KM3NeT: Towards a km^3 Mediterranean Neutrino Telescope

U.F. Katz

University of Erlangen-Nuremberg, Physics Institute

Abstract

The observation of high-energy extraterrestrial neutrinos is one of the most promising future options to increase our knowledge on non-thermal processes in the universe. Neutrinos are e.g. unavoidably produced in environments where high-energy hadrons collide; in particular this almost certainly must be true in the astrophysical accelerators of cosmic rays, which thus could be identified unambiguously by sky observations in "neutrino light". To establish neutrino astronomy beyond the detection of single events, neutrino telescopes of km^3 scale are needed. In order to obtain full sky coverage, a corresponding detector in the Mediterranean Sea is required to complement the IceCube experiment currently under construction at the South Pole. The groups pursuing the current neutrino telescope projects in the Mediterranean Sea, ANTARES, NEMO and NESTOR, have joined to prepare this future installation in a 3-year, EU-funded Design Study named KM3NeT (in the following, this name will also denote the future detector). This report will highlight some of the physics issues to be addressed with KM3NeT and will outline the path towards its realisation, with a focus on the upcoming Design Study.

Key words: neutrino astronomy, neutrino telescopes, KM3NeT

1. Physics with KM3NeT

The energy range accessible to neutrino telescopes is intrinsically limited by the detection method to some 10 GeV at its lower end, while at energies beyond roughly 10^{17} eV the neutrino flux is expected to fade below detection thresholds even for future km^3-scale detectors. The lower-energy region is dominated by the flux of *atmospheric neutrinos* (cf. Fig. 3), produced in reactions of cosmic rays with the atmosphere. There are three approaches to identify cosmic muon signals on top of this background:

(i) Neutrinos from specific astrophysical objects (*point sources*) produce excess signals associated to particular celestial coordinates.
(ii) Neutrinos not associated to specific point sources (*diffuse flux*) are expected to have a much harder energy spectrum than the atmospheric neutrinos and to dominate the neutrino flux above $10^{14} - 10^{15}$ eV.
(iii) Exploitation of coincidences in time and/or direction of neutrino events with observations by telescopes (e.g. in the radio, visible, X-ray or gamma regimes) and possibly also by cosmic ray detectors (*multimessenger method*).

The various astro- and particle physics questions to be addressed with the resulting data have been

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Email address: `katz@physik.uni-erlangen.de` (U.F. Katz).

Preprint submitted to Elsevier Science *14th April 2006*

summarised e.g. in [1] and references therein. Here, we will focus on a few central topics, including a recent development:

1.1. *Neutrinos from galactic shell-type supernova remnants*

The shock waves developing when supernova ejecta hit the interstellar medium are prime candidates for hadron acceleration through the Fermi mechanism. Recent observations of gamma rays up to energies of about 40 TeV from two shell-type supernova remnants in the Galactic plane (RX J1713.7-3946 and RX J0852.0-4622) [2,3] with the H.E.S.S. Čerenkov telescope support this hypothesis and disfavour explanations of the gamma flux by purely electromagnetic processes. The detection of neutrinos from these sources would, for the first time, identify unambiguously specific cosmic accelerators. Note that this is only possible with Northern-hemisphere neutrino telescopes which, in contrast to the South Pole detectors, cover the relevant part of the Galactic plane in their field of view (see Fig. 1).

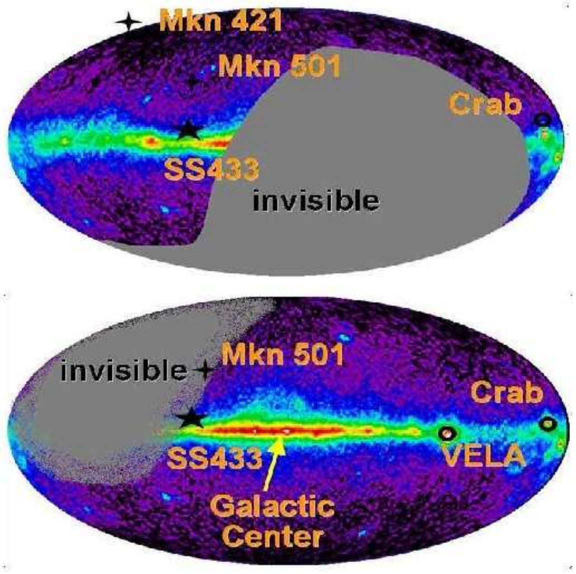

Figure 1. Field of view of a neutrino telescope at the South Pole (top) and in the Mediterranean (bottom), given in galactic coordinates. A 2π-downward sensitivity is assumed; the gray regions are then invisible. Indicated are the positions of some candidate neutrino sources.

The expected event rates can be estimated using the rough assumptions that the gamma flux follows a power-law spectrum without high-energy cut-off and the muon neutrino and gamma fluxes are in relation $\phi_{\nu_\mu}/\phi_\gamma = 1/2$, taking into account the relative production probabilities of charged and neutral pions, their decay chains and neutrino oscillations. Preliminary calculations indicate that the first-generation Mediterranean neutrino telescopes may have a chance to observe a few events, whereas a significantly larger signal is expected in a future cubic-kilometre set-up; a tentative estimate of the neutrino sky map of RX J0852.0-4622 after 5 years of data taking with KM3NeT is shown in Fig. 2.

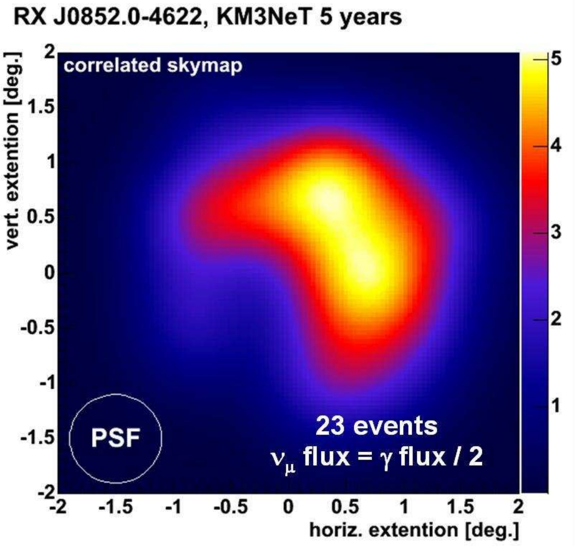

Figure 2. A skymap of the simulated neutrino signal from RX J0852.0-4622 as seen by a km^3-scale neutrino telescope in the Mediterranean Sea after 5 years of data taking. In the simulation, a power-law gamma spectrum without energy cut-off and the relation $\phi_{\nu_\mu}/\phi_\gamma = 1/2$ have been assumed. The background of atmospheric neutrinos, not included in the plot, can be efficiently reduced by adjusting the lower energy cut without affecting significantly the signal. The circle in the lower left corner indicates the average angular resolution (point spread function).

1.2. *The diffuse neutrino flux*

The sensitivity of current and future experiments is compared to various predictions of diffuse neutrino fluxes in Fig. 3 (following [4,5]). Whereas some of the models are already now severely constrained by the data, others require km^3-size neutrino telescopes for experimental assessment and potential discoveries. The measurement of the diffuse neutrino flux would allow for important clues on the properties of the sources, on their cosmic distribution, and on more exotic scenarios such as neutrinos from decays of topological defects or superheavy particles (*top-down scenarios*).

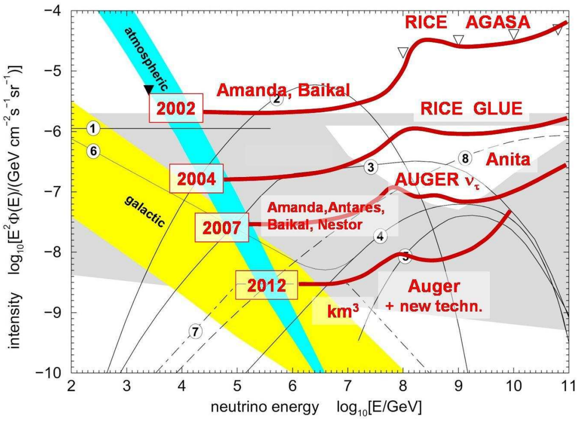

Figure 3. Experimental sensitivity to the diffuse neutrino flux for various current and future experiments (red lines), compared to different models for contributions to the diffuse flux (numbered lines). See [5] for detailed explanations. The flux of atmospheric neutrinos is indicated as blue band. Plot provided by courtesy of C. Spiering.

1.3. *Search for dark matter annihilation*

The major part of the matter content of the universe is nowadays thought to be formed by *dark matter*, i.e. non-baryonic, weakly interacting massive particles (WIMPs); an attractive WIMP candidate is the lightest supersymmetric particle, the neutralino. Complementary to direct searches for WIMPs, indirect WIMP observations could be possible by measuring neutrinos produced in WIMP annihilation reactions in regions with enhanced WIMP density. Such accumulations may in particular occur due to gravitational trapping, e.g. in the Sun or the Galactic Centre.

The WIMP signal would be an enhanced neutrino flux from these directions, with a characteristic upper cut-off in the energy spectrum below the WIMP mass, M_{WIMP}. Although there is no generic upper constraint on M_{WIMP}, supersymmetric theories prefer values below 1 TeV. Substantial detection efficiency down to order 100 GeV is therefore essential for indirect WIMP searches through neutrinos. The expected sensitivity depends strongly on assumptions on the WIMP density profile, on M_{WIMP} and on the energy spectrum of neutrinos from WIMP annihilations. At least for some supersymmetric scenarios this sensitivity is compatible or even better than for direct searches [1].

2. Requirements for KM3NeT

In 2002 the *High Energy Neutrino Astronomy Panel (HENAP)* of the PaNAGIC [1] Committee of IUPAP [2] has concluded that "a km^3-scale detector in the Northern hemisphere should be built to complement the IceCube detector being constructed at the South Pole" [6]; one major argument in favour of this effort is the coverage of the Southern sky including the central part of the Galactic plane (cf. Fig. 1 and Sect. 1).

The major challenges in constructing such a deep-sea neutrino telescope are the high pressure of several 100 bar; the uncontrollable environment with currents, sedimentation and background light from ^{40}K decays and bioluminescent organisms; the chemically aggressive environment reducing the selection of suited materials basically to titanium, glass and certain plastics. A further aspect of this difficult environment is that the deployment and maintenance operations, employing surface vessels and manned or remotely-operated deep-see submersibles, are expensive and weather-dependent, thus maximising the need for high operation stability.

These issues have been sucessfully addressed by the Mediterranean neutrino telescope projects ANTARES [7,8] (under construction near Toulon), NEMO [9,10] (R&D for a cubic kilometre detector) and NESTOR [11,12] (under construction

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[1] Particle and Nuclear Astrophysics and Gravitation International Committee

[2] International Union of Pure and Applied Physics

near the west coast of the Pelopones). Suitable technical solutions have been identified and tested in the context of these first-generation projects, and the feasibility of large deep-sea detectors has been proven. Nevertheless, further R&D work is necessary for KM3NeT, a.o. in order to

- improve cost effectiveness;
- optimize the geometrical layout of a km^3-scale detector and the corresponding mechanical structures;
- find the optimal combination of photosensor, readout and data acquisition options;
- define the deep-sea infrastructure and the deployment and maintenance procedures;
- provide suitable interfaces addressing the needs of the deep-sea science communities.

The instrumented water volume of KM3NeT is thought to be about one km^3, which is the "canonical size" to cover the physics objectives described above. However, it is anticipted that the results of this detector may imply the need for increasing the sensitivity further, thus requiring an extension in volume. It is therefore considered an intrisic requirement for the KM3NeT design to be extendable.

An important constraint is imposed by the timeline of the IceCube neutrino telescope [13] currently being installed in the Antarctic ice. IceCube will be completed by 2011, and it is a major objective for KM3NeT to be operational in time to take data concurrently with IceCube.

3. The KM3NeT Design Study

The 6th Framework Programme of the European Union offers support for the development of future research infrastructures by funding *Design Studies* as *Specific Support Actions*. A corresponding application has been submitted in March 2004 and was approved in September 2005. The Design Study project has started in February 2006 and will run for 3 years. It is funded with 9 million Euro by the EU and has an overall volume of about 20 million Euro, which will mainly be used for personnel and costs for prototyping, deployment tools and tests, etc.

3.1. *The KM3NeT Consortium*

The KM3NeT consortium is composed of 29 particle/astroparticle physics and 7 sea science/ technology institutes from Cyprus, France, Germany, Greece, Italy, the Netherlands, Spain and the United Kingdom. The Design Study comprises, amongst others, the groups involved in ANTARES, NEMO and NESTOR, and is coordinated by the University of Erlangen, Germany.

3.2. *Objectives of the Design Study*

The major objective of the KM3NeT Design Study is to work out the technical foundation for the construction of the neutrino telescope, to be documented in a *Technical Design Report (TDR)*. The TDR and and an intermediate *Coceptual Design Report (CDR)* will be the main deliverables of the Design Study. Their preparation will require

- a critical review of current technical solutions;
- development and thorough tests of new solutions;
- the assessment of quality control and assurance;
- the exploration of links to industry, in particular in the fields of photodetection, information technology and deep-sea technology;
- careful studies of the interrelation between the different aspects and the optimisation of the solutions found.

The goal is to design a neutrino telescope with sensitivity down to neutrino energies E_ν of a few 100 GeV. The low level of light scattering in deep-sea water is to be exploited to reach a pointing resolution limited by the average angle between incoming neutrino and secondary muon up to $E_\nu \sim 10\,\text{TeV}$ and better than 0.1° above this energy. The vision of the proponents is that KM3NeT will be a pan-European research infrastructure, giving open access to the neutrino telescope data, allowing to assign "observation time" to external users by adapting the online filter algorithms to be particularly sensitive in predefined celestial directions, and providing access to long-term deep-sea measurements to the marine sciences communities.

Three possible sites for the KM3NeT infrastructure have been identified: the ANTARES site near

Toulon, the NEMO site near Capo Passero in Sicily and the NESTOR site near Pylos on the Pelopones. The existing studies on the characteristics of these sites (water transparency, currents, sedimentatiion, bioluminescence, etc.) will be consolidated during the Design Study, and the site parameters (depth, distance to shore, etc.) will be taken into account in the optimisation of the physics sensitivity, where the figure of merit will be *physics output per Euro*. The results of these studies will provide the scientific input to the site decision, which will be a political process to be initiated towards the end of the Design Study.

In parallel with preparing the site decision process, also funding and governance models and options will be investigated, so that the corresponding decisions can be taken in due time.

3.3. *Some Key Questions to be Addressed*

The list of requirements given in Sect. 2 directly translates into major activities during the Design Study, of which a few key examples are to be discussed in the following.

Detector architecture: Although all first-generation projects use large-diameter photomultipliers (PMs), they pursue different approaches for the arrangement and mechanical support of the PMs. A choice has to be made between flexible stings (like in ANTARES), towers formed by rigid structures (NESTOR), towers formed by rigid arms connected to each other by ropes forming a tetrahedral structure (NEMO), a combination of these, or yet other solutions. This question is closely related to a variety of aspects, like

- the physics sensitivity, which strongly depends on the geometrical arrengement of the photosensors (see also [14]);
- the dee-sea infrastructure (cables, power distribution, data transport);
- the deployment procedures;
- the calibration methods;
- readout and data acquisition.

This example demonstrates how strongly the different technical issues are interrelated. It will be an essential part of the Design Study to assess these interdependencies.

Photodetection: The KM3NeT timeline (see Sect. 4) is too tight to embark on the development of alternative photodetection methods, such as HPDs or silicon PMs. Nevertheless, there are different options (again having specific implications for various aspects) that have to be assessed. It has e.g. been suggested to use smaller PMs arranged in cylindrical glass vessels (see Fig. 4 for an illustration). Careful studies are required to investigate the physics sensitivity of such arrangements [14], to optimise the readout, to assess the implications for the overall detector cost, etc.

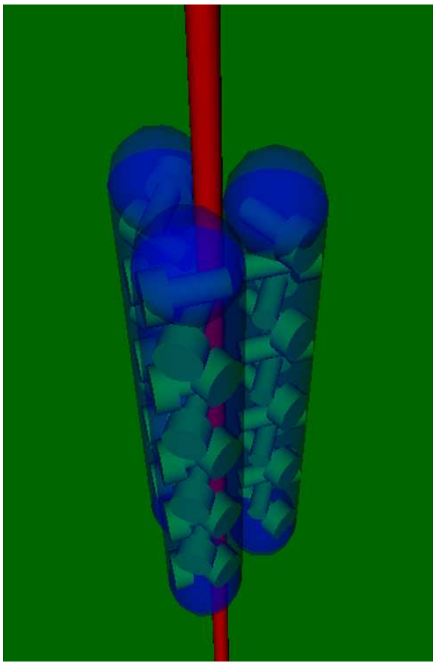

Figure 4. Sketch of a possible arrangement of several photomultiplier tubes in three glass cylinders.

Deployment and deep-sea infrastructure: For the deployment of the detector modules, different approaches have been developed by the first-generation projects (e.g. connections performed by remotely-operated submersibles or at surface, deploymnt from ships or dedicated platforms, etc.) which need to be adapted to the needs of the KM3NeT infrastructure. Further issues to be addressed include the architecture of the deep-sea cable net, including the choice of the components and the installation and maintenance procedures.

4. The Path to KM3NeT Construction

The KM3NeT Design Study will last until January 2009. Thereafter, a phase of funding negotiations and construction preparation has to be foreseen, lasting 1–2 years. This phase might be supported within the 7th Framework Programme of the European Union; an important step into ths direction is the inclusion of the KM3NeT project into the *List of Opportunities* [15] of the *European Strategy Forum for Research Infrastructures (ESFRI)*. If the decision to realise the KM3NeT infrastructure is taken in this preparation phase, installation could start as early as 2010 and be concluded in 2012. First data would thus become available in 2011, concurrently with data from the IceCube telescope.

5. Conclusions

Neutrino astronomy is an emerging field in astroparticle physics offering exciting prospects for gaining new insights into the high-energy, non-thermal processes in our universe. The current neutrino telescope projects in the Mediterranean Sea are approaching installation and promise exciting first data. They have reached a level of technical maturity allowing for the preparation of the next-generation cubic-kilometre detector to complement the IceCube telescope currently being installed at the South Pole. The interest in this project has been further enhanced by the recent H.E.S.S. observations of high-energy gamma rays from shell-type supernova remnants in the Galactic plane, indicating that these objects could well be intense neutrino sources, which would, however, be invisible to IceCube.

The technical design of the future Mediterranean km^3 neutrino telescope will be worked out in the 3-year EU-funded KM3NeT Design Study starting in February 2006. The construction of the KM3NeT neutrino telescope during the first years of the next decade thus appears to be possible.

Acknowledgement: The author wishes to thank the organisers of the VLVnT2 Workshop in Catania for their overwhelming hospitality and a very intense, productive and perfectly organised workshop.

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