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Critical Literature Review
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What do the results from the IceCube Neutrino Detector teach us about Dark Matter?

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Abstract:
Cosmological measurements have revealed that matter familiar to us makes up only approximately 5% of the energy density of our universe. The remainder has been labelled Dark Matter (about 26%) and Dark Energy (the rest). This paper summarises how the IceCube Neutrino Observatory situated at the South Pole is being used to search for direct evidence of Dark Matter. Supersymmetry (SUSY) models are regarded as the most promising extensions of the Standard Model, and the paper describes the tests of SUSY predictions for the annihilation of Dark Matter in the core of the sun. The lack of an observable signal is used to constrain the set of values for free parameters within the SUSY model. IceCube's results complement those from other experiments which use different detectors for Dark Matter interactions, and together are placing meaningful constraints upon the most promising SUSY models.

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1. Introduction

Our current understanding of the fundamental structure of the universe indicates that only 4.9% of the energy density can be explained by matter that we can describe accurately, with 26.5% being categorised as Dark Matter, and the remainder as Dark Energy (Ade et al., 2016). The "Dark" adjective not only describes the physical invisibility, but also our state of knowledge.

Antarctica's dry, cold and stable atmosphere makes it well suited for making astronomical observations, and there are several telescopes and observatories located at the South Pole. While establishing a roadmap of science priorities for the next 20 – 30 years, the Scientific Committee on Antarctic Research (SCAR) has recognised the unique contributions Antarctic observatories can make both to near-earth space science and to fundamental questions such as "What is the nature of the Dark Universe and how is it affecting us?" (Kennicutt et al., 2015).

This paper seeks to summarise how the IceCube neutrino detector at the South Pole is being used to search for Dark Matter, what we know to date, and the current status of one search. For the purposes of brevity, the abbreviations DM = Dark Matter, and SM = Standard Model are used through this paper.

2. Introduction to neutrinos and the Standard Model

Neutrinos were first hypothesized by Pauli in an unpublished letter to colleagues in 1930 to explain radioactive decay: a neutron would change into a proton and an electron with the proposed neutrino required to balance the observed momentum. Neutrinos were first experimentally detected in 1956 (Cowan and Reines, 1956).

The Standard Model has been developed to describe all known particle interactions except gravity, and has been remarkably successful, even though it is recognised to be incomplete because it excludes gravity. The particles are summarised in Figure 1. Quarks and leptons constitute matter, with the gauge bosons intermediating the strong, weak and electromagnetic interactions. The Higgs boson is related to the gauge bosons, but rather than intermediating a force is ultimately responsible for particles having a non-zero mass (which means they interact with gravity). Fermions are spin-1/2 particles, bosons have integer spin, where the spin is a fundamental property which determines the behaviour of a collection of the particles – atomic structure and chemistry originates from the fact that two fermions cannot be in identical states.

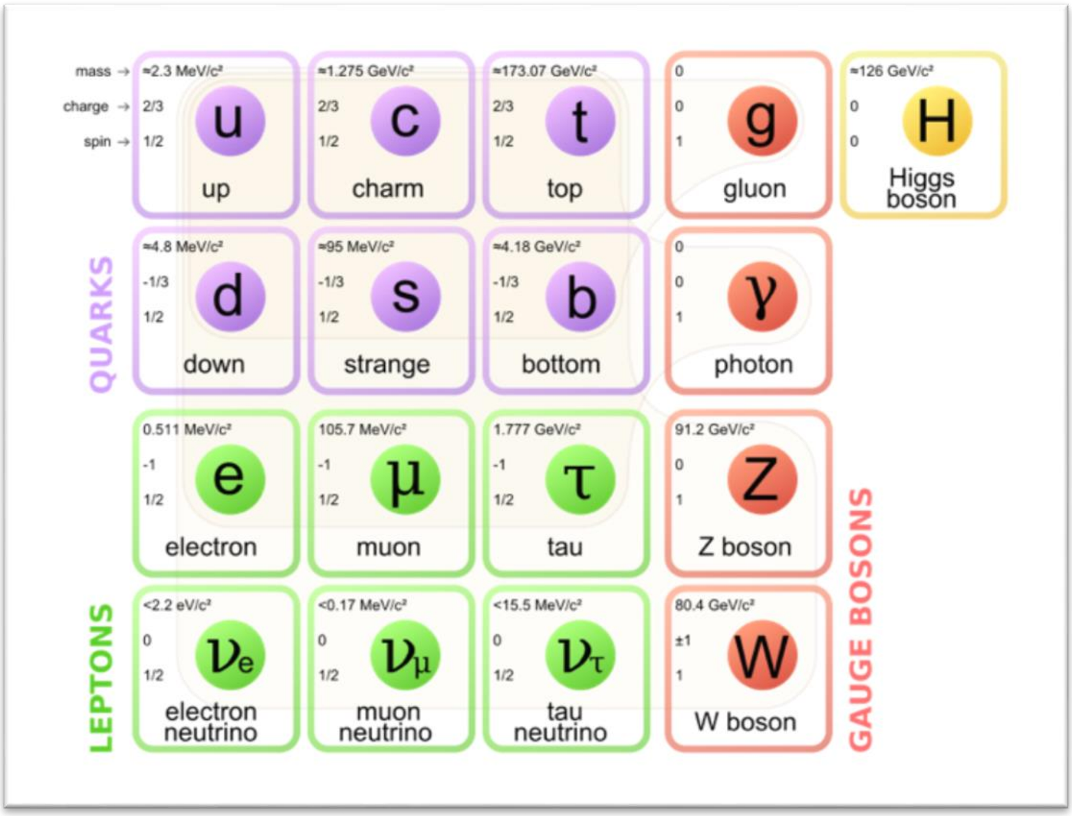

Figure 1: the particles of the Standard Model (Wikipedia, 2017)

The Standard Model organises the fermions into families, with the lightest being the u & d quarks, the electron and its neutrino, labelled ν_e. The interactions mediated by the gauge bosons describe how particles can be converted from one to another, subject to the conservation of energy. This means that particles in the families beyond the first rapidly decay and can only be observed in specially constructed detectors. Muons from the second family are relatively long-lived, decaying only through the Weak Interaction with a mean lifetime of 2.2 X 10^{-6} seconds (C. Patrignani et al., 2016).

Neutrinos interact with other particles only through the Weak Interaction, which at everyday energies has a relative strength compared to electromagnetism of 10^{-5} (*Particle Data Group Website, Electroweak Interactions*). That explains why low-energy neutrinos interact very weakly with each other and with matter – approximately 6.5 X 10^{10} neutrinos produced in the fusion reactions in the Sun pass through each cm^2 of us and our surroundings every second with no effect (Grupen, 2005).

3. Neutrino astronomy, IceCube, and the South Pole

The IceCube Neutrino Observatory in Antarctica was designed to detect neutrinos originating from ultra-high energy cosmic rays (UHECRs), extending the range of energy at which neutrinos have been observed. Weakly interacting neutrinos mean that the size of the detector is very important and at $1km^3 = 1 \times 10^9$ m^3 it is the biggest in operation (the ANTARES telescope in the Mediterranean has detectors covering 3 X 10^6 m^3 volume).

IceCube does not "see" neutrinos directly. The detector is triggered when a charged particle passes through at a speed higher than the speed of light in the ice and generates Cherenkov radiation, which is visible light emitted by the particle, and is analogous to the bow-wave of a ship travelling faster than the speed of waves on water. This happens when a neutrino interacts with the protons and neutrons in the ice producing an energetic muon which travels a significant distance before it decays.

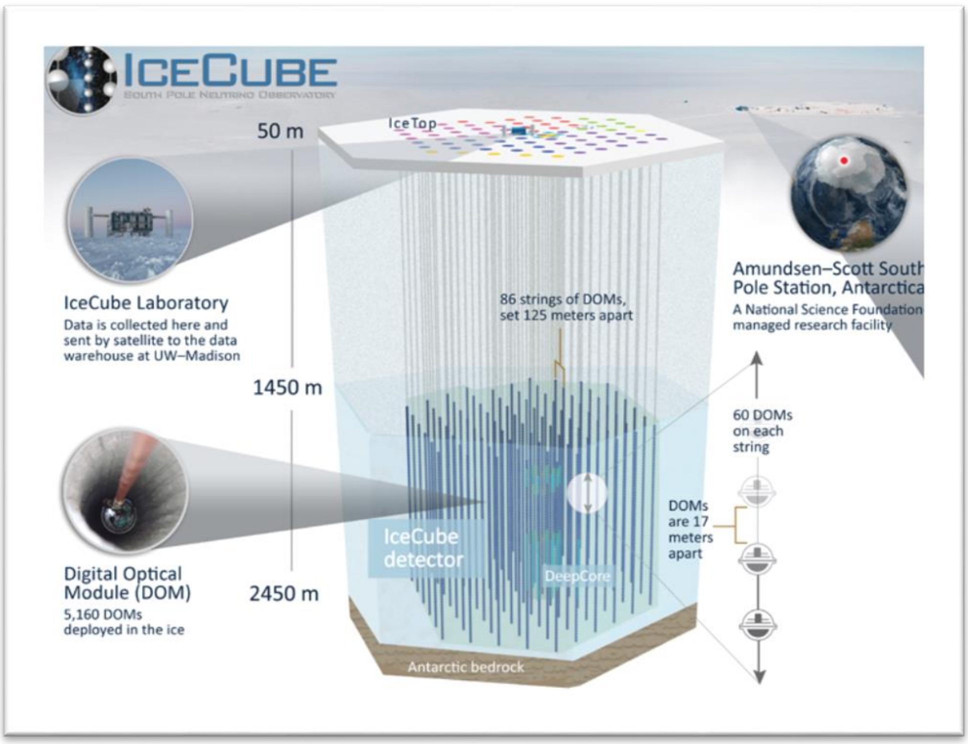

Figure 2: Schematic of the IceCube Detector (*IceCube Neutrino Observatory Website*)

Figure 2 provides an overview of the detector, which in essence consists of long strings of light-sensitive detectors (DOMs) buried deep in the ice. The detectors start 1450m under the ice, to shield them from cosmic ray background. The ice in Antarctica is so old and compacted that light can travel a long way. The optical properties are consistent across large volumes, although this represents one of the main areas of uncertainty in calibrating the detector. After drilling the holes and inserting the string of DOMs, they freeze into the ice. While this is potentially an issue for maintenance, it is a less hostile environment in terms of material degradation than corrosive seawater used in ANTARES.
The strings of DOMs were initially placed 125 meters apart, optimised to detect neutrinos from ultra-high-energy cosmic rays (UHECRs). Subsequently, strings were added in the middle of the detector at narrower separation so as to improve the sensitivity to lower energies, allowing the telescope to be used in searches for Dark Matter.

Figure 3 shows how the information regarding the intensity of the light and its time of detection is used to reconstruct an event within the detector, providing both the direction of travel and the energy of the muon involved.

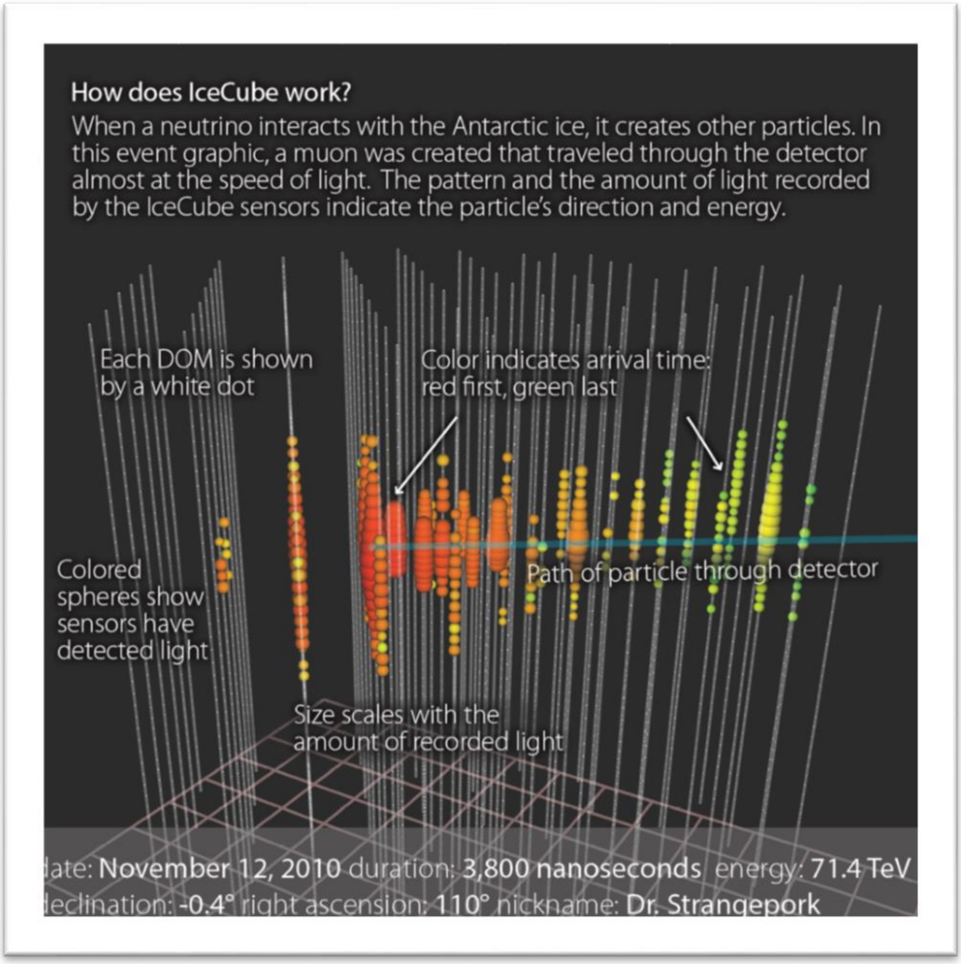

Figure 3: Neutrino-muon event in IceCube (*IceCube Neutrino Observatory Website*)

4. What is Dark Matter?

Dark Matter was proposed by Zwicky (1933) to explain measurements of galaxies in the Coma Cluster. Measurements of galaxy rotation by Rubin and Ford (1970) showed that additional mass was required to explain observations.

The Cosmic Background Explorer, COBE, (Smoot et al., 1992) and Wilkinson Microwave Anisotropy Probe, WMAP, (Komatsu et al., 2013) measurements of the Cosmic Microwave Background (CMB) show a fine structure (anisotropy), which provides information on the distribution of matter at the time the CMB formed. Analyses reveal that matter alone is insufficient to explain the observed clustering (see Figure 4.). Recent measurements by the Planck Collaboration (Ade et al., 2016) conclude that 26.5% of the energy density of the universe comes from Dark Matter, 4.9% from matter (described by the Standard Model) and the rest is Dark Energy, responsible for the increasing rate of expansion of the universe.

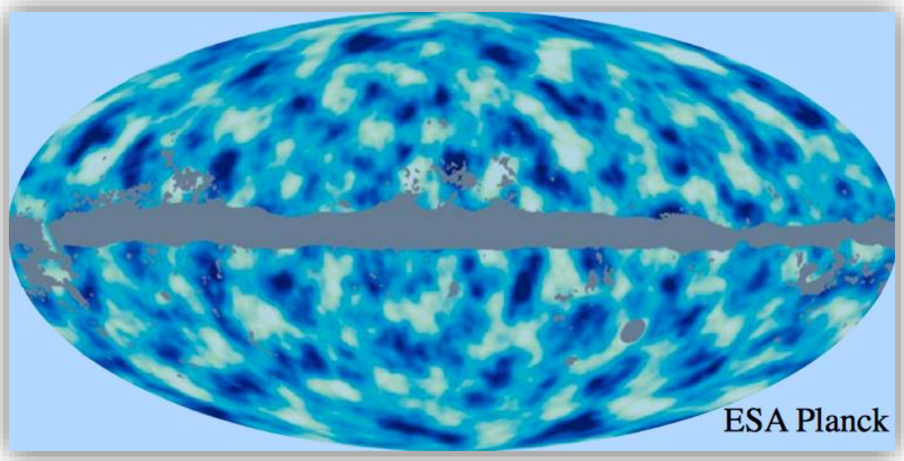

Figure 4: Planck Collaboration all-sky image of the distribution of dark matter via distortions on CMB by gravitational lensing (April 2013) as reported by Maruyama (2014)

Hypotheses consistent with the Standard Model as to what could constitute the invisible mass include massive neutrinos (Hot Dark Matter, HDM), and MACHOs (Massive Compact Halo Objects) such as black holes, neutron stars and planets. Measurements of neutrino mass, and scans seeking the effects of gravitational lensing appear to rule against these explanations as reviewed by Silverwood (2016).

Current knowledge of DM can be summarised:

- It is electrically neutral
- It interacts with normal matter through gravity
- It must be stable on long timescales so as to explain both the anisotropy in the CMB and the results of galaxy rotation measurements
- It interacts weakly with itself. Observations of the Bullet Cluster show very low levels of interaction compared to “ordinary matter” (Clowe, Gonzalez, and Markevitch, 2004)

Theoretical models extending the Standard Model are useful as frameworks to explore further the nature of DM, since they may predict possible signals to search for experimentally. A range of different frameworks have been suggested to date, each producing potentially stable DM particles:

- Axions, particles originating from additional symmetry-breaking mechanisms, similar to those in the Standard Model (Preskill, Wise, and Wilczek, 1983).
- Sterile neutrinos, “right-handed” partners of the known neutrinos, which are “left-handed”[1], and have masses in the keV range (Dodelson and Widrow, 1994).
- Supersymmetry (SUSY) particles – the lightest stable particle is the neutralino.

It has also been recently proposed that the effects attributed to DM are not in fact additional particles, but rather modifications of how gravity works at scale (Verlinde, 2016).

With so many competing ideas to explain the observed phenomena, it is very important to gather more observational data about DM, in order to get some handle on what mechanisms are actually involved.

5. Searches for Dark Matter

The current focus of most DM searches is for particles generically described as WIMPs (“Weakly Interacting Massive Particles”) which interact weakly with matter, but are massive, and so interact through gravity. WIMP and DM particle are often used synonymously. The working assumption is that they can be described by super-symmetric (SUSY) models. These extend the Standard Model by means of additional symmetries between particles of odd- and even-spin, helping to address theoretical issues within the Standard Model. A consequence of the additional (broken) symmetries is the addition of partners to all SM particles, such as spin-1 squarks as partners for the spin-1/2 quarks, and spin-1/2 neutralinos as partners of the particles mediating the weak interactions. At least one of the neutralinos is expected to be stable, and is thus a candidate for DM.

The mechanisms underlying searches for DM can be summarised as “make it”, “shake it”, or “break it”, as summarised in Figure 5. It is assumed that there is some interaction mechanism linking DM and matter (other than gravity). Such an interaction would mean that it could be possible (a) to make DM particles through the annihilation of two SM particles; (b) to observe interactions in which a DM particle scatters off a SM particle; (c) to identify SM particles originating from the annihilation of DM particles.

[1] Left-handed and right-handed fermions are those with the particle spin aligned respectively against and with the direction of motion. The Weak Interaction of the SM interacts only with left-handed fermions and right-handed anti-fermions.

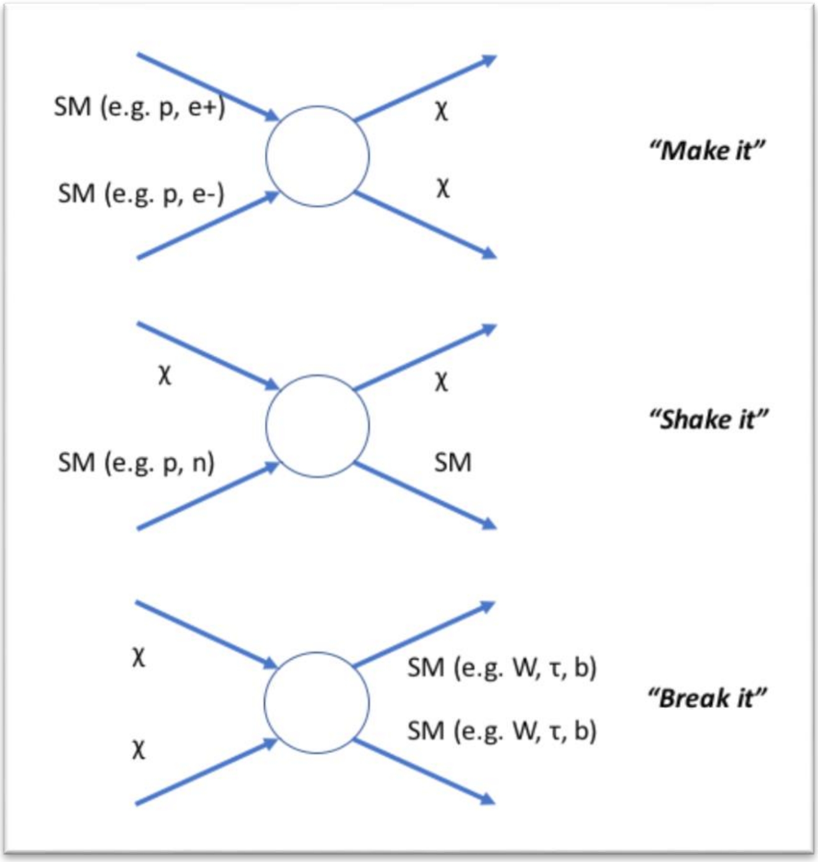

Figure 5: DM interactions with SM particles

Thus, there are three types of searches for WIMPs experimentally:

1. Creation ("Make it")
   Particle colliders are designed to investigate the creation of new particles as a result of interactions between SM particles. The Large Hadron Collider (LHC) succeeded with this approach in 2012 to discover the Higgs Boson, the final building block predicted by the Standard Model. Current results from the LHC do not indicate the existence of any particles beyond those expected in the Standard Model (Cosa, 2015). The search boundaries of "create it" are limited by the energy available in colliders.
2. Direct detection ("Shake it")
   A DM particle interacts with a target substance in a dedicated detector, and properties of the DM particle can be inferred from the resultant measurements of the reaction products.
3. Indirect detection ("Break it")
   Dark Matter is distributed throughout space, but through its gravitational attraction, clusters around massive objects. Thus, it ought to be possible to observe the products of DM annihilation in large-mass structures, such as the sun, the galactic centre or galaxy clusters.

Direct and indirect searches do not suffer from the energy constraint, since both rely on the prior existence of DM particles. While there are different mechanisms involved, the underlying theoretical model predicts relationships between them. Thus, while to date DM has not been created in a collider, combining complementary information from direct and indirect searches is beginning to constrain the parameter space available for SUSY models.

6. Searches for Dark Matter in the sun with IceCube

The IceCube detector carries out a number of indirect searches for DM, focussed on areas of the sky in the direction of concentrated mass, such as the Sun, the centre of our galaxy, and the centre of nearby sub-dwarf galaxies, looking for the results of "break it" processes. That pre-supposes that DM particles can annihilate each other. In the case of SUSY models, the lightest stable SUSY particle is the neutralino, which is its own antiparticle so that two neutralinos can annihilate.

Theoretical predictions

The SUSY framework provides some insight into the mechanisms by which DM annihilation can occur, but the actual probability of that happening depends upon the value of parameters used within the model. Even the Minimal Supersymmetric Model (MSSM) contains 178 free parameters, although these can be reduced through the imposition of various assumptions. In the following a version with 25 free parameters (MSSM-25) will be compared with experimental observations (Silverwood et al., 2013).

Computer programs such as DarkSUSY (Gondolo et al., 2004) have been developed to calculate the expected signal from various DM events and include the details of detector configuration and topology. This allows theoretical predictions to be expressed in signals directly comparable with experimental results.

Both theoretical predications and experimental results are expressed in terms of cross-sections, which are independent of a particular experiment and therefore allow comparison of results. A cross-section (traditionally labelled σ) is a measure of probability that a particular interaction, such as scattering, will take place when a particle is fired at a target. It is expressed as an area, expressed in units of 10^{-24} cm^2, called 1 barn. Nuclear reactions (such as neutrons scattering on atomic nuclei) have cross-sections measured in barns. Neutrino interactions with protons have cross-sections of the order of 10^{-38} cm^2 or less, underlining the need for large detector masses with many protons in order to achieve reasonable event rates.

While the details of the calculations are beyond the scope of this paper, the following seeks to motivate how the DM annihilation processes ("break it") in the sun can be linked to the scattering cross-sections ("shake it") measured in the direct experiments.

DM particles interact with themselves and matter through gravity, so that DM forms spherical haloes around the sun as a massive object. Through "shake-it" scattering interactions, DM particles collide with solar material, lose energy and gradually slow down, accumulating in the centre of the sun. It is there that DM particles annihilate. While the scattering process adds to the numbers of DM particles in the solar core, annihilation events reduce the number. It is assumed this process has achieved equilibrium, so that the total number is not changing, i.e. the rate of capture is twice the rate of annihilation (since 2 DM particles are annihilated). Thus, the cross-section for DM annihilation is ½ that for capture, i.e. half that for scattering.

Figure 6 illustrates the scenario being tested, with the main steps in the process that results in muon-neutrinos reaching the IceCube detector and being detected as muons.

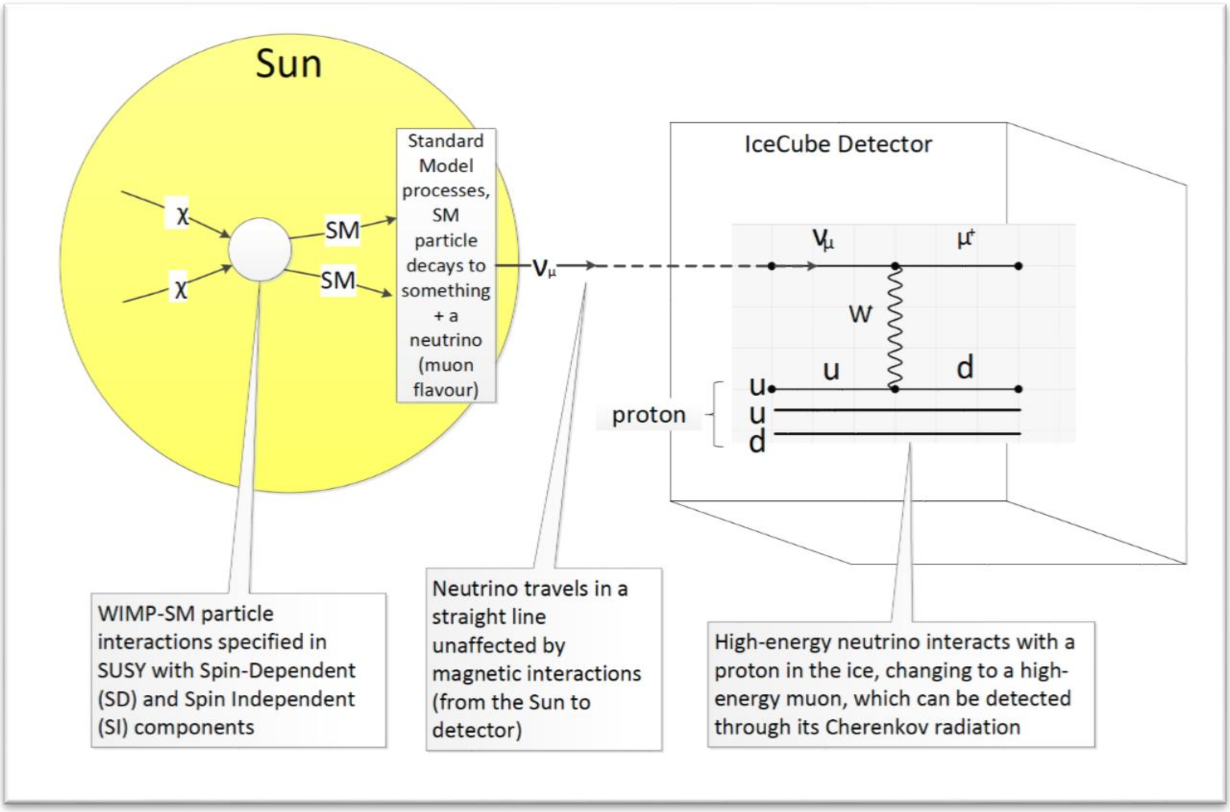

Figure 6: Schematic of the DM annihilation process in the sun

The DarkSUSY program generates the probability of producing particular SM products with the most likely routes

$$\chi + \overline{\chi} \xrightarrow{yields} \tau + \overline{\tau}\,;\;\; \mathrm{W}^+ + W^-\,; \quad \mathrm{b} + \overline{\mathrm{b}}$$

where χ is the DM particle, and in each alternative, a particle-antiparticle pair of heavy SM particles is created (a bar over the particle symbol signifies the antiparticle). The SM particles are short-lived, and decay into lighter SM particles, including in some cases neutrinos. Neutrinos are not affected by electromagnetic fields, so travel in a straight line. The experimental signature of these events is a concentration of high-energy neutrino events originating from the direction of the sun.

Experimental Challenges – handling the massive background from cosmic rays

IceCube detects Cherenkov light from muons passing through the ice. There is no label attached to each event, explaining its origin, so the challenge is to link the events seen to the ones being sought. This is especially challenging because cosmic ray radiation hitting earth's atmosphere generate the order of 3000 events per second in IceCube. An illustrative picture of a cosmic ray shower is shown in Figure 7. The search for DM-related events has to extract a signal from that much larger background.

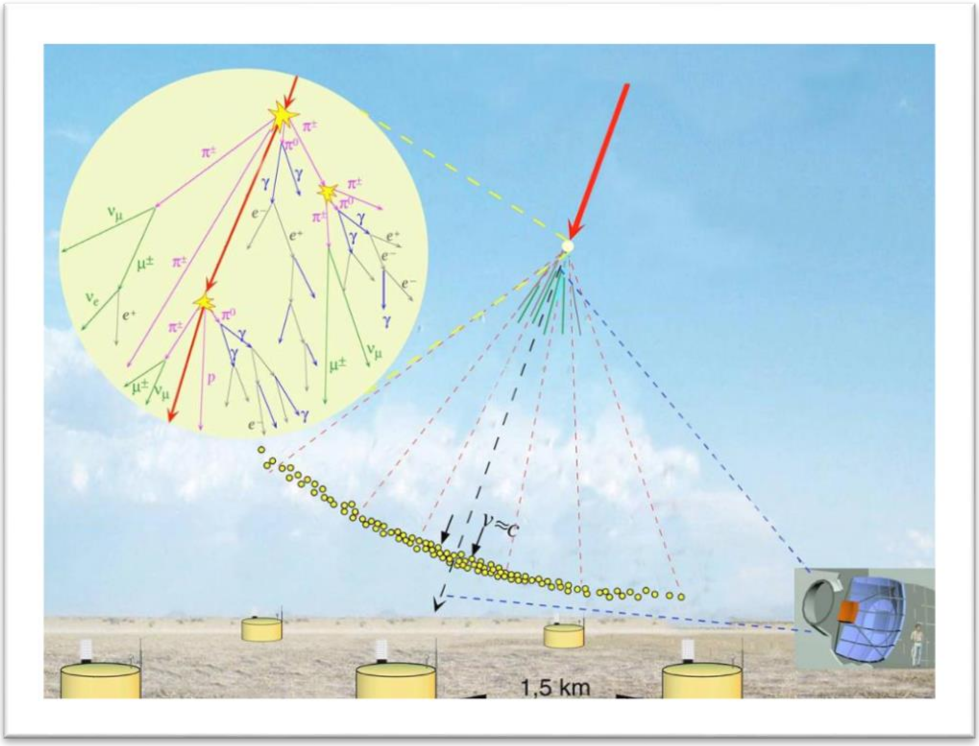

Figure 7: Illustration of a cosmic ray shower (*Pierre Auger Observatory*)

There are many techniques employed to filter the dataset so as to maximise the signal relative to the background (Aartsen et al., 2013, including

- Focussing only on events that clearly originate within the volume of the detector;
- Restrict the search to the DeepCore part of IceCube, and explicitly exclude events that have more tracks in the outer part; and
- Separate the data into Winter and Summer sets. The sun is below the horizon during winter, and background events are shielded by the Earth.

The separation of astrophysical neutrino events from those originating in cosmic ray interactions is a critical aspect of the analysis, and requires a thorough understanding of the detector's behaviour and sensitivity.

7. Results from IceCube searches for DM-annihilation in the sun

SUSY models predict two different types of coupling between DM and SM particles, one spin-dependent (SD) and the other independent of spin (SI), and so the rate of events from annihilation of two DMs is related to two scattering ("shake it") cross-sections, $\sigma_{SD,p}$ and $\sigma_{SI,p}$.

Spin-independent Cross-sections

Figure 8 shows the IceCube results (Aartsen et al., 2013) for the maximum possible spin-independent cross-section for DM with protons compared with that measured by a number of other experiments as well as predictions from MSSM (Minimally SuperSymmetric Models).

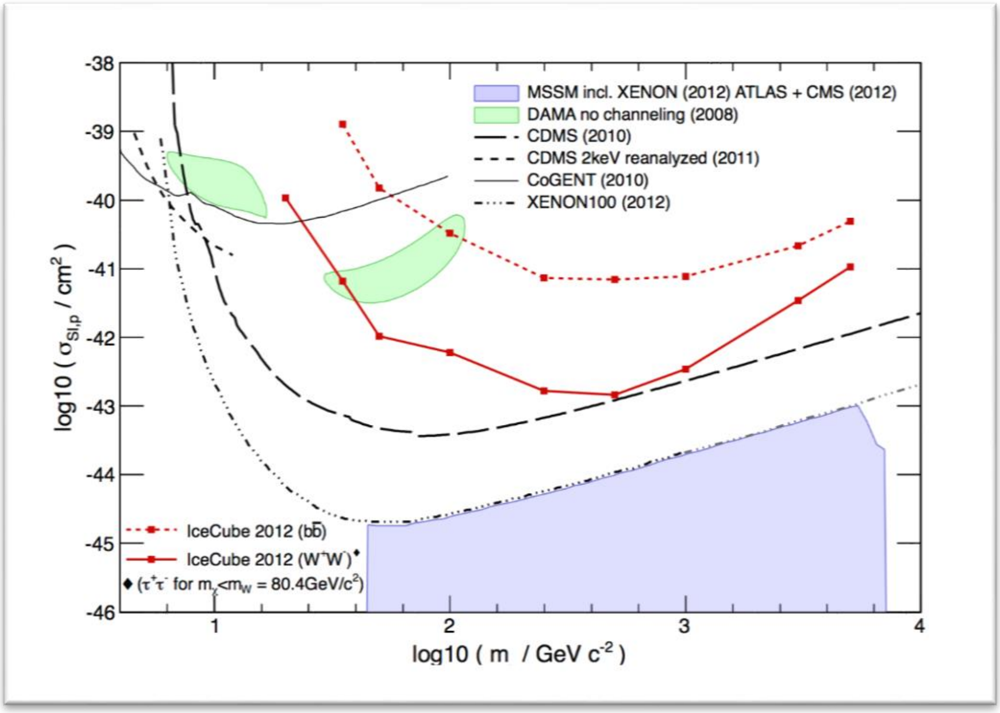

Figure 8: Results from the IceCube collaboration for $\sigma_{SI,p;}$ see Aartsen et al. (2013) for references to the results from other detectors

The IceCube results are plotted as results of the cross-section measured assuming a specific value for the mass of the WIMP (m_χ) measured in GeV /c^2 along the x-axis. Each point is the maximum cross-section possible which is consistent with the lack of events that are not accounted by the background. The curves should thus be read as the experimental upper limits on the cross-section, and any theoretical predictions lying above the curves are inconsistent with current observations.

Results from direct experiments ("shake it") are also shown. The spin-independent cross-section is proportional to A^2 (where A is the atomic number of the target). Direct detection experiments use targets with high "A" (e.g. Xenon has A = 54) to maximise the chance of detecting events, which in turn means that they can place more stringent limits on $\sigma_{SI,p}$ than IceCube.

The predictions from MSSM are shown by the (purple) shaded region. The diagram shows that it is the results from XENON100 (Aprile et al., 2012) and LHC (the Atlas & CMS experiments, Cosa, 2015) that place constraints on the spin-independent properties of DM particles in MSSM.

Spin-dependent Cross-sections

Figure 9 shows the results for the spin-dependent cross-section $\sigma_{SD,p}$. In this case IceCube provides the most stringent limits. There is no enhancement of sensitivity for direct detection through changing the atomic number of the target.

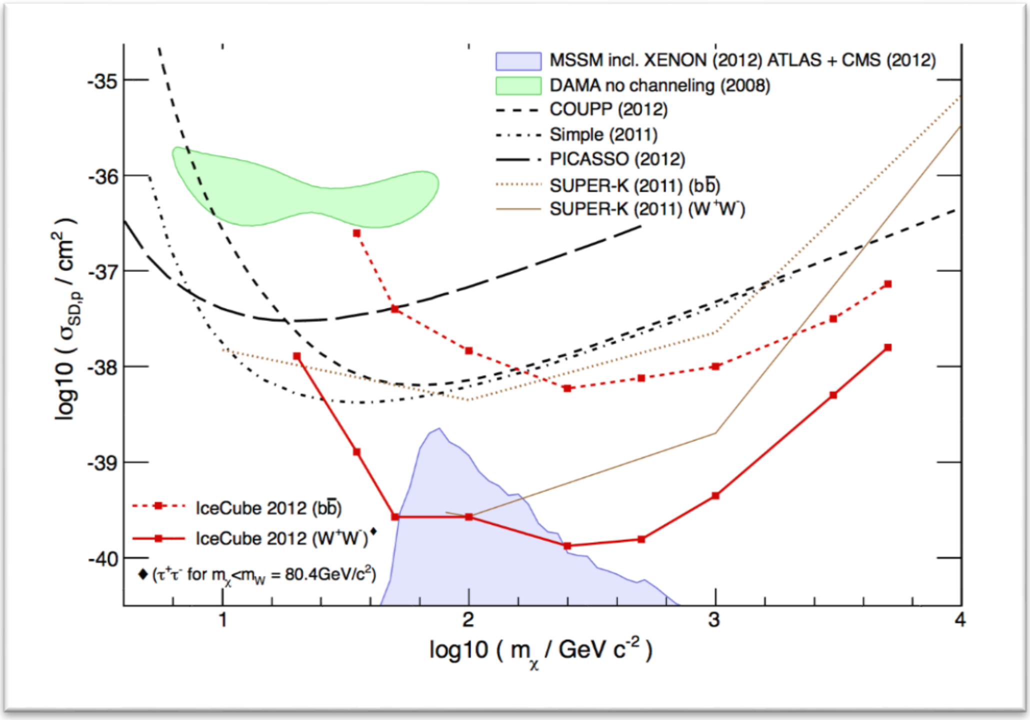

Figure 9: Results from the IceCube collaboration for $\sigma_{SD,p}$ see (Aartsen et al., 2013) for references to the results from other detectors

The (purple) shaded region represents the potential range of predictions from MSSM models that have not yet been explicitly ruled out by previous experiments failing to find the predicted signal.

The annihilation channel $\chi + \overline{\chi} \xrightarrow{yields} \tau + \overline{\tau}$; $W^+ + W^-$ (just τ at energies below the W threshold) is the most sensitive and can be seen to further constrain the parameter space of the MSSM models beyond the limits placed by LHC and direct detection experiments.

8. Future directions for IceCube DM searches

The current results from IceCube place constraints on the MSSM parameter set, and the more data collected, i.e. the more live-time for the telescope, the stronger those constraints will become. If a signal is detected, they will serve to complement the results of other detection methods to begin to tie down parameter ranges in the models.

IceCube has also achieved its design objective and observed a number of very high energy neutrinos (Aartsen et al., 2013), which originate outside the atmosphere, a discovery which has generated a lot of interest and excitement.

There are currently two proposals to upgrade the IceCube detector. IceCube Gen2 aims to extend the area/volume covered to increase the sensitivity to UHECRs by adding new strings 250m apart, increasing the detector volume tenfold. The second proposal is called PINGU (Precision IceCube Next Generation Upgrade) aiming to extend the DeepCore component to enhance sensitivity for DM searches, and to investigate further the relationships between the three neutrinos of the Standard Model. As of January 2017, neither proposal has yet received funding approval.

9. Summary & Conclusions

A number of cosmological measurements, including galactic movements and the Cosmic Microwave Background indicate that there is material in the universe not explained by the Standard Model. It has been called Dark Matter, not only because it is invisible, but also reflecting our state of knowledge about it.

Many theoretical models have been proposed to extend or fundamentally replace the Standard Model, but experimental data are required to constrain or refute these. Many experiments are being carried out to test predictions from these new models, but to date, no detector has observed a signal uniquely attributable to DM. Nor can one detector alone provide a complete picture. The IceCube detector's DM searches complement those of other experiments, and provide the most stringent constraints to some components of the most popular theoretical models. While we are still none the wiser as to what exactly Dark Matter is, experimental constraints such as those placed by IceCube make it seem unlikely that it can be explained by Supersymmetry (SUSY).

Acknowledgements
I would like to thank Jenni Adams and Hamish Silverwood for enlightening conversations, and Hamish explicitly for the "make it", "shake it", "break it" labels. A conversation with Ryan Bay from the RAID (Rapid Access Ice Drill) collaboration was very illuminating in regard to the difficulties in calibrating the optical properties of the ice in the IceCube detector.

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