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IceCube Dark Matter Searches and Future Perspectives

CARSTEN ROTT

DEPARTMENT OF PHYSICS, SUNGKYUNKWAN UNIVERSITY

ABSTRACT

Dark matter could be detected indirectly through the observation of neutrino originating from dark matter annihilations or decays. The world's largest neutrino telescope, IceCube, is at the forefront of indirect searches for evidence of beyond the standard model physics. Analyses of IceCube data have resulted in some of the most stringent constraints on dark matter annihilations, interactions with nucleons, and excited imaginations with the yet to be determined origin of the recently observed high-energy astrophysical neutrino flux. In the future, improved analyses methods with larger datasets and detector extensions will provide significant discovery potential for dark matter.

INTRODUCTION

While the presence of dark matter (DM) in the universe has been inferred from imprints on the cosmic microwave background, structure formation, and rotational curves of galaxies, its nature remains a mystery. Weakly Interacting Massive Particles (WIMPs) are one of the most promising and experimentally accessible DM candidates, which are predicted in extensions of the Standard Model (SM) of particle physics. WIMPs may be captured in large celestial bodies like the Sun, where self-annihilation to SM particles could produce neutrino fluxes accessible with terrestrial neutrino detectors. Indirect searches for DM are particularly sensitive to the WIMP-proton scattering cross section, which initiates the capture process in the Sun. Further dark matter annihilations in the Galactic dark matter halo, or from other dense accumulations,

such as dwarf spheriodals or the Galactic center are excellent targets for searches.

The cubic kilometer neutrino telescope, IceCube, has produced some of the strongest bounds to date on WIMP properties, constraining the spin-dependent scattering cross section with protons to $1.3 \times 10^{-40} \text{ cm}^2$ for WIMP masses of 250 GeV. The dark matter self-annihilation cross section averaged over the velocity distribution can be constrained to $10^{-22} \text{ cm}^3 \text{ s}^{-1}$ for masses above 1TeV. Based on the neutrino searches, some scenarios motivated by claims of annual modulation signals in direct detection experiments and rise in positron fraction observed by PAMELA and AMS-02 could be rejected. Striking neutrino signatures, such as a high-energy neutrino flux from the Sun provide high discovery potential.

THE ICECUBE NEUTRINO OBSERVATORY

The IceCube Detector

The IceCube detector [1] shown in Figure 1 is a neutrino detector of a cubic kilometer volume. It is located at the geographic South Pole and was completed at the end of 2010 after seven years of construction. IceCube exploits ice as natural occurring detector medium with excellent optical properties that have been extensively studied [2, 3]. This multipurpose detector consists of 5160 optical sensors buried between 1450 and 2450 meters below the surface of the Antarctic ice sheet. Sixty optical sensors (see Figure 3) are connected together to vertical

strings, each of which was lowered into 60 cm diameter holes drilled using up to 85 °C heated water.

IceCube was optimized and designed to detect interactions of neutrinos of astrophysical origin, but is also sensitive to downward-going highly energetic muons and neutrinos produced in cosmic-ray-induced air showers. The observatory includes a densely instrumented subdetector, DeepCore, able to detect neutrinos with energies above 10GeV. A surface tank array, IceTop, complements the in-ice detector with sensitivity to cosmic-ray induced extended air showers with primary energies above 1PeV [4].

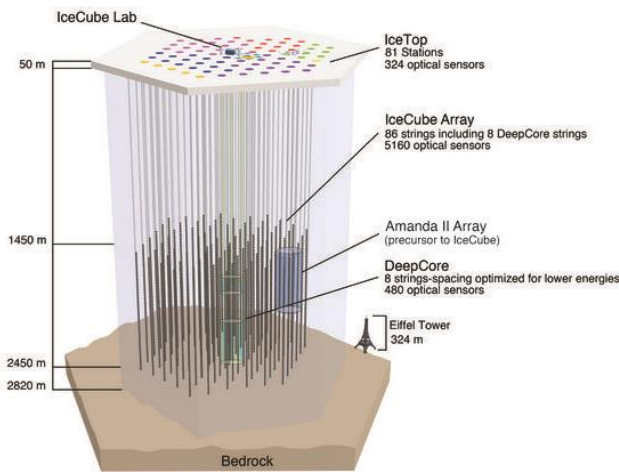


Fig.1: The IceCube Neutrino Observatory instruments a volume of roughly one cubic kilometer of clear Antarctic ice with 86 strings anchored at depth of about 2450m and each containing 60 digital optical modules (DOMs). The observatory includes a densely instrumented subdetector, DeepCore, and a surface air shower array, IceTop.

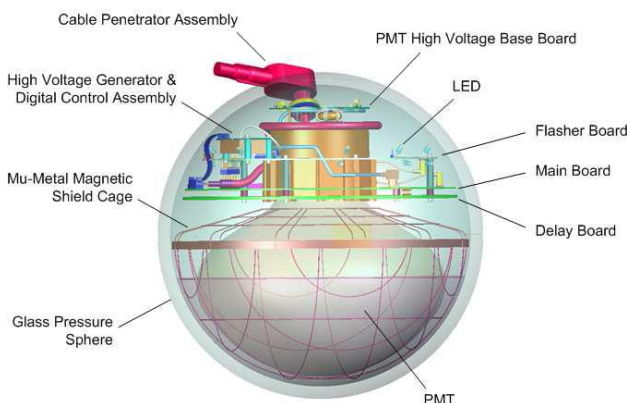


Fig.2: Digital optical modules (DOMs) are spherical, pressure resistant glass spheres, each containing a

Hamamatsu photomultiplier tube (PMT) of 25 cm diameter and the associated electronics necessary for waveform digitization [5, 6].

IceCube detects neutrinos by observing Cherenkov radiation from the charged particles produced in neutrino interactions. Different event topologies allow for an easy separation of charge-current muon neutrino interactions from other interactions. The first case produces a muon that carries on average 80% of the energy of an energetic neutrino or 50% for a neutrino of 10 GeV. Electron and tau neutrino interactions show similar spherical topologies (cascade) that are generally indistinguishable with exception of yet to be observed double bang events caused by the boosted lifetime of taus in the PeV range [7-10]. In neutral-current interactions a small fraction of the neutrino energy is transferred to a nuclear target, resulting in a cascade produced by the hadronic shower.

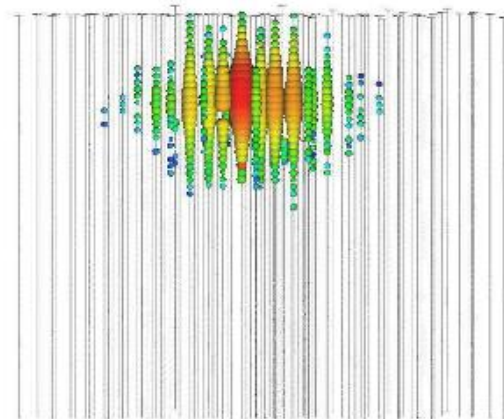


Fig.3: The most energetic neutrino event observed with an energy of about 2PeV [11]. This event nicknamed “Big Bird” shows a spherical topology as expected from an electron neutrino interaction.

IceCube operates at a 99% uptime and records about 10^{11} events per year. The vast majority of these are downward-going atmospheric muons from cosmic ray airshowers, out of which about 10^5 atmospheric neutrinos can be extracted and recently a high-energy astrophysical neutrino component was identified at 5.7σ [11, 12]. The most outstanding component of the astrophysical flux originates from cascade events, like the one shown in Figure 3, which are more detectable due to lower atmospheric backgrounds [13] and were the first ones to be observed [14].

First Discoveries and Scientific Objectives

IceCube results have already surpassed initial expectations and with the observation of high-energy neutrinos of astrophysical origin, IceCube has proven its discovery potential. The ability to detect individual neutrinos from a few GeV to beyond PeV as well as MeV neutrino supernova burst signals, give IceCube a neutrino energy coverage more than 12 orders of magnitude. Sub degree pointing resolution for muon neutrino induced muons above a TeV as well as good energy resolution on cascades from electron and tau neutrinos allow for a large variety of analyses. Recent results from IceCube include a measurement of atmospheric neutrino fluxes [15], observation of a cosmic-ray anisotropy [16], constraints on slow moving monopoles [17], and measurement of atmospheric neutrino mixing parameters compatible, and comparable in precision, to those of dedicated oscillation experiments [18].

With every high-energy neutrino event detected, IceCube moves closer to solving the century old mystery about the origin of the high-energy cosmic rays, which has been left open since the Viktor Hess's discovery. Energetic neutrinos are produced in the dense environments of the cosmic accelerators through decays of pions. The observed high-energy neutrino events, shown in Figure 3, are consistent with an isotropic distribution and no source correlations have been established. Primary source candidates are massive blackholes in the center of large active galaxies, starburst galaxies, gamma-ray bursts, though already tightly constrained [19]. Lively discussions are on-going about the origin of the PeV events, including numerous scenarios involving exotic physics or dark matter have been proposed.

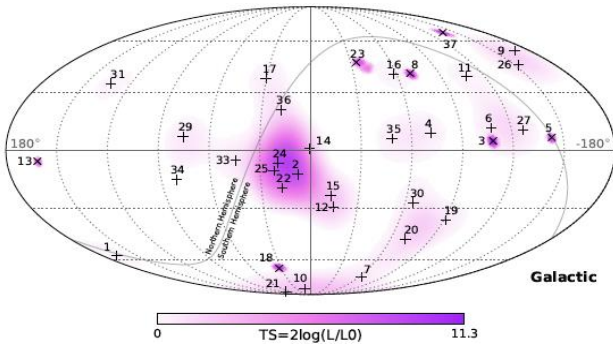


Fig.4: Skymap in galactic coordinates using the highest energy neutrino event sample arrival directions. Shower-like events (median angular resolution <15deg)

are denoted by +, while those containing a tracks (<1deg) with x. The purity fraction of the astrophysical sample is about 60%, with the remaining events expected from atmospheric backgrounds. No significant clustering is present, as derived from the test statistic of a point source clustering test shown in color [11].

DARK MATTER SEARCHES WITH NEUTRINOS

Dark Matter Annihilation

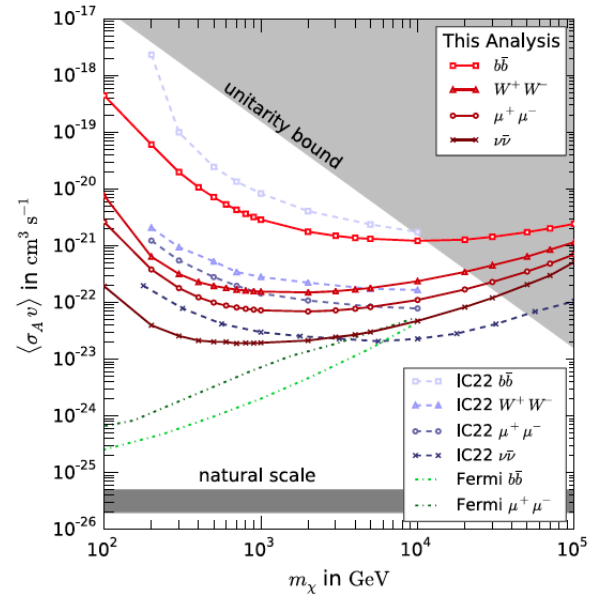


Fig.5: Limit on the dark matter self-annihilation cross section are shown [20, 21].

Neutrinos are expected to be produced in dark matter annihilations through sequential decays of annihilation products. As neutrinos are weakly interacting and not charged they travel unimpeded to us. The Milky Way is engulfed in a large dark matter halo, which is peaked toward the Galactic center. Self-annihilations could be detected with IceCube, through the observation of an anisotropy in the neutrino arrival distribution. Figure 5 shows the result of a search using one year of IceCube data. A high purity neutrino sample was obtained, by selecting upwards going muons, which can only originate from neutrinos traversing the Earth and interacting near the detector. The sample is dominated by near isotropic distributed atmospheric neutrinos, from which a dark matter signal could be distinguished by its anisotropy. No anisotropy was observed and limits on the dark matter self-annihilation cross section computed.

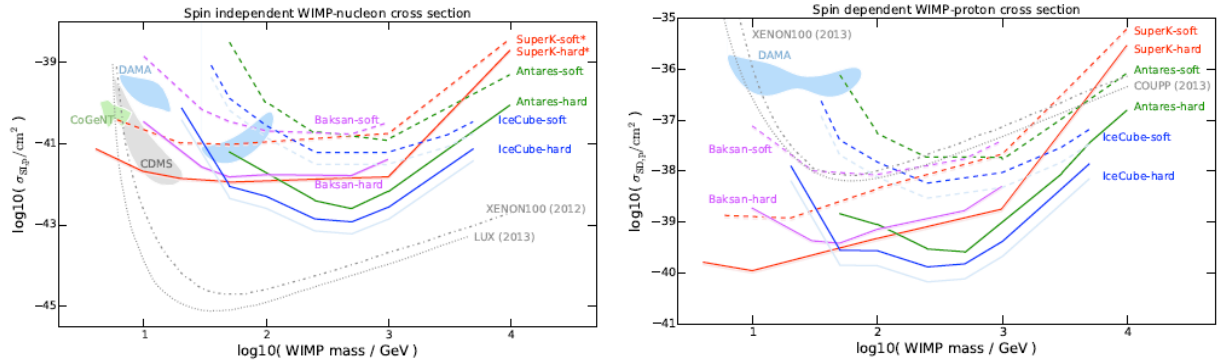


Fig.6: Upper limits at 90% CL on spin-dependent (left plot) and spin-independent (right plot) scattering of WIMPs with nucleons are shown for hard and soft annihilation channels over a range of WIMP masses from IceCube [26], Super-K [27], ANTARES [28], and Baksan [29]. Direct search results from COUPP [30], XENON100 [31, 32], LUX [33], and tentative signal regions [34-36] are shown for comparison.

Results are rather insensitive against assumptions on the dark matter distribution as an extended area is surveyed. This distinguishes IceCube's results from most searches with gamma-rays, which often focus on small dense objects. To compliment targeted gamma-ray searches, IceCube has also looked at the Galactic center and dwarf spheroidal galaxies and placed constraints on the dark matter self-annihilation cross-section [22]. IceCube is unique in placing bounds on the annihilation into neutrinos which is of high theoretical interest [23].

Capture in the Sun

WIMPs from the Milky Way dark matter halo could accumulate in the Sun and give rise to detectable neutrino signals. A WIMP scattering of a nucleon in the Sun could result in a large enough energy loss for the WIMP to fall below the escape velocity and to be gravitationally captured. The probability of such an interaction, which is the same underlying physics process as being searched for in direct detection experiments, depends on the WIMP-nucleon scattering cross section. As WIMPs accumulate in the Sun they will start to annihilate at an increasing rate. The rate increases steadily with the number of thermalized WIMPs near the center of the Sun up to a point where it becomes equal to half the capture rate. At this point as many WIMPs will be captured as annihilate away; once equilibrium is established the annihilation rate is independent of the self-annihilation cross section and as such the neutrino flux from the Sun only depends on the WIMP-Proton scattering cross section. Equilibrium is typically established on time scales less than the age of the Sun. WIMP capture is rather intensive to assumptions on the

dark matter halo model [24, 25]. Capture is in particular dependent on the spin-dependent WIMP-proton scattering cross section, as the Sun is primarily a proton target, making indirect bounds strongest compared to direct searches.

IceCube data has been searched for excess neutrinos from the direction of the Sun. The observed flux was consistent with the background expectations and limits on the WIMP-nucleon scattering were derived. The latest results compared with direct detection constraints and other indirect searches are shown in Figure 6. The expected neutrino flux and spectrum depends on the annihilation channels. We show a few representative cases for annihilation into b-quarks and W bosons (tau below the W mass), denoted by soft and hard channel respectively

Decaying Dark Matter

Decaying dark matter can also be constrained by looking for neutrino signals from the Galactic dark matter halo. IceCube has ruled out dark matter decaying into neutrinos falling short of lifetimes of 10^{10} times the age of the universe for mass above 10TeV [21].

FUTURE PERSPECTIVE

Following the success of IceCube, a low energy infill array and a high-energy extension are currently envisioned as upgrades to IceCube. The Precision IceCube Next Generation Upgrade (PINGU) [37], foresees the creation of

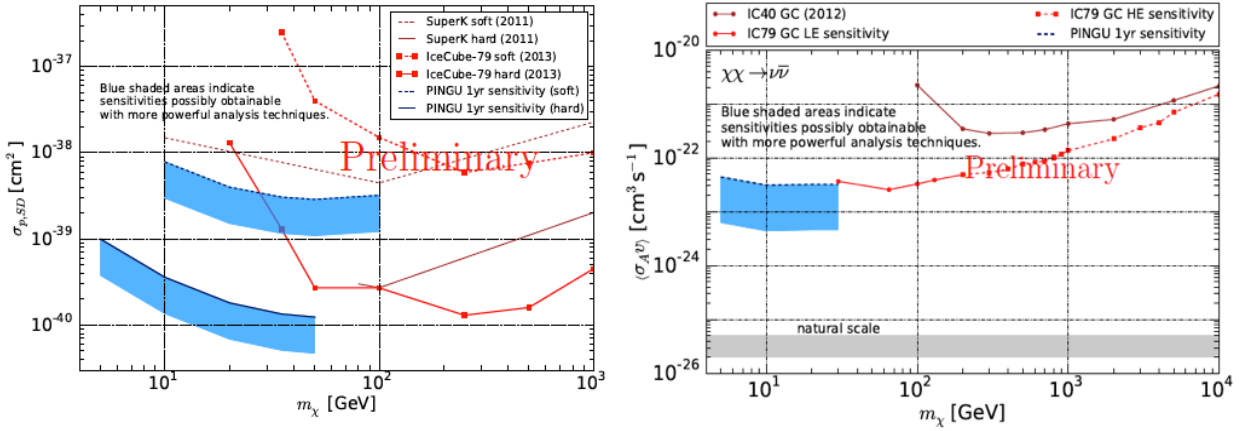


Fig.7: Sensitivity with one year of PINGU data to the spin-dependent WIMP-proton scattering (left) and dark matter annihilating in the Galactic center (right) [37].

a high-precision neutrino detector with a threshold of about one GeV, through the deployment of 40 densely instrumented strings. IceCube-Gen2 [38] would increase the effective area by roughly a factor of ten for neutrinos about 10 TeV through the deployment of about 100 widely spaced strings.

IceCube-Gen2

IceCube-Gen2 would deliver substantial increases in the astrophysical neutrino sample for all flavors to determine the origin and sources of the high-energy astrophysical neutrino flux. It would precisely measure the neutrino spectrum, flavor ratios, and arrival distributions. Exotic scenarios of heavy decaying dark matter become testable.

PINGU

The main physics objectives of this detector are determining the hierarchy of the neutrino mass states and search for dark matter in the experimentally interesting mass range of a few to 100 GeV. PINGU is designed to distinguish between the normal and inverted neutrino mass hierarchy at 3σ significance with less than four years of data. PINGU would significantly improve sensitivity to WIMP masses below 100 GeV in searches for dark matter captured in the Sun or from annihilations in the Galactic center and Milky Way halo. As such PINGU can extend solar WIMP searches into the region currently favored by some dark matter direct detection experiments. Figure 7 shows PINGU's sensitivities using a 40 strings benchmark geometry.

CONCLUSIONS

With the discovery of high-energy astrophysical neutrinos, IceCube has reigned in a new era in astroparticle physics. This new vibrant field that provides copious connections between particle physics and astrophysics continues to grow rapidly. Indirect searches for neutrinos from dark matter annihilations provide a high discovery potential and striking signatures, like the one expected from dark matter captured in the Sun, would leave little doubt about its origin. The constraints on spin-dependent scattering of dark matter have already excluded some of the dark matter direct detection claims. With PINGU signals should be observable for the majority of these scenarios.

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Carsten Rott is an assistant professor at Sungkyunkwan University and a co-convener of the beyond standard model working group of the IceCube Experiment. He received his Ph.D. from Purdue University in 2004. He has been an IceCube Collaboration member since 2005.