NEUTRINO ASTRONOMY

Claudio Kopper, University of Alberta

ICRC 2015
COSMIC RAYS AND NEUTRINOS

Search for the sources of Cosmic Rays
COSMIC RAYS

where
Cosmic Rays

We know their energy spectrum over 11 orders of magnitude.

Their sources (especially at the highest energies) are still mostly unknown.
› **Nuclei** can be deflected by magnetic fields

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**Multi-messenger astrophysics with neutrinos**
Multi-messenger astrophysics with neutrinos

- **Nuclei** can be deflected by magnetic fields

Astrophysical beam dump
Nuclei can be deflected by magnetic fields.
Multi-messenger astrophysics with neutrinos

- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed

Astrophysical beam dump
Multi-messenger astrophysics with neutrinos

- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
Multi-messenger astrophysics with neutrinos

- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines
Observing astrophysical neutrinos allows conclusions about the acceleration mechanism of Cosmic Rays

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

or \( p, \ldots \)

\[
\leftrightarrow \gamma + \gamma + p
\]

\[
\rightarrow \pi^+ + n
\]

\[
\leftrightarrow \mu^+ + \nu_\mu + n
\]

\[
\leftrightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu + n
\]

(can also be from leptonic processes...)

**TeV gamma rays**

**Cosmic rays?**

**TeV neutrinos**
Neutrinos above 1 TeV

Sketch of the different expected neutrino flux components
ATMOSPHERIC NEUTRINOS ($\pi/K$)
dominant $< 100$ TeV

ATMOSPHERIC NEUTRINOS (CHARM)
“prompt” $\sim 100$ TeV

ASTROPHYSICAL NEUTRINOS
maybe dominant $> 100$ TeV

COSMOGENIC NEUTRINOS
$> 10^6$ TeV
ATMOSPHERIC NEUTRINOS ($\pi$K)
dominant < 100 TeV

ATMOSPHERIC NEUTRINOS (CHARM)
“prompt” ~ 100 TeV

Paolo Desiati - “Recent Observations of Atmospheric Neutrinos with the IceCube Observatory” - August 5, 17:00 (highlight)
**DETECTING TEV NEUTRINOS**

Interaction cross-sections are very small

\[ \sigma(E) \text{ [cm}^2\text{]} \] per km water

Interaction probability

\[ 10^{-6} \text{ per km water} \]
Benchmark astrophysical flux: \(O(10^5)\) per km\(^2\) per year above 100 TeV

Need **km\(^3\)-scale** detectors!

Large volumes, use natural water or ice
Detecting Neutrinos

Neutrinos are detected by looking for...

- Deep-inelastic scattering
- Cherenkov cone
NEUTRINO TELESCOPE SITES

depth natural sites with water/ice (deep sea, lakes, glaciers)
Neutrino telescope sites
deep natural sites with water/ice (deep sea, lakes, glaciers)
NEUTRINO TELESCOPE SITES

deep natural sites with water/ice (deep sea, lakes, glaciers)

ANTARES
NEUTRINO TELESCOPE SITES

depth natural sites with water/ice (deep sea, lakes, glaciers)

ANTARES

KM3NET
NEUTRINO TELESCOPE SITES

Deep natural sites with water/ice (deep sea, lakes, glaciers)

- ANTARES
- KM3NET
- BAikal
- GVD
NEUTRINO TELESCOPE SITES

deep natural sites with water/ice (deep sea, lakes, glaciers)

- ANTARES
- KM3NET
- BAikal
- GVD
- ICECUBE
A possible signal from WIMP annihilation in the Sun would appear as an excess of upward going muons over atmospheric spheric muons (see Fig. 2). For an energy cutoff of 20 PeV, the expected event rate is less than 1/100 km$^3$ yr for WIMP masses of 1/1000 km$^3$ yr.

Within systematic and statistical uncertainties there are no indications for excess muons. The 90% C.L. upper limits on the muon flux from the Sun are obtained as $F_{\mu} < 2.9 \times 10^{-4} \text{cm}^{-2} \text{s}^{-1}$ for 20 TeV neutrinos arriving from the direction of Sun. We have applied two sorts of quality cuts, optimized for high and low WIMP masses.

Our search for high energy extraterrestrial neutrinos is based on studies of bright cascades detected in the telescope NT200. A typical spectrum of high energy neutrino telescopes is shown in Fig. 3. The presented results are preliminary, the cut-off energy depends on the analysis requirements.

The physics program of the Baikal experiment covers the search for extraterrestrial high-energy neutrinos and a limit on the neutrino flux associated with gamma-ray bursts. The detected excess of upward going muons is compared to the corresponding off-source background expectation.

The neutrino detection is based on the induced emission of Cherenkov light by high energy muons originating from charged current neutrino interactions inside or near the in-station, where a computer farm filter the data for coincident signals in several adjacent OMs.

Figure 1. The neutrino detection principle: Muon/sun events in NT200, where the hits with the expectation from the Cherenkov signal of a muon track.

Details on the event reconstruction are given in Ref. [6]. For WIMP masses $10^{-4}$ km$^3$, the NT200 sensitivity for high energy neutrinos is shown in Fig. 4. The presented results are preliminary, the cut-off energy depends on the analysis requirements.

Two main backgrounds for the search for astrophysical neutrinos can be identified: down-going atmospheric muons and atmospheric muons originating in cosmic ray induced air showers at the opposite side of the Earth. Depending on the requirements of the analysis both backgrounds can, at least partially, be separated by cosmic ray energy and look for a correlation between the direction of the muon and the Sun within the containment area, which is about $2 \times 10^5$ km$^2$ yr.

Figure 2. Reconstructed cascade energy distribution for data (dots) and for MC-generated atmospheric muons (boxes); true MC energy distribution given as histogram. In $\cos(\psi)$ histogram, we show the results for the sample of larger, sparser events per bin. For an energy cutoff of 20 PeV, the expected event rate is less than 1/100 km$^3$ yr for WIMP masses of 1 km$^3$ yr.

The ANTARES telescope [11]. For WIMP masses $10^{-4}$ km$^3$, the NT200 sensitivity for high energy neutrinos is shown in Fig. 4. The presented results are preliminary, the cut-off energy depends on the analysis requirements.

The world's neutrino telescopes: lakes, sea, glaciers. NT-200+ (Lake Baikal, 1/2000 km$^3$, 228 PMTs), Antares (Mediterranean Sea, 1/100 km$^3$, 885 PMTs), IceCube (South Pole glacier, 1 km$^3$, 5160 PMTs). Larger, sparser → higher energies.
First cluster of the gigaton detector deployed in April 2015

Plan: 8-12 such arrays
First cluster of the gigaton detector deployed in April 2015

**Plan:** 8-12 such arrays

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**Bair Shaybovov** - “The first construction phase of the Baikal-GVD neutrino telescope” - August 1, 14:15 - NU 03
The ANTARES Neutrino Telescope

- Deployed in 2001
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Timing res
~ 0.5 ns

Position
< 10 cm

“storey” with 3 OMs

Anchor/line socket
Interlink cables
Junction box (since 2002)
THE ANTARES NEUTRINO TELESCOPE

Clancy James - “Highlights from ANTARES, and prospects for KM3NeT” - August 4, 17:30 (highlight)
The IceCube Neutrino Observatory
Deployed in the deep glacial ice at the South Pole

- **5160 PMTs**
- **1 km³ volume**
- **86 strings**
- **17 m vertical spacing**
- **125 m string spacing**
- **Completed 2010**
**NEUTRINO EVENT SIGNATURES**

*Signatures of signal events*

## CC Muon Neutrino

\[ \nu_\mu + N \rightarrow \mu + X \]

- track (data)
- factor of \( \approx 2 \) energy resolution
- \(< 1° \) angular resolution at high energies

## Neutral Current / Electron Neutrino

\[ \nu_e + N \rightarrow e^- + X \]
\[ \nu_x + N \rightarrow \nu_x + X \]

- cascade (data)
- \( \approx \pm 15\% \) deposited energy resolution
- \( \approx 10° \) angular resolution (in IceCube)
  (at energies \( \gtrapprox 100 \) TeV)

## CC Tau Neutrino

\[ \nu_\tau + N \rightarrow \tau + X \]

- “double-bang” (\( \approx 10 \) PeV) and other signatures (simulation)
- (not observed yet: \( \tau \) decay length is 50 m/PeV)
Neutrino event signatures

**Signatures of signal events**

**CC Muon Neutrino**

\[ \nu_{\mu} + N \rightarrow \mu + X \]

- track (data)
- factor of \( \approx 2 \) energy resolution
- \( < 1^\circ \) angular resolution at high energies

**Neutral Current / Electron Neutrino**

\[ \nu_e + N \rightarrow e + X \]
\[ \nu_x + N \rightarrow \nu_x + X \]

- cascade (data)
- \( \approx \pm 15\% \) deposited energy resolution
- \( \approx 10^\circ \) angular resolution (in IceCube)
- (at energies \( \geq 100 \) TeV)

**CC Tau Neutrino**

- "double-bang" (\( \geq 10 \) PeV) and other signatures (simulation)

- not observed yet: \( \tau \) decay length is \( 50 \) m/PeV

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**Dawn Williams** - “A Search for Astrophysical Tau Neutrinos in Three Years of IceCube Data” - August 3, 15:15 - NU 04
DETECTION PRINCIPLE (MUON IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles.
DETECTION PRINCIPLE (MUON IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles.
DTETECTION PRINCIPLE (CASCADE IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles.
DETECTION PRINCIPLE (CASCADE IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles.
DETECTION PRINCIPLE (CASCADE IN ICE)

Another Shower
DETECTION PRINCIPLE (CASCADE IN ICE)

Another Shower

ν

1 TeV EMines, 0.01% of all photons

t = 627

time delay vs. direct light

"on time" ➔ delayed
DETECTION PRINCIPLE (CASCADE IN WATER)

This is how it would look in sea water (KM3NeT/ANTARES)
DETECTION PRINCIPLE (CASCADE IN WATER)

This is how it would look in sea water (KM3NeT/ANTARES)

ν
isolating neutrino events

two strategies
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks

\( \nu \)-dominated

\( \nu \) only

Atmosphere
(exaggerated)

North
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks

IceCube

ν only

Atmosphere (exaggerated)

North

ν-dominated

Upsilon-dominated

Upsilon-dominated
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks

IceCube

Air shower

North

Atmosphere (exaggerated)

ν only

μ-dominated

ν

Isolating neutrino events.

Two strategies:

- Up-going tracks
  - IceCube
  - North
  - Air shower
  - Atmosphere (exaggerated)

- ν only
  - μ-dominated
ISOLATING NEUTRINO EVENTS

Two strategies

Up-going tracks

Air shower

North

μ-dominated

v only

Atmosphere (exaggerated)
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks

Air shower

North

Atmosphere (exaggerated)

Air shower

ν-only

μ-dominated
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks

Air shower

North

Astrophysical source

ν-dominated

v only

Atmosphere (exaggerated)

Air shower

ν

µ-dominated

ν only

ν

µ
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks

Air shower

North

Astrophysical source

Atmosphere (exaggerated)

\( \nu \)-dominated

\( \nu \) only

Earth stops penetrating muons

Effective volume larger than detector

Sensitive to \( \nu_\mu \) only

Sensitive to “half” the sky
Isolating neutrino events

Two strategies

Up-going tracks

- Air shower
- North
- Astrophysical source
- Earth stops penetrating muons
- Effective volume larger than detector
  - Sensitive to $\nu_\mu$ only
  - Sensitive to “half” the sky

Active veto

- $\mu$-dominated
- $\nu$ only
- $\nu$ only
- Atmosphere (exaggerated)
**ISOLATING NEUTRINO EVENTS**

*two strategies*

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**Up-going tracks**

- Air shower
- Up-going tracks
- North
- Astrophysical source
- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to $\nu_\mu$ only
- Sensitive to “half” the sky

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**Active veto**

- Air shower
- $\nu$-dominated
- $\nu$ only
- Atmosphere (exaggerated)
- $\mu$-dominated
- $\mu$ only
- Veto
Isolating neutrino events

Two strategies

**Up-going tracks**
- Air shower
- North
- Astrophysical source
- Earth stops penetrating muons
- Effective volume larger than detector
- Sensitive to $\nu_\mu$ only
- Sensitive to “half” the sky

**Active veto**
- Veto
- $\mu$
- $\nu_\mu$

($\nu_\mu$-dominated $\nu$ only)
isolating neutrino events

two strategies

**Up-going tracks**

- Air shower
- North
- Astrophysical source
- Earth stops penetrating muons
- Effective volume larger than detector
  - Sensitive to $\nu_\mu$ only
  - Sensitive to “half” the sky
- $\mu$-dominated

**Active veto**

- Veto detects penetrating muons
- Effective volume smaller than detector
  - Sensitive to all flavors
  - Sensitive to the entire sky

$\nu$-only

$\nu_{\mu}$

$\mu$

$\nu_{\mu}$
**LED** flashers on each DOM

In-ice calibration **laser**

Cosmic ray **energy spectrum**

Moon **shadow**

Atmospheric neutrino energy spectrum

**Minimum-ionizing** muons

Moon Shadow in Cosmic Rays
Muons in IceCube (59 strings)
Studying Neutrinos

Many different analyses

High-energy:
- Point-source searches looking for clustering in the sky
- Diffuse fluxes above the atmospheric neutrino background
- Gamma-ray bursts/transient searches (GRB models excluded by IceCube: Nature 484 (2012))
- Ultra-high energy “GZK” neutrinos from proton interactions on the CMB

Low energy:
- Neutrino oscillations + more with PINGU/ORCA upgrades

Others:
- Dark Matter / WIMPs
- …
THE (VERY) HIGH-ENERGY TAIL

Update of the high-energy astrophysical flux discovery analysis
### Signals and Backgrounds

<table>
<thead>
<tr>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominated by showers (~80% per volume) from oscillations</td>
<td>Track-like events from Cosmic Ray muons and atmospheric $\nu_\mu$</td>
</tr>
<tr>
<td>High energy (benchmark spectrum is typically $E^{-2}$)</td>
<td>Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)</td>
</tr>
<tr>
<td>Mostly in the Southern Sky due to absorption of high-energy neutrinos in the Earth</td>
<td>Muons in the Southern Sky, neutrinos from the North</td>
</tr>
</tbody>
</table>
Explicit contained search at high energies (cut: $Q_{tot}>6000$ p.e.)

**400 Mton** effective fiducial mass

Use atmospheric muon veto

Sensitive to all flavors in region above 60TeV deposited energy

Estimate background from data
Atmospheric neutrino self-veto

\[ \sin(\delta) = -\cos(\theta) \text{ at the South Pole} \]

Some neutrinos are absorbed in the Earth

Interactions km\(^{-3}\) sr\(^{-1}\) yr\(^{-1}\) \(E_\nu > 100\) TeV

astrophysical \(\nu\)
Some neutrinos are absorbed in the Earth

\[\sin(\delta) = -\cos(\theta)\] at the South Pole

Interactions km\(^{-3}\) sr\(^{-1}\) yr\(^{-1}\) \(E_\nu > 100\) TeV

astrophysical \(\nu\)

conventional \(\nu_\mu\)

conventional \(\nu_e\)
Atmospheric neutrino self-veto

Some neutrinos are absorbed in the Earth

Primary cosmic ray

astrophysical $\nu$

1.5 km of ice

$\sin(\delta) = -\cos(\theta)$ at the South Pole

Some neutrinos are absorbed in the Earth

An active muon veto removes down-going atmospheric neutrinos.

Conventional $\nu_\mu$

Conventional $\nu_e$

10$^{-3}$

10$^{-2}$

10$^{-1}$

10$^0$

10$^1$

Interactions $\text{km}^{-3} \text{sr}^{-1} \text{yr}^{-1}$ $E_\nu > 100 \text{ TeV}$


Atmospheric neutrino self-veto

Some neutrinos are absorbed in the Earth

Interaction km$^3$ sr$^{-1}$ yr$^{-1}$ $E_{\nu} > 100$ TeV

$\sin(\delta) = -\cos(\theta)$ at the South Pole

An active muon veto removes down-going atmospheric neutrinos.

1.5 km of ice


Some neutrinos are absorbed in the Earth.

Increased muon veto removes down-going atmospheric neutrinos.

Primary cosmic ray

$\sin(\delta) = -\cos(\theta)$ at the South Pole


Atmospheric neutrino self-veto

\[ \sin(\delta) = - \cos(\theta) \text{ at the South Pole} \]

- Some neutrinos are absorbed in the Earth
- Prompt atmospheric neutrinos are vetoed, too.


Atmospheric neutrino self-veto

The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

Effective Volume / Target Mass

Fully efficient above 100 TeV for CC electron neutrinos
36(+1) events observed!

Estimated background:

6.6$^{+5.9}_{-1.6}$ atm. neutrinos

8.4±4.2 atm. muons

One of them is an obvious (but expected) background coincident muons from two CR air showers

full likelihood fit of all components:

5.7σ for 36(+1) events

PRL 113, 101101
53(+1) events observed!

Estimated background:

9.0^{+8.0}_{-2.2} atm. neutrinos

12.6\pm5.1 atm. muons

One of them is an obvious (but expected) background coincident muons from two CR air showers

full likelihood fit of all components: 6.5\sigma for 53(+1) events
What did IceCube find? (4 years)

54 events!

53(+1) events observed!

Estimated background:

9.0^{+8.0}_{-2.2} atmos. neutrinos

12.6\pm5.1 atmos. muons

One of them is an obvious (but expected) background

coincident muons from two CR air showers

Full likelihood fit of all components: 6.5\sigma for 53(+1) events

Poster 278 (Poster 3 DM and NU)
WHAT DID ICECUBE FIND?

some examples

declination: -13.2°
deposited energy: 82 TeV

declination: -0.4°
deposited energy: 71 TeV

declination: 40.3°
deposited energy: 253 TeV
Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold (Qtot > 6000)

Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)
Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold ($Q_{tot} > 6000$)

Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)
Harder than any expected atmospheric background

Merges well into background at low energies

Potential cutoff at about 2-5 PeV (or softer spectrum)

Best fit spectral index: $E^{-2.3}$
Somewhat compatible with benchmark $E^{-2}$ astrophysical model or single power-law model, but looks like things are more complicated

Best fit assuming $E^{-2}$ (not a very good fit anymore):

$0.84 \pm 0.3 \times 10^{-8} \ E^{-2} \ GeV \ cm^{-2} \ s^{-1} \ sr^{-1}$

Best fit spectral index: $E^{-2.58}$
assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino
UNFOLDING TO NEUTRINO ENERGY
updated from PRL plot version with priors for backgrounds - 4

assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino
SPECTRAL FIT
Normalization vs. spectral index contour plot

Note: 3-year data re-fit since PRL with priors for backgrounds
No significant clustering observed (three years)

(all p-values are post-trial)
SKYMAP / CLUSTERING

No significant clustering observed (three years)

ICECUBE PRELIMINARY

(all p-values are post-trial)
Analyzed with a variant of the standard PS method (w/o energy) (i.e. scrambling in RA)

Most significant excess close to (but not at!) the Galactic Center

Significance: 44% (not significant)

Other searches (multi-cluster, galactic plane, time clustering, GRB correlations) not significant either
Analysis of the galactic center “excess” (only limit)

No hint of neutrino point source as of now, flux confirmation needs bigger detector (KM3NeT!)
WHERE ARE THE SOURCES?
There is still no evidence for point sources of high-energy neutrinos.

ANTARES 4-year up-going muon point source search: 2.6% chance probability

IceCube 6-year though-going muon point source search
Northern-sky muons: 35% chance probability
> PeV southern-sky muons: 87%

WHERE ARE THE SOURCES?
There is still no evidence for point sources of high-energy neutrinos.

Stefan Coenders - “Results of neutrino point source searches with 2008-2014 IceCube data above 10 TeV” - August 3, 15:00 - NU 04

IceCube 6-year though-going muon point source search
Northern-sky muons: 35% chance probability
> PeV southern-sky muons: 87%
ANTARES can observe the southern sky through the Earth → lower threshold, better limits in the south

IceCube has a larger effective area → more events, better limits in the north

**New:** combined IceCube/ANTARES search
Constraints on Point Sources

ANTARES can observe the southern sky through the Earth → lower threshold, better limits in the south

IceCube → more events, better limits in the north

New: combined IceCube/ANTARES search

Javier Barrios Martí - “Search for point-like neutrino sources over the Southern Hemisphere with the ANTARES and IceCube neutrino telescopes” - August 3, 14:00 - NU 04
What happens to the astrophysical flux below 60 TeV?

How large is the neutrino flux from atmospheric charm?

→ Need to observe lower-energy neutrinos, especially from the southern sky.
**IMPROVED VETO TECHNIQUES**

What happens to the astrophysical flux below 60 TeV?

**PRD 91, 022001**

**Outer-layer veto**

Neutrino-dominated for $E_{\text{dep}} > 60$ TeV

**Energy-dependent veto**

Neutrino-dominated for $E_{\text{dep}} > 1$ TeV

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**Thicker veto at low energies** suppresses penetrating muons without sacrificing high-energy neutrino acceptance.
10^6 > 10 \text{ TeV}, 9 > 100 \text{ TeV} (7 \text{ of those already in high-energy starting event sample})

Conventional atmospheric neutrino flux observed at expected level with starting events

Astrophysical excess continues down to 10 \text{ TeV} in the southern sky

Deviation from model at 30 \text{ TeV} (statistical fluctuation)

Model-dependent upper limit on flux from charmed meson decay: 1.4 \times \text{ERS prediction}
Other Channels

Most of the “starting” sample consists of showers, with a high acceptance in the southern sky.

Deposited (i.e. measured) energies closely related to neutrino energies.

Great for discovering a signal.

Highest energy: 2 PeV
28 High Energy Events

High-Energy Starting Event Search ("HESE")
**Other Channels**

*Two years of data*

IceCube has now seen a similar flux in the muon channel - at $3.7 \sigma$

Highest energy: $\sim 550$ TeV
(neutrino energy likely in PeV range)

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accepted by PRL, arXiv:1507.04005
first significant $\nu_\mu$-based and northern sky-dominated measurement of the astrophysical neutrino flux for $E^{-2}$ spectral assumption - (best fit is $E^{-2.2}$)

Normalization for $E^{-2}$: $0.99^{+0.4}_{-0.3} \times 10^{-8} \text{ E}^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

accepted by PRL, arXiv:1507.04005
Upgoing Muons - Spectral Components

Three years of data

New @ ICRC - now looking at up to 6 years of muon data (work in progress) - re-analyzed 3 years (presented here) and working on details of the 6 year result.
New @ ICRC - now looking at up to 6 years of muon data (work in progress) - re-analyzed 3 years (presented here) and working on details of the 6 year result

Leif Rädel - “A measurement of the diffuse astrophysical muon neutrino flux using multiple years of IceCube data” - August 4, 15:00 - **NU 05**
up-going (i.e. not a CR muon)

**deposited energy:**
2.6±0.3 PeV
(lower limit on neutrino energy)

**date:** June 11, 2014

**direction:**
11.48° dec / 110.34° RA
Upgoing Muons

an interesting event in the six-year sample!

ν

up-going (i.e. not a CR muon)

deposited energy:

2.6±0.3 PeV (lower limit on neutrino energy)

date: June 11, 2014

direction:

11.48° dec / 110.34° RA

Leif Rädel - “A measurement of the diffuse astrophysical muon neutrino flux using multiple years of IceCube data” - August 4, 15:00 - NU 05
GLOBAL FIT OF ICECUBE ANALYSES

interesting results such as flavour ratio

fit for flavour ratio, spectral shape and cutoff

\[ \nu_e : \nu_\mu : \nu_\tau \text{ at source} \]

- 0:1:0
- 1:2:0
- 1:0:0

IceCube Preliminary

GLOBAL FIT OF ICECUBE ANALYSES

fit for flavour ratio, spectral shape and cutoff

Lars Mohrmann - “Combined Analysis of the High-Energy Cosmic Neutrino Flux at the IceCube Detector” - August 4, 15:15 - NU 05

IceCube searches for extremely high-energy events from neutrinos generated by interactions of CR particles on the CMB

Just updated to 6 years of data
IceCube searches for extremely high-energy events from neutrinos generated by interactions of CR particles on the CMB

Just updated to 6 years of data

Aya Ishihara - “A search for extremely high energy neutrinos in 6 years of IceCube data” - Poster 3

DM and NU - 287
DARK MATTER

(High-Energy) Neutrino Signals from the Sun, the Galactic Center, Halo and more!
Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe

- Dwarf spheroidal galaxies
- Galactic Halo
- Galactic Center
- Clusters of Galaxies
- Local sources (Sun & Earth)

Indirect Dark Matter Searches

- MSSM - neutralino
- WIMP

WIMP

$$p^+, e^-, \gamma, \nu$$

$$p^-, e^+, \gamma, \nu$$

accumulate due to WIMP-proton elastic scattering
Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe.
Mohamed Rameez - “Search for Dark Matter annihilations in the Sun using the completed IceCube neutrino telescope” - July 30, 15:00 - NU 05
Mohamed Rameez - “Search for Dark Matter annihilations in the Sun using the completed IceCube neutrino telescope” - July 30, 15:00 - NU 05 and many more!
THE FUTURE

Extending the sensitivity to higher energies, new hemispheres
The KM3NeT Neutrino Telescope

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in “building blocks”, started construction

KM3NeT “building block”

Multi-PMT digital optical module (“DOM”)

string with OMs
31 x 3” PMTs
Hamamatsu, ETL, HZC

Light collection ring
20–40% gain in PC for free

Low power
<10 W / DOM

FPGA readout
sub-ns time stamping
time over threshold

Calibration
LED & acoustic piezo

Optical fibre data transmission
DWDM with 80 wavelengths
Gb/s readout
ARCA: “Astrophysical Research with Cosmic in the Abyss”

Study astrophysical neutrino fluxes at $E > 100 \text{ GeV}$

2 “blocks” at the Italian site (~10% being constructed right now!)

ORCA: “Oscillations Research with Cosmics in the Abyss”

Resolve the neutrino mass hierarchy ($1 \text{ GeV} < E < 100 \text{ GeV}$)

1 “block” at the French site (~5% being constructed right now!)
KM3NET: ARCA AND ORCA

**ARCA:** “Astrophysical Research with Cosmic in the Abyss”

Study astrophysical neutrino fluxes at $E > 100$ GeV

2 “blocks” at the **Italian** site (~10% being constructed right now!)

**ORCA:** “Oscillations Research with Cosmics in the Abyss”

Resolve the neutrino mass hierarchy ($1 \text{ GeV} < E < 100 \text{ GeV}$)

1 “block” at the **French** site (~5% being constructed right now!)

**Clancy James** - “Highlights from ANTARES, and prospects for KM3NeT” - August 4, 17:30 (highlight)
**ARCA:** “Astrophysical Research with Cosmic in the Abyss”

Study astrophysical neutrino fluxes at $E > 100$ GeV

2 “blocks” at the Italian site (~10% being constructed right now!)

**ORCA:** “Oscillations Research with Cosmics in the Abyss”

Resolve the neutrino mass hierarchy ($1$ GeV $< E < 100$ GeV)

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**Paolo Piatelli** - “All-flavour high-energy neutrino astronomy with KM3NeT/ARCA” - July 31, 14:18 - **NU 02**
**KM3NET: ARCA AND ORCA**

two different building blocks

**ARCA:** “Astrophysical Research with Cosmic in the Abyss”
Study astrophysical neutrino fluxes at $E > 100$ GeV
2 “blocks” at the Italian site (~10% being constructed right now!)

**ORCA:** “Oscillations Research with Cosmics in the Abyss”
Resolve the neutrino mass hierarchy ($1$ GeV < $E < 100$ GeV)
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**Jürgen Brunner** - “KM3NeT - ORCA: Measuring neutrino oscillations and the mass hierarchy in the Mediterranean” - July 31, 14:36 - NU 02
KM3NET CONSTRUCTION
strings are ready to deploy!
IceCube has provided an amazing sample of events, but is still limited by the small number of events few 10’s of astrophysical neutrinos per year

The IceCube-Gen2 High-Energy Array will instrument a significantly larger volume (~10km³)
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The IceCube-Gen2 High-Energy Array will instrument a significantly larger volume (~10km$^3$)

Erik Blaufuss - “The IceCube-Gen2 High-Energy Array” - July 31, 14:54 - NU 02
similar to the current “IceTop” surface array (or alternative technology) - CR physics and veto neutrinos from CR air showers at the ice surface

increase volume for starting tracks

R&D is underway!
similar to the current “IceTop” surface array (or alternative technology) - CR physics and veto neutrinos from CR air showers at the ice surface increase volume for starting tracks

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David Seckel - “Cosmic Ray Science Potential for an Extended Surface array at the IceCube Observatory” - August 5, 11:30 - CR 19
similar to the current “IceTop” surface array (or alternative technology) - CR physics and veto neutrinos from CR air showers at the ice surface increase volume for starting tracks

R&D is underway!

**David Seckel** - “Cosmic Ray Science Potential for an Extended Surface array at the IceCube Observatory” - August 5, 11:30 - **CR 19**

**Jan Auffenberg** - “Motivations and Techniques of a Surface Detector to Veto Air Showers for Neutrino Astronomy with IceCube at the Southern Sky” - August 1, 14:00 - **NU 03**
ICECUBE-GEN2: PINGU
measuring the mass hierarchy using atmospheric neutrinos

cover energies down to a couple of GeV

add 40 strings to IceCube/DeepCore

22m string spacing

2m DOM spacing

use the difference in MSW effect for $\nu$ and anti-$\nu$

combine with difference in $\nu$ and anti-$\nu$ cross-section
ICECUBE-GEN2: PINGU
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Cascade-Like Events

Track-Like Events

PRELIMINARY

\[(N_{IH} - N_{NH})/\sqrt{N_{IH}N_{NH}}\]

\[(N_{IH} - N_{NH})/\sqrt{N_{IH}N_{NH}}\]
very similar concepts, ORCA in water, PINGU in ice
both claim to be able to measure the mass ordering at 3sigma after ~3 years of operation
MORE HIGH-ENERGY NEUTRINOS AT ICRC
Point Sources, Neutrino Astronomy
Stefan Coenders - “Results of neutrino point source searches with 2008-2014 IceCube data above 10 TeV” - Aug 3, 15:00 - NU 04
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Luigi Antonio Fusco - “Search for an enhanced emission of neutrinos from the Southern Sky with the ANTARES telescope” - Aug 4, 14:30 - NU 05
Stefan Coenders - “Results of neutrino point source searches with 2008-2014 IceCube data above 10 TeV” - Aug 3, 15:00 - NU 04

Hans Niederhausen - “High energy astrophysical neutrino flux characteristics for neutrino-induced cascades using IC79 and IC86-string IceCube configurations” - Aug 4, 14:15 - NU 05

Luigi Antonio Fusco - “Search for an enhanced emission of neutrinos from the Southern Sky with the ANTARES telescope” - Aug 4, 14:30 - NU 05
MORE HIGH-ENERGY NEUTRINOS AT ICRC

Follow-up and multi-messenger observations
Markus Ahlers - “Multi-Messenger Aspects of Cosmic Neutrinos” - August 1, 16:30 (highlight)
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Marcos Santander - “Searching for TeV gamma-ray emission associated with IceCube high-energy neutrinos using VERITAS” - July 30, 12:00 - GA01 EGAL

Azadeh Keivani - “AMON Searches for Jointly-Emitting Neutrino + Gamma-Ray Transients” - July 30, 12:15 - GA01 EGAL
Markus Ahlers - “Multi-Messenger Aspects of Cosmic Neutrinos” - August 1, 16:30 (highlight)

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Geraldine Golup - “Correlation between the UHECRs measured by the Pierre Auger Observatory and Telescope Array and neutrino candidate events from IceCube” - Aug 3, 15:45 - NU 04
MORE HIGH-ENERGY NEUTRINOS AT ICRC
M O R E  H I G H - E N E R G Y  N E U T R I N O S  A T  I C R C

everyone I forgot or did not have the time to mention!
THANK YOU!