First LIGO Search for Binary Inspirals

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Executive Summary

We searched for inspiral signals from binary neutron star systems using matched filtering

Each mass in the range $M_\odot$ to $3M_\odot$

Used S1 data from the two 4-km interferometers

Analysis “pipeline” checked for coincidence when possible, but otherwise accepted single-interferometer events

Total observation time after data selection cuts: 236 hours

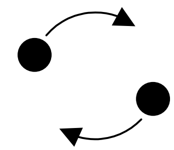
Used Monte Carlo to determine efficiency of pipeline

For a model of sources in the Milky Way and Magellanic Clouds

Set an upper limit: $R < 1.8\times10^2$ per year per MWEG (90% conf.)

Complete draft of paper will be distributed to LSC next week

Gravitational Waves from Binary Inspirals

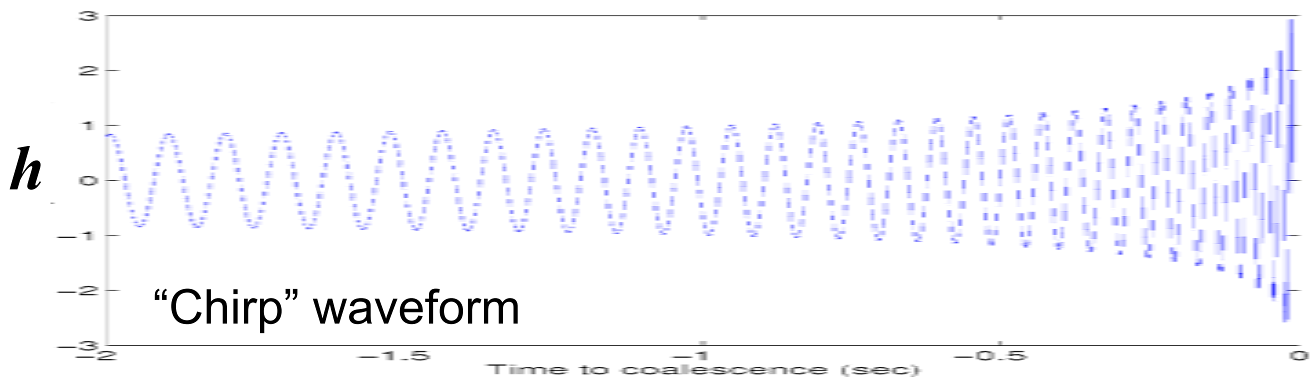


Binary in tight orbit emits gravitational waves

Loss of angular momentum causes orbit to decay

Decay rate accelerates as orbital distance shrinks

Waveform is well known if masses are small

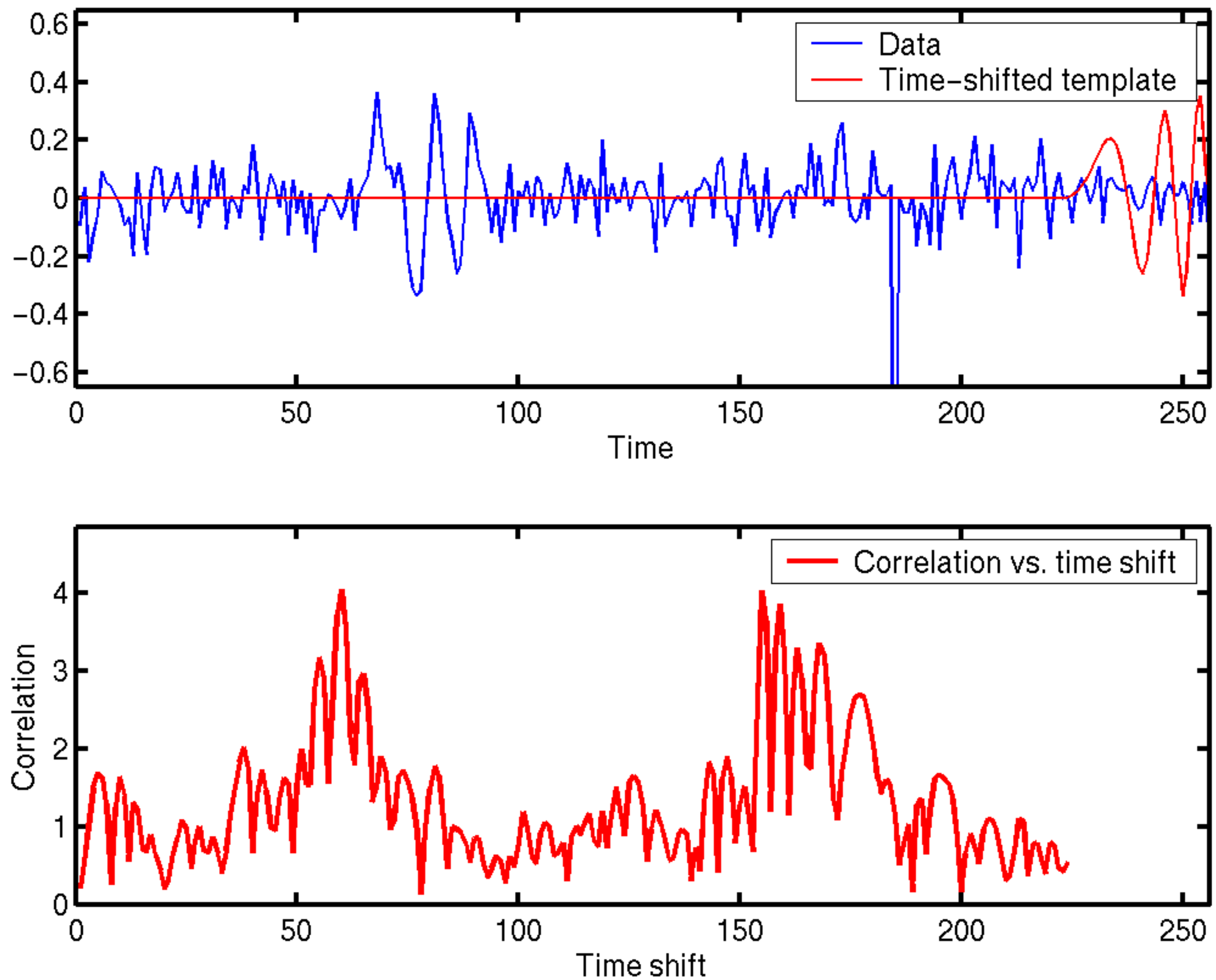


Enters LIGO sensitive band ~seconds before coalescence

Binary neutron star systems are known to exist !

e.g. PSR 1913+16

Illustration of Matched Filtering



Optimal Filtering in Frequency Domain

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

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

Correlate, weighting by power spectral density of noise:

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

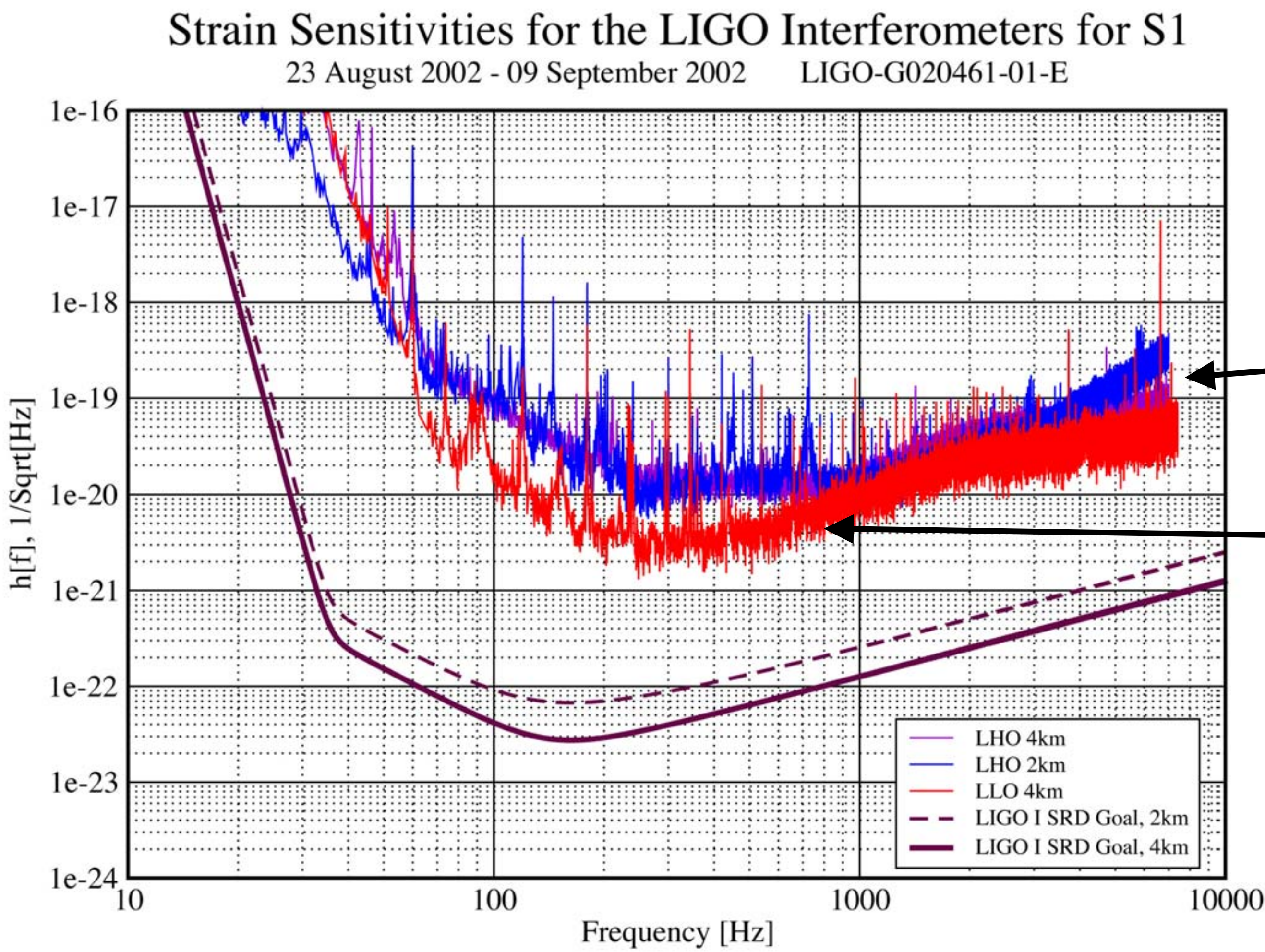
Then inverse Fourier transform gives you the filter output at all times:

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

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

Characterize these by *signal-to-noise ratio* (SNR) and *effective distance*

Strain Sensitivities During S1



Distance at which an optimally oriented 1.4+1.4 $M_{\odot}$ inspiral would yield SNR=8:

H1 & H2
~45 kpc

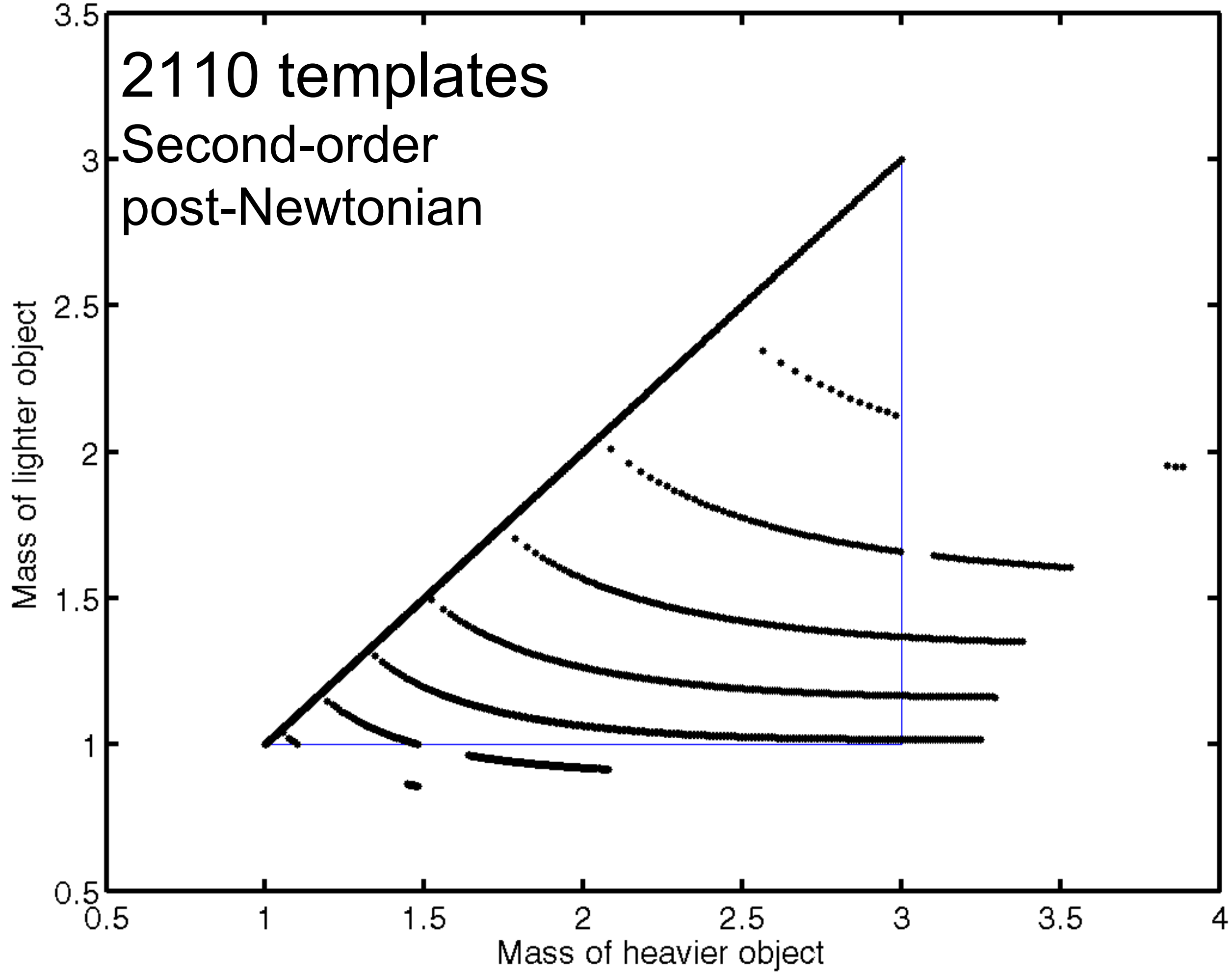
L1
~175 kpc

Template Bank Used for S1

Covers desired region of mass param space

Calculated based on L1 noise curve

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



Chi-Squared Test

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

A real inspiral has signal power distributed over frequencies in a particular way

Divide template into p parts, each expected (on average) to contribute equally to SNR, and calculate a χ^2 :

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

(We use p = 8)

"Veto" events with large χ^2

Allow for large signals which may fall between points in the template bank

$$\chi^2(t) \leq 5 \left(p + \mathrm{SNR}^2 \delta^2 \right)$$

Data Processing

The search was performed using routines in 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 number crunching for this analysis was done on the UWM LDAS system →

Each job processed 256 seconds of data

- Consecutive jobs overlapped by 32 seconds
- Triggers which exceeded an SNR threshold of 6.5 and passed the chi-squared test were written to the LDAS database

Statistical analysis was done with C programs, Tcl scripts, Matlab, …

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 a χ^2 value well below the cut

Real Detectors…

… are not on all the time

- ⇒ Only process the good data (requires bookkeeping)
- ⇒ Need to decide how to use the data from each detector

… have time-varying response

- ⇒ Need calibration as a function of time

… have time-varying noise

- ⇒ Discard data when detector was not very sensitive (“epoch veto”)
- ⇒ Estimate noise power spectral density, $S_h(f)$, from the data input to each 256-second-long LDAS job

… have “glitches”

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

Making Choices about the Analysis

Wanted to avoid bias when deciding:

- How to use data from the different interferometers
- Epoch veto thresholds
- Auxiliary-channel vetoes

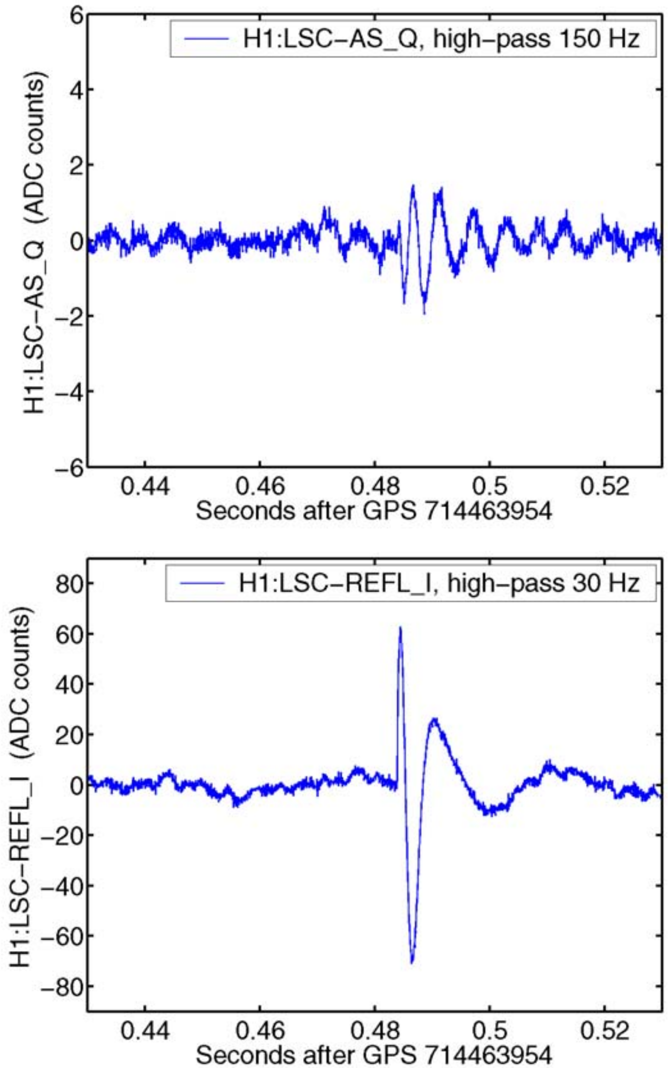
There could be bias if these decisions were made based on the set of events from which the result is calculated

Solution: set aside a fraction of the data as a "playground"

- Selected ~10 hours of data from various times during S1
- Made all decisions based on studying this sample
- Hoped it would be representative of the full data set
- Avoided looking at the remaining data until all choices have been made

Final result was calculated from the remaining data

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 for almost all such glitches in H1

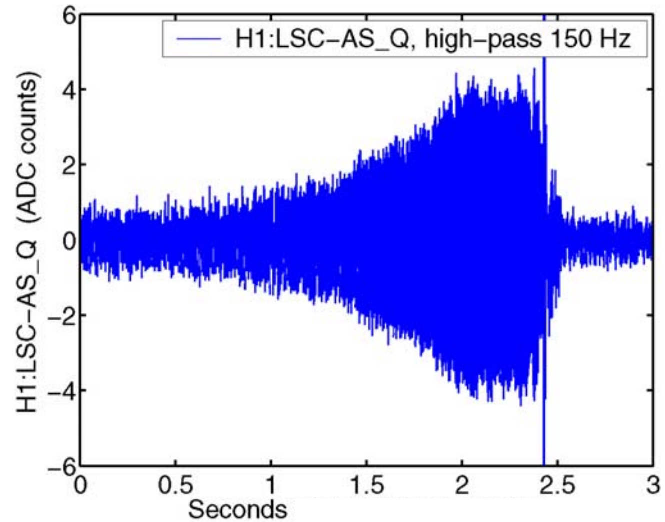
Use "glitchMon" software to generate *veto triggers*

(Thanks to burst group for help)

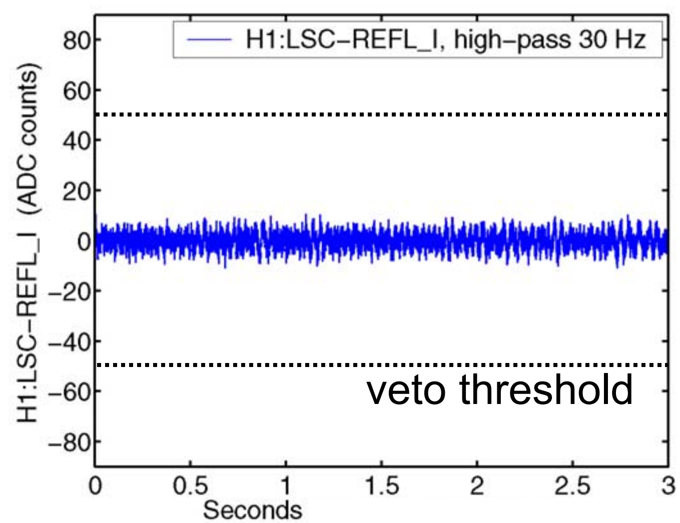
Veto Safety

Have to be sure a real gravitational wave wouldn't couple into the auxiliary channel strongly enough to veto itself !

Check using hardware signal injection data

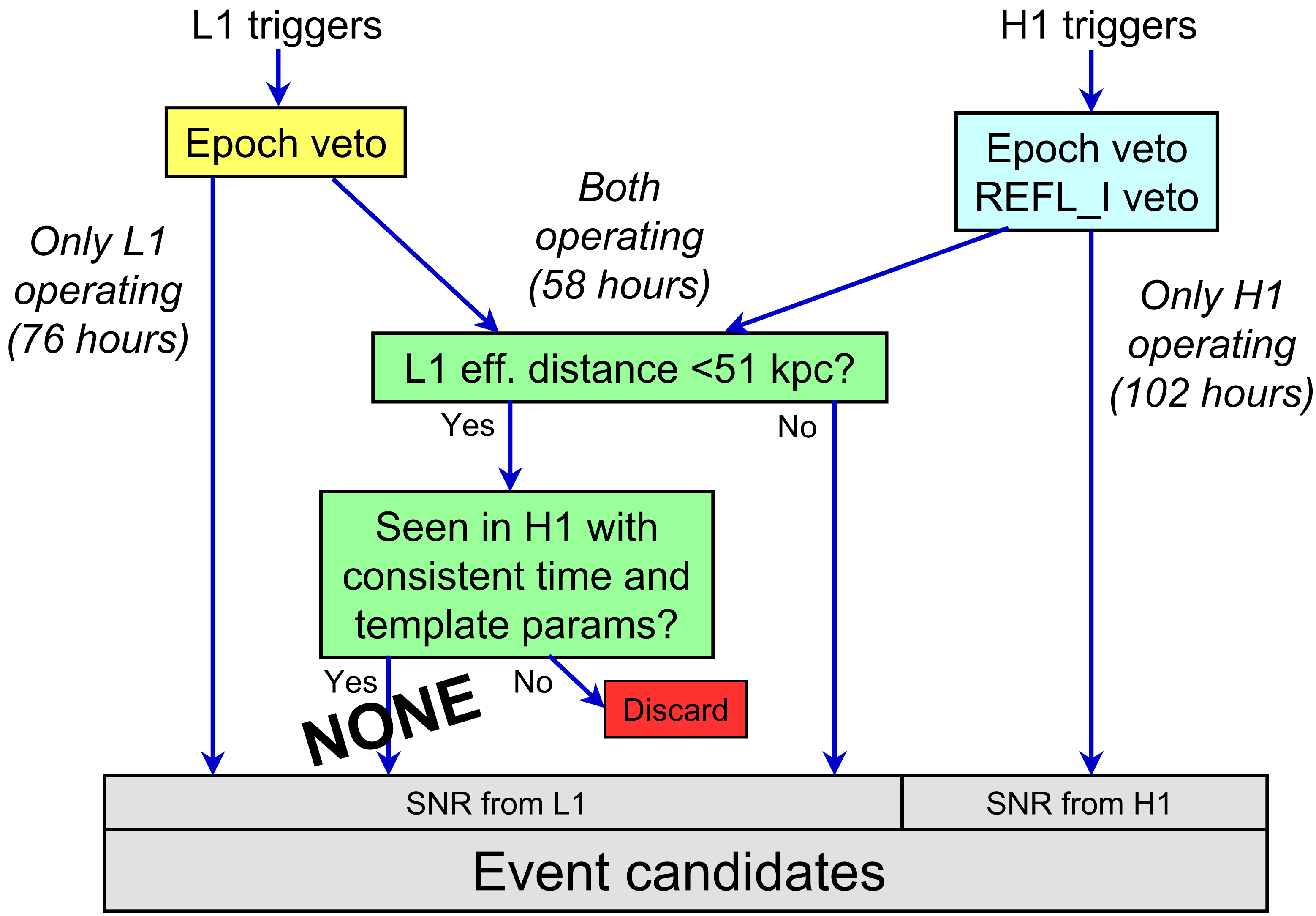


No sign of signal in REFL_I



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

Analysis Pipeline



Upper Limit Calculation

Add together SNR distributions from all 4 categories

No reliable way to estimate the background for single-interferometer events

Would not claim a detection based on this summed-SNR sample

Hard to know *a priori* where one should set SNR threshold
⇒ Use the "maximum-SNR statistic" to set upper limit

Makes a statistical statement about population above max observed SNR

Useful since background events are so sharply peaked at low SNR

Yields a frequentist upper limit

$$R < \frac{2.3}{N \varepsilon \, T}$$

at 90% C.L.

Size of target population (N)

Efficiency of analysis pipeline, requiring SNR > max SNR in data (ε)

Observation time (T)

Determining the Efficiency of the Analysis Pipeline

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

- N = 1.13 ± 0.06 Milky Way Equivalent Galaxies (MWEG)
- Mass and spatial distributions taken from simulations by Belczynski, Kalogera, and Bulik, Ap J **572**, 407 (2002)
- Orbital orientations chosen randomly

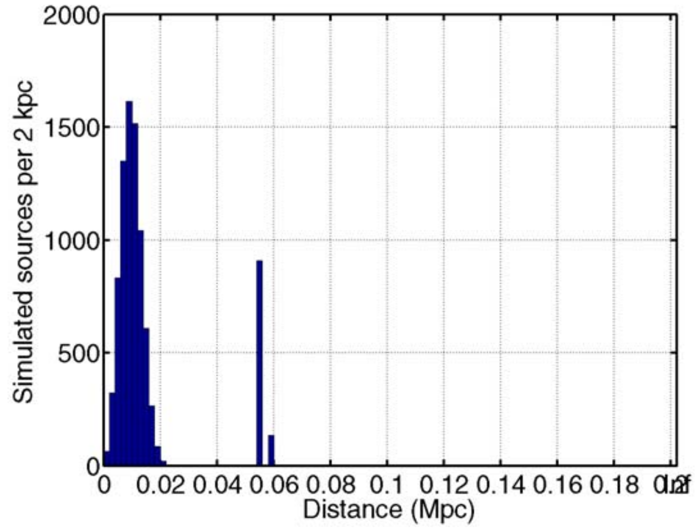
Add simulated waveforms to the real S1 data

Run the full analysis pipeline

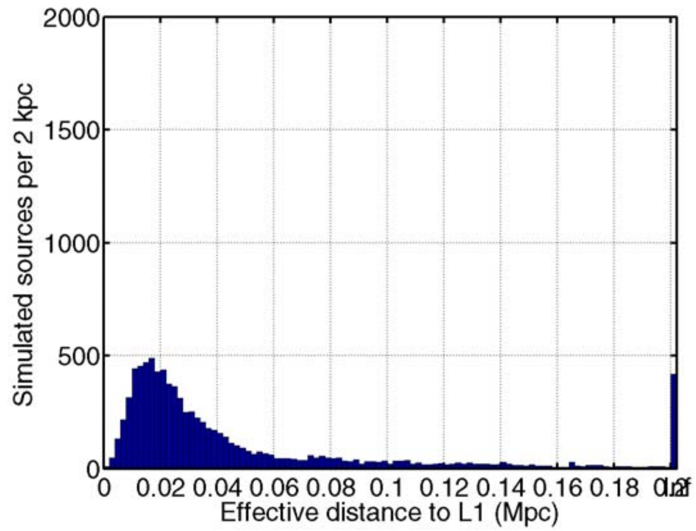
See what fraction of simulated events are found

Distributions from the Simulation

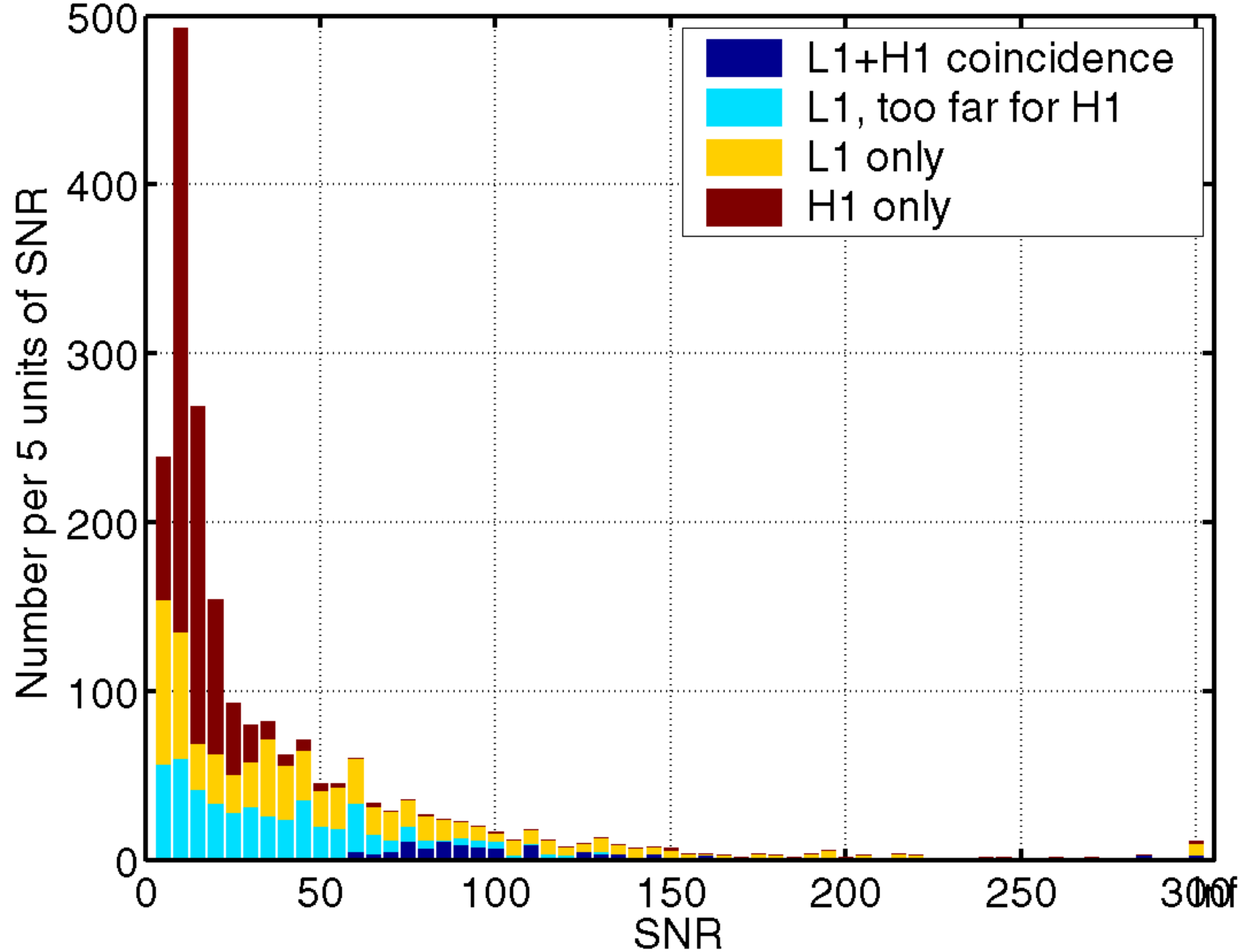
Actual Distance



Effective Distance



SNR Distribution from Simulation



Upper Limit Result

Analyzing full dataset yields a maximum SNR of 15.9

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

Found to be associated with saturation of the photodiode electronics

Several others with SNR>12 (inconsistent with Gaussian stationary noise)

Pipeline efficiency from Monte Carlo (requiring SNR≥15.9) :

$$\varepsilon = 0.51^{+0.07}_{-0.06}$$

Uncertainties from calibration and possible waveform inaccuracies

Observation time = 236 hours

To be conservative, calculate upper limit assuming

N = 1.13–0.06 = 1.07 and ε = 0.51–0.06 = 0.45

$\Rightarrow$ $R < 1.8\times10^2$ per year per MWEG at 90% C.L.

Sociology

A small group of LSC members contributed to this analysis

14 in all, by my count; number of FTEs was maybe ~4

Only a few more are showing signs of being active in S2 data analysis

Communication requires extra effort

Weekly telecons; occasional face-to-face meetings; web-based notebook

Individuals generally play very distinct roles

Analysis pipeline, vetoes, statistical method decided by one or two people

It's *very* hard to check what others have done in sufficient detail

Mistakes were made and not discovered for a long time

Software errors in Monte Carlo simulation

Missing events from some LDAS jobs which failed to insert into database

As a group, we're still learning how to scrutinize sufficiently…

Plans for Future Inspiral Searches

Avoid repeating past mistakes!

Include more interferometers, as appropriate

Better knowledge of data quality and inter-channel coupling

Study additional signal consistency checks

- The chi-squared veto does not use “off-chirp” information

Search for higher-mass binaries

- Challenge to get accurate waveforms

Search for low-mass MACHO binaries

- Primordial black holes in halo of our galaxy ?

Do coherent analysis of data from multiple detectors

- Restructure analysis pipeline

Implement hierarchical search algorithm(s)

Summary

The S1 run provided good data

- We had good efficiency for sources throughout our galaxy

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

- Software, mechanics of data processing
- Calibration, vetoes, multi-detector strategy, statistical methods, …

We managed to do a fairly sophisticated, scientifically valid analysis for one particular class of sources

There are plans to do more with S2 and future data

- There are lots of ideas waiting to be made reality
- It takes a lot of time and effort to develop and fully implement data analysis techniques, and to manage the bookkeeping, studies and cross-checks that are necessary to validate an analysis