Searching for Counterparts to Cosmic Neutrinos Using the Fermi LAT Satellite

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11 August 2017
TeVPA 2017
Multimessenger event: an astrophysical event seen with two or more of the four messengers (photons, neutrinos, cosmic rays, gravitational waves)

No known sources of high-energy astrophysical neutrinos

Many models predict correlated neutrino and gamma ray production

Time sensitive coincident analysis can identify or limit neutrino/gamma coincidences
- FOV: 2.4 steradians (20% of full sky)
- Surveys whole sky every 3 hours
- Energy range of 100 MeV to 300 GeV
- Data concurrent with IceCube 40-string (IC40) and 59-string (IC59)
- Chance to see coincident neutrinos and gamma rays
Coincidence requirements:
Temporal: $\Delta t = \pm 100$ s
Spatial: $\Delta \theta < 5^\circ$

IC40 run:
April 2008 to May 2009
Fermi begins operation in July 2008
$1.3 \times 10^4$ neutrinos
$1.6 \times 10^7$ photons

IC59 run:
May 2009 to May 2010
$1.1 \times 10^5$ neutrinos
$1.8 \times 10^7$ photons

Sky map of fermi events concurrent with IC59 (top) and the IC59 neutrinos (bottom).
● Arrival direction of particles is uncertain, given by Point Spread Function (PSF)
● Localize coincidence by max overlap of PSFs
● Rank coincidence by log likelihood statistic:
\[ \lambda = 2 \ln \left( \frac{P_{y1}P_{y2}...P_{yn}}{n!(P_v)} \right) \frac{n!}{B(\hat{x})^n} \]
● Higher Lambda - more significant coincidence

Top: a four particle multiplet with one neutrino (red) and three photons (blue)
Bottom: overlap of the four PSFs
Scrambled Results

- Results of 10000 background scrambles:
  - IC40:
    - BG - 1089.7±30 events
    - Data - 1128 events
  - IC59:
    - BG - 11056±98 events
    - Data - 11143 events
- Two ways to identify a cosmic signal:
  - Look for excess high lambda events
  - Inject signal events

Cumulative histograms of lambda values for IC40 (top) and IC59 (bottom). Null distributions are in blue, signal in red.
- Distribution of lambda gives us threshold limits
- 1 event per 10 scrambles:
  - IC40: $\lambda > 64$
  - IC59: $\lambda > 160$
- 1 event per 100 scrambles:
  - IC40: $\lambda > 100$
  - IC59: $\lambda > 210$
- IC40 results:
  - $\lambda_{\text{max}} = 98.3$
- IC59 results:
  - $\lambda_{\text{max}} = 118.5$

254 photons arising from GRB 090902426, in coincidence with a scrambled IceCube neutrino. $\lambda = 3907.7$
- Create signal events by:
  1. Center photon and neutrino PSFs, and place all particles weighted by their psfs
  2. Put coincidence at random sky location
  3. Calculate lambda value
- Inject signal events into the null distribution
- Use Anderson-Darling k-sample test to test for statistical excess of signal events

Anderson Darling (AD) k-sample test statistic vs number of injected signal events for IC40 (red) and IC59 (blue).

<table>
<thead>
<tr>
<th></th>
<th>1% P-value</th>
<th>0.1% P-value</th>
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<tbody>
<tr>
<td>IC40</td>
<td>240 events</td>
<td>320 events</td>
</tr>
<tr>
<td>IC59</td>
<td>980 events</td>
<td>1280 events</td>
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Results of the Anderson-Darling test shown with the residuals of different signal injections. IC40 has a p-value of 63%. IC59 has a p-value of 8%.
- IceCube background different in north/south hemispheres
- Statistical excess only persists in northern hemisphere
- Possible causes of low-\(\lambda\) excess:
  - Correlation between neutrino and photon positions
  - Signal with a soft power law
  - Systematic error in IceCube PSF

Residuals shown with 1% and 0.1% signal injections for both the Northern hemisphere (top, p-value of 6%) and the Southern hemisphere (bottom, p-value of 45%)
Histogram of photon count rate (photons s\(^{-1}\) cm\(^{-2}\) per healpix pixel) at the location of scrambled northern IceCube neutrinos. Value for the real data shown in black.
Upper Plots: Histograms of photon-neutrino spatial (left) and temporal (right) separation. Background is shown in red.

Bottom Plots: Results of a chi square test for each scrambled dataset (blue histogram) plotted with a theoretical chi square distribution (5 DOF). Unscrambled results shown in black.
● Developed a time sensitive coincident analysis for IceCube and Fermi data
● Methods sensitive to rare high-multiplicity events, such as gamma-ray bursts
● Methods also sensitive to a population of cosmic signals
● Analysis can be extended to cover all archival Fermi and IceCube data
● Working on real time analysis code to be included in the AMON architecture
● Keivani, A. et al. 2015, ICRC2015
● Murase, K. 2014, ArXiv.org, 1410.3680