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Neutrino astrophysics and telescopes

Teresa Montaruli

Universitá di Bari and INFN, Via Amendola 173, Bari, Italy, e-mail: montaruli@ba.infn.it

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Abstract. The interest in detecting high energy neutrinos of astrophysical origin is motivated by the potentials of these weakly interacting particles. As a matter of fact, they would open a new window on the universe, complementing gamma-astronomy. Cherenkov detectors of huge dimensions are needed due to the small neutrino cross section and the low expected fluxes from sources. Moreover, these detectors need to be located in sea/lake depths or in the South Pole ice in order to be shielded by the huge amount of particles produced in atmospheric showers. Here we describe the neutrino telescope experimental technique, that is optimized for very high energies. The current status of running and under construction neutrino telescopes is summarized.

1 Introduction to neutrino astronomy

Extensive air shower (EAS) experiments measure cosmic rays of energies larger than 10^{20} eV. Most probably any man made machine will never be able to produce such high energy events. In order to understand how the universe is able to produce them, we need powerful probes at high energies to observe it. As a matter of fact, photons are reprocessed inside sources and absorbed during their propagation to us. Due to energy losses by pair production with background photons, it is expected that photons of energies larger than 10 TeV cannot bring information from distances $\gtrsim 100$ Mpc. By now no photon above these energies has ever been observed. Between stable particles, protons can be used for astronomy when their energy is above $\sim 10^{19.5}$ eV, so that they are marginally deflected by intergalactic and galactic magnetic fields and point back to their sources. But they are absorbed above these energies due to photopion production (the so-called GZK cut-off) and so they are expected to reach us from distances $\lesssim 50$ Mpc. Hence, detection of neutrinos and also of gravitational waves are considered as frontiers of modern astrophysics capable of discovery potentials.

A deep connection should exist between the observed highest energy cosmic rays (UHECR) and neutrinos, since they could be produced by the same processes in sources. Neutrino experiments, together with new generation EAS arrays, such as the P. Auger experiment [1], could help in solving the puzzle on what sources can produce such high energy events [2]. The UHECR statistics is still too low to understand if the spectrum steepens according to the GZK cut-off. UHECR and ν connection provides also a clue to calculate an upper limit on neutrino fluxes from extragalactic sources (hereafter W&B limit) in the case in which the sources are transparent to nucleons [3]. The W&B limit is derived in the hypothesis that EAS observe protons and that these are produced by neutrino sources. Moreover, the observed proton flux at 10 EeV is extrapolated at lower energies using an E^{-2} source spectrum, characteristic of Fermi acceleration mechanisms. This limit represents an important limitation to possible ν observations, though it can be evaded considering other proton spectral dependences; moreover magnetic field effects and uncertainties in photohadronic interactions can reduce the number of protons able to escape, hence affecting the limit [4]. AMANDA-II [5,6] is already at the level of testing the limit for completely opaque sources in [4], while the W&B flux limit will be tested after 1 yr of operation of the km^3 detector IceCube [7].

Neglecting energy losses, a particle of charge Z can be accelerated up to a maximum energy of $E_{max} \sim Z\frac{B}{\mu\mathrm{G}}\frac{R}{1\mathrm{kpc}} \times 10^{18}$ eV provided that its Larmour radius in the magnetic field B is smaller than the acceleration region R [8]. This argument singles out interesting extra-galactic candidate ν sources, such as blazars (that are active galaxies with the jet oriented toward the observer), gamma-ray bursters (GRBs) or massive association of stars (e.g. the galactic one, Cygnus OB2, recently observed emitting TeV photons by HEGRA [9]). Galactic sources are not subject to the W&B limit due to their proximity and models predict up to hundreds of events/ km^2/yr (for a review see [10] and references therein). Interesting galactic candidate ν emitters are micro-quasar binary systems (the most promising being persistent ones, such as GX339-4 and SS433) exploding stars and consequent fast rotating neutron stars in supernova remnants (SNRs), plerions and magnetars.

The production of neutrinos in sources involves bottom up mechanisms, such as a "celestial beam dump" where protons or nuclei, accelerated by an engine, interact on a gas of matter or photons. These interactions result in neutral and charged pions which decay into photons and neutrinos. This explains the expectation that observed gamma fluxes and neutrino ones should be of the same order of magnitude and with similar spectral shape, a power law with spectral index of around $-2 \div -2.5$, as expected from Fermi acceleration. Moreover, if all muons can decay in sources, the resulting fluxes would be characterized by the flavor ratio $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 2 : \lesssim 10^{-5}$. In light of solar and atmospheric ν results and of constraints from reactor experiments, oscillations through baselines larger than tens of kpc would lead to $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$. More speculative top-down production processes can be envisaged, where supermassive particles or topological defects decay into neutrinos. Moreover, granted high energy ν sources should be CR interactions with the cosmic MW background and on the galactic interstellar matter.

Beam dump models for ν production imply hadroproduction, e.g. pions. Currently there is no firm evidence of gamma production from π^0 decays, except for a claim of the CANGAROO experiment [11] that the TeV γ spectrum from the SNR RX J1713.7-3946 is in disagreement with expected spectra of photons from bremsstrahlung and inverse Compton. Most probably a more precise measurement both of the source position and of the spectrum will be done by the HESS experiment. This has been the case for the Galactic Center from which CANGAROO has measured a TeV photon spectrum in disagreement with the flux measured by HESS above 165 GeV in the direction of the supermassive black hole Sgr A^* [12].

2 Cherenkov neutrino telescopes

Neutrinos can be detected through Cherenkov light emitted by charged particles produced in their interactions by a 3-D array of optical modules (OMs). OMs are pressure resistant glass spheres containing phototubes (PMTs), located in polar ice or sea/lake water depths in order to reduce the surface μ flux by orders of magnitude. OMs distances are optimized considering light transmission properties in these transparent media and construction constraints. The selection of detector sites is determined by transmission light properties, environmental backgrounds, stability of media properties in the implemented region, mechanical, construction and infrastructure constraints.

The parameters that govern light transmission properties are: the absorption length, that determines the distance at which photons travel and, hence, the distances between OMs, and the scattering length, that affects the direction of photons and their arrival time on OMs, hence the angular resolution. Typical absorption length in sea water vary between $50-65$ m, while in the South Pole ice it achieves values larger than 100 m. The effective scattering length, which takes into account the angular distribution of scattered photons, is much longer in sea water ($\gtrsim 100$ m), than in ice (at $1.5-2$ km depths it is ~ 25 m). Moreover, the ice properties depend on depth and bubbles can form around OMs after drilling, so that this is one of the main sources of systematics in this media. On the other hand, sea water presents much larger environmental background rates. ANTARES [13] has performed a long term measurement (~ 100 d) of optical backgrounds using a prototype string deployed in 2003. Counting rates show large and short lived peaks due to bioluminescence, over a continuous baseline rate of ~ 60 kHz due to ^{40}K β decays and bacteria, that varies up to ~ 250 kHz. Correlations between bioluminescence, sea currents and string movements have been proved. A better quality of the media has been found by NEMO.RD close to the Sicily coast. NEMO.RD, an Italian project for a cubic-km detector in the Mediterranean sea, reported an average rate of 28.5 kHz in the selected site [14]. Another collaboration is proposing a site suitable for the construction of a km^3 in the Mediterranean, a ~ 4500 m deep site off-shore Pylos, Greece. NESTOR [15] deployed a 12 PMT prototype, finding that bioluminescence contributes to the triggered event sample by $\sim 1\%$.

Neutrino telescopes were originally born to detect muons from ν_μ charged current (CC) interactions. Since the ν cross-sections and the μ range increase with energy, the effective target mass for ν interactions increases. As a matter of fact, the performances of this technique are better the larger the energy, up to a saturation that depends on the detector dimensions. Moreover, for $E_\nu \gtrsim 10$ TeV the muon has the same direction of the parent neutrino allowing to point sources. A very useful parameter to describe neutrino telescope performances is the effective area for ν's, that is the sensitive area 'seen' by ν's producing detectable μ's when entering the Earth. This is a function of the energy and of the local angles. It includes tracking and selection cut efficiencies, the effect of neutrino absorption in the Earth, and it allows to directly determine event rates. In fact, the event rate for a ν model predicting a spectrum $\frac{d\Phi}{dE_\nu d\Omega_\nu}$ is given by: $N_\mu = \int\int dE_\nu d\Omega_\nu A_\nu^{eff}(E_\nu, \Omega_\nu) \frac{d\Phi}{dE_\nu d\Omega_\nu}$. Being the area strongly energy dependent, detectors respond in different regions to ν's with different spectra: the harder the spectrum the highest is the mean energy of the corresponding detectable events (e.g. ~ 100 GeV for typical $E^{-3.6}$ atmospheric ν spectra, ~ 10 TeV for typical E^{-2} cosmic ν spectra). The neutrino effective area, as estimated by ANTARES, is shown in Fig. 1. It is impressive how such huge detectors are reduced to areas of the order of tens of m^2, due to the weakly interacting properties of neutrinos, as can be understood by the area definition itself:

$$A_\nu^{eff}(E_\nu, \Omega) = \epsilon \cdot V_{gen} \cdot N_A \rho \sigma_\nu(E_\nu) \cdot P_{Earth}(E_{\nu,\Omega}) \quad (1)$$

where $\epsilon = \frac{N_{sel}(E_\nu, \Omega)}{N_{gen}(E_\nu, \Omega)}$. N_{gen} is the number of generated events in the generation volume V_{gen} (whose dimensions depend on the muon range), N_{sel} is the number of selected events after track reconstruction quality cuts and cuts for background rejection. The neutrino absorption probability for a given neutrino of energy E_ν and direction, if the small effect of NC interactions in the Earth is neglected, is:

$$P_{Earth}(E_\nu) = e^{-N_A \sigma_\nu(E_\nu) \int \rho(l) dl} \quad (2)$$

with N_A the Avogadro number and $\rho(l)$ is the Earth column depth in the neutrino direction, and σ_ν is the neutrino CC cross section.

Track reconstruction in neutrino telescopes is based on times and positions of PMTs hit by Cherenkov light

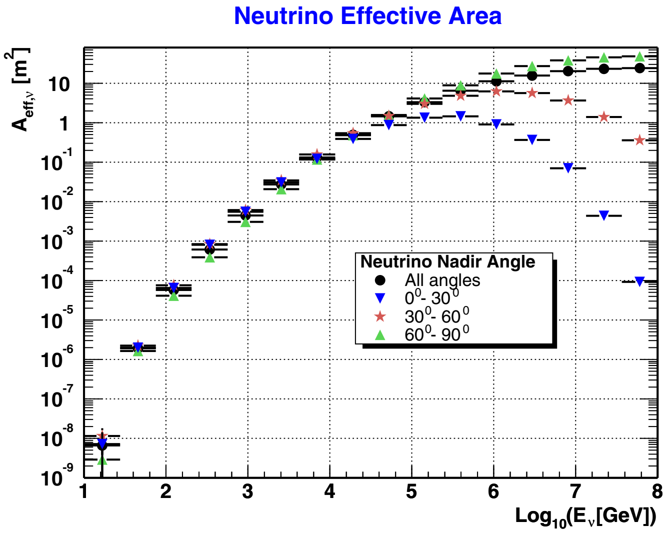

Fig. 1. The ANTARES effective area for neutrinos as a function of neutrino energy and in nadir angle bins. The decrease of the area in the vertical region is due to the shadowing effect of the Earth due to the cross-section increase with energy

emitted by relativistic particles. Charge amplitudes are used to measure μ and shower energies. The amount of light increases with energy, improving reconstruction of μ tracks and of cascades induced by $\nu_{e,\tau}$ and neutral current interactions (NC). Hadronic or electromagnetic showers produced by ν_e and ν_τ CC interactions and NC's of all ν flavors appear as 'balls' of light of extension depending on ν energy. Also background rejection improves with energy since the signal to noise ratio increases due to the steeper atmospheric μ and ν fluxes ($\sim E^{-3.6}$), compared to fluxes expected from sources ($\sim E^{-2}$). The possibility to find an energy estimator that allows to define an energy cut for background rejection is fundamental for searches of diffuse fluxes of astrophysical neutrinos. Moreover, the rejection of atmospheric μ's is achieved looking at events from the lower hemisphere, induced by ν's crossing the Earth. Nevertheless, for $E \gtrsim 1$ PeV $\nu_{\mu,e}$ absorption in the Earth is not negligible except for horizontal directions and ν_μ and ν_e cannot reach the detector from the lower hemisphere. Hence, down-going neutrinos can be selected among the large atmospheric μ background crossing the detector, when a high energy cut is applied against atmospheric muons and showers from ν vertexes are identified in the instrumented region.

The case of τ neutrinos is peculiar with respect to ν_μ and ν_e events: their propagation through the Earth causes energy losses (a pile-up at energies $\sim$ PeV) but not absorption[16], due to the regeneration chain of CC ν_τ interactions and τ decays, producing another ν_τ. Tau neutrinos can produce a background free topology, the so-called 'double bang' events, where two showers from the ν vertex and the τ decay are connected by a τ track, long enough to separate the showers. These interesting events, that would prove ν oscillations in an astrophysical beam, are expected to be very rare, due to the short τ range (~ 100 m for $E_\tau \gtrsim 2$ PeV).

3 The current experimental status

The neutrino telescopes currently taking data are AMANDA-II at the South Pole [5] and NT200 (192 OMs on 8 strings) in Lake Baikal (Siberia) [17] at 1.1. km depth. Baikal effective area for μ's is ~ 2000 m^2 at 1 TeV and the sensitivity to cascades is competitive to AMANDA. Baikal was the first underwater telescope to reconstruct atmospheric ν's in 1996.

AMANDA is running now in the AMANDA-II configuration with 677 OMs with 8-inch PMTs on 19 strings implemented between 1.5-2 km deep in the ice (see Fig. 2). The previous configuration AMANDA-B10 consisted in 302 OMs on 10 strings. The effective area for μ's, that has largely improved in the horizontal direction, is $\sim 0.02-0.04$ km^2 for an E^{-2} ν flux depending on the source declination. From the two 'calibration' test beams of atmospheric μ's and ν's a systematic error of $\sim 25\%$ on the detector acceptance is derived mainly due to OM sensitivity and ice optical property knowledge.

For what concerns the upper hemisphere, ANTARES [13] is under construction and will be completed in 2007. A schematic view of this underwater detector is in Fig. 3. It will be located in front of Toulon, South France, 40 km off-shore at a depth of 2500 m. It will consist of 12 strings carrying 75 OMs each, containing 10-inch PMTs. The key component is the so-called 'storey', which comprises 3 OMs, an electronics container and monitoring equipment. PMTs look downward at 45° from the vertical, so that sedimentation reduces OM transparencies negligibly. The electro-optical cable (EOC) already connects since Dec. 2002 the shore station to the junction box, that distributes data and power to strings. Submarine connec-

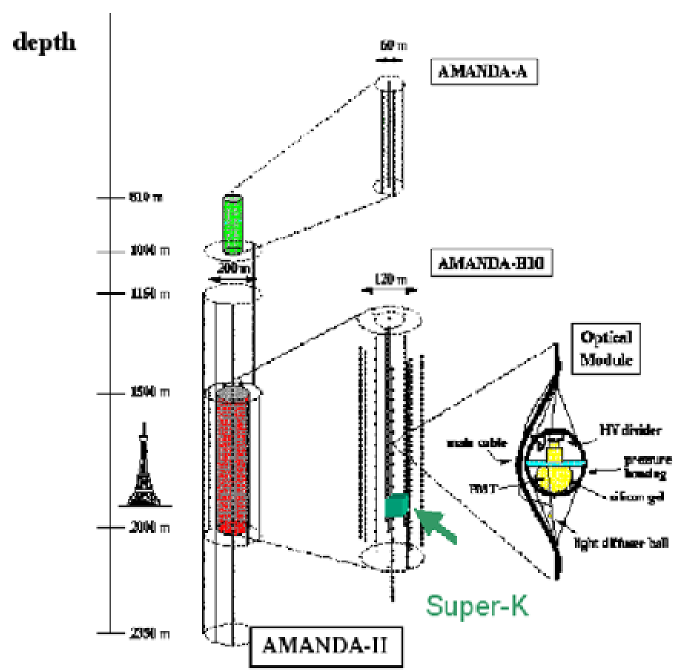

Fig. 2. Layout of the AMANDA detector. For comparison, the Eiffel tower and the Super-Kamiokande detector dimensions are shown

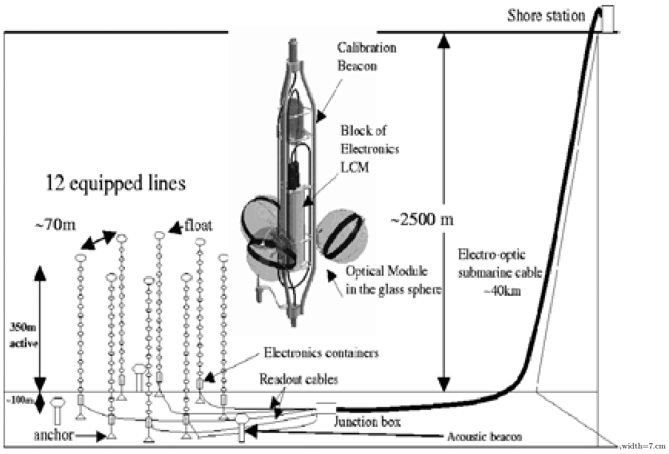

Fig. 3. Layout of the ANTARES detector. The detail of a storey is shown also

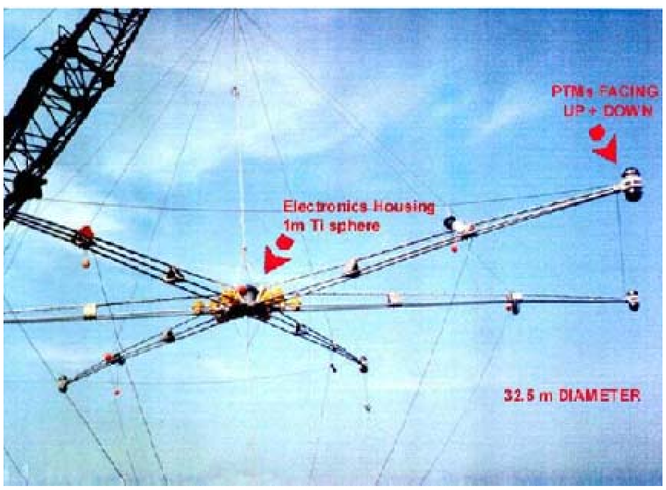

Fig. 4. A photograph taken during the deployment of NESTO test floor

tions were successful in Mar. 2003 when a prototype (1/5 of a string with 15 OMs), was deployed together with an instrumentation string for environmental parameter measurements.

NESTOR [15] is aiming at the construction of a NT close to Pylos (Greece) at ~ 4 km depth. Proposed towers are made of 12 hexagonal floors of 32 m diameter spaced by 30 m each carrying 6 upward-looking and 6 down-ward looking OMs with 15-inch PMTs. The effective area for $E_\mu > 10$ TeV is ~ 0.02 km^2. In Mar. 2003 a prototype floor (see Fig. 4) was deployed and PMT data were transmitted to shore trough a 35-km EOC.

In the next future the community is aiming at the construction of detectors at the scale of km^3. The IceCube project [7] is already funded and the detector construction will start in the Austral summer of 2004-5 and will continue for about 6 years. It will consist of 4800 DOMs (digital OMs) on 80 strings each with 60 10-inch PMTs vertically spaced by 17 m extending from 2.4 km up to 1.4 km depths. The strings are at vertexes of equilateral triangles with 125 m long side. Close to each string hole

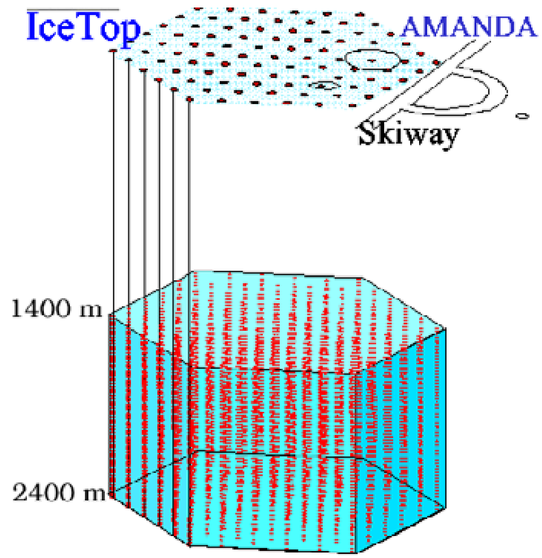

Fig. 5. Layout of the IceTop and IceCube layout. Also the dimensions of AMANDA are shown. First strings of IceCube will profit of the AMANDA-II detector to reconstruct events

there will be 2 iced water tanks seen by 2 DOMs, forming the IceTop array for CR composition measurements and absolute pointing determination. The IceCube and IceTop layout is shown in Fig. 5. The μ declared effective area after selection requirements is > 1 km^2 above 10 TeV, the angular resolution is expected to be $< 1°$ at high energies, the energy resolution $\sim 30\%$ in $\log E_\mu$ and $\sim 20\%$ in E for cascades.

In order to cover the entire sky, particularly the region of the Galactic Center, a km^3 detector is envisaged also in the Mediterranean Sea. It will also provide complementarity respect to IceCube for what concerns media properties and environmental backgrounds. The NEMO project [14] for a km^3 ν telescope has started in 1998 an R&D activity on the selection of the optimal site through more than 20 sea campaigns, on electronics and materials suitable for long-term undersea measurements, on large area photo-sensors. The selected optimal site is Capo Passero, 80 km off-shore Catania, 3400 m deep. More recently the realization of an underwater laboratory close to Catania connected to shore by an 28 km-long EOC, where a couple of prototype towers will be deployed, has been funded. Performance studies have produced a modular detector concept made of towers ~ 700 m high at distances $\gtrsim 120$ m. Configurations with ~ 5000 OMs should achieve at $E_\mu > 100$ TeV effective areas > 1 km^2 and angular resolutions $< 0.1°$.

3.1 Results on diffuse flux and point-like source searches

Both μ tracks or cascades are used for diffuse flux searches. Diffuse fluxes can be produced by a distribution of sources in the sky. Typically, the direction of ν induced cascades is detected with worse resolution than for μ's (typically

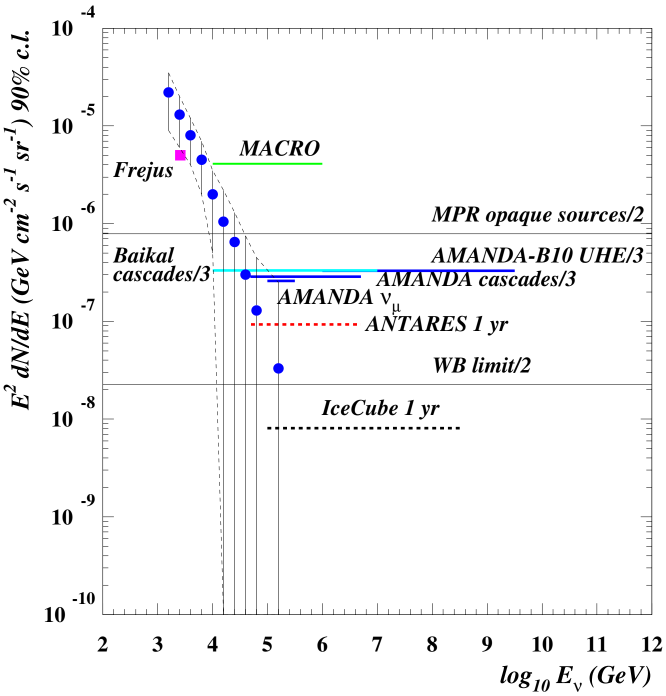

Fig. 6. 90% c.l. limits on diffuse E^{-2} fluxes of $\nu_\mu + \bar{\nu}_\mu$ in the hypothesis of equal fluxes for all flavors at the Earth due to oscillations as measured by AMANDA-II [6], Baikal [17] and MACRO [18]. Limits for other flavors than ν_μ (cascades) have been divided by the number of contributing flavors. Also the expected sensitivities for ANTARES [19] and IceCube [7] are shown. Dots are the measured atmospheric ν flux by AMANDA-II [5]

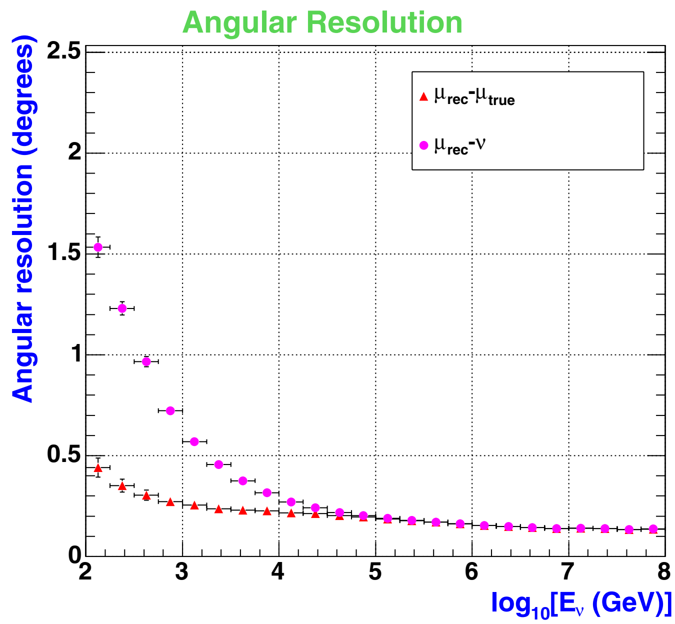

Fig. 7. ANTARES expected angular resolution vs neutrino energy. The *dots* represent the median angle between the simulated neutrino and the reconstructed muon direction (that is the pointing capabilities for a neutrino source), while the *triangles* are the median of the angle between the simulated muon and the reconstructed one (the intrinsic angular resolution)

$\lesssim 30°$ above 10 TeV), while the energy resolution is competitive (for μ's $\sim 30-40\%$ in logE, for showers $\sim 20\%$ in E above 10 TeV). Results and sensitivities for diffuse fluxes are shown in Fig. 6.

Point-like source search strategies look for statistically significant clusters of ν_μ events with respect to atmospheric ν's. Background rejection is achieved through directional cuts. In case of time-dependent emissions, such as for GRBs, further time requirements strongly reduce the backgrounds. It is clear that a relevant parameter for point-like source searches is the angular resolution for tracks $\Delta\theta$, since the signal to noise ratio is given by:

$$S/\sqrt{N} \propto \sqrt{AT}/\Delta\theta\,, \tag{3}$$

where A is the effective area and T the detection time. The angular resolution of AMANDA-II is about 2° and in ANTARES it is expected to be $\sim 0.2°$ for $E_\nu \gtrsim 10$ TeV, as shown in Fig. 7.

A collection of results and foreseen sensitivities for point-like source searches is is shown in Fig. 8. The AMANDA-II sensitivity shown for 2 years is already at the level of testing micro-quasars models [10].

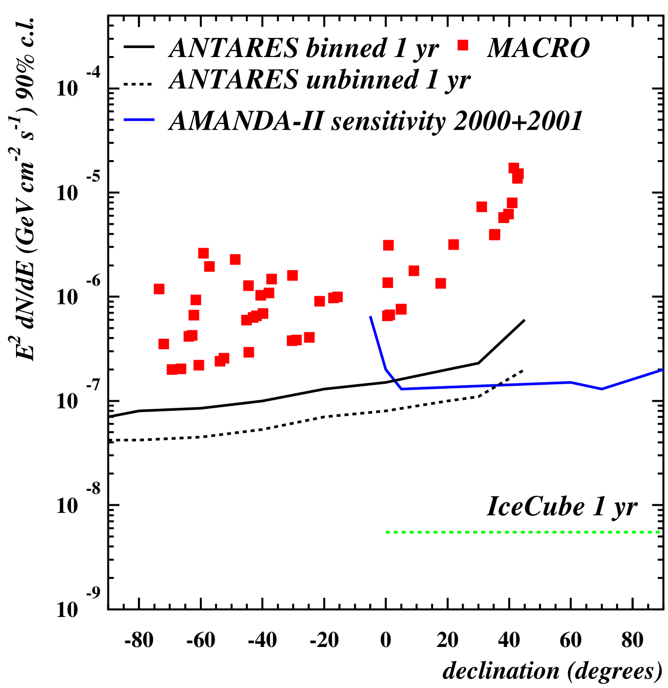

Fig. 8. Upper limits (90% c.l.) on E^{-2} neutrino fluxes as a function of the source declination for MACRO (*squares*) [20], expected sensitivity of AMANDA-II corresponding to 2000-1 data [6], IceCube [7] and ANTARES [21] (for different search methods). AMANDA and IceCube lines cover the upper hemisphere region since upgoing events are used

4 Conclusions

We have summarized the current status of neutrino telescopes: AMANDA-II is starting to be sensitive to interesting models for neutrino production, but the lack of any evidence after 4 years of data indicates that the proper scale of the field of ν astronomy is the cubic kilometer one. The first two strings of IceCube will be drilled in ice next winter and construction will last up to 2010. For what concerns a possible km^3 detector in the Mediterranean sea, a common effort between the 3 collaborations of ANTARES, NEMO.RD and NESTOR is an R&D proposal to the European Community. This project should come out with a common agreement on the site where the detector should be deployed and a common will to build it in a short term to be competitive with the IceCube schedule.

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