Recent Results from IceCube

Searches for high-energy neutrinos and future plans
Cosmic Rays
Where (and how) are they accelerated?

- Charged particles with energies up to $10^{21}$ eV (ZeV) (!)
- Their sources (especially at the highest energies) are still mostly unknown
Observing astrophysical neutrinos allows conclusions about the acceleration mechanism of Cosmic Rays.

**TeV Neutrinos**

Neutrinos from cosmic ray interactions in:
- Atmosphere
- Cosmic Microwave Background
- Gamma Ray Bursts (Acceleration Sites)
- Active Galactic Nuclei (Acceleration Sites)
- ?

\[ p + \gamma \rightarrow \pi^0 + p \]
\[ \rightarrow \gamma + \gamma + p \]
\[ \rightarrow \pi^+ + n \]
\[ \leftrightarrow \mu^+ + \nu_\mu + n \]
\[ \leftrightarrow e^+ + \nu_\mu + \nu_e + \nu_\mu + n \]

(\text{can also be from leptonic processes...})

**TeV gamma rays**

**Cosmic rays?**

**TeV neutrinos**

![Cosmic Ray Spectra of Various Experiments](image)
Why Neutrinos?
Neutrinos are ideal astrophysical messengers

- Travel in straight lines
- Very difficult to absorb in flight
Interesting Neutrinos above 1 TeV

- **Atmospheric neutrinos** ($\pi/K$)
  - dominant < 100 TeV

- **Atmospheric neutrinos** (charm)
  - “prompt” ~ 100 TeV

- **Astrophysical neutrinos**
  - maybe dominant > 100 TeV

- **Cosmogenic neutrinos**
  - >10^6 TeV
The IceCube Neutrino Observatory
Deployed in the deep glacial ice at the South Pole

- 5160 PMTs
- 1 km$^3$ volume
- 86 strings
- 17 m vertical spacing between PMTs
- 125 m string spacing
- Completed 2010
Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers).
The IceCube Neutrino Observatory

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)
The IceCube Neutrino Observatory

- South Pole station
- Skiway
- IceCube’s footprint
- IceCube Lab (ICL)
- Drill camp

The IceCube Neutrino Observatory is a large underground laboratory for the study of neutrinos, located in Antarctica near the South Pole station. Its footprint and drill camp are shown in the image.
**Neutrino Event Signatures**

Signatures of signal events

### CC Muon Neutrino

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

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

### 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 \( \gtrapprox 100 \text{ TeV} \))

### CC Tau Neutrino

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

- “double-bang” (\( \approx 10 \text{ PeV} \)) and other signatures (simulation)
- (not observed yet)
Directional Resolution for Showers

Shower directions reconstructed from timing profile
Backgrounds and Systematics

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

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

A bundle of muons from a CR interaction in the atmosphere (also observed in the “IceTop” surface array)
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 Spectrum
- Minimum-ionizing muons

Moon Shadow in Cosmic Rays
Muons in IceCube (59 strings)
Studying Neutrinos
Many possible analyses!

- **High-energy:**
  - Point-source searches looking for clustering in the sky
  - Diffuse fluxes above the atmospheric neutrino background
  - Gamma-ray bursts searches (models excluded by IceCube: Nature 484 (2012))
  - Ultra-high energy “GZK” neutrinos from proton interactions on the CMB

- **Low energy:**
  - Neutrino oscillations + more with PINGU upgrade!

- **Others:**
  - Dark Matter / WIMPs
  - …
IceCube at CAP

- Francis Halzen: IceCube and the Discovery of High-Energy Cosmic Neutrinos (Plenary, Thursday, 11:45, CCIS L2-190)
- Tania Wood: Atmospheric Neutrino Measurement with IceCube Neutrino Observatory (this session)
- Benedikt Riedel: Long-Term Stability of Backgrounds in the IceCube Neutrino Observatory (this session)
- Sarah Nowicki: Direct reconstruction - a new event reconstruction algorithm for the IceCube Neutrino Observatory (this session)
- Ken Clark: Deep Core and PINGU - Studying Neutrinos in the Ice (T3-5, Tuesday 16:45, CAB 235)
The (Very) High-Energy Tail
Update of the high-energy astrophysical flux discovery analysis (now 4 years of data, up from 3 years in PRL 113, 101101)
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 from the North
“Starting Event” Analysis
Specifically designed to find 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 deposited energy
- Estimate background from data
Effective Volume / Target Mass

Fully efficient above 100 TeV for CC electron neutrinos
About 400 Mton effective target mass
What Did We Find?
37 events in 3 years of IceCube data (PRL 113, 101101) (988 days between 2010–2013)

- 36(+1) events observed!
- 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

full likelihood fit of all components: 5.7$\sigma$ for 36(+1) events
What Did We Find?

54 events in 4 years of IceCube data (1347 days between 2010–2014)

- 53(+1) events observed!
- Estimated background:
  - $9.0^{+8.0}_{-2.2}$ atm. neutrinos
  - $12.6\pm5.1$ atm. muons
- One of them is an obvious (but expected) background
  - coincident muons from two CR air showers

full likelihood fit of all components: 6.5$\sigma$ for 53(+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
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)
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)
Energy Spectrum (3 years)
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 spectral index: $E^{-2.3}$
Energy Spectrum (4 years)
Somewhat compatible with benchmark $E^{-2}$ astrophysical model or single power-law model, but looks like things are more complicated

- Best fit assuming $E^{-2}$ (per-flavor flux) (not a very good fit anymore):
  - $0.84 \pm 0.3 \times 10^{-8} E^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- Best fit spectral index: $E^{-2.58}$
Energy Spectrum
Compatible with benchmark $E^{-2}$ astrophysical model
Unfolding to Neutrino Energy

Unfolded to true neutrino energy, simultaneously fitting for backgrounds - updated from PRL plot version with priors for backgrounds - 3 years

- Assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

Graph showing differential spectrum with best-fit and fit with charm fixed at IC59 90% C.L.
4 years - mostly new events at lower energies, not so many more at the PeV-level - still compatible within errors

assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino
Normalization vs. spectral index contour plot
Note: 3-year data re-fit since PRL with priors for backgrounds

**Spectral Fit**

IceCube Preliminary
No significant clustering observed (three years)
Skymap / Clustering

No significant clustering observed (four years)

(all p-values are post-trial)
Skymap / Clustering
No significant clustering observed

- Analyzed with a variant of the standard PS method (w/o energy) (i.e. scrambling in RA)
- Most significant excess close to (but not at!) the Galactic Center
- Significance: 18% (not significant)
- Other searches (multi-cluster, galactic plane, time clustering, GRB correlations) not significant either
Improved Veto Techniques

(arXiv:1410.1749 - only 2 years of data so far - more data being added right now)

- What happens to the astrophysical flux below 60 TeV?
- How large is the neutrino flux from atmospheric charm?

- Need to observe lower-energy neutrinos, especially from the southern sky.
**Improved Veto Techniques**

What happens to the astrophysical flux below 60 TeV?

**Outer-layer veto**

**Energy-dependent veto**

**Neutrino-dominated for** $E_{\text{dep}} > 60$ TeV

**Neutrino-dominated for** $E_{\text{dep}} > 1$ TeV

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**Thicker veto at low energies**

suppresses penetrating muons

without sacrificing high-energy neutrino acceptance
Results

283 cascade and 105 track events in 2 years of data

- 106 > 10 TeV, 9 > 100 TeV (7 of those already in high-energy starting event sample)
- Conventional atmospheric neutrino flux observed at expected level with starting events
- Astrophysical excess continues down to 10 TeV in the southern sky
- Deviation from model at 30 TeV (statistical fluctuation)
- Model-dependent upper limit on flux from charmed meson decay: 1.4 x ERS prediction
Other Channels?

Most of the “starting” sample consists of showers, with a high acceptance in the southern sky

- Deposited (i.e. measured) energies closely related to neutrino energies
- Great for discovering a signal

- Highest energy: ~550 TeV (neutrino energy likely in PeV range)
- Highest energy: 2 PeV

Events with contained vertex
- Mostly Southern hemisphere
- Neutrino events above 60 TeV:
  - Astrophysical: 6/yr
  - Atmospheric: 1/yr
- Significance in first 2 years of data: 4.1 σ (prelim.)
Other Channels?

We have now seen a similar flux in the muon channel - at 3.7σ

Similar flux in more “traditional” muon channel, accepting incoming muons, looking below the horizon (northern sky)

- Highest energy: ~550 TeV
  (neutrino energy likely in PeV range)
Upgoing Muons - Spectral Components

Two years of data - for $E^{-2}$ spectral assumption - best fit is $E^{-2.2}$

Normalization for $E^{-2}$: $0.99^{+0.4}_{-0.3} \times 10^{-8} \text{E}^{-2} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$
Global Fit (of several IceCube analyses)

Publication under review - interesting results such as flavour ratio
The Future

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)
Note

For pointing searches we can tolerate more background!

- “Starting Event” analysis provides a sample with very low background (from atm. neutrinos and muons)
- HE flux likely continues down to lower energies, hidden in the atm. background
- Pointing searches can tolerate a bit more background!
The Future

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
The Future
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

IceCube Preliminary
The Future

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
The Future
How do we get more tracks?

- Or, of course, both!
The Future

R&D for a surface array

- Similar to the current “IceTop” surface array
  - using simplified versions of the current IceTop tanks
- R&D is underway!
The Future

An upgraded IceCube detector for high energies

- Current threshold at about 1 TeV
- Can afford a slightly higher threshold of ~30 TeV

assuming ~100 new strings

Artist conception
Here: 120 strings at 300 m spacing
The Future
An upgraded IceCube detector for high energies - in addition to low energies (PINGU!)

- “Next generation” detector upgrade, extending the energy range
- PINGU
  - O(40) densely packed strings
  - Neutrino mass hierarchy, neutrino physics, dark matter,…
- “High-Energy Upgrade” (to be named)
  - O(100) strings, 5-10 km³
  - Identify astrophysical sources of neutrinos (and cosmic rays!), neutrino and particle physics
- Surface component: veto downgoing background, CR physics,…
Conclusions

Stay tuned!

- 53(+1) events with energies above $\approx 50$ TeV found in three years of IceCube data
- We see this in other channels (incoming muons) and down to energies of 10 TeV now!
- Statistics are steadily increasing, we are now working on characterizing the flux better and better
- We are planning future upgrades to measure this even better and look for the sources of these neutrinos
The IceCube Collaboration

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)

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Japan Society for the Promotion of Science (JSPS)
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)
Thank you!

2 PeV event - “Big Bird”
Backup
Indirect Dark Matter Searches

(High-Energy) Neutrino Signals from the Sun, the Galactic Center, Halo and more!
Indirect Dark Matter Searches

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

Dwarf spheroidal galaxies:
- IceCube-59 limits

Clusters of Galaxies:
- IceCube-59 limits

Local sources (Sun & Earth):
- IceCube-79 limits (PRL 110 (2013) 131302)

Galactic Halo:
- IceCube-22 limits (PRD 84 (2011) 022004)

Galactic Center:
- IceCube-79 sensitivity

Look for potential sources that are well defined and have low or understood astrophysical backgrounds.

WIMP candidates:
- $p^-, e^+, \gamma, \nu$
- $p^+, e^-, \gamma, \nu$

MSSM - neutralino accumulate due to WIMP-proton elastic scattering.
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!**

- **Up-going**
  - No containment

- **Up-going**
  - strong containment

- **Down-going**
  - strong containment

\[\nu\]
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

![Diagram showing experimental data and WIMP signal at the galactic center](image)
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:**
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- **Clusters of galaxies:**
  - IC59 PRD 88 (2013) 122001

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![Graph showing dark matter signals](Image)

- IC22 Halo
- IC40 GC
- IC79 in preparation
- IC59 Dwarf galaxy stacking
- IC59 Virgo cluster (subhalo)
- Fermi Dwarf galaxy

**IceCube Preliminary**

- XX$^-$μ$^-$

**Fermi data**

- PAMELA data$^*$

**natural scale**

$^*$interpreted for DM [Meade et al. (2010)]
High-Energy Analysis Details
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)
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 and estimate for deposited energy
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**
Background 1 - Atmospheric Muons

What’s “early charge”?

Throughgoing muon

- Total detector
- Veto region

\[ Q/\text{pe} \]

\[ T_{250} = \text{time at which } Q = 250 \text{ pe} \]

Contained cascade

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

\[ Q/\text{pe} \]

\[ dQ/dt \]
Estimating Muon Background From Data

Use known background from atmospheric muons tagged in an outer layer to estimate the veto efficiency.

- Add one layer of DOMs on the outside to tag known background events.
  - Then use these events to evaluate the veto efficiency.
- Avoids systematics from simulation assumptions/models!
- Can be validated at charges below our cut (6000 p.e.) where background dominates.
Effective Area

Differences at low energies between the flavors due to leaving events at constant charge threshold
Atmospheric Neutrino Spectrum
Measured with IceCube in $\nu_\mu$ and $\nu_e$

FIG. 4. (Color online) The electron neutrino spectrum (green line), prompt $\nu_\mu$, prompt $\nu_e$, conventional $\nu_\mu$, conventional $\nu_e$, Frejus $\nu_\mu$, Frejus $\nu_e$, AMANDA $\nu_\mu$, unfolding $\nu_\mu$, unfolding $\nu_e$, forward folding $\nu_\mu$, forward folding $\nu_e$.