First LIGO Search for Binary Inspirals

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of the LIGO Scientific Collaboration

CaJAGWR Seminar
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Outline

The First Science Run

Inspiral Search Fundamentals

Practical Matters

Rate Limit Calculation

The Future

The First Science Run — S1

August 23 – September 9, 2002 (17 days)

GEO ran simultaneously with LIGO

Collected data around the clock

Observatories manned by operators and scientific monitors

Operators keep interferometers working properly

Scimons watch data quality, work on "investigations"

Control-room tools:

Fully computerized control system

Data visualization software

Electronic logbook

Many computer/video screens!

State of LIGO Interferometers During S1

All three interferometers operated with power recycling

- Livingston 4 km — L1
- Hanford 4 km — H1
- Hanford 2 km — H2

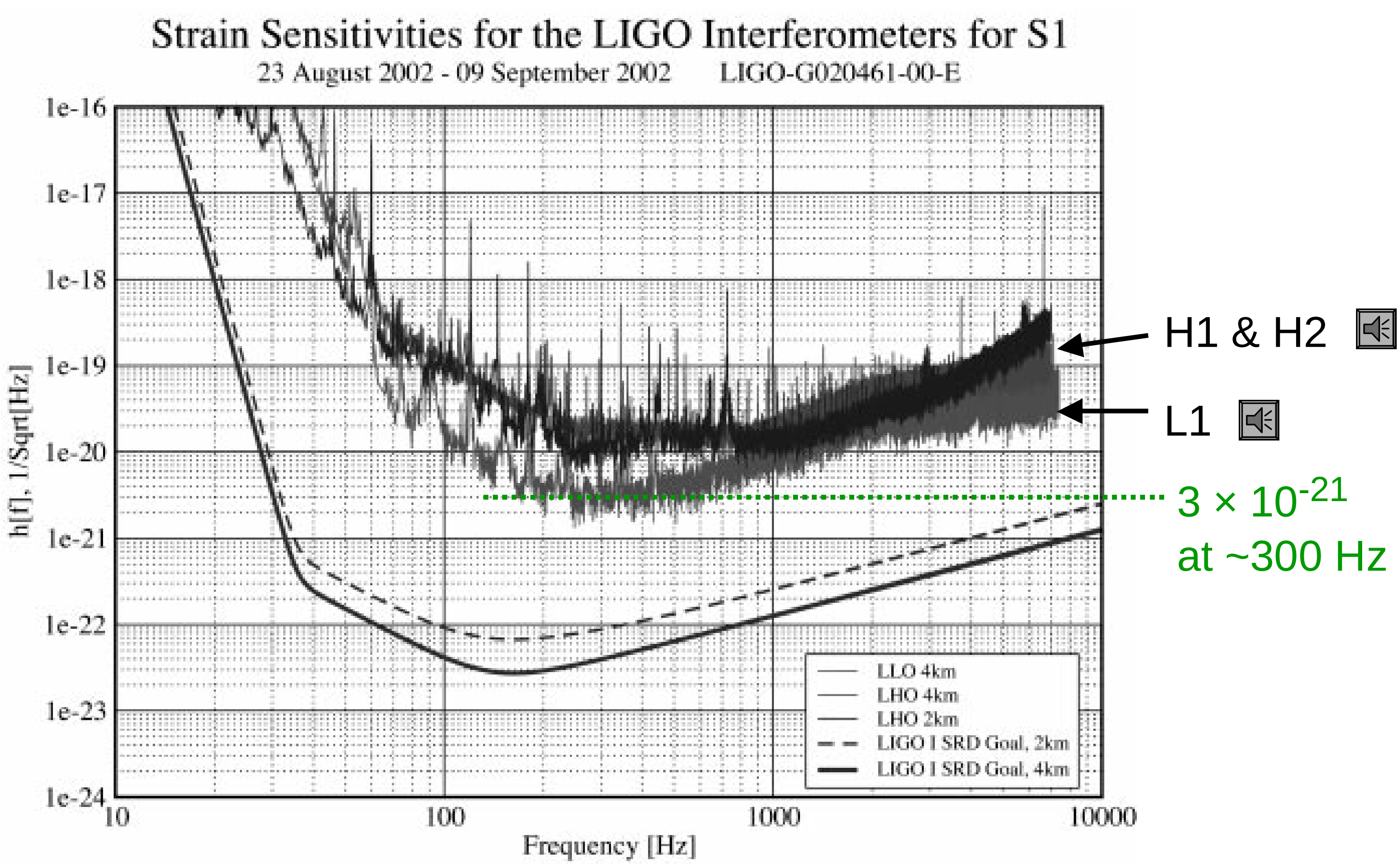
H2 was at full laser power, others at reduced power

All three used "common-mode servo" and Earth-tide compensation

Limitations:

- Ground noise at Livingston generally made it impossible to lock the interferometer during workdays
- Very little of auto-alignment system was operational ⇒ drifts
- Occasional extended difficulties with locking – due to alignment sensitivity?

Strain Sensitivities During S1



Ranges for Binary Neutron Stars

For an optimally oriented 1.4+1.4 $M_\odot$ system, to yield SNR=8 :

L1 : ~175 kpc

H1 : ~40 kpc

H2 : ~35 kpc

Notes

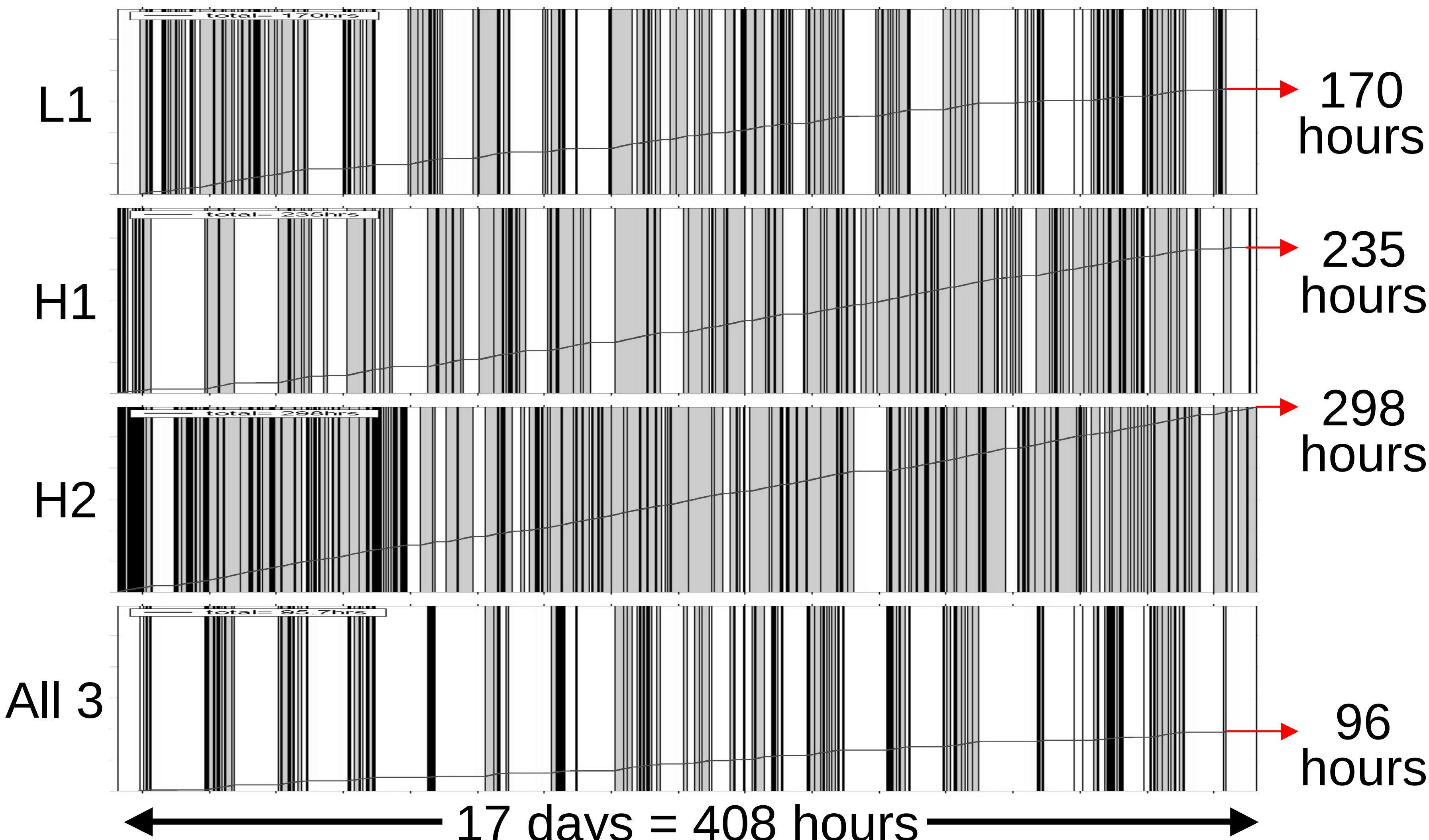
Averaging over orientations reduces these by a factor of ~2.2

Range is nearly proportional to total mass of binary system

⇒ We could see most sources in the Milky Way !

L1 could see out to the Magellanic Clouds

S1 Data Statistics



S1 Data

Data stream includes thousands of channels

- The “gravitational-wave channel”, LSC-AS_Q
- Auxiliary interferometer sensing & control channels
- Environmental monitoring (seismometers, accelerometers, microphones, magnetometers, etc.)
- Control settings

AS_Q and aux Interferometer channels sampled at 16384 Hz

- Digital servo system
- Use whitening / dewhitening filters to avoid ADC / DAC digitization noise
- Data volume: 5.8 MB/sec from Hanford, 2.9 MB/sec from Livingston

Full data set written to disk at observatories

- Full data set sent to Caltech and U. of Wisconsin–Milwaukee
- Reduced data set generated and sent to MIT

Data Analysis Organization

Data Analysis is the job of the LIGO Scientific Collaboration

Four LSC “upper limit” working groups were formed

- Organized around signal types: burst, inspiral, continuous-wave, stochastic
- Most data analysis is done in the context of one of these groups

Interact via weekly teleconferences, email lists, electronic notebooks, occasional face-to-face meetings

Inspiral Upper Limit Working Group

- Led by Patrick Brady (UWM) and Gabriela González (LSU)
- Others who contributed to this analysis:
  Bruce Allen (UWM), Duncan Brown (UWM), Jordan Camp (Goddard), Vijay Chickarmane (LSU), Nelson Christensen (Carleton), Jolien Creighton (UWM), Carl Ebeling (Carleton), Valera Frolov (LLO), Brian O’Reilly (LLO), Ben Owen (Penn State), B. Sathyaprakash (Cardiff), Peter Shawhan (CIT)

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Overview of the S1 Inspiral Search

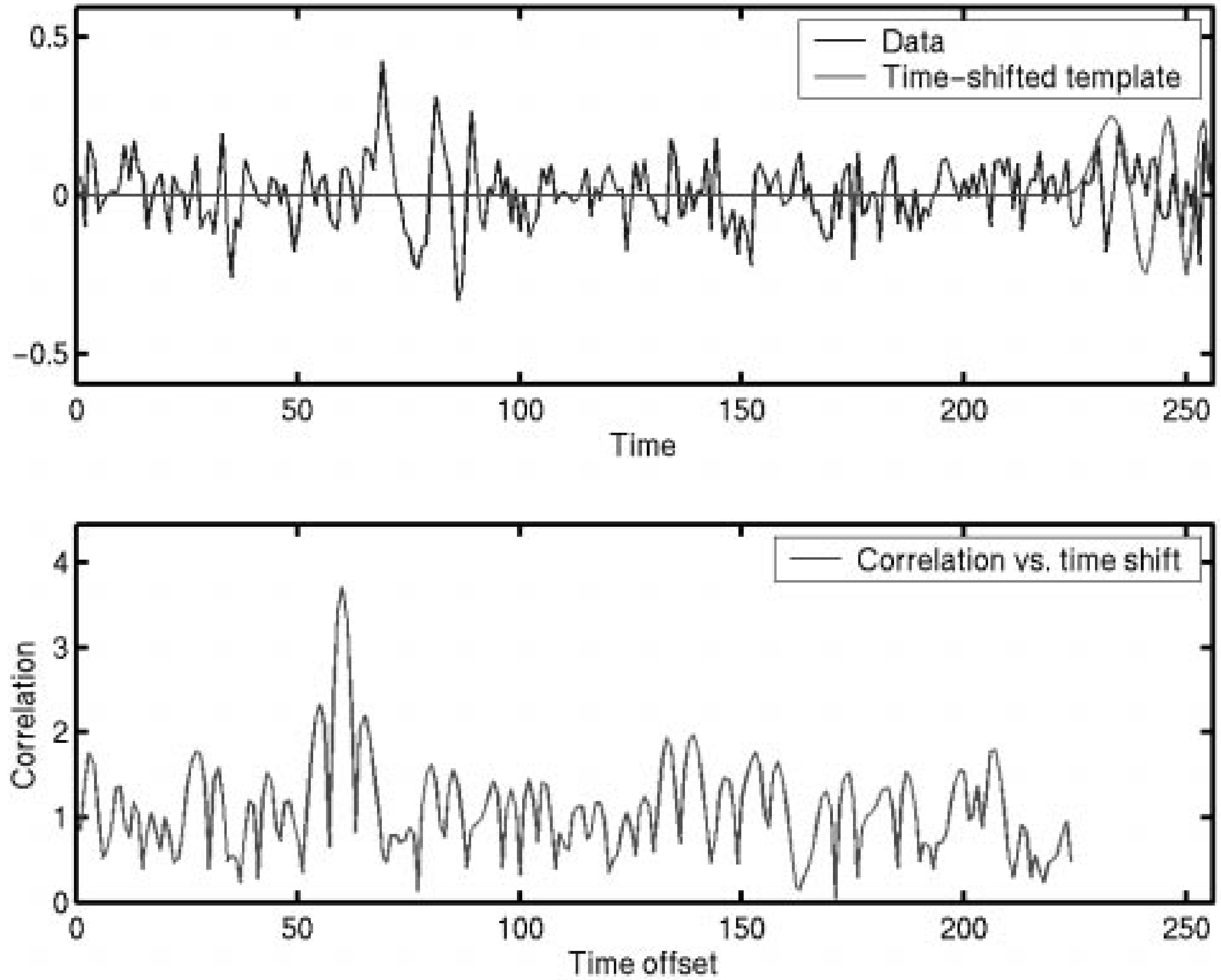
Use optimal matched filtering to search for the known waveforms of binary inspirals

Do filtering in frequency domain, weighting according to noise spectrum

Lay out a "bank" of templates to catch any signal for which each component in the binary system has a mass between $M_\odot$ and 3 $M_\odot$

Check that candidate signals have the expected distribution of signal power as a function of frequency

Illustration of Matched Filtering



Optimal Filtering Using FFTs

Transform data to frequency domain : $\tilde{h}(f)$

Calculate template in frequency domain : $\tilde{s}(f)$

Combine, weighting by power spectral density of noise:

$$\frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_h(|f|)}$$

Then inverse Fourier transform gives you the filter output at all times:

$$z(t) = 4 \int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_h(|f|)}\ e^{2\pi i f t}\ df$$

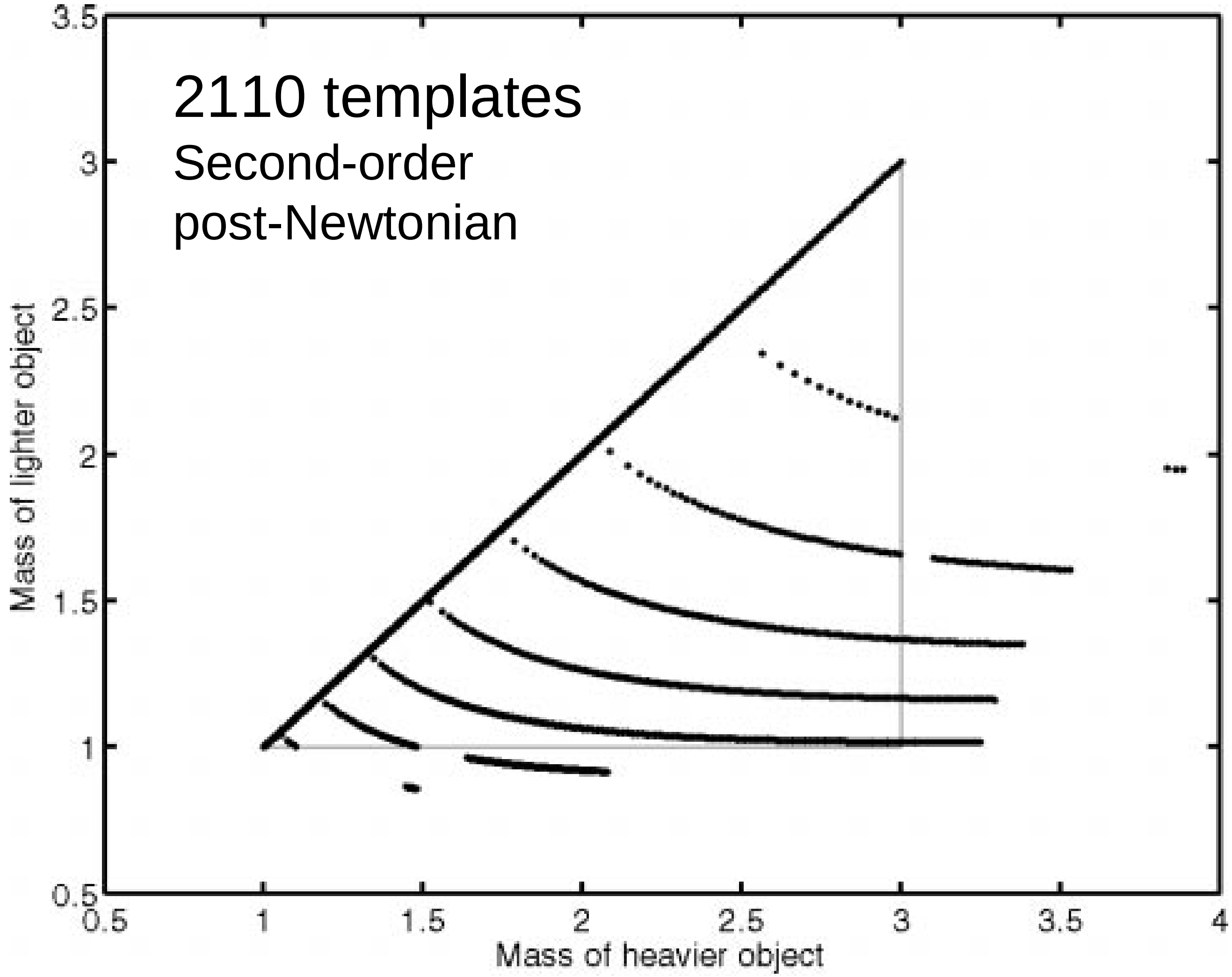
Find maxima of $|z(t)|$ **over arrival time and phase**

Characterize event by signal-to-noise ratio, ρ

Template Bank

Calculated based on L1 noise curve

Templates placed for maximum mismatch of $\delta = 0.03$



“Chi-Squared Veto”

Any large glitch in the data can lead to a large filter output

The essence of a “chirp” is that the signal power is distributed over frequencies in a particular way

Divide template into sub-bands and calculate a χ^2-like quantity:

$$r^2(t) = \sum_{l=1}^{p} \left| z_l(t) - z(t)/p \right|^2$$

Correct for large signals which fall between points in the template bank:

$$\alpha^2(t) = r^2(t) \Big/ \left(1 + \rho^2 \delta^2 / p\right)$$

We use p = 8 and make the cut $\alpha^2 \leq 5$

Data Processing

The search is performed using routines from the LIGO Algorithm Library (LAL), running within the LIGO Data Analysis System (LDAS)

- Template bank is divided up among many PCs working in parallel ("flat" search)
- Most of the processing for this analysis was done on the UWM LDAS system, which has 296 PCs →

Each LDAS job processes 256 seconds of data

- Consecutive jobs overlap by 32 seconds
- Events which exceed an SNR threshold of 6.5 and pass the chi-squared veto are written to the LDAS database

Can we really detect a signal?

We used LIGO's hardware signal injection system to do an end-to-end check

- Physically wiggle a mirror at the end of one arm
- Measure the signal in the gravitational-wave channel

Injected a few different waveforms at various amplitudes

- Example: 1.4+1.4 $M_\odot$, effective distance = 7 kpc

Signal was easily found by inspiral search code

- The 1.4+1.4 $M_\odot$ template had the highest SNR (= 92)
- Reconstructed distance was reasonably close to expectation
- Yielded an α^2 value well below the cut

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Real Detectors…

… are not on all the time

- ⇒ Need to do bookkeeping when running jobs
- ⇒ Need to decide how to combine data from multiple detectors

… have time-varying noise

- ⇒ Discard data when detector was not very sensitive
- ⇒ Estimate noise from the data

… have a time-varying response

- ⇒ Calibration

… have “glitches”

- ⇒ Chi-squared veto
- ⇒ Veto on glitches in auxiliary interferometer channels

Making Choices about the Analysis Pipeline

Need to avoid the possibility of human bias when deciding:

- Which interferometers to use
- What data to discard
- Chi-squared veto cut
- Auxiliary-channel vetoes

Can't make these decisions based on looking at the data from which the result is calculated !

Set aside 10% of triple-coincidence data as a "playground"

- Make all decisions based on studying this sample
- Hope it is representative of the full data set
- Avoid looking at the remaining data until all choices have been made

Final result is calculated from the remaining data

Data Set Selection

We chose to use L1 and H1 only

- H2 was the least sensitive, and glitchier than the others

Even when locked, interferometer may not be stable

- Settling down at the beginning of a lock
- Periodic tuning of alignment to maximize arm powers

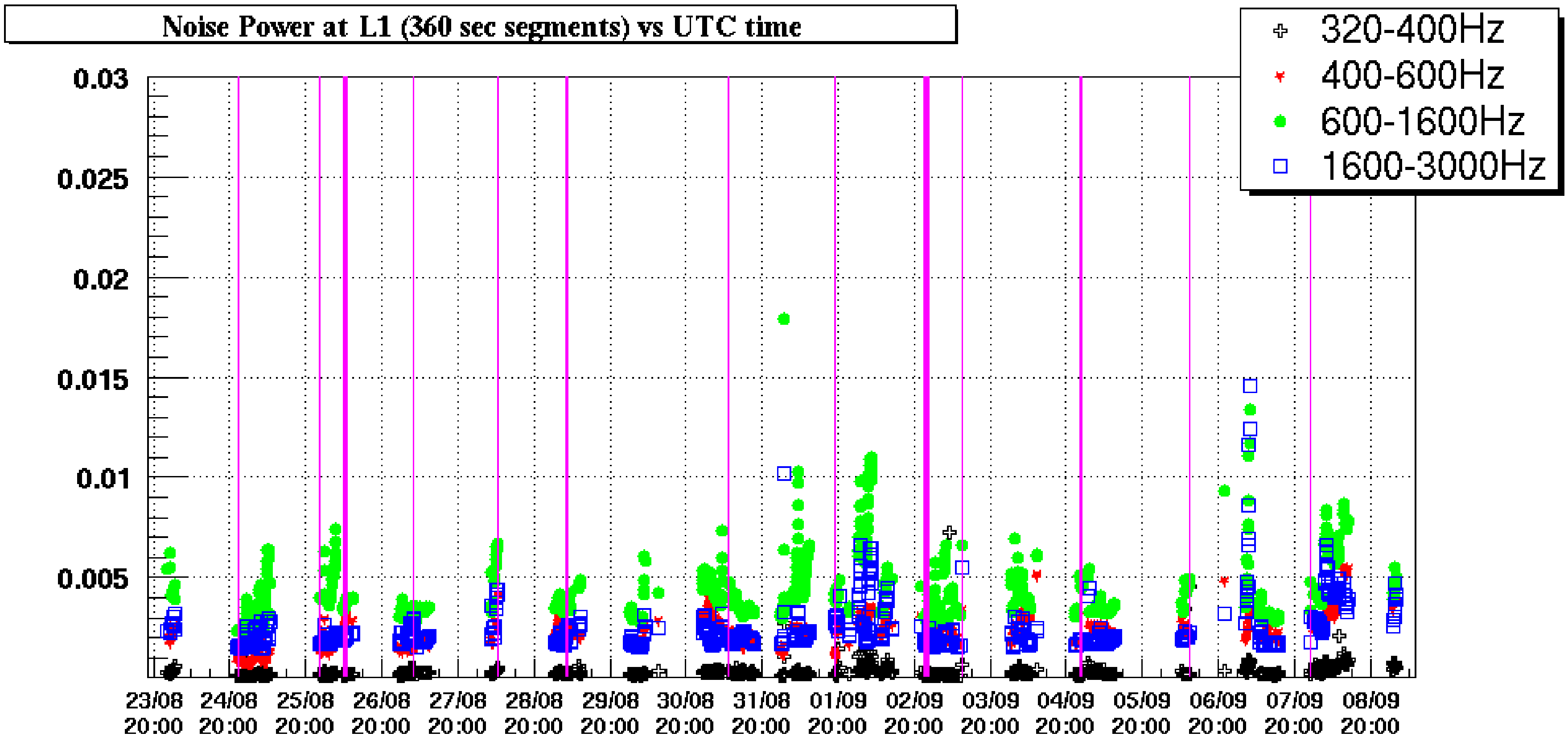
Operators mark “science mode” data while running

- Guarantees that no control settings are being changed

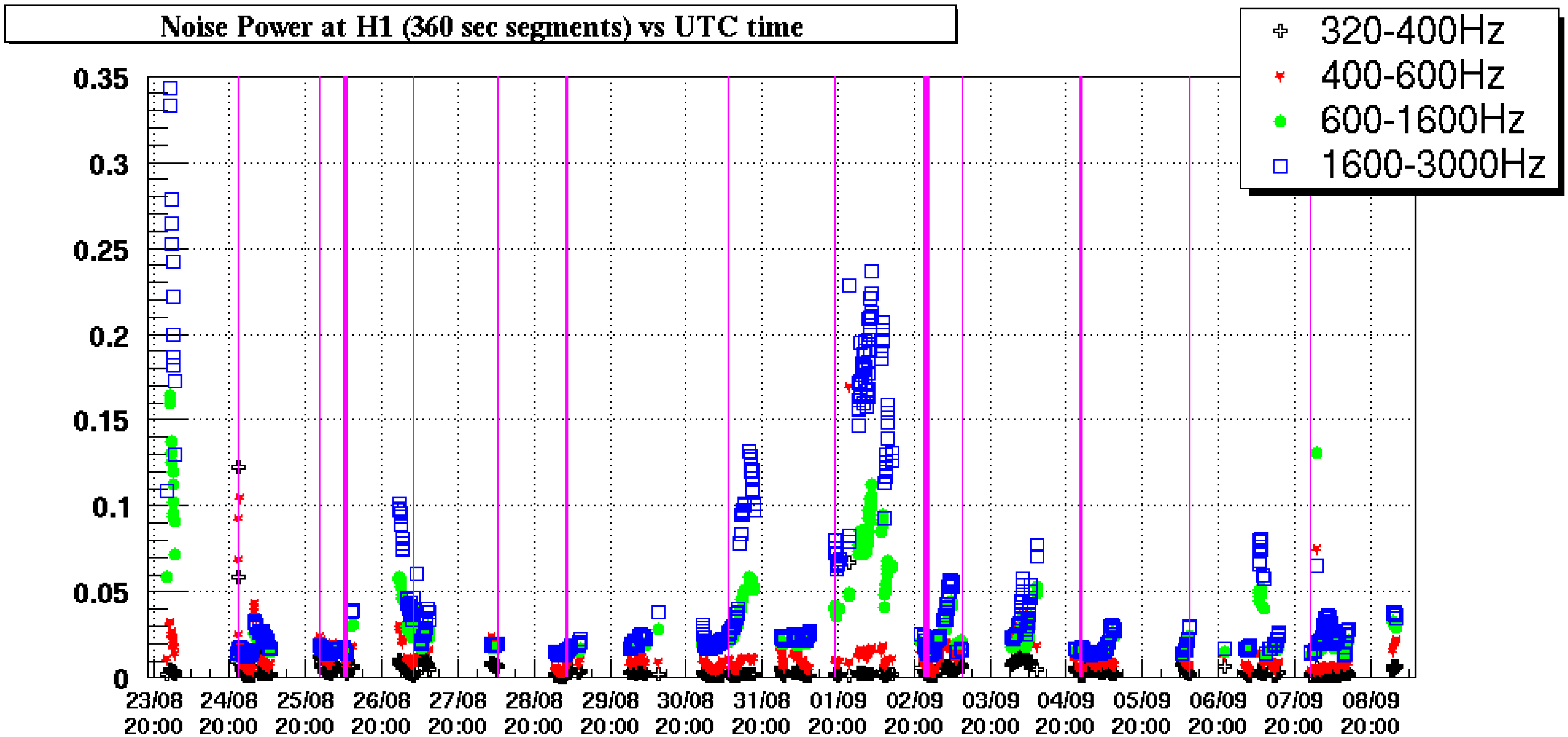
We choose to discard science-mode data when noise is larger than normal — “Epoch veto”

- Power calculated in four frequency bands
- Segment of data is discarded if any band exceeds a threshold
- Cuts 23% of L1 data, 31% of H1 data

Epoch Veto Bands for L1



Epoch Veto Bands for H1



Noise Estimation

Crucial, since it enters into the calculation of SNR

Power spectral density of noise is calculated from the data which is input to each LDAS job

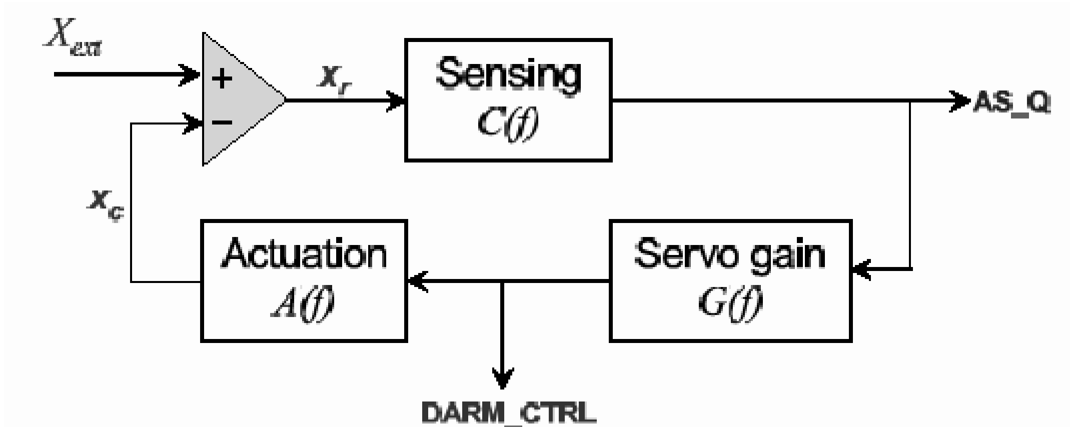
- Calculated by averaging PSDs from 7 overlapping 64-sec time intervals
- Note that this includes any signal which may be in the data

Optimal filtering in frequency domain requires us to assume that the PSD is constant for the whole job

Calibration

Optical sensing is inherently frequency-dependent

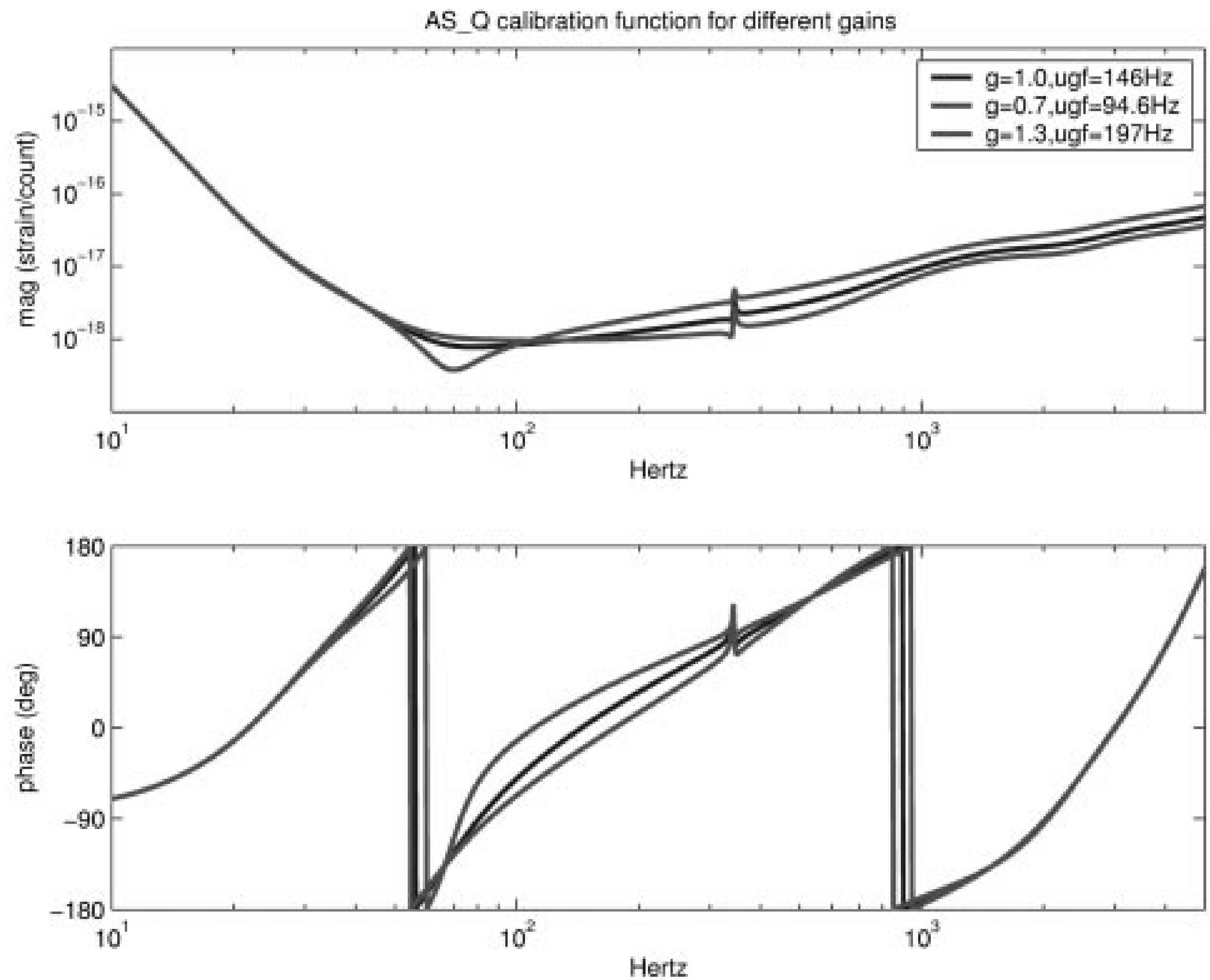
Servo system introduces additional frequency dependence



Periodically measure complete transfer function

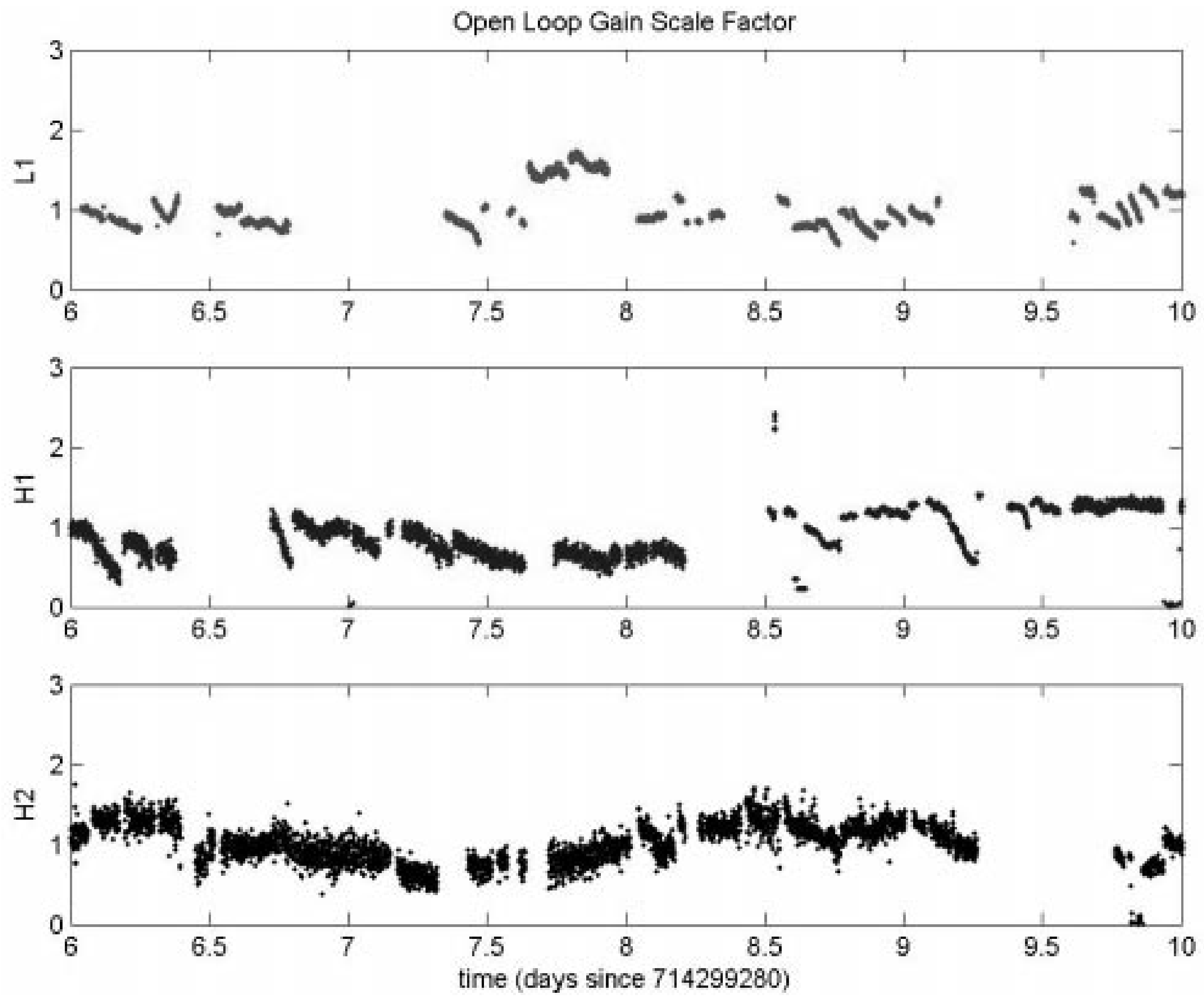
Also, continuously inject "calibration lines" (sinusoidal wiggles on an end mirror) at a few frequencies to track variations in the optical response over time

Effect of Changing Optical Gain



Affects phase as well as amplitude—important for matched filtering

Calibration Stability



Auxiliary-Channel Vetoes

“Glitches” in the gravitational-wave channel

- Seen, at some level, in all three interferometers
- Chi-squared veto eliminates many, but not all

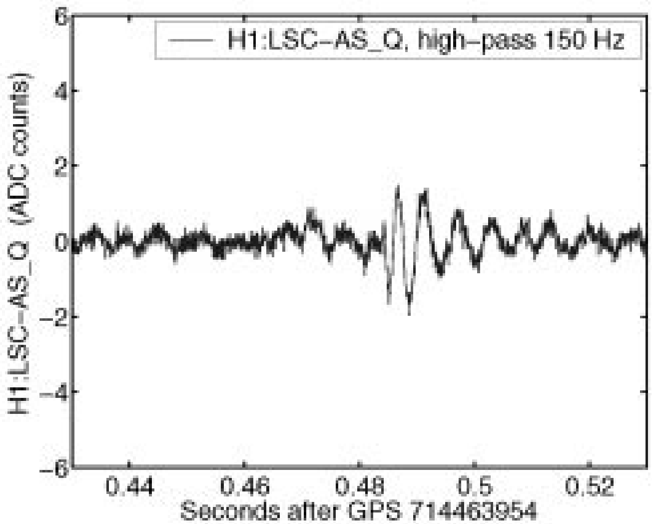
We checked for corresponding signatures in other channels

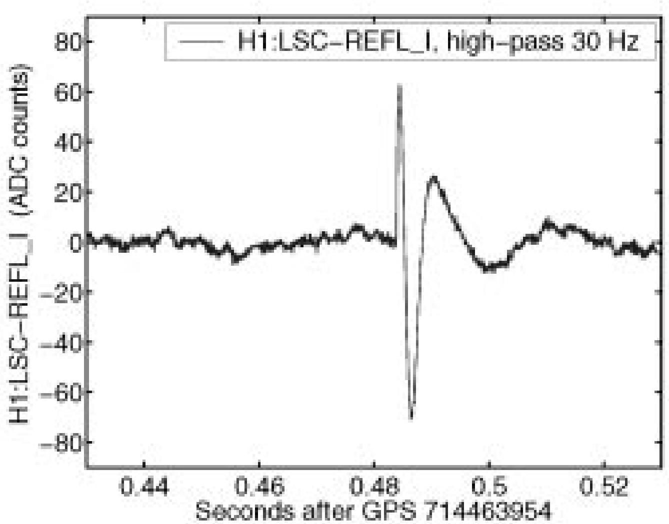
- Environmental channels (accelerometers, etc.)
- Auxiliary interferometer channels

Tried a few glitch-finding algorithms

- absGlitch
- glitchMon
- Inspiral search code (!)

Big Glitches in H1





Found by inspiral search code with SNR=10.4

These occurred ~4 times per hour during S1

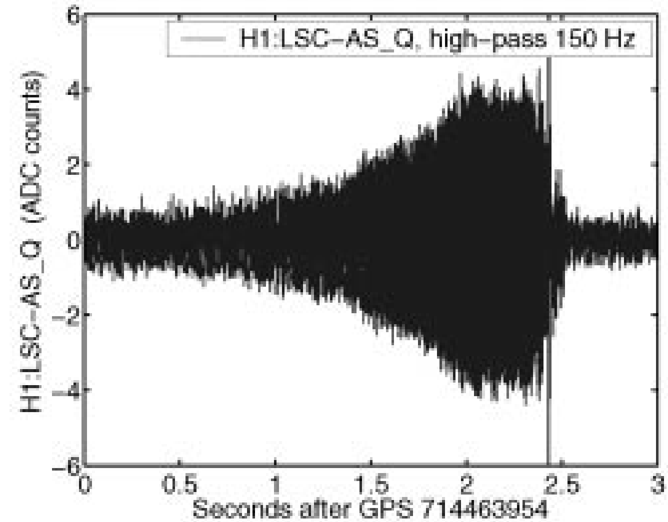
REFL_I channel has a very clear transient

Use glitchMon to generate veto triggers

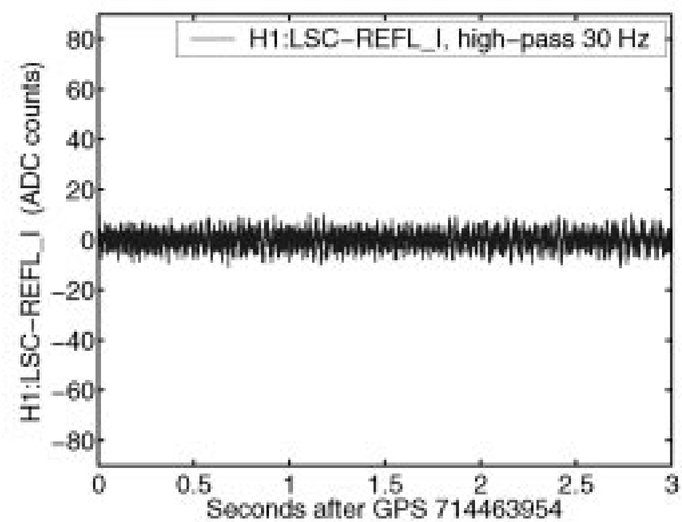
Veto Safety

Have to be sure there aren't couplings between channels which would cause a real gravitational wave to veto itself !

Look at large injections

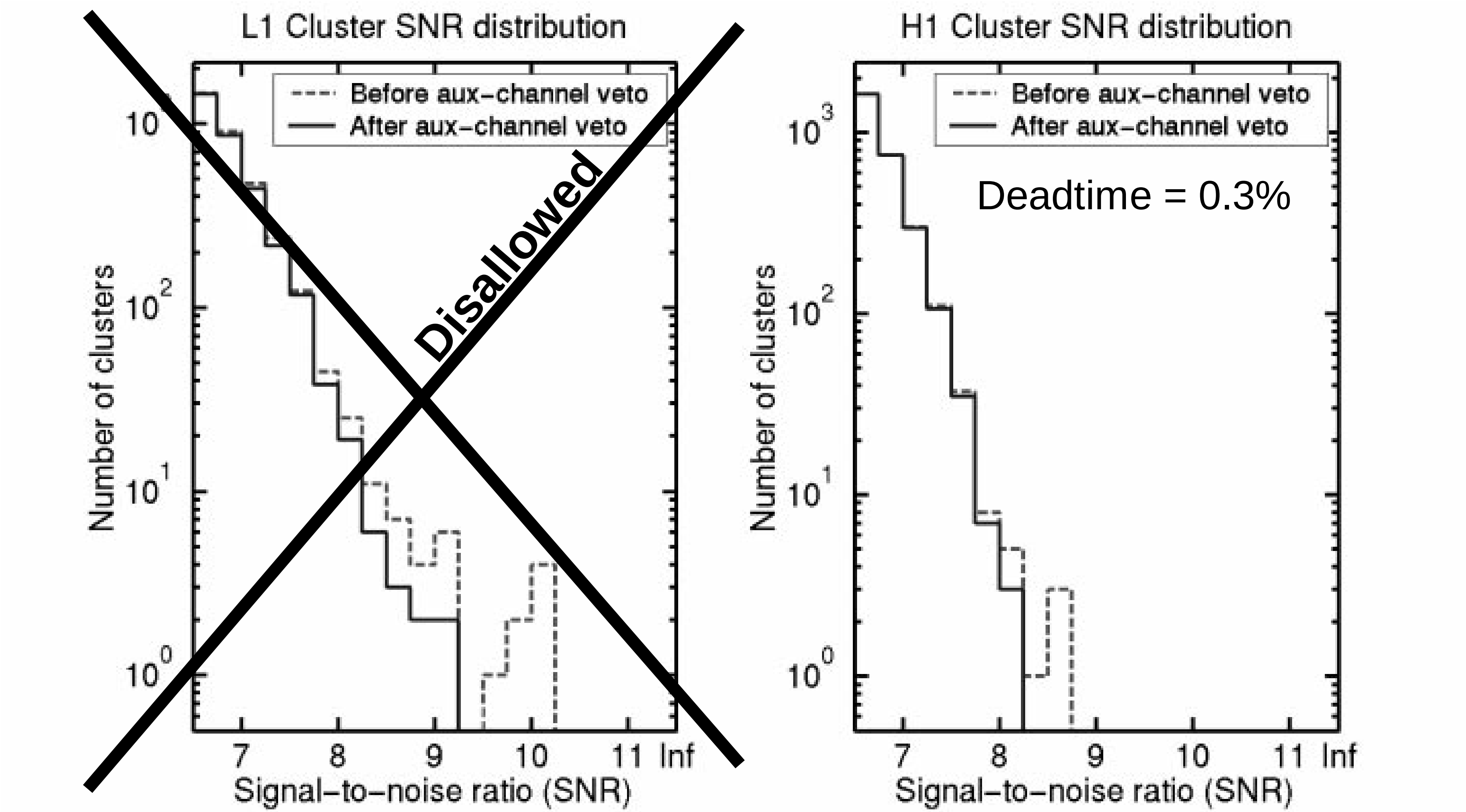


No sign of signal in H1:LSC-REFL_I



Best veto channel for L1 (AS_I) was disallowed because there was a small coupling

Effect of Vetoes
on Playground Data



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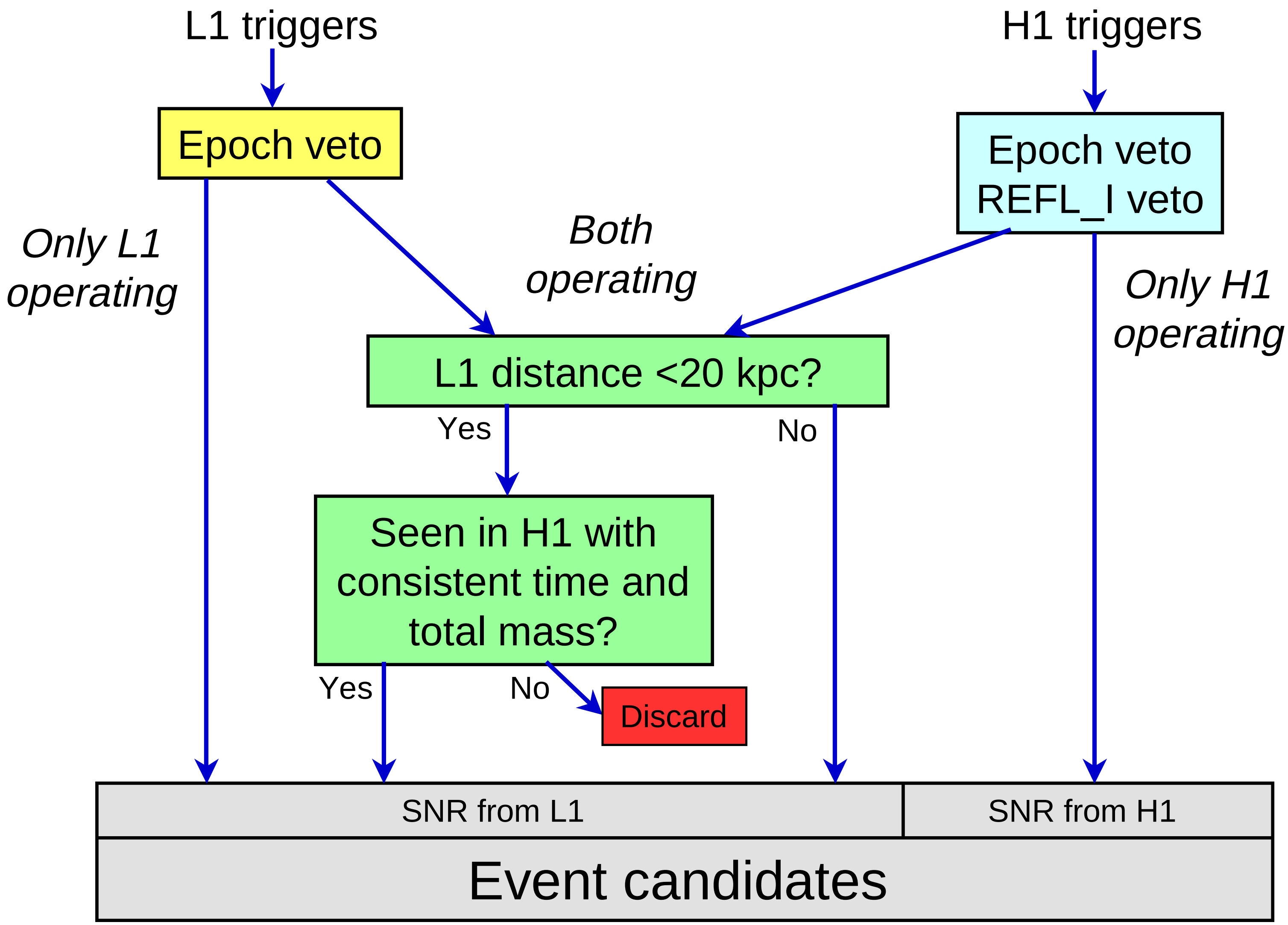
Analysis Pipeline



Statistical Method

***Expected* rate in Milky Way is very low !**

Philosophy: concentrate on getting best upper limit
$\Rightarrow$ Use all four categories of event candidates

- Yields 289 hours of observation time, vs. 116 hours of simultaneous L1+H1 operation

Add together SNR distributions from each category

Use the "maximum-SNR statistic"

- Because it's hard to know *a priori* where one should set a threshold
- Useful since candidate events are so sharply peaked at low SNR
- Yields a frequentist upper limit, $R(90\%) < 2.3 / (\varepsilon \, T)$

ε: Efficiency of analysis pipeline above observed max SNR

T: Observation time

Calculating the Efficiency of the Analysis Pipeline

Use a Monte Carlo simulation of sources in the Milky Way and Magellanic Clouds

- Mass and spatial distributions taken from simulations by Belczynski, Kalogera, and Bulik, Ap J **572**, 407 (2002)
- Inspiral orientation chosen randomly
- Distribution of Earth orientation is same as for S1 data

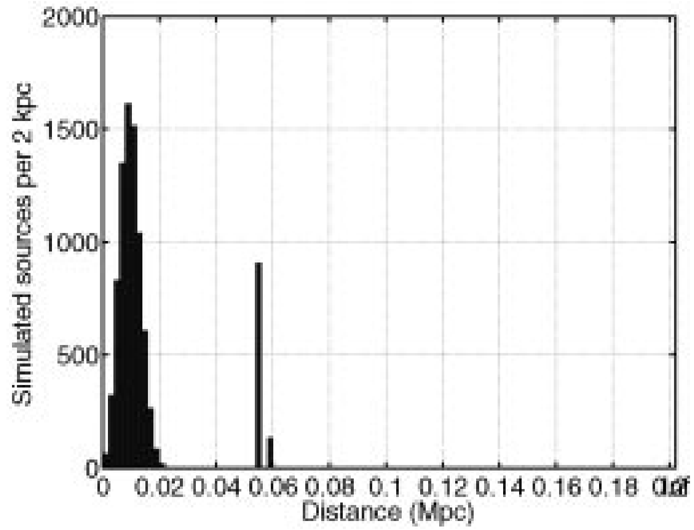
Add simulated waveforms to the real S1 data

Run the full analysis pipeline

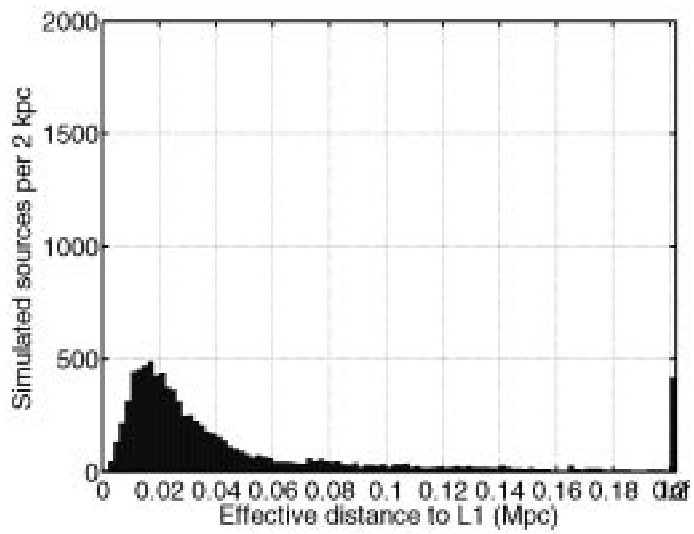
Look at what simulated events are found

Distributions from the Simulation

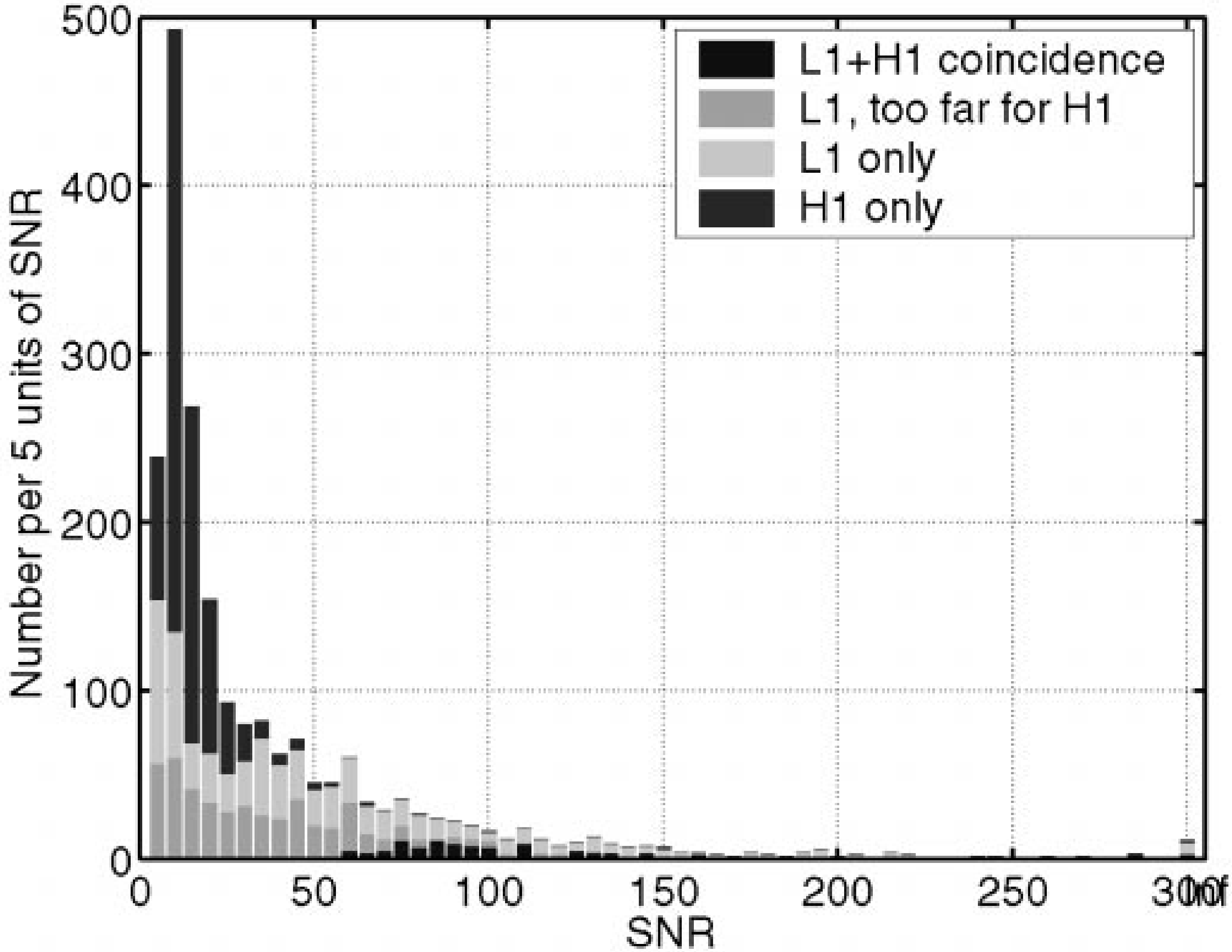
Actual Distance



Effective Distance



SNR Distribution from Simulation



Preliminary Result
(as presented at AAAS Meeting)

Analyzing full dataset yields a maximum SNR of 15.9

An event seen in L1 only, with effective distance = 95 kpc

There are no event candidates in the coincidence category

⇒ **Pipeline efficiency for Monte Carlo = 0.35**

Observation time = 295.3 hours

⇒ **R(90%) = 170 per year**

Note: This is not the final result

It was calculated without using the epoch veto

Final result will not be too different

Plans to Finish This Analysis

Systematics have not really been evaluated

- Calibration uncertainty
- Uncertainties in power spectrum estimation
- Modeling of sources in galaxy

A paper has been drafted

- Focuses on method as well as giving the result
- Has been reviewed by LSC internal review committee
- Now available to all members of the LSC
- Will be presented at the LSC Meeting next week
- Hope to submit it in the next few weeks

We *must* finish this soon and move on to later data

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The S2 Run

Now in progress !

Began February 14, runs through April 14

Detector sensitivities are much better than for S1

Duty factors are about the same, so far

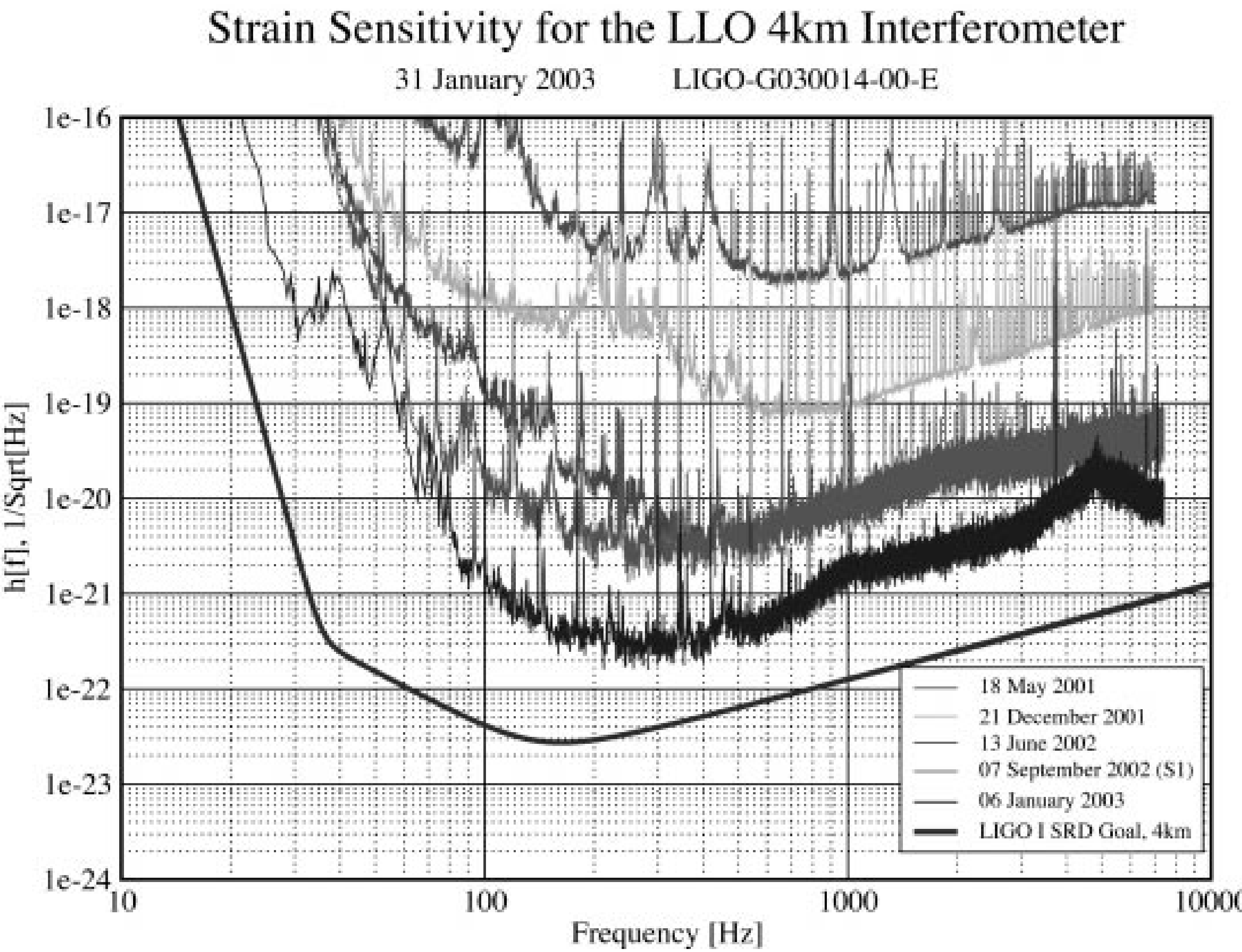
Improvements since S1:

Better alignment control, especially for H1

Better monitoring in the control rooms

Inspiral search code is being run in near-real-time for monitoring purposes

Sensitivity Continues to Improve



L1 should now reach Andromeda and M33 !

H1 and H2 have improved greatly too

Future Directions for Inspiral Searches

Re-think analysis pipeline

May be better to keep categories separate rather than folding them all together

Study additional veto criteria

Some obvious glitches survive the chi-squared veto

Search for higher-mass binaries

Hard to get accurate waveforms

Search for low-mass MACHO binaries

Implement hierarchical search algorithms

Summary

The S1 run provided good data

- We see our whole galaxy

We've learned a lot about the details of doing a full analysis

- Mechanics of data processing
- Calibration, vetoes, statistical methods, …

Much better data is being collected now

- But only yields a modest increase in number of inspiral sources
- The real payoff will come when we reach the Virgo Cluster

⇒ This is only the first of many inspiral searches !