

Swift and CALET による 非電磁波(ニュートリノ) アラートの フォローアップ観測

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P. Evans (U of Leicester)

Contents

- Swift

- Introduction of Swift
- Unique Swift's characteristics
- Follow-up IceCube alerts (2011-2014)
- Follow-up ANTARES alerts
- Follow-up real-time IceCube alerts (2016-)
- IceCube-160217: Triplet event

- CALET

- Introduction of CALET
- Search for EM counterpart of IceCube events

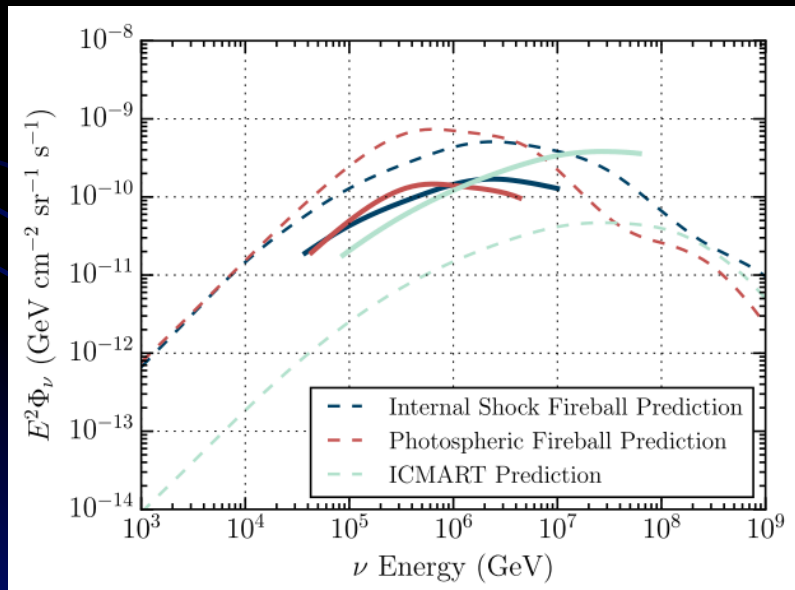
GRBs as the sources for UHECR?

(Aartsen+ 2017, astro-ph/1702.06868)

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

IceCube:

508 GRBs (Northern Hemisphere), 664 GRBs (Southern Hemisphere)



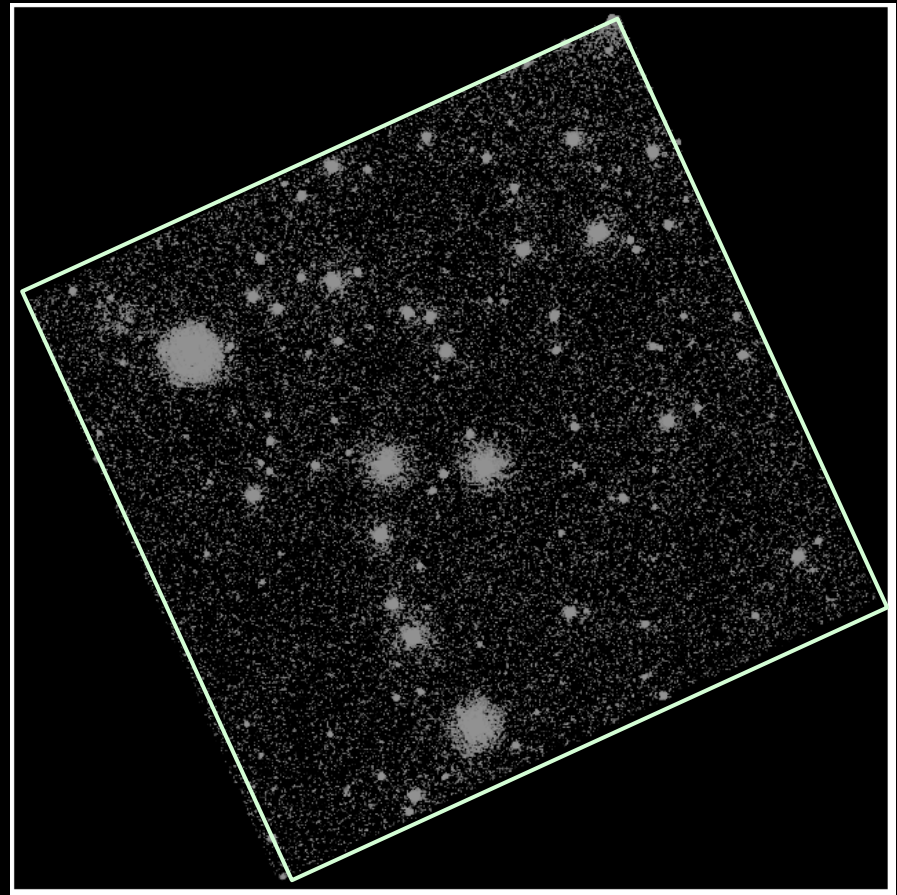
Why X-ray?

(Question) Find the afterglow of GRB 161219B

X-ray (Swift/XRT)



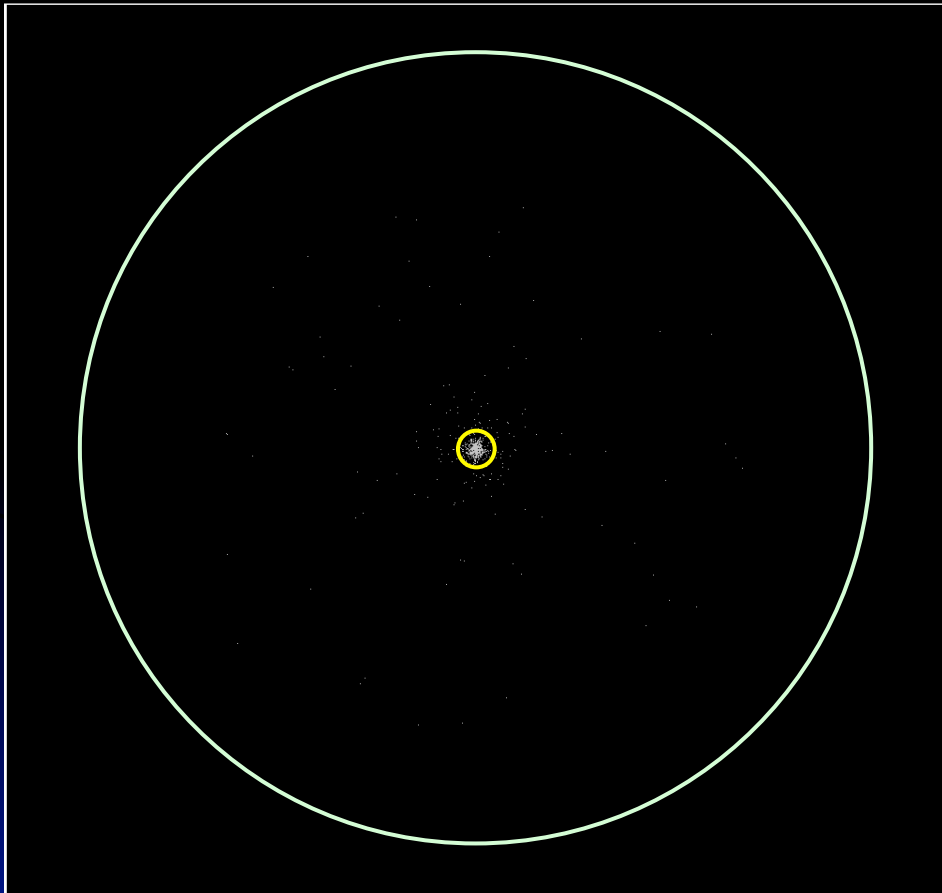
Optical (Swift/UVOT)



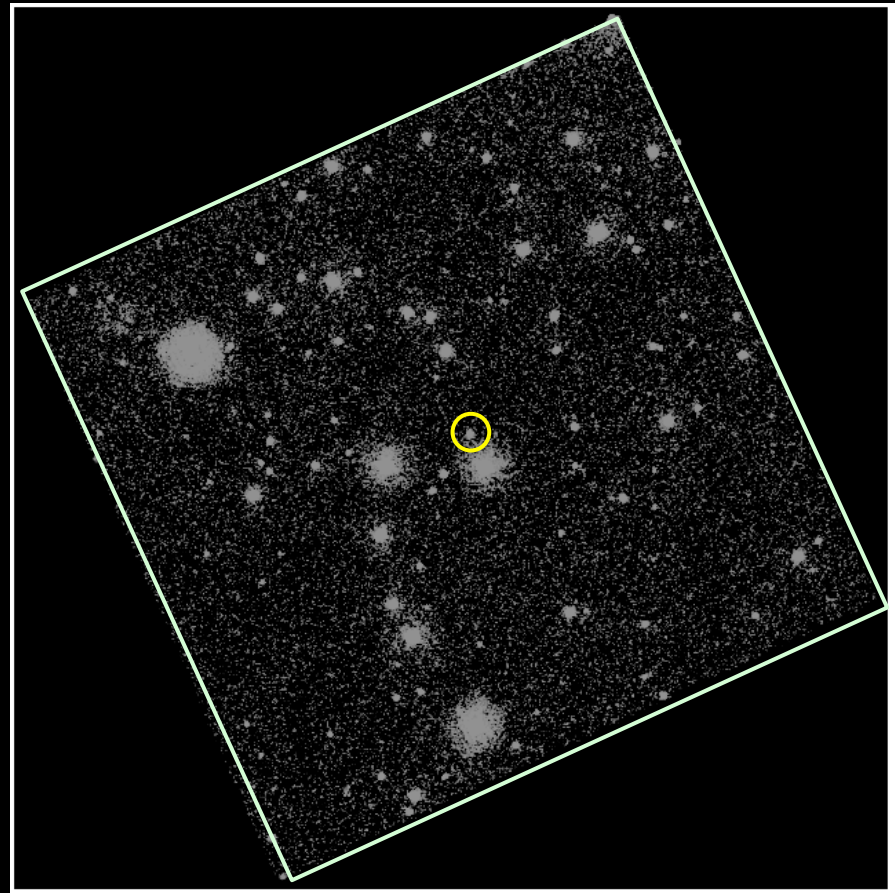
Why X-ray?

(Question) Find the afterglow of GRB 161219B

X-ray (Swift/XRT)



Optical (Swift/UVOT)



Swift



2004-



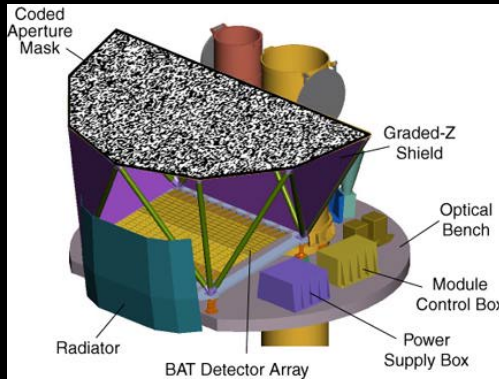
Swift Gamma-ray Burst Explorer Mission



- NASA's Medium-Class Explorers (MIDEX)
 - Jan 1999: Selected for Phase A study
 - Oct 1999: Selected for flight
 - Nov 2004: Launch
- International collaboration (mainly US, UK and Italy)
 - Burst Alert Telescope (BAT): New development at NASA/GSFC and LANL
 - X-ray Telescope (XRT): Mirror (JET-X FM unit), CCD (XMM-Newton EPIC MOS); PSU, INAF and UL
 - Ultra-Violet/Optical Telescope (UVOT): Copy of XMM-Newton OM; PSU and MSSL
- Successful mission extension
 - 2016 NASA Astrophysics Senior Review **ranked #1!**



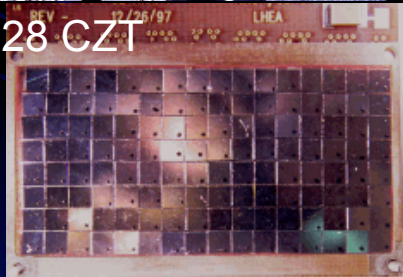
Burst Alert Telescope (BAT)



Mask



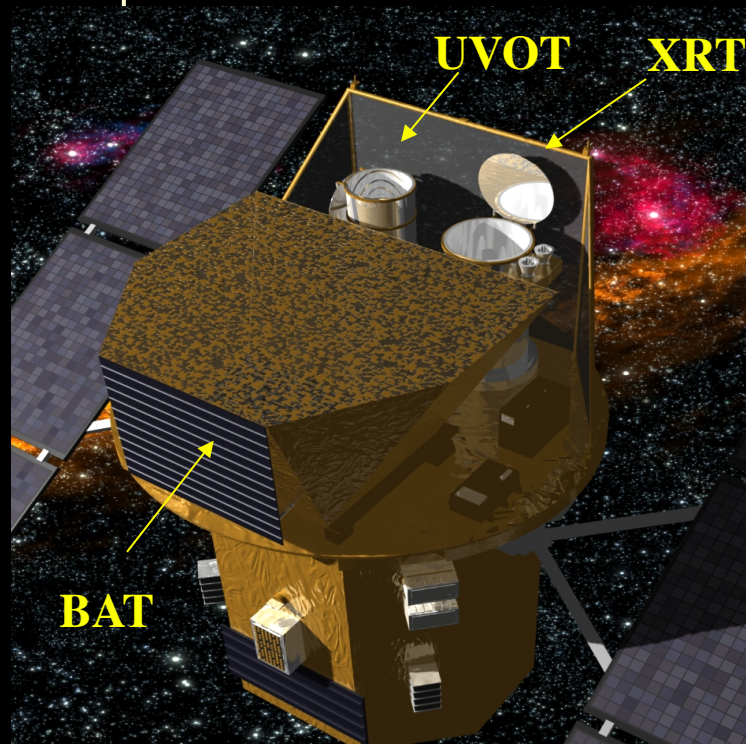
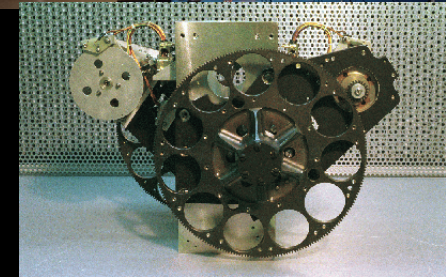
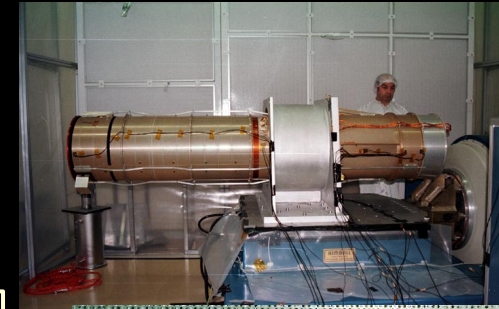
128 CZT



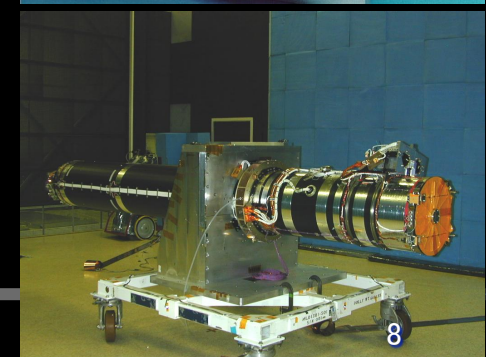
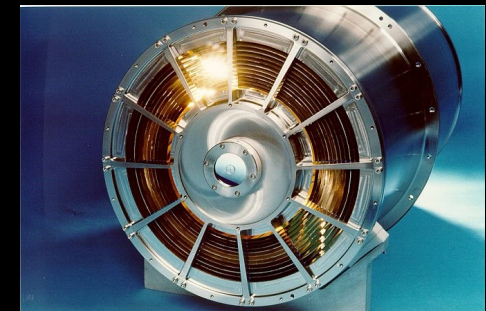
E_range: 15-150 keV (15-350 keV)
 Det: CdZnTe ($4 \times 4 \times 2 \text{ mm}^3$)
 # of detectors: 32,768 (256×128)
 FOV: 120 deg x 90 deg
 Pos: $1' - 3'$

UV/Optical Telescope (UVOT)

Aperture: 30 cm (XMM OM)
 Det: MCP+CCD (XMM OM)
 FOV: $17' \times 17'$
 7 filters (UV - Opt)+2 grism



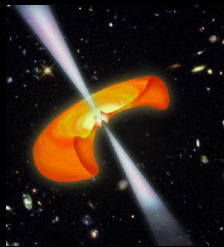
X-Ray Telescope (XRT)



E_range: 0.3-10 keV
 Focal Length: 3.5m
 Det: X-ray CCD (XMM MOS)
 FOV: $23' \times 23'$

Fully Automated Observations

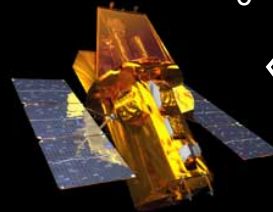
Observations of afterglows right off the bat (no human in the loop).



XRT & UVOT Observation
($T_0 + 75-120$ s)

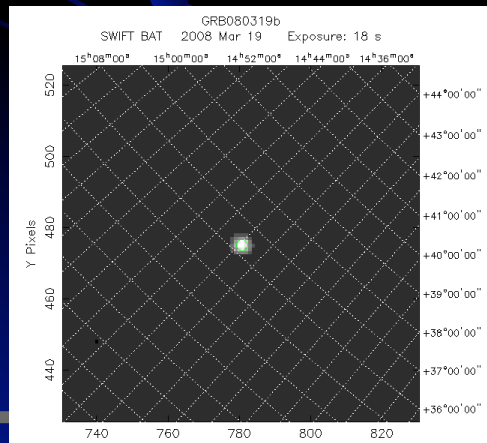
BAT GRB detection: T_0
BAT GRB position: $T_0 + \sim 20$ s (3')

$T_0 + (20-75$ s)

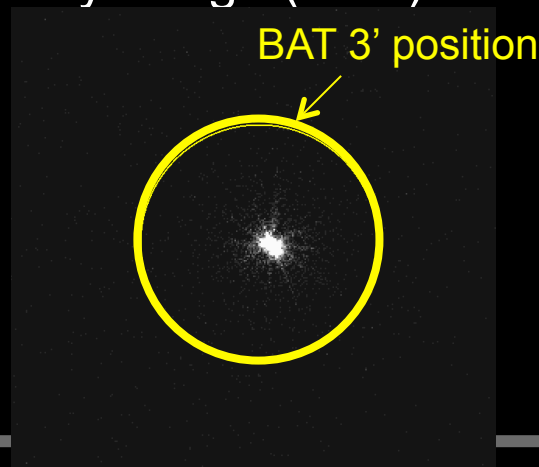


Images: GRB 080319B

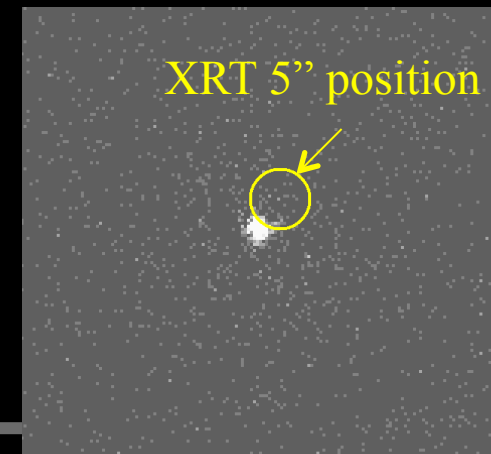
Gamma-ray Image (BAT)



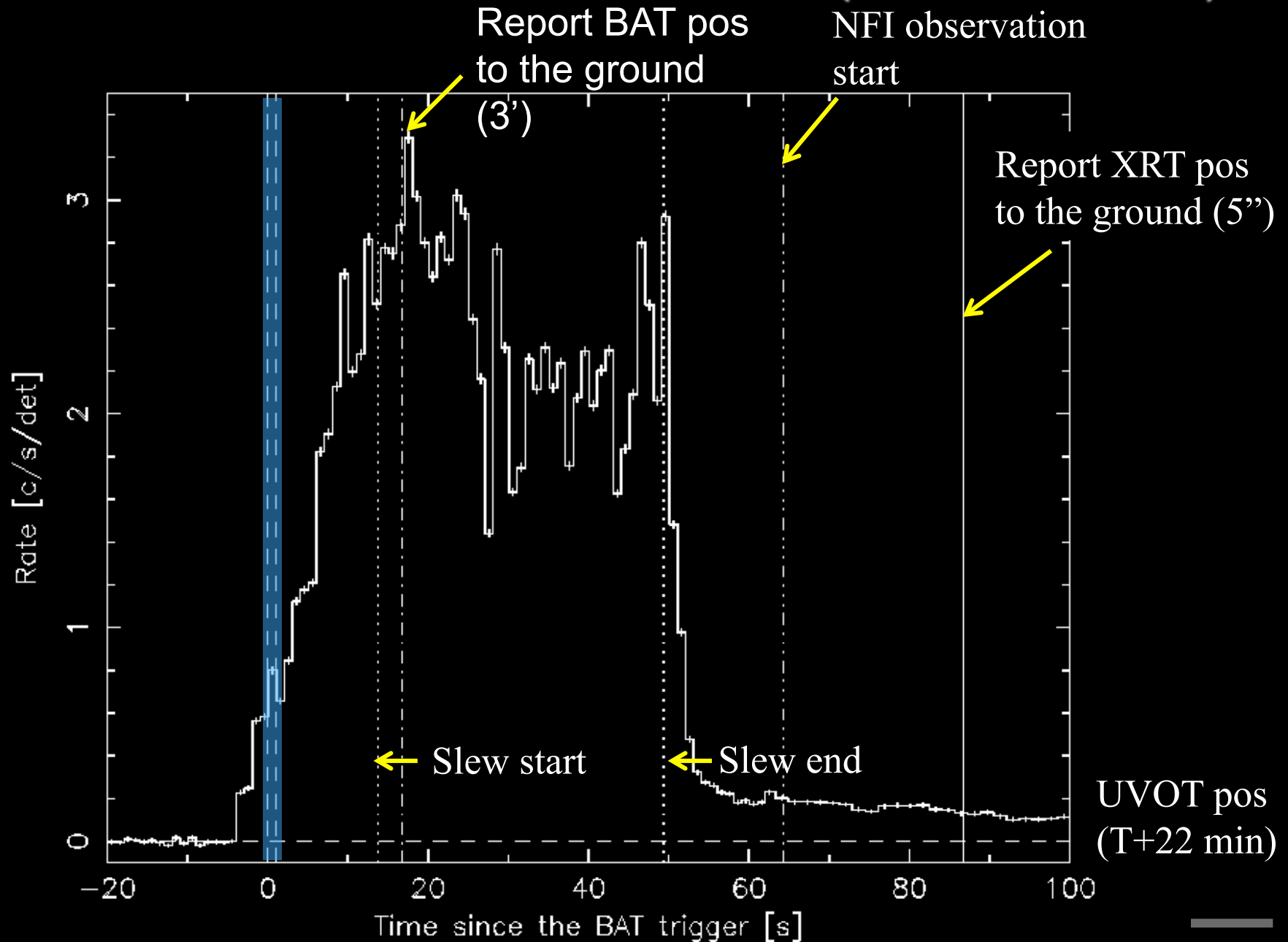
X-ray Image (XRT)



Optical Image (UVOT)



Automatic Swift GRB Observation (GRB 080319B)



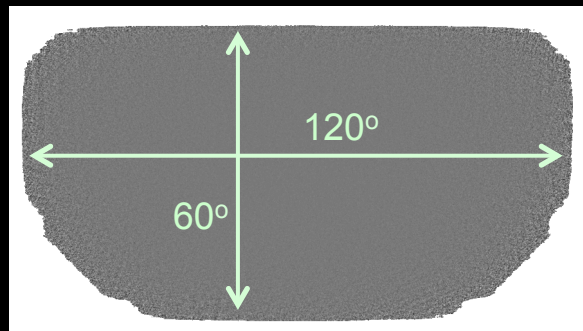
Swift Operation and Available Data

- BAT on-board trigger
 - Automatic XRT/UVOT Observations ($T_0 + \sim 100\text{s}$)
 - BAT event data ($T_0 - 250\text{ s} - T_0 + 1000\text{ s}$)
- Target of Opportunity (ToO) observation
 - Fast ToO is possible (within an hour)
 - New X-ray (XRT) and UV/optical (UVOT) data of the field
 - Possible tiling observation
- Regular operation
 - BAT: raw light curve data (64 ms, 1.6 s), scaled map data and survey data

Challenges for non-EM Counterpart Search

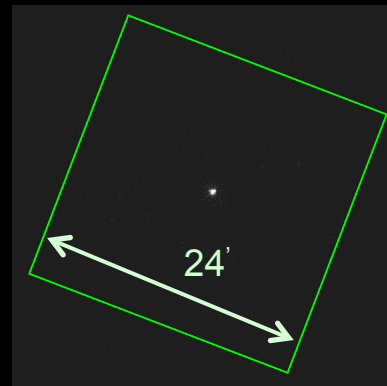
- Large error region (~scale of degrees)

BAT



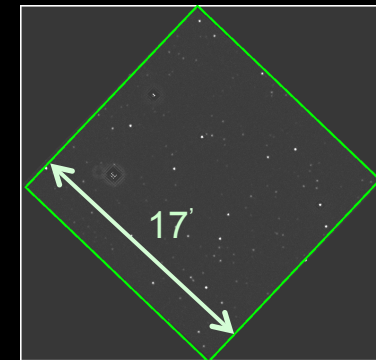
FOV: Enough
Sensitivity: Not good
($\sim 10^{-9}$ erg cm $^{-2}$ s $^{-1}$)

XRT



FOV: Not enough
Sensitivity: Good
($\sim 5 \times 10^{-14}$ erg cm $^{-2}$ s $^{-1}$)

UVOT



FOV: Not enough
Sensitivity: Good (~ 20 mag)

- When is the good time to search?
 - Strongly depends on the physical source

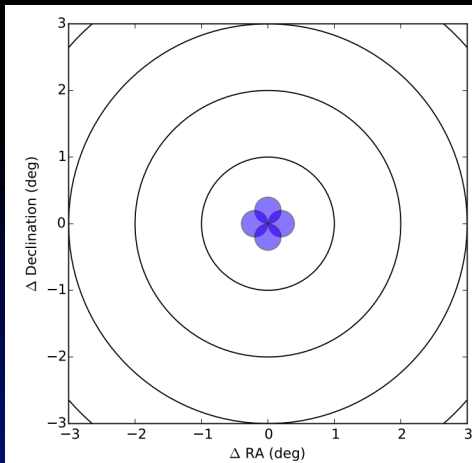
Automatic Tiling Observation

Automatic tiling observation capability
(Part of the BAT on-board software)

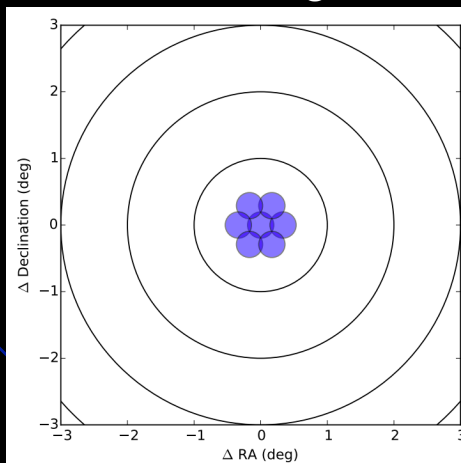
- Try to observe all N tiles in the first orbit
- Continue observing until the requested observing time (min exp/tile = 60 s)

Tiling patterns (figures from J. Kennea)

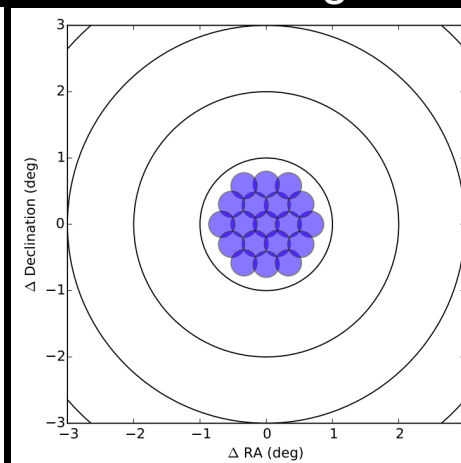
4-tiling



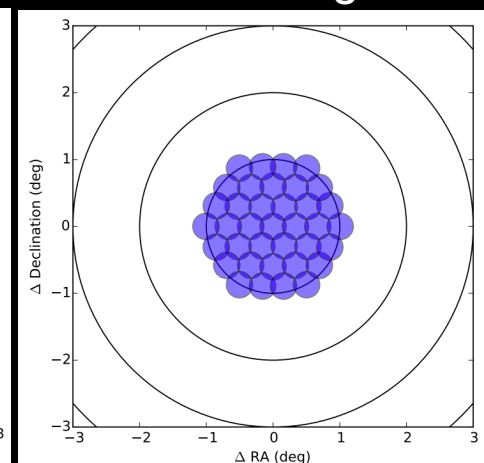
7-tiling



19-tiling



37-tiling



Required tiling pattern
to cover 1° diameter

Required tiling pattern
to cover 2° diameter

2011 March – 2014 August

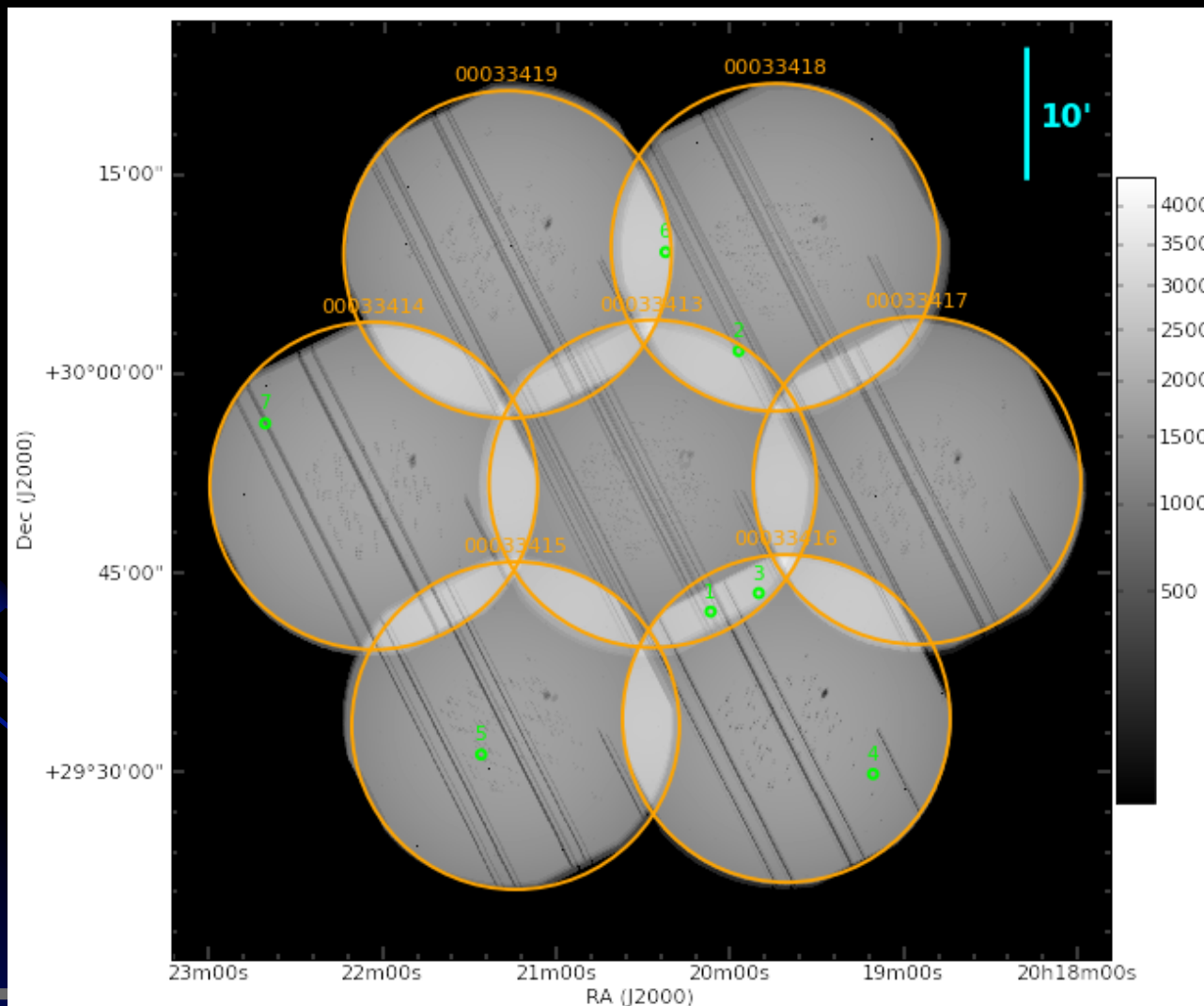
IceCube 20 doublet triggers

(Evans+, 2015)

- 7 tiling observations to cover the IceCube 50% error radius (typically 0.5°)
- Typically within 5 hours from the IceCube trigger time
- Typical exposure per tile is 1-2 ksec
- Sensitivity: $6\text{-}10 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (more sensitive than the ROSAT All Sky Survey: $2.8 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$)

IceCube 20 doublet triggers

(Evans+, 2015)

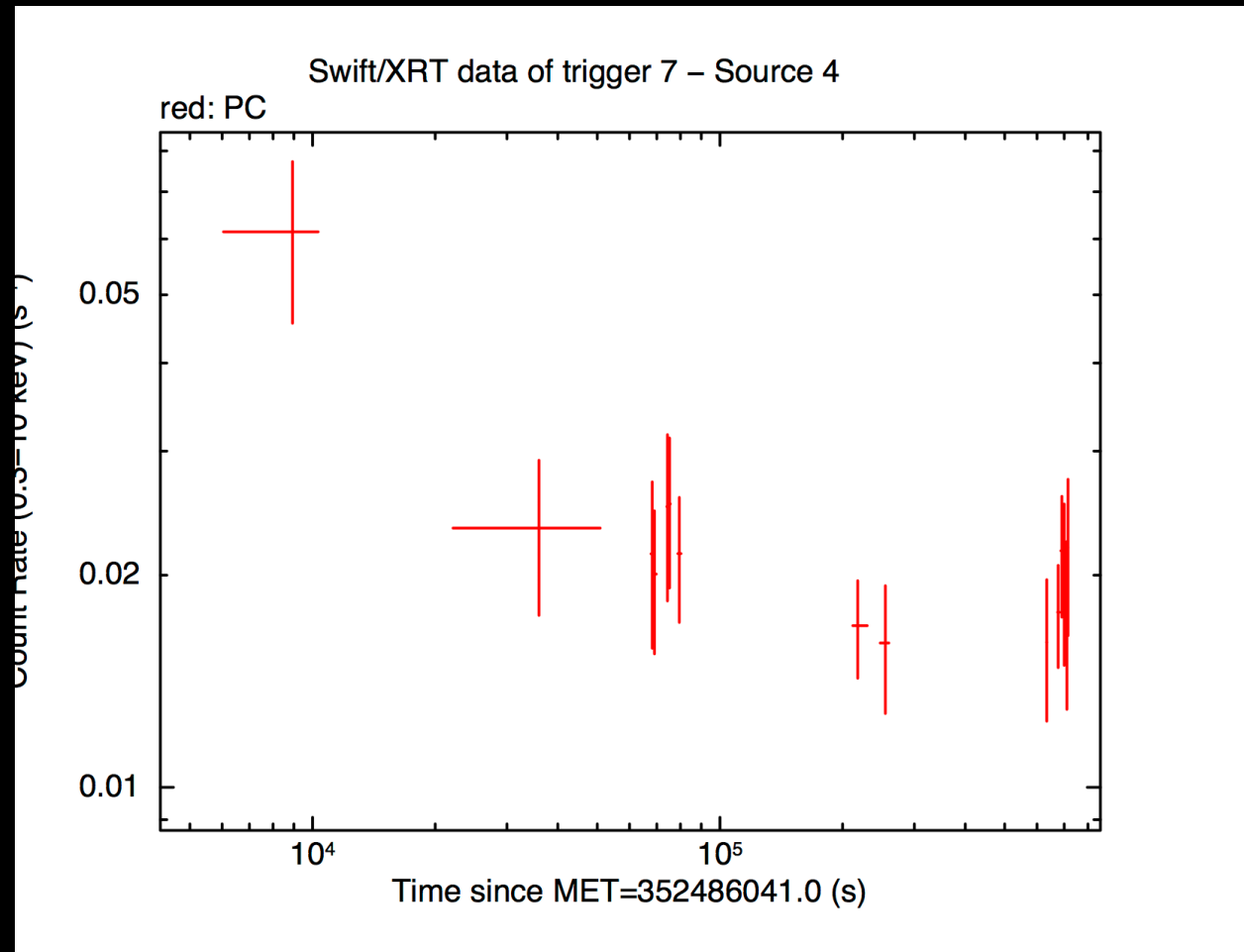


IceCube 20 doublet triggers

This source was found in XRT follow up of an IceCube trigger.

And turned out not to be a transient.

Not all fading objects are the counterpart.



(Evans+ 2015)

IceCube 20 doublet triggers

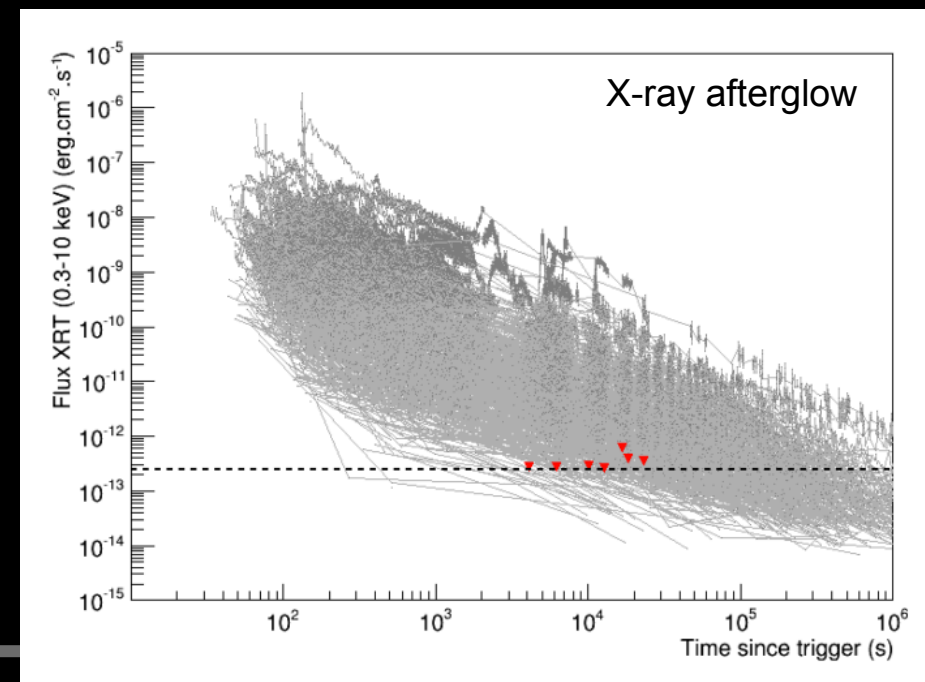
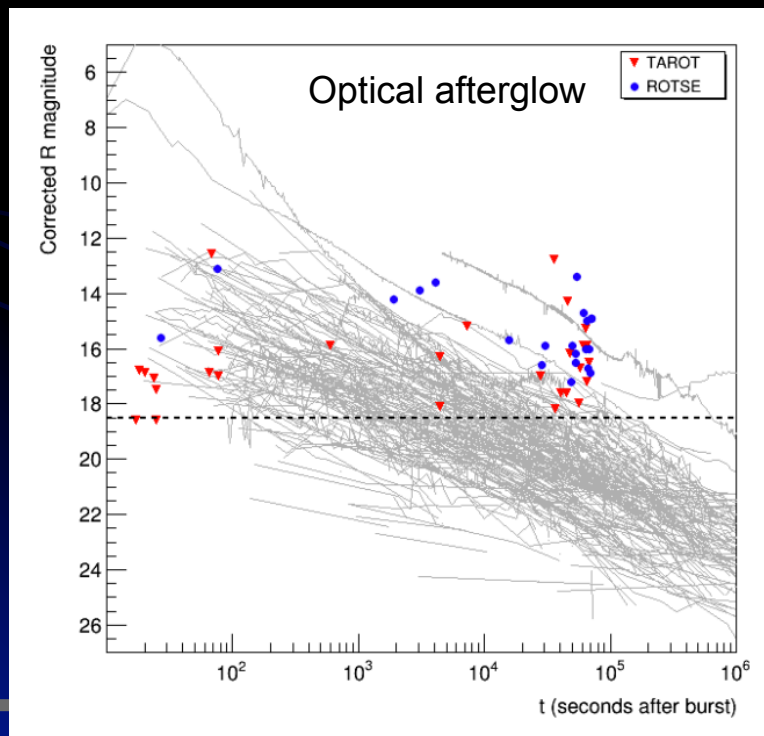
In follow up of 20 doublet triggers, XRT detected **119 sources**, only **30** of which were previously **catalogued X-ray sources** (Evans+ 2015).

The lack of a ‘smoking gun’ counterpart doesn’t mean we didn’t find one, just that we didn’t find one ***that looks like we expected.***

Follow-up ANTARES triggers

- ANTARES triggered Swift, ROTSE and TAROT.
- 42 with optical follow up (ROTSE/Tarot)
- 7 with X-ray follow up (XRT).
- Combination of multiplet triggers, or single high-energy events.
- No counterparts were found in any wavelength (Adrián Martínez+ 2016). Suggests the neutrino were not from GRBs.

(Martinez+ 2016)



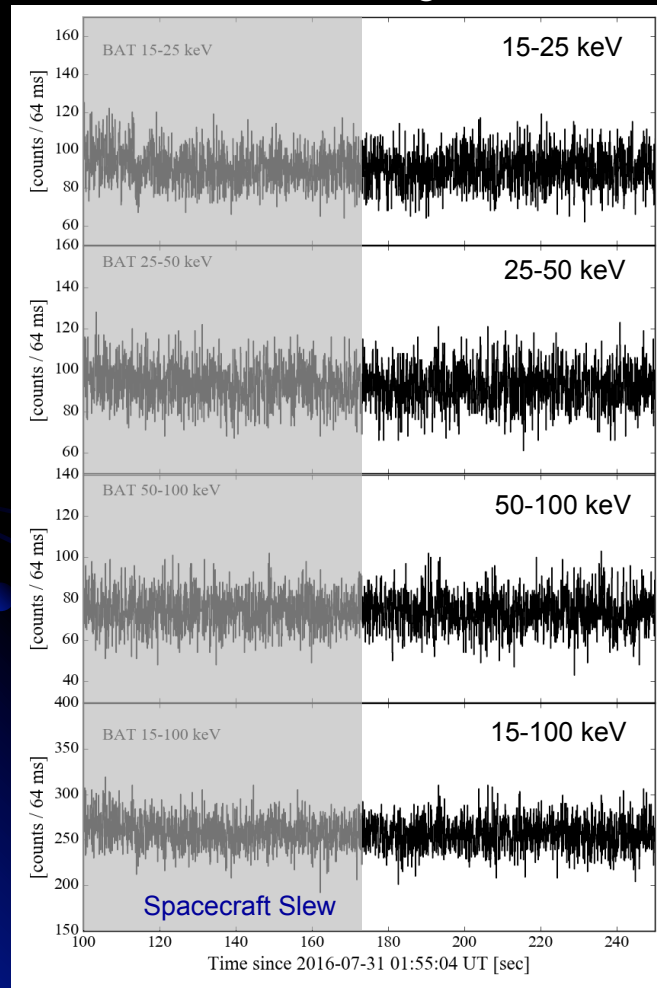
Real-time IceCube Alert

Trigger Time	Type	Position	Error (50% radius)	XRT follow-up	BAT FOV?
2016-07-31 01:55:04.00	HESE/ EHE	(215.109, -0.458)	20.99'	Yes	T_0+175 s
2016-08-06 12:21:33.00	EHE	(122.798, -0.733)	6.67'	No	$T_0+1.0$ hr
2016-08-14 21:45:54.00	HESE	(199.310, -32.016)	28.79'	No	$T_0+1.1$ hr
2016-11-03 09:07:31.12	HESE	(40.874, +12.615)	39.00'	Yes	$T_0+21.4$ min
2016-12-10 20:06:40.31	EHE	(45.854, +15.785)	14.99'	No	$T_0+3.9$ hr

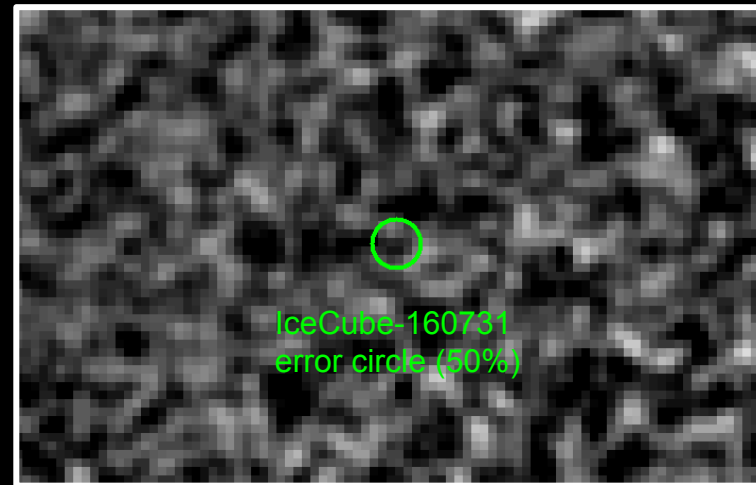
- HESE: High Energy Starting Event; a single-neutrino with an energy in the sub-PeV to 1 PeV
- EHE: Extremely High Energy; a single-neutrino with an energy higher than several hundred TeV

IceCube-160731: BAT Prompt Data

BAT 64 ms raw light curve



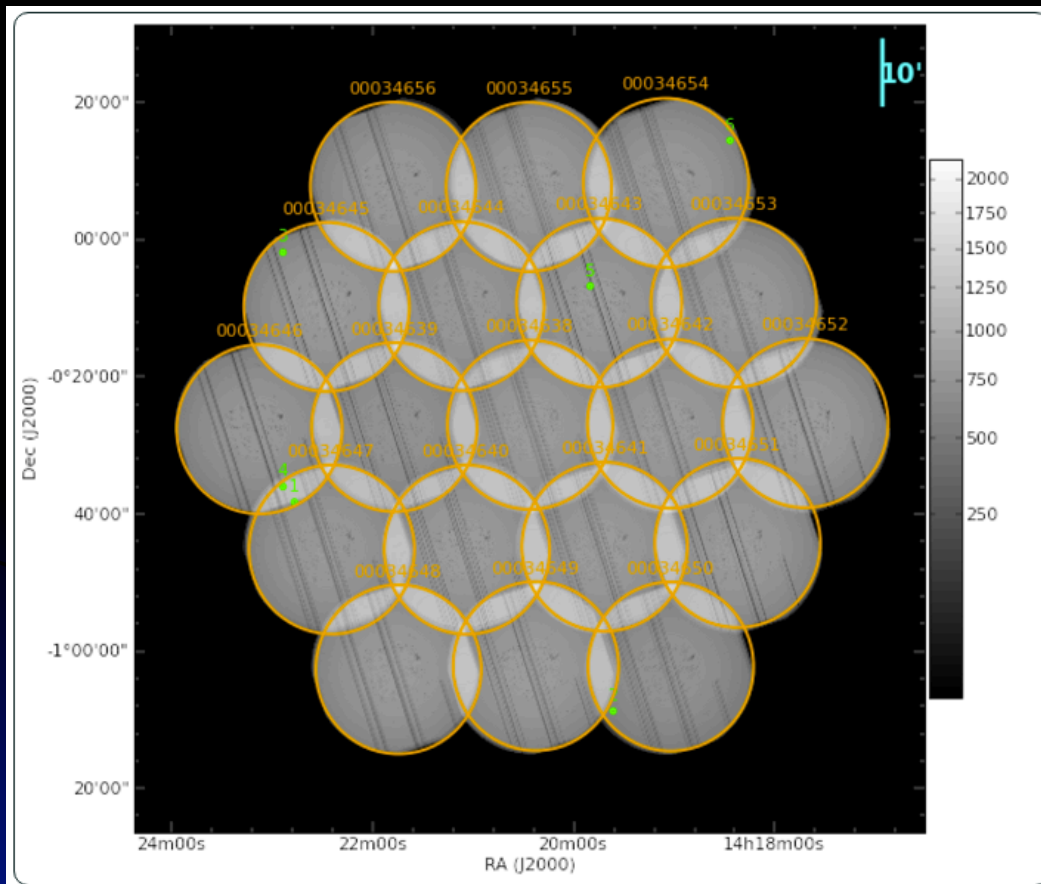
BAT 15-150 keV sky image



- No significant emission in the 64 ms light curve data (T_0+175 s – T_0+250 s)
- No unknown source in the BAT sky image (T_0+185 s – T_0+462 s) at $>5\sigma$
- 5- σ 15-150 keV UL: 3×10^{-9} erg cm $^{-2}$ s $^{-1}$ (assuming E^{-2} ; 300 s exposure)

IceCube-160731: XRT/UVOT Follow-up

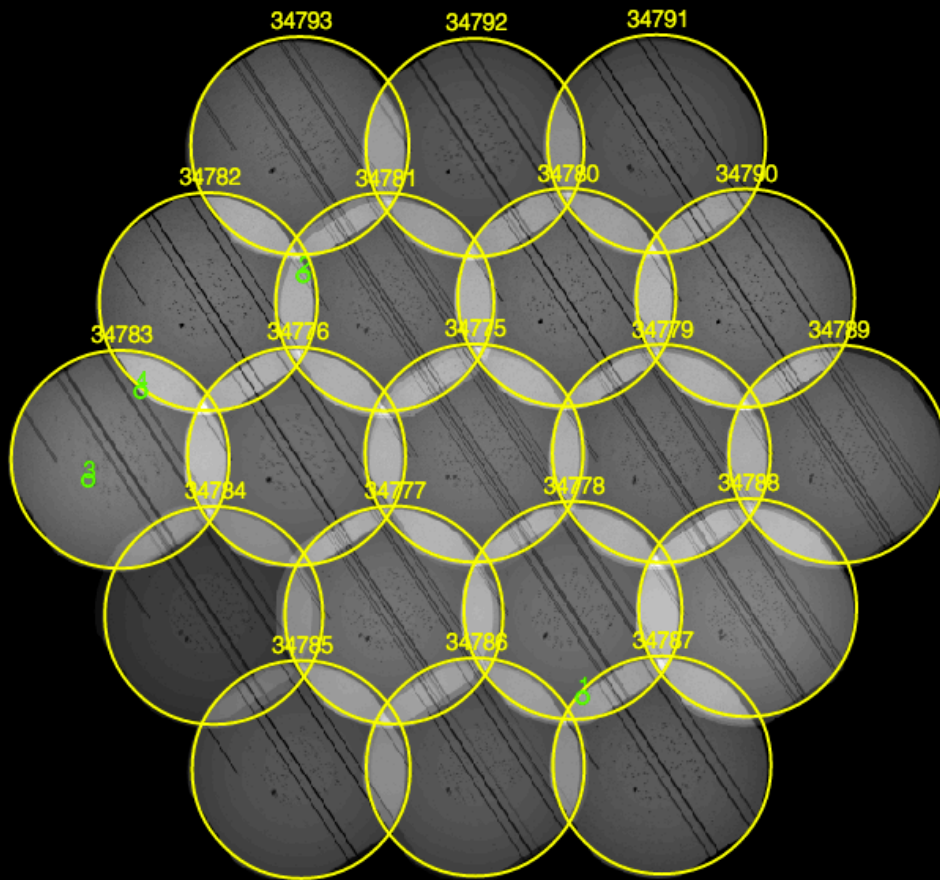
(Evans+ 2016, GCN Circ. 19747)



- 19 tiling observation (800 s per tile)
- $T_0 + 3.9$ ks to $T_0 + 46.5$ ks
- Six X-ray sources (all ID)
 - Two stars
 - Three quasars
 - One known XRT source
- No transient sources in UVOT
- 3- σ X-ray UL: $(3.1-4.3) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.3-10 keV; typical AGN spectrum)
- 3- σ optical UL: 18 mag (u)

IceCube-161103: XRT Follow-up

(Evans+ 2016, GCN Circ. 20125)

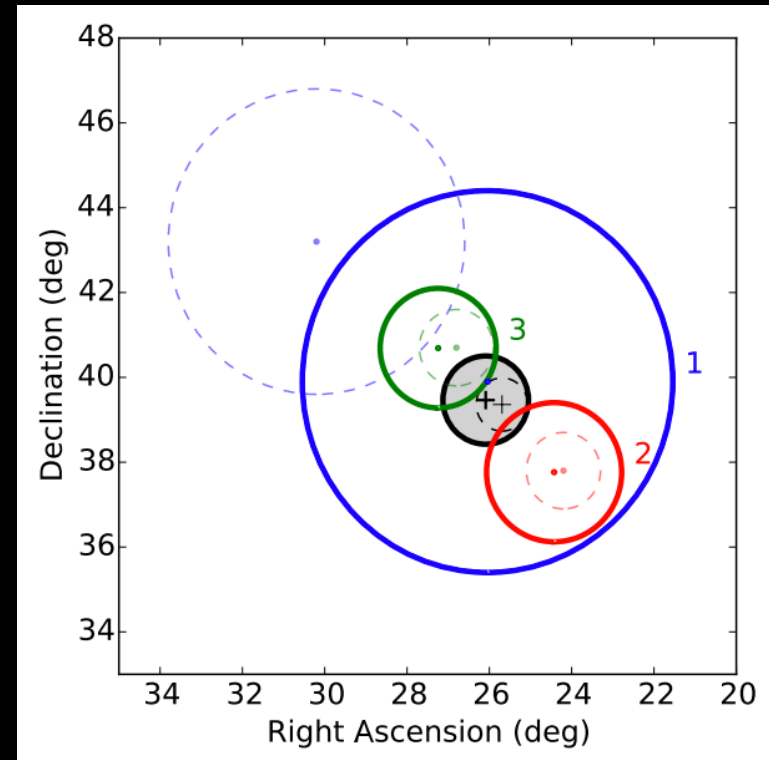


- 19 tiling observation (150-250 s per tile)
- $T_0 + 17.5$ ks to $T_0 + 35.5$ ks
- Four X-ray sources (all un-ID), but all faint (fainter than the RASS limits)
- $3\text{-}\sigma$ X-ray UL: $(8.1\text{-}12) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.3-10 keV; typical AGN spectrum)

IceCube-160217: Triplet event

(Aarten+ 2017, astro-ph/1702.06131)

- T_0 : 2016-02-17 19:21:31 (arrival time of the first event)
- All three events arrived within less than 100 s
- Swift-BAT, Fermi-LAT, HAWC
- Swift-XRT/UVOT, ASAS-SN, LCO, MASTER, VERITAS

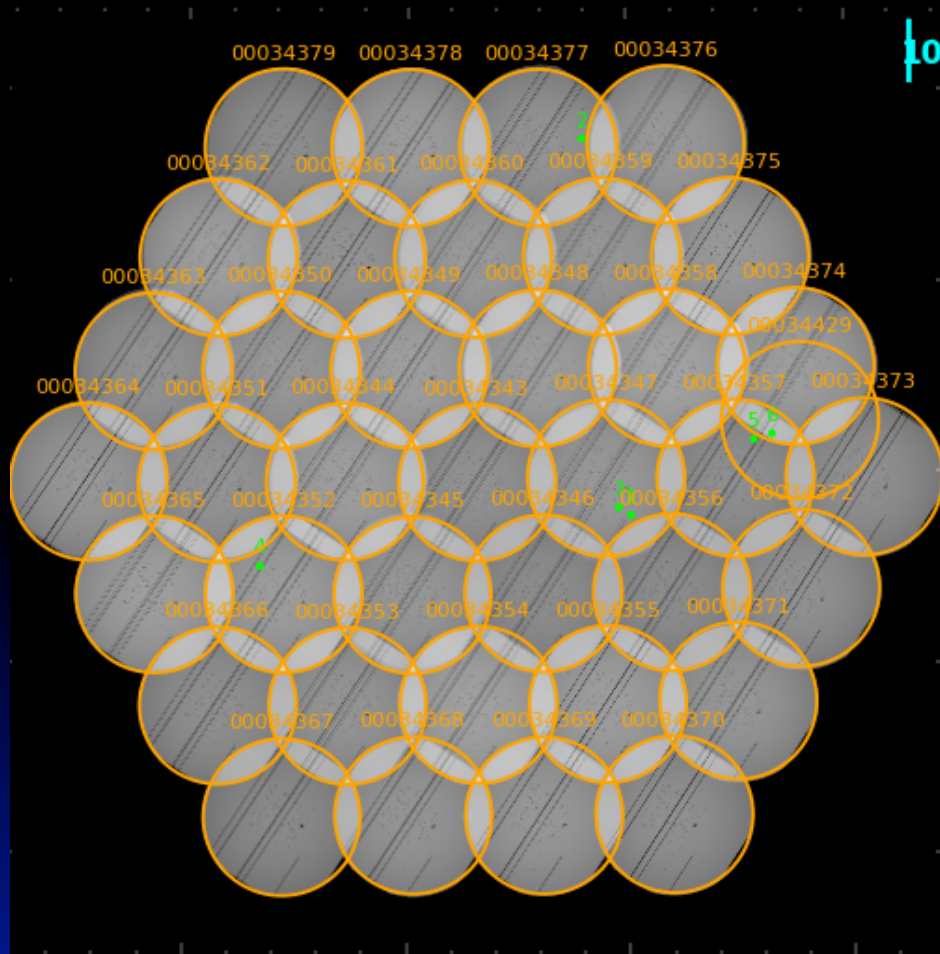


ID	IceCube Event ID	Alert ID	Time (s)	R.A. (°)	Dec. (°)	Error (°)	Deposited Energy (TeV)
1	62474825	7, 8	0	26.0 [30.2]	39.9 [43.2]	4.5 [3.6]	0.26
2	62636100	7	+55.4	24.4 [24.2]	37.8 [38.4]	1.6 [0.9]	1.1
3	62729180	8	+87.3	27.2 [26.8]	40.7 [40.7]	1.4 [0.9]	0.52

IceCube-160217: Triplet event

XRT/UVOT Follow-up

(Aarten+ 2017, astro-ph/1702.06131)

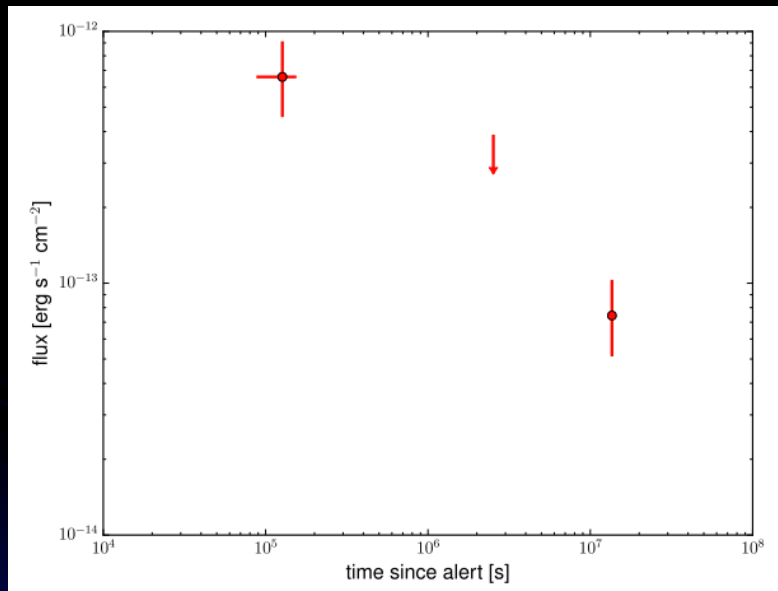


- 37 tiling observation (300-400 s per tile)
- $T_0 + 22.6 \text{ hr} - T_0 + 1.2 \text{ day}$
- Six X-ray sources (one un-ID)
 - One AGN
 - Four stars
- No transient sources in UVOT
- 3- σ X-ray UL: $(6.3-8.9) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.3-10 keV; typical AGN spectrum)
- 3- σ optical UL: 17.4 mag (u)

IceCube-160217: Triplet event

Un-ID X-ray source X6

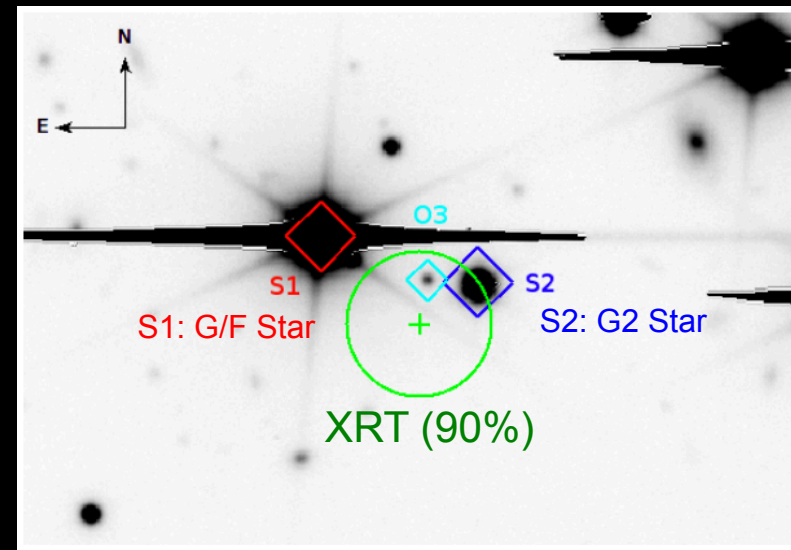
Follow-up XRT observations of X6:
 $T_0 + 29$ day (1 ks) and $T_0 + 156$ day (8.6 ks)



- $t^{-0.5}$ decay (over 5 months)

Unlikely to be a GRB afterglow

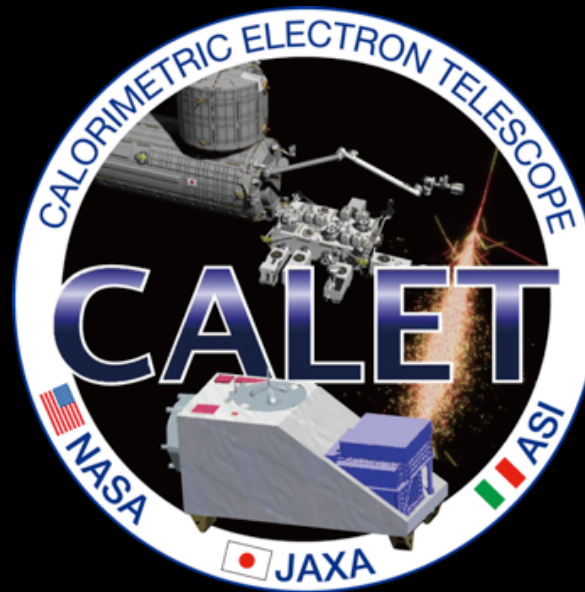
Keck/LRIS image



X6: Stellar flare? Distance AGN?
But **unlikely related to the**
IceCube-160217

CALET

(CALorimetric Electron Telescope)

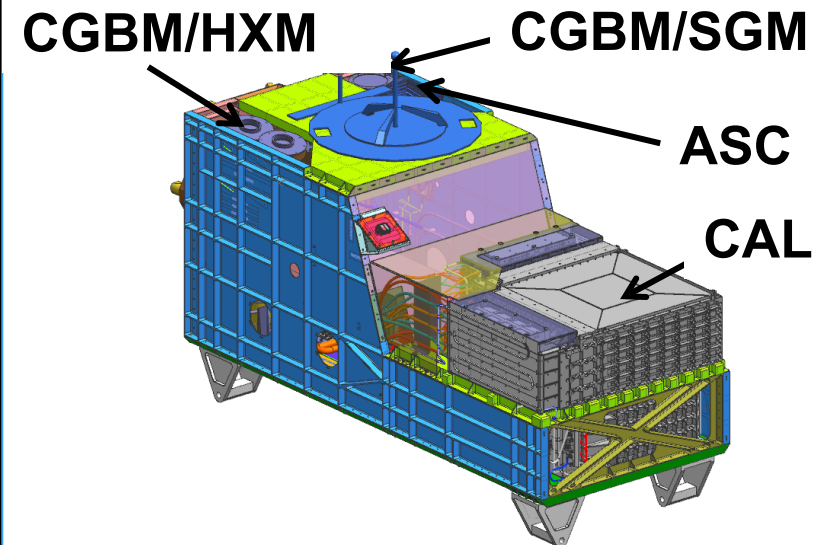
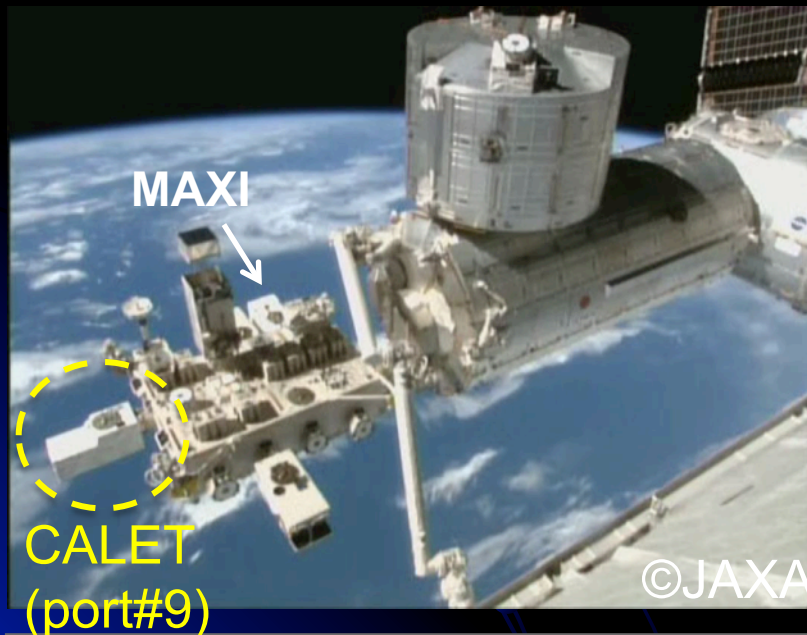


CALET

(CALorimetric Electron Telescope)

Observatory of high energy electrons and gamma-rays

- Observation of high energy cosmic-rays
- All sky gamma-ray survey (> 10 GeV)
- High energy transients (GRBs, SGRs, ...)



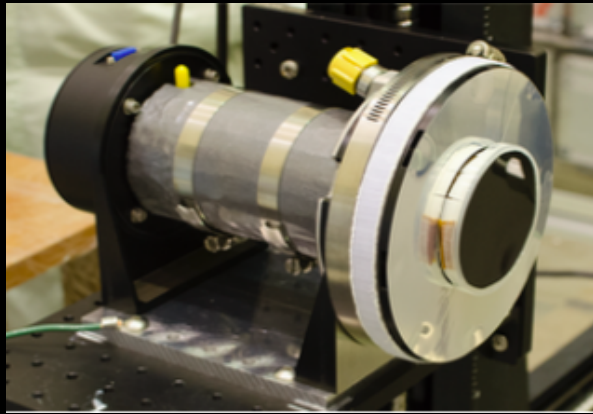
Scientific instruments:

- **CALorimeter (CAL)**
 - Electrons: 1 GeV – 20 TeV
 - Gamma-rays: 10 GeV – 10 TeV (1 GeV – 10 TeV)
 - Protons and Heavy ions: (~ 10 GeV – 1 PeV)
- **CALET Gamma-ray Burst Monitor (CGBM)**
 - Hard X-ray Monitor (HXM): 7 keV – 1 MeV
 - Soft Gamma-ray Monitor (SGM): 100 keV – 20 MeV

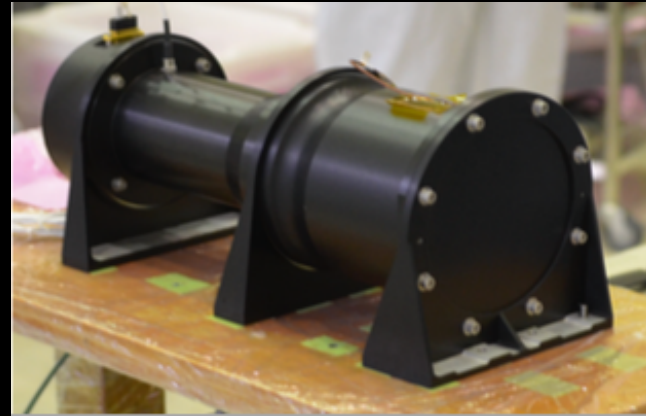
CALET

Gamma-ray Burst Monitor (CGBM)

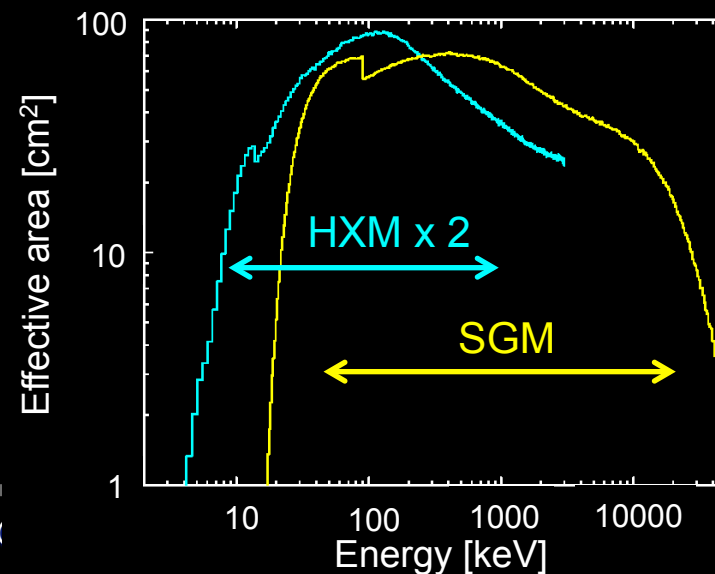
Hard X-ray Monitor (HXM)



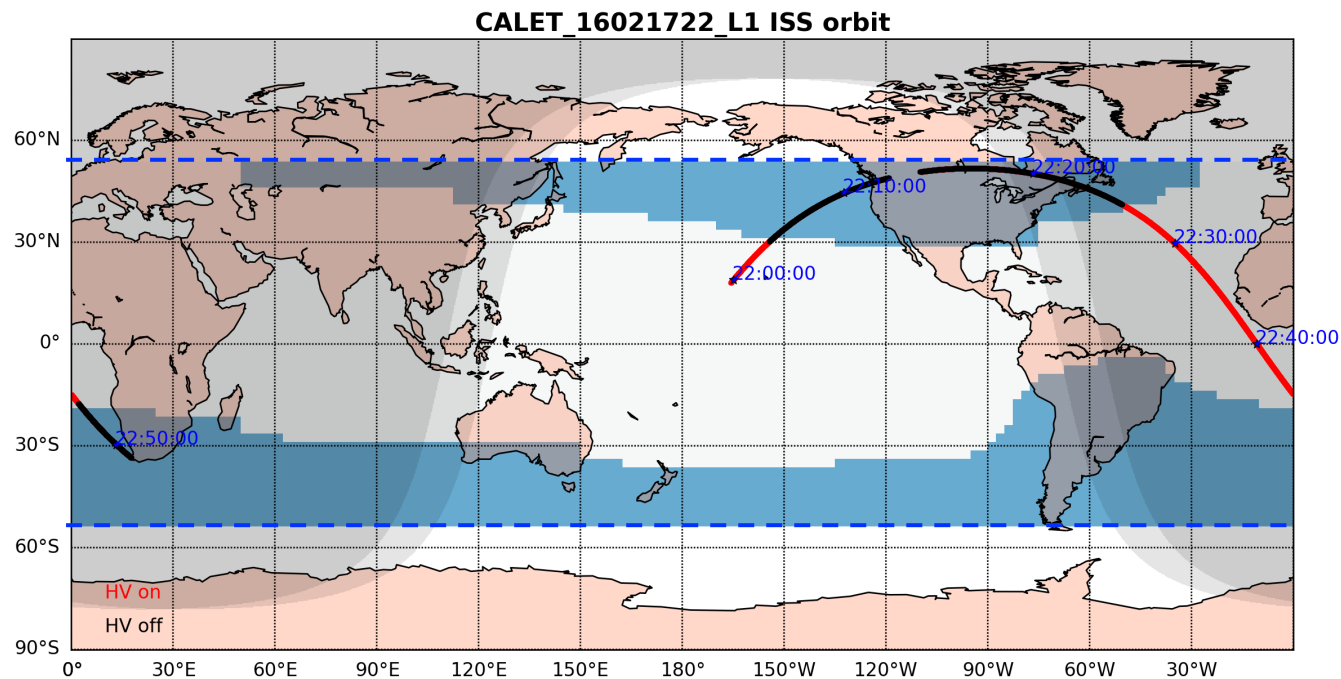
Soft Gamma-ray Monitor (SGM)



	HXM	SGM
Detector (Crystal)	LaBr ₃ (Ce)	BGO
Number of detector	2	1
Diameter [mm]	61	102
Thickness [mm]	12.7	76
Energy range [keV]	7-1000	100-20000
Energy resolution@662 keV	~3%	~15%
Field of view	~3 sr	~2p sr



CGBM Observation Efficiency



HV-on time: ~60%

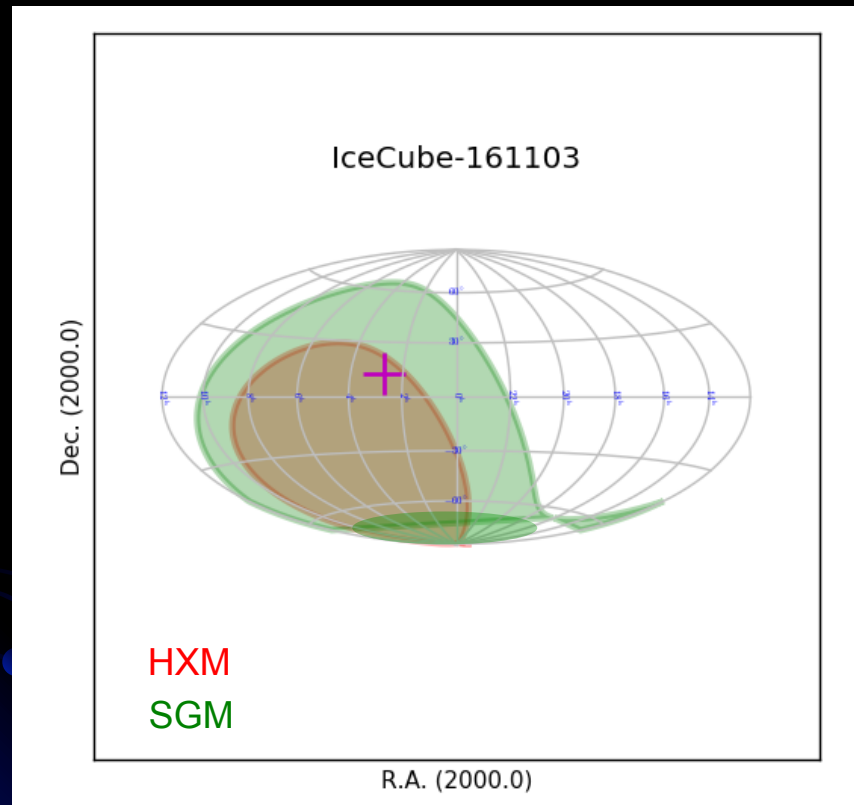
Summary of IceCube Event Search by CGBM

Trigger Time	Type	Comment	GCN
2016-07-31 01:55:04.00	HESE/EHE	Below horizon	-
2016-08-06 12:21:33.00	EHE	HV-off	-
2016-08-14 21:45:54.00	HESE	HV-off	-
2016-11-03 09:07:31.12	HESE	Non-detection	20162
2016-12-10 20:06:40.31	EHE	Non-detection	20253

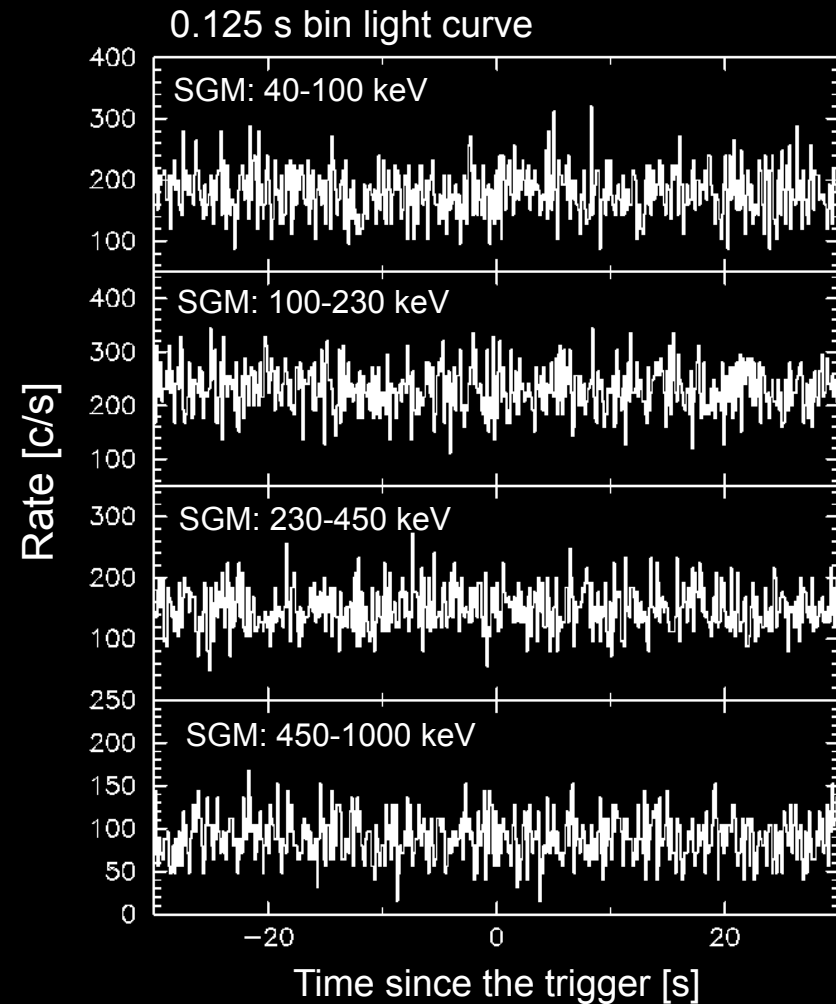
- HESE: High Energy Starting Event; a single-neutrino with an energy in the sub-PeV to 1 PeV
- EHE: Extremely High Energy; a single-neutrino with an energy higher than several hundred TeV

IceCube-161103

(Kawakubo et al. GCN Circ. 20162)



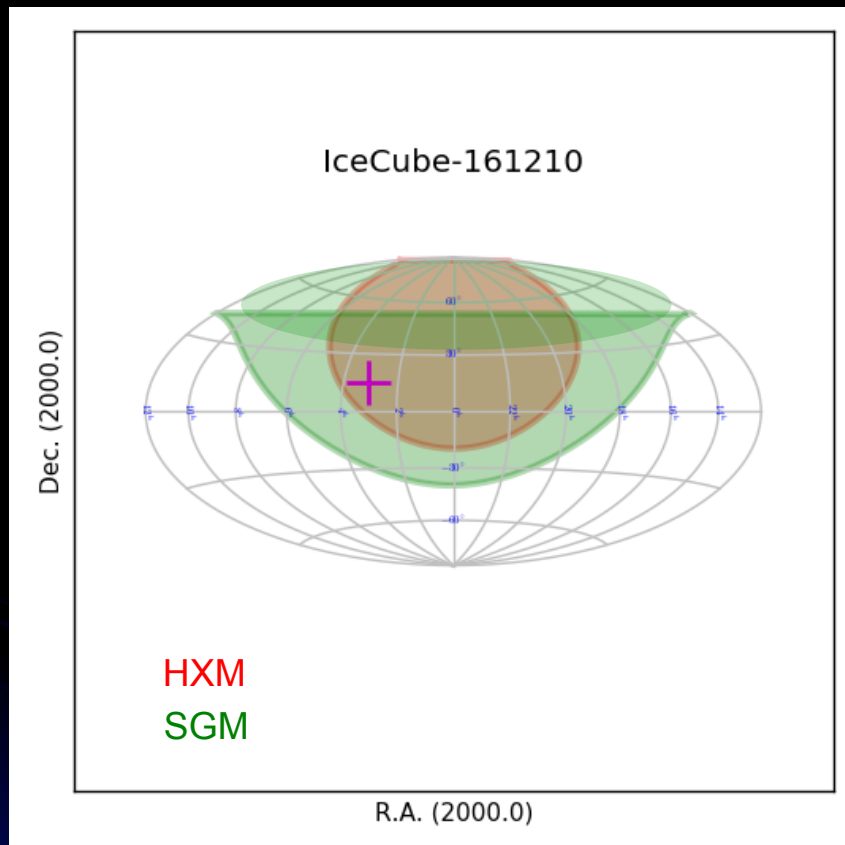
7 sigma upper limit (50-1000 keV; 1 s):
- $5.0 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$ (assuming E^{-2})



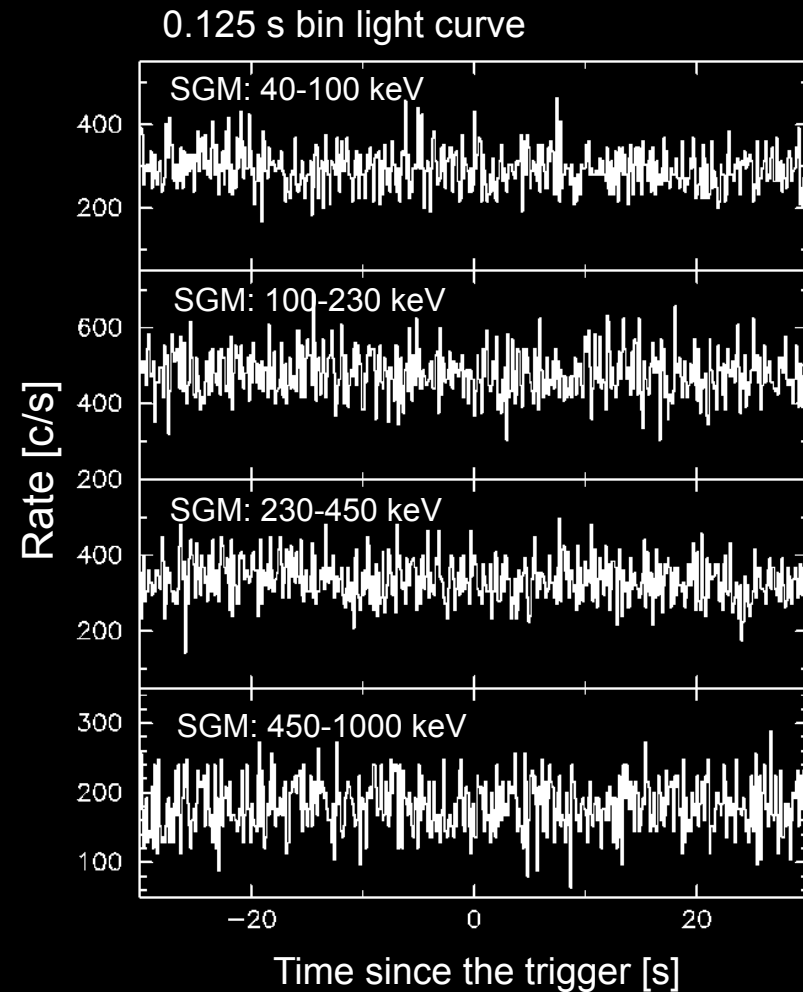
No significant emission $>4.2 \sigma$

IceCube-161210

(Kawakubo et al. GCN Circ. 20253)

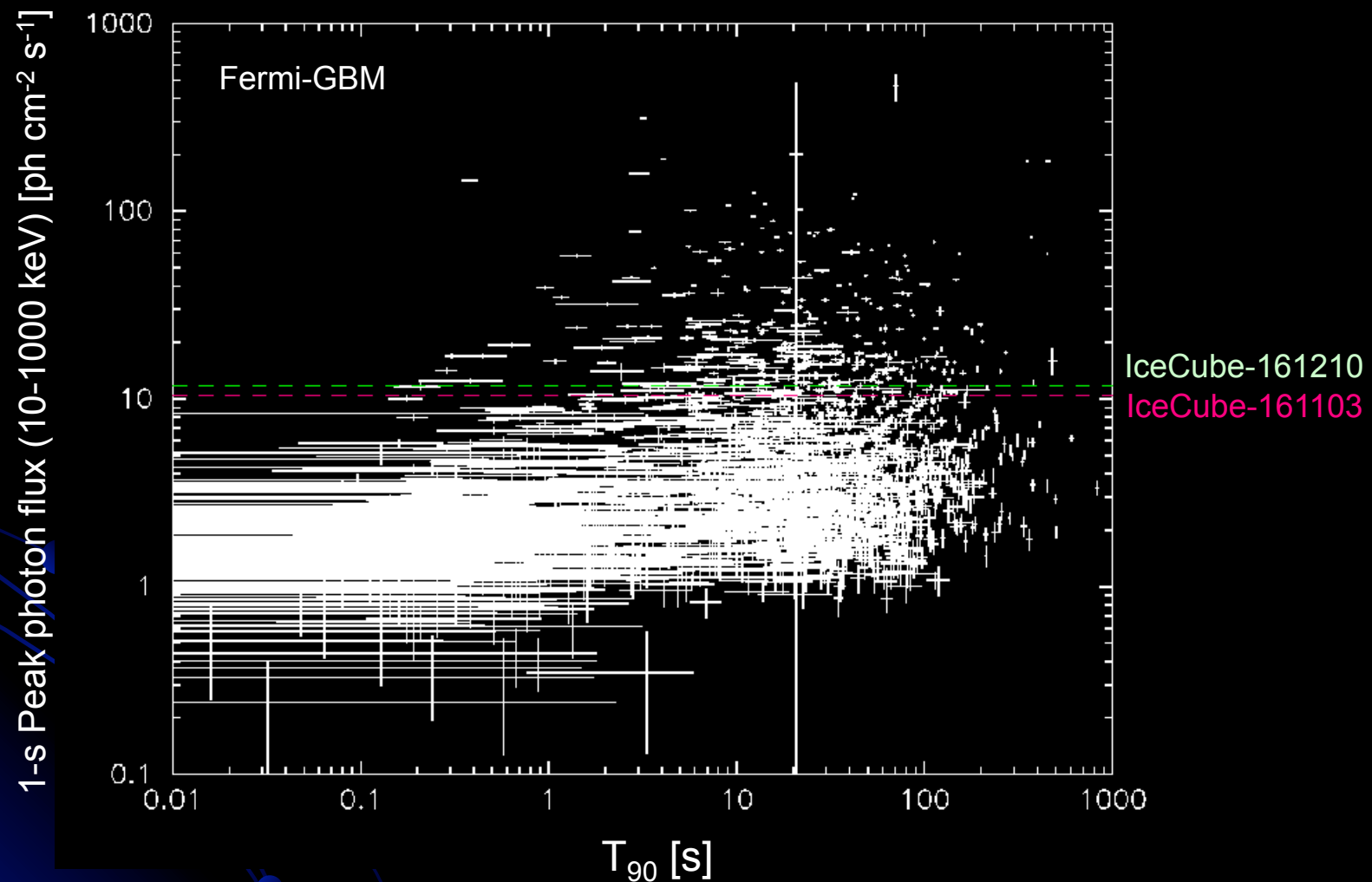


7 sigma upper limit (50-1000 keV; 1 s):
- $5.6 \times 10^{-7} \text{ erg cm}^{-2} \text{ s}^{-1}$ (assuming E^{-2})



No significant emission $>3.1 \sigma$

Comparison to GRBs



Summary

- EM counterpart search based on the alert from neutrino detectors has just began.
- No success for identifying the EM counterpart of neutrino events.
- Space observatories such as Swift and CALET are ready to follow-up neutrino events.