Searching for inspiraling and merging binaries in LIGO-Virgo data

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LIGO-G1100103v5
Overview

- **Detectors**
  - LIGO & Virgo

- **Sources**
  - compact binaries including NS & BH

- **Search methods**
  - matched filter, coincidence, signal-based veto, statistical significance

- **S6/VSR2/VSR3 analysis**
  - science run 2009-2010, search results and status

- **Blind Injection Challenge**

- **Challenges for future analysis**
A network of detectors

- LIGO Hanford (WA)
  LIGO Livingston (LA)
- Virgo (Cascina)
- Fabry-Perot Michelson interferometers
- Arm lengths 4km+2km (Hanford)
  4km (Livingston)
  3km (Virgo)
  600m (GEO600, data not used in search)
- LIGO-Virgo sensitive to strain of few $\times 10^{-23}$/√Hz
  at frequencies of order 200Hz
- See H. Grote’s talk
Astrophysical sources

- ‘Compact Binaries’: emit via time-varying quadrupole
  - Inspiraling / merging neutron stars and/or stellar mass BH
  - Hulse-Taylor observation: decay of orbital energy in binary pulsar
  - Less dense objects would be disrupted by tidal forces at lower frequencies

- Source populations are highly uncertain
  - Few NS binaries known
  - No NS-BH or BH-BH binaries observed, consider population synthesis models & plausible formation histories
  - Survey of rates for Initial and Advanced detectors:
    J. Abadie et al., Class.Quant.Grav.27:173001,2010
Observable source rates

<table>
<thead>
<tr>
<th>Source</th>
<th>( \dot{N}_{\text{low}} , \text{yr}^{-1} )</th>
<th>( \dot{N}_{\text{re}} , \text{yr}^{-1} )</th>
<th>( \dot{N}_{\text{high}} , \text{yr}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-NS</td>
<td>( 2 \times 10^{-4} )</td>
<td>0.02</td>
<td>0.2</td>
</tr>
<tr>
<td>NS-BH</td>
<td>( 7 \times 10^{-5} )</td>
<td>0.004</td>
<td>0.1</td>
</tr>
<tr>
<td>BH-BH</td>
<td>( 2 \times 10^{-4} )</td>
<td>0.007</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- ‘Low’, ‘Realistic’, ‘High’ rates quoted
- for NS, BH masses \((1.4,10) \, M_\odot\) visible above detector noise

J. Abadie et al., Class.Quant.Grav.27:173001,2010
Searching LIGO-Virgo data

- Matched filter with waveform templates
- ‘Lowmass’ search: analytic relativity waveforms
  » SPA with 3.5PN phase evolution
  » Used for total masses between 2 – 25 M☉
- ‘Highmass’ search: inspiral-merger-ringdown EOBNR templates
  » Hybrid of analytic and numerical relativity
  » Merger & ringdown parts of waveform contribute significantly for heavier systems
  » Used for total mass between 25 – 100 M☉

“All-sky” search pipeline

- Generate ‘triggers’: local maxima of SNR over time/masses
  - Produced separately for each detector
- Demand *coincidence* in time and mass between detectors
- Rank coincident events by SNR and chisq fit to templates
  - Chisq calculation is essential to suppress non-Gaussian noise transients in data streams – ‘glitches’
- Estimate noise background by *time-shifting* detectors relative to each other (by more than light travel time)
- 100 time shifts performed in blind analysis: false alarm probability of order \((10^{-2})\) indicates interesting candidate
- More time shifts required to establish a confident detection
S6/VSR2/VSR3 searches

- Joint LSC-Virgo science run
  June 7 2009 – October 20 2010
- Detector operation enhanced over S5/VSR1
  » Increased laser power
  » Prototype Advanced technologies deployed
- First search of Virgo data over full mass range
  » VSR1 data searched for BNS only
- Lowmass search results unblinded with latency of few weeks (compare 1-2y latency for S5)
- Rapid feedback of data quality info to instrumentalists
  » Identify, chase up and (sometimes!) fix detector artefacts
Distance where (1.4, 1.4) $M_\odot$ inspiral with optimal geometry gives SNR=8

- Dotted lines show modes of S5 and VSR1 ranges
  - LHO 4km
  - LLO 4km
  - LHO 2km
  - Virgo
Range vs. mass over time

- Beginning of S6/VSR2: Virgo sensitivity much improved on VSR1
- End of S6/VSR3: LIGO surpassed best S5 sensitivity, Virgo did not recover level of VSR2
Status of searches and preliminary results

- S5/VSR1 lowmass results published
- S5 highmass results paper submitted to journal (arXiv:1102.3781)
- S6/VSR2,3 data up to Oct 20 2010 have been analyzed in lowmass search
The Blind Injection Challenge

- End-to-end test of detection capability in LSC-Virgo
- A compact binary signal was injected into S6/VSR3 data: search groups were *unaware* (blinded)
- The injection was **found by the lowmass search**
  - LHO-LLO coincident event louder than all background in 100 time shifts
  - Extended background estimate found 5 louder time-shifted events in $2 \times 10^5$ y background time
  - Resulting FAR estimate is 1 per 7,000 y [including trials factors]
- A detection paper was written and approved (earlier this month) for submission to Phys. Rev. Letters
- Then we found out it was an injection…
Signal seen in the lowmass search

- Detector strain spectra at the event time
- Diagonal lines show signal strength above noise for search templates with maximal SNR
  - LHO (SNR=15, solid)
  - LLO (SNR=10, dashed)
- No trigger seen in Virgo above threshold SNR $\geq 5.5$
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- **S6/VSR2,3 data up to Oct 20 2010 have been analyzed in lowmass search**

- **No candidate GW events, loudest events have false alarm rate (few)/year**

- **These results have not yet been finalized: minor checks remain to be done**

- **S6/VSR2,3 highmass search analysis is ongoing**
  > Separating GW signals from glitches significantly harder than in lowmass range
Challenges for future searches

- Current searches use non-spinning signal templates
  - Signals from systems with spinning BH seen with lower efficiency
  - Reduced match with non-spinning templates ⇒ lower search SNR
  - Blind Injection signal was spinning – but also loud!

- Spinning systems have much larger parameter space
  - Challenge to increase search efficiency: find more signals without also finding more noise

- Develop coherent search techniques
  - Matched-filter appropriate sums of detector data streams
  - More information to distinguish signals from glitches
  - Full coherent search is complex and computationally (more) heavy

- Improved waveforms – e.g. (30 + 1) $M_\odot$ binaries
Searches for GW from compact binary coalescence ("CBC") have strong astrophysical motivation

Most recent joint LIGO-Virgo data were searched for signals with total mass 2 – 100 M☉

“Lowmass” (2 – 25 M☉) preliminary search result: We found the Blind Injection and no other candidates
  » BIC is a significant test of LSC-Virgo ability to detect ✔

“Highmass” (25 – 100 M☉) search is ongoing

Developments / improvement to search methods will continue into Advanced detector era (2015 onwards)
Other CBC searches

- Externally triggered GRB search
  - Analyze selected short periods around GRB alerts with optimized search pipeline
  - S6/VSR2,3 results in process of review

- Ringdown
  - Search for BBH systems with masses above 100 $M_\odot$
  - Signals have very short duration in detector sensitive band
  - Significant challenges in separating signals from glitches
  - S5 search in process of optimization