All sky search for long duration gravitational-wave transients

Valentin Frey
PHENIICS Fest – 31 May 2017

Laboratoire de l'Accelerateur Lineaire (CNRS/IN2P3 et universite Paris Sud)
Outline

Let's come back 1.3 billion years ago.
- Binary black hole waltz
- Effect of gravitational vibration through the Earth
- Interferometric detector, ears of gravitational wave astronomy

Long duration GW transients
- What is a « long duration» GW transient ?
- Long GW transient sources

Initial LIGO detectors, S5/S6 data search results

Advanced LIGO detectors, O1 data search overview

Conclusion and perspectives
GW generation
GW effect on the earth

Scale of Effect Vastly Exaggerated
See Angelique's poster for more information about interferometric detectors and upgrades.
Long duration GW burst

Unmodeled search for long duration gravitational waves (>10s)

Promising search
- Search for promising sources in part of the parameters space, unexplored so far
- Bridging burst/stochastic/continuous waves parameters space.

Using stochastic background search techniques (cross-correlation)
- Large parameter space
- Model-independent search
- All-sky/all-time search
Sources

- Many potential sources, but rough modelling
- Waveforms models:
  - van Putten accretion disk instabilities and fragmentation (ADI) [1]
  - Rotational instabilities in proto-neutron star (PNS) remnants [2]
  - Proto-neutron star convection [3]
  - Fallback accretion on neutron stars [4]
  - Instabilities in central magnetars [5]
  - Neutron star r-modes
  - ...

Use of adhoc waveforms to completely span the parameters space.

STAMP-AS pipeline

Detector 1
Cross-correlation
Coherent FTmap
Clustering
Triggers

Detector 2

All sky search

No signal assumption
Parameter space
Frequency range: 40-1000Hz
Time window: 500 s

Frequency range: 40-1000Hz
Time window: 500 s
Noise (spectral & glitch)

The data are not Gaussian → We cannot estimate the background using Monte Carlo methods.
Time slide methods

Insert a time shift between the two detectors data stream.

Every coincident event is not astrophysical => this is a false alarm
We can estimate the background of the search considering the distribution of false alarms
S5/S6 results

Advanced detector era
S5/S6 scientific run :
- Two detectors **H1** (Hanford) **L1** (Livingston)
- **S5 run** : Nov 5, 2005 - Sep 30 2007
  - 283 days of coincident data
- **S6 run** : Jul 7, 2009 - Oct 20 2010
  - 133 days of coincident data
- **Combining S5/S6** : more than 1 year of coincident data

- First search for long-duration transients with LIGO data.

Analysis :
- Background studies.
- Results from the full S5/S6 run.
- Search efficiency estimated using physical (ADI) and ad-hoc waveforms (15 waveforms total).
S5/S6 background


Final distribution close to Gaussian noise expectation

Some outliers due to instrumental noise → suppressed by vetoes

Example of instrumental noise
S5/S6 results

- No significant GW candidate.
- Search results are consistent with expectations for noise.
S5/S6 sensitivity

\[ \begin{array}{|c|c|c|c|}
\hline
\text{name} & \text{Fmin [Hz]} & \text{Fmax [Hz]} & \text{Duration [s]} & \text{Distance @ 50 \% [Mpc]} \\
\hline
\text{Adi A} & 135 & 166 & 39 & 5.4 \\
\text{Adi B} & 110 & 209 & 9.4 & 16.3 \\
\text{Adi C} & 130 & 250 & 236 & 8.9 \\
\text{Adi D} & 111 & 234 & 76 & 11.5 \\
\hline
\end{array} \]

\[ \sim 10 - 20 \text{ Mpc} \rightarrow \text{sensitive to the local univers.} \]
O1 results

- Advanced detector era

**VSR1**
- **VSR2**
- **VSR3**
- **VSR4**

**L1**
- S5
- S6

**H1**
- S5
- S6

**Jan 2006**
- S5
- VSR1

**Jan 2007**
- S5
- VSR2

**Jan 2008**
- S6
- VSR3

**Jan 2009**
- S6
- VSR4

**Jan 2010**
- S6

**Jan 2011**
- S6

**Jan 2012**
- S6

**Jan 2013**
- S6

**Jan 2014**
- S6

**Jan 2015**
- S6

**Jan 2016**
- O1

**Jan 2017**
- O2
New detectors
- Advanced LIGO is a complete new detector.
- New instrumental noise sources.
- Expect factor 3 on the search sensitivity.

O1 :
- 2 detectors H1 & L1
- *From Sep 12, 2015 to Jan 12, 2016* – 48 days of coincident data.

Pipeline
- Parameter space extended:
  \([40-1000] \text{ Hz} \rightarrow [24-2000] \text{ Hz}\)
- 3 additional pipelines.
- New physical waveforms added (magnetar & fallback accretion).
O1 preliminary analysis

- Data noisier than S5/S6 ...
- But expected background distribution close to a Gaussian distribution after all selection steps applied.

Analysis complete. Improvement : Factor ~3 wrt S5/S6 search sensitivity. Example : ADI sensitivity distance ~30-60 Mpc
O1 predicted sensitivity

Energy computed for a source at 10kpc for an efficiency of 50%:

$$E_{GW} = \frac{c^3 r^2}{4G} \int_{-\infty}^{\infty} \langle h_+^2 + h_x^2 \rangle dt,$$

Sensitivity improvement ~ factor 3 wrt S5/S6 run.
O2 search
O2 search

- Analysis on going
  - Low latency analysis (week by week)
  - Background estimated
  - Understanding new noises families

- To be done
  - Estimated sensitivity
  - Add new waveforms models
Conclusion & perspective

Summary
- Long duration GW transients: recent search in the Virgo-LIGO Scientific Collaboration
- Difficulties: rather large parameter space & no signal waveform assumptions
- We have developed many selection cuts that significantly reduce the background outliers

Promising search
- Bridging burst/stochastic/continuous waves parameter space
- Advanced detectors' sensitivity allows searches covering interesting astrophysical distances

Perspectives
- Source parameters estimation (need of more accurate astrophysical models)
- Increase parameter space: from long duration to very long duration transients
- (1 day → several weeks) work in progress.
Detector
GW 151226

- **Noise**
  - Black: Background excluding only GW150914
  - Purple: Background excluding all search results

- **Search Result**
  - Orange markers

- **Strain**
  - Green: GW Frequency
  - X: Peak GW amplitude

- **Frequency vs. Time**
  - Frequency (Hz)
  - Time (s)

- **Detection statistic $\hat{\rho}_c$**
  - Number of events

- **GW151226**
GW combinason
### Parameters Estimation

<table>
<thead>
<tr>
<th>Event</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal-to-noise ratio $\rho$</td>
<td>23.7</td>
<td>13.0</td>
<td>9.7</td>
</tr>
<tr>
<td>False alarm rate FAR/yr$^{-1}$</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>0.37</td>
</tr>
<tr>
<td>p-value</td>
<td>$7.5 \times 10^{-8}$</td>
<td>$7.5 \times 10^{-8}$</td>
<td>0.045</td>
</tr>
<tr>
<td>Significance</td>
<td>$&gt; 5.3\sigma$</td>
<td>$&gt; 5.3\sigma$</td>
<td>$1.7\sigma$</td>
</tr>
<tr>
<td>Primary mass $m_1^{\text{source}}/M_\odot$</td>
<td>$36.2^{+5.2}_{-3.8}$</td>
<td>$14.2^{+8.3}_{-7.7}$</td>
<td>$23^{+18}_{-6}$</td>
</tr>
<tr>
<td>Secondary mass $m_2^{\text{source}}/M_\odot$</td>
<td>$29.1^{+3.7}_{-4.4}$</td>
<td>$7.5^{+2.3}_{-2.3}$</td>
<td>$13^{+4}_{-5}$</td>
</tr>
<tr>
<td>Chirp mass $M^{\text{source}}/M_\odot$</td>
<td>$28.1^{+1.8}_{-1.5}$</td>
<td>$8.9^{+0.3}_{-0.3}$</td>
<td>$15.1^{+1.4}_{-1.1}$</td>
</tr>
<tr>
<td>Total mass $M^{\text{source}}/M_\odot$</td>
<td>$65.3^{+4.1}_{-3.4}$</td>
<td>$21.8^{+5.9}_{-1.7}$</td>
<td>$37^{+13}_{-4}$</td>
</tr>
<tr>
<td>Effective inspiral spin $\chi_{\text{eff}}$</td>
<td>$-0.06^{+0.14}_{-0.14}$</td>
<td>$0.21^{+0.20}_{-0.10}$</td>
<td>$0.0^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>Final mass $M_f^{\text{source}}/M_\odot$</td>
<td>$62.3^{+3.7}_{-3.1}$</td>
<td>$20.8^{+6.1}_{-1.7}$</td>
<td>$35^{+14}_{-4}$</td>
</tr>
<tr>
<td>Final spin $a_f$</td>
<td>$0.68^{+0.05}_{-0.06}$</td>
<td>$0.74^{+0.06}_{-0.06}$</td>
<td>$0.66^{+0.09}_{-0.10}$</td>
</tr>
<tr>
<td>Radiated energy $E_{\text{rad}}/(M_\odot c^2)$</td>
<td>$3.0^{+0.5}_{-0.4}$</td>
<td>$1.0^{+0.1}_{-0.2}$</td>
<td>$1.5^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>Peak luminosity $\dot{\epsilon}_{\text{peak}}/(\text{erg s}^{-1})$</td>
<td>$3.6^{+0.5}_{-0.4} \times 10^{56}$</td>
<td>$3.3^{+0.8}_{-1.6} \times 10^{56}$</td>
<td>$3.1^{+0.8}_{-1.8} \times 10^{56}$</td>
</tr>
<tr>
<td>Luminosity distance $D_L/\text{Mpc}$</td>
<td>$420^{+150}_{-180}$</td>
<td>$440^{+180}_{-190}$</td>
<td>$1000^{+150}_{-500}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
<td>$0.20^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>Sky localization $\Delta \Omega/\text{deg}^2$</td>
<td>230</td>
<td>850</td>
<td>1600</td>
</tr>
</tbody>
</table>
Localization