Vol. 37 (2006) ACTA PHYSICA POLONICA B No 7

THE AMANDA–ICECUBE NEUTRINO TELESCOPES AND INDIRECT DARK MATTER SEARCH*

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(Received May 22, 2006)

The high energy neutrino telescope IceCube is currently under construction in the deep ice of the South Pole glacier. With its $1\mathrm{km}^3$ instrumented volume, it is designed to ensure the detection of extraterrestrial neutrino in the TeV–PeV energy range. Its Predecessor AMANDA, taking data since 1997, has provided along with many useful technical informations increasingly precise limits on a variety of potential astrophysical neutrino sources. After a brief description of these detectors we will focus on the indirect search of Dark Matter performed with the AMANDA telescope.

PACS numbers: 95.85.Ry, 95.55.Vj, 95.35.+d

1. Introduction

Neutrinos as astronomical messengers open a new window on the high energy Universe. Thanks to the fact that they interact only weekly, the Universe is almost completely transparent to them and they travel in straight line, pointing back to their sources. They are hence complementary to γ-rays, which interact with the infrared and microwave cosmological backgrounds, or protons, which at ultrahigh energies interact with the cosmological microwave background and which trajectory is at lower energies bent by magnetic fields. Another very interesting feature is that they are thought to be produced whenever high energy charged pions are produced through their decay. This analogy with the production mechanism of γ-rays through the decay of neutral pions leads to two important consequences.

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* Presented at the Cracow Epiphany Conference on Neutrinos and Dark Matter, Cracow, Poland, 5–8 January 2006.

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First, giving the already observed diffuse γ-rays flux which is thought to come, at least partly, from pions decay, one gets an almost guaranteed equivalent neutrino flux. Secondly, neutrinos could on the same phenomenological basis help to distinguish from hadronic or electromagnetic nature of some cosmic ray accelerators, being absent from the second ones.

Besides, high energy neutrinos can provide an insight on a variety of galactic and extragalactic sources, from supernovae remnants, violent objects like micro-quasars, black holes or active galactic nuclei and gamma-ray bursts to more exotic physics like Lorentz Invariance Violation or Wimps indirect detection on which we will focus here. On the other hand, the very small interaction cross section of these particles makes the use of huge detection volumes inevitable, leading on a technical and economical point of view to the use of natural detection media like liquid water or ice.

2. The Amanda and IceCube neutrino telescopes

Construction of the AMANDA-II telescope began in 1995 [1] at the South Pole station, Antarctica and was completed in 2000, resulting in a detector consisting of 677 optical modules spread across 19 strings deployed between 1500 and 2000 metres in the polar ice cap. The optical properties of the detector medium have been measured with in-situ light sources within the detector. Most of the optical modules use analog signal technology, in which pulses are transmitted via electrical or fibre optic cables. A prototype digital string was deployed as part of AMANDA in order to test new technologies used in IceCube, where trigger, high voltage, and waveform digitalisation is done locally within Digital Optical Modules.

Neutrinos are detected in several ways in AMANDA type deep telescopes. All flavours of neutrino will produce hadronic cascades from charged and neutral current interactions within and close to the detection volume. The yield Cherenkov light spreads on a known pattern away from the interaction vertex. The timing and amplitudes of the detections by the optical modules will enable to reconstruct the properties of the incoming neutrino. Muon neutrinos may interact in the ice or rock far from the detector in a charged current interaction resulting in a muon strongly collimated with the trajectory of the incoming neutrino. The informations will then be reconstructed from the Cherenkov light produced along these kilometer long muon tracks.

Cosmic-ray interactions in the Earth's atmosphere produce two types of background for extraterrestrial neutrinos searches. Atmospheric muons having a range of several kilometers, can be suppressed by looking through the Earth. Atmospheric neutrinos, which would not be absorbed by the Earth will have to be suppressed by energy based cuts. The AMANDA telescope sees respectively 10^9 and 10^3 such events per year.

Following the footsteps of AMANDA which has provided many physical and technical results [2], the kilometer-scale IceCube neutrino and air shower detector is now under construction at South Pole station. It will consist of a deep-ice component, 4800 optical sensors deployed across 80 strings between 1450 and 2450 metres depth, and the IceTop surface air-shower array consisting in 80 (one per string) stations of 4 optical sensors in ice tanks. IceCube which has now 9 deployed and working strings together with 16 IceTop stations is to be completed in 2010. With a sensitivity 30 times better than AMANDA, flavour determination and enhanced pointing and energy resolution, IceCube should hopefully guarantee the detection of neutrino in the TeV–PeV range and open a new window on a wide range of phenomena.

3. Dark Matter searches with Amanda and IceCube

Cosmological observations have long suggested the presence of non-baryonic dark matter on all distance scales. The WMAP results [3] confirmed our current understanding of the Universe, summarised in the concordance model. In this model the Universe contains about 23% non-baryonic cold Dark Matter, but nothing is predicted about the nature of this Dark Matter.

A massive, weakly interacting and stable particle appears in Minimally Supersymmetric extensions to the Standard Model that assume R-parity conservation. Indeed, the supersymmetric partners of the electroweak neutral Standard Model bosons mix into an interesting Dark Matter candidate, the neutralino, whose mass is expected in the GeV–TeV range [4].

On their trajectory through the Universe these particles will scatter weakly on normal matter and lose energy. Eventually, the Dark Matter particles will be trapped in the gravitational field of heavy celestial objects, like the Earth and the Sun [5]. The particles accumulated in the center of these bodies can annihilate pairwise. The neutrinos produced in the decays of the Standard Model annihilation products can then be detected with a high energy neutrino detector as an excess over the expected atmospheric neutrino flux.

We will present here the results of searches with the AMANDA detector for neutralino dark matter accumulated in the Earth (1997–1999 data set) and the Sun (2001 data set). We also summarise current techniques that continue these efforts on higher statistics data samples accumulated during recent years.

Reconstruction of muons, with their long range, offers the angular resolution required to reject the atmospheric background and search for a neutralino-induced signal, which, due to the geographic location of AMANDA, yields vertical upward-going (Earth) or horizontal (Sun) tracks in the instrumented volume. Indeed, it is possible to eliminate the dominant background, downward-going atmospheric muons. However, upward-going atmospheric neutrinos will always contaminate the final, selected data sample.

3.1. Signal and background simulation

We have used the DARKSUSY program [7] to generate Dark Matter induced events for seven neutralino masses between 50 GeV and 5000 GeV, and two annihilation channels for each mass: the W^+W^- channel produces a hard neutrino energy spectrum ($\tau^+\tau^-$ for a 50 GeV neutralino), while $b\bar{b}$ yields a soft spectrum. The cosmic ray showers in the atmosphere, in which downward-going muons are created, are generated with CORSIKA [8] with a primary spectral index of $\gamma = 2.7$ and energies between 600 GeV and 10^{11} GeV. The atmospheric neutrinos are produced with NUSIM [9] with energies between 10 GeV and 10^8 GeV and zenith angles above 80°.

4. Search for neutralino annihilations in the center of the Earth

A neutralino-induced signal from the center of the Earth was searched for in AMANDA data collected between 1997 and 1999, with a total effective live-time of 536.3 days. To reduce the risk of experimenter bias, the complete data set of 5.0×10^9 events was divided in a 20% subsample, used for optimisation of the selection procedure, and a remaining 80% sample, on which the selection was applied and final results calculated. Similarly, the sets of simulated events were divided into two samples: the first for use in the selection optimisation and the second for the selection efficiency calculations. The simulated atmospheric muon sample contains 4.2×10^9 triggered events (equivalent to an effective live-time of 649.6 days). The sample of atmospheric neutrinos totals 1.2×10^8 events, which corresponds to 2.2×10^4 triggers when scaled to the live-time of the analysis.

First, we try to suppress the dominant atmospheric muon background which is about 10^6 times more abundant than the atmospheric neutrino background. This is partially done by selecting the events that are reconstructed as upward-going and that satisfy a cut correlated with reconstruction quality ("filter level 3"). However, only a 10^{-3} reduction of the atmospheric muons is obtained this way (Fig. 1(a)) and more elaborate selection criteria are needed to reject downward-going muon tracks misreconstructed as upward-going. Depending on the detector configuration and the neutralino model under study, the characteristics of the signal differ, which influences selection efficiencies significantly at this point. Therefore, all further cuts are fine-tuned separately for each neutralino model and year of data taking. At filter level 4, a neural network is trained using between 8 and 10 input observables, reaching another 10^{-3} reduction. Filter level 5 cuts sequentially on observables, with the goal of removing downward-going muons that resemble signal events.

At filter level 5 the data sample is dominated by atmospheric neutrinos (see Fig. 1(a)). With no significant excess of vertical tracks observed, the final selection on reconstructed zenith angle (filter level 6) was optimised for the average lowest possible 90% confidence level upper limits on the muon flux. From the number of observed events and the amount of (simulated) background in the final angular search bin, we infer the 90% confidence level upper limit on the number of signal events. Combined with the effective volume at the final cut level and the live-time of the collected data, this yields an upper limit on the neutrino-to-muon conversion rate, which can then be related to the muon flux [10] (see Fig. 1(b)).

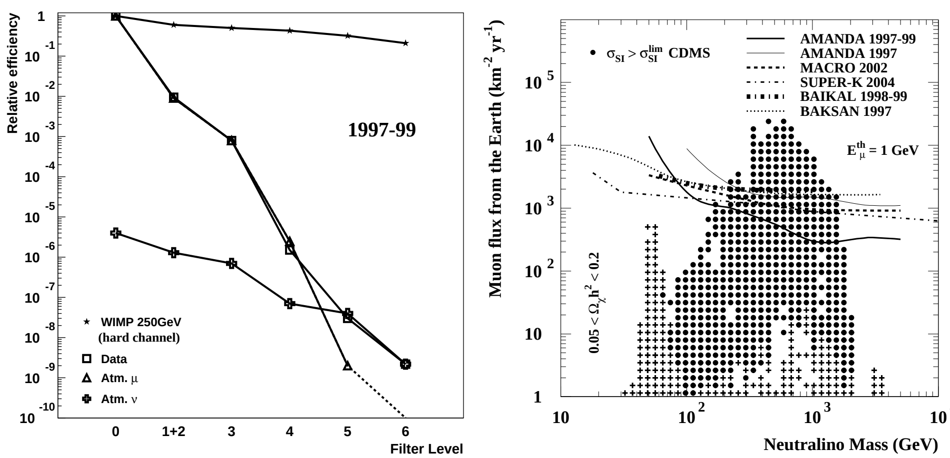

Fig. 1. (a) Detection efficiencies relative to trigger level for the different filter levels in the terrestrial neutralino analysis ($m_\chi = 250\,\text{GeV}$, hard spectrum) for 1997–1999 data, neutralino signal, atmospheric muons and neutrinos. (b) As a function of neutralino mass, the 90% confidence level upper limit on the muon flux coming from hard neutralino annihilations in the center of the Earth compared to our results from 1997 data [11] and other indirect experiments [12]. Markers show predictions for cosmologically relevant MSSM models, the dots represent parameter space excluded by CDMS [13].

4.1. Search for neutralino annihilations in the Sun

The AMANDA data used in the search for solar neutralinos consists of 8.7×10^8 events, corresponding to 143.7 days of effective live-time, collected in 2001. In contrast to the search in Section 4, reducing the risk of experimenter bias in this analysis can be achieved by randomising the azimuthal angles of the data. The advantage of this procedure is that it allows the use of the full data set for cut optimisation. The azimuthal angles are restored once the optimisation is finalised and results are calculated. The simulated atmospheric background sample at trigger level totals 1.6×10^8 muons (equivalent to 32.5 days of effective live-time) and 1.9×10^4 neutrinos.

The solar neutralino analysis suffers the same backgrounds as the terrestrial neutralinos, but the signal is expected from a direction near the horizon, due to the trajectory of the Sun at the South Pole. This analysis was only possible after completion of the AMANDA-II detector, whose 200 m diameter size provides enough lever arm for robust reconstruction of horizontal tracks.

We adopted a similar analysis strategy as in Section 4. First, we select events with well-reconstructed horizontal tracks (filter level 1–3). The remaining events are passed through a neural network that was trained separately for the neutralino models under study and used data as background (filter level 4). Although a data reduction of $\sim 10^{-5}$ compared to trigger level is achieved, the data sample is still dominated by misreconstructed downward-going muons. As shown in Fig. 2(a), they are removed with extra cuts on observables related to reconstruction quality (filter level 5).

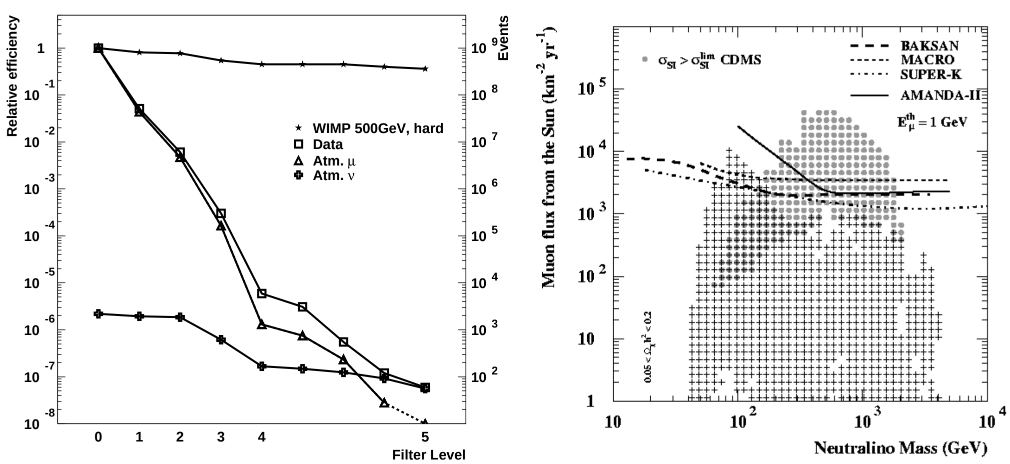

Fig. 2. (a) Detection efficiencies relative to trigger level for the different filter levels in the solar neutralino analysis ($m_\chi = 500\,\mathrm{GeV}$, hard spectrum) for 2001 data, neutralino signal, atmospheric muons and neutrinos. (b) As a function of neutralino mass, the 90% confidence level upper limit on the muon flux coming from hard neutralino annihilations in the center of the Sun compared to other indirect experiments [12]. Markers show predictions for cosmologically relevant MSSM models, the dots represent parameter space excluded by CDMS [13].

There was no sign of a significant excess of tracks from the direction of the Sun in the final data sample. The expected background in the final search bin around the Sun was estimated from off-source data in the same declination band, which eliminates the effects of uncertainties in background simulation. Combining this with the number of observed events, the effective volume and the detector live-time, we obtain 90% confidence level limits on the muon flux coming from annihilations in the Sun for each considered neutralino mass [14], as shown in Fig. 2(b).

4.2. Discussion and outlook

Figs. 1(b) and 2(b) present the AMANDA limits on the muon flux from neutralino annihilations into W^+W^- (hard channel) in the Earth and the Sun respectively, together with the results from other indirect searches. Limits have been rescaled to a common muon threshold of 1 GeV using the known energy spectrum of the neutralinos. Also shown are the cosmologically relevant MSSM models allowed (crosses) and disfavoured (dots) by the direct search from CDMS [13]. Compared to our search for a terrestrial neutralino signal in 1997 AMANDA data [11], the limit has been improved by a factor which is more than that expected from additional statistics alone. This is due mainly to the separate cut optimisation for each neutralino mass, which exploits the characteristic muon energy spectrum of each model.

In 2001 an extra trigger was installed that lowered the energy threshold of the detector. This trigger takes into account spatio-temporal correlations in the event hit pattern. A preliminary analysis with data taken in 2001 and 2002 shows an improvement of a factor of about 5 in the effective volume in the search for 50 GeV neutralinos (soft annihilation channel) from the Earth with respect to the analysis presented in this note. We are currently performing searches for a Dark Matter signal both from the Earth and the Sun with data taken from 2000 and later. The increased detector exposure combined with improved reconstruction techniques and the new trigger setting will result in improved limits from these analyses (note that a 4-year exposure alone would already give an improvement of a factor of two).

The author would like to thank Daan Hubert for fruitful discussion. The IceCube Collaboration acknowledges the support from the following agencies: National Science Foundation-Office of Polar Program, National Science Foundation-Physics Division, University of Wisconsin Alumni Research Foundation, Department of Energy, and National Energy Research Scientific Computing Center (supported by the Office of Energy Research of the Department of Energy), the NSF-supported TeraGrid system at the San Diego Supercomputer Center (SDSC), and the National Center for Supercomputing Applications (NCSA); Swedish Research Council, Swedish Polar Research Secretariat, and Knut and Alice Wallenberg Foundation, Sweden; German Ministry for Education and Research, Deutsche Forschungsgemeinschaft (DFG), Germany; Fund for Scientific Research (FNRS-FWO), Flanders Institute to encourage scientific and technological research in industry (IWT), Belgian Federal Office for Scientific, Technical and Cultural Affairs (OSTC), the Netherlands Organisation for Scientific Research (NWO), M. Ribordy acknowledges the support of the SNF (Switzerland); J.D. Zornoza acknowledges the Marie Curie OIF Program (contract 007921).

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