Indirect Searches For Dark Matter with the ANTARES Neutrino Telescope

Adrian Saina

asaina@km3net.de

May 26th, 2022

Motivation for WIMP Dark Matter

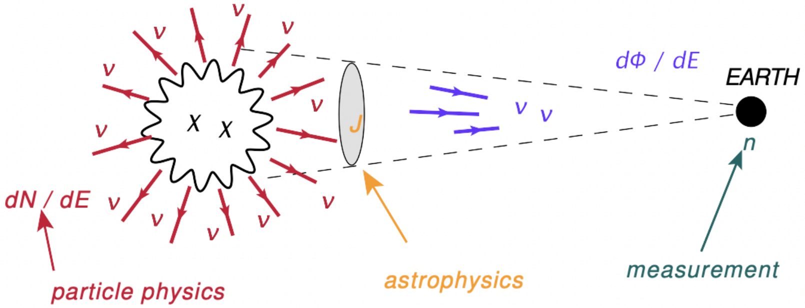
- Gravitational probes and cosmological observations provide hints on the properties of the dark matter particle: stable, neutral, complying with BBN and producing the observed relic abundance
- The observed relic abundance of dark matter can be reproduced via thermal production by a weakly interacting particle in the $\sim$ GeV-TeV mass range- a WIMP
- Heavier, secluded WIMPs are also of interest for indirect detection experiments

Dark Matter Detection

WIMPs annihilate/decay into Standard Model particles:

$$WIMP + WIMP \xrightarrow{annihilation} SM\ products \rightarrow \nu\bar{\nu}$$

Indirect searches are conducted with neutrino and gamma ray telescopes: search for excesses of events in regions where large amounts of dark matter accumulate



Astrophysical Sources of Dark Matter

Where to look for dark matter?

1. The Sun

- WIMPs scatter off nuclei in the Sun and get trapped in its gravitational potential
- Neutrinos that are produced can escape the dense solar medium
- Very little and well known background

2. The Galactic Center

- Assume a dark matter density profile for the Milky Way: Navaro-Frenk-White is the usual choice
- Describe the amount of dark matter with J-factor: integral of the (squared) dark matter density along the line of sight

From Neutrino Events to WIMP Cross-Sections

Neutrino telescopes measure the number of events, which translates to the number of WIMP annihilations

$$\frac{n}{t} = \frac{1}{2} < \sigma\nu > \int_0^{M_{WIMP}} \frac{dN}{dE} dE \frac{1}{4\pi} J_{NFW} \frac{1}{M_{WIMP}^2} \mathcal{A}(M_{WIMP})$$

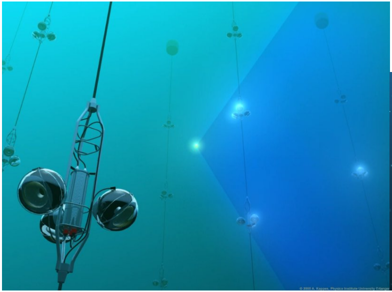
- Galactic Center searches can measure the thermally-averaged annihilation cross section
- The Sun: equilibrium between capture and annihilation$\rightarrow$ can put limits on the WIMP-nucleon scattering cross section

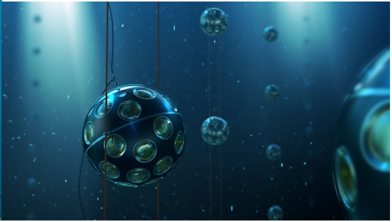
Neutrino Telescopes

- Operates by detecting Cherenkov radiation of leptons in the transparent detector medium
- Track-like and shower-like event topologies are produced by the associated lepton depending on the neutrino flavour
- ANTARES and KM3NeT are placed in the sea: background from bioluminescence and ^{40}K decays, along with atmospheric muons and neutrinos
- Use quality cuts to remove bioluminescence and noise
- To remove atmospheric muons, search for neutrinos below the horizon: detection of leptons produced by neutrinos passing through the Earth and scattering in the vicinity of the detector

ANTARES and KM3NeT

Photomultiplier tubes placed in Optical Modules, which are grouped in lines: ANTARES had 12 lines, with the KM3NeT ORCA and ARCA detectors currently having 10 and 8 lines each





ANTARES KM3NeT

Signal Identification

- Can use unbinned likelihood to determine the most likely number of signal events, n_s^*:

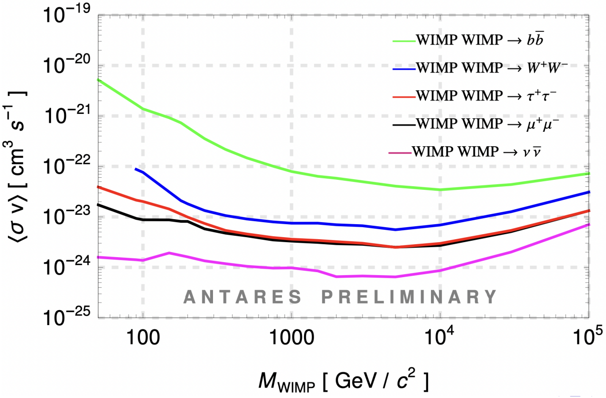
$$\mathcal{L} = \prod^{N_{tot}} n_s * P_s(\Psi, E) + n_{bg} * P_{bg}(\Psi, E)$$

$$TS = log[\frac{\mathcal{L}(n_s^*)}{\mathcal{L}(n_s = 0)}]$$

- A binned approach is used in dark matter searches towards the Sun: consists of finding optimum selection cuts and search cone around the source to minimize the flux sensitivity

Dark Matter in the Galactic Center

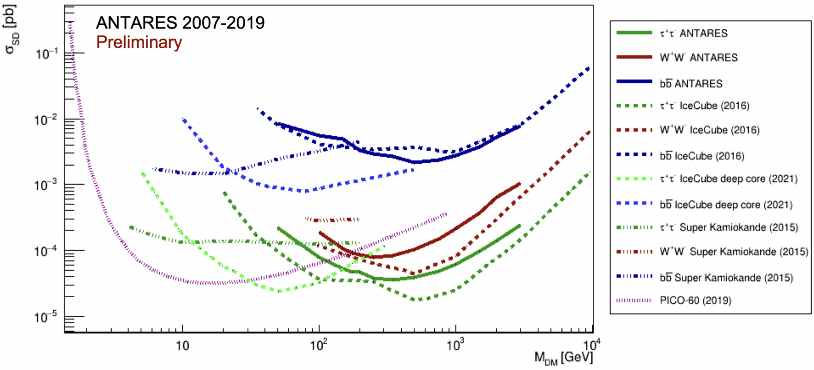
- An unbinned likelihood approach, considering both track-like and shower-like events, using 14 years of ANTARES data. (3845 days livetime, 11174 tracks, 225 showers) [3]
- Data is compatible with background, limits are set on $< \sigma\nu >$



Dark Matter in the Sun

Equilibrium between capture and annihilation: can obtain limits on WIMP-nucleon scattering cross sections, $\boldsymbol{\sigma_{SD}}, \sigma_{SI}$ [4]

$$\frac{d\Phi}{dE} = \frac{\Gamma}{4\pi d^2}\frac{dN_\nu}{dE_\nu} \qquad \Gamma = \frac{C}{2}$$



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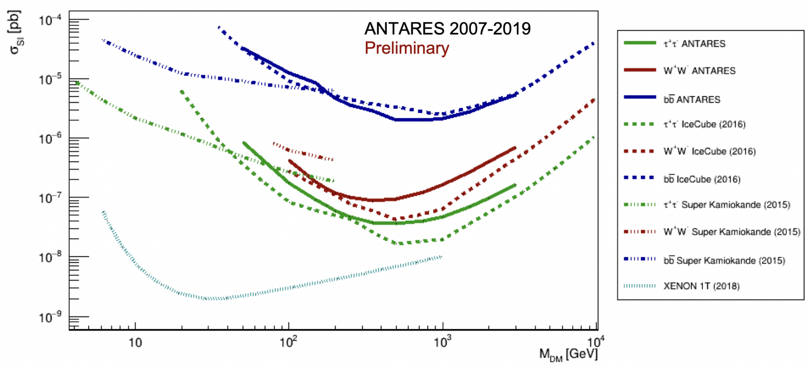
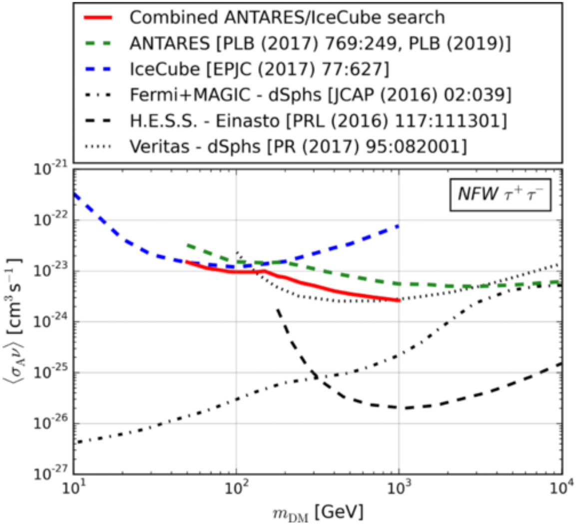


Combined Galactic Center Search with IceCube



A combined-likelihood search with a joint dataset: the unification of model parameters and likelihoods improves results in the 50 GeV- 1 TeV mass range by a factor of 2 [1]

Motivation for Secluded Dark Matter Searches

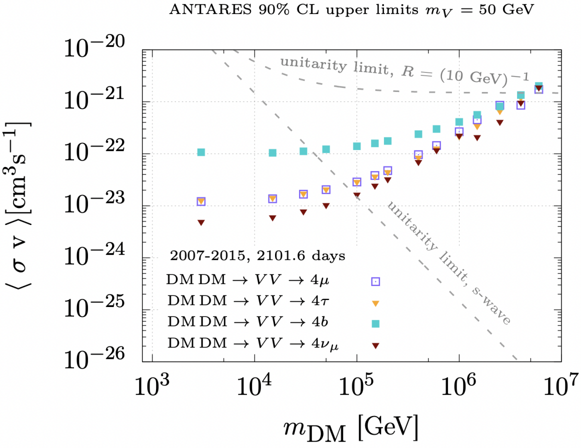
- WIMPs in the GeV-TeV range have so far avoided detection, making theoretical models of heavier WIMPs more interesting
- A heavier WIMP requires a mediator particle ($\tau < 0.1$ s) in order to evade the unitarity bound: secluded DM models

$$WIMP + WIMP \rightarrow V + V \qquad V + V \rightarrow 4\mu, 4\tau, 4b, 4\nu_\mu$$

- The energy scale of neutrinos is controlled by mediator mass $\rightarrow$ can use standard tools to obtain neutrino spectra such as PPPC4DMID which computes first order electroweak corrections for $m_V < 10$ TeV

Secluded Dark Matter Searches with ANTARES

- Unbinned likelihood search towards the Galactic Center [2]
- Tested dark matter masses 3 TeV$< m_{DM} <$ 6 PeV, and mediator masses: m_V = 50 **GeV**, 250 GeV, 1 TeV



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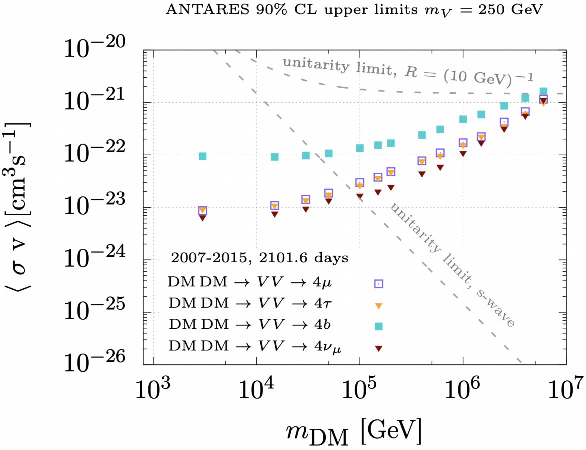

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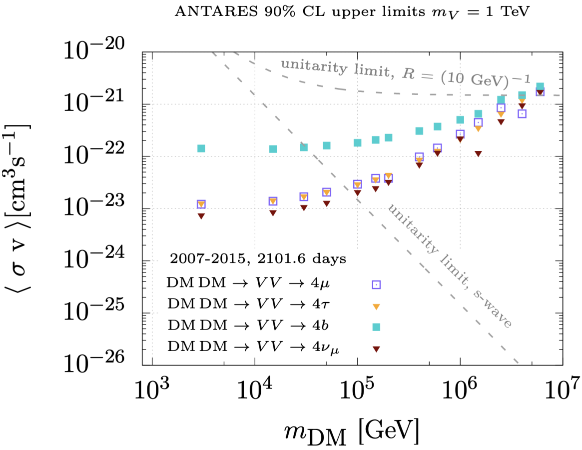

Conclusions

- ANTARES has stopped taking data on February 12th, 2022, 15 years after its deployment
- Legacy analysis: search for dark matter using the entire ANTARES dataset currently ongoing
- Throughout the 15 year period, competitive limits on the couplings of dark matter to the SM were set using different sources and testing a wide parameter space
- KM3NeT ARCA and ORCA are the ANTARES successors: the two detectors can search for dark matter candidates in a wider mass range
- Dark matter searches already being conducted with the current configurations

Thank you!

References

[1] A Albert et al. "Combined search for neutrinos from dark matter self-annihilation in the Galactic Center with ANTARES and IceCube". In: *Physical Review D* 102.8 (2020), p. 082002.

[2] A Albert et al. "Search for secluded dark matter towards the Galactic Centre with the ANTARES neutrino telescope". In: *arXiv preprint arXiv:2203.06029* (2022).

[3] Sara Rebecca Gozzini et al. "Indirect dark matter searches with neutrinos from the Galactic Centre region with the ANTARES and KM3NeT telescopes". In: *Journal of Instrumentation* 16.09 (2021), p. C09006.

[4] Chiara Poirè, ANTARES Collaboration, et al. "Indirect Dark Matter search towards the Sun with the ANTARES neutrino telescope". In: *Journal of Physics: Conference Series*. Vol. 2156. 1. IOP Publishing. 2021, p. 012039.

Backup

Dark Matter Searches in the center of the Earth

- Results of the search for dark matter towards the center of the Earth
- A binned approach, using 6 years of data