Seeking the Sources of High-Energy Neutrinos with Swift

Azadeh Keivani
Penn State University

Collaborators:
Doug Cowen, James DeLaunay, Derek Fox, Jamie Kennea, Gordana Tešić, Colin Turley (Penn State University)
Phil Evans, Julian Osborne (University of Leicester)
Frank Marshall (NASA GSFC)

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The Ohio State University
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Swift Searches for EM counterpart to IceCube neutrinos

Swift follow-up campaigns:
- Powerful approach to search for luminous EM counterparts to high-energy cosmic neutrinos
- Set useful constraints on associated transients
- Use XRT and UVOT telescopes
- Under our NASA Swift Cycle 12 Guest Investigator program
Current IceCube public real-time streams

- Two high energy real-time public streams:
  - **High Energy Starting Events (HESE)**
    - Since April 2016
    - Six events so far
    - Only track-like
  - **Extremely High Energy (EHE)**
    - Since July 2016
    - Four events so far
    - Track-like

- Distribute via:
  - Astrophysical Multimessenger Observatory Network (AMON)
  - Gamma-ray Coordinates Network (GCN)
  - [https://gcn.gsfc.nasa.gov/amon.html](https://gcn.gsfc.nasa.gov/amon.html)

- Triggered *Swift* follow-up observations of:
  - IceCube-160731A
  - IceCube-161103A
  - IceCube-170312A
  - IceCube-170321A
IceCube Event Properties

<table>
<thead>
<tr>
<th>Events</th>
<th>Stream</th>
<th>Charge (p.e.)</th>
<th>Signalness*</th>
<th>$R_{50}$ Rev0</th>
<th>$R_{90}$ Rev0</th>
<th>$R_{50}$ Rev1</th>
<th>$R_{90}$ Rev1</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube-160731A</td>
<td>HESE/EHE</td>
<td>15814</td>
<td>0.91</td>
<td>0.42° (HESE)</td>
<td>1.23° (HESE)</td>
<td>0.35°</td>
<td>0.75°</td>
</tr>
<tr>
<td>IceCube-161103A</td>
<td>HESE</td>
<td>7546</td>
<td>0.30</td>
<td>0.42°</td>
<td>1.23°</td>
<td>0.65°</td>
<td>1.1°</td>
</tr>
<tr>
<td>IceCube-170312A</td>
<td>HESE</td>
<td>8858</td>
<td>0.78</td>
<td>0.42°</td>
<td>1.23°</td>
<td>-</td>
<td>&lt; 0.5°</td>
</tr>
<tr>
<td>IceCube-170321A</td>
<td>EHE</td>
<td>6214</td>
<td>0.28</td>
<td>0.32°</td>
<td>-</td>
<td>-</td>
<td>1.2°</td>
</tr>
</tbody>
</table>

* Signalness for EHE is an estimate probability that the event is due to an astrophysical neutrino. It is called "signal_trackness" for HESE reflecting the likelihood that the neutrino being both signal-like and track-like.
Swift Observations of IceCube Events

- Priority 1 TOO
- Mosaic of 19 pointings for HESE and 7 pointings for EHE
- Automated analysis of XRT data: software at University of Leicester, Phil Evans

<table>
<thead>
<tr>
<th>Events</th>
<th>Swift Start Obs Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube-160731A</td>
<td>~ 1 hr</td>
</tr>
<tr>
<td>IceCube-161103A</td>
<td>~ 5 hrs</td>
</tr>
<tr>
<td>IceCube-170312A</td>
<td>~ 2 hrs</td>
</tr>
<tr>
<td>IceCube-170321A</td>
<td>~ 6 hrs</td>
</tr>
</tbody>
</table>
Swift Observations of IceCube-160731A

- Observations taken 3.9 to 46.5 ks after the neutrino trigger
- Covered 2.1 deg²
- Covered 64.2% of the neutrino revised $r_{90}$ error region
- Collected ~ 800 s per field of PC mode data per tile
- Six X-ray sources were detected
  - Known X-ray emitters
  - Catalog objects with expected X-ray emission
- Flux upper limits (0.3-10 KeV):
  - $4.3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ for a typical AGN spectrum ($N_H=3 \times 10^{20}$ cm$^{-2}$, $\gamma=1.7$)
  - $3.1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ for overlapped areas
## Swift XRT Observations

<table>
<thead>
<tr>
<th>Events</th>
<th>Total Obs Time (ks)</th>
<th>Pointing Coverage (deg²)</th>
<th>Neutrino Coverage (rev1 r₉₀ error region)</th>
<th>Time per tile (s)</th>
<th>Src #</th>
<th>3σ flux UL (erg cm⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube-160731A</td>
<td>42.6</td>
<td>2.1</td>
<td>64.2 %</td>
<td>~ 800</td>
<td>6</td>
<td>4.3 x 10⁻¹³</td>
</tr>
<tr>
<td>IceCube-161103A</td>
<td>17.7</td>
<td>2.1</td>
<td>68 %</td>
<td>~ 150 - 250</td>
<td>4</td>
<td>1.2 x 10⁻¹²</td>
</tr>
<tr>
<td>IceCube-170312A</td>
<td>47.6</td>
<td>2.1</td>
<td>82.3 %</td>
<td>~ 800</td>
<td>5</td>
<td>4.1 x 10⁻¹³</td>
</tr>
<tr>
<td>IceCube-170321A</td>
<td>14.1</td>
<td>0.5</td>
<td>22.1 %</td>
<td>~ 900</td>
<td>2</td>
<td>1.5 x 10⁻¹³</td>
</tr>
</tbody>
</table>

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**GCN circulars:**
Swift UVOT observations

<table>
<thead>
<tr>
<th>Events</th>
<th>Filter used</th>
<th>Exposure (s)</th>
<th>Limiting sensitivity (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube-160731A</td>
<td>U</td>
<td>420</td>
<td>18.9</td>
</tr>
<tr>
<td>IceCube-161103A</td>
<td>U (16 pointings) + UVW1 (3 pointings)</td>
<td>250</td>
<td>18.9</td>
</tr>
<tr>
<td>IceCube-170312A</td>
<td>U</td>
<td>110</td>
<td>18.9</td>
</tr>
<tr>
<td>IceCube-170321A</td>
<td>U</td>
<td>922</td>
<td>18.9</td>
</tr>
</tbody>
</table>

No transient sources were discovered in any of these searches associated with the IceCube trigger.
• A library of 192 Swift XRT light-curves
• Power-law fits
• Assume neutrino detection time to be coincident with the GRB
• Median X-ray afterglow, 80% and 50% confidence ranges
• X-ray flux limits for neutrino events averaged over all tiles of each mosaic pointing
• The flux limit: the # of source photons to yield an excess over background with p-value < 10^{-6} in a single source aperture
• Such excesses occur via Poisson fluctuation of the background in ~10% (4%) of 19(7)-tile observing campaigns
$P_{\Delta t,x}$ of the X-ray afterglows of *Swift*-detected GRBs would be recovered by the follow-up campaigns, assuming the burst occurred within the FOV of the observations.

<table>
<thead>
<tr>
<th>Events</th>
<th>$P_{\Delta t,x}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube-160731A</td>
<td>65%</td>
</tr>
<tr>
<td>IceCube-161103A</td>
<td>30%</td>
</tr>
<tr>
<td>IceCube-170312A</td>
<td>55%</td>
</tr>
<tr>
<td>IceCube-170321A</td>
<td>43%</td>
</tr>
</tbody>
</table>
AGILE’s Candidate $\gamma$-Ray Precursor to IceCube-160731A

- Precursor to the IceCube-160731A
- No detection in $\pm 1$ ks of $T_0$
- Use AGILE-GRID Automatic Quick Look procedure over 48-hrs time bins:
  - Excess $> 100$ MeV
  - $T_0 - 1.8 < T < T_0 - 0.8$ days
  - Consistent with $\nu$ error region
  - Post-trial significance $\sim 4\sigma$
  - AGL J1418+0008
- Fermi-LAT had a low exposure during the AGILE $\gamma$-ray transient
- Dedicated Swift ToO data $\rightarrow$ no X-ray counterparts
- Check Swift BAT data for possible $\gamma$-ray counterparts

arXiv:1707.08599
Conclusions and Prospects

• Four *Swift* follow-up campaigns so far seeking to identify transient or variable X-ray or UV/optical sources that might be associated with IceCube high-energy cosmic muon neutrinos

• Observations covered 64.2%, 68.0%, 82.3% and 22.1% of the 90% containment regions for the four neutrino events

• No compelling candidate X-ray or UV/optical counterpart for any of the events identified

• $3\sigma$ upper limits on the flux for a typical AGN spectrum placed

• 30%-65% of X-ray afterglows of *Swift*-detected GRBs would be recovered by the follow-up campaigns of these neutrinos

• A paper in preparation with upper limits considering more source scenarios: blazars and supernovae

• Plan to continue *Swift* follow-up observations of IceCube high-energy neutrinos at a rate of roughly four campaigns per year