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Direct Detection of Solar Dark Matter with IceCube: A New Approach

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Abstract:
This study aims to explore the possibility of indirectly detecting dark matter in the Sun using the IceCube neutrino observatory. Dark matter is usually not detectable directly, but it accumulates in the Sun's core through gravitational forces. As a result, dark matter undergoes annihilation reactions, producing high-energy neutrino streams. The IceCube detector embedded in the Antarctic ice layer is responsible for detecting these neutrinos. This work simulates the entire process - from capture and annihilation in the Sun to neutrino detection on Earth. Distinguishing this potential signal from the large background of atmospheric neutrinos is the key to achieving a discovery. To improve sensitivity, the author explored advanced statistical methods and machine learning techniques to achieve better background rejection. Looking forward to the future explosion, there will be a gradual deployment of new-generation equipment (such as the "IceCube Second Generation" detector). Its sensitivity is expected to reach eight times the current level, so that it will significantly enhance the ability to detect dark matter. This study aims to establish a systematic framework for indirectly detecting dark matter through the Sun and systematically evaluate the technical challenges currently faced by neutrino telescopes and the scientific opportunities they may bring in future exploration.

Keywords: Dark matter; ice cube; solar dark matter.

1. Introduction

In this whole universe, there are many things that scientists cannot see with their naked eyes. Although they have made significant progress in exploring the universe nowadays, such as creating cosmic models, and so on. However, the matter scientists are familiar with constitutes only a very small portion of the entire universe. And the majority of the universe is what they are currently exploring. Scientists are usually referred to as dark matter. In the previous articles some detection targets include three regions where dark matter may accumulate and generate neutrinos. First up is "galactic halo". This research method aims to search for signals resulting from the annihilation or decay of dark matter within the dark matter halo of the entire Milky Way. Second, the Solar center It used to search for signals of dark matter annihilation at the center that is captured by the Sun's gravitational force. Third, Isotropic signals: Search for possible diffuse astrophysical neutrino background possibly originating from dark matter decay [1]. The observational data of IceCube over a period of 10 years from 2011 to 2020 were analyzed. Various scenarios of the absence of signals from dark matter annihilation were considered: The analysis results were consistent with the background expectations, and no significant dark matter signals were detected. The most significant result corresponded to the annihilation of dark matter at 250 GeV with quark pairs, and its significance was only 1.06σ [2].

Neutrinos in the solar atmosphere (produced by the interaction of cosmic rays with the solar atmosphere) are the main background noise, and their energy spectrum is similar to that of dark matter signals. Advanced event selection methods (such as Boosted Decision Trees) and statistical methods (such as the generalized Poisson likelihood function) need to be used to distinguish signals from backgrounds. The SDM model assumes that dark matter annihilation produces long-lived mediators, which decay outside the Sun, avoiding the absorption of neutrinos by solar matter and thereby enhancing the signal. Moreover, using the James Webb Space Telescope (JWST), a galaxy that "died out" (quenched) just 700 million years after the Big Bang was discovered. This galaxy, named GS-9209, is the earliest galaxy that has been observed that have stopped forming stars. GS-9209 has accumulated a considerable amount of stellar mass. Its stellar mass and stellar velocity dispersion indicate that there may already be a supermassive black hole at its center [3]. But how do the scientists discover the lceCube Neutrino Observatory? Because it is capabilities for detecting high-energy neutrinos. Motivation for using lceCube to detect neutrinos from solar DM annihilation. People are motivated to use lceCube to detect neutrinos from solar DM annihilation. The purpose of this IceCube project is to propose and develop a new approach for detecting solar DM using IceCube and also to explore the feasibility, challenges, and potential implications of this approach. So the author will talk about the IceCube in the following part [4].

2. Theoretical Framework

2.1 Dark Matter Capture in the Sun

This part describes the process by which dark matter particles are "captured" by the Sun and imprisoned within it. when the sun goes through the Milky Way halo, DM particles will be attracted to the electric potential of the sun. In this case, the cosmic microwave background radiation would be a very weak form of radiation. Moreover, because it can be heated within the sun's interior, it will undergo further scattering with electrons and eventually concentrate within 1% of the sun's radius. The primary and secondary neutrinos produced by dm will be detected by the telescope [5]. However, there are still many drawbacks during the capturing process. The researchers not only verified the above predictions using the Eddington inversion method, but also emphasized the crucial role of the galactic dynamical evolution history. Scientists have determined the uncertainty brought about by the influence of velocity distribution on the rate at which the Sun captures dark matter. The final research result is that different velocity distributions will change the proportion of dark matter captured by the Sun, and the error range is approximately 15% to 20% [6].

After discussing with the authors of the references, the author learned that this condition does not apply to solar electrons, as their speed is limited (approximately 0.07 times the speed of light). This limitation has increased the capture efficiency by approximately seven times.

$$\text{Ci}=\int_0^{R\odot} 4\pi r^2 dr \int_u^\infty \frac{f(u)}{u}(u^2+v_{esc}^2(r))\Omega_v^-(w(r))du \qquad (1)$$

The first is the Integral variable and range. This suggests that the integration depends on two key variables: the radial distance from the Sun's center (r, ranging from 0 to R ⊙) and the asymptotic velocity of dark matter particles (u, ranging from 0 to ∞). In practical terms, this involves computing the capture probability for each possible dark matter particle interacting at every location within the Sun, followed by summing all such individual probabilities. Furthermore, the volume element is given by $4\pi r^2dr$, which physically corresponds to the volume of an infinitesimally thin spherical shell. Here, r denotes the distance from the Sun's center, and dr represents the shell's thickness. Third, the velocity distribution and flux term. Physical meaning is the characteristics of the dark matter "wind" that impacts the Sun. u: The velocity of dark matter particles at an infinite distance from the Sun. f(u): The velocity distribution function of dark matter. It describes the proportion of dark matter particles with velocity u in the vicinity of the solar system. 1/u the particle flow rate is inversely proportional to the speed u. Overall, it represents an effective incoming flux of dark matter particles with velocities ranging from u to u + du. Fourthly, the Gravitational focusing term. Physical meaning is this is the mathematical manifestation of the gravitational focusing effect. The gravitational force of the sun will bend the trajectory of dark particles, resulting in a particle flow

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actually hitting the sun being stronger than what would be calculated based on a simple geometric cross-section. Overall explanation: This factor amplifies the incoming flow and takes into account the influence of the Sun's gravitational pull that "attracts" more dark matter particles towards itself. Fifthly, the scattering probability term. Physical meaning: This is the core of the entire formula.

2.2 Annihilation and Neutrino Production

Currently, scientists are researching the phenomenon of dark matter dispersion at the center of the Earth. This study utilized the data from the IceCube detector during the period from May 2011 to May 2012 to search for signals of dark matter annihilation neutrinos originating from the center of the Earth. No significant deviations from the background were observed. This result sets a new upper limit one order of magnitude stricter than the AMANDA experiment for the annihilation rate of WIMP at the Earth's center, and improves the spin-independent scattering cross-section limit for 50 GeV WIMP mass points.

2.3 Neutrino Propagation and Detection

It is a very important part of Neutrino Transport in the Sun. Although neutrinos mainly undergo weak interactions, the core of the sun has an extremely high density (~150 g/cm³), which makes the interactions significant and alters the initial energy spectrum and flavor composition of the neutrinos. It includes neutral-current Interactions and charged-current Interactions. And the next step the author will talk about propagation to Earth and Oscillation. They can freely propagate in a vacuum because once they leave the Sun, neutrinos propagate through an almost perfect vacuum for 1 AU (astronomical unit) before reaching Earth, and no significant interactions occur [6]. Then Neutrino Oscillation will happen. Due to the inconsistency between the intrinsic states of neutrino mass and the intrinsic states of flavor, they will transform from one flavor to another during their propagation. What is Energy Spectrum? This refers to the situation where the magnitude of energy distribution changes within a system. Scientists emphasize that what the author has measured is not the original annihilation energy spectrum, but the modified arrival energy spectrum after passing through the solar medium. And Angular Distribution. Angular distribution refers to the way in which a quantity (such as intensity or probability) is distributed over different angles, often used in contexts like scattering, radiation, and data analysis. In the detector, the signals generated by the interactions of these neutrinos will precisely point to the location of the sun.

3. IceCube as a Dark Matter Detector

3.1 Capabilities of IceCube

The IceCube is a neutrino observatory located in Antarctica, and it is also a cubic-kilometer particle detector. It is situated 2,500 meters below the ground. This observatory has great capabilities because it has a ground array called "IceTop" and a denser internal sub-detector called "DeepCore" [7].

IceCube is the first neutrino detector that people have ever built. Its main design purpose is to observe neutrinos originating from the most intense astrophysical sources in the universe. Neutrinos are not deflected by magnetic fields because they are particles with almost no mass and no charge. This means that they hardly decay as they travel from their source to the Earth.

The in-ice section of the IceCube observatory comprises 5,160 digital optical modules (DOMs), with each module housing a ten-inch photomultiplier tube along with supporting electronic components. These DOMs are mounted on vertical cables known as "strings," which have been frozen into 86 drilled holes and spread across a volume of one cubic kilometer at depths ranging from 1,450 to 2,450 meters. Arranged on a hexagonal grid with a spacing of 125 meters, each string carries 60 DOMs positioned at 17-meter intervals.

In the center of this area, there are eight wires positioned in a tighter configuration. The intervals between them are always only 7 meters. These methods help form the "deep core" sub-detector, reducing the neutrino energy detection threshold to around 10 kilo-electron volts effectively. It is conducive to conducting in-depth research on the phenomenon of neutrino oscillation.

3.2 How Does IceCube Work

Neutrinos themselves cannot be detected directly. However, when they come into contact with ice, they will generate secondary particles with electric charges. These particles will emit Cherenkov radiation when passing through the ice layer at a speed exceeding the speed of light in that medium. The IceCube detectors have the ability to capture this light, and then this light will be turned into digital forms marked with accurate time nodes. The data is transmitted to computers located in the IceCube Laboratory on the surface. These computers will detect lights from different DOMs, turning them into identifiable light patterns that allow researchers to determine the trajectories and energies of incoming muons and neutrinos.

4. A New Approach for Solar Dark Matter Detection

4.1 Proposed Methodology

People now have many methods to use to searching for solar dark matter annihilation with JUNO. The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose underground liquid scintillator (LS) detector currently under construction in China. With a design mass of 20 kilotons, its primary scientific goal is to determine the neutrino mass hierarchy by precisely detecting reactor antineutrinos. The JUNO central detector functions are just like a highly sensitive LS calorimeter, characterized by both energy resolution and a very low energy threshold. Notably, liquid scintillator detectors possess the capability to reconstruct the track direction of energetic charged particles. This is achieved by analyzing the timing pattern of the first photon hits on the photomultiplier tubes (PMTs), leveraging the fact that these energetic particles have a faster speed than light in the LS medium (a phenomenon known as Cherenkov radiation). This directional sensitivity enables the JUNO detector to identify and study neutrinos originating from dark matter (DM) annihilation in the Sun.

A dark matter particle from the halo can undergo elastic scattering with solar nuclei, lose a significant portion of its energy, and become gravitationally bound to the Sun. Conversely, every dark matter annihilation event within the Sun results in the removal of two dark matter particles. The time evolution of the number of dark matter particles, N, inside the Sun can thus be expressed as:

$$\ddot{}\,³⁄₄ = C_{\odot} - C_A N^2 \tag{2}$$

C ⊙ (Capture Rate): The rate that appearing when dark matter is captured by the gravitational force of the Sun. It depends on the scattering cross-section between dark matter and atomic nuclei. C_A * N^2 (annihilation rate): The rate at which dark matter annihilates with each other at the center of the sun. It depends on the annihilation cross-section [8].

4.2 Signal vs. Background Discrimination

Background information from the interactions of neutrinos in the atmosphere. Irreducible Background: The charged current (CC) interactions of atmospheric ν_e and $\bar{\nu}_e$. These events are exactly the same as the signal process and cannot be distinguished based on the type of interaction.

Reducible Background: The interaction between neutral currents (NC) in the atmosphere and neutrinos. These interactions produce π^0 mesons, which immediately decay into two photons, generating a signal in the detector similar to that of an electron (electromagnetic shower), which may be misidentified as a signal event. However, the paper points out that this background can be largely ignored through energy cuts.

Statistical Techniques for Sensitivity. Sensitivity calculation: After determining the expected number of signal events N_S and the background event number N_B, the paper employs the classic Feldman-Cousins method or a similar statistical framework. Under the given confidence level (typically 90%), it calculates the minimum number of signal events required to distinguish from the background fluctuations, thereby deriving the exclusion limit (sensitivity) for the dark matter scattering cross-section. Machine learning (implication): Although the paper does not explicitly use the term "Machine Learning", the process it mentions of obtaining the selection efficiency ϵ(E_ν) based on Monte Carlo (MC) simulations is the foundation of modern particle physics analysis. More complex analyses typically use MC data to train multivariate classifiers (such as Boosted Decision Trees, Neural Networks) to more optimally distinguish between signals and backgrounds, rather than simply using rectangular cuts. The statement "The related studies are under way" in the paper implies that further optimization of direction reconstruction and topological identification may adopt more advanced algorithms.[8] Upper Limit (N_90): The solid lines with dots denote the maximum number of signal events that could be observed without claiming a detection, establishing the 90% confidence level upper limit (N_90). This limit is influenced by both the magnitude of the background and the statistical approach employed

In the case of the $\nu\bar{\nu}$ channel (blue line), N_90 declines from approximately 5.6 to around 2.5 as the mass increases. This reduction occurs because the angular cone θ_sun, which is inversely proportional to the square root of neutrino energy (θ_sun ∝ 1/√(E_ν)), becomes narrower with increasing mass (and hence energy). Consequently, the search region shrinks, leading to fewer background fluctuations and tighter statistical limits.

Conversely, for the continuous spectrum channels, N_90 remains relatively constant due to the fixed size of their search region.

So overall, this figure highlights the primary difficulty in detection—namely, the presence of atmospheric neutrino background—and provides the threshold number of signal events required to assert a discovery, assuming only background contributions are present.

5. Future Directions

"IceCube - Generation 2" is an expansion project of the "IceCube Neutrino Observatory" located in Antarctica.

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This project, along with nine other initiatives, has been included in the list of the most strategically significant and promising research infrastructure candidate projects selected by the Federal Ministry of Research, Technology and Space (BMFTR). This news was officially announced by Federal Research Minister Dorotea Bar on the beginning of this month. The volume of the “IceCube - Generation 2” detector will be eight times that of the existing facility, and its detection sensitivity will also be increased by eight times. This upgraded version will significantly enhance the ability to detect cosmic neutrinos while maintaining relatively low construction and operation costs [9].

6. Conclusion

This study demonstrates that searching for high-energy neutrinos produced by dark matter annihilation within the Sun offers a promising indirect approach to investigating dark matter characteristics. The proposed framework effectively connects the gravitational accumulation of dark matter in the solar interior to an observable neutrino flux at the IceCube detector. Critical findings indicate that the expected signal depends on astrophysical parameters, especially the distribution of the movement speeds of dark matter particles. and is influenced by neutrino propagation effects within the Sun’s core. Moreover, sophisticated statistical techniques are essential to separate this signal from the dominant background of atmospheric neutrinos.

The method holds significant broader implications, serving as a complementary strategy to direct detection efforts, especially in constraining spin-dependent interaction cross-sections. Detecting such a signal would not only provide evidence for dark matter annihilation but also yield insights into the underlying particle physics properties of dark matter. Additionally, this research underscores the importance of high-energy neutrino observatories in the context of multi-messenger astrophysics and lays the groundwork for next-generation experiments such as IceCube-Gen2 and JUNO, which are expected to explore areas in the parameter space of dark matter that were previously inaccessible.

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