Status, Results and Future of the DESY Astroparticle Physics Group

Report to the 64. PRC, Hamburg, Nov. 2007

Content

1. Introduction

The DESY astroparticle group in Zeuthen has a 20-year tradition in high-energy neutrino astronomy. With its prominent activities in Baikal and AMANDA it was a pioneer in this field. In IceCube, DESY is the strongest partner after the lead institution University of Wisconsin, Madison. DESY provides backbone services (organizational, technical, financial and on the computing sector) for other German IceCube participants.

The group develops a multi-messenger approach to high-energy astroparticle physics. Already now a Helmholtz-University Young Investigators Group (DESY/Humboldt University) participates in MAGIC. A newly created W3 position at Potsdam University will be combined with that of a leading scientist on astroparticle theory in DESY, a scenario that will further strengthen this concept. DESY is also participating in the design study for a large Cherenkov Telescope Array, CTA. The multi-messenger concept opens the way to an extremely rich astrophysics and particle physics programme and strengthens the ties in the local cluster with Humboldt University Berlin (H.E.S.S., CTA, IceCube) and Potsdam University and AIP Potsdam (optical and X-ray astronomy and cosmology).

DESY also pioneers an R&D program for acoustic detection techniques, with the aim to provide a method for future IceCube extensions towards extremely high energies.

Given the significant investment in AMANDA and IceCube and, more importantly, the dramatic boost in sensitivity and in discovery potential expected for the years 2008-2012, the highest priority of the next years will be the physics analysis of IceCube data, flanked by the necessary steps towards the future beyond IceCube.

2. Structure of the Group

The following table illustrates the personnel structure of the Zeuthen astroparticle group. It consists of 5 senior staff members (R. Nahnhauer, S. Schlenstedt, C. Spiering, M. Walter, R.Wischnewski). E. Bernardini coordinates the Young Investigators group, with one post-doc and one PhD student contributed by DESY and two PhD students from the Young Investigators fund. The remaining annex personnel consists of 3 post-docs and 5 PhD students, with one of the post-docs financed by SFB 676 "Particles, Strings and the Early Universe". The work of the DESY group is closely linked to astroparticle activities at Humboldt University/Berlin: H. Kolanoski is HU professor and DESY leading scientist, M. Kowalski leads an Emmy Noether group. Both are IceCube members and are, besides analysis, involved in recruiting and supervision of Diploma and PhD students at DESY. E. Bernardini represents a similar link from DESY to the Humboldt University. A newly created W3 position at Potsdam University will be combined with that of a leading scientist on astroparticle theory in DESY and provide another connection to local Universities.

	DESY-budget		**Third Party Funding**	
Staff members	Nahnhauer, Schlenstedt, Spiering, Walter, Wischnewski			
Lead Young Investigators Group			Bernardini	
Post-Docs	2	1		1
PhD students	5	1	2	
		Young Investigators Group NG 205		SFB 676

3. The Baikal Neutrino Telescope

The Baikal Neutrino Telescope started full operation in its NT200-configuration in 1998. Most milestones for the project, as formulated in 2004, have been successfully passed. In particular, NT200 was upgraded towards the four times more sensitive NT200+ (see Figure 3.1), with DESY contributing a new calibration laser and playing a lead role in a substantially improved DAQ including its maintenance. First methodical results from NT200+ have been presented at conferences.

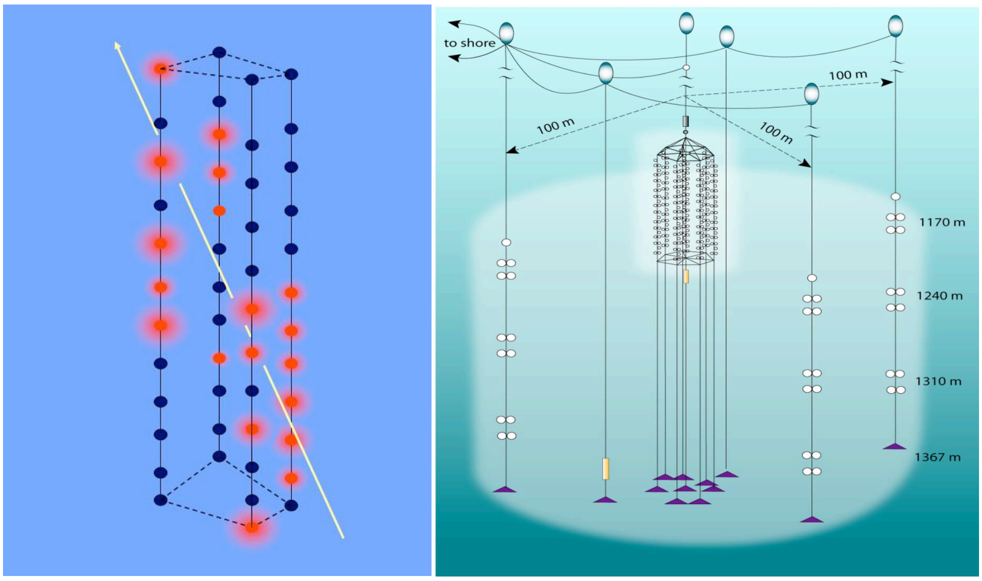

Figure 3.1:
Left: A first text-book up-going muon from a neutrino reaction, recorded with the 4-string stage of the Baikal telescope in 1996.
Right: The present Baikal NT200+ configuration with NT200 as a high density core.

Publication of final multi-year results from NT200 is underway, starting with the search for extraterrestrial diffuse fluxes of neutrinos [Astropart. Phys. 25 (2006) 140]. This analysis improved previous Baikal results by a factor of 2 and has been competitive with 2005/06 AMANDA-II results (see also Fig. 5.2). NT200+ has a fourfold better sensitivity and can test limits obtained with AMANDA.

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Limits from indirect dark matter searches (WIMPs) and searches for relativistic magnetic monopoles have also been lowered substantially (see Figure 5.4). Results of the Baikal 5-year monopole search, only recently bypassed by the AMANDA analysis, have been submitted to Astroparticle Physics Journal. Other publications close to submission cover the search for astrophysical point sources and the search for neutrinos from WIMP annihilations in the Earth. A search for WIMP neutrinos from the Sun is in progress, as well as searches for coincidences with GRB and a Soft Gamma Repeater.

The Russian part of the collaboration is working on a design study for a km-size Baikal neutrino telescope named GVD (Gigaton Volume Detector). DESY will not participate in GVD but has supported in-situ tests of new components and subsystems. The tests are largely based on the DAQ system for NT200+ which can be extended to fit km3-detector requirements and was completely renewed by DESY.

After the afore mentioned series of publications and NT200+ operating, DESY considers its mission accomplished and will terminate its official membership in 2008, after 20 years of a memorable collaboration which included, among others, the pioneering operation of the first underwater telescope in 1993 and results competitive over many years with those from AMANDA. The recent progress of ANTARES, now the largest Northern neutrino telescope, adds another argument to focus DESY's efforts in neutrino astronomy to IceCube alone.

4. IceCube Status

4.1 Formal Status

At present, IceCube includes 29 institutions from eight countries, with DESY being the second strongest in scientific manpower, after the University of Wisconsin, Madison, see Fig. 4.1.

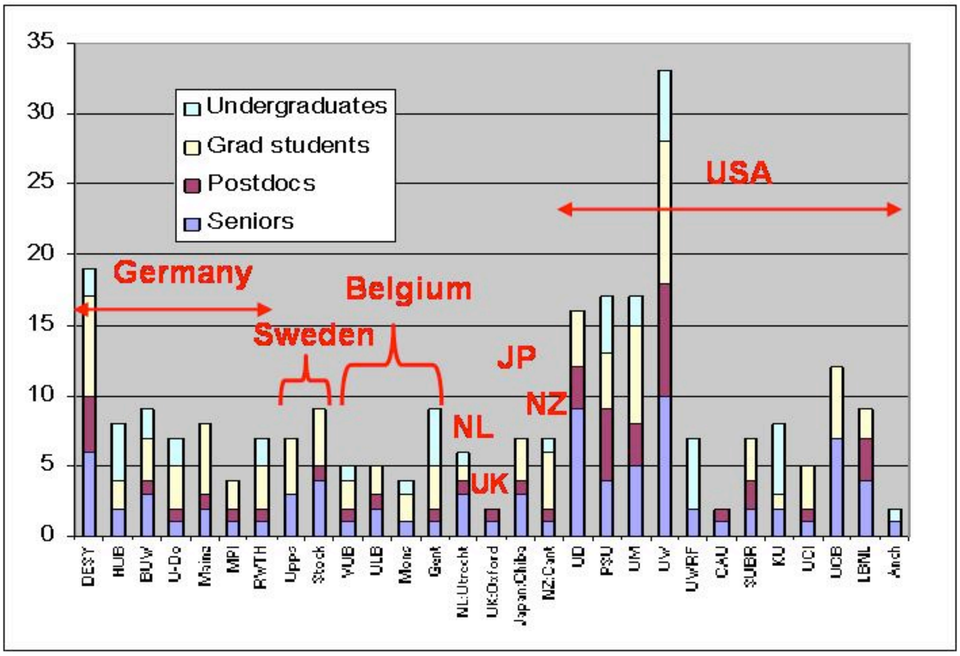

Figure 4.1: Personnel contributions of IceCube institutions

The other German participants are (in the order of the graphics): Humboldt University Berlin, Universities Wuppertal, Dortmund and Mainz, MPI Heidelberg (via an Emmy Noether group) and RWTH Aachen. The dominant US partners are University of Delaware, Penn State University, University of Maryland, and University of Wisconsin (again in the order of the graphics).

DESY physicists took formal responsibilities at different levels. C. Spiering has served as AMANDA co-spokesman and Level-3 lead for AMANDA integration until March 2005, and as IceCube spokesman until March 2007, and is now ex-officio member of the Executive Committee. S. Schlenstedt is Level-3 lead for reconstruction, member of the Speakers Committee since 2005, and is currently its chair. E. Bernardini is chair of the point-source working group and H. Kolanoski co-chair of the cosmic ray working group. R. Nahnhauer is chair of the acoustic working group.

4.2 IceCube construction status and DESY contributions

In its original design, the IceCube detector was conceived to consist of 4800 Digital Optical Modules (DOMs) on 80 strings in the deep polar ice, complemented by the air shower detector IceTop on the surface. Due to an apparent cost overrun, the baseline was reduced to 70 strings in 2005, but re-adjusted to 75 strings in 2007. The remaining contingency budget does not exclude further re-adjustment to 80 strings. End-game scenarios will strongly depend on the drilling speed to be achieved in the next seasons.

The beginning of the deployment was slower than originally planned – one string in the season 2004/05, and eight in 2005/06. In the recent season, the benchmark of 12 strings per season has been passed, with actually 13 deployed strings. Since March 2007 IceCube is taking data with 1320 DOMs on 22 strings in the ice and 104 DOMs in 52 IceTop tanks. Given the technological improvements added meanwhile, the collaboration is now rather confident to deploy 14 strings or more per coming seasons and complete the detector in January 2011 (a delay of only one year). See also Fig. 4.2.

DOM assembly: A total of 5300 DOMs will be assembled and tested in Madison, Sweden and DESY (1300). DESY has delivered 60 DOMs in 2004, 160 in 2005 and 258 in 2006, in accordance with collaboration-wide production plans. Until September 2007, additional 360 DOMs have been shipped from DESY to Christchurch/New Zealand, further 120 DOMs will follow until the end of the year. DOM production is scheduled to be completed in 2008 (unless IceCube will be extended by a high density core – see below). With 2%, the failure rate of DOMs during freeze-in is smaller than expected. Only 2 DOMs (less than 0.2%) have failed in the months/years after freezing.

Other DESY detector contributions: DESY has developed the DOM Readout (DOR) card, is still supervising initial testing and maintenance and is presently installing a firmware upgrade allowing for doubling the transmission rate. Moreover, DESY supplies the magnetic shielding for all DOMs of IceCube as well as all steel chains holding the DOMs.

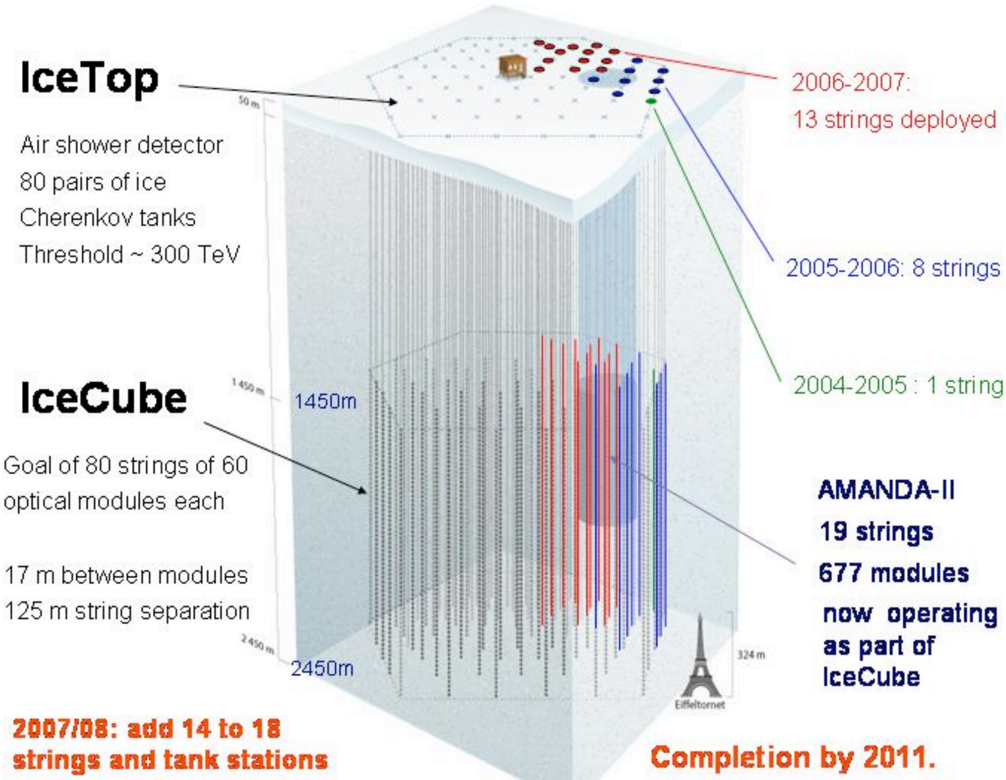

Figure 4.2: IceCube configuration

Maintenance and operation: DESY is coordinating writing and implementation of the reconstruction software, including online reconstruction at Pole. It is also processing data and performs mass Monte Carlo simulation. First GRID tools have been installed. DESY is the European data centre of IceCube. At the end of 2007, 260 of 400 cores available for IceCube will be devoted to IceCube Monte Carlo simulation. DESY is also involved in IceTop calibration and monitoring, as well as in general IceCube monitoring.

3.3 End-game configuration scenarios

It was clear from beginning, that physics arguments – in the ideal case first signal indications – may lead to modifications or extensions of the original IceCube configuration.

Low energy core: At present, the most probable extension appears to be the installation of additional 6-9 strings in the very centre of IceCube, dubbed DeepCore. They would be instrumented only below 2100 meters where the ice is extremely transparent. With 40 DOMs vertically arranged over 400 meters, the vertical spacing would be much smaller than for normal IceCube strings. Well shielded by IceCube from all sides and from the top, DeepCore would replace AMANDA as a dense core with low energy threshold.

Compared to AMANDA, its performance would be significantly improved, due to the complete IceCube veto and the better ice. Regrettably, AMANDA operation is likely to be terminated in 2 years from now, due to snow accumulation around the counting house and other technical/logistics reasons. DeepCore would allow observation of the Southern sky, extension of the indirect dark matter search to lower WIMP masses, slightly improved point source sensitivity for steep source spectra and, possibly, oscillation studies in a hitherto unexplored energy regime. An application for funding of 6 strings has been submitted by the Swedish colleagues to the Wallenberg foundation, and contributions from Germany and Belgium are under discussion.

High energy re-configuration: In addition to the low energy extension, the final 8-10 of the baseline strings might be arranged in a large circle around IceCube, with 250-300 meter spacing. This would possibly enhance the sensitivity at 100 TeV - 1 PeV by a factor 1.5-2. It would also allow testing of radio and acoustic signal transmission over more than 1 km distance – a last performance check towards a possible hybrid radio-acoustic array on the 100 km^2 scale.

5. AMANDA physics results

4.1 Overview

In accordance with our 2004 plans, results from long-term analyses have been published in journals or as conference contribution:

a) search for point sources based on data taken in 2000-2004 (astro-ph/0611063, Phys.Rev. D75 (2007) 102001) – see also section 5.2.,
b) search for diffuse extraterrestrial fluxes with muon neutrinos (2000-2003 data, astrop-ph/0611773, accepted by Phys.Rev.D),
c) measurement of the energy spectrum of atmospheric muon neutrinos up to 100 TeV (2000-2003 data, submitted to ICRC 2007, see supplementary material ICRC). This analysis also confirmed the limit derived in b) with a complementary method.
d) search for diffuse extraterrestrial fluxes with cascades, i.e. dominantly electron and tau neutrinos (2000-2004 data, submitted to ICRC 2007, see supplementary material ICRC).
e) search for diffuse extraterrestrial fluxes at PeV-EeV energies (higher than the TeV-PeV energies characteristic for the analyses a)-d). One analysis used data from 2000-2002, the other data from 2003-04 taken with the TWR (Transient Waveform Recorder) system.
f) search for neutrinos coinciding with Gamma Ray Bursts (GRB), using GRB satellite triggers from the years 1997-2003 (408 bursts). The present AMANDA limit is close to the so-called Waxman-Bahcall model which assumes that all cosmic rays above the “ankle” are produced by GRB.

Analyses a)-d) have improved the limits available in 2004 by about a factor four, analysis e) by a factor 2.5 and exclude various theoretical models. Analyses a)-d) are all based on data filtered and processed in DESY, analyses a) and d) have been performed in DESY.

Figure 5.1 shows the spectrum of atmospheric neutrinos as measured with AMANDA. Figure 5.2 gives a compilation of past and present limits on diffuse fluxes. The latest limits from AMANDA have been derived in DESY ("cascades 2000-04") and for the Ultra-High Energy (UHE) region at University of California, Irvine (UCI), the latter based on data taken with the Transient Waveform Recorder (TWR) system developed by Wuppertal University, DESY and UCI. The cascade 2000-04 limit is the most stringent of all limits. Also given are the limits expected from one year of full IceCube, using only muon neutrino data, and from three years combining muon and cascade data.

Figure 5.3 compares the AMANDA limit on neutrinos in coincidence with GRB to the Waxmann-Bahcall model. Actually the AMANDA limit comes close within a factor 1.5 to the WB model. With the full IceCube, this assumption can be proved or disproved within about six months.

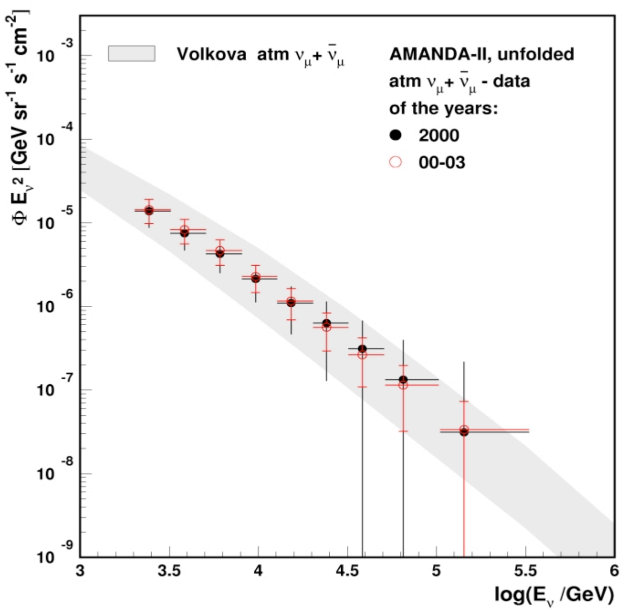

Figure 5.1: Spectrum of atmospheric muon neutrinos measured with AMANDA. The grey band sketches the model predictions for vertical (lower border) and horizontal (upper border) neutrinos. AMANDA data are averaged over the full lower hemisphere. The picture demonstrates the excellent agreement of the measurement with the model predictions.

Other analyses have substantially improved the limits for neutrinos from WIMP annihilation in the Sun or the Earth. An analysis started in DESY and finished at RWTH

Aachen has searched for relativistic magnetic monopoles and established improved limits (see figure 5.4). Further analyses concern violation of Lorenz invariance and non-standard neutrino oscillations, cosmic ray nuclear composition, or neutrinos in coincidence with a possible galactic Supernova. In this context we note that AMANDA is operating within SNEWS, the Supernova Early Network System.

Present analyses performed at DESY concern point source/multi-messenger analyses (see section 5.2) and search for diffuse fluxes using the cascade signature (mostly electron and tau neutrinos).

Activities on cascades have lead to the presently best limit on diffuse extraterrestrial fluxes (see item *d* above) and are presently focused on

- the development and test of new simulation and reconstruction methods for the investigation of very high energy cascades in the IceCube detector,
- the development of new reconstruction and filter algorithms for the cascade search with present and future IceCube data, together with the Emmy Noether group of M. Kowalski at the Humboldt University.

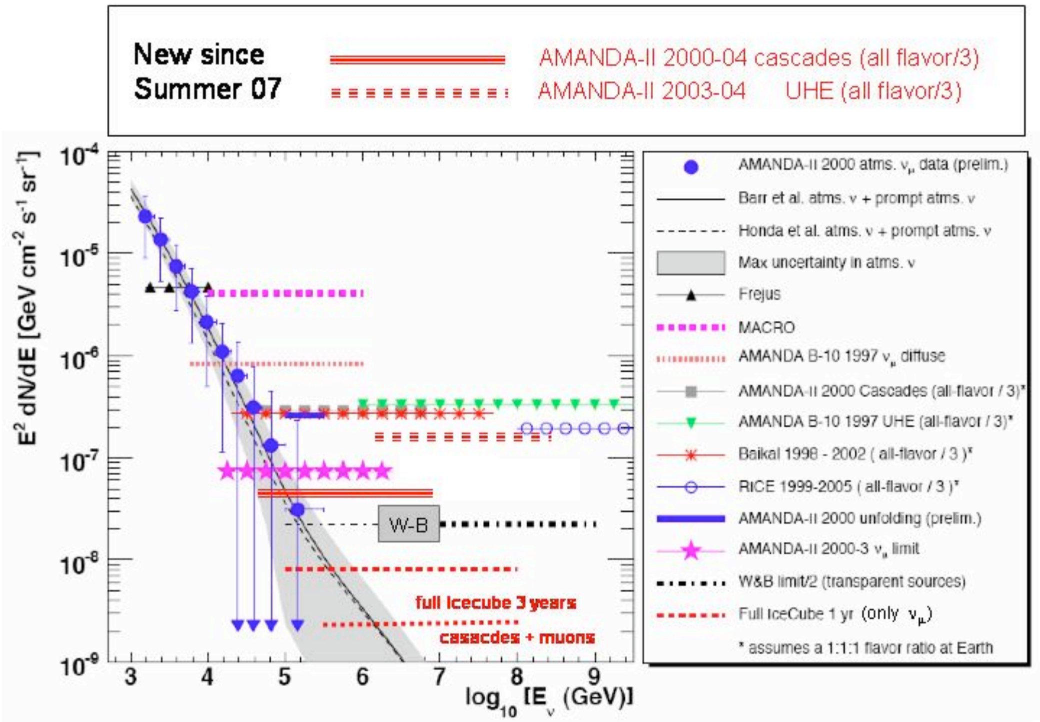

Figure 5.2: Development of the limits on the diffuse extraterrestrial neutrino flux.

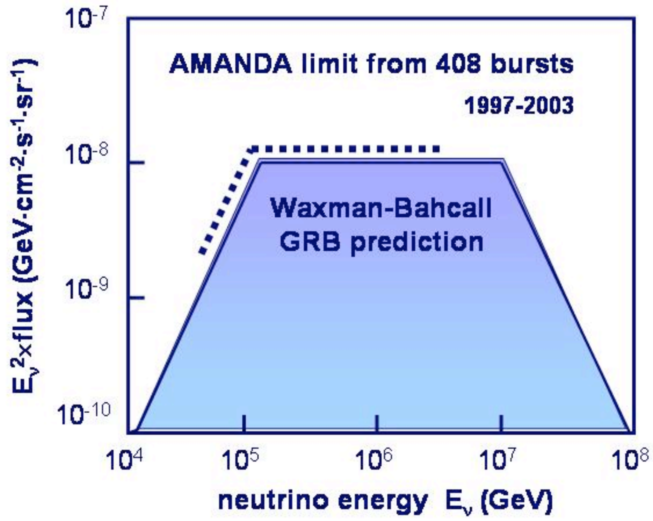

Figure 5.3: Limit on neutrinos from GRB (dashed line) compared to the WB GRB prediction.

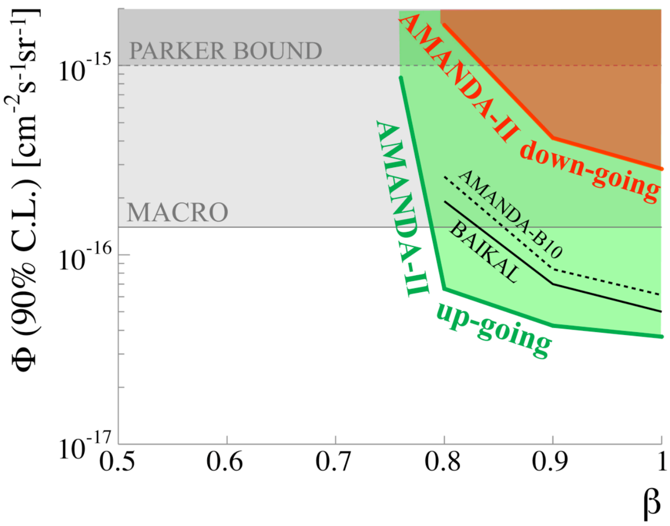

Figure 5.4.: Limits on relativistic magnetic monopoles

An overview on physics results from AMANDA can be found in the collection of papers submitted to the 2007 ICRC, provided as supplementary material to this report and will be also available on the *astrop-ph* server and on the PRC web page. Papers published in refereed journals are compiled in section 11.

4.2 Point Source Analyses

The DESY work on point source searches is performed within the Young Investigators Group "Multi-Messenger Astronomy" (abbreviated YIG in the following).

<u>*Steady sources, 5 year data:*</u>

The analysis of data collected with AMANDA to search for point sources of neutrinos has been essentially completed. The search with the largest statistics has been performed by DESY (Achterberg et al., Phys.Rev.D, vol.75 (2007) 102001). Actually, this set of filtered and processed data serves as a standard sample for a series of analyses in other IceCube institutions (see also the compilation of ICRC reports).

The analysis of data collected with AMANDA in 2000-04 yields a sample of 4282 neutrino events (Figure 5.5). The distribution of the events is compatible with all neutrinos being of atmospheric origin, resulting in the tightest upper limits to the flux of cosmic muon and tau neutrinos, namely $1.1 \cdot 10^{-10}$ TeV^{-1} cm^{-2} s^{-1} (average for objects at the Northern hemisphere, assuming a spectral index of 2). These limits substantially constrain neutrino production in selected objects (M. Ackermann et al., "Upper limits on neutrino fluxes from point-like sources with AMANDA-II", Proceedings of the Multi-Messenger Conference, Barcelona 2006, Astrophys. and Space Science ASTRPA-63). This analysis included not only the ν_μ but also the ν_τ channel which was never considered before although it also yields muon tracks. Due to neutrino oscillations, this channel turned out to contribute with up to 16% (energy dependent) to the overall sensitivity. The analysis provided also the most detailed study of the systematic uncertainties of AMANDA analyses covering the energy range between about 100 GeV and a few PeV, and serves as input to several other AMANDA/IceCube publications.

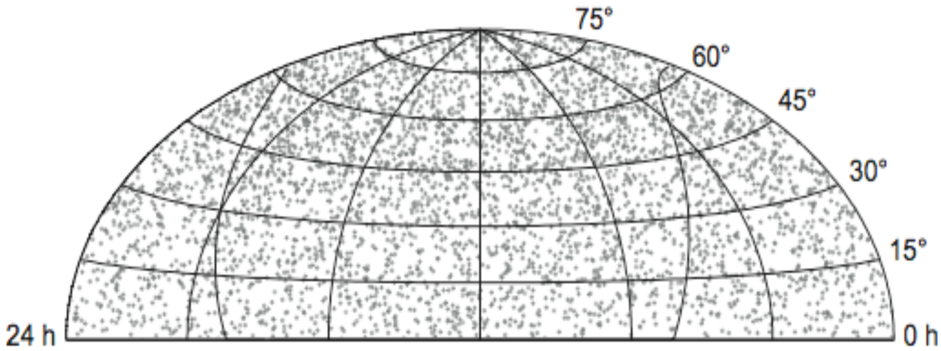

Figure 5.5: Sky map of the 4282 AMANDA neutrino events detected in 2000-2004

Other analyses use stacking methods (one combining Active Galactic Nuclei, a second Starburst Galaxies) or search for neutrinos from the Galactic Plane (work done in Dortmund and Aachen).

Extension to high energies:

In addition to "standard" searches for point source of neutrinos, the YIG works on the extension of the sensitivity to both higher and lower energies. At energies above few PeV the absorption of neutrinos in the Earth becomes relevant, and events are expected to come from close to or even above the horizon. For this purpose the group is developing new concepts for event reconstruction and selection, which focuses on bright events around the horizon. First results are encouraging and reported in [R. Franke et al, ICRC 2007].

Time variable searches and multi-messenger studies

Multi-messenger studies can enhance the chance to discover cosmic neutrinos by using information from established signals. The most obvious example is the search for neutrinos accompanying GRB (see also section 5.1, Fig. 5.3). Another example is the study of objects flaring in gamma rays over hours, days or weeks, like Active Galactic Nuclei (AGN). The collaboration and in particular the YIG follows the traditional *off-line* as well as *on-line* approaches. In order to quantify corresponding studies, the YIG has compiled available gamma ray time series from selected objects as complete as possible.

a) Off-line analyses

Focusing neutrino searches to the time periods in which the observed gamma-ray emission is unusually enhanced, the accumulated background can be radically suppressed and the significance of an observation improved. An example presented already earlier to the PRC are data from 2002 which have revealed a tantalizing coincidence in time of two neutrinos from the direction of the active galaxy ES1959+650 with gamma flares observed for this object. No exact significance could be assigned to this effect, but assuming it to be real, it would have resulted in highly significant 60 events in a cubic kilometre detector. In a more elaborated approach we have recently applied this method to data collected with AMANDA in 2004-06 [K. Satalecka et al, "Cluster search for neutrino flares from predefined directions", ICRC 2007].

b) On-line methods

Target of Opprotunity (NToO): The field of view and the duty cycle of Air Cherenkov Telescopes (ACT) are small. Therefore the information on the gamma-ray emission of interesting sources at the time when a neutrino event is detected is limited, making cross-correlation analyses difficult. To increase the probability to collect gamma-ray data (quasi-) simultaneous to high-energy neutrinos, the YIG has developed a Neutrino triggered Target of Opportunity program (NToO). A neutrino event from anyone of several pre-determined directions of sources known to flare occasionally is used to trigger gamma-ray observations of the corresponding object. A positive coincidence between neutrino events and a gamma flare can dramatically enhance the discovery chance. Generally, this method will increase the availability of simultaneous observations. The method has been technically implemented for AMANDA triggering MAGIC and was successfully realized in a two-months test (Sept.-Dec. 2006). Five alerts have been sent to MAGIC and two follow-up observations took place. The observations are compatible with background triggers, results were presented in [Ackermann et al., for the IceCube and MAGIC collaborations "Neutrino Triggered Target of Opportunity (NToO) test run with AMANDA and MAGIC", ICRC 2007]. This first cooperation between a neutrino and a gamma-ray telescope serves as a prototype for a NToO program with IceCube, using the developed guidelines and toolboxes for the exchange of information. A new campaign is envisaged for 2008/09, when a large part of Icecube will be running stably. The YIG is currently working on data quality assessment, on the development of tools for on-line analyses with IceCube and on the extraction of high significance triggers.

<u>*Optical follow up:*</u> Another promising on-line method is being developed at Humboldt University. The observation of a couple of neutrino events from the same direction within a short time interval would trigger robotic optical telescopes and enhance the detection chance for extragalactic supernovae or GRB [A. Kappes, M. Kowalski et al., "Detecting GRBs with IceCube and optical follow-up observations", ICRC 2007].

c) Long time coverage gamma-ray light curves

In order to obtain the largest possible coverage of gamma-ray data and perform statistical characterization of the probability to observe unusual gamma-ray flares, the YIG has developed a method to cross calibrate and combine data collected by different instruments. The results are unsurpassed in their completeness and coverage and allow new investigations of the phenomenology of the sources. An example is given in Figure 5.7.

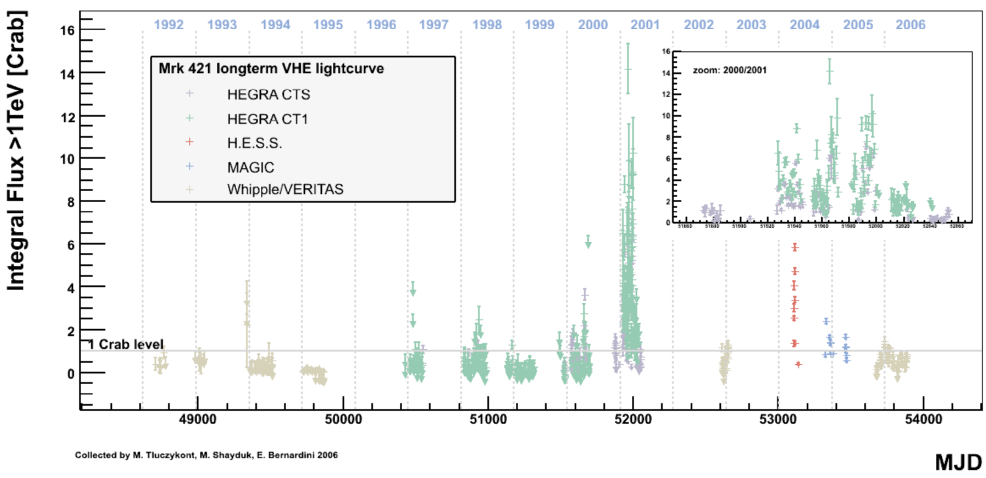

Figure 5.7: Combined light curve of the prominent BL-Lac-object Mrk 421, obtained by combining more than 15 years of data (more than 1500 hours of observation).

6. MAGIC participation of the YIG

In the context of the multi-messenger concept, three members of the YIG have joined the MAGIC collaboration. The MAGIC Cherenkov telescope has the right geographical location with respect to IceCube: both observe the Northern sky. Primary interest is the characterization of the gamma-ray emission of AGNs. Via an extra funding granted to the YIG in 2007, DESY also contributes to the construction of the second MAGIC telescope. MAGIC's low threshold (below 100 GeV) will be further lowered by its second telescope MAGIC-II scheduled to start operation in fall 2008. This second telescope also offers a test bed to test new photo-sensors, be it for the current and or the next generation telescopes.

Hardware contribution

Low energy sensitivities pay off when studying distant objects like AGN and GRB, since energetic gamma rays are absorbed by the intergalactic infrared and 3K radiation. A low energy threshold is also relevant for the observation of many galactic objects, like pulsars and micro-quasars with low intrinsic cut-off energies. To lower the energy threshold, the MAGIC collaboration is studying new photo-sensors with high quantum efficiency (QE). Examples of these photo-sensors are Hybrid photo-diodes (HPDs), and Ultra Bialkali PMTs (UBA) for which Hamamatsu achieved up to 50% and 43% QE, respectively (compared to 25% of classical PMTs). A demonstration of HPD and UBA application in MAGIC is planned for 2008. The YIG funding allows contributing to the purchase of a part of the new devices.

Data analysis and Monte Carlo production

Information on the recurrence of periods of enhanced gamma-ray emission is of primary importance for the study of correlations with neutrinos. However, the frequency of recurrences is not known for most sources, and its assessment requires the availability of large statistics of gamma-ray data, desirably un-biased by the observations of high states of emission at other wavelengths. This deficit is addressed by a program of AGN monitoring which was launched by the MAGIC collaboration in 2006. The YIG will contribute to the analysis of those data records. In addition, in order to increase the statistics of gamma-ray data of AGNs, it will analyze non-standard data records, as those collected during nights with moon-light, with larger night sky background, compared to observations typically used in analysis. This approach has been already successfully explored in MAGIC. The front-end electronics has however been recently upgraded from a 300 MSamples/s to a 2 GSamples/s FADC system, to better resolve the time development of the Cherenkov signal (which is different for gamma-rays and hadrons) and to reduce the integrated light of the night sky. The YIG will work on the development of the analysis of moon-light data collected with new read-out system. For the purpose, the YIG is going to produce dedicated moon-light Monte Carlo data for MAGIC-I. It will also contribute to the production of simulated data for MAGIC-II. The group is currently setting up a benchmarking system to test the performance of the DESY cluster with MAGIC Monte Carlo simulation software.

7. IceCube: performance and first physics results

Performance results of the first (2005) IceCube string have been published (Astropart. Phys. 26 (2006) 155). First results on atmospheric neutrinos obtained with the 9-string detector operated in 2006 have been presented at ICRC 2007 and is accepted by Phys RevD for publication. DESY efforts in analysis are being consistently moved from AMANDA to IceCube. At present, first IceCube analyses on point sources above the horizon and on cascades yield physics results. Beside IceCube, there is a very visible DESY activity in IceTop, together with Humboldt University. H. Kolanoski is the co-chair of the IceTop Working group. Again, first physics results have been presented in 2007. E. Bernardini (DESY) chairs the point source working group. Within the SFB 676, a DESY search on magnetic monopoles has been started in 2007.

Below we give information on DESY contributions to IceCube software development and to Maintenance and Operation, and illustrate first physics results using the examples of point source searches and cosmic ray studies with IceTop

7.1 Software development, Maintenance and Operation

Reconstruction software: The reconstruction programs of IceCube have been developed in a common effort of the IceCube project and the collaboration. The task is to write sustainable, maintainable, extendable software of a high standard, well documented and tested. S. Schlenstedt is the project lead and release manager of that software effort. Other colleagues at DESY designed and implemented important software modules, reviewed code and verified the performance of different algorithms for use in analysis.

Monte Carlo production: DESY is processing data and performs mass Monte Carlo simulation. First GRID tools have been installed. DESY is the European data center of IceCube. End of 2007, 260 of 2.3 GHz 400 cores available for IceCube will be devoted to IceCube Monte Carlo simulation.

Quality verification: In the context of neutrino alerts, the DESY group has installed on-line algorithms to test the data quality, including both low-level and high level filters and has developed a series of other data verification tools.

7.2 Physics Results, Point source searches

A first search for point sources of neutrinos with IceCube has been performed in Wisconsin using data collected with 9 strings (year 2006). Results are compatible with the background from atmospheric neutrinos, see Figure 6.1.

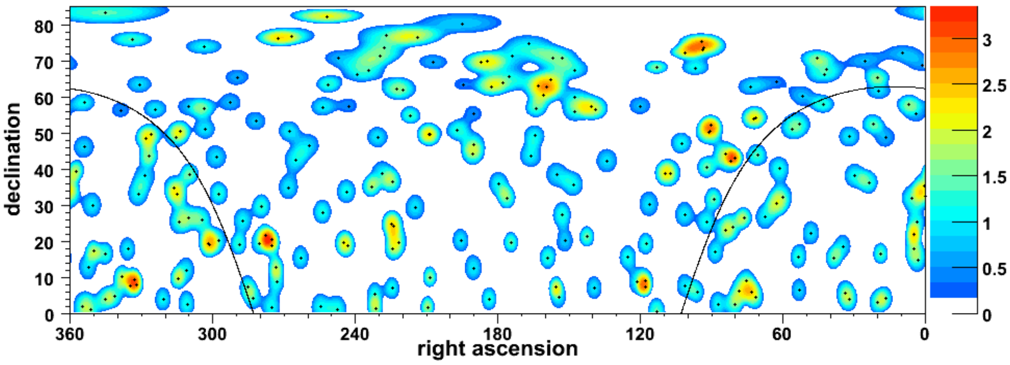

Figure 7.1: Significance sky map from the analysis of data collected with the IceCube 9-string stage in 2006.

The YIG is working on the analysis of data collected with 22 strings (2007), to extract a standard up-going neutrino sample (energy range from few TeV to few PeV) as well as a sample of horizontal events (multi-PeV energy). The goal is the development of multi-channel methodologies, in which different event classes are combined, to enlarge the energy region of sensitivity. The methodologies developed will also be tested on data filtered at Pole, with the goal of developing on-line analysis of the events and development of on-line alerts for follow-up observations, starting in 2008. Together with the Emmy Noether group of E. Resconi (MPIK Heidelberg), the YIG also explores the potential of the combined AMANDA/IceCube detector. The denser instrumentation of AMANDA allows a better reconstruction of low energy events, with a threshold possibly lowered to 30 GeV (compared to the 100 GeV IceCube threshold).

7.3 Cosmic Ray Physics with IceTop

Overview

The IceTop air shower array is located on the ice surface above the IceCube detector. It consists of 80 stations, close to the position of the strings, with a spacing of 125 m. In the year 2007, 26 stations are installed and operational (Fig.4.2). Each IceTop station consists of two ice tanks employed as Cherenkov detectors which are linked together by a local trigger coincidence. IceTop is an integrated part of the IceCube Observatory. It uses the same optical system as the deep ice detector and the trigger and data acquisition system is common to both.

The purpose and the physics goals of IceTop are:

- measurement of the cosmic ray energy spectrum around the knee and above (about 0.3 to 100 PeV);
- determination of the chemical composition of the cosmic rays in this energy range;
- provision of a veto against high energy air showers for IceCube;
- employment for directional calibration of IceCube;

- monitoring of flux variation to study heliospheric physics and possibly transient events of other astrophysical origin.

The dominant physics motivation for the construction of IceTop is certainly the separation of contributions from different nuclei to the primary cosmic rays. For this purpose, IceTop has the unique possibility to exploit air shower measurements on the surface in coincidence with the detection of muon bundles in the in-ice detector.

DESY/Humboldt contributions

The DESY/Humboldt subgroup working on IceTop has a leading role in the analysis of the first data. The main IceTop activity is located at the University of Delaware (USA). At present, the only other European IceTop group is from University of Gent, but a second German University group shows interest to participate in IceTop analysis. This activity is considered to be important, not only to ensure a participation in this additional IceCube program, but also, for example, as support of our central topic, the point source search, employing the direction calibration feature.

In the framework of a Humboldt/DESY doctoral thesis, the first energy spectrum is being determined using data from the 26-station array of 2007. This work will lead to the first physics publication using IceTop data, scheduled for completion in early 2007. A preliminary analysis using the 2006 data with 16 stations has been presented at the ICRC 2007 [S. Klepser et al., "Lateral Distribution of Air Shower Signals and Initial Energy Spectrum above 1 PeV from IceTop", ICRC 2007] – see Figure 8.1.

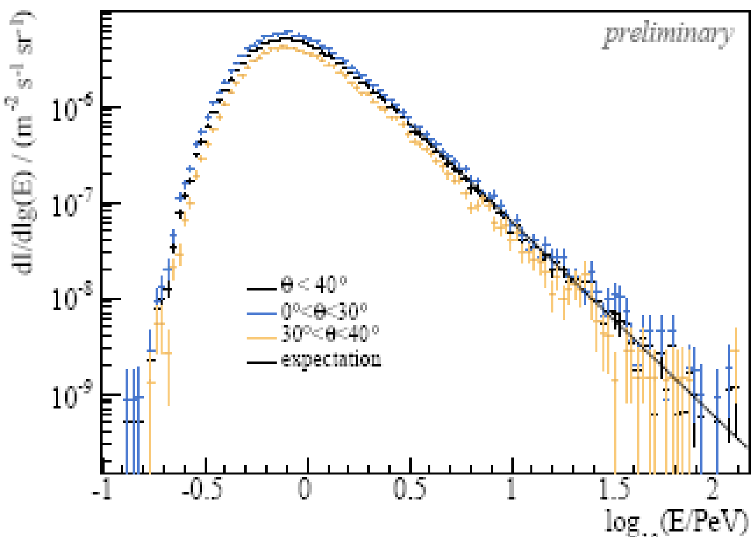

Figure 8.1: Preliminary raw energy spectrum without acceptance correction.

This work lays also the ground for future IceTop air showers analyses. Most prominent is the development of reconstruction algorithms for the energy and direction of air showers using the deposited charge in the tanks. Important input for a likelihood reconstruction is the understanding of statistical fluctuations of pulse heights and arrival times of the signals. This has been covered by a diploma thesis (to be finalized in November 2007). In another diploma thesis the influence of the atmospheric conditions on the shower development was studied.

Besides the development of reconstruction algorithms the DESY/Humboldt team has contributed various software tools: a ‘waveform processor’, analysing the recorded tank pulses, a single-muon calibration fit procedure, a description of light collection efficiencies in the tanks for simulation and other tools and algorithms.

The next step will be a participation in the composition measurements, mainly based on a doctoral thesis to be started in February 2008. The intended direction of this thesis is the exploitation of coincidences with the in-ice detector. However, alternative measures of composition will also be investigated, like the information provided by the waveforms, which is currently a topic of yet another diploma thesis.

8. Acoustic Neutrino Detection

The effective volume needed for the detection and study of the feeble cosmogenic neutrino flux from the interaction of charged cosmic particles with the 3K background (GZK neutrinos) is about two orders of magnitude larger than the instrumented volume of the cubic kilometre neutrino telescopes presently built (IceCube) or under preparation (KM3NeT). Cost-affordable solutions require signals that propagate with much less absorption than light. Detection of radio and acoustic signals from extremely energetic neutrino interactions would allow larger sensor spacing and therefore a larger sensitive volume, at a less progressive cost. The feasibility and specific design of an acoustic array as part of a 100 km^3 hybrid detector in ice was simulated with DESY participation. It depends on the ice properties for signal creation, transmission and background, which are presently under exploration.

Since long, the DESY group is spearheading efforts to detect acoustic signals from neutrino interactions. Sensitive acoustic detectors for in-ice application have been designed and tested at accelerator beams and in the laboratory. Self-noise as low as 11 mPa has been reached with signal-to-noise ratios 50 times better than for a good commercial hydrophone. For the acoustic in-situ study at the South Pole, the South Polar Acoustic Test Setup – SPATS – has been built under DESY leadership. It is aimed to evaluate the acoustic attenuation length, speed of sound and refraction behaviour as well as background noise level and transient event rates.

SPATS consists of three vertical strings that were deployed in the upper 400 m of three IceCube holes which form a triangular array with inter-string distances of 125, 302 and 421 m. Each string has seven acoustic stages. The upper part of the ice has a larger density gradient, therefore a larger variation of the acoustic properties is expected and the distance between stages increases with depth. Figure 8.1 shows a schematic view of the SPATS array and its in-ice and on-ice components.

Figure 8.1:

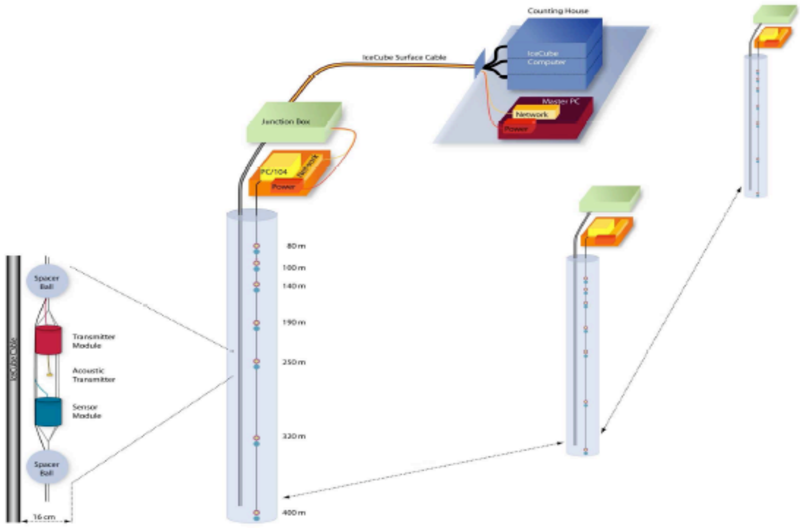

Figure 1: Schematic of the SPATS array, with the three strings each with 7 acoustic stages.

SPATS was successfully installed and commissioned between December 2006 and February 2007. All 21 transmitters and 53 out of 63 sensor channels are working normally. Data taking is ongoing. Ambient noise is stable and Gaussian and decreases with depth. During the first three months is increased slightly and then levelled off. The transient event rate is as small as one event per minute per sensor channel. The speed of sound has been measured at different depths with a precision of 0.2%. Refraction has been found negligible from these measurements. Transmitter signals have been detected from each string to every other string. Their amplitude was found lower than expected. The current data do not significantly constrain the attenuation length.

To improve the data quality and get more information from different distances between transmitters and sensors in the ice at the same depth, a fourth string has been build and tested under laboratory conditions. It will be deployed in December 2007 to a maximum depth of 500 m. Besides mechanically and electronically improved SPATS sensors and transmitters, it will carry two new sensors build at University of Wuppertal and a new transmitter from EPFL Lausanne. In addition a specially prepared transmitter will be moved up and down in several empty IceCube holes, directly between drilling and deployment of optical sensors. It will send continuously acoustic signals with a repetition frequency of 1 Hz. Being registered by the SPATS sensors, these signals will provide the possibility of detailed sound speed and attenuation length studies.

At present, SPATS has reached two of its three goals. Both acoustic noise and acoustic signal refraction seem small enough for embedding the acoustic technology in the conceived huge hybrid radio/acoustic array. The remaining task is to prove or disprove the theoretical estimations that the acoustic attenuation length in South Polar ice is significantly larger than that of light. If the 07/08 deployment season is successful, the answer to this question will be given hopefully in a year from now.

A more precise determination of the attenuation requires larger baselines for signal propagation. Such a possibility could be offered by the possible re-configuration of the last IceCube strings and their arrangement on a ring with one kilometre radius. A decision about this high energy configuration is expected for next summer. Until then, simulation calculations will show what additional questions can be answered if radio and acoustic sensors would be added to the optical ones. Questions like whether energy thresholds could be kept very low and whether one can hope to detect a handful of coincident radio/acoustic events should be answered. One also could study the technical performance of prototype hybrid strings, operating at kilometre-scale distances. The deployment of these test strings, if logistically feasible and positively evaluated, would happen in the season 2010/11 or 2011/12. Therefore a decision about a new hybrid test project is necessary not later than end of 2008.

9. CTA

DESY has joined a design study preparing the construction of CTA, the next generation Cherenkov Telescope Array to measure high-energy gamma-rays. This research line will complement the IceCube activities and considerably enrich the astrophysics and particle physics programme at DESY.

Cherenkov gamma-ray telescopes like H.E.S.S. and MAGIC have already revealed an exciting variety of new phenomena. In gamma ray astronomy, the next step leads from telescopes observing single positions to arrays that cover significant parts of the sky. For this purpose, the CTA observatory is planned which will operate a multitude of robotic telescopes. CTA is listed as an “Emerging proposals” in the ESFRI list of Large European Research Infrastructures 2006. CTA and AGIS (the US equivalent) are ranked very high in the European and US-American roadmaps for astro-particle physics and will likely join their efforts.

The proposed Cherenkov Telescope Array aims for an increased sensitivity in the core energy range from about 100 GeV to about 10 TeV by about one order of magnitude, and will at the same time expand the energy range both to lower and higher energies, effectively increasing the usable energy coverage by a factor of ten as shown in the Figure 9.1

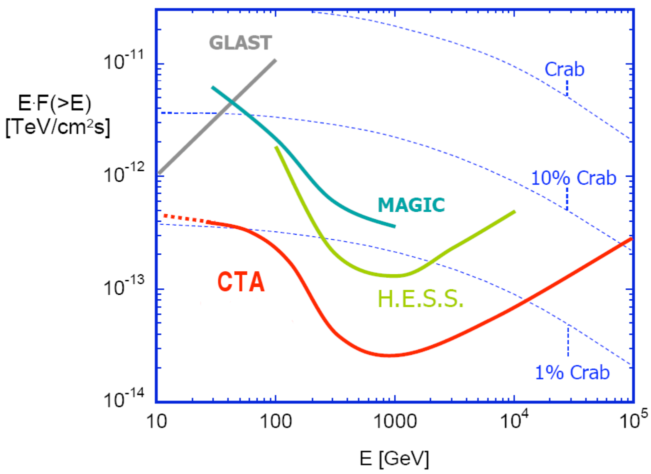

Figure 9.1: Expected sensitivity of the future CTA compared with current high-energy gamma ray telescopes. The Crab nebula is used as a standard candle.

CTA will allow for efficient surveys of large fractions of the sky and the study of extended structures. The increase of the effective detection area into the few-km^2 range will lead to unprecedented detection rates and make transient phenomena detectable over much shorter time scales. In addition, a significant improvement of the angular resolution is crucial for morphological studies of extended source regions. With CTA, the number of very high-energy gamma ray sources is expected to increase from currently about 70 to O(1000).

The structure of the international CTA consortium was formed in summer 2007 preparing an EU-application in the FP7 framework. A work package structure and a time line for the design of CTA have been developed. Based on current estimates it seems possible to start operating CTA, at least with a core system, in five to six years from now. The CTA collaboration effectively comprises the entire very-high-energy gamma-ray community in Europe, as well as many new participants from other fields. Work is going on to write a Letter of Intent. Applying for a 'Helmholtz Alliance on Cosmic Particle' sharpened the understanding what rôle DESY could play in CTA.

An essential part of the mission of the Helmholtz Association is to build and operate research systems of great complexity with our large-scale facilities and scientific infrastructure, cooperating closely with national and international partners. In particular, DESY has a long track record in the operation and control of large astro-particle physics experiments and the development of software frameworks for data processing and data storage. This experience will serve, in close collaboration with partners from the community, as a basic ingredient for the development of the operation and control system of CTA. It would extend the present engagement of the Helmholtz–University Young Investigators Group and also strengthen the ties in the local cluster with the Humboldt University Berlin (H.E.S.S., CTA, IceCube).

In the case of CTA, we plan to perform optimization studies, and construct and operate prototype telescope(s), which will additionally increase the scientific potential of existing instruments:

- To achieve the envisaged sensitivity, a coherent, intense **simulation effort is** needed to extract optimized basic parameters on telescope types and sizes. DESY activities will be embedded in collaboration-wide activities, with strong contributions from German, French and US partners. The simulation studies will strongly impact the design of CTA and allow determining the physics potential.
- **Telescope structures and drive and control system:** The lead institutes of MAGIC and H.E.S.S. will use their extensive experience to design, together with industrial partners, the telescope structures, aiming for a high degree of built-in reliability as well as cost-effective mass production and installation. DESY would contribute to the design and cost optimisation of the drive and control system as one of the key systems for a robotic operation of the telescopes. These efforts will be incorporated into the development of the drive and control system of the prototype telescopes.
- **Array Operation and control system**: To maximize the scientific output, the CTA facility will – for the first time in this field – operate as an open observatory, providing observation time and data to a wide community. This will result in significant challenges in the scheduling of observations given the high degree of flexibility in the operating modes of the facility, the reliable and highly efficient operation, and in making data readily accessible to the scientific community. To ensure the optimal performance of CTA, the control, operation, and administration of the facility should be concentrated in a single centre. Helmholtz institutes like DESY are ideally suited for such a task based on their experience in long-term, reliable operation of large facilities. Together will Erlangen, a prototype system for the operation and control system for CTA shall be designed and developed.

10. Conclusions

a) AMANDA physics analyses are going to be finished with record limits on various astrophysical and exotic particle fluxes, as well as with the measurement of spectra of atmospheric neutrinos and of charged cosmic rays. DESY has played a leading role in AMANDA construction, maintenance and physics analysis.
b) DESY's mission in the Baikal experiment, after provision of essential hardware and analysis contributions over 20 years, will be accomplished in 2008 with the release of final results obtained with NT200 and with first results from NT200+. NT200 was the pioneer of the field and has produced a variety of important results.
c) The DESY group is significantly contributing to IceCube construction, primarily producing a quarter of the IceCube optical modules. DESY is producing a large fraction of the IceCube simulation data. GRID tools will play an essential role in this process. The group is well-positioned for the analysis of IceCube data, covering point source searches, studies of diffuse fluxes using cascades, cosmic ray studies with IceTop and the search for slowly moving particles. The years 2008-2012 promise a boost in sensitivity and discovery potential, and the group is determined to make full use of this unique chance. IceCube analysis will be the top priority of the next years.
d) The formation of the Young Investigators Group helped bundling the point source efforts in an effective way and also resulted in first impressive steps towards multi-messenger astronomy. Via the MAGIC collaboration, first practical experience in gamma astronomy/analysis is being collected.
e) A newly created W3 position at Potsdam University will be combined with that of a leading scientist on astroparticle theory in DESY, further strengthening the multi-messenger activities and the ties to astrophysicists in Potsdam.
f) DESY is a pioneer in attempts to detect neutrinos by acoustic signals. A first medium-scale test setup has been successfully installed at the South Pole and will be upgraded in a few months. Further R&D work will provide the necessary information to assess and to plan a large radio/acoustic hybrid array for detection of EeV neutrinos at the South Pole.
g) To define the future DESY strategy it is mandatory to start already now the exploration of projects beyond IceCube. CTA is a natural project to complement and extend the physics, which is addressed by IceCube. Therefore, a moderate part of the resources will be devoted to the CTA design study.
h) Both activities f) and g) will be subject to an evaluation preparing the next Helmholtz Program Oriented Funding (POF) cycle.

11. Publications in refereed journals 2006/07

<u>*IceCube and Amanda*</u>

A. Achterberg et al (IceCube Collab.)
Limits on the Muon Flux from Neutralino Annihilations at the Center of the Earth with AMANDA
Astroparticle Physics 26 (2006) 129-139

A. Achterberg et al (IceCube Collab.)
First Year Performance of the IceCube Neutrino Telescope
Astroparticle Physics 26 (2006) 155-173

A. Achterberg et al (IceCube Collab.),
On the Selection of AGN Neutrino Source Candidates for a Source Stacking Analysis with Neutrino Telescopes
Astroparticle Physics 26 (2006) 282-300

A. Achterberg et al (IceCube Collab.)
Limits on the High-Energy Gamma and Neutrino Fluxes from the SGR 1806-20 Giant Flare of 27 December 2004 with the AMANDA-II Detector
Physical Review Letters 97 (2006) 221101

A. Achterberg et al (IceCube Collab.)
Five Years of Searches for Point Sources of Astrophysical Neutrinos with the AMANDA-II Neutrino Telescope
Physical Review D75 (2007) 102001

A. Achterberg et al (IceCube Collab.)
Detection of Atmospheric Muon Neutrinos with the IcCube 9-String Detector
Physical Review D76 (2007) 027101

A. Achterberg et al (IceCube Collab.)
Search for Neutrino-Induced Cascades From Gamma-Ray Bursts with AMANDA
Astrophysical Journal 664 (2007) 397-410

A. Achterberg et al (IceCube Collab.)
Multiyear Search for a Diffuse Flux of Muon Neutrinos with AMANDA-II
Physical Review D76 (2007) 042008

M. Ackermann et al (AMANDA Collab.)
The IceCube prototype string in AMANDA
Nucl.Instrum.Meth.A556:169-181, 2006 and astro-ph/0601397

A. Achterberg et al (IceCube Collab.)

Multi-year search for a diffuse flux of muon neutrinos with AMANDA-II
Accepted for publication in Phys. Rev. D and arXiv:0707.1315

A. Achterberg et al (IceCube Collab)
The Search for Muon Neutrinos from Northern Hemisphere Gamma-Ray Bursts with AMANDA
Accepted by Astrophysical Journal and arXiv:0705.1186

A. Achterberg et al (IceCube Collab.)
Search for neutrino-induced cascades from gamma-ray bursts with AMANDA
Accepted by Astrophysical Journal and arXiv:astro-ph/0702265

Baikal

V. Aynutdinov et al. (Baikal Collab.),
Search for a diffuse flux of high-energy extraterrestrial neutrinos with the NT200 neutrino telescope.
Astropart. Phys. 25 (2006), 140-150 and astro-ph/0508675

V. Aynutdinov et al. (Baikal Collab.),
High-frequency acoustic noise of Lake Baikal.
Acoust. Phys. 52 (2006), 495-504

V. Aynutdinov et al. (Baikal Collab.),
Search for relativistic magnetic monopoles with the Baikal Neutrino Telescope,
submitted to Astropart. Phys., September 2007.