Indirect search for dark matter in the Sun and the Galactic Centre with the ANTARES neutrino telescope

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The ANTARES Neutrino Telescope
Neutrino detection

- Neutrinos are the lightest leptons and only interact via the **weak force** (and gravity)

- They can only be detected indirectly via weak interactions producing detectable particles

- These particles have to be distinguished from the same particles coming from other sources.

![Diagram](image-url)

### Drei Generationen der Materie (Fermionen)

<table>
<thead>
<tr>
<th>Generation</th>
<th>Quarks</th>
<th>Leptonen</th>
<th>Eichbosonen</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>u, c, t</td>
<td>e, μ, τ</td>
<td>H (Higgs)</td>
</tr>
<tr>
<td>II</td>
<td>d, s, b</td>
<td>e, μ, τ</td>
<td>Z (Z boson)</td>
</tr>
<tr>
<td>III</td>
<td>up, charm, top</td>
<td>μ, τ</td>
<td>W (W boson)</td>
</tr>
</tbody>
</table>

### Massen und Ladungen

- Massen: 2.3 MeV, 1.275 GeV, 173.07 GeV, 125.9 GeV
- Ladungen: 1/2, 2/3, 3/2
Neutrino Telescopes

Neutrinos from astrophysical sources pass close to the detector.

There these neutrinos produce leptons in interactions with nucleons.

- The muons produced by the muon-neutrinos move at velocities close to that of light in vacuum.
- This is generating a cone-shaped emission pattern (Cherenkov light).

This light is then detected by ANTARES.
Physics Goals

Physics scope of Neutrino Telescopes:
- Neutrinos from astrophysical sources
- Neutrino mass hierarchy
- Dark Matter (and other „exotics“)

Detector
- Denser
- Larger

MeV  GeV  TeV  PeV  EeV

Supernovae
Oscillations
Dark Matter (WIMPS)
Astrophysical Sources
GZK
Atmospheric muons

- Neutrino telescopes are background--dominated experiments
- The main background are muons produced in the atmosphere (in the decay of mesons created by cosmic ray interactions)
- These muons come from above and are very numerous
- Neutrinos can cross the earth without interaction
The Antares Neutrino Telescope

- Located 2.5 km below the ocean surface
- 40 km off the shore of Toulon at the Southern French coast

- 12 lines separated by 60-75 m on the ocean floor
- 25 storeys per line
- 3 Optical Modules per storey
A storey is 2 m high and has a titanium alloy supporting frame

Each storey has three 17-inch, pressure-resistant spheres (Optical Modules, OMs) with 10-inch PMTs

Each OM has two analogue ring samplers (ARSs) for data acquisition

They are connected to a local control module that hosts the control electronics

The detector lines consist of electro-optical cables capable to stand the corresponding tension and torsions.

The alignment of the lines is measured using a set of hydrophones, acoustic transponders and tilt-meters on the storeys.
Reconstruction strategies

**BBFit:**
- Better for low energies (< 250 GeV)
- Can reconstruct single-line events (only zenith angle provided)
- The main event selection parameter is tchi2 (~χ)

**AAFit:**
- Better for high energies (> 250 GeV)
- Event selection parameters are λ (reconstruction quality) and β (angular error estimate)
ANTARES Time Calibration
A 20 MHz square signal is generated on-shore and broadcasted to the whole detector.

The signal round-trip-time is used for a calibration of delays from the cables and part of the electronics.

Additional delays from the PMTs and the analogue ring sampler have to be calibrated differently.

A first time calibration is made on-shore in the laboratory with a pulsed light source and optical fibres connected to the OMs.
The ANTARES Optical Beacon

Every line has an OB on the storeys: 2, 9, 15 and 21 (starting from the bottom)

Each OB has 6 hardware boards arranged into a hexagon and facing outwards

The OB flashes are detected via internal PMTs

Each board has 6 LEDs

The LEDs have a peak wavelength of 472 nm with a width of 10 nm and a rise-time between 1.9 and 2.2 ns
Time calibration is done using the time difference between the flashing of the OB and signals from that OB in the PMT:

\[ T_{corr} = t_{OM} - t_{OB} - \frac{d_{OM-OB}}{v_g} \]

- Histograms of time differences between the flashing of the OB and the signal in the corresponding PMT are generated.
- A fit is used to determine the average time difference and corrections due to different effects are applied.
- Some of the calibrations have to be manually revised.

![Diagram showing storeys 2, 9, 15, and 21 with time calibration process]

storey 21

storey 15

storey 9

storey 2
Time Calibration

- Most calibrations lead to a correction of less than 2 ns
- Of the 1770 ARS 1059 to 798 can be calibrated, 30% of the total ARS have to be manually revised
- Calibrations are carried out every 2 months
- The spread of the corrections do not increase significantly over time
- Aside of lost OMs only a minor degradation

An example of the difference between the old and the new clock offset values for June 2015. RMS: 2.1 ns
## Statistics

<table>
<thead>
<tr>
<th>Application start date</th>
<th>root mean square of corrections [ns]</th>
<th>number of corrected ARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>03.02. 2014</td>
<td>1.9</td>
<td>1059</td>
</tr>
<tr>
<td>31.03. 2014</td>
<td>2.5</td>
<td>1056</td>
</tr>
<tr>
<td>04.06. 2014</td>
<td>1.8</td>
<td>1000</td>
</tr>
<tr>
<td>28.07. 2014</td>
<td>2.2</td>
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<tr>
<td>30.09. 2014</td>
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<tr>
<td>01.12. 2014</td>
<td>0.9</td>
<td>589</td>
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<tr>
<td>09.02. 2015</td>
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<td>830</td>
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<tr>
<td>27.04. 2015</td>
<td>2.1</td>
<td>853</td>
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<tr>
<td>29.06. 2015</td>
<td>2.1</td>
<td>866</td>
</tr>
<tr>
<td>31.08. 2015</td>
<td>2.1</td>
<td>805</td>
</tr>
<tr>
<td>26.10. 2015</td>
<td>2.1</td>
<td>798</td>
</tr>
<tr>
<td>21.12. 2015</td>
<td>2.1</td>
<td>809</td>
</tr>
</tbody>
</table>
Search for Dark Matter
Dark Matter is a nonbaryonic type of matter. About 5 times as abundant as baryonic matter. It can only interact via gravity and potentially via weak scale force. Weakly Interacting Massive Particles (WIMPs) are one of the favoured hypotheses. All evidence for Dark Matter uses gravity. The exact properties of dark matter are largely unknown. The detection of Dark Matter could work via "weak" interactions.
Evidence for Dark Matter

Evaluating the Virial Theorem for nearby galaxy clusters shows a mass of the clusters greater than the visible mass (Jan Oort 1932 & Fritz Zwicky 1933)

Velocity distribution of stars in galaxies indicate the presence of a dark matter halo (Vera C. Rubin & W. Kent Ford 1970)

Gravitational lensing shows the presence of excess matter in many celestial objects (galaxies and galaxy clusters)

Temperature fluctuations in the cosmic microwave background indicate the presence of dark matter in the early universe

The Big Bang nucleosynthesis requires the presence of dark matter. The observed deuterium to helium ratio, which strongly depends on the baryon density, can only be explained assuming dark matter.

N-body simulations of large scale structures of the Universe indicate that without dark matter the filament and void-type structures observed could not form

Without dark matter the initial overdensities would not have enough time to form the large scale structures that we observe now.
Types of Searches

These types of searches are complementary.

Direct detection experiments are sensitive to the local dark matter density.

Collider searches allow for a more specific search.

Indirect detection experiments are sensitive to dark matter halo models.

**Direct Detection**
- XENON, LUX, PICO, CDMS

**Indirect Detection**
- ANTARES, IceCube, HESS, FERMI

**Production at Colliders**
- LHC
Searches with neutrinos

- Relic WIMPs accumulate in massive celestial bodies like the Sun, the Galactic Centre, the Earth or galaxy clusters
- They annihilate into $W$, $Z$, $H$ bosons, $c$, $b$, $t$ quarks and leptons can lead to significant neutrino fluxes
### Advantages

#### Sun
- In the Sun a signal would be very clean. The Sun does emit neutrinos, but they are low energy.
- The Sun’s journey through the Galaxy makes dark matter “collection” less sensitive to halo uncertainties
- Annihilation rates depend only weakly on WIMP velocity distribution and the search is more sensitive to the low energy end
- The search is sensitive to spin–dependent cross-sections
- The Sun is massive enough and not too far away

#### Galactic Center
- High energy neutrinos are not absorbed (unlike neutrinos in the Sun or gammas)
- There is a possible astrophysical background, but is expected to be small
- Galactic Centre location below horizon (most of the time) in Northern hemisphere
- The Galactic Centre provides the highest of all signal expectations for indirect searches
Analysis Method
A likelihood function is used to identify signal, in contrast to a "cut and count" or binned method.

The likelihood function uses the angular distance between event and source and other parameters.

This likelihood function is constructed from an understanding of the detector response and signal characteristics.

The signal-background discrimination power of the likelihood has to be studied by simulation.
Pseudo Experiments

- Maps of simulated background events (PEs) are generated using histograms of time-scrambled data.
- Simulated signal events are introduced into these PEs.
- They are generated from Monte-Carlo simulation, expected signal spectra and source morphologies, which are also used to create parts of the likelihood function.
Likelihood Function

The PEs are analysed using a likelihood function that describes the probability of an event map to contain signal events:

$$\log [L(n_s)] = \sum_{i=1}^{N_{tot}} \log [n_s S(\psi_i, \beta, N_{hits}) + N_{bg} B(\text{dec}_i, \beta, N_{hits})] - N_{bg} - n_s$$

S is the likelihood of an event at a certain position, with certain parameters to be signal, B is the analogous term for the background.
The likelihood function is then optimised with respect to the number of signal events \((n_s)\) and a parameter called the test statistic \((TS)\) is calculated:

\[
\log [TS] = \log [L^{max}] - \log [L(n_s = 0)]
\]

- For an average of inserted signal events TS distributions are generated using poissonian weights.
- Sensitivities and limits are calculated comparing TS distributions for different signal strengths.
- This parameter is used to distinguish samples of pure background from those with different number of signal events.
To avoid any bias, the analysis is optimised using only the PEs, not the actual data ("blinding")

Time scrambling ensures that the background PEs and likelihood are "blinded"

The analysis uses a number of quality parameter cuts to optimise the sensitivities. These are tuned on the blinded data

The actual data are then analysed using the cuts previously established ("unblinding")
Limit Computation

The initial limits are expressed in terms of detected events

The acceptance relates the number of detected signal events to the incident signal neutrino flux:

$$\Phi_\nu \cdot \text{Acc} \cdot T_{\text{live}} = \mu_{\text{det}}$$

The acceptance is calculated from the detector Monte Carlo simulation

These limits are then translated into bounds on dark matter parameters

$$\text{Acc}(m_{\text{WIMP}}, \text{Ch}) = \int_{E_{th}}^{m_{\text{WIMP}}} A_{\text{eff}}(E_{\nu \mu}) \left( \frac{dN_{\nu \mu}}{dE_{\nu \mu}} \right)_{\text{Ch}} dE_{\nu \mu} + \int_{E_{th}}^{m_{\text{WIMP}}} A_{\text{eff}}(E_{\bar{\nu} \mu}) \left( \frac{dN_{\bar{\nu} \mu}}{dE_{\bar{\nu} \mu}} \right)_{\text{Ch}} dE_{\bar{\nu} \mu}$$

$$w_2 = l_\theta \cdot l_{\text{Energy}} \cdot (1 - P_{\text{Earth}}) \cdot \sigma_{\text{CC}} \cdot V_{\text{ol}} \cdot \rho_N \cdot E^\gamma \cdot T$$
The expected neutrino spectra were calculated using the "PPP 4 DM ID: Poor Particle Physicists Cookbook for Dark Matter Indirect Detection" code from Marco Cirelli (JCAP03 (2011)051) for the Galactic Centre and the WIMPSIM code for the Sun.

**WIMPSIM** calculates the spectra for the bottom quark-, the W boson and the tauon channel.

For the Galactic Centre the muon and the neutrino channel are also used.

These channels present extreme cases, with the bottom quark channel being the softest and the tau (neutrino) channel being the hardest.

Neutrino oscillations were taken into account.
The Sun
Unblinding

- After unblinding, no significant excess is found
- TS calculated for the unblinded data was below or at the level of the background median
- Exclusion limits were set

Distribution of separation angle for AAFit (magenta) BBFit(blue). 2007-2012 ANTARES data
The initial limits are very stable over the WIMP mass range

Therefore, the limits on the neutrino flux essentially follow the inverse of the acceptance
The neutrino fluxes are converted to cross sections assuming an equilibrium between annihilation and capture, i.e. the capture rate is twice the annihilation rate.

The capture rate is then linked to the cross sections assuming a maxwellian velocity distribution.
Spin-dependent cross-sections

90% of nuclei in the Sun are hydrogen. The analysis is most sensitive to the spin-dependent cross-section.
Direct detection experiments usually are the most sensitive to the spin-independent cross-section. For the spin-independent cross-section older results from IceCube were chosen for the comparison.
The Galactic Centre
Unblinding

After unblinding, no significant excess is found

The TS calculated for the unblinded data was significantly below the background median

Exclusion limits were set

The data recorded from 2007 to 2015 has been used
Neutrino Flux

The initial limits are very stable over the WIMP mass range considered and the behaviour of the flux limits is the inverse of the one of the acceptance.
The J-Factor is the integral along the line of sight of the dark matter density squared:

\[ J(\theta) = \int_0^{l_{\text{max}}} \rho_{\text{DM}}^2 \sqrt{R_{\text{SC}}^2 - 2lR_{\text{SC}} \cos(\theta) + l^2} \, dl \]

The J-Factor is necessary to convert a flux into the thermally averaged annihilation cross section \(<\sigma v>\):

\[ \frac{d\phi_\nu}{dE} = \frac{<\sigma v>}{2} J_{\Delta \Omega} \frac{R_{\text{SC}} \rho_{\text{SC}}^2}{4\pi m^2_\chi} \frac{dN_\nu}{dE} \]

The total J-factor is calculated by integrating the J-factor over the solid angle of the search cone.
Three halo models were used: The Navarro-Frenk-White (NFW), the Burkert and the "McMillan" profile.

- The NFW profile is cusped and gives the most point like source.
- The Burkert profile is cored and gives the most extended source.
- The "McMillan" profile uses more profile parameters as variables and presents an intermediate case.
Finally limits for the three different halo models and all five annihilation channels are computed.
Limits

\[ \langle \sigma v \rangle \text{ in [cm}^3\text{s}^{-1}\rangle \]

- **ANTARES GC \( \tau^+ \tau^- \)**
- **IceCube GC \( \tau^+ \tau^- \)**
- **IceCube GC + cascade \( \tau^+ \tau^- \)**
- **FERMI dSphs**
- **FERMI + MAGIC dSphs**
- **HESS GC Einasto \( \tau^+ \tau^- \)**

\[ \text{WIMP Mass [GeV/c}^2\text{]} \]

[Graph showing limits for different experiments and models, with axes for cross-section per velocity and mass range.]
Dissemination of Results

Papers:

• „Limits on Dark Matter Annihilation in the Sun using the ANTARES Neutrino Telescope“, Physics Letters B, Volume 759, 2016, Pages 69–74, Corresponding Author: Christoph Tönnis

• „Results from the search for dark matter in the Milky Way with 9 years of data of the ANTARES neutrino telescope“, Physics Letters B PLB-D-16-02062R1, Corresponding Author: Christoph Tönnis

Conferences:

• The 34th ICRC in The Hague in 2015
• The DSU conference 2014 in Cape Town
• The DSU conference 2015 in Kyoto
• The 9th Multidark meeting in Alcala de Henares in 2013
• The 10th Multidark meeting in Valencia in 2014
• The 11th Multidark meeting in Santiago de Compostela in 2014
• The 12th Multidark meeting in Salamanca in 2015
• The 13th Multidark meeting in Madrid in 2015
Summary

- The calibrations using LED beacons were performed for the years 2014 and 2015 and indicate a persistent calibration quality.

- Competitive limits for the search in the Sun have been produced.

- The limits for the Galactic Centre are the best amongst all indirect detection limits for WIMP masses above 30 TeV.

- All main results of this thesis have been published in two papers (Physics Letters B).