Snowmass2021 - Letter of Interest

Letter of Interest on Dark Matter Physics with the IceCube Neutrino Observatory

Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
□ (NF7) Applications
□ (NF8) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (CF1) Dark Matter: Particle-like
■ (CF2) Dark Matter: Wave-like

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Abstract: (maximum 200 words)

The search for new phenomena is one of the main science targets of large volume neutrino detectors. IceCube, Super-Kamiokande, and ANTARES have placed some of the most stringent constraints on the particle nature of dark matter. During the next decade, neutrino telescopes, foremost IceCube and its extensions will be essential to indirect searches for dark matter. IceCube has established an excellent track record in delivering very high impact science both in particle physics and in astrophysics. IceCube's data was undoubtedly the most critical for the indirect search landscape with neutrinos over the last decade. The US is well positioned to continue the leadership in instrumentation with IceCube-Gen2, and a combined program with very strong US based data analysis and theoretical efforts can maximize scientific returns.

[1] https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube
[2] https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube-gen2

Introduction

IceCube has ushered in a new era in astroparticle physics through the observation of high-energy extra-terrestrial neutrinos[1–3]. In doing so, we have observed neutrinos with unprecedented energies and coming from further than any previous measurements. These unique neutrinos push forward not only our understanding of the high-energy hadronic Universe, but also allow us to learn about the neutrino in new scenarios[4–6]. Through IceCube-Gen2 a new frontier for discoveries will be opened up during the next two decades as the accessible sample sizes increases significantly. This multipurpose detector naturally covers a very broad science including Beyond the Standard Model (BSM) physics as one of the main priorities. The program is unique to study BSM phenomena at an energy scale beyond the reach of LHC, or very rare processes such as those studied in Kaon factories or high-intensity anthropogenic neutrino beams. IceCube has proven this through leading results in BSM physics that are often not accessible by any other experiment. In this letter, we would like to highlight the importance of IceCube in searching for corpuscular dark matter.

Solar Dark Matter - dark matter-nucleon scattering cross section

Importance & Status: Dark matter could be captured in the Sun and lead to observable signals in neutrino telescopes when the dark matter annihilates in the center of the stellar body[7–10]; see for recent calculations of the neutrino yield in this scenario[11,12]. Searches have resulted in some of the most stringent constraints on spin-dependent dark matter-proton scattering that are extremely robust against any astrophysical uncertainty in the underlying dark matter velocity distribution[10,13,14]. The dark matter velocity distribution dependence is distinctively different than the dependence underlying direct searches, offering prospects for combined searches independent of halo models[15,16].

Outlook & Priorities: The IceCube Upgrade will significantly enhance solar dark matter sensitivities in a mass range of 10 - 100 GeV[17] and the exploration of dark matter-nucleon scattering cross sections at an order of magnitude below the best current bounds by Super-K[18] and IceCube[19]. IceCube-Gen2 will significantly enhance the sensitivity to searches for energetic neutrinos from the Sun, which could provide a signature of secluded dark matter[20–23]. In these scenarios, energetic neutrinos that would otherwise be severely attenuated due to absorption in the Sun above 1 TeV can instead escape from the Sun. During the next decade IceCube has good prospects to reach the solar atmospheric neutrino floor[24–27]. Advancing solar dark matter searches comes with high prospects for the discovery of this guaranteed signal. Solar atmospheric neutrinos expand the scientific scope of the solar dark matter analysis and offer new opportunities for discoveries. Dark matter sensitivity can be extended below the neutrino floor, but will require precise characterization of the solar atmospheric neutrino flux.

Dark Matter Decay

Importance & Status: The most stringent bounds on heavy decaying dark matter have been achieved with IceCube excluding lifetimes of up to 10^{28} s depending on the decay mode[28,29]. Bounds are extremely competitive to indirect searches with γ-rays[30] and are the world's strongest for dark matter masses above 10 TeV. These searches continue to explore BSM scenarios with dark matter masses beyond the reach of LHC and have a high discovery potential. Neutrino signals from heavy decaying dark matter have been discussed extensively[31–34].

Outlook & Priorities: Characterizing the high-energy astrophysical neutrino flux and determining its origins is the single most important challenge of the next two decades in astroparticle physics. Does the astrophysical neutrino flux contain any signals of BSM physics, such as heavy decaying dark matter as having been speculated in the literature[33–42]. A significant increase in event statistics will be required to solve these scientific questions.

Dark Matter Self-annihilation

Importance & Status: IceCube has provided some of the most stringent bounds on self-annihilating dark matter exploiting a variety of targets with large dark matter accumulations, such as the Galactic halo[43,44], Galactic center[45], or clusters of galaxies[46]. These searches are essential to test dark matter models with dominant annihilation to neutrinos (see Refs.[47–54] for examples of models and Ref.[55] for a recent summary of constraints) and are an integral part of indirect searches with γ-rays, x-rays, and radio. Searches for self-annihilating dark matter from the Galactic halo are characterized by a small dependence on dark matter halo model[43]. Results can be enhanced by combining data from different instruments[56].

Outlook & Priorities: Reaching sensitivity to probe annihilation rates near the thermal relic cross section with neutrinos will remain a major challenge, though it can be reached with neutrinos[55,57,58]. The priority for future measurements is in the combination with different messengers to cover a comprehensive set of annihilation channels.

Probing the sub-GeV dark sector, neutrino-dark matter scattering and rare processes

Importance & Status: New interactions of neutrinos with matter may alter the propagation of neutrinos by reducing the flux[59,60] or changing neutrino flavors[61,62]. The interaction of neutrinos with dark matter could suppress the flux of neutrinos from distant astrophysical sources[60], introduce spectral features, or result in an anisotropy of the diffuse isotropic astrophysical neutrino flux due to interactions with the Galactic dark matter halo[59]. These searches can also effectively test scenarios of light dark matter with masses below the GeV scale. If the dark matter is light and interacts in a flavor-diagonal way, it can preserve the neutrino flavor[62] or if it is non-diagonal, change it[61] from standard expectations.

Outlook & Priorities: The identification of additional distant astrophysical neutrino sources in the future is of highest interest in the field and will allow to test rare processes. A large sample of astrophysical neutrinos will enhance sensitivities to search for dark matter-neutrino interactions in the halo.

Axion dark matter

The detailed timing and energy spectrum of neutrinos from a Galactic core-collapse supernova can be used to probe sub-GeV dark sector or axion-like particles[63–65]. Readiness to precisely record a Galactic supernova burst has to remain a high priority. Sensitivity could be enhanced by reducing optical sensor module noise rates, requiring local coincidences to reduce random noise.

Boosted dark matter

Searches for boosted dark matter can probe a variety of scenarios with dark matter masses ranging from PeV scales to sub-GeV particles[66–69]. Signatures might be enhanced by new detection methods involving delayed light from meson decays[70,71].

IceCube as platform for dark matter direct detection

The interest in explaining the anomalous annual modulation observed by DAMA-LIBRA[72] remains very high and is further fueled by rapid progress towards repeating the measurement, with an independent sodium-iodine based experiment[73–75]. IceCube can provide an ideal environment for a dark matter direct detection experiment on the Southern hemisphere as having been proven by DM-Ice17[76]. Future deployments at the IceCube site offer opportunities for a conclusive test of the DAMA-LIBRA annual modulation signal.

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