Improved methods for solar Dark Matter searches with the IceCube neutrino telescope

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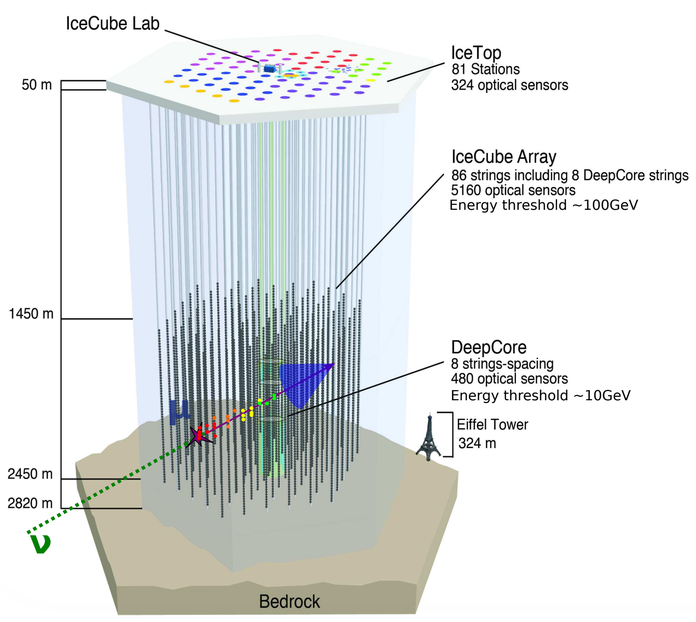
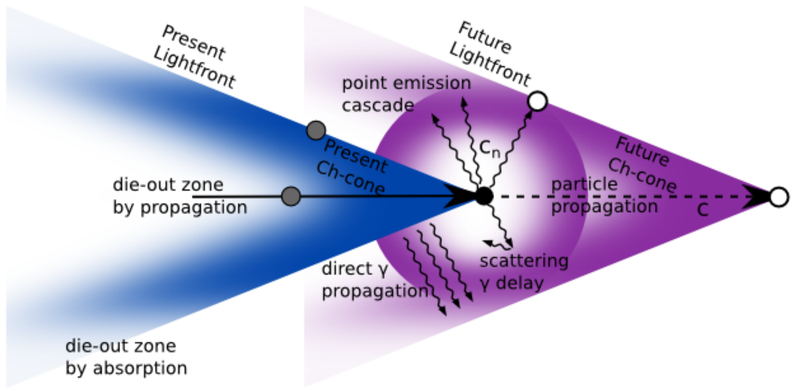
The IceCube Detector

IceCube is a cubic-kilometer sized neutrino detector installed in the glacial ice at the geographic South Pole between depths of 1450m and 2450m. Finished 2010 the detector consists of an array of 5160 DOMs assembled on 86 so-called strings. The DOMs detect the light emitted whenever a neutrino undergoes an interaction on a nucleus in the ice (hit). Only the CC interaction of a muon neutrino creates an energetic and therefore long-ranged muon, whereas the products of all other interactions lose all their energy in particle showers with a typical size of a few meters. Events in IceCube thus leave two distinct hit patterns in the detector: tracks, identified by the extended pattern of Cherenkov-light emitted as the muon propagates O(km), and spherical cascades, caused by particle showers in NC and CC interactions, as well as by stochastic losses along a muon-track, which can dominate in terms of the amount of light emitted. All IceCube analysis reconstructs events recorded in the detector by fits to these two very distinct light distribution patterns.



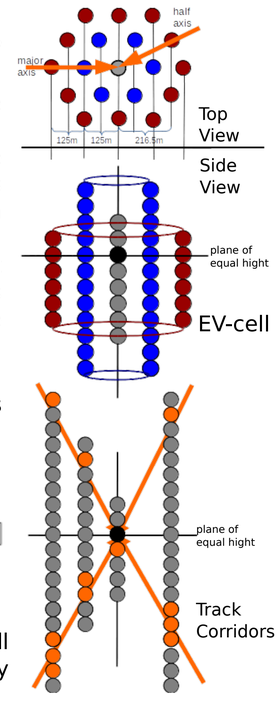
Event-Splitter IceHive

In IceCube data two effects of nuisance are found: detector noise (500-700Hz per DOM) and event coincidences, where two or more events are simultaneously present inside the detector (~10% of events). Both effects lead to errors in event reconstructions which need to be addressed. A novel event-splitter named IceHive has been developed based on clustering of DOM-hits in space and time with an imposed multiplicity requirement. It is based on the determination of whether any two hits are causally connected, i.e. caused by a common source of light (physics hit), different from stochastic noise (noise hit). Collecting physics hits into clusters while excluding noise hits allows the separation of individually developing sub-events in the detector.



The relation between two physics hits are:

- hits are located on different geometrical/ topological sites of the same light-front, thus are spatially separated with no or little time separation
- hits are caused by photons of the same light-front travelling between DOMs, thus hits are connected by the speed of photon propagation
- hits are caused by light-emission at different positions along a muon-track, thus hits are connected by the speed of particle propagation



The causal connection between hits is determined by the binary estimator

$$E(h_1,h_2) = [(h_2 \in EV_{\text{static}}(h_1)) \wedge (\alpha^-_{\infty} \le R_{\infty}(h_1,h_2) \le \alpha^+_{\infty})] \vee [(h_2 \in EV_{\text{photon}}(h_1)) \wedge (\alpha^-_{c_{\text{ice}}} \le R_{c_{\text{ice}}}(h_1,h_2) \le \alpha^+_{c_{\text{ice}}})] \vee [(h_2 \in EV_{\text{particle}}(h_1)) \wedge (\alpha^-_{c_{\text{vac}}} \le R_{c_{\text{vac}}}(h_1,h_2) \le \alpha^+_{c_{\text{vac}}})]$$

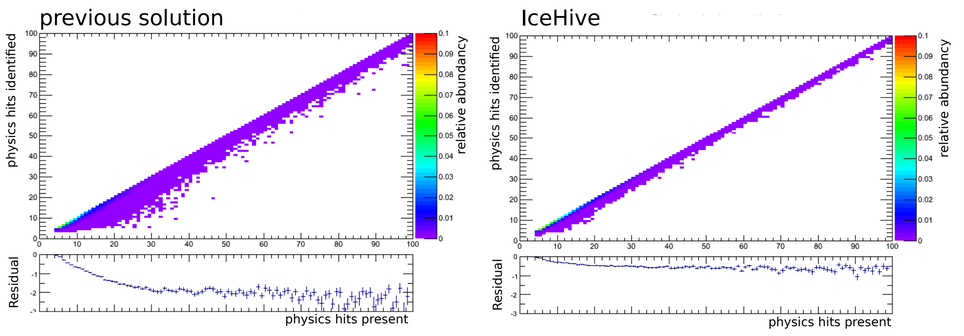
based on the arrival time residual

$$R_v = (t_1 - t_2) - |\vec{r}_1 - \vec{r}_2|/v$$

and eligibility volume (EV) containing all DOMs to which a specific hit can possibly connect.

Results

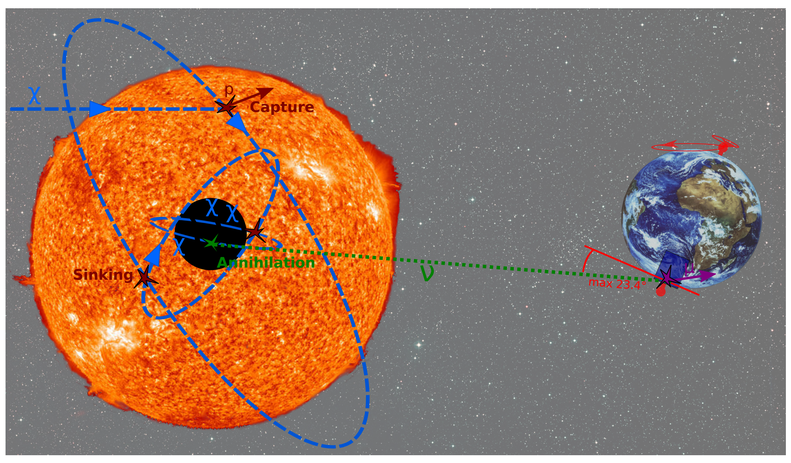
This refined model and the careful selection of involved parameters make IceHive very robust against the influence of noise, so that its application on the raw detector readout becomes possible. Applied before online reconstructions and filters, IceHive could demonstrate an additional background reduction of 30% for muon topologies and 65% for cascades. Coincident events were separated at a success rate of 87%. This poses a significant improvement over previous approaches.



Comparing the selection of physics hits. Optimal performance is indicated along the diagonal. The residual shows the number of missed physics hits in each algorithm.

Solar WIMP Analysis with one year of IceCube data

Dark Matter in the form of Weakly Interacting Massive Particles (WIMP) can be gravitationally captured by the Sun. Sinking to its core, the WIMPs accumulate which facilitates self-annihilations into SM particles, of which only neutrinos, also created in secondary processes, can possibly escape the Sun and be detected with a neutrino telescope like IceCube.



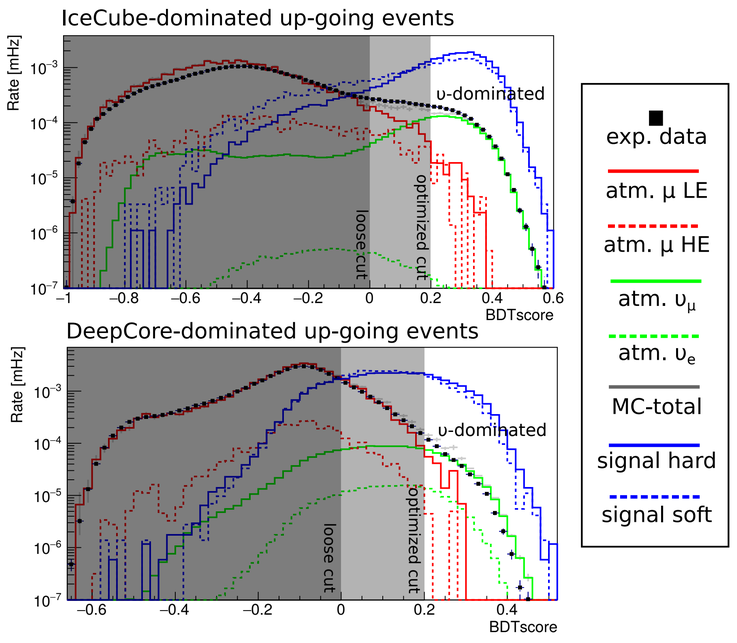
This analysis uses one year of IceCube data recorded in 2011/12 with the fully completed detector (IC86). We utilize the excellence of the newly developed event-splitter IceHive as well as other refined methods in the event selection and simulation.
Solar WIMP signal is simulated using WimpSim for several WIMP masses and annihilation channels. Depending on the chosen WIMP model the expected signal muon neutrinos at the detector range in energy from just a few GeV up to some TeV.

Event Selection

The regular IceCube (IC) array has a threshold on the neutrino energy ~100GeV while the more densely instrumented region DeepCore (DC) lowers this threshold to ~10GeV. All IceCube neutrino analyses suffer from a strong background of muons and neutrinos created from cosmic ray showers in the upper atmosphere. Atmospheric muons will be observed only as down-going while atmospheric neutrinos are found at all directions.

The event selection is based on all recorded events (~800Hz) during one year of live-time (337.4d). After initial event reconstruction minimum quality cuts are enforced. Then the sample is subdivided into a DC-dominated (low energy) part and a IC-dominated (high energy) part. Events observed as down-going are required to be starting deep within the detector volume, which can only be fulfilled by true neutrino-events.

In further treatment the events are subjected to further straight variable cuts and classified by a BDT trained on containment variables. A second, energy sensitive BDT trained on signal properties selects only the most neutrino-signal like events in each sample. It's output score can be used as a tuning-parameter in order to optimize the event selection for the analysis code that is being used. A such optimized cut brings the selection down to 1.4mHz in the IC-dominated sample and 0.4mHz in the DC-dominated sample, both now dominated by neutrino events suitable for analysis.



Likelihood-Analysis

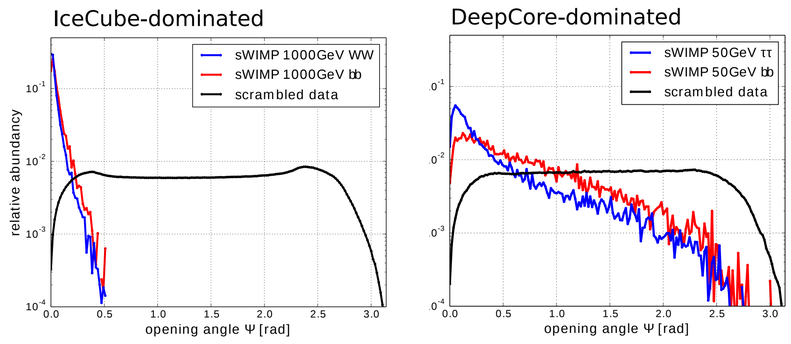
We use a shape likelihood based on the opening angle Ψ of the observed event direction compared to the current position of the Sun.

The Likelihood for observing μ signal events in a sample of N_{obs} events is given by

$$\mathcal{L}(\mu) = \prod_i^{N_{\text{obs}}} g(\vec{e}_i|\mu)$$

$$g(\vec{e}=(\Psi)|\mu) = \frac{\mu}{N_{\text{obs}}} f_s(\Psi) + (1 - \frac{\mu}{N_{\text{obs}}}) f_{\text{bg}}(\Psi)$$

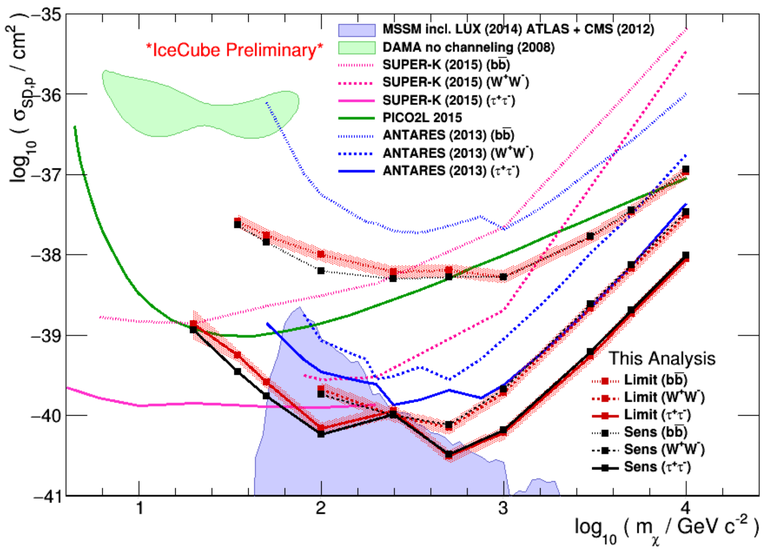
where $f_s(\Psi)$ and $f_{bg}(\Psi)$ are probability distribution functions (PDF). The signal PDF is obtained by direct tabulation from solar WIMP simulation of any specific WIMP model. The background PDF is obtained from experimental data by scrambling the apparent Sun azimuth.

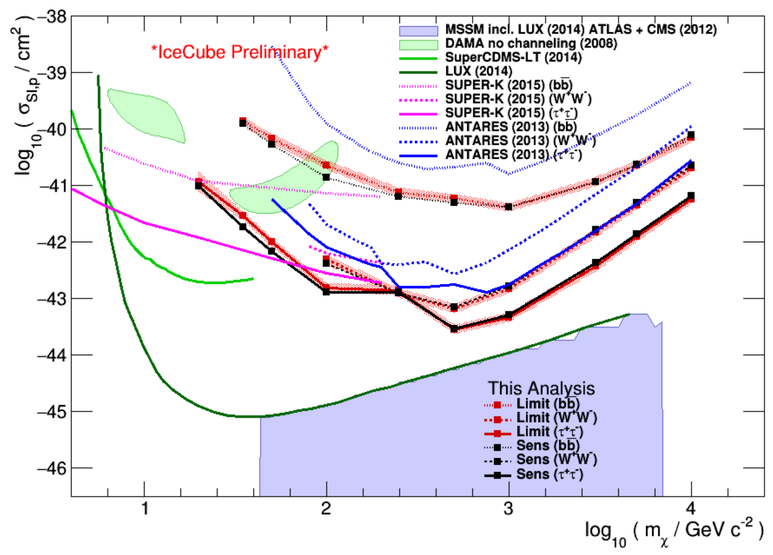


In the evaluation of our data sample, we limit ourselves to data obtained in the winter months (174 days of live-time) when the Sun is below the horizon and all sensitivity is obtained from up-going neutrino events.

Results

This analysis found no significant excess in muon neutrinos from the direction of the Sun. Under the assumption of a local DM density at 0.3 GeV/cm^3, a standard Maxwellian velocity distribution in the galactic WIMP halo and the Standard Solar Model the obtained limit can be converted to a limit on the spin-dependent and spin-independent WIMP-nucleon scattering cross-section for each such probed WIMP model.





Compared to the previous IceCube solar WIMP analysis conducted with 79 deployed strings, the improvement ranges from a factor up to 10 at the lowest WIMP mass at 20GeV to a factor 2 for higher WIMP masses up to 10TeV.

Please note that we have carried out a second independent analysis on the same dataset presented as a separate contribution (ICRC 1209)