ASTROPARTICLE PHYSICS WITH HIGH ENERGY NEUTRINOS

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ABSTRACT

Interest in cosmic sources of high energy neutrinos dates back to the late 1950’s. This paper outlines the interdisciplinary scientific agenda, which span the fields of astronomy, particle physics, and cosmic ray physics. While the general detection principles based on optical Cherenkov radiation have been understood for many years, the unusual geographic locations of suitable detector sites have challenged the ingenuity of experimentalists. Two high energy neutrino programs are now operating (NT200 in Lake Baikal and the AMANDA detector), with the expectation of ushering in the era of multi-messenger astronomy. Two Mediterranean-based programs have made impressive progress. These detectors are optimized to detect neutrinos with energies of the order of 1-10 TeV, although they are capable of detecting neutrinos over a much broader range of energies. For $E_\nu > 10^{15}$ eV, several new ideas are being exploited to expand the effective volume of the detector. These techniques are based on the detection of neutrino-initiated cascades. We describe the ongoing worldwide efforts to develop expandable techniques and offer an assessment of their relative capabilities.

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Fig. 1. Relevant energy scales for various cosmic messengers. Due to the weak interaction strength, the neutrino can propagate throughout the Universe without attenuation. The diffuse infrared background attenuates photons with energies above 10 TeV. Cosmic rays point back to the sources if they have sufficiently high energy, but interactions with the cosmic microwave background photons limit the propagation length to less than 50 Mpc.

1 Introduction

The Universe is opaque to photons above several tens of TeV, so information must be carried by different messengers. Soon after the discovery of the neutrino in the 1950’s, Reines, Greisen, Markov and others immediately recognized the tremendous potential of the neutrino messenger for astronomy. At high energies, only neutrinos can directly convey astrophysical information from the most distant reaches of the Universe (Fig. 1) or from deep inside the most breathtakingly powerful regions of the sky we know.

Neutrinos provide a unique view of how nature accelerates particles. In particular, they clarify the role of strongly interacting particles in the astrophysical milieu. Once produced, neutrinos are unaffected by intervening matter or photons. Being uncharged, they propagate through the universe undisturbed by magnetic fields. The neutrino messenger may provide the only clear route to the sources of extremely energetic cosmic rays. The great versatility of the neutrino messenger is revealed by the richness of the science goals proposed for neutrino astronomy, which span the fields of cosmology, particle physics, and astrophysics. At the highest energies yet measured, neutrinos may be the only experimental probe of the critical physics mechanisms affecting the
Approximately fifty years after the neutrino was first suggested as a powerful new messenger, detectors in Lake Baikal and the South Pole were commissioned to provide the first exploratory views of the neutrino sky at $\sim$ TeV energies. Their success, and the rapid progress by similar efforts in the Mediterranean, suggest that high energy neutrino telescopes are ready to inaugurate the field of multi-messenger astronomy. This paper attempts to summarize the science motivation and experimental progress achieved thus far, and to describe various ideas on how to improve the sensitivity of neutrino detection. The highest energy frontier holds great promise for dramatic advances.

Theorists have identified a variety of potential sites of high energy (HE) neutrino production, and several extensive reviews of this topic have appeared recently in the literature.\textsuperscript{2-4} For example, Protheroe has summarized the astrophysical predictions of diffuse neutrino intensities between 1 TeV and the GUT scale. During the mid-1980s, theoretical work concentrated on galactic sources such as X-ray binaries or pulsars. This work was inspired by encouraging reports from underground muon detectors and air shower arrays sensitive to $\sim$PeV gamma rays. Unfortunately, more sensitive devices did not confirm those observations, and consequently, the early optimism has faded. However, the field of extra-galactic gamma ray astronomy has rapidly grown during the past decade. Recently, Gamma Ray Bursts (GRBs) have occupied the theoretical spotlight with the discovery that they are distant extragalactic phenomena and therefore the most energetic transient phenomenon observed in the Universe. On time scales of 0.1 - 100 seconds, these bursts can release of order $10^{52}$ ergs at x-ray/soft gamma-ray wavelengths. Waxman and Bahcall\textsuperscript{5} have argued that GRBs are the sources of the extremely high energy (EHE: for the purposes of this lecture, the EHE regime occurs at particle energies in excess of $10^{18}$ eV) cosmic rays and prodigious sources of high energy neutrinos. The predicted flux is tied to the measured power density of EHE cosmic rays, which also has been used to constrain the neutrino flux in proton blazar models of AGN.\textsuperscript{6} Though this procedure is still generating significant debate,\textsuperscript{7,8} there is no doubt that models should not over-produce cosmic rays.

Just as multi-wavelength studies have provided unparalleled insight on many astronomical sources, multi-messenger studies by neutrino, gamma ray, and gravity wave detectors may be the Rosetta stone of cosmic accelerators. For example, the AMANDA neutrino facility, located at the South Pole, contemporaneously observes the same sky as new, powerful gamma ray telescopes in the northern hemisphere. Coincidence experiments can also be contemplated with space-based gamma ray observatories and gravi-
tational wave detectors such as LIGO or VIRGO. At the very highest energies, charged cosmic rays are expected to deviate only slightly from line-of-sight trajectories. Should the HiRes and Auger Observatories identify sources of extremely energetic particles, then concurrent observations by neutrino telescopes can provide additional information on the local environment of the accelerator.

Due to the interdisciplinary nature of this field, it is not practical to fully review all related science issues, so no attempt is made to cover low energy neutrino phenomena and those detectors which address these issues (e.g. MACRO, Soudan-II). A large water Cherenkov experiment called SuperKamiokande has provided wonderful results on low energy neutrino physics. It was the subject of several speakers at this school and will not be discussed in great detail here. Also, this paper will not discuss recent ideas to use large arrays of photomultiplier tubes in long baseline oscillation experiments. Out of necessity, we provide a rather incomplete summary of cosmic ray physics and only outline recent advances in our understanding of dark matter, but fortunately, several excellent reviews have recently appeared in the literature.\textsuperscript{9,10} Finally, the reader will notice that the discussion is biased toward the AMANDA detector, since the author is most familiar with the strengths and weaknesses of this program. In any case, in this short lecture series, it is impossible to provide a satisfactory account of the remarkable achievements by the current generation of the HE neutrino projects.

2 Science Overview

With very few exceptions, the majority of models of particle acceleration predict that the flux decreases with energy. Currently known technologies for neutrino detection cannot fully compensate for this expected dependence on energy. In addition, the Earth attenuates the flux of neutrinos with energies above \( \sim 10^{15} \) eV (or 1 PeV), which mitigates the substantial advantages of using the muon mode of neutrino detection. This leads to a strategy to develop experimental techniques best suited for neutrino energies between 1 TeV and 1 PeV. At these energies, neutrinos act as surrogate messengers for the extremely energetic, but far rarer, cosmic rays. Recently, the potential of neutrino telescopes to observe \( \nu_\mu \) at energies \( \sim 10^{18} \) (\( > 1 \) EeV) has been emphasized.\textsuperscript{11,12} At these energies, background from cosmic ray muons is not significant. The authors argue that it may be possible to extract signal events from the enormous flux of lower energy background particles.
Fig. 2. Neutrinos can be detected over an enormous interval of energies, spanning many orders of magnitude. However, if the energy distribution obeys an inverse power law, as expected from shock acceleration mechanisms, then the technology must change to compensate for the decreasing flux. We illustrate the techniques that have been implemented or suggested by sketching the effective volume of the technology as a function of the neutrino energy. Water and ice Cherenkov techniques dominate the lower energies, but cascade and shower techniques become more attractive at extreme energies. The signal to noise ratio for cascade events is significantly improved by the relatively localized deposition of macroscopic quantities of energy. Consequently, much sparser and cheaper systems can be used to detect these events.
2.1 Astrophysical Sources

The primary motivation to construct very large neutrino telescopes is driven by the dream to identify galactic or extragalactic sources, which may be point-like or diffuse. The high energy frontier holds the most promise to achieve this scientific priority. The atmospheric neutrino and muon backgrounds decrease with energy, the effective area of the detector increases with energy, and angular resolution is likely to improve with energy. Detection of diffuse sources requires good energy resolution with well understood tails, but only marginal angular resolution.

Theoretical activity has centered on modeling two classes of objects: galaxies with active nuclei, or AGN, and gamma ray bursts (GRBs). These objects are known to emit high energy photons, and may also be the accelerators of the highest energy cosmic rays. At TeV energies, the luminosities of some AGN are observed to flare by an order of magnitude in about a day, suggesting very compact central engines. Models of the acceleration mechanism within AGN differ ingeniously. The intensity of neutrino emission ranges from negligible in models that rely solely on electron acceleration to detectable in the most optimistic models based on hadron acceleration. Neutrino observatories are likely to play a key role in settling the debate.

If hadronic acceleration is present in AGN, then a diffuse glow of neutrino emission should be observed uniformly over the sky, originating from distant (and more powerful) AGN. Fig. 3 shows the energy spectrum for a representative sample of neutrino models.

Figure 4, taken from Protheroe,\textsuperscript{3} converts the neutrino intensity predictions into an event rate for a detector with an effective area of 0.1 km\textsuperscript{2}. The calculations include absorption by the Earth, which becomes important for energies $\geq 100$ TeV (Ref. 2). Several models predict more optimistic rates shown in Fig. 4. For example, quasar core models\textsuperscript{16} predict 340 events per year which could be observed by AMANDA-II, but this rate violates the Waxman-Bahcall limit. As Fig. 3 shows, present experimental limits from Frejus,\textsuperscript{25} Baikal NT-200 (Ref. 107), and AMANDA\textsuperscript{20} rule out one of the earliest models for neutrino emission from the core of AGN, and they are beginning to constrain other core models for AGN.

Diffuse sources can be distinguished from the atmospheric neutrino background by a flattening energy spectrum above $\sim 100$–1000 TeV. Some models can be differentiated by their cutoff at the highest energies and spectral shape. The lower energy atmospheric neutrino background can be eliminated by energy-dependent selection cri-
Fig. 3. Figure adapted from Learned and Mannheim. Representative survey of models predicting $\nu_\mu + \bar{\nu}_\mu$ emission from sources diffusely distributed in the sky. The fluxes of $\nu_e + \bar{\nu}_e$ are similar in most models. In the absence of neutrino oscillations, $\nu_\tau$ are highly suppressed. The atmospheric neutrino fluxes are from Agrawal et al., for both vertical (lower boundary) and horizontal (upper boundary) fluxes. The curves include prompt neutrinos from charm production, but this contribution is not well known at the higher energies. Numbered lines: (1) Model of Nellen et al. for the core emission from 3C273 due to p+p interactions; (2) model for p+$\gamma$ interactions in the core of AGN; (3) model for p+$\gamma$ interactions in extragalactic sources; (4) representative model for blazar jets according to Mannheim et al.; (5) model of neutrino production by GZK mechanism; (6) low energy extension of blazar jet model due to p+p interactions in host galaxies of blazar jets; (7) GRB model by Waxman and Bahcall; (8) representative prediction of a class of topological defect (TD) models. Experimental limits: The energy bounds on the AMANDA-B10 limit are restricted to the approximate region of sensitivity of the detector for an assumed spectrum of $E^{-2}$. Fly’s Eye limit from upward going events. Radio Cherenkov techniques were applied to obtained the RICE limit. Dotted curves are expected sensitivity from operating and planned detectors assuming several years of operation.
teria only if the non-gaussian tails of the energy response function are understood with excellent precision. It remains to be seen if the muon response function can be determined with sufficient precision. The “observed” energy corresponds to the local muon energy, not the energy at the interaction point which may be kilometers distant from the center of the detector, nor the energy of the neutrino. Muons with energy above several TeV will radiate a few bursts per kilometer which deposit $\sim 10\%$ of the energy. The highly stochastic nature of the energy deposition may be a useful signature in water detectors, but it is mitigated by scattering in ice detectors. Fortunately, energy information gathered by HE neutrino telescopes does not need to be extremely precise. As the representative models in Fig. 4 show, there is little reduction in signal until the energy threshold exceeds 10-100 TeV.

At the most extreme energies shown in Fig. 3, EHE neutrinos are produced with near certainty by interactions between the ultra-high energy cosmic rays (UHECR) and microwave photons. The flux predictions vary by an order of magnitude, depending on somewhat uncertain assumptions related to the cosmologic evolution of sources of UHECR production and the assumed extrapolation of the charged-current (CC) cross section. The most optimistic predictions may be testable by the current generation of HE neutrino detectors such as AMANDA-II. The absence of signal can be used to constrain the neutrino cross section, which can approach strong interaction cross sections in some models.

More speculative mechanisms of EHE neutrino production include topological defects created during grand unified phase transitions or superheavy relic particles. The decay spectrum of topological defects is consistent with all present observational constraints. The decay of superheavy relic particles (SHP) has been a subject of intense activity. The flux of SHPs can be normalized under the Z-burst scenario, where the observed trans-GZK events are produced locally by the interaction of ultra high energy relic neutrinos with the cosmic neutrino background radiation. In other models, SHPs decay directly to EHE neutrinos.

The observation of EHE cosmic rays or neutrinos may be the most straightforward path to verify these remnant phenomena. Therefore, the search for EHE neutrinos provides a beautiful example of how HE neutrino telescopes can be used to probe the structure and physics of the early Universe, and perhaps the best opportunity for discovery with the potential to alter our “world view”. Since neutrinos do not penetrate the Earth, neutrino observatories must rely on specialized signatures induced by downgoing neutrinos in the atmosphere or limited column density above the buried detectors.
This topic will be covered in the “Detection Modes” chapter.

A few caveats should be kept in mind when interpreting figures of differential diffuse flux. (1) The only “background” shown in Fig. 4 is due to upgoing atmospheric neutrinos, but the rejection of down-going atmospheric muons represents a non-trivial hurdle that must be surmounted. Since atmospheric muons completely dominate the neutrino-induced muons in the down-going direction, the atmospheric neutrino background is only relevant for $2\pi$ steradians of the upgoing hemisphere. (2) Point sources can be located to within a small fraction of a steradian, and the atmospheric neutrino background decreases accordingly. Signal significance increases as $\sim \sqrt{\Delta A_{\text{eff}} / \delta(\theta)}$, where $\delta(\theta)$ is the angular extent of the source (or if considering a point source, proportional to the angular resolution of the detector) and $\Delta A_{\text{eff}}$ is the relative increase in effective area due to the relaxed rejection criteria. (3) Correlated photon observations of GRBs by BATSE provide a special opportunity. Events rates are determined by inte-
grating over all GRB events, and predicted to be $\sim 50$/year. However, the background livetime is only integrated over the duration of the bursts, which is $\sim 10^{-5}$ years. In addition, the search for neutrino emission from GRBs is greatly simplified by the contemporaneous direction measurements by satellites. Assuming a directional accuracy of 6 degrees, the background is reduced by a factor $d\Omega/(2\pi) = 5 \times 10^{-3}$. Combining directional and temporal information leads to a background reduction of $\sim 5 \times 10^{-8}$ relative to a search for steady diffuse sources. The relaxed rejection criteria increases the effective area of the detector. The increase in effective area is constrained primarily by the requirement to maintain sufficient angular resolution. Alternatively, by raising the energy threshold of the events, angular correlation may not be necessary to reduce the background to manageable levels. It is apparent that searches for transient phenomena enjoy many experimental advantages due to the reduced background (and consequent improvement in sensitivity).

2.1.1 Physics at the Extreme

The origin of the cosmic rays remains one of the most enduring mysteries in astrophysics. It is generally believed that the sources of the highest energy cosmic rays are extragalactic, or at the very least, not confined to the plane of the galaxy due to the isotropic distribution of the detected events. There is some evidence that a new component becomes important at energies above $E > 10^{18}$ eV, primarily the hardening of the spectrum and changes in the average depth of shower maximum. The energy at which the extragalactic component dominates the cosmic ray spectra is critical to the calculation of the total power required by a putative class of sources.

Many “beam dump” models of neutrino production postulate hadronic acceleration to very high energies. A survey of energetic objects reveals several classes (e.g. AGN, quasars, GRBs) of sources that supply the necessary power to create the highest energy cosmic rays. Several calculations assume a transition energy of $\sim 3 \times 10^{18}$ eV and normalize the extragalactic component at an energy that is relatively well measured. However, the uncertainty in value for the transition energy may be an order of magnitude or more. Equally, important is the extrapolation to lower energies where galactic contributions dominate. Even if the extragalactic fluxes are smaller than galactic fluxes, most of the energy content is at lower energies if the spectral index, $\Gamma$, is larger than 2.0 (for simple power law approximation, $dN/dE \sim E^{-\Gamma}$). Recent measurements of cosmic particles that exceed $10^{20}$ eV, the so called trans-GZK events, require relatively
nearby sources. These too may contribute power at lower energies, and therefore must be subtracted from the measured cosmic ray spectrum.

We present a simple argument based on energetics to set the scale for event rates from putative neutrino sources (which follows the treatment of Ref. 50). It is generally assumed that the sources of the highest energy cosmic rays generate an $E^{-2}$ differential spectrum, as predicted (approximately) by shock acceleration models. Normalizing the total integrated energy density for a steeply falling energy spectrum is fraught with uncertainty, but several authors obtain $\rho_{EG} \sim 2 \times 10^{-19}$ erg/cm$^3$ using

$$\rho_E = \frac{4\pi}{c} \int E \phi(E) dE$$  \hspace{1cm} (1)

and $\phi(E) = dN/dE$. In the source region, the average energy density in cosmic rays is related to the average production rate per unit volume, $q(E)$, by

$$\rho_E = q(E) \times \tau_{esc}(E) = q(E) \times \tau_{diff}(E) = q(E) \times \tau_H,$$  \hspace{1cm} (2)

where $\tau_{esc}(E)$ is the time spent in the accelerating region, which we replace with the Hubble time, $\tau_H$ in this estimate. Assuming a cosmological distribution of sources, Eqn. 2 leads to an estimate of $q_{EG} \sim 10^{37}$ erg/Mpc$^3$/s. Several classes of extragalactic sources satisfy this numerical relationship. For example, the density of active galaxies is $\sim 10^{-7}$/Mpc$^3$ and the typical emitted power is $10^{44}$ erg/s. Gamma ray bursts flash at a rate of 1000 per year. If the average energy per burst is $3 \times 10^{52}$ ergs, then GRBs become suitable candidate sources of EHE cosmic rays. In terms of energetics, both GRBs and AGNs are plausible sources of EHE cosmic rays if they accelerate particles to sufficiently high energies, which also is plausible.

The result for $q_{EG}$ assumes that the extragalactic spectrum includes particles with energies down to $\sim 1$ GeV and is exponentially cut off at energies above $5 \times 10^{19}$ eV (to allow for yet another source of trans-GZK events). The injected power density can be estimated by assuming that the extragalactic cosmic rays diffuse through the Universe with a diffusion time scale comparable to the Hubble time, $\tau_H \sim 10^{10}$ years. The diffusion velocity is assumed to be close to the speed of light. This assumption neglects evolution at large redshift and possible effects due to intergalactic magnetic fields (so particles can travel as much as one Hubble distance in the age of the Universe). The possibility of large intergalactic magnetic fields and local concentration of sources has been considered in more thorough treatments of this issue.

The connection between EHE cosmic rays and neutrino fluxes is given by

$$q_\nu(E) = f \times q_{EG}(E) = f \times 30 \text{ events/km}^2/\text{yr},$$  \hspace{1cm} (3)
where $f$ is the efficiency for neutrino production in cosmic ray interactions either within the source or intergalactic medium. The last expression was generated by assuming that the spectral index is 2.0 for both the neutrino and cosmic ray energy spectrum. The Waxman-Bahcall upper bound,\(^6\) which applies to sources that are transparent to neutrons, is obtained by setting $f = 1$. If evolution is included, the estimate produced in Eqn. 3 may be increased by a factor of five if the cosmic ray sources evolve in the same way as star formation. The bound is weakened because photoproduction and pair production attenuate ultra-high energy protons from large redshift, but neutrinos propagate without attenuation.

The trans-GZK events motivated Weiler\(^{31}\) to propose a new mechanism for cosmic ray production. If there was an abundant source of ultra high energy neutrinos from the early universe, they would annihilate with relic neutrinos to produce high energy cosmic rays locally. The absorption cross section at the $Z$ resonance is very large, so the event rates can be made consistent with observation. The required energy to produce the resonant interaction is greatly reduced if the relic neutrinos have mass, as suggested by recent atmospheric and solar data,

$$E^R_\nu = M_Z^2/2m_\nu = 4 \times 10^{21} \text{ (eV}/m_\nu) \text{ eV}.$$  \hspace{1cm} (4)

Neutrinos with the requisite energy are thought to be produced in the early universe. If they annihilate within the GZK cutoff distance of 50 Mpc to produce a $Z$-boson, then the decay products ($\sim 30 \gamma$, 3 nucleons, 28 $e^+e^-$ pairs, and 80 $\nu$) can propagate to the Earth. The rate of “$Z$-bursts” may be enhanced by local accumulation of relic neutrinos, but phase space constraints set an upper bound. Of course, the source of the high flux of neutrinos is unknown. To explain the trans-GZK events, the flux of $\nu$ at the resonant energy must be approximately the same as the GZK flux at $10^{20}$ eV, a rather discomforting requirement. Nevertheless, using only standard model physics, the Weiler process simultaneously solves the GZK mystery and provides the first observation of relic neutrinos.

Horizontal air shower techniques can be employed to explore the neutrino sky at extremely high energies.\(^{37}\) Conceivably, with $\sim 10$ km\(^3\) of water equivalent target volume for $E_\nu > 10^{19}$ eV, the Auger air shower array will have the sensitivity to search for neutrinos from cosmic ray interactions with the cosmic microwave background and more speculative signals from topological defects.
2.2 Point Sources

The term “point sources” refers to those objects that have sufficient intensity to generate a statistically significant enhancement of $\nu_\mu$-induced muon events from the same direction in the sky. The angular direction of the muon can be measured with 0.5 – 3.0 degree precision (depending on the detector architecture, muon energy at the detector, and propagation parameters). The angular correlation between the neutrino and the outgoing lepton produced in charge current interaction is similar to the experimental precision ($\delta \theta \sim 1.5/\sqrt{E_\nu}$, where $\theta$ is in degrees, and $E_\nu$ has units of TeV). In this section, we describe the theoretical motivation for both galactic and extragalactic sources of point emission. Obviously, such a survey cannot cover all of the interesting ideas in the literature.

The production mechanism for cosmic rays is not yet fully understood. Shocks from galactic supernova are widely believed to accelerate cosmic rays to $\sim 10^{15}$ eV, while the sources of cosmic rays at the most extreme energies are produced by accelerators outside our galaxy. Plausible models of particle acceleration exist for both galactic and extra-galactic sites, but supporting evidence is largely circumstantial. The observation of high-energy (HE) neutrinos from point sources would unequivocally confirm the hadronic nature of those accelerators. Once the basic mechanism is established, models can evolve quickly in detail and predictive power. Unfortunately, the neutrino flux from galactic and extra-galactic point sources, such as active galactic nuclei (AGN), is predicted to be very low, although the uncertainties in the model parameters lead to considerable variation in the flux predictions. An independent estimate of neutrino flux can be derived by naively scaling the observed gamma spectrum of sources of TeV photons (assuming that they are produced by hadronic interactions), but we caution that this scenario produces an optimistic value for the neutrino flux if proton synchrotron radiation is responsible for a sizeable fraction of the observed TeV photons.$^{38}$

It appears that supernova remnants (SNR) are one of the few classes of galactic sites that have the capability to supply the power to accelerate the galactic cosmic rays, but even these sites must convert the energy of the shock wave into relativistic particles with suspiciously high efficiency (10-30%). The diffusive shock mechanism naturally produces a power law spectrum of $dN/dE \sim E^{-2.1}$, which is consistent with the deduced spectral index of cosmic rays. [The measured spectral index is $E^{-2.7}$, but the local measurements must be corrected for nuclear interactions as cosmic rays propagate in the galaxy]. Recent observations of TeV gamma rays from plerions such as the Crab
Nebula and supernova remnants (e.g., SN1006) provide direct evidence for particle acceleration to TeV energies. However, these observations do not provide compelling evidence for hadronic acceleration due to an unfortunate ambiguity: it is possible (and even probable) that electrons are solely responsible for these observations. In particular, HE gamma rays from SNR may be generated by electrons accelerated by the SN shock. But if SNRs are the sources of cosmic rays, they must accelerate hadrons, and a class of models exploits this idea. They suggest that both protons and electrons are accelerated by the supernova shock. High energy photons are generated by proton collisions with ambient material in the accelerating region. Pions, both neutral and charged, are produced in the nuclear collisions, which in turn decay to HE gamma rays and neutrinos.

While the notion of particle acceleration by supernova shocks provides a credible and largely consistent picture, not all observations neatly fit this scheme. For example, the site(s) of cosmic ray acceleration are expected to generate significant fluxes of gamma rays via $\pi^0$ decay, but only one of the nearby SNR, SN1006, generates an observational flux of high energy photons. Moreover, the inferred energy spectrum for photons between GeV and TeV energies does not support an $E^{-2}$ distribution. For most of the SNR, upper limits by the Whipple collaboration imply a spectral break between MeV and TeV energies, which is not expected if they were the sites of galactic cosmic rays. This moderately disconcerting state-of-affairs has motivated at least one author to suggest that most cosmic rays originate from extragalactic sources. The close connection between neutrino production and hadron acceleration reduces some of the speculative uncertainty associated with the information provided by the study of sources of high energy gamma rays. Alternative sites for cosmic ray acceleration may emerge from a detailed study of the neutrino sky.

Even though the cosmic ray puzzle provides powerful motivation to explore the sky for neutrino emission, not all sources of high energy neutrinos need to contribute to the cosmic ray flux. In particular, a powerful galactic accelerator may be surrounded by too much material to emit high energy photons or cosmic rays (they would interact and cascade down to lower energies), but the high energy nature of this accelerator could be discovered by exploiting the neutrino messenger. For example, a one solar mass black hole accreting at the Eddington limit releases $\sim 10^{38}$ ergs. If 10% of this energy is converted into neutrino emission with an $E^{-2}$ spectrum, a source at a distance of 10 kpc would produce of order 1 neutrino event per year in AMANDA-B10. A more massive black hole in the galactic center could conceivably produce a much bigger signal, but this galactic location is not visible to neutrino telescopes in the southern
hemi-
sphere.

Turning to extra-galactic sources, active galactic nuclei (AGNs) are among the most luminous objects in the Universe and promising sources of neutrinos. Present models construct a central engine that consists of a supermassive black hole surrounded by an accretion disk. In these models, high energy neutrino fluxes are generated near the central engine or in the jets of radio-loud AGNs (e.g., Blazars, a class of objects where the jet intersects the line of sight of the observer). Neutrino energies may extend to $\sim 10^{10}$ GeV. The fact that gamma ray emission has been detected from nearby blazars Markarian 421 and 501 provides strong evidence for particle acceleration to high energies. The time averaged energy spectrum from Mk501 during 1997 is consistent with an unbroken power law up to 20 TeV. In general, high-energy photons at TeV scales may interact with material or photon fields in the source, or interact with the diffuse infrared background photons during their flight, losing energy by the mechanism $\gamma + \gamma \rightarrow e^+ + e^-$. Due to this reprocessing, the measured photon energy spectrum may not trace the energy spectrum of the source. Recent measurements of the diffuse infrared background are much larger than theoretically expected. Consequently, the attenuation length for photons in excess of 10 TeV is much shorter than the distance to Mk501. After correction for absorption by the infrared background, the energy spectrum at the source rises dramatically above 10 TeV. If the energy spectrum of neutrinos is similar in shape, then relatively modest sized detectors such as AMANDA-B10 and NT-200 possess sufficient sensitivity to test this assumption.

Recently, it has been argued that the rapid time variability of the high energy photon emission from AGN Blazars and the correlated variation between X-ray and TeV regimes disfavors hadronic acceleration models for this particular class of objects, but others have shown that rapid and correlated variability can be accommodated by modest extensions to the existing hadronic acceleration models. At least one model for blazar emission can produce comparable fluxes for $\nu$ and $\gamma$. High energy photons and neutrinos are produced by the decay of pions. The pions are generated during the collision between clouds of gas with relativistic velocities and the interstellar medium of the host galaxy near the central engine of the AGN. In any case, the vigorous debate suggests that high energy neutrino detectors can play a central role in deciphering the acceleration mechanism, but the challenge is not easy. In general, the sensitivity of kilometer scale detectors should improve linearly with $A_{eff}$, but the energy response

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8 See the recent review by Catanese and Weekes for a complete list of detected VHE gamma-ray sources.
must improve commensurately to take full advantage of this capability. To illustrate the general difficulty, Fig. 5 (from Ref. 50) shows the differential signal of neutrino-induced muons from a source with \( \phi_\nu = \phi_\gamma \) where \( \phi_\gamma \) is the measured flux from Markarian 501 during a period of maximum intensity. For this particular source, the period of maximum intensity was about six months during the last 3 year interval, but it is always possible that this situation can change to more favorable conditions. Also shown is the steeply falling background from atmospheric neutrinos. The integral under the dotted curve gives a small, but measurable, rate of 30 events per year in a kilometer scale detector. However, the curves do not include the dispersion introduced by the convolution of the finite energy resolution. It is clear that non-gaussian tails on the energy response must be controlled with (perhaps unrealistically) high precision and this remains an open question. The signal events are assumed to be fully contained within a circular patch on the sky with a radius of 1 degree. This may be realistic for water detectors which expect to achieve angular resolution substantially better than 1 degree, but it is probably optimistic by a factor of a few for kilometer scale ice detectors for muon energies of 1 TeV.

Figure 6 provides a summary of model predictions for the flux of high energy neutrinos. It also contains the flux limit reported by the AMANDA collaboration for sky bins with declinations greater than 30 degrees. As mentioned, most theoretical models of potential astrophysical sources of neutrinos predict that the energy spectrum is very hard, approximately \( E^{-2} \). Due to the hard energy spectrum and the energy dependence of \( \sigma \), the cross section for the weak interaction, the range of the muon, and the effective area of the detector, the most probable energy of the detected neutrino is well above 1 TeV (typically 10–30 TeV for hard spectra).

### 2.3 Physics Potential

Obviously, the desire to understand the optical and physical properties of the local environment create many interdisciplinary opportunities. Underwater neutrino observatories provide the facilities to monitor the time variability of bioluminescence, temperature, salinity, water currents, biofouling, etc. The NESTOR collaboration has secured funding to deploy an optical cable from shore to the site off Pylos instrumented with sensors of interest to oceanographers and neutrino physicists. Multidisciplinary opportunities encourage interactions between seismologists and neutrino physicists to construct a large seismic array for tomographic studies of the Earth’s interior. The
Fig. 5. Differential signal of neutrino-induced muons from a source with $\phi_\nu = \phi_\gamma$, where $\phi_\gamma$ is set to the gamma flux from Markarian 501 that was observed during a period of maximum intensity. Detector resolution is not included. See text and Gaisser$^{50}$ for discussion.
Fig. 6. Survey of $\nu + \bar{\nu}$ flux predictions from cosmic accelerators of high energy neutrinos (adapted from the recent review by Learned and Mannheim\textsuperscript{4}). The atmospheric neutrino fluxes are from Agrawal \textit{et al.}\textsuperscript{13} for both vertical (1) and horizontal (2) fluxes within a circle defined by a half angle of 4 degrees (labeled “4 deg bin”). The curves do not include the normalization uncertainty, possibly 20% in magnitude. Numbered lines: (3) AMANDA-B10 limit reported here. (4) Model of Nellen, \textit{et al.}\textsuperscript{15} for the core emission from 3C273 due to pp interactions. It also represents neutrino emission from the AGN Blazar Mk501 during 1997 if it emits half of its TeV gamma ray flux in neutrinos. (5) Crab Nebula, Model I from Bednarek, \textit{et al.}\textsuperscript{52} (6) Coma cluster according to Cola, \textit{et al.}\textsuperscript{53} (7) Core emission from 3C273 due to p-$\gamma$ interactions\textsuperscript{16} (8) Model\textsuperscript{54} for the relativistic jet of 3C273 including p-p and p-$\gamma$ interactions. Supernova remnant gamma-Cygni (9) and IC 444 (10) according to Gaisser, \textit{et al.}\textsuperscript{55} The energy bounds on the AMANDA limit are restricted to the approximate region of sensitivity of the detector.
Baikal detector monitors the seasonal water exchange processes in this unique Siberian lake.57

In the next few subsections, we briefly comment on the potential of HE neutrino arrays to contribute to questions in particle physics.

2.3.1 GRB-related science

It is now known that most Gamma Ray Bursts occur at cosmological distances with redshift near unity58 (although different GRB scenarios do exist59). Evidence is accumulating that photon emission is produced by a relativistically expanding fireball.60 If particles are accelerated to ultrahigh energies, then HE neutrinos may be produced by the decay of pions generated in photonuclear interactions. The neutrinos from GRBs would arrive at the Earth in a burst coincident with the photons. Waxman and Bahcall5 point out that observations of HE neutrinos from GRBs can test special relativity and the weak equivalence principle with unmatched precision by measuring the time delay between photon and neutrino signals. It is conceivable that the neutrino mass can be extracted from the time delay between the photon and neutrino signals. Assuming photons travel at the speed of light, the time delay is given by:

\[
\Delta t \sim 10 \text{ ms} \left( \frac{E_{\nu}}{5 \text{ GeV}} \right)^{-2} \left( \frac{L}{\text{Gpc}} \right) \left( \frac{m_{\nu}}{1 \text{ eV}} \right),
\]

where \( L \) is the distance to the GRB. The duration time for HE neutrino emission is unknown, but models predict values of the order of ms. The time delay between GeV \( \nu \) emission and MeV \( \gamma \) emission is also not known. If the energy threshold of HE neutrino arrays can be reduced to \( \sim 5 \) GeV for tagged GRB events, and the \( \nu \) fluxes are large enough to produce signals, then the mass of the heaviest neutrino species can be determined with reasonable accuracy. At these energies, the detection probabilities and event topologies of all neutrino flavor interactions are similar, so the maximum time delay is related to the largest mass. GRBs offer the exciting possibility to study neutrino oscillation over cosmological baselines. As in any astrophysical environment which produces neutrinos from \( p + p \) or \( p + \gamma \) interactions, the direct production of \( \nu_\tau \) is expected61 to be \( \sim 10^{-5} \Phi(\nu_\mu) \). Scenarios which transform \( \nu_\mu \) into \( \nu_\tau \) provide a reasonable mechanism to dramatically boost the flux of \( \nu_\tau \) to a level comparable to the other neutrino flavors. Therefore, the appearance of \( \nu_\tau \) provides strong evidence for oscillation over baselines of a Gigaparsec or more.

Unfortunately, unambiguous detection of \( \nu_\tau \) is very difficult in HE neutrino detectors, as discussed in section 3.1.3. Several potential signatures have been proposed,
but all face rather long odds for success unless current HE $\nu$ detectors soon observe an astrophysical source. This is beautifully illustrated by Alvarez-Muniz, Halzen, and Hooper.\textsuperscript{12} They show that the probability to observe the Double Bang signature is very low; typically a few percent of the probability to detect $\nu_\mu$-induced muons with similar energies. Unless current generation detectors soon discover $\nu_\mu$ emission from GRBs, the limited effective volume for Double Bang events strongly disfavors their detection in kilometer scale arrays. Without adequate statistics, it will be difficult to use angular or energy dependent handles to confirm $\nu_\tau$ detection.

Halzen and Saltzberg\textsuperscript{62} have proposed another mechanism for $\nu_\tau$ detection, but the backgrounds are severe if a comparable flux of $\nu_\mu$ exist. They point out that the Earth is not opaque to $\nu_\tau$ at any energy because charged current and neutral current interactions produce a $\tau$ in the final state, which in turn decays back to a $\nu_\tau$ before losing a significant fraction of its energy. Eventually, the energy of the $\nu_\tau$ decreases to the point where the Earth is no longer opaque. The characteristic “transparency” energy is $\sim 1$ PeV, depending weakly on the column depth through the Earth. At these energies, the shower separation between the initial interaction and subsequent decay of the tau lepton is too short to be identified in HE neutrino arrays. However, a small excess (or pile-up) of events is expected at the transparency energy. The angular distribution of these events is somewhat flatter than expected from the other neutrino flavors. The Halzen-Saltzberg signature must be extracted from a background generated by charged current $\nu_\mu$ interactions. (Obviously, at the characteristic transparency energy, $\nu_\mu$ can propagate through the Earth without attenuation.) Since the detection probability for muons from $\nu_\tau$ decays below the detector is only 17% of the probability from $\nu_\mu$, due to the branching ratio of the $\tau$ to $\mu$ channel, the background rate is substantial. In the distant future, the slight difference between angular distributions of $\nu_\tau$- and $\nu_\mu$-induced muons may be exploited if the acquired statistics is very high.

Can $\nu_\tau$ from GRB be revealed by measuring cascade events? The superior energy resolution of the cascade mode may be sufficient to show the pile-up feature at the transparency energy. Unfortunately, the reconstructed angular resolution is poor, so the subtle difference in the angular distributions cannot be exploited. The background from NC interactions and $\nu_e$ CC interactions compounds the problem.
2.3.2 WIMP searches

Neutrinos may be emitted from the center of the Sun or Earth as a consequence of the annihilation of weakly-interacting cold dark matter particles (WIMPs) that accumulate at the centers of these objects. Galactic WIMPs, scattering off nuclei, lose energy and may become gravitationally trapped. One interesting class of WIMP candidates arise from minimal supersymmetric (SUSY) theory. Within this framework, Bergstrom et al. and recently, Feng, et al. have calculated the discovery potential for neutrino observatories and beautifully illustrate their power to complement other search methods. Apparently, the parameterized ignorance of SUSY models is too vast to be completely constrained by a single search technique. Bergstrom et al. have attacked this worrisome deficiency by combining the limits from cosmic ray antiproton instruments with the anticipated sensitivity of gamma ray satellites and neutrino observatories. A comprehensive search strategy for SUSY particles benefits enormously from the complementary information provided by neutrino telescopes. Combining astrophysical data from special purpose and multipurpose survey instruments creates an intriguing blueprint for future search strategies.

The AMANDA and Baikal collaborations restrict their atmospheric neutrino analysis to the nearly vertical direction to search for high energy neutrinos from the decay of weakly interacting massive particles (WIMPS) from the center of the Earth (see Fig. 7 for one example). The detectors are very efficient for $\cos(\theta_{\text{rec}}) < -0.9$. Therefore, the effective area is somewhat larger than achieved by the all sky measurement of atmospheric neutrinos. From the lack of excess of events in the nearly vertical angular bins, flux limits can be obtained. Figure 8 compares the AMANDA limits with existing limits for a broad class of supersymmetric models, illustrating the potential of the technique.

2.3.3 Relativistic Monopoles

A magnetic monopole with Dirac charge $g = (137/2)e$ emits Cherenkov radiation if its velocity exceeds $0.75c$ in water or ice. The particle would emit more photons than a single charged particle by a factor of $\sim 10^4$, and the linear variation in the photon emission rate is quite small compared to an equivalently bright muon. Figure 9 summarizes the current status of experimental limits. The AMANDA and Baikal limits were obtained by searching for upward going particles. A rather large lower limit on the mass of the monopole is required to have the requisite kinetic energy to traverse the
Fig. 7. **Left:** Angular distribution of the data (full line) and simulated atmospheric neutrino events (dashed line) after the application of strong selection criteria. The angular range is between 165 and 180 degrees. The atmospheric neutrino sample has been normalized to the live-time of the experiment. **Right:** Angular distribution of the fraction of simulated WIMP signal for the same selection criteria. The WIMP properties were assumed to produce hard neutrino spectra. Its mass was taken to be 250 GeV.

2.3.4 Supernova Detection

A transient burst of low energy neutrino emission from supernova explosions or Gamma Ray Bursts (GRBs) can be detected by AMANDA-II by summing the random noise signals from the photomultiplier tubes in the optical modules within the array. A supernova burst would manifest itself as a statistically significant increase in the summed signal due to the excess photons generated by the low energy neutrino interactions. Sensitivity to transient events is improved by embedding the array in an environment such as polar ice, where the random noise level is low because the internally generated noise of a photomultiplier tube is reduced at cold temperatures and the externally generated background light from radioactive impurities is negligible. The AMANDA collaboration agreed to join the Supernova Early Alert Network\(^{69}\) to confirm galactic supernovae and determine the direction by triangulation of the neutrino wavefront, which can precede the photon signal by several hours or more. The polar location of AMANDA simplifies the task of triangulation, but the angular resolution of elastically scattered electrons...
Fig. 8. Experimental limits from AMANDA, SuperK, MACRO, and Baksan. High energy neutrino flux predictions and experimental limits due to the annihilation of supersymmetric particles in the center of the Earth. See Bergstrom, et al. for explanation of symbols and corrections applied to normalize the various experimental limits to the same energy threshold. The AMANDA result does not include systematic error, which is expected to weaken the limit.
Fig. 9. Experimental flux limits (in units of cm$^{-2}$s$^{-1}$sr$^{-1}$) for relativistic monopoles. The AMANDA and Baikal results assume that the monopole is supermassive. The dashed line shows that limits may be extended below the velocity threshold for Cherenkov emission because sub-threshold monopoles will scatter high energy electrons (delta-rays) that will emit Cherenkov photons.
in the SuperKamiokande experiment\textsuperscript{70} may be superior. Future neutrino observatories could search for nearby extragalactic bursts by increasing the collection efficiency of the optical sensors (larger PMTs, use of wavelength shifters), implementing techniques to reduce the intrinsic noise, and increasing the number of sensors in the array beyond several tens of thousand.

The low rate of intrinsic noise generated by photomultiplier tubes in Antarctic ice is a unique feature of the AMANDA detector. It results from two effects. First, the concentration of radioactive contaminants in the ice is very low compared to sea-water. Second, thermionic emission from the photocathode is minimized due to the low ambient temperatures. AMANDA-II has sufficient sensitivity to see to the center of our galaxy,\textsuperscript{71} whereas IceCube is expected to extend the reach by a factor of 2.5 in distance to cover the most of galaxy. The rather modest improvement in sensitivity is a consequence of the $\sqrt{N_{OM}}$ scaling,\textsuperscript{72} where $N_{OM}$ is the number of optical modules in the array.

### 2.3.5 Neutrino Oscillation

The growing evidence for neutrino oscillation\textsuperscript{73} in the atmospheric neutrino data has triggered the neutrino telescope community to investigate the physics capabilities of their detectors for this particular science objective. The energy spectrum of atmospheric neutrinos (hashed box, figure taken from Protheroe’s review paper\textsuperscript{3}) is a steep power law, suggesting that the detected events will be predominantly medium energy and the rate will be influenced by the energy threshold. Therefore, using atmospheric neutrinos to search for neutrino oscillation requires energy thresholds of 5–20 GeV. Detectors, such as Baikal NT-200 and NESTOR, or the insertion of high density strings into the AMANDA-II array, are designed to achieve this goal.

Atmospheric neutrinos reveal oscillation physics in several ways. A deviation from the expected angular distribution would be strong evidence for oscillations. HE neutrino detectors can contribute to this science by virtue of their large detection area and consequent increase in statistical significance. Unfortunately, these are difficult measurements for neutrino arrays. For the simplest case of two oscillating neutrino species, the probability that a neutrino $\nu$ of flavor $i$ ($e, \mu, \tau$) will oscillate into a different flavor $x$ is given by

\[
P(\nu_i \rightarrow \nu_x) = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 \frac{L(\text{km})}{E_\nu(\text{GeV})}\right),
\]  

(6)
Fig. 10. Expected viewing distance for supernovae similar to SN1987a. For these calculations, the ambient noise rates and non-poissonian fluctuations are taken from measurements by the AMANDA collaboration. The colors correspond to arrays with $N_{OM} = 100, 1000, 5000$. 
where $\theta$ is the mixing angle, $\Delta m^2$ is the difference in mass squared in eV$^2$ of the two mass eigenstates, $L$ is the pathlength between generating vertex and detector, and $E_\nu$ is the energy of the neutrino.

Unless the neutrino-induced muon event is completely contained within the detector, the neutrino energy is not well measured. For the current generation of neutrino detectors, through-going upward muons are the most likely detection mode, but this only establishes a lower limit on the neutrino energy. Moreover, the energy threshold for muons which traverse the array is relatively high, so as $E_\nu$ increases, angular deviations become very subtle. For parameters of $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$ and maximal mixing, the angular and energy dependence of the detector area must be determined to 5% or better. It remains to be seen if this accuracy can be achieved in practice. Also $\nu_e$ events must be differentiated from $\nu_\mu$ events, which has yet to be shown conclusively.

A second idea takes advantage of the particular strengths of the existing neutrino arrays. The linear symmetry of string-based designs results in excellent sensitivity to nearly vertical tracks. The long lengths of instrumentation can contain neutrino-induced events over a large interval of energies. By concentrating on nearly vertical tracks, backgrounds are easier to reject. The small vertical spacing of optical sensors (compared to the horizontal spacing of the strings) reduce the energy threshold to interesting levels. The detection efficiency as a function of energy can be calculated more accurately than for the entire hemisphere. In addition, the AMANDA array can calibrate its vertical sensitivity with a well defined muon beam using coincidence events that simultaneously trigger another array at 900 meters. If the vertex is contained within the central part of the array, then the light from the interaction vertex and outgoing muon can be modeled to establish the energy of the neutrino with sufficient accuracy. Obviously, the event rates are much lower for a restricted solid angle, but the large detection area results in sufficient statistics. However, the same concern about being able to differentiate $\nu_e$ and $\nu_\mu$ events applies to this technique. For kilometer-scale detectors, a significant fraction of neutrino-induced atmospheric muons will be contained within the actively instrumented volume, so a calorimetric measurement of the neutrino energy is possible. However, the larger spacing between sensors results in higher energy thresholds which may be above the energies of interest. Medium energy physics objectives can be retained if the kilometer-scale array surrounds a first generation neutrino array. The composite detector can identify and reject atmospheric muons, reducing background rejection requirements in the denser central region of the composite array.

A third method to search for neutrino oscillation over long pathlengths (or base-
lines) utilize accelerators to direct a beam of $\nu_\mu$ particles with a known energy spectrum toward the detector.

Perhaps the best method to study $\nu_\mu$ oscillation parameters involves dedicated long baseline experiments with high intensity and well-characterized neutrino beams and large volume detectors placed at great distances. Long-baseline programs such as K2K and Minos are currently investigating oscillation parameters deduced by atmospheric neutrino studies. Next generation long baseline experiments are considering several energy ranges for neutrino beams. At large distances or at low energies, the meager event rates dictate both large intensity beams and large volume for the end detectors. It has been suggested that HE neutrino telescopes located at distances between 1000 and 10000 km could play a role. While most discussion has involved CERN and planned neutrino telescopes in the Mediterranean, the idea works the same for any accelerator and neutrino observatory as long as a neutrino beam can be pointed in the right direction. Even without flavor or charge sign ID, conventional wide band neutrino beams directed at HE neutrino telescopes could measure the sign and magnitude of $\Delta m_{13}^2$, and $\theta_{13}, \theta_{23}$.

Several new ideas for the end detector are under discussion with performance characteristics more suitable for long baseline physics than are available from HE neutrino arrays, such as low energy threshold, reliable discrimination between $\mu - e$, and charge sign identification of the lepton. The UNO detector extends the water Cherenkov technique, used in SuperKamiokande and other large nucleon decay experiments, to a very large fiducial mass. The initial design envisions a fiducial mass of $\sim 10^6$ tons, making it an attractive target for high-intensity neutrino beams from anywhere on Earth. Two scenarios for long-baseline physics are being explored. Using a beam from a 30–50 GeV muon storage ring (or “neutrino factory”) several thousand km away, hundreds of thousands of neutrino interactions would be recorded for each year of running. In addition to a very precise measurement of $\nu_\mu$ disappearance, wrong-sign muon appearance could be observed by placing large magnets between sub-segments of the detector to measure the charge of energetic muons. A difference in rate between $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ transitions would be clear evidence of CP violation in the leptonic sector. At the other end of the energy scale, a 100–500 MeV $\nu_\mu$ beam could be exploited to detect $\nu_e$ appearance with negligible background, apart from $\nu_e$ contamination present in the initial beam. The cross section for neutrino interactions at such energies is small, but the very large target mass of UNO would allow a measurable signal to be observed even 2000 km from the source. At that distance, the $\delta m^2$ region corresponding to the large-
mixing angle solution to the solar neutrino problem would be accessible. At shorter
distances, where matter effects in the Earth are unimportant, CP violation could also be
probed.

3 Detection Principles

The essential characteristics of a neutrino telescope have been known for more than
two decades. Markov suggested in 1960 that the ocean would be a suitable site for
constructing a large neutrino detector based on the detection of Cherenkov light, and
most important features were discussed and specified during a series of workshops de-

coted to developing the DUMAND concept. Halzen and Learned introduced a twist
on the general scheme by promoting polar ice as a suitable medium. Until recently,
workable implementations of these sensible ideas have been thwarted by unusual tech-
nical and logistical challenges associated with the remote deployment of hardware in
media that differ from ordinary purified water in several important details. All current
architectures for high energy neutrino facilities bury a sparse array of optical sensors
within deep ice, ocean or lake waters. The optical sensors respond to the UV dominated
Cherenkov radiation emitted by neutrino-induced muons or neutrino-induced hadronic
and electromagnetic cascades. Large detector volumes are required because the pre-
dicted flux of cosmic neutrinos and the known interaction probabilities at the energies
of interest are relatively small. The detection probability, defined as the ratio between
the range of the muon to the interaction mean free path of the neutrino, is only \(10^{-6}\)
for a \(\nu_\mu\) with an energy of 1 TeV. Moreover, the rare signal events must be extracted
from a large flux of atmospheric muon background. For example, at sea level the num-
ber of background muons per unit area exceeds the expected neutrino-induced muon
signal by \(\sim 10^{11}\), so neutrino detectors are constructed at large depths to reduce this
unwanted signal. Even at depths of 2 km of water equivalent, down-going background
exceeds predicted signal by a factor of \(\sim 10^5\). The combination of large volume, large
overburden, and desire to minimize material costs leaves experimentalists with few op-
tions other than to construct a detector within a remote, naturally occurring, transparent
medium such as ice or water (no excavated caves or mines are large enough). The
formidable technical challenge of remote operation distinguishes high energy neutrino
facilities from existing solar and accelerator-based neutrino detectors. It is one factor
which has spurred the continuing discussion of surface detectors (e.g., GRANDE and
HANUL) despite the daunting background difficulties.
Fig. 11. Schematic of detection method for charged current $\nu_\mu$ signature. Muon trajectories can be reconstructed by timing the passage of the Cherenkov wavefront.
Cherenkov techniques are now well understood and are illustrated in Fig. 11. A high energy neutrino can be detected only if it converts to a charged lepton, such as a muon, or induces a cascade. Astronomy is possible because the muon direction is aligned with the incident neutrino to within a degree, if the energy is greater than 1 TeV. The angular correlation between charged lepton and neutrino improves as the $1/\sqrt{E}$, so eventually multiple Coulomb scattering becomes the dominant factor in the angular resolution. Conceivably, neutrino directions can be determined to $\sim 0.1^\circ$ in some designs. Source localization can be improved by the detection of multiple events, but unless the event rate is unexpectedly large, the angular resolution is not competitive with conventional astronomy. Therefore sources must be identified statistically - by searching for a class of objects that lie within the angular error boxes. Confidence will be bolstered if theoretical models of that class of objects are consistent with high energy neutrino production. The relatively limited number of potential sites of high energy neutrino production suggests that source confusion is unlikely to be a problem.

The muon is detected by distributing photon sensors (large diameter photomultiplier tubes — PMTs) over the largest possible volume of transparent medium and recording the arrival times and intensity of the Cherenkov wavefront. Accurate reconstruction relies on actively tracking events over linear dimensions exceeding tens of meters and measuring the arrival of the Cherenkov wavefront to tens of nanoseconds or better. Geometries of the arrays are optimized according to the optical properties of the detector media – those media that generate less precision in the arrival time of the Cherenkov wavefront can be compensated by larger detectors with greater average pathlength. The instrumented volume can be increased by utilizing a medium with a large optical attenuation length. Naturally, volumes increase with with additional sensors, so per unit costs become an important design factor.

Muons from neutrino interactions are distinguished from the vastly more numerous atmospheric muons by direction; upward-traveling muons (through the detector) can only originate from nearby neutrino interactions. The Earth filters out all other known particles. Great care must be taken to reject the “down-going” atmospheric muons. In practice, muons are properly reconstructed if they traverse typically $\sim 100$ m of path-length within the boundaries of the array defined by the outermost strings, although dense arrays have demonstrated good reconstruction with shorter tracks. Complications arise from the lack of fixed fiducial volume, the presence of events containing multiple muons, decaying muons in flight, and fluctuations in the generation of Cherenkov photons resulting from high energy physics processes. Muon trajectories can pass near
enough to trigger the array, but too far outside the detector boundary for proper reconstruction.

Reconstruction is tied to specific assumptions about the event topology. For example, it is usual to assume that the characteristics for a neutrino-induced muon event are: 1) one and only one particle traversing the array, 2) continuous, uniform production of photons from a minimally ionizing charged particle, 3) propagation at the speed of light, and 4) traversal of the entire instrumented volume of the detector. Deviation from these assumptions, such as stopping muons or decays-in-flight, multiple-muon events, or energetic muon-bremsstrahlung, result in poorer reconstruction of the event trajectory and energy. Once the event is reconstructed, selection criteria are applied to reject events that are likely to be poorly reconstructed. It is obviously desirable to develop selection criteria that maintain good efficiency for signal events.

As mentioned, the dominant source of background in high energy neutrino detectors is downward muon tracks generated by cosmic ray interactions in the atmosphere. This background can be avoided by constructing a detector at ≥10 kmwe (kilometers of water equivalent) depths, but such depths are logistically impossible to attain. Rather, large volume detectors are constructed at intermediate depths, and the background must be removed by other methods. In principle, the angular direction distinguishes astrophysical neutrino signals from the background of atmospheric muons — muons originating from below the horizon must originate from neutrino interaction. However, errors in the reconstructed direction of the muon trajectory can result in misinterpreting down-going muons as upward going muons. For detector sites at depths between 1 and 4 kmwe, and energy thresholds of ~ 10 GeV, the rate of down-going muons exceeds potential signal rates by factors of $10^3 - 10^5$ (assuming atmospheric neutrinos are the baseline signal). Therefore, an important design specification involves the rejection factor, $R$, defined as $R = \frac{A_{\text{eff}}(\text{signal})}{A_{\text{eff}}(\text{mis})}$, where $A_{\text{eff}}(\text{mis}) = F_m \times A_{\text{eff}}(\mu_{\text{atm}})$. $A_{\text{eff}}(\mu_{\text{atm}})$ is the effective area for the detection of down-going muons, and $F_m$ is the fraction of down-going muons misidentified as upward going. The rejection factor must be greater than $10^3$ for the best case conditions, and typically $10^6$ for detectors located at depths of 2 kilometers water equivalent (kmwe). In the simplest description, $F_m$ is a constant, but it may be treated as an angular dependent scattering probability $P(\theta, \theta')$ in more complex descriptions. As the energy threshold of the detector is increased to ~ $10^{15}$ eV, the ratio of down-going atmospheric muons to expected signal decreases, reaching unity in the vicinity of 1 PeV. Since the required level of rejection is less at higher energy thresholds, event selection criteria can be optimized to achieve much larger effective
areas than could be achieved with larger rejection requirements. Detection methods with sufficient energy resolution to identify PeV events can be used to search the entire sky. Simulations show\textsuperscript{81,82} that the energy of $\nu_e$-induced cascades may be measured with sufficient accuracy, assuming the vertex is contained within the volume of the array. The quoted values in the literature for effective detection area cause much confusion because they are a function of lepton energy, zenith angle, and required rejection factor which differs between physics objectives. The effective volume becomes useful when the range of the muon is comparable to the largest dimension of the array. For muon detection at medium energies (and for all cascade events), the effective volume becomes a convenient parameter of detector sensitivity, but it too depends on energy and rejection factor.

Atmospheric neutrinos form an irreducible background in the sense that they cannot be differentiated from non-terrestrial neutrino signals on an event by event basis. Since the energy spectra and angular distributions of atmospheric neutrinos are reasonably well known from measurement and calculation, statistical techniques using energy spectra, spatial and temporal correlation, etc. can confirm or reject a hypothesis involving atmospheric neutrinos.

### 3.1 $E_\nu < 1$ PeV: Detection Modes of Optical Cherenkov Arrays

In this section, we discuss the most common detection signatures for HE neutrino telescopes. The neutrino signature depends on flavor and whether the neutrino initiates a charged current or a neutral current interaction.

1. **Charged current (CC) interactions initiated by $\nu_\mu$.** For $E_\mu > 1$ TeV, the range of the muon exceeds several kilometers and the effective volume can greatly exceed the instrumented volume, which is the reason why this mode has been the primary focus of recent detector designs utilizing optical Cherenkov radiation.

2. **Cascades initiated by neutral current (NC) interactions, $\nu_e$ and $\sim 80\%$ of $\nu_\tau$ charged current interactions.**

3. **Double Bang events are generated by $\nu_\tau$.** For $E_\nu > 10^{16}$ eV, the decay length of the tau lepton is comparable to the scale of the instrumented volume of high energy neutrino arrays. The initial interaction produces a large hadronic cascade as does the eventual decay of the tau lepton. The distinct separation of two large cascade events provides a unique signature. However, since the vertices of both cascades must be contained, the effective volume of this mode is a few percent of the CC $\nu_\mu$ signature.
Table 1 summarizes the primary backgrounds, advantages, and disadvantages for the most common detection modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Background</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_\mu) atm. (\nu_\mu), downgoing atm (\mu)</td>
<td>Best (V_{eff})</td>
<td>(0.1V_{eff})</td>
<td></td>
</tr>
<tr>
<td>(\nu_e) cascades (\mu)-brem, (\nu_\mu^{NC})</td>
<td>BG systematics</td>
<td>(E_{th} &gt; 10) TeV</td>
<td>poor angular resolution</td>
</tr>
<tr>
<td>(\nu_\tau) Double Bang little</td>
<td>clean downgoing signature</td>
<td>must be contained, (\sim 0.01V_{eff})</td>
<td></td>
</tr>
<tr>
<td>(\nu_\tau) by excess (\nu_e) (\nu_e) and (\nu_\mu^{NC})</td>
<td>long baseline oscillation</td>
<td>(E_{\nu} = 1-10) PeV, only downgoing</td>
<td>very challenging signature</td>
</tr>
</tbody>
</table>

The following sections give more detail on each detection mode.

### 3.1.1 Muon Detection

The largest effective detector volumes are achieved by measuring the flux of high energy muons. For energies between 0.1 TeV and 1000 TeV, the enormous flux of atmospheric muons, generated cosmic ray collisions in the atmosphere, overwhelms the meager signal expected from neutrinos. Restricting the observations to upgoing directions can eliminate this background. The Earth filters out the atmospheric muons, leaving only muons induced by neutrinos that happen to interact near the active volume of the detector. Assuming that the range of the muon is larger than the characteristic dimension of the active volume of the detector, the signal rate is the convolution

\[
Signal \sim A_{eff} \otimes R_\mu \otimes \sigma_\nu(E, y) \otimes \phi_\nu,
\]

where \(R_\mu\) is the muon range in g/cm\(^2\), \(y = \frac{E_\nu - \mu}{E_\nu}\) is the mean inelasticity so \(1 - y\) is the fraction of energy transferred to the muon, and \(A_{eff}\) is the energy dependent effective area of the detector. The range and cross section both increase linearly with energy into the TeV region. Stochastic processes begin to dominate over continuous ionization losses at energies above 0.5 TeV, and therefore the energy loss per unit length also increases. Assuming a linear scaling between Cherenkov emission and \(dE/dx\), high energy muons become “brighter” and more readily detected. The effective area increases with energy because the muon can be detected from greater distances. Since muons can be detected beyond the instrumented volume, it is possible for the effective area to be larger than the instrumented cross-sectional area of the array of photomultiplier tubes. In practice, strong background rejection requirements usually result in effective areas that are smaller than the geometric area. The energy dependence of \(A_{eff}\) must be included in the calculations of the event rate.
The usual procedure for calculating the flux involves several simplifying approximations to estimate the event rate (and avoid the convolution calculation). First, the charged-current cross section is usually averaged over the $y$-distribution, and small differences in the average between $\nu$ and $\bar{\nu}$ are ignored. This approximation is excellent for $E_\nu > 10^{15}$ eV. The mean value of $y$ converges to 0.2 for the neutrino and anti-neutrino, and only weakly depends on energy. Second, the energy dependence of the detector can be factored out of the convolution by calculating the neutrino induced muon spectrum at the detector, $dN_\mu/dE$. The flux of muons with energy $E_\mu$ induced by neutrinos with energy $E_\nu$ is

$$
\frac{d^2N_\mu}{dE_\mu dE_\nu} = \int_0^\infty dX \int_{E_\mu}^{E_\nu} dE_\mu' g(X, E_\mu, E_\mu') N_A \frac{d\sigma}{dE_\mu'} \frac{dN_\nu}{dE_\nu}
$$  \(8\)

where the last two factors are, respectively, the charged current cross section and the differential energy spectrum of the neutrinos. The factor, $g$, is the differential probability that a muon produced with energy $E_\mu'$ travels a distance $X$ and retains an energy $E_\mu$. By ignoring range straggling of the muon, $g$ can be written:

$$
g(X, E_\mu, E_\mu') \approx \frac{\delta(X - X_0)}{\alpha(1 + \beta E_\mu'/\alpha)}
$$  \(9\)

where the constants in rock are $\alpha \approx 2$ MeV/(g/cm$^2$) and $\epsilon = \alpha / \beta = 510$ GeV. These parameters vary by less than 20% from $10^{12}$–$10^{20}$ eV. Lipari and Stanov have discussed a more accurate treatment of muon propagation at high energy. If the small variations in these parameters are ignored, then $X_0$ is determined by

$$
\beta X_0 = \ln \left[ \frac{E_\mu' + \epsilon}{E_\mu + \epsilon} \right].
$$  \(10\)

Using these approximations, we see that the differential muon energy spectrum at the detector is related to the differential neutrino spectrum, $dN_\nu/dE_\nu$, by

$$
\frac{d^2N_\mu}{dE_\mu dE_\nu} \approx \frac{dN_\nu}{dE_\nu} \frac{dP_\nu}{dE_\mu} \frac{N_A}{\alpha(1 + \beta E_\mu'/\alpha)} \int_{E_\mu}^{E_\nu} \frac{d\sigma}{dE_\mu'} \frac{dN_\nu}{dE_\nu}
$$  \(11\)

where the probability that a neutrino of energy $E_\nu$ directed toward a detector produces a detectable muon is $P_\nu$. The event rate can now be calculated from Equation 11:

$$
Signal = \int_{E_\mu}^{\infty} \int_0^\infty \frac{d^2N_\mu}{dE_\mu dE_\nu} A_{eff}(E_\mu) dE_\nu dE_\mu
$$  \(12\)

\(^{\dagger}\) Range straggling refers to the variation in range due to fluctuations in energy losses. Therefore, a beam of particles with identical energy will not travel the same distance for the same energy loss.
\[
\begin{align*}
\int_{E_{\mu}^{th}}^{\infty} \int_{0}^{\infty} \frac{dN^{\nu}}{dE_{\nu}} \frac{dP_{\nu}}{dE_{\mu}} A_{\text{eff}}(E_{\mu}) \, dE_{\nu} \, dE_{\mu} & = \int_{0}^{\infty} \int_{E_{\mu}^{th}}^{\infty} \frac{dN^{\nu}}{dE_{\nu}} \frac{dP_{\nu}}{dE_{\mu}} A_{\text{eff}}(E_{\mu}) \, dE_{\nu} \, dE_{\mu} \\
& = \int_{0}^{\infty} \int_{0}^{\infty} \frac{dN^{\nu}}{dE_{\nu}} \frac{dP_{\nu}}{dE_{\mu}} A_{\text{eff}}(E_{\mu}) \, dE_{\nu} \, dE_{\mu}.
\end{align*}
\] (13)

According to Eqn. 14, the integrated probability of detection must be weighted according to the effective area of detection. If the energy dependence of \( A_{\text{eff}} \) is assumed small, then \( A_{\text{eff}} \) can be removed from the integral:

\[
\begin{align*}
\text{Signal} & = A_{\text{eff}} \int_{0}^{\infty} \int_{E_{\mu}^{th}}^{\infty} \frac{dN^\nu}{dE_{\nu}} \frac{dP_{\nu}}{dE_{\mu}} \, dE_{\nu} \, dE_{\mu} \\
& = A_{\text{eff}} \int_{0}^{\infty} \frac{dN^\nu}{dE_{\nu}} P_{\nu} \, dE_{\nu},
\end{align*}
\] (15)

where \( E_{\mu}^{th} \) is the minimum detectable muon energy for a given detector, which in general depends on the zenith angle and the rejection requirements of the analysis (i.e., it is analysis specific). Note that the probability, \( P_{\nu}(E_{\nu}) = \int_{E_{\mu}^{th}}^{\infty} \frac{dP_{\nu}}{dE_{\mu}} \, dE_{\mu} \) only depends on the minimum detectable muon energy, not the initial neutrino spectrum. Graphical illustrations\(^8\) and analytical expressions for \( P_{\nu} \) can be found in literature for several values for \( E_{\mu}^{th} \), with the assumption of constant effective area. These analytical expressions are useful for order-of-magnitude estimates, but it is important to keep in mind the restrictions.

For the energy interval \( 10^{-3} < E_{\nu} < 1 \text{ TeV} \), the probability is averaged for identical fluxes of neutrinos and anti-neutrinos

\[
P_{\nu} \simeq 1.3 \times 10^{-6} (E/\text{TeV})^{2.2}.
\] (17)

The scaling with energy directly reflects the energy dependence of the neutrino cross section and the average range of the muon. The cross section is proportional to energy below 1 TeV, but then changes to a weaker energy dependence due to the effect of the W propagator. A similar change in the energy dependence occurs for the range of the muon, so for \( 1 < E_{\nu} < 10^{3} \text{ TeV} \), the probability becomes

\[
P_{\nu} \simeq 1.3 \times 10^{-6} (E/\text{TeV})^{0.8}.
\] (18)

For energies greater than 10 PeV, the effect of the W propagator becomes more pronounced, and the cross sections\(^8\) scale with energy approximately as \( E^{0.36} \). Unfortunately, the cross sections are not well determined because different assumptions about the parton distribution functions at very small \( x \) lead to uncertainties of a factor of 2
Muon Effective Area versus Zenith Angle

Fig. 12. The effective area for muon detection as a function of zenith angle for $E_\mu$ between 0.1 TeV and 100 TeV (180° is vertically up in local detector coordinates).

at $10^{20}$ eV. Keeping these limitations in mind, the probability for muon detection is approximated as:

$$P_\nu \simeq 10^{-2} (E/EeV)^{0.4},$$  \hspace{1cm} (19)

where $E$ is now in units of EeV ($10^{18}$ eV).

The current generation of HE neutrino detectors are constructed with approximate cylindrical symmetry, and oriented vertically. This leads to angular dependence in the effective area, $A_{\text{eff}}(\theta)$, where $\theta$ is the zenith angle. As figure 12 shows, this is certainly the case with AMANDA. Moreover, the energy dependence of $A_{\text{eff}}$ cannot be ignored. To allow for these effects, we can write Eqn. 12 more generally as

$$Signal = \int_{E_{\mu,\text{th}}}^{\infty} \int_{\theta}^{\infty} \frac{dN_\mu}{dE_\mu dE_\nu} A_{\text{eff}}(E_\mu, \theta) dE_\nu dE_\mu.$$  \hspace{1cm} (20)
Neutrinos with $E_\nu < 100$ TeV are not strongly attenuated by the Earth, and much of the solid angle near the horizon remains accessible to energies as large as 1 PeV. Although the Earth is transparent to low energy neutrinos, an Earth diameter ($1.1 \times 10^5$ kmwe) exceeds the interaction length of neutrinos with energy higher than about 40 TeV. It is convenient to introduce an exponential factor to account for the absorption of neutrinos as they travel along the chord of the Earth, $X(\theta)$,

$$f(E_\nu, \theta) = \frac{dN_\nu}{dE_\nu} e^{-\sigma_{int}(E_\nu) N_A X(\theta)}$$  \hspace{1cm} (21)

which assumes that the reaction products generate no detectable signal. The attenuation factor can be averaged over azimuth angle to produce a “differential shadow factor” that is equivalent to the effective solid angle for upward traveling muons. Uncertainties in the density profile of the Earth and the neutrino cross section contribute to the error in this calculation. For neutrino energies above 10$^{20}$ eV, horizontal and slightly downgoing neutrinos encounter sufficient material to attenuate the flux (keep in mind that we are discussing underground detectors with overburdens of several kilometers of water equivalent or more). There is one notable exception to these conclusions. Tau neutrinos will regenerate themselves because both the charged and neutral current interactions produce a tau neutrino in the final state. Regeneration causes the tau neutrino to lose energy until $\sim 10^{15}$ eV, the energy at which the Earth becomes transparent to all neutrino flavors. In practice, this signature is difficult to use to identify $\nu_\tau$ if the cosmological sources produce nearly equal fluxes of $\nu_\mu$ and $\nu_e$ with power law spectra. Under these assumptions, the high energy $\nu_\tau$ signal will be overwhelmed by the signal from lower energy $\nu_\mu$. At this point, statistical discriminants must be employed based on angular dependence of the signal or a rare high energy event traveling vertically upward. Unfortunately, the statistics of high energy events by current or next generation detectors is unlikely to be high enough to utilize this discriminant effectively.

The calculations above ignore range straggling and other details of muon energy loss. They are valid only if the range of the muon is less than the column density of matter surrounding the detector. For upgoing neutrinos penetrating the Earth, this condition is valid, but does not hold for detectors at relatively shallow depths for neutrino-induced muons in the downward direction. As a consequence, downgoing signals from neutrinos are concentrated near the horizontal direction, where the column density is greatest.
3.1.2 Cascade Detection

There are several important processes that generate cascades of high energy particles, which are summarized below:

\[ \nu_e (\bar{\nu}_e) + N \rightarrow e^- (e^+) + \text{hadrons}, \]  
\[ \nu_\mu (\bar{\nu}_\mu) + N \rightarrow \nu_\mu (\bar{\nu}_\mu) + \text{hadrons}, \]  
\[ \nu_e + e^- \rightarrow W^- \rightarrow X. \]

Neutrino-induced electrons produce electromagnetic cascades that generate very bright, localized bursts of Cherenkov photons. The longitudinal development of hadronic and mixed cascades is somewhat less localized on average, and they occasionally produce muons that travel for 50 m. The narrow resonance reaction indicated by the third line can be used to calibrate the energy response of the detector, but the event rates induced by atmospheric neutrinos is negligible for kilometer scale detectors. However, if astrophysical sources of 6.4 PeV neutrinos exist, then this reaction may become important in kilometer scale detectors. While the energy resolution for cascade events is expected to be much better than that for muon tracks, whether it is sufficient to extract resonant events from the continuum induced by charged current reactions on nuclei remains an open issue. Initial studies of the IceCube detector performance show that this requirement represents a non-trivial challenge.

Although the directional information is poor compared to muon tracks, the energy resolution is far superior. In media with moderate scattering, the sensors nearest the cascade vertex provide the directional information, while distant sensors sample from a expanding diffusive wavefront to provide a calorimetric measurement. The spherical topology of the cascade events readily distinguishes them from the most common atmospheric muon backgrounds. For example, atmospheric $\nu_e$ are highly suppressed at these energies because the muons produced in the air shower are far more likely to interact than decay. At energies above 1 TeV, the irreducible flux of atmospheric $\nu_e$ is less than $\nu_\mu$, because fewer atmospheric muons decay before reaching the detector as the muon energy increases. Therefore, neutral current interactions by $\nu_\mu$-induced bremsstrahlung and pair production are the dominant background, apart from instrumental enhancement of the more abundant, lower-energy phenomena. Recent work has shown that the latter two physics backgrounds can be eliminated while retaining good efficiency for signal events. Once these backgrounds are rejected, neutral current interactions by atmospheric $\nu_\mu$ form an irreducible background. In this sense, the techniques of detecting
\( \nu_\mu \) and \( \nu_e \) are complementary. The good angular precision and superior sensitivity of muon detection is traded for improved energy resolution and lower background rates. For kilometer-scale detectors, the large spacing between strings leads to a rather large energy threshold for simple trigger schemes, but fractional energy resolution of \( \sim 25\% \) is expected.\(^{82}\)

One common practice seen in the literature is to present integral limits in plots of differential spectra, which is acceptable if the energy resolution of the detector is rather poor. However, this practice makes it difficult to interpret the results and gives an overly optimistic impression of the sensitivity of the detector. Given the energy resolution expected for cascade events, it is more informative to plot differential sensitivity as a function of neutrino energy. This point is illustrated in Fig. 13, which was taken from Ref. 82. The figure shows that several models can be probed by current and next generation HE neutrino detectors. In general, differential limits convey information more transparently, but in practice, each model must be compared on a case-by-case basis by calculating the expected event rate for each unique flux prediction and then comparing to background rates to obtain flux limits.

Due to the suppression of the atmospheric \( \nu_e \) flux at high energies (relative to \( \nu_\mu \)), hadronic cascades induced by neutral current interactions of atmospheric \( \nu_\mu \) generate an irreducible background for astrophysical sources, unless it becomes possible to distinguish NC interactions from \( \nu_e \)-initiated cascades. The background shown in Fig. 13 has several important consequences. First, it is possible to search for a diffuse flux of \( \nu_e \) by integrating over the complete sky (\( 4\pi \) sr) by imposing a software energy threshold of 100 TeV. Sensitivity to downgoing neutrinos is particularly important for energies above \( 10^{15} \) eV because the column depths are too small to significantly attenuate the neutrino signal. It will be very difficult to use the muon mode to search for down-going muons with comparable energies, so cascades may be the only mechanism for a single detector to integrate signal from the complete sky. Second, Wu\(^{82}\) estimated the effective volume for \( \nu_e \) in a typical kilometer-scale detector after the application of background rejection criteria. It is comparable to the effective volume for the \( \nu_\mu \) mode in AMANDA-II. Since the best studied mechanisms for high energy neutrino production predict comparable fluxes of \( \nu_\mu \) and \( \nu_e \), most models accessible to study by the \( \nu_e \) mode in kilometer scale detectors will be tested by the current generation of HE neutrino detectors. Discovery by current generation detectors will provide strong incentive to optimize the next generation detector for flavor composition studies of neutrino emission.
Fig. 13. Diffuse flux predictions and experimental limits for cascade events initiated by $\nu_e$. The experimental limits were obtained from AMANDA-A, Frejus (triangle), and the Baikal NT detector. AMANDA-B diff and AMANDA-B int are the differential and integral limits. The curve labeled IceCube $\nu_e(1)$ corresponds to the minimum detectable flux for one year of livetime, assuming an $E^{-2}$ differential spectrum and ignoring atmospheric background. The curve labeled IceCube $\nu_e(2)$ is the minimum detectable differential flux, taking into account the irreducible background from NC interaction. The atmospheric neutrino flux, GRB flux and AGN flux are shown for comparison.
3.1.3 $\nu_\tau$ detection using Double Bang mode

The strong interest in neutrino oscillation and flavor composition of the neutrino flux from astrophysical sources strongly motivates experimentalists to find a mechanism to identify tau neutrinos. Learned and Pakvasa\textsuperscript{62} suggested that the tau neutrino may be identified by observing an event characterized by pair of energetic cascades separated by the flight distance of the tau lepton. The signature is known as the “Double Bang” mechanism.

The flight distance, $L$, of the tau lepton produced in CC interactions is given by

$$L = cT \frac{E}{m_\tau} = \left( \frac{87 \text{ m}}{1.8} \right) \left( \frac{E_\tau}{1 \text{ PeV}} \right).$$

(25)

The flight distance is approximately 100 m for $E_\tau = 2 \text{ PeV}$, which is large enough to observe with a HE neutrino facility. The initial cascade from the charged current interaction contains $\sim 30\%$ of $E_\nu$. The energy lost by the tau lepton is largely ionization, since the heavy mass suppresses bremsstrahlung and pair production. The subsequent decay of the tau lepton produces an even more spectacular cascade containing 70\% of the neutrino energy. The simultaneous observation of two cascades separated by a minimally ionizing track would be unambiguous and profound.

The backgrounds for the Double Bang signature are expected to be very small, but the effective volume in optical arrays is greatly reduced by the requirement to contain both showers.\textsuperscript{61,12} The lack of reconstruction tools for this unusual topology makes it difficult to estimate the minimum and maximum separations that produce sufficient energy resolution and background rejection, but first pass estimates of the effective volume is only a few percent of the volume for $\nu_\mu$. Apparently, event rates will be very small compared to other modes accessible to current HE neutrino detectors. Also, the requirement for well-separated showers constrains the lower energy limit to several PeV. At this energy, attenuation by the Earth becomes severe so only half the sky is accessible. Despite these obstacles, the discovery of one or more astrophysical sources by current generation detectors will motivate the development of analysis tools tuned for the Double Bang signature.

At EeV energies, the Double Bang signature is more readily detected by facilities employing the air fluorescence techniques such as HiRes, Auger, and EUSO/OWL. In this case, the detection strategy utilizes a variant of the horizontal air shower method.
3.2 $E_\nu > 1$ PeV: Optical Cherenkov

The AMANDA collaboration\textsuperscript{11} has recently suggested that present generation optical arrays can be used to detect $\nu_\mu$ with energies above $10^{18}$ eV. The muon is ejected with 80\% of the neutrino energy and propagates for tens of kilometers. Except near the horizon, the limited column thickness above the detector suggests that the energy losses are modest. Since the muons are detected with energies close the production energy, the effective area of AMANDA is very large. Simulations show that muons with $E_\mu = 10^{18}$ eV can be detected more than 500 m from the center of the array. The arrival time distribution of photons characterizes the distance, while the quantity and topology characterizes the energy. Atmospheric muon backgrounds are small at these energies, but instrumental artifacts (from cross-talk in the electronics, for example) must be understood. The response of the optical sensors to large light levels can be calibrated by \textit{in situ} light sources. An early stage of analysis, which includes background rejection criteria, shows that the aperture of AMANDA is $\sim 5\text{--}10\text{ km}^3\text{sr}$, comparable to the Auger sensitivity from horizontal air showers. The expected sensitivity for AMANDA at EHE energies is indicated by the dotted curves in Fig. 3 and compared to Auger, OWL, and RICE.

Most of the EHE events are detected well outside the instrumented volume so angular reconstruction and energy resolution are not likely to be very good. Since signal events tend to arrive from the horizon while background events cluster near zenith, the lack of angular reconstruction eliminates this powerful statistical test. Fortunately, it is probable that IceCube can reconstruct the angular parameters of EHE muons with much better accuracy. The energy threshold could be reduced relative to AMANDA-II because background topologies are easier to recognize. Even though the overall sensitivity of IceCube will be comparable to AMANDA and Auger, it can verify discovery claims with improved performance (relative to AMANDA) or with independent systematic errors (relative to Auger).

3.3 $E_\nu > 1$ PeV: Alternative Techniques

Above $\sim 10$ PeV, the predicted event rates for optical arrays are rather meager.\textsuperscript{89} Alternative techniques for $10^9$ GeV neutrinos are being considered through coherent radio\textsuperscript{90--92} or acoustic\textsuperscript{93} pulses. At EHE energies, acoustic and ice-based radio techniques run out of rate unless an enormous extrapolation in size is assumed. Instead, new techniques which utilize the enormous energy deposition by EHE $\nu$’s interactions are under
development. We briefly discuss horizontal air shower measurements with conventional arrays or with fluorescent light either from the ground or from orbiting detectors.

3.3.1 Radio and Acoustic Techniques

Nearly 40 years ago, Askaryan predicted that the development of high energy electromagnetic cascades in normal matter should produce a charge excess. Photon and electron scattering processes that pull electrons from the surrounding material into the cascade create an excess negative charge of 20-30%. This effect has been confirmed by a beautiful measurement at SLAC Final Focus Test Beam Facility.

Techniques based on the detection of coherent radio emission from neutrino-induced electromagnetic cascades are being pursued in several ways. The RICE experiment exploits the dielectric properties of cold Antarctic ice. At radio wavelengths, the attenuation length in ice is approximately 1 km, nearly an order of magnitude larger than optical absorption lengths, suggesting that much larger volumes of ice can be instrumented for a given number of sensors. Relatively little of the neutrino energy is transformed into radio power, so the energy threshold of this technique is rather high. However, the large attenuation lengths at radio wavelengths assures that once the signal to noise exceeds unity for a given receiver, it will remain detectable to large distances between cascade and receiver. At the moment, more than a dozen radio receivers are buried in the same holes used by the AMANDA collaboration. The sensors are placed at depths of several hundred meters, which stems from two competing conditions. At increasing depths, the ice temperature increases (so attenuation length is reduced) and the transmission of high frequency signals becomes more difficult. At shallow depths, the index of refraction changes rapidly due to the changing density of the firn ice layer. The primary aim of the RICE collaboration is to study reliability, backgrounds, calibration, and the position resolution of vertex reconstruction. Present analysis shows that the vertex of the cascade can be determined with a resolution of 10 m. The RICE collaboration is developing higher gain antennas and new transmission technologies based on optical fibers to increase the bandwidth. D. Seckel has speculated that radio techniques may be the best technique with the capability to achieve an effective volume of 100 km³. Long term issues such as power, signal transmission, servicing, and triggering over vast distances on the Antarctic plateau remain to be solved.

The interaction of EHE neutrinos near the surface of the lunar regolith may produce

\[ \text{positive charge is removed by in-flight annihilation of positrons in the cascade} \]
radio frequency pulses. The large target mass compensates for the small solid angle and limited exposure time on large telescopes. The acceptance of this technique is $\sim 10^3 \text{km}^3\text{sr}$ for $E_\nu > 10^{20} \text{eV}$, which is a factor of 100 larger than expected for optical arrays. However, the exposure time for optical arrays is typically years whereas time allocation on radio telescopes is typically a few days. Backgrounds from high energy cosmic rays may pose a problem. Recent work scanned the limb of the moon. It was thought that total internal reflection would suppress radio emission by cascades initiated by cosmic rays. However, recent work which has included the LPM effect has shown the detection probabilities for cosmic ray events dominate near the limb. Imperfections from sphericity on the lunar surface may create background “hot spots” as well. Fortunately, the neutrino detection probabilities dominate cosmic ray probabilities near the center of the moon, but refraction reduces the acceptance.

Both water and ice media can be used to detect acoustic pulses which are generated by cascades when ionization energy losses are converted into heat. While heat is deposited into the medium very quickly (a few nanoseconds), it dissipates very slowly. The approximate step function expansion creates a coherent bipolar pressure wave. The signal strength scales linearly with energy, as given by

$$P \propto \frac{KE}{CRd^2},$$

where $P$ is the amplitude of the pressure wave, $K$ is the expansion coefficient, $C$ is the heat capacity, $d$ is the diameter of the cascade development, $R$ is the distance between the cascade and detector, and $E$ is the energy of the neutrino. Note that the “seeing distance” is linearly proportional to deposited energy for a fixed receiver sensitivity. This explains why acoustic techniques become attractive at >PeV energies. One critical parameter is the bulk coefficient of thermal expansion, $K$, which increases with water temperature, which makes the relatively warm water of the Mediterranean an excellent site.

The pressure amplitude from background noise (which is highly variable due to surface waves) decreases as $1/f$, whereas thermal noise in the receivers scales linearly with frequency. Thermal noise dominates above 20 KHz, which sets an upper bound for the optimal frequency of operation. The recent review by Learned and Mannheim summarizes the current experimental efforts to develop this technique.
3.3.2 Horizontal Air Shower Technique

Given the general power law dependence of the neutrino flux expected from most models, the lowest energies are best explored by optical Cherenkov detectors. Radio and acoustic techniques have the potential to extend the search to the energy interval $10^{15}$–$10^{18}$ eV because they can detect downgoing neutrinos with greater sensitivity than optical methods. The upper limit is approximate, determined by event rate, even though the effective volume for these techniques is potentially several orders of magnitude greater than kilometer scale arrays. At the highest energies, large area sparse arrays of particle detectors are sensitive to the macroscopic quantities of energy deposited in the atmosphere during the development of extensive air showers (EAS). We use the word “shower” instead of “cascade” to remind us that the event extends laterally over several kilometers. At these energies, impressively large areas are required to observe a few events per year. For example, the Auger project is now constructing a 3000 km$^2$ array in Argentina, and plans to duplicate that effort in the northern hemisphere.

The previous method requires “contained” events in the sense that particles must strike the detectors in the active volume, necessitating large areas of instrumentation. Alternatively, pixellated optical telescopes have the sensitivity to detect optical photons generated in the air shower due to nitrogen fluorescence and Cherenkov radiation. The de-excitation of the nitrogen atoms is isotropic, while Cherenkov radiation is co-aligned with the direction of the shower. Therefore, telescopes designed to search for $\sim$ TeV particles rely on Cherenkov radiation, whereas higher energies are best probed by fluorescence techniques because the particle trajectory need not point at the telescope. Compared to surface arrays, far fewer optical telescopes are required to achieve the same aperture, but they are much more sophisticated and operate only on moonless nights ($\sim 10\%$ duty cycle). The Auger project employs both techniques.

Horizontal air shower techniques can be employed to explore the neutrino sky at extremely high energies.$^{37,23}$ In the vertical direction, the atmosphere is about 10 interaction lengths thick, but the column thickness grows with zenith angle. No shower initiated by a strongly interacting particle can penetrate to the detector from near the horizon. Therefore, horizontal air showers can only be created by deeply penetrating particles, such as neutrinos and muon-induced bremsstrahlung cascades. Even at EHE energies, the interaction length of weakly interacting particles is very long compared to the column thickness, so cascade vertices will be uniformly distributed throughout the atmosphere. In particular, a large fraction of neutrino interactions occur at large depths.
Neutrino showers can be differentiated from electromagnetic showers by exploiting differences in the shape and timing parameters of the shower front, but systematic difficulties involved in both the detection and analysis of inclined showers has hampered efforts in the past. Conceivably, with an acceptance $\sim 20 \text{ km}^3 \text{sr}$ of water equivalent target volume for $E_\nu > 10^{19}$ eV, the Auger air shower array will have the sensitivity to search for neutrinos from cosmic ray interactions with the cosmic microwave background, and for more speculative signals from topological defects.

Fluorescence techniques measure the longitudinal development of the shower, so energy determination and background rejection are straightforward given an accurate trajectory, and the EUSO/OWL project is designed to take advantage of this. Initially, a large field-of-view mirror with pixellated light sensors is installed on the International Space Station. Flying at altitudes of $\sim 400$ km, downward-oriented mirrors can scan a very large volume of the Earth’s atmosphere. Preliminary simulations of performance show that the neutrino aperture is sufficient to detect of order 10 events per year from GZK or from the more optimistic parameterizations of topological defect and Z-burst models. The effective volume of the detector system can be increased by eventually launching several mirrors on free-flying satellites to higher altitudes. Potentially, this system increases the sensitivity to HE particles by several orders of magnitude beyond Auger if the technical hurdles are overcome. The “Double Bang” signature for tau neutrinos is quite striking at EHE energies. For $E_\nu = 10^{19}$ eV, the shower pairs are separated by 500 km. In addition to fluorescence photons from horizontal air showers, Cherenkov photons from upward traveling vertical events can be used to identify tau neutrinos. As mentioned in section 2.3.1, the Earth filters all known particles with energies above 1 PeV except $\nu_\tau$. At the transparency energy, tau leptons produced in CC $\nu_\tau$ interactions will travel a distance $\gamma c \tau$ of approximately 50 m (or $\sim 50$ mwe since most of these interactions occur in the ocean). For interactions less than 50 m beneath the surface, the tau lepton will emerge and decay to generate an extensive air shower. This process yields a target mass of $10^{14}$ metric tons at a transparency energy of $10^{15}$ eV for a baseline target area of $10^6$ km$^2$.

Since the Cherenkov photons are strongly peaked in the forward direction, the energy threshold is greatly reduced for those events that travel toward the instrument. The vertical trajectory suggests that few pixels detect light, so backgrounds and triggering will be challenging. For example, the event rate of upward traveling muons from CC $\nu_\mu$ will dominate the $\nu_\tau$ flux due to the much longer range. A fraction of these muons may radiate high energy photons that may confuse flavor indentification.
4 High Energy Neutrino Detectors

4.1 General Considerations

The visionary decision by the DUMAND collaboration over 25 years ago to construct a large telescope nearly 5000 m under the ocean and 40 km from shore launched the experimental effort to construct a neutrino observatory. The design goals then were much the same as they are now: threshold energy of $\sim 10 - 100 \text{ GeV}$, optimized for muon energies of $1-10 \text{ TeV}$, effective detection area $= 20,000 \text{ m}^2$, number of optical sensors $= 200$. Unfortunately, this pioneering effort fell victim to expensive logistical difficulties and was de-funded.

At present, four groups are competing in the construction of high energy neutrino observatories: two in the Mediterranean — NESTOR$^{100,56}$ and ANTARES$^{101}$ — one in Lake Baikal, Siberia, called NT-200$^{102}$ — and one in deep ice at the South Pole called AMANDA.$^{103-105}$ Baikal’s NT-200 and AMANDA-II are taking data, and feasibility studies are being carried out at the Mediterranean sites. The geographical location is shown in Fig. 4.1.

AMANDA anchors the effort in the southern hemisphere and complements the sky coverage of the Siberian and planned Mediterranean observatories, as shown in fig. 15. Several new concepts for surface neutrino observatories are being discussed,$^{79}$ and a new effort to study undersea sites near Sicily and Ponza Island in Italy (NEMO),$^{106}$ but I will not cover those ideas here.
Fig. 15. Comparison of sky coverage by northern hemisphere detectors (top) and AMANDA (bottom). The top scale indicates the fraction of time observing a given region of the sky. The darkest patches show the regions of greatest efficiency. The figure shows that both northern and southern hemisphere detectors are required for uniform sky coverage.
The relative merits of each site and technological implementations are sufficiently attractive to warrant several on-going efforts because the decision tree is not yet mature. Many factors contribute to a complex matrix of project cost. These include optical properties, temporal and spatial variability of the medium, deployment complexity, logistical support, physics emphasis, sensor density and overall geometry, \textit{in situ} component reliability, system architecture, signal transport, sophistication of front end electronics and data acquisition system, repair, maintenance, etc. Photon scattering concerns strongly favor water, but absorption lengths are largest in ice. There is little doubt that track reconstruction is easier in water, but AMANDA has shown that they can cope with the scattering properties of ice. Intrinsic noise rates in the photomultiplier tubes are higher in sea-water, but local coincidence techniques provide a robust solution. Larger depths reduce background but strain mechanical and penetrator connections. In addition, the Baikal NT-200 and AMANDA have shown that background rejection is possible for the shallower depths, so great depths are not necessary. Short distances to the surface offer greater freedom in the choice of architectures to avoid single point failures, but standard engineering practices provide redundant reliable solutions for long distance communication. Given sufficient time and resources, there is no reason to doubt eventual success for any of the programs discussed in the next few sections. At the end of the day, what matters most is reliable operation of deployed sensors.

4.2 NT-200 at Lake Baikal

The Baikal collaboration has been accumulating experience with the construction and operation of water-based neutrino observatories since 1993, the longest track record of any group. Those initial efforts were followed by intermediate stages of construction that included configurations with 96 and 144 optical sensors and culminated with NT-200, which was completed in April 1998 (see figure 16). It consists of 192 optical sensors positioned at a depth of 1.1 km below the surface of the lake. The sensors are arranged in pairs and operated in coincidence to suppress unrelated signals from bioluminescence and internally generated random noise. Deployment, the “Achilles Heel” of remotely located neutrino observatories, has been solved by utilizing the seasonal ice cover on Lake Baikal. The solid platform can be accessed for significant periods of time, enabling reliable detector assembly and repair of detector elements.

An umbrella-like frame maintains eight vertical strings of optical sensors, consist-
Fig. 16. Schematic diagram of the NT-200 neutrino array located in Lake Baikal. The smaller array on the right is a view of the partial detector deployed in 1996.
ing of a glass pressure vessel and a photomultiplier tube (PMT) with a diameter of 37 cm. The operation and performance of the Baikal detector is understood. They have shown that the optical properties of the water medium and 1.1 km depth are adequate to measure the angular spectrum of atmospheric muons with good accuracy and to identify atmospheric neutrinos (Fig. 17). This result bodes well for the Mediterranean sites because they are deeper (so less background from atmospheric muons) and the optical properties are better. Neutrino events were extracted from 234 days of livetime. After reconstruction, neutrino events were selected by imposing a restriction on the chi-squared of the fit and requiring consistency between the reconstructed trajectory and the locations of sensors registering photons. In this context, sensors that do not register photons carry important information as well. Finally, the non-gaussian tails of the angular distribution were reduced by imposing the condition that events must traverse more than 35 m within the array.

The high PMT density of the NT-200 design results in a low energy threshold — advantageous for medium-energy science goals — but limits the effective area at high energies to $\sim 5 \times 10^3$ m$^2$, presumably too small to detect neutrinos from non-terrestrial sources. A strawman design for a 2000 sensor array has been presented. The effective area would be $\sim 10^5$ m$^2$, while retaining a 10–20 GeV energy threshold. It could fill the niche between the current generation of neutrino detectors and future kilometer-scale arrays with, presumably, much higher energy thresholds.

4.3 ANTARES

A flurry of research and development activities have occupied the ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch — hopefully, it sounds better in French) collaboration as they assess the relevant physical and optical parameters of their site. Deployment methods are being developed and refined through a series of operations using barges, research and military vessels. The NESTOR and ANTARES groups envision quite different deployment schemes, array designs, and signal processing. Technological solutions are being sought which are affordable, reliable, and expandable.

Over the past few years, the ANTARES collaboration has methodically determined the critical optical parameters of a 2400 m deep site off the coast of Toulon, France. Significant R&D has concentrated on string deployment and retrieval. They have reported that one string has been installed at the site and recovered after one year of flawless op-
Fig. 17. Angular distribution of atmospheric neutrino signal by NT-200 experiment. The shaded histogram is the distribution expected from Monte Carlo simulations.
Fig. 18. Downgoing angular distribution of cosmic ray muons from the ANTARES single string prototype. The figure shows good agreement between the expected and measured distributions.
eration. This success paves the way for more complex and difficult operations, such as the deployment of a fully functional string of sensors, deployment of multiple strings, or the insertion of a string within an existing array.

Precision attenuation and scattering measurements at a wavelength of 450 nm are extremely encouraging. The collaboration has reported an absorption length greater than 50 m and scattering length greater than 200 m for blue wavelengths.\textsuperscript{109,110} Environmental studies at the Toulon site show that upward facing PMTs lose sensitivity over time due to the accumulation of organic debris, so the ANTARES design consists of only downward looking PMTs. Deep sea currents have been measured over a period of a year and show no unusual excursions from expected values. The collaboration concludes that the optical and environmental properties at the selected site satisfy the requirements of their telescope design.

Simulations of an array consisting of 15 triads of strings (\sim 1000 PMTs) indicate that neutrino events can be cleanly identified. Random noise exceeding 50 kHz per optical sensor has been measured, but can be eliminated by straightforward coincidence requirements between neighboring elements in the array. Bioluminescent flashes do not affect local coincidence rates due to the relatively weak intensity of the output and the relatively long duration of the burst. Muon directions should be identified with sub-degree angular resolution.

To gain experience with the complex deployment procedures, a demonstrator line was deployed. This 350 m line consists of two vertical cables supporting 16 frames of a pair of optical modules. It was equipped with appropriate sensors for precise positioning of the detector elements and measuring environmental parameters. A series of deployment operations in 1998 demonstrated reliable solutions for deployment, positioning, and recovery of strings in the deep sea.\textsuperscript{110} The string was then equipped with 8 optical modules and signal transmission electronics and deployed to a depth of 1100 m for long term operation. Signals were transmitted to shore using an electro-optical cable 37 km in length. Figure 18 shows the angular distribution of downward atmospheric muons that were reconstructed from a subset of data collected since November, 1999. The excellent agreement between the measured and predicted angular distributions represents an important milestone\textsuperscript{108} for undersea detectors.
Fig. 19. Reconstructed downgoing muon event.\textsuperscript{108} Data collected by the single string prototype installed by the ANTARES collaboration in Mediterranean.
4.4 NESTOR

NESTOR\textsuperscript{100,111} plans to deploy an array of 168 optical sensors at a depth of 3.5–4.0 km. The site is located 7.5 miles off the coast of Pylos, Greece. The large depth significantly reduces the background of down-going atmospheric muons, but places greater stress on the penetrator connections. Hexagonal floors, rather than strings, comprise the basic unit. The array consists of 12 floors, fixed in place with an extensive network of wire guides, and assembled to form a 200 m tall tower. Horizontal separations between optical modules on a given floor are slightly larger than 34 meters. At each corner of the hexagonal floor is a pair of two photomultiplier tubes, 15 inches in diameter (one facing up and the other facing down). The NESTOR collaboration plans to deploy the complete array in 2001.

The NESTOR collaboration has been active since 1991. The flux and angular distribution of atmospheric muons was measured at depths as great as 4200 m. Site testing is complete, showing excellent optical properties. For example, the attenuation length at blue wavelengths is 55 m. Like the Baikal design, a symmetric up-down arrangement of PMT orientations will insure better uniformity in its angular acceptance. At the NESTOR site, it is believed that upward facing PMTs will not suffer from obscuration due to sedimentation or biological growth. The array design is expected to achieve a low energy threshold due to the relatively high density of optical sensors.

Recently, the NESTOR collaboration has performed mechanical tests by successfully towing a single floor out to sea and deploying it to a depth of $\sim 2600$ m. In the near future, they have a far more ambitious plan to deploy two, fully instrumented, floors to depth. It is hoped that these tests will establish the electro-mechanical durability of the signal processing and transmission systems. Assuming operational success of the first tower, the collaboration anticipates seeking funding for six additional towers. They would be deployed in a hexagonal pattern around the first tower, at a radial distance of 150 m. This array would have an effective detection area of $10^5$ m\(^2\) for 1 TeV muons, and provide 1 degree pointing resolution.

4.5 AMANDA

The AMANDA-B10 high energy neutrino detector was constructed between 1500–2000 m below the surface of the Antarctic ice sheet where the optical properties are suitable for track reconstruction\textsuperscript{71} (see Fig. 20). The instrumented volume forms a cylinder with outer diameter of 120 m. The surface electronics are located within a kilometer
Fig. 20. Schematic representation of the AMANDA detector. AMANDA-A consists of 80 optical modules (OMs) deployed to a depth between 800–1000 meters. It was the first array deployed in Antarctica. AMANDA-B10 is the central 10 strings of 302 OMs deployed between 1500–2000 meters. An exploded view of AMANDA-A and AMANDA-B10 appears in the center column. The first phase of AMANDA-II construction began with the deployment of three strings between 1150–2350 m. Data was collected with the 13-string array during 1998 and 1999. AMANDA-II was completed in January, 2000. It consists of 19 strings (677 OMs), but does not include AMANDA-A.

of the Amundsen-Scott Research Station at the geographic South Pole. The detector was commissioned in February 1997,\textsuperscript{112,113} and initial scientific results were presented at the XXIVth International Cosmic Ray Conference.\textsuperscript{71} Reconstruction methods and detector calibration techniques were introduced in a previous publication.\textsuperscript{104}

AMANDA-B10 consists of 302 optical modules (OMs) that contain an 8 inch diameter photomultiplier tube controlled by passive electronics and housed in a glass pressure vessel. They are connected to the surface by an electrical cable that provides high voltage and transmits the signals from the OM. The simple, reliable system architecture is responsible for the low fraction of OM failure (< 10% after several years of
operation, although most of the failures occur within a week of deployment).

In January, 2000, AMANDA-II was completed. It consists of 19 strings with a total of 677 OMs arranged in concentric circles, with the ten strings from AMANDA-B10 forming the central core of the new detector. New surface electronics consolidates several triggering functions and adds functionality. New scalers were installed that provides millisecond resolution — important for supernova studies. Several technologies were deployed to evaluate their utility and readiness for future expansion to larger systems. The analysis procedure utilizes two essential characteristics of the signal to simplify the analysis relative to atmospheric neutrino measurements. First, the sources are assumed to be point sources in the sky, so only events within a selected angular region are considered. Secondly, we use the topological characteristics of a spectrally hard neutrino signal to reject poorly reconstructed atmospheric muons and atmospheric neutrinos, both of which have softer spectra. Topological variables include an estimate of muon energy and an assessment of the spatial fluctuation of the detected signals in a given event. The complete suite of variables was able to differentiate signal events from several classes of background topologies. Several important results from the simulation programs were tested by comparing the background simulation to the experimental data at various steps along the analysis chain.

Monte Carlo based simulation programs determined the effective area for background and neutrino-induced muons. Simulations for upgoing signals of several energies are shown in Fig. 21. AMANDA-B achieved an important milestone by becoming the first 10,000 m²-class detector, while AMANDA-II is expected to break the 30,000 m² barrier for 1 TeV muons. The space angle resolution should improve to 1–2 degrees, and the fractional energy resolution for muon events is expected to improve to a factor of 2–3.

The search for point sources of HE neutrino emission used an iterative analysis procedure to maximize the \( S/\sqrt{BG} \), where the signal, \( S \), was computed with an energy spectrum proportional to \( E^{-2} \) for the source. \( BG \) is background from atmospheric muons. After optimizing the analysis parameters, the sensitivity was evaluated for power law spectra with indices between 2.0 and 3.0.

The space angle resolution is determined from simulation. The upper panel of Figure 22 shows that the median resolution is 3 degrees, and the lower panel indicates that this value only weakly depends on neutrino energy. Two studies were used to check the angular resolution and absolute offset. First, events that simultaneously trigger the GASP ACT\textsuperscript{114} and AMANDA provide a “test beam” containing single muons with
Fig. 21. The effective area of AMANDA II as a function of zenith angle, $\theta$. The area is computed for neutrino-induced muons with either 1 TeV or 100 TeV of energy at the interaction vertex. Selection criteria from the point source analysis in AMANDA-B10 were applied. The different curves correspond to muon energies of 1 TeV and 100 TeV at the detector.
Fig. 22. (Plot taken from talk presented by the author at Neutrino 2000.) Error in the space angle for simulated signal events with energy spectra proportional to $E^{-2}$. **Top:** distribution of error averaged over declination. **Bottom:** Space angle error as a function of neutrino energy.

directional information provided by GASP. To improve the statistical accuracy of the investigation, a second study involved events which simultaneously trigger the SPASE air shower array and AMANDA. The geometric relationship between SPASE and AMANDA is shown in Fig. 23. Although the interpretation of these special events is complicated by the presence of multiple muons, which tend to reconstruct with worse angular precision than single muon events, the response of the detector to these events appears to be correctly modeled.

The point source analysis yields an event sample of 1097 events which are dis-
Fig. 23. Side view of the geometric relationship between surface air shower arrays (SPASE1 and SPASE2) and AMANDA. Events that have simultaneously triggered both the SPASE and AMANDA detectors were used to confirm that the angular response of the AMANDA array is well described by the detector simulation programs.
Fig. 24. Sky distribution of 1097 events in point source analysis. Coordinates are Right Ascension (RA) and declination (dec).

distributed on the sky as shown in Fig. 24.

Guided by the estimate of angular resolution, the sky was divided into 319 non-overlapping angular bins. The distribution of counts per sky bin is consistent with random fluctuations, which were determined by selecting all events within a declination band and randomly redistributing them in Right Ascension.

The neutrino limits were computed according to

\[
\phi_{\nu}^{\text{limit}} (E_{\nu} > E_{\nu}^{\text{min}}) = \frac{\mu(N_b, N_0)}{T_{\text{live}} \cdot \epsilon \cdot \bar{A}_{\text{eff}}} ,
\]

where \(\bar{A}_{\text{eff}}\) is the neutrino effective area weighted by the assumed neutrino energy spectrum. This quantity is related to the muon effective area shown in Figure 12. The factor \(T_{\text{live}}\) is the livetime, and \(\epsilon\) is the efficiency due to finite angular resolution and also accounts for non-central source placement within an angular bin. The term \(\mu(N_b, N_0)\) generates the 90\% CL according to Feldman and Cousins\(\text{\cite{116}}\) for signal events given the measured number of events in the bin, \(N_0\) and the expected background \(N_b\) determined
Fig. 25. Preliminary neutrino flux limit (90% CL) on point sources of high energy neutrinos as a function of declination, averaged over RA.\textsuperscript{20,113} The limit is computed for a lower energy threshold of 10 GeV. Note that the power law exponent refers to the neutrino energy spectrum. Also, neutrino absorption by the Earth is taken into account.

from the events in the declination band containing the source bin. The results of this calculation are shown in Figure 25 for various assumed spectral indices.

One example of particular interest is the search for neutrinos from Markarian 501 (see Fig. 26). The limit clearly contradicts a model where the neutrino spectrum at the source is identical to a photon spectrum inferred by Protheroe and Meyer.\textsuperscript{45} If the results of Protheroe and Meyer are confirmed, the neutrino limit provides additional evidence that nonstandard physics is involved in either the production or transit of the
Several models of neutrino flux from Markarian 501 are compared to the AMANDA limit assuming an energy dependence proportional to $E^{-2}$. The models assume that the time averaged neutrino flux is identical to the gamma ray flux observed in 1997. A second model assumes that the neutrino flux is identical to the gamma ray flux after correction for absorption by the infrared background. The inferred limits on neutrino flux apply to point sources with continuous emission (or episodic emission averaged over a time interval of approximately 0.6 years) and power law energy spectra with a fixed spectral index above the energy threshold of the detector. The limits for sources at large positive declination are comparable to the best published limits in the Southern sky.

The known source of atmospheric neutrinos can be used to confirm the absolute sensitivity of the AMANDA detector, to within a systematic error of ±30%. In a recent paper, the AMANDA collaboration provided evidence for the detection of atmospheric neutrinos. The absolute rate and angular distribution of events is consistent with predictions generated by computer simulation. The distributions of simulated
background events agree with data at low rejection levels, but disagree after stronger rejection criteria are applied. A large number of “event quality” distributions were compared at the strongest selection criteria, and they agree with atmospheric neutrino simulations, including the distribution of the number of optical modules participating in an event, $N_{OM}$. This parameter is crudely related to the energy deposited near the array. The final event sample in the search for point sources contains both atmospheric neutrinos and poorly reconstructed downgoing muons. The fraction of atmospheric $\nu$ in the sample can be enhanced at the expense of sensitivity. Experimental data is dominated initially by background events — typically downward going atmospheric muons with poorly known directions. This can be seen in figure 27, as indicated by the flat behavior for less restrictive selection criteria (quality < 4.2). As selection criteria become progressively more restrictive (increasing values along the $x$-axis), the asymptotic flattening of the ratio (experimental data)/(Signal MC A tm. $\nu$) indicates that the evolution of the experimental data becomes consistent with signal expectation in the vicinity of the plot where the (BG MC)/Exp ratio approaches zero. From this evidence (and visual inspection on the individual events), they conclude that the contamination in the atmospheric neutrino sample from known physics effects is small (< 15%) for values of the event quality parameter greater than five. Background simulations with much greater statistical precision are underway.

Figure 28 shows that the angular distribution of 188 events is also consistent with the simulated distribution of atmospheric $\nu$ events. Due to the elongated cylindrical geometry of AMANDA-B10, the acceptance shows strong dependence on zenith angle.

Thus, the angular dependence of the atmospheric neutrino sample is consistent with expectation and background simulations indicate that contamination from known physics backgrounds is small. Finally, the distribution of the number of OMs in an event is also consistent with expectation (see figure 29).

Unlike detectors with well-defined triggers that insure that particles travel within a fixed geometry, the effective area for high-energy neutrino detectors depends on muon energy and zenith angle. Also, the energy threshold of the detector must be understood in great detail for those physics objectives that involve steeply falling power law spectra, since the detected muon signals are mostly from the lowest energy neutrinos. This is particularly true for the measurement of atmospheric neutrinos. Since the designs for high energy neutrino detectors involve no obvious fiducial volume, the effective areas must be estimated by detector simulation programs. The predictions of the programs can be confirmed by studying known physics signals such as downgoing atmo-
Fig. 27. Ratios of passing rates for simulated background (BG MC), simulated atmospheric neutrino signal (Signal MC atm. $\nu$), and reconstructed experimental data (Exp) as a function of “event quality”, a variable which measures the severity of the selection criteria.\textsuperscript{20}
Fig. 28. Reconstructed zenith angle distribution. The simulated atmospheric neutrino events (shaded boxes) are normalized to data (filled circles). The vertical widths of the boxes indicate the errors computed using binomial statistics.
Fig. 29. Distribution of the number of optical modules (or “channels”) participating in each event in the atmospheric neutrino sample. The MC simulation for atmospheric and a generic spectrum $10^{-5} E^{-2} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{GeV}^{-1}$ are also shown. The channel number provides a simple, although not very precise, measure of the muon event within the array. Note that the experimental data agree with the atmospheric neutrino spectrum. From the non-observation of an excess of events with high channel counts, the AMANDA collaboration presented a preliminary limit shown in Fig. 3. The collaboration is evaluating systematic errors.
spheric muons and atmospheric neutrinos, although the systematic uncertainties in flux are rather large at the energies of interest. T. Gaisser has estimated the uncertainty in the absolute neutrino flux to be $\pm 30\%$, which is dominated by two components: the uncertainty in the flux of the primary cosmic rays and uncertainty in the kaon production cross section. AMANDA captures neutrino-induced muons with energies between 50 GeV and somewhat larger than 2 TeV (see fig. 30). The energy of the primary cosmic ray particles (which are 85% protons at these energies) responsible for the production of these neutrinos spans from 1 TeV to 10 TeV. Unfortunately, relatively few measurements of the cosmic ray spectrum exist for energies above 100 GeV, so the systematic uncertainty is $\sim 25\%$, if estimated from the variation in the absolute flux measurements.

The primary cosmic ray spectrum is not the only source of uncertainty in the flux calculations. Several sources of theoretical uncertainty are introduced due to inadequate understanding of the proton-nucleus interaction cross section. In particular, the differential kaon production cross sections are not well measured are the relevant values of Feynman $x$, and theoretical uncertainties due to model variations are relatively large. This limitation becomes important for HE neutrino detectors because kaon decay (not pion decay!) is the dominant source of atmospheric neutrinos for energies above 200 GeV. It appears that uncertainties introduced by muon tracking programs (such as Muprop or Mucedx) are relatively small except near the horizon.

Additional systematic errors are generated by uncertainties in description and implementation of detector response. Although these uncertainties are detector specific, in general, it may be instructive to discuss the issues for one of the architectures. For AMANDA, the spatial and wavelength variation of the optical parameters of the bulk ice creates distinct calibration challenges. Additional complication arises from the modification of the local optical properties associated with the re-frozen hole. Water-based detectors have a distinct advantage due to the uniformity of the optical properties. All detectors must contend with uncertainty from obscuration by cables and harness hardware, wavelength-dependent quantum efficiency and absorption by glass and optical coupling materials. The collection efficiency (the fraction of photoelectrons produced at the cathode that strike the first dynode in the photomultiplier tube) is not easy to measure in practice and it may be affected by ambient magnetic fields. The efficiency is correlated with the direction of the magnetic field relative to the dynode structure, but this information is not easily obtained for remotely deployed strings of sensors. Nor is it easy to control the azimuth angle during deployment of long strings
Fig. 30. Energy spectrum of the neutrinos responsible for the muon signal in the AMANDA detector. Figure taken from Gaisser.¹¹⁹

of cables, and no effort was made by the AMANDA collaboration to control the azimuthal orientation. Underwater detectors may be able to reduce this systematic by placing magnetometers at several locations along each string or floor. Experience has shown that the uncertainty in the detection efficiency of 1 photoelectron signals and uncertainties in the in situ geometry of the array and transit time calibration are small compared to the other uncertainties. The combined detector-related uncertainty is likely to be comparable to the flux uncertainties, but these details require additional study.

 Detection efficiency is defined as the fraction of 1 photoelectron signals from the PMT that exceed a minimum discriminator threshold. Typically, this efficiency is greater than 85%.
5 New techniques

5.1 Kilometer scale arrays

It may not be strictly accidental that deployment methods based on solid surfaces have enjoyed greater success at this moment, but there is no reason to doubt that present off-shore, deep-water efforts will develop appropriate deployment methods. In the long term, they will be challenged to demonstrate that reliability and budget issues remain competitive with AMANDA and NT-200. While the current generation of neutrino observatories represent remarkable achievements, they are only a fraction of the size ultimately required to probe the hadronic sky. In fact, all current programs have the potential for expansion to kilometer scales — it is one of the important design requirements of the current generation of neutrino detectors. Several arguments have been used to coalesce around a detector with kilometer dimensions. A survey of theoretical models of neutrino emission from GRBs and AGN produce fluxes that could be detectable with kilometer-scale detectors — with orders of magnitude bracketing the maximum and minimum flux predictions. Given the current state of theoretical uncertainty, the bigger the detector, the better the chances, although the improvement can be modest for several objectives. More persuasively, the symmetric shape and larger volumes offer significant experimental advantages: particle trajectories are reconstructed with much higher efficiency, down-going atmospheric muon background will be simpler to reject, and energy resolution will be improved, perhaps dramatically. The simulated event topologies shown in Fig. 31 and Fig. 32 illustrate the point that it may be possible to distinguish each of the three known neutrino flavors.\(^1\)

Several workshops have been held worldwide to discuss ideas for future expansion of the neutrino observatories. Scientific goals and priorities were actively debated, and the sensitivity of several strawman designs were studied. The relatively mature IceCube concept was optimized within the rough constraint of 5000 OMs distributed on fewer than 80 strings. A reasonable estimate of cost, scaling from the default analog-based technology, is $7000 per optical sensor. Systems with superior technical capabilities are being evaluated during the concept study and design phases of the project. Deployment, logistics, quality assurance, data management, data processing, data acquisition, and project management tasks introduce non-trivial extrapolations from present systems. Remotely located systems, by their very nature, tend to be manpower intensive. After engineering and technical reviews which evaluated design, construction,
Fig. 31. Schematic of a 1 PeV electron neutrino event in IceCube. The energy is contained within the volume, resulting in excellent energy resolution. The effective detection volume for this signature is 10 percent of the volume for $\nu_\mu$.

personnel, inflation, risk and contingency issues, the IceCube project is expected to cost $\sim$250M. This figure represents a reasonable lower limit for the baseline cost for any future kilometer-scale array, unless system designs require little R&D. The construction of IceCube should be completed before the end of the decade, given a reasonable projection of the drilling capacity and standard contingency estimates for construction delays. The Baikal collaboration envisions an expansion to 2000 OMs. Similarly, the NESTOR and ANTARES groups anticipate significant expansion after successful operation of the first generation detectors.

We summarize the performance and sensitivity of kilometer scale detectors to various astrophysics and physics goals. If the scaling is linear, then limits should improve by an order of magnitude or more if the system is operated for 5–10 years. If the presently operating arrays are capable of “background limited” operation, then the minimum detectable flux of future arrays scales as the square root of the product of exposure time and $V_{\text{eff}} \propto A_{\text{eff}} \times R_\mu$. Of course, there are caveats that may improve
Fig. 32. Schematic of a 10 PeV tau neutrino event in IceCube. The energy is contained within the volume, resulting in excellent energy resolution. The effective detection volume for this signature is a few percent of the volume for $\nu_\mu$. 
A few comments are in order. From table 2, it is clear that transient and point source physics provides the main experimental motivation for kilometer-scale arrays. The background can be reduced to negligible levels for transient sources with external tags from satellites or surface monitors, so sensitivity should improve linearly for kilometer-scale and larger arrays. The promise of flavor ID depends on the results of present generation of neutrino telescopes. Assuming approximately equal fluxes, then detectable fluxes of $\nu_e$ or $\nu_\tau$ should be revealed by the $\nu_\mu$ mode in the near future with present arrays. On the other hand, the lack of signal in current and next generation detectors would begin to constrain models that predict dissimilar flavor composition. Clearly, discovery by present generation detectors is preferred. If so, the next generation detectors should measure energy and angular parameters with much better resolution. Finally, the sensitivity to cascades induced by $\nu_e$ interactions is listed with a $\sqrt{}$ because next generation detectors face a background from NC interactions by atmospheric $\nu_\mu$.

Table 2. Summary of scaling relationships for various physics objectives proposed for kilometer-scale detectors relative to present generation detectors (e.g., AMANDA-II, ANTARES). The $\sqrt{}$ symbol indicates that the minimum detectable flux improves as the square root of the product of exposure time and effective volume.

<table>
<thead>
<tr>
<th>Physics Goal</th>
<th>Scaling of Sensitivity</th>
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<tr>
<td>GRB</td>
<td>linear</td>
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<tr>
<td>$&lt;\text{PeV}$ diffuse</td>
<td>$\sqrt{}$</td>
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<tr>
<td>$&lt;\text{PeV}$ point</td>
<td>linear</td>
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<tr>
<td>WIMP from Earth</td>
<td>$\sqrt{}$</td>
</tr>
<tr>
<td>WIMP from Sun</td>
<td>linear</td>
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<tr>
<td>SNa</td>
<td>$\sqrt{}$</td>
</tr>
<tr>
<td>EHE diffuse</td>
<td>$\sqrt{}$</td>
</tr>
<tr>
<td>$\nu$ oscillation (atm.)</td>
<td>requires low energy threshold</td>
</tr>
<tr>
<td>$\nu$ oscillation (Long Baseline)</td>
<td>not optimal</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>few % of $\nu_\mu$</td>
</tr>
<tr>
<td>$\nu_e$, cascades</td>
<td>$\sim 10%$ of $\nu_\mu$</td>
</tr>
<tr>
<td>$\gamma$-ray astronomy with muons</td>
<td>$\sqrt{}$</td>
</tr>
<tr>
<td>Glashow $\tilde{\nu}_e$</td>
<td>$\sqrt{}$</td>
</tr>
<tr>
<td>exotica (PBH, monopoles, etc.)</td>
<td>?</td>
</tr>
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</table>

6 Conclusions

The late Fred Reines, father of neutrino physics, was fond of saying that one should choose to work on physics topics worthy of a lifetime’s study. The broad diversity of
scientific capabilities and enormous potential of high energy neutrino astrophysics certainly qualifies. In view of the large number of possible sources discussed by theorists and even larger variation in their predicted intensity of neutrino emission, it is plausible that some will be detected by current, or soon-to-be upgraded, neutrino detectors such as AMANDA-II. If history is a guide, there will be surprises as well, as these detectors begin to survey the great canvas of the unknown.

High energy neutrino facilities are developing during an era of exciting discoveries in related areas of particle astrophysics: the detection of rapidly varying multi-TeV gamma ray signals from AGN, the discovery that GRBs are extremely distant, the reports of cosmic rays exceeding $10^{20}$ eV — beyond the Greisen-Zatsepin-Kuzmin limit — and strong evidence for neutrino oscillation from atmospheric neutrino data. At the close of the millennium, the hadronic sky is being probed with first generation neutrino detectors. They constitute bold, essential, first steps toward the realization of multimessenger astronomy.

The recently commissioned AMANDA-II detector should achieve several important milestones. For diffusely distributed sources and WIMP searches from the Earth, its sensitivity after several years of operation will be limited by the atmospheric neutrino background up to energies of $\sim 1$ PeV. Future arrays can only improve as the square root of the exposure, which is proportional to $\sim A_{eff} \times $livetime. At EHE energies, the sensitivity of AMANDA-II will be comparable to Auger (now under construction) and to future kilometer scale arrays, because the muon can be detected at great distances from the instrumented volume of the detector. Optical telescopes in space, such as the EUSO/OWL concept, represent the next real leap in sensitivity at these energies. The effective volume of AMANDA-II for $\nu_\mu$ is comparable or larger than the effective volume of cubic kilometer arrays for the $\nu_e$ or $\nu_\tau$ detection modes. Therefore, AMANDA-II (or ANTARES or NESTOR, when completed) must detect astrophysical sources of neutrinos in order for the next generation detector to determine the flavor composition of neutrino emission, unless a reasonable model can be constructed to produce $\nu_\tau$ with significantly greater efficiency than the other flavors. Just as importantly, the lack of signal in AMANDA-II offers critical guidance for the design of the next generation kilometer-scale detector. Cubic architectures may need to be re-evaluated if the horizontal $\nu_\mu$ mode becomes the most effective tool to extend the sensitivity. However, the sensitivity for GRBs, WIMPs from the Sun, and point sources should grow linearly with exposure and $A_{eff}$ because these science objectives are not background limited at the energies of interest. In some scenarios, the factor of ten or so improvement in
sensitivity can be achieved on time scales much shorter than suggested by the 7–10 year construction schedule. For example, placing 20% of the strings envisioned for IceCube around AMANDA-II creates a composite system with an effective area of $\sim 0.5$ km$^2$. Consideration of “background free” science objectives argues for optimized sensitivity for $E_\nu$ between 10–100 TeV, and fortunately, these objectives can be attacked in the short term by modest extensions to existing arrays or detectors under construction. This fortuitous condition is a consequence of the slow growth of $A_{\nu FF}$, approximately as the square root of the number of optical sensors for fixed length strings, and the presence of powerful arrays of 200-700 OMs. Not surprisingly, it is conceivable that the results from the current generation of HE neutrino detectors will strongly impact the optimal architectures for the next generation array. However, this prudence must be balanced by the competing desire to develop the next generation device as quickly as possible. Fortunately, the multi-year construction schedule anticipated for kilometer scale arrays provides an opportunity for significant modification during the latter phases of construction, if consistent with standard engineering practices. Given a carefully designed architecture for the next generation detector, it is not unreasonable to imagine that the insights revealed by the neutrino messenger will soon rival those deduced by observing the electromagnetic sky. This is the challenge for this millennium.

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