Extragalactic neutrinos from the South Pole

IceCube Observatory

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1. Physics
2. Detector theory
3. Detector construction
4. Extragalactic >1 TeV neutrino analysis
5. Future detectors
6. Going to Pole...
Gamma-rays: Absorbed at highest energies, multiple emission mechanisms

Protons: Scrambled by magnetic fields, only point at extremely high energies

Neutrinos: Neutral charge and low cross-section mean they point back to sources and are not absorbed

Neutrinos are excellent candidates for high-energy astronomy
Cosmic Rays and Neutrinos

Driving theme: Origin of Cosmic Rays

The $\gamma - \nu$ connection for hadronic accelerators

Accelerator

Target

$\pi^\pm$, $\pi^0$, $\mu^\pm$, $\nu\nu\gamma\gamma$
TeV Neutrinos

Observing astrophysical neutrinos allows conclusions about the acceleration mechanism of Cosmic Rays

\[ p + \gamma \rightarrow \pi^0 + p \]

or \( p, \ldots \)

\[ \rightarrow \gamma + \gamma + p \]

\[ \rightarrow \pi^+ + n \]

\[ \rightarrow \mu^+ + \nu_\mu + n \]

\[ \rightarrow e^+ + \nu_\mu + \nu_c + \nu_\mu + n \]

TeV gamma rays

TeV neutrinos

(can also be from leptonic processes…)

Neutrinos from cosmic ray interactions in:

- Atmosphere
- Cosmic Microwave Background
- Gamma Ray Bursts (Acceleration Sites)
- Active Galactic Nuclei (Acceleration Sites)
- ?
Neutrino Detection Principle

Observe the charged *secondaries* via Cherenkov radiation detected by a 3D array of optical sensors.

Need a huge volume (km$^3$) of an optically transparent detector material.
What is so special about the South Pole?

Antarctic ice is the most transparent natural solid known.
What is so special about the South Pole?

Optical properties of the ice track mineral dust concentration which tracks past climate.
Neutrino Event Signatures

CC Muon Neutrino

\[ \nu_\mu + N \rightarrow \mu + X \]

track (data)
factor of \( \approx 2 \) energy resolution
< \( 1^\circ \) angular resolution

Neutral Current / Electron Neutrino

\[ \nu_e + N \rightarrow e + X \]
\[ \nu_x + N \rightarrow \nu_x + X \]
cascade (data)
\( \approx \pm 15\% \) deposited energy resolution
\( \approx 10^\circ \) angular resolution
(at energies \( \geq 100 \text{ TeV} \))

CC Tau Neutrino

\[ \nu_\tau + N \rightarrow \tau + X \]

“double-bang” and other signatures
(simulation)
(not observed yet)
Backgrounds and Systematics

- **Backgrounds:**
  - Cosmic Ray Muons
  - Atmospheric Neutrinos

- **Largest Uncertainties**
  - Optical Properties of Ice
  - Energy Scale Calibration
  - Neutral current / $\nu_e$ degeneracy

Bundle of muons from a CR interaction in the atmosphere (Also observed in IceTop)
Calibration
Various calibration devices/methods to control detector systematics

- LED flashers on each DOM
- In-ice calibration laser
- Cosmic ray energy spectrum
- Moon shadow
- Atmospheric Neutrino Energy
- Minimum-ionizing muons

Moon Shadow in Cosmic Rays
Muons in IceCube (59 strings)
The IceCube Neutrino Observatory

2004: Project Start

2011: Project completion

Digital Optical Module (DOM)

DeepCore
8 strings – spacing optimized for lower energies
480 optical sensors

Configuration chronology
2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86
BUILDING ICECUBE
Amundsen-Scott Station

Geographical South Pole

Skiway

IceCube footprint

Counting house

DeepCore footprint

Drill Camp
The Digital Optical Module

Complete data acquisition system:

Digitization and time stamping of PMT pulses
Onboard PMT gain and time calibration
Transmitting digital data to the surface

Power consumption: 3W
Deadtime: << 1%
Dark noise rate: < 400 Hz
Local Coincidence rate: ~15 Hz
Timing: ~1ns
IceCube Drilling

- Snow
  - Firn
  - Ice

Water level (30-50m)

- Pump
- Hot water drill
- 70°C – 90°C
- 2400 m
- 55 cm

Heaters
- 200g
- 1000psi

Tank

High pressure pumps

Drill to following:
- 2400 m depth
- 60 cm diameter
- Deviation from vertical is +1 m
- Drill rate 60-100 m/hr
IceCube Site

5 megawatt power plant
one of 21 drill modules arrive in Antarctica
Hose reel
Drill tower
Hot water generator
IceTop Tanks

5 megawatt hot water drilling system
drilling and deployment

2 days per hole
3.5 cm/second
the IceCube project transforms a billion tons of ice into a particle physics detector and pc start their journey to 2500 m
Current IceCube Science Topics

• Neutrinos:
  – Atmospheric neutrinos (from cosmic ray interactions in Earth’s atmosphere)
  – **Point source searches**
    • Targeted (from particular gamma-ray sources, for instance)
    • Untargeted (look for any “hot spot” in the sky)
  – **Search for diffuse extragalactic neutrinos**
  – **Transient source searches**
    • Coincidences with GRB’s observed by satellite
    • Untargeted (look for any “burst” of events closely-spaced in time)
  – Neutrino oscillation
  – Supernova detection

• Cosmic Rays:
  – Composition and spectrum of cosmic rays
  – Anisotropy of cosmic ray arrival directions
  – Relationship to solar phenomena (flares, etc.)
  – Relationship to atmospheric phenomena (pressure, temperature, etc.)

• Searches for Dark Matter and Exotic Particles
  – WIMP’s from the center of the Earth, Sun, and Galaxy
  – Magnetic monopoles

• Glaciology and ice properties

• “Big Data” and GPU computing
No evidence of point sources was found in four years of detector data

- Search for time-independent sources
- 394,000 total events
  - 178k neutrino candidates in North, 216k atmospheric muons in South
- Livetime: 1371 days, including first year of completed detector
No evidence of point sources was found in four years of detector data

- Search for time-independent sources
- 394,000 total events
  - 178k neutrino candidates in North, 216k atmospheric muons in South
- Livetime: 1371 days, including first year of completed detector

\[-\log_{10}(p) = 5.039 \quad RA: 11.45^\circ \quad Dec: 31.35^\circ\]
\[n_{\text{Src Best}} = 40.17 \quad \gamma_{\text{Best}} = 3.45\]

\[-\log_{10}(p) = 5.958 \quad RA: 296.95^\circ \quad Dec: -75.75^\circ\]
\[n_{\text{Src Best}} = 16.16 \quad \gamma_{\text{Best}} = 2.34\]

Most significant spots

Post trials p-values:
Northern Sky: 37.6%
Southern Sky: 9.3%
All searches for transient sources are also consistent with background.

Untriggered flare search, 79-string detector configuration.

See 2013 ICRC, contribution #0649
The Neutrino Landscape above 1 TeV

- \( E^3 \times 10^4 \) to \( E^10^11 \)
- \( \pi/K \) Atmospheric Neutrinos (dominant < 100 TeV)
- Charm Atmospheric Neutrinos ("prompt", visible \( \sim 100 \) TeV)
- Astrophysical Neutrinos (maybe dominant > 100 TeV)
- Cosmogenic Neutrinos (> \( 10^6 \) TeV)
The (Very) High-Energy Tail
Searching for a signal above the atmospheric neutrino background
Signals and Backgrounds

**Signal**
- Dominated by showers (~80% per volume) from oscillations
- High energy (benchmark spectrum is typically $E^{-2}$)
- Mostly in the Southern Sky due to absorption of high-energy neutrinos in the Earth

**Background**
- Track-like events from Cosmic Ray muons and atmospheric $\nu_\mu$
- Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)
- Muons in the Southern Sky, neutrinos in from the North
Hint in upgoing muons

Study using the “IC59” partial detector during construction: 1.8 $\sigma$
Another Hint in Shower
Study using the “IC40” partial detector during construction: 2.4 $\sigma$

![Graph showing event distribution and signal region](image)
GZK Neutrino Analysis
Simple search to look for extremely high energies ($10^9$ GeV) neutrinos from proton interactions on the CMB

- **Upgoing muons**
  - Always neutrinos
  - Background: atm. neutrinos
  - High threshold (1 PeV)

- **Downgoing muons (VHE)**
  - Cosmic Ray muon background
  - Very high threshold (100 PeV)
Results (GZK search)
Appearance of \( \sim 1 \) PeV cascades as an at-threshold background

- Two very interesting events in IceCube (between May 2010 and May 2012)
  - shown at Neutrino 2012
  - \( 2.8 \sigma \) excess over expected background in GZK analysis
  - PRL 111, 021103 (2013)

- There should be more
  - GZK analysis is only sensitive to very specific event topologies at these energies
What are they?

Studying individual events in IceCube
What are they?
Systematics in Energy Reconstruction

- **Energy scale: better than \( \approx 10\% \)**
  - From minimum ionizing muons: \( \pm 5\% \)
  - Scales very well to higher energies over orders of magnitude (measured with in-ice calibration laser)

- **Modeling of photon transport in ice**
  - Measured with in-ice calibration LEDs and other devices (dust logger, ...)

- **Statistical error at 1 PeV is negligibly small**
Directional Resolution for Showers

- Angular error distributions on the order of 10°-15° depending on the ice model assumption
  - two ice examples are shown
  - aggregate resolution in black
Things We Know

- At least two PeV neutrinos in a 2-year dataset
- Events are downgoing
- Seems not to be GZK ((MUCH) too low in energy)
- Higher than expected for atmospheric background
- Spectrum seems not to extend to much higher energies
  - (assuming unbroken $E^{-2}$)
Things We Wanted to Learn

- Isolated events or tail of spectrum?
- Spectral slope/cutoff
- Flavor composition
- Where do they come from?
- Astrophysical or air shower physics (e.g., charm)?
- Need more statistics to answer all of these!
High-Energy Contained Vertex Search

How we found more...
Follow-up Analysis
Specifically designed to find these contained events.

- Explicit contained search at high energies (cut: $Q_{\text{tot}}>6000$ p.e.)
- 400 Mton effective fiducial mass
- Use atmospheric muon veto
- Sensitive to all flavors in region above 60TeV
- Three times as sensitive at 1 PeV
- Estimate background from data
Background 1 - Atmospheric Muons
Mostly incoming atmospheric muons sneaking in through the main dust layer

- Reject incoming muons when “early charge” in veto region
- Control sample available: tag muons with part of the detector - known background
- $6 \pm 3.4$ muons per 2 years (662 days)
Background 1 - Atmospheric Muons

What’s “early charge?”

Throughgoing muon

- Total detector
- Veto region

- $Q/pe$ (cumulative)
- $dQ/dt$

- $T_{250} = \text{time at which } Q = 250 \text{ pe}$

Contained cascade

- Total detector
- Veto region – barely contained cascade
- Veto region – well contained cascade

- $Q/pe$
- $dQ/dt$

- $T_{250} = \text{time at which } Q = 250 \text{ pe}$
Vetoing Atmospheric Neutrinos

- Atmospheric neutrinos are made in air showers
- For downgoing neutrinos, the muons will likely not have ranged out at IceCube
- Downgoing events that start in the detector are extremely unlikely to be atmospheric

- Note: optimal use requires minimal overburden to have the highest possible rate of cosmic ray muons!
**Effective Area**

Differences at low energies between the flavors due to leaving events at constant charge threshold.
Effective Volume / Target Mass
Fully efficient above 100 TeV for CC electron neutrinos
About 400 Mton effective target mass
What Did We Find?

26 more events!
What Did We Find?
28 events in 2 years of IceCube data
(662 days between 2010–2013)

- 28 events observed!
  - 26 new events in addition to the two 1 PeV events!

- Estimated background
  - $4.6^{+3.7}_{-1.2}$ atm. neutrinos
  - $6.0 \pm 3.4$ atm. muons

significance w.r.t. reference bkg. model:
- $3.3 \sigma$ for 26 events
- combining with $2.8 \sigma$ from GZK result:
  - $4.1 \sigma$ for 26+2 events
  - full likelihood fit of all components:
    - $4.1 \sigma$ for 28 events
What Did We Find?
37 events in 3 years of IceCube data
(988 days between 2010–2013)

- 37 events observed!
  - 35 new events in addition to the two 1 PeV events!

- Estimated background
  - $6.6^{+5.9}_{-1.6}$ atm. neutrinos
  - $8.4\pm4.2$ atm. muons

- One of them is an obvious (but expected) background
  - coincident muons from two CR air showers

combining with $2.8\sigma$ from GZK result:
  - $4.8\sigma$ for 35+2 events
  - full likelihood fit of all components:
  - $5.7\sigma$ for 36(+1) events
What Did We Find?

Some examples

- declination: -13.2°
deposited energy: 82 TeV

- declination: -0.4°
deposited energy: 71 TeV

- declination: 40.3°
deposited energy: 253 TeV
Event Reconstruction

Generic full-sky likelihood scan for each event (works with shower and track signatures)

- Fits for deposited energy along a “track” in each skymap direction based on hit pattern using a detailed model of the glacial ice optical properties
- Result: direction with uncertainty
Charge Distribution

- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold ($Q_{\text{tot}}>6000$)

- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)
Compatible with benchmark $E^{-2}$ astrophysical model

- Harder than any expected atmospheric background
- Merges well into background at low energies
- Potential cutoff at about 2-5 PeV (or softer spectrum)
- Best fit (per-flavor flux):
  - $0.95 \pm 0.3 \times 10^{-8} \text{ E}^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
Unfolding to Neutrino Energy

An attempt to plot the spectrum unfolded true neutrino energy, simultaneously fitting for backgrounds.

IceCube Preliminary
Declination Distribution
Or: “zenith Distribution” because we are at the South Pole

- Compatible with isotropic flux
- Events absorbed in Earth from Northern Hemisphere
- Minor excess in south compared to isotropic, but not significant
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![Graph showing Declination Distribution](Image)
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![Graph showing declination distribution with IceCube Preliminary label](image-url)
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![Graph showing Declination Distribution](image)

- IceCube Preliminary

Graph legend:
- $E_{dep} > 230$ TeV
- Background Atmospheric Muon Flux
- Bkg. Atmospheric Neutrinos (ν/K)
- Background Stat. and Syst. Uncertainties
- Atmospheric Neutrinos (90% CL Charm Limit)
- Signal+Bkg. Best-Fit Astrophysical $E^{-2}$ Spectrum
- Data
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![Graph showing Declination Distribution]

- **Southern Sky (downgoing)**
- **Northern Sky (upgoing)**

- **$E_{dep} > 300$ TeV**
- Background Atmospheric Muon Flux
- Bkg. Atmospheric Neutrinos ($\pi$/K)
- Background Stat. and Syst. Uncertainties
- Atmospheric Neutrinos (90% CL Charm Limit)
- Signal+Bkg. Best-Fit Astrophysical $E^{-2}$ Spectrum
- Data

**IceCube Preliminary**
Skymap / Clustering

No significant clustering observed (first two years)
No significant clustering observed (three years)

**Shower events**
p-value: 7%

**All events**
p-value: 84%
Skymap / Clustering

No significant clustering observed (three years)
Into the future...

PINGU
DM-ICE
ARA

Next Generation IceCube
High energy neutrinos
At the highest energies: “neutrino = extraterrestrial source”

- **Lots of cascades, only a few tracks**
  - cascades are limited by angular resolution $O(10 \text{deg})$, dominated by ice systematics
  - great for measuring a diffuse flux, not so great for astronomy

- **We need more tracks!**
  - (and of course we need to continue improving our systematics on the ice for cascades)
At the highest energies: “neutrino = extraterrestrial source”

- We have a few nice starting tracks!
  - e.g. “event #5” - starts three layers of strings inside the detector
How do we get more tracks?

- Add a large surface array, extending several km - can act as a CR veto
  - enlarged volume for “starting” tracks
How do we get more tracks?

- **Add more strings, with wider spacing**
  - enlarges volume for starting tracks (and “ordinary” tracks)
  - long lever arm ➔ better resolution
How do we get more tracks?

- Or, of course, both!
The Future

Some of the things we are thinking about…
Phased IceCube Next Generation Upgrade

PINGU

40 additional strings (~2400 pDOMs) in the 30 MT DeepCore volume

Enhanced low-energy capabilities:
Neutrino oscillations/hierarchy
Indirect Dark Matter searches
Supernova neutrinos
DM-Ice 17kg pilot detector

Detectors
• Two 8.5 kg NaI detectors (total: 17 kg)
• Crystals from NAIAD

Goals
• Establish radiopurity of Antarctic ice / hole ice
• Assess the feasibility of deploying NaI(Tl) crystals in Antarctic ice for a dark matter detector
• Explore the capability of IceCube to veto muons

Future Plans
• 250 kg detector (Now funded @ Yale)
• Segmented crystals
• Multiple deployment options
DM-Ice 17kg pilot detector

Two detectors installed in Dec 2010
Stable data taking since March
Data transmitted over satellite

Estimated contributions to event rate

<table>
<thead>
<tr>
<th>Material</th>
<th>$^{238}$U</th>
<th>$^{232}$Th</th>
<th>nat K</th>
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<td>drill ice [27]</td>
<td>0.076±0.046</td>
<td>0.47±0.14</td>
<td>&lt;262</td>
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<td>Antarctic ice</td>
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<td>PMT [26]</td>
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<tr>
<td>steel PV [27]</td>
<td>0.2</td>
<td>1.6</td>
<td>442</td>
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<tr>
<td>NaI</td>
<td>0.005</td>
<td>0.005</td>
<td>10</td>
</tr>
</tbody>
</table>

Goal is ~1

Preliminary

239 keV: Pb-212 from Th chain
352 keV: Pb-214 from U chain
609 keV: Bi-214 from U chain
860 keV: Ti-208 from Th chain
1173 keV: Co-60
1460 keV: K-40
Testing DAMA’s Dark Matter Claim

Control or eliminate possible sources of background & annual modulation

- Change the environment / background
- Go deeper, tag possible bgds, or ...
- Go to the southern hemisphere

Eliminate uncertainties due to astrophysics, detector effects, and dark matter models

- Use same detector medium: NaI(Tl)

Definitive (5σ) detection or exclusion

- 500 kg-yr NaI(Tl) (DAMA x 2 yrs)
- same or lower threshold (< 2 keV
- background < (DAMA x 5)

500 kg•year NaI detector sensitivity
(2 - 4 keV) with bgd of 1, 2, and 5 cnts/keV/kg/day.

Cherwinka et al. arXiv:1106.1156
Environmental Backgrounds and Mitigation in Underground Laboratories

**South Pole Ice**

**Cosmic rays, muons**
- Underground laboratories under mountains
- Muon tagging and veto

**Environmental Gammas**
- Lead and copper shielding
  - Radioactivity in Antarctic ice = $10^{-7} \times$ rock
  - ~1 Bq of $^{238}$U in (10m)$^3$

**Spallation Neutrons**
- Neutron moderators (water, borated polyethylene)
DM-Ice: Full Scale

**Detector**
- ~250 kg of low background NaI(Tl)
- Closely-packed inside pressure vessel for coincidence veto
- Two PMTs/Crystal

**Location**
- South Pole, ~ 2500 m deep in the ice
- Near the center of IceCube for additional veto

**Electronics**
- Compact, low power to accommodate all channels
- Pulse digitization inside the vessel
- Power from SP Station or IceCube Counting Lab
- Remotely controllable

**Pressure vessel**
- Withstand > 7000 psi of freeze-back pressure
- Low-background stainless steel
- Low background copper shielding where needed
ARA: Askaryan Radio Array
Askaryan Effect

In electron-gamma shower in matter, there will be \(~20\%\) more electrons than positrons.

Compton scattering: \(\gamma + e^-_{(at\ rest)} \rightarrow \gamma + e^-\)

Positron annihilation: \(e^+ + e^-_{(at\ rest)} \rightarrow \gamma + \gamma\)

In dense material, \(R_{\text{Moliere}} \sim 10\text{cm}:\)

\(<< R_{\text{Moliere}} \) (optical case), random phases \(P\) \(N\)

\(>> R_{\text{Moliere}} \) (microwaves), coherent \(P\) \(N^2\)

\[ \frac{dP_{CR}}{d\nu} \propto \nu d\nu \]
Validation at SLAC

ANITA I beamtest at SLAC (June06): proof of Askaryan effect in ice
- Coherent (Power \( \sim E^2 \))
- Linearly Polarized

“Little Antarctica”
Array of single dipole antennas deployed between 100 and 300m near the Pole

- Much of the instrumentation was deployed in AMANDA holes
- Pioneered technique in the ice

Special radio detectors and pulsers in IceCube

- Balloon payload of horn antennas
- Surveys the ice cap from high altitude for RF refracted out of the ice
- High fidelity data acquisition system >Giga/sec waveform capture

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA) heritage:
Existing and previous instruments using radio in Polar ice
Members of all three efforts are currently involved with ARA
Askaryan Radio Array (ARA) - a very large radio neutrino detector at the South Pole

Scientific Goal:
• Discover and determine the flux of highest energy cosmic neutrinos.
• Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:
Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick ice sheet at the South Pole

Areal coverage: ~150km^2

Design goals and choices:

- Every station is a fully functioning detector.
- Lower energy threshold: nearby events (300m) can be reconstructed.
- Background rejection:
  - Embedded strings: Allow good vertex resolution and high vertical resolution for background rejection.

10^7 to 10^{11} GeV: Radio ice Cherenkov detection
Physics conclusions

Stay tuned!

- 28, 36(+1) events with energies above $\approx 50$ TeV found in two, three years of IceCube data
- Increasing evidence for high-energy component beyond the atmospheric spectrum
- Original 2-year sample inconsistent at $4.1 \sigma$ with standard background assumptions
- Less clear what it is - compatible with astrophysical explanations
- (Even) more data coming soon!
Some Comments

Stay tuned!

- This is probably from many far-away sources (extragalactic)
  - [or maybe from a really close-by source??]
- We need a bigger detector! (And a better veto - maybe at the surface?)
  - Tracks point, but they are rare if you want high signal purity
- We just started (this is using only the first two years of the final detector with 86 strings)
The IceCube Collaboration

39 Institutions
~220 collaborators

International Funding Agencies

- Fonds de la Recherche Scientifique (FRS-FNRS)
- Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
- Federal Ministry of Education & Research (BMBF)
- German Research Foundation (DFG)
- Deutsches Elektronen-Synchrotron (DESY)
- Knut and Alice Wallenberg Foundation
- Swedish Polar Research Secretariat
- The Swedish Research Council (VR)
- University of Wisconsin Alumni Research Foundation (WARF)
- US National Science Foundation (NSF)
DM-Ice Collaboration

University of Wisconsin – Madison
University of Sheffield
Boulby Underground Science Facility
SNOLAB
University of Alberta
Penn State
Fermilab
Shanghai Jiao Tang University
University of Illinois at Urbana-Champaign
NIST-Gaithersburg
University of Stockholm

Special thanks to the IceCube team!
ARA Collaboration

- ARA is an international Collaboration
  - 14 institutions
  - ~50 authors
"Nobody lives at the South Pole, 'cause it's too cold... and besides, they'd fall off!"
GOING TO THE SOUTH POLE & ONCE YOU’RE THERE
New Year Day Photo of ARA and IceCube field team members
Winter Over Experiments Operator

Degree Requirements

M.S. in Physics, Electrical Engineering, Computer Science or related field is required. B.S. in Physics, Electrical Engineering, Computer Science, or related field and substantial (equivalent to a masters degree) experience will be considered.

Job Requirements

A minimum of three years of work experience in the following areas:

- Administering UNIX (preferably Linux) operating systems.
- Configuring UNIX core services and network management.
- Writing systems shell scripts (bash, python, perl).
- Ability to take initiative (must be a self starter).
- Excellent communication and organization skills.

Preferred Experience

- Computer systems security methodology and experience with host based security tools.
- Skills in maintaining and debugging of high-performance computing hardware.
- Data storage products such as magnetic tape backups and RAID disk arrays.
- Use of standard laboratory equipment such as oscilloscopes, function generators, spectrum analyzers, and OTDRs.
- Understanding of TCP/IP networking
- General electronics debugging and repair skills.
- Experience working at Polar and high altitude sites and remote locations.
- Physics background.

Principal Job Duties

Training for two candidates is anticipated to begin in Madison, WI in August. Deployment to the South Pole is expected to be in early October for 12-13 months with no possibility of leaving during the winter months from mid-February to mid-October. Expertise will be balanced between the two candidates over the range of skills required. Individuals will be required to have a good working knowledge of the entire system.

The candidates will be members of a small isolated community at the South Pole for eight months of the year. Community members participate in a wide range of activities including fire or trauma team, kitchen tasks, general cleaning, and station opening and closing duties. The candidates need to be physically qualified to work at polar and high altitude sites for one year.
Backup Slides
Season by season construction of the detector
In the Shadow of the Moon

Cosmic rays blocked by the moon cause point-like deficit in angular distribution of down-going muons in the detector.

Moon shadow seen with $\approx 10^4$
Systematic pointing error $< 0.1^\circ$
Verification of PSF for track reco.

Need high statistics and good angular resolution!
Atmospheric Neutrinos

High-purity atmospheric neutrino sample obtained with quality cuts on event reconstruction variables

IceCube $\nu_\mu$ spectrum up to 400 TeV

Phys. Rev. D83 (2011) 012001
Neutrino Oscillations in PINGU?

PINGU is a concept for even higher density infill to DeepCore that lowers the energy range of IceCube to several GeV range with MT’s effective volume.


Statistical significance of Normal versus Inverted Mass Hierarchy.

Sets PINGU requirements on:
1) Energy Resolution
2) Angular Resolution
3) Particle ID, Bkgrd
4) Systematic Errors

We are currently studying the feasibility of reaching the needed requirements.

Size matters: need for a km$^3$ neutrino detector

Rate = Neutrino flux \times Neutrino Effective Area
       = Neutrino flux \times Neutrino Cross Section \times Absorption in Earth
       \times Size of detector \times (Range of muon for $\gamma$)

Expected GZK neutrino rates in 1 km$^3$ detector: $\sim$ 1 per year
Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube.
Indirect Dark Matter Searches

Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe.

Clusters of Galaxies

Dwarf spheroidal galaxies

WIMP $\rightarrow p^+, e^-, \gamma, \nu$

WIMP $\rightarrow p^-, e^+, \gamma, \nu$
Indirect Dark Matter Search: Solar WIMPs

Data collected when the Sun is below the horizon at the South Pole

No excess of events from the Sun, observation consistent with the expected background

⇒ upper limit on the number of signal events at 90% CL: \[ \bar{\nu}_s \]

⇒ 90% CL limit on the neutrino to muon conversion rate:

\[ \Gamma_{\nu \rightarrow \mu} = \frac{\mu_s}{V_{\text{eff}} \times T} \]

⇒ 90% CL limit on the neutralino annihilation rate in the Sun:

\[ \Gamma_A = \kappa^{-1}(\chi) \times \Gamma_{\nu \rightarrow \mu} \]
Indirect Dark Matter Search: Solar WIMPs

IceCube/AMANDA results from 1065 days of livetime between 2001-2008

90% CL **muon flux limit** from the Sun
(compared to MSSM scans)

90% CL **neutralino-p Xsection limit**
(compared to MSSM scans)

\[ 0.05 < \Omega_c h^2 < 0.20 \]

**IceCube Preliminary**

Muon flux from the Sun [km\(^{-2}\)y\(^{-1}\)]

- \( \sigma_{SI}^{(\text{CDMS}(2010)+XENON100(2011))} \)
- IC/Amanda 2001-2008, \( W^+ W^- \) (*)
- IC/Amanda 2001-2008, \( b\bar{b} \)
- IC86 180 days sensitivity, \( W^+ W^- \) (*)
- Super-K 2001
- (*) \( \tau^+ \tau^- \) for \( m_\chi < m_W \)

\[ 0.05 < \Omega_c h^2 < 0.20 \]

**IceCube Preliminary**

Neutralino-proton SD cross-section [cm\(^2\)]

- CDMS 2010
- COUPP 2008
- KIMS 2007
- Picasso 2009
- IC/Amanda 2001-2008, \( W^+ W^- \) (*)
- IC/Amanda 2001-2008, \( b\bar{b} \)
- IC86 180 days sensitivity, \( W^+ W^- \) (*)
- (*) \( \tau^+ \tau^- \) for \( m_\chi < m_W \)

\( \Phi \mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{Xp} \)

(particle physics and solar model)
Indirect Dark Matter Search: Galactic Halo

IC22 (275 days)

Expected relative neutrino flux from DM self-annihilation in GH

No observed excess over background
IceCube-79 Solar WIMP Search

All-year search: three cuts to search for neutrinos above background from the Sun’s direction, even when looking up in the Summer!

- **Northern Hemisphere: (winter - looking down)**
  - look for incoming and starting (contained) events

- **Southern Hemisphere: (summer - looking up)**
  - look for events starting deep in the detector to reduce downgoing background

- 317 days of livetime, down to neutrino energies of ~10GeV!
IceCube-79 Solar WIMP Search

- Complementary to direct detection search efforts
  - fills out WIMP picture by testing other properties
- Most stringent SD cross-section limit for most models
Galactic Center Dark Matter Search

IceCube-79 string configuration

- **Two different analyses:**
  - DeepCore and DeepCore+IceCube
- **lower the energy threshold to ~10 GeV**
- **Improved muon veto**
- **Use scrambled data for background estimation**
Galactic Halo Dark Matter Search

IceCube-79 string configuration

- Compare background and signal skymaps
- Use a multipole analysis to find large-scale anisotropies
Various Potential Dark Matter Signals
Various analyses looking at different source distributions

- **Galactic Halo:**
  - IC22 PRD 8 (2011) 022004
  - IC79 in preparation

- **Galactic Center:**
  - IC79 in preparation

- **Dwarf spheroids:**
  - IC59 PRD 88 (2013) 122001

- **Clusters of galaxies:**
  - IC59
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Neutrino Oscillations with DeepCore

Vertically up-going neutrinos, $L = \text{Earth's diameter}$

- $\nu_\tau$ appearance
- $\nu_\mu$ disappearance

Atm. $\nu_e$ disappearance MC

- 3-flavor oscillations
- Signal simulation only
- Livetime = 1 year IC79
IceCube Deep Core (low energy & contained events)

Motivation:
- Low mass WIMP search (indirect DM)
- Neutrino oscillation physics
  - extend LE, $n_m$ disappearance, $n_t$ appearance
- southern hemisphere $\rightarrow 4\pi$ detector
Low Energy Cascades (DeepCore)

- Cascades are the signature of neutral current, $\nu_e$ and $\nu_\tau$
- First observation of atmospheric neutrino-induced cascades in IC79 with DeepCore
Standard Atmospheric Neutrino Oscillation in the energy region of interest for DeepCore

Search Strategies for Astrophysical Neutrinos

1) Point Source & GRB search use direction [and] timing to look for signal above isotropic atmospheric neutrino background.
Gamma Ray Bursts

- Gamma-Ray Bursts are short bursts of gamma rays, a few seconds in duration
- Brighter than rest of gamma ray sky
- Afterglow lasting much longer
- First observed in Vela satellites (1960s)
- Several generations of satellite-based observations have shown:
  - Extra-galactic origin
  - Gamma-ray emission beamed
- Internal shocks in GRBs are a compelling candidate for the source of acceleration for UHECRs.
- Acceleration conditions required to produce the observed gamma rays would also be sufficient for UHECR production
- Observed gamma-ray burst energy injection rate into Universe well matched to observed UHECR energy
- Waxman-Bahcall modeled neutrino production from photon-hadron interactions in fireball
IceCube GRB search

- IceCube performed a stacked search for a neutrino signal in coincidence with observed GRB gamma signals
  - All Northern hemisphere GRB bursts are considered.
- Combination of spatial and time correlation yields very low background (~Background Free Search)
- Per-burst neutrino fluence and spectra are calculated based on the measured gamma-ray spectra. Parameterization of Guetta, et al. (Astropart.Phys. 20 (2004) 429-455)

![Graph showing the analysis and results from IceCube's GRB neutrino search.](image)

- 90% c.l. = 0.27 model
- 8.4 events expected
- 0 events observed

*Nature Vol 484, 351 (2012)*
IceCube GRB Summary

• Three successive seasons (IC 22, 40, 59) without a GRB neutrino discovery

• Combined (IC40, IC59) search results
  – Expect 8.4 events, see $0 \rightarrow 0.27$ Guetta et al prediction

• Where are the neutrinos? $\rightarrow$ Nature Paper

• Do we already rule out GRB as The CR source?
  – Input assumptions in modeled GRB neutrino flux
    • Bulk Lorentz factor, fraction of energy in electrons relative to protons, dynamics of time structure, particle physics

• Has generated activity in the theory of GRB’s
  – Recalculations reduce predicted neutrino significantly

• IC79, 86 (~3x sensitivity of current limit) already recorded
  – IceCube sees n’s within “years” or rule out GRB as THE CR source
Searches for a Diffuse Neutrino Flux

**Diffuse Flux** = effective sum from all (unresolved) extraterrestrial sources (e.g. AGNs)
Possibility to observe diffuse signal even if flux from any individual source is too weak for detection as a point source

Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos

Advantage over point source search: can detect weaker fluxes

Disadvantages:
- high background
- must simulate background precisely

Sensitive to all three neutrino flavors
2) Diffuse Searches use energy to separate from isotropic atmospheric Neutrino background
Current $n_m$ Diffuse limits (single flavor)
Cosmic Rays in IceCube

By measuring downward going muons from air showers, IceCube can study the arrival direction distribution of cosmic rays in the energy range ~10 TeV to several 100 TeV and produce a cosmic ray sky map of the southern sky.

Muons produced in downward going cosmic ray air showers are detected by IceCube at a rate of > 1000 Hz.

The median energy of the cosmic ray primaries is 20 TeV, and the median angular resolution is 3° (not to be confused with the resolution for neutrinos in IceCube!)
EHE neutrinos from GZK mechanism

Cosmic rays with energy > 100 EeV will collide with the cosmic microwave background photons, producing pions (and thus neutrinos)

\[ p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+ \]

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

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

A search using 79- and 86-string IceCube (2 years, or 672.7 days)...

...while eliminating most background

![Signal simulation](image1.png)

keep the signal

![Background simulation](image2.png)
EHE neutrinos from “GZK” mechanism

Two cascade-like events pass selection criteria. Background expectation: 0.14 events.

Primary IceCube Sensitivity 2010-2012

IceCube 2010-2012

Preliminary

Aug 9th, 2011

Jan 3rd, 2012
Relative Intensity of Cosmic Rays

Observation of anisotropy in the arrival directions of cosmic rays

not 180° between min/max → not a dipole

<table>
<thead>
<tr>
<th>Year</th>
<th>Rate (Hz)</th>
<th>LiveTime</th>
<th>CR Median Energy</th>
<th>Median Angular Resolution</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 (IC22)</td>
<td>240</td>
<td>~226 days</td>
<td>~19 TeV</td>
<td>3°</td>
<td>4·10⁹</td>
</tr>
<tr>
<td>2008 (IC40)</td>
<td>780</td>
<td>~324 days</td>
<td>~19 TeV</td>
<td>3°</td>
<td>1.9·10¹⁰</td>
</tr>
<tr>
<td>2009 (IC59)</td>
<td>1200</td>
<td>~324 days</td>
<td>~19 TeV</td>
<td>3°</td>
<td>3.3·10¹⁰</td>
</tr>
</tbody>
</table>
Cosmic Ray anisotropy

Anisotropy seen in Southern Sky by IceCube is continuation of anisotropy seen in Northern Sky

Cause of anisotropy not known. Speculations include:
• Isolated nearby and recent SNR
• Configuration of magnetic fields in or near solar system
• Compton-Getting effect (not consistent with data)

Further studies of anisotropy vs energy, angular scale, time variability, spectral properties, ...
Cosmic ray anisotropy at higher energies?

Non-diffusive effects in propagation of the particles? Nearby SNe?

Structure in the magnetic fields of our near neighborhood (~1 parsec)?