Neutrino Telescopy in the Mediterranean Sea

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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". On the one hand, neutrinos are ideal messengers for astrophysical observations since they are not deflected by electromagnetic fields and interact so weakly that they are able to escape even from very dense production regions and traverse large distances in the universe without attenuation. On the other hand, their weak interaction poses a significant problem for detecting neutrinos. Huge target masses up to gigatons must be employed, requiring to instrument natural abundances of media such as sea water or antarctic ice. The first generation of such neutrino telescopes is taking data or will do so in the near future, while the second-generation projects with cubic-kilometre size is under construction or being prepared. This report focuses on status and prospects of current (ANTARES, NEMO, NESTOR) and future (KM3NeT) neutrino telescope projects in the Mediterranean Sea.

1 Current neutrino telescope projects in the Mediterranean Sea

World-wide, two neutrino telescopes (AMANDA at the South Pole [1, 2] and one in Lake Baikal [3]) are taking data, two are under construction in the Mediterranean Sea (ANTARES [4, 5], NESTOR [6, 7]), and the cubic-kilometre telescope IceCube [8] is being installed at the South Pole. Preparatory work for a corresponding installation in the Mediterranean Sea is being performed in the R&D project NEMO [9]; from early 2006 on, all groups involved in the current Mediterranean projects will join into a 3-year EU-funded Design Study towards the future km^3-scale neutrino telescope in the Northern hemisphere (KM3NeT) [10].

1.1 Detection principle

Interactions of neutrinos with target material in the neutrino detector or its vicinity produce charged secondary particles with velocities exceeding the speed of light in water or ice, which therefore radiate Čerenkov light. This light is detected by an array of photomultipliers placed deep below the surface. The range of neutrino energies for which neutrino telescopes are sensitive is limited by this 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 giant detectors.

From the photomultiplier positions, the arrival time of the light (measured to nanosecond precision) and the signal amplitudes, the direction and energy of the incoming neutrino are reconstructed. The achievable resolutions depend on the reaction type: Charged-current reactions of muon neutrinos[1], $\nu_\mu N \rightarrow \mu X$, produce high-energy muons with a range of up to several kilometres in water or ice; the detection of these muons allows for a precise reconstruction of the neutrino direction[2] (resolution in water better than 0.3° for neutrino energies $E_\nu \gtrsim 10\,\text{TeV}$) and an estimate of the neutrino energy accurate to within a factor of 2 for $E_\nu \gtrsim 1\,\text{TeV}$. Due to the good angular resolution and the increased sensitivity resulting from the large muon range, neutrino telescopes are predominantly optimised for this reaction type. On the other hand, charged-current reactions of electron or tau neutrinos, $\nu_{e,\tau} N \rightarrow (e,\tau)X$, and neutral-current reactions, $\nu_x N \rightarrow \nu_x X$, produce hadronic and/or electromagnetic particle cascades (*showers*) which act as localised sources of intense Čerenkov light. Such reactions occurring inside the instrumented volume allow for a rather precise measurement of the shower energy, with an angular resolution degraded to several degrees in water, and even worse in ice.

In order to shield the experiments against background daylight and muons originating from cosmic ray interactions in the upward-hemisphere atmosphere (*atmospheric muons*), they are located in a depth of several kilometres. Yet, for most of the abovementioned energy range the atmospheric muon background is prohibitive for observing neutrinos arriving from above. Therefore, the field of view of neutrino telescopes is the downward hemisphere; observing the Southern sky including the Galactic Centre hence requires an experiment in the Earth's Northern hemisphere. A comparison of the fields of view from the South Pole and the Mediterranean Sea is shown in Fig. 1. At highest energies beyond roughly 10^{15} eV the atmospheric muon flux fades away and the view opens to the upper hemisphere; at the same time, the downward view becomes obscured by the fact that, due to the increase of the neutrino cross section with energy, the Earth becomes opaque even for neutrinos.

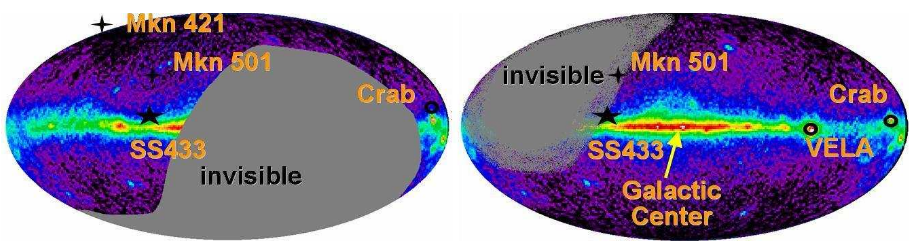

Figure 1. Field of view of a neutrino telescope at the South Pole (left) and in the Mediterranean (right), given in galactic coordinates. A 2π-downward sensitivity is assumed; the gray regions are then invisible. Indicated are the positions of some candidate neutrino sources.

1.2 General conditions in sea water

The major challenges in constructing deep-sea neutrino telescopes 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.

In addition to requirements implied by pressure and material choices, the parameters that affect the detector design most strongly are the water transparency and the background light. In the Mediterranean deep-sea environment, the absorption length of blue light is close to 60 m, implying distances of detection units of this order or less. The light scattering length exceeds 200 m, resulting in a very good angular resolution, by far superior to the one achievable in polar ice where scattering is much stronger. The presence of ^{40}K causes a steady background of single-photon signals, amounting to about 30−40 kHz per 10-inch photomultiplier; bioluminescence light causes additional steady and burst-like background components. This situation requires a high data transmission bandwidth as well as stringent coincidence triggers exploiting the good timing resolution.

[1]In the following, the term *neutrino* is generically used to denote both neutrinos and antineutrinos

[2]When referring to angular resolution in the following, this event type is assumed.

1.3 ANTARES

The ANTARES neutrino telescope [4] is currently under construction off the French Mediterranean coast near Toulon. It will be situated in 2500 m depth and will consist of 12 lines (*"strings"*) that are anchored to the sea bed at distances of about 70 m from each other and kept vertical by buoys (see Fig. 2). Each string is equipped with 75 optical modules (OMs) [11] arranged in triplets (*storeys*) sustained by titanium frames that also support water-tight titanium containers for the electronic components. The OMs are glass spheres housing one 10-inch photomultiplier each, directed at an angle of 45° towards the sea bed. The storeys are spaced at a vertical distance of 14.5 m and are interconnected with an electro-optical-mechanical cable supplying the electrical power and the control signals and transferring the data to the string bottom. Submersible-deployed electro-optical link cables connect the strings to the *junction box (JB)*, which acts as a fan-out between the main electro-optical cable to shore and the strings. Each string carries optical beacons for timing calibration and acoustic transponders used for position measurements. The detector will be complemented by an *instrumentation line* supporting devices for measurements of environmental parameters as well as tools used by other scientific communities, such as e.g. a seismometer.

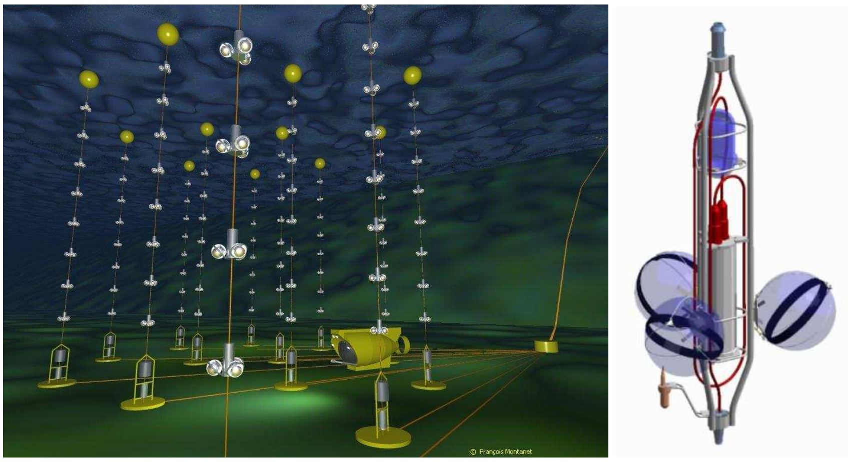

Figure 2. An artist's view of the ANTARES detector (left, not to scale) and a schematic view of a storey (right) with the three glass spheres for the photomultipliers, an optical beacon for time calibration (blue) and a hydrophone for position measurement (below front sphere).

The main electro-optical cable and the junction box are installed and operational since 2002. Two prototype strings, one with 5 optical storeys and one with auxiliary instrumentation, were deployed, connected and operated in 2003. Based on the results of these prototypes, the design was finalised and scrutinised using two further test strings deployed in 2005. The full functionality of the detector has been verified to design specifications. Currently, the first full detector line is awaiting deployment; the detector installation is expected to be completed by 2007.

For a detailed summary of the results of the ANTARES test deployments see [12].

1.4 NESTOR

The site selected for the NESTOR neutrino telescope is off Pylos at the West coast of the Peloponnese, at a depth of 3800 m. The NESTOR design is based on rigid, hexagonal star-like structures (*floors*) with a diameter of 32 m, carrying 6 pairs of upward- and downward-looking photomultipliers each as well as a titanium sphere for the readout electronics in the centre (see Fig. 3). 12 floors will be connected vertically at a distance of 30 m to form a *tower*. The deployment operations are performed by lifting the existing structure to the surface, connecting the new module(s) and redeploying the extended set-up, thus avoiding the use of submersibles.

In 2003, a single floor of reduced size has been deployed, connected to the cable to shore and operated for more than a month [13]. In this time, more than 2 million 4- or higher-fold coincidence triggers have been collected [14]. These data allowed the NESTOR collaboration to reconstruct the angular distribution of the atmospheric muons and to compare the result to simulations and previous measurements. The good agreement

Figure 3. Reduced-size NESTOR floor during preparation for deployment.

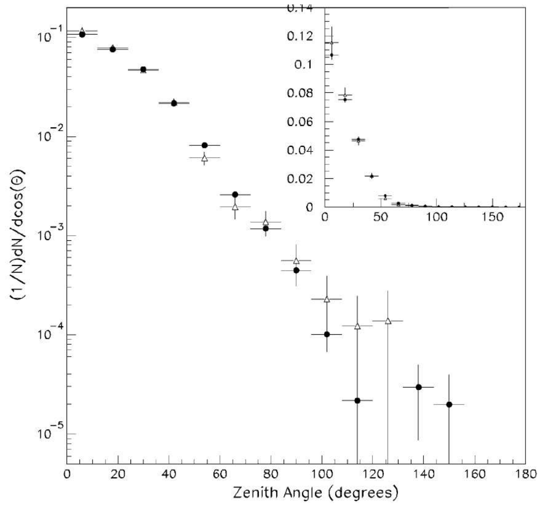

Figure 4. Zenith angle distribution of atmospheric muons measured by NESTOR during the test deployment (triangles), compared to the result of a simulation (filled circles). The insert shows the same data with a linear vertical scale. The figure has been taken from [13].

found (cf. Fig. 4) confirms that the functionality of the detector complies with the specifications and that a detailed level of detector understanding has been reached.

1.5 NEMO

In the framework of the Italian R&D project NEMO, a candidate site for a future km^3-scale detector has been identified at a depth of 3340 m off the East coast of Sicily near Capo Passero, and new solutions for various detector components have been developed. Amongst these is a new design of a mechanical structure, consisting of 20 m-long rigid arms connected to each other by ropes and kept vertical by a buoy. The ropes form a tetrahedral structure, sustaining successive arms orthogonally to each other at a distance of 40 m (see Fig. 5). Each arm carries 2 pairs of upward- and downward-looking photomultipliers. One advantage of this flexible tower structure is that a tower can be deployed folded into a compact structure which unfurls when released after reaching the sea bottom. A further NEMO development is a composite junction box, consisting of an inner, pressure-resistant steel vessel embedded in an oil-filled plastic tank, thus separating the resistance against pressure and salt water.

For assessing the newly developed components, a test site at a depth of 2000 m has been identified and connected to the shore station by an electro-optical cable. Within the forthcoming year, it is foreseen to deploy and connect to this cable a junction box and a prototype of a flexible tower.

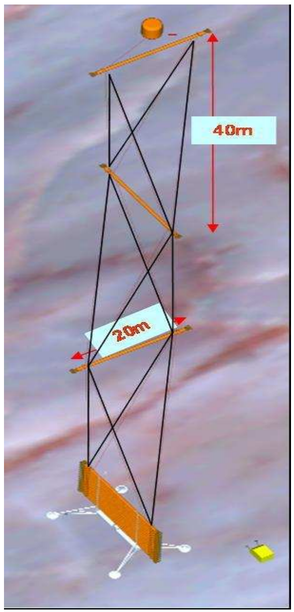

Figure 5. Schematic view of a flexible NEMO tower.

2 Towards a km^3 neutrino telescope in the Mediterranean Sea

Already in 2002 the *High Energy Neutrino Astronomy Panel (HENAP)* of the PaNAGIC[3] Committee of IUPAP[4] has concluded that "a km^3-scale detector in the Northern hemisphere should be built to complement

[3]Particle and Nuclear Astrophysics and Gravitation International Committee
[4]International Union of Pure and Applied Physics

the IceCube detector being constructed at the South Pole" [15]; 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. 3). This has triggered a joint activity of the groups involved in the Mediterranean neutrino telescopes towards establishing a common future project. The EU-funded KM3NeT Design Study (see below) has been approved to prepare this project. Concurrently, the *European Strategy Forum for Research Infrastructures (ESFRI)* has included the KM3NeT neutrino telescope in its *List of Opportunities* [16], thus assigning high priority to this project.

2.1 The KM3NeT Design Study

Even though making use of the experience and expertise gained in the current projects, a major R&D program has to be executed to arrive at a cost-effective design for a km^3-scale deep-sea neutrino telescope, optimised for scientific sensitivity, fast and secure production and installation, stable operation and maintainability. The KM3NeT Design Study [10] will address these issues in a 3-year program, with a 20 M€ budget, of which 9 M€ are provided by the EU. Participants are 29 particle/astroparticle and 7 sea science/technology institutes from altogether 8 European countries, coordinated by the University of Erlangen.

Amongst the major issues to be studied and decided upon are the mechanical structures, the choice of the photo-sensors, the readout, data acquisition and online filter methods, the deep-sea infrastructure and deployment techniques; for all of these, detailed simulation work will be necessary.

The main deliverable of the Design Study is a *Technical Design Report (TDR)*, laying the foundation for funding negotiations and concrete project preparation. 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 directions, and also providing access to long-term deep-sea measurements for the marine science communities.

2.2 Timelines towards realisation

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 European FP7 program. If the decision to realise the KM3NeT infrastructure is taken in this 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 which will be ready by then.

3 Physics with neutrino telescopes

After the above summary of the status and developments of the Mediterranean neutrino telescopes, we will now highlight some of the physics issues related to the interpretation of their data.

The lower part of the energy range defined in Sect. 1.1 is dominated by the flux of *atmospheric neutrinos* (cf. Fig. 7), produced in reactions of cosmic rays with the Earth's atmosphere. The atmospheric neutrinos establish a highly useful calibration source for the detectors, but at the same time form an irreducible background in searching for extraterrestrial neutrinos.

There are three basic search strategies to fight this background:

1. Neutrinos from specific astrophysical objects (called *point sources*) produce excess signals associated to particular celestial coordinates and can thus be identified on a statistical basis.

2. Cosmic neutrinos are in general expected to have a much harder energy spectrum than the atmospheric neutrinos. Neutrinos not associated to specific point sources (*diffuse flux*) can thus be identified, again on a statistical basis, by analysing the energy distribution of registered neutrino events.

3. Exploiting 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 can be used to optimise search strategies and to increase drastically the significance of observations of transient sources (*multimessenger method*).

The various astro- and particle physics questions to be addressed with the resulting data have been summarised e.g. in [17] and references therein. Here, we will focus on a few central topics and a recent development:

1. Neutrinos from galactic shell-type supernova remnants:
   The shock waves developing when supernovae 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) [18, 19] 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 (cf. Sect. 1.1).

   The expected event rates can be estimated using the rough assumption that 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. 6.

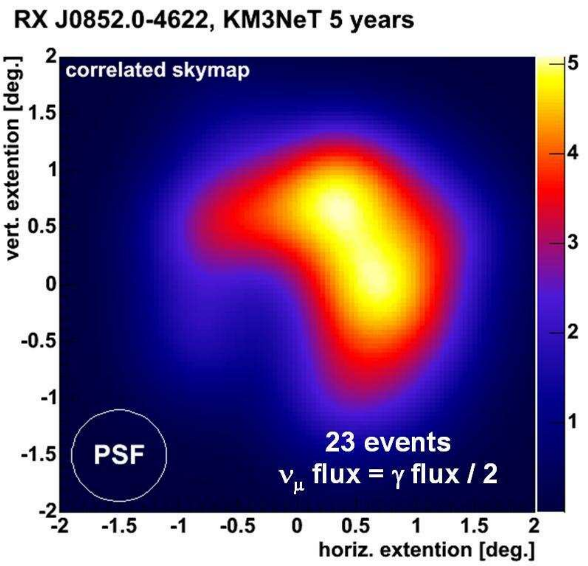

Figure 6. A skymap of the simulated neutrino signal from RX J0852.0-4622 as seen by a km^3-scale neutrino telescope in the Mediterranean Sea after 5 years of data taking. The assumption $\phi_{\nu_\mu}/\phi_\gamma = 1/2$ has been used for the simulation. The background of atmospheric neutrinos, not included in the plot, amounts to a few events and can be efficiently eliminated 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).

2. The diffuse neutrino flux
   The sensitivity of current and future experiments is compared to various predictions of diffuse neutrino fluxes in Fig. 7 (following [20, 21]). 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*).

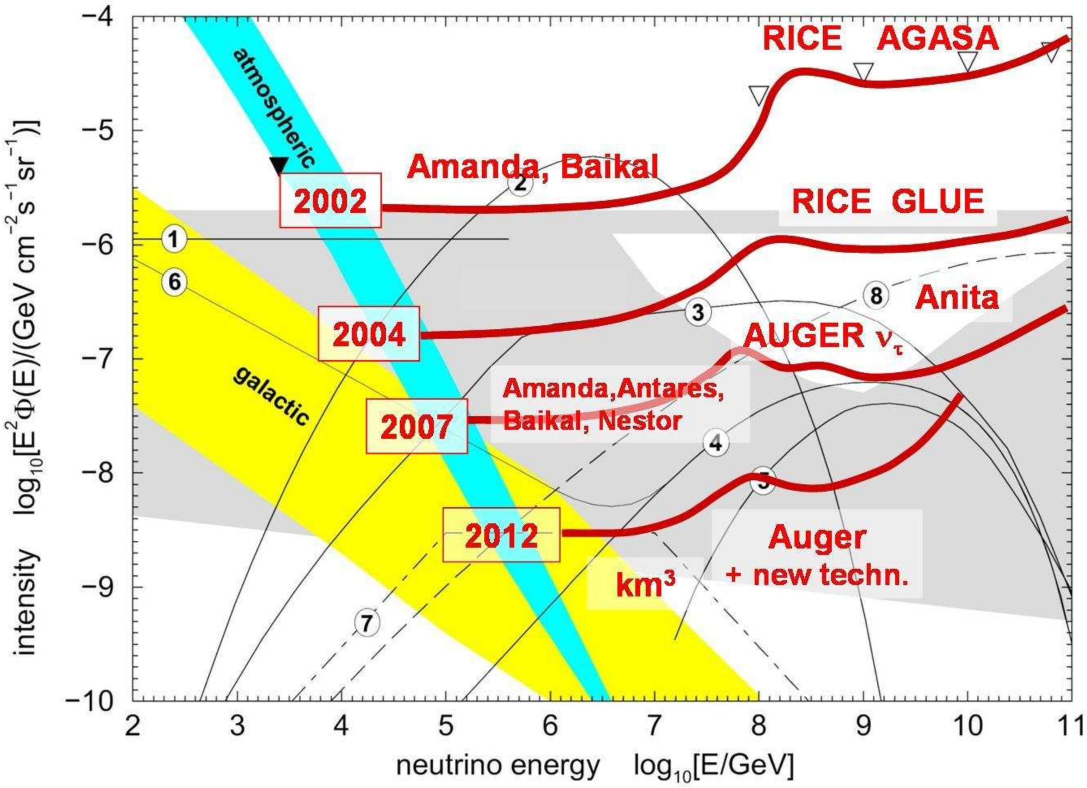

Figure 7. Experimental sensitivity to the diffuse neutrino flux for various current and future experiments (red lines), compared to different models for contributions to the diffuse flux (numbered lines). See [21] for detailed explanations. The flux of atmospheric neutrinos is indicated as blue band. Plot provided by courtesy of C. Spiering.

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 in cryogenic underground detectors, indirect WIMP observations could also be possible by measuring neutrinos produced in WIMP annihilation reactions in regions where the WIMP density is enhanced. 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 the M_{WIMP}, supersymmetric theories prefer values below 1 TeV. It is therefore essential for indirect WIMP searches through neutrinos to extend the detection threshold down to order 100 GeV. 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 [17].

4 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.

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