Abstract

High energy neutrinos have been detected by IceCube, but their origin remains a mystery. Determining the sources of this flux is a crucial first step towards multi-messenger studies. In this work we systematically compare two classes of sources with the data: galactic and extragalactic. We build a likelihood function on an event by event basis including energy, event topology, absorption, and direction information. We present the probability that each high energy event with deposited energy $E_{\text{dep}} > 60$ TeV in the HESE sample is galactic, extragalactic, or background. The galactic fraction of the astrophysical flux has a best fit value of 1.3\% and is $< 9.5\%$ at 90\% CL.
The Galactic Contribution to IceCube’s Astrophysical Neutrino Flux

Peter B. Denton

TeVPA 2017

August 10, 2017

1703.09721 JCAP (as of Tuesday)
with Tom Weiler and Danny Marfatia
IceCube Detects Astrophysical Neutrinos

IC’s 6 yr HESE: ICRC 2017

Energy Threshold

Events per 2078 Days

Deposited EM-Equivalent Energy in Detector (TeV)

IceCube Preliminary
IceCube Detects Astrophysical Neutrinos

50 events with $E_{\text{dep}} > 60$ TeV from IC 6 year HESE
IceCube Detects Astrophysical Neutrinos

50 events with $E_{\text{dep}} > 60$ TeV from IC 6 year HESE
High energy neutrinos are absorbed by the Earth

\[
dP \over d\cos \theta_z
\]

- 1 TeV
- 10 TeV
- 100 TeV
- 1 PeV
- 10 PeV

Importance and Characterization of PeV-scale Neutrinos

Neutrino Oscillations

Neutrino Masses

Structure of the Earth's Interior

Neutrino Physics at High Energies

Neutrino Observation and Implications

Neutrino Physics and Cosmology

Neutrino Physics and Astrophysics

Neutrino Physics and Particle Physics

Neutrino Physics and Other Sciences

Neutrino Physics and the Universe

Neutrino Physics and Society

Neutrino Physics and the Future
IceCube Detects Astrophysical Neutrinos

The 18 new events from the two latest years
Event 14
$E = 1 \text{ PeV}$
$1.2^\circ$ from the GC
$\alpha_{50\%} = 13.2^\circ$
Significance of the Galaxy as the Source

Galactic Plane with $|b| < \theta_{\text{max}}$

$p_{\text{post}} = 0.028$ at $\theta_{\text{max}} = 7.5^\circ$

$\theta_{\text{max}}[\circ]$
Galactic or Extragalactic?

Various methods to search for anisotropies:

- Windowed search around the Galactic center/plane.
  
  IC: \(1311.5238, 1405.5303\)
  
  Ahlers, Murase: \(1309.4077\)
  
  Anchordoqui, et. al.: \(1410.0348\)
  
  Palladino, Vissani: \(1601.06678\)

- Known Galactic sources:
  
  CRs, \(\gamma\)-ray correlations, GC, misc. Galactic catalogs, . . .
  
  IC: \(1406.6757 + 1707.03416\)
  
  Ahlers, et. al.: \(1505.03156\)
  
  Troitsky: \(1511.01708\)
  
  Celli, Palladino, Vissani: \(1604.08791\)

- Known extragalactic sources: AGNs, blazars, SFGs, GRBs, . . .
  
  Bechtol, et. al.: \(1511.00688\)
  
  Murase: \(1511.01590\)
  
  Padovani, et. al.: \(1601.06550\)
A More General Approach

- Treat the extragalactic flux as isotropic, $\Phi_{\text{exgal}}(\Omega) = \frac{1}{4\pi}$.

- Scale the galactic flux with the matter distribution $\rho_{\text{gal}}$,

$$\Phi_{\text{gal}}(\Omega) = \frac{\int ds \rho_{\text{gal}}(s, \Omega)}{\int dsd\Omega' \rho_{\text{gal}}(s, \Omega')}.$$  

- Cross checked results with SNR and PWN distributions.

  - Case, Bhattacharya: astro-ph/9807162

- $f_{\text{gal}}$ is the fraction of the astrophysical flux from the Galaxy,

$$\Phi_{\text{astro}}(\Omega, f_{\text{gal}}) = f_{\text{gal}} \Phi_{\text{gal}}(\Omega) + (1 - f_{\text{gal}}) \Phi_{\text{exgal}}(\Omega).$$
Expected Distribution From the Galaxy
Galactic or Extragalactic?

Given that an event is astrophysical, the conditional likelihoods are,

\[ \mathcal{L}_{\text{gal}|\text{astro},i}(f_{\text{gal}}) = f_{\text{gal}} \int d\Omega \Phi_{\text{gal}}(\Omega)f_{\text{vMF}}(\theta, \kappa_i), \]

← IC’s psf

\[ \mathcal{L}_{\text{exgal}|\text{astro},i}(f_{\text{gal}}) = (1 - f_{\text{gal}})\frac{1}{4\pi}. \]

The likelihood that event \( i \) is described by this model is,

\[ \mathcal{L}_{i}(f_{\text{gal}}) = \mathcal{L}_{\text{bkg},i}\frac{1}{4\pi} + \mathcal{L}_{\text{astro},i} \left[ \mathcal{L}_{\text{gal}|\text{astro},i}(f_{\text{gal}}) + \mathcal{L}_{\text{exgal}|\text{astro},i}(f_{\text{gal}}) \right], \]

and the total likelihood is the product,

\[ \mathcal{L}(f_{\text{gal}}) = \prod_i \mathcal{L}_{i}(f_{\text{gal}}). \]

► For \( E_{\text{dep}} > 60 \) TeV, we expect < 6 events from backgrounds.

IC: 1405.5303

► Results independent of spectral fit, use data directly.
Galactic contribution to the flux

\[ \phi \cdot E^{-2} \left[ \text{GeV s}^{-1} \text{cm}^{-2} \right] \]

\[ \log(E_{\nu} / \text{GeV}) \]


Julia Tjus’s Monday plenary.
Results

Updated with 6 years of HESE data.

$\hat{f}_{gal} = 0.044 \rightarrow 0.013$

$f_{gal} = 0$ consistent at $< 1\sigma$

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<td>$3\sigma$</td>
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Likelihoods to Probabilities

\[ p_{\text{gal},i} = \frac{\mathcal{L}_{\text{gal}|\text{astro},i}(\hat{f}_{\text{gal}})\mathcal{L}_{\text{astro},i}}{\mathcal{L}_i(\hat{f}_{\text{gal}})} , \]

\[ p_{\text{exgal},i} = \frac{\mathcal{L}_{\text{exgal}|\text{astro},i}(\hat{f}_{\text{gal}})\mathcal{L}_{\text{astro},i}}{\mathcal{L}_i(\hat{f}_{\text{gal}})} , \]

\[ p_{\text{bkg},i} = \frac{1}{4\pi} \frac{\mathcal{L}_{\text{bkg},i}}{\mathcal{L}_i(\hat{f}_{\text{gal}})} . \]

\[ \sum_i p_{\text{gal},i} = 0.6 , \quad \sum_i p_{\text{exgal},i} = 45.3 , \quad \sum_i p_{\text{bkg},i} = 4.1 . \]
## 50 Event-By-Event Probabilities at $\hat{f}_{gal} = 0.013$

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Conclusions

- IceCube has measured the astrophysical neutrino flux.
- 50 events with $E_{\text{dep}} > 60$ TeV in the clean HESE data set.
- The astrophysical neutrino flux is largely extragalactic.
  - A subleading galactic component $< 10\%$ (90\% CL) is allowed.
  - Consistent with models: galactic component $< 10\%$.

Julia Tjus’s plenary on Monday.
Marek Kowalski’s plenary on Tuesday.
Mike Richman’s parallel on Tuesday.

- Independent of details of galactic distribution and spectrum shape.
Backups
Muon energy correction

The energy deposited in tracks is not the true neutrino energy because the muon carries some of the energy out of the detector.

- Muon energy loss rate: $\frac{dE_\mu}{d\ell} = -(a + bE_\mu)$.
- Inelasticity parameter $y \equiv E_{\text{had}}/E_\nu$.
- For a finite sized detector $\ell_{\text{max}} = 1$ km, we can relate the deposited and neutrino energies by,

$$\frac{E_{\text{dep}}}{E_\nu} \approx \langle y \rangle + (1 - \langle y \rangle) b\ell_{\text{max}},$$

which is valid in the region of interest.

Anchordoqui, Weiler, et. al. 1611.07905

- $\langle y \rangle \in [0.25, 0.55]$ for relevant energies.

Gandhi, Quigg, Reno, Sarcevic, hep-ph/9512364
HESE vs. Track ⇒ Galactic Center vs. Galactic Plane

IceCube finds better sensitivity with cascades than with tracks:
$2.5 \times 10^{-11}$ vs. $3 \times 10^{-11}$ TeV cm$^{-2}$ s$^{-1}$ (IC preliminary)

as viewed with **throughgoing tracks**

as viewed with **cascades**

Mike Richman’s Tuesday parallel