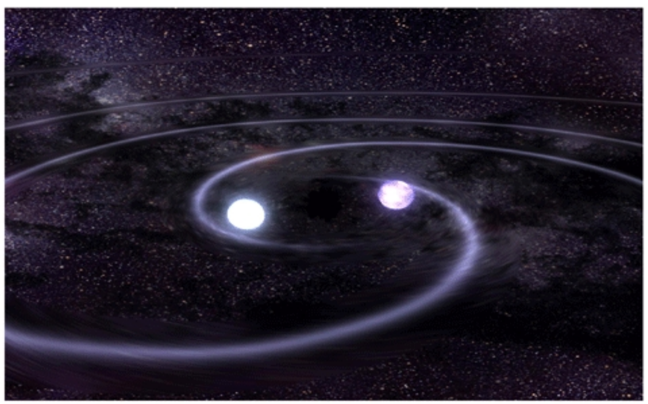
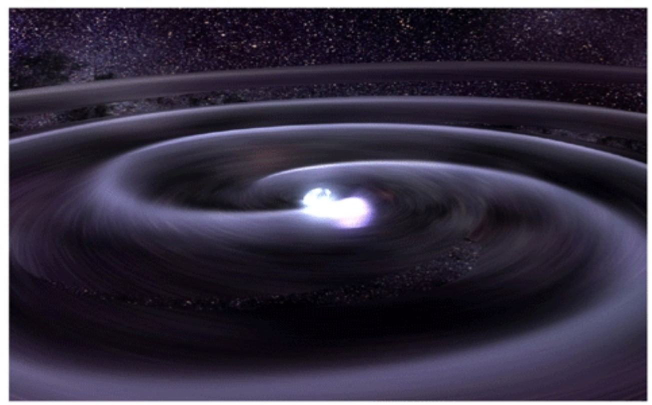
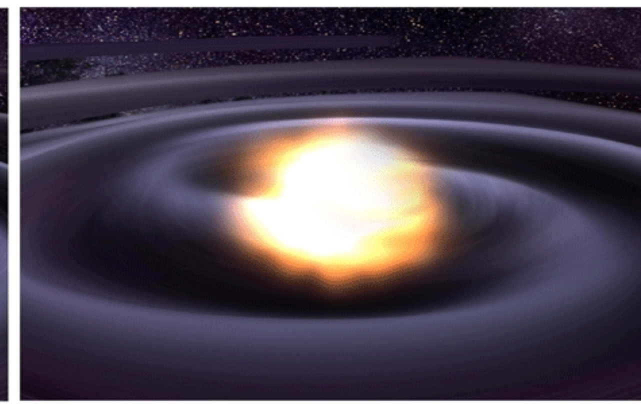
Electromagnetic Follow Up Observations of Gravitational Wave Candidates







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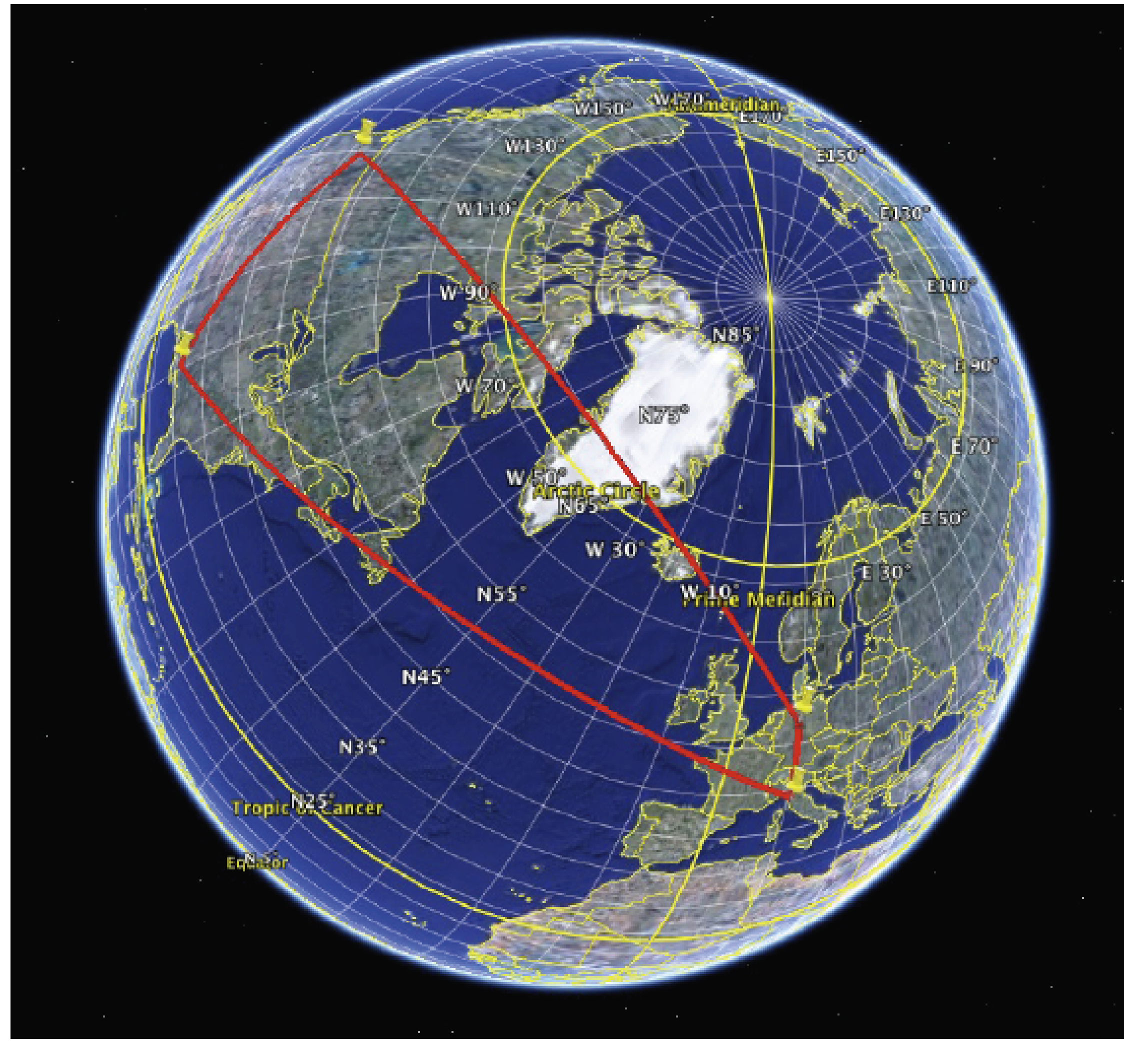
GW Detectors

- Interferometers with test masses at the end of 3-4km long arms.
- Two detectors in the United States, the Laser Interferometer Gravitational wave Observatory (LIGO)
- The Virgo detector in Italy
- GEO 600m detector in Germany
- Ran in coincidence during the 6th LIGO, and the 2nd and 3rd Virgo science runs.
- Dec 17 2009 to Jan 8 2010 – Winter Run
- Sep 4 to Oct 20 2010 – Autumn Run

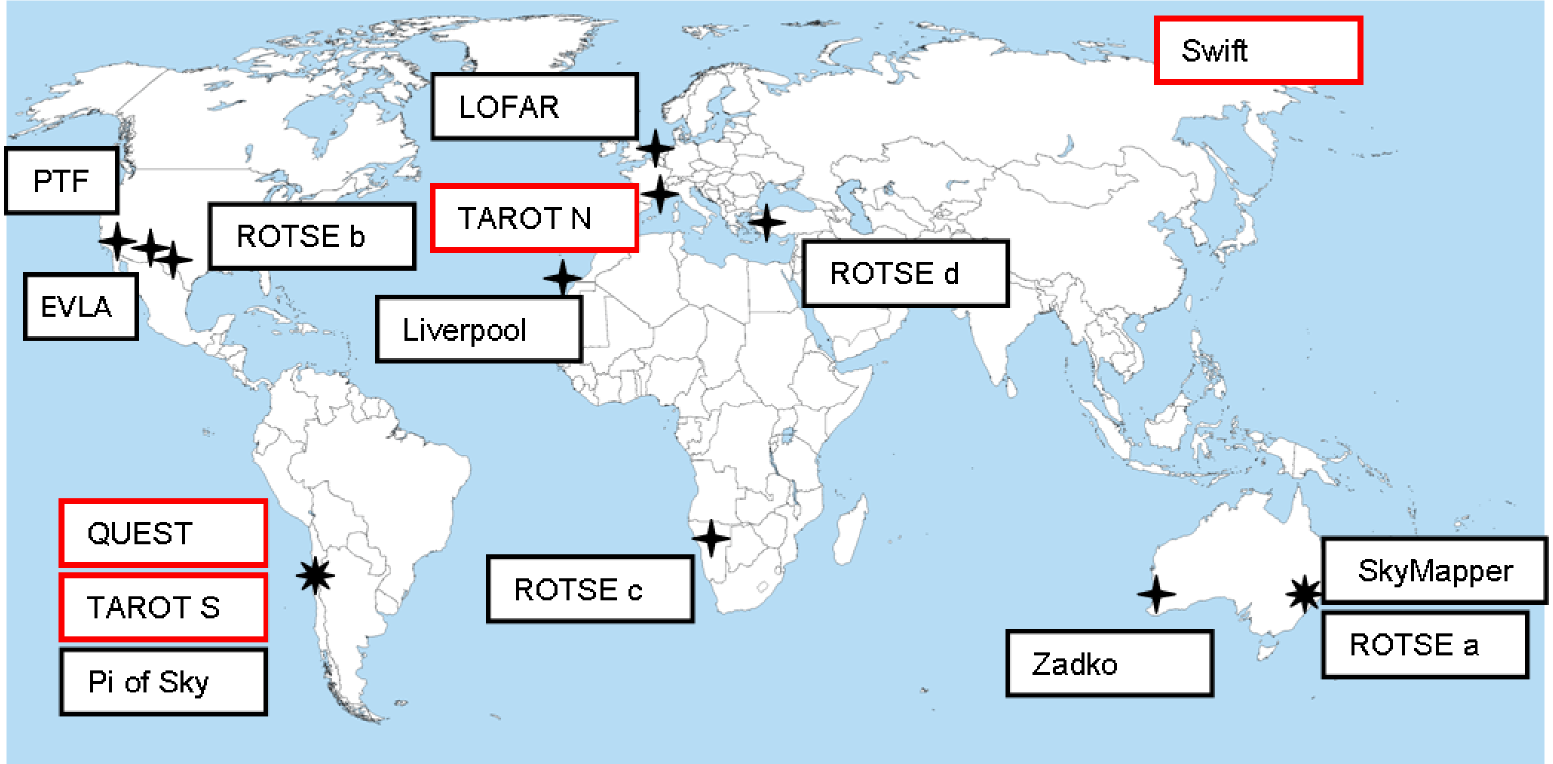
Electromagnetic Follow Up

- Network of a minimum of 3 gravitational wave (GW) detectors allows us to triangulate possible source sky localisation.
- Many transient sources of GWs expected to provide electro-magnetic counterparts (Long and Short GRBs, Supernovae, etc)
- The EM follow up campaign during the most recent science run was aimed at imaging these potential source regions as quickly and thoroughly as possible.



Map taken from Google Earth

Partner Telescopes + Fields of View



Winter/Autumn

Autumn

Taken from Abadie et al. 1109:3498

Optical Telescopes:

- TAROT – 3.4 sq. deg.
- Zadko – 0.17 sq. deg.
- ROTSE – 3.4 sq deg.
- QUEST – 9.4 sq. deg.
- SkyMapper – 5.7 sq. deg.
- Pi of the Sky – 400 sq. deg.
- PTF – 7.8 sq deg.
- Liverpool – 21 sq. arcmin.

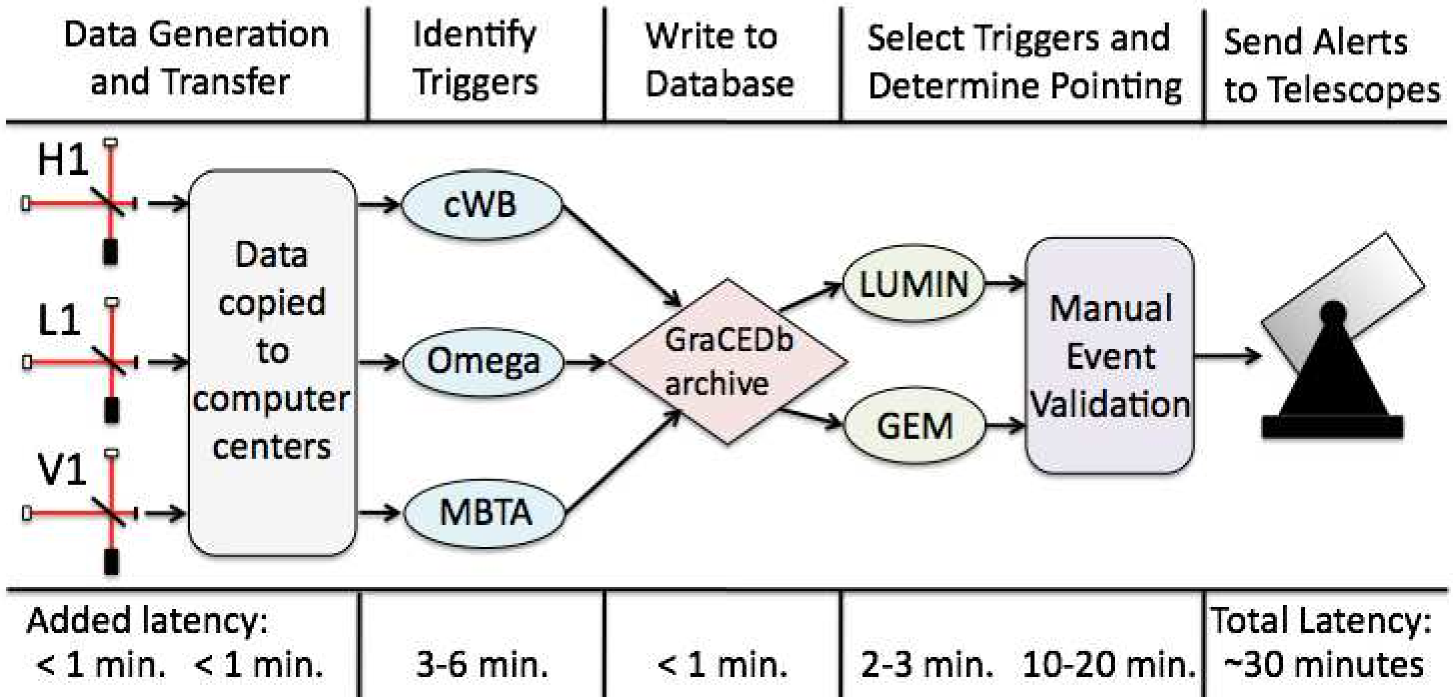
Radio Interferometers:

- LOFAR (30 – 240 MHz) – 25 sq. deg.
- EVLA (5 GHz) – 7 sq. arcmin.

X-Ray and UVOT:

- Swift – 0.15 sq. deg.

Event Validation

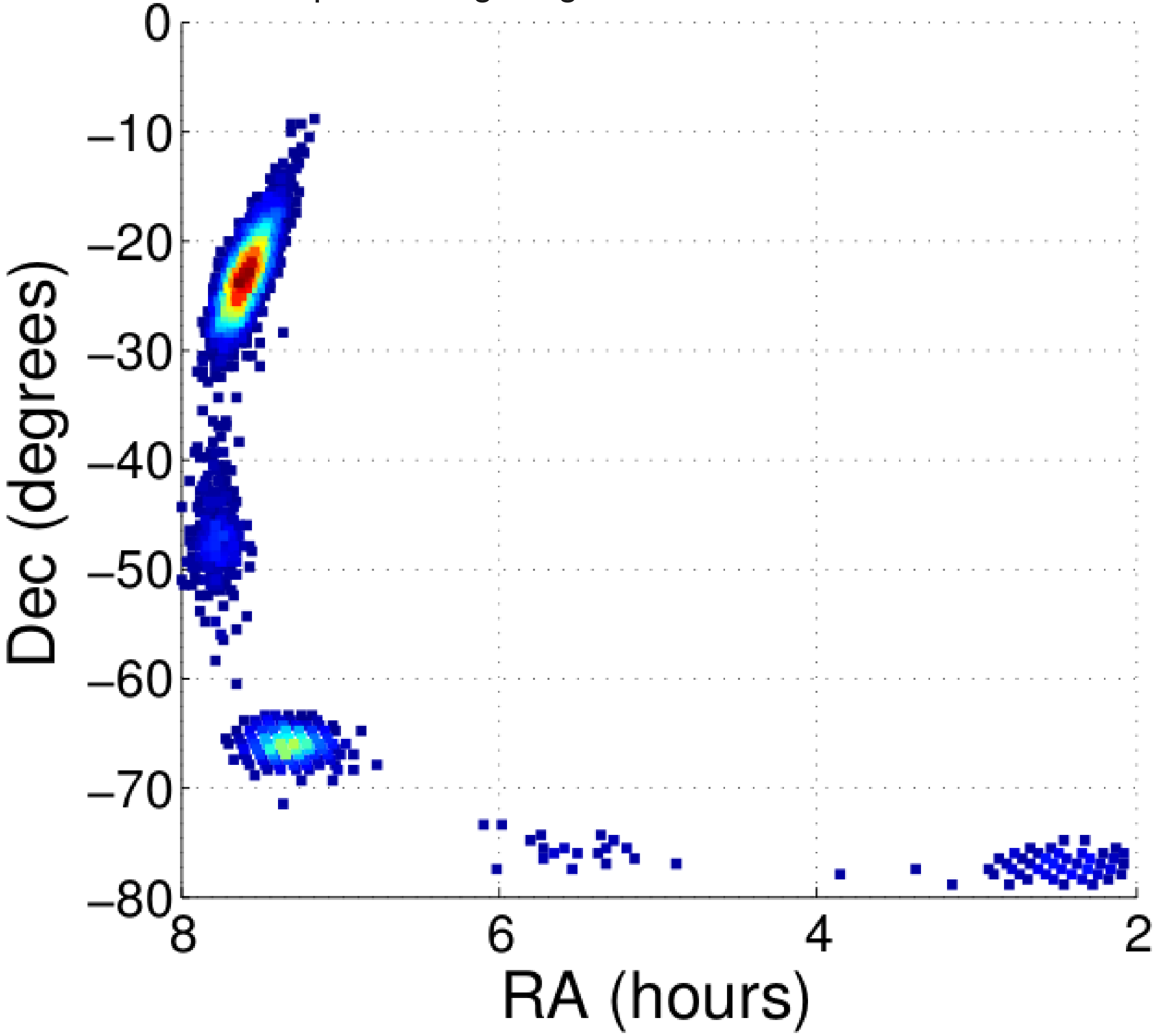


Taken from Abadie et al. 1109:3498

- Triggers chosen with significant power above threshold estimated from background events (False Alarm Rate, FAR)
- Winter Run: FAR<1.00 per day
- Autumn Run: FAR<0.25 for most telescopes, <0.1 for PTF and Swift

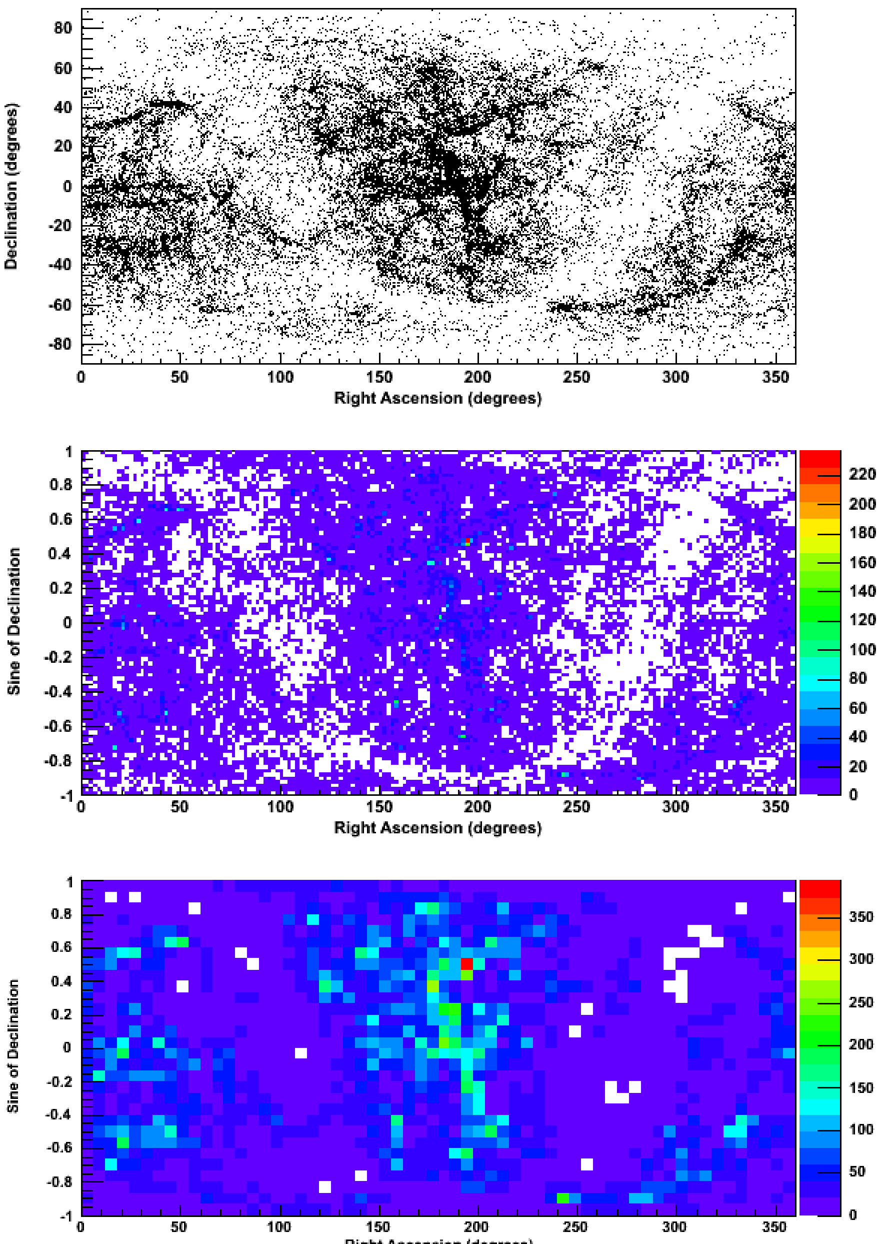
Sky Localization

http://www.ligo.org/science/GW100916/



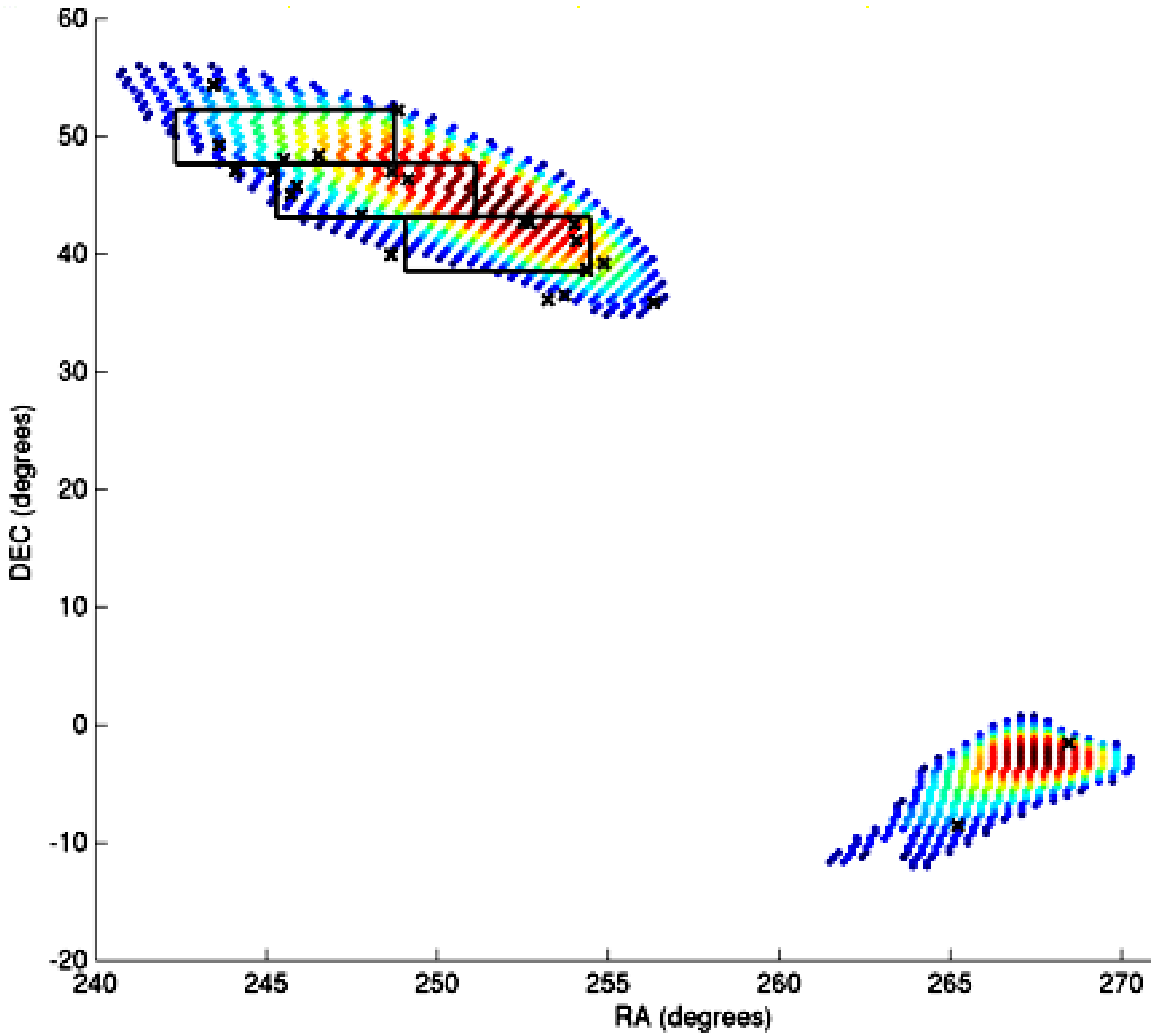
- Sky position error is typically larger that the field of view of most wide field telescopes.
- Need prior knowledge of mass distribution to decide which part of the sky to image.
- Constructed a list of galaxies from various sources to allow us to decide where to image in real time.

Gravitational Wave Galaxy Catalogue



- Catalogue of ~50,000 galaxies within 100 Mpc.
- Published in CQG: White et al, 28, 085016, 2011.
- Uses Principal Galaxy Catalogue (PCG) identifier to improve removal of degenerate galaxies from multiple catalogues.
- Easily updated to provide most recent results from sky surveys.

Region Selection



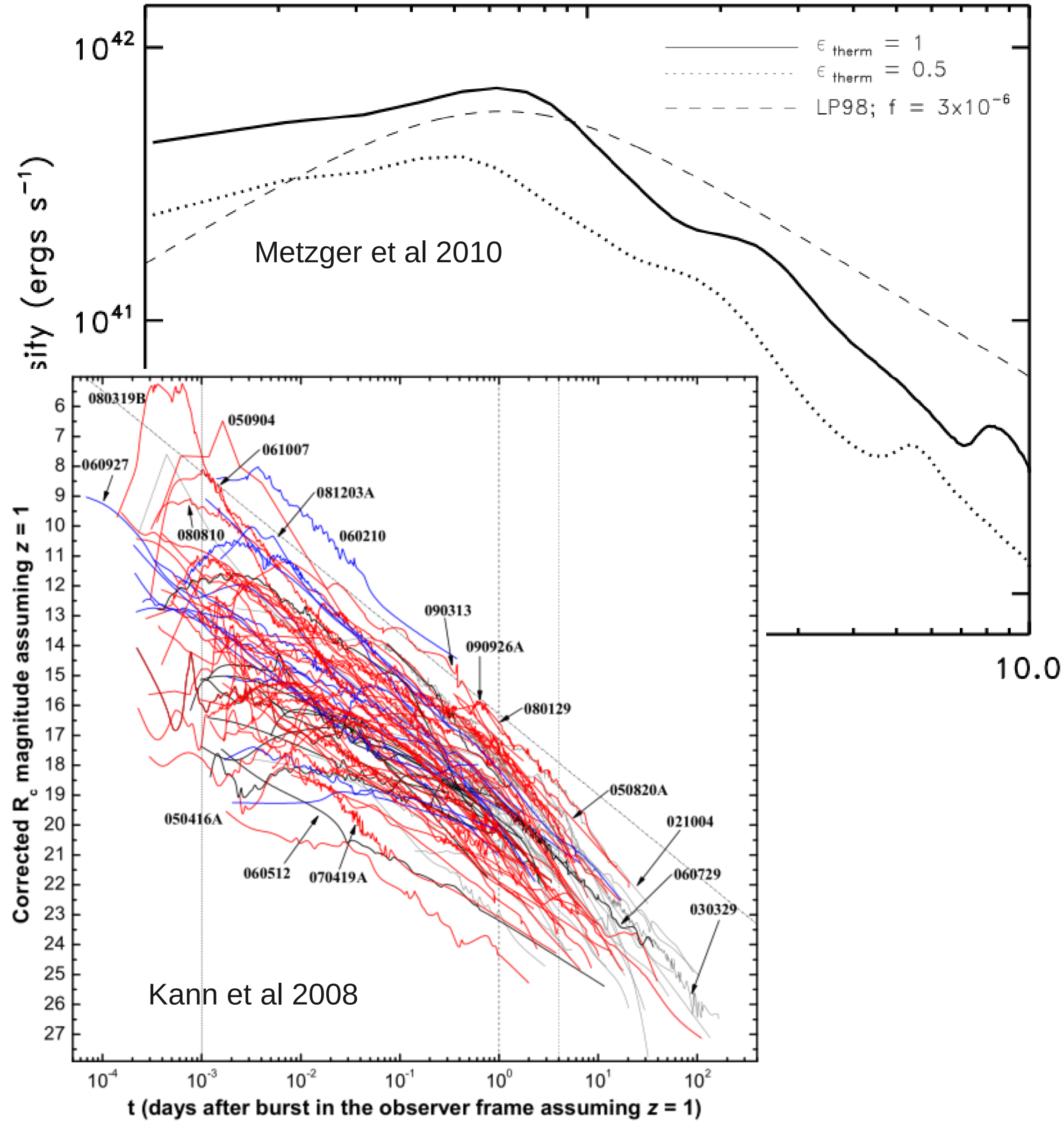
- Using the "likelihood" statistic from the GW data, and the galaxies from the GWGC, we can estimate a "probability":

$$P = \frac{L_B \times Likelihood}{Distance}$$

- Blue luminosity chosen as a proxy for star formation.
- Position wide field telescopes to capture as much probability as possible, and point narrow field telescopes at most likely galaxies.

Image Analysis

- Must identify transients in large, often crowded, sometimes noisy fields.
- Need to remove background or contaminating transients:
  - Optical – Novae, variable stars, minor planets, etc
  - Radio – atmospheric noise (eg. meteor trails), varying ionosphere, AGN variability from MW scintillation.
- Compare with predicted light curves for expected sources.



Optical Image Analysis

Winter Run

- Sent 8 alerts, with 4 observed by at least one telescope.

Autumn Run

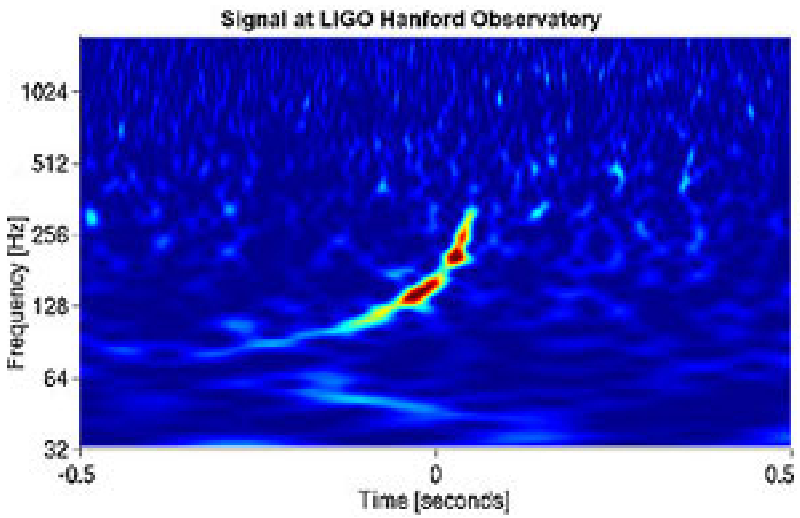
- Sent 6 alerts with 5 observed by at least one telescope.

Obtained almost 1800 images in total!

Creating tools to calibrate, analyse, and calculate efficiencies of these images is a big task.

Blind Injection:

- One of the Autumn triggers was found to be a blind injection.
- Used to test our GW analysis pipelines.
- Gives us confidence!



Taken from: http://www.ligo.org/news/blind-injection.php

Optical Image Analysis

Several pipelines are being developed to analyse images from optical telescopes.

Generally split into two methods:

Image Subtraction

- Reference image subtracted from images.
- Resulting image contains transients.
- Thresholds used to remove background.
- Used by PTF, ROTSE, SkyMapper and Liverpool.

Catalogue based search

- Catalogues of object fluxes in fields created.
- Track variability across multiple images.
- Threshold flux changes used to find interesting transients
- Used by TAROT, QUEST, Zadko and POTS.

Swift Image Analysis

2 alerts sent and observed.

X-ray images:

- Detect X-ray sources.
- Compare to expected sources in a typical field.

UVOT images:

- Check UVOT images for counterparts to X-ray sources.
- Compare against archival images for new/varying sources.

Compare light curves to those of expected sources.

Radio Image Analysis

LOFAR:

- 5 alerts sent and observed
- Flag and remove atmospheric noise

EVLA:

- 2 alerts sent and observed
- Remove varying AGN sources

Detect and analyse transient light curves

Conclusion

- Most recent joint science run allowed us to collect a large amount of data associated with possible GW events.
- Data analysis is currently ongoing, but at a mature stage.
- Vital lessons have been learnt for the advanced detector era.

Any questions?

Further information can be found in “Implementation and testing of the first prompt search for gravitational wave transients with electromagnetic counterparts” by Abadie et al. arXiv:1109.3498