Results from the search for spinning binary systems in S3 LIGO data

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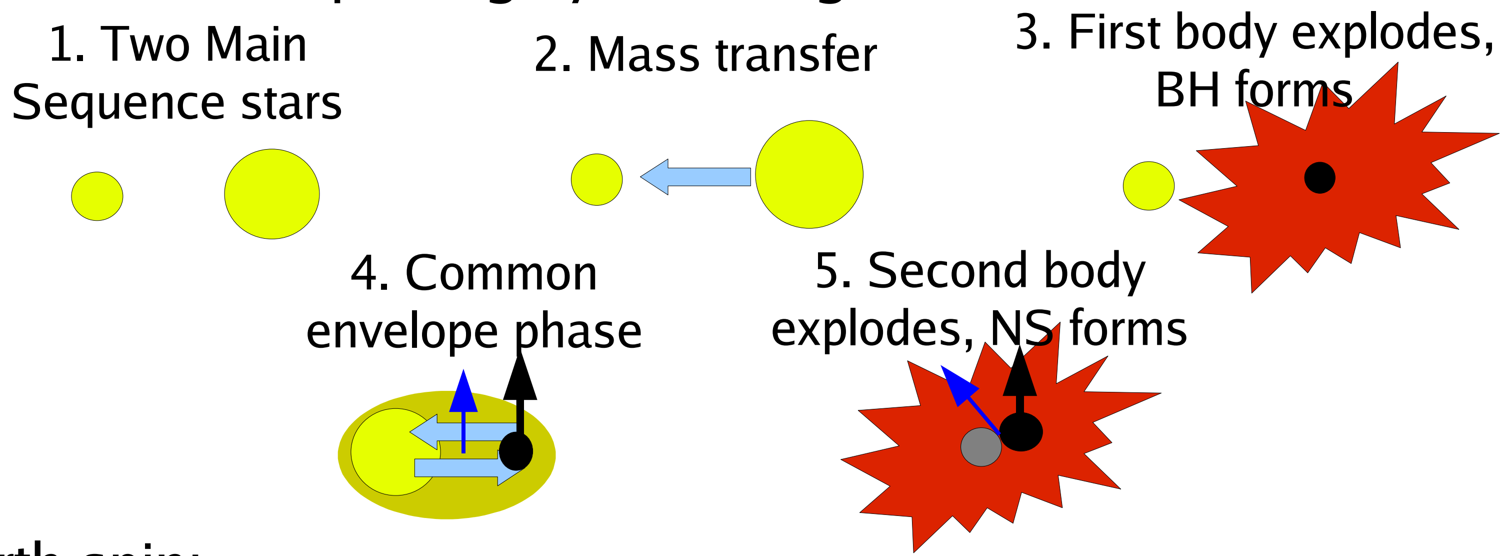
Overview

- Spinning binary systems
  - Evolution of spinning systems
  - Spin induced precession and modulation of gravitational wave
- Detection Template Family
  - Template placement
  - Testing of template bank
- The S3 LIGO data set
- Parameter Tuning and Vetoes
- Full data results
  - Follow up of loudest event candidates
- Upper limit calculation
- Summary and current status

Spinning binary systems

- Evolution of spinning systems e.g. NS-BH



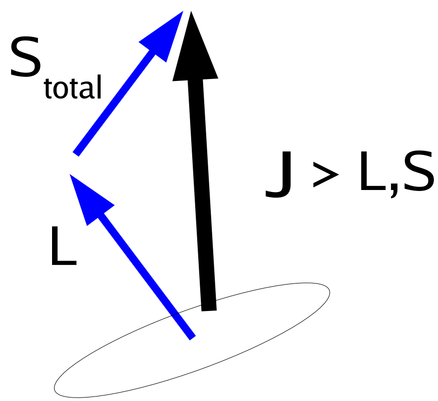
- Birth spin:
  - Observations of radio pulsars: a~0.005-0.02
  - Uncertainties: Spin-down? Supernova ejecta fall-back?
- Spin from accretion:
  - Observations of X-ray binaries
  - Common-envelope phase -> large spin
- Maximal spin values?
  - BH: a < 0.998 (Thorne 1974)
  - NS: a <~0.7 (Cook et al 1993)

Kalogera, ApJ. 541: 319-328 (2000)
R.O'Shaughnessy et al, ApJ. 632: 1035-1041 (2005)

Spinning binary systems

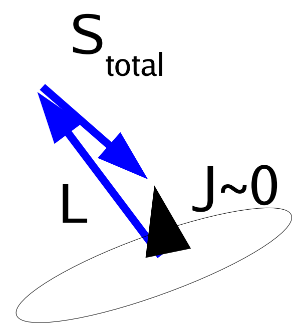
- Interactions between spin and orbital momentum lead to precession of orbital plane:

Simple Precession



L precesses about near constant J

Transitional Precession



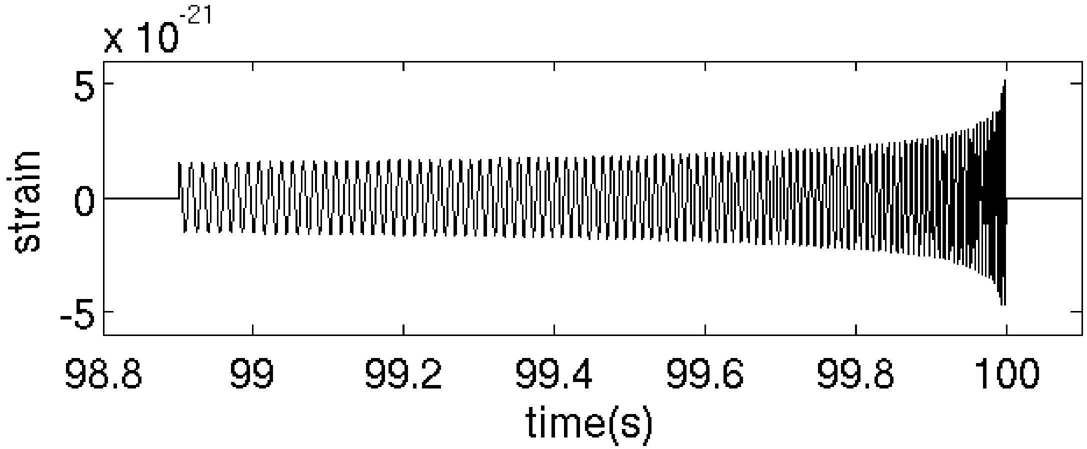
System "loses gyroscopic bearings" and tumbles chaotically

- Modulation of emitted gravitational waveform
- Spin effects increase as:
  - Spin-magnitude increases (a -> 1)
  - Spin-orbital angular momentum misaligned
  - Mass-ratio decreases (system becomes more asymmetric)

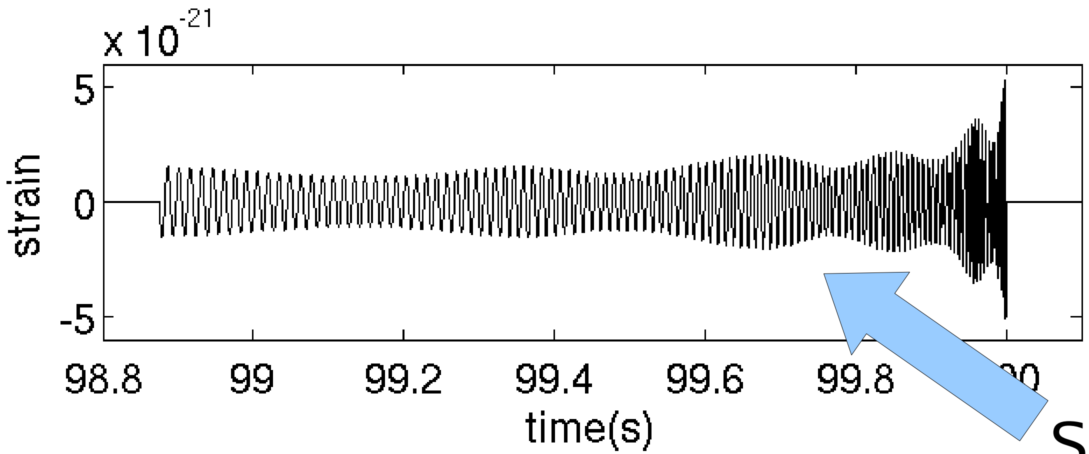
ACST, Phys. Rev. D 49 6274 (1994)

Spinning binary systems

Non-spinning components



Spinning components



Spin modulation

- Waveforms generated using PN approximations
- Require up to 17 physical parameters
- Spin-orbit and spin-spin coupling (2PN)

Detection Template Family

- For matched-filter search, templates must accurately describe modulation caused by spin-induced precession
- "BCVSpin" templates describe GW emission of spinning system using 11 *phenomenological* parameters:

Amplitude — Phasing — Termination condition

$$h(\psi_{\rm NM}, \mathcal{A}_k, t_0, \alpha_k; f) = \left[\sum_{k=1}^{3} (\alpha_k + i\alpha_{k+3})\mathcal{A}_k(f)\right] e^{2\pi i f t_0} e^{i\psi_{\rm NM}(f)} \theta(f_{\rm cut} - f)$$

$$\begin{aligned} \mathcal{A}_1 &= f^{-7/6} \\ \mathcal{A}_2 &= f^{-7/6}\cos(\beta f^{-2/3}) \\ \mathcal{A}_3 &= f^{-7/6}\sin(\beta f^{-2/3}) \end{aligned}$$

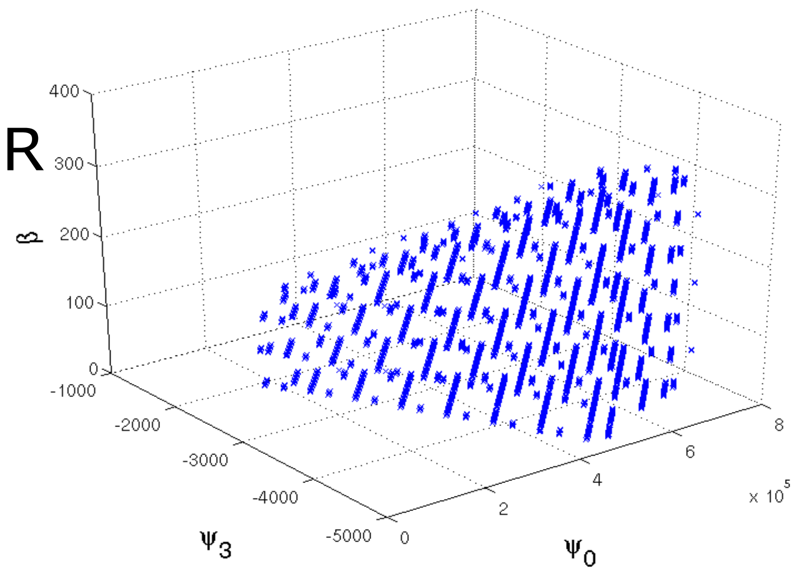
$$\psi_{\rm NM} = f^{-5/3}(\psi_0 + \psi_3 f)$$

- Designed as detection templates (not for parameter estimation)
- Adiabatic approximation; bodies follow quasi-circular orbits
- FF >= 97% for BH-BH, FF ~ 0.93 NS-BH

BCV2, Phys. Rev. D 67, 104025 (2003). PRD gr-qc/0211087

Template Bank

- 11 phenomenological parameters to describe template:
- 7 are extrinsic
  - Amplitudes alpha1..6
  - time of coalescence
  - found automatically by max. of SNR
- 4 are intrinsic:
  - **Psi0, Psi3**: ~masses
  - **Beta**: spin effects
  - $\mathbf{f_{cut}}$: ending condition
  - require placement of templates

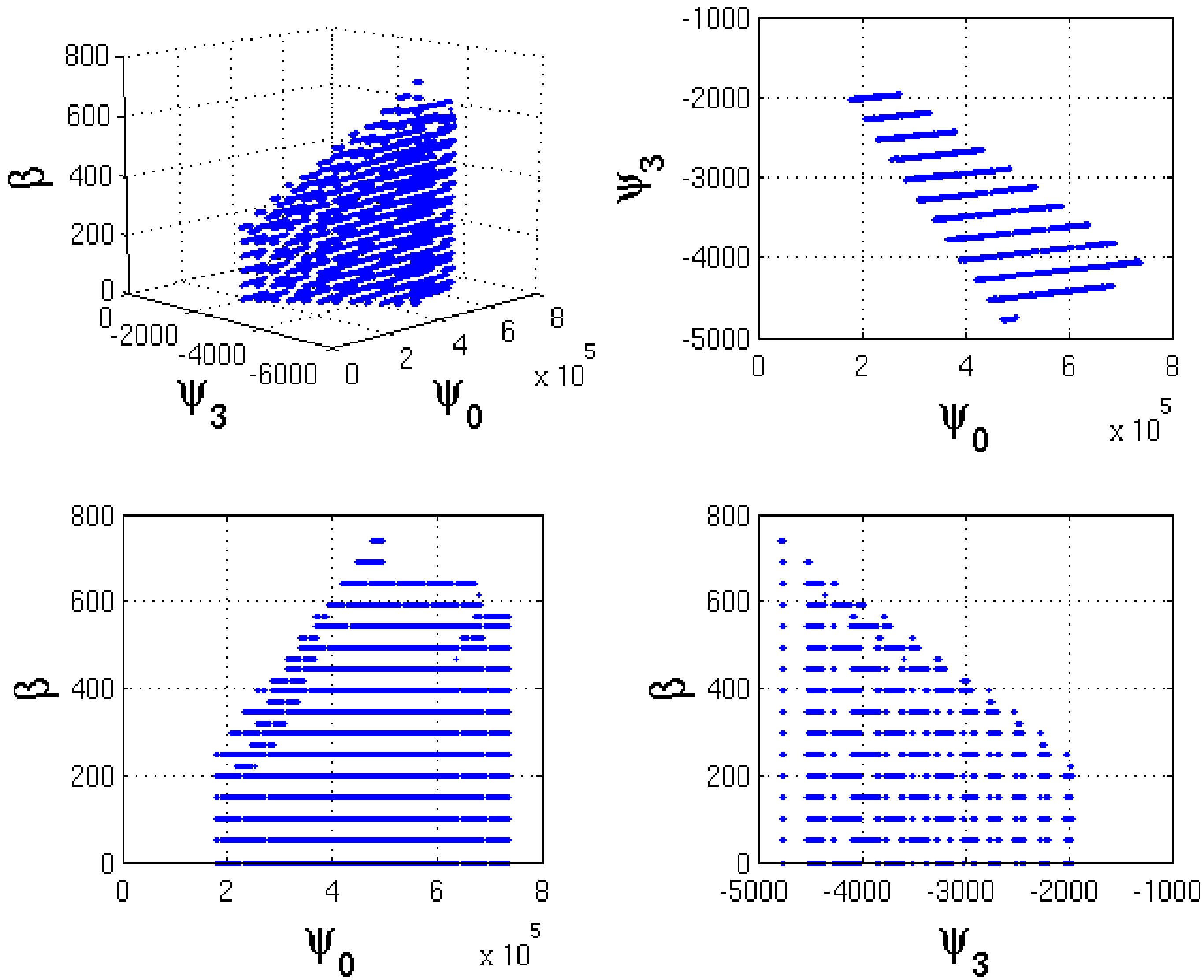


- Template placement
  - Simplified metric based upon “strong modulation approximation”
  - Bank designed to cover ~[1-3]*[6-12]M_{sol} region

Owen and Hanna

Template Bank

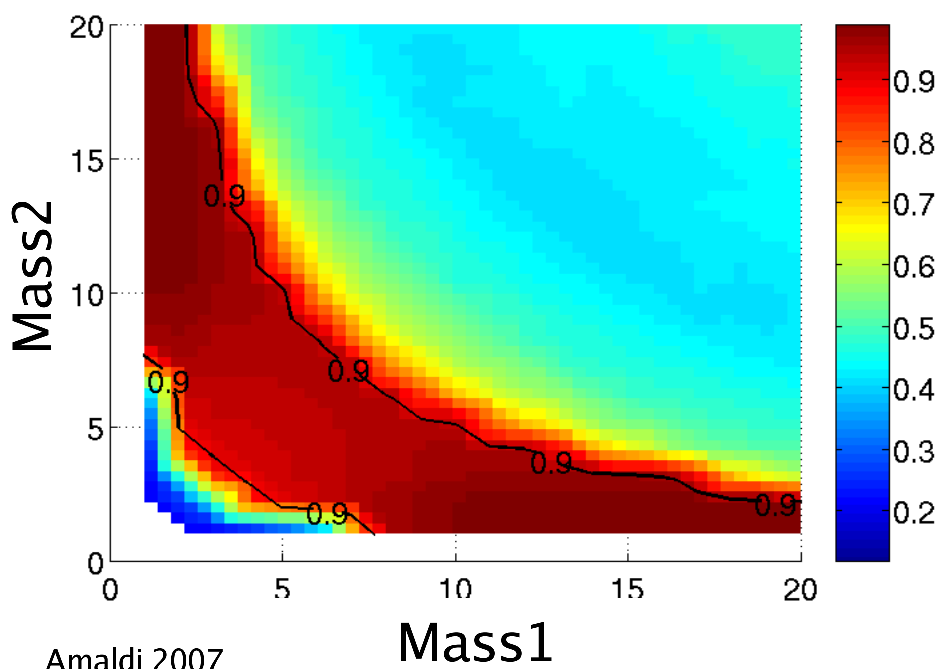
- Example template bank using a representative S3 power spectrum



Testing the template bank

- Bank designed to cover ~[1-3]*[6-12]M_{sol} region
- Uncertainty in relationship between physical mass and phenomenological Psi params
- Test effectiveness and coverage of the bank
- Systematic injection of physical PN spinning waveforms (ACST, Kidder) using LIGO design PSD

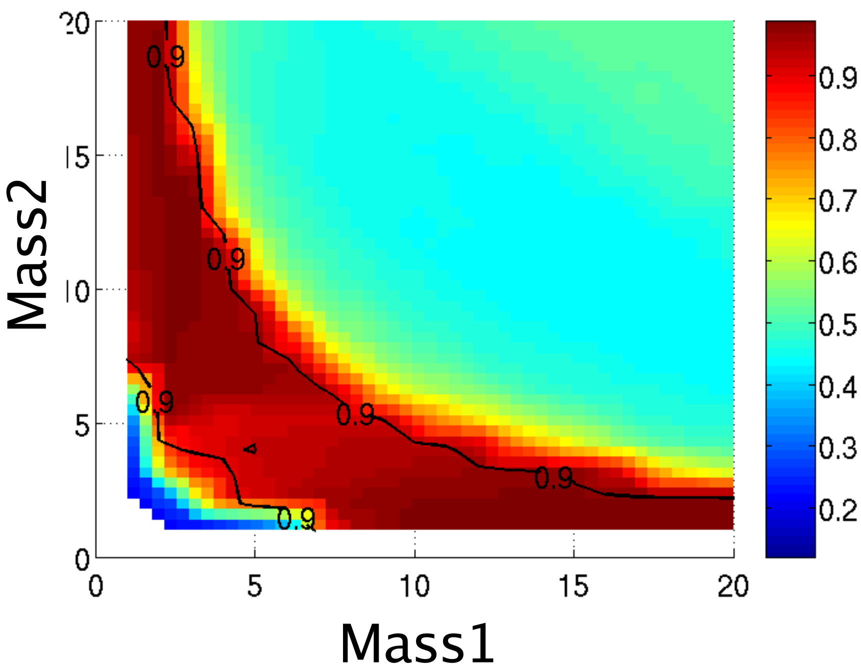
- Match > 90%
- Non-spinning bodies:

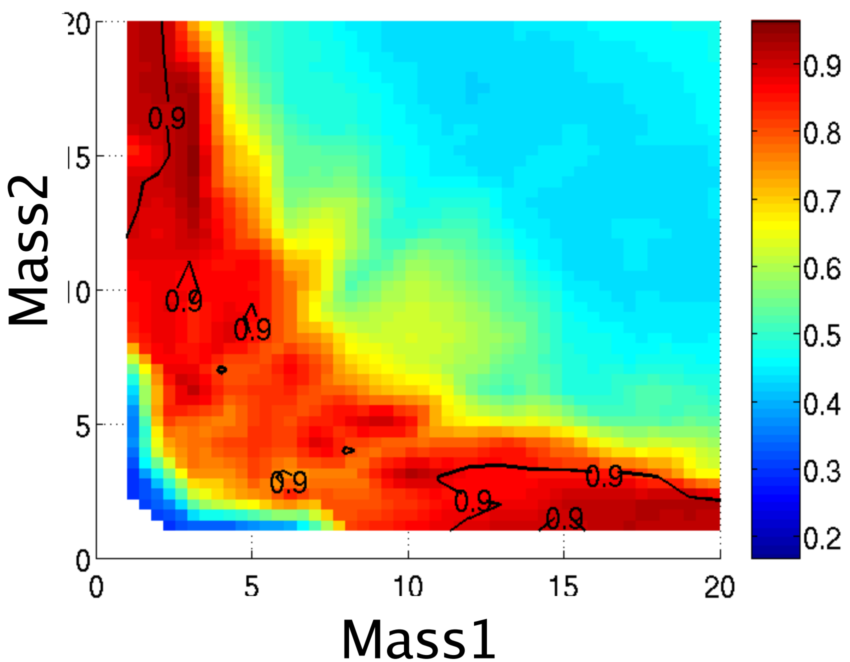


Testing the template bank

- Single spinning body
- Precession can occur

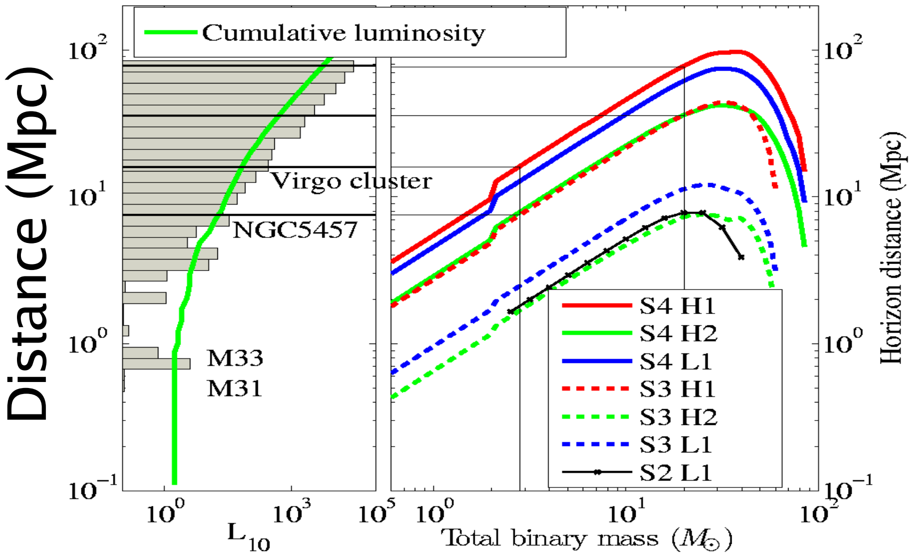
- Both bodies spinning
- As expected we do best in the non-equal mass regime
- ~[1-3]*[12-20]M_{sol}





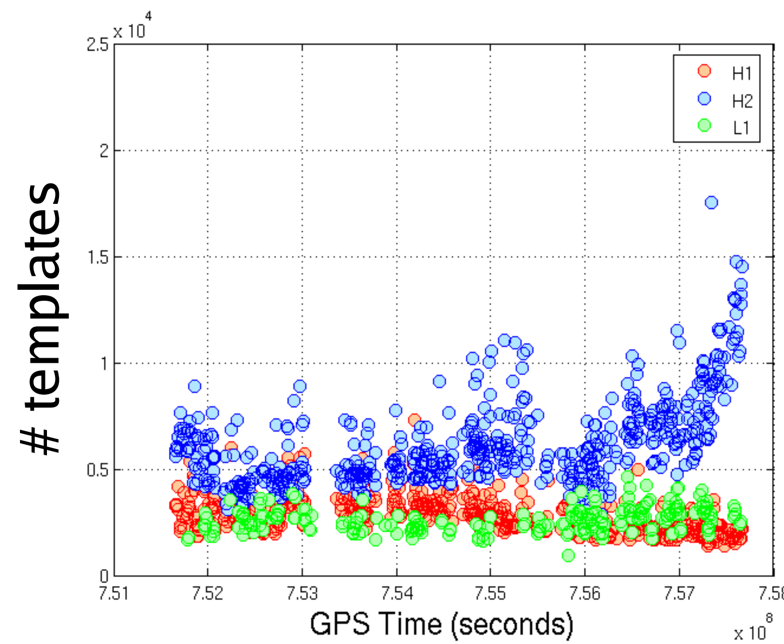
S3 LIGO Data Set

- S3: 70 days between October 31st 2003 and January 9th 2004



- Horizon distance: distance at which optimally oriented (non-spinning) system achieves SNR = 8
- L_{10} = 10^{10} blue light lum. of sun

- H2 requires huge number of templates ~18,000 towards end of S3 (flattening of PSD)
- Only search Hanford detectors when both are in lock
- Searched data set:
  - **H1H2: 604.1 hrs (56.4 hrs)**
  - **H1H2L1: 184.2 hrs (17.0 hrs)**



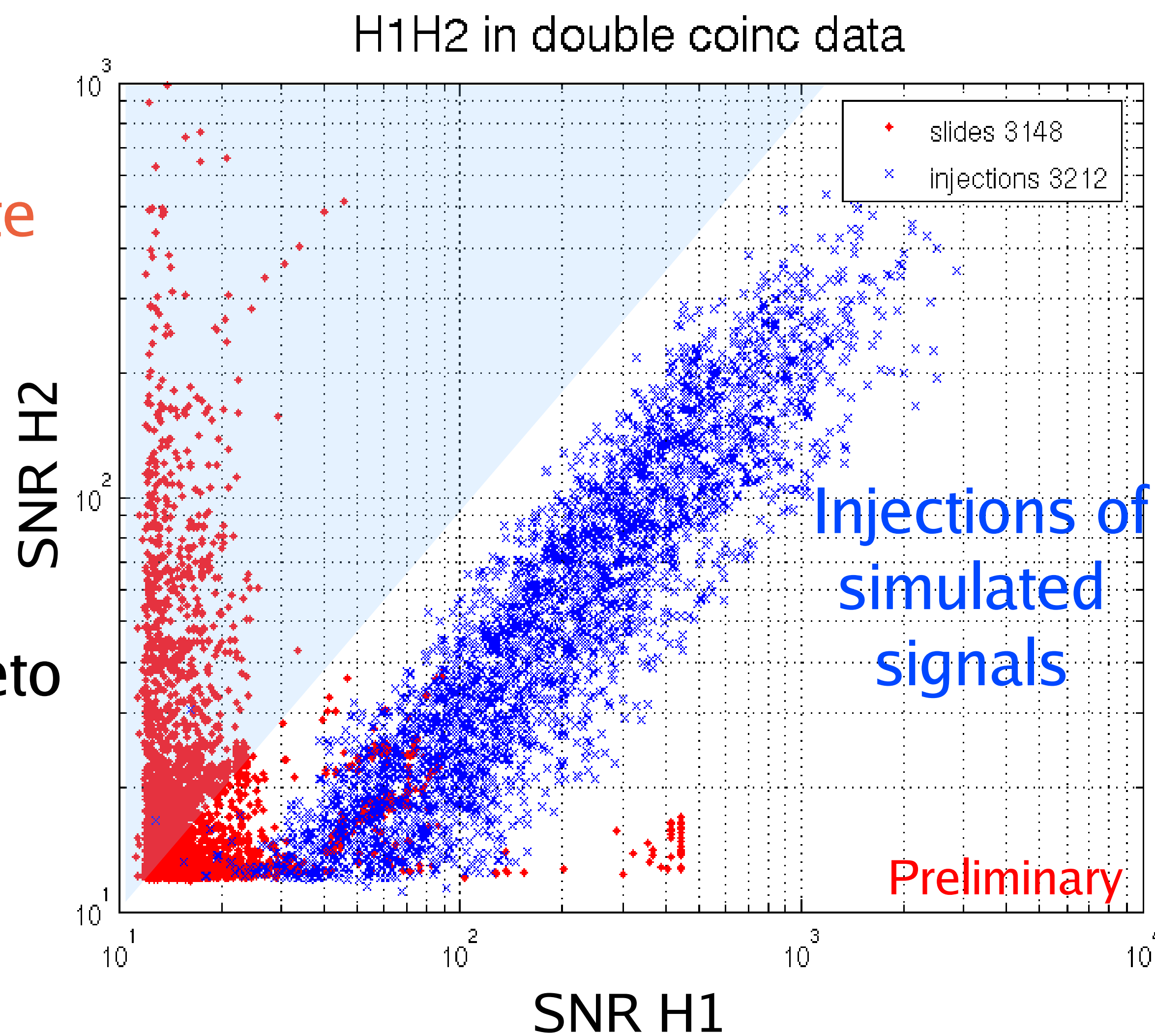
Parameter Tuning and Vetoes

Preliminary

Time shifts background estimate

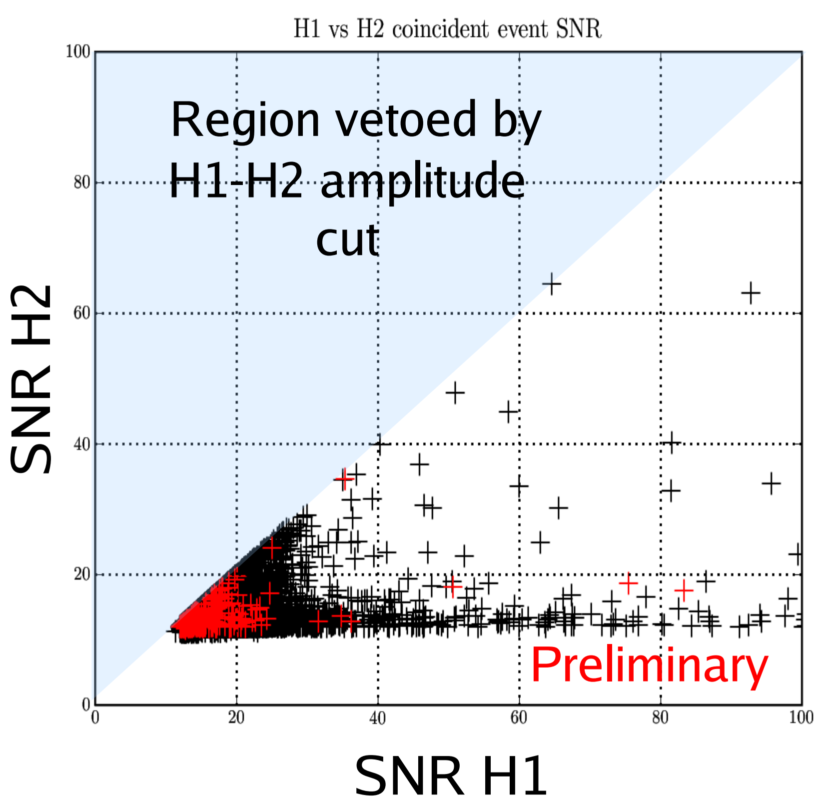
time shift ifo1 triggers w.r.t. Ifo2 triggers to estimate non-GW background

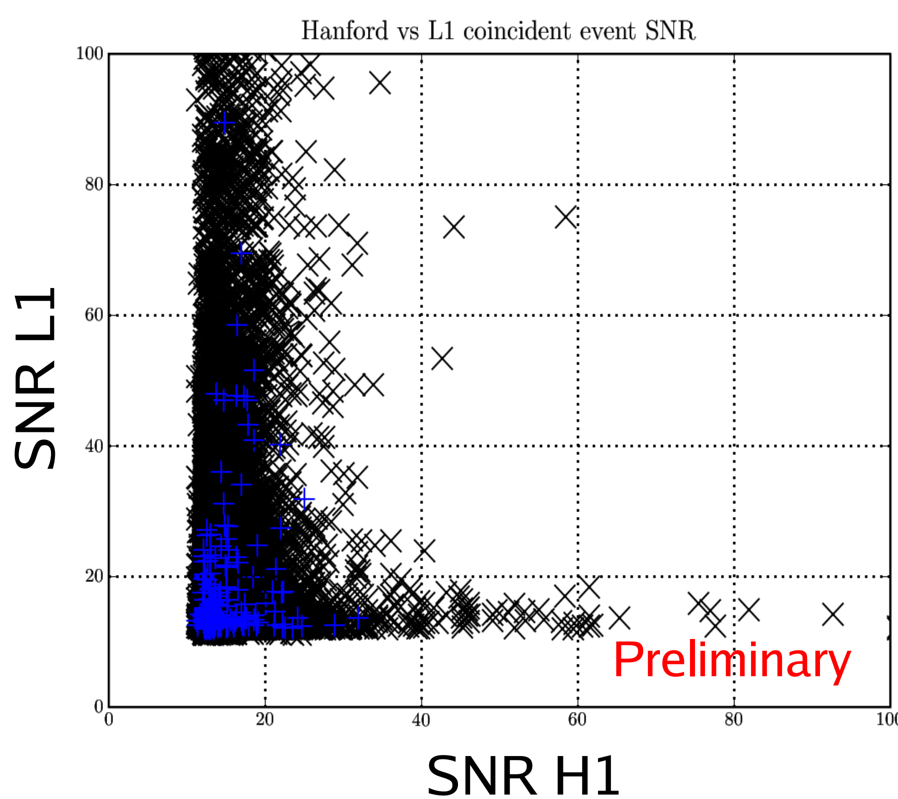
Amplitude based veto for H1-H2 triggers



Full Data Results

- No H1-H2-L1 coincident event candidates
- SNR-SNR scatter plots:

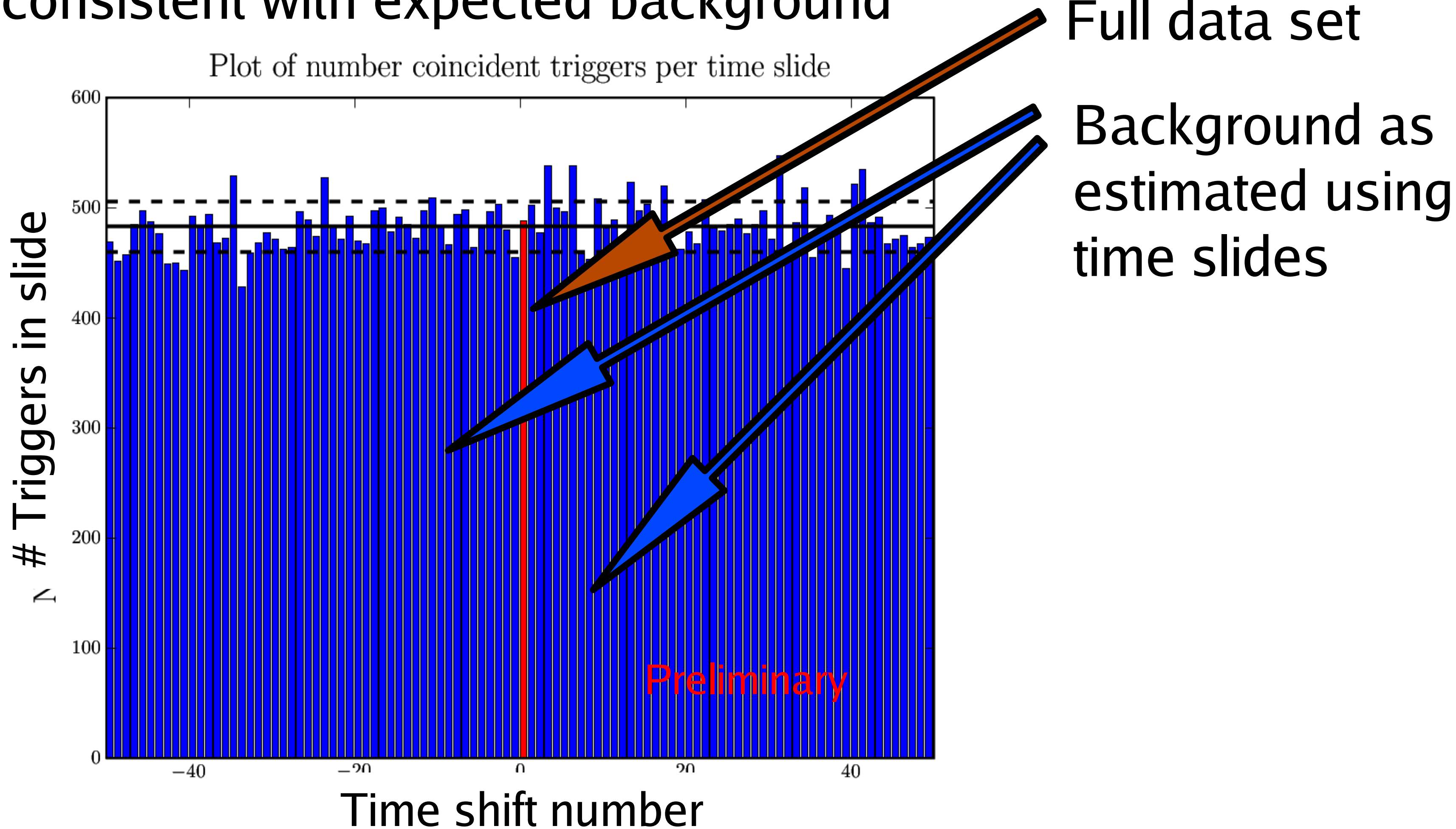




Full Data Results

Preliminary

- Estimate background rate using time-shifts
- Number of coincident events above threshold is consistent with expected background

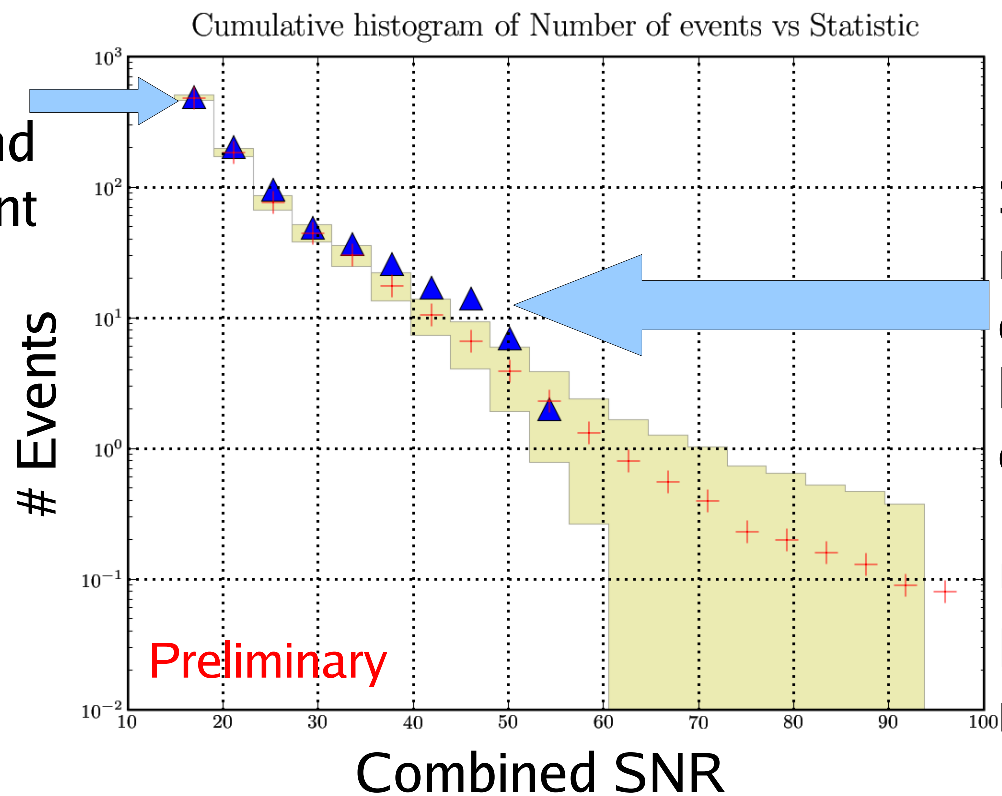


Full Data Results

Preliminary

- Cumulative histogram showing number of events with combined SNR > value

Background and foreground are consistent at threshold

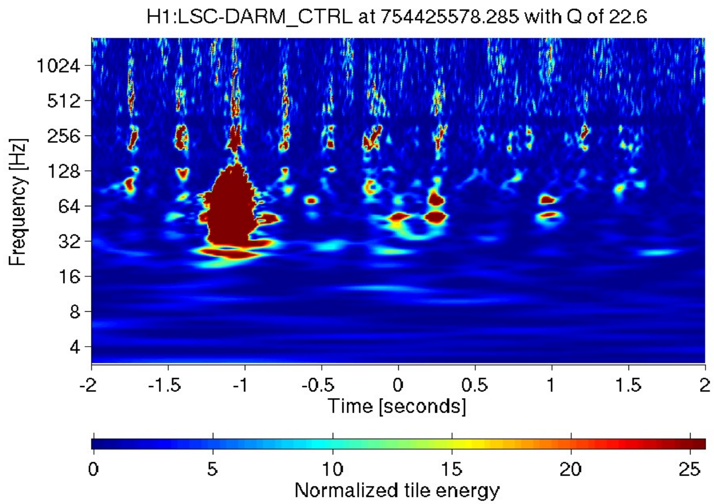


Small excess in number of H1H2 coincidences at high values of combined SNR

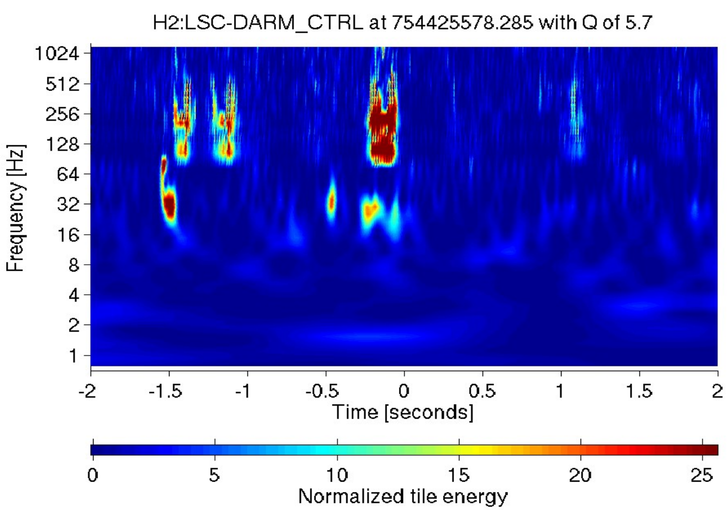
Underestimation of H1-H2 background rate by time-shifts

Full Data Results

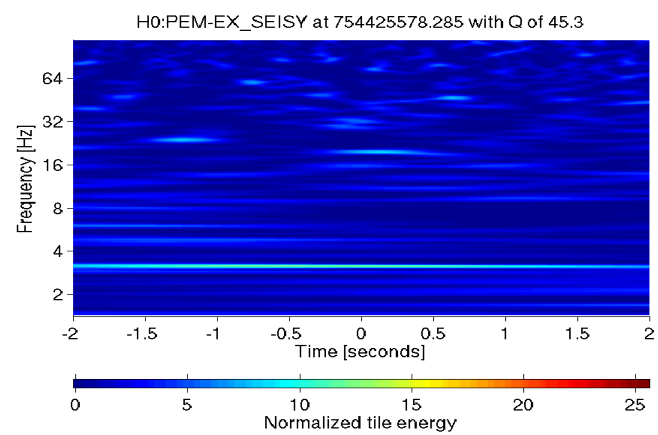
Preliminary



- All statistical excesses explained
- Follow up study of loudest event candidate:
  - H1H2 triggers at 754425577
  - L1 not in science mode
  - Combined SNR = 58.297
  - Also observed during search for non-spinning black holes
  - "Dust" data quality flag



Seismic activity



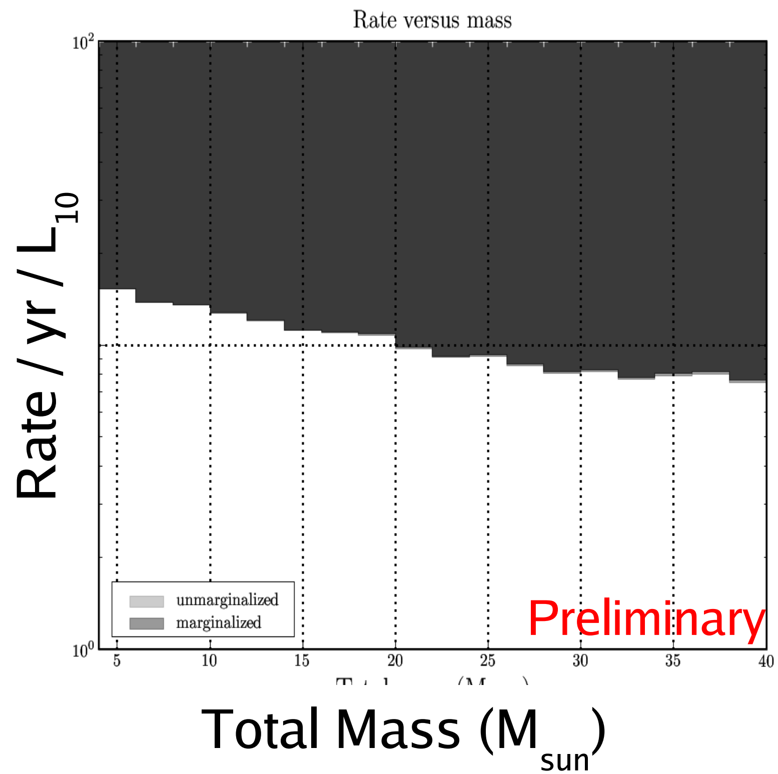
Upper Limit

Preliminary

- No plausible gravitational wave candidates...
- Bayesian upper limit calculation based upon the loudest event
- Efficiency of search finding simulated sources
- Estimated luminosity of Universe that we were sensitive to
- Marginalize systematic errors:
  - Monte Carlo simulations
  - Detector calibration
  - Distance and Lumosity estimation

- Before marginalization of systematic errors: $12.68\ yr^{-1}\ L_{10}^{-1}$
- After marginalization of systematic errors: $12.73\ yr^{-1}\ L_{10}^{-1}$

L_{10} = 1.7 Milky Way Equivalent Galaxies



Summary

- First dedicated search for spinning systems
  - Template bank sensitive to ~[1-3]x[12-20]M_{sol}
- Search of S3 LIGO data completed
  - Loudest event candidates investigated
  - No detection of gravitational waves
  - Analysis and code review nearing completion
- Upper limits on number of coalescences calculated
  - 12.73 yr^{-1} L_{10}^{-1} after marginalization of errors
- Mature draft of results paper under review

Extra slides

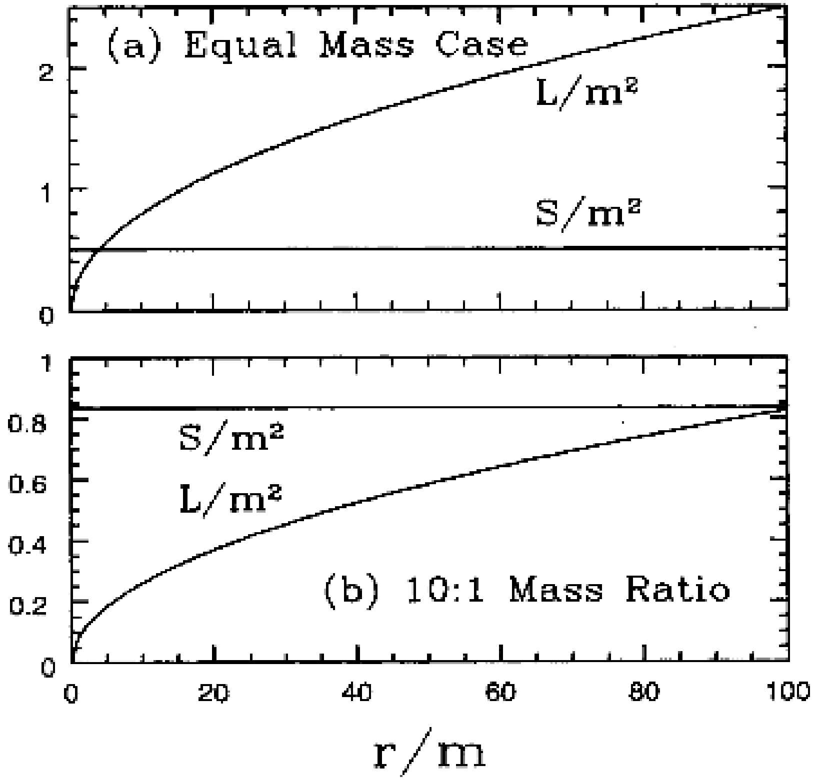
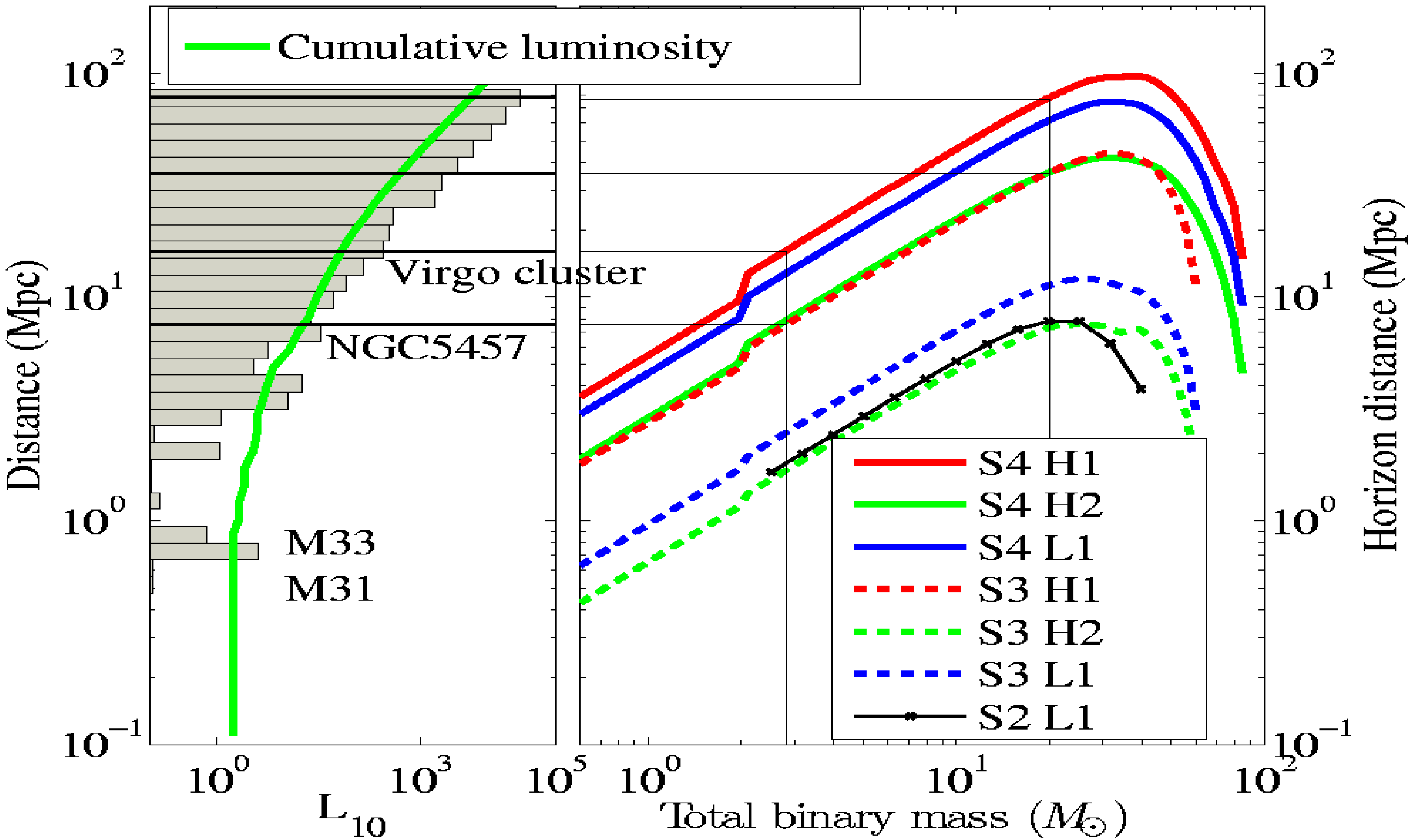


FIG. 3. A comparison of the magnitudes of the orbital angular momentum and spin angular momentum as the binary inspirals. (a) The equal mass case (assuming the bodies are maximally spinning). (b) The case of a 10:1 mass ratio.

L. E. Kidder, Phys. Rev. D 52, 821 (1995)

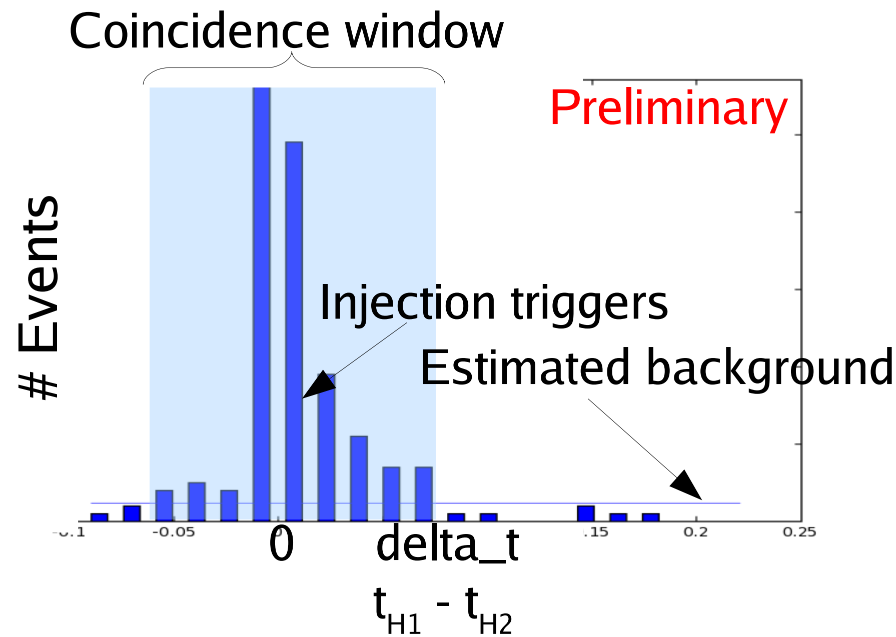
S3 Sensitivity

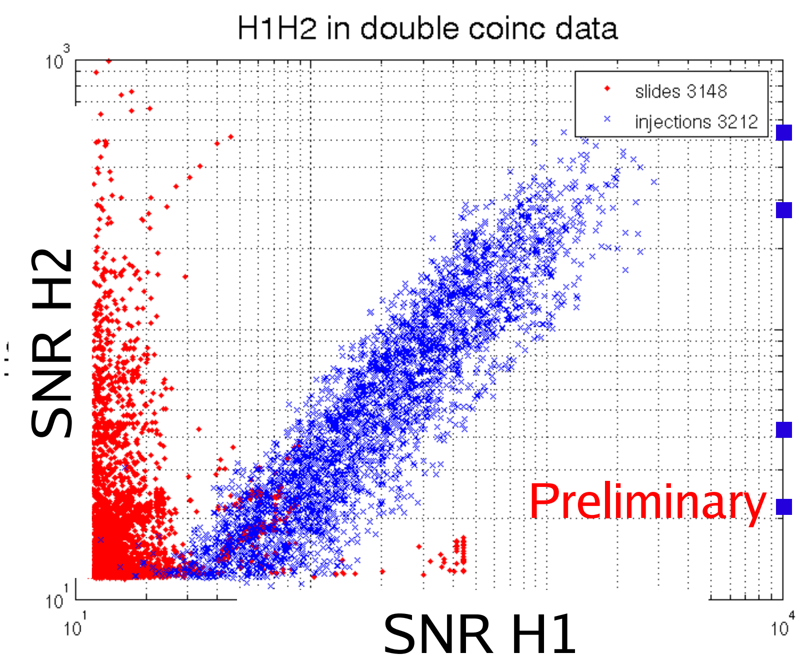


Parameter Tuning and Vetoes

Preliminary

- Tuning “coincidence” windows
- Coincidence if $|t_{ifo1}-t_{ifo2}| < t_{window}$
- Find signals which lie above estimated background
- “Loose windows” philosophy





- SNR-SNR plot
- Time shifts background estimate
  - time shift ifo1 triggers w.r.t. Ifo2 triggers to estimate non-GW background
- Injections
- Amplitude based for H1-H2 triggers