Search for Black Hole Ringdown Signals in LIGO Data

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for the LIGO Scientific Collaboration

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Overview

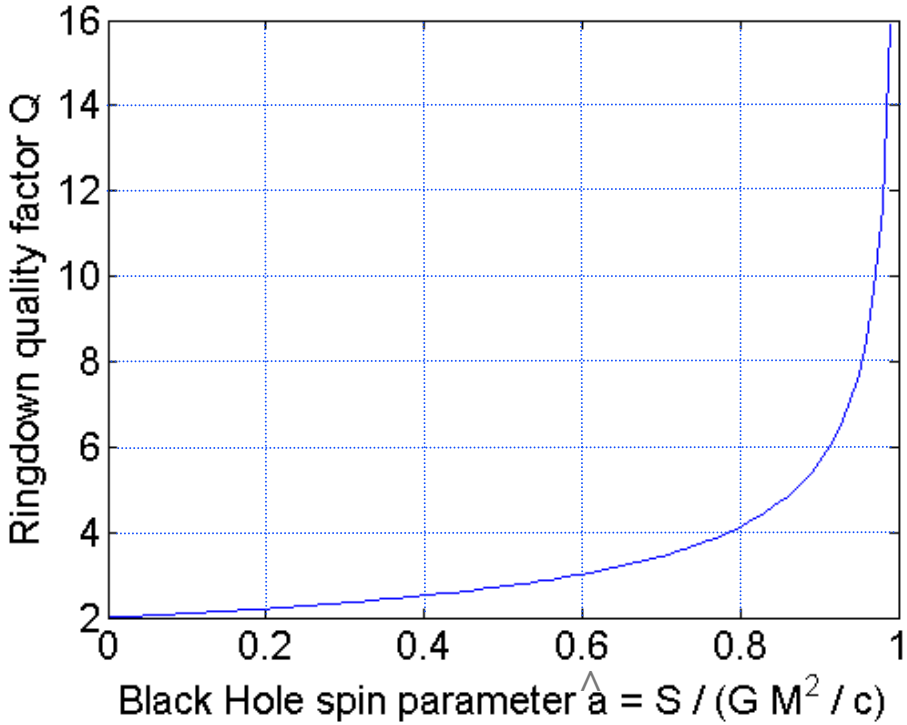
- **Black hole Perturbations**
  - Quasi-normal Modes
  - Astrophysical Motivation
- **Ringdown Analysis Pipeline**
  - Methods
  - Tuning
- **S4 Ringdown Search**
  - Background estimation
  - Software Injections
  - Playground analysis
- **Preliminary Results**

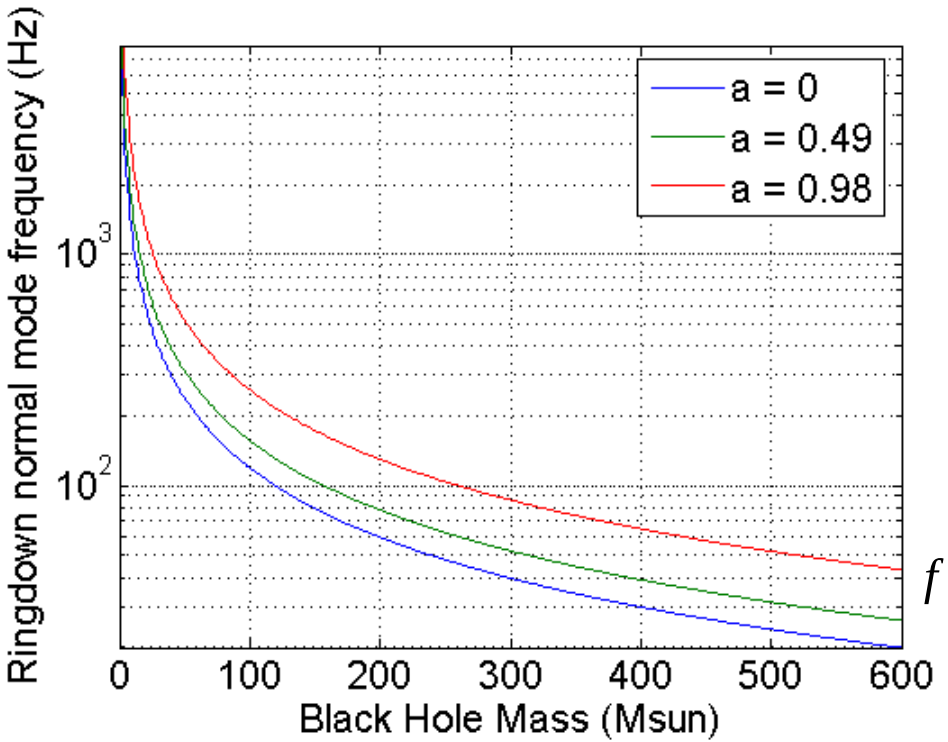
Black Hole Perturbations

- If a black hole exists in a perturbed state, the perturbations will be radiated away as gravitational waves.
- Superposition of quasi-normal modes, each with a distinct frequency and damping time (Veshveshwara '71).
- Dominant mode is expected to be a spheroidal harmonic of spin weight 2 (Teukolsky '73).
- Detection of a single mode would allow us to determine the mass and spin of the black hole, while multi-mode detection would provide a direct test of the Kerr nature of the source.
  (Dorband et al, arxiv :gr-qc/0608091)

Black Hole Perturbations

- **Waveform Parameters to Astrophysical quantities**
  - For the Y_2^2 mode, f_0 & Q are unique and invertible functions of mass and spin





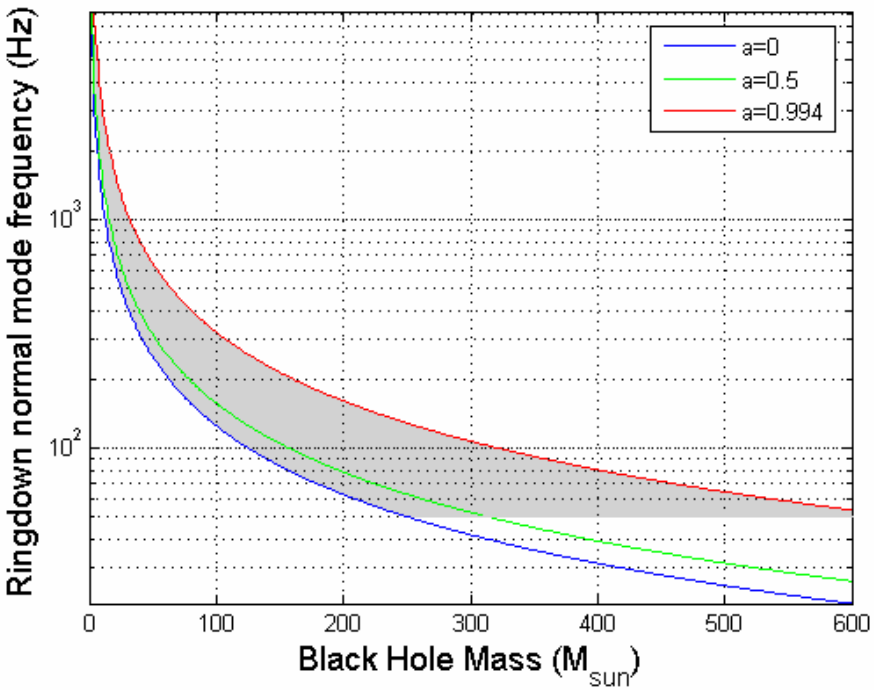
$$Q \approx 2(1-\hat{a})^{-\frac{9}{20}}$$

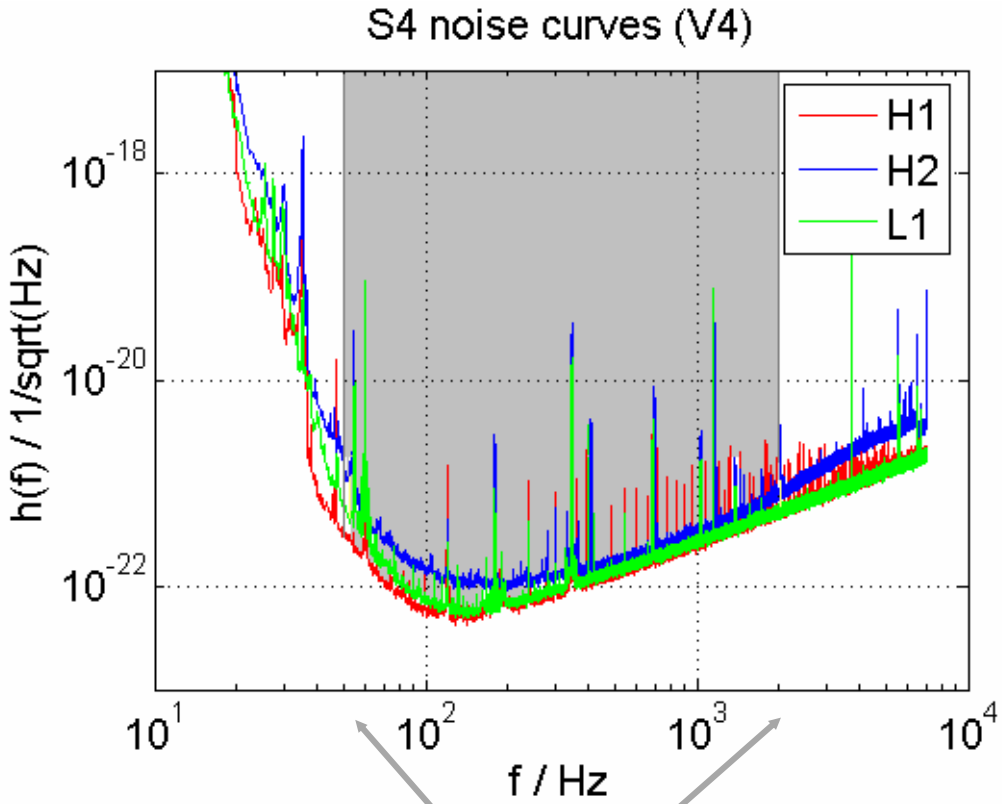
$$f = \frac{c^3}{2\pi GM}\left[0.63(1-\hat{a})^{\frac{3}{10}}\right]$$

[Echeverria '88]

Black Hole Perturbations

- **Waveform Parameters to Astrophysical quantities**



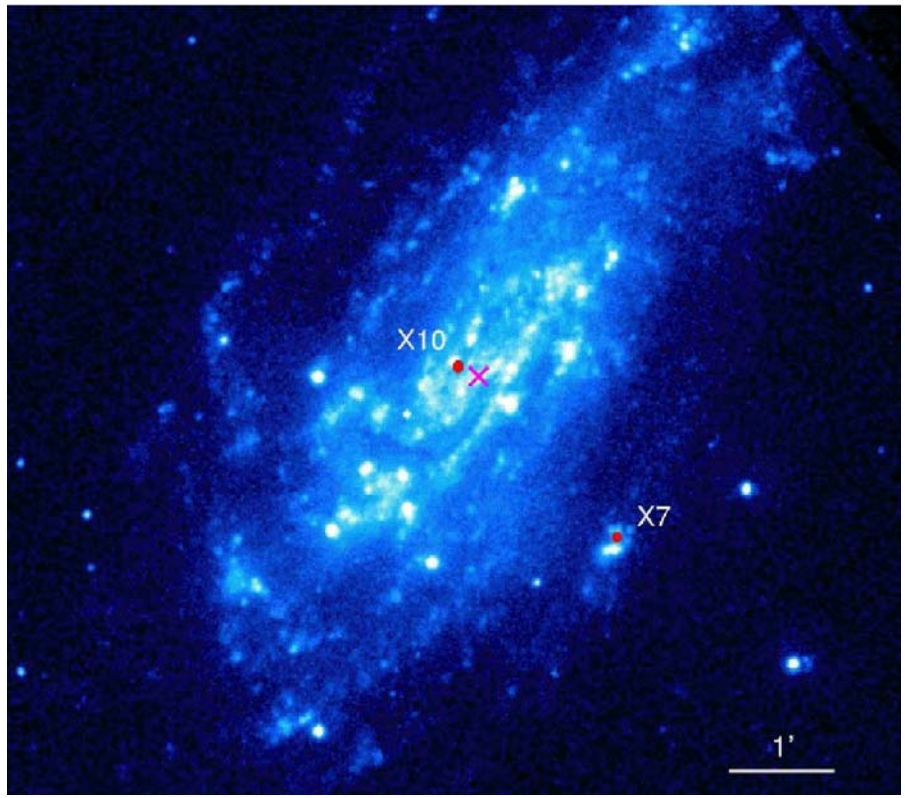


Sensitive between 50Hz and 2kHz

IMBH range

Intermediate Mass Black Holes (IMBH)

- $10^2\ M_{sun} < M < 10^5\ M_{sun}$
- Less evidence for their existence than for stellar and supermassive BH's
- Observational hints from studies of
  - ultraluminous X-ray sources
  - kinematics of central regions of nearby galaxies and globular clusters
- Formation scenarios include
  - Runaway growth of a supermassive star, collapsing to a BH
  - core collapse of massive young star cluster



NGC 4559, XMM-Newton image, Cropper et al 2004

Detection of gravitational waves from black holes in this mass range would provide key evidence for the existence of IMBHs.

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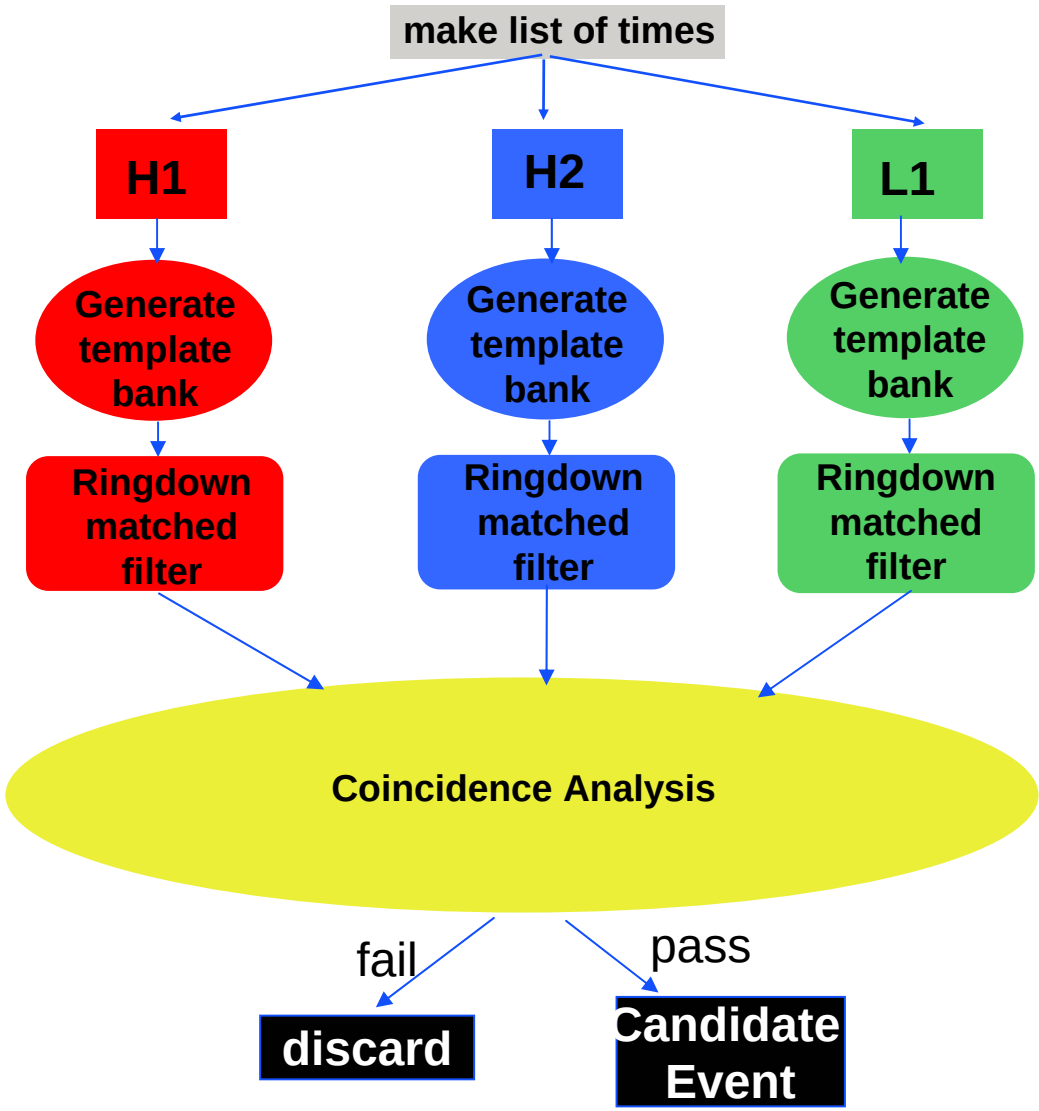
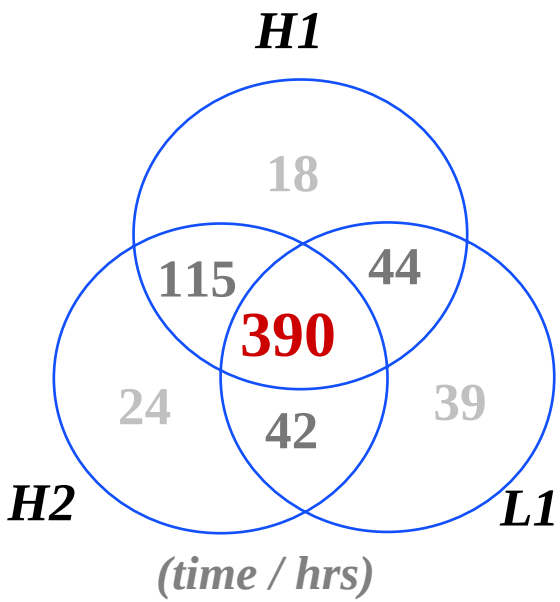
Ringdown Analysis Pipeline



Ringdown Analysis Pipeline

Segment Selection

- S4 took place over 30 days, February 22nd to March 24th, 2005
- Considering times when all three interferometers were taking science data for the upper limit calculation
- In addition, look at coincidences between two interferometers for detection purposes
- Results show here are from triple times only



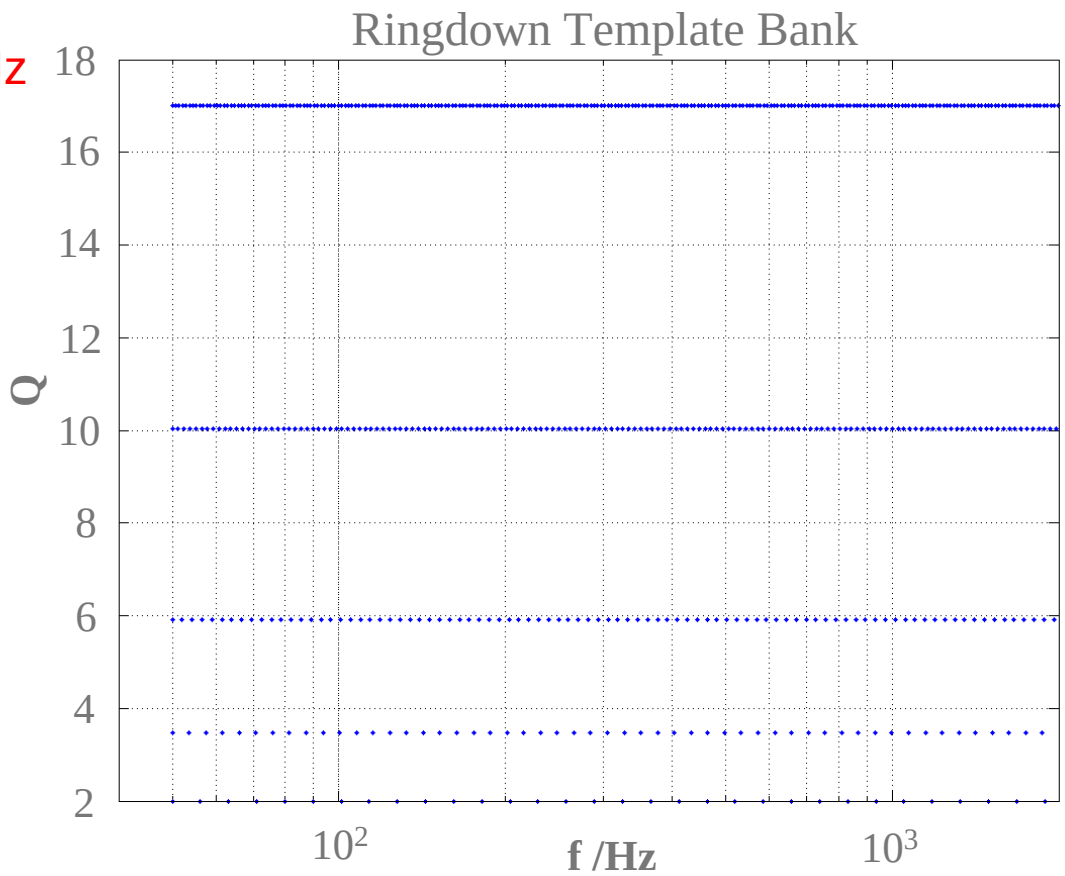
Ringdown Analysis Pipeline

❑ Generate Template Bank

- In frequency 50Hz < *f* < 2kHz
  & quality 2 < *Q* < 20
- According to metric
  [J. Creighton '99]:

$$ds^2 \approx \frac{1}{8}\frac{dQ^2}{Q^2} - \frac{1}{4}\frac{dQ}{Q}\frac{df}{f} + Q^2\frac{df^2}{f^2}$$

- maximum mismatch of 3%
- ~ 580 templates



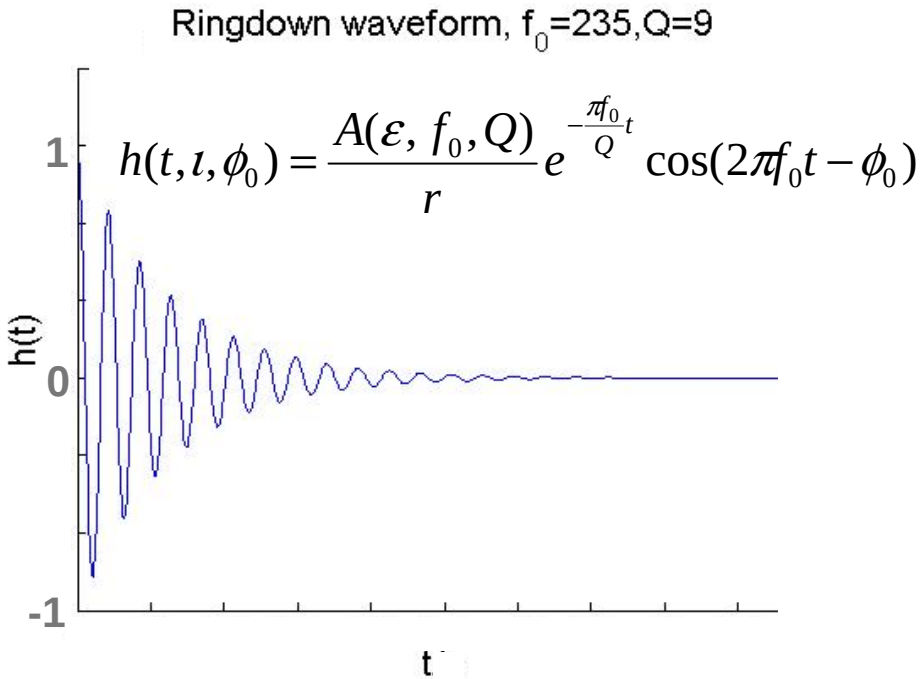
Ringdown Analysis Pipeline

Matched Filtering

- Ringdown template is a damped sinusoid
- Filter with data, get signal to noise ratio ρ.
- Keep trigger if ρ greater than threshold $\rho^*=5.5$
- Calculate effective distance d_{eff} to source (distance from which the source would produce the same signal if optimally oriented)

$$d_{eff} = \frac{\sigma}{\rho}$$

Variance of matched filter output due to detector noise



- Assume the percentage of mass emitted as gravitational waves, ε = 1%. d_{eff} scales as $\varepsilon^{1/2}$

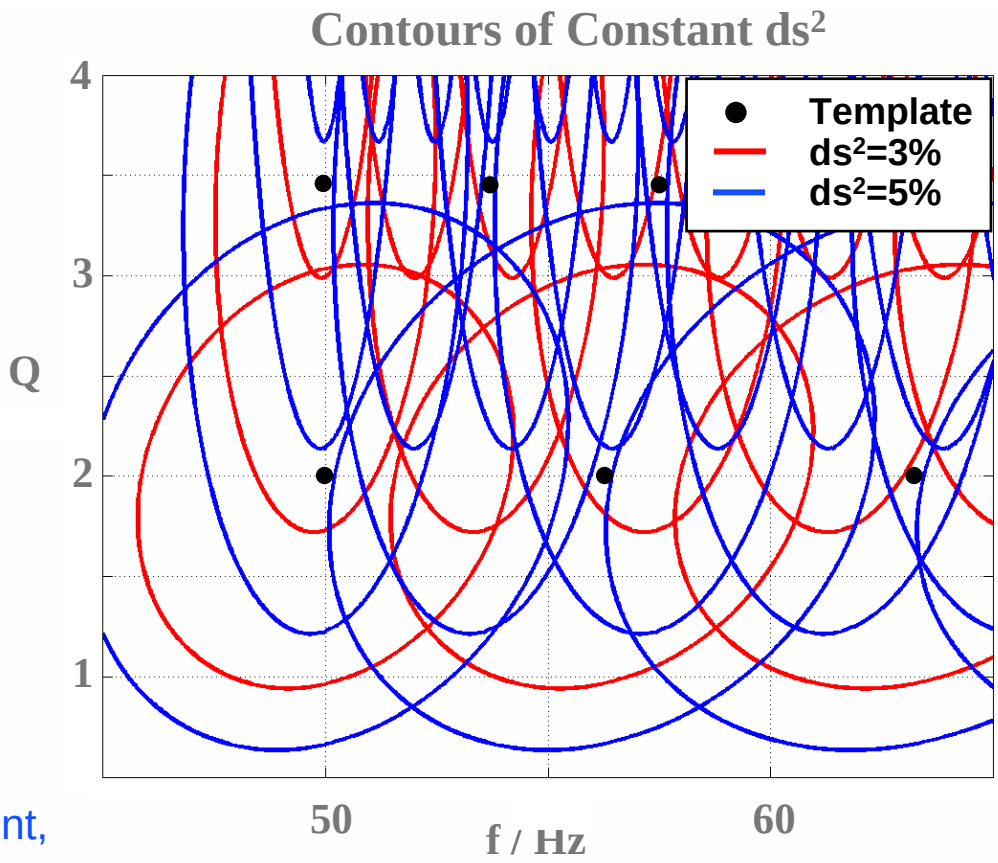
Ringdown Analysis Pipeline

❑ Coincidence Requirements

- Time:
  - ❖ $\Delta t = \pm 2$ms (+light travel time)
- Waveform parameters
  - ❖ Combine f & Q via the metric

$$ds^2 \approx \frac{1}{8}\frac{dQ^2}{Q^2} - \frac{1}{4}\frac{dQ}{Q}\frac{df}{f} + Q^2\frac{df^2}{f^2}$$

  - ❖ Contours of constant ds^2
  - ❖ Specify threshold ds^2
  - ❖ For templates from different interferometers to be coincident, contours must overlap



Tuning the Search

Injections

- Add simulated signals to the data stream, run the pipeline and see how well the parameters are recovered.
- Ringdown injections are uniform in waveform parameters, sky position and orientation

Timeslides

- Slide data sets with respect to one-another 100 times and look for ‘false’ coincidences
- For each slide shift H2 by 5s and L1 by 10s

Playground

- We look at ~1 tenth of the data upfront, compare with background

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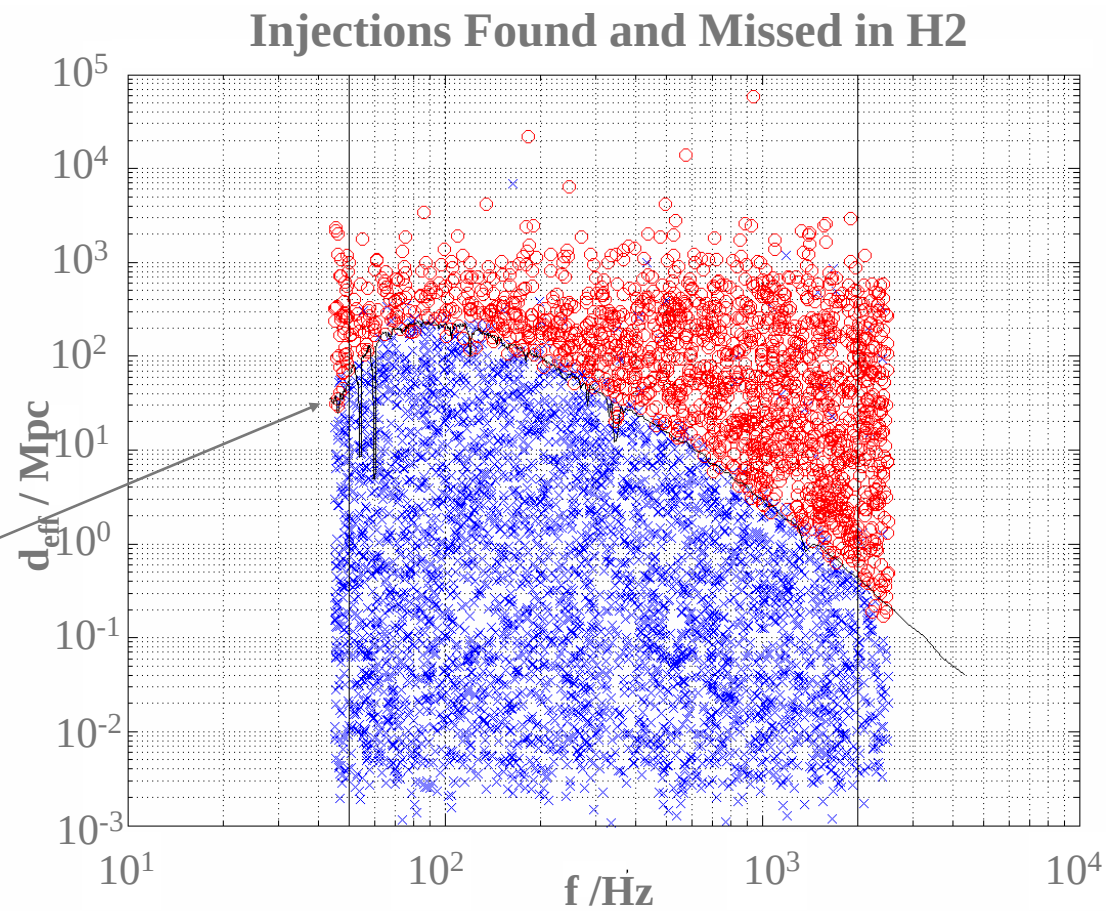
S4 Ringdown Search

❑ Injections

- ➢ May be found in one …

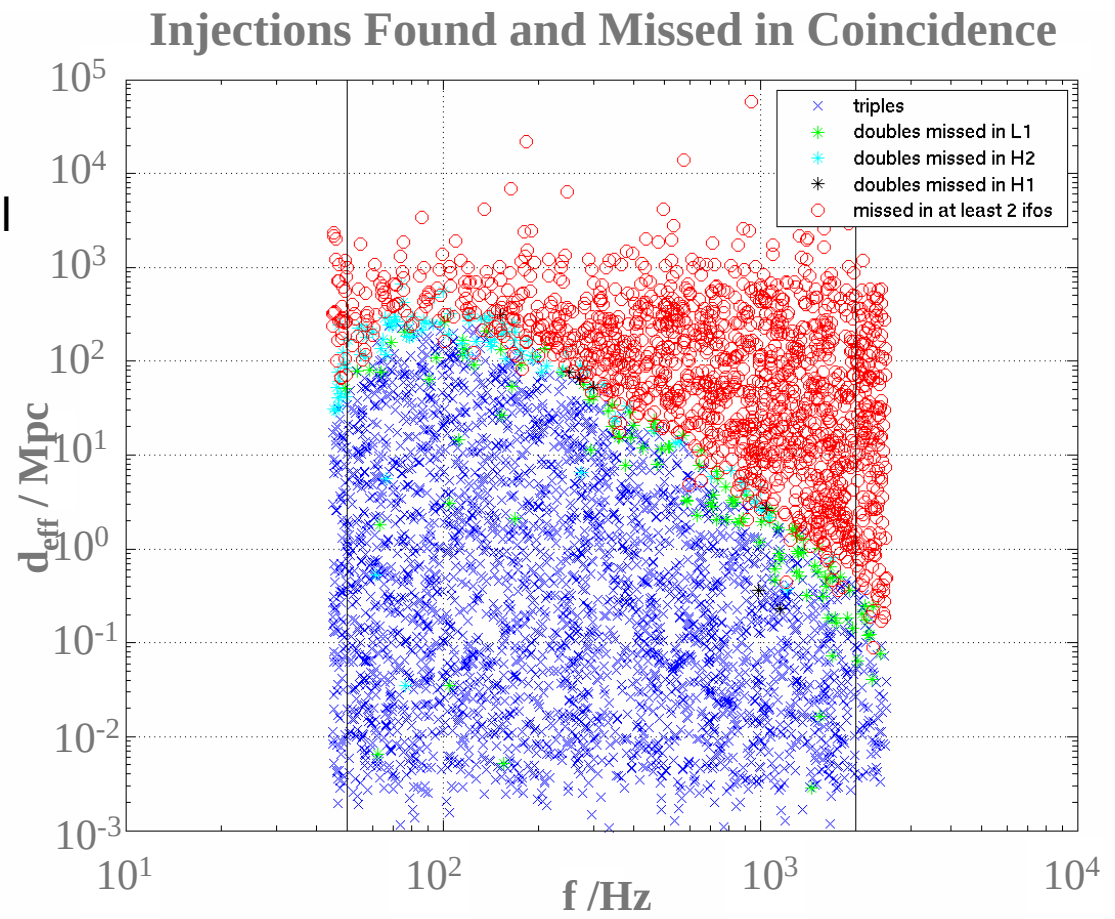


Horizon distance: distance to an optimally oriented and located source with $\hat{a}$=0.98 producing ρ =5.5 in detector

S4 Ringdown Search

❑ Injections

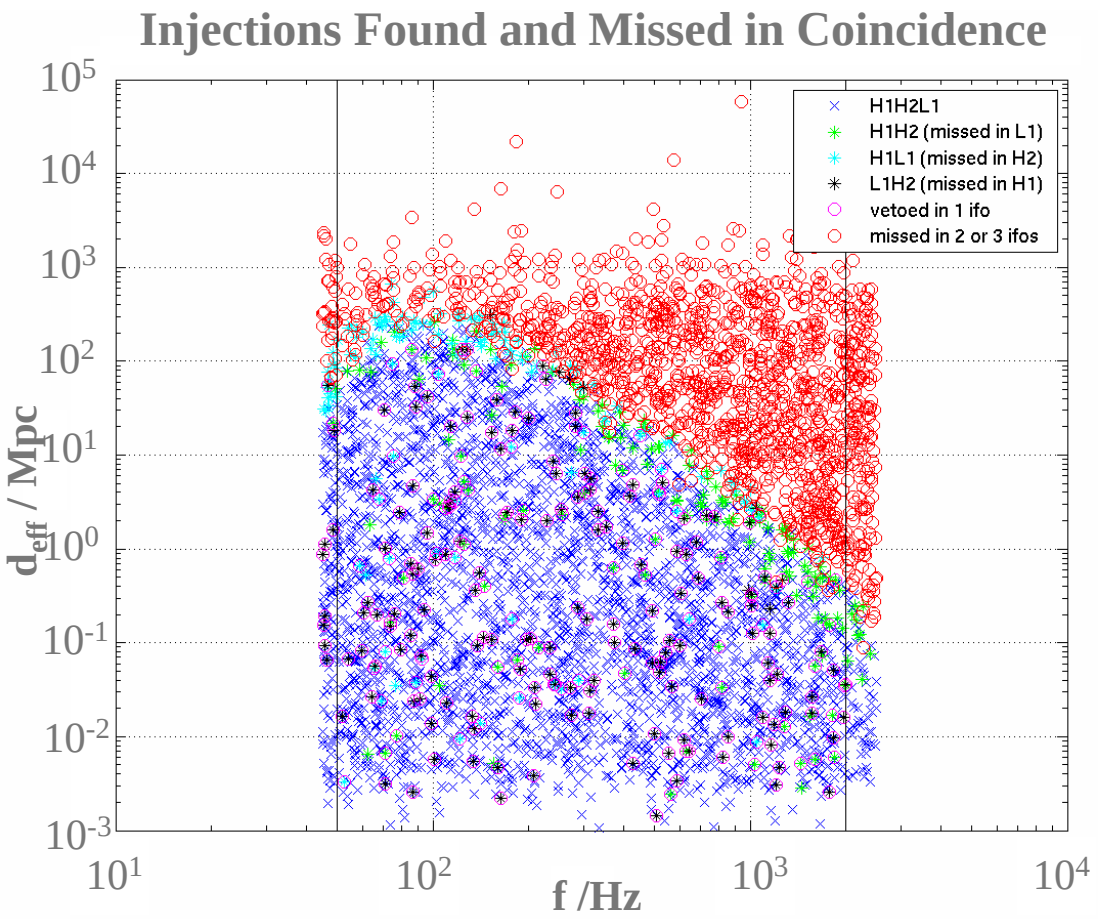
- May be found in one, two (double coincidence) or all three (triple coincidence) interferometers



S4 Ringdown Search

❑ Injections

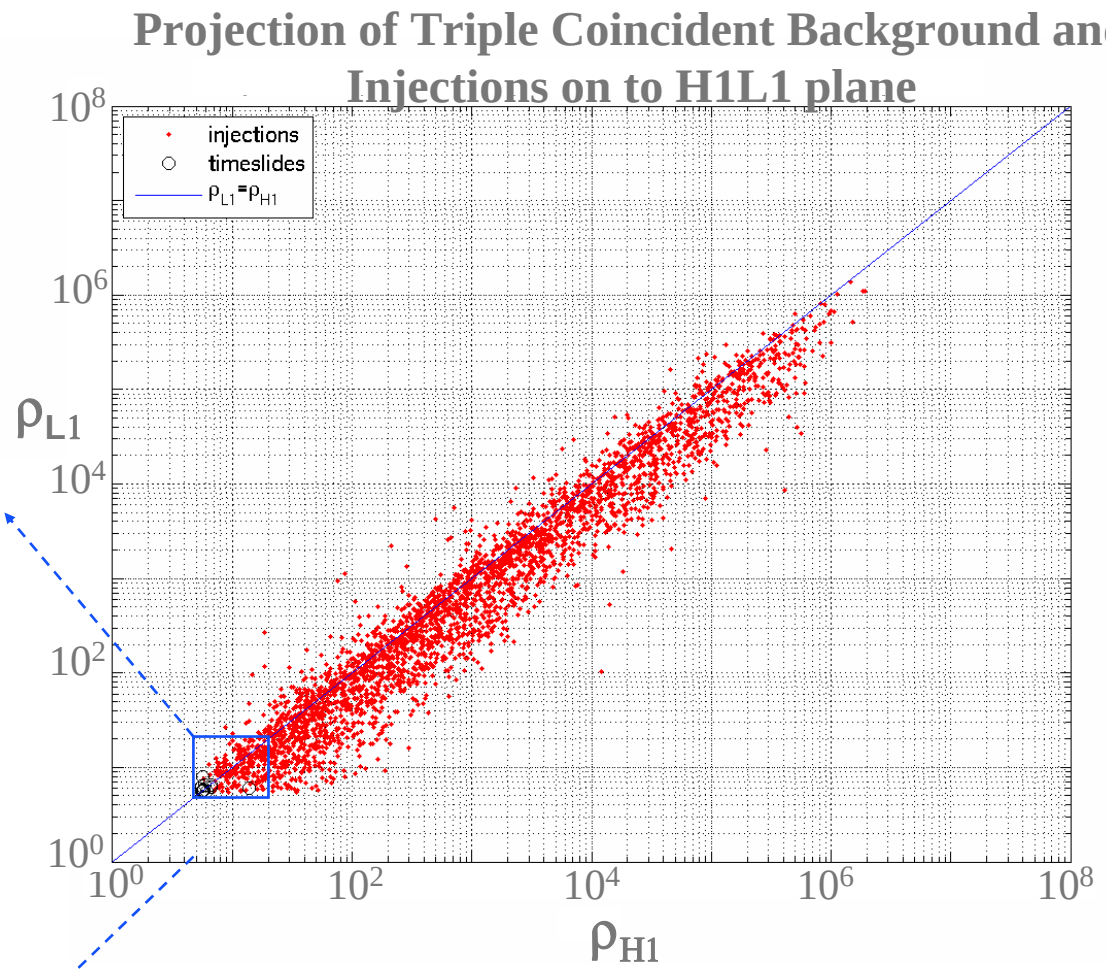
- May be found in one, two (double coincidence) or all three (triple coincidence) interferometers
- Veto times when we know there was activity that effected the quality of the data (e.g. seismic disturbances, hardware injections)

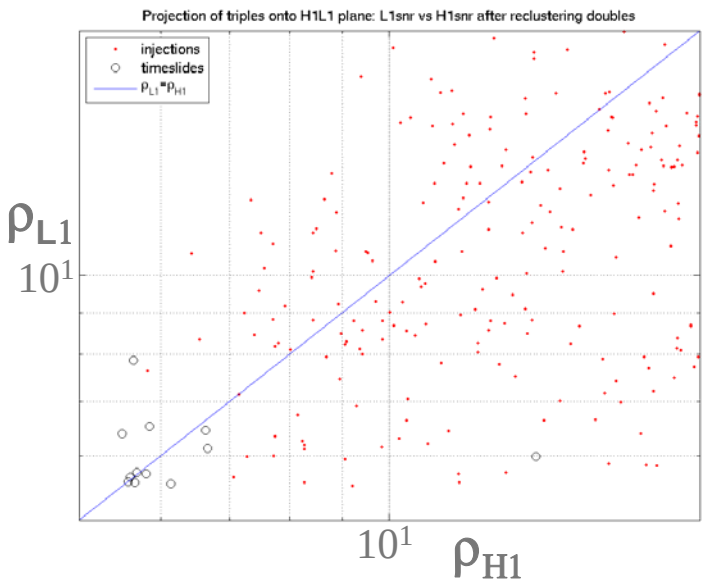


S4 Ringdown Search

❑ Triple Coincidence Background Estimation

- Low rate of background in triple coincidence, less than 1 false coincidence per S4 run

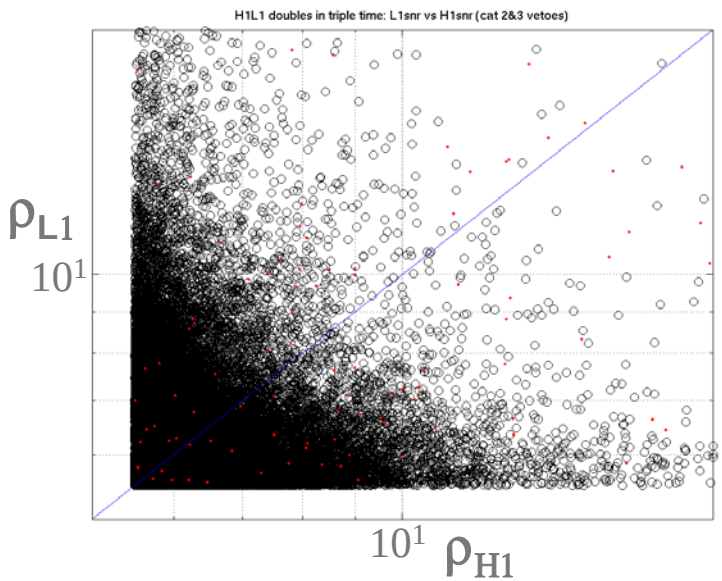


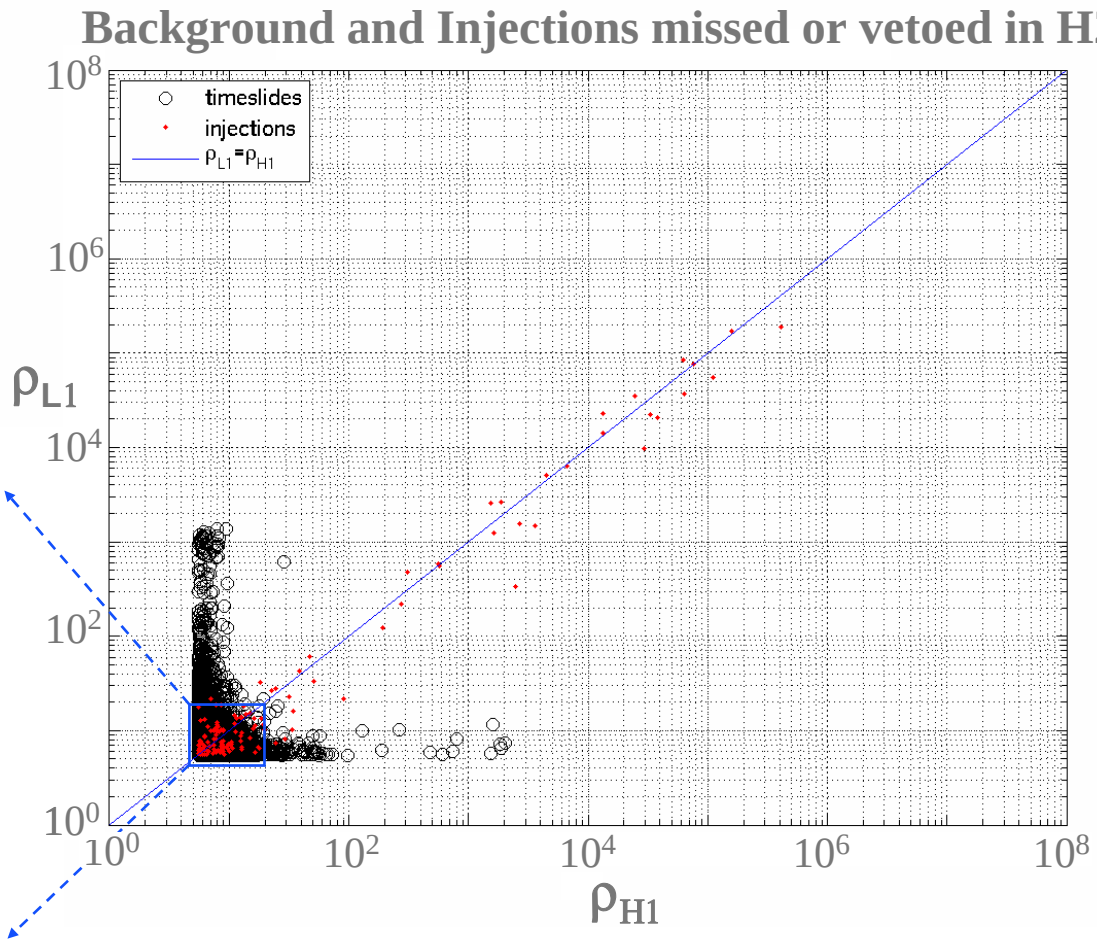


S4 Ringdown Search

❑ Double Coincidence Background Estimation

- High rate of background in double coincidence, ~2 false coincidences per hour of triple time

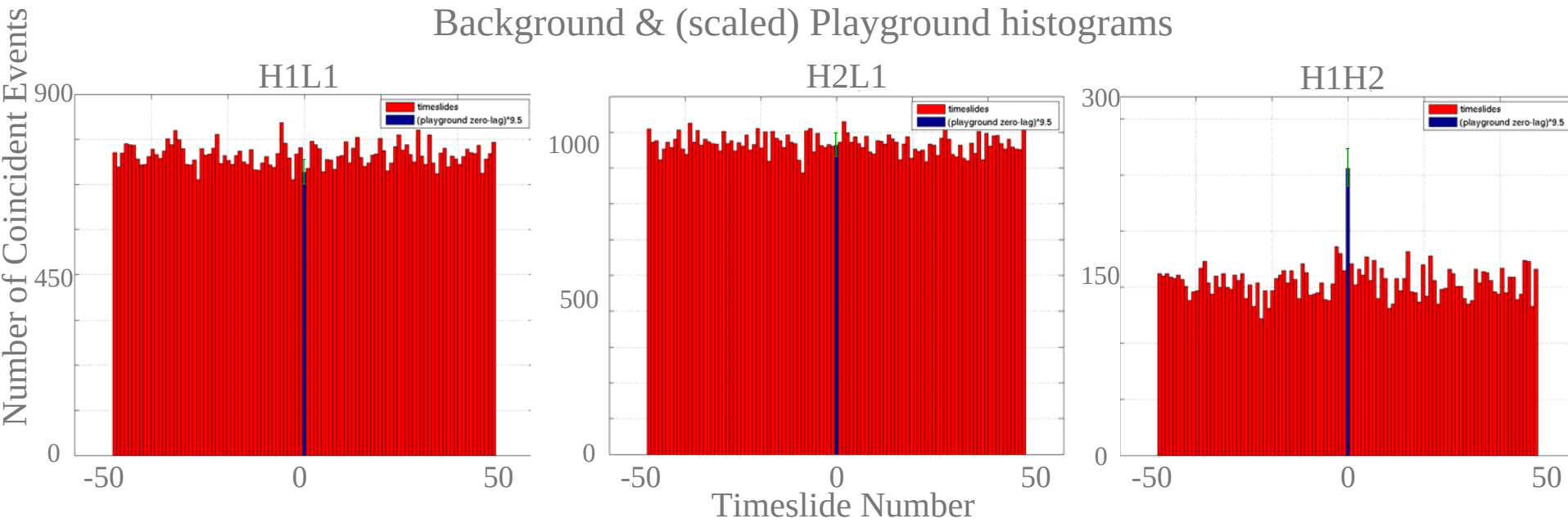




S4 Ringdown Search

❑ Playground (~10% of data set)

- ➢ No triple coincident events found in the playground
- ➢ Double coincidences found in the playground consistent with background in H1L1 and H2L1. The H1H2 background more difficult to estimate



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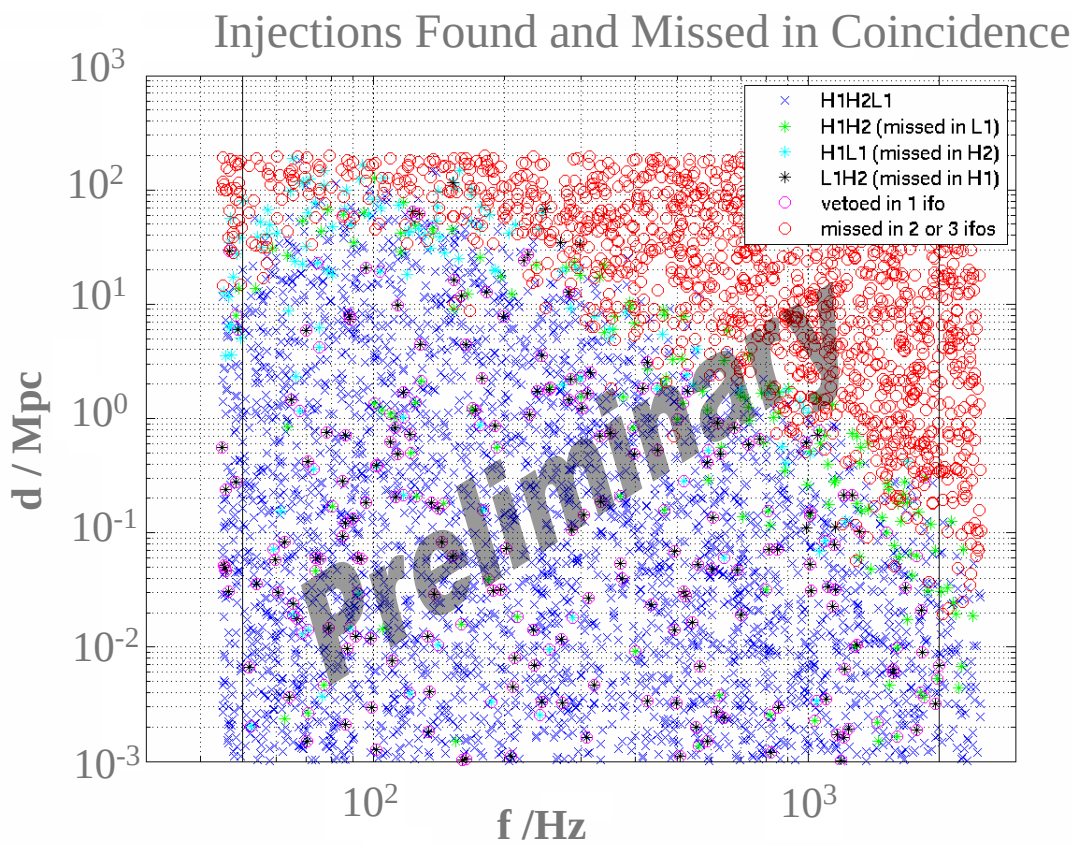
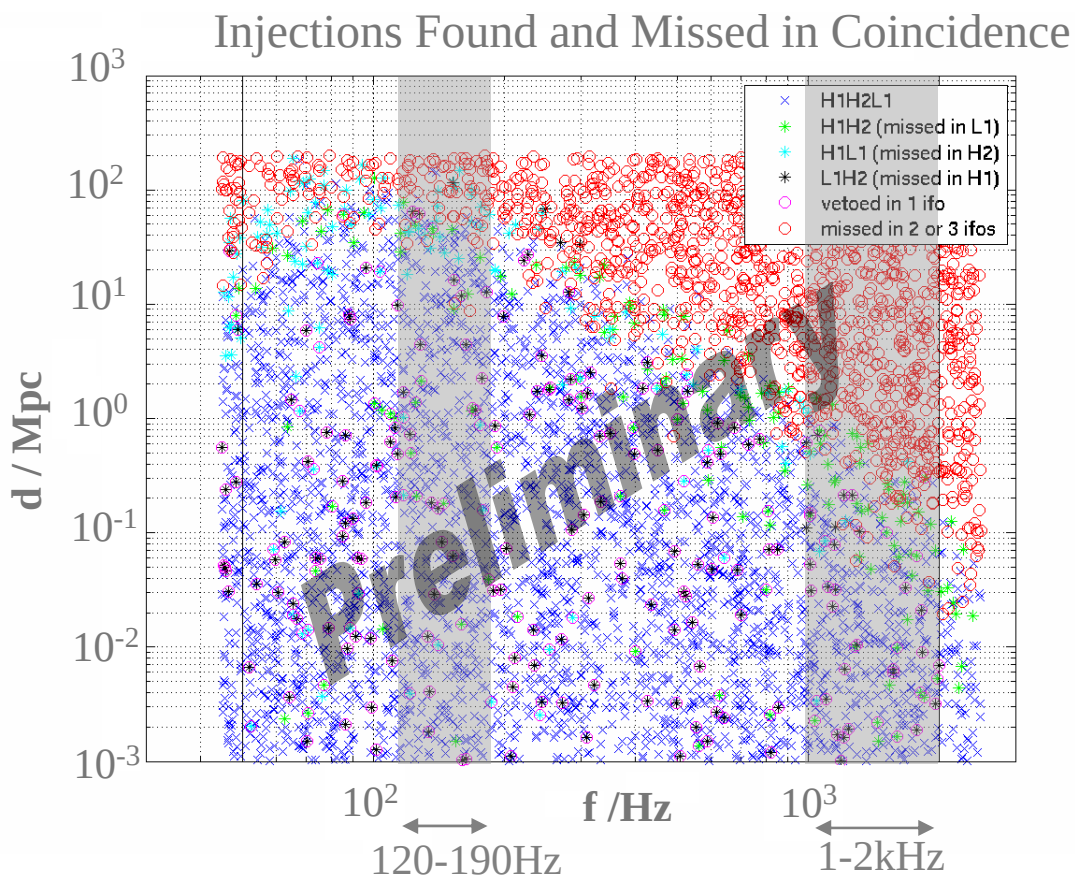
Full Data Set

- **Box has been opened**
  - results are under LSC review
  - Using injections can estimate efficiency at threshold



Full Data Set

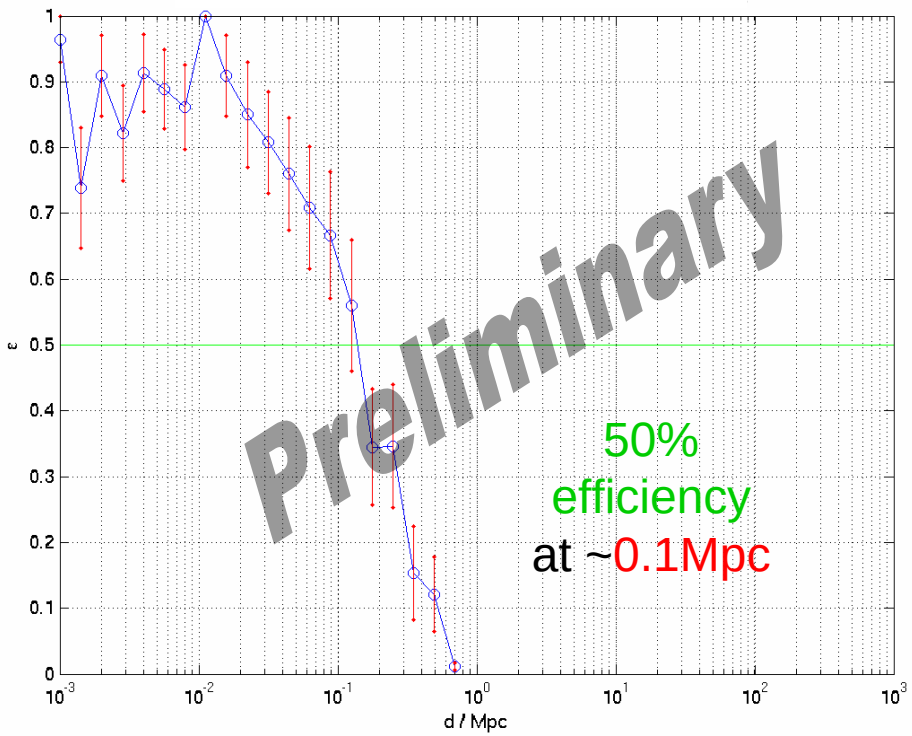
- **Box has been opened**
  - results are under LSC review
  - Using injections can estimate efficiency at threshold
  - However, efficiency is frequency dependent,
    => look at *f* bands



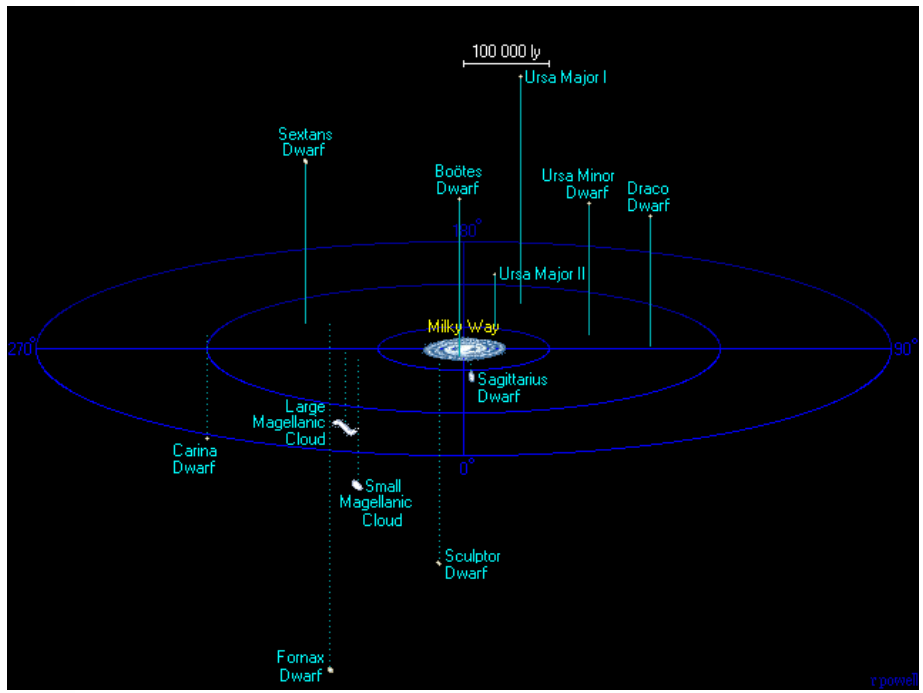
Full Data Set

- **Efficiency** (threshold $\rho = 5.5$, $\varepsilon = 1\%$)
  - depends on frequency band

1kHz < f < 2kHz, ($11M_{sun} < M < 22M_{sun}$ for $\hat{a}=0.9$)



Pic: Richard Powell

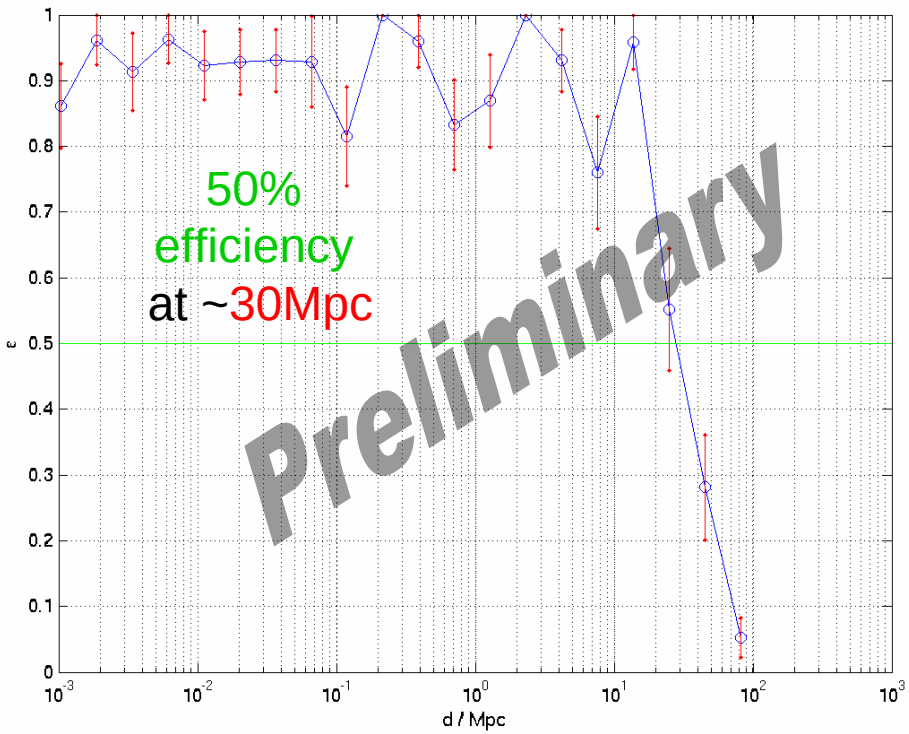


1 large galaxy, 12 dwarf galaxies

Full Data Set

- **Efficiency** (threshold $\rho = 5.5$, $\varepsilon = 1\%$)
  - depends on frequency band

120Hz < f < 190Hz, ($120M_{sun} < M < 180M_{sun}$ for $\hat{a}=0.9$)



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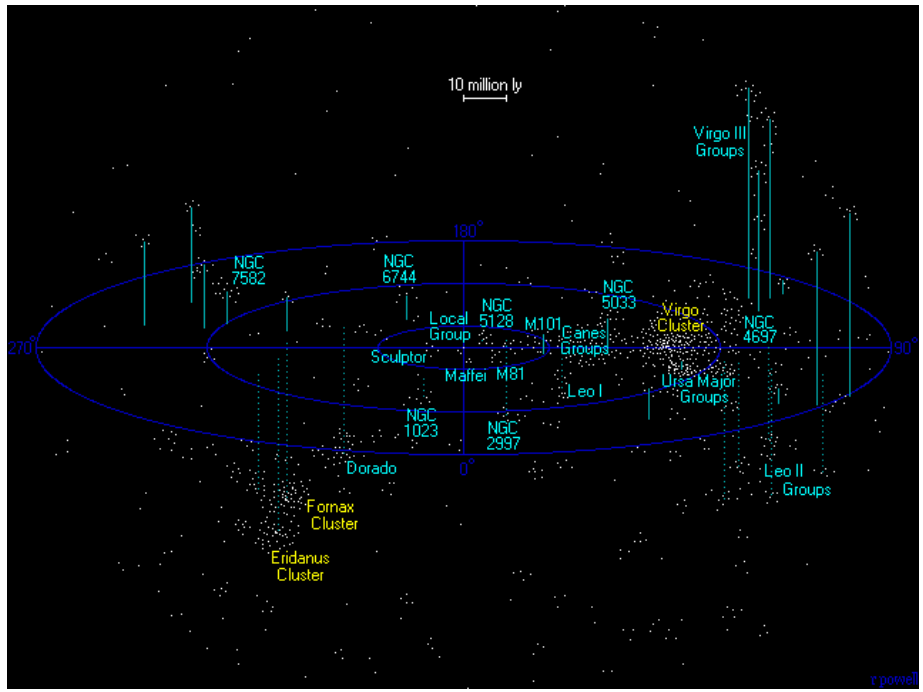


2,500 large galaxies, 50,000 dwarf galaxies

Summary

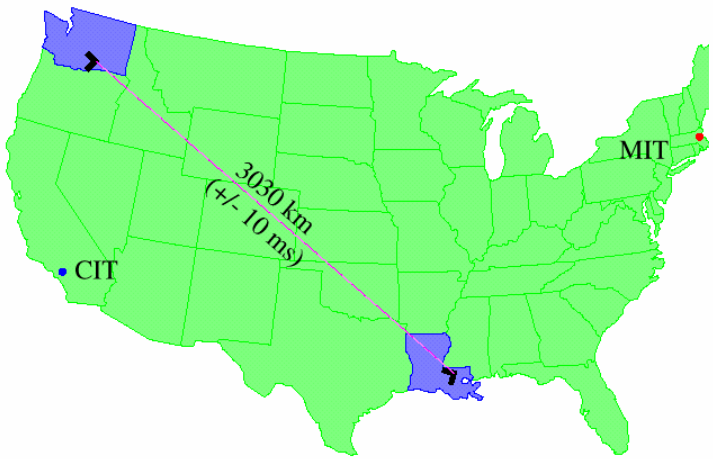
- Ringdown analysis complete on S4 data. Search is currently undergoing LSC review
- Preliminary results show 50% efficiency in recovering injected signals above a threshold of 5.5 at ~30Mpc (in the mass range $120M_o < M < 180M_o$ for $\hat{a} = 0.9$), $\varepsilon = 1\%$
- We also plan to carry this search out on S5 data
- Inspiral-Burst-Ringdown and full coalescence *(see poster by P. Ajith et al)* matched filtered searches also under development within the LSC

The End

LIGO Interferometers

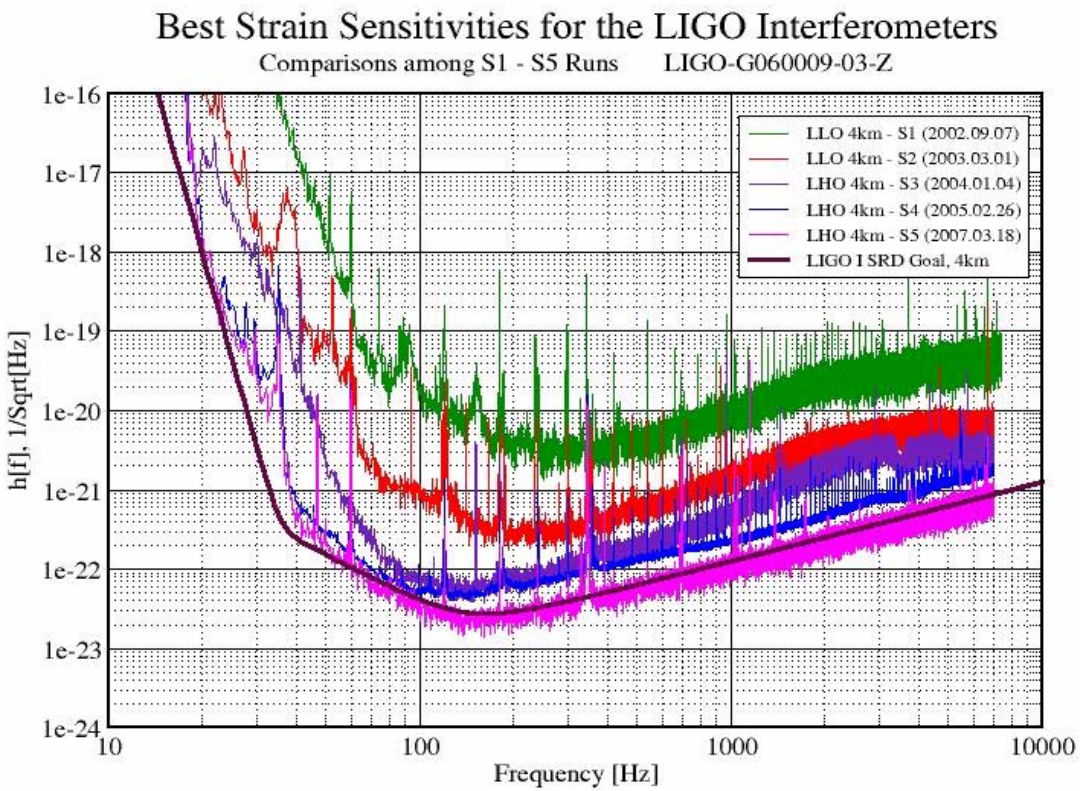
Hanford, WA (LHO)

H1 4km IFO, H2 2km IFO



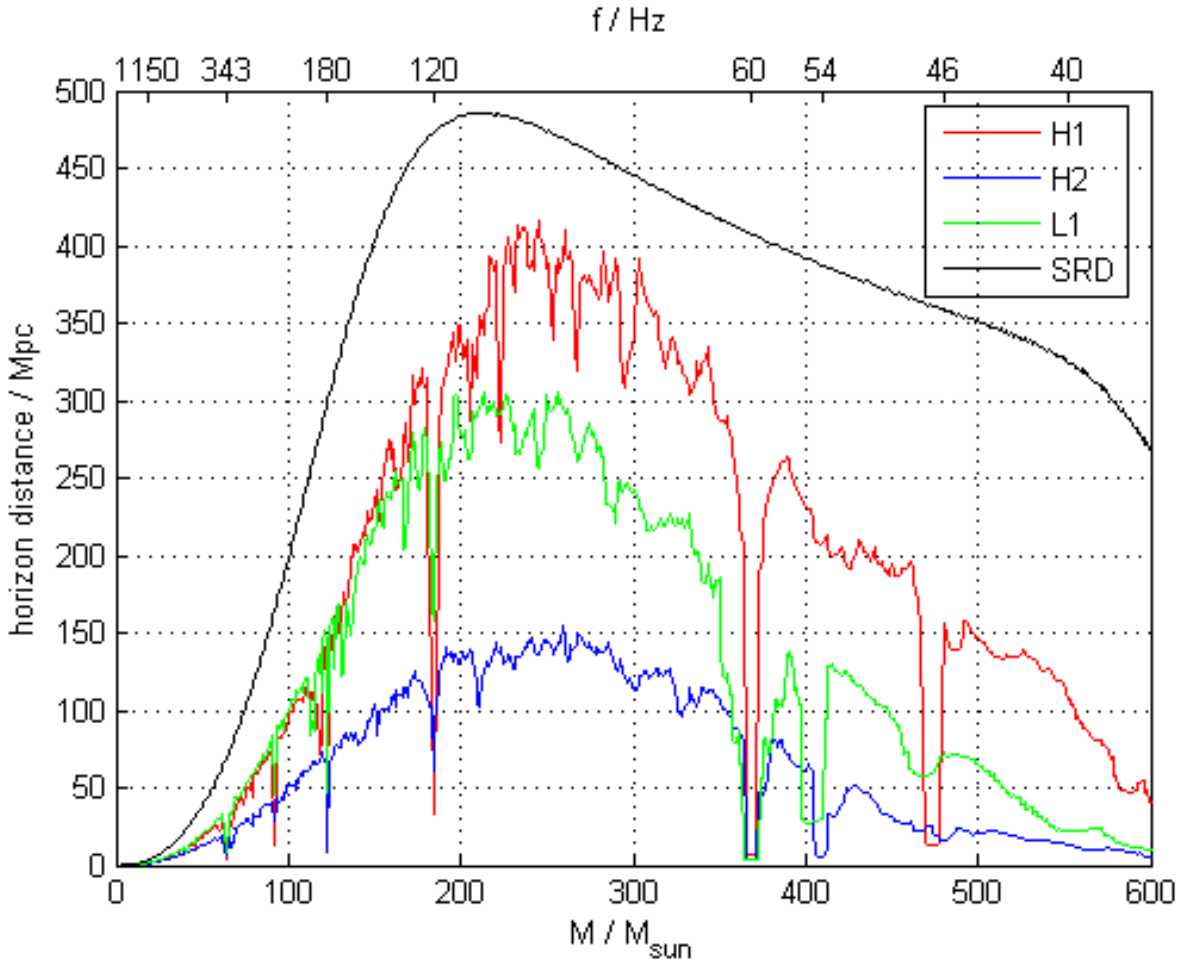
Livingston, LA (LLO)

L1 4km IFO



- **4th LIGO Science Run, S4**
  - February 22nd to March 24th, 2005

S4 Search



(based on average noise spectra)

- Optimally oriented source
- Single detector signal-to-noise ratio = 8
- Spin a = 0.9

For $M=230M_{sun}$, sensitive to black hole ringdowns at a distance of

H1: 400 Mpc

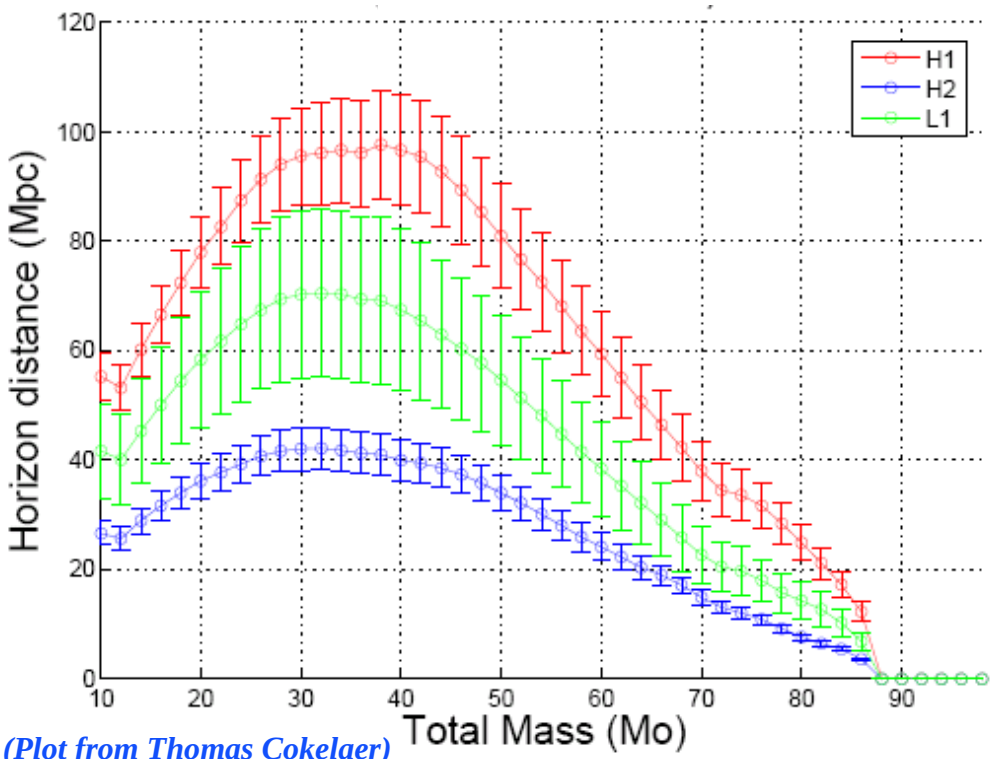
H2: 150 Mpc

L1: 300 Mpc

Binary Coalescence

- Ringdowns are produced during the final stage of binary coalescence
- There is an overlap between the mass range of the binary black hole (BBH) inspiral search and the ringdown search

Inspiral phase (S4 BBH search)



(Plot from Thomas Cokelaer)

Ringdown phase (S4)