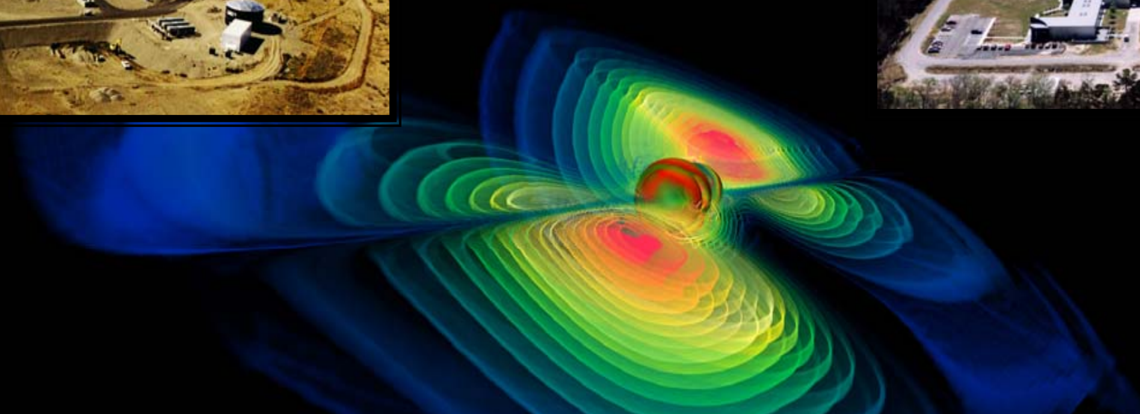


LIGO's Eyes-Wide-Open Search for Gravitational Wave Bursts

Laura Cadonati
Massachusetts Institute of Technology

Caltech – March 23, 2006

"Colliding Black Holes" Credit: National Center for Supercomputing Applications (NCSA)

LIGO-G060174-00-Z

Outline

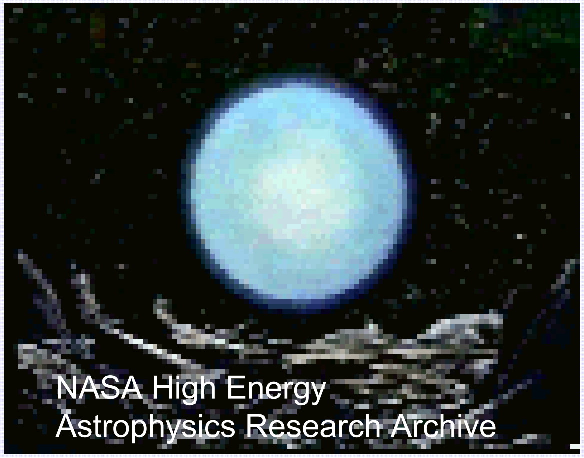
1. Bursts of Gravitational Waves
   - » Goal of the “eyes-wide-open” search
2. The analysis pipeline: from data selection to candidate events
   - » Coincidence and vetoes and how they perform on S4 data
3. How to interpret a burst result
   - » From S1 to S4
4. Outlook for S5
5. Collaborative analysis
   1. Done or in progress (TAMA, AURIGA, GEO)
   2. Future (VIRGO, IGEC2)

Gravitational Wave Bursts

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

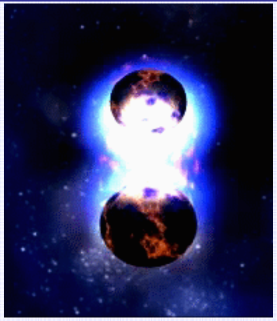
Examples:

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



Supernovae:

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

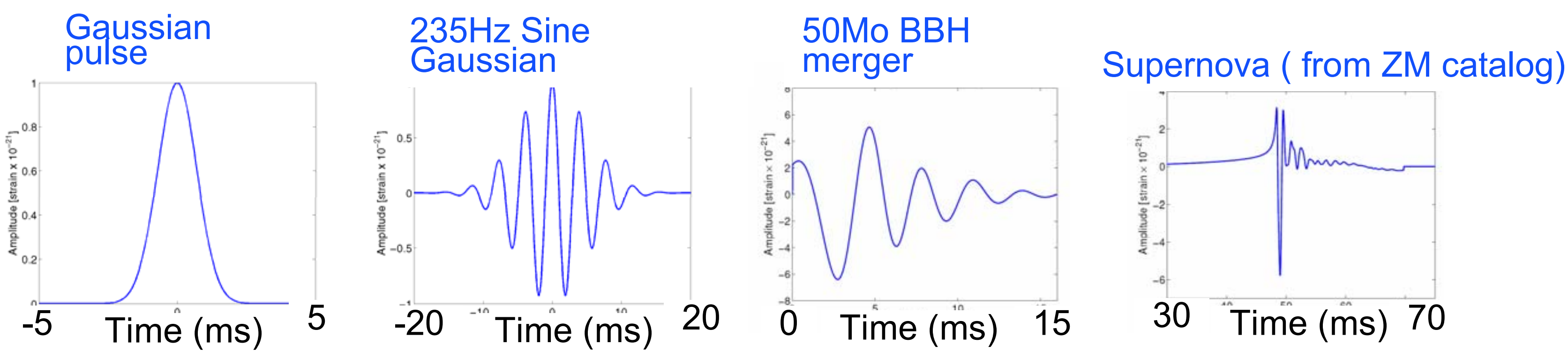


Black Hole / Black Hole binaries:

❑ 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

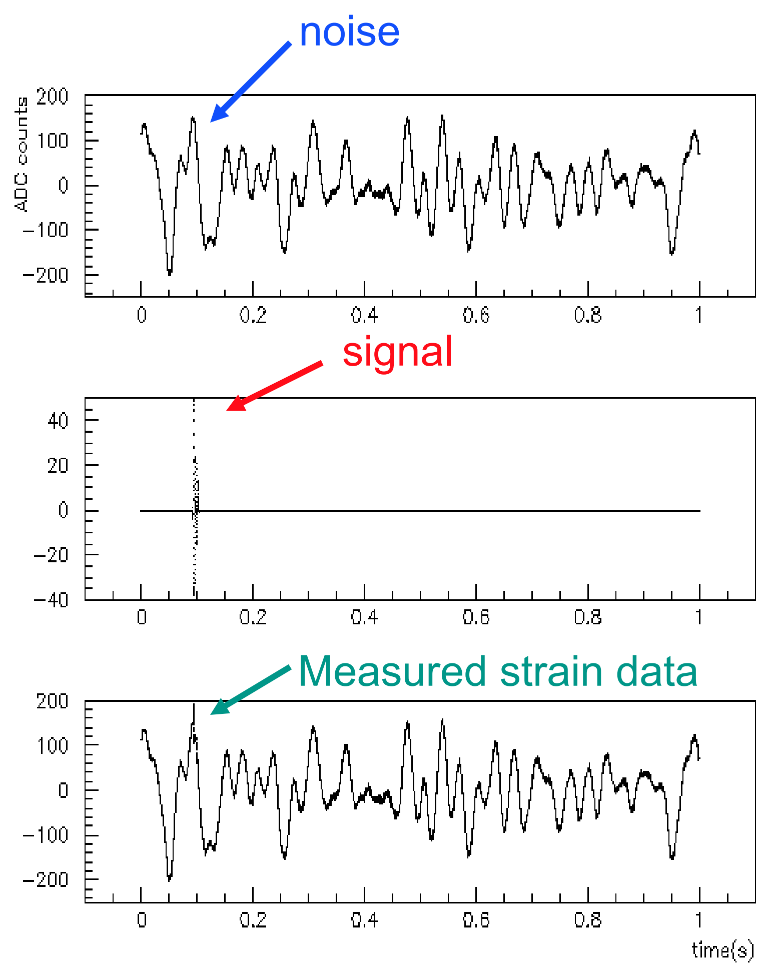
A classical problem: extracting a weak signal from noise.
With an additional complication:
unknown signal morphology

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

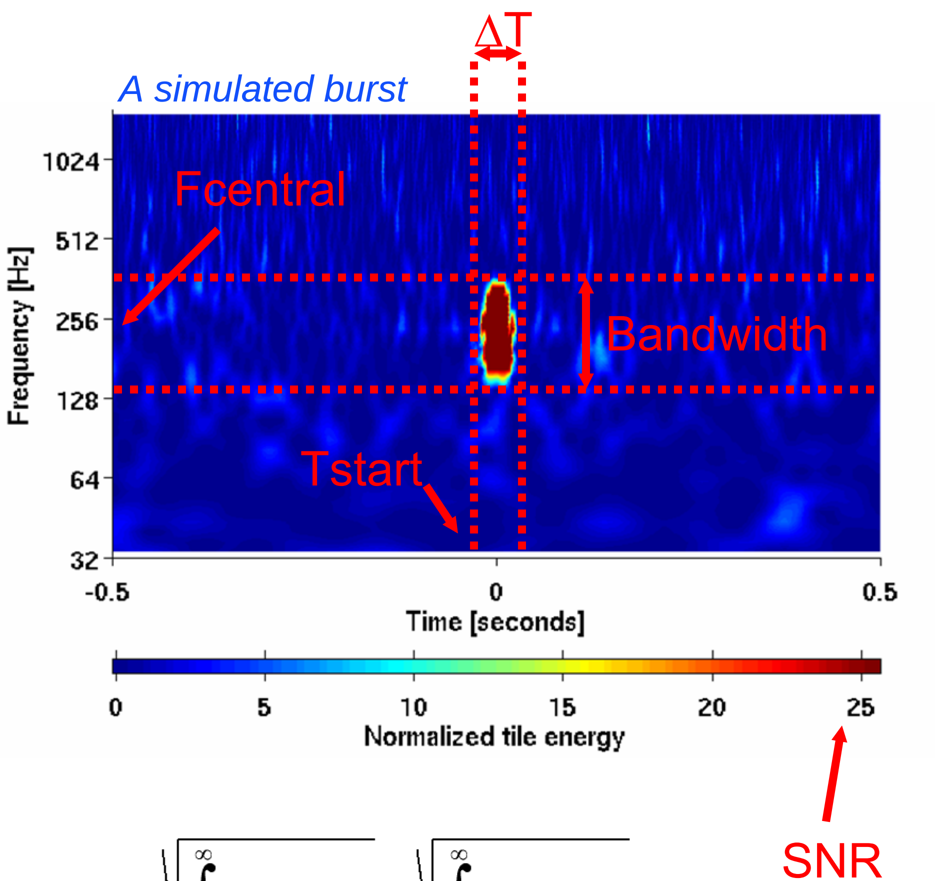
Our solution:

analysis of candidate event triggers

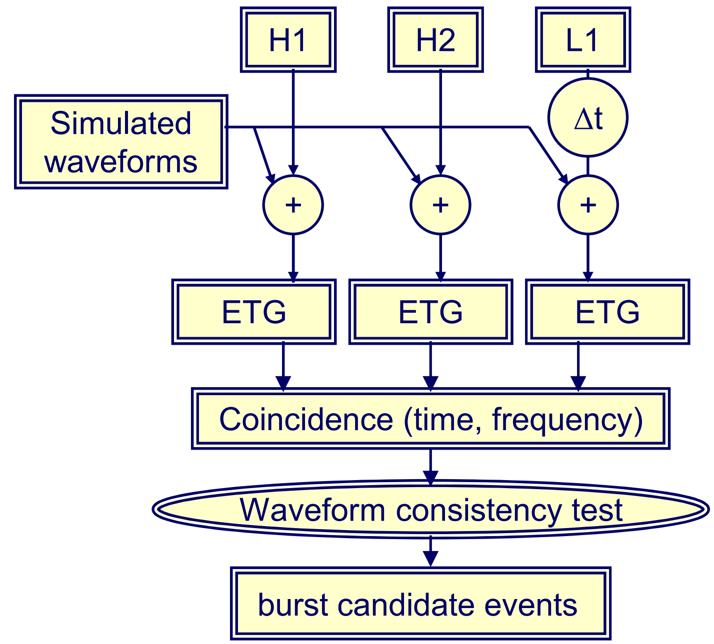
indicators for gravitational wave events, when a transient "anomaly" (excess power or amplitude) appears in the detector's time series.



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 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

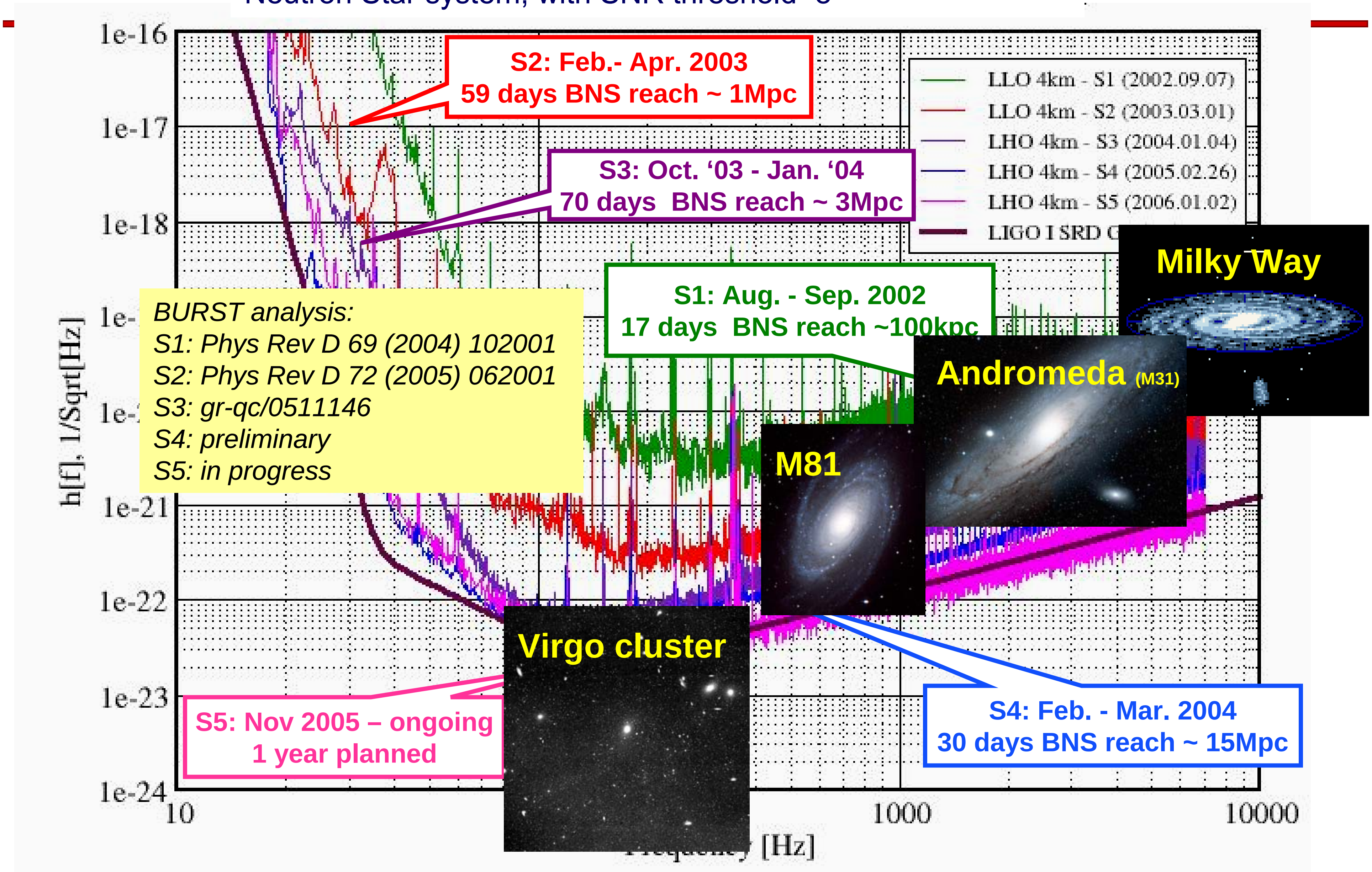
This sounds obvious, but…
while some criteria are undisputable
(e.g. interferometers are locked, no ADC overflows, calibration is available)
others we are need to be more cautious about, not to waste data or miss GWs
(e.g. seismic disturbances, dust, instrumental transients)

2. Exploit the availability of multiple detectors

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

A measure of sensitivity: BNS reach

how far we can see a 1.4-1.4 $M_\odot$ optimally oriented Binary Neutron Star system, with SNR threshold=8



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

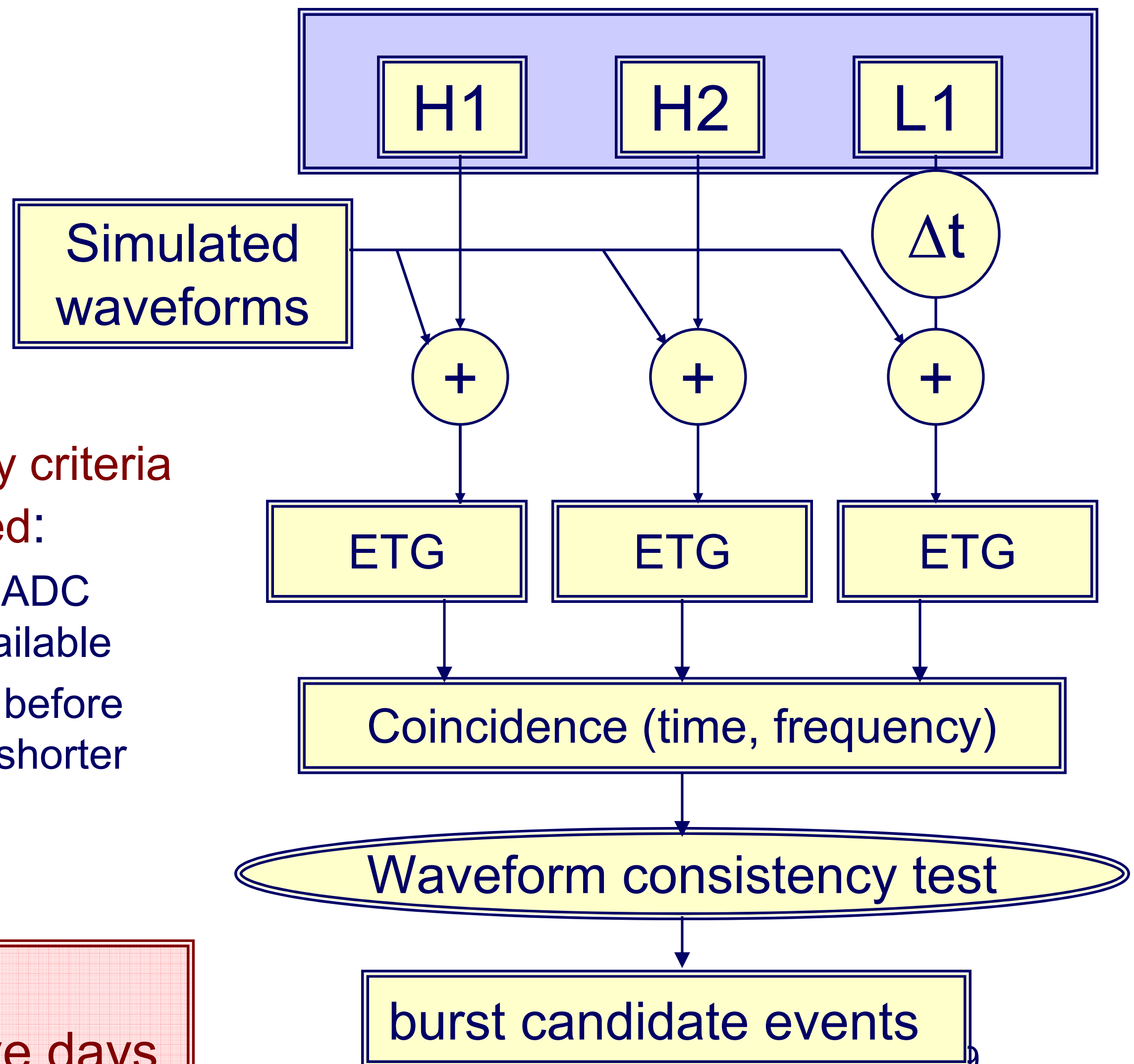
Use a minimal set of data quality criteria for data segments to be analyzed:

– no hardware injections, no ADC overflows, calibration is available

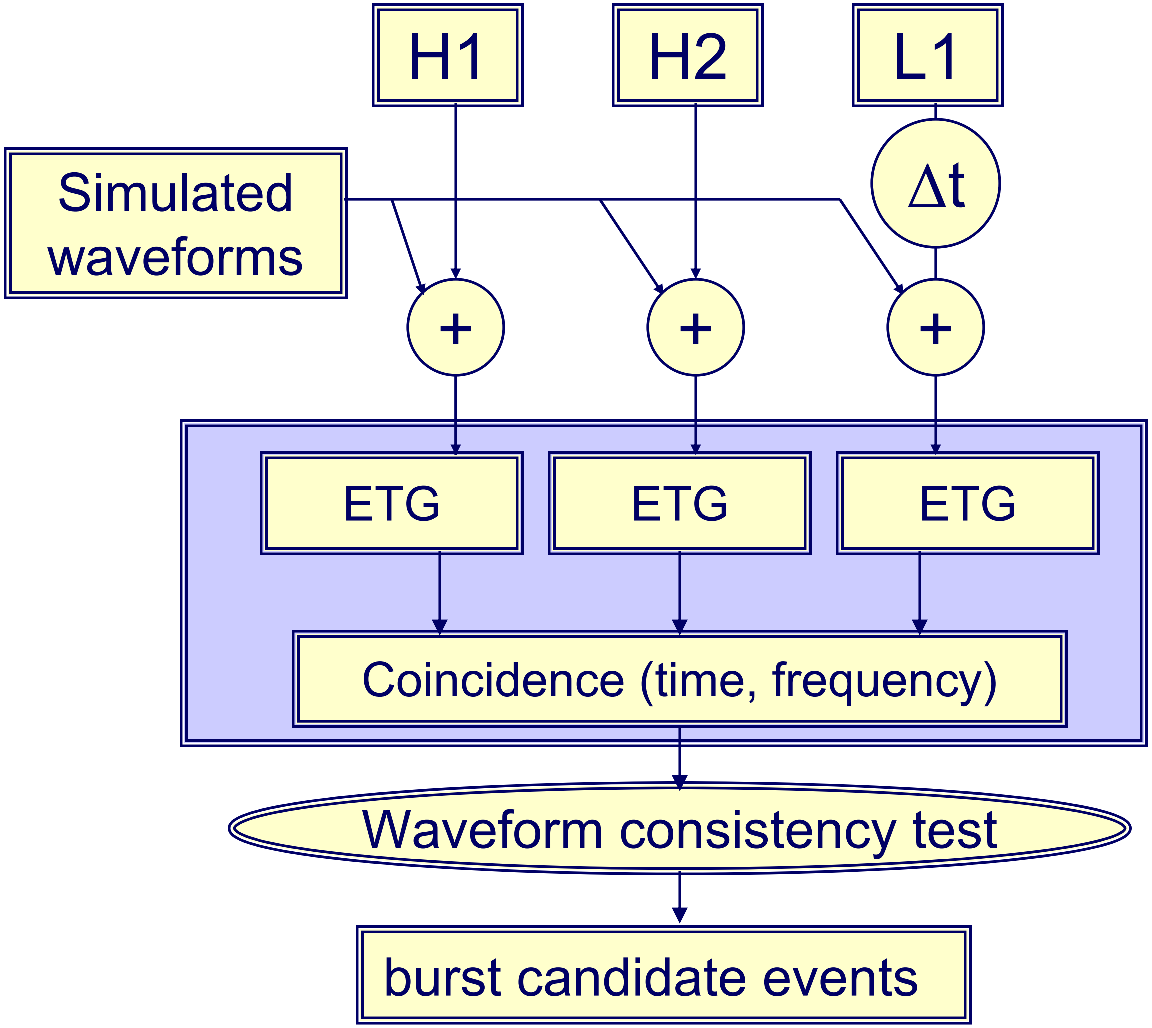
– Discarded last 30 seconds before loss of lock and segments shorter than 300 sec

S4:

30 calendar days ⇒ 16.4 live days



Coincident Event Trigger Generation



ETG= Event Trigger Generator

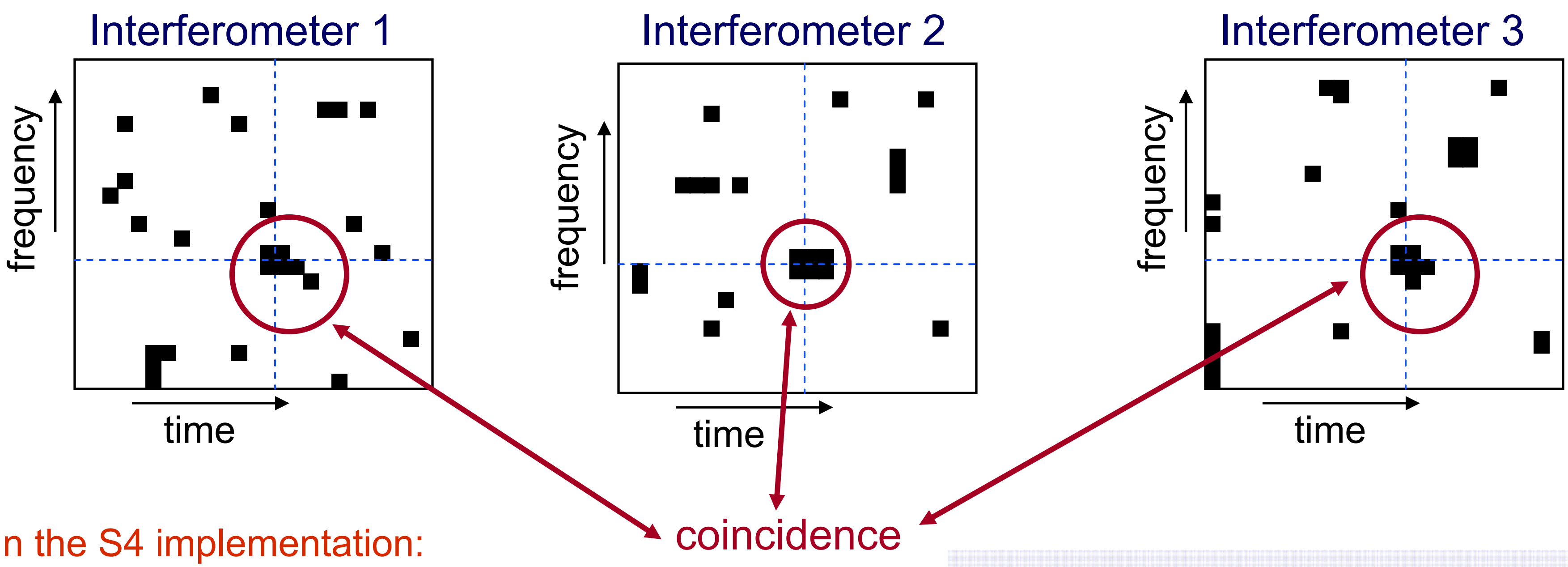
GC threshold

WaveBurst

Excess power in wavelet time-frequency plane.

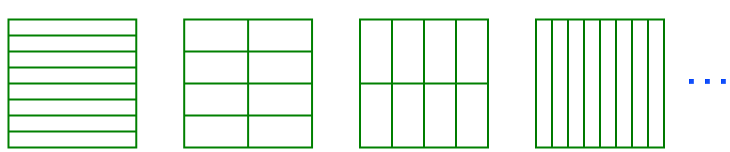
Ref: Class. Quantum Grav. 21 (2004) S1819

10% black pixel probability



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

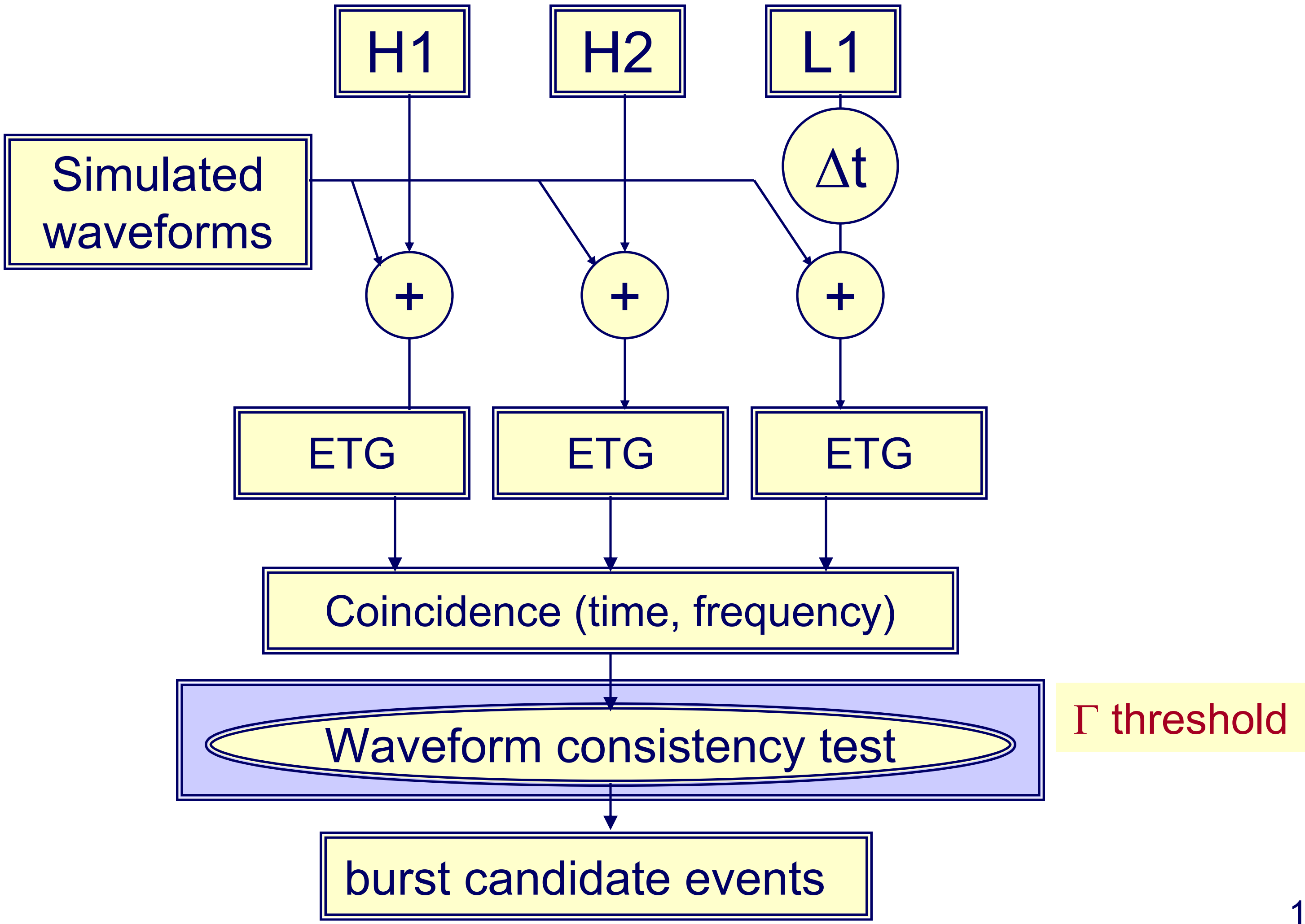


Frequency content cut: required to overlap 64–1600 Hz band

WaveBurst outputs coincident events with their significance in each of the three interferometers.
Parameter estimation: time, duration, frequency, signal amplitude at Earth

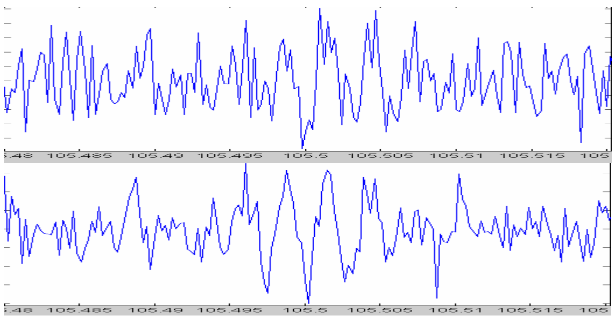
Threshold on combined significance of the triple coincident event (GC)

The *r*-statistic
Waveform Consistency Test



The *r*-statistic Waveform Consistency Test

simulated signal+noise in 2 Iinterferometers



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

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

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

< > = 0

The *r*-statistic Waveform Consistency Test

Ref: L.C. *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:

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

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

The incident GW direction is unknown

→ allow time delay (Δt) between the two data series 11ms H1-L1 and H2-L1 ; 1ms H1-H2

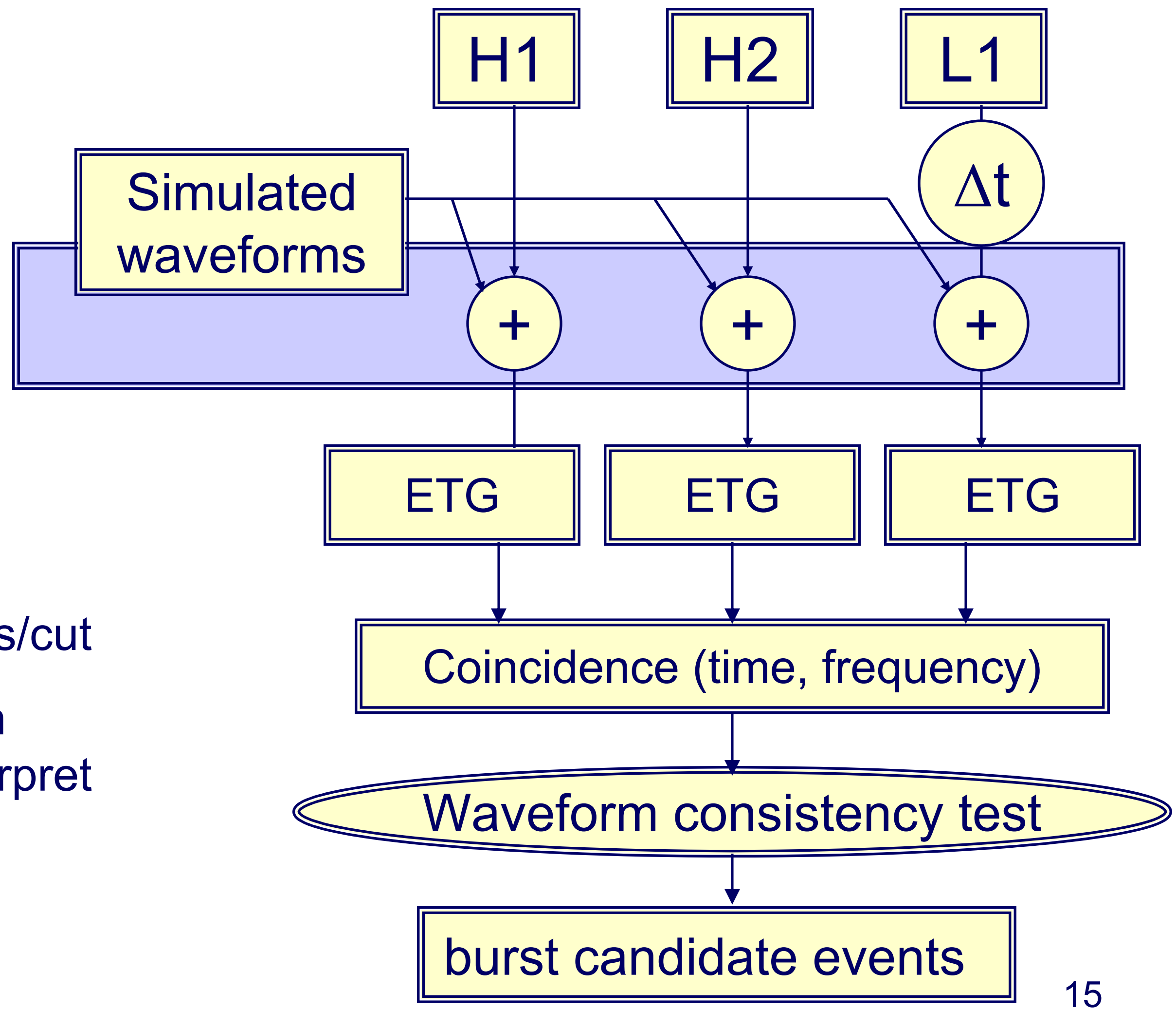
Combine interferometer pairs and search possible signal duration (20, 50, 100 ms) to maximize the final statistic Γ

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

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

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

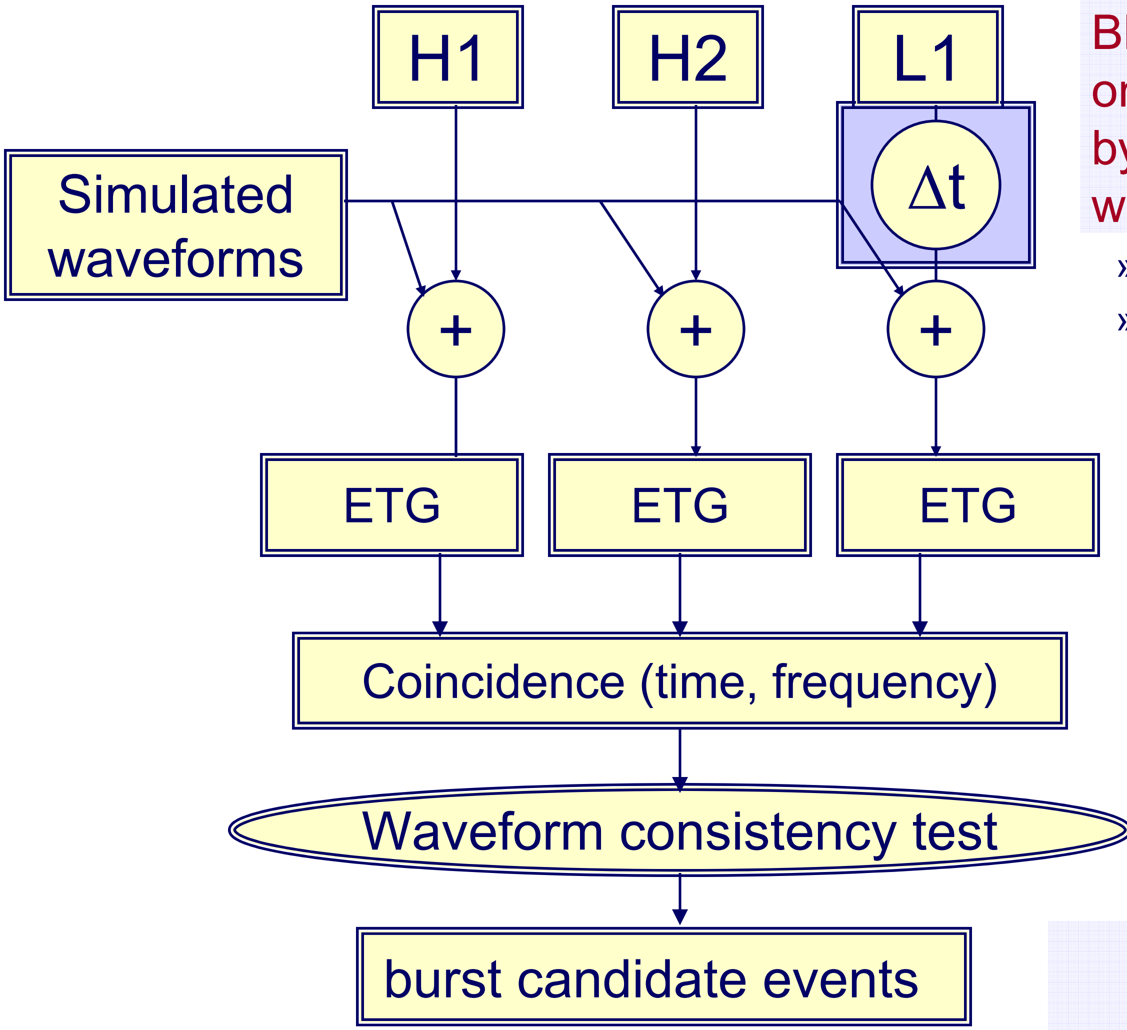
Simulated Waveforms



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.

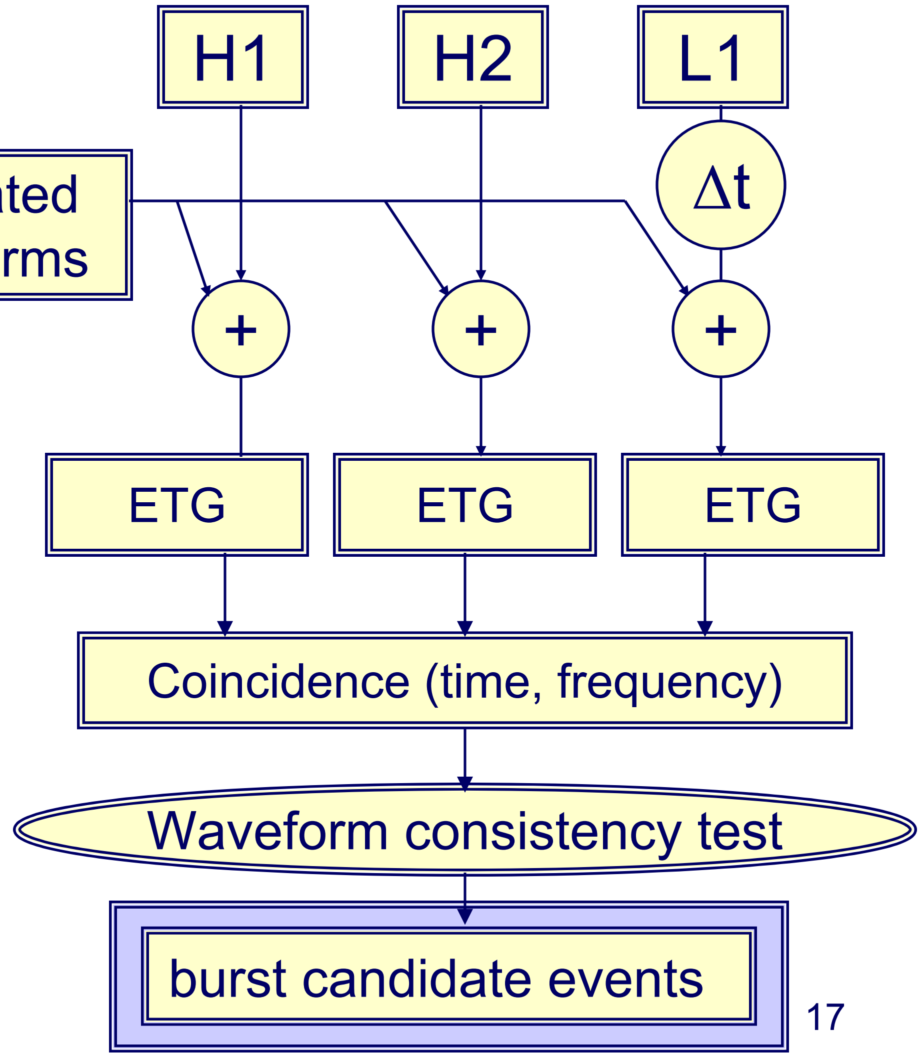
Burst Candidate Events

More cuts:

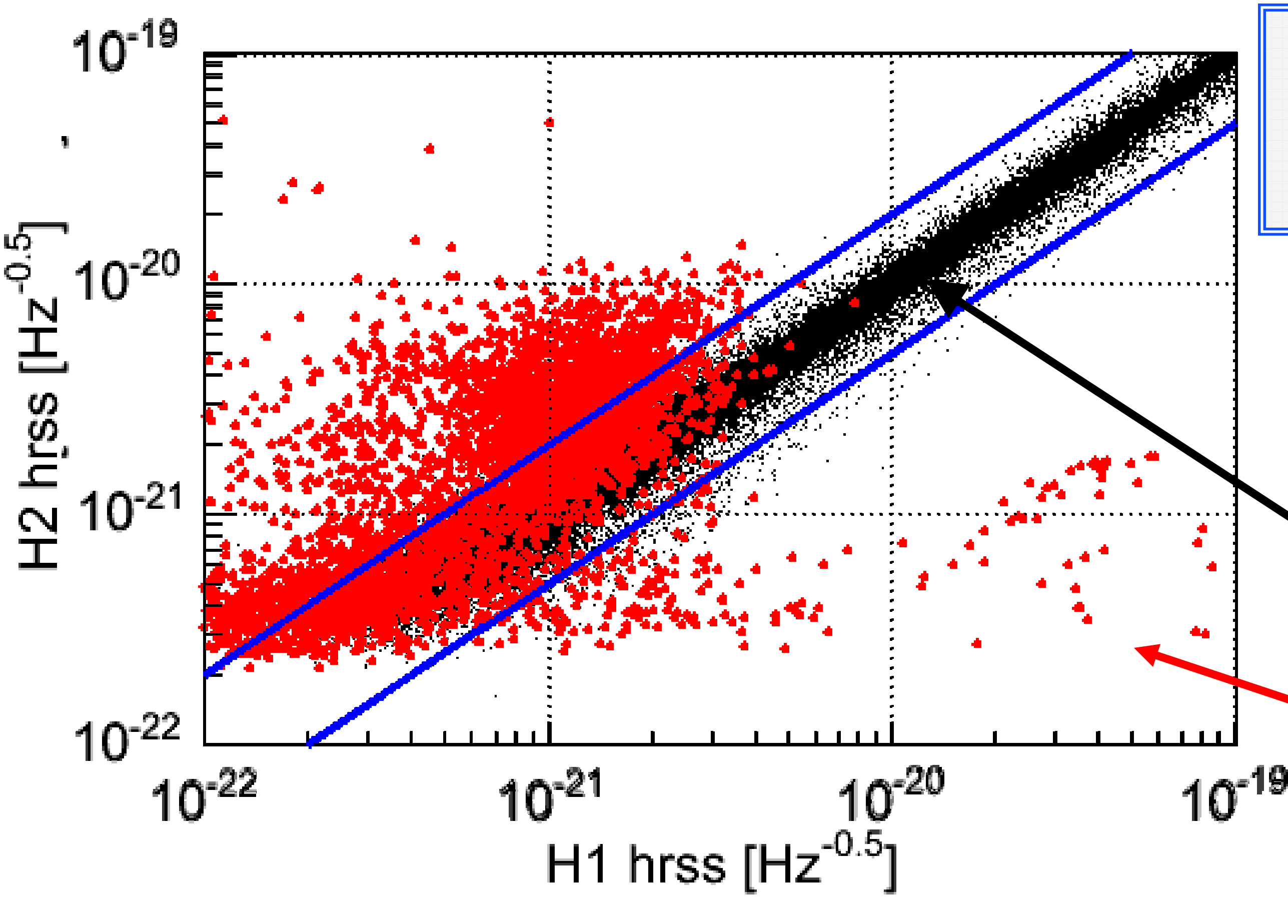
- H1/H2 amplitude cut
- Additional data quality criteria
- Auxiliary channel vetoes

Set analysis thresholds

Detection or Upper limit?

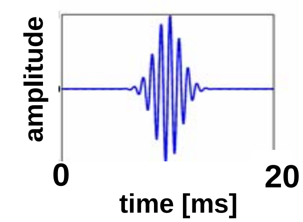


H1/H2 Amplitude Cut



$0.5 < (H1/H2) < 2$

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)

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

h_{rss}^2 is the total energy in the burst

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:

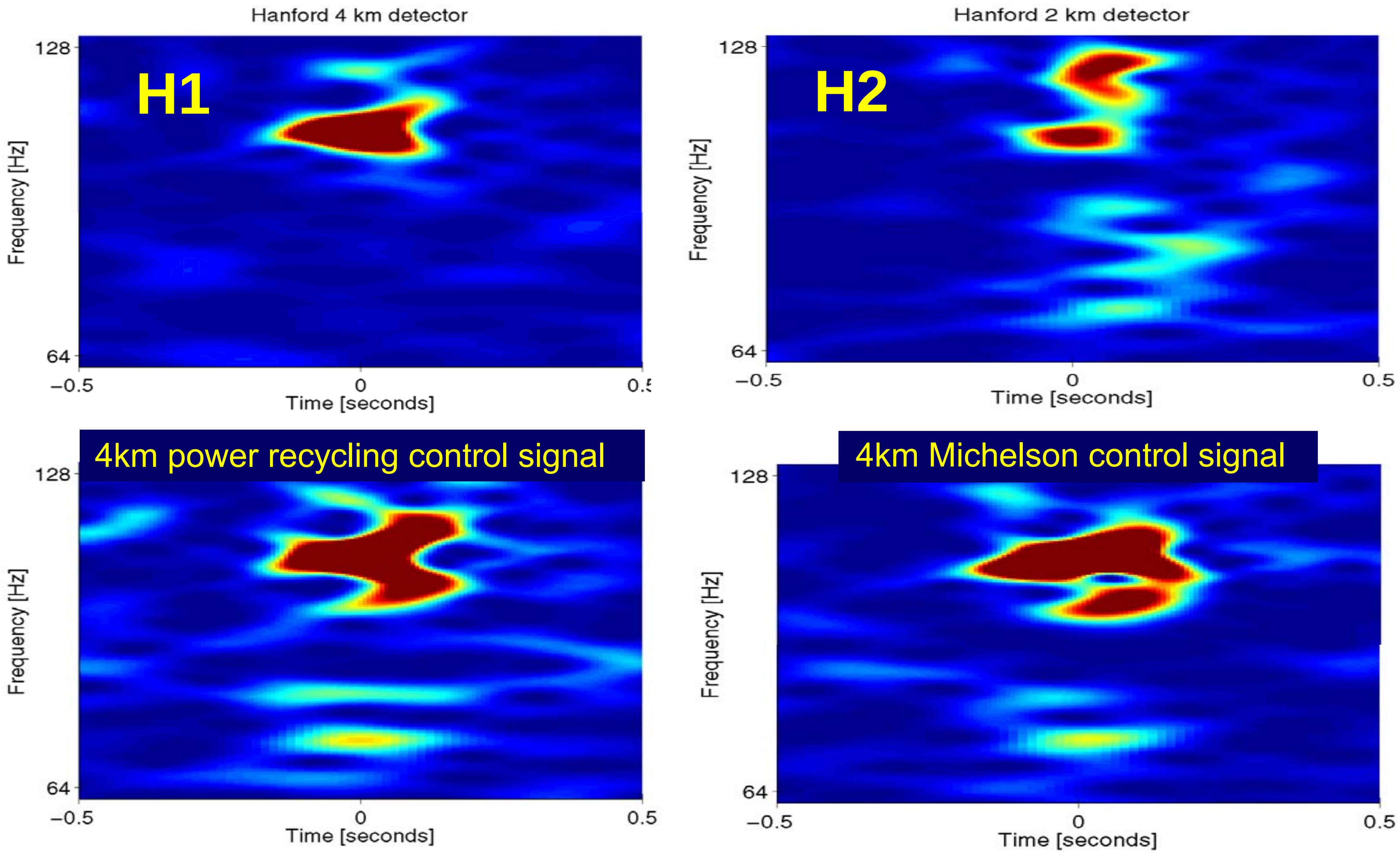
- Calibration line dropouts
- Dips in arm cavity stored light
- Elevated DC light level (H1 and L1)
- Elevated seismic noise in 0.9–1.1 Hz band at Hanford
- Jet plane fly-over at Hanford
- Wind over 35 mph [62 km/h] at Hanford

Net loss of observation time: 5.6%

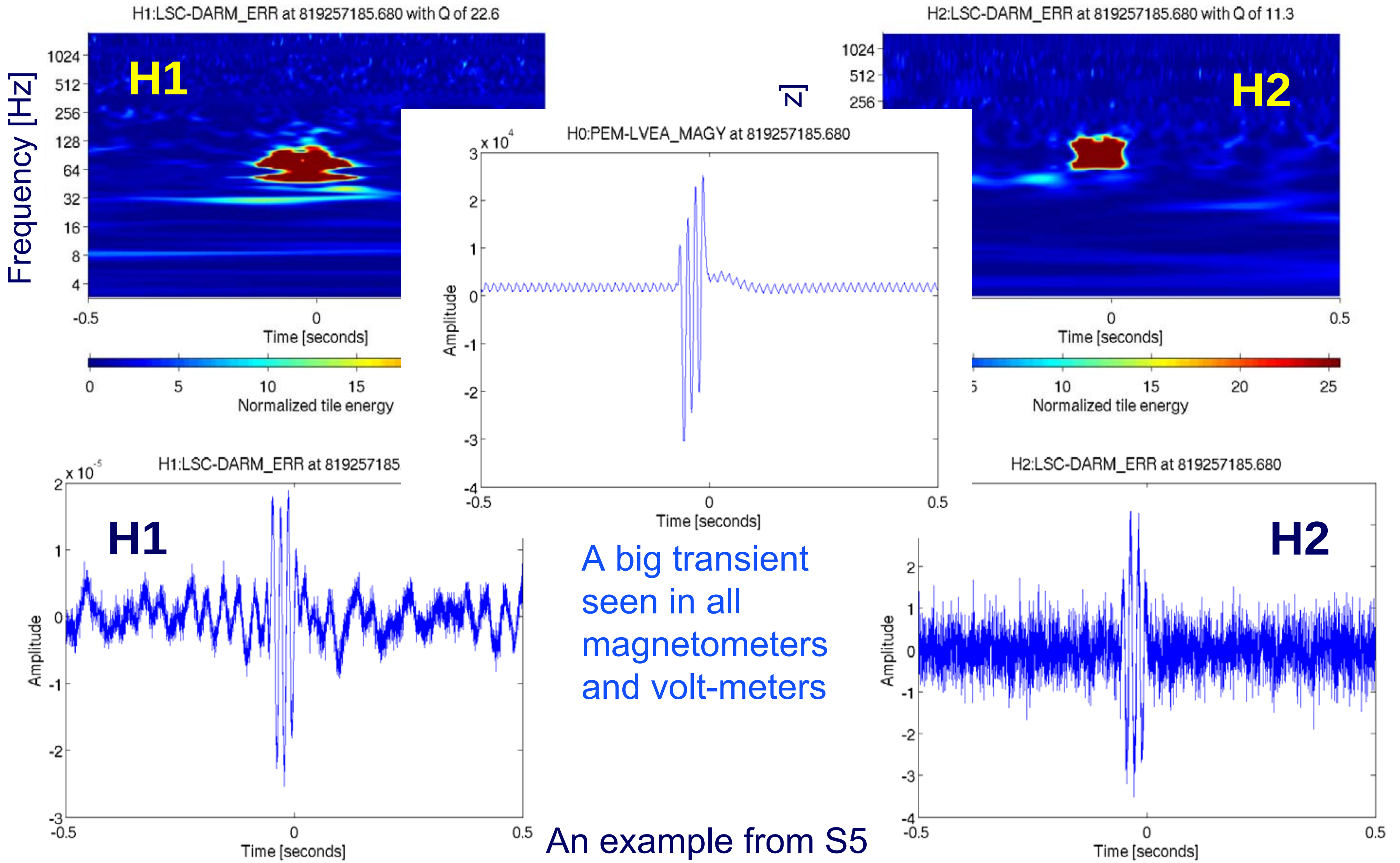
Then there are auxiliary-channel vetos…

Detector Transients

An example from S2



H1-H2 coincidence excess

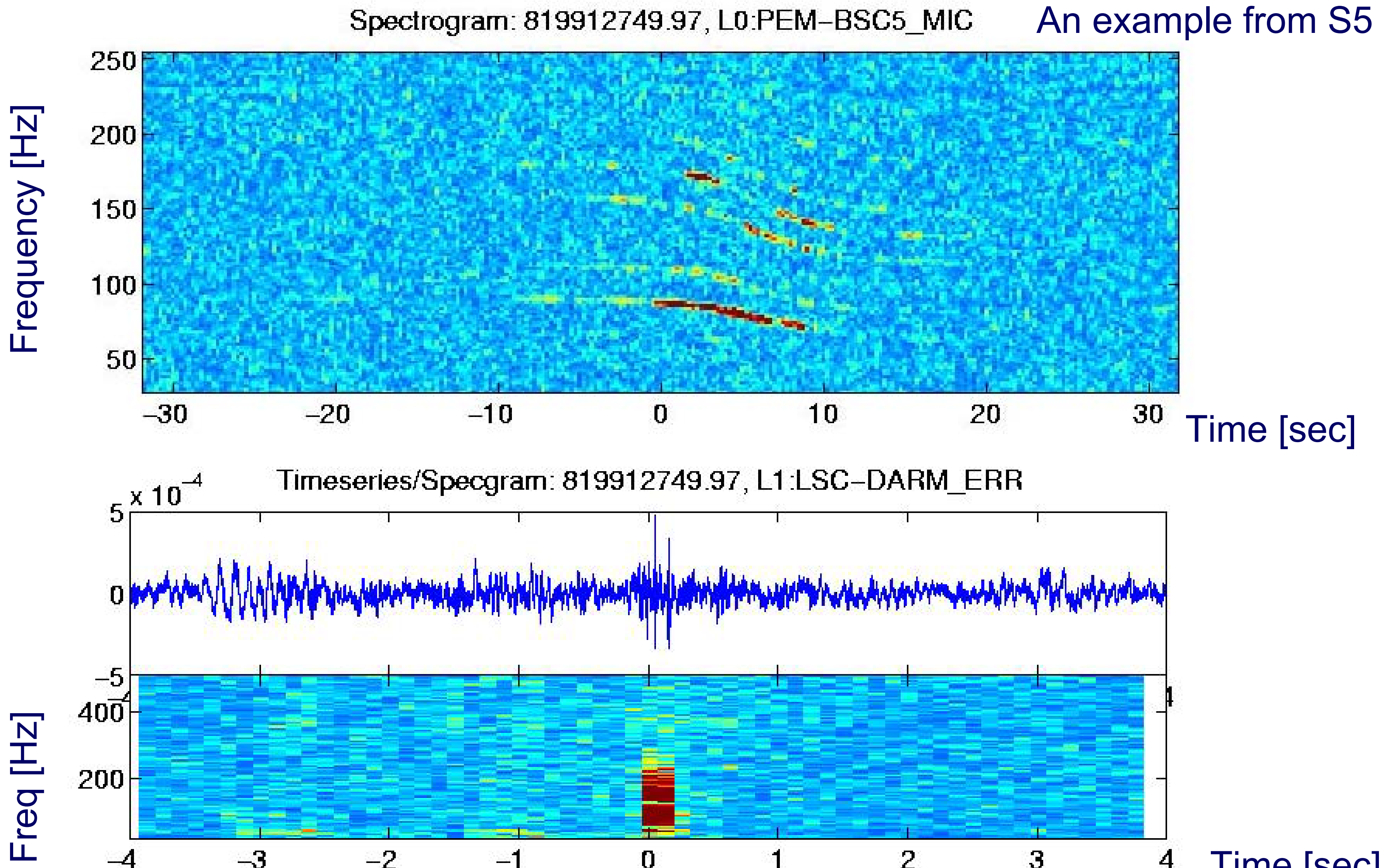


A big transient seen in all magnetometers and volt-meters

An example from S5

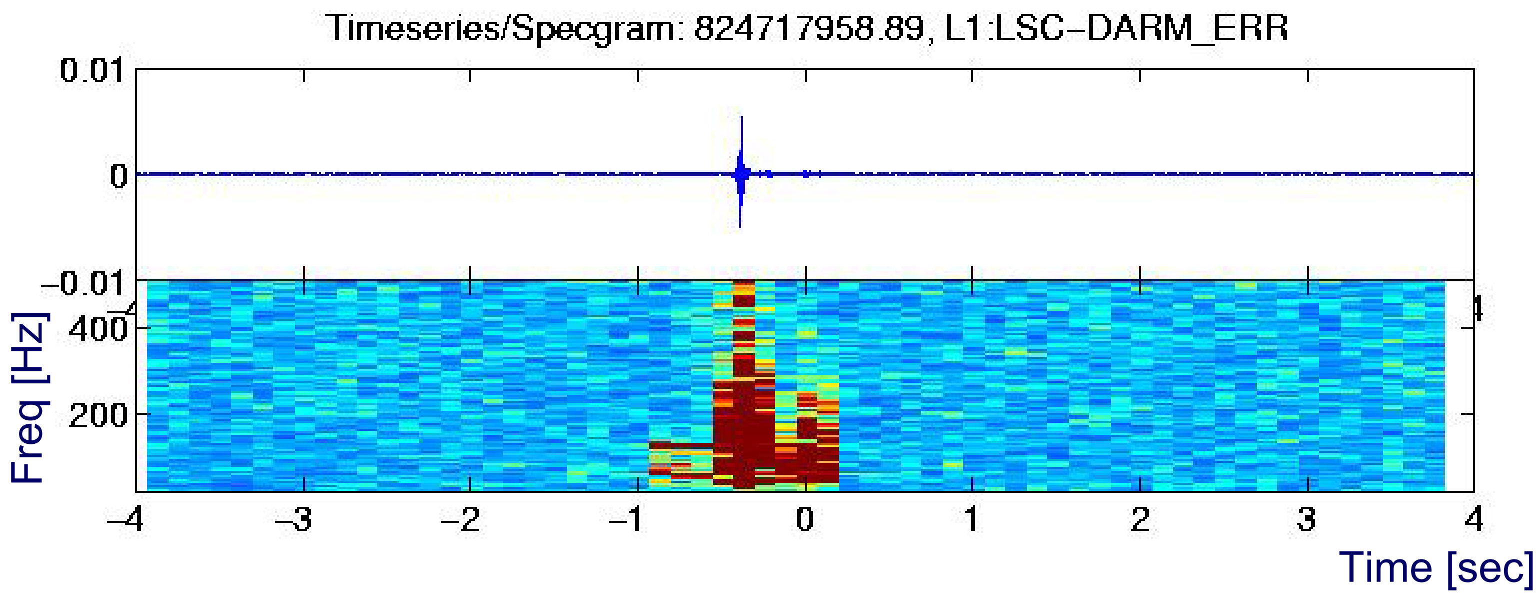
Acoustic disturbances (planes and helicopters)

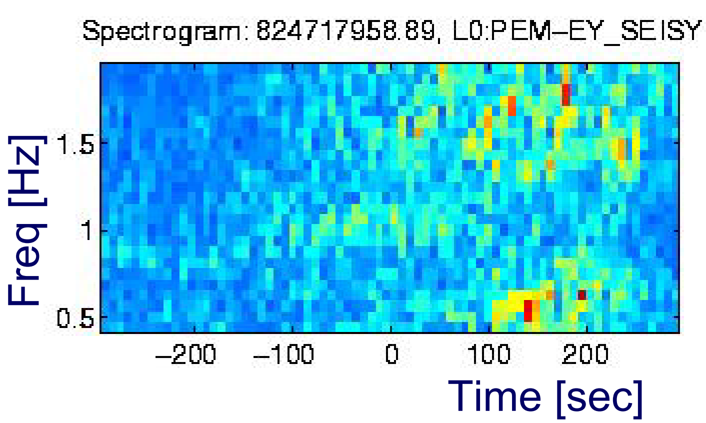
An example from S5

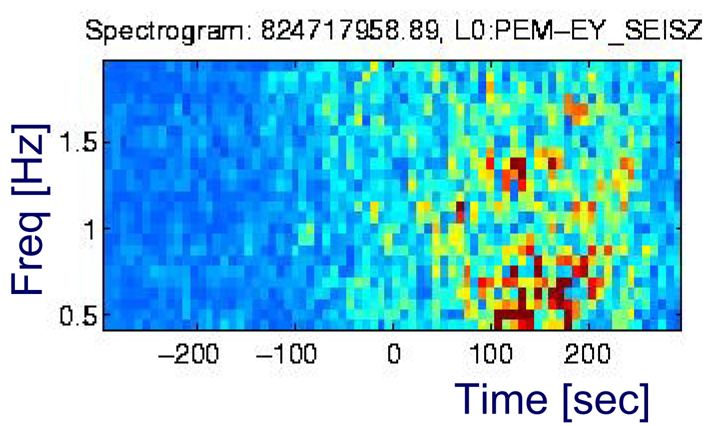


Seismic Disturbances

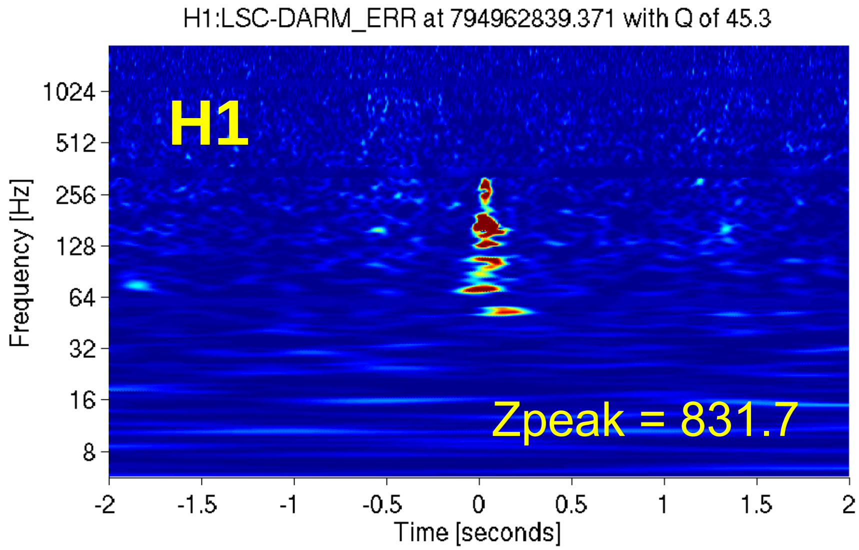
15 minutes before a train during S5…

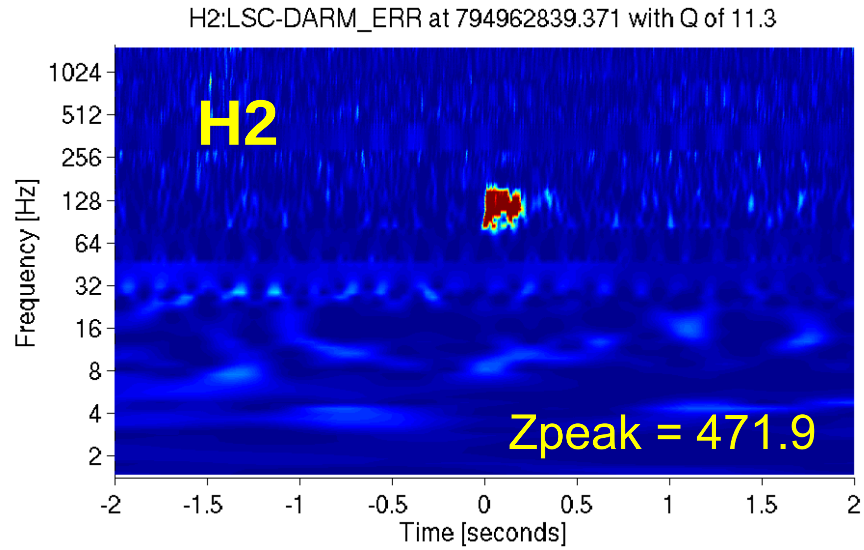


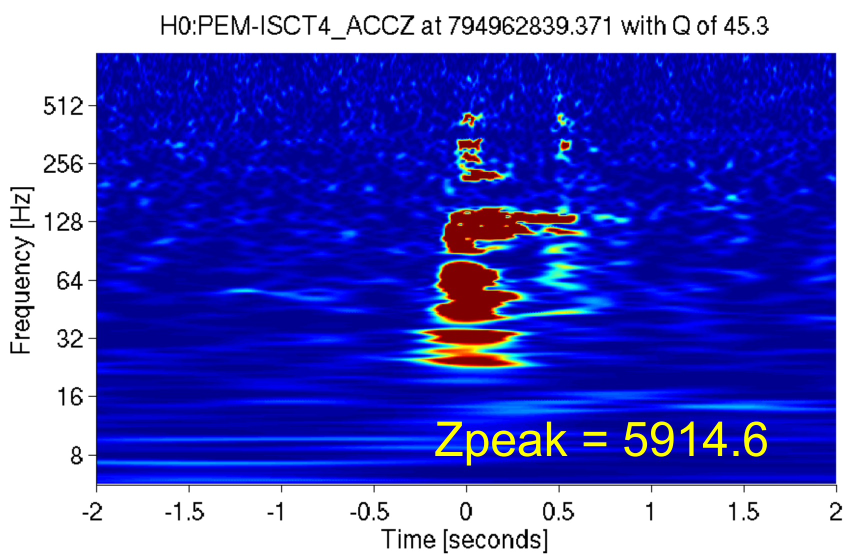




Local seismic disturbances





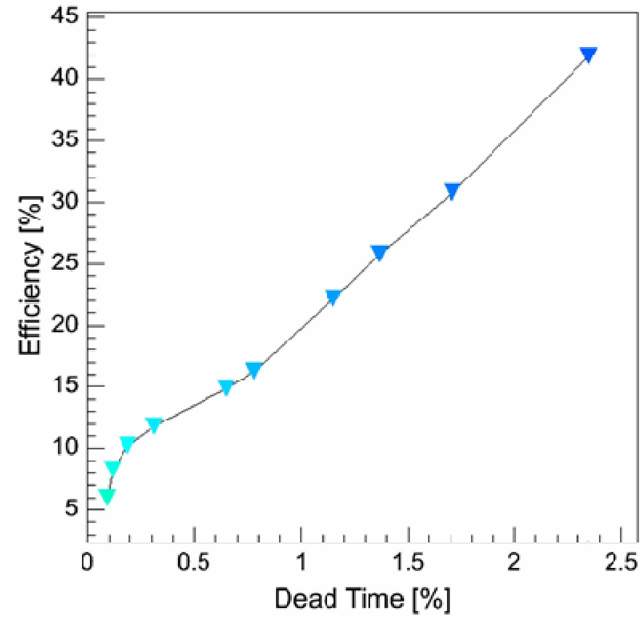


Vetoes

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)

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

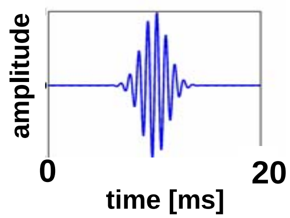


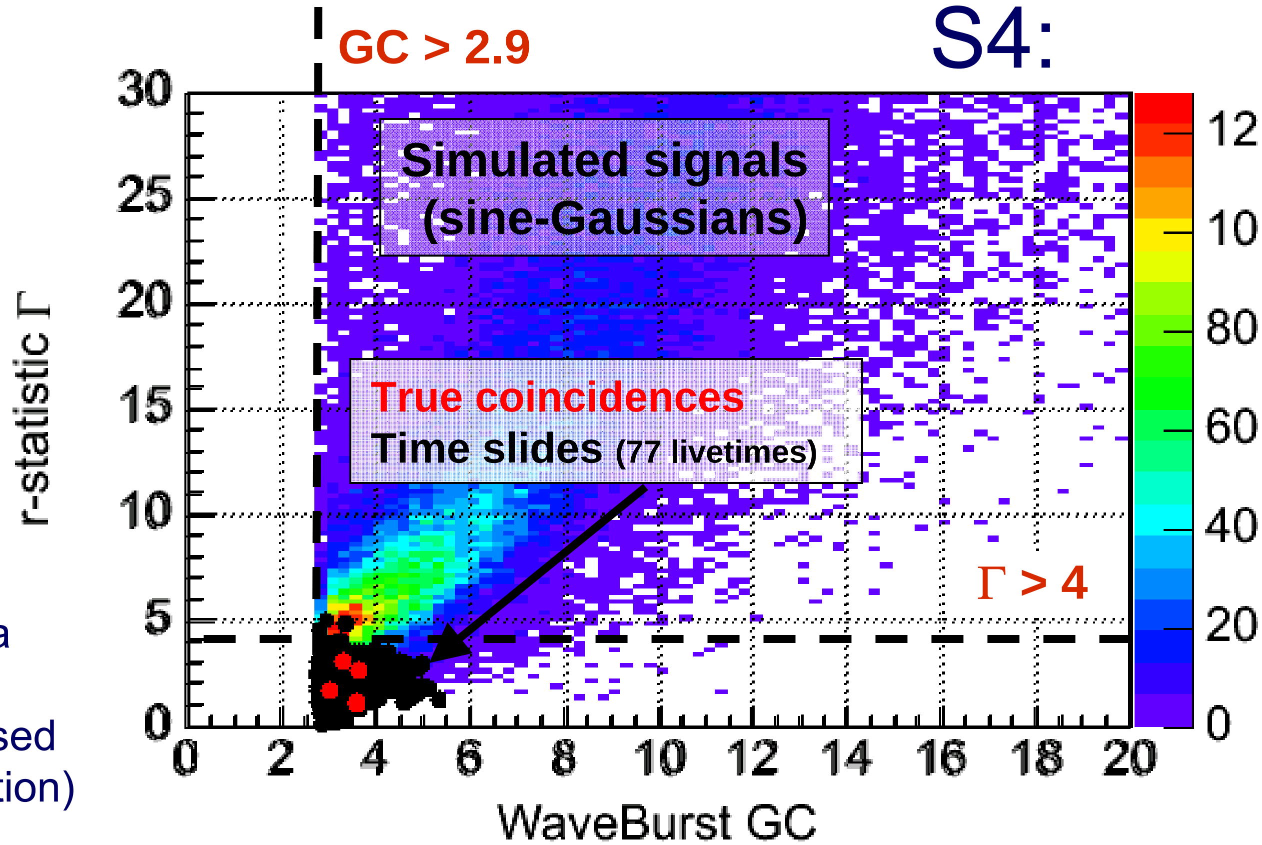
Effective deadtime is:

- ► less than 1% for signals near detection threshold,
- ► about 2% for very large (long) signals

Account for this in detection efficiency, not observation time

Analysis thresholds and S4 coincidence rates





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:

$R_{90\%}$ = 2.303 / 15.53 days = 0.15 /day

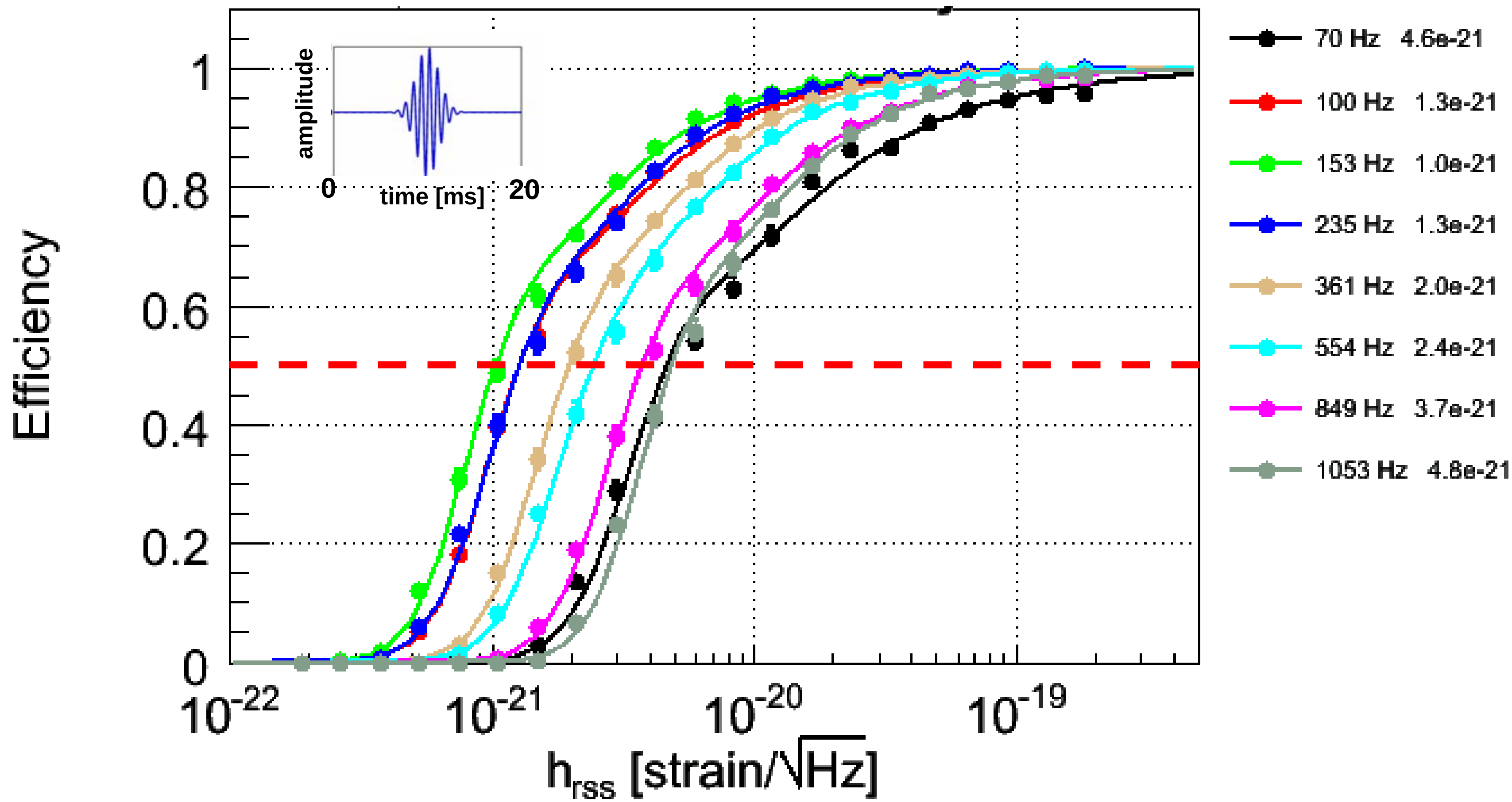
How do we interpret a burst result?

S1 to S4

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…

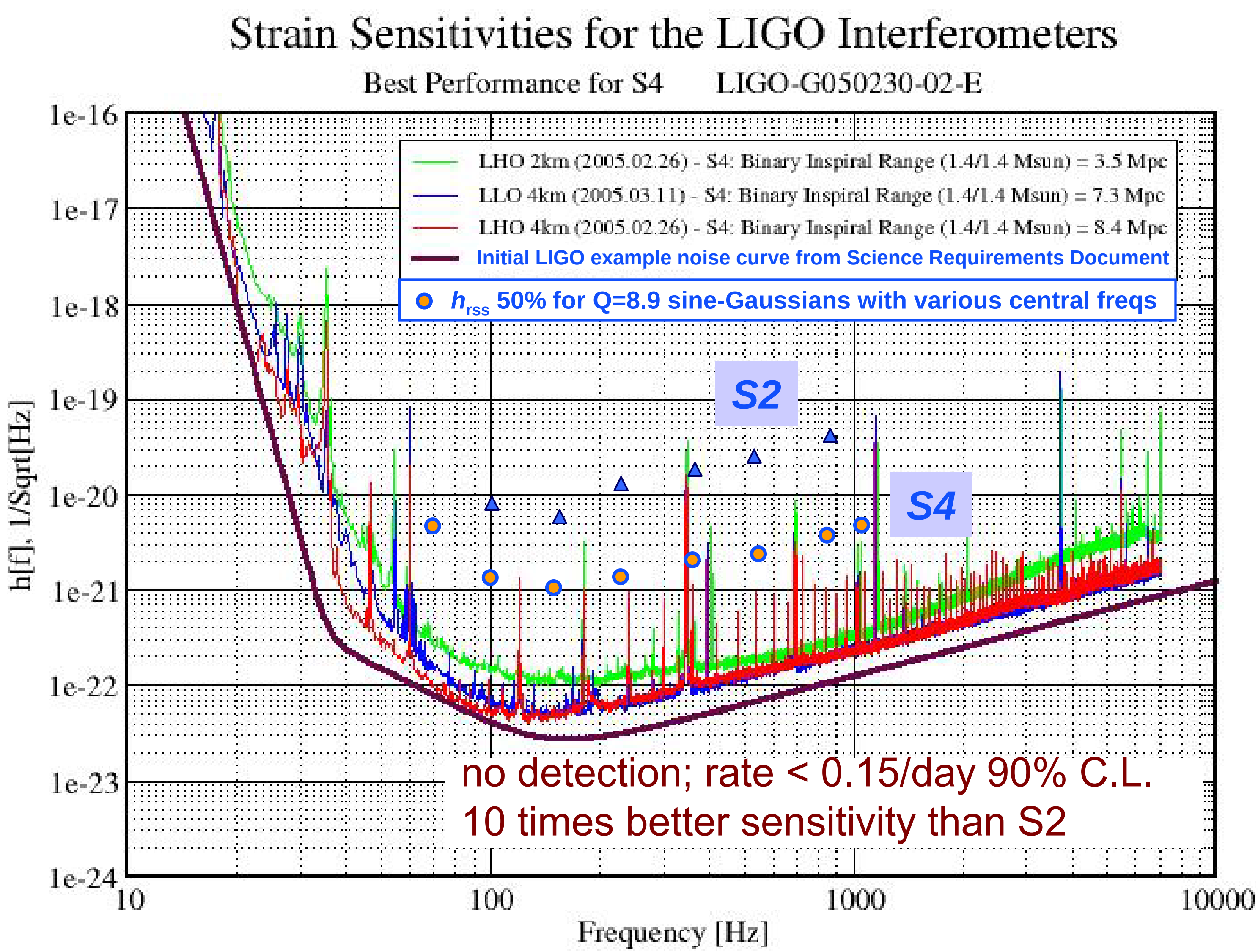
Efficiency Curve for Q=8.9 Sine-Gaussians (S4 preliminary)

Linearly polarized; random sky position & polarization angle



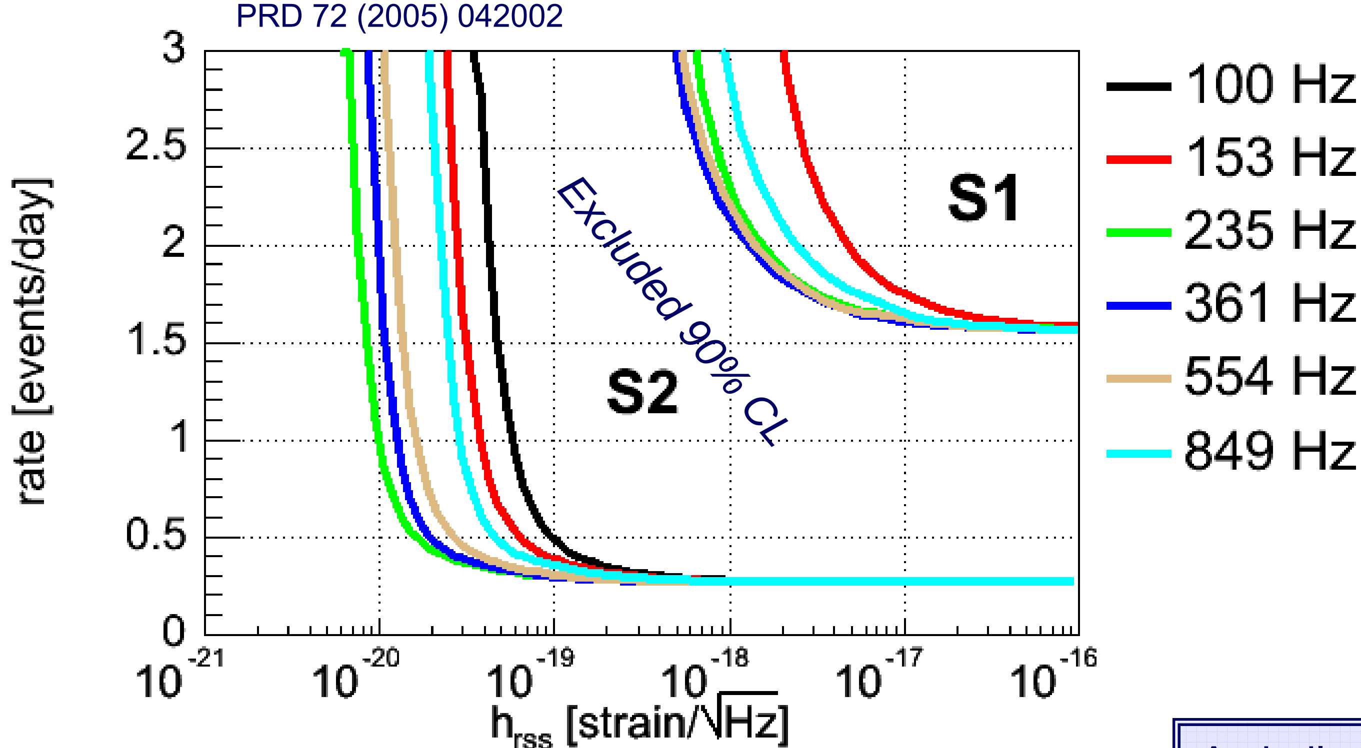
Caveats: preliminary calibration; auxiliary-channel vetoes *not* applied

S4 preliminary results



“Interpreted” Upper Limit

PRD 72 (2005) 042002



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

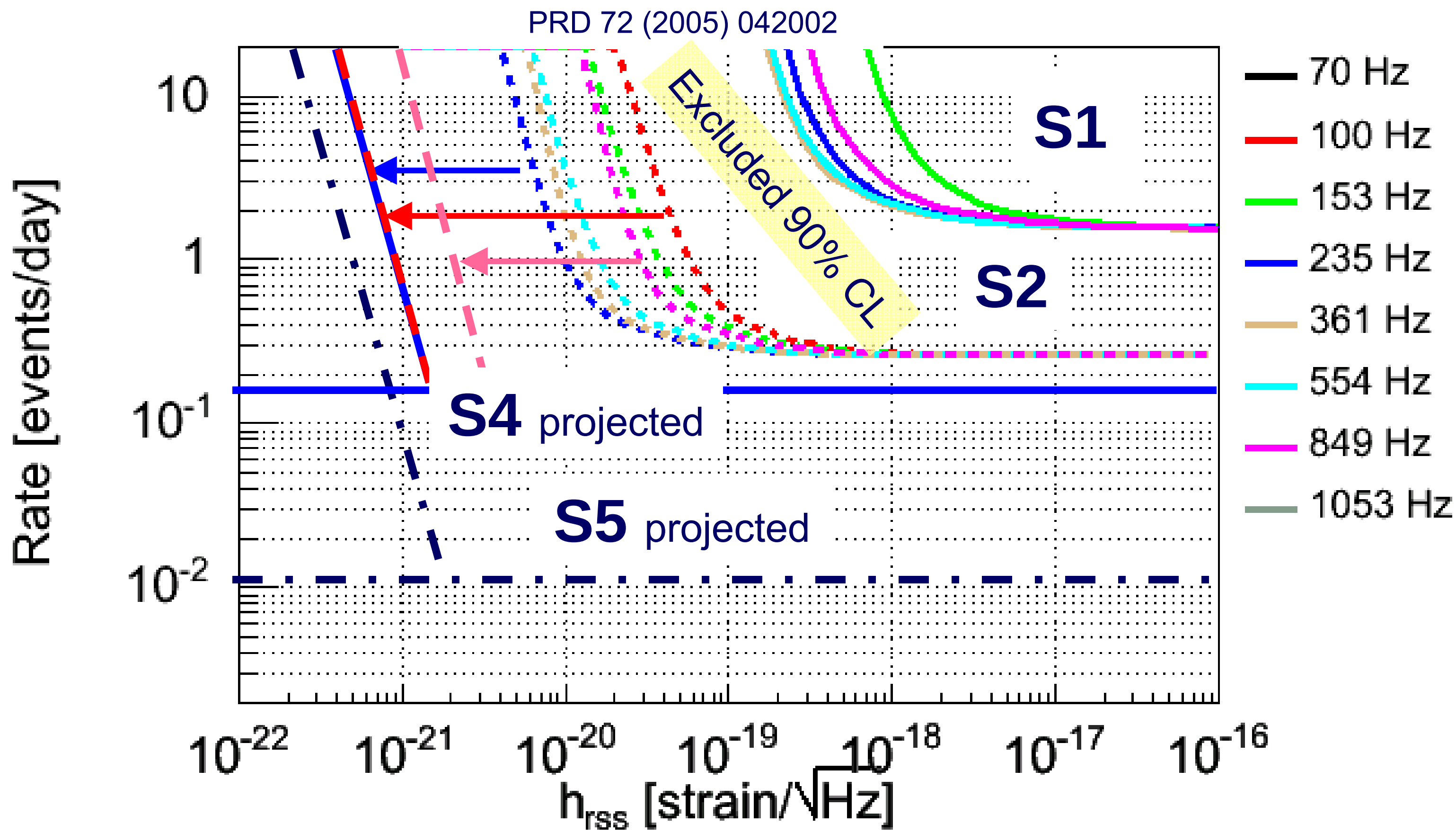
$$R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$$

η = upper limit on event number

T= live time

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

“Interpreted” Upper Limit



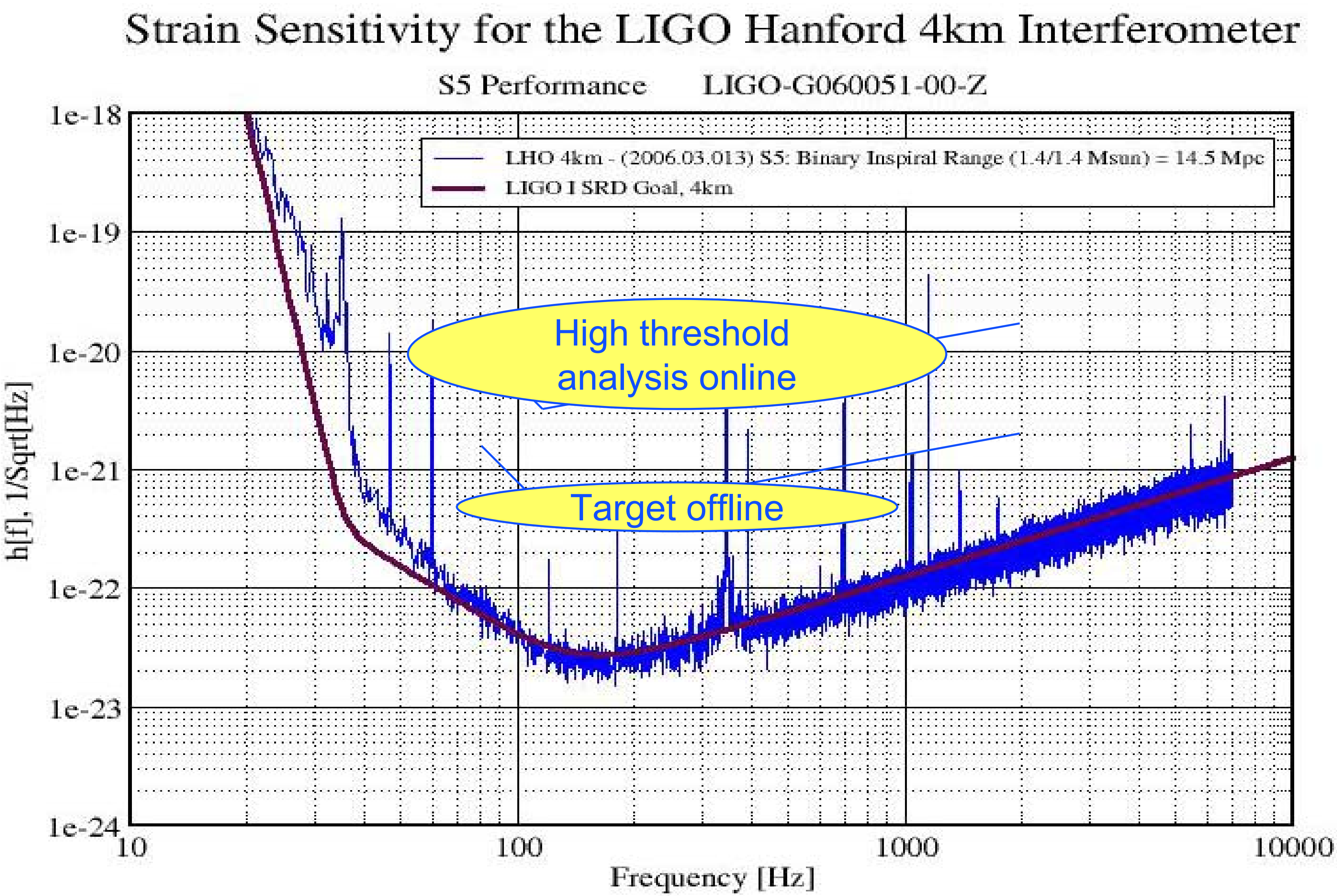
$$R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$$

η = upper limit on event number

T= live time

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

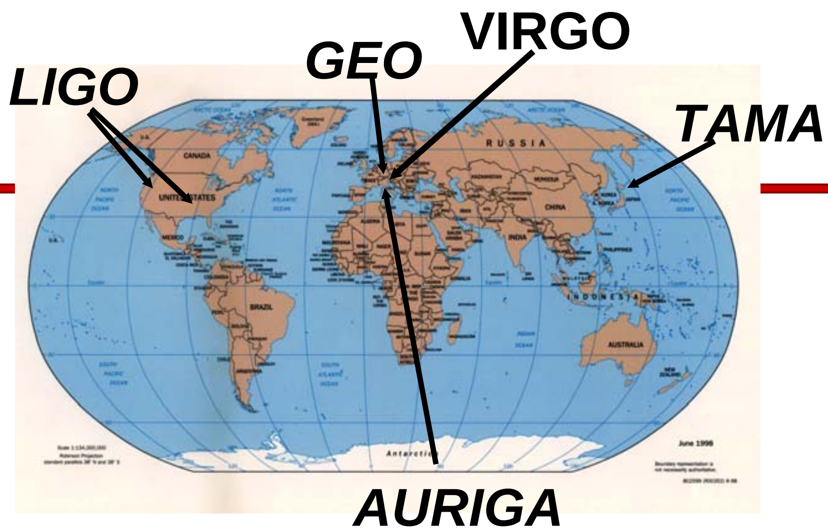
Outlook for the S5 run



Outlook for S5

Some plausible added feature to the S5 burst search:

- » Cross Correlation search (r-statistic test applied non-hierarchically in CorrPower)
- » Null-stream veto (especially for H1-H2!)
- » Directional Analysis (pointing to galactic center or to interesting positions in the sky)
- » Collaboration with VIRGO (incoherent+coherent analysis)
- » Towards a global detection system (joint with IGEC2?)



Collaborative analysis

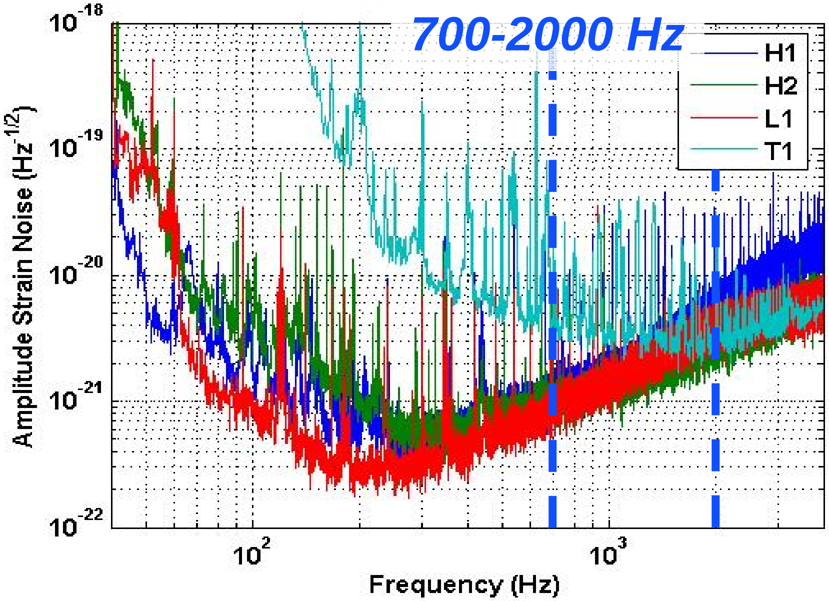
benefits and costs:

» Reduction of false alarm rate
» Increase in observation time
» Confidence in a coincident detection

» Sensitivity restricted to common band, limited by the least sensitive detector

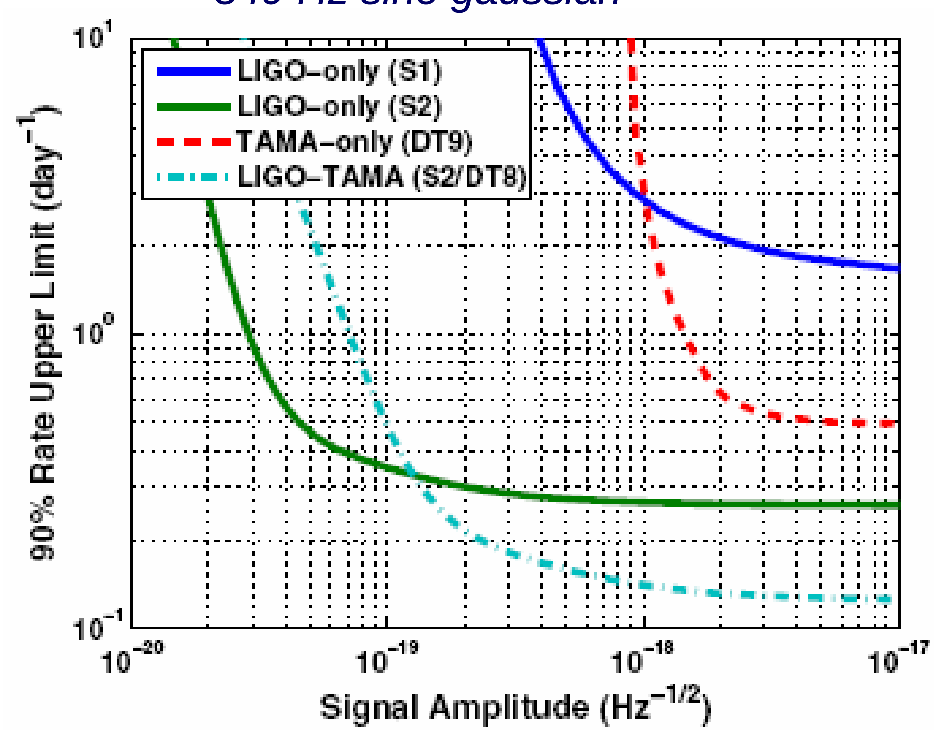
S2: LIGO-TAMA

TAMA300 Mitaka (Japan)



detector combination	observation time (hr)	fraction of total observation time
H1	1040	74%
H2	821	58%
L1	536	38%
T1	1158	82%
H1-H2-L1-T1	256	18%
H1-H2-nL1-T1	320	23%
H1-H2-L1-nT1	62	4%
network totals	638	45%

849 Hz sine gaussian

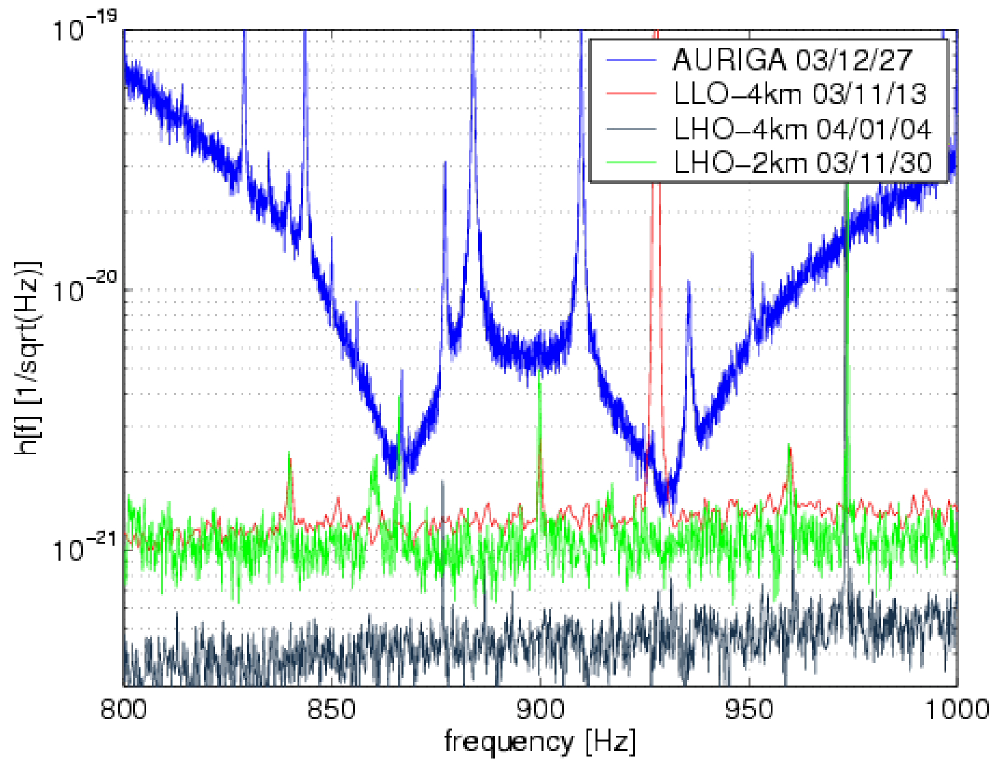


PHYSICAL REVIEW D **72**, 122004 (2005)

S3:LIGO-AURIGA

LIGO S3 run: Oct 31 2003 – Jan 9 2004

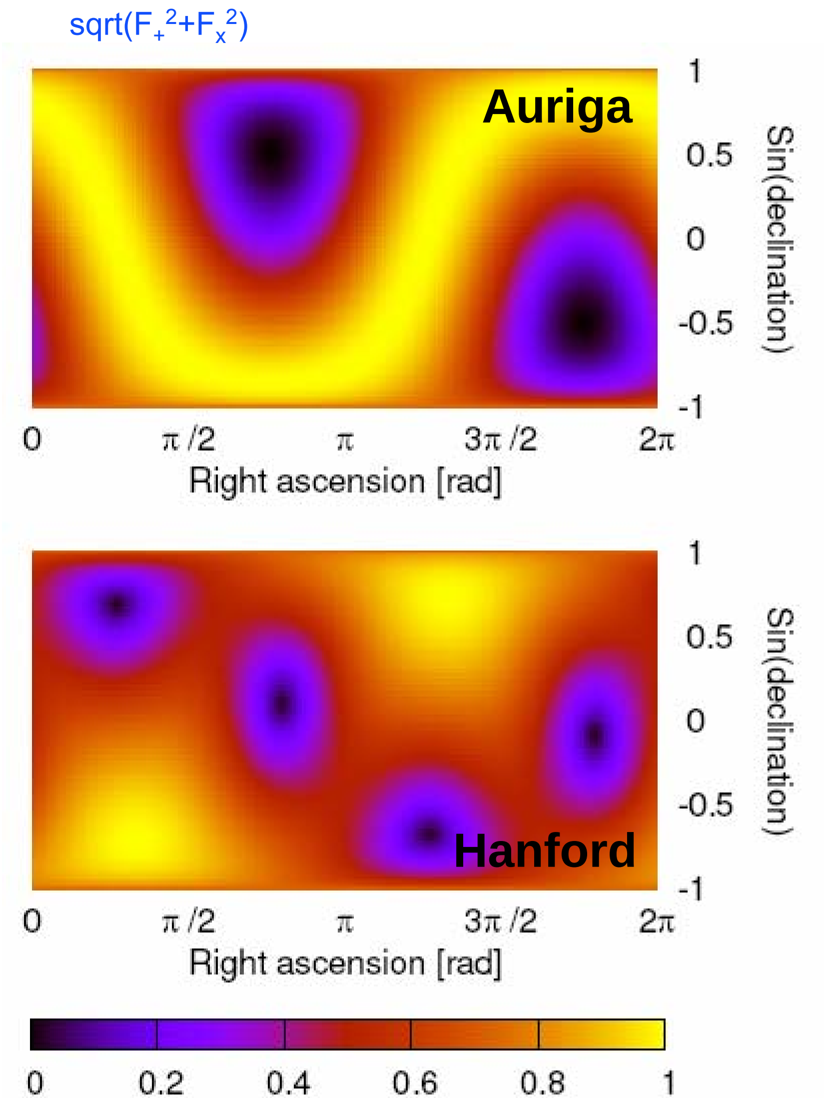
AURIGA run 331: Dec 24 2003 – Jan 14 2004



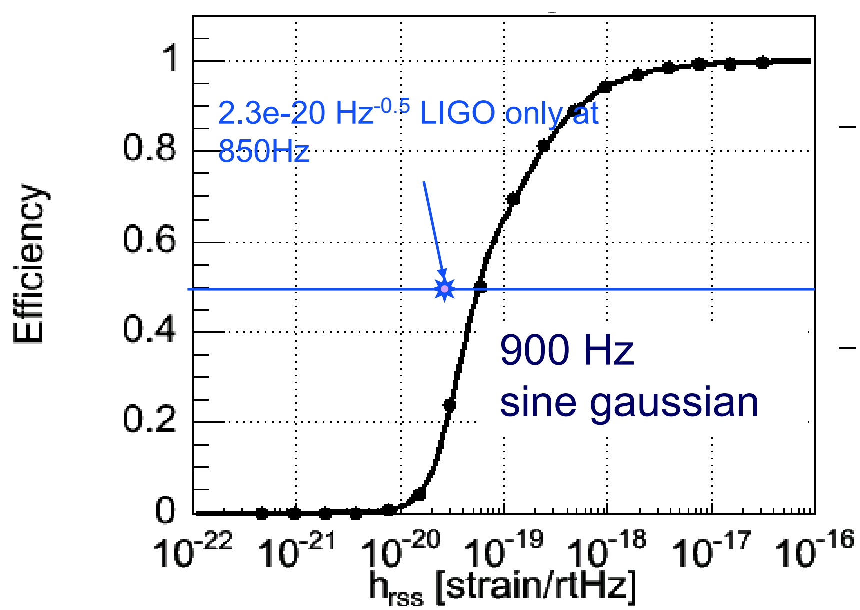
Best performance during the 331 and the S3 run:

- LIGO S3: large rate of transients, noise variability
- AURIGA 331: poor data quality (un-modeled excess noise)

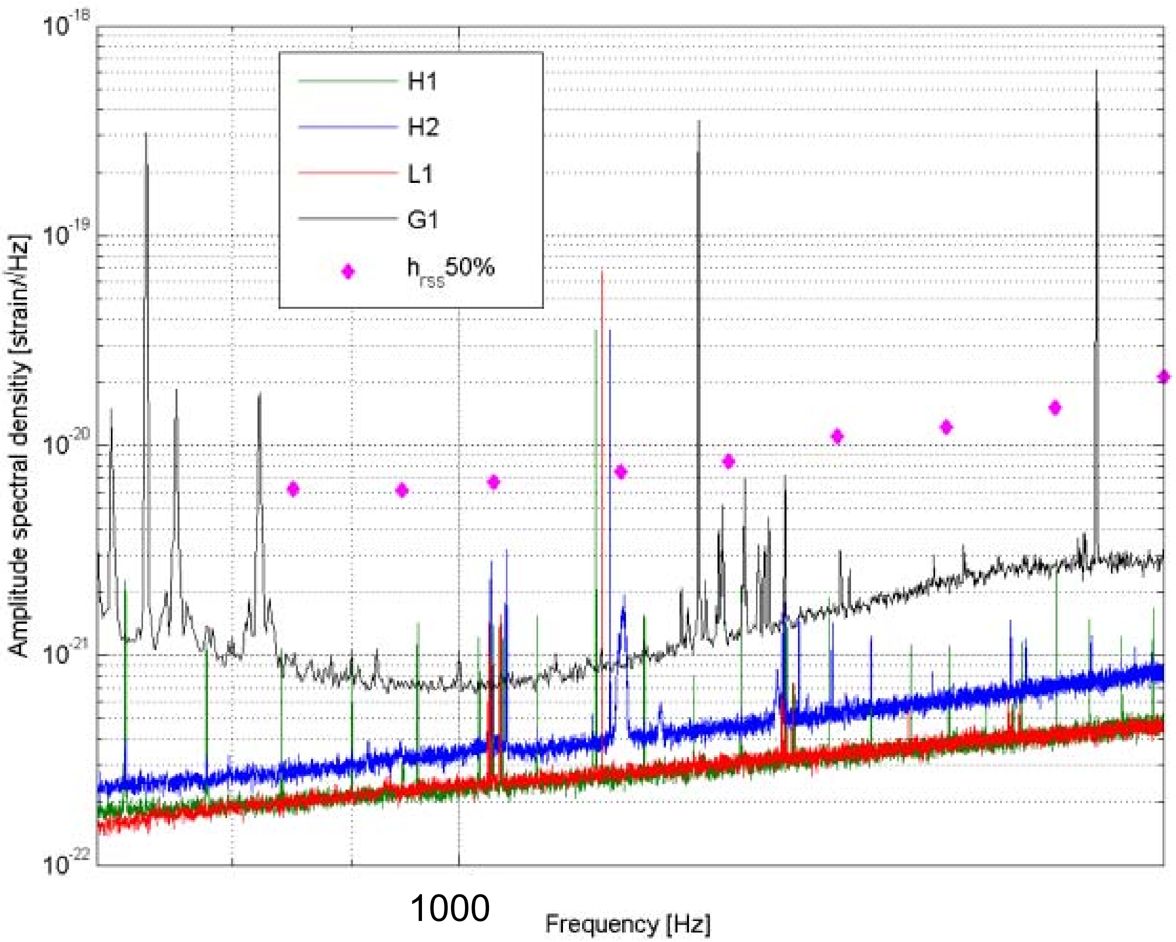
S3:LIGO-AURIGA



Method: r-statistic test (LIGO cross-correlation) around the time of the AURIGA triggers.



S4: LIGO-GEO



Method: 4-detector waveburst and r-statistic test. (direct extension of LIGO pipeline). Larger frequency.

GEO600 (British-German)
Hanover, Germany

S5+: LIGO-VIRGO, LIGO-IGEC2


VIRGO Cascina, Italy

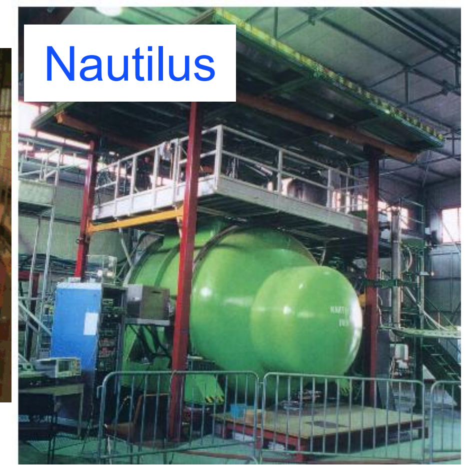
LIGO-VIRGO:

Now exploring methods of analysis and data exchange.
Merging efforts?

IGEC 2

Exploring methods for
- detection validation (no joint upper limit);
- communication protocols,
  early warning alert


Explorer


Nautilus


Auriga


Allegro