Systematic effects in gravitational-wave data analysis

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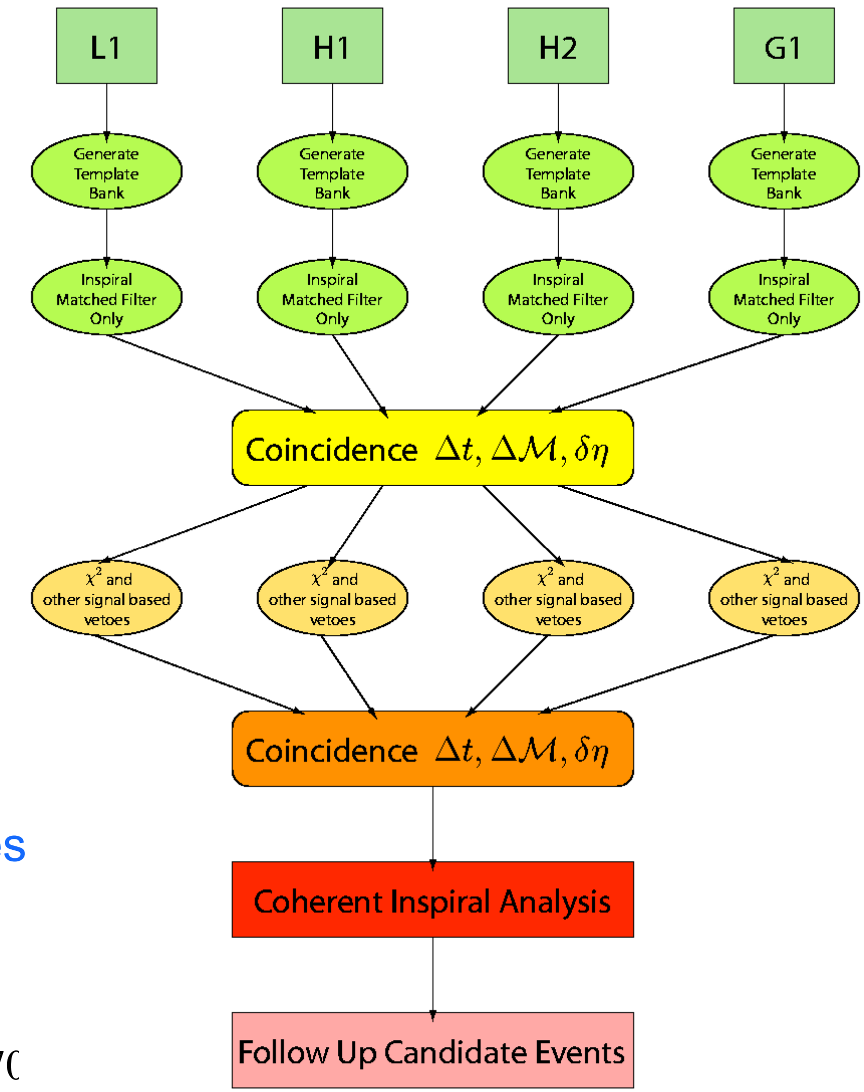
Overview

- The Inspiral Search Pipeline
- Parameter estimation and multi-detector coincidence
- Inclusion of Ringdown search
- Systematic Uncertainties
  - » Calibration
  - » Waveform
- Conclusions

The Inspiral Pipeline

- Multi Detector Pipeline
- Duncan's talk described
  - » Template bank
  - » Inspiral Matched Filter
  - » χ^2 signal based veto
- Other features
  - » Coincidence required between multiple detectors
  - » Coherent follow up of coincidences



Coincidence Requirements

- Require a coincident trigger between at least two detectors.

- Coincidence parameters:
  - » Mass -- particularly chirp mass
  - » End time -- also used for estimation of sky location
  - » Distance -- only important for co-located Hanford instruments
  - » Tuned by injecting simulated signals into the data stream in software

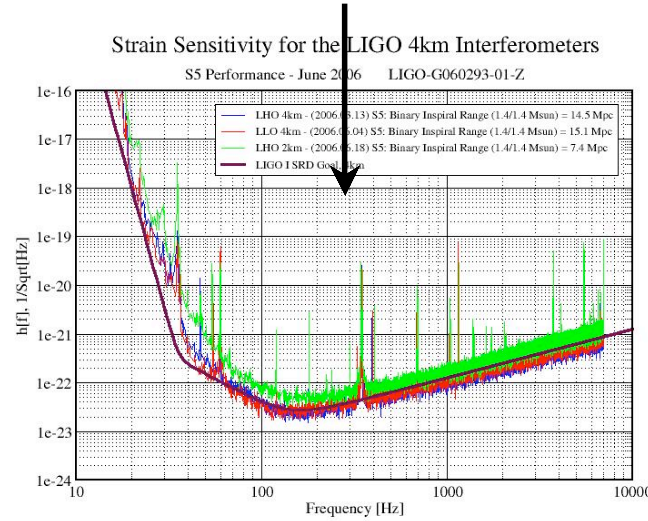
- Competing considerations:
  - » Windows must be loose enough that potential signals are not missed
  - » Tighter coincidence windows give a reduced false alarm rate.

Coincidence Requirements

- Coincidence windows depend upon accuracy with which we can determine various parameters

  - » Depends on the match M between e.g. $h(\mathcal{M})$ and $h(\mathcal{M} + \delta\mathcal{M})$

$$M(h_1, h_2) = \frac{< h_1|h_2 >}{|h_1||h_2|} \quad \text{where} \quad < h_1|h_2 >= \int df \frac{\tilde{h}_1(f)\,\tilde{h}_2^*(f)}{S(f)}$$



  - » The ability to determine parameters
    - – improves for longer waveforms
    - – improves with larger SNR

Example from LIGO analysis

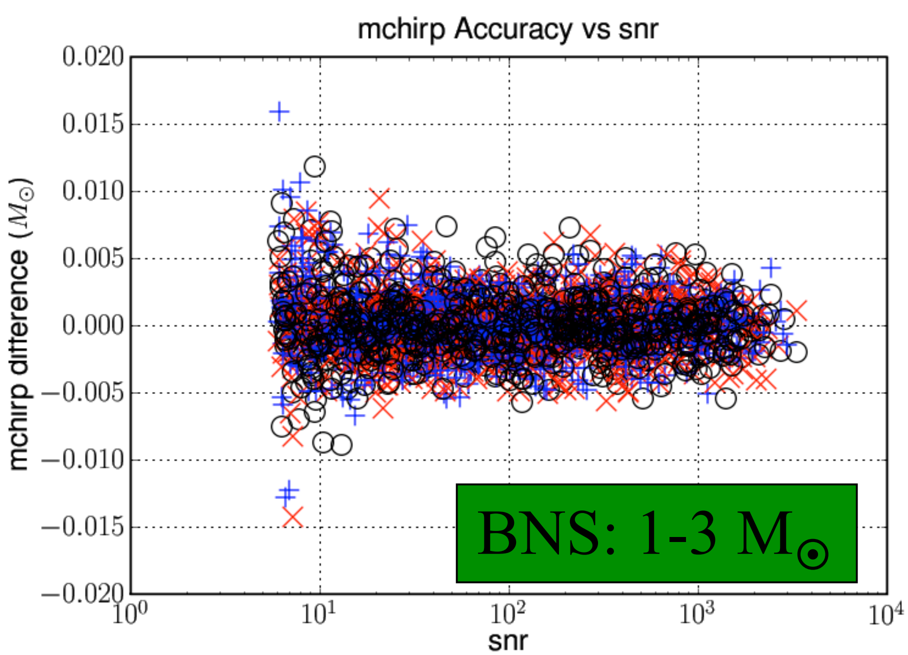
- Inject simulated inspiral signals into the data, recover using the LSC inspiral analysis pipeline
- Following example considers ideal case
  - » Inject and recover using (virtually) the same waveform
- Use 2nd order post Newtonian waveform
  - » Inject in the time domain
  - » Recover using frequency domain stationary phase templates

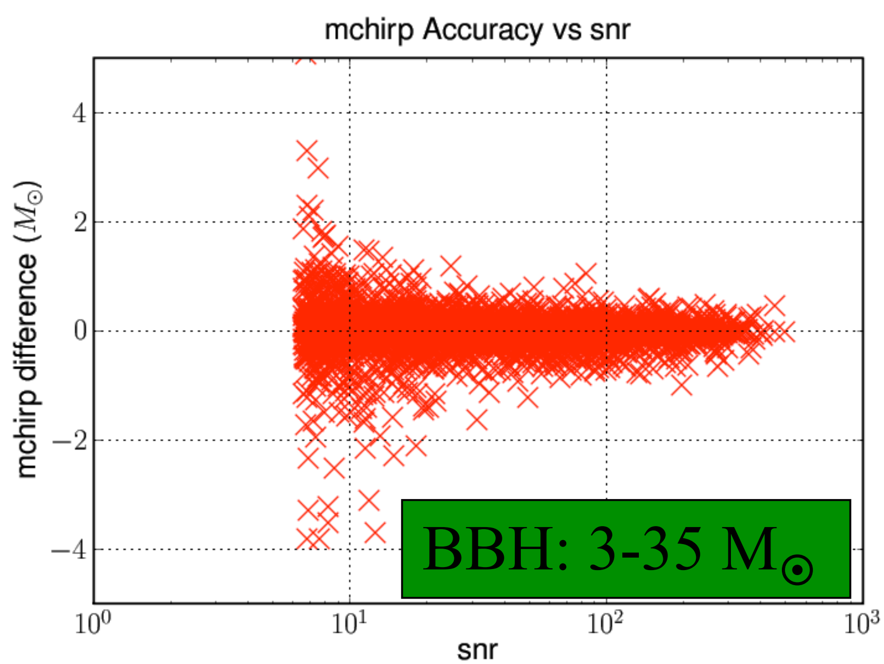
Mass Accuracy

- Good accuracy in determining chirp mass.

$$\mathcal{M} = M\eta^{3/5} \text{ where } \eta = \frac{m_1 m_2}{M^2}$$

- Accuracy decreases significantly with higher mass



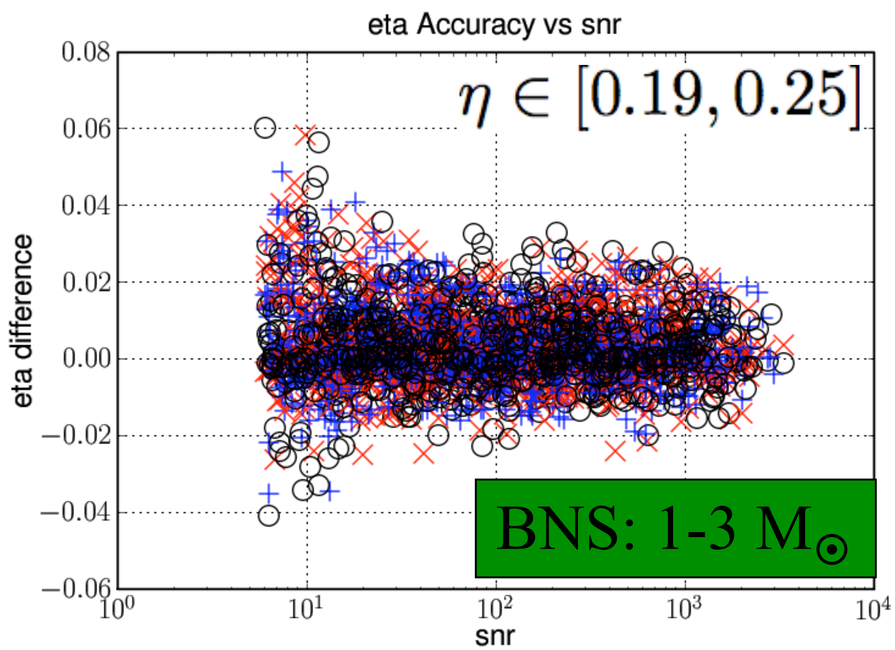


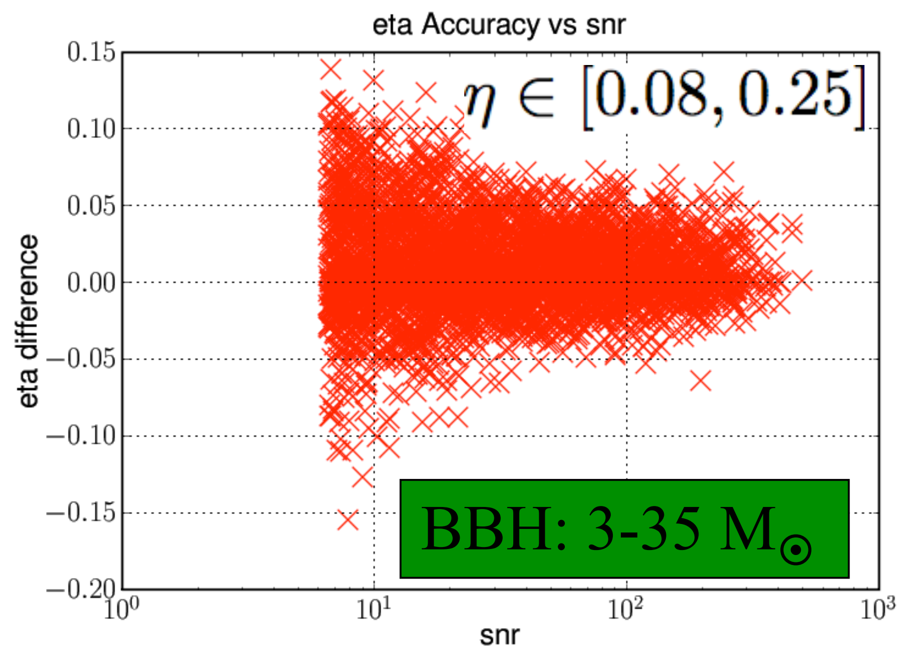
Mass Accuracy

- Very little ability to distinguish mass ratio.

$$\eta = \frac{m_1 m_2}{M^2}$$

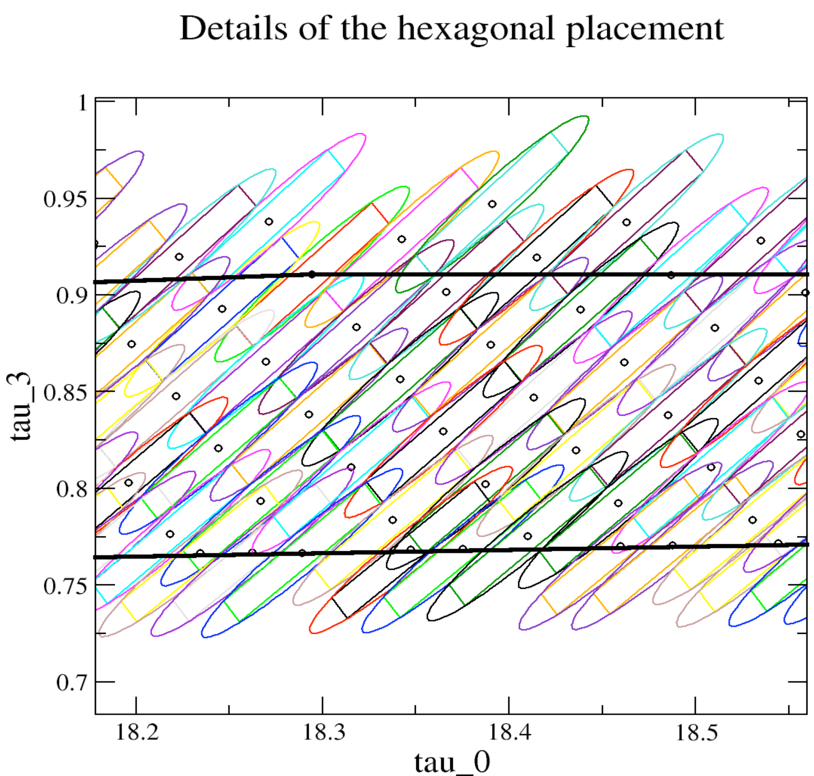
- Width of accuracy plots similar to entire search range.



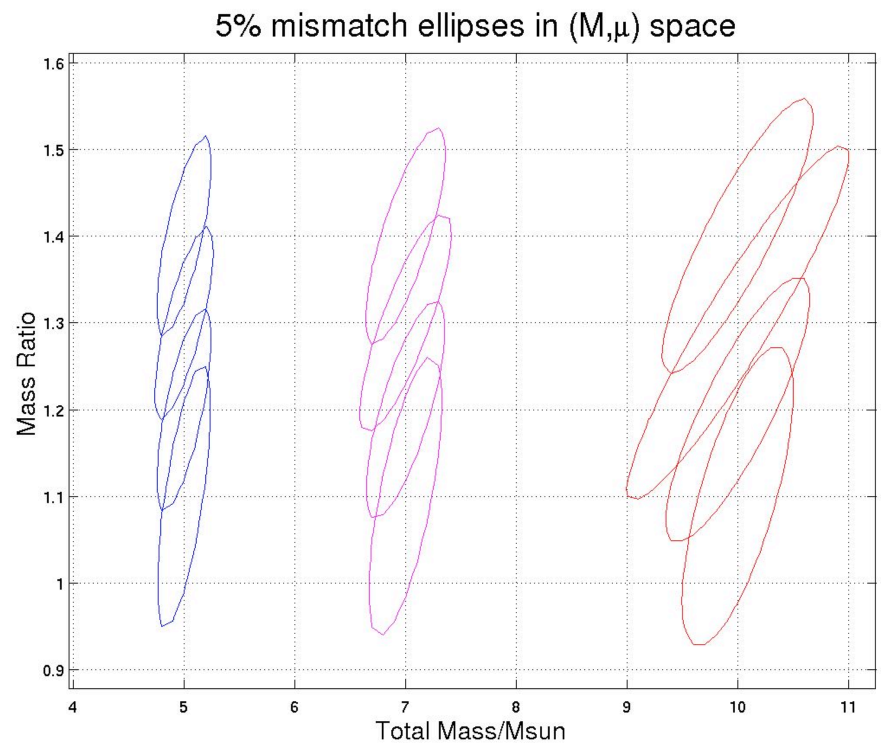


Input from numerical relativity

- Example:
  - » Would including the merger allow us to better determine the mass ratio?
    - – Compare PN results to numerical relativity.



Plot from LSC inspiral notebook



Plot from AEI and Jena groups

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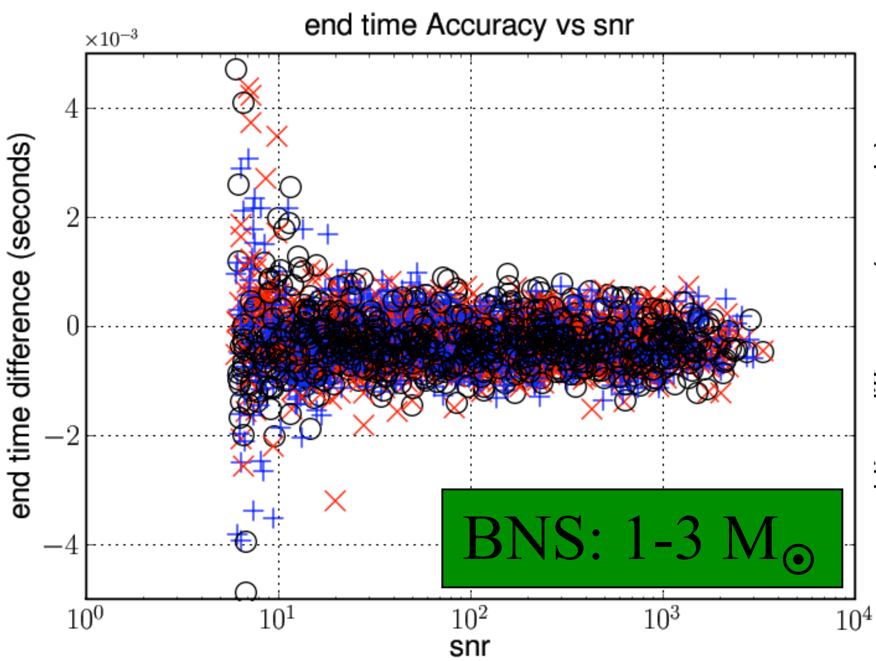
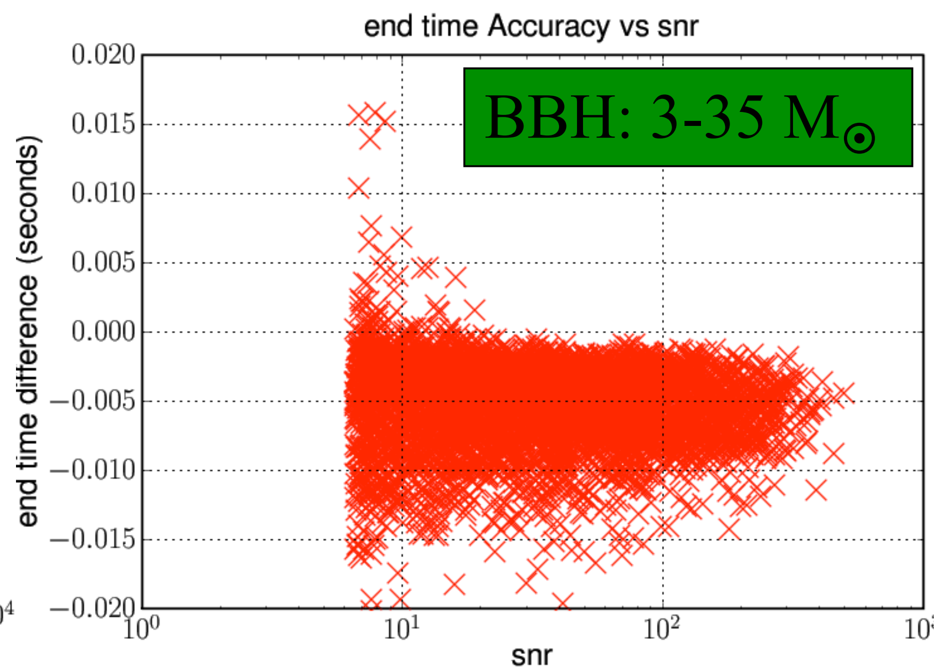
Timing Accuracy

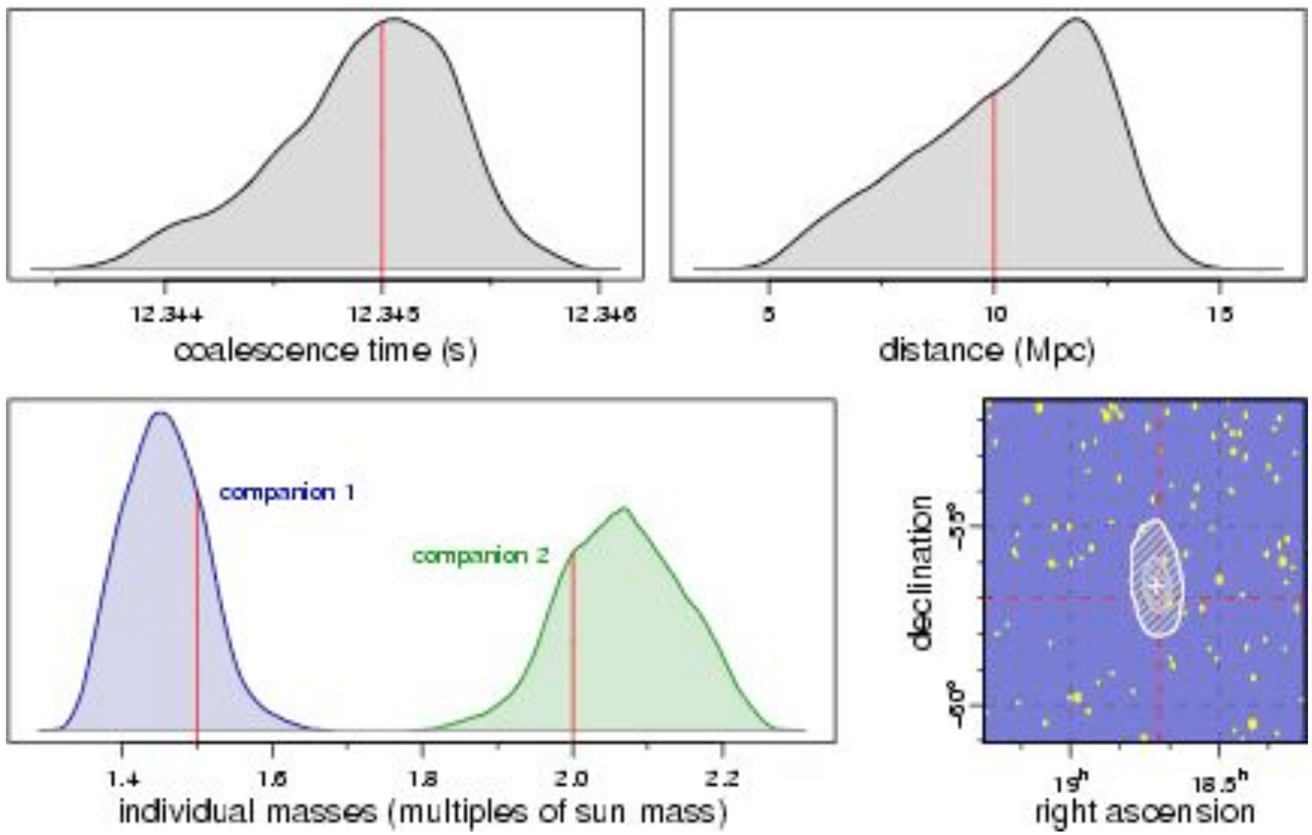
- As before, parameter accuracy better for longer templates.
- Timing accuracy determines ability to recover sky location
- Timing systematic is due to injecting TD, recovering FD.
  - » Overall systematic (same at all sites) does not affect sky location.





Markov Chain Monte Carlo Parameter Estimation

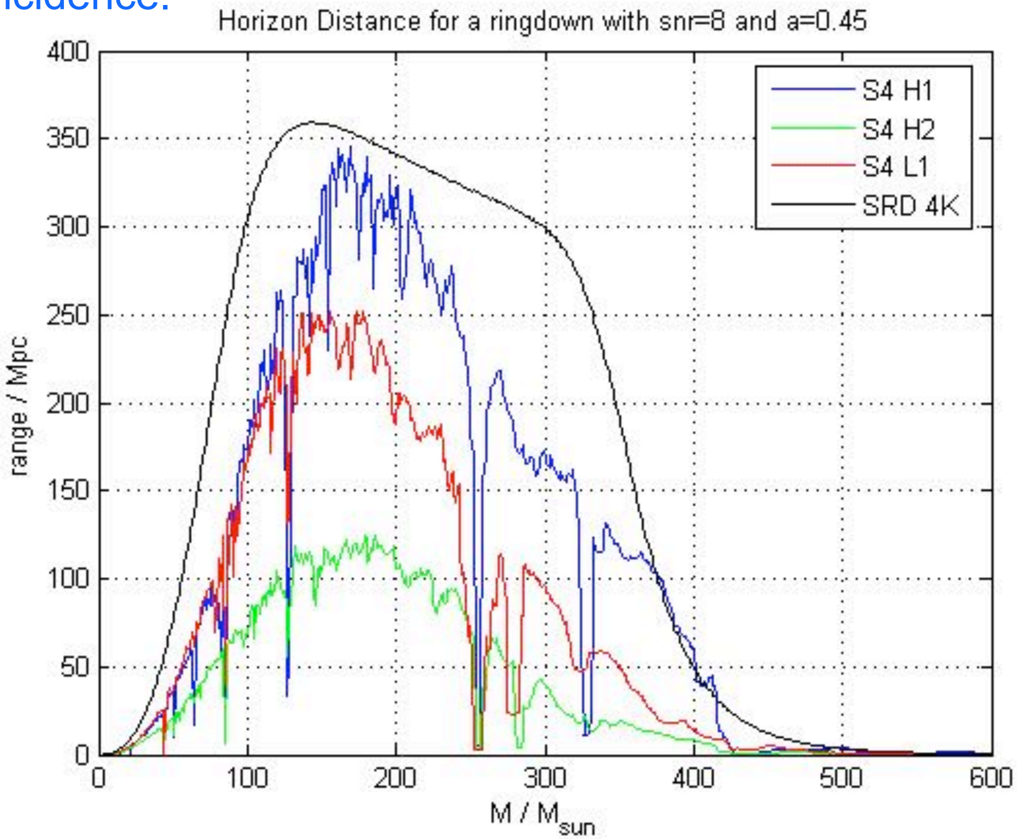
- A candidate would be followed up with MCMC parameter estimation routine.
- Example from simulated LIGO-Virgo data with injection.



Plot from Christian Roever, Nelson Christensen and Renate Meyer

Ringdown Search

- There is a separate ringdown search
  - » Search over frequency, f, and quality factor, Q, using a template bank.
  - » These can be converted to M and a (for a given mode).
  - » Will look for inspiral-ringdown coincidence.



- Use similar multi-IFO analysis pipeline as for inspiral.

- Systematic uncertainty
  - » Unknown power contained in the ringdown.
  - » Which modes are excited.
  - » Assume 1% of final mass emitted in l=2, m=2 mode.

Systematic Uncertainties

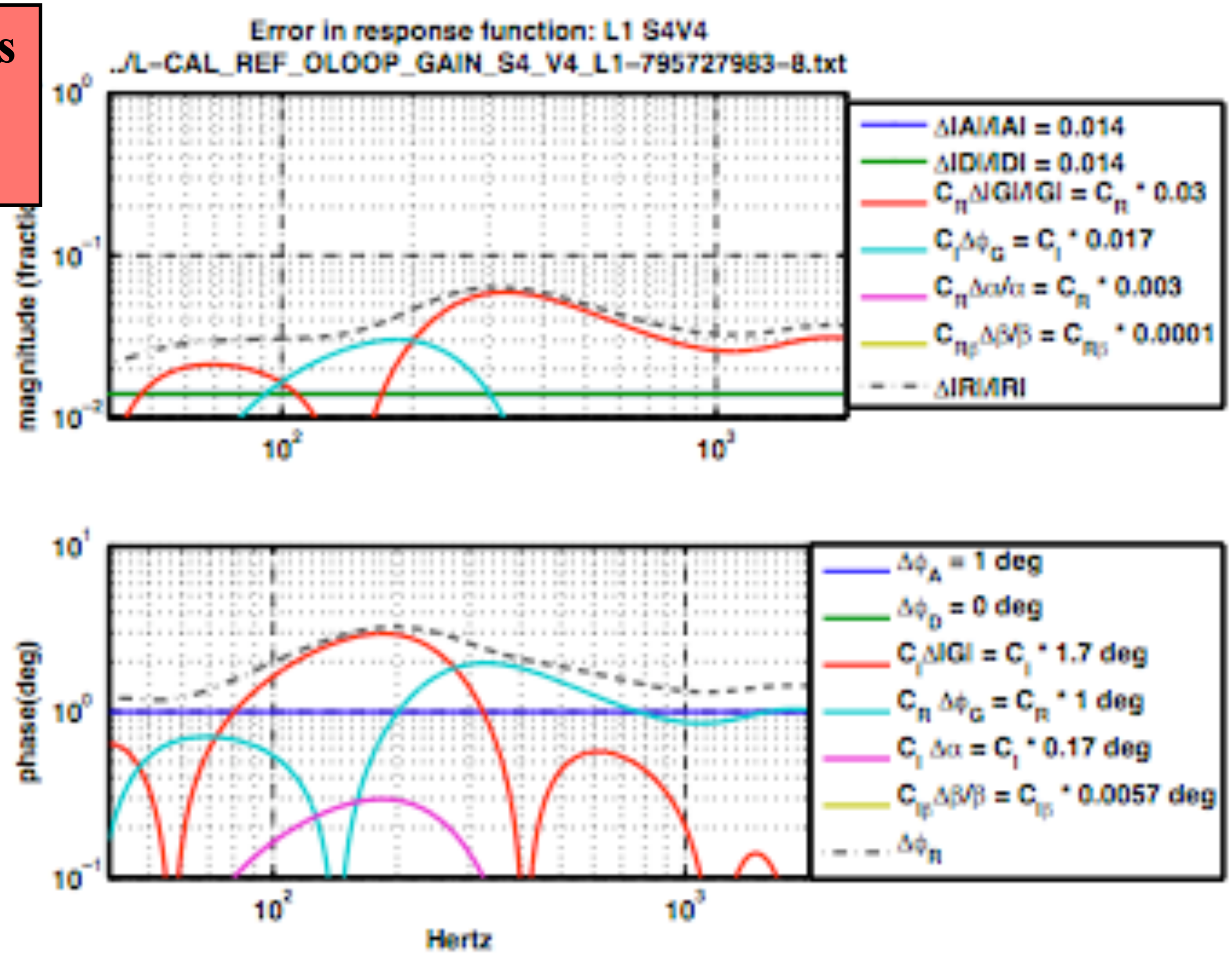
- Calibration Uncertainty
  - » Data from anti-symmetric port is recorded, v(t).
  - » This is then converted to gravitational wave strain, h(t).
  - » In the frequency domain:

$$h(f) = R(t,f)\,v(f)$$

    - – Requires a model for the interferometer response, $R(t,f)$
    - – Time dependence of response measured by injecting "calibration lines" at fixed frequency.

Calibration Uncertainties -- L1 during S4

Summary Numbers
~5% Amplitude
~5° Phase

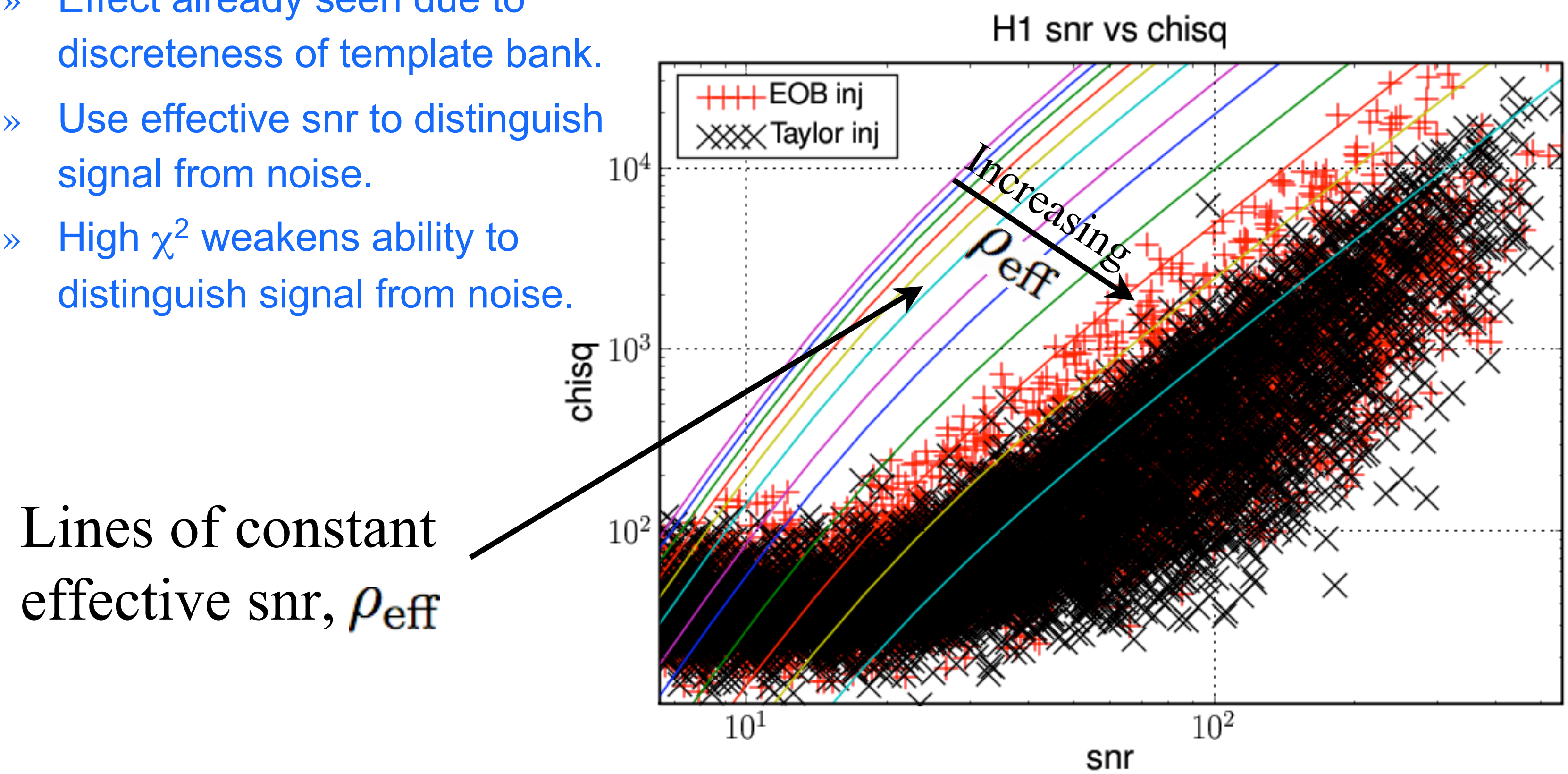


Uncertainty of Waveform

- The physical waveform is not accurately known
  - » Particularly close to the merger
- Current philosophy
  - » Inject with everything we have, and test the effect
    - – Standard PN, Effective One Body, Pade Approximants
    - – Spinning waveforms
    - – Would like to add numerical relativity waveforms
  - » What's the effect?
    - – Reduction of SNR. A 10% loss leads to a 30% rate reduction
    - – Affects waveform consistency tests.

Effect on χ^2 signal consistency test

- Waveform or calibration errors mean that the power in the waveform and template will not be distributed identically.
  - Will cause an increase in χ^2.
  - Effect already seen due to discreteness of template bank.
  - Use effective snr to distinguish signal from noise.
  - High χ^2 weakens ability to distinguish signal from noise.



Summary

- Waveform accuracy is important in various stages of an inspiral search
  - » Determination of template bank
  - » Loss of SNR due to waveform errors
  - » Determination of coincidence windows
  - » Effect on signal based vetoes
  - » Parameter estimation

- Main systematic uncertainties
  - » Unknown waveform
  - » Calibration

- Injecting numerical waveforms and doing search would help us to evaluate waveform uncertainty.