Just add photons

Science by joining LIGO with astrophysical triggers

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Abstract

With LIGO sensitivity extending to astrophysically significant distances, gravitational wave detectors can now add value to even marginally significant sources detected by other means. As an example, we discuss GRB 070201, a short GRB whose error box intersects the spiral arms of the Andromeda galaxy (M31). Given the close proximity of M31, LIGO could rule out a binary merger origin at and beyond the distance to M31, though the system remains consistent with a nearby SGR or a much more distant and accidentally coincident burst. Even without such fortuitously close events, because the time of the event is known (and in some cases because observations provide additional temporal structure, such as with SGR 1806-20) LIGO data can be searched in coincidence at a lower threshold than untriggered gravitational wave searches. Motivated by this and other examples, we briefly review the potential improvements given by triggered searches, discuss existing efforts to follow up external triggers such as GRBs, and describe the astrophysical benefits these searches will soon provide.

Overview

LIGO's reach depends not only on the intrinsic GW luminosity of the source but also on

- whether **something about the signal model is known** and
- **the amount of data that must be searched**, which can be significantly reduced by any combination of sky location and timing

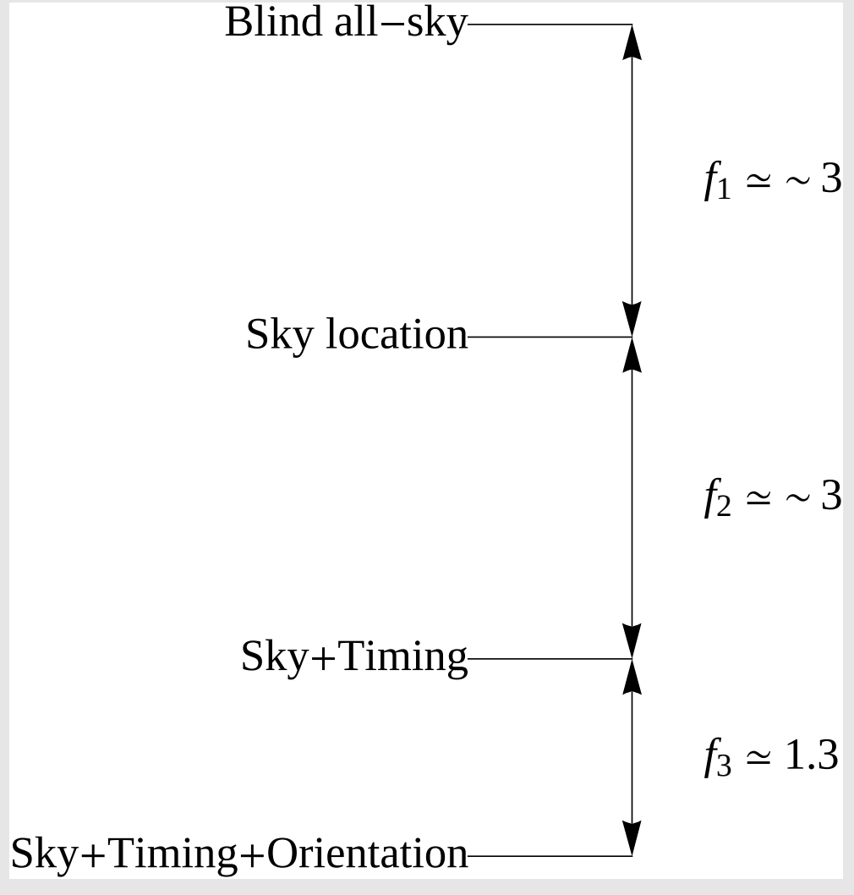
Information from optical and neutrino observatories can improve the latter (triggers) and guide the former (model). For example, the LIGO search for the Crab pulsar benefits from a *known model* (spin timing), *sky location*, and even *projected sky orientation* [2].

Additionally, gravitational wave data associated with optical signals from

- **a well-defined population can be stacked**, creating a population-based limit

that, with sufficiently many candidate events, can be significantly better than the accuracy of any individual measurement.

LIGO sensitivity (range) gain



Yardsticks for blind versus targeted searches: There is no universal yardstick for how much even a similar piece of information helps:

- Search algorithms are continually being improved, particularly for coherent multi-detector searches [1]
- Nongaussian noise in the detector (glitches) are getting easier to identify and distinguish from signal candidates.
- "Similar" information isn't always so similar: Sky location matters relative to detector; detector performance fluctuates; etc

This poster shows some concrete examples of how external information has permitted LIGO to do better than it would without information provided through photons.

Sample Yardstick: Crab pulsar: Three pieces of information about the Crab pulsar give a better upper limit over a blind search at all frequencies [2]. Given severe computational search limitations for all-sky coherent searches, pulsar searches benefit more than most other searches from astrophysical input.

References:

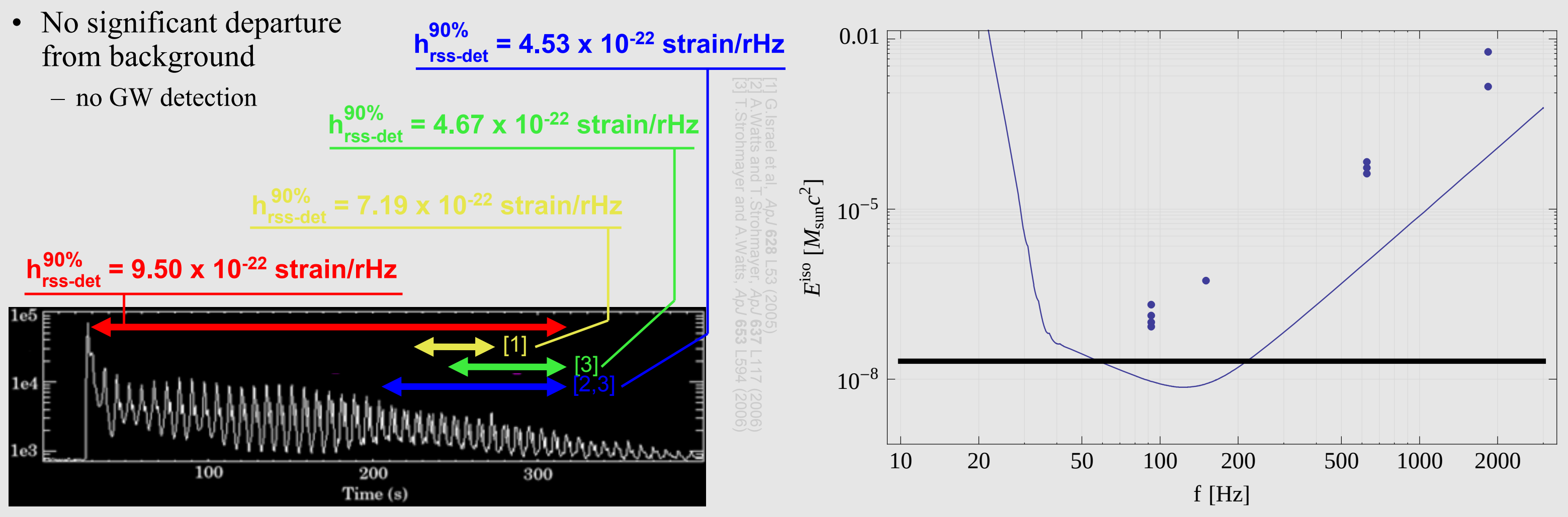
1 B. Abbott et al, Astrophysically Triggered Searches for Gravitational Waves: Status and Prospects, arXiv:0802.4320

2 B. Abbott et al, Beating the spin-down limit on gravitational wave emission from the crab, in preparation

Example 2: GW from NS transients: Magnetar flares, glitches, and accretion on NS

LIGO has used external information regarding known pulsars (sky location, timing, and even distance information) to perform a significantly more precise targeted search for steady-state emission [1]. Not only does detailed timing information allow searches that are roughly 10 times more sensitive than all sky searches, but even sky location information alone improves upon all-sky sensitivity by a factor 3.

Similarly, transient events like the giant flare of SGR 1806-20 exhibit enough obvious structure in their photon emission to suggest targeted gravitational wave searches.



LIGO limits on the Dec 27, 2004 flare of SGR 1806-20 (Left panel): This powerful electromagnetic burst exhibited quasiperiodic oscillations in its decay. LIGO searched for gravitational waves at these frequencies and in these intervals.

The best LIGO limit on GW emission at QPO frequencies seen in the light curve is close to the photon burst energy. (right panel) For the different QPOs seen at different times and different frequencies in the SGR 1806-20 decay, limits on the isotropic gravitational wave energy emitted versus frequency. For comparison, we show the approximate S4 sensitivity to narrowband bursts at an ideal detection limit SNR=1 [4]. Data from this figure taken from Table II in [2].

References

1 B. Abbott et al., All-sky search for periodic gravitational waves in LIGO S4 data, PRD 77, 022001 (2008)

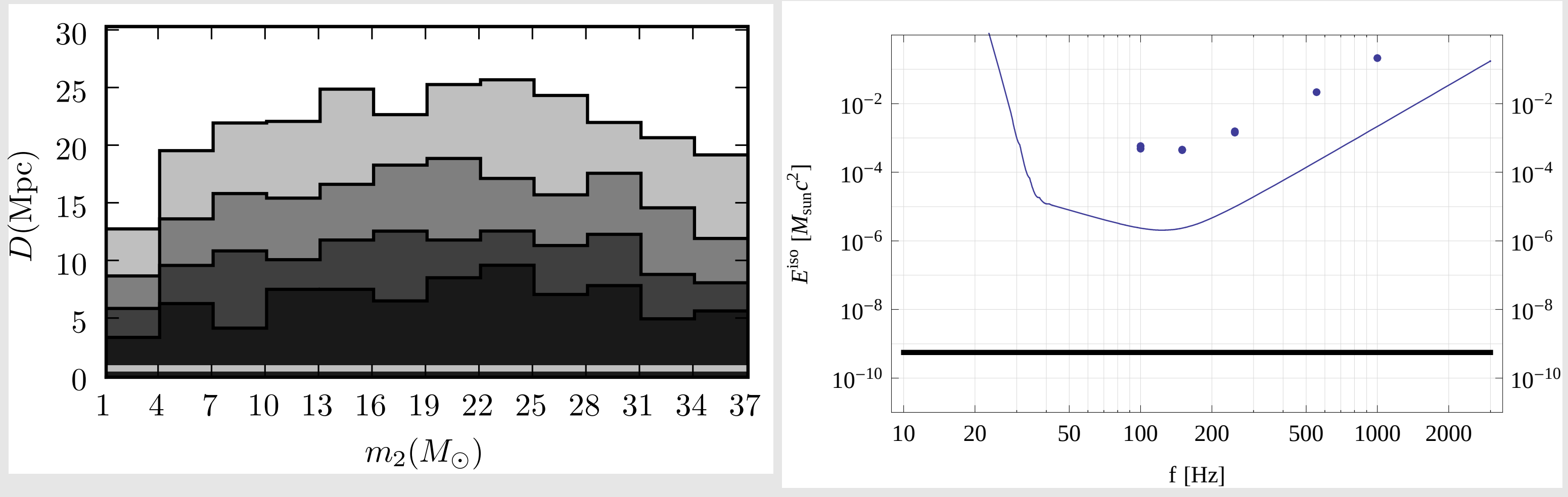
2 B. Abbott et al., Search for gravitational wave radiation associated with the pulsating tail of the SGR 1806-20 hyperflare of 27 December 2004 using LIGO, PRD 96, 062003 (2007)

3 B. Abbott et al., LIGO Search for Gravitational Waves Associated with SGR Bursts, in preparation

4 Past and present sensitivity curves for LIGO are available at `http://www.ligo.caltech.edu/~jzweizig/distribution/LSC_Data/`

Example 1: GRB 070201

The short GRB 070201 had a sky location box overlapping the spiral arms of M31. Previous optical studies of short GRBs had suggested a neutron star merger model origin for many short GRBs. Since no inspiral waves were detected by the LIGO Hanford detectors, which were operating at the time and adequately aligned with the source (with a beampattern-induced range reduction factor $F_{RMS} \simeq 0.3$), either the source is not a merger or not in M31 [1] [Figure 1]. [Note that GRB 070201 has an energy flux consistent with an "average" short GRB at a distance comparable to the largest which are excluded in the left panel in Figure 1. This bursts' energy emission if at M31 (10^{45} erg) is much more consistent with the known emission from magnetars, such as SGR 1806-20. A search for *completely unmodeled emission* found no sign of gravitational waves. As shown in the figure below, however, LIGO's upper limit on the gravitational wave energy flux is many orders of magnitude greater than the known optical flux.



Left panel: The short GRB 070201 cannot be a neutron star merger nearby. From the lack of any gravitational wave inspiral signal, this figure shows the 90%, 75%, 50%, and 25% exclusion regions in distance and mass of a NS companion, from darkest to lightest respectively. The distance to M31 is indicated by the horizontal line at D=0.77 Mpc: an inspiral in M31 is excluded at $> 99\%$ confidence. Both amplitude calibration uncertainty and Monte-Carlo statistics are included in this result; apparent fluctuations as a function of mass are due to Monte Carlo uncertainty. This figure appears in and is discussed in more detail in [1].

Right panel: LIGO's limit on the gravitational wave energy flux is much higher than the observed optical flux, even at the most sensitive frequencies. For comparison, we show the ideal (design-)sensitivity that the 4km LIGO detector at Hanford would have for this burst, assuming perfect knowledge of the narrowband burst waveform [1,3] and the ability to search in the noise down to the (unrealistically) low level SNR=1, corresponding to a $1-\sigma$ detection in gaussian noise.

References:

1 B. Abbott et al. Implications for the Origin of GRB 070201 from LIGO Observations, to appear in ApJ; arXiv:0711.1163

2 M. Mazets et al. A giant flare from a soft gamma repeater in in the Andromeda galaxy, M31, arXiv:0712.1502

3 Past and present sensitivity curves for LIGO are available at `http://www.ligo.caltech.edu/~jzweizig/distribution/LSC_Data/`

Example 3: GRB Population searches

In addition to searching for the signature of individual bursts, as with 070201, LIGO is also examining the composite significance of all on-source GRB data for any possible photon-gravitational wave correlation [1]. In simplest form the search is a classical student-t test for the null hypothesis of on source and off-source time being statistically similar in mean and variance of SNR [3,4]. Our range should increase as (roughly)

$$D = D_o N^{1/2}$$

for moderate N. At large N we are limited by our ability to estimate the background. Due to the highly nongaussian nature of the background, a more sophisticated test was applied to compare the on-source results with an extensively examined off-source noise distribution and search for outliers [1,2].

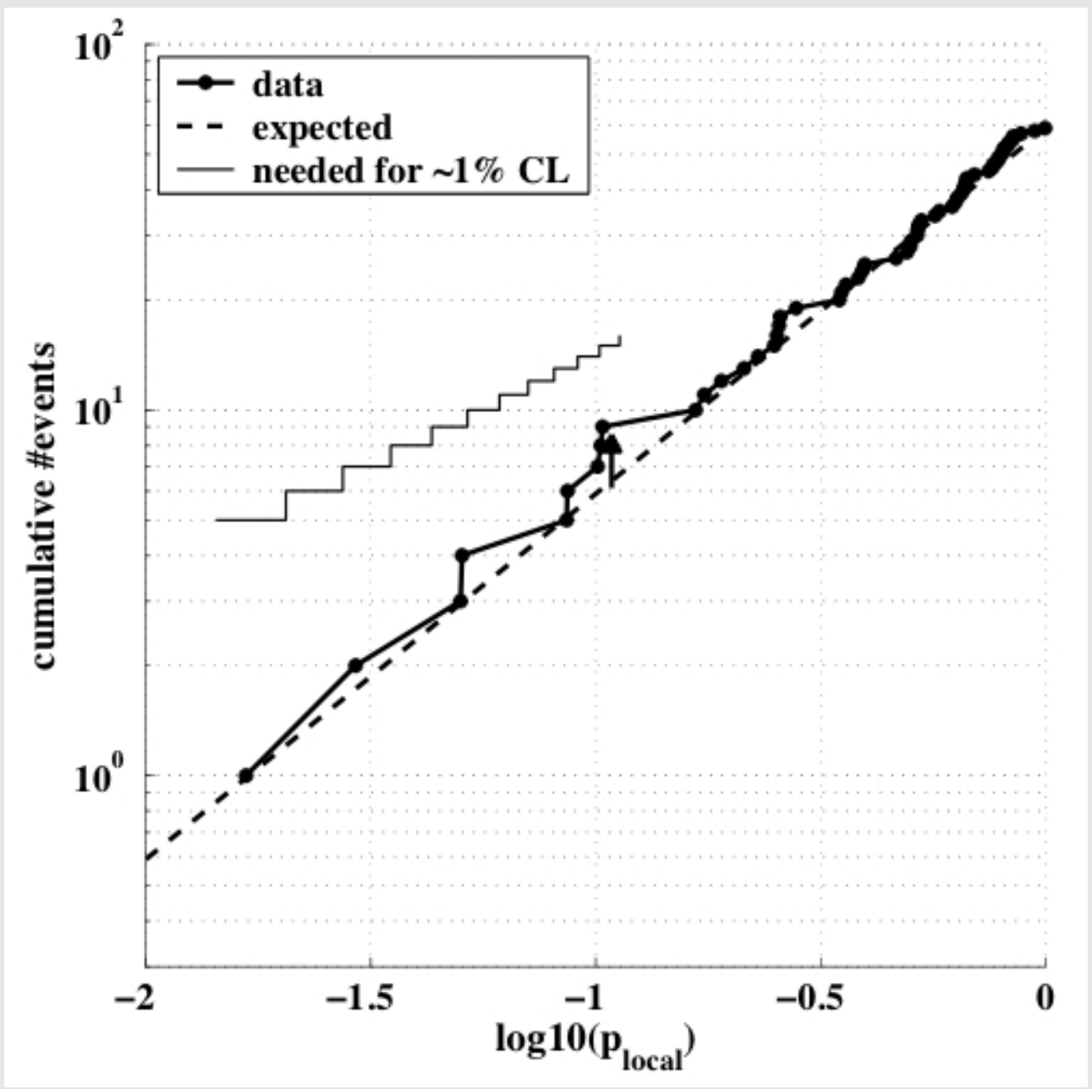
References:

1 B. Abbott et al, Search for gravitational waves associated with 39 gamma-ray bursts using data from the second, third, and fourth LIGO runs, PRD 77 062004 (2008)

2 S. D. Mohanty, Population study of gamma ray bursts: detection sensitivity and upper limits, CQG 26, 723 (2006)

3 L.S. Finn, P.J. Sutton, and B. Krishnan, Swift Pointing and the Association between Gamma-Ray Bursts and Gravitational Wave Bursts, ApJ 607, 384 (2004)

4 L.S. Finn, S.D. Mohanty, and J.D. Romano, Detecting an association between gamma ray and gravitational wave bursts, PRD 60, 121101 (1999)



Population study of 39 GRBs from LIGO S2, S3, and S4 data. The cumulative distribution of false alarm probabilities for data coincident with each of these GRBs. The expected distribution under the null hypothesis is the bold,dashed line. The excess needed for 1% confidence in the null hypothesis is shown by the solid line. Data used in this figure taken from [1].

Acknowledgments: R.O. was supported by National Science Foundation awards PHY 06 -53462 and the Center for Gravitational Wave Physics. The Center for Gravitational Wave Physics is supported by the George A. and Margaret M. Downsbrough Endowment and by the National Science Foundation under cooperative agreement PHY 01-14375. The LIGO lab is supported by the NSF (US); the GEO-600 detector is supported by the Science and Technology Facilities Council (UK), the Max-Planck Society and State of Niedersaschen/Germany (DE). Research by the LSC is also supported by the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educación y Ciencia, the Conselleria d'Economia, Hisenda i Innovació of the Govern de les Illes Balears, the Scottish Funding Council, the Scottish Universities Physics Alliance, The National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

Astronomical input enables high-impact LIGO science:

- perform focused searches
  - sky, timing, and even template/frequency targeted
- with shorter turn-around
  - less background to study; detector fluctuations smaller
- of objects known to exist and to be interesting

Other ideas under consideration: For triggers or sources that we know are seen regularly, we're searching explicitly, with as much information as is available:

- Long and short GRBs
- SGR flares, pulsar glitches, & ringdowns
  - targeting theoretical quasinormal mode candidates
- Accreting pulsars : bursty, continuous, ?
  - X-ray coherence?
  - QPOs?
- Galactic center pulsars
- Galactic center bursts (excess)
- Supernovae
- Neutrino-triggered
- Ultra-energetic cosmic-ray triggered

Plausible searches (no optical triggers...yet...) For plausible sources we could detect, we are searching, but would benefit from photon triggers if any are produced:

- Parabolic BH-BH, BH-NS encounters in globular clusters
- Intermediate-mass BHs capturing NS, BH
- BH-BH mergers in nearby young protoclusters ($<$ 300 Mpc) interacting galaxies?
- Umodelled long-lived (seconds/minutes) transients

HEAD, Los Angeles. April 2008