432.27

AAS 217

13 Jan 2011

Follow-Ups to Gravitational-Wave Signal Candidates

Ryan Quitzow-James (University of Oregon) for the LIGO Scientific Collaboration and the Virgo Collaboration

LIGO-G1001056

Introduction

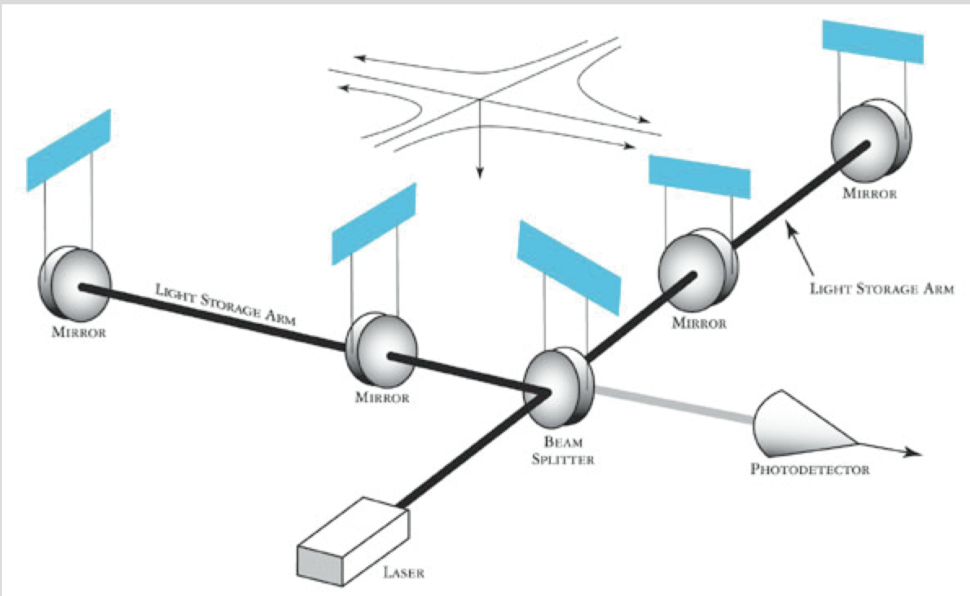


Diagram of LIGO Detector

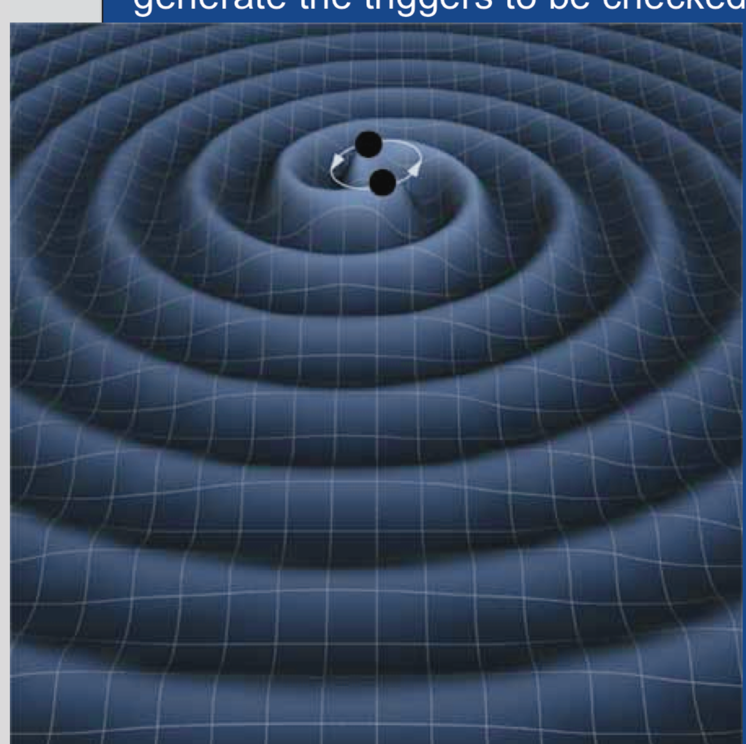
General Relativity predicts the existence of gravitational waves (GWs), which are perturbations in the geometry of space-time emitted when massive objects change their shape or orientation rapidly. Indirect evidence for GWs has been observed already with the timing measurements of binary pulsar PSR 1913+16. The aim of LIGO and Virgo is to directly detect GW emissions from energetic astrophysical events such as mergers of neutron stars and black holes, core collapse of massive stars, quasinormal modes of disturbed neutron stars, cosmic string cusps, and more. Towards this end, LIGO [1] and Virgo [2] utilize complex laser interferometers, the largest and most sensitive gravitational wave detectors used to date, with "arms" up to 4 km long that function by measuring changes in length on the order of 10^{-18} m, a thousandth the diameter of a proton.

Many sources predicted to generate gravitational waves are likely to give off electromagnetic (EM) radiation. If GW candidates are found with well determined positions, the EM detectors can be employed in near real-time to look for accompanying electromagnetic signals. These EM follow-ups would lower the threshold for confident detection and act as an additional confirmation of a GW. LUMIN and GEM are software programs that handle the alerts for possible GW candidates, generated by the search algorithms Omega Pipeline [3], coherent WaveBurst (cWB) [3, 4] and Multi-Band Template Analysis (MTBA) [5], as well as pass information to the telescopes. GEM handles alerts for Swift's X-ray Telescope (XRT) and UV-Optical Telescope (UVOT) and LUMIN handles alerts for the other telescopes: ROTSE, TAROT, SkyMapper, QUEST, Pi of the sky, Zadko Telescope, Liverpool Telescope and PTF (Palomar Transient Factory) with fields of view ranging from 0.3x0.3 degrees to 20x20 degrees. In addition to X-ray and optical images, follow-ups using radio telescopes are also being developed (LOFAR).

The LIGO Hanford Observatory in Washington State

Find Event Candidates

One challenge of successfully getting EM follow-ups to GW candidates is to find them in the first place. The data from the three detectors must be transferred and analyzed in near-real time; as the data becomes available three search algorithms run over the data and generate triggers for event candidates. During the S6/VSR3 science run, it typically took ~10 minutes for the software to generate the triggers to be checked by team members.



Two of the search algorithms, Omega Pipeline and coherent WaveBurst, search for unmodeled transients (bursts), while the third, Multi-Band Template Analysis, searches for compact binary inspirals. An event candidate must have power above certain thresholds calculated from the distribution of background events as well as be coincident in the three detectors. Different telescopes require the candidates to be below different false alarm rates (FAR); once every four days for most telescopes, with once every ten days for PTF and once every thirty-five days for Swift.

Above: Artist's impression of gravitational waves from two orbiting black holes. [Image: K. Thorne (Caltech) and T. Carnahan (NASA GSFC)]

Limit Search to Nearby Galaxies

We can also constrain our search to galaxies within the range of the detectors to narrow our search [7]. For example, in S6/VSR3 a stellar-mass black hole / neutron star binary inspiral could be detected out to a maximum distance of ~50 Mpc (expected to be ~500 Mpc in the advanced detector era). Therefore, we could focus on galaxies within 50 Mpc when selecting coordinates for follow-up imaging.

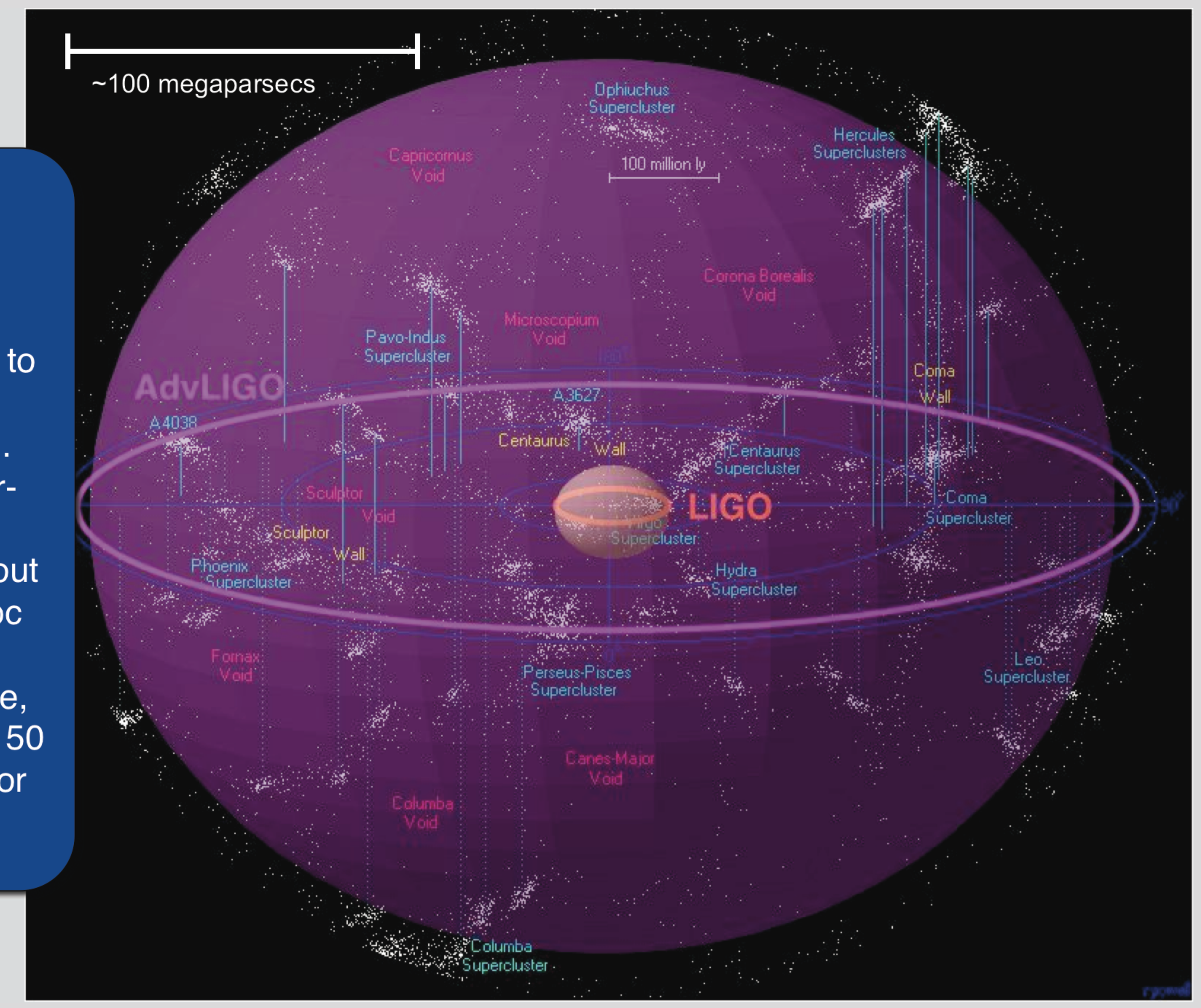
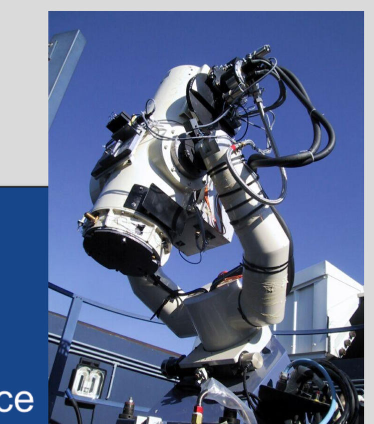


Illustration of the anticipated "reach" of Advanced LIGO. Each small dot in the figure represents a galaxy.

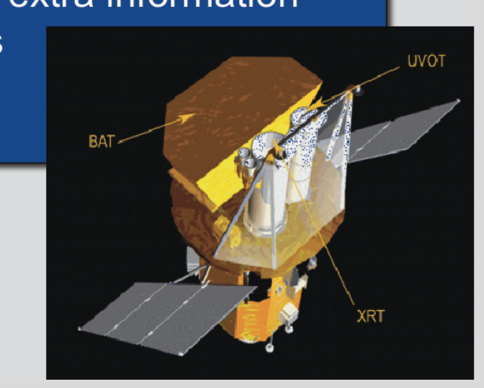
Analyze Data!

Credit: TAROT



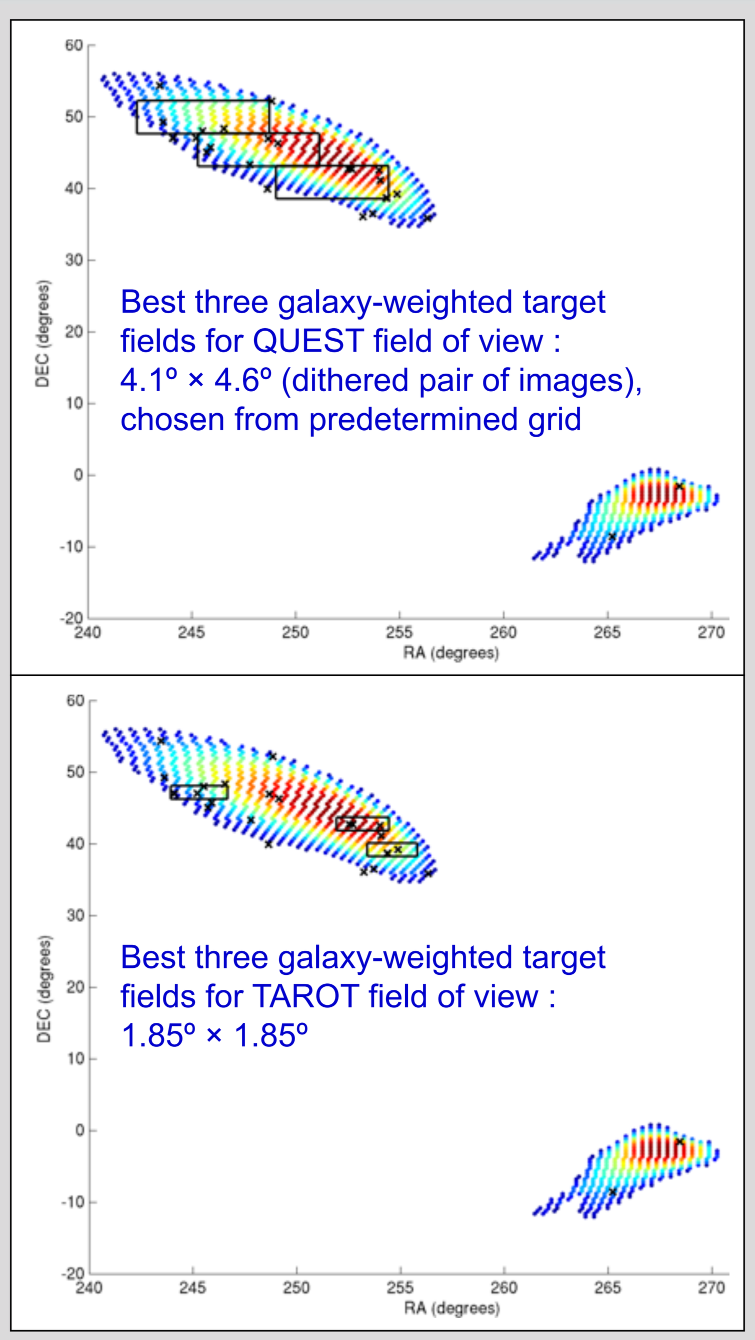
Images are analyzed to check for transients by comparing with reference images taken earlier or later. In principle, if an optical transient can be identified quickly, then larger-aperture telescopes with various instruments could be brought to bear.

Few (possibly none) of the GW candidates are expected to be confirmed as real events at the current sensitivity level. All significant gravitational wave candidates are subject to considerable scrutiny and the extra information available from the EM images justifies the effort.



Credit: Swift

Right: Position reconstruction for a simulated GW event is shown as a function of sky position. The most likely positions for the GW source are dark red. Black crosses indicate locations of known galaxies within 50 Mpc. Rectangles indicate telescope fields chosen to maximize chance of catching the optical transient (assuming there is one coming from a galaxy) for three pointings of the QUEST (top) and TAROT (bottom) cameras. The position reconstruction was performed by the coherent WaveBurst software.



Determine GW Source Sky Position

Triple coincidence among the three detectors is required to (1) reduce greatly the number of spurious event candidates and (2) reconstruct the position of the candidate event, which is done mostly by the timing delays.

Strong signals can be localized to just 1-2 degrees, while signals that are near threshold are localized to about 5-10 degrees, possibly in several disconnected patches [6]. For this reason, telescopes with wide fields of view (FOVs) are useful for analysis.

Check Data and Request EM Images

After an event candidate is found, team members are notified through GEM for Swift and LUMIN for the other telescopes. If the candidate passes the software and sanity checks performed by team members, imaging requests are sent to telescopes determined to be in good observation positions by the software. This entire process would typically be completed within 30 minutes.

Table 1: Notable Parameters	
Latency	~ 30 min
GW Sky Localization (LIGO + Virgo)	~1-2 degrees for strong signal, ~5-10 degrees near threshold
GW Distance Sensitivity (BNS)	LIGO: ≤ 50 Mpc aLIGO: ≤ 500 Mpc

Project Status

LOOC-UP and GEM were implemented and run in late 2010 and successfully sent triggers to participating telescopes, which included Swift, LOFAR, TAROT and QUEST. Images from follow-ups to event candidates are still being analyzed and will be presented at a later date.

A major goal of this effort was to gain experience in preparation for the Advanced LIGO (aLIGO) / Advanced Virgo era. LIGO is currently being decommissioned in preparation for installation of the components of aLIGO, which is expected to begin taking data in 2014-2015, ultimately with a factor of 10 improvement in sensitivity. A similar improvement and timeline is expected for the Advanced Virgo project.

LIGO-Australia is a proposed fourth detector*. It's position would compliment the existing detectors and the uncertainty in source sky position would be 5 to 10 times smaller [8]. The NSF approved providing LIGO-Australia with the components of one of the three Advanced LIGO interferometers. Australia must still find funding for the operation and infrastructure of the observatory: staff, buildings, roads, vacuum chamber, etc.

* See poster 432.23. The Benefits for Multi-Messenger Gravitational Wave Astronomy with a LIGO-Australia Detector, Aidan F. Brooks, Linqing Wen, Stan Whitcomb

REFERENCES

[1] B. Abbott et al., Rept. Prog. Phys. 72, 076901 (2009)
[2] F. Acernese et al., Class.Quantum Grav. 25, 184001 (2008)
[3] J. Abadie et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D 81, 102001 (2010)
[4] S.Klimenko et al, Classical Quantum Gravity 25, 114029 (2008)
[5] D Buskulic et al 2010 Class. Quantum Grav. 27 194013
[6] Erik Katsavounidis for the LVC, talk at the14th Gravitational Wave Data Analysis Workshop, http://www.roma1.infn.it/GWDAW14/
[7] J. Kanner et al., "LOOC UP: locating and observing optical counterparts to gravitational wave bursts", *Classical and Quantum Gravity* **25**, 184034 (2008)
[8] LIGO Document T1000251, https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=11604