Astroparticle Physics with High Energy Neutrino Telescopes

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Abstract

The first optical modules of the Baikal high energy neutrino telescope have recently been deployed. Commissioning of the AMANDA, DUMAND and NESTOR detectors will follow soon. Before discussing the detectors we review the arguments that pinpoint 0.1 km$^2$ as the natural scale of a neutrino telescope. Though present detectors do not quite reach this goal, their techniques, if successful, can be exploited to build km$^2$ detectors for a cost not exceeding one hundred million dollars. Motivations for the construction of km$^2$ deep underground detectors include

i) neutrino astronomy and the search for cosmic accelerators: we will focus our discussion on recent claims that active galactic nuclei are the accelerators of the highest energy cosmic rays. If this is true they are inevitably high-flux sources of very energetic neutrinos;

ii) neutrino oscillations using the atmospheric neutrino beam: we emphasize the unique capability of surface neutrino telescopes, i.e. detectors positioned at a depth of roughly 1 km, to detect neutrinos and muons of similar energy. In a $\nu_\mu$ oscillation experiment one can therefore tag the $\pi$ progenitor of the neutrino by detecting the muon produced in the same decay. This eliminates the model dependence of the measurement inevitably associated with the calculation of the primary cosmic ray flux. We will show that planned surface neutrino telescopes probe the parameter space $\Delta m^2 \gtrsim 10^{-3}$ eV$^2$ and $\sin^2 2\theta \gtrsim 10^{-3}$ using this technique. Recently underground experiments have given hints for neutrino oscillations in this mass range.

iii) the search for neutrinos from the annihilation of dark matter particles in our galaxy;

iv) the possibility to observe the thermal neutrino emission from supernovae even though the nominal threshold of the detectors exceeds the neutrino energy by several orders of magnitude.

v) to make the serendipitous discovery. No astronomical telescope, detecting photons of any wavelength, has ever viewed sites in the Universe shielded by more than a few hundred grams of matter.

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1. Introduction

With supernova 1987A underground detectors became very credible astronomical telescopes[1, 2]. Their earlier mission was mainly particle physics: proton decay, neutrino oscillations and the like. It was soon realized, however, that the natural scale of a neutrino telescope is 1 km$^2$. The only guaranteed source of high energy neutrinos I am aware of is the plane of our own galaxy. This source is guaranteed by the very existence of high energy cosmic rays. A flux of diffuse neutrinos from decay of charged pions is produced when cosmic ray nuclei interact with interstellar gas. Even from the direction of a dense target such as the galactic center, the ratio of neutrinos and cosmic rays is less than $10^{-4}$ and a detection area of at least 1 km$^2$ is required to observe the effect[3].

Fortunately, astronomy, as well as the search for neutrino mass, for dark matter, and the detection of supernova is possible with smaller detectors.

2. The Gamma-Neutrino Connection

Although observations of PeV (10$^{15}$ eV) and EeV (10$^{18}$ eV) gamma-rays are controversial, cosmic rays of such energies do exist and their origin is at present a mystery. The cosmic-ray spectrum can be understood, up to perhaps 1000 TeV, in terms of shock wave acceleration in galactic supernova remnants[4]. Although the spectrum suddenly becomes steeper at 1000 TeV, a break usually referred to as the “knee,” cosmic rays with much higher energies are observed and cannot be accounted for by this mechanism. This can be understood by simple dimensional analysis as the EMF in the supernova shock is of the form

$$E = ZcBRc,$$  

where $B$ and $R$ are the magnetic field and the radius of the shock. For a proton Eq. (1) yields a maximum energy

$$E_{\text{max}} = \left[10^5 \text{TeV}\right]\left[\frac{B}{3 \times 10^{-6} \text{G}}\right]\left[\frac{R}{50 \text{pc}}\right]$$

and therefore $E_{\text{max}}$ is less than 10$^5$ TeV for the typical values of $B, R$ shown. The actual upper limit is much smaller than the value implied by the dimensional argument.

Cosmic rays with energy in excess of 10$^{20}$ eV have been observed. The measured spectrum tells us that 10$^{34}$ particles are accelerated to 1000 TeV energy every second. We do not know where or how. We do not know whether they are protons or iron or something else. If their cosmic accelerators exploit the 3$\mu$Gauss field of our galaxy they must be much larger than supernova remnants in order to reach 10$^{21}$ eV energies. Eq. (1) indeed requires that their scale be of order 30 kpc and this exceeds...
the dimensions of our galaxy. Although imaginative arguments exists to avoid this impasse, an attractive alternative is to look for large size accelerators outside the galaxy. Nearby active galactic nuclei (quasars, blazars...) distant by order 100 Mpc are the obvious candidates. With magnetic fields of tens of µGauss over distances of kpc acceleration to $10^{21}$ eV is possible; see Eq. (1).

One can visualize the AGN accelerator in a very economical way in the Blanford-Zraelek mechanism. The horizon of the black hole acts as a rotating conductor immersed in an external magnetic field. By simple dimensional analysis this creates a voltage drop

$$\frac{\Delta V}{10^{20} \text{volts}} = \frac{a}{M_{\text{BH}}} \frac{B}{10^4 \text{G}} \frac{M_{\text{BH}}}{10^9 M_\odot},$$

(3)
corresponding to a luminosity

$$\frac{L}{10^{45} \text{erg s}^{-1}} = \left( \frac{a}{M_{\text{BH}}} \right)^2 \left( \frac{B}{10^4 \text{G}} \right)^2 \left( \frac{M_{\text{BH}}}{10^9 M_\odot} \right)^2.$$  

(4)

Here $a$ is the angular momentum per unit mass of a black hole of mass $M_{\text{BH}}$.

All this was a theorist’s pipe dream until recently the Whipple collaboration reported the observation of TeV ($10^{12}$ eV) photons from the giant elliptical galaxy Markarian 421\[5\]. With a signal in excess of 6 standard deviations, this is the first convincing observation of TeV gamma rays from outside our Galaxy. That a distant source such as Markarian 421 can be observed at all implies that its luminosity exceeds that of galactic cosmic accelerators such as the Crab, the only source observed by the same instrument with comparable statistical significance, by close to 10 orders of magnitude. More distant by a factor $10^5$, the instruments’s solid angle for Markarian 421 is reduced by $10^{-10}$ compared to the Crab. Nevertheless the photon count at TeV energy is roughly the same for the two sources. The Whipple observation implies a Mrk 421 photon luminosity in excess of $10^{43}$ ergs per second. It is interesting that these sources have their highest luminosity above TeV energy, beyond the wavelengths of conventional astronomy.

Why Markarian 421? Whipple obviously zoomed in on the Compton Observatory catalogue of active galaxies (AGN) known to emit GeV photons. Markarian, at a distance of barely over 100 Mpc, is the closest blazar on the list. Stecker et al.\[6\] recently pointed out that TeV gamma rays are efficiently absorbed on infra-red starlight, anticipating that TeV astronomers will have a hard time observing powerful quasars such as 3C279 at a redshift of 0.54. Production of $e^+e^-$ pairs by TeV gamma rays interacting with IR background photons is the origin of the absorption. The absorption is, however, minimal for Mrk 421 with $z = 0.03$, a distance close enough to see through the IR fog.

This observation was not totally unanticipated. Many theorists\[7\] have identified blazars such as Mrk 421 as powerful cosmic accelerators producing beams of very high energy photons and neutrinos. Acceleration of particles is by shocks in the jets (or, possibly, in shocks in the accretion flow onto the supermassive black hole
which powers the galaxy) which are a characteristic feature of these radio-loud active galaxies. Many arguments have been given for the acceleration of protons as well as electrons. Inevitably beams of gamma rays and neutrinos from the decay of pions appear along the jets. The pions are photoproduced by accelerated protons on the dense target of optical and UV photons in the galaxy. The latter are the product of synchrotron radiation by electrons accelerated along with the protons. There are of course no neutrinos without proton acceleration. The arguments that protons are indeed accelerated in AGN are rather compelling. They provide a “natural” mechanism for i) the energy transfer from the central engine over distances as large as 1 parsec, ii) the heating of the dusty disc over distances of several hundred parsecs and iii) the near-infrared cut-off of the synchrotron emission in the jet. Protons, unlike electrons, efficiently transfer energy over large distances in the presence of high magnetic fields.

Powerful AGN at distances of order 100 Mpc and with proton luminosities of $10^{46}$ erg/s or higher are therefore obvious candidates for the cosmic accelerators of the highest energy cosmic rays, especially those with energy in excess of $10^{18}$ eV which are not confined by the magnetic field of our galaxy. The neutrino flux from such accelerators can be calculated by energy conservation

$$\mathcal{L}_p N \epsilon_{\text{eff}} = 4\pi d^2 \int dE \left[ E \frac{dN_\nu}{dE} \right],$$

where $N_\nu$ is the flux at Earth, $d$ the average distance to the sources, $N$ the number of sources and $\epsilon_{\text{eff}}$ the efficiency for protons to produce pions. We assume order 1 neutrino per interacting proton. This yields

$$E \frac{dN_\nu}{dE} = \frac{N \epsilon_{\text{eff}} 1.4 \times 10^{-8}}{4\pi} \frac{1}{E \text{(TeV)}} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$  

for $\mathcal{L}_p = 10^{46}$ erg/s and $d = 100$ Mpc. With $\epsilon_{\text{eff}}$ of order $10^{-1}$ to $10^{-2}$ and $N$ in the range 1 to 100, we obtain neutrino fluxes which are well within reach of 0.1 km$^2$ neutrino telescopes. For $N \epsilon_{\text{eff}} = 1$ we obtain a diffuse neutrino flux which is a factor 2 larger than the one predicted by a detailed model worked out by Biermann and collaborators[8]. It successfully accommodates the observed spectrum of cosmic rays with energy in the EeV range. We predict 610 up-coming muon events per year in a $10^5$ m$^2$ detector. The calculation is straightforward and follows reference[9]. Neutrino absorption in the Earth has been included. The relative large contribution of very high energy neutrinos to the signal is otherwise overestimated.

We now turn our attention to individual sources. We take Mrk 421 as an example and normalize all calculations to the observed high energy photon flux

$$\int_{1/2 \text{ TeV}} dE \frac{dN_\gamma}{dE} = 1.5 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}.$$  

We will assume that $N_\gamma$ has a power spectrum with spectral index $\gamma$. We work with the blazar jet model of Biermann et al.[7] which accommodates fluxes of active galaxies
at all wavelengths and whose predictions we have parametrized in a convenient form. The maximum particle energies are given by

\[ E_{p,\text{max}} \simeq 10 E_{\gamma,\text{max}} = 2 \times 10^{20} \text{eV} \left[ \frac{\Gamma}{10} \right]^{1/2} \left[ \frac{1 \text{ Gauss}}{B} \right]^{1/2}, \quad (8) \]

where \( \Gamma \) is the Doppler shift to the comoving frame, \textit{i.e.} from the frame where acceleration takes place to our Earth frame. One has to realize that for some blazars the jet is beaming particles in our direction. The optical depth of the source, \textit{i.e.} the jet, is given by

\[ \tau_{\text{optical}} = 2 \left[ \frac{B}{1 \text{ Gauss}} \right]^{1/2} \left[ \frac{E_{\gamma}}{1 \text{ TeV}} \right]. \quad (9) \]

For a 1 G field the optical depth of the source is unity for the 0.5 TeV photons observed by Whipple. Although the value of the \( B \)-field in the jet is a guess which ranges from \( 10^{-4} \) to \( 10^4 \) G, \( 10^3 \) G is the typical assumed value.

We compute the gamma ray flux inside the source by correcting the observed flux \( \overline{\mathcal{F}} \) for absorption in the jet. The optical depth is given by (9). The answer depends critically on the magnitude of the \( B \)-field which is understandable because photon energy loss inside the source is primarily on the magnetic field in the jet. We subsequently estimate the neutrino flux assuming 1 neutrino per gamma ray, which should approximately hold for pion decay, \textit{i.e.} \( N_{\nu} = [N_{\gamma}]_{\text{before absorption}}. \)

Our results are shown in Table 1 for a range of assumptions for \( B \) and the spectral index \( \gamma \). We conclude that, even with the most pessimistic assumptions, Mrk 421 should produce a handful of upcoming muon events per year in our generic \( 10^5 \) m\(^2\) detector. A 1 km\(^2\) detector is necessary for guaranteed detection. Notice, however, that for most of the \( B, \gamma \) parameter space the predicted event rates are much larger. For \( B \)-fields of 100 G and more the predicted rate is so large that even the smallest underground detector should already have detected Mrk 421. This leads to some interesting considerations. Because the source is positioned in the northern hemisphere, only a southern neutrino telescope is sensitive. This excludes all underground facilities except for the small KGF experiment which has relatively poor angular resolution. Soon AMANDA, under construction at the South Pole, will have an uninterrupted view of Mrk 421.

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
B \text{ (Gauss)} & \gamma & E_{p,\text{max}} & E_{\gamma} \text{ for } \tau_{\text{opt}} = 1 & \mathcal{L}_{\gamma} & N \\
\hline
10^{-4} & 1 & 2 \times 10^{22} \text{eV} & 50 \text{ TeV} & 30 & 2 \\
& 0.8 & & & 500 & 11 \\
& 0.4 & & & 10^6 & 450 \\
1 & 1 & 2 \times 10^{21} \text{eV} & 500 \text{ GeV} & 200 & 13 \\
10 & 1 & 6 \times 10^{19} \text{eV} & 150 \text{ GeV} & 3000 & 270 \\
10^4 & 1 & 2 \times 10^{18} \text{eV} & 5 \text{ GeV} & - & \text{unreasonable} \\
\hline
\end{array}
\]

Table 1: Number of upcoming muons (\( N \)) per \( 10^5 \) m\(^2\) per y for the different scenarios. \( \mathcal{L}_{\gamma} \) is in \( 10^{43} \text{erg/s} \).
It is important to point out that while the assumption that $\gamma = 1$, i.e. a normal $E^{-2}$ energy spectrum, is usually optimistic, in this case it is not. In the blazar model where acceleration is by shocks in the jet rather than in the accretion disc, $\gamma$ is actually zero near $E_{\text{max}}$. The reason is interesting. The photon target on which the protons photoproduce pions has itself an $E^{-2}$ spectrum. As protons are accelerated they encounter an increasing number of photons with sufficient energy to photoproduce pions. This is the origin of the very flat spectrum. The neutrino output of a blazar can be conveniently parametrized as [7]

$$E \frac{dN_\nu}{dE} = 1.6 \times 10^{-17} \text{cm}^{-2}\text{s}^{-1} \left[ \frac{L_\gamma}{10^{45}\text{erg/s}} \right] \left[ \frac{0.54}{z} \right]^2 \left[ \frac{10}{\Gamma} \right] \left[ \frac{B}{1\text{ Gauss}} \right]^{1/2}. \quad (10)$$

The formula is scaled to 3C279. Predictions for neutrino event rates based on this formula are shown in Fig. 1 for Mrk 421 and for the total luminosities $10^{46}$ (solid), $10^{47}$ (dotted) and $10^{48}$ erg/s (dashed), upper (lower) curves are without (with) earth absorption. The event rates are similar to those previously estimated on the basis of the Whipple observation.

![Fig. 1: Predictions for neutrino event rates for Mrk 421 and for the total luminosities $10^{46}$ (solid), $10^{47}$ (dotted) and $10^{48}$ erg/s (dashed), upper (lower) curves are without (with) earth absorption.](image)

One should appreciate that weakly interacting neutrinos will make their way to our detectors unattenuated by ambient matter in the source or by IR light. So, while high energy photons are absorbed on intergalactic IR photons for AGNs much further than Mrk 421, neutrinos are not and sources should be detected with no counterpart in high energy photons. The known AGN’s form a cast of thousands and theorists have estimated that their collective flux will actually dominate the atmospheric flux for PeV neutrino energies.

3. Neutrino Oscillations in the Atmospheric Neutrino Beam

Data from the KAMIOKANDE[10] and IMB[11] collaborations indicate a deficit in the measured ratio of $\nu_\mu/\nu_e$ atmospheric neutrino events when compared with a
calculation of their relative flux in the atmospheric cosmic ray beam. There has been considerable interest in experiments capable of verifying this result, e.g. long-baseline experiments observing an accelerator neutrino beam in an underground detector located elsewhere[12]. The advantages of such experiments are important: i) a long baseline is obtained, e.g. up to 6000 km between Fermilab and the detector[13] in Hawaii, and ii) the properties of the accelerator neutrino beam are known (or can be measured on site), thus eliminating the model dependence associated with the calculation of the primary cosmic ray fluxes in the KAMIOKANDE and IMB experiments. Using this technique it is anticipated that the parameter space $\Delta m^2 \gtrsim 10^{-3}$ and $\sin^2 2\theta \gtrsim 10^{-3} \text{eV}^2$ can be probed[12]. A new generation of surface neutrino telescopes can achieve the same goals by measuring the ratio of up- and down-going muons. The fact that surface detectors, unlike underground experiments, can measure up-going $\nu_\mu$'s and down-going $\mu$'s of similar energy will be crucial.

The argument can be best introduced as follows. The KAMIOKANDE experiment typically observes 500 MeV neutrinos which are, on average, the decay products of 20 GeV pions. Instead of calculating the 20 GeV pion flux, on which the oscillation measurement depends, we could measure it by tagging the muon in the $\pi \rightarrow \mu \nu_\mu$ decay along with the oscillating neutrino. Such GeV-energy muons, produced high in the atmosphere, do not reach sea level. In order to count them one could fly the detector in a balloon. Doing this experiment has, in fact, been advocated[14] although the use of a different detector is quite inevitable. This straightforward idea does not really work as $\nu_\mu$ are also produced by $\mu \rightarrow e\nu_e\nu_\mu$ decay and this muddles the analysis.

Our main point is that such measurement can be performed in surface neutrino telescopes[13]. The ratio of muon energy to the neutrino-induced muon energy from the same pion parent is somewhat less than a factor 10. The threshold for neutrino detection in a detector such as AMANDA is between 2–50 GeV and the tagging muons therefore have energies in the 200 GeV range by pion decay kinematics. This is precisely the threshold by energy-loss for down-going muon in this instrument positioned under 1 km of polar ice. The parent pion flux of the oscillating neutrinos can therefore be tagged in the relevant energy range by measuring the down-going muon flux. Obviously the atmospheric parent pion flux of such muons is the same above the detector as on the other side of Earth where the detected $\nu_\mu$ originated. Also, at these energies muons do not decay and there are no other significant sources of cosmic ray muons. The down-going muons therefore determine the atmospheric pion and $\nu_\mu$ flux. The necessity of a calculation has thus been eliminated. In reality, of course, some secondary dependence on Monte Carlo calculations will remain, e.g. to account for the fact that the detectors are unlikely to have perfectly symmetric up/down acceptance. The primary handicap in atmospheric neutrino experiments, that the flux of the primary beam is less well understood than in accelerator neutrino experiments, is essentially eliminated.

The key variables in evaluating the capabilities of the experiment are the length of the baseline, the muon energy threshold and the minimum measurable oscillation
probability $\epsilon$. The last variable parametrizes the inherent systematical errors of the measurement [12]. It represents the “quality” of the instrument. We will vary $\epsilon$ between an optimistic 1% and a rather pessimistic 10%.

For illustration we study the sensitivity or $\epsilon$ plots in the $\nu_\mu \leftrightarrow \nu_\tau$ case. Fig. 2(a) shows the region of $\Delta m^2_{0}$ and $\sin^2 2\theta_0$ space that can be probed by an experiment sensitive to $P_{ab} > \epsilon$, for $\epsilon = 1\%$, 3% and 10%. Previous discussions of long-baseline neutrino oscillation experiments have usually stopped here, after arguing that systematic errors were reasonably under control. It is, however, essential to realize that the statistical errors involved will be quite important in these experiments. This is true whether one uses the accelerator or cosmic ray beam. We emphasize that it is critical to introduce criteria for observation of oscillation based on statistical errors. We illustrate this point by calculating the excluded regions in $\Delta m^2_{0}$ and $\sin^2 2\theta_0$ for $4\sigma$ deviations from the expected muon detection rate after 1 year of operation; see Fig. 2(b).

Fig. 2(a): The search regions (in $\Delta m^2_{0}$ vs. $\sin^2 2\theta_0$) based on a (left to right) 1%, a 3% and a 10% measurement of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation probability.

Fig. 2(b): The $4\sigma$ measurement search regions for surface neutrino detector with area of (left to right) $10^5$ m$^2$, $2 \times 10^4$ m$^2$ and $2 \times 10^3$ m$^2$. This figure is for the case of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation.
The sensitivity of AMANDA is in the end similar to that of long-baseline experiments using accelerator neutrinos. We will use for comparison the DUMAND detection of a Fermilab neutrino beam. Calculating the detected event rates following Refs. [13] and the Fermilab neutrino beam spectrum given in Ref. [12], we show the $4\sigma$ reach in $\Delta m^2$, $\sin^2 2\theta$ of the long-baseline experiment in Fig. 3 for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. We again assumed one year of running. With a baseline of 6000 km and a threshold of 20 GeV the observable oscillations are essentially identical to those of a generic surface neutrino telescope of similar area, i.e. 20000 km$^2$ for the example shown. The plot shows residual $\sin^2 (1.27 \Delta m^2 L/K)$ oscillations behavior, which is absent in the surface detector plots due to the broader (in energy) atmospheric neutrino flux and the varying neutrino paths $L$ through the Earth. The net result is still that the two different types of experiments are able to place comparable limits on $\Delta m^2$ and $\sin^2 2\theta_0$, though they are able to exclude somewhat different regions of parameter space.

Fig. 3: The $4\sigma$ measurement search regions for long-baseline experiment using the Fermilab neutrino beam with muon thresholds of (left to right) 10 GeV, 20 GeV and 40 GeV. This figure is for the case of $\nu_\mu \leftrightarrow \nu_\tau$ oscillation.

4. Neutrino Telescopes as Dark Matter Detectors

There is compelling evidence for the presence of dark matter in our galaxy. Some dark matter particle candidates, e.g. WIMPs, annihilate into photons, electrons and protons thus providing an indirect signature for their existence. They also annihilate into neutrinos and neutrino telescopes can therefore also be used to search for dark matter.

If supersymmetry is Nature’s extension of the Standard Model it must produce new phenomena on the scale of several TeV or below. A very attractive feature of supersymmetry is that it provides cosmology with a natural dark matter candidate[14].
The supersymmetric partners of the photon, $Z_0$, and the two Higgs particles form four neutral states, the lightest of which is the stable neutralino. If this lightest supersymmetric particle has an appreciable relic abundance it may also be responsible for the dark matter known to exist in the galactic halo. Neutralinos in the halo will scatter off elements in the Sun and become gravitationally trapped. The trapped neutralinos will annihilate, producing high-energy neutrinos which may be detected on Earth. The KAMIOKANDE[17] and Irvine-Michigan-Brookhaven (IMB)[18] collaborations have already demonstrated that this indirect neutrino signature provides us with a powerful tool for searching for dark matter. They extended the limits on neutralino mass into the 30–80 GeV window by using this technique.

If neutralinos have masses greater than a few TeV, they “overclose” the Universe. Supersymmetry has therefore been framed inside a well defined GeV–TeV mass window. Here we ask the question, “What size telescope is required to search this range?” We will conclude that neutrino detectors of order 1 km$^2$ are required, although clearly progress is possible with any experiment larger than KAMIOKANDE[19].

The parameter space of supersymmetric models is complicated, even in the so-called minimal supersymmetric standard model (MSSM). The model is specified by the top mass $m_t$ and five parameters: two unphysical masses $M_2$ and $\mu$, the ratio of the Higgs vacuum expectation values $\tan \beta = v_2/v_1$, the mass of the lightest Higgs $M_{H_2}$, and the squark masses $M_{\tilde{q}}$. Some of these parameters are constrained by accelerator searches and by cosmological considerations. The ratio of the Higgs vacuum expectation values is bracketed by the values $(1, m_t/m_b)$, where $m_b$ is the bottom-quark mass. Radiative corrections tend to drive the ratio above unity, and the upper bound results from constraints on electroweak symmetry breaking in supergravity models[20]. Unsuccessful accelerator searches have pushed the lightest Higgs mass above 50 GeV[21]. Finally, naturalness and cosmology favor values of $M_2$ and $\mu$ less than or of the order of 10 TeV; some would argue much less. This still leaves us with a large parameter space to search. In order to perform a manageable analysis of the problem, we choose $M_2$ and $\mu$ as our independent parameters, and fix all other parameters to reasonable values. We set $m_t = 120$ GeV, $\tan \beta = 2$, $M_{H_2}$=50 GeV and, the squark masses to be infinite (which minimizes interactions involving quarks and leptons, thereby maximizing the relic abundance but minimizing capture rates). The dependence on these parameters is discussed in reference [19].

Once these parameters have been specified, standard Big-Bang cosmology can be used to determine the relic abundances of neutralinos in the Universe. Some of the parameter space can be readily eliminated since the corresponding models result in an unacceptably large relic density, i.e. $\Omega_\chi h^2 \gtrsim 1$ where $\Omega_\chi$ is the fraction of critical density contributed by neutralinos and $h$ is the Hubble parameter in units of 100 km sec$^{-1}$ Mpc$^{-1}$. On the other hand, since the fraction of critical density contributed by halos is $\Omega_{\text{halo}} \sim \mathcal{O}(0.1)$ and $h$ may be $\sim 0.5$, we say that if $\Omega_\chi h^2 \lesssim 0.02$ the neutralino relic abundance is cosmologically consistent but too small to account for the halo dark matter. In models where $\Omega_\chi \gtrsim \Omega_{\text{halo}}$ it is reasonable to assume that the
galactic halo dark matter is made up of neutralinos and that the local mass density in neutralinos is 0.4 GeV cm$^{-3}$. The shaded regions in Fig. 4 are thus excluded as dark-matter candidates; i.e. the models do not satisfy $0.02 \lesssim \Omega \chi h^2 \lesssim 1$. The dependence of the relic density on the squark mass is important: for a detailed discussion see reference [19].

Our main conclusions follow from Fig. 5(a) which shows the detector area required to observe one neutrino event per year. This quantity is shown as a function of $M_2$ and $\mu$. Various annihilation thresholds are clearly visible. Most noticeable are the thresholds associated with the $W$ and $Z$ masses near 100 GeV. The graphs confirm that a detector of km$^2$ scale is required to study the full neutralino mass range. The scatter plot of Fig. 5(b) shows the information in Fig. 5(a) in a slightly different way. Each dot gives the event rate for a point in the $M_2$-$\mu$ plane in which the neutralino is a good dark-matter candidate ($0.02 \lesssim \Omega \chi h^2 \lesssim 1$). Note that the density of points is proportional to the area in the $M_2$-$\mu$ plane. The figure clearly shows that, except for some very special parameters, the discovery of supersymmetric dark matter is within reach of any detector exceeding 10$^5$ m$^2$ area; a more realistic evaluation of the sensitivity of experiments can be found in reference [19]. It is expected that the Earth will produce a signal similar in magnitude to the one calculated from the Sun. For the high end of the GeV–TeV mass range investigated here, the signals from the Sun dominate by a factor of roughly five [22]. This result is however reversed for the lower neutralino masses. For low-mass neutralinos, signals from the Earth will significantly increase sensitivity.
Fig. 5: Events m⁻² yr⁻¹. Figure (a) shows contours of constant detection rate in the $M_2$-$\mu$ plane for $\tilde{q} = \infty$. Figure (b) shows the same information as figure (a) but in a slightly different way. Each dot gives the event rate for a point in the $M_2$-$\mu$ plane in which the neutralino is a good dark-matter candidate ($0.02 \lesssim \Omega_\chi h^2 \lesssim 1$). Note that the density of points is proportional to the area in the $M_2$-$\mu$ plane. We fix $m_t = 120$ GeV, $\tan \beta = 2$, $M_{H_2} = 50$ GeV, and $\tilde{q} = \infty$. 
We conclude that a neutrino telescope of $10^5 \text{ m}^2$ or more is clearly a superb instrument to search for supersymmetric dark matter and offers great promise for discovery should the galactic halo be composed of neutralinos. Its failure to observe dark matter particles would force supersymmetrists to fine-tune their models into small regions of parameter space. Progress in the search for neutralinos can, however, be made with any detector larger than KAMIOKANDE.

5. Supernova Detection with High Energy Neutrino Telescopes?

The neutrino events detected in the KAMIOKANDE\textsuperscript{1}, IMB\textsuperscript{2} and, arguably, the Baksan\textsuperscript{23} and LSD\textsuperscript{24} detectors prior to the optical discovery of supernova 1987A represented a most remarkable birth of neutrino astronomy. Despite observation by four experiments, the data has left us with some lingering doubts. Most prominent is our inability to understand the time of the Mont Blanc neutrino burst\textsuperscript{24} and the directionality of the IMB events\textsuperscript{25}. The success of the theory in anticipating the features of the high statistics KAMIOKANDE and IMB data leads us to suspect that these problems are instrumental rather than real. The history of 1987A nevertheless underscores the importance of collecting as much information as possible when presented with the rare opportunity of observing the next nearby supernova. The high energy neutrino telescopes, discussed here, can contribute information, even though their nominal neutrino threshold are far too high.

First generation high energy neutrino telescopes consist of approximately 200 optical modules (OM) deployed in deep, clear water or ice shielded from cosmic rays\textsuperscript{26}. Coincident signals between the OMs detect the Čerenkov light of muons with energy in excess of a few GeV. Electromagnetic showers initiated by very high energy electron neutrinos are also efficiently detected. The idea has been debated for some time whether these instruments have the capability to detect the MeV neutrinos from a supernova. The production of copious numbers of positrons of tens of MeV energy in the interaction of $\bar{\nu}_e$ with hydrogen, will suddenly yield signals in all OMs for the 10 seconds duration of the burst. Clearly such a signal, no matter how weak, will become statistically significant for a sufficient number of OMs. We recently performed a complete simulation of the signal and its detection and concluded that the 200 OMs of detectors such as DUMAND and AMANDA are sufficient to establish the occurrence of a neutrino burst in coincidence with the optical display of a supernova. A 1987A-type supernova in the center of the galaxy will generate almost $10^4$ events in the AMANDA detector resulting into an observation in excess of 5 $\sigma$. We also showed that the same detectors can actually serve as a supernova watch, i.e. a “fake” signal occurs less than once a century, by increasing the number of OMs by a factor of three. This is much less than the roughly 7000 OMs which are projected for a next-generation detector\textsuperscript{26}.

In the end the observations remarkably confirmed the established ideas for the
supernova mechanisms. Most of the energy is liberated after de leptonization in a burst lasting about ten seconds. Roughly equal energies are carried by each neutrino species. The time scale corresponds to the thermalization of the neutrinosphere and its diffusion within the dense core. Since the $\bar{\nu}_e$ cross-section for the inverse beta decay reaction on protons exceeds the characteristic cross sections for the other neutrino flavors, $\bar{\nu}_e$ events dominate by a large factor after including detection efficiency. In this reaction free protons absorb the antineutrino to produce a neutron and a positron which is approximately isotropically emitted with an energy close to that of the initial neutrino. For the purpose of illustration we use typical parameters, derived from SN1987 observations, which are consistent with those previously estimated in supernova models. From the energy distributions of the observed events the average temperature of the neutrino sphere in SN1987A was deduced to be 4.0 MeV.

It is straightforward to make a back-of-the-envelope derivation of the distance over which optical modules in high energy neutrino telescopes can detect supernova neutrinos. After convoluting the 4 MeV thermal Fermi distribution of the neutrinos with a detection cross section rising with the square of the neutrino energy, one obtains an event distribution peaked in the vicinity of 20 MeV. The tracklength of a 20 MeV positron is roughly 10 centimeters and therefore over 3000 Čerenkov photons are produced. This number combined with a typical quantum efficiency of 25% leaves 800 detected photons in each event. It is easy to estimate either by analytic calculation or by a detailed Monte Carlo simulation. For OMs such as those used in the AMANDA detector with collecting area $A_M = 0.028$ m$^2$ and for an attenuation length $R_{\text{att}} = 25$ m typical of ice, one obtains $V_{\text{eff}} \sim 130$ m$^3$ per optical module for detecting the Čerenkov radiation from neutrino-induced electrons. This result can be used to rescale SN1987 observations to a supernova at a distance $d_{\text{kpc}}$. From 11 events observed in 2.14 kton KAMIOKANDE detector we predict:

$$N_{\text{Events}} \sim 11 N_M \left[ \frac{\rho V_{\text{eff}}}{2.14 \text{ kton}} \right] \left[ \frac{52 \text{ kpc}}{d_{\text{kpc}}} \right]^2$$  \hspace{1cm} (11)

for a detector with $N_M$ optical modules. Here $\rho$ is the density of ice. For a 130 m$^3$ effective volume of each of the 200 OMs we obtain 5300 events. A detailed simulation of the full detector leads to an event rate which is 50% larger.

We next must require a meaningful detection of this signal in the presence of the continuous background counting rate of all phototubes. Over the 10 s duration of the delayed neutrino burst from a supernova, the rms fluctuations of the combined noise from all the OMs is:

$$\sigma_{\text{1 p.e.}} = \sqrt{10 \nu_{\text{1 p.e.}} N_M}$$  \hspace{1cm} (12)

where the background counting rate in each module at the 1 photoelectron level is represented by $\nu_{\text{1 p.e.}}$. The probability that the noise in the OMs fakes a supernova signal can be estimated assuming Poisson statistics. The expected rate of supernova explosions in our galaxy is about $2 \times 10^{-2}$ y$^{-1}$. If the detector is to perform a
supernova watch we must require that the frequency of fake signals is well below this rate. The signal should therefore exceed $n_\sigma \geq 6$ which corresponds to a probability of $9.9 \times 10^{-10}$. The corresponding number of 10 seconds intervals indeed exceeds a century. Clearly the requirement can be relaxed if we just demand that the detector can make a measurement in the presence of independent confirmation. For an average noise rate of 1 kHz, a typical value for the OMs in AMANDA, the rms fluctuation of the 20 million hits expected in an interval of ten seconds is 1400. This implies that detection of a galactic supernova is near the 4 $\sigma$ level for the 200 module configuration, while detection should not represent a problem for the next generation detector which consists of 7,000 OMs. Since the signal in the present detector is marginal, it is necessary to do a more realistic calculation of the event rate. We will conclude that our rough estimate is somewhat conservative.

Background noise in the modules clearly plays a critical role so that low noise environments such as ice have an intrinsic advantage. Furthermore, the noise is expected to be reduced drastically at the 2 photoelectron level. This will unfortunately also imply a reduction in effective volume for event detection as we will see further on. Signal to noise is proportional to the ratio $V_{\text{eff}}/\sqrt{\nu}$. Obviously increased attenuation length in the medium and larger effective area of the OM results in an enhanced effective volume. Considering parameters appropriate for DUMAND, an attenuation length of 40 m in water and OMs with double diameter, we expect a factor 10 increase in effective volume per optical module. This should readily compensate for a noise rate higher by a factor 100. We therefore expect DUMAND and AMANDA to have comparable sensitivity as supernova detectors. Detailed calculations can be found in reference [28].

6. Kilometer Scale Detectors?

It should by now be clear that a high-energy neutrino telescope is a multi-purpose instrument which can make contributions to astronomy, astrophysics and particle physics. Because photons, whatever their wavelength, are absorbed by a few hundred grams of matter, high-energy neutrinos provide us with a first opportunity to do a tomographic study of the Universe. Therefore the hope, and greatest probability based upon the history of forays into new wavelength regions, is to discover unanticipated phenomena. It is nevertheless important to simulate the performance of a future telescope in all manner of more mundane physics circumstances in order to determine its natural size. It is intriguing that our previous estimates all point to the necessity of building 1 km$^3$ detectors[30, 31]. We close with a discussion of the possibility of building a 1 km scale neutrino detector based on the experience gained in designing the instruments now under construction, specifically AMANDA, Baikal, DUMAND and NESTOR which we will briefly review[32, 33]. One can confidently predict that such a telescope can be constructed at a reasonable cost, e.g. a cost similar to Superkamiokande[34], to which it is complimentary in the sense that its volume
Detectors presently under construction have a nominal effective area of $2 \times 10^4 \, \text{m}^2$. This area depends on the energy of the muon and the trigger; for the AMANDA detector it varies from $0.6 \sim 3 \times 10^4 \, \text{m}^2$ for 1–100 TeV muon energy \cite{35}. The DUMAND area is about $1.2 \times 10^4 \, \text{m}^2$ at 1 TeV averaged over the lower hemisphere, and grows roughly logarithmically with energy to an area of over $4 \times 10^4 \, \text{m}^2$ at 100 TeV \cite{36}.

The difference between DUMAND and AMANDA in energy dependence is due to the difference in predicted optical properties of ice and deep seawater, and the different size of photomultipliers used in the two experiments. The threshold is in the 2–10 GeV energy range for AMANDA and is about 10 GeV for DUMAND. Both detectors also have a large detection volume for showers initiated by $W$’s produced by electron-antineutrinos on atomic electrons at 6.4 PeV, with DUMAND reaching $\sim 0.2 \, \text{km}^3$.

Relative to a 1 km scale detector, the experiments under construction are only “few” percent prototypes. Yet, using natural water or ice as a detection medium, these neutrino detectors can be deployed at roughly 1% of the cost of conventional accelerator-based neutrino detectors which use shielding and some variety of tracking chambers. It is thus not hard to believe that the Cherenkov detectors can be extended to a larger scale at reasonable cost. The first generation telescopes consist of roughly 200 optical modules (OM) sensing the Cherenkov light of cosmic muons. The experimental advantages and challenges are different for each experiment and, in this sense, they nicely complement one another. Briefly,

- DUMAND is positioned under 4.5 km of ocean water, below most biological activity and well shielded from cosmic ray muon backgrounds. One nuisance of the ocean is the background light resulting from radioactive decays, mostly K$^{40}$, plus some bioluminescence, yielding an OM noise rate of 50–100 kHz. On the other hand, deep ocean water is fantastically clear, with an attenuation length of order 40 m in the blue \cite{37}. The deep ocean is stable, quiet, and completely shielded from electromagnetic interference. There is also an unlimited quantity of territory within 30 km of easily accessible and habitable shore locations. Yet, the deep ocean is a difficult location for access and service, not at all like a laboratory experiment. Detection equipment must be built to high reliability standards, and the data must be transmitted to the shore station for processing. It has required years to develop the necessary technology and learn to work in an environment foreign to high-energy physics experimentation, but hopefully that is now accomplished satisfactorily.

- AMANDA is operating in deep clear bubble-free ice. The ice provides a convenient mechanical support for the detector. The immediate advantage is that all electronics can be positioned at the surface. Only the optical modules are deployed into the deep ice. Polar ice is a sterile medium with a concentration of
radioactive elements reduced by more than $10^{-4}$ compared to sea or lake water. The low background results into an improved sensitivity which allows for the detection of high energy muons with very simple trigger schemes which are implemented by off-the-shelf electronics. Being positioned under only 1 km of ice it is operating in a cosmic ray muon background which is over 100 times larger than DUMAND. The challenge is to reject the down-going muon background relative to the up-coming neutrino-induced muons by a factor larger than $10^6$. The group claims to have met this challenge with an up/down rejection which is at present superior to that of the deep detectors\textsuperscript{[35]}. The polar environment is difficult as well, with restricted access and one shot deployment of photomultiplier strings. The ice may not be as clear as deep ocean water. It has, however, been shown by three independent methods that in-situ polar ice has an attenuation length exceeding 20 meters at 800 meters depth\textsuperscript{[38]}. A shorter optical attenuation length in ice compared to seawater may or may not be a limitation in that the AMANDA 8 inch photomultiplier tubes do not see muons far enough to suffer that limit. In the ocean, the economic studies indicate that larger detectors are optimal. The economics of hot water hole drilling (fuel cost limited) dictate limited depth and diameter of holes. We note that future technology employing long cylindrical photomultipliers could be a nice match to this problem.

- **NESTOR** is similar to DUMAND in being placed in the deep ocean (the Mediterranean), except for two critical differences. Half of its optical modules point up, half down. The angular response of the detector is being tuned to be much more isotropic than either AMANDA or DUMAND, which will give it advantages in, for instance, the study of neutrino oscillations. Secondly, NESTOR will have a higher density of photocathode (in some substantial volume) than the other detectors, and will be able to make local coincidences on lower energy events, even perhaps down to the supernova energy range (tens of MeV)\textsuperscript{[39]}.

- **BAIKAL** shares the shallow depth with AMANDA, and has half its optical modules pointing up like NESTOR\textsuperscript{[40]}. It is in a lake with 1.4 km bottom, so it cannot expand downwards and will have to grow horizontally. Optical backgrounds similar in magnitude to ocean water have been discovered in Lake Baikal. They vary with season and their nature is not well understood. The difficulties in Russia make progress somewhat uncertain, but even so the Baikal group has deployed an array with 36 Quasar photomultiplier (a Russian-made 15 inch tube) units in April 1993, and may well count the first neutrinos in a natural water Cherenkov detector (though with an area similar to the IMB mine based instrument).

- Other detectors have been proposed for near surface lakes or ponds (e.g. GRANDE, LENA, NET, PAN and the Blue Lake Project), but at this time
none are in construction[11]. These detectors all would have the great advantage of accessibility and ability for dual use as extensive air shower detectors, but suffer from the $10^{10}-10^{11}$ down-to-up ratio of muons, and face great civil engineering costs (for water systems and light tight containers). Even if any of these are built it would seem that the costs would be too large to contemplate a full km scale detector.

In summary, there are four major experiments proceeding with construction, each of which have different strengths and face different challenges. All have successfully operated small prototypes, all have funding at some level to proceed, and all four may well be operating with detectors in the few times $10^4$ m$^2$ by 1996 or so. It is thus not too soon to begin to contemplate the next stage.

For the construction of a 1 km scale detector one can imagine[20] any of the above detectors being the basic building block for the ultimate 1 km$^3$ telescope. The present AMANDA design, for example, consists of 9 strings on a 30 meter radius circle with a string at the center (referred to as a 1 + 9 configuration). Each string contains 20 OMs separated by 12 m. Imagine AMANDA “supermodules” which are obtained by extending the basic string length (and module count per string) by a factor of 4.5. Supermodules would then consist of 1 + 9 strings with, on each string, 90 OMs separated by 12 meters for a length of 1080 meters. A 1 km scale detector then might consist of a 1 + 7 configuration of supermodules, with the 7 supermodules distributed on a circle of radius 540 meters, and have a total of about 7200 phototubes. Such a detector can be operated in a dual mode:

- it obviously consists of $4.5 \times 8$ of the presently planned AMANDA array modules, leading to an effective area of $\sim 0.75$ km$^2$. Importantly, the characteristics of the
detector, including threshold, are the same as those of the original AMANDA array module.

- the 1 + 7 Supermodule configuration, looked at as a whole, instruments with OMs a 1 km³ cylinder with a diameter and height of 1080 m. High-energy muons will be superbly reconstructed as they can produce triggers in 2 or more of the modules spaced by large distance. Reaching more than one supermodule requires 100 GeV energy to cross 500 m. For a 1 km deep detector the threshold for downgoing muons is thus raised from 200 to 300 GeV. We note that this is the energy for which a neutrino telescope has optimal sensitivity to a typical $E^{-2}$ source (background falls with threshold energy, and until about 1 TeV little signal is lost).

Alternate methods to reach the 1 km scale have been discussed by Learned and Roberts[42]. How realistic are the construction costs for such a detector? AMANDA’s OMs cost roughly $4K for each photomultiplier tube, pressure vessel, cable and electronics. Therefore an array module of 200 OMs costs $0.8M and the final detector about $30M in hardware and data acquisition. Even if one doubles the OM costs to account for construction and deployment, the final cost of the postulated 1 + 7 array of supermodules is still below that of Superkamioka (with 11,200 × 20 inch photomultiplier tubes in a 40 m diameter by 40 m high stainless steel tank in a deep mine). Using deep water and large OMs as in DUMAND II, (i.e. 15 inch instead of 8 inch AMANDA PMTs), increases the cost per OM by a factor of 2 relative to AMANDA. However, the effective muon capture area per optical module is also increased, by perhaps a factor of ten. Deployment in deep water involves additional hardware costs such as junction boxes and cables bringing data to shore (best estimate is about $10k/OM amortizing all costs).

Both types of detectors would realize some economy of large numbers. In any case, we offer no judgement here on the choice of basic type of module, array style, nor the choice of experimental location. Actual performance of the in-situ detectors will be available in two years, so a better comparison awaits field experience. The important point we do want to stress is that the costs, with these two rather different approaches we have sketched, are rather close. No matter which way you wish to estimate, the cost for a 1 km² array seems likely to be under $100M. Since this is of the same order as the SUPERKAMIOKANDE detector presently under construction in Japan such a cost for a non-accelerator project is certainly not unprecedented nor outrageous by present high energy physics standards.

7. Summary and Plea

The imminent activation of high energy neutrino experiments in Baikal, Greece, Hawaii and South Pole will provide an ideal testing ground for the design of an
“array module” and an evaluation of the variations in hardware design, depth and medium for deployment. Having effective areas for high energy neutrinos exceeding existing underground detectors by about two orders of magnitude they will certainly open new frontiers in cosmic muon and neutrino physics. Hopefully these experiments will make serendipitous discoveries. Yet, we must acknowledge that those instruments now building for operation by 1995 will probably not be large enough to really undertake neutrino astronomy. It will require another step of about two orders of magnitude to be well into business, and for that it is not too early for dreams, plans, and studies.

We strongly feel that the construction of the next generation detector should be a collaborative effort of all the institutions involved in high-energy neutrino astronomy, a world cooperative effort. It might even consist of 2 parts, possibly using different techniques, with complementary sky coverage and independent operation such that the usual checks can be made!

At the 1 km$^2$ size it seems inescapable, based upon present calculations and simple energetic considerations extrapolating from observations with gamma rays and lower-energy photons, that such point sources must be seen. At this size then, one would truly be in the business of astronomy: not just counting sources but able to observe a multiplicity of sources with enough statistics to begin extracting information from energy spectra and temporal behaviour, particularly in comparison with photon observations (e.g. in the episodic behaviour of AGNs, and the timing in binaries). Indeed the suggestion that one may be able to “neutrino ray” the companion star in a galactic X-ray binary (such as Her X-1), could mean that we know more about the density profile of a distant star than about that of our own sun. It is unlikely that these observations can be carried out with detectors smaller than 1 km$^2$. And then there are all the other possibilities...

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