Electromagnetic Follow-ups of Candidate Gravitational Wave Triggers in the Recent LIGO and Virgo Science Runs

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for the LIGO and Virgo Collaborations
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Multi-messenger GW-EM Astronomy in the Advanced Detector Era

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

<table>
<thead>
<tr>
<th>Gravitational Wave Signal</th>
<th>Light curve and spectrum</th>
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<tbody>
<tr>
<td>• Bulk motion dynamics</td>
<td>• Host galaxy</td>
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<tr>
<td>• Luminosity distance</td>
<td>• Gas environment</td>
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<tr>
<td>• Progenitor mass</td>
<td>• Red shift distance</td>
</tr>
<tr>
<td>• Direct probe of central engine</td>
<td>• Precise Sky Localization</td>
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</tbody>
</table>

**Full picture of progenitor physics**

Plus: coincident observation of EM signal can dramatically increase detection confidence of a gravitational wave candidate event (good reason not to wait for a detection)
Goal of LIGO-Virgo EM Follow-Up program

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Goal of LIGO-Virgo EM Follow-Up program

- “Externally triggered searches” have been conducted for many years with gravitational wave strain data analyzed well after the fact
- The LIGO-Virgo EM follow-up program is part of an effort to add the other direction to the flow of data
- Sky location should be sent to telescopes within minutes, requiring near real-time processing
- Send “sub-prime” events, don’t wait for gold-plated candidate
Rapid Online Analysis

Trigger generators

H1 data → DQ/ vetoes → Data copied to computer centers → cWB
L1 data → DQ/ vetoes → Omega → GraCEDb archive
V1 data → DQ/ vetoes → MBTA

Pointing and event downselection

LUMIN → Humans validate event
GEM → alerts to telescopes

Time required:
<1 min.  ~1 min.  <1 min.  2-5 min.  <1 min  2-3 min.  10-20 min.

Total Latency: ~30 min.
LIGO-Virgo EM Follow-up Info at GWPAW

**Talks:**
- Introduction and Telescopes used – Brennan Hughey (me)
- The online *compact binary coalescence* search – Larry Price
- Performance studies with simulated *burst* waveforms – Jonah Kanner

**Posters:**
- Focus on real-time event vetting – Amber Stuver
- Several posters on sky localization and low latency analysis in Advanced detector era
Telescope Network

- Used in winter and autumn run
- Autumn run only

Map of global telescope network with labels for PTF, TAROT S, TAROT N, LOFAR, Liverpool, ROTSE b, ROTSE d, ROTSE c, SkyMapper, Zadko, and ROTSE a.
Optical Telescopes

◆ **TAROT** and **ROTSE** networks
1.86° X 1.86° FOV
0.25 m and 0.45 m, respectively
◆ **QUEST** camera on
ESO Schmidt scope
4.1° X 4.6° FOV, on 1.2 meter
allowed 3 tiles per follow-up
◆ **Zadko**
1.4° X 1.4° FOV, 1 meter
took large number of images
◆ **SkyMapper**
5.7 square degree FOV
1.35 meter survey telescope
◆ **Liverpool** telescope
4.6 X 4.6 arcminute FOV, 2 meter
◆ **Pi of the Sky**
21° X 21° FOV
◆ **Palomar Transient Factory**
Required stricter criteria for follow-up
1.2 m and 1.5 m
Other Instruments

X-Ray

◆ Swift Satellite
  - Allowed at most a few follow-ups
  - Used both XRT and UVOT
  - 0.4° X 0.4° FOV
  - Up to 5 pointings per follow-up

Radio

◆ LOFAR
  - 10 – 250 MHz radio range
  - Dipole array
  - In commissioning during run
Observations Performed

◆ Winter run Dec ‘09 – Jan ’10
   – Earlier version of procedures with only 3 telescopes
   – 8 triggers sent, 4 followed up

◆ Autumn run Sep – Oct ’10
   – More mature version of analysis
   – 6 triggers sent, 4 followed up

(both periods preceded by extensive dry-run tests)

- Analysis of images underway
- Addressing issues of EM background rate, etc.
- Methods paper describing EM follow-up program being written
- Results paper happening on longer timescale