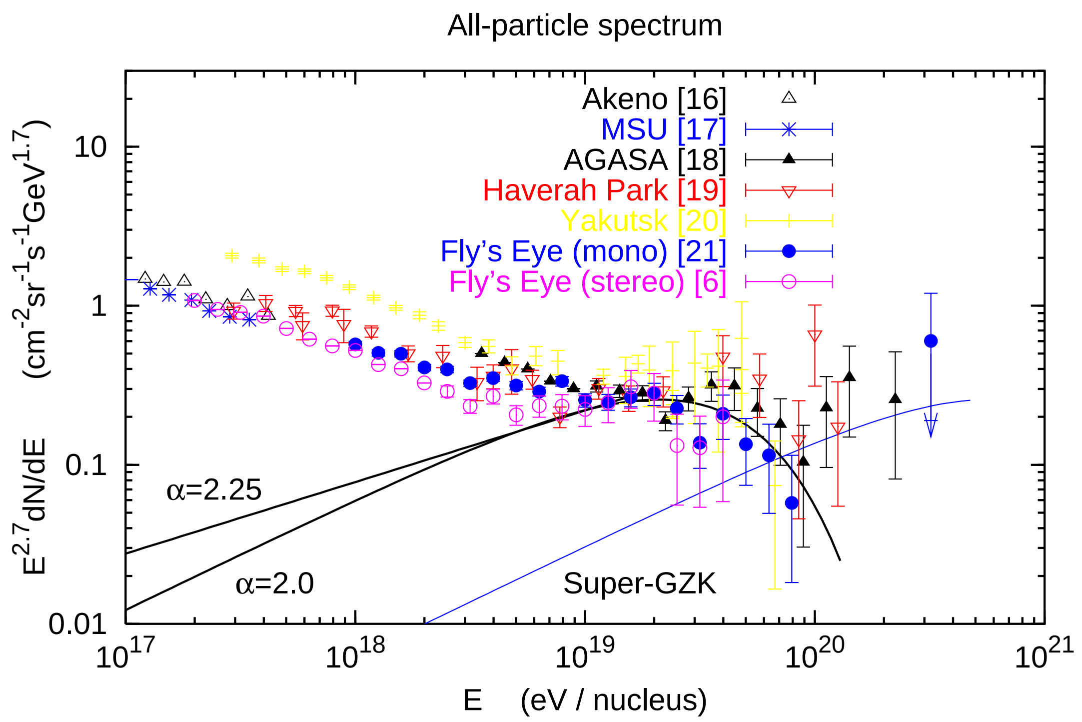



Figure 1: The high energy cosmic rays spectrum. See text for explanation of curves. Data are from Refs. 12,13,14,15,16,17,18.

therefore are unlikely to reach us from more distant sources. The excess of data above the curve for $E < 10^{19}$ eV may be attributed to the high energy tail of the galactic cosmic-ray spectrum. Integrating the energy content under this curve in Fig. 1 gives the energy density in cosmic rays of extragalactic origin, $\rho_{EG} \sim 2 \times 10^{-19}$ erg/cm$^3$. Shifting the normalization point lower (or higher) by half a decade in energy would increase (decrease) this estimate by roughly a factor of two. This is comparable to the systematic differences among the different measurements of the spectrum. If the spectrum is steeper (indicated by the upper solid curve in Fig. 1, as expected for acceleration by relativistic shocks) then the energy content will be somewhat[9)] larger. We will return to the super-GZK flux further on.

A standard technique to search for high energy neutrinos of astrophysical origin is to look for upward-moving muons induced by $\nu_\mu$ that have penetrated the Earth. The signal is the convolution

$$\text{Signal} \;\sim\; \text{Area} \otimes R_\mu \, N_A \otimes \sigma_\nu \otimes \phi_\nu, \tag{1}$$

where $R_\mu$ is the muon range in g/cm$^2$ and $N_A$ is Avogadro's number. The range and cross section both increase linearly with energy into the TeV region, after which the rate of increase slows. Neutrinos with $E_\nu < 100$ TeV are not strongly attenuated by the Earth, and much of the solid angle away from the nadir remains accessible up to 1 PeV [19)]. Thus the optimum range for $\nu_\mu$-induced upward muons is from a TeV to a PeV. Also in this energy range the muon energy loss is greater than minimum ionizing, which is a potential way to discriminate against the background of atmospheric neutrinos, which have a steeply falling spectrum. We will return to the importance of energy measurement further on.

Using our estimate of the energy in the extragalactic component of the cosmic ray spectrum and assuming a spectral index $\alpha \sim 2.0$ for the neutrinos as well as the cosmic rays, one predicts a neutrino event rate of $f \times 30$ events/km$^2$/yr [20], where $f$ is the efficiency for production of neutrinos relative to cosmic rays. For $f = 1$ this is essentially the Waxman-Bahcall "upper bound"[10], which applies for sources that are transparent to neutrons.

The "upper bound" can be evaded in several ways, each leading to the association of larger neutrino fluxes with the sources of the extragalactic cosmic rays:

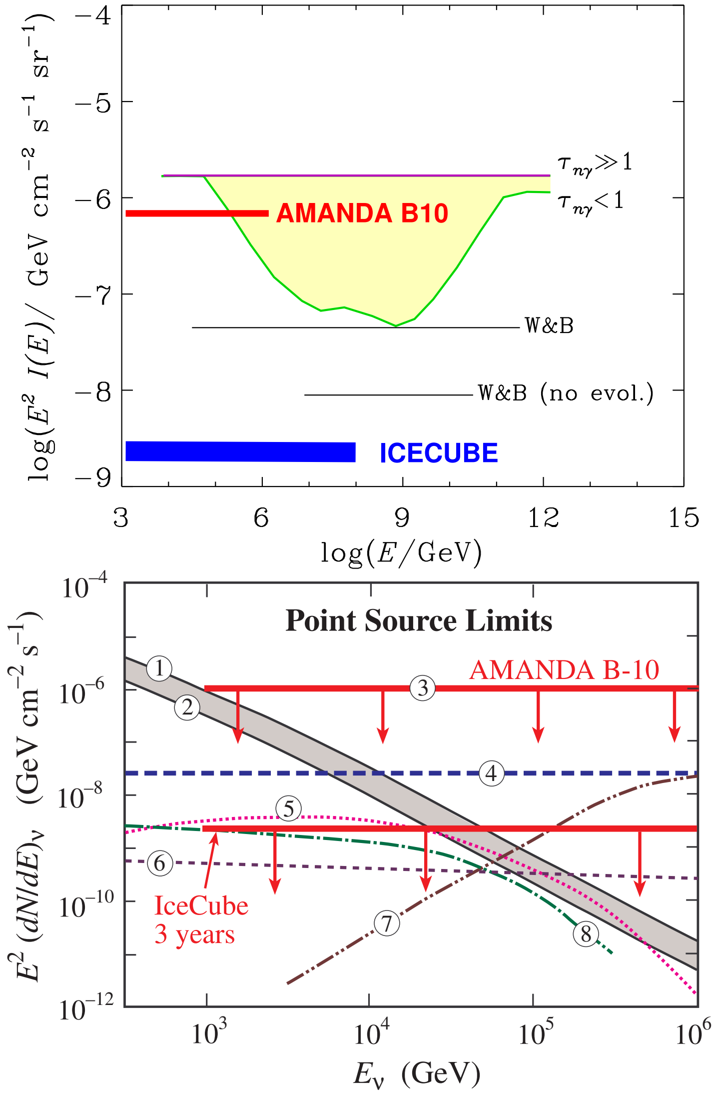
- If evolution is included, the above estimate of the neutrino rate may be increased by a factor of five if sources are assumed to evolve similarly to the rate of star formation[10,21]. This is because the ultra-high energy protons from high redshift would be attenuated by photoproduction and pair production while the neutrinos would not. Thus the neutrino flux would be greater for a given cosmic-ray flux at the normalization point.
- If the spectrum of extragalactic cosmic rays to which the normalization is made has $\alpha > 2.0$, then the corresponding estimated neutrino flux in the TeV to PeV range and the corresponding signal could also be larger.
- If the sources are not transparent and the cosmic rays are partially absorbed in the source.
- If, for a class of sources, the particular sources that produce the highest energy cosmic rays are different from the ones that produce the highest neutrino fluxes.

The above discussion is summarized in Fig. 2.

### *3.2. The Highest Energy Cosmic Rays: Models*

We may summarize the previous paragraphs by saying that an argument based on energetics coupled with a natural association between cosmic particle accelerators and their secondary neutrino beams suggests that a kilometer-scale detector will be needed to see the neutrinos. A similar conclusion is reached by relating the neutrino flux to the source of the highest energy cosmic rays in the context of specific models.

In a recent review[22] Learned and Mannheim have summarized recent work on models of AGN, GRB and other sources of high energy astrophysical neutrinos. As relevant examples, we quote here just two new papers that appeared since Ref. 22. Schuster, Pohl and Schlickeiser[23] work out the consequences of a model of AGN blazars[24] in which the TeV $\gamma$-rays come from decay of neutral pions produced in




1/2 Atmospheric neutrinos, horizontal/vertical
3 AMANDA limit
4 3C273 *pp* neutrinos
5 Crab Nebula
6 Coma Cluster
7 3C273 $p\gamma$ neutrinos
8 Supernova IC443

Figure 2: Top) Cosmic ray bounds on extragalactic neutrino fluxes, The generic bound obtained by Mannheim, Protheroe and Rachen[21] for the optically thin ($\tau_{n\gamma} < 1$) and thick case ($\tau_{n\gamma} \gg 1$) are shown together with the limit inferred from Waxman and Bahcall[10] with and without source evolution. They are compared to the present Amanda limit and to the limit expected from 3 years IceCube operation. Bottom) How the science reach of AMANDA and IceCube translates into a sensitivity for typical point sources of high energy neutrinos.

proton-proton collisions as a relativistic cloud of dense plasma plows into the ambient interstellar medium of the host galaxy. In this picture, there is a similar flux of TeV neutrinos from decay of charged pions. They conclude that the neutrino flux from a typical bright TeV $\gamma$-blazar would be detectable at the 3 $\sigma$ level above atmospheric background in an exposure of a km$^2$-year. During an extended flare, such as occurred for Mrk 501 during half of 1997[25)], the rate would be correspondingly higher in this model.

The frequently quoted estimates[26,27,28)] of neutrino production in GRB sources by collisions of extremely energetic protons with MeV photons in the gamma-ray jets typically produces $\sim 100$ TeV neutrinos at a level sufficient to produce a few events per km$^2$-year. Now Mészáros and Waxman[29)] argue that in gamma-ray bursts that involve collapse of massive progenitors, there will be an earlier phase of production of multi-TeV neutrinos from collisions of energetic protons with X-rays as the jet pushes through the envelope of the progenitor. They predict that there may be a class of collapses so massive that the jets do not emerge. These would not appear as visible gamma-ray bursts but would generate neutrino bursts. The event rates estimated range from a few hundred to a thousand per year over the whole sky, depending on the ratio of "choked" to "bursting" fireballs. The northern hemisphere bursts would be detectable by IceCube.

### *3.3. Neutrinos as a Diagnostic of TeV Gamma-Ray Sources*

The question whether the intriguing sources of TeV $\gamma$-rays such as Markarian 421, 501 are cosmic accelerators has not been answered. Although their emission may be a signature of neutral pion decay, the high energy photons can also be produced by radiative processes from accelerated electrons. Only neutrinos can present us with incontrovertible evidence of proton acceleration. In general, high-energy neutrino astronomy has the potential to discriminate between hadronic and electromagnetic origin of the TeV emission from objects as diverse as supernova remnants, gamma-ray bursts and active galactic nuclei. With this capability, neutrino telescopes may resolve the oldest puzzle in high energy astrophysics — the origin of cosmic rays — by unambiguously identifying the acceleration to high energy of protons in the source.

As was done for the cosmic ray flux in the previous section, we can use the measured TeV photon fluxes to determine the scale of a neutrino telescope that is needed. If observed TeV photons from a particular source or class of sources are the decay products of neutral pions, one can estimate the accompanying flux of neutrinos in a largely model-independent way by assuming the production of 2 charged pions for every neutral one which decays into two photons.

Like our previous estimate using cosmic rays, also this one is subject to ambiguity when quantitatively deriving event rates. For instance, TeV photons can be the decay products of $\pi^0$'s produced by accelerated protons in either $pp$ or $p\gamma$ interactions depending on the relative target density of photons and protons in the source region where protons are accelerated[30)]. The muon neutrino flux $(dN_{\nu_\mu+\bar{\nu}_\mu}/dE_\nu)$ produced by the decay of charged pions in the source can be derived from the observed gamma ray flux by imposing energy conservation:

$$\int_{E_{\gamma\min}}^{E_{\gamma\max}} E_\gamma \frac{dN_\gamma}{dE_\gamma} dE_\gamma = K \int_{E_{\nu\min}}^{E_{\nu\max}} E_\nu \frac{dN_\nu}{dE_\nu} dE_\nu \tag{2}$$

where $E_{\gamma\mathrm{min}}$ ($E_{\gamma\mathrm{max}}$) is the minimum (maximum) energy of the photons that have a hadronic origin. $E_{\nu\mathrm{min}}$ and $E_{\nu\mathrm{max}}$ are the corresponding minimum and maximum energy of the neutrinos. The proportionality constant $K = 1, 4$ depending on whether the $\pi^0$'s are of $pp$ or $p\gamma$ origin. Important parameters in relating the neutrino flux to the gamma ray flux are the maximum and minimum energies of the produced photons and neutrinos. They appear as limits on the integrals in Eq. (2). The maximum neutrino energy is fixed by the maximum energy of the accelerated protons ($E_p^{\mathrm{max}}$), and depends on whether the neutrino is produced in $pp$ or $p\gamma$ interactions.

Calculation of the minimum and maximum energy of the photons is not straightforward because high energy photons may cascade in the source, reprocessing their energy. As a result they emerge as lower energy photons. In other words, the spectral index of photons can be modified by cascading and can therefore be different from the one for neutrinos. We can finesse the complicated details of photon cascading by treating the slope of the photon spectrum as a parameter in the energy conservation relation (Eq. 2).

An addititional complication is that high energy photons are absorbed in the interstellar infrared radiation separating the source form the telescope. Because the amount of absorption depends on the distance to the source and on the poorly known infrared background[31)] we are simply going to use as $E_{\gamma\mathrm{max}}$ the maximum observed energy, keeping in mind that this assumption leads to an underestimate of the neutrino flux.

Following Ref. 32, and taking account of Lorentz boosting of the acceleration region where relevant, the results of this scaling exercise are summarized in Table 1. The normalization is based on the assumption that the photons with energies exceeding 1 TeV are from decay of neutral pions. Neutrino event rates are estimated from the Crab Nebula, the supernova remnant (SNR) Cassiopeia A, the SNR-like shell Sagittarius A East and from the active galaxies Mkn 421 and Mkn 501.

Inspection of Table 1 strongly suggests that elucidating the physics at the origin of TeV-photons requires a kilometer-scale neutrino detector. Obviously, the observed TeV gamma-rays may not be of hadronic origin — data mostly suggest that they are not. Then we are left with the scaling argument based on the highest energy cosmic rays. But Nature does accelerate particles to energies exceeding $10^8$ TeV, and, whatever the site, the arguments presented here are likely to be approximately valid.

## 4. Determining Neutrino Flavors: Neutrino-Induced Cascades

A kilometer-scale neutrino observatory, though optimized for detecting muon neutrinos of TeV to PeV energy, is also well-suited to study events of higher energy by

Table 1: $N_{\nu_\mu+\bar{\nu}_\mu}$ events per km$^2$ from the Crab, Cassiopeia A, Sagittarius A East and Mkn 421 in one year and from Mkn 501 during the 8 months of flaring activity in 1997. We are assuming $\alpha_\nu = 2$ for all sources except for Sgr A for which we take $\alpha_\nu = 2.1$. In the case of Mkn 421 we have used the observed flux with $E_\gamma^{\max} = 7$ TeV given by HEGRA[33]. $E_{\gamma \min}$ and $E_{\nu \min}$ are expressed in GeV. The expected event rate of atmospheric neutrinos (assuming Volkova's flux[34]) in a $1^\circ \times 1^\circ$ bin on the sky is also shown for the same period of time taking into account the nadir angle of the source[35]. The last row is the Poisson probability of observing a background of atmospheric neutrino events equal to the total signal.

| Source | Crab | Crab | Cas A | Cas A | Sgr A | Sgr A | Mkn 421 | Mkn 421 | Mkn 501 | Mkn 501 |
|---|---|---|---|---|---|---|---|---|---|---|
| $E_{\gamma \min}$ | 1 | $10^3$ | 1 | $10^3$ | 1 | $10^3$ | 1 | $10^3$ | 1 | $10^3$ |
| $E_{\nu \min}$ | 400 | 400 | 400 | 400 | 400 | 400 | $8 \cdot 10^6$ | $8 \cdot 10^6$ | $8 \cdot 10^6$ | $8 \cdot 10^6$ |
| $N_{\nu_\mu+\bar{\nu}_\mu}$ | 40 | 2 | 1.5 | 0.3 | 243 | 1.3 | 3.3 | 0.06 | 2.0 | 0.8 |
| $N^{\rm atm}_{\nu_\mu+\bar{\nu}_\mu}$ | 3.2 | 3.2 | 1.9 | 1.9 | 2.8 | 2.8 | 2.4 | 2.4 | 2.3 | 2.3 |
| Poisson | $4 \cdot 10^{-33}$ | 0.14 | 0.22 | 0.3 | $\sim 0$ | 0.17 | $1.8 \cdot 10^{-2}$ | 0.4 | 0.15 | 0.24 |
| 51.8 | 50.2 | 50.2 | | | | | | | | |

measuring the energy deposition of large cascades produced in or near the detector. Such cascades can be produced by catastrophic energy loss of neutrino-induced muons, by charged current interactions of $\nu_e$ or by interactions of $\nu_\tau$. Each flavor has its own signature, which will allow discrimination among them.

### *4.1. EeV Science: Energy Measurement is Critical*

The capability to measure energy allows one to attack a major scientific problem, the enigmatic super-GKZ radiation in the Universe. Speculations regarding its origin include heavy relics from the early Universe and topological defects which are remnant cosmic structures associated with phase transitions in grand unified gauge theories[36,37,38]. Interactions of ultra-high energy neutrinos with massive neutrinos in the galactic halo is also a possibility[39]. Such models predict a sizeable flux of neutrinos in a much higher range of energy than the neutrinos associated with the GRB and AGN models mentioned above. Detection of neutrinos produced in interactions leading to the GZK cutoff is also a possibility, although their level is relatively low.

Since the Earth becomes increasingly opaque to neutrinos with energy in the PeV range and higher, it is necessary to use events from horizontal and downward neutrinos. Fortunately, setting an energy threshold in the PeV energy region is high enough to be clear of atmospheric backgrounds. With a threshold in the PeV region, IceCube and similar instruments will be complementary to detectors such as Auger, OWL and RICE which have thresholds of 10 EeV and higher. The lower threshold means that comparable event rates may be possible even though its effective volume is much smaller.

We illustrate the point by comparing IceCube to OWL[40] for the following theorized sources of ultra-high energy neutrinos:

- generic topological defects with grand-unified mass scale $M_X$ of order $10^{15}$ GeV and a particle decay spectrum consistent with all present observational constraints[36],
- superheavy relics[37,38], which we normalize to the Z-burst scenario[39] where the observed cosmic rays with $\sim 10^{20}$ eV energy, and above, are locally produced by the interaction of super-energetic neutrinos with the cosmic neutrino background,
- neutrinos produced by superheavy relics which themselves decay into the highest energy cosmic rays[41], and
- the flux of neutrinos produced in the interactions of cosmic rays with the microwave background[42]. This flux, which originally inspired the concept of a kilometer-scale neutrino detector, is mostly shown for comparison.

In Table 2 we compare the event rates for IceCube with those for OWL calculated in Ref. 40. The conclusion is clear, while effective volume and area for OWL apparently exceed those of IceCube by many orders of magnitude, the events rates are comparable. This is a consequence of the duty cycle, reduced efficiency, and higher threshold of the OWL detector. Note that the primary mission of OWL is cosmic ray, not neutrino physics. An equally valid conclusion is that OWL can reach similar event rates to a dedicated neutrino detector.

Table 2: Comparison of neutrino event rates for three representative neutrino fluxes for OWL[40] and IceCube[43].

| | Volume | Eff. Area | Threshold |
|---|---|---|---|
| OWL | $10^{13}$ ton | $10^6$ km$^2$ | $3 \times 10^{19}$ eV |
| IceCube | $10^9$ ton | 1 km$^2$ | $10^{15}$ eV* |
| | | Events per Year | |
| | TD | $Z_{\mathrm{burst}}$ | $p\gamma_{2.7}$ |
| OWL $\nu_e$ | 16 | 9 | 5 |
| IceCube $\nu_\mu$ | 11 | 30 | 1.5 |

*actual threshold $\sim$100 GeV; requiring >1 PeV eliminates atmospheric $\nu$ background.

The observed events in IceCube are dominated by muon neutrinos interacting in the ice or atmosphere *above* the detector and near the horizon. Up-going neutrinos are suppressed by more than an order of magnitude; see Table 3. The zenith angle distribution of neutrinos associated with EeV signals forms a striking signature for their extremely high energy origin. For a detailed discussion, see Ref. 43

*4.2. Tau Neutrino Detection*

High energy tau neutrinos can be detected using the characteristic double-bang events in which the production and decay of a $\tau$ lepton can be identified[44]. It may also be possible to identify $\sim$PeV $\nu_\tau$ by a long, minimum-ionizing track that enters the detector and ends in a huge burst as the $\tau$ lepton decays to a final state with hadrons or an electron. The entering $\tau$, because of its large mass, would not emit bursts of radiation characteristic of a muon of similarly high energy. In what follows, however, we discuss only the "double-bang" signature, which gives a conservative estimate of possible rates.

In a charged current $\nu_\tau$ deep inelastic scattering (DIS) interaction with a nucleus, a $\tau$ lepton of energy $(1-y)E_{\nu_\tau}$ is produced as well as a hadronic shower of energy $yE_{\nu_\tau}$ which is initiated in the fragmentation of the nucleus. Here $y$ is the fraction of energy transferred to the hadronic vertex in the interaction. The $\tau$ lepton travels on average a distance $R_\tau$ along the medium before decaying, given by:

$$R_\tau = \frac{E_\tau}{m_\tau} ct_0 = \frac{(1-y)E_{\nu_\tau}}{m_\tau} ct_0 \tag{3}$$

where $E_\tau$ and $m_\tau$ are the energy and mass of the $\tau$ respectively and $t_0$ is its rest lifetime. In its decay it produces another $\nu_\tau$ and an electromagnetic or hadronic shower $\sim$ 82% of the times. Assuming a typical detector dimension $D$, there are several conditions that have to be fulfilled for the detection of a double-bang event induced by a $\nu_\tau$:

- The $\nu_\tau$ has to interact through a charged current DIS interaction producing a hadronic shower contained inside the instrumented volume of the detector ($\sim D^3$).
- The $\tau$ lepton must decay inside the detector through a channel that produces an electromagnetic or hadronic shower which again has to be contained inside the neutrino telescope.
- $R_\tau$ has to be large enough so that both showers are sufficiently separated from each other to be distinguished.
- Both showers have to be energetic enough to trigger the detector.

Using these criteria we have calculated the probability of detecting a double-bang event in a neutrino telescope of linear dimension $D = 1$ km using a simple one-dimensional Monte Carlo. We take the energy threshold for detecting showers to be $E_{\rm shower} \sim 1$ TeV and fix 250 m as the minimum distance the $\tau$ has to travel to distinguish the Cherenkov light from both showers. This number is mainly determined by the separation between PMT's which is 125 m. Our Monte Carlo accounts for the fluctuations in the fraction of energy transferred to the $\tau$ in the interaction, as well as for the fluctuations in its range. The result of the Monte Carlo is shown in Fig. 3 along with the probability of observing a $\nu_\mu$-induced muon. Differences from the analytic estimates[45)] are due to the fluctuations in range of the $\tau$ lepton included in the Monte Carlo.

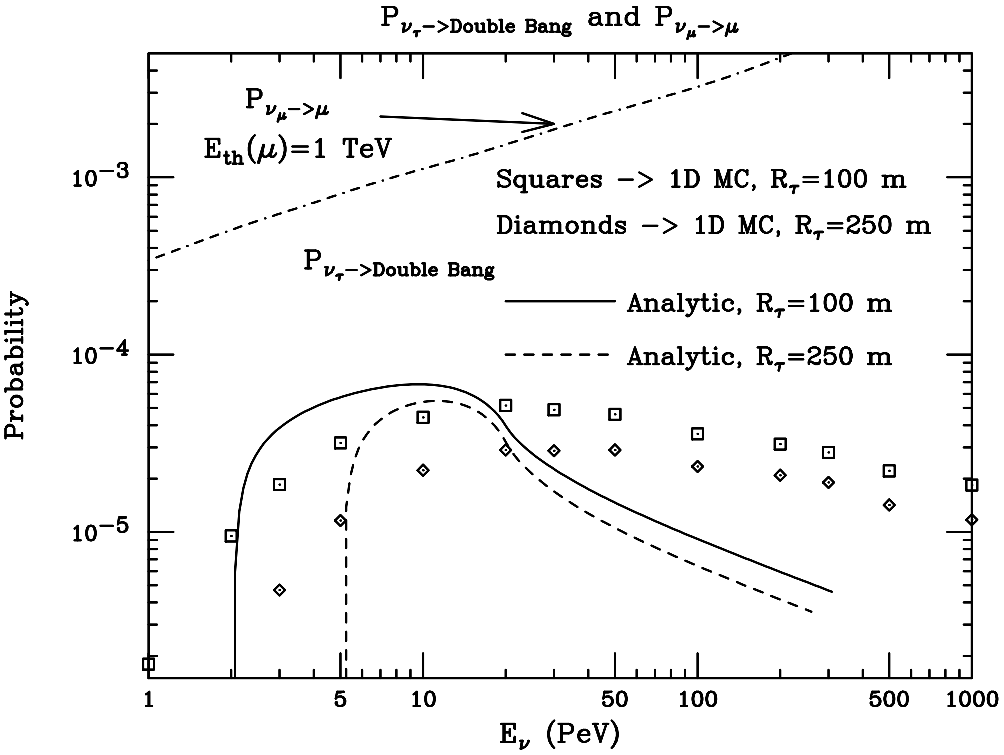



Figure 3: Probability of detecting $\nu_\tau$ induced double-bang events in IceCube or a similar km-scale detector, obtained with Monte Carlo simulation and using the analytic expression given by Athar et al.[45)]. The probability is shown for $R_\tau = 100$ m and 250 m. Also shown is the probability of detecting a $\nu_\mu$-induced muon.

We calculate the number of $\nu_\tau$ events in the standard way[30)], convoluting the probability of observing the double-bang events with the $\nu_\tau + \bar{\nu}_\tau$ flux:

$$N_{\text{events}} = A_{\text{eff}} \int \Phi_{\nu_\tau+\bar{\nu}_\tau}(E_{\nu_\tau}) P_{\nu_\tau \to \text{ double-bang}}(E_{\nu_\tau}) dE_{\nu_\tau} \tag{4}$$

where we will take $A_{\text{eff}} = 1$ km$^2$. $P_{\nu_\tau \to \text{ double-bang}}$ is the probability of observing a double-bang event as shown in Fig. 3.

By far the largest uncertainty in this expression is the $\nu_\tau + \bar{\nu}_\tau$ flux. $\nu_\tau$ production is expected to be very small in most astrophysical scenarios where $\nu$'s are produced in $pp$ or $p\gamma$ collisions. Several calculations suggest a ratio at production of[45)]:

$$F_{\nu_\tau/\nu_\mu} = \frac{\Phi(\nu_\tau + \bar{\nu}_\tau)}{\Phi(\nu_\mu + \bar{\nu}_\mu)} \sim 10^{-5} \tag{5}$$

Table 3: double-bang events per km$^2$ per year in $2\pi$ stereoradian for representative $\nu_\mu + \bar{\nu}_\mu$ fluxes in the literature assuming $F_{\nu_\tau/\nu_\mu} = 0.5$. Attenuation has been taken into account to calculate $\nu_\mu$ events but not for $\nu_\tau$ events. The GRB event rate takes into account fluctuations in distance, gamma factor and energy of the GRB's normalizing to 1000 GRB's/year. The TD's models correspond to maximal predictions of Fig. 2 in Ref. 36. The neutrino flux from the decay of Superheavy Relics is taken from Ref. 37.

| Flux | double-bang events | $\nu_\mu + \bar{\nu}_\mu$ (upgoing) events |
|---|---|---|
| $10^{-6}\ E^{-2}(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$ | 6 | 10,779 |
| GRB (Fluctuation model) | $\sim 1$ | 43 |
| TD, $M_X = 10^{14}$ GeV, $Q_0 = 6.31 \times 10^{-35}$, p=1 | $6 \times 10^{-2}$ | 12 |
| TD, $M_X = 10^{14}$ GeV, $Q_0 = 6.31 \times 10^{-35}$, p=2 | $1.5 \times 10^{-2}$ | 3 |
| TD, $M_X = 10^{15}$ GeV, $Q_0 = 1.77 \times 10^{-34}$, p=0 | 120 | 48,605 |
| TD, $M_X = 10^{15}$ GeV, $Q_0 = 1.58 \times 10^{-34}$, p=1 | $5.5 \times 10^{-2}$ | 9 |
| TD, $M_X = 10^{15}$ GeV, $Q_0 = 1.12 \times 10^{-34}$, p=2 | $1.1 \times 10^{-2}$ | 2 |
| Superheavy Relics $M_X = 10^{14}$ GeV | $3 \times 10^{-2}$ | $4 \times 10^{-4}$ |

Oscillation scenarios in which $\nu_\mu$'s convert themselves into $\nu_\tau$'s may be the most promising sources of $\nu_\tau$'s. In fact the detection of $\nu_\tau$ events in numbers which are not compatible with the expected astrophysical production may be indicative of such oscillations. In any case the non-observation of events may place limits on several oscillation scenarios. Making the rough assumption that $F_{\nu_\tau/\nu_\mu} = 0.5$ we obtain the number of events in Table 3 for representative $\nu_\mu + \bar{\nu}_\mu$ fluxes in the literature. In Fig. 4 we also show the energy distribution of the events. They all resemble the shape of the probability function of Fig. 3.

For more details and references, see J. Alvarez et al., Detection of Tau Neutrinos in IceCube, on http://pheno.physics.wisc.edu/icecube/ at IceCube publications.

## 5. Summary: The Reach of a Kilometer-Scale Neutrino Detector

With the identification of extraterrestrial sources of high energy neutrinos as the main goal, kilometer-scale neutrino detectors will have a considerable science reach. Using IceCube as an example:

- IceCube will reach a sensitivity for diffuse fluxes of a few $10^{-9}\cdot E^{-2}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is more than one order of magnitude below conservative "upper bounds" derived from cosmic ray observations, and three orders of magnitude below bounds derived from gamma ray observations alone. The published AMANDA limit has already improved previous experimental limits by more than a factor 10 and will be improved by IceCube by an additional 2.5 orders of magnitude. Within this range of sensitivity, models predict between "several" and thousands of events per year.

- Point source searches will reach a sensitivity of at least $10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ for energies greater than 1 TeV. This is nearly two orders of magnitude below

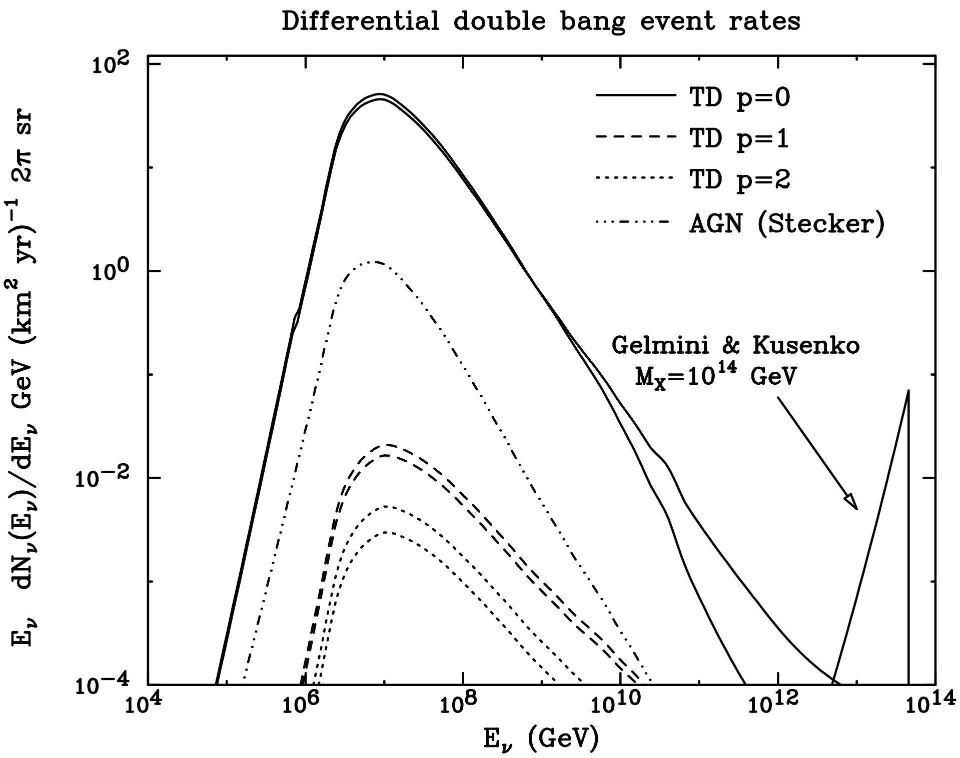



Figure 4: Differential $\nu_\tau$ induced double-bang event rates for different fluxes assuming $F_{\nu_\tau/\nu_\mu} = 0.5$. The upper lines at $10^7$ GeV for the Topological Defect models correspond to $M_X = 10^{14}$ GeV and the lower ones to $M_X = 10^{15}$ GeV.

the observed Mk501 flux during its flaring phase. Predictions for some steady or quasi-steady sources reach a few tens of events per year.

- Supernova models predict 10–100 events shortly before and after the SN burst.
- Gamma Ray Bursts are expected to yield 10–100 events per year.
- IceCube has also significant EeV capabilities. Event numbers predicted by top-down scenarios (like topological defects) lead to 1–30 events per year, comparable to expectations for dedicated EeV experiments.
- IceCube has a realistic chance to identify tau neutrinos via "double-bang" events, with up to 100 events per year expected for certain topological defect models.

IceCube is a multi-purpose detector. In addition to high energy neutrino astronomy, it can be used to investigate a series of other questions:

- Magnetic monopoles: Present limits for the flux of relativistic monopoles can be improved by two orders of magnitude. This is a factor of 1000 below the

Parker limit. One also can search for slow monopoles catalyzing proton decay, or for strange quark matter.

- Neutrinos from WIMP annihilation: IceCube can play a complementary role to future direct detection experiments, particularly for high WIMP masses. The instrument is unique for TeV dark matter.

- MeV neutrinos from supernova bursts: IceCube will detect a supernova burst over the whole Galaxy, and as far as the Magellanic clouds.

- As a by-product, neutrino oscillations, physics (and gamma ray astronomy) with downward muons, or even questions of glaciology can be investigated.

However, being a detector a hundred times larger than Amanda and a thousand times larger than underground detectors, IceCube will hopefully keep the promise for any detector opening a new window to the Universe: to detect phenomena *not* mentioned in the list above.

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