Dark Matter Searches at the South Pole

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Neutrinos Beyond IceCube
April 24, 2014
Arlington, VA
Evidence for Dark Matter

• Many gravitational evidence for dark matter

All consistent with ~25% dark matter.

But... what is it?
What is Dark Matter?

**Leading Candidates:**

**Axions**
- mass $\sim 10^{-3} – 10^{-6}$ eV
- Arises in the Peccei-Quinn solution to the strong-CP problem

**WIMPs: Weakly Interacting Massive Particles**
- mass of 1 GeV – 10 TeV
- weak scale cross sections results in observed abundance

$$\sigma \approx 10^{-39} - 10^{-46} \text{cm}^2$$
$$\langle \sigma A \rangle \approx 10^{-26} \text{cm}^3/s$$

$m_\chi \approx 100$ GeV

**Observational evidence indicates:**
- Non-baryonic
- Cold and massive (non-relativistic and exerts gravity)
- Interact little with ordinary matter
- Stable and long-lived
Dark Matter Distribution

Large scale dark matter distribution
Millenium Simulation
http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Planck all-sky image of the distribution of dark matter via distortions on CMB by gravitational lensing (April 2013)

Artist’s impression of the Milky Way galaxy. The blue halo of material surrounding the galaxy indicates the expected distribution of dark matter. (ESO/Calçada)
Regions Dense in Dark Matter

- **Extra-galactic**: Small halo model dependence, boost factors
- **Milkyway Halo**: Large DM content, nearby source, $O(10)$ larger flux than extra-galactic
- **Galactic Center**: Very dense DM accumulation, nearby source
- **Dwarf Spheriodals**: No astrophysical backgrounds
- **Clusters of Galaxies**: Large DM content, high boost factors from sub structure
Detecting WIMPs

**annihilation**

**“Indirect Detection”**
Look for decay products from self-annihilation of dark matter collected in massive objects.

**scattering**

**“Direct Detection”**
Let dark matter recoil off of nuclei
Look for nuclear recoil

**production**

**Colliders**
Create dark matter. Look for the missing energy
Detecting WIMPs

**annihilation**

"Indirect Detection"
Look for decay products from self-annihilation of dark matter collected in massive objects.

Colliders
Create dark matter. Look for the missing energy

**production**

**scattering**

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IceCube

DM-Ice
Current Detectors: Annihilation signals

- Neutrinos
- Gamma rays
- Electrons, positrons
- Protons, antiprotons
- Deuterons, antideuterons
- Cherenkov telescopes & satellites
  - IceCube
  - Antares
  - SuperK

Neutrino Telescopes

- Fermi
- HESS

WIMP Dark Matter Particles

\[ E_{\text{CM}} \approx 100 \text{GeV} \]

\[ \chi \to W^-/Z/q \]

\[ \chi \to W^+/Z/\bar{q} \]

\[ \chi \to \pi^0, \gamma \]

\[ \pi^+ \to \mu^+, \nu_\mu, \bar{\nu}_e \]

\[ \pi^- \to \mu^-, \bar{\nu}_\mu, \nu_e \]

\[ \mu^+ \to e^+, \bar{\nu}_\mu, \nu_e \]

\[ \mu^- \to e^-, \bar{\nu}_e, \nu_\mu \]

\[ e^+ \to \bar{\nu}_e, \nu_\mu \]

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Annihilation Signals

- Identify dense regions of matter
  \[ \Rightarrow \text{self-annihilation can occur at significant rates} \]

- Pick prominent Dark Matter target

- Understand backgrounds

- Features in the signal can be used to better distinguish backgrounds
  - Line / End-point

- Neutrinos and gammas point straight back to the source
Regions Dense in Dark Matter

- **Milkyway Halo**: Large DM content, nearby source, \(O(10)\) larger flux than extra-galactic. Anisotropy.
- **Galactic Center**: Very dense DM accumulation, nearby source. Extended Source.
- **Dwarf Spheriodals**: No astrophysical backgrounds. Point source.
- **Clusters of Galaxies**: Large DM content, high boost factors from sub structure. Extended source.

Very strong dependence on DM density profile. Cored profiles favored, less flux. Understanding of boost factors.
Galactic Halo

- Galactic Center (GC) is on the southern hemisphere for IceCube
  - large backgrounds from down-going muons
- For the northern hemisphere IceCube searches for anisotropy using the high-purity up-going neutrino sample
- Assume annihilation into $\nu\nu, \bar{b}b, \mu\mu, \tau\tau, WW$

### 22-strings Halo Analysis
276 days (2007 - 2008)
- up-going (northern sky)
- down-going (southern sky)

### 79-strings multipole analysis
316 days (2010 - 2011)

[Graphs and diagrams showing neutrino event distributions and multipole analysis results]

Galactic Center

Use IceCube external strings as a veto:
- 3 complete layers around DeepCore (~ 375m)
- **Full sky sensitivity**: access to southern hemisphere

Separate Low energy and High energy optimizations:
GC is above the horizon
→ Fiducial volume in central strings
→ refined muon veto from surrounding layers
Use scrambled data for background estimation

IceCube Preliminary

sensitivity to reach down to WIMP masses of 30GeV
Testing Pamela’s Positron Excess

IceCube can probe models motivated by the observed lepton anomalies.
Dwarf Spheroidal Galaxies

- Dwarf spheriodal galaxies, clusters of galaxies, and large galaxies represent well defined sources of Dark Matter.
- Dark Matter distribution critical for optimization, assume conservative density profile.
- IceCube measurements are complementary to Pamela, Fermi, & HESS.

340 days of IceCube 59 string data
Event selection via Boosted Decision Tree
For robustness the search windows and cut values were optimized for 5 TeV WIMPs and used for all WIMP-masses.

Solar WIMP Searches

- Neutrino detectors are competitive for spin-independent scattering
- IceCube competitive for higher mass WIMPS
- IceCube extension will increase the reach both low and high energy
- Solar WIMP searches mostly sensitive to WIMP-proton cross section
Origin of the PeV Events?

**What do the two IceCube events tell us?** and the additional 26 events?

<table>
<thead>
<tr>
<th>Origin</th>
<th>Description</th>
<th>Likely?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GZK neutrinos</strong></td>
<td>a few events at ~ 100 TeV - 1 PeV implies many more events at higher energies</td>
<td>Impossible</td>
</tr>
<tr>
<td><strong>Conventional atm. neutrinos</strong></td>
<td>Very low flux predictions. Flavor ratio favors strongly favors muon neutrinos</td>
<td>Implausible</td>
</tr>
<tr>
<td><strong>Prompt</strong></td>
<td>Coincidence in down-going events. Possible only if proton composition; upward statistical fluctuation needed</td>
<td>Unlikely</td>
</tr>
<tr>
<td><strong>Astrophysical</strong></td>
<td>Most natural. Events are isotropic. Cannot be continuum spectrum. power law with break at ~ 2 PeV ?</td>
<td>Plausible</td>
</tr>
<tr>
<td><strong>Dark Matter</strong></td>
<td>2 events overlap in energy</td>
<td>Intriguing</td>
</tr>
</tbody>
</table>

Many papers based on the 2 IceCube Events: e.g. R.Laha et al. Phys. Rev. D 88, 043009
Looking Forward: PINGU

- High density instrumentation:
  - baseline geometry: 40 strings x 60 DOMs
  - Threshold ~ 1 GeV
- Test low mass WIMP region -- capable to comfortably test DAMA/Libra

Spin-dependent scattering

Spin-independent scattering
Detecting WIMPs

annihilation

“Indirect Detection”
Look for decay products from self-annihilation of dark matter collected in massive objects.

“Direct Detection”
Let dark matter recoil off of nuclei
Look for nuclear recoil

production

Colliders
Create dark matter. Look for the missing energy

scattering

Fermi/LAT

X

WIMP

nuclear recoil

IceCube

X

Sun

Earth

IceCube

DM-Ice
Local Dark Matter Density / Velocity

Maxwellian is reasonable

Velocity distribution still not very well understood

Local dark matter density
~0.3 GeV/cm³

small recoils
“easiest” to be captured in the Sun/Earth - indirect searches

large recoils
“best sensitivity” with direct detection
Direct Detection Search Strategies

1. Count individual nuclear recoils
2. Look for annual modulation
3. Diurnal directional modulation

(Modified from: NASA/CXC/M.Weiss)
Direct Detection Experiments

here: recent results + future

SNOLab
DEAP/CLEAN
Picasso
COUPP

Boulby
ZEPLIN
DRIFT

Homestake
LUX

Modane
EDELWEISS

Soudan
SuperCDMS
CoGeNT

Canfranc
ArDM
Rosebud
ANAIS

Gran Sasso
XENON
CRESST
DAMA/LIBRA
DarkSide
WARP

YangYang
KIMS

Kamioka
XMASS
Newage

South Pole
DM Ice

Jinping
Panda-X
CDEX

Laura Baudis
DM Overview
Neutrino 2012
Direct Detection, Current and Future

Spin Independent WIMP-nucleon cross section

Spin Dependent - neutron

Spin Dependent - proton

SNOWMASS 2013: arXiv:1310.8327
Hints and Claims for Direct Detection of DM

Low Mass WIMPs?

SNOWMASS 2013: arXiv:1310.8327

The present crux (interesting times)

Juan Collar, arXiv:1401.3295

Challenges: Astrophysics, Particle Physics, & Instrumental Effects
Dark Matter Signal or Background?

DAMA

CDMS-Si

CoGeNT


arXiv:1308.5109

arXiv:1304.4279

arXiv:1401.3295
Does DAMA see Dark Matter?

**Inconsistent Picture for WIMPs**

**Challenges:** Astrophysics, Particle Physics, & Instrumental Effects

**Solution:** Repeat the same experiment with same detector medium, but with better handle on background(s)
Testing DAMA’s Dark Matter Claim

Definitive ($5\sigma$) detection or exclusion with
- 500 kg-yr NaI(Tl) (DAMA x 2 yrs)
- same or lower threshold (< 2 keVee)
- background < (DAMA x 5)

![Graph showing Neutrinos and Astrophysics in Antarctica, April 24, 2014](image)

<table>
<thead>
<tr>
<th></th>
<th>DM-Ice17</th>
<th>NAIAD-scale</th>
<th>DAMA-scale</th>
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<tbody>
<tr>
<td></td>
<td>Years</td>
<td>17.0 kg</td>
<td>44.5 kg</td>
</tr>
<tr>
<td>$x8$ DAMA</td>
<td>1</td>
<td>0.45</td>
<td>0.72</td>
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<td>background</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.77</td>
<td>1.25</td>
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<tr>
<td></td>
<td>5</td>
<td>1.00</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1.18</td>
<td>1.91</td>
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<tr>
<td>$x4$ DAMA</td>
<td>1</td>
<td>0.63</td>
<td>1.02</td>
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<td></td>
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<td></td>
<td>3</td>
<td>1.09</td>
<td>1.77</td>
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<td></td>
<td>5</td>
<td>1.41</td>
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<tr>
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<tr>
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<tr>
<td>DAMA</td>
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<td>1.20</td>
<td>1.94</td>
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<td>7</td>
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<td>5.14</td>
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<tr>
<td>1/10 DAMA</td>
<td>1</td>
<td>3.80</td>
<td>6.15</td>
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<td>background</td>
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<td></td>
<td>3</td>
<td>6.58</td>
<td>10.65</td>
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<td>5</td>
<td>8.50</td>
<td>13.75</td>
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<td>7</td>
<td>10.06</td>
<td>16.27</td>
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500 kg\cdot year NaI detector sensitivity

(2 - 4 keV) with bgd of 1, 2, and 5 cnts/keV/kg/day.

Additional Information by lowering the threshold below 2 keV.
Phased Program for DM-Ice

- low-background NaI(Tl) target
- moveable detector array
- access to both Northern & Southern Hemispheres

A Phased Experimental Program

DM-Ice17

Test Detector at South Pole
17 kg of NaI(Tl) at 2450m depth at South Pole

DM-Ice 250 North

Modulation Search in Northern Hemisphere
portable 250 kg NaI(Tl) detector, first deployment in the Northern Hemisphere

DM-Ice 250 South

Modulation Search at the South Pole
if modulation seen in North & ice drilling becomes available
DM-Ice17 - Deployment, Operation, Data Taking

Built in summer 2010

Deployed at the South Pole in December 2010
Test Detector Operation & Data

uses NaIAD crystals

Light Collection and Energy Resolution

DM-Ice17: 4-6 pe/keV

Energy Spectrum < 100 keV

Event ROI dominated by $^{40}$K, $^{210}$Pb, and $^{129}$I in the crystal.

3 keV peak from $^{40}$K observed
DM-Ice17 - A Proof of Concept

Stable Operation for >2 Years

Calibration achieved using internal contamination
Negligible environmental background
(drill Ice and glacial Ice ≲ 0.1 dru)
Temperature stability, high livetime (> 98%)

Ongoing Analyses
Cosmogenic production

DM-Ice17 demonstrated feasibility of dark matter search at South Pole
DM-Ice / IceCube Coincident Event

DOM 60 highlighted

December 2012- Event #14

~10% of muons seen in Det-1 in DM-Ice17 trigger in muon channel in IceCube
New Low-Background NaI(Tl) Crystals

Development of NaI(Tl) detectors with Alpha Spectra, Inc (ASI) in CO, USA
Three groups work with Alpha Spectra: DM-Ice, ANAIS, KIMS.
Communication and sharing of R&D results

- 2 x 18 kg crystals from Alpha Spectra are at Fermilab MINOS near hall for testing.

- If these crystals confirm specifications, total of 250 kg can be grown and encapsulated as detectors at ASI in less than 12 months.

Backgrounds are within acceptable levels for an experiment with 2 counts/day/keV/kg. Sufficient to test the DAMA signal at > 5σ with 3 years of data.
DM-Ice250 Simulations

Close-Packed Detector Array

Sensitivity to DAMA Modulation Signal
assume 225 kg exposure/yr (90% livetime)

1 year: 3.3σ
2 years: 4.6σ
3 years: 5.7σ

Based on MC sample of modulated signal, using same binning and analysis method as DAMA, fit to fixed phase and period.

DM-Ice250 Background
2-6 keV region: 1.75 dru average (worst case with veto)
Summary

The fields of direct and indirect dark matter searches are highly active and rapidly evolving.

- The race is on!
- Solar WIMP paper is still the most cited physics paper in IceCube.
- Neutrino detectors leads in spin-dependent dark matter searches.
- Neutrinos point back to sources and have fewer background sources. Complementary to searches with gamma and charged particles.
- IceCube & DM-Ice have established the South Pole as a viable “underground” laboratory.
- DM-Ice will directly test DAMA’s claim for lab-based observation for dark matter.
DM-Ice Collaboration

**Yale University**
Reina Maruyama, Karsten Heeger, Brooke Russell

**University of Wisconsin – Madison**
Francis Halzen, Albrecht Karle, Matthew Kauer, Mike DuVernois, Walter Pettus, Zachary Pierpoint, Antonia Hubbard, Bethany Reilly

**University of Sheffield**
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**University of Alberta**
Darren Grant

**University of Illinois at Urbana-Champaign**
Liang Yang

**Fermilab**
Lauren Hsu

**Shanghai Jiao Tang University**
Xiangdong Ji, Changbo Fu

**Penn State**
Doug Cowen, Ken Clark

**NIST-Gaithersburg**
Pieter Mumm

**University of Stockholm**
Chad Finley, Per Olof Hult, Klas Hultqvist, Christian Walach

**DigiPen**
Charles Duba, Eric Mohrmann

**Boulby Underground Science Facility**
Sean Paling

**SNOLAB**
Bruce Cleveland