PROCEEDINGS OF SCIENCE

Dark matter searches in the centre of the Milky Way with IceCube

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Neutrino detectors, such as IceCube, can be used to perform indirect dark matter searches. Under the assumption that dark matter annihilates or decays, e.g. for the Weakly Interacting Massive Particles (WIMPs) scenarios, Standard Model particles are expected to be created by its annihilation or decay. These Standard Model particles could in turn produce neutrinos detectable by neutrino telescopes. As our Galaxy is believed to be embedded in a halo of dark matter whose density increases towards its centre, the Galactic Centre represents an ideal target for indirect searches, with the strongest dark matter annihilation signal at Earth being expected from this direction. In this contribution, the results of a dark search towards higher energies are presented, along with the sensitivities of a low energy indirect search for dark matter in the Galactic Centre, both using IceCube data. For the neutrino-line analysis, five years of IceCube data are considered to search for neutrinos from the annihilation and the decay of dark matter particles with masses between 10 GeV and 40 TeV. When considering the $\nu\bar{\nu}$ channel, this analysis provides the strongest limits on the thermally-averaged self-annihilation cross-section for masses below 1 TeV, as well as the leading lower limits in terms of dark matter decay lifetime from neutrino experiments. The second presented analysis is a low energy dark matter search using eight years of DeepCore data to probe dark matter masses ranging from 5 GeV to 1 TeV, for annihilation through $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^- and $b\bar{b}$. When considering dark matter annihilation into $\tau^+\tau^-$, the sensitivities on the thermally-averaged dark matter self-annihilation cross-section achieved by this analysis demonstrate an improvement by an order of magnitude over previous searches with IceCube and other neutrino telescopes, with $\langle\sigma_A v\rangle = 3.25 \times 10^{-24}\text{cm}^3\text{s}^{-1}$ at 10 GeV for the Navarro-Frenk-White halo profile.

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1. Introduction

Indirect dark matter (DM) searches can be conducted with large volume neutrino detectors. Under the assumption that DM particles annihilate or decay, such as for Weakly Interacting Massive Particles(WIMPs) [1], standard model (SM) particles are expected to be created in their annihilation or decay. These SM particles could in turn yield stable particles such as neutrinos. The DM searches presented in this proceeding used data from the IceCube neutrino telescope, which is a cubic-kilometre detector buried in the South Pole ice sheet between depths of 1,450 m and 2,450 m [2]. In this contribution, two DM searches using data from the DeepCore sub-detector [3], which is located at the centre of IceCube, are presented. The first analysis focuses on the search for neutrino line signatures from DM annihilation or decay, while the second analysis targets DM annihilation at low energies, both looking at the Galactic Centre (GC).

2. Dark matter phenomenology

The expected differential neutrino flux from DM annihilation can be evaluated from:

$$\left(\frac{\mathrm{d}\phi_\nu}{\mathrm{d}E_\nu}\right)_{\mathrm{ann}} = \frac{1}{4\pi}\,\frac{\langle\sigma_\mathrm{A}\upsilon\rangle}{2\,m_{\mathrm{DM}}^2}\,\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_{\Delta\Omega}\mathrm{d}\Omega(\Psi)\int_{\mathrm{l.o.s}}\rho_{\mathrm{DM}}^2\left(r(l,\Psi)\right)\,\mathrm{d}l\,, \tag{1}$$

where m_{DM} is the mass of the DM particles, ρ_{DM} is the DM density and $\langle\sigma_\mathrm{A}\upsilon\rangle$ is the thermally-averaged self-annihilation cross-section. The integral term of the equation is commonly referred to as the J-factor and consists of the integral over the solid angle, Ω, and the line-of-sight, l, of the squared DM density. Similarly, the differential neutrino flux from DM decay can be expressed as:

$$\left(\frac{\mathrm{d}\phi_\nu}{\mathrm{d}E_\nu}\right)_{\mathrm{dec}} = \frac{1}{4\pi}\,\frac{1}{\tau_{\mathrm{DM}}\,m_{\mathrm{DM}}}\,\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_{\Delta\Omega}\mathrm{d}\Omega(\Psi)\int_{\mathrm{l.o.s}}\rho_{\mathrm{DM}}\left(r(l,\Psi)\right)\,\mathrm{d}l\,, \tag{2}$$

where τ_{DM} is the DM lifetime and the integration over the DM density is known as the D-factor. The term $\mathrm{d}N_\nu/\mathrm{d}E_\nu$ refers to the number of neutrinos produced at a given energy E_ν per annihilation or decay, respectively. Both DM searches presented in this proceeding consider neutrino spectra taken from the PPPC4 tables [4], which take into account electro-weak corrections according to [5]. In order to make up for the uncertainty on the shape of the DM halo, both a "cuspy" and a "cored" DM halo profiles are considered in the two analyses, i.e. the Navarro-Frenk-White (NFW) [6] and the Burkert [7] profiles, respectively.

3. Search for neutrino lines from DM annihilation and decay with IceCube

Five years of IceCube data recorded from 2012 to 2016 are used for this search for neutrinos from DM annihilation or decay in the GC. As mentioned previously, this search focuses on neutrino line signal signatures from annihilation and decay of DM into the neutrino channel, under the 1:1:1 flavour assumption denoted as $\nu\bar{\nu}$. For such scenarios, the neutrino spectra would ideally, if no radiative corrections were considered, consist of a δ-function with $E_{\mathrm{DM}} = m_{\mathrm{DM}}$ and $E_{\mathrm{DM}} = m_{\mathrm{DM}}/2$, respectively. Therefore, the event selection focuses on DeepCore cascade events, which present a better energy resolution than track-like events. Cascade events originate from the neutral-current

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interaction of all neutrino flavours, as well as the charged-current interaction of electron and tau neutrinos for the energy range relevant to this analysis, while track events are created by the charged-current interaction of muon neutrinos. As the GC is located above the horizon of IceCube ($\delta_{\rm GC} \sim -29°$), a veto is required in order to reduce the background contribution from atmospheric muon when looking at the centre of our Galaxy. Selecting events passing the DeepCore filter allows a considerable reduction of atmospheric background. The final event selection is divided into two separate event selections developed using Boosted Decision Trees (BDTs). For the low energy sample, the BDT was trained with a soft neutrino spectrum as a benchmark signal (100 GeV DM annihilating into $b\bar{b}$), while for the high energy sample, a harder spectrum is considered (300 GeV DM annihilating through W^+W^-).

A binned likelihood method is applied to this event selection in order to search for an excess of signal neutrino in the direction of the GC. This method compares the data distribution to what is expected from the background and signal distributions. The likelihood function is defined as the product of the Poisson probabilities to observe $n^i_{\rm obs}$ events in bin i:

$$\mathcal{L}(\mu) = \prod_{i=min}^{max} \frac{\left(n^{\rm tot}_{\rm obs}\, f^i(\mu)\right)^{n^i_{\rm obs}}}{n^i_{\rm obs}!} e^{-n^{\rm tot}_{\rm obs}\, f^i(\mu)} , \tag{3}$$

with $n^{\rm tot}_{\rm obs}$ being the total number of events in the sample and $\mu \in [0, 1]$ corresponding to the fraction of signal events in the total sample. The fraction of events within a specific bin i is given by:

$$f^i(\mu) = \mu\, f^i_s \;+\; (1-\mu)\, f^i_{\rm bg} . \tag{4}$$

where $f_{\rm bg}$ is the background PDF and $f_{\rm sig}$ is signal PDF. Under the assumption that the atmospheric background is uniform in right ascension (RA), the background PDFs can be estimated by scrambling data in RA. The signal PDFs are obtained from simulations weighted accordingly to Equation 1 and Equation 2 for DM annihilation and decay, respectively. The shape of the signal PDFs relies on the choice of DM mass, the annihilation or decay channel, and the halo profile. A total of 19 masses ranging from 10 GeV to 40 TeV are considered in this analysis. Although focusing on the neutrino channel, i.e. $\nu\bar{\nu}$, this DM search also considers annihilation and decay into $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^- and $b\bar{b}$, for both the NFW and Burkert halo profiles.

To account for potential signal contamination in the scrambled data distribution, such as $f_{\rm scr.data} = (1-\mu) f_{\rm BG} + \mu f_{\rm scr.sig}$, a signal contamination likelihood can be used. In the case of signal subtraction, the fraction of events within bin i can be rewritten as:

$$f^i(\mu) = \mu\, f^i_{\rm sig} + f^i_{\rm scr.data} - \mu f^i_{\rm scr.sig} , \tag{5}$$

where $f_{\rm scr.data}$ is the background PDF obtained from scrambled data and $f_{\rm scr.sig}$ is the scrambled signal PDF. The best estimate on the signal fraction, $\mu_{\rm best}$, is obtained by maximising the likelihood function. If this value is consistent with the background-only hypothesis, an upper limit on the signal fraction at the 90% confidence level (CL), $\mu_{90\%}$, can be drawn using the likelihood interval method [8]. These limits can then be re-expressed in terms of $\langle\sigma_{\rm A} v\rangle$ using the total number of observed events in the sample, as well as the estimated number of events for a specific combination of DM mass, annihilation channel and halo profile.

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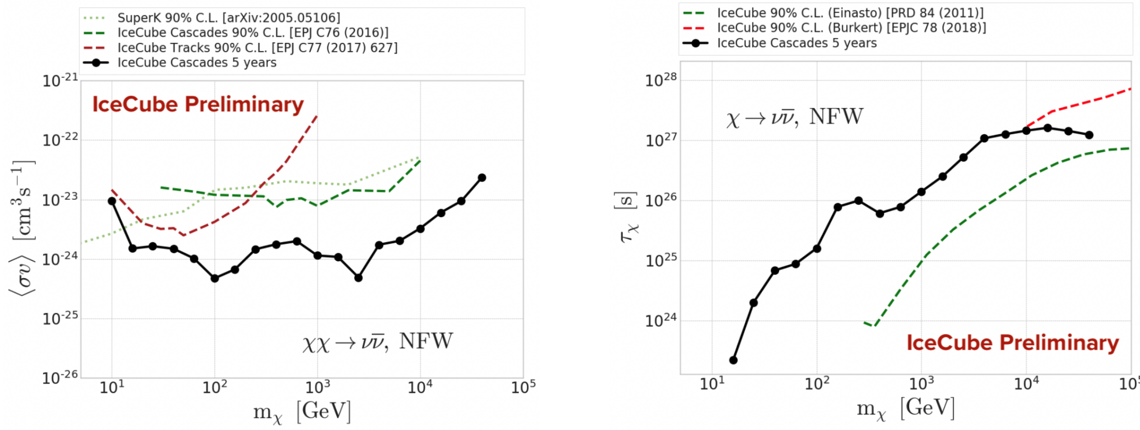

Figure 1: 90% CL limits on the $\langle\sigma_A v\rangle$ as a function of the DM mass for DM annihilation (left) and decay (right) for the $\nu\bar{\nu}$ channel, assuming the NFW halo profile, shown along previous limits from IceCube [9–12] and Super-Kamiokande [13].

No significant excess of neutrino over the background was found after unblinding. As a result, upper limits on the thermally-averaged DM self-annihilation cross-section, as well as lower limits on the DM decay time were computed for all the DM signal combinations considered. These limits are shown in Figure 1 for both DM annihilation (left) and decay (right) into the $\nu\bar{\nu}$ channel, assuming the NFW halo profile. These two plots show an improvement of the limits on $\langle\sigma_A v\rangle$ and τ_{DM} with respect to previous IceCube [9–12] and Super-Kamiokande [13] results.

4. Low energy dark matter search with eight years of IceCube data

For this DM search, 8.03 years of IceCube data taken from 2012 to 2020 are considered. A preexisting event selection initially developed for atmospheric neutrino oscillation measurements, called oscNext, is used. In particular, this event selection focuses on low-energy events starting in the DeepCore fiducial volume and originating from all neutrino flavours. Two of the cuts applied for the official oscNext event selection were removed for this analysis. The first of these cuts consisted of removing all down-going events from the sample, including events coming from the GC, while the second cut restricted the energy range to events with energies below 100 GeV.

The analysis method applied for this analysis is identical to the one presented for the neutrino-line search, with the exception that no signal subtraction is required as the background PDF is here built from MC simulations instead of scrambled data. More precisely, the background PDF is built from MC simulated muons and neutrinos weighted with the expected atmospheric flux. The signal PDFs are also obtained from generic neutrino simulations weighted with the source morphology and the neutrino spectrum according to Equation 1. The 90% CL sensitivity is evaluated from a sample of 100,000 pseudo-experiments generated from the background-only PDF and consists of the median value of the upper limits obtained for each of these pseudo-experiments.

For each of the possible combinations of DM mass, annihilation channel and halo profile, a distinct signal PDF is computed. This search probe DM particles with masses ranging from 5 GeV to 8 TeV and annihilating through either $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, W^+W^-, $\mu^+\mu^-$ $\tau^+\tau^-$, or $b\bar{b}$, with a

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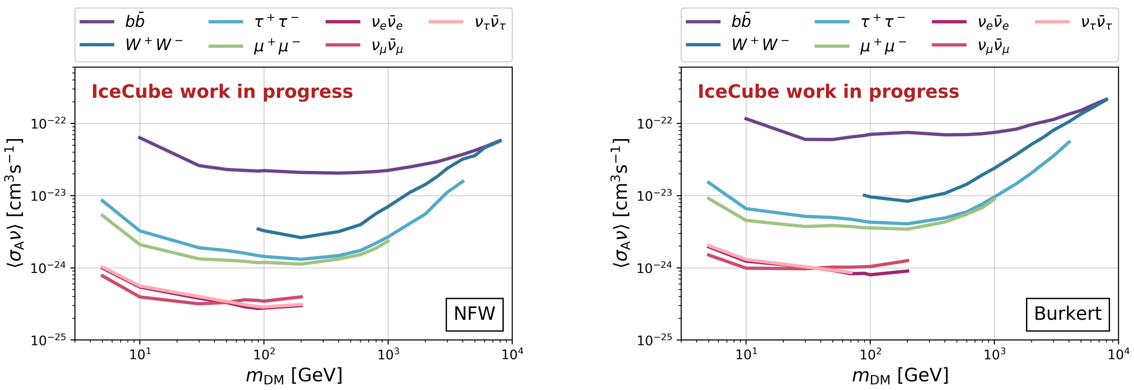

Figure 2: 90% CL sensitivities on $\langle\sigma_A \upsilon\rangle$ as a function of the DM mass for all the considered annihilation channels and both the NFW (left) and Burkert (right) halo profiles.

100% branching ratio. These particular channels are selected to cover a wide range of spectral shapes, with the softest spectrum given by $b\bar{b}$ and the hardest spectra given by the $\nu_i\bar{\nu}_i$ channels, with i indicating the flavour of neutrino. Both the NFW and the Burkert halo profile distributions are considered. In the case of the neutrino channels, $\nu_i\bar{\nu}_i$, DM masses above 200 GeV are not scanned as the signal peaks at energies outside the energy response of the detector. In order to avoid this specific case, we introduce a cut restricting the possible parameter combinations. For each combination of DM mass, annihilation channel and halo profile, the weighted median of the distribution in reconstructed energy, E_{reco}, is computed. In the case where the resulting median fall above the upper bound of the region containing 95% of the background, the corresponding signal combination is discarded, such as for masses above 200 GeV for DM annihilation through $\nu_i\bar{\nu}_i$.

In order to conduct this low-energy DM search, three-dimensional PDFs are used, which include the angular information alongside information about the energy and the neutrino flavour of the event. The three dimensions of the PDFs are the opening angle to the GC (Ψ_{reco}), the energy ($\log_{10}(E_{\mathrm{reco}})$) and the reconstructed neutrino flavour, under the form of the particle ID (PID). The binning in PID is chosen to optimise the separation between track-like and cascade-like events, with three bins divided as [0, 0.5, 0.85, 1]. PID values close to zero hint that the event is cascade-like, while values close to 1 suggest a track-like event. A Kernel Density Estimation (KDE) is applied in order to obtain smooth background and signal distributions, as well as to avoid empty bins in the background PDF. This KDE method is applied on the two-dimensional distributions of the events in Ψ_{reco} and E_{reco} for each bin in PID separately. The resulting distributions are then binned to obtain the three-dimensional histograms used in the binned likelihood method.

The 90% CL sensitivities on the thermally-averaged DM self-annihilation cross-section, $\langle\sigma_A \upsilon\rangle$, obtained for this analysis are shown in Figure 2 for both the NFW (left) and Burkert (right) halo profiles. These plots show the 90% CL sensitivities for all the combinations of DM masses and annihilation channels. The sensitivities obtained for this low-energy search show considerable improvement over previous IceCube results [10], with up to two orders of magnitude for the lowest DM masses. This is visible in Figure 3, where the sensitivity obtained for the $\tau^+\tau^-$ annihilation channel and the NFW halo profile is shown alongside previous IceCube results, as well as the latest ANTARES limit [14].

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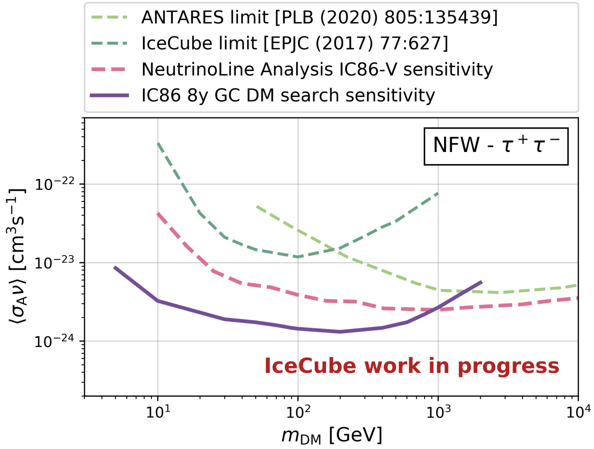

Figure 3: 90% CL sensitivity on $\langle\sigma_A v\rangle$ from the low-energy DM search and 90% CL limit from the neutrino line search for DM annihilation through $\tau^+\tau^-$ assuming the NFW profile, shown along previous limits from IceCube [10] and ANTARES [14].

5. Conclusion and outlooks

We discussed two distinct DM searches, a search for neutrino-line signatures, for which results are presented, and a low-energy search, for which sensitivities are shown. The results of the first neutrino-line oriented analysis using both the energy and spatial information show no significant excess of neutrino over the background. Therefore, upper (lower) limits are set on the thermally-averaged DM annihilation cross-section (DM decay lifetime). These limits show a large improvement over previously set limits, especially for energies below 1 TeV. The sensitivities obtained for the low-energy DM search also present a non-negligible improvement over the previous IceCube results, with up to two orders of magnitude improvement at the lowest energies. These sensitivities are already better than the limits obtained by the neutrino-line analysis for energies below 1 TeV, making them the best sensitivities from neutrino experiments at these energies. This offers future prospects for discovery or stronger bounds.

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