Search for Dark Matter with IceCube

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Dark Matter in LHC Era
Kolkata 2011
Outline

- Weakly Interacting Massive Particles as Cold Dark Matter
- The IceCube neutrino detector
- Search for neutrino signals of WIMP annihilations in the Sun and near the Galactic Centre
- IceCube + DeepCore: prospects for Dark Matter discovery in the coming years
Evidence for Dark Matter from observations
Indirect detection

Dark matter
Observations

Galaxy rotation curves

Gravitational lensing

*Begeman et al. 1991*

![Graph of Galaxy rotation curves for NGC 6503 showing dark halo, light, and gas components.](image1.png)

![Double Einstein Ring SDSSJ0946+1006 observed by Hubble Space Telescope.](image2.png)
WIMPs as cold Dark Matter

- **Weakly Interacting Massive Particles**
- Non-relativistic at freeze-out
- Mass [GeV-TeV]
- Can make up cold DM with observed abundance

\[
\Omega_{\chi} = \frac{\rho_{\chi}}{\rho_{\text{crit}}} \sim \frac{10^{-25}}{\langle \sigma_{\text{Ann}} v \rangle} \text{cm}^3 \text{s}^{-1}
\]

\(\approx 0.21 \text{ WMAP}\)

\(\Omega_{\chi} \approx 0.21\) WMAP

\(\langle \sigma_{\text{Ann}} v \rangle \approx 10^{-25} \text{ cm}^3 \text{s}^{-1}\)

\(O(\text{Weak interactions})\)
Detection

Dark matter search strategies

1. Direct detection

2. Indirect detection

< 3. Production at the Large Hadron Collider
Indirect detection

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DM in IceCube
Mission
Instrument
Neutrino detection

IceCube
IceCube Mission

- search for extra-terrestrial neutrinos → natural accelerators producing HE cosmic rays
- Such as
  - Active Galactic Nuclei
  - Gamma Ray Bursts
  - SuperNovae
- Indirect Dark Matter search
- Cosmic ray air showers with IceTop
IceCube detector

Array of 80 strings with 60 Digital Optical Modules

Control room
IceTop

AMANDA

-1450m

-2450m
IceCube detector

IceTop

Control room

AMANDA

DeepCore

-1450m

-2450m

DeepCore

- Denser spacing
- Low energy GeV-TeV
- Southern hemisphere
Neutrino detection & reconstruction

- Record Cherenkov light pattern
- Reconstruct muon track
- Assume muon track aligned to neutrino path

\[ \theta(v, \mu) \approx 30^\circ \cdot \sqrt{\frac{1}{E(GeV)}} \]

1TeV $\rightarrow$ 1°
NEUTRINO SIGNATURES

Tracks
- Through-going muons
- 1° pointing resolution

Cascades
- Neutral current
- Charged current $\nu_e$
- 10% resolution in log(energy)

Composites
- Starting tracks, double bangs
- Good directional and energy resolution
Pointing resolution

- Simulation: 1 TeV muon → $\Delta \Psi \approx 1^\circ$
- Moon shadow observation → $\Delta \Psi \leq 1.25^\circ$
  - IC40 (2008) 8 lunar months
  - 5$\sigma$ deficit in atmospheric muon flux
IceCube was completed on 18 December!

(Nature.com) Giant, frozen neutrino telescope completed - December 18, 2010

ScienceDaily (Dec. 19, 2010) — Culminating a decade of planning, innovation and testing, construction of the world's largest neutrino observatory, installed in the ice of the Antarctic plateau at the geographic South Pole, was successfully completed December 18, 2010, New Zealand time.
WIMP annihilations in the Sun
WIMP annihilations near the Galactic Centre

SEARCH FOR DARK MATTER
Different strategies

• Neutrinos from WIMP annihilations in the Sun: AMANDA, IC22

• Neutrinos from WIMP annihilations in the galactic halo and near the galactic centre: IC22, IC40

• Neutrinos from WIMP annihilations in the centre of the Earth: work in progress
Data filtering
Muon flux and WIMP annihilation rate
WIMP-proton scattering cross section

**Solar WIMPs**
Solar WIMPs: detection principle

\[ \rho_\chi \]

velocity distribution

\[ \sigma_{\text{scatt}} \]

\[ \Gamma_{\text{capture}} \]

\[ \Gamma_{\text{annihilation}} \]

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

\[ W^\pm, Z, H \]

\[ \chi \rightarrow \tilde{\ell} \]

\[ \nu_{\mu} \]

Detector

Earth


signal and background

- **BG** A few $10^4$ atmospheric neutrinos per year from northern hemisphere
- **signal** Max. a few neutrinos per year from WIMPs
- **BG** $\sim 10^{10}$ atmospheric muons per year from southern hemisphere
Data filtering

• Muon tracks from $\nu_\mu$ Charged
• Current interactions
• When Sun below horizon: March-September
• Nearly horizontal tracks

Different levels of filtering

1 TeV WIMP, hard channel selection efficiency $\approx 20\%$

data $\approx \Sigma$ (atm BG)

Atm $\mu+\mu\mu$

Atm. $\nu$

Relative efficiency

Cut Level
Signal content from fit

\[ f(\psi | \mu) = \frac{\mu}{n_{\text{obs}}} f_S(\psi) + \left(1 - \frac{\mu}{n_{\text{obs}}} \right) f_B(\psi) \]

Model dependent
From off-source data

Neutralino 250 GeV to WW
Data, AMANDA 812d
Background
Best fit

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DM in IceCube
## Search results

<table>
<thead>
<tr>
<th>AMANDA dedicated search M(WIMP) [50-5000 GeV]</th>
<th>Angular resolution 3 – 7 degrees</th>
<th>812 days livetime</th>
<th>2001-06</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube 22 strings dedicated search M(WIMP) [250-5000 GeV]</td>
<td>≈ 3 degrees</td>
<td>104 days</td>
<td>2007</td>
</tr>
</tbody>
</table>

- No evidence for a signal in ~ 900 days livetime
- → upper limits on neutralino annihilation rate in Sun & resulting muon flux
Annihilation rate & muon flux

\[ \Gamma_{\nu \rightarrow \mu} = \frac{\mu^{90\%}}{V_{\text{eff}} T_{\text{live}}} \]

**MSSM MC simulation**

**DarkSusy**

**neutralino annihilation rate**

**Muon flux**

\[ \phi_\mu(E \geq E_{\text{th}}) = \Gamma_A \left[ \frac{1}{4\pi R_\odot^2} \int_{E_{\text{th}}}^{\infty} dE_\mu \frac{dN}{dE_\mu} \right] \]
Neutralino models considered

- Assume MSSM with R-parity conservation
- Neutralino $\chi_0^1$ (LSP) is popular CDM candidate: weakly interacting, stable, massive

- Consider 7 masses $50 \text{ GeV} < m(\chi_0) < 5000 \text{ GeV}/c^2$
- and 2 annihilation channels

  $\chi\chi \rightarrow W^+W^- (\tau^+\tau^-) \rightarrow \nu$  
  hard $E_\nu$ spectrum

  $\chi\chi \rightarrow \bar{b}b \rightarrow \nu$  
  soft $E_\nu$ spectrum

- Simulation with WIMPSIM (Blennow & Edsjo JCAP 2008)
Muons flux from solar neutralinos

AMANDA 01-06 preliminary

Super-K Desai (PRD 2004)

IceCube 2007 Abassi (PRL 2009)

MSSM model predictions allowed by colliders & direct searches
Scattering cross section

- muon flux $\rightarrow$ scattering cross section
- Assume
  - equilibrium between capture in Sun and annihilation
  - Spin-dependent scattering dominates capture in Sun
- For given final state $\chi\chi \rightarrow f\bar{f}$

\[
\phi^f_\mu = \Gamma_A \left[ \eta^f(m_\chi) \right]
\]

\[
\Gamma_{\text{Annihilation}} = \frac{1}{2} C_{\text{capture}}
\]

\[
C_C \propto \sigma^{\chi N} \Rightarrow \sigma^{SD} = \frac{\lambda^{SD}(m_\chi)}{\eta^f(m_\chi)} \phi^f_\mu
\]

Wikström & Edsjö, JCAP 2009
Spin dependent scattering cross section

$0.05 < 0.20$

- AMANDA 2001-2006 (Soft channel)
- AMANDA 2001-2006 (Hard channel)
- IceCube 22 (Soft channel)
- IceCube 22 (Hard channel)
- IC80+DC6 sens.(1800d) (Hard channel)

Direct searches
CDMS
COUPP
KIMS

Super-K
Desai (PRD 2004)

AMANDA 01-06
preliminary

MSSM model predictions
allowed by colliders & direct searches

IceCube-2007
Abassi (PRL 2009)

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DM in IceCube
LKP annihilations in the Sun

- IC22 data re-interpreted in model of Universal Extra Dimensions
- KK-parity conserved → Lightest Kaluza Klein Particle $\gamma^{(1)}$ is DM candidate
- similar observed muon energy spectra for neutralino & LKP
LKP annihilations in the Sun

Experiment – IC22 angular distribution

\[ \Gamma_{90\%}^{\nu \rightarrow \mu} = \frac{\mu_{90\%}}{V_{eff} T_{live}} \]

UED MC simulation

LKP annihilation rate in Sun

\[ \Gamma_{\nu \rightarrow \mu} = \Gamma_A \cdot [factor] \]

DarkSusy

Muon flux at Earth

\[ \phi_\mu (E \geq E_{th}) = \Gamma_A [factor] \]

\[ \sigma^{SD} = K_f^S D \left( m_{\gamma^{(1)}} \right) \phi_\mu^f \]

\( \gamma^{(1)}p \) Scattering cross section

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DM in IceCube
LKP-proton SD cross section

\[ \Delta q(1) = \frac{m(q^{(1)}) - m(\gamma^{(1)})}{m(\gamma^{(1)})} \]

IceCube 2007
Large scale anisotropy near Galactic Centre
Dedicated GC search
Self-annihilation cross section

**WIMPs in the halo**
Large scale neutrino anisotropy

- Search for anisotropy near Galactic Centre in IC22 point source sample
- Background in ‘ON’ = BG in ‘OFF’ = atmospheric $\nu + \mu$

Northern hemisphere = IceCube $\nu$ field of view
Large scale neutrino anisotropy

- 5114 events in 276 days in 2007
- No anisotropy found


Northern hemisphere = IceCube $\nu$ field of view
Neutralino annihilation in the halo

\[
\frac{d\Phi_v}{dE} = \frac{\langle \sigma_A \nu \rangle}{2} J(\psi) \frac{R_{sc} \rho_{sc}^2}{4\pi m_{\chi}^2} \frac{dN_v}{dE}
\]

Halo models

Measure

Constrain

Halo

SUSY

DM in IceCube
Limits on self-annihilation cross section

\[ < \sigma_{Ann} > \]

- IC22 anisotropy
- NFW halo model
- 4 annihilation channels
Neutrinos from Galactic Centre

- Search in IC40 point source sample (2008) for excess in direction of Galactic Centre
- Southern hemisphere: use few outer layers as veto against atmospheric muon background
- No excess found in GC search bin
Limits

- IC22 anisotropy
- IC40 Galactic centre search
- NFW halo model
- 4 annihilation channels
IceCube + DeepCore prospects
DeepCore and WIMPs

- **DeepCore**: low energy extension in deep clear ice
- **Use IceCube as veto against downgoing atmospheric muons**
- **Extend field of view to southern hemisphere in [10GeV-fewTeV] domain**

- Galactic Centre
- **year round solar WIMPs**
Muon flux from solar neutralinos

\[ 0.05 < \Omega_\chi^2 < 0.20 \]

\[ \sigma_{\text{Si}} < \sigma_{\text{Si}}^{\text{CDMS(2010)+XENON100(2010)}} \]

\[ \sigma_{\text{Si}} < 0.001 \sigma_{\text{Si}}^{\text{CDMS(2010)+XENON100(2010)}} \]

- AMANDA 2001-2006 (Soft channel)
- AMANDA 2001-2006 (Hard channel)
- IceCube 22 (Soft channel)
- IceCube 22 (Hard channel)
- IC80+DC6 sens.(1800d) (Hard channel)
- SUPER-K 1996-2001

**AMANDA 01-06**

**IceCube 2007**

**IceCube + DeepCore**

5 years sensitivity
Neutralino scattering in Sun
Summary

• Icecube/AMANDA data was used to search for indirect neutrino signal from WIMP annihilations in Sun & near Galactic Centre
• No signal was found & upper limits were set on muon flux at Earth and Spin Dependent cross sections
• IceCube is completed and is largest ν detector in operation
• Within 5 years sensitivity to DM signals will
  ➢ improve by order of magnitude in [30GeV-5TeV]
  ➢ Unclude sources in Southern hemisphere
IceCube collaboration

Icecube.wisc.edu

The IceCube Collaboration
36 INSTITUTIONS ~250 PHYSICISTS
Backup material
Neutralinos annihilation in Sun
<table>
<thead>
<tr>
<th>Wimp Mass (hard channel) [GeV]</th>
<th>$\sigma_{\chi p}^{SD}$ [pb]</th>
<th>$\sigma_{\chi p}^{SI}$ [pb]</th>
<th>err. scale $1 - / + \frac{\Delta r}{r}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>$1.55 \cdot 10^{-3}$</td>
<td>$5.92 \cdot 10^{-6}$</td>
<td>0.69 / 1.72</td>
</tr>
<tr>
<td>100</td>
<td>$5.98 \cdot 10^{-4}$</td>
<td>$1.34 \cdot 10^{-6}$</td>
<td>0.78 / 1.4</td>
</tr>
<tr>
<td>250</td>
<td>$2.53 \cdot 10^{-4}$</td>
<td>$3.16 \cdot 10^{-7}$</td>
<td>0.83 / 1.28</td>
</tr>
<tr>
<td>500</td>
<td>$3.82 \cdot 10^{-4}$</td>
<td>$3.52 \cdot 10^{-7}$</td>
<td>0.85 / 1.27</td>
</tr>
<tr>
<td>1000</td>
<td>$7.06 \cdot 10^{-4}$</td>
<td>$5.45 \cdot 10^{-7}$</td>
<td>0.85 / 1.25</td>
</tr>
<tr>
<td>3000</td>
<td>$1.22 \cdot 10^{-2}$</td>
<td>$8.38 \cdot 10^{-6}$</td>
<td>0.84 / 1.25</td>
</tr>
<tr>
<td>5000</td>
<td>$3.50 \cdot 10^{-2}$</td>
<td>$2.34 \cdot 10^{-5}$</td>
<td>0.85 / 1.2</td>
</tr>
</tbody>
</table>
neutralinos from centre of Earth
Halo anisotropy data
DeepCore effective area

Preliminary

IceCube + DeepCore

IceCube
Effective Area

\[ m^2 \]

\[ 10^{-3} \]
\[ 10^{-2} \]
\[ 10^{-1} \]
\[ 1 \]
\[ 10 \]
\[ 10^2 \]
\[ 10^3 \]

\( \log_{10} E / \text{GeV} \)

- IC80+DC6, \( \delta = (0^\circ, 30^\circ) \)
- IC80+DC6, \( \delta = (30^\circ, 60^\circ) \)
- IC80+DC6, \( \delta = (60^\circ, 90^\circ) \)
- IC40, \( \delta = (0^\circ, 30^\circ) \)
- IC40, \( \delta = (30^\circ, 60^\circ) \)
- IC40, \( \delta = (60^\circ, 90^\circ) \)
Halo anisotropy & GC SEARCH

Green Area: PAMELA-Fermi-HESS allowed region [P. Meade, M. Papucci, A. Strumia, T. Volansky, [0905.0480]]

Arxiv:0912.5183
J.Huelss DPG

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