The new messengers from the universe
The ‘First Light’ of the high energy neutrino astronomy
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Space explored by *invisibles*

ally filled with so many ‘light’ view

Supernova  NA49
white: visible light
blue: x-ray
red: infra-red

Visible light  X-rays
Neutrinos from Supernova

Before
The large Magellanic Clouds
(1987)

After
Neutrinos are “ghost” particles

\[ \sigma_{\nu N} = 10^{-38} \left( \frac{E_\nu}{\text{GeV}} \right) \text{ cm}^2 \sim 10^{-15} \sigma_{\text{Thompson}} \]

\[ \lambda = \left( N_A \rho \sigma \right)^{-1} \sim 10^4 R_{\text{earth}} \]

x 10,000 !!
Neutrino Astronomy

Scan star core
Solar neutrinos come from the Sun’s core

Visible lights are emitted from its surface

Explore the energetic phenomena in the deep universe

VLA image of Cygnus A

The High Energy Neutrino Astronomy
Radio
CMB
Visible
GeV γ-ray

1 TeV
= 1 LHC

400 microwave photons per cm$^3$
The most energetic universe

The Cosmic Rays

Mostly protons

Some light nuclei
  He, Li, ....

Heavy nuclei (ex. Fe) *may* dominate at higher energies

Not so sure at the highest energy end

Theoretically favors protons
The challenge

No clear correlations.....

Two possibilities

1. Our hypotheses on the high energy cosmic ray emitters are totally wrong
   We may not be so smart.

2. Cannot handle pointing them back to their radiation points
   Magnetic field?
   Particle charge?
   Proton or even iron?
Solutions

1. Correct more and more events
   A super high statistics may resolve B, charge, and source locations, all of which are uncertain at the moment

2. Neutrinos!!
   No electric charge. Coming to us straight
   Highly complementary – $\nu$ can travel over a LONG distance

   The cons : measurement of $\nu$’s is really a tough business
   They are weakly interacting particles $\rightarrow$ a huge detector
   The atmospheric $\nu$ or $\mu$ backgrounds dominates $\rightarrow$ needs excellent filtering programs

Main topic in this talk
Why $\nu$ is so powerful to explore high energy universe?

$\nu$ has a high energy from $\nu$-cosmic rays and can be used to explore the high energy universe. The GZK cutoff is a significant feature in high energy physics, indicating the energy limit for cosmic rays. The diagram shows the relationship between particle energy and distance, with different regions colored for various types of clusters and galaxies. The Super Cluster (超銀河団) and SDSS (Sloan Digital Sky Survey) areas are highlighted, with Our Galaxy and Distant Young Universe marked for comparison.
The Cosmic Neutrinos
Production Mechanisms

“On-source” \( \nu \)

\( \text{pp} \rightarrow \pi \rightarrow \nu \)

“GZK” cosmogenic \( \nu \)

\( \gamma p \rightarrow \pi \rightarrow \nu \)
photopion production

CMB

\( \gamma p \rightarrow \pi \rightarrow \nu \)
The Neutrino Flux: overview

- Solar $\nu$ ($^8$B)
- SN relic $\nu$
- Atmospheric $\nu$

The main background for astro-$\nu$

- "On-source" astro-$\nu$ produced at the UHECR sources
  - Not established yet

- "GZK" cosmogenic $\nu$ produced in the CMB field
  - Not detected yet
The IceCube Neutrino Observatory

Completed: Dec 2010

2004: Project Start 
2011: Project completion

Configuration chronology
2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86

Full operation with all strings since May 2011

Digital Optical Module (DOM)
The IceCube Collaboration

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)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (Vr)
University of Wisconsin Alumni Research Foundation (WARP)
US National Science Foundation (NSF)
Neutrino Detection Principle

Observe the charged secondaries via Cherenkov radiation detected by a 3D array of optical sensors.

Need a huge volume (km$^3$) of an optically transparent detector material.

Antarctic ice is the most transparent natural solid known (absorption lengths up 200 m).
Topological signatures of IceCube events

**Down-going track**
- atmospheric $\mu$
- secondary produced $\mu$ from $\nu_\mu$
- $\tau$ from $\nu_\tau$ @ $\gg$ PeV

**Up-going track**
- atmospheric $\nu_\mu$

**Cascade (Shower)**
- directly induced by $\nu$
  - inside the detector volume
    - via CC from $\nu_e$
    - via NC from $\nu_e$, $\nu_\mu$, $\nu_\tau$
  - all 3 flavor sensitive
Neutrino Signatures

UHE (>100 PeV) VHE (>100 TeV)

Background:
Atmospheric muon

\[ \nu_{\mu,\tau}, \nu_e, \nu_{\tau,\mu} \]

\[ \text{CR} \]

\[ \mu, \mu \]

\[ \text{VHE} \]

\[ \nu_\mu \]

\[ \text{UHE} \]

\[ \nu_{\mu,\tau} \]

Mis-reconstructed atms. \( \mu \)

Dowgoing atms. \( \mu \)

Atmospheric \( \nu \)

TeV astrophysical \( \nu \)

PeV – EeV GZK \( \nu \)
DOM
Digital Optical Module

HV Base
“Flasher Board”
Main Board (DOM-MB)
10” PMT
13” Glass (hemi)sphere
Calibration of DOM

Effective detection area

Reference PMT
Absolutely calibrated

DOM
Reference PMT
Absolutely calibrated

Effective detection area

4\pi mapping

DOM
Reference PMT
Absolutely calibrated

X-stage

LED

NDfilter

Slit 1mm

Reflectivity: 14.5\% \pm 0.73
Transmission: 50.7\% \pm 2.54

Systematic error \sim 7\% \text{ @ room}
Photon Detection Efficiency

Good agreements over the wavelengths.

337nm 8.22%
365nm 16.1%
470nm 17.6%
520nm 10.7%
572nm 4.99%

Absolute calibration of DOM

PMT + Glass/Gel

Good agreements over the wavelengths.
Constructions
2005-2011

Detectors shipped from Japan

Drill House

The IceCube Lab 「Beer Can」

Researchers working on deployment
The Construction
The Construction
The Construction
The Construction
The Construction
The Construction
The Construction
The Construction
The Construction
UHE-UltraHigh Energy $\nu$ search

$> \text{PeV} = 10^{15} \text{ eV}$

The 1$^{\text{st}}$ evidence of astrophysical $\nu$

Phys. Rev. Lett. 111, 021103

Phys. Rev. D 88, 112008

The stringent constraints on cosmic $\nu$ fluxes at PeV and EeV($=1000$ PeV)

The 1$^{\text{st}}$ astrophysically meaningful constraints on UHE cosmic ray origin by $\nu$
The dataset

"IC79"
2010-2011 - 79 strings
May/31/2010-May/12/2011
Effective livetime 319.18 days

"IC86"
2011-2012 – 86 strings
May/13/2011-May/14/2012
Effective livetime 350.91 days

9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)
Data Filtering at South Pole

PY 2012~ season
86 strings ~ the completed IceCube

Simple Majority Trigger
8 folds with 5 μ sec

~ 2.8 kHz

“2nd level” trigger

Muon Filter
selects “up-going” tracks
~40 Hz

EHE Filter
selects “bright” events
~1 Hz

Cascade Filter
selects “cascade”-like events
~34 Hz

Extremely High Energy

NPE > 1000 p.e.

To Northern Hemisphere

Many others
Min Bias
Moon
IceTop
etc
Ultra-high Energy $\nu$ search

Detection Principle

- Secondary $\mu$ and $\tau$ from $\nu$
  - Through-going track
  - Sensitive to $\nu_{\mu}$, $\nu_{\tau}$
- Starting track/cascade
  - Directly induced events from $\nu$
  - Sensitive to $\nu_e$, $\nu_{\mu}$, $\nu_{\tau}$

And tracks arrive horizontally

Ultra-high Energy $\nu$ search

Detection Principle

The blind analysis scheme
Use 10% of the data (test-sample) with masking the rest of them in optimizing the search algorithm with MC simulation
### On the Analysis level

The final-level selection criteria in the plain of NPE-cos(zenith)

**Number of events (z-axis) per the test-sample livetime**

<table>
<thead>
<tr>
<th>test-sample data</th>
<th>atmospheric $\mu$</th>
<th>atmospheric $\nu$</th>
<th>signal GZK $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
</tr>
<tr>
<td>IC86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
</tr>
</tbody>
</table>
Two events passed the final criteria

2 events / 615.9 days (excluding the test-sample livetime)

The Expected Backgrounds

<table>
<thead>
<tr>
<th></th>
<th>p-value 9.0x10^{-4} (3.1σ)</th>
<th>p-value 2.9x10^{-3} (2.8σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>including prompt</td>
<td>0.082 +0.041 -0.057</td>
<td></td>
</tr>
<tr>
<td>conventional only</td>
<td>0.050 +0.028 -0.047</td>
<td></td>
</tr>
</tbody>
</table>

Super-nicely contained cascades!

Run118545-Event63733662  
August 9th 2011 ("Bert")  
NPE 6.9928x10^4  
Number of Optical Sensors 354

Run119316-Event36556705  
Jan 3rd 2012 ("Ernie")  
NPE 9.628x10^4  
Number of Optical Sensors 312
We can still reconstruct the directions they came from

More scattered Cherenkov light in the backward direction

EHE-Jan-2012 “Ernie”

Calibrated ATWD waveform above and below the highest charged DOM (S63-29)

Zenith Angles

Bert ~ 70 deg
Ernie ~ 20 deg

$\Delta \theta \sim 20$ deg
The in-situ verification on the photon measurement

337 nm pulsed Nitrogen Laser

Laser shot event view

Experimentally "simulate" cascade events

Z=2150m
The in-situ verification on the photon measurement

Improving the ice model

The data/MC agreement involves:
- the optical characteristics of the glacier
- detector response to a luminous photon bulk
The Follow-up analysis

Mr. Snuffleupagus

250TeV
A search for events originated within the detector interior look for only events with their interaction vertices within the fiducial volume.
Effective Areas expanding down to 100 TeV’s

Area \times \nu\text{ flux} \times 4\pi \times \text{livetime} = \text{event rate}

IC79+IC86 livetime 670.1 days
sub-PeV $\nu$ samples

Charge Threshold

- Bkg. Atmospheric Muon Flux (Tagged Data)
- Bkg. Atmospheric Neutrinos ($\pi/K$)
- Bkg. Uncertainties (All Atm. Neutrinos)
- Atmospheric Neutrinos (Benchmark Charm Flux)
- Atmospheric Neutrinos (90% CL Charm Limit)
- Signal+Bkg. Best-Fit Astrophysical $E^{-2}$ Spectrum
- All Events (Trigger Level)
- Data

Bert & Ernie
sub-PeV $\nu$ samples

28 events observed against bg of $10.6^{+5.0}_{-3.6}$
(4.1$\sigma$ excess)

$E^2 \phi_{\nu_e+\mu+\tau}(E) \sim (3.6^{+1.2}_{-1.0}) \times 10^{-8}$
[GeV/cm$^2$ sec sr]
**sub-PeV ν samples**

+ additional 2013 data = 988 day sample

37 events observed against bg of $14.0^{+7.2}_{-4.5} \ (5.7\sigma \text{ excess})$

- Big Bird (2 PeV)
- Bert & Ernie

$$E^2 \phi_{\nu_{e+\mu+\tau}}(E) \sim (2.9^{+0.9}_{-0.9}) \times 10^{-8} \ [\text{GeV/cm}^2 \ \text{sec sr}]$$
The hottest spot (p-value 8% - NOT statistically significant)
Sub-PeV $\nu$ samples

+ additional 2013 data = 988 day sample

The hottest spot (p-value 7% - **NOT** statistically significant)

icecube preliminary
sub-PeV $\nu$ samples
+ additional 2013 data = 988 day sample

icecube preliminary
sub-PeV $\nu$ samples
+ additional 2013 data = 988 day sample

Southern Sky (downgoing)  Northern Sky (upgoing)

Less background in Southern Sky due to the atmospheric background veto
Better sensitivity for Southern Sky

$E_{\text{dep}} > 60$ TeV
The executive summary

The model-independent upper limit on flux in UHE

null observation in this regime

clearly exclude

- radio-loud AGN jets
- \( m > 4 \) for \((1+z)^m\)
- emission maximally allowed by the Fermi \( \gamma \)

Bert & Ernie + O(10) sub-PeV events

4.1 \( \sigma \) excess over atmospheric
The Cosmic Neutrinos Production Mechanisms

"On-source" ν

pp → π → ν

GZK" cosmogenic ν

CMB

100EeV p

vee photon ion production
On-source $\nu$ flux estimates: model-independent analytical approach

$$\frac{dJ_\nu}{dE} \sim F_{GZK \ CR} \frac{R_{\text{cosmic}}}{R_{\text{GZK}}} \ E^{-\alpha} \ \tau(E) \ \zeta(z, m, z_{\text{max}}, E)$$

Primary Extragalactic CR proton flux $\sim E^{-\alpha}$

We do NOT know how large: strongly depends on $\alpha$.

$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production

optical depth ($<1$)

The cosmological term to account the source evolution
Constraints on the optical depth and extra-galactic CR flux

\[ \frac{dJ_\gamma}{dE} \sim F_{\text{GZK CR}} \frac{R_{\text{cosmic}}}{R_{\text{GZK}}} E^{-\alpha} \]

\[ \tau(E) \]

\[ \zeta(z, m, z_{\text{max}}, E) \]

Constrain them by the IceCube 100TeV-PeV observation

\[ \gamma p \rightarrow \pi \rightarrow \nu \]

photopion production

optical depth (\(<1\))

Fixed to the Star Formation Rate
Constraints on the optical depth and extra-galactic CR flux

extra-galactic proton flux must be $> 10^{-2}$ of the all-particle CR flux @ 10 PeV

optical depth must be $\geq 10^{-2}$

Yoshida, Takami in preparation
Constraints on the optical depth and extra-galactic CR flux

- Quasars/FR-II (internal shock)
- GRBs

- BL Lac/FR-I (external shock)
- GRBs

Strong evolution
The Constraints on evolution (=emission history) of UHE cosmic ray sources

\[ \frac{dJ}{dE} \sim F_{GZK} \frac{R_{\text{cosmic}}}{R_{GZK}} E^{-\alpha} \]

\[ \tau(E) \]

\[ \zeta(z, m, z_{\text{max}}, E) \]

Fixed to \( E^{-2.3} \)

Constrain them by the IceCube 100TeV-PeV observation
Tracing *history* of the particle emissions with \( \nu \) flux

Intensity gets higher if the emission is more active in the past because \( \nu \) beams are penetrating over cosmological distances.

The cosmological evolution

Many indications that the past was more active.

Star formation rate \( \rightarrow \)

The spectral emission rate

\[ \rho(z) \sim (1+z)^m \]

\( m = 0 \) : No evolution

The Cosmic Neutrinos
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"On-source" $\nu$

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TeV - PeV

"GZK" cosmogenic $\nu$

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photopion production

EeV

100EeV $p$

$\gamma p \rightarrow \pi \rightarrow \nu$

CMB
The Neutrino Flux: overview

- Solar $\nu$ ($^8$B)
- SN relic $\nu$
- Atmospheric $\nu$

The main background for astro-$\nu$

"On-source" astro-$\nu$ produced at the UHECR sources
Not established yet

"GZK" cosmogenic $\nu$ produced in the CMB field
Not detected yet
Ultra-high energy $\nu$ intensity depends on the emission rate in far-universe

Yoshida and Ishihara, PRD 85, 063002 (2012)

$\rho(z) \sim (1+z)^m$

more than an order of magnitude difference

"quiet" "dynamic"

particle emissions in far-universe

intensity above 1 EeV($=10^{18}$ eV)
The Constraints on evolution (=emission history) of UHE cosmic ray sources

\[ \rho(z) \sim (1+z)^m \]

\[ z < Z_{\text{max}} \]

AGNs with radio-loud jets

IceCube collaboration
Phys. Rev. D 88, 112008

The solid bound by the GZK \( \nu \)
The Constraints on evolution (=emission history) of UHE cosmic ray sources

\[ \rho(z) \sim (1+z)^m \]

\[ z < Z_{\text{max}} \]

90\% C.L.

\[ \tau = 0.1 \]

\[ E \sim 2.5 \]

AGNs with radio-loud jets

no high-redshift emission consistent with the star formation rate

Yoshida, Takami in preparation

The solid bound by
the GZK \( \nu \)

by the on-source \( \nu \)
if optical depth \( \sim 0.1 \)
A Personal View: Diffuse Search Vs. Point Sources

But we want to ID a source(s) in the end!

This is THE UHECR SOURCE!

PKS0XYZ+0xy
(ICECUBE J1XYZ-3xy)
The Multi Messengers: 
\[ \text{UHE } \nu \rightarrow \gamma \]

look up this direction!

\[ \nu \quad \text{“GFU”} \quad \gamma \]
The Multi Messengers: 

UHE $\nu \rightarrow \gamma$

The IceCube UHE $\nu$ search

- sensitive to $\nu > O(10^{PeV})$
- the robust algorithm

$\sim 2$ events/year for $\nu_{e+\mu+\tau}$ of $E^2\phi = 3\times10^{-8}$GeVm$^{-2}$sec$^{-1}$sr$^{-1}$

BG: $\sim 0.1$ event/year

new event topology separation

cascade $\leftrightarrow$ track

$\Delta\theta \sim 1$deg
Outlook for IceCube and Neutrino Astronomy

- UHE (> PeV) $\nu \rightarrow \gamma$ multi-messenger
- Super UHE ($\sim$ EeV) $\nu$ search with 2013-2014 data
  GZK $\nu$ search $\rightarrow$ understanding of the origin of highest energy cosmic rays

A fair chance to see 100PeV-EeV $\nu$ with $\delta\theta \lesssim 2\text{deg}$


some technical improvements
- track $\leftrightarrow$ cascade separation
- airshower veto

the projected sensitivity
Outlook for IceCube and Neutrino Astronomy

bigger, and get more events.....

120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing
Outlook for IceCube and Neutrino Astronomy

bigger, and get more events.....
ARA detector assembly and calibration

PeV (可視光の千兆倍のエネルギー)よりもっと高エネルギーな宇宙ニュートリノ探索目指せ 1000 PeV: GZK ν detection!

製作したARA実験用検出器の信号応答を電波暗室中で測定
どんなサイエンスをねらうか？

研究の価値とは

\[ V = I \times C \]

value（価値） Importance（重要性） Completeness（達成度）

\( I \sim C \) が理想的。\( I < C \) でも OK

私の方程式

\[ V = \exp[I] \times C \]

\( I < C \) じゃだめ。\( I > C \) くらいじゃないと。

\( I >> C \) になってしまうリスクをとって対策を講じておく。