# Multi-messenger Astronomy and Gravitational-wave Bursts: Past, Present and Future

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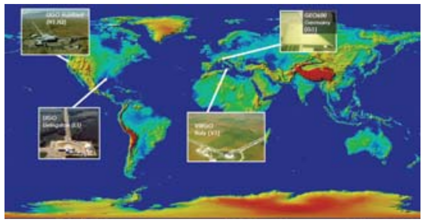
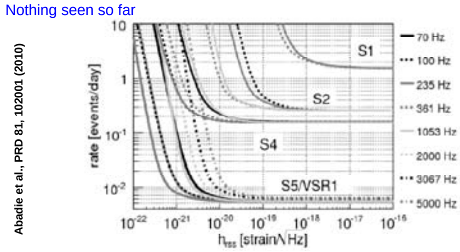
## 1: Large laser interferometers for gravitational-wave detection

- Gravitational waves are described within General Relativity as perturbations in the space-time metric arising when massive objects move or change their configuration.
- LIGO, GEO and VIRGO use km-scale interferometry with broadband sensitivity in order to detect such GWs of astrophysical and cosmological origin.
- In October 2010 the instruments completed their coincidence science running in their initial configurations.
- Advanced LIGO installation is well under way and data taking is expected to commence in ~2015. A range of new technologies are expected to bring a factor of ~10 improvement in strain sensitivity, factor of ~1000 in volume surveyed.



## 2: Gravitational-wave bursts

- Short-lived signals, lasting only a few cycles within the frequency band of the instruments: typically from few milliseconds to few seconds and with frequency content in the 100 Hz - few kHz regime.
- Sources include core-collapse supernovae, the merger phase of binary compact objects, neutron star instabilities, cosmic string cusps and kinks, the unexpected!
- Need to make minimal assumptions about the candidate signal: their waveforms are unknown or poorly known!
- Search methodology: use of excess power techniques, coincidence criteria, cross-correlation and coherent network analyses – work closely with inspiral searches to pursue the full evolution of binary compact stars.
- All-sky searches: eyes wide open searches for anything that does not fall under a model and may look like a transient in the detectors
- Nothing seen so far




- Upper limits on the rate of events --- astrophysical sensitivity ~$2\times10^{-8}$ $M_\odot c^2$ at 10 kpc , ~0.05 $M_\odot c^2$ at 16 Mpc

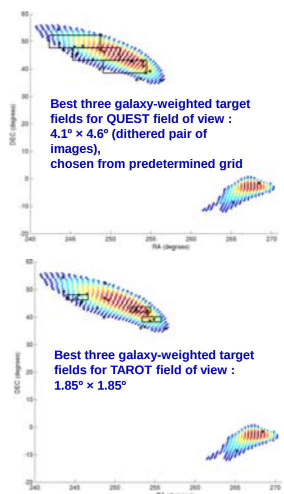
## 3: Beyond un-triggered, all-sky searches

- Combine observations of the transient sky in the electromagnetic and particle sectors (neutrinos): perform targeted, externally triggered searches starting with Gamma-Ray Bursts (GRBs), Soft Gamma Repeaters (SGRs), anomalous X-ray Pulsars (AXPs) and neutron star glitches.
- Their central engines may give rise to GW bursts but this time the knowledge of the time and direction of such events can offer better background rejection and improved search sensitivity with respect to an un-triggered, all-sky search.
- Non-detection statements can be astrophysically interesting.
- GRB-triggered burst searches through the years have used initially cross-correlation of pairs of detectors (2002-2005). A coherent network analysis of GW data collected during the 2005-2007 run around the times of 137 GRBs provided no evidence for GW emission associated with them [Abbott et al. ApJ 715, 1438 (2010)], Among them, GRB 070201 whose error box included M31 at ~770kpc [Abbott et al., ApJ 681, 1419 (2008)].
- Searched for GW signals associated with the Dec. 2004 "giant" flare of SGR 1806–20 as well as 190 flares from SGR 1806–20 and SGR 1900+14 in 2005-2006. A reanalysis of the SGR 1900+14 storm by "stacking" the GW data around the times of individual soft-gamma bursts further enhanced the sensitivity to GW emission. Upper limits placed on the energy going into GWs (at 10 kpc) were at the level of $2\times10^{45}$ – $6\times10^{50}$ erg [Abbott et al., PRL 101, 211102 (2008), ApJ 701 L68-L74 (2009)]. Additional searches from six SGRs/AXPs in 2006-2009 found no evidence of GWs associated with them [Abadie et al. arXiv:1011.4079v2].
- Similar searches for GW associated with the August 2006 timing glitch of the Vela pulsar yielded null result and placed uper limits on the peak strain amplitude (and corresponding energy) emitted in GWs [Adabie et al. arXiv:1011.1357v3].


## 4: Sky source localization

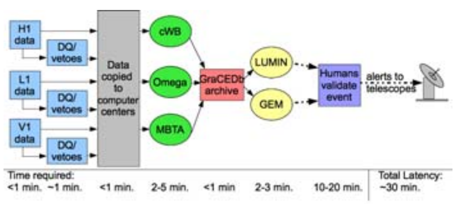
- With three detector sites operating at comparable sensitivity we had the ability to localize in the sky candidate sources of GW bursts.
- Using Monte Carlo simulations with GW source signals of different morphology, polarization states, frequency and signal strength we have studied how well sources can be localized in the sky.

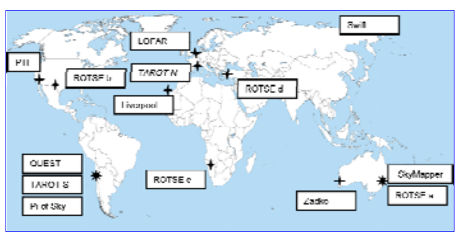
**Right:** Position reconstruction for a simulated GW event is shown as a function of sky position. The most likely positions for the GW source are dark red. Black crosses indicate locations of known galaxies within 50 Mpc. Rectangles indicate telescope fields chosen to maximize chance of catching the 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.




## 5: Low latency GW searches and EM follow-up

- A big goal of the 2009-2010 run of the LIGO-Virgo detectors has been the implementation of online searches for GW bursts. The ability of the 3-detector network to perform source localization will enable for the first time their prompt follow-up in the Electromagnetic (EM).
- A GW source is reasonably likely to radiate in the EM too – it must though be an extremely energetic event and/or be located relatively nearby.
- Several technical challenges in the implementation of these searches have been addressed successfully: data were streamed to the compute centers and analyzed within minutes, data quality and trigger significance were assessed promptly. Triggers are then checked against the instrument FOV and ability to tile the error area with few pointings.
- The EM follow-up program was implemented and carried out collaboratively with Swift, TAROT, ROTSE and other telescope colleagues

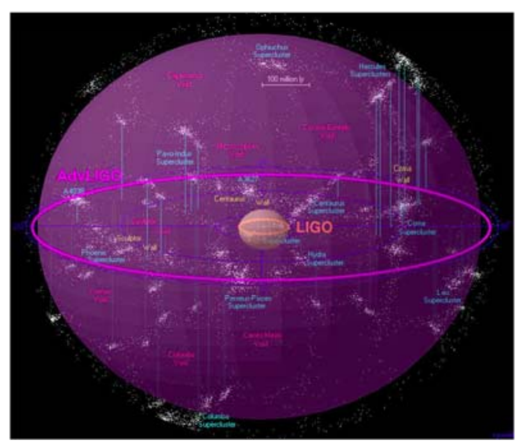



- A handful of GW candidate events have been passed on to the ground-based optical telescope partners and Swift in the Dec 2009 – Jan 2010 and Sep-Oct 2010 periods

## 6: Multi-messenger astronomy

- Kilometer-scale interferometry works! The first generation instruments have explored in their 2003-2010 science runs the GW sky at an unprecedented sensitivity but with null results so far. While doing so, significant steps toward GW astronomy were made.
- The next big step toward GW astronomy involves the Advanced detectors and the factor of 10 improvement in sensitivity that they will bring. They are expected to start taking data in ~2015.
- The LIGO and Virgo Collaborations are getting ready to transition from upper limits to first detections and source astrophysics; this is intimately connected with pursuing GW transients as part of the bigger picture of transient astronomy involving all EM wavelengths and particle messengers associated with violent, highly energetic events in our Universe.
- EM and GW astronomy will need to work synergistically in the advanced detectors regime in extracting the most out of the science reach of the km-scale interferometers. GWs will be the direct probe of the central engine of the emitting source providing information on the progenitor mass, bulk motion dynamics and luminosity distance. EM observations accompanying such measurement will reinforce the GW detection confidence and will provide position of the source with much reduced error area, information on the host galaxy, redshift, information on the gas environment of the progenitor.
- We have pursued several modes of multi-messenger astronomy with the network of the first generation GW detectors.
- We performed targeted searches for known transient events in the electromagnetic like GRBs, SGRs, AXPs and neutron star glitches-- several others are under way (involving neutrinos, optical supernovae.)
- We also carried out a program for joint GW-EM observations in the most recent science run of the instruments. This was an important path-finding exercise for the advanced detector regime. Such a program will play a significant role in improving our chances of capturing the EM signatures of GW transients that may be missed otherwise (e.g. beaming effects, simply because not looking at the right time at the right place).
- Several lessons were learned– will shape up both the actual work and the policy in place of how real-time astronomy with the advanced detectors will take place.
- Stay tuned!

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