Search for gravitational wave bursts with the first science data from LIGO

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Commissioning/Observation History

L4k strain noise @ 150 Hz [Hz^{-1/2}]

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21}

1999 2000 2001 2002 2003

Inauguration

E1 E2 E3 E4 E5 E6 E7 E8 E9

One Arm Power Recycled Michelson Recomibined Interferometer Full Interferometer

First Lock

Washington 2K Louisiana 4k Washington 4K

Washington earthquake LHO 2k wire accident Now
Science runs

- “Upper limit” runs:
  - S1: 23 Aug 2002 – 9 Sep 2002 (408 hr)
  - S2: Feb 14, 2003 – April 14, 2003 (8 weeks)

- Search begins in earnest with ~6 month run starting fall 2003

- All 3 IFO’s in coincidence. GEO600 and TAMA 300 as well!
  - also ALLEGRO and GRBs

- By S1, all 3 IFO’s operating in complete optical configuration
  - Power-recycled Michelson with Fabry-Perot arms

- All 3 IFOs operating round-the-clock, with operators and scimons.

- Focus on duty-cycle, and stationarity, not noise
  - Factor of ~ 10 improvement in sensitivity from E7 → S1
  - ALL 3 IFO's achieved lock for significant fraction of the time
  - Great improvement in stationarity of GW signal relative to earlier engineering runs
S1-Run Sensitivities for the Three LIGO Interferometers

Strain Sensitivities for the LIGO Interferometers for S1

23 August 2002 - 09 September 2002   LIGO-G020461-00-E
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“Upper Limits”

S1, S2 Data Analysis Groups

- LSC Upper Limit Analysis Groups
  - Typically ~25 physicists
  - One experimentalist / One theorist co-lead each group

- Compact binary inspiral: “chirps”
- Supernovae / GRBs / mergers: “bursts”
- Pulsars in our galaxy: “periodic”
- Cosmological Signal “stochastic background”
Frequency-Time Characteristics of GW Sources

- **Bursts** are short duration, broadband events
- **Chirps** explore the greatest time-frequency area
- **BH Ringdowns** expected to be associated with chirps
- **CW** sources have FM characteristics which depend on position on the sky (*and source parameters*)
- Stochastic background is stationary and broadband
- For each source, the optimal signal to noise ratio is obtained by integrating signal *along* the trajectory
  - If SNR >> 1, kernel ∝ |signal|^2
  - If SNR ≤ 1, kernel ∝ |template* signal| or |signal|* signal
  - Optimal filter: kernel ∝ 1/(noise power)

\[
\frac{\delta f}{f} \approx 2.6 \times 10^{-4}
\]

\[
\frac{\delta f}{f} \approx 4 \times 10^{-6}
\]
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burst waveforms: t-f character

Generic statements about the sensitivity of our searches to poorly-modeled sources can straightforwardly be made from the t-f “morphology”...

• 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 SN waveforms)
  • These SN waveforms are distance-calibrated; all others are parameterized by a peak or rms strain amplitude
Zwerger-Müller SN waveforms

- **Rationale:**
  - These are astrophysically-motivated waveforms, computed from detailed simulations of axi-symmetric SN core collapses.
  - There are only 78 waveforms computed, in different classes:
    - “regular” infall, bounce, ringdown
    - Multiple bounces, on centrifugal barrier of rapidly-rotating core
    - “rapid collapse” – rapid change in adiabatic index
  - Almost all waveforms have duration < 0.2 sec
  - Work is in progress to get many more, including relativistic effects, etc.
  - These waveforms are a “menagerie”, revealing only crude systematic regularities. They are wholly 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.

- **Signals have an absolute normalization!**

**Parameters:**
- Distance R
- Orientation relative to line of sight: \( \sin \theta \)
In the Z-M simulations, start with rotating star, with varying total angular momentum \( \beta = E_{\text{rot}}/E_{\text{pot}} \) and differential rotation profile \( (A) \), in hydrodynamic equilibrium (2-dim).

Core collapse is induced by suddenly reducing adiabatic index \( \Gamma \) from 4/3 to \( \Gamma_r < 4/3 \).

As the collapse, bounce, stall, re-energizing, explosion proceeds, follow local density, velocity, grav potential; calculate 2-Dim quadrupolar integral.

Only one polarization.

Explore parameter space \( (A, \beta, \Gamma_r) \Rightarrow 78 \) different waveforms.

\[
\tilde{I}(r, z = r \cos \theta) \sim A_{20}^{E_2}(t) = \frac{G}{c^4} \frac{16\pi^{3/2}}{\sqrt{15}} \int_{-1}^1 \int_0^\infty q(r, z, t) \left[ v_rv_r(3z^2 - 1) + v_\theta v_\theta(2 - 3z^2) - v_\phi v_\phi - 6v_r v_\theta z\sqrt{1 - z^2} + r_\phi\Phi (3z^2 - 1) + 3\partial_\theta \Phi z\sqrt{1 - z^2} \right] r^2 dr dz 
\]

\[
h_{\theta\theta}^{TT} = \frac{1}{8} \sqrt{\frac{15}{\pi}} \sin^2 \theta \frac{A_{20}^{E_2}(t)}{R} \equiv h_+ 
\]
The 78 ZM waveforms differ in

- initial angular momentum (A parameter), governing degree of differential rotation
- initial rotational energy (B, or $\beta = E_{rot}/E_{pot}$). $A, B$ roughly govern how many bounce peaks
- Within each (AB) set, the adiabatic index $\Gamma_i$ is varied from 1.325 to 1.28 (stiff to soft), and the peak amplitude of the wave depends strongly on this parameter (right).
Relativistic core collapse (DFM) waveforms


Relativistic effects stiffen the system, pushing to shorter duration and higher frequency waveforms.
Ad-hoc signals: (Sine)-Gaussians

These have no astrophysical significance;
But they are well-defined in terms of waveform, duration, bandwidth, amplitude;
They can constitute a “basis set” to span the detection band
If our algorithms can detect these, they can detect any waveform with similar duration, bandwidth, amplitude
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 Burst search goals

- **Search for short-duration bursts with unknown waveforms**
  - Short duration: < 1 second; more typically, < 0.2 seconds.
  - 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
  - Although the waveforms are a-priori unknown, we must require them to be in the LIGO S1 sensitivity band (~ 100-3000 Hz)

- **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 gravitational wave bursts associated with gamma-ray bursts**
  - The result of this search is a bound on the strength of gravitational waves associated with gamma-ray bursts.
  - Work in progress by Marka, Rahkola, etc – *not reported on today!*
Gamma Ray Bursts during S1 and LIGO coverage

Focus on HETE-2 detector

(good directional info, for LIGO coincidence)

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<th>Timestamp</th>
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<th>Description</th>
<th>Right Ascension</th>
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<tr>
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<td>n/a</td>
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<td>−20.930 ± 0.066</td>
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<tr>
<td>715157639 GPS 2002.09.04 06:53:46 UTC</td>
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<td>Probable GRB</td>
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<td>n/a</td>
<td>Marginal®</td>
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</tr>
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</tr>
<tr>
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<td></td>
<td></td>
<td>No</td>
</tr>
</tbody>
</table>

* Marginal coincidence refers to lock stretches which started less than 5 seconds before the trigger or lasted less than 120 seconds after the trigger
Search goals (2)

- Rely on multi-detector coincidences (in time and in burst properties) to eliminate most or all fake bursts.
  - Use S1 triple-coincidence data (H2, H1, L1)
  - GEO data were analyzed in parallel, but not taken to the end; not included in S1 paper!
  - Have not yet decided how to make use of double-coincidences, or triple coincidences with 4 detectors…

- Given the S1 sensitivity, we do not expect to detect GWs
  - Assume that any coincident bursts are fake, estimate background through time-lag analysis, set upper limits only
  - Plan to work much harder on demanding consistency amongst observed coincident bursts before claiming detection
  - Analysis pipeline designed to work for both upper limits and detection, but have not worked out detailed (blind) criteria for detection
Detection Confidence

With all the noise faking GW signals, how can we be sure we’ve seen the real thing (for first time)?

- Multiple interferometers – coincidence!
  - Three interferometers within LIGO (H1 = LHO-4K; H2 = LHO-2K; L1 = LLO-4K)
  - Other detectors (GEO, TAMA, VIRGO, bars)
  - 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 (Asym-port-Q-phase, aka LSC-AS_Q), 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!
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Alan Weinstein, Caltech
For the LSC Burst ULWG
CaJAGWR Seminar
April 22, 2003
S1 data quality

- S1 coincident data
- Playground sample
- Non-stationarity and burstiness
- Variation of noise floor, and Epoch Veto
- Time-dependence of calibration, and Calibration Veto
- Final data set for analysis
<table>
<thead>
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<th>Station</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
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<tr>
<td>H1</td>
<td>235</td>
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<tr>
<td>H2</td>
<td>298</td>
</tr>
<tr>
<td>All 3</td>
<td>96</td>
</tr>
</tbody>
</table>

17 days = 408 hours
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.
Veto on BLRMS

Histograms: 6-min segment BLRMS.
vertical lines at 1σ and 3σ
Veto segments beyond, 3σ
Time-dependence of calibration: Monitoring calibration lines

\[ ASQ = X_{ext} \frac{C(f)}{1 + H(f)} \rightarrow X_{ext} \frac{\alpha C(f)}{1 + \alpha \beta H(f)}. \]

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

---

**Veto epochs with no, or low \( \alpha \).**

**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
- **Epoch veto:** 54.6 hours
- **Keep only well-calibrated data:** 35.5 hours
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**Data processing pipeline**

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

User pipeline request
⇒ frameAPI
⇒ datacondAPI
⇒ mpiAPI
⇒ wrapperAPI
⇒ LAL code
⇒ eventmonAPI
⇒ metadataAPI
⇒ metaDB
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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
    - Flanagan, Anderson, Brady, Katsavounidis
  - TFCLUSTERS - Search for clusters of pixels in the time-frequency plane.
    - Sylvestre
  - SLOPE - Time-domain templates for large slope or other simple features
    - Daw, Yakushin

- All three of these ETGs ran online during S1

- NEW filters under development:
  - WaveBurst (Klimenko, Yakushin) Performs t-f analysis in wavelet domain, working with pairs of IFOs.
  - BlockNormal (Finn, Stuver) look for changes in time of mean and variance of data

- We have more implemented algorithms than time to evaluate them: an embarrassment of riches!
- 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
ETGs for this analysis

- In principle, the POWER ETG is the easiest to interpret (in terms of excess power), and careful work (Anderson et al) have established that it is as efficient as matched filtering, when large template banks are required.

- 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; much more work is required!

- For this analysis, we use SLOPE and TFCLUSTERS as-is, with no claim of optimal performance.

- These ETG’s generate event triggers that indeed correspond to bursts of excess power; and they provide an (uncalibrated, waveform-dependent) measure of the energy in the burst (as determined from simulation, discussed later).

- Both ETG’s required whitened, HPF’ed data. This pre-filtering also lacked careful optimization, and can certainly be improved.
Data conditioning in *datacond*

- All of our burst filters are expected to work best with (at least, approximately) whitened data.
- This is not matched filtering: don’t need to know detector response function to find excess power.
- In *datacondAPI*, we (approximately) whiten and HP (at 150 Hz) the data with pre-designed linear filters.
- New filters with better performance are under design.
- No attempt (yet) at line removal: but we believe that this will eventually be very necessary.
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Veto Channels

- Run DMT monitors glitchMon and absGlitch on many different channels
  - PEM channels not observed to be useful; filtering of environmental noise works well!
  - Focus on IFO channels
- Look for channels and thresholds that:
  - are 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
Efficacy of vetoes in E7 – L1

PSL glitch is in time with AS_Q; really cleans up L1.

broad tail of events is cleaned up by L1 veto.
L1 had lots of PSL glitching, so bulk of histogram is affected.
In contrast to E7, no auxiliary channel vetoes were found to be very efficacious with S1 data.

This is good! Burstiness in auxiliary channels was much lower in S1 than in E7 (due to the efforts of the IFO commissioners), and couplings to the GW channel were relatively weak (due to good design and diagonalization of the control plant).

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 of these closely-coupled channels is required before vetoes can be safely and confidently employed.

For this analysis, NO vetoes on auxiliary channel bursts!
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Event triggers

slope – measures amplitude

tfclusters – measures power
Cuts on coincident event triggers

- We choose to work with the lowest practical trigger thresholds, maximizing our sensitivity, at the cost of fake coincidences. Rely heavily on triple coincidence to make the fake rate manageable!
- We 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!!
• In addition to temporal coincidence of events, we require that \textit{tfclusters} give a central frequency at the two IFOs that are within 500 Hz of each other.

• Frequency information not yet available in \textit{slope}.
Cross-correlate filtered GW channel to check for waveform consistency.

Here, applied to coincident hardware injections, H1/L1.

Not employed for S1 analysis!
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Raw SLOPE trigger rates

SLOPE trigger rates (1 min averages) from each of the 3 IFOs versus hour for the ~36 hours of data used for the upper limits.

Strong variation in SLOPE trigger rate is a reflection of the fixed thresholding in presence of varying noise level (tfclusters uses adaptive thresholding).

Poisson-predicted number of accidentals in each 1-min time interval.

All 5 coincident SLOPE triggers come from one noisy stretch at ~ 14 hours.
Background: Accidental coincidence rate

- Determine accidental rate by forming time-delayed coincidences
- Trigger rate is non-stationary, and triggers can extend over 1-2 secs. Carefully choose time lag steps, windows: calculated with 100 lags (2 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

- 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

<table>
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<tr>
<th>ETG</th>
<th>TFCLUSTERS</th>
<th>SLOPE</th>
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<td>Zero-lag coincidences</td>
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<tr>
<td>Background mean</td>
<td>10.6 ± 0.3</td>
<td>1.9 ± 0.14</td>
</tr>
<tr>
<td>Background RMS</td>
<td>3.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Poisson fit</td>
<td>10.7 ± 0.4</td>
<td>2.5 ± 0.2</td>
</tr>
<tr>
<td>F-C 90% CL band</td>
<td>0 – 2.1</td>
<td>0.5 – 8.0</td>
</tr>
<tr>
<td>90% CL UL on excess event rate</td>
<td>2.1/(35.5 hrs) = 1.4 /day</td>
<td>8/(35.5 hrs) = 5.4 /day</td>
</tr>
</tbody>
</table>
Search for gravitational wave bursts with the first science data from LIGO

Outline:

- The first LIGO science run
- Searches for GWs with LIGO
- Burst waveforms
- Burst search goals
- S1 data quality, final dataset
- Data processing pipeline
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- Coincident events
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- Coincident efficiency, sky average
- Results: rate vs strength
- Improvements for S2
- Conclusions
Burst Simulations - GOALS

- Test burst search analysis chain from:
  - IFO (ETM motion in response to GW burst) →
  - GW channel (AS_Q) data stream into LDAS →
  - search algorithms in LDAS →
  - burst triggers in database →
  - post-trigger analysis (optimizing thresholds and vetoes, clustering of multiple triggers, forming coincidences)

- Evaluate pipeline detection efficiency for different waveforms, amplitudes, source directions, and different algorithms (ETGs)

- Tune ETG thresholds and parameters (playground data only!)
  - Figure of merit: minimize background rate / efficiency

- In burst search, simulated signal is injected at an early stage in LDAS (in datacondAPI)

- Compare simulated signals injected into IFO with signals injected into data stream: make sure we understand IFO response
Efficiency for injected signals

- Generate a digitized burst waveform $h(t)$ (in this example, SG554 with varying $h_{\text{peak}}$)
- Filter through calibration (strain $\rightarrow$ AS_Q counts)
- Add to raw AS_Q data, sampling throughout S1 run
- 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 $h_{\text{peak}}$.
  - Nonetheless, it tracks $h_{\text{peak}}$, for a fixed waveform.
  - true for all ETG’s, even slope.
ETG “power” vs $h_{\text{peak}}$, and efficiency vs $h_{\text{peak}}$
Effect of time-dependent calibration

Comparison between "old" and "new" efficiency curves

OLD: simulations performed in the S1 playground, single point calibration.

NEW: simulations performed in a sample of the final data set, with Time-dependent calibration.

The size and sign of the effect depends on the IFO, epoch, waveform, central frequency, and ETG!

The time-dependent calibration is probably our largest systematic error.
Sine-Gaussians: “$h_{\text{rms}}$” at 50% efficiency

$$h_{\text{rms}} = \sqrt{\int |h(t)|^2 \, dt}$$
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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.

\[
\langle \mathcal{E} \rangle(h) = \int d\cos\theta \, d\phi \, d\psi \, \mathcal{E}(R(\theta, \phi, \psi)h)
\]
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.

\[
\langle \mathcal{E}_c \rangle (h) = \int d \cos \theta \, d\phi \, d\psi \, \mathcal{E}_a (R_a (\theta, \phi, \psi) h) \mathcal{E}_b (R_b (\theta, \phi, \psi) h) \ldots
\]
Coincident efficiency vs $h_{peak}$ for different waveforms, ETGs

tfclusters

slope
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tfclusters detects less than 1.4 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 → counts); choose conservative right-most band

Repeat, for each waveform and ETG
Results, for tfclusters and slope

tfclusters

- Gaussian $\tau = 1.0 \text{ ms}$

- Sine–Gaussian $f = 554 \text{ Hz}$

slope

- Gaussian $\tau = 1.0 \text{ ms}$

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The S2 Run

- Eight-week run just ended!
  - February 14 - April 14 2003
- Detector sensitivities are much better than for S1
- Duty factors are about the same
- Improvements since S1:
  - Better alignment control, especially for H1
  - Better monitoring in the control rooms
  - Fewer episodes of greatly increased BLRMS noise in GW channel
  - Careful attention to calibration lines, monitoring
  - Burst and inspiral search codes ran in near-real-time for monitoring purposes
- With improved noise and stability, will burstiness be better or worse than S1? Under study!
Sensitivity Continues to Improve

During S2, L1 inspiral reach extended to \(~\) 1 Mpc, including Andromeda and M33!

H1 and H2 have improved greatly too.
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!