A Search for Decaying Dark Matter in Galaxy Clusters and Galaxies

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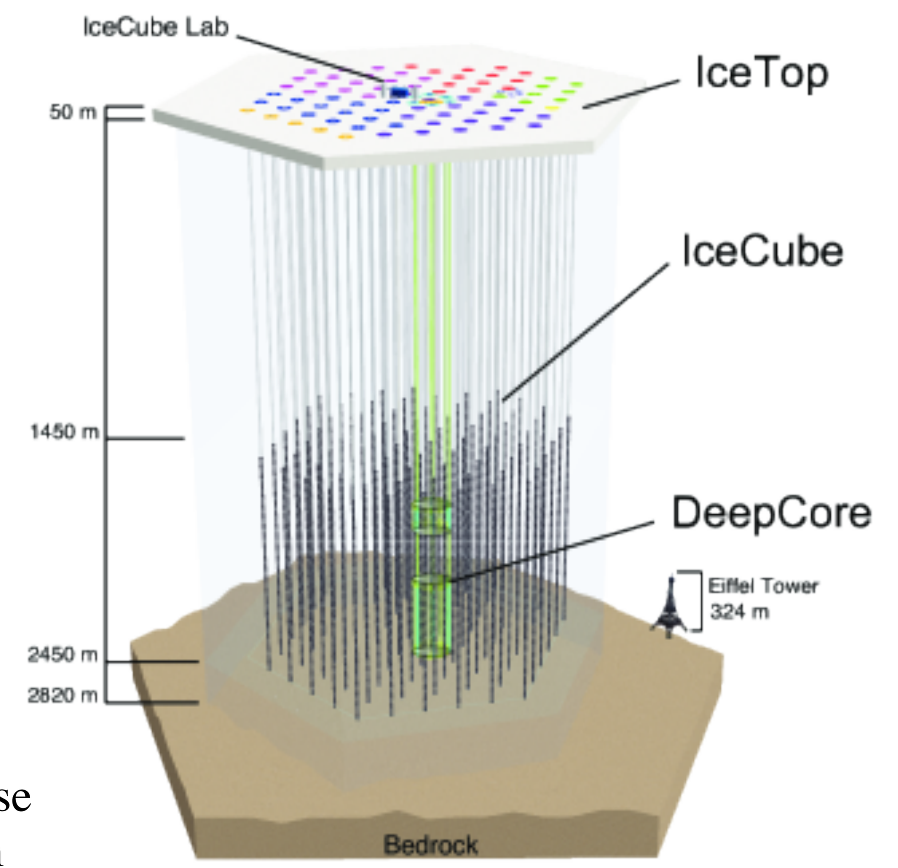
Abstract

The observed dark matter abundance in the Universe can be explained with non-thermal, heavy dark matter models. In order for dark matter to still be present today, its lifetime has to far exceed the age of the Universe. In these scenarios, dark matter decay can produce highly energetic neutrinos, along with other Standard Model particles. To date, the IceCube Neutrino Observatory is the world's largest neutrino telescope, located at the geographic South Pole. In 2013, the IceCube collaboration reported the first observation of high-energy astrophysical neutrinos. Since then, IceCube has collected a large amount of astrophysical neutrino data with energies up to tens of PeV, allowing us to probe the heavy dark matter models using neutrinos. We search the IceCube data for neutrinos from decaying dark matter in galaxy clusters and galaxies. The targeted dark matter masses range from 10 TeV to 10 PeV. In this contribution, we present the method and sensitivities of the analysis.

Introduction

- Decaying heavy dark matter, which was non-thermally produced in the early Universe and has a longer lifetime than the age of the Universe, is a well motivated candidate for dark matter [1].
- The IceCube Neutrino Observatory is a cubic-kilometer scale neutrino telescope, located at the geographic South Pole.
- IceCube consists of 86 strings, each equipped with 80 Digital Optical Modules (DOMs).
- The DOMs measure the Cherenkov radiation from charged particles produced by neutrino interactions with the ice nuclei.
- High-energy astrophysical neutrinos with energies up to ~10 PeV have been observed in IceCube [2-4].
- Theoretical studies suggest that some of these astrophysical neutrinos could originate from the decay of dark matter particles [5-7].



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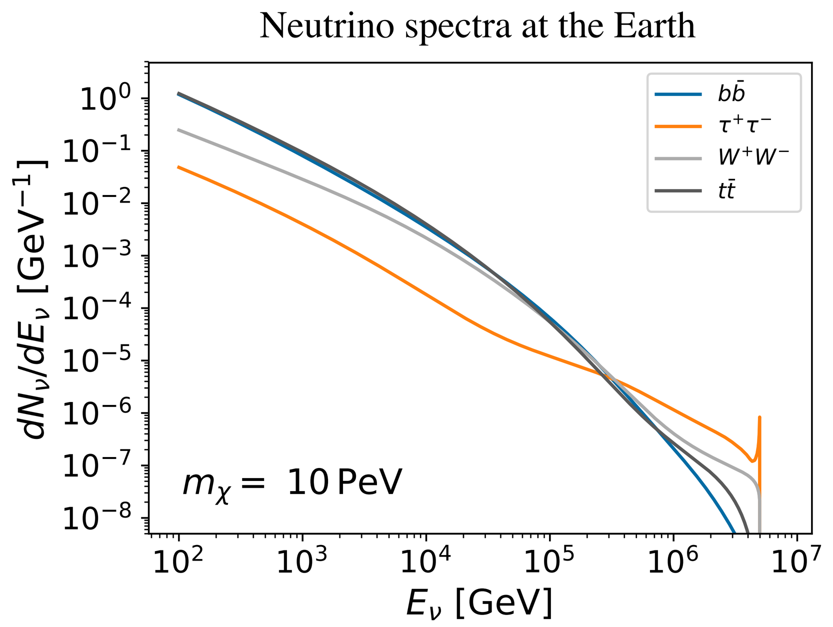
Signal and Background

The differential neutrino flux from the decay of dark matter particles in an astrophysical source is as below:

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu) = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN_\nu}{dE_\nu}(E_\nu)\int_0^{\Delta\Omega} d\Omega \int_0^\infty \rho_\chi(l\hat{n})dl,$$

with m_χ being the dark matter mass, τ_χ the dark matter lifetime, $\hat{n}$ the direction of the line-of-sight, and dN_ν/dE_ν the differential neutrino spectrum per dark matter particle decay.



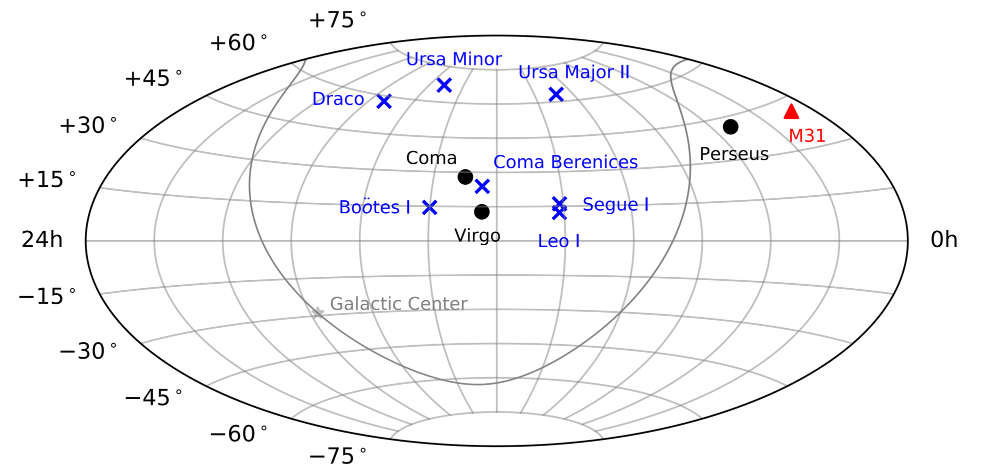
The spectrum is calculated assuming that dark matter decays into a pair of Standard Model particles with a branching ratio of 100%.

In this analysis, galaxy clusters, dwarf galaxies, and the Andromeda galaxy are used as targets. We adopt the models for dark matter halos of various sources presented in [8-10]. Then we evaluate the integral of the equation above, referred to as D-factor, for each of the sources with $\Delta\Omega = 2\pi\cos\theta$, where θ is the angular distance from the center of the source. After that, the sources with maximum D-factors over 10^{18} GeV/cm² and in the Northern Sky are selected. The locations of the targets are shown in the skymap below, together with the Galactic Center and Galactic Plane.

Properties of the targets

Source	Type	RA[°]	Dec [°]	θ_{max} [°]	D_{max} $[GeV/cm^2]$
Virgo	galaxy cluster	186.63	12.72	6.11	2.54×10^{20}
Coma	galaxy cluster	194.95	27.94	1.30	1.49×10^{19}
Perseus	galaxy cluster	49.94	41.51	1.35	1.44×10^{19}
Andromeda	galaxy	10.68	41.27	8.00	1.70×10^{20}
Draco	dwarf galaxy	260.05	57.92	1.30	1.54×10^{19}
Leo I	dwarf galaxy	152.12	12.3	0.45	1.19×10^{18}
Ursa Minor	dwarf galaxy	227.28	67.23	1.37	1.41×10^{18}
Boötes I	dwarf galaxy	210.03	14.5	0.47	1.46×10^{18}
Coma Berenices	dwarf galaxy	186.74	23.9	0.31	1.53×10^{18}
Segue 1	dwarf galaxy	151.77	16.08	0.35	2.05×10^{18}
Ursa Major II	dwarf galaxy	132.87	63.13	0.53	5.23×10^{18}

Locations of the targets



Backgrounds include the atmosphere muons and neutrinos, and the isotropic astrophysical neutrinos. The distribution of background events is estimated using experimental data.

Data Sample and Statistical Methods

We use a subset of the all-sky track-like event sample established for point-like source searches [11]. Among the 10 years of data, we use the last 6 years, recorded from 2012 to 2018.

We perform a hypothesis test, using the test statistic defined as

$$\lambda = -2\log\frac{\mathscr{L}(n_s = 0)}{\mathscr{L}(\hat{n}_s)}.$$

(n_s: number of expected signal events, $\hat{n}_s$: best-fit value of n_s)

The likelihood function is defined as the following:

$$\mathscr{L}(n_s) = \prod_{i=1}^{N}\left[\frac{n_s}{N}S(\alpha_i,\delta_i,\sigma_i,E_i|n_s) + \left(1-\frac{n_s}{N}\right)B(\alpha_i,\delta_i,\sigma_i,E_i|n_s)\right].$$

(S, B : signal, background PDFs, i : event index, α, δ : reconstructed RA, Dec, σ : angular uncertainty, N: number of observed events, E: reconstructed neutrino energy)

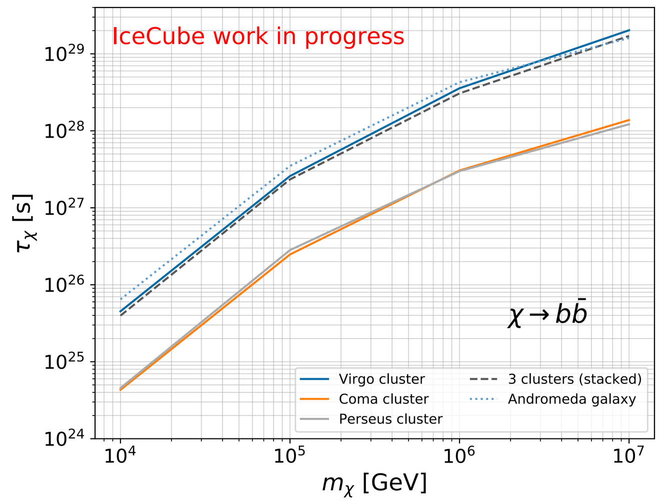
We calculate the sensitivity of the analysis, at 90% C.L., on the expected number of signal events using the Neyman method [12]. This number is converted to the sensitivity on the dark matter decay lifetime using the following equation:

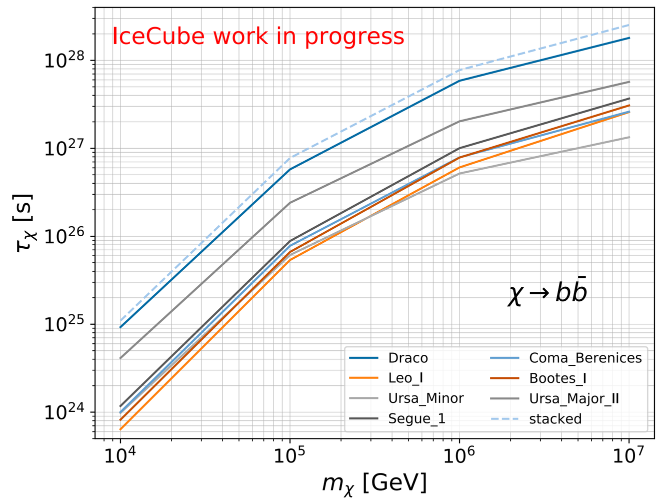
$$n_s = T_{live}\int_0^{\Delta\Omega} d\Omega \int_{E_{min}}^{E_{max}} dE_\nu A_{eff}(\hat{n},E_\nu)\frac{d\Phi_\nu}{d\Omega dE_\nu}(\hat{n},E_\nu),$$

(T_{live}: detector livetime, A_{eff} : effective area, E_{min}, E_{max} : min., max. of the expected neutrino energy)

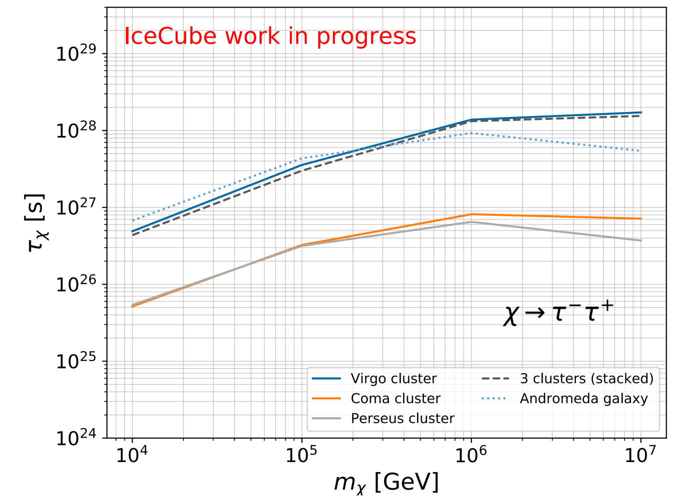
Sensitivities

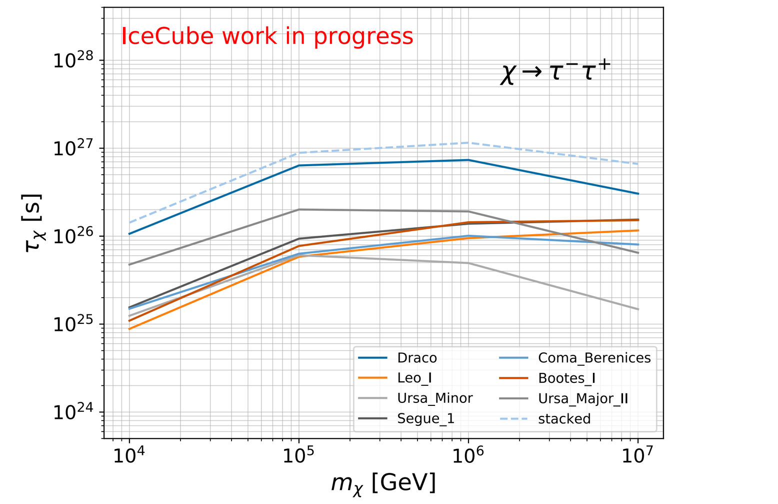
The right panels show the 90% C.L. sensitivities of the analysis for the $b\bar{b}$ channel. The top plot shows the sensitivities for the galaxy clusters and the Andromeda galaxy. The solid lines represent the sensitivities for the individual sources, while the dashed line is for stacking the three galaxy clusters. The second plot shows the sensitivities for the seven dwarf galaxies (solid lines) and those obtained after stacking all of the dwarf galaxies (dashed line). It can be seen that the Virgo cluster and the Andromeda galaxy are the most promising sources. Also, the sensitivities obtained by the stacking are not better than those for the best sources.

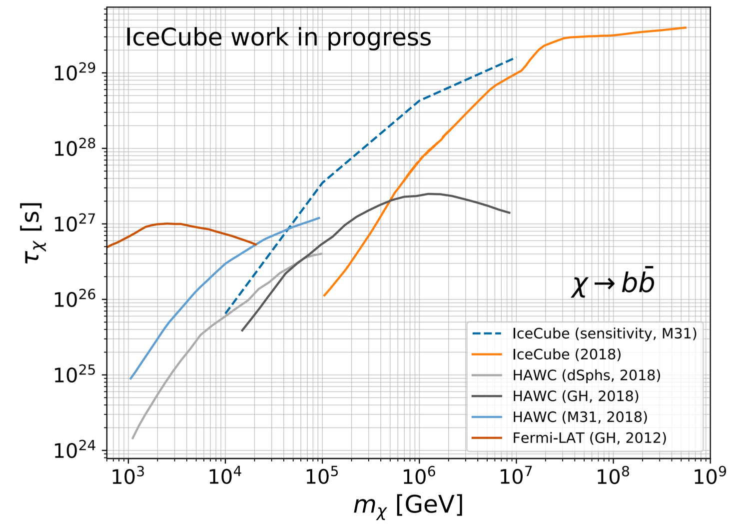




The two panels below show the sensitivities for the $\tau^+\tau^-$ channel. Similar tendencies are observed as for the case of the $b\bar{b}$ channel. Note that the sensitivities do not keep increasing with increasing dark matter mass, for some sources. This is due to the opacity of the Earth that increases with the source declination and neutrino energy.







The plot on the left side shows a comparison of our sensitivities and the observed limits from other decaying dark matter searches. The dashed line represents the sensitivities of this analysis for the Andromeda galaxy and the $b\bar{b}$ channel. The solid lines are the limits from different experiments [13-17] obtained assuming the same dark matter decay channel. It can be seen that the sensitivities calculated for this analysis are competitive with other experiments.

Conclusions and Outlook

- We calculated the sensitivities of the analysis, at 90% C.L., for the $b\bar{b}$, $\tau^+\tau^-$ channels for dark matter masses between 10 TeV and 10 PeV.
- The sensitivities for the Virgo cluster and the Andromeda galaxy are competitive with other leading experiments.
- We plan to study other dark matter decay channels. Sources in the Southern Sky could be included in the list of targets.