Swift Satellite
Follow-Up of
Gravitational Wave Candidate Triggers from LIGO/Virgo

Brennan Hughey for
The LIGO Scientific and Virgo Collaborations + Swift Collaborators

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(See arXiv:1205.1124 with additional background in arXiv:1109.3498)
Multi-messenger Transient
GW-EM Astronomy

Gravitational waves (GWs) tell us different things than electromagnetic (EM) signals
*You learn different things by hearing than you do by seeing*

**Gravitational Wave Signal**
- Bulk motion dynamics
- Luminosity distance
- Progenitor mass
- Direct probe of central engine

**Light curve and spectrum**
- Host galaxy
- Gas environment
- Red shift distance
- Precise Sky Localization

**Full picture of progenitor physics**

Plus: coincident observation of EM signal can dramatically increase
detection confidence of a gravitational wave candidate event
Pointing with Interferometers

- Network of interferometers capable of constraining gravitational wave event to a region of ~tens of square degrees through coherent analysis methods using timing and amplitude information (see talk by Marco Drago)

- Further constraints can be placed if we assume origin of event was close to a relatively nearby (<50 Mpc) galaxy by convolving skymap with known mass
Program of sending triggers to partner telescopes operated over two ~few week periods in 2009 and 2010 (see arXiv:1109.3498)

Mostly meter-class ground-based optical telescopes, plus Swift satellite....
Pointing Ability

Probability Skymap, close-up

Pointing Success rate for various FOV and tiles

- QUEST (3 tiles)
- Swift (5 tiles)
- TAROT/ROTSE (1 tile)

September event

(Roughly network SNR)
The Swift Satellite

- Burst Alert Telescope (BAT) is wide FOV Instrument scanning for GRBs

Two narrow FOV follow-up instruments:

- X-Ray Telescope (XRT) with 0.4° X 0.4° FOV

- UV/optical Telescope (UVOT) with slightly smaller FOV

Re-pointing in ~2 minutes for Swift triggers
~0.5-4.0 hours for non-Swift triggers

Targets typically visible for 25-45 minutes of 96 minute orbit
Main joint source: GRBs

- Short/Hard GRBs originating from compact binary coalescence
- Possibly also Long/Soft GRBs originating from core collapse

- LIGO/Virgo network has been performing archival searches in coincidence with Swift and other GRB triggers, see e.g. arXiv:1205.2216

- Swift agreed to follow up ~1 trigger per month from LIGO/Virgo during previous runs: Required stricter criteria in terms of false alarm rate, sky localization, data quality relative to other observatories
Selected Triggers

8:46 UTC January 7\textsuperscript{th}, 2010
5 tiles selected
Reduced threshold test of system

6:42 UTC September 16\textsuperscript{th}, 2010
2 tiles selected
Blind injection – GW100916, aka “the Big Dog"

Both triggered “coherent WaveBurst” algorithm
No significant events, above triggers from reduced threshold (1.5 sigma analysis)

Number of sub-threshold detections consistent with expectation from 2XMMi-DR3

Variability tests on detections reveal nothing beyond 2.5 sigma
UVOT Analysis

- UVOT analysis of XRT detections shows none correspond to transient or variable source in optical (though some fell off UVOT field)

- Blind search for optical transients reveals ~6800 sources 11 show >7 sigma variability but consistent with normal variable stars or active galaxies

- Thus, no evidence in ultraviolet or optical for anything out of the ordinary
Joint Event Significance

- Measurement involves
  - $\eta$: GW Burst statistic (a measure of signal-to-noise ratio)
  - $p_m(\Omega)$: sky-map, where $\Omega \equiv [RA, \text{dec}]$
  - $S$: X-ray flux observed by Swift, $\Omega$ - location of X-ray counterpart

- Introduce joint detection statistic to be the logarithm of the likelihood ratio:
  $\Lambda_{\text{joint}}(\eta, S, \Omega) = \Lambda_{\text{GW}}(\eta) \Lambda_{\text{EM}}(S) \Lambda_{\text{cor}}(\Omega)$

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

- $\Lambda_{\text{GW}}(\eta)$ can be measured from GW data and signal simulations
- $\Lambda_{\text{EM}}(S)$ can be estimated from the 2XMMi-DR3 catalog of serendipitous sources for a range of viable GRB X-ray fluxes $S$
- $\Lambda_{\text{cor}}(\Omega)$, 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
- Joint Detection Statistic calculated for both background and simulation, lets us determine false alarm probability and efficiency for simulated joint observations....
Joint Search Result

- ROC curve showing enhancement of detection confidence with X-ray transient fluxes of different magnitudes

- Curves for both 5 (solid) and 10 (dashed) Swift pointings

- Demonstrates substantial potential for increase in GW detection confidence from multi-messenger observation (only counting statistical enhancement and not qualitative science benefits)
Conclusions and Outlook

- Successful prototype test run of EM follow-up program with Swift satellite

- Details available at arXiv:1205.1124, jointly written by Swift and LIGO/Virgo scientists

- A future publication will address EM Follow-Up image analysis from ground-based telescopes

- Exciting prospects for multi-messenger astronomy in Advanced detector era, development work currently underway

- New strategies being developed by Swift team for multi-tile follow-ups to mosaic larger areas than is now possible

- X-ray and gamma-ray satellites provide important piece of multi-messenger Information, valuable to have missions running at the same time as Advanced LIGO/Virgo
Backup Slides
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