LIGO

Swift Follow-up Observations of Candidate Gravitational-wave Transient Events

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on behalf of
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LIGO Scientific Collaboration and the Virgo Collaboration

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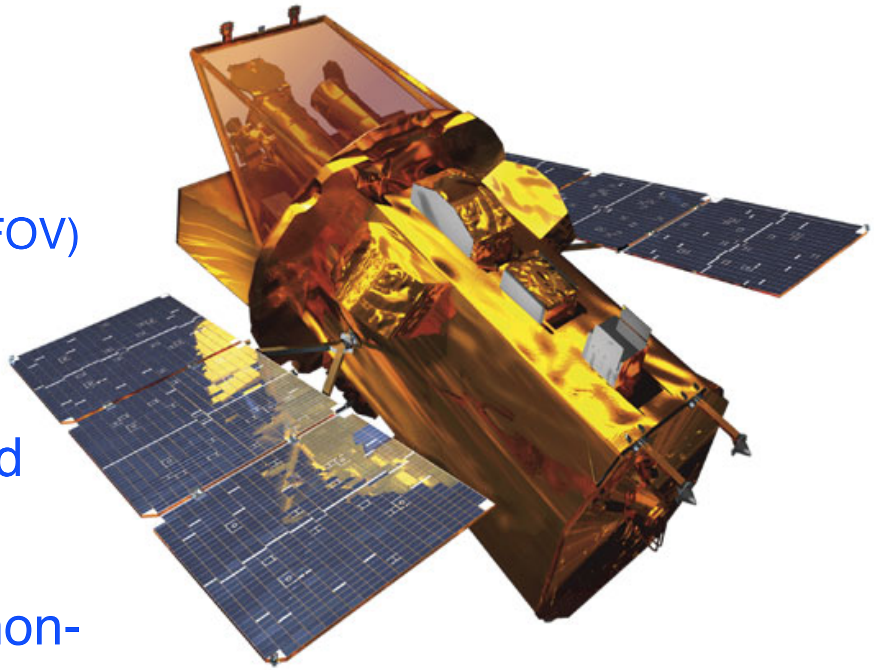
Scientific rationale

- Gravitational-wave (GW) sources are reasonably likely to emit in the Electromagnetic (EM) too
  - » UV/optical afterglows from supernovae/GRBs have been observed peaking on time scales of hours to days
  - » prompt X-ray outbursts, bright X-ray afterglows have been observed in connection with core-collapse supernovae, GRBs
- Also likely for GW sources to be nearby (so that to be detected with initial instruments), EM detection generally easier
- EM signatures may be missed (e.g. beaming effects, simply because not looking at the right time at the right place)
- The scientific payoff in case of a discovery will be tremendous
  - » reinforce GW detection
  - » provide position of the source with much reduced error circle
  - » host galaxy, distance
- Connecting observations from many wavelengths and GWs → place GW observations in astrophysical and cosmological context

The Swift observatory

- NASA's Gamma-Ray Burst mission
- Broad wavelength sensitivity, rapid response
- Three telescopes on one platform:
  - BAT: γ-rays (15-150keV), wide field of view (FOV)
  - XRT: X-rays (0.3-10keV), 0.4x0.4 deg^2 FOV
  - UVOT: 170-600nm, 0.28x0.28 deg^2 FOV
- Autonomous fast slewing (~ 2 min)
- Pre-planned science timelines generated daily
- Re-pointing can be achieved in ~2 mins (for Swift triggers) and ~0.5-4.0 hours (non-Swift triggers)



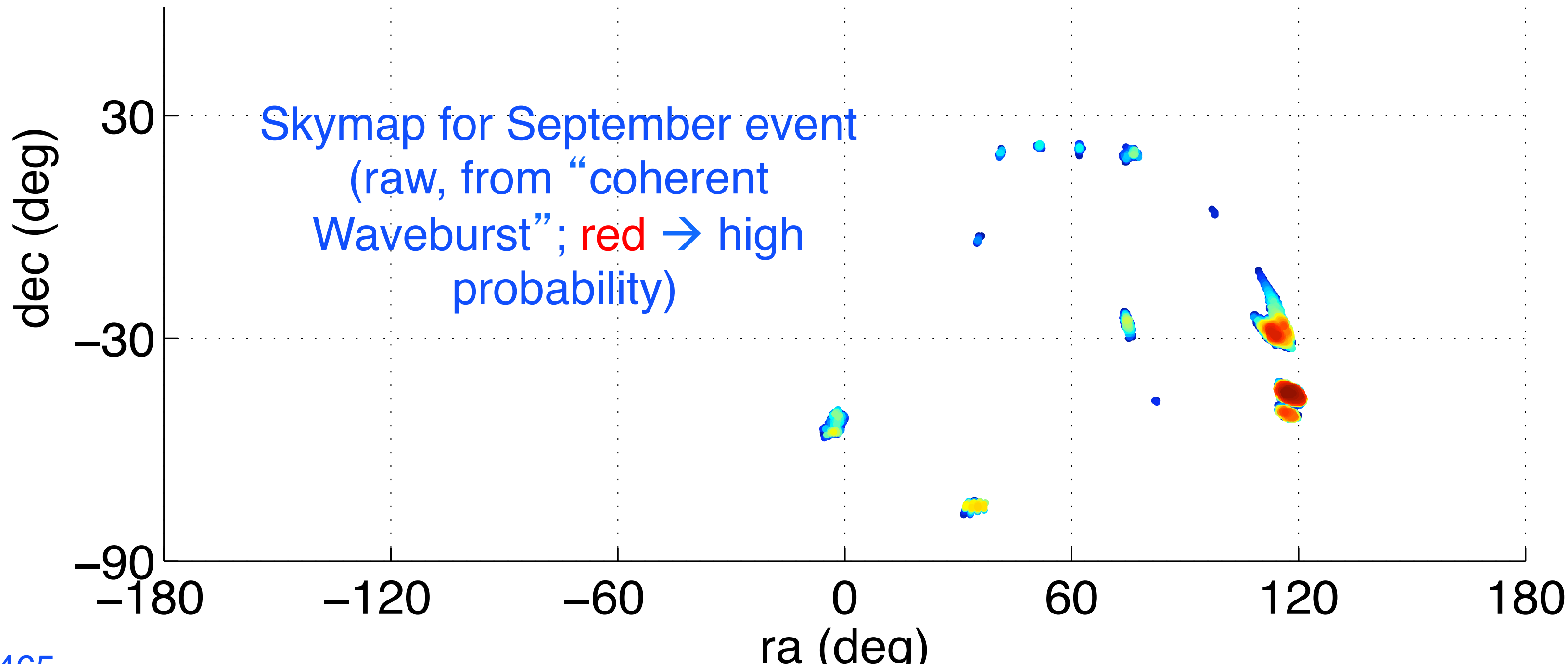
- Any target remains visible for 25-45 minutes at a time, and is occulted for the remainder of the 96 minute orbit
- Provided few pointings to GW transient candidates via a Target-of-Opportunity (ToO) program in 2009-2010

GW event selection

- LIGO-Virgo run time:
  Dec 17, 2009 to Jan 08, 2010
  Sep 02, 2010 to Oct 20, 2010
- Search methods invoked: un-modeled bursts and compact binary coalescences, all running in low latency (~10min)
- Primary selection criterion: false alarm rate (FAR) corresponding to a candidate event less than 1 in 35 days
- Other considerations: event must have reasonable chance (20%, or greater) of getting localized within a nominal of five (0.4x0.4 deg^2) Swift fields
- Events must pass all automated and manual data quality checks
- Two events passed selection criteria:
  January 07, 2010 8:46 UTC (thresholds lowered to collect a sample)
  September 16, 2010 6:42 UTC (later revealed to be a blind injection)

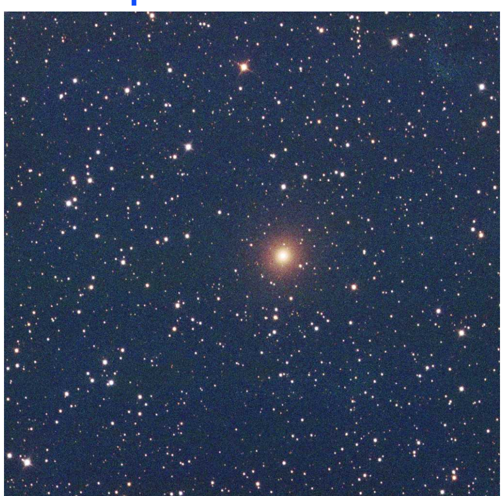
Swift tiling

- GW detectors (in their 2009-2010 run) provided source localization at the O(100) deg^2 level for triggers near the threshold
- Meeting the O(1) deg^2 constraints for Swift observations: use galaxy targeting within 50Mpc (White et al 2011)
- Recalculate sky map probabilities (from GW measurement alone) to reflect prior on galaxy, blue luminosity and distance (and renormalize)
- Rank tiles according to the new probability and observe the top 5 with Swift

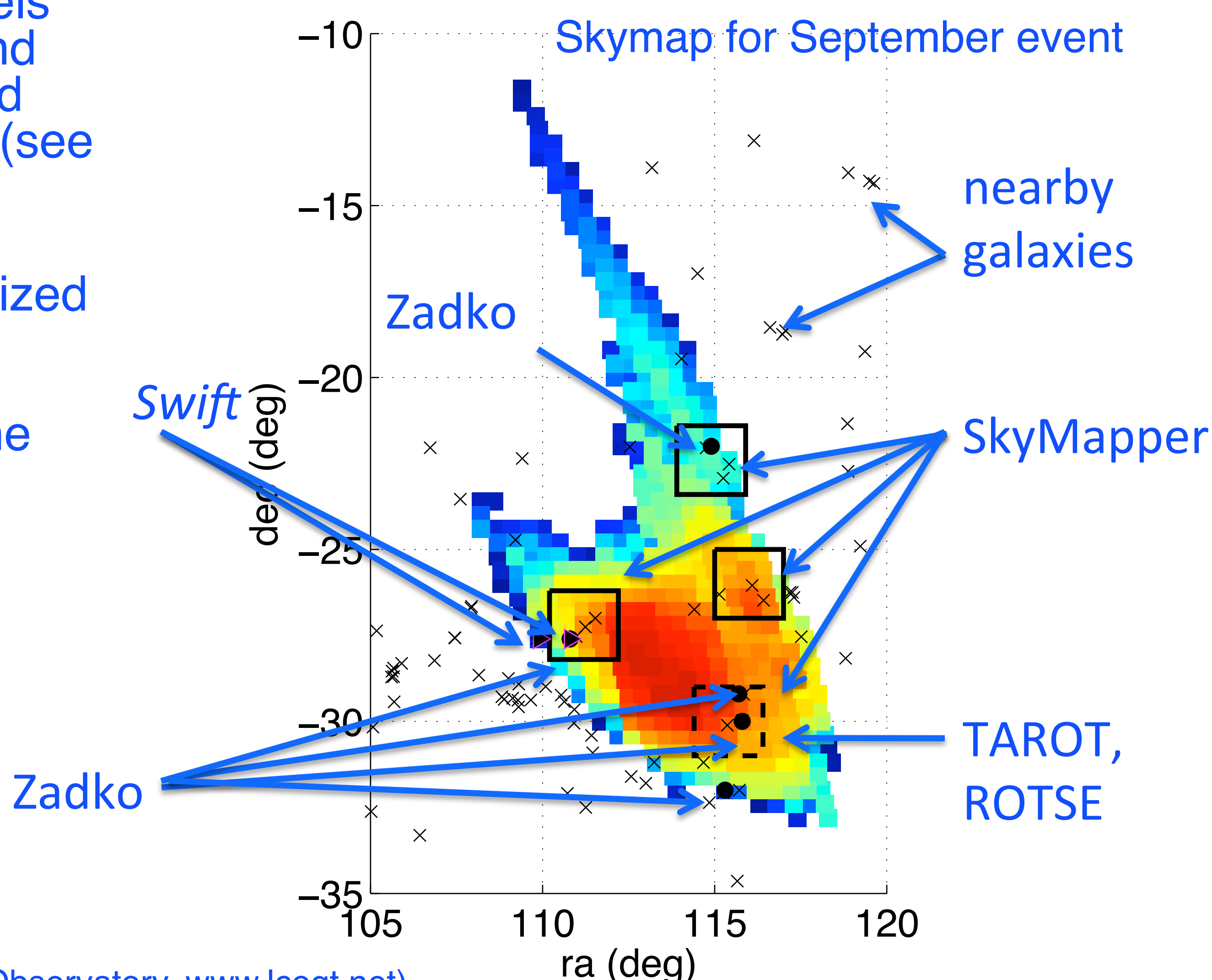


Regions to be imaged

- Top probability pixels imaged by Swift and other ground-based optical telescopes (see poster by Marica Branchesi)
- Swift pixels maximized probability on NGC2380 and ESO492-010 for the September event

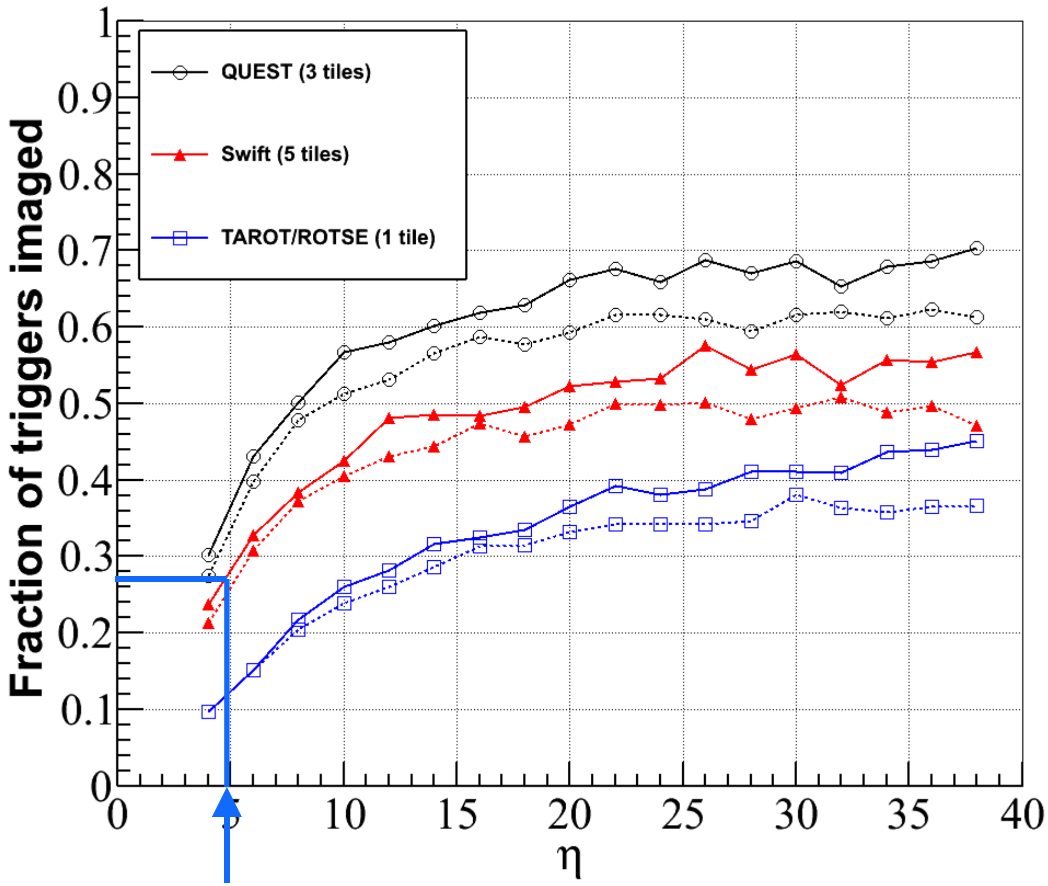


NGC2380 (Credit: Las Cumbras Observatory, www.lcogt.net)



Probability to image true source

- Monte Carlo simulations of un-modeled bursts originating from known galaxies within 50Mpc and undergoing the same analysis as the one leading to Swift observations were used to measure the ability of the pipeline to image true source location



LSC+Virgo, A&A 539, A124 (2012)

η=4.34 for September event (coherent network SNR)

Main Search Form

Browse Query Results

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swift

swiftmastr

Click mission tabs (middle tab level) to display table tabs. Move cursor over tabs to see more information.

Table Legend:

Display all parameters for a row

Sort by a column in order: 1,2,3 Sort by column in reverse order: 3,2,1 / Current table sort

Services links: O: Digitized Sky Survey image, R: ROSAT All-Sky Survey image, N: NED objects near coordinates,
S: SIMBAD objects near coordinates, D: get list of data products, H: analyze data products using Hera,
B: ADS bibliography holdings, G: GRB Coordinate Network (GCN) notices, F: FOV plot for observation

Data Products: Click checkbox to add row to Data Product Retrieval List

Swift Master Catalog (swiftmastr) Bulletin

Search radius used: 40.00 '

Select All	Related Links	Services	name	obsid	ra	dec	start time	processing date	xrt exposure [s]	uvot exposure [s]	bat exposure [s]	archive date	Search Offset ['] from (target)
	BAT UVOT XRT	O R N S D H	PGC580623	00031575001	05 56 03.01	-40 57 31.0	2010-01-07 13:01:20	2010-01-13	1988.29100	1978.23600	2022.00000	2010-01-14	23.349 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J089.1-40.8	00031576001	05 56 33.13	-40 48 07.2	2010-01-07 14:31:42	2010-01-13	1701.26600	1690.83900	1735.00000	2010-01-14	31.280 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J088.6-40.8	00031577001	05 54 23.43	-40 48 51.9	2010-01-07 15:55:31	2010-01-13	1809.49300	1795.06700	1841.00000	2010-01-14	11.982 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J088.1-40.8	00031578001	05 52 17.09	-40 47 40.8	2010-01-07 17:21:21	2010-01-13	1988.41300	1985.15300	2021.00000	2010-01-14	23.021 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J088.8-41.2	00031579001	05 54 49.55	-41 09 36.1	2010-01-07 20:22:00	2010-01-13	1995.82100	1991.48600	2012.00000	2010-01-14	13.394 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J088.1-40.8	00031578002	05 52 15.14	-40 46 56.8	2010-01-11 13:15:56	2010-01-17	1384.01900	1382.11600	1419.00000	2010-01-18	23.731 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J089.1-40.8	00031576002	05 56 30.70	-40 46 08.1	2010-01-11 15:56:01	2010-01-17	1130.79500	1125.89800	1146.00000	2010-01-18	31.678 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J088.6-40.8	00031577002	05 54 23.70	-40 45 32.8	2010-01-11 17:32:01	2010-01-17	1623.21600	1612.71500	1640.00000	2010-01-18	15.132 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	J088.8-41.2	00031579002	05 55 05.43	-41 10 02.6	2010-01-11 18:02:01	2010-01-17	1455.17800	1438.79200	1521.00000	2010-01-18	15.902 (88.5, -41.0)
	BAT UVOT XRT	O R N S D H	PGC580623	00031575002	05 56 00.93	-40 55 08.2	2010-01-11 19:08:00	2010-01-17	1623.21600	1614.28200	1640.00000	2010-01-18	23.344 (88.5, -41.0)

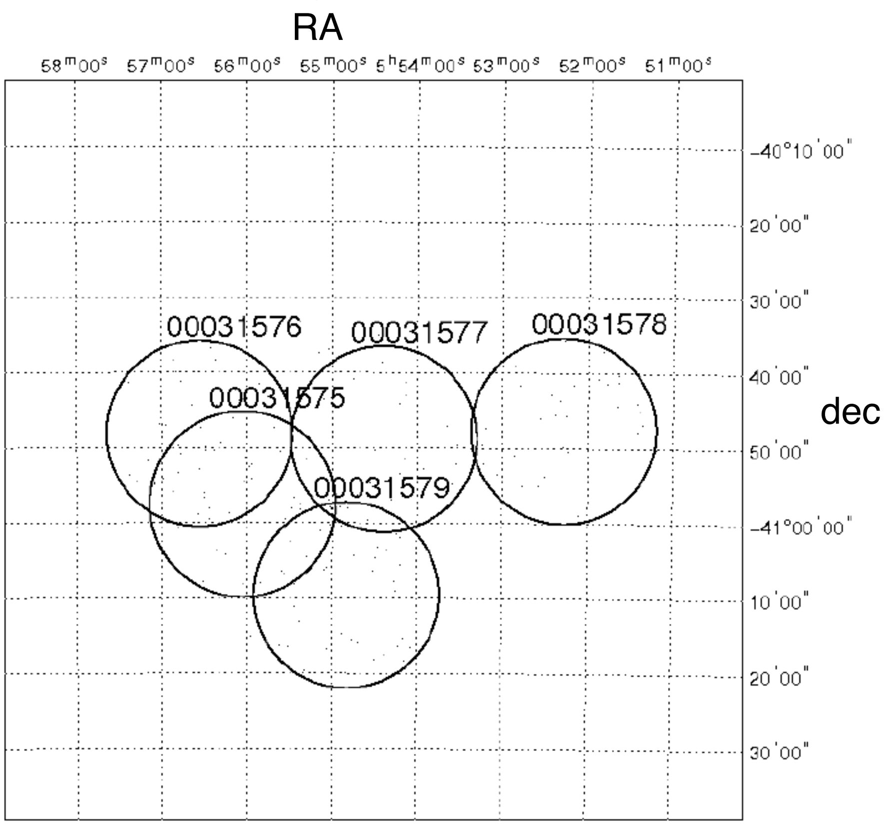
10 rows retrieved from swiftmastr

XRT analysis

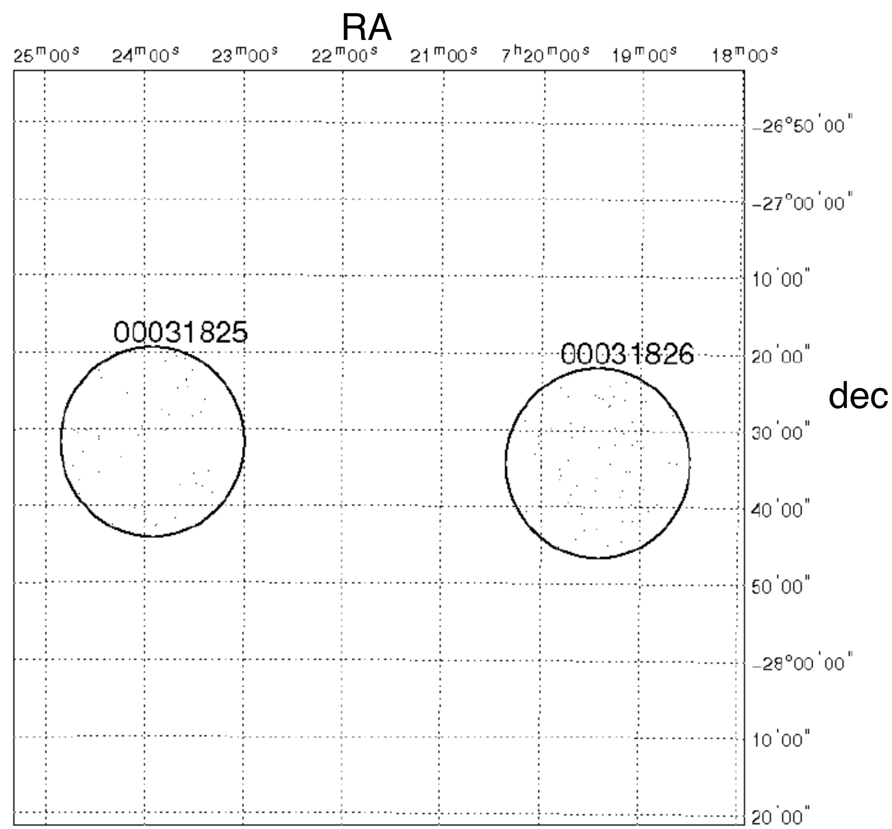
- Combined all of the data per field and produced a combined image and exposure map
- Used source detection and point spread function fitting code to identify sources in the field
  - Used a sliding-cell detection algorithm with a cell size fixed at 21x21 pixels
- No sources were found at SNR threshold of 3
- A reduced threshold search was performed at 1.5σ
  - A Bayesian approach determined the probability of there being a source present
- This approach assumes a homogeneous background, and does not correct for the exposure map
- Several reduced-threshold sources were identified
  - All were few photon sources
  - Used PIMMS (http://heasarc.nasa.gov/Tools/w3pimms.html) to convert count rates to fluxes– resulting values typically in the 10^{-14} – 10^{-13} ergs cm^{-2} s^{-1} range

XRT images

January event

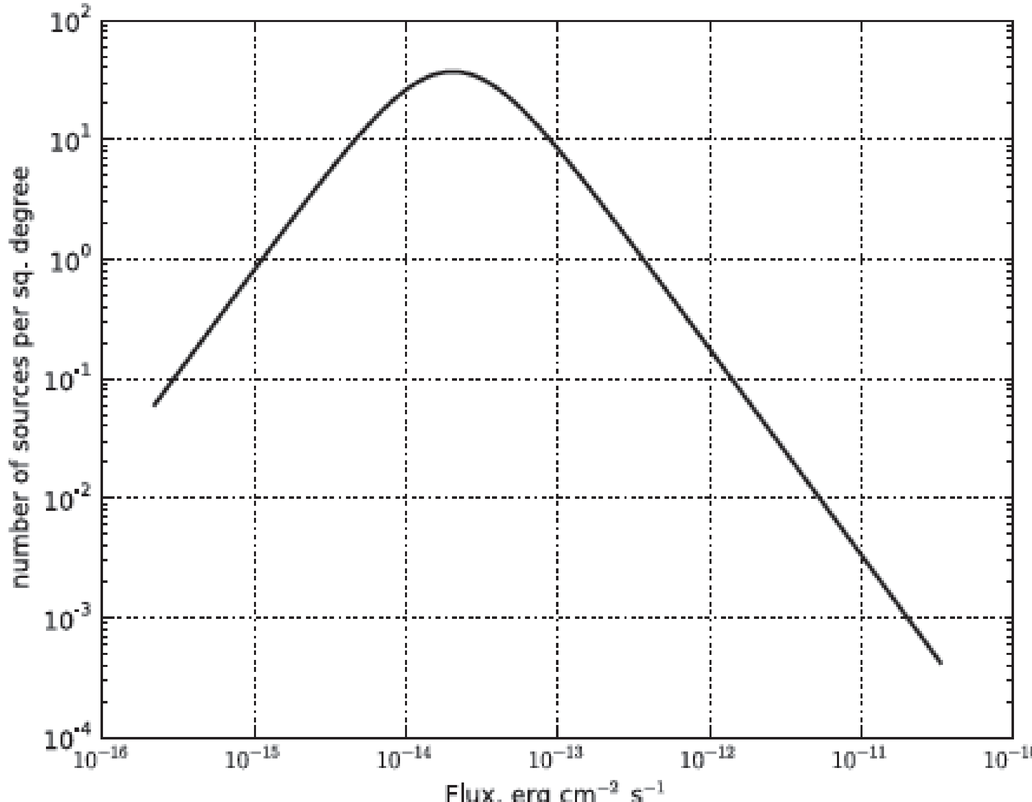


September event



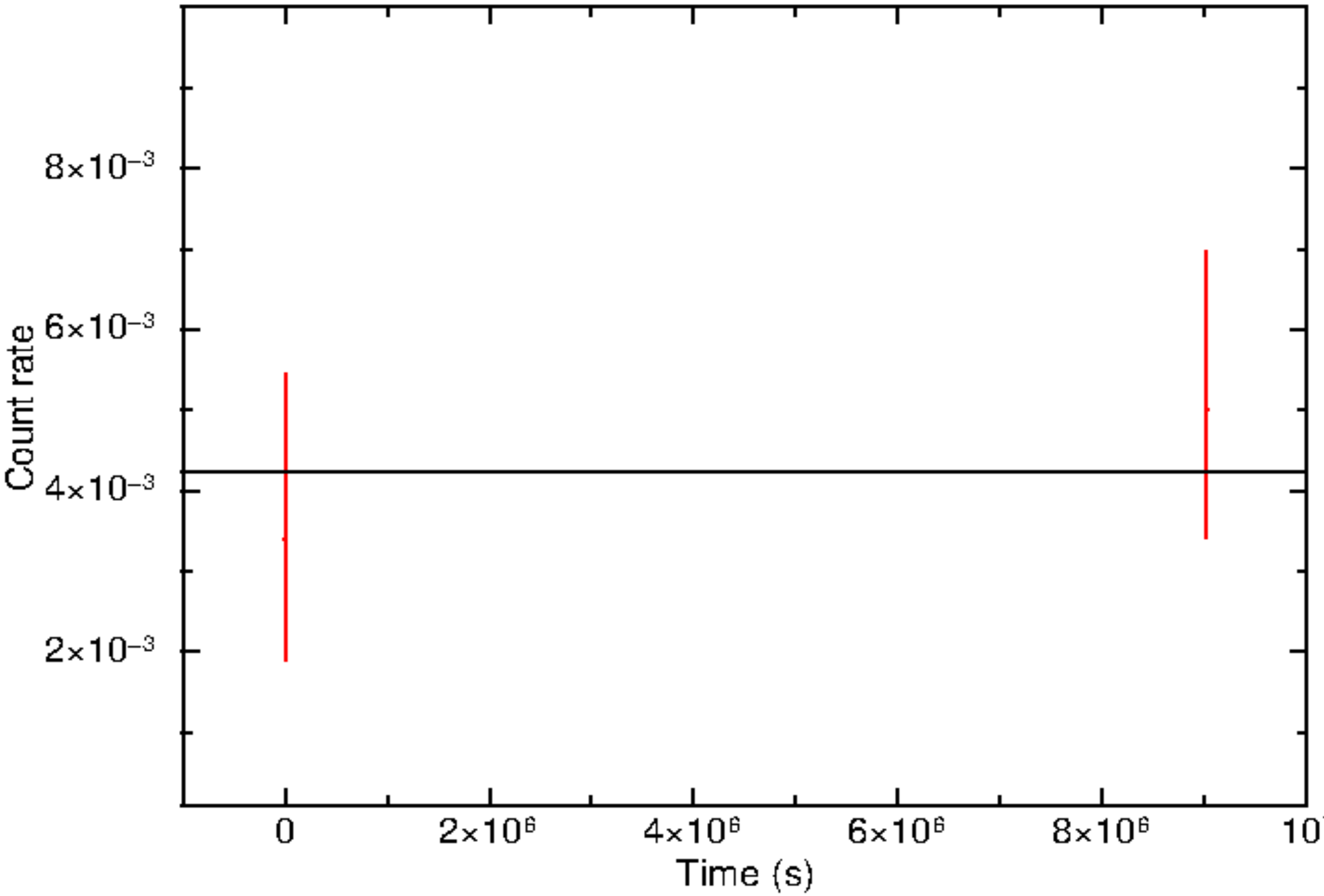
Serendipitous XRT sources

- Assess the likelihood of serendipitous source detection using the 2XMMi-DR3 catalog and assuming homogenous distribution of sources
- In order to compare with 2XMM data we had to take into account the different effective area (w/r/t Swift)



- This yielded the number of expected serendipitous sources for each Swift-XRT reduced-threshold source
  - » All sources consistent with serendipitous detections (on a source-by-source basis)
  - » For the January event we expected a total of 7.5 serendipitous sources with 8 detections
  - » For the September event we expected 17 serendipitous sources with 12 detections

Variability test



- Poor man's light curve: check for consistency with a straight line for the two measurements
- No significant (beyond 3σ) variation seen

Summary of XRT detections

TABLE 3
THE REDUCED-THRESHOLD DETECTIONS IN THE X-RAY DATA FOR THE JANUARY EVENT.

Source #	Right ascension (RA) (J2000)	Declination (dec) (J2000)	Error ($''$ 90% conf.)	Count Rate (0.3–10 keV, ks^{-1})	N_s^1	Variability[2] significance (σ)
1	05h 55m 1.00s	-40°58′ 00.8″	4.5	$5.9^{+1.5}_{-1.2}$	0.9	2.05
2	05h 57m 4.80s	-40°54′ 45.4″	4.3	$5.9^{+2.1}_{-1.6}$	0.9	0.26
3	05h 54m 12.72s	-40°44′ 05.8″	4.3	$4.6^{+1.5}_{-1.2}$	1.3	0.45
4	05h 54m 59.29s	-40°54′ 19.6″	4.5	$3.2^{+1.3}_{-1.0}$	2.4	0.75
5	05h 51m 57.66s	-40°46′ 10.9″	5.6	$2.8^{+1.8}_{-1.1}$	2.9	1.10
6	05h 51m 41.12s	-40°44′ 46.4″	5.5	$1.4^{+1.1}_{-0.7}$	7.5	0.74
7	05h 52m 6.29s	-40°59′ 14.3″	6.5	$2.3^{+1.2}_{-0.8}$	3.9	0.91
8	05h 52m 55.88s	-40°46′ 14.9″	5.2	$2.9^{+1.7}_{-1.2}$	2.8	0.00

TABLE 4
THE REDUCED-THRESHOLD DETECTIONS IN THE X-RAY DATA FOR THE SEPTEMBER EVENT.

Source #	Right ascension (RA) (J2000)	Declination (dec) (J2000)	Error ($''$ 90% conf.)	Count Rate (0.3–10 keV, ks^{-1})	N_s	Variability significance (σ)
1	07h 23m 22.99s	-27°26′ 10.1″	4.4	$2.8^{+0.9}_{-0.7}$	2.9	1.47
2	07h 23m 22.34s	-27°33′ 09.5″	4.4	$2.3^{+1.1}_{-0.7}$	3.9	1.09
3	07h 23m 34.43s	-27°23′ 32.4″	5.4	$2.4^{+1.1}_{-0.8}$	3.7	1.47
4	07h 24m 34.95s	-27°31′ 31.1″	6.1	$1.8^{+1.2}_{-0.7}$	5.5	1.01
5	07h 23m 53.50s	-27°23′ 06.5″	4.4	$0.6^{+0.3}_{-0.2}$	17	1.30
6	07h 24m 27.89s	-27°35′ 40.8″	6.5	$2.3^{+1.1}_{-0.7}$	3.9	2.48
7	07h 23m 54.14s	-27°42′ 29.5″	6.4	$2.2^{+1.0}_{-0.7}$	4.2	1.20
8	07h 19m 30.22s	-27°45′ 42.5″	4.1	$8.8^{+3.4}_{-2.4}$	0.5	0.44
9	07h 19m 37.14s	-27°33′ 12.0″	5.2	$2.4^{+1.1}_{-0.8}$	3.7	0.60
10	07h 19m 25.72s	-27°31′ 37.0″	5.8	$0.9^{+0.6}_{-0.3}$	12	0.36
11	07h 19m 18.04s	-27°25′ 15.4″	5.0	$1.7^{+0.9}_{-0.6}$	5.9	0.97
12	07h 19m 41.92s	-27°39′ 58.1″	5.0	$1.6^{+1.2}_{-0.7}$	6.4	1.02

XRT detections were consistent with expectation for serendipitous sources. None showed significant variability

UVOT analysis

- The 20 reduced-threshold XRT detections were also examined in Swift's UVOT
  - 4 of them fell off the UVOT field (it is smaller w/r/t XRT's)
  - 7 of them had no counterparts in the UVOT
  - 6 of them were also found in the UVOT but had corresponding sources in the Digital Sky Survey and showed no photometric variation
  - 3 of them had marginal/spurious UVOT counterparts
- No XRT detection corresponds to an optical transient or a variable source

Joint event significance

- Measurement involves
  - » η : GW Burst statistic (a measure of signal-to-noise ratio)
  - » $p_m(\Omega)$: sky-map, where $\Omega \equiv$[RA,dec]
  - » S : X-ray flux observed by Swift, Ω - location of X-ray counterpart
- Introduce joint detection statistic to be the logarithm of the likelihood ratio:

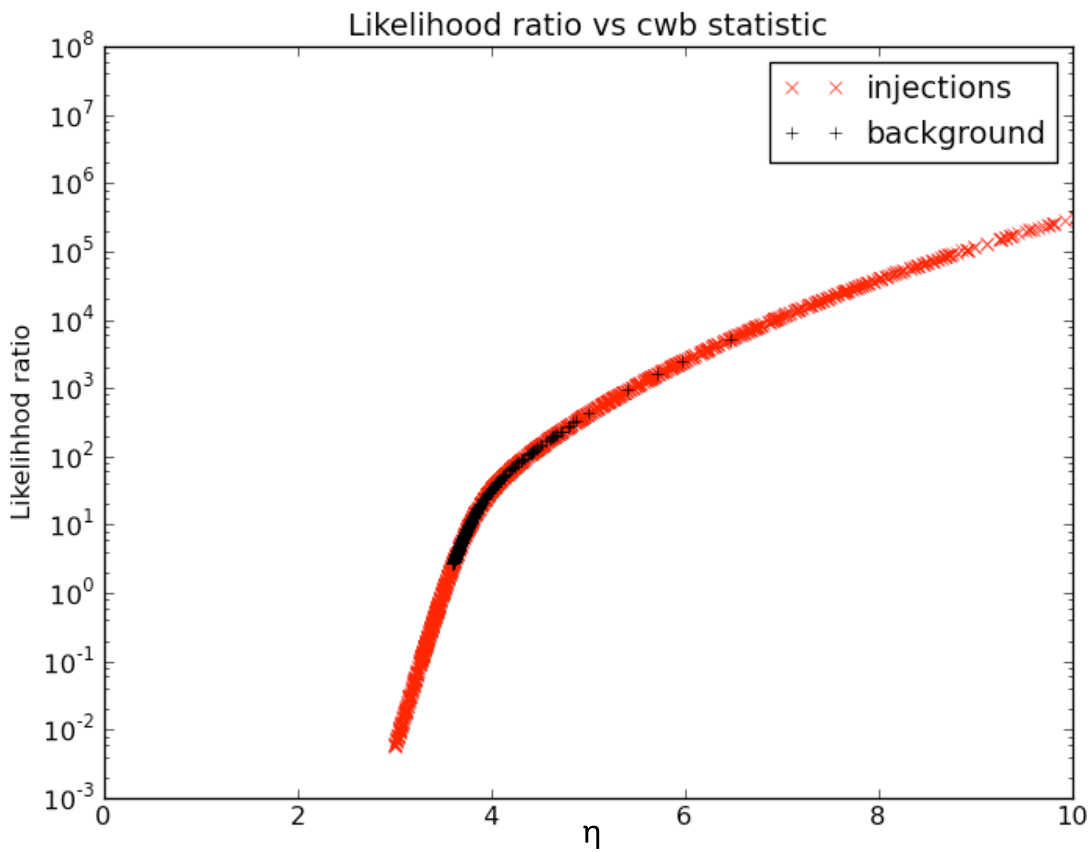
$$\Lambda_{joint}(\eta,S,\Omega) = \Lambda_{GW}(\eta)\ \Lambda_{EM}(S)\ \Lambda_{cor}(\Omega)$$

where $\Lambda_{GW}=p(\eta|\mathrm{signal})/p(\eta|\mathrm{noise})$, $\Lambda_{EM}(S) = p^{-1}_0(S)$ and $\Lambda_{cor}(\Omega) = p_m(\Omega)$

- $\Lambda_{GW}(\eta)$ can be measured from GW data and simulations
- $\Lambda_{EM}(S)$ can be estimated from the 2XMMi-DR3 catalog of serendipitous sources
- $\Lambda_{cor}(\Omega)$, which measures the positional correlation between GW and EM signals, because of the small number of pixels that were observed it was found to have small effect and dropped from the detection statistic of the search

Gravitational-wave likelihood [$\Lambda_{GW}(\eta)$]

- Used GW background events to measure p(η| noise)
- Used GW simulations sampling known galaxies within 50Mpc [~same set as in LSC +Virgo, A&A 539, A124 (2012)] in order to measure p(η|signal)

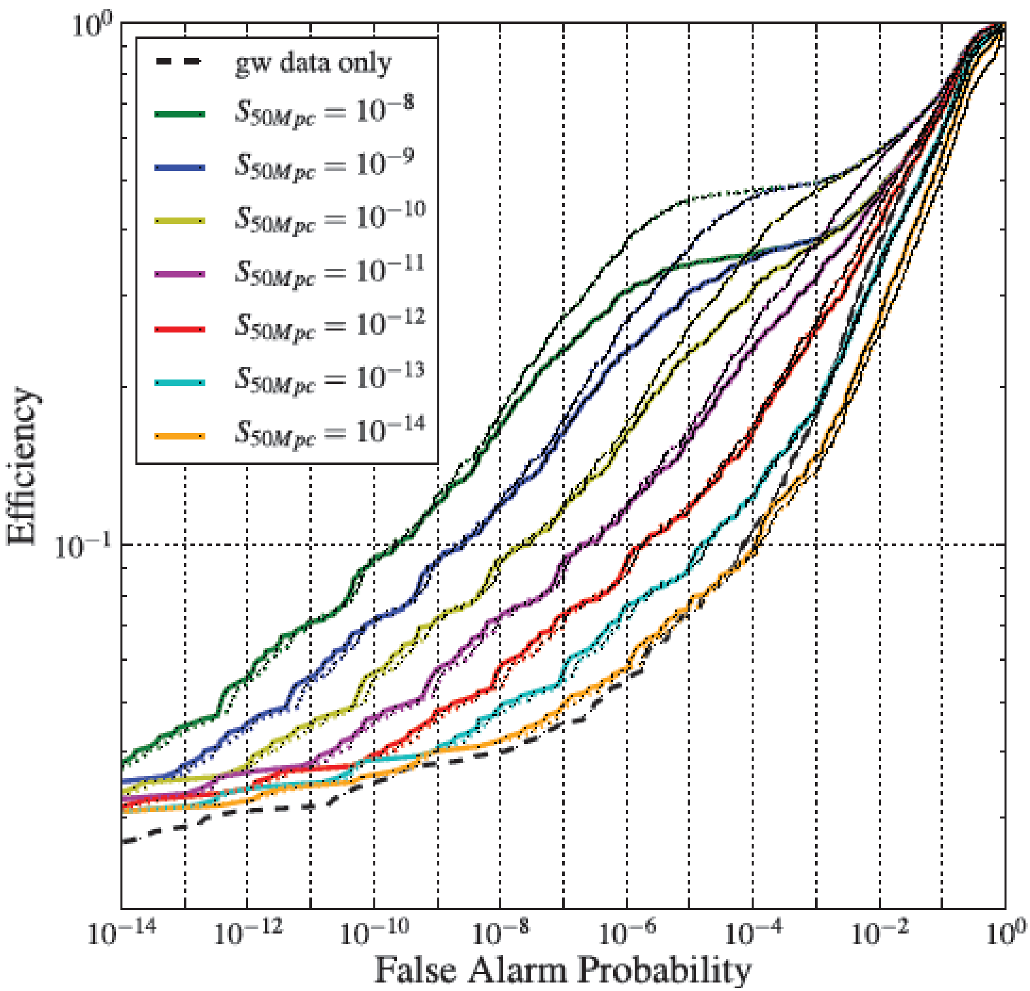


Bringing these all together…

- Added to the simulated population of GW signals (used in the previous slide) EM counterparts with possible X-ray fluxes S
- Flux values for X-ray counterparts based on GRB afterglows observed by Swift
- Main goal to sample brightness over different GRB types and different times (on the light curve) at which we might initiate an X-ray observation: S_{50Mpc} ranging $10^{-14} – 10^{-8}$ erg cm^{-2} s^{-1}
- Calculate ρ_{joint} for both simulated and background events
- For any given ρ_{joint} measure the False Alarm Probability and efficiency in detecting simulated GW-EM events

Joint search result

- Present efficiency to detect simulated GW-EM pairs as a function of the False Alarm Probability
- The solid (dotted) curves represent performance of the joint search with five (ten) pixels observed by Swift for various models of X-ray counterpart defined by the value of flux for a source 50Mpc away, S_{50Mpc}
- The dashed line is the curve for the GW only search



Summary and Outlook

- A first, low latency follow up with Swift of GW transients took place in the last science run of LIGO and Virgo (2009-2010)
- Methods for planning, performing and analyzing joint observations were developed and tested end-to-end
- EM observations were consistent with expectations for serendipitous sources
- Simulations demonstrated the considerable added value joint observations may bring
- Characterizing the background of X-ray/optical transients is an important element for joint searches
- Improvements on both sides, GW and EM, are expected to bring us in a better position to pursue joint searches
  - » Advanced Gravitational-wave detectors are expected to start science runs in 2015
  - » Optimized faint source detection scheme for Swift-XRT, automatic and flexible scheduling of Swift observations covering error areas larger than its FOV
- Stay tuned!