Search for Dark Matter with IceCube

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Dark Matter in LHC Era
Kolkata 2011
• 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

Dark halo
light
gas

Double Einstein Ring SDSSJ0946+1006

Hubble Space Telescope • ACS/WFC

NASA, ESA, R. Gavazzi and T. Treu (University of California, Santa Barbara), and the SLACS Team
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

\[ \Omega_{\chi} \approx 0.21 \text{ WMAP} \]

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

\( O(\text{Weak interactions}) \)
Dark matter search strategies

1. Direct detection

2. Indirect detection

3. Production at the Large Hadron Collider
Indirect detection
Mission
Instrument
Neutrino detection

IceCube
Amundsen Scott South Pole Station

IceCube observatory
Ø 1km
At 1.5-2.5 km depth

Station
Skiway
Control room
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

-1450m
-2450m
IceCube detector

- IceTop
- Control room
- IceCube
- AMANDA
- DeepCore
- IceCube 12

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

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

1 TeV → 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

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DM in IceCube
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

- \( \rho_\chi \) (density of WIMPs)
- Service of WIMP distribution
- Sun
- \( G_{\text{capture}} \) (capture rate)
- \( G_{\text{annihilation}} \) (annihilation rate)
- Earth
- \( q\bar{q} \) (quark-antiquark pair)
- \( W^+, Z, H \) (particle final states)
- Detection process: \( \chi \chi \rightarrow \bar{q} q \rightarrow W^+, Z, H \rightarrow \nu_\mu \)

The diagram illustrates the process of WIMP detection, showing the interaction between WIMPs and Earth, leading to the detection of particles like \( \nu_\mu \).
signal and background

**BG**

A few 10,000 atmospheric neutrinos per year from northern hemisphere

Max. a few neutrinos per year from WIMPs

**BG**

$\sim 10^{10}$ atmospheric muons per year from southern hemisphere
• Muon tracks from $\nu_\mu$ Charged Current interactions
• When Sun below horizon: March-September
• Nearly horizontal tracks

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

data $\approx \Sigma$(atm BG)

Atm $\mu$+µµ
Atm. $\nu$

AMANDA

IceCube
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 MC simulations

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

From off-source data

Catherine De Clercq DM in IceCube
<table>
<thead>
<tr>
<th>Search results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AMANDA dedicated search</strong></td>
</tr>
<tr>
<td>M(WIMP) [50-5000 GeV]</td>
</tr>
<tr>
<td><strong>IceCube 22 strings dedicated search</strong></td>
</tr>
<tr>
<td>M(WIMP) [250-5000 GeV]</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

\[ \Gamma_{\nu \to \mu} = \frac{1}{4\pi R_\odot^2} \int dE_\nu \sigma_{\nu N} (E_\nu) \rho_N \text{BR}_{\chi \bar{\chi} \to X} \left( \frac{dN}{dE_\nu} \right)_X \]

Muon flux

\[ \phi_\mu (E \geq E_{th}) = \frac{1}{4\pi R_\odot^2} \int_{E_{th}}^{\infty} dE_\mu \frac{dN}{dE_\mu} \]

Neutralino annihilation rate

Experiment

MSSM MC simulation

DarkSusy
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
  \[
  \chi\chi \rightarrow W^+W^- (\tau^+\tau^-) \rightarrow \nu \quad \text{hard } E_\nu \text{ spectrum}
  \]
  \[
  \chi\chi \rightarrow \bar{b}b \rightarrow \nu \quad \text{soft } E_\nu \text{ spectrum}
  \]

• Simulation with WIMPSIM (Blennow & Edsjö JCAP 2008)
Muon flux from solar neutralinos

$$0.05 < \Omega \chi^2 < 0.20$$

$\sigma_{\text{Si}} < \sigma_{\text{Si}}^m \text{CDMS}(2010)+\text{XENON100}(2010)$

$\sigma_{\text{Si}} < 0.001 \sigma_{\text{Si}}^m \text{CDMS}(2010)+\text{XENON100}(2010)$

AMANDA 01-06 preliminary

Super-K Desai (PRD 2004)

MSSM model predictions allowed by colliders & direct searches

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

IceCube 2007 Abassi (PRL 2009)
Scattering cross section

• muon flux → scattering cross section

• Assume
  – equilibrium between capture in Sun and annihilation
  – Spin-dependent scattering dominates capture in Sun

• For given final state

\[ \chi \chi \rightarrow ff \]

\[ \phi_{\mu}^f = \Gamma_A \left[ \eta^f (m_\chi) \right] \]

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

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

Wikström & Edsjö, JCAP 2009
Spin dependent scattering cross section

0.05 < \Omega \chi^2 < 0.20

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MSSM model predictions allowed by colliders & direct searches

Direct searches
CDMS
COUPP
KIMS

IceCube-2007 Abassi (PRL 2009)
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

![Graph showing muon energy spectra with IC22 data re-interpreted in model of Universal Extra Dimensions.](image)
LKP annihilations in the Sun

Experiment – IC22 angular distribution

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

UED MC simulation

LKP annihilation rate in Sun

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

DarkSusy

Muon flux at Earth

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

\[ \sigma^{SD} = K'_{f}^{SD} \left( m_{\gamma^{(1)}} \right) \phi_{\mu}^{f} \]

\( \gamma^{(1)}p \) Scattering cross section
LKP-proton SD cross section

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

allowed \( m_{\gamma})(, \Delta q^{(n)} \)

IceCube-22 LKP \( \gamma^{(1)} \) (2007)

CDMS (2008)
COUPP (2008)
KIMS (2007)

\[ \Delta q^{(n)} = 0.01 \]
\[ \Delta q^{(n)} = 0.1 \]
\[ \Delta q^{(n)} = 0.5 \]

\( 0.05 < \Omega_{CDM} h^2 < 0.20 \)
\( 0.1037 < \Omega_{CDM} h^2 < 0.1161 \) WMAP 1\( \sigma \)
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

Diagram showing the Northern and Southern hemispheres with 'On-source' and 'Off-source' regions highlighted.
Large scale neutrino anisotropy

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

Northern hemisphere = IceCube ν field of view

Neutralino annihilation in the halo

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

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

\(< \sigma_{Ann} \nu >\)

- 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

Muons from the Sun (km² y⁻¹)

Neutralino mass (GeV)

0.05 < Ωχ² < 0.20

σ_{SI} < σ_{SI}^{mCDS}(2010)+XENON100(2010)

σ_{SI} < 0.001×σ_{SI}^{mCDS}(2010)+XENON100(2010)

AMANDA 01-06

AMANDA 2001-2006 (Soft channel)

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IceCube 2007

IceCube + DeepCore
5 years sensitivity

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DM in IceCube
Neutralino scattering in Sun

0.05 < Ω_χ^2 < 0.20

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IceCube + DeepCore
5 years sensitivity

AMANDA 01-06

IceCube 2007
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
The IceCube Collaboration

36 INSTITUTIONS ∙ ~250 PHYSICISTS