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GW150914 Detection Case

The LSC-Virgo Data Analysis Council

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On September 14, 2015, during Engineering Run 8, the online burst analysis triggered on a significant event at GPS 1126259462.398, with low false alarm rate. The event was initially referred to as G184098 (from its Coherent WaveBurst GraceDB ID), and renamed GW150914 once it was recognized as the first detection candidate in the Advanced Detector Era. The detection procedure was initiated by the Burst group [1].

This document presents a detection case for event GW150914, as required by Step 1 of the Detection Procedure [2]. It includes the main evidence for the detection case from Burst and CBC searches, as well as highlights from parameter estimation and detector characterization, with links to the documents where additional information can be found. The status of the instruments at the time of the events is described in separate documents [3, 4].

A high level collection of links and documentation is maintained under the DAC wiki at:
`https://wiki.ligo.org/DAC/G184098`.

1 Case for detection: Burst Searches

The event was found by the two burst low latency searches cWB and oLIB. The event was recovered with high significance by three all-sky pipelines used in the burst searches: cWB, cWB+BWB, oLIB, and this discovery was also validated by X-pipeline. These searches target broad classes of short-duration and long duration burst signals. Specialized versions of those searches are also performed to target a wide class of CBC sources including, intermediate mass black holes (IMBBH), eccentric inspirals (eBBH) and intermediate mass ratio inspirals (IMRI).

Coherent WaveBurst (cWB) is the baseline pipeline used by the group in several analyses. BayesWavesBurst (BWB) follow-ups to cWB triggers (cWB+BWB) are used to enhance the pipeline performance for some source classes. Omicron-LALInferenceBurst (oLIB) is an independent burst pipeline, and thus provides an important validation of observed burst events.

In addition, one of the long-duration search pipelines, X-pipeline, has been run over a small amount of data, and detected the event as well [5].

1.1 Coherent WaveBurst (cWB)

The cWB pipeline [6, 7] found the event in the *online* analysis with a detection statistic of $\rho = 14.1$ [8].

Several *off-line* background runs have been completed or are in progress to assess the False Alarm Rate (FAR) of this candidate. Based on 4563 years of ER8a playground data collected before September 12, this event is louder than all background triggers, leading to an Inverse False Alarm Rate (IFAR) estimate better than 4500 years [9]. This playground data have been used to tune selection cuts and study data quality flags.

The ER8b period (September 12-26) has been analyzed by the CWB pipeline with two thresholds on the detection statistic ρ_c: high (ρ_c >9.2), yielding 8295 years worth of background data, and low (ρ_c >7.1), yielding 8.5 years of background livetime. The high threshold was used to measure the GW150914 detection significance with the large number of time lags, and save on computing. The low threshold was used to reveal possible low SNR zero-lag triggers and measure their FAR with a small number (589) of time lags.

Along with the above un-modeled search, the *constrained set*, the background was estimated for a number of specialized searches: the low chirp mass *chirp set* and high chirp mass *IMBBH set*. Figure 1 shows the background estimates obtained with the constrained and chirp sets. The GW150914 IFAR is greater than 8295 years in both those analyses. The FAR is shown as a function of the coherent network SNR (cWB detection statistic), which is a biased estimator of the matched filter SNR.

Pipeline	Data Set	Background	Result	Notes
cWB	ER8a	4,563 yrs	IFAR $>$ 4500 yrs	Used for tuning
cWB	ER8b	8,295 yrs	IFAR $>$ 8,295 yrs	CAT2 & hveto applied
oLIB	ER8b	15 yrs	Not yet available	In progress
oLIB	S6	10 yrs	IFAR $>$ 10 yrs	
cWB+BWB	ER8a	1,500 yrs	IFAR $>$ 1500 yrs	Used for tuning
cWB+BWB	ER8b	8,295 yrs	Not yet available	In progress
X-pipeline	Sept 14	1.4 yrs	IFAR $>$ 1.4 yrs	long duration search

Table 1: Summary for Burst results for GW150914.

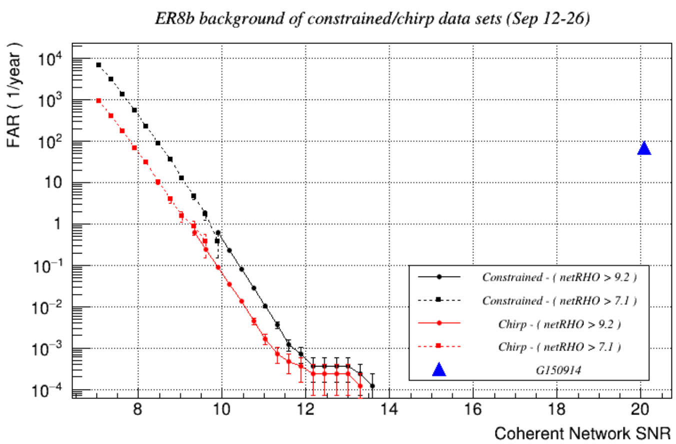

Figure 1: False alarm rate vs coherent network SNR for the cWB searches targeting un-modeled bursts (black) and binary black holes (red). The results from the low (dashed line) and high (solid line) threshold background runs are presented.

1.2 omicron-LALInferenceBurst (oLIB)

The oLIB pipeline found the event in the *online* analysis with $\log B_{CI} = 14.3$ [10].

This pipeline compares background and injection distributions to construct a log likelihood statistic as a detection statistic, similar in spirit to gstlal-SVD. The log-likelihood for this event is 70. In a study of 10 years of S6 background, the most significant event had a log-likelihood of 30, suggesting that this event is highly significant. High statistics background estimates are challenging for this pipeline due to computational limitations. However, the event is clearly inconsistent with expectations from background in this independent pipeline. This satisfies the Burst group validation procedure.

1.3 BayesWave Burst follow-up of cWB (cWB+BWB)

The BayesWave Burst (BWB) follow-up to this event reported $\log B_{SG} = 34$.

BWB follows up all cWB triggers above a certain ρ threshold, both in the time-slides and zero lag [11]. So far, BWB has followed up 99% of the triggers with $\rho > 8$ in 1500 years of CWB time-slides with playground data, and found a loudest background event of $\log B_{SG} = 17$. BWB will also follow-up all the $\rho > 8$ cWB triggers from the 5,000 year background study using the 5-day data set, when this is available. A study of 10,000 years worth of timeslides of S6D data had a loudest background event of $\log B_{SG} = 22$, suggesting this event is highly significant [12].

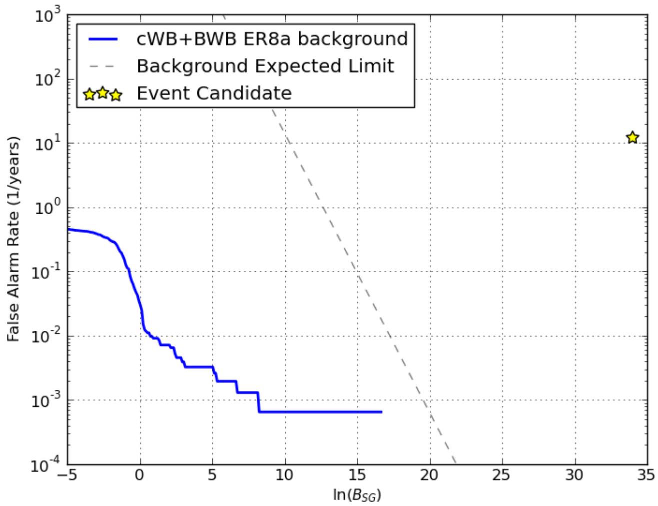

Figure 2: Detection candidate and background estimate in the unmodeled search using cWB+BWB. The background data shown is 1500 years of ER8a "playground" data used for tuning.

1.4 Review status of Burst searches [13]

At the time of this writing:

- **cWB**: changes implemented during the summer are being reviewed, including online versus offline run parameters. The review team is preparing the report [14].
- **oLIB**: the remaining review item is the investigating of discrepancies between the Omicron and Omega pipelines. The review should be able to wrap up in 2-3 weeks [15].
- **BWB**: The code review is signed off [16].

2 Case for detection: CBC Searches

The CBC group analyzes the data for detection with three on-line pipelines (gstlal-SVD, gstlal-SPIIR, MBTA) and and two off-line pipelines (pyCBC and gstlal-SVD). The search targets binary neutron star [17], neutron star-black hole [18], binary black hole [19], and intermediate-mass black hole [20] binaries. The characterization of interesting events is pursued with the Parameter Estimation pipelines which can run on-line with the main purpose of producing reliable skymaps for EM-followup circulars (BAYESTAR, LALInference) and off-line for a complete characterization of an event (LALInference).

2.1 On-line analysis

Reviewed versions of gstlal-SVD and MBTA were running at the time of the event, searching for BNS and NSBH candidates as described in the search plans. Neither pipeline detected it, which is consistent with the limitation of the search space to chirp mass less than 5 $M_\odot$, maximum total mass less than 15 $M_\odot$. The estimated chirp mass and total mass of the event is significantly larger (around 30 $M_\odot$ and 70 $M_\odot$ respectively).

As the event was not detected and no trigger was submitted to graceDB, the BAYESTAR pipeline did not produce a sky-map for this event. The LALInference parameter estimation pipeline was run manually on

Pipeline	Inc. IFAR (yr)	H1 SNR	L1 SNR	Time	mchirp	m1	m2
pycbc	$> 1.069 \times 10^4$	19.71	13.28	1126259462.43	36.4	47.9	36.6
gstlal-SVD	$> 1.263 \times 10^4$	20.08	13.35	1126259462.43	36.4	47.9	36.6

Table 2: Overview of CBC triggers for GW150914.

the time of the trigger as soon as the chirp-like appearance of the candidate was apparent, with initial results documented in section 3.2.

2.2 Off-line analysis

The BNS, NSBH and BBH offline searches are conducted simultaneously by combining the mass space into a single large template bank which is analysed by two separate algorithms, pycbc and gstlal-SVD. The (slight) differences between versions of both pipelines used in the analysis and their latest reviewed releases, are under review at present. The searches were configured with the same template bank, based on the harmonic mean of the power spectra of H1 and L1. It contained 249,077 templates with total mass up to $100\,\mathrm{M}_\odot$, with neutron star spin up to 0.05 and black hole spin up to 0.9895 [21, 22]. TaylorF2 waveforms accurate to third-and-a-half post-Newtonian order were used for templates with $m_1 + m_2 < 4$ and $\mathcal{M} < 1.73$ for pycbc and gstlal-SVD pipelines respectively, while SEOBNRv2_ROM_DoubleSpin waveforms were used for more massive systems [21, 23]. Both searches ran on the same period of data, using the same data quality vetoes, allowing us to easily cross-validate the search results. The period containing the candidate,"ER8b", spanned GPS times 1126051216 to 1127271616), and contained 5.7 days of coincident data over a period of around 14 calendar days.

The candidate event was clearly seen by both search pipelines, and both found the template which best matched the data to have component masses $47.93\,\mathrm{M}_\odot$ and $36.60\,\mathrm{M}_\odot$, with dimensionless spins $c^2J/Gm^2 = 0.96$ and -0.90. The event was louder than all background in the given analysis time, so false alarm rates quoted can only be thought of as bounds, not point estimates. The omega scans generated around the time of the event very clearly show an event and appear to have no obvious glitch-like features, see figure 3. Figure 6 show the best-fitting template reported by the PyCBC search plotted against the $h(t)$ data for each detector, and the residuals when the best-fit template subtracted. Waveforms were generated using the best-fit mass and spin parameters and the template time-of-arrival and gravitational-wave phase as reported by the PyCBC search for each of the L1 and H1 detectors. These data were then subtracted from the strain data to produce residuals for each detector. There is no obvious structure remaining in the residuals, indicating a good fit to the data. The search pipeline triggers are summarised in table 2, with further details of the output of the pipelines given below.

2.3 gstlal-SVD

gstlal-SVD implements the LLOID algorithm described in [24], which uses singular value decomposition and the Nyquist sampling theorem to reduce the computational cost of matched filtering techniques in the time domain. Single IFO triggers are used to estimate the probability density functions (PDFs) describing the background of each sub-bank. These are used to assign likelihood ratios, Λ, [25, 23] to candidate coincident events, which serve as the detection statistic. The events from each bank are merged together and clustered over an 8 second window. The likelihoods are used to assign false alarm rate and probability as described in [26].

gstlal-SVD found the event at 1126259462.4264 a non-extrapolated, bounded FAR that was computed by leaving the event in its own background, this was 2.51×10^{-12} Hz. Trigger details are given in table 2.

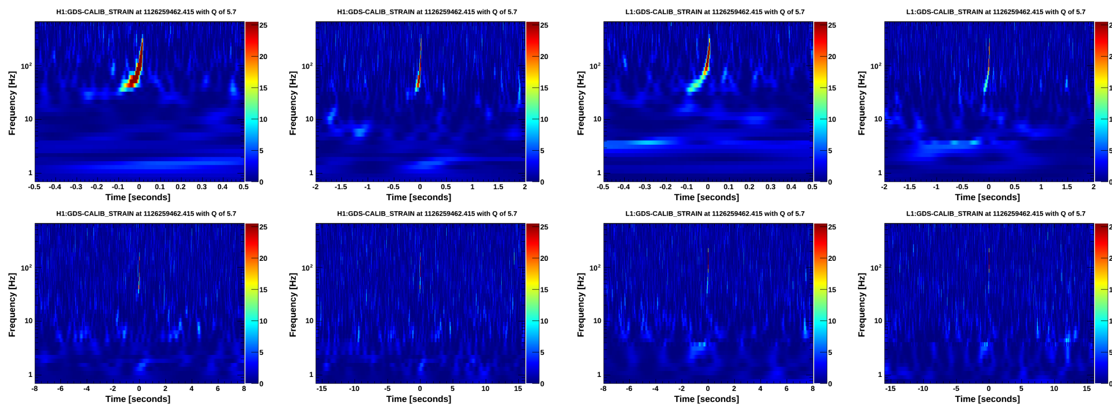

Figure 3: Omega scans for times around the event

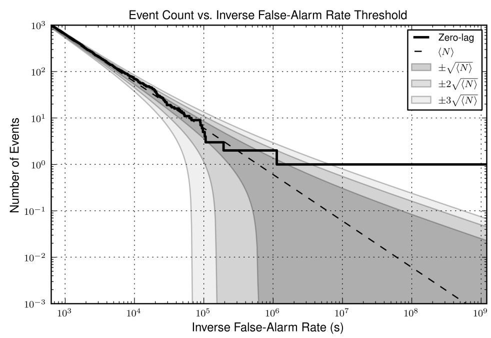

Figure 4: Event Count vs Inverse False-Alarm Threshold from off-line gstlal

The gstlal-SVD search found signal-to-noise ratios $\rho_{H1} = 20.08$, $\rho_{L1} = 13.35$, and $\chi^2_{H1} = 1.04$, and $\chi^2_{L1} = 0.73$. GW150914 stands out clearly in the count vs IFAR plot in figure 4, and has a log likelihood ratio of 76.9. Complete summary pages can be found at [27] and [28].

2.4 pycbc

The pycbc analysis, described in [29, 21], uses a detection statistic "newSNR" based on a tuned combination of matched-filter SNR [30] and the Allen χ^2 statistic[31], designed to exclude transient background glitches which do not resemble gravitational waves. The analysis was devided in three mass bins: *bns*, *bulk* and *edge*, which were determined based on preliminary analysis of ER8 data before the event, in an attempt to separate the different background characteristics in different regions of the mass parameter space.

A clear detection candidate was identified in the *edge* bin, with parameters given in table 2. It was found with a combined newSNR (detection statistic) of 23.56, with a false alarm rate $< 10000^{-1}$ per year, and a false alarm probability $< 1.33 \times 10^{-6}$. The candidate had SNRs $\rho_H = 19.71$, $\rho_L = 13.28$ and χ-squared statistics $\chi^2_H = 1.05$, $\chi^2_L = 0.45$ in H1 and L1 respectively. The candidate event is clearly visible in the plots of foreground and background data. Figure 5 shows the cumulative false alarm rate vs detection statistic, where the candidate is visible as the blue triange at foreground rate ~ 80 per year (inverse of ER8b duration). The background evaluated at the highest estimable value of the detection statistic was $< 10^{-4}$ per year, meaning only a lower limit can be placed on the FAR with the data accumulated in ER8b. Additional data from subsequent O1 time must be used to extend the estimate of the background distribution and improve upon this estimate. Complete open box results can be found at [32].

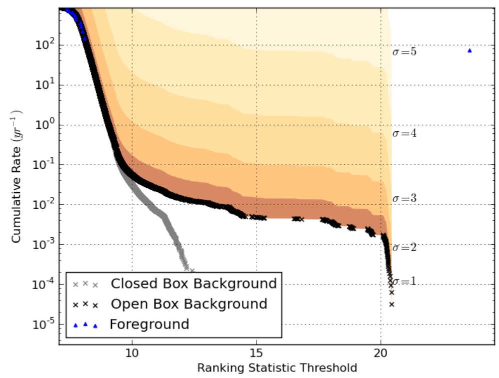

Figure 5: Cumulative Rate vs Ranking Statistics from pyCBC analysis of ER8b.

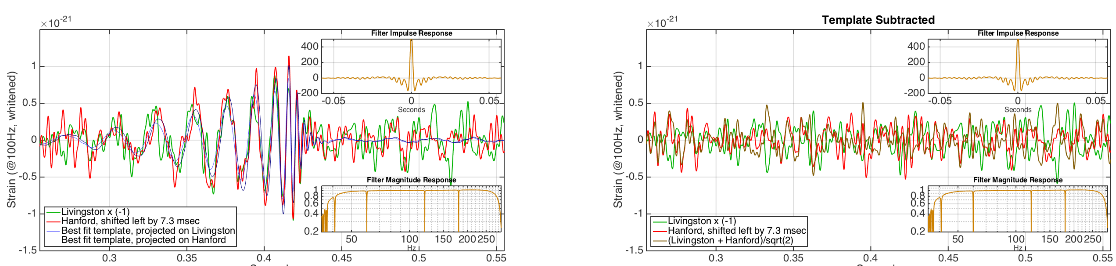

Figure 6: Left: Best fitting template from pycbc search plotted against h(t). Right: Residual data with template subtracted An SEOBNRv2 waveforms was generated using for a source with $m_1 = 47.9 M_\odot, m_2 = 36.6 M_\odot, s_1^z = 0.962, s_2^z = -0.900$. The phase of the coalescence template was set to 0.58 radians (H1) and -2.77 radians (L1), with arrival times of 1126259462.422 (H1) and 1126259462.415 (L1) and an effective distance of 1195 Mpc (H1), and 970 Mpc (L1), as reported by the PyCBC search.

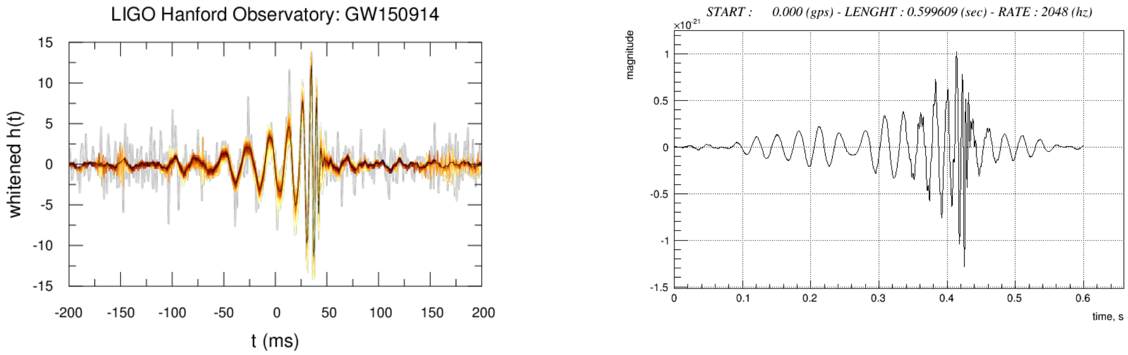

Figure 7: Time-domain reconstructed waveforms in H1 by BWB (left) and cWB (right) for whitened data and strain response, respectively. These time-domain waveforms are constructed without a template bank, and so the fact that they match expectations for a BBH merger is is evidence that this represents an astrophysical source. Comparing waveforms from either pipeline with GR simulations leads to an overlap of greater than 90%. The waveforms used here were generated by GTs Maya code, a version of the Einstein Toolkit. The majority of these simulations were published in [35] and described in Table 1 of that paper. Some were also used and validated in the NRAR and NINJA2 collaborations. The rest were computed in a similar manner.

3 Preliminary results of parameter estimation

3.1 Burst Group

Based on results from Burst group analysis, the following conclusions can be drawn about this source:

- The reconstructed waveform (Figure 7) is consistent with a binary black hole merger. The cWB and BWB waveform overlap with waveforms generated from General Relativity are 92% and 95%, respectively.
- Network SNR: 23 – 24
- Chirp Mass: 25 – 30 $\mathrm{M}_{\odot}$
- Distance: 300 – 450 Mpc
- See references [33, 34] for estimates of component masses and spins.

3.2 CBC Group

Parameter estimation for CBC signals is performed using the LALInference Bayesian parameter estimation code. The version of LALInference used has progressed slightly from the latest reviewed release, but the differences are under review at present. The CBC group has run preliminary analyses of the data around the time of the event using several waveform models, the most relevant being SEOBNRv2_ROM_DoubleSpin and IMRPhenomP. There is strong evidence for a coherent signal: the log Bayes factor between coherent and incoherent inspiral models is in the range $10 - 11$, which is high even by the standards of software injections in Gaussian noise.

The masses and spins of the system have been estimated using several assumptions about the waveform, with an overview posted at [36], and summarised at [37]. The range of parameter estimates are consistent within expectations of variation between models and calibration uncertainty. The system parameters are

- Masses: Chirp mass $27 < \mathcal{M} < 33\,\mathrm{M}_{\odot}$ with 90% confidence. Total mass $65 < M_{total} < 78\,\mathrm{M}_{\odot}$ with 90% confidence. Component masses are comparable, with a heavily correlated error bar which

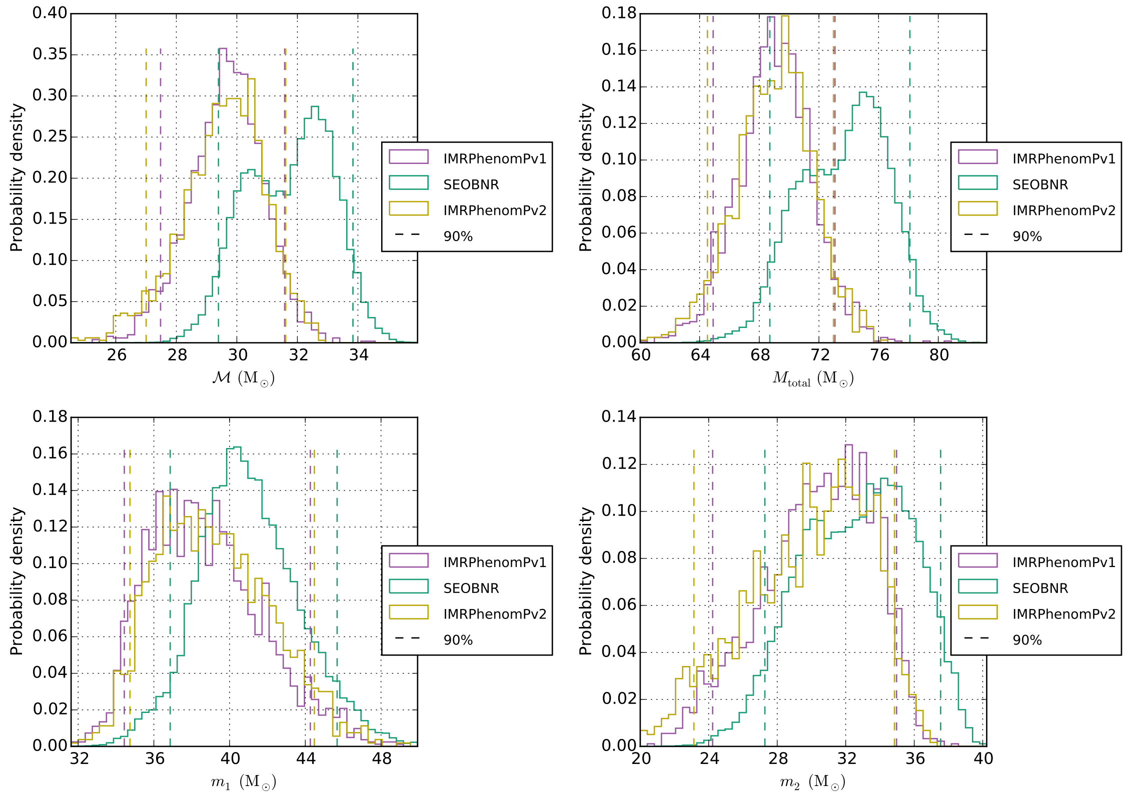

Figure 8: Estimated mass parameters of the system under three different waveform approximants.

includes equal mass systems where $m_1 = m_2 = 36\,\mathrm{M}_\odot$. The one-dimensional marginal distributions are shown in Figure 8. This indicates a binary black hole.

- Distance: Luminosity distance $200 < d_L < 700$ Mpc with 90% confidence.
- Orientation: Appears to be near circularly polarised, i.e. total angular momentum is directed around 0° or 180° from the line of sight.
- Location: In the southern hemisphere, on a ring with time delay of $\approx$ 7 ms between Livingston and Hanford.

We compared the parameter estimates for this event to single-detector triggers classified as chirp-like by detector characterisation, resembling GW150914. We found that the posterior distributions of chirp mass, mass ratio, spins and orientation parameters are distinctly different from that seen for the detection candidate. Posterior distributions tend to be multi-modal, having shapes and peak locations which are not consistent with parameter estimates on the event [38]. This shows that the event is structurally different from the chirp-like glitches.

4 Data quality and environment

While work remains to be done on Detector Characterization items, there is no evidence to date that indicates a non-GW source for the signal seen in GW150914. The survey of possible coherent EM sources of disturbance is the primary outstanding item to be pursued. *Detection Checklist Items 48-92 are in DetChar scope; numbers in parentheses point to this list.*

4.1 General Data Quality

No online vetoes were made of this event from hveto, OVL/iDQ (after removal of a bad channel), or UPV (56). No Auxiliary channels showed unusual behavior (52, 53). Trigger rates from Omicron and Qscans were normal (57, 75, 76). Listening to audio files reveals nothing suspicious (84).

There were no substantial issues noted in the Data Quality (DQ) reports for the time of event (59).

DQ veto definers have been supplied to CBC and Burst for off-line analysis, and all of the appropriate and needed data quality flags applied in the CBC and Burst searches. (50,51). There is no DQ flag of concern that overlaps with the event (82). An initial version of the ER8 flags has been developed covering 12-26 September; the flags are described at [39, 40].

This event does not resemble any known glitch class in either instrument in the epoch of the event (78).

4.2 Specific Data Quality issues

Feature at approximately 500 Hz: There is a 508Hz glitch at the time of the event in H1 which was likely due to a calibration artifact around the violin mode frequencies (83). Frequent glitches at this frequency are seen at 508 Hz, and this may be a normal chance occurrence (90).

Feature at approximately 40 Hz: There are multiple lines at 40.9589, 35.8922, and 36.6998 which beat together leading to a time-varying amplitude at about 40 Hz. It appears this was by chance at a high level at the time of GW150914. CWB sees the signal as coherent at H1 and L1; work ongoing (83).

Search for similar signals in single-ifo coincident data: There are some glitches that bear a resemblance in spectrographs to GW150914 at LLO (look to have an increase in frequency somewhat similar to an inspiral). However, these *chirp like* tracks in spectrograms are not reconstructed as chirps with BayesWave. BayesWave does a phase coherent reconstruction of the entire event, while spectrograms lose the phase information. No glitches in the reconstructed waveforms look sufficiently like a chirp to be confused with one (79).

The time of the event does not line up with a second boundary or have other unique characteristics (48). The event ocurred 2871s after start of segment, 5229s before end, so start/stop transients are not an issue (60).

4.3 Potential sources of single-interferometer glitches at time of GW150914

The overall health and functioning of the Physical Environment Monitor (PEM) is still being checked. Some largely redundant sensors were not operating but the system was sufficiently complete (68, 69, 91). A broad assessment is underway (92). Omega-scan and/or omiscan on RDSs/raw frames and on all available instruments in the network of detectors do not show any disturbances that could have caused this signal (87).

- There are no cosmic ray data for LLO, but the LHO data show no evidence of a mass cosmic ray event near GW150914. Moreover, it seems unlikely that a cosmic ray event would cause a chirp-like signal. (62).
- Wind noise at LHO low, and unlikely to contribute (65).
- No sign of airplanes at the time of the event over the sites were seen. The monitor did not find any evidence of a plane, and visual inspection of the microphones confirm that there is no significant excitation (66).
- Seismic noise was studied in one seismometer per site and found to be quiet at both sites, and unlikely to induce strain artifacts. Follow-up with other seismometers is ongoing (67).

- RF beatnotes at L1 do not appear and are calculated to be distant at time of GW150914. At H1 a full set of omega scans was made around the event. There do appear to be *whistle-like* features in the IMC PZTs, but they have a completely different morphology, and are at higher frequencies than the event itself (72).
- DAC *major carry transition* glitches appear ok (71). We did not find any significant relationship between the DAC crossings and omicron glitches. There were no ADC/DAC saturations at H1; in L1 there were a few overflows that generated triggers within $\pm 100\,\mathrm{s}$ of the event, but not considered problematic (74).
- ESD and Coil Drivers TBD, no problems seen yet, but studies are still in progress (73).

4.4 Potential sources of coincident noise at the two observatories

A study is underway to establish if the PEM system registered anything that could conceivably have caused a correlated event at the sites (92). EM Worldwide activity is being researched and documented as per Big Dog; this is a key remaining DetChar activity.

4.5 Hardware Injections

There were no hardware injections in the days around the event, or at the time of the event, except for CW injections in L1. The injection program at that time had a bug which made small short impulse glitches every 20 seconds. The closest glitch of this kind to the event was more than 4 seconds distant. There were no Stochastic or CW injections that started, stopped, or glitched near to the time of the event (89).

No Blind Injection program was underway; we did not have the technical capability to make a credible blind injection at that time and the channels in question were investigated and found clean. The Photon Calibrator drive and monitor photodiodes show no injected signal at that time. More detail in the Instrument Status section (49) and [3].

Subsequent injections of similar signals lead to correct recovery of the waveform in amplitude and relative phase (61). The SNR is consistent with the GW150914 SNR.

5 Detection Checklist

The Burst, CBC, and DetChar groups separately created detection checklists; some of these had been practiced on injections and previous experience. These were collected into a single spreadsheet, and the redundant or overly general items refined or marked as such.

There were three collaborative one-hour meetings to:

1. refine the questions to make them actionable, clearer, and adding/removing several elements;
2. make assignments to carry out the research needed to develop an answer.

There are a number where progress has been made, and for a number the contributors consider the checklist element successfully addressed. The Detection Committee is in the process of evaluating those, and have signed off on a number of the Detector Characterization elements.

Separate documents have been provided which address questions of Instrument status [3] and the status of the Observatories [4]; in particular, together they indicate that an accidental or *rogue* injection is effectively excluded as an explanation for this signal.

On mechanics: the detection checklist file is a Google spreadsheet, at

`https://docs.google.com/spreadsheets/d/1w-VTSGe_bwt71ar-4W-0du4dq2tiylKZpiYkW7THL5k/edit?usp=sharing`

There is version control. All LVC members may see and may edit this file, using `ligo.org` credentials; it is not open to the public. It is being copied to an Excel File periodically and put in the DCC under LIGO-T1500504 [41] – that file should not be edited.

Conclusion: A general assessment of the Detector Characterization entries, and the intermediate progress on the other entries, shows no evidence that this is a false alarm.

6 Next steps

The Burst, CBC and Detchar group, together with DAC, will continue their work to complete the Detection checklist, review the analyses and finalize parameter estimation and offline background estimates. Also the analysis will be re-run once the final calibration is available. However we believe the case for detection is already strong enough to warrant a transition into Step 2 of the detection procedure.

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