Gravitational Wave Triggers and Electromagnetic Follow-up In the Advanced Detector Era

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The GW-EM Connection

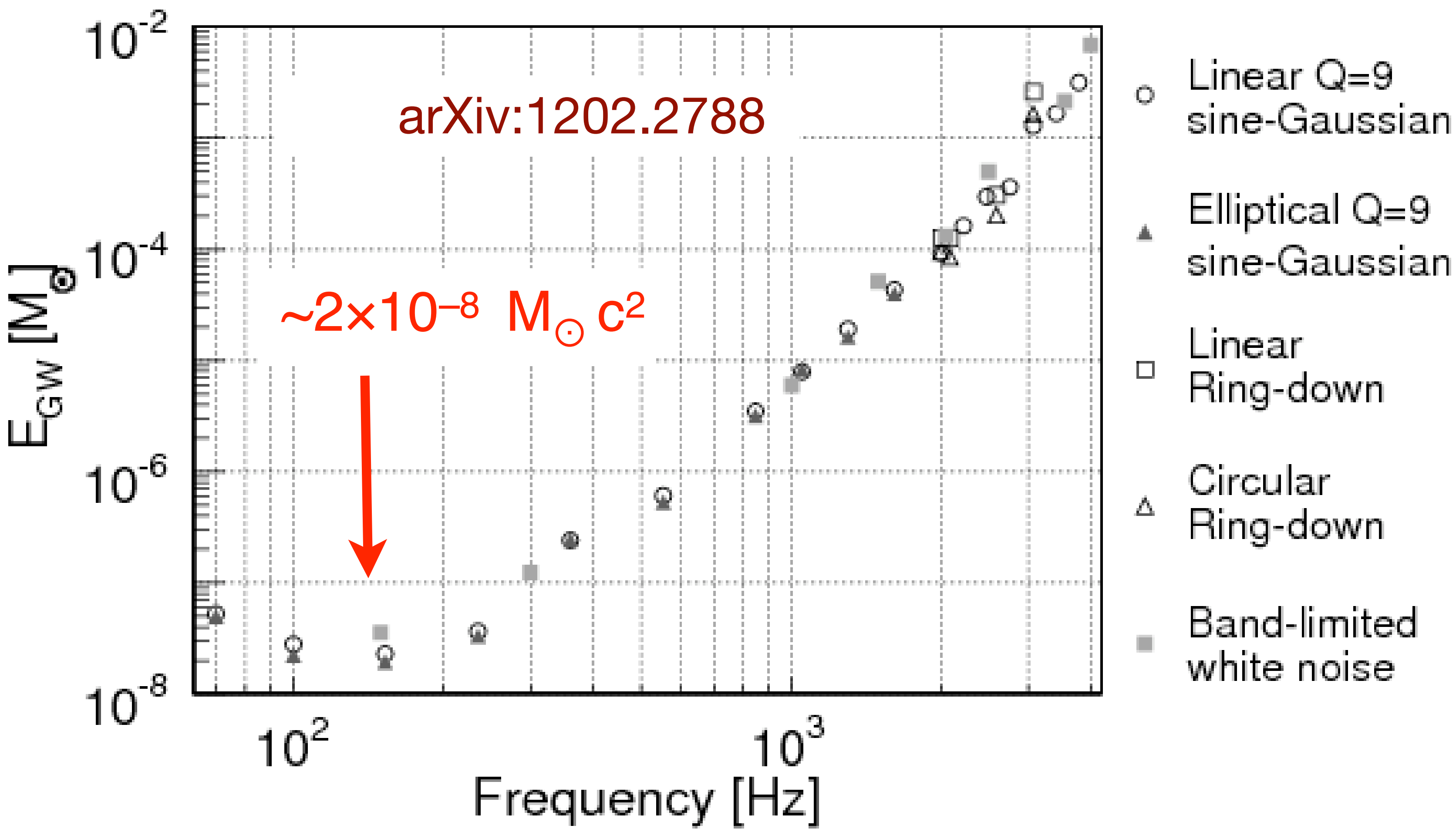
Detectable GW transients in the LIGO/Virgo band require bulk motion of mass on short time scales: emission in other channels is also plausible

- Coalescence of Compact Objects (neutron stars and/or black holes)
  - ➡ Short Hard Gamma Ray Bursts
  - ➡ Optical Kilonovae
- Core collapse of massive stars
  - ➡ Long Soft Gamma Ray Bursts
  - ➡ Supernovae

Scientific stakes are high, but technical challenges:

- ➡ localization for GW is difficult
- ➡ uncertainty on relative timing of GW-EM signals

Initial LIGO/Virgo
Sensitivity to Gravitational Wave Transients



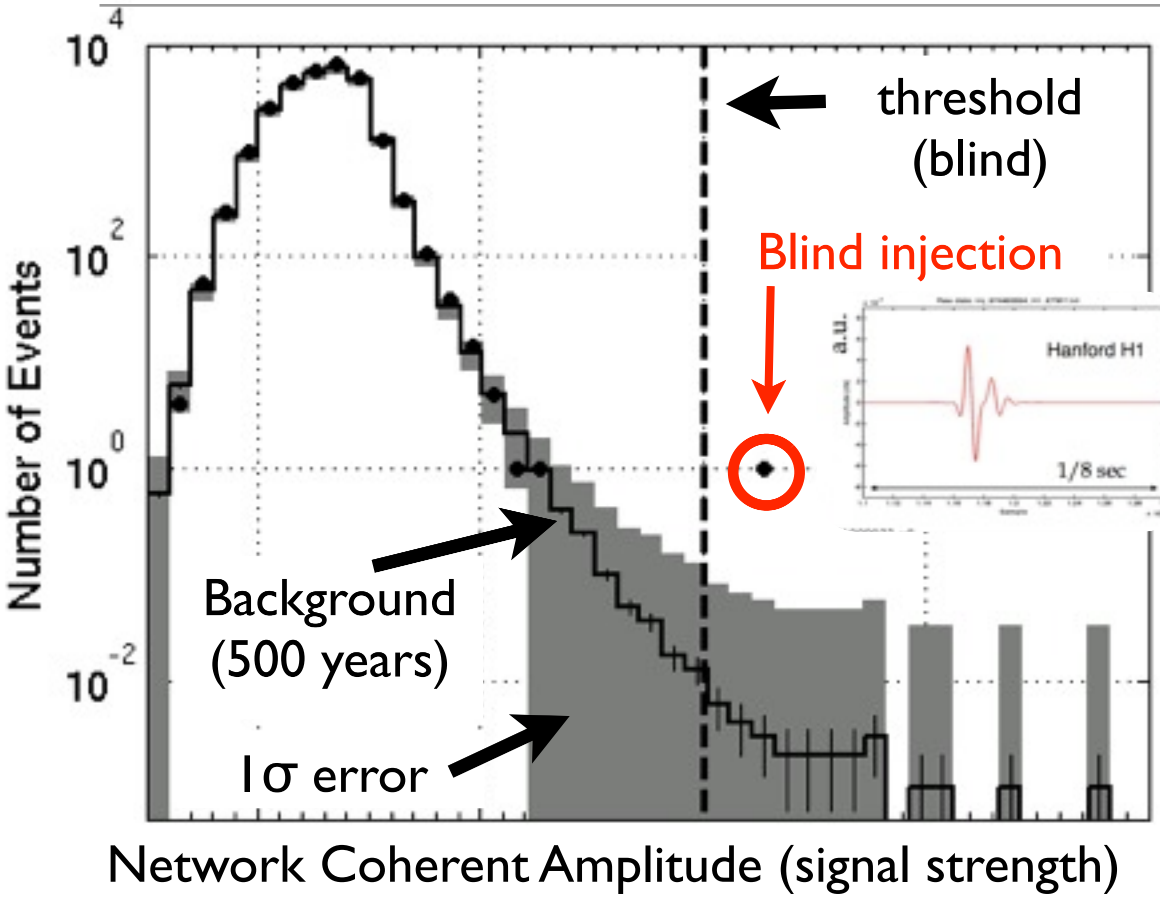
GW energy in short pulses **from the galactic center,** detectable with 50% probability. Function of frequency and waveform.

$E_{GW} \propto (\text{distance})^2$
for other distance

Core Collapse Supernovae numerical simulations: E_{GW} up to $10^{-7}\ M_{\odot}c^2$
Analytical calculations for extreme CCSN models: E_{GW} up to $10^{-2}\ M_{\odot}c^2$

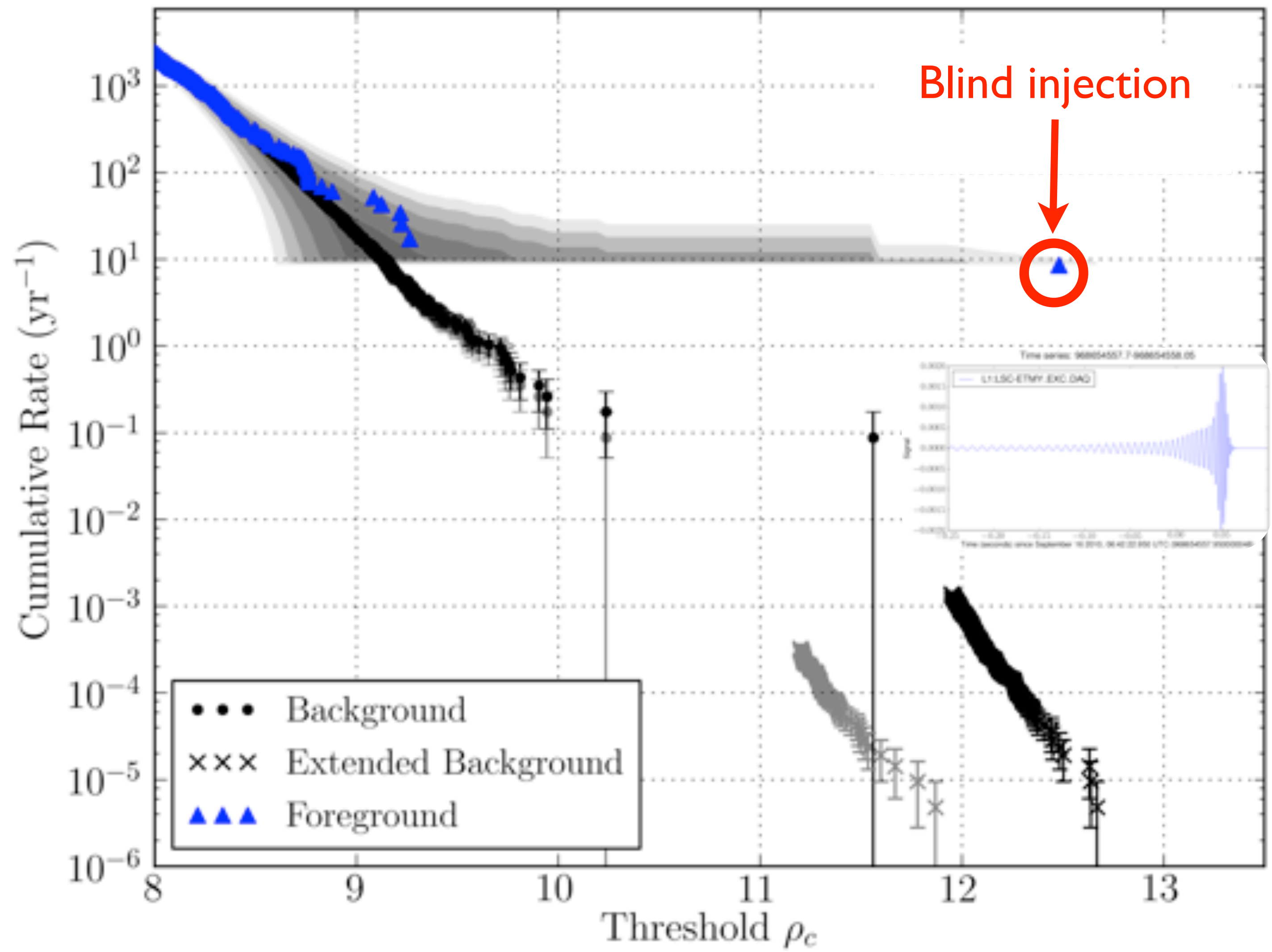
Matched filtering and stronger GW emission allow for further reach for compact binary coalescences: binary containing Neutron Stars detectable to ~50 Mpc in Initial detectors

False Alarm Rates and Significance: Blind Injection Challenges in Initial LIGO/Virgo



- ***The Equinox Event* - 09/21/2007**
- Expect FAR < 1/500 yrs in Gaussian noise
- Actual FAR = 1/43 yrs [1/5 yrs with trials factor]
- The probability of seeing one background event as loud as this was ~10%, too high to exclude a possible accidental origin of this event

PRD 81 (2010) 102001



- ***The Big Dog Event - 09/16/2010***
- FAR = 1/40,000 yrs [1/7,000 with trials factor]
- Would have declared a detection (had it not been an injected signal)

PRD 85 (2012) 082002

Motivation for a Follow-up Program

- Catch a counterpart
  - missed GRB, orphan afterglow from off-axis or “failed” GRB, kilonova...
- Optical/Radio/X-ray transient would make an event “stronger”: increase confidence in the astrophysical origin of a gravitational wave candidate
  - detect weaker GW events?
  - More precise localization (in a host galaxy or outside?)
  - Compare GW and EM emissions (strength, time...) for insight into the progenitor and environment physics
- Complementary information gives clues to open questions
  - are compact object mergers engines for short GRBs?
  - birth and evolution of black holes?
  - tests of GR (propagation speed and polarization)

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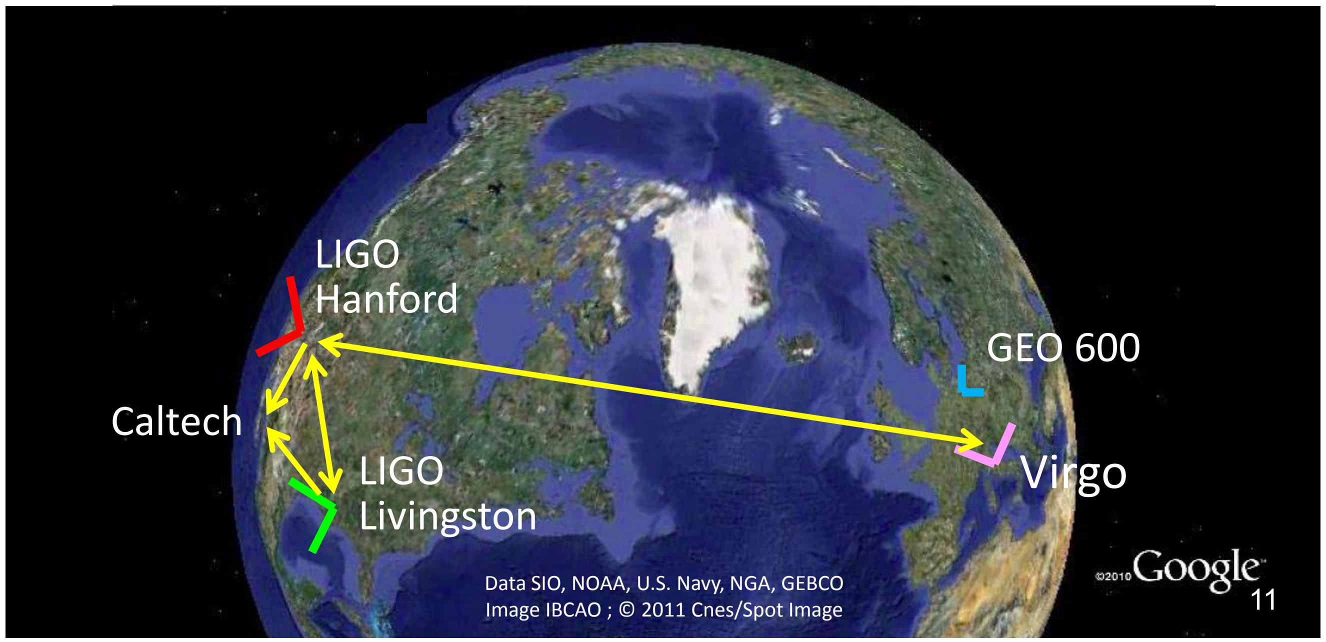
Managing accidental coincidences will require expertise from both sides

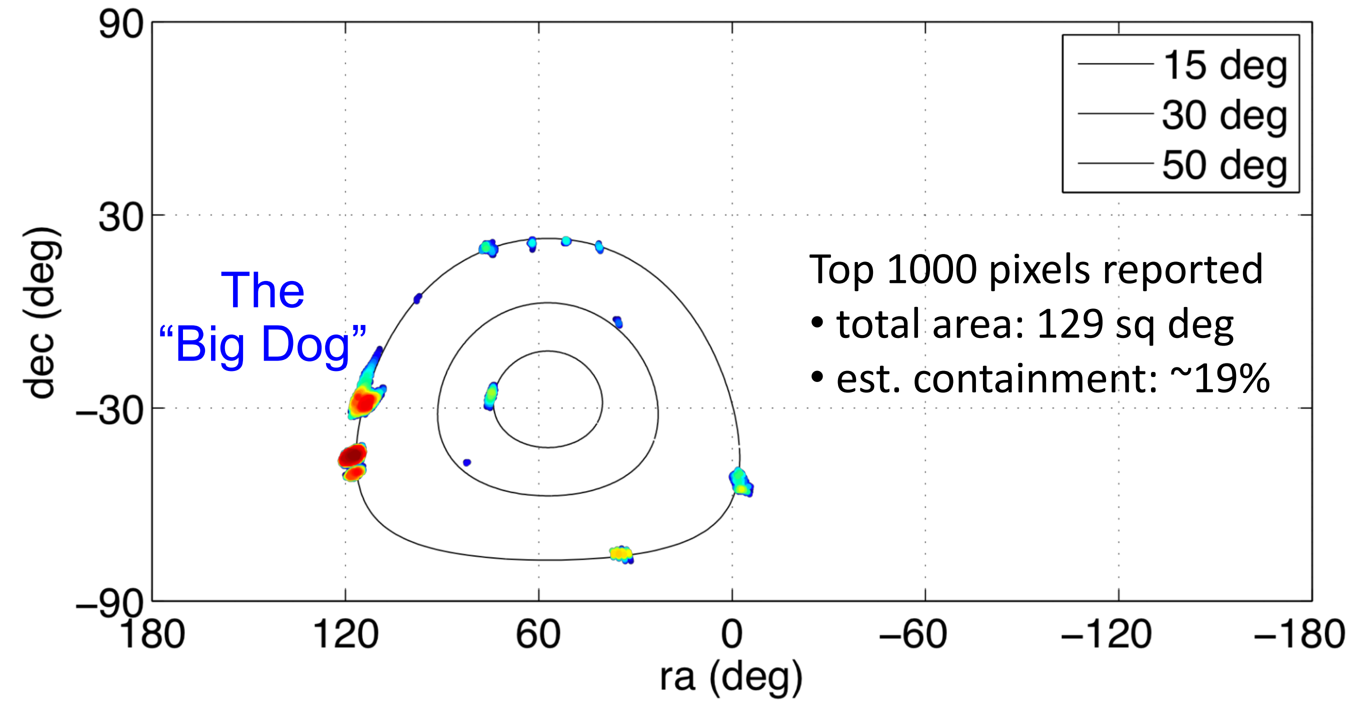
what is the normal populations of similar transients (in GW and EM)?

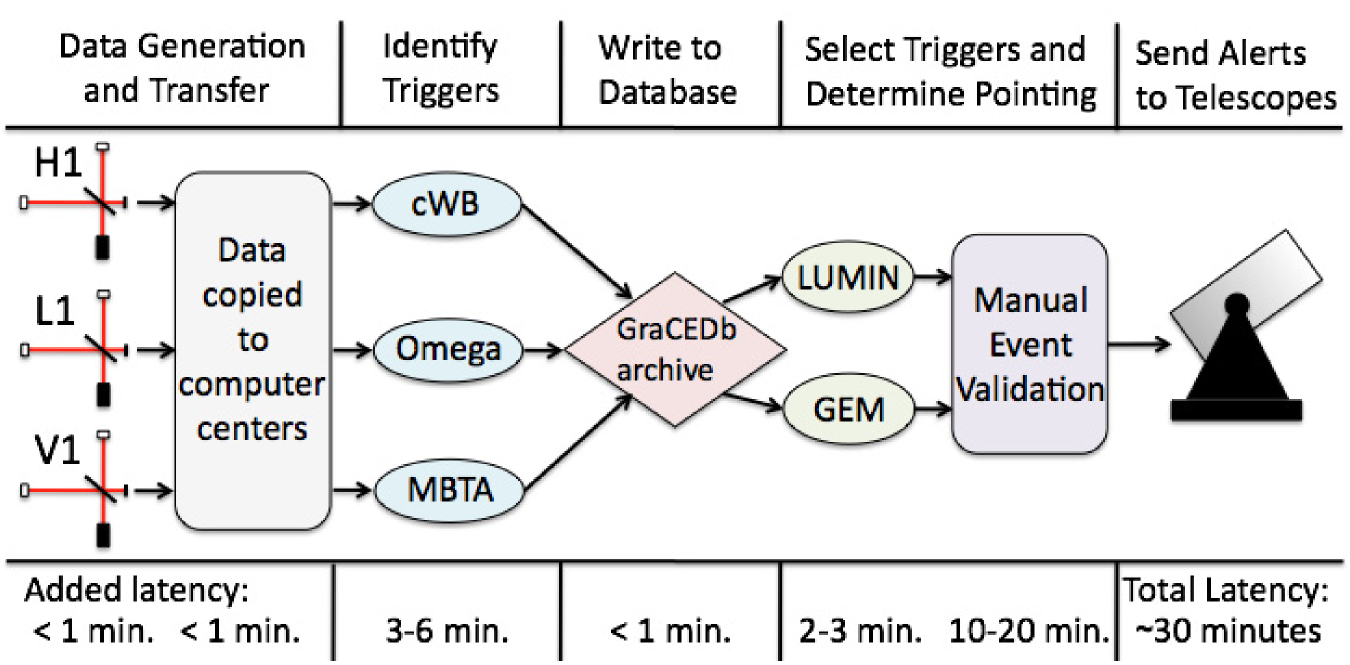
The 2009-2010 EM Followup Program

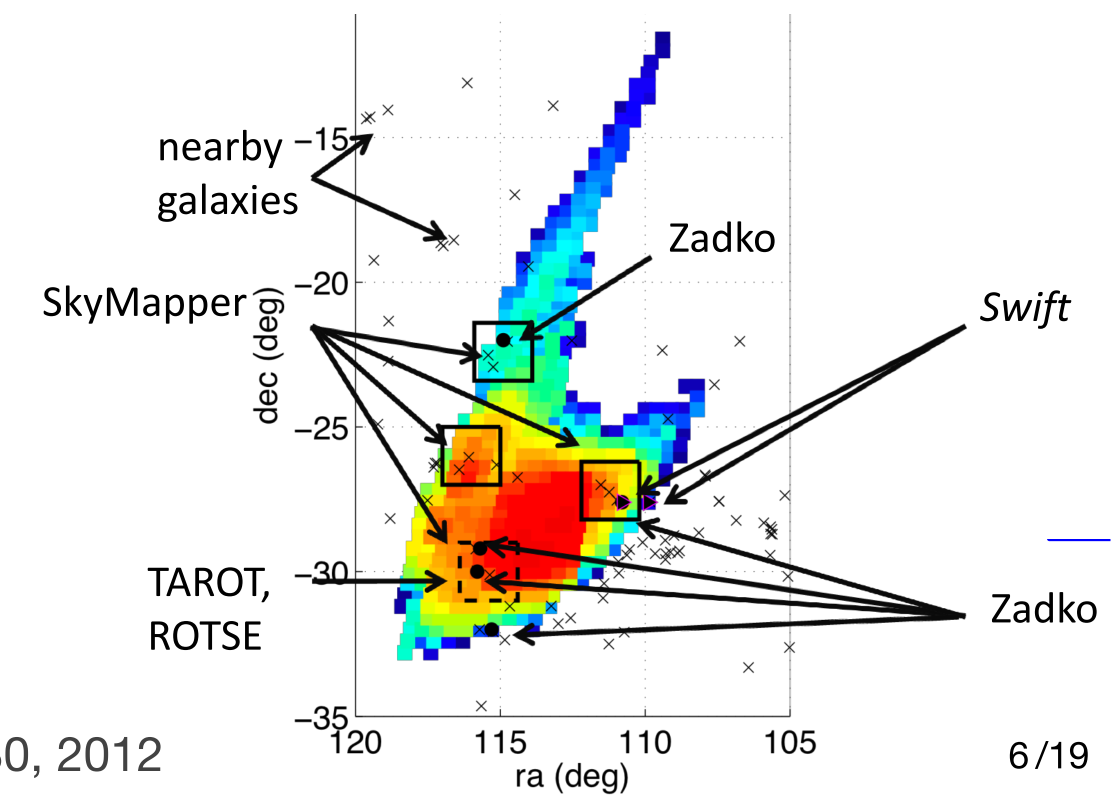
Abadie et al. 2012 A&A 539; Abadie et al. 2012 A&A 541



Coherent WaveBurst probability sky map:



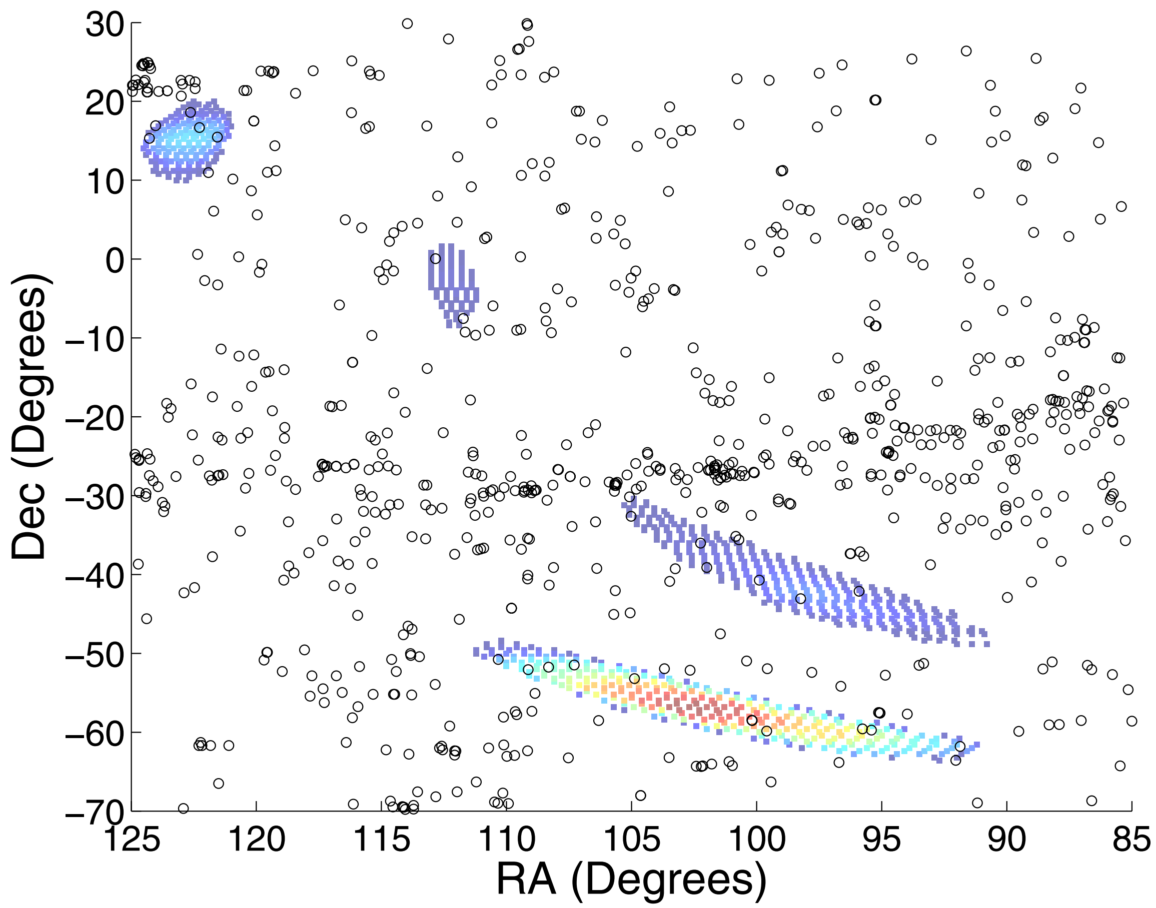


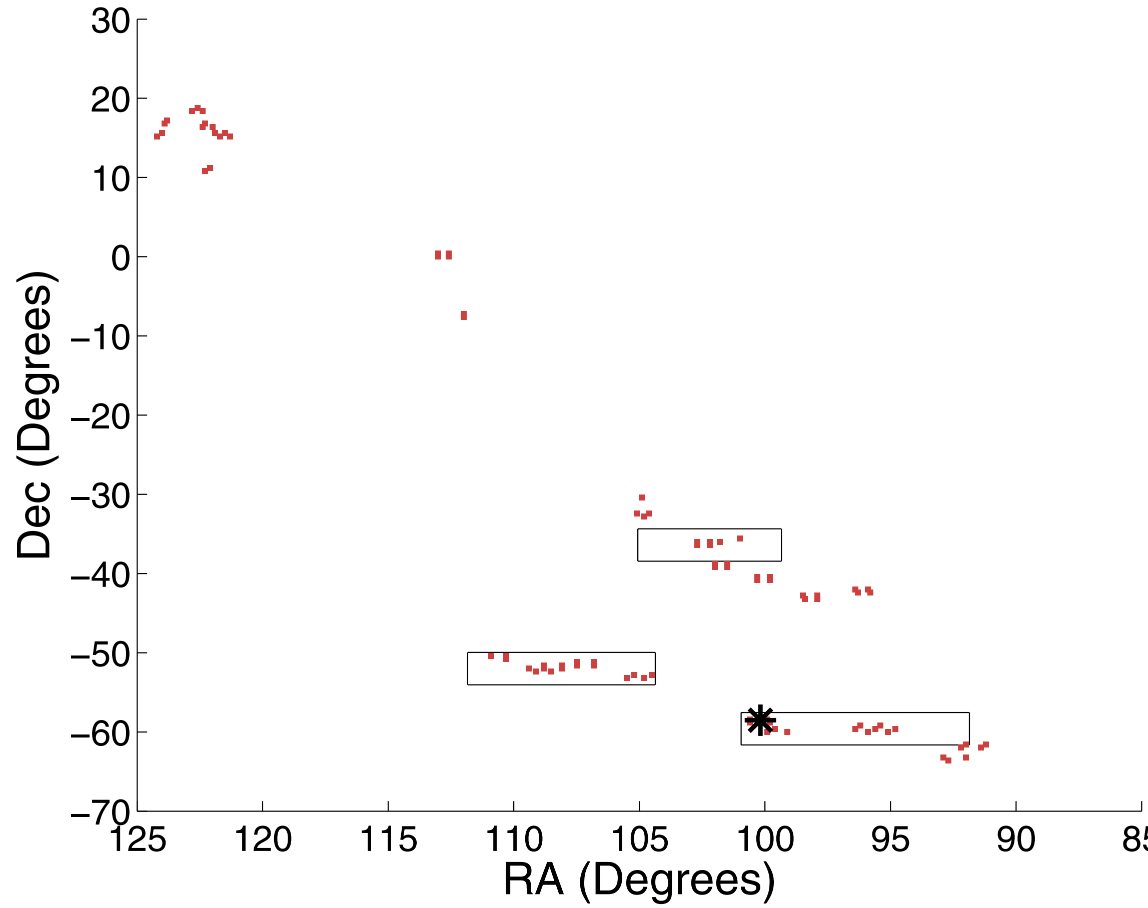


The 2009-2010 EM Followup Program: LUMIN Galaxy Targeting

Abadie et al. 2012 A&A 539; Abadie et al. 2012 A&A 541

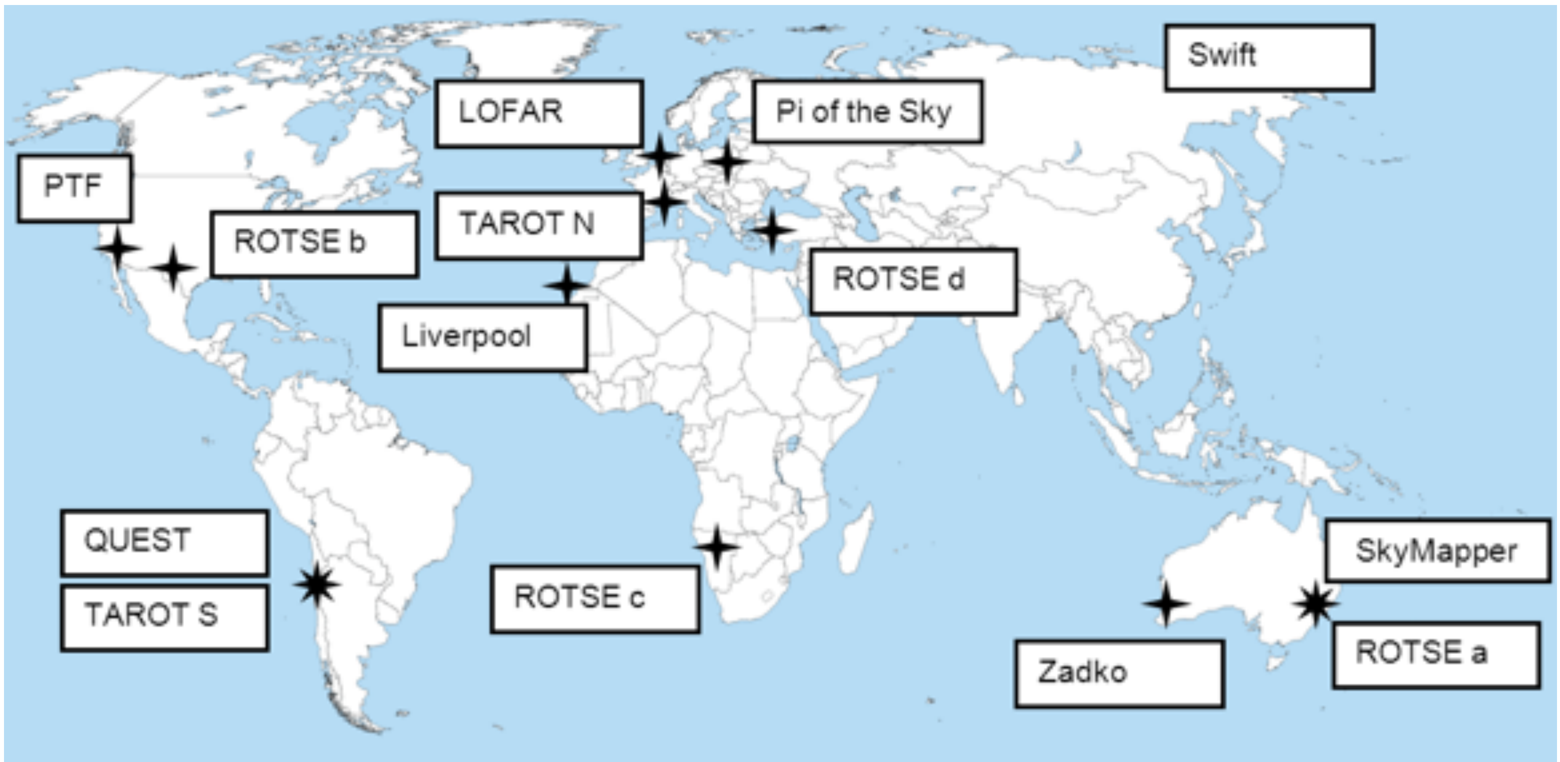
- Used positions of known galaxies within 50 MPc White et al, CQG 28, 085016
- Weight by blue light luminosity, inversely by distance
- CBC candidates: only consider galaxies closer than measured effective distance for the trigger





The 2009-2010 EM Followup Program: Observing Partners

Abadie et al. 2012 A&A 539; Abadie et al. 2012 A&A 541



Mostly wide field optical, but also LOFAR (radio) and Swift (X-ray, UV) Agreement by MOU

- **Optical telescopes:**
  - Winter run: 8 alerts sent, 4 observed by at least one telescope
  - Fall run: 6 alerts sent, 5 observed by at least one telescope (incl. big dog)
- **SWIFT satellite:**
  - 2 GW alerts sent and observed (XRT, UVOT)
- **Radio Interferometers:**
  - LOFAR: 5 GW alerts sent and observed
  - Expanded VLA: 2 GW alerts observed in high latency (weeks) followup

The 2009-2010 EM Followup Program: Optical Image Analysis

- Search for EM transient object counterpart by analyzing a series of images taken in consecutive epochs - still in progress.

- Astronomy skills needed for identification of transient objects, removal of “contaminating events”, complication of large sky area to be analyzed

- Optical false alarm rate depends on the telescope, image analysis procedure, source position... importance of all-sky surveys independent of GW triggers

The 2009-2010 EM Followup Program: SWIFT

- 2 events followed up (incl. Big Dog):
  - FAR 1/35d
  - > 20% skymap covered by up to 5 XRT tiles
- X-ray analysis (0.4°x0.4° fields): 20 detections (1.5 σ)
- Optical/UV: 6800 detections
- All consistent with expected serendipitous sources; no single source with significant variability
- improved efficiency vs false alarm probability

arXiv:1205.1124

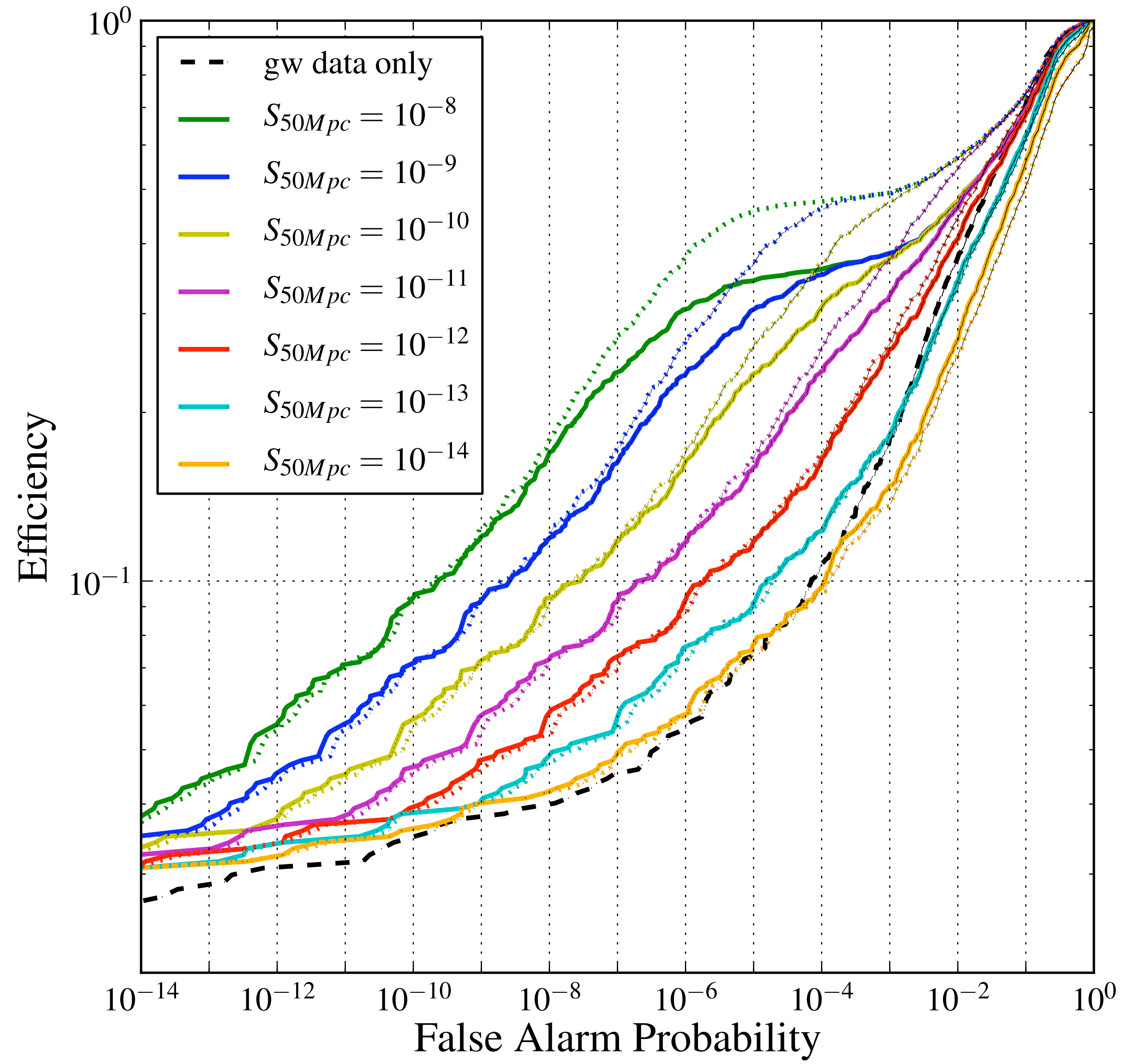


FIG. 3.— Efficiency as a function of false alarm probability for the joint LIGO-Virgo and Swift search. The solid (dotted) curves represent performance of the joint search with five (ten) fields observed by Swift for various values of the flux of an X-ray counterpart (in units of erg s^{-1} cm^{-2}) at a distance of 50 Mpc, $S_{50\mathrm{Mpc}}$. The dashed line is the curve for the GW only search.

1999 2001 2003 2005 2007 2009 2011 2013 2015

S5/VSR1 S6/VSR2,3 Advanced

Inauguration

Full Lock

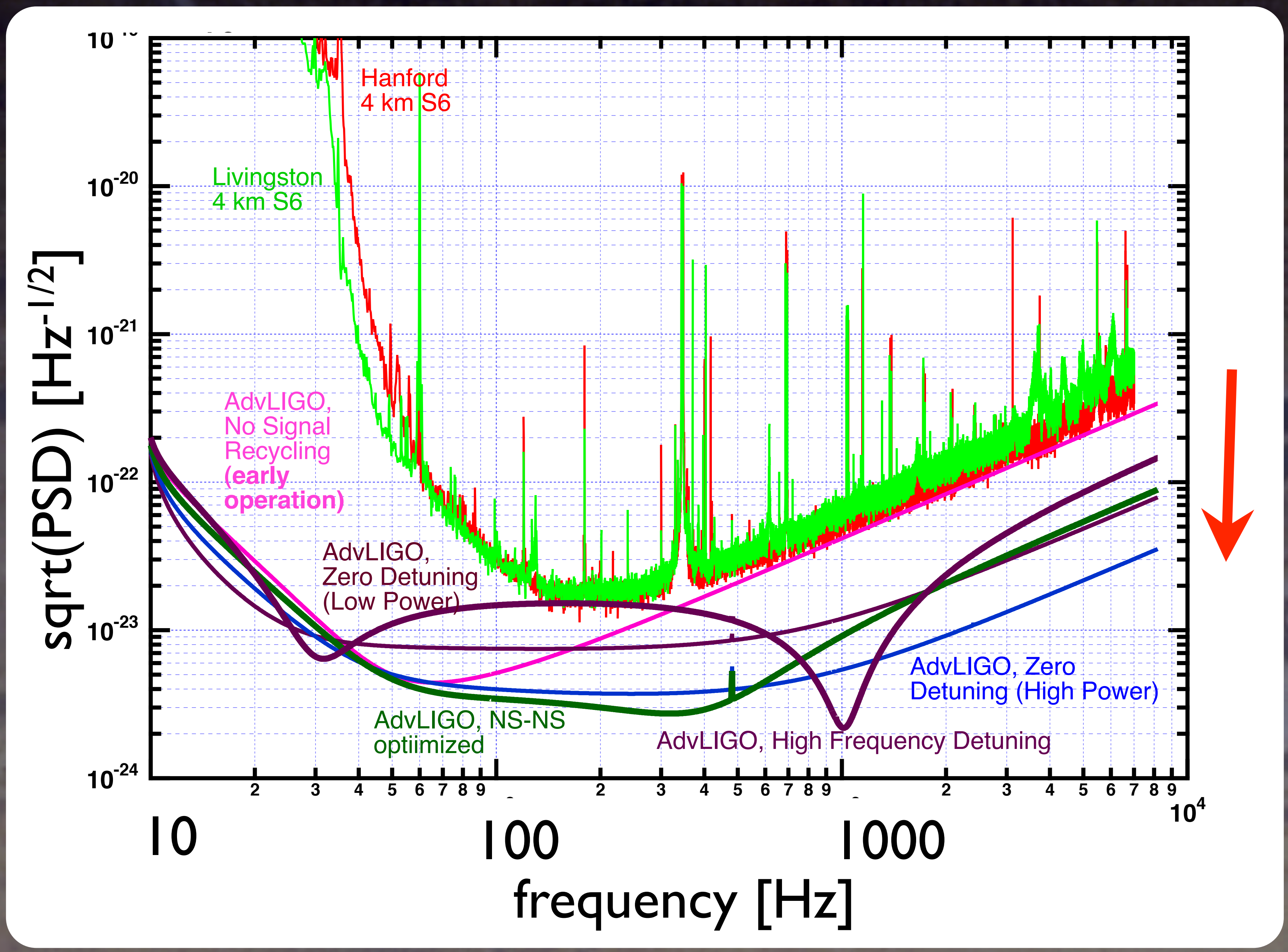
Initial LIGO/Virgo

Enhanced LIGO/Virgo

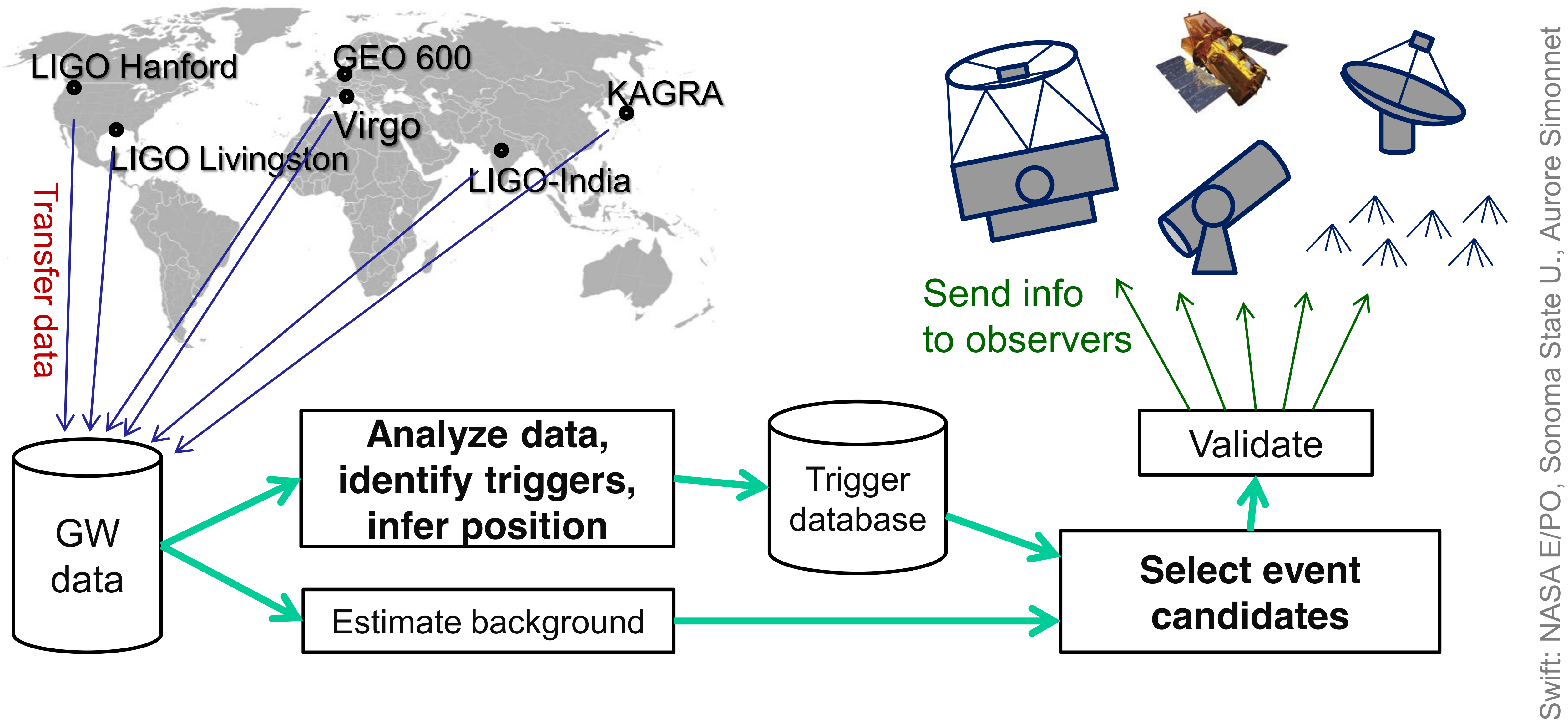
Advanced LIGO/Virgo

10^{-17} 10^{-19} 10^{-21} 10^{-22} 4×10^{-23}

Strain noise at 150 Hz [$Hz^{-1/2}$]



EM Followup with Advanced Detectors: The Plan



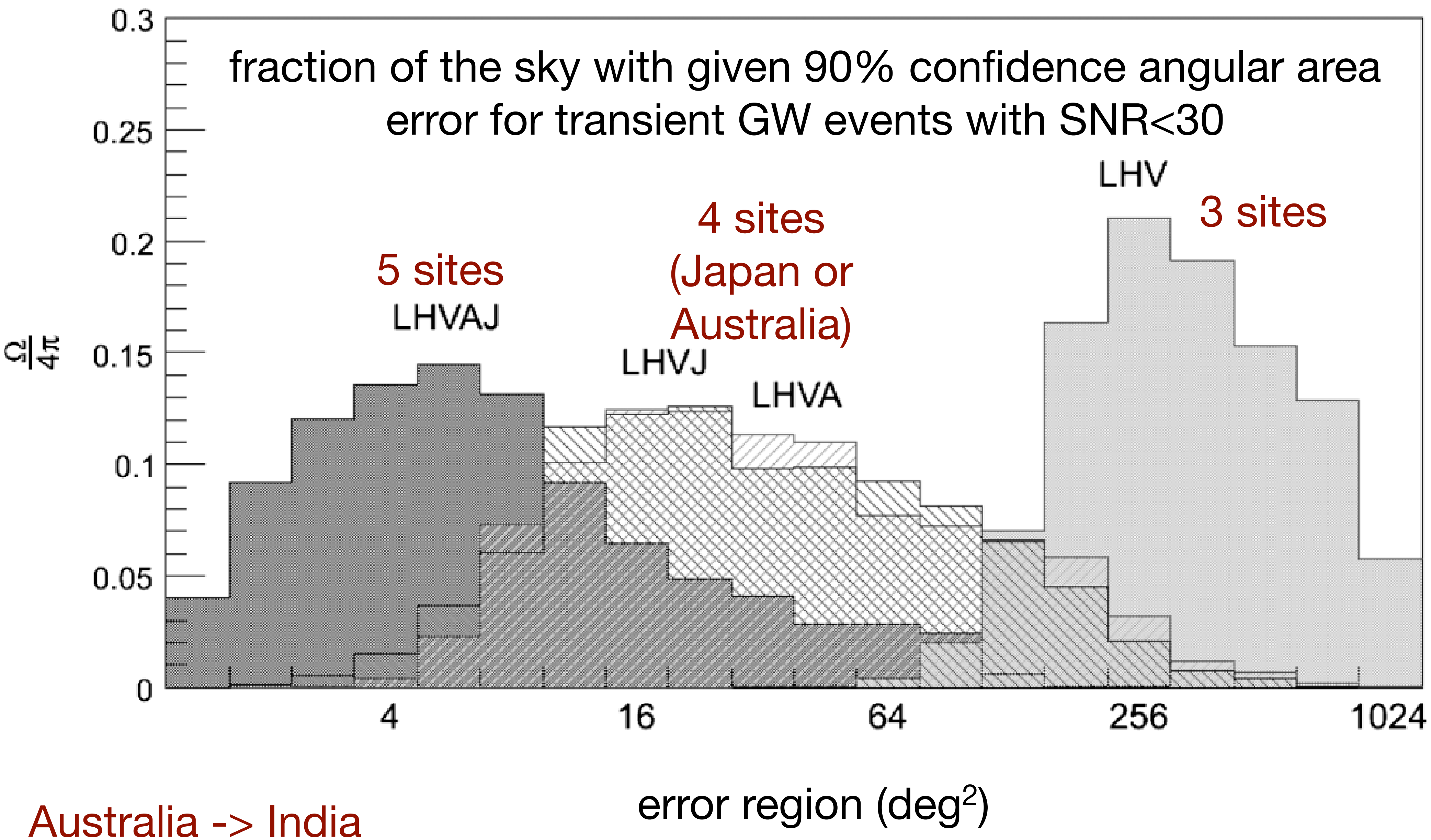
EM Followup with Advanced Detectors: Requirements

- Coordination of science runs and downtime to maximize coverage, localization
- Calibrate data, transfer to computing centers (Latency ~1 minute)
- Run the analysis, collect triggers (Latency ~ 3-6 minutes)
- Map out distribution of detection statistic for random coincidences, estimate false alarm rate for each trigger, validate data quality, etc. before accepting as event candidate (Latency ~10-30 minutes)
- Localize position (see Fairhurst's talk)

2 detectors: ~1000 square degrees (annulus)
3 detectors: 100s square degrees
4 detectors: 10s square degrees

Some signals will be localized better

EM Followup with Advanced Detectors: Network and Error Regions



Australia -> India

Klimenko et al, PRD 83 (2011) 102001

EM Followup with Advanced Detectors: Communication with Observers

- **Collect event candidate information**
  - Signal type, significance, time, sky map, estimated physical parameters
  - Standardized format (VOEvent?)
- **Send alert to observers**
  - Plan to use standard channels (GCN/TAN, VOEventNet)
  - May have revised information to distribute later

- LSC and Virgo are committed to releasing public alerts in the long run; but until first few GWs are detected, work with partners through MOUs
  - ➡ https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=M1200055

EM Followup with Advanced Detectors: Trigger Release Policy

LIGO DCC M1200055

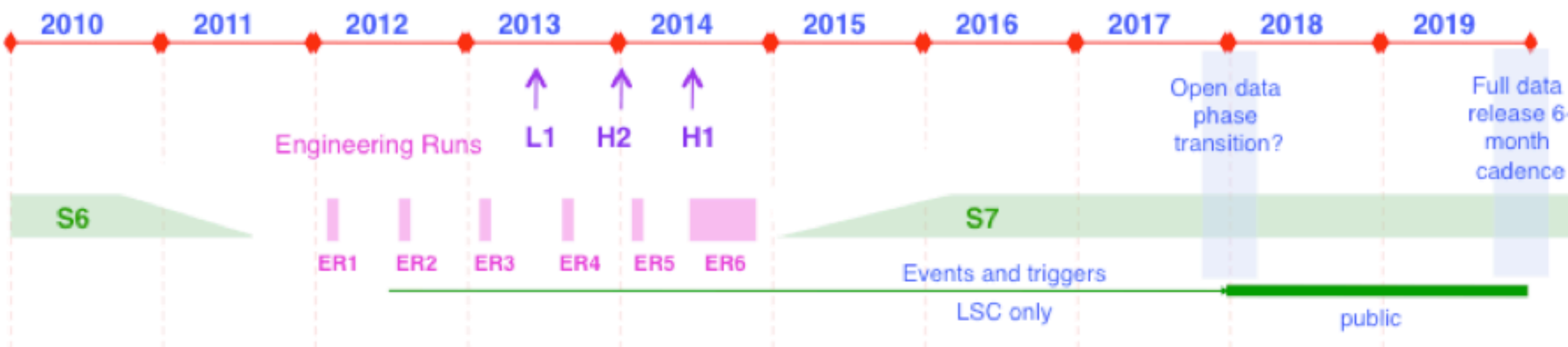
The LSC and Virgo recognize the great potential benefits of multi-messenger observations, including rapid electromagnetic follow-up observations of GW triggers. Both Collaborations (the LSC and Virgo) will partner with astronomers to carry out an inclusive observing campaign for potentially interesting GW triggers, with MoUs to ensure coordination and confidentiality of the information. They are open to all requests from interested astronomers or astronomy projects which want to become partners through signing an MoU. They encourage colleagues to help set up and organize this effort in an efficient way to guarantee the best science can be done with gravitational wave triggers.

After the published discovery of gravitational waves with data from LSC and/or Virgo detectors, both the LSC and Virgo will begin releasing especially significant triggers promptly to the entire scientific community to enable a wider range of follow-up observations. This will take effect after the Collaborations have published papers (or a paper) about 4 GW events, at which time a detection rate can be reasonably estimated. The releases will be done as promptly as possible, within an hour of the detected transient if feasible. Initially, the released triggers will be those which have an estimated false alarm rate smaller than 1 per 100 years.

Partners who have signed an MoU with the LSC and Virgo will have access to GW triggers with a lower significance threshold and/or lower latency, according to the terms of the MoU, in order to carry out a more systematic joint observing campaign and combined interpretation of the results.

Throughout the Advanced Detectors era, the LSC and Virgo will release appropriate segments of data from operating detectors corresponding to detected gravitational waves presented in LSC/Virgo authored publications, at the time of the publication, including the first claimed detection of gravitational waves.

EM Followup with Advanced Detectors: Timeline



Similar timeline expected for Virgo; LIGO-India 2020-2022 (?)

- **Detector acceptance**: all subsystems are installed, integrated, and have passed stand-alone in-situ testing; the detector can acquire the locked state for two hours - expected mid 2014

- **Discovery Phase** (2015-2016?) Collaboration with partners with MOUs (open call)

- **Observational Phase** (after 4 detected GW events, 2017/8+?): significant triggers released to the public with low latency. LIGO GW data released to the public with some latency (~2 years?), and periodic cadence (~6 months?)

Data Release Sample: GRB051103
http://www.ligo.org/science/GRB051103

LIGO DATA RELEASE ASSOCIATED WITH GRB051103

This page has been prepared by the LIGO Scientific Collaboration (LSC) to make data associated with two LIGO gravitational wave detectors taken around the time of GRB051103 available to the broader community.

INFORMATION ABOUT GRB051103

- Science Summary: Implications For The Origin Of GRB 051103 From LIGO Observations
- The publication describing the analysis (arXiv)
- Repository of data used for figures in the publication
- Gamma-Ray Bursts: Introduction To A Mystery
- `Magnetars', Soft Gamma-repeaters & Very Strong Magnetic Fields
- An introduction to gravitational waves from compact binary coalescence
- An introduction to gravitational wave bursts

SUMMARY OF OBSERVATION

GRB 051103 was a short-duration, hard-spectrum gamma-ray burst (GRB) which occurred at 09:25:42 UTC on 3 November 2005 (Hurley et al. 2010) and was possibly located in the nearby galaxy M81, at a distance of 3.6 Mpc from Earth (Fig 1 from paper). It was observed by instruments on seven different spacecraft.

Two LIGO detectors were taking science-quality data during the 2190 seconds surrounding GRB051103: the 2km detector at LIGO Hanford Observatory (LHO), known as H2, and the 4km detector at LIGO Livingston Observatory (LLO), known as L1.

Data from these two LIGO detectors were searched for coincident signals consistent with a gravitational wave incident on both detectors.

It is widely believed that most short-hard GRBs result from the gravitational-radiation-induced coalescence of a binary system containing either two neutron stars or one neutron star and a black hole, so we focus on that scenario here. In such a scenario, gravitational waves would arrive at the earth within a few seconds of the gamma rays, so we look within a 6-second interval around the GRB time.

Times in the 6-second interval between 09:25:37 and 09:25:43 UTC on 3 November 2005 are referred to as "on source". This is where we search for a signal associated with GRB051103. There are 324 6-second intervals that are referred to as "Off source" times, selected between 08:54:25 and 09:30:55 UTC (excluding the on-source time and a buffer region around it). These are used to estimate the background distribution of random noise triggers that are also present in the "on source" interval.

As reported in the LIGO publication, no signal was observed above background in the LIGO data.

LIGO data contain, in addition to potentially detectable gravitational wave signals, non-stationary, non-Gaussian noise. Noise fluctuations can register as "triggers", at a rate high enough that they can be accidentally coincident (within fractions of a second) between the H2 and L1 detectors - the background that can fake a signal. Coincident triggers are observed in the "on-source" observation time. However, the rate and significance ("loudness") of those triggers is statistically consistent with those from "off-source" times, where we expect to see only background. Hence, we observe no loud signal above background in the LIGO data.

GRAVITATIONAL-WAVE DETECTOR DATA

- The calibrated data from the LIGO detectors that were used for our GRB051103 analysis is provided here for scientists who wish to do their own analysis. Any publication making use of such data should properly credit the LIGO Scientific Collaboration. We request that anyone interested in publishing anything using these data please first consult with us at datainfo@ligo.org.
- Note that proper analysis and interpretation of this data requires careful consideration of the detector noise -- which is non-white and non-stationary -- as well as the response of the detectors, which depends on the arrival direction and polarization content of the incoming gravitational wave.
- Here we provide raw data on the locations and orientations of the detectors, excerpted from the file LALDetectors.h contained in the LALSuite analysis library, as well as some further notes and illustrations of the detector geometry.
- The overall fractional uncertainty in amplitude calibration is estimated at 25% for both H2 and L1 data, in the band between 40 and 2000 Hz (and uncalibrated outside this band). This is significantly larger than typical science run calibration uncertainties (see e.g., *Calibration of the LIGO Gravitational Wave Detectors in the Fifth Science Run*) as fewer calibration measurements were available from the data taking around the GRB051103 time.
- The data files may be found in this repository.
- The data are provided in two formats: HDF5 and gzipped ascii text. Many data analysis environments can read in data from HDF5 files, including Python (see the h5py package), MATLAB, C/C++, and IDL. Links to example python scripts for reading and plotting the HDF5 files can be found below.

STRAIN DATA AT 16384 HZ

Strain h(t) time series for individual detectors (H2 and L1), starting at GPS 815043278 (Thu Nov 03 08:54:25 GMT 2005), duration 2190 sec, sampled at 16384 Hz, and high-pass filtered to remove the dominant noise below 20 Hz.

- HDF5:
  H2-STRAIN_16384Hz-815043278-2190.hdf5 (274 MB)
  L1-STRAIN_16384Hz-815043278-2190.hdf5 (274 MB)
- gzipped ascii text:
  H2-STRAIN_16384Hz-815043278-2190.txt.gz (329 MB)
  L1-STRAIN_16384Hz-815043278-2190.txt.gz (329 MB)

STRAIN DATA AT 4096 HZ

Strain h(t) time series for individual detectors (H2 and L1), starting at GPS 815045078 (Thu Nov 03 09:24:25 GMT 2005), duration 256 sec, sampled at 4096 Hz, and even more high-pass filtered to remove the dominant noise below 30 Hz.

- HDF5:
  H2-STRAIN_4096Hz-815045078-256.hdf5 (4.1 MB)
  L1-STRAIN_4096Hz-815045078-256.hdf5 (4.1 MB)
- gzipped ascii text:
  H2-STRAIN_4096Hz-815045078-256.txt.gz (9.8 MB)
  L1-STRAIN_4096Hz-815045078-256.txt.gz (9.8 MB)

NOISE SPECTRA

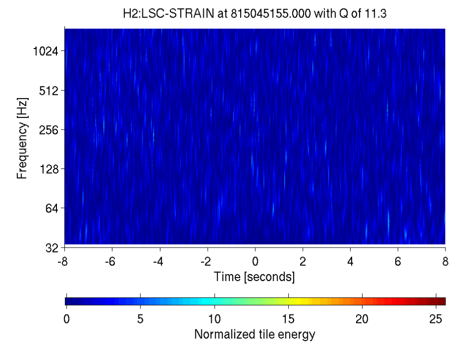
The one-sided detector strain noise amplitude spectra around the time of GRB051103, as hdf5, gzipped ascii text files and plots (png and pdf). The vertical scale is strain per sqrt Hz.

- HDF5:
  H2-SPEC-815043278-2190.hdf5
  L1-SPEC-815043278-2190.hdf5
- gzipped ascii text:
  H2-SPEC-815043278-2190.txt.gz
  L1-SPEC-815043278-2190.txt.gz
- Figures: H2_asd.png and H2_asd.pdf; L1_asd.png and L1_asd.pdf.
- More figures and information here.

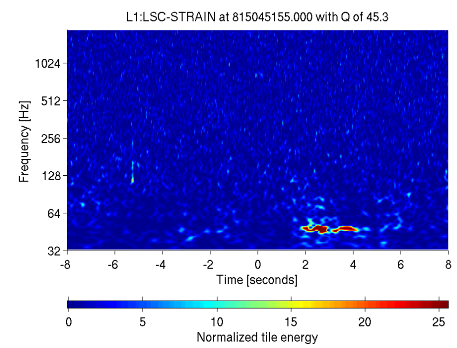
SPECTROGRAMS AND OMEGAGRAMS

Spectrogams of the strain h(t) time series for individual detectors, starting at GPS 815045078 (Thu Nov 03 09:24:25 GMT 2005), duration 256 sec, sampled at 4096 Hz:
H2_spectrogram.png and H2_spectrogram.pdf; L1_spectrogram.png and L1_spectrogram.pdf
More figures and information here.

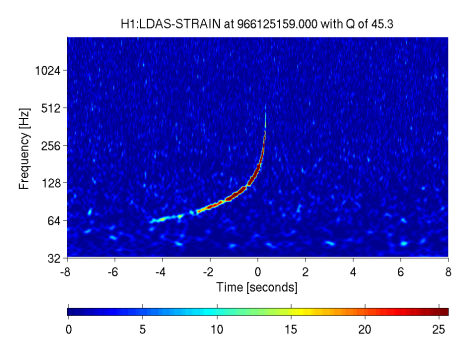
Omegagrams are time-frequency plots of the sort shown above. For their definition and further plots, see here.



Omegagram of strain data from H2 near the time of GRB051103. (For more information on omegagrams, see here).



Omegagram of strain data from L1 near the GRB051103 time. The red blob near the bottom between 2 and 4 seconds is a detector data glitch which is mostly below 40 Hz. Our BNS templates start at 40 Hz because the detector noise rises sharply at lower frequencies, so they are largely insensitive to these kinds of glitches.



Omegagram of strain data from H1 near a simulated BNS signal at 3.5 Mpc injected in to the detector.

For more information on omegagrams, see here.

DATA QUALITY

Data quality for individual detectors, starting at GPS 815043278 (Thu Nov 03 08:54:25 GMT 2005):
None of these data are vetoed due to problems with the data quality; all data from both detectors during this time are unvetoed and are of good science quality.

SEARCH TRIGGERS

If GRB051103 was produced by the binary merger (coalescence) of a neutron star with a black hole or another neutron star in M81, it would produce a characteristic Compact Binary Coalescence (CBC) waveform in the LIGO detectors. Event triggers from the CBC search in data around GRB051103 are available as described here.

DATA DOCUMENTATION AND EXAMPLE SCRIPTS

- GRB051103 data release notes.
- Data properties may be reproduced using the scripts plot_data.py (python) or plot_data.m (MATLAB), which read in the data files and makes plots displayed in this Data properties page.
- asd_ranges.py reads in the noise spectra files, makes a comparison plot, and computes the detector inspiral sensitive distance, as described at the bottom of this page.

ABOUT THE INSTRUMENTS AND COLLABORATIONS

THE LIGO OBSERVATORY

The Laser Interferometer Gravitational-Wave Observatory (LIGO) consists of two widely separated installations within the United States — one in Hanford Washington and the other in Livingston, Louisiana — operated in unison as a single observatory. LIGO is operated by the LIGO Laboratory, a consortim of the California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT). Funded by the National Science Foundation, LIGO is an international resource for both physics and astrophysics.

THE GEO600 DETECTOR

The GEO600 project aims at the direct detection of gravitational waves by means of a laser interferometer of 600 m armlength located near Hannover, Germany. Besides collecting data for gravitational wave searches, the GEO600 detector has been used to develop and test advanced instrumentation for gravitational wave detection.

THE LIGO SCIENTIFIC COLLABORATION

Conclusions

- Scientific potential and challenges of an EM followup program
- The program was successfully tested with initial LIGO/Virgo during the 2009-2010 data acquisition campaign
- In the Advanced Detector era, significant triggers will be released with low latency, full data set with slower cadence
- Early on (before first detections, and during shake-down) collaboration with observing partners will be by agreement/MOU, but broad participation is welcome and encouraged