Searching for gravitational waves from black hole binaries in data from the LIGO detectors: challenges and prospects

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Inspiral Working Group

LIGO Scientific Collaboration

Outline

- **Status of LIGO interferometers**
- Target signals
- Searching for inspiraling binaries
  - » Matched filtering
  - » Analysis method
- Black hole binaries (BHB)
  - » Challenges
  - » Dealing with the challenges
- Prospects
  - » In the absence of detection ...
  - » If we have a detection...
- Future directions of the Inspiral Working Group

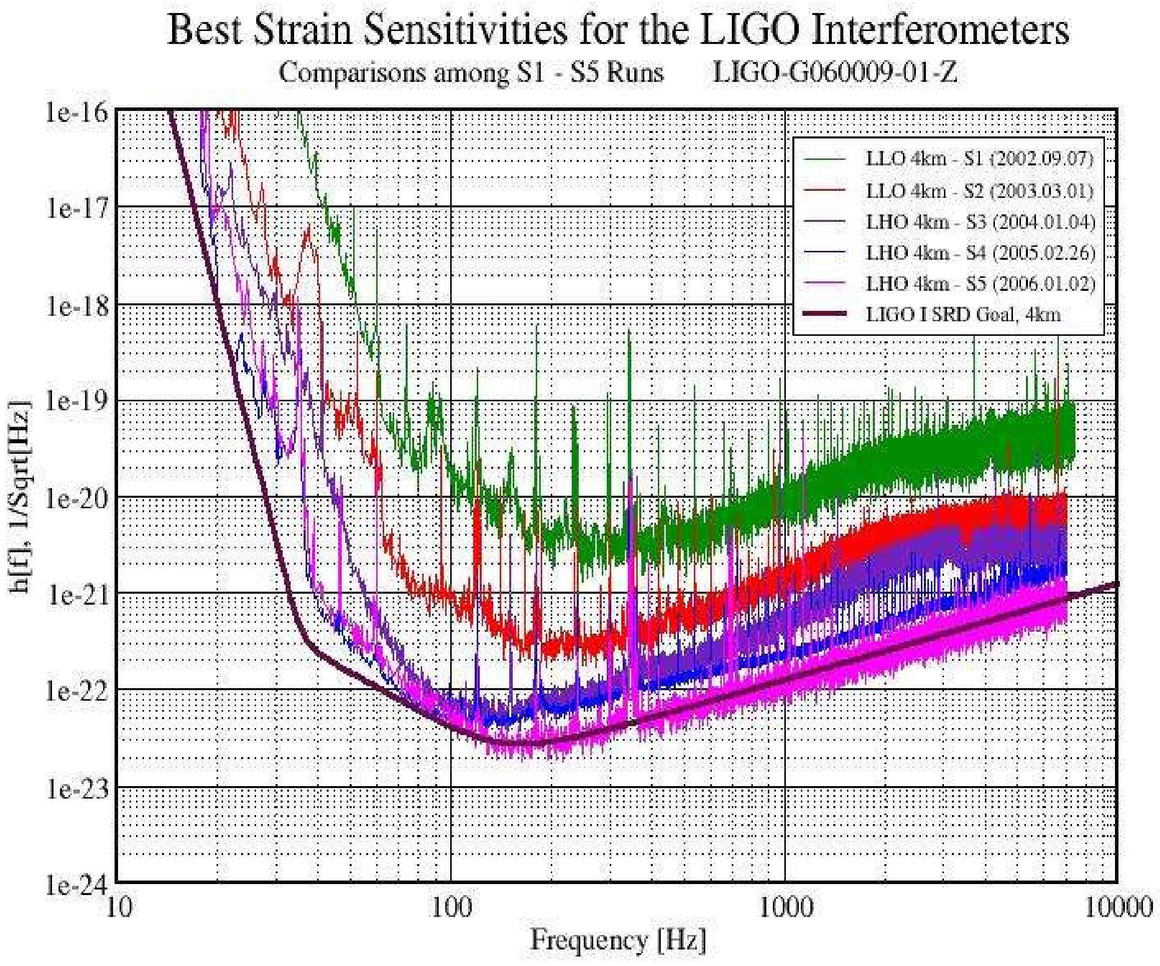
LIGO Interferometers

Hanford, WA (LHO):
- 4 km (H1)
- 2 km (H2)

Livingston, LA (LLO):
- 4 km (L1)

Current status of the interferometers

- Reached design sensitivity
- Four completed science runs:
  - » S1 – S4
  - » S5 in progress



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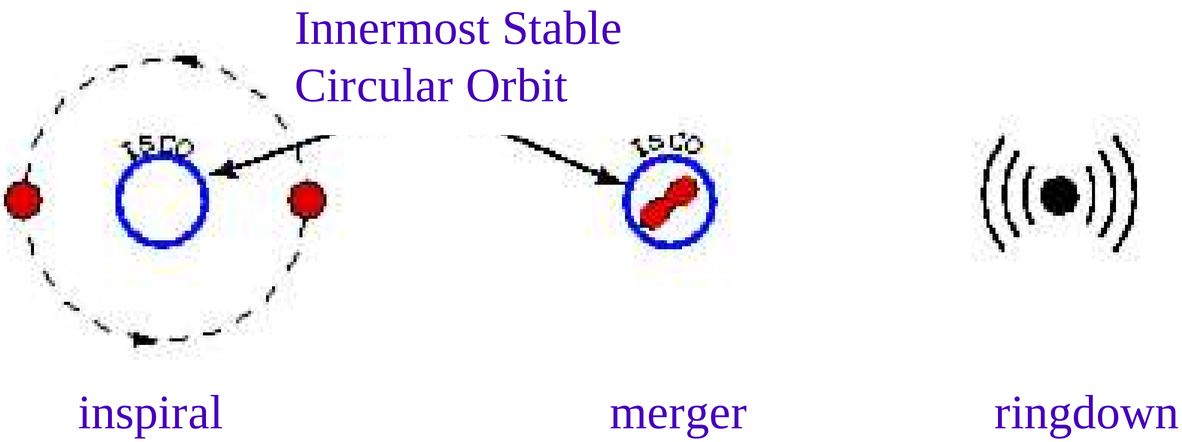
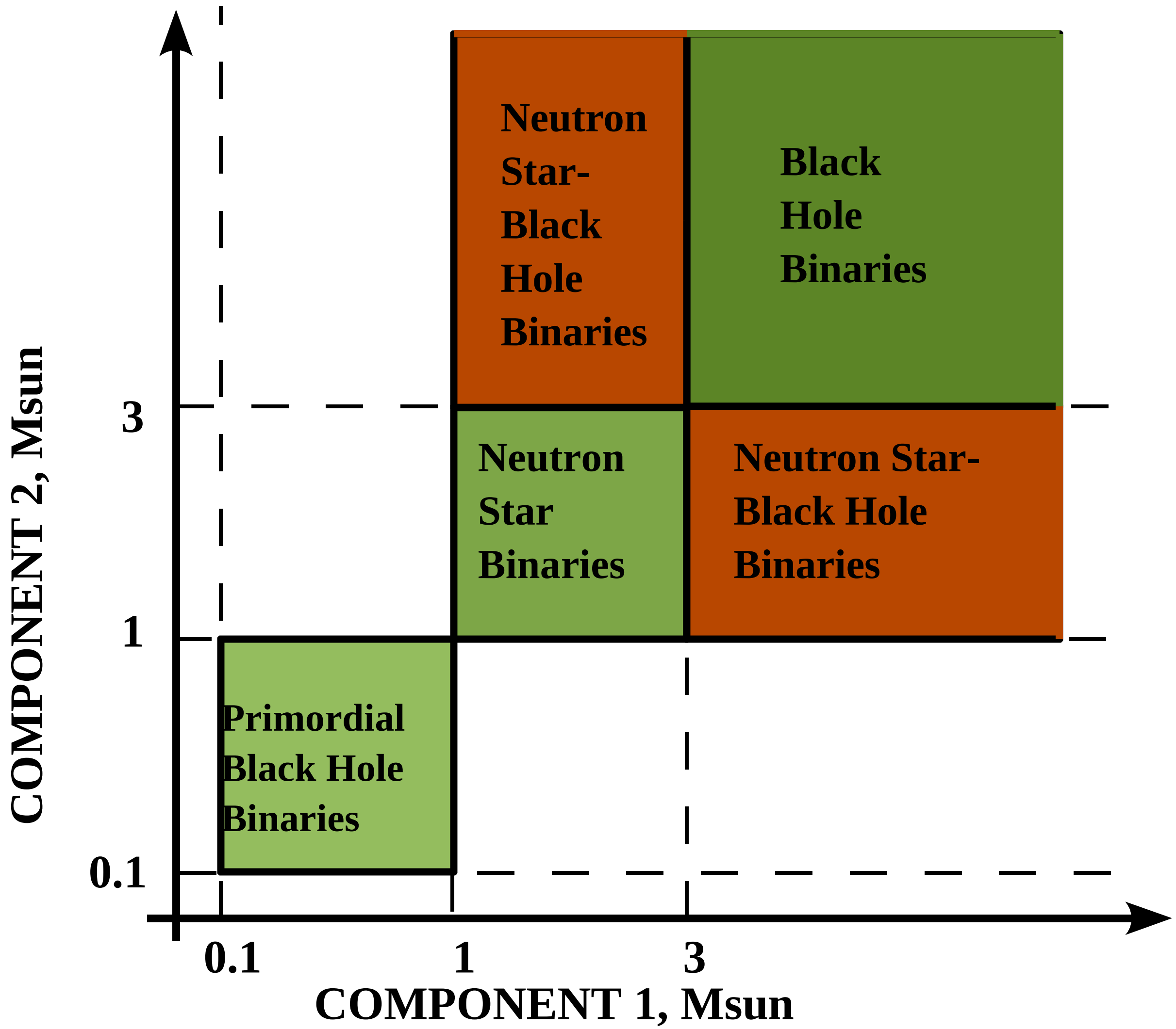
Target signals



- Searching for coalescences of binary systems
- The inspiral and ringdown waveforms can be computed
- The duration and frequency content vary depending on the component masses
- The waveforms depend on intrinsic spin of the components

Target sources



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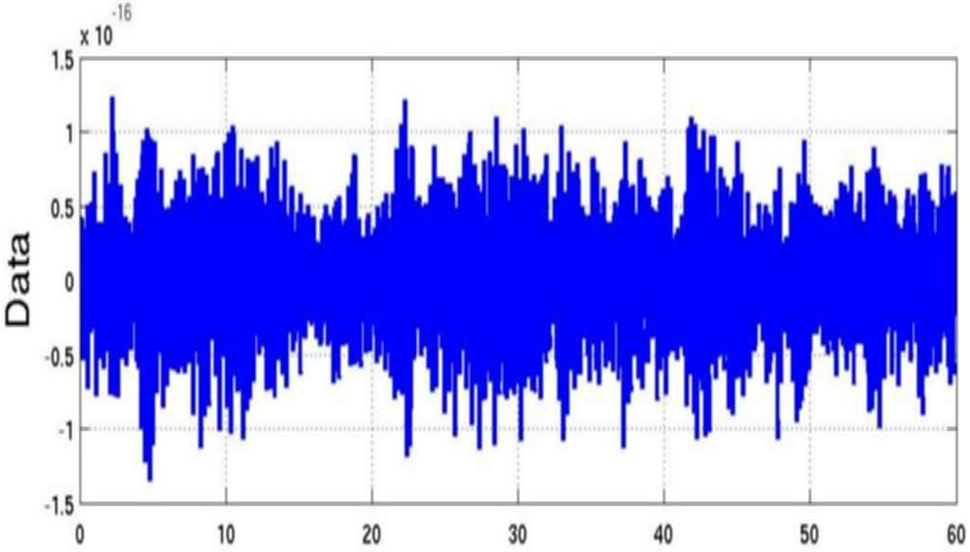
Matched filtering

The signal is buried in the noise



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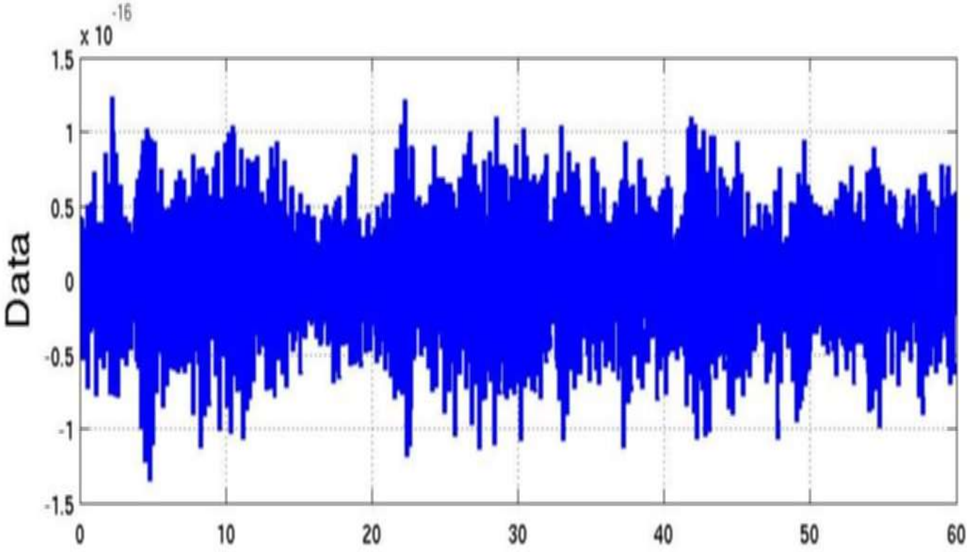

Signal-to-Noise Ratio (SNR):

$$\rho = \int_0^{\infty} df\, s(f)\, h^{cc}(f)\, S_h^{-1}(f)$$

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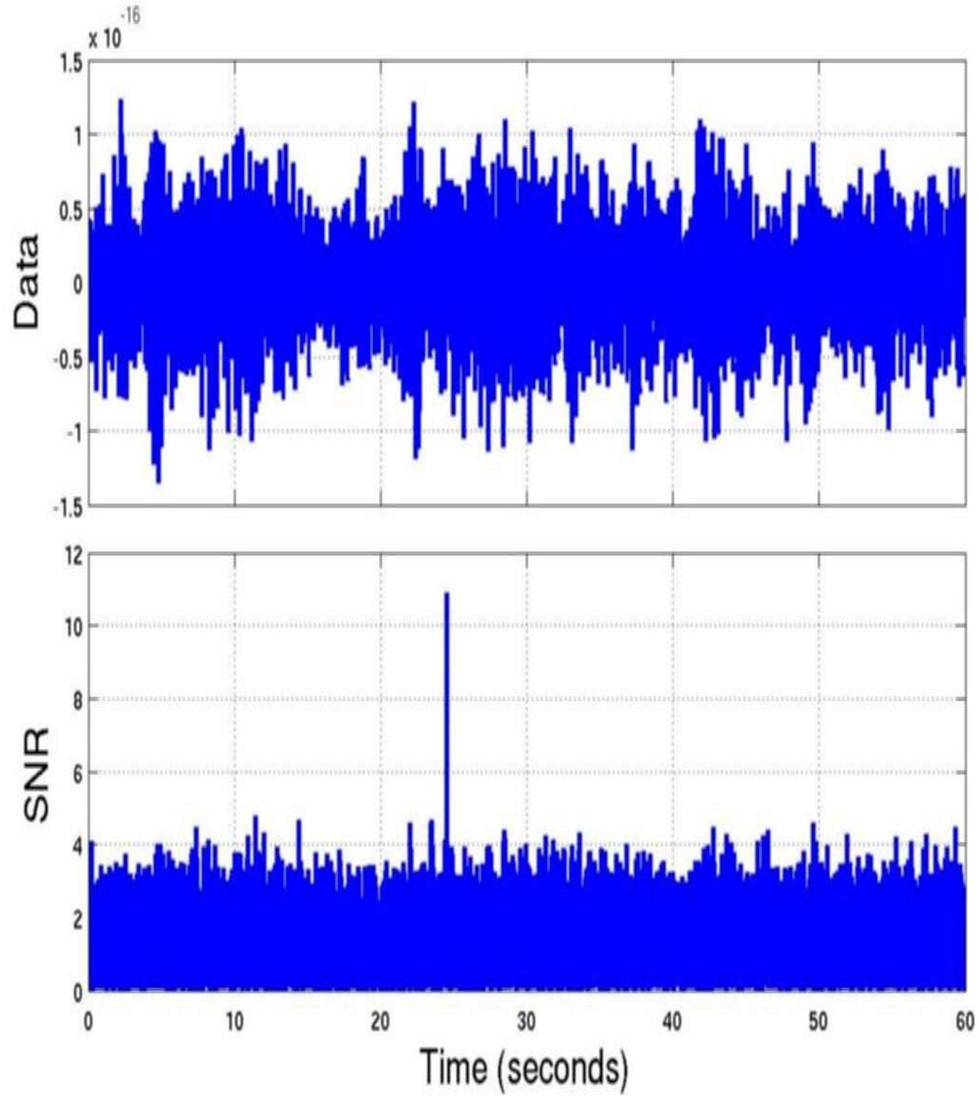

Analysis method

- Identify data appropriate for analysis

- Run the *analysis pipeline* on the data
  - » Generate a bank of template waveforms for each interferometer
  - » Match-filter the data from each interferometer & threshold on the SNR
  - » Record "triggers"
  - » Require coincidence in time and in waveform parameters
  - » Apply signal-based vetoes
  - » Apply instrumental vetoes

- Run *time-shifts* on the data
  - » Rate of accidental coincidences (background)

- Run the pipeline on the data with *injections* added
  - » Tuning of the pipeline parameters
  - » Estimation of sensitivity

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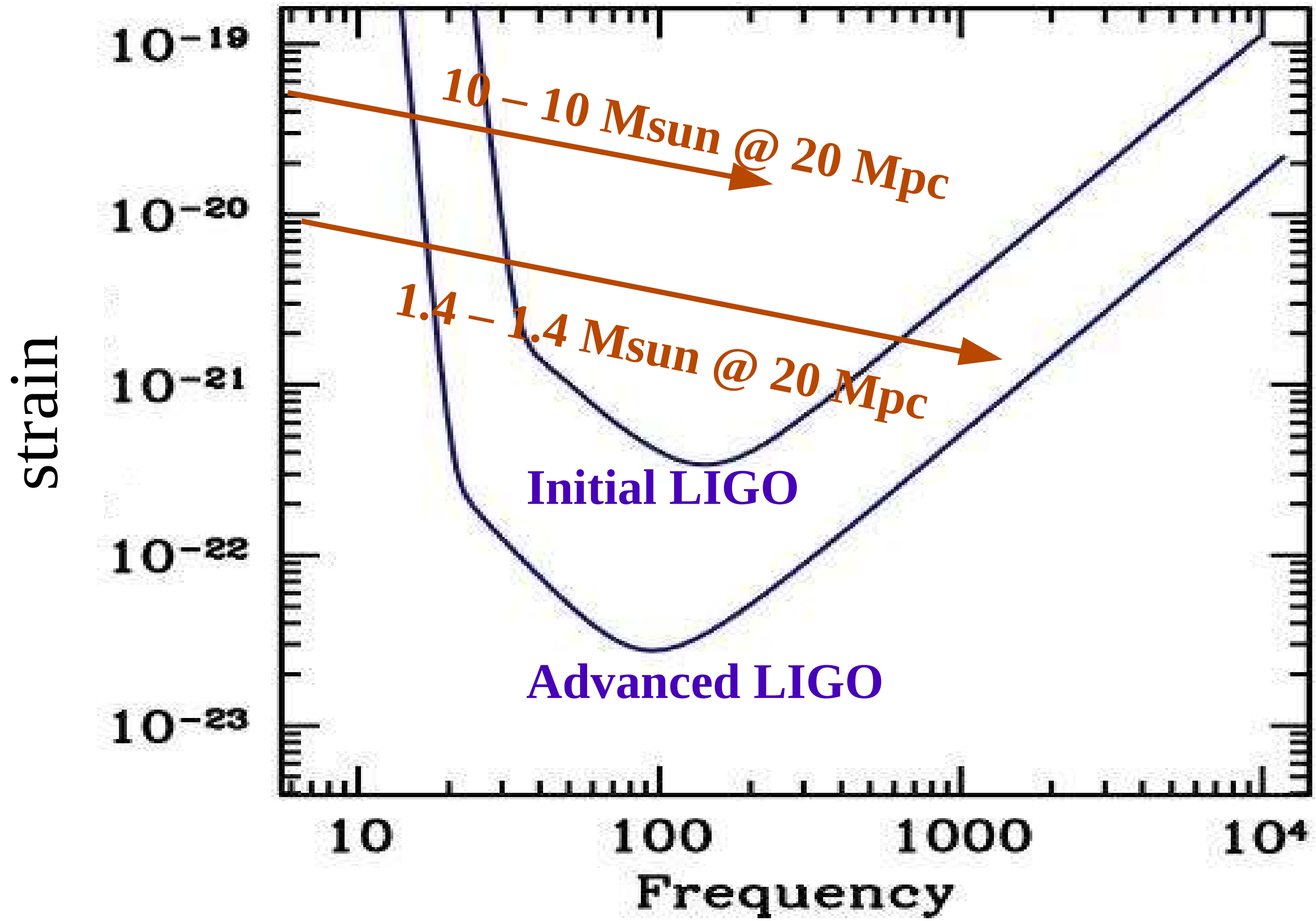
Signal sweep for inspirals across frequencies



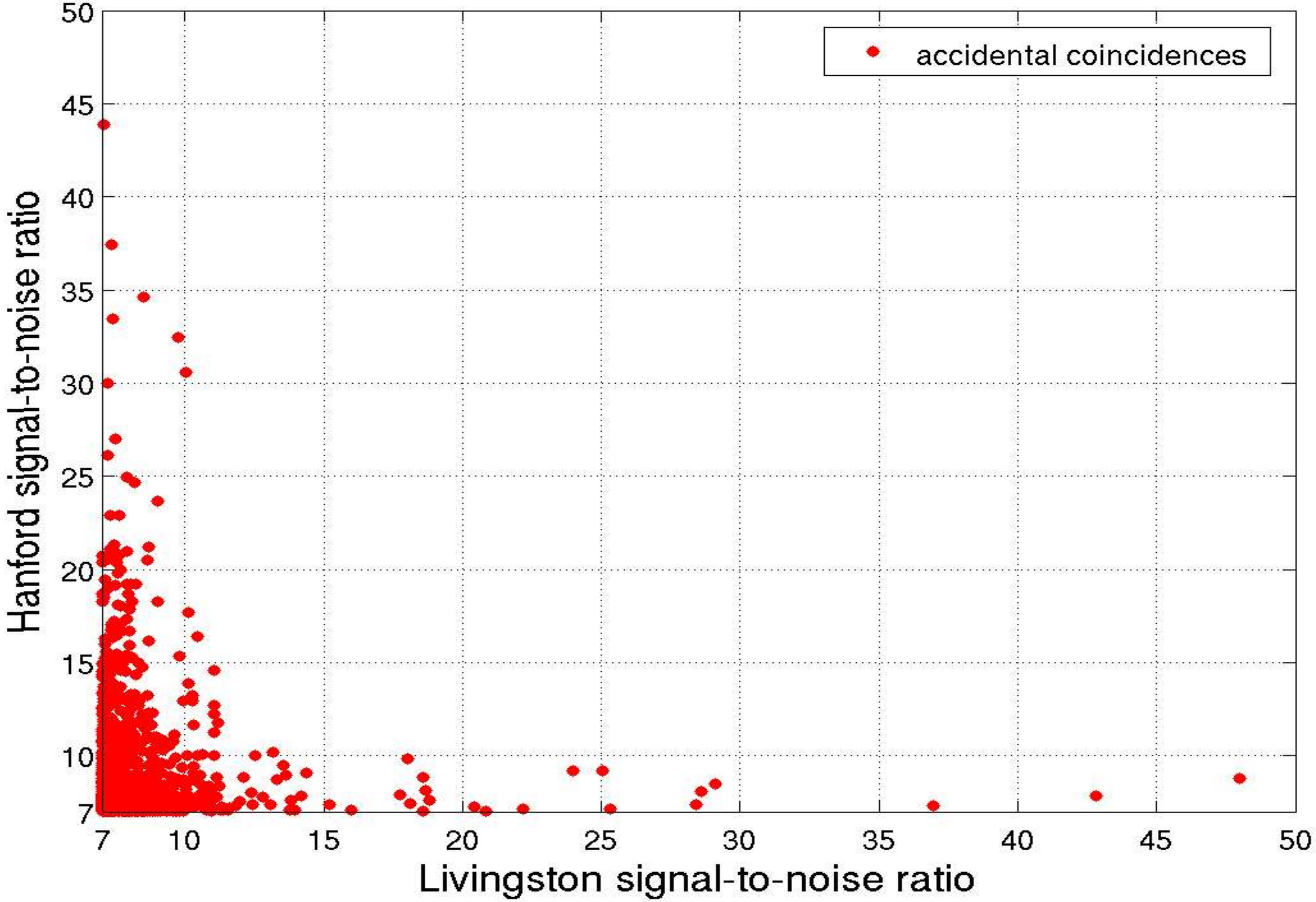
BHB inspirals: search challenges

- Ground-based interferometers are sensitive to signals above 30 or 40 Hz
- Innermost stable circular orbit frequencies are only a bit higher
  - » 55 Hz for a 40 – 40 Msun inspiral
- Inspiral waveforms are not known with precision
  - » Different approximation schemes give different predictions for the last few cycles of the inspiral
- Waveform consistency test not yet adequate for high-mass BHBs
  - » Too few cycles in band for a reliable chi-squared test
- There is a large part of energy released in the merger
  - » The merger frequency for BHB is at the “sweet spot” of the ground-based interferometers

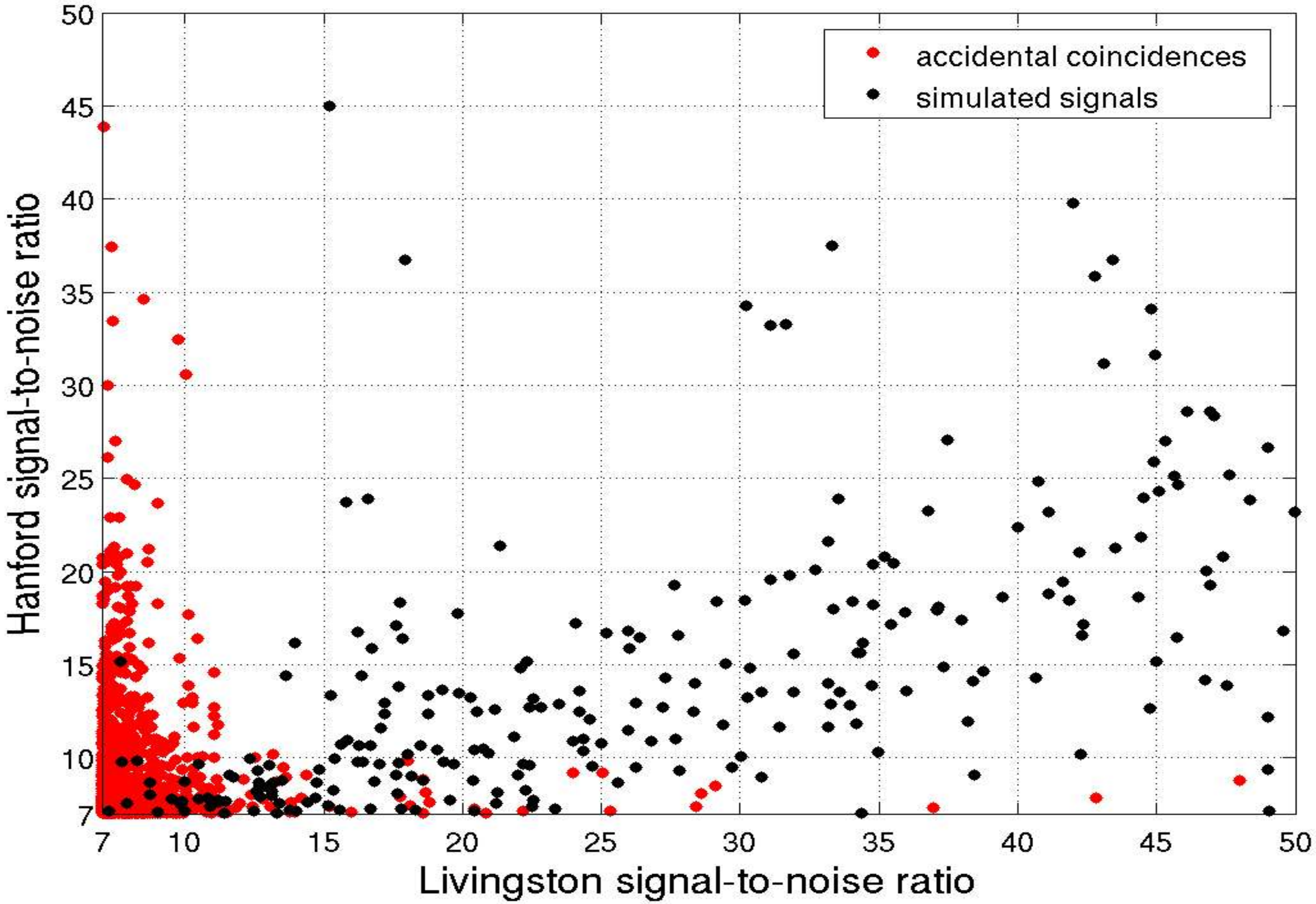
BCV templates

- Use phenomenological templates for the matched filtering
- BCV templates:
  - Buonanno, Chen, Vallisneri, PRD, 67, 2003
  - $h(f)=f^{-7/6}(1-\alpha f^{2/3})\theta(f_{cut}-f)\exp[i(\phi_0+2\pi t_0 f+\psi_0 f^{-5/3}+\psi_3 f^{-2/3})]$
- Benefits
  - 95% - 99% match with model-based inspiral waveforms
  - Can pick up signals "in between" the various model-based waveforms
  - Can extend into the plunge phase of the gravitational waveforms
  - Good for identifying BHB inspiral waveforms in the data
- Drawbacks
  - Give high SNRs for instrumental and environmental noise events
  - More false alarms than post-Newtonian templates
  - Not appropriate for parameter estimation

BHB inspirals: S2 search



BHB inspirals: S2 search



How can we make the search better?

- Things that reduce the false alarms:
  - Coincidence reduces false alarms dramatically
  - H1-H2 amplitude consistency test
  - Instrumental vetoes

- Things we plan to incorporate:
  - Waveform consistency test for the longer BHB signals
  - Other signal-based vetoes

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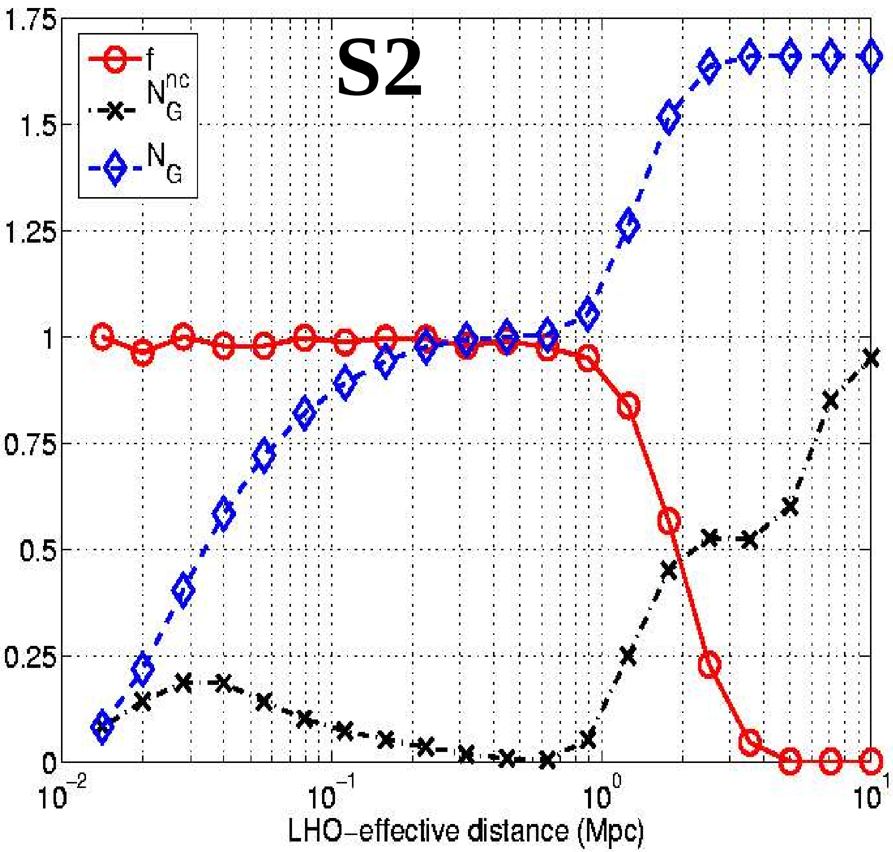
In the absence of a detection...

- Upper limit on the rate of BHB coalescences in the Universe
- $R_{90} < 2.303/(T_{obs} N_G)$
- Assumptions for the BHB population
  - » Black holes are distributed in galaxies according to the galaxy's blue light
  - » The component mass distribution is uniform. The masses range from 3 to 20 Msun
  - » The component spins are negligible
  - » The waveforms are a mixture of EOB, PadeT1 and TaylorT3
- $T_{obs}^{S2} = 0.04\ years,\ N_G^{S2} = 1.6603$

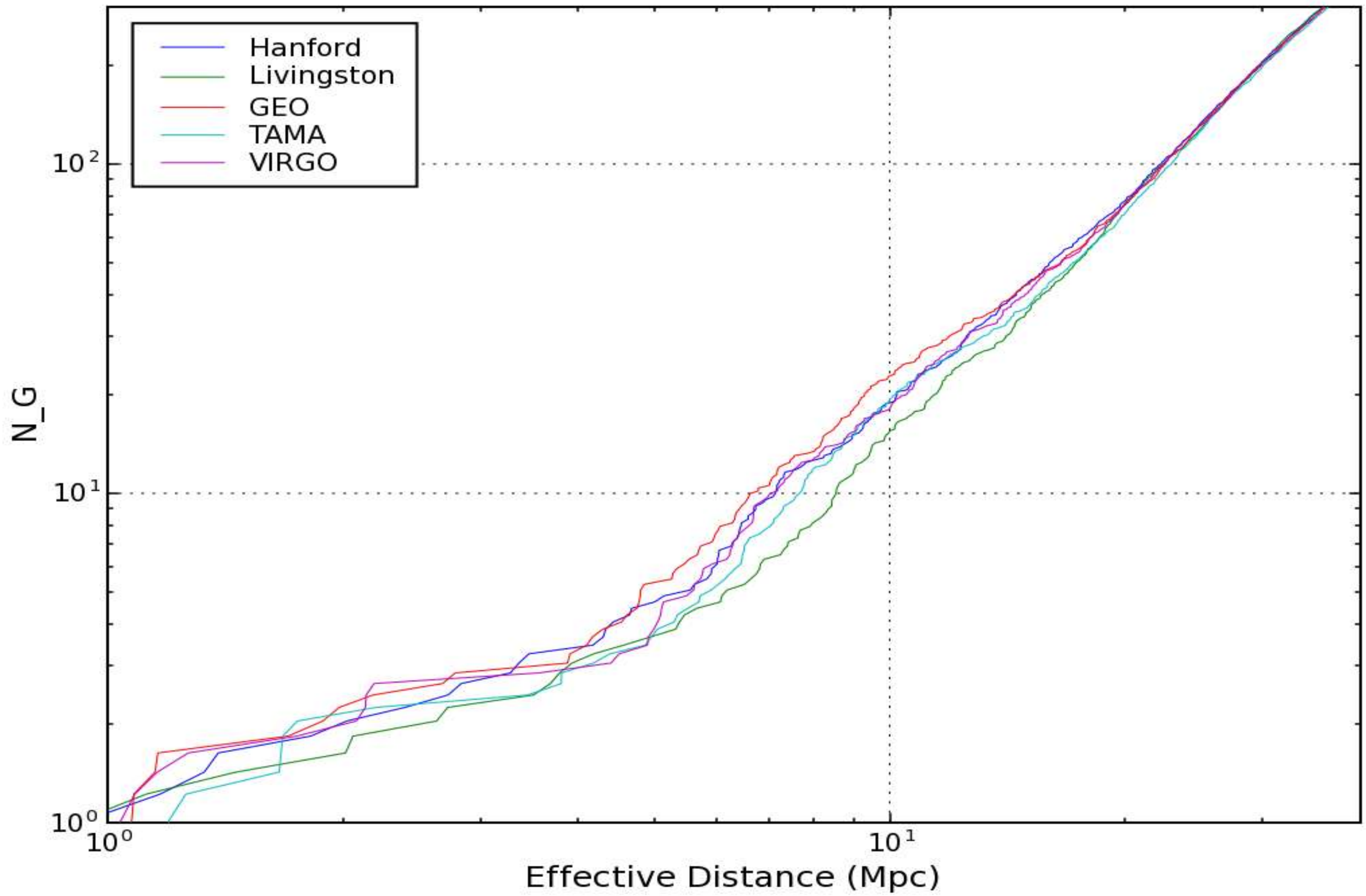


$$R_{90}^{S2} < 38\ year^{-1}\ MWEG^{-1}$$

Reach of BHB search

- 5 – 5 Msun, optimally oriented binary, SNR = 8:
  - **S2:** 7 Mpc for L1, 3 Mpc for H1
  - **S3:** 12 Mpc for L1, 39 Mpc for H1
  - **S4:** 51 Mpc for L1, 58 Mpc for H1
  - **S5: 55 Mpc for L1, 70 Mpc for H1 (preliminary)**

Number of MWE galaxies



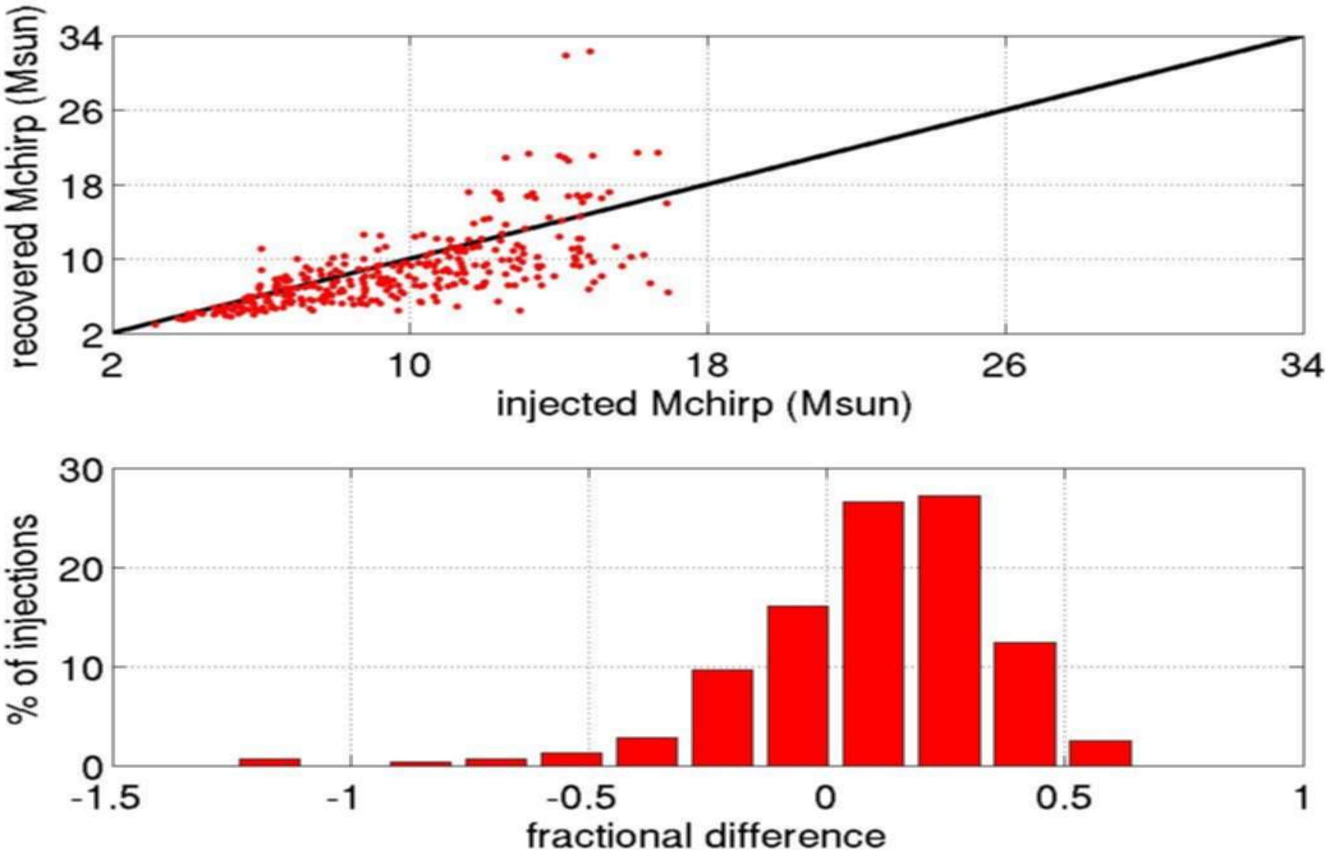
Sample rate upper limit estimate

- 1 year of data
- Focus on binaries of component mass between 3 and 20 Msun
- $N_G = 1200\, MWEGs$
- $R_{90} < 0.002\, year^{-1}\, MWEG^{-1}$

If we have a detection...

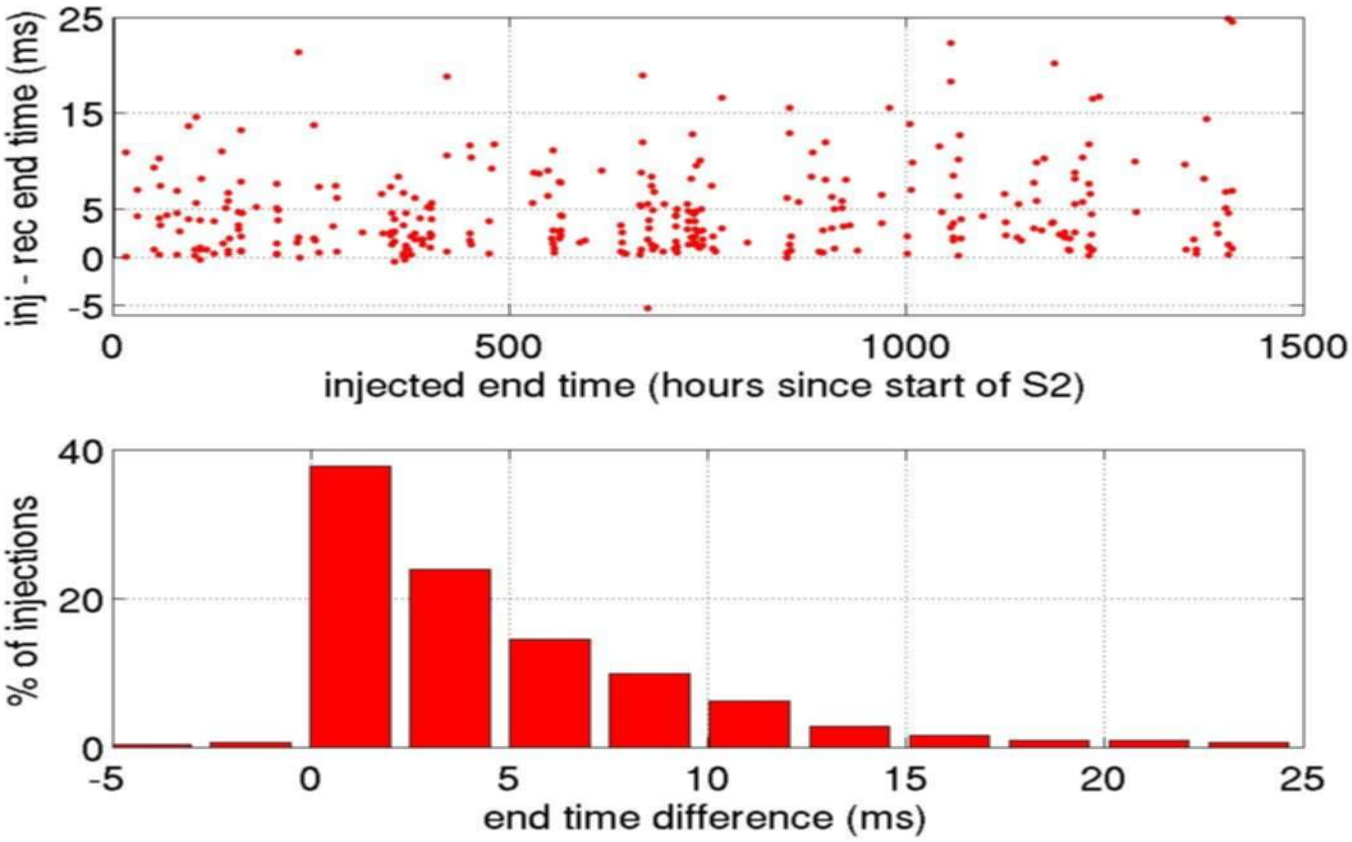
- Calculate the physical parameters of the signal
  - » Masses
  - » Time of arrival
  - » Source location (distance, sky position)
- The BCV templates are not appropriate for parameter estimation
  - » The masses do not show up in the templates
  - » The templates are not normalized to a physical distance
- Some parameters may be estimated with the BCV templates
  - » Chirp mass: $(m_1 m_2)^{3/5}(m_1+m_2)^{-1/5}$
  - » Time of arrival

Chirp mass estimation (S2)



S2 NSB search: the chirp mass accuracy was 0.002 Msun

Time of arrival estimation (S2)



S2 NSB search: the time of arrival accuracy was 1 ms

Parameter estimation

- How can we do better?
- Follow-up with model-based waveforms
  - » Accurate estimate of the masses of the binary
  - » Accurate estimate of the time of arrival at each site
    - – The time difference between sites gives an annulus on the sky
  - » Accurate estimate of the "effective distance" of the source
- Work in progress; some issues
  - » What accuracy can we get?
  - » What is the performance across the different families of model-based waveforms?

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Future directions of the IWG

- Include spin of the black holes
  - » BCV2 templates
  - » The first search is almost complete
- Model-based waveform follow-up of signals
  - » Work in progress
- Inspiral-burst coincidence
  - » Take the merger into account
- Include Virgo in the analysis pipeline
  - » Fewer false alarms for the same detection probability
  - » Locate the position in the sky (2 positions)
- Break up the parameter space differently than we have so far
  - » Do waveform consistency test for the longer signals