Recent results from IceCube and the future high energy extension

Aya Ishihara

KEK 東海キャンパス
Feburary 20, 2015
Extremely-high energy emission in the Universe

A particle beam injected from Universe

Energies upto $10^{19.5}\text{eV}$

Aya Ishihara KEK at Tokai
High energy emission in the Universe

Atmospheric Neutrinos

- Cosmic-ray up to knee: $\nu$ from $\pi$ and K decay
- Around and above knee: $\nu$ from charmed meson decay

$\nu_\mu$ from $\pi$ and K decay

Air Nuclei

FLUX [$\text{GeV cm}^2 \text{sec sr}^{-1}$]

ENERGY [eV]

Aya Ishihara KEK at Tokai
Ultra-high energy neutrinos in the Universe

Atmospheric neutrino

Astrophysical neutrino

FLUX [(GeV cm$^2$ sec sr)$^{-1}$]

ENERGY [eV]

$p+p$ or $p+\gamma$ astrophysical photon or matter
Extremely-high energy neutrinos in the Universe

Cosmogenic neutrinos are produced by the off-source (<50 Mpc) interactions of cosmic-ray and CMB photons via GZK (Greisen-Zatsepin-Kuzmin) mechanism.
Questions for the ultra-high energy neutrinos

\[\gamma\text{-ray} > 100\text{TeV}\]

Cosmic Microwave Background

Charged Particles

NEUTRINOS

Aya Ishihara KEK at Tokai
Multi-Messenger detections and constraints

Still in the same origin, it is critical to observe them as multi-messengers!

\[ p + p \rightarrow \pi^+, \pi^-, \pi^0 \]

\[ p + \gamma \rightarrow \pi^+, \pi^0 \]

\[ \pi^0 \rightarrow 2\gamma \]

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

\[ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \]
\[ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \]

\[
E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma
\]

E.g. 10PeV CR – 500TeV ν – PeV γ

Aya Ishihara KEK at Tokai
The Largest Underground Detector in the world: The IceCube Detector

1km

Array of 78 sparse and 8 dense strings

5160 optical sensors

1.5km

South Pole

Dome (old station)

Amundsen-Scott South Pole station

Aya Ishihara KEK at Tokai
Digital Optical Module

- PMT: 10 inch Hamamatsu
- Power consumption: 3 W
- Digitize at 300 MHz for 400 ns with custom chip
- 40 MHz for 6.4 μs with fast ADC
- Flasherboard with 12 LEDs
- Local HV

Waveforms, times digitized in each DOM

- Dynamic range 500 photoelectron/15ns

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

25 cm PMT
33 cm Benthosphere

Aya Ishihara
Waveform examples from spe to 10000 pe

25 cm PMT

O(10000)pe

NPE = Integrated charge/PMT gain

Aya Ishihara
The IceCube LAB
60 photomultipliers/string
The IceCube Collaboration

http://icecube.wisc.edu

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
The IceCube Construction and Runs

IC86 = full IceCube (2011~)

IC79 (2010-2011)

IC59 (2009-2010)

Very stable full operation since May 2011 - Now taking 4th year physics run with the full IceCube configuration

IC22 (2007-2008)

IC40 (2008-2009)

IC9 (2006-2007)

IC1(2005-2006)

Aya Ishihara KEK at Tokai
Detection Principle

An array of photomultiplier tubes

Dark and transparent material

μ, τ or cascades

Cherenkov light

Digitized Waveform
IceCube event topological signatures

With 40 strings, 2008 Dec

With 59 strings 2009

With 22 strings 2007

130TeV Cascade-like event

~100TeV up-going muon track event

high energy cosmic-ray induced atmospheric muon bundle event

Aya Ishihara KEK at Tokai
Searches for diffuse neutrinos

\[ \phi_{\text{diffuse}}(E|L, z) = \int \int \int \phi_{\text{single}}(E|L, z) \frac{d^2n(L, z)}{dz dL} dz dL d\Omega \]

Diffuse neutrino fluxes: Powerful tool to search abundant sources

- Advantage: Accumulate neutrinos from many many sources even at very far Universe, different direction, and of different types
- Disadvantage: Accumulate background from all the direction and time (good understanding needed), indirect identification of sources

Aya Ishihara KEK at Tokai
Background for cosmic diffuse neutrinos

Atmospheric Neutrinos
- Cosmic-ray up to knee: $\nu$ from $\pi$ and K decay
- Around and above knee: $\nu$ from charmed meson decay

Atmospheric muons
- Dominant but removable since track-like trajectories of Cherenkov photons and its directions is able to be reliably reconstructed

Aya Ishihara KEK at Tokai
Expected signals in diffuse $\nu$ search

**Conventional Atm. neutrinos**
- Neutrinos from decays of pions and kaons in atmosphere

**Prompt Atm. neutrinos**
- Neutrinos from decays of short-lived mesons in atmosphere

**Astrophysical neutrinos**
- Neutrinos from decays of pions in astrophysical sources

"Features" in the energy spectra:

- Steepening of neutrino spectra: $\phi \propto E^{-\gamma}$, $\gamma \sim 3.7 (+\Delta^*) \Rightarrow \gamma \sim 2.7 (+\Delta^*) \Rightarrow \gamma \sim 2.0 (+\alpha^{**})$
  
  *$\Delta$ is due to cosmic-ray steepening (knee), **$\alpha$ is possible softening at CR acceleration site*

- Neutrino "flavor"
  - Flavor changes with energy:
    - Conventional: $\nu_{\mu}$
    - Prompt: $\nu_{\mu} + \nu_e$  
    - Astrophysical: $\nu_{\mu} + \nu_e + \nu_{\mu}$ (?)

- Event "directions"
  - Zenith angle distribution changes with energy:
    - Conventional: Horizontal enhanced
    - Prompt: Isotropic
    - Astrophysical: Isotropic (?)

This is true at surface, after propagation in Earth, high energy $\nu$ is highly reduced in the upward-going region
Atmospheric $\nu$ measurements

- Super-K $\nu_\mu$
- Frejus $\nu_\mu$
- AMANDA $\nu_\mu$
- unfolding
- forward folding
- IceCube $\nu_\mu$
- unfolding
- forward folding

$E^2 \phi_\nu$, [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$]

- $\nu_\mu$
- Data: 2008-2009
- 100 GeV to 400 TeV

Phys. Rev. D 83, 012001 (2011) by IceCube

- $\nu_e$
- Data: 2010-2011
- DeepCore
- 80 GeV to 6 TeV


Aya Ishihara KEK at Tokai
Up-Track astrophysical $\nu_\mu$ search

Trigger rates:
Atm. muons: $\sim 3$ kHz,
$\sim 200$ atm. $\nu$ /day
(with $E > 100$ GeV in IceCube)

Aya Ishihara KEK at Tokai
Astrophysical and Atmospheric $\nu_\mu$

Data: 2010-2012 (2 years) fit results

IceCube Preliminary

Aya Ishihara KEK at Tokai
Data: 2010-2012 (2 years)

- Best fit results of $\phi_{\text{astro}} \propto E^{-2}$ for $\nu_{\mu}$
  
  
  $$E^2 \phi = (1.01^{+0.36}_{-0.34}) \times 10^{-8} \, [\text{GeV cm}^{-1} \, \text{s}^{-1} \, \text{sr}^{-1}]$$

- Background-only hypothesis disfavored at 3.9σ
Extraterrestrial neutrino search with cascades

Data: 2008-2009

3 additional events

2.7 sigma excess over background only

Data: 2009-2010

no event above 10 TeV

3 flavor upper limit on \( \phi_{\text{astro}} \propto E^{-2} \) (43 TeV - 6.3 PeV)

\[ E^2 \phi = 1.7 \times 10^{-8} \text{ [GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1}] \]

Aya Ishihara KEK at Tokai

3 flavor upper limit on \( \phi_{\text{astro}} \propto E^{-2} \) (43 TeV - 6.3 PeV)

\[ E^2 \phi = 1.7 \times 10^{-8} \text{ [GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1}] \]

Aya Ishihara KEK at Tokai
The extremely high energy neutrino search

below ~PeV, upward-going tracks and cascade-like topology is important

400 TeV

350 TeV

200 PeV

2 EeV

2 EeV

‘Very bright’ is an important condition

Select both type of events with a ‘brightness’ of events

from MC simulation

Aya Ishihara KEK at Tokai
IceCube EHE Event NPE Distributions

NPE > 3000 (10% test sample)


Aya Ishihara KEK at Tokai
Extremely high energy neutrino search above PeV


2.8sigma excess over $0.08^{+0.04}_{-0.06}$ events of default atmospheric background

Number of photoelectrons: $N_{PE} \propto$ Visible Energy

2010-2012 (2 years)

Aya Ishihara KEK at Tokai
Are these 2 events cosmogenic in origin?

The Kolmogonov-Smirnov test implies that the estimated energies (assuming GZK spectra on surface) can not be explained by the cosmogenic neutrino models.

No!

The predicted $E_v$ cumulative probability:

Data

The test tells that they are very (at 90%CL) inconsistent.

Aya Ishihara KEK at Tokai
Model independent quasi-differential upper limit

- Including Energy PDF of the two events
  - PeV region upper limits are weakened by the 2 event observation
- Significantly improved from the previous upper limits
- IceCube becoming more and more sensitive to cosmogenic fluxes above \(100\ \text{PeV} (10^8\ \text{GeV})\) and started to constrain the highest energy cosmic-ray source evolutions
- \(E^{-2}\) flux integrated limit taking into 2 observations:
  \[
  E^2 \phi(\nu_e + \nu_\mu + \nu_\tau) = 2.5 \times 10^{-8} \text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1} (1.6\ \text{PeV} - 3.5\ \text{EeV})
  \]
Constraint on the highest energy neutrino fluxes and cosmic-ray sources

\[ p(m, z_{\text{max}}) = (1 + z)^m \left( z < z_{\text{max}} \right) \]

- Highly evolving source models of the highest energy cosmic-ray protons can be excluded.
- Disfavoring a generic expression of the evolution parameter \( m \) larger than ~4 which includes radio loud active galaxies (FRII)
High Energy Starting Event Analysis

- Followup analysis on the UHE cascade-like events

- Atmospheric muon/neutrino background largely reduced by vetoing events with initial photons in outer layers

- Events with NPE > 6000 (the case for EHE, NPE > 60000), sensitivity extended down to 30TeV
Atmospheric muon and neutrino veto

- Down-going atmospheric neutrinos are also reduced by vetoing atmospheric muon events

- This changes atmospheric neutrino zenith angle distributions to upward-going dominated
Effective Areas
Propositional to expected event rates

\[ \text{Area} \times \nu \text{ flux} \times 4\pi \times \text{livetime} = \text{event rate} \]
Starting event energy distribution

- 26 new events found
  (19 cascades, 7 with tracks)

- over background expectation of 10.6 $\pm$ 3.6 total atmospheric muons
  (6.0 $\pm$ 3.4) and atmospheric neutrinos (4.6 $\pm$ 3.7)

- **Best fit results**
  $E^2 \phi = (1.2 \pm 0.4) \times 10^{-8}$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$] with a hard cut off at 1.6 PeV
Starting Events in 3 year sample

2010-2013 (3 years)

- 9 new events found
- 7 cascades, 1 with tracks, and 1 coincident muon event (not plotted)
- 5 from southern sky and 3 from northern sky
- The highest energy 2PeV event in the test sample
- 28+9 over background expectation of $15.0^{+7.2}_{-4.5}$ atmospheric muons $8.4 \pm 4.2$ and atmospheric neutrinos $6.6^{+5.9}_{-1.6}$

Extraterrestrial neutrino search with starting events

- Atmospheric background: $13.0^{+7.2}_{-4.5}$
- Inconsistent with background only model at $4.1\sigma$ with 28 events (science 2013) and $5.7\sigma$ with additional 7 events (preliminary)
- Event features (reconstructed energy, zenith angle and topology) consistent with background + astrophysical ($\phi_{\text{astro}} \propto E^{-2}$) fluxes
- Best fit flux $E^2\phi = (0.95 \pm 0.3) \times 10^{-8}$ [GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$] with a hard cut off around 2.0 PeV or a softer spectra with a spectral index $\gamma = 2.3 \pm 0.3$
Zenith angle distributions

- Low energy atmospheric muons in downward-going geometry
- Atmospheric neutrinos in horizontal to upward-going region
- High energy astrophysical component dominant in the downward-going region

Veto method suppress a large fraction of southern atmospheric neutrino background but not the astrophysical neutrinos

Aya Ishihara KEK at Tokai
Diffuse neutrino flux summary

From starting event analysis with a 2 PeV cut off:

\[ E^2 \phi = (0.95 \pm 0.3) \times 10^{-8} \text{ [GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}] \]

From upgoing muon analysis:

\[ E^2 \phi = (1.01^{+0.36}_{-0.34}) \times 10^{-8} \text{ [GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1}] \]

2 years data cascade channel results soon to come
High energy starting event clustering

No evidence of (significant) spatial clustering

cascades
p-value = 7%

all events
p-value = 84%
More quests for $\nu$ point sources

- all-sky through-going muons unbinned point source analysis
- 4 years (IC40+IC59+IC79+IC86) 1373 days

Hottest spot:
- RA 29.25, DEC 10.55
- $-\log_{10}(\text{pre trial p-value}) = 5.32$

All sky search: post-trial p-value 23% no evidence for a neutrino source
Neutrinos in coincidence with gamma-ray bursts?

• 4 years (IC40 + IC59 + IC79 + IC86-1)
• 506 GRBs
• No significant event observed

Upperlimit on a double broken power law type of GRB neutrino fluxes

\[
\frac{dN}{dE} = \phi_\nu \begin{cases} 
    E^{-1} \epsilon_b^{-1} & E < \epsilon_b \\
    E^{-2} & \epsilon_b < E < 10\epsilon_b \\
    E^{-4} \epsilon_b^{-2} & 10\epsilon_b < E
\end{cases}
\]

• Direction plus time (10-100s) cuts reduces background significantly
• Upperlimits are below the Waxman Bahcall model
Implication to the neutrino-nucleus cross sections

Aperture: Detector + Geometry

Interaction

Absorption

Astro $\nu$ flux

Aya Ishihara KEK at Tokai
Implication to the neutrino-nucleus cross sections

Zenith = 180 deg
cos(Zen) = -1.0
Ave $\rho$ = 8.5 g/cm$^3$
Dist = 12,742 km

Zenith = 150 deg
cos(Zen) = -0.87
Ave $\rho$ = 4.0 g/cm$^3$
Dist = 11,035 km

Zenith = 120 deg
cos(Zen) = -0.5
Ave $\rho$ = 3.2 g/cm$^3$
Dist = 6,371 km

Zenith = 90-100 deg
will provide a near zero-absorption baseline at 1 TeV

Zenith = 100 deg
cos(Zen) = -0.17
Ave $\rho$ = 2.6 g/cm$^3$
Dist = 2,213 km

Sandra Miarecki
<miarecki@berkeley.edu>
Implication to the neutrino-nucleus cross sections


Figure 3.3: Neutrino-nucleon and antineutrino-electron scattering cross-sections as a function of neutrino energy from [67] based on data from [64]. From bottom to top at low energy, the cross-sections are for \( \bar{\nu} \) NC, \( \nu \) NC, \( \bar{\nu} \) CC, \( \bar{\nu} \) total, \( \nu \) CC, and \( \nu \) total. The resonance peaked at 6.3 PeV is the antineutrino-electron resonance.
What’s beyond IceCube?

IceCube found:
• Working well at South Pole
• High level of astrophysical neutrino flux
  ✓ cosmic ray sources are efficient neutrino sources
• Neutrinos above 1 PeV from Southern sky (3 events/3 years)
• Spectral indices and shape, $\phi \propto E^{-2.3}$ at high energies

We need more:
• Discoveries
  – neutrino point sources, PeV tau neutrinos, $\bar{\nu}_e e^- \rightarrow W^-$ Glashow resonance events, GZK neutrinos (E>10 PeV)
• Precision measurements
  – cosmic neutrino spectra, flavors, anisotropy
• Particle physics
• And more…
the Next Generation IceCube: 
IceCube-Gen2

High Energy extension
Scale: 100 strings, 10,000 PMT
  volume 5 ~ 10 km³, area 5 ~ 8 km²
• optimal spacing under study

Surface component a la IceTop
A large surface extension for vetoing
downgoing background
Up to 6 km from detector
• optimal size and density under study
A baseline configuration

- more statistics at high energy
- increase volume with more strings

PINGU: extra strings inside original IceCube

100 new strings
240 m spacing

Aya Ishihara KEK at Tokai
IceCube-Gen2 Geometry

120 more strings

78 strings for HE $\nu$

$\approx 4$ km

IceCube

240m string spacing
"benchmark"

300m string spacing

IceCube-86 ($V_{\text{inst} + 60\text{ m}} = 1.26\text{ km}^3$)

240m ($V_{\text{inst} + 60\text{ m}} = 9.73\text{ km}^3$)

300m ($V_{\text{inst} + 60\text{ m}} = 14.24\text{ km}^3$)

Neutrino Frontier Workshop 2014
New Optical Modules design proposal from Chiba for IceCube-Gen2: “D-EGG”

- Realize higher photon detection efficiency
- Up/down symmetric PMT configuration
- 8” SBA PMT R5912-100
- 300mm to 534mm

- More signal events
- Better angular resolution
- Better muon veto

Neutrino Frontier Workshop 2014

50
PMT + Glass measurement

Glass + PMT

ref. PMT
LED/splitter
The present IceCube DOM

detection eff. @ 340nm
bare PMT 27%
PMT + glass 24%

~24%@340nm

8% @ 337nm

PMT + Glass photon detection efficiency
Summary

• IceCube has been fully operational since 2011, accumulated 3-full year samples + 4 years of partial operation data (22, 40, 59, and 79 strings)
• Observed extraterrestrial diffuse neutrinos from different analysis methods as an excess from background only hypothesis
  o more than 3σ with muon neutrino upgoing track channel and more than 5σ level achieved with the starting event search with muon veto technique
• No indication of transient/continuous point sources yet
• High energy extension of the IceCube proposed – 5 times or more signal events to study the nature of neutrino fluxes and detect point sources. Improvements on the hardwares.
• Stay tuned!