Search for Dark Matter from the Galactic Halo with the IceCube Neutrino Observatory – Paper Review

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Review of
R. Abbasi *et al.* (IceCube Collaboration), Phys. Rev. D **84**, 022004 (2011).

Introduction

The dark matter problem is a central issue in astrophysics. There is substantial observational evidence that the majority of mass in the Universe is composed of matter that neither emits nor absorbs electromagnetic radiation – so called dark matter. Zwicky proposed the existence of dark matter, motivated by observations of the Coma Cluster of galaxies [2]. Observing the velocities of the galaxies and applying the virial theorem, he calculated the amount of mass that must be present in the cluster to keep the galaxies gravitationally bound. Then, he used the brightness of the galaxies to determine the number of stars in galaxies in the cluster. The number of stars is insufficient to support the mass needed to gravitationally bind the cluster, advancing the idea that dark matter is present. Rubin's measurements of the rotation speeds of stars in spiral galaxies [3] gave even more support to the idea of dark matter. By measuring the rotation speed of stars as a function of galactic radius, the distribution of mass as a function of galactic radius can be inferred. This inferred distribution of mass disagrees sharply with the observed distribution of stars: while stellar populations are denser near the centers of galaxies, the distribution of mass is seen to be almost constant. Today, much more observational evidence exists to support the existence of dark matter, and so its existence is generally accepted. Determining the identity of dark matter is an important pursuit for both cosmology and particle physics. In cosmology, the properties of dark matter are important in deciding the evolution of the universe. In particle physics, the existence of dark matter motivates new theories.

Weakly Interacting Massive Particles (WIMPs) are a leading possible solution to the dark matter problem. Their existence is motivated by the gauge hierarchy problem in particle physics. The Higgs mechanism of the standard model requires a Higgs boson of mass $m_h \sim 100\ \text{GeV}$. The physical Higgs boson mass must be obtained from renormalization, where the Higgs boson's coupling with other particles provides corrections to its mass. Letting Δm_h be the corrections to the mass from couplings and Λ be the energy scale where the standard model is invalid, then:

$$\Delta m_h^2 \sim \frac{\lambda^2}{16\pi^2} \Lambda^2$$

Where $\lambda \sim 1$ expected from naturalness. But in the standard model $\Lambda \sim 10^{19}$ GeV, where quantum gravity becomes important. But Δm_h^2 should be of smaller order than m_h^2, which requires that $\frac{\lambda^2}{16\pi^2} \sim 10^{-36}$. Such a small λ is unnatural and would be an incredible coincidence of nature. However, if new physics exists at $\Lambda \sim 10^3$ GeV, natural values of λ are restored. Among the candidate theories at these scales are supersymmetry and extra dimensions. Theories providing such new physics often have a WIMP: a particle of mass $m_\chi \sim 10 - 10^3$ GeV that interacts only through gravity and the weak interaction. Such WIMPs are produced by the Big Bang as a thermal relic. After the Big Bang, the universe is hot enough to produce these WIMPs. However, WIMP production is heavily suppressed when the temperature of the universe drops below $\sim m_\chi c^2 / k_B$. But the universe cools as it expands: the WIMPs self-annihilation is inhibited by the decreasing density of the universe. Thus, a relic abundance of WIMPs will remain that is determined by their self-annihilation cross section. The natural cross section of a WIMP can be determined through dimensionality arguments and m_χ. The so called WIMP miracle is that this natural cross section produces a WIMP relic density close to the measured density of dark matter. [4]

Many experiments are attempting to reveal the identity of dark matter by finding a signal from its interactions, like self-annihilation or decay. PAMELA, a satellite-based magnetic spectrometer, has detected an excess of ~ 10 GeV positron cosmic rays. ATIC, a balloon-based ionization calorimeter, reported an electron/positron excess at $\sim 300 - 800$ GeV; whereas the Fermi-LAT's ionization calorimeter reported a different electron/positron excess at ~ 200 GeV. These signals could be from astrophysical sources, such as pulsars, that are unaccounted for. However, they may also be interpreted as the products of dark matter interactions. Given how some results are inconsistent and given that more data is needed to distinguish astrophysical sources from dark matter interactions, it is important to have experiments searching for a variety of signals. The IceCube neutrino telescope is thus an important part of the dark matter search because of its ability to probe for neutrino signals. [5]

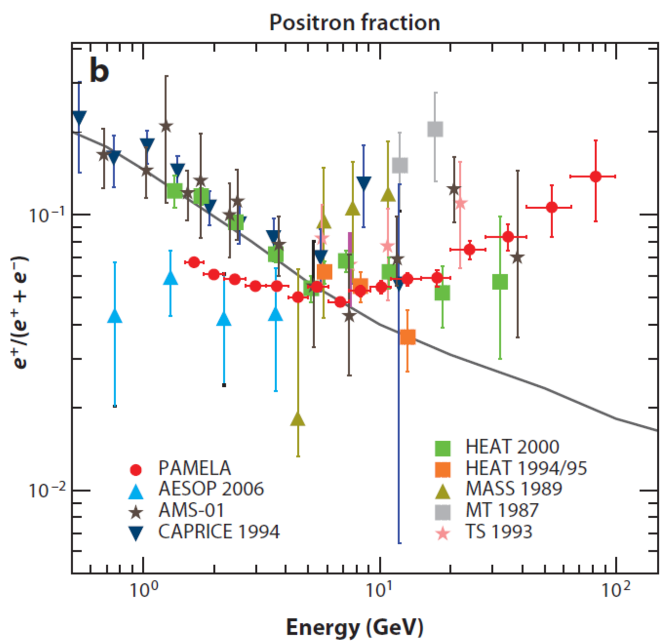

Figure 1. Cosmic-ray positron fraction as measured by PAMELA and other experiments. Reprinted from [5].

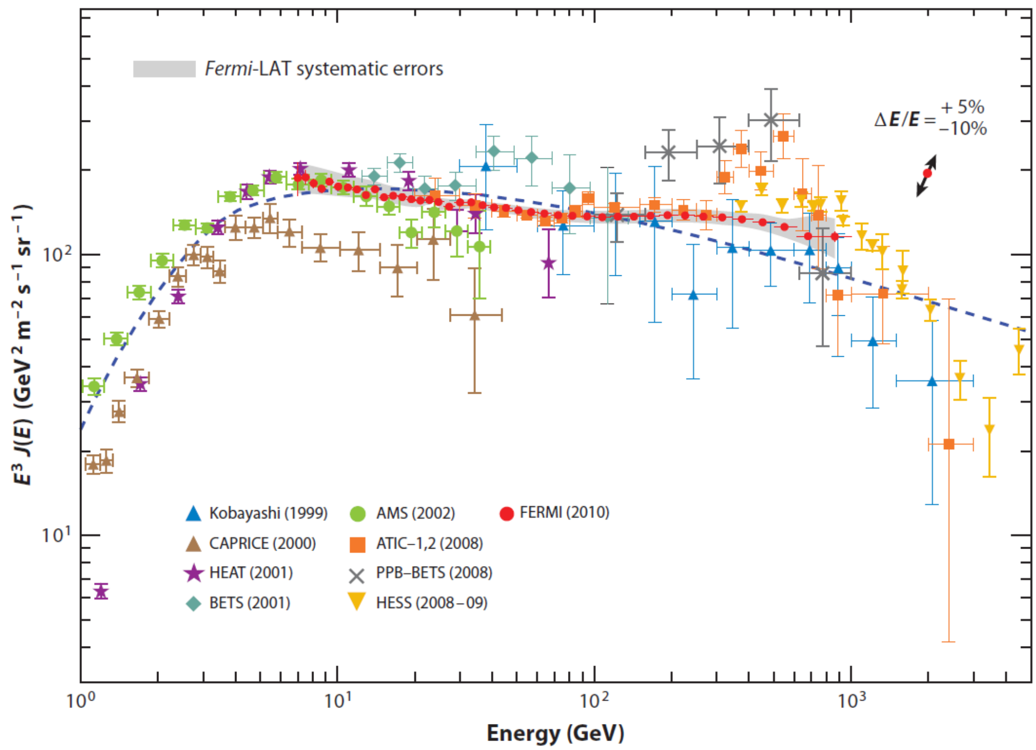

Figure 2. Combined cosmic-ray electron and positron spectrum as measured by ATIC, Fermi-LAT, among other measurements. Reprinted from [5].

The reviewed paper uses the IceCube neutrino telescope to search for neutrinos produced by dark matter self-annihilation or decay in the galactic halo. The Milky Way galaxy is thought to be surrounded by a large halo of dark matter. The dark matter may produce neutrinos directly as products of its interactions, or indirectly through the decay of those products. IceCube's neutrino observations can be used to constrain $\langle \sigma_A v \rangle$, where σ_A is the self-annihilation cross section and the average is taken over the dark matter velocity distribution. The dark matter lifetime can also be constrained.

IceCube

Located at the South Pole, the IceCube Neutrino Observatory's main detector is the IceCube neutrino telescope. The neutrino telescope is a cubic kilometer of ice instrumented with 86 strings of digital operating modules (DOMs), spanning depths 1450 m to 2450 m. The DOMs each have a photomultiplier tube and data acquisition circuits. The strings are cable bundles facilitating power transmission from and communication to the surface. DeepCore is

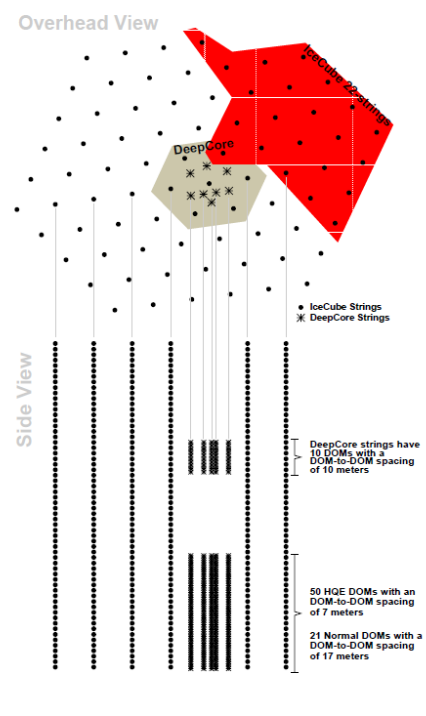

Figure 3. Schematic view of the IceCube Neutrino Observatory including the low energy extension DeepCore. Shown in red is the partially instrumented detector, which was the only portion used in the reviewed paper. Reprinted from [1].

a subset of IceCube strings that are more densely instrumented with DOMs. The reviewed paper uses data taken with the partially constructed detector, composed of 22 strings.

The IceCube neutrino telescope detects neutrinos through the Cherenkov radiation emitted by the products of a neutrino's interaction with the ice. Through a charged current interaction, a neutrino can interact with a nucleon in the ice and transform into its partner charged lepton. If this charged lepton has sufficient kinetic energy, it will exceed the speed of light in ice and produce Cherenkov radiation. The DOMs record the time at which their photomultiplier tubes observe this light. Because they only interact weakly, neutrinos follow straight line paths from their sources and are not easily obstructed, allowing the sources to be located. DeepCore allows IceCube to detect lower energy neutrinos because the DOMs are closer together. A lower energy neutrino will produce a lower energy charged lepton, which will travel a shorter distance before decaying or stopping. Thus, more closely spaced detectors are needed to effectively see lower energy neutrino interactions.

IceCube's primary background is cosmic ray air showers. When a cosmic ray hits the upper atmosphere and interacts with air, it produces an air shower of particles mostly consisting of pions and kaons through the strong interaction. The kaons decay into leptons or pions, and the pions decay into leptons; the dominant leptons produced are muons and muon neutrinos. The muons from cosmic ray showers are seen by IceCube as downward going tracks; muons produced on the other side of the Earth interact with the Earth or decay before reaching IceCube. To easily remove this background, only upward going tracks are considered; however, the background from the air shower neutrinos produced on the other side of the Earth remains.

Signal Expectations

The dark matter halo profile of the Milky Way has been studied observationally and theoretically, giving robust halo profile models. Gravitational lensing studies have found the profile observationally, while N-body simulations of galaxy formation have provided predictions of the profile. Models tend to agree on the distribution at large distances from the galactic center, as the region is easier to resolve in simulation and easier to observe. The reviewed paper considers four different halo profile models, with two acting as extreme cases to test their analysis's dependence on halo model. The models are normalized to give the correct galactic rotational velocity at the solar system's orbit, 8.5 kpc.Since the detector accepts neutrinos from the Northern sky, galactic radii of $4-20$ kpc are observed by IceCube. Fortunately, halo profiles agree well at these radii. The halo is taken to end at 40 kpc.

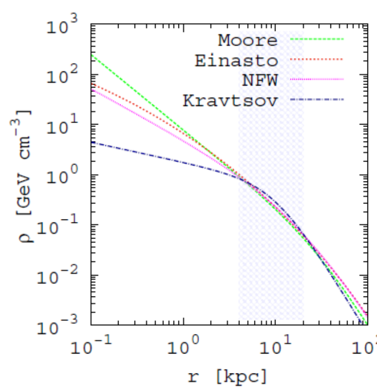

Figure 4. Comparison of the dark matter density distribution, as a function of distance from the Galactic Center as described by the Einasto, NFW, Kravtsov, and Moore halo profiles. The shaded area indicates the region where the reviewed paper's analysis is sensitive. Reprinted from [1].

The muon neutrino flux is calculated because muon neutrinos are the easiest for IceCube to identify. Muons appear as long tracks, since the muon is not deflected much by the ice molecules. Electron neutrinos appear as “bangs” because electrons lose energy in the ice more easily than muons. Taus decay promptly, and leave behind muons, electrons, or hadrons.

The neutrino flux from self-annihilations is proportional to the square of dark matter density ρ^2 integrated along the line of sight through the galactic halo, whereas the neutrino flux from decays is proportional to the dark matter density ρ integrated along the line of sight through the galactic halo.

Instead of considering the neutrino spectrum of some specific WIMP models, the reviewed paper considers 100% branching ratio to each of a set of products. The energy spectrum of the muon neutrinos resulting from those products or their decays is calculated using the software DarkSUSY, assuming the dark matter is a WIMP. The spectrum will depend on the WIMP mass m_χ, and will be modified by neutrino oscillation. Because of the large distance to the galactic halo, the long baseline limit of neutrino oscillation can be used.

Combining the WIMP self-annihilation $\langle\sigma v\rangle$, integral of halo density squared ρ^2 over the line of sight, and WIMP self-annihilation neutrino energy spectrum, an expected muon neutrino flux from self-annihilation can be calculated. Similarly, combining the WIMP lifetime τ, integral of halo density ρ over the line of sight, an expected muon neutrino flux from decay can be calculated, assuming that the WIMP decays into neutrinos.

Data

The data are selected from events that are reconstructed as upward-going muon neutrino events. The angular uncertainty of the track is determined from the event reconstruction. Also, the reconstructed track is used to determine an expected time of arrival of unscattered Cherenkov radiation to the DOMs. Differences between the expected time and the recorded time are used to judge the quality of the reconstruction. Reconstruction is repeated with the best fit track constrained to be downward going; if this downward-going reconstruction is sufficiently good, the event is considered to be downward-going and thus an atmospheric muon. These selection criteria give a set of neutrino candidates of 90% purity.

The objective of the search is to find a large scale aniostropy in the neutrino flux, caused by the dark matter in the galactic halo. In the northern sky that IceCube observes, an on-source region is defined in the direction of the galactic center where the halo density is greatest, and an off-source region 180 degrees from it in right ascension. (Right ascension can be considered to be like a longitude with respect to the stars in the sky.) The northern sky does not contain the galactic center, and so astrophysical sources of neutrinos at the galactic center are avoided. The background of atmospheric neutrinos is expected to be isotropic, so any anisotropy would be from dark matter interactions. The angular size of these regions is determined by a simulation of the number of signal events that can be expected from a WIMP of

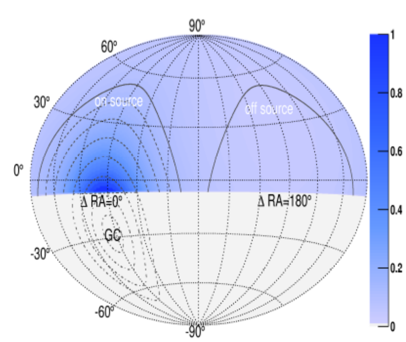

Figure 5. The relative expected neutrino flux from dark matter self-annihilation in the northern celestial hemisphere of the Milky Way Galaxy halo. Reprinted from [1].

characteristic annihilation cross-section $\langle\sigma_A v\rangle_0$. Since the number of signal events is proportional to $\langle\sigma_A v\rangle$ and the number of background events is proportional to the amount of sky observed, the ratio $S/\sqrt{B}$ of signal events S and background events B in the on-source can be maximized in simulation by optimizing the angular size of the regions.

Uncertainties

Since the number of background events in the on-source region can be well estimated by considering the number of events in the off-source region, where few signal events are expected, the systematic uncertainties in the background only come from anisotropies. A small anisotropy of scale 0.2% in cosmic ray events has been measured by the TIBET ice shower array, as well as in downward going muon flux in IceCube. Also, the exposure of the partially constructed IceCube to neutrino events is anisotropic in right ascension. However, if this efficiency is rotated by 180 degrees in right ascension, the difference with the unrotated exposure is 0.1%. This difference is taken as the uncertainty, since it represents the difference in exposure in between the off-source and on-source regions. These estimates are combined into a conservative 0.3% systematic uncertainty in the number of background events.

Many factors contribute to the systematic uncertainty in signal acceptance. The greatest such uncertainties are uncertainties in the properties of the ice and simulation limitations. These errors were previously studied by IceCube, where data showed a maximal excess near the horizon of 30% compared to the atmospheric neutrino flux predictions. Track reconstruction efficiency as a function of azimuth and altitude combined with detector exposure as a function of right ascension result in another uncertainty of 1%. The photon detection efficiency of the DOMs causes the uncertainty in track reconstruction efficiency to depend on neutrino energy, WIMP mass, and annihilation channel. The WIMP mass and annihilation channel determine a neutrino energy spectrum, and the neutrino energy determines a track length; longer tracks are detected by more DOMs and are less affected by DOM efficiency.

Finally, statistical Monte Carlo errors in signal acceptance from the simulation also depend on WIMP mass and annihilation channel. These statistical uncertainties are lower for channels with higher energy neutrinos.

Results

The results are compatible with the null hypothesis, so an upper limit is placed on the WIMP self-annihilation $\langle\sigma_A v\rangle$ and a lower limit is placed on the decay lifetime τ. In the final data, 1389 events are observed in the off-source region, while 1367 are observed in the on-source region, a deficit of 22 events. The limits are Neyman confidence belts, limits created by a frequentist approach. Assuming some true value of $\langle\sigma_A v\rangle$ and annihilation channel (or τ and neutrino decays), the uncertainties in signal acceptance is determined. Since the number of signal events is proportional to $\langle\sigma_A v\rangle$, the predicted signal can be determined for any $\langle\sigma_A v\rangle$ by simply scaling the DarkSUSY calculation for $\langle\sigma_A v\rangle_0$. Then, a Monte Carlo simulation is run where the numbers of background and signal events are chosen from distributions arising from the observed background, background uncertainties, predicted signal, and signal acceptance uncertainties. From this Monte Carlo, a distribution in the difference between the numbers of on-source and off-source events is formed. Then, it can be determined if the observed deficit of 22 events is within the 90% acceptance interval of this $\langle\sigma_A v\rangle$ and annihilation channel (or τ). The set of $\langle\sigma_A v\rangle$ or τ for which the observation is within the 90% acceptance interval form the 90% confidence interval.

The choice of halo model changes the signal expectation. The reviewed paper takes the Einsato profile as the benchmark mode; the halo uncertainty is the maximal differences in the limits obtained by using the other halo models. It is apparent that the halo model choice does not change the limits appreciably.

The upper limits on WIMP self-annihilation $\langle\sigma_A v\rangle$ are still a few orders of magnitude above the natural scale required by the WIMP miracle. Thus, the observed null result does not rule out WIMP dark matter.

The lower limits on the WIMP lifetime τ are many orders of magnitude above the minimum lifetime of a WIMP. A WIMP is only required to have a lifetime longer than the age of the Universe, $\sim 4 \times 10^{17}$ s.

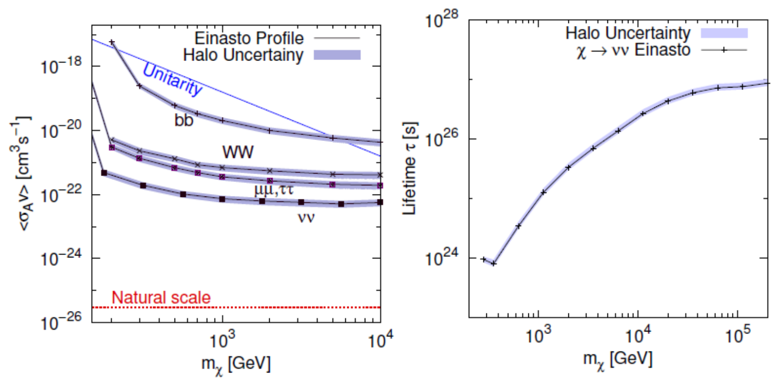

Figure 6. 90% confidence level upper limit on the dark matter self annihilation cross section for five different annihilation channels and lower limit on WIMP lifetime assuming decay into neutrinos. Reprinted from [1].

The reviewed paper than considers the effects of halo substructure on the analysis. Halo profile models give a galactic scale distribution of dark matter, but galaxy formation theory predicts that the halo has substructure within this galactic scale distribution. The frequency of neutrino self-annihilation depends on the local ρ^2, which depends greatly on the substructure, whereas a galactic scale average $\langle\rho^2\rangle$ is used. That is to say, WIMPs are more likely to interact in a dense substructure than is expected by considering the average density of dark matter in the region containing that substructure. WIMP decays are not affected as decay rates are proportional to ρ. A boost factor can be defined from the average ratio of $\rho^2/\langle\rho\rangle^2$ at a certain radius, determined by considering some substructure model. The boost factors increase the predicted signal, making the self-annihilation limit tighter by ~ 0.6.

The effect of the assumption that the halo ends at 40 kpc is also investigated. Increasing this assumption to 100 kpc in calculating the expected signal gives no appreciable effect. The outer parts of the halo have very little dark matter density, so adding more extent to the halo does not add many more WIMPs.

Comparison with Phenomenological Models

The lepton excesses seen by PAMELA, ATIC, Fermi-LAT, and other experiments can be interpreted as signals of WIMP dark matter self-annihilation using phenomenological models. Because electrons/positrons lose energy quickly during propogation, the source of these excesses must be from within ~ 1 kpc. The IceCube upper limits on $\langle \sigma_A v \rangle$ are compared with the limits on $\langle \sigma_A v \rangle$ from PAMELA and Fermi-LAT, under the assumption that the lepton excesses are due to WIMP dark matter with 100% decay annihilation into muons or taus. Even though the IceCube dataset used is small, and obtained with a partially constructed detector, IceCube's limits approach the values consistent with these phenomenological models.

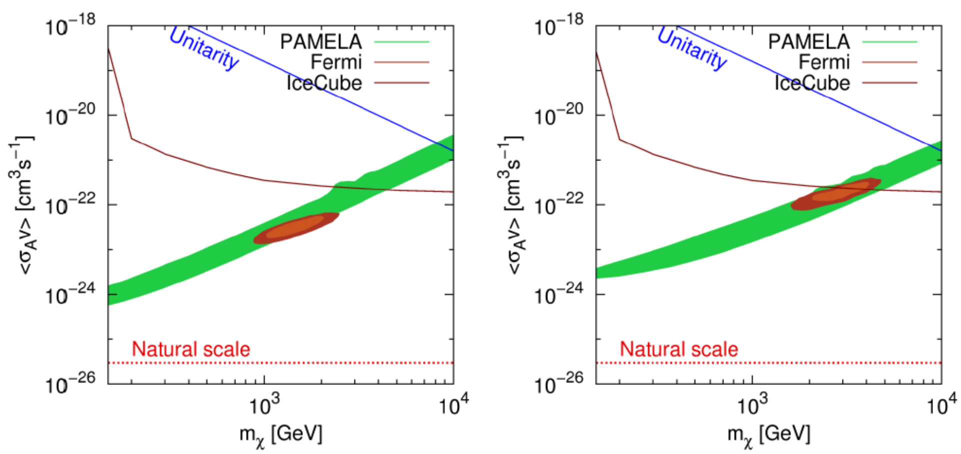

Figure 7. 90% confidence level upper limit on the dark matter self-annihilation cross section assuming the Einasto profile and annihilation into muons (left panel) and taus (right panel). Limits are compared to a preferred phenomenological model to explain the PAMELA excess (green) together with Fermi electrons (brown). Reprinted from [1].

Outlook

The analysis presented in the reviewed paper would provide a distinct discovery signal for dark matter interactions. If such large scale anisotropy is found, it would be apparent that some sort of large scale signal was being detected; given the extent of the galactic halo on the sky, dark matter self-annihilations would be an appealing explanation. The analysis is sensitive to WIMP masses of the scale required for the WIMP miracle and already overlaps with phenomenological models for other astropaticle experiment results. More data from the completed IceCube neutrino telescope will only make these limits better.

A much improved constraint could be obtained by trying to observe the galactic center, where dark matter density is highest. This sort of search will be possible with the completed IceCube detector. Since the galactic center is in the southern sky, galactic center neutrinos need to be distinguished from downward going muons. With the full detector, neutrinos can be found by considering only events that start within the interior of the detector. A neutrino will only start a track when it first interacts in the detector, whereas a muon will start a track as soon as it enters the detector. The galactic center has many astrophysical sources of neutrinos, however, which could pose a problem for distinguishing any dark matter interactions.

The reviewed paper used 5114 IceCube candidate neutrinos observed in 275.7 days of livetime using the partially instrumented IceCube neutrino telescope to search for large scale neutrino anisotropy. Such anisotropy would be expected from WIMP dark matter interactions in the galactic halo, but no such anisotropy is found. Upper limits were placed on the WIMP self-annihilation cross section $\langle\sigma_A v\rangle$ for several channels, and lower limits were placed on the WIMP decay lifetime τ, assuming decay into neutrinos. These limits do not yet approach the natural scale of WIMP self-annihilation cross section, so but do start to overlap with phenomenological models of the PAMELA and Fermi-LAT lepton excesses. This analysis has not yet said much on WIMP dark matter, but more data and any consequent observations by other astroparticle experiments may yield insight into the nature of dark matter in the future.

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