Seeking the Sources of High-Energy Neutrinos with *Swift*

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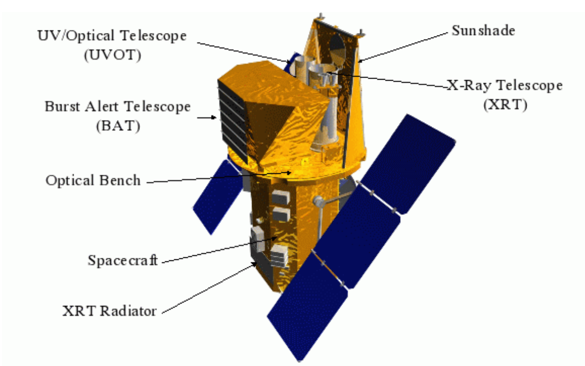
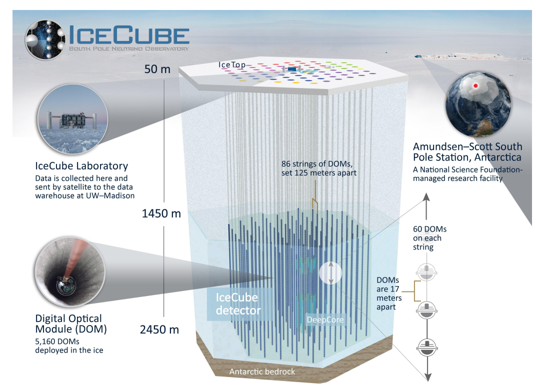
TeVPA 2017
Center for Cosmology and AstroParticle Physics
The Ohio State University
August 9

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:

James DeLaunay's Talk

  - Astrophysical Multimessenger Observatory Network (AMON)
  - Gamma-ray Coordinates Network (GCN)
  - https://gcn.gsfc.nasa.gov/amon.html
- Triggered *Swift* follow-up observations of:
  - IceCube-160731A
  - IceCube-161103A
  - IceCube-170312A
  - IceCube-170321A

IceCube Event Properties

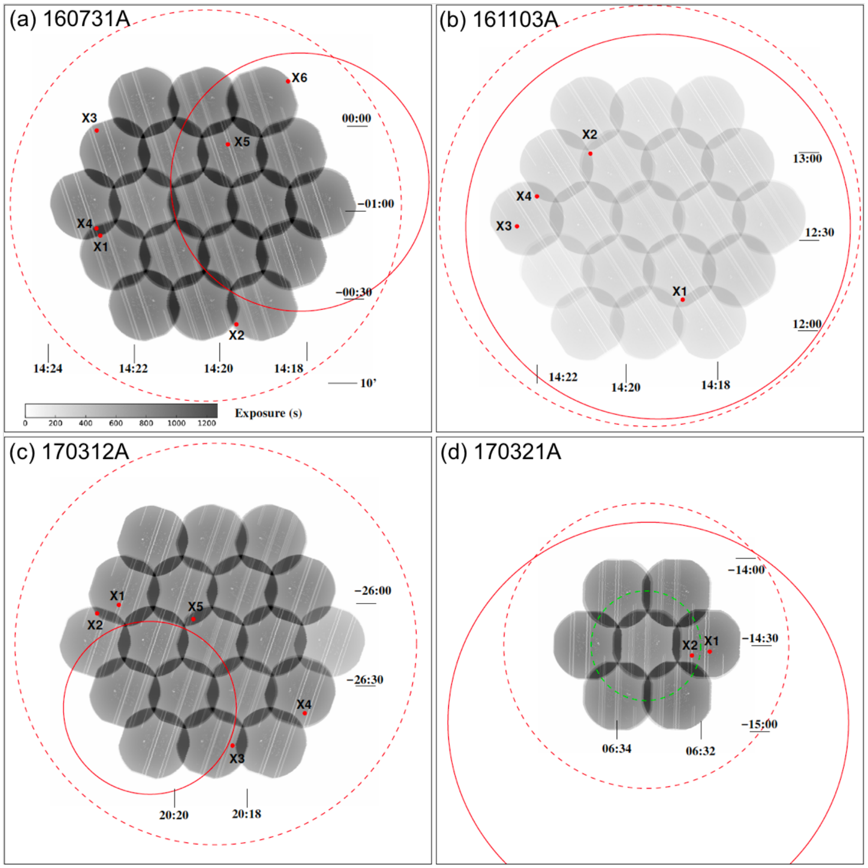
Events	Stream	Charge (p.e.)	Signalness*	R_{50} Rev0	R_{90} Rev0	R_{50} Rev1	R_{90} Rev1
IceCube-160731A	HESE/EHE	15814	0.91	0.42° (HESE) 0.17° (EHE)	1.23° (HESE)	0.35°	0.75°
IceCube-161103A	HESE	7546	0.30	0.42°	1.23°	0.65°	1.1°
IceCube-170312A	HESE	8858	0.78	0.42°	1.23°	-	< 0.5°
IceCube-170321A	EHE	6214	0.28	0.32°	-	-	1.2°

* 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

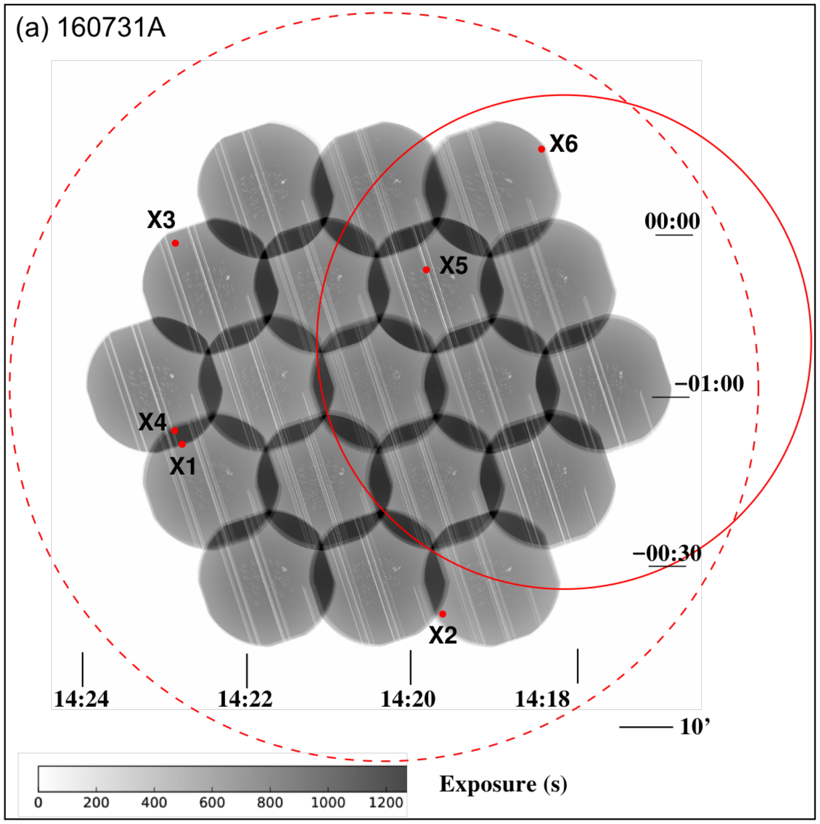
- Priority 1 TOO
- Mosaic of 19 pointings for HESE and 7 pointings for EHE
- Automated analysis of XRT data: software at University of Leicester, Phil Evans

Events	Swift Start Obs Latency
IceCube-160731A	~ 1 hr
IceCube-161103A	~ 5 hrs
IceCube-170312A	~ 2 hrs
IceCube-170321A	~ 6 hrs



Swift Observations of IceCube-160731A

- Observations taken 3.9 to 46.5 ks after the neutrino trigger
- Covered 2.1 deg^2
- 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):
  - 4.3×10^{-13} erg cm^{-2} s^{-1} for a typical AGN spectrum ($N_H = 3 \times 10^{20}$ cm^{-2}, $\gamma = 1.7$)
  - 3.1×10^{-13} erg cm^{-2} s^{-1} for overlapped areas



Swift XRT Observations

Events	Total Obs Time (ks)	Pointing Coverage (deg^2)	Neutrino Coverage (rev1 r_{90} error region)	Time per tile (s)	Src #	3σ flux UL (erg cm^{-2} s^{-1})
IceCube-160731A	42.6	2.1	64.2 %	~ 800	6	4.3×10^{-13}
IceCube-161103A	17.7	2.1	68 %	~ 150 - 250	4	1.2×10^{-12}
IceCube-170312A	47.6	2.1	82.3 %	~ 800	5	4.1×10^{-13}
IceCube-170321A	14.1	0.5	22.1 %	~ 900	2	1.5×10^{-13}

GCN circulars:

- https://gcn.gsfc.nasa.gov/gcn3/19747.gcn3
- https://gcn.gsfc.nasa.gov/gcn3/20125.gcn3
- https://gcn.gsfc.nasa.gov/gcn3/20890.gcn3
- https://gcn.gsfc.nasa.gov/gcn3/20964.gcn3

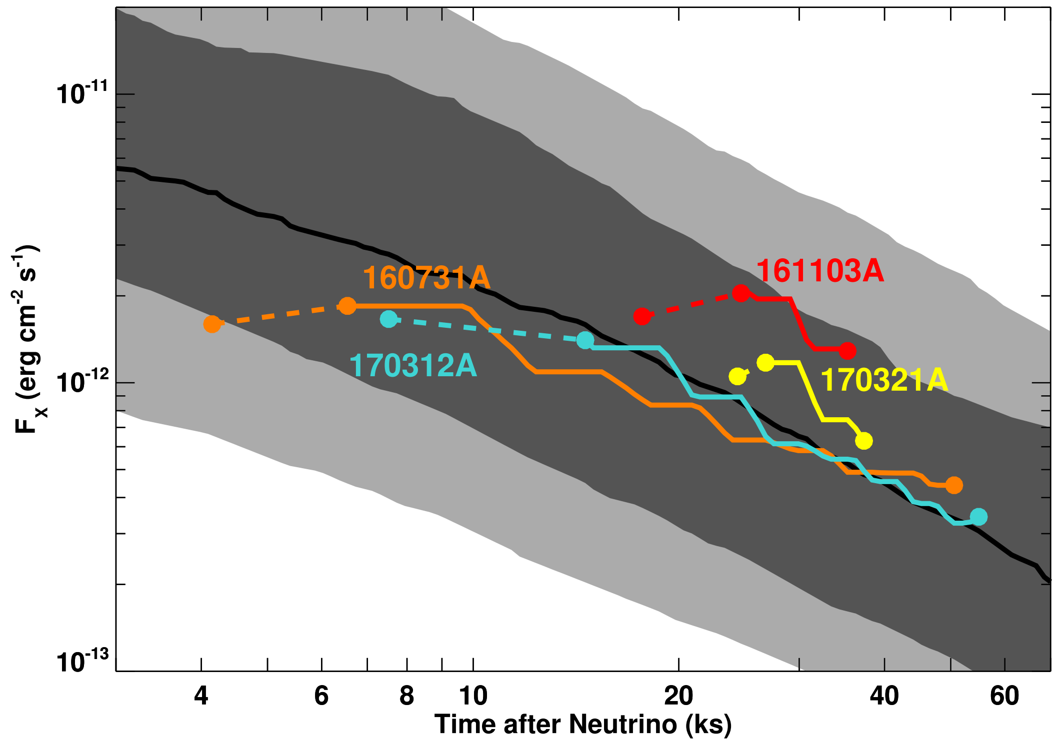
Swift UVOT observations

Events	Filter used	Exposure (s)	Limiting sensitivity (mag)
IceCube-160731A	U	420	18.9
IceCube-161103A	U (16 pointings) + UVW1 (3 pointings)	250	18.9
IceCube-170312A	U	110	18.9
IceCube-170321A	U	922	18.9

No transient sources were discovered in any of these searches associated with the IceCube trigger.

GRB X-ray afterglow

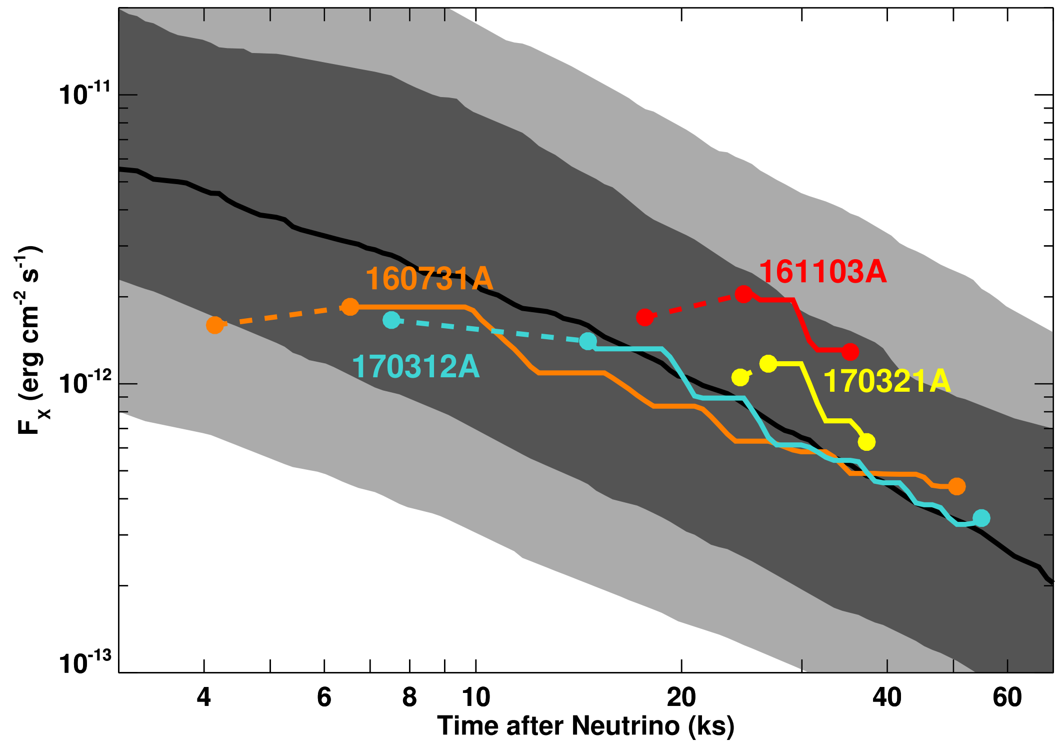
- A library of 192 *Swift* XRT light-curves
- Power-law fits
- Assume neutrino detection time to be coincident with the GRB
- Median X-ray afterglow, 80% and 50% confidence ranges
- X-ray flux limits for neutrino events averaged over all tiles of each mosaic pointing
- The flux limit: the # of source 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



GRB X-ray afterglow constraints

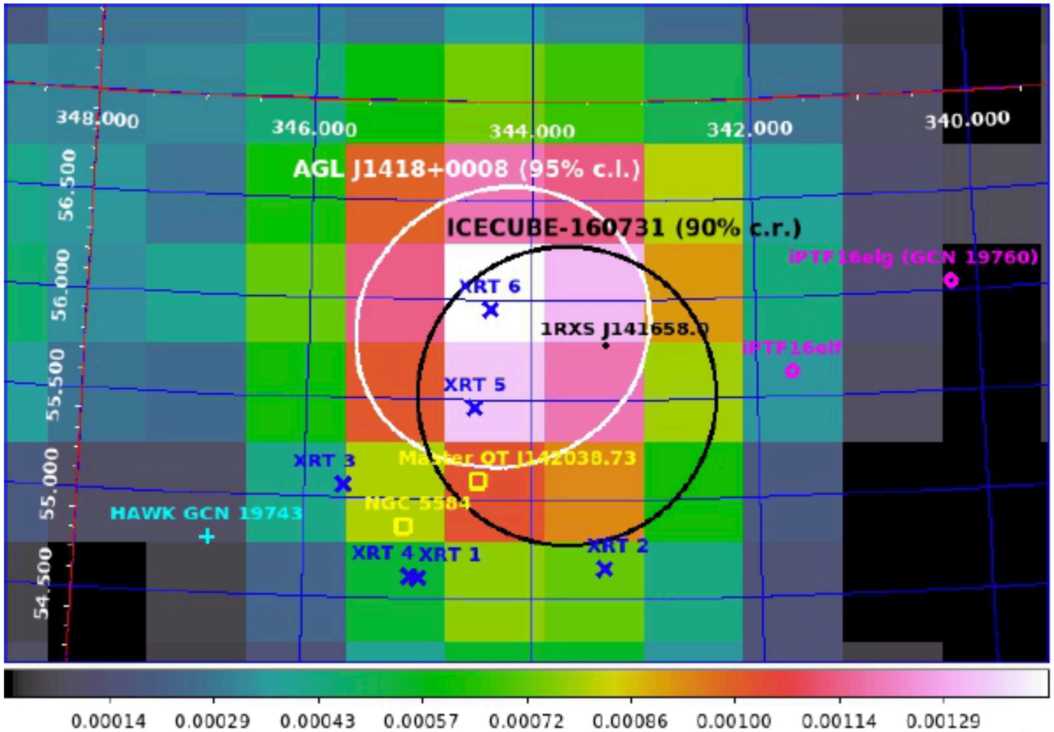
$P_{\Delta t,x}$ of the X-ray afterglows of *Swift*-detected GRBs would be recovered by the follow-up campaigns, assuming the burst occurred within the FOV of the observations

Events	$P_{\Delta t,x}$
IceCube-160731A	65%
IceCube-161103A	30%
IceCube-170312A	55%
IceCube-170321A	43%



AGILE's Candidate γ-Ray Precursor to IceCube-160731A

- Precursor to the IceCube-160731A
- No detection in ±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 ν error region
  - Post-trial significance ~ 4σ
  - AGL J1418+0008
- Fermi-LAT had a low exposure during the AGILE γ-ray transient
- Dedicated *Swift* ToO data → no X-ray counterparts
- Check *Swift* BAT data for possible γ-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
- 3σ 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