High-Energy Neutrino Astronomy in Ice and Water

Very brief overview of neutrino astronomy (and recent results from IceCube)

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TeV Neutrinos

Observing astrophysical neutrinos allows conclusions about the acceleration mechanism

Neutrinos from cosmic ray interactions in:

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

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

TeV gamma rays

Cosmic rays?

TeV neutrinos

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

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

- **Atmospheric neutrinos (π/K)**
  - dominant < 100 TeV
- **Atmospheric neutrinos (charm)**
  - “prompt” ~ 100 TeV
- **Astrophysical neutrinos**
  - maybe dominant > 100 TeV
- **Cosmogenic neutrinos**
  - >10^6 TeV
Detection Principle

Observe Cherenkov light using a lattice of photomultipliers (PMTs) in an optically transparent medium.
High-Energy Neutrino Detectors

...Dumand
ANTARES
Nestor
KM3Net
IceCube
AMANDA
Baksan
Hyper-K
Super-K
Lake Baikal
GVD
Active
Retired
Prototype
Planned

from ICRC 2013 plenary by F. Halzen
The ANTARES Neutrino Telescope

In the Mediterranean Sea (near Toulon, France)

- Deployed in 2001
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

- 350 m
- 100 m
- ~70 m

Position < 10 cm
Timing res ~ 0.5 ns

Talk by A. Margiotta in this session!

from ICRC 2013 plenary by A. Kouchner
The KM3NeT Neutrino Telescope
Multi-site installation in the Mediterranean Sea (France, Italy, Greece), instrumented in “building blocks”, starting construction!

KM3NeT “building block”

Multi-PMT digital optical module (“DOM”)

string with OMs
The KM3NeT Neutrino Telescope

Planned multi-site installation in the Mediterranean Sea (France, Italy, Greece), instrumented in “building blocks”

- **31 x 3” PMTs**
  - Hamamatsu, ETL, HZC
- **Light collection ring**
  - 20–40% gain in PC for free
- **Low power**
  - <10 W / DOM
- **FPGA readout**
  - sub-ns time stamping
  - time over threshold
- **Calibration**
  - LED & acoustic piezo
- **Optical fibre data transmission**
  - DWDM with 80 wavelengths
  - Gb/s readout
The KM3NeT Neutrino Telescope
Planned multi-site installation in the Mediterranean Sea (France, Italy, Greece), instrumented in “building blocks”

use noise from $^{40}$K decays as a calibration tool!
The KM3NeT Neutrino Telescope

String deployment by rolling up the string, deploying it to depth and the letting it unfurl
The IceCube Neutrino Observatory
Deployed in the deep glacial ice at the South Pole

- 5160 DOMs (single-PMT)
- 1 km³ volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 125 m string spacing
- Completed 2010
The IceCube Neutrino Observatory

- South Pole station
- Skiway
- IceCube's footprint
- Drill camp
- Counting house
Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers).

The IceCube Neutrino Observatory
The IceCube Neutrino Observatory

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

**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

A bundle of muons from a CR interaction in the atmosphere (also observed in the “IceTop” surface array)
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 (many models excluded by IceCube: Nature 484 (2012))
  - Ultra-high energy “GZK” neutrinos from proton interactions on the CMB

▷ Low energy:
  - Neutrino oscillations with IceCube and ANTARES

▷ Others:
  - Dark Matter / WIMPs, ...
The 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
Observables

Different observables probe different properties

- **Spectral slope**
  - separate extraterrestrial flux from atmospheric, accelerator properties

- **Position of possible cutoff in energy**
  - accelerator properties, maybe different population of sources above/below CR knee?

- **Flavor composition**
  - physics of production process, discrimination against backgrounds

- **Zenith distribution**
  - comparison to backgrounds

- **Full arrival direction**
  - source locations once significant clustering is observed (skymap!)
Study using the “IC59” partial detector during construction: $1.8\sigma$

Hint in upgoing muons

![Graph showing log10(dE/dx) vs. events.]

- IC59 data
- conv. atms. $\nu_\mu$ (HKKM2007)
- conv. atms. $\nu_\mu$ (HKKM2007 + best fit nuisance)
- astrophysical $\nu_\mu$, $E^2$ (best fit)
- astrophysical $\nu_\mu$, $E^2$ (90%CL upper limit)
- prompt $\nu_\mu$ (90%CL upper limit)
Another Hint in Shower

Study using the “IC40” partial detector during construction: $2.4\sigma$
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
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 ’12
  - $2.8\sigma$ excess over expected background in GZK analysis
  - paper published in PRL 111 (2013) 021103

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

Image: 
- "Bert" $\sim$1.1PeV
- "Ernie" $\sim$1.2PeV
Things We Know

- At least two PeV neutrinos in a 2-year dataset
- Events are downgoing
- Seems not to be GZK (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
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
Analysis of dataset taken from May 2010 to May 2012 (662 days of livetime)

- Explicit contained search at high energies (cut: $Q_{\text{tot}}>6000$)
- 400 Mton effective fiducial mass
- Use atmospheric muon veto
- Sensitive to all flavors in region above 60 TeV
- Three times as sensitive at 1 PeV
- Estimate background from data
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 bkg.
- $6 \pm 3.4$ muons per 2 years (662 days)
Background 1 - Atmospheric Muons
What’s “early charge”?

Throughgoing muon

Total detector

Veto region

$T_{250}$ = time at which $Q = 250$ pe

Contained cascade

Total detector

Veto region – barely contained cascade

Veto region – well contained cascade

$T_{250}$ = time at which $Q = 250$ pe
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
Very low at PeV energies

- Typically separated by energy
- Very low at PeV energies (order of 0.1 events/year)
- Large uncertainties in spectrum at high energies
- $4.6^{+3.7}_{-1.2}$ events in two years (662 days)
- Rate accounts for events vetoed by accompanying muon from the same air shower in the Southern Sky
- Baseline model: Enberg et al. (updated with cosmic-ray Knee model)
- 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 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?

26 more events in the 2 years of IceCube data (2010/2011 season: “IC79”&“IC86”)

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

- **Track events (x) can have much higher neutrino energies than deposited energies**
  - also true on a smaller scale for shower events for all signatures except charged-current $\nu_e$

- **Background: $10.6^{+5.0}_{-3.6}$**
  - (or $12.1\pm3.4$ for reference neutrino background model)

(preliminary significance w.r.t. reference bkg. model: $3.3\sigma$ for 26 events; $4.1\sigma$ for 28 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 Distribution in Detector

Uniform in fiducial volume

- Backgrounds from atm. muons would pile up preferentially at the detector boundary
- No such effect is observed!
Systematic Studies and Cross-Checks

- Systematics were checked using an extensive per-event re-simulation
  - varied the ice model and energy scale within uncertainties for each iteration and repeated analysis

- Different fit methods applied to the events show consistent results

- Tracks:
  - good angular resolution (<1deg)
  - inherently worse resolution on energy due to leaving muon

- Showers:
  - larger uncertainties on angle (about 10°-15°)
  - good resolution on deposited energy (might not be total energy for NC and ντ)
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
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
  - at $1.6^{+1.5}_{-0.4}$ PeV when fitting a hard cutoff
- Best fit:
  - $1.2 \pm 0.4 \times 10^{-8}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}
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
Skymap / Clustering

No significant clustering observed

ICECUBE PRELIMINARY

* All p-values are post-trial

shower events p-value = 8%

all events p-value = 80%
Conclusions

Stay tuned!

- 28 events with energies above $\approx 50$ TeV found in two years of IceCube data (2010 & 2011)
- Increasing evidence for high-energy component beyond the atmospheric spectrum
- Inconsistent at $4.1\sigma$ with standard background assumptions
- Less clear what it is - compatible with astrophysical explanations
- More data coming soon!