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Recent Results from IceCube
COSMIC RAYS AND NEUTRINOS
Search for the sources of 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
- Gamma rays can be absorbed
- Neutrinos are difficult to stop and travel in straight lines

Astrophysical beam dump
**Neutrinos Above 1 TeV**

Sketch of the different expected neutrino flux components

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**Atmospheric Neutrinos ($\pi/K$)**
- Dominant $< 100$ TeV

**Atmospheric Neutrinos (Charmed)**
- "Prompt" $\sim 100$ TeV

**Astrophysical Neutrinos**
- Maybe dominant $> 100$ TeV

**Cosmogenic Neutrinos**
- $> 10^6$ TeV
Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers).
Neutrino telescope sites

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

- ANTARES
- KM3NET
- BAikal
- GVD
- ICECube
obtained with the Baikal neutrino telescope NT200 is a 90% C.L. upper limit on the neutrino flux of all flavours. We have selected 510 and 2376 upward going muon candidates in two data samples for 1007 live days. The distributions of sorts of quality cuts, optimized for high and low WIMP masses. We have a significant excess above the expected background from atmospheric muon flux from annihilation of hypothetical weakly interacting massive particles (WIMPs) in the Sun, and a limit on the neutrino flux associated with gamma-ray bursts.

A search for extraterrestrial high-energy neutrinos on studies of bright cascades detected in the telescope NT200. A full cascade reconstruction algorithm (for vertex, direction, and reconstructed cascade energy) was applied to the 1038 live days of data taken in 1998–2002. Cuts were then placed on this correlation angles between these muons and the Sun were compared to the corresponding off-source background expectation. The muon direction is then determined by maximising a likelihood which compares the time of the hits with the expectation from the Cherenkov signal of a muon track. Details on the energy muons originating from charged current neutrino interactions inside or near the in-leaves, sea, glaciers.

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-leaves, sea, glaciers. The ANTARES telescope [3] became fully operational in 2008. The detector comprises 2475 m long and host a total of 885 optical modules.

The physics program of the Baikal experiment covers the typical spectrum of high energy neutrino telescopes. In Figure 3, we show the results for the sample of larger Going atmospheric muons which have been mis-reconstructed as upgoing and atmospheric muons (boxes); true MC energy distribution given as histogram.

Figure 1. Reconstructed cascade energy distribution for data (dots) and for MC-generated atmospheric muons (boxes); true MC energy distribution given as histogram. Figure 2. 2.2. A search for WIMP neutrinos from the Sun. Within systematic and statistical uncertainties there are no indications for excess muons were found. The 90% C.L. upper limits on the muon flux from the Sun are obtained as upper limits on the diffuse astrophysical neutrino flux, upper limits on the flux associated with gamma-ray bursts.

A possible signal from WIMP annihilation in the Sun would be an excess of upward going muons over atmospheric muon flux from annihilation of hypothetical weakly interacting massive particles (WIMPs) in the Sun, and a limit on the neutrino flux associated with gamma-ray bursts. Figure 3. Reconstructed cascade energy distribution for data (dots) and for MC-generated atmospheric muons (boxes); true MC energy distribution given as histogram.
Mediterranean Sea
Drill camp
South Pole station
Skiway
IceCube Lab (ICL)
IceCube's footprint
South Pole Glacier
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
- \(< 1^\circ \) angular resolution at high energies

**Neutral Current / Electron Neutrino**

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

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

**CC Tau Neutrino**

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

- “double-bang” \((\approx 10\text{PeV})\)
- and other signatures (simulation)
- (not observed yet: \( \tau \) decay length is \( 50 \text{ m/PeV} \))
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.
BACKGROUND: PENETRATING MUONS

100 TeV single muon

Single-muon energy distribution at 41 deg zenith

steep spectrum
ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks

IceCube

nu-dominated

v only

Air shower

North

Atmosphere (exaggerated)

Air shower

Astrophysical source

Earth stops penetrating muons
Effective volume larger than detector
Sensitive to \( v_\mu \) only
Sensitive to “half” the sky

Active veto

Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky
High-energy:
• Point-source searches looking for clustering in the sky
• Diffuse fluxes above the atmospheric neutrino background
• 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
Two very interesting events in IceCube (between May 2010 and May 2012)

2.8\sigma excess over expected background in GZK analysis (PRL 111, 021103 (2013))

There should be more

GZK analysis is only sensitive to very specific event topologies at these energies

"HISTORY"

Appearance of ~1 PeV cascades as an at-threshold background
Explicit contained search at high energies (cut: $Q_{\text{tot}}>6000$ p.e.)

**400 Mton** effective fiducial mass

Use atmospheric muon veto

Sensitive to all flavors in region above $60\text{TeV}$ deposited energy

Estimate background from data
Atmospheric neutrino self-veto

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

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


53(+1) events observed!

 Estimated background:

 \[9.0^{+8.0}_{-2.2}\ \text{atm. neutrinos}\]

 \[12.6 \pm 5.1\ \text{atm. muons}\]

 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

 presented at ICRC2015 / PoS(ICRC2015)1081
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
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):

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

Best fit spectral index: $E^{-2.58}$
assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino
SKYMAP / CLUSTERING

No significant clustering observed (four years)

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

No significant clustering observed

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

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

PoS(ICRC2015)1047


ANTARES 4-year up-going muon point source search: ~2% chance probability (post-trial)
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
LIGO just discovered gravitational waves! Did we see any neutrinos from their source? (Search in ANTARES and IceCube)

Search within a time window of +/-500s of GW150914 - 3 neutrino candidates in IceCube, none of them compatible in direction (and rather low in energy).

Consistent with background.

joint IceCube/ANTARES/LIGO publication currently at: https://dcc.ligo.org/LIGO-P1500271/public
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.
Thicker veto at low energies suppresses penetrating muons without sacrificing high-energy neutrino acceptance.
106 events > 10 TeV, 9 events > 100 TeV (7 of those in high-energy starting event sample)

Conventional atmospheric neutrino flux observed at expected level with starting events

Astrophysical excess continues down to 10 TeV in the southern sky

Deviation from model at 30 TeV (statistical fluctuation)

Model-dependent upper limit on flux from charmed meson decay: $1.4 \times$ ERS prediction
Highest energy: 2 PeV
28 High Energy Events

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
IceCube has now seen a similar flux in the muon channel ($3.7\sigma$ in 2 years)

Highest energy: ~550 TeV
(neutrino energy likely in PeV range)
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 $E^{-2}$: $0.99^{+0.4}_{-0.3} \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

PRL 115, 081102 (2015)
Now looking at up to 6 years of muon data (2009-2015) - good data/MC agreement
Preliminary fit: $\Phi(E_\nu) = 0.82^{+0.30}_{-0.26} \times 10^{-18} \text{GeV}^{-1}\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1} (E_\nu/100\text{TeV})^{-(2.08\pm0.13)}$

prompt fits to 0, upper limit details under study
90% C.L. contours of various IceCube analyses - all single unbroken power-law fits

some tension between **6-year track** sample and **global fit** of previous results

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**6-year tracks**
(previous slides, $\nu_\mu$, Northern Sky)

PRD 91, 022001 (2015)
(all-flavor)

PoS(ICRC2015)1081
(all-flavor, previous slides)

PoS(ICRC2015)1066
(combined fit, all-flavor)

PoS(ICRC2015)1109
(cascades)

PRL 115, 081102 (2015)
($\nu_\mu$, Northern Sky)
starting events (unfolding)
(dominated by showers)

6 year up-going $\nu_\mu$ analysis

- threshold order of 60 TeV
- softer index driven by lower energy bins
- threshold of about 200 TeV
- compatible at higher energies
Up-going Muons
an interesting event in the six-year sample!

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
For standard oscillations, only a small region of flavor ratios is allowed at Earth.
fit for flavor ratio, spectral shape and cutoff

- **muon-damped (0:1:0)**
- **pion decay (1:2:0)** → compatible
- **neutron decay (1:0:0)** → excluded at 3.7σ

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should be able to identify a “double-bang” signature above ~PeV - not observed yet!

at lower energies identification is more challenging - IceCube just set new limits!

lower energy tau study
PRD 93, 022001 (2016)
we try to alert other experiments as soon as we see an interesting event.

Alerts/Follow-ups

PTF (optical)

Swift (X-Ray)

“The North”

Iridium

Veritas/
H.E.S.S./
MAGIC/…

SN/GRB/…

IceCube

working on extending this effort significantly!
IceCube searches for extremely high-energy events from neutrinos generated by interactions of CR particles on the CMB

Updated to 6 years of data

PoS(ICRC2015)1064
THANK YOU!