Astrophysical neutrino searches with IceCube

Stéphanie Bron, Teresa Montaruli

Joint Annual Meeting of SPS and APS
August 24, 2017
Cosmic ray spectrum

How to find cosmic ray sources?

- Cosmic rays (= nuclei) are deflected by magnetic fields
- Gamma rays are absorbed
- Neutrinos travel undeflected, only candidate to point back at sources
IceCube experiment

- Completed in 2010
- 1 km$^3$ volume
- 86 strings
- 125 m string spacing
- 5160 PMTs
- 17 m vertical spacing
Neutrino events in the detector

Tracks
- angular resolution $\sim 1^\circ$
- poor energy resolution

Cascades
- angular resolution $\sim 10^\circ$
- good energy resolution
Background and signal in IceCube

- $E_\nu > 10$ GeV
- $\mu$ rate: 2.5 kHz - $\nu$ rate $\sim$ mHz
- $\sim$ 100’000 high energy $\nu$/year
The IceCube neutrino flux

Conventional atmospheric neutrinos from $\pi/K$, dominant $< 100$ TeV

Prompt atmospheric neutrinos from charm

Astrophysical neutrinos dominant $> 100$ TeV

Astrophysical flux: unbroken powerlaw with $\phi_0$, $\gamma_{astro}$

$$\frac{d\phi}{dE} = \phi_0 \cdot \left( \frac{E}{100\text{TeV}} \right)^{-\gamma_{astro}}$$

* $\phi_0$, $\gamma_{astro}$ = free parameters that are fit in analyses

Isolating astrophysical signal

- event starts inside detector → reduces muon background
- energy threshold \( \sim 60 \) TeV → increases purity
- this selection is called High Energy Starting Events (HESE)

https://arxiv.org/abs/1311.5238
Latest results of HESE

HESE - 6 years

80 events observed

15.6$^{+11.4}_{-3.9}$ atmospheric neutrinos

25.2 ± 7.3 atmospheric muons

Result of the fit:

- $\phi_0 = 2.46 \pm 0.8 \ [10^{-8} \ \text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$
- $\gamma_{\text{astro}} = 2.92^{+0.33}_{-0.29}$

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There is an astrophysical flux...

So what produces it??

Seyfert galaxy: NGC 1097

Active galactic nuclei: Centaurus A

Quasar
Search for point sources

Time integrated

- **Hypothesis**: neutrino source = clustering of events in the sky
- **HESE**: strict constraint on energy $\rightarrow$ few events
- Use bigger sample starting from $E_\nu > 1$ TeV
- need the best pointing: tracks

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**Unbinned likelihood method: Point source searches**

- data = mixture of signal and background:
  \[
  \mathcal{L}(\vec{r}_{\text{src}}, n_s, \gamma) = \sum_{N} \left( \frac{n_s}{N} S_i + \frac{1-n_s}{N} B_i \right), \quad n_s = \text{number of signal event}
  \]
Search for point sources

Time integrated

Signal PDF: time integrated

\[ S_i = P_i^{\text{sig}}(\sigma_i, \vec{r}_i|\vec{r}_{\text{src}}) \cdot \epsilon_i^{\text{sig}}(E_i, \delta_i|\gamma) \]

- 2 free params: \( n_s, \gamma \)

Hemisphere

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_s )</td>
<td>27.22</td>
<td>15.54</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>1.95</td>
<td>2.84</td>
</tr>
<tr>
<td>p-value</td>
<td>44%</td>
<td>39%</td>
</tr>
</tbody>
</table>

→ no significant spatial clustering found!
Search for point sources
Time dependent - Gaussian flare

Hypothesis: time clustering of events at time $T_0$ around a Gaussian with width $\sigma_T$

Add time PDF, $T_i^{\text{sig}}$

Signal PDF: time dependent

$$S_i = P_i^{\text{sig}}(\sigma_i, \bar{r}_i | \bar{r}_{src}) \cdot \epsilon_i^{\text{sig}}(E_i, \delta_i | \gamma) \cdot T_i^{\text{sig}}$$

4 free params: $n_s, \gamma, T_0, \sigma_T$

Best Gaussian fit - North Hemisphere

- p-value: 16%

Best Gaussian fit - South Hemisphere

- p-value: 23%

→ no significant time clustering found!
Search for point sources

Time dependent - Gamma-ray flare

- Hypothesis: time clustering of events in coincidence with gamma-ray flare of selected transient sources from Fermi-LAT
- $E_\gamma$ range: $\sim 100$ MeV-300 GeV
- Add time PDF, $T_{\text{sig}}$

Signal PDF: time dependent

- $S_i = P_{\text{sig}}^i (\sigma_i, \vec{r}_i | \vec{r}_{\text{src}}) \cdot \epsilon_{\text{sig}}^i (E_i, \delta_i | \gamma) \cdot T_{\text{sig}}^i$
- 4 free params: $n_s, \gamma, \text{threshold, lag}$

→ no significant correlation found!

→ p-value: 30.18%

May 2009-May 2015

Most significant source: blazar PKS 0507+17

May-July 2015

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Search for point sources

Time dependent - Gamma-ray flare

- **Hypothesis**: time clustering of events in coincidence with gamma-ray flare of selected transient sources from Fermi-LAT
- \( E_\gamma \) range: \( \sim 100 \text{ MeV-}300 \text{ GeV} \)
- Add time PDF, \( T_{\text{sig}} \)

**Signal PDF: time dependent**

- \( S_i = P_{\text{sig}}^i (\sigma_i, \vec{r}_i|\vec{r}_{\text{src}}) \cdot \epsilon_{\text{sig}}^i (E_i, \delta_i|\gamma) \cdot T_{\text{sig}}^i \)

\( \rightarrow \) no significant correlation found!

- Same analysis on shorter time scale: 1 month
- Automatic analysis from source selection to results on webpage
- Ongoing analysis: no results yet

May 2009-May 2015
Most significant source: blazar PKS 0507+17

May-July 2015
\( \rightarrow \) p-value: 30.18%
Search for point sources
Correlation with ultrahigh-energy cosmic rays

- Unbinned likelihood analysis
- Test correlation between neutrinos and ultrahigh-energy cosmic rays

<table>
<thead>
<tr>
<th>Data sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>cosmic rays</td>
</tr>
<tr>
<td>neutrinos</td>
</tr>
</tbody>
</table>

Tested deflection hypotheses: $\theta = [3^\circ, 6^\circ, 9^\circ] \cdot 100$ EeV/$E_{CR}$

$\rightarrow$ most significant result
Search for point sources
Correlation with ultrahigh-energy cosmic rays

previous analysis: $\sim 3\sigma$

This analysis = addition of 2 years of IceCube data: $\sim 2\sigma$

→ no significant correlation found!
Summary and outlook

- Diffuse *astrophysical flux* detected with more than $5\sigma$ significance
Summary and outlook

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- Sources of astrophysical neutrinos still unknown
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- Searches for sources
  - scanning the whole sky
  - correlations in space and time with gamma rays
  - correlations in space with cosmic rays
Summary and outlook

- Diffuse astrophysical flux detected with more than $5\sigma$ significance
- Sources of astrophysical neutrinos still unknown
- Searches for sources
  - scanning the whole sky
  - correlations in space and time with gamma rays
  - correlations in space with cosmic rays
- Searches for sources targeting shorter time scales:
  - monthly correlation with gamma-rays
  - real time alerts send IceCube events details to a global telescope network for follow-up
Thank you!
Additional slides
Tracks - 8 years

Astrophysical neutrino searches with IceCube

Conv. atmospheric $\nu_\mu + \bar{\nu}_\mu$ (best-fit)
Prompt atmospheric $\nu_\mu + \bar{\nu}_\mu$ (flux limit (2016))
Astrophysical $\nu_\mu + \bar{\nu}_\mu$ (best-fit)

HESE unfolding: PoS(ICRC2017)981

IceCube Preliminary
Cascades - 4 years

Northern sky

Southern sky

IceCube preliminary

- astro. ν
- mc sum
- atm. μ
- prompt ν
- conv. ν
- data

NEvents [livetime⁻¹]

E_reco [GeV]
Fit comparison: spectral index $\gamma_{\text{astro}}$

**Warning:** Plot made with older data than just presented!

90% confidence level regions for the value of $\gamma_{\text{astro}}$

$\rightarrow$ tension : broken power law??
Results of the fit

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\phi_0$ [$10^{-8}$ GeV cm$^{-2}$s$^{-1}$sr$^{-1}$]</th>
<th>$\gamma_{astro}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HESE-6yrs</td>
<td>2.46 ± 0.8</td>
<td>2.92$^{+0.33}_{-0.29}$</td>
</tr>
<tr>
<td>Tracks-8yrs</td>
<td>1.01$^{+0.25}_{-0.23}$</td>
<td>2.19±0.10</td>
</tr>
<tr>
<td>Cascades-4yrs</td>
<td>1.57$^{+0.23}_{-0.22}$</td>
<td>2.48±0.08</td>
</tr>
</tbody>
</table>
Correlation with galactic plane

How much from the diffuse neutrino flux we observe comes from interaction of cosmic rays with the **interstellar gas of our Galaxy**?

Analysis method:

- take models of gamma-ray emission: KRA-$\gamma$ (50 PeV cutoff) model
- search for anisotropy corresponding to model in neutrino arrival directions

Maximum of **14%** of the diffuse flux comes from Galactic plane.
Looking for sources with HESE

- events directions from HESE sample put on a skymap
- neutrino source = clustering of events in the sky
- maximum-likelihood method with two free parameters: number of source events, spectral index

→ constraint on energy is very strict: too few events
Real time alerts

- **HESE/EHE**: Single event over a certain energy threshold reconstructed to high level and details sent to Astrophysics Multimessenger Observatory Network
- **Optical follow up**: Accumulation of events coming from a single point in the sky within 100s targeting SN or GRB. Information sent to PTF, SWIFT and XRT
- **Gamma follow up**: Accumulation of events coming from a single point in the sky up to 3 weeks from a selection of known AGNs. Information sent to Magic and Veritas.
IceCube-Gen2

→ statistically significant samples in the PeV to EeV range
Systematic uncertainties

- neutrino detection uncertainties
  - optical efficiency of the detector
  - neutrino-nucleon cross section
  - muon energy loss cross section
  - optical properties of Antarctic ice
- atmospheric flux uncertainties
  - flux normalizations
  - spectral shape
  - composition of cosmic-ray spectrum in the knee region
  - spectral index of primary cosmic-ray spectrum
  - relative production of pions and kaons in the atmosphere
Muon energy losses

- Muon energy inferred from muon energy losses along its track inside detector
- Below 1 TeV: ionization dominating, cst, Cherenkov light produced $\approx$ independent of energy
- Above 1 TeV: stochastic interactions, most of Cherenkov light produced from secondary particles along the muon's path

Average energy loss of muon

$$\frac{dE_\mu}{dx} = A + BE_\mu$$

$A = 0.0024\text{GeV (g/cm}^2\text{)$^{-1}$}, B = 0.000032\text{GeV (g/cm}^2\text{)$^{-1}$}$

Compared to expected number of photoelectrons for a fixed energy loss of 1 GeV/m

At TeV energies, muons travel several kilometers in the ice.
Glashow resonance

→ Glashow resonance events contribute to high energy $\nu_\mu$ events

http://arxiv.org/abs/1407.3255