THE SEARCH FOR NEUTRINO SOURCES
BEYOND THE SUN

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The hope is that in the near future neutrino astronomy, born with the identification of thermonuclear fusion in the sun and the particle processes controlling the fate of a nearby supernova, will reach throughout and beyond our Galaxy and make measurements relevant to cosmology, astrophysics, cosmic-ray and particle physics. The construction of a high-energy neutrino telescope requires a huge volume of very transparent, deeply buried material such as ocean water or ice, which acts as the medium for detecting the particles. The AMANDA[^1] muon and neutrino telescope, now operating 4 strings of photomultiplier tubes buried in deep ice at the South Pole, is scheduled to be expanded to a 10-string array. The data collected over the first 2 years cover the 3 basic modes in which such instruments are operated: i) the burst mode which monitors the sky for supernovae, ii) the detection of electromagnetic showers initiated by PeV-energy cosmic electron neutrinos, and iii) muon trajectory reconstruction for neutrino and gamma-ray astronomy. We speculate on the possible architectures of kilometer-scale instruments, using early data as a guideline.
1 HIGH ENERGY NEUTRINO ASTRONOMY: SCIENCE REACH

Attempts to push astronomy beyond the GeV photon energy of satellite-borne telescopes, to wavelengths smaller than $10^{-16}$ cm, have been initiated over the last several decades. Doing gamma-ray astronomy at TeV energies and beyond has turned out to be a formidable challenge. Not only are the fluxes small, they are buried under a flux of cosmic-ray particles which is larger by typically two orders of magnitude. Detection by air-Cherenkov telescopes of the emission of TeV gamma rays from the Crab supernova remnant and from a pair of nearby active galaxies has proven that the problems are not insurmountable. Efforts are also underway to probe the sky in the corresponding energy region by detecting neutrinos. The information from both observations should nicely complement each other. The case for neutrino astronomy has been reinforced by the recent realization that TeV gamma rays are efficiently absorbed on interstellar light, rendering the Universe opaque for all but the very closest sources. In general, high-energy photons, unlike weakly interacting neutrinos, do not carry information on any cosmic sites shielded from our view by more than a few hundred grams of intervening matter. Hopefully, as exemplified time and again, the development of a novel way of looking into space invariably results in the discovery of unanticipated phenomena.

Are there cosmic sources of high-energy neutrinos? In heaven, as on Earth, high-energy neutrinos are produced in beam dumps which consist of a high-energy proton accelerator and a target. Gamma rays and neutrinos are generated in roughly equal numbers by the decay of pions produced in nuclear cascades in the beam dump. For every $\pi^0$ producing two gamma rays, there is a $\pi^+$ and $\pi^-$ decaying into a $\mu$ and a $\nu_\mu$. If the kinematics is such that muons decay in the dump, more neutrinos will be produced. We want to stress that in efficient cosmic beam dumps with an abundant amount of target material, high-energy photons may be absorbed before escaping the source. Laboratory neutrino beams are an example. Therefore, the most spectacular neutrino sources may have no counterpart in high-energy gamma rays.

1.1 Guaranteed Cosmic Neutrino Beams from Cosmic Ray Interactions

By their very existence, high-energy cosmic rays guarantee the existence of sources of high-energy cosmic neutrinos. Cosmic rays represent a beam of known luminosity, with particles accelerated to energies in excess of $10^{20}$ eV. They produce pions in interactions with the Earth’s atmosphere, the sun and moon, interstellar gas in our galaxy, and the cosmic photon background in our Universe. These interactions are the source of calculable fluxes of diffuse photons and neutrinos. The atmospheric neutrino beam represents a well-understood beam dump. It can be used to study neutrino oscillations over distances of 10 to $10^4$ km.

The study of extremely energetic, diffuse neutrinos produced in the interactions of the highest energy, extra-galactic cosmic rays with the microwave background is of special interest. The magnitude and intensity of this cosmological neutrino flux are determined by the maximum injection energy of the ultra-high-energy cosmic rays and by the distribution of their sources. If the sources are relatively near, at distances of order tens of Mpc, and the maximum injection energy is not much greater than the highest observed cosmic-ray energy (few $\times 10^{20}$ eV), the generated neutrino fluxes are small. If, however, the highest energy
cosmic rays are generated by many sources at large redshift, then a large fraction of their injection energy would be presently contained in gamma-ray and neutrino fluxes. The effect may be amplified if the source luminosity were increasing with redshift \( z \), i.e. if cosmic-ray sources were more active at large redshifts — “bright-phase models”\(^3\).

### 1.2 Active Galactic Nuclei: Almost Guaranteed

Although observations of PeV \((10^{15} \text{ eV})\) and EeV \((10^{18} \text{ eV})\) gamma rays are controversial, cosmic rays of such energies do exist and their origin is at present a mystery. Cosmic rays with energies up to some \(10^{14} \text{ eV}\) are thought to be accelerated by shocks driven into the interstellar medium by supernova explosions. The Lorentz force on a particle near the speed of light in the galactic magnetic field \( (\sim 3 \mu \text{G}) \) multiplied by the extent of a typical supernova shock \( (\sim 50 \text{ pc}) \) is only \(\sim 10^{17} \text{ eV}\). Our own Galaxy is too small, and its magnetic fields too weak, to accelerate particles to \(10^{20} \text{ eV}\). This energy should require, for instance, a 100 \(\mu\)G field extending over thousands of light years. Such fields exist near the supermassive black holes which power active galactic nuclei (AGNs). This suggests the very exciting possibility that high-energy cosmic rays are produced in faraway galaxies and carry cosmological information — on galaxy formation, for example.

Recent observations of the emission of TeV \((10^{12} \text{ eV})\) photons from the giant elliptical galaxy Markarian 421\(^4\) may represent confirming evidence. Why Mrk 421? Although Mrk 421 is the closest of these AGNs, it is one of the weakest. The reason its TeV gamma rays are detected whereas those from other, more distant, but more powerful, AGNs are not, must be that the TeV gamma rays suffer absorption in intergalactic space through the interaction with background infrared photons. The absorption is, however, minimal for Mrk 421 with \(z\) as small as 0.03. In a study of nearby galaxies the Whipple instrument detected TeV emission from the blazar Mrk 501 with redshift \(z = 0.018\), a source which escaped the scrutiny of the Compton GRO observatory. All this strongly suggests that many AGNs may have significant, very high-energy components, but that only Mrk 421 and 501 are close enough to be detected by gamma-ray telescopes. The opportunities for neutrino astronomy are wonderfully obvious. It is likely that neutrino telescopes will contribute to the further study of the high-energy astrophysics pioneered by space-based gamma-ray detectors, such as the study of gamma-ray bursts and the high-energy emission from quasars.

Powerful AGNs at distances \(\sim 100 \text{ Mpc}\) and with proton luminosities \(\sim 10^{45} \text{ erg/s}\) or higher are clearly compelling candidates for the cosmic accelerators of the highest energy cosmic rays. Their luminosity often peaks at the highest energies, and their proton flux, propagated to Earth, can quantitatively reproduce the cosmic-ray spectrum above \(10^{18} \text{ eV}\)\(^5\). Acceleration of particles is by shocks in the jets (or, possibly, in the accretion flow onto the supermassive black hole which powers the galaxy) which are a characteristic feature of these radio-loud, active galaxies. Inevitably, beams of gamma rays and neutrinos from the decay of pions appear along the jets. The pions are photoproduced by accelerated protons interacting with optical and UV photons in the galaxy which represent a target density of \(10^{14} \text{ photons per cm}^{-3}\).

A simple estimate of the AGN neutrino flux can be made by assuming that a neutrino is produced for every accelerated proton. This balance is easy to understand once one realizes that in astrophysical beam dumps the accelerator and production target form a symbiotic
system. Although larger target mass may produce more neutrinos, it also decelerates the protons producing them. Equal neutrino and proton luminosities are therefore typical for the astrophysical beam dumps considered[2] and implies that:

\[ 4\pi \int dE \left( \frac{E dN_\nu}{dE} \right) \sim L_{CR} \sim 7.2 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}, \]  

which simply states that the sources generate 1 neutrino for each observed high-energy cosmic ray. Conservatively, the luminosity \( L_{CR} \) has been obtained by only integrating the highest energy component of the cosmic-ray flux above \( 10^{17} \) eV. These particles, above the “ankle” in the spectrum, are almost certainly extra-galactic and are observed with a \( E^{-2.71} \) power spectrum. Assuming an \( E^{-2} \) neutrino spectrum, the equality of cosmic-ray and neutrino luminosities implies:

\[ E \frac{dN_\nu}{dE} = \frac{1}{4\pi} \frac{7.5 \times 10^{-10}}{E (\text{TeV})} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \]  

The flux of Eq. 2 is at the low end of the range of fluxes predicted in models where acceleration is in shocks in the jet[5] and accretion disc[6, 7]; see Fig. 1. It is clear that our estimate is rather conservative because the proton flux reaching Earth has not been corrected for absorption in ambient matter in the source and in the interstellar medium. The neutrino flux corresponds to 300 upcoming muons per year in a neutrino detector with \( 10^6 \) m\(^2\) effective area. Model predictions often exceed this estimate by several orders of magnitude.

![Figure 1: Summary of neutrino fluxes.](image)

1.3 Interdisciplinary Aspects of High Energy Neutrino Astronomy

The neutrino sky above 1 GeV is summarized in Fig. 1. Shown is the flux from the galactic plane as well as a range of estimates (from generous to conservative) for the diffuse
fluxes of neutrinos from active galaxies and from the interaction of extragalactic cosmic rays with cosmic photons. At PeV energies and above, all sources dominate the background of atmospheric neutrinos.

It should be emphasized that high-energy neutrino detectors are multi-purpose instruments whose science-reach touches not only astronomy and astrophysics, but also particle physics, cosmic-ray physics, glaciology and paleoclimatology (oceanography) for the ice (water) telescopes. Here we enumerate issues which represent, along with the science already discussed, high priorities in considerations for the design and operation of high-energy neutrino detectors.

i) Study of neutrino oscillations by monitoring the atmospheric neutrino beam
Recent underground experiments have given tantalizing hints for neutrino oscillations in the mass range $\Delta m^2 \gtrsim 3 \times 10^{-2} \text{eV}^2$ [2]. High energy neutrino telescopes may be able to study and extend this mass range by measuring the zenith angle distribution of atmospheric neutrino-induced muons. For angles of arrival of atmospheric neutrinos ranging from vertically upward to downward, the neutrino path length (distance from its production to its interaction in the deep detector) ranges from the diameter of the Earth ($\sim 10^4 \text{km}$) to the height of the atmosphere ($\sim 10 \text{km}$). With sufficient energy resolution it is possible to observe the oscillatory behavior of the flux over the oscillation length of several hundred kilometers suggested by the “atmospheric neutrino anomaly”. Only a mature and well-calibrated instrument can be expected to do this precision measurement.

ii) Search for neutrinos from annihilation of dark matter particles in our Galaxy
An ever-increasing body of evidence suggests that cold dark matter particles constitute the bulk of the matter in the Universe. Big-bang cosmology implies that these particles have interactions of order the weak scale, i.e. they are WIMPs [8]. We know everything about these particles (except whether they really exist!). We know that their mass is of order of the weak boson mass; we know that they interact weakly. We also know their density and average velocity given that they constitute the dominant component of the density of our galactic halo as measured by rotation curves. WIMPs will annihilate into neutrinos with rates that are straightforward to estimate; massive WIMPs will annihilate into high-energy neutrinos.

WIMP detection by high-energy neutrino telescopes is greatly facilitated by the fact that the sun represents a dense and nearby source of cold dark matter particles. Galactic WIMPs, scattering off protons in the sun, lose energy. They may fall below escape velocity and be gravitationally trapped. Trapped WIMPs eventually come to equilibrium temperature and stop near the center of the sun. While the WIMP density builds up, their annihilation rate into lighter particles increases until equilibrium is achieved where the annihilation rate equals half of the capture rate. The sun has thus become a reservoir of WIMPs which annihilate predominantly into heavy quarks and, for the heavier WIMPs, into weak bosons. Their leptonic decays turn the sun into a source of high-energy neutrinos with energies in the GeV to TeV range, rather than in the keV to MeV range typical for neutrinos from thermonuclear burning. The neutrino flux of WIMP origin is only a function of the WIMP mass. In standard cosmology their capture and annihilation interactions are weak, and dimensional analysis is sufficient to compute the neutrino flux from their measured density in our galactic halo. The result is shown in Fig. 2. The interpretation of the above arguments in the framework of
supersymmetry is explicitly stated in Ref. [2].

![Graph showing event rates of solar, high-energy neutrinos of WIMP origin.](image)

Fig. 2: Event rates of solar, high-energy neutrinos of WIMP origin.

We emphasize that experimental data, dimensional analysis and Standard Model particle physics are sufficient to evaluate the performance of detectors searching for such particles either directly (e.g. by their scattering in germanium detectors), or indirectly (by observing their annihilation into neutrinos in a high-energy neutrino telescope). The competing direct method is superior only if WIMP interact coherently and their mass is lower or comparable to the weak boson mass. In all other cases, i.e. for relatively heavy WIMPs and for WIMPs interacting incoherently, the indirect method is competitive or more powerful. For heavier WIMPS the indirect detection technique is especially effective and should easily extend to WIMP masses $>500$ GeV, the upper limit reachable by future accelerators. A kilometer-size detector probes WIMP masses well into the TeV range, beyond which they are excluded by cosmological considerations. The rule of thumb is that a kilogram of germanium target is roughly equivalent to a $10^4$ m$^2$ neutrino telescope.

### iii) Gamma-Ray Astronomy with Neutrino Telescopes

The potential versatility of neutrino telescopes is dramatically illustrated by the recent suggestion of using neutrino detectors as gamma-ray telescopes. Underground detectors are designed to measure the directions of up-coming muons of neutrino origin. They can, of course, also observe down-going muons which originate in electromagnetic showers produced by gamma rays in the Earth’s atmosphere. Although gamma-ray showers are muon-poor, it can be shown that they produce a sufficient number of muons to detect the sources observed by GeV and TeV telescopes. With a gamma-ray threshold higher by one hundred and a probability of muon production by the gammas of about 1%, even the shallower, lower threshold AMANDA and Lake Baikal detectors have to overcome a $10^{-4}$ handicap. They can nevertheless match the detection efficiency of a GeV-photon satellite detector because their effective area is larger by a factor $10^4$. 


The hundred-GeV muons observed in shallow detectors are sufficiently energetic to leave tracks that can be adequately measured by the Cherenkov technique. The direction of the parent photon can be inferred with degree accuracy. They originate in TeV gamma showers whose existence has been demonstrated, at least for two galactic and two extra-galactic sources, by air-Cherenkov telescopes. A multi-TeV air shower will produce a 100 GeV muon with a probability of order 1%, sufficient to observe the brightest sources using relatively modest size detectors with effective area of order 1000 m$^2$ or more. Although muons from such sources compete with a large background of down-going cosmic-ray muons, they can be identified provided the detectors achieve sufficient effective area and angular resolution.

The key here is that for doing astronomy the muons must be sufficiently energetic for accurate reconstruction of their direction. Very energetic muons on the other hand are rare because they are only produced by higher energy gamma rays whose flux is suppressed by the decreasing flux at the source and by absorption on interstellar light. There is however a window of opportunity for muon astronomy in the 100 GeV energy region which nicely matches the threshold energies of the AMANDA and Lake Baikal detectors. It is conceivable that instruments in their developing stages detect gamma-ray sources before meeting the considerable challenge of identifying up-going muons of neutrino origin in the large backgrounds of down-going cosmic-ray muons.

### iv) Supernova Search

The AMANDA detector has the capability to observe the thermal neutrino emission from supernovae\[10\], even though the nominal threshold of the detector exceeds supernova neutrino energies by several orders of magnitude. The AMANDA 4-string detector is presently monitoring our entire Galaxy and can do so over decades in a most economical fashion. We will present details further on.

It is intriguing that, just as for the detection of AGNs, numerical studies\[2, 11\] of the other science goals also point to the necessity of commissioning telescopes with at least $10^5$ m$^2$ effective area, or more than $10^7$ m$^3$ volume; see e.g. Figs. 1, 2.
2 HIGH ENERGY DETECTORS: AREA VERSUS THRESHOLD

In order to achieve the large effective detection volumes required by the science, one optimizes the detector at high energies where: i) neutrino cross sections are large and the muon range is increased to several kilometers, ii) the angle between the muon and parent neutrino is less than \(\sim 1\) degree, and iii) the atmospheric neutrino background is small. High energy neutrino telescopes, just like the pioneering IMB and Kamiokande detectors, use phototubes to detect Cherenkov light from muons, but optimize their detector architecture to perform TeV astronomy. Inevitably the threshold is increased to \(\sim 1\) GeV from the MeV range characteristic for IMB and Kamiokande. Such instruments can be operated as a muon tracking device, a shower calorimeter and a burst detector. We discuss this next.

- In a Cherenkov detector the direction of the neutrino is inferred from the muon track which is measured by mapping the associated Cherenkov cone traveling through the detector. The arrival times and amplitudes of the Cherenkov photons, recorded by a grid of optical detectors, are used to reconstruct the direction of the radiating muon. For neutrino astronomy the challenge is to record the muon direction with sufficient precision to unambiguously separate the much more numerous down-going cosmic-ray muons from the up-coming muons of neutrino origin, using a minimum number of optical modules (OMs). The down-going muons may reveal TeV gamma-ray sources, as previously discussed. Critical parameters are the transparency of the Cherenkov medium, the depth of the detector, which determines the level of the cosmic-ray muon background, and the noise rates in the optical modules which will sprinkle the muon trigger with false signals. Sources of noise include radioactive decays such as decay of potassium-40 in water, bioluminescence and, inevitably, the dark current of the photomultiplier tube.
- The grid of optical modules can also map PeV electromagnetic showers initiated by electron neutrinos, e.g. showers from the production of intermediate bosons in the interactions of cosmic electron neutrinos with atomic electrons in the detector. This technique can also detect the bremsstrahlung of very high-energy muons of neutrino origin. Notice that there is no atmospheric background for such events once their energy exceeds 10 TeV, although the precise value is model-dependent; see Fig. 1. Detection of neutrinos well above this energy would constitute the discovery of cosmic sources.
- The passage of a large flux of MeV-energy neutrinos from a supernova burst lasting several seconds will be detected as an excess of single counting rates in all individual optical modules of a neutrino telescope. The interaction of \(\bar{\nu}_e\) with hydrogen produces copious numbers of positrons with tens of MeVs of energy. These will yield signals in all OMs during the (typically 10 second) duration of the burst. Such a signal, even if statistically weak in a single OM, will become significant for a sufficient number of OMs. The same method may be used to search for gamma ray bursts provided they are, as expected in currently favored models, copious sources of neutrinos.
3 BUILDING UPON FIRST DATA FROM THE FOUR-STRING AMANDA ARRAY

3.1 Calibration of the AMANDA Detector

Using a hot-water drill, four strings with 20 OMs each were positioned at depths between 800 and 1000 meters in the South Pole ice. The optical modules consist of an 8-inch EMI 9353/9351 phototube (PMT) and nothing else. The time and amplitude of the signal are carried over a coaxial cable to the electronics positioned at the surface above the detector. The high voltage is brought down to the OMs on the same cable. During deployment 3 out of 80 OMs were lost. Four other OMs, although operating, are to a varying degree problematic. Most of these problems were associated with the first string. We adjusted our deployment procedures and, except for a single OM, strings 3 and 4 are perfect. Operation of the detector has been totally stable since its deployment almost two years ago. Also deployed was a laser calibration system which pulses light into a nylon diffuser ball positioned 30 cm below each OM. This system is fully functional.

With 4 AMANDA strings as well as a laser calibration system in place we were able to calibrate ice as a particle detector. Our detailed measurements of in-situ ice exploited the laser calibration system as well as the light emitted by cosmic-ray muons. A YAG laser was used to drive a dye laser which pulses light of different colors into the fiber optic calibration system. A nylon sphere deployed with each photomultiplier tube (PMT) isotropically radiated light which was detected by other PMTs. The time resolution of each PMT is 2 ns. By measuring the distribution of arrival times of the pulses, both the optical properties of the ice and the position of the tubes were accurately derived. We found that:

- The absorption length of deep South Pole ice has the astonishingly large value of $\sim 310$ m for the 350 to 400 nm light to which the PMTs are sensitive; see Fig. 3. A value of only 8 m had been anticipated from laboratory measurements. For many applications the detector volume scales linearly with the absorption length, e.g. for supernova detection. The results in Fig. 3 were first obtained by studying the timing distribution of laser pulses at different distances of the source. Given their importance, we have verified them with 3 independent measurements: i) by counting photons as a function of the distance from the laser pulse (rather than measure their timing), ii) by studying the propagation of the Cherenkov photons radiated by cosmic-ray muons, and iii) by studying coincident muon events between AMANDA and the SPASE air shower array at the surface.

Though at first surprising, these results are understandable in terms of conventional optics. The PMTs operate in a range of wavelengths where neither atomic nor molecular excitations absorb the light. It seems that, in this color interval, scattering has previously been confused with absorption for ice as well as other transparent crystals. Calculations of the magnitude of scattering in defect-free media and in media containing point defects and dislocations show that the largest contribution to scattering (with a Rayleigh $\lambda^{-4}$ dependence) is due to dislocations that have been decorated with impurities. The approximately $\lambda^{-4}$ structure often seen near the minimum in published absorption spectra of transparent solids such as LiF, NaCl, diamond, BaTiO$_3$, and ice, is probably due to scattering from small defects, not absorption. The superb transparency is a direct consequence of the high purity of the deep ice.
Fig. 3: The absorption length of light in ice as a function of its color. Shown are the results of measurements using the AMANDA laser calibration system (diamonds) and the Cherenkov photons from muons (dotted line). The results for bubble-free laboratory ice are shown for comparison.

- Ice contains residual air bubbles at 1000 m. Studies of the scattering of laser light on residual bubbles reveal a linear decrease of their density between 800 and 1000 m in the AMANDA 4-string detector. The effective scattering length increases from 0.25 to 1 meter at depths of 800–1000 km. At higher pressure (greater depth) air bubbles transform indeed into a solid form of ice. Air hydrate crystals are formed in a phase transition from hexagonal ice + air bubbles to hexagonal ice + cubic clathrate hydrate crystals. Independent of any theoretical model, microscopic studies of ice cores from various Greenland and Antarctic sites show that bubbles and clathrate crystals co-exist over depths of hundreds of meters but that in no case bubbles survive to depths greater than 1550 m. Ice is bubble-free at 1250 m (Vostok), 800 m (Dome C), 1100 m (Byrd), 1400 m (Camp Century), and 1550 m (Dye-3). The last two measurements are in very young Greenland ice. With our new drilling capabilities, future deployment beyond 1550 m should not represent a problem.
- Ice is a sterile medium. The background noise measured in the in-situ OMs is determined by the dark current of the photomultiplier and measured to be only $\sim 1850$ Hz, a factor 30 lower than in ocean water.

3.2 AMANDA events: A First Glimpse at Muon Tracking, High Energy Showers and Supernova Search

- Muon trigger. With the complete calibration results, obtained during the 94–95 Antarctic campaign, we have been able to simulate the performance of the detector in detail. Reconstruction of muon trajectories in the presence of large-angle scattering on bubbles is straightforward, now that the propagation of light in the detector medium is adequately understood. The detector operation more closely resembles that of a drift chamber rather
than a Cherenkov detector. Using the timing information obtained with the laser calibration system, we determine, for each optical module in the trigger, the expected number of photons and their arrival times as a function of the module’s impact parameter relative to the muon track. The expected spread in arrival time is also known. This information is used to determine the muon direction; see Fig. 4. By simply fitting a plane wave to events subjected to only a multiplicity cut (>6) and a time-over-threshold cut, most muons can be reconstructed with sufficient precision (better than 5 degrees in zenith angle) to obtain trigger rates and a zenith angle distribution consistent with that expected for cosmic-ray muon rates; see Fig. 5. One should realize here that although the timing information is degraded by scattering, the clarity of the ice compensates as in minimum-bias muon triggers (6 OMs on 3 strings) over 30 OMs report time and amplitude information. More accurate reconstruction should be achieved by refitting tracks using only OMs triggered with short times and large amplitudes. This work is in progress.

Fig. 4: a) [Top left] Example of a muon bundle triggered in coincidence with the SPASE air shower array. The size of the dots represent the amplitude for each PMT reporting in the trigger. Times are listed next to the corresponding dot starting around 2500 ns, the time delay between surface and deep detector.
b) [Bottom left] Arrival times (in nanoseconds) and [bottom right] trigger rates (in events per day with a given OM multiplicity) are simulated for a range of assumptions for the absorption length of light at the peak acceptance of the PMTs.
Fig. 5: The measured angular distribution of cosmic-ray muons is compared to the expected one. Shown are raw AMANDA data after a multiplicity (more than 6 PMTs) and a time-over-threshold cut only; track reconstruction has not been attempted.

- **Shower Trigger.** The AMANDA detector represents by over an order of magnitude the largest effective volume instrumented for the detection of PeV electromagnetic showers. Such showers are produced by cosmic electron-neutrinos or by the radiation of very high-energy muons. Once their energy exceeds 100 TeV the background from atmospheric muons and neutrinos should be negligibly small for the effective area of the present four strings; see Fig. 1. The residual bubbles cause the Cherenkov photons from high-energy cascades to diffuse inside the detector. The light radially propagates from the vertex of the interaction leaving a characteristic imprint which is easy to detect and reconstruct. We have simulated the response of the 4-string detector to 1 TeV to 10 PeV cascades by propagating the shower photons according to simulations that quantitatively describe the calibration measurements. We find that due to the large number of photons generated by such cascades, the time of arrival of the first photon detected by an OM (Leading Edge time or LE) has a small timing error provided the cascade starts within approximately 40 meters of the PMT. The energy of an event can be determined from a fit of LE time and of TOT (time-over-threshold) versus distance to the PMT; see Fig. 6. The very large TOTs at intermediate distances result from the rather broad distribution of the photon arrival time created by the scattering on bubbles. The key here is that because of the delay of the photons by scattering on bubbles the PMT signal now adequately differentiates between a small signal originating nearby and a large signal far away.

![Fig. 6: Simulated leading edge time [left] and time-over-threshold [right] of PMTs as a function of their radial distance to the vertex of 1 TeV and 10 PeV cascades.](image)
Candidate cascade events are extracted from the AMANDA data stream by selecting events with a duration of more than 5.5 microseconds that contain at least two unusually large TOT values; a candidate event of 4 TeV energy is shown in Fig. 7. The present detector can clearly be operated as a crude calorimeter with an effective volume for such showers of order $10^6 \text{ m}^3$. This may lead to detection or improved upper limits on the fluxes of neutrinos from AGN.

![Shower event with an energy of 4 TeV. The ordinate is PMT time (ns); the abscissa is PMT number. A shower starts at PMT 49 in string 8 and propagates through the array. It reaches strings 0,9 at PMTs 10,69 and, subsequently, string 1 at PMT 29. Notice the faster propagation of light along strings in the downward direction (larger PMT number) as a result of the reduced density of bubbles. The event is fitted as a pure electromagnetic shower; there is no evidence for Cherenkov emission from a muon track which is characterized by small TOTs at short times. It is an electron-neutrino candidate.](image)

**Supernova Trigger.** The discovery of the large absorption length of Cherenkov light in ice has transformed AMANDA into a supernova detector. The effective detection volume is indeed proportional to the absorption length in the wavelength region where the PMTs detect Cherenkov photons, an increase by a factor $310/8$. A specialized trigger has been installed and detailed simulations have been performed of the response of the detector to the stream of low-energy neutrinos produced by a supernova. The effective radius of a module for detecting the electrons made by supernova neutrinos is $\sim 7 \text{ m}$, yielding a counting rate of 300 events per optical module for the duration of a supernova at the center of our Galaxy. This increase over the background counting rate of 1850 Hz in 73 (stable) optical modules combines to a $17 \sigma$ observation for a galactic supernova of the 1987A type. Theoretically, such a signal is not mimicked by a dedicated supernova data acquisition system over the relevant time scale of $10^2 \text{ years}$. The system has been taking uninterrupted data since February 1995. We have found that the noise distributions of the PMTs are well described by Gaussian distribution although the width is 3 times Poissonian. A detailed analysis of the detector’s counting rate patterns is in progress.
4 WHAT NEXT?

Even though the ultimate goal of neutrino astronomy is to commission kilometer-size instruments, the immediate target is to demonstrate the adequate performance of water and ice as particle detectors using a technology that can be scaled up in a cost-effective way. For the AMANDA project the next priority is to study the scattering length as a function of depth, especially below 1500 meters where scattering of the light is determined by the scattering on dust, air hydrates and crystal boundaries. One of the advantages of building a detector in polar ice is that deployment of OMs is not restricted to a rigid, predesigned frame. Future OMs will be deployed below 1.5 km in order to avoid residual bubbles and improve reconstruction of muon trajectories. (We do not exclude the possibility to expand the kilometer-level detector as well, depending on its performance as a shower calorimeter previously described). Larger spacings between strings, as well as between OMs on a string, will be implemented in order to exploit the $\sim 300$ m absorption length. In Antarctic summer 95–96 six strings will be deployed to form a pyramid in which the existing 4 strings form an apex at 0.8 to 1 km. The base, at 1.5 to 1.9 km, will consist of a large pentagon of 5 strings surrounding a central string on a circle of 40–60 meters radius; see Fig. 8. Each string will contain 20 OMs with a vertical spacing of 20 m.

![AMANDA Architecture](image)

Fig. 8: AMANDA Architecture
The architecture for the deployment of OMs after 1996 will, obviously, be adjusted for any science, calibration or technological information obtained. It is important to draw a first lesson from the initial AMANDA experience. The present activities are dominated by muon reconstruction, mostly for attempting gamma-ray astronomy, the search for TeV–PeV showers and the implementation of the supernova watch. None of these topics are even mentioned in the proposal written 4 years ago. This is exploratory science and surprises should be expected. The instrumentation itself, frozen into the deep ice, will not become obsolete, and the electronics and logic located at the surface can be updated as new ideas arise.

Future deployments will follow science as well as calibration of the ice as a particle detector below 1 km. Given a number of OMs, design choices typically fall between extremes: dense packing of the OMs in order to achieve good angular resolution and low threshold, or instrumenting the largest volume of ice in order to achieve large telescope area.

- **Dense-Pack Architecture.** The first approach, pioneered by the DUMAND[14] and Baikal[15] experiments, achieves the lowest thresholds and is therefore ideal for WIMP or neutrino oscillation searches. One can imagine backfilling the deep detector shown in Fig. 8, especially if the scattering length in bubble-free ice turns out to be much smaller than the absorption length. Such detectors achieve large effective area by detecting muons far outside the instrumented volume. The range of TeV-muons is indeed several kilometers. A well-known handicap of these detectors is that the energy of the muon is only determined on a logarithmic scale, e.g. by measuring quantities such as the number of optical modules triggered by the muon. The resolution is such that energy will be measured quantized in 1,10,100,1000 TeV increments. Further problems arise because of the confusion of an energetic muon with a bundle of low energy ones.

- **Distributed Architecture.** The alternative approach where large volumes of ice are instrumented with widely spaced OMs looks very promising, especially after the first experience with analyzing large shower events. It emphasizes the search for the rare very high-energy events expected from active galaxies. When the instrumented array dimensions approach 1km, then the sensitivity to search for AGN neutrinos is about the same whether one observes cascades or muon tracks. For smaller arrays this is not true since you can detect cascades only in the relatively small instrumented volume, while you can see muons which originate from kilometers away. This benefit is reduced (or the challenge to reconstruct muons far outside the detector does not have to be met) once the array size is comparable to the characteristic muon range. The power to search for AGN neutrinos is now similar for muon tracks or cascades. Also, for large arrays operated as shower detectors, scattering represents no limit to the physics objectives as already illustrated by the deployed AMANDA detector.

The energy resolution of such a detector may be much better that that of a “dense-pack” instrument. Simulations of the energy resolution of the deployed AMANDA detector using quantized 1,10,100,1000 TeV increments, suggests a resolution of 0.25 in \( \log(\frac{E_{\text{measured}}}{E_{\text{input}}}) \). This assumes a Gaussian resolution function and, at present, this has not been demonstrated. It does suggest however that the muon energy may eventually be measured to “a factor”, a precision unlikely to be matched by a “dense-pack” detector.
Does this approach preclude the observation of point sources? Probably not. Track reconstruction is much easier once the origin of one (or more!) cascades reveals a point (points) on the track. With only one known vertex, 2 rather than 5 parameters are to be fitted. Track reconstruction may even work in the presence of small scattering lengths and bubbles.

The long absorption lengths in ice really seduces one to construct a cheap kilometer-scale detector with relatively high threshold, probably not much less than 1 TeV. Once the instrumented volume reaches that size, the details of the ice properties become relatively unimportant or, rather, cease to be show-stoppers. The approach is reminiscent of the instruments detecting acoustic or radiowave signals produced by ultra-TeV neutrinos or muons. These methods were developed to exploit the large absorption length of acoustic and giga-Hertz radiowaves in water or ice, allowing the deployment of detector elements on a grid with large spacings. In the case of ice, light shares that property. From all other points of view light has significant advantages: PMTs represent a cheap and well-understood technology, the ambient backgrounds are understood and the threshold of the detector is lower by one or, most likely, several orders of magnitude.

Ice is a natural place to build “distributed” detectors. The duration of triggered events increases with the physical size of the detector and so does, inevitably, the number of noise hits confusing trigger reconstruction. On a kilometer scale this becomes a problem, especially when using large OMs. In sterile ice the challenge is easier to meet though it is not to be ignored.

The National Science Foundation has funded the deployment of an additional 400 OMs following the completion of the detector shown in Fig. 8. How to build up this prototype is a complex issue, as the previous discussion illustrates. It involves science choices. The answers may become obvious after study of the ice properties below 1 km. If not, hybrid detectors combining both architectures not only suggest themselves, they have already been proposed.

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