Results from IceCube
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)
Fondazione Cariplo
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
Tom Gaisser for the IceCube Collab.

German Research Foundation (DFG)
University of Wisconsin Alumni Research Foundation (WARF)
The Swedish Research Council (VR)
US National Science Foundation (NSF)
Construction phase: 2002-2010

2002: Proposal
2003-04 First shipments
2004-05 1 1
2005-06 8 9
2006-07 13 22
2007-08 18 40
2008-09 19 59
2009-10 20 79
2010-11 7 86

IceTop
81 stations, 324 DOMs

DeepCore
8 strings

IceCube
86 strings, 5160 DOMs
IceCube Digital Optical Module and deployment

Main board for digitizing & time stamping

LED Flasher board

HV board
Detecting neutrinos in $\text{H}_2\text{O}$

*Proposed by Greisen, Reines, Markov in 1960*

- **Heritage:**
  - DUMAND
  - IMB
  - Kamiokande
  - Baikal
  - AMANDA

- **IceCube:** 86 strings & 81 IceTop stations: completed 2010-11

- **ANTARES**
  - All use Cherenkov light from charged products of $\nu$ interactions
A 3-D cosmic-ray detector:
Two different kinds of events
Closely related scientifically:
- Neutrinos from cosmic ray sources
- Cosmic rays after propagation and oscillation
- $\nu_e:\nu_\mu:\nu_\tau = 1:2:0 \rightarrow 1:1:1$

Neutrinos from all directions
Primarily $\nu_\mu$-induced $\mu$
from below

 cosine ray showers from above

Atmospheric muons

South Pole
2835 m.a.s.l.
Event types in IceCube

• Downward muons ($10^{11}$/yr)
  – From cosmic-ray interactions above IceCube
  – Typical energies at production: TeV (to reach 2 km)
• Neutrino-induced muons ($10^5$/yr)
  – Long $\mu$ range – interactions often outside IceCube
  – Require several layers of selection for pure sample
• Cascade events
  – Charged current interactions of $\nu_e$ or neutral current interactions of any flavor
  – CC interactions of $\nu_\tau$ ($E_\nu < \text{PeV}$)
  – $\nu_\tau > \text{PeV}$ may be identified by unique structure
    • ``double bang'', ``lollipop'', etc. due to $\tau$-lepton track
    • Astrophysical origin due to oscillations
    • Atmospheric background of $\nu_\tau$ is negligible
High-energy muons in IceCube

Color code: red/orange = earlier; magenta/blue = later

Atmospheric muon with 80 TeV burst

\sim 100 \text{ TeV} \nu_{\mu} \text{ induced muon}
High energy cascade candidate

A cascade event, candidate for a high energy $\nu_e \sim 50$ TeV (or $\nu_\tau$)
Downward muon bundle illuminates Deep Core subarray

Cascade event candidate in Deep Core
More big events

~EeV event in IC-40

~100 PeV primary cosmic ray

~300 muons in deep IceCube
Air shower in IceCube/IceTop

Zenith angle = 5.6 deg, E ~ 170 PeV
Main goal of IceCube: ν astronomy

• Find high-energy, astrophysical ν
  – Unique probe of cosmic ray origin
  – Complementary to photon astronomy

• Photons and neutrinos
  – Photons: plentiful but complicated
    • Interactions in sources & in transit modify spectrum
    • Can be electromagnetic in origin or hadronic
  – Neutrinos: clean but rare
    • Hadronic origin
    • No interactions in sources
    • (few in detector)
Two ways of producing $\gamma$ & $\nu$

1. At the sources of UHECR
   - Depends on details of accelerated spectrum
   - Depends on cosmic evolution of sources
   - Depends on conditions in/near the sources

2. During propagation
   - Depends on injected spectrum
     - As function of red shift and energy
   - But not on conditions at the sources
UHECR

- Energy content of UHECR determines possible sources
- Assume extra-galactic origin
- Location of transition from galactic to extra-galactic affects energy estimate

\[ E \frac{dN}{d \ln E} \approx 3 \times 10^{-8} \, \text{GeV cm}^2 \text{s}^{-1} \text{sr}^{-1} \]

at \( 10^{10} \, \text{GeV} \) (\( 10^{19} \, \text{eV} \))
Power for extragalactic cosmic rays (assuming transition at the ankle)

• Energy in extra-galactic cosmic rays per $ln(E)$:

$$\frac{4\pi}{c} \frac{E dN}{d \ln E} \approx 2 \times 10^{-20} \text{ erg cm}^{-3}$$

• Divide by Hubble time to estimate power required:

$$\frac{dL}{d \ln E} \approx 2 \times 10^{36} \text{ erg Mpc}^{-3} \text{s}^{-1}$$

• Power required $\geq 10^{37} \text{ erg/Mpc}^3/\text{s}$
  – Estimates depend on cosmology + extragalactic magnetic fields:
    – $3 \times 10^{-3}$ galaxies/Mpc$^3$  $5 \times 10^{39}$ erg/s/Galaxy
    – $3 \times 10^{-6}$ clusters/Mpc$^3$  $4 \times 10^{42}$ erg/s/Galaxy Cluster
    – $10^{-7}$ AGN/Mpc$^3$  $10^{44}$ erg/s/AGN
    – $\sim 300$ GRB/(Gpc$^3$yr)  $10^{51}$ erg/GRB
Generic model I

- CR acceleration occurs in jets
  - AGN or GRB
- Intense radiation fields
  - Models assume photo-production:
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma \gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case ( ~ “Waxman-Bahcall limit”)
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Energy content in neutrinos $\approx$ fraction x energy in UHECR
- This picture disfavored as limits go below W-B


http://www.ucd.ie/math-phy/rieger/science.gif
Generic model II

• UHECR are accelerated in external shocks analogous to SNR
  – See E.G. Berezhko, 0809.0734 & 0905.4785
  – mixed composition (accelerate whatever is there)
  – Low density of target material
  → lower level of TeV-PeV neutrino production

Detecting muon neutrinos

- Rate = Neutrino flux
  - Absorption in Earth
  - Neutrino cross section
  - Size of detector
  - Range of muon (for $\nu_\mu$)

- Range favors $\nu_\mu$
  - $\sim$4 to 15 km.w.e. for $E_\nu \sim 10$ to 1000 TeV

Earth becomes opaque to $\nu$, first for vertically upward ($\sim$30 TeV) then for more horizontal ($\sim$PeV)
Atmospheric neutrinos in IceCube

Recent measurement of $\nu_e$ in IceCube

0.1 – 1 TeV

"Prompt" $\nu$ from decay of charm not yet measured
Lower energy $\nu$ using DeepCore

$\sim 100$ GeV $\nu_e, \nu_\mu$ (NC) measured

Oscillation (disappearance) of $<30$ GeV $\nu_\mu$
Upward $\nu_\mu$ in IceCube

Zone 1, $\lambda$: -30 to -90; 3.14 sr
Zenith: $90 < \theta < 120^\circ$
(40% of Zone 1 is over the Antarctic continent)

Zone 2, $\lambda$: -30 to +30; 2.30 sr
Zenith: $120 < \theta < 150^\circ$

Zone 3, $\lambda$: +30 to +90, 0.84 sr
Zenith: $150 < \theta < 180^\circ$

Cosmic ray produces $\nu$ in atmosphere that puts a muon into the detector
Point source search in IceCube

Total (IC40+IC59) events: 57460 (upgoing) + 87009 (downgoing)

Livetime: 348 days (IC59) + 375 days (IC40)

Note high energy threshold for downward events
IceCube selected sources
(13 galactic SNR etc, 30 extragalactic active galaxies, etc.)

<table>
<thead>
<tr>
<th>Source</th>
<th>RA (deg)</th>
<th>Dec (deg)</th>
<th>Type</th>
<th>Distance</th>
<th>P-value</th>
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<tr>
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<td>UNID</td>
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<td>MGRO J2019+37</td>
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<tr>
<td>Geminga</td>
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<td>Pulsar</td>
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<td>Crab Nebula</td>
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<tr>
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<td>29.67</td>
<td>FRII</td>
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<td>38.13</td>
<td>FSRQ</td>
<td>z = 1.814</td>
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</table>

PKS 0235+164 | 39.66   | 16.62     | LBL        | z = 0.94  | 0.18    |
| PKS 0528+134 | 82.73   | 13.53     | FSRQ       | z = 2.060 | 0.49    |
| PKS 1502+106 | 226.10  | 10.49     | FSRQ       | z = 0.56/1.83 | --      |
| 3C 273      | 187.28   | 2.05      | FSRQ       | z = 0.158 | --      |
| NGC 1275    | 49.95    | 41.51     | Seyfert Galaxy | z = 0.017559 | --      |
| Cyg A       | 299.87   | 40.73     | Radio-loud Galaxy | z = 0.056146 | 0.44    |
| Sgr A*      | 266.42   | -29.01    | Galactic Center | 8.5 kpc  | 0.49    |
| PKS 0537-441 | 84.71   | -44.09    | LBL        | z = 0.896 | 0.44    |
| Cen A       | 201.37   | -43.02    | FRI        | 3.8 Mpc  | 0.14    |
| PKS 1454-354 | 224.36   | -35.65    | FSRQ       | z = 1.42  | 0.14    |
| PKS 2155-304 | 329.72   | -30.23    | HBL        | z = 0.116 | --      |
| PKS 1622-297 | 246.53   | -29.86    | FSRQ       | z = 0.815 | 0.27    |
| QSO 1730-130 | 263.26   | -13.08    | FSRQ       | z = 0.902 | --      |
| PKS 1406-076 | 212.24   | -7.87     | FSRQ       | z = 1.494 | 0.36    |
| QSO 2022-077 | 306.42   | -7.64     | FSRQ       | z = 1.39  | --      |
| 3C279       | 194.05   | -5.79     | FSRQ       | z = 0.536 | 0.45    |
| TYCHO       | 6.36     | 64.18     | SNR        | 2.4 kpc  | --      |
| Cyg X-1     | 299.59   | 35.20     | MQSO       | 2.5 kpc  | --      |
| Cyg X-3     | 308.11   | 40.96     | MQSO       | 9 kpc    | --      |
| LSI 303     | 40.13    | 61.23     | MQSO       | 2 kpc    | --      |
| SS433       | 287.96   | 4.98      | MQSO       | 1.5 kpc  | 0.48    |
Neutrino Flux Limits

Assuming an $E^{-2}$ emission

For interesting sources

IC40 + 59 + 79

1ES1959+650
Compare IceCube limits on $\nu$ to TeV photons from active galaxies

![Graph showing comparison between IceCube limits and TeV photons from active galaxies.](image-url)
A closer look at 1ES 1959+650

Neutrino Limit translated to γ limit at source assuming 1:1 ratio of π⁰ to π⁺/⁻

γ flux attenuated with EBL

γ flux attenuated with EBL, with secondary γ created by e⁺/e⁻


Search for neutrinos from GRB

$T_0$: From a satellite GCN

Off-time ↔ On-time ↔ Off-time

- Precursor (~100 s)
- Prompt
- Model Independent (24 h)
- Background (full year)

Very low background
One event can be significant

Individual modeling of GRBs
(Guetta et al. 2004)

IC-59
98 northern GRBs

$E_\nu$ [GeV]

$E_\nu \phi_\nu$ [GeV cm$^{-2}$ s$^{-1}$]

Total Individual Spectra
Waxman & Bahcall
New limit on $\nu$ from GRB (IC40/IC59)

Limits on $\nu$ from GRB at level of $10^{-9}$ GeV cm$^{-2}$sr$^{-1}$s$^{-1}$

IceCube: Nature, 19 April 2012

Mumbai, 11/12/12
Tom Gaisser for the IceCube Collab.
Search for diffuse flux of $\nu$

- Neutrinos are not absorbed. Therefore
  
  *All sources out to Hubble radius contribute*

- Hard spectrum
  - Expect -2.0 to -2.4 differential spectral index
  - Compared to -3.0 to -3.7 for atmospheric $\nu$

- Measure spectra of $\nu_\mu$, and of $\nu_e$
  - Distinguish contribution of prompt atmospheric $\nu$ (from charm)
  - Look for excess of high-energy events above background of atmospheric neutrinos
  - Look for $\nu_\tau$

- What flux of neutrinos to expect from unresolved sources?
Compare atmospheric $\mu$, $\nu_\mu$ and $\nu_e$

Prompt contribution is the same for all

Muons:
Highest rate (by far!)
Highest conventional background

Muon neutrinos:
lower conventional background,
but only muon energy loss is
directly measured

Electron neutrinos:
Lowest conventional background;
Containment required
→ Lower rates
→ But full $\nu$ energy visible
Expected for $\nu_\mu \rightarrow \mu$ (IC-59)

- Predicted $\nu$ spectrum
  - $\Phi_\nu(E_\nu) \times A_{\text{eff}}(E_\nu)$
  - $\phi_{\text{Atm}}$ very steep
  - $\phi_{\text{Prompt}}$ less steep
    - Like cosmic-ray spectrum at Earth
  - $\Phi_{\text{astro}}$ is harder
    - Reflects cosmic-ray spectrum at source
    - Here assumed $E^{-2}$
IC59: all $\nu_\mu$ from below horizon

Event display for most energetic event
Limit on prompt $\nu$ in IC-59

- Fitted prompt normalization: 0
- However:
  - Upper limit on prompt $\nu$ is higher than QCD model (red band)
Limits on astrophysical $\nu$:

Below atmospheric $\nu$ for $E_\nu < 200$ TeV

![Graph showing limits on atmospheric $\nu$ for $E_\nu < 200$ TeV](image)
Comment on current limits

- Limits on neutrino fluxes from unresolved sources are below the level of extra-galactic cosmic rays
  - GRB all sky limit at $< 2 \times 10^{-9}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$
  - Diffuse search with $\nu_\mu$ at $10^{-8}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$
- These are levels at which we expect to see neutrinos if they are produced inside the sources of ultra-high energy cosmic rays
  - E.g. jets of AGN or GRB
Cosmogenic (GZK) neutrinos

- Cosmic ray connection - II
- UHECR exist, therefore
  - Neutrino production occurs during propagation via
    - \( p + \gamma_{\text{CMB}} \rightarrow \pi^+ \rightarrow \nu \)
    - \( E_{\text{th}} \sim 5 \times 10^{19} \text{ eV} \)
    - Even if no \( \nu \) from CR sources
- Intensity depends on
  - Spectrum at sources
  - Evolution of sources
  - Composition of UHECR (Heavy nuclei give less \( \nu \))

ANITA  arXiv:1011.5004
IceCube limits on cosmogenic $\nu$

- GZK search looks for
  - very bright events
  - near the horizon
  - with compact initial burst of light
  - Complementary to diffuse $\nu_{\mu}$ search that starts by measuring atmospheric $\nu_{\mu}$
  - Blue lines show results including cascades
  - Model 6 (Fermi max): expect 0.4 events

All-flavor limits assuming $\nu_\mu \sim \nu_\tau \sim \nu_e$
2 $\nu_e$-like PeV events in IceCube 86

Found in search for cosmogenic neutrinos with IC79 & IC86 (May 2010 – May 2012)
Both events are just above the brightness threshold for the search for cosmogenic $\nu$

Nathan Whitehorn discussed these events in detail yesterday in the $\nu$ parallel session

Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10^4
Number of Optical Sensors 312

Run118545-Event63733662
August 9th 2011
NPE 6.9928x10^4
Number of Optical Sensors 354
From Nathan’s talk yesterday

Things We Know

- At least two PeV neutrinos in 2-year dataset
- Events may be downgoing – angular resolution not enough for statistical significance from 2 events
- Seem not to be GZK events (too low in energy)
- Higher than expected for atmospheric background
- Spectrum seems not to extend to much higher energies (unbroken $E^{-2}$ would have made 8-9 more above 1 PeV)

Comparison to Expectations

PRELIMINARY
Cascade events in IceCube

- Inspection of data below the EHE threshold in IC-79 & IC-86 is underway but not yet ready
- Study of cascades in IC-40 finds a few events above 100 TeV
  - The smaller detector (half full size) makes it more difficult to reject background

Mumbai, 11/12/12
Tom Gaisser for the IceCube Collab.
IC-40 cascade analysis (low E)

• Atm. $\mu$
  – can sneak in between strings and brem
  – Hard cuts needed in low-energy search (> 3 TeV)
  – Can loosen cuts for >100 TeV
• Harder for $\mu$ to sneak in
IC-40 Cascade analysis (high E)

- Events < 100 TeV
  - Consistent with atmospheric $\nu$ + sneaky atmospheric $\mu$
- More events than expected > 100 TeV
  - $2.4 \sigma >$ expectation for atmospheric $\nu$
    - including prompt,
    - but without intrinsic charm
Cosmic-ray results from IceCube

Will be covered in my talk in High Energy CR parallel session

• CR spectrum/composition 300 TeV to EeV
• Solar flare GLEs with IceTop tank rates
• Atmospheric muons – 50 billion TeV µ /yr
  – CR anisotropy 20 TeV ~ 20 PeV (+IceTop)
  – Atmospheric lepton spectra to PeV
    • Look for charm where there is no astrophysical background (!)
  – Seasonal & short-term correlations with stratosphere
Searching for DM with IceCube*

"Indirect Targets" for ν
Individual sources and diffuse

IceCube Analyses:

**Galactic Halo:**
Limits from IceCube-22

**Galactic Center:**
Limits from IceCube-40
Various channels, including line

**Dwarf Galaxies:**
→ Search with IceCube-59

**Clusters of Galaxies:**
→ Search with IceCube-59

**Sun:**
Combined Limits form AMANDA, IC22, IC40+AMANDA
→ Search with IceCube-79

**Searches beyond “standard” SUSY:**
→ Secluded dark matter sector

**Earth:**
Limits from AMANDA, IceCube analysis in progress

*See talk by Carsten Rott at Seoul, Nov 5-9 for full presentation of IceCube DM results
IceCube limits: $\nu$ from DM annihilation in the Sun

Preliminary

Spin-dependent interactions

Spin-independent interactions

( in preparation for submission to PRL )
Dark matter in the Milky Way

Three targets:
1) Search for a neutrino anisotropy (outer halo)
2) Galactic Center (down-going events)
3) Dwarf Spheriodals

Limits on $\nu$ from DM annihilation in nearby dwarf galaxies

Limits computed at 90% C.L. as function of WIMP mass assuming branching fraction of 100% WW and NFW profile

IceCube Preliminary $\chi\chi \rightarrow W^+W^-$

$\langle \sigma A \rangle$ (cm$^3$ s$^{-1}$)

$10^{-18}$

$10^{-19}$

$10^{-20}$

$10^{-21}$

$10^3$  $10^4$  $10^5$

WIMP mass (GeV)

Draco

Coma Berenices

Segue 1

Stacking (Seg1+UMaII)

Mumbai, 11/12/12

Tom Gaisser for the IceCube Collab.
Concluding comments

• Atmospheric neutrinos in IceCube
  – $\nu_\mu$ to $> 100$ TeV
  – $\nu_e$ to TeV with deep core
  – cascades $\{ \nu_e (cc) + \nu (nc) \}$ to 30 TeV

• Apparent excess of high energy $\nu$
  – 2 PeV cascades in IC79+IC86
  – More 100 TeV cascades than expected in IC40
  – Systematic exploration of region above 100 TeV is in progress