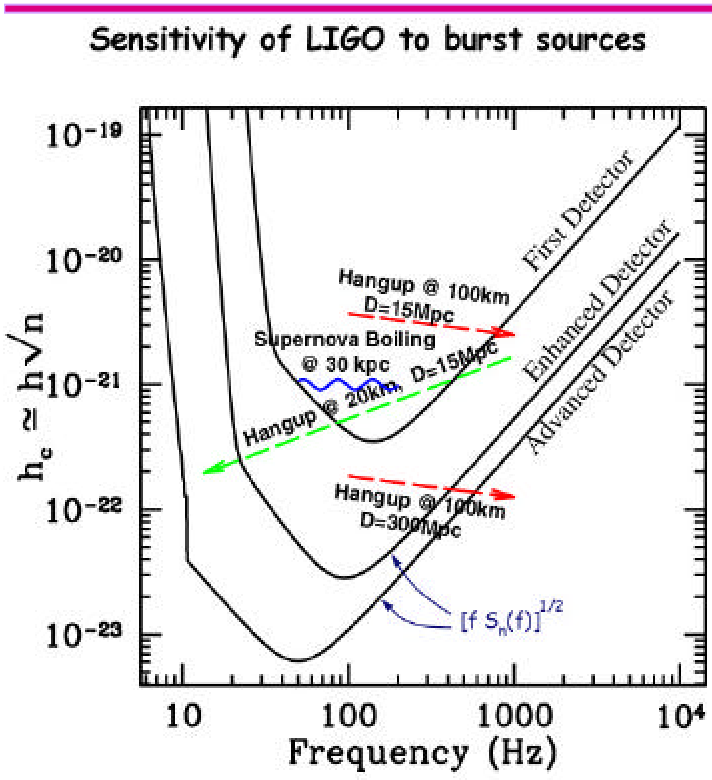
First Upper Limits from LIGO on Gravitational wave bursts



Outline:

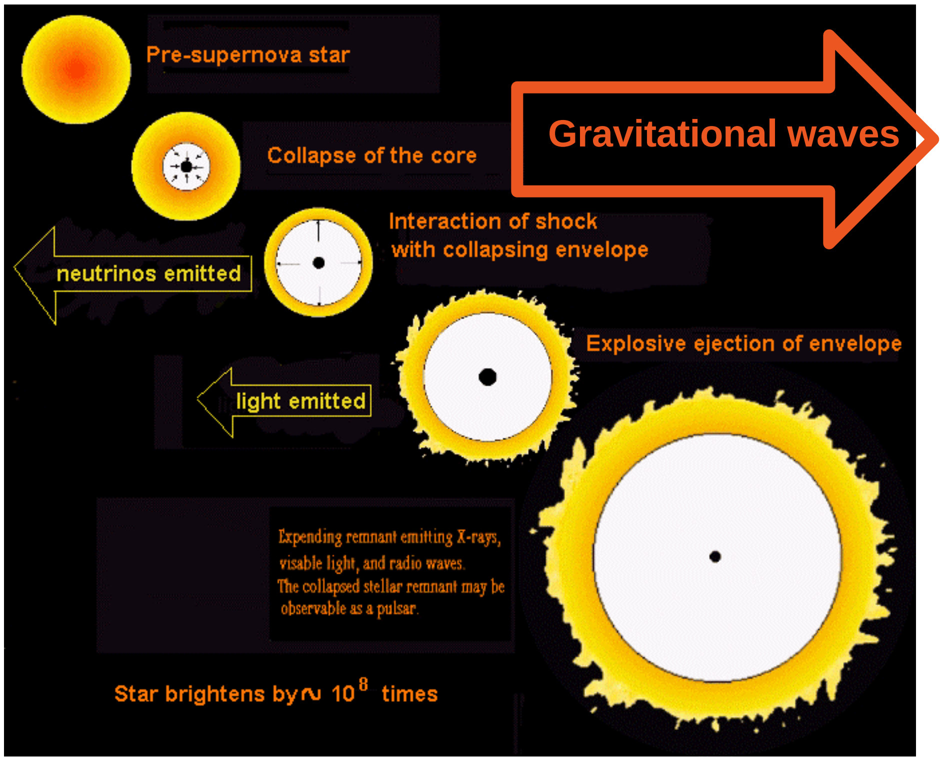
- Bursts: what are we looking for?
- Burst search goals
- S1 data quality, final dataset
- Data processing pipeline
- Event Trigger Generators (ETG's)
- Vetoes
- Coincidences and backgrounds
- Excess event rate
- Burst simulations, efficiencies
- Results: rate vs strength
- Improvements for S2
- Conclusions

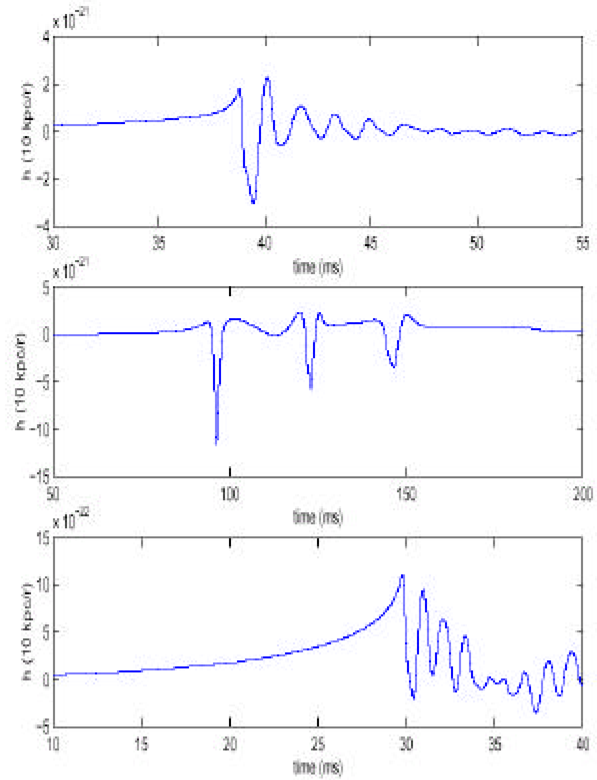
Alan Weinstein, Caltech
For the LSC Burst ULWG

Amaldi 5,
May 6, 2003
G030340-00-Z

All results still PRELIMINARY

Bursts: what are we looking for?

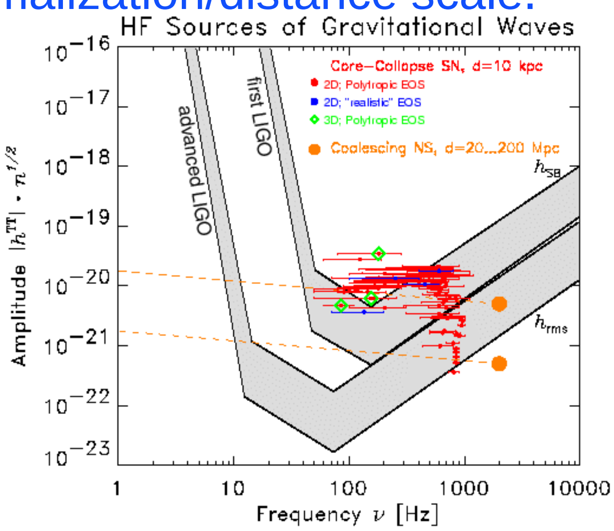


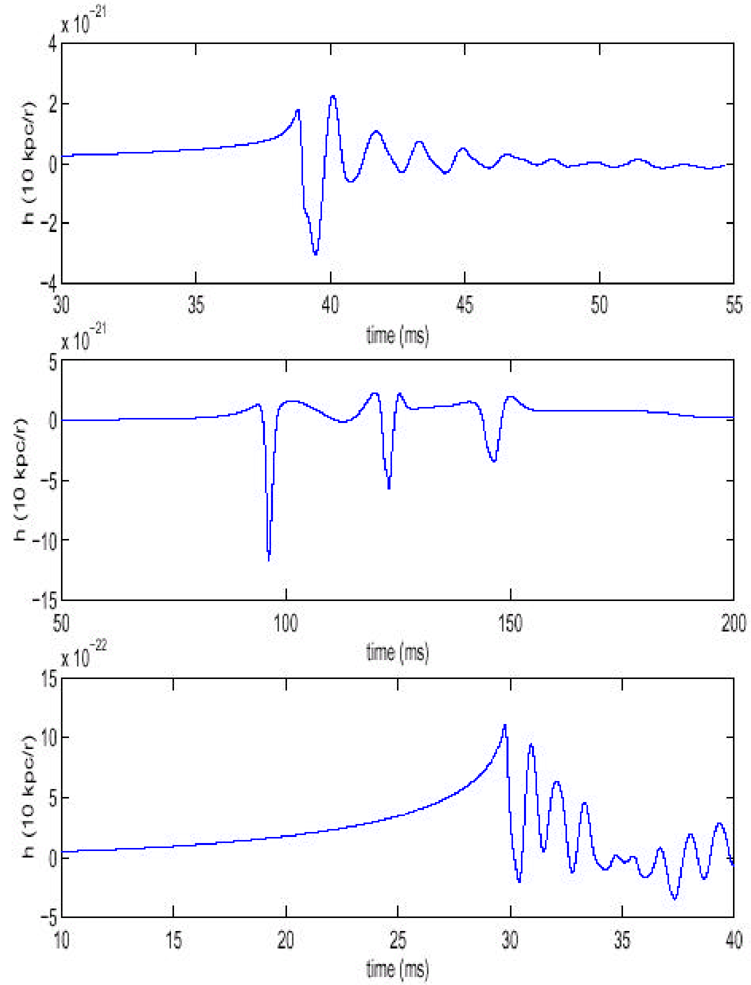


- We look for short-duration GW bursts from SN's, PNS bar modes, r-modes, mergers, ringdowns, GRB's, the unknown – *cf* talks by Kokkotas and others.
- Unlike the other LIGO S1 searches, a burst "signal" is ill-defined; waveforms unknown or untrustworthy – a menagerie!

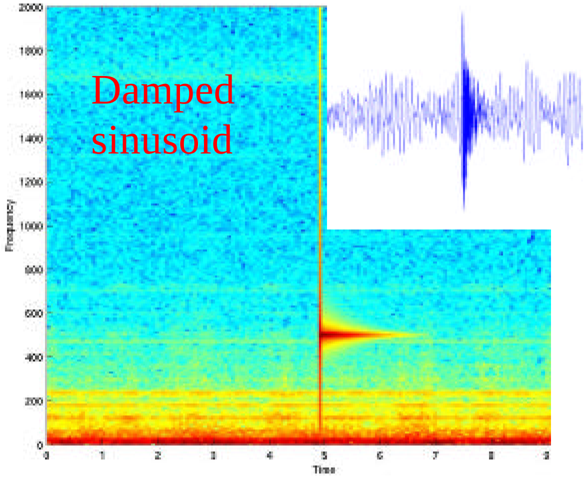
Zwerger-Müller SN waveforms

- astrophysically-motivated waveforms, computed from simulations of axi-symmetric SN core collapses.
- A “menagerie”, revealing only crude systematic regularities. Inappropriate for matched filtering or other model-dependent approaches.
  - » Their main utility is to provide a set of signals that one could use to compare the efficacy of different filtering techniques.
- Almost all waveforms have duration < 0.2 sec
- Absolute normalization/distance scale.





Bursts: time-frequency character



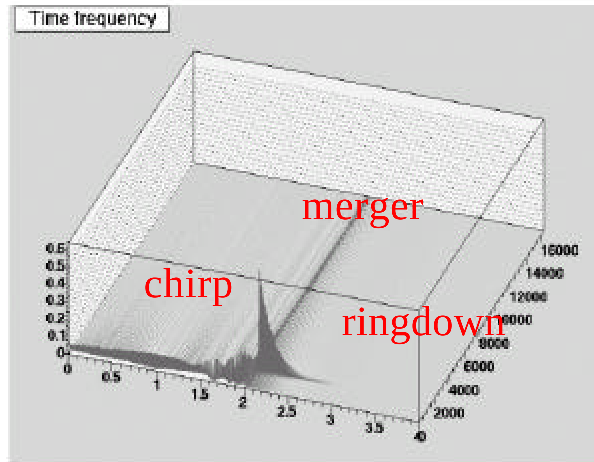
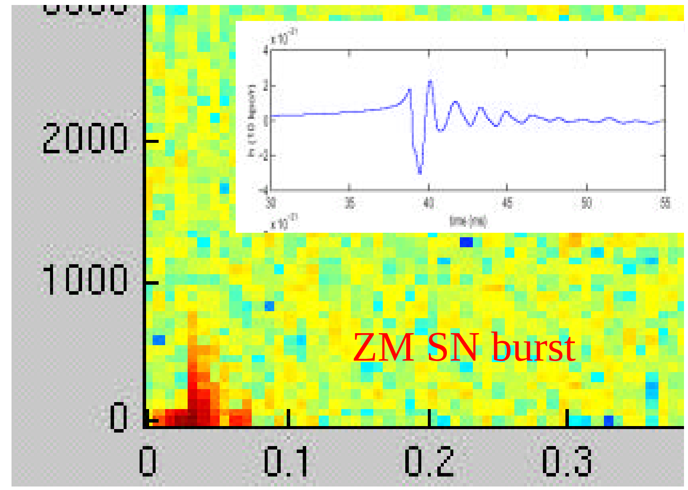
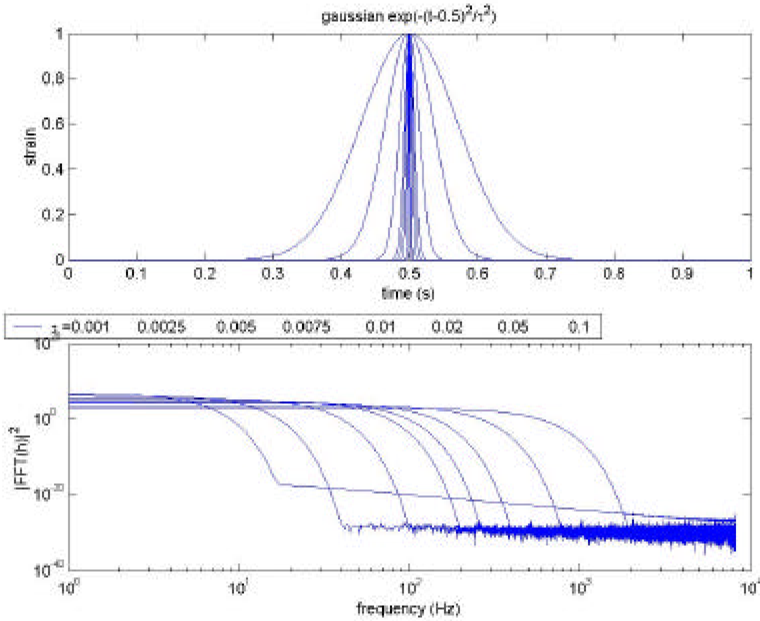


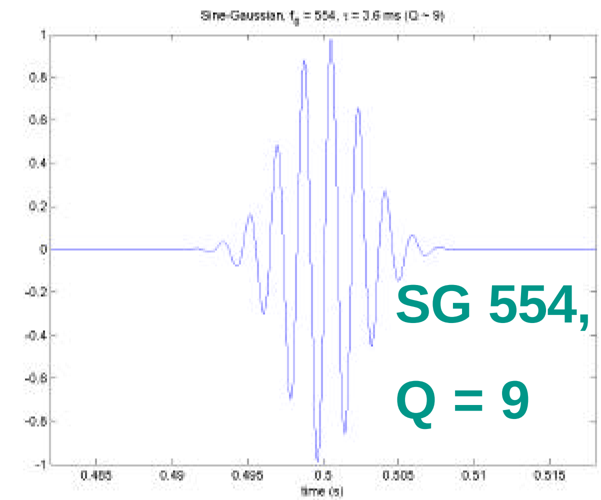
Fig. 3 Spectrogram of a composite signal



- We aim to be sensitive to bursts with generic t-f properties:
  - longish-duration, small bandwidth (ringdowns, Sine-gaussians)
  - longish-duration, large bandwidth (chirps, Gaussians)
  - short duration, large bandwidth (BH mergers)
  - In-between (Zwerger-Muller or Dimmelmeier supernova simulation waveforms)
  - Characterize bursts by duration, frequency band, “amplitude”

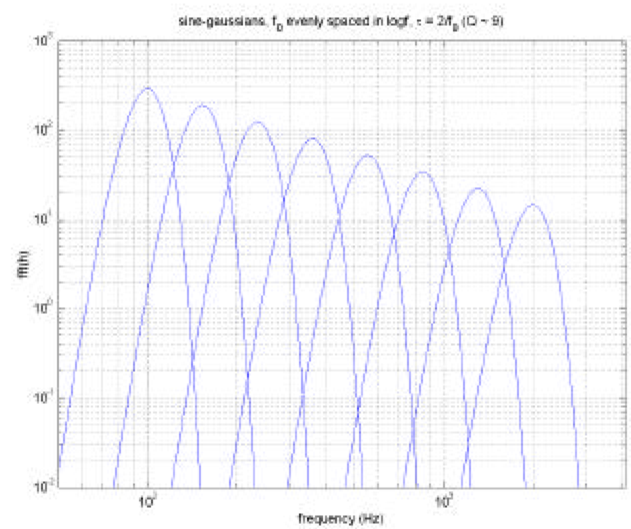
Ad-hoc signals: (Sine)-Gaussians





SG 554,

Q = 9



These have no astrophysical significance;

But they are well-defined in terms of waveform, duration, bandwidth, amplitude;

They can constitute a crude “basis set” to “span” the detection band

If our algorithms can detect these, they can detect any waveform with similar duration, bandwidth, amplitude

Burst search goals

- Search for short-duration bursts with unknown waveforms
  - » Short duration: < 1 second; more typically, < 0.2 seconds.
  - » Although the waveforms are a-priori unknown, we must require them to be in the LIGO S1 sensitivity band (~ 150-3000 Hz)
  - » Matched filtering techniques are appropriate for waveforms for which a model exists. Hard to be sure they won't miss some unknown waveform. Explicitly exclude, here!
  - » Instead, focus on *excess power* or *excess oscillation* techniques
- Search for gravitational wave bursts of unknown origin
  - » Bound on the rate of detected gravitational wave bursts, viewed as originating from fixed strength sources on a fixed distance sphere centered about Earth, expressed as a region in a rate v. strength diagram.
- Search for GW bursts associated with gamma-ray bursts (GRB's)
  - » The result of this search is a bound on the strength of gravitational waves associated with gamma-ray bursts.
  - » Work in progress – *not reported on today!*

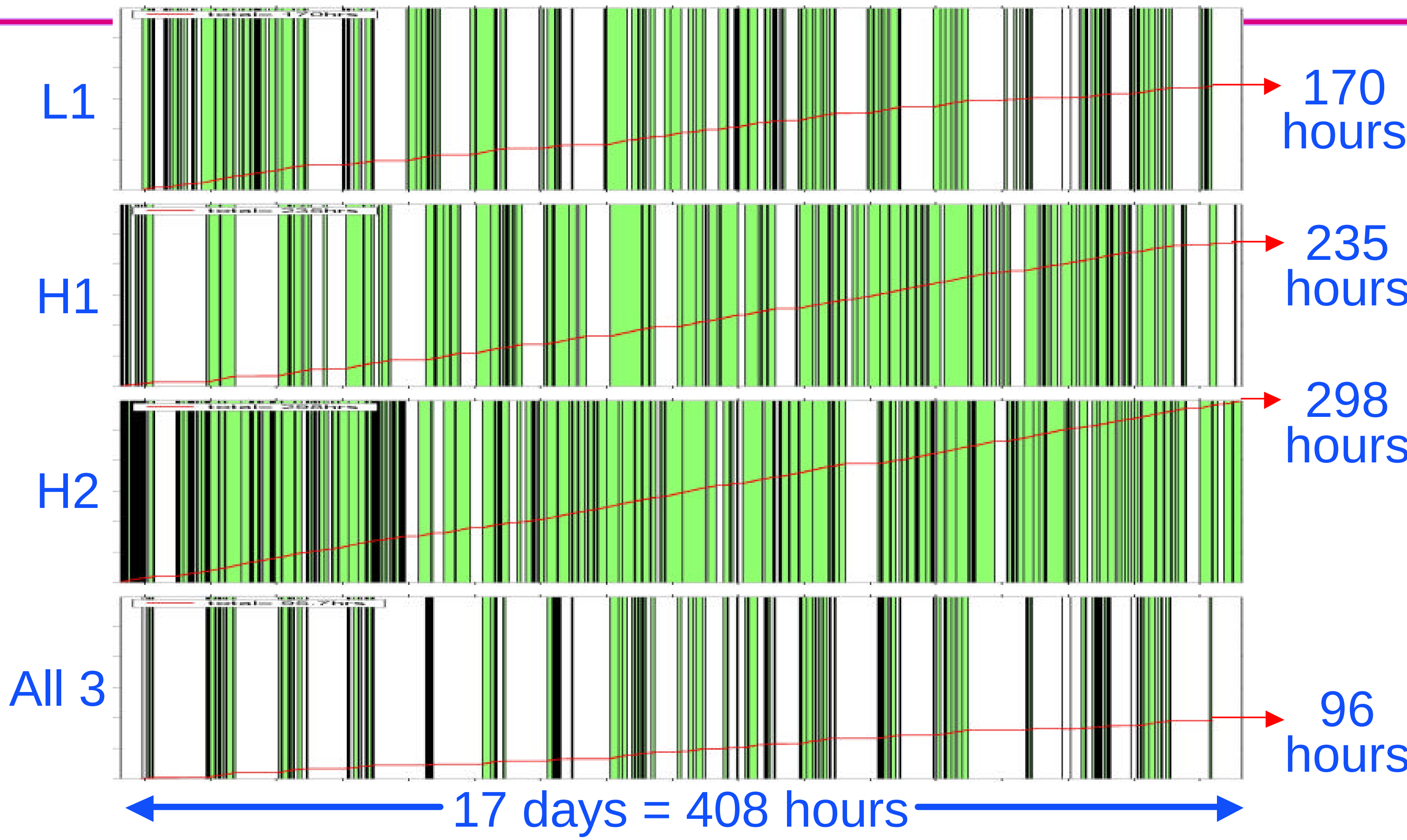
Detection Confidence

- Multiple interferometers – coincidence!
  - Three interferometers within LIGO (H1 = LHO-4K; H2 = LHO-2K; L1 = LLO-4K)
  - GEO data were analyzed in parallel, but not taken to the end; not included in S1 paper!
  - No use yet made of double-coincidences, or triple coincidences with 4 detectors…
  - Timing accuracy of ~ 100 usec (16 kHz digitization); 10 msec light travel time between LHO/LLO
- Veto environmental or other instrumental noise
  - Veto time coincidences with bursty glitches in environmental channels (seismic, acoustic, E-M, …) which are known to feed into GW channel
  - Bursty glitches in auxiliary interferometer channels (eg, PSL, or SymPort signals), which can feed into GW channel, but which would not respond measurably to a real GW signal
- Detection computation
  - Efficient filters for model-able signals
  - As tight a time-coincidence window as possible
  - Consistency amongst burst signals from multiple detectors, in amplitude, frequency band, waveform
- Data quality is really important in this analysis!

Detection Confidence (?)

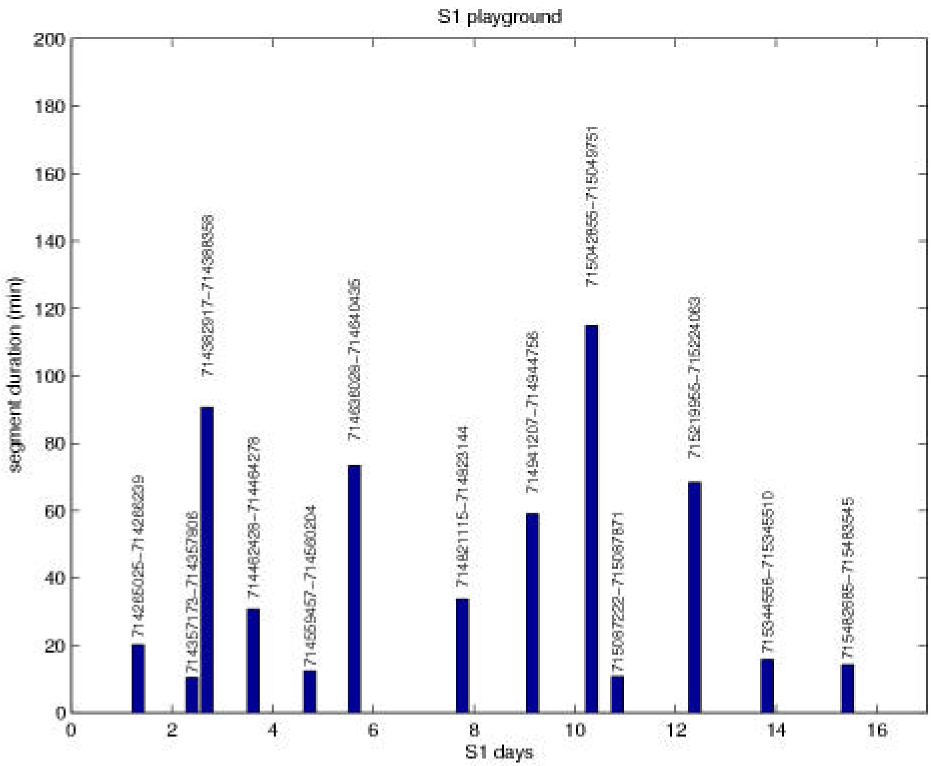
- ***DETECTION*** requires:
  - well understood detector:
    - Minimal and stationary burstiness
    - Stationarity and Gaussianity of noise
    - (and good sensitivity!)
  - well understood, tuned and tested, data processing algorithms and procedures.
  - Clearly established criteria for establishing confidence in real GW signal
- NONE of these were firmly in place for S1
  - estimate background rate
  - quote upper limits only (using Feldman-Cousins technique)

S1 Data Statistics



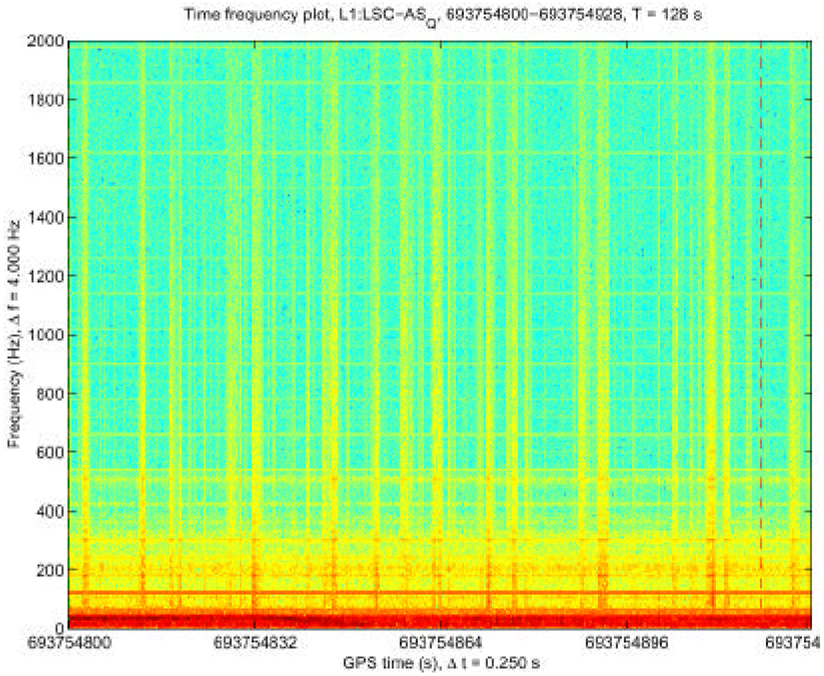
Playground data

- Search algorithms require tuning!
- Avoid bias: use playground data.
- We chose a representative sample of 13 locked segments, from the triple coincidence segments. They add up to 9.3 hours.
- All tuning of ETG and veto trigger thresholds done on playground data only.
- Choose threshold: Aim for Order(1) accidental coincidences in full S1
- We do not include these 9.3 hours in the full analysis and results.

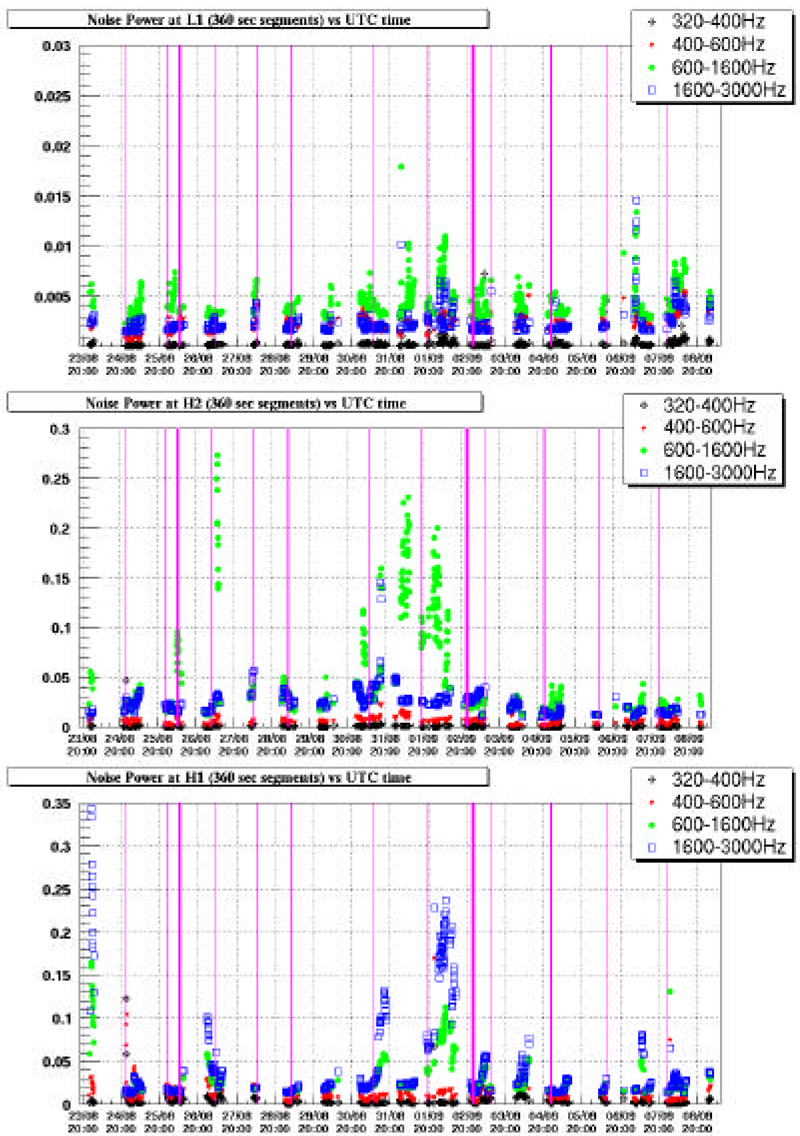


Non-stationarity, and Epoch Veto

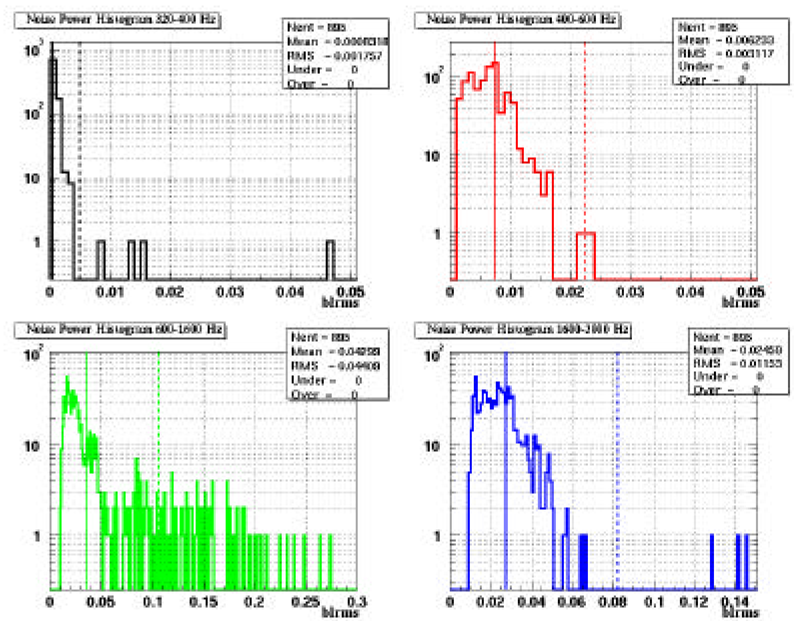
- BLRMS noise in GW channel is not stationary.
- Detector response to GW (calibrated sensitivity) is not stationary.
- Bursty-ness of GW channel is not stationary.
- Fortunately, these varied much less in S1 than in E7, thanks to efforts of detector and DetChar groups.
- Much of this is driven by gradual misalignment during long locked stretches.
- Under much study!



Stationarity of noise: BLRMS



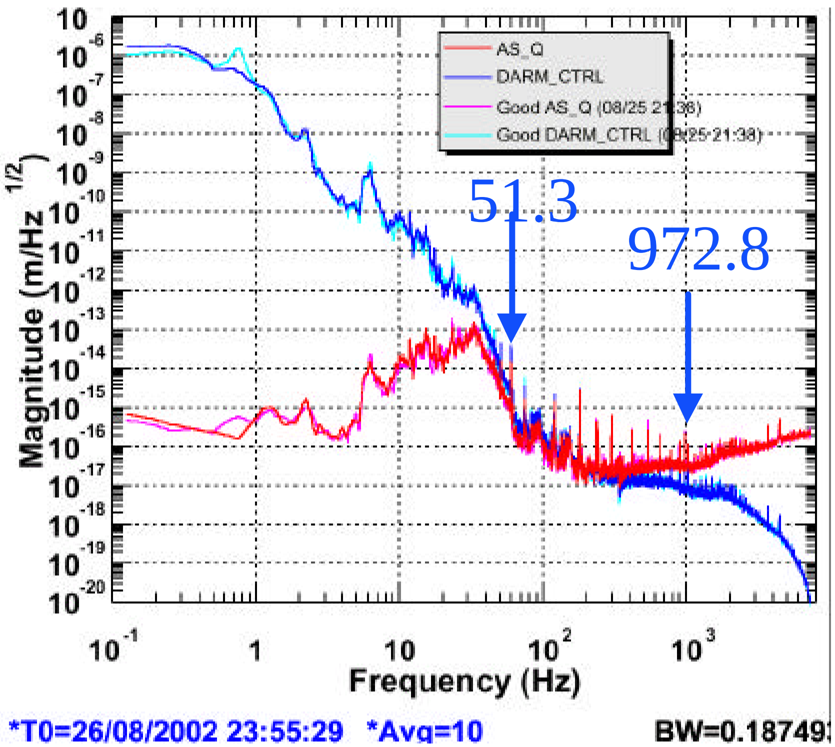
- BLRMS noise is far from stationary.
- Playground data (pink vertical lines) are not very representative.
- We veto certain epochs based on excessive BLRMS noise in some bands.

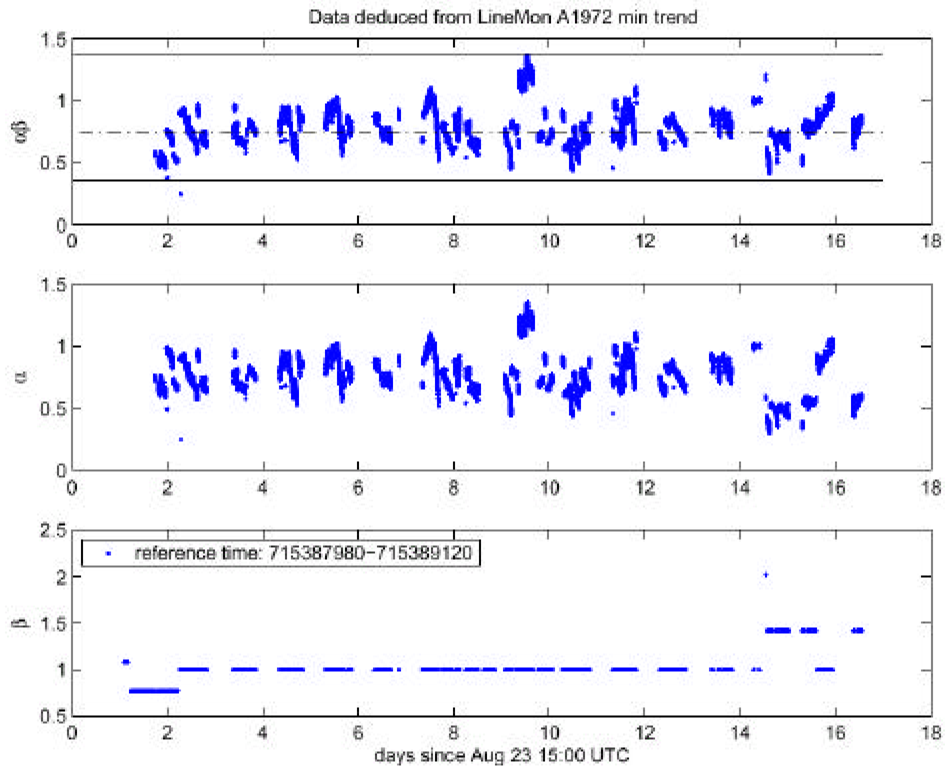


Time-dependence of calibration: Monitoring calibration lines

$$AS\_Q = X_{ext} \frac{C(f)}{1+H(f)} \rightarrow X_{ext} \frac{\alpha C(f)}{1+\alpha\beta H(f)}.$$

C(f) is sensing function;
H(f) is open-loop-gain





Veto epochs with no, or low α.

Require calibration line present and strong!

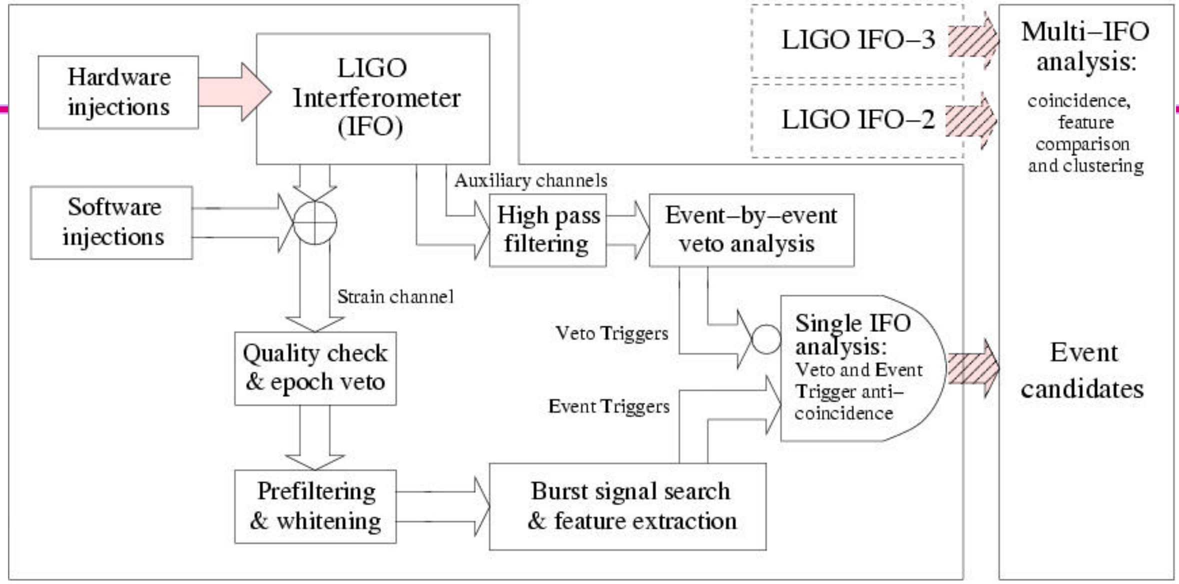
Did not anticipate this…

Final dataset for analysis

- S1 run: 408.0 hours
- 3 IFOs in coincidence: 96.0 hours
- Set aside playground: 86.7 hours
- Granularity in pipeline (360 sec): 80.8 hours
- BLRMS cut: 54.6 hours
- Keep only well-calibrated data: 35.5 hours



Data processing pipeline

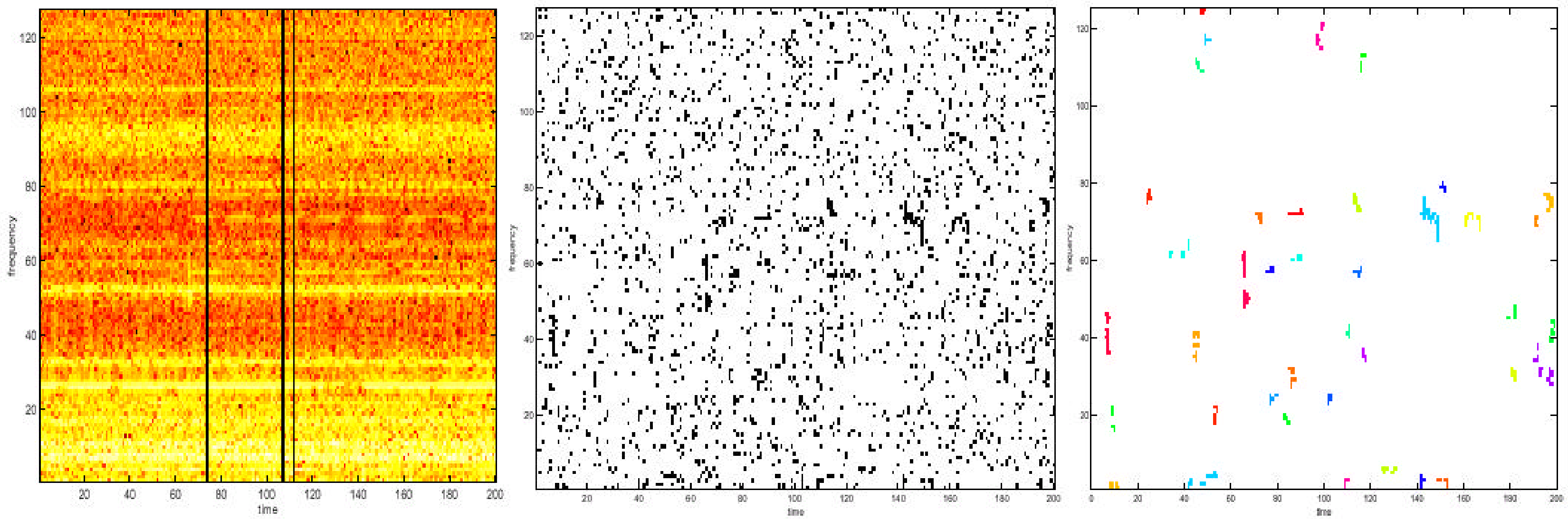


- Event trigger: indicator of grav. wave event (SLOPE, TFCLUSTERS)
  - » LDAS: LIGO Data Analysis System
- Auxiliary channels: indicator of instrumental or environmental artifacts
  - » DMT: Data Monitoring Tool (part of Global Diagnostic System)
- IFO trigger: event triggers not vetoed (ROOT, Matlab)
  - » Vetoes eliminate particularly noisy data (6 minute epoch averages)
- Coincident events: “simultaneous” IFO triggers (ROOT, Matlab)
  - » Time window: maximum of {light travel time between detectors, uncertainty in signal arrival time identification}
  - » Frequency window for TFCLUSTERS

Event Trigger Generators

- Three LDAS filters (ETG's or DSOs) are now being used to recognize candidate signals:
  - » POWER - Excess power in tiles in the time-frequency plane
  - » TFCLUSTERS - Search for clusters of pixels in the time-frequency plane.
  - » SLOPE - Time-domain templates for large slope or other simple features
- However, the POWER ETG was not well optimized in time for this analysis, and technical problems forced it to be set aside.
- The SLOPE and TFCLUSTERS ETG's performed reasonably well in this analysis, but it is clear that they both could have been better tuned and optimized
- For this analysis, use SLOPE and TFCLUSTERS as-is, no claim of optimal performance.
- These ETG's generate event triggers that indeed correspond to bursts of excess power; and provide an (uncalibrated, waveform-dependent) measure of the energy in the burst
- Both ETG's required whitened, HPF'ed data.
  This pre-filtering also lacked careful optimization, and can certainly be improved.
- NEW filters under development!
  - » Multi-detector coherence, matched filtering, wavelets, non-stationarity detectors…
  - » We have more implemented algorithms than time to evaluate them:
    an embarrassment of riches!

tfclusters



- Compute t-f spectrogram, in 1/8-second bins
- Threshold on power in a pixel, get uniform black-pixel probability
- Simple pattern recognition of clusters in B/W plane;
  threshold on size, or on size and distance for pairs of clusters

Veto Channels

- look for glitches on many different channels
  - correlated in time with GW channel glitches
  - would not have registered real GW's
  - significantly reduce single-IFO background burst rate, while producing minimal deadtime
- PEM channels not observed to be useful; filtering of environmental noise works well!
- IFO channels: In contrast to E7, no auxiliary channel vetoes were found to be very efficacious with S1 data.
- This is good! The most promising auxiliary channels were the ones most closely coupled with the GW (AS-Q) channel: AS-I, SP-I, SP-Q, MICH-CTRL.
- This is too close for comfort! Further study is required before such vetoes can be safely and confidently employed.
- For this analysis, NO vetoes on auxiliary channel bursts!

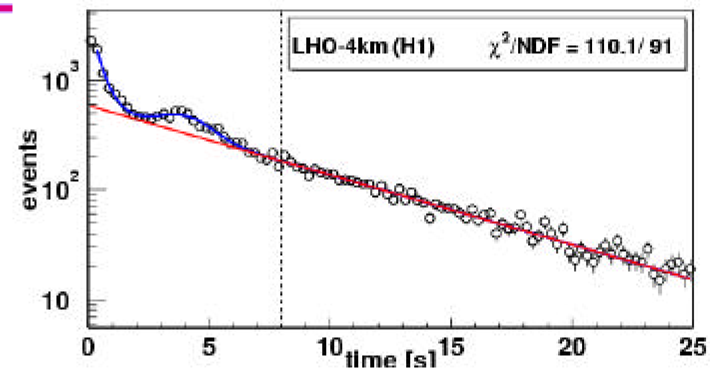
- **LSC-AS_Q (GW channel)**
- **LSC-AS_I**
- **LSC-REFL_Q**
- **LSC-REFL_I**
- **LSC-POB_Q**
- **LSC-POB_I**
- **LSC-MICH_CTRL**
- **LSC-PRC_CTRL**
- **LSC-MC_L**
- **LSC-AS_DC**
- **LSC-REFL_DC**
- **IOO-MC_F**
- **IOO-MC_L**
- **PSL-FSS_RCTRANSPD_F**
- **PSL-PMC_TRANSPD_F**

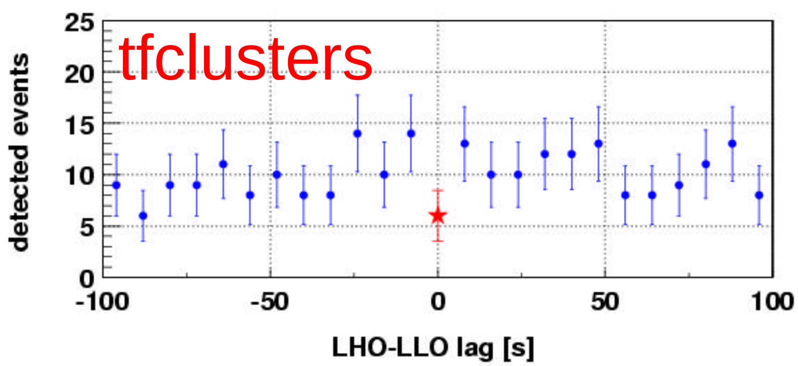
Coincident event triggers

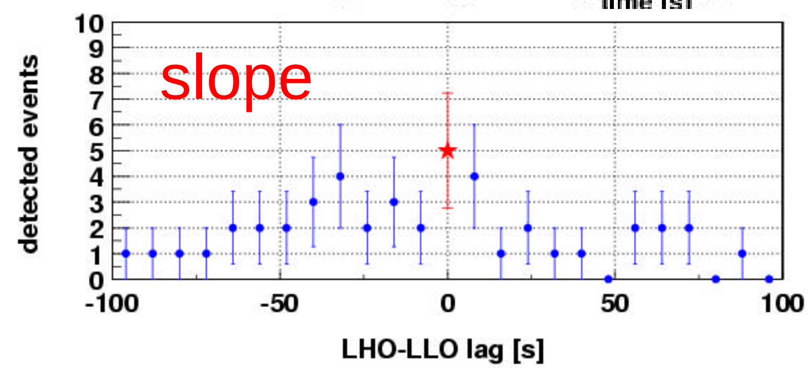
- Choose lowest practical trigger thresholds, maximizing our sensitivity, at the cost of fake coincidences.
- Rely heavily on triple coincidence to make the fake rate manageable!
- Might optimize differently if our goal is detection, not upper limit.
- Require temporal coincidence: trigger windows (start time, duration) must overlap within coincident window.
- *tfclusters* ETG (currently) finds clusters in t-f plane with 1/8 second time bins
  - » can't establish coincidences to better than that granularity.
  - » Currently, coincidence window for *tfclusters* triggers is 500 msec.
  - » *tfclusters* also estimates frequency band; require consistency
- *slope* ETG has no such limitation
  - » currently, coincidence window for *slope* triggers is 50 msec.
  - » *slope* does not yet estimate frequency band
- More work required to tighten this to a fraction of ±10 msec light travel time between LHO/LLO.
- No cut, yet, on consistency of burst amplitude (calibrated), or waveform coherence. These are an essential next step!!

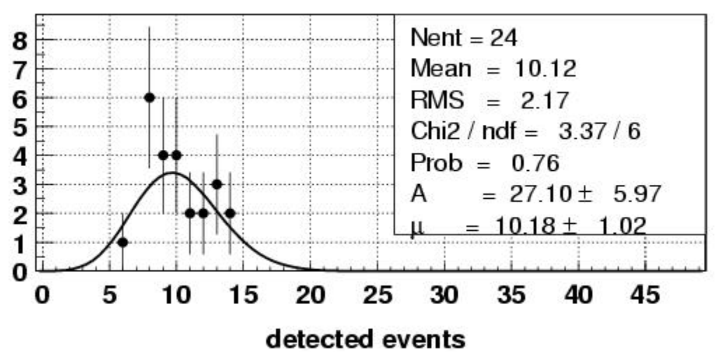
Background: Accidental coincidence rate

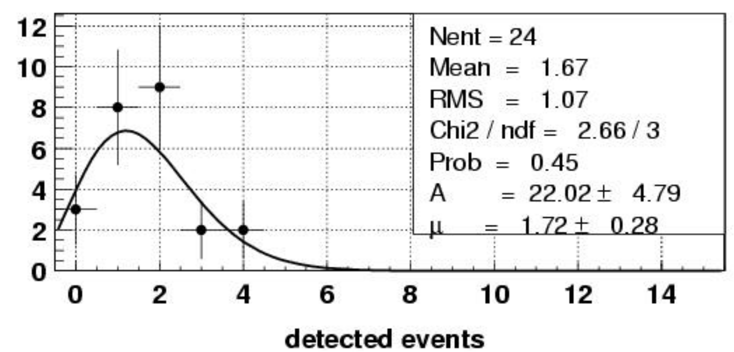
- Determine accidental rate by forming time-delayed coincidences
- Trigger rate is non-stationary, and triggers can extend over 1-8 secs. Carefully choose time lag steps, windows: calculated with 24 lags (8 sec steps, -100 to + 100 sec). Background rate is reasonably Poissonian.
- Correlated noise between H1 and H2? Study accidental rate using LHO-LLO time lag, keeping H1&H2 in synch.











Coincident events, estimated background, excess event rate and UL PRELIMINARY

- Combine the observed coincident event rate with the background estimate and its uncertainty
- Use the Feldman-Cousins technique for establishing confidence bands for counting experiments in the presence of background (a standard technique in HEP)
- Marginalize over uncertainty in the background rate.
  - The statistical uncertainty is small because of many independent time lags. Searched for, and found no evidence for systematic bias in estimate of background rate.
  - The marginalization over the background rate uncertainty has insignificant effect on the limits
- Note: if we had zero signal and zero background, the 90% CL upper limit would be 2.44 events

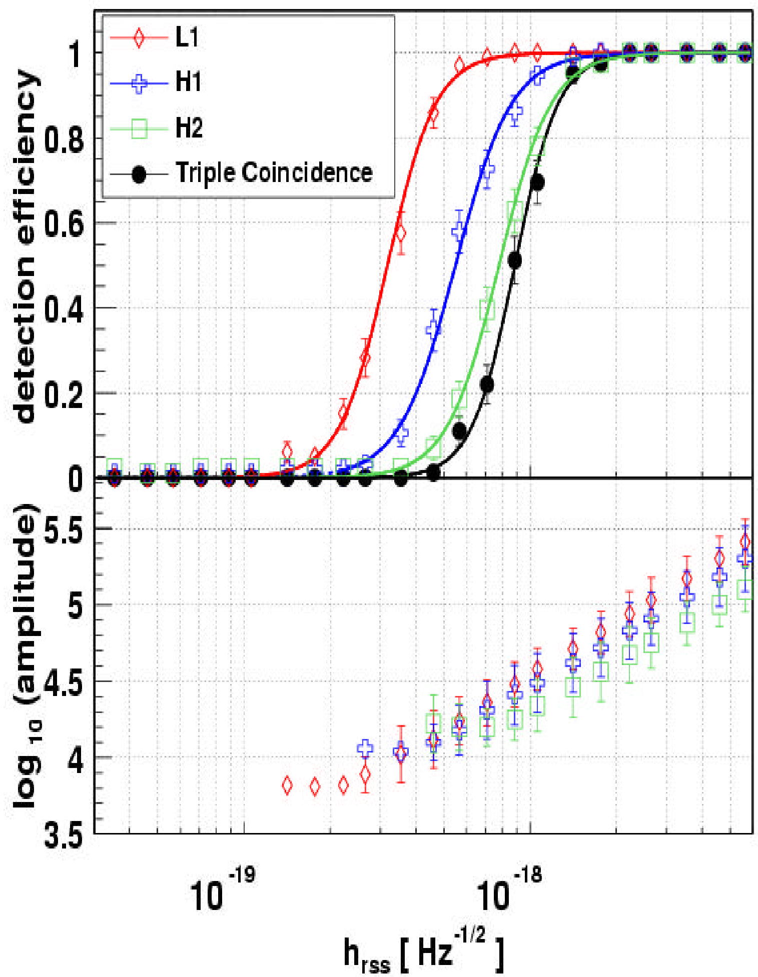
ETG	TFCLUSTERS	SLOPE
Zero-lag coincidences (35 hrs)	6	5
Background mean (per 35 hrs)	10.1 ± 0.6	1.7 ± 0.3
F-C 90% CL band (per 35 hrs)	0 – 2.3	0.7 – 8.3
F-C 95% CL band (per 35 hrs)	0 – 3.5	0.2 – 9.6
F-C 99% CL band (per 35 hrs)	0 – 5.9	0 – 12
90% CL rate (per 24 hrs) UL	1.6 / day	5.7 / day

Statistical significance of SLOPE results

- Using the SLOPE algorithm, the F-C 90% CL band rate (0.7 – 8.3 per 35 hours) excludes 0!
- However, all 5 observed events were during a 10-minute period when all three IFO's were particularly noisy;
  the properties of the event triggers are more consistent with accidental noise coincidence than with GW detection.
- The F-C prescription is designed to provide unambiguous statistical evidence for non-zero signal, as long as all systematic errors are understood; but…
- We certainly DO NOT feel confident about declaring a detection based on this statistical evidence.
- Nonetheless, we quote our upper limit in terms of the F-C prescription, because it is a standard in HEP.

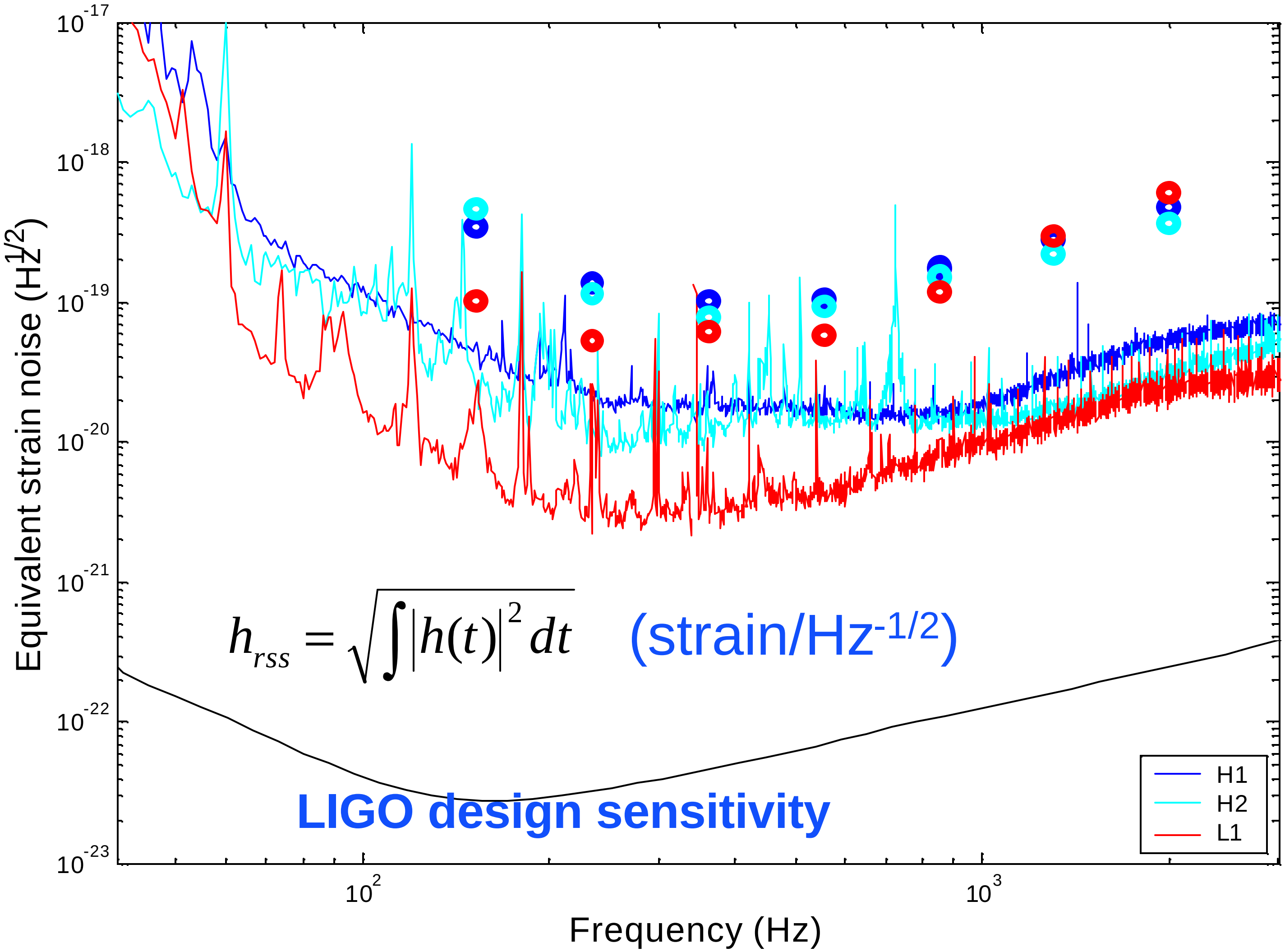
Efficiency for injected signals

- Generate a digitized burst waveform h(t) (in this example, SG554 with varying h_{peak})
- Filter through calibration (strain $\rightarrow$ AS_Q counts)
- Add to raw AS_Q data, sampling throughout S1
- Pre-filter and pass to ETG, as usual
- Look for ETG trigger coincident with injection time
- Repeat many times, sampling throughout S1 run
- Average, to get efficiency for that waveform, amplitude, IFO, ETG combo
- Deadtime due to vetoes not counted in efficiency
- Can also evaluate triple coincidence efficiency, assuming optimal response of all 3 detectors (unrealistic) – black curve.
- Note that ETG power (on which we threshold) tracks input peak strain amplitude well.
  - ETG power is a very ETG-specific quantity; not directly related to GW energy or h_{rss}.
  - Nonetheless, it tracks h_{rss} , for a fixed waveform.
  - true for all ETG's, even slope.



Sine-Gaussians:

root-sum-square *"h_{rss}"* at 50% efficiency



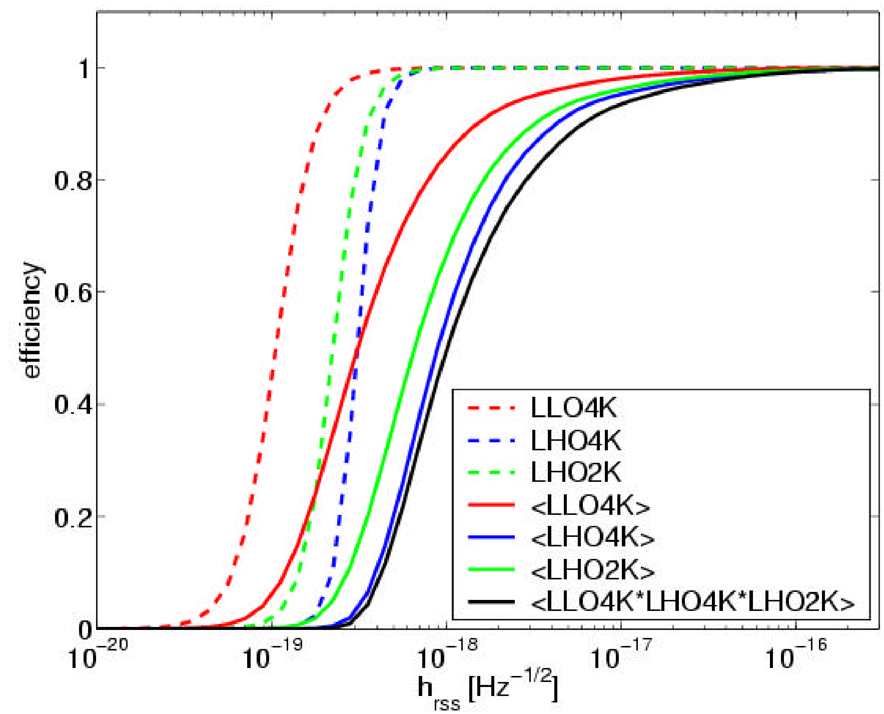
How best to characterize "amplitude"?

$$
\begin{aligned}
h_{peak} &\equiv \max(|h(t)|) && \text{(strain)} \\
h_{rss} &\equiv \sqrt{\int |h(t)|^2 dt} && (\text{strain}/\sqrt{Hz}) \\
h_{char} &\equiv f_c \tilde{h}(f_c) && \text{(strain)} \\
h_c &\equiv \left[\frac{3}{2} \int |\tilde{h}(f)|^2 f \, df\right]^2 && \text{(strain)}
\end{aligned}
$$

- For a given waveform, all are equivalent
- All are well defined, independent of detector sensitivity
- For different waveforms with similar duration and frequency band, which best characterizes our sensitivity?
- Which is most easily recognized by the GW community?
- Which is easiest for the interested physicist to understand?

Averaging over source direction and polarization

- Generate single-IFO efficiency curve vs signal amplitude, assuming optimal direction / polarization.
  - » **Different for each data epoch**
  - » **Different for each IFO**
  - » **Different for each waveform.**
  - » **Different for each ETG / threshold**
- Assuming source population is isotropic, determine single-IFO efficiency versus amplitude, averaged over source direction and polarization, using single-ifo response function.
- This is easily accomplished with simple Monte Carlo; no need to go back to detailed LDAS simulations.
- But, this is *wrong*, if both polarizations are present, with different waveforms.

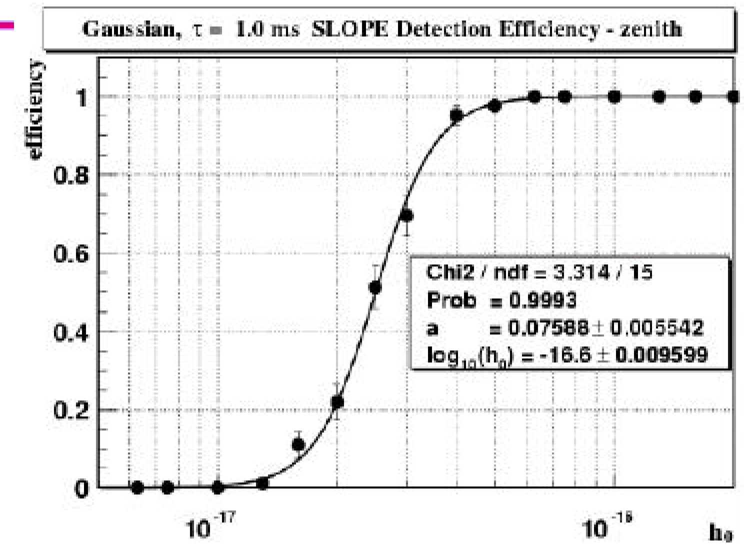


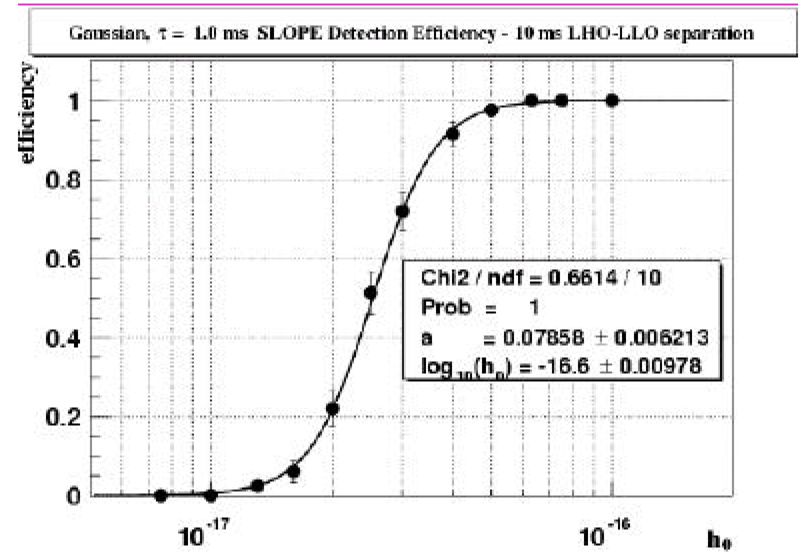
$$\left\langle e \right\rangle (h) = \int d\cos q \; df \; dy \; e\left(R(q, f, y)h\right)$$

Coincidence efficiency, averaged over source direction & polarization

- Efficiency for coincidences is the product of single-IFO efficiencies, evaluated with the appropriate response of each IFO to GWs of a given source direction / polarization.
- This assumes that detection is a random event, uncorrelated between detectors.
- Easily accomplished with simple Monte Carlo, using knowledge of detector position and orientation on Earth. No need to go back to detailed LDAS simulations.
- Must estimate any additional loss of efficiency due to post-coincidence event processing (for S1, this is negligible).
- Check against coincident simulations, including ±10 msec time delay.

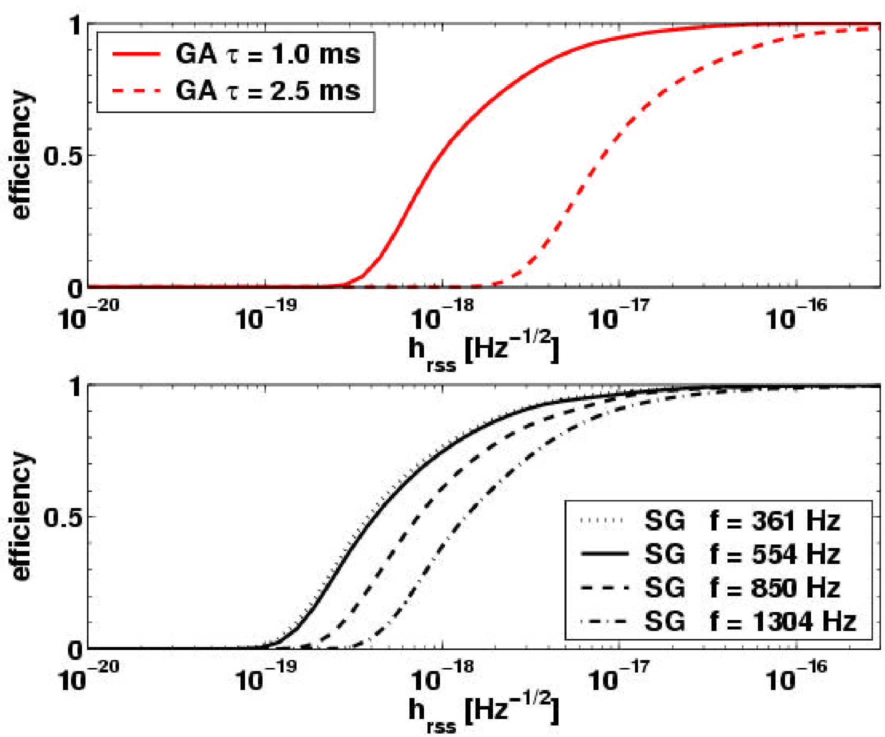
$$\left\langle e_c \right\rangle(h) = \int d\cos q \, df \, dy \; e_a(R_a(q,f,y)h) e_b(R_b(q,f,y)h) \cdots$$



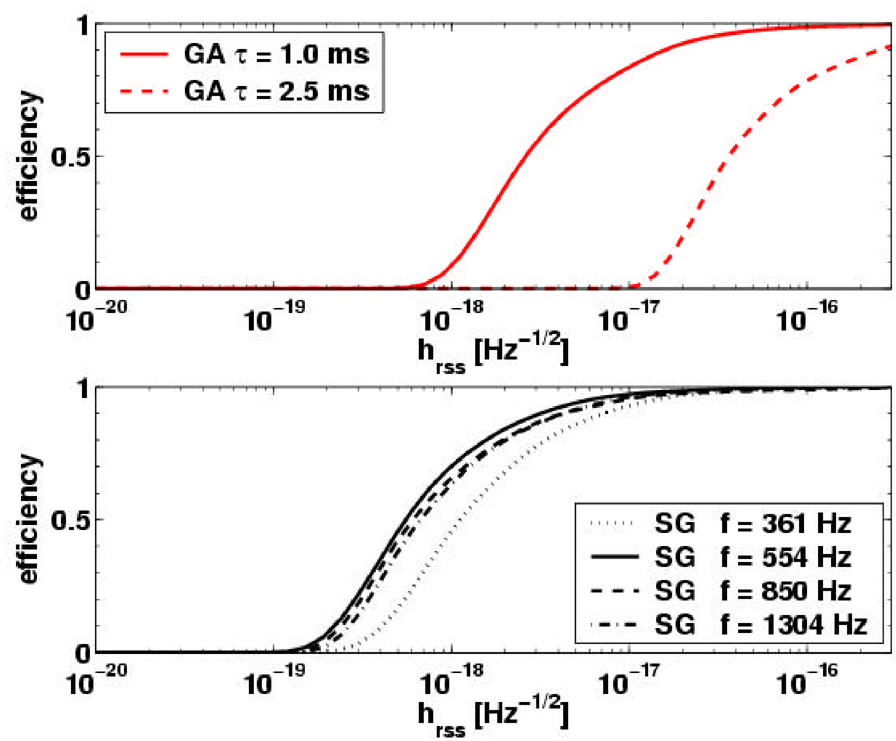


Coincident efficiency vs h_{rss} for different waveforms, ETGs

tfclusters



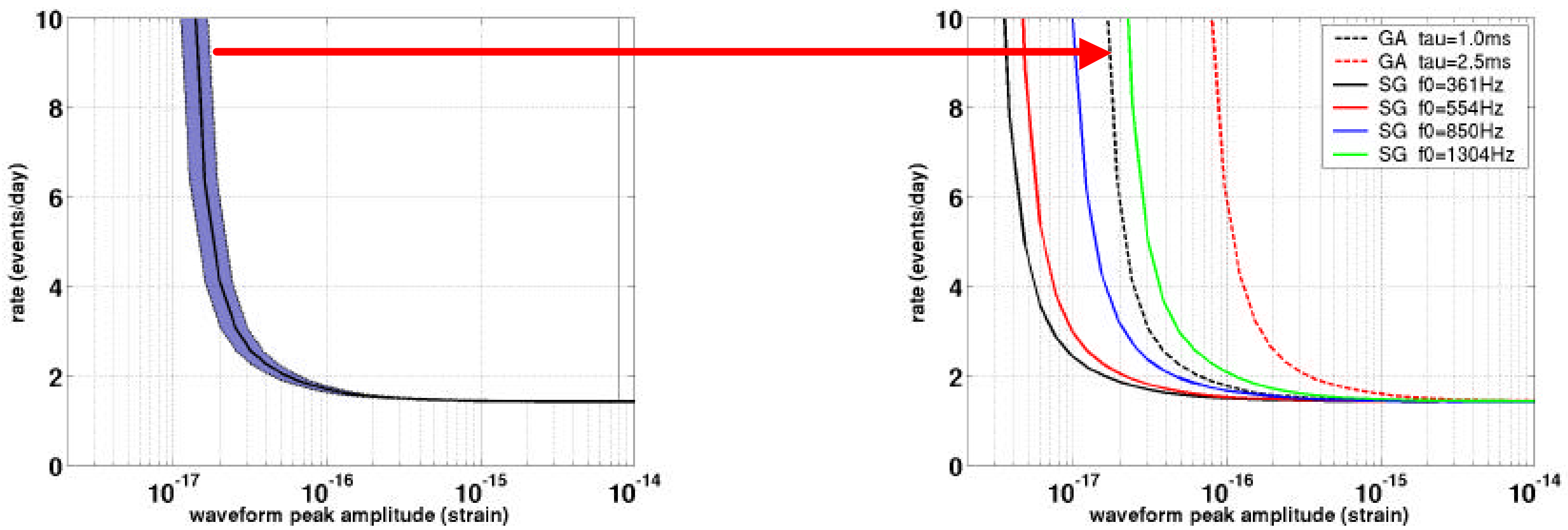
slope



For these waveforms, tfclusters wins by a nose;
but both ETG's need better tuning!

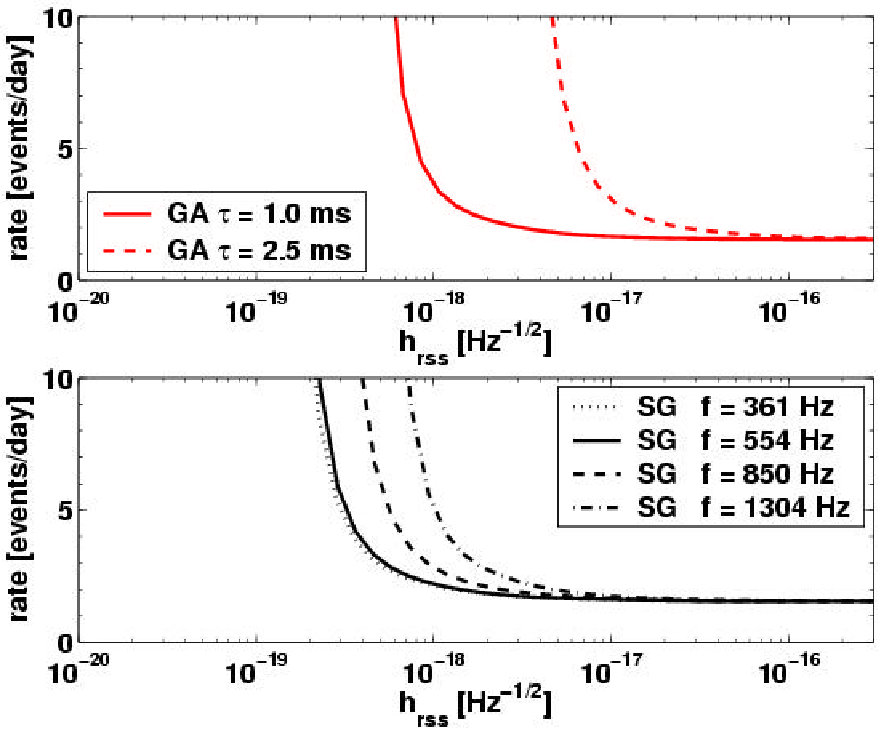
Result: rate vs strength

- tfclusters detects less than 1.6 events/day at 90% CL
- Divide by efficiency curve for a particular waveform, to get rate vs strength exclusion region
- 20% uncertainty in calibration (strain $\rightarrow$ counts); choose conservative right-most band
- Repeat, for each waveform and ETG

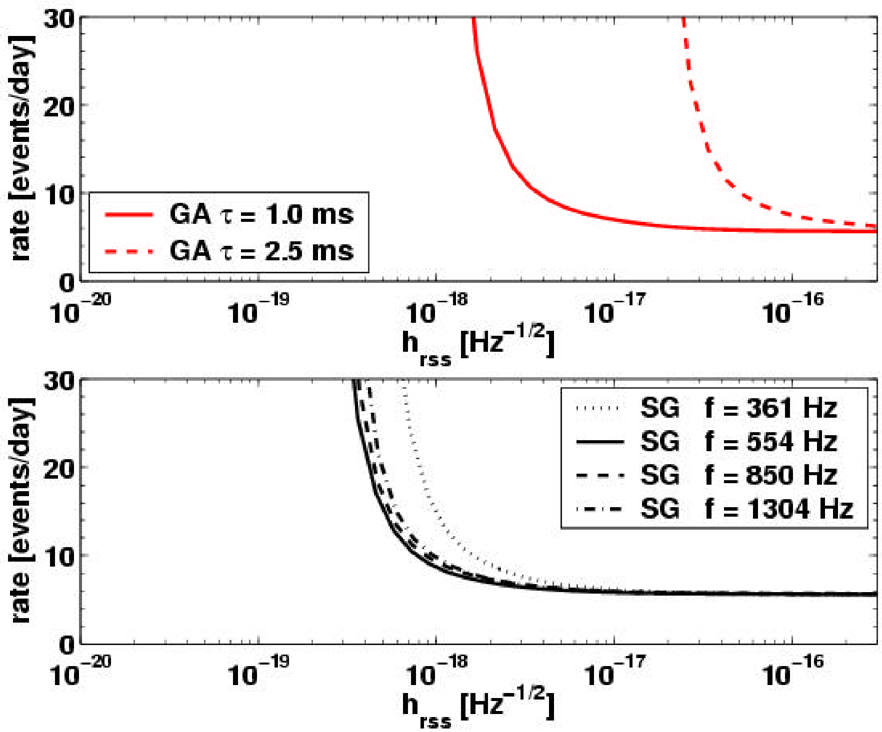


Results, for tfclusters and slope (ALL PRELIMINARY)

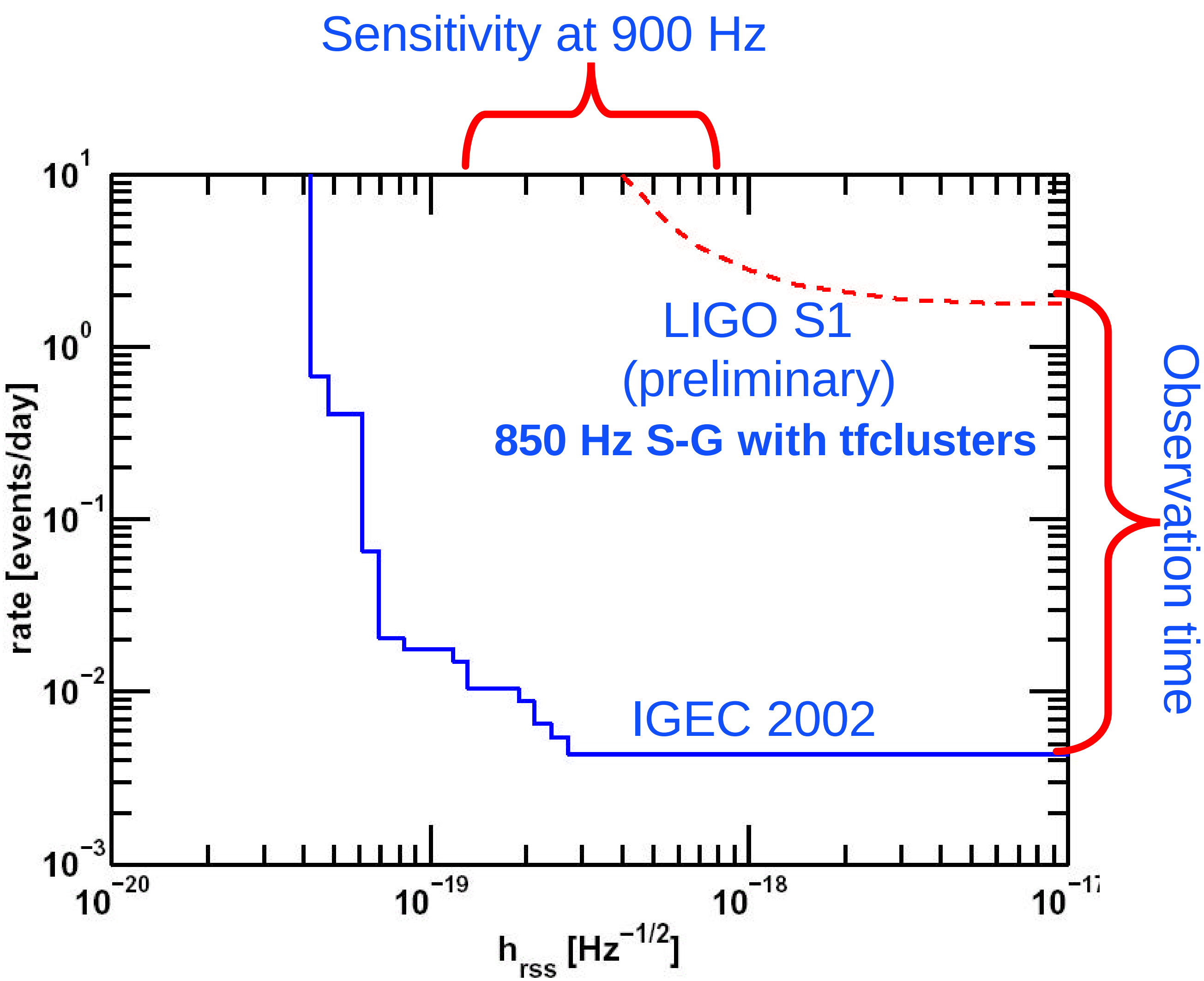
tfclusters



slope



Comparison with IGEC results



- comparison only at 900 Hz, not over full LIGO band
- With only a handful of events, for which we have no confidence in detection, LIGO makes no sidereal hour distribution

Improvements for S2

S1 analysis leaves MUCH room for improvement for S2 and beyond!

- GW channel prefiltering (HPF, whitening, basebanding?) needs optimization
- ETG's need careful tuning and optimization for best efficiency / fake rate
  - » Choice of thresholds, clustering of multiple triggers associated with one event
- Minimize loss of useful data associated with epoch and calibration vetoes
- Find and employ effective and safe vetoes on auxiliary channels; quantify cross-coupling to and from GW channel
- Post-coincidence processing: Go back to raw data!
  - » Determine trigger start time to sub-msec precision
  - » Determine calibrated peak amplitude, require consistency
  - » Determine signal bandwidth, require consistency
  - » Determine cross-correlation between coincident waveforms and require consistency
- Make use of double coincidences
- Incorporate GEO, TAMA, VIRGO

More improvements

- More, and better motivated, simulations
  - » Establish clear method to translate results to arbitrary burst waveforms
- Limits for astrophysically-motivated waveforms (Zwerger-Müller, DFM, others…?)
- More detailed studies of cross-couplings, calibration, and simulations, using hardware injections
- Fully coherent approach: WaveBurst
- Matched filtering: choice of basis set.
  - » "Delta functions" as in bar detectors
  - » Sine-gaussians with varying Q.
- Establish well-defined criteria for detection!
- The "inverse" problem: determine waveform associated with detected event, location in sky, quasi-realtime alert to telescopes
- Sidereal time distribution of events (galactic disk)
- Targeted upper limits (galactic center, disk)

Conclusions

- The S1 burst analysis is a first step towards full exploitation of the LIGO detectors for discovery of GW bursts
- The resulting limits are weak, not easy to interpret, and not of astrophysical interest…
- BUT, we know how to improve these things!
- Moving on to S2, and discovery!