Exploring the origin of UHECRs with very-high energy neutrinos

The IceCube 7 year-long UHE $\nu$ searches and the connection of neutrinos to ultra-high energy cosmic rays

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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 Cosmic Neutrinos
Production Mechanisms

"On-source" $\nu$

$pp \rightarrow \pi \rightarrow \nu$

$CMB$

"GZK" cosmogenic $\nu$

EeV

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

photopion production

TeV - PeV

$matter$

radiation

100EeV $p$
Bert & Ernie kicks off the Discovery of Cosmic $\nu$ flux

Found by the IceCube UHE (GZK) $\nu$ searches

IceCube collaboration
Mid Energy (60 TeV-)

look for only events with their interaction vertices within the fiducial volume
Mid Energy (60 TeV-)

IceCube 3 years data (2010-2013)

IceCube collaboration
Phys. Rev. Lett. 113, 101101

2PeV “Big Bird”
Mid Energy (60 TeV-)

IceCube 3 years data (2010-2013)

TS = 2 log(L/L0)

0 11.3

TeV PeV EeV

Bert

Big Bird

Gal.Center

Ernie

Galactic
VHE (100 TeV-PeV)

The "traditional" $\nu_\mu$ search looking into upgoing tracks

IceCube 2 years data (2010-2012)

$\nu_\mu \rightarrow \mu$
detected as up-going track

IceCube collaboration
Phys. Rev. Lett. 115, 081102

3.9 $\sigma$ excess over the atmospheric BG

$E^2 \phi(E) \sim 9.9 \times 10^{-9}$

$[\text{GeV/cm}^2 \text{ sec sr}]$

$E_\nu = O(100\text{TeV})$
VHE (100 TeV-PeV)

up-going $\nu_\mu$ flux detected by IceCube

With 6 year-long data (2009-2015)

$E^2 \phi(E) \approx 8 \times 10^{-9}$ GeV/cm$^2$sec sr per flavor flux
Summary of the IceCube Diffuse Flux measurements

Ultra-High Energies
The model-independent upper limit on flux

Effective $\nu_{e+\mu+\tau}$ detection exposure

$E^2 \phi(E_\nu) [\text{GeV cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}]$

$\log_{10}(E_\nu/\text{GeV})$

- IceCube 2 years data (2010-2012)
- systematics included
- any model adjacent to the limit is disfavored by the observation

$6 \times 10^7 \text{ m}^2 \text{ days sr} @ 1\text{EeV} = 0.2 \text{ km}^2 \text{ sr year}$

Note: $\phi_{CR}(>1\text{EeV}) \sim 20/\text{km}^2 \text{ sr year}$

$\nu$ with CR comparable flux should have been detected
The IceCube Neutrino Observatory

IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

IceCube detector
2450 m

IceTop
50 m

86 strings of DOMs, set 125 meters apart

Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

60 DOMs on each string

DOMs are 17 meters apart

Antarctic bedrock
UHE $\nu$ search with 7 year long data

“IC40” 2008-2009 354.8 day
“IC59” 2009-2010 342.8 day
“IC79” 2010-2011 312.5 day
“IC86” 2011-2015 1406.2 day
UHE (PeV-EeV)

Detection Principle – All flavor sensitive

Signal Domain

atmospheric $\mu$ (bundle)

atmospheric $\nu$

“Energy”

$\cos(\text{Zenith})$
Event Distribution on NPE ("brightness" ~ "Energy") Vs cos(zenith) plane

GZK ν

Background sum
(Atm µ + Conv. Atm ν + Prompt Atm ν)
If more than 2 IceTop hits occurs in 1.2 usec window → Label as backgrounds

vetoed by the air-shower array

We have the IceTop array on the IceCube ice surface
The $\nu$ detection effective area

$\text{PeV} < E < 10 \text{ PeV}$  $\nu_e$ sensitive

$100 \text{PeV} < E$  $\nu_\mu, \nu_\tau$ sensitive
Expected Signal Event Distribution
with GZK-type of spectra

The main energies: EeV (=1000 PeV)
Open the box: What we found

Two PeV-ish events

1\textsuperscript{st} event: shower (cascade) event in 2013 sample

(Probably) the most energetic upgoing event detected by IceCube

Preliminary
Reconstructed Parameters

Diposited Energy
808 TeV
zenith angle
174 deg
~20 deg uncernt.
Open the box: What we found

Two PeV-ish events

2nd event: track event in 2014 sample

Preliminary
Reconstructed Parameters

Diposited Energy
2.6 ± 0.3 PeV

8 deg off TeVCat
3 deg off 2-3FGL
~0.5 deg uncernt.

the most energetic event ever detected by IceCube
What are these events?

They are not the atmospheric background

The background-only hypothesis rejected by $\sim 3.66 \sigma$
(expected background rate 0.064)

They are not the GZK cosmogenic $\nu$

The GZK hypothesis rejected by $\sim 2.75 \sigma$
favoring $\sim E^{-2}$ type of spectrum

A sort of similar situation when the UHE search found two PeV-Energy events in 2012
A part of the sub PeV cosmic neutrino bulk?

consistent but must have a cutoff energy
Implications to UHECR origin with the IceCube PeV-EeV data

Two PeV-ish events | No EeV-ish events

Test on the GZK $\nu$ models to constrain UHECR sources

Robust and solid constraints, but UHECR composition limited
(Only sensitive to proton-dominated case)

Test on the on-source PeV-EeV-energy $\nu$ models (ex AGN jets)

Model-dependent arguments but mixed-composition case reachable
Testing PeV-EeV cosmic $\nu$ models

- No events except Two PeV events

**Data**

**Atmospheric background**

**$\nu$ Signal**

**Likelihood Ratio Test**

- Preliminary
### The Score Board

Many EeV-energy $\nu$ models are excluded

<table>
<thead>
<tr>
<th>$\nu$ Model</th>
<th>GZK Y&amp;T m=4,zmax=4</th>
<th>GZK Ahlers Best Fit 10EeV</th>
<th>GZK Ahlers Best Fit 1EeV</th>
<th>GZK Koter SFR</th>
<th>GZK Aloisio SFR</th>
<th>AGN Murase $\gamma=2.0$ Load.fac 10</th>
<th>Young Pulsar Ke+ SFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expect. # of events</td>
<td>6.9</td>
<td>5.3</td>
<td>2.9</td>
<td>3.6</td>
<td>4.8</td>
<td>15.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Model Rejection Factor</td>
<td>0.34</td>
<td>0.41</td>
<td>0.99</td>
<td>1.2</td>
<td>0.93</td>
<td>0.36</td>
<td>0.99</td>
</tr>
<tr>
<td>p-value</td>
<td>1.0x10^{-3}</td>
<td>2.0x10^{-3}</td>
<td>9.5x10^{-2}</td>
<td>2.2x10^{-1}</td>
<td>7.8x10^{-2}</td>
<td>2.8x10^{-5}</td>
<td>7.8x10^{-2}</td>
</tr>
</tbody>
</table>

- **Excluded**
- **Mildly Excluded**
Implications to UHECR origin with the IceCube PeV-EeV data

- Two PeV-ish events
- No EeV-ish events

Test on the GZK $\nu$ models to constrain UHECR sources

Robust and solid constraints,
but UHECR composition limited
(Only sensitive to proton-dominated case)

Test on the on-source PeV-EeV-energy $\nu$ models (ex AGN jets)

Model-dependent arguments
but mixed-composition case reachable
GZK cosmogenic $\nu$ models

- Kotera, Allerd, Olinto 2010
- Ahlers et al 2010
- Aloisio et al 2014

The IceCube observation range

Source evolution

EBL

The highest E of UHCRs

IceCube signal event energy distribution
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

IceCube Tests on the GZK $\nu$ model

The GZK $\nu$ models assuming proton-dominated CRs

only very weak evolution scenario is allowed
GZK cosmogenic $\nu$ intensity @ 1EeV in the phase space of the emission history

Yoshida and Ishihara, PRD 85, 063002 (2012)

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

$0<z<z_{\text{max}}$

GZK $\nu$ flux $\phi = (m, z_{\text{max}})$

$\times$ IceCube Exposure

Event distribution on plane of (E, cos(zenith))

The observed event distribution

FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, $J \, [\text{cm}^{-2} \, \text{sec}^{-1} \, \text{sr}^{-1}]$, on the plane of the source evolution parameters, $m$ and $z_{\text{max}}$. 
The Constraints on evolution (=emission history) of UHE cosmic ray sources

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

\[ 0 < z < z_{\text{max}} \]

UHECR source is cosmologically LESS evolved

Any sources with evolution compatible or stronger than star formation rate are disfavored

AGNs

GRBs
What IceCube tells if UHECRs are not proton-dominated?

Move on to the on-source ν model-dependent constraints

Example: AGN(Blazar) inner jets taking into account the Blazar sequence
(Murase, Inoue, Dermer, PRD 2014)

FSRQs (QHB) → ν

middle class → γ

BL Lac → UHECRs

The highest energy CRs are HEAVY nuclei
IceCube tests on on-source $\nu$ models

AGN (Blazar) Inner Jet

Murase, Inoue, Dermer, PRD 2014

$\nu$ flux $\propto \frac{L_{CR}}{L_\gamma}$

$\nu$ flux upper limit by IceCube

$100$ if $E^{-2.3}$
$4$ if $E^{-2.0}$

If UHECRs are 100% AGN-originated (heavy) nuclei, we would have already seen EeV neutrinos

AGN unlikely though not completely ruled out
New-Born young pulsars

Ke, Kotera, Olinto, Murase, PRD 2014

The highest energy CRs are HEAVY nuclei

If the fast-spinning pulsars evolves with cosmic time like the standard star formation, we would have EeV seen $\nu$ s

Pulsars unlikely

though not completely ruled out
IceCube generic constraints on \textit{on-source} EeV $\nu$ models

\[ E^2 \phi(E) \sim \text{a few } x10^{-9} \] \hspace{1cm} \text{[GeV cm}^2 \text{ s}^{-1} \text{ sr}^{-1}]
Connections between the observed TeV-PeV $\nu$ flux and UHECRs

If the TeV-PeV $\nu$ emitters are also EeV (not 100EeV)-CR sources…. the observed cosmic ray flux extending to EeVs
Extra-galactic protons must dominate in the EeV-energy Cosmic Rays

- extra-galactic proton flux must *dominate* in the all-particle CR flux @ 1 EeV (=1000 PeV)
- optical depth must be ~1
Summary

Two PeV-ish events detected. No EeV events in the IceCube 7 year-long data

IF UHECRs are proton-dominated
(consistent with the TA’s claim)

- UHE sources are not populated at far universe
  - AGN
  - GRB

The “standard” UHRCR models are dead

IF UHECRs are nuclei-dominated
(Auger is right !)

- Exclusion of some on-source $\nu$ models started to constrain popular sites for UHECR production

Blazar jets may no longer be a plausible UHECR source candidate
Next move

**Multi messenger astronomy**

IceCube triggers ToO/follow-up observations in various wavelengths
IceCube Realtime Analysis Chain

**muon singlet**
- TeV
- PeV
- EeV
- Good angular resolutions
- Muon neutrino sensitive
- Large background chance

**veto-based**
- TeV
- PeV
- EeV
- High chance of real cosmic neutrino signals
- All neutrino flavor sensitive
- Angular resolutions mostly poor

**HESE**
- TeV
- PeV
- EeV
- High chance of real cosmic neutrino signals
- All neutrino flavor sensitive
- Good angular resolutions
- Signal flux highly uncertain

**Ultra-High Energies**
- TeV
- PeV
- EeV
- High chance of real cosmic neutrino signals
- All neutrino flavor sensitive
- Good angular resolutions
- Signal flux highly uncertain
IceCube Realtime Analysis Chain

South Pole

O(hrs)
Quick results

Will start sending $\nu$ alerts to the MoU-singed observatory next year!

Northern Hemisphere

O(1-2days)
refined results from iterated reconstructions