Data Analysis Techniques for LIGO

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Lesson Plan

Yesterday:

1. Introducing the problem: GW and LIGO
2. Search for Continuous Waves
3. Search for Stochastic Background

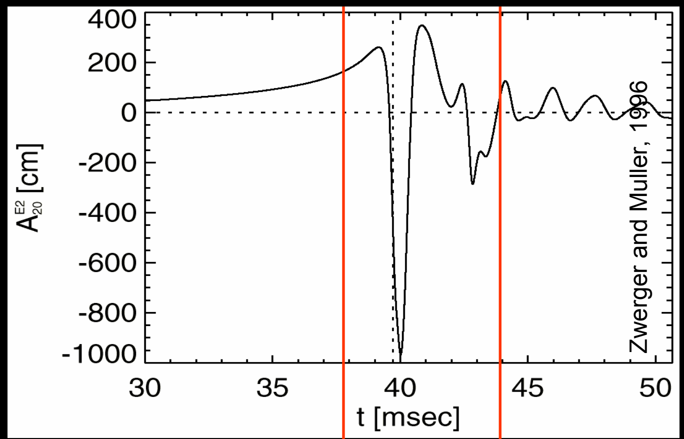
Today:

4. Search for Binary Inspirals
5. Search for Bursts
6. Network Analysis

Detecting GW Bursts

What does the signal look like?

A generic short duration transient (less than 1 second)
No prediction on waveform or population



$\delta t \sim 0.005s$

How do we quantify it?

$$h_{rss} = \sqrt{\int_{-\infty}^{\infty} |h(t)|^2 dt} = \sqrt{\int_{-\infty}^{\infty} |\tilde{h}(f)|^2 df}$$

How do we look for it?

Incoherent coincidence of transients in multiple detectors, with a coherent follow-up.
If there is an external trigger (for instance, a GRB): cross-correlate.

Gravitational Wave Bursts

Bursts: any non-inspiral, gravitational-wave transients for which we have no exact waveform or close approximation.

GWB sources are typically not well understood, involving complicated (and interesting!) physics.

They are more difficult to detect, but the scientific payoff from GWB detections could be very high.

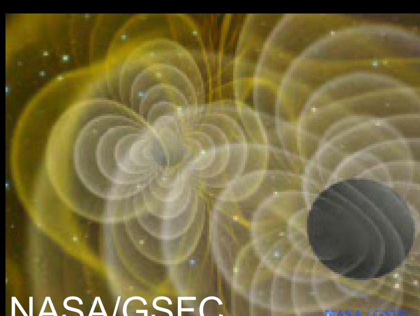
Examples:

- ❑ Black Hole / Neutron Star mergers
- ❑ Stellar core collapses
- ❑ Instabilities in nascent neutron stars
- ❑ Kinks and cusps in cosmic strings

SN1987A

Supernovae:

- ❑ GWs are emitted if there are asymmetries in the core collapse.
- ❑ Galactic rate: 1/50y
- ❑ Virgo cluster rate: 3/y



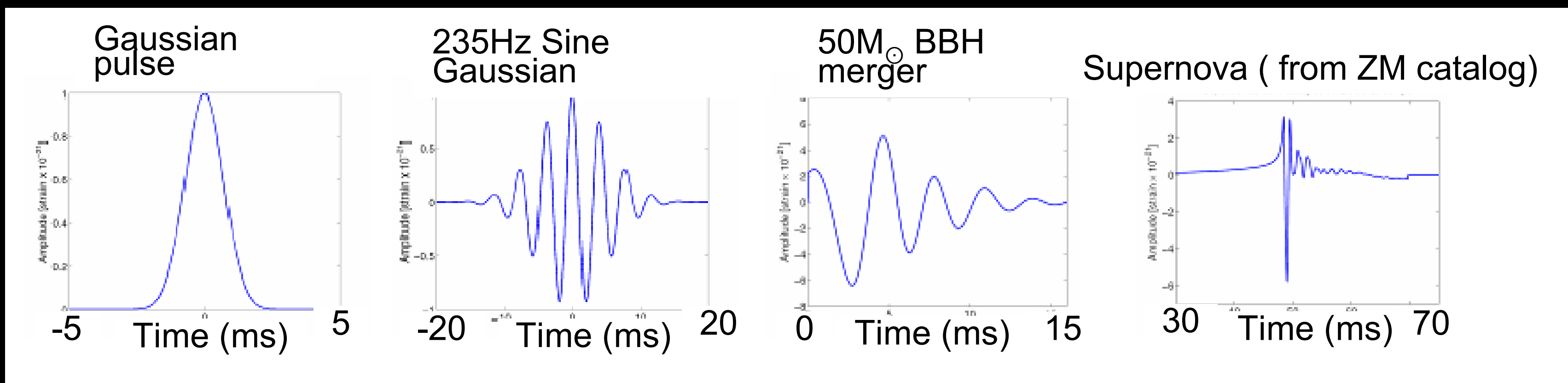
NASA/GSFC

Black Hole / Black Hole binaries:

- ❑ chirp at low frequency, short time in LIGO band
- ❑ templates not well known
- ❑ match filter not as effective as with neutron star binaries, makes sense looking for the merger
- ❑ no prediction on rate

The Eyes-Wide-Open Search for GW Bursts

All-sky, all-times, broadband (in S4: 64Hz-1600Hz)
search for un-modeled short transients (few ms – 1 sec)
open to unexpected sources and serendipity



Parallel efforts:

Externally Triggered Search -- Gamma Ray Bursts, supernovae (optical/neutrino)

Exploit coincidence with electromagnetic observations.

Waveforms still unknown, but time and direction are potentially known.

Matched filtering – ringdowns, cosmic string cusps

Ongoing targeted searches that use optimal filtering for a few known waveforms.

Un-triggered Burst Search

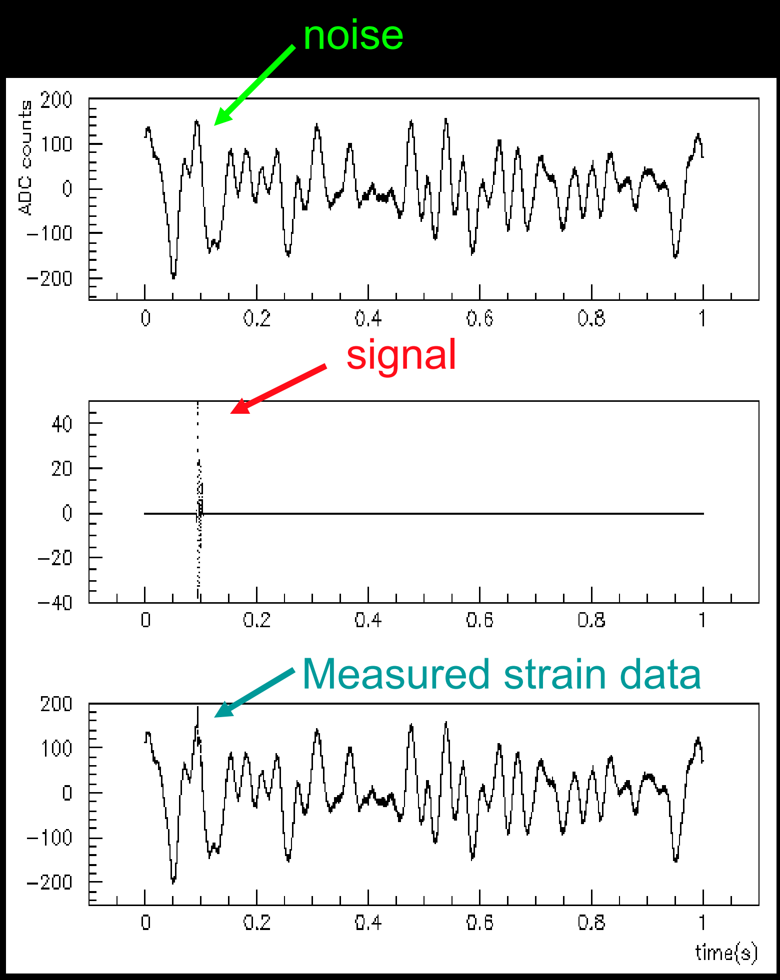
A classical problem: extracting a weak signal from noise.
With an additional complication:
unknown signal morphology

We cannot use matched filtering, as we do not know the waveform!

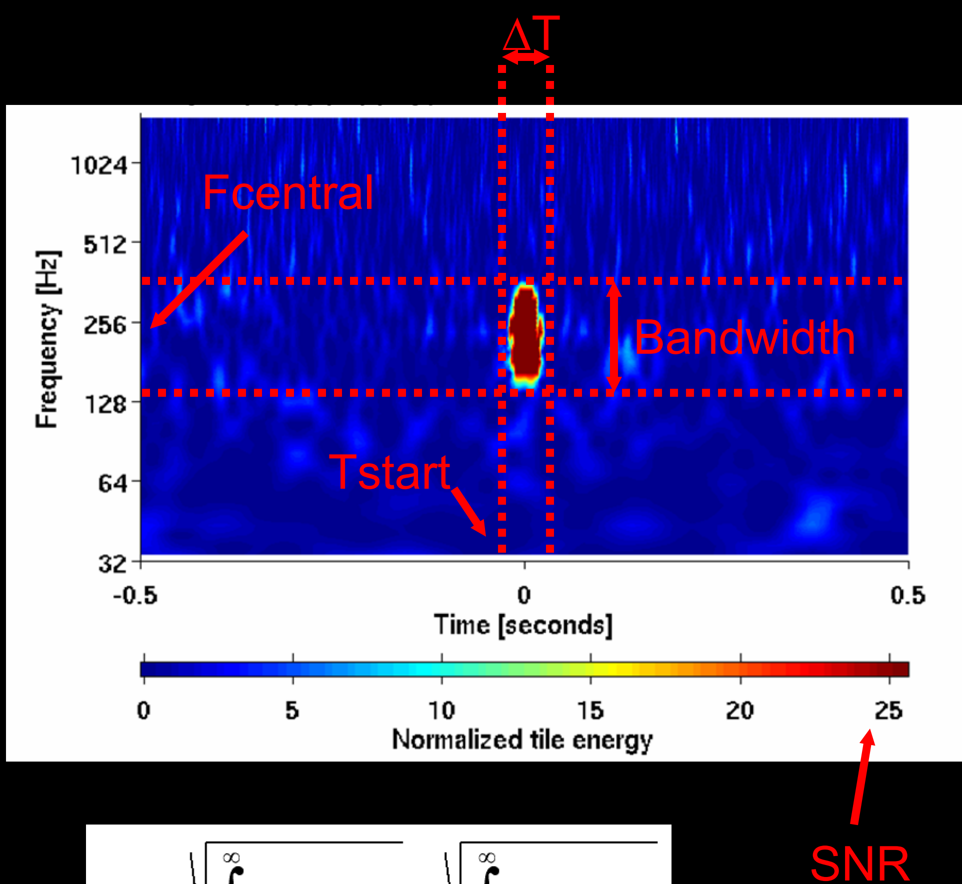
Solution:

analysis of candidate event triggers

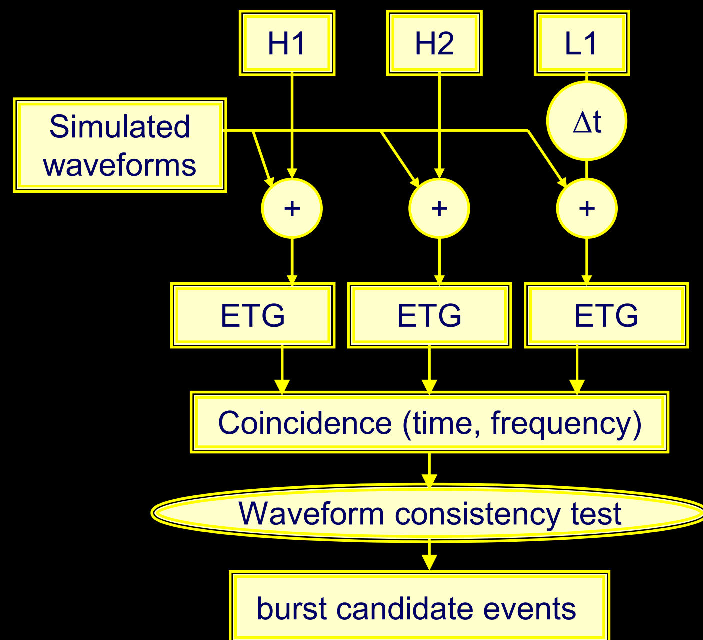
indicators for gravitational wave events, when a transient “anomaly” (excess power or amplitude) appears in the detector’s time series.



Burst Candidate Events



The Burst search pipeline is designed to find bursts buried in noise without being blinded by false alarms



$$h_{rss} = \sqrt{\int_0^\infty |h(t)|^2 dt} = \sqrt{\int_{-\infty}^{\infty} |\tilde{h}(f)|^2 df}$$

h_{rss}^2 is proportional to the total energy in the burst
Measure of the transient's amplitude with no template assumption

Defense Against False Alarms

1. Choose good quality data

This sounds obvious, but…
while some criteria are undisputable
(e.g. interferometers are locked, no ADC overflows, calibration is available)
others we are need to be more cautious about, not to waste data or miss GWs
(e.g. seismic disturbances, dust, instrumental transients)

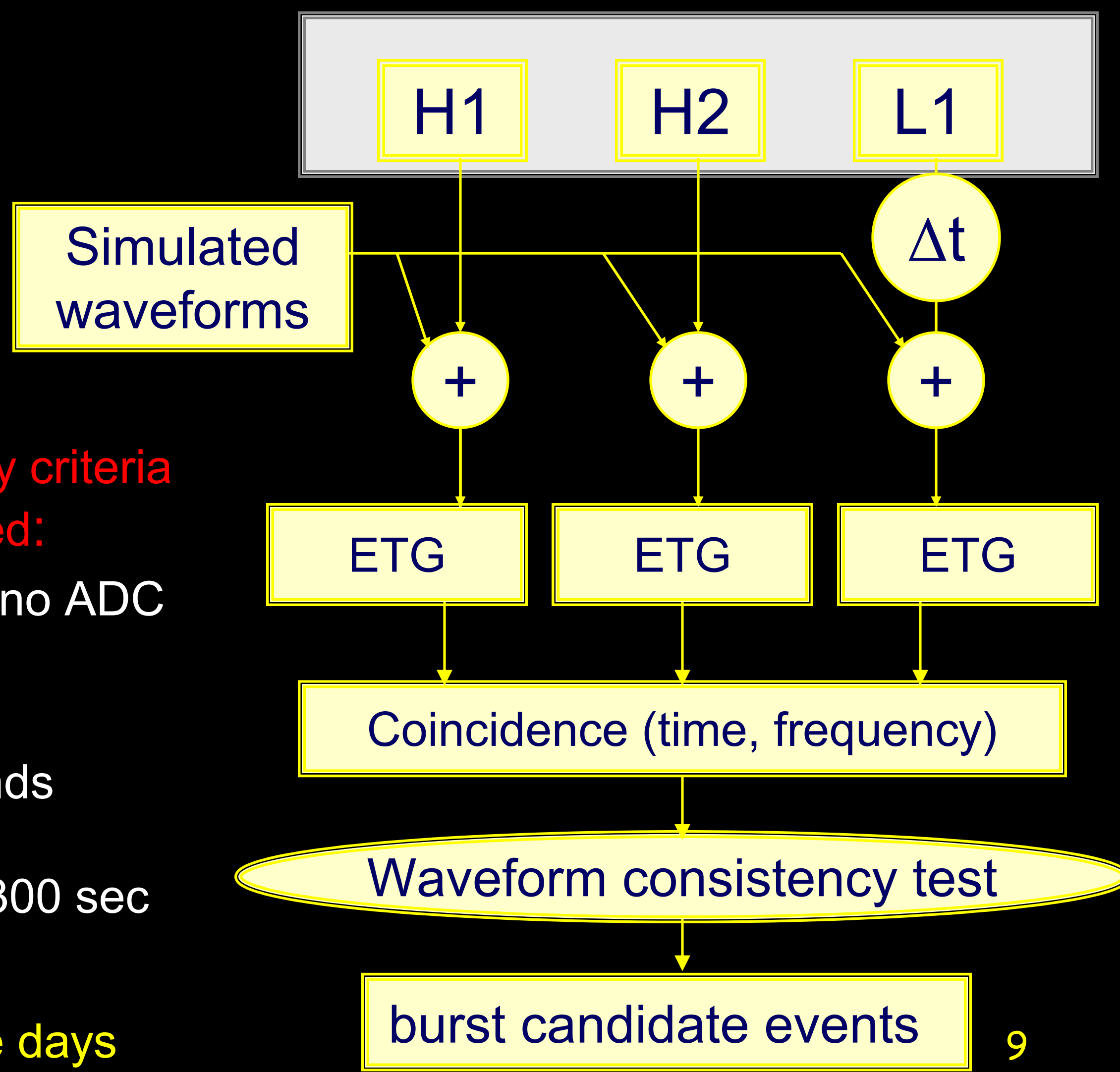
2. Exploit the availability of multiple detectors

Coincidence, coincidence, coincidence…
a GW burst "simultaneously" produces a trigger with similar characteristics
in all detectors

Data Selection

Always require multiple detectors

- triple-coincidence H1+H2+L1 in a LIGO-only search
- 2 detector combinations in joint searches with other instruments



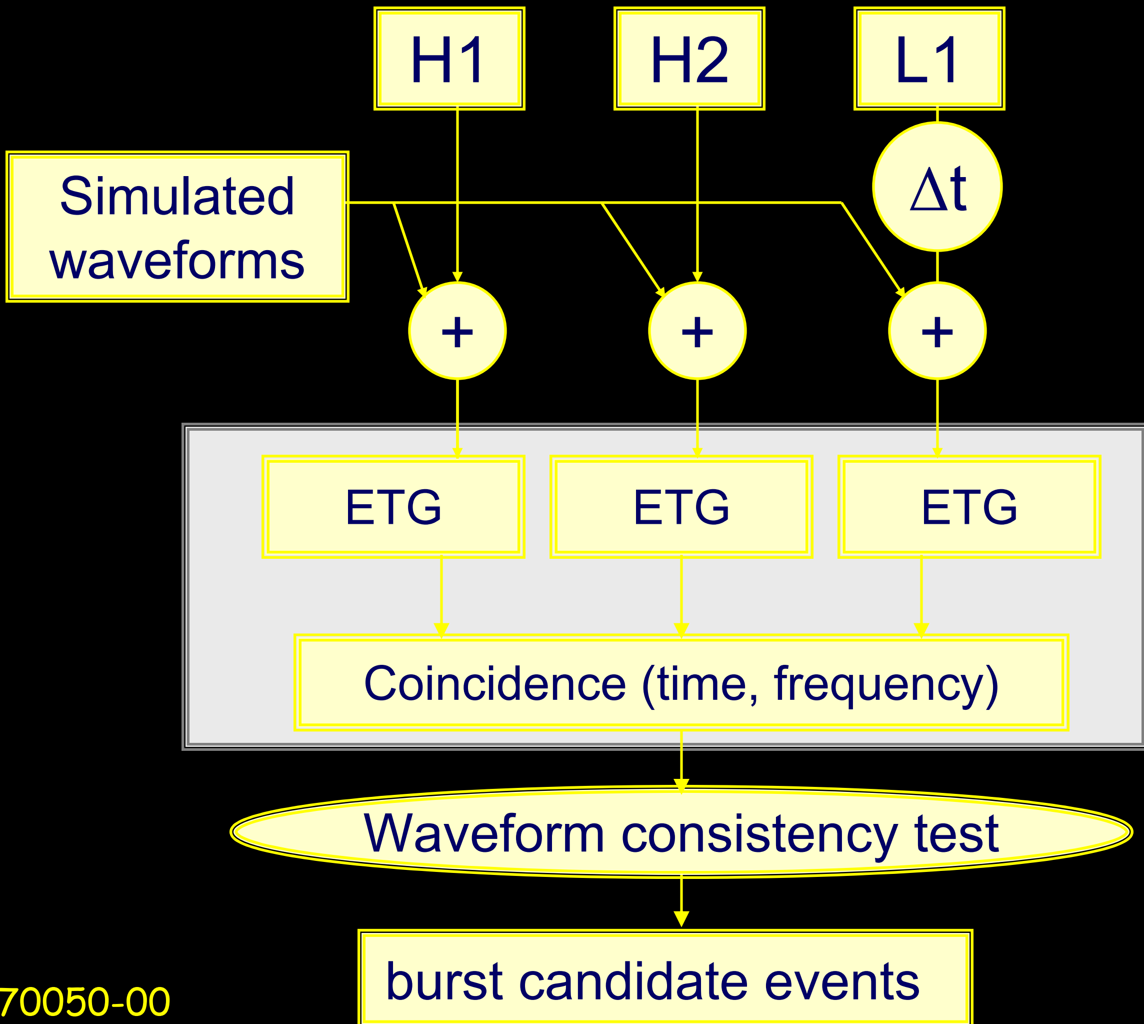
Use a minimal set of data quality criteria for data segments to be analyzed:

- no hardware injections, no ADC overflows, calibration is available
- Discarded last 30 seconds before loss of lock and segments shorter than 300 sec

For instance, in S4:

30 calendar days ⇒ 16.4 live days

Coincident Event Trigger Generation



ETG= Event Trigger Generator

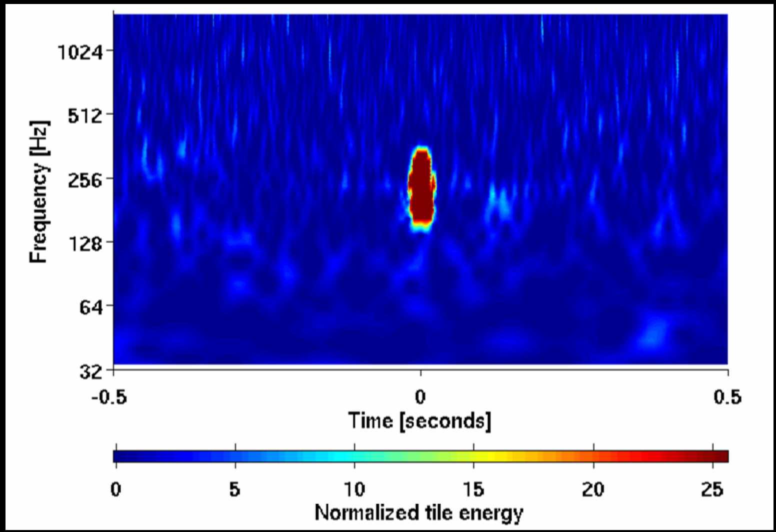
Each coincident event comes with a combined significance

Excess power detection

Look for transient increase in power in some time-frequency region, with minimal assumptions about the signal:

- Duration: 1 to 100 ms
  - characteristic time scale for stellar mass objects
- Frequency: 60 to 2,000 Hz
  - Determined by detector's sensitivity
- Many different implementations
  - Fourier modes, wavelets, sine-Gaussians
  - Multiple time/frequency resolutions
  - Provide redundancy and robustness

A simulated burst

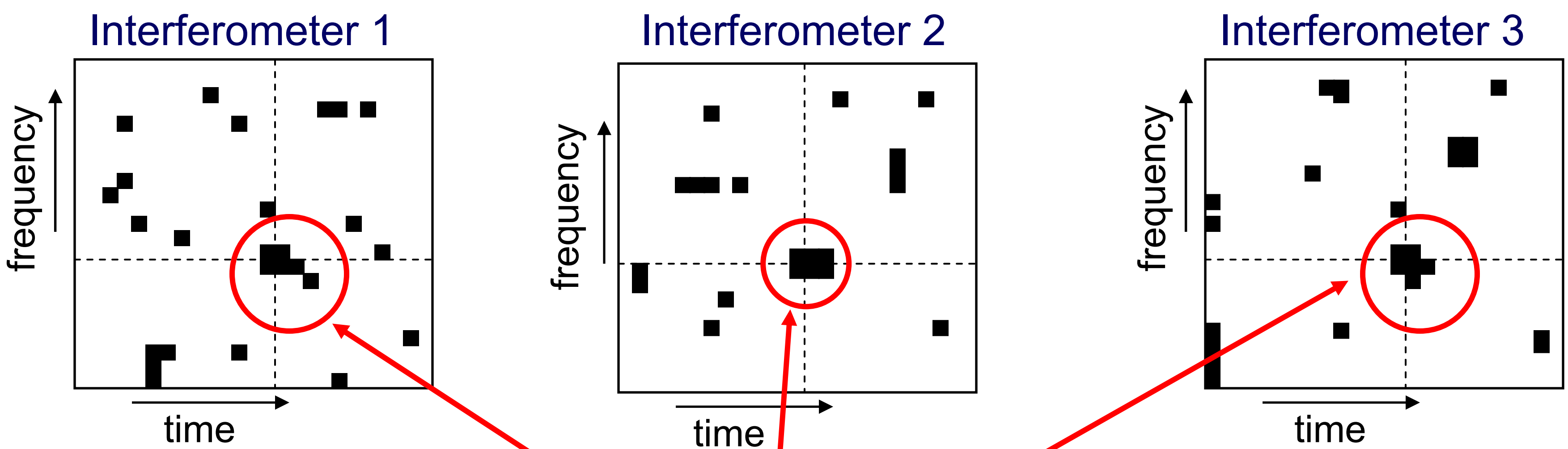


WaveBurst

Excess power in wavelet time-frequency plane.

Ref: Class. Quantum Grav. 21 (2004) S1819

10% black pixel probability



coincidence

In the S4 implementation:

Wavelet decomposition from 64–2048 Hz with 6 different resolutions from 1/16 sec × 8 Hz to 1/512 sec × 256 Hz

Frequency content cut: required to overlap 64–1600 Hz band

WaveBurst outputs coincident events with their significance in each of the three interferometers.

Parameter estimation: time, duration, frequency, signal amplitude at Earth

Threshold on combined significance of the triple coincident event (Z_g)

From the Burst S3 paper: Class. Quant. Grav. **23**, S29-S39 (2006)

The Waveburst algorithm [5], also used for the S2 analysis [8], generates triggers on coincident excess power in the wavelet domain across the raw gravitational-wave data streams. The data first undergo a complete wavelet packet decomposition, giving for each detector a uniform time-frequency map of the signal indexed in time by i and in frequency by j. Significant tiles in each decomposition are defined by the largest 10% of wavelet coefficients at each effective frequency. They are assigned a *significance* according to their energy-determined rank within the set of tiles at fixed frequency j:

$$y_{ij} = -\ln\left(R_{ij}/N\right), \tag{1}$$

where the rank, R_{ij}, is equal to 1 for the most energetic and N for the least energetic of the selected N tiles. The significant tiles with closely matching tiles in time and frequency across the three data streams are determined to be "in coincidence", and a clustering routine clusters nearby tiles from the set of coincident tiles for each detector separately.

These single detector clusters are thus built from the triple-coincident energy in the wavelet domain. Each cluster of k tiles, $C(k)$, is characterized by its *cluster significance*, z, given by

$$z = Y - \ln\left(\sum_{m=0}^{k-1}\frac{Y^m}{m!}\right) \quad \text{where} \quad Y = \sum_{i,j\in C(k)} y_{ij}\,, \tag{2}$$

which has an exponential distribution regardless of cluster size. The *trigger significance*, Z_g, is calculated as the geometric average of the cluster significances for a particular H1/H2/L1 coincident triplet of clusters. Z_g provides a measure of the confidence of each triple-coincident event trigger, and is used for future thresholding.

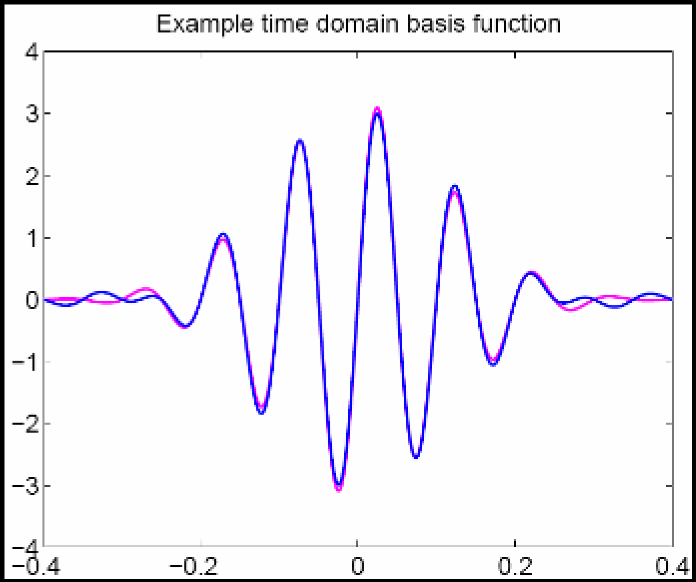
A different option: Q-pipeline

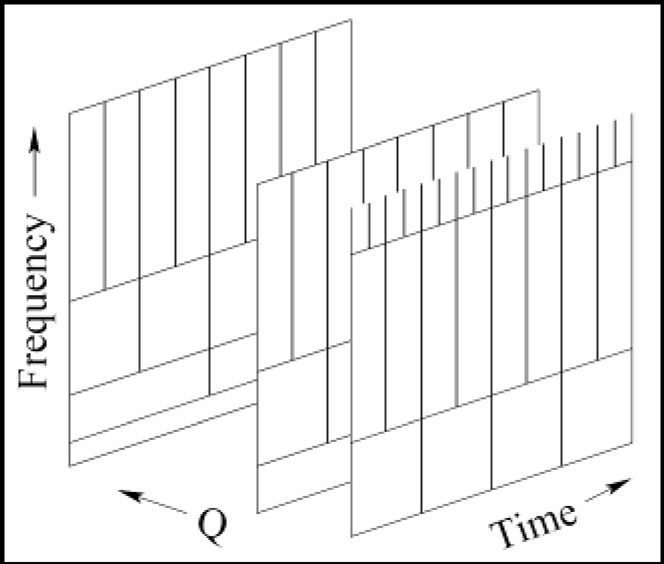
Project onto multiresolution basis of minimum uncertainty waveforms

- - overcomplete basis, desirable for detection
- Template placement scheme similar to inspiral matched filter approach

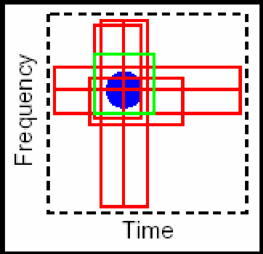
$$X(\tau,\phi,Q) = \int_{-\infty}^{+\infty} x(t)\, w(t-\tau,\phi,Q)\, e^{-i2\pi\phi t}\, dt$$

$$Z = |X|^2 / \langle |X|^2 \rangle$$



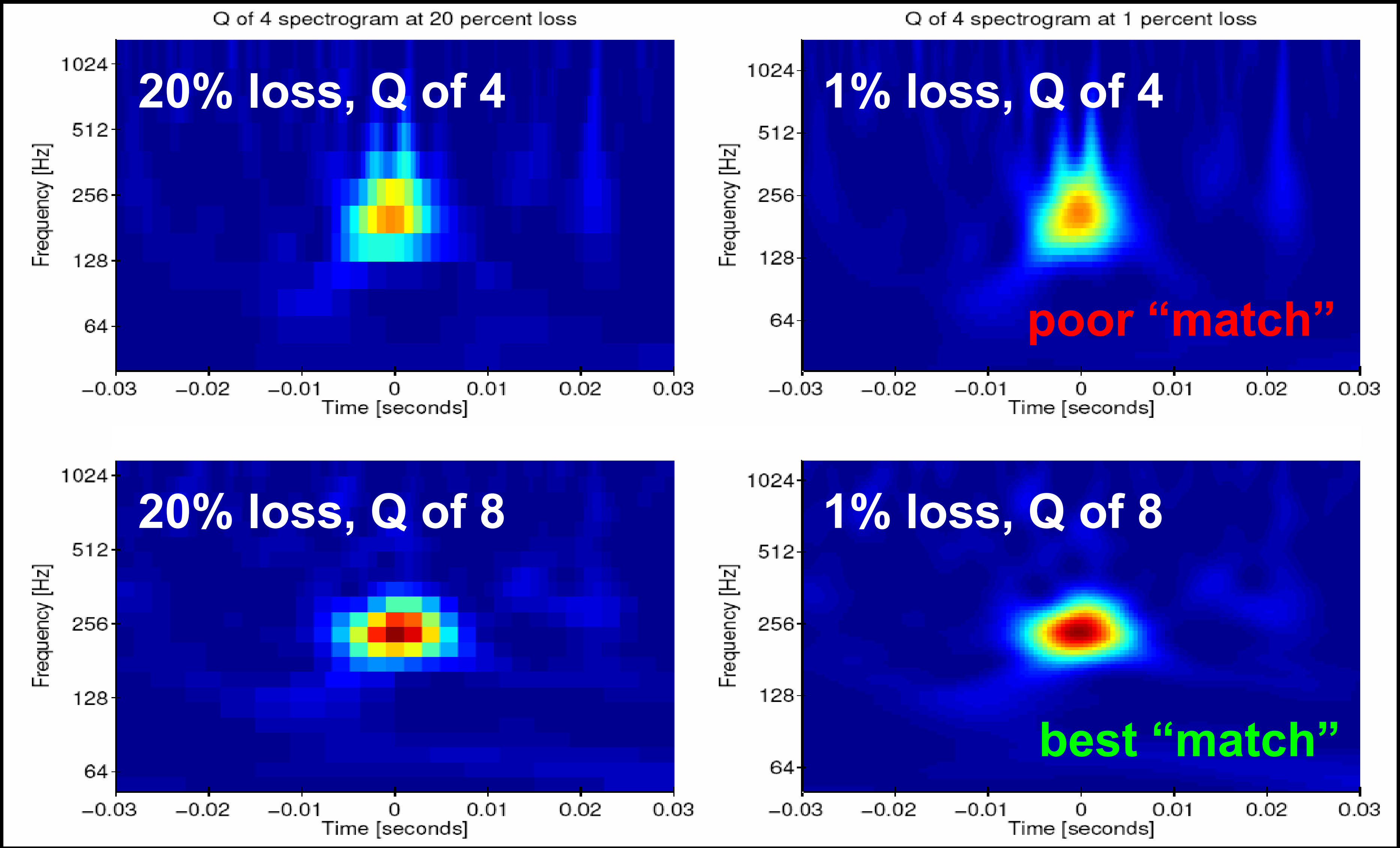


How to cluster "triggers" into "events"?



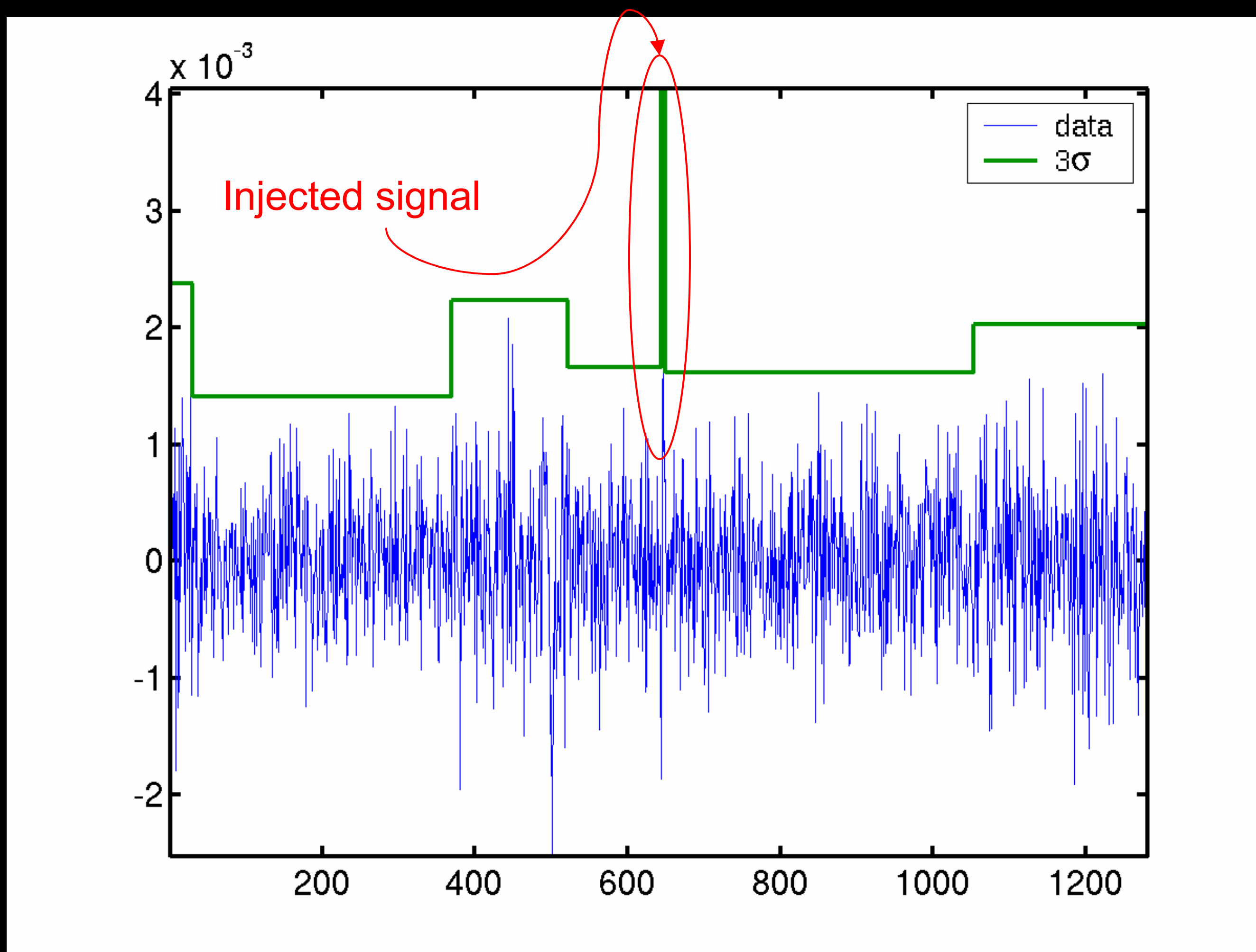
Example Q transform

- Simulated 256 Hz sinusoidal Gaussian burst with Q of 8

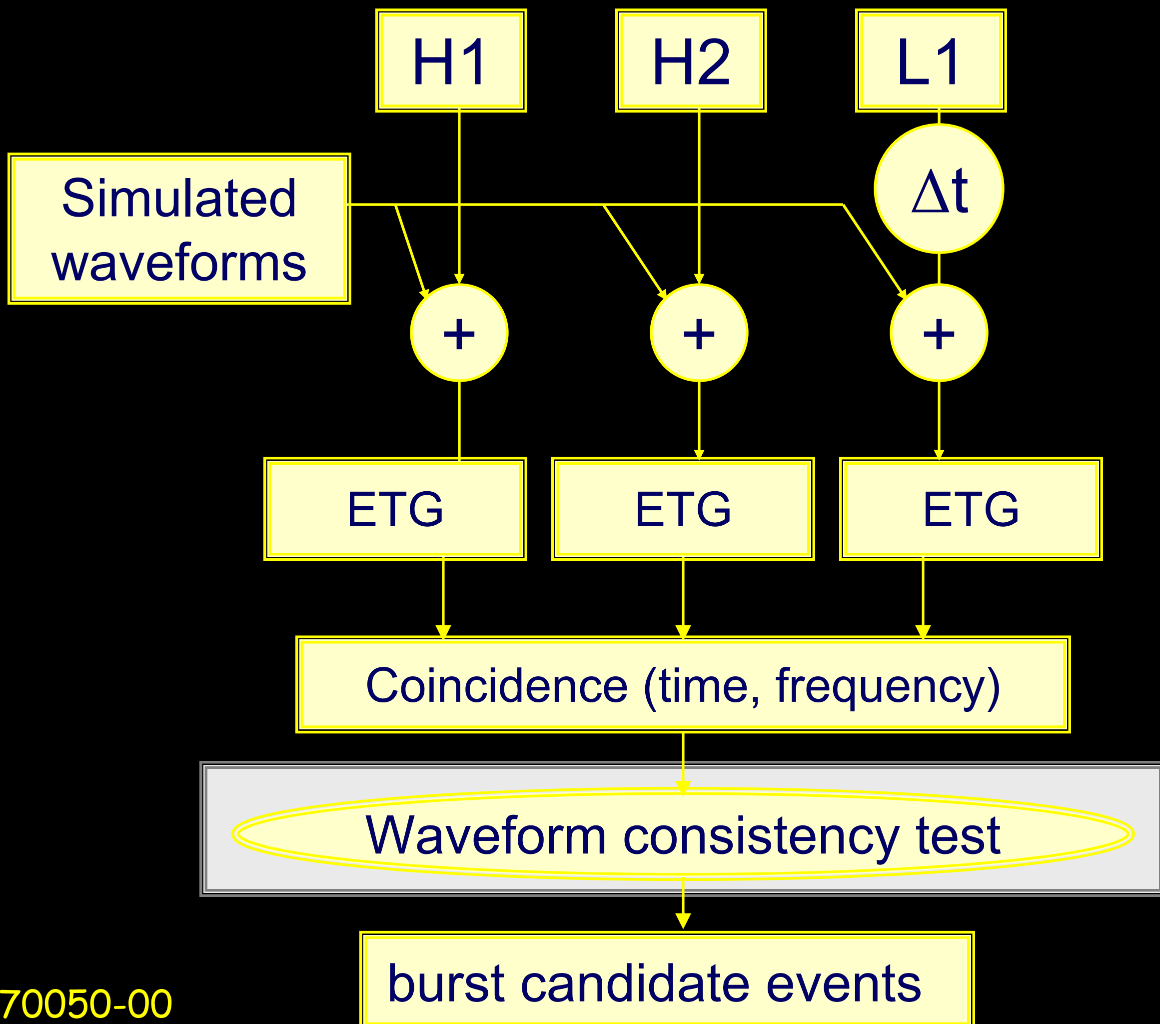


It can also be done in time domain: BlockNormal

BlockNormal searches data for statistical "*change points*" and divides the data into blocks of data with consistent mean and variance. A block is reported if it differs by a significant amount from the statistics of the larger data set.

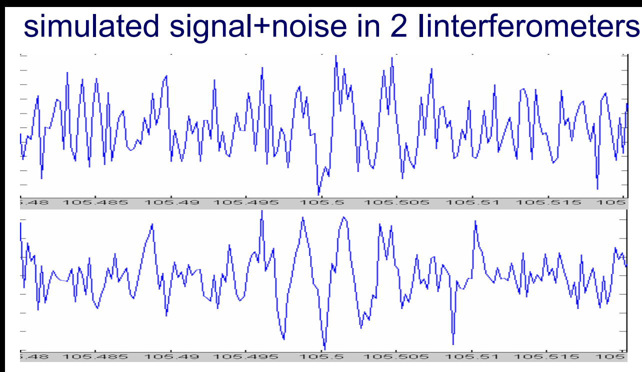


The *r*-statistic Waveform Consistency Test



Assigns a significance on how correlated the signals in different detectors are: Γ

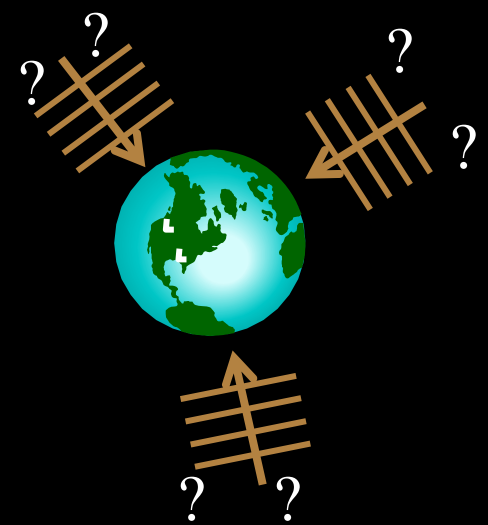
The *r*-statistic Waveform Consistency Test



$$s_1(t) = h(t - t_1) + n_1(t)$$

$$s_2(t) = h(t - t_2) + n_2(t)$$

t_1-t_2 depends on the source position in the sky



we cannot match-filter to a waveform, but we can match waveforms from different interferometers, with cross-correlation

$$C(t, t_w, t_{off}) = \int_{t-t_w/2}^{t+t_w/2} s_1(t')s_2(t'+t_{off})dt'$$

$$\approx \int_{t_w} h^2(t)dt + \int_{t_w} n_1(t)n_2(t)dt$$

tw: burst duration, UNKNOWN

toff : source position UNKNOWN

h_{rss}^2

$\langle\ \rangle = 0$

The *r*-statistic Waveform Consistency Test

Ref: *Class. Quantum Grav. 21 S1695-S1703*

Process **pairs** of interferometers (whitened data, 64-2000 Hz) and ask the question:

What is the probability that the two data sequences are un-correlated ?

r-statistic:

$$r_k = \frac{\sum_i (x_i-\bar{x})(y_{i+k}-\bar{y})}{\sqrt{\sum_i (x_i-\bar{x})^2}\sqrt{\sum_i (y_{i+k}-\bar{y})^2}}$$

Significance of null-hypothesis:

$$S = \text{erfc}\left(\sqrt{r^2\frac{N}{2}}\right)$$

$$C_M = \max_{\Delta t}\,(-\log_{10} S(\Delta t))$$

The incident GW direction is unknown
→ allow time delay (Δt) between the two data series 11ms H1-L1 and H2-L1 ; 1ms H1-H2

Combine interferometer pairs and search possible signal duration (20, 50, 100 ms) to maximize the final statistic Γ

Threshold on Γ : arithmetic mean of three pair-wise confidences

$$\Gamma = \max(C_M^{L1H1} + C_M^{L1H2} + C_M^{H1H2})/3$$

R0 : signed correlation of H1 and H2 with zero relative time shift: has to be positive

Data Conditioning in the r-statistic test

Decimate and high-pass few seconds of data around event ⇒100-2048 Hz

Remove predictable content (effective whitening/line removal): train a linear predictor error filter over 10 s of data (1 s before event start), emphasis on transients, avoid non-stationary, correlated lines.

Linear Prediction:
Assume each sample is a linear combination of the previous M samples.

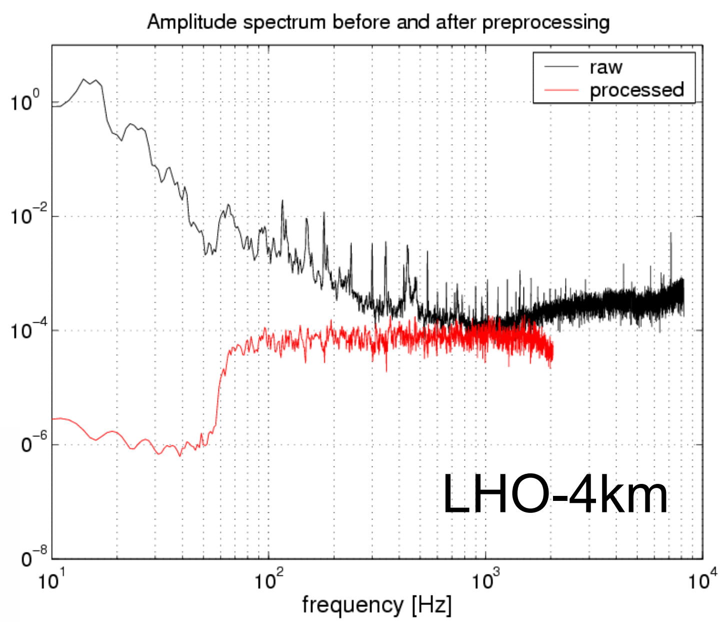
$$\tilde{x}[n] = \sum_{m=1}^{M} c[m]x[n-m]$$

Prediction Error:
We are interested in the unpredictable signal content.

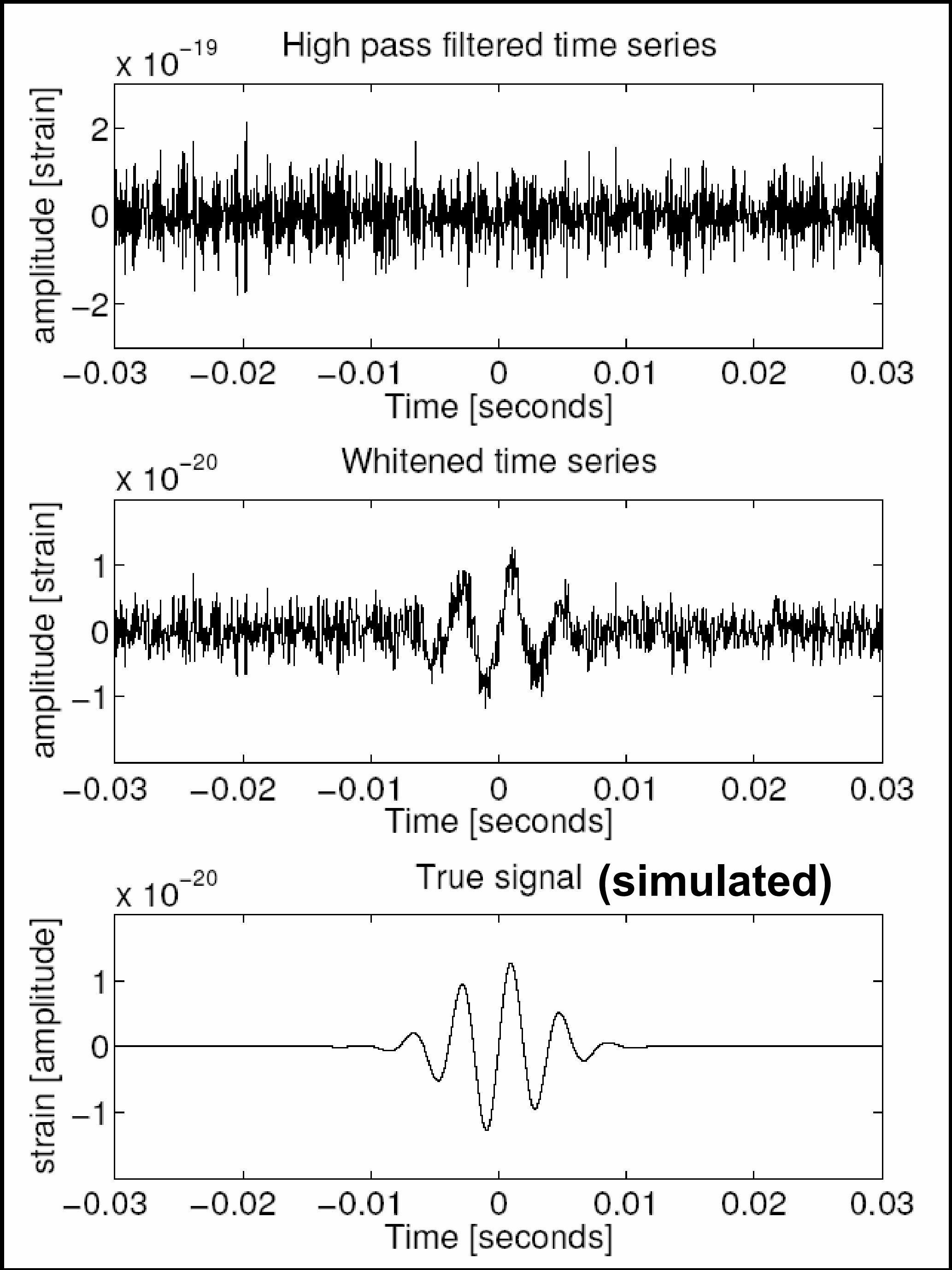
$$e[n] = x[n] - \tilde{x}[n]$$

Training:
Choose c[m] to minimize the mean squared prediction error.

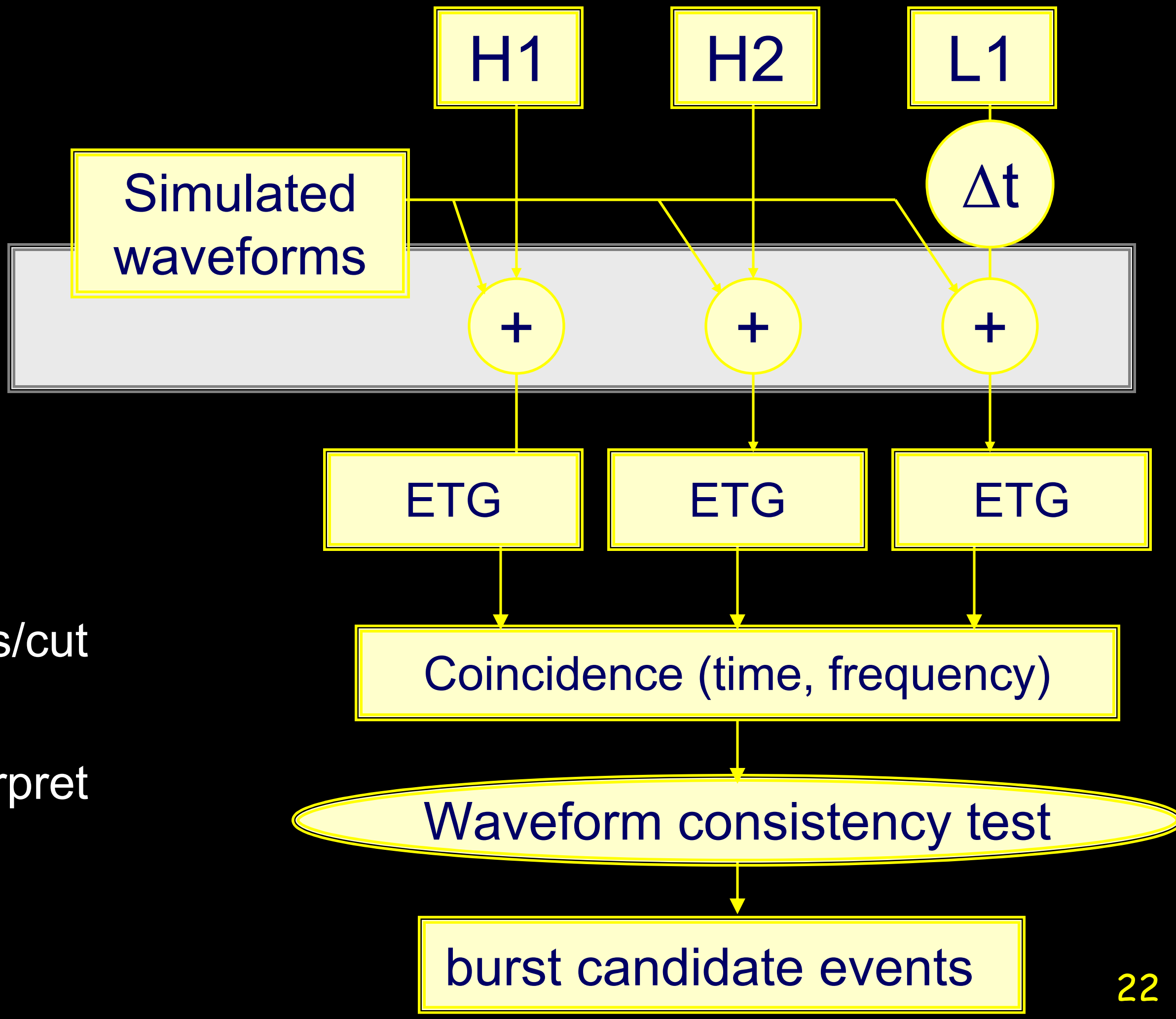
$$\sigma_e^2 = \frac{1}{N}\sum_{n=1}^{N} e[n]^2$$



applied as second order section model using zero-phase filtering


High pass filtered time series
x 10^−19
amplitude [strain]
2
0
−2
−0.03 −0.02 −0.01 0 0.01 0.02 0.03
Time [seconds]
Whitened time series
x 10^−20
amplitude [strain]
1
0
−1
−0.03 −0.02 −0.01 0 0.01 0.02 0.03
Time [seconds]
True signal (simulated)
x 10^−20
strain [amplitude]
1
0
−1
−0.03 −0.02 −0.01 0 0.01 0.02 0.03
Time [seconds]

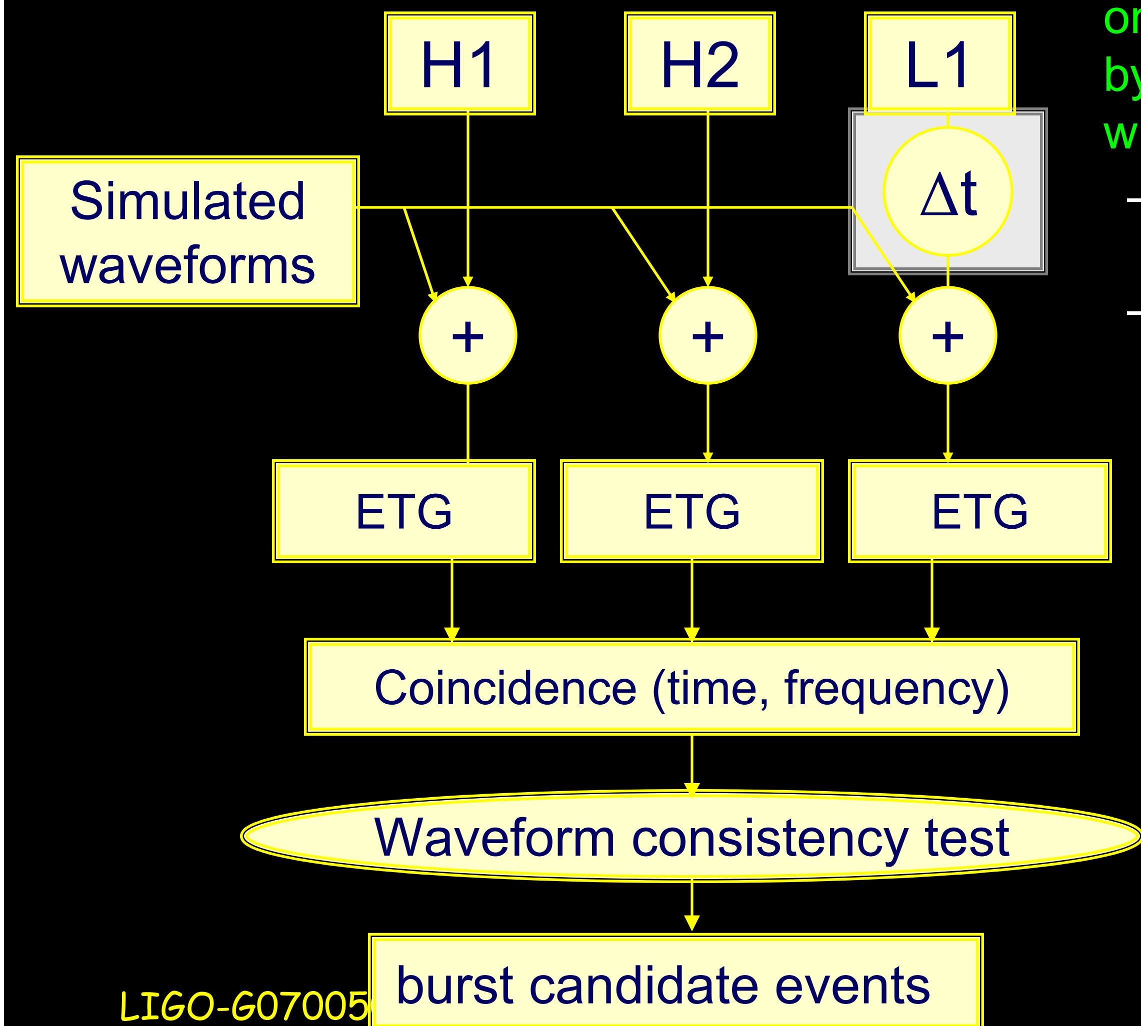
Simulated Waveforms



Used to:

- Tune all thresholds/cut
- Estimate detection efficiency and interpret results

Time slides for Pipeline Tuning and Background Estimation



Blind Analysis: the pipeline is tuned on replicas of the data set, obtained by time-shifting the Livingston data with respect to the Hanford data.

– In the S4 implementation: 100 time shifts

– -156.25 to +156.25 sec in 3.125-sec increments (excluding ±3.125)

The background is estimated using a different set of time-shifted 3-fold coincidences.

In the S4 implementation:

– LLO data shifted relative to LHO

– 100 × 5s time shifts (5s ≤ |Δt| ≤ 250s)

All shifted data is processed with identical pipeline and cuts.

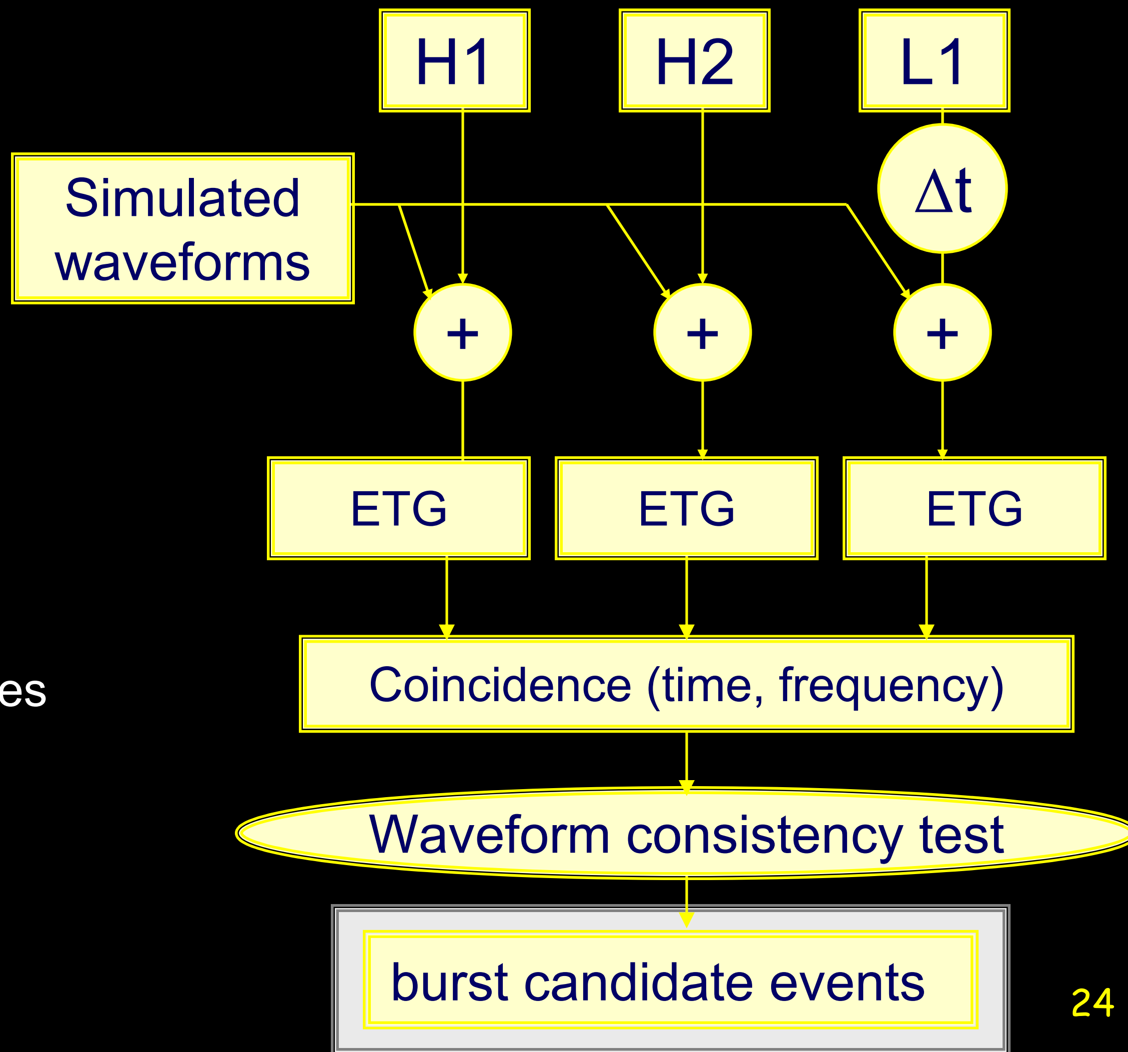
Burst Candidate Events

More cuts:

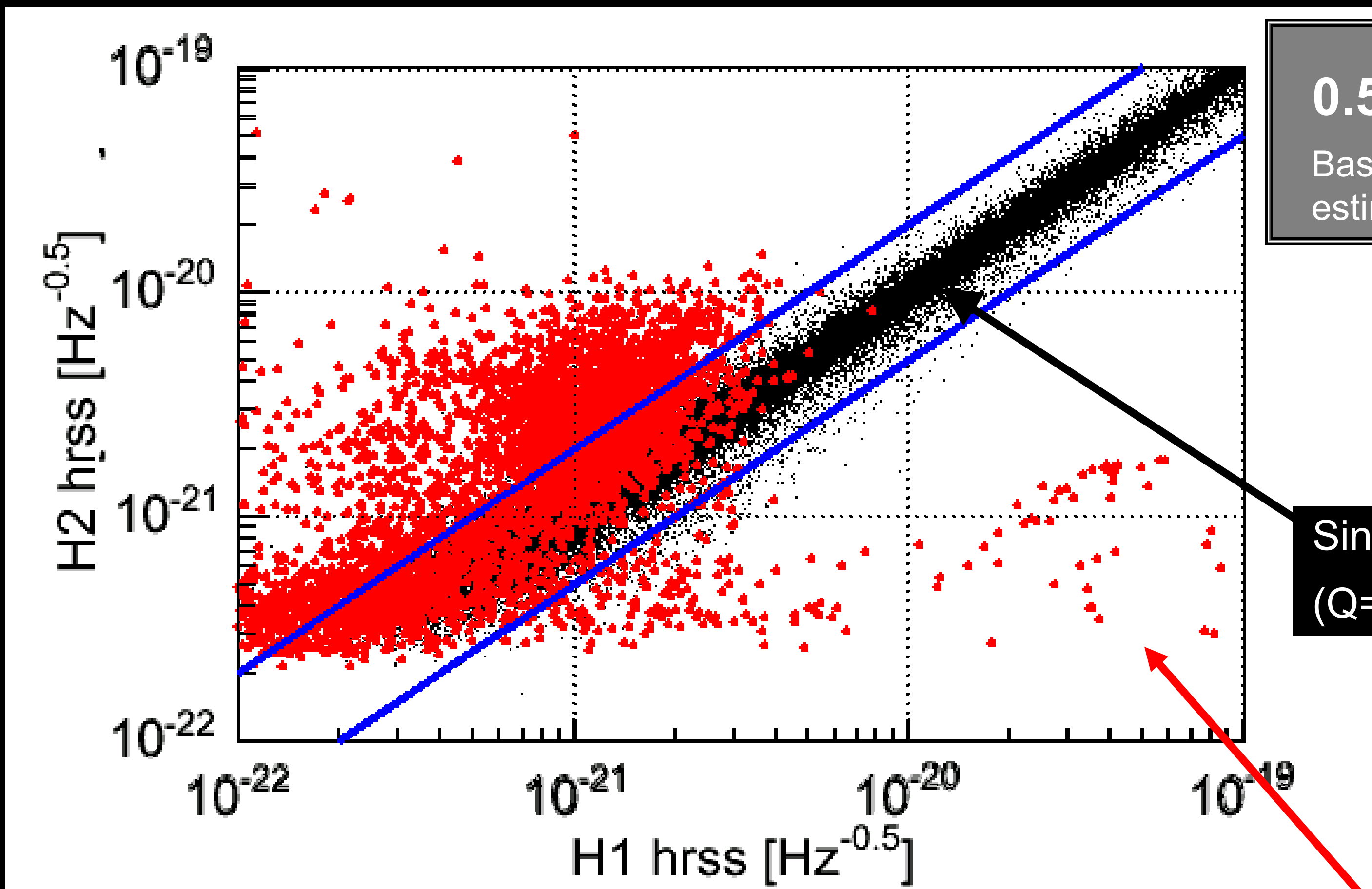
- H1/H2 amplitude cut
- Additional data quality criteria
- Auxiliary channel vetoes

Set analysis thresholds

Detection or Upper limit?

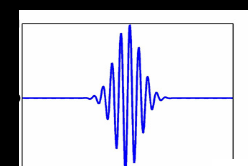


H1/H2 Amplitude Cut



$0.5 < (H1/H2) < 2$

Based on calibrated h_{rss} estimated by WaveBurst



Sine-Gaussians

(Q={3,8.9}, 70–1053 Hz)

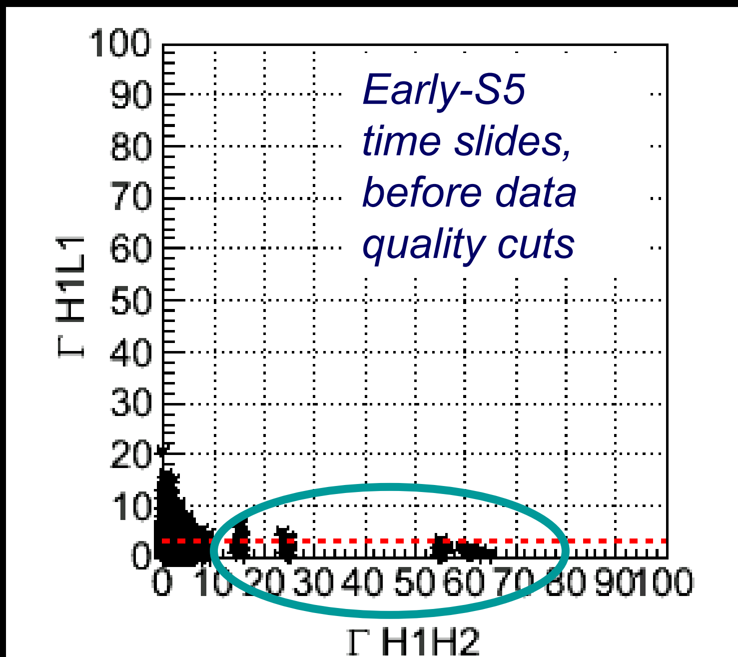
0.5% of these simulated signals fail amplitude cut

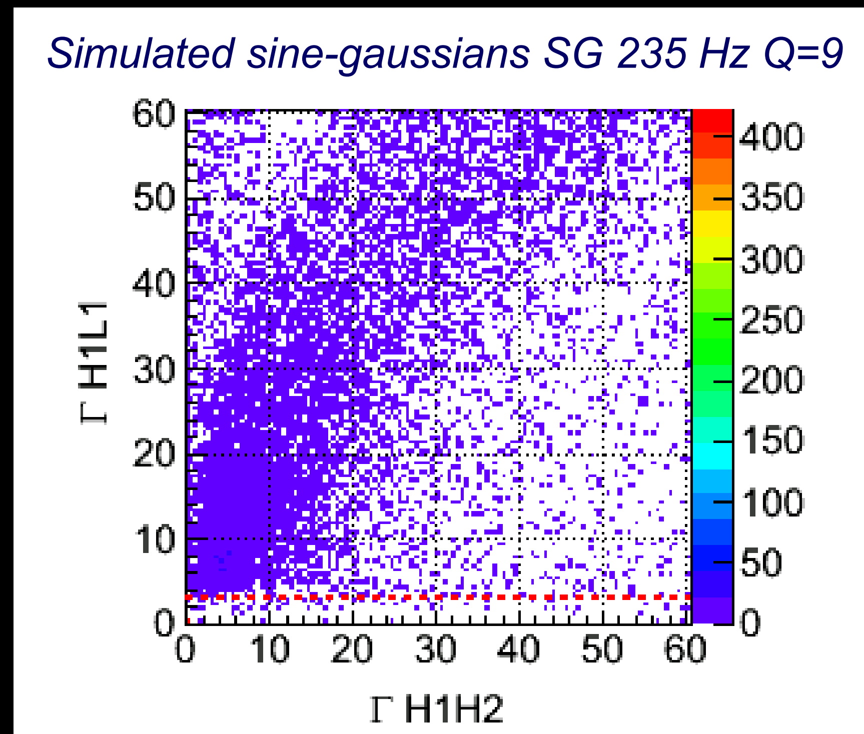
S4 false alarms

(time-shifted)

$$h_{rss} = \sqrt{\int_0^\infty |h(t)|^2 dt} = \sqrt{\int_{-\infty}^\infty |\tilde{h}(f)|^2 df}$$

New Cut in S5 analysis: Threshold on H1 L1 Correlation





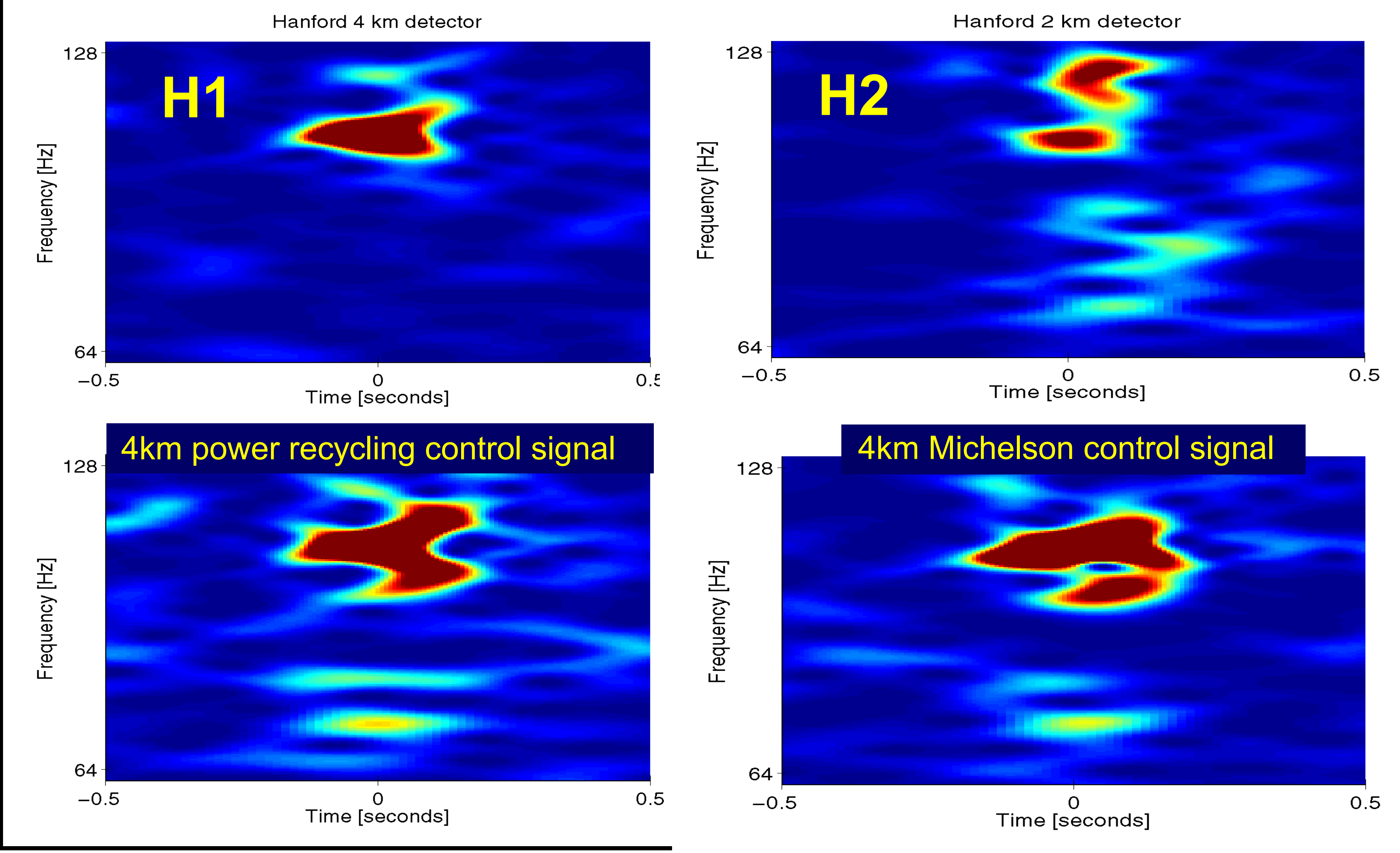
After cuts on the H1-H2 amplitude and the sign of the correlation, we are left with H1-H2 glitches dominating $\Gamma=\Gamma^{L1H1} + \Gamma^{L1H2}+\Gamma^{H1H2})/3$

Vetoed by requiring ΓH1L1 above threshold

Choice: ΓH1L1> 3 (less than 0.1% probability to get the measured *r* from uncorrelated noise at L1 and H1)

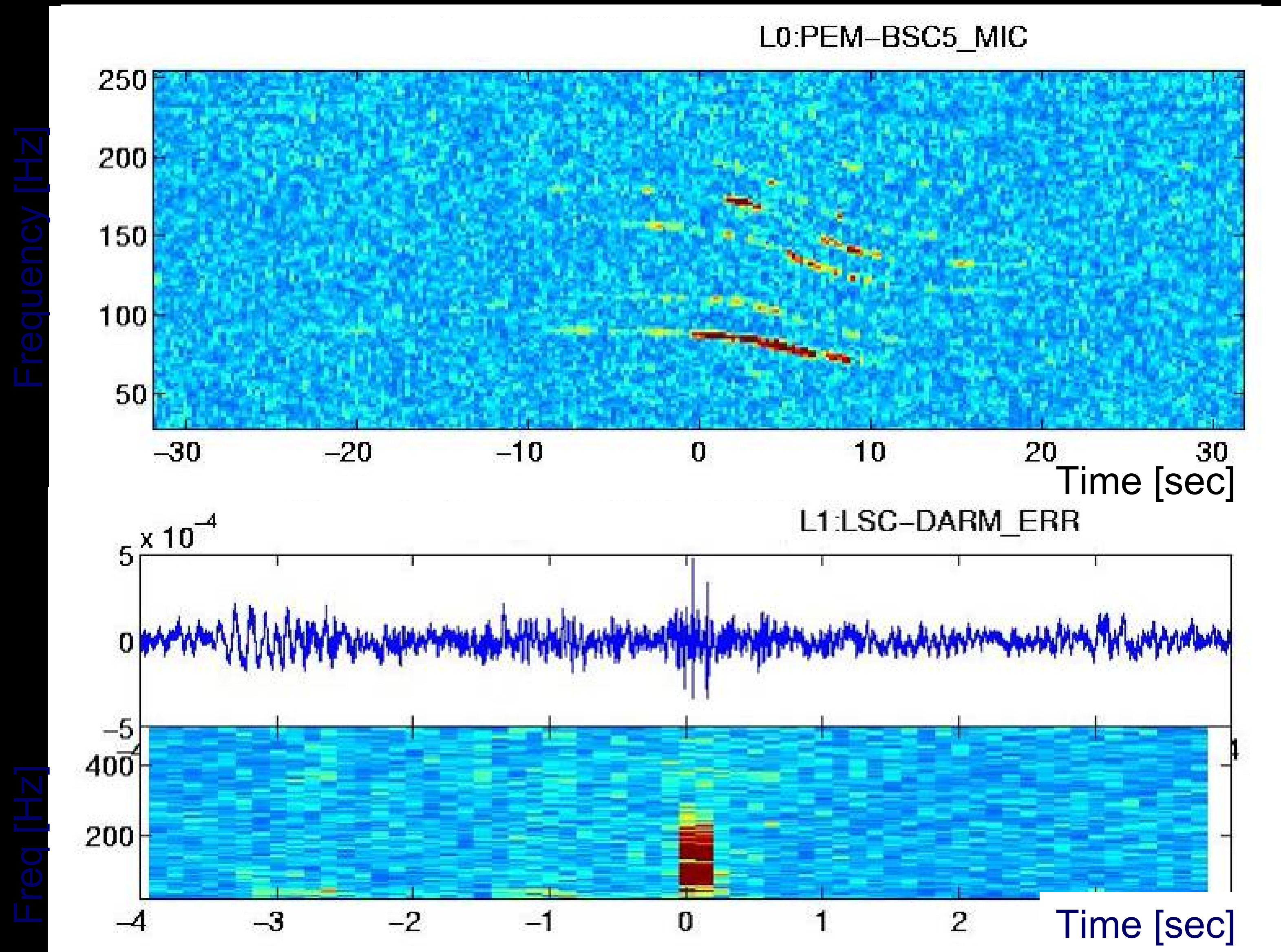
Detector Transients

An example from S2



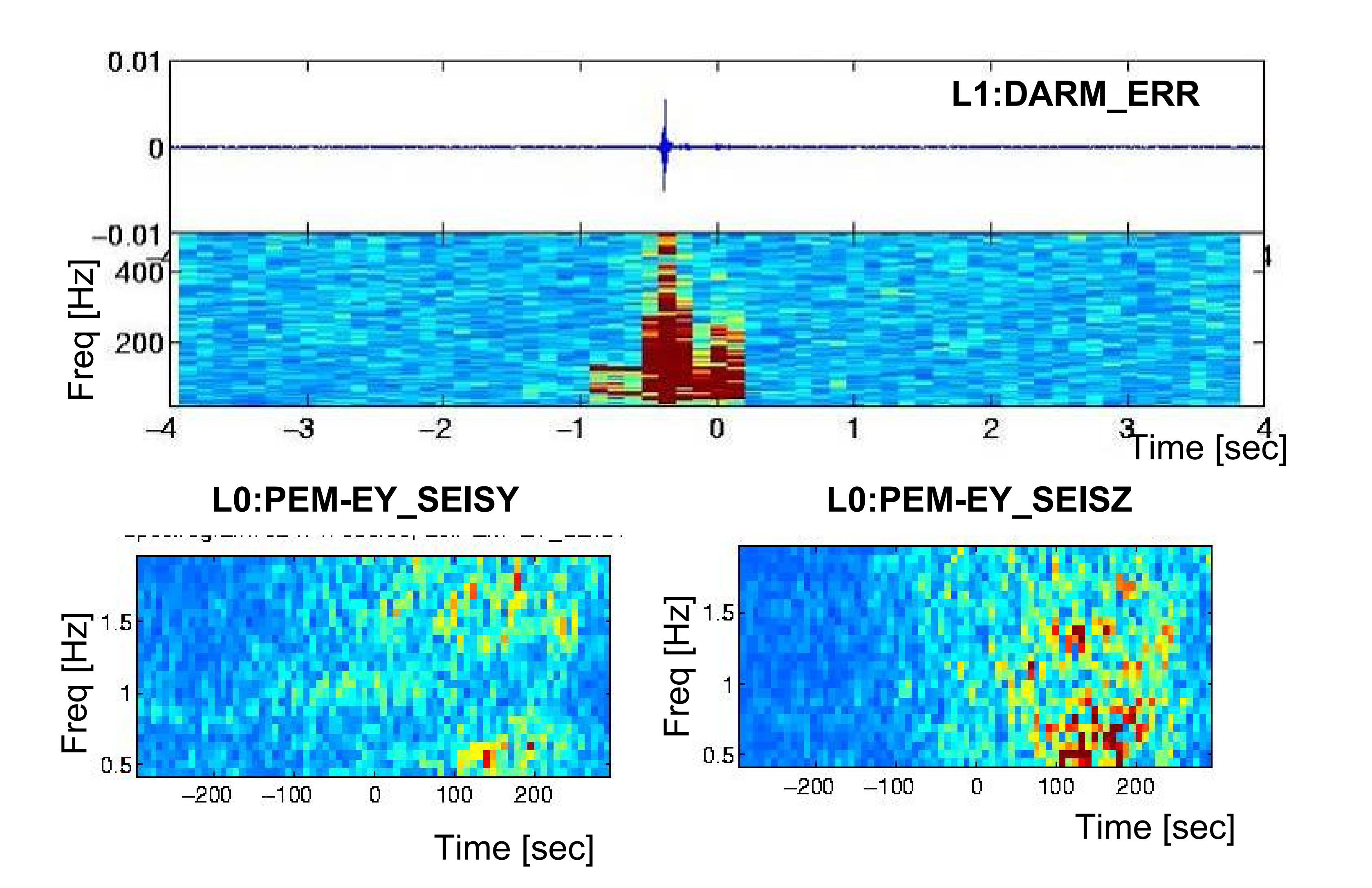
Acoustic disturbances (planes and helicopters)

An example from S5

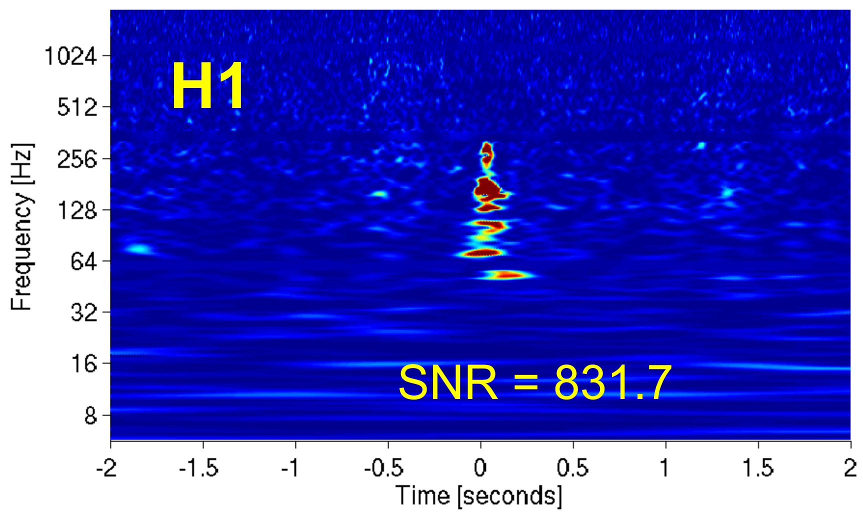


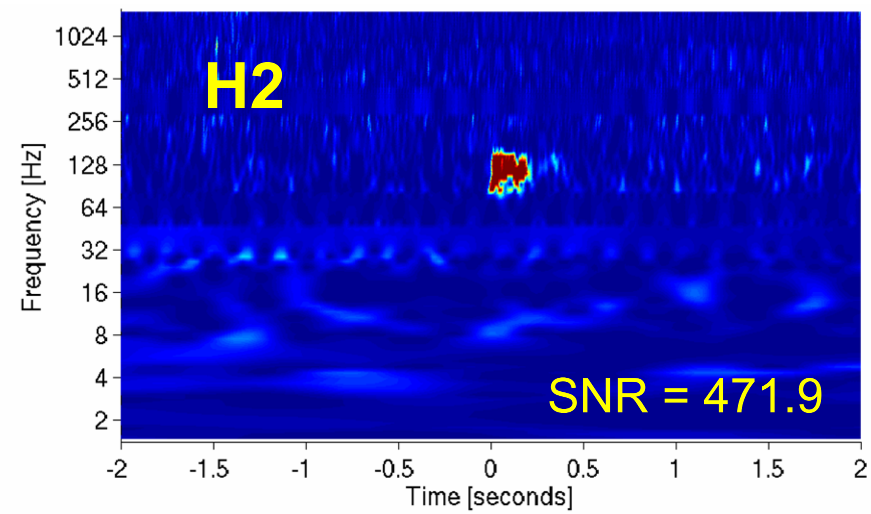
Seismic Disturbances

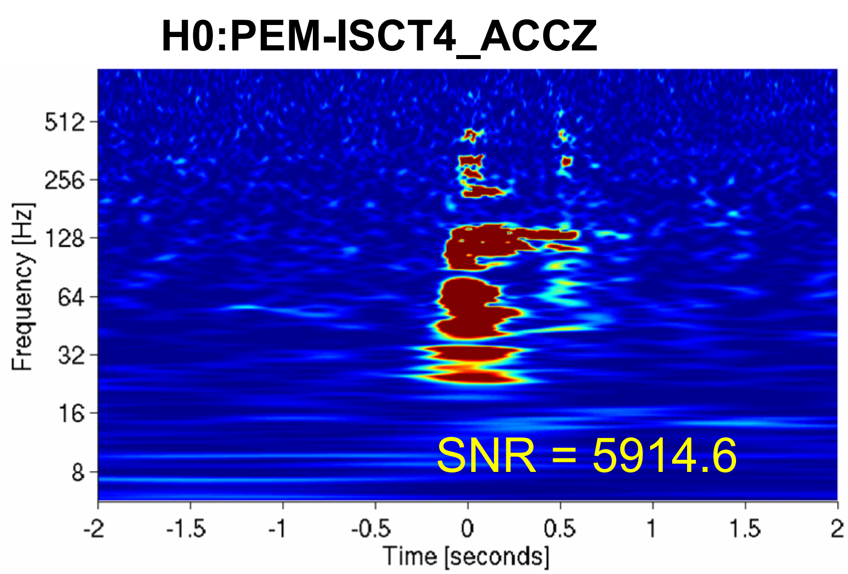
15 minutes before a train during S5…



Local seismic disturbances







Data Quality Cuts

Additional data-quality cuts for short segments (~minute scale) are applied to coincident events; some are chosen a priori, others are based on efficiency studies with single-interferometer transients

S4:

- Calibration line dropouts
- Dips in arm cavity stored light
- Elevated DC light level (H1 and L1)
- Elevated seismic noise in 0.9–1.1 Hz band at Hanford
- Jet plane fly-over at Hanford
- Wind over 35 mph [62 km/h] at Hanford

Net loss of observation time: 5.6%

Then there are auxiliary-channel vetos…

S5 Data Quality Veto Strategy

Cited examples are for the S5 Burst search.
Very similar choices in Inspiral search, with some subleties in the Cat 1-2 distinction

Category 1	Inspiral: data not worth analyzing Burst: Minimal data quality vetoes, for the selection of data segments to be analyzed *(e.g. calibration problems, test injections, photodiode saturations)*
Category 2	"Unconditional" post-processing vetoes: data is unreliable and there is an established one-on-one correlation with loud transients. *(e.g. saturations in the alignment control system, glitches in the power main)*
Category 3	"Conditional" post-processing vetoes, for upper limit: statistical correlation to loud transients. We still look for detection candidates at those times, exerting caution when establishing detection confidence. *(e.g. train/seismic flags, 1 minute pre-lockloss, "dips" of light stored in the arm cavities)*
Category 4	Advisory flags: no clear evidence of correlation to loud transients, but if we find a detection candidate at these time, we need to exert caution *(e.g. high wind and certain data validation issues)*

In addition: event-by-event veto based on correlated glitching on auxiliary channels

Ref: LIGO-G060628-00

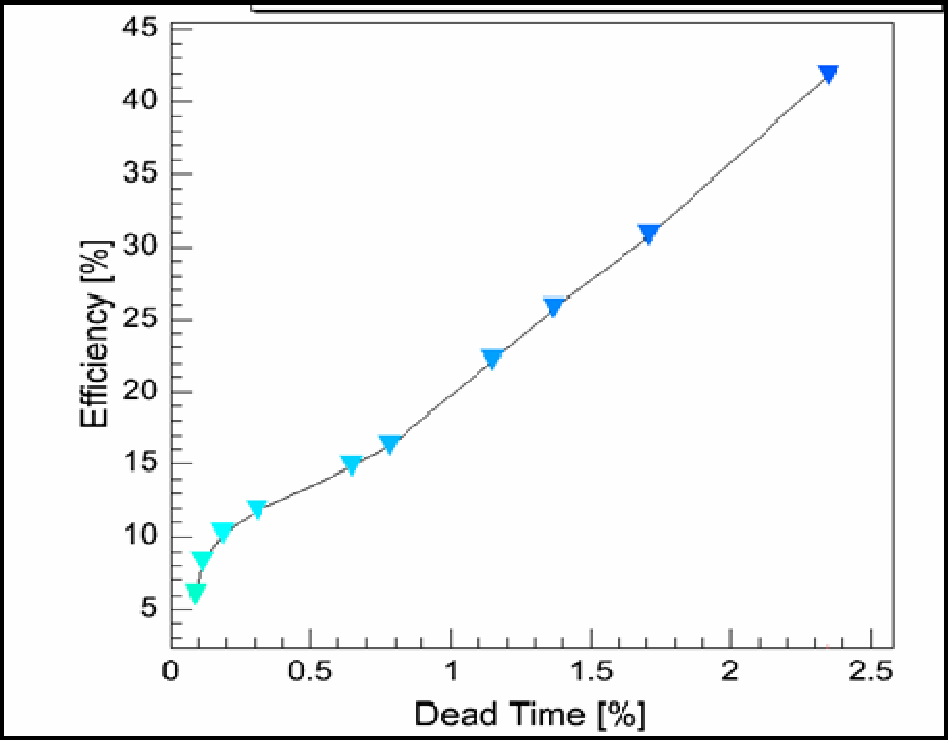
Auxiliary Channel Vetoes

Exploit transients on auxiliary channels

- Found by the KleineWelle algorithm 2004 *Class. Quantum Grav.* **21** S1809
- Establish "safe" veto conditions with hardware injections
- Balance between veto efficiency and livetime loss (false dismissal)

For example, in S4:

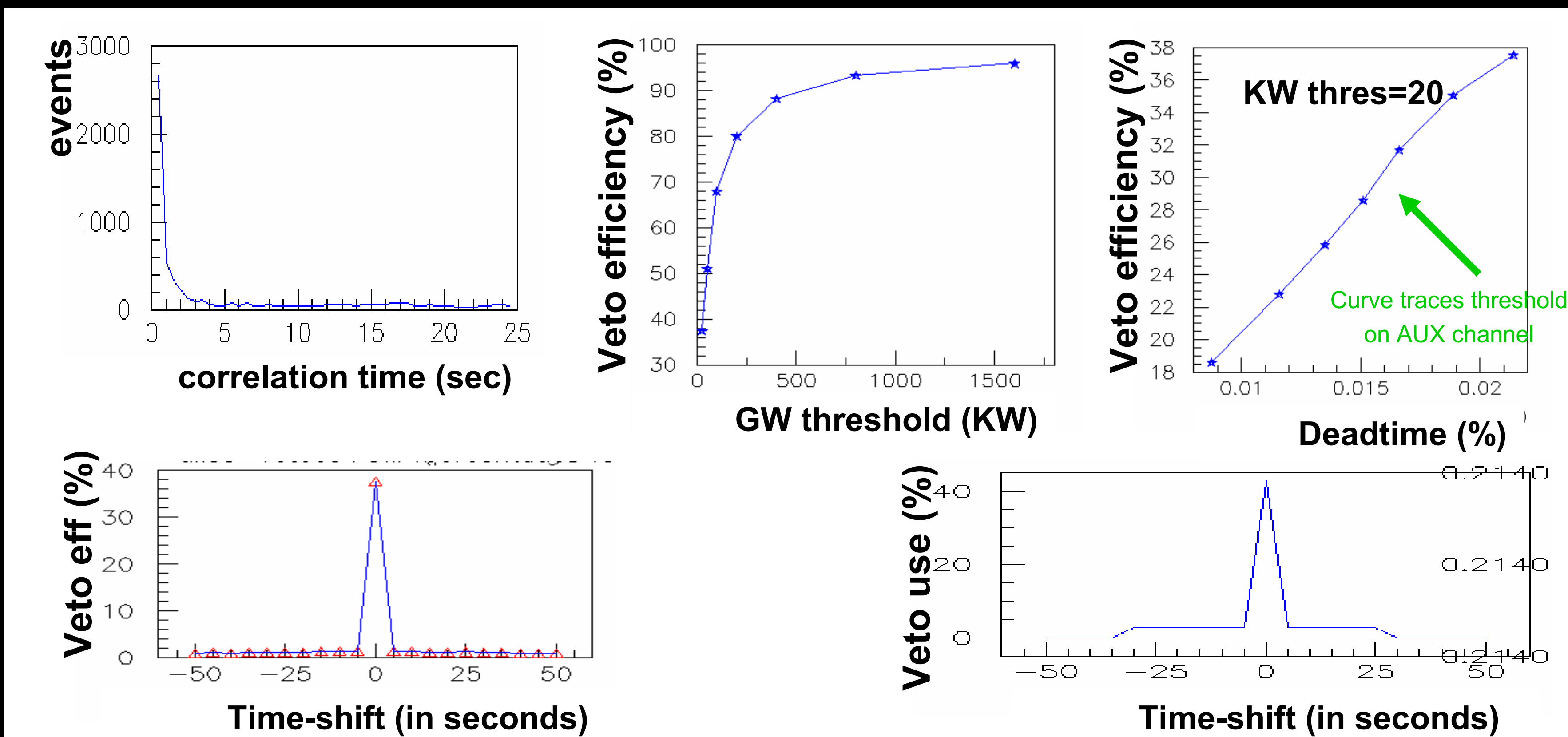
Identified in studies of time-shifted data 7 veto conditions at Hanford from anticoincidence with transients on auxiliary channels
⇒ vetoed 6 out of the 10 loudest events with 1-2% effective deadtime



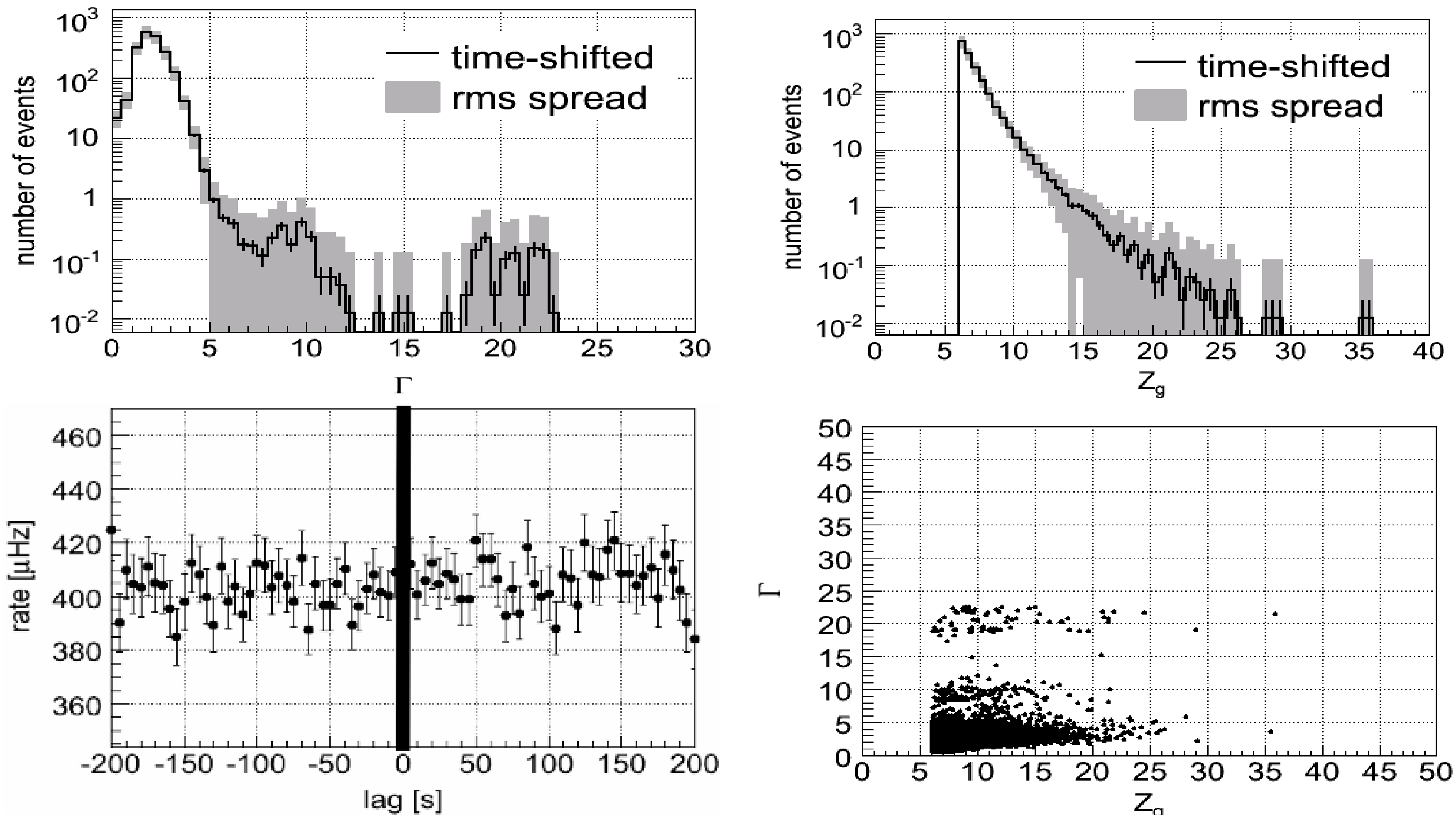
GW-AUX correlations and vetoes

- Features studied in a first pass:
  - Overlap as a function of trigger frequency and trigger amplitude
  - Formal veto analysis, i.e., study of the veto efficiency vs dead time, time-lag analysis, use percentage
  - Cross-correlations
- GW – ASI example in L1 over the first 103 days of S5

Ref: LIGO-G060638-00

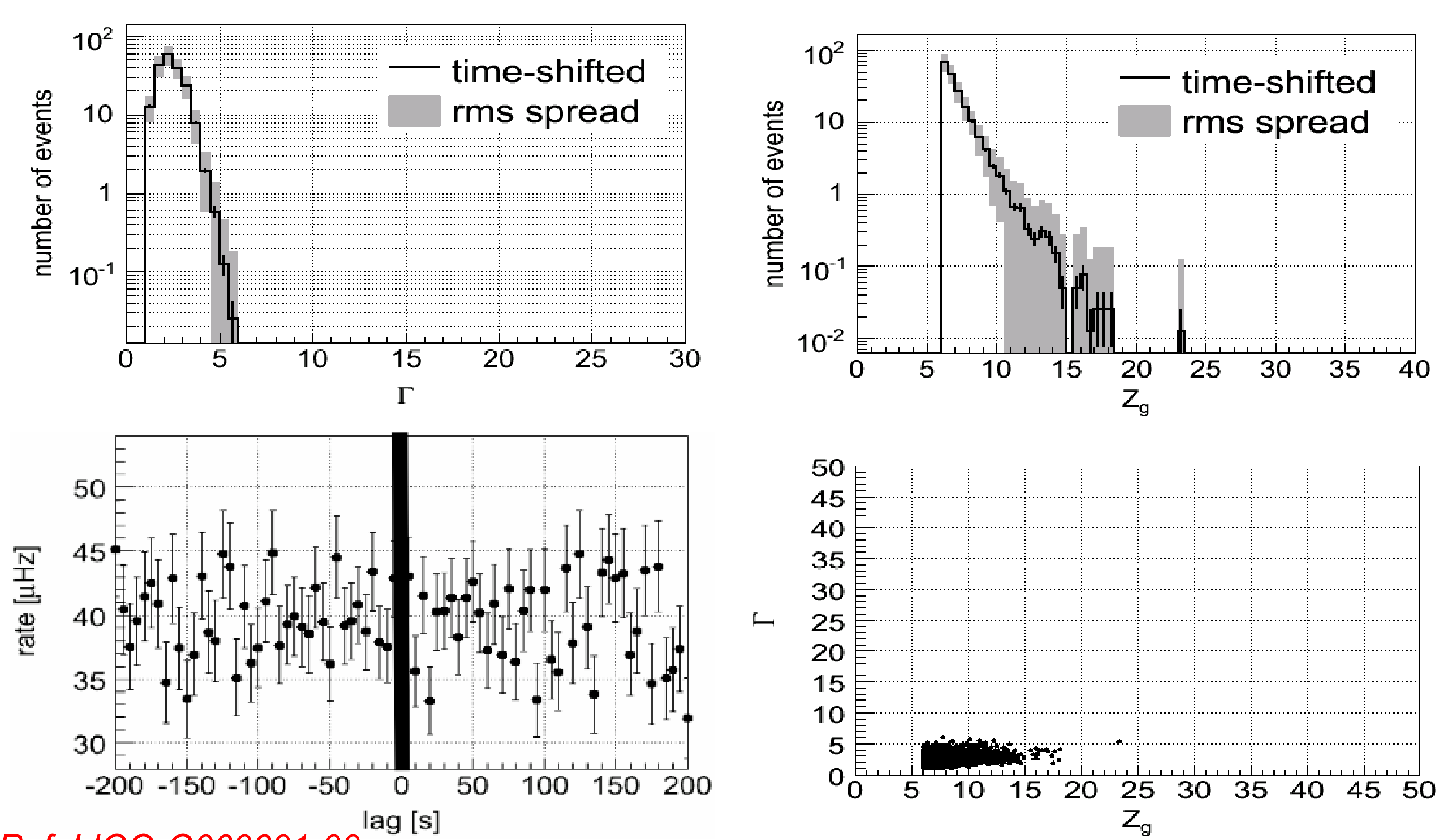


First 5 months of S5: Before Analysis and DQ Cuts



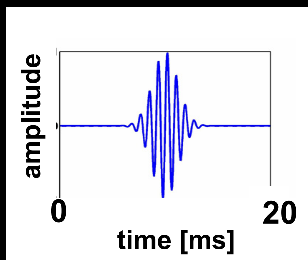
Ref: LIGO-G060601-00

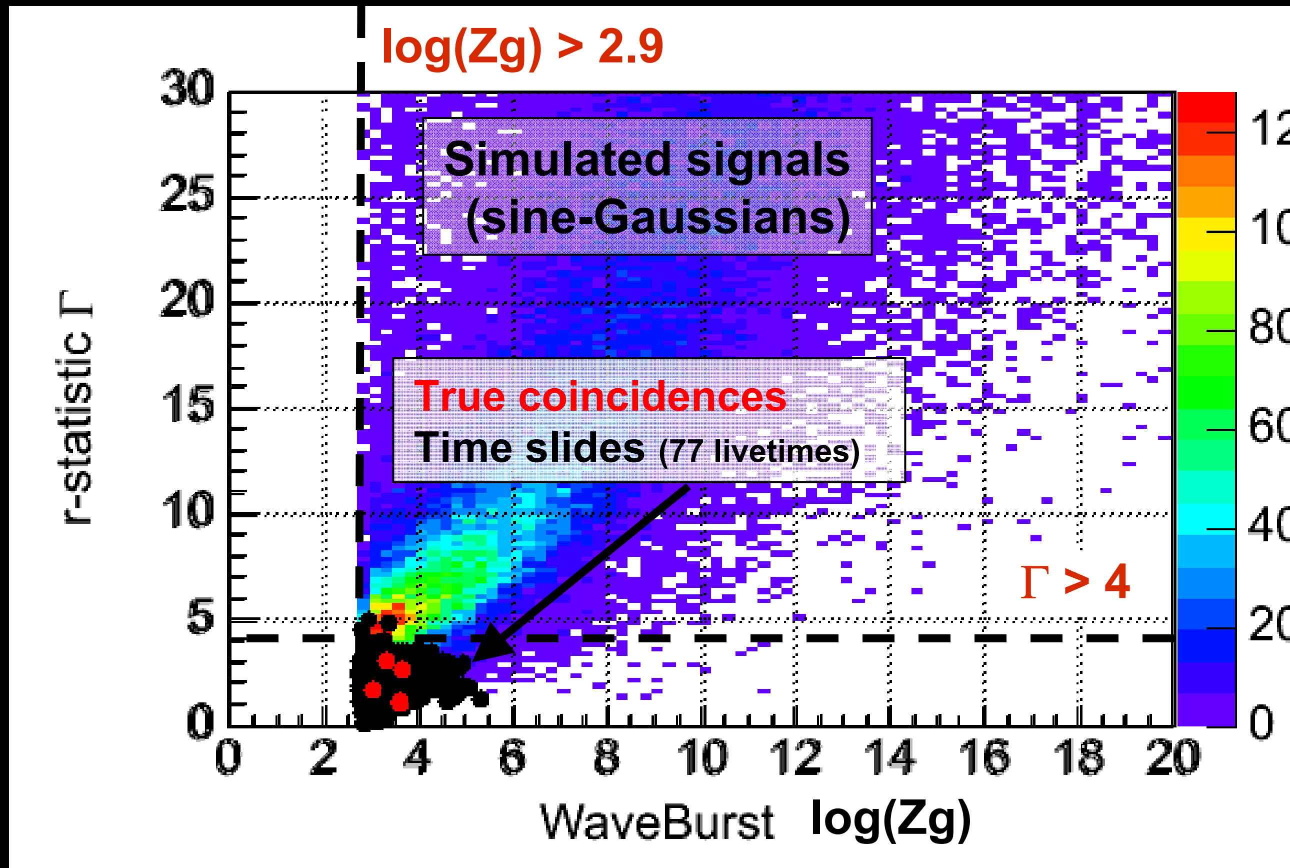
First 5 months of S5: After Analysis and DQ Cuts



Ref: LIGO-G060601-00

Analysis thresholds and coincidence rates - S4 analysis





Blind analysis:

thresholds chosen on a set of 100 time-slides (different from those used for background estimation)

Expected 0.04 events

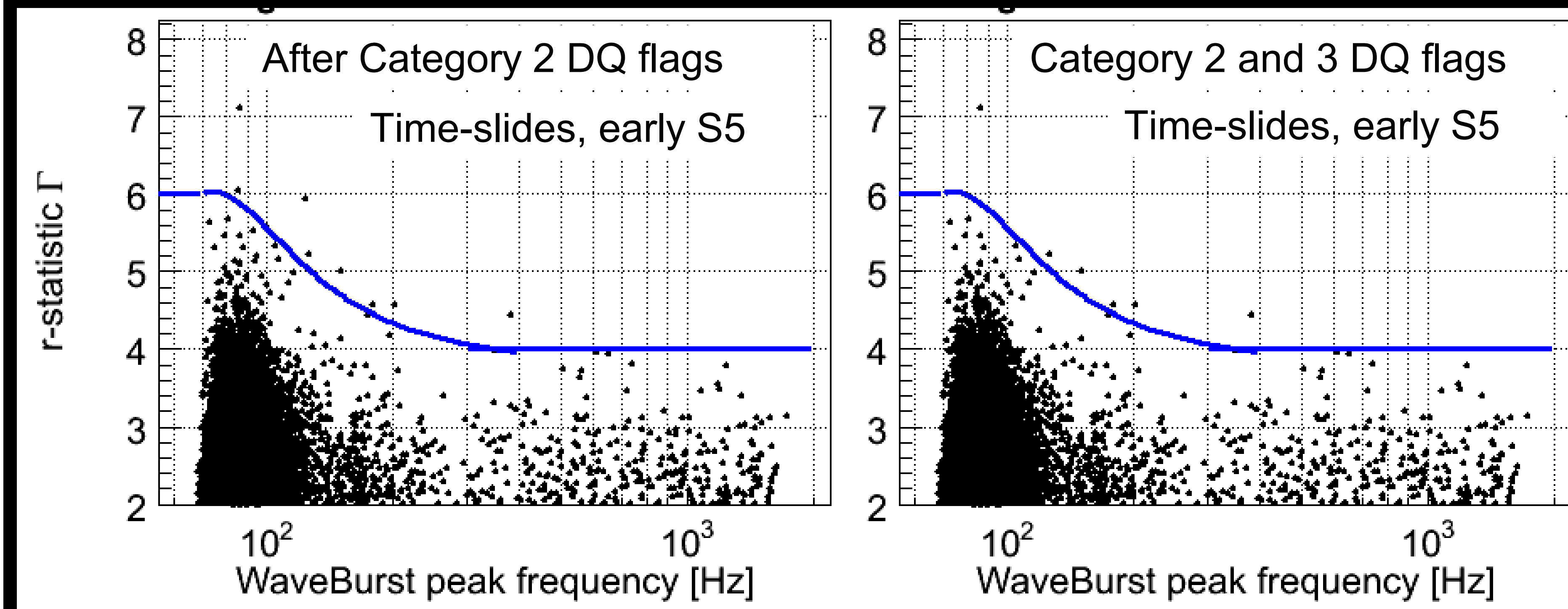
Frequentist one-sided upper limit (90% C.L.) based on zero events passing all cuts in S5: $R_{90\%}$ = 2.303 / 15.53 days = 0.15 /day

LIGO-G070050-00

PRELIMINARY

In S5: frequency-dependent cut

Empirically chosen, frequency-dependent threshold
~1/(f-64Hz) in 100-300Hz, 4 at high frequency, 6 at low frequency
Target rate of accidental coincidences: << 1 per analysis period
Expected: 0.06 in early S5, 0.4/year



Ref: LIGO-G060601-00

How do we interpret a burst result?

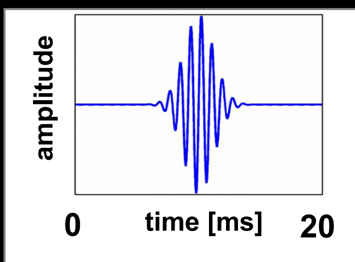
This is where we break our "no assumption" rule: to measure our efficiency, we MUST pick a waveform! So we keep it as general as possible…

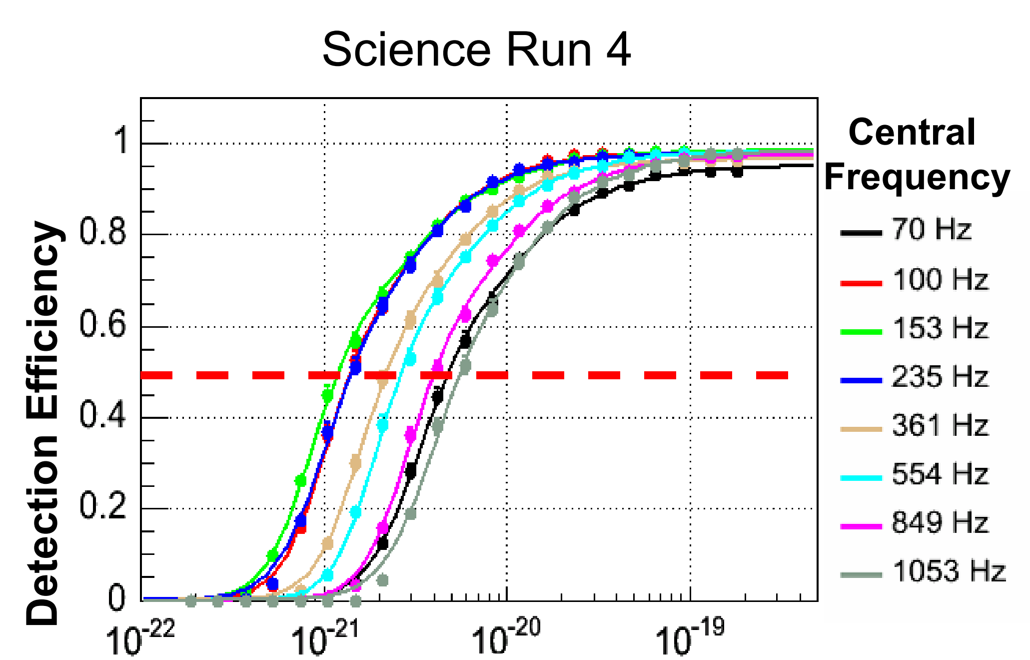
Detection Efficiency

Test sensitivity by adding simulated GWBs to the data.

– Eg: Gaussian-modulated sinusoid.

Linearly polarized; random sky position & polarization angle

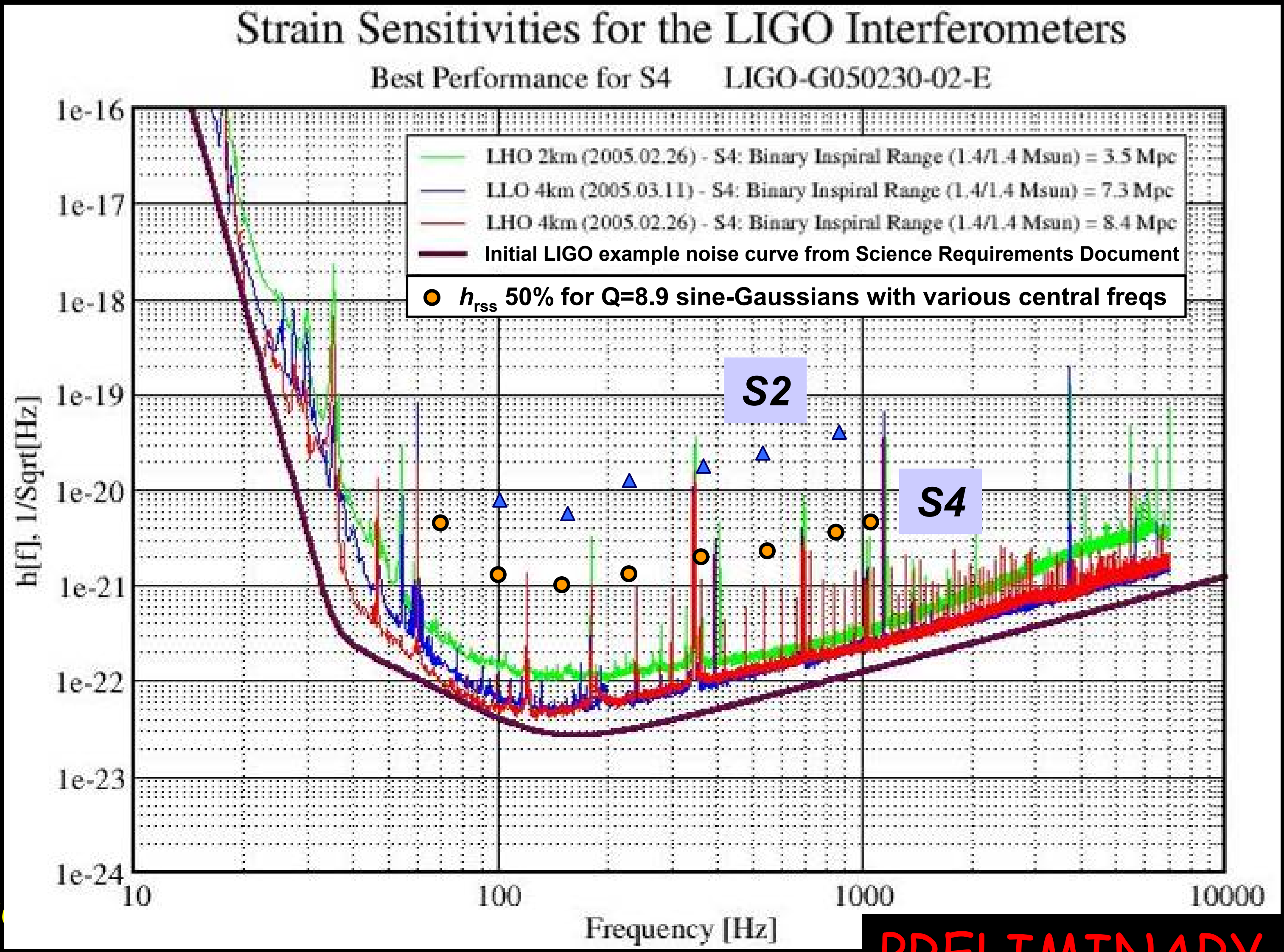




$$h_{\rm rss} \equiv \sqrt{\int (|h_+(t)|^2 + |h_\times(t)|^2)\, dt}$$

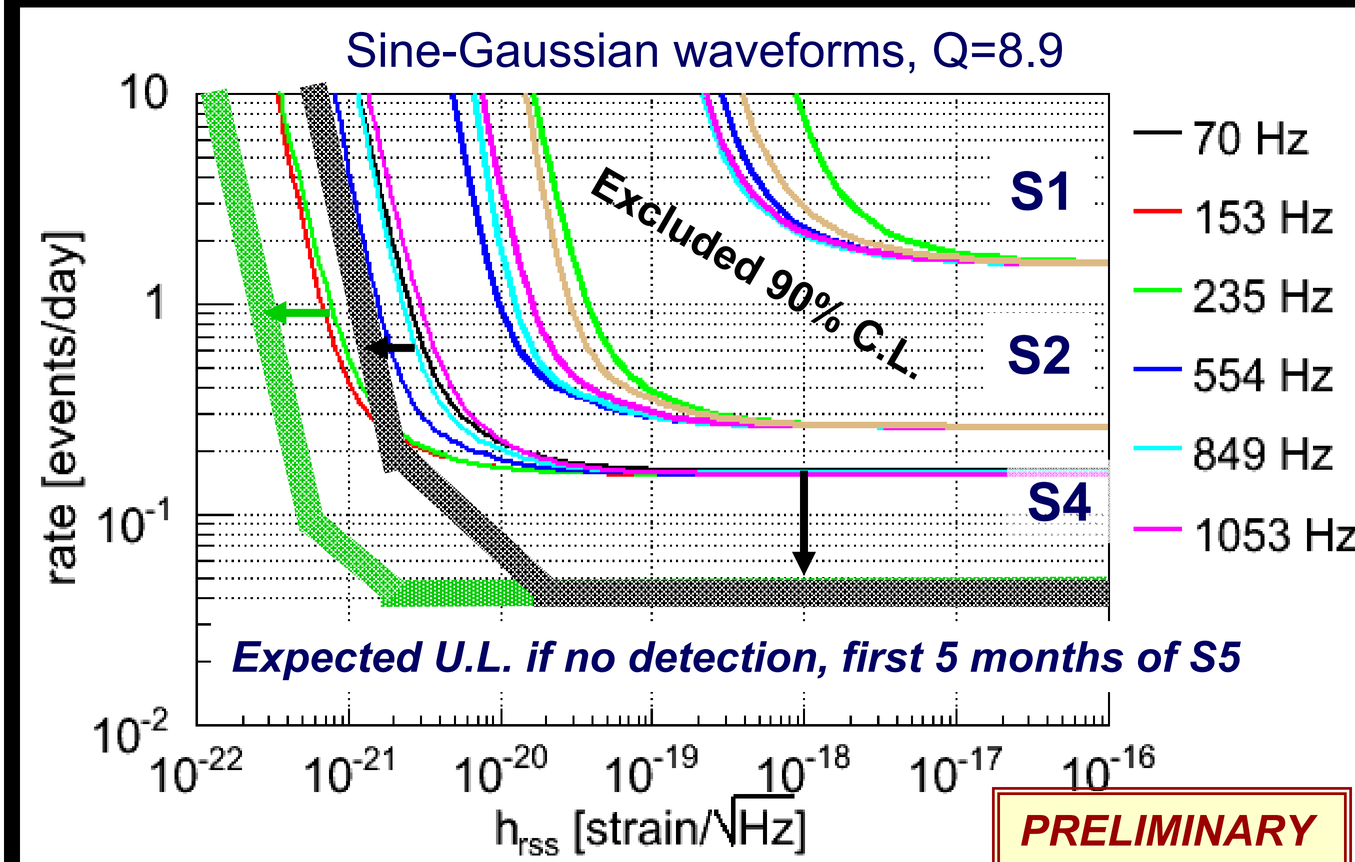
PRELIMINARY

S4 Sensitivity



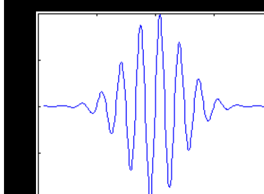
PRELIMINARY

"Interpreted" Upper Limit



Lower rate limits from longer observation times

Lower amplitude limits from lower detector noise



$$R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$$

η = upper limit on event number

T= live time

$\varepsilon(h_{rss})$ = detection efficiency

A similar upper limit curve for each simulated template (Gaussian, black-hole mergers, supernovae…)

Ref: LIGO-G060601-00

Astrophysical interpretation

- start from instantaneous energy flux emitted by a gravitational wave source in the two independent polarizations $h_+(t)$ and $h_\times(t)$

$$\frac{\mathrm{d}^2 E_{\mathrm{GW}}}{\mathrm{d}A\,\mathrm{d}t} = \frac{1}{16\pi}\frac{c^3}{G} < (\dot{h}_+)^2 + (\dot{h}_\times)^2 >$$

Shapiro S L and Teukolsky S A 1983 *Black Holes, White Dwarfs, and Neutron Stars* (New York John Wiley & Sons)

- Following derivation in LIGO-T040055-00, we get an order-of-magnitude estimation of the detectable energy for isotropic GW emission of sine-gaussian pulses with Q>>1

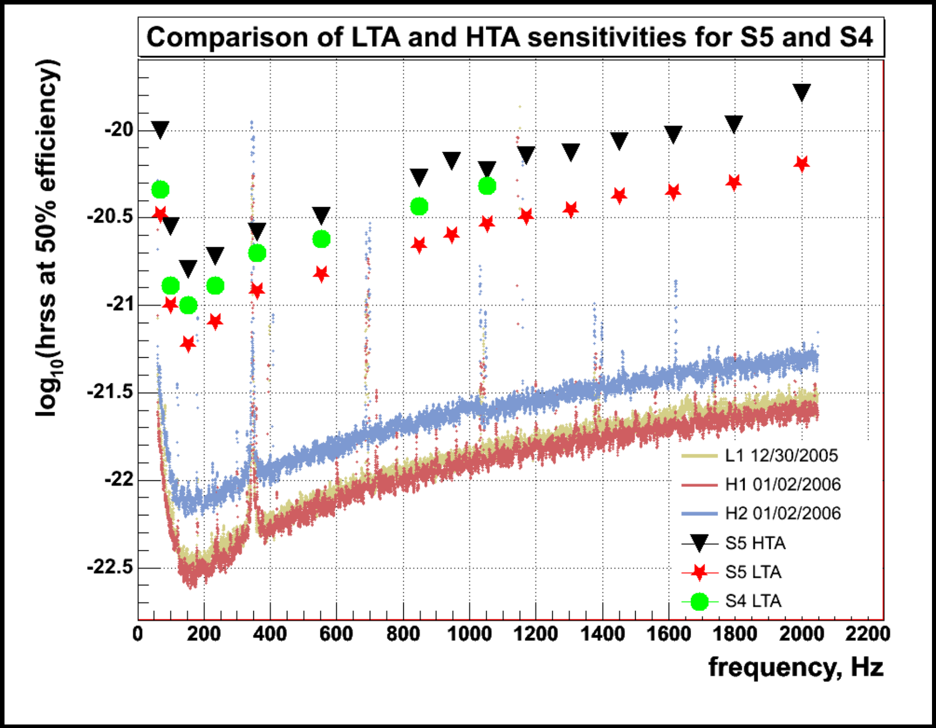
$$E_{\mathrm{GW}} = \frac{r^2 c^3}{4G}(2\pi f_0)^2 h_{\mathrm{rss}}^2$$

In S5: $E_{GW} \sim 10^{-1}\ M_\odot$ at 20 Mpc (153 Hz case)

PRELIMINARY

Online High Threshold Analysis

PRELIMINARY



Ref: LIGO-G060601-00

- Aimed at detection: finding loud events right away
- High Z_g threshold ~21
- No Γ cut
- No data quality or veto cuts.
- About 2.5 times less sensitive than what is expected from low threshold analysis.
- 162 (100 time slides) +1 (zero lag) triggers found as of Oct-24-2006.
- Single zero-lag event fails H1-H2 Amplitude cut.

Triggered Searches

- search LIGO data at time of GRB triggers from Swift, HETE-2, etc…
- Cross correlate data
- Target search to sky position when known
- Place limit on GW emission from individual GRBs and from the population
- No GW signal found associated with 39 GRBs in S2, S3, S4 runs
- set limits on GW signal amplitude
- ~ 10 GRB triggers per month during S5

PRELIMINARY