IceCube - Status & First Results

Spencer Klein, LBNL

- Cosmic-rays and Neutrinos
- Neutrino Sources and Rates
- IceCube Status & 1st results
- Conclusions
- Bartol Research Institute, Delaware, USA
- Pennsylvania State University, USA
- UC Berkeley, USA
- UC Irvine, USA
- Clark-Atlanta University, USA
- Univ. of Maryland, USA
- University of Alaska, Anchorage, USA

- IAS, Princeton, USA
- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- University of Kansas, USA
- Southern University and A&M College, Baton Rouge, USA

- Université Libre de Bruxelles, Belgium
- Vrije Universiteit Brussel, Belgium
- Université de Mons-Hainaut, Belgium
- Universität Mainz, Germany
- DESY-Zeuthen, Germany
- Universität Dortmund, Germany
- Humboldt University, Germany

- Chiba University, Japan
- University of Canterbury, Christchurch, NZ

- Universität Wuppertal, Germany
- Uppsala university, Sweden
- Stockholm university, Sweden
- Imperial College, London, UK
- Oxford university, UK
- Utrecht, university, Netherlands
Air showers have been observed with energies up to $3 \times 10^{20}$ eV.

At moderate energies:
- Significant component of $A > 1$ nuclei
- Supernova may be sources

High energies composition & sources unknown:
- Proton fraction may increase with energy
- AUGER does not see correlations between individual event directions
- GZK interactions limit range to $\sim 50$ megaparsecs
  - $p + \gamma_{3K} \rightarrow \Delta$

Decay/annihilation of supermassive particles???
Cosmic-Ray sources

- Shocks waves ‘power’ acceleration in most models
- B field * size determines maximum energy
  - Supernova remnants
    - Crab nebula produces 10 TeV photons
      - spectrum fits synchrotron radiation + inverse Compton scattering
    - Known source of heavy nuclei
    - B field allows acceleration of $10^{15-17}$ eV/A nuclei
- Relativistic jets may also work
  - Active Galactic Nuclei
  - GRBs
Neutrinos probe CR sources

- Photons are absorbed by matter at the source and interact with cosmic microwave photons in transit.
- Charged cosmic ray are bent in transit.
- \( \nu \) come straight to us.
- Cross sections are small.
  - A large detector is needed.
Cosmic-ray acceleration occurs in low-density matter

‘Beam-gas’ interaction produce $\pi$ and K which decay before interacting

- $\pi^\pm , K^\pm \rightarrow \mu \nu_{\mu}, \mu \rightarrow e \nu_e \bar{\nu}_\mu$
- $\nu$ vs $\bar{\nu}$-bar difference usually neglected
- c, b -> $\nu X$ may also contribute

For distant sources oscillations change $\nu_{\mu} : \nu_e \sim 2:1$ from $\pi, K$ decay into $\nu_e : \nu_{\mu} : \nu_\tau \sim 1:1:1$
- Muon energy loss also alters ratio at high energy

A>1 ions can photodissociate
- Produced isotopes may $\beta$ decay, producing $\nu_e$
- Since energy from a single cosmic-ray is shared by many nucleons, the HE $\nu$ flux from ions is much lower than from protons.
Two $\nu$ flux calculations

- Source density & known CR spectrum set number of $\nu$-producing interactions
  - $\nu$ come from ions that don’t escape the source – could be more numerous than those that do
    - “Choked” bursts
  - Maximum $\nu$ energy is a few % of ion energy

- Assume photon production from $\pi^0 \rightarrow \gamma\gamma$
  - $N(\pi^0) = N(\pi^\pm)$; $\pi^\pm$ decay chain emits $\nu$
  - Avoids uncertainty due to CR composition

- Conclusion from many calculations using these or other approaches: a 1 km$^3$ $\nu$ detector should see signals.
Active Galactic Nuclei

- Galaxies with central supermassive black holes emit relativistic jets.
  - Jet-matter interactions produce $\nu$ & $\gamma$
- Markarian 501 seen from radio waves to 10 TeV
  - Spectrum shows probably not electromagnetic acceleration
  - Similar spectra from galactic center
- Expect ~ 1000 $\nu$/year with $E > 1$ TeV from all AGN
  - Diffuse source
  - Are individual AGNs visible?
ν production in Gamma-ray bursters

- Bursts of γs with energies up to at least 10 GeV
  - γ and ν emission expected up to ~10^{16(+)} eV
- Short bursts (<2 s) from colliding compact objects (e.g. neutron stars/black holes)
- Longer bursts (2-100? s) from ‘hypernovae:’ collapses of supermassive stars
- Large burst-to-burst variation in flux
  - Depends on distance, spectral index…
  - Optimal search focuses on biggest bursts
    - Use photons to select ‘biggest’
    - IceCube should see ~ 1-2 ν from the these bursts
Other Physics

- Neutrino Cross-sections
- Supernova monitor in our galaxy & LMC
  - Count total photoelectrons in all PMTs
- Dark Matter
  - $\nu$ from weakly interacting massive particles annihilation in the center of the earth or the sun
- Supersymmetric particles produced in $\nu$ interactions
  - Pairs of upward going charged sparticles
    - Separation $\sim 100$ m
- Fast magnetic monopoles, Q-balls, strangelets, etc.
Measuring $\sigma_{\nu N}$ by neutrino absorption in the earth

- The earth is opaque to neutrinos with energies $> \sim 200$ TeV
- Determine absorption by measuring flux as $f(\text{energy, angle})$
  - Usable up to $E_\nu \sim \text{few PeV}$
    - Maximum energy depends on poorly known $\nu$ flux & on detector acceptance near horizon
  - Absorption $\sim \sigma_{\nu N}$
    - Sensitive to weak charge (quarks) to $x \sim \text{few } 10^{-4}$

Absorber thickness
Depends on zenith angle

J. Jalilian-Marian, 2004
Supernova Monitor

AMANDA II: 95% of Galaxy

IceCube: Milky Way + LMC

msec time resolution
WIMP searches

- Search for $\nu_\mu$ produced by WIMP annihilation in the Earth and the sun
- Set limits on dark matter masses & cross-sections
  - E.g. limits on neutralino masses.

Limits on muon flux from Earth

$E_\mu > 1 \text{ GeV}$

$0.05 < \Omega \chi^2 < 0.2$

Disfavored by direct search (CDMS II)

Limits on muon flux from Sun

$1 \text{ km}^3$ (IceCube)

Antares 3 years

$E_\mu^\text{in} = 1 \text{ GeV}$

$0.05 < \Omega \chi^2 < 0.2$

$\sigma^\text{lim} = \sigma_{\text{CDMS 2004}}$

$\sigma^\text{lim} > \sigma_{\text{Si}}$

$0.1 \sigma^\text{lim} > \sigma_{\text{Si}}$

$\sigma_{\text{Si}} > \sigma_{\text{lim}}$

$\sigma_{\text{Si}} < \sigma_{\text{lim}}$
Extra-terrestrial Neutrino Search Strategies

- Point Sources
  - $\nu_\mu$

- Diffuse Searches
  - $\nu_e$, $\nu_\mu$ & $\nu_\tau$
  - More sensitive if there are many sources

- Triggered (e.g. GRB) & untriggered burst searches, and searches for continuous emission.
\( \nu_e, \, \nu_\mu \, \text{&} \, \nu_\tau \)

- **\( \nu_\mu \)**
  - \( E \sim dE/dx \), \( E > 1 \, \text{TeV} \)
  - Range: 1 km (1 TeV) - 20 km
  - Angles to a few degrees
  - Atmospheric \( \nu \) background

- **\( \nu_e \)**
  - \( E \sim \text{visible energy} \)
  - \( \Delta \log(E) \sim 11\% \)

- **\( \nu_\tau \)**
  - Double-bang signature above \( \sim 1 \, \text{PeV} \)
  - Other topologies possible
  - Very low background
AMANDA Point source analysis

2000-2004: 4282 events 1001 days live-time

Search for an excess of events
- from candidate sources
- anywhere on the northern sky

Optimal search window

Atm-ν Background from ‘off-source’ data

No detection yet, flux upper limits set
Diffuse $\nu_\mu$ searches

- Air showers produce diffuse $\nu$
  - $\pi$,K decay, mostly to $\nu_\mu$
  - $\pi$,K Decay probability decreases with energy as $\gamma \beta c \tau$ rises
    - $dN_\nu/dE \sim E^{-3.7}$
  - Steeper than extra-terrestrial sources (typically $E^{-2}$)
- High energies better for extra-terrestrial searches
- AMANDA set limits on $E^{-2}$ spectrum:
  - $E^2 \Phi_{\nu\mu}(E) < 2.6 \cdot 10^{-7}$ GeV/ cm$^2$ s sr
    - For 100 TeV < $E$ < 300 TeV
Ice Detectors

- A 1 km$^3$ observatory requires natural media
  - Ice or Water
- Pioneered by AMANDA (1992)
  - Observed atmospheric $\nu_\mu$
  - Learned many lessons
- Ice is inhomogeneous
  - Air bubbles in upper 1,000 m
  - Dust layers cause scattering
- Ice has a $\sim$100 m absorption length
  - But … scattering length $\sim$ 25 m
- Cold & Dark --> Low Dark rates ($\sim$300 Hz)
- Transmission to surface nontrivial

A $\mu$ in AMANDA
IceCube

- ~4800 optical modules in 1 km$^3$
  - 10” phototube in a 13” sphere
  - ~80 strings with 60 modules
    - 125 m hexagonal grid
  - 1400 to 2400 m deep
- IceTop surface array
  - 160 detectors in 1 km$^2$
- AMANDA is continuing as a high-density infill array for IceCube
  - Useful for lower energy events
  - Contained events
Hose reel
Drill tower
5 Megawatt
Hot water
generator
IceTop tanks
Hot-water drilling
Hole Drilling

- 2500 m deep, 60 cm dia. holes
- 5 Megawatt hot water drill
  - (Mostly) reliable operation
- Single heater, hose, two towers
  - Set up one, drill with the other
- Speeds to 2.2 m/minute
  - Design goal
  - ~40 hours to drill a hole
- 2004/5 – 1 string
- 2005/6 – 8 strings
- 2006/7 – 13 strings
Ice Properties

- Dust logger measures scattering
- Emits light perpendicular to hole
  - Measures light scattered by dust
- Are the dust layers constant across IceCube?

![Graph showing Dust Logger Signal depth (m) for Hole 50 (preliminary) and Hole 21]
IceTop Surface array
160 ice-filled tanks covering 1 km²

~ 300 TeV -10^{19} eV air showers
Cosmic Ray Composition
- Surface particles : subsurface $\mu$
- High $p_T$ muons in CR air showers
  - pQCD based composition studies

IceCube calibrations
Veto for downgoing cosmic rays
$\gamma$ detector (w/ IceCube as a veto)

Each tank contains 2 DOMs
Optical Modules

- 10” Photomultiplier w/ HV
- 300 MHz waveform digitizer
  - Custom SCA+ADC chip
  - 3 parallel 10-bit digitizers give 14 bits of dynamic range
- 40 MHz 10-bit fast ADC
- Autonomous operation
  - Self triggering with ~1/4 photoelectron threshold
  - Sends time-stamped, packetized Digital data to surface
- <5 Watts of power
- 700 Hz Dark rate
  - 350 Hz w/ 51 µs deadtime
- “Rapcal” timing calibration
- Calibration LEDs
Calibrations

- Calibrations studied with muons, LEDs & N₂ laser
- Timing Calibrations via “RapCal”
  - Surface & DOM exchange identical pulses
- Timing Resolution ~ < 2 nsec
- Ice model is key part of calibrations
  - Scattering & Absorption in ice
Particle ($\mu$) Tracking

- $\mu$ tracks lose energy by emitting $\gamma$, $e^+e^-$ pairs and hadronic interactions (via virtual $\gamma$)
  - Charged particles emit Cherenkov radiation
    - angle $\theta = \cos^{-1}(1/n) = 41^\circ$
    - The photons scatter ($\Lambda \sim 25$ m)
    - Some ($<10^{-6}$) photons are observed in photodetectors
  - We measure points 0-30 meters from the $\mu$ track
    - Tracking is very hard & we do not have the optimal solution
      - Angular resolution $< 1^\circ$
Atmospheric Neutrinos

- 90 days of data with 9 strings
- 156 events observed
- 144 ± 12 ± 48 events expected
  - 138 atmospheric $\nu_\mu$
  - 4.4 single cosmic-ray $\mu$
  - 2.3 overlapping cosmic-ray $\mu$
  - 2 independent showers at the same time
- Paper draft is circulating
- $\nu$ rate increases with larger detector, slightly more efficient data taking and optimized tracking & selection criteria
  - Expect 100,000 atmospheric $\nu$/year with full detector

24 DOMs hit in 2 strings
Future Plans

- Above $\sim 10^{16}$ eV, the expected $\nu$ rates in IceCube are small.
- A $\sim 100 \text{ km}^3$ detector is needed to see GZK $\nu$ and other high-energy signals.
  - Protons & $\gamma$ have limited range.
  - $\nu$ only probe sensitive to EHE universe $> 50$ megaparsecs away.
- Coherent radio and/or acoustic detection of EHE showers may allow for an affordable detector.
  - $300 \text{ m}$ deep holes on a $1 \text{ km}$ grid?

Coherent radio and/or acoustic detection of EHE showers may allow for an affordable detector.

- 300 m deep holes on a 1 km grid?
UC Contributions

- LBNL
  - DOM electronics design & construction, surface electronics, DAQ, time & amplitude calibration, cascades ($\nu_e$) searches

- UC Berkeley
  - Calibrations devices (standard candle, dust logger, etc) & calibrations, monitoring, GRBs, glaciology, acoustic studies

- UC Irvine
  - AMANDA waveform digitizers, EHE events
Conclusions

- Extraterrestrial $\nu$ will shed light on the origin and composition of UHE cosmic rays.
- IceCube will probe supernova $\nu$, $\nu$-nucleon cross section, WIMP annihilation in the Sun & Earth, and study neutrino properties.
- Construction is well underway.
  - We have deployed 22 out of 70-80 strings.
  - Completion expected in 2011.
- The hardware is working well.
  - Time resolution $\sim$ 2 nsec across the array
  - > 98% of DOMs are working as designed.
- We have seen atmospheric neutrinos and first physics results are coming out.
- A future 100 km$^3$ radio/acoustic array may probe the EHE universe out to cosmological distances.
Backups, etc.
Detector Basics

- ~1 km\(^3\) detector needed for extraterrestrial signals
  - Natural media
- Cherenkov radiation from charged particles
  - Sparse sampling optical detectors
- Water
  - Homogenous (+)
  - Long scattering Length (+)
  - Relatively short absorption length (-)
  - \(^{40}\text{K} & \text{bioluminescence background in seawater} (-)
  - Ocean currents (-)
- Pursued by DUMAND (1980’s), BAIKAL, NESTOR, ANTARES & NEMO
  - European Km\(^3\) initiative in Mediterranean
Neutrinos Observed

A 2005 Neutrino candidate
49 DOMs hit in String 21

Time residuals from fit
Direct & scattered photons

2006 Neutrino candidate
24 DOMs hit in 2 strings
Multi-parameter measurement with IceCube/IceTop

- IceTop measures air shower energy, direction & core position
- InIce measures:
  - Muon energy, by dE/dx
    - Muon bundles near shower core
  - Muon $p_T$, by distance from core
    - (away from core region)
    - $p_T = E_\mu \cdot \text{core\_distance/production\_height}$
- Perform standard (collider-like) pQCD studies
  - Sensitive to cosmic-ray composition

---

S. Klein, astro-ph/0612051
A high-multiplicity event

Time residuals vs. depth

\[
\begin{align*}
\theta &= 152.18^\circ \\
t_0 &= 1038.47 \text{ ns} \\
d &= -3.91 \text{ m} \\
z_0 &= -1841.92 \text{ m} \\
r_{th} &= 6.95 \\
N_{ch} &= 158
\end{align*}
\]
IceTop Surface Array

- 160 ice-filled tanks covering 1 km$^2$
  - Energy to $10^{19}$ eV
- ~ 300 TeV air shower threshold
- 2 water tanks near each string
  - 1.8 m diameter
  - Controlled freeze to minimize bubbles
- Physics:
  - Cosmic Ray Composition
    - Surface particles: subsurface $\mu$
    - High $p_T$ muons in CR air showers
      - pQCD based composition studies
  - Calibrate IceCube
  - Veto downgoing cosmic rays
  - $\gamma$ detector (w/ IceCube as a veto)
Good directional information

Background from atmospheric $\nu$

$\mu$ lose energy by bremsstrahlung, direct pair production & photonuclear interactions

- $dE/dx \sim E$ for $E > 1$ TeV

Range depends on energy

- 1 TeV $\rightarrow$ 1 km in ice
- 1 PeV $\rightarrow$ 20 km range
  - Effective area is much larger than detector volume

Measure range &/or ‘$dE/dx$’ to get energy

- $E_\mu = 10$ TeV, 90 hits
- $E_\mu = 6$ PeV, 1000 hits
Optical properties of the ice

Measurements:
in-situ light sources
atmospheric muons
Dust Logger

Average optical ice parameters:
\( \lambda_{\text{abs}} \sim 110 \text{ m @ 400 nm} \)
\( \lambda_{\text{sca}} \sim 20 \text{ m @ 400 nm} \)

optical WATER parameters:
\( \lambda_{\text{abs}} \sim 50 \text{ m @ 400 nm} \)
\( \lambda_{\text{sca}} \sim 200 \text{ m @ 400 nm} \)
Digital Optical Module
Mainboard

- 300 kgate FPGA w/ ARM 7 CPU
- Crystal oscillator Allen Variance < 5*10^{-11}
- Custom Switched Capacitor Array
  - 128 sample
  - 300 MSPS
  - 2/board
Time Calibration

In-ice DOMs

IceTop

round trip time resolution for 76 DOMs

round trip time [ ns ]

entries

DOM 32 width 1.60 ns

entries

Time automatic every few seconds

=1000
DOM Occupancy
probability a DOM is hit in events that have >7 hits on a string

Features in DOM occupancy are affected by ice properties (scattering, absorption)
$\nu_e$ interactions: Electromagnetic Showers

- Good energy resolution
- Bloblike $\rightarrow$ poor directional determination
- Peak in cross section for $e > W \rightarrow l\nu$, hadrons
  $\sim$ “Glashow Resonance”
- Techniques are much less developed than for $\nu_\mu$

Gandhi, Quigg, Reno & Sarcevic, 1996
Neutrino Production from Nuclear propagation

- For ions, photodissociation replaces Δ production
  - Breaks nucleus up into lighter ions, protons, neutrons….
  - Neutrons and fragments can β decay
    - ν_e, but with quite low energies
- Since \( \sigma_\nu \sim E_\nu \), signal drops quickly as A rises
  - Very little signal for A>4

Hooper, Taylor and Sarkar, 2004
\( \nu_\tau \) interactions

- \( \nu_\tau N \rightarrow \tau X \)
  - \( \gamma \beta c \tau = 500 \text{ m at } E = 10^{16} \text{ eV} \)
- Double-bang signature
  - 1 shower when the \( \tau \) is produced
  - 2nd shower when the \( \tau \) decays
  - A minimum ionizing track connects the showers

Learned and Pakvasa, 1994

\( E_\tau = \text{few PeV} \)
Search for steady point sources

Search cone 1° opening half-angle + ”soft” energy cut (< 1 TeV)

Sensitivity point sources (1 y):

\[ 5.5 \cdot 10^{-9} \text{ E}^{-2} \text{ (cm}^{-2}\text{s}^{-1}\text{GeV}) \]
Angular resolution as a function of zenith angle

→ above 1 TeV, resolution ~ 0.6 - 0.8 degrees for most zenith angles

Waveform information not used. Will improve resolution for high energies!
Effective Area of IceCube

Effective area vs. zenith angle after rejection of background from downgoing atmospheric muons.

Effective area vs. muon energy
- after trigger
- after rejection of atm $\mu$
- after cuts to get the ultimate sensitivity for point sources (optimized for 2 benchmark spectra)
Transient point sources – e.g. GRB

Essentially background-free search: spatial and temporal correlation with independent observation!

For ~1000 GRB’s observed/year expect (looking in Northern sky only)
- signal: 12 $\nu$ (Waxmann/Bahcall model)
- background (atm): 0.1 $\nu$

Sensitivity GRB (1 y):
~0.2 $\Phi_{WB}$

Excellent prospects for detection of GRB $\nu$’s within 1 year (if WB model realistic)
Search for diffuse excess of extra-terrestrial high energy neutrinos

\[ \log_{10} \left( \frac{E_\nu^2 \Phi(E_\nu)}{\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}} \right) \]

\[ \log E_\nu / \text{GeV} \]

- Atmospheric
- Galactic
- WB bound
- Gamma bound
- Cosmogenic
Neutrino Production from propagating protons

- “Guaranteed” (albeit small) source
- $p + \gamma (3^0K) \rightarrow \Delta^+ \rightarrow n\pi^+$
  - $\pi \rightarrow \mu \nu_\mu, \mu \rightarrow e\nu_e \nu_\mu$
    - $E_\nu/E_{\text{initial}}p \sim 1\%$
- ~ Few events/year
  - 0.2/km$^3$ target volume/year
    - Engel, Seckel and Stanev, 2001
  - 2/km$^3$ target volume/year
    - Hooper, Taylor and Sarkar, 2004
- “GZK neutrinos”
\( \nu \) production in AGNs

- Scale TeV photon data to estimate \( \nu \) spectra
  - Estimate \( \gamma \) absorption
  - \( \nu \) attenuation in earth
  - Assume \( \gamma \) come from \( \pi^0 \)
- Total of \( \sim 1,000 \) upward \( \nu_\mu \) /year from all AGNs
  - with \( E_\nu > 1 \) TeV
  - Diffuse Flux
  - Are individual AGNs visible?

R. Gandhi, C. Quigg, M Reno and I. Sarcevic, 1996