Latest Results on Searches for Dark Matter from IceCube

Matthias Danninger for the IceCube Collaboration
The Oscar Klein Centre for Cosmoparticle Physics, Stockholm University

36th International Conference on High Energy Physics
Indirect Search with IceCube

Look for potential sources that are well defined and have low or understood astrophysical backgrounds.

**Dwarf spheroidal Galaxies:**  
→ IceCube-59 sens. *new*

**Clusters of Galaxies:**  
→ IceCube-59 sens. *new*

**Galactic Halo:**  
Limits from IceCube-22

**Galactic Center:**  
Limits from IceCube-40

**Local sources:**

**Sun:**  
Combined Limits form AMANDA, IC22, IC40+AMANDA  
→ IceCube-79 final sensitivity *new*

**Searches beyond “standard” SUSY:**  
→ secluded dark matter sector *new*

**Earth:**  
Limits from AMANDA  
(new analysis with IceCube-86 ongoing)
Very brief recap:

1. **Halo WIMPs scatter** on nuclei in the **Sun/Earth**
2. Some lose enough energy in the scatter to be **gravitationally bound**
3. Scatter some more, sink to the **core**
4. **Annihilate** with each other, producing **neutrino**
5. **Propagate+oscillate** to the South Pole, **convert** into muons in CC interactions
6. Look for **Cerenkov radiation** from the \( \mu \)

All processes depend on WIMP mass

**WIMP candidates:**
- **MSSM**: (LSP) neutralino, \( m(\chi^0) \) [35 GeV – 5 TeV]
  - Hard channel \( (\tau^+\tau^- / W^+W^-) \)
  - Soft channel \( (b\bar{b}) \)
- **UED**: (LKP), \( B^{(1)} \) or \( \gamma^{(1)} \)
  - fixed branching ratios: \( m(\gamma^{(1)}) \) [250 GeV–3 TeV]
- New model independent method for theories of new physics (later in talk)
IceCube detector

IceCube 86-strings
- 1.5 km - 2.5 km deep
- typically 125 m spacing between strings
  (~70 m in DeepCore, 10x higher DOM density)
- 60 Modules per string
- 1 km -- 1 Gton instrumented volume

✗ O(km) muon tracks from $\nu_\mu$ CC
✗ O(10m) cascades from $\nu_e$ CC, low energy $\nu_\tau$ CC, and $\nu_x$ NC
✗ Cherenkov radiation detected by 3D array of optical sensors (DOMs)

DeepCore
8 add. densely instrumented strings
Galactic searches, dwarf spheroidal galaxies & nearby clusters of galaxies
Galactic & galaxy cluster limits

Limits computed at 90% C.L. as function of WIMP mass and for various annihilation channels assuming branching fractions of 100%

multi-wavelength approach to dark matter searches:
IceCube can test DM models motivated by PAMELA & Fermi data (e.g. Meade et al. 2008)
multi-wavelength approach to dark matter searches:
IceCube can test DM models motivated by PAMELA & Fermi data (e.g. Meade et al. 2008)
Solar Dark Matter searches
IC40

More details on limits

Combined multi-year limit from AMANDA, IceCube-22 and IceCube-40+AMANDA data
Total livetime of 1065 days
IceCube 79 string analysis

Solar WIMP analysis with 79 strings (sensitivity)
- Incl. DeepCore
- Performed separately for austral winter & summer (152d + 167d livetime)
- Low energies (look for contained or partially contained events)

Analysis performed separately for:
- austral summer (Sun above horizon)
- austral winter (Sun below horizon)

MSSM model scan

1. MSSM model scan
2. IceCube-79 (b5) Summer
3. IceCube-79 (W'W') Summer
4. IceCube-79 combined (b5)
5. IceCube-79 combined (W'W')
6. IceCube-79 combined (W'W') DC-low

Preliminary
IceCube 79 string sensitivity
Sensitivity extends to WIMP masses of 20 GeV

Only 1 year of data

Data unblinding soon!

also search for UED models (not shown here)
New model independent method for theories of new physics
(Solar Dark Matter searches)
Global SUSY analysis with IceCube


Include IceCube event level data in a global statistical fit.

→ **parameter estimation rather than model exclusion**

Composite likelihood made up of observations from all over:

- Dark matter relic density from WMAP
- Precision electroweak tests at LEP & LEP limits on sparticle masses
- B-factory data (rare decays, $b \rightarrow s\gamma$)
- Muon anomalous magnetic moment
- LHC searches, direct detection *(not yet included in examples)*

+ *IceCube*

**unbinned likelihood**

$$
L_{\chi}^C(\Theta) = L_{\chi}^C(n \mid \theta_s(\Theta) + \theta_b) \prod_{k=1}^n L_{\text{spec}}(E_k \mid \Theta) L_{\text{ang}}(\cos\phi_k \mid \Theta)
$$

- $\Theta$: WIMP or SUSY parameters
- $n$: **Number** of muon events
- $E_k$: Muon **energy**
- $\cos\phi_k$: Muon **angle** from Sun
Global SUSY analysis with IceCube


CMSSM, IceCube-22

Contours indicate 1σ and 2σ credible regions
Grey contours correspond to fit without IceCube data
Shading+contours indicate relative probability only, not overall goodness of fit
Global SUSY analysis with IceCube

**CMSSM, IceCube-22 with 100x boosted effective area**

(indication for IceCube-79 and 86-string prospects)

- Contours indicate 1σ and 2σ credible regions
- Grey contours correspond to fit **without** IceCube data
- Shading+contours indicate *relative* probability only, not overall goodness of fit

IceCube is extending Dark Matter searches, including new sources → dwarf spheroidal galaxies & nearby galaxy clusters

IceCube already provides world best limits on SD WIMP-proton scattering cross-section for $m_\chi > 200$ GeV

Solar WIMP Analysis on 79 strings to be unblinded soon.... → Incl. DeepCore (6 densely instrumented strings) → $4\pi$ detector → full year-round DM searches → improved sensitivity for low-mass WIMPs

New framework for directly comparing event-level IceCube data to individual points in theory parameter spaces is in place → requisite tools available in new DarkSUSY release (version 5.0.6) → Event data will be released in a form digestible by the tools → SUSY analyses of IC79 data are on the way
Additional slides
New SUSY analysis with IceCube

What can the muon signal tell me?


Roughly:

✗ **Number** – how much annihilation is going on in the Sun
   ⇒ info on $\sigma_{SD}$, $\sigma_{SI}$ and $<\sigma v>$

✗ **Spectrum** – sensitive to WIMP mass $m_\chi$ and branching fractions $BF$ into different annihilation channels $\chi$

✗ **Direction** – how likely it is that they come from the Sun

In model-independent analyses a lot of this information is either discarded or not given with final limits

Goal:

Use as much of this information on $\sigma_{SD}$, $\sigma_{SI}$, $<\sigma v>$, $m_\chi$ and $BF (\chi)$ as possible to directly constrain specific points and regions in WIMP model parameter spaces
Dark Matter in the Milky Way:

- Outer halo relatively well understood
- Inner halo still subject of debates (cusp/core structure)
- Can probe DM self-annihilation cross section

\[
\frac{d\phi}{dE} = \frac{\langle \sigma_A \rangle}{2} J_a(\Psi) \frac{R_{sc}^2 \rho_\chi^2}{4\pi m_\chi^2} \frac{dN}{dE}
\]

- Halo distribution
- SUSY \((\chi\chi \rightarrow \mu^+\mu^-, \tau^+\tau^- ...\))
- Measurement
e.g. IC40 event map

\(\rho_{DM}(r) [\text{GeV/c}^2\text{cm}^{-3}]\)

Galactic-Center and Halo search

Neutrino Energy \(E_{\nu}\) (GeV)

E^2 dN/dE (GeV)

IC40 event map
 Galactic-Center and Halo search

Analysis strategy:
Look for an excess of events in the on-source region w.r.t. the off-source

Galactic Center:
✗ on-source region above the horizon
✗ need to veto downgoing muons.
✗ Use central strings of detector as fiducial volume, surrounding layers as veto.

IC22 (Halo analysis – 275 days):
oberved on-source: 1367 evts
observed off-source: 1389 evts
Event selection dominated by atm. $\nu$

IC40 (G-Center analysis – 367 days):
oberved on-source: 798842 evts
predicted from off-source: 798819 evts
Event selection dominated by atm. $\mu$

Observations in both analyses were consistent with background-only expectations
multi-wavelength approach to dark matter searches: IceCube can test DM models motivated by PAMELA & Fermi data (e.g. Meade et al. 2008)

For more details on analysis and systematics discussions:
Phys. Rev. D 84, 022004 (2011) (IC22)
ICRC 2011 (2011) (IC40)
Solar Dark Matter searches

Analysis strategy:

✗ Remove atmospheric muon events until data sample is dominated by atmospheric neutrino events

✗ signal events within IceCube may have low mean muon energy in detector → short tracks with few hits

✗ cut on quality and reconstruction parameters, maximizing horizontal low energy muon track selection (linear cuts & multivariate cuts)

✗ final data selection → determine $V_{\text{eff}}$ & $A_{\text{eff}}$

✗ DM searches directional: good additional handle on event selection → distribution-shape analysis

Signal & background pdf's of $\Psi$: angle between reconstructed track and direction of the Sun
Combined multi-year limit from AMANDA, IceCube-22 and IceCube-40+AMANDA data

Total livetime of 1065 days

Equation: \( \Gamma_{\nu\mu} \leq \frac{N_{90}}{V_{\text{eff}} \cdot t} \)

Experimentally obtained quantity

\( \Phi_{\mu} \)

\( C_c \sim \sigma_{SD} \)

Events close to the direction of the Sun
Analysis Results from the Sun

More details on limits
Abbasi et al., *PRL*. 102, 201302 (2009) (IC22)
Abbasi et al., *PRD* 81, 057101 (2010) (IC22)
Abbasi et al., *PRD* 85, 042002 (2012) (IC40+AMANDA)

Combined multi-year limit from AMANDA, IceCube-22 and IceCube-40+AMANDA data
Total livetime of 1065 days
Analysis Results from the Sun

More details on limits
Abbasi et al., *PRL*. 102, 201302 (2009) (IC22)
Abbasi et al., *PRD* 81, 057101 (2010) (IC22)
Abbasi et al., *PRD* 85, 042002 (2012) (IC40+AMANDA)

limits & sensitivity:
Only data, when Sun is below the horizon

main syst. uncertainty:
Photon propagation in the ice & absolute DOM efficiency (~20%)

relate muon flux and WIMP - nucleon cross-section:

\[ \Gamma_A = \frac{1}{2} C_C. \]
Solar WIMP Equilibrium

- Dark Matter accumulates and starts annihilating $\rightarrow$ Neutrinos are the only particles that can make it out.
- At equilibrium ($\Gamma_A = 1/2 \Gamma_C$) the neutrino flux does not depend on the self annihilation cross section!

**Self-annihilation cross section:**

**WIMP-Nucleon scattering:**

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

- $N = \#$WIMPs
- Capture Rate ($C_C$)
- Annihilation Rate ($C_A$)
- Evaporation

- $\#$WIMPs in the Sun
- Capture Rate / 2
- Annihilation Rate

Carsten Rott

Slide taken from Carsten Rott (Neutrino 2012)
Solar WIMP Equilibrium

- Dark Matter accumulates and starts annihilating → Neutrinos are the only particles that can make it out.

- At equilibrium ($\Gamma_A = 1/2\Gamma_C$) the neutrino flux does not depend on the self-annihilation cross section!

**Self-annihilation cross section:**

**WIMP-Nucleon scattering:**

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N$$

**Annihilation Rate**

**Capture Rate / 2**

**#WIMPs in the Sun**

**#WIMPs in the Sun**

**Capture Rate / 2**

**Annihilation Rate**

**Indirect WIMP Searches**
IceCube detector