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Indirect search for dark matter towards the centre of the Earth with the ANTARES neutrino telescope

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The ANTARES neutrino telescope is a water Cherenkov detector and currently the largest operating neutrino telescope in the Northern Hemisphere. One of the main scientific goals of ANTARES is the indirect search for dark matter, as the Weakly Interacting Massive Particle (WIMP). WIMPs could scatter on normal matter and therefore be gravitational bound in massive astronomical objects like the Earth. Therefore an indirect search for dark matter can be performed by looking for an excess of the neutrino flux from the Earth's core. The exact spectrum of the neutrino flux from the Earth would depend on the WIMP mass, the annihilation channel, the spin independent scattering cross section and the thermally averaged annihilation cross section of the WIMPs. Such a search has been done with the data taken by ANTARES from 2007 to 2012. First limits from this search will be presented.

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1. Introduction

The hypothetical Weakly Interacting Massive Particles (WIMPs) are widely regarded as excellent dark matter (DM) candidates. WIMPs arise most prominently in supersymmetric models [1] like the Minimal Supersymmetric Extension of the Standard Model (MSSM). In most cases the lightest supersymmetric particle (LSP) is the lightest neutralino. To ensure baryon and lepton number conservation in the MSSM it is often assumed that a multiplicative quantum number called R-parity is conserved. The LSP would then be stable, making the neutralino an excellent dark matter candidate.

WIMPs can be detected directly via the observation of the nuclear recoils from the scattering of WIMPs off nuclei (recent such experiments include XENON100[2][3] and Lux [4]), or indirectly via the observation of products from WIMP self-annihilations. The latter is possible for massive astrophysical objects in which WIMPs can accumulate, like the Earth [1][5], the Sun [6][7] or the Galactic Center [8]. This paper deals with the indirect search for WIMPs from the center of the Earth.

Capturing of WIMPs in the Earth is dominated by spin-independent elastic scattering on the heavy nuclei abundant in the Earth and is kinematically suppressed if the mass of the WIMP is not close to the mass of the particle or nucleus the WIMP is scattering on. This is because the dark matter velocity dispersion is around $270\,\mathrm{km/s}$ [1], but the escape velocity from Earth is only about $11.1\,\mathrm{km/s}$ at the surface and $14.8\,\mathrm{km/s}$ at the center. The WIMP annihilation rate in the Earth today can be written as [1]:

$$\Gamma(t) = \frac{1}{2} C_C \tanh^2\left(\frac{t}{(C_C C_A)^{-0.5}}\right) \tag{1.1}$$

Here t is the age of the Earth, C_A depends linearly on the thermally averaged annihilation cross section times velocity $<\sigma v>$ and C_C is the WIMP capture rate which depends linear on the spin-independent elastic scattering cross section of the WIMP to protons σ_p^{SI}. The exact form of C_A and C_C can be found in [1] and [9].

Assuming the annihilation cross section for dark matter in the Earth the same as during the freeze out of WIMPs, the conditions for equilibrium in the Earth ($t \geq 2(C_C C_A)^{-1/2}$) are not generally satisfied. It would however be possible that $<\sigma v>$ becomes boosted in the case of low velocities for some reason, e.g. the Sommerfeld effect.

In this paper, we present limits on σ_p^{SI}, derived from data taken by ANTARES from 2007 to 2012. We consider WIMP masses between 25 GeV and 1 TeV. The lower bound was chosen under consideration of the capability of ANTARES to reconstruct neutrinos of low energy, the upper bound was chosen roughly one order of magnitude higher than the masses of elements in the Earth. We consider WIMPs which annihilate either into the soft $b\bar{b}$ channel, the hard $\tau^+\tau^-$ or W^+W^- channel or the monochrome, non-SUSY $\nu_\mu\bar{\nu}_\mu$ channel. We consider both enhanced and non-enhanced scenarios for $<\sigma v>$.

2. Simulations

The neutrino flux from dark matter annihilation in the Earth was simulated with WimpSim [10][11]. It simulates WIMP pair annihilations inside the Earth without any assumptions about the

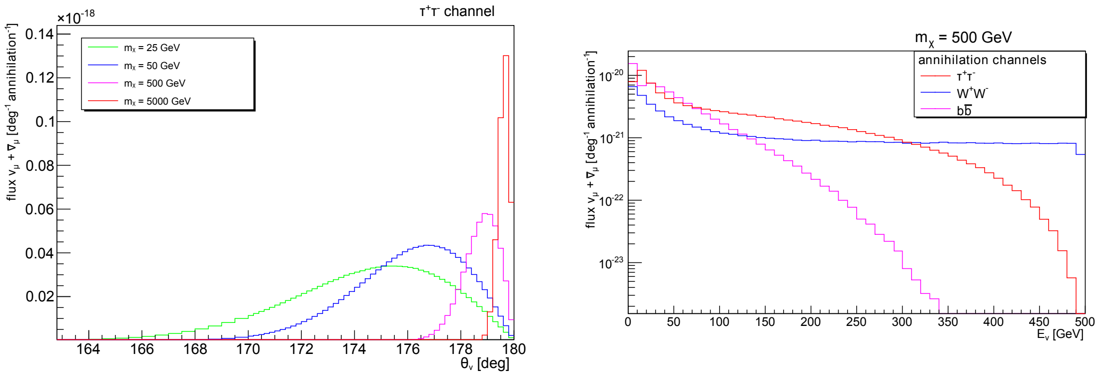

Figure 1: Zenith and energy spectrum of the $\nu_\mu + \overline{\nu}_\mu$ flux from WIMP pair annihilations for different WIMP masses (left) or annihilation channels (right) at the surface of the Earth as simulated with WimpSim.

dark matter model except the WIMP mass and the annihilation channel (a 100% branching ratio is assumed) and the subsequent decay of the products. The resulting neutrino flux is propagated to the surface of the Earth while neutrino oscillations are taken into account in a full three flavour scenario. For an example of such fluxes, see Figure 2.

The primary sources of background in this analysis consist of muons and muon-neutrinos, which have their origin in interactions of cosmic rays with the atmosphere of the Earth. The atmospheric muons are simulated with the MUPAGE [12] package (the parametric formulas of the fluxes of muon bundles can be found in [13] and [14]). For the background from atmospheric neutrinos only the contributions from charged current interactions from atmospheric muon (anti-)neutrinos contribute significant to this analysis. For the conventional neutrino flux the parametrization of [15] is used with a prompt contribution according to [16].

The flux of particles resulting from neutrino interactions in the vicinity of the detector is simulated with the GENHEN package. For the propagation of the Cherenkov light through the sea water, both light absorption and scattering are taken into account.

3. Event selection criteria

The signal neutrinos can be discriminated from the background by their zenith angle (by only selecting events which were reconstructed as up-going close to the vertical direction, i.e. with zenith angle close to 180°) and energy (by not selecting events with reconstructed energy near or higher than the WIMP mass). This analysis relies on reconstruction algorithms providing direction and energy of the neutrino candidates, and on cuts defined to select neutrinos from the direction of the Earth center, produced by WIMPs of a given mass. For the muon direction, the BBfit [17], AAfit [18] and ZAV algorithms have been used. The latter is an algorithm for verifying the reconstructed zenith angles of the former. It was designed specifically for this analysis, where all signal events reach the detector from roughly the same direction (close to the nadir). It is based on the examination of the measured light pulses and to the comparison to that expected from an up-going, vertical muon.

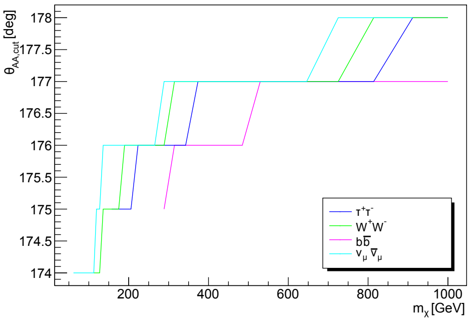

Figure 2: Optimized value of $\theta_{AA,cut}$ in dependency of the WIMP mass and annihilation channel.

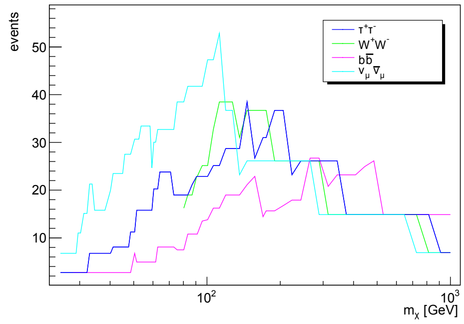

Figure 3: Number of atmospheric neutrinos expected according to simulations in dependency of the event selection criteria optimized for different WIMP masses and annihilation channels.

Two analysis chains were used. The first, BBchain, uses BBfit as its main method of zenith reconstruction and is more suitable for lower WIMP masses with softer annihilation channels, the second, AAchain, uses AAfit. Each analysis chain consists of several event selection criteria, derived from either BBfit, AAfit or ZAV. The selection is based on the reconstructed zenith angles of both strategies, the angular error estimate, the fit qualities, the brightness of the events in terms of its position in the detector to avoid background from edge effects. For both analysis chains, the cut parameters have been tuned individually. The event selection criteria are optimized with the approach for unbiased cut selection for optimal upper limits presented in [19]. The WIMP annihilation rate $\Gamma(t)$ is used as scaling parameter of the source flux. The optimization is done individually for each annihilation channel and several WIMP masses in the considered mass range.

For higher WIMP masses harder zenith angle cuts and looser energy cuts are expected. As an example, the optimized values of the AAfit zenith angle cut $\theta_{AA,cut}$ versus WIMP mass and annihilation channels are shown in Figure 2.

The expected background neutrino events according to simulations are shown in Figure 3. Due to the limited statistics in the Monte Carlo simulations, the expected background muons events according to simulations were always 0. The structures on Figure 3 depend on the fact that for each mass bin, the set of cuts on the parameters defined in section 3 allow a different number of background events.

4. Results

After the aforementioned blinded optimization, the ANTARES data collected from 2007 to 2012 (corresponding to a livetime of 1191 days) were analysed. For each set of the cut parameters, defined in the optimization procedure for each WIMP mass interval and decay channel, the number of data events was determined. These numbers are shown in Figure 4.

In the comparisons of the data in Figure 4 and the background of Figure 3, no significant excess of events was observed. In particular, as shown in [20], the overall normalization factor for atmospheric neutrinos yielding the background given in Figure 3 must be increased by a factor about 25%. The no observation of an excess can be translated to a 90% CL upper limit on the WIMP

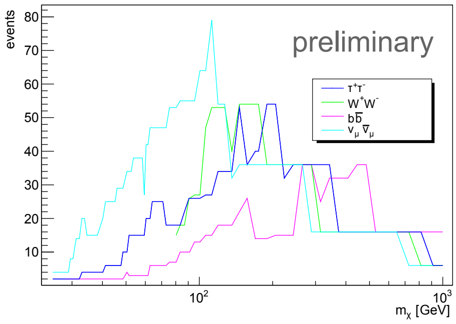

Figure 4: Number of events observed in dependency of the event selection criteria optimized for different WIMP masses and annihilation channels for ANTARES 2007 - 2011.

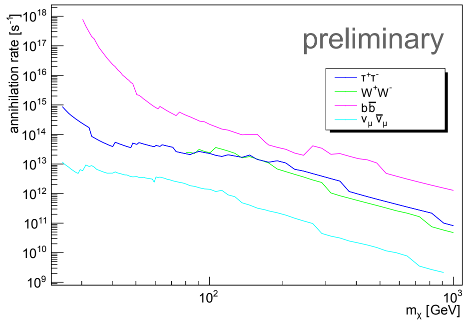

Figure 5: 90% CL upper limits on Γ as a function of the WIMP mass for WIMP pair annihilation to 100% into either $\tau^+\tau^-$, W^+W^-, $b\bar{b}$ or $\nu_\mu\bar{\nu}_\mu$, for ANTARES 2007 - 2012.

annihilation rate in the Earth (1.1). 90% CL. upper limits on Γ were calculated with the TRolke module from ROOT [21], where uncertainties in the background and efficiency are considered with a fully frequentist approach [21] with the profile likelihood method [22]. As a first step, a 90% CL. event upper limit $\mu_{90,R}$ was calculated. Then, the limit on Γ was then calculated as:

$$\Gamma_{90} = \frac{\mu_{90,R}}{n_s} \cdot \Gamma_0 \tag{4.1}$$

Where $\Gamma_0 = 1\,\mathrm{s}^{-1}$ and n_s is the number of signal events expected for this experiment and for $\Gamma = \Gamma_0$. It was assumed that the signal follows a Poisson distribution and that the background and efficiency can be modelled as gaussian. A systematic uncertainty of 15% on the efficiency was assumed (following the studies in [23]); a systematic uncertainty of 30% was assumed for the atmospheric neutrino background (compare with [23] and [24]). For the treatment of the atmospheric muon background, the most conservative approach (yielding the highest upper limit) was chosen by assuming that the atmospheric muon expectation is always 0. See Figure 5.

The limits on the annihilation rate are the main result of this analysis and the limits on σ_p^{SI} were calculated from this result using [1][9][25]. The limits on σ_p^{SI} are shown assuming that $<\sigma v>$ for dark matter in the Earth is the same as during the freeze out ($<\sigma v> = 3\cdot 10^{-26} cm^3 s^{-1}$) and for the annihilation channels allowed in SUSY ($\tau^+\tau^-$, W^+W^- and $b\bar{b}$). The results are shown as σ_p^{SI} versus m_χ in Figure 6, in comparison to the limits from other indirect and direct dark matter searches. Compared to the results from other indirect dark matter searches. This search from center of the Earth yields more stringent limits for the WIMP mass range from about 40 to 70 GeV (the mass range for which the capture rate of WIMPs would be enhanced due to the composition of the Earth). For completeness, recent limits from direct searches are shown as well. See Figure 6.
Additionally it was considered that $<\sigma v>$ of DM in the Earth is enhanced (compared to its value during the freeze out) by a boost factor. Here the $\nu_\mu\overline{\nu_\mu}$ annihilation channel is also considered. The limits are shown as σ_p^{SI} versus the boost factor on $<\sigma v> = 3\cdot 10^{-26} cm^3 s^{-1}$ for $m_\chi = 52.5$ (for which capturing of WIMPs in the Earth would be strongly enhanced due to the composition of the Earth) and 407.65 GeV, compared to the results from Lux [4] (which provide the most stringent

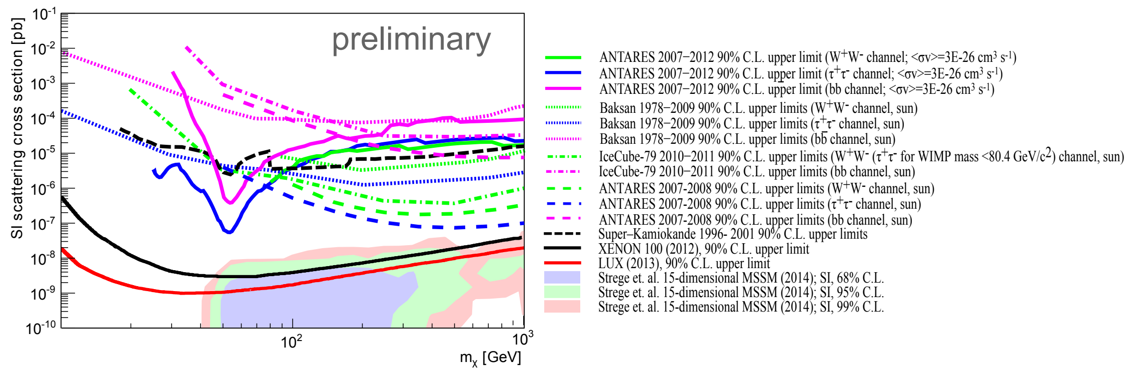

Figure 6: 90% CL upper limits on σ^{SI} as a function of the WIMP mass for $<\sigma v>= 3\cdot 10^{-26} cm^3 s^{-1}$ and WIMP pair annihilation to 100% into either $\tau^+\tau^-$, W^+W^- or $b\bar{b}$, for ANTARES (Earth) 2007 - 2012, Baksan 1978 - 2009 [26] (from [6]), IceCube-79 2010 - 2011 [7] (from [6]), Super-Kamiokande 1996- 2001 [27], ANTARES (Sun) 2007 - 2012 (preliminary), Xenon100 [3] and Lux [4]. Also shown are the profile likelihood maps of a 15-dimensional MSSM from Strege et. al. [28]. Plot modified from [29].

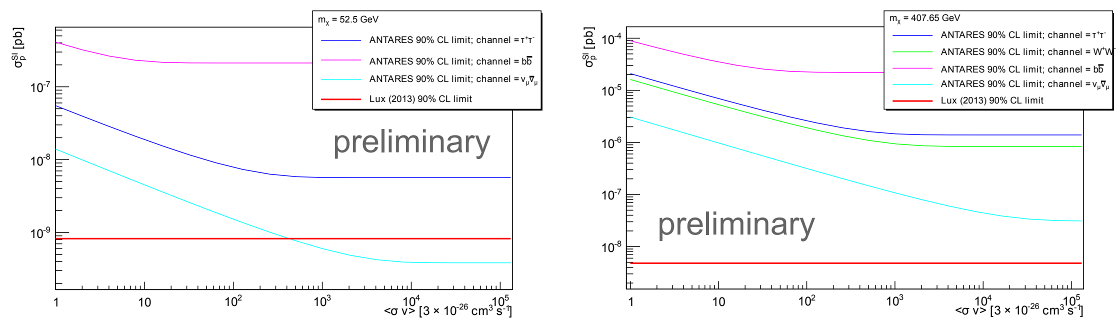

Figure 7: 90% CL upper limits on σ^{SI} as a function of $<\sigma v>$ and WIMP pair annihilation to 100% into either $\tau^+\tau^-$, W^+W^- or $b\bar{b}$, for a WIMP mass of 52.5 GeV (left) and 407.65 GeV (right), for ANTARES 2007 - 2011 and Lux [4].

limits on σ^{SI} so far). See Figure 4.

Here the upper limits on σ_p^{SI} decrease with increasing boost factor, until equilibrium would be reached. Assuming the WIMP would mainly annihilate into $\nu_\mu\bar{\nu}_\mu$ channel and $<\sigma v>\approx 1.510^{-23} cm^3 s^{-1}$, this search yields the so far most stringent limits on σ_p^{SI}. It should however be noted that this scenario would not be possible if DM were mainly made up by SUSY particles or the lightest Kaluza-Klein particle.

5. Conclusion and Outlook

A search for dark matter from the center of the Earth has been performed with the data data collected from 2007 to 2012 by ANTARES neutrino telescope. No significant excess over the background expectation has been found. 90% CL upper limits on the WIMP self annihilation rate were set as a function of the WIMP mass for WIMP pair annihilation to 100% into either $\tau^+\tau^-$, W^+W^-, $b\bar{b}$ or $\nu_\mu\bar{\nu}_\mu$. These were translated to limits on the spin independent scattering cross section of WIMPs to protons. Here a scenario were the annihilation cross section for dark matter in the Earth is enhanced compared to the value during the freeze out of WIMPs was also considered. It could be demonstrated that the indirect search for dark matter towards the center of the Earth can be competitive with other types of dark matter searches, both direct and indirect. The discovery potential of such experiments strongly depends on the mass of the WIMP, its preferred annihilation channel and the thermally averaged annihilation cross section times velocity in the Earth today. A promising candidate for an improved future search is Km3Net [30] with the ORCA extension [31].

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