The IceCube Neutrino Observatory
Status and Recent Results

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Very High Energy Phenomena in the Universe
La Thulie, March 12, 2013
Multi-messenger paradigm

- Neutrino astronomy:
  - natural extension: “optical”
    - + “multi-wavelength”
    - + “multi-messenger”
  - closely related to cosmic rays (CRs) and \( \gamma \)-rays
  - smoking-gun of CR sources
  - weak interaction during propagation

- Challenges:
  - low statistics
  - large backgrounds
Multi-messenger paradigm

- pion production in CR interactions with ambient radiation & matter

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu \]
\[ \pi^0 \rightarrow \gamma \gamma \]

- inelasticity:

\[ E_\nu \simeq E_\gamma / 2 \simeq \kappa E_p / 4 \]

- relative multiplicity:

\[ K = N_{\pi^\pm} / N_{\pi^0} \]

- pion fraction via optical depth:

\[ f_\pi \simeq 1 - e^{-\kappa \tau} \]
Multi-messenger paradigm

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\( \omega_{\gamma - \text{bgr}} \simeq 6 \times 10^{-7} \text{ eV/cm}^3 \)

\( \omega_{\text{UHECR}} \simeq 1 \times 10^{-7} \text{ eV/cm}^3 \)

\( \omega_{\nu, \text{all}} \lesssim 2 \times 10^{-8} \text{ eV/cm}^3 \)
High-energy neutrino detection

• High energy neutrino collisions with nuclei are **rare**.

→ Secondary charged particles can be detected by their **Cherenkov radiation** in transparent media.

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**back-of-the-envelope** ($E_\nu \sim 10^{15}$ eV):

- **flux of neutrinos**:
  \[
  \frac{d^2 N_\nu}{dt \, dA} \sim \frac{1}{\text{cm}^2 \times 10^5 \, \text{yr}}
  \]

- **cross section**:
  \[
  \sigma_{\nu N} \sim 10^{-33} \, \text{cm}^2
  \]

- **targets**:
  \[
  N_N \sim N_A \times V/\text{cm}^3
  \]

→ **rate of events**:

\[
\dot{N}_\nu \sim N_N \times \sigma_{\nu N} \times \frac{d^2 N_\nu}{dt \, dA} \sim \frac{1}{\text{year}} \times \frac{V}{1 \, \text{km}^3}
\]
High-energy neutrino detection

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The IceCube Observatory

- **price tag**: 279 million USD
- **78 IceCube strings**
  125 m apart on triangular grid
- **60 digital optical modules (DOMs)** per string
- **2 days to drill a hole; 18,000 l fuel consumption**
- **1/2 day string deployment; 7 days to freeze-in**
- **8 DeepCore strings**
  DOMs in particularly clear ice
- **81 IceTop stations**
  two tanks per station, two DOMs per tank
- **surface 2,300 meters above sea level (680 g/cm²)**
The IceCube Observatory

incorporate the disciplines of manufacturing and systems engineering into a group that had little experience with large-scale high-reliability production of anything, let alone highly complex digital sensors that had to survive deep-ice deployments—that in itself is a story to fill many pages.

Somehow in this time we worked through the design issues, spun out three further revisions of the mainboard, assembled and tested DOMs, and wrote software to read out the sensors. We also built three production sites including the enormous deep freezer laboratories to cold-test each and every module at -55 °C while being subjected to a battery of functional tests and optical calibrations, bought a bunch of cables, and adapted a standard ship-sending container already at the South Pole and equipped it with electronics to make a temporary IceCube counting house. Vivid memories remain of the numerous meetings and telephone calls, travels, tense moments and outright arguments, diagrams drawn, nails bitten, and plan Bs.

And so in 2005 there was one string—string 21—that made it into the ice and when we turned it on, voila! all modules were working fine. One module started to spark several weeks after deployment, but this case was happily resolved by turning down the high voltage applied to the phototube.

It was a great relief to us all that all the DOMs were talking with the surface. Despite previous experience with AMANDA modules and all the engineering that went into making the IceCube DOMs even more robust, no one really knew that everything would work until the modules were in the ice.

Each DOM's pressure housing had been tested to 10,000 psi but the refreezing ice could have easily crushed the cabling or snapped the penetration point where the cable enters the glass sphere. Building a laboratory to simulate refreeze seemed a project as big as IceCube so we had to cross our fingers at this point.

The design, having been proved in ice, did not change significantly from that first year. The one major design flaw with the DOM, an improperly spec'd signal transformer, was fixed along with some other minor changes. A later "high quantum efficiency" DOM was produced beginning in 2008 for IceCube's DeepCore extension;
The IceCube Observatory
The IceCube Observatory

Drilling with new IceTop tanks
Inside an IceTop Tank
The IceCube Observatory

Firn & Ice Drilling
The IceCube Observatory

String & Optical Module
The **individual and combined results** of IceCube, DeepCore and IceTop and the unique geographical location allows for a wide scientific program:

- atmospheric neutrino fluxes and oscillations
- diffuse high-energy neutrino fluxes
- point source fluxes
- cosmic ray flux in the knee region
- CR anisotropies in the Southern hemisphere
- CR composition measurements
- indirect dark matter detection
- galactic supernova
- exotic signals
- ...
Atmospheric neutrino flux and diffuse limit

- high-energy atmospheric $\nu_\mu/\nu_e$-spectrum as seen by IC-40 & IC-79/DC
  [IceCube'11,'12]

- diffuse $\nu_\mu$ limit from IC-59 (90% C.L.) (preliminary)

- predicted prompt atmospheric $\nu$-fluxes (charmed meson decay)
  [Enberg et al.'08]

- theoretical limit on diffuse astrophysical $\nu_\mu$’s
  [Waxman&Bahcall '98]
Steady point-source search

![Graph showing upper limits and sensitivities for point-like sources with an $E^{-2}$-spectrum as function of declination.]

Upper limits (symbols) and sensitivities (lines) (90% CL) for point-like sources with an $E^{-2}$-spectrum as function of declination.
Steady point-source search

IC-40+59+79 point source results

- hottest spot: $p \approx 10^{-4.7}$ (pre-trial)
- post-trial: $p \approx 56.8\%$

→ no significant excess so far!
GRB neutrino emission

- Neutrino production at various stages of gamma-ray burst (GRB), from precursor to afterglow [Waxman&Bahcall’97,’00;Razzaque,Meszaros&Waxman’03]
- Neutrino emission of GRBs is one of the best-tested models: [IceCube, Nature’12]
  - **cosmological sources** (“one per day and $4\pi$”)
  - **wealth of data** from Swift and Fermi
  - **good information on timing and location** (→ background reduction)

![Diagram of GRB emission](image-url)
GRB neutrino emission

- Limits on neutrino emission coincident with 215 (85) northern (southern) sky GRBs between April 2008 and May 2010 (IC-40+59). [IceCube’11,’12]

- Stacked point-source flux below “benchmark” prediction by a factor 3-4. [Guetta et al.’04]

- IceCube limit below benchmark diffuse models normalized to UHE CR data. [Waxman&Bahcall’03; Rachen et al.’98]

→ IceCube’s results challenge GRBs as the sources of UHE CRs!
GRB neutrino emission

“Search for Neutrino Flares from AGN with the IceCube Detector.”

Angel Cruz, Zeuthen, Germany
Cosmogenic neutrinos

- “Guaranteed” neutrino production from UHE CR propagation in cosmic radiation background.

\[ p\gamma \rightarrow \Delta \rightarrow n\pi^+ \text{ with CMB: } E_{\text{CR}} < E_{\text{GZK}} \approx 40\text{EeV} \]

- peak neutrino contribution at \( E_\nu \approx 1\text{EeV} \)

**UHE CR spectrum**

**radiation background**

[Particle Data Group'12]
Cosmogenic neutrinos

...“guaranteed”, but model-dependent, in particular UHE CR composition.
Extremely-high energy analysis

- Study for cosmogenic neutrino fluxes in **IC-79+86**
- optimized cuts on zenith angle and “brightness” (NPE: number of photo-electrons)
- two “background” events above NPE threshold

![Graph showing cosmogenic neutrino flux models and event distributions](image_url)
Follow-up studies of background events: energy, orientation, ... 

→ Are there more contained events?

1.0 ± 0.2 PeV

"Bert"

1.1 ± 0.2 PeV

"Ernie"
Extremely-high energy analysis

“A search for extremely high energy cosmogenic neutrinos with the IceCube detector.”

Keiichi Mase, Chiba, Japan
Cosmic ray anisotropies

- CR anisotropy studies by atmospheric muons with IC-79

\[
\frac{\Delta N}{\langle N \rangle} = \frac{N(\alpha, \delta) - \langle N(\alpha, \delta) \rangle}{\langle N(\alpha, \delta) \rangle}
\]

- **significant** CR anisotropy of 1% at various (median) CR energies and angular scales

  → South Pole unique:

  ✓ study of the Southern hemisphere

  ✓ stable atmospheric conditions over >24h

- pattern persists in the few 100 TeV to few PeV energy region (in IceCube & IceTop)
Cosmic ray anisotropies

- Compton-Getting effect? Amplitude **too low** and **wrong** phase. [Compton&Getting’35]
- pattern appears to be a **continuation** of anisotropies observed in the Northern hemisphere [Milagro’08 (≈TeV); Tibet’06,’11 (≈TeV); ARGO-YBJ’09 (≈TeV)]
- anisotropy pattern at few 10 TeV already present in AMANDA (’00-’06) ➔ stable on scales of ≈ **13 years**
- indications for small scale anisotropy in data (IC-59)

![Angular power spectra for the relative intensity maps showing the power spectrum before and after the subtraction of the dominant dipole and quadrupole terms from the relative intensity map.](IceCube'11)

**Equation (8):**

\[
\delta I(\alpha, \delta) = m_0 + p_x \cos \delta \cos \alpha + p_y \cos \delta \sin \alpha + p_z \sin \delta + \frac{1}{2} Q_1 (3 \cos^2 \delta - 1) + Q_2 \sin^2 \delta \cos \alpha + Q_3 \sin^2 \delta \sin \alpha + Q_4 \cos^2 \delta \cos^2 \alpha + Q_5 \cos^2 \delta \sin^2 \alpha.
\]
Cosmic ray flux and composition

- IceTop’s average atmospheric depth:
  \[ X_{\text{IceTop}} \approx 680 \text{ g/cm}^2 \]

- e.g., proton shower maxima at PeV-EeV:
  \[ 550 \text{ g/cm}^2 \lesssim \langle X_{\text{max}} \rangle \lesssim 720 \text{ g/cm}^2 \]

  ✔ good resolution for \( \langle X_{\text{max}} \rangle \approx X_{\text{IceTop}} \)

- energy estimation via lateral distribution function:
  \[ \log_{10} E \approx p_0 + p_1 \log_{10} S_{125} + p_2 (\log_{10} S_{125})^2 \]

  \( p_0, p_1 \) and \( p_2 \) are fixed by MC studies and depend on zenith angle and primary mass
composition analysis via zenith-dependence (IT-73)

- e.g., mixed composition model (“H4a”) with five CR mass groups [Gaisser’12]
Cosmic ray flux and composition

$E^{2.7} \times J(E) \ [\text{GeV}^{1.7} \text{ m}^2 \text{ sr}^{-1} \text{s}^{-1}]$

$10^4$

$10^6$ $10^7$ $10^8$ $10^9$

Primary Energy [GeV]

IceTop 73, SIBYLL, Gaisser model assumption, Preliminary
Kascade-Grande, QGSJet-II
GAMMA 2008
Tunka-133
Tibet III, SIBYLL
Summary

- The **fully-instrumented** IceCube observatory has been running smoothly for more than two years.

- The IceTop, IceCube and DeepCore sub-detectors have mutual benefits and enable a large scientific program.

- Actually, *too large* for this talk:
  - indirect dark matter detection (**IC-79** solar, **IC-59** dwarf gal./gal.clusters)
  - atmospheric neutrino oscillations (**IC-79**)
  - search for exotic particles (**IC-86**)
  - Earth core analysis with atmospheric neutrinos (**IC-40**)
  - Galactic supernova (**SN trigger**)
  - …

- A recent **highlight**: observation of two PeV cascades in **IC-79+86**

- Follow-up analysis of these “background events” and dedicated searches for high-energy contained events in IceCube are under way. (**talk by Keiichi**)