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The ANTARES experiment: sensitivity to dark matter candidates

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Abstract: The ANTARES collaboration is building an undersea neutrino telescope at 2400 m depth in the Mediterranean Sea. The experiment aims to detect high-energy cosmic neutrinos using a 3D array of 900 photomultipliers (PMTs) arranged in 12 strings. The first strings of ANTARES have been deployed in 2006, and data taking has begun. In this contribution the use of ANTARES for the indirect detection of Dark Matter particles is discussed. In supersymmetric models, the lightest particle is expected to be stable and quite massive (40 - 400 GeV). This particle, which is known as the neutralino, is a favourite dark matter candidate. The annihilation of two neutralinos in the core of massive celestial objects such as the Sun can lead to the emission of high-energy neutrinos in the subsequent decay chains. The expected performance of ANTARES for the observation of these neutrinos is discussed.

Introduction

Cosmology is undergoing an explosive period of activity, fueled by new accurate astrophysical data. Cosmological parameters such as the total density of the Universe and the rate of cosmological expansion are being precisely measured for the first time, and a consistent standard picture of the Universe is beginning to emerge. Nevertheless there are some "old" problems still open: though the case for *Dark Matter* holding together galaxies has been around for a long time (since 1970), the nature of the dark matter in the Universe is still unknown. Most likely astroparticle physics research will soon yield the answer that we are waiting for.

Currently there are two different experimental results (the acceleration of the Universe and its curvature) that are compatible with each other and identify two regions in the plane of possible values of Ω_M (matter contribution to the density of the Universe) and Ω_Λ (Dark Energy contribution to the density of the Universe) which have a common intersection. In this common zone Ω_M assumes the value $\sim$ 0.3 supporting the result obtained from measurements of the hydrogen velocities in galaxies leading to similar estimates.

Contribution of visible matter to Ω_M is obtained from total luminosity of all sources: $\Omega_{lum} \sim 3 \times 10^{-3}$. So the greater contribution to the Ω_M component of the Universe is due to dark (non-luminous) matter.

The estimate of the contribution of ordinary (baryonic) matter to Ω_M can be done using three different methods, all of which give the same answer. The most accurate of these methods comes from considering the formation of light elements during Big Bang nucleosynthesis, i.e. ^4He, D, ^3He and ^7Li produced in the first few minutes after the Big Bang. However, only if the density of ordinary baryons is within a certain narrow range, the predicted production is consistent with what we actually measure. The production of Deuterium is the most sensitive indicator of the baryon density. Recent measurements of the Deuterium to Hydrogen ratio, together with predictions from standard Big Bang nucleosynthesis give: $\Omega_B \sim 0.02$.

Moreover, different experiments studying solar, atmospheric and reactor neutrinos, now provide evidence that neutrinos have mass; they have placed a lower limit on the mass of the heaviest neutrino at about 0.05 eV. This implies that neutrinos contribute at most 0.1% of the mass-energy of the Universe.

Since Dark Matter is diffusely distributed in external halos around individual galaxies or in a sea through which cluster of galaxies move, Dark Matter particles cannot strongly interact with ordinary matter, if at all; moreover we can be confident that they are uncharged and have only very weak interactions. In addition, the formation of structures in the Universe tells us that early after the Big Bang dark matter particles must have been cold (i.e., moving at non-relativistic speeds) rather than hot (i.e., moving relativistically).

Weakly Interacting Massive Particles (or WIMPs) can explain the growth of structures and are the natural candidates for Dark Matter particles. A promising WIMP candidate is predicted by electroweak-scale supersymmetry (SUSY). SUSY was hypothesized in particle physics to cure the naturalness problem with fundamental Higgs bosons at the electroweak scale. The unification of coupling costants at the GUT scale is improved with SUSY, and SUSY is an essential ingredient in theories that unify gravity with the other three fundamental forces. It is usually assumed that the lightest supersymmetric particle is the *neutralino* (χ). This should be a linear superposition of the supersymmetric partners of the photon, the Z and of the two neutral and $CP-even\ Higgs$ bosons predicted by the *Minimal Supersymmetric Standard Model* (*MSSM*). In supersymmetric theories R-parity is conserved. The fact that the neutralino is stable opens up the possibility that neutralinos are still present in the Universe as a cosmological relic.

The ANTARES detector

The ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) collaboration is building a neutrino underwater telescope which is being deployed at a depth of 2500 m in the Mediterranean Sea near the Southern French coast[1, 2].

The experiment aims to detect neutrinos with energies above 10 GeV by means of the Cherenkov light emitted in sea water by charged particles which are produced in neutrino interactions.

In ANTARES the Cherenkov light is detected by a 3D-array of optical modules (OMs): pressure-resistant glass spheres containing phototubes (PMTs). Photon arrival times and PMT charge amplitudes allow the reconstruction of the tracks and an estimate of their energy. The ANTARES detector consists of 12 lines with an effective area of about 0.05 km^2 at 100 TeV. It can be considered as a first step towards the construction of a km^3 detector in the Mediterranean. A junction box distributes the power and clock synchronization signals to the lines and collects the data. It is connected to the shore by a 42 km electro-optical cable. The lines are kept straight by the floating force of a buoy at the top and an anchor at the bottom. They consists of 25 storeys, spaced by 14.5 m starting from 100 m above the sea floor. Each storey contains three 45^0 downward looking $10''$ photomultipliers inside the pressure resistant glass sphere. The electronics boards are inside a titanium cylinder at the center of the storey. Some of them contain supplementary calibration equipment like acoustic or optical beacons. Tests have shown that an overall time resolution of ~ 1 ns can be achieved mainly limited by the transit time spread of the PMTs.

The main background for these kind of experiments comes from atmospheric muons. To suppress this background one selects the ν_μ events only out of events that have been reconstructed as up-going ones. The ANTARES angular resolution is about 0.3^0 for $E_\nu > 10$ TeV, where pointing accuracy is limited by the transit time spread of the PMTs and by light scattering in water. At lower energies the pointing accurancy is limited by the angle between the neutrino and the induced muon so that the median angle between the neutrino and the reconstructed muon is for instance 0.7^0 at 1 TeV.

The first five lines of the detector have already been deployed and are taking data since February 2007, while the complete 12-line detector will be operational bye the beginning of 2008. As an example, a reconstructed muon track is shown in Fig. 1.

Neutralino detection

The WIMPs in the galactic halo will pass through massive bodies in the galaxy and can lose energy by scattering off nuclei so as to become gravitationally bound. Over time, WIMPs concentrate

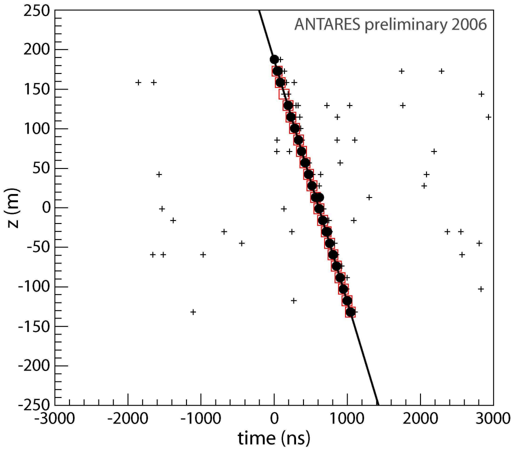

Figure 1: Reconstruction of an event (a downgoing muon): height (Z) along the string $vs.$ the measured hit times wrt an arbitrary zero. Crosses correspond to all the hits within a 1 μs time window, black dots to hits in coincidence while those used in the event fit are surrounded by a red square.

near the centres of these bodies and annihilate producing (among others) Standard Model particles. The exact rate depends on the time the WIMPs have had to accumulate and the annihilation cross section. The products of these annihilations will possibly decay and produce neutrinos which will be able to escape from the centre of these bodies and would potentially be visible as a neutrino flux at the surface of the Earth. The advantage of this detection method, which is common to the case of gamma rays too (contrary, instead, to antimatter searches), is that neutrinos do not interact in the outer space, and therefore the direction from which they arrive points at the location where they were produced. A high-energy neutrino signal in the direction of the centre of the Sun is therefore an excellent experimental signature, which may stand up against what is the main limitation of the technique itself, namely the neutrino background generated by cosmic-ray interactions in the Earth's atmosphere.

Quantitatively, the neutrino flux from neutralino annihilations depends on the one hand on the particle physics setup, i.e. on the details of the decay chain of a neutralino of a given mass and composition; on the other hand, a crucial role is played by the capture versus annihilation balance in the core of the celestial bodies and on the physics of the propagation of the relevant SM decay products. The differential neutrino flux is given by

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} = \frac{\Gamma_A}{4\pi D^2}\sum_f B_\chi^f \frac{\mathrm{d}N_\nu^f}{\mathrm{d}E_\nu} \tag{1}$$

where Γ_A is the annihilation rate, D is the distance of the detector from the source, f is the neutralino pair annihilation final state and B_χ^f are the branching ratios into the final state, each giving rise to the energy distribution of neutrinos $\frac{\mathrm{d}N_\nu^f}{\mathrm{d}E_\nu}$. The differential flux of neutrino-induced muons reaching the detector is then provided by

$$\frac{\mathrm{d}N_\mu}{\mathrm{d}E_\mu} = \int_{E_\mu^{th}}^{+\infty}\mathrm{d}E_\nu \int_0^{+\infty}\mathrm{d}R \int_{E_\mu}^{E_\nu}\mathrm{d}E'_\mu \cdot$$
$$\cdot P\left(E_\mu, E'_\mu; R\right) \frac{\mathrm{d}\sigma\left(E_\nu, E'_\mu\right)}{\mathrm{d}E'_\mu}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \tag{2}$$

where from right to left we can identify

- $\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}$: the differential neutrino flux given by eq. 1;
- $\frac{\mathrm{d}\sigma\left(E_\nu, E'_\mu\right)}{\mathrm{d}E'_\mu}$: the production cross section of a μ of energy E'_μ from a ν_μ of energy E_ν;
- $P\left(E_\mu, E'_\mu; R\right)$: the probability for a μ of initial energy E'_μ to end up with an energy E_μ after traversing a path-length R;
- R is the μ range in the material surrounding the detector.

At this point, the only missing ingredient for the computation is the annihilation rate Γ_A which, in turn, depends on the details of the neutralino interactions. Some assumptions and models must then be made which can affect the final result of the computation. Moreover the composition of the Sun and the Earth are quite different because the Sun is mainly constituted of hydrogen while the Earth is mostly composed of nuclei with zero spin. This in turn implies that the flux from the two sources are respectively dominated by spin-dependent and spin-independent processes.

ANTARES sensitivity to Neutralinos

The sensitivity of ANTARES to signals from neutralino Dark Matter annihilation has been extensively studied in the context of mSUGRA[3] through MonteCarlo simulations. Results are shown in Fig. 2. The effective area (which is the detector sensitive area including reconstruction ef-

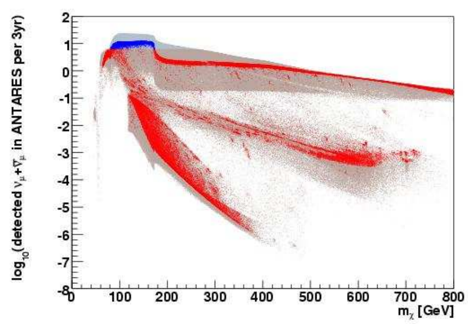

Figure 2: Number of expected events in ANTARES per 3 years plotted against m_χ. In blue the excludable values and in red the not excludable.

ficency) is calculated as a function of neutralino energy and optimised with respect to the angular size cut (Fig. 3). For any assumed neutralino mass,

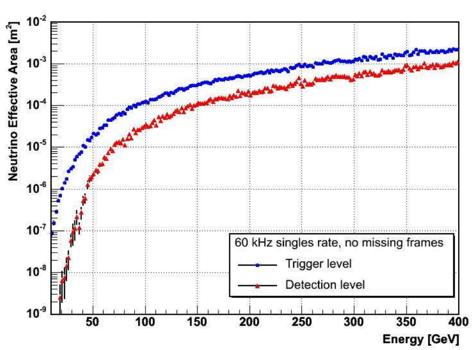

Figure 3: Effective area for isotropic upgoing neutrinos.

the expected background inside the cone is calculated and the 90% confidence level limit set using the Feldman and Cousins[4] method to yield a neutrino flux limit. This is in turn converted to a muon flux limit using the muon yield per neutrino provided by the `DarkSUSY`[5] program. Superimposed on Fig. 2 are a number of points which correspond to the theoretical predictions within mSUGRA framework. The fall-off in sensitivity at low energies arises from using a reconstruction package optimised for higher energies: dedicated studies to improve low energy reconstruction efficiencies and to evaluate the sensitivity to neutrino fluxes from neutralino annihilation in the Earth are under way.

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