IceCube and high energy neutrino astronomy

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Lecture, March 4,
Physics 734
High energy particles in the Universe

- **Cosmic Rays**
  - Observed up to $10^{21}$ eV
  - Diffuse, mass composition

- **Gamma Rays**
  - Observed up to ~100 TeV
  - Numerous TeV point sources resolved

- **Neutrinos**
  - Atmospheric neutrinos observed up to 300 TeV
  - Solar neutrinos and SN1987a at lower energies
Cosmic Rays and Neutrino Sources

**Candidate sources (from acceleration region):**

Cosmic ray related:
- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

Other:
- Dark Matter
- Exotics

**Guaranteed sources (known targets):**

- Atmospheric neutrinos (from $\pi$ and $K$ decay)
- Galactic plane: CR interacting with ISM, concentrated on the disk
- GZK (cosmogenic neutrinos)
$pp \rightarrow NN + \text{pions}; \quad p\gamma \rightarrow p\pi^0, n\pi^+$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

**Fermi Acceleration**

**Predicts E^{-2} Spectrum**
Highest energy cosmic rays can produce neutrinos during interglacictic propagation

\[ p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0 \]
\[ \quad \rightarrow n + \pi^+ \]

Interaction with microwave background photons

Cosmic Microwave Background

Cosmogenic Neutrinos

Threshold: \(10^{10} \text{ GeV}\)

411 photons / cm\(^3\)

2.725 K
High energy neutrino astronomy:
Small fluxes,
Need large detectors,
Note wide energy range

MeV energy neutrino astrophysics
Neutrinos as Cosmic Messengers

**Protons**: deflected by magnetic fields.

**Photons**: easily absorbed by CMB and IR backgrounds. EM/Hadronic discrimination difficult.

**Neutrinos**: not deflected by magnetic fields. Low interaction cross-section.
Cosmic rays, muons and neutrinos in the atmosphere

a constant rain of muons and neutrinos is produced by cosmic rays crashing into the atmosphere

IceCube measures about 100000 neutrinos/year generated by the rain of cosmic rays hitting the Earth.
Cosmic rays and atmosphere

• Cosmic rays bombarding Earth’s atmosphere produce energetic secondary particles. Important for underground detectors: Muons and neutrinos

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

and the same for \( \pi^- \)

• Why are there fewer \( \nu_e \) than \( \nu_\mu \)?
  – Electron neutrinos have lower energy
  – Muon decay is increasingly suppressed at high energies. Life time of 2.2µsec much longer due to time dilatation (Lorentz factors of > 1000).

• For completeness: \( \pi^0 \rightarrow \gamma + \gamma \) make e.m. showers, which can be nicely used for ground based detectors
Muons and neutrinos at depth

- Neutrino-induced muons from all directions: 50000 / day
- Downward atmospheric muons: 300 million / day

→ Neutrinos: Use Earth as filter; look for neutrinos from below (GeV to PeV)
→ Cosmic ray muons:
How to detect high energy neutrinos – the challenge:

- Rates are small!
- The “cross section” is small!
- Backgrounds from cosmic ray muons are high
neutrino travels through the earth and ... sometimes interacts to make a muon that travels through the detector

depth detector shielded by water or ice

Muon

Neutrino

Charged Current
Cherenkov light emission

- Charged particles, eg muons, when traveling faster than \( c_{\text{medium}} \), emit light at a characteristic angle where coherent superposition takes place.
- In ice: \( n = 1.33 \)

- Cherenkov angle: \( \cos \theta = \frac{1}{n\beta} = 41^\circ \)

- Yield (300-600nm):
  \[ \frac{dN}{dx} \approx 200 \text{photons/cm} \]
  \[ \approx 2 \times 10^7 \text{photons/km} \]
  for a minimum ionizing muon.
  - About 0.01% of all energy deposited will be radiated in Cherenkov photons
  - Example: A high energy cascade of \( 10^{14} \text{eV} \) will produce about \( 10^{10} \) photons in visible range.
Simulated $\mu$-track of energy 1.2 TeV propagated through 1km of South Pole Ice

1% of all photons are shown until they are absorbed.
Absorbtion length: 100-200m
‘Effective’ Scattering length: 20 – 50m
**Photomultiplier Tube**

**Principle:**
Photoelectric effect + electron multiplication

A better name would be *secondary electron multiplier*

*IceCube PMT (Hamamatsu)*
Diameter 25cm^2
**quantum efficiency: 25% (35)**
Gain: 10^7
(Single photoelectrons ≈ 10mV)
time resolution spe: 3 ns
Dynamic range: 300pe/10ns
The IceCube Digital Optical Module
Digital Optical Module (DOM)

Each sensor is almost an independent detector

- PMT: 10 inch Hamamatsu
- Power consumption: 3 W
- Digitize at 300 MHz
- Dynamic range: 1 – 10000 photoelectrons
- Flasherboard with 12 LEDs
- Local HV

Clock stability: $10^{-10} \approx 0.1 \text{ nsec / sec}$
Synchronized to GPS time every $\approx 10 \text{ sec}$
Time calibration resolution = 2 nsec

Digitized Waveform
Time resolution:
~1ns for bright pulses

- Time difference between neighboring DOMs fired with (bright) flasher pulses: ~1 ns.
  (this includes clock timing)

  Single photoelectron pulse resolution limited by PMT.
  RMS in the peak: ~2ns

  Lab measurement with laser.

  FWHM = 5 ns
IceCube

• Total of 86 strings and 160 IceTop tanks;
• Completion with 86 strings: January 2011
• Full operation with all strings since May 2011.

A. Karle, UW-Madison
IceCube Laboratory

Operational support:
ICL maintenance
~60 kW power to electronics
90 GB/day over satellite
2 winterovers
summer population (around 5-7 pop Dec - Jan)
All sensors are equipped with a set of 12 LED flashers. A 30 ns pulse of only 10 billion photons (400nm) is visible to a distance of 600m.

These measurements are used to calibrate the detector:
- time
- geometry
- optical properties of the ice
Topology of neutrino interactions
neutrino-induced showers

“Mixed” showers
\[ \langle E_{\text{electromagnetic}} \rangle \approx 80\% E_{\text{nu}} \]
\[ \langle E_{\text{hadronic}} \rangle \approx 20\% E_{\text{nu}} \]

Hadronic showers
\[ \langle E \rangle \approx 20\% E_{\text{nu}} \]

EM or Hadronic

graphics: Jaime Alvarez
Event types

- **Throughgoing muons** – the workhorse for neutrino astronomy.
  - Vertex can be far outside the detector. Increased effective volume!

- **Cascade events:**
  - $\nu_e, \nu_\tau$ and neutral current
  - High energy resolution (fully active calorimeter, all energy gets deposited in the detection volume)

- Starting tracks: downgoing neutrino astronomy (reject background of throughgoing cosmic ray muons)
Rare and complex event types: $\nu_\tau$

- Tau events
  
  $\nu_\tau + N \rightarrow \tau + X$

- The tau will decay
  
  $\tau \xrightarrow{Tau\_decay} \nu_\tau + X$

- At low energies ($<1$TeV), the tau will decay “instantly”

- At high energies the decay length is long enough for a second interaction to become detectable
  
  $l_\tau = \gamma c t_\tau \sim 50 \left( E_\tau / $\text{PeV}$ \right) \text{m}$

- “Double bang” signature
- Also possible, partially contained first or second interaction only.
- Energy loss of tau is smaller than that of a muon.
IceCube

background:
downgoing cosmic ray muons

~ 1500 per second

signal:
upgoing muons initiated by neutrinos

~ 10 per hour
Simulation: 1 ms of μ’s and noise

Trigger rate: 3kHz of muons
Shown are also muons that will not form a trigger
noise rate: only 300 photoelectrons/s (at -30°C)
Simulation: 1 milli second of μ’s and noise

Trigger rate: 3kHz of muons
Shown are also muons that will not form a trigger
noise rate: only 300 photoelectrons/s (at -30°C)
- take care of coincident “events”
Muon energy loss, range

Muon energy loss, range

Muon energy loss, range
Neutrino-nucleon cross-section

- Cross section rises with energy
- “Glashow-resonance” at 6.3 PeV
A neutrino of 70 TeV has an interaction length $l$ equal to the diameter of the earth.

$$\lambda^{-1}_\nu = n \sigma_v (E_v)$$

$$P_{\text{survival}} = \exp \left( - \frac{l}{\lambda_\nu} \right)$$

$$n = \rho N_A$$
Neutrino effective areas

Why can neutrino telescopes operate over such a huge energy range?

- Area at 100 TeV (1TeV)
  AMANDA-II: 3m² (0.005)
  IceCube 86: 100m² (0.3)

- Deep Core lowers threshold from 100 GeV to 10 GeV.

Effective area for $n_m$
- Strong rise with energy:
  - $\sigma \propto E_\nu$
  - Increase of muon range with energy up to PeV
Neutrino fluxes
Neutrino fluxes

Atmospheric neutrinos
Neutrino fluxes

Atmospheric neutrinos

IceCube 59:
> 30000 neutrinos from 0.3 to 300 TeV / year
(full detector > 50k/yr)
Atmospheric Neutrinos

Very large neutrino sample: > 50k events per year of purity,

Muon neutrinos into 100’s of TeV

Now also Electron neutrinos up to TeV energies

Approaching the ability to test prompt models

arXiv:1212.4760
40+59 String all-sky neutrino map

Northern hemisphere
Background: atmospheric neutrinos

Southern hemisphere
Background: atmospheric muons
Reduced by $10^{-5}$ using energy cut on downgoing events

Analyze skymap cosmic neutrinos using
1) energy,
2) point sources
3) transient sources
or all three! Example: GRB

Kolanoski (IceCube Coll)
ICRC 2011
arXiv: 1111.5188
IceCube diffuse neutrino searches

Look for neutrino events at high energy, above the rapidly falling atmospheric neutrino spectrum.

1. $\nu_\mu$ signal looks for upward going tracks
   - Results from IC 59 search

2. Cascade search
   - Cascade events ($CC \, \nu_e$ and $\nu_\tau$, $NC \nu_\mu,\tau,e$) contained showers
   - updated Results for IC 40---string search

3. Extremely high energy events, downgoing events at energies above downgoing muons background

4. New strategies for all flavor searches with contained vertex
1. Search for diffuse $\nu_\mu$ flux

Search for upward going tracks at energies above atmospheric neutrino spectrum.
Relative rates in IceCube (at trigger level, before analysis cuts)

Conventional $\nu_\mu$: Honda 2006
Prompt $\nu_\mu$: Engberg et al.
Astrophysical $E^{-2}$: at IC40 limit
IC 59 diffuse $\nu_\mu$ flux

Data from 2009-2010: 348 days of livetime, 21943 events
IC 59 highest energy events

Fitted muon energy: 84 TeV
Diffuse $n_m$ flux limits

![Graph showing diffuse $n_m$ flux limits with IC59 limit and sensitivity marked.]
GZK/EHE Neutrino Search

Data from 2010-2012: 319+351 days of livetime with 90%-100% complete detector.
Analysis looks for EHE neutrinos where no background is expected.
Two very interesting events were found at ~1 PeV—do not appear to be part of a GZK flux, however.
Two events found at PeV energies

**Preliminary**

<table>
<thead>
<tr>
<th>Event</th>
<th>Date (GMT)</th>
<th>Number of Photoelectrons</th>
<th>Number of recorded DOMs</th>
<th>Reconstructed energy</th>
<th>Reconstructed z vertex</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>August 8, 2011</td>
<td>$7.0 \times 10^4$</td>
<td>312</td>
<td>$1.0 \pm 0.2$ PeV</td>
<td>121.8 m</td>
</tr>
<tr>
<td>2</td>
<td>January 3, 2012</td>
<td>$9.6 \times 10^4$</td>
<td>354</td>
<td>$1.1 \pm 0.2$ PeV</td>
<td>24.6 m</td>
</tr>
</tbody>
</table>

Error on vertex position: ~ 5m
Observed neutrino event at $E=1.1 \times 10^6$ GeV

- Waveforms provide useful information
- Shown is one event with best fit (blue) and forced reverse direction (red)
- Event contains 354 waveforms and a total of > 105 photoelectrons

- Good absolute agreement with predictions for either $\nu_e$ or neutral-current
- Width of waveforms related to direction of Cherenkov cone
- Height proportional to energy
- Preliminary pointing established (blue arrow)
- Energy uncertainty of $+15\%$ $-13\%$
PeV Events Compared to Models

- The two events are not from muon background!
- The two events are difficult to explain as conventional atmospheric origin. (2.7 sigma tension to conventional atmospheric neutrino flux; very high prompt flux would be needed (15 times Enberg).
- The two PeV events are compatible with the diffuse $E^{-2}$ limit, but such a spectrum would also predict additional events at higher energies.
- Seeing two such events would be relatively surprising for GZK fluxes which peak at higher energies.

Figure: Aya Ishihara
Background free neutrino astronomy?

Schoenert et al.  
arXiv:0812.4308

- Atmospheric neutrinos are made in air showers.
- Downgoing energetic neutrinos (100 TeV, zenith less than 50°) are almost always accompanied by muons down to several km of depth.
Veto probability vs energy and zenith angle

Schoenert et al.
arXiv:0812.4308
The Idea

- Atmospheric neutrinos come almost exclusively from charged pions and kaons decays
  - 99.99% of pions and 63.4% of kaons decay into a muon and muon neutrino
- The created muons have a “guaranteed” energy which can be calculated with relativistic kinematics and are nearly collinear with the neutrino
- The result is that muon neutrinos from air showers always have at least one accompanying muon which can penetrate to the depth of IceCube if the muon’s energy is large enough to survive the trip through the ice
  - Muons need \( \sim 300 \text{ GeV} \) of energy to survive
- This makes it relatively easy to find astrophysical neutrinos with IceCube since astrophysical neutrinos may interact within the detector volume leaving no energy at the detector’s edge while atmospheric neutrinos with an accompanying muon will almost always leave energy at the detector’s edge
Kinematics

\( i = \pi \text{ or } K \)

\( c = 1 \)

In CM Frame

\[
P_i = (m_i, 0, 0, 0) \quad P_\mu = (E_\mu, p_\mu) \quad P_v = (E_v, p_v)
\]

\[
P_i = P_\mu + P_v \rightarrow P_v = P_\mu - P_i
\]

\[
P_v^2 = (P_\mu - P_i)^2 \rightarrow P_v^2 = P_\mu^2 + P_i^2 - 2P_\mu P_i
\]

\[
P_\mu P_i = E_i E_\mu - p_\mu p_\mu = m_i E_\mu
\]

\[
P_v^2 = 0
\]

\[
0 = m_\mu^2 + m_i^2 - 2m_i E_\mu \rightarrow E_\mu = \frac{m_i^2 + m_\mu^2}{2m_i}
\]

\[
E_v = E_i - E_\mu = m_i - \frac{m_i^2 + m_\mu^2}{2m_i}
\]

\[
E_v = \frac{m_i^2 - m_\mu^2}{2m_i}
\]

Boosting Into Lab Frame

\[
E_\mu = \gamma (E_\mu^{CM} + \beta p_{\mu x}^{CM})
\]

\[
P_{\mu x}^{CM} = |p^{CM}| \cos \theta_v
\]

\[
p_{\mu x}^{CM} = |p^{CM}| \cos (\theta_v - \pi) = -|p^{CM}| \cos \theta_v
\]

\[
E_v = \gamma |p^{CM}| (1 + \cos \theta_v)
\]

\[
E_\mu = \gamma |p^{CM}| \left( \frac{m_i^2 + m_\mu^2}{m_i^2 - m_\mu^2} - \cos \theta_v \right)
\]

\[\text{In the worst case } \cos \theta_v = 1\]

\[
E_v = 2\gamma |p^{CM}| \quad E_\mu = 2\gamma |p^{CM}| \left( \frac{m_\mu^2}{m_i^2 - m_\mu^2} \right)
\]

\[
E_\mu \geq E_v \left( \frac{m_\mu^2}{m_i^2 - m_\mu^2} \right)
\]

\( E_i > \text{several GeV makes } \beta \sim 1 \)
Can also show that the neutrino and muon deviate less than 1m (10m) over a 10 km path for neutrino energies greater than 1 TeV originating from a pion (kaon) decay.

These calculations prove that a nearly collinear muon with at least 1.342 TeV (48 GeV) in energy is created for almost all atmospheric muon neutrinos with energy over 1 TeV which originated from pion (kaon) decays.
What Can Be Done With This Information?

- Using \( E_{\mu,\text{min}}(x) = 0.73 \text{TeV} \times \left( e^{\frac{x}{2.8 \text{km.w.e}}} - 1 \right) \) from Muon Monte Carlo to give an estimate of the muon’s energy at depth one can produce the plot below.
- The plot shows that for neutrino energies above \( \sim 10^4 \text{ GeV} \) and zenith angles less than \( \sim 55^0 \) there exists a region where an atmospheric muon neutrino will have an accompanying muon.
- To find events one searches for events that are starting tracks above a certain energy and below a certain zenith angle.
- This is the basis for the search done by Nathan and Claudio.
Strategy to remove all background
- neutrino telescope going up-side down at E>100TeV

Goal of background free region for E > ~100 TeV
(but: need to fold in zenith angle resolution)
Strategy to remove all background
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Goal of background free region for E > ~100 TeV
(but: need to fold in zenith angle resolution)
Neutrino oscillations
IceCube - DeepCore:

**DESIGN**

- Eight special strings in filled in the bottom center of IceCube
- ~5x higher effective photocathode density than regular IceCube
- Result: ~20 MTon detector with ~10 GeV threshold, will collect $\mathcal{O}(100k)$ physics quality atmospheric $\nu$/yr

**VETO**

- IceCube’s top and outer layers of strings provide an active veto shield for DeepCore
- Effective $\mu$-free depth much greater
- Atm. $\mu/\nu$ trigger ratio is $\sim 10^6$
- Vetoing algorithms expected to reach well beyond $10^6$ level of background rejection (Muon flux after veto comparable to Sudbury depth)
DeepCore Atmospheric Muon Veto

- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
- ~40 horizontal layers of modules above; 3 rings of strings on all sides
- Effective μ-free depth much greater
- Can use to distinguish atmospheric μ from atmospheric or cosmological ν
- Atm. μ/ν trigger ratio is ~10^6
- Vetoing algorithms expected to reach at least 10^6 level of background rejection
Neutrino Oscillations

Sensitive to $\Theta_{23}$ over long baselines from atmospheric neutrinos – zenith-dependent suppression of CC $\nu_\mu$ as different chords of the Earth are traversed.

$\chi^2$/ndof=52.7/20 (no oscillations) $\chi^2$/ndof=19.4/20 (std. oscillations)

Extremely high statistics available with multi-megaton Deep Core subarray – first observation of neutrino oscillations in IceCube.
Define:

**Photon effective area** =

\[
\text{Number of PMT} \times \text{Cathode area} \times \text{Quantum efficiency}
\]

= equivalent area of 100% photon detection.

(collection efficiency not included here.)

Photon effective area prop. \~ 1/Energy threshold.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

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**Table:**

<table>
<thead>
<tr>
<th></th>
<th>IceCube</th>
<th>DeepCore</th>
<th>PINGU</th>
<th>AMANDA</th>
<th>ANTARES</th>
<th>KM3Net</th>
<th>BAIKAL GVD4</th>
<th>LBNE</th>
<th>SuperK</th>
<th>HyperK</th>
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<td>6</td>
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<td>Total No of PMT, OMS</td>
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<td>500</td>
<td>1400</td>
<td>677</td>
<td>885</td>
<td>12800</td>
<td>10368</td>
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<td>11410</td>
<td>100000</td>
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<td>1080</td>
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<tr>
<td>No. of PMT or OMs/Mton</td>
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<td>3</td>
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<td>285250</td>
<td></td>
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<tr>
<td>Photon eff. area/mass [m²/Mt]</td>
<td>0.07</td>
<td>0.46</td>
<td>4</td>
<td>0.409</td>
<td>0.603</td>
<td>0.114</td>
<td>0.128</td>
<td>5481</td>
<td>17115</td>
<td>8400</td>
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<tr>
<td>Energy &quot;threshold&quot; [GeV]</td>
<td>300</td>
<td>15</td>
<td>2</td>
<td>60</td>
<td>40</td>
<td>300</td>
<td>200</td>
<td>0.005</td>
<td>0.003</td>
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</table>

Footnote/Disclaimer: Some figures are estimates. Definitions of threshold vary somewhat within factor of two in some cases. Threshold for nu telescopes above Deep Core are for muon neutrinos.
PINGU Physics

- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
  - enhanced sensitivity to neutrino mass hierarchy
- Gain increased sensitivity to supernova neutrino bursts
  - Extension of current search for coherent increase in singles rate across entire detector volume
  - Only $2\pm1$ core collapse SN/century in Milky Way
  - need to reach out to our neighboring galaxies
- Gain depends strongly on noise reduction via coincident photon detection (e.g., in neighbor DOMs)

Ref. on Supernova detection:
- L. Demiroers, M. Ribordy, M. Salathe
  arXiv:1106.1937
- Poster 30-3: M. Voge et al
Mass hierarchy

Figure and Analysis from:
Akhmedov, Razzaque, Smirnov, arXiv: 1205.7071
See poster by E. Resconi et al. (IceCube and PINGU)

- Expected significance for observed number of events for IH vs NH are shown in energy vs. zenith plot
- If required energy and directional resolution is achievable:
  → high statistical significance

Conclusion (Akhmedov et al.):
“Our preliminary estimates show that after 5 years of PINGU 20 operation the significance of the determination of the hierarchy can range from 3 to 11 (without taking into account parameter degeneracy), depending on the accuracy of reconstruction of neutrino energy and direction.”

Assumed above:
- Energy resolution: 4 GeV,
- Angular resolution: 0.3 in cos(θ)
- Exposure: 10 Mt yr