

Summary of Working Group 4: High Energy Neutrino Telescopes

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Abstract.

The field of high-energy neutrino astronomy is rapidly developing. A number of new experiments are currently being deployed and developed. Additionally, the recent successes of TeV gamma-ray astronomy have exciting implications for future neutrino telescopes. Here we will summarize these and other issues as they were discussed in the TeV II workshop's neutrino astronomy working group.

1. Theory Summary

The neutrino astronomy working group featured a roughly equal number of theoretical and experimental talks. The theory talks consisted of:

Guaranteed and prospective sources of galactic TeV neutrino sources	<i>Matthew Kistler</i>
Potential neutrino signals from galactic TeV gamma-ray sources	<i>Alexander Kappes</i>
Are diffuse neutrinos from starburst galaxies observable?	<i>Floyd Stecker</i>
UHE neutrinos from collapsars as evidence for GRB central engines	<i>Taka Kajino</i>
Neutrinos from UHE nuclei	<i>Nicolas Busca</i>
Event rates vs. cross sections at neutrino telescopes	<i>Shahid Hussain</i>

In the following section, we will summarize some aspects of these talks.

1.1. Galactic Sources of High-Energy Neutrinos

Bolstered by the recent observations of HESS and MAGIC, a great deal of attention has been given recently to sources of TeV neutrinos from galactic cosmic ray accelerators. Known galactic TeV gamma-ray sources now include 7 supernova remnant candidates, 12 pulsar wind nebula candidates, 3 binary systems, 1 source of diffuse emission from cosmic ray interactions and 7 sources currently without useful counterparts at other wavelengths. Despite this rather large and rapidly growing catalog, it is not yet completely clear whether all, some, or none of these accelerators generate TeV gamma-ray through leptonic processes (such as inverse Compton scattering, $e^- \gamma \rightarrow \gamma e^-$) or through hadronic processes ($\pi^0 \rightarrow \gamma \gamma$). On top of this question are other related puzzles which remain unanswered: What are the unidentified HESS and EGRET sources? What is the end of the galactic cosmic ray source spectrum, and what can we learn from it? And perhaps most interesting, Where and how are the galactic cosmic rays produced? To each of these questions, neutrino astronomy may be able to provide answers.

Source	ϕ_γ	Γ	E_ν^{cut} (TeV)	$N_\mu(> 1 \text{ TeV})$
Vela Jr. (RX J0852.0-4622)	21.0	2.1	10-50	3.1-6.1
GC Diffuse	5.2	2.29	20-50	0.5-0.7
RX J1713.7-3946	15.0-20.4	2.19-1.98	50-6	2.2-2.8
Vela X	9.0	1.45	7	4.5
Crab (IceCube)	33.0	2.57	50	2.7
HESS J1514-591	5.7	2.27	25-50	0.9-1.1
HESS J1632-478	5.5	2.12	10-50	0.8-1.5
HESS J1745-303	2.5	1.8	10-50	0.5-1.2

Table 1. The integrated $(\nu_\mu + \bar{\nu}_\mu)$ -induced muon rates, assuming a pionic spectrum, for a 1 TeV E_μ threshold and neutrino spectrum exponential cutoff E_ν^{cut} . For one year of km³ Mediterranean detector operation (unless noted), accounting for observable time below the horizon. The HESS differential flux at 1 TeV is given in terms of $10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$, with spectral index Γ . (Adapted from Ref. [1])

In distinguishing between leptonic and hadronic acceleration mechanisms, neutrino astronomy has a especially useful role. Whereas leptonic mechanisms do not generate high energy neutrinos, hadronic acceleration must generate TeV neutrinos along with TeV gamma-rays, as charged pions ($\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_e \nu_\mu$) are unavoidably produced along with neutral pions ($\pi^0 \rightarrow \gamma\gamma$).

Among the known sources of TeV gamma-rays which are most likely to also provide observable fluxes of TeV neutrinos are the diffuse emission from the galactic center, Vela Jr, the supernova remnants RX J1713-3946 and RX J0852-4622, and the pulsar wind nebula HESS J1825-137. These sources, and several others, are expected to generate a rate in a kilometer-scale neutrino telescope that is near the threshold for detection. Kistler and Beacom [1] estimate a rate of 2.2 to 2.8 muons above 1 TeV per year from RX J1713-3946 in a square kilometer detector in the Mediterranean (see table I). Kappes *et al.* [2] estimate 7 to 11 events above 1 TeV, and 2.6 to 6.7 above 5 TeV.¹ Kistler and Beacom find between 5 and 9 HESS sources which are expected to produce one or more events per year per square kilometer above 1 TeV. Kappes *et al.* predict such neutrino fluxes from even more sources.

1.2. Extra-Galactic Sources of High-Energy Neutrinos

Recently, Loeb and Waxman have argued that starburst galaxies constitute a guaranteed observable flux of high-energy diffuse neutrinos [3]. Following this result, however, Stecker [4] revisited this class of sources and found a somewhat lower prediction for the neutrino flux from these objects.

The basic argument that leads to an estimate of the neutrino flux from starburst galaxies is as follows. Core collapse supernovae in starburst galaxies are expected to inject relativistic protons and electrons. Observations of synchrotron radio emission from starbursts implies the presence of these relativistic electrons. Relativistic protons, losing their energy through pion production, and thus generating high-energy neutrinos. By normalizing the radio synchrotron through the known FIR-radio correlation, it becomes possible to convert observables into the expected neutrino flux.

Loeb and Waxman estimate a diffuse flux from starburst galaxies of a few times $10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ in the TeV-PeV range (just below the Waxman-Bahcall upper bound [5]), whereas Stecker places an upper bound on this flux of $2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

¹ An error which has since been corrected has led to the numbers shown at the TeV II workshop being different from those given here. See Ref. [2].

The neutrino astronomy working group also discussed several other extra-galactic/cosmological sources of high-energy neutrinos. In particular, Kajino discussed collapsar Gamma-Ray Bursts (GRB) within this context. Among other interesting points, he pointed out that – in addition to pion production – other mesons may play a significant role at very high energies in environments with very large magnetic fields, in particular the rho and epsilon.

A flux of high-energy neutrinos long thought to be almost certain to exist at a level observable in next generation experiments is that generated through the interactions of ultra-high energy cosmic rays – the cosmogenic neutrino flux. As discussed in our working group by Busca, if the ultra-high energy cosmic ray spectrum is not dominated by protons, but instead by heavy nuclei, then the corresponding neutrino flux can be considered altered [6].

1.3. High-Energy Neutrinos as a Probe of Fundamental Physics

Once high-energy neutrinos begin to be observed in sizable numbers, they can be used to study the astrophysical processes through which they are produced. In addition to this, however, high-energy neutrinos also provide a new window into the interactions of neutrinos, and can be used to constrain or study a great deal of exotic physics scenarios.

In particular, if neutrino-nucleon cross sections depart substantially at high-energies from the prediction of the Standard Model, neutrino telescopes will be well suited to determine this. Whereas the highest center-of-mass energy collision to be observed at the LHC is 14 TeV, a 10^{19} eV neutrino colliding with a proton at rest constitutes a center-of-mass energy of more than 100 TeV.

Particle physics scenarios which can be probed in this way include models with low-scale quantum gravity. By studying the angular and energy distribution of events in neutrino telescopes, this class of models can be identified by an excess of downgoing events in comparison to the upgoing rate (neutrinos passing through the Earth) [7]. Future experiments may be able to significantly constrain such scenarios.

2. Summary of experimental issues

The following speakers discussed experimental issues and analysis results related to neutrino telescopes or radio detection. The topics refer to a variety of experiments, both existing or under construction:

Results from Antares	<i>Mieke Bouwhuis</i>
Status of the NEMO project	<i>Giorgio Riccobene</i>
Radio wave shower detection	<i>Dave Besson</i>
Tau neutrinos in IceCube	<i>Doug Cowen</i>
A novel tau signature in neutrino telescopes	<i>Ty De Young</i>
Implications of neutrino flux limits	<i>Julia Becker</i>
Multiwavelength approach to transient neutrino source candidates	<i>Elisa Resconi</i>

A common theme addressed by the talks concerns ways to extend the reach of neutrino telescopes by improved sky and energy coverage or by the inclusion of τ neutrinos in the analyses. Other talks were related to improvements in analysis sensitivity, e.g. by employing source stacking methods or by utilizing correlations with γ - and X-ray data.

2.1. Mediterranean projects and radio detection

ANTARES is an underwater detector of 350 m active height, installed at 2500 m depth in the deep Mediterranean Sea close to Toulon. Data taking commenced immediately after the deployment of the first string in February 2006, which was followed by a second string in September; the fully equipped 12-string ANTARES detector is expected to take data in 2007. The reconstruction of muons and muon bundles based on the first string was clearly

demonstrated in the talk by Bouwhuis, showing the advantage of the low scattering environment in the deep ocean. Even with only one string read out, the direction can be unambiguously determined, provided that both time and amplitude information is used.

NEMO, a project supported by Italian universities and institutions, is one of the groups collaborating in the KM3NeT design study for a $> 1 \text{ km}^3$ neutrino telescope in the Mediterranean. KM3NeT, expected to cost less than 200 MEUR, is supported by an EU funded Design Project with the aim to complete a technical design report in 2009. Fig. 1 sketches the time development of accumulated $\text{km}^3\text{-years}$ for northern and southern hemisphere neutrino telescopes. Meanwhile, NEMO is pursuing an R&D effort with the aim to deploy a fully equipped tower in 2007 at the Capo Passero site at 3450 m depth, about 100 km from shore. At these depths, surprisingly low bioluminescence, weak currents and little sedimentation were registered. The philosophy behind NEMO's design is to reduce the number of structures and underwater connections and to use remote operated vehicles for underwater work whenever possible; the number of towers and optical modules are very similar to those of IceCube. Rigid structures, fixing the positions of four photomultipliers at each depth, unfold when released in the ocean.

The advantages of radio detection for ultrahigh energy showers stem from the extreme transparency of ice and water to radio waves (2 km compared to 40 -100 m in water or ice) and from the quadratic growth of signal power due to coherent radio emission (linear in case of optical detection). Unfortunately, $1/f$ noise restricts radio detection to very high neutrino energies, e.g. above $\approx 10^{17} \text{ eV}$ in the case of RICE and $\approx 10^{19} \text{ eV}$ in the case of ANITA. Besson noted that the experiments offer rather poor energy resolution; therefore, flux limits shift with the assumption made on the spectral index. We refer to the summary talk on "New Technologies" for the discussion of the many spirited proposals for interesting new experiments.

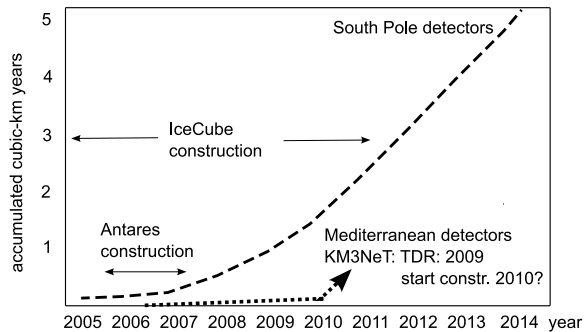


Figure 1. Accumulated km^3 years of South Pole (AMANDA/IceCube combined) and Mediterranean detectors. For point source searches, pointing resolution and sky coverage are additional important parameters.

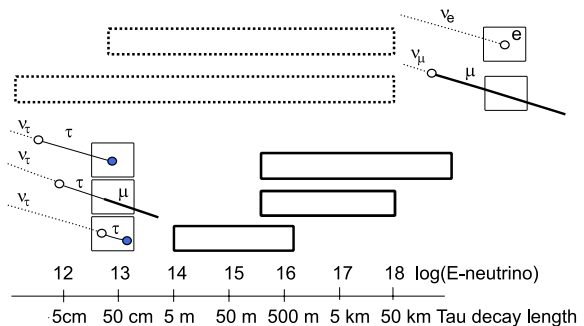


Figure 2. Energy range best suited to the detection of ν_e , ν_μ , and ν_τ (three topologies) in PMT-based neutrino telescopes. Sketches illustrate the relevant topologies.

2.2. Tau neutrino detection and tau identification with neutrino telescopes

Assuming that neutrinos at an extended far-away source are produced in the ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, that θ_{23} is maximal, and that θ_{13} is very small, the fluxes of all neutrino species are expected to be equal at the detector. Incorporating reconstructed τ neutrinos in the analysis therefore considerably increases the statistics, offers a rich set of signatures, provides 4π acceptance in the 10^{14-15} energy range due to tau-regeneration, and consequently provides a very clean tag for the cosmological neutrino origin. It also promises low background for $E > 1$

TeV for some topologies, as the background due to atmospheric neutrino oscillations and from open charm is negligible. On the other hand, severe challenges need to be met: the granularity of the detectors is coarse, the expected event rates are low, and τ branching fractions have to be taken into account. Furthermore, the various topologies can be discriminated against background only in limited energy ranges.

While accelerator experiments detect τ 's barely traveling for millimeters with micro vertex detectors, extremely high energetic τ 's from cosmic accelerators may survive impressive distances (≈ 50 m per PeV). The classic ‘‘Double Bang’’ signature, containing both the production and decay vertex in the detector, is detectable when the vertices can be disentangled with the coarse grid of optical modules, typically spaced 30 m apart. Studies shown by Cowen show, however, that geometrically overlapping showers can be resolved by making use of the good time resolution of the pulse digitizing systems in detectors being deployed. One hopes that the lower energy limit for detecting taus in this topology can be reduced to about 10^{14} eV. On the high energy frontier, events where solely the τ *decay vertex* is registered may actually exhibit lower background than Double Bang events. One is no longer limited to events where both production and decay vertex fit into the detector so that taus with energies well above 10^{18} eV may be identified. At these energies, the τ track length may be as long as 100 km!

Another interesting topology, discussed by De Young, is based on the $\tau \rightarrow \mu$ decay, which has a 18% branching ratio. The detection method employs the fact that τ 's predominantly lose energy by nuclear interactions, giving less light output than the pair produced leptons dominating in the case of muons. The six-fold increase in brightness for energies around 10^{15} eV, that occurs when the τ turns into a muon, may be detectable [8].

2.3. AMANDA flux result and multi-wavelength studies

AMANDA has recently updated its search for neutrino point sources to the data of 2000-2004, which correspond to 1001 days of livetime. A total of 4282 reconstructed neutrinos were selected after applying selection criteria optimized to the search for neutrinos produced with a spectral index between two and three. The understanding of systematic uncertainties was greatly improved with respect to earlier analyses. No statistical significant excess – which should correspond to at least 5σ in the case of a full sky search – has been observed.

The sensitivity of the detector to certain source classes can be improved by a method called source stacking. The method assumes that neutrino fluxes are correlated with the known gamma fluxes. Source signals are ranked according to the measured gamma luminosity and added until an optimal sensitivity is reached. Typically, an order of magnitude improvement in sensitivity is achieved. No significant signal in the data of 2000-2004 has been seen.

The sensitivity of the detector can also be improved by reducing the trial penalties of the experiment. For example, external signals of gamma or X-rays can be used to search for correlated signals. Resconi emphasizes that statistical issues in these low rate searches need to be thoroughly understood before a neutrino detector can act as a 24/24 monitor of its visible sky. One needs, e.g., well defined hypotheses on flares to be tested in a blind analysis with the statistical interpretation defined beforehand. While the sky is constantly monitored for X-rays, potentially interesting TeV gamma sources are only intermittently checked for flares. To trigger gamma telescopes, neutrino candidates from the AMANDA experiment are being selected in real time at the South Pole and signals are being sent to the MAGIC experiment for test purposes.

A new multi-year analysis of AMANDA data taken in the years 2000-2003 has been presented recently aiming to detect an overall excess of high energy neutrinos w.r.t. to the atmospheric background. No such excess was registered, yielding an improved flux limit of $\phi < 8.8 \times 10^{-8}/E^2 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$ for an assumed E^{-2} energy dependence of the flux. Becker explained that the contribution of TeV blazars to such a diffuse flux can be estimated by combining the limits for *resolved* blazars and applying a conservative correcting for the absorption

of TeV- γ 's at large distances. This procedure sets a limit to the blazar contributions [9] that is almost two orders of magnitude lower than the diffuse limit discussed above. If one compares these limits to specific models with an energy dependence other than E^{-2} , the assumed energy dependence of the model has to be folded into the limit calculation. The original AGN model by Stecker and Salomon [10] which was normalized to X-ray measurements, is excluded by these data; however, a recently revised version [11], which was instead normalized to gamma data, is not challenged at present.

3. Conclusions and Outlook

This summary is meant as a “teaser” to consult the interesting write-ups of the 13 contributions that were shown and discussed in working group 4. Progress has been both achieved in theory and experiment. In a field driven by the hope to find something unexpected, it is good to know whether there are guaranteed sources to study: galactic sources, e.g., including those recently discovered by HESS, should produce a few detected neutrinos each at energies above 1 TeV in km^3 detectors. The challenge to extract exciting physics from the low statistics typical for neutrino experiments is met by the development of new analysis methods to increase detection power and by the construction of km^3 -size detectors. By 2009, South Polar detectors will have accumulated the equivalent of 1 km^3 years, rising to 3 km^3 years by the time IceCube is completed in 2011. Also in 2009, a technical design report for a km^3 Mediterranean detector will be finalized, which will bear on 2 years of experience gained with the smaller ANTARES presently under construction. The construction of a km^3 Mediterranean detector will hopefully start soon thereafter.

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