Indirect Dark Matter Searches with the IceCube Neutrino Observatory

Martin Wolf for the IceCube Collaboration
The Oskar Klein Centre for Cosmoparticle Physics, Stockholm University

WIN 2015
Heidelberg, June 9, 2015
**Indirect DM Search Principle**

Target over-dense regions of DM where self-annihilation may occur at significant rate

\[ \chi \rightarrow \nu, e^+, \mu^+, \tau^+, W^+, Z, b, t \]
\[ \bar{\chi} \rightarrow \bar{\nu}, e^-, \mu^-, \tau^-, W^-, Z, \bar{b}, \bar{t} \]

- Annihilation products may decay, producing neutrinos
- Sensitive DM mass range for IceCube: \( \sim 10 \text{ GeV} - \sim 100 \text{ TeV} \)
- Consider 100% branching ratio for each channel
- Consider “extrema” soft & hard ann. channels to bracket possible real neutrino spectrum
- Setting upper limits on:
  - DM velocity-averaged self-ann. cross-section \( \langle \sigma_A v \rangle \) ((extra-)gal. analyses)
  - DM-nucleon scattering cross-sections (Sun, Earth analyses)
Indirect DM Searches with IceCube

The Milky Way

Galactic Dark Matter Halo

DM Clumps

Dwarf Spheroidal Galaxies

Sun / Earth
Indirect DM Searches with IceCube

Dwarf spheroidal Galaxies & Clusters of Galaxies:

→ IceCube-59 limits
  (*PRD 88 (2013) 122001*)

→ IceCube-86 analysis
Indirect DM Searches with IceCube

Galactic Halo:
→ IceCube-22 limits (PRD 84 (2011) 022004)
→ IceCube-79 multipole limits (EPJ-C 01/2015 75(20))
→ Multi-year track LH analysis
→ IC86 PeV Gravitino decay analysis
Indirect DM Searches with IceCube

Galactic Center:

→ IceCube-79 limits using tracks
  (arXiv:1505.07259 submitted to EPJ-C)

→ IceCube-86 analysis using cascades
Indirect DM Searches with IceCube

Sun:
→ IceCube-79 limits
   (PRL 110 (2013) 131302)
→ Specific models & Global fits
   (JCAP 11 (2012) 057)
→ IceCube-86 analysis

Earth:
→ IceCube-86 analysis
Neutrino telescopes – detection principles

- Neutrinos interact in or near the detector

- \( O(km) \) muon tracks from \( \nu_\mu \ W^-\text{-int.} \) (CC)

- \( O(10m) \) cascades from \( \nu_e \) CC, low energy \( \nu_\tau \) CC, and \( \nu_l \) \( Z^0\)-int. (NC)

- Cherenkov radiation detected by 3D array of optical sensors
The IceCube Neutrino Observatory

IceCube
1.5 km – 2.5 km deep
typically 125 m spacing between strings
(~70 m in DeepCore)
60 modules per string
1 km$^3$ | 1 Gton instr. volume

DeepCore
10 GeV < $E_\nu$ < 100 GeV
30% higher QE PMTs
Important for low WIMP mass searches
IceCube Solar WIMP searches

- WIMPs could be captured by the Sun through WIMP-nucleon scattering
  - WIMP annihilation
- Capture & Annihilation rate in equilibrium
  - Analysis sensitive to WIMp scattering cross-sections (SI & SD)
- Dependent on WIMP mass & ann. channel

\[
\frac{dN}{dt} = C_{\text{capt.}} - C_{\text{ann.}}
\]

\[
C_{\text{ann.}} = C_{\text{capt.}} \Rightarrow \sigma_{\text{total}}
\]

Expected sens. vs. observed result (IC79 Solar WIMP)
**IceCube Solar WIMP searches**

Split 1 year data into 3 samples

1. **Summer** (Sun above horizon → atm. muon background)
2. **Winter Low-Energy** (Sun below horizon → atm. neutrino background)
3. **Winter High-Energy**

- Select starting events in DeepCore
- Use surrounding IceCube as veto
- DeepCore most sensitive to $E < 120$ GeV as low as 10 - 20 GeV

- Select upwards-going events
- Use Earth as atm. muon absorber
- Maximum $\nu$ effective area for HE

→ Use **combined Maximum LH analysis** with signal & background PDFs
→ weight samples by livetime & effective volume
IceCube-79 Solar WIMP search results

Most stringent SD cross-section limit for most models $m_\chi > 200$ GeV

Complementary to direct detection search efforts

Different astrophysical & nuclear form-factor uncertainties

**IceCube-86 Solar WIMP search**

- Improved event selection & LH analysis (utilizing event energy information)
- One-year analysis shown below → soon to be extended to 3 years

![Graph showing IceCube Preliminary results](image-url)
Galactic Indirect DM searches

Neutrino flux from DM annihilation:

\[
\frac{d\Phi_{\nu}}{dE}(E, \theta, \phi) = \frac{1}{4\pi} \frac{\langle \sigma_A \nu \rangle}{2m_\chi^2} \sum_f \frac{dN_{\nu}}{dE} B_f \times
\]

Particle Physics

Dark Matter Distribution

\[
\int_{\Delta \Omega(\theta, \phi)} d\Omega' \int_{\text{l.o.s.}} dl(r, \phi') \rho^2(r(l, \phi'))
\]

\(\rho\) is defined by the DM density model, e.g. NFW [APJ 462, 563 (1996)] or Burkert [APJ 447, L25 (1995)] and their parameter values, e.g. the local DM density.
**Galactic Indirect DM searches**

- **IC59 Dwarf Galaxy & Clusters of Galaxies analysis**
  - Source stacking analysis (340 days)
  - Optimized cuts & size of search window for 5 TeV WIMPs

(all IceCube limits at 90% C.L.)
Galactic Indirect DM searches

IC22 Cut&Count (275d) & IC79 Multipole (316d) analysis
- Small halo-model dependency
- Multipole Analysis: focus on large scale anisotropies (l<100)

\[ \rho_{\text{local}} = 0.471 \, \text{GeV cm}^{-3} \]
[JCAP 1307, 016 (2013)]
Galactic Indirect DM searches

IC22 Cut&Count (275d) & IC79 Multipole (316d) analysis
- Small halo-model dependency
- Multipole Analysis: focus on large scale anisotropies ($l < 100$)

High WIMP mass limits

$\rho_{\text{local}} = 0.471 \text{ GeV cm}^{-3}$

[JCAP 1307, 016 (2013)]
Galactic Indirect DM searches

IC79 GC Maximum LH analysis (320d)
- 2 event selections (LE & HE)
- Explicit use of DeepCore & new veto techniques

\[ \rho_{\text{local}} = 0.471 \text{ GeV cm}^{-3} \]

[JCAP 1307, 016 (2013)]
IceCube-79 Galactic Center Analysis

- Galactic Center above horizon
  - veto down-going CR muon bg
- 2 event selections (LE & HE)
- Choice based on best sensitivity for particular mass & ann. channel

Shape max. likelihood analysis
2D skymap PDFs generated with healpix

scrambled background

Galactic Center @ 266° RA; -29° Dec

\[ \chi \chi \rightarrow \nu \bar{\nu} \]

\[
\left( \frac{\sigma_{A\nu}}{m_{\chi}} \right) \quad [\text{cm}^3 \text{s}^{-1}]
\]

- \( m_{\chi} \) [GeV]

- NFW

2 event selections (LE & HE)
Choice based on best sensitivity for particular mass & ann. channel
IceCube-79 Galactic Center Analysis

Results compatible with background-only hypothesis (2σ under-fluctuation)

**Stringent limits on direct neutrino annihilation channel**

→ complementary to searches by gamma-ray telescopes

- Consider flat-cored DM density profile “Burkert”
  [APJ 447, L25 (1995)]
Future IceCube Detector Extensions

- IceCube Lab
- Skiway
- Amundsen-Scott South Pole Station
- IceCube
- DeepCore
- PINGU

High Energy Extension (astrophysical neutrinos)  
[arXiv: 1412.5106]

Surface Veto Array
**Indirect DM Searches with Generation 2**

**PINGU**

Improved sensitivity for Solar WIMP Searches to masses near 5 GeV

Estimates indicate the ability to reach world-competitive spin-dependent limits with approximately 1 year of data

PINGU Collaboration arXiv:1401.2046

Preliminary

**High Energy Extension**

Improved sensitivity high mass DM

Potential to rule out the Very Heavy DM scenario (astrophysical neutrinos) in 3-5 years

Murase, Laha, Ando, Ahlers arXiv:1503.04663v1
**Indirect DM Searches with Generation 2**

**PINGU**

Improved sensitivity for Solar WIMP Searches to masses near 5 GeV

Estimates indicate the ability to reach world-competitive spin-dependent limits with approximately 1 year of data

![PINGU Collaboration arXiv:1401.2046](image)

**High Energy Extension**

Improved sensitivity high mass DM

Potential to rule out the Very Heavy DM scenario (astrophysical neutrinos) in 3-5 years

![Murase, Laha, Ando, Ahlers arXiv:1503.04663v1](image)
**Summary**

- Neutrinos provide high discovery potential for indirect Dark Matter searches
  - complementary to searches using other astrophysical messengers & direct detection searches
- **DeepCore** accesses Southern Hemisphere for low WIMP masses
- First neutrino analysis looking at **GC for low WIMP masses** (30 GeV - 10 TeV)
- More signal detection channels via **cascade** event detection
- IceCube provides **most stringent limits on the SD-WIMP-proton scattering** cross section for WIMP masses above 200 GeV
- Improved Solar WIMP search under way
- Future LE & HE detector extensions could improve WIMP searches and could rule out VHDM scenarios within 3-5 years
PINGU Solar WIMP sensitivity

- PINGU LoI: [arXiv 1401.2046]
- 40 add. strings within DeepCore
- 1 year live-time
- $\nu_e + \nu_\mu$ signal channel
- Cut-&-Count analysis approach
- $10^\circ$ search cone around the Sun
- WIMP masses as low as 5 GeV