Neutrino point-source searches for multi-messenger astronomy with IceCube

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Contents

- Neutrinos as messengers
- The IceCube neutrino telescope
- The discovery of cosmic neutrinos
- Where do they come from?
PeV photons interact with microwave photons (411/cm$^3$) before reaching Earth.
Neutrinos: a probe of the universe

- Electrically neutral
- Track nuclear processes
- Reveal the sources of CRs

... but difficult to detect:
how large a detector?
The generic messenger Source: the Cosmic Beam Dump

Accelerator is powered by large gravitational energy (e.g. black hole, neutron star)

**Hadronuclear** (e.g. star burst galaxies and galaxy clusters)

\[
\begin{align*}
pp &\rightarrow \pi^0 \rightarrow \gamma \gamma \\
\pi^+ &\rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\
\pi^- &\rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu
\end{align*}
\]

**Photohadronic** (e.g. gamma-ray bursts, active galactic nuclei)

\[
\begin{align*}
p\gamma &\rightarrow \Delta^+ \rightarrow p \pi^0 \rightarrow p \gamma \gamma \\
n\pi^+ &\rightarrow n \mu^+ \nu_\mu \\
n &\rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu
\end{align*}
\]
IceCube neutrino Observatory

1 km³ = Gigaton instrumented ice

Digital Optical Module (DOM)
- 86 strings
- 5160 optical sensors

1450 m
2450 m
2820 m
50 m

Began full operation May 2011
Principle of detection

• A muon neutrino produces a muon
• Lattice of photomultipliers to detect cone of Cherenkov light
Track-like event (28 Oct 2010)

Muon energy: ~604 TeV
Neutrino energy: ~880 TeV
Radius ~ number of photons
Time: red $\rightarrow$ purple
Event topologies

- $\nu_\mu$ charged-current (CC) interactions
- Atmospheric $\mu$
- $\nu_\tau$ CC interactions with muonic tau decay
- Good angular resolution: $< 0.3^\circ$ ($>100$ TeV)
- Energy resolution: x2

- All neutral-current (NC) interactions
- $\nu_e$, $\nu_\tau$ CC interactions
- Angular resolution: $\sim 10^\circ$ ($>100$ TeV)
- Good energy resolution: $\sim 15$

- Very high-energy ($>2$ PeV)
  - $\nu_\tau$ CC interactions with hadronic/electronic tau decay
  - $\sim 2$ expected in 6 years
Signal and background

• 2 kinds of backgrounds:
  • Atmospheric $\mu$
  • Atmospheric $\nu$

• 3 components in neutrino flux:
  • Conventional atmospheric $\nu$ from K/\(\pi\) decays in air-showers
  • Prompt atmospheric $\nu$ from decays of charmed hadrons in air-showers
  • Astrophysical $\nu$, power-law energy spectrum

• Muons detected per year:
  • Atmospheric $\mu$ $\sim 10^{11}$ (3000 per second)
  • Atmospheric $\nu$ $\rightarrow$ $\mu$ $\sim 10^5$ (1 every 6 minutes)
  • Cosmic $\nu$ $\rightarrow$ $\mu$ $\sim 1$-10 (> 50 TeV)
Cosmic neutrino fluxes

\[ \frac{dN}{dE} \sim E^{-2} \]

1-10 events/year > 50 TeV for a fully efficient km\(^3\) detector
The discovery of cosmic neutrinos

- 2-year dataset (May 2010 to May 2012)
- 28 neutrino events detected
- Expected atmospheric background: $10.6^{+5.0}_{-3.6}$
- $30 < E < 1200$ TeV

Latest results (ICRC19)
Astrophysical neutrinos, 9 years of data

IceCube Preliminary

- Astrophysical \((1.44 \times (E/E_0)^{-2.28})\)
- Conventional Atm.
- Prompt Atm.
- Sum
- Exp. Data

\(E^{-2.28}\) best-fit spectral slope

- Independent analysis using thorough-going muon events from the Northern Hemisphere

Excess of a high-energy component clearly visible
Single power law astrophysical neutrino spectra

- Single power law may not be possible, e.g. contribution of sources of different nature to fluxes?
Lessons so far

• Diffuse flux of neutrinos of astrophysical origin
• A Galactic component cannot be excluded
  • But galactic neutrino searches for emission from the Galactic plane revealed no significant correlations so far
• Where do they come from?
• Where are the gammas counterpart of PeV neutrinos from same sources?
  → multi-messenger searches
Lessons so far

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→ multi-messenger searches
IceCube Realtime Public Alerts

- Operating since 2016
- ~ 8 public track alerts per year with \(E > 10^{14}\) eV
- ~ 3 have probability of being of cosmic origin > 50% (depends on assumed cosmic spectrum)
- Alerts transmitted via satellite to GCN (Gamma-ray Coordination Network) in < 1 min
2017 September 22: Alert event IceCube-170922A

- 23.7 ± 2.8 TeV muon energy loss in the detector
  → most probable neutrino energy ~ 290 TeV
    (upper limit at 90% CL is 4.5 (7.5) PeV for a spectral index of -2.13 (-2))
- Signalness: 56.5 %

RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon...
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28 Sept 2017, Fermi-LAT gamma-ray observations

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4 Oct 2017, MAGIC VHE gamma-ray observations

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First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

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21
Looking at neutrinos from TXS 0506+056 back in time

- Analysis of 9.5 yr in 6 independent periods
- 150 day flare in Dec 2014 of 19 events
- Inconsistent with background at 3.5σ
- Spectrum $E^{-2.1}$

Science 361 (2018) no.6398, 147-151
... so where do they come from?

All sky combined 10 year search

- 1.1M neutrino events
- ~1-10 cosmic neutrino/year expected above 50 TeV

Using high energy through-going tracks and tracks optimized for point source searches

Hottest spot in Northern Hemisphere coincides with 2.9sigma excess at the position of NGC 1068 → evidence of non-uniform map

arXiv:1908.05993v1
... so where do they come from?

All sky combined 10 year search

Source list of 110 Galactic and Extragalactic objects

1. NGC 1068
2. TXS 0506 + 056
3. PKS 1424 + 240
4. GB6 J1542+6129

Source list search is incompatible with background at 3.3σ (2.25σ without TXS 0506)

arXiv:1908.05993v1
• Are blazars the sources of the diffuse neutrinos and CRs?
• Or galaxy mergers?
• Starburst galaxies?
• Gamma ray bursts?
• Neutron stars?
Many other point-source searches

- Combined ANTARES, IceCube, Auger and Telescope Array search for common origin of ultra-high energy CRs and high-energy neutrinos
- IceCube follow up on internal and external triggers
- IceCube follow up of Gravitational Wave events
- Searches for time-dependent neutrino emissions from blazars

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ICRC 2019
Neutrinos and CRs

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- Track nuclear processes
- Reveal the sources of CRs
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Method: stacked unbinned likelihood:

\[
\ln \mathcal{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \ln \left( \frac{n_s}{N_{\text{CR}}^i S^i_{\text{Auger}}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}^i B^i_{\text{Auger}}} \right) + \sum_{i=1}^{N_{\text{TA}}} \ln \left( \frac{n_s}{N_{\text{CR}}^i S^i_{\text{TA}}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}^i B^i_{\text{TA}}} \right).
\]

\(n_s\) = number of UHECR signal event (free parameter)
\(N_{\text{CR}}\) = total number of CR events
\(S^i_{\text{CR experiment}}\) = signal PDF
\(B^i_{\text{CR experiment}}\) = background PDF

Gal. magnetic deflection

<table>
<thead>
<tr>
<th>Gal. magnetic deflection</th>
<th>(2.4°, 3.7°)</th>
<th>(4.8°, 7.4°)</th>
<th>(7.2°, 11.1°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-values (tracks)</td>
<td>underfluctuation</td>
<td>underfluctuation</td>
<td>underfluctuation</td>
</tr>
<tr>
<td>p-values (cascades)</td>
<td>underfluctuation</td>
<td>0.41</td>
<td>0.29</td>
</tr>
</tbody>
</table>

0.90 post-trial
Many other point-source searches

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- Joint Southern sky search with ANTARES
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![Neutrino cascades and UHECR arrival directions](image)
Many other point-source searches

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- …
Search for IceCube events in the direction of ANITA neutrino candidates

- ANITA detected 2 events consistent (with caveats) with upgoing astrophysical $\nu_\tau$ and 1 neutrino candidate from Askaryan emission searches
- Are the events originating from astrophysical point sources?
- Search for lower energy neutrino counterparts in IceCube: search for spatial and temporal clustering in IceCube data

Results consistent with background

A. Barbano, T. Montaruli

arXiv:1908.08060v1
Outlook: IceCube upgrade

- 7 new strings in the DeepCore region (~20m inner-string spacing)
- Planned to deploy in 2022-2023
- New multi-PMT sensors
- New calibration devices
- Precision measurement of atmospheric neutrino oscillation

June 2019: NSF gave 20M for IceCube upgrade

The upgrade will have world-leading sensitivity to tau neutrino appearance
The future: IceCube-Gen2

- Multi-component facility (low- and high-energy and multi-messenger)
- In-ice high-energy Cherenkov array with 6-10 km$^3$ volume
- Will be sensitive to 5x fainter sources
- Wide-band neutrino observatory with optical and radio detectors, surface array
• Origin of cosmic neutrinos still unknown
• Stay tuned for more neutrinos and future upgrades!
Backup
High-Energy Starting Events (HESE)

- No light in the veto region
- Active veto for atmospheric $\mu$ entering from outside the detector
- Indirect veto for atmospheric $\nu$ that are typically accompanied by muons
- All sky, all flavors
- Selection on $Q_{\text{tot}} > 6000$ p.e.
- Sensitive above 60 TeV
Flavor composition

“Double-double”
Observed 2014

- First best-fit non zero in each flavor component!
- First probe of neutrino oscillations over cosmological baselines and at TeV energies
- Consistent with previous measurement and expectation of 1:1:1 for astrophysical neutrinos

Best-fit $\nu_e:\nu_\mu:\nu_\tau = 0.29:0.50:0.21$

![Diagram showing flavor composition and best-fit ratios.](image)

WORK IN PROGRESS
... so where do they come from?

All sky combined 10 year search: source population results

Search for excess of hotspots → A significant p-value demonstrates inconsistency with background-only for entire catalog.

- Probability of k or more sources passing a threshold out of a catalog of N
- 4σ pre-trial where k = 4 in Northern Catalog → 3.3 σ post-trial (2.25 σ w/o TXS 0506+056) to account for N other possible excesses
- Includes NGC 1068, TXS 0506+056, PKS 1424+240, GB6 J1542+6129
Is there a Galactic component?

- Stacked search for IceCube neutrino emission from HAWC TeV gamma-ray sources in 2HWC catalog
- Template analysis for neutrino emission from Galactic plane including morphology of gamma-ray emission
- More significant result for J1857+027 (p-value 0.02 before trial correction)