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Search for Decaying Dark Matter in Galaxy Clusters and Galaxies with IceCube

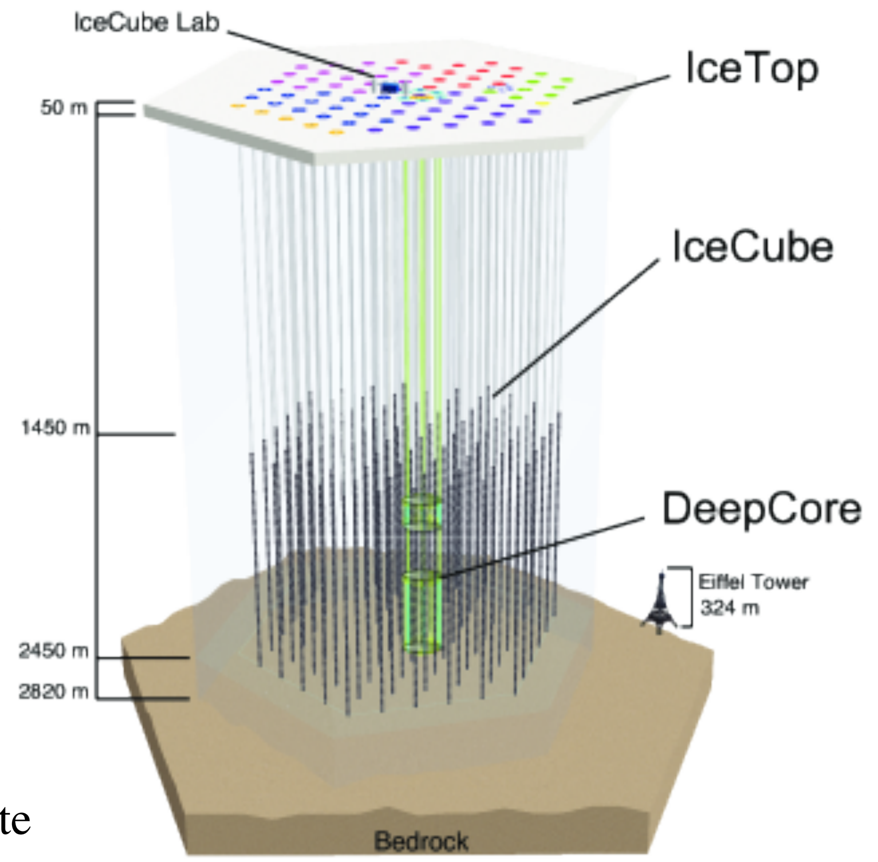
Minjin Jeong on behalf of the IceCube Collaboration
Department of Physics, Sungkyunkwan University, Suwon 16419, South Korea

Abstract

The inferred abundance of dark matter in the Universe could be explained with heavy decaying dark matter. According to heavy dark matter models, the decay of dark matter in astronomical objects can produce highly energetic neutrinos detectable at the Earth. The IceCube Neutrino Observatory, located at the geographic South Pole, is to date the world's largest neutrino telescope. Over the past decade, a large amount of high-energy astrophysical neutrino events were observed with this detector, allowing us to test the heavy decaying dark matter hypotheses. We search IceCube data for neutrinos from dark matter decay in galaxy clusters, dwarf satellite galaxies of the Milky Way, and the Andromeda galaxy. The analysis uses a 9-year sample of upward-going track events. Sensitivities obtained with our analysis are compared for individual sources in the northern sky and stacked multiple targets. We focus on heavy dark matter with masses between 10 TeV and 10 PeV,, decaying into a pair of Standard Model particles. The analysis covers energies around 10 TeV where multiple theoretical works have claimed inclusion of dark matter contribution would improve fits of the diffuse astrophysical neutrino spectrum.

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 [5-6].



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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:

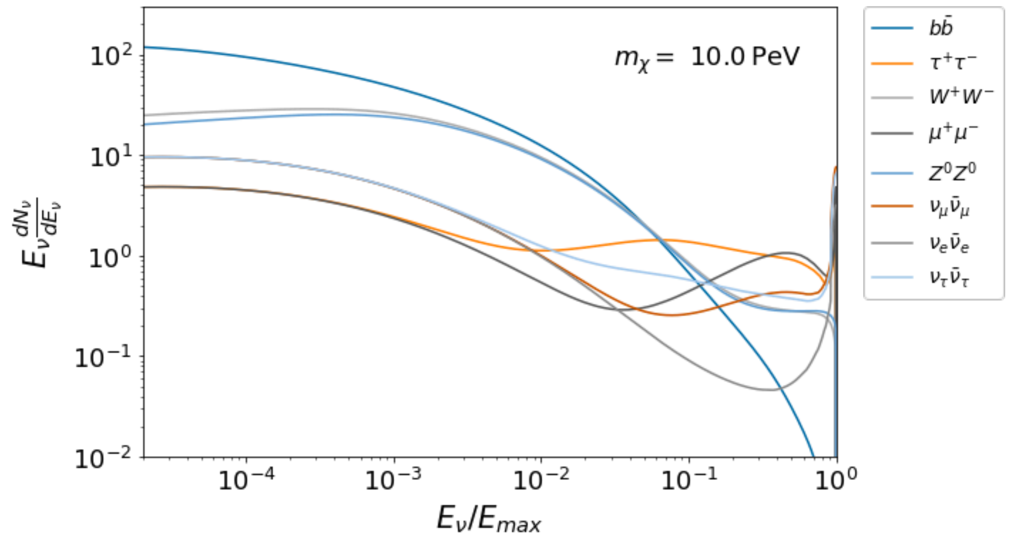
$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu) = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN_\nu}{dE_\nu}(E_\nu)D, \qquad D = \int_0^{\Delta\Omega} d\Omega \int_0^{\infty} \rho_\chi(\hat{n}l)dl,$$

with m_χ being the dark matter mass, τ_χ the dark matter lifetime, and dN_ν/dE_ν the differential neutrino spectrum per dark matter particle decay. D is called D-factor and is calculated by integrating dark matter mass density along the line of sight ($\hat{n}$) and over the view angle ($\Delta\Omega$).

The differential neutrino spectrum is calculated using the $\chi arov$ software package [7]. We assume that dark matter decays into a pair of Standard Model particles with a branching ratio of 100%. The software takes into account neutrino oscillation and electroweak corrections.

In the analysis, 3 galaxy clusters, 7 dwarf galaxies, and the Andromeda galaxy are used as targets. We adopt the models for dark matter halos of these sources presented in [8-10]. Their D-factors are calculated up to the angular distances from their centers, θ_{max}, where $D(\theta)$ saturates. These targets have D-factors over 10^{18} GeV/cm² and are located in the northern sky. The D-factors and the distribution of D-factors, as function of RA and Dec, are calculated using the CLUMPY software package [11].

The analysis background includes atmosphere muons, conventional atmospheric neutrinos, and the diffuse astrophysical neutrino flux. The distribution of background events is estimated from experimental data.



Neutrino spectra expected at the Earth

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}
Ursa Major II	dwarf galaxy	132.87	63.13	0.53	5.23×10^{18}
Segue 1	dwarf galaxy	151.77	16.08	0.35	2.05×10^{18}
Coma Berenices	dwarf galaxy	186.74	23.9	0.31	1.53×10^{18}
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Boötes I	dwarf galaxy	210.03	14.5	0.47	1.46×10^{18}
Ursa Minor	dwarf galaxy	227.28	67.23	1.37	1.41×10^{18}
Leo I	dwarf galaxy	152.12	12.3	0.45	1.19×10^{18}

The selected targets and their properties (presented in [12])

Data Sample and Statistical Methods

We use a 9-year sample of upward-going track-like events established for point-like source searches [13]. The sample has a very high neutrino purity and good angular resolution.

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

$$\lambda = -2\log\frac{\mathscr{L}(n_s=0)}{\mathscr{L}(\hat{n}_s)}. \qquad \left(\begin{array}{l} n_s\text{: number of expected signal events} \\ \hat{n}_s\text{: best-fit value of } n_s \end{array}\right)$$

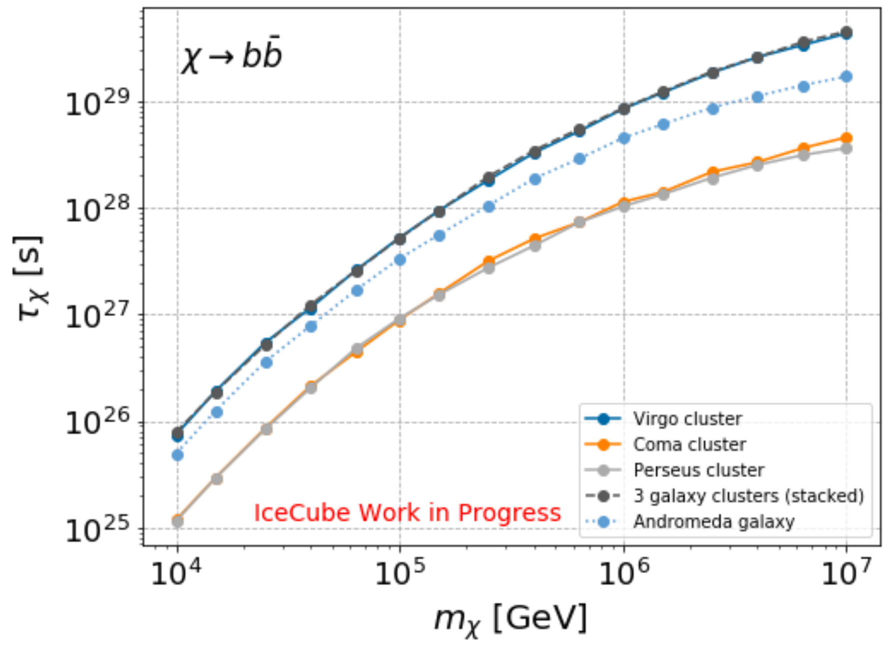
The likelihood function is defined as the following:

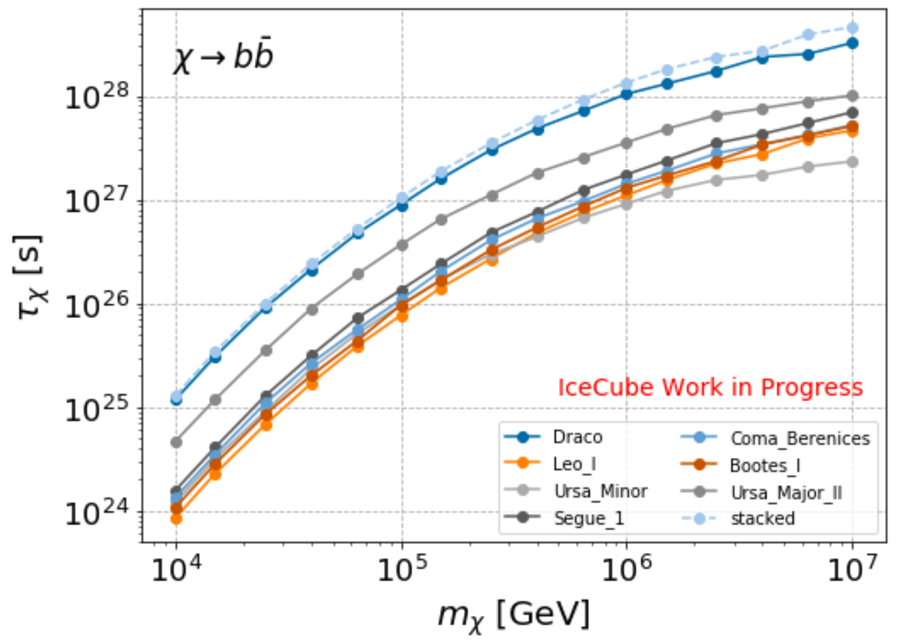
$$\mathscr{L}(n_s) = \prod_{i=1}^{N}\left[\frac{n_s}{N}S(\alpha_i,\delta_i,\sigma_i,E_i|n_s) + \left(1-\frac{n_s}{N}\right)B(\alpha_i,\delta_i,\sigma_i,E_i|n_s)\right]. \qquad \left(\begin{array}{l} S,\ B\text{: signal, background PDFs,} \quad i\text{: event index,} \\ \alpha,\ \delta\text{: reconstructed RA, Dec,} \quad \sigma\text{: angular uncertainty,} \\ N\text{: number of observed events,} \\ E\text{: reconstructed neutrino energy} \end{array}\right)$$

We calculate the sensitivity of the analysis, at 90% C.L., to the expected number of signal events using one-sided intervals. This number is converted to the sensitivity to the dark matter lifetime using the equation below:

$$n_s = T_{live}\int_0^{\Delta\Omega} d\Omega \int_{E_{min}}^{E_{max}} dE_\nu A_{eff}(\hat{n},E_\nu)\frac{d\Phi_\nu}{d\Omega dE_\nu}(\hat{n},E_\nu), \qquad \left(\begin{array}{l} T_{live}\text{: detector livetime,} \quad A_{eff}\text{: effective area} \\ E_{min},\ E_{max}\text{: min., max. of the expected neutrino energy} \end{array}\right)$$

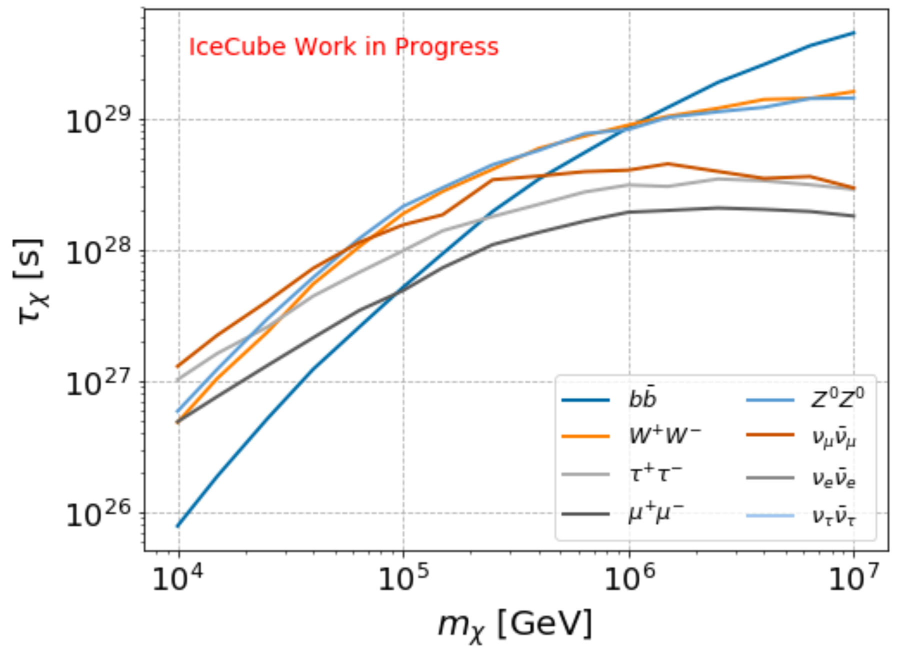
Sensitivities

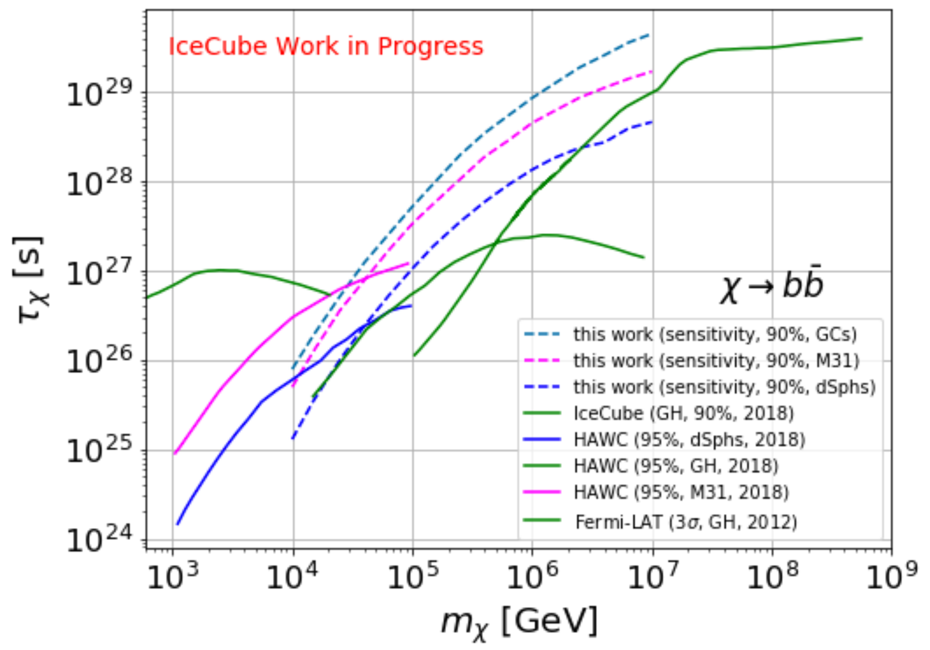




The plots above show the sensitivities of the analysis calculated for the $b\bar{b}$ channel. The sensitivities have been calculated at 90% C.L. without systematic uncertainties. In the left panel, the solid lines represent the sensitivities for the individual galaxy clusters, and the dashed line is for the stacking of the three clusters. The dotted line is for the Andromeda galaxy. The right panel shows the sensitivities for the individual and stacked dwarf galaxies.

It is shown that stacking targets does not improve sensitivities dramatically. However, the stacking method could reduce the impact of uncertainties on the D-factors.





The left panel in the above figure presents the sensitivities obtained by stacking the three galaxy clusters. The right panel compares the sensitivities of the presented analysis (dashed lines) to the observed limits from recent indirect dark matter searches (solid lines) [14-18]. The sensitivities are calculated using three different source classes. Note that the confidence levels associated with the analyses are not consistent. The IceCube limits were calculated at 90% C.L.. The HAWC limits and Fermi-LAT limits were calculated at 95% and 3 σ, respectively. Also, these sensitivities do not include systematic uncertainties.

Conclusions and Outlook

- We present an analysis aimed to search for dark matter decay using 3 galaxy clusters, 7 dwarf galaxies, and the Andromeda galaxy.
- We calculated the sensitivities of the analysis, at 90% C.L., for 8 different dark matter decay channels for dark matter masses between 10 TeV and 10 PeV.
- Systematic uncertainties of the analysis are currently under investigation, and we expect to unblind 9 years of IceCube data in the near future.