Towards the first coherent multi-ifos search for NS binaries in LIGO

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Acknowledgment: Allen, Christensen, Gonzalez, Heng, Koranda, Seader

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Talk Plan

• What is a coherent multi-detector inspiral search?
  » What is the motivation for it?
  » What are the expectations of it vis a vis a single detector search?
• The LIGO Science Run #2, and the case for a coherent inspiral search
• Coherent search studies on the S2 “Playground” data
  » Software injections
  » Hardware injections
  » Comparisons with single detector search results
Motivation for a coherent search

- Is the optimal search strategy (in Gaussian noise)
- Allows one to draw a single figure-of-merit on data from multiple detectors
- Is a veto in itself (in a “coincidence” sense)
  - Sets a coincidence time-window
  - Vetos candidates that lack consistent parameter information across a network of detectors
- *Vis a vis* a single detector search:
  - Should give you somewhat better SNR (by $\sim\sqrt{\text{# of detectors}}$)
  - Information on a larger set of source parameters
  - A better detection efficiency or a tighter upper limit
A Coherent Multi-detector statistic

- Strain at a single detector, $A$:

$$s^A(t) = F_+^A(\phi, \theta, \psi) h_+(t - \tau^A; t, \vartheta^\alpha) + F_\times^A(\phi, \theta, \psi) h_\times(t - \tau^A; t, \vartheta^\alpha)$$

$$= \mathcal{K}\left( (E_A^* S^A) e^{i\delta_c} \right)$$

where the $E'$s are functions of $F'$s and $i$.

- The strains from $M$ detectors form a vector:

$$\mathbf{s} = \left( s^1, s^2, ..., s^M \right)$$

- And the detection statistic is:

$$\ln \Lambda = \sum_{A=1}^{M} \langle s^A, x^A \rangle_{(A)} = \langle h_+(t; t, \vartheta^\alpha), X_+ \rangle + \langle h_\times(t; t, \vartheta^\alpha), X_\times \rangle$$
A Coherent Multi-detector statistic (contd.)

- Maximizing $\Lambda$ over $(\kappa, \delta_c, \psi, \iota)$ gives:
  - For two aligned detectors:
    \[
    \Lambda(\tau) = \frac{1}{\sqrt{2}} \left| C_1(t) + C_2(t; \tau_{(2)}) \right|
    \]
    where
    \[
    C_A(t; \tau_{(A)}) = \langle S^A(t), x^A(t; \tau_{(A)}) \rangle_{(A)}
    \]
  - And for two non-aligned detectors:
    \[
    \Lambda(t) = \sqrt{|C_1(t)|^2 + |C_2(t; \tau_{(2)})|^2}
    \]
Allowing for time delay

\[ \Lambda(t) = \sqrt{\left| C_1(t) \right|^2 + \left| C_2(t; \tau_{(2)}) \right|^2} \]

Hanford

Livingston

22 ms
The Coherent SNR

\[ \Lambda(t) = \sqrt{|C_H(t)|^2 + |C_L(t;\tau_L)|^2} = \sqrt{\rho_H^2(t) + \rho_L^2(t;\tau_L)} \]
LIGO Science Run #2: Case for a coherent search

**Comparable sensitivities:**
Run-avg. sensitivity to optimally oriented \( \{1.4, 1.4\} \) Msun NS binary at SNR = 8 in playground:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Range (Mpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLO 4k (L1)</td>
<td>1.8</td>
</tr>
<tr>
<td>LHO 4k (H1)</td>
<td>0.9</td>
</tr>
<tr>
<td>LHO 2k (H2)</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Studies on S2 Software Injections

- 2 sets of sources (1.4,1.4)Msun were injected into the playground

<table>
<thead>
<tr>
<th>End Times (734146000+)</th>
<th>703</th>
<th>803</th>
<th>903</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eff. Dist. (Mpc)</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Eff. Dist. (Mpc)</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

We examined these injections with the following thresholds:

<table>
<thead>
<tr>
<th>SNR &gt;</th>
<th>H1 MW (M33)</th>
<th>L1 MW (M33)</th>
<th>Coherent H1-L1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.7 (7.0)</td>
<td>7.7 (7.0)</td>
<td>6.5</td>
</tr>
<tr>
<td>CHI-sq</td>
<td>30.0</td>
<td>30.0</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NONE</td>
</tr>
</tbody>
</table>
SW Injections: Milky Way SNRs

Coherent vs Single IFOs

Coherent candidates only
SW Injections: Milky Way Effective Distances

Coherent vs Single IFOs

Coherent candidates only
SW Injections: Milky Way
Observed effective distances

Coherent candidates only
SW Injections: Milky Way Observed / Injected eff_dist

Coherent candidates only
SW Injections: Milky Way
SNR vs Mass
SW Injections: Milky Way Time Delay accuracy

LHO End Time - LLO End Time

![Graph showing time delay accuracy between LHO and LLO end times.](Image)
SW Injections: “Andromeda” SNRs

Coherent vs Single IFOs

Coherent candidates only
SW Injections: “Andromeda” Effective Distances

Coherent vs Single IFOs

Coherent candidates only
SW Injections: “Andromeda”
SNR vs Mass
SW Injections: “Andromeda”
End Time accuracy

LLO-only End Time error

Coherent cand. End Time error
A set of 7 HW injections were done on April 10th, towards the end of S2, at the following GPS times (in seconds):

<table>
<thead>
<tr>
<th>Times</th>
<th>8116</th>
<th>8416</th>
<th>8716</th>
<th>9016</th>
<th>9316</th>
<th>9616</th>
<th>9916</th>
</tr>
</thead>
<tbody>
<tr>
<td>733988000+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strengths (Mpc)</td>
<td>5</td>
<td>2.5</td>
<td>1.25</td>
<td>0.62</td>
<td>0.31</td>
<td>0.15</td>
<td>0.075</td>
</tr>
</tbody>
</table>

We examined these Hardware injections with both the coherent search pipeline and the single-detector pipelines.
The thresholds chosen for the various searches were:

<table>
<thead>
<tr>
<th></th>
<th>H2</th>
<th>H1</th>
<th>L1</th>
<th>Coherent H1-L1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H1</td>
<td>L1</td>
<td>H1-L1</td>
<td></td>
</tr>
<tr>
<td>SNR</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Chi-sq</td>
<td>10.0</td>
<td>10.0</td>
<td>30.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

The search was done on data re-sampled at 4096 Hz.
Hardware Injections: Chirp’s end time

<table>
<thead>
<tr>
<th>Injection start time (sec)</th>
<th>733988000+</th>
<th>8116</th>
<th>8416</th>
<th>8716</th>
<th>9016</th>
<th>9316</th>
<th>9616</th>
<th>9916</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs. End Times (sec)</td>
<td>Not seen</td>
<td>Not seen</td>
<td>8741</td>
<td>9041</td>
<td>9341</td>
<td>9641</td>
<td>9941</td>
<td></td>
</tr>
</tbody>
</table>

H1 only

H2 only

artifacts
Hardware Injections: Chirp’s end time (contd.)

L1 only

Coherent H1-L1

artifact
HW Injections: Effective Distances

H1 only

H2 only

artifacts
HW Injections: Effective Distances (contd.)

L1 only

Coherent H1-L1
Coincident HW Injections: Time delays

(H1 only) – (H2 only)  CoherentH1L1 – (L1 only)
Summary

1. The SW / HW injection plots show that:

   » All effective distances found within 15-20% of injected value
   » All of the detected injections in the Coherent H1-L1 search were within a time-point of the corresponding events in L1.
   » All 4 of the detected HW injections in H2 were within a time-point of the corresponding events in H1

2. Note that in a coherent H1-L1 search, even with a looser chi-square threshold (~twice as large as in the single-detector searches), but with the same SNR threshold, all (and only) the injected events are detected
   • Does this imply that the detection efficiency (on the playground data) of a coherent H1-L1 search is better than an H1 (only) search and an L1 (only) search?

3. Errors in observed $\left(\psi, i\right)$ needs to be studied