The Baikal Neutrino Experiment: status and results

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1 Introduction

The Baikal Neutrino Telescope is operated in Lake Baikal, Siberia, at a depth of 1.1 km. The present stage of the telescope, NT-200 [1], was put into operation at April 6th, 1998 and consists of 192 optical modules (OMs). An umbrella-like frame carries 8 strings, each with 24 pairwise arranged OMs. Three underwater electrical cables and one optical cable connect the detector with the shore station. The OMs are grouped in pairs along the strings. They contain 37-cm diameter $QUASAR$ - photo multipliers (PMs). The two PMs of a pair are switched in coincidence in order to suppress background from bioluminescence and PM noise. A pair defines a *channel*. A *trigger* is formed by the requirement of $\geq N$ *hits* (with *hit* referring to a channel) within 500 ns. N is typically set to 3 or 4. For such events, amplitude and time of all fired channels are digitized and sent to shore. A separate *monopole trigger* system searches for clusters of sequential hits in individual channels which are characteristic for the passage of slowly moving, bright objects like GUT monopoles.

Lake Baikal deep water is characterized by an absorption length of L_{abs}(480 nm)=20 $\div$24 m, a scattering length of L_s =30 $\div$70 m and a strongly anisotropic scattering function $f(\theta)$ with a mean cosine of the scattering angle $\overline{\cos}(\theta) = 0.85 \div 0.9$. Fig. 1 shows the cascade detection volume and the muon detection area of a single BAIKAL OM. Here, we define detection area and detection volume by the condition that the mean number of photoelectrons has to be $\geq$1. In contrast to underground detectors, open configurations in highly transparent media like water or ice allow to observe a huge volume beyond their geometrical boundaries. The detection volume of an OM rises from $1{\cdot}10^5$ m^3 for 1 TeV to $7{\cdot}10^7$ m^3 for 1 EeV cascade energy.

Here we present selected results obtained from data taken in 1998 - 2000 (780 live days). Data taken in 2001 are presently being analyzed. We also describe NT-200+ − an upgrade of NT-200 by three sparsely instrumented distant outer strings which increase the fiducial volume for high energy cascades to order of 10 Mtons. Two of three outer strings where deployed, and electronics, data acquisition and calibration systems for NT-200+ have been tested in March 2004.

2 Atmospheric Muon Neutrinos

The clearest signature of neutrino induced events is a muon crossing the detector from below. Track reconstruction algorithms as well as background rejection have been described elsewhere [1]. The energy threshold of NT-200 for this particular analysis (15-20 GeV) is much smaller than of Amanda ($\sim$50 GeV) but still too high for a clear appearance of oscillation effects, given the low statistics and the systematic uncertainties. Atmospheric neutrinos

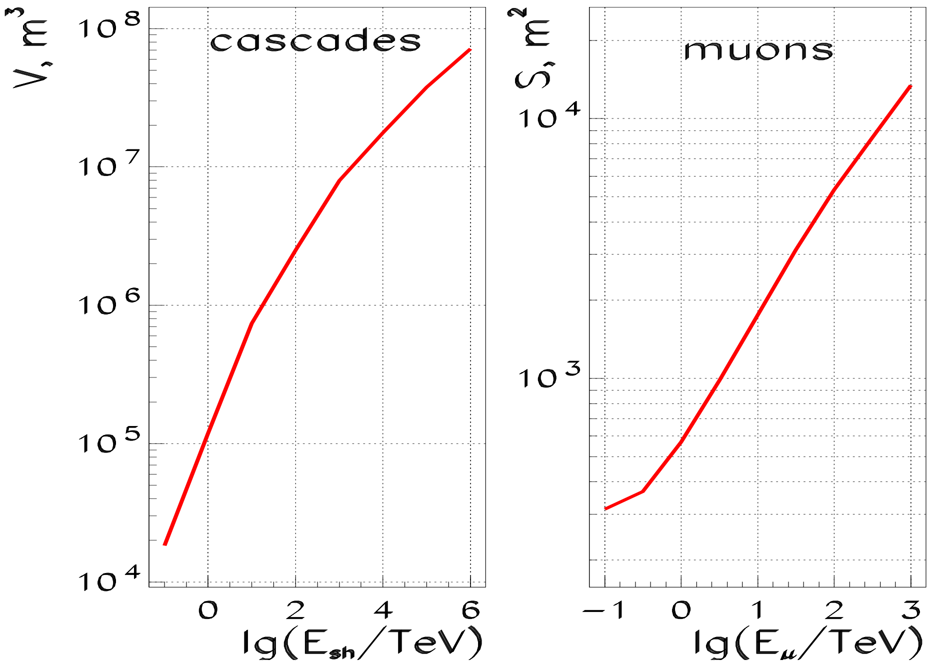


Figure 1: Detection volume (left) and detection area (right) of a single BAIKAL OM for neutrino induced high energy cascades and high energy muons, respectively.

serve as an important calibration tool and demonstrate the understanding of the detector performance. The data set of years 1998+1999 yields 84 upward going muons. The MC simulation of upward muon tracks due to atmospheric neutrinos gives 80.5 events. The angular distribution for both experiment and simulation as well as the skyplot of upward muons are shown in Fig. 2.

3 Search for Neutrinos from WIMP Annihilation

The search for WIMPs with the Baikal neutrino telescope is based on a possible signal of nearly vertically upward going muons, exceeding the flux of atmospheric neutrinos. The method of event selection relies on the applica-

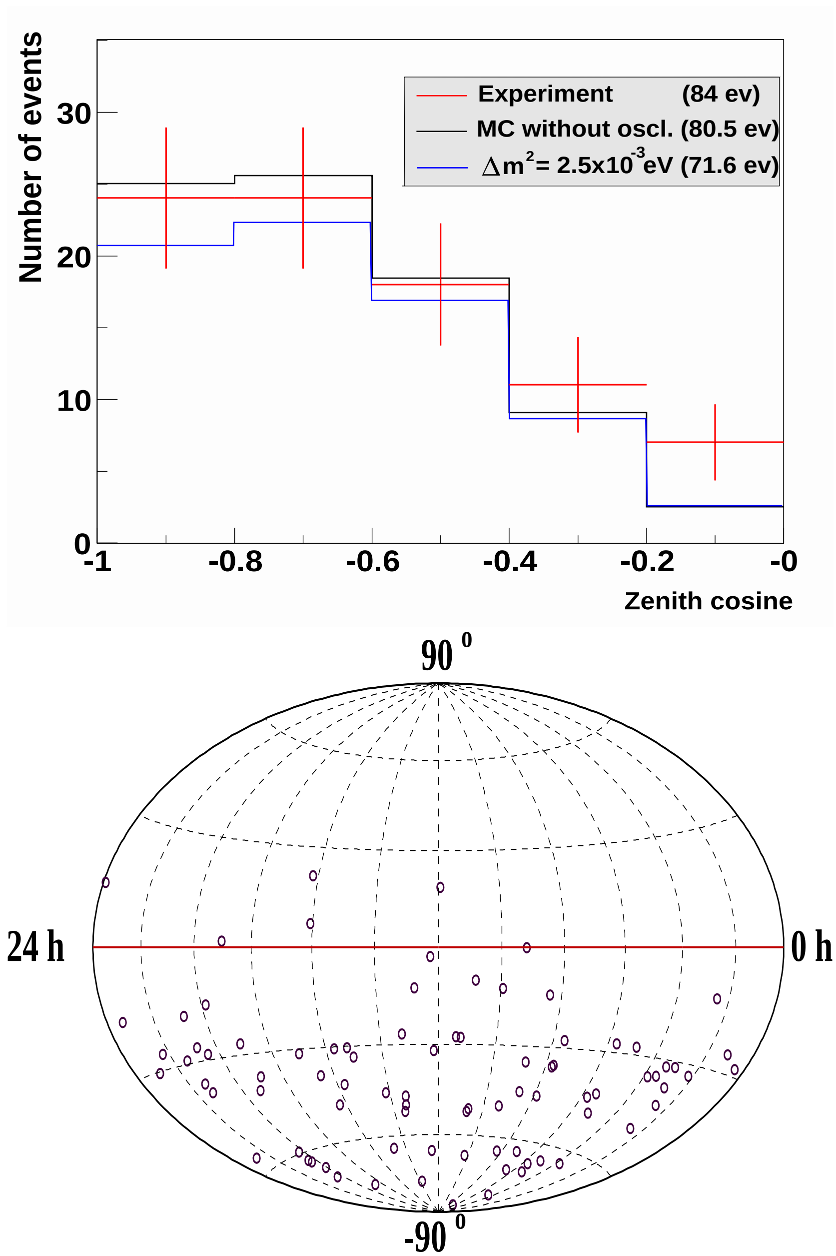


Figure 2: Upper: Angular distribution of experimental events and MC data. Lower: Skyplot (equatorial coordinates) of neutrino events.

tion of a series of cuts which are tailored to the response of the telescope to nearly vertically upward moving muons [1]. The applied cuts select muons with -1< cos(θ) <-0.75 and result in a detection area of about 1800 m^2 for vertically upward going muons. The energy threshold for this analysis is

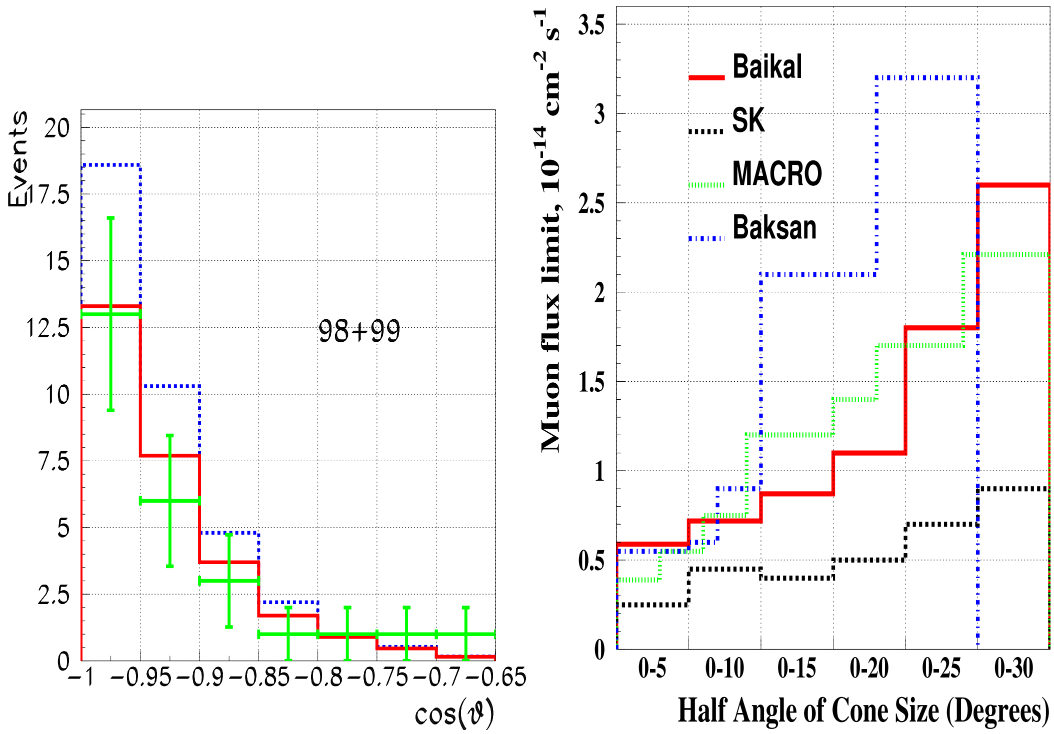


Figure 3: Left: Angular distributions of selected neutrino candidates as well as expected distributions in a case with and without oscillations (solid and dashed curves respectively). Right: Limits on the excess muon flux from the center of the Earth versus half-cone of the search angle.

$E_{\text{thr}} \sim 10$ GeV i.e. significantly lower then for the analysis described in section 2 ($E_{\text{thr}} \sim 15$ GeV). Therefore the effect of oscillations is stronger visible. We expect a muon event suppression of (25-30)% due to neutrino oscillations assuming $\delta m^2 = 2.5 \cdot 10^{-3}$ eV^2 with full mixing, $\theta_m \approx \pi/4$.

From 502 days of effective data taking between April 1998 and February 2000, 24 events with -1< cos(θ) <-0.75 have been selected as clear neutrino events. The angular distribution of these events as well as the MC - predicted distributions are shown in Fig. 3 (left panel). For the MC simulations we used the Bartol96 atmospheric neutrino flux [2] without (dashed curve) and with (solid curve) oscillations. Within 1σ statistical uncertainties the experimental angular distribution is consistent with the prediction including neutrino oscillations.

Regarding the 24 detected events as being induced by atmospheric neutrinos, one can derive an upper limit on the additional flux of muons from the center of the Earth due to annihilation of neutralinos - the favored candidate for cold dark matter. The 90% C.L. muon flux limits for six cones around the opposite zenith as well as muon flux limits for different neutralino masses obtained with NT-200 ($E_{\rm thr}$ >10 GeV) in 1998/99 are shown in Fig. 3 (right panel) and Fig. 4 (left panel), and compared to limits obtained by Baksan, MACRO, Super-Kamiokande and AMANDA [3].

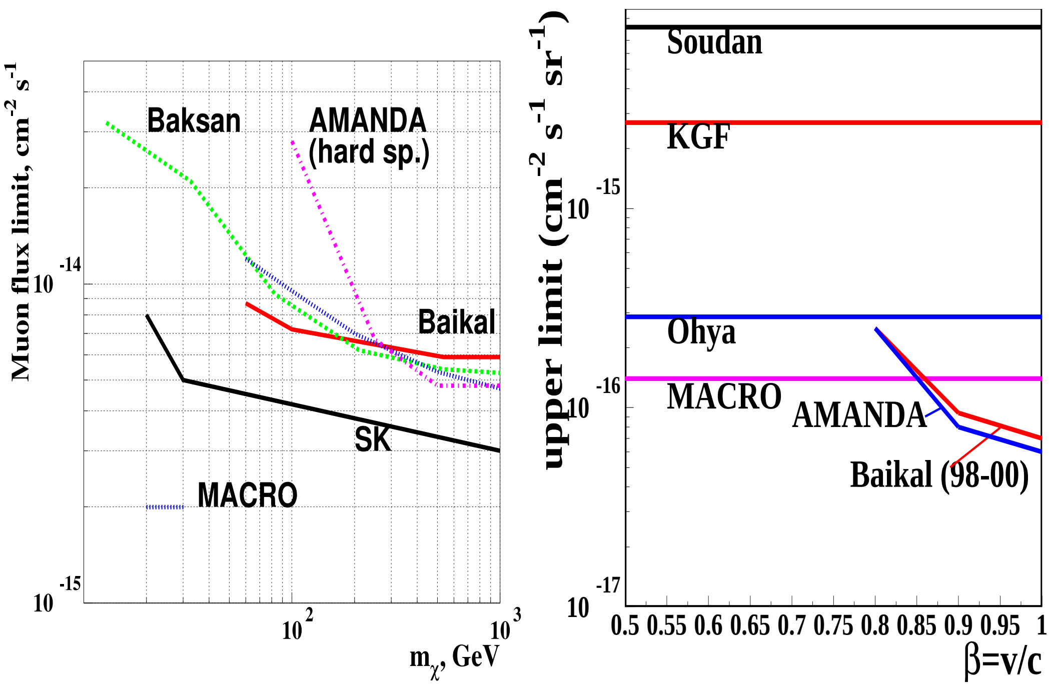


Figure 4: Left: Limits on the excess muon flux from the center of the Earth as a function of WIMP mass. Right: Upper limits on the flux of fast monopoles obtained in different experiments.

4 Search for Relativistic Magnetic Monopoles

Events due to relativistic monopoles ($\beta > 0.75$) are distinguished by their high light output, allowing identification of events beyond the geometrical boundaries of the detector. The search strategy has been described in [1]. An improved analysis including data from 1996 to 2000 yields a limit about a factor of four below the limit published earlier. This limit is compared to those from other experiments [4] in Fig. 4 (right panel).

5 A Search for Extraterrestrial High Energy Neutrinos

The BAIKAL survey for high energy neutrinos searches for bright cascades produced at the neutrino interaction vertex in a large volume around the neutrino telescope. Lack of significant light scattering allows to monitor a volume exceeding the geometrical volume by an order of magnitude. This results in sensitivities of NT-200 comparable to those of the much larger AMANDA detector. The background to this search are bright bremsstrahlung flashes along downward muons passing far outside the array.

For the analysis of data recorded in 1998 - 2000 (780 live days) we used 18384 events with hit channel multiplicity $N_{\rm hit}$ >15 and $t_{min} = min(t_i - t_j) > -10$ ns. The parameter t_{min} is a smallest of all arrival time differences of hit channels on each hit strings. Positive and negative values of t_{min} relate to upward and downward propagation of a light signal in detector, respectively.

The experimental event distributions in the (t_{min}, N_{hit})-parameter space are consistent with the background expectation. No statistically significant excess over the background expectation from atmospheric muons has been observed.

Looking for events outside the area populated by background events in the (t_{min}, N_{hit})-parameter space we can derive upper limits on the fluxes of high energy neutrinos which are predicted by different models of neutrino sources. The detection volume $V_{\rm eff}$ for neutrino produced events was calculated as a function of neutrino energy and zenith angle θ. $V_{\rm eff}$ rises from $2{\cdot}10^5$ m^3 for 10 TeV up to $6{\cdot}10^6$ m^3 for 10^4 TeV and significantly exceeds the geometrical volume $V_g \approx 10^5$ m^3 of NT-200 (Fig. 5 left panel).

Given an E^{-2} behaviour of the neutrino spectrum and a flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, the 90% C.L. upper limit obtained with the Baikal

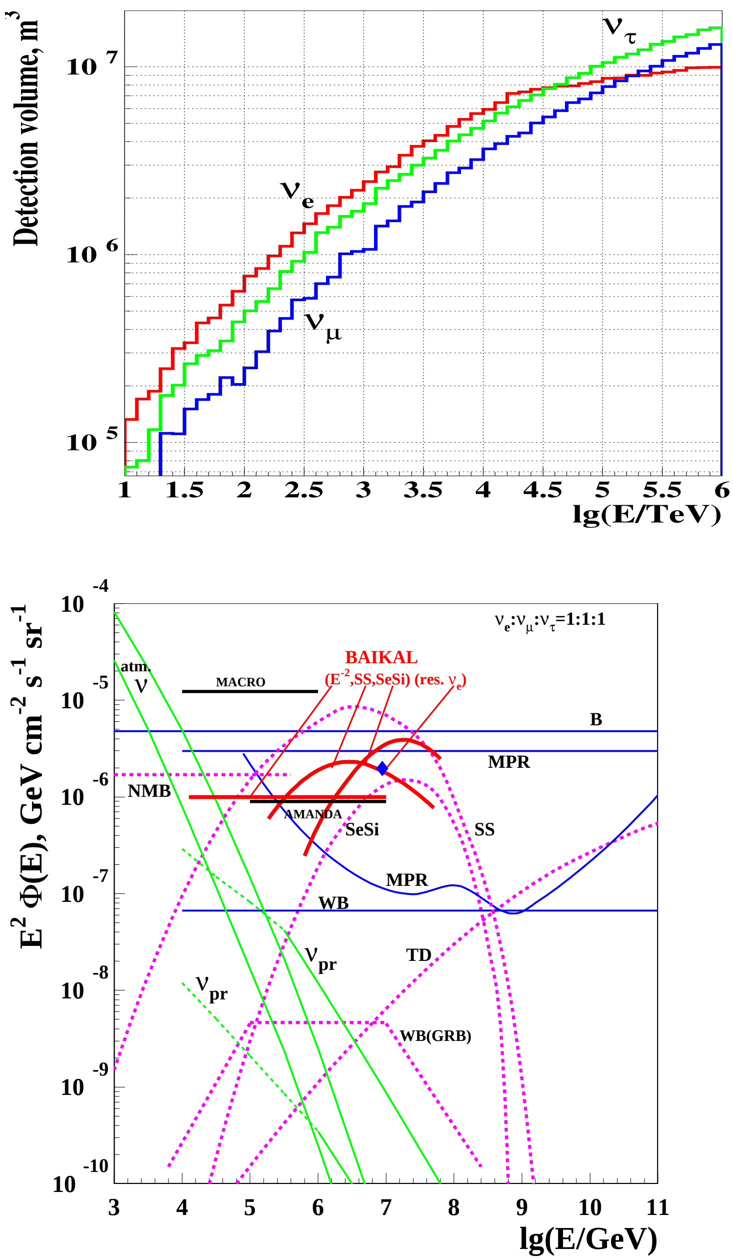


Figure 5: Upper: Energy dependence of effective volume. Lower: Experimental upper limits on the neutrino fluxes as well as flux predictions from different models of neutrino sources (see text).

neutrino telescope NT-200 (780 days) is:

$$\Phi_{(\nu_e+\nu_\mu+\nu_\tau)}E^2 < 1.0 \cdot 10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}. \quad (1)$$

The model independent limit on $\tilde{\nu_e}$ at the W - resonance energy is:

$$\Phi_{\tilde{\nu_e}} \leq 4.2 \times 10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}. \quad (2)$$

Fig. 5 (right panel) shows our upper limits on $(\nu_e+\nu_\mu+\nu_\tau)$ diffuse fluxes from AGNs shaped according to the model of Stecker and Salamon (SS), of Semikoz and Sigl (SeSi) and on E^{-2} spectrum according to Nellen et al. (NMB) [5] as well as the model independent limit on the resonant $\bar{\nu}_e$ flux (diamond).

Also shown are the limits obtained by AMANDA and MACRO experiments [6], theoretical bounds obtained by Berezinsky (B), by Waxman and Bahcall (WB), by Mannheim et al. (MPR) [7], predictions for neutrino fluxes from topological defects (TD) and from GRB (WBGRB) [5].

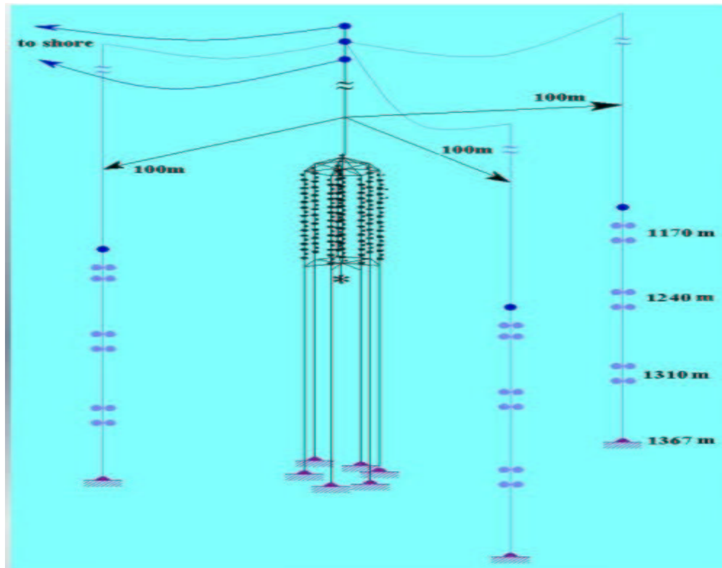
6 NT-200+ AND BEYOND

Recently derived upper limits on ν_e fluxes by BAIKAL and AMANDA are about $E^2\Phi(\nu) \approx (3 \div 5)10^{-7}$ cm^{-2} s^{-1} sr^{-1} GeV and cover the region of optimistic theoretical predictions. However, a flux sensitivity at the level of $E^2\Phi(\nu) < 10^{-7}$ cm^{-2} s^{-1} sr^{-1} GeV which would test a variety of other models, requires detection volumes of order of 10 Mtons.

We envisage an upgrade of NT-200 to this scale by three sparsely instrumented distant outer strings. The basic principle will be the search for cascades produced in a large volume below NT-200. This configuration, christened NT-200+, will not only result in an increased detection volume for cascades, but also allow for a precise reconstruction of cascade vertex and energy within the volume spanned by the outer strings.

A schematic view of NT-200+ is shown in Fig. 6 (left panel). A water volume of $4.4 \cdot 10^6$ m^3 is surrounded by the outer strings and NT-200.

The detection volumes for isotropic ν_e and ν_μ fluxes are shown in Fig. 6 (right panel). Most of the expected events would be produced by neutrinos from the energy range $\mathrm{E}_\nu > 10^2$ TeV. In Fig. 7 (left panel), reconstructed vs. simulated coordinates of cascades in NT-200+ (rectangles) and NT-200 (crosses) are shown. The reconstruction accuracy significantly improves in the case of NT-200+.



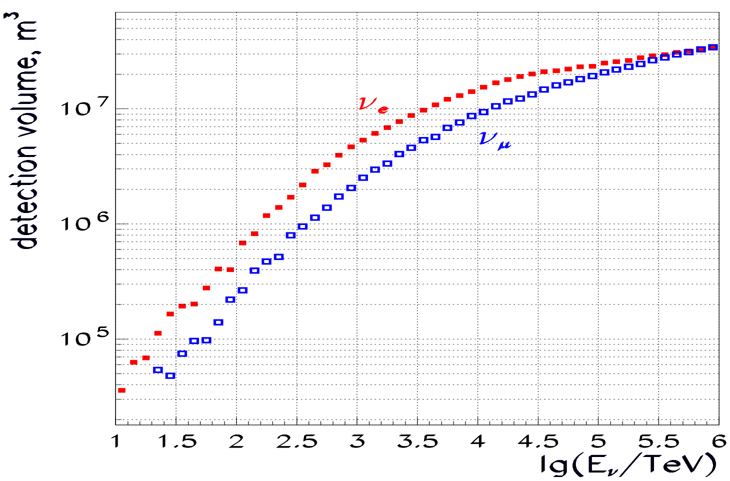


Figure 6: Left: Sketch of NT-200+. Right: Detection volume of NT-200+ for ν_e and ν_μ events which survive all cuts.

Assuming $\gamma = 2$ and a flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ =1:1:1, a 90% C.L. limit on the ν_e flux of

$$\Phi_{(\nu_e+\tilde{\nu_e})}E^2 < 9 \cdot 10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV} \tag{3}$$

could be established from three years recorded data .

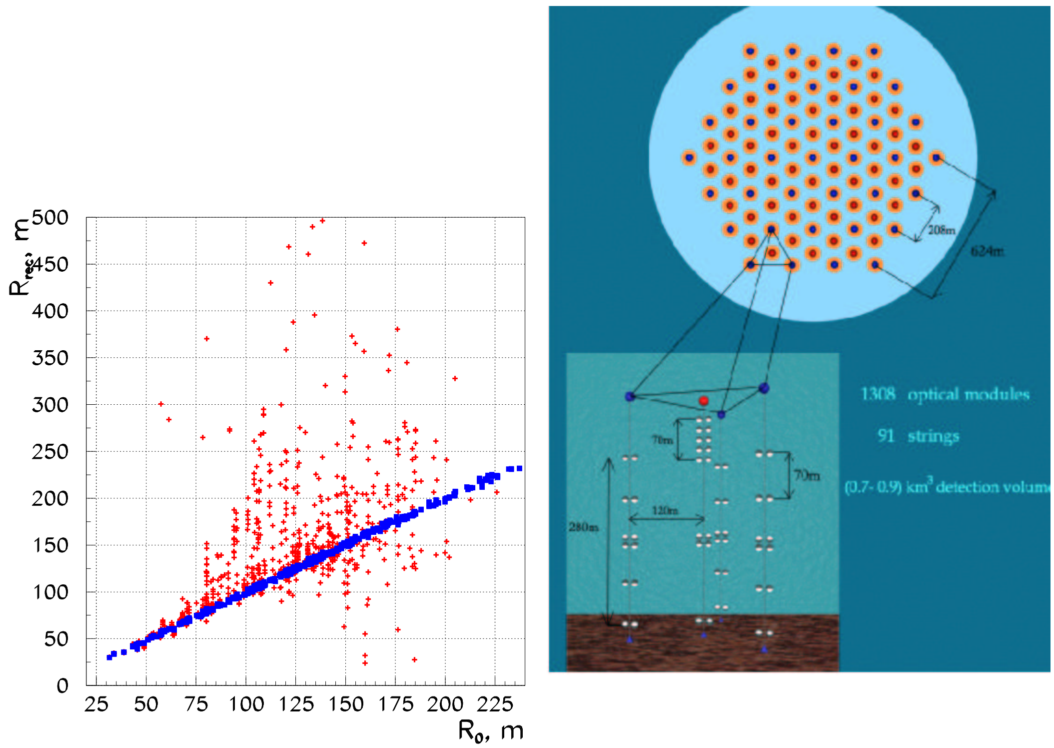


Figure 7: Left: Reconstructed vs. simulated coordinates of cascades in NT-200+ (rectangles) and NT-200 (crosses). Right: Top view of GVD as well as sketch of one of its sub-arrays.

MC simulations have shown that the detection volume of NT-200+ for PeV cascades would vary only moderately, if NT-200 as the central part of NT-200+ is replaced by a single string of OMs. For neutrino energies higher than 100 TeV, such a configuration could be used as a basic sub-array of a Gigaton Volume Detector (GVD). Rough estimations show that $0.7 \div 0.9$ Gton detection volume for neutrino induced high energy cascades may be achieved with about 1300 OMs arranged at 91 strings. A top view of GVD as well as sketch of one basic sub-array are shown in Fig. 7 (right panel). The physical capabilities of GVD at very high energies cover the typical spectrum of cubic kilometer arrays. We are presently working on simulations to optimize the response for TeV muons, maintaining at the same time the cubic kilometer scale for cascades with energy above 100 TeV.

7 CONCLUSIONS AND OUTLOOK

The deep underwater neutrino telescope NT-200 in Lake Baikal is taking data since April 1998. Using the first 502 live days, 84 neutrino induced upward going muons have been selected. Limits on the diffuse high energy fluxes as well as on the $\bar{\nu}_e$ flux at the W-resonance energy have been derived. Also limits on an excess of the muon flux due to WIMP annihilation in the center of the Earth and on the flux of fast magnetic monopoles have been obtained.

In 2005 we plan to put in operation the 10 Mton detector NT-200+ with a sensitivity of approximately 10^{-7}cm^{-2}s^{-1}sr^{-1}GeV for a diffuse neutrino flux within the energy range E>10^2 TeV. NT-200+ will search for neutrinos from AGNs, GRBs and other extraterrestrial sources, neutrinos from cosmic ray interactions in the Galaxy as well as high energy atmospheric muons with E_μ > 10 TeV. In parallel to this short term goal, we started research & development activities towards a Gigaton Volume Detector in Lake Baikal.

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